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# EXPONENTIAL FUNCTORS, $R$-MATRICES AND TWISTS 

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#### Abstract

In this paper we show that each polynomial exponential functor on complex finite-dimensional inner product spaces is defined up to equivalence of monoidal functors by an involutive solution to the Yang-Baxter equation (an involutive $R$-matrix), which determines an extremal character on $S_{\infty}$. These characters are classified by Thoma parameters, and Thoma parameters resulting from polynomial exponential functors are of a special kind. Moreover, we show that each $R$-matrix with Thoma parameters of this kind yield a corresponding polynomial exponential functor.

In the second part of the paper we use these functors to construct a higher twist over $S U(n)$ for a localisation of $K$-theory that generalises the one classified by the basic gerbe. We compute the indecomposable part of the rational characteristic classes of these twists in terms of the Thoma parameters of their $R$-matrices.


## 1. Introduction

This paper consists of two parts: In the first part we study exponential functors on the category $\mathcal{V}_{\mathbb{C}}^{\mathrm{Cin}}$ of complex finite-dimensional inner product spaces. Such a functor is defined to be monoidal with respect to the direct sum on the domain and the tensor product on the codomain, i.e. it comes with a natural isomorphism

$$
\tau_{V, W}: F(V \oplus W) \rightarrow F(V) \otimes F(W)
$$

and a corresponding unit isomorphism $\iota: F(0) \rightarrow \mathbb{C}$, such that associativity and unitality conditions hold (see Def. 2.1). A classical example of an exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ is the full exterior algebra $V \mapsto \bigwedge^{*} V$, which is also a polynomial functor in the sense of [20, App. A]. If the domain is restricted to the subgroupoid $\mathcal{V}_{\mathbb{C}}^{\text {iso }} \subset \mathcal{V}_{\mathbb{C}}^{\text {fin }}$, then the top exterior power $V \mapsto \bigwedge^{\text {top }} V$ provides another example.

We employ the theory of polynomial functors developed by Macdonald in $[20$, App. A] to show that isomorphism classes of polynomial exponential functors $\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ correspond to equivalence classes of involutive solutions to the Yang-Baxter equation. On $W \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}\right)$ this equation asks for linear transformations $R: W^{\otimes 2} \rightarrow W^{\otimes 2}$ that satisfy

$$
\left(R \otimes \mathrm{id}_{W}\right)\left(\mathrm{id}_{W} \otimes R\right)\left(R \otimes \mathrm{id}_{W}\right)=\left(\mathrm{id}_{W} \otimes R\right)\left(R \otimes \mathrm{id}_{W}\right)\left(\mathrm{id}_{W} \otimes R\right)
$$

on $W^{\otimes 3}$. Solutions to this equation are called $R$-matrices. If they are involutive (i.e. if they additionally satisfy $R^{2}=\mathrm{id}_{W}$ ), then they give rise to
representations of all symmetric groups $S_{n}$ and to extremal characters of the infinite symmetric group $S_{\infty}$. The group $S_{\infty}$ has infinite conjugacy classes and is therefore not type I. Nevertheless, its extremal characters were fully classified by Thoma in [34] (see also [25, Sec. 2.3]) by the Thoma parameters $\left(\left(\alpha_{i}\right)_{i \in \mathbb{N}},\left(\beta_{j}\right)_{j \in \mathbb{N}}\right)$. These are two sequences of positive real numbers lying in the Thoma simplex $\mathbb{T}$ (see Sec. 2.1.1).

The characters and their Thoma parameters corresponding to $R$-matrices were identified in [19] using subfactor theory. In the current paper we show that each polynomial exponential functor $F$ gives rise to an $R$-matrix acting on the linearisation of $F$, which characterises it up to isomorphism. We also show that the tensor product of exponential functors is linked to the box sum of $R$-matrices defined in [19, Def. 4.1]. It turns out to be more convenient to work with Thoma parameters rescaled by the dimension of the representation as in [19, (4.13)]. We prove:

Theorem 1.1. Let $F: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ be a polynomial exponential functor. Let $\left(F_{n}\right)_{n \in \mathbb{N}}$ be its homogeneous summands. Let $W=F_{1}(\mathbb{C})$. Then there is an involutive solution $R$ : $W^{\otimes 2} \rightarrow W^{\otimes 2}$ to the Yang-Baxter equation associated to $F$ called the $R$-matrix of $F$. It has the following properties:
a) The $R$-matrix determines $F$ up to natural monoidal equivalence (Def. 2.2) of exponential functors (Lem. 2.18).
b) The rescaled Thoma parameters of $R$ are of the form $(0, b)$ for a finite sequence of non-negative integers $b=\left(b_{1}, \ldots, b_{m}\right)$ (Lemma 2.11).
c) For each involutive $R$-matrix $R: W^{\otimes 2} \rightarrow W^{\otimes 2}$ with rescaled Thoma parameters $\left(0,\left(b_{1}, \ldots, b_{m}\right)\right)$ for non-negative integers $b_{i}$, there exists a polynomial exponential functor $F^{R}$ such that its $R$-matrix is $R$ (Thm. 2.17).
d) The rescaled Thoma parameters determine $F$ up to natural equivalence of functors (i.e. neglecting the monoidal transformation, Def. 2.2) and for any choice of parameters as in b) there exists an exponential functor with these parameters (Lem. 2.10, [19, Thm. 4.8] and Thm. 2.15).
e) The $R$-matrix of the tensor product $F \otimes G$ of two exponential functors $F$ and $G$ with associated $R$-matrices $R$ and $S$, respectively, is given by the box-sum $R \boxplus S$ (Thm. 2.14).

Our motivation for viewing exponential functors from this new angle will become clear in the second part of the paper, where they yield the input datum for a construction of higher twists over $S U(n)$ in a localisation of $K$-theory generalising the twist given by the basic gerbe [23, 24].

Twisted $K$-theory first appeared in [11] and is the $K$-theoretic analogue of ordinary cohomology with local coefficients. It associates $K$-groups to a pair consisting of a topological space $X$ and an extra structure over $X$, called a twist, which plays the role of a coefficient bundle. Up to isomorphism the twists in [11] were classified by $H^{1}(X, \mathbb{Z} / 2 \mathbb{Z}) \times \operatorname{Tor}\left(H^{3}(X, \mathbb{Z})\right)$. This was generalised in $[5,6]$ to include non-torsion elements in $H^{3}(X, \mathbb{Z})$. These twists have several geometric interpretations, e.g. in terms of bundles of
compact operators as in $[11,5,6]$ or in terms of (bundle) gerbes [7, 24, 23, 35], which can be viewed as generalisations of line bundles.

Twists over Lie groups gained increasing importance in the subject: By results of Freed, Hopkins and Teleman the equivariant twisted $K$-theory of the group with respect to multiples of the basic gerbe is related to the representation theory of the corresponding free loop group [14, 16, 15]. This result is also closely connected to the modular invariants of rational conformal field theories associated to the loop groups [12].

Looking at the case of non-equivariant twists from a homotopy theoretic viewpoint the appearance of $H^{1}(X, \mathbb{Z} / 2 \mathbb{Z}) \times H^{3}(X, \mathbb{Z})$ is not a surprise. In fact, any $E_{\infty}$-ring spectrum $R$ has a spectrum of units $g l_{1}(R)$ and the first delooping $B G L_{1}(R)$ of its underlying infinite loop space classifies the twists of $R$-theory [4]. For the complex $K$-theory spectrum $K U$ we obtain an equivalence of spaces

$$
B G L_{1}(K U) \simeq K(\mathbb{Z} / 2 \mathbb{Z}, 1) \times B B U_{\otimes}
$$

where the second factor is the delooping of the classifying space of virtual one-dimensional vector bundles with respect to the tensor product. The twists described above are the ones that factor through the natural map from $K(\mathbb{Z} / 2 \mathbb{Z}, 1) \times B B U(1)$ to $B G L_{1}(K U)$. For example, the basic gerbe represents a generator of $H^{3}(S U(n), \mathbb{Z}) \cong[S U(n), B B U(1)] \cong \mathbb{Z}$.

The goal in the second part of this paper is to study a generalisation of this twist. The input datum is an exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ on the groupoid $\mathcal{V}_{\mathbb{C}}^{\text {iso }} \subset \mathcal{V}_{\mathbb{C}}^{\text {in }}$ containing only the unitary isomorphisms as morphisms. The functor $F$ induces an $A_{\infty}$-map $B U_{\oplus} \rightarrow B U_{\otimes}\left[\frac{1}{d}\right]$ for $d=$ $\operatorname{dim}(F(\mathbb{C}))$, which deloops to a map $B B U_{\oplus} \rightarrow B B U_{\otimes}\left[\frac{1}{d}\right]$. This result will be proven via monoidal categories in Sec. 3.1. Another model for $B B U_{\otimes}\left[\frac{1}{d}\right]$ using $\mathcal{I}$-spaces is given in an appendix. The twists $\tau_{F}^{n}$ over $S U(n)$ are then defined as the following compositions

$$
\tau_{F}^{n}: S U(n) \rightarrow S U \simeq B B U_{\oplus} \rightarrow B B U_{\otimes}\left[\frac{1}{d}\right]
$$

where $S U(n) \rightarrow S U$ is the colimit inclusion and $S U \simeq B B U_{\oplus}$ is a consequence of Bott periodicity. The case of the basic gerbe corresponds to the choice $F=\bigwedge^{\text {top }}$. For this functor $d=\operatorname{dim}(F(\mathbb{C}))=1$ and we will see in Thm. 3.10 that it represents a generator of $H^{3}(S U(n), \mathbb{Z}) \subset H^{3}(S U(n), \mathbb{Q})$. This should be compared with the construction of the basic gerbe over $U(n)$ given in [24]. A similar approach to twists of $K_{G}(X)[[t]]$ based on exponential maps has been used in [33, (3.12)]. Instead of an extension by a formal variable $t$ the price to be paid in our approach is that the result will be a twist of the localisation $K U\left[\frac{1}{d}\right]$.

Even though the generalised cohomology theory defined by the infinite loop space $B B U_{\otimes}$ has some subtle features over the integers, its rationalisation $\left(B B U_{\otimes}\right)_{\mathbb{Q}}$ is well-understood. The logarithm composed with the first
delooping of the Chern character induces an equivalence

$$
\left(B B U_{\otimes}\right)_{\mathbb{Q}} \simeq \prod_{k \in \mathbb{N}} K(\mathbb{Q}, 2 k+1)
$$

If we apply the above equivalence to the composition of $\tau_{F}^{n}$ with the canonical map $B B U_{\otimes}\left[\frac{1}{d}\right] \rightarrow\left(B B U_{\otimes}\right)_{\mathbb{Q}}$ we obtain odd degree rational characteristic classes

$$
\delta^{F, n}=\delta_{3}^{F, n}+\delta_{5}^{F, n}+\ldots \quad \in H^{\text {odd }}(S U(n), \mathbb{Q}) \cong \Lambda_{\mathbb{Q}}^{*}\left[a_{3}, a_{5}, \ldots, a_{2 n-1}\right] .
$$

Suppose that $\delta^{F, n}=\sum_{i=1}^{n-1} \kappa_{i} a_{2 i+1}+r$, where $r$ denotes the remainder consisting of all decomposable terms. If $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ is a polynomial exponential functor, then $\kappa_{i}$ can be expressed in terms of the Thoma parameters $\left(b_{1}, \ldots, b_{m}\right)$ associated to the $R$-matrix of $F$. More precisely, it is shown in Thm. 3.8 that $\kappa_{i}$ is the $i$ th coefficient in the Taylor expansion of the function

$$
\kappa(x)=\sum_{j=1}^{m} \log \left(\frac{1+b_{j} e^{x}}{1+b_{j}}\right) .
$$

In particular, it follows that $\tau_{F}^{n}$ in general does not factor through the classifying space of classical twists and therefore is indeed a higher twists.

The twisted $K$-groups for $\tau_{F}^{n}: S U(n) \rightarrow B B U_{\otimes}\left[\frac{1}{d}\right]$ can now be obtained by applying [3, Def. 2.27] to $R=K U\left[\frac{1}{d}\right]$. In joint work with Dadarlat the author also developed an operator algebraic model for twists of this type in $[10,9,27]$. To explain how the current paper fits together with these ideas and how exponential functors come into the game we will end with an outlook on how to represent the twists $\tau_{F}^{n}$ via Fell bundles. This approach is a generalisation of the construction in [27, Rem. 4.4] used to describe twists over suspensions. Fell bundles originated in the theory of $C^{*}$-dynamical systems and can be seen as generalised bundle gerbes with $C^{*}$-correspondences replacing lines. A full description of this construction can be found in [13]. One of its appealing features is that it is equivariant with respect to the adjoint action of $S U(n)$ on itself and therefore provides an equivariant higher twist over $S U(n)$ generalising the one used in [14, 16, 15].
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## 2. Exponential Functors on $\mathcal{V}_{\mathbb{C}}^{\text {fin }}$

Let $\mathcal{V}_{\mathbb{C}}^{\text {in }}$ be the category of finite-dimensional complex inner product vector spaces and linear maps as morphisms. This is a monoidal category in two ways: The direct sum $\oplus$ with the zero vector space as its unit object
provides the first structure, the tensor product $\otimes$ and $\mathbb{C}$ as its unit object the second. Note in particular that both, the direct sum and the tensor product, can be equipped with inner products in a canonical way. Both monoidal structures can be extended to symmetric monoidal ones using the canonical isomorphisms $V \oplus W \rightarrow W \oplus V$ and $V \otimes W \rightarrow W \otimes V$ respectively. However, we will ignore these for now.

Definition 2.1. A triple $(F, \tau, \iota)$ consisting of a functor $F: \mathcal{V}_{\mathbb{C}}^{\text {in }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ and natural unitary isomorphisms $\tau_{V, W}: F(V \oplus W) \rightarrow F(V) \otimes F(W)$ and $\iota: F(0) \rightarrow \mathbb{C}$ is called a (unitary) exponential functor if the following conditions hold:
a) $F$ preserves adjoints, i.e. for all $f: V \rightarrow W$ we have $F\left(f^{*}\right)=F(f)^{*}$.
b) The transformation $\tau$ is associative in the sense that the following diagram commutes:

where we neglected the associators in $\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}, \oplus\right)$ and $\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}, \otimes\right)$ in the notation.
c) The transformation $\iota$ makes the following diagrams commute

in which the unlabelled horizontal arrows are the canonical isomorphisms and the unlabelled vertical isomorphisms are the ones induced by the canonical maps $V \oplus 0 \rightarrow V$ and $0 \oplus V \rightarrow V$.

Equivalently, $F$ is a unitary monoidal functor $F:\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}, \oplus\right) \rightarrow\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}, \otimes\right)$.
The next definition introduces two ways of comparing exponential functors, both of which will become important in the following.

Definition 2.2. Let $F, G: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ be exponential functors. We say that $F$ and $G$ are naturally (unitarily) isomorphic as functors if there exists a natural equivalence given by a unitary isomorphism $v(X): F(X) \rightarrow G(X)$. This will be denoted by $F \sim_{f} G$

We will say that $F$ and $G$ are monoidally isomorphic or naturally isomorphic as monoidal functors if there exists a natural equivalence $v(X)$ as
above which additionally makes the following diagram commute:


We will denote this by $F \sim_{\otimes} G$.
The following definition is taken from [20, Appendix A, Def. 1.1].
Definition 2.3. A functor $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ is called polynomial if for each pair of vector spaces $V, W$ and $n$-tuple of linear maps $f_{1}, \ldots, f_{n}: V \rightarrow W$ the linear transformation

$$
F\left(\lambda_{1} f_{1}+\cdots+\lambda_{n} f_{n}\right): F(V) \rightarrow F(W)
$$

is a polynomial in the variables $\lambda_{1}, \ldots, \lambda_{n} \in \mathbb{C}$ with coefficients in the vector space of linear maps $\operatorname{hom}\left(F(V), F(W)\right.$ ) (depending on $f_{1}, \ldots, f_{n}$ ). If $F\left(\lambda_{1} f_{1}+\cdots+\lambda_{n} f_{n}\right)$ is homogeneous of degree $n$ for all choices of $f_{1}, \ldots, f_{n}$, then $F$ is called homogeneous of degree $n$ as well.

It is shown in [20, Appendix A, Sec. 2] that any polynomial functor decomposes into a direct sum of homogeneous functors. We briefly recall how this is done: By assumption the image of the multiplication operator $\lambda \mathrm{id}_{V}: V \rightarrow V$ under $F$ can be decomposed as follows

$$
F\left(\lambda \mathrm{id}_{V}\right)=\sum_{n \in \mathbb{N}_{0}} u_{n}(V) \lambda^{n}
$$

with only finitely many nonzero coefficients $u_{n}(V)$. The functor properties imply that the linear maps $u_{n}(V) \in \operatorname{End}(F(V))$ are idempotents, which add up to $\operatorname{id}_{F(V)}$ and satisfy $u_{n}(V) u_{m}(V)=0$ for $n \neq m$. Let $F_{n}(V)$ be the image of $u_{n}(V)$. Then we have a direct sum decomposition

$$
F(V)=\bigoplus_{n \in \mathbb{N}_{0}} F_{n}(V)
$$

Let $f: V \rightarrow W$ be a linear transformation. Linearity implies $f \circ\left(\lambda \mathrm{id}_{V}\right)=$ $\left(\lambda \operatorname{id}_{W}\right) \circ f$, which yields $F(f) u_{n}(V)=u_{n}(W) F(f)$. Thus, the association $V \mapsto F(V)$ restricts to a collection of functors $V \mapsto F_{n}(V)$, in which $F_{n}$ is homogeneous of degree $n$, and this collection satisfies

$$
F \cong \bigoplus_{n \in \mathbb{N}_{0}} F_{n}
$$

where the natural isomorphism is induced by the inclusion and projection maps $F_{n}(V) \rightarrow F(V)$ and $F(V) \rightarrow F_{n}(V)$.

If $F$ preserves adjoints, then the decomposition of $F$ into its homogeneous components $F_{n}$ is orthogonal, since $F\left(f^{*}\right)=F(f)^{*}$ implies

$$
F\left(\lambda \operatorname{id}_{V}\right)=F\left(\bar{\lambda} \operatorname{id}_{V}\right)^{*}=\sum_{n \in \mathbb{N}_{0}}\left(u_{n}(V) \bar{\lambda}^{n}\right)^{*}=\sum_{n \in \mathbb{N}_{0}} u_{n}(V)^{*} \lambda^{n}
$$

which yields that $u_{n}(V)=u_{n}(V)^{*}=u_{n}(V)^{2}$ are orthogonal projections for all $n \in \mathbb{N}_{0}$ and $V \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\text {fin }}\right)$.

Lemma 2.4. Let $F: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ be a polynomial unitary exponential functor and let $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$ be its decomposition into homogeneous components as explained above. Then the isomorphisms $\tau_{V, W}$ restrict to natural unitary isomorphisms

$$
\tau_{V, W}^{n}: F_{n}(V \oplus W) \rightarrow \bigoplus_{i+j=n} F_{i}(V) \otimes F_{j}(W) .
$$

Proof. Note that $\lambda \operatorname{id}_{V \oplus W}=\lambda \operatorname{id}_{V} \oplus \lambda \mathrm{id}_{W}$. Since $\tau_{V, W}$ is natural in $V$ and $W$, the following diagram commutes:


Comparing the coefficients of the resulting polynomials we obtain

$$
\tau_{V, W} \circ u_{n}(V \oplus W)=\sum_{i+j=n}\left(u_{i}(V) \otimes u_{j}(W)\right) \circ \tau_{V, W}
$$

where $\left(u_{k}(X)\right)_{k \in \mathbb{N}_{0}}$ are the idempotents inducing the direct sum decomposition of $F(X)$ as above. Observe that $\left(u_{i_{1}}(V) \otimes u_{j_{1}}(W)\right)\left(u_{i_{2}}(V) \otimes u_{j_{2}}(W)\right)=0$ unless $i_{1}=i_{2}$ and $j_{1}=j_{2}$. Since $F_{k}(X)$ was defined to be the image of $u_{k}(X)$, this implies that $\tau_{V, W}^{n}$ restricts to a well-defined homomorphism $\tau_{V, W}^{n}: F_{n}(V \oplus W) \rightarrow \bigoplus_{i+j=n} F_{i}(V) \otimes F_{j}(W)$. A similar argument shows that $\tau_{V, W}^{-1}$ restricts to an inverse of $\tau_{V, W}^{n}$ proving that the latter is an isomorphism. Since $\tau_{V, W}^{n}$ is a restriction of a unitary map, it preserves inner products and hence is a unitary isomorphism itself.

Recall the definition of the linearization from [20, Appendix A, Sec. 3]. Let $F_{n}: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be a homogeneous polynomial functor of degree $n$. Let $V=V_{1} \oplus \cdots \oplus V_{n}$ and $M_{\lambda_{1}, \ldots, \lambda_{n}}: V \rightarrow V$ be the linear map that multiplies by $\lambda_{i}$ on $V_{i}$. Using a similar argument as above, we obtain a direct sum decomposition

$$
F_{n}\left(V_{1} \oplus \cdots \oplus V_{n}\right)=\bigoplus_{i_{1}+\cdots+i_{n}=n} F_{i_{1}, \ldots, i_{n}}\left(V_{1}, \ldots, V_{n}\right)
$$

where $F_{i_{1}, \ldots, i_{n}}\left(V_{1}, \ldots, V_{n}\right)$ is fixed by the property that $F_{n}\left(M_{\lambda_{1}, \ldots, \lambda_{n}}\right)$ acts on it by multiplication by $\lambda_{1}^{i_{1}} \cdots \lambda_{n}^{i_{n}}$. In particular, the linearization of $F_{n}$ is given by the functor $L_{F_{n}}\left(V_{1}, \ldots, V_{n}\right)=F_{1, \ldots, 1}\left(V_{1}, \ldots, V_{n}\right)$, i.e. it is the natural direct summand of $F_{n}\left(V_{1} \oplus \cdots \oplus V_{n}\right)$, on which $F_{n}\left(M_{\lambda_{1}, \ldots, \lambda_{n}}\right)$ acts via multiplication by $\lambda_{1} \cdots \lambda_{n}$.

Lemma 2.5. Let $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be a polynomial exponential functor and let $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$ be its decomposition into homogeneous components. For $n \geq 1$ the linearization of $F_{n}$ is naturally isomorphic to the functor

$$
L_{n}\left(V_{1}, \ldots, V_{n}\right)=F_{1}\left(V_{1}\right) \otimes \cdots \otimes F_{1}\left(V_{n}\right) .
$$

Proof. By Lemma 2.4 we can decompose $F_{n}\left(V_{1} \oplus \cdots \oplus V_{n}\right)$ using the natural isomorphisms $\tau_{V_{1}, V_{2} \oplus \cdots \oplus V_{n}}^{k_{1}}, \tau_{V_{2}, V_{3} \oplus \cdots \oplus V_{n}}^{k_{2}}, \ldots \tau_{V_{n-1}, V_{n}}^{k_{n-1}}$ as follows

$$
F_{n}\left(V_{1} \oplus \cdots \oplus V_{n}\right) \cong \bigoplus_{i_{1}+\cdots+i_{n}=n} F_{i_{1}}\left(V_{1}\right) \otimes \cdots \otimes F_{i_{n}}\left(V_{n}\right) .
$$

Naturality of the above decomposition implies that $F_{n}\left(M_{\lambda_{1}, \ldots, \lambda_{n}}\right)$ acts via multiplication by $\lambda_{1}^{i_{1}} \cdots \lambda_{n}^{i_{n}}$ on the summand $F_{i_{1}}\left(V_{1}\right) \otimes \cdots \otimes F_{i_{n}}\left(V_{n}\right)$. Therefore the natural isomorphism used to obtain the decomposition identifies the linearization of $F_{n}$ with the functor $\left(V_{1}, \ldots, V_{n}\right) \mapsto F_{1}\left(V_{1}\right) \otimes \cdots \otimes F_{1}\left(V_{n}\right)$.

Remark 2.6. By [20, p. 150, Rem. 2] we have that for any polynomial functor $F$ with homogeneous components $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$ all objects $F_{0}(V)$ (i.e. the "constant terms") are canonically isomorphic to $F_{0}(0)$. For an exponential polynomial functor the unit transformation $\iota$ from Def. 2.1 identifies $F_{0}(0)$ with $F(0) \cong \mathbb{C}$. Thus, the above theorem is still true for $n=0$ if we define $L_{0}$ to be the functor from the trivial category on one object to $\mathcal{V}_{\mathbb{C}}^{\text {in }}$ mapping the object to $\mathbb{C}$.
2.1. The $R$-matrix of an exponential functor. Consider a polynomial exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ with homogeneous components $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$. Note that the permutation group $S_{n}$ acts unitarily on $V^{n}=V \oplus \cdots \oplus V$ by permuting the summands. Therefore it also acts on $F_{n}(V \oplus \cdots \oplus V)$ by unitary transformations. We will denote this representation by $\eta$. If $M_{\lambda_{1}, \ldots, \lambda_{n}}$ denotes the multiplication operator defined above and $\sigma \in S_{n}$, then the following diagram commutes


In particular, the linear map $\eta(\sigma)$ restricts to a unitary automorphism of the linearization $L_{F_{n}}(V, \ldots, V)$. Using Lemma 2.5 we obtain a unitary representation $\rho^{(n)}$ of $S_{n}$ on $L_{n}(\mathbb{C}, \ldots, \mathbb{C})$. Let $W=F_{1}(\mathbb{C})$ and consider the unitary automorphism $R: W \otimes W \rightarrow W \otimes W$ representing the nontrivial element $\tau \in S_{2}$ on $L_{2}(\mathbb{C}, \mathbb{C})$. Denote by $R_{i}: W^{\otimes k} \rightarrow W^{\otimes k}$ for $1 \leq i \leq k-1$ the linear map

$$
R_{i}=\mathrm{id}_{W^{\otimes(i-1)}} \otimes R \otimes \mathrm{id}_{W^{\otimes(k-i-1)}}
$$

i.e. it coincides with $R$ on the $i$ th and $(i+1)$ st tensor factor of $W^{\otimes k}$.

Lemma 2.7. Let $n \in \mathbb{N}$ and let $\tau_{i} \in S_{n}$ for $i \in\{1, \ldots, n-1\}$ be the transposition of the ith and $(i+1)$ st element. Let $W=F_{1}(\mathbb{C})$ and let $\rho^{(n)}: S_{n} \rightarrow U\left(W^{\otimes n}\right)$ be the representation defined above. Then

$$
\rho^{(n)}\left(\tau_{i}\right)=R_{i} .
$$

In particular, the linear map $R$ satisfies $R^{2}=\mathrm{id}_{W \otimes W}$ and the Yang-Baxter equation

$$
R_{1} R_{2} R_{1}=R_{2} R_{1} R_{2} .
$$

Proof. Let $\eta_{n}$ be the representation of $S_{n}$ on $F_{n}(\mathbb{C} \oplus \cdots \oplus \mathbb{C})$ as defined above. The transposition $\tau_{i}$ interchanges the $i$ th and the $(i+1)$ st summand and acts as the identity on all other summands. Since the projection $F_{n}(\mathbb{C}, \ldots, \mathbb{C}) \rightarrow L_{n}(\mathbb{C}, \ldots, \mathbb{C})$ and inclusion $L_{n}(\mathbb{C}, \ldots, \mathbb{C}) \rightarrow F_{n}(\mathbb{C}, \ldots, \mathbb{C})$ are natural transformations, it follows that $\rho^{(n)}\left(\tau_{i}\right)$ acts trivially on all tensor factors except for the $i$ th and $(i+1)$ st. To describe the action on these factors observe that

$$
F_{1}(\mathbb{C})^{\otimes(i-1)} \otimes F_{2}(\mathbb{C} \oplus \mathbb{C}) \otimes F_{1}(\mathbb{C})^{\otimes(n-i-1)}
$$

is isomorphic to a natural direct summand of $F_{n}(\mathbb{C} \oplus \cdots \oplus \mathbb{C})$ using the same method applied in the proof of Lemma 2.5. Restricted to this summand $\eta_{n}\left(\tau_{i}\right)$ agrees with $\operatorname{id}_{F_{1}(\mathbb{C})^{\otimes(i-1)}} \otimes \eta_{2}(\tau) \otimes \operatorname{id}_{F_{1}(\mathbb{C})^{\otimes(n-i-1)}}$, where $\tau \in S_{2}$ denotes the nontrivial element. Thus, if we restrict further to $F_{1}(\mathbb{C})^{\otimes n}$ we see that $\rho^{(n)}\left(\tau_{i}\right)$ agrees with $R_{i}$. This also implies that the stated relations hold, since they are satisfied by the generators $\tau_{i} \in S_{n}$.

The last lemma shows that polynomial exponential functors naturally give rise to unitary involutive $R$-matrices. These were studied in [19] up to the first of the following two equivalence relations:

Definition 2.8. Two unitary involutive $R$-matrices $R: W_{R}^{\otimes 2} \rightarrow W_{R}^{\otimes 2}$ and $S: W_{S}^{\otimes 2} \rightarrow W_{S}^{\otimes 2}$ are called (unitarily) equivalent if the associated representations $\rho_{R}^{(n)}: S_{n} \rightarrow U\left(W_{R}^{\otimes n}\right)$ and $\rho_{S}^{(n)}: S_{n} \rightarrow U\left(W_{S}^{\otimes n}\right)$ are unitarily equivalent for all $n \in \mathbb{N}$. We will denote this by $R \sim_{u} S$.

Two $R$-matrices as above will be called strongly equivalent if they are equivalent in the sense of the last definition and the unitary intertwiner $v_{n}: W_{R}^{\otimes n} \rightarrow W_{S}^{\otimes n}$ between $\rho_{R}^{(n)}$ and $\rho_{S}^{(n)}$ can be chosen to be of the form

$$
v_{n}=v_{1} \otimes \cdots \otimes v_{1}
$$

for a unitary isomorphism $v_{1}: W_{R} \rightarrow W_{S}$. Since this relation will be seen to be closely related to monoidal equivalence of exponential functors, we will denote it by $R \sim \otimes S$.

The following was proven in [20, Appendix A, Thm. 5.3] and provides a complete classification of homogeneous polynomial functors in terms of representations of permutation groups.

Theorem 2.9. Let $F_{n}$ be a homogeneous polynomial functor of degree $n$ with linearization $L_{F_{n}}$. Then there exists a natural isomorphism of functors

$$
F_{n}(V) \cong\left(L_{F_{n}}(\mathbb{C}, \ldots, \mathbb{C}) \otimes V^{\otimes n}\right)^{S_{n}}
$$

where $S_{n}$ acts on $L_{F_{n}}(\mathbb{C}, \ldots, \mathbb{C})$ via the representation induced by permuting the summands of $\mathbb{C} \oplus \cdots \oplus \mathbb{C}$ as described above and on $V^{\otimes n}$ by permuting the tensor factors.

We will use the above theorem to identify isomorphism classes of polynomial exponential functors with equivalence classes of $R$-matrices. The first step is to show the compatibility of the various equivalence relations. We will start by comparing $\sim_{f}$ and $\sim_{u}$ in the next lemma and defer the comparison of the monoidal equivalences to the end of the next section.

Lemma 2.10. Let $F, G: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be polynomial exponential functors. Let $R, S$ be the $R$-matrices associated to $F$ and $G$ respectively. Then

$$
F \sim_{f} G \quad \Leftrightarrow \quad R \sim_{u} S .
$$

Proof. First suppose that $F \sim_{f} G$ and let $v(X): F(X) \rightarrow G(X)$ be a unitary isomorphism between $F$ and $G$. Let $u_{n}^{F}(X), u_{n}^{G}(X)$ be the orthogonal projections appearing as coefficients of $\lambda^{n}$ in $F\left(\lambda \mathrm{id}_{X}\right), G\left(\lambda \mathrm{id}_{X}\right)$, respectively. By naturality the following diagram commutes

and a comparison of coefficients implies that $v(X) u_{n}^{F}(X)=u_{n}^{G}(X) v(X)$. Thus, $v(X)$ restricts to natural unitary isomorphisms

$$
v_{n}(X): F_{n}(X) \rightarrow G_{n}(X)
$$

of the homogeneous summands of degree $n$. Now fix $n \in \mathbb{N}$ and consider the operator $M_{\lambda_{1}, \ldots, \lambda_{n}}: V \oplus \cdots \oplus V \rightarrow V \oplus \cdots \oplus V$ as above. Naturality implies that the following diagram commutes as well:

$$
\begin{aligned}
& \quad F_{n}(V \oplus \cdots \oplus V) \xrightarrow{v_{n}(V \oplus \cdots \oplus V)} G_{n}(V \oplus \cdots \oplus V) \\
& F_{n}\left(M_{\left.\lambda_{1}, \ldots, \lambda_{n}\right)} \downarrow\right. \\
& \quad F_{n}(V \oplus \cdots \oplus V) \xrightarrow[v_{n}(V \oplus \cdots \oplus V)]{ }{ }^{(V)} G_{n}(V \oplus \cdots \oplus V)
\end{aligned}
$$

and in particular $v_{n}(\mathbb{C} \oplus \cdots \oplus \mathbb{C})$ restricts to a unitary isomorphism $v_{n}^{L}$ of the linearizations of $F$ and $G$, i.e.

$$
v_{n}^{L}: L_{F_{n}}(\mathbb{C}, \ldots, \mathbb{C}) \rightarrow L_{G_{n}}(\mathbb{C}, \ldots, \mathbb{C})
$$

Let $W_{R}=F_{1}(\mathbb{C})$ and $W_{S}=G_{1}(\mathbb{C})$. By Lemma 2.5 the linearizations can be identified with $L_{n}^{F}(\mathbb{C}, \ldots, \mathbb{C})=W_{R}^{\otimes n}$ and $L_{n}^{G}(\mathbb{C}, \ldots, \mathbb{C})=W_{S}^{\otimes n}$, respectively. Let $v_{n}^{R, S}: W_{R}^{\otimes n} \rightarrow W_{S}^{\otimes n}$ be the unitary corresponding to $v_{n}^{L}$ under this identification. A similar argument as above shows that $v_{n}^{R, S}$ intertwines the two representations $\rho_{R}^{(n)}: S_{n} \rightarrow U\left(W_{R}^{\otimes n}\right)$ and $\rho_{S}^{(n)}: S_{n} \rightarrow U\left(W_{S}^{\otimes n}\right)$ for each $n \in \mathbb{N}$, since these are induced by the isomorphism permuting the summands of $V \oplus \cdots \oplus V$. Hence, $R \sim_{u} S$.

To prove the other direction let $W_{R}=F_{1}(\mathbb{C}), W_{S}=G_{1}(\mathbb{C})$ and assume that $R \sim_{u} S$. Let $v_{n}: W_{R}^{\otimes n} \rightarrow W_{S}^{\otimes n}$ be the isometric intertwiner between the representations $\rho_{R}^{(n)}$ and $\rho_{S}^{(n)}$. By Thm. 2.9 there are natural isomorphisms

$$
\begin{align*}
& F_{n}(V) \cong\left(W_{R}^{\otimes n} \otimes V^{\otimes n}\right)^{S_{n}} \\
& G_{n}(V) \cong\left(W_{S}^{\otimes n} \otimes V^{\otimes n}\right)^{S_{n}} \tag{1}
\end{align*}
$$

where $S_{n}$ acts on $W_{R}^{\otimes n}, W_{S}^{\otimes n}$ via $\rho_{R}^{(n)}, \rho_{S}^{(n)}$, respectively. Therefore $v_{n}$ induces a natural unitary isomorphism $v_{n}(V): F_{n}(V) \rightarrow G_{n}(V)$. Since $F(V) \cong \bigoplus_{n \in \mathbb{N}_{0}} F_{n}(V)$ and similarly for $G$, this isomorphism extends to a natural unitary isomorphism between $F$ and $G$. Thus, $F \sim_{f} G$, which finishes the proof of the statement.
2.1.1. Thoma parameters. Denote by $S_{\infty}$ the infinite symmetric group, i.e. the union over all $S_{n}$ with respect to the inclusions $S_{n} \rightarrow S_{n+1}$ induced by permuting the first $n$ elements of $\{1, \ldots, n+1\}$. The elements of $S_{\infty}$ are precisely all permutations of $\mathbb{N}$ with finite support. Let $\tau_{n}: M_{d}(\mathbb{C})^{\otimes n} \rightarrow \mathbb{C}$ be the normalised trace. Let $\chi_{R}^{(n)}: S_{n} \rightarrow \mathbb{C}$ be defined by $\chi_{R}^{(n)}=\tau_{n} \circ \rho_{R}^{(n)}$. Then $\chi_{R}^{(n+1)}$ restricts to $\chi_{R}^{(n)}$ on $S_{n}$. Thus, the sequence $\left(\chi_{R}^{(n)}\right)_{n \in \mathbb{N}}$ gives rise to a character $\chi_{R}: S_{\infty} \rightarrow \mathbb{C}$. It turns out that $\chi_{R}$ belongs to the class of extremal characters on $S_{\infty}$. These were classified by Thoma [34]: Let $\mathbb{T}$ denote the collection of all sequences $\left\{\alpha_{i}\right\}_{i \in \mathbb{N}},\left\{\beta_{i}\right\}_{i \in \mathbb{N}}$ of real numbers with the following properties
i) $\alpha_{i} \geq 0$ and $\beta_{i} \geq 0$,
ii) $\alpha_{i} \geq \alpha_{i+1}$ and $\beta_{i} \geq \beta_{i+1}$,
iii) $\sum_{i} \alpha_{i}+\sum_{j} \beta_{j} \leq 1$.

Then the extremal characters $\chi$ are in 1:1-correspondence with the elements of $\mathbb{T}$. On an $n$-cycle $c_{n} \in S_{\infty}$ for $n \geq 2$ the character $\chi$ corresponding to $\left(\left(\alpha_{i}\right)_{i \in \mathbb{N}},\left(\beta_{i}\right)_{i \in \mathbb{N}}\right)$ takes the value

$$
\chi\left(c_{n}\right)=\sum_{i} \alpha_{i}^{n}+(-1)^{n+1} \sum_{i} \beta_{i}^{n} .
$$

We will call the pair $\left(\left(\alpha_{i}\right)_{i \in \mathbb{N}},\left(\beta_{i}\right)_{i \in \mathbb{N}}\right)$ the Thoma parameters of $\chi$. The two characters $\chi_{R}$ and $\chi_{S}$ associated to the two $R$-matrices $R$ and $S$ agree if and only if $\operatorname{dim}\left(W_{R}\right)=\operatorname{dim}\left(W_{S}\right)$ and $R \sim_{u} S$ (see Def. 2.8).

The main result of [19] states that the characters $\chi_{R}$ are parametrised by Thoma parameters that lie in the following subspace
i) only finitely many $\alpha_{i}, \beta_{i}$ are non-zero,
ii) all $\alpha_{i}$ and $\beta_{i}$ are rational,
iii) $\sum_{i} \alpha_{i}+\sum_{j} \beta_{j}=1$.

Since we consider exponential functors $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$, finite-dimensionality imposes a constraint that has consequences for the possible Thoma parameters of $\chi_{R}$ for the $R$-matrix associated to $F$.
Lemma 2.11. Let $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be a polynomial exponential functor, let $W=F_{1}(\mathbb{C})$ and let $R: W \otimes W \rightarrow W \otimes W$ be the $R$-matrix associated to $F$. Then the Thoma parameters of the extremal character $\chi_{R}$ associated to $R$ satisfy the following conditions:
a) all $\alpha_{i}=0$,
b) only finitely many $\beta_{j}$ are non-zero, rational and add up to 1 .

Proof. Part b) of the statement is clear from the classification of extremal characters arising from unitary involutive $R$-matrices. Thus, it remains to prove part a). Since $F(\mathbb{C})$ is finite-dimensional, only finitely many summands in its homogeneous decomposition are nonzero. Let $N \in \mathbb{N}$ have the property that $F_{k}(\mathbb{C})=0$ for all $k \geq N$. By Thm. 2.9 the dimension of the space $F_{m}(\mathbb{C})$ agrees with the multiplicity of the trivial representation $\iota_{\mathbb{C}}: S_{m} \rightarrow U(1)$ in $\rho_{R}^{(m)}$. Denote by $\langle\lambda, \rho\rangle$ the multiplicity of the irreducible representation $\lambda$ of $S_{n}$ in the representation $\rho$. By the considerations above we conclude that

$$
\left\langle\iota \mathbb{C}, \rho_{R}^{(m)}\right\rangle=0
$$

for all $m \geq N$. It was shown in [19, Prop. 5.7] that this condition holds if and only if the Young diagram of $\iota$ contains a rectangle of height $\ell(\alpha)+1$ and width $\ell(\beta)+1$, where $\ell(\alpha)$ and $\ell(\beta)$ are the numbers of nonzero $\alpha_{i}$ and $\beta_{i}$, respectively. The Young diagram of the trivial representation $\iota$ of $S_{m}$ is a rectangle of height 1 and width $m$. In particular, we must have $\ell(\alpha)=0$.

The Thoma parameters do not take into account the dimension $d_{R}=$ $\operatorname{dim}(W)$ of the vector space the $R$-matrix acts on. Thus, it is often more convenient to work with the rescaled Thoma parameters

$$
a_{i}=d_{R} \alpha_{i} \quad, \quad b_{i}=d_{R} \beta_{i} .
$$

By [19, Thm. 3.6] these are natural numbers with the property that $R \sim_{u} S$ if and only if the rescaled Thoma parameters of $R$ and $S$ agree [19, Thm. 4.8].
2.2. Classification of exponential functors. In the following we will give examples of polynomial exponential functors $F^{W}$ (depending on a vector space $W$ ), which have rescaled Thoma parameters $\left(0, b_{1}\right)$ for any $b_{1} \in \mathbb{N}$. Afterwards we extend this to exhaust the list of all possible Thoma parameters discovered in Lemma 2.11.

Observe that the exterior algebra functor $V \mapsto \bigwedge^{*}(V)$ is polynomial and exponential. We will examine a modified version of it defined as follows: Fix a finite-dimensional inner product space $W$ and consider the functor

$$
\begin{equation*}
F^{W}(V)=\bigoplus_{k=0}^{\infty} W^{\otimes k} \otimes \bigwedge^{k}(V) \tag{2}
\end{equation*}
$$

where we define $W^{\otimes 0}=\mathbb{C}$. Since $\bigwedge^{k}(V)=0$ for $k>\operatorname{dim}(V)$, the sum is actually finite and the functor $F^{W}: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ is well-defined. It is also a polynomial functor with homogeneous components

$$
F_{k}^{W}(V)=W^{k} \otimes \bigwedge^{k}(V)
$$

since $V \mapsto \bigwedge^{k}(V)$ is homogeneous of degree $k$. Observe that there is a natural equivalence

$$
\begin{aligned}
F_{k}^{W}\left(V_{1} \oplus V_{2}\right) & =W^{\otimes k} \otimes \bigwedge^{k}\left(V_{1} \oplus V_{2}\right) \\
& \cong \bigoplus_{i+j=k}\left(W^{\otimes i} \otimes \bigwedge^{i} V_{1}\right) \otimes\left(W^{\otimes j} \otimes \bigwedge^{j} V_{2}\right) \\
& =\bigoplus_{i+j=k} F_{i}^{W}\left(V_{1}\right) \otimes F_{j}^{W}\left(V_{2}\right)
\end{aligned}
$$

where the second line follows from the first by applying the isomorphism $\bigwedge^{k}\left(V_{1} \oplus V_{2}\right) \cong \bigoplus_{i+j=k} \bigwedge^{i} V_{1} \otimes \bigwedge^{j} V_{2}$ and then interchanging $W^{\otimes j}$ with $\bigwedge^{i} V_{1}$. Moreover, there is a natural isomorphism $F^{W}(0) \cong \mathbb{C}$. We can extend these identifications to natural unitary isomorphisms

$$
\tau_{V_{1}, V_{2}}: F^{W}\left(V_{1} \oplus V_{2}\right) \rightarrow F^{W}\left(V_{1}\right) \otimes F^{W}\left(V_{2}\right)
$$

and $\iota: F^{W}(0) \rightarrow \mathbb{C}$, which satisfy the associativity and unitality conditions in Def. 2.1 and therefore turn $F^{W}$ into a polynomial exponential functor. The linearization of $F^{W}$ can now be read off from Lemma 2.5 and is naturally equivalent to

$$
\begin{aligned}
L_{n}\left(V_{1}, \ldots, V_{n}\right) & \cong F_{1}^{W}\left(V_{1}\right) \otimes \cdots \otimes F_{1}^{W}\left(V_{n}\right) \cong W \otimes V_{1} \otimes \cdots \otimes W \otimes V_{n} \\
& \cong W^{\otimes n} \otimes V_{1} \otimes \cdots \otimes V_{n}
\end{aligned}
$$

To understand the $R$-matrix $R: W^{\otimes 2} \rightarrow W^{\otimes 2}$ we have to look at the $S_{2}=$ $\mathbb{Z} / 2 \mathbb{Z}$-action on the space

$$
F_{2}^{W}(\mathbb{C} \oplus \mathbb{C})=W^{\otimes 2} \otimes \bigwedge^{2}(\mathbb{C} \oplus \mathbb{C})
$$

induced by interchanging the two summands of $\mathbb{C} \oplus \mathbb{C}$. On the top degree summand of $\bigwedge^{2}(\mathbb{C} \oplus \mathbb{C})$ this transposition corresponds to multiplication by $(-1)$. Thus, the $R$-matrix is given by $-\mathrm{id}_{W \otimes W}$. Using [19, Thm. 4.8] we compute the Thoma parameters of the $R$-matrix of $F^{W}$ to be $(0, \operatorname{dim}(W))$. We summarise these results in the next lemma:

Lemma 2.12. The functor $F^{W}$ defined in (2) is polynomial and exponential with respect to the unitary natural isomorphisms $\tau$ and $\iota$ defined above. The linearization of $F^{W}$ is naturally equivalent to $L_{n}^{W}$ with

$$
L_{n}^{W}\left(V_{1}, \ldots, V_{n}\right)=W^{\otimes n} \otimes V_{1} \otimes \cdots \otimes V_{n}
$$

Let $d_{W}=\operatorname{dim}(W)$, then the rescaled Thoma parameters of the extremal character $\chi_{R}$ associated to the $R$-matrix of $F^{W}$ are $\left(0, d_{W}\right)$.

Given two $R$-matrices $R: W_{R}^{\otimes 2} \rightarrow W_{R}^{\otimes 2}$ and $S: W_{S}^{\otimes 2} \rightarrow W_{S}^{\otimes 2}$ we can define another $R$-matrix denoted by $R \boxplus S:\left(W_{R} \oplus W_{S}\right)^{\otimes 2} \rightarrow\left(W_{R} \oplus W_{S}\right)^{\otimes 2}$ as follows: On the summand $W_{R}^{\otimes 2}$ it agrees with $R$, on $W_{S}^{\otimes 2}$ it agrees with $S$ and on $\left(W_{R} \otimes W_{S}\right) \oplus\left(W_{S} \otimes W_{R}\right)$ it is given by interchanging the two summands. This is [19, Def. 4.1] and the details of this construction can be found in [19, Sec. 4.1]. We will see that this operation corresponds to forming tensor products of exponential functors.

Let $F$ and $G$ be polynomial exponential functors. Observe that $V \mapsto$ $(F \otimes G)(V)=F(V) \otimes G(V)$ is again polynomial. It is also exponential with respect to the natural transformation $\tau^{F \otimes G}$ induced by

$$
\tau^{F} \otimes \tau^{G}: F(V \oplus W) \otimes G(V \oplus W) \rightarrow F(V) \otimes F(W) \otimes G(V) \otimes G(W)
$$

and the isomorphism interchanging the two middle tensor factors. The unit transformation $\iota^{F \otimes G}: F(0) \otimes G(0) \rightarrow \mathbb{C}$ is given by $\iota^{F} \otimes \iota^{G}$ followed by the canonical isomorphism $\mathbb{C} \otimes \mathbb{C} \cong \mathbb{C}$.

Let $F\left(\lambda \operatorname{id}_{V}\right)=\sum_{n \in \mathbb{N}_{0}} u_{n}^{F}(V) \lambda^{n}$ and $G\left(\lambda \operatorname{id}_{V}\right)=\sum_{n \in \mathbb{N}_{0}} u_{n}^{G}(V) \lambda^{n}$ be the decompositions of the multiplication operator. The coefficients are the projections onto the homogeneous components of $F$ and $G$, respectively. Then we have

$$
(F \otimes G)\left(\lambda \operatorname{id}_{V}\right)=F\left(\lambda \operatorname{id}_{V}\right) \otimes G\left(\lambda \operatorname{id}_{V}\right)=\sum_{i, j} u_{i}^{F}(V) \otimes u_{j}^{G}(V) \lambda^{i+j}
$$

This implies that the degree $n$ homogeneous component $(F \otimes G)_{n}$ of $F \otimes G$ is given by

$$
(F \otimes G)_{n}(V)=\bigoplus_{i+j=n} F_{i}(V) \otimes G_{j}(V)
$$

In particular, we obtain $(F \otimes G)_{1}(V) \cong F_{0}(V) \otimes G_{1}(V) \oplus F_{1}(V) \otimes G_{0}(V)$. Thus, combining Lemma 2.5 and Remark 2.6 we see that the linearization of $F \otimes G$ is naturally isomorphic to

$$
L_{n}^{F \otimes G}\left(V_{1}, \ldots, V_{n}\right)=\left(F_{1}\left(V_{1}\right) \oplus G_{1}\left(V_{1}\right)\right) \otimes \cdots \otimes\left(F_{1}\left(V_{n}\right) \oplus G_{1}\left(V_{n}\right)\right) .
$$

To identify the permutation part of $R \boxplus S$ we need the following Lemma.
Lemma 2.13. Let $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be a polynomial exponential functor with homogeneous decomposition $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$. Let $\tau_{\mathbb{C}, \mathbb{C}}^{1}: F_{1}(\mathbb{C} \oplus \mathbb{C}) \rightarrow F_{1}(\mathbb{C}) \oplus F_{1}(\mathbb{C})$ be the natural isomorphism induced by $\tau$ as in Lemma 2.4, where we identify
$F_{0}(\mathbb{C}) \cong \mathbb{C}$ (see Rem. 2.6). Let $f_{V}: V \oplus V \rightarrow V \oplus V$ be the map interchanging the two summands. Then the following diagram commutes


Proof. First note $F_{1}(0)=0$ and the map $F_{1}(\mathbb{C} \oplus 0) \rightarrow F_{1}(\mathbb{C})$ induced by $\tau_{\mathbb{C}, 0}^{1}: F_{1}(\mathbb{C} \oplus 0) \rightarrow F_{1}(\mathbb{C}) \oplus 0 \cong F_{1}(\mathbb{C})$ coincides with the one induced by the canonical isomorphism $\mathbb{C} \oplus 0 \rightarrow \mathbb{C}$ as a consequence of the unitality condition in Def. 2.1 c$)$. Let $p_{i}^{V}: V \oplus V \rightarrow V$ for $i \in\{1,2\}$ be the projection onto the $i$ th summand. Thus, by naturality the following diagram commutes

where the unlabelled arrow on the right is induced by $\mathbb{C} \oplus 0 \rightarrow \mathbb{C}$. In particular, we obtain $p_{1}^{F_{1}(\mathbb{C})} \circ \tau_{\mathbb{C}, \mathbb{C}}^{1}=F_{1}\left(p_{1}^{\mathbb{C}}\right)$ and similarly with $p_{1}$ exchanged by $p_{2}$. Let $\iota_{j}^{V}: V \rightarrow V \oplus V$ be the inclusion onto the $j$ th summand. A similar argument shows that

$$
\tau_{\mathbb{C}, \mathbb{C}}^{1} \circ F_{1}\left(\iota_{j}^{\mathbb{C}}\right)=\iota_{j}^{F_{1}(\mathbb{C})}
$$

Since $F_{1}$ is homogeneous of degree 1 , it is additive. Note that $f_{V}$ can be expressed as follows: $f_{V}=\iota_{1}^{V} \circ p_{2}^{V}+\iota_{2}^{V} \circ p_{1}^{V}$. Thus,

$$
\begin{aligned}
& \tau_{\mathbb{C}, \mathbb{C}}^{1} \circ F_{1}\left(f_{\mathbb{C}}\right)=\tau_{\mathbb{C}, \mathbb{C}}^{1} \circ F_{1}\left(\iota_{1}^{\mathbb{C}} \circ p_{2}^{\mathbb{C}}+\iota_{2}^{\mathbb{C}} \circ p_{1}^{\mathbb{C}}\right) \\
= & \tau_{\mathbb{C}, \mathbb{C}}^{1} \circ F_{1}\left(\iota_{1}^{\mathbb{C}}\right) \circ F_{1}\left(p_{2}^{\mathbb{C}}\right)+\tau_{\mathbb{C}, \mathbb{C}}^{1} \circ F_{1}\left(\iota_{2}^{\mathbb{C}}\right) \circ F_{1}\left(p_{1}^{\mathbb{C}}\right) \\
= & \iota_{1}^{F_{1}(\mathbb{C})} \circ p_{2}^{F_{1}(\mathbb{C})} \circ \tau_{\mathbb{C}, \mathbb{C}}^{1}+\iota_{2}^{F_{1}(\mathbb{C})} \circ p_{1}^{F_{1}(\mathbb{C})} \circ \tau_{\mathbb{C}, \mathbb{C}}^{1} \\
= & f_{F_{1}(\mathbb{C})} \circ \tau_{\mathbb{C}, \mathbb{C}}^{1}
\end{aligned}
$$

Now we are able to prove our previous guess about the $R$-matrix of tensor products:

Theorem 2.14. Let $F, G$ be polynomial exponential functors with homogeneous decompositions $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$ and $\left(G_{n}\right)_{n \in \mathbb{N}_{0}}$, respectively. Let $W_{R}=F_{1}(\mathbb{C})$ and $W_{S}=G_{1}(\mathbb{C})$ and denote by $R: W_{R}^{\otimes 2} \rightarrow W_{R}^{\otimes 2}$ and $S: W_{S}^{\otimes 2} \rightarrow W_{S}^{\otimes 2}$ the $R$-matrices associated to $F$ and $G$, respectively. Then the $R$-matrix associated to $F \otimes G$ is $R \boxplus S$.

Proof. Let $\tau \in S_{2} \cong \mathbb{Z} / 2 \mathbb{Z}$ be the non-trivial element, which we will identify with the isomorphism interchanging the two summands of $\mathbb{C}^{2}$. The $R$-matrix of $F \otimes G$ is the restriction of $(F \otimes G)_{2}(\tau)$ on $(F \otimes G)_{2}\left(\mathbb{C}^{2}\right)$ to

$$
L=(F \otimes G)_{1}(\mathbb{C}) \otimes(F \otimes G)_{1}(\mathbb{C}) \subset(F \otimes G)_{2}\left(\mathbb{C}^{2}\right)
$$

By our observation about tensor products of polynomial functors the 2homogeneous summand $(F \otimes G)_{2}\left(\mathbb{C}^{2}\right)$ is naturally isomorphic to

$$
\begin{equation*}
F_{2}\left(\mathbb{C}^{2}\right) \otimes G_{0}\left(\mathbb{C}^{2}\right) \quad \oplus \quad F_{1}\left(\mathbb{C}^{2}\right) \otimes G_{1}\left(\mathbb{C}^{2}\right) \quad \oplus \quad F_{0}\left(\mathbb{C}^{2}\right) \otimes G_{2}\left(\mathbb{C}^{2}\right) . \tag{3}
\end{equation*}
$$

Observe that $(F \otimes G)_{2}(\tau)$ acts via $F_{i}(\tau) \otimes G_{j}(\tau)$ on $F_{i}\left(\mathbb{C}^{2}\right) \otimes G_{j}\left(\mathbb{C}^{2}\right)$ in the above decomposition. The space $L$ is obtained from (3) in the following way: The first summand of $(3)$ contains $F_{1}(\mathbb{C}) \otimes F_{1}(\mathbb{C}) \otimes G_{0}(\mathbb{C}) \otimes G_{0}(\mathbb{C})$, on which $(F \otimes G)_{2}(\tau)$ acts like $R$ after identifying $G_{0}(\mathbb{C})$ with $\mathbb{C}$. The last summand contains $F_{0}(\mathbb{C}) \otimes F_{0}(\mathbb{C}) \otimes G_{1}(\mathbb{C}) \otimes G_{1}(\mathbb{C})$, on which $(F \otimes G)_{2}(\tau)$ restricts to $S$ after identifying $F_{0}(\mathbb{C}) \cong \mathbb{C}$. The second summand contains (4) $F_{1}(\mathbb{C}) \otimes F_{0}(\mathbb{C}) \otimes G_{0}(\mathbb{C}) \otimes G_{1}(\mathbb{C}) \oplus F_{0}(\mathbb{C}) \otimes F_{1}(\mathbb{C}) \otimes G_{1}(\mathbb{C}) \otimes G_{0}(\mathbb{C})$.

Since $(F \otimes G)_{2}(\tau)$ acts like $F_{1}(\tau) \otimes G_{1}(\tau)$ on the second summand of (3), Lemma 2.13 implies that $(F \otimes G)_{2}(\tau)$ restricts to the action that interchanges the two summands of $(4)$ after identifying $F_{0}(\mathbb{C})$ and $G_{0}(\mathbb{C})$ with $\mathbb{C}$. These are all summands of $L$. Thus, we see that the $R$-matrix of $F \otimes G$ turns out to be $R \boxplus S$.

Let $R, S$ be two unitary involutive $R$-matrices with rescaled Thoma parameter sets $(a, b)=\left(\left\{a_{1}, \ldots, a_{m}\right\},\left\{b_{1}, \ldots, b_{n}\right\}\right)$ and ( $\left.a^{\prime}, b^{\prime}\right)$, respectively. Then the parameter set of $R \boxplus S$ is given by $\left(a \cup a^{\prime}, b \cup b^{\prime}\right)$ [19, Prop. 4.4 ii) and (4.14)].
Theorem 2.15. For any polynomial exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ there is a sequence of finite-dim. inner product spaces $W_{1}, \ldots, W_{n} \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{Cin}}\right)$ with the property that

$$
F \sim_{f} F^{W_{1}} \otimes \cdots \otimes F^{W_{n}}
$$

Proof. Let $\left(F_{n}\right)_{n \in \mathbb{N}_{0}}$ be the homogeneous components of $F$, let $W=F_{1}(\mathbb{C})$, $d_{W}=\operatorname{dim}(W)$ and let $R: W^{\otimes 2} \rightarrow W^{\otimes 2}$ be the $R$-matrix associated to $F$. By Lemma 2.11 the rescaled Thoma parameters of $R$ have the form

$$
(a, b)=\left(0,\left(b_{1}, \ldots, b_{n}\right)\right)
$$

for positive integers $b_{i}$ that satisfy $\sum_{i} b_{i}=d_{W}$. Let $W_{i}=\mathbb{C}^{b_{i}}$. Let $R_{i}$ be the $R$-matrix of the polynomial exponential functor $F^{W_{i}}$. Its rescaled parameters are $\left(0, b_{i}\right)$ by Lemma 2.12. By Thm. 2.14 the $R$-matrix of $F^{W_{1}} \otimes$ $\cdots \otimes F^{W_{n}}$ is $R_{1} \boxplus \cdots \boxplus R_{n}$, the parameters of which are $\left(0,\left(b_{1}, \ldots, b_{n}\right)\right)$ by the observation in the preceding paragraph. In particular, the $R$-matrices of $F$ and $F^{W_{1}} \otimes \cdots \otimes F^{W_{n}}$ are equivalent in the sense of Def. 2.8 and the statement follows from Lemma 2.10.
2.3. From $R$-matrices to exponential functors. Theorem 2.15 gives a full classification of polynomial exponential functors up to the first equivalence relation $\sim_{f}$. In this section we study how monoidal equivalence of exponential functors is related to strong equivalence of their respective $R$ matrices. We start by constructing a polynomial exponential functor from a given $R$-matrix with the right Thoma parameters. For a given $V \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\text {fin }}\right)$
let $T: V^{\otimes 2} \rightarrow V^{\otimes 2}$ be the isomorphism interchanging the tensor factors. Let $R \boxtimes T:(W \otimes V)^{\otimes 2} \rightarrow(W \otimes V)^{\otimes 2}$ be the tensor product of the two $R$-matrices [19, Eq. (4.15)]. Define

$$
\begin{equation*}
\left.F^{R}(V)=\bigoplus_{n \in \mathbb{N}_{0}}\left((W \otimes V)^{\otimes n}\right)\right)^{S_{n}} \tag{5}
\end{equation*}
$$

where $S_{n}$ acts on $(W \otimes V)^{\otimes n}$ via $\rho_{R \boxtimes T}^{(n)}, S_{0}$ and $S_{1}$ are trivial groups and we set $(W \otimes V)^{\otimes 0}=\mathbb{C}$. A priori this is a polynomial functor from $\mathcal{V}_{\mathbb{C}}^{\text {fin }}$ to the category $\mathcal{V}_{\mathbb{C}}$ of (not necessarily finite-dimensional) inner product spaces. Its homogeneous components $\left(F_{n}^{R}\right)_{n \in \mathbb{N}_{0}}$ are given by

$$
F_{n}^{R}(V)=\left((W \otimes V)^{\otimes n}\right)^{S_{n}}
$$

To see that $F^{R}$ is in fact an exponential functor, we have to analyse its behaviour with respect to direct sums. Let $i, j \in \mathbb{N}_{0}$ with $i+j=n$ and consider the embedding

$$
\iota_{i, j}:\left(W \otimes V_{1}\right)^{\otimes i} \otimes\left(W \otimes V_{2}\right)^{\otimes j} \rightarrow\left(W \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n}
$$

induced by the two inclusions $W \otimes V_{k} \rightarrow W \otimes\left(V_{1} \oplus V_{2}\right)$ for $k \in\{1,2\}$. Let $T_{k}$ be the $R$-matrix interchanging the tensor factors of $V_{k}^{\otimes 2}$. The analogous $R$-matrix for $V_{1} \oplus V_{2}$ is $T_{1} \boxplus T_{2}$. In particular,

$$
F_{n}^{R}\left(V_{1} \oplus V_{2}\right)=\left(\left(W \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n}\right)^{S_{n}}
$$

where $S_{n}$ acts via $\rho_{R \boxtimes\left(T_{1} \boxplus T_{2}\right)}^{(n)}$. Let $X_{i, j}=S_{n} /\left(S_{i} \times S_{j}\right), N_{i, j}=\binom{n}{i}$ and choose representatives $\sigma_{1}=e, \sigma_{2}, \ldots, \sigma_{N_{i, j}} \in S_{n}$ for each element of $X_{i, j}$. Define the homomorphism

$$
\varphi_{i, j}:\left(W \otimes V_{1}\right)^{\otimes i} \otimes\left(W \otimes V_{2}\right)^{\otimes j} \rightarrow\left(W \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n}
$$

by $\iota_{i, j}$ followed by averaging over the action of the representatives of $X_{i, j}$, i.e. by

$$
\begin{equation*}
\varphi_{i, j}(x)=\frac{1}{\sqrt{N_{i, j}}} \sum_{k=1}^{N_{i, j}} \sigma_{k} \cdot \iota_{i, j}(x), \tag{6}
\end{equation*}
$$

where $S_{n}$ again acts by $\rho_{R \boxtimes\left(T_{1} \boxplus T_{2}\right)}^{(n)}$. Note that the definition of $\varphi_{i, j}$ depends on the choice of representatives $\sigma_{1}, \ldots, \sigma_{N_{i, j}}$.

To understand the action of $S_{n}$ we employ the following description of $\left(V_{1} \oplus V_{2}\right)^{\otimes n}$ : Fix $i, j \in \mathbb{N}_{0}$ with $i+j=n$. Let

$$
a_{i, j}:\{1, \ldots, n\} \rightarrow\{1,2\} \quad, \quad x \mapsto \begin{cases}1 & \text { for } 1 \leq x \leq i \\ 2 & \text { else }\end{cases}
$$

Note that $a_{i, j} \circ \tau=a_{i, j}$ for all $\tau \in S_{i} \times S_{j}$. We have an isomorphism

$$
\begin{equation*}
\left(V_{1} \oplus V_{2}\right)^{\otimes n} \cong \bigoplus_{i+j=n} \bigoplus_{[\sigma] \in X_{i, j}} V_{i, j,[\sigma]} \tag{7}
\end{equation*}
$$

with $V_{i, j,[\sigma]}=V_{a_{i, j}(\sigma(1))} \otimes \cdots \otimes V_{a_{i, j}(\sigma(n))}$. An element $\tau \in S_{n}$ maps $V_{i, j,[\sigma]}$ to $V_{i, j,[\tau \cdot \sigma]}$. Thus, our choice of representatives implies that all summands in $\varphi_{i, j}(x)$ are orthogonal. In particular, $\varphi_{i, j}$ is injective. The factor $\frac{1}{\sqrt{N_{i, j}}}$ ensures that $\varphi_{i, j}$ also preserves inner products. Define

$$
\widehat{\kappa}_{V_{1}, V_{2}}^{n}: \bigoplus_{i+j=n}\left(W \otimes V_{1}\right)^{\otimes i} \otimes\left(W \otimes V_{2}\right)^{\otimes j} \rightarrow\left(W \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n}
$$

as the sum over all $\varphi_{i, j}$. The decomposition (7) shows that each each summand of the domain is mapped to a different orthogonal summand of the codomain. Hence, $\widehat{\kappa}_{V_{1}, V_{2}}^{n}$ is still injective.

Given $k \in\left\{1, \ldots, N_{i, j}\right\}$ and $\sigma \in S_{n}$, there is $\ell(k)$ and $\tau \in S_{i} \times S_{j}$ with the property that $\sigma \cdot \sigma_{k}=\sigma_{\ell(k)} \cdot \tau$ and for fixed $\sigma$ the map $k \mapsto \ell(k)$ is a bijection. Let $x \in\left(\left(W \otimes V_{1}\right)^{\otimes i}\right)^{S_{i}} \otimes\left(\left(W \otimes V_{2}\right)^{\otimes j}\right)^{S_{j}}$. Then we obtain

$$
\begin{aligned}
\sigma \cdot \varphi_{i, j}(x) & =\frac{1}{\sqrt{N_{i, j}}} \sum_{k=1}^{N_{i, j}}\left(\sigma \cdot \sigma_{k}\right) \cdot \iota_{i, j}(x)=\frac{1}{\sqrt{N_{i, j}}} \sum_{k=1}^{N_{i, j}} \sigma_{\ell(k)} \cdot \tau \cdot \iota_{i, j}(x) \\
& =\frac{1}{\sqrt{N_{i, j}}} \sum_{k=1}^{N_{i, j}} \sigma_{k} \cdot \iota_{i, j}(x)=\varphi_{i, j}(x)
\end{aligned}
$$

where we used the equivariance of $\iota_{i, j}$ with respect to the action of $S_{i} \times S_{j}$ on both sides. This implies that $\widehat{\kappa}_{V_{1}, V_{2}}^{n}$ restricts to a natural isometry

$$
\kappa_{V_{1}, V_{2}}^{n}: \bigoplus_{i+j=n}\left(\left(W \otimes V_{1}\right)^{\otimes i}\right)^{S_{i}} \otimes\left(\left(W \otimes V_{2}\right)^{\otimes j}\right)^{S_{j}} \rightarrow\left(\left(W \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n}\right)^{S_{n}}
$$

Note that $\kappa_{V_{1}, V_{2}}^{n}$ no longer depends on our initial choice of coset representatives $\sigma_{k}$.

Lemma 2.16. Let $R: W^{\otimes 2} \rightarrow W^{\otimes 2}$ be an $R$-matrix with rescaled Thoma parameters $\left(0,\left(b_{1}, \ldots, b_{m}\right)\right)$. Let $F_{n}^{R}$ be the functor and $\kappa_{V_{1}, V_{2}}^{n}$ be the natural transformation constructed above. Then $\kappa_{V_{1}, V_{2}}^{n}$ is a unitary isomorphism for every $V_{1}, V_{2} \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}\right)$. In particular, it induces a natural isomorphism

$$
\tau_{V_{1}, V_{2}}^{n}: F_{n}^{R}\left(V_{1} \oplus V_{2}\right) \rightarrow \bigoplus_{i+j=n} F_{i}^{R}\left(V_{1}\right) \otimes F_{j}^{R}\left(V_{2}\right)
$$

with $\tau_{V_{1}, V_{2}}^{n}=\left(\kappa_{V_{1}, V_{2}}^{n}\right)^{-1}$. Moreover, $F_{n}^{R}(V)=0$ for sufficiently large $n$ (depending on $V$ ) and $F^{R}(V)$ as defined in (5) is finite-dimensional.

Proof. We have already seen that $\kappa_{V_{1}, V_{2}}^{n}$ is injective. Thus, it suffices to show that the dimensions of domain and codomain agree. This is obvious for $n \in\{0,1\}$. Fix $n \geq 2$ and let $U \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\text {fin }}\right)$. Consider the action of $S_{n}$ on $(W \otimes U)^{\otimes n}$ via $\rho_{R \boxtimes T}^{(n)}$. Let $d_{U}=\operatorname{dim}(U)$. The $R$-matrix $R \boxtimes T$ has rescaled Thoma parameters $\left(0,\left(b_{1}, \ldots, b_{1}, b_{2}, \ldots, b_{2}, \ldots, b_{m}, \ldots, b_{m}\right)\right.$, where each $b_{i}$ is repeated $d_{U}$ times [19, Lemma 4.9].

The dimension of $\left((W \otimes U)^{\otimes n}\right)^{S_{n}}$ agrees with the multiplicity $\left\langle\iota_{\mathbb{C}}, \rho_{R \boxtimes T}^{(n)}\right\rangle$ of the trivial representation $\iota_{\mathbb{C}}$ in $\rho_{R \boxtimes T}^{(n)}$. This multiplicity was computed in [19, Prop. 5.7] in terms of the Thoma parameters and evaluates to

$$
\begin{aligned}
& \left\langle\iota_{\mathbb{C}}, \rho_{R \boxtimes T}^{(n)}\right\rangle=\left[(1 \otimes \omega) \circ \Delta\left(s_{n}\right)\right]\left((0, \ldots, 0),\left(b_{1}, \ldots, b_{1}, \ldots, b_{m}, \ldots, b_{m}\right)\right) \\
= & e_{n}\left(b_{1}, \ldots, b_{1}, \ldots, b_{m}, \ldots, b_{m}\right)=\sum_{s_{1}+\cdots+s_{m}=n}\binom{d_{U}}{s_{1}} \cdots\binom{d_{U}}{s_{m}} b_{1}^{s_{1}} \cdots b_{m}^{s_{m}}
\end{aligned}
$$

where we refer the reader to [19, Sec. 5.2] for the notation used here. For sufficiently large $n$ there will always be at least one summand $s_{k}$ that is larger than $d_{U}$. Hence, this expression vanishes for large $n$, which proves the second statement.

For $k \in\{1,2\}$ let $d_{k}=\operatorname{dim}\left(V_{k}\right)$ and let $T_{k}: V_{k}^{\otimes 2} \rightarrow V_{k}^{\otimes 2}$ be the map interchanging the tensor factors. Let $T_{12}$ be the corresponding operation on $\left(V_{1} \oplus V_{2}\right)^{\otimes 2}$. Using the following identity for the binomial coefficients

$$
\sum_{i+j=n}\binom{d_{1}}{i}\binom{d_{2}}{j}=\binom{d_{1}+d_{2}}{n}
$$

we can compare the dimensions of the domain and codomain of $\kappa_{V_{1}, V_{2}}^{n}$ :

$$
\begin{aligned}
& \sum_{i+j=n}\left\langle\iota_{\mathbb{C}}, \rho_{R \boxtimes T_{1}}^{(i)}\right\rangle\left\langle\iota_{\mathbb{C}}, \rho_{R \boxtimes T_{2}}^{(j)}\right\rangle \\
= & \sum_{i+j=n} \sum_{\substack{s_{1}+\cdots+s_{m}=i \\
t_{1}+\cdots+t_{m}=j}}\binom{d_{1}}{s_{1}}\binom{d_{2}}{t_{1}} \cdots\binom{d_{1}}{s_{m}}\binom{d_{2}}{t_{m}} b_{1}^{s_{1}+t_{1}} \cdots b_{m}^{s_{m}+t_{m}} \\
= & \sum_{x_{1}+\cdots+x_{m}=n}\left(\sum_{s_{1}+t_{1}=x_{1}}\binom{d_{1}}{s_{1}}\binom{d_{2}}{t_{1}}\right) \cdots\left(\sum_{s_{m}+t_{m}=x_{m}}\binom{d_{1}}{s_{m}}\binom{d_{2}}{t_{m}}\right) b_{1}^{x_{1}} \cdots b_{m}^{x_{m}} \\
= & \sum_{x_{1}+\cdots+x_{m}=n}\binom{d_{1}+d_{2}}{x_{1}} \cdots\binom{d_{1}+d_{2}}{x_{m}} b_{1}^{x_{1}} \cdots b_{m}^{x_{m}}=\left\langle\iota_{\mathbb{C}}, \rho_{R \boxtimes T_{12}}^{(n)}\right\rangle
\end{aligned}
$$

This proves that $\kappa_{V_{1}, V_{2}}^{n}$ is in fact an isomorphism. Thus, $\tau_{V_{1}, V_{2}}^{n}$ is welldefined.

The transformations $\tau_{V_{1}, V_{2}}^{n}$ yield natural isomorphisms

$$
\tau_{V_{1}, V_{2}}: F^{R}\left(V_{1} \oplus V_{2}\right) \rightarrow F^{R}\left(V_{1}\right) \otimes F^{R}\left(V_{2}\right)
$$

Moreover, there is a canonical isomorphism $\iota: F^{R}(0) \rightarrow \mathbb{C}$. We are now finally ready to state the main result of this section, that rounds off the classification of polynomial exponential functors on $\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$.

Theorem 2.17. Let $W \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\text {iin }}\right)$ and let $R: W^{\otimes 2} \rightarrow W^{\otimes 2}$ be a unitary involutive $R$-matrix with rescaled Thoma parameters $\left(0,\left(b_{1}, \ldots, b_{m}\right)\right)$. Let $F^{R}: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be the functor defined in (5) and let $\tau_{V_{1}, V_{2}}$ and $\iota$ be the natural isomorphisms defined above. Then $\left(F^{R}, \tau, \iota\right)$ is a well-defined polynomial exponential functor. The $R$-matrix associated to $F^{R}$ is $R$.

Proof. We have seen in Lemma 2.16 that $F^{R}(V)$ is finite-dimensional for every $V \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\text {fin }}\right)$. In particular, $F^{R}: \mathcal{V}_{\mathbb{C}}^{\text {in }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ is a well-defined polynomial functor with homogeneous components $\left(F_{n}^{R}\right)_{n \in \mathbb{N}_{0}}$.

It is straightforward to check that $\widehat{\kappa}_{V, 0}^{n}$ coincides with the canonical homomorphism $(W \otimes V)^{\otimes n} \otimes \mathbb{C} \rightarrow(W \otimes(V \oplus 0))^{\otimes n}$ and likewise for $\widehat{\kappa}_{0, V}^{n}$. This implies that $\iota$ makes the diagram in Def. 2.1 c) commute.

It remains to be shown that $\tau_{V_{1}, V_{2}}$ satisfies the associativity condition in Def. 2.1 b ). For this it suffices to see that

$$
\begin{equation*}
\varphi_{i, j+k}^{1,2 \oplus 3} \circ\left(\operatorname{id}_{\left(W \otimes V_{1}\right)^{\otimes i}} \otimes \varphi_{j, k}^{2,3}\right)=\varphi_{i+j, k}^{1 \oplus 2,3} \circ\left(\varphi_{i, j}^{1,2} \otimes \operatorname{id}_{\left(W \otimes V_{3}\right)^{\otimes k}}\right) \tag{8}
\end{equation*}
$$

on $\left(\left(W \otimes V_{1}\right)^{\otimes i}\right)^{S_{i}} \otimes\left(\left(W \otimes V_{2}\right)^{\otimes j}\right)^{S_{j}} \otimes\left(\left(W \otimes V_{3}\right)^{\otimes k}\right)^{S_{k}}$. The left hand side involves averaging over the coset space $X_{j, k}$ and then over $X_{i, j+k}$. Identify $X_{j, k}$ with the set of representatives $\sigma_{s}^{(2)} \in S_{j+k} \subset S_{i+j+k}$, where $S_{j, k}$ embeds into $S_{i+j+k}$ as the subgroup permuting the last $j+k$ elements. Likewise, let $\sigma_{r}^{(1)} \in S_{i+j+k}$ be the representatives for the elements of $X_{i, j+k}$. Let $X_{i, j, k}=S_{i+j+k} /\left(S_{i} \times S_{j} \times S_{k}\right)$ and note that

$$
\begin{equation*}
X_{i, j+k} \times X_{j, k} \rightarrow X_{i, j, k} \quad, \quad\left(\sigma_{r}^{(1)}, \sigma_{s}^{(2)}\right) \mapsto\left[\sigma_{r}^{(1)} \cdot \sigma_{s}^{(2)}\right] \tag{9}
\end{equation*}
$$

is a bijection. In particular, $\left(\sigma_{r}^{(1)} \sigma_{s}^{(2)}\right)_{r, s}$ is a collection of representatives in $S_{i+j+k}$ for the elements in $X_{i, j, k}$. The right hand side of (8) involves averaging first over $X_{i, j}$, then over $X_{i+j, k}$. A similar argument as above yields a bijection $X_{i+j, k} \times X_{i, j} \rightarrow X_{i, j, k}$ proving that the product of the corresponding coset representatives yields another set of representatives for the elements in $X_{i, j, k}$. As was already observed above, the maps $\kappa_{U_{1}, U_{2}}^{p, q}$ are independent of the choice of representatives. Hence, the two procedures both yield the average over $X_{i, j, k}$ and therefore give the same result on $\left(\left(W \otimes V_{1}\right)^{\otimes i}\right)^{S_{i}} \otimes\left(\left(W \otimes V_{2}\right)^{\otimes j}\right)^{S_{j}} \otimes\left(\left(W \otimes V_{3}\right)^{\otimes k}\right)^{S_{k}}$.

Let $\tau \in S_{2}$ be the non-trivial element. The $R$-matrix of $F^{R}$ is obtained by restricting the action of $S_{2}$ on $F_{2}^{R}\left(\mathbb{C}^{2}\right)$ given by interchanging the two summands to the direct summand $F_{1}^{R}(\mathbb{C}) \otimes F_{1}^{R}(\mathbb{C})$, that is embedded into $F_{2}^{R}\left(\mathbb{C}^{2}\right)$ via $\varphi_{1,1}$. Observe that $F_{1}^{R}(\mathbb{C})=W \otimes \mathbb{C} \cong W$ by definition and that $\varphi_{1,1}: W \otimes W \rightarrow\left(W \otimes \mathbb{C}^{2}\right)^{\otimes 2}$ is given by

$$
\varphi_{1,1}\left(w_{1} \otimes w_{2}\right)=\frac{1}{\sqrt{2}}\left(w_{1} \otimes e_{1} \otimes w_{2} \otimes e_{2}+\rho_{R \boxtimes T}^{(2)}(\tau)\left(w_{1} \otimes e_{1} \otimes w_{2} \otimes e_{2}\right)\right),
$$

where $\left\{e_{1}, e_{2}\right\} \subset \mathbb{C}^{2}$ is the standard basis of $\mathbb{C}^{2}$. The $R$-matrix $T$ interchanges the two factors of $\left(\mathbb{C}^{2}\right)^{\otimes 2}$, i.e. it switches $e_{1}$ and $e_{2}$ in the above expression. This implies that the $S_{2}$-action on $W \otimes \mathbb{C}^{2}$ that interchanges the summands restricts to $\rho_{R}^{(2)}(\tau)=R$ on $W \otimes W$.

Lemma 2.18. Let $F, G: \mathcal{V}_{\mathbb{C}}^{\text {in }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ be polynomial exponential functors. Let $R, S$ be the $R$-matrices associated to $F$ and $G$ respectively. Then

$$
F \sim_{\otimes} G \quad \Leftrightarrow \quad R \sim_{\otimes} S .
$$

In particular, $F \sim_{\otimes} F^{R}$.
Proof. We will first show $F \sim_{\otimes} F^{R}$ and deduce the first statement from this. There is a natural isomorphism $F_{1}(\mathbb{C}) \otimes V \cong F_{1}(V)$ (cf. [20, App. A, (5.1)]) and throughout this proof we will identify the two spaces. Let $\ell_{n}(V): F_{n}(V) \rightarrow F_{n}^{R}(V)$ be the isomorphism in (1). Denote by $\Delta_{k}^{V}: V \rightarrow$ $V^{\oplus k}$ the isometric linear embedding with

$$
\Delta_{k}^{V}(x)=\frac{1}{\sqrt{k}}(x, \ldots, x) .
$$

Let $q_{n}^{V}: F_{n}(V) \rightarrow\left(F_{1}(V)^{\otimes n}\right)^{S_{n}} \cong F_{n}^{R}(V)$ be the self-adjoint projection onto $L_{F_{n}}(V, \ldots, V)^{S_{n}}$ followed by the identification of $L_{F_{n}}(V, \ldots, V)^{S_{n}}$ with $\left(F_{1}(V)^{\otimes n}\right)^{S_{n}}$ as in Lemma 2.5. Then we have $\ell_{n}(V)=q_{n}^{V} \circ F_{n}\left(\Delta_{n}^{V}\right)$. Consider the isomorphisms

$$
\begin{aligned}
& \left(\tau_{V_{1}, V_{2}}^{n}\right)^{-1}: \bigoplus_{i+j=n} F_{i}\left(V_{1}\right) \otimes F_{j}\left(V_{2}\right) \rightarrow F_{n}\left(V_{1} \oplus V_{2}\right), \\
& \left(\tau_{V_{1}, V_{2}}^{R, n}\right)^{-1}: \bigoplus_{i+j=n} F_{i}^{R}\left(V_{1}\right) \otimes F_{j}^{R}\left(V_{2}\right) \rightarrow F_{n}^{R}\left(V_{1} \oplus V_{2}\right) .
\end{aligned}
$$

For fixed $i, j \in \mathbb{N}$ with $i+j=n$ they restrict to isometric embeddings

$$
\begin{aligned}
& \kappa_{i, j}: F_{i}\left(V_{1}\right) \otimes F_{j}\left(V_{2}\right) \rightarrow F_{n}\left(V_{1} \oplus V_{2}\right), \\
& \kappa_{i, j}^{R}: F_{i}^{R}\left(V_{1}\right) \otimes F_{j}^{R}\left(V_{2}\right) \rightarrow F_{n}^{R}\left(V_{1} \oplus V_{2}\right) .
\end{aligned}
$$

To show $F \sim_{\otimes} F^{R}$ it suffices to prove that the following diagram commutes:


Let $\iota_{i, j}^{\oplus}: V_{1}^{\oplus i} \oplus V_{2}^{\oplus j} \rightarrow\left(V_{1} \oplus V_{2}\right)^{\oplus n}$ be the isometric embedding that adds zeroes in the last ( $n-i$ ), respectively first $(n-j)$, components. Let $N_{i, j}=\binom{n}{i}$ and let $\sigma_{k}$ for $k \in\left\{1, \ldots, N_{i, j}\right\}$ be coset representatives for the elements of $S_{n} /\left(S_{i} \times S_{j}\right)$. Analogous to the definition of $\varphi_{i, j}$ in (6) let $\psi_{i, j}: V_{1}^{\oplus i} \oplus V_{2}^{\oplus j} \rightarrow$ $\left(V_{1} \oplus V_{2}\right)^{\oplus n}$ be the linear map given by

$$
\psi_{i, j}(x, y)=\sum_{k=1}^{N_{i, j}} \sigma_{k} \cdot \iota_{i, j}^{\oplus}\left(c_{1} x, c_{2} y\right)
$$

for $x \in V_{1}^{\oplus i}, y \in V_{2}^{\oplus j}, c_{i}>0$ and where $S_{n}$ acts on $\left(V_{1} \oplus V_{2}\right)^{\oplus n}$ by permuting the summands. Note that the constants $c_{1}, c_{2}$ can be chosen such that $\psi_{i, j} \circ\left(\Delta_{i}^{V_{1}} \oplus \Delta_{j}^{V_{2}}\right)=\Delta_{n}^{V_{1} \oplus V_{2}}$. Let

$$
\kappa_{V_{1}^{\oplus i}, V_{2}^{\oplus j}}: F_{i}\left(V_{1}^{\oplus i}\right) \otimes F_{j}\left(V_{2}^{\oplus j}\right) \rightarrow F_{n}\left(V_{1}^{\oplus i} \oplus V_{2}^{\oplus j}\right)
$$

be defined analogous to $\kappa_{i, j}$, but with $V_{1}^{\oplus i}$ in place of $V_{1}$ and $V_{2}^{\oplus j}$ instead of $V_{2}$. Let $\widehat{\kappa}_{i, j}=F_{n}\left(\psi_{i, j}\right) \circ \kappa_{V_{1}^{\oplus i}, V_{2}^{\oplus j}}$ and consider the diagram

$$
\begin{aligned}
& F_{i}\left(V_{1}\right) \otimes F_{j}\left(V_{2}\right) \xrightarrow{\kappa_{i, j}} F_{n}\left(V_{1} \oplus V_{2}\right) \\
& \begin{array}{r}
F_{i}\left(\Delta_{i}^{V_{1}}\right) \otimes F_{j}\left(\Delta_{j}^{V_{2}}\right) \downarrow \\
F_{i}\left(V_{1}^{\oplus i}\right) \otimes F_{j}\left(V_{2}^{\oplus j}\right) \xrightarrow{\widehat{\kappa}_{i, j}} F_{n}\left(\left(V_{1} \oplus V_{2}\right)^{\oplus n}\right)
\end{array} \\
& q_{i}^{V_{1}} \otimes q_{j}^{V_{2}} \downarrow \downarrow q_{n}^{V_{1} \oplus V_{2}} \\
& F_{i}^{R}\left(V_{1}\right) \otimes F_{j}^{R}\left(V_{2}\right) \xrightarrow[\kappa_{i, j}^{R}]{ } F_{n}^{R}\left(V_{1} \oplus V_{2}\right)
\end{aligned}
$$

The naturality of $\kappa_{i, j}$ and our choice for $c_{1}, c_{2}$ implies that the upper square commutes. Restricted to $\left(F_{1}\left(V_{1} \oplus V_{2}\right)^{\otimes n}\right)^{S_{i} \times S_{j}}$ the map $F_{n}\left(\sum_{k} \sigma_{k}\right)$ corresponds to a multiple of the orthogonal projection to $\left(F_{1}\left(V_{1} \oplus V_{2}\right)^{\otimes n}\right)^{S_{n}}$, while $F_{n}\left(\iota_{i, j}^{\oplus}\left(c_{1} \cdot, c_{2} \cdot\right)\right)$ restricts to a scalar multiple of $\iota_{i, j}$ on $F_{i}^{R}\left(V_{1}\right) \otimes F_{j}^{R}\left(V_{2}\right)$. Hence, the lower square commutes up to a scalar. But since the outer square is a diagram of isometric embeddings, this scalar has to be 1 .

Thus, to prove the first statement it suffices to see that $F^{R} \sim_{\otimes} F^{S}$ implies $R \sim_{\otimes} S$ and vice versa. As was shown in the proof of Lemma 2.10 the unitary isomorphism $v_{n}\left(\mathbb{C}^{\oplus n}\right): F_{n}^{R}\left(\mathbb{C}^{\oplus n}\right) \rightarrow F_{n}^{S}\left(\mathbb{C}^{\oplus n}\right)$ restricts to a unitary intertwiner $v_{n}^{R, S}: W_{R}^{\otimes n} \rightarrow W_{S}^{\otimes n}$ between the representations $\rho_{R}^{(n)}$ and $\rho_{S}^{(n)}$, where $W_{R}=F_{1}^{R}(\mathbb{C})$ and $W_{S}=F_{1}^{S}(\mathbb{C})$. Let $\kappa_{i, j}^{R}, \kappa_{i, j}^{S}$ be the isometric embeddings for $R$ and $S$, respectively. Let $c_{i, j}: W_{R}^{\otimes i} \otimes W_{R}^{\otimes j} \rightarrow W_{R}^{\otimes n}$ be the canonical isomorphism. The associativity condition (Def. 2.1 b)) implies that the following diagram commutes:

where the unlabelled vertical arrows identify $W_{R}^{\otimes k}$ with $L_{F_{k}^{R}}(\mathbb{C}, \ldots, \mathbb{C})$ and embed it into $F_{k}^{R}\left(\mathbb{C}^{\oplus k}\right)$. Together with the naturality of $v$ this implies that $v_{n}^{R, S}=v_{i}^{R, S} \otimes v_{j}^{R, S}$ and thus $v_{n}^{R, S}=v_{1}^{R, S} \otimes \cdots \otimes v_{1}^{R, S}$. Hence, $R \sim_{\otimes} S$.

In the other direction let $v_{1}: W_{R} \rightarrow W_{S}$ be a unitary isomorphism witnessing the equivalence $R \sim_{\otimes} S$. It induces a unitary isomorphism

$$
\hat{v}_{i}(V):\left(W_{R} \otimes V\right)^{\otimes i} \rightarrow\left(W_{S} \otimes V\right)^{\otimes i}
$$

by letting $v_{1}^{\otimes i}$ act on the tensor factor $W_{R}^{\otimes i}$. This makes the following diagram commute:

$$
\begin{gathered}
\left(W_{R} \otimes V_{1}\right)^{\otimes i} \otimes\left(W_{R} \otimes V_{2}\right)^{\otimes j} \xrightarrow{\varphi_{i, j}^{R}}\left(W_{R} \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n} \\
\hat{v}_{i}\left(V_{1}\right) \otimes \hat{v}_{j}\left(V_{2}\right) \mid \\
\left(W_{S} \otimes V_{1}\right)^{\otimes i} \otimes\left(W_{S} \otimes V_{2}\right)^{\otimes j} \underset{\varphi_{i, j}^{S}}{\stackrel{\hat{v}_{1}\left(V_{1} \oplus V_{2}\right)}{\longrightarrow}}\left(W_{S} \otimes\left(V_{1} \oplus V_{2}\right)\right)^{\otimes n}
\end{gathered}
$$

Here we use the fact that $\hat{v}_{n}\left(V_{1} \oplus V_{2}\right)$ restricts to $\hat{v}_{i}\left(V_{1}\right) \otimes \hat{v}_{j}\left(V_{2}\right)$ on the direct summand $\left(W_{R} \otimes V_{1}\right)^{\otimes i} \otimes\left(W_{R} \otimes V_{2}\right)^{\otimes j}$. Taking the sum over the homogeneous components we see that the restriction $v_{n}(V)$ of $\hat{v}_{n}(V)$ to the $S_{n}$-invariant subspace $\left(\left(W_{R} \otimes V\right)^{\otimes n}\right)^{S_{n}}=F^{R}(V)$ induces a monoidal equivalence between $F^{R}$ and $F^{S}$. This proves the statement.

## 3. Twists via Exponential Functors

In this section we will study a natural map $\tau_{F}: B B U_{\oplus} \rightarrow B B U_{\otimes}\left[\frac{1}{d}\right]$ induced by an exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ with $d=\operatorname{dim}(F(\mathbb{C}))$. Combined with the equivalence $S U \simeq B B U_{\oplus}$ obtained from Bott periodicity this yields the twists $\tau_{F}^{n}: S U(n) \rightarrow B B U_{\otimes}\left[\frac{1}{d}\right]$ alluded to in the introduction.

We will then study how they behave in rationalised $K$-theory $K U_{\mathbb{Q}}$. Since the Chern character identifies $K U_{\mathbb{Q}}$ with ordinary cohomology in even degrees, the twists correspond to odd degree cohomology classes. To compute these for $\tau_{F}^{n}$ we will employ maps $S \mathbb{C} P^{n-1} \rightarrow S U(n)$ detecting the generators of $H^{*}(S U(n), \mathbb{Z})$.
3.1. The twist induced by an exponential functor. Let $\mathcal{V}_{\mathbb{C}}^{\text {iso }}$ be the isomorphism subcategory of $\mathcal{V}_{\mathbb{C}}^{\text {fin }}$ and note that $\mathcal{V}_{\mathbb{C}}^{\text {iso }}$ is essentially small. A skeleton is constructed as follows: Let $\mathcal{B} U_{\oplus}$ be the subcategory of $\mathcal{V}_{\mathbb{C}}^{\text {iso }}$ with objects $\mathbb{N}_{0}$ (with $k \in \mathbb{N}_{0}$ corresponding to $\mathbb{C}^{k}$ ) and

$$
\operatorname{hom}(m, n)=\left\{\begin{array}{ll}
\emptyset & \text { if } m \neq n \\
U(n) & \text { otherwise }
\end{array} .\right.
$$

The geometric realisation of the nerve of this category is clearly given by

$$
\left|\mathcal{B} U_{\oplus}\right|=\coprod_{n \in \mathbb{N}_{0}} B U(n)
$$

Moreover, $\mathcal{B} U_{\oplus}$ has a monoidal structure given by the addition of natural numbers on objects and the block sum on morphisms. This reflects the monoid structure on isomorphism classes of vector bundles given by direct sum. On the geometric realisation it corresponds to maps

$$
B U(n) \times B U(m) \rightarrow B U(n+m)
$$

induced by the group homomorphism $U(n) \times U(m) \rightarrow U(n+m)$ given by the block sum. By [21, Cor. 11.7] the space $\left|\mathcal{B} U_{\oplus}\right|$ is a topological monoid
and its group completion is

$$
\Omega B\left|\mathcal{B} U_{\oplus}\right| \simeq B U_{\oplus} \times \mathbb{Z}
$$

where $B U_{\oplus}$ is the classifying space of the colimit $U$ of the unitary groups $U(n)$ with respect to the inclusions $U(n) \rightarrow U(n+1)$. Note that the classifying space $B U$ has two natural $H$-space structures corresponding to the direct sum and the tensor product of vector bundles, respectively. We will decorate $B U$ accordingly, if we want to stress the $H$-space structure we have in mind.

Given an exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ let $W=F(\mathbb{C})$ and let $\mathcal{B} U_{\otimes}^{W}$ be the category with objects $\mathbb{N}_{0}$ and

$$
\operatorname{hom}(m, n)=\left\{\begin{array}{ll}
\emptyset & \text { if } m \neq n \\
U\left(W^{\otimes n}\right) & \text { otherwise }
\end{array},\right.
$$

where $U\left(W^{\otimes n}\right)$ is the group of unitary automorphisms on the inner product space $W^{\otimes n}$. This is a monoidal category. The tensor product is given by the addition of natural numbers on the objects and by the tensor product of unitaries

$$
U\left(W^{\otimes m}\right) \times U\left(W^{\otimes n}\right) \xrightarrow{\otimes} U\left(W^{\otimes(m+n)}\right) \quad, \quad\left(u_{1}, u_{2}\right) \mapsto u_{1} \otimes u_{2}
$$

on the morphisms. Note that we understand

$$
\left.W^{\otimes n}=(\ldots(W \otimes W) \otimes W) \otimes \ldots\right),
$$

i.e. we fix a choice of brackets for the tensor powers of $W$. In particular, the associators of $\mathcal{B} U_{\otimes}^{W}$ are identities. The maps $W^{\otimes m} \otimes W^{\otimes n} \rightarrow W^{\otimes n} \otimes W^{\otimes m}$, which interchange the tensor factors, turn $\mathcal{B} U_{\otimes}^{W}$ into a permutative category via conjugation. The geometric realisation of this category is

$$
\left|\mathcal{B} U_{\otimes}^{W}\right|=\coprod_{n \in \mathbb{N}_{0}} B U\left(W^{\otimes n}\right) .
$$

Let $d=\operatorname{dim}(W)$ and denote by $1_{d} \in U(W)$ the identity matrix. The tensor product described above induces an embedding of $U\left(W^{\otimes n}\right)$ into $U\left(W^{\otimes(n+1)}\right)$ defined by

$$
\iota_{n}: U\left(W^{\otimes n}\right) \rightarrow U\left(W^{\otimes(n+1)}\right) \quad, \quad u \mapsto u \otimes 1_{d},
$$

which is a group homomorphism.
Let $\mathbb{Z}\left[\frac{1}{d}\right] \subset \mathbb{Q}$ be the subring of the rationals given by all fractions $\frac{p}{q}$ with $q$ an arbitrary power of $d$. By [32, Thm. 2.2] there is a topological space $B U_{\otimes}\left[\frac{1}{d}\right]$ and a continuous map $\ell: B U \rightarrow B U_{\otimes}\left[\frac{1}{d}\right]$, such that the pair is a localisation of the simply connected space $B U$ in the sense of [32, Def. 2.1] with respect to the set of prime factors of $d$, i.e. with $\mathbb{Z}_{\ell}=\mathbb{Z}\left[\frac{1}{d}\right]$. For further details we refer the reader to [1, Chap. 3]. The following is a wellknown result from homotopy theory. Since we could not find a proof in the literature, we give one here.

Lemma 3.1. The group completion of $\left|\mathcal{B} U_{\otimes}^{W}\right|$ satisfies

$$
\Omega B\left|\mathcal{B} U_{\otimes}^{W}\right| \simeq B U_{\otimes}\left[\frac{1}{d}\right] \times \mathbb{Z} .
$$

Proof. The homomorphism $\iota_{n}$ induces $B \iota_{n}: B U\left(W^{\otimes n}\right) \rightarrow B U\left(W^{\otimes(n+1)}\right)$. The collection of all $B \iota_{n}$ gives a continuous map $B \iota_{\infty}:\left|\mathcal{B} U_{\otimes}^{W}\right| \rightarrow\left|\mathcal{B} U_{\otimes}^{W}\right|$. Let $\left|\mathcal{B} U_{\otimes}^{W}\right|_{\infty}$ be the mapping telescope of the sequence

$$
\left|\mathcal{B} U_{\otimes}^{W}\right| \xrightarrow{B \iota_{\infty}}\left|\mathcal{B} U_{\otimes}^{W}\right| \xrightarrow{B \iota_{\infty}}\left|\mathcal{B} U_{\otimes}^{W}\right| \xrightarrow{B \iota_{\infty}} \ldots
$$

Given a finite dimensional inner product space $V$ denote by $U_{\infty}(V)$ the colimit over $m$ of $U\left(\bigoplus_{k=1}^{m} V\right) \rightarrow U\left(\bigoplus_{k=1}^{m+1} V\right)$ defined by $w \mapsto w \oplus \mathrm{id}_{V}$. The embedding into the upper left hand corner induces a continuous map $B U(V) \rightarrow B U_{\infty}(V)$. The following diagram commutes:


The map $B U\left(W^{\otimes n}\right) \rightarrow B U\left(W^{\otimes(n+1)}\right)$ induced by $u \mapsto u \otimes 1_{d}$ classifies the tensor product of the universal bundle with the trivial vector bundle with fibre $W$, which has rank $d$. It induces multiplication by $d$ on all homotopy groups $\pi_{k}$ with $k>0$. The analogous statement is true for the bottom line of the diagram. Thus, the vertical maps induce a weak equivalence of the respective colimits. Each space $B U_{\infty}\left(W^{\otimes n}\right)$ is homotopy equivalent to $B U$. By [22, Prop. 6.61] the colimit over the maps in the last row is equivalent to the localisation $B U_{\otimes}\left[\frac{1}{d}\right]$. This gives the homotopy type of the path components of $\left|\mathcal{B} U_{\otimes}^{W}\right|$. Furthermore $\pi_{0}\left(\Omega B\left|\mathcal{B} U_{\otimes}^{W}\right|\right) \cong \mathbb{Z}$. As a consequence we obtain

$$
\left|\mathcal{B} U_{\otimes}^{W}\right|_{\infty} \simeq B U_{\otimes}\left[\frac{1}{d}\right] \times \mathbb{Z} .
$$

Note in particular that each path component is simply connected. Since $\mathcal{B} U_{\otimes}^{W}$ is permutative, the topological monoid $\left|\mathcal{B} U_{\otimes}^{W}\right|$ is homotopy commutative. The statement now follows from [28, Cor. 1.2] and the observation that $\left|\mathcal{B} U_{\otimes}^{W}\right|_{\infty}^{+} \simeq\left|\mathcal{B} U_{\otimes}^{W}\right|_{\infty}$.

Remark 3.2. The path components of $\left|\mathcal{B} U_{\otimes}^{W}\right|$ are labelled by natural numbers, where $k \in \mathbb{N}$ corresponds to the space $B U\left(W^{\otimes k}\right)$ classifying vector bundles of rank $d^{k}$. Thus, we should think of the path component of $\Omega B\left|\mathcal{B} U_{\otimes}^{W}\right|$ labelled by $k \in \mathbb{Z}$ as the one classifying "localised" virtual vector bundles of virtual dimension $d^{k}$ and hence of the factor $\mathbb{Z}$ as sitting inside $\mathbb{Z}\left[\frac{1}{d}\right]$ via the embedding $k \mapsto d^{k}$.

The exponential functor $F$ induces homomorphisms $U(n) \rightarrow U\left(F\left(\mathbb{C}^{n}\right)\right)$. Let $\tau_{m, n}=\tau_{\mathbb{C}^{m}, \mathbb{C}^{n}}$ be the natural transformation that is part of the structural data of $F$. By splitting off tensor factors via $\tau_{1, k}$ we obtain a unitary
isomorphism

$$
\tau_{n}: F\left(\mathbb{C}^{n}\right) \rightarrow W^{\otimes n}
$$

The associativity of $\tau_{\mathbb{C}^{m}, \mathbb{C}^{n}}$ implies that the following diagram commutes


Moreover, we have

$$
\tau_{m, n} \circ F\left(u_{1} \oplus u_{2}\right)=F\left(u_{1}\right) \otimes F\left(u_{2}\right) \circ \tau_{m, n}
$$

by naturality of $\tau_{m, n}$. Define $\kappa_{n}: U(n) \rightarrow U\left(W^{\otimes n}\right)$ by $u \mapsto \tau_{n} \circ F(u) \circ \tau_{n}^{-1}$. For $u_{1} \in U(m)$ and $u_{2} \in U(n)$ we obtain

$$
\begin{align*}
\kappa_{m+n}\left(u_{1} \oplus u_{2}\right) & =\left(\tau_{m} \otimes \tau_{n}\right) \circ \tau_{m, n} \circ F\left(u_{1} \oplus u_{2}\right) \circ \tau_{m, n}^{-1} \circ\left(\tau_{m} \otimes \tau_{n}\right)^{-1}  \tag{10}\\
& =\left(\tau_{m} \circ F\left(u_{1}\right) \circ \tau_{m}^{-1}\right) \otimes\left(\tau_{n} \circ F\left(u_{2}\right) \circ \tau_{n}^{-1}\right) \\
& =\kappa_{m}\left(u_{1}\right) \otimes \kappa_{n}\left(u_{2}\right) .
\end{align*}
$$

This implies that the collection of all $\kappa_{n}$ combines to a (strict) monoidal functor $\kappa: \mathcal{B} U_{\oplus} \rightarrow \mathcal{B} U_{\otimes}^{W}$. Thus, we obtain a continuous monoid homomorphism $|\kappa|:\left|\mathcal{B} U_{\oplus}\right| \rightarrow\left|\mathcal{B} U_{\otimes}^{W}\right|$, which induces a map $B|\kappa|: B\left|\mathcal{B} U_{\oplus}\right| \rightarrow B\left|\mathcal{B} U_{\otimes}^{W}\right|$ that restricts to

$$
\tau_{F}: B\left(B U_{\oplus} \times\{0\}\right) \rightarrow B\left(B U_{\otimes}\left[\frac{1}{d}\right] \times\{0\}\right) .
$$

The codomain is equivalent to the 1-connected cover of $B G L_{1}\left(K U\left[\frac{1}{d}\right]\right)$ classifying twists of localised complex $K$-theory.

Remark 3.3. In the construction it suffices to have an exponential functor $F: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ on the isomorphism groupoid. An important example of a functor of this type without an extension to $\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ is the top exterior power functor $\Lambda^{\text {top }}$. The map $B U(n) \rightarrow B U\left(F\left(\mathbb{C}^{n}\right)\right) \simeq B U(1)$ induced by $\bigwedge^{\text {top }}$ agrees with the one induced by the determinant and the corresponding map $\tau_{\text {det }}: B B U_{\oplus} \rightarrow B B U_{\otimes}$ factors as

$$
\tau_{\mathrm{det}}: B B U_{\oplus} \rightarrow B B U(1) \rightarrow B B U_{\otimes}
$$

3.2. Detecting the cohomology of $S U(n)$ via $\mathbb{C} P^{n}$. In this section we will construct maps $f_{n}: S \mathbb{C} P^{n-1} \rightarrow S U(n)$ detecting the generators in cohomology. This will be applied to compute the rational characteristic classes of the twists $\tau_{F}$ in Sec. 3.3. Fix $n \in \mathbb{N}$, let $e \in M_{n}(\mathbb{C})$ be the rank 1-projection onto the first component of $\mathbb{C}^{n}$ and let $\omega: I \rightarrow S U(n)$ be given by

$$
\omega(t)=\left(I_{n}-(1-\exp (2 \pi i t)) e\right) \exp \left(-2 \pi i \frac{t}{n}\right),
$$

where $I_{n} \in M_{n}(\mathbb{C})$ denotes the identity matrix. Now consider the map $\widehat{f}_{n}: I \times S U(n) \rightarrow S U(n)$ defined by

$$
\widehat{f}_{n}(t, u)=u \omega(t) u^{*}
$$

Observe that $\widehat{f}_{n}(t, u)$ only depends on the class of $u$ in the homogeneous space $S U(n) / S(U(1) \times U(n-1))$, which is homeomorphic to $\mathbb{C} P^{n-1}$ via the map that sends $[v] \in S U(n) / S(U(1) \times U(n-1))$ to $\left[x_{1}: \cdots: x_{n}\right] \in \mathbb{C} P^{n-1}$ with $x=v e_{1}$. Moreover, $\omega(0)=I_{n}$ and $\omega(1)=\exp \left(2 \pi i \frac{1}{n}\right)$. Hence, $\widehat{f}_{n}$ induces a well-defined map

$$
\begin{equation*}
f_{n}: S \mathbb{C} P^{n-1} \rightarrow S U(n) \tag{11}
\end{equation*}
$$

from the (unreduced) suspension of $\mathbb{C} P^{n-1}$ to $S U(n)$.
The cohomology rings of these spaces are well-known: For $S U(n)$ we obtain an exterior algebra over $\mathbb{Z}$ on generators in odd degrees between 3 and $2 n-1$, i.e.

$$
H^{*}(S U(n), \mathbb{Z}) \cong \Lambda_{\mathbb{Z}}\left[a_{3}, a_{5}, \ldots, a_{2 n-1}\right]
$$

Up to a sign the generators $a_{2 k+1} \in H^{*}(S U(n), \mathbb{Z})$ are obtained inductively as follows: Let $p_{S U(n)}: S U(n) \rightarrow S^{2 n-1}$ be defined by $p_{S U(n)}(v)=v e_{n}$. This is a fibration with fibre $S U(n-1)$ to which the Leray-Hirsch theorem applies. We obtain the isomorphism

$$
H^{*}(S U(n), \mathbb{Z}) \cong H^{*}(S U(n-1), \mathbb{Z}) \otimes H^{*}\left(S^{2 n-1}, \mathbb{Z}\right)
$$

For $n=2$ the map $p_{S U(2)}$ is a homeomorphism and choosing a generator of $H^{3}\left(S^{3}, \mathbb{Z}\right)$ fixes $a_{3} \in H^{3}(S U(2), \mathbb{Z})$ as well. For $n>2$, the generators $a_{3}, \ldots, a_{2 n-3} \in H^{*}(S U(n), \mathbb{Z})$ are all fixed by the fact that the restriction to $S U(n-1)$ maps them to the corresponding generators there. The remaining element $a_{2 n-1} \in H^{2 n-1}(S U(n), \mathbb{Z})$ is the image of a generator of $H^{2 n-1}\left(S^{2 n-1}, \mathbb{Z}\right)$ under $p_{S U(n)}^{*}: H^{2 n-1}\left(S^{2 n-1}, \mathbb{Z}\right) \rightarrow H^{2 n-1}(S U(n), \mathbb{Z})$.

We will also need the cohomology ring of $U(n)$, which is a similar exterior algebra, but with one more generator in degree 1:

$$
H^{*}(U(n), \mathbb{Z}) \cong \Lambda_{\mathbb{Z}}\left[c_{1}, c_{3}, \ldots, c_{2 n-1}\right]
$$

The cohomology ring of $\mathbb{C} P^{n-1}$ is a truncated polynomial ring on one generator $t$ in degree 2, i.e.

$$
H^{*}\left(\mathbb{C} P^{n-1}, \mathbb{Z}\right) \cong \mathbb{Z}[t] /\left(t^{n}\right)
$$

where the element $t \in H^{2}\left(\mathbb{C} P^{n-1}, \mathbb{Z}\right)$ is the Chern class of the canonical line bundle over $\mathbb{C} P^{n-1}$. On cohomology the inclusion map $\iota: S U(n) \rightarrow U(n)$ sends $c_{1}$ to 0 and identifies $c_{2 k+1}$ with $a_{2 k+1}$ for $k \in\{1, \ldots, n-1\}$. Thus, to understand $f_{n}^{*}: H^{*}(S U(n), \mathbb{Z}) \rightarrow H^{*}\left(S \mathbb{C} P^{n-1}, \mathbb{Z}\right)$ it suffices to consider

$$
\iota \circ f_{n}: S \mathbb{C} P^{n-1} \rightarrow U(n)
$$

However, this map is homotopic to

$$
\begin{equation*}
h_{n}: S \mathbb{C} P^{n-1} \rightarrow U(n) \quad, \quad h_{n}([t, u])=I_{n}-(1-\exp (2 \pi i t)) \text { ueu* } \tag{12}
\end{equation*}
$$

The class $c_{2 n-1} \in H^{2 n-1}(U(n), \mathbb{Z})$ is the image of a generator under the homomorphism induced by $p=p_{U(n)}: U(n) \rightarrow S^{2 n-1}$ with $p(v)=v e_{n}$. We define $g_{n}=p \circ h_{n}: S \mathbb{C} P^{n-1} \rightarrow S^{2 n-1}$. The inclusion $S U(n-1) \rightarrow S U(n)$ into the upper left hand corner induces an embedding $S \mathbb{C} P^{n-2} \rightarrow S \mathbb{C} P^{n-1}$.

With respect to the homeomorphism $S U(n) / S(U(1) \times U(n-1)) \cong \mathbb{C} P^{n-1}$ described above this map corresponds to the suspension of $\mathbb{C} P^{n-2} \subset \mathbb{C} P^{n-1}$ which identifies $\left[x_{1}: \cdots: x_{n-1}\right]$ with $\left[x_{1}: \cdots: x_{n-1}: 0\right]$. The effect of $g_{n}$ on the top-dimensional cell of $S \mathbb{C} P^{n-1}$ was described in [36, Lem. 6.1] with the following result:

Lemma 3.4. The map $g_{n}$ induces a homeomorphism

$$
\bar{g}_{n}: S \mathbb{C} P^{n-1} / S \mathbb{C} P^{n-2} \rightarrow S^{2 n-1} .
$$

Let $\sigma: H^{k}(S X, \mathbb{Z}) \rightarrow H^{k-1}(X, \mathbb{Z})$ for $k>1$ be the suspension isomorphism. We are now ready to prove that the homomorphisms $f_{n}^{*}$ together with the suspension isomorphisms detect the generators of $H^{*}(S U(n), \mathbb{Z})$.
Lemma 3.5. The map $f_{n}$ defined in (11) induces the following homomorphism on cohomology

$$
\sigma \circ f_{n}^{*}: H^{2 k+1}(S U(n), \mathbb{Z}) \rightarrow H^{2 k}\left(\mathbb{C} P^{n-1}, \mathbb{Z}\right)
$$

The generators $a_{2 k+1} \in H^{*}(S U(n), \mathbb{Z})$ can be chosen in such a way that the above homomorphism satisfies

$$
\left(\sigma \circ f_{n}^{*}\right)\left(a_{2 k+1}\right)=t^{k}
$$

for $k \in\{1, \ldots, n-1\}$.
Proof. We will prove the statement by induction over $n$. For $n=2$ the map $p_{S U(2)}$ is a homeomorphism and $p_{S U(2)} \circ f_{2}$ is homotopic to $g_{2}: S \mathbb{C} P^{1} \rightarrow S^{3}$, which in turn is a homotopy equivalence by Lemma 3.4 and the contractibility of $S \mathbb{C} P^{0} \cong I$. Thus, if $x_{3} \in H^{3}\left(S^{3}, \mathbb{Z}\right)$ is a generator, then $\sigma \circ f_{2}^{*} \circ$ $p_{S U(2)}^{*}\left(x_{3}\right)$ has to agree with $\pm t \in H^{2}\left(\mathbb{C} P^{1}, \mathbb{Z}\right) \cong \mathbb{Z}$, but $p_{S U(2)}^{*}\left(x_{3}\right)=a_{3}$.

Let $\iota: S U(n) \rightarrow U(n)$ be the inclusion map. As was already pointed out above we have $\iota^{*}\left(c_{2 k+1}\right)=a_{2 k+1}$ for $k \in\{1, \ldots, n-1\}$ and $f_{n}^{*} \circ \iota^{*}=h_{n}^{*}$. Hence, it suffices to show that $h_{n}^{*}\left(c_{2 k+1}\right)=t^{k}$. Assume that we have proven this statement in all dimensions $m \in\{2, \ldots, n-1\}$. To prove that it follows for $m=n$ as well note that the following diagram commutes

where $j_{n-1}$ and $\iota_{n}$ denote the inclusions described above. Observe that $\iota_{n}: U(n-1) \rightarrow U(n)$ induces the homomorphism

$$
\begin{gathered}
\iota_{n}^{*}: \Lambda_{\mathbb{Z}}\left[c_{1}, \ldots, c_{2 n-3}, c_{2 n-1}\right] \rightarrow \Lambda_{\mathbb{Z}}\left[c_{1}^{\prime}, \ldots, c_{2 n-3}^{\prime}\right], \\
\iota_{n}^{*}\left(c_{2 k-1}\right)= \begin{cases}c_{2 k-1}^{\prime} & \text { if } 1 \leq k \leq n-1 \\
0 & \text { if } k=n\end{cases}
\end{gathered}
$$

whereas $j_{n-1}^{*}$ can be identified with the quotient homomorphism

$$
j_{n-1}^{*}: \mathbb{Z}[t] /\left(t^{n}\right) \rightarrow \mathbb{Z}\left[t^{\prime}\right] /\left(\left(t^{\prime}\right)^{n-1}\right) .
$$

For $k \in\{1, \ldots, n-2\}$ our induction hypothesis implies

$$
\left(t^{\prime}\right)^{k}=h_{n-1}^{*}\left(c_{2 k+1}^{\prime}\right)=h_{n-1}^{*}\left(\iota_{n}^{*}\left(c_{2 k+1}\right)\right)=j_{n-1}^{*}\left(h_{n}^{*}\left(c_{2 k+1}\right)\right)
$$

and therefore $h_{n}^{*}\left(c_{2 k+1}\right)=t^{k}$. Hence, it only remains to be seen that we can choose the generators $c_{2 n-1}$ such that $h_{n}^{*}\left(c_{2 n-1}\right)=t^{n-1}$. It suffices to prove that $h_{n}^{*} \circ p^{*}=g_{n}^{*}$ is an isomorphism. The long exact sequence of the pair $\left(S \mathbb{C} P^{n-1}, S \mathbb{C} P^{n-2}\right)$ shows that $H^{2 n-1}\left(S \mathbb{C} P^{n-1}, S \mathbb{C} P^{n-2}, \mathbb{Z}\right) \rightarrow$ $H^{2 n-1}\left(S \mathbb{C} P^{n-1}, \mathbb{Z}\right)$ is an isomorphism. The domain is isomorphic to the cohomology of the quotient and the commutative diagram

together with Lemma 3.4 proves that $g_{n}$ is indeed an isomorphism.
3.3. Twists over $S U(n)$ from Bott periodicity. Bott periodicity yields a homotopy equivalence

$$
B\left(B U_{\oplus} \times \mathbb{Z}\right) \simeq U
$$

The map $B\left(B U_{\oplus} \times \mathbb{Z}\right) \rightarrow B \mathbb{Z}$ induced by the projection corresponds to the determinant map on the right hand side. Therefore, Bott periodicity restricts to an equivalence $B B U_{\oplus}=B\left(B U_{\oplus} \times\{0\}\right) \simeq S U$ of the corresponding homotopy fibres. The group $S U$ is the colimit over all $S U(n)$ over the embeddings $S U(n) \rightarrow S U(n+1)$. In particular, we obtain twists of the form

$$
\begin{equation*}
\tau_{F}^{n}: S U(n) \longrightarrow S U \simeq B B U_{\oplus} \xrightarrow{\tau_{F}} B B U_{\otimes}\left[\frac{1}{d}\right] \tag{13}
\end{equation*}
$$

These twists over $S U(n)$ provide a (non-equivariant) generalisation of the one described by the basic gerbe [23, 14, 24] in the following sense: Let $\tau_{\text {det }}$ be the map associated to the exponential functor $\Lambda^{\text {top }}: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ as in Rem. 3.3. As we will see below, the associated twist $\tau_{\text {det }}^{n}$ corresponds to a generator $a_{3} \in H^{3}(S U(n), \mathbb{Q}) \cong H_{S U(n)}^{3}(S U(n), \mathbb{Q}) \cong \mathbb{Q}$ and therefore agrees with the one given by the basic gerbe.

The rationalisation of the generalised cohomology theory associated to the infinite loop space $B B U_{\otimes}$ is well-understood [33, Prop. 3.5]. Up to equivalence it agrees with rational ordinary cohomology in odd degrees starting with 3, i.e.

$$
\begin{equation*}
\left(B B U_{\otimes}\right)_{\mathbb{Q}} \simeq \prod_{n \in \mathbb{N}} K(2 n+1, \mathbb{Q}) . \tag{14}
\end{equation*}
$$

To obtain a map inducing the above equivalence note that the Chern character provides a $E_{\infty}$-ring map that identifies rational topological $K$-theory $K U_{\mathbb{Q}}$ with even rational cohomology $H \mathbb{Q}$. It restricts to an equivalence $B G L_{1}\left(K U_{\mathbb{Q}}\right) \rightarrow B G L_{1}(H \mathbb{Q})$. Restricting to the 1-connected cover and
composing this transformation with the natural logarithm on rational cohomology [29, Sec. 2.5, Prop. 2.6], we obtain the equivalence (14).

Composing (13) with the natural map $B B U_{\otimes}\left[\frac{1}{d}\right] \rightarrow\left(B B U_{\otimes}\right)_{\mathbb{Q}}$ and then applying (14) we obtain a class

$$
\begin{equation*}
\delta^{F, n}=\delta_{3}^{F, n}+\delta_{5}^{F, n}+\delta_{7}^{F, n}+\ldots \quad \in H^{\text {odd }}(S U(n), \mathbb{Q}), \tag{15}
\end{equation*}
$$

which can be expressed in terms of the generators $a_{2 k+1} \in H^{2 k+1}(S U(n), \mathbb{Q})$. We will employ Lemma 3.5 to make this explicit. Hence, we need to understand $f_{n}^{*}\left(\delta^{F, n}\right) \in H^{\text {odd }}\left(S \mathbb{C} P^{n-1}, \mathbb{Q}\right) \cong H^{\text {even }}\left(\mathbb{C} P^{n-1}, \mathbb{Q}\right)$. A first step in this direction is provided by the next lemma.

Lemma 3.6. Let $f_{n}: S \mathbb{C} P^{n-1} \rightarrow S U(n)$ be the map defined in (11). Let $\alpha_{n}: \mathbb{C} P^{n-1} \rightarrow B U_{\oplus}$ be the continuous map that is adjoint to

$$
\Sigma \mathbb{C} P^{n-1} \simeq S \mathbb{C} P^{n-1} \xrightarrow{f_{n}} S U(n) \longrightarrow S U \simeq B B U_{\oplus}
$$

Then $\alpha_{n}$ classifies the virtual vector bundle $[H]-[\mathbb{C}]$, where $H$ is the tautological line bundle over $\mathbb{C} P^{n-1}$.

Proof. Let $\iota: S U(n) \rightarrow U(n)$ and $\iota_{\infty}: S U \rightarrow U$ be the inclusion maps. Let $h_{n}: S \mathbb{C} P^{n-1} \rightarrow U(n)$ be the map defined in (12). In the following diagram the triangle commutes up to homotopy, while the square commutes.


This implies that the two maps $\mathbb{C} P^{n-1} \rightarrow \Omega U$ adjoint to $\iota_{\infty} \circ \alpha \circ f_{n}$ and $\alpha \circ h_{n}$, respectively, agree up to homotopy. Moreover, the homotopy equivalences $\Omega S U \simeq B U_{\oplus}$ and $\Omega U \simeq B U_{\oplus} \times \mathbb{Z}$ identify $\Omega \iota_{\infty}: \Omega S U \rightarrow \Omega U$ with the inclusion map $B U_{\oplus} \rightarrow B U_{\oplus} \times \mathbb{Z}$ onto the 0-component. Hence it remains to be proven that the map adjoint to $\alpha \circ h_{n}$ classifies the stable isomorphism class of $H$ in reduced $K$-theory, which corresponds to $[H]-[\mathbb{C}]$, when $\widetilde{K}^{0}\left(\mathbb{C} P^{n-1}\right)$ is viewed as formal differences of unreduced classes.

To see why this is true, we have to take a look at the equivalence $U \simeq$ $B\left(\coprod_{n \in \mathbb{N}_{0}} B U(n)\right)$. We follow the proof of Bott periodicity given in [17]. Let $\mathbb{K}$ be the compact operators on a separable infinite dimensional Hilbert space $H$ and denote by $\mathcal{P}(\mathbb{K})$ the space of all projections in $\mathbb{K}$ with the norm topology. Let $\left|X_{\bullet}\right|$ be the geometric realisation of the simplicial space $\left(X_{n}\right)_{n \in \mathbb{N}_{0}}$ with $X_{0}=\{\mathrm{pt}\}$ and

$$
X_{n}=\left\{\left(p_{1}, \ldots, p_{n}\right) \in \mathcal{P}(\mathbb{K})^{n} \mid p_{i} p_{j}=0 \text { for all } i \neq j\right\}
$$

for $n>0$, where the face maps take sums of projections and the degeneracy maps add a zero projection to the tuple. The spectral decomposition of
elements in $U$ yields a homeomorphism [17, Sec. 2, p. 451]

$$
s:\left|X_{\bullet}\right| \rightarrow U \quad, \quad\left[\left(t_{1}, \ldots, t_{n}\right),\left(p_{1}, \ldots, p_{n}\right)\right] \mapsto \exp \left(2 \pi i \sum_{i=1}^{n} t_{i} p_{i}\right) .
$$

Let $\mathcal{P}_{e}(\mathbb{K}) \subset \mathcal{P}(\mathbb{K})$ be the subspace of rank 1 projections. Note that this has the homotopy type of the classifying space $B U(1)$. Let $j: S \mathcal{P}_{e}(\mathbb{K}) \rightarrow\left|X_{\bullet}\right|$ be the canonical map that identifies $[t, p] \in S \mathcal{P}_{e}(\mathbb{K})$ with the corresponding point in $\left|X_{\bullet}\right|$. The map $h_{n}$ can be rewritten as follows

$$
h_{n}([t, u])=\exp \left(2 \pi i t u e u^{*}\right) .
$$

Thus, if we define $k_{n}: \mathbb{C} P^{n-1} \rightarrow \mathcal{P}_{e}(\mathbb{K})$ by $k_{n}([u])=$ ueu $^{*} \in \mathcal{P}_{e}(\mathbb{K}) \subset X_{1}$, then the following diagram commutes


The proof of Bott periodicity in [17] proceeds by constructing two simplicial spaces $\left(Z_{n}\right)_{n \in \mathbb{N}_{0}}$ and $\left(Y_{n}\right)_{n \in \mathbb{N}_{0}}$ and equivalences

$$
U \cong\left|X_{\bullet}\right| \simeq\left|Z_{\bullet}\right| \simeq\left|Y_{\bullet}\right| \simeq B\left(\coprod_{n \in \mathbb{N}_{0}} B U(n)\right) .
$$

Tracing the map $j$ through these equivalences we see that it agrees up to homotopy with

$$
\bar{j}: S B U(1) \xrightarrow{(1)} \Sigma B U(1)_{+} \xrightarrow{(2)} B\left(\coprod_{n \in \mathbb{N}_{0}} B U(n)\right)
$$

where $B U(1)_{+}$denotes the space $B U(1)$ with a disjoint basepoint, (1) is the quotient map and (2) is induced by the inclusion of the 1 -skeleton. Thus, the bundle classified by the map adjoint to $\Sigma \mathbb{C} P^{n-1} \simeq S \mathbb{C} P^{n-1} \rightarrow$ $B\left(\coprod_{n \in \mathbb{N}_{0}} B U(n)\right)$ agrees with the one classified by $k_{n}: \mathbb{C} P^{n-1} \rightarrow \mathcal{P}_{e}(\mathbb{K})$. Up to the homotopy equivalences described above this agrees with the quotient map

$$
U(n) / U(1) \times U(n-1) \rightarrow U(H) / U(1) \times U\left(e_{1}^{\perp}\right)
$$

classifying the tautological bundle $H \cong U(n) / U(n-1) \rightarrow \mathbb{C} P^{n-1}$.
Corollary 3.7. Let $f_{n}: S \mathbb{C} P^{n-1} \rightarrow S U(n)$ be the map defined in (11). The map $\psi_{n}$ adjoint to

$$
f_{n}^{*} \tau_{F}^{n}: \Sigma \mathbb{C} P^{n-1} \simeq S \mathbb{C} P^{n-1} \xrightarrow{f_{n}} S U(n) \xrightarrow{\tau_{F}^{n}} B B U_{\otimes}\left[\frac{1}{d}\right]
$$

classifies the bundle $\frac{1}{d} F(H)$, where $H \rightarrow \mathbb{C} P^{n-1}$ denotes the tautological line bundle.

Proof. This is now a direct consequence of Lemma 3.6. Note that $F(H)$ is classified by a map $\mathbb{C} P^{n-1} \rightarrow B U_{\otimes}\left[\frac{1}{d}\right] \times\{1\} \subset B U_{\otimes}\left[\frac{1}{d}\right] \times \mathbb{Z}$ (see Remark 3.2) and we have $[F(H)]=\left[\psi_{n}\right] \cdot[F(\mathbb{C})]$ as classes in $\left[\mathbb{C} P^{n-1}, B U_{\otimes}\left[\frac{1}{d}\right] \times \mathbb{Z}\right]$.

With Cor. 3.7 we now have all the tools in place to compute the indecomposable terms in the rational characteristic classes of $\tau_{F}^{n}$ for a polynomial exponential functor $F$ in terms of the generators of $H^{\text {odd }}(S U(n), \mathbb{Q})$.

Theorem 3.8. Let $n \in \mathbb{N}$, let $F: \mathcal{V}_{\mathbb{C}}^{\text {fin }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {fin }}$ be a polynomial exponential functor and let $\left(b_{1}, \ldots, b_{k}\right) \in \mathbb{N}^{k}$ be the rescaled Thoma parameters of its $R$ matrix. The class $\delta^{F, n} \in H^{\text {odd }}(S U(n), \mathbb{Q})$ obtained from the rationalisation of the twist $\tau_{F}^{n}: S U(n) \rightarrow B B U_{\otimes}\left[\frac{1}{d}\right]$ as in (15) takes the form

$$
\delta^{F, n}=\kappa_{1} a_{3}+\kappa_{2} a_{5}+\cdots+\kappa_{n-1} a_{2 n-1}+r \in H^{\text {odd }}(S U(n), \mathbb{Q})
$$

where $\kappa_{i}$ is the ith coefficient in the Taylor expansion of

$$
\kappa(x)=\sum_{j=1}^{k} \log \left(\frac{1+b_{j} e^{x}}{1+b_{j}}\right)
$$

and $r \in H^{\text {odd }}(S U(n), \mathbb{Q})$ only contains decomposable terms.
Proof. Let $\tau_{F, \mathbb{Q}}^{n}: S U(n) \rightarrow(B B U)_{\mathbb{Q}}$ be the composition of $\tau_{F}^{n}$ with the natural map $B B U_{\otimes}\left[\frac{1}{d}\right] \rightarrow(B B U)_{\mathbb{Q}}$. As described in the paragraph after (14) the class $\delta^{F, n}$ is represented by the map $B(\log \mathrm{ch}) \circ \tau_{F, \mathbb{Q}}^{n}$. By Lemma 3.5 the coefficient $\kappa_{i}$ agrees with the coefficient of $t^{i}$ of the class

$$
f_{n}^{*} \delta^{F, n} \in H^{\text {odd }}\left(S \mathbb{C} P^{n-1}, \mathbb{Q}\right) \cong H^{\text {even }}\left(\mathbb{C} P^{n-1}, \mathbb{Q}\right) \cong \mathbb{Q}[t] /\left(t^{n}\right) .
$$

By Cor. 3.7 this class agrees with $\log \operatorname{ch}\left(\frac{1}{d} F(H)\right)$. In particular, it only depends on the isomorphism class of $F(H)$. Let $F^{b_{i}}=F^{\mathbb{C}^{b_{i}}}$. We can now apply Thm. 2.15 to obtain

$$
\begin{aligned}
\log \operatorname{ch}(F(H)) & =\log \operatorname{ch}\left(F^{b_{1}}(H) \otimes \cdots \otimes F^{b_{k}}(H)\right) \\
& =\log \left(\operatorname{ch}\left(F^{b_{1}}(H)\right) \cdots \operatorname{ch}\left(F^{b_{k}}(H)\right)\right)=\sum_{i=1}^{k} \log \operatorname{ch}\left(F^{b_{i}}(H)\right)
\end{aligned}
$$

Note that we have $d=\left(1+b_{1}\right) \cdots\left(1+b_{k}\right)$. Thus, we are left with the computation of $\frac{1}{1+b_{i}} \operatorname{ch}\left(F^{b_{i}}(H)\right)$. This turns out to be

$$
\frac{1}{1+b_{i}} \operatorname{ch}\left(F^{b_{i}}(H)\right)=\frac{1}{1+b_{i}}\left(\operatorname{ch}\left(\mathbb{C} \oplus \mathbb{C}^{b_{i}} \otimes \Lambda^{1}(H)\right)=\frac{1+b_{i} e^{t}}{1+b_{i}}\right.
$$

which proves the statement.
Corollary 3.9. Let $F: \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}} \rightarrow \mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}$ be a polynomial exponential functor and let $\left(b_{1}, \ldots, b_{k}\right)$ be the rescaled Thoma parameters of its associated $R$-matrix. For the characteristic classes $\delta^{F, 2}$ and $\delta^{F, 3}$ associated to the twists $\tau_{2}^{F}$ over
$S U(2)$ and $\tau_{3}^{F}$ over $S U(3)$, respectively, we obtain

$$
\begin{aligned}
& \delta^{F, 2}=\delta_{3}^{F, 2}=\sum_{i=1}^{k} \frac{b_{i}}{b_{i}+1} a_{3}, \\
& \delta^{F, 3}=\delta_{3}^{F, 3}+\delta_{5}^{F, 3}=\sum_{i=1}^{k}\left(\frac{b_{i}}{b_{i}+1} a_{3}+\frac{b_{i}}{2\left(b_{i}+1\right)^{2}} a_{5}\right) .
\end{aligned}
$$

Proof. The rational cohomology of $S U(2)$ is $H^{*}(S U(2), \mathbb{Q}) \cong \Lambda_{\mathbb{Q}}\left[a_{3}\right]$. Since all products are trivial in this ring, there are no decomposable terms. Likewise, $H^{*}(S U(3), \mathbb{Q}) \cong \Lambda_{\mathbb{Q}}\left[a_{3}, a_{5}\right]$. Therefore all decomposable expressions live in degree 8 , which is even.

Finally, it is also possible to treat the classical twists obtained from the basic gerbe over $S U(n)$ using the techniques developed above as explained in the next theorem.

Theorem 3.10. Let $\tau_{\text {det }}^{n}: S U(n) \rightarrow B B U_{\otimes}$ be the twist associated to the exponential functor $\bigwedge^{\text {top }}: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ (see Rem. 3.3 and the beginning of this section). The associated class $\delta^{\text {det }, n} \in H^{\text {odd }}(S U(n), \mathbb{Q})$ satisfies

$$
\delta^{\mathrm{det}, n}=a_{3}
$$

Proof. We proceed as in the proof of the previous theorem. For $F=\Lambda^{\text {top }}$ we obtain $F(H) \cong H$ and $d=1$. Therefore

$$
\log \operatorname{ch}(F(H))=\log \operatorname{ch}(H)=\log \exp (t)=t
$$

Therefore $\kappa_{1}=1$. But since $\tau_{\text {det }}^{n}$ factors through $B B U(1)$, the class $\delta^{\operatorname{det}, n}$ can only be non-trivial in degree 3 .
Remark 3.11. Observe that for a fixed suspension coordinate $t$ the image of $f_{n}$ is the adjoint orbit of $\omega(t)$ in $S U(n)$ consisting of all matrices with one eigenvalue $\exp \left(2 \pi i t \frac{n-1}{n}\right)$ and $(n-1)$ eigenvalues of the form $\exp \left(-2 \pi i t \frac{1}{n}\right)$. This can be interpreted in terms of the decomposition of $S U(n)$ as a simplicial space as in [23, Eq. (18)]: The suspension coordinate runs along one of the edges in the 1 -skeleton of that decomposition. Using a different edge we obtain analogous maps

$$
S G r_{k}^{n} \rightarrow S U(n)
$$

where $G r_{k}^{n}$ denotes the Grassmann manifold of complex $k$-dim. subspaces in $\mathbb{C}^{n}$. We will leave it as an open question whether these maps yield more information about the rational cohomology classes of $\tau_{F}^{n}$ if an analogous analysis as the one above is performed with them.
3.4. From twists to Fell bundles. We end this paper with an outline of the operator algebraic description of the twists $\tau_{F}^{n}$ in terms of Fell bundles. For reasons of brevity we will only present a sketch here. The proofs of the claims made in this section will be part of upcoming work (see [13]). A Fell bundle consists of a groupoid $\mathcal{G}$ together with a Banach bundle $\pi: \mathcal{E} \rightarrow \mathcal{G}$
over the space of morphisms of $\mathcal{G}$ equipped with the following additional structure: Let $\mathcal{G}^{(2)} \subset \mathcal{G} \times \mathcal{G}$ be the subspace of composable arrows and let

$$
\mathcal{E}^{(2)}=\left\{\left(e_{1}, e_{2}\right) \in \mathcal{E} \times \mathcal{E} \mid\left(\pi\left(e_{1}\right), \pi\left(e_{2}\right)\right) \in \mathcal{G}^{(2)}\right\}
$$

The Fell bundle $\mathcal{E}$ carries a bilinear and associative multiplication map $\mathcal{E}^{(2)} \rightarrow \mathcal{E}$ denoted by a dot and an operator $*: \mathcal{E} \rightarrow \mathcal{E}$ inverting the underlying arrows of $\mathcal{G}$. The norm on the fibres should be submultiplicative and satisfy the $C^{*}$-condition $\left\|e^{*} \cdot e\right\|=\|e\|^{2}$. As a consequence the fibres of $\mathcal{E}$ over the objects of $\mathcal{G}$ are $C^{*}$-algebras and provide bimodules for the corresponding source and target algebras over the non-identity fibres. If these bimodules are Morita equivalences, the Fell bundle is called saturated. For the full details of the definition we refer the reader to $[8,18]$. In case $\mathcal{G}=Y^{[2]}$ is the pair groupoid of a fibration $Y \rightarrow X$ over a topological space $X$ and $\mathcal{E} \rightarrow \mathcal{G}$ is a line bundle the construction boils down to that of a bundle gerbe in the sense of [24].

Our construction is now based on the same idea as in [24]: For $g \in S U(n)$ let $\mathrm{EV}(g) \subset S^{1}$ be the set of distinct eigenvalues of $g$. Given $\lambda \in \mathrm{EV}(g)$ let $\operatorname{Eig}(g, \lambda) \subset \mathbb{C}^{n}$ be the eigenspace of $g$ with respect to $\lambda$. Fix a total order on $S^{1} \backslash\{1\}$ and define

$$
Y=\left\{(g, z) \in S U(n) \times\left(S^{1} \backslash\{1\}\right) \mid z \notin \mathrm{EV}(g)\right\}
$$

The fibre product $Y^{[2]}=\left\{\left(g, z_{1}, z_{2}\right) \in S U(n) \times\left(S^{1} \backslash\{1\}\right) \mid z_{1}, z_{2} \notin \mathrm{EV}(g)\right\}$ decomposes into three disjoint subspaces: the space $Y_{+}^{[2]}$ consisting of those triples $\left(g, z_{1}, z_{2}\right)$ with $z_{1}<z_{2}$ and at least one eigenvalue of $g$ between $z_{1}$ and $z_{2}$, the space $Y_{0}^{[2]}$ containing all triples with no eigenvalues between $z_{1}$ and $z_{2}$ and $Y_{-}^{[2]}$ obtained by interchanging the role of $z_{1}, z_{2}$ in $Y_{+}^{[2]}$.

Let $F: \mathcal{V}_{\mathbb{C}}^{\text {iso }} \rightarrow \mathcal{V}_{\mathbb{C}}^{\text {iso }}$ be an exponential functor and let $M_{F}=\operatorname{End}\left(F\left(\mathbb{C}^{n}\right)\right)^{\otimes \infty}$ be the infinite tensor product of the full matrix algebra $\operatorname{End}\left(F\left(\mathbb{C}^{n}\right)\right)$. This is a uniformly hyperfinite $C^{*}$-algebra. In particular, it is strongly selfabsorbing. Define $\mathcal{E}^{+} \rightarrow Y_{+}^{[2]}$ fibrewise as follows:

$$
\mathcal{E}_{\left(g, z_{1}, z_{2}\right)}^{+}=\bigotimes_{\substack{z_{1}<\lambda<\lambda z_{2} \\ \lambda \in \operatorname{EV}(g)}} F(\operatorname{Eig}(g, \lambda)) \otimes M_{F} .
$$

Each fibre is a right Hilbert $M_{F}$-module where $M_{F}$ acts by right multiplication on the tensor factor $M_{F}$. Let $W=\operatorname{Eig}(g, \lambda) \subset \mathbb{C}^{n}$. There are natural isomorphisms $F\left(\mathbb{C}^{n}\right) \cong F\left(W \oplus W^{\perp}\right) \cong F(W) \otimes F\left(W^{\perp}\right)$ induced by the exponential structure of $F$. As a consequence the infinite UHF-algebra $M_{F}$ absorbs the $C^{*}$-algebra

$$
\bigotimes_{\substack{z_{1} \lll z_{2} \\ \lambda \in \operatorname{EV}(g)}} \operatorname{End}(F(\operatorname{Eig}(g, \lambda)))
$$

and there is an isomorphism $\mathcal{K}_{M_{F}}\left(\mathcal{E}_{\left(g, z_{1}, z_{2}\right)}^{+}\right) \cong M_{F}$, where the left hand side denotes the compact $M_{F}$-linear operators on the Hilbert module $\mathcal{E}_{\left(g, z_{1}, z_{2}\right)}^{+}$.

This structure turns $\mathcal{E}_{\left(g, z_{1}, z_{2}\right)}^{+}$into an $M_{F}-M_{F}$-Morita equivalence. We have that $\mathcal{E}^{+} \rightarrow Y_{+}^{[2]}$ is a Banach bundle and the isomorphisms described above can be chosen in such a way that they form a bilinear associative multiplication

$$
\mathcal{E}_{\left(g, z_{1}, z_{2}\right)}^{+} \times \mathcal{E}_{\left(g, z_{2}, z_{3}\right)}^{+} \rightarrow \mathcal{E}_{\left(g, z_{1}, z_{3}\right)}^{+}
$$

for all $\left(g, z_{1}, z_{2}\right),\left(g, z_{2}, z_{3}\right) \in Y_{+}^{[2]}$. Moreover, if we define

$$
\mathcal{E}^{0}=Y_{0}^{[2]} \times M_{F} \quad \text { and } \quad \mathcal{E}_{\left(g, z_{1}, z_{2}\right)}^{-}=\left(\mathcal{E}_{\left(g, z_{2}, z_{1}\right)}^{+}\right)^{\mathrm{op}}
$$

then the multiplication extends to the disjoint union $\mathcal{E} \rightarrow Y^{[2]}$, is still bilinear and associative and turns $\mathcal{E}$ into a saturated Fell bundle over $\mathcal{G}=Y^{[2]}$. Choosing a Haar system on $\mathcal{G}$ we can now look at the $C^{*}$-algebra $C^{*}(\mathcal{E})$ of sections of $\mathcal{E}$. Pulling back continuous functions from $S U(n)$ to $Y^{[2]}$ we see that each $f \in C(S U(n))$ acts as a mutiplier on $C^{*}(\mathcal{E})$ and as such provides a central element. This turns $C^{*}(\mathcal{E})$ into a continuous $C(S U(n))$ algebra, whose fibres are all isomorphic to $M_{F} \otimes \mathbb{K}$, where $\mathbb{K}$ denotes the compact operators. The algebra $C^{*}(\mathcal{E})$ satisfies the Fell condition stated in [10, Def. 4.1]. Thus, by [10, Thm. 4.2] it is isomorphic to the section algebra of a locally trivial bundle of $C^{*}$-algebras over $S U(n)$ with fibre $M_{F} \otimes \mathbb{K}$. But since

$$
\left[S U(n), B \operatorname{Aut}\left(M_{F} \otimes \mathbb{K}\right)\right] \cong\left[S U(n), B B U_{\otimes}\left[\frac{1}{d}\right]\right]
$$

by [9] (with $d=\operatorname{dim}(F(\mathbb{C}))$ ) the bundle obtained from $C^{*}(\mathcal{E})$ corresponds to a twist, which we claim agrees with $\tau_{F}^{n}$. The upshot of this construction is that the adjoint action of $S U(n)$ on itself lifts to an action of $S U(n)$ on $\mathcal{E}$ in a canonical way, since $h \in S U(n)$ maps $\operatorname{Eig}(g, \lambda)$ to $\operatorname{Eig}\left(h g h^{-1}, \lambda\right)$ mimicking the equivariant bundle gerbe in the classical case [24].

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## Appendix A. An $\mathcal{I}$-monoid model for $B U_{\otimes}\left[\frac{1}{d}\right]$

In this appendix we present a model for the infinite loop space $B U_{\otimes}\left[\frac{1}{d}\right]$ as a commutative $\mathcal{I}$-monoid. It provides an alternative to the model via permutative categories used in Sec. 3.1. We include it here, since it might be of independent interest.

Let $\mathcal{I}$ be the category with objects the finite sets $\mathbf{n}=\{1, \ldots, n\}$ (including the empty set $\mathbf{0}$ ) and injective maps between them as morphisms. This category is symmetric monoidal: The tensor product is given by concatenation $\mathbf{m} \sqcup \mathbf{n}=\{1, \ldots, m+n\}$, where $\mathbf{m}$ corresponds to the first $m$ entries and $\mathbf{n}$ to the last $n$. The symmetry isomorphisms are the obvious shuffle maps $s_{m, n}: \mathbf{m} \sqcup \mathbf{n} \rightarrow \mathbf{n} \sqcup \mathbf{m}$. Let $\mathcal{T} o p_{*}$ be the category of pointed topological spaces and basepoint preserving continuous maps.

An $\mathcal{I}$-space is a functor $X: \mathcal{I} \rightarrow \mathcal{T} o p_{*}$. An $\mathcal{I}$-monoid is an $\mathcal{I}$-space $X$ together with a natural transformation

$$
\mu: X \times X \Longrightarrow X \circ \sqcup
$$

given by maps $\mu_{m, n}: X(\mathbf{m}) \times X(\mathbf{n}) \rightarrow X(\mathbf{m} \sqcup \mathbf{n})$ that satisfy associativity and unitality conditions in the sense that the basepoint of $X(\mathbf{0})$ acts as a unit for $\mu$. An $\mathcal{I}$-monoid is called commutative if the following diagram commutes


For details about this construction we refer the reader to [30, 31]. Let $W$ be a complex inner product space with $d=\operatorname{dim}(W)$ and define

$$
\mathcal{B}_{\otimes}^{W}(\mathbf{n})=B U\left(W^{\otimes n}\right)
$$

A permutation $\sigma: \mathbf{n} \rightarrow \mathbf{n}$ acts on $W^{\otimes n}$ by permuting the tensor factors. The adjoint action of the corresponding unitary yields $\mathcal{B}_{\otimes}^{W}(\sigma)$. For the proper inclusion $\iota: \mathbf{m} \rightarrow \mathbf{n}$ we define $\mathcal{B}_{\otimes}^{W}(\iota): B U\left(W^{\otimes m}\right) \rightarrow B U\left(W^{\otimes n}\right)$ to be the continuous map induced by the group homomorphism

$$
\left.U\left(W^{\otimes m}\right) \xrightarrow{u \mapsto u \otimes 1} U\left(W^{\otimes m} \otimes W^{\otimes(n-m)}\right)\right)=U\left(W^{\otimes n}\right)
$$

Any morphism $f: \mathbf{m} \rightarrow \mathbf{n}$ can be written as $\sigma \circ \iota$, where $\sigma: \mathbf{n} \rightarrow \mathbf{n}$ is the permutation that maps $1, \ldots, m$ to $f(1), \ldots, f(m)$ and fills the gaps with the element $m+1, \ldots, n$ in ascending order. It is straightforward to see that the definition $\mathcal{B}_{\otimes}^{W}(f):=\mathcal{B}_{\otimes}^{W}(\sigma) \circ \mathcal{B}_{\otimes}^{W}(\iota)$ indeed yields a functor. This fixes $\mathcal{B}_{\otimes}^{W}: \mathcal{I} \rightarrow \mathcal{T} o p_{*}$ completely and gives it the structure of an $\mathcal{I}$-space. It can be equipped with an $\mathcal{I}$-monoid structure, where the multiplication

$$
\mu_{m, n}^{\otimes}: \mathcal{B}_{\otimes}^{W}(\mathbf{m}) \times \mathcal{B}_{\otimes}^{W}(\mathbf{n}) \rightarrow \mathcal{B}_{\otimes}^{W}(\mathbf{m} \sqcup \mathbf{n})
$$

is induced by the tensor product of unitaries. With respect to these definitions $\mathcal{B}_{\otimes}^{W}$ is a commutative $\mathcal{I}$-monoid $[30,31]$. However, it is not convergent.

We will determine the homotopy type of $\left(\mathcal{B}_{\otimes}^{W}\right)_{h \mathcal{I}}$ in the next lemma. Let $\mathcal{N}$ be the poset $\mathbb{N}$ considered as a category with a unique arrow from $m$ to $n$ if and only if $m \leq n$. Note that $\mathcal{N}$ embeds into $\mathcal{I}$ by sending $n \in \mathcal{N}$ to $\mathbf{n} \in \mathcal{I}$. and the arrow $m \rightarrow n$ in $\mathcal{N}$ to the embedding $\iota: \mathbf{m} \rightarrow \mathbf{n}$ in $\mathcal{I}$ as defined above. We define

$$
\left(\mathcal{B}_{\otimes}^{F}\right)_{\infty}=\operatorname{hocolim}_{\mathcal{N}}\left(\mathcal{B}_{\otimes}^{F}\right)
$$

Lemma A.1. Let $W \in \operatorname{obj}\left(\mathcal{V}_{\mathbb{C}}^{\mathrm{fin}}\right)$ and let $d=\operatorname{dim}(W)$. We have

$$
\left(\mathcal{B}_{\otimes}^{W}\right)_{\infty} \simeq B U_{\otimes}\left[\frac{1}{d}\right]
$$

and the continuous $\operatorname{map}\left(\mathcal{B}_{\otimes}^{W}\right)_{\infty} \rightarrow\left(\mathcal{B}_{\otimes}^{W}\right)_{h \mathcal{I}}$ is a homotopy equivalence.
Proof. Since $\left(\mathcal{B}_{\otimes}^{W}\right)_{\infty}$ agrees up to homotopy equivalence with the path component labelled by $1 \in \mathbb{Z}$ of the space $\left|\mathcal{B} U_{\otimes}^{W}\right|_{\infty}$ that we considered in Lemma 3.1, the first statement of the lemma is clear.

We will prove the second statement by showing that there exists a model for $B U\left(W^{\otimes n}\right)$ which satisfies the conditions of [2, Thm. 3.1 and Thm. 3.3]. Combining these theorems we obtain that

$$
\left(\mathcal{B}_{\otimes}^{W}\right)_{\infty} \simeq\left(\mathcal{B}_{\otimes}^{W}\right)_{\infty}^{+} \simeq\left(\mathcal{B}_{\otimes}^{W}\right)_{h \mathcal{I}}
$$

where we used that $B U_{\otimes}\left[\frac{1}{d}\right]$ is simply connected to obtain the first equivalence. Let $H$ be a separable infinite-dimensional Hilbert space, denote by $\mathbb{K}$ the compact operators on $H$ and let $e \in \mathbb{K}$ be a projection of rank 1. The unitary group $U(W \otimes H)$ endowed with the norm topology is contractible by Kuiper's theorem. Identify $W$ with the subspace $W \otimes e H \subset W \otimes H$. The space

$$
U(W \otimes H) / U(W) \times U\left(W^{\perp}\right)
$$

is a model for $B U(W)$. The map $u \mapsto u\left(\mathrm{id}_{W} \otimes e\right) u^{*}$ induces a homeomorphism

$$
\begin{equation*}
U(W \otimes H) / U(W) \times U\left(W^{\perp}\right) \cong \mathcal{P}_{\operatorname{id}_{W} \otimes e}(\operatorname{End}(W) \otimes \mathbb{K}) \tag{16}
\end{equation*}
$$

where the path component of $\mathrm{id}_{W} \otimes e$ in the space of self-adjoint projections in the $C^{*}$-algebra $\operatorname{End}(W) \otimes \mathbb{K}$ is equipped with the norm topology. This space is a Banach manifold. Let $q=\mathrm{id}_{W} \otimes e$ and

$$
\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n})=\mathcal{P}_{q^{\otimes n}}\left((\operatorname{End}(W) \otimes \mathbb{K})^{\otimes n}\right)
$$

Note that $\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{0})=\left\{\operatorname{id}_{\mathbb{C}}\right\}$. A permutation $\sigma: \mathbf{n} \rightarrow \mathbf{n}$ acts on $(W \otimes H)^{\otimes n}$ by permuting the tensor factors. Thus, it acts on $\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n})$ via the corresponding adjoint action. This defines $\mathcal{B}_{\otimes}^{\mathcal{P}}(\sigma)$. Let $\iota: \mathbf{m} \rightarrow \mathbf{n}$ be the inclusion that identifies $\mathbf{m}$ with the first $m$ entries of $\mathbf{n}$. Then $\mathcal{B}_{\otimes}^{\mathcal{P}}(\iota)$ maps $p \in \mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{m})$ to $p \otimes q^{\otimes(n-m)} \in \mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n})$. As in the construction above this turns $\mathcal{B}_{\otimes}^{\mathcal{P}}$ into an $\mathcal{I}$-space. It is a commutative $\mathcal{I}$-monoid with respect to the multiplication

$$
\mu_{m, n}: \mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{m}) \times \mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n}) \rightarrow \mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{m} \sqcup \mathbf{n}) \quad, \quad \mu_{m, n}\left(p_{1}, p_{2}\right)=p_{1} \otimes p_{2}
$$

For $f: \mathbf{m} \rightarrow \mathbf{n}$ the induced map $\mathcal{B}_{\otimes}^{\mathcal{P}}(f)$ embeds $\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{m})$ into $\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n})$ as a closed submanifold. All of these maps are cofibrations by [26, Thm. 7].

Moreover, if $p_{1}=p_{2} \otimes e \in \mathbb{K} \otimes \mathbb{K}$ is a projection it follows that $p_{2}$ has to be a projection as well. Therefore, $\mu_{m, n}\left(p_{1}, p_{2}\right)$ is in the image of $\mathcal{B}_{\otimes}^{\mathcal{P}}(f)$ for a strict inclusion $f$ if and only if $p_{1}$ or $p_{2}$ is. Thus, $\mathcal{B}_{\otimes}^{\mathcal{P}}$ satisfies the hypotheses of [2, Thm. 3.3].

We will now construct an $\mathcal{I}$-monoid $\mathcal{B}_{\otimes}^{E U}$ together with $\mathcal{I}$-monoid morphisms $\mathcal{B}_{\otimes}^{W} \rightarrow \mathcal{B}_{\otimes}^{E U}$ and $\mathcal{B}_{\otimes}^{\mathcal{P}} \rightarrow \mathcal{B}_{\otimes}^{E U}$ that are object-wise homotopy equivalences. Let

$$
\mathcal{B}_{\otimes}^{E U}(\mathbf{n})=E U\left((W \otimes H)^{\otimes n}\right) / U\left(W^{\otimes n}\right) \times U\left(\left(W^{\otimes n}\right)^{\perp}\right),
$$

where $W^{\otimes n}$ embeds as a direct summand into $(W \otimes H)^{\otimes n}$ via $e$ like above. The adjoint action of the permutation of tensor factors defines $\mathcal{B}_{\otimes}^{E U}(\sigma)$ for all $\sigma: \mathbf{n} \rightarrow \mathbf{n}$ and the group homomorphism $U\left((W \otimes H)^{m}\right) \rightarrow U\left((W \otimes H)^{n}\right)$ given by $u \mapsto u \otimes \operatorname{id}_{(W \otimes H)^{\otimes(n-m)}}$ induces $\mathcal{B}_{\otimes}^{E U}(\iota)$. The $\mathcal{I}$-monoid structure is induced by the homomorphism

$$
U\left((W \otimes H)^{\otimes n}\right) \times U\left((W \otimes H)^{\otimes m}\right) \rightarrow U\left((W \otimes H)^{\otimes(n+m)}\right)
$$

given by taking the tensor product of two unitaries. Note in particular, that this maps the subgroup $U\left(W^{\otimes n}\right) \times U\left(\left(W^{\otimes n}\right)^{\perp}\right) \times U\left(W^{\otimes m}\right) \times U\left(\left(W^{\otimes m}\right)^{\perp}\right)$ into $U\left(W^{\otimes(n+m)}\right) \times U\left(\left(W^{\otimes(n+m)}\right)^{\perp}\right)$, since these are the stabilisers with respect to the adjoint action of the projections $q^{\otimes n}, q^{\otimes m}$ and $q^{\otimes(n+m)}$, respectively. This structure turns $\mathcal{B}_{\otimes}^{E U}$ into a commutative $\mathcal{I}$-monoid. Using the homeomorphism (16) each space $\mathcal{B}_{\otimes}^{E U}(\mathbf{n})$ yields a locally trivial bundle

$$
\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n}) \rightarrow \mathcal{B}_{\otimes}^{E U}(\mathbf{n}) \rightarrow B U\left((W \otimes H)^{\otimes n}\right)
$$

where the first map is the inclusion of the fibre over the basepoint. It is straightforward to check that the homeomorphism (16) transforms the commutative $\mathcal{I}$-monoid structure on the fibre of $\mathcal{B}_{\otimes}^{E U}(\mathbf{n}) \rightarrow B U\left((W \otimes H)^{\otimes n}\right)$ to the one on $\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n})$. Moreover, the group $U\left((W \otimes H)^{\otimes n}\right)$ is contractible (again by Kuiper's theorem). Therefore the map $\mathcal{B}_{\otimes}^{\mathcal{P}}(\mathbf{n}) \rightarrow \mathcal{B}_{\otimes}^{E U}(\mathbf{n})$ is a homotopy equivalence for all $\mathbf{n} \in \operatorname{obj}(\mathcal{I})$. The embedding $U\left(W^{\otimes n}\right) \rightarrow U\left((W \otimes H)^{\otimes n}\right)$ induces a map $E U\left(W^{\otimes n}\right) \rightarrow E U\left((W \otimes H)^{\otimes n}\right)$, which yields a homotopy equivalence

$$
E U\left(W^{\otimes n}\right) / U\left(W^{\otimes n}\right) \rightarrow E U\left((W \otimes H)^{\otimes n}\right) / U\left(W^{\otimes n}\right) \times U\left(\left(W^{\otimes n}\right)^{\perp}\right)
$$

Therefore we obtain homotopy equivalences

$$
\mathcal{B}_{\otimes}^{W}(\mathbf{n})=B U\left(W^{\otimes n}\right) \rightarrow \mathcal{B}_{\otimes}^{E U}(\mathbf{n}),
$$

for all $\mathbf{n} \in \operatorname{obj}(\mathcal{I})$. These are compatible with all maps defining the commutative $\mathcal{I}$-monoid structure.

