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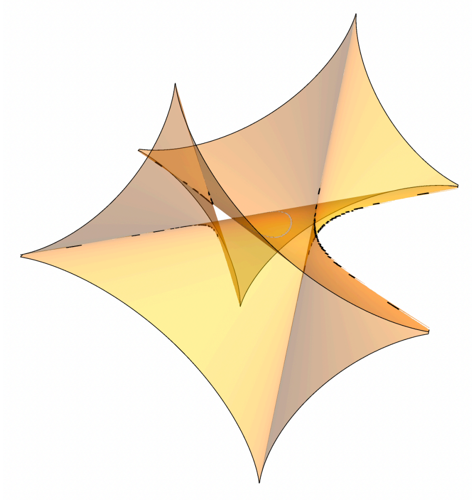

Yifei Zhu

Southern University of Science and Technology

2025.1.11

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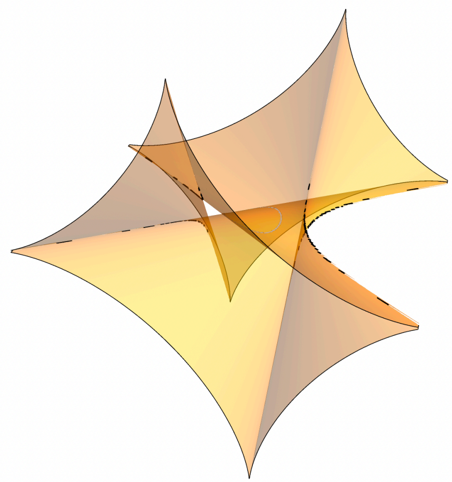

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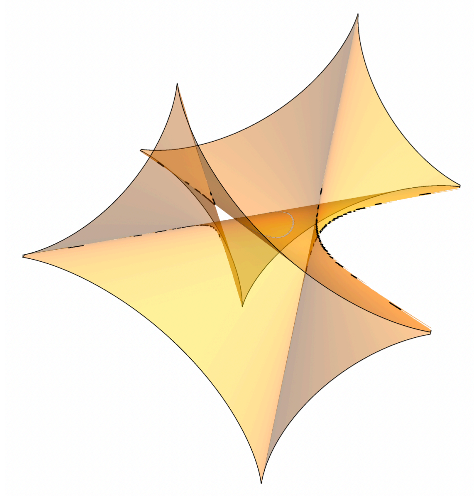

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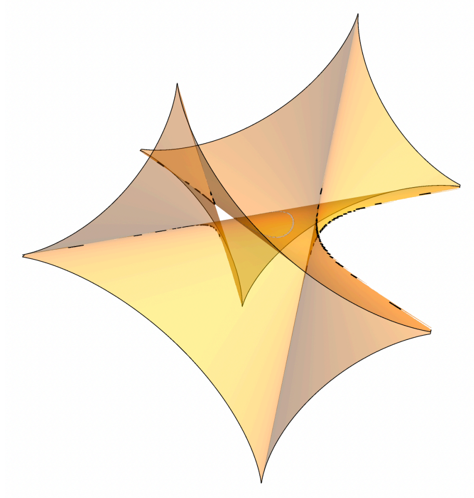

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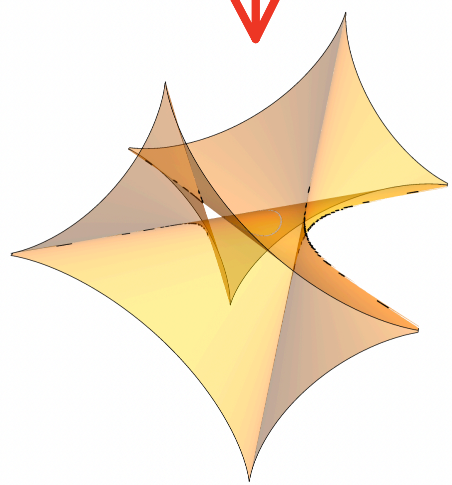

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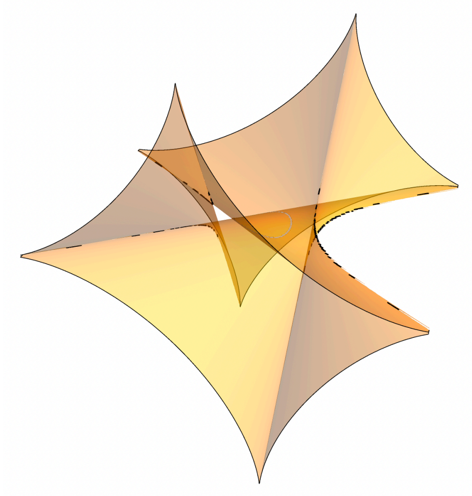

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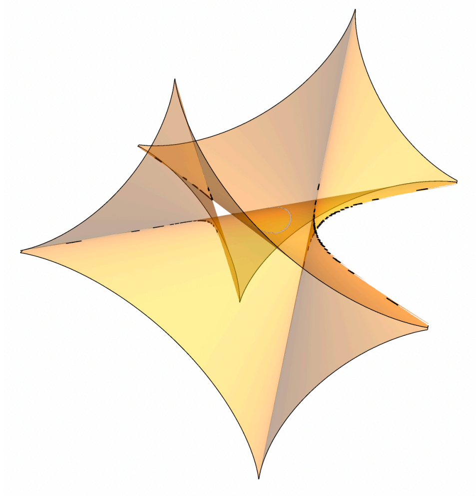

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Holography, optical devices,
absorption devices, …

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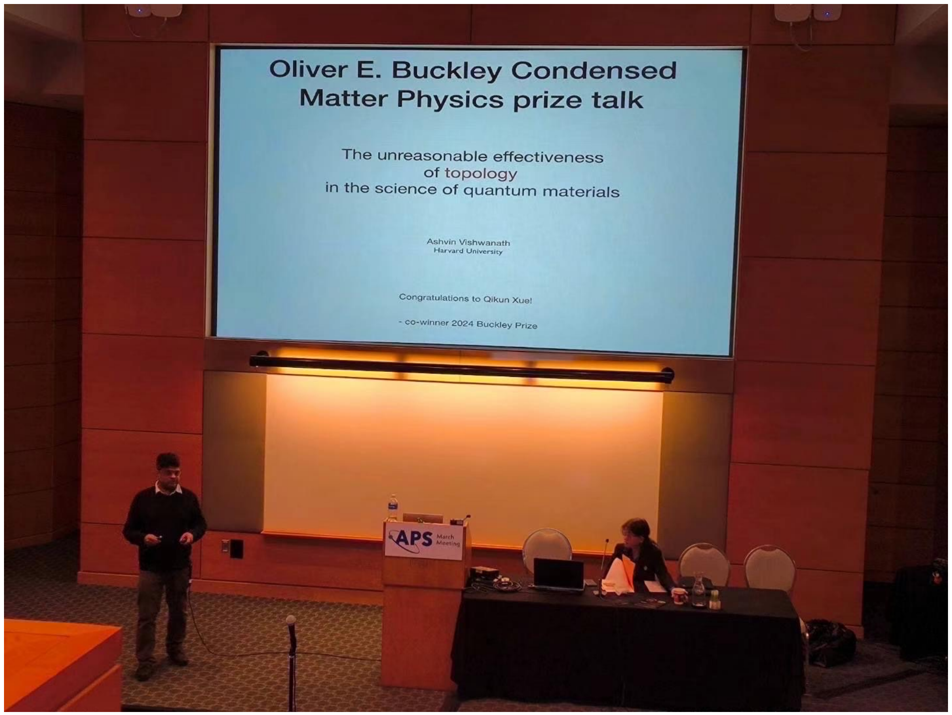

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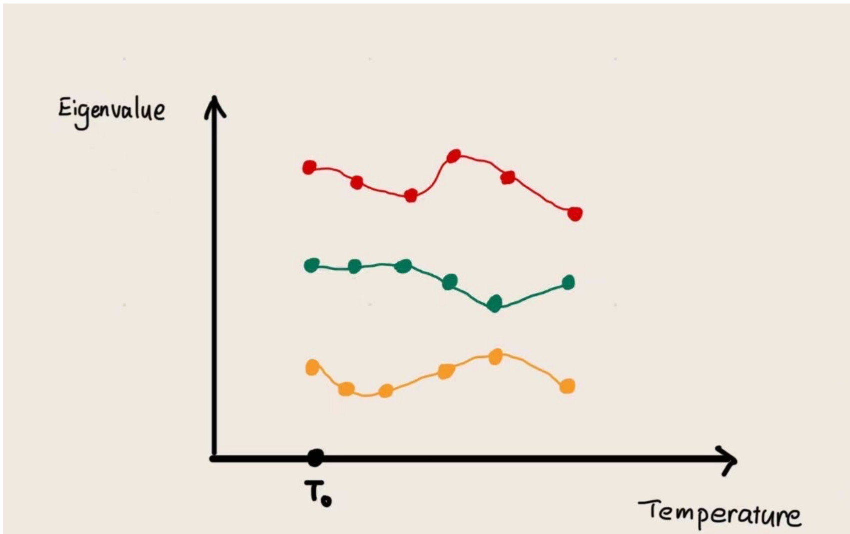
Mathematical modeling of electronic energy *band structures* therein



energy $\longleftrightarrow$ *eigenvalue*

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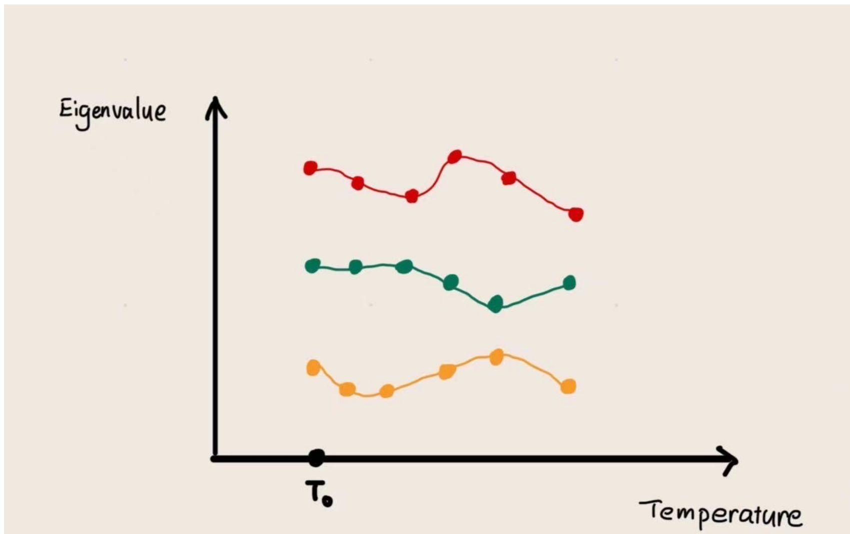

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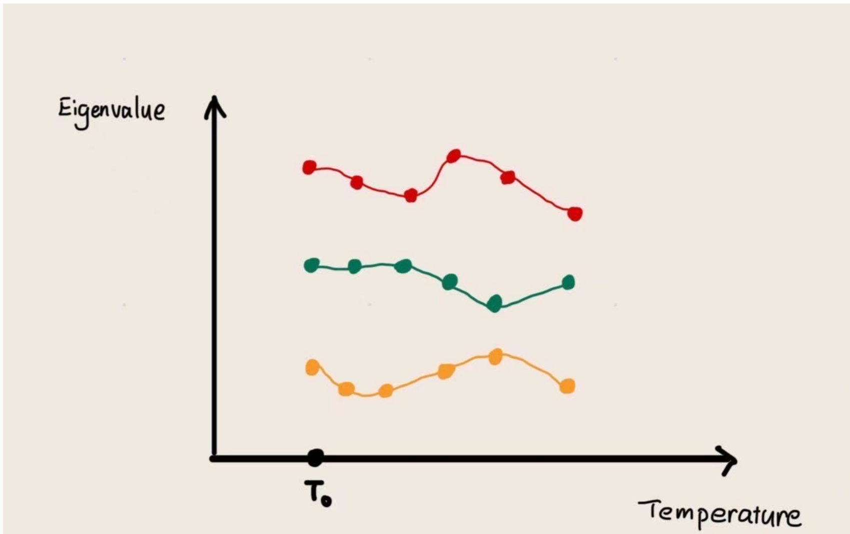

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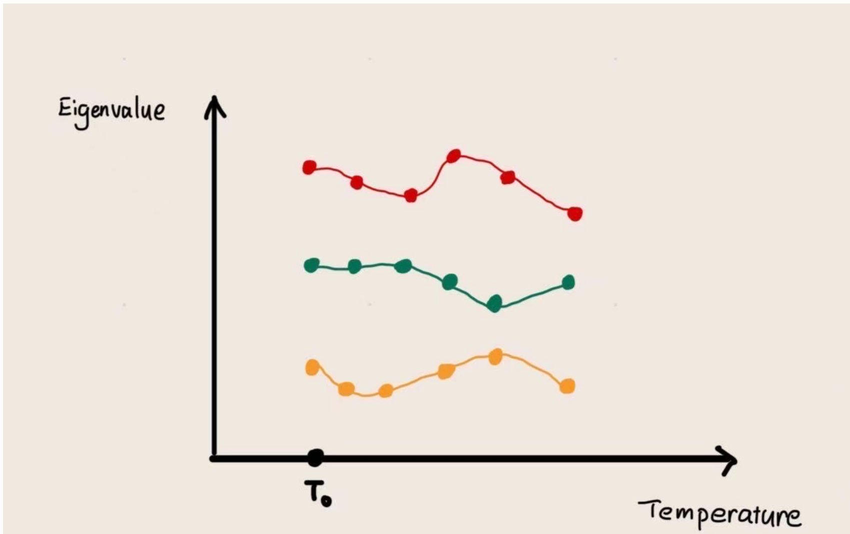

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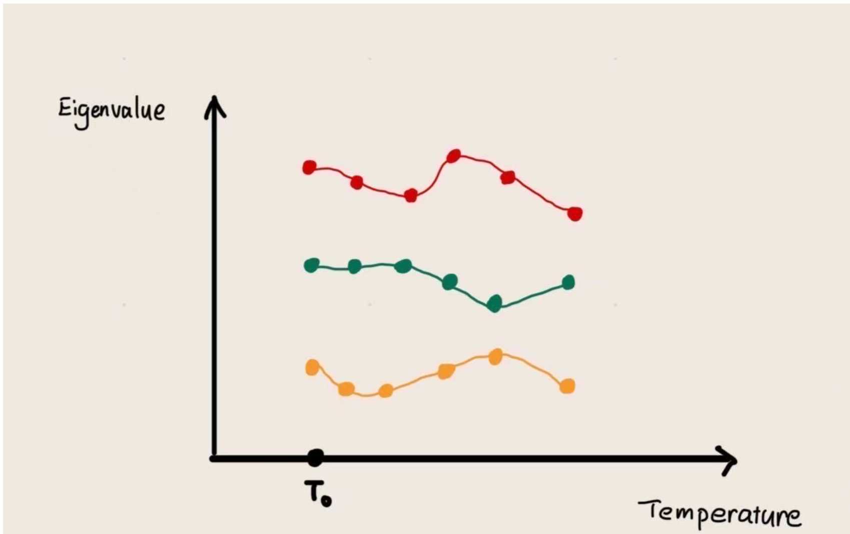

Hermitian

real eigenvalues (observable energies)

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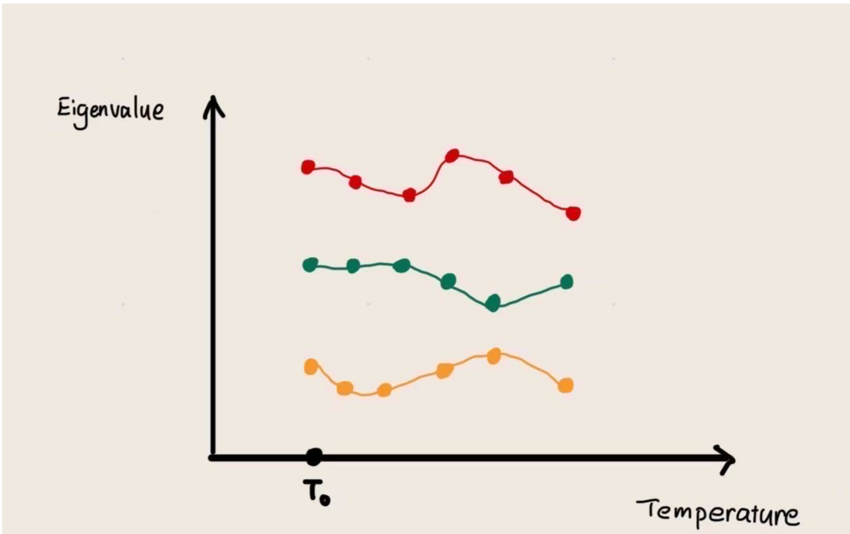

Hermitian vs.
non-Hermitian

real eigenvalues (observable energies) vs.
eigenvalues with imaginary part (counts for energy exchange with surrounding environment or other systems)

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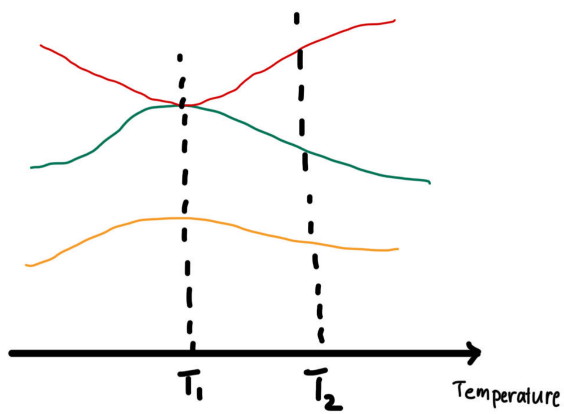

phases of matter
H_2O*: solid, liquid, gas*

T_1 : singular points (points where eigenvalues degenerate)
$H(T_1)$: gapless Hamiltonian
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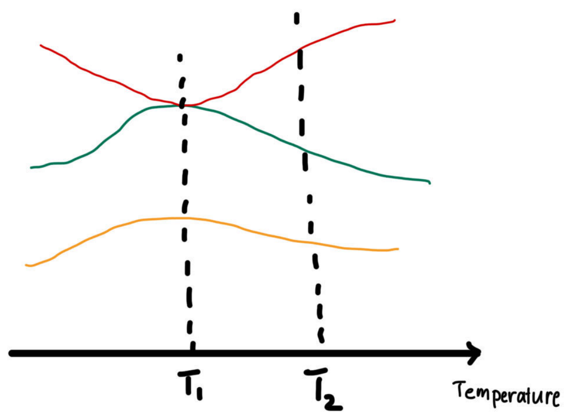

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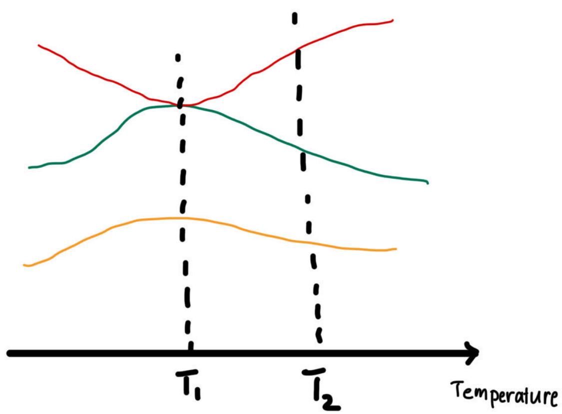

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It is indeed "pointless" and is better understood as a functor!

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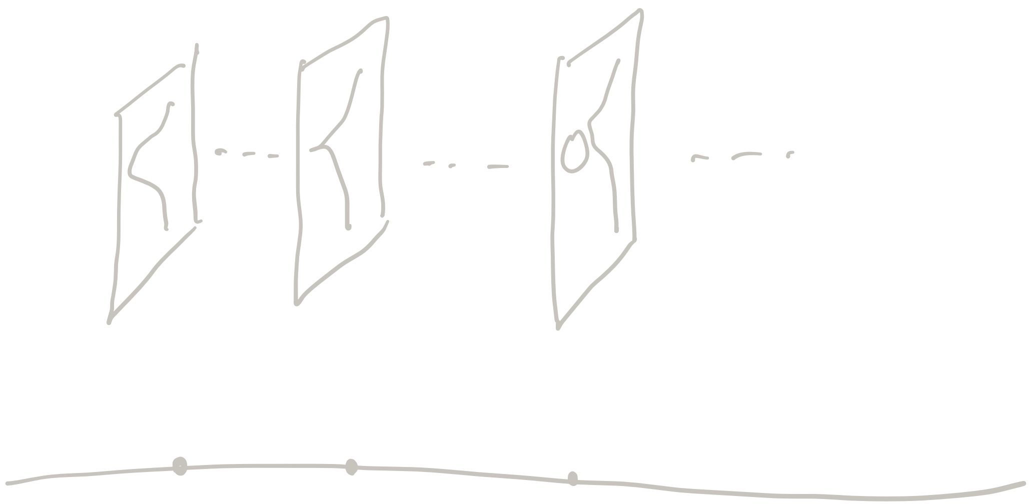

family of objects

parametrized by

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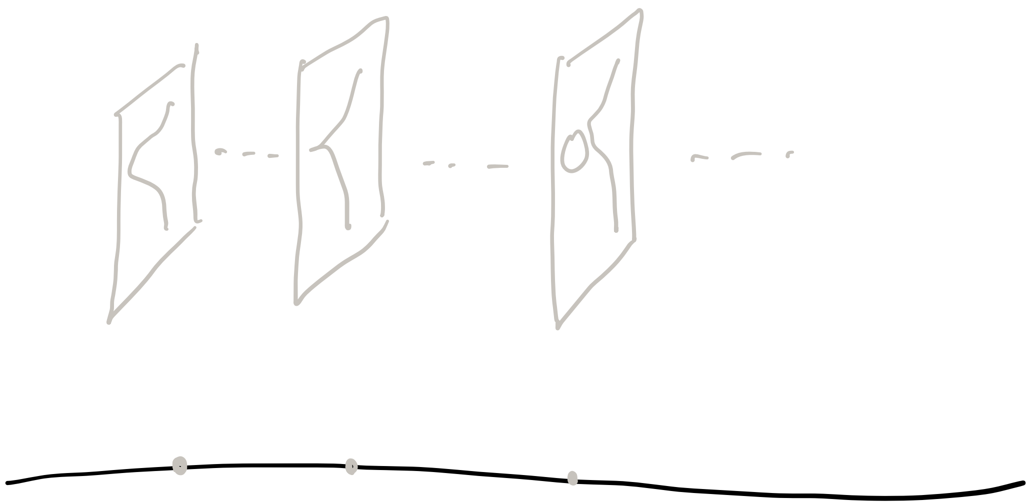

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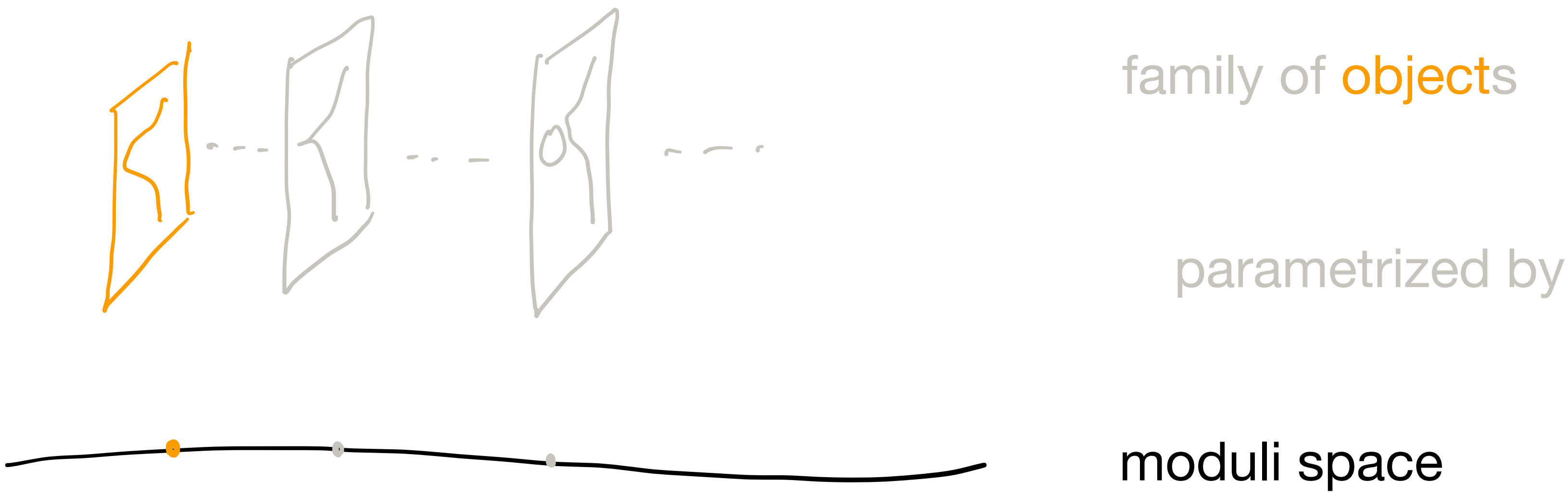

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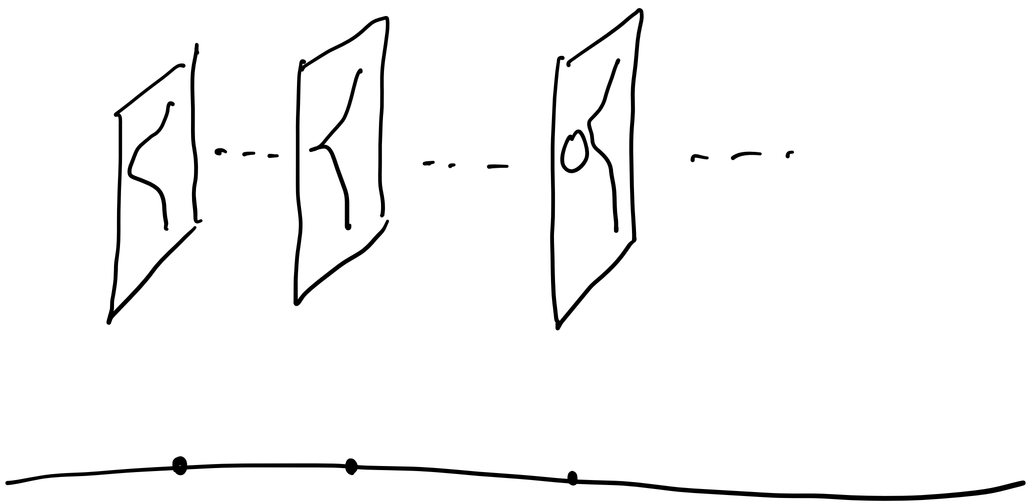

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- In this sense, studying moduli spaces is of the second-order nature.

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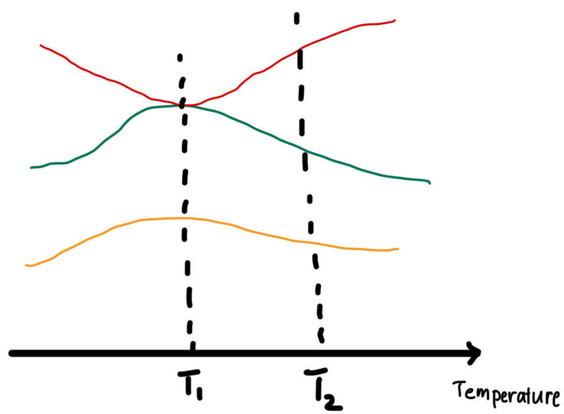

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*Guzman et al., Model-free characterization of topological edge and corner states in mechanical networks, **PNAS** 2024.*

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- H. Jia, R.-Y. Zhang, J. Hu, Y. Xiao, S. Zhang, **Y. Zhu**, and C. T. Chan. *Topological classification for intersection singularities of exceptional surfaces in pseudo-Hermitian systems*. ***Communication Physics***, 6:293, 2023.

- J. Hu, R.-Y. Zhang, Y. Wang, X. Ouyang, **Y. Zhu**, H. Jia, and C. T. Chan. *Non-Hermitian swallowtail catastrophe revealing transitions among diverse topological singularities*. ***Nature Physics***, 19:1098–1103, 2023.

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Thanks to Hopf bundles and Higgs bundles as *eigenbundles*, we now have a conceptually more systematic, visibly more intuitive understanding of the topic. The structure of Higgs bundles also hints at certain deeper aspects of mathematics as well as physics.

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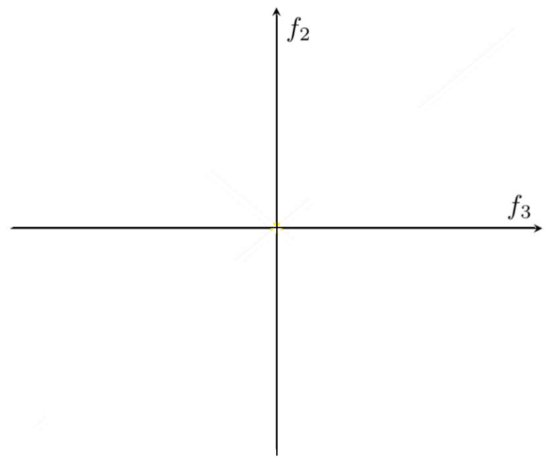

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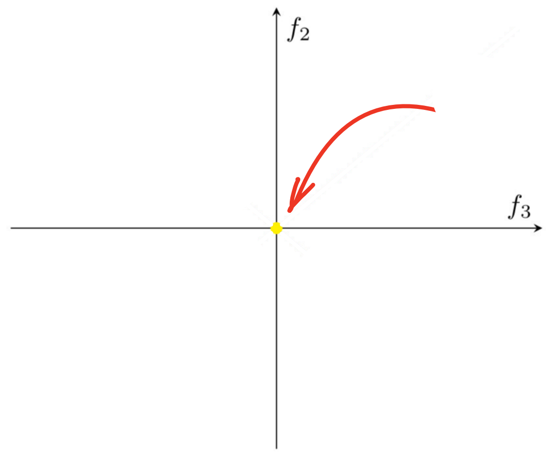

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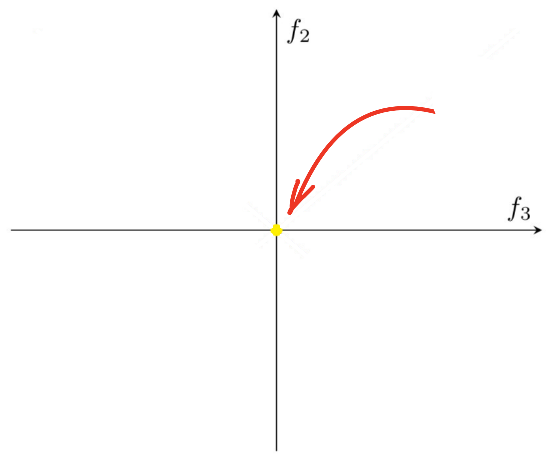

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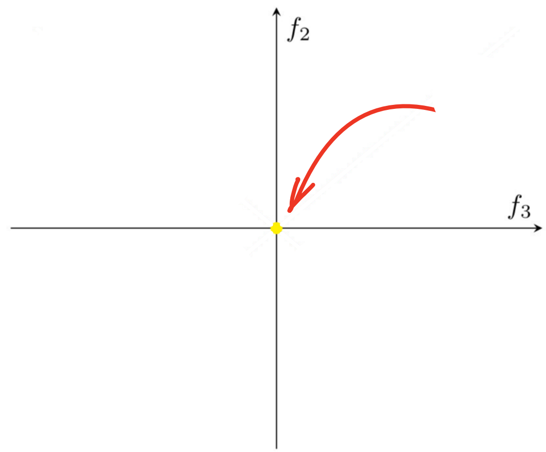

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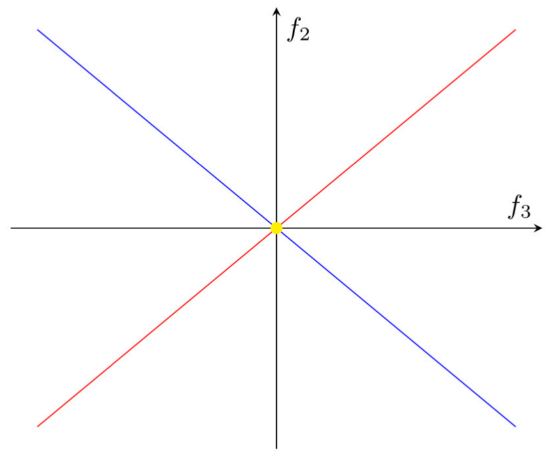

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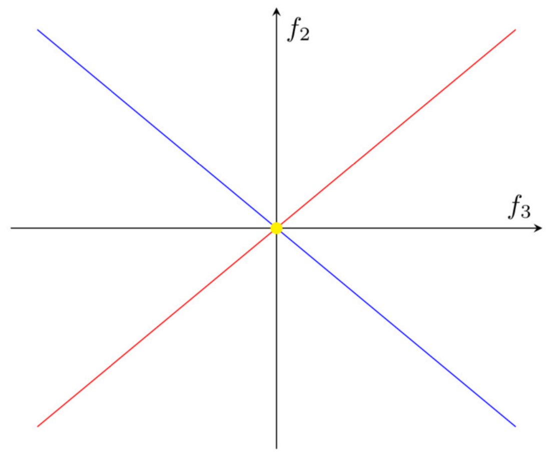

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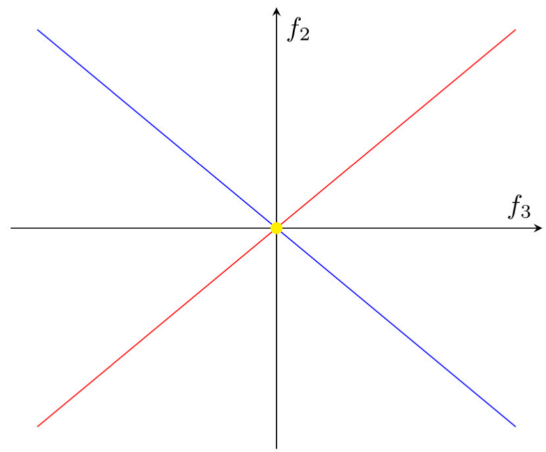

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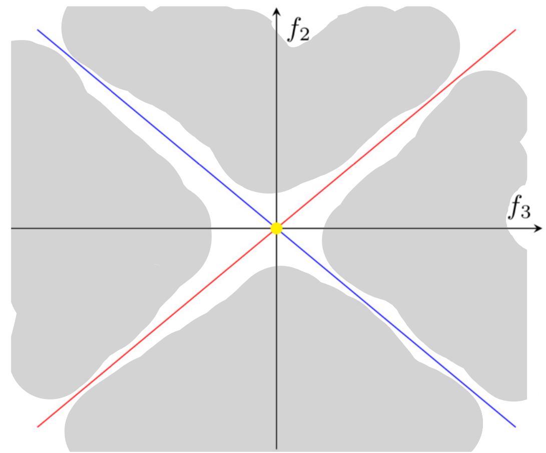

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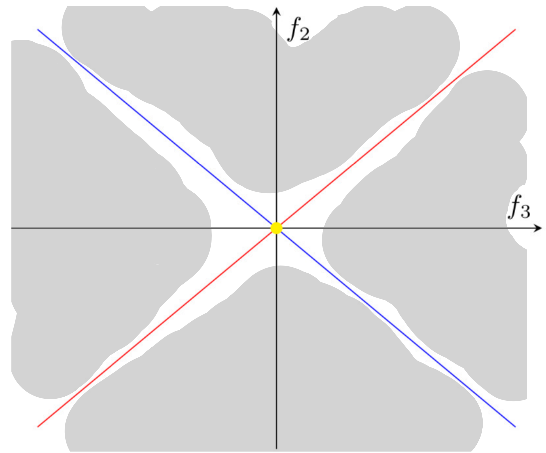

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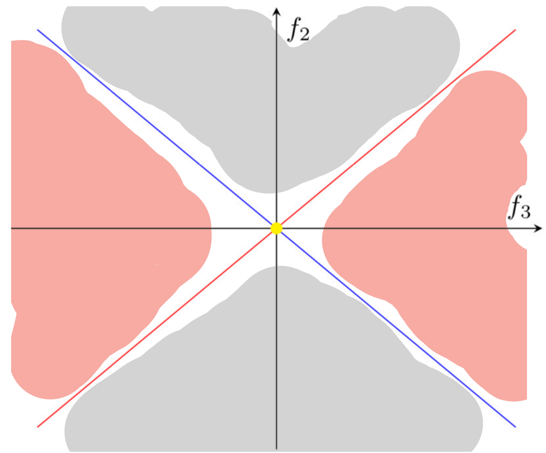

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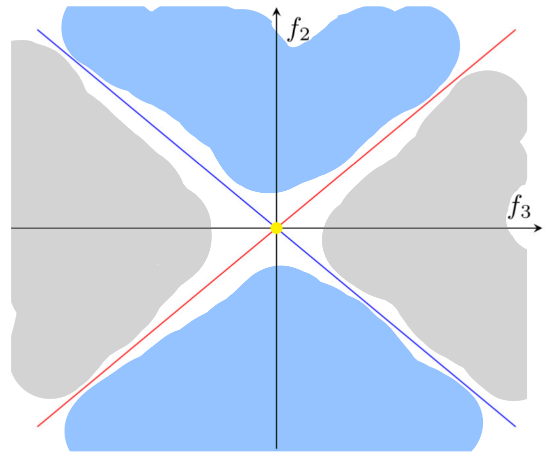

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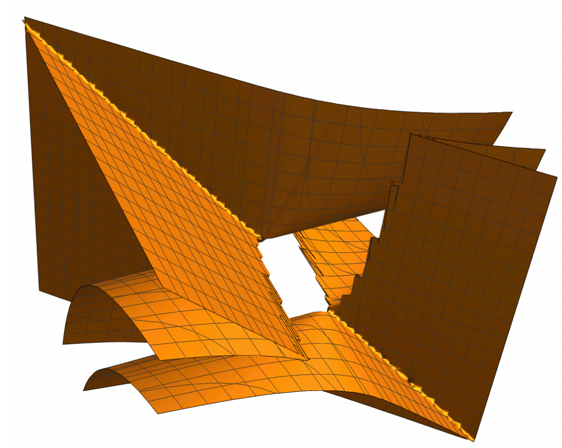
Governing eigenvalues with multiplicity, the discriminant surface of its characteristic polynomial is a pair of *swallowtails* in the $f_1 f_2 f_3$-space:

The equation for this surface is a non-homogeneous real polynomial in f_1, f_2, f_3 of degree 6.



Swallowtail couple sw2

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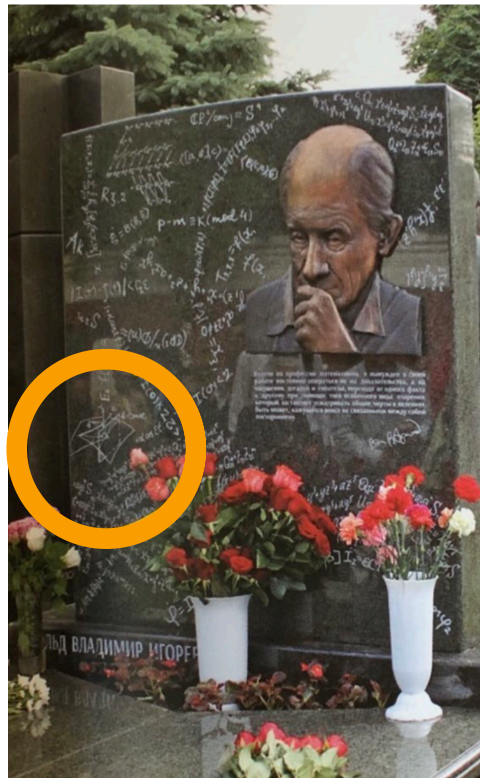

V. I. Arnold's tombstone at the Novodevichy Cemetery in Moscow

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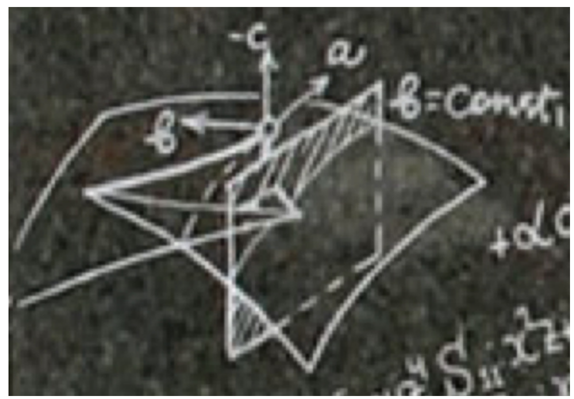

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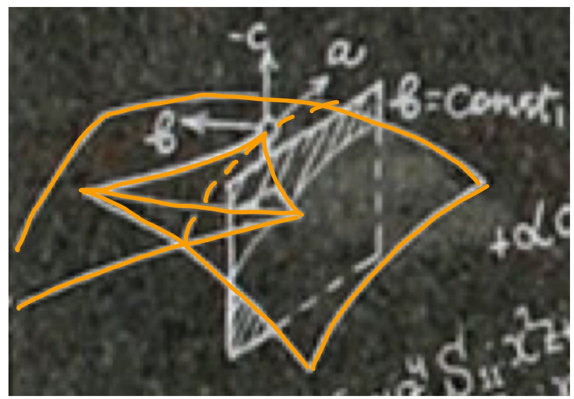

A local model for moduli spaces of 3-band Hamiltonians

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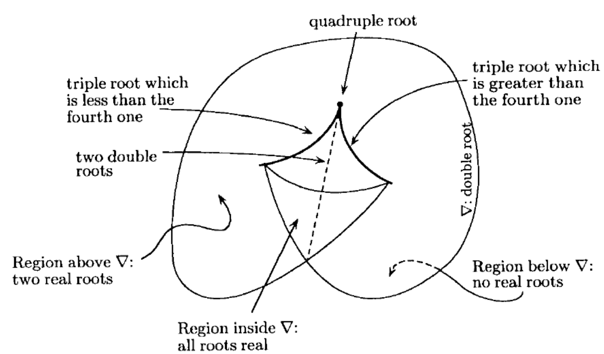
Arnold, Braids of algebraic functions and the cohomology of swallowtails, 1968.

Homological stability of braid groups

Portrait from Gelfand, Kapranov, Zelevinsky, Discriminants, resultants, and multidimensional determinants.



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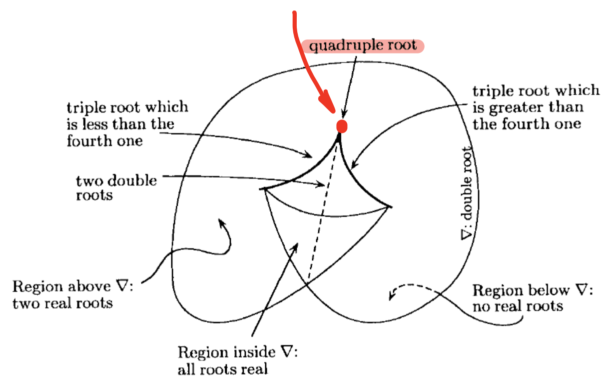

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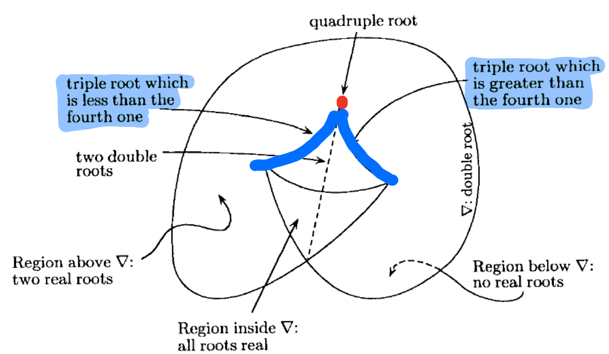

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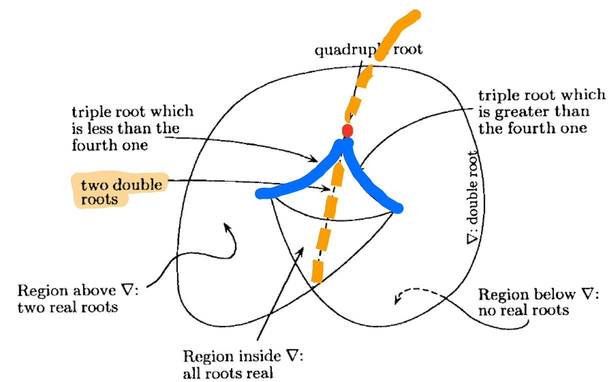

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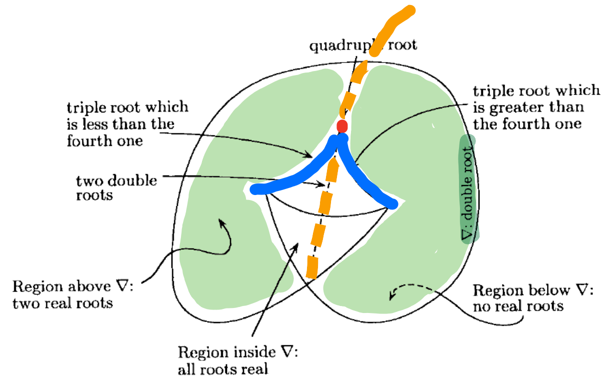

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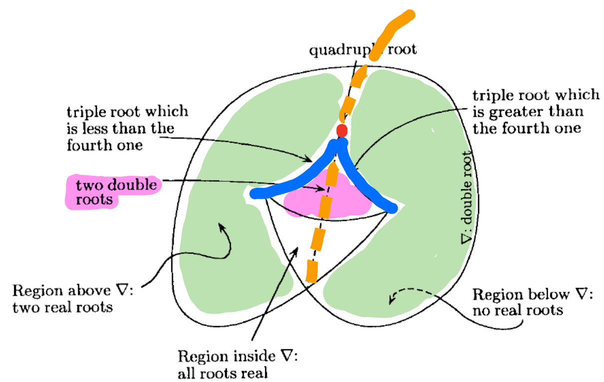

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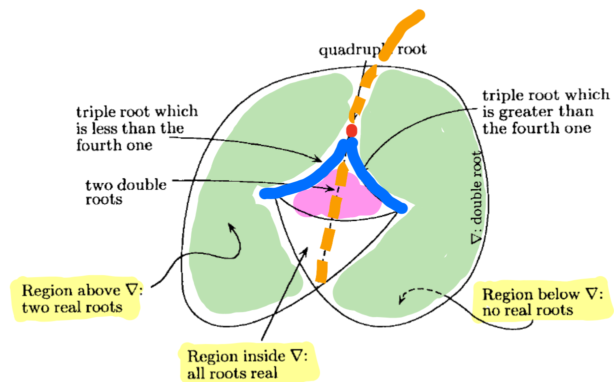

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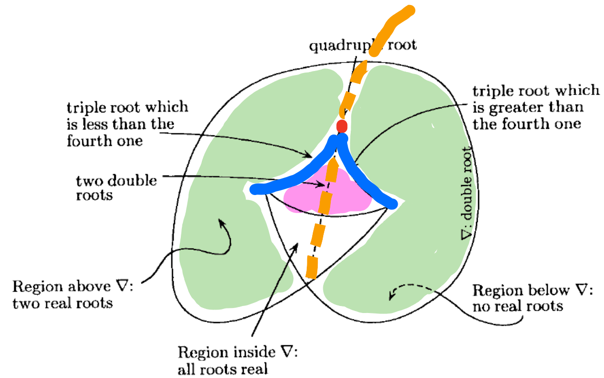

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Again, we aim to find computable algebraic invariants that systematically classify the evolutions of eigenvectors along loops in such stratified parameter spaces, including when they cross the discriminant surface resulting in degeneracies of various sorts.

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Remarks on eigenvalues and eigenvectors of Hermitian matrices, Berry phase, adiabatic connections and quantum Hall effect, 1995.

Also: Polymathematics, 2000.

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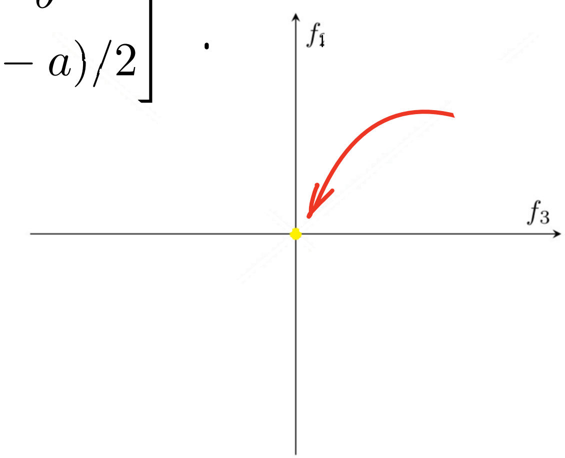

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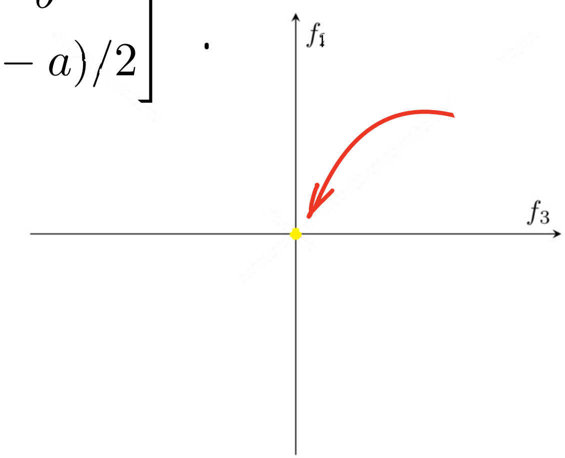

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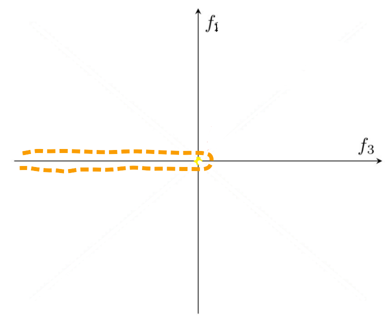

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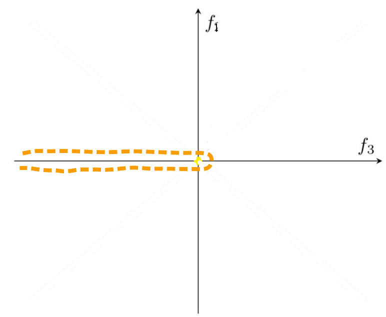

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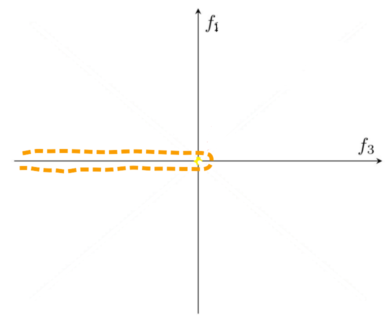

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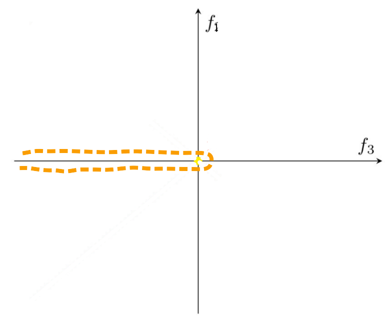

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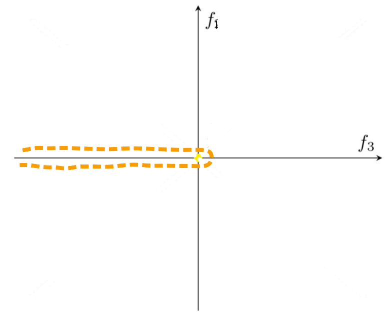

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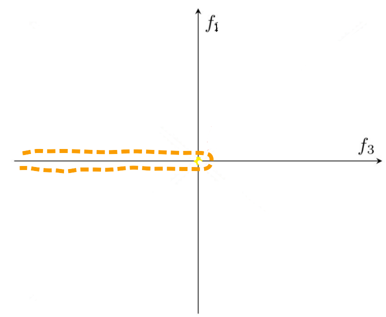

$$\begin{bmatrix} f_3-\sqrt{f_1^2+f_3^2} & f_1 \\ f_1 & -f_3-\sqrt{f_1^2+f_3^2} \end{bmatrix} \xrightarrow{-f_3-\sqrt{f_1^2+f_3^2}\neq 0 \iff \cancel{f_1=0,\ f_3\leq 0}}$$

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$$\rightarrow \begin{bmatrix} 0 & 0 \\ f_1 & -f_3-\sqrt{} \end{bmatrix} \Rightarrow v_+ = \begin{bmatrix} f_3+\sqrt{f_1^2+f_3^2} \\ f_1 \end{bmatrix} \overset{\begin{cases} f_3=\cos\theta \\ f_1=\sin\theta \end{cases} \quad -\pi<\theta<\pi}{=\!=\!=\!=\!=} \begin{bmatrix} \cos\theta+1 \\ \sin\theta \end{bmatrix}$$

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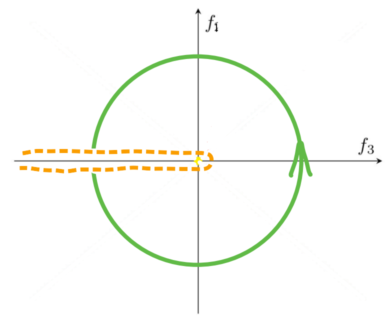

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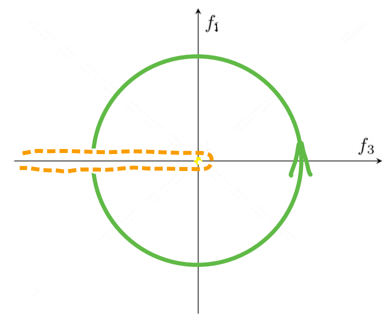

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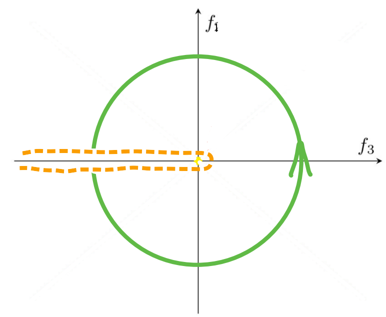

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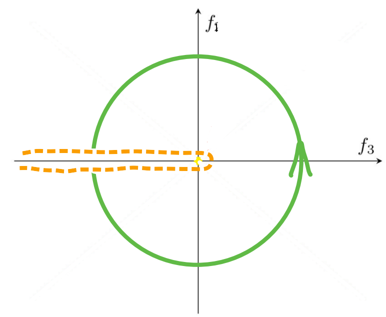

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We compute that

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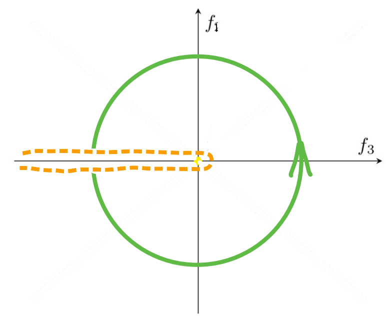

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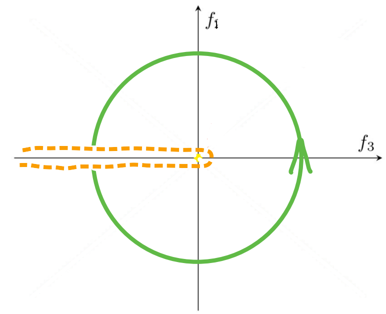

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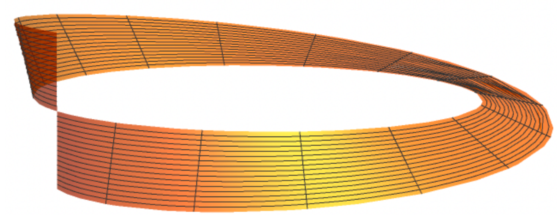

Eigenframe rotation as vector bundles: Revisiting the Hermitian case

Lemma. The universal rank-1 eigenbundle for Hermitian 2-band systems is given by the Hopf bundle

$$\begin{array}{lcl} S^0 \hookrightarrow S^1 \to S^1 & & \mathbb{R} \\ S^1 \hookrightarrow S^3 \to S^2 & \text{if the Hamiltonian is over} & \mathbb{C} \\ S^3 \hookrightarrow S^7 \to S^4 & & \mathbb{H} \end{array}$$

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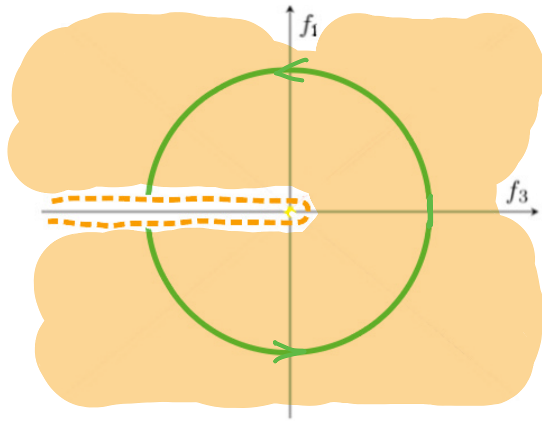

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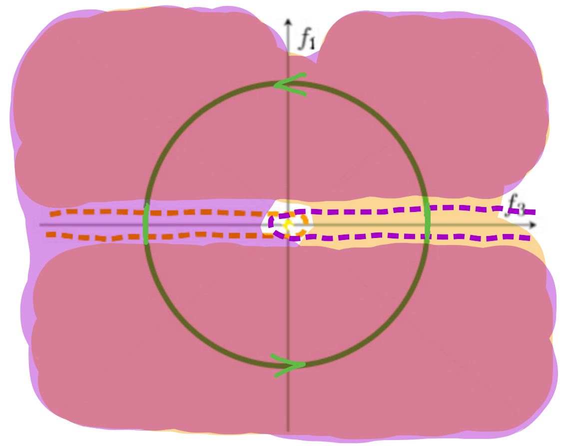

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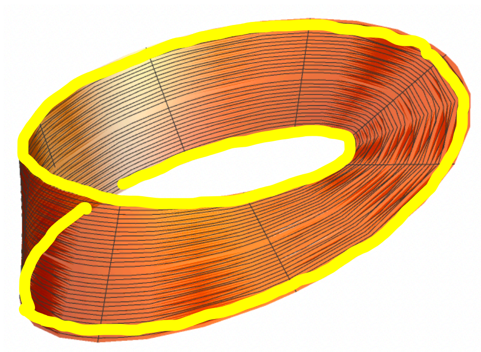

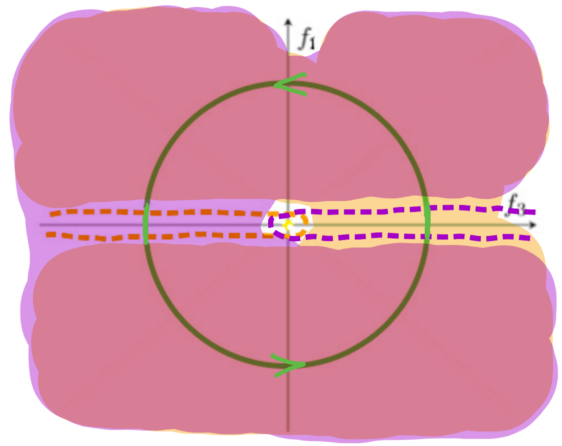

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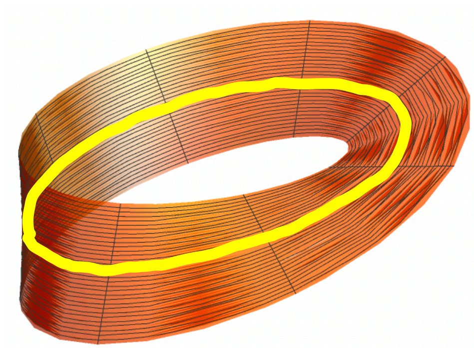

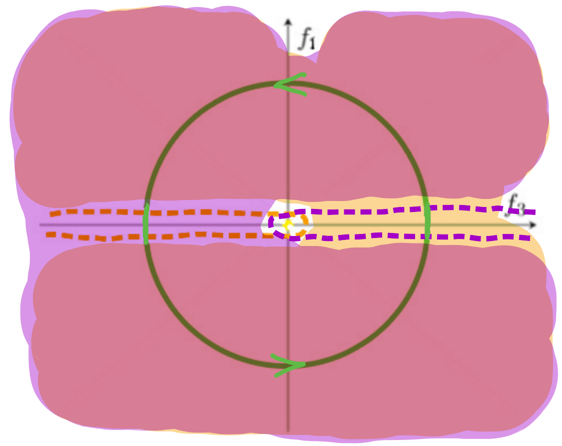

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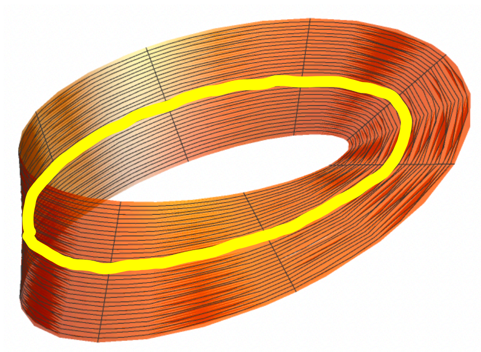

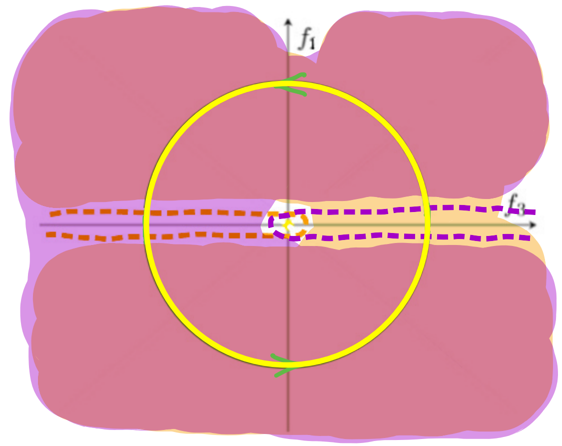

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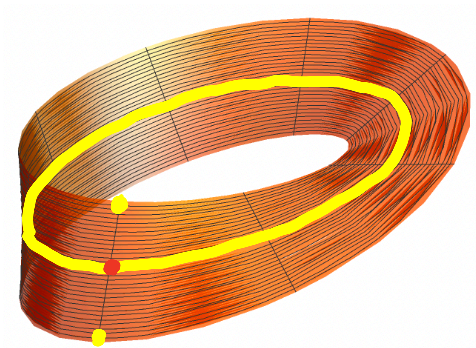

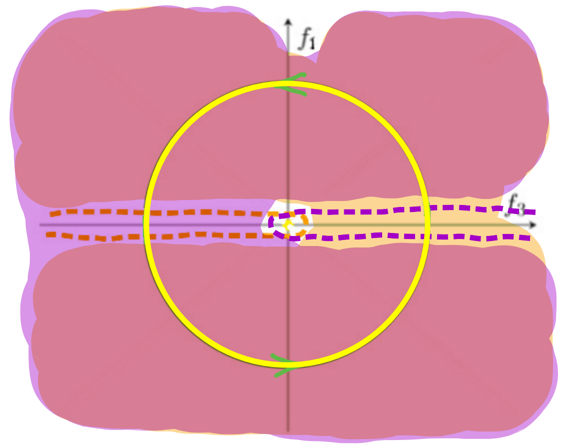

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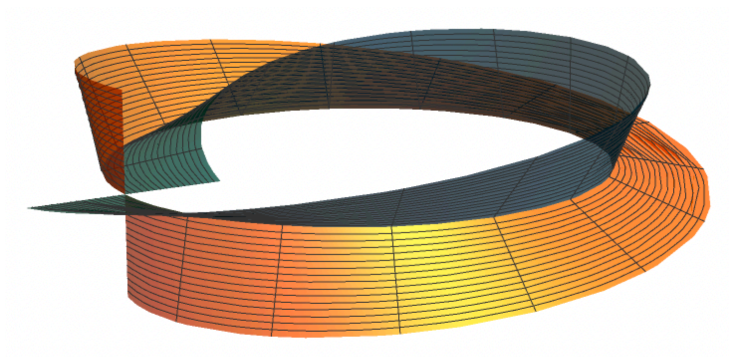

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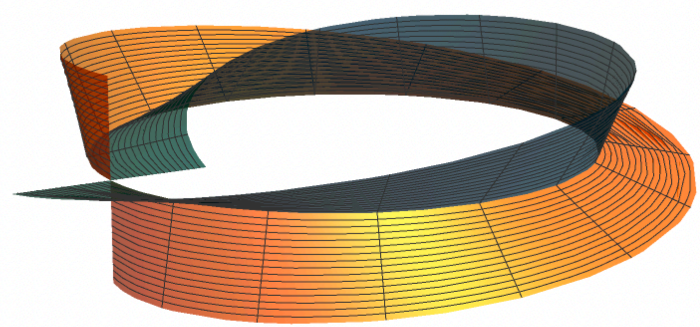
Corollary. The universal eigenbundle for real Hermitian 2-band systems is given by a pair of orthogonally intersecting half Möbius bands over the unit circle in the punctured parameter plane.



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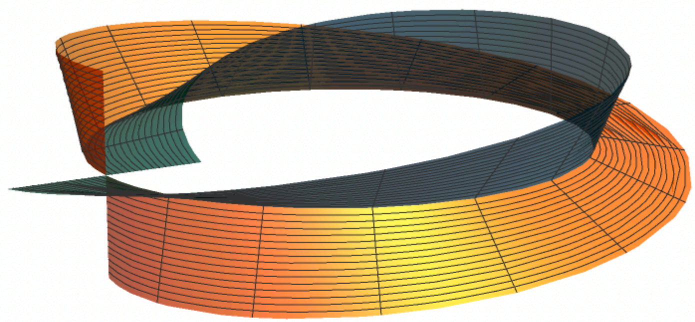

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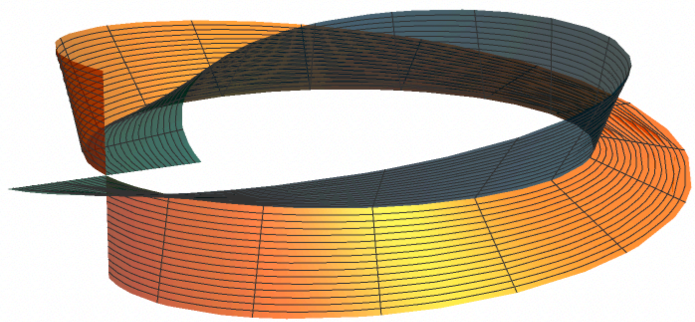

Eigenframe evolution as Higgs bundles: The non-Hermitian case

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Recall that non-Hermitian 2-band systems

$$H(f_2, f_3) = \begin{bmatrix} f_3 & f_2 \\ -f_2 & -f_3 \end{bmatrix}$$

Eigenframe evolution as Higgs bundles: The non-Hermitian case

Recall that non-Hermitian 2-band systems have a stratified parameter plane:

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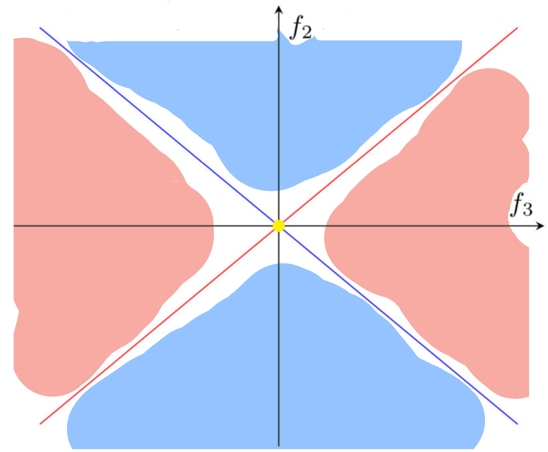

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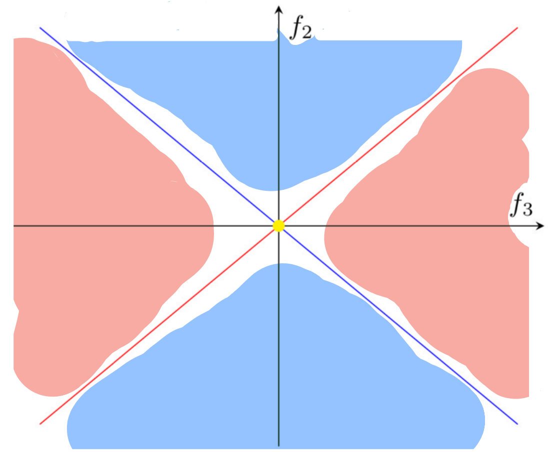

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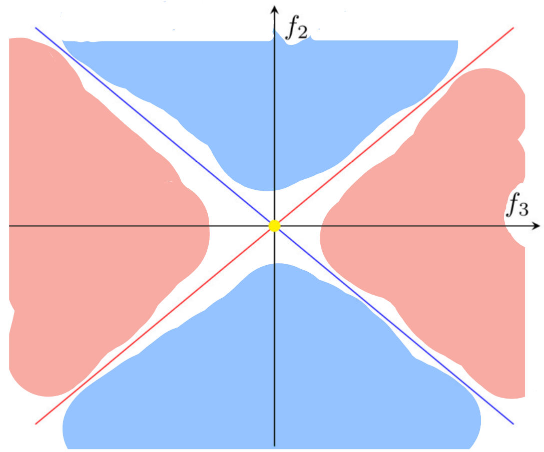

0. Over $\{(0, 0)\}$, H has a double eigenvalue, whose eigenspace is 2-dimensional.
1. Over $\{f_2 = \pm f_3\} - \{(0, 0)\}$, again H has a double eigenvalue, but its eigenspace is of dimension 1.

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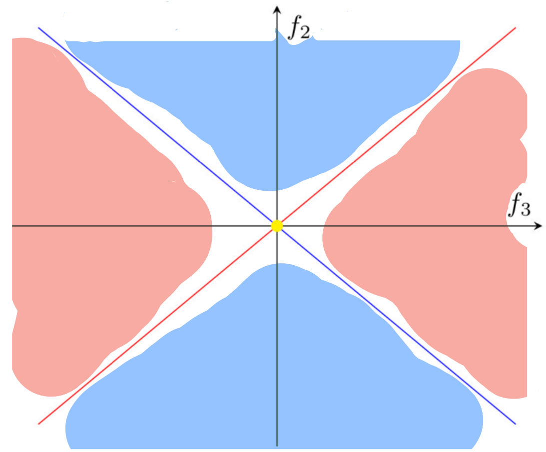

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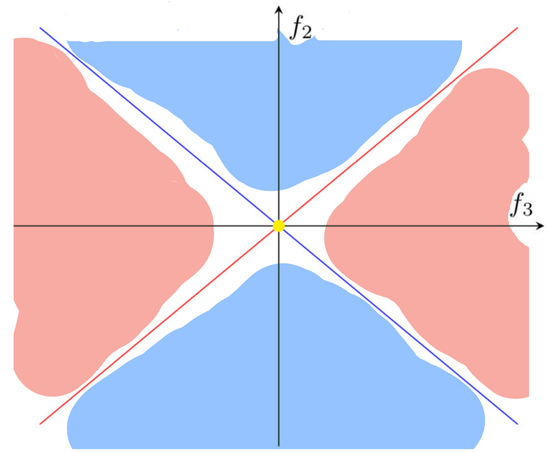

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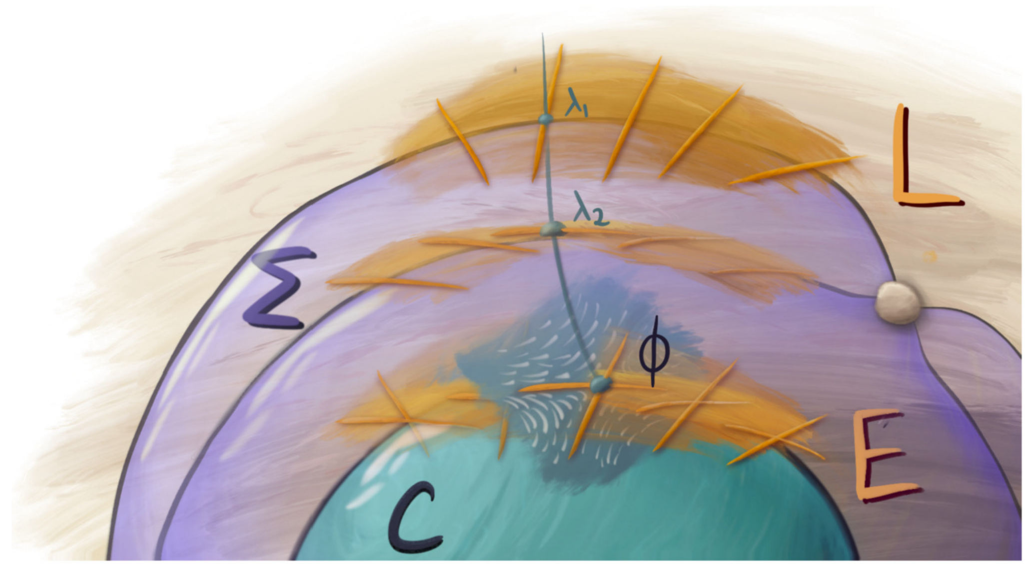
A *Higgs bundle* $(E, \phi) \to C$ is essentially a family of matrices



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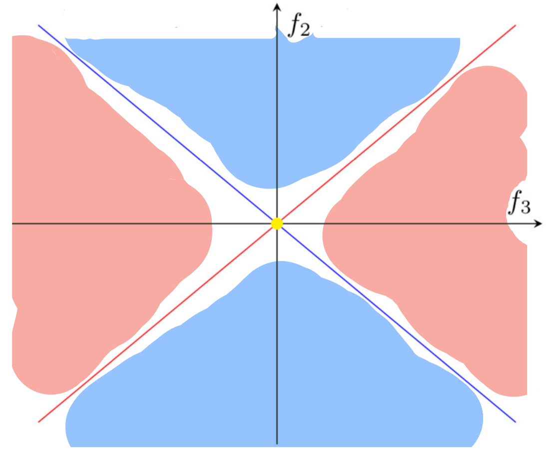

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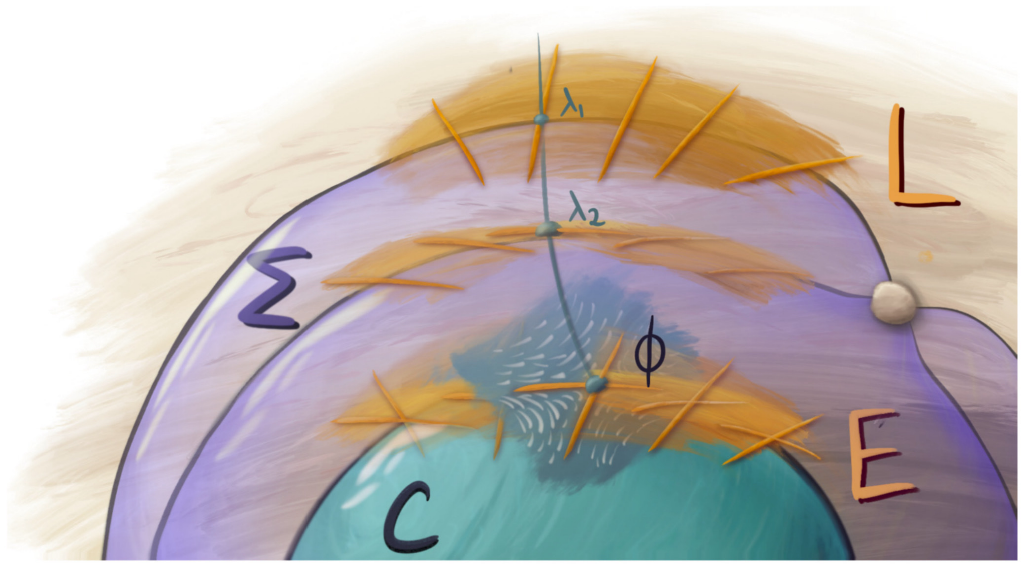
Peter Higgs (bosons)



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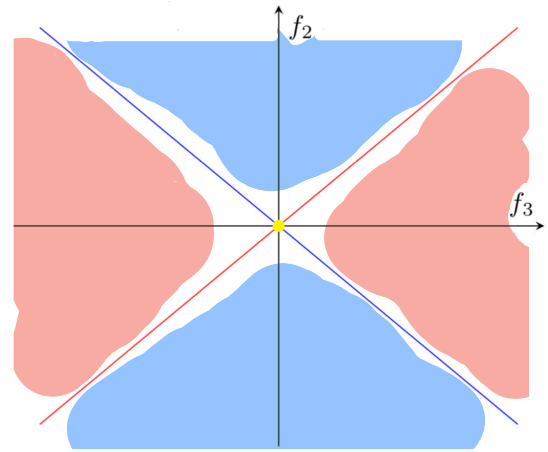

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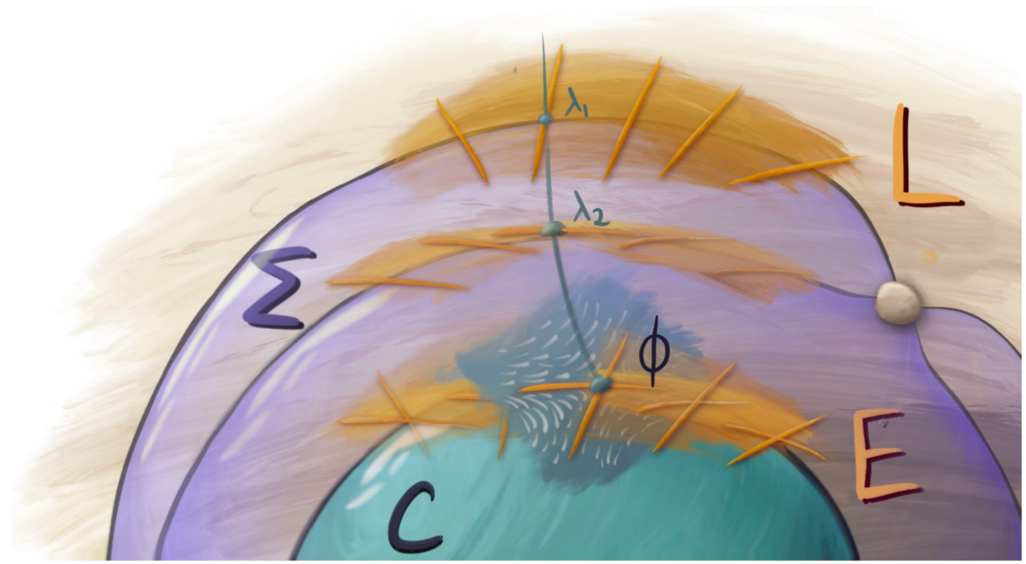

Peter Higgs (bosons)

1929–2024

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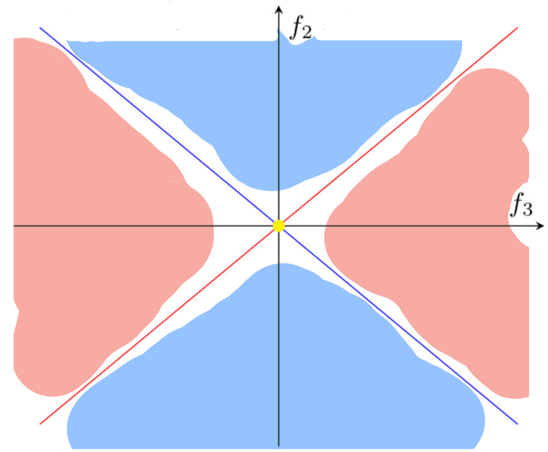

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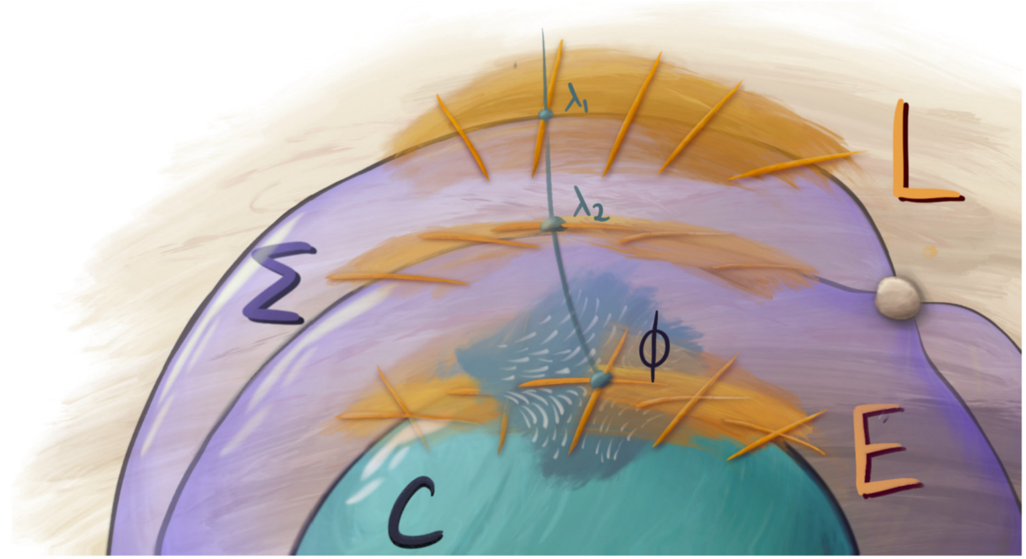
Peter Higgs (bosons)

Nigel Hitchin 1987



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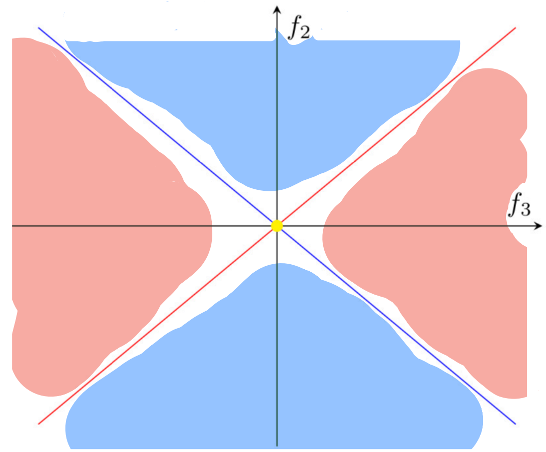

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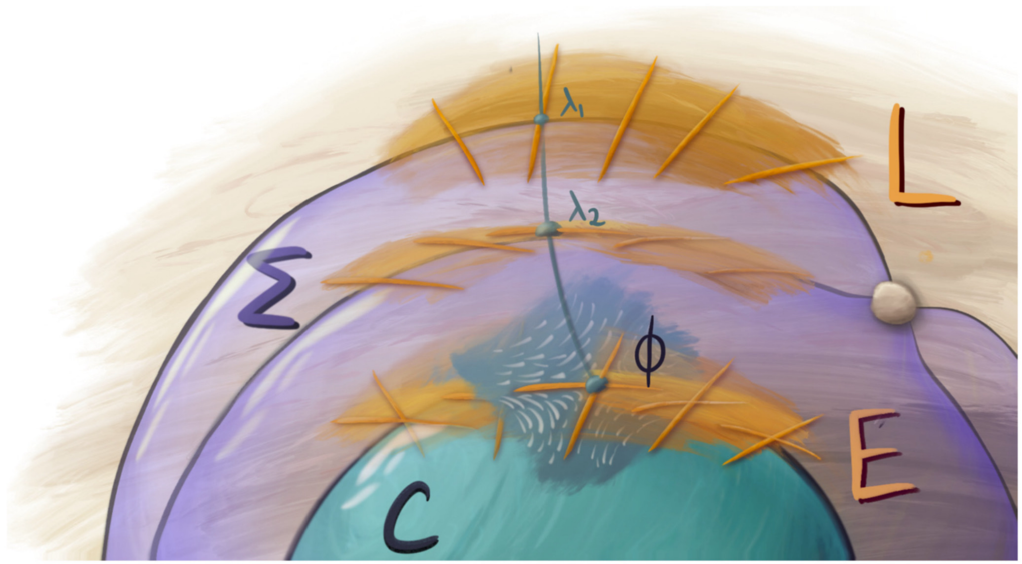
Peter Higgs (bosons)

Nigel Hitchin 1987

C compact Riemann surface



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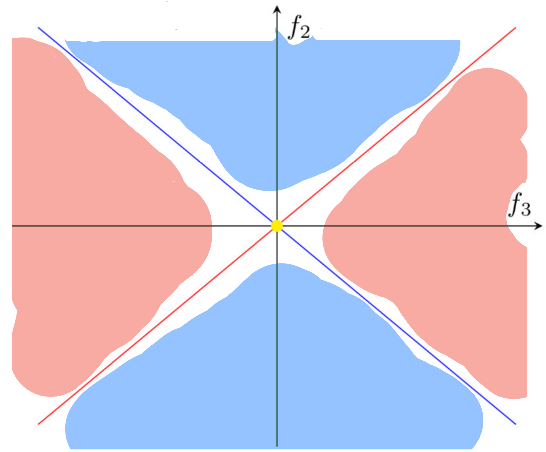

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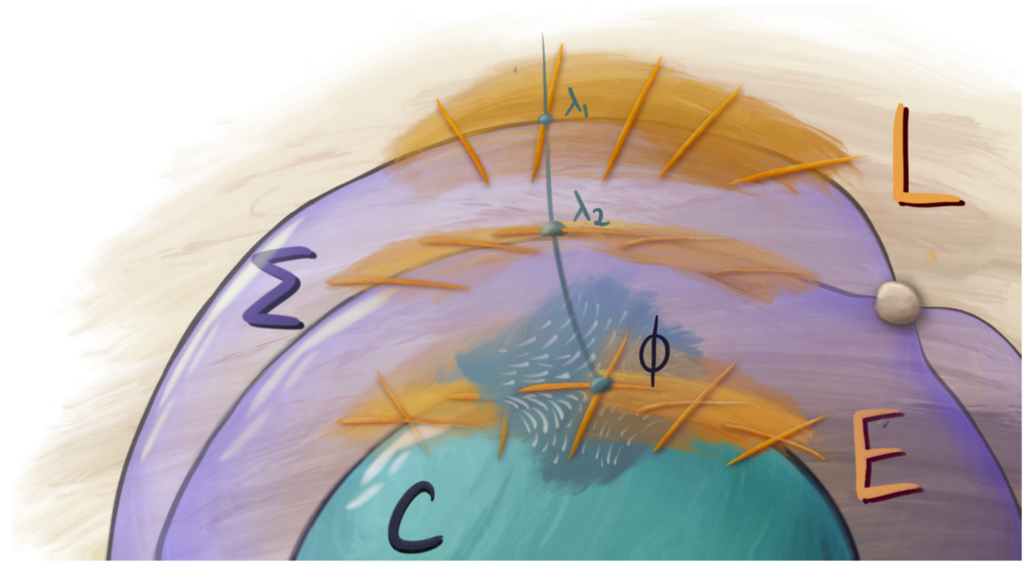
Peter Higgs (bosons)

Nigel Hitchin 1987

C compact Riemann surface
E holomorphic vector bundle



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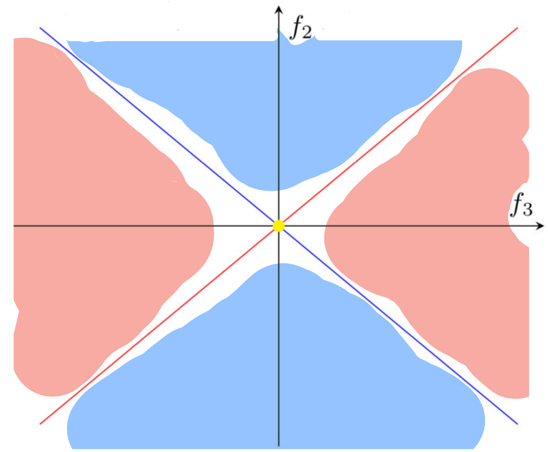

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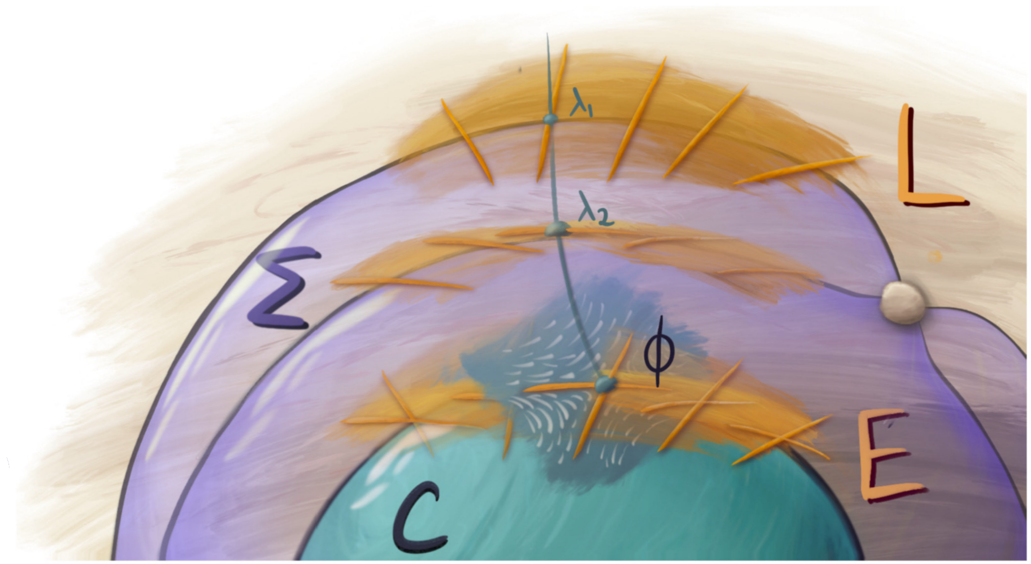
Peter Higgs (bosons)

Nigel Hitchin 1987

C compact Riemann surface
E holomorphic vector bundle
ϕ Higgs field: a holomorphic 1-form taking values in the bundle of endomorphisms of E



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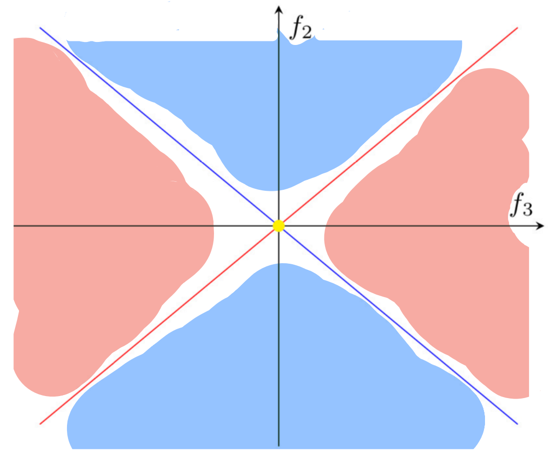

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Nigel Hitchin 1987

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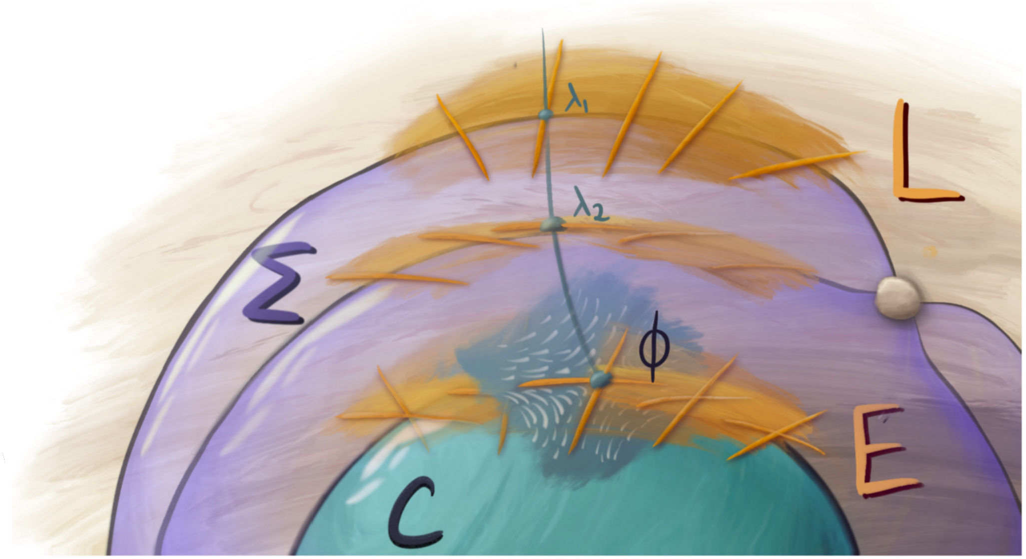

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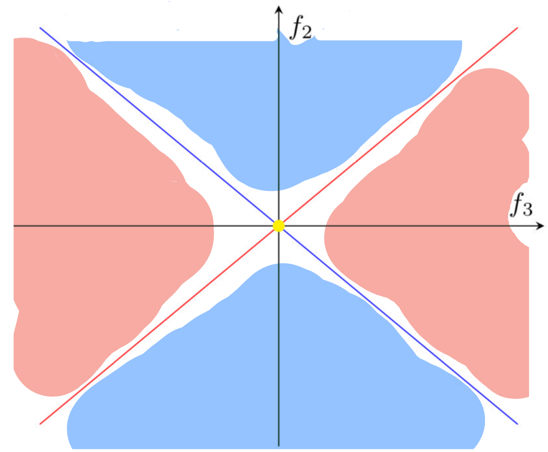

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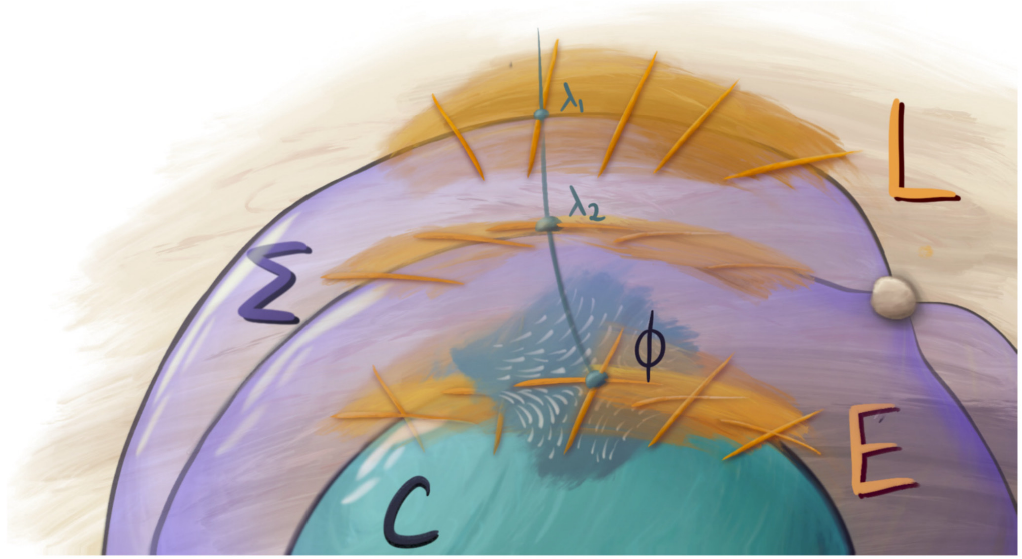

Peter Higgs (bosons)

Nigel Hitchin 1987
Carlos Simpson

C compact Riemann surface (or more generally Kähler manifold)
E holomorphic vector bundle
ϕ Higgs field: a holomorphic 1-form taking values in the bundle of endomorphisms of E such that $\phi \wedge \phi = 0$

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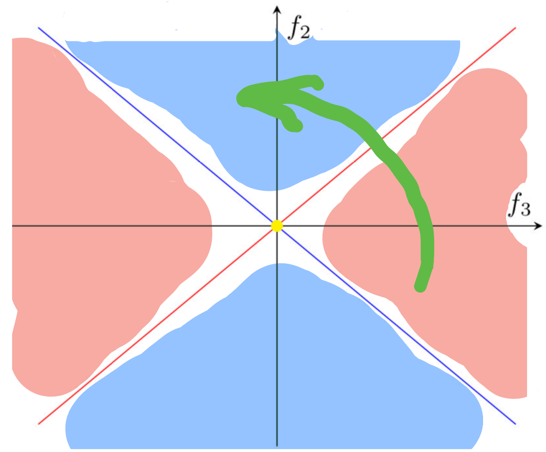

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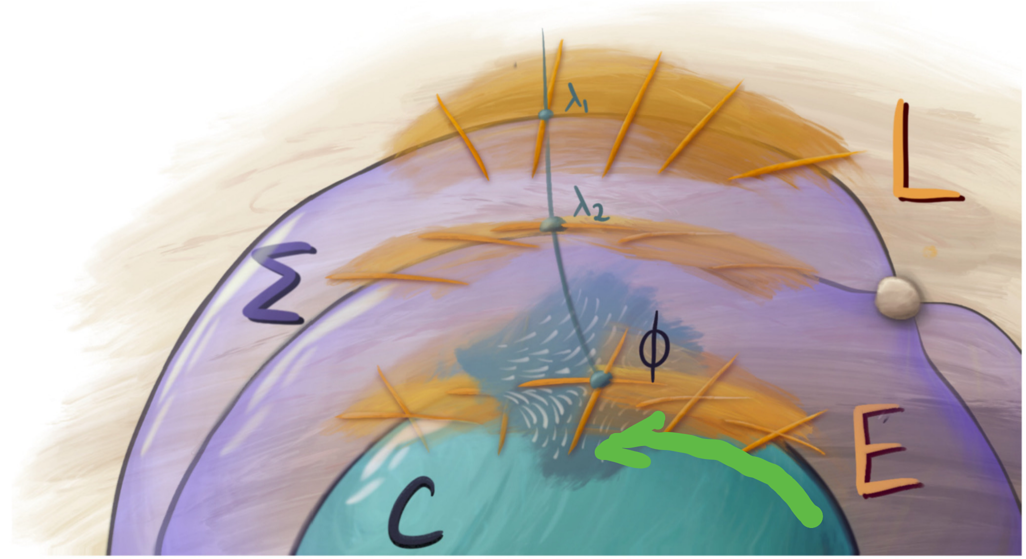
$$\phi_x \in \mathrm{End}(E_x), x \in C$$



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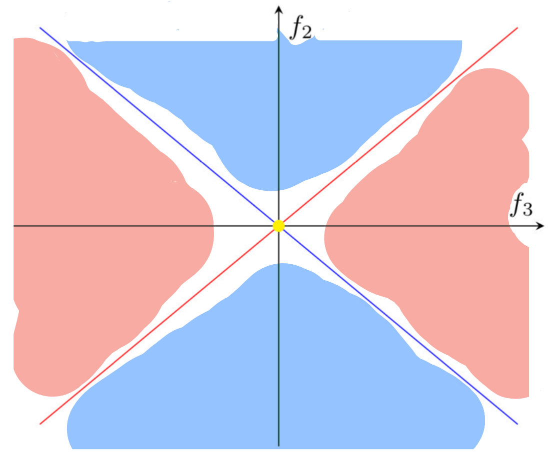

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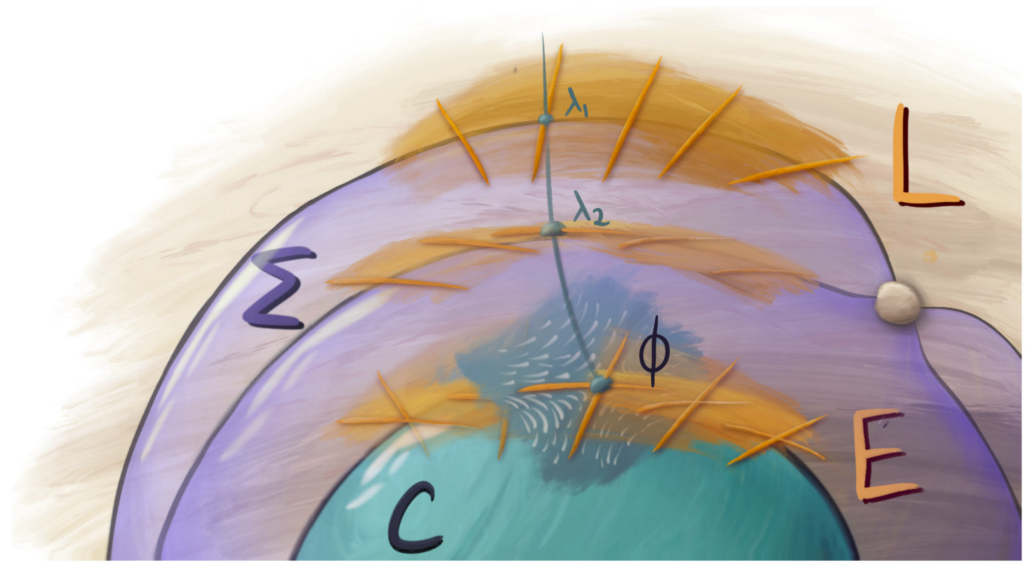

Portrait from Kienzle and Rayan, *Hyperbolic band theory through Higgs bundles*, ***Adv. Math.***, 2022.

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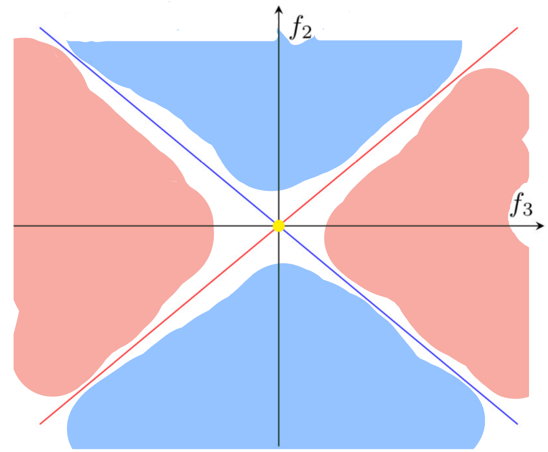

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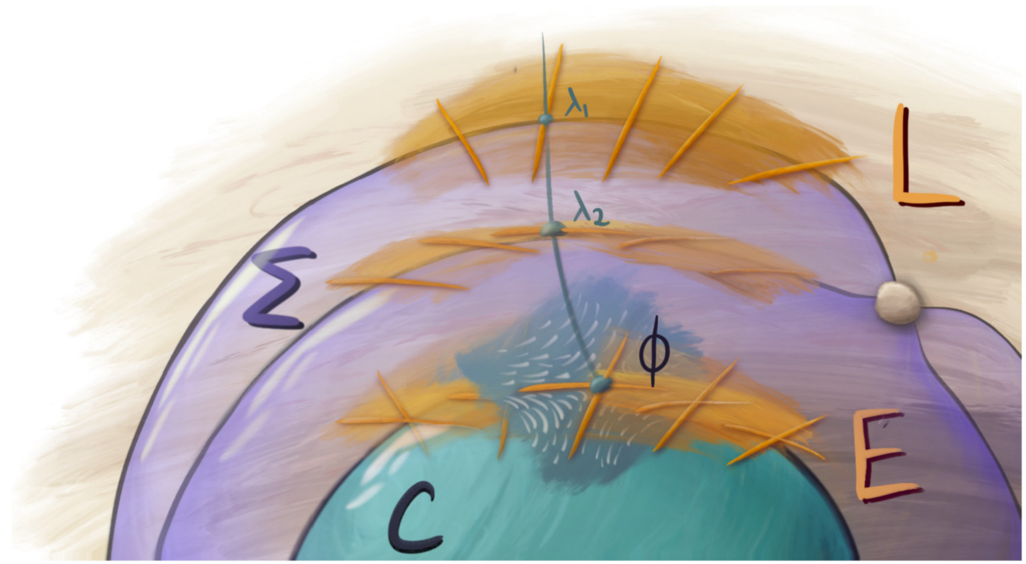

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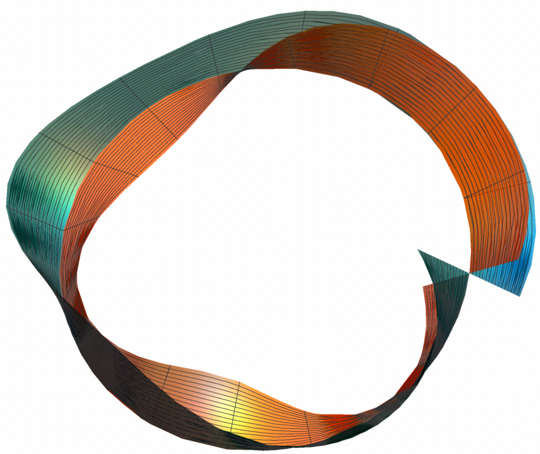
*Hyperbolic metric on the base C. Kollár et al., **Nature**, 2019.*

Eigenframe evolution as Higgs bundles: The non-Hermitian case

Proposition. The universal eigenbundle for non-Hermitian 2-band systems is given by a pair of kissing half Möbius bands



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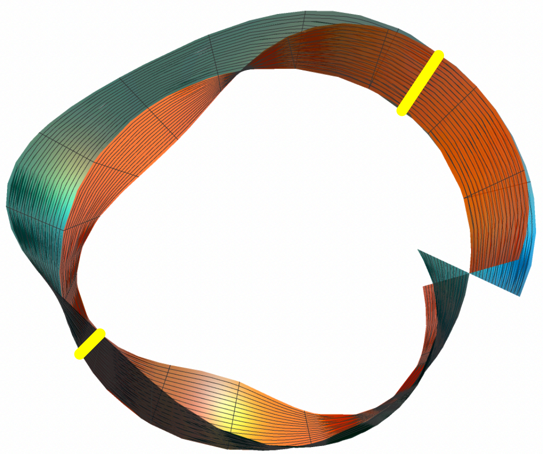

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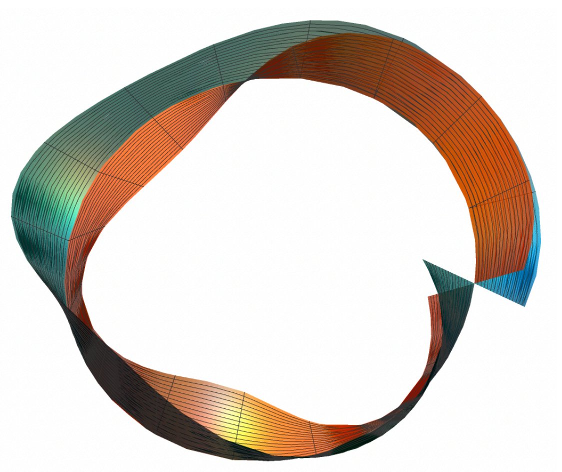
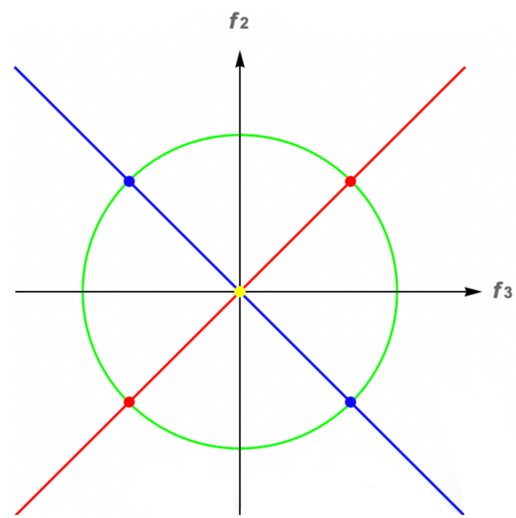
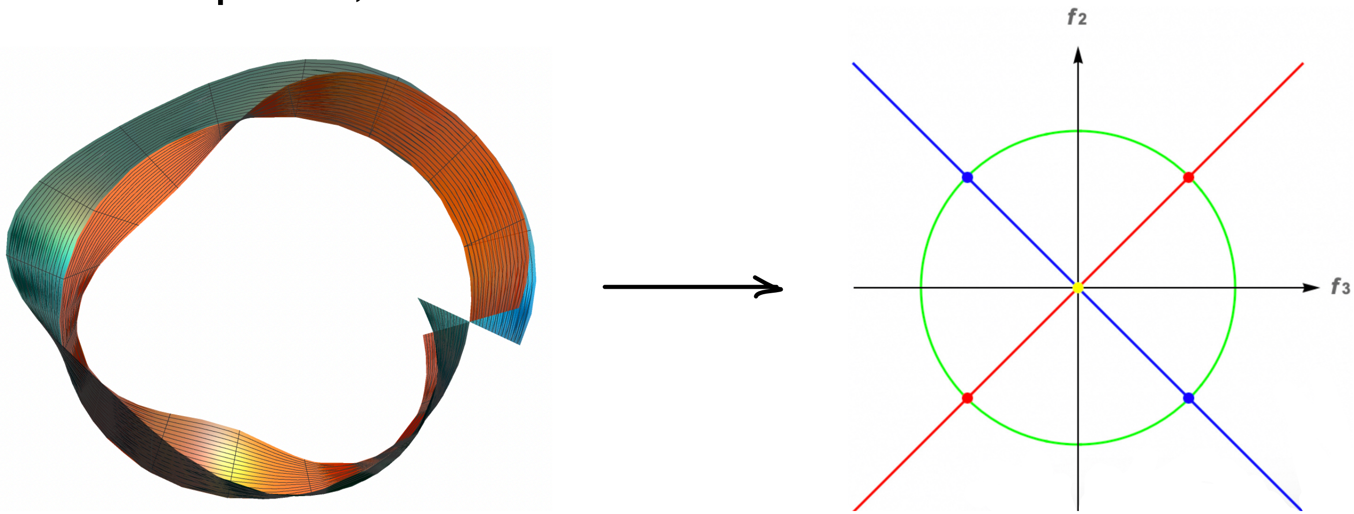




Eigenframe evolution as Higgs bundles: The non-Hermitian case

Proposition. The universal eigenbundle for non-Hermitian 2-band systems is given by a pair of kissing half Möbius bands over the stratified unit circle in the punctured parameter plane, whose 0-dimensional stratum consists of 4 points.



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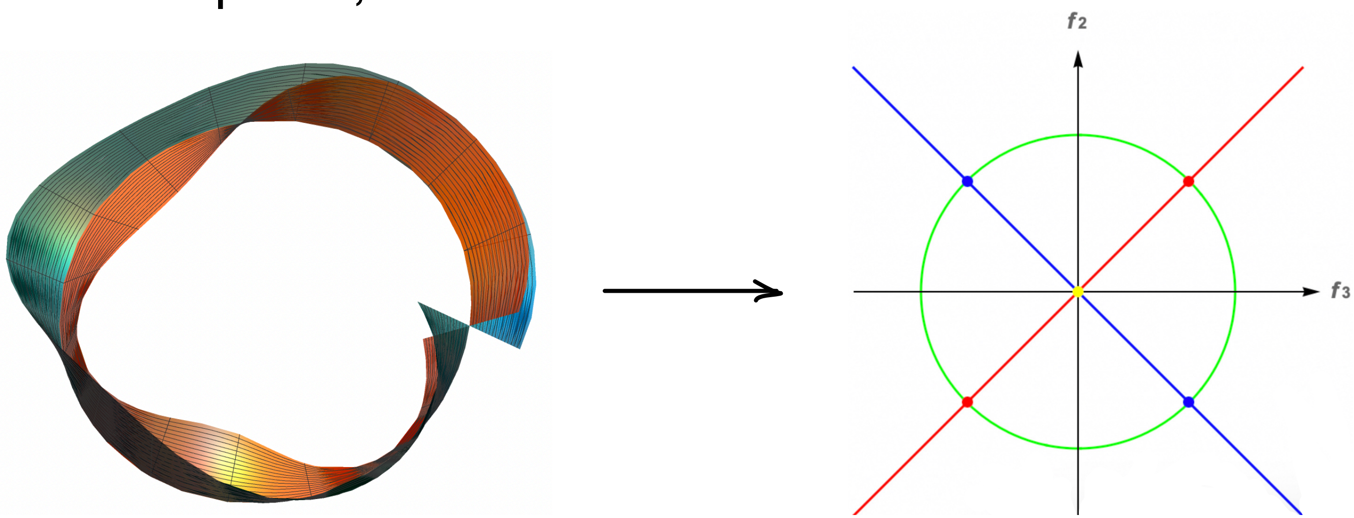

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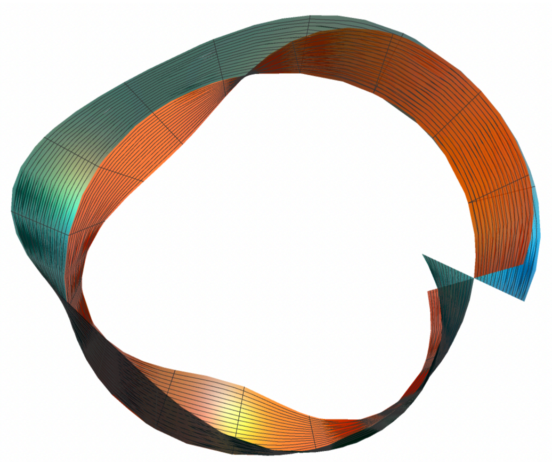

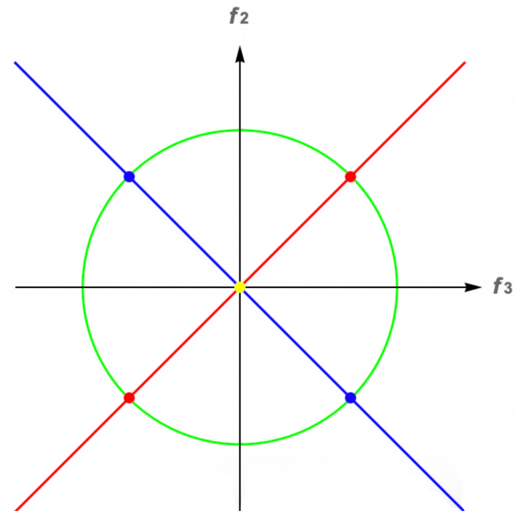

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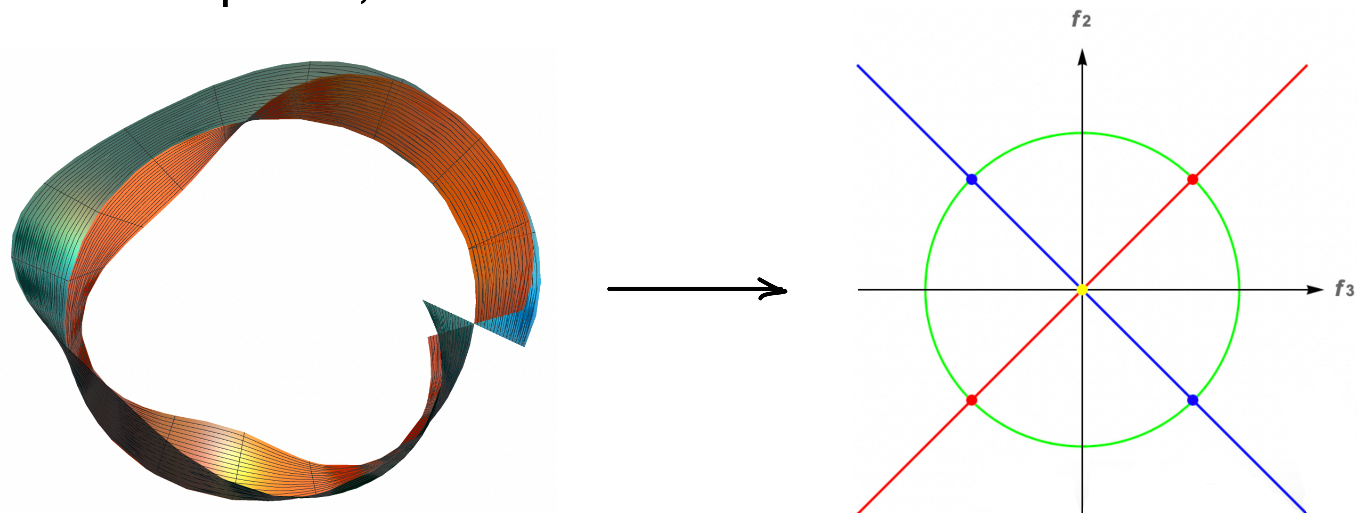

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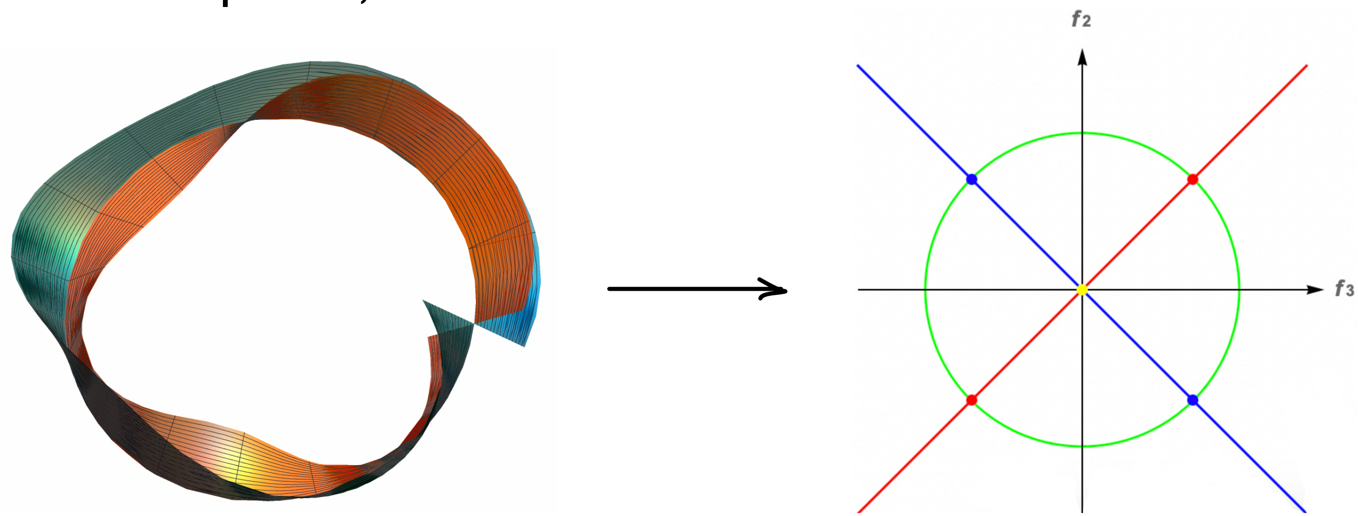

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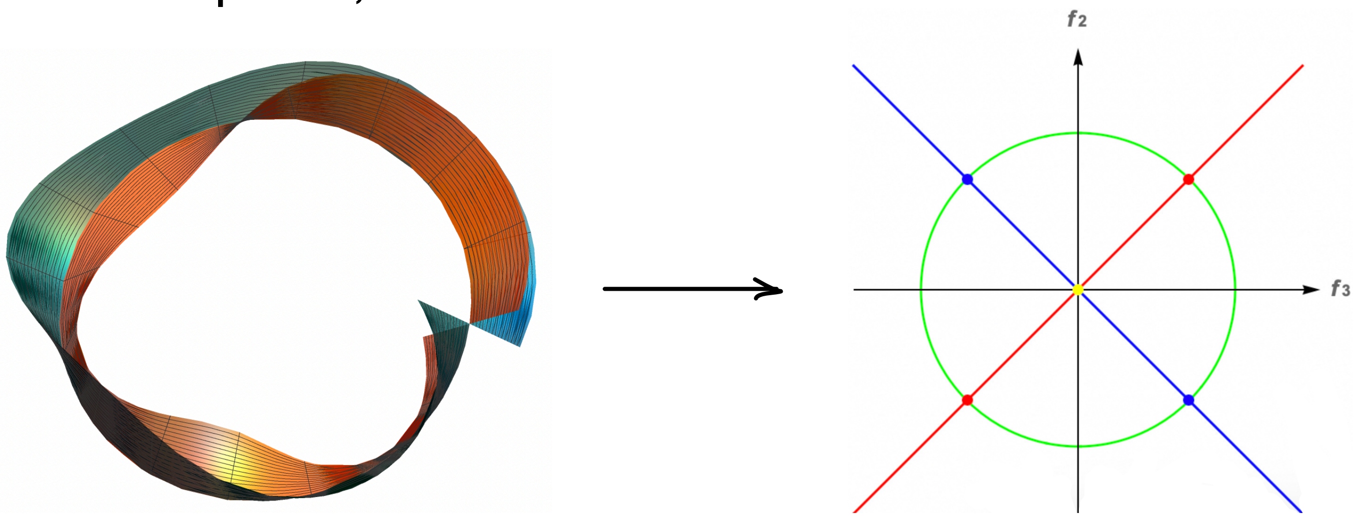

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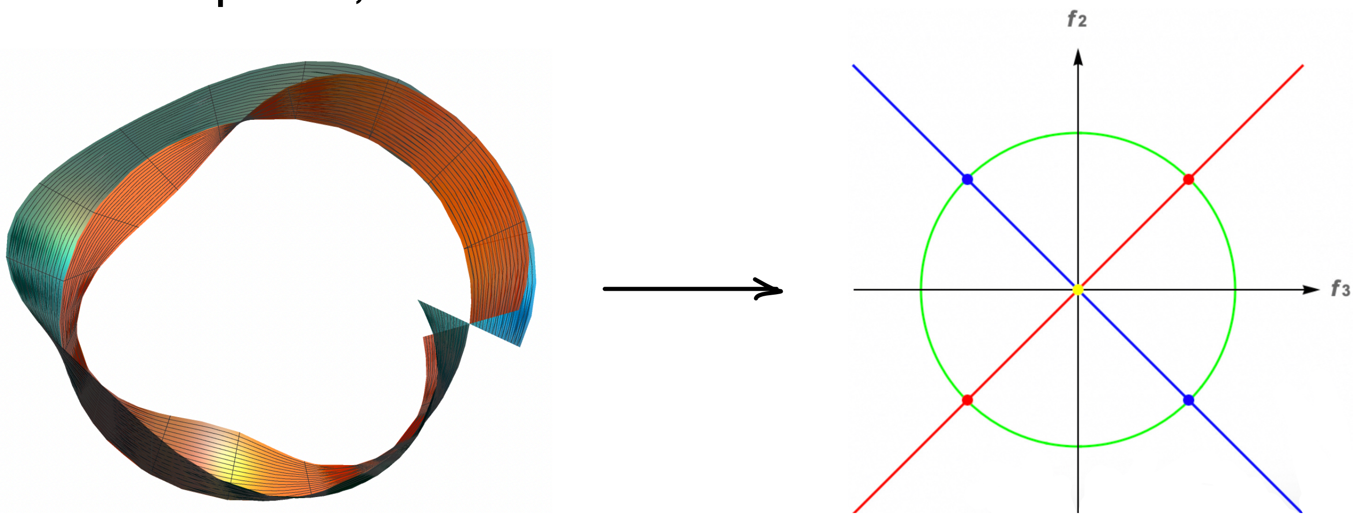

Here is a video showing the eigenframe evolution: https://yifeizhu.github.io/swallowtail/rotate.mp4

Note. In the non-Hermitian case, since the eigenvectors are in $\mathbb{C}^2$, we have adopted (a variant of) the *Hermitian angle* to properly characterize the eigenframe rotation and deformation:

$$\frac{\langle v_+, v_- \rangle_{\mathbb{C}}}{|v_+|\,|v_-|} = \rho e^{i\psi}, \quad \cos(v_+, v_-)_{\mathrm{Herm}} := \rho$$

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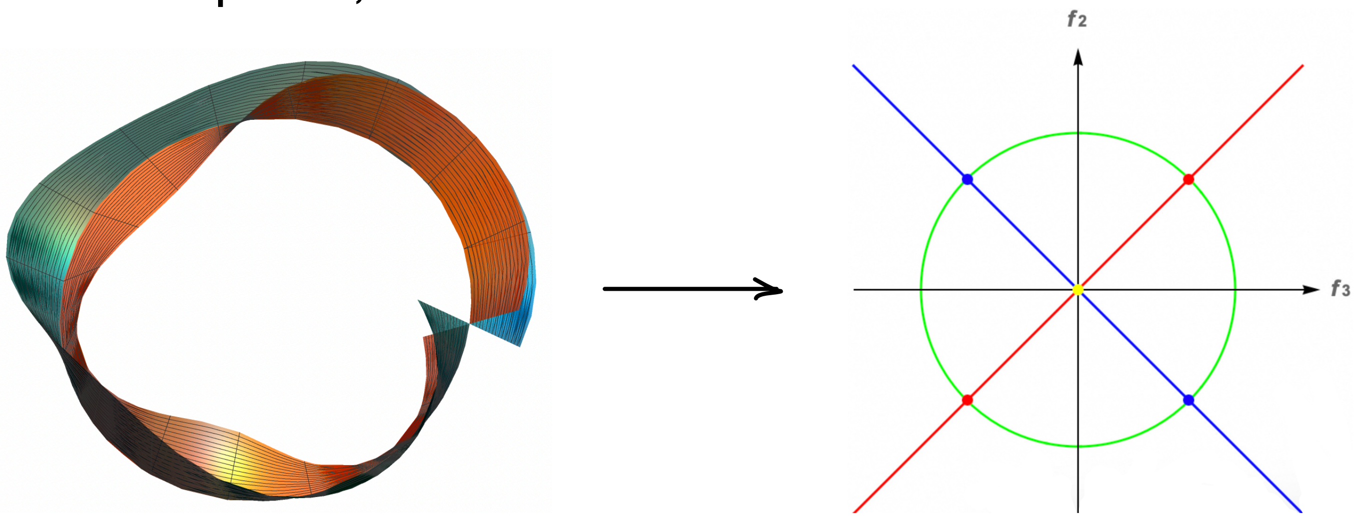

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The intrinsic geometry should be independent of real/complex coordination, though.

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universal bundle

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\begin{tikzcd}
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- Describe the universal bundle
- Find computable and effective algebraic invariants (topological charge) for the classifying/moduli space

Eigenframe evolution as Higgs bundles: The non-Hermitian case

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In progress: Need to compute the *intersection fundamental group* of the stratified moduli space.

Gajer, The intersection Dold–Thom theorem,
***Topology**, 1996. (Ph.D. student of Blaine Lawson, 1993)*

Goresky and MacPherson, 1974.

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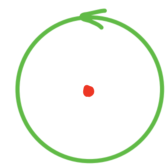

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$$
\begin{array}{c|c|c|c}
\mathbb{Z} & \mathbb{Z} & \mathbb{Z} & \mathbb{Z} \\
\mathbb{Z} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}
\quad {}_{0} \quad {}_{1} \quad {}_{2} \longrightarrow \bar{p}
$$

Intersection homology of $\mathbb{R}^2$ with one singular point: from top to bottom are $I^{\bar{p}}H_0, I^{\bar{p}}H_1, I^{\bar{p}}H_2,$ where $\bar{p}$ is the perversity function.

From blue to red regions, they detect the singular point.

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Tolerance of ill-behaved cycles

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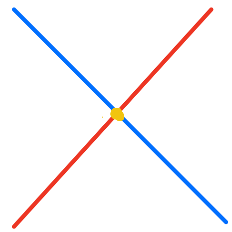

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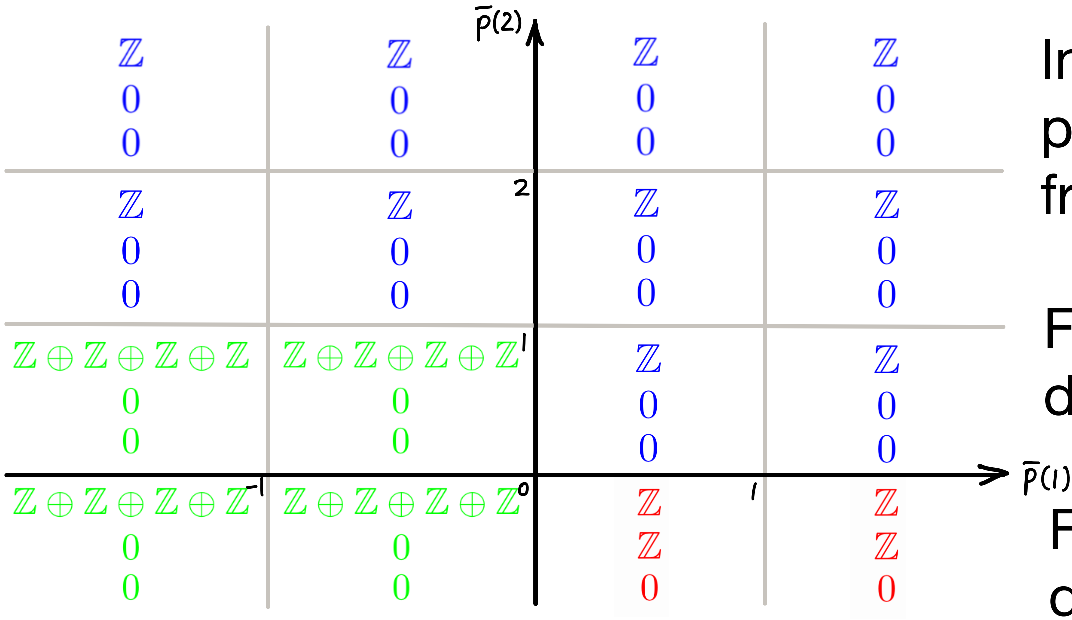

Intersection homology of $\mathbb{R}^2$ with a pair of intersecting singular lines: from top to bottom are $I^{\bar{p}}H_*$ with $* = 0, 1, 2.$

From green to blue regions, they detect the singular lines.

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- Still need compatibility with our earlier ad hoc non-Hermitian classification:

$$\pi_1\left(S^1 \vee S^1 \vee S^1\right) \cong \mathbb{Z} * \mathbb{Z} * \mathbb{Z}$$

May need to work at the chain level.

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$$\begin{bmatrix} 1 & f_1 & f_2 \\ -f_1 & -1 & f_3 \\ -f_2 & f_3 & -1 \end{bmatrix}$$

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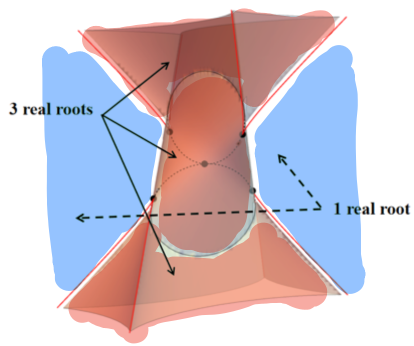

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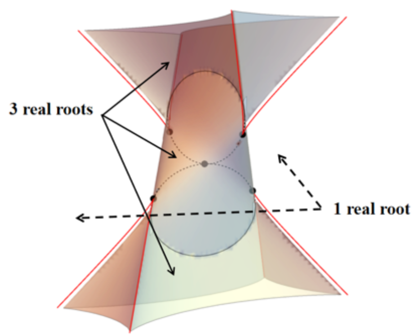

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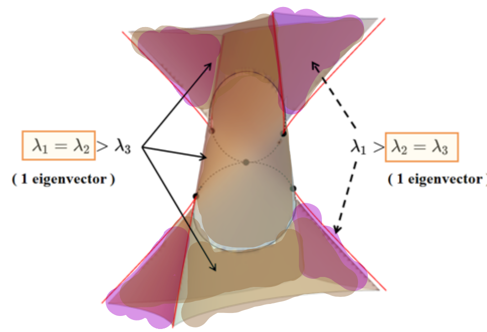

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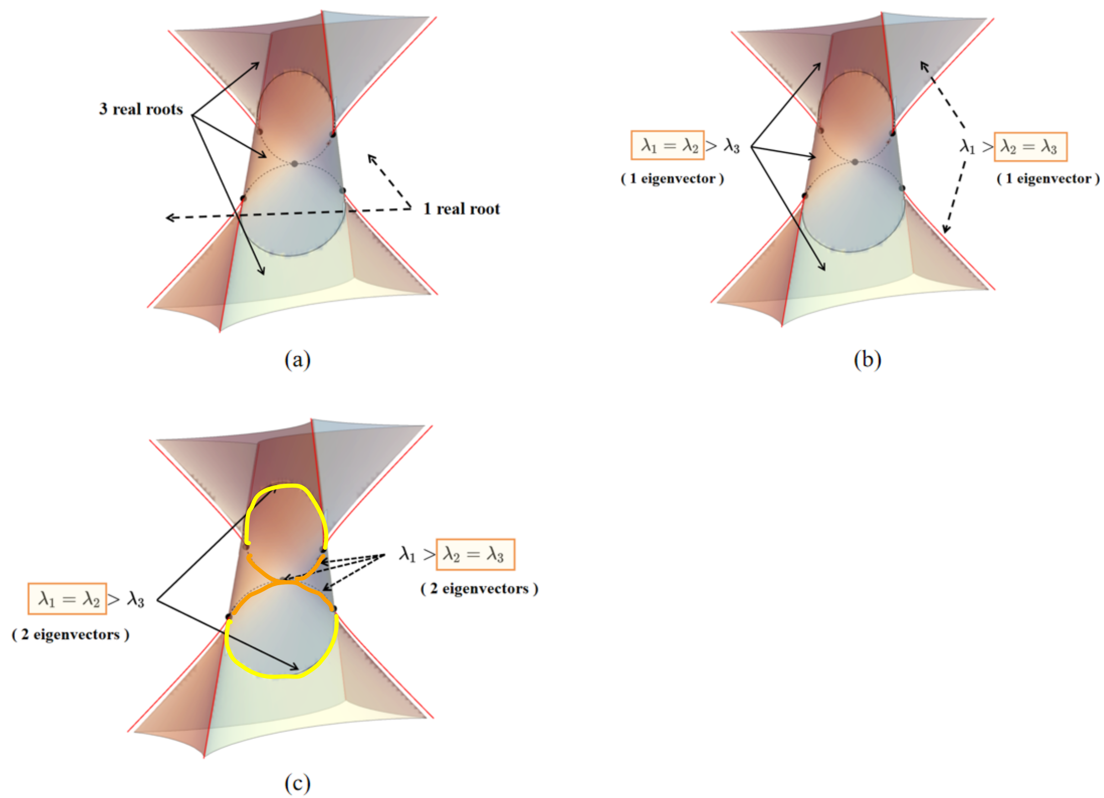

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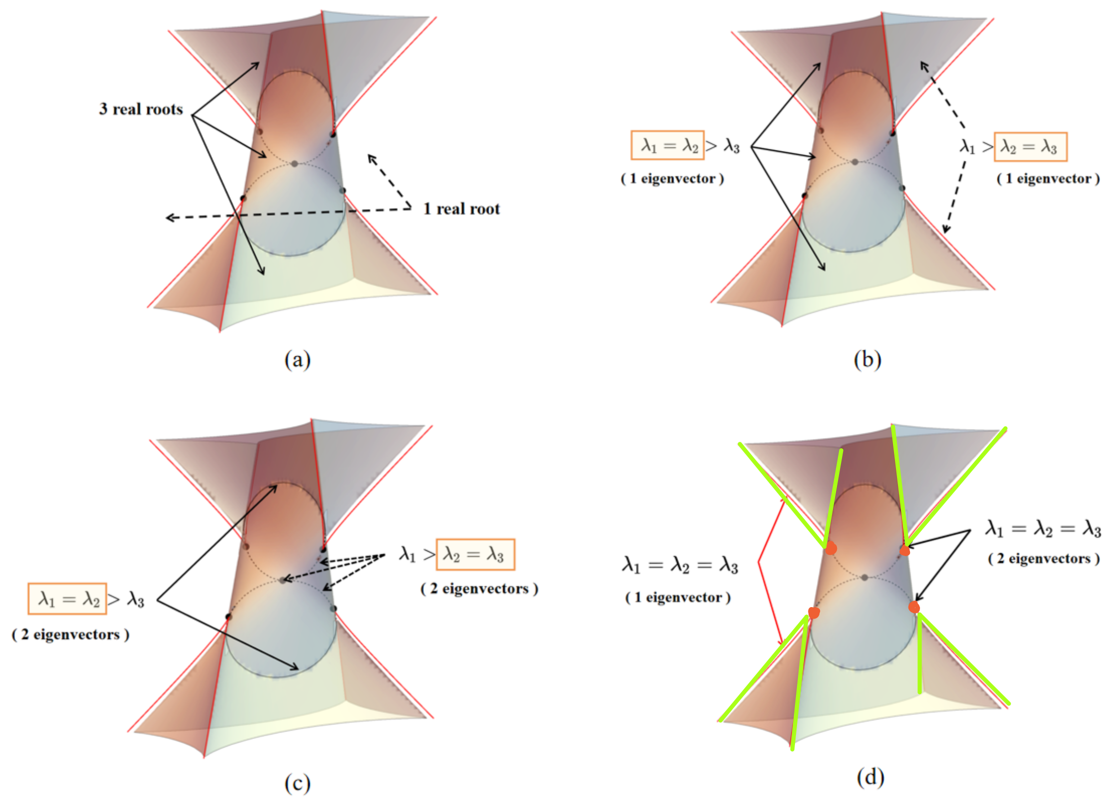

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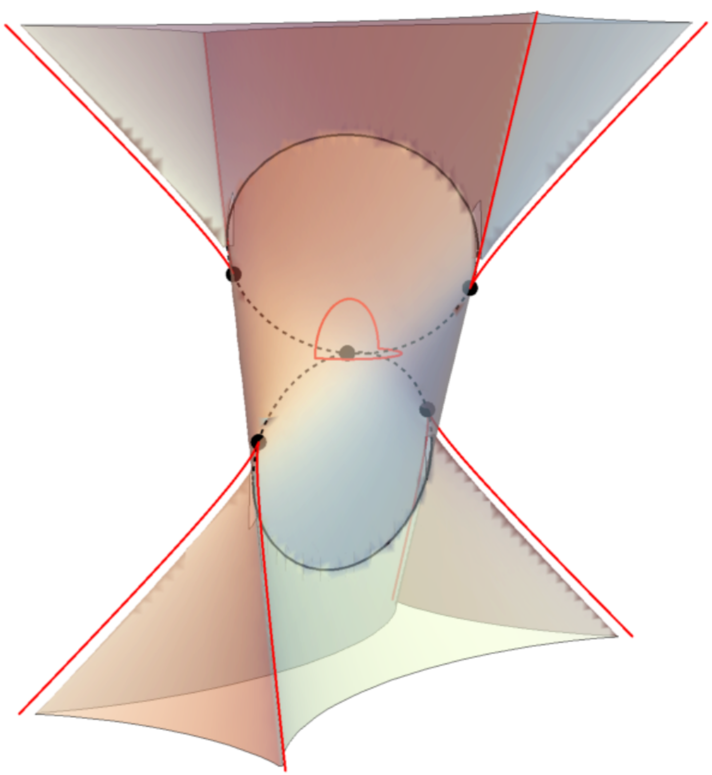

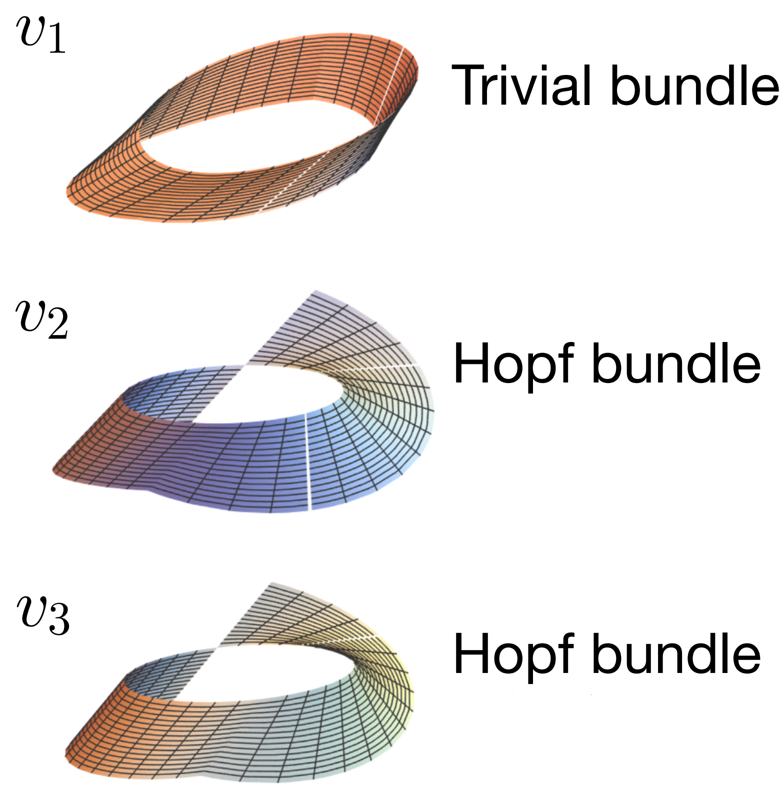

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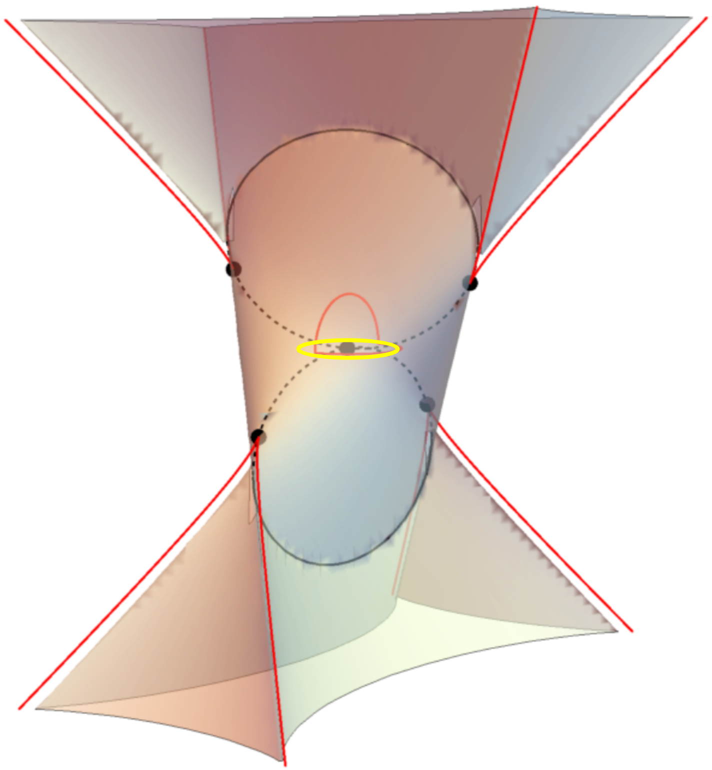

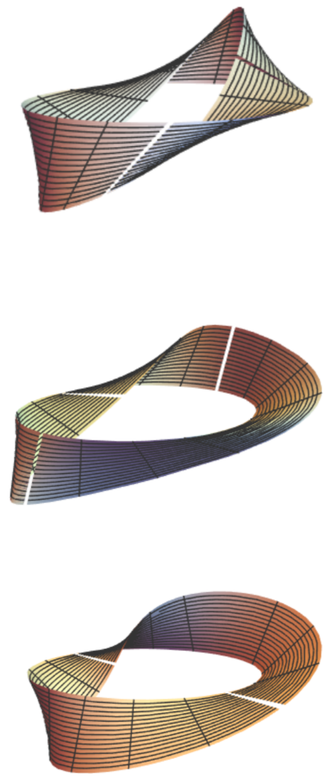

v_1 Trivial bundle

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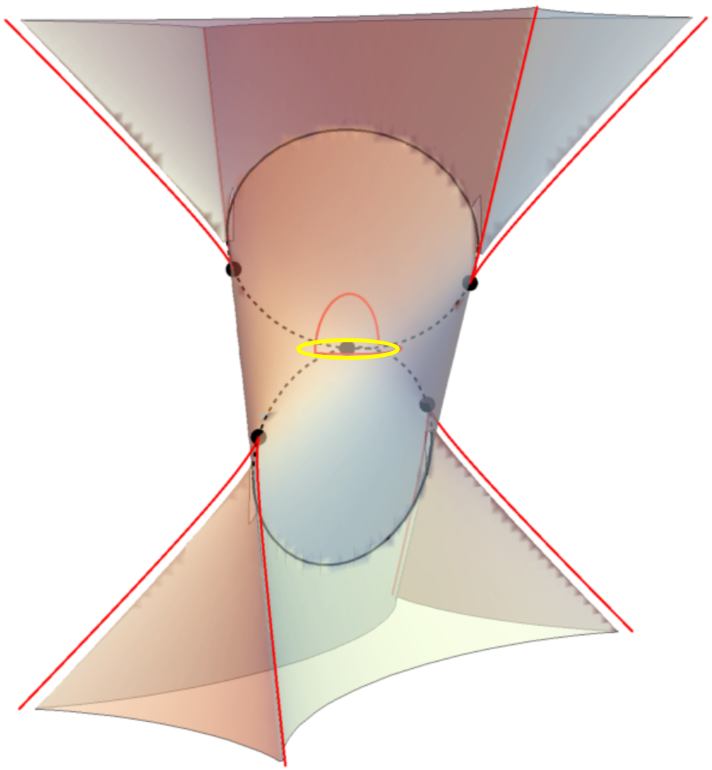

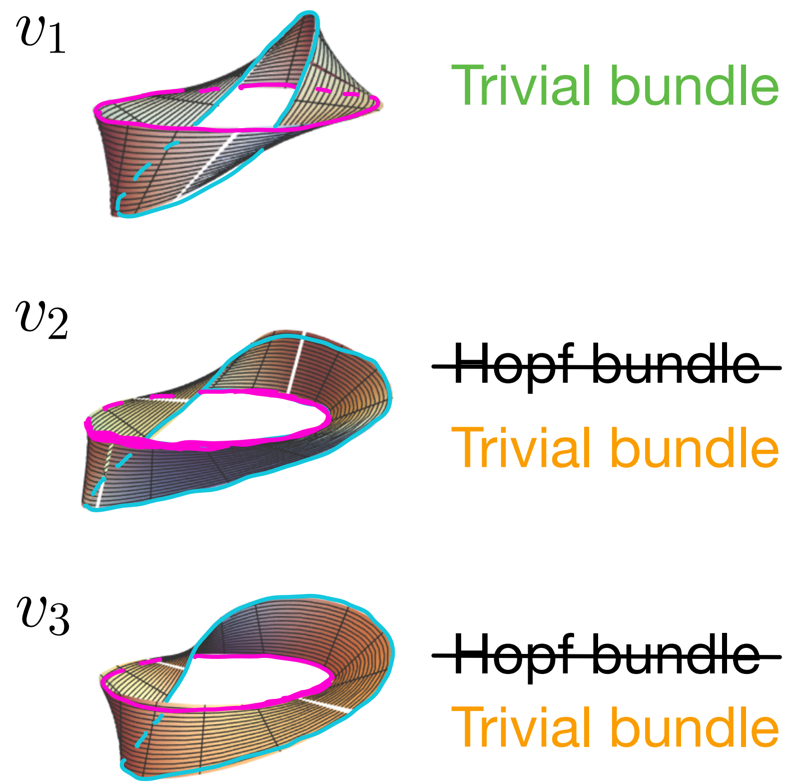

Linking number is "over-sensitive" when it involves a loop in the base space and a loop in the total space.

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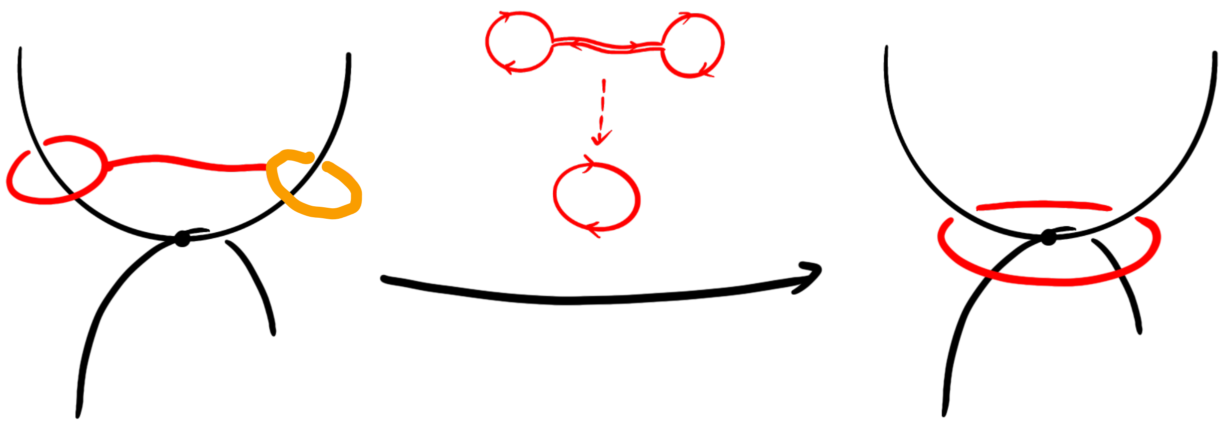

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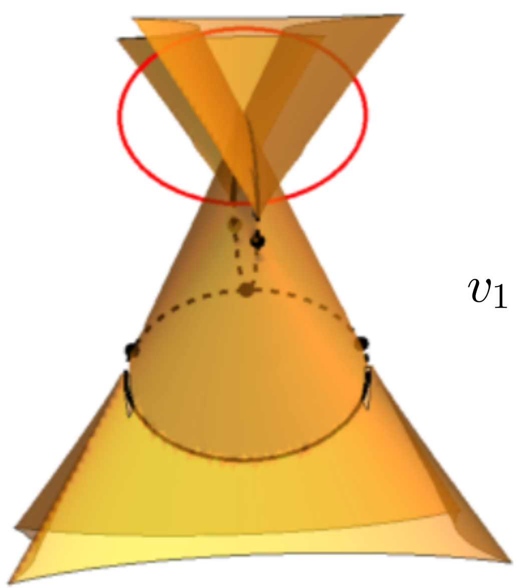

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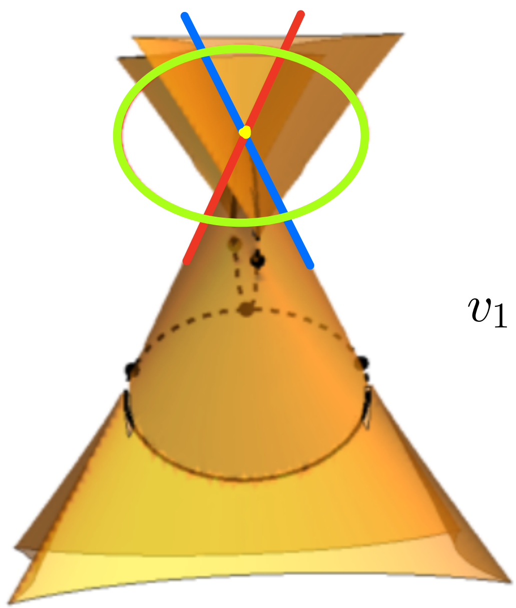

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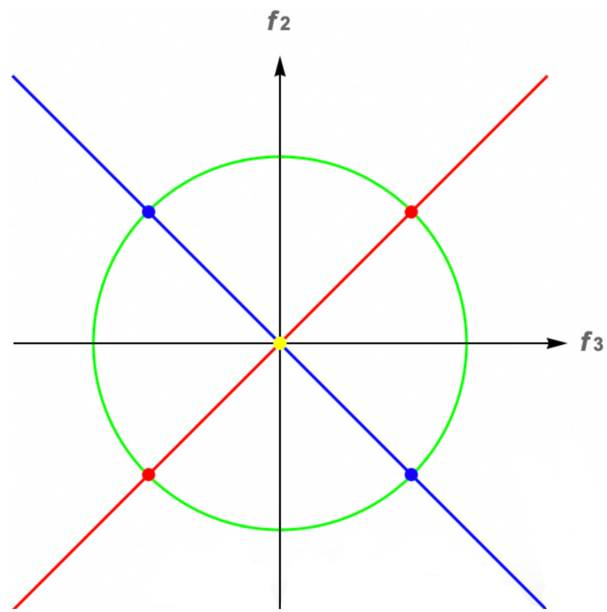

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Example (Family of swallowtail ensembles, including the couple $\mathrm{sw2}$ and the quadruple $\mathrm{sw4}$)**.**

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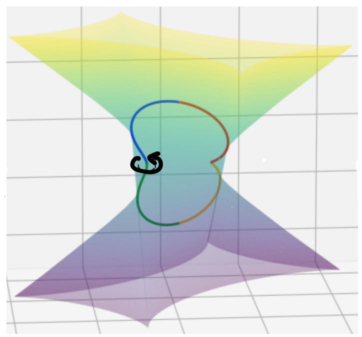

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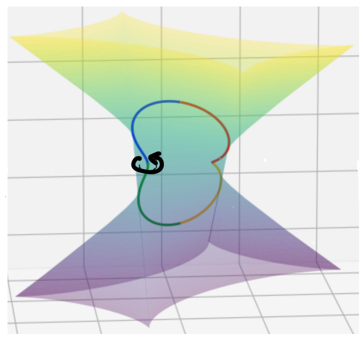

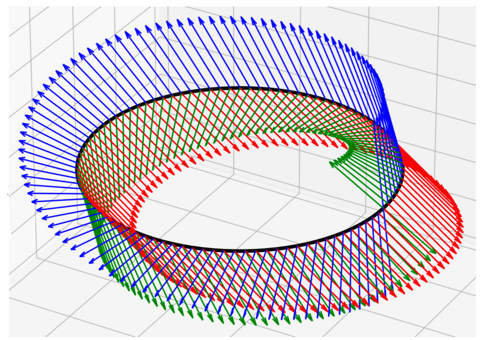

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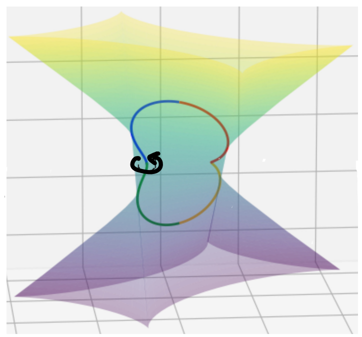

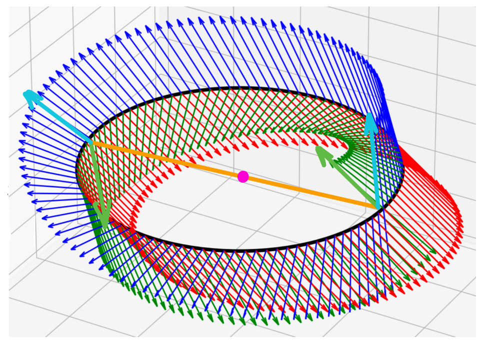

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Across the center (nodal line), the blue and green eigenstates swap

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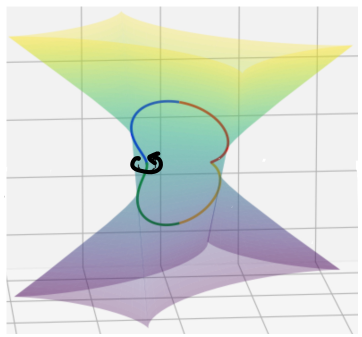

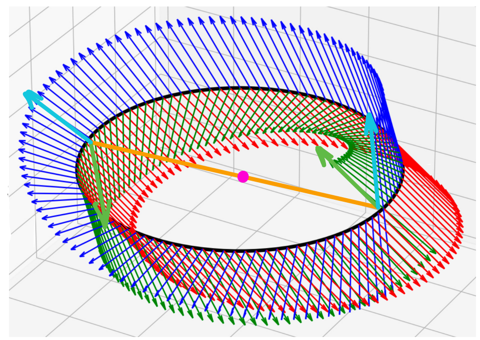

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Across the center (nodal line), the blue and green eigenstates swap — "band inversion."

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Visualizing at https://www.wolframcloud.com/env/zhuyf0/Presentation.nb

- Opening of 2 tunnels and a new “big” loop around, along which the rank-3 eigenbundle is trivial
- Merging of 8 cuspidal lines into 4
- Ruledness (specific parametrization)

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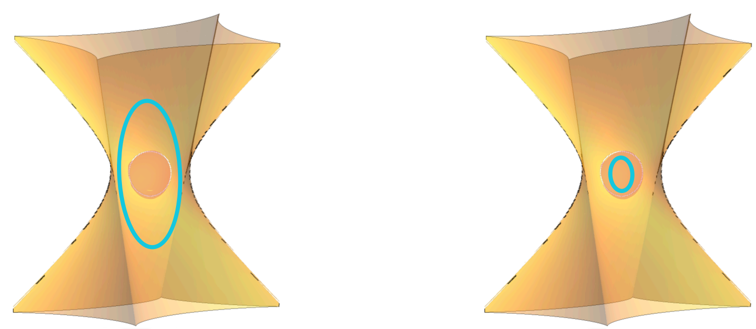

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Shrinking this loop into the enclosed region, we find the eigenbundle along it remains trivial.

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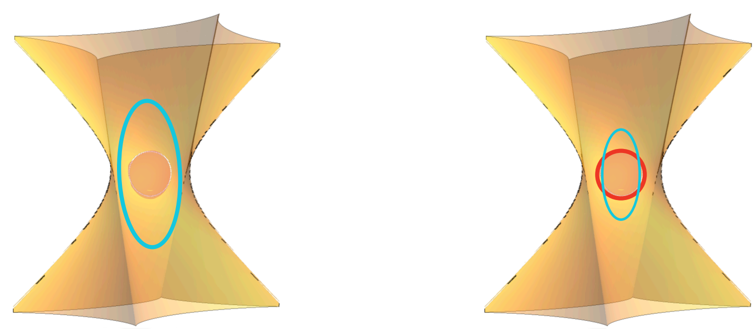

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What about loops transversing the nodal intersection lines? Band inversion again?

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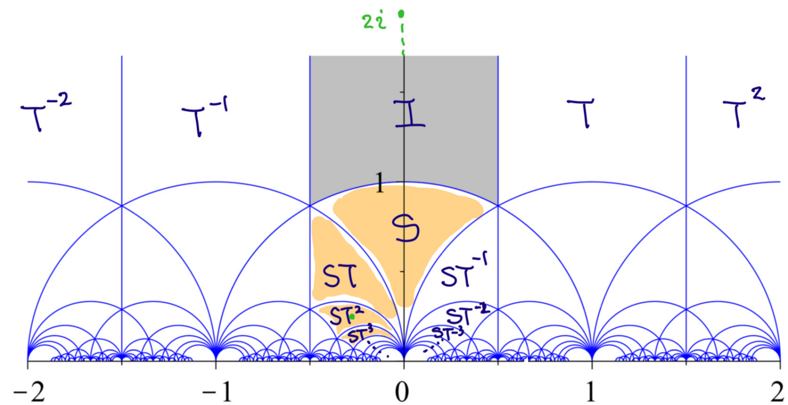

A prototypical 2D hyperbolic lattice with a straight-line boundary

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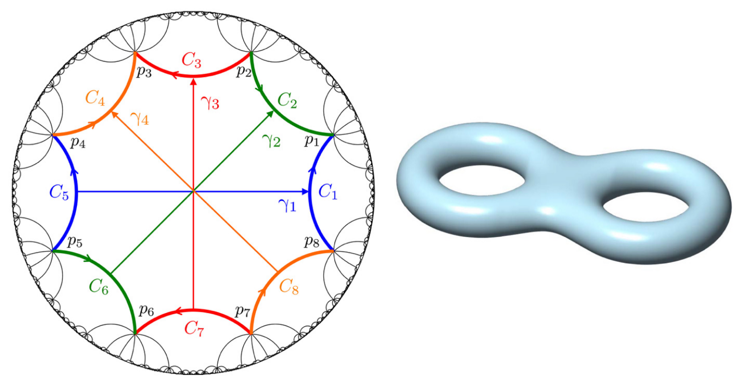

Another basic example of a hyperbolic lattice associated to a genus-2 surface
(from Maciejko and Rayan, *Hyperbolic band theory*, ***Sci. Adv.***, 2021)

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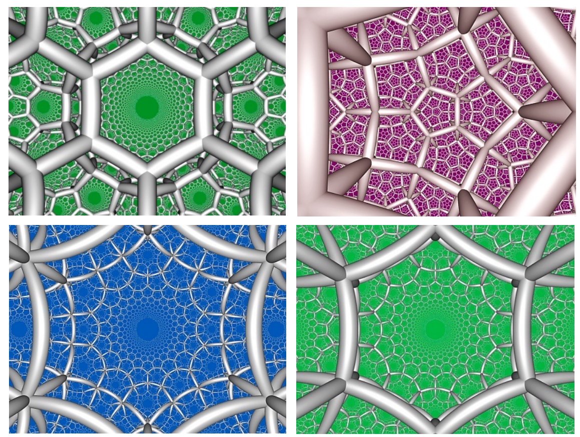

Four 3D hyperbolic lattices tiling up the hyperbolic 3-space $\mathbb{H}^3$ (from John Baez's blog)

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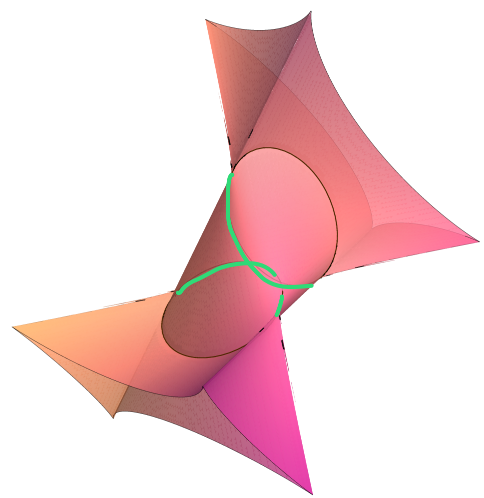

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Existence of nodal curves inside also gives evidence, supporting nontrivial loops around (generating a free group on 3 letters) acting on a 3D hyperbolic lattice.

Moduli of Higgs bundles

There are moduli spaces for Higgs bundles of various sorts.

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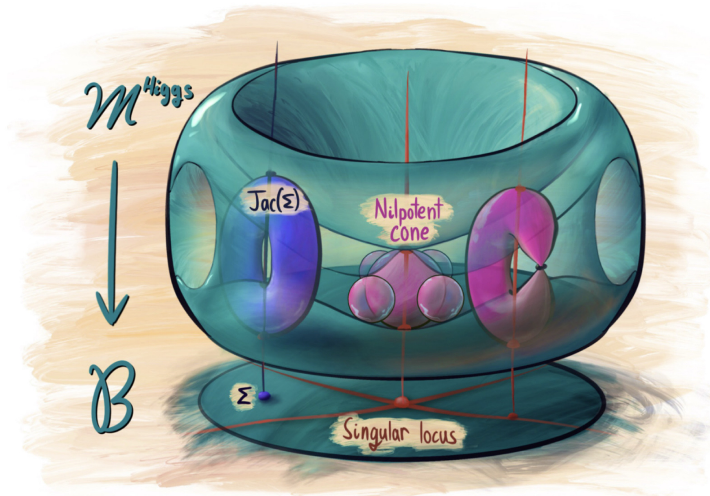

Portrait by Elliot Kienzle

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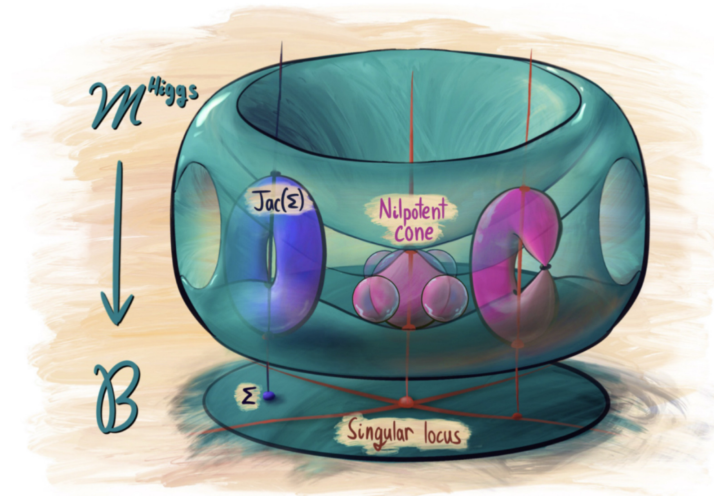

$$h\colon \mathscr{M}^{\mathrm{s}}_{\mathrm{Higgs}}\big(\mathrm{SL}_n(\mathbb{C})\big) \longrightarrow \bigoplus_{i=2}^{n} H^0(\Sigma; K^i) =: \mathscr{B}$$
$$(E,\phi) \;\mapsto \big(p_2(\phi),\ldots,p_n(\phi)\big)$$

where each p_i is a homogeneous polynomial of degree i.

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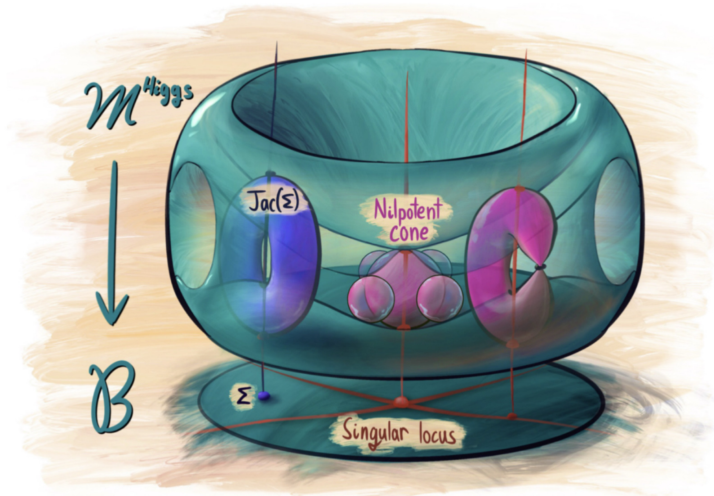

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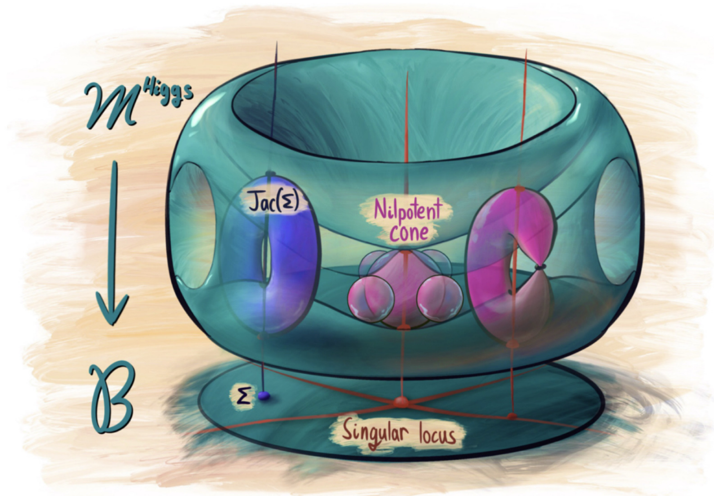

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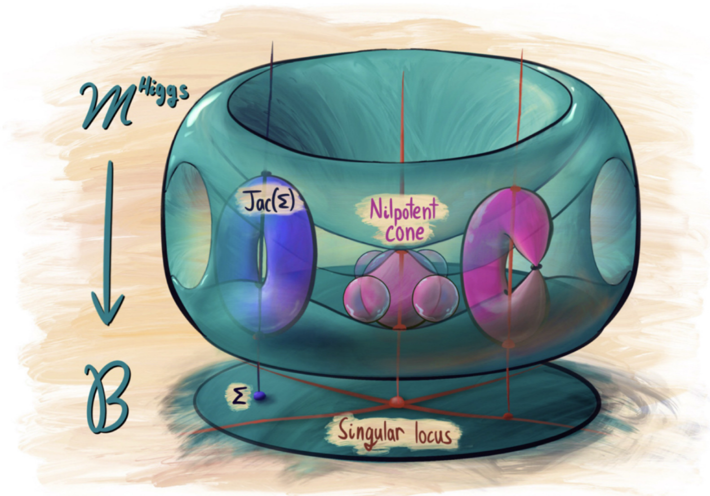

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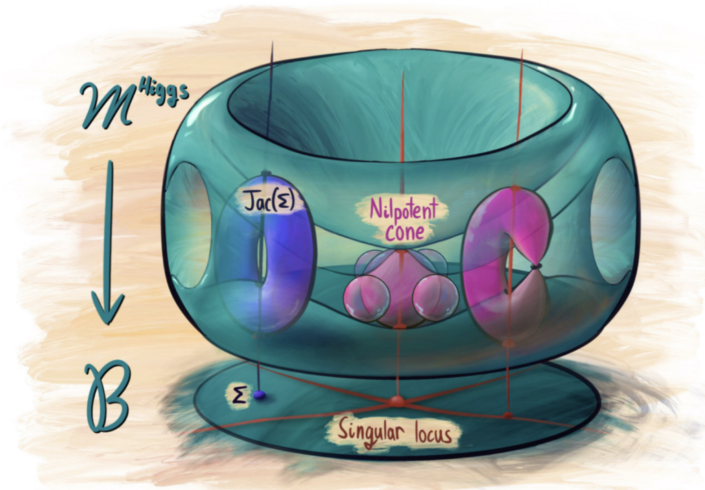

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- Nilpotent cone: The most degeneration occurs over $0 \in \mathscr{B}$. The fiber $h^{-1}(0)$ is called the nilpotent cone.

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Example (2-band non-Hermitian system).

Moduli of Higgs bundles

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Recall

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and compute that $\operatorname{tr} H = 0, \det H = f_2^2 - f_3^2.$

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Since there is no nontrivial *H*-invariant subbundle, this Higgs bundle is stable.

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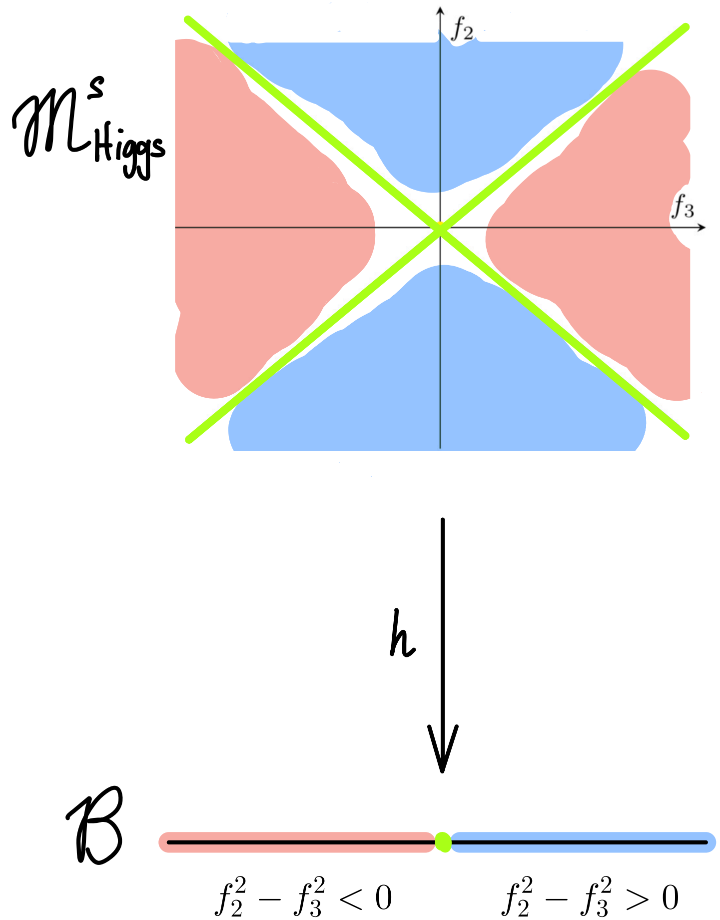

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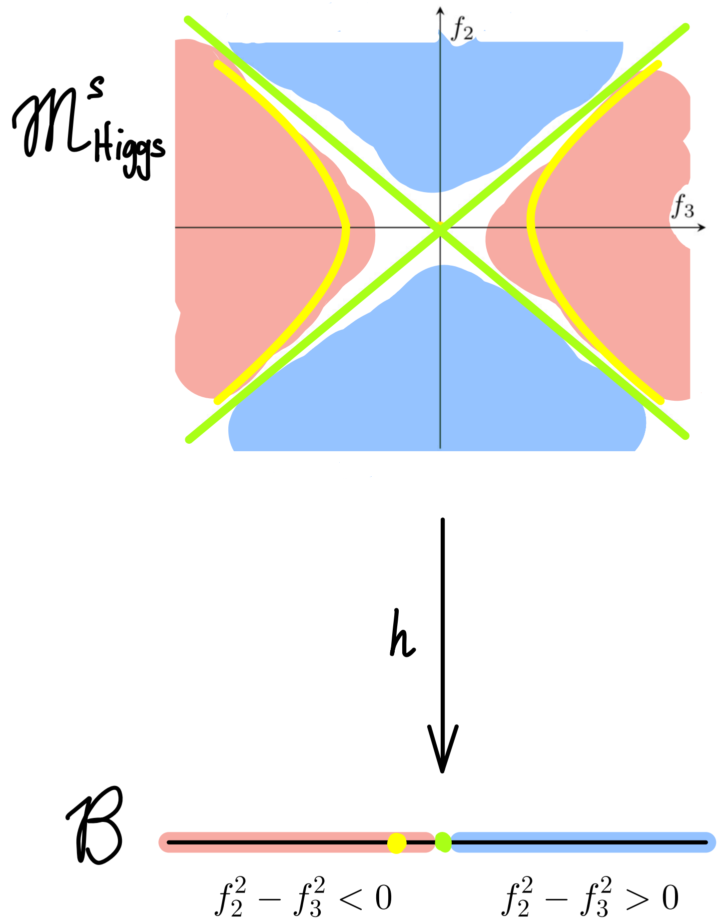

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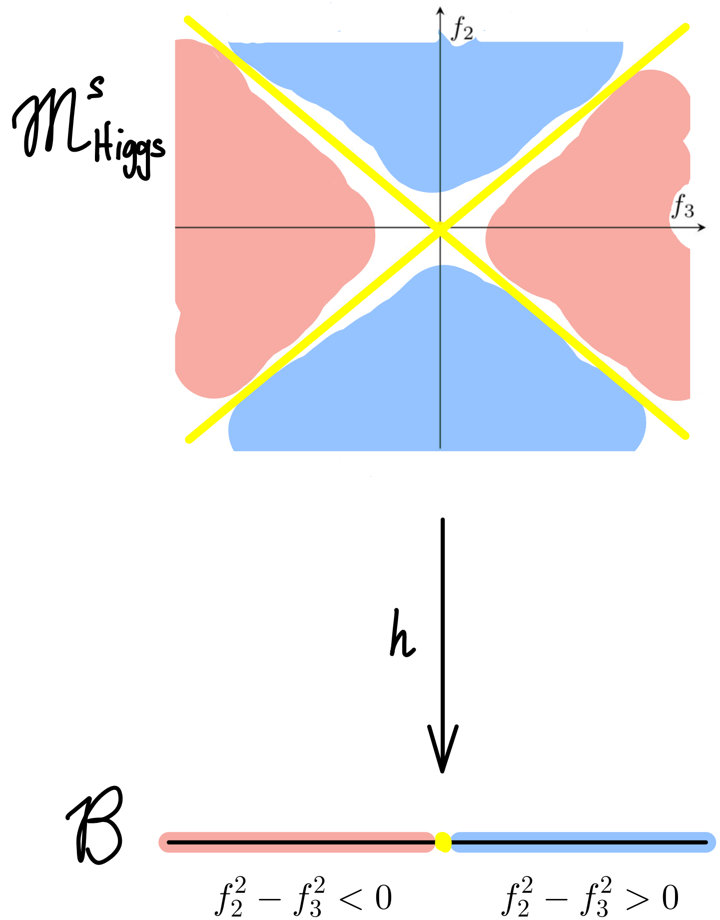

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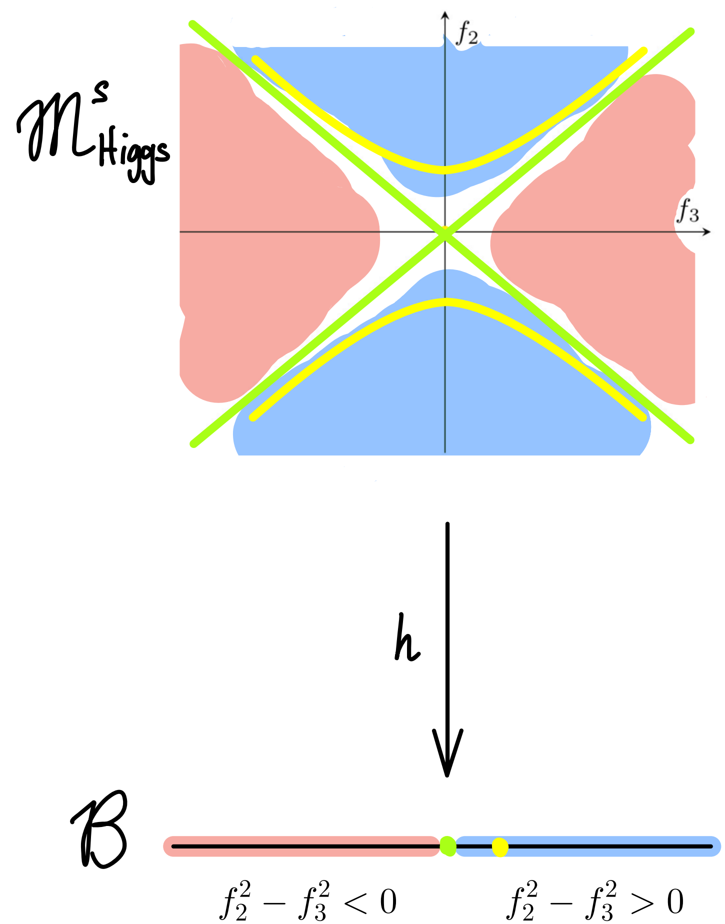

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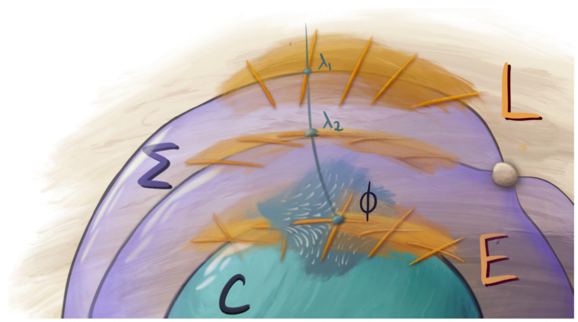

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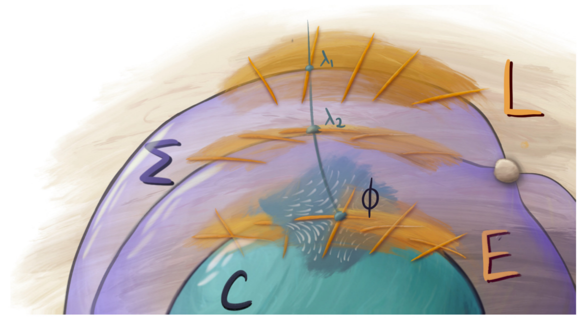

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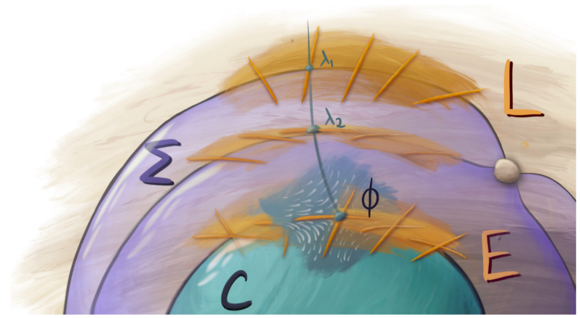

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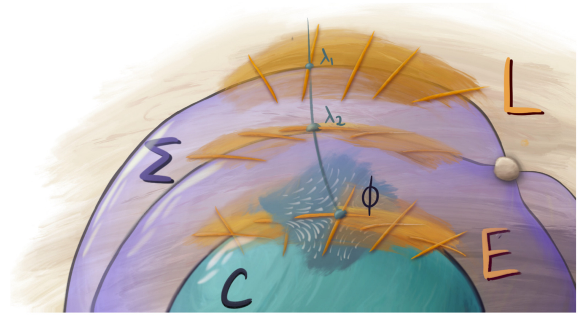

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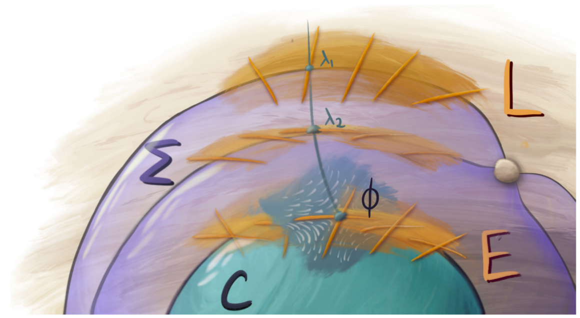

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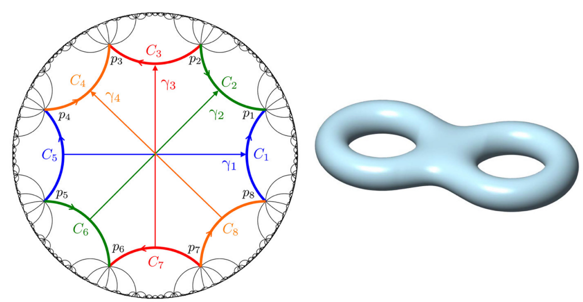

Maciejko–Rayan '21

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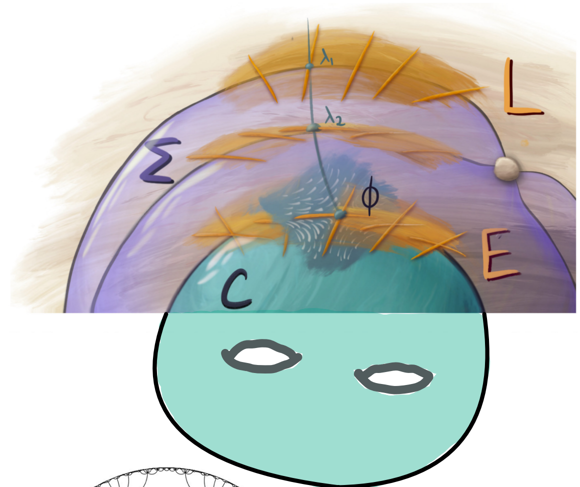

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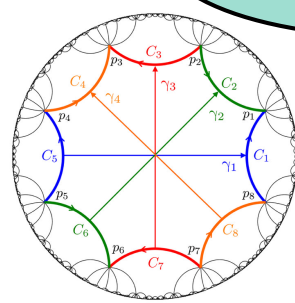

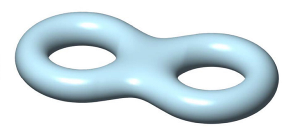

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More precisely, e.g., the bulk–edge correspondence relates a topological invariant of the bulk insulator (the first Chern number of the Bloch eigenbundle, also called the Hall conductance) with an invariant of a surface state (the winding number about the Fermi energy in the complex Bloch variety). Moreover, any topological invariant is determined from the band structure over the nilpotent cone.

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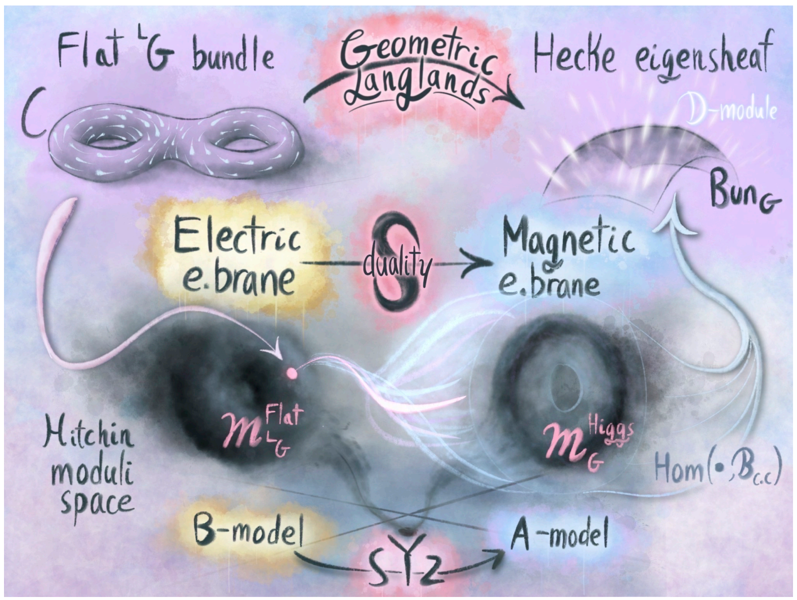

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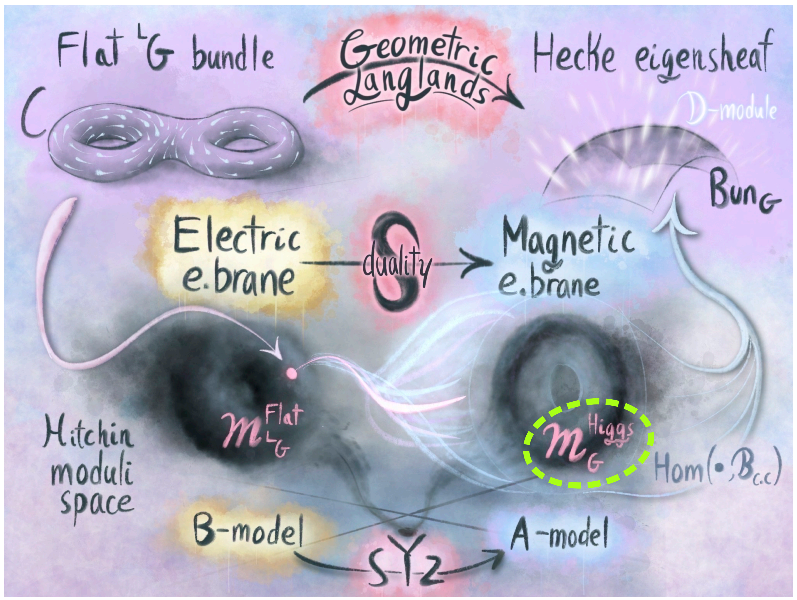

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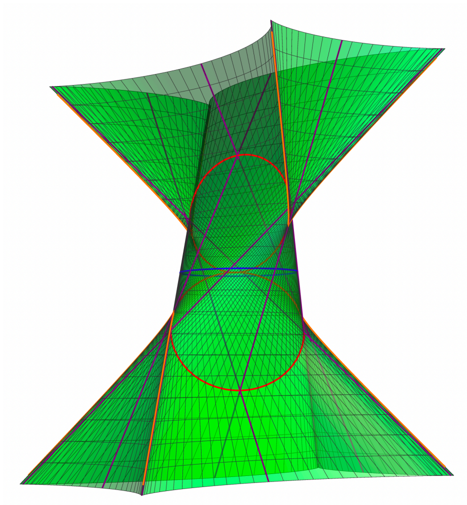

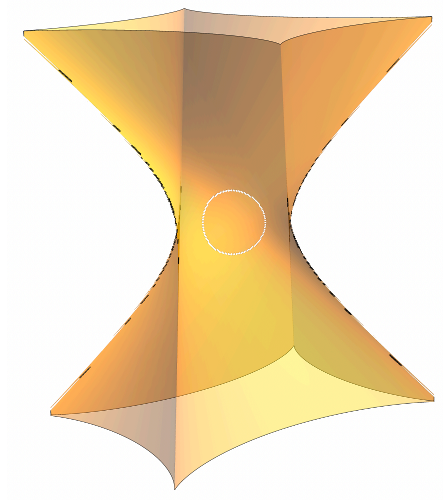

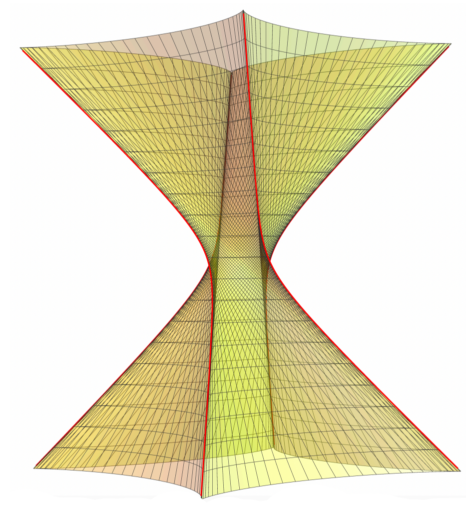

Thank you.