Multiterminal Josephson Junctions (MTJJs): non-hermiticity, topology and reflectionless modes

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Universität Konstanz

Universidad Autónoma de Madrid

19. March 2025

Multiterminal Josephson Junctions (MTJJs): non-hermiticity, topology and reflectionless modes

1) MTJJs are an excellent platform to study engineered non-hermitian topology

2) Refectionless scattering modes are a source of topology in MTJJs

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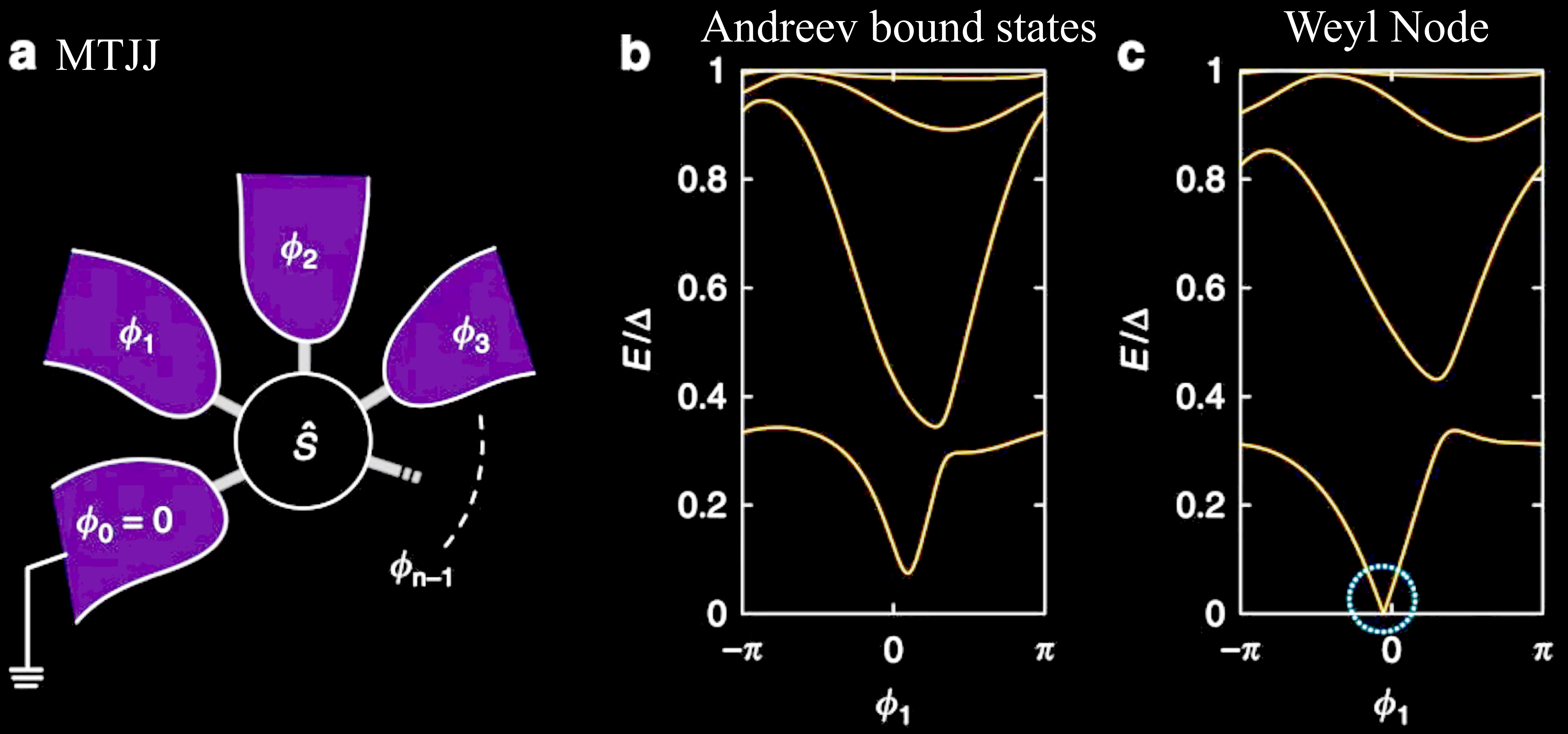
Topology in Multiterminal Josephson junctions (MTJJs)



R.-P. Riwar, et. al., Nature Commun. 7, 1 (2016)
E. Eriksson, et. al., Phys. Rev. B 95, 075417 (2017)
H.-Y. Xie, et. al., Phys. Rev. B 96, 161406(R) (2017)
R. L. Klees, et. al., Phys. Rev. Lett. 124, 197002 (2020)
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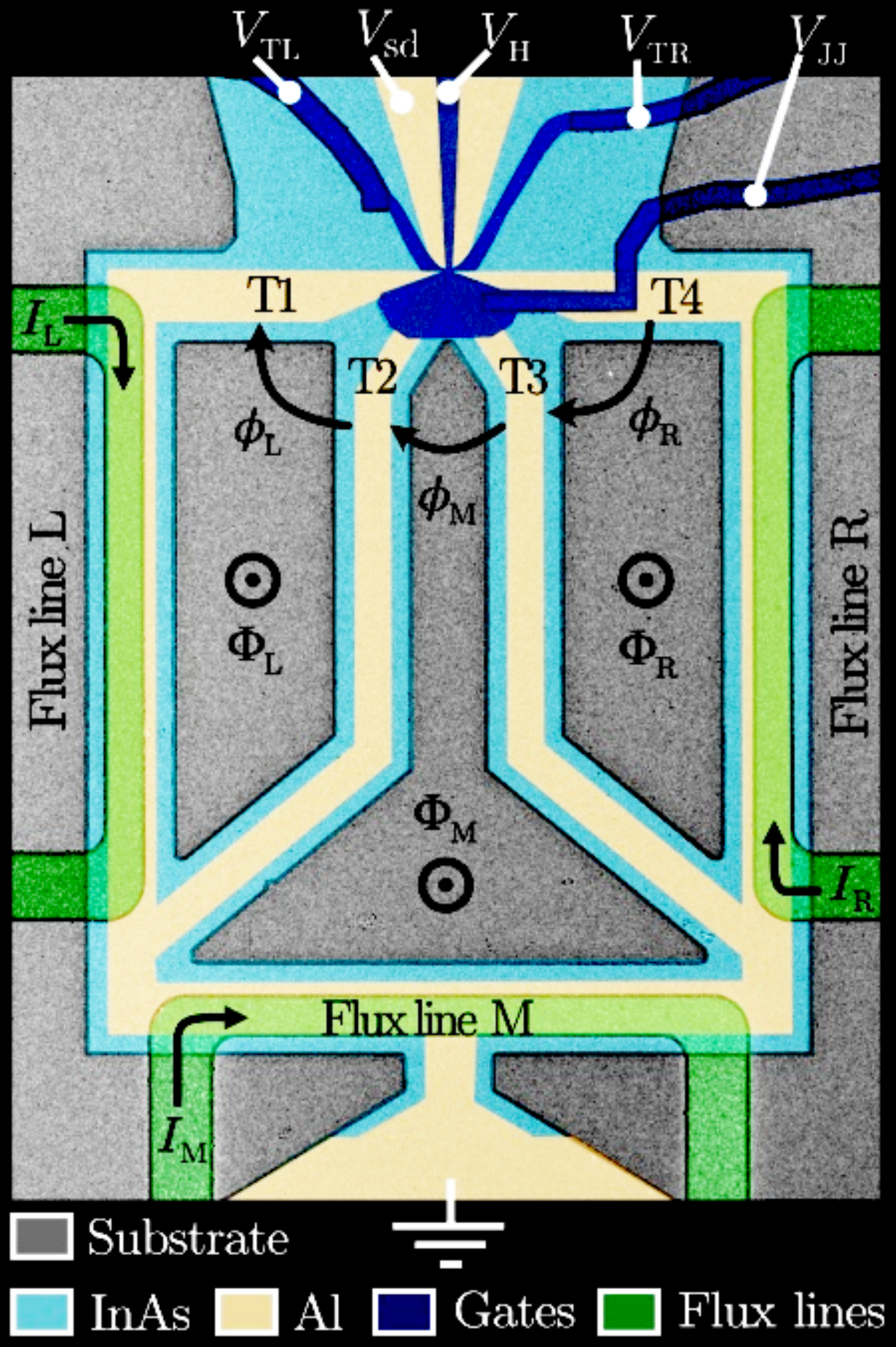
Experiments on MTJJs: Topology?

Topography of
4-terminal MTJJ



T. Antonelli, et. al., arXiv:2501.07982 (2025).

Experiments on MTJJs: Topology?

Topography of
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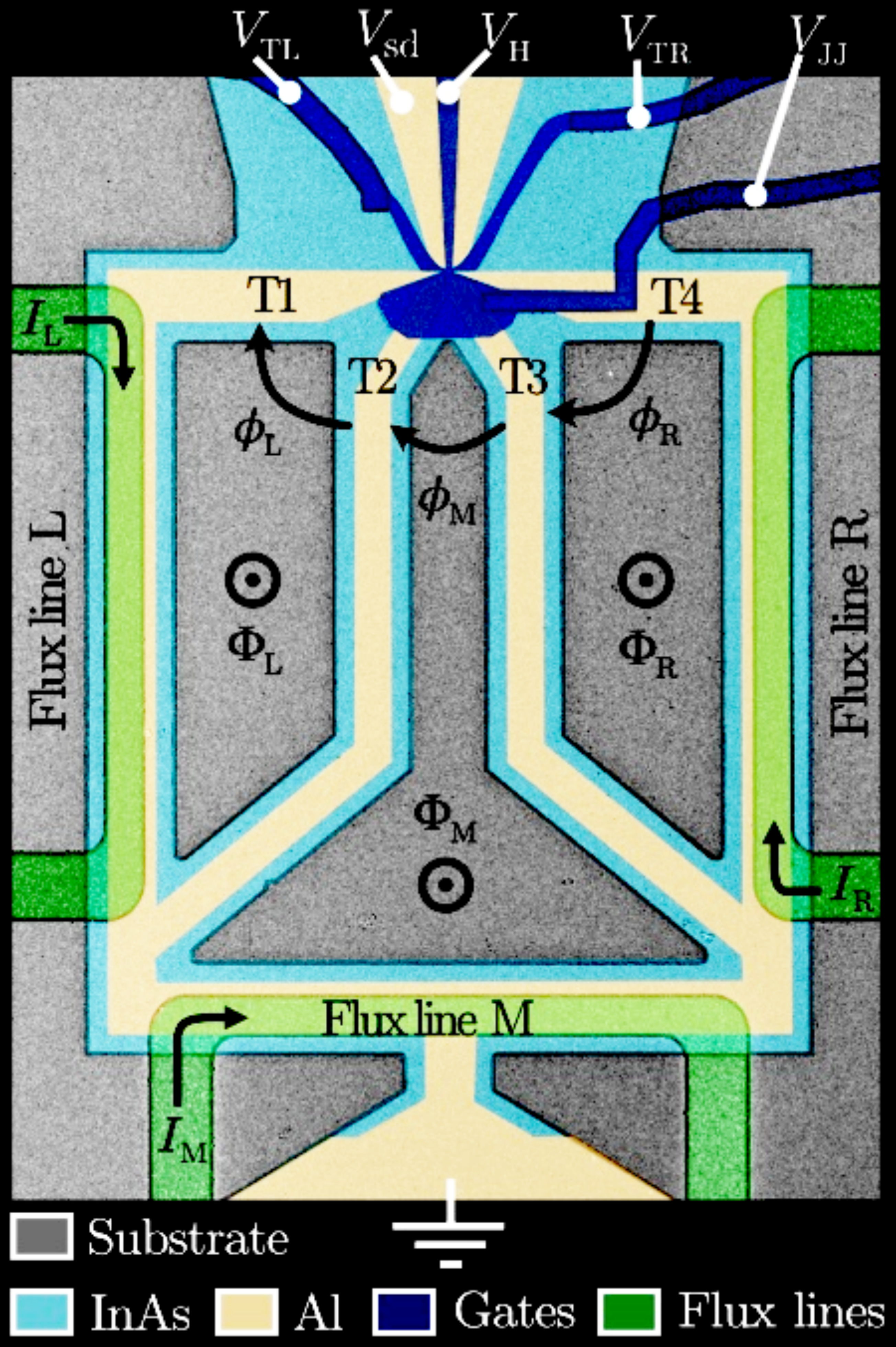
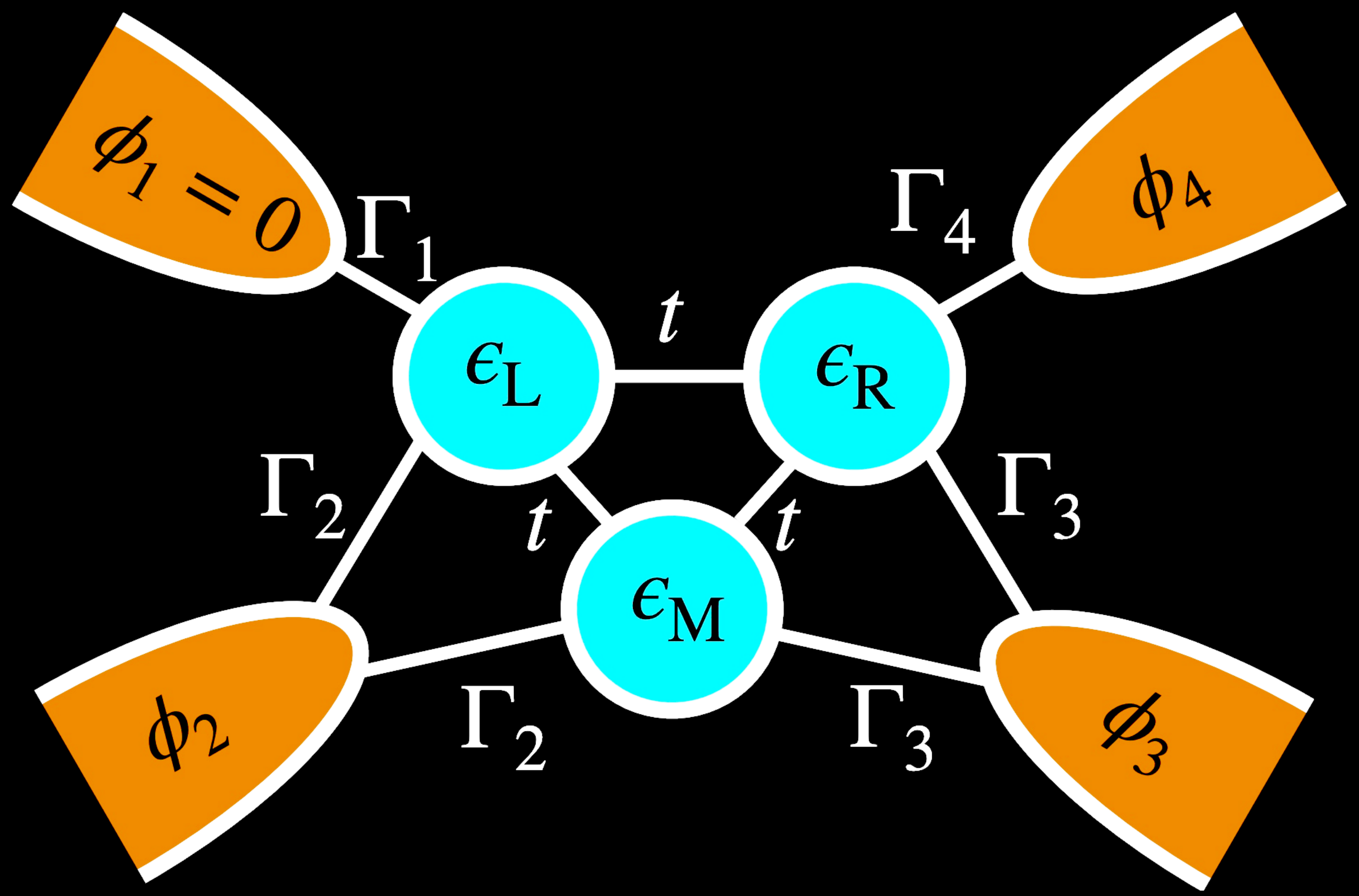


Three state Andreev molecule model



T. Antonelli, et. al., arXiv:2408.01281 (2024).

Experiments on MTJJs: Topology?

Topography of
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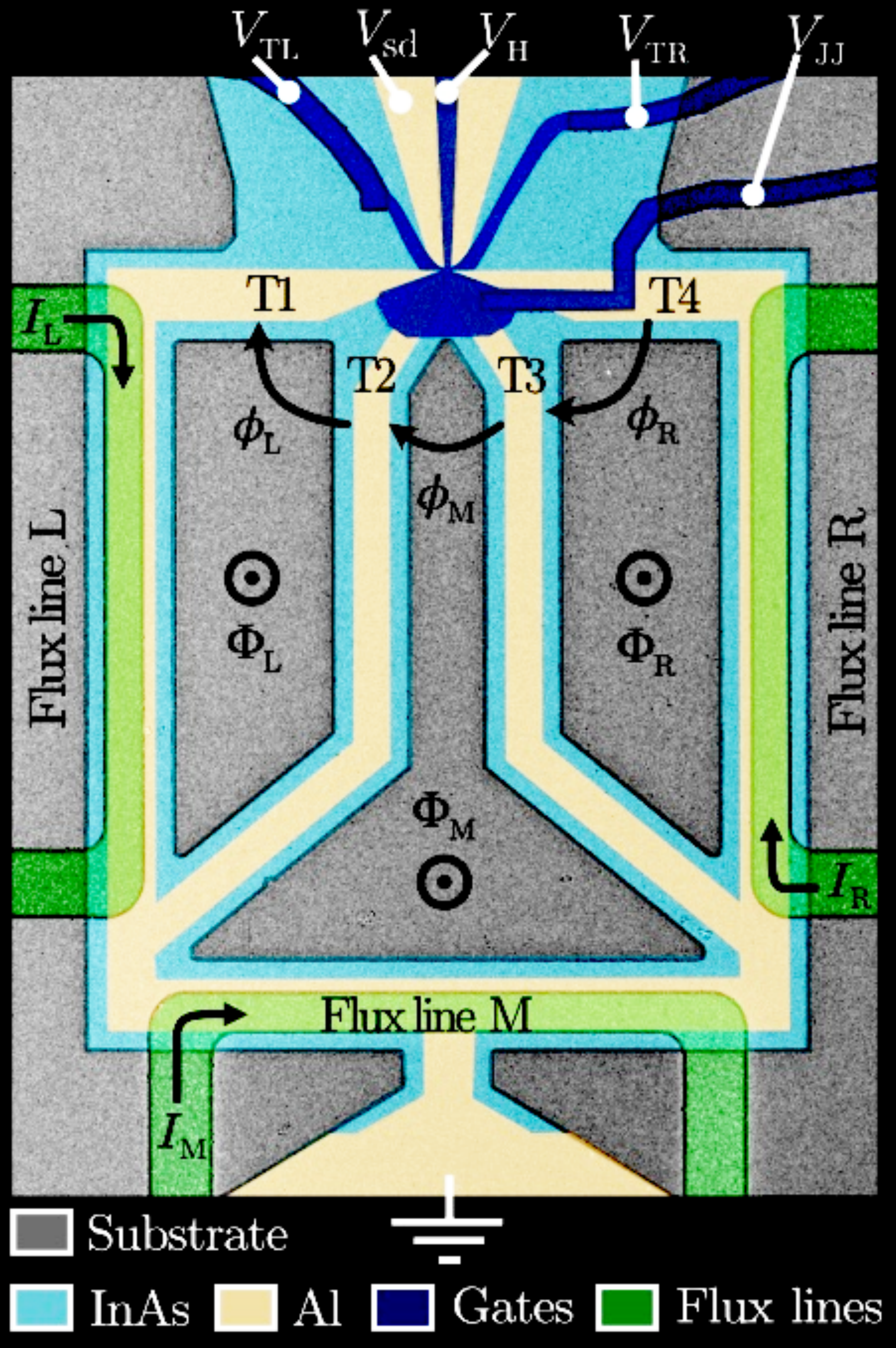

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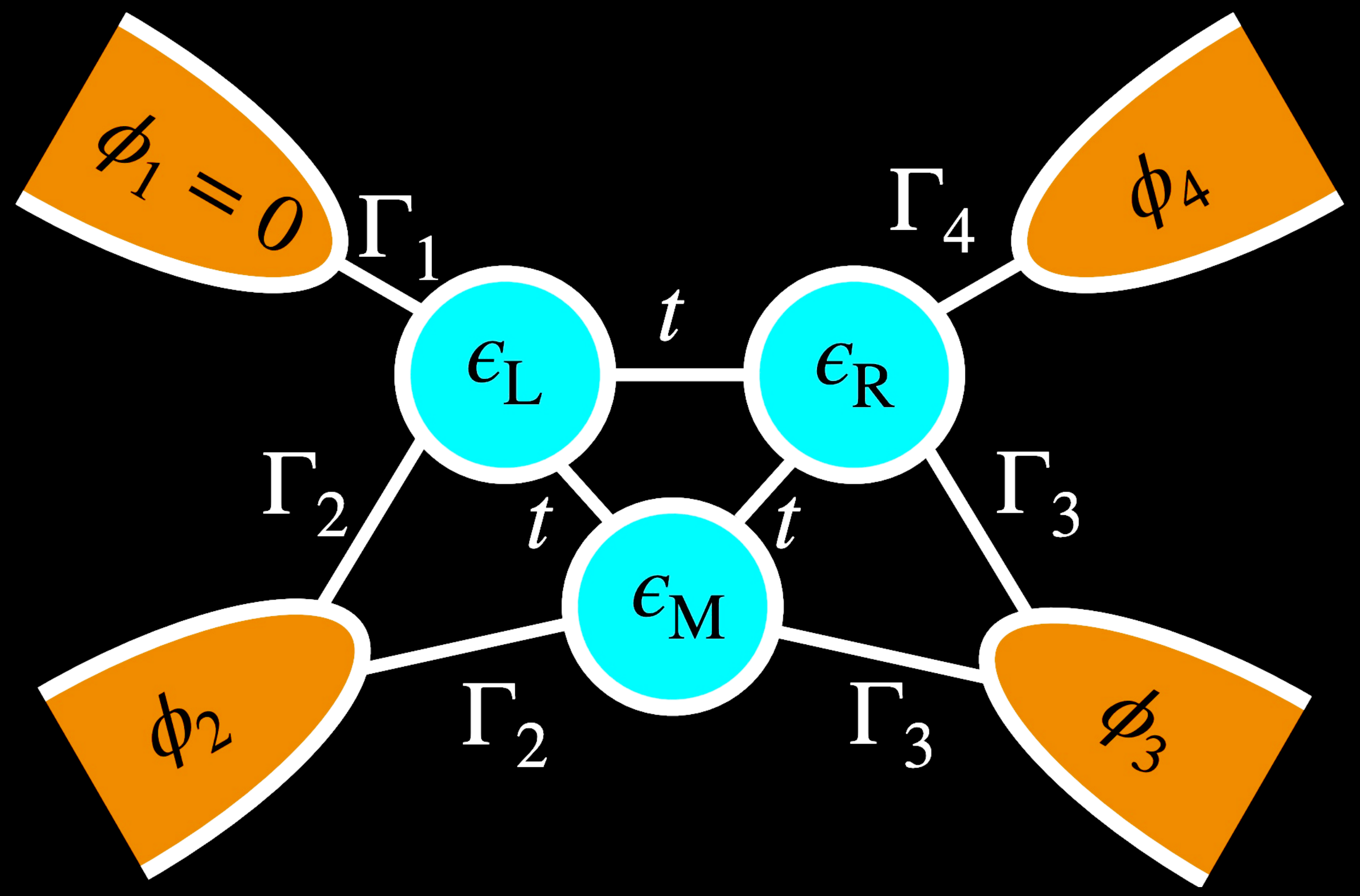
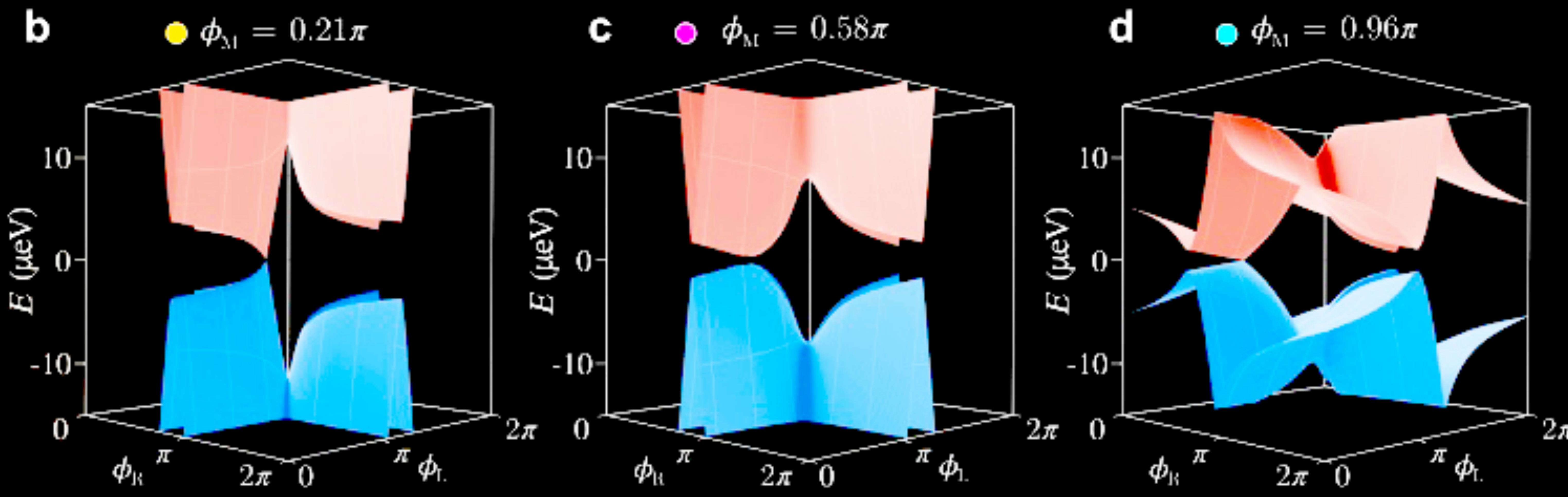


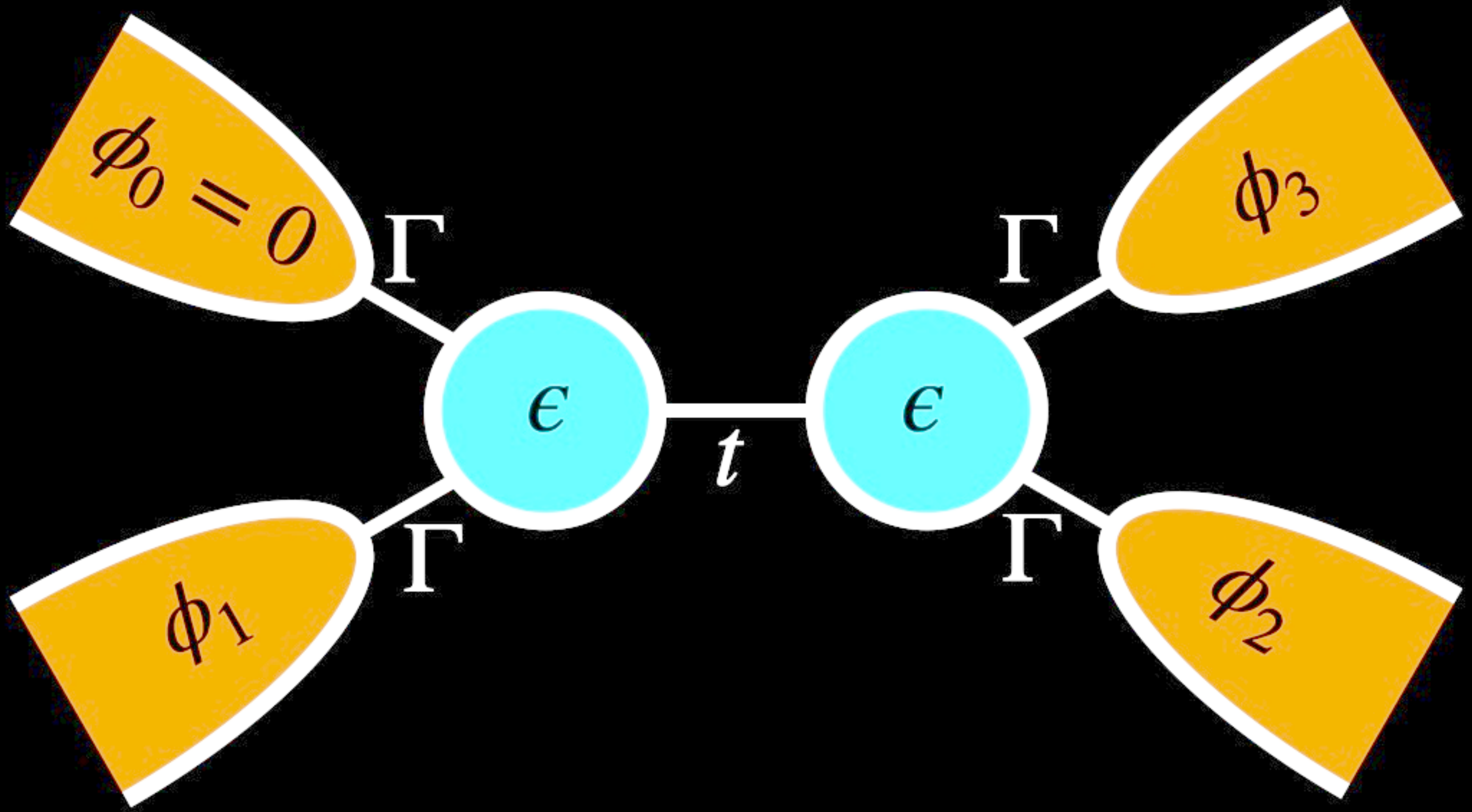
Model predicts non-trivial Topology



T. Antonelli, et. al., arXiv:2408.01281 (2024).

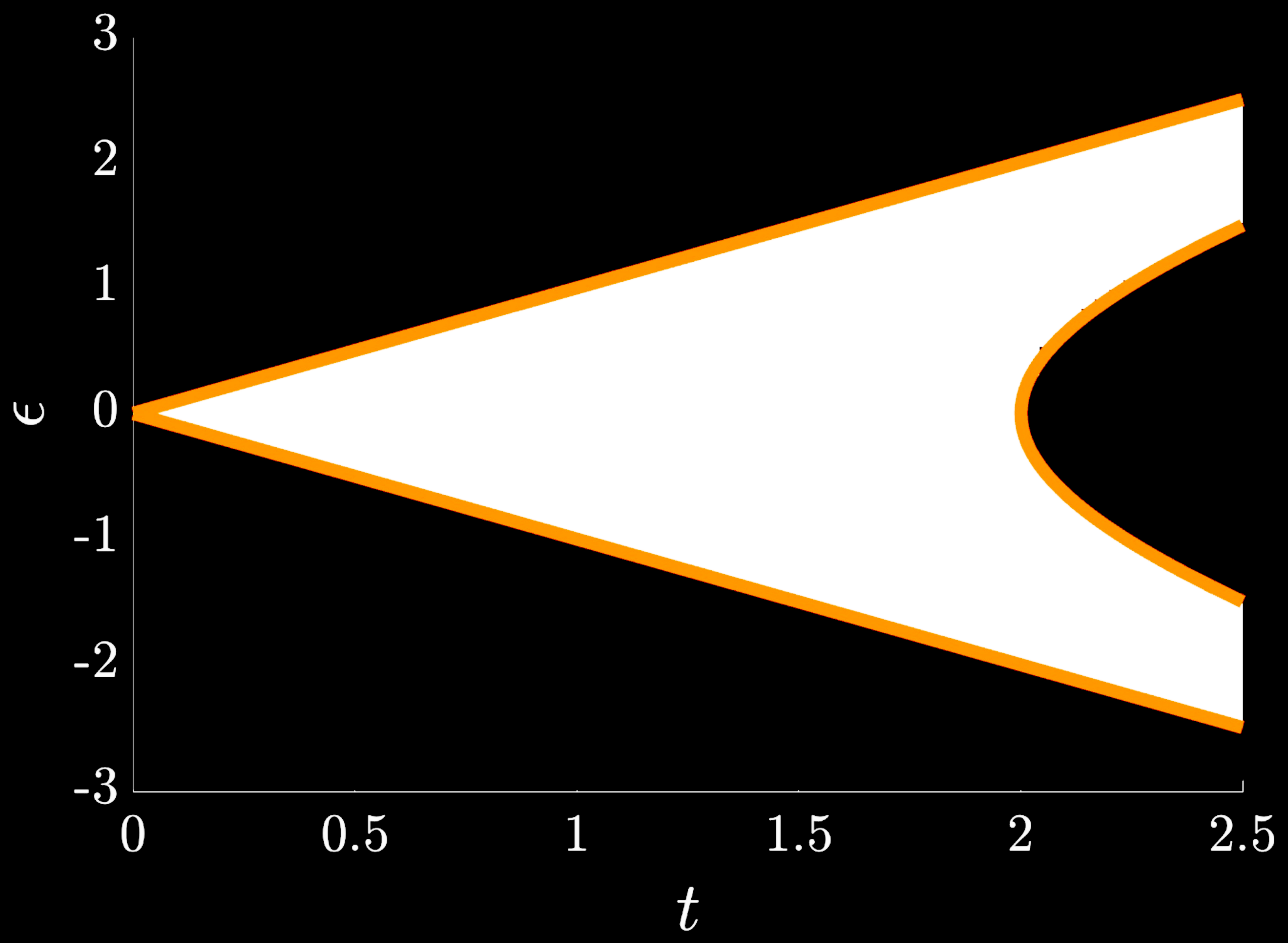
What's the source of topology in MTJJs?

4-terminal MTJJ with two dots



L. Teshler, et. al., SciPost Phys. 15, 214 (2023)

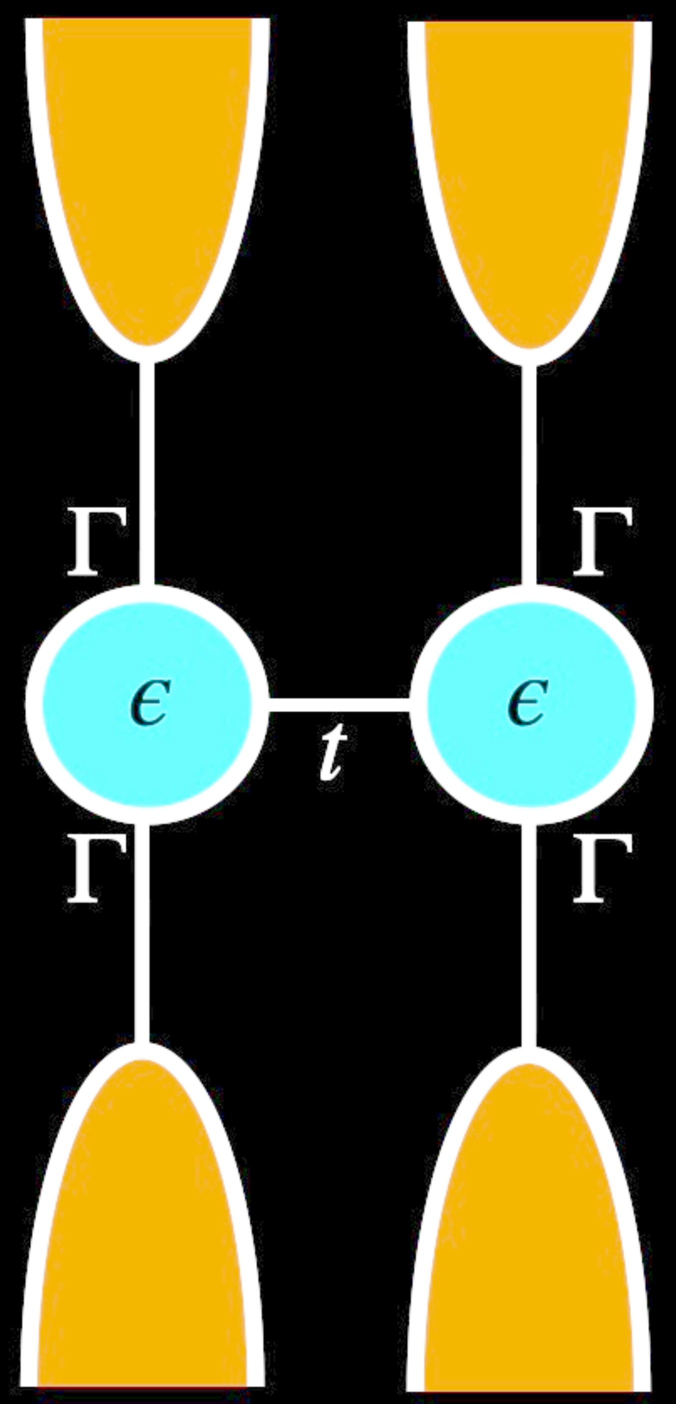
Topological phase diagram



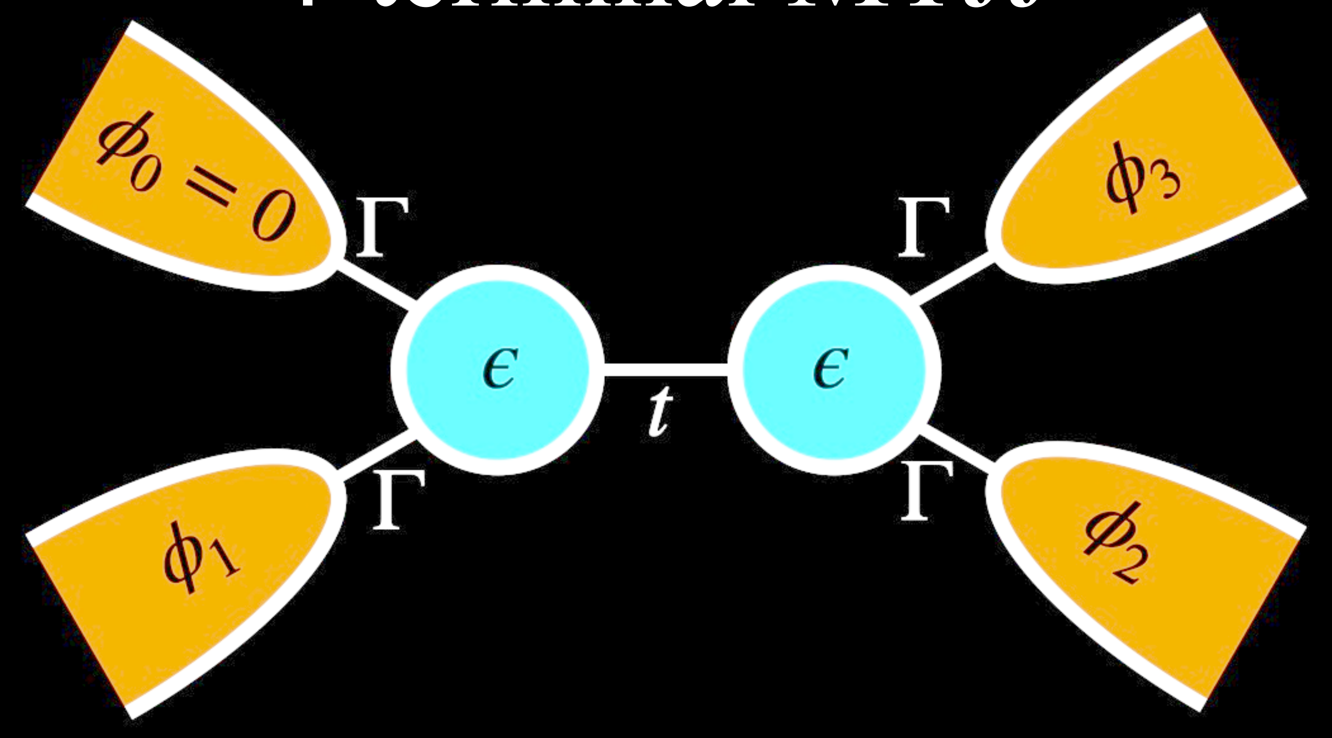
non-trivial Chern number in superconducting phase space $\{\vec{\phi}\}$

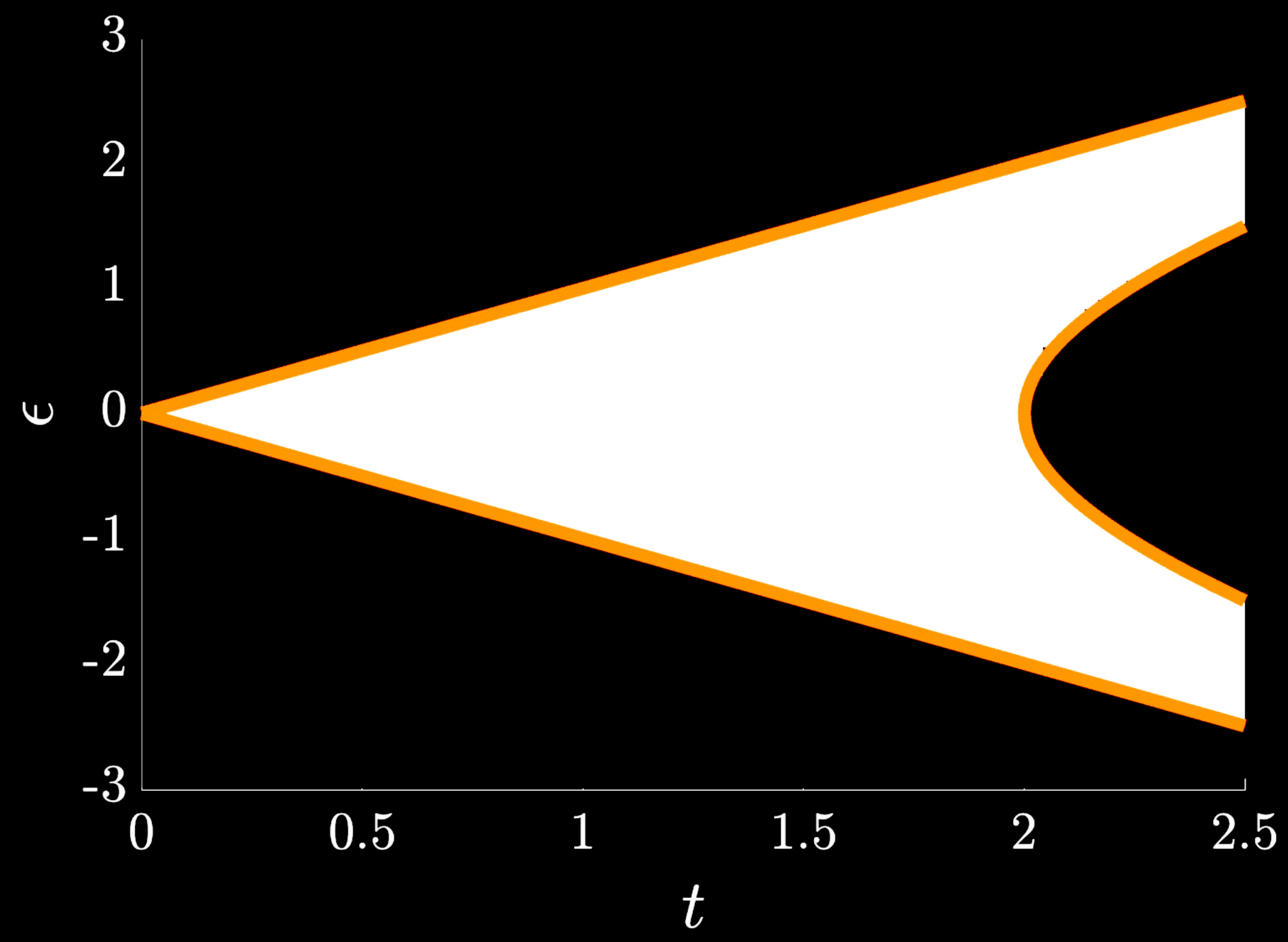
Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



4-terminal MTJJ





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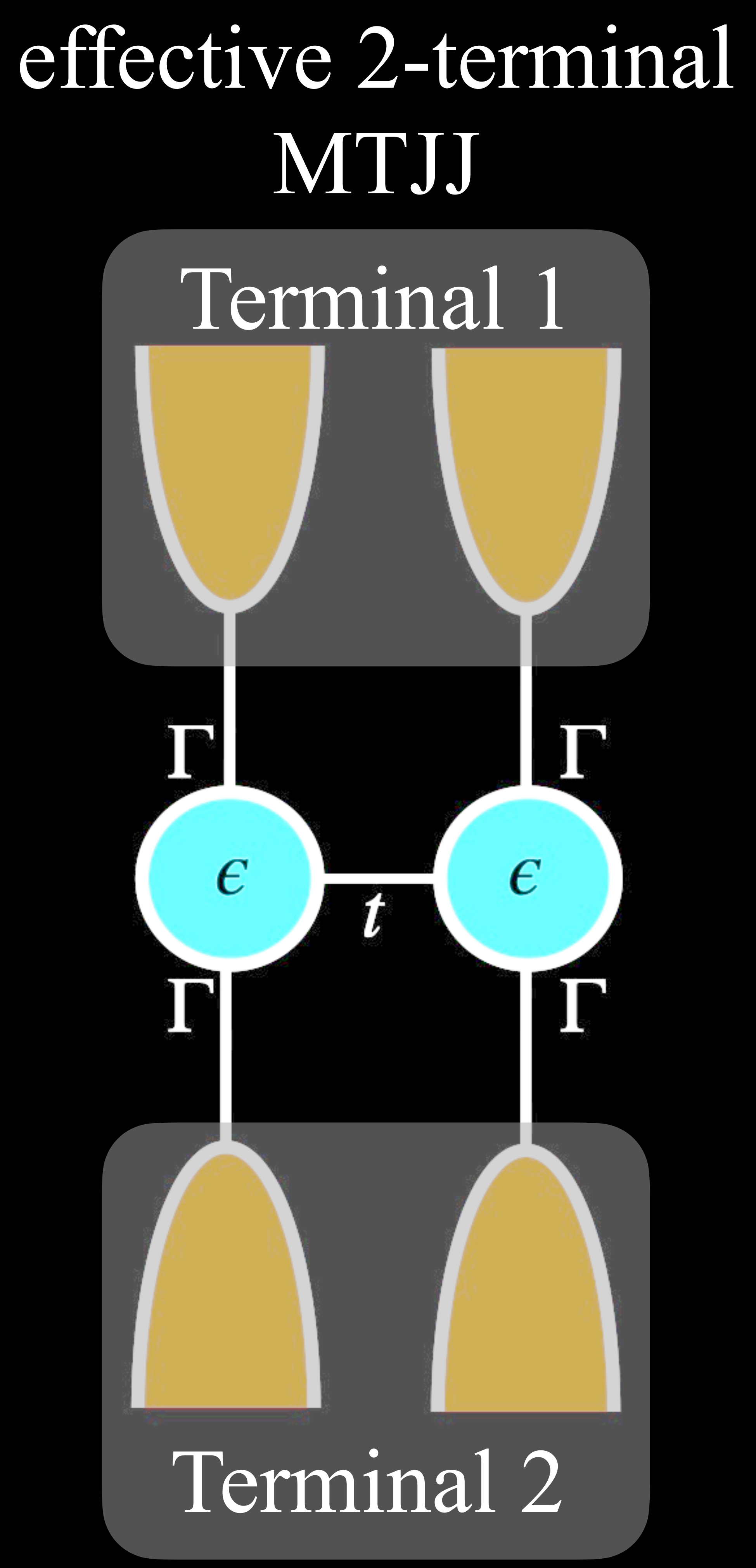

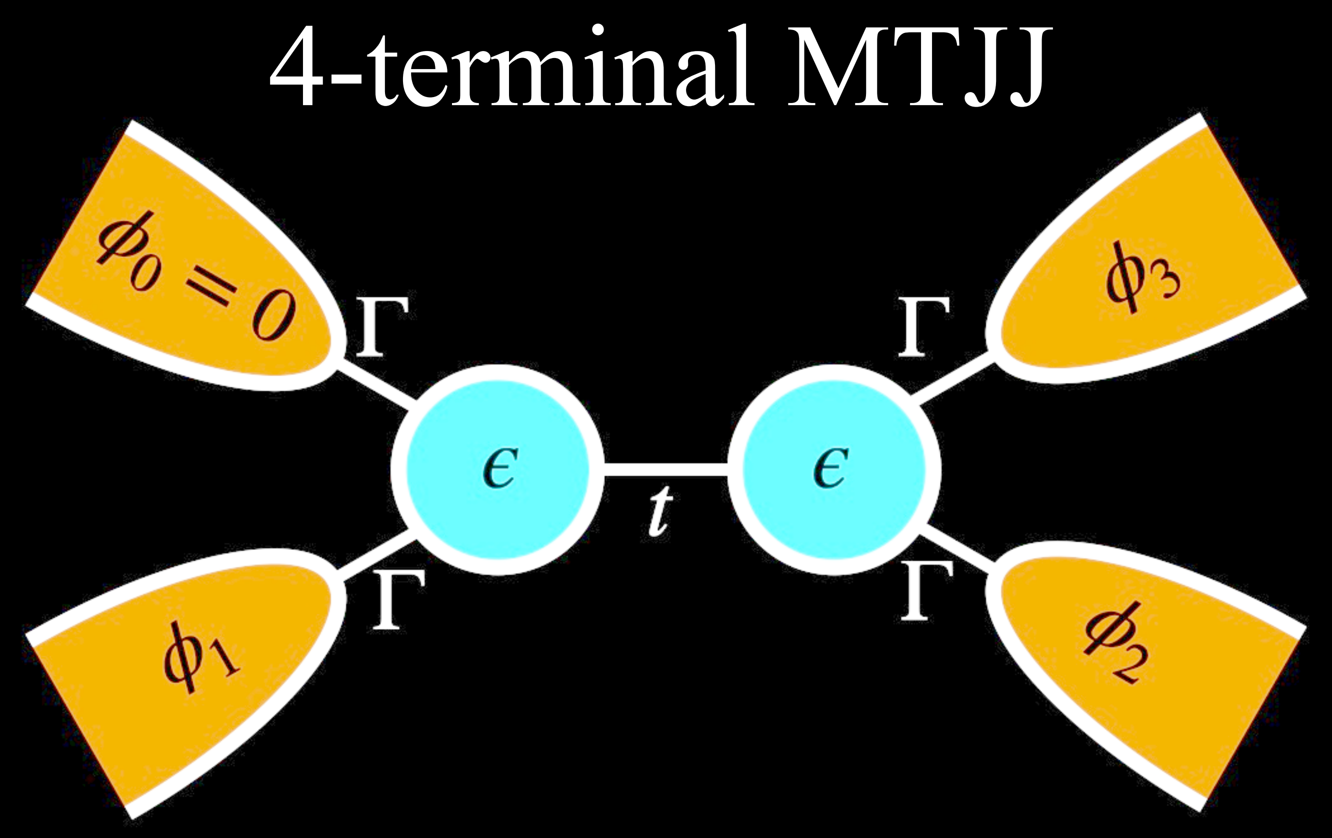

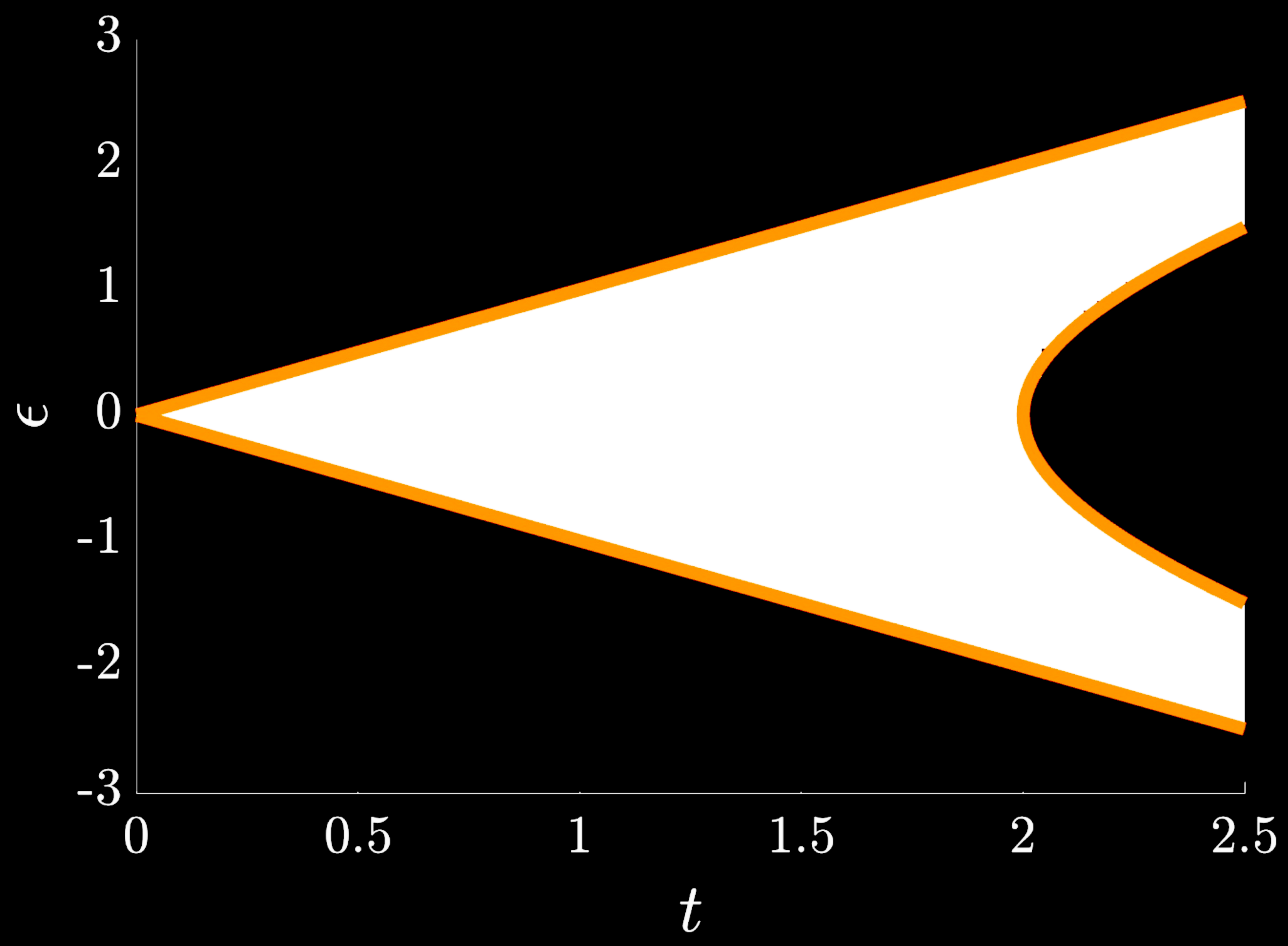

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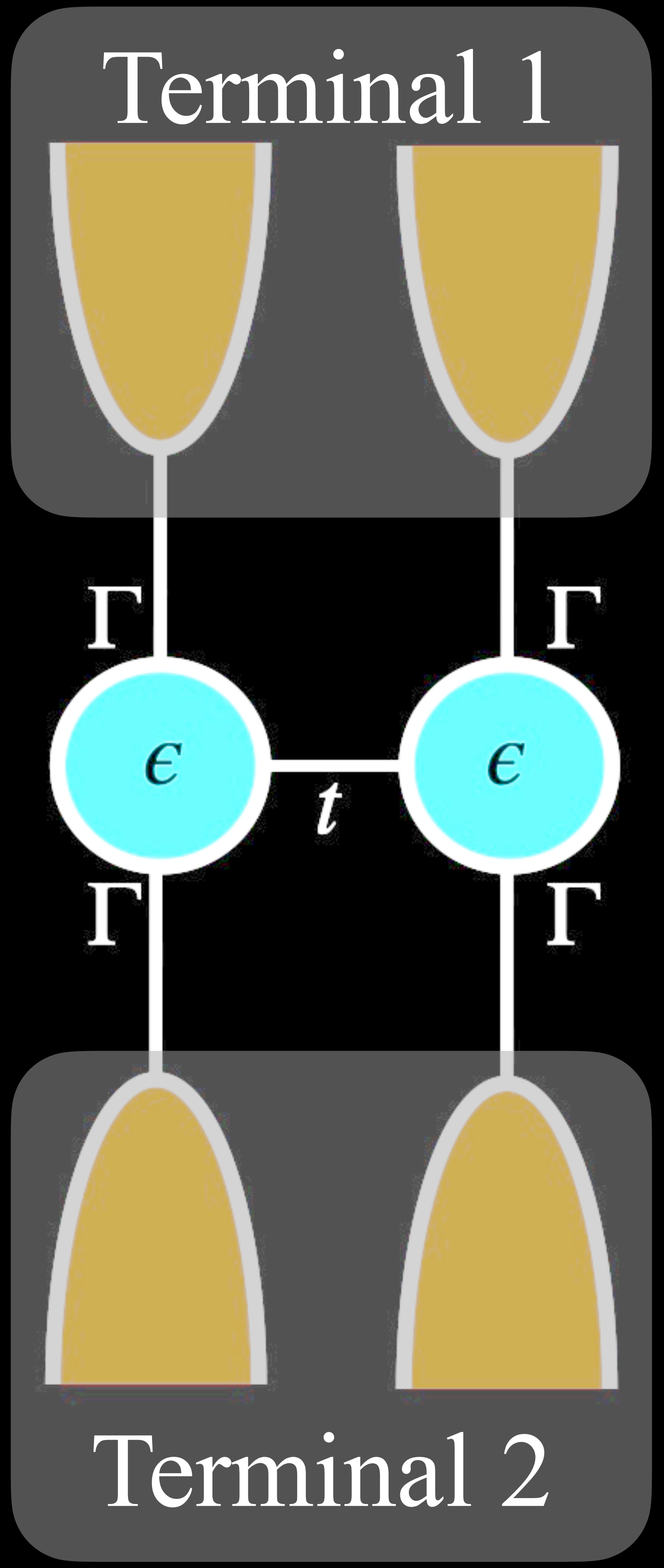
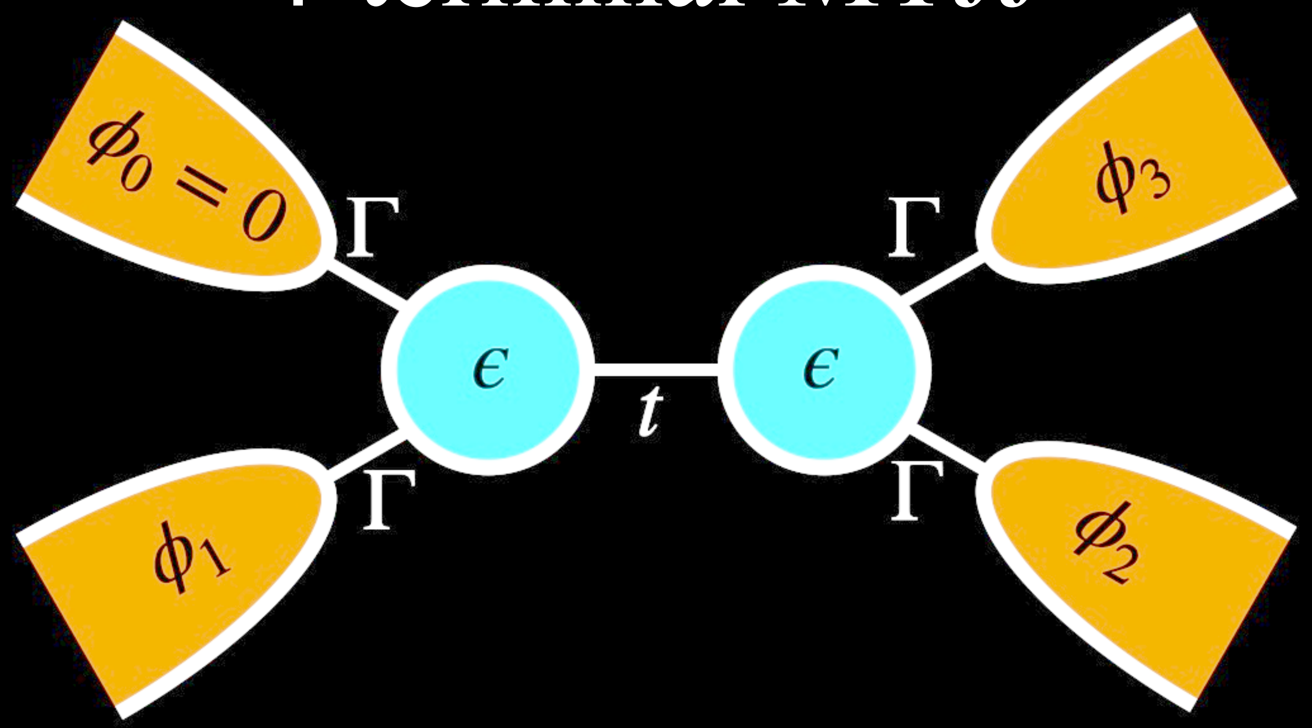
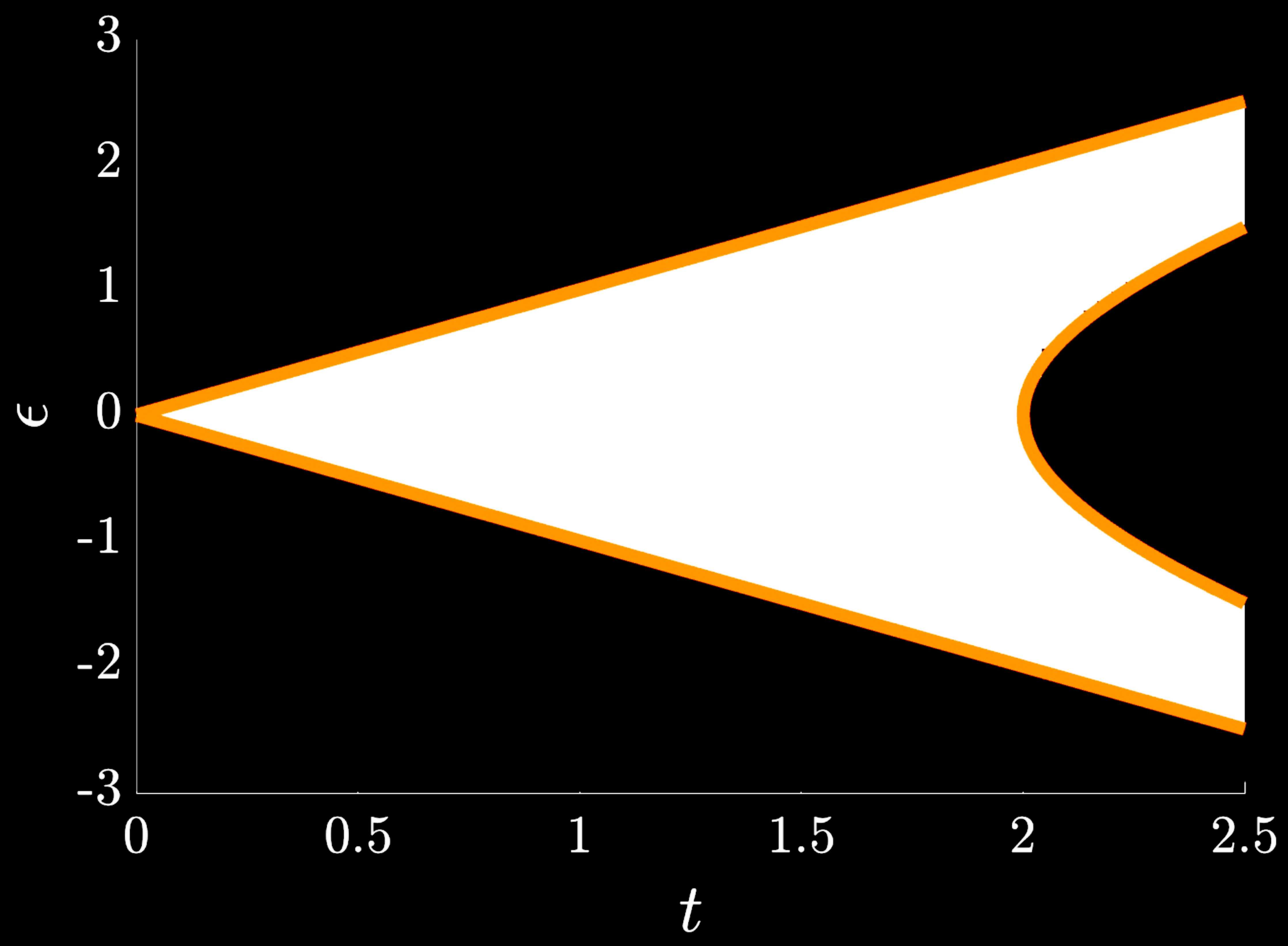


Normal state
Scattering matrix

$$S_{\mathrm{N}} = \begin{pmatrix} r_{2\times2} & t_{2\times2} \\ t'_{2\times2} & r'_{2\times2} \end{pmatrix}$$

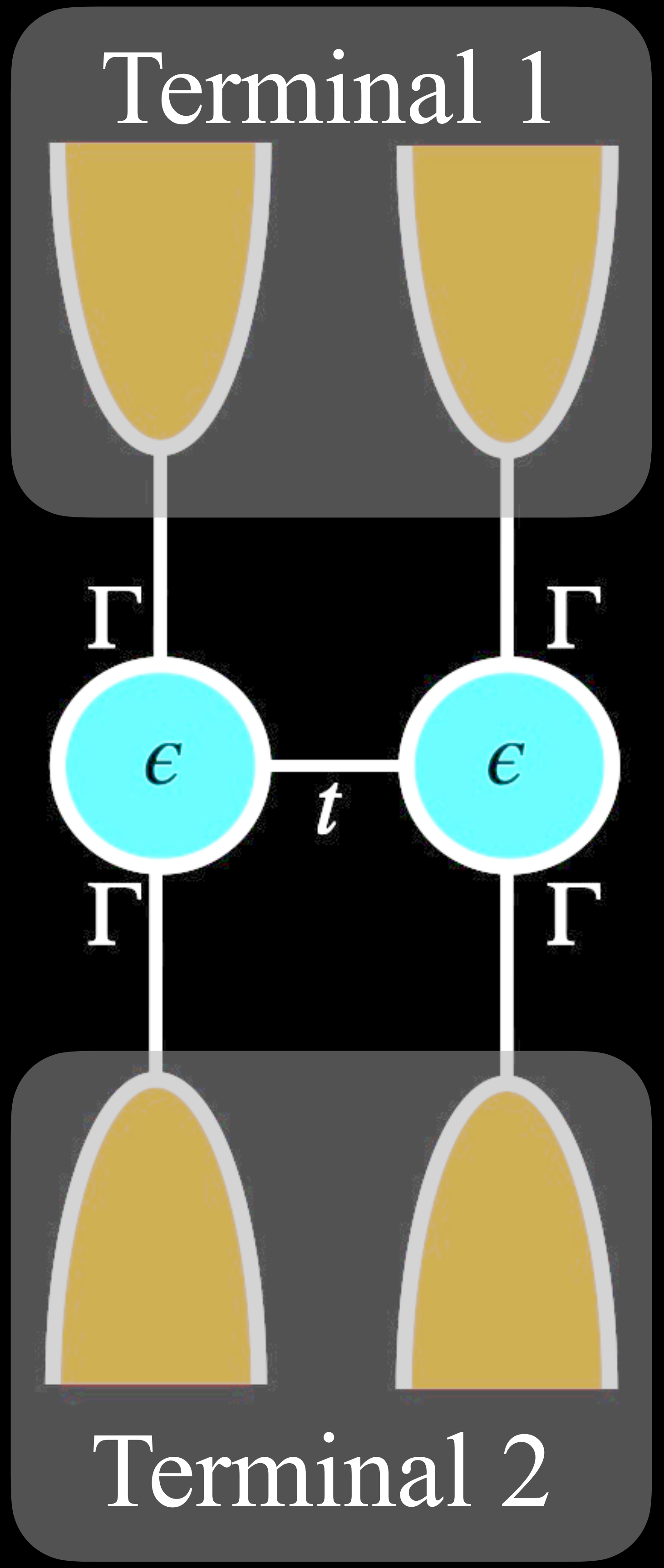
4-terminal MTJJ





Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



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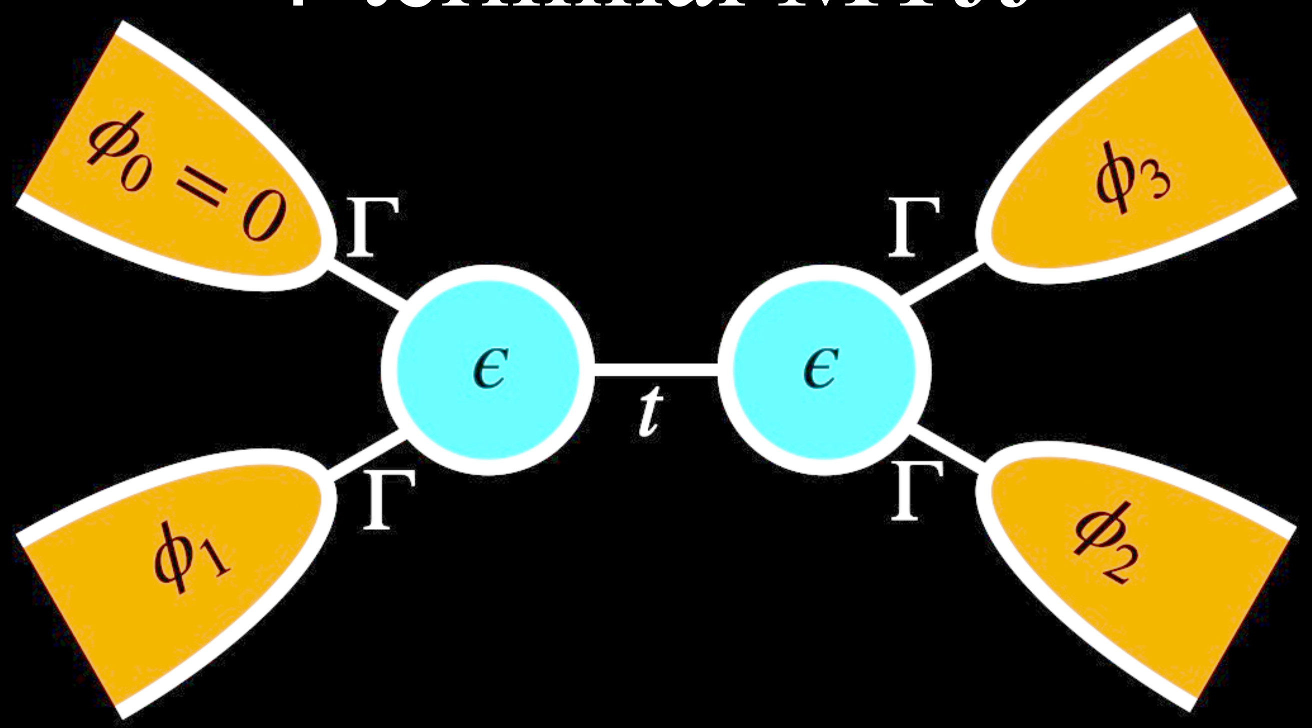
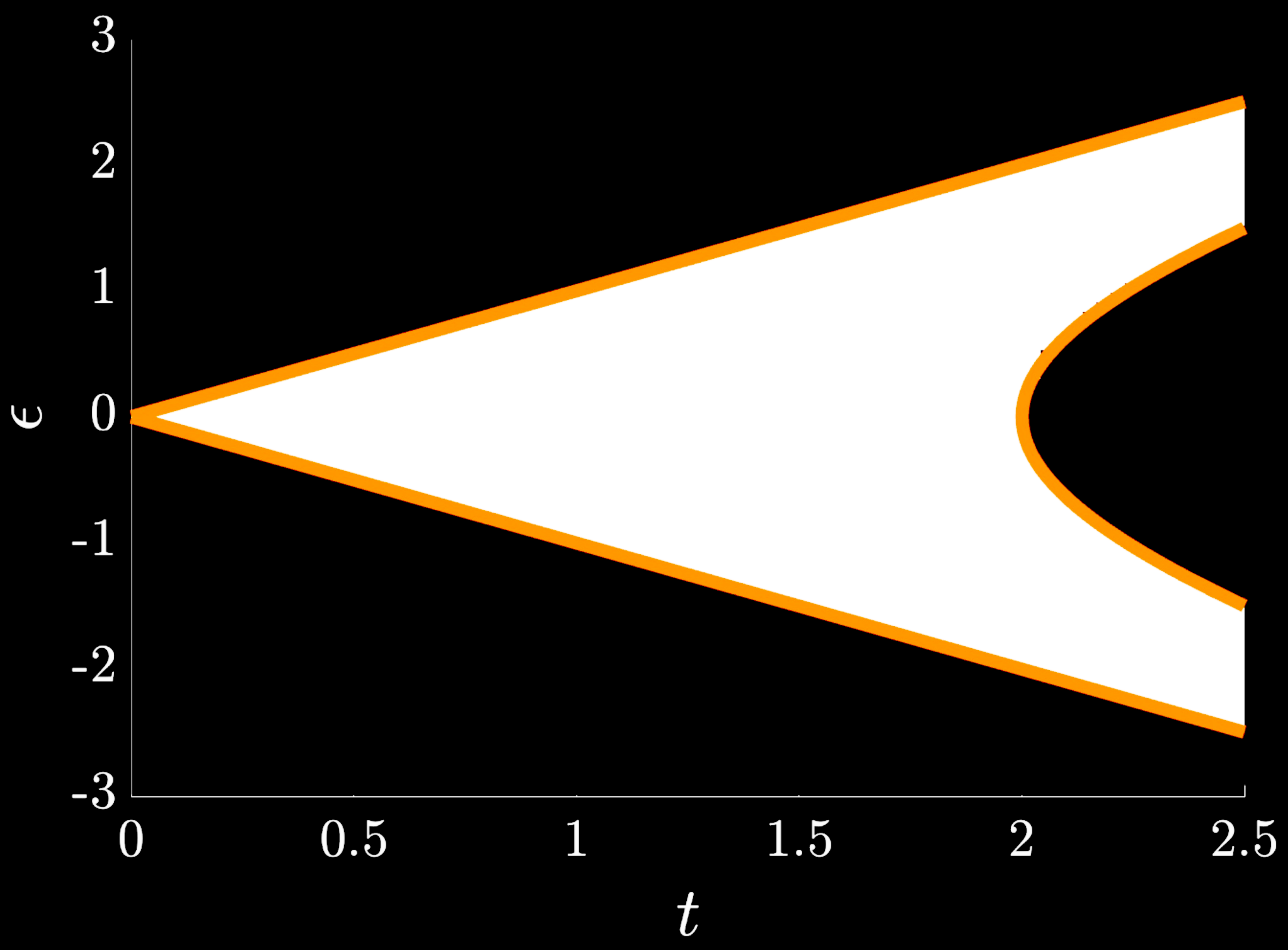
Diagonalized refl. matrix

$$D_{r_{2\times2}} = \begin{pmatrix} \dfrac{E-(\epsilon-t)}{E-(\epsilon-t-2\imath\Gamma)} & 0 \\ 0 & \dfrac{E-(\epsilon+t)}{E-(\epsilon+t-2\imath\Gamma)} \end{pmatrix}$$

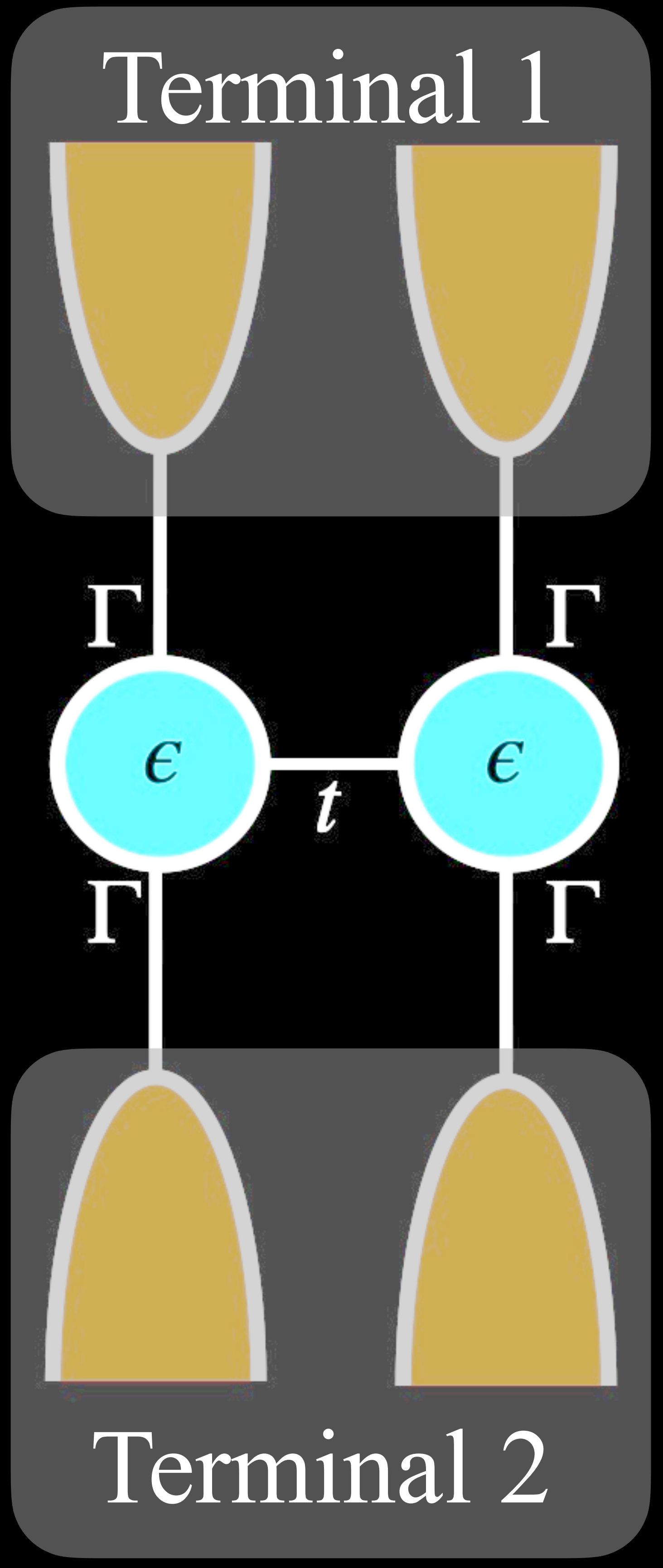
4-terminal MTJJ





Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



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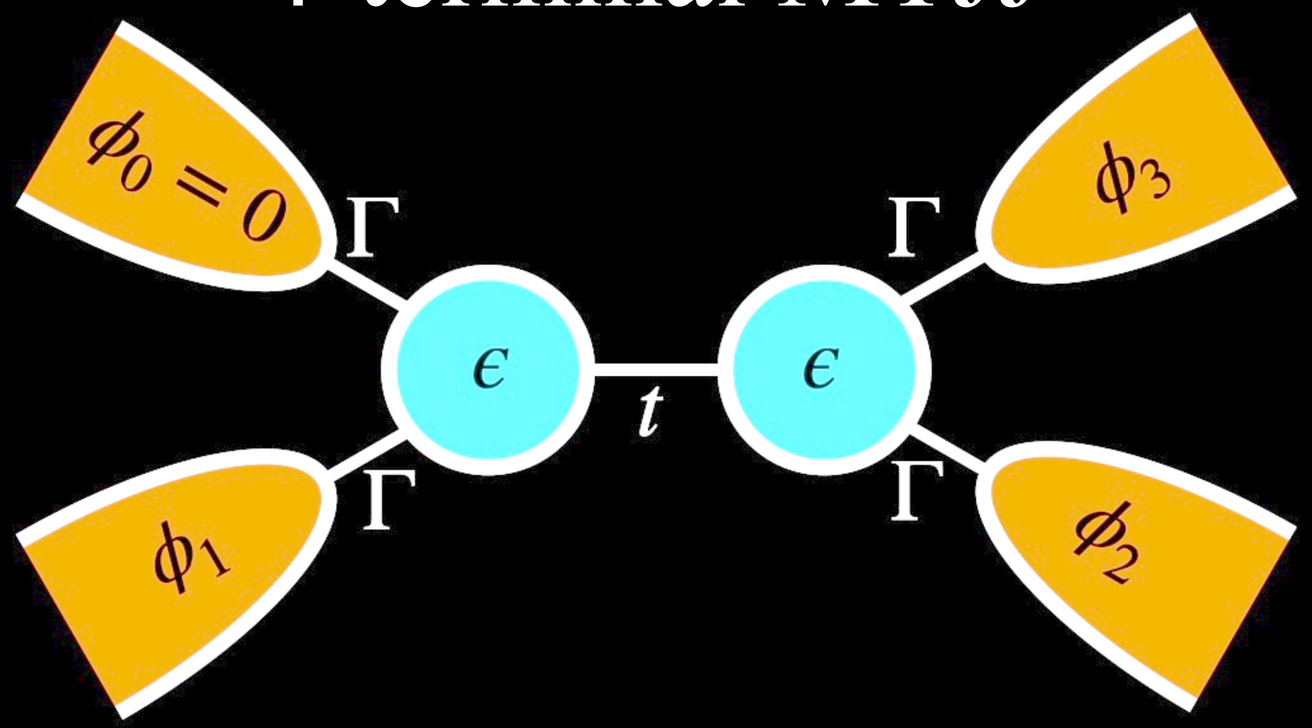
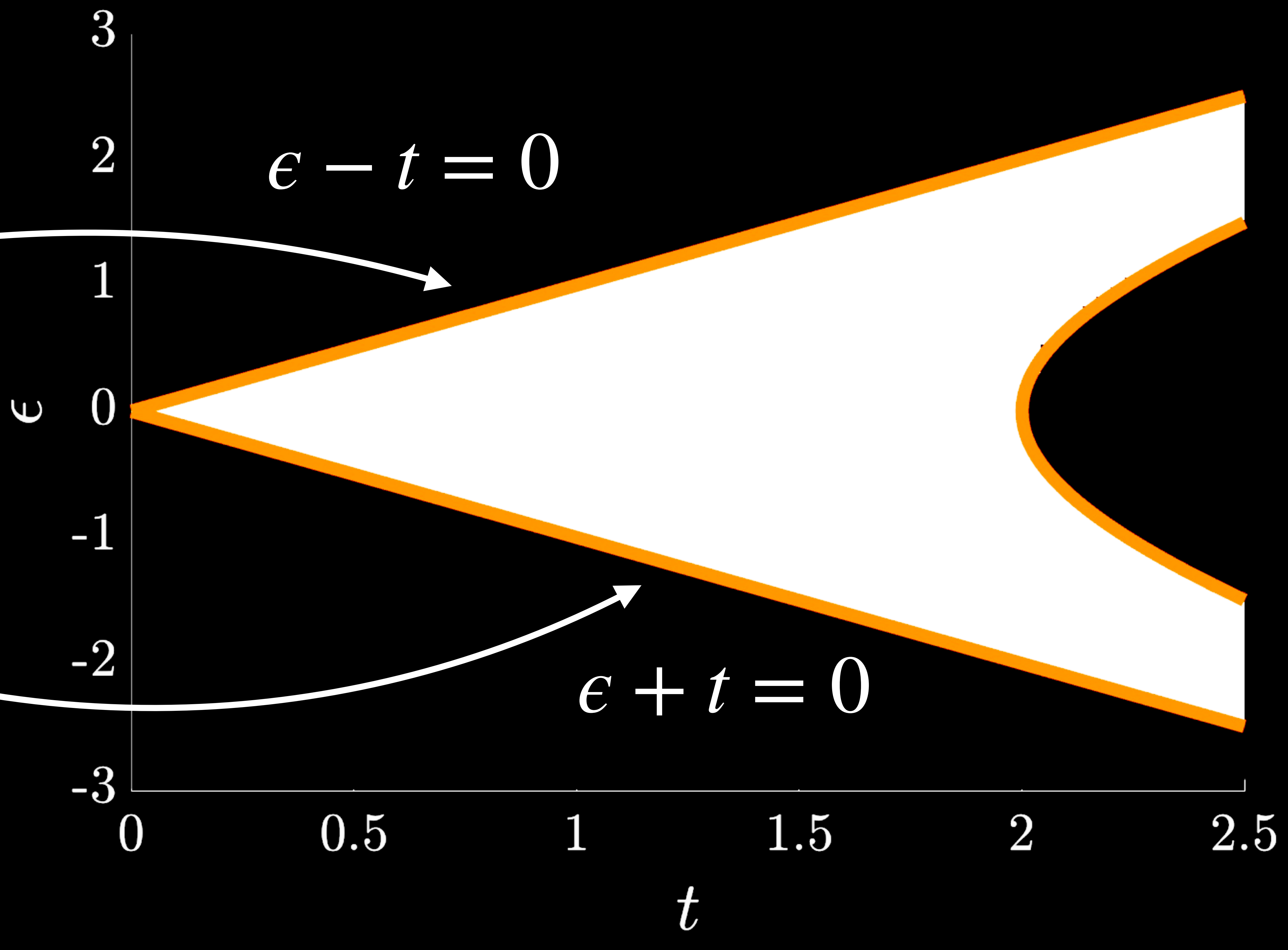
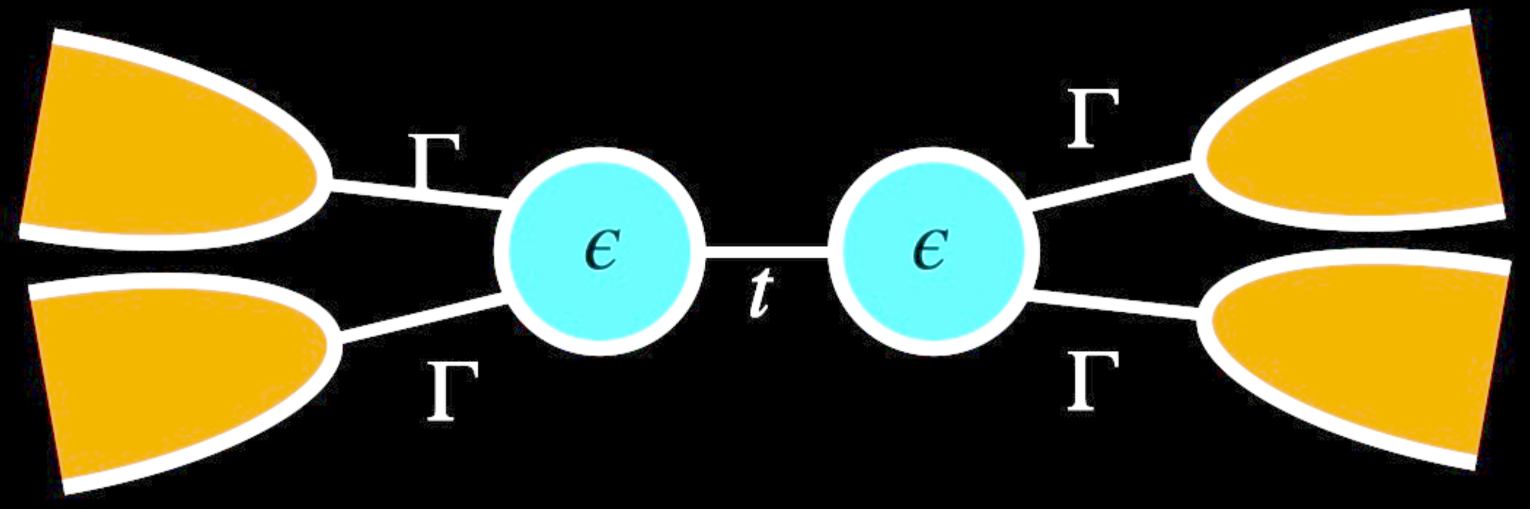


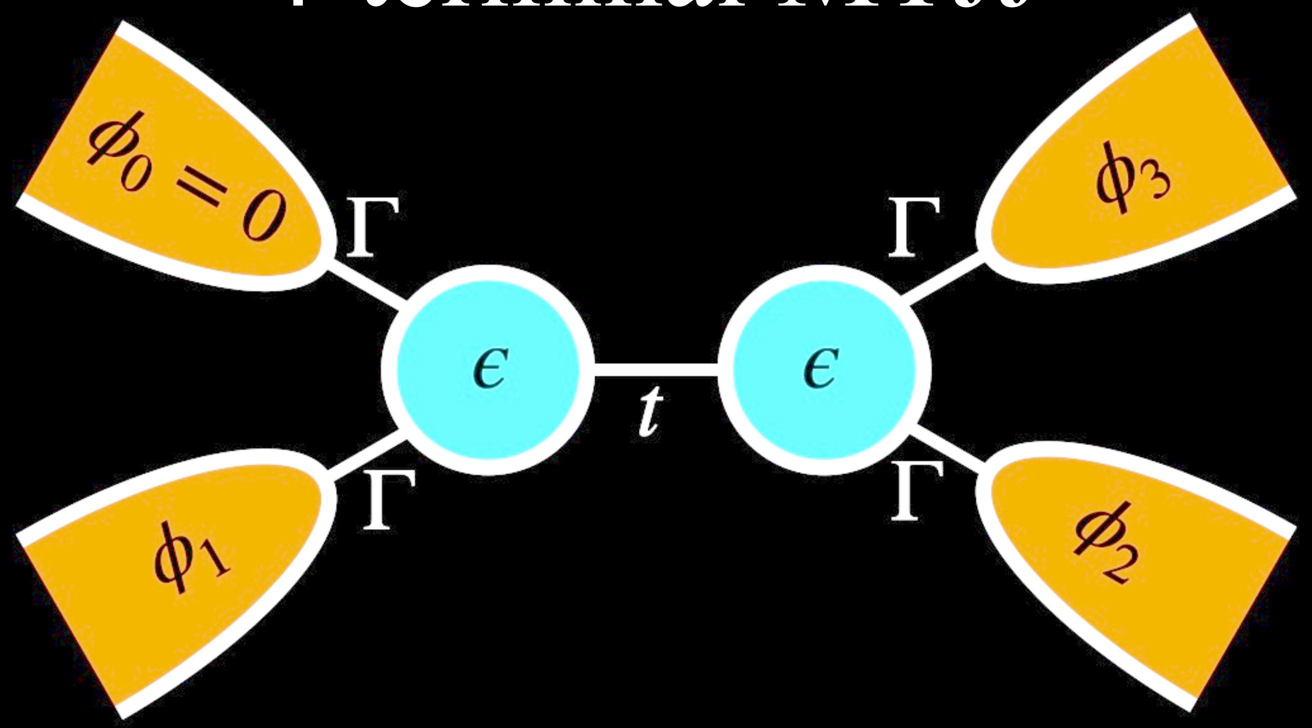


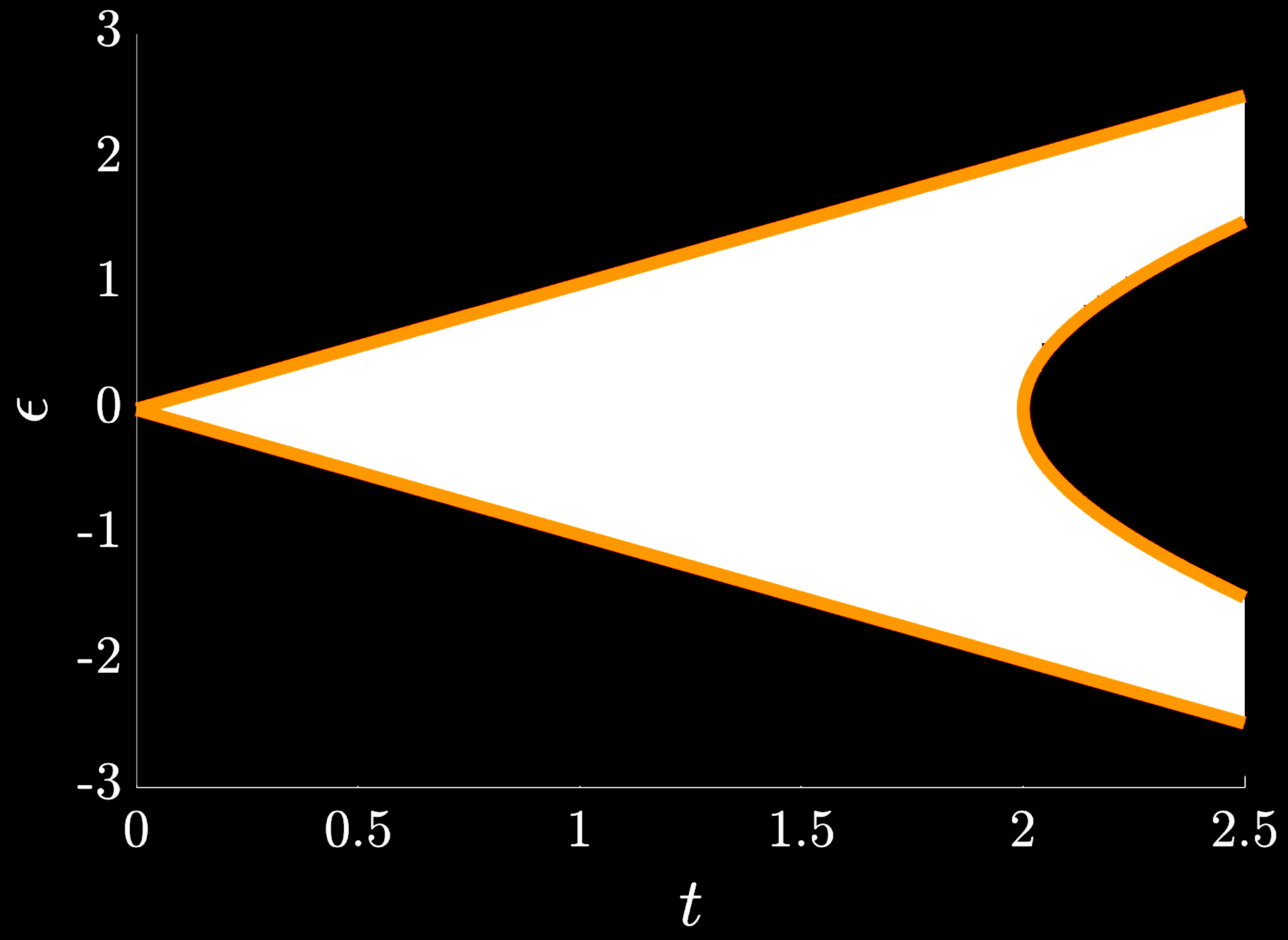
Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



4-terminal MTJJ





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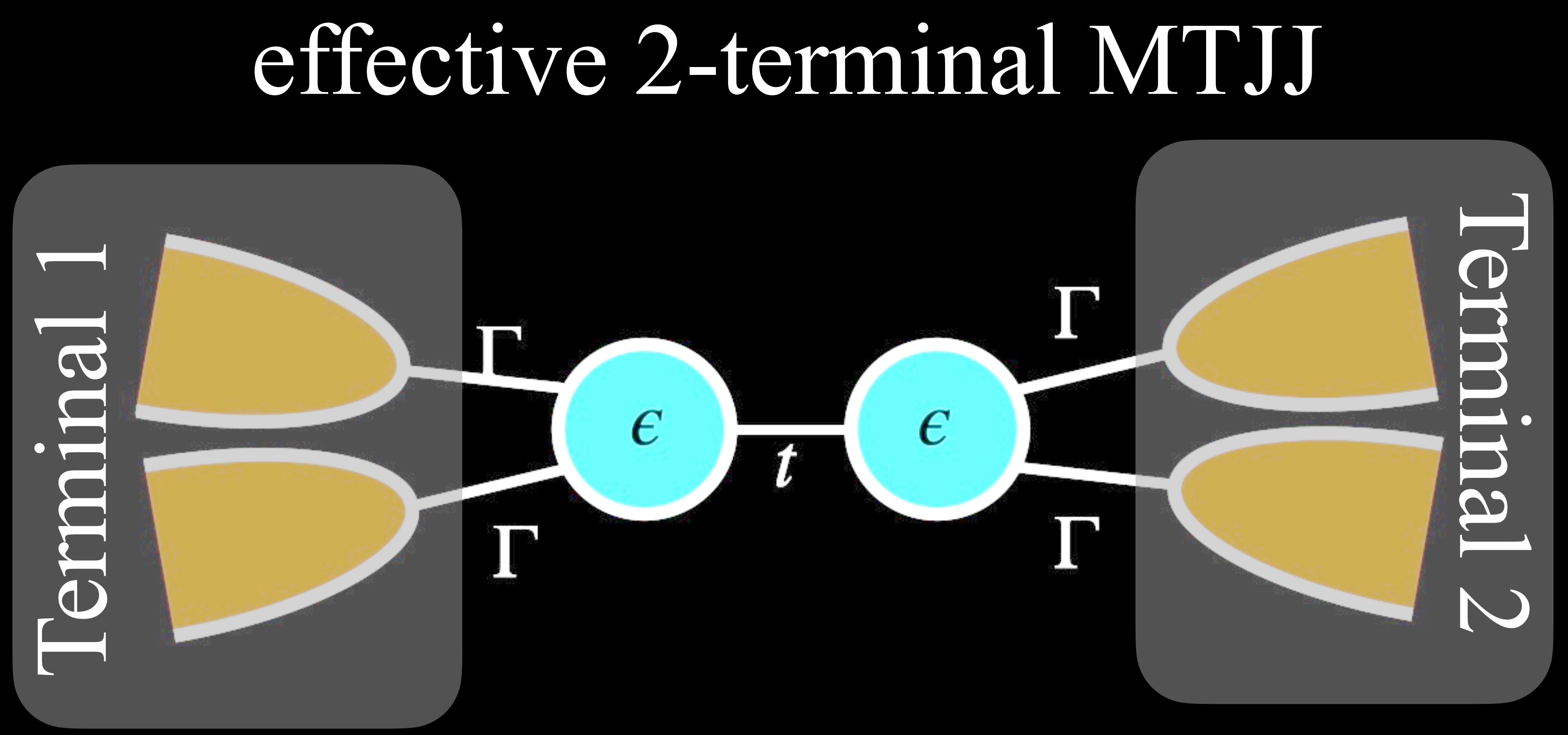
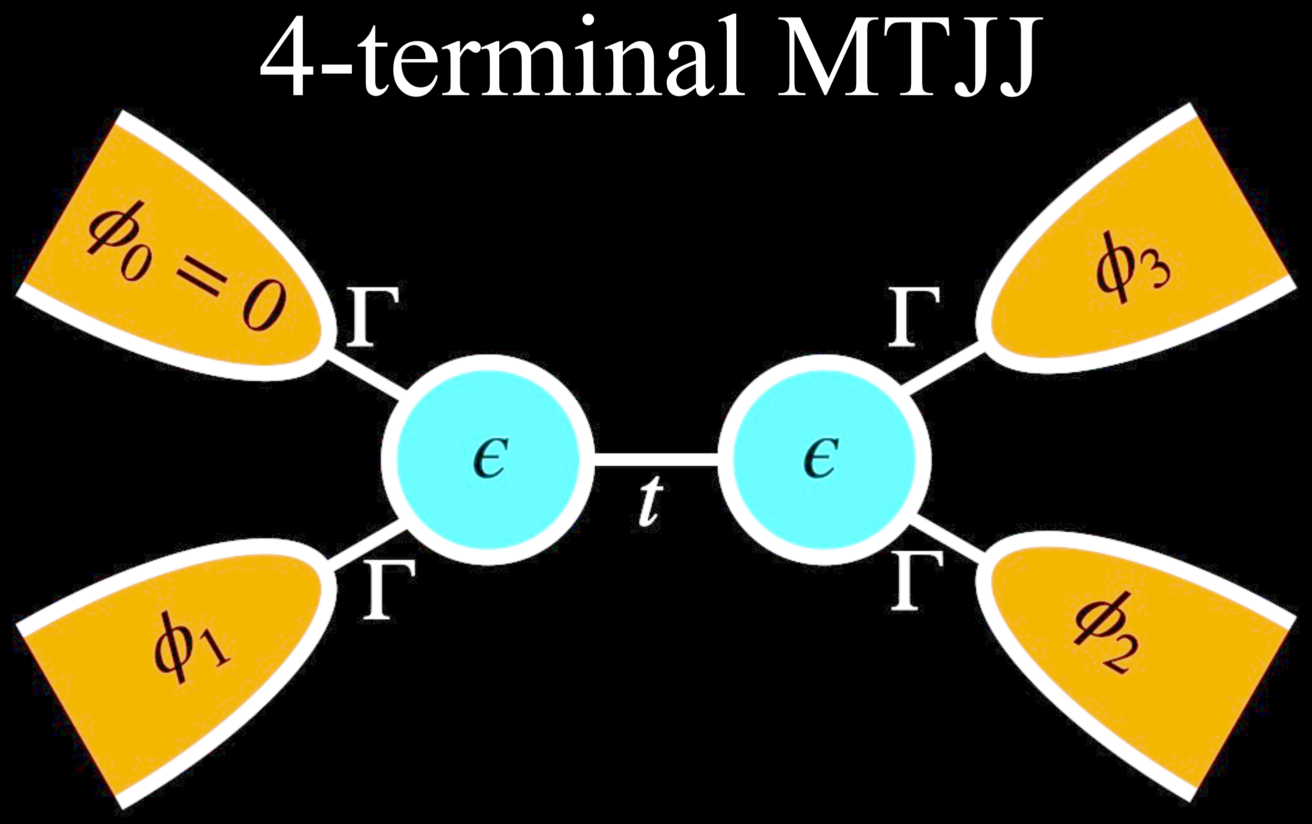
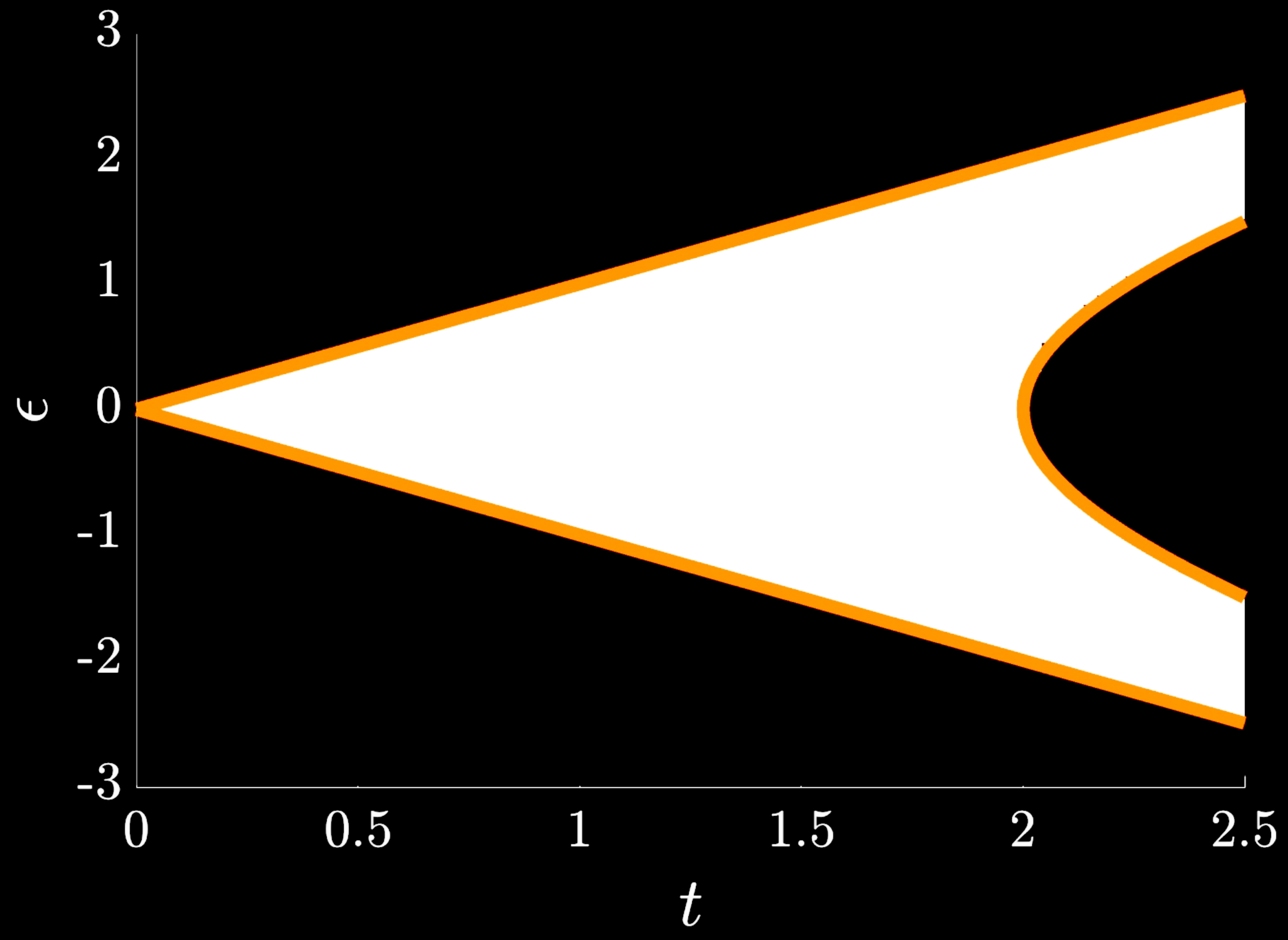
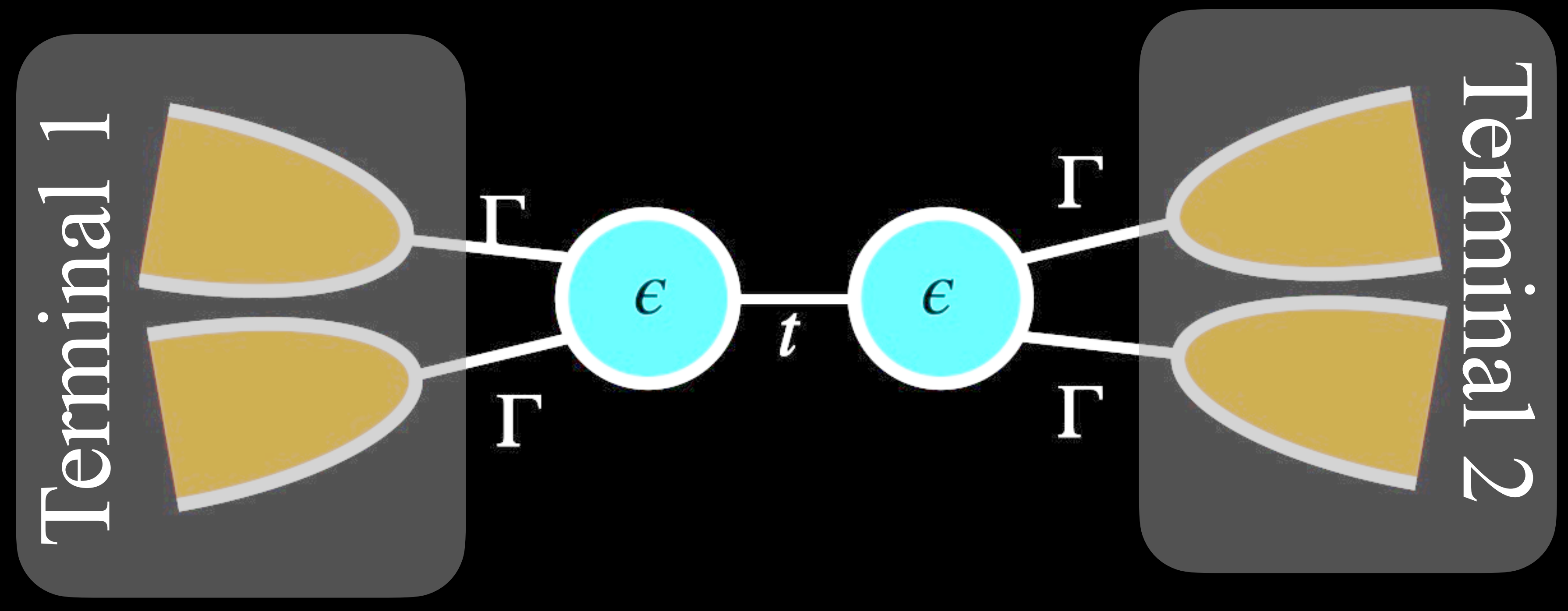






Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



Scattering matrix

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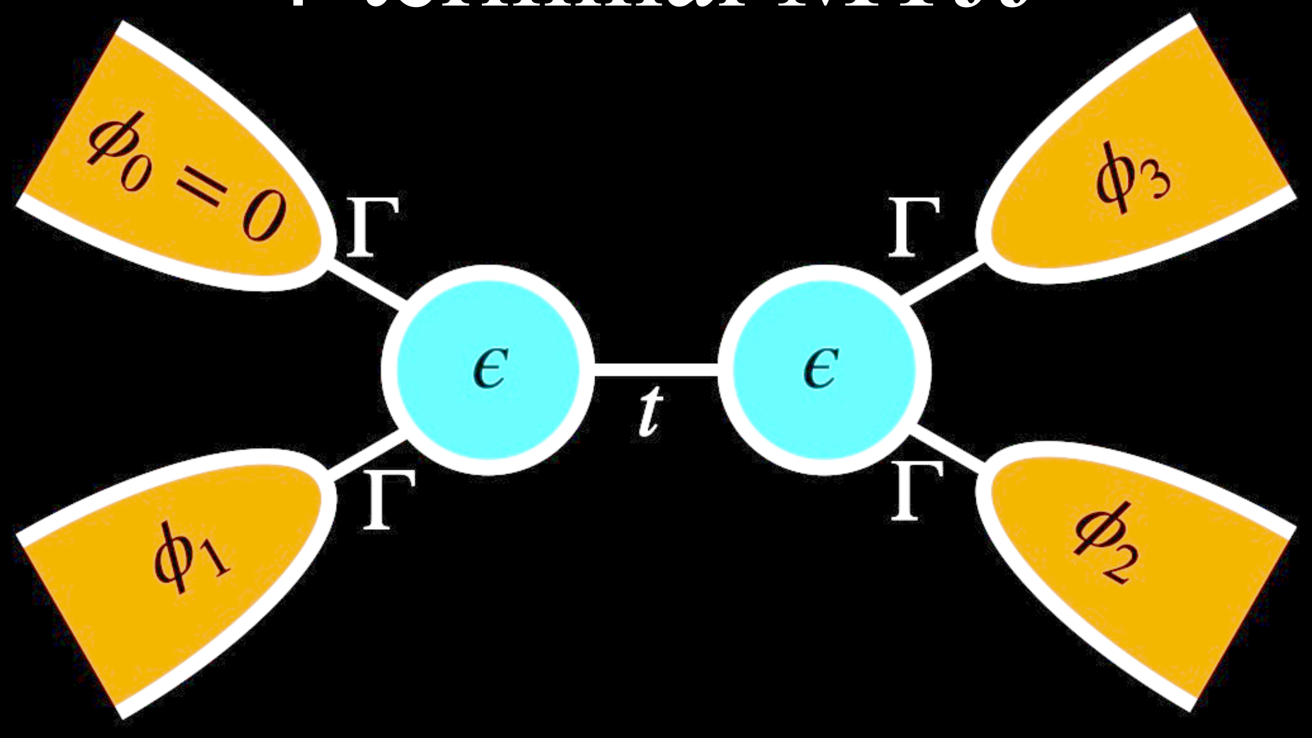
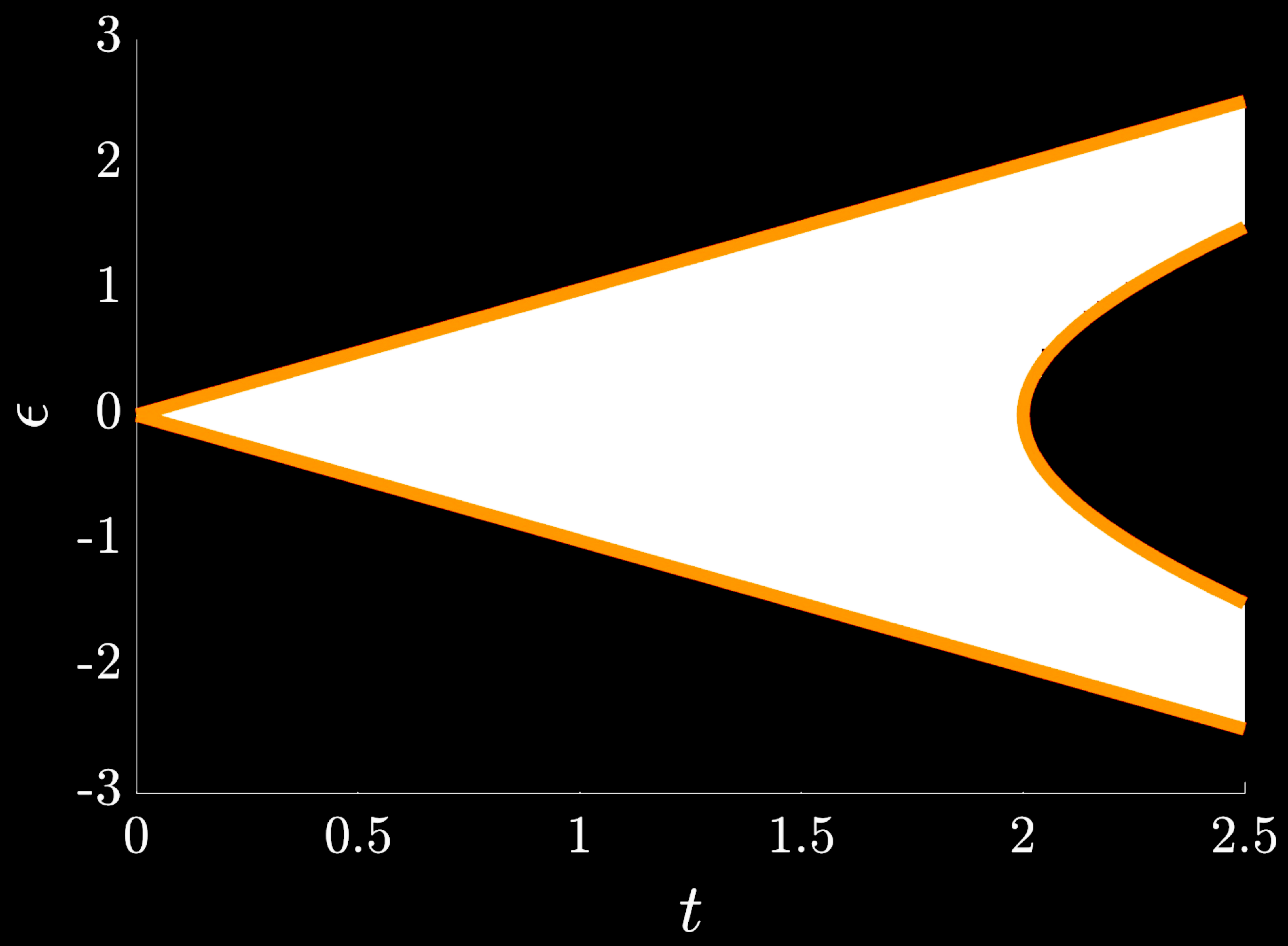
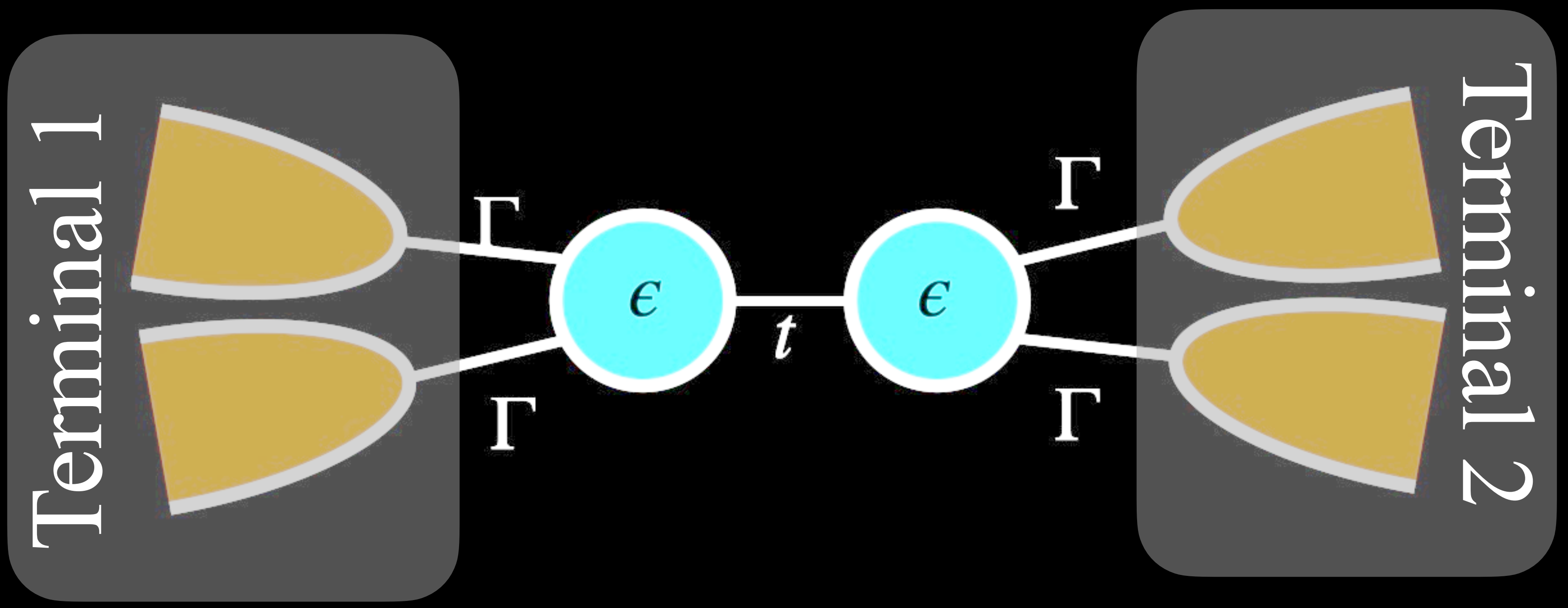
4-terminal MTJJ





Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



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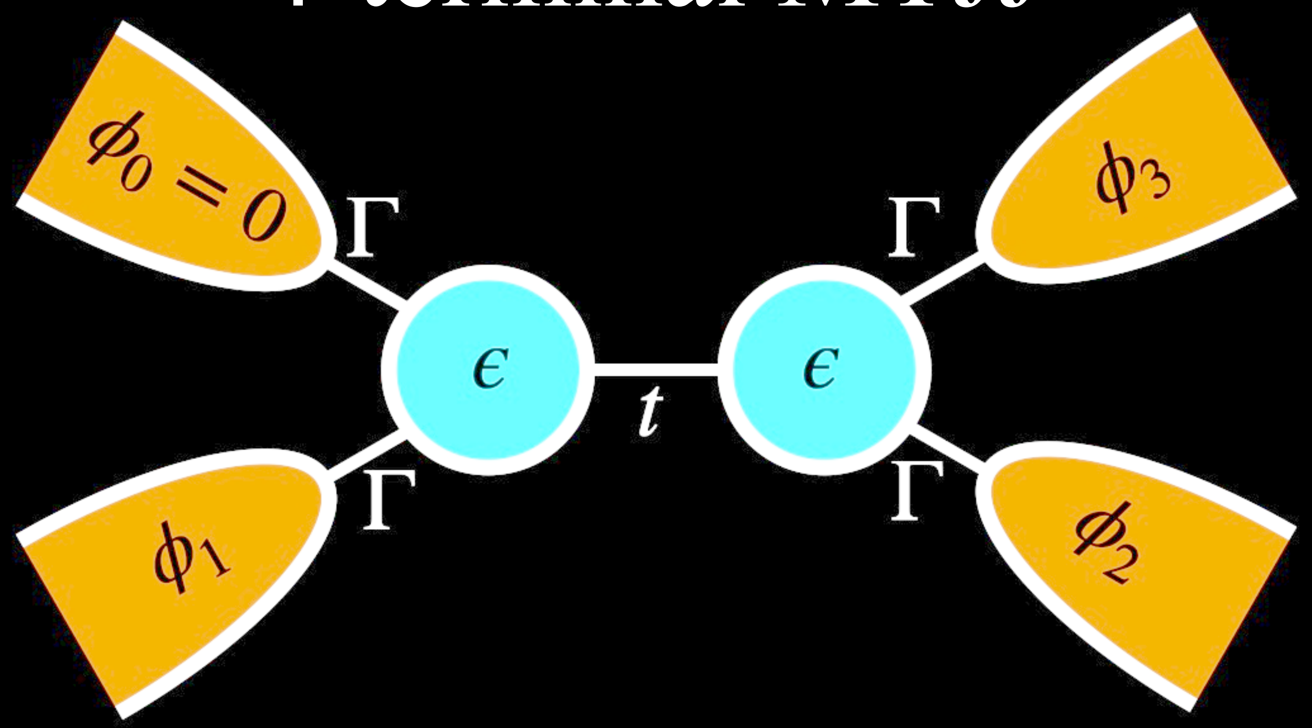
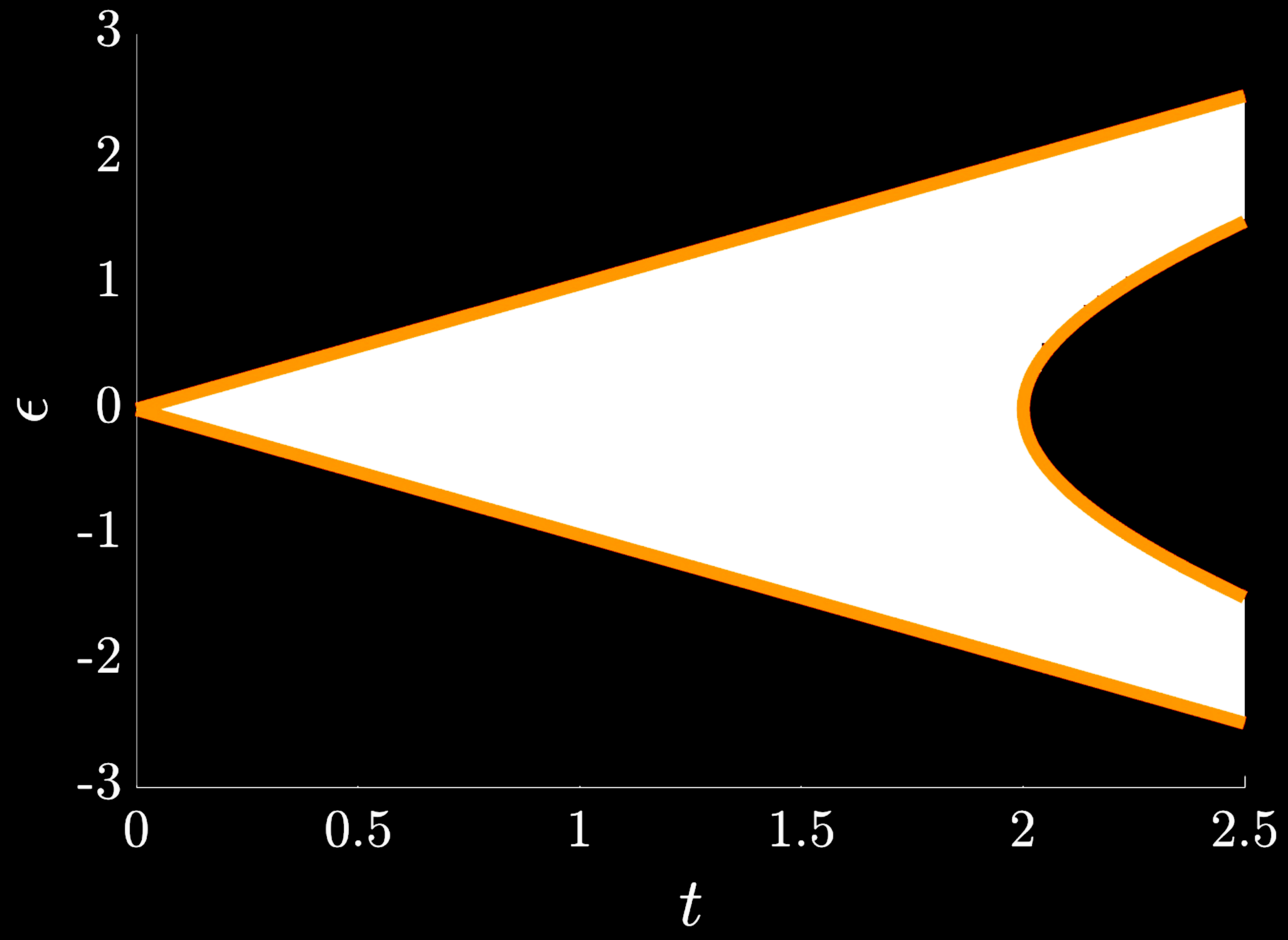
Diagonalized refl. matrix

$$D_{r_{2\times2}} = \begin{pmatrix} \left[E(E-e) - \left(t^2 - \epsilon^2 - 4\Gamma^2\right)\right]/D(E) & 0 \\ 0 & 1 \end{pmatrix}$$

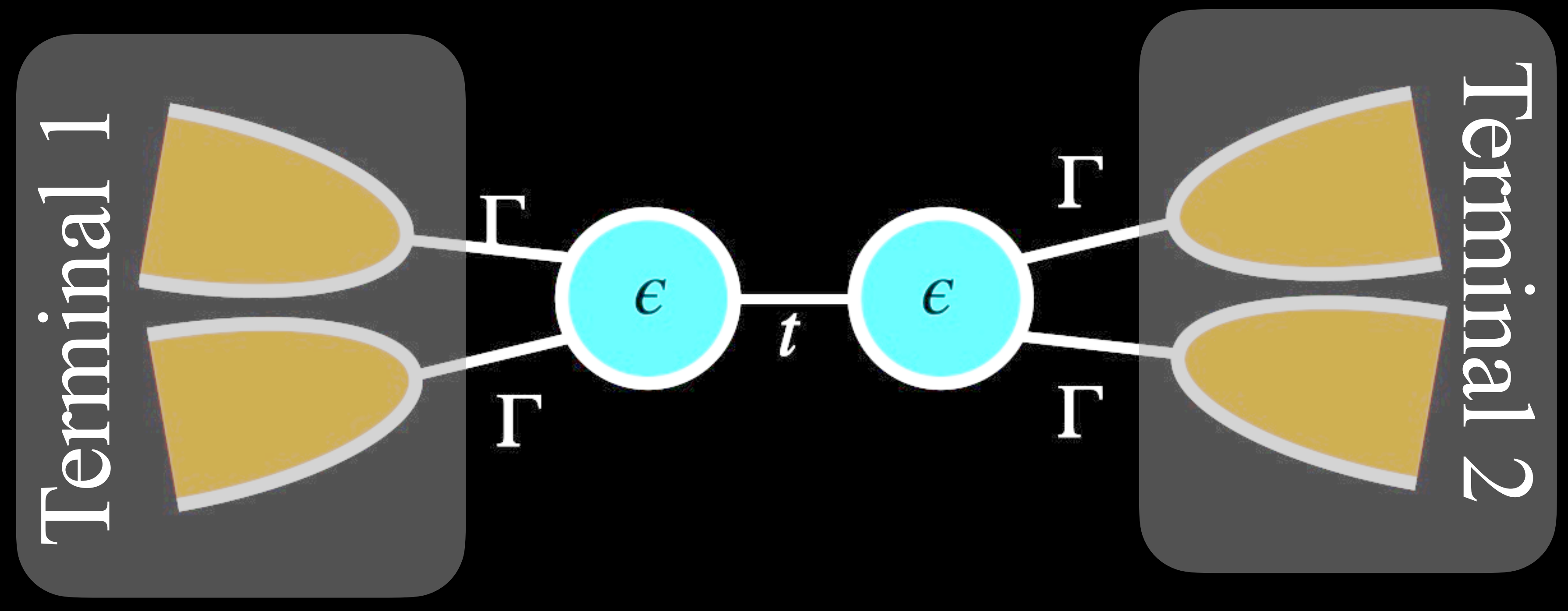
4-terminal MTJJ



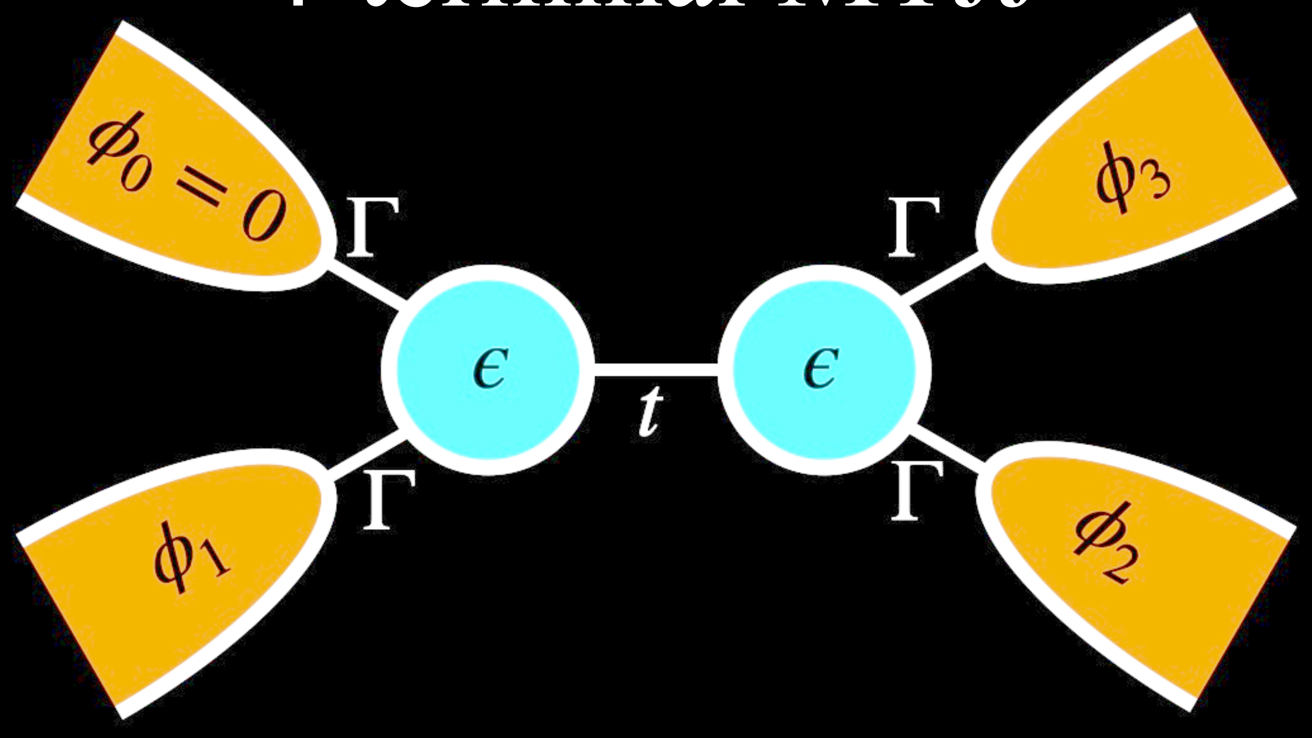


Reflectionless modes as source of Weyl Nodes

effective 2-terminal MTJJ



4-terminal MTJJ



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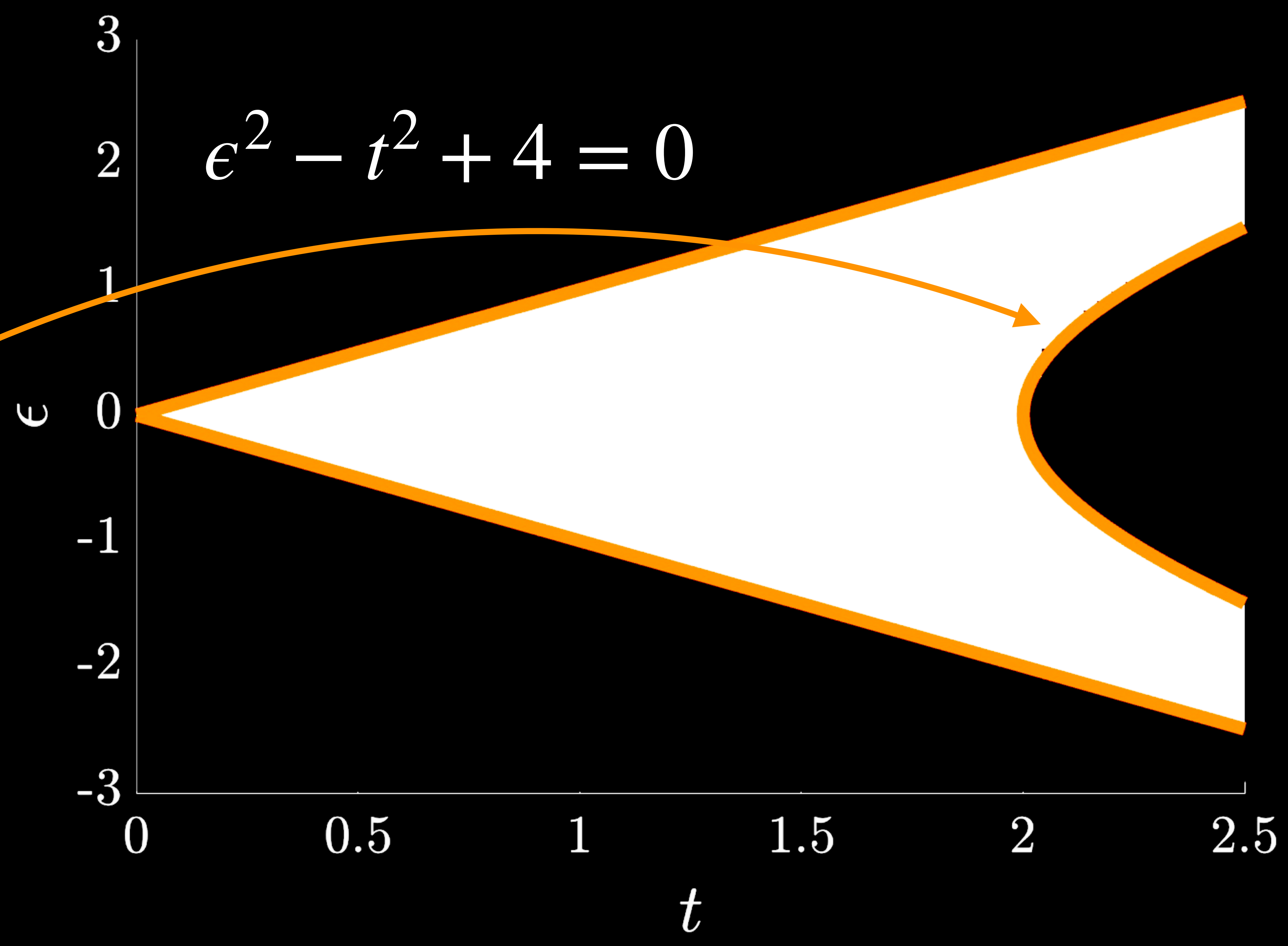
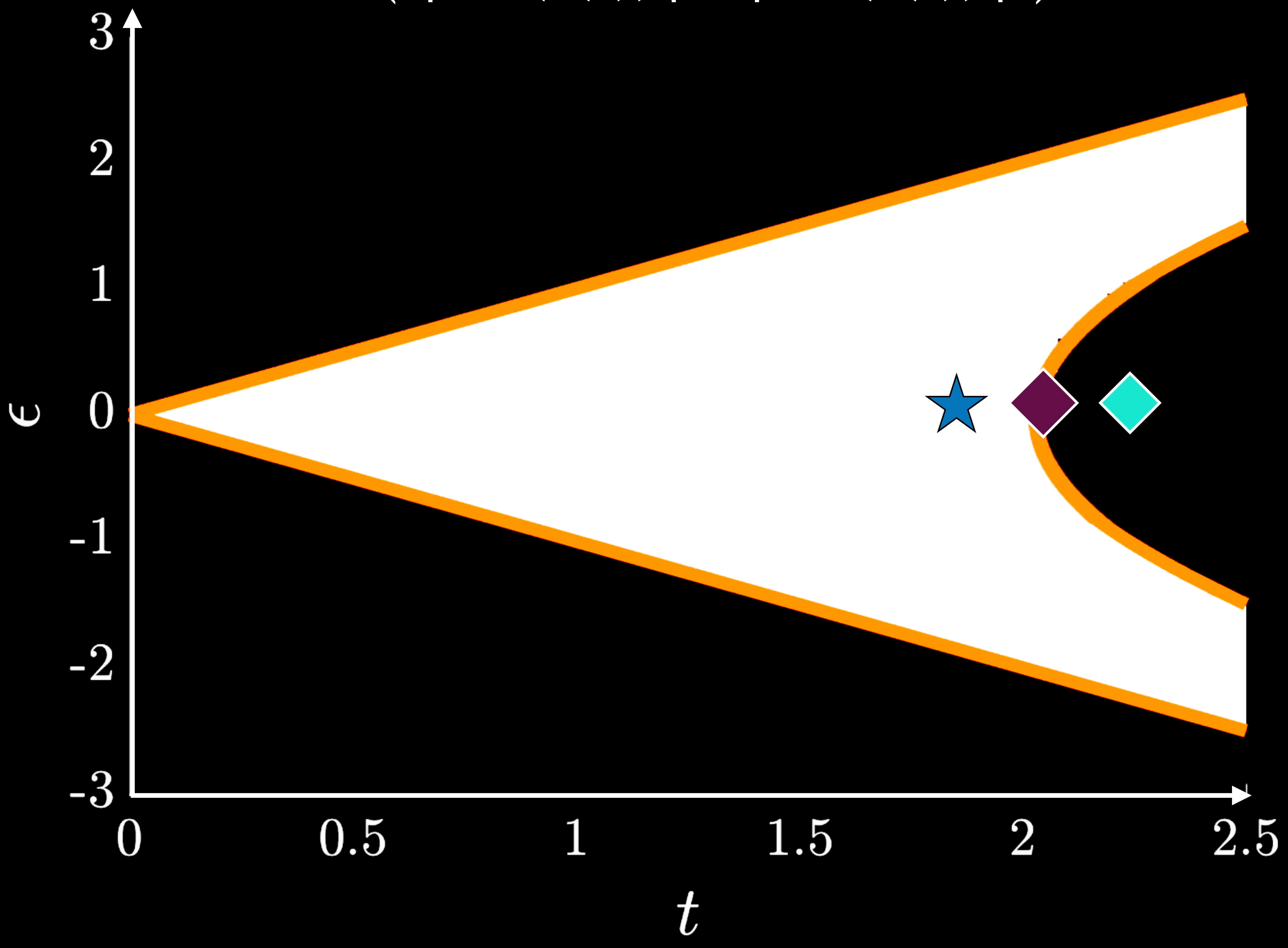


Topological charge of refl. less modes

$$\vec{V} = \left(\frac{\mathrm{Re}\,\det(r(z))}{|\det(r(z))|}, \frac{\mathrm{Im}\,\det(r(z))}{|\det(r(z))|} \right)$$

complex energy
$z \in \mathbb{C}$



W. R. Sweeney, et. al., Phys. Rev. A 102, 063511 (2020)

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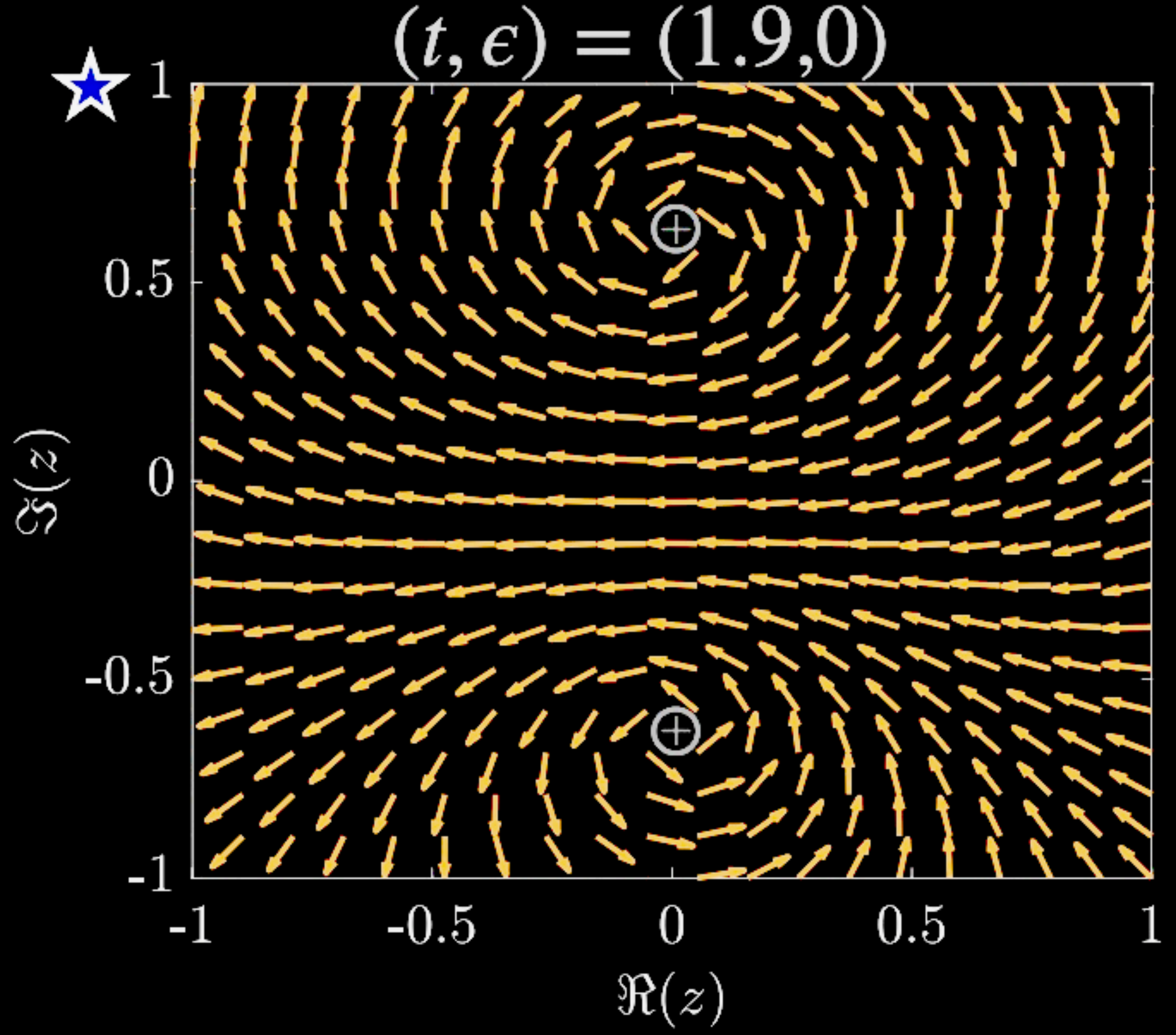

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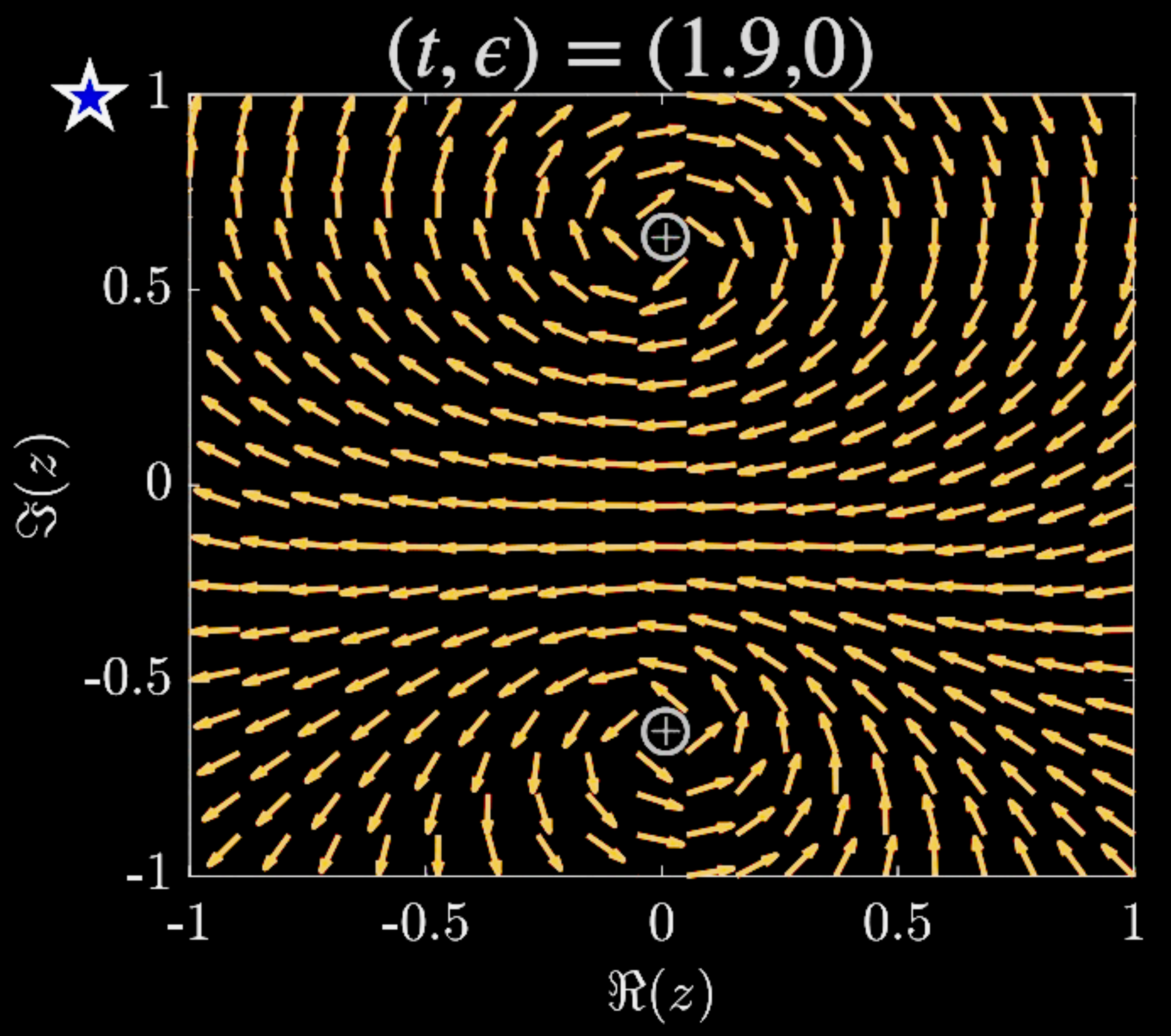

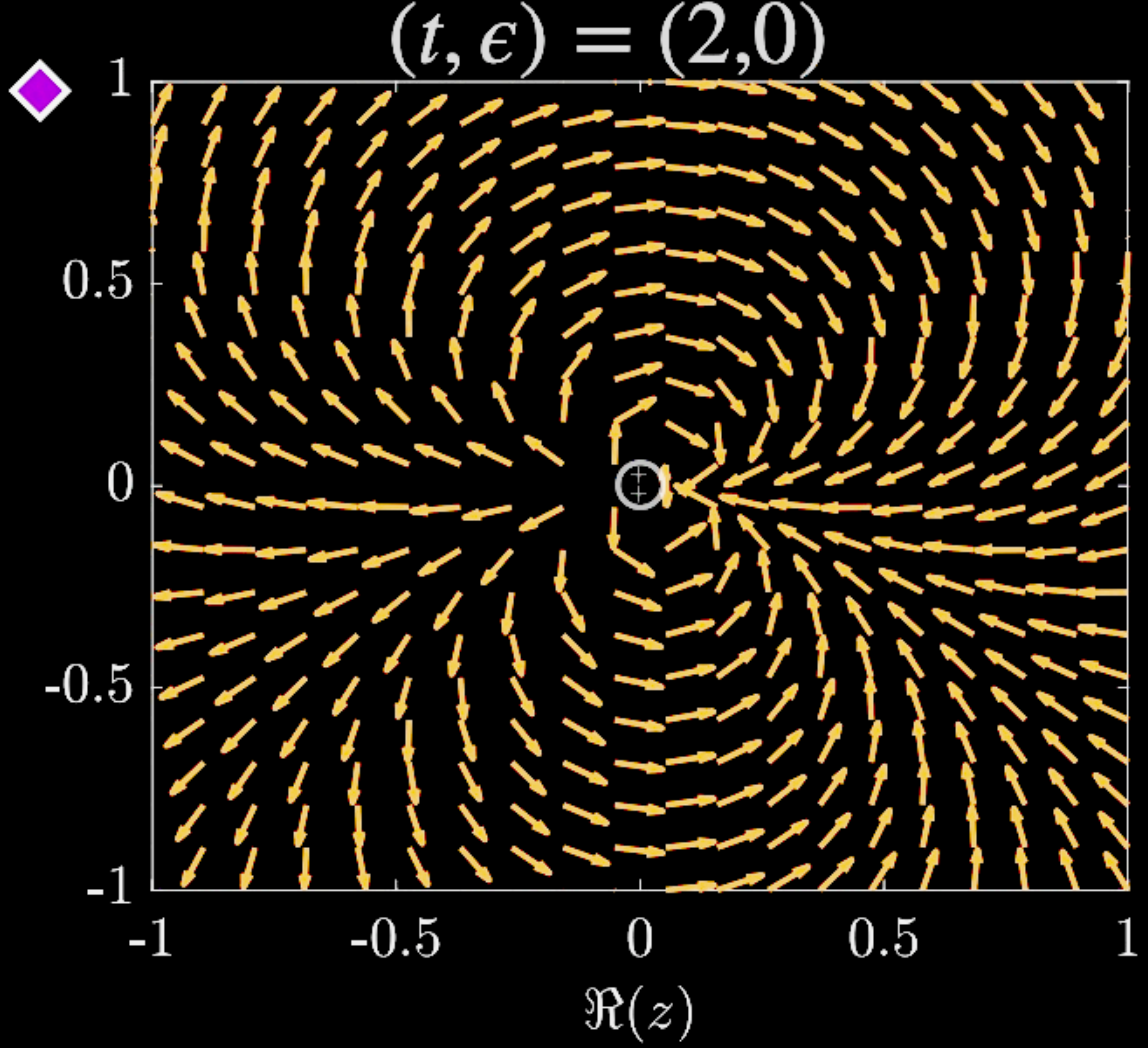

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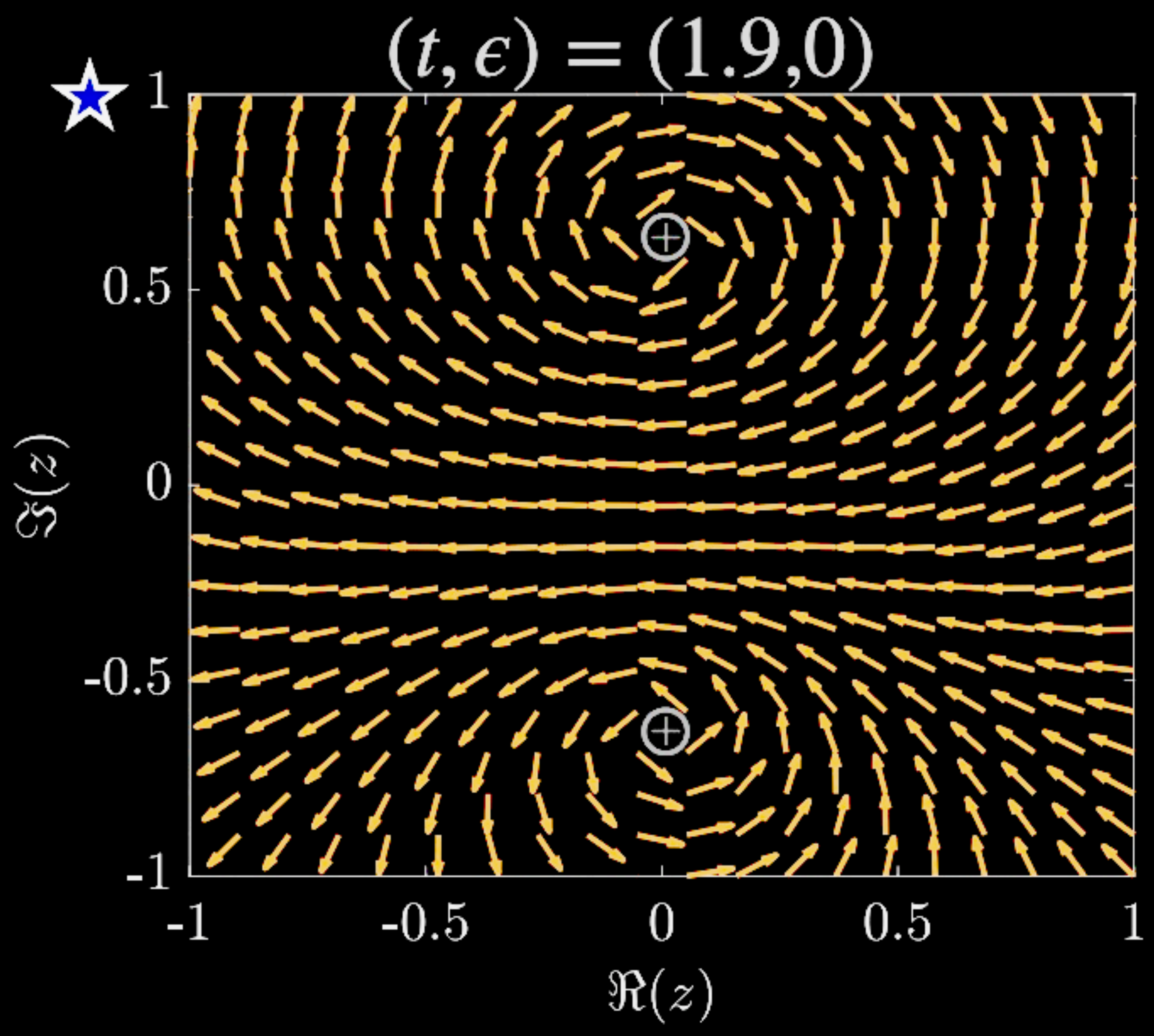
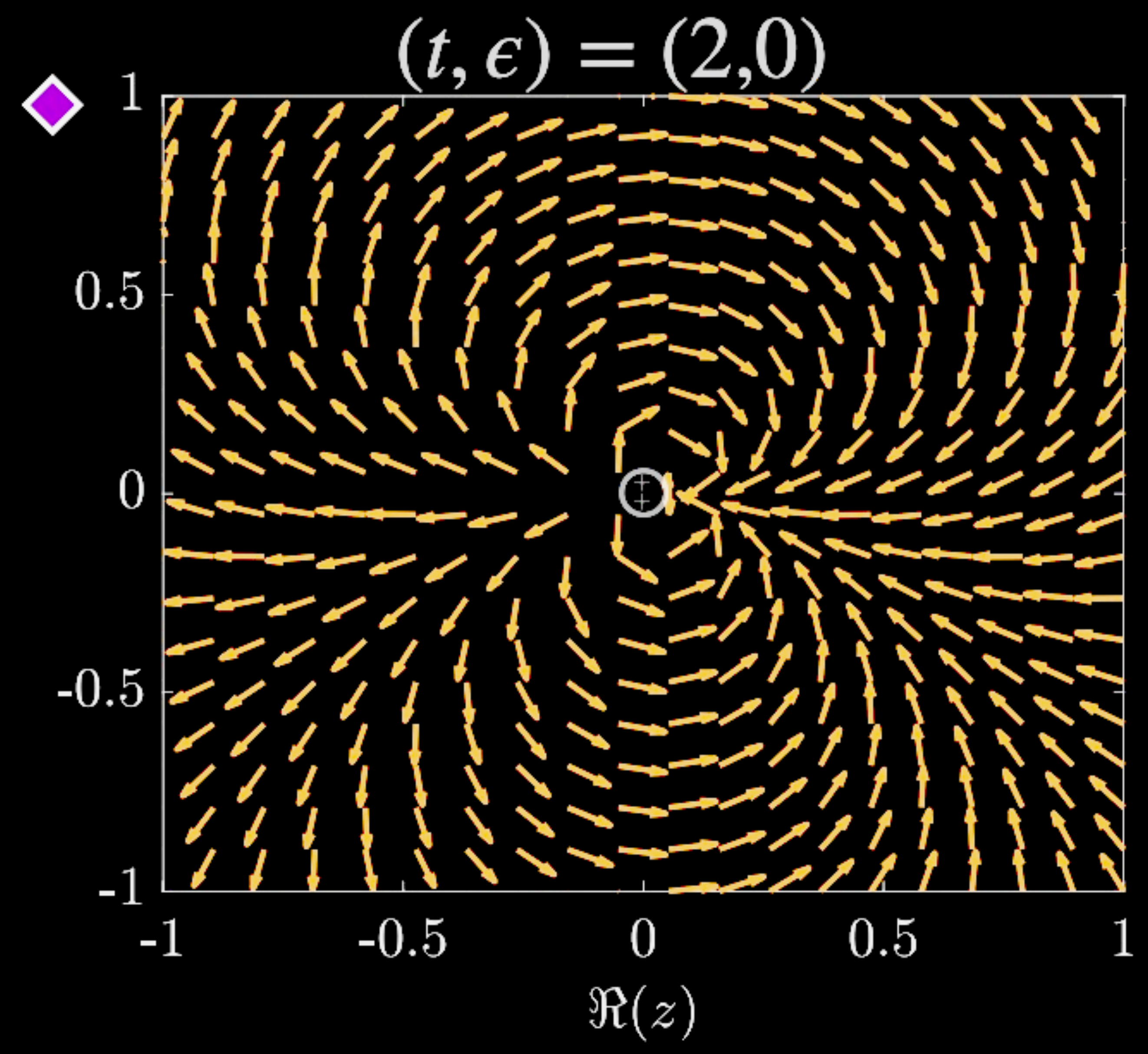
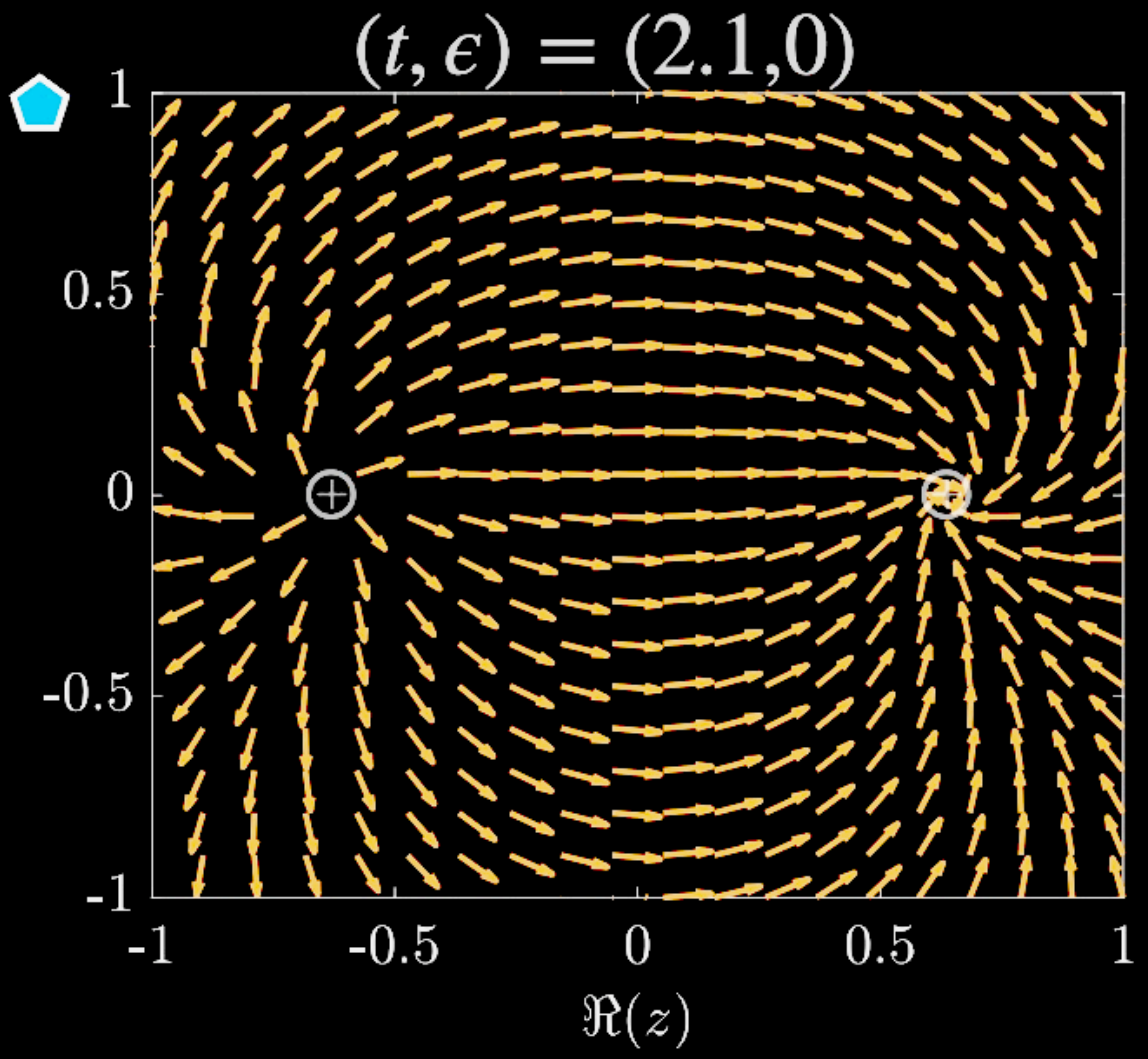






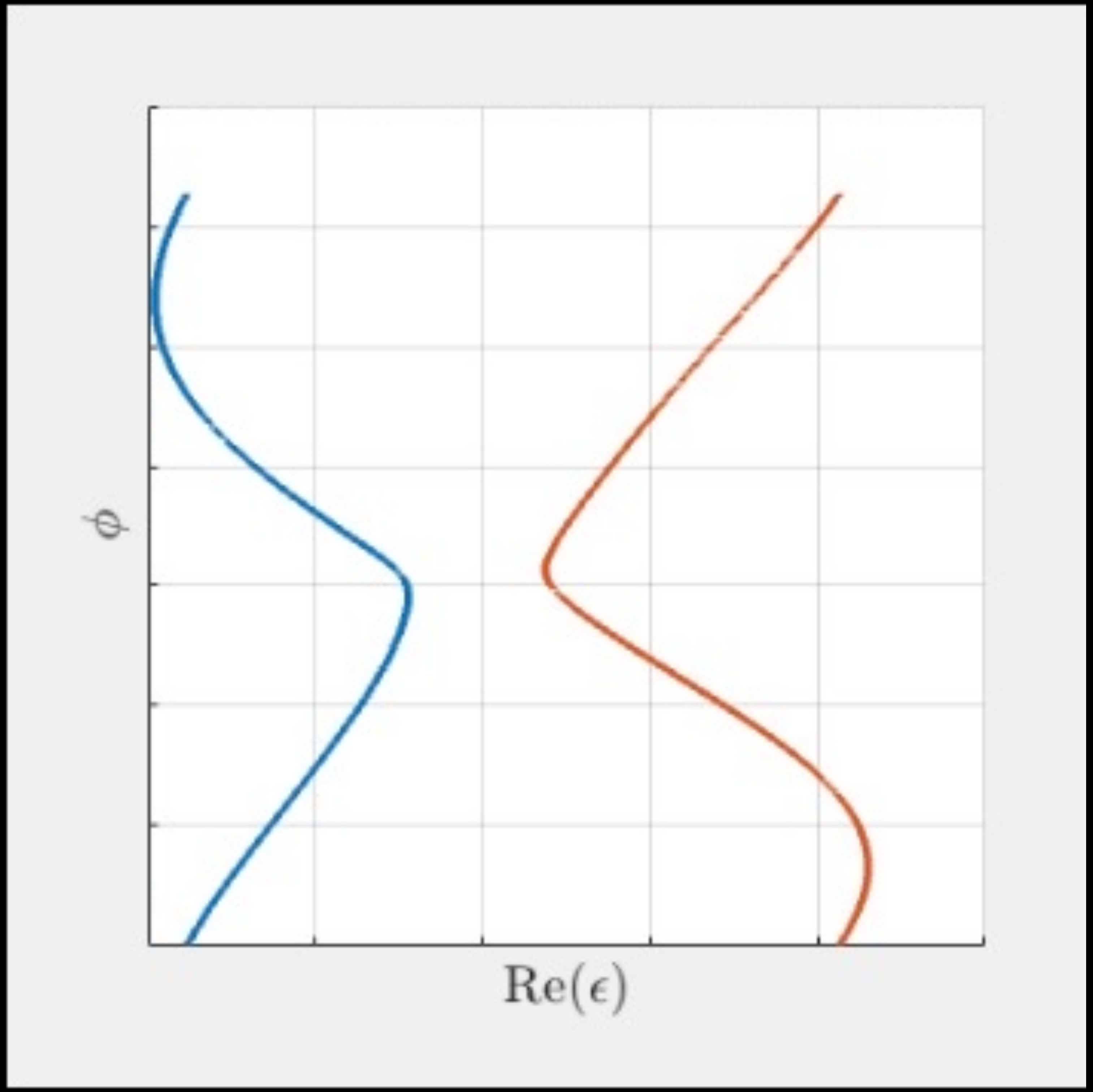
Hermitian physics

Hermitian

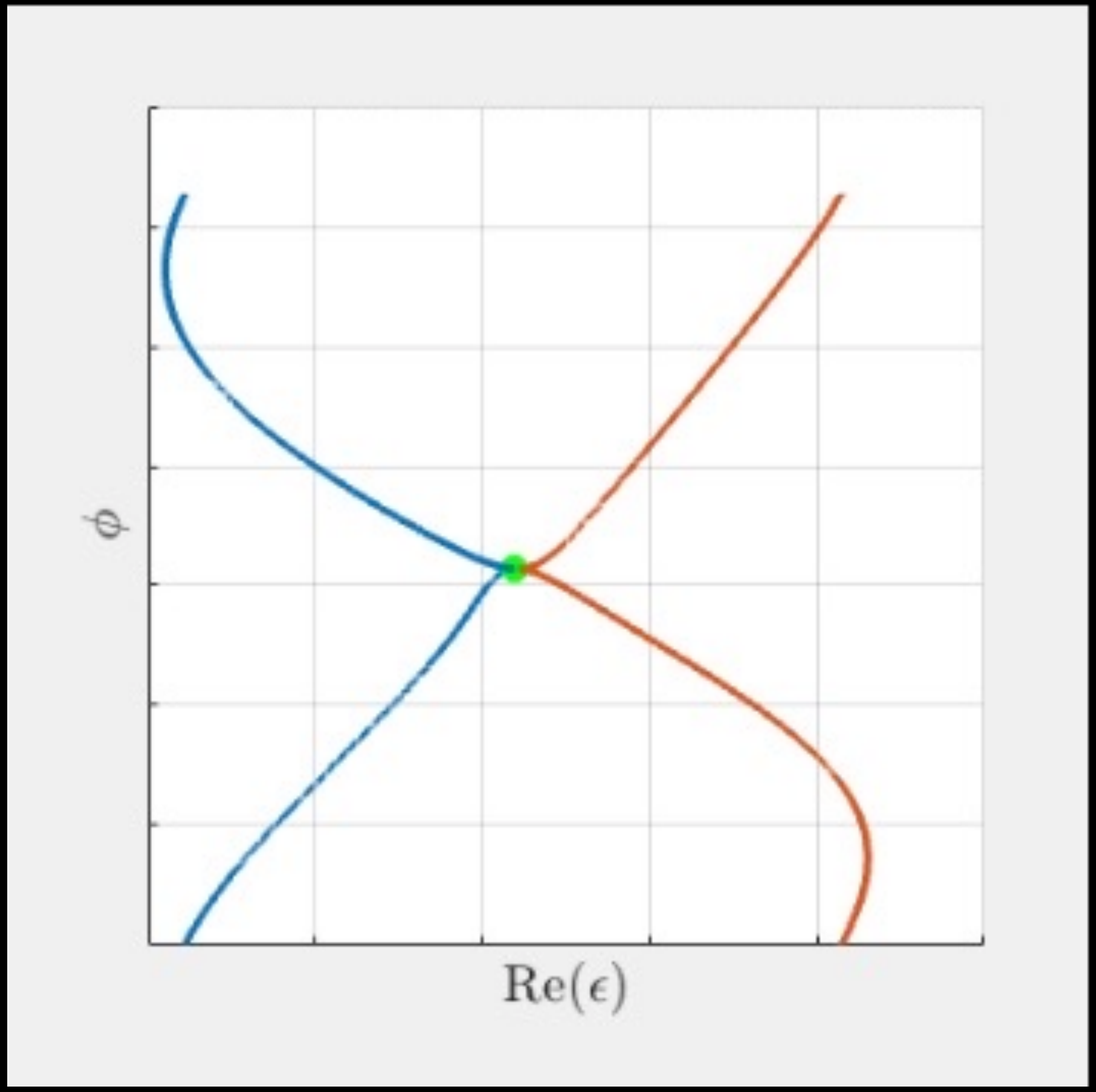
$$H = H^\dagger$$

$$\epsilon_\alpha \in \mathbb{R}$$

Gapped



Ungapped



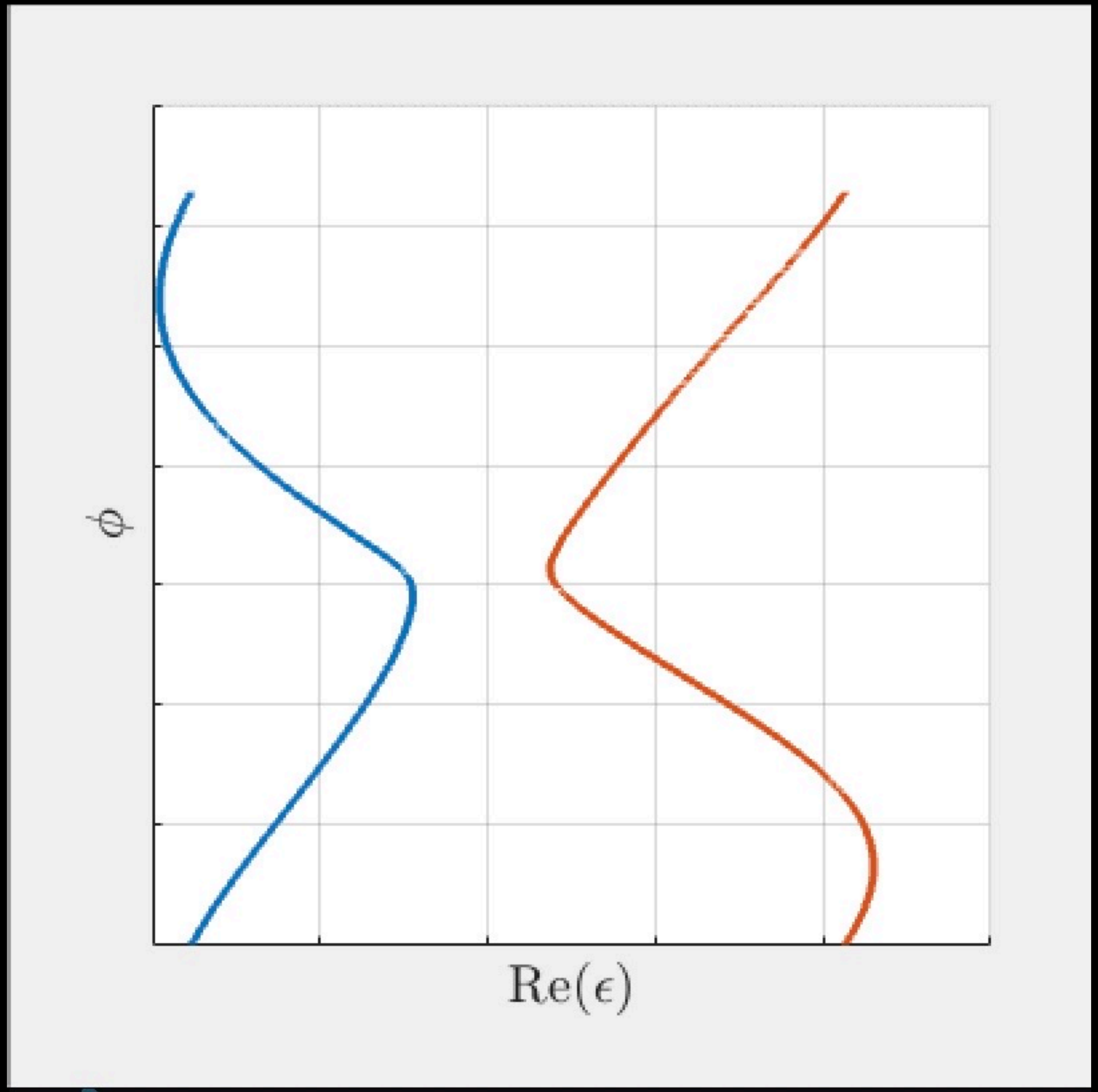
Non-hermitian physics

Kohei Kawabata, et. al., Phys. Rev. X 9, 041015 (2019)

non-Hermitian

$$H \neq H^\dagger$$

$$\epsilon_\alpha \in \mathbb{C}$$



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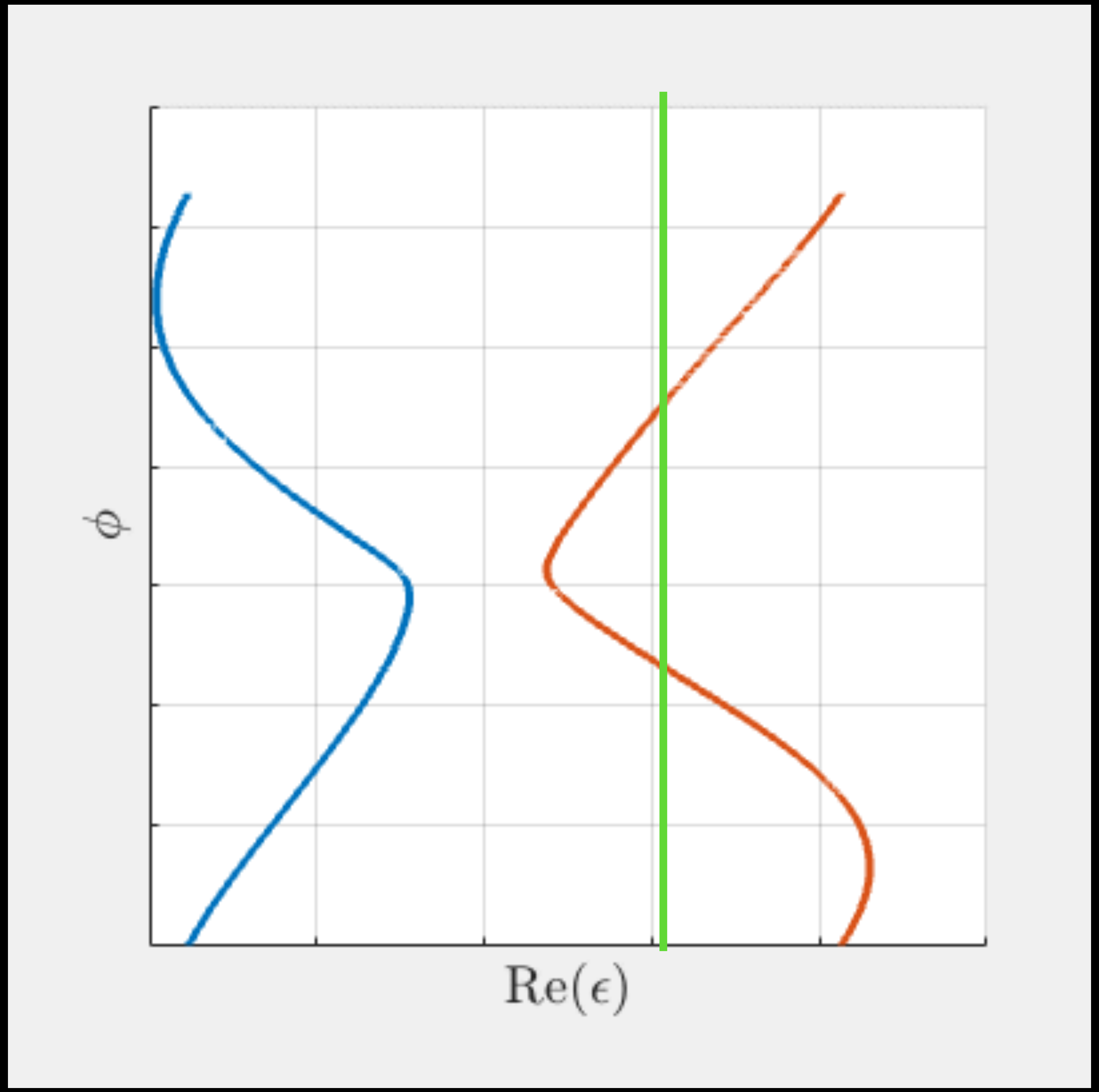
Line Gap



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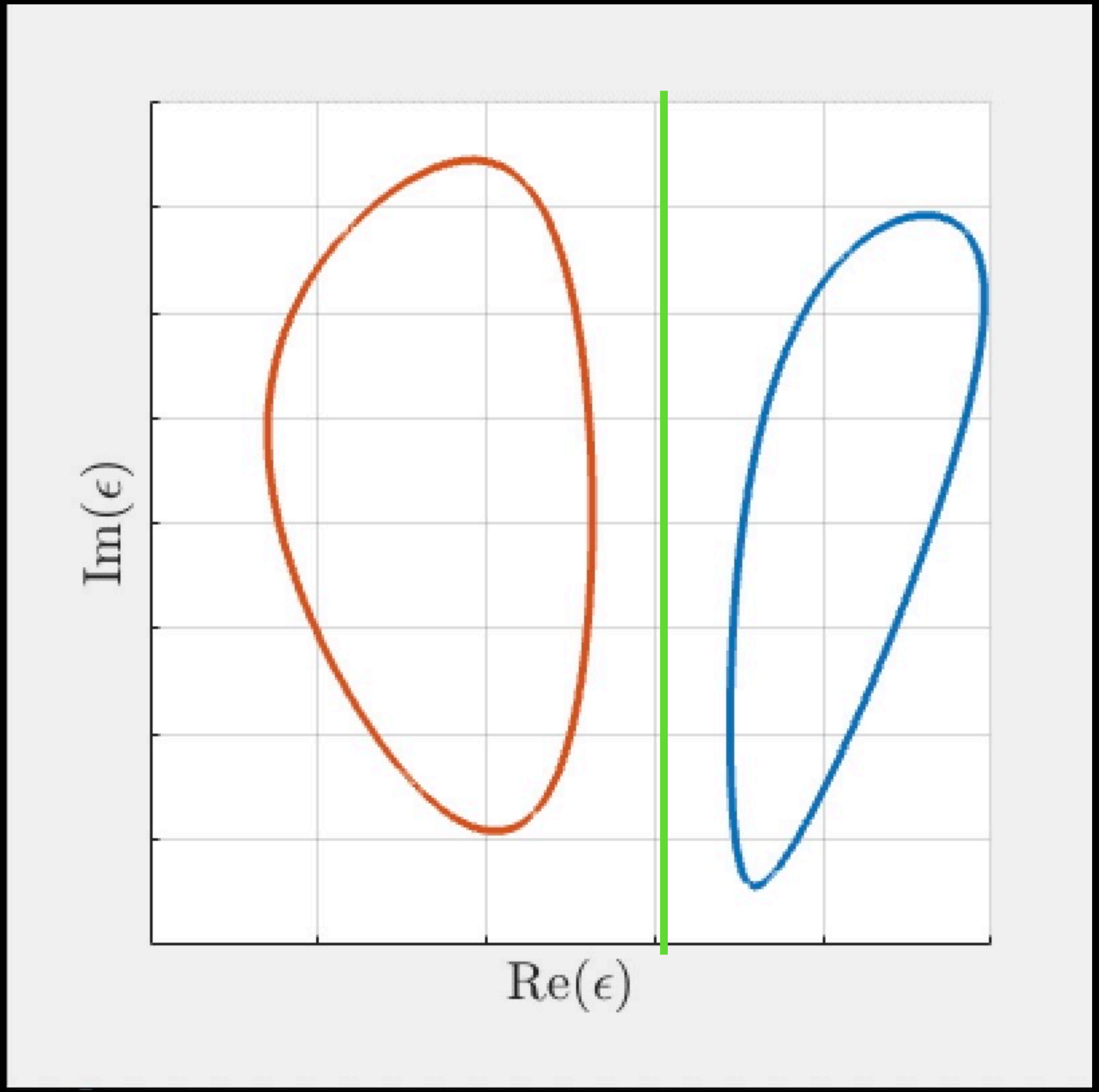

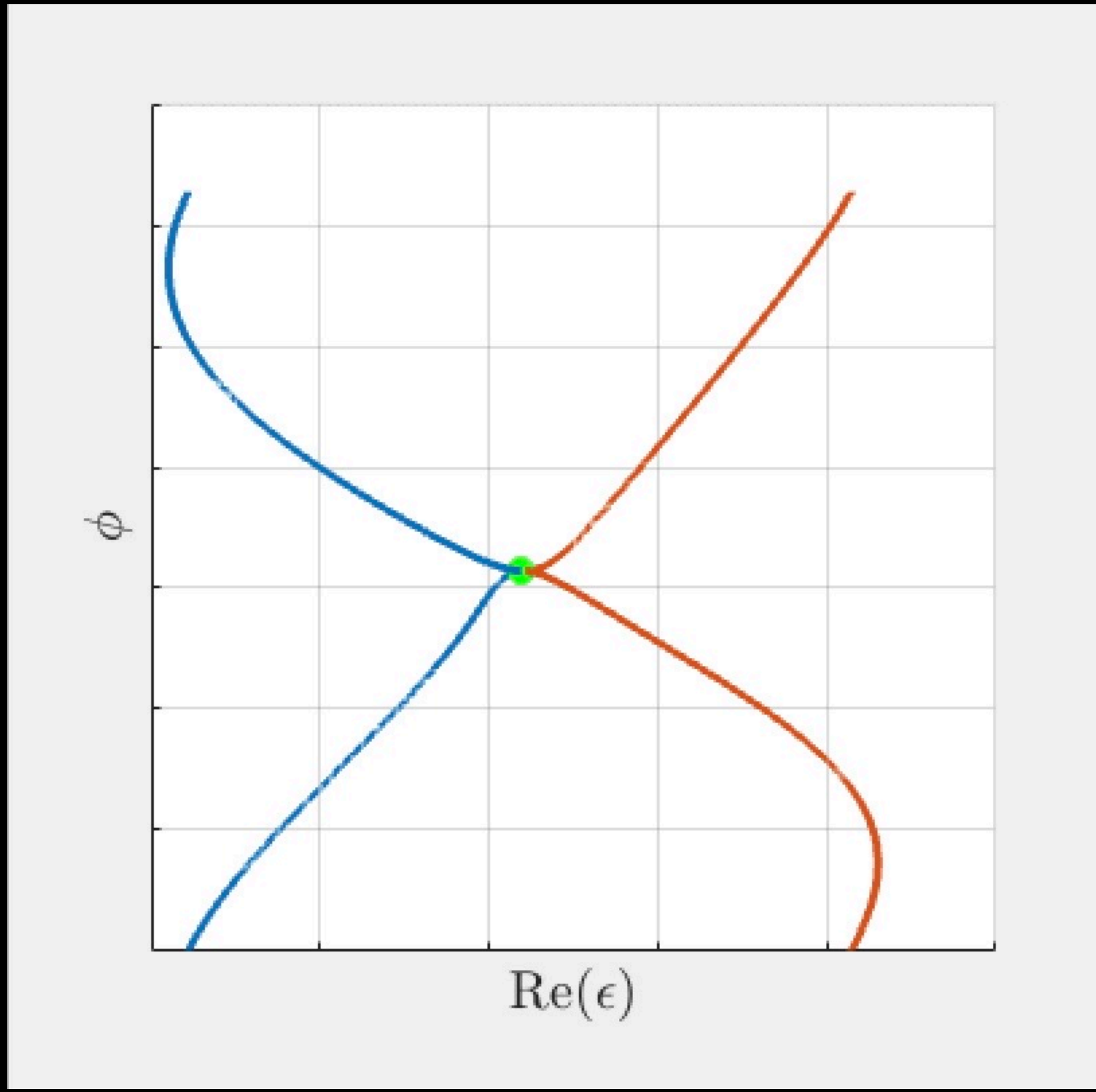

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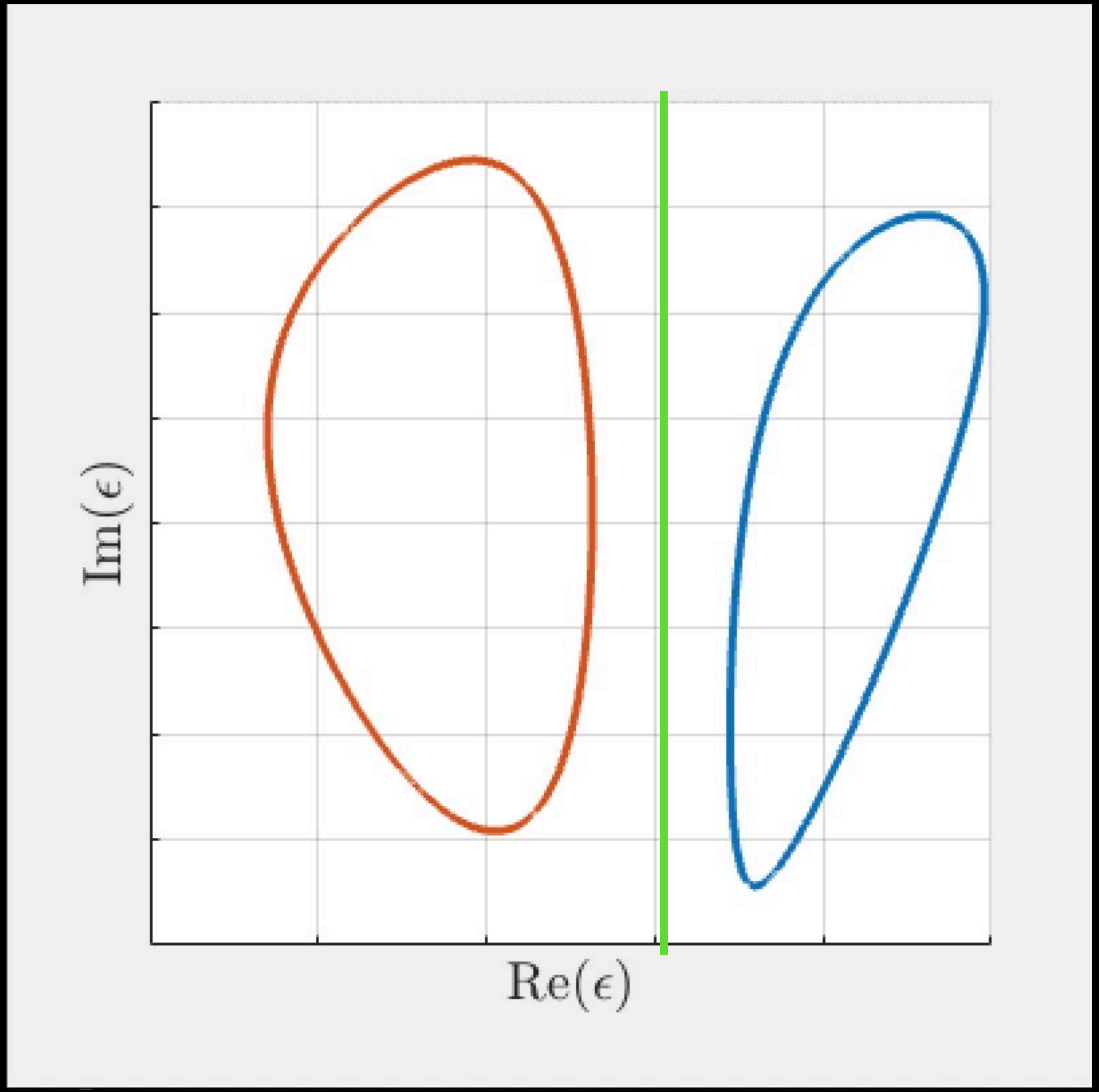
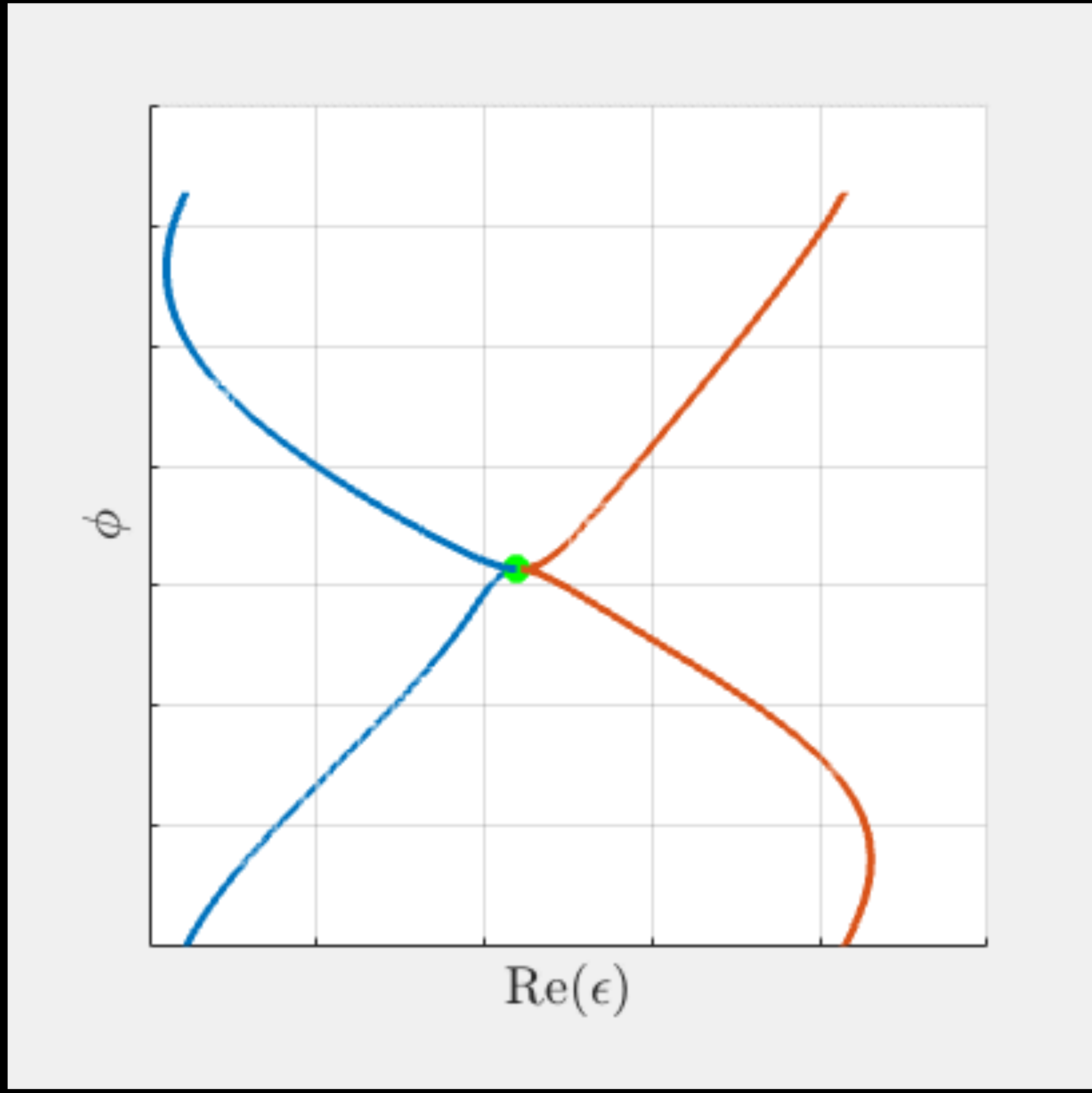


Exceptional Point (EPs)



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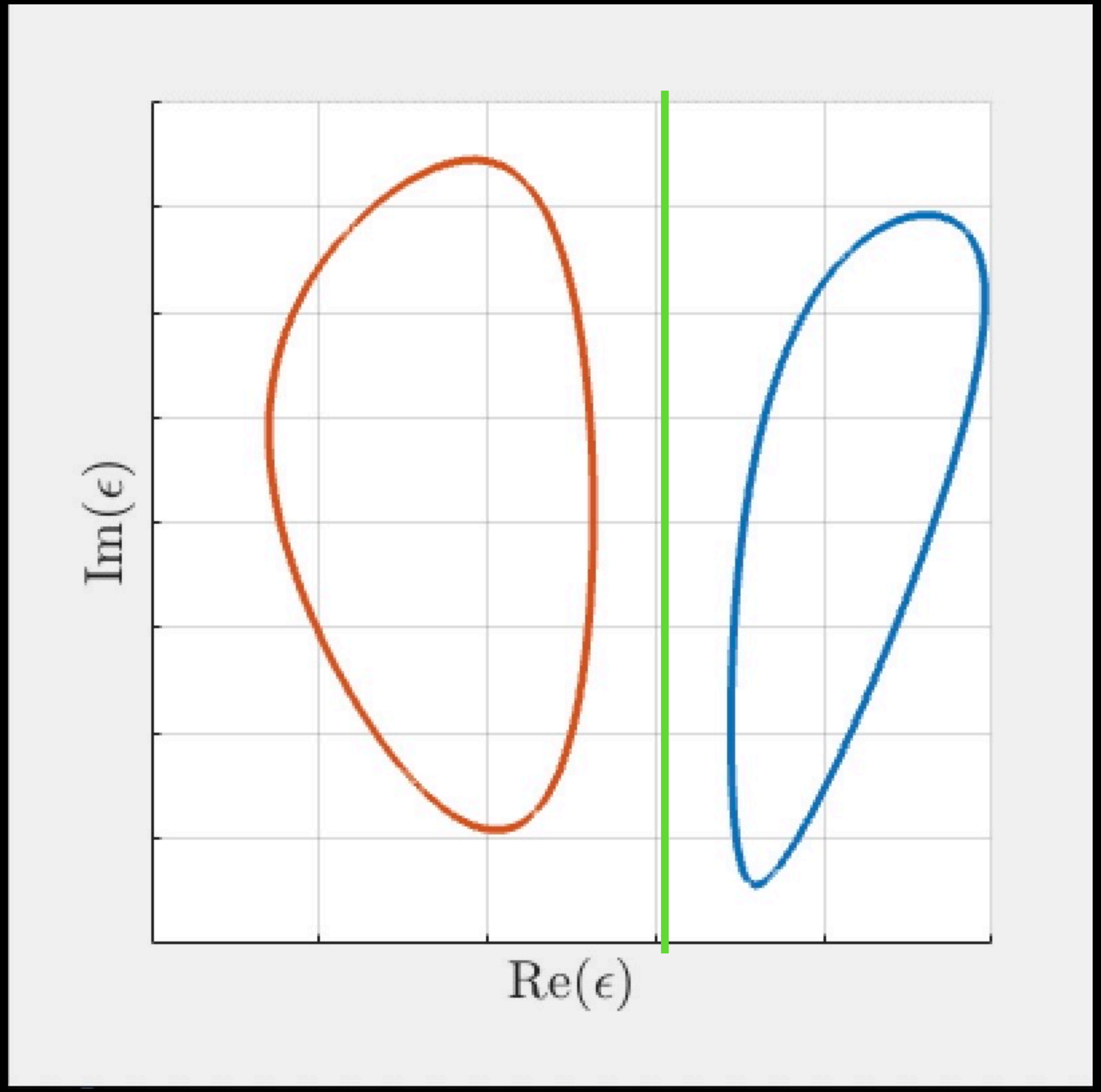

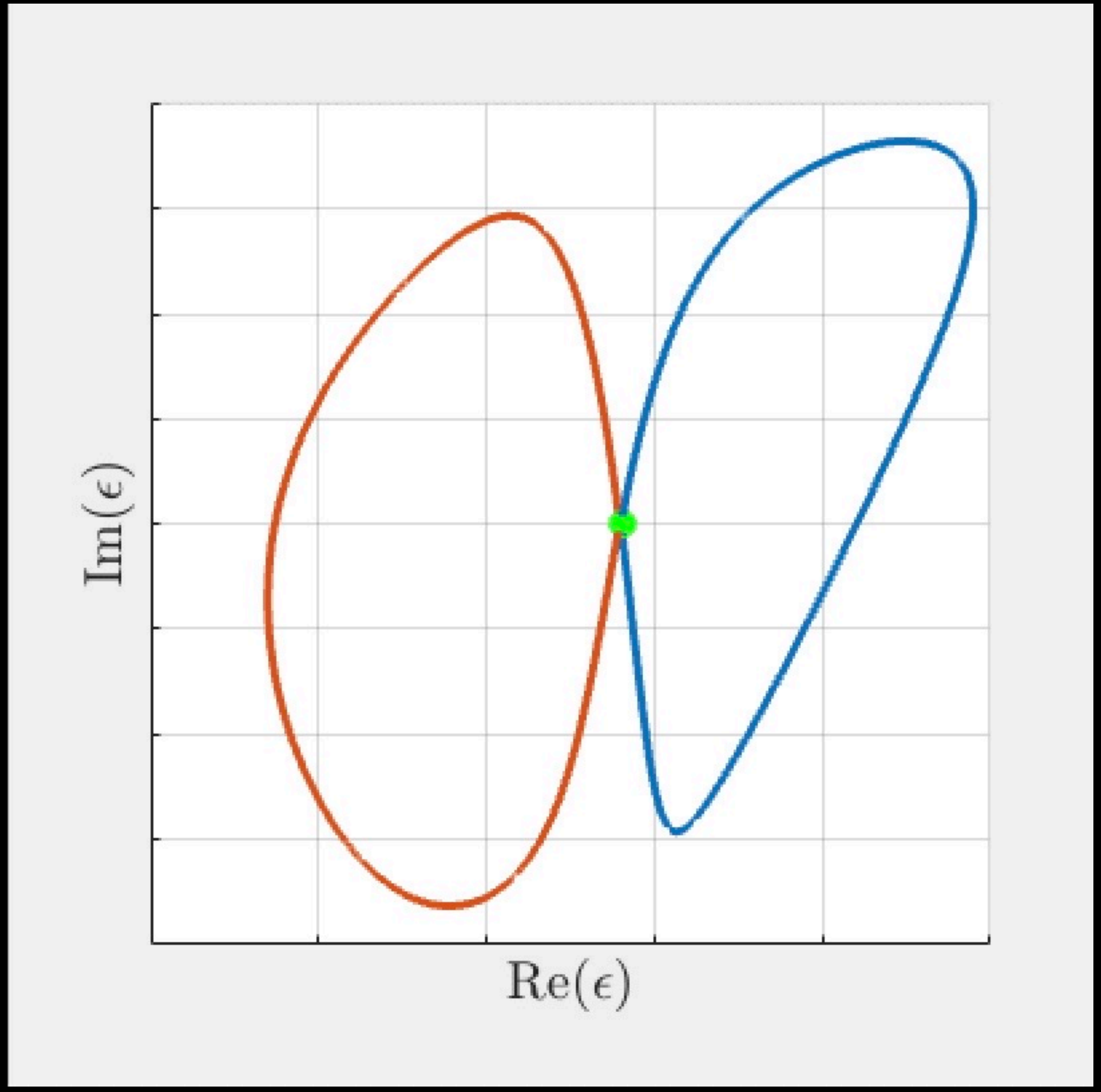

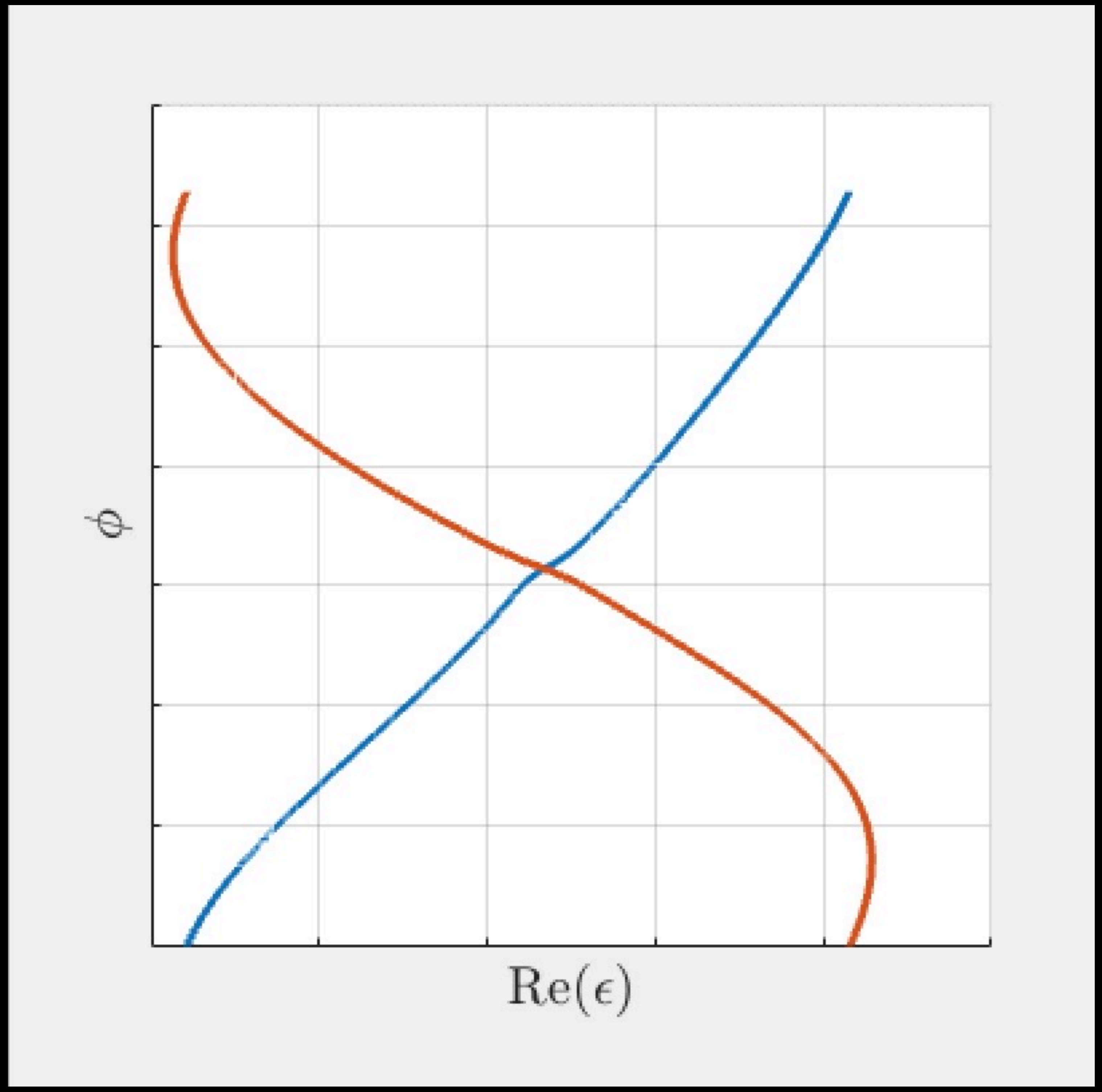

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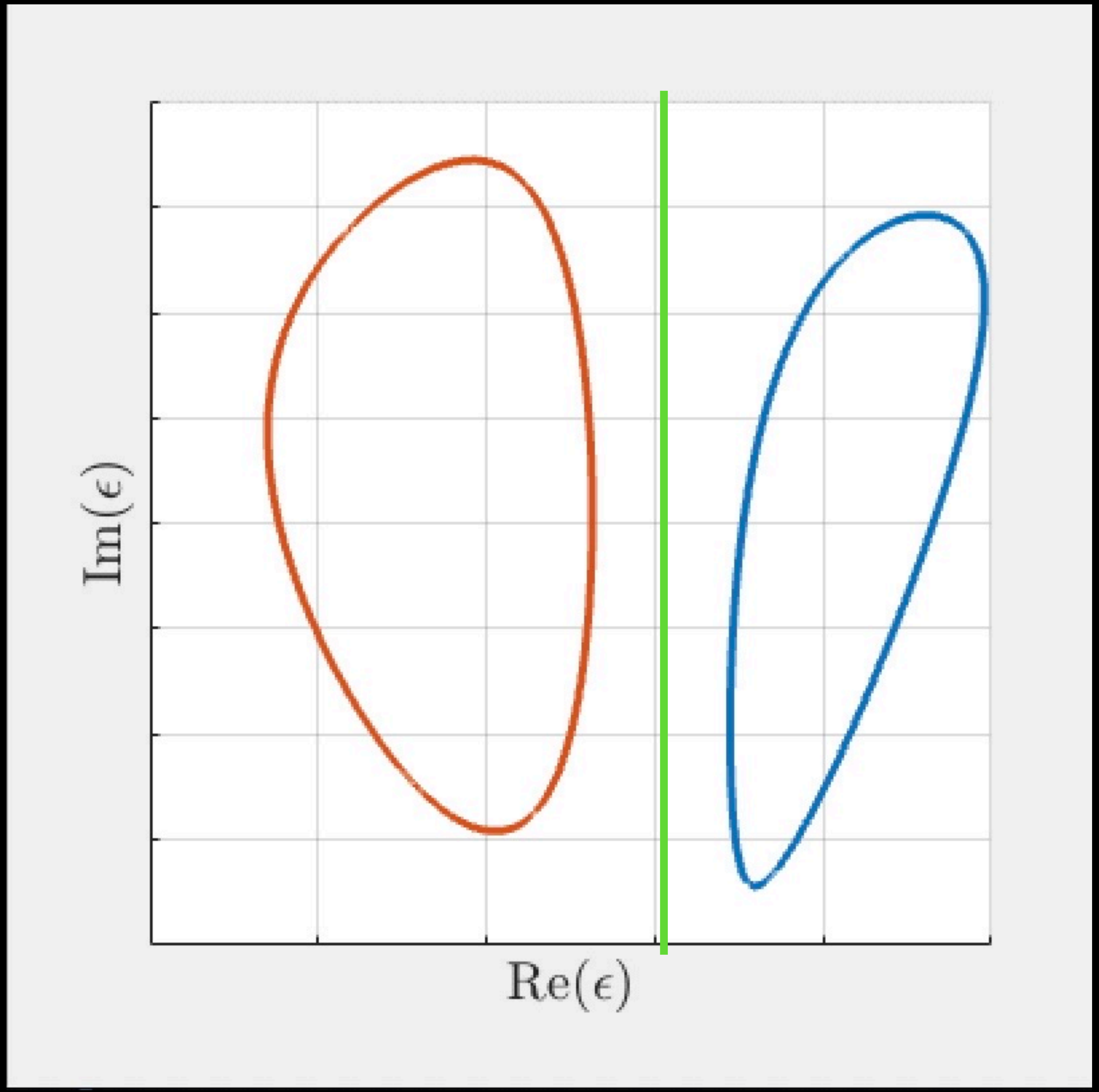
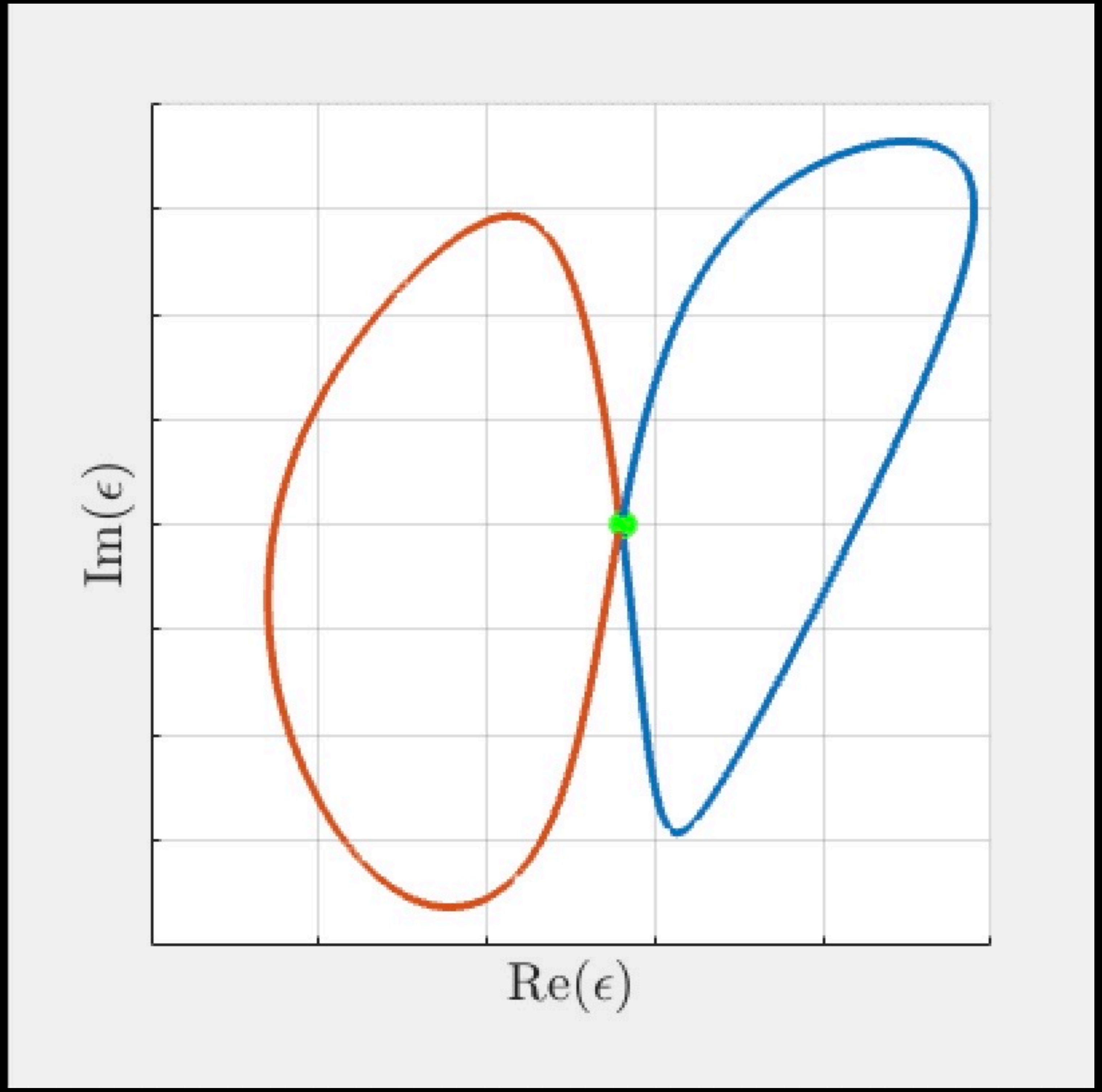
$$H \neq H^{\dagger}$$

$$\epsilon_{\alpha} \in \mathbb{C}$$

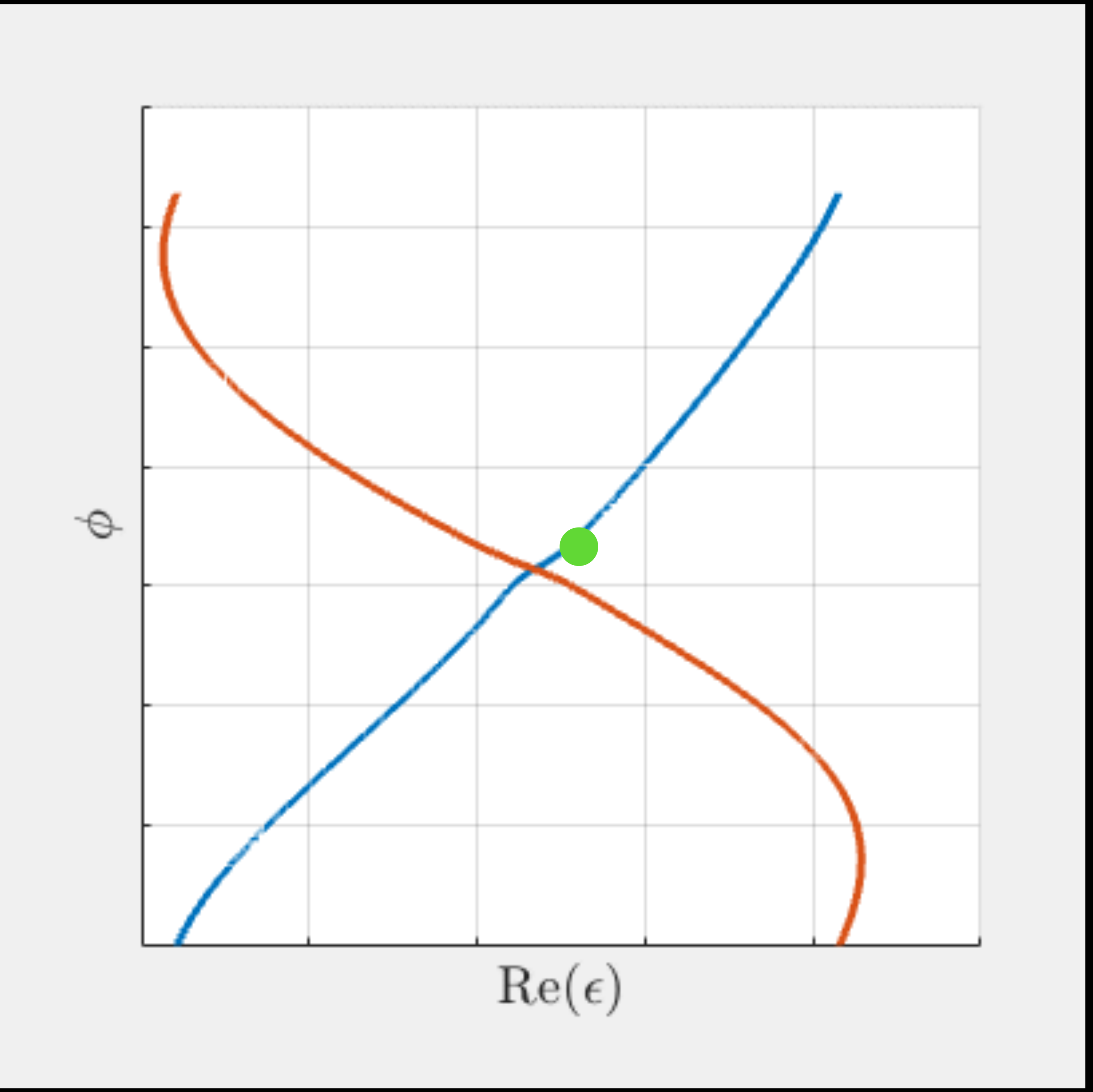
Line Gap



Exceptional Point (EPs)



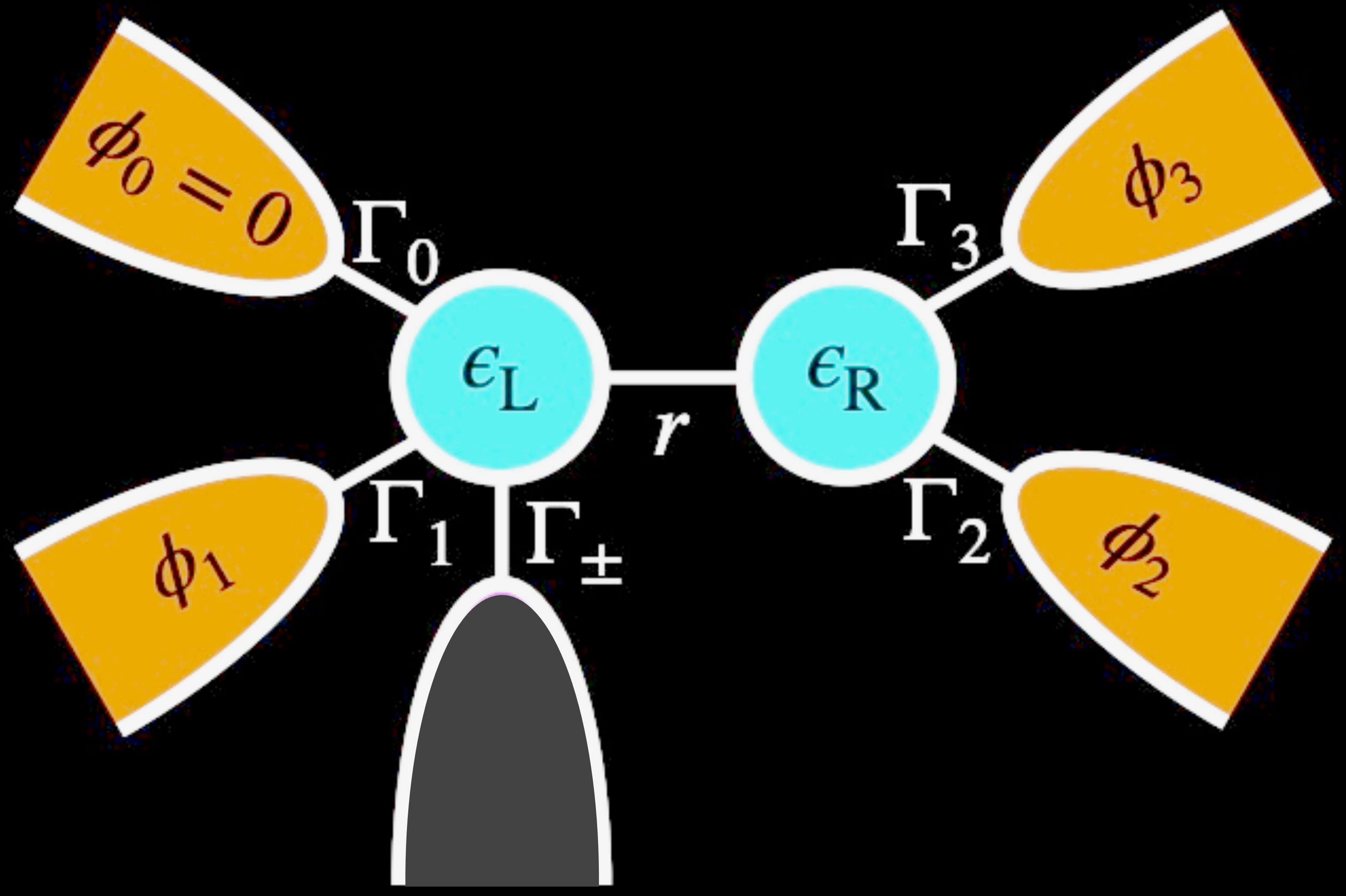
Point Gap



Non-hermitian topology in MTJJs

D. C. Ohnmacht, et. al., arXiv:2408.01289 (2024) (accepted in PRL)

Breaking spin-rotation symm.



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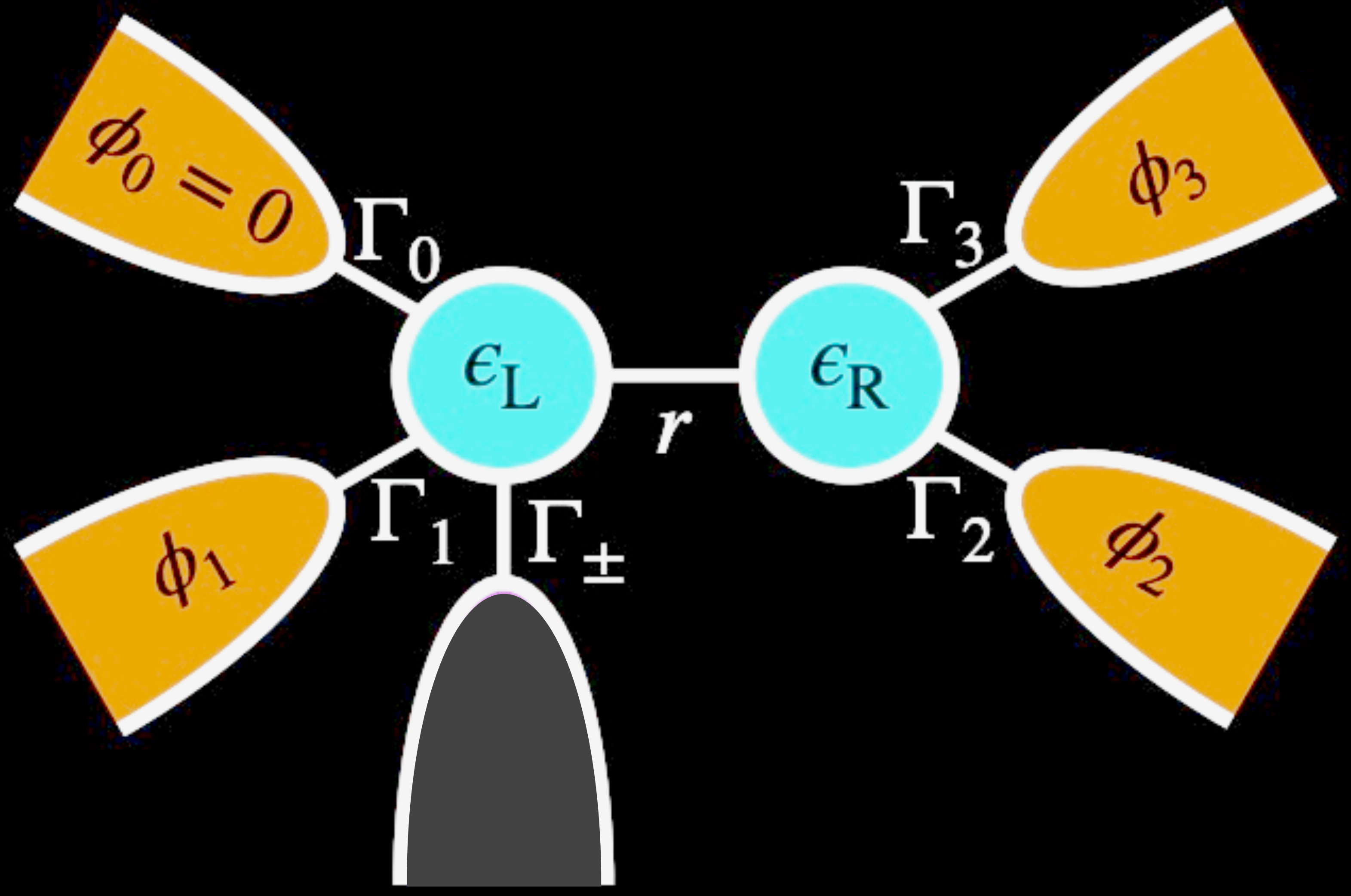

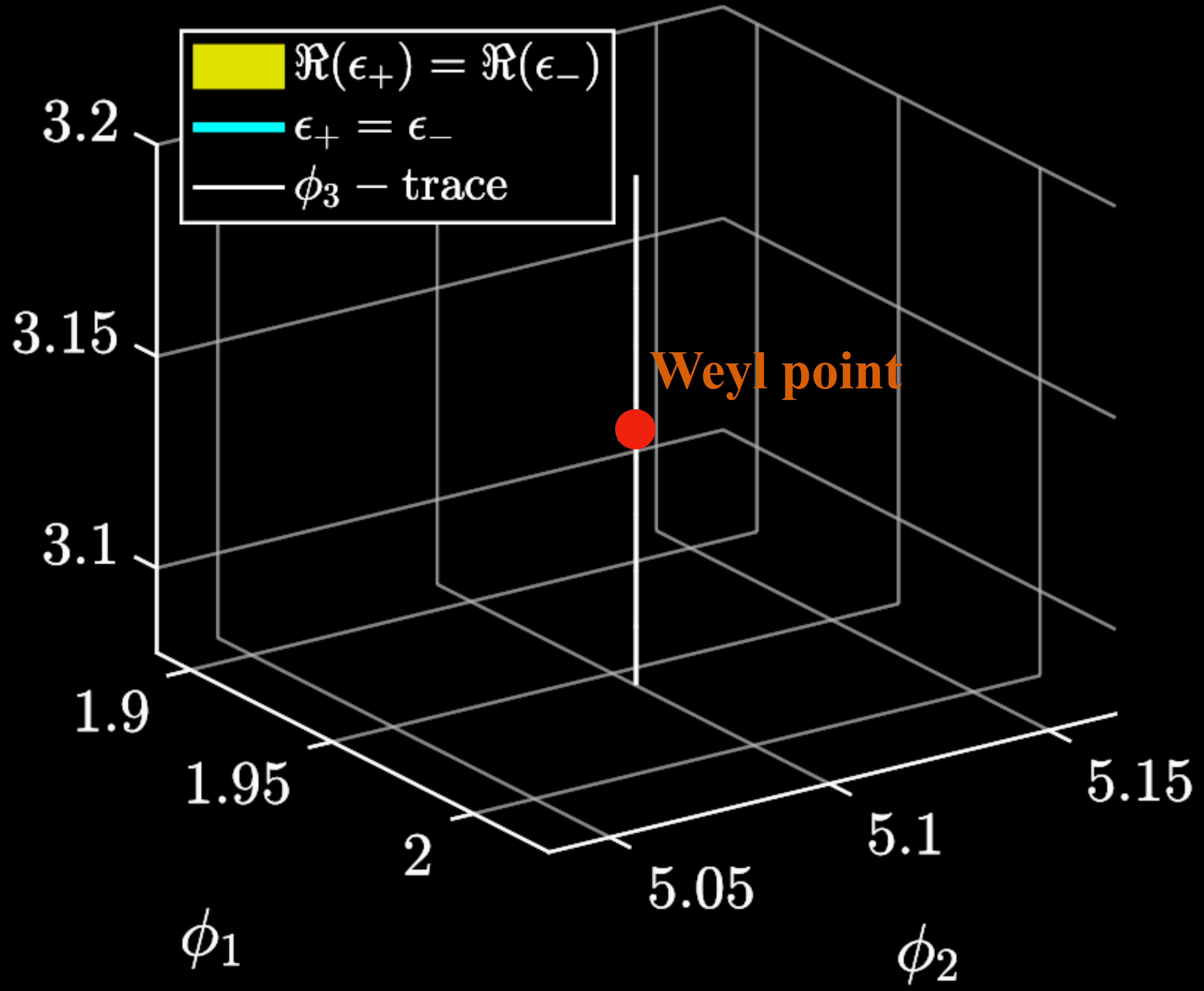

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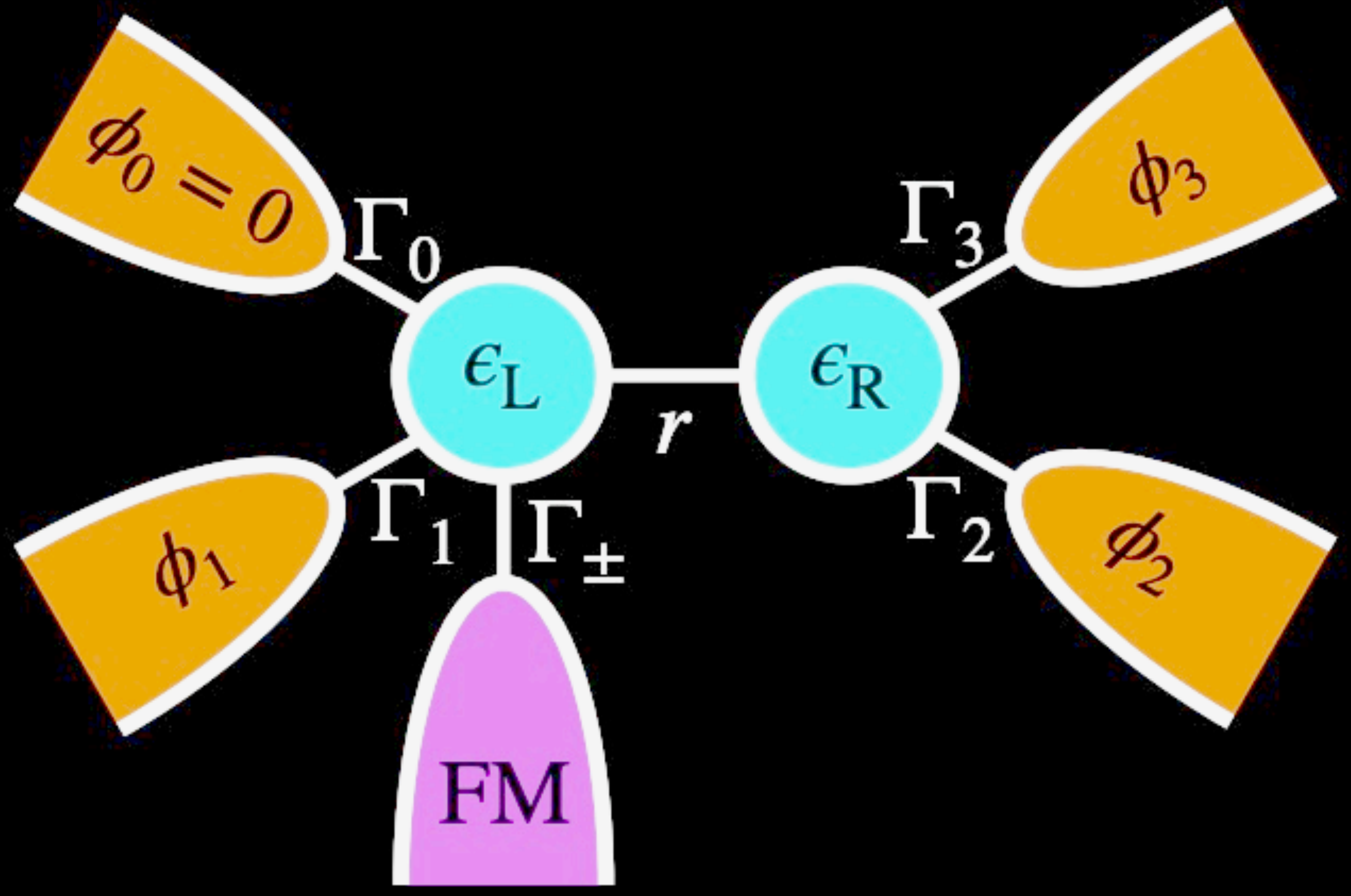

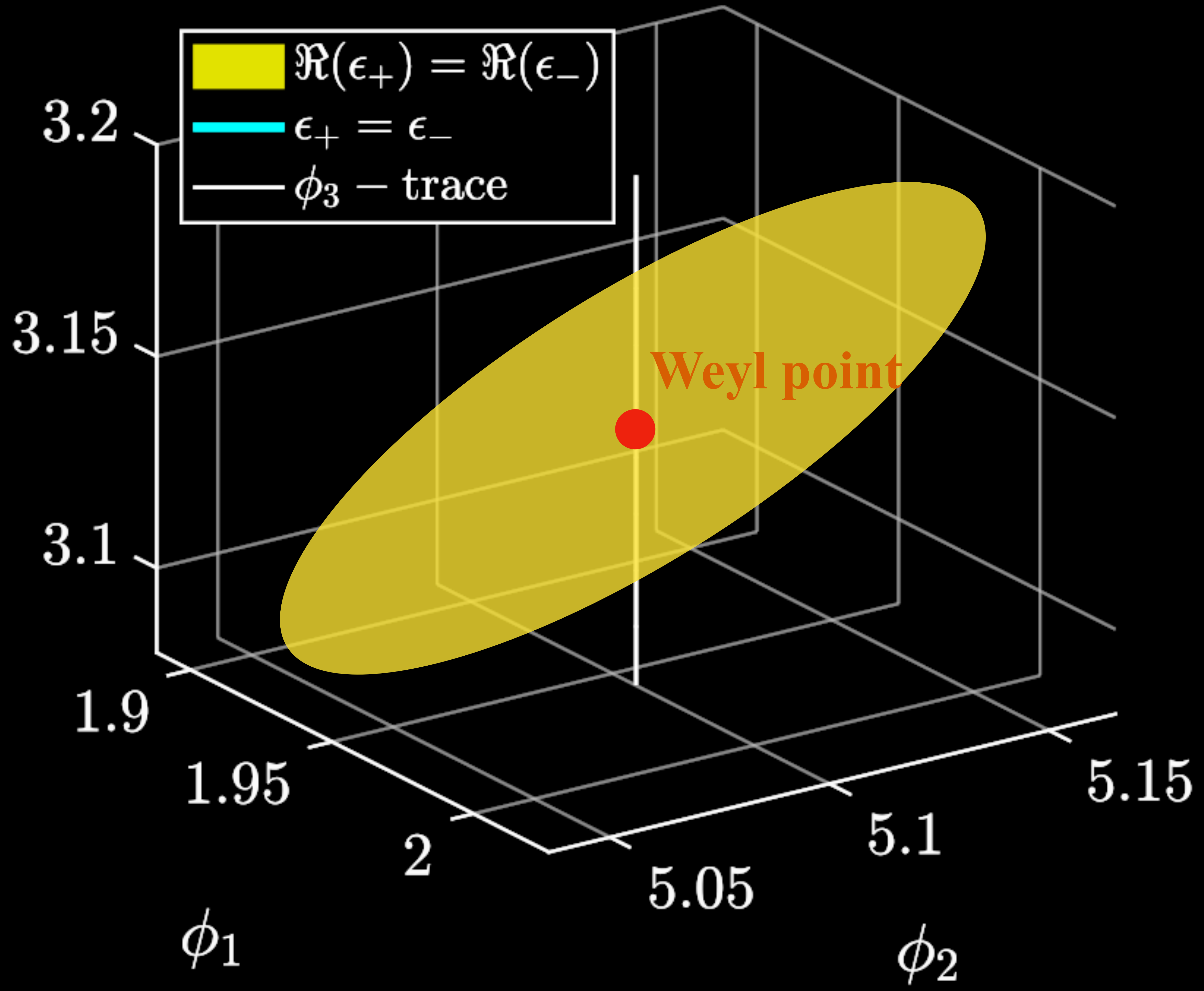

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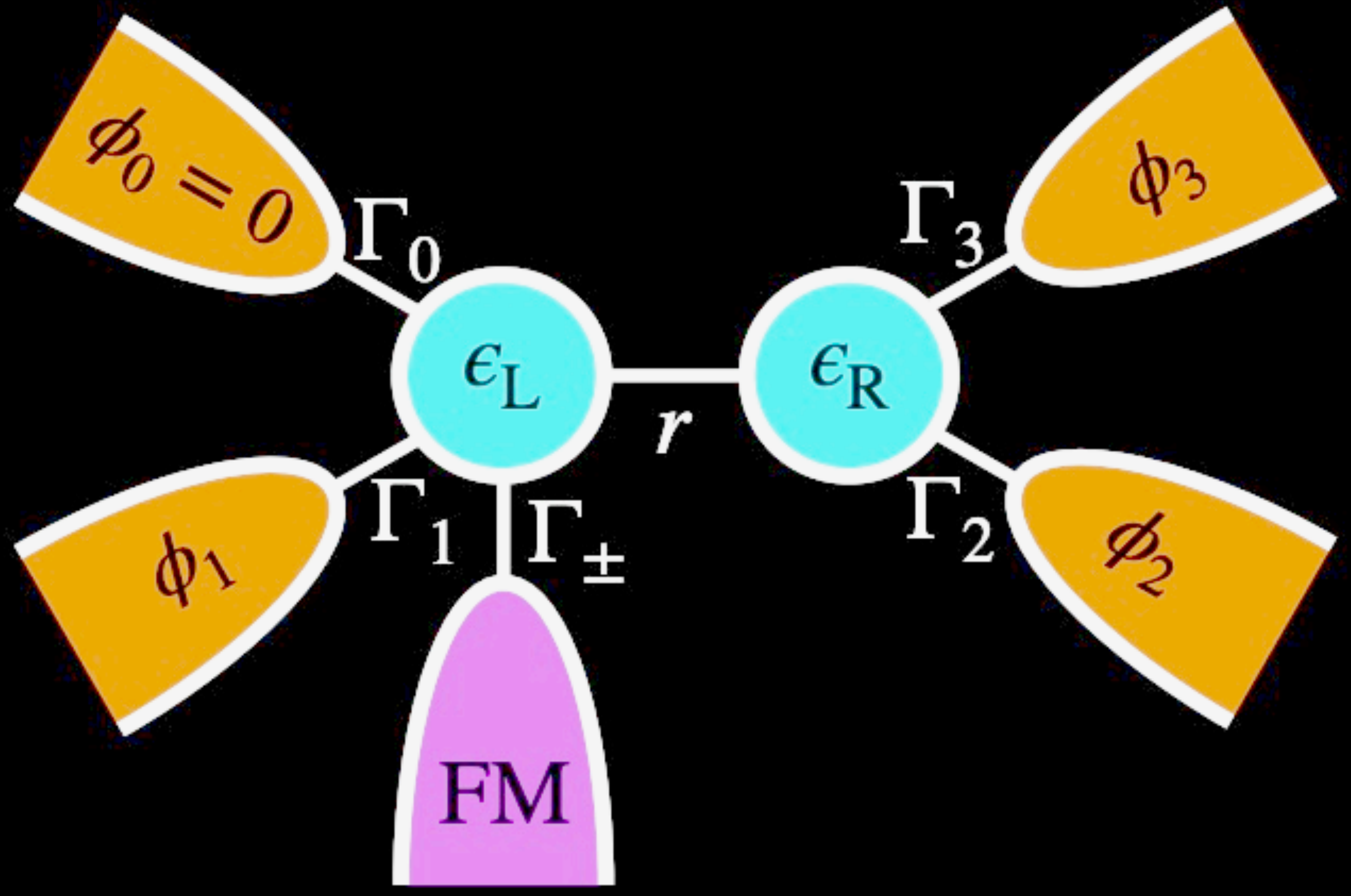
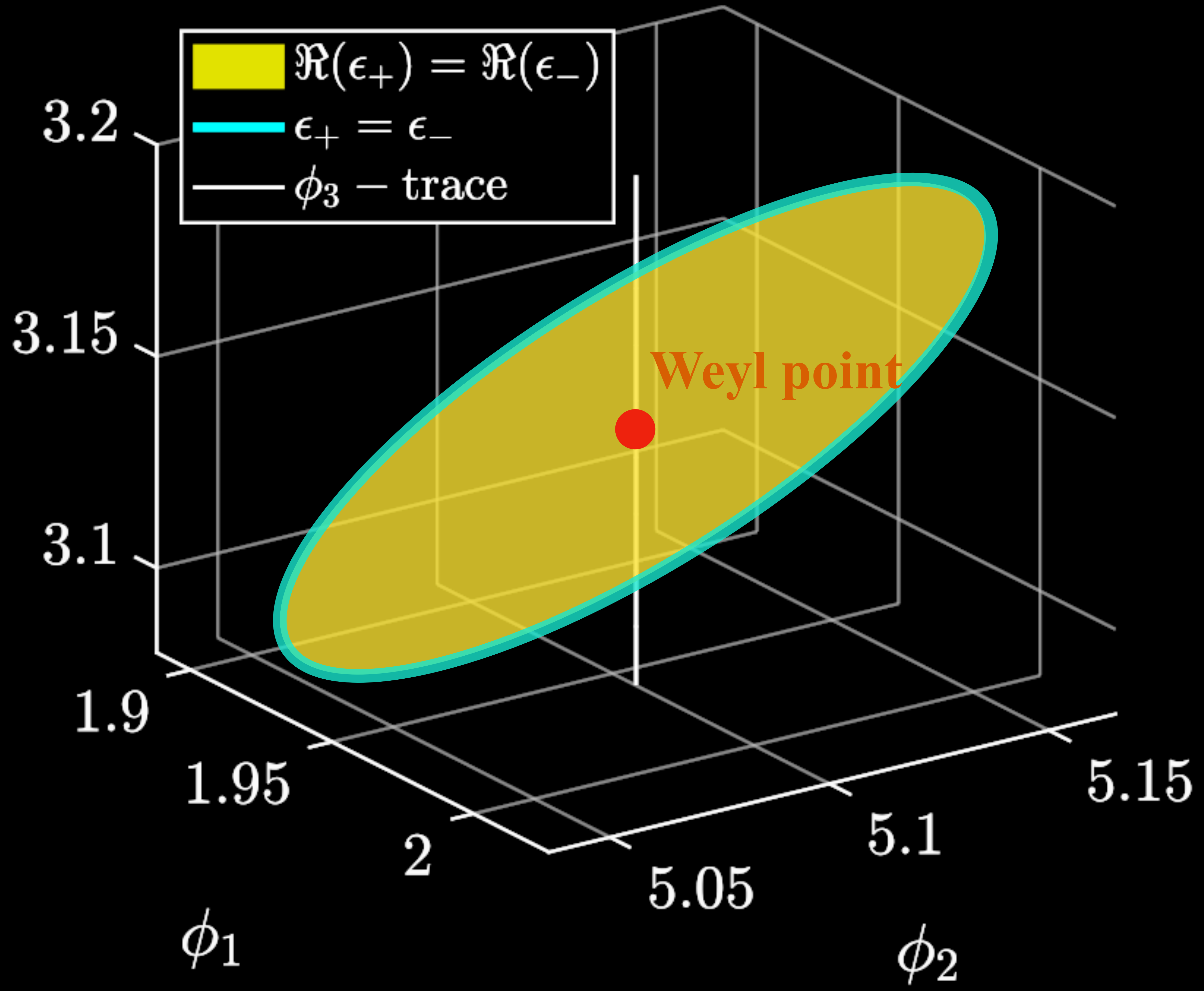


Exceptional Ring



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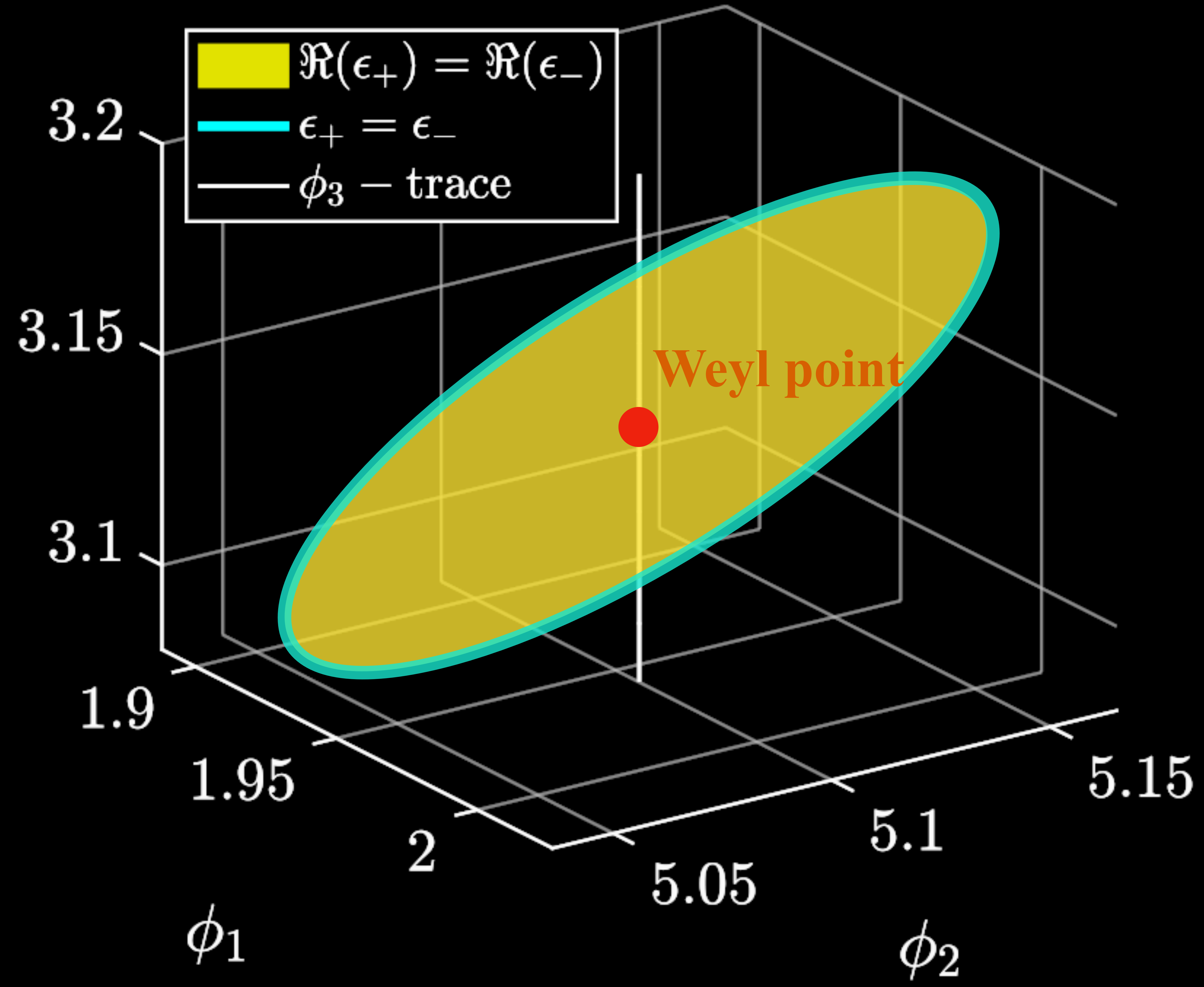
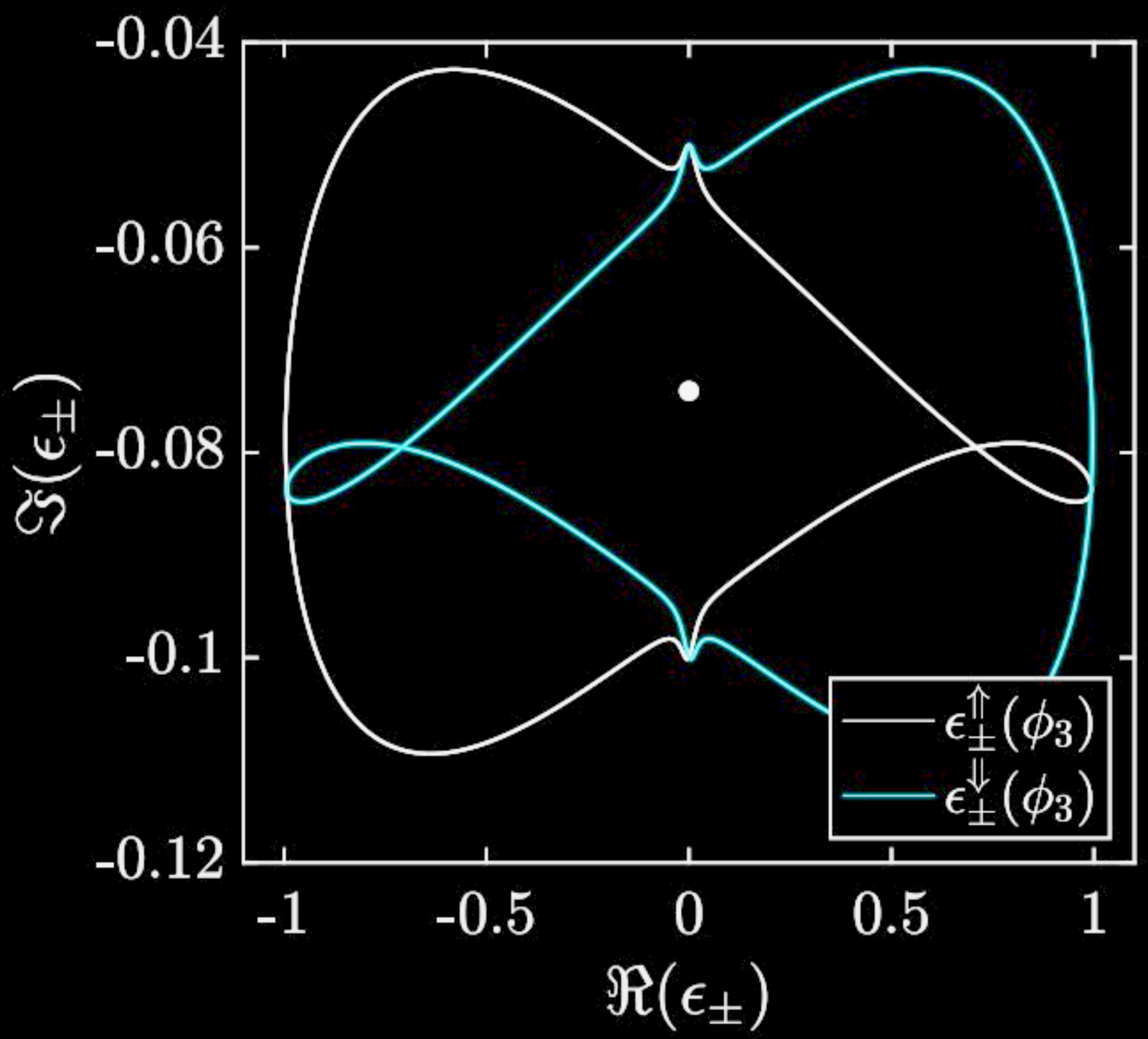


Point Gap



Effective classification parameter

Jeffrey C. Y. Teo and C. L. Kane Phys. Rev. B 82, 115120 (2010), Fan Zhang and C. L. Kane Phys. Rev. B 90, 020501(R) (2014)

Point gap in system with 1 superconducting phase $d_\phi = 1$ ($d_k = 0$)

$$d = d_k - d_\phi \mod 8 = 7$$

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AZ class	Gap	Classifying space	$d=0$	$d=1$	$d=2$	$d=3$	$d=4$	$d=5$	$d=6$	$d=7$
$C^\dagger$	P	$\mathcal{R}_5$	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
	L_r	$\mathcal{R}_6$	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
	L_i	$\mathcal{R}_4$	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0

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$\mathrm{C}^\dagger$	P	$\mathcal{R}_5$	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
	$\mathrm{L_r}$	$\mathcal{R}_6$	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
	$\mathrm{L_i}$	$\mathcal{R}_4$	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0

winding number
NOT allowed

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$\mathrm{C}^\dagger$	P	$\mathcal{R}_5$	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
	$\mathrm{L_r}$	$\mathcal{R}_6$	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
	$\mathrm{L_i}$	$\mathcal{R}_4$	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0

winding number NOT allowed

Break spin-rotation symmetry!

AZ class	Gap	Classifying space	$d=0$	$d=1$	$d=2$	$d=3$	$d=4$	$d=5$	$d=6$	$d=7$
A	P	$\mathcal{C}_1$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
	L	$\mathcal{C}_0$	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0

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$\mathrm{C}^\dagger$	P	$\mathcal{R}_5$	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
	$\mathrm{L_r}$	$\mathcal{R}_6$	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
	$\mathrm{L_i}$	$\mathcal{R}_4$	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0

winding number
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A	P	$\mathcal{C}_1$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
	L	$\mathcal{C}_0$	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0

winding number
allowed!

Conclusion

1) MTJJs are an excellent platform to study engineered (non-hermiticity) topology

Non-hermitian topology in MTJJs
Accepted in PRL: arXiv:2408.01289 (2024)

Topology in three state Andreev Molecule
arXiv:2501.07982 (2025)

2) Refectionless scattering modes are a source of topology in MTJJs

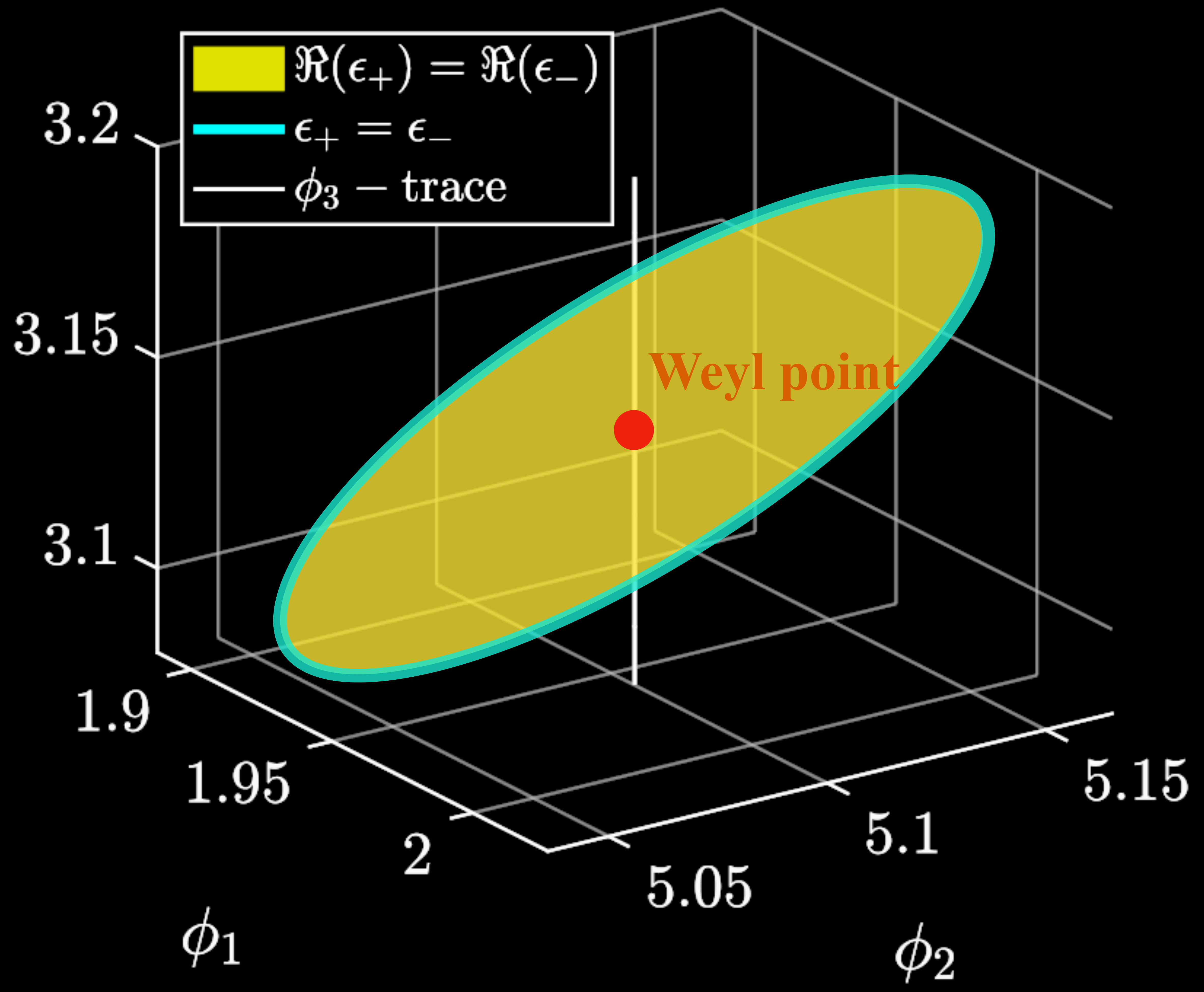
Reflectionless Modes lead to Weyl nodes in MTJJs
arXiv:2503.10874 (2025)

david.ohnmacht@uni-konstanz.de

Thank you!

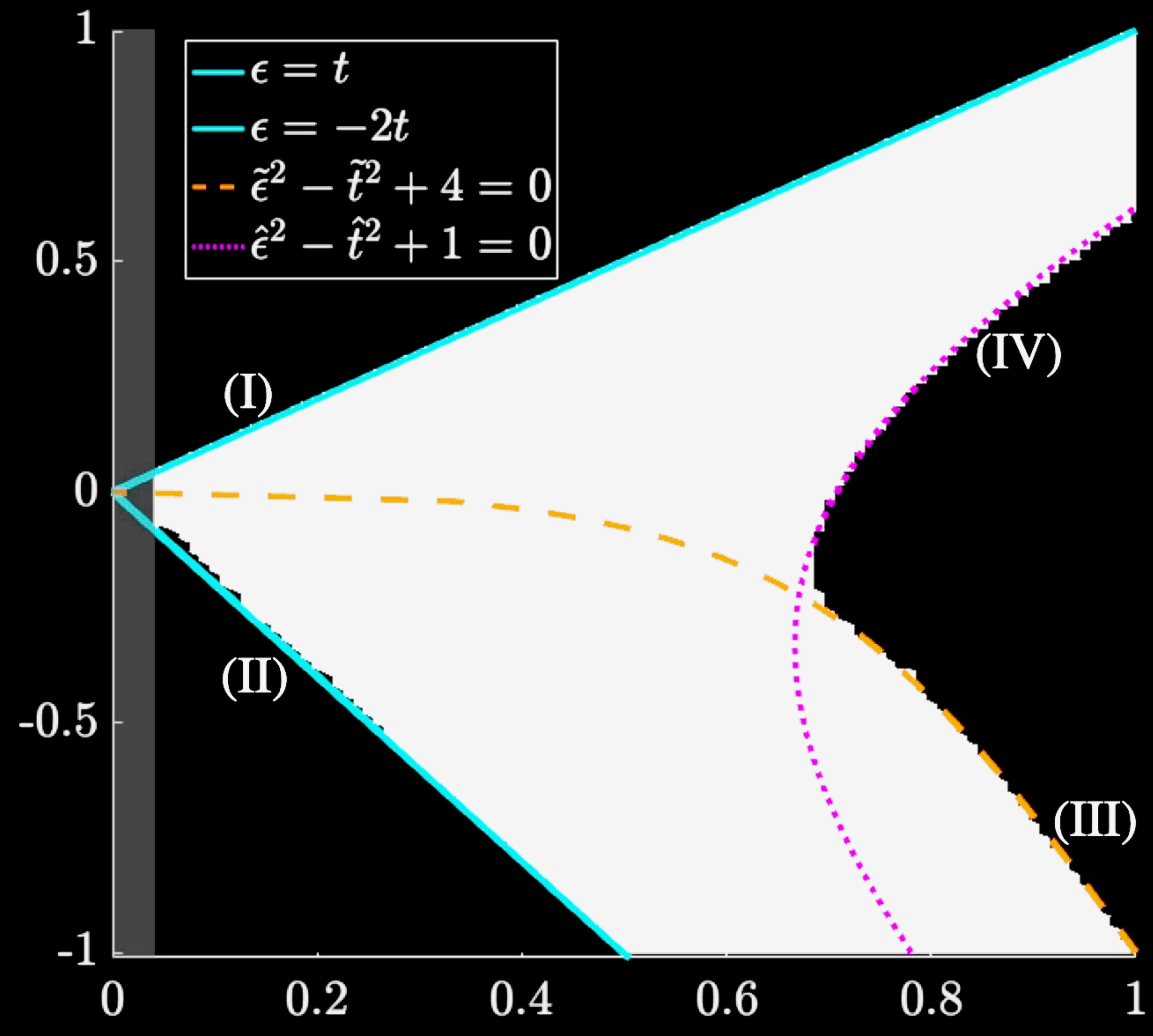
Non-hermitian topology in MTJJs

D. C. Ohnmacht, et. al., arXiv:2408.01289 (2024) (accepted in PRL)



Reflectionless modes as a source of Weyl nodes in multiterminal Josephson junctions

D. C. Ohnmacht, et. al., arXiv:2503.10874 (2025)



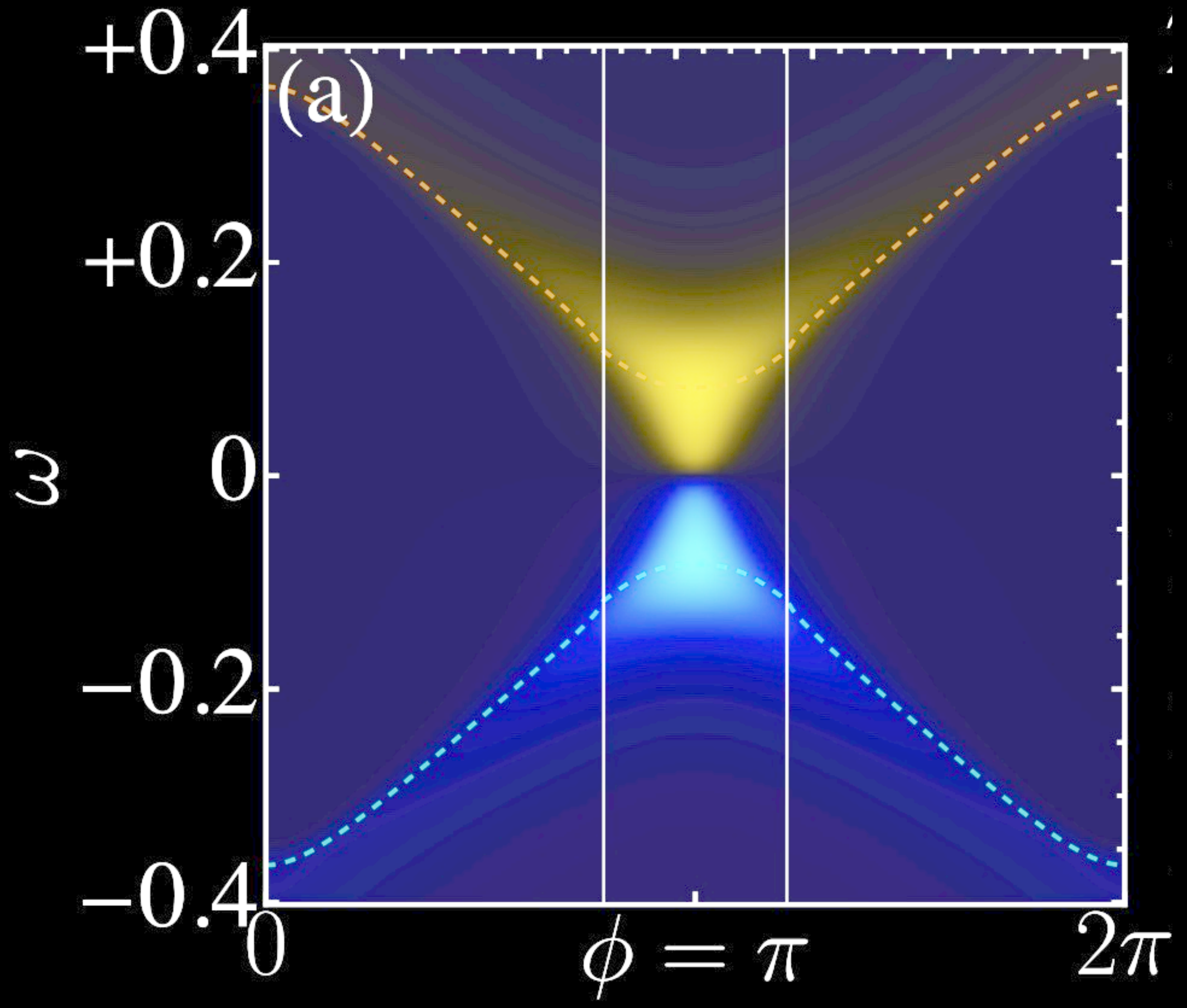
Why care about non-Hermiticity and (MT)JJs?

Non-hermitian topology generalisation of hermitian topology

Enhanced sensing, undirectional laser, bulk-fermi arcs, …

Superconductors offer tuneability via superconducting phases

Measurability in current susceptibility



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Making sense of effective dimensions

RESEARCH ARTICLE | MAY 14 2009

Periodic table for topological insulators and superconductors

Alexei Kitaev

AIP Conf. Proc. 1134, 22–30 (2009)
https://doi.org/10.1063/1.3149495

The Hamiltonian of a translationally invariant systems can be written in the momentum representation:

$$\hat{H} = \frac{i}{4}\sum_{\mathbf{p}}\sum_{j,k} A_{jk}(\mathbf{p})\hat{c}_{-\mathbf{p},j}\hat{c}_{\mathbf{p},k}, \qquad (19)$$

where j and k refer to particle flavors. The matrix $A(\mathbf{p})$ is skew-Hermitian but not real; it rather satisfies the condition $A_{jk}(\mathbf{p})^* = A_{jk}(-\mathbf{p})$. By abuse of terminology, such matrix-valued functions are called "functions from $\bar{\mathbb{R}}^d$ to real skew-symmetric matrices", where $\bar{\mathbb{R}}^d$ is the usual Euclidean space with the involution $\mathbf{p} \leftrightarrow -\mathbf{p}$ (cf. [29]).

By a *real vector bundle* over the *real space* X we mean a complex vector bundle E over X which is also a real space and such that

(i) the projection $E \to X$ is real (i.e. commutes with the involutions on E, X);

(ii) the map $E_x \to E_{\bar{x}}$ is anti-linear, i.e. the diagram

$$\begin{array}{ccc} \mathbf{C}\times E_x & \to & E_x \\ \downarrow & & \downarrow \\ \mathbf{C}\times E_{\bar{x}} & \to & E_{\bar{x}} \end{array}$$

commutes, where the vertical arrows denote the involution and $\mathbf{C}$ is given its standard real structure $(\tau(z) = \bar{z})$.

Normally, symmetries defined by

$$U_C H_i^*(k) U_C^{-1} = -H_i(-k)$$

But phase is **unusual** dimension:

$$U_C H_i^*(\phi) U_C^{-1} = -H_i(+\phi)$$

$\Rightarrow$ Phase is "just" a parameter

Solution: Effective Parameter

Effective classification parameter

$$d = d_k - d_\phi \bmod 8 = \begin{cases} 0 \ , \ d_k = d_\phi = 0 \\ 7 \ , \ d_k = 0 \ , \ d_\phi = 1 \end{cases}$$

Jeffrey C. Y. Teo and C. L. Kane Phys. Rev. B 82, 115120 (2010)
Fan Zhang and C. L. Kane Phys. Rev. B 90, 020501(R) (2014)

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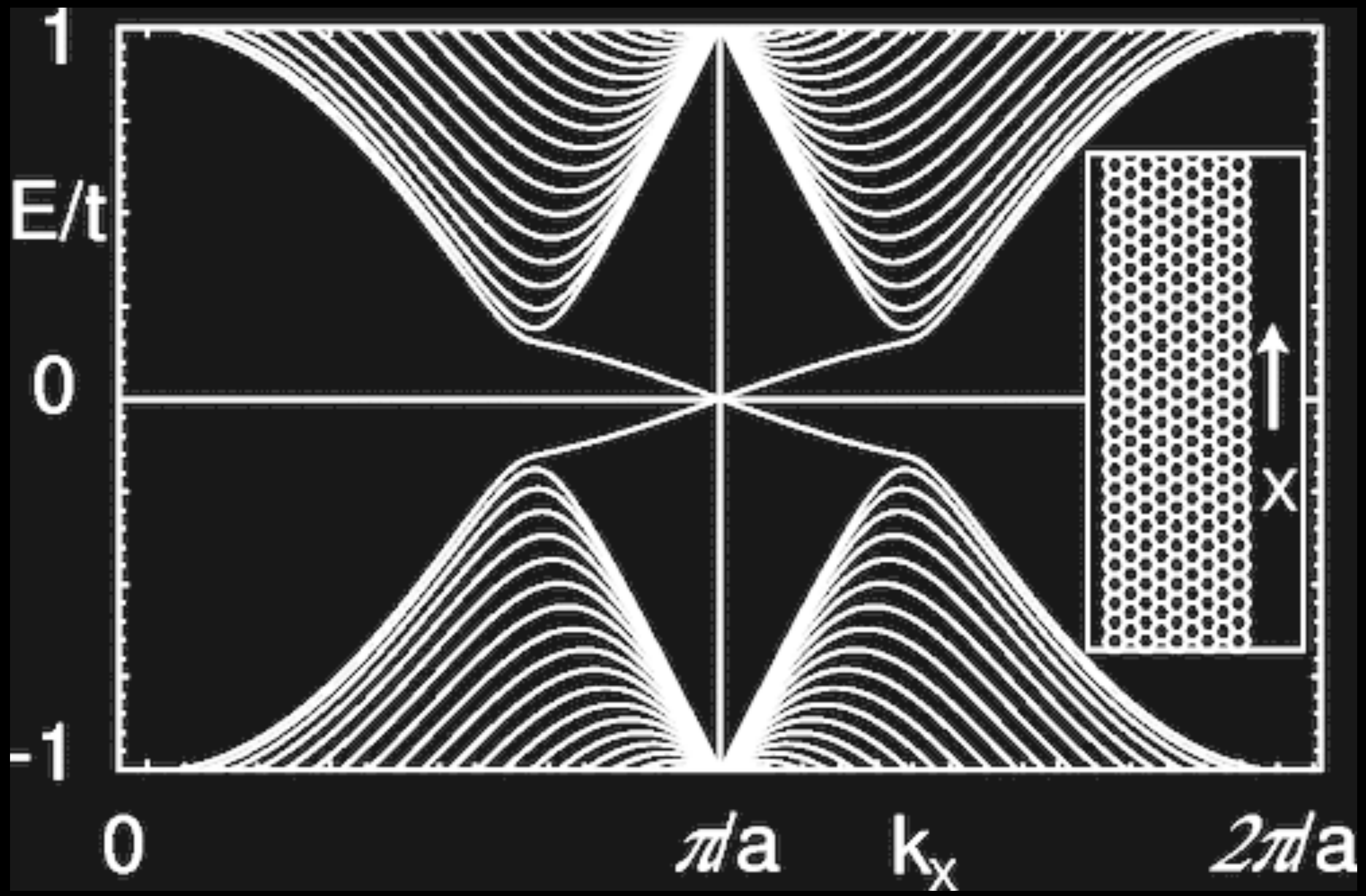
	L	$\mathcal{C}_0$	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0

winding number NOT allowed

winding number allowed!

Why care about topology?

Topological Phases of Matter



C. L. Kane and E. J. Mele Phys. Rev. Lett. 95, 226801 (2005)
König, M. et al. Science 318, 766–770 (2007)

Fundamental Insights into Symmetry and Topology

Class	T	C	S	1	2	3
A	0	0	0	0	$\mathbb{Z}$	0
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$
AI	1	0	0	0	0	0
BDI	1	1	1	$\mathbb{Z}$	0	0
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0
DIII	-1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
AII	-1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$

Altland and M. R. Zirnbauer, Phys. Rev. B 55, 1142 (1997)
Andreas P. Schnyder, et. al., Phys. Rev. B 78, 195125 (2008)

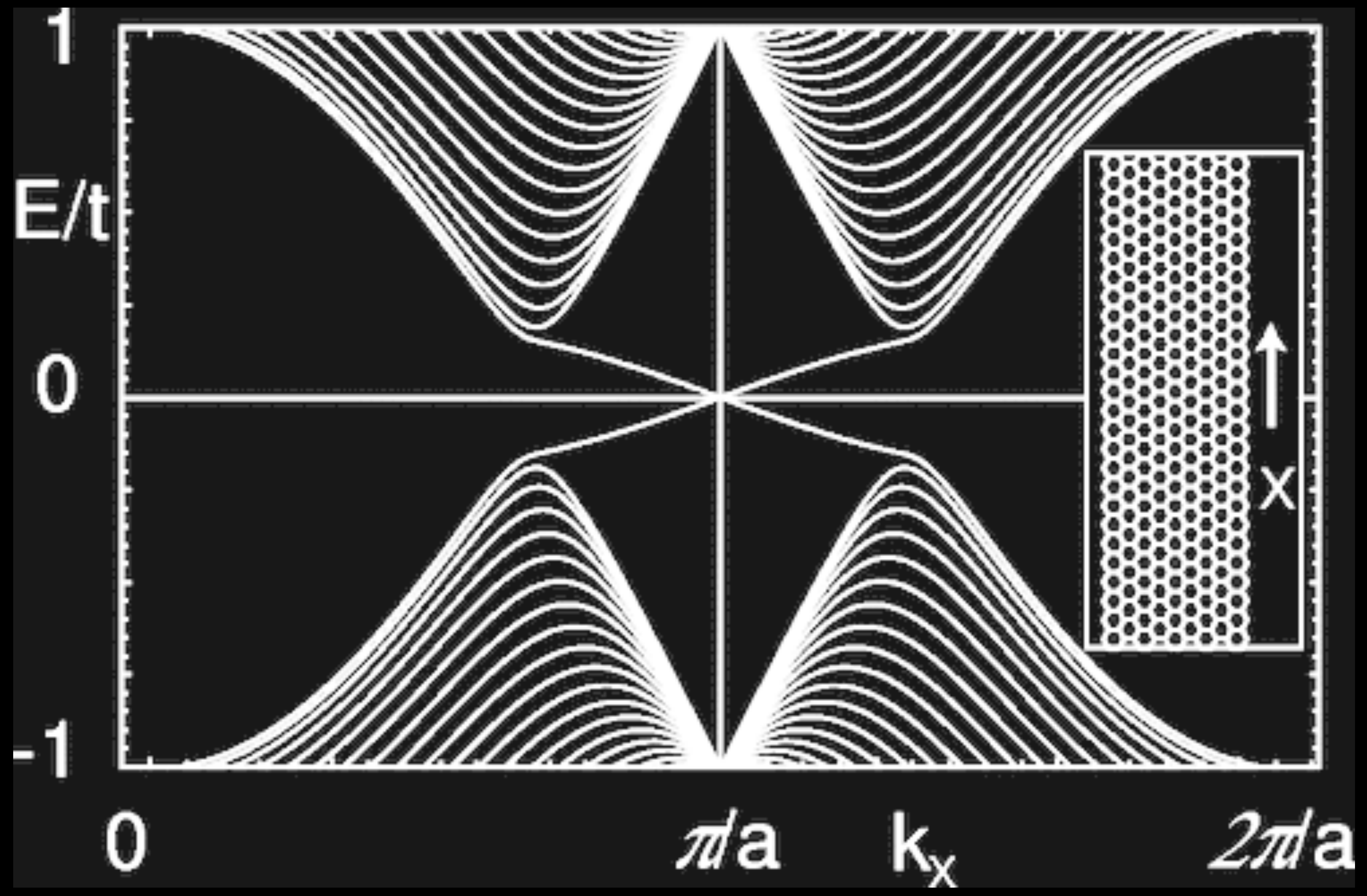
Stability Against Perturbations

Applications in Quantum Computing and Electronics

…

Why care about topology?

Topological Phases of Matter



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D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0
DIII	-1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
AII	-1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$

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Stability Against Perturbations

Applications in Quantum Computing and Electronics

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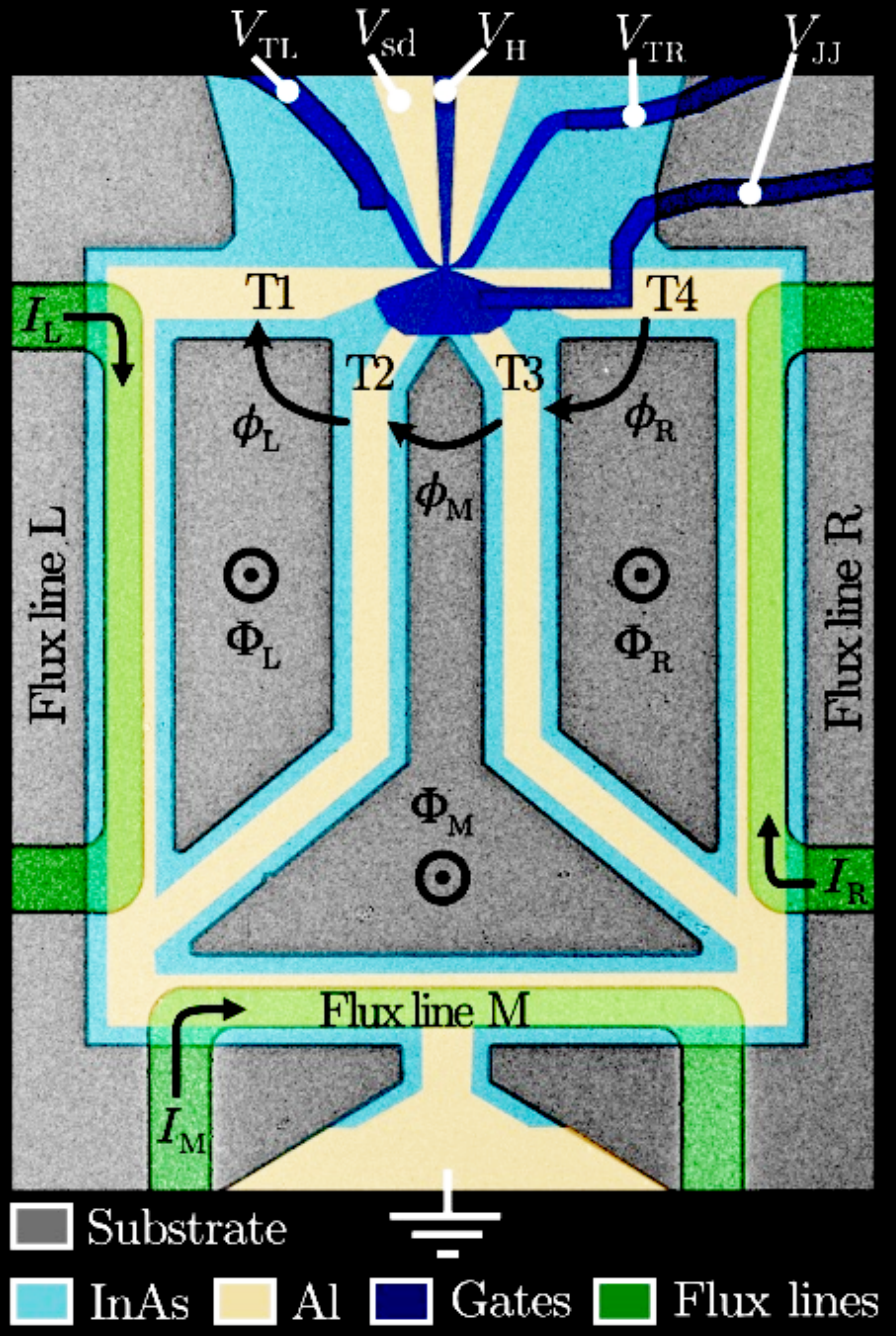
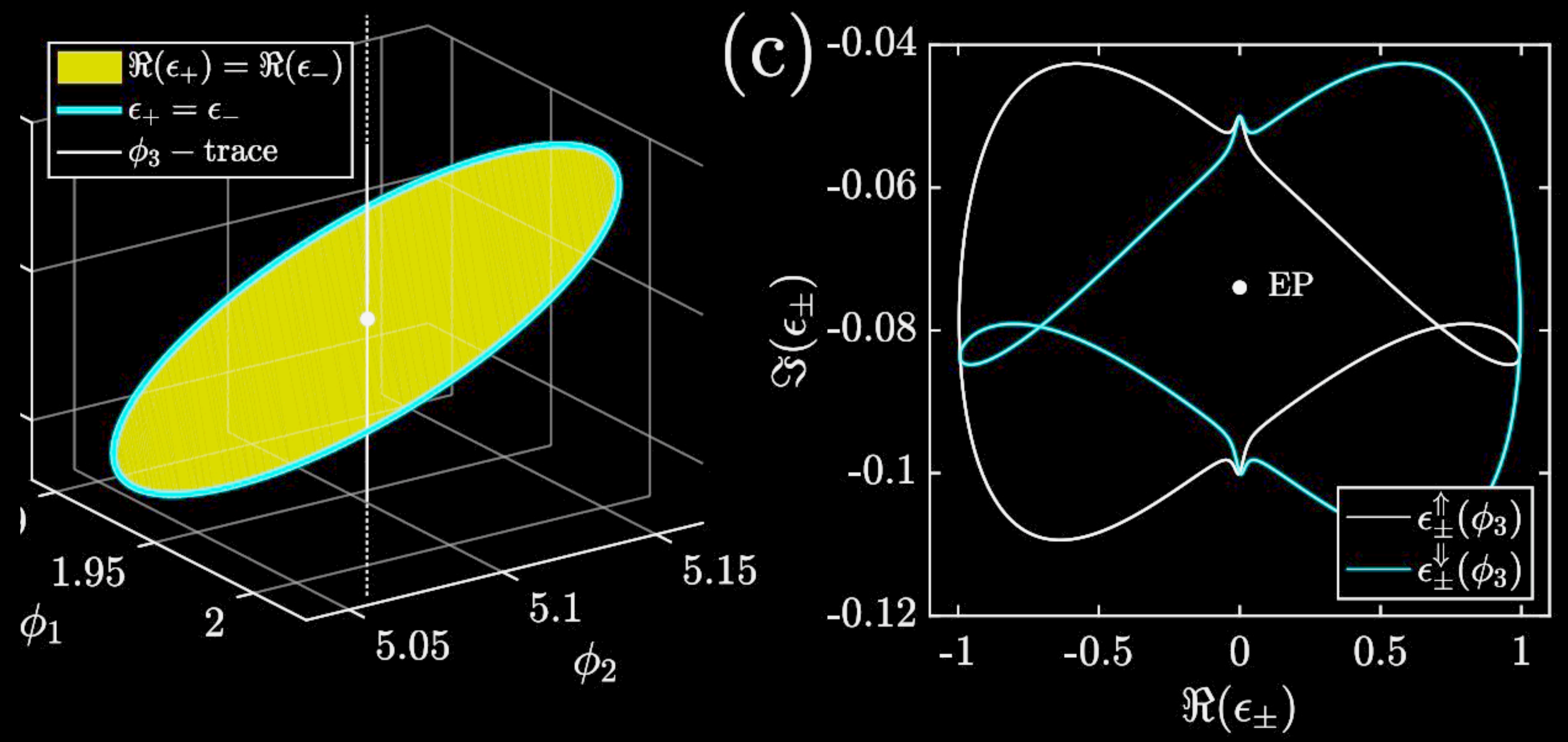
Thank you!

4-terminal MTJJ



MTJJ as non-herm. top. matter



arXiv:2408.01289 (2024)

Reflectionless Modes