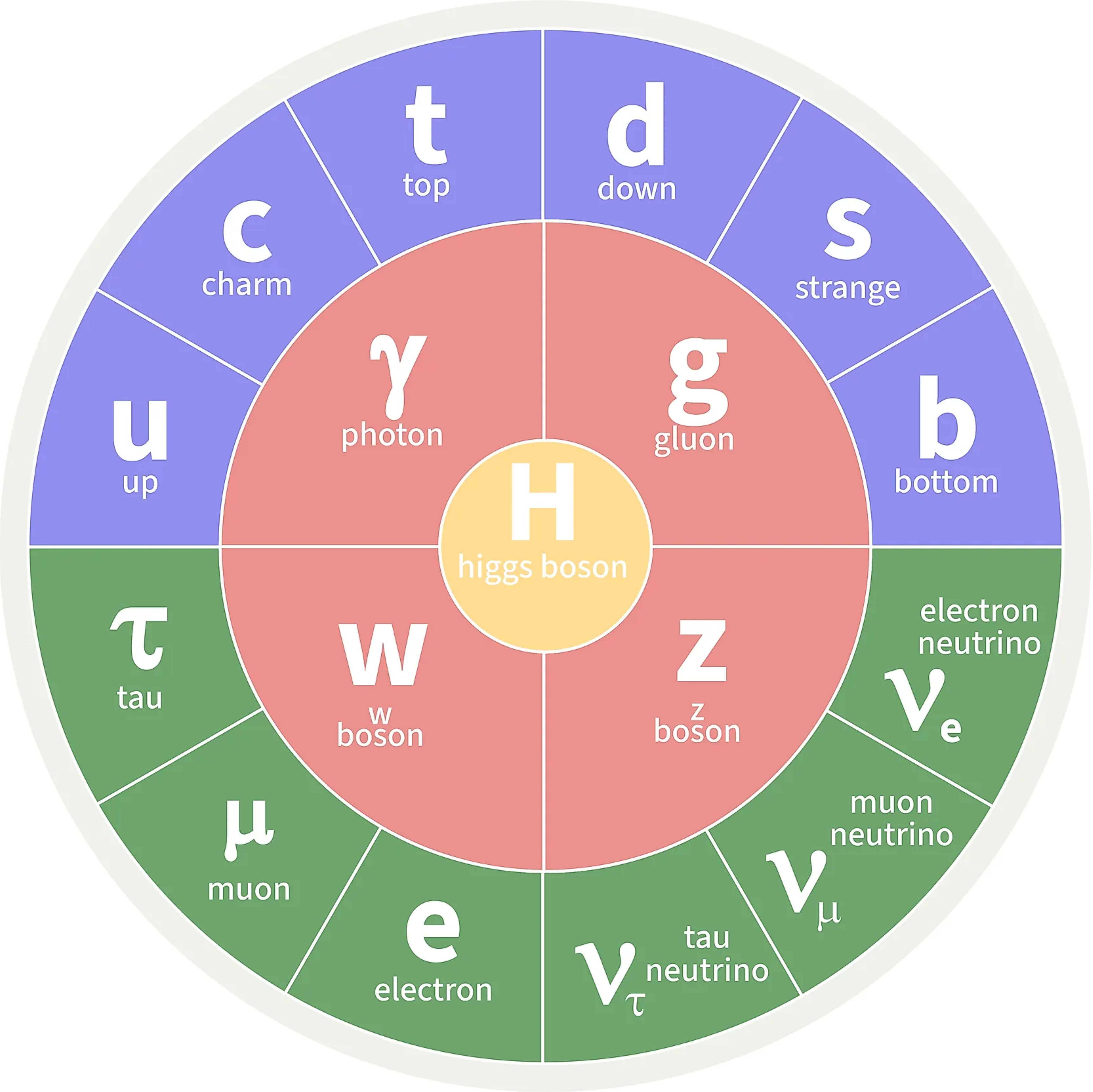
Baryogenesis in an Axiverse

David Cyncynates, ICTP Trieste

Based on [2511.XXXXX] and [26XX.XXXXX] with Pouya Asadi & Stefania Gori

TeVPA 2025



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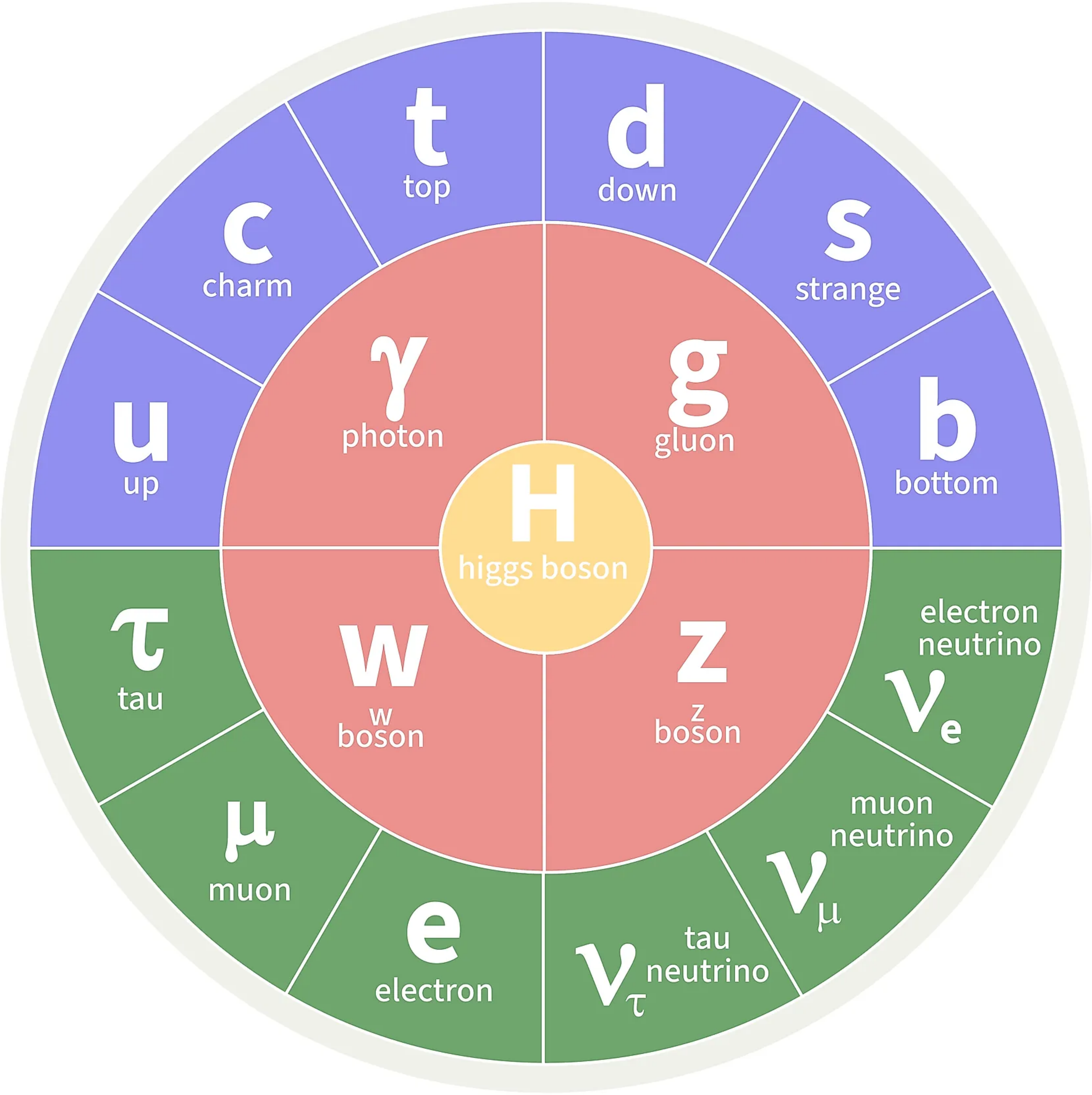

Cosmological constant

Gauge hierarchy

Flavor

Strong CP

Dark Matter

Baryon asymmetry

Quantum gravity

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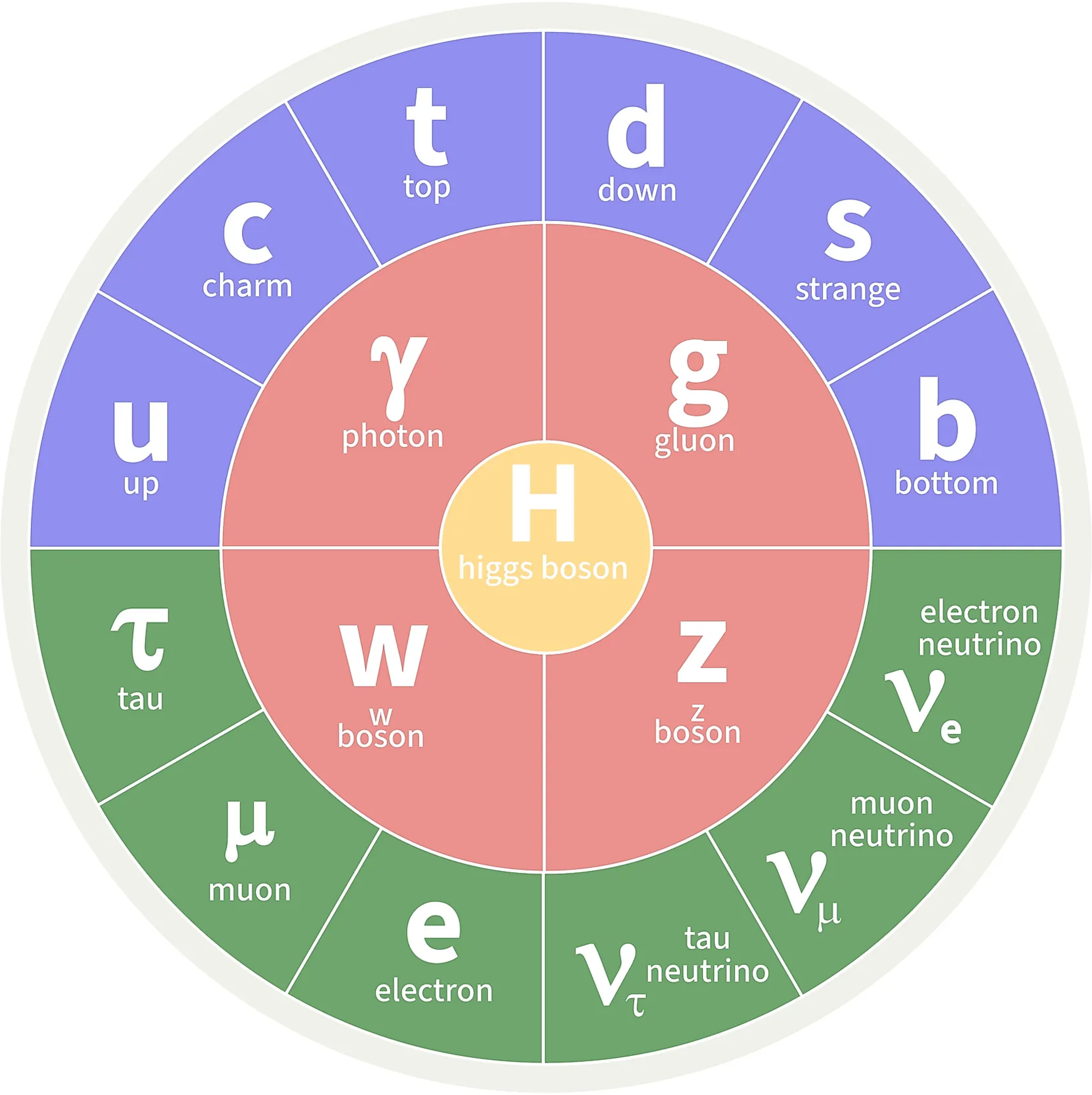

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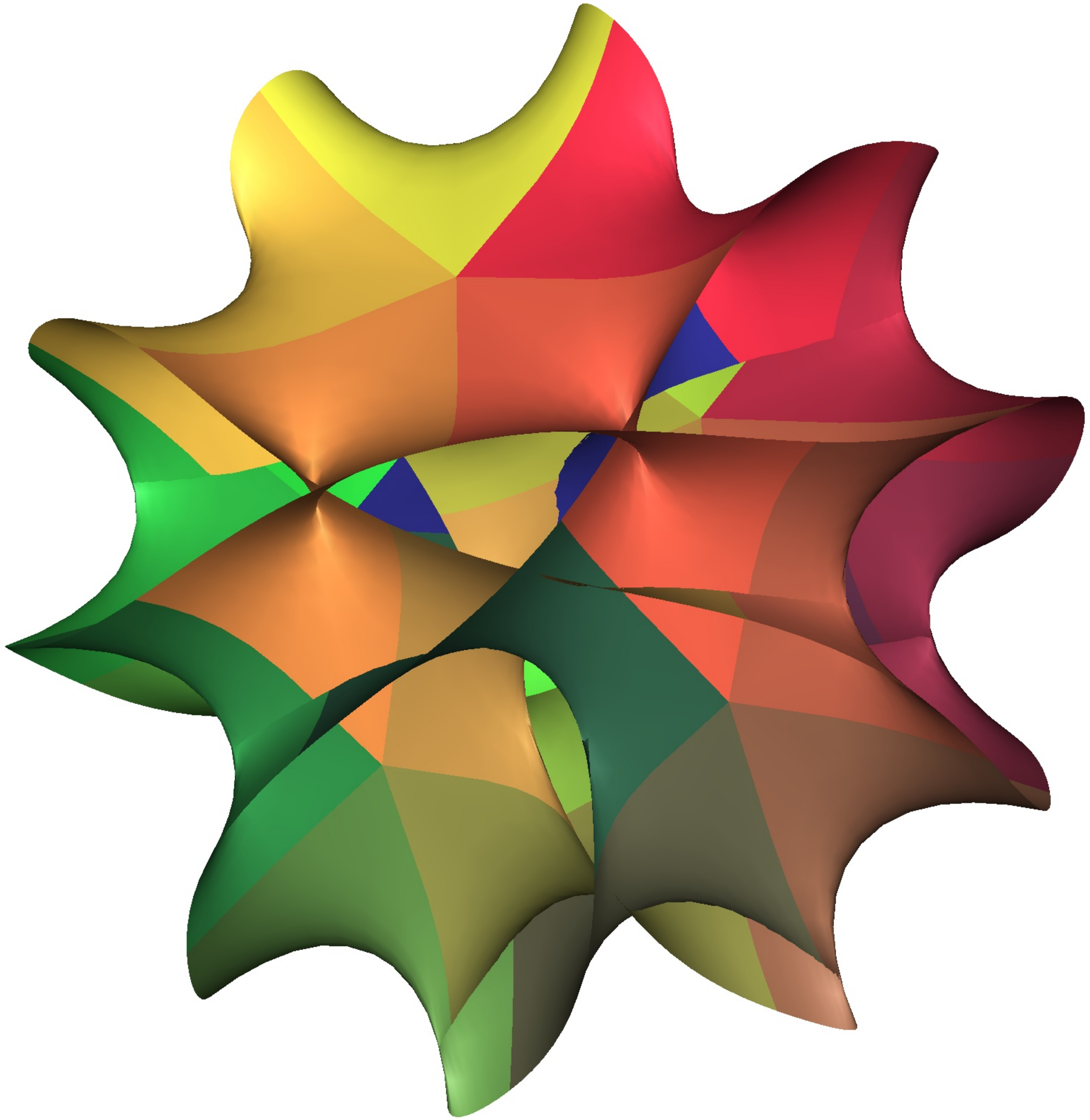

ICTP Trieste

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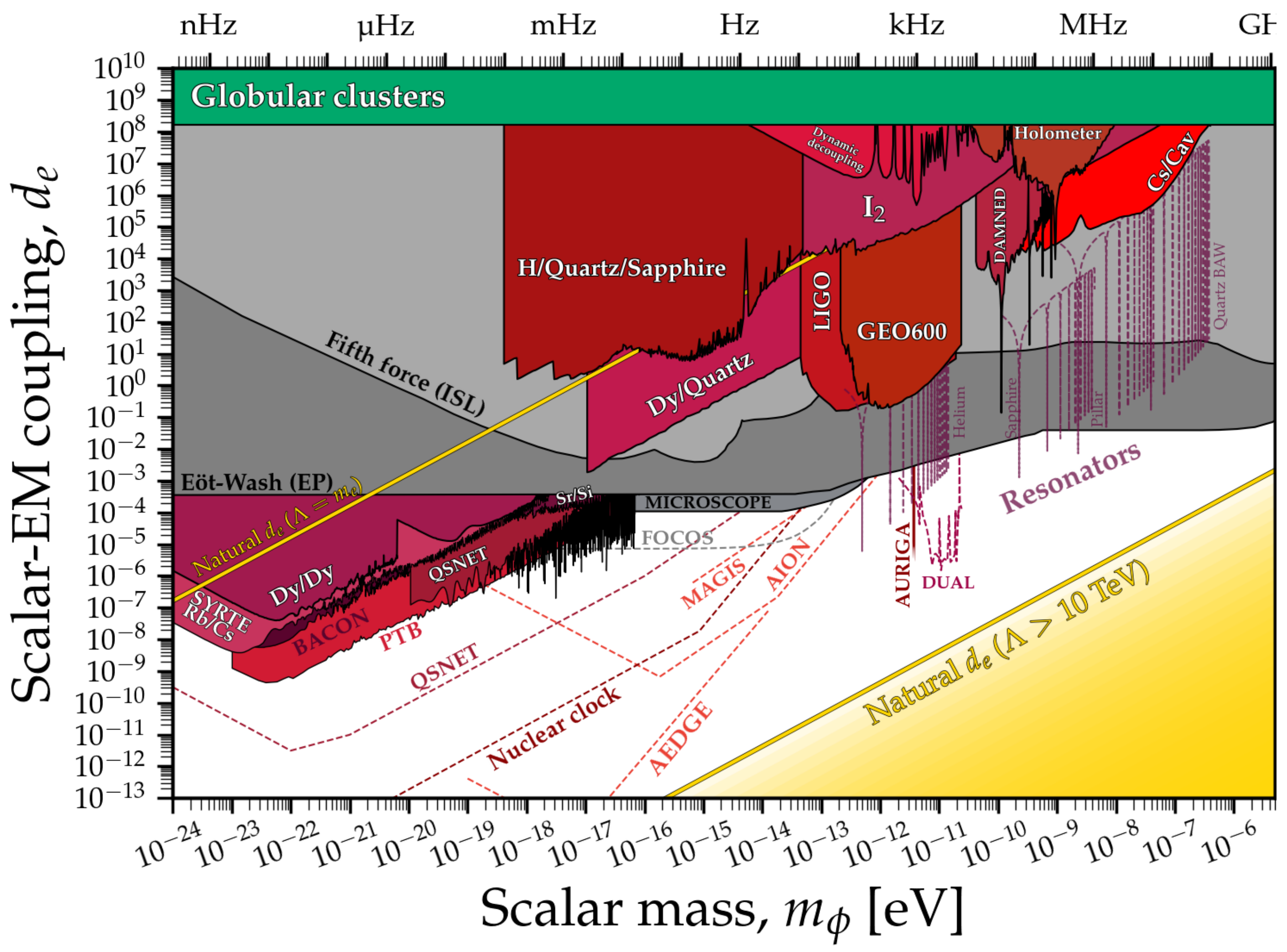

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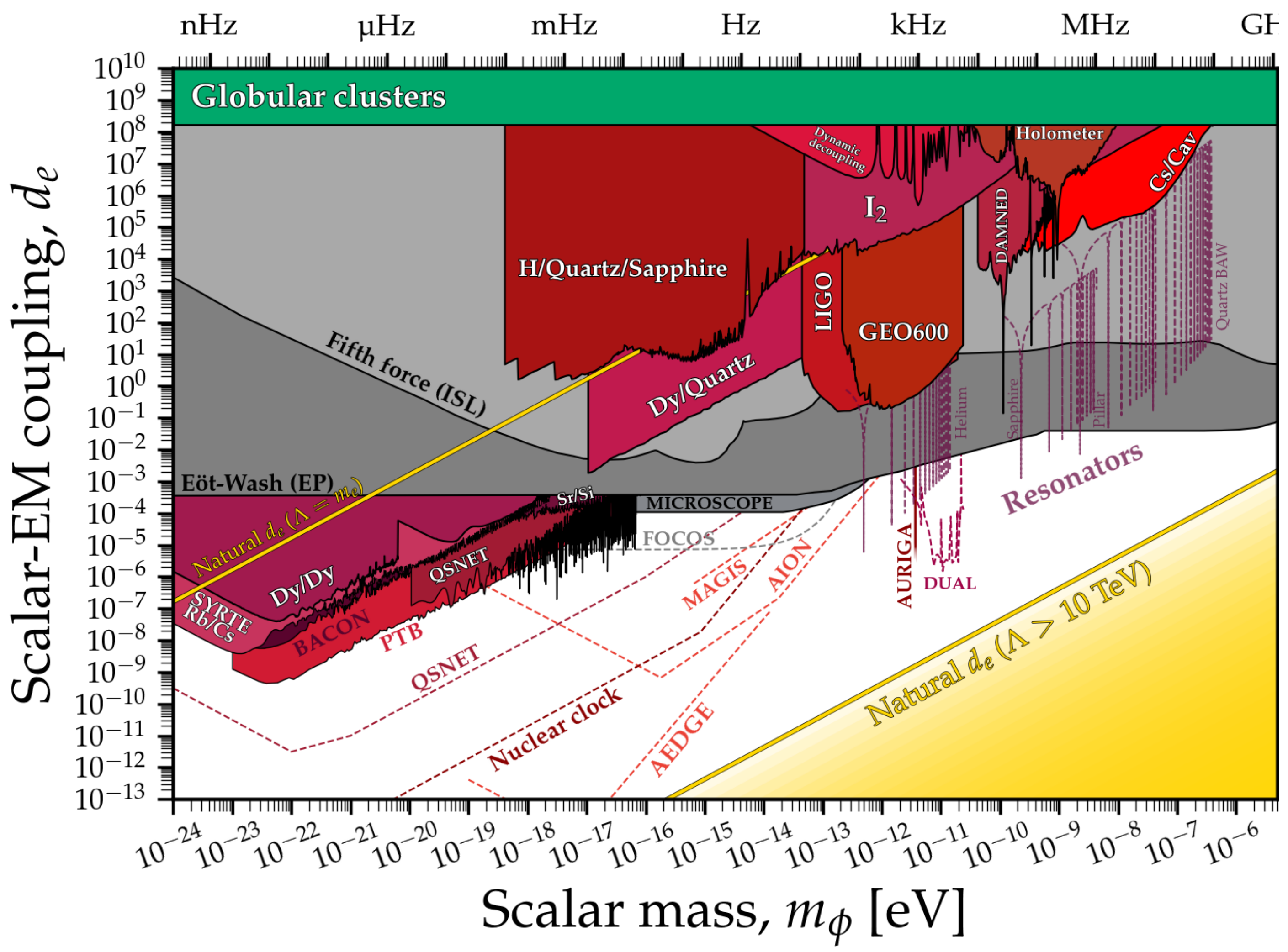

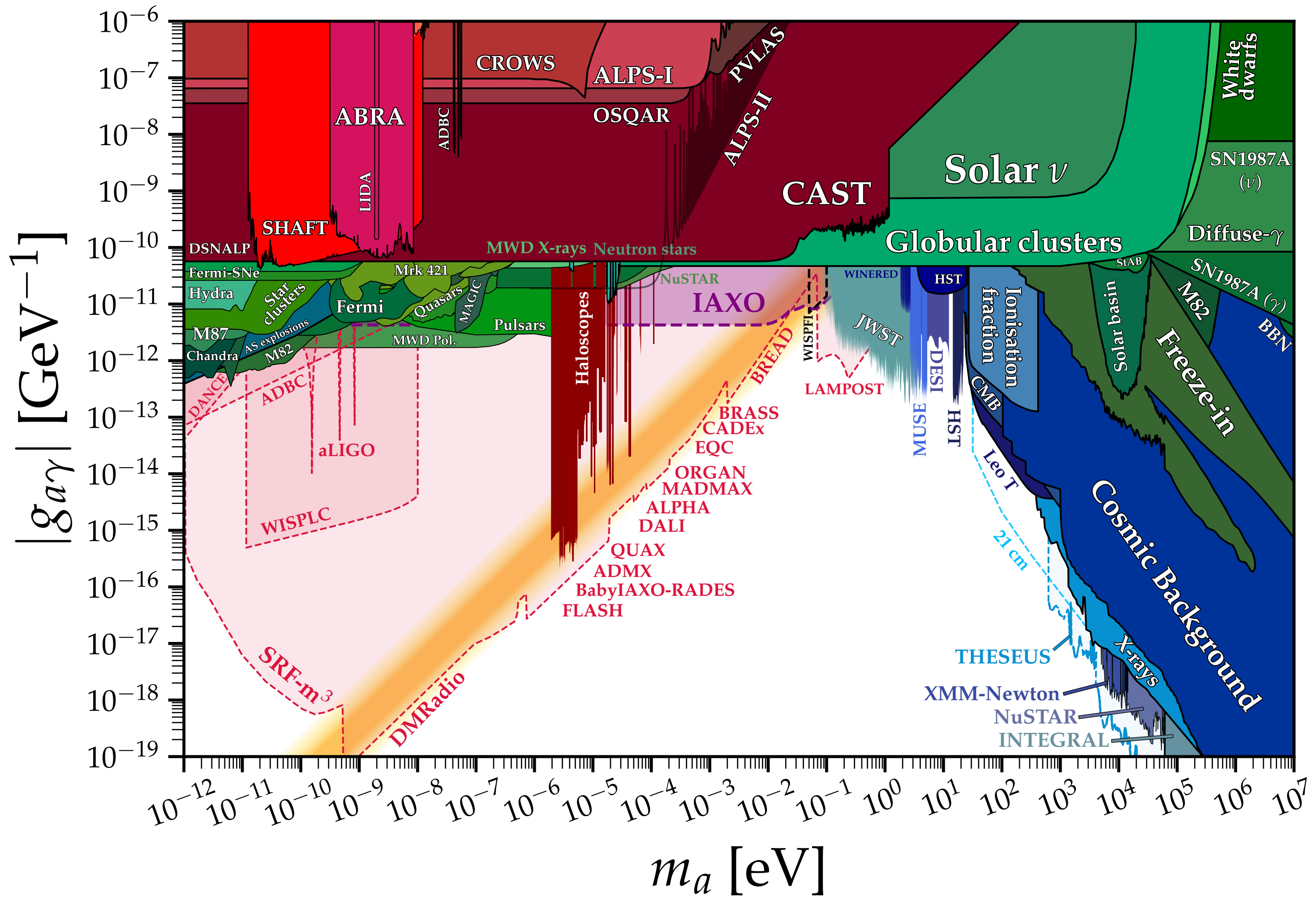

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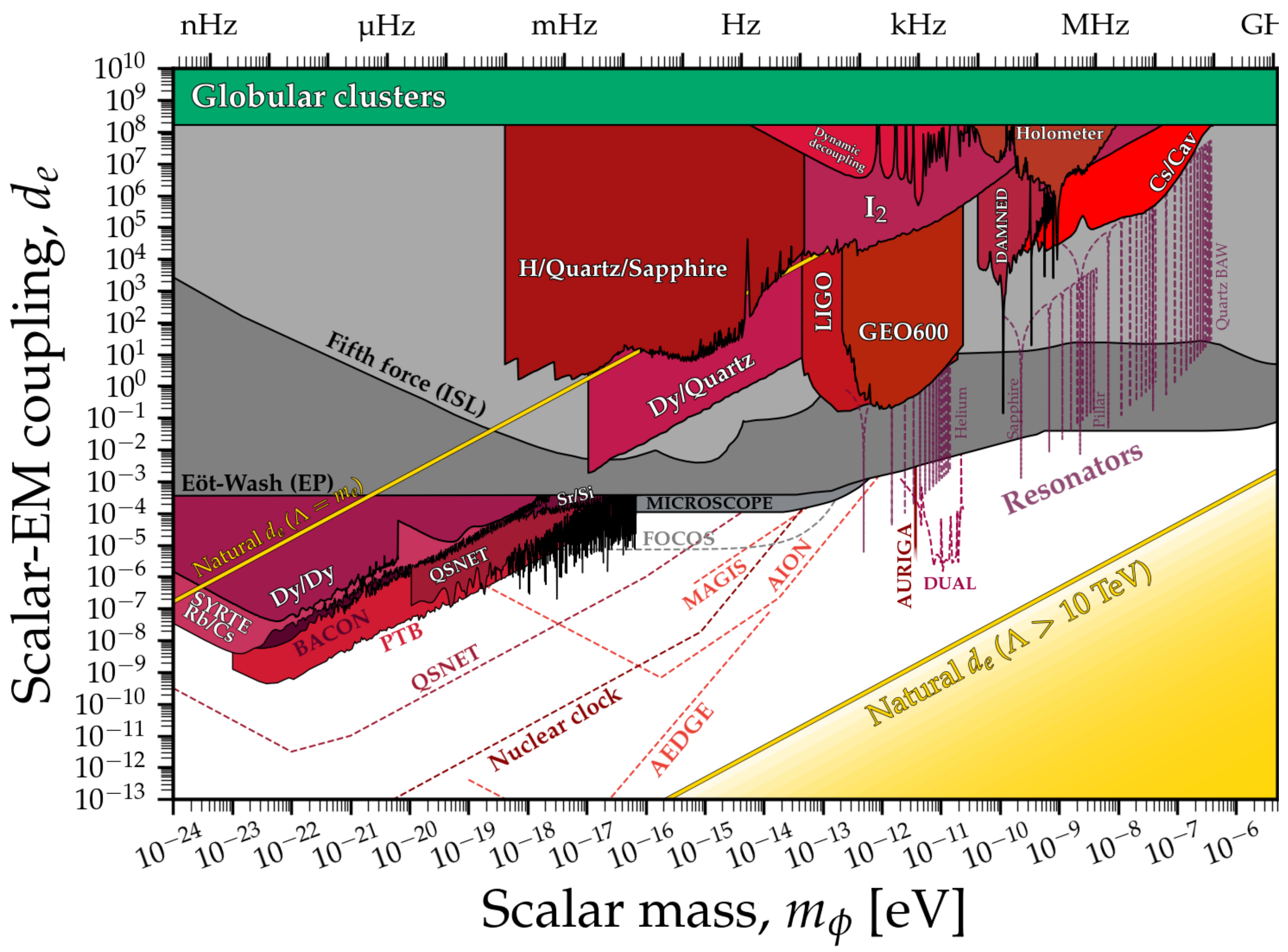

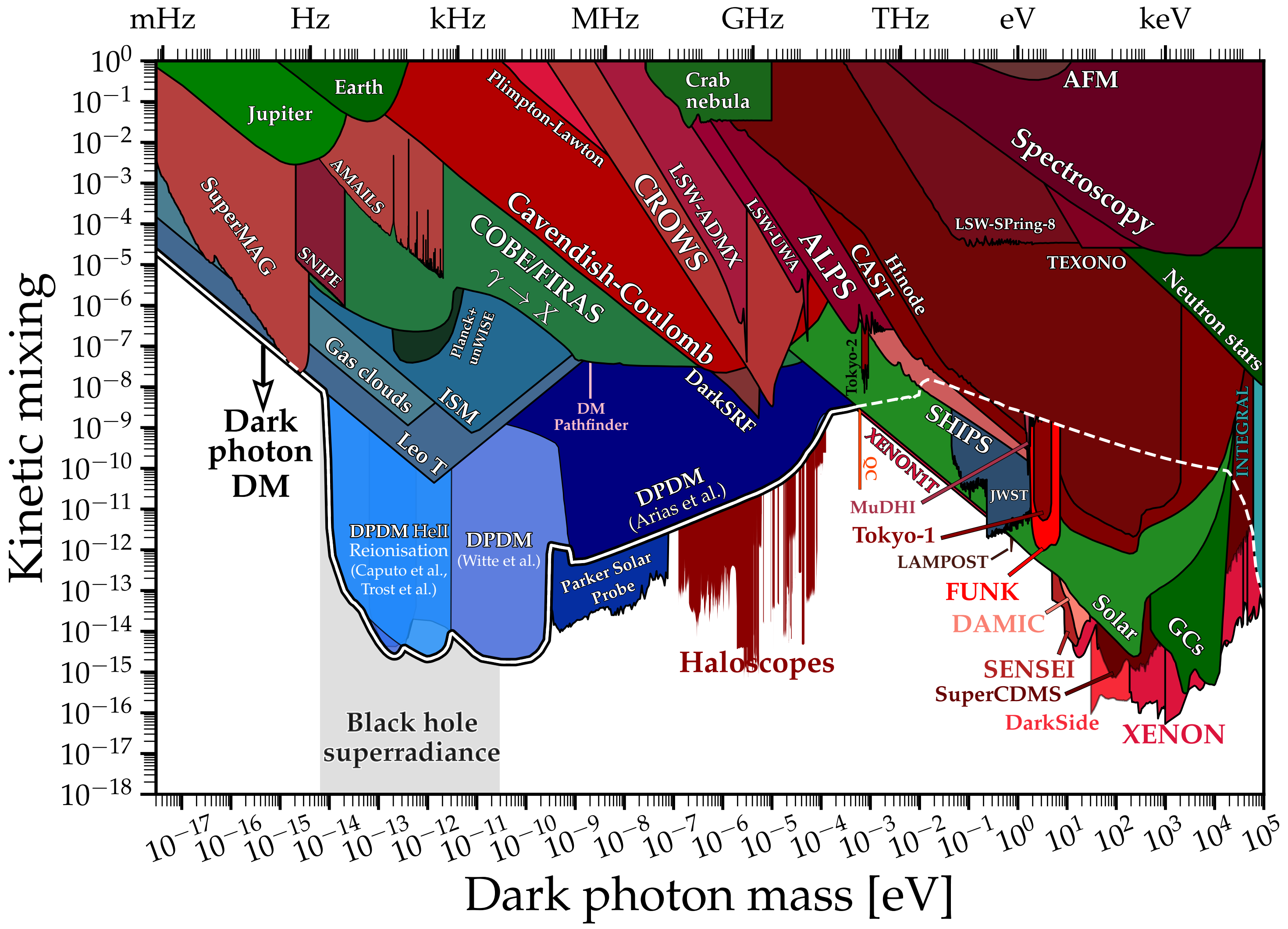

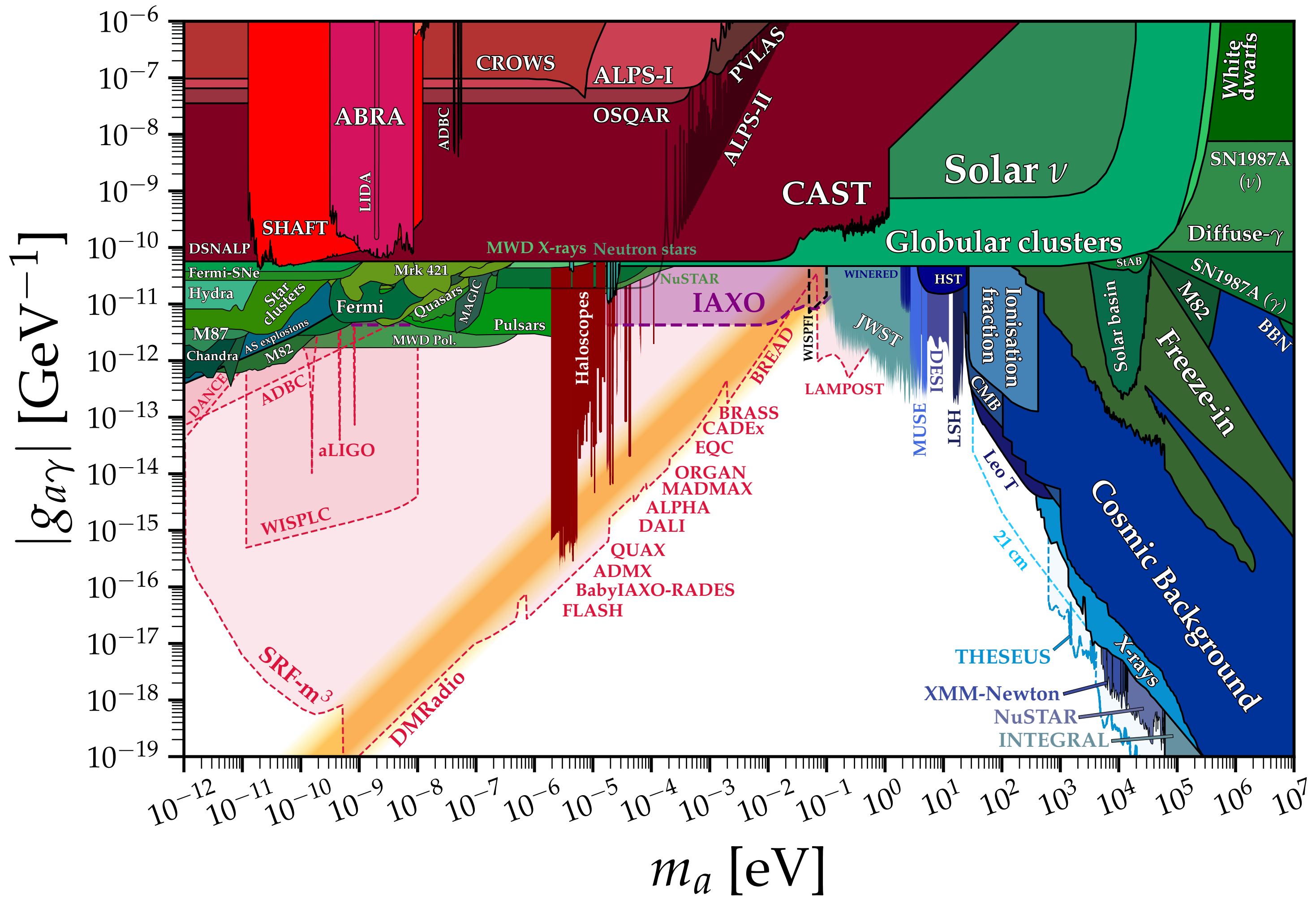

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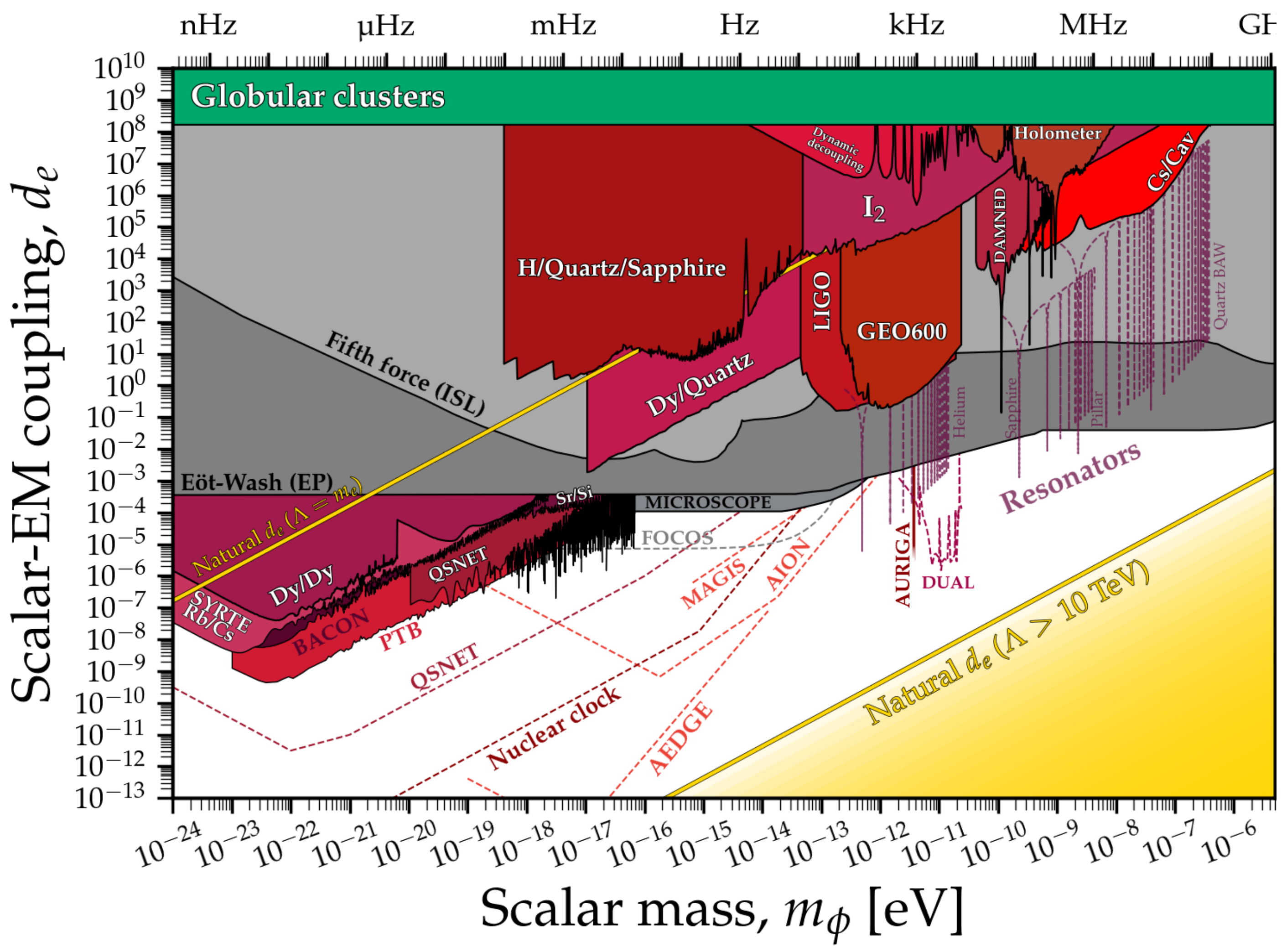

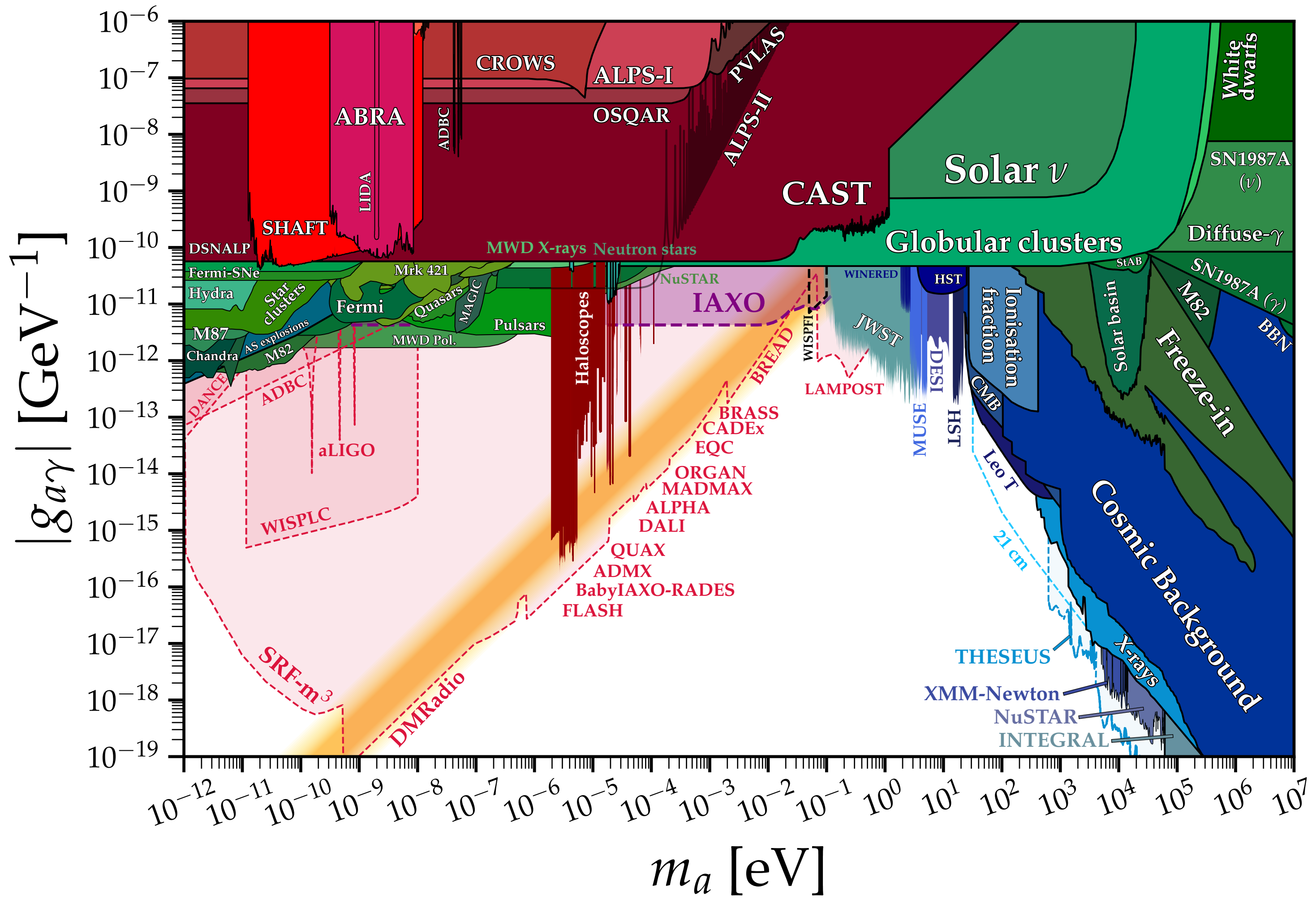

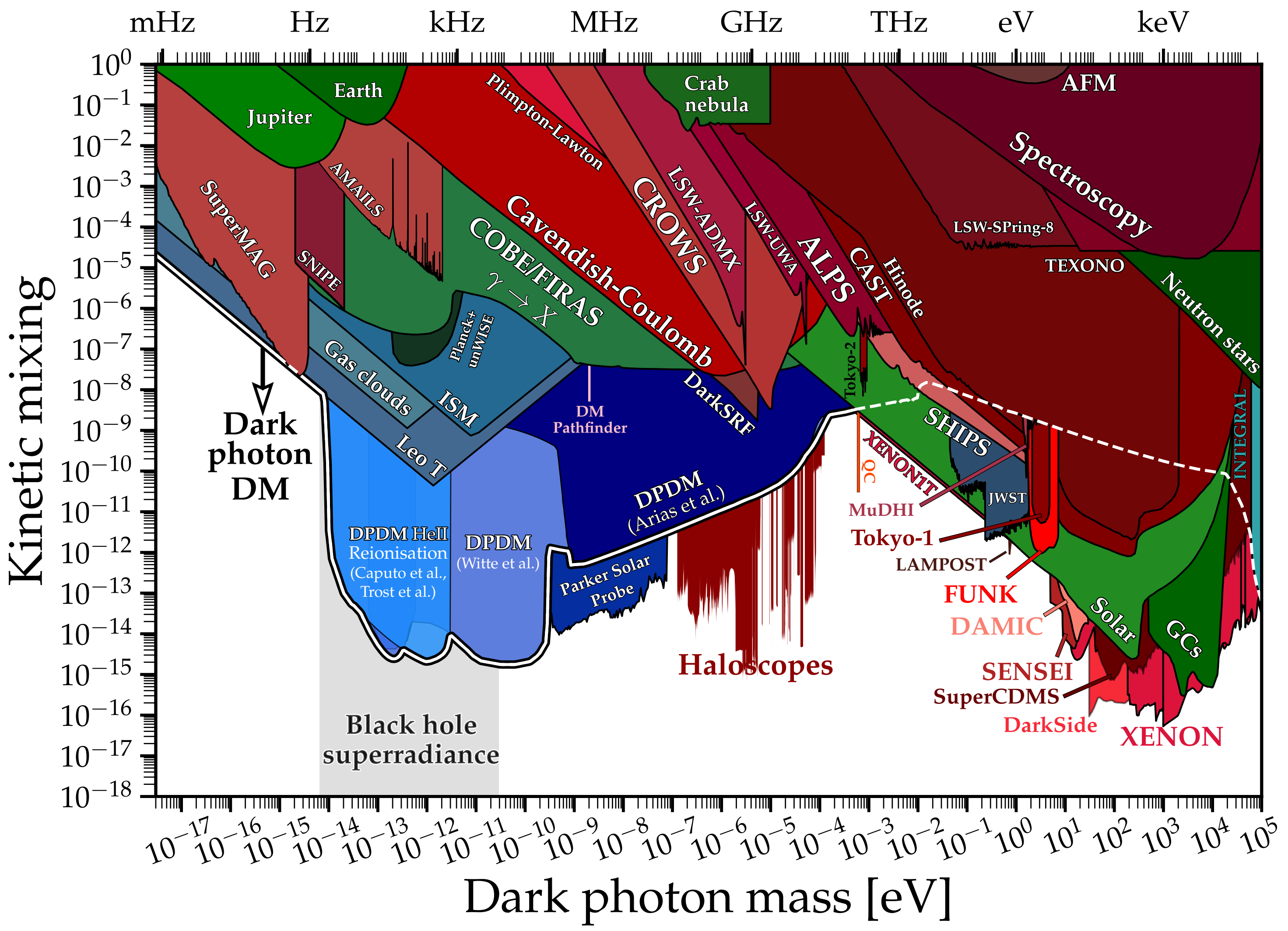

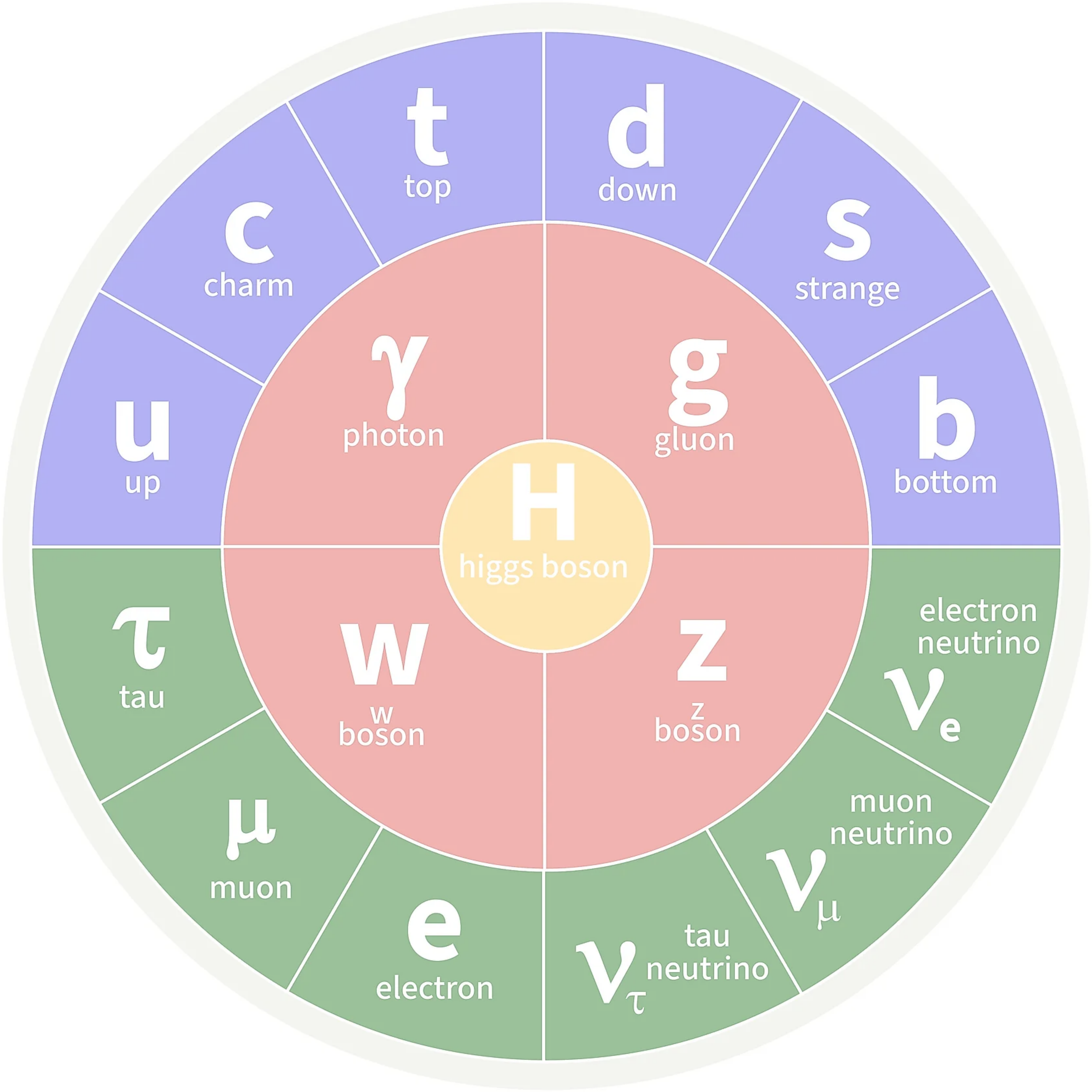

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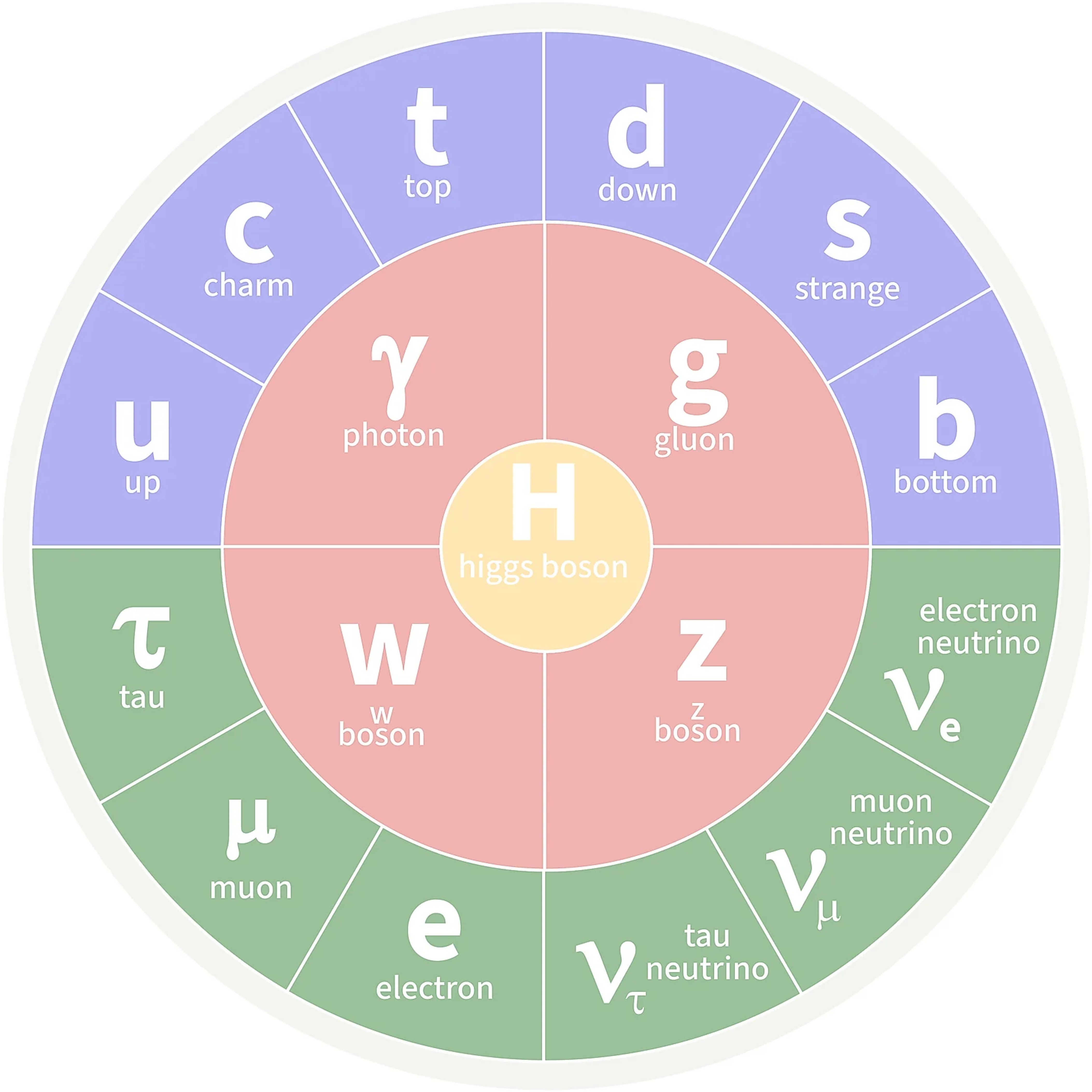

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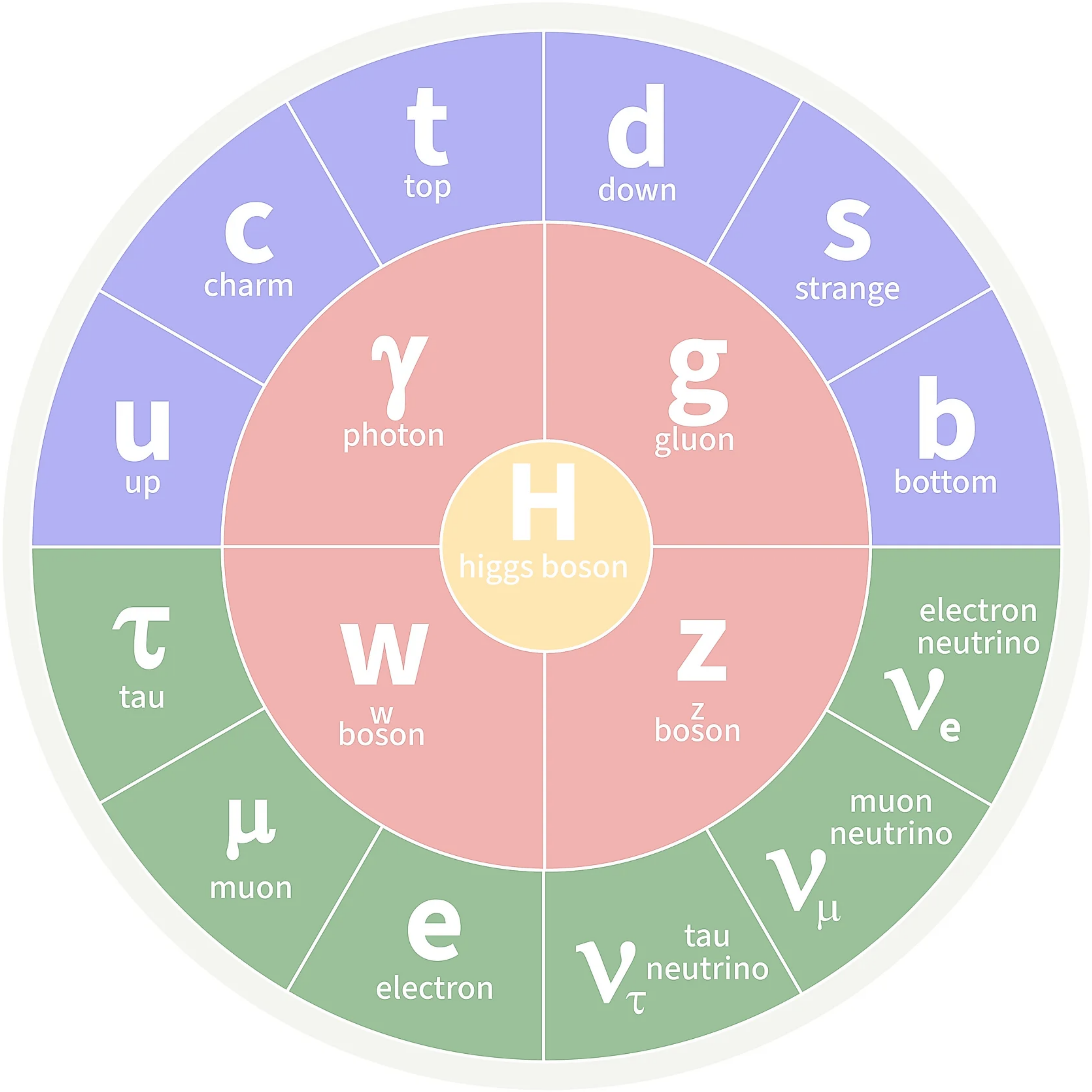

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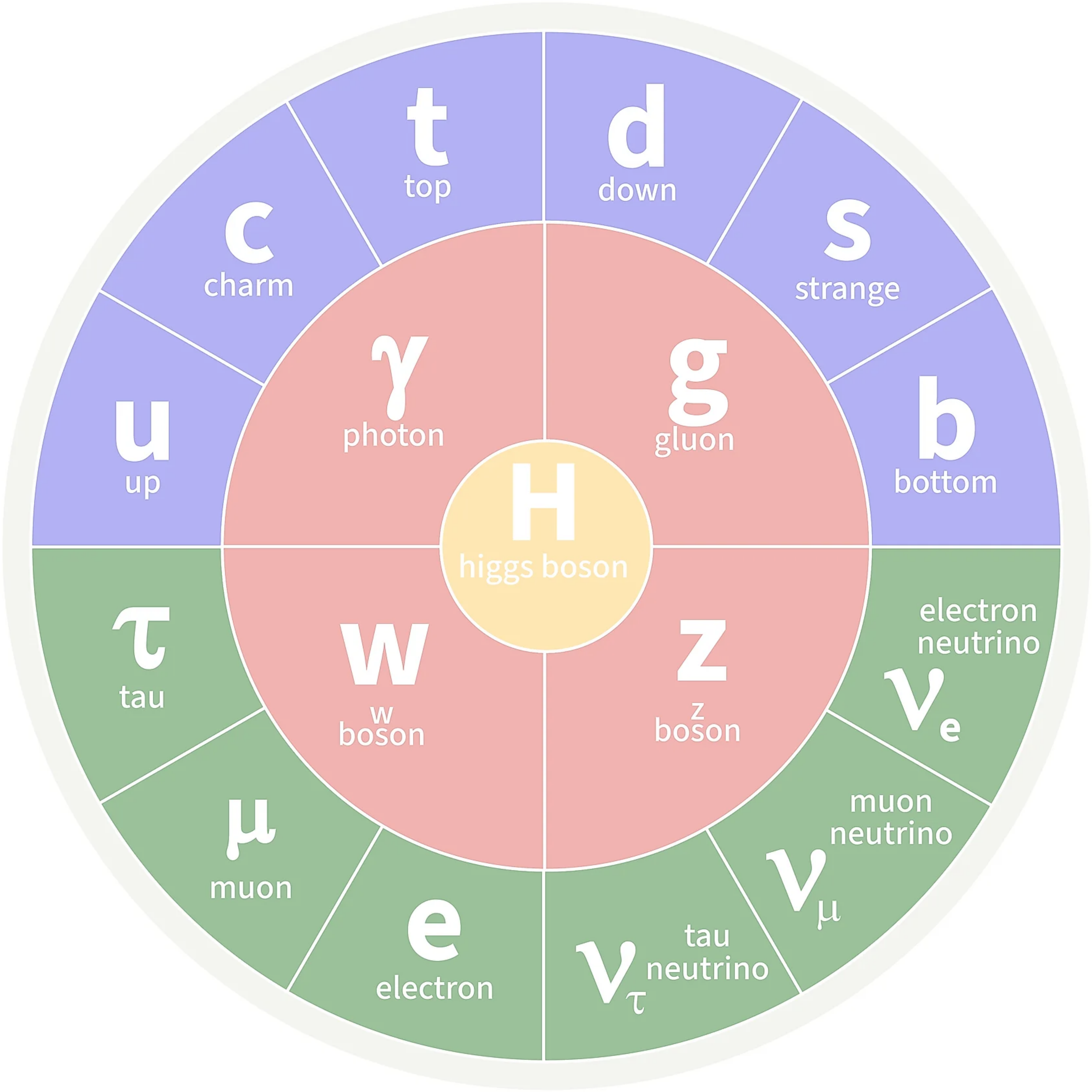

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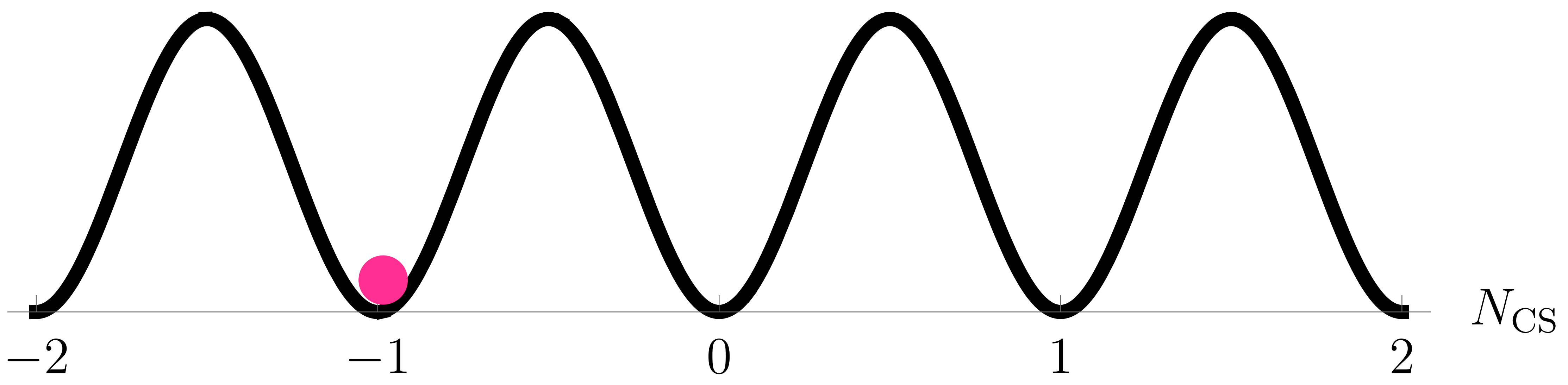

Axiogenesis

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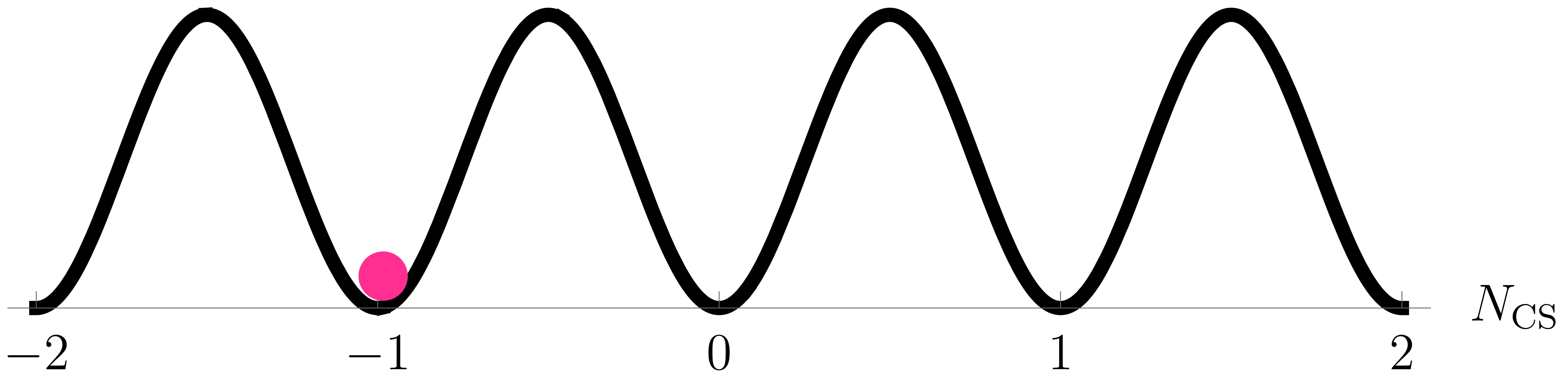

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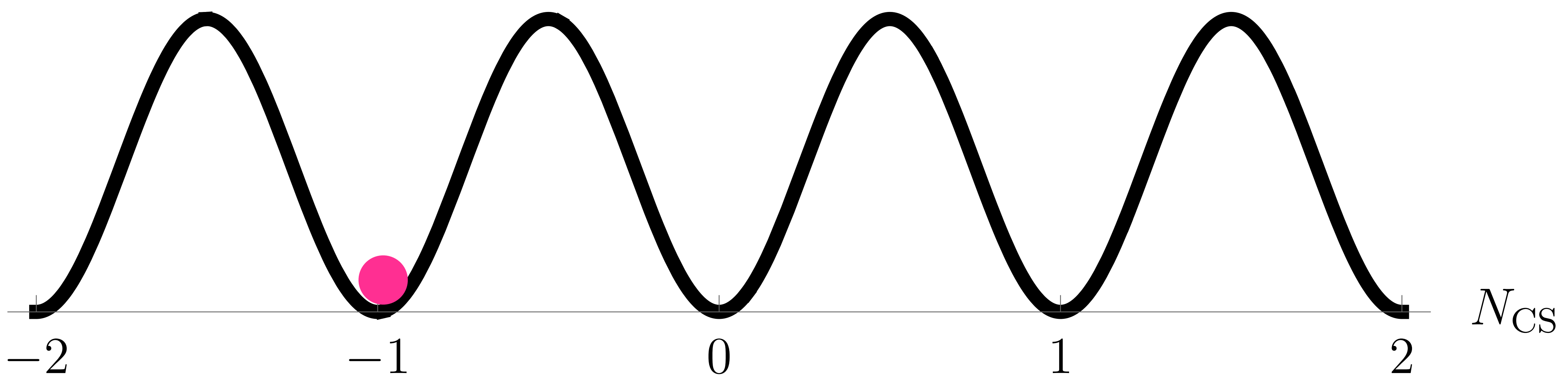

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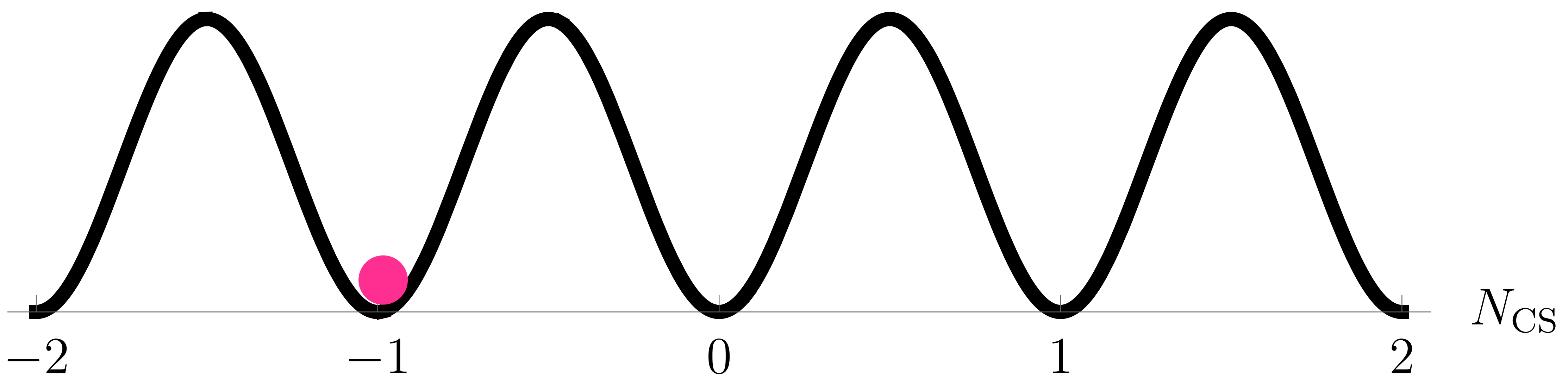

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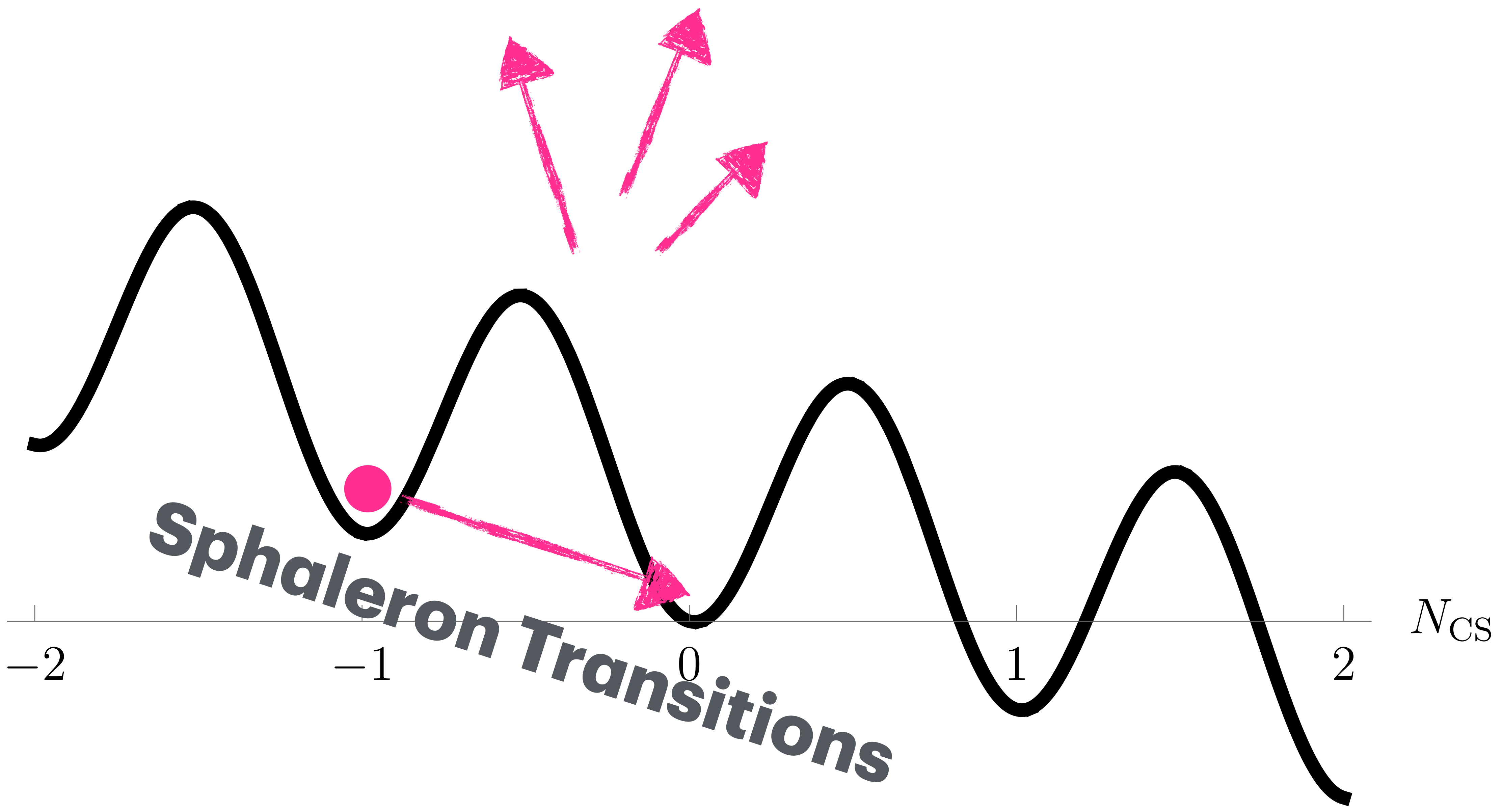

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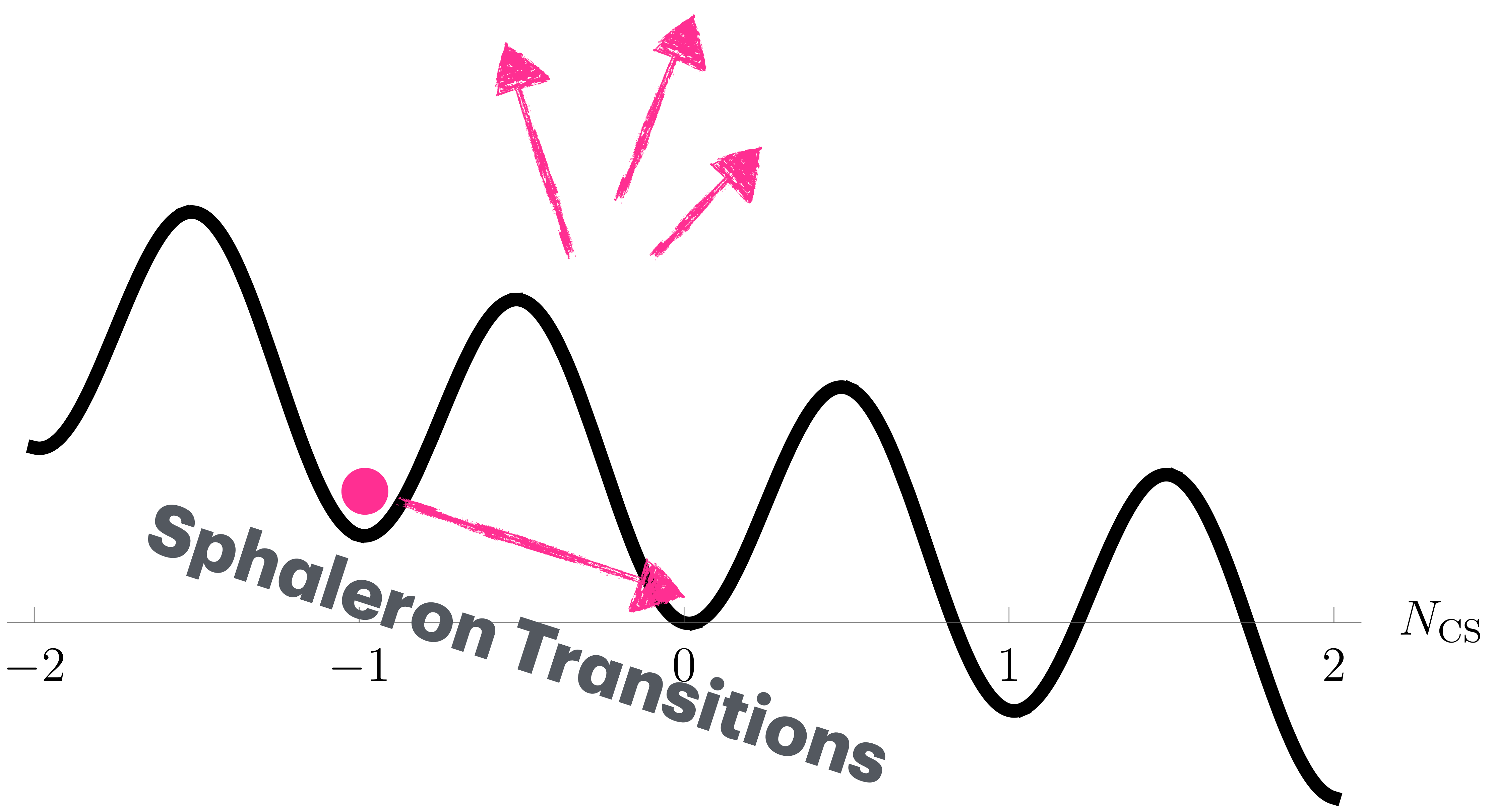
$$Y_B \simeq \frac{45}{2\pi^2 g_{\star S}} \frac{3}{158} \frac{\sum_g \left(7y_{u_g}^{-2} + 5y_{d_g}^{-2}\right)}{\frac{T^4}{\Gamma_s} + \sum_g \left(y_{u_g}^{-2} + y_{d_g}^{-2}\right)} \frac{\dot{\theta}}{T}$$



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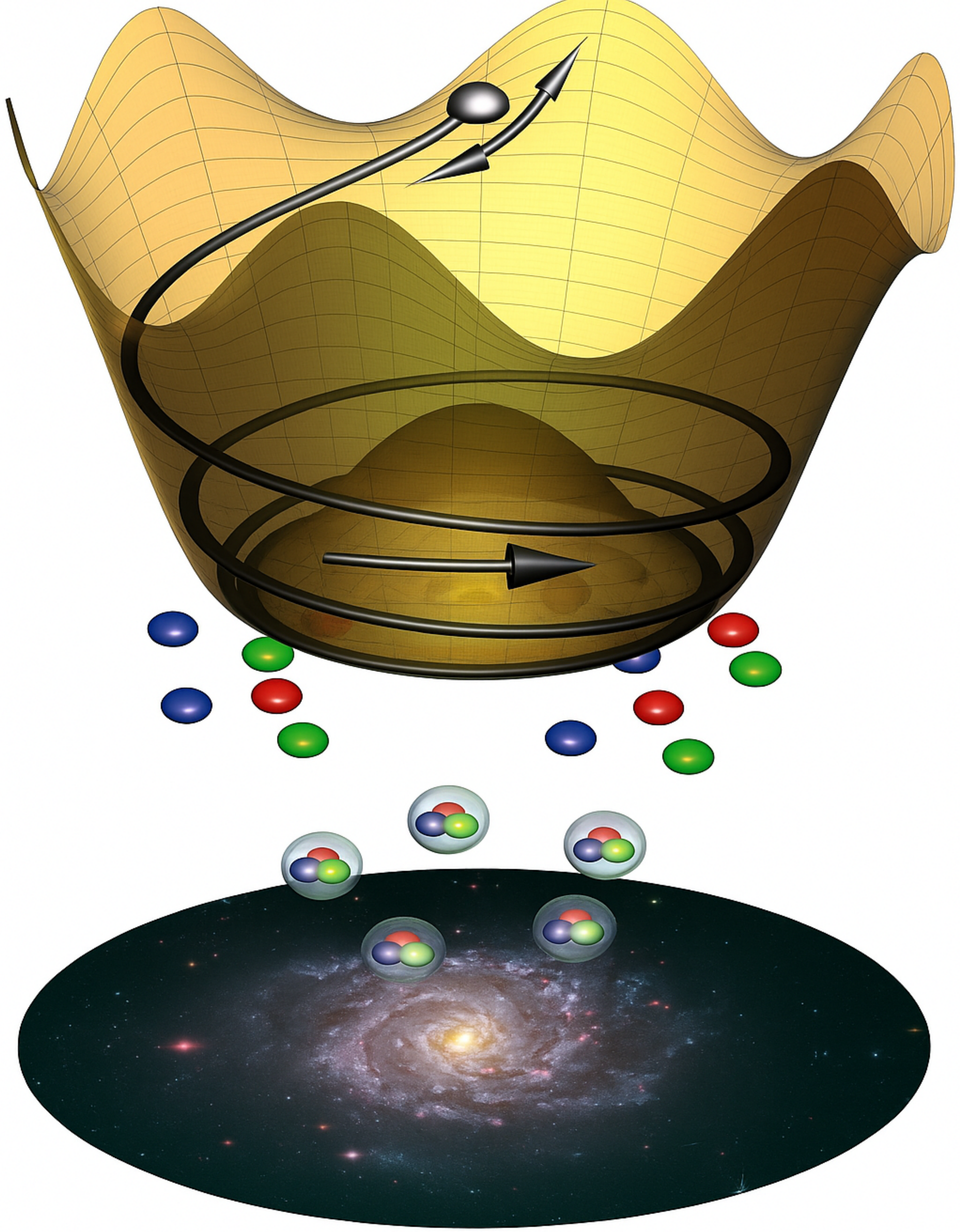

[Harigaya & Co PRL (2020)]

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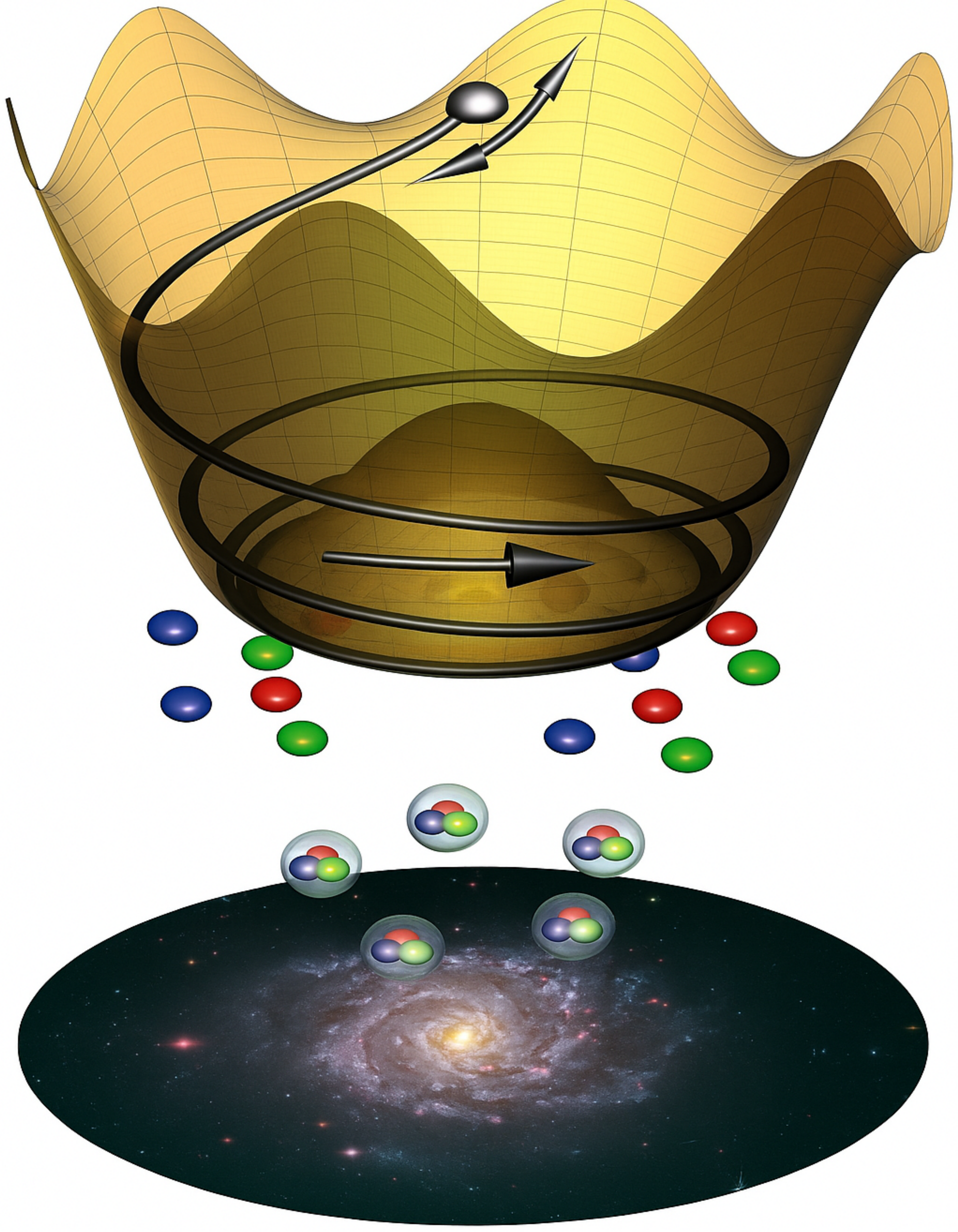

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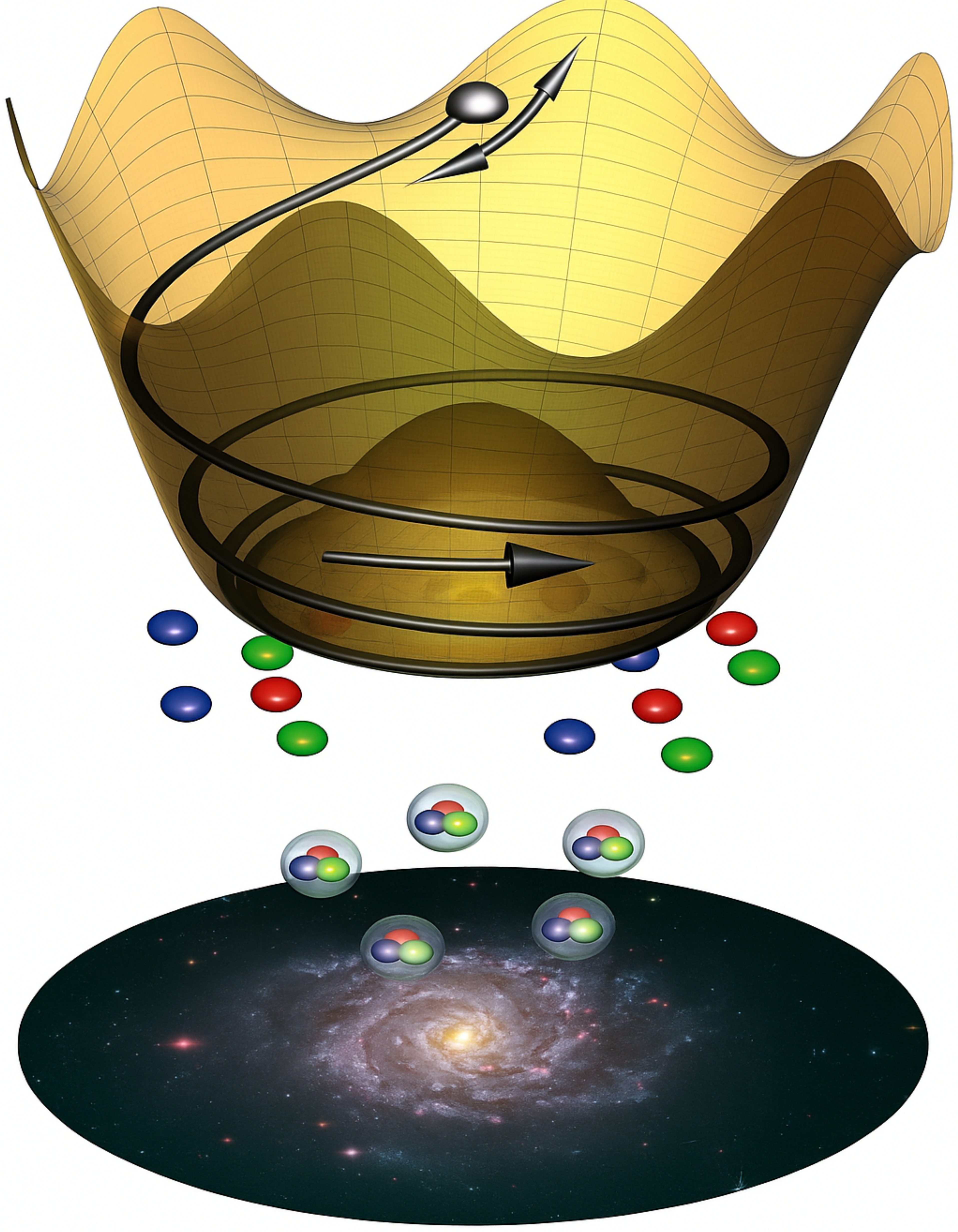

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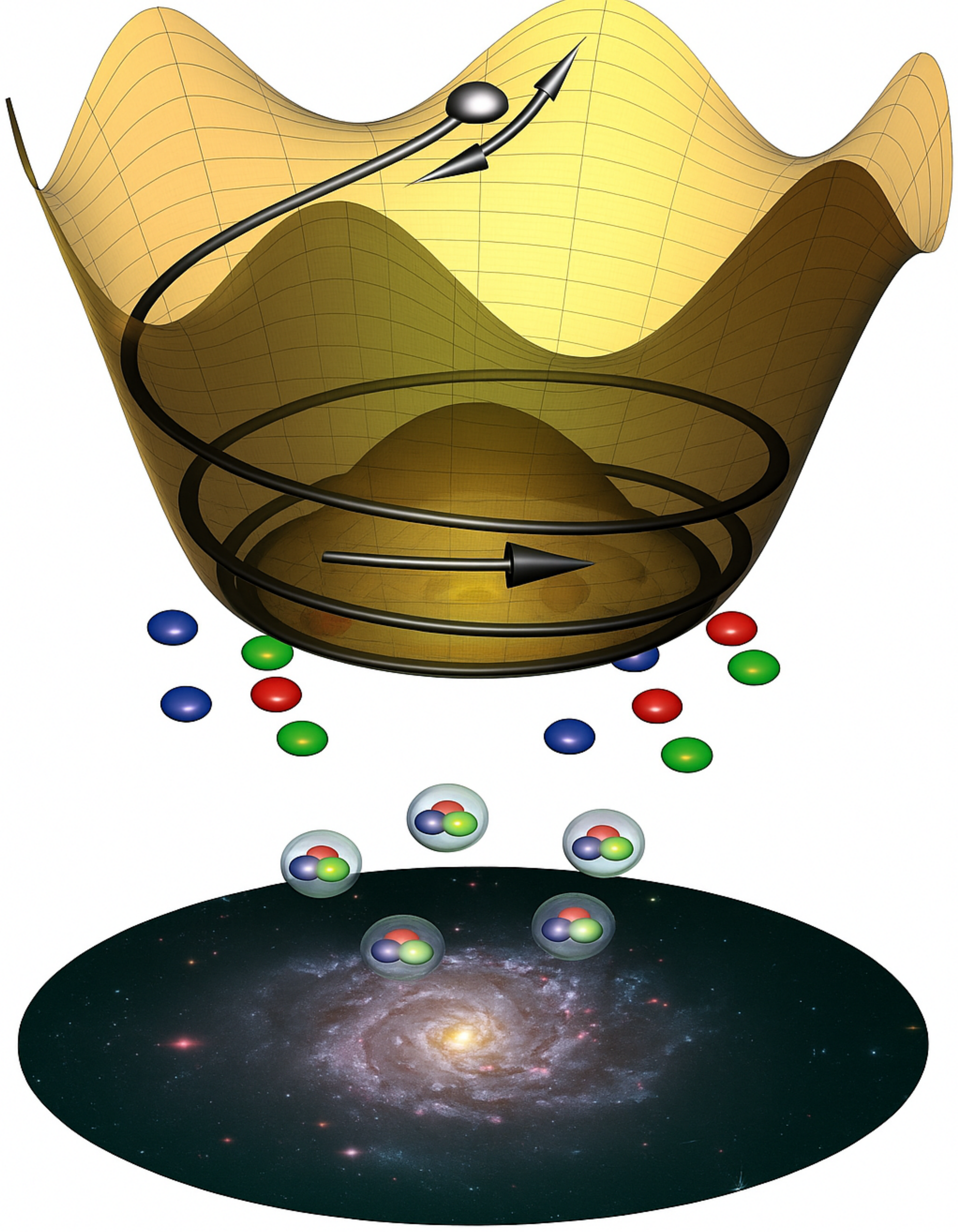

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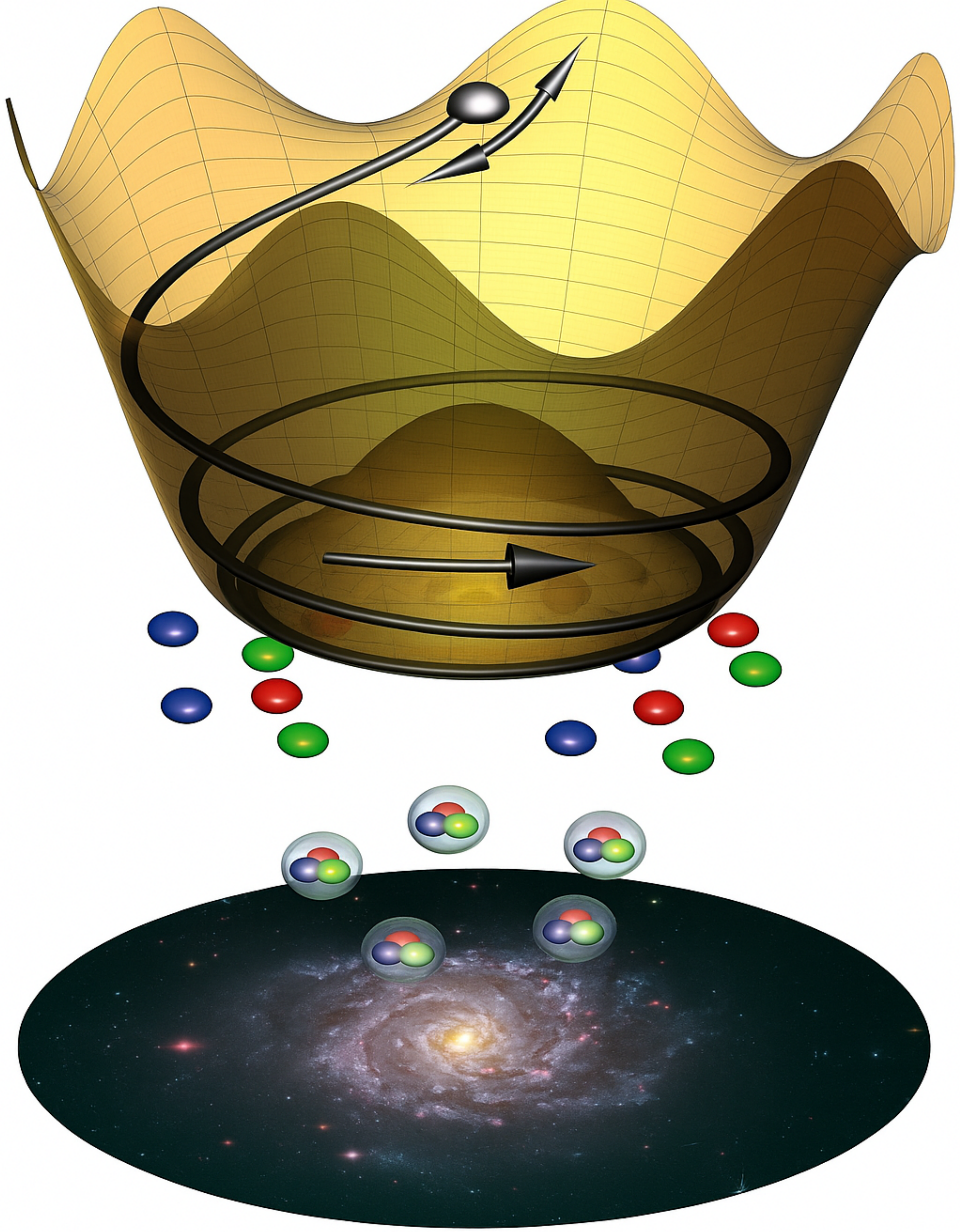

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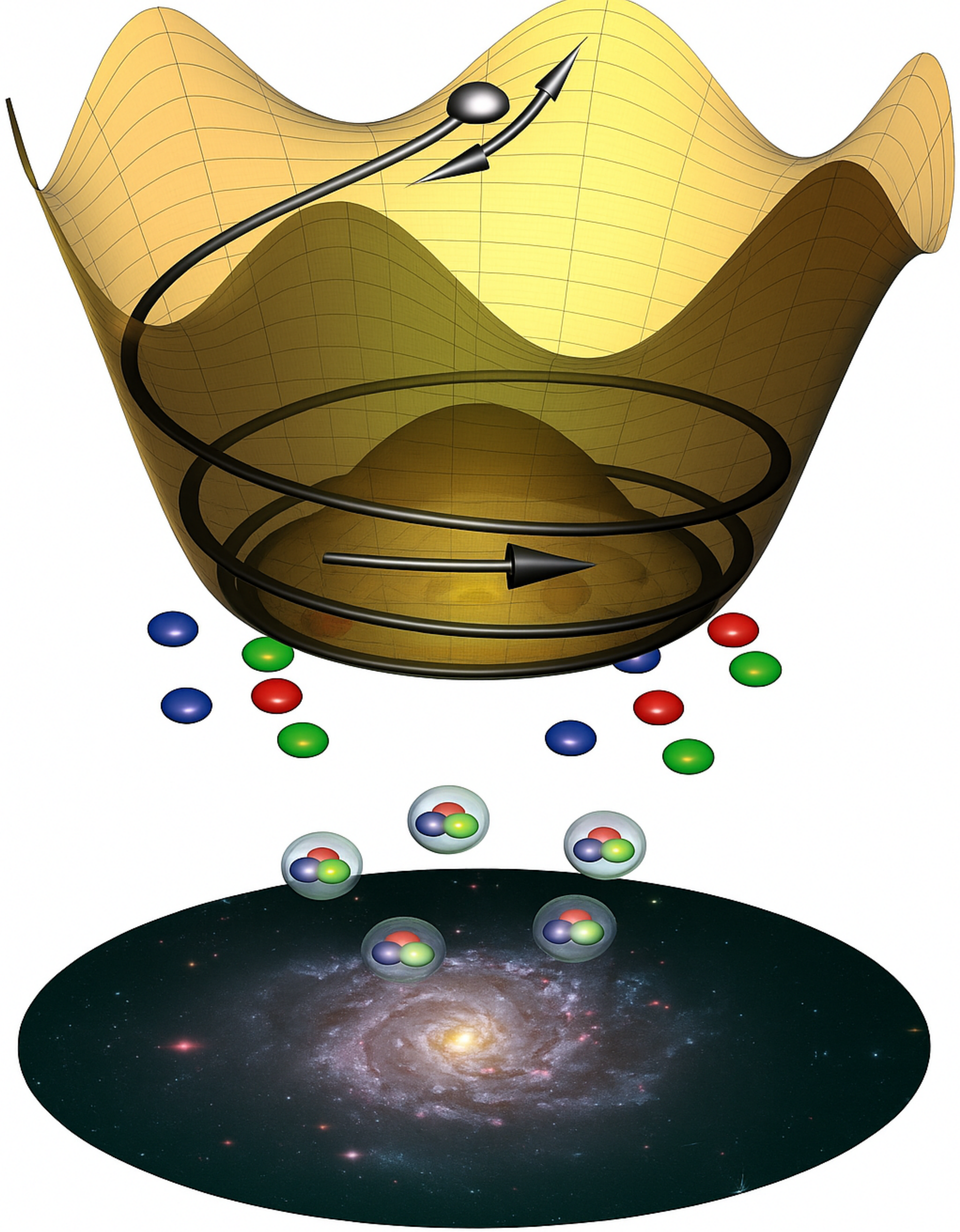

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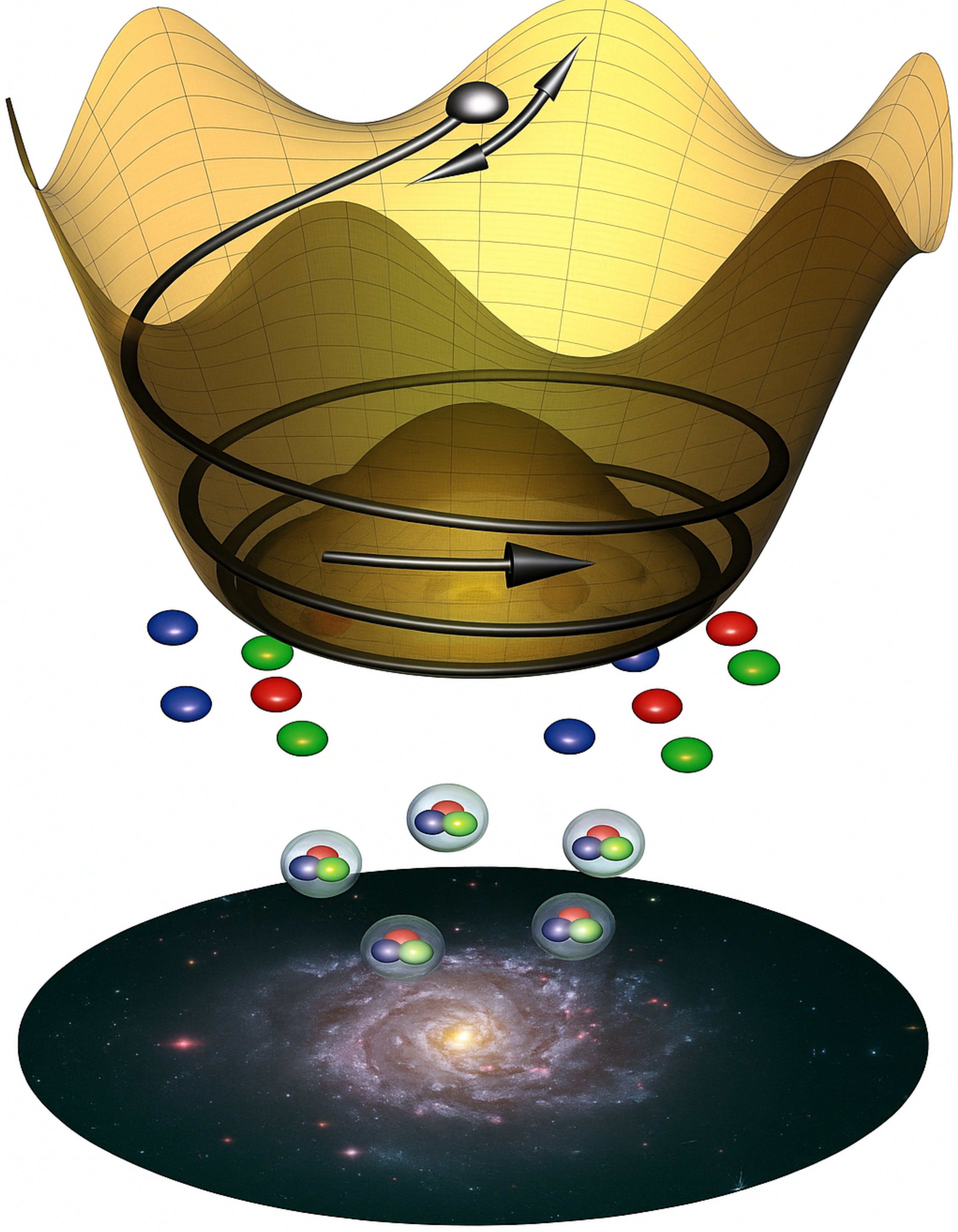
  - Axion velocity survives until EWPT



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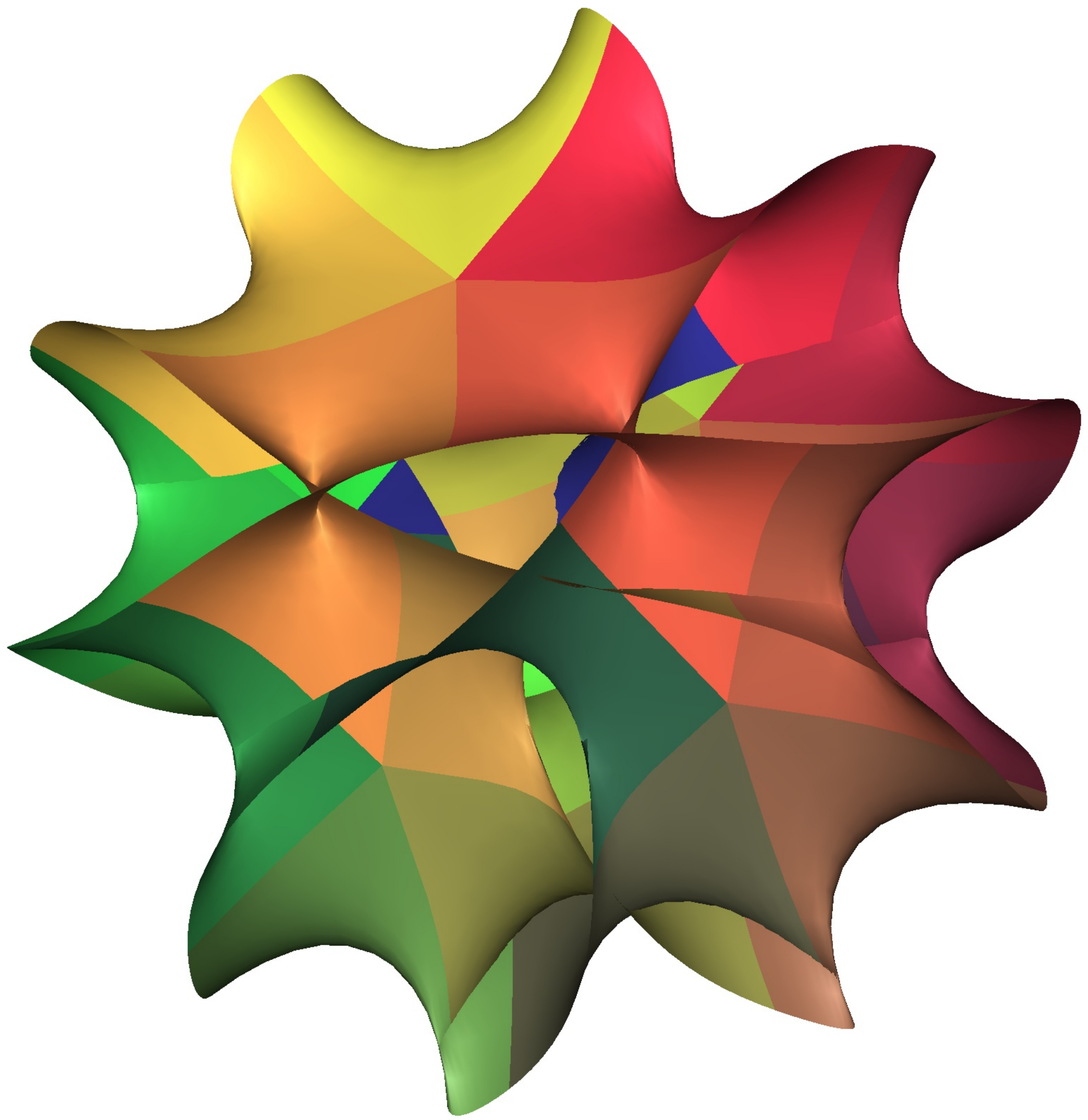
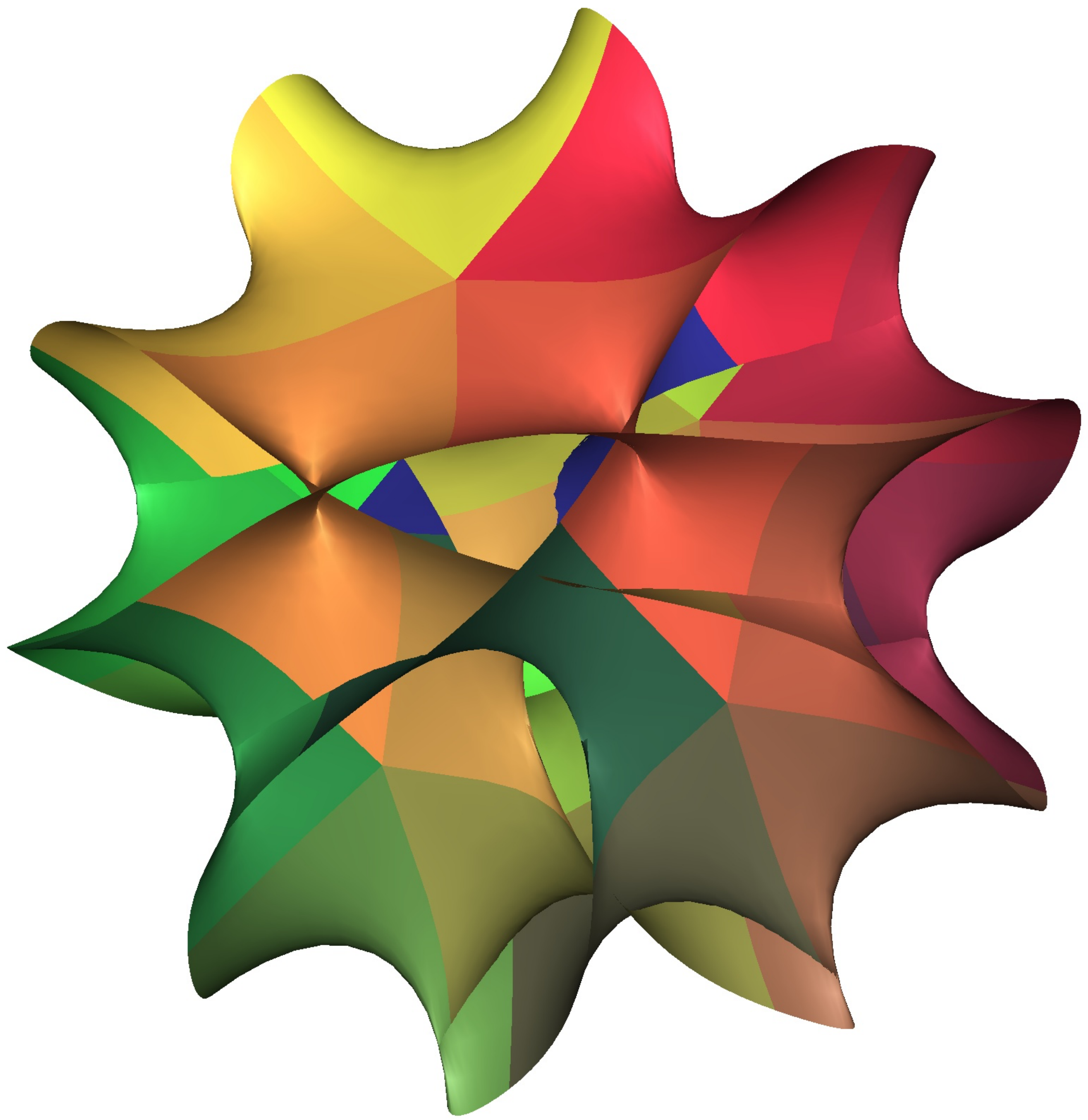
- Both resolved naturally if the QCD axion is one of many in the String Axiverse

The string axiverse



The string axiverse

- Axions arise as zero-modes of gauge fields in extra dimensions



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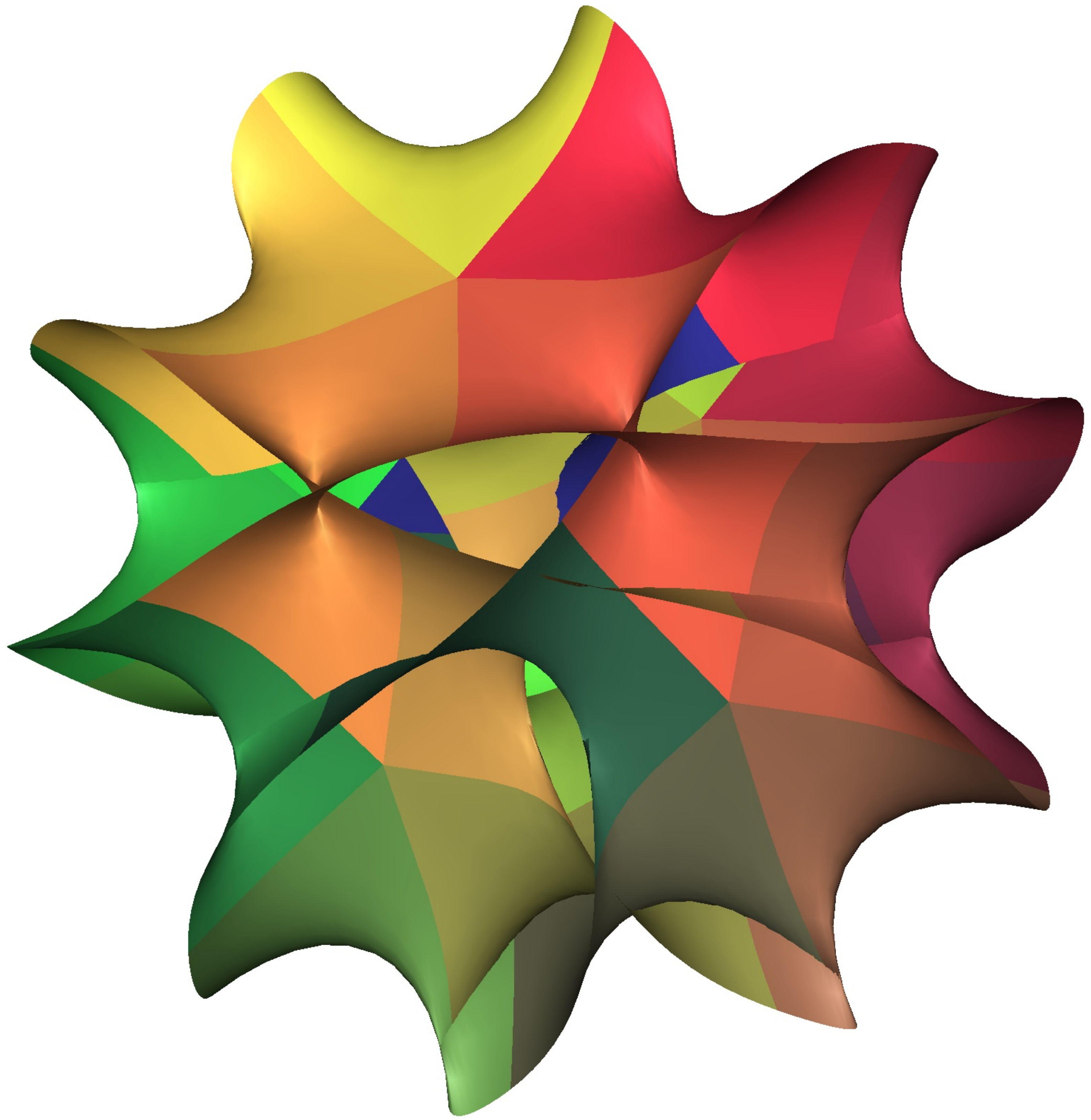

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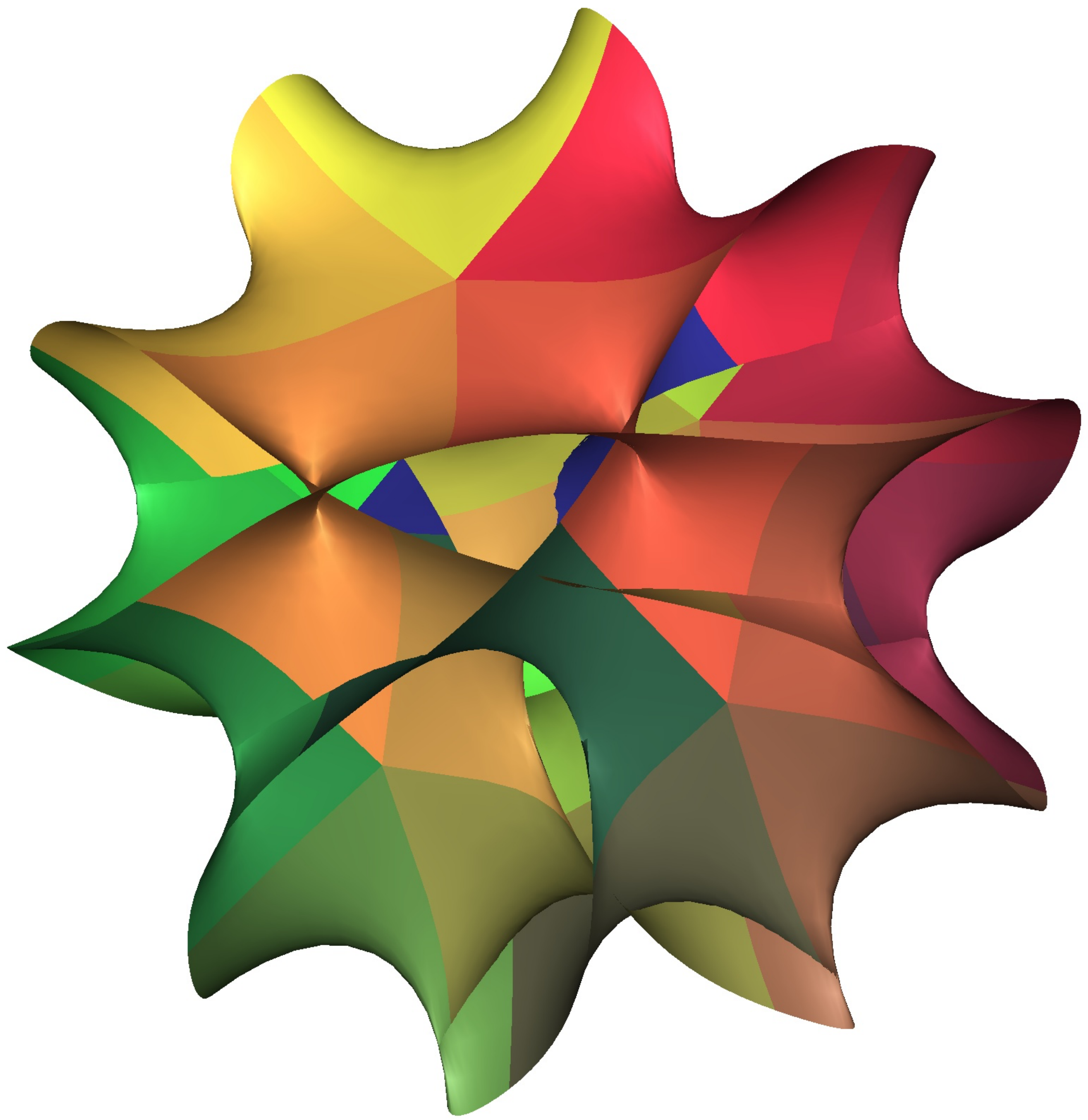

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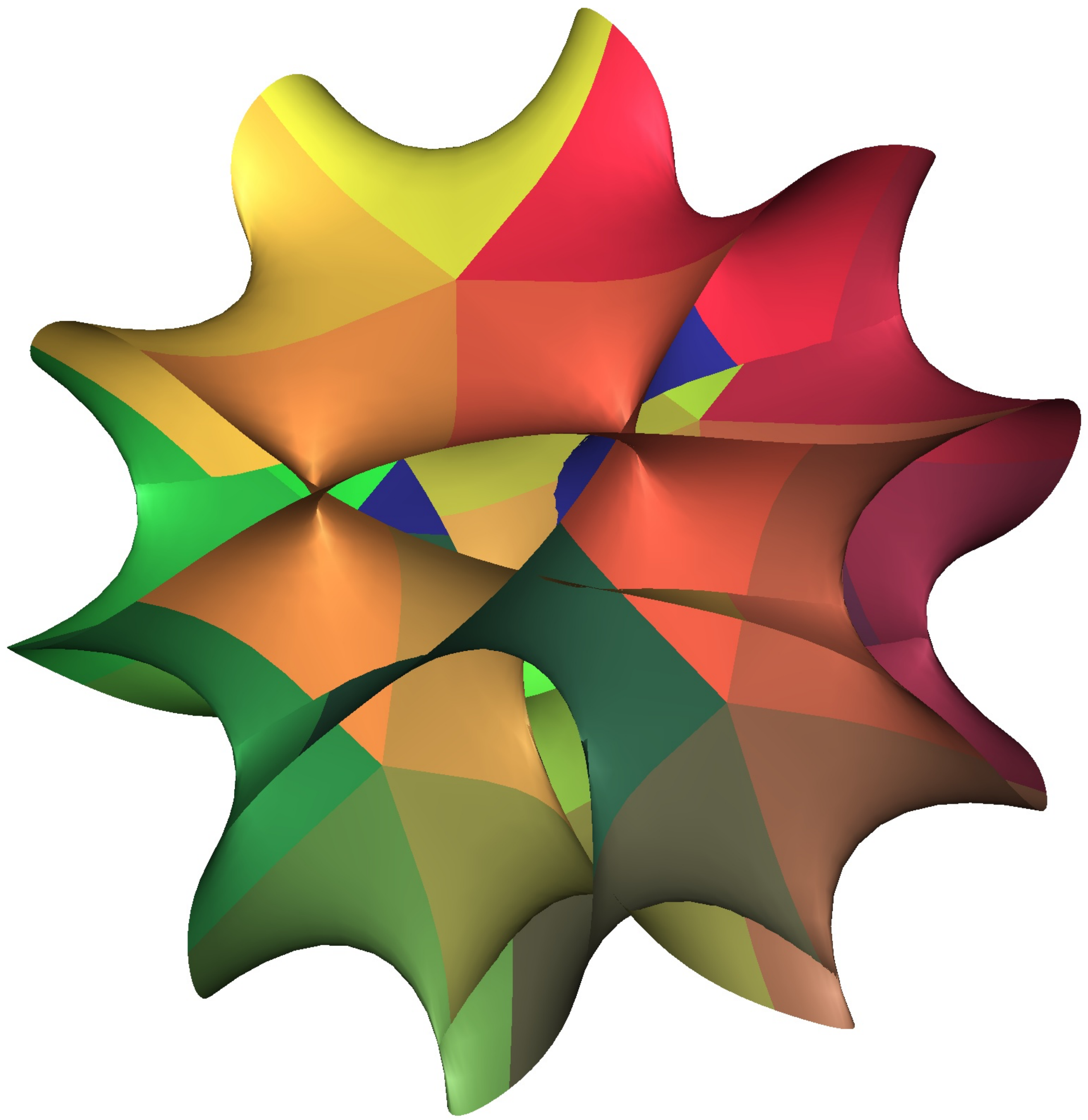

4D Confining gauge groups

Extra-dimensional instantons

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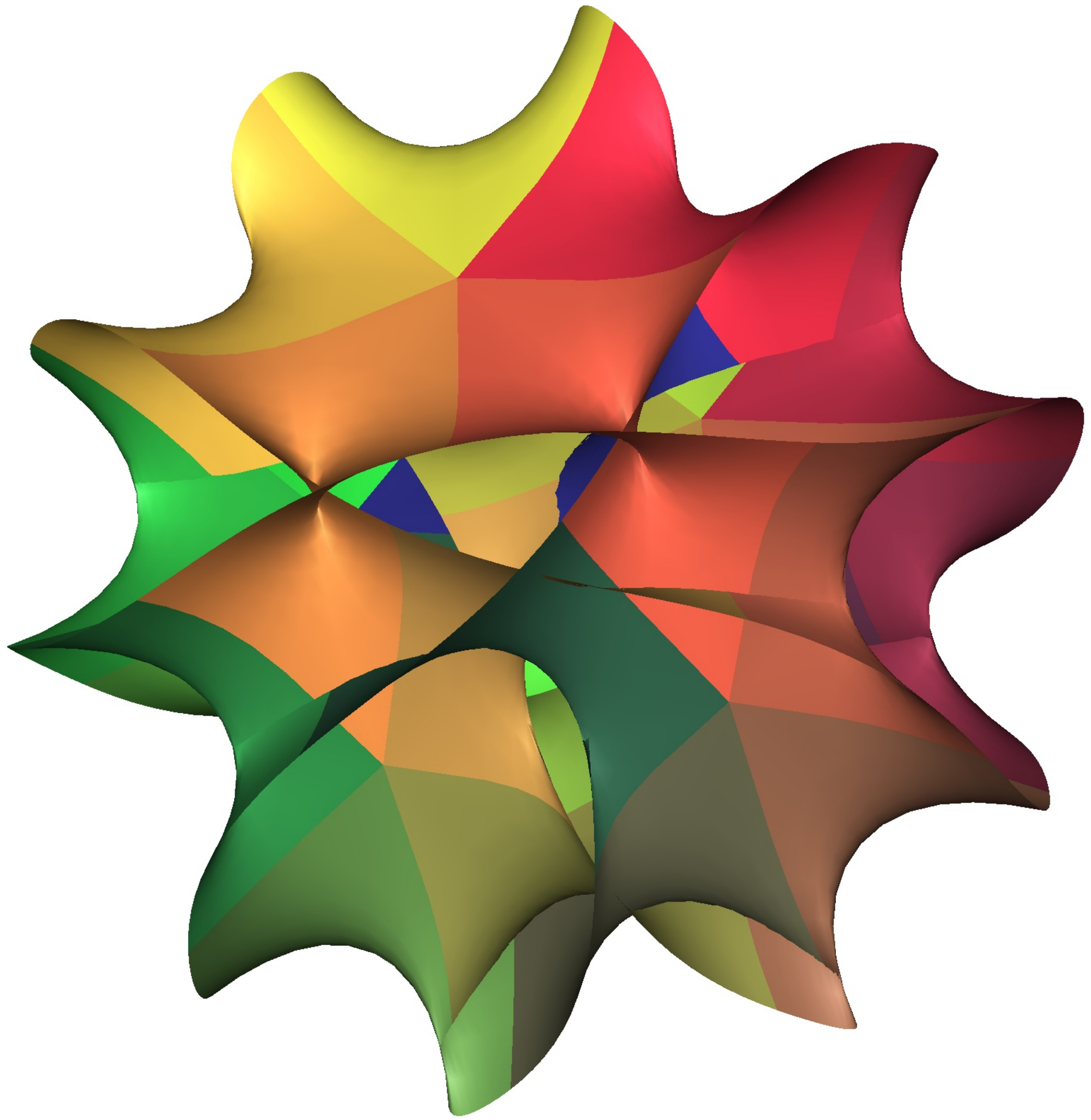

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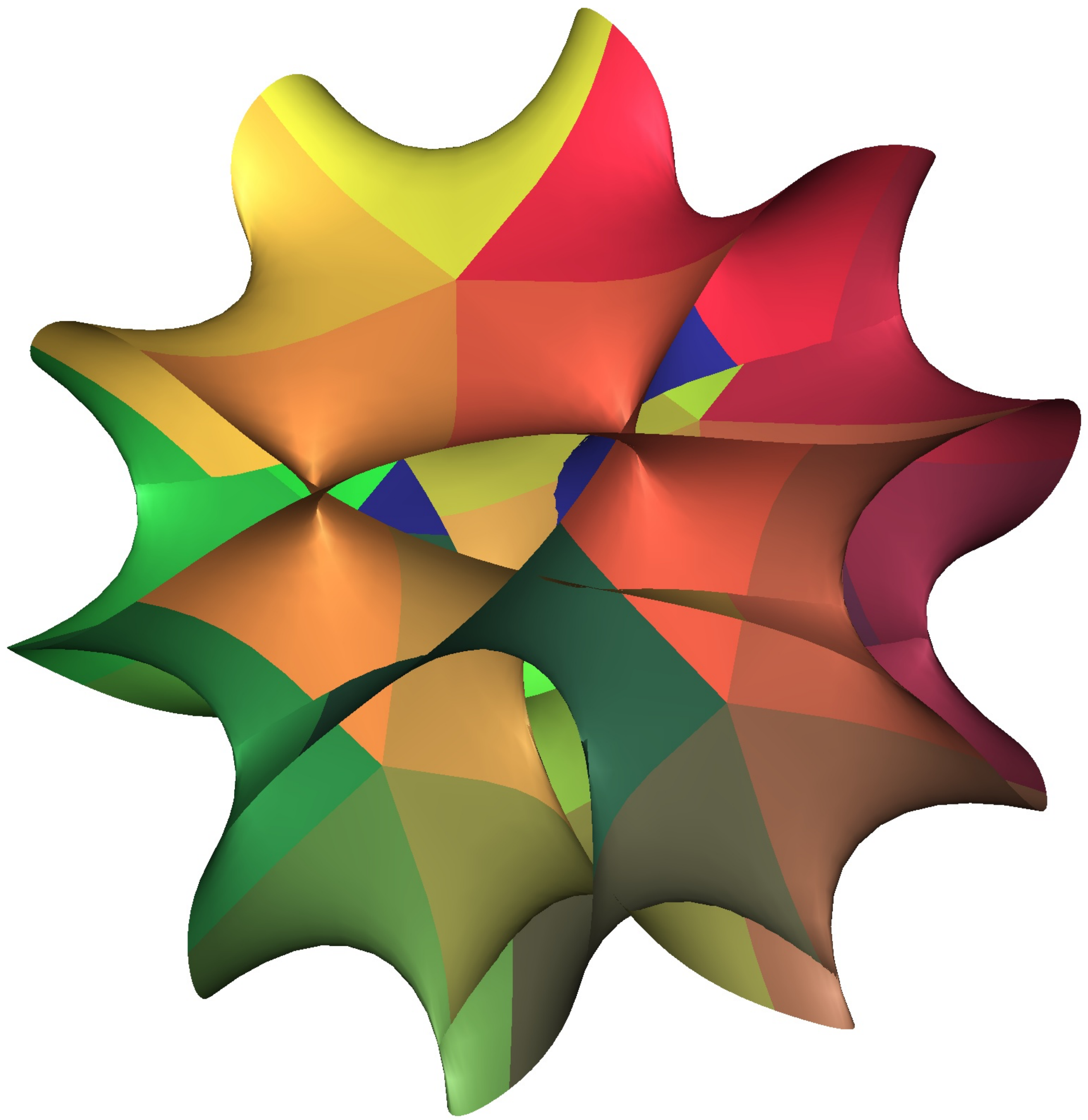

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Most-general two-axion Lagrangian that solves strong CP

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- Dark sector was in thermal equilibrium with SM

A two-axion example

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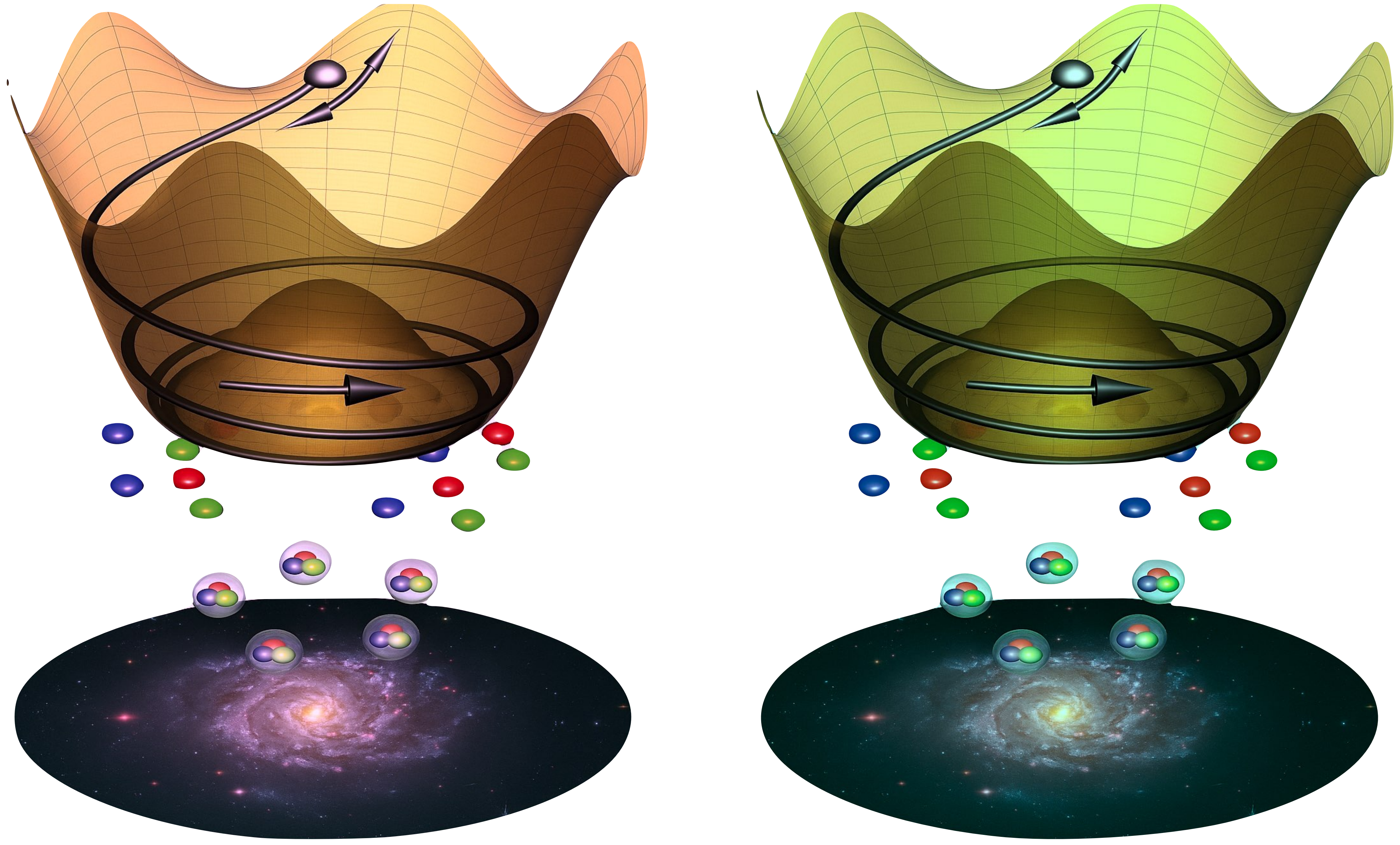

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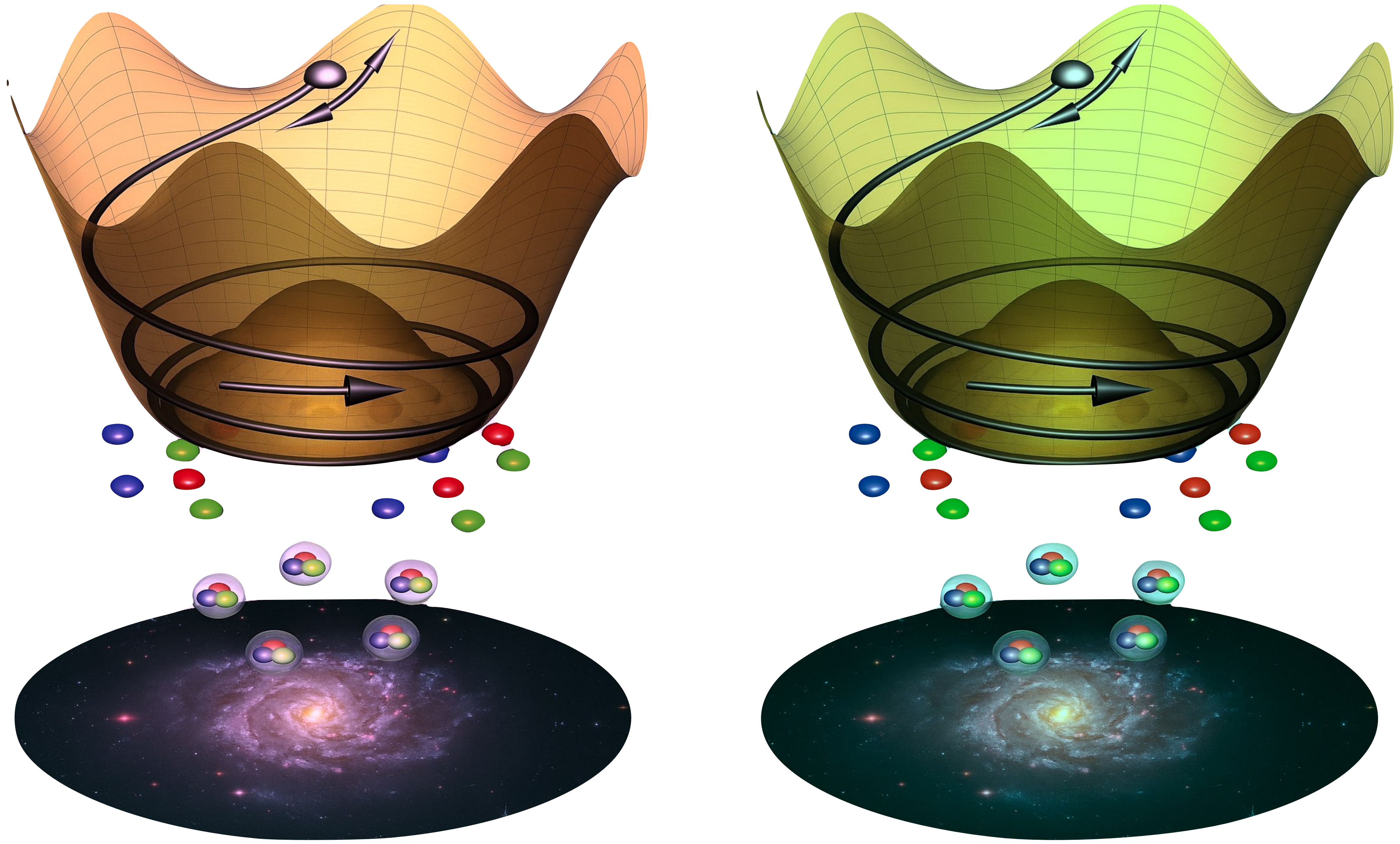

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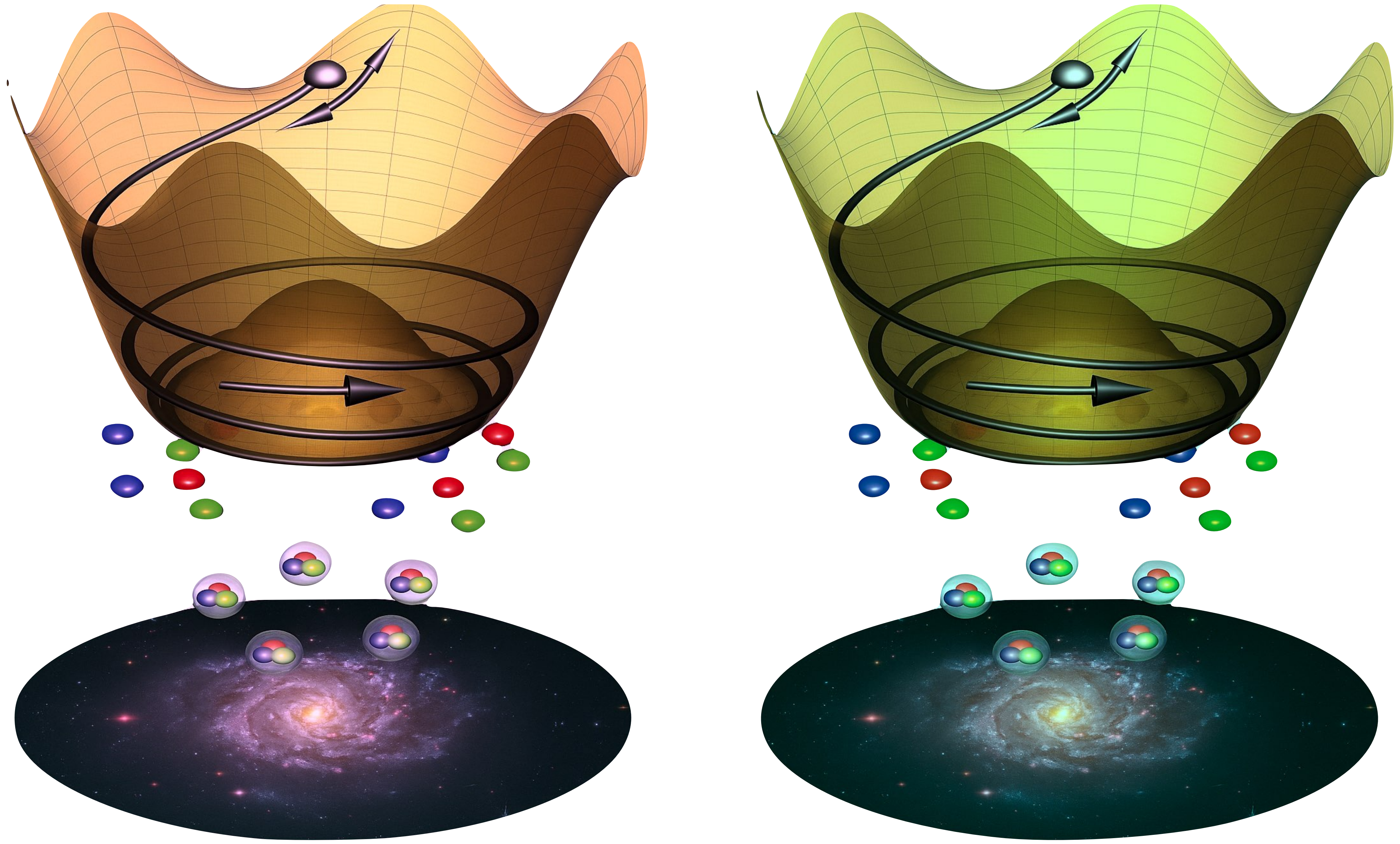

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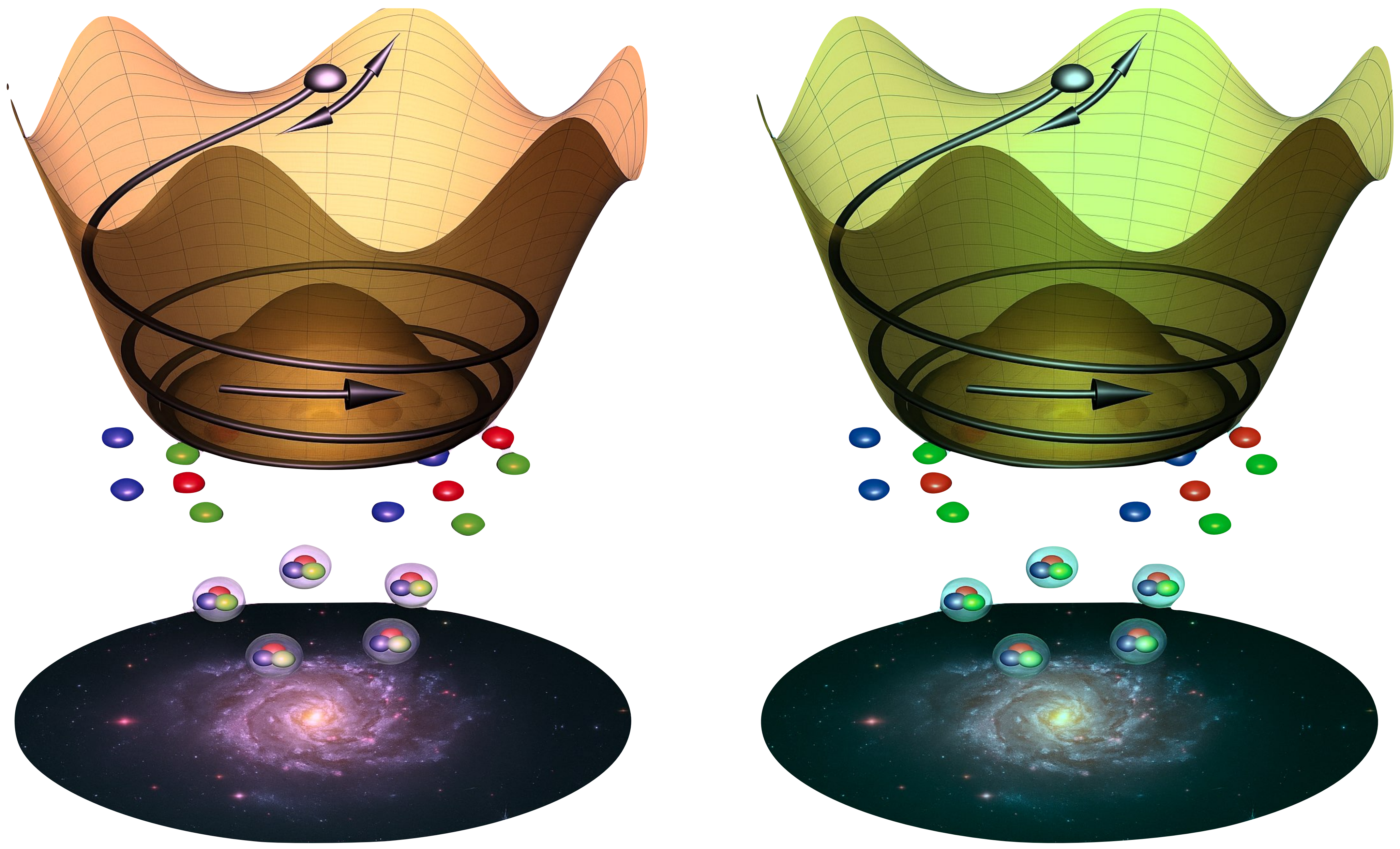

A two-axion example

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2} f_1^2 (\partial\theta_1)^2 + \frac{1}{2} f_2^2 (\partial\theta_2)^2 + \frac{\alpha_c}{8\pi}(C_1\theta_1 + C_2\theta_2)\tilde{G}_c G_c + \frac{\alpha_d}{8\pi}\theta_2 \tilde{G}_d G_d$$

- **Quality & IC:**
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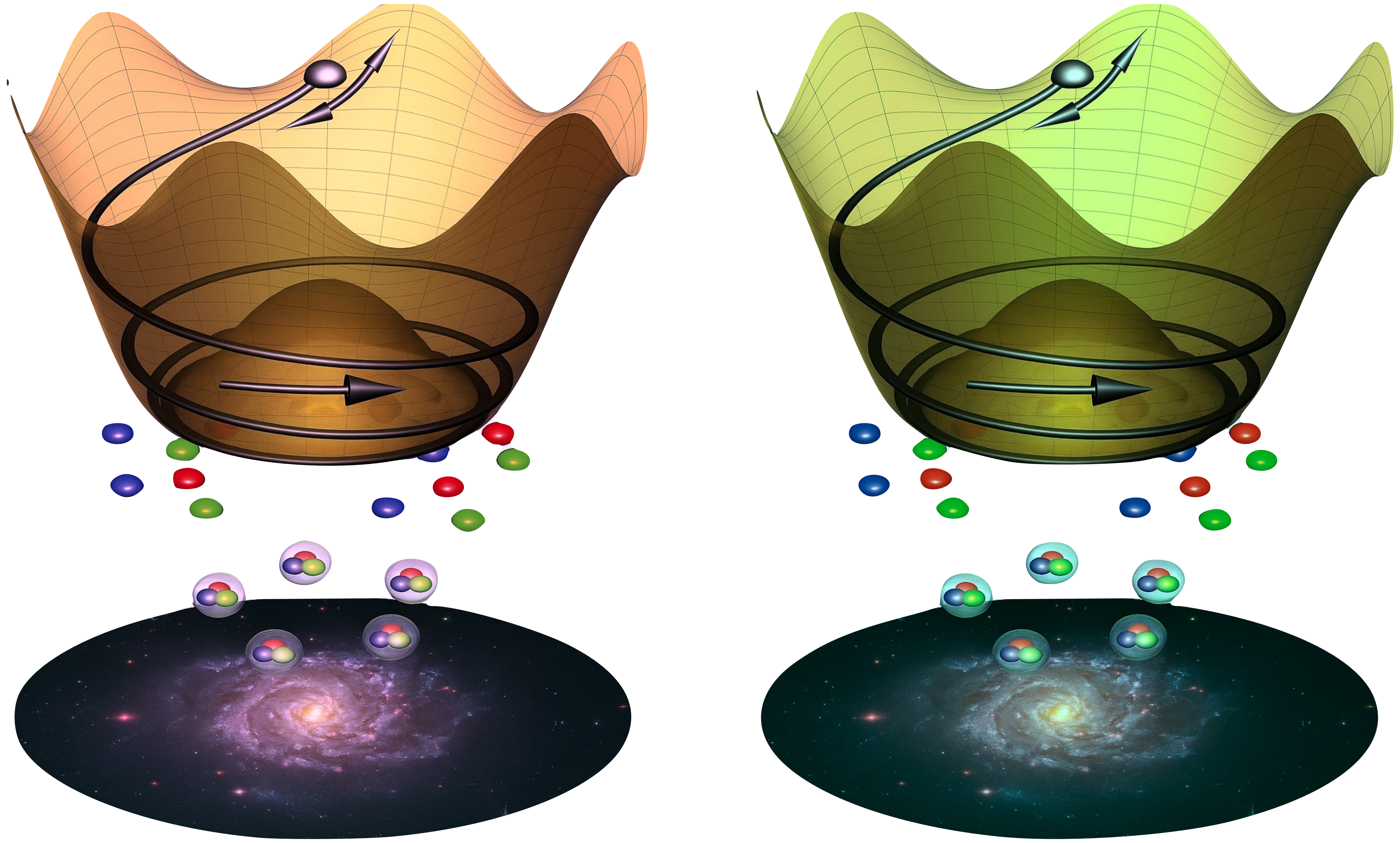
$$\cancel{\Phi^n / M_{\rm pl}^{n-4} + \text{h.c.}}$$



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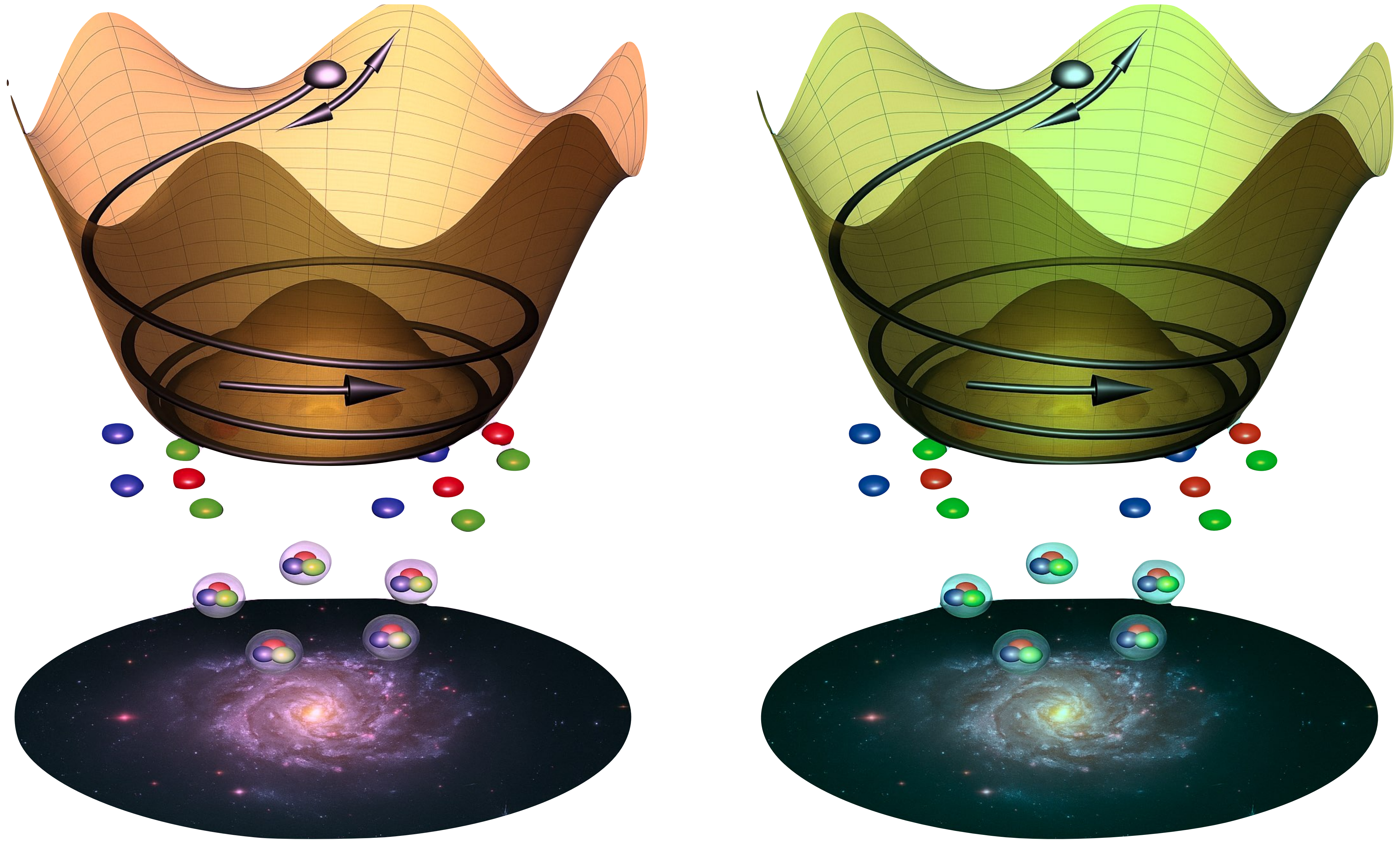
  - PQ breaking provided radion dynamics (e.g. in Goldberger Wise mechanism)



A two-axion example

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2} f_1^2 (\partial\theta_1)^2 + \frac{1}{2} f_2^2 (\partial\theta_2)^2 + \frac{\alpha_c}{8\pi}(C_1\theta_1 + C_2\theta_2)\tilde{G}_c G_c + \frac{\alpha_d}{8\pi}\theta_2 \tilde{G}_d G_d$$

- **Quality & IC:**
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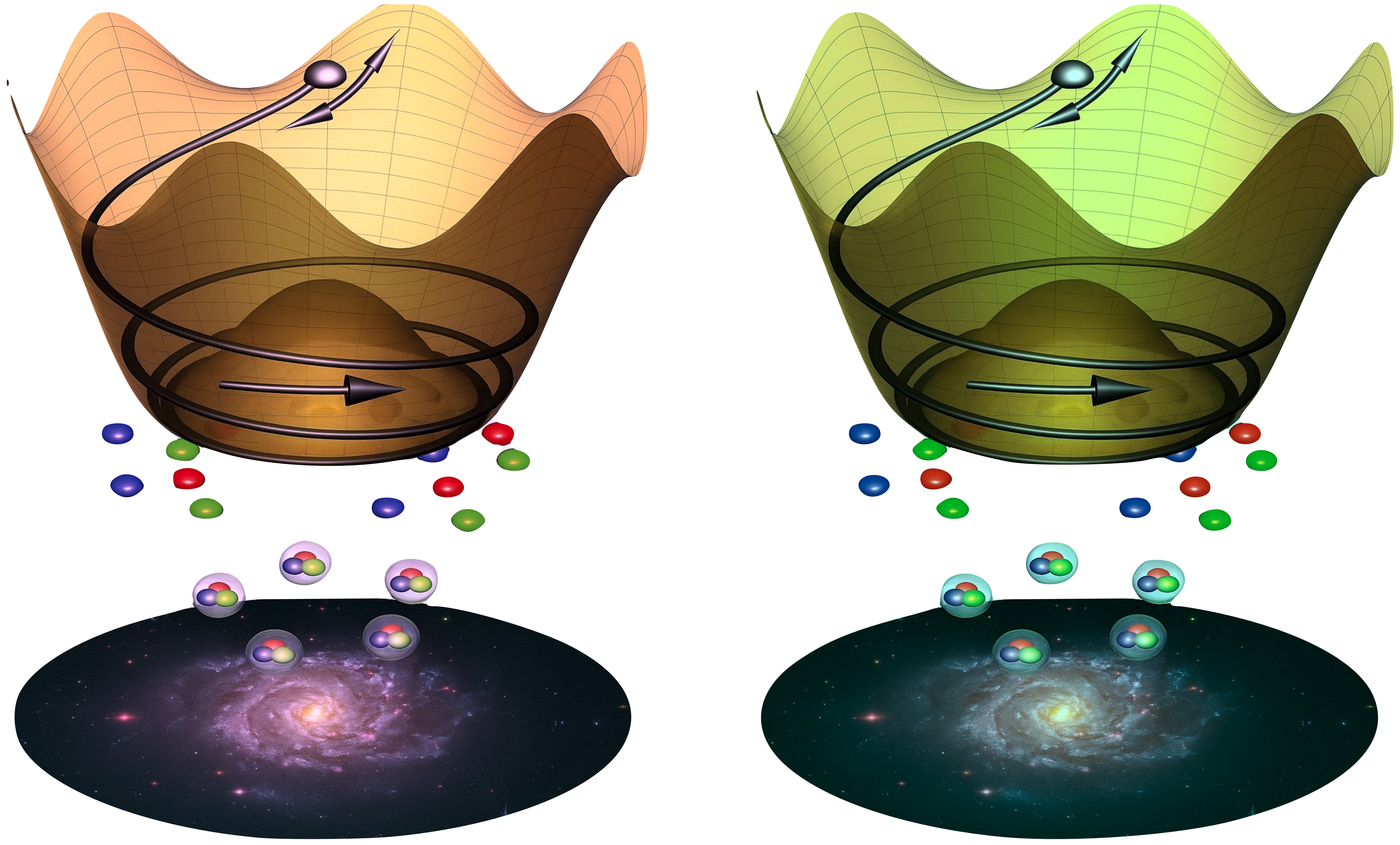
  - PQ breaking provided radion dynamics (e.g. in Goldberger Wise mechanism)

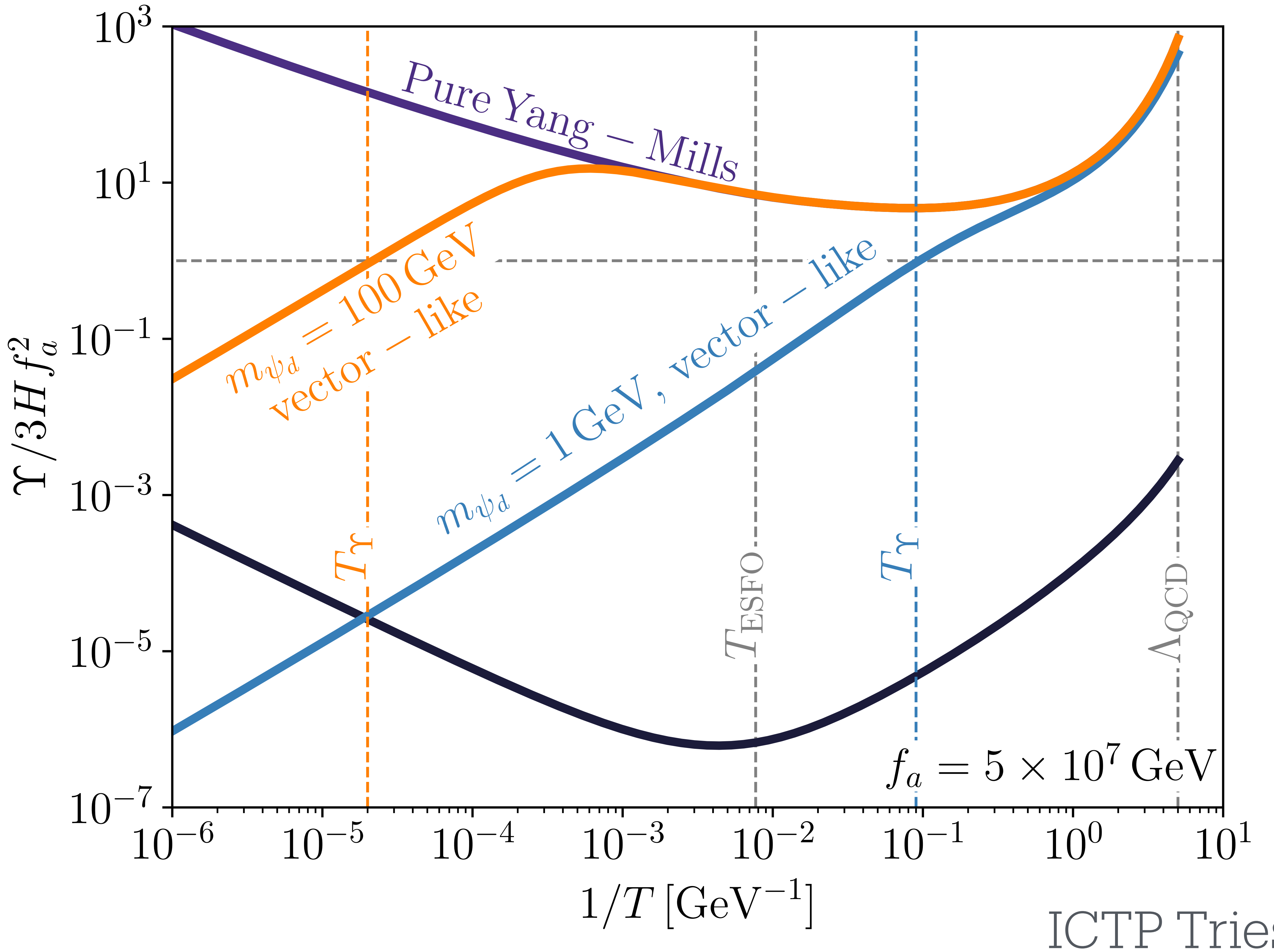
$$V_{\not{P}\not{Q}} = e^{-ML}\cos(n_1\theta_1 + n_2\theta_2)$$

$$V(L) \sim M^4(e^{\alpha ML} + e^{-\beta ML})$$



A two-axion example

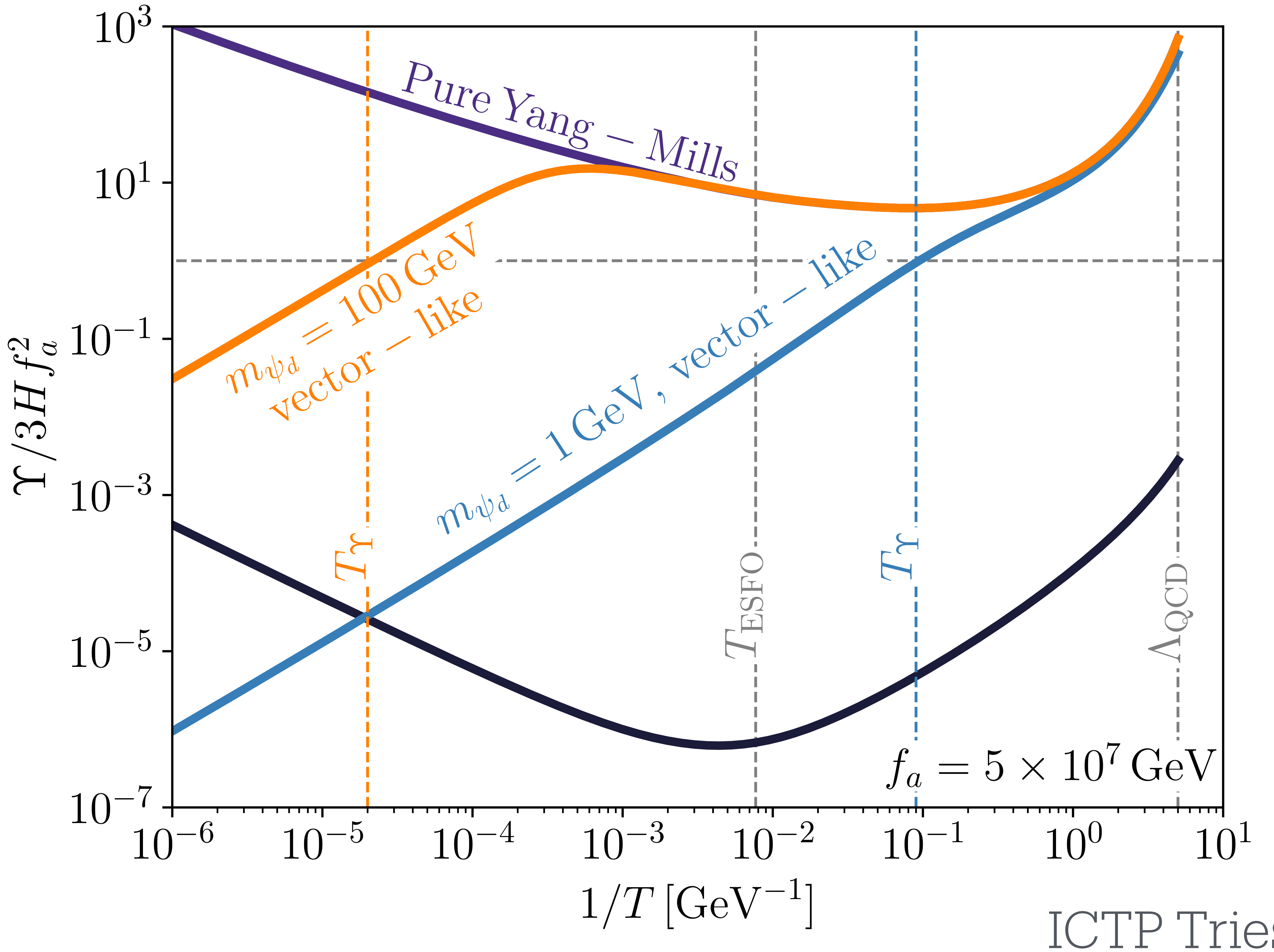
$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{2} f_1^2 (\partial\theta_1)^2 + \frac{1}{2} f_2^2 (\partial\theta_2)^2 + \frac{\alpha_c}{8\pi}(C_1\theta_1 + C_2\theta_2)\tilde{G}_c G_c + \frac{\alpha_d}{8\pi}\theta_2 \tilde{G}_d G_d$$



A two-axion example

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2} f_1^2 (\partial\theta_1)^2 + \frac{1}{2} f_2^2 (\partial\theta_2)^2 + \frac{\alpha_c}{8\pi}(C_1\theta_1 + C_2\theta_2)\tilde{G}_c G_c + \frac{\alpha_d}{8\pi}\theta_2 \tilde{G}_d G_d$$

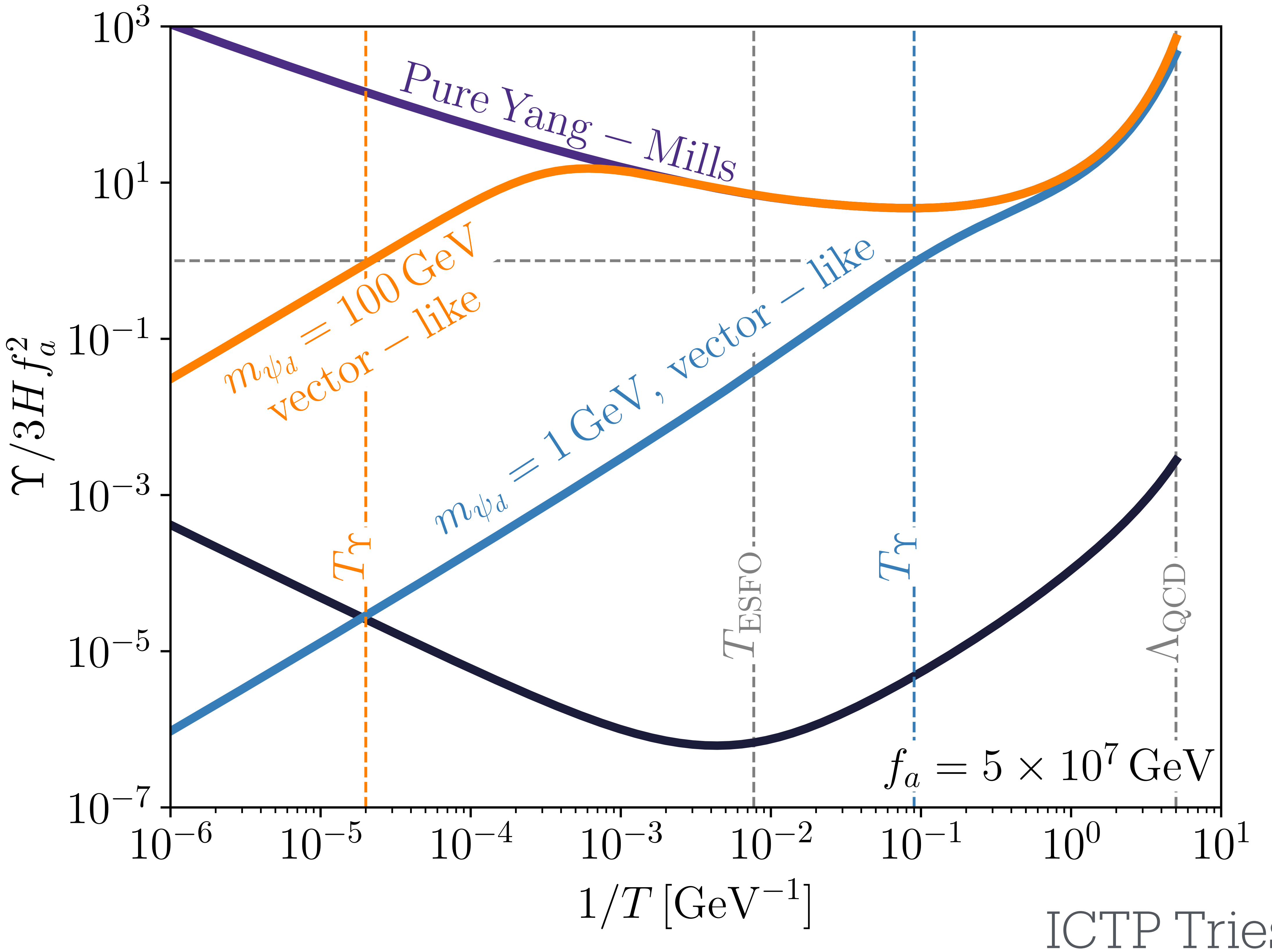
- **Overclosure:** $SU(N_d)$ sphalerons absorb θ_2 energy



A two-axion example

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{2}f_1^2(\partial\theta_1)^2 + \frac{1}{2}f_2^2(\partial\theta_2)^2 + \frac{\alpha_c}{8\pi}(C_1\theta_1 + C_2\theta_2)\tilde{G}_c G_c + \frac{\alpha_d}{8\pi}\theta_2\tilde{G}_d G_d$$

- **Overclosure:** $SU(N_d)$ sphalerons absorb θ_2 energy
  - No light fermions with $SU(N_d)$ charge $\rightarrow$ strong sphaleron damping of $\dot{\theta}_2$



A two-axion example

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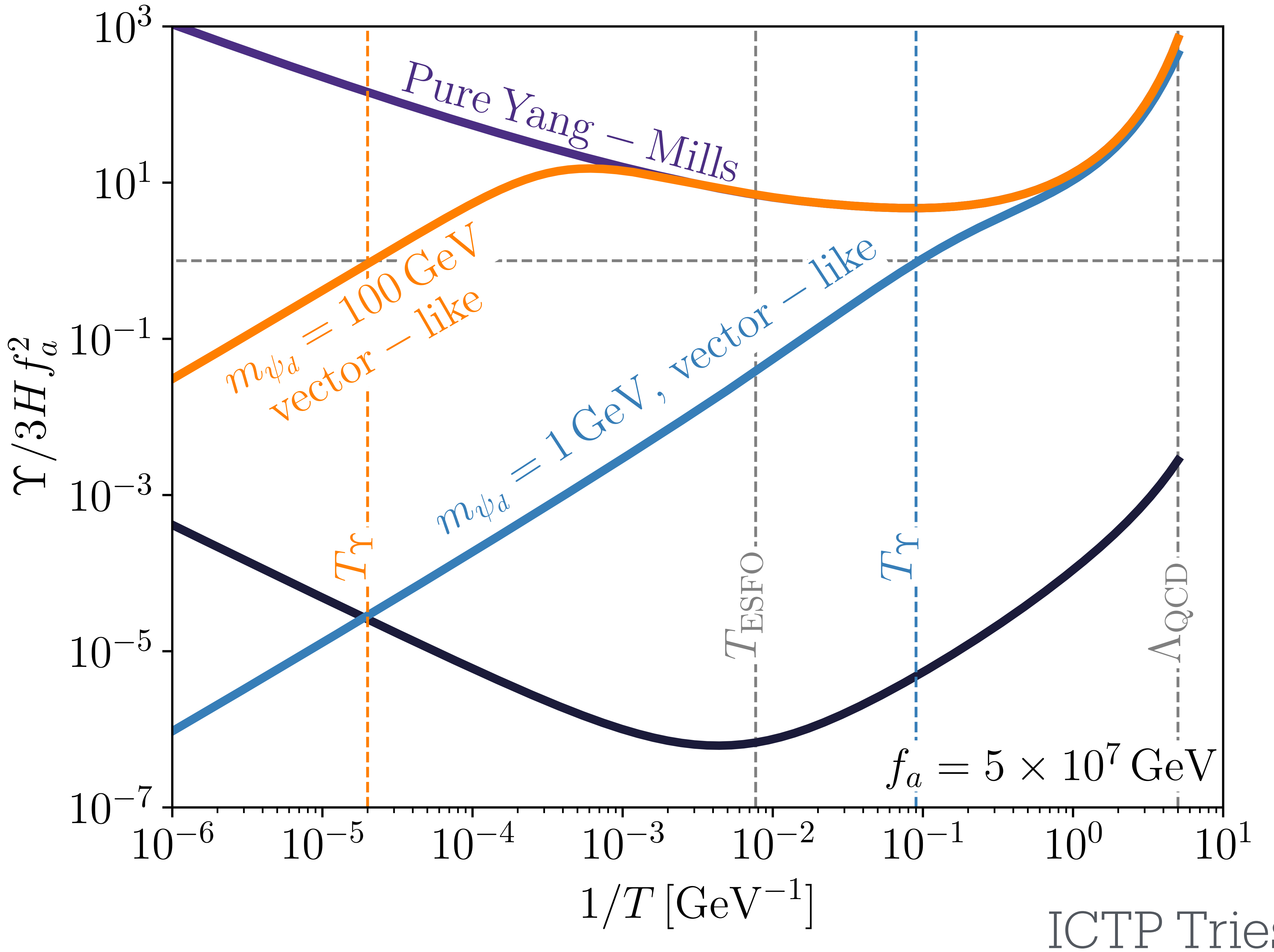
  - Mixing with θ_1



A two-axion example

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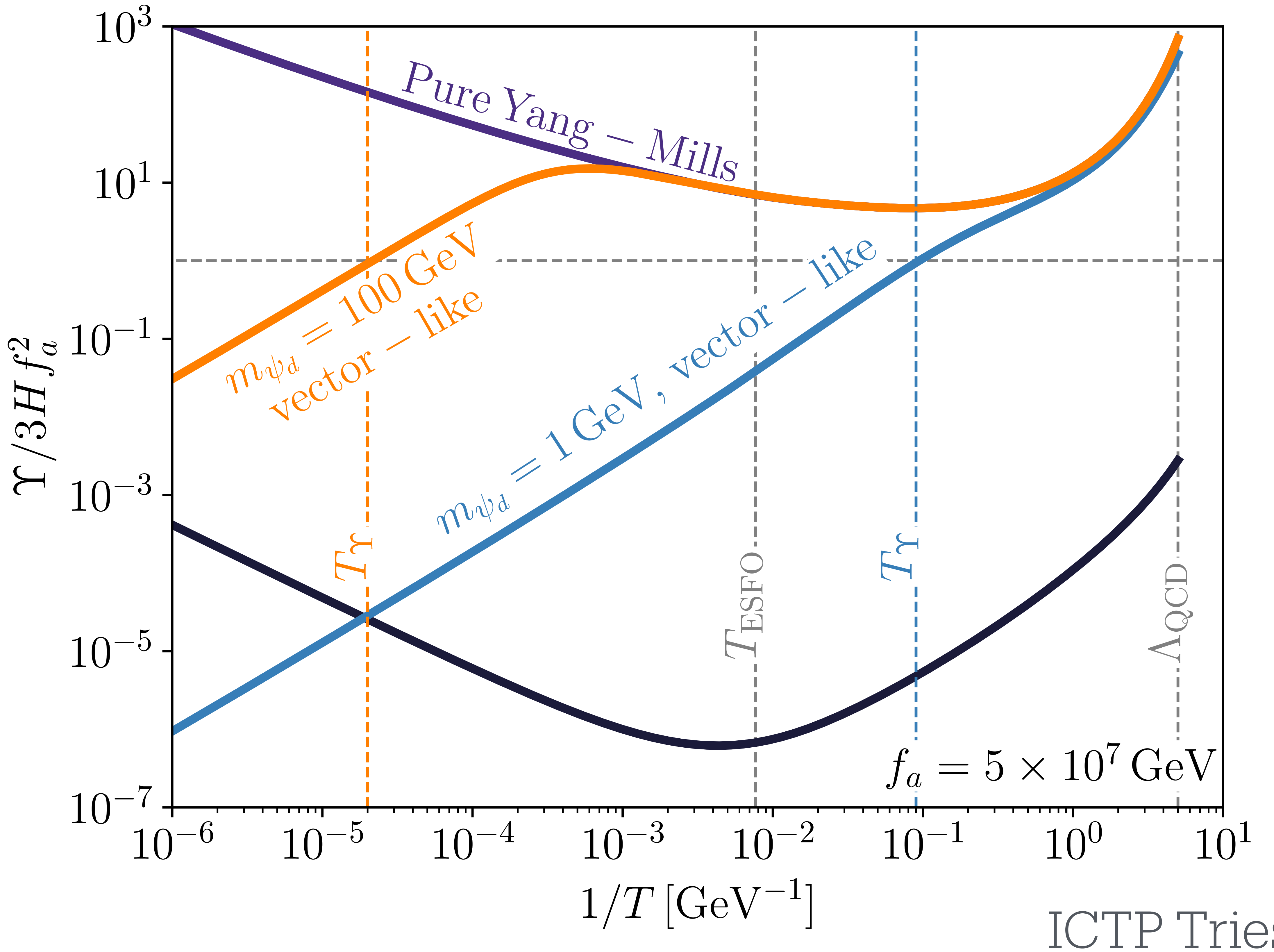
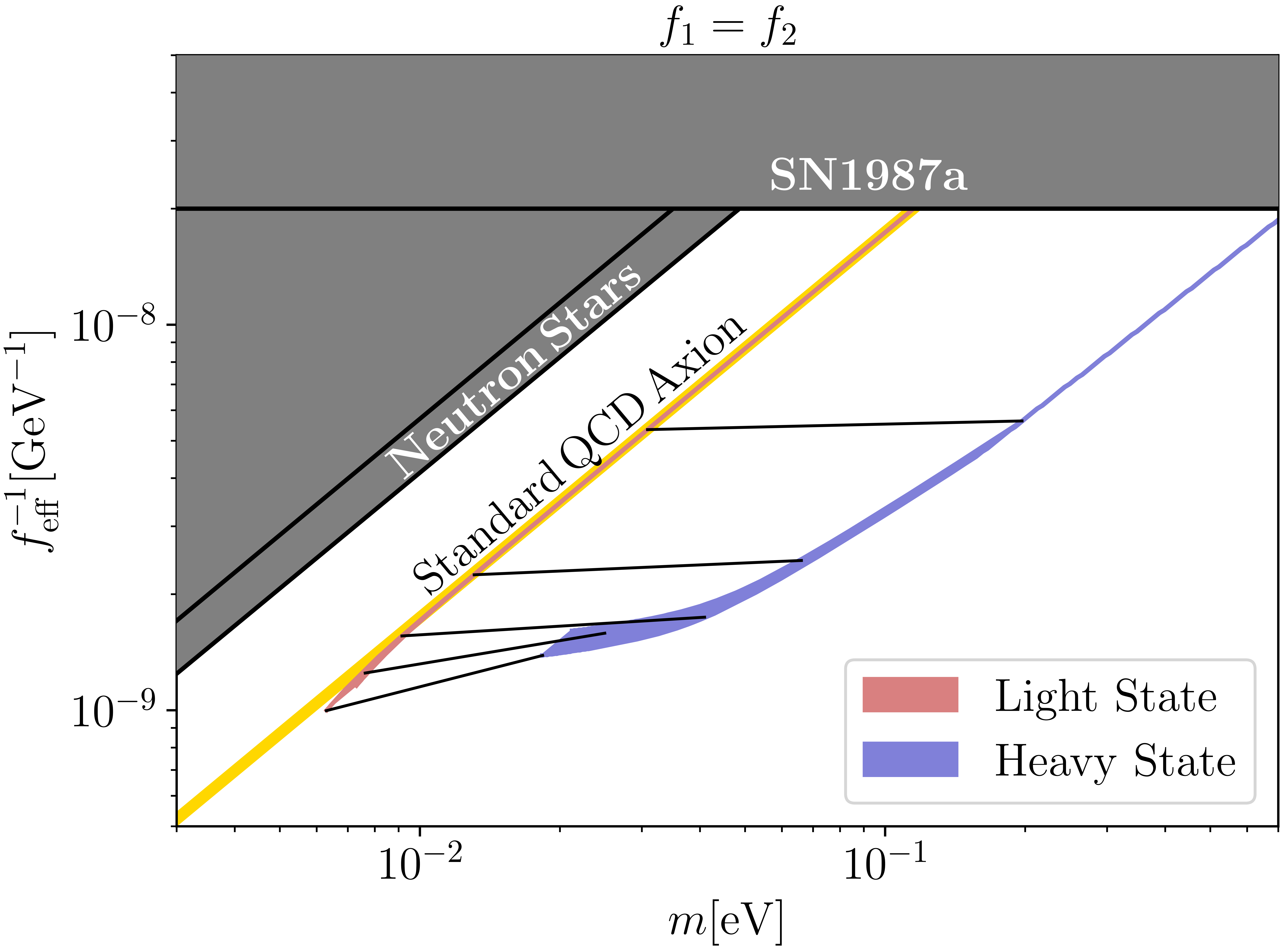
- **Overclosure:** $SU(N_d)$ sphalerons absorb θ_2 energy
  - No light fermions with $SU(N_d)$ charge $\rightarrow$ strong sphaleron damping of $\dot{\theta}_2$
  - Mixing with θ_1
    - Avoid overclosure

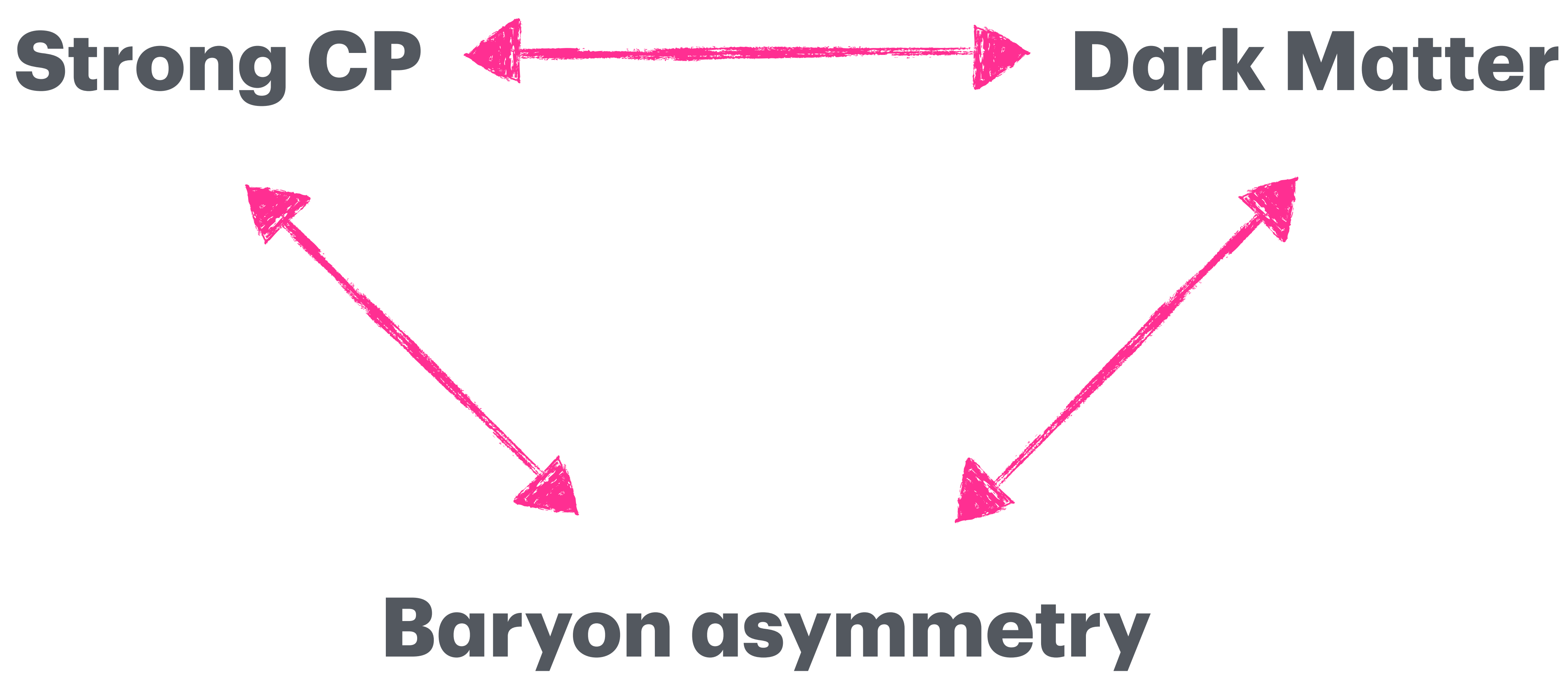




$f_1 = f_2$
SN1987a
Neutron Stars
Standard QCD Axion
Light State
Heavy State
10^{-8}
10^{-9}
$f_{\rm eff}^{-1}\,[\mathrm{GeV}^{-1}]$
10^{-2}
10^{-1}
$m\,[\mathrm{eV}]$

Phenomenology

- **Haloscope:** EV-scale QCD-like axion and heavier partner
- **Collider:** new weak-charged fermions with $m_f \in [0.25, 4.0]\,\mathrm{TeV}$
- **Astrophysics:** Axion minihalos
- **Cosmology:** Dark glueball decay signatures from BBN

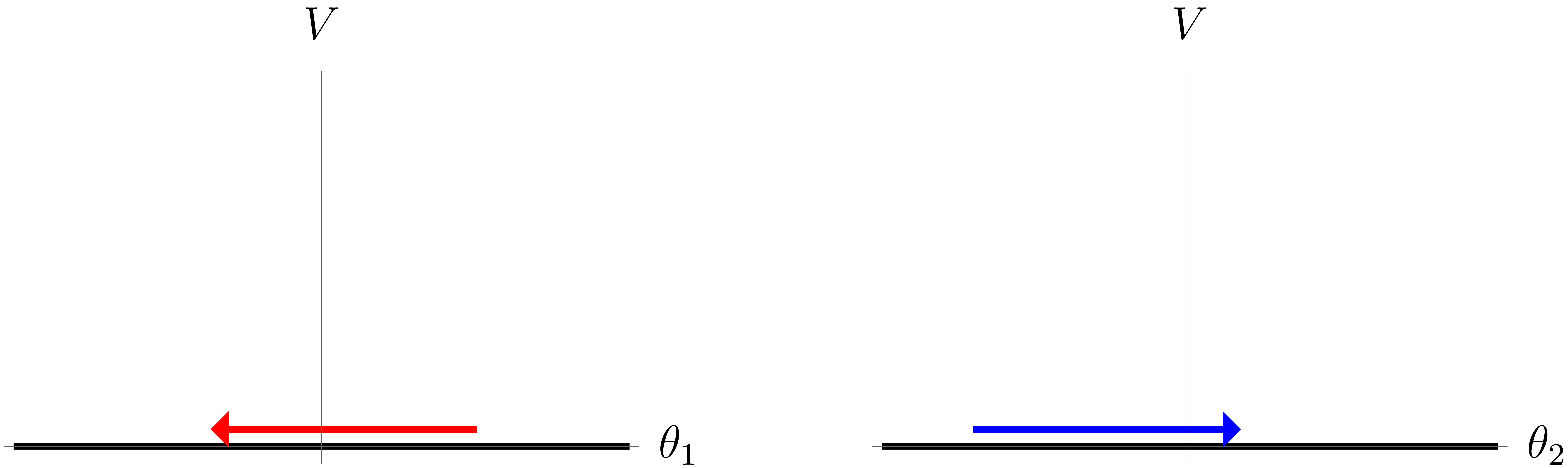


Thank you

Dynamics

$$0 = \ddot{\theta}_1 + 3H\dot{\theta}_1 + \frac{\chi_c}{f_1^2}\sin(\theta_1 + \theta_2)$$

$$0 = \ddot{\theta}_2 + \left(3H + \frac{\Upsilon_d}{f_2^2}\right)\dot{\theta}_2 + \frac{\chi_c}{f_2^2}\sin(\theta_1 + \theta_2) + \frac{\chi_d}{f_2^2}\sin\theta_2$$



Dynamics

$$0 = \ddot{\theta}_1 + 3H\dot{\theta}_1 + \cancel{\frac{\chi}{f_1^2}} \sin(\theta_1 + \theta_2)$$

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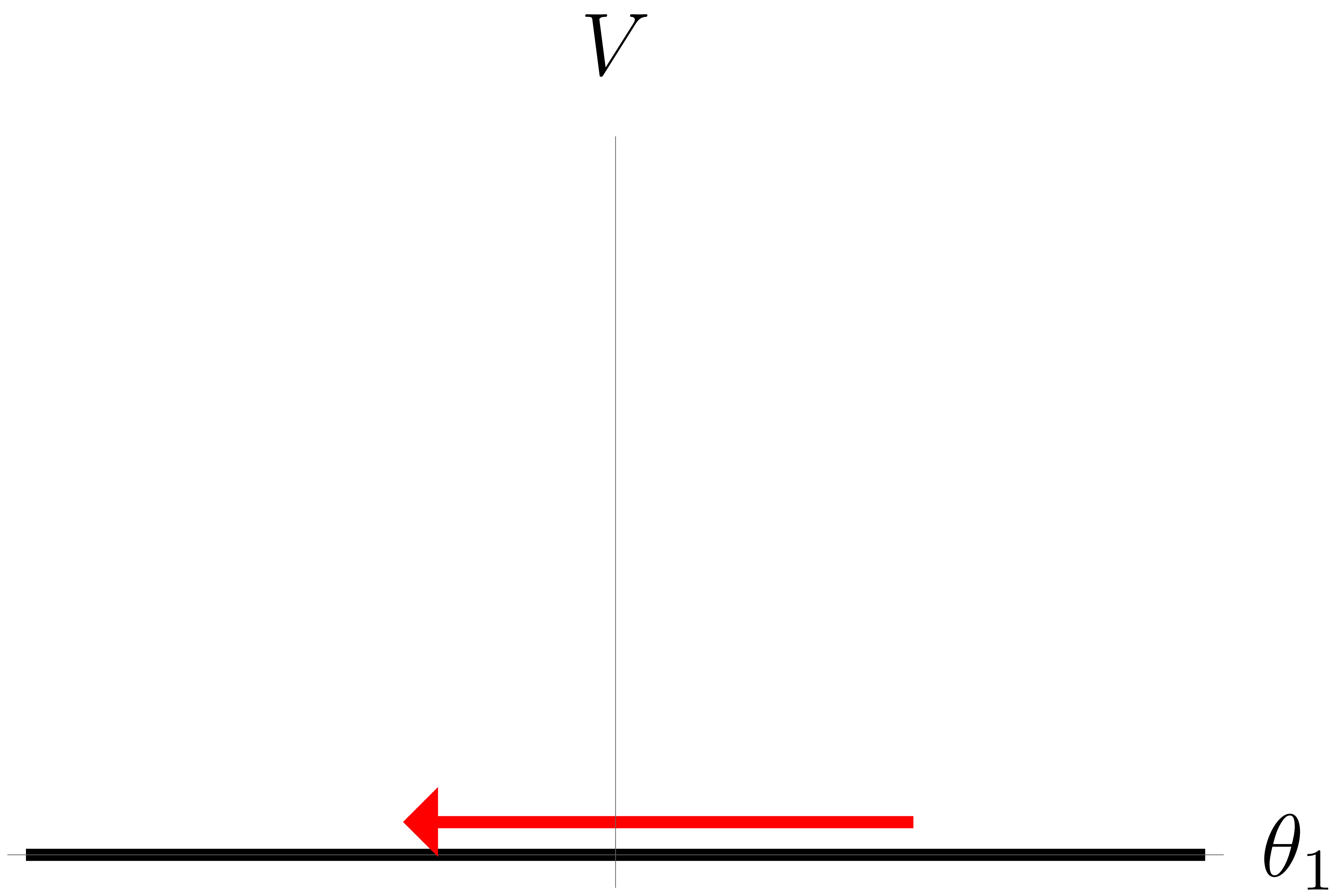

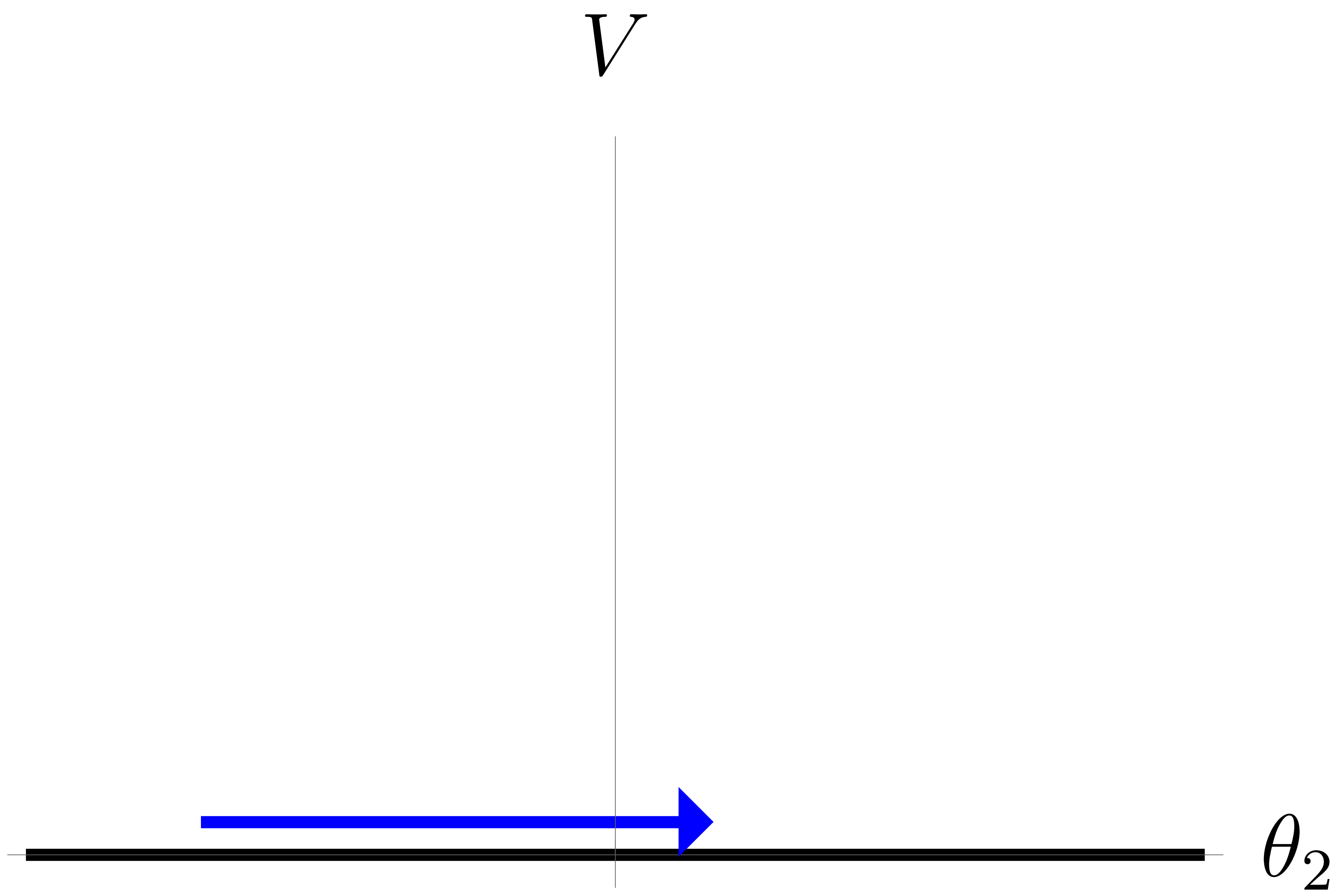

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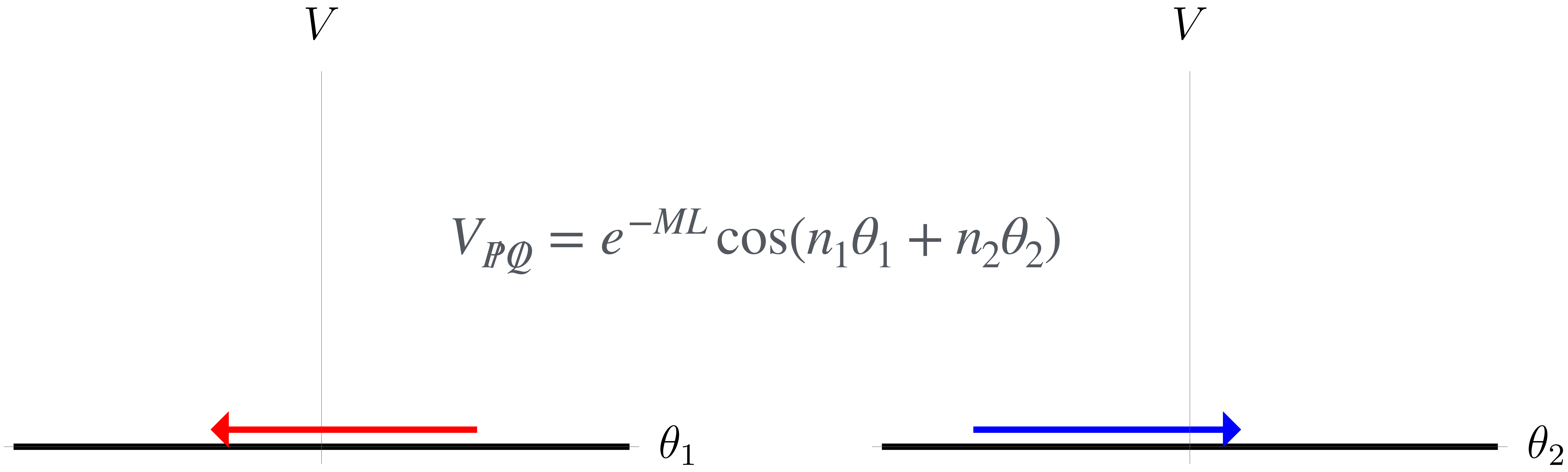

$$V_{\not P \not Q} = e^{-ML}\cos(n_1\theta_1 + n_2\theta_2)$$

Dynamics

$$0 = \ddot{\theta}_1 + 3H\dot{\theta}_1 + \cancel{\frac{\chi}{f_1}} \sin(\theta_1 + \theta_2)$$

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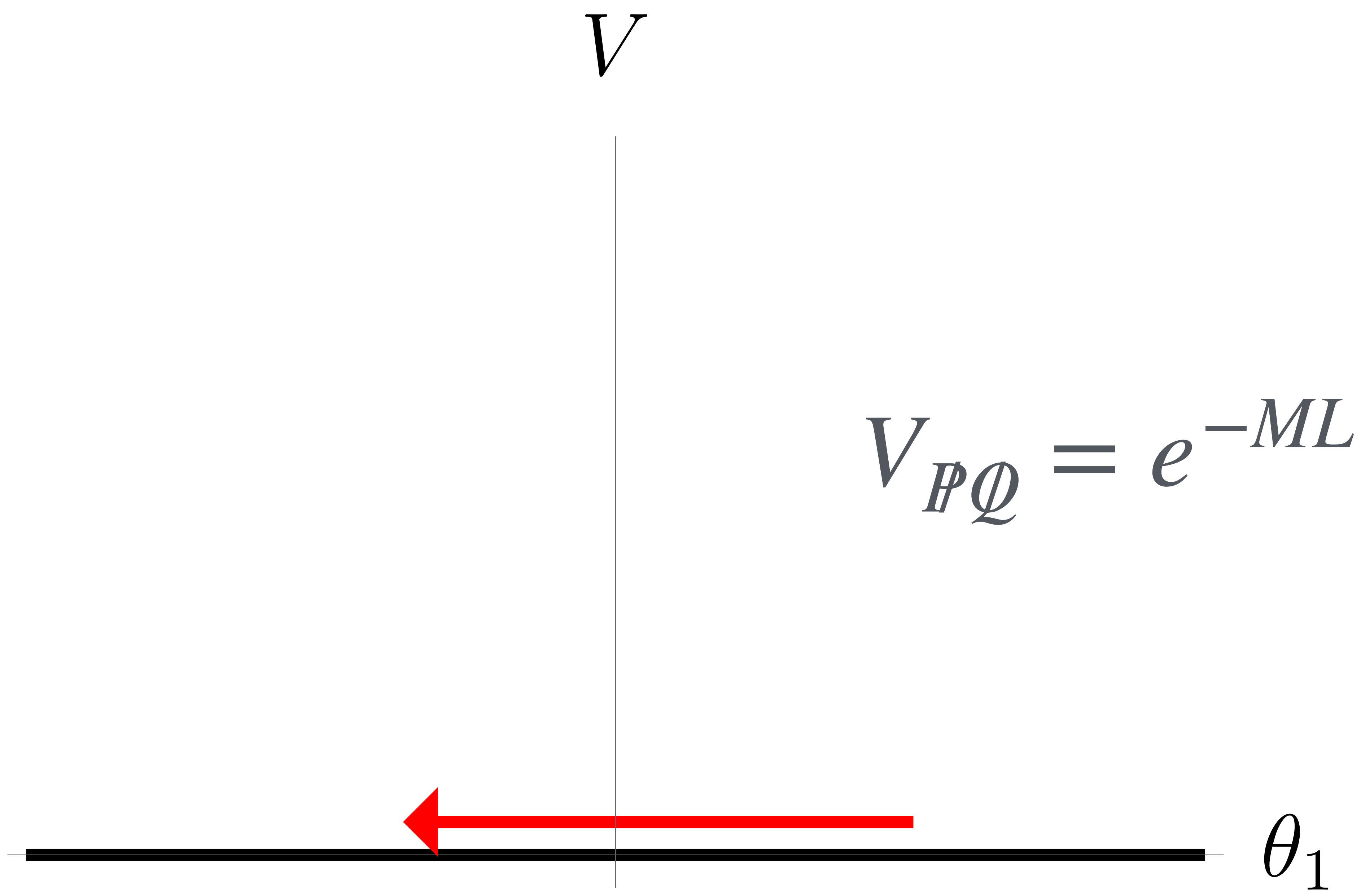

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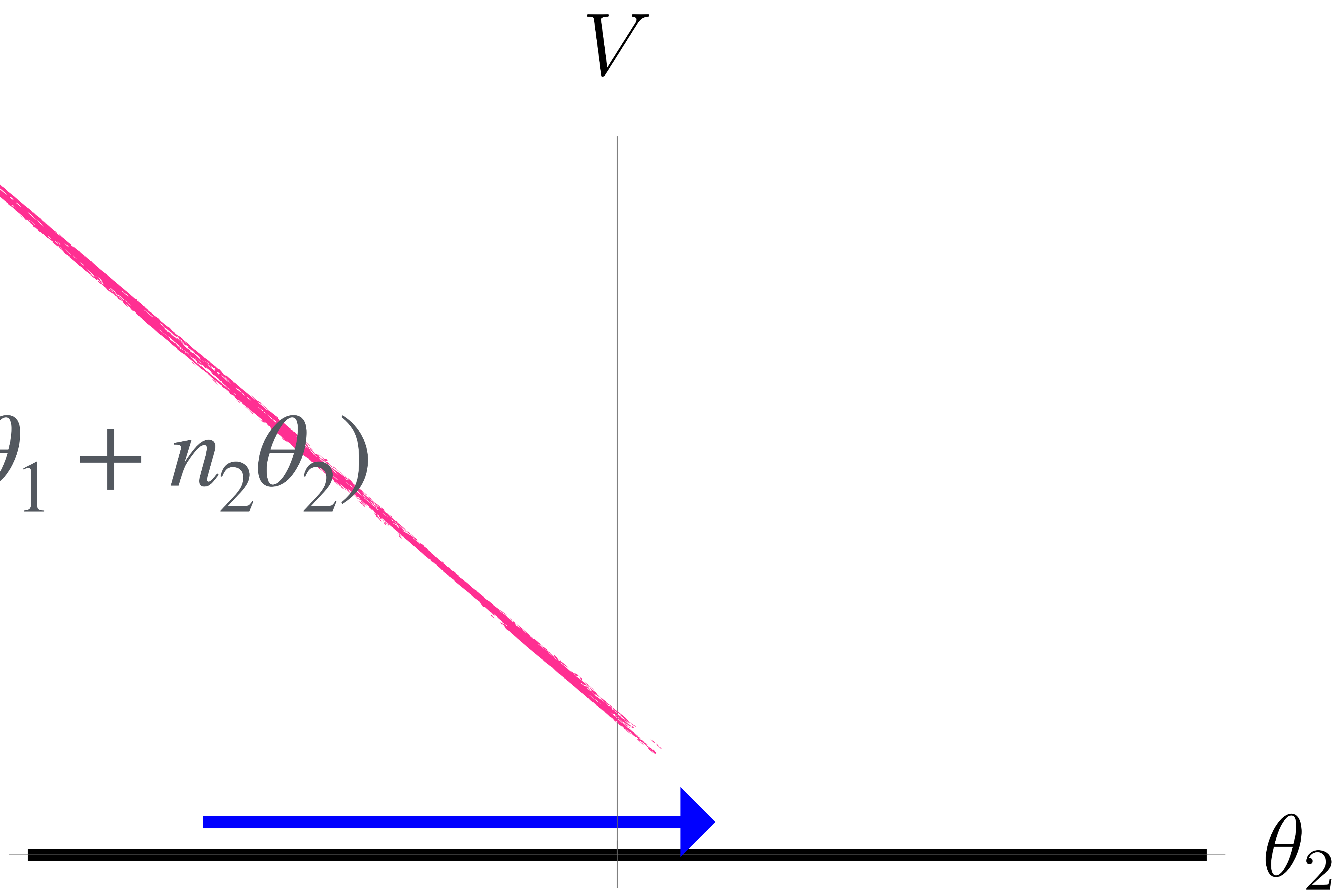

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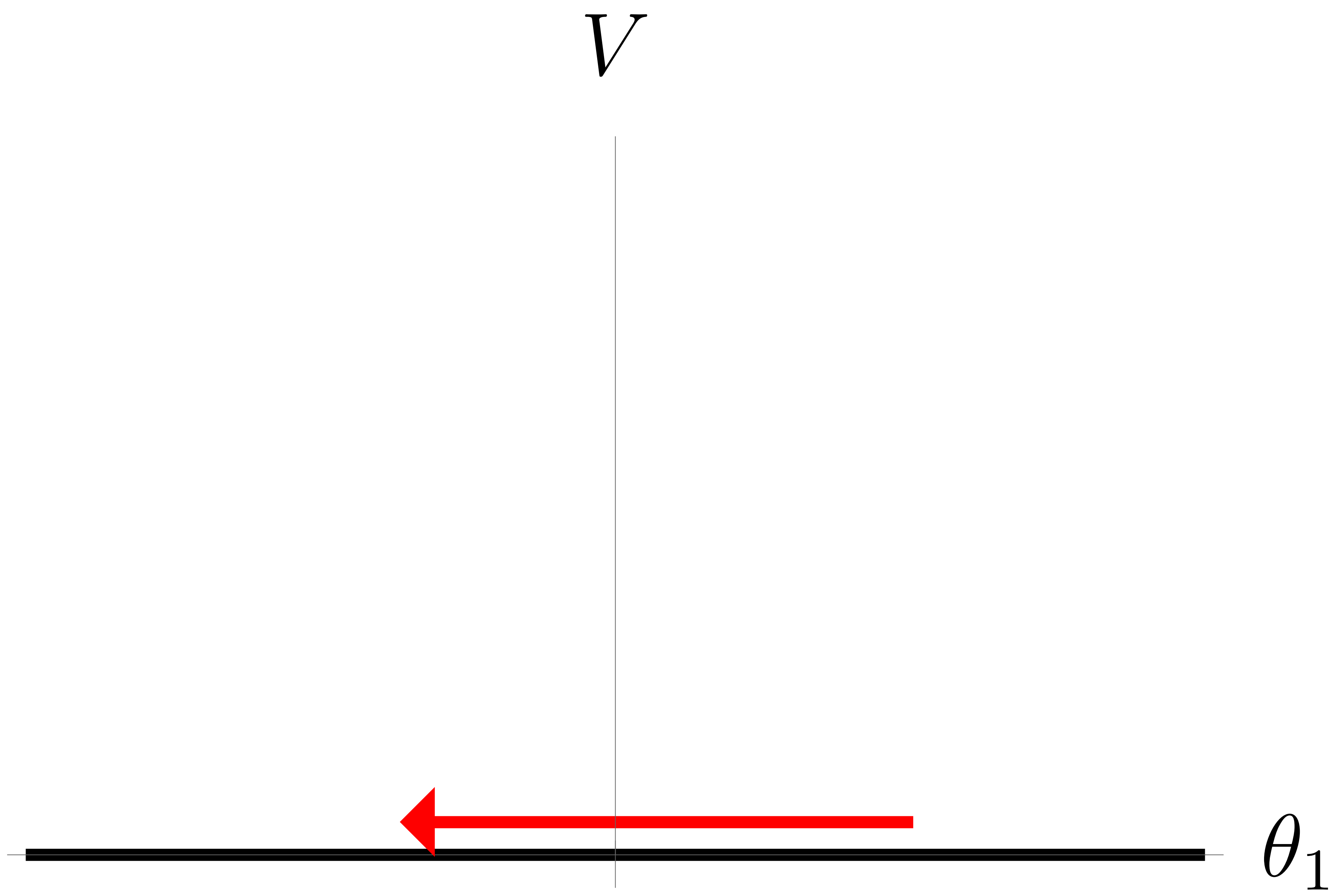

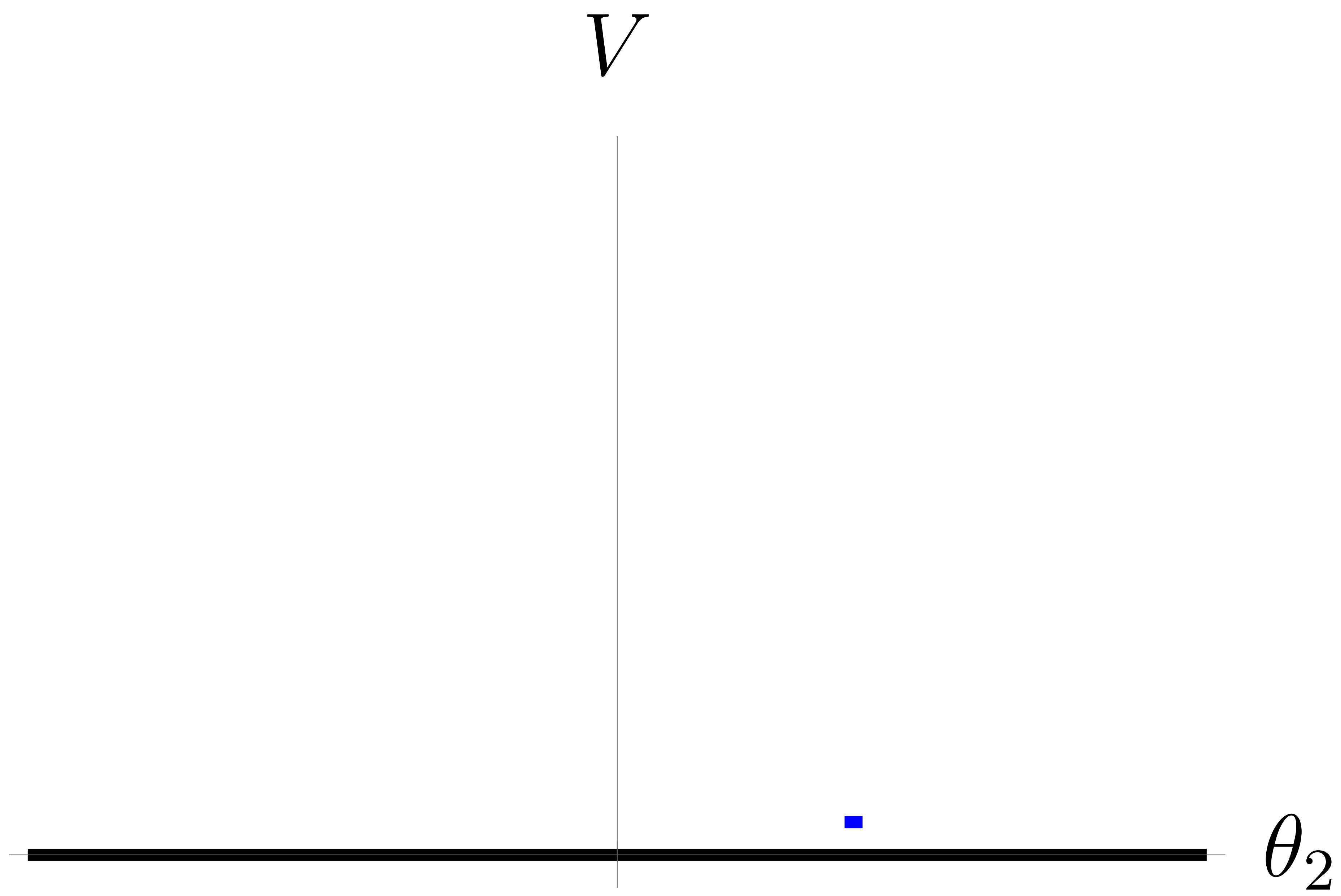

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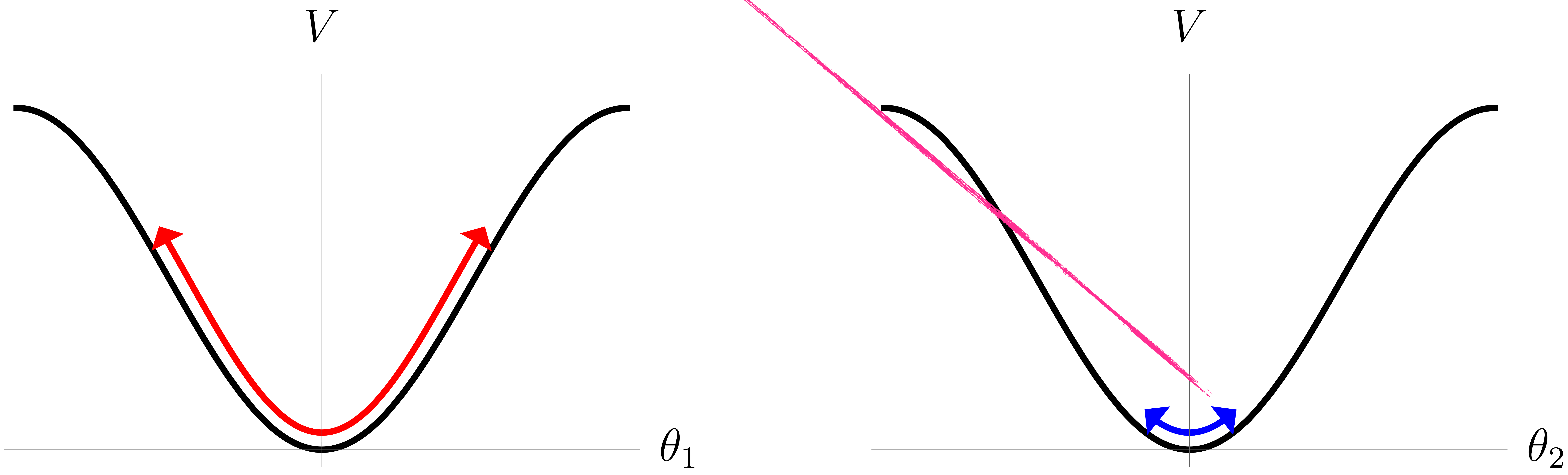

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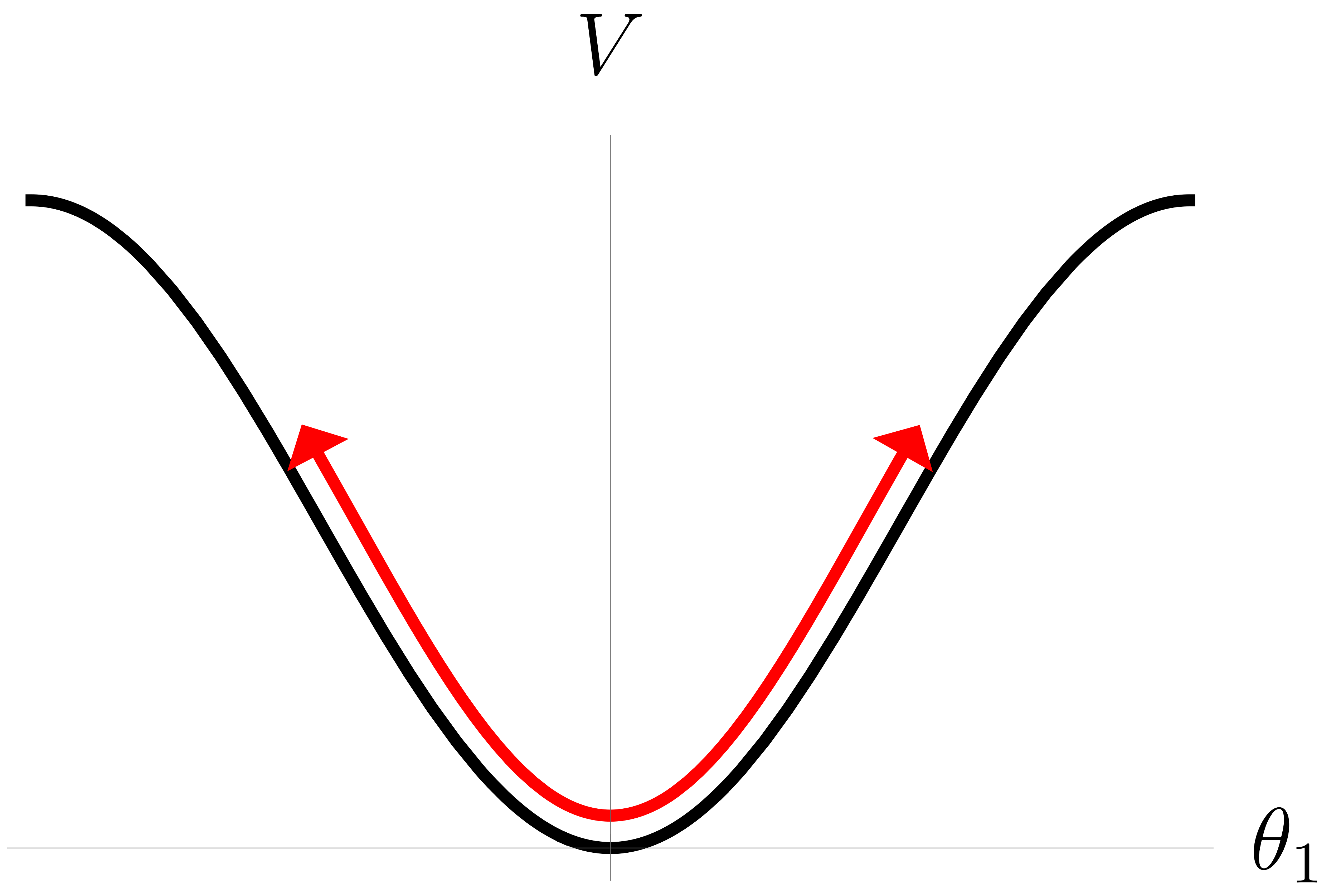

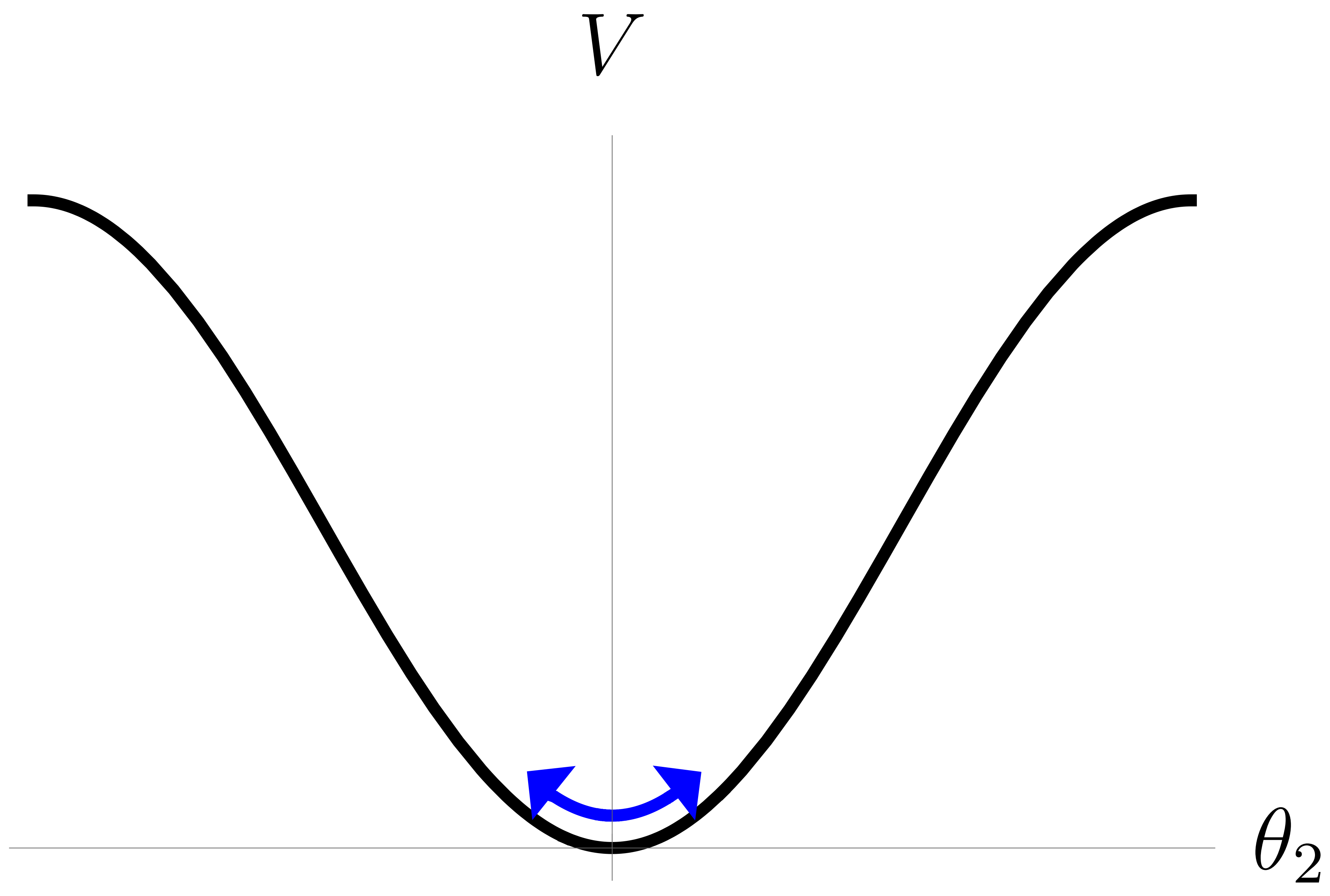

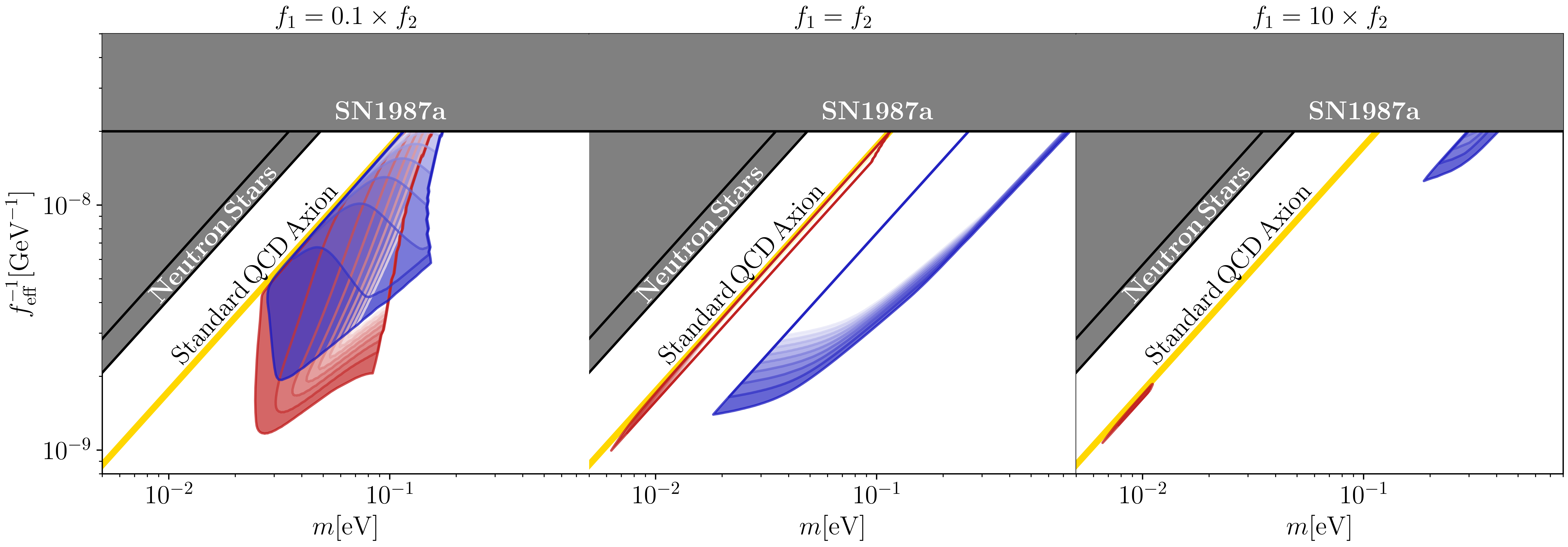
$f_1 = 0.1 \times f_2$
$f_1 = f_2$
$f_1 = 10 \times f_2$
SN1987a
SN1987a
SN1987a
Neutron Stars
Standard QCD Axion
Neutron Stars
Standard QCD Axion
Neutron Stars
Standard QCD Axion
$f_{\rm eff}^{-1}[\mathrm{GeV}^{-1}]$
10^{-8}
10^{-9}
10^{-2}
10^{-1}
$m[\mathrm{eV}]$
10^{-2}
10^{-1}
$m[\mathrm{eV}]$
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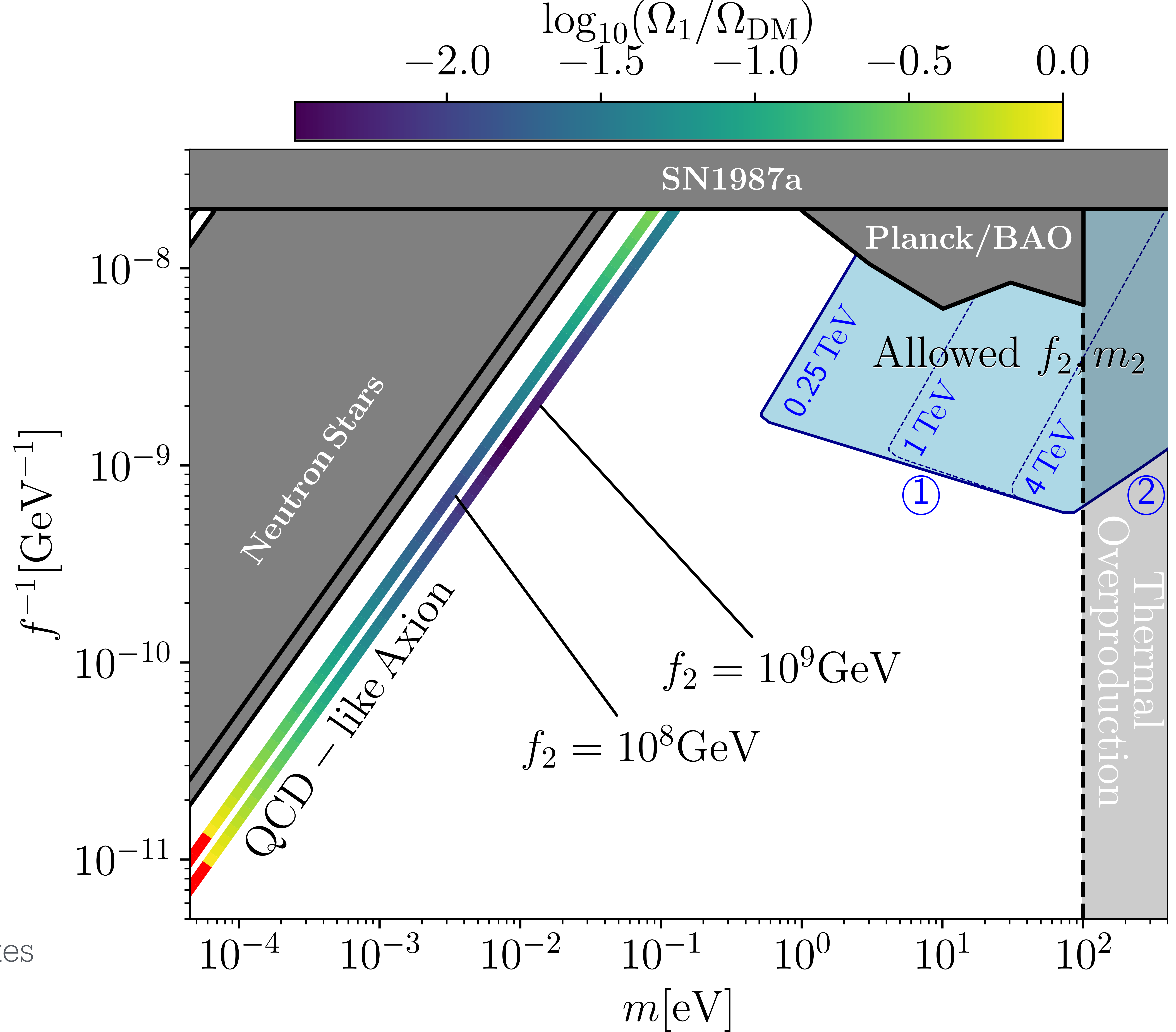
10^{-1}
$m[\mathrm{eV}]$



$\log_{10}(\Omega_1/\Omega_{DM})$
-2.0 -1.5 -1.0 -0.5 0.0
SN1987a
Planck/BAO
Neutron Stars
Allowed f_2, m_2
0.25 TeV
1 TeV
4 TeV
①
②
QCD − like Axion
$f_2 = 10^9\mathrm{GeV}$
$f_2 = 10^8\mathrm{GeV}$
Thermal Overproduction
$f^{-1}[\mathrm{GeV}^{-1}]$
10^{-8} 10^{-9} 10^{-10} 10^{-11}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
$m[\mathrm{eV}]$