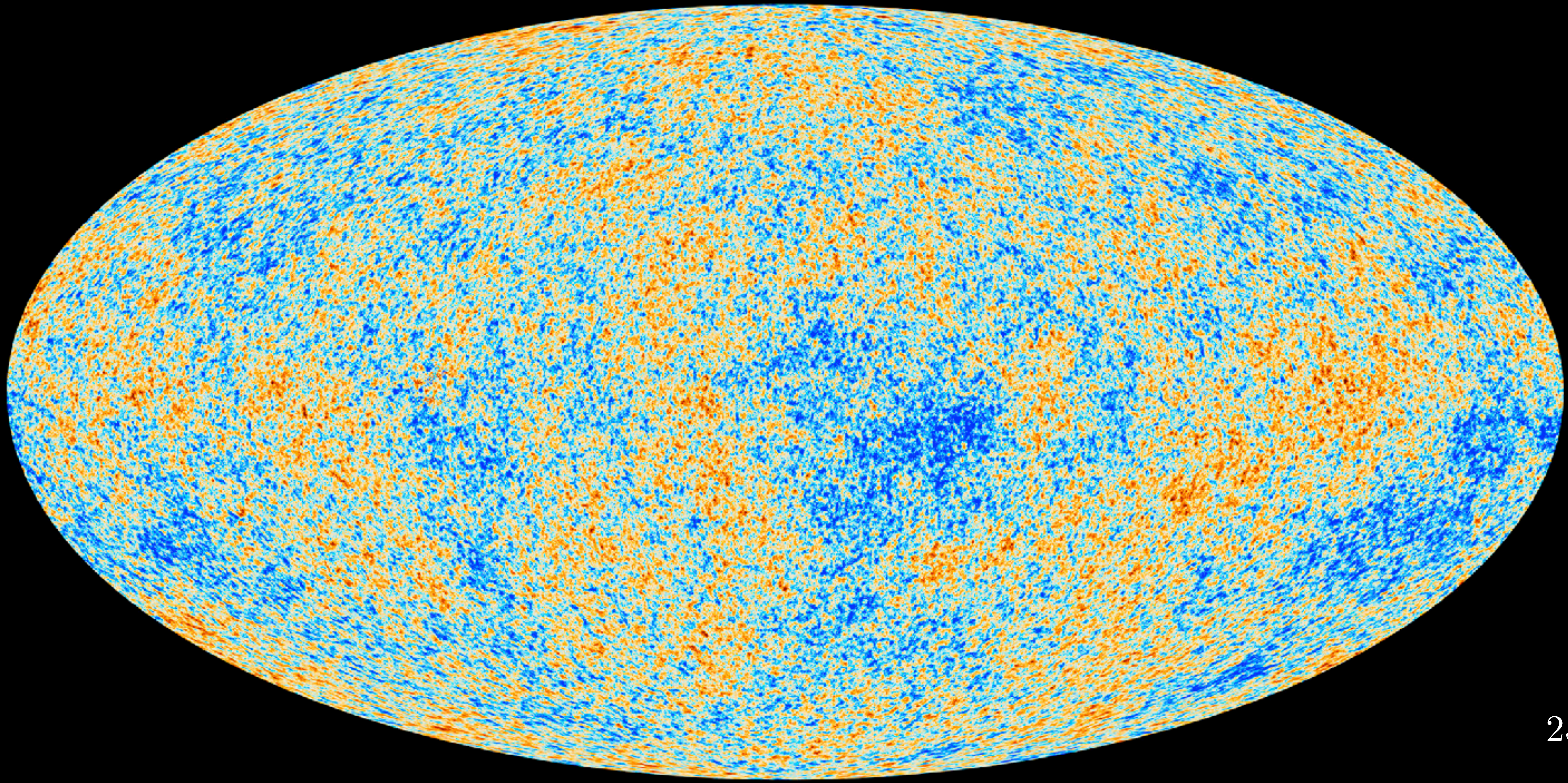
Dark Radiation from the Axiverse



Christopher Dessert

2507.xxxxx w/ Ruderman, Kumar

NYU FLATIRON INSTITUTE

Credits: ESA/Planck Collaboration

The Standard Model

- Nature is described by internal symmetries, e.g.

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

and spacetime symmetries

$$C, P, T$$

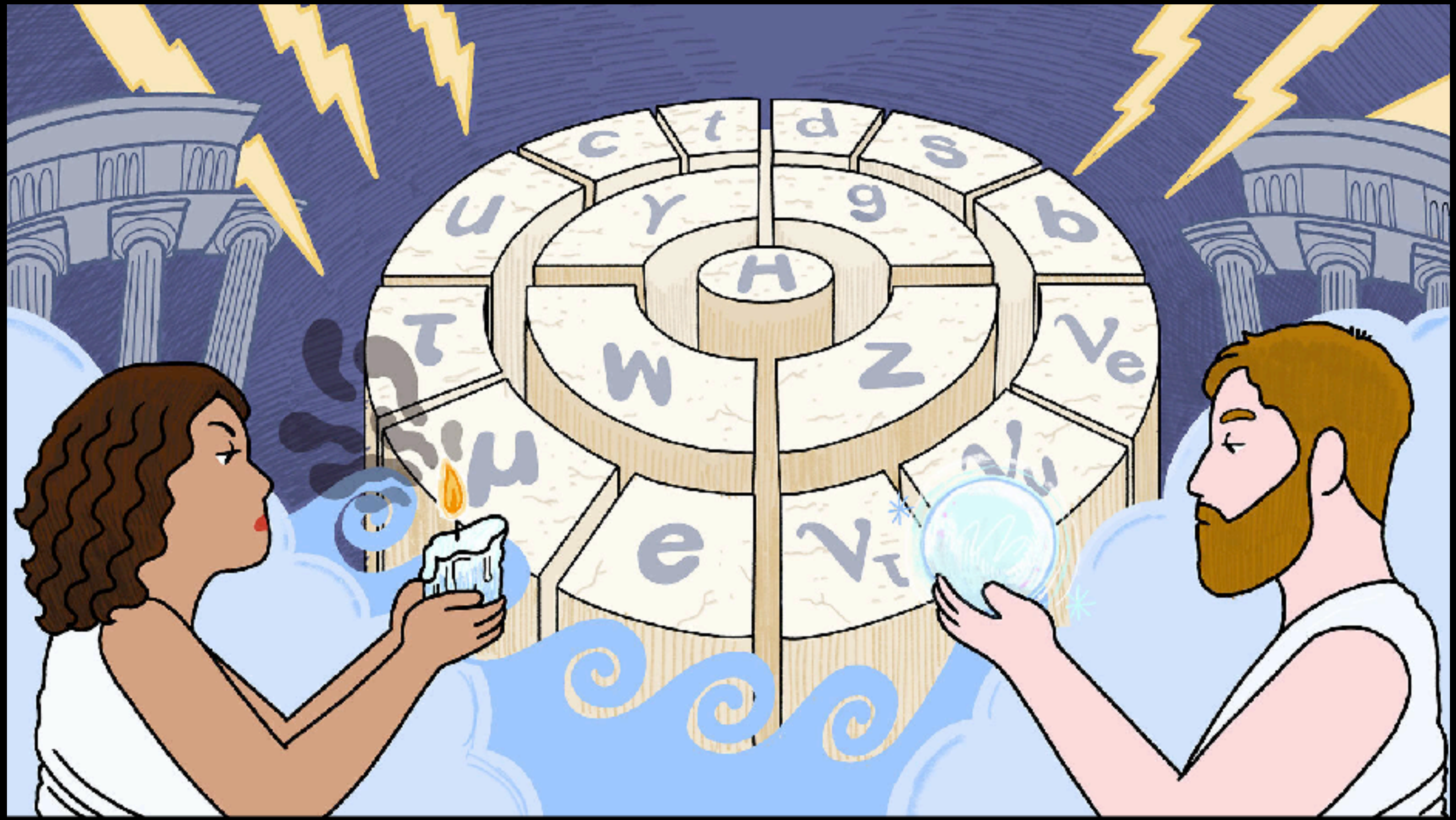


Illustration by Sandbox Studio, Chicago with Corinne Mucha

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  → EWSB
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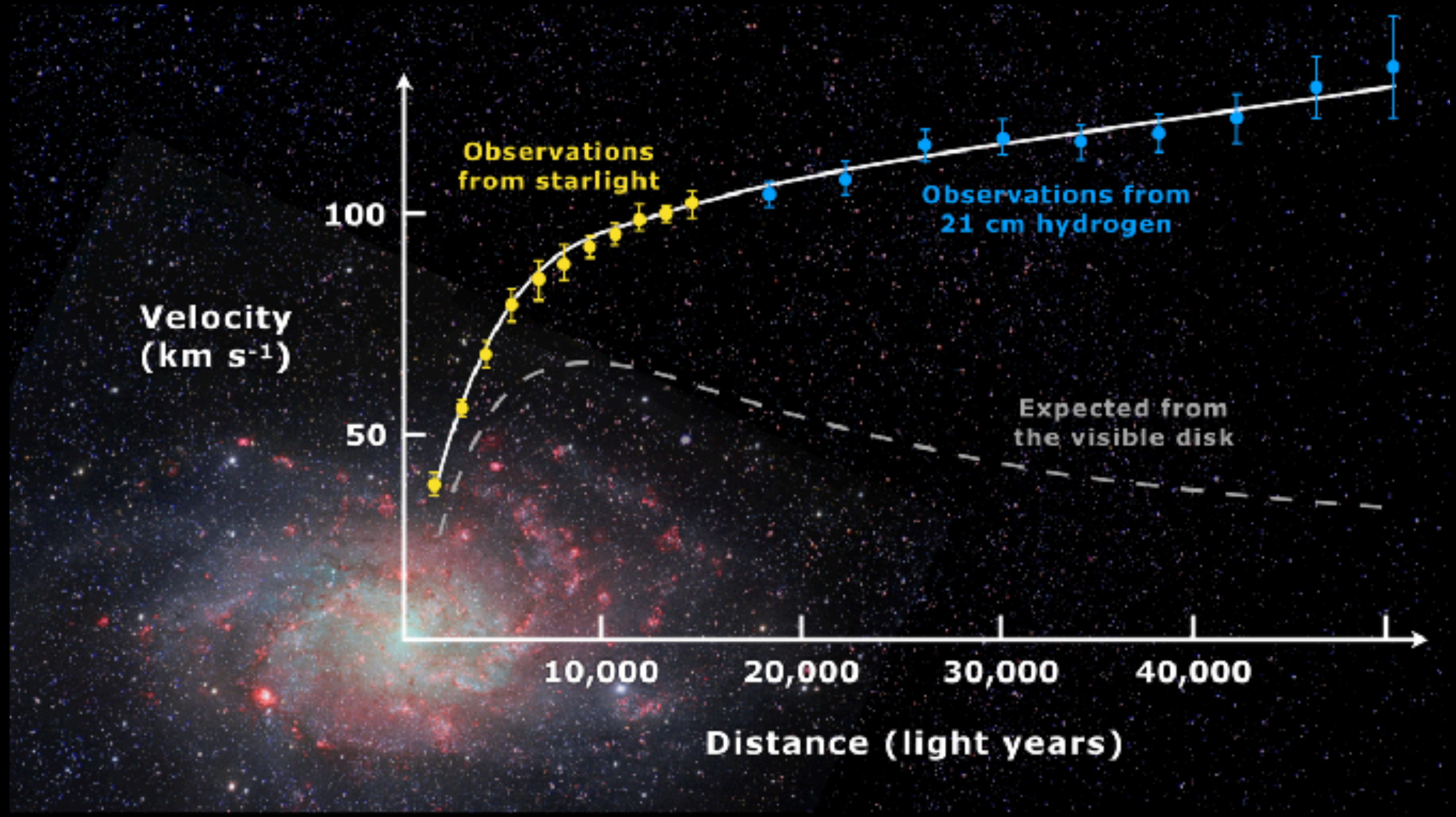
→ ~~Dark Matter (observation)~~ ✗



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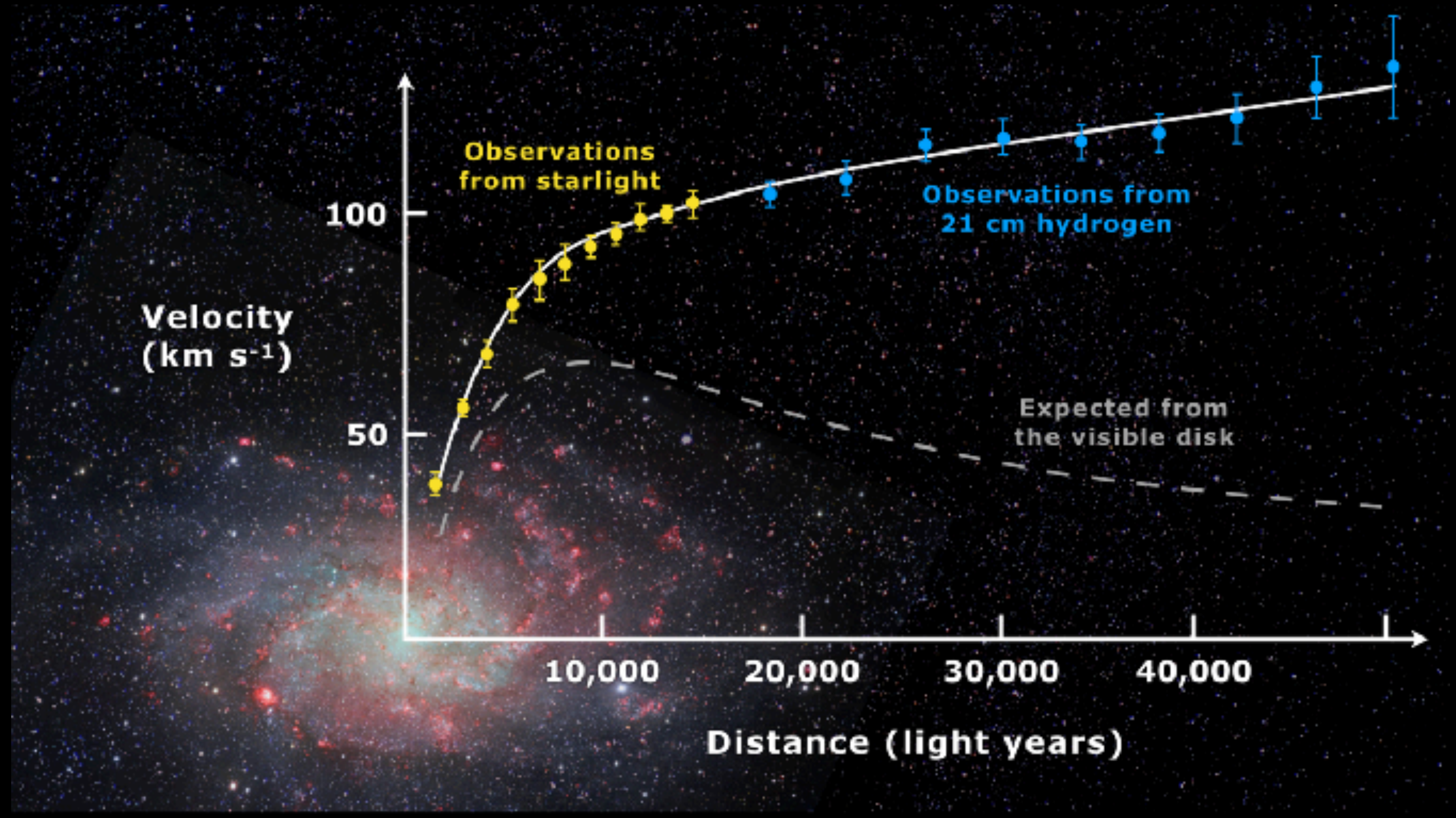
Dark Matter (observation)

~~CP~~ (theoretical)



CP Violation in the SM

- $\not{CP}$ from weak sector (δ) and strong sector (θ):
  - Weak $\not{CP}$ $\rightarrow$ Kaon decays, etc. $\delta \sim 1.2$ rad
  - Strong $\not{CP}$?

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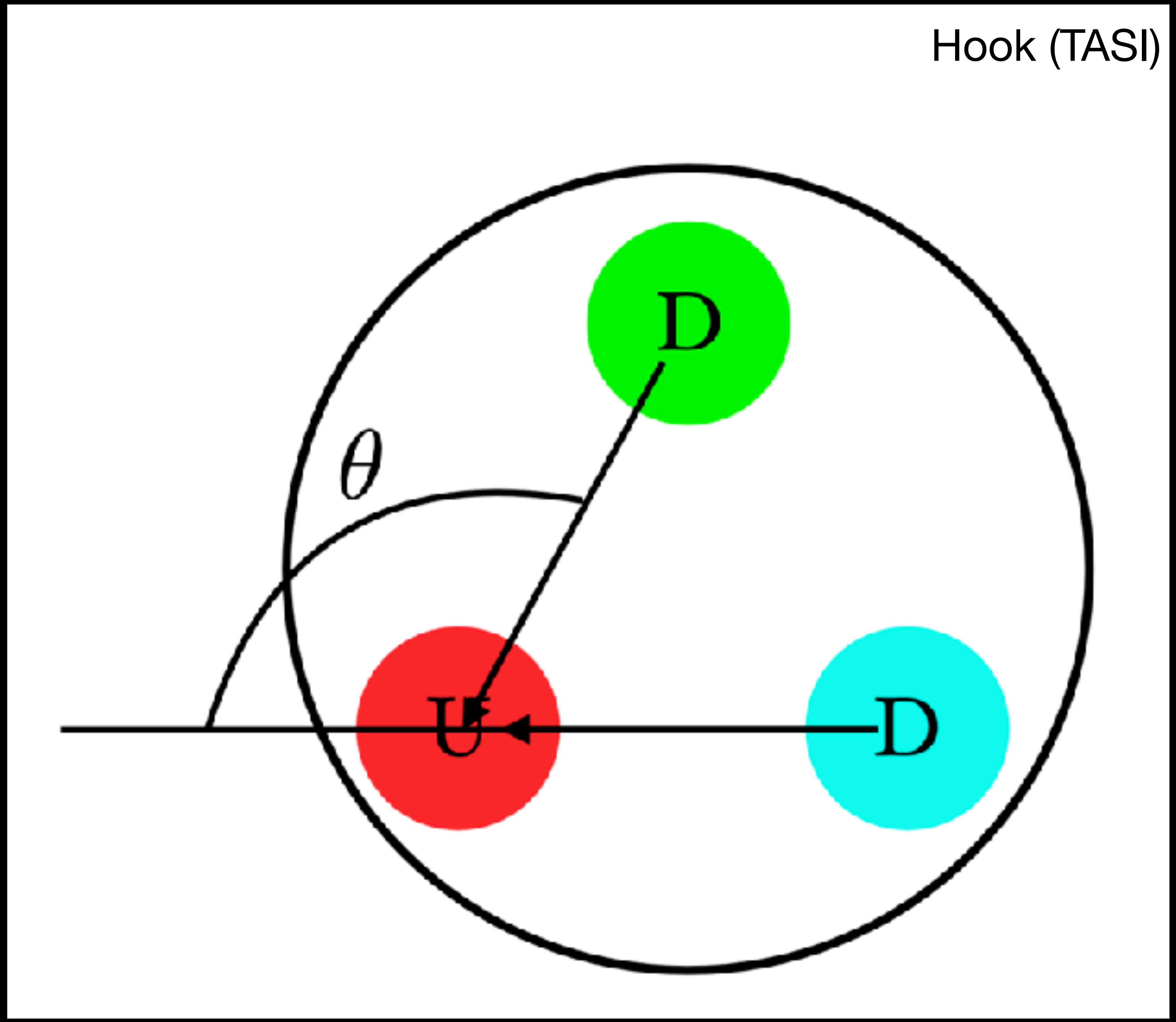
$$|d_n| \sim 10^{-16}\theta \; e \cdot \text{cm}$$



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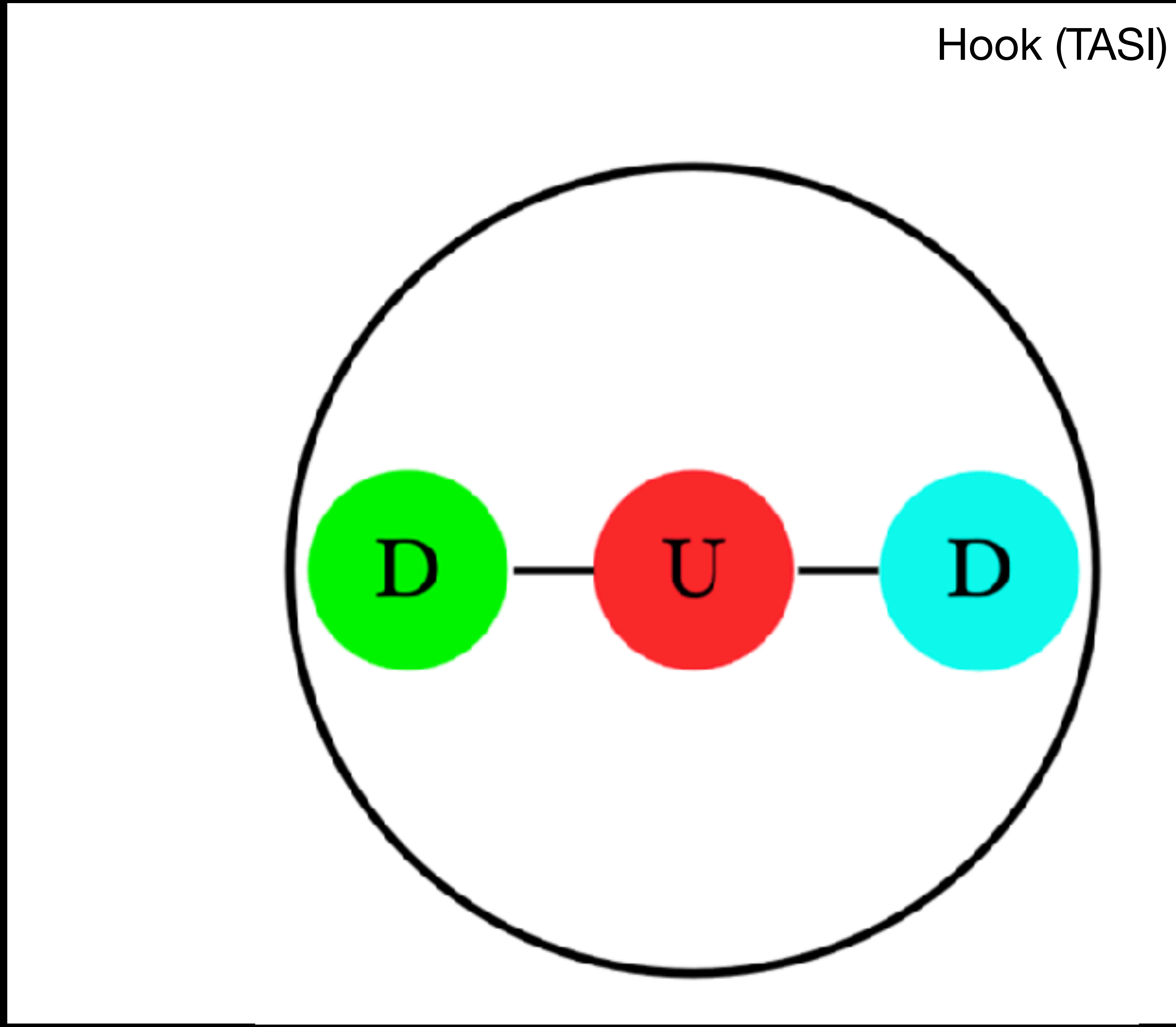

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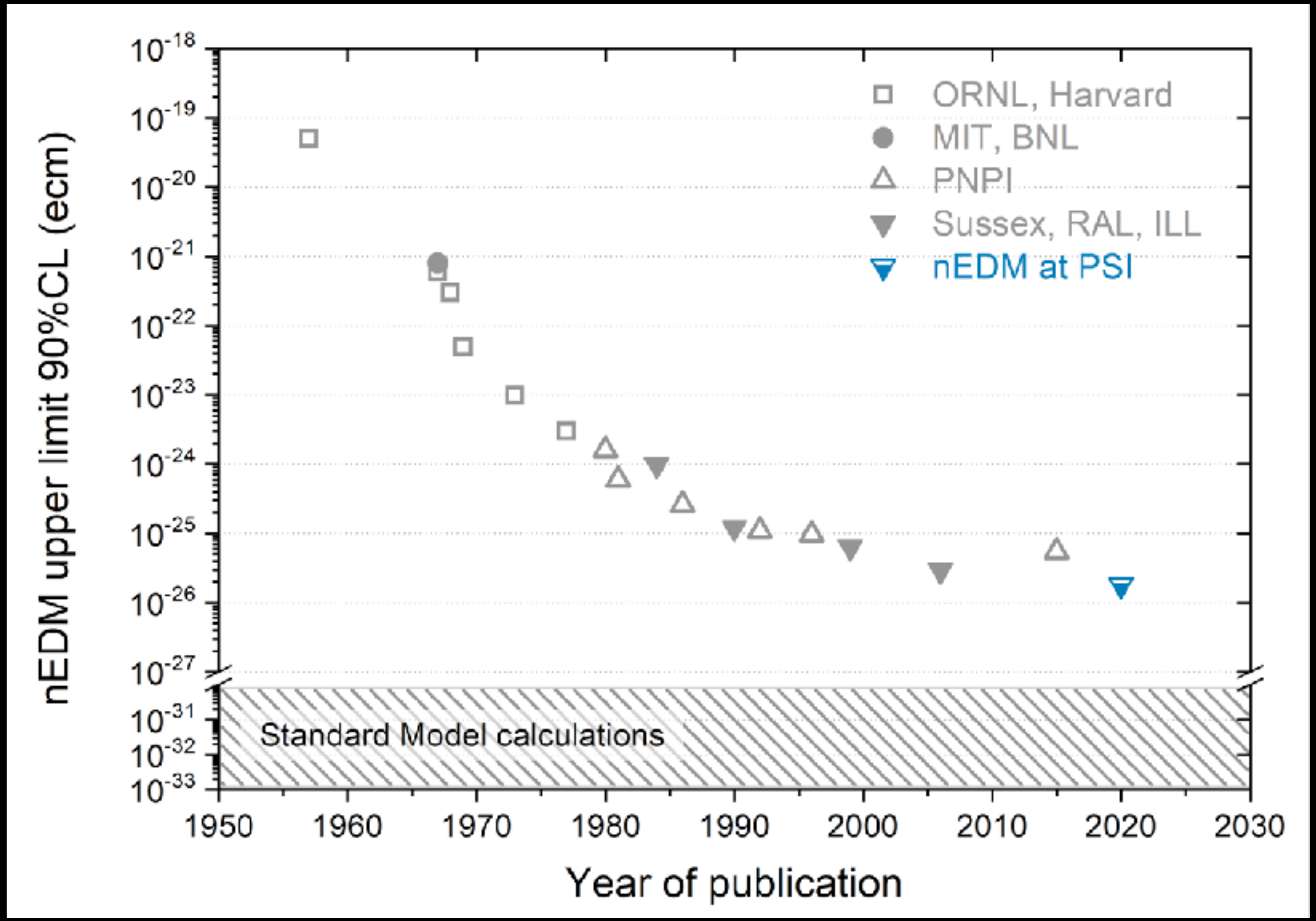

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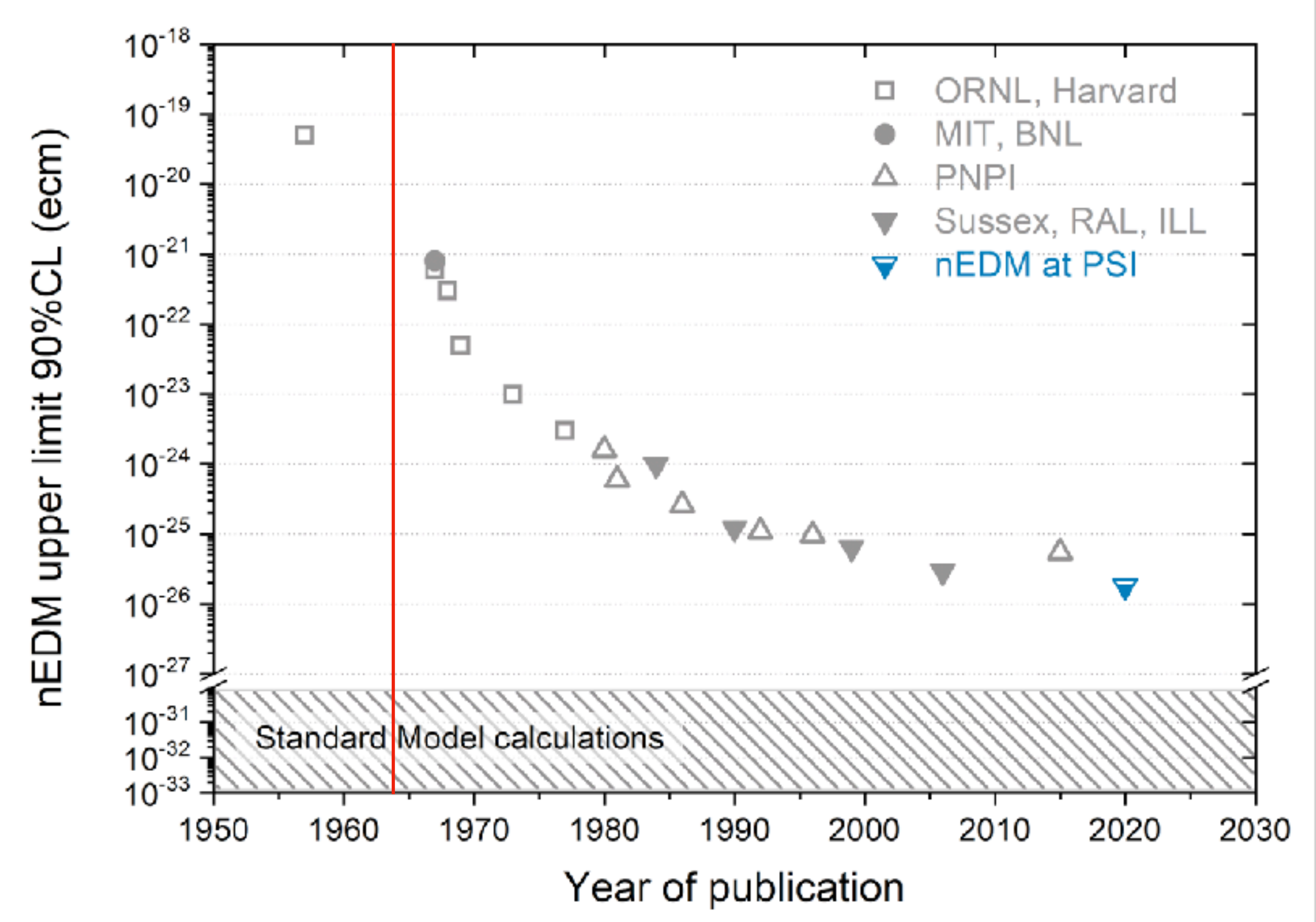
Weak $\not{C}\not{P}$ discovered



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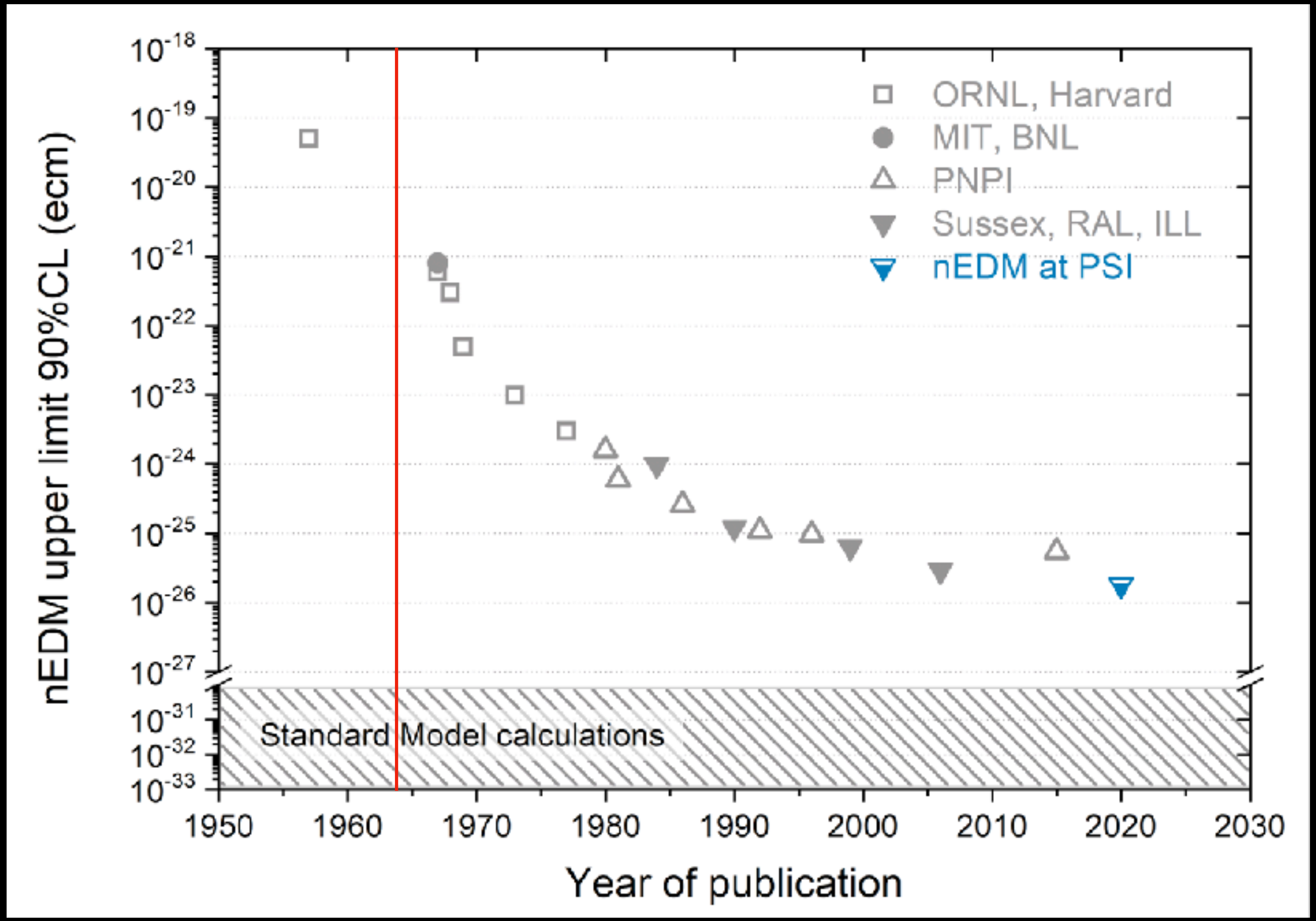
  - Weak $\not{C}\not{P}$ $\rightarrow$ Kaon decays, etc. $\delta \sim 1.2$ rad
  - Strong $\not{C}\not{P}$ $\rightarrow$ nEDM, $\theta \lesssim 10^{-10}$ rad
- Strong CP Problem: Why do the strong interactions conserve CP while the weak interactions maximally violate CP?

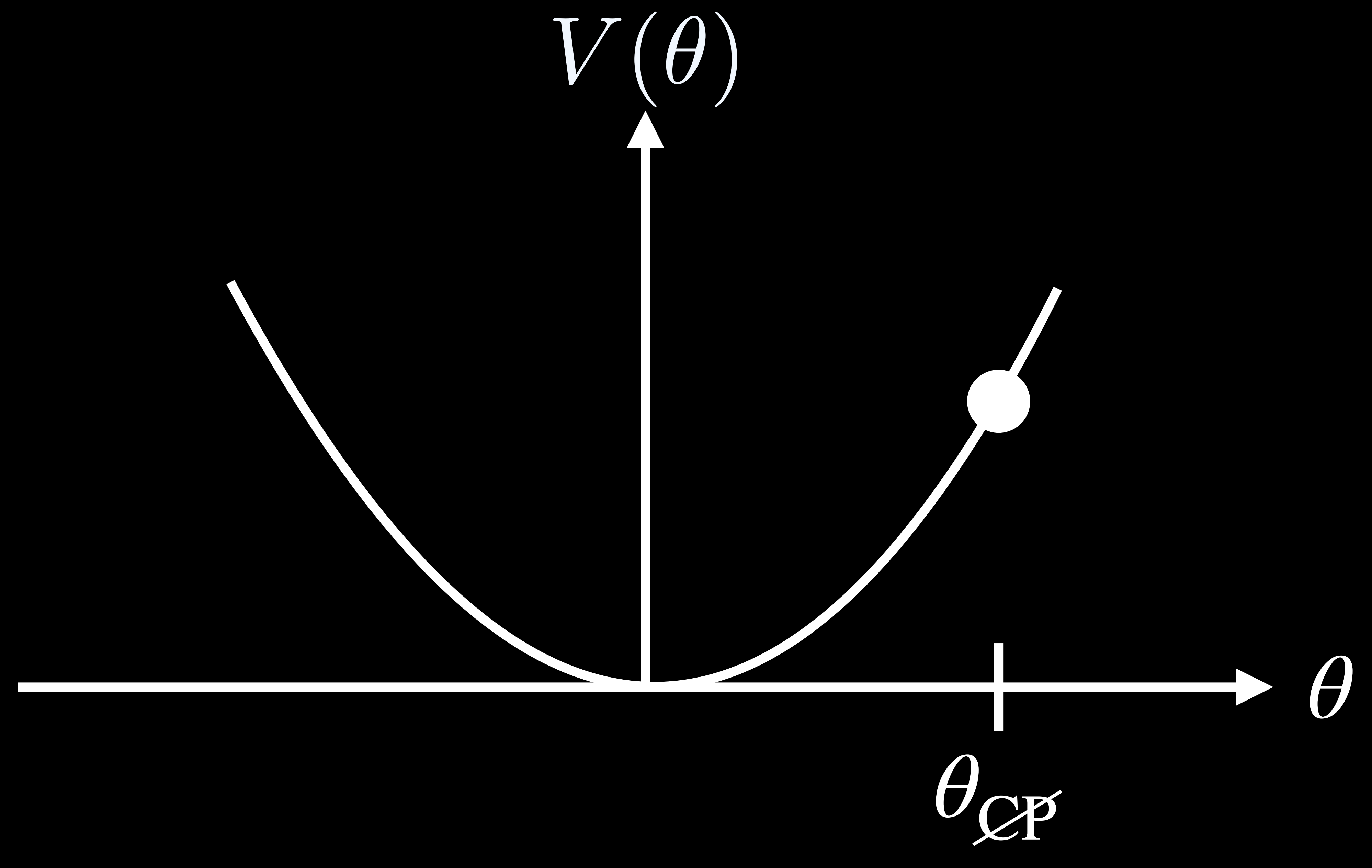
Weak $\not{C}\not{P}$ discovered



Solving the Strong CP Problem

- Peccei-Quinn mechanism:

$$\mathcal{L} \supset \frac{\theta}{16\pi^2} G\tilde{G} \longrightarrow \frac{\theta + a/f_a}{16\pi^2} G\tilde{G}$$



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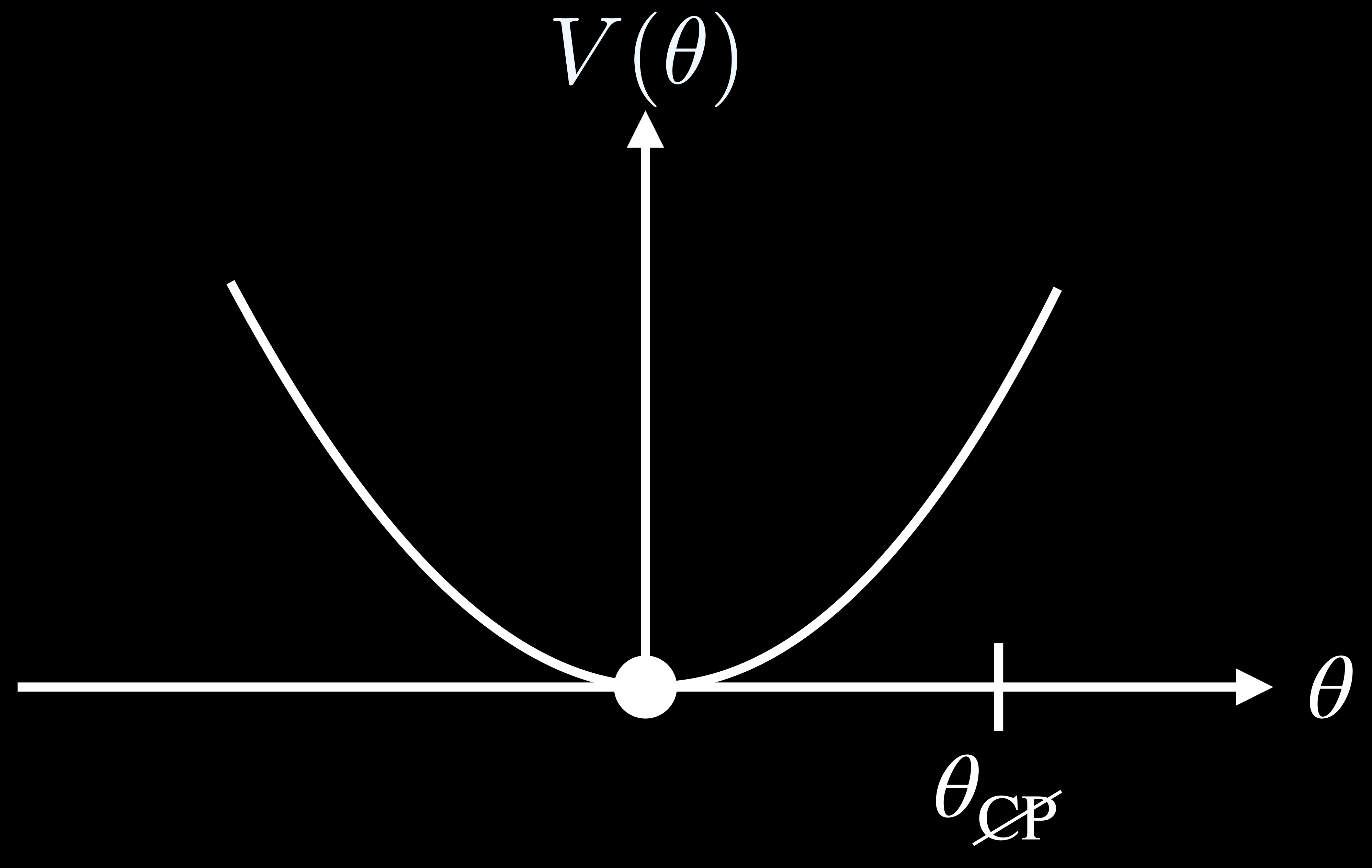
- Oscillations around minimum correspond to DM today



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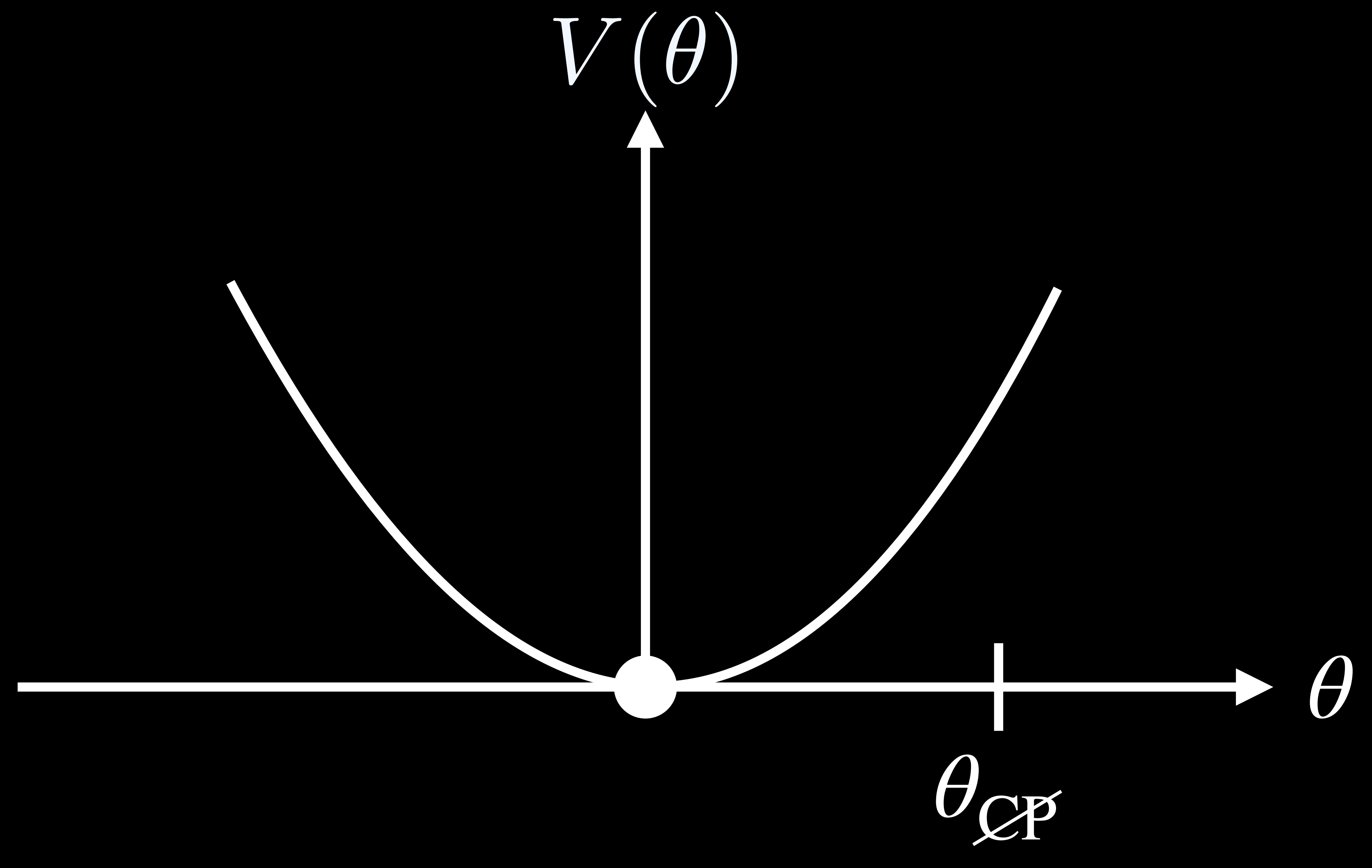
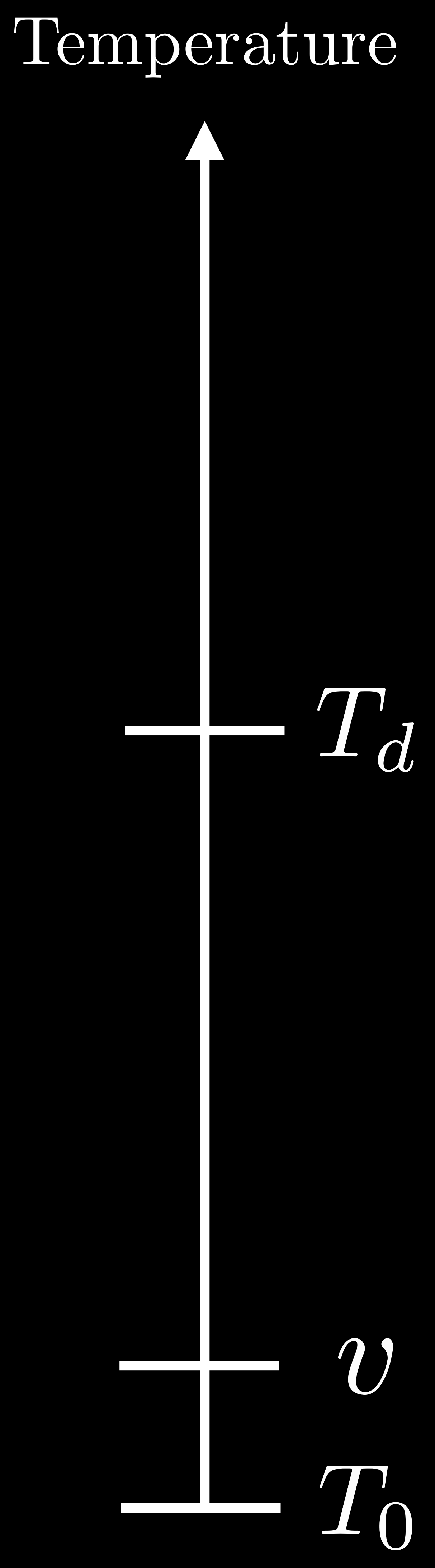
- Very light DM:

$$m_a \sim \mu\text{eV} \left(\frac{10^{12}\ \text{GeV}}{f_a} \right)$$



Light Relics



$$\Gamma_{\rm int}(T) > H(T)$$

$$\Gamma_{\rm int}(T) = H(T)$$

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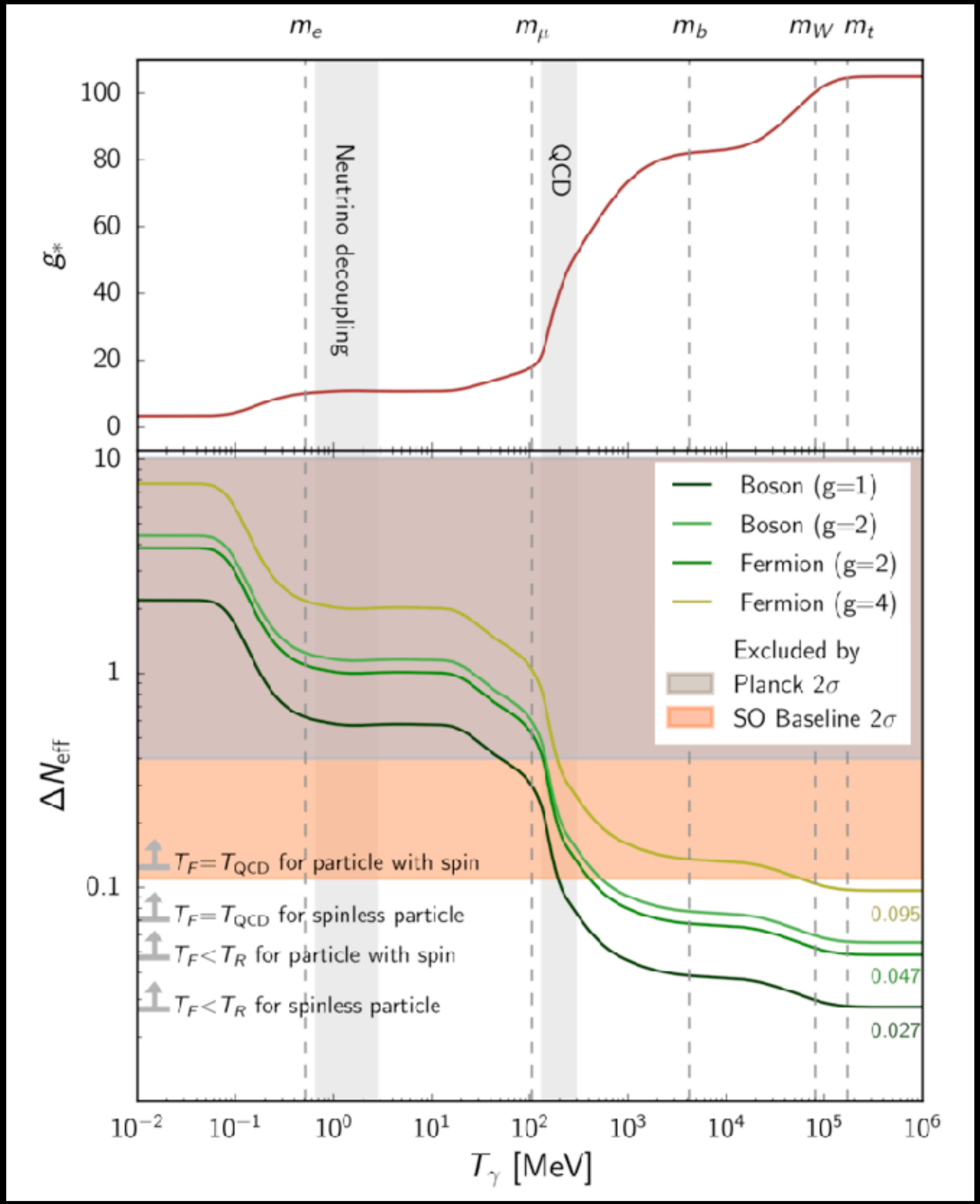

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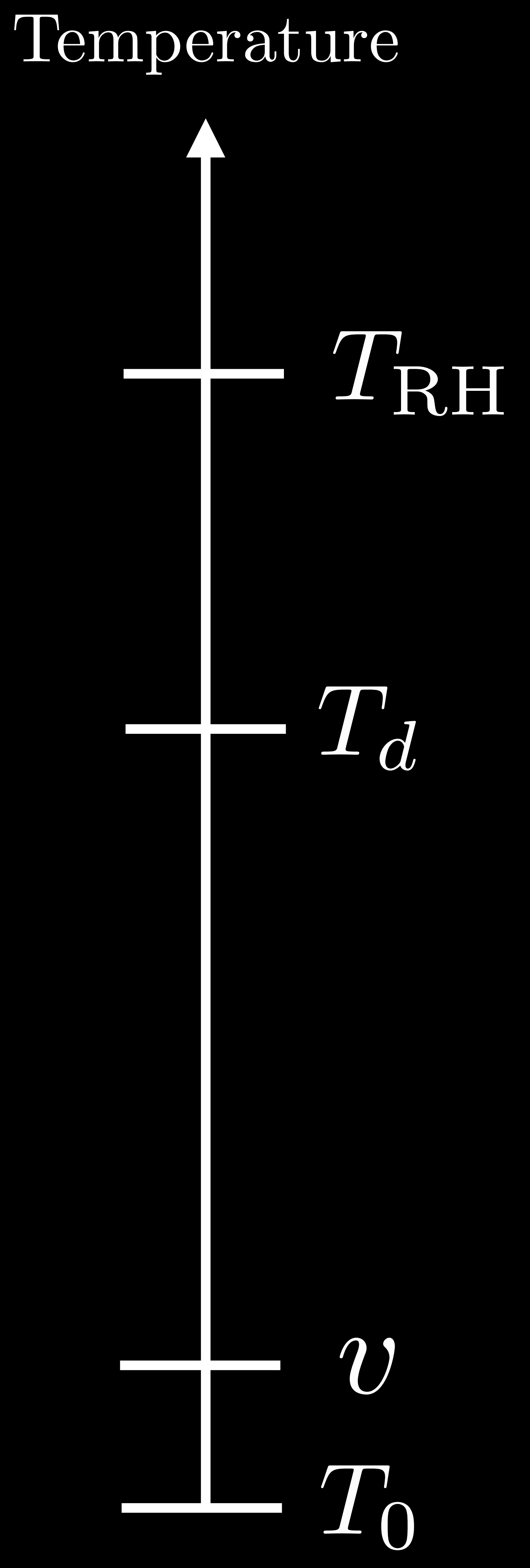

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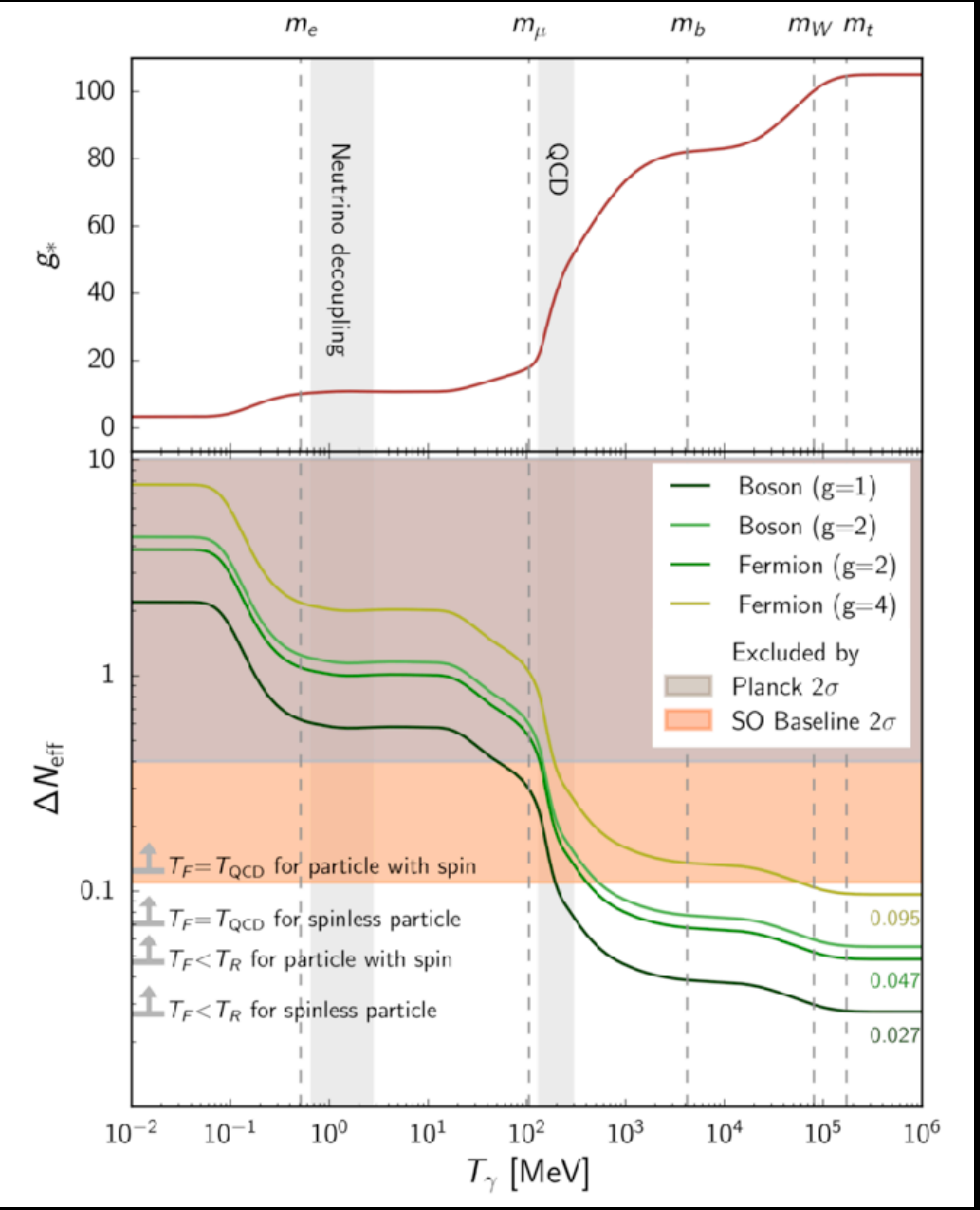
Dark radiation around today!



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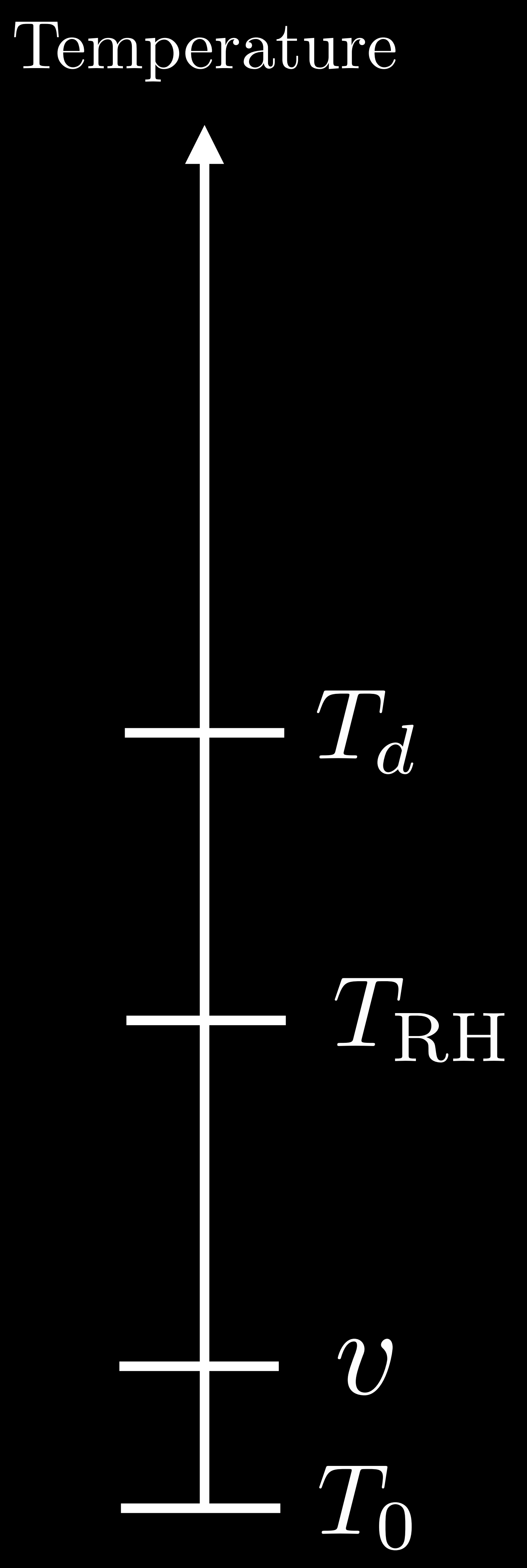

$$\Gamma_{\rm int}(T) > H(T)$$

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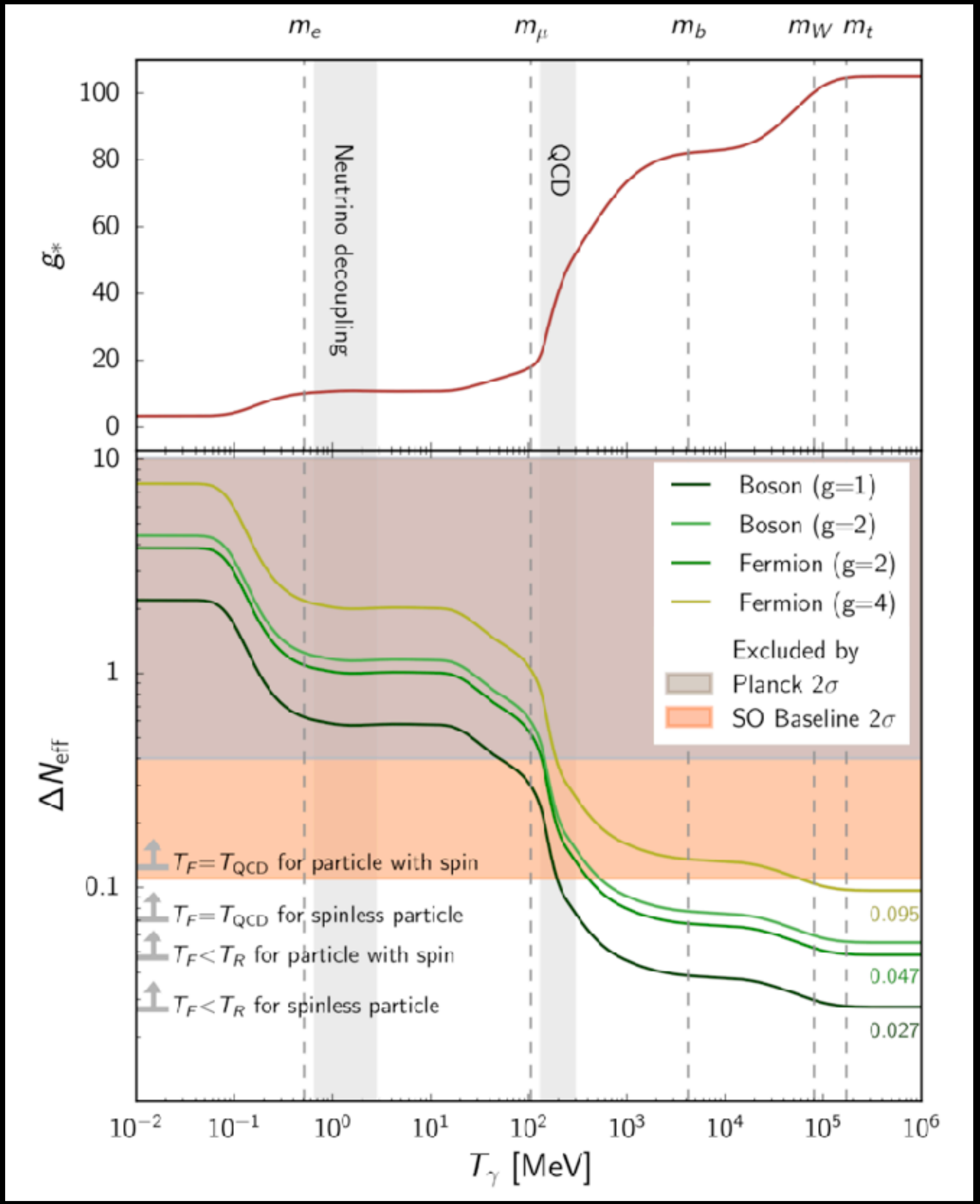
No dark radiation today*



*DR could freeze-in, but would not thermalize.

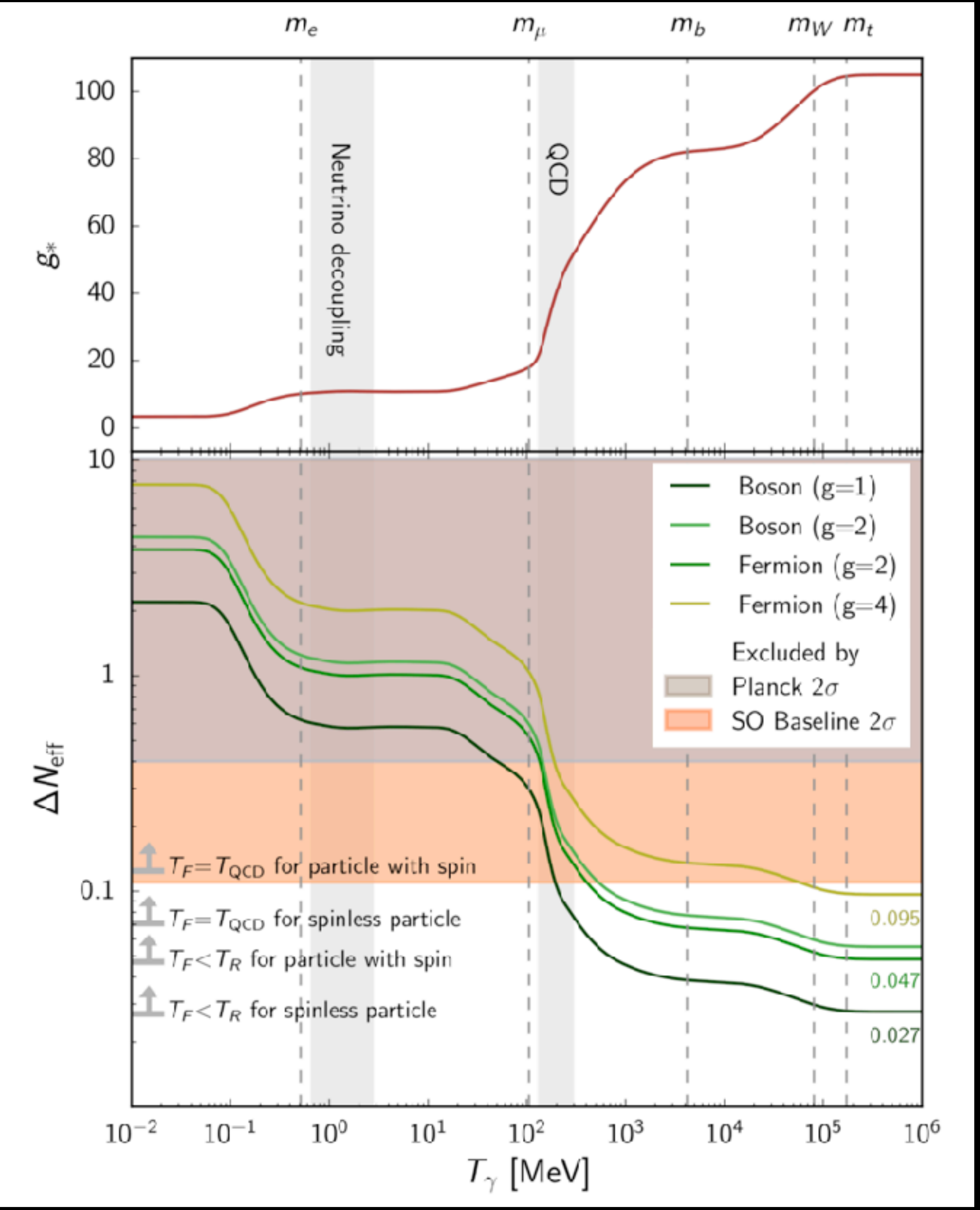
Light Relics

- Dark radiation at recombination contributes to N_{eff}
- $N_{\text{eff}}^{SM} = 3.044$, enhanced by dark radiation

$$\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\text{DR}}}{\rho_{\text{CMB}}}$$

- Boson* decoupling above the weak scale:

$$T_d \gg v \implies \Delta N_{\text{eff}} = \frac{4}{7}\left(\frac{10.75}{106.75}\right)^{4/3} g_{\text{DR}}$$
$$\approx 0.027 g_{\text{DR}}$$



*Weyl (Dirac) fermions would result in a factor 7/4 (7/2) larger N_{eff}.

CMB & Light Relics

- Exciting time to think about the CMB:

Atacama (complete)
$\Delta N_{\text{eff}}^{95\%} = 0.17$

Simons (ongoing)
$\Delta N_{\text{eff}}^{95\%} = 0.12$

CMB-S4 (future)
$\Delta N_{\text{eff}}^{95\%} = 0.05$

CMB & Light Relics

- Exciting time to think about the CMB:

Atacama (complete)

$\Delta N_{\rm eff}^{95\%} = 0.17$

$g_{\rm DR} \leq 6$

Simons (ongoing)

$\Delta N_{\rm eff}^{95\%} = 0.12$

$g_{\rm DR} \leq 4$

CMB-S4 (future)

$\Delta N_{\rm eff}^{95\%} = 0.05$

$g_{\rm DR} \leq 2$

Light Relics

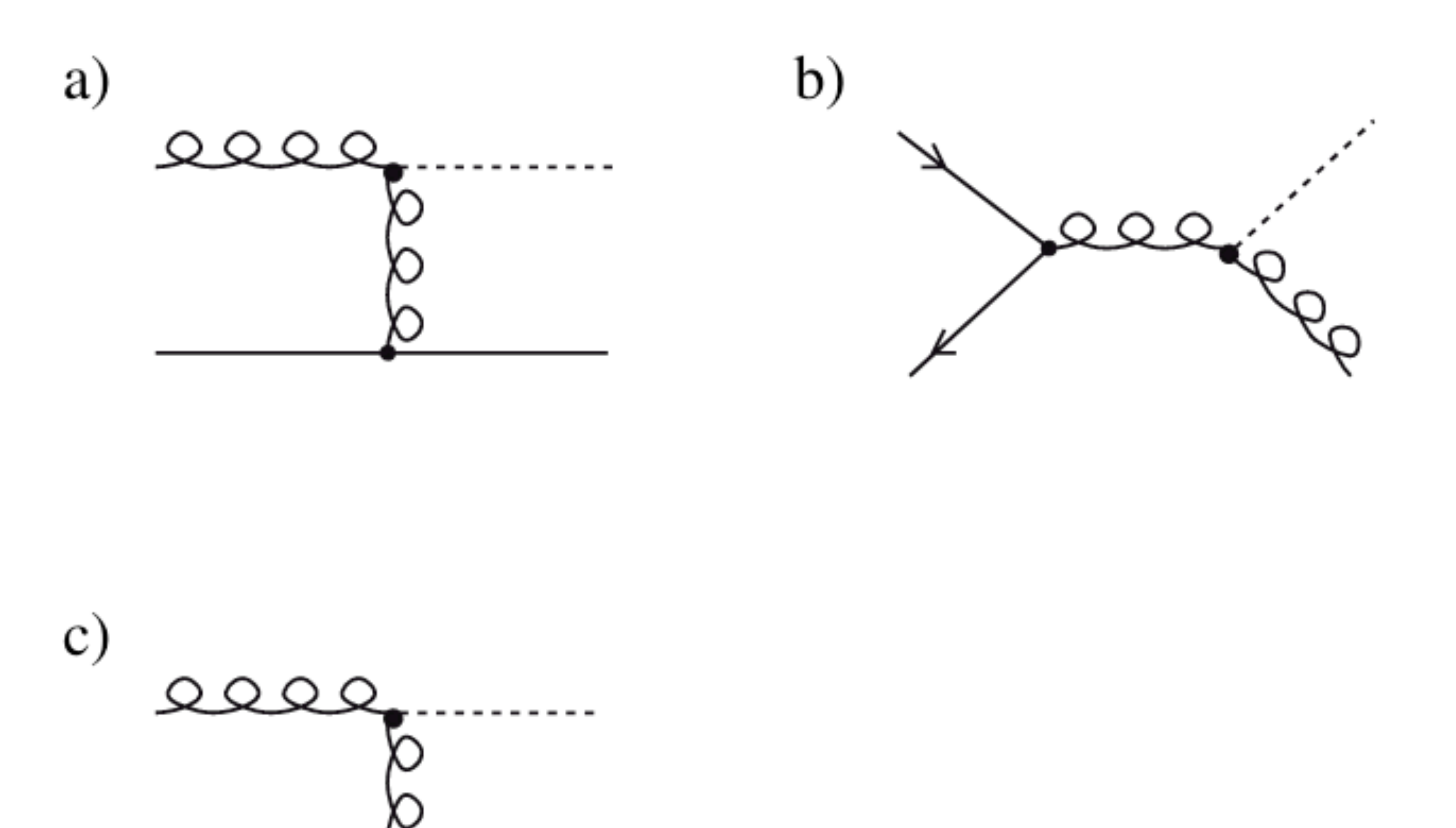
- N_{eff} from the QCD axion*:

$$\Gamma \gtrsim H \implies \alpha_s^3 \frac{T^3}{f_a^2} \gtrsim \frac{T^2}{M_P}$$

$$\implies T_d \approx 10^{12}\ \text{GeV} \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^2$$

- If $T_{\text{RH}} > T_d$,

$$\Delta N_{\text{eff}} \approx 0.027$$

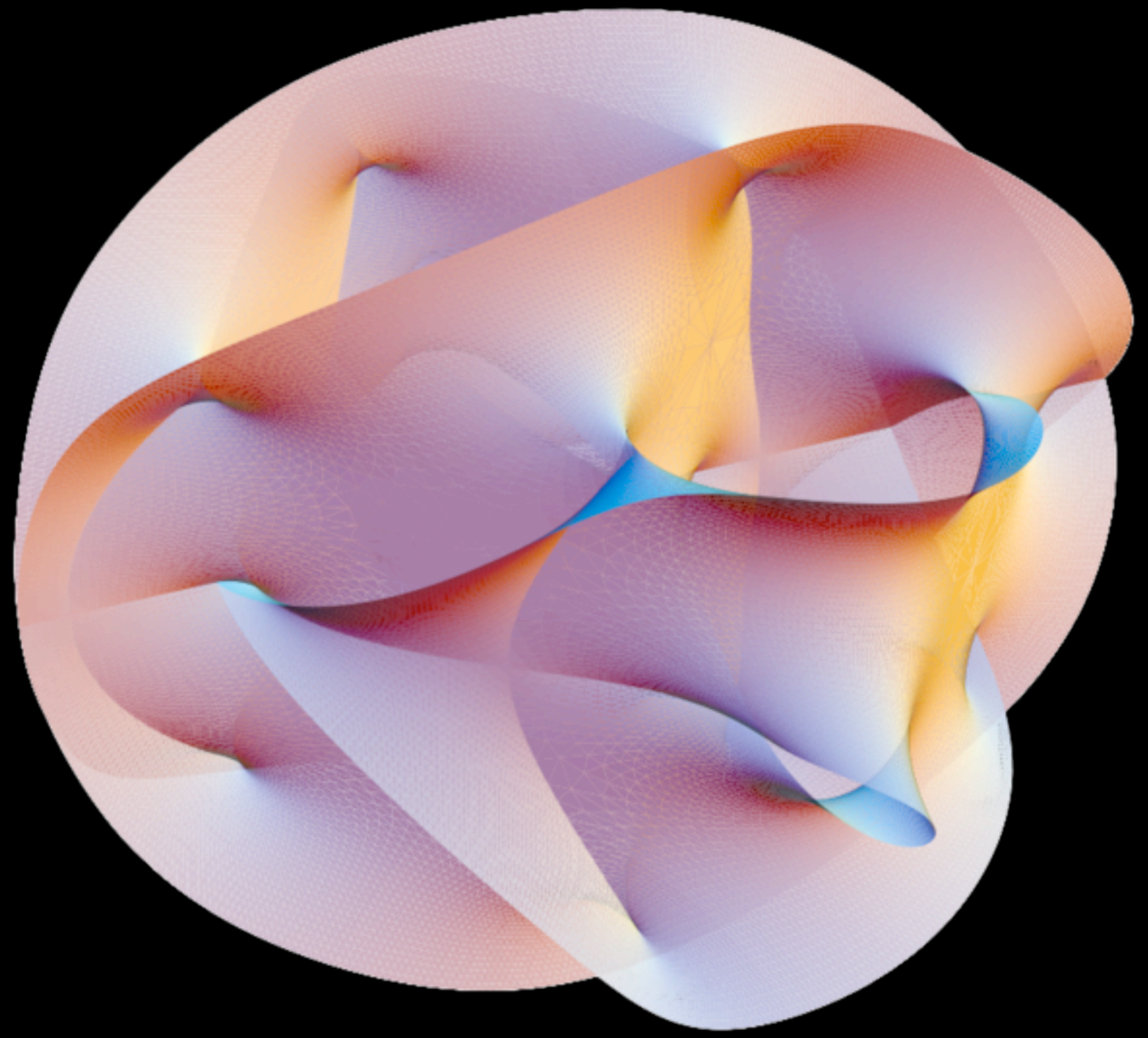


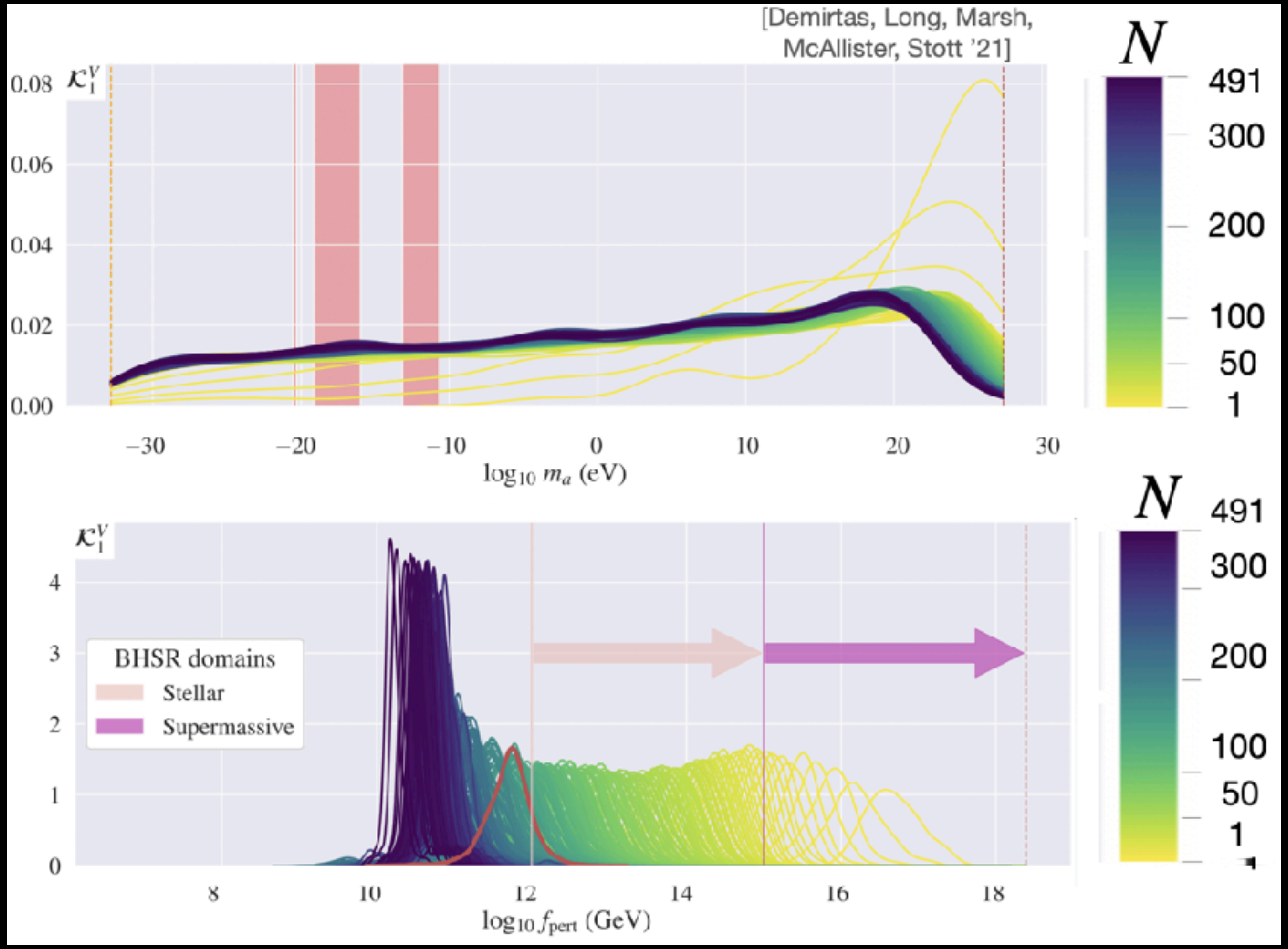
Axions: Theory, Cosmology, and Experimental Searches (2007)

*In KSVZ UV completions, the decoupling temperature could be much lower.

The Axiverse

- String theory → $\mathcal{O}$(100s) axions arise from 0-modes of gauge fields
- Log-uniform masses and similar decay constants





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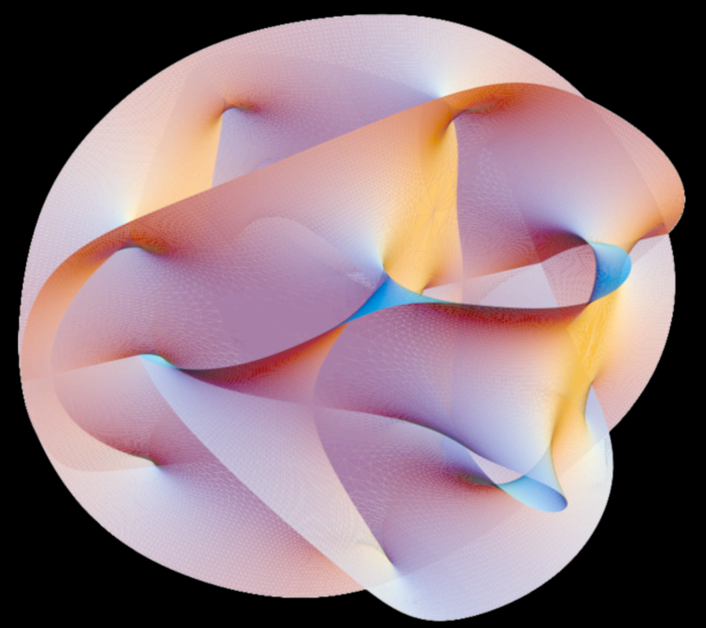

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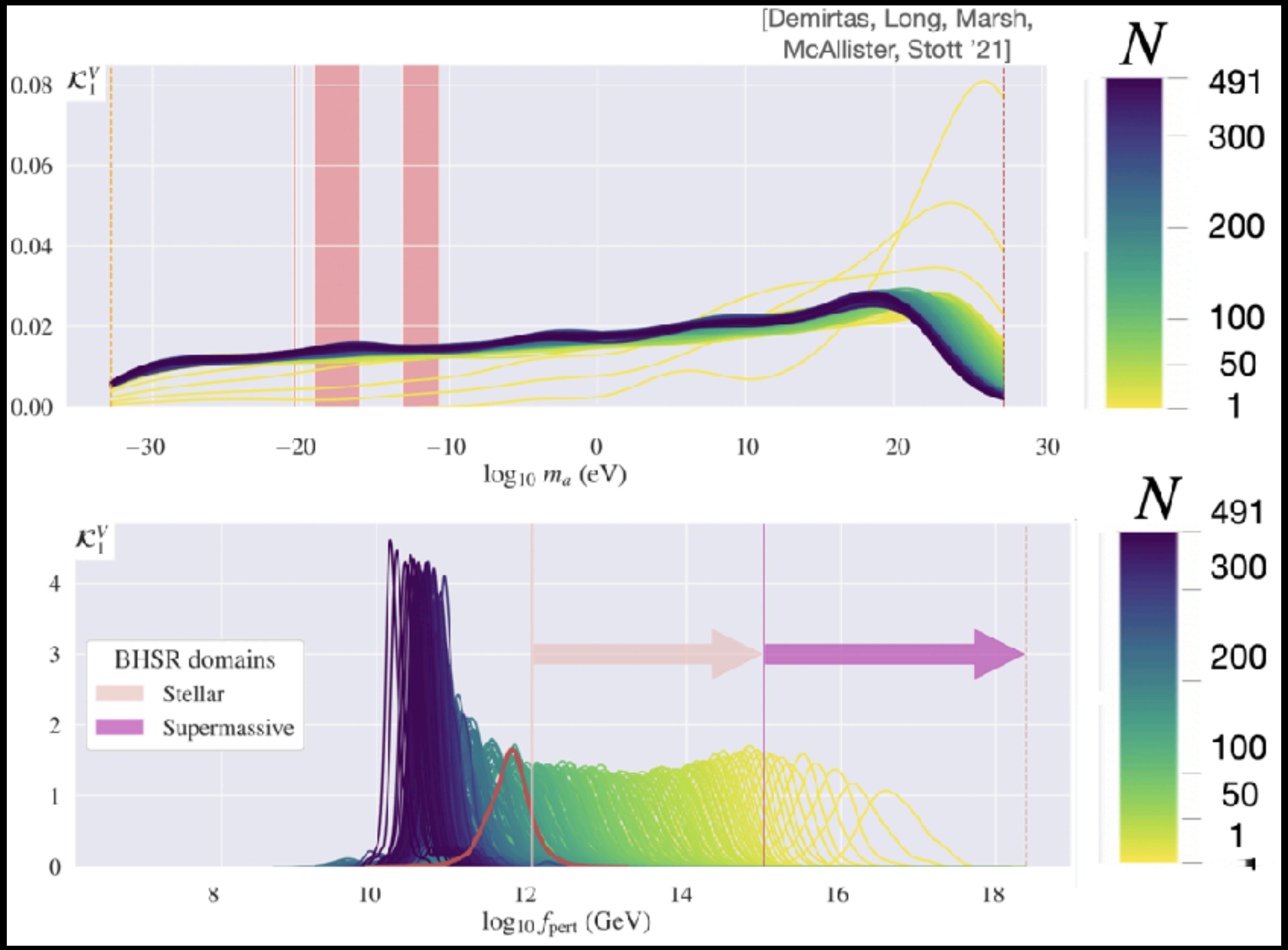
$$\Delta N_{\text{eff},\text{Axiverse}} \stackrel{?}{=} 0.027 N_{\text{ax}}$$



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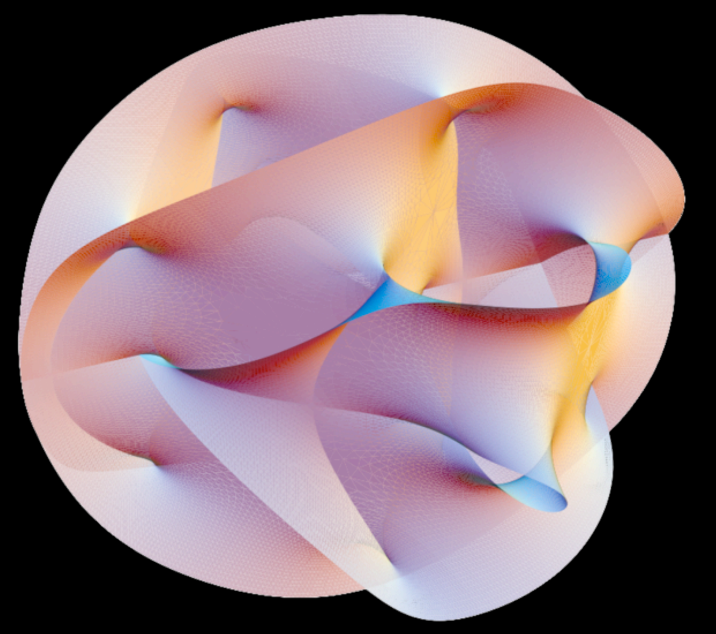
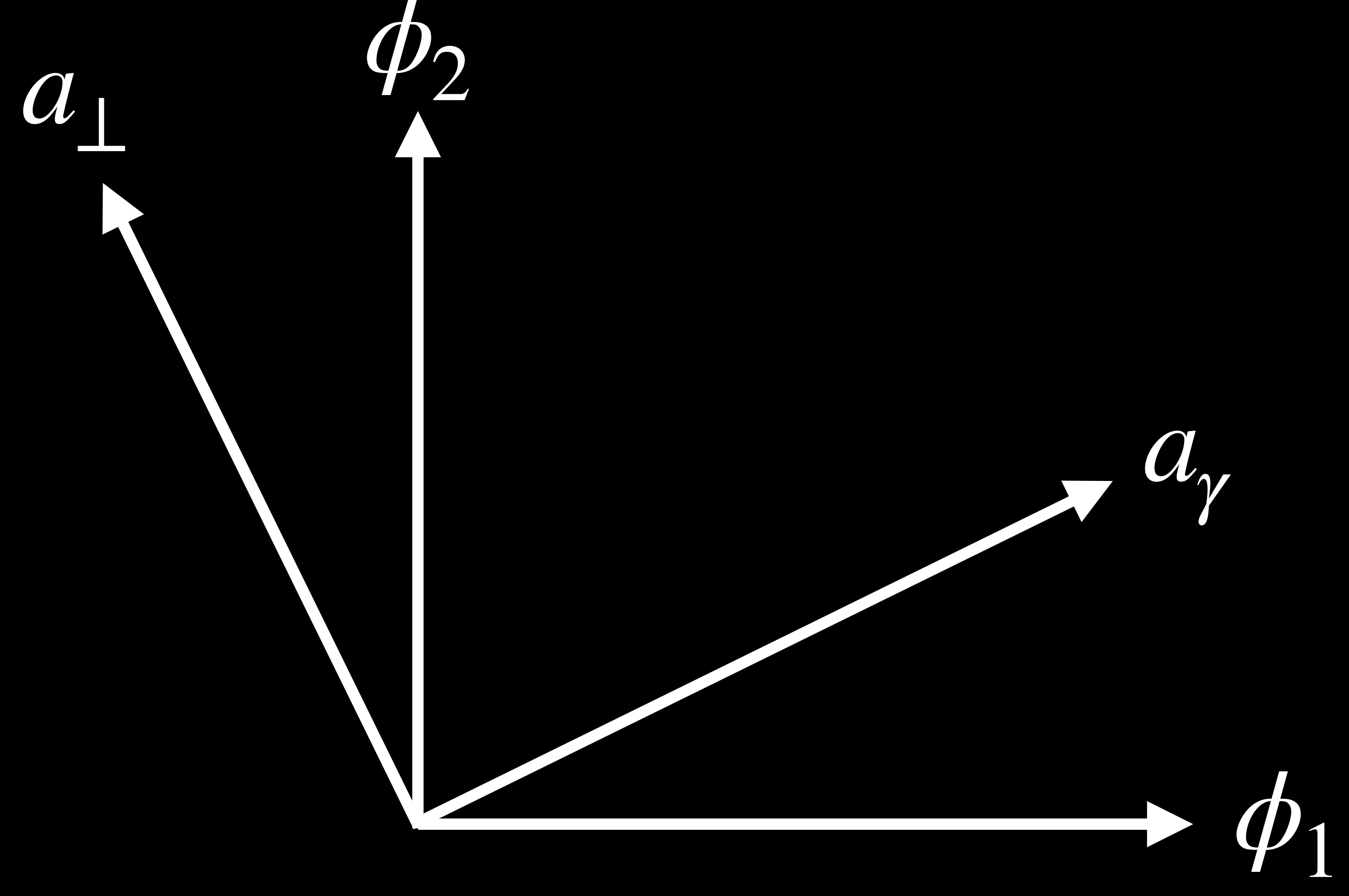


- String theory → $\mathcal{O}$(100s) axions arise from 0-modes of gauge fields
- Log-uniform masses and similar decay constants
- Toy $N_{\mathrm{a}} = 2$ example

$$\begin{aligned}\mathcal{L} &= -\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - g_i\phi_i F\tilde{F} \\ &= -\frac{1}{2}\partial_\mu a_i\partial^\mu a_i - g_{a\gamma\gamma}a_\gamma F\tilde{F}\end{aligned}$$



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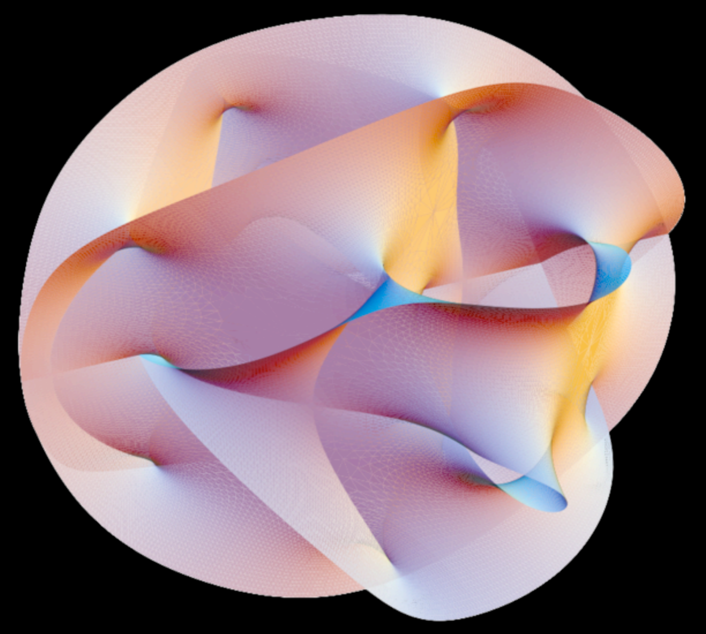

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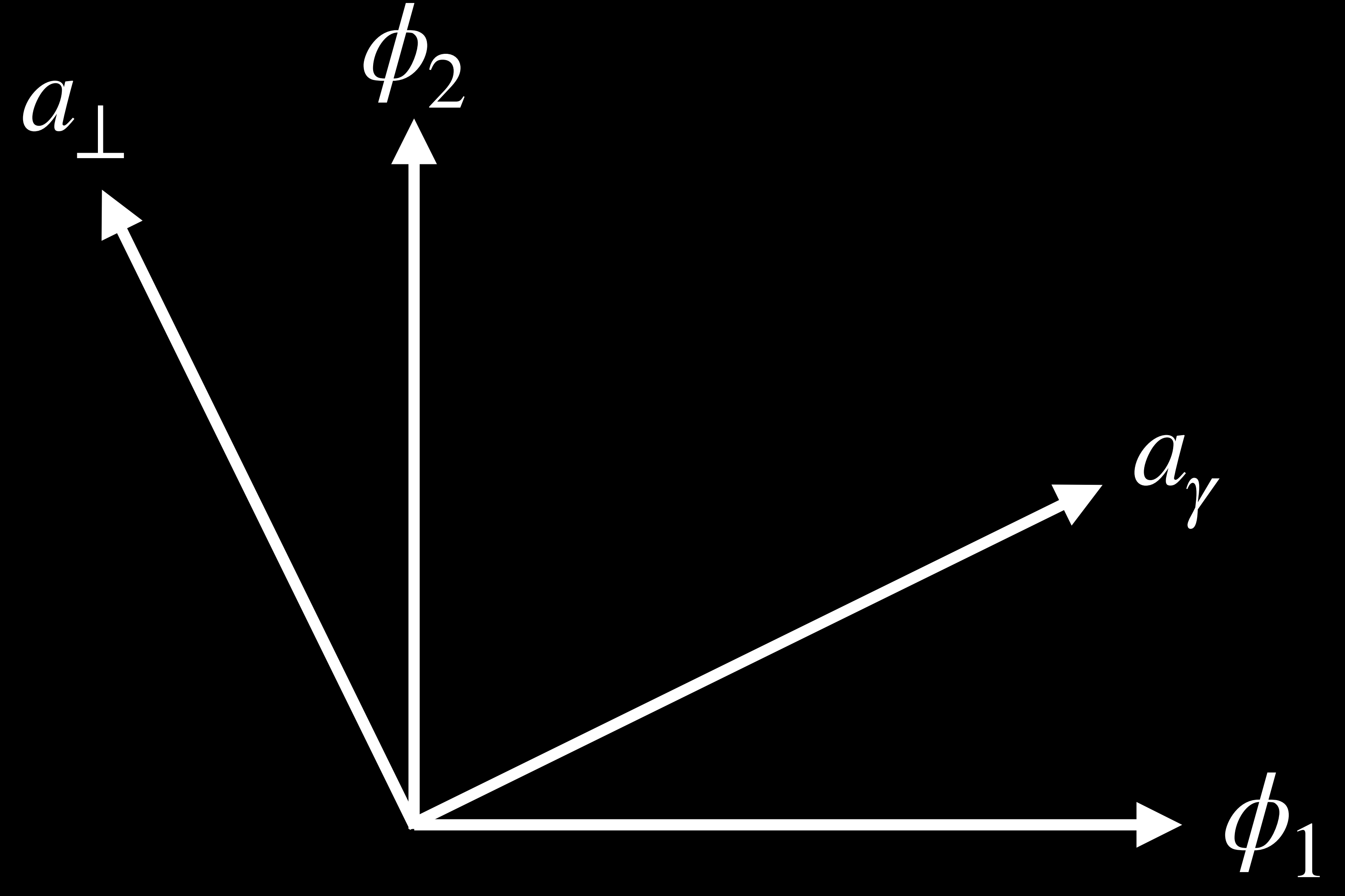

- $\Delta N_{\rm eff} = 0.027$ per $c_i \phi_i \mathcal{O}_{\rm SM} \subset \mathcal{L}$
- Recall ACT constrains $g_{\rm DR} \leq 6$

Axiverse EFT at dim-5

- Axion EFT at dimension 5 > weak scale: N_a axions ϕ_i + SM (Bauer+ 2021)

$$\mathcal{L}_5 = \sum_G \frac{c_i^G \alpha_G}{4\pi} \frac{\phi_i}{f_a} G\tilde{G} + \sum_\Psi \frac{\partial_\mu \phi_i}{f_a} \overline{\Psi} \gamma^\mu c_i^\Psi \Psi + c_i^H \frac{\partial_\mu \phi_i}{f_a} (H^\dagger D_\mu H + h.c.)$$

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$$\begin{pmatrix} \Psi_1^* & \Psi_2^* & \Psi_3^* \end{pmatrix} \gamma_0 \gamma_\mu \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{12}^* & c_{22} & c_{23} \\ c_{13}^* & c_{23}^* & c_{33} \end{pmatrix}_i^\Psi \begin{pmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{pmatrix}$$

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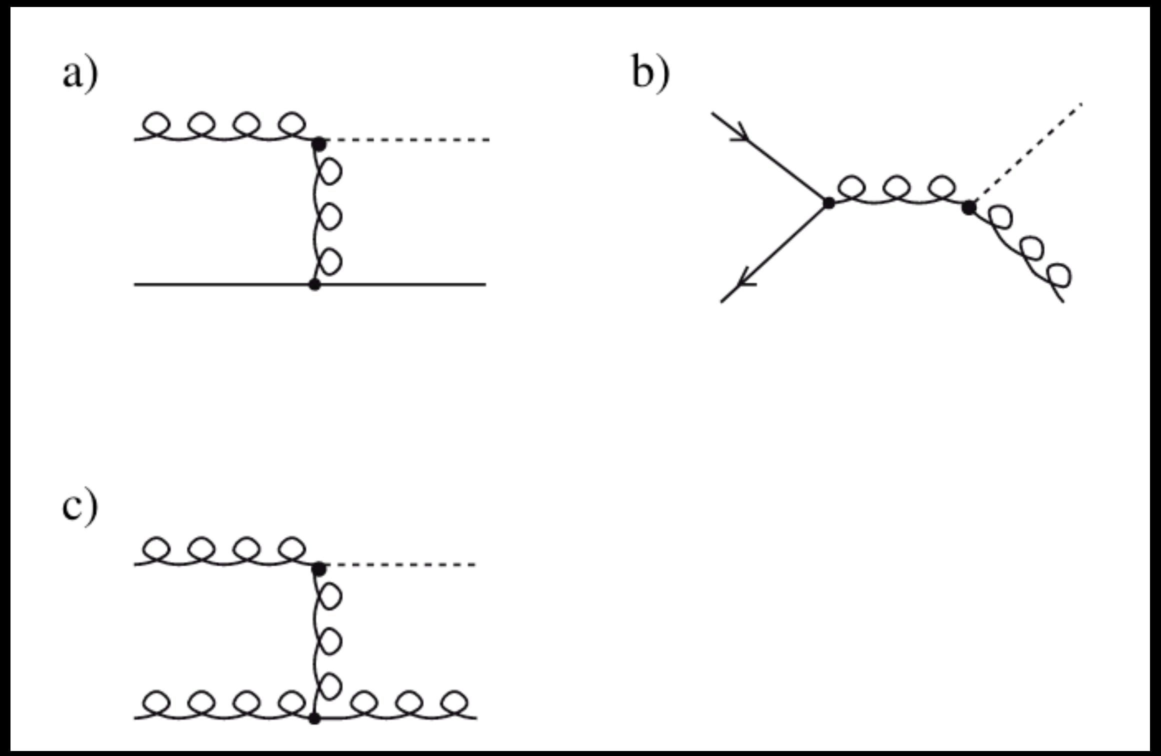
- Use Gram-Schmidt orthogonalization procedure for "flavor" basis

$$\begin{aligned}\mathcal{L}_5 = & \frac{c_s \alpha_s}{4\pi} \frac{a_{\mathrm{QCD}}}{f_a} G\tilde{G} + [\text{couplings to all other operators}] \\ & + \ \frac{c_2 \alpha_2}{4\pi} \frac{a_2}{f_a} W\tilde{W} + [\text{couplings to all other operators except QCD}] \\ & + \ \ldots \\ & + \ [N - N_{\mathrm{SM}} \text{ sterile axions}]\end{aligned}$$



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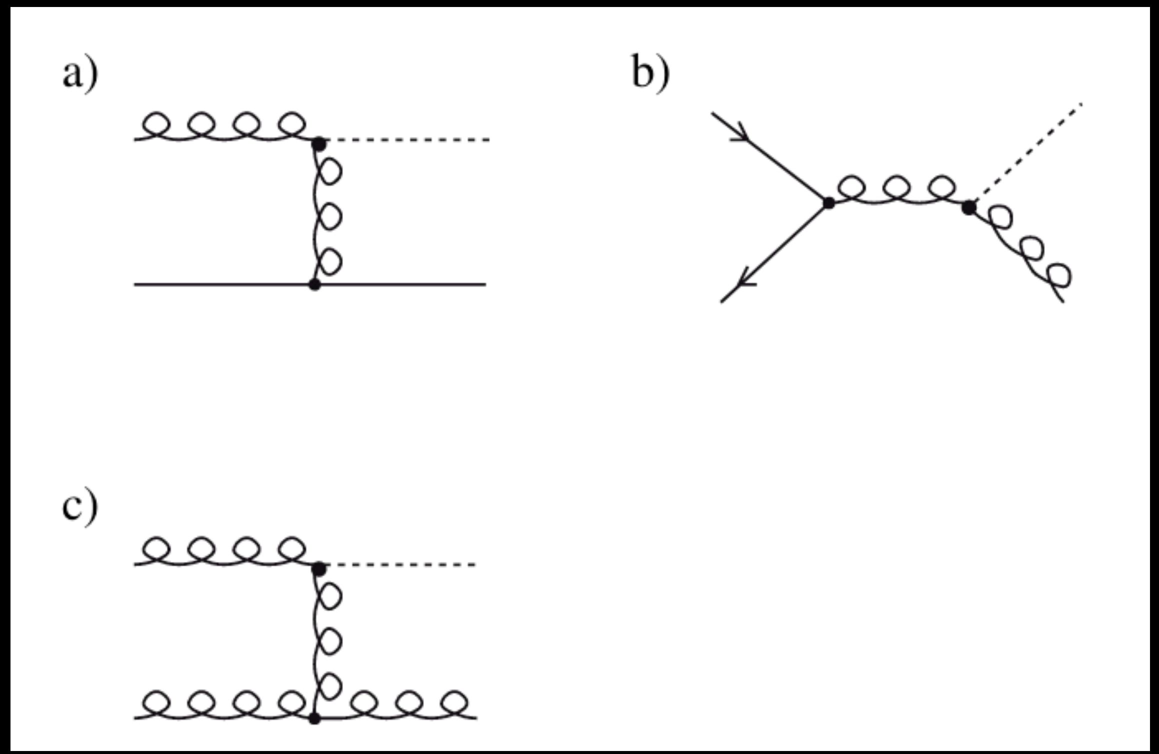

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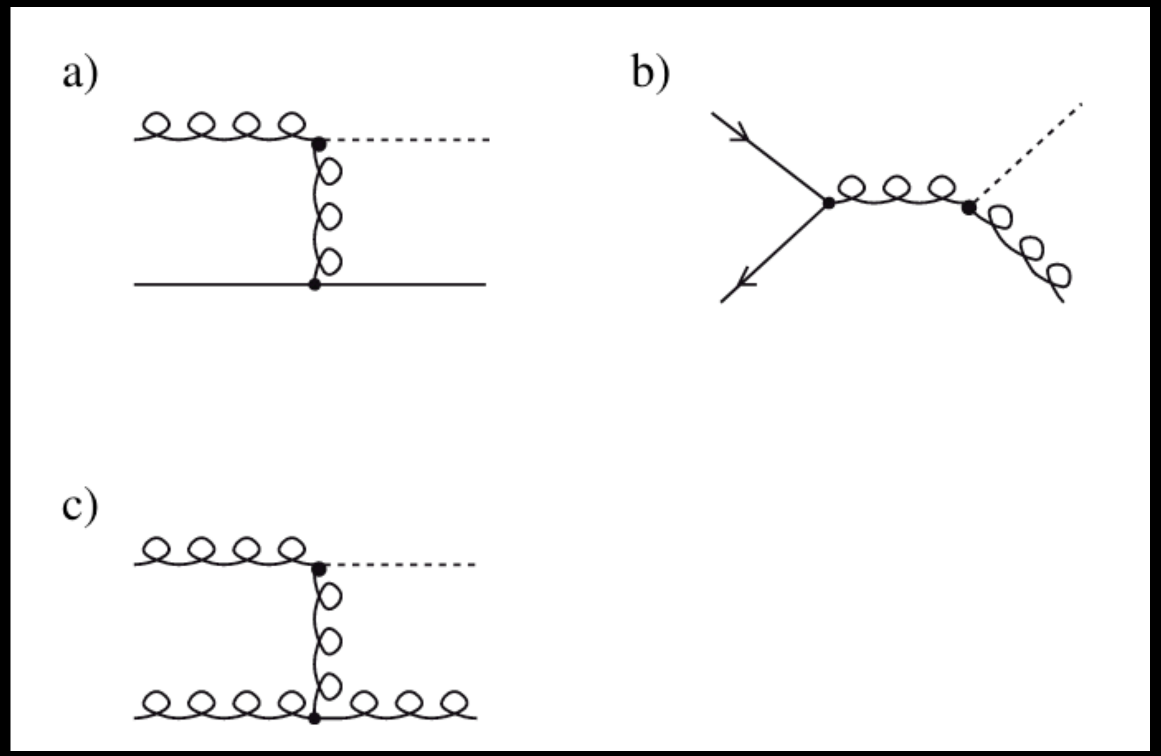
$$N_a^{\rm th} = 3 + 9\times 5 + 1 = 49$$



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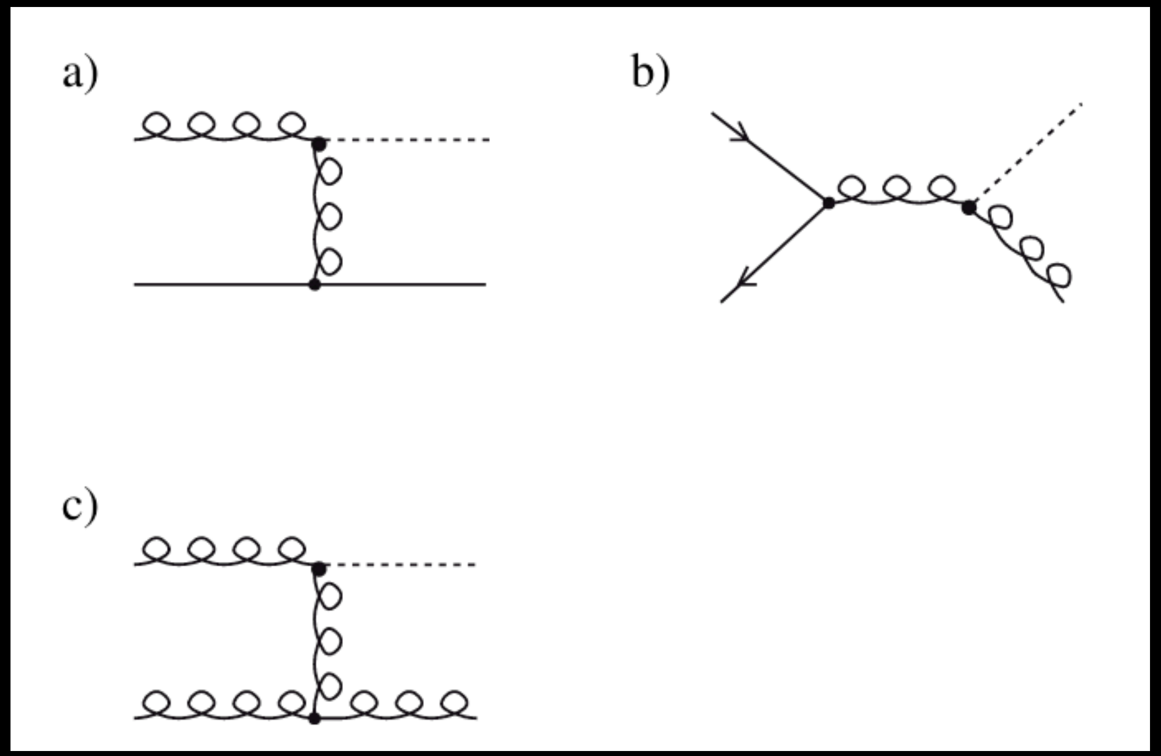
- But there are redundant operators:

$$\Psi \to \exp\left(ic\frac{a}{f_a}Q_\Psi\right)\Psi, H \to \exp\left(ic\frac{a}{f_a}Q_H\right)H$$



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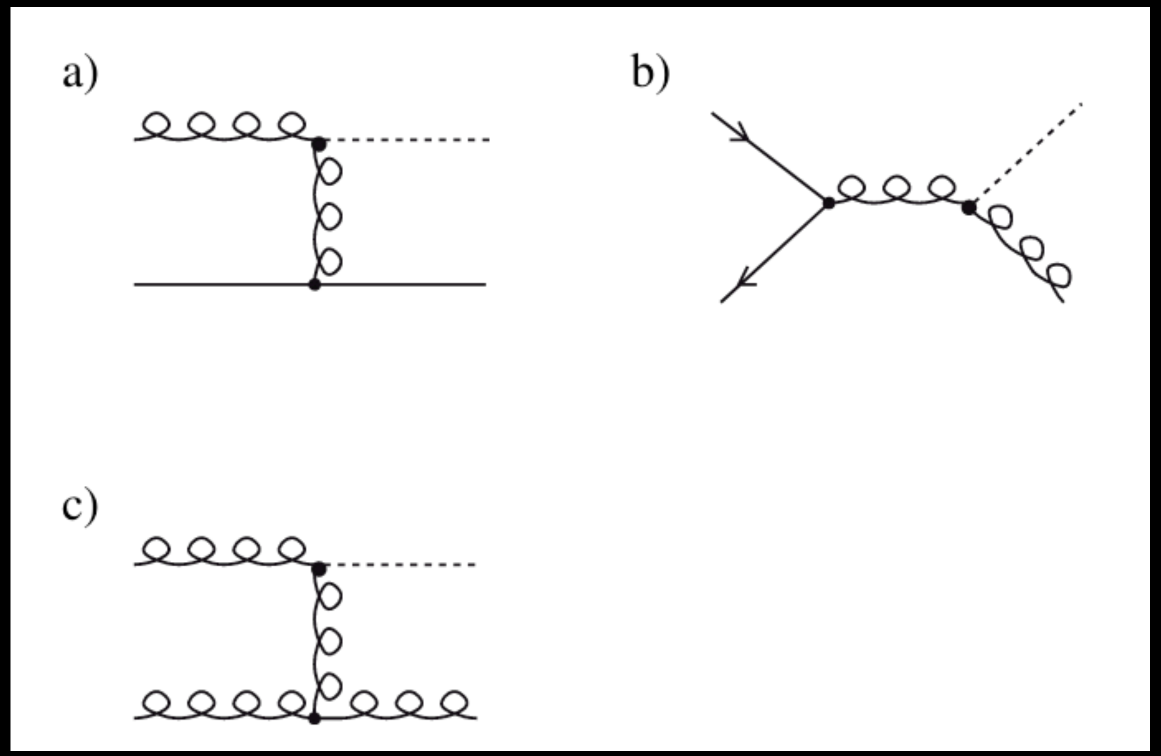

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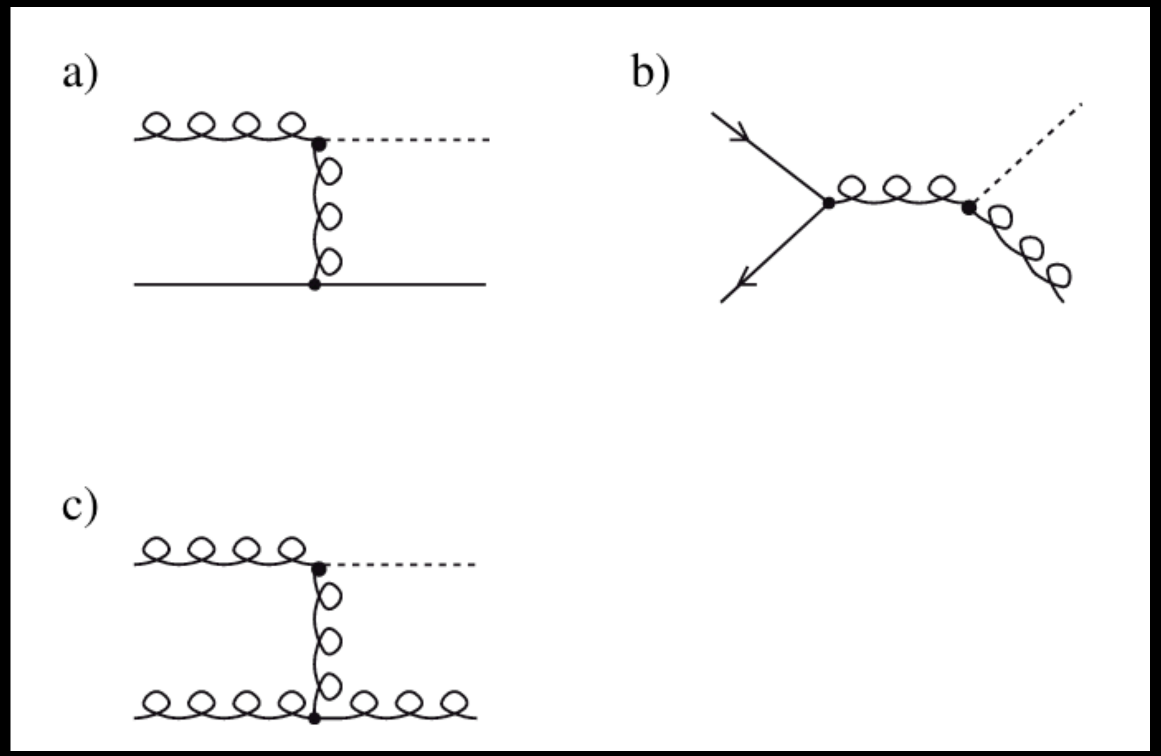
} Overcounted by 5 operators



Axiverse EFT at dim-5

- Summary at dim-5:
  - Each operator can thermalize an independent axion direction
  - 44 operators at dim-5 $\gg$ *existing* constraints from CMB
  - Not all operators are strong enough to thermalize
- Strongly depends on expectations for fermion couplings

Expectations for Fermion Couplings

- No calculation of axion-fermion couplings in Axiverse
- We consider these scenarios:
  1. Hadronic Axiverse
  2. Flavor Anarchy
  3. Froggatt-Neilsen mechanism ($\Lambda_{FN} \gg f_a$)
  4. Minimal Flavor Violation

(i) Hadronic Axiverse

- Every axion is KSVZ — no tree-level coupling to fermions

$$\mathcal{L}_5 = \sum_G \frac{c_G \alpha_G}{4\pi} \frac{a_G}{f_a} G\tilde{G} + \sum_\Psi \frac{\partial_\mu a_\Psi}{f_a} \overline{\Psi} \gamma^\mu c_\Psi \Psi$$

$$N_a^{\text{th}} = 3$$

- If the SM is embedded into a simple GUT, then $N_a^{\text{th}} = 1$.

(i) Hadronic Axiverse

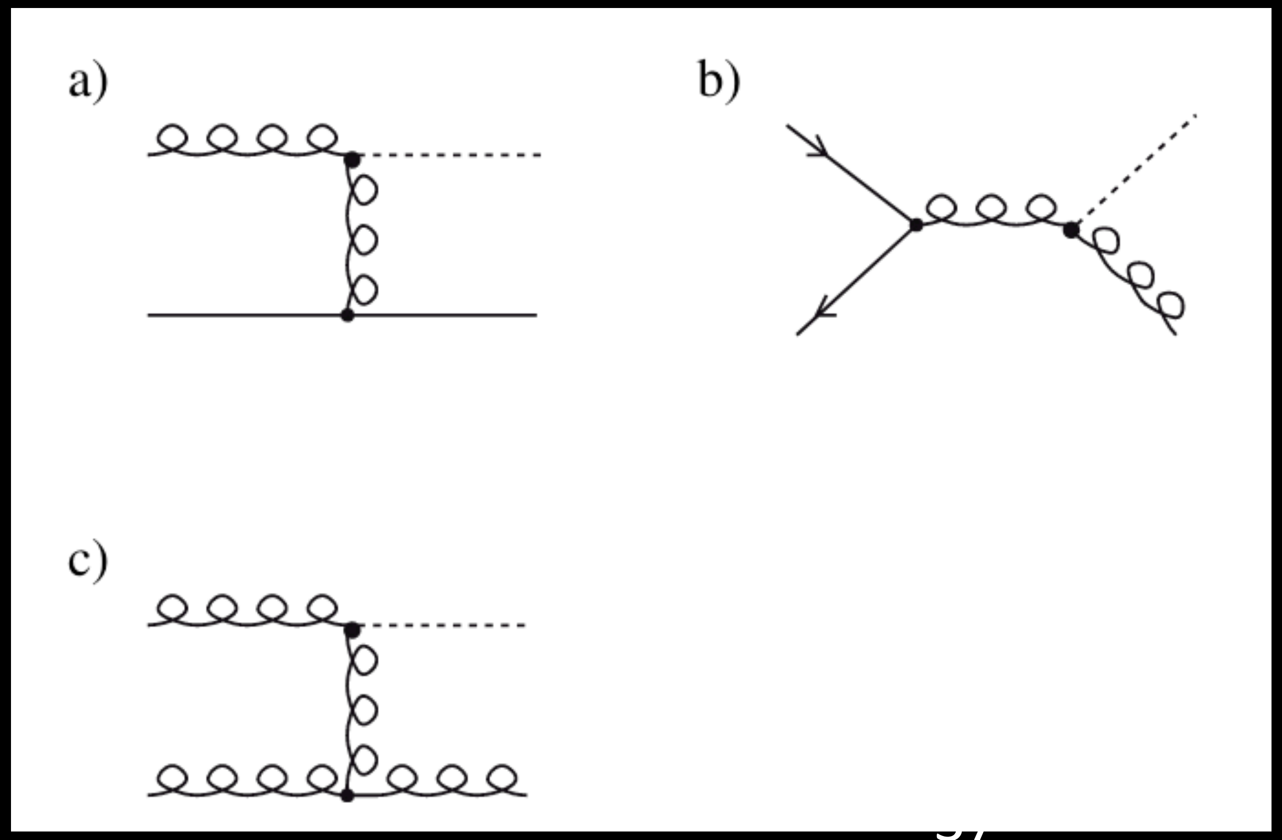
- Every axion is KSVZ — no tree-level coupling to fermions

$$\mathcal{L}_5 = \sum_G \frac{c_G \alpha_G}{4\pi} \frac{a_G}{f_a} G\tilde{G} + \cancel{\sum_\Psi \frac{\partial_\mu a_\Psi}{f_a} \overline{\Psi} \gamma^\mu c_\Psi \Psi}$$

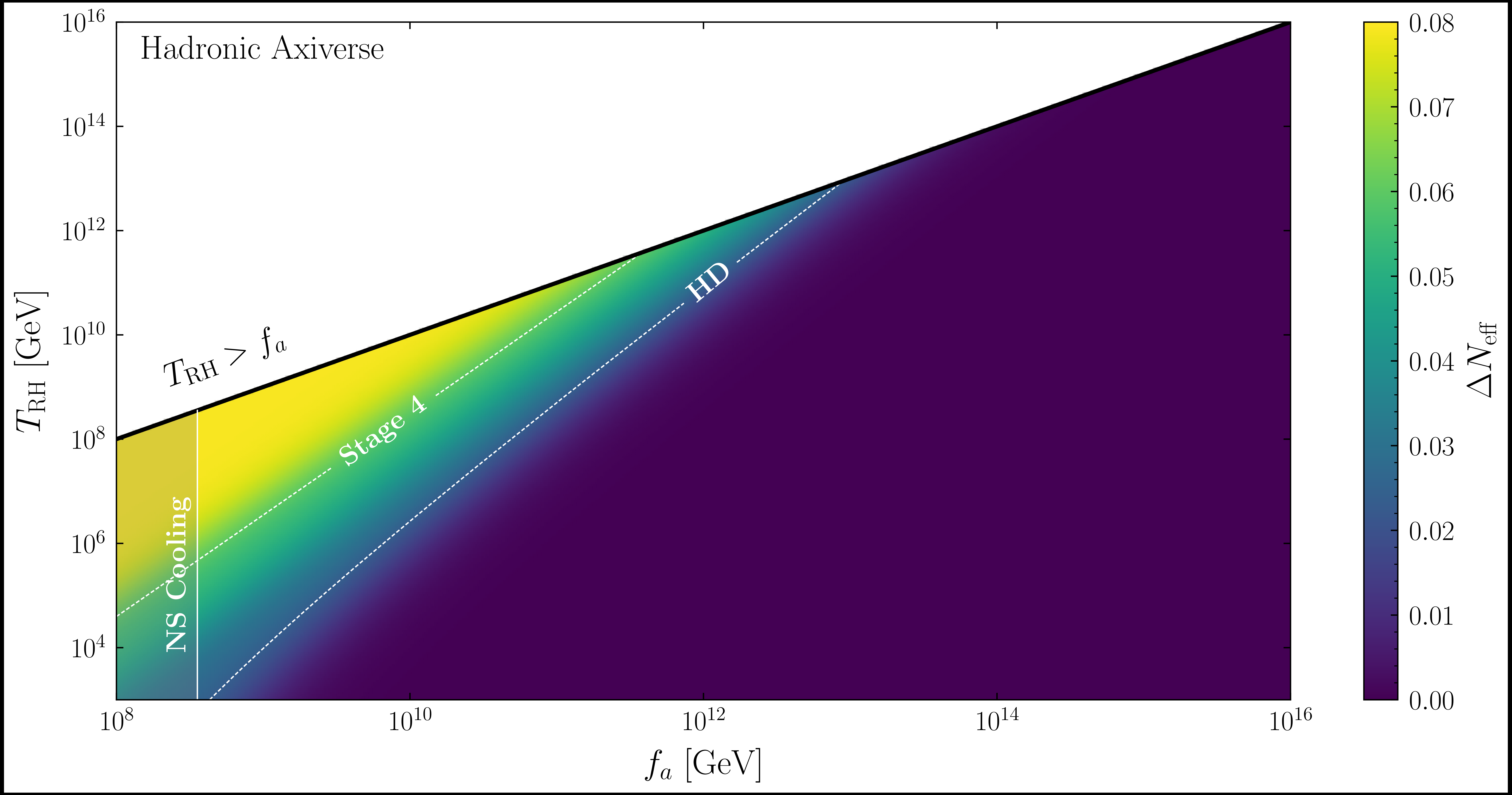
$$N_a^{\rm th} = \quad 3$$

- If the SM is embedded into a simple GUT, then $N_a^{\rm th} = 1$.

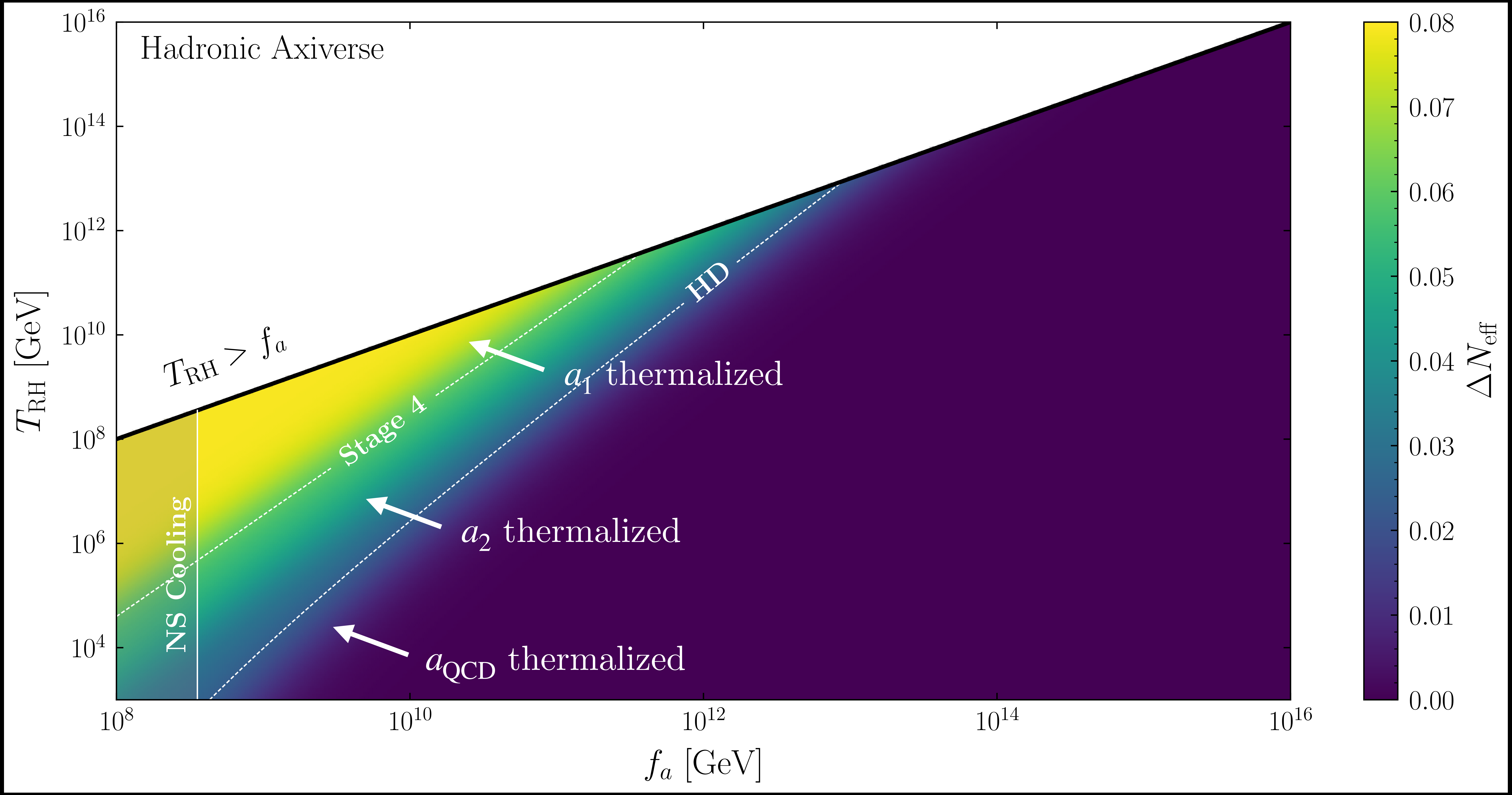
$$T_d \approx 10^{12}\ \text{GeV} \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^2 \left(\frac{0.05}{\alpha} \right)^3$$



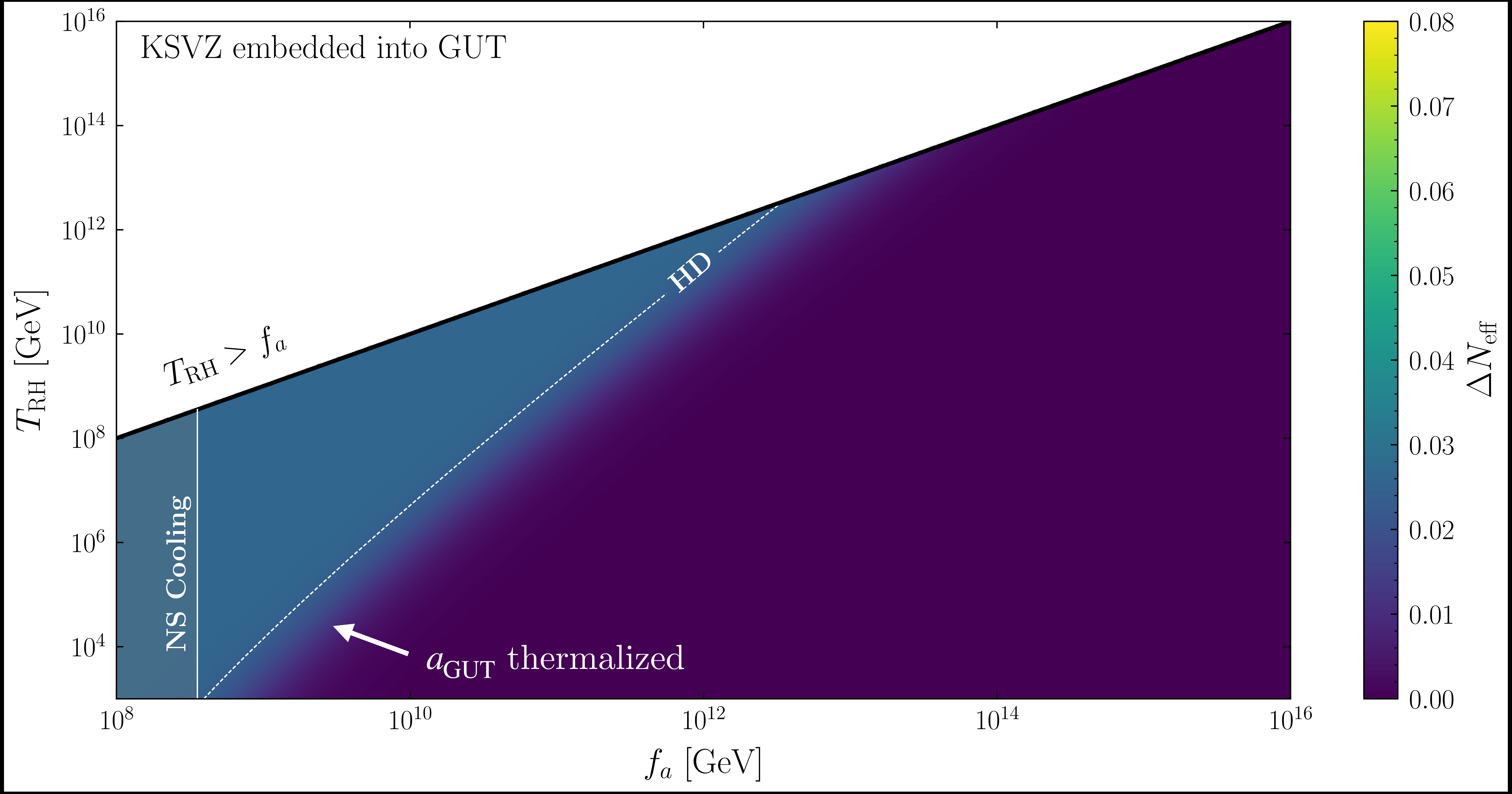
Hadronic Axiverse, Dim-5



Hadronic Axiverse, Dim-5



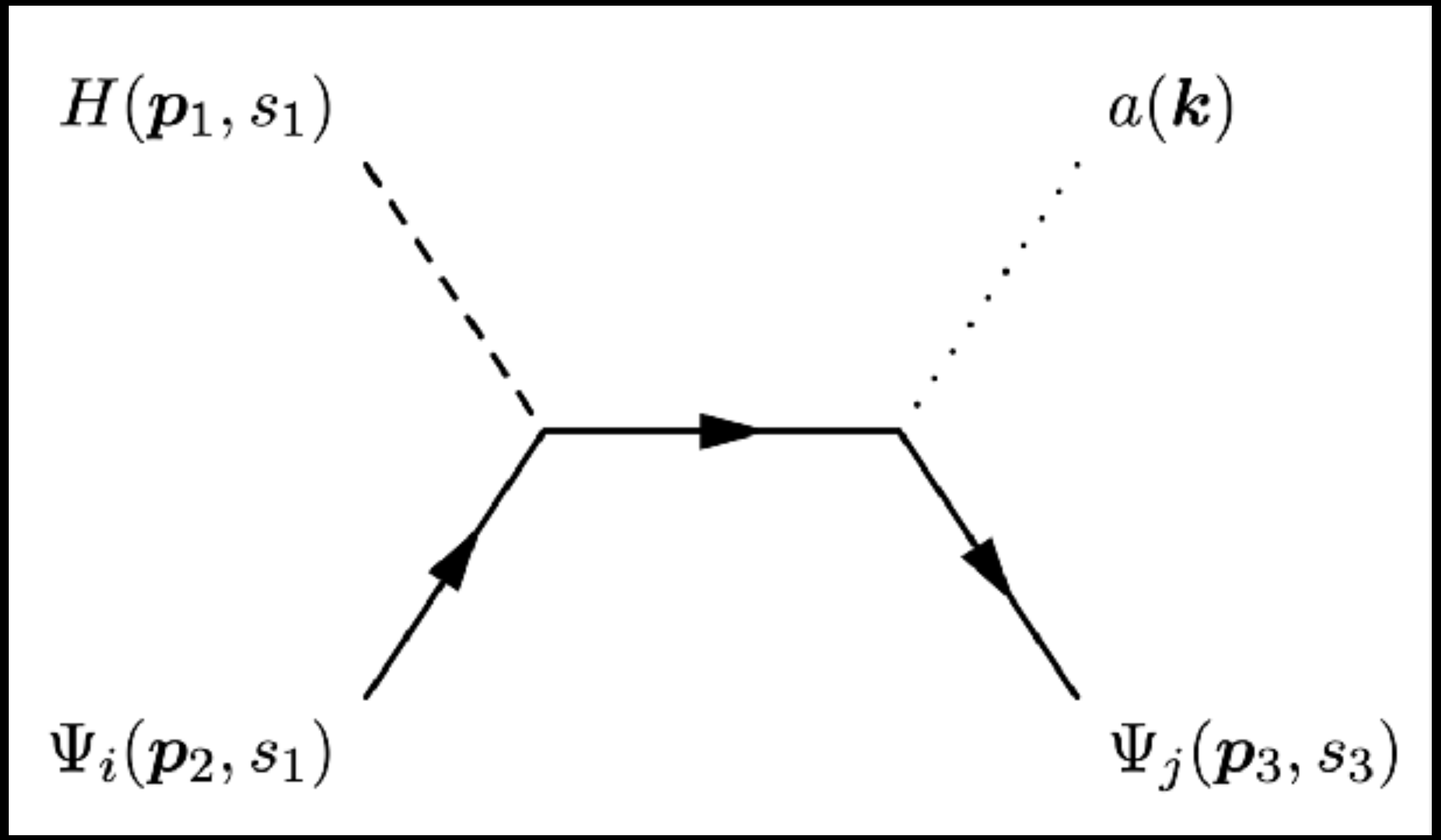
Hadronic Axiverse, Dim-5



Axion Production Rate

- Axion production rates controlled by fermion Yukawas

$$\Gamma_{H\Psi_i \to a\Psi_j} \approx \frac{c_{ij}^2 (Y_i + Y_j)^2}{4\pi} \frac{T^3}{f_a^2}$$



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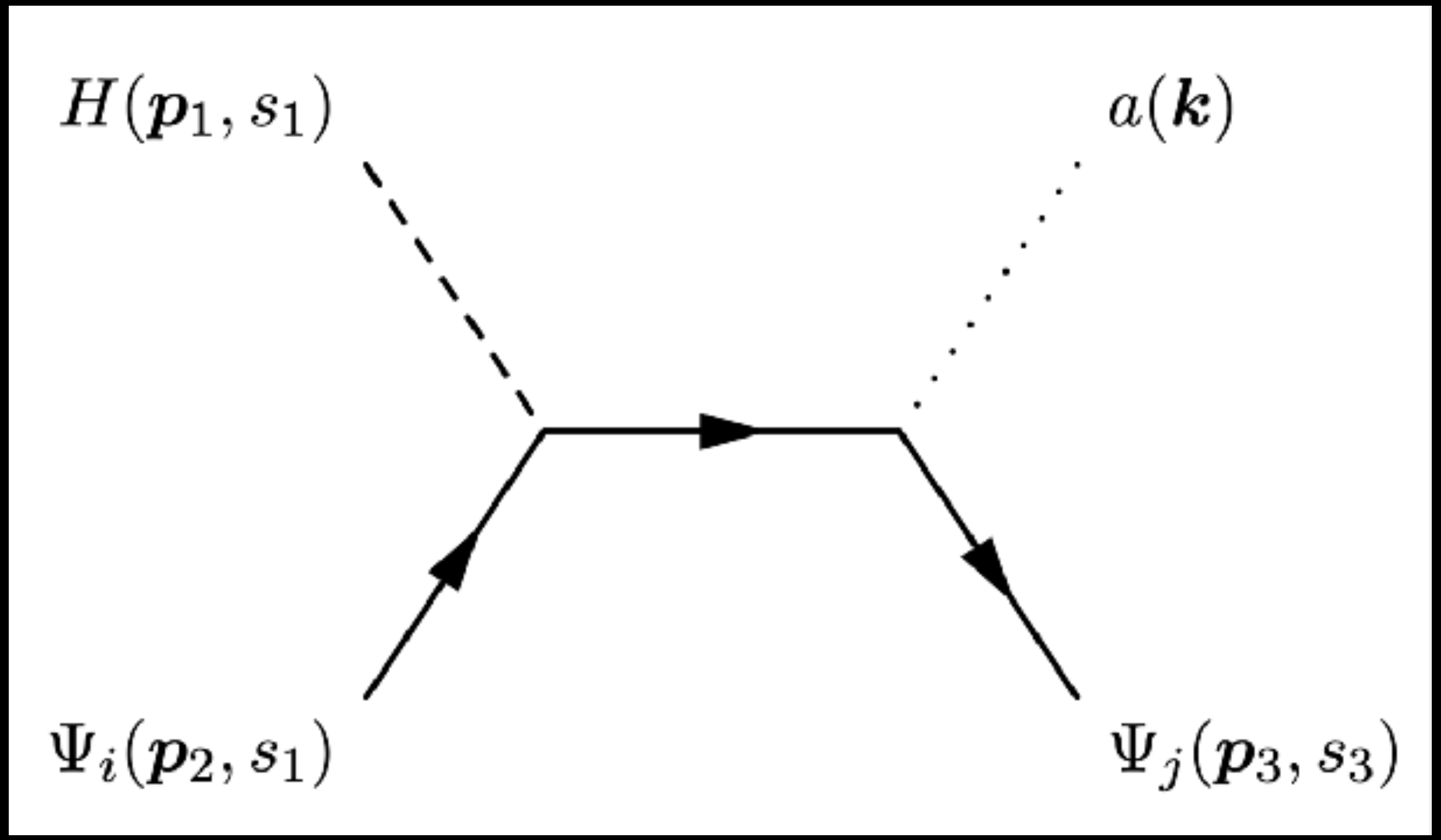
$$\implies T_d \approx 10^7 \text{ GeV} \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^2 \left(\frac{1}{cY_f} \right)^2$$



Froggatt-Neilsen Flavor Model

- Model c_Ψ as that required to solve the flavor puzzle
- Froggatt-Neilsen mechanism: Yukawas arise as VEV of a scalar S

$$\mathcal{L} = Y^d_{ij} H Q_i \bar{d}_j + Y^u_{ij} \tilde{H} Q_i \bar{u}_j \longrightarrow \left(\frac{\langle S \rangle}{\Lambda_{FN}}\right)^{n^d_{ij}} Q_i H \bar{d}_j + \left(\frac{\langle S \rangle}{\Lambda_{FN}}\right)^{n^u_{ij}} Q_i \tilde{H} \bar{u}_j$$

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- Axion-fermion operators $\quad \dfrac{\partial_\mu a_\Psi}{f_a} \overline{\Psi} \gamma^\mu c_\Psi \Psi \implies c^{ij}_\Psi \propto \left(\dfrac{\langle S \rangle}{\Lambda_{\mathrm{FN}}}\right)^{|H(\Psi_i) - H(\Psi_j)|}$

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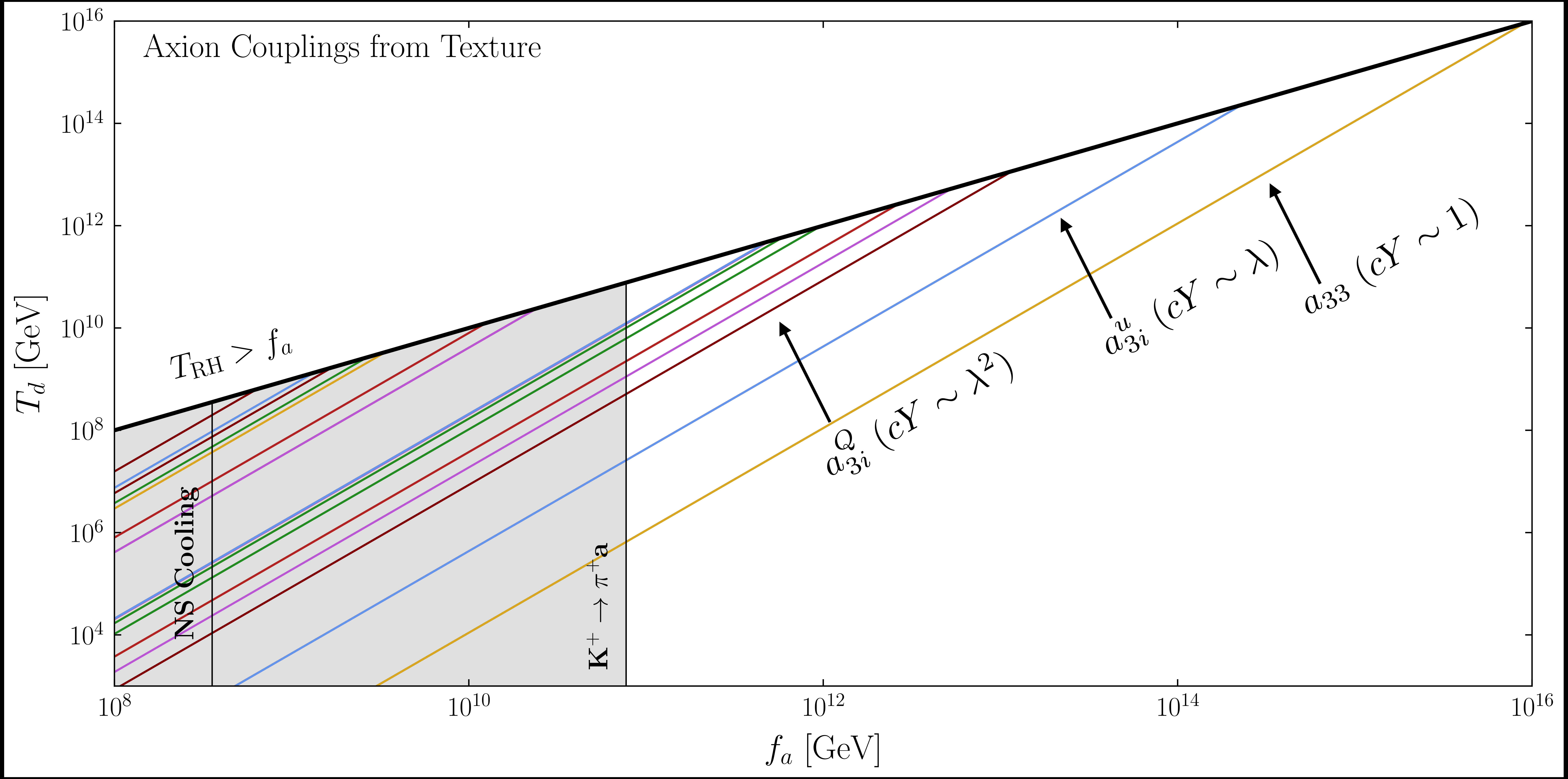
- EX:

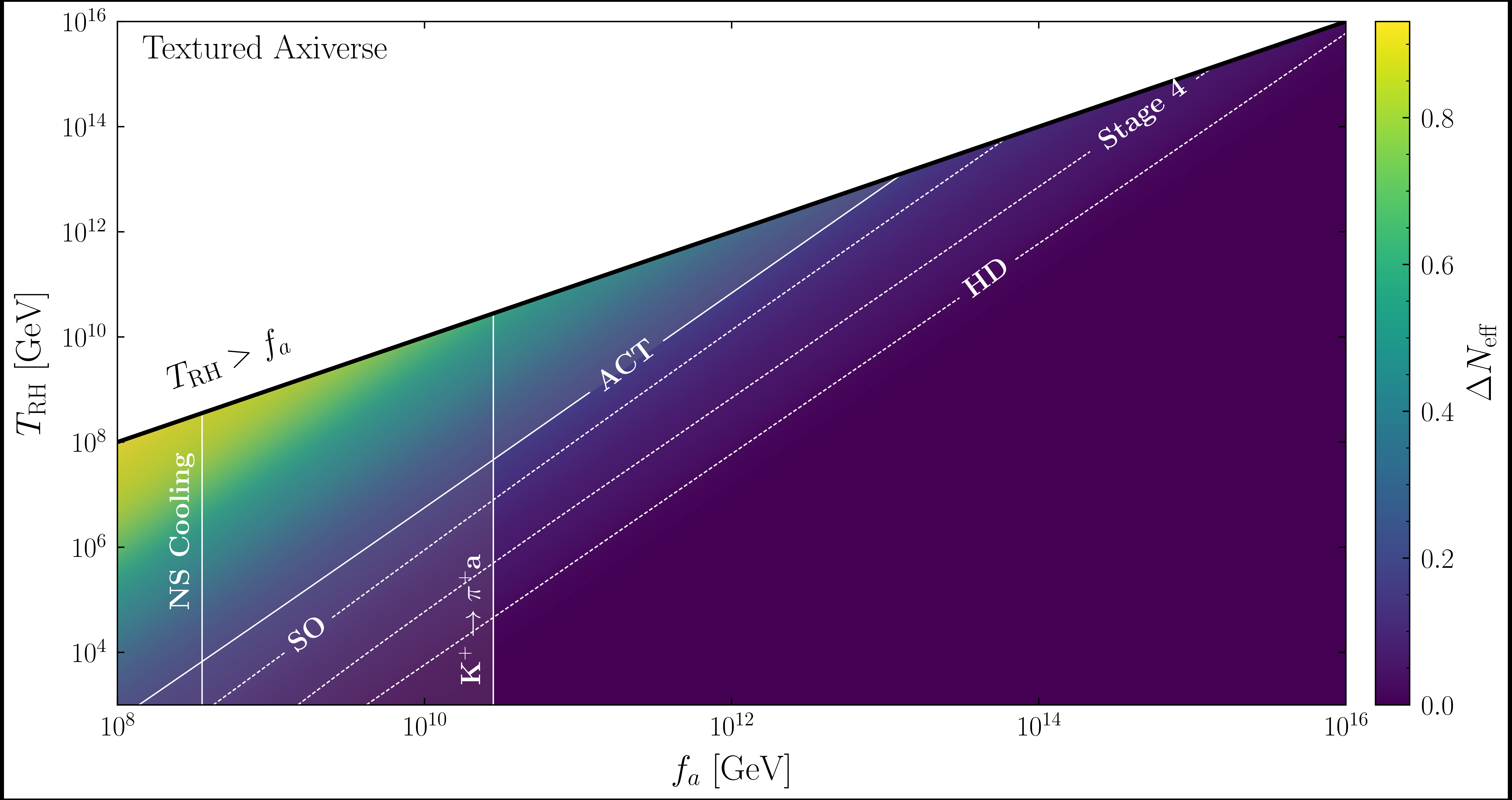
Q_1	Q_2	Q_3	$\bar{d}_1$	$\bar{d}_2$	$\bar{d}_3$	$\bar{u}_1$	$\bar{u}_2$	$\bar{u}_3$
(3)	(2)	(0)	(3)	(2)	(2)	(3)	(1)	(0)

$$\implies c_Q = \begin{pmatrix} \lambda^0 & \lambda^1 & \lambda^3 \\ \lambda^1 & \lambda^0 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^0 \end{pmatrix} \simeq \begin{pmatrix} 1 & 0.23 & 0.01 \\ 0.23 & 1 & 0.05 \\ 0.01 & 0.05 & 1 \end{pmatrix}$$

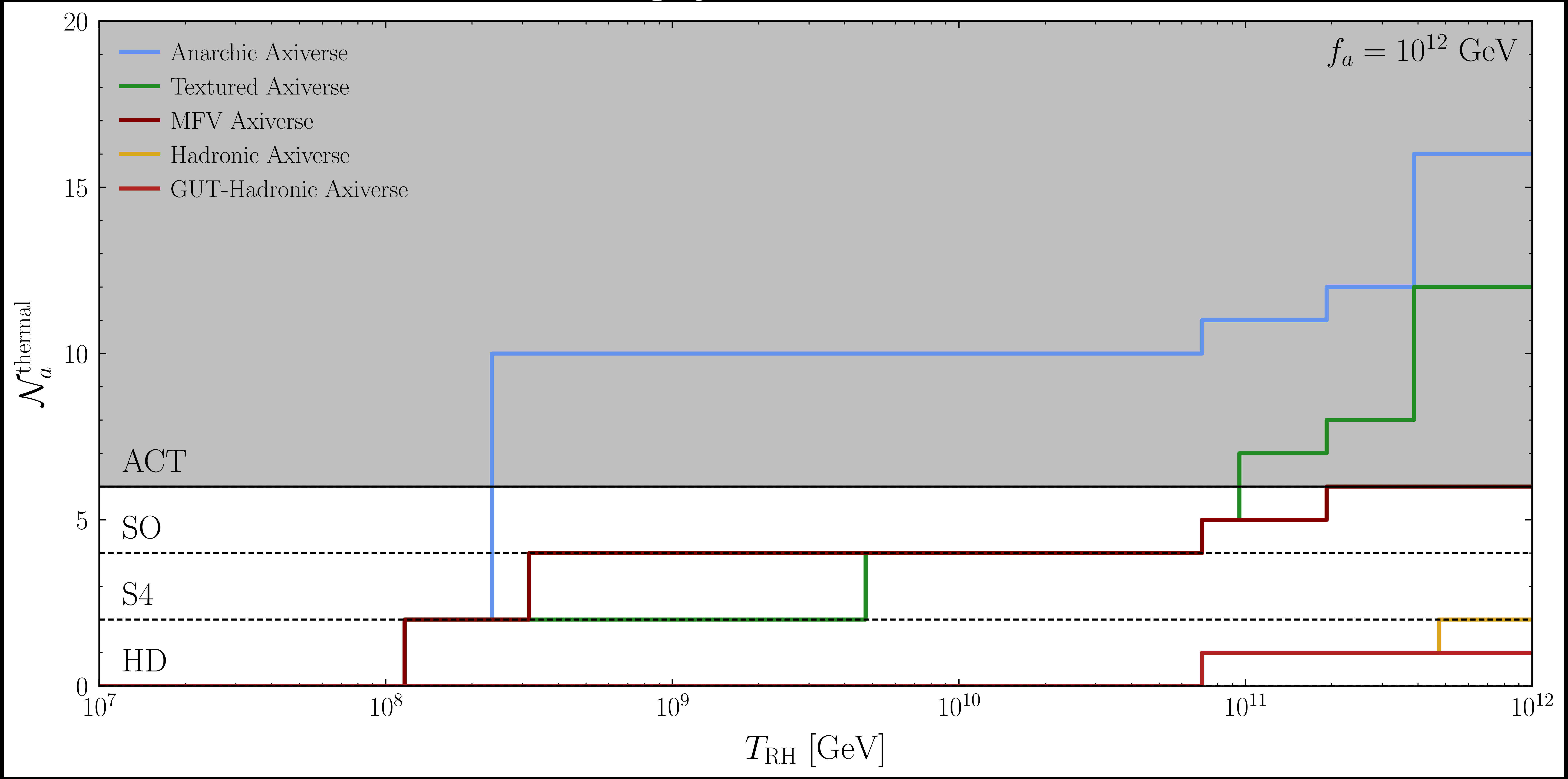
Textured Axiverse



Textured Axiverse



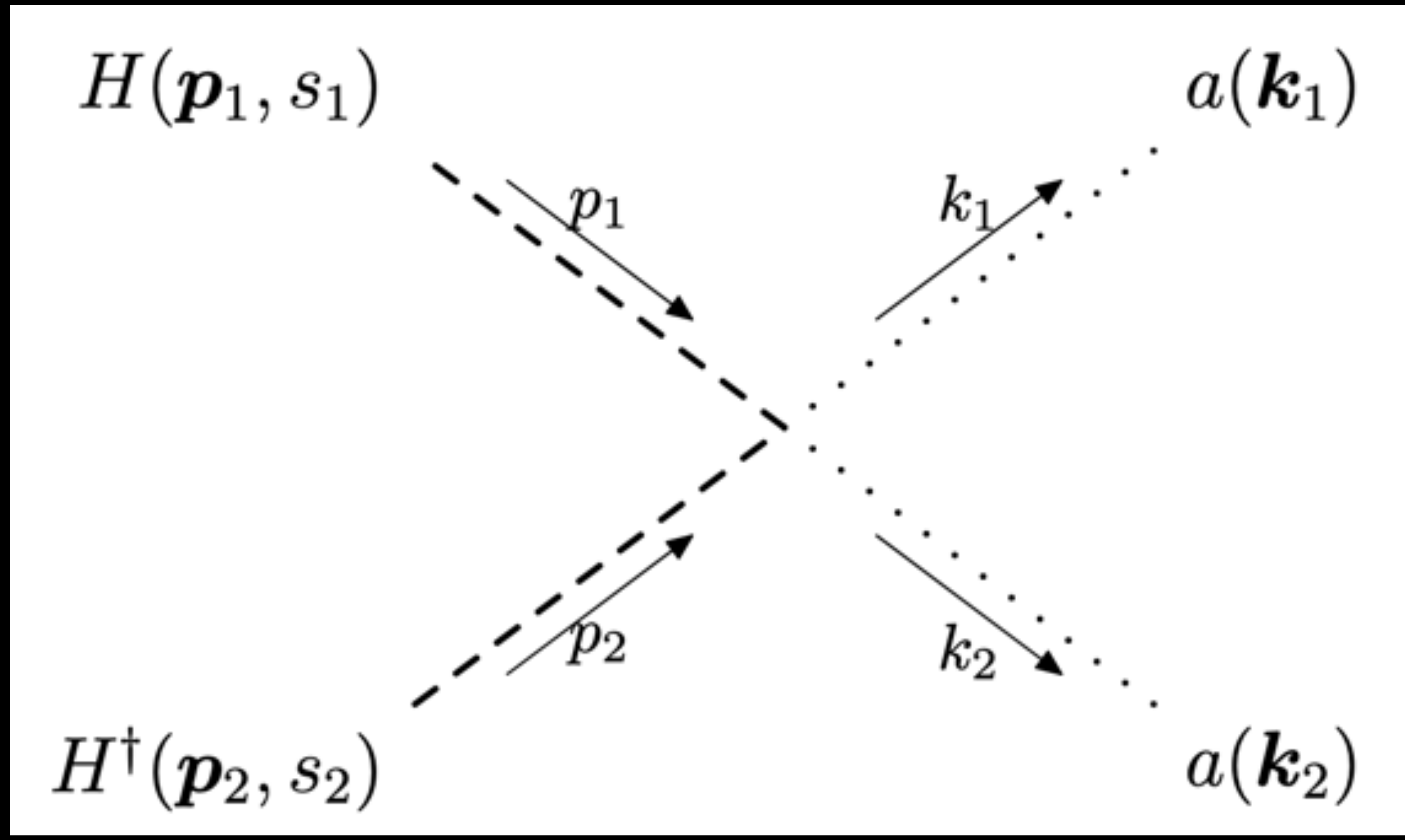
Cosmology Dependence



Axiverse EFT at dim-6

- As $T \sim f_a$, EFT begins to break down

$$\mathcal{L}_6 = -(\partial_\mu \phi_i)\frac{c_{ah}^{ij}}{f_a^2}(\partial^\mu \phi_j)|H|^2 - (\partial_\mu \phi_i)\frac{c_{aF}^{ij}}{f_a^2}(\partial_\nu \phi_j)F^{\mu\nu}$$
$$= -\frac{\lambda_{ah}^i}{f_a^2}(\partial a_i)^2|H|^2 - \frac{\lambda_{aF}^i}{f_a^2}(\partial a_i)(\partial b_i)F$$



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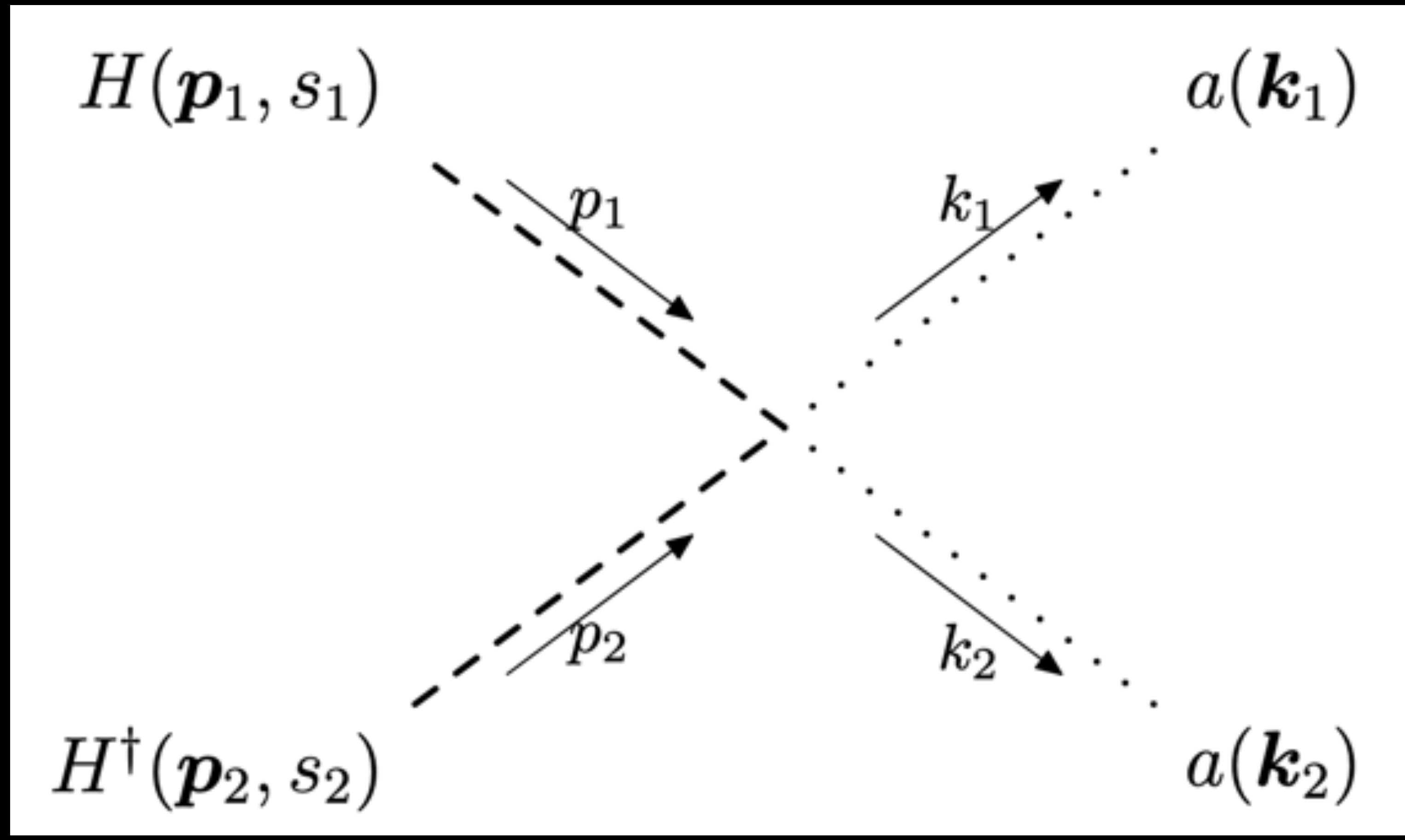
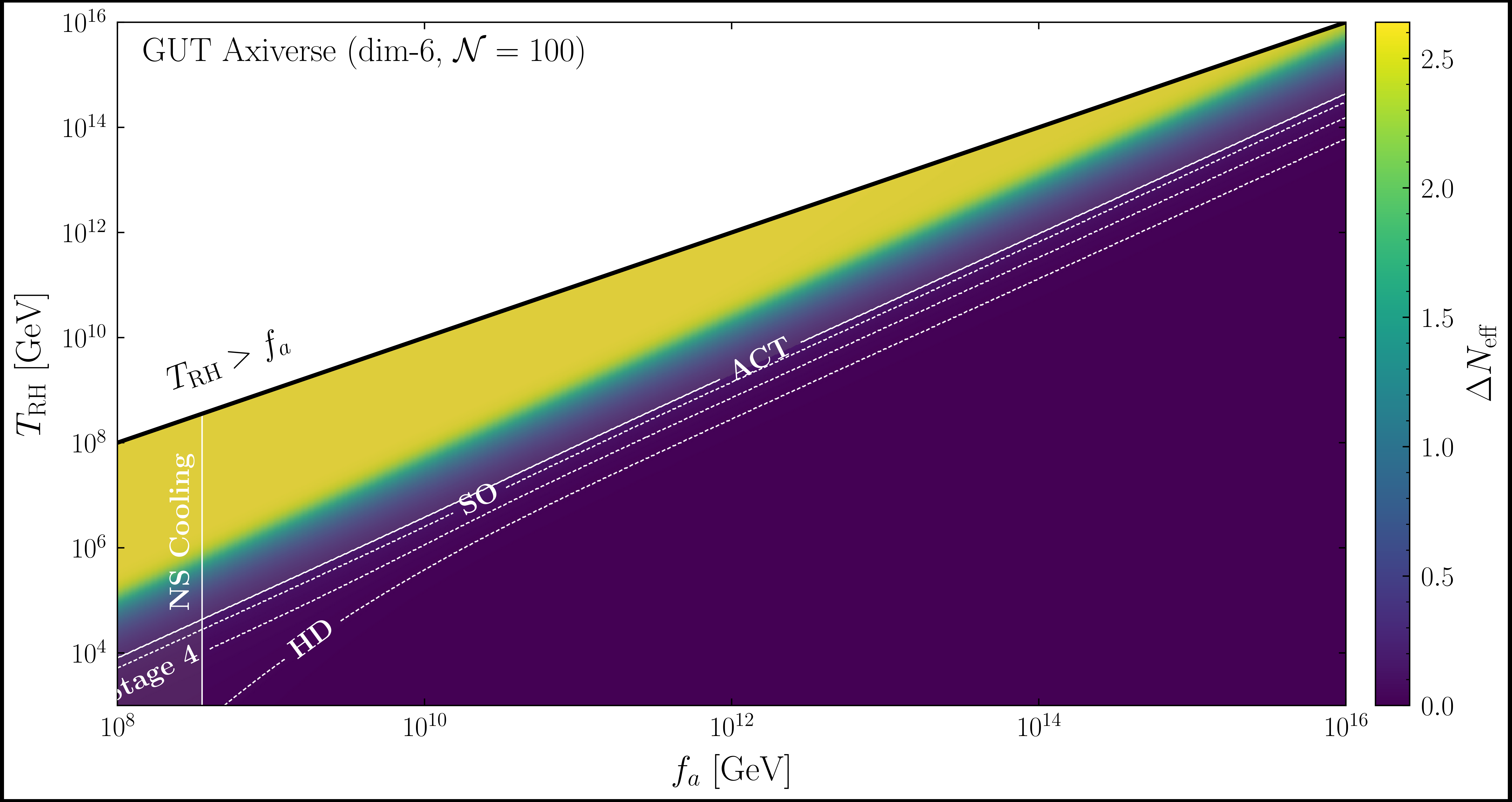


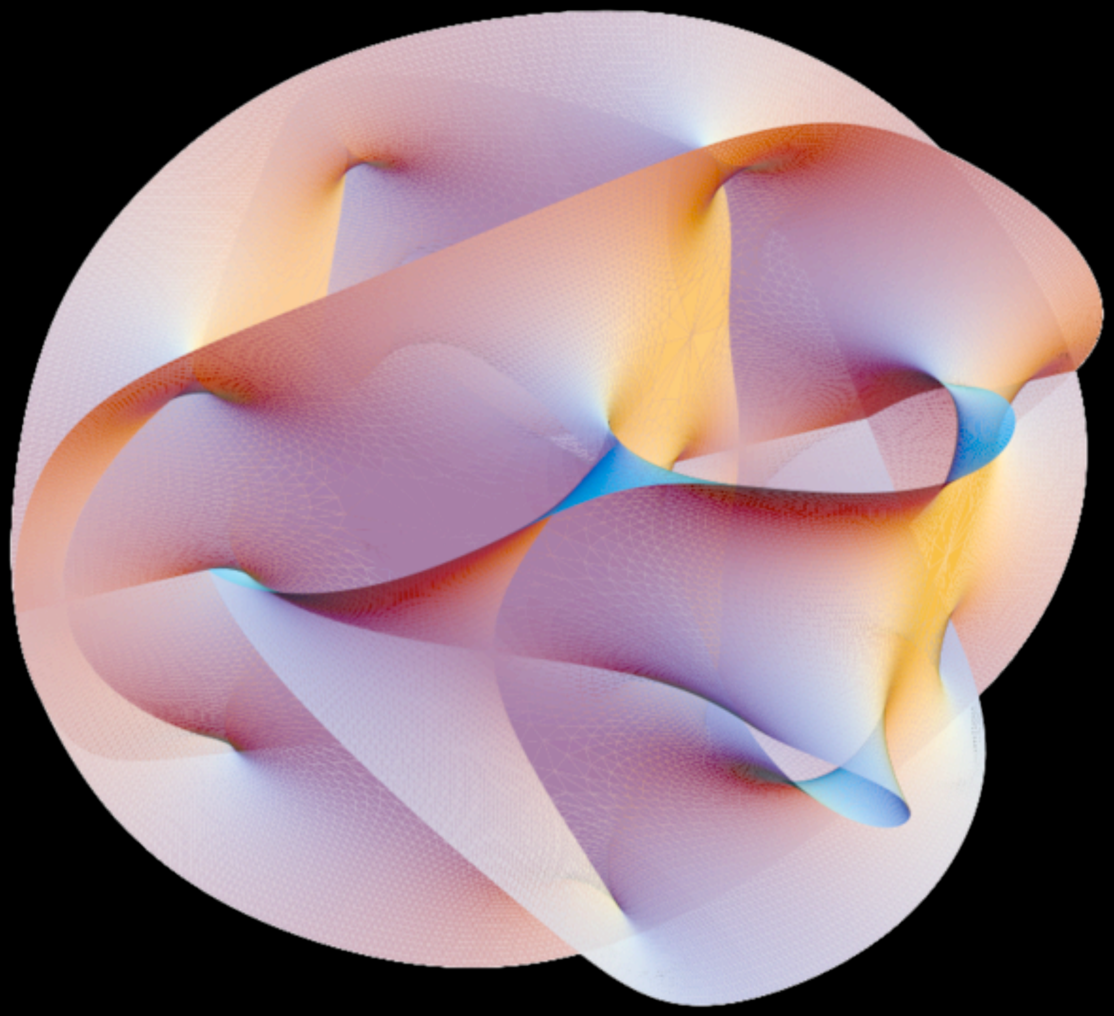
- Quadratic in axion field $\Longrightarrow$ thermalizes $\mathrm{rank}(c_{ah}), \mathrm{rank}(c_{aF})$ axions!
- Due to large yield, freeze-in also important

Hadronic Axiverse, Dim-6



Conclusions

- Axiverse phenomenology rich and underexplored
- Reheat temperatures must be low in the Axiverse
- Bottom-up approach here: need top-down too
- May lead to large N_{eff} signals at ongoing CMB experiments
- Our approach generalizes to computing abundances of N copies of any particle



Thank you!

(ii) Anarchic Fermion Couplings

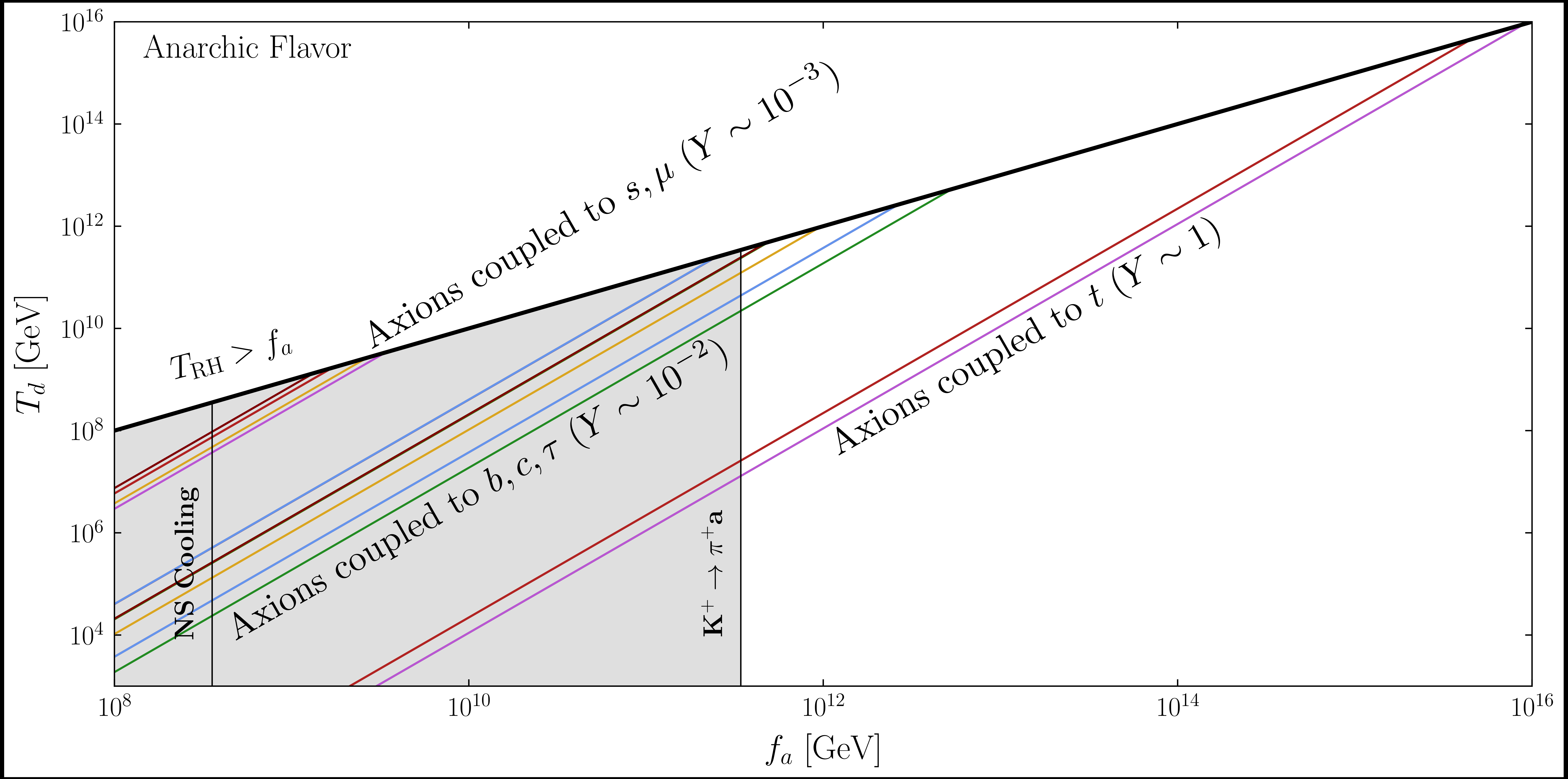
$$\mathcal{L}_5 = \sum_G \frac{c_G \alpha_G}{4\pi} \frac{a_G}{f_a} G\tilde{G} + \sum_\Psi \frac{\partial_\mu a_\Psi}{f_a} \overline{\Psi} \gamma^\mu c_\Psi \Psi$$

- Assume c_Ψ entries are $\mathcal{O}(1)$ random numbers:

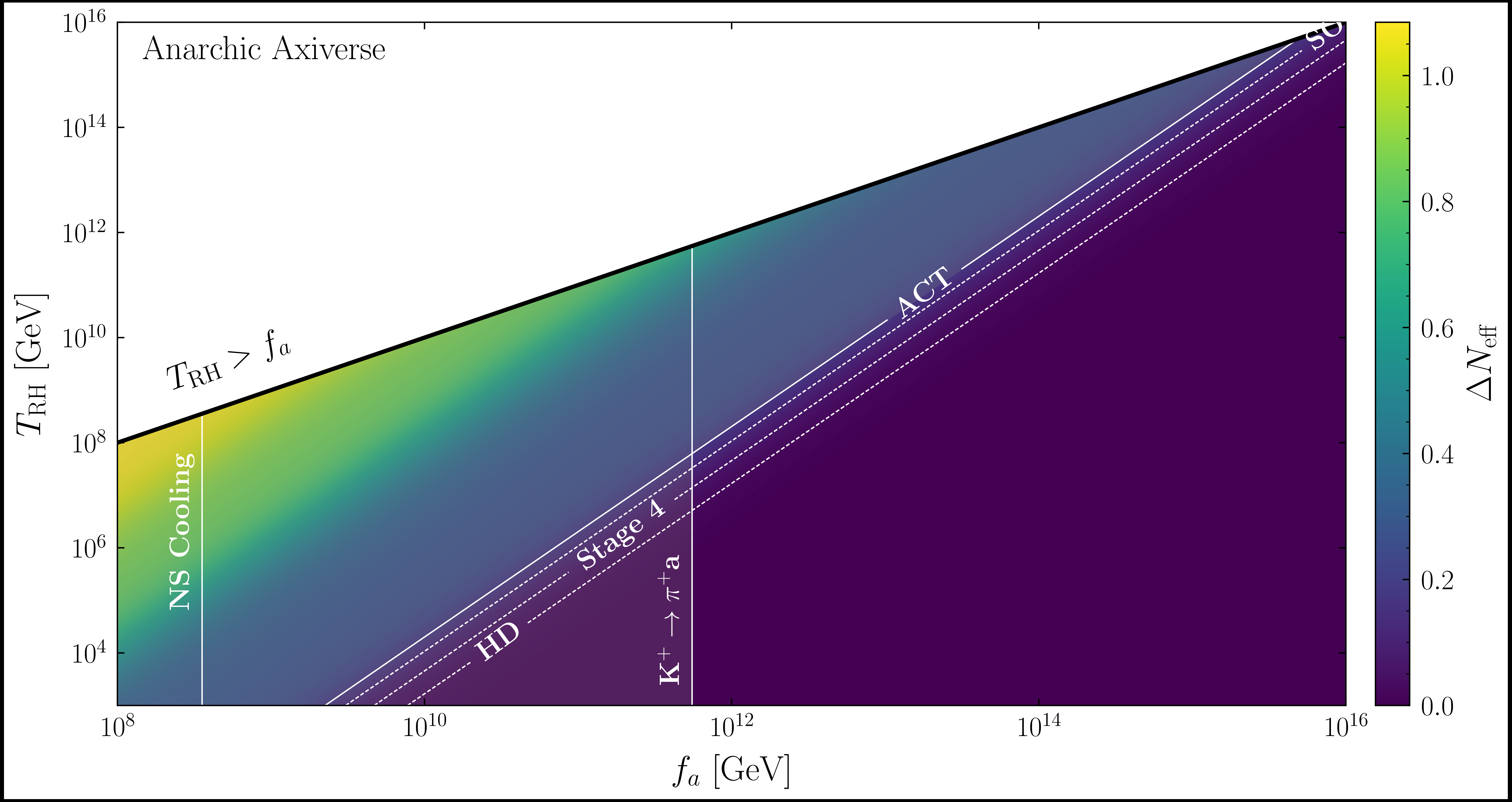
$$c_\Psi = \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

- Each operator thermalizes a different axion

Anarchic Axiverse



Anarchic Axiverse



(iv) Minimal Flavor Violation Model

- Assume the only source of flavor violation is the SM Yukawas.
- Treat c_Ψ as a spurion under $SU(3)_\Psi$:

$$c_Q = c_Q^{(0)} I + c_Q^{(1)} Y_u Y_u^\dagger + c_Q^{(2)} Y_d Y_d^\dagger + \mathcal{O}(Y^4)$$

$$c_u = c_u^{(0)} I + c_u^{(1)} Y_u^\dagger Y_u + \mathcal{O}(Y^4)$$

$$c_d = c_d^{(0)} I + c_d^{(1)} Y_d^\dagger Y_d + \mathcal{O}(Y^4)$$

$$c_L = c_L^{(0)} I + c_L^{(1)} Y_e Y_e^\dagger + \mathcal{O}(Y^4)$$

$$c_e = c_e^{(0)} I + c_e^{(1)} Y_e^\dagger Y_e + \mathcal{O}(Y^4)$$

(iv) Minimal Flavor Violation Model

- Assume the only source of flavor violation is the SM Yukawas.
- Treat c_Ψ as a spurion under $SU(3)_\Psi$:

$$c_Q \approx c_Q^{(0)} I + c_Q^{(1)} y_t^2/3 \, \mathrm{diag}(-1,-1,2)$$

$$c_u \approx c_u^{(0)} I + c_u^{(1)} y_t^2/3 \, \mathrm{diag}(-1,-1,2)$$

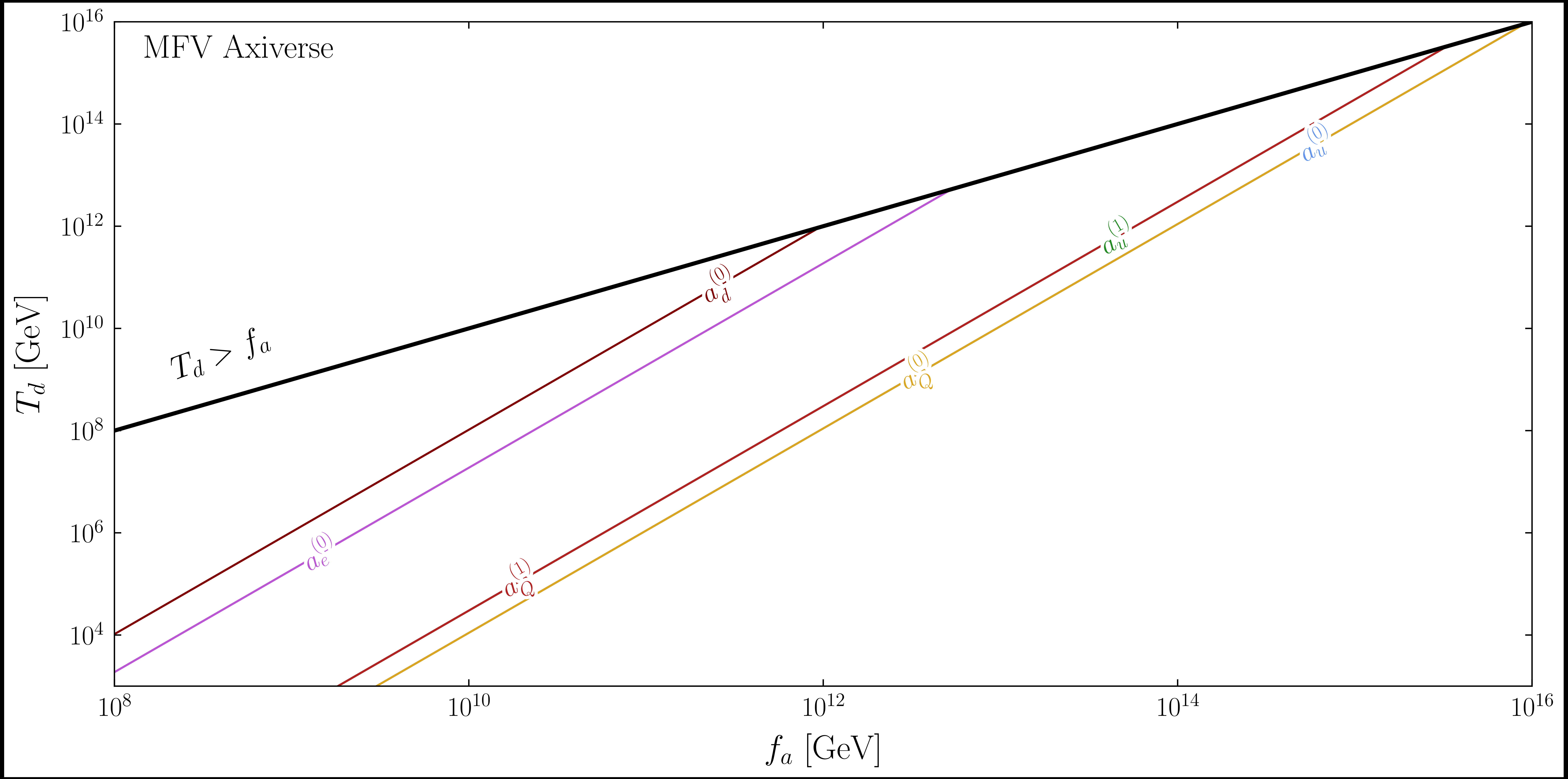
$$c_d \approx c_d^{(0)} I$$

$$c_L \approx c_L^{(0)} I$$

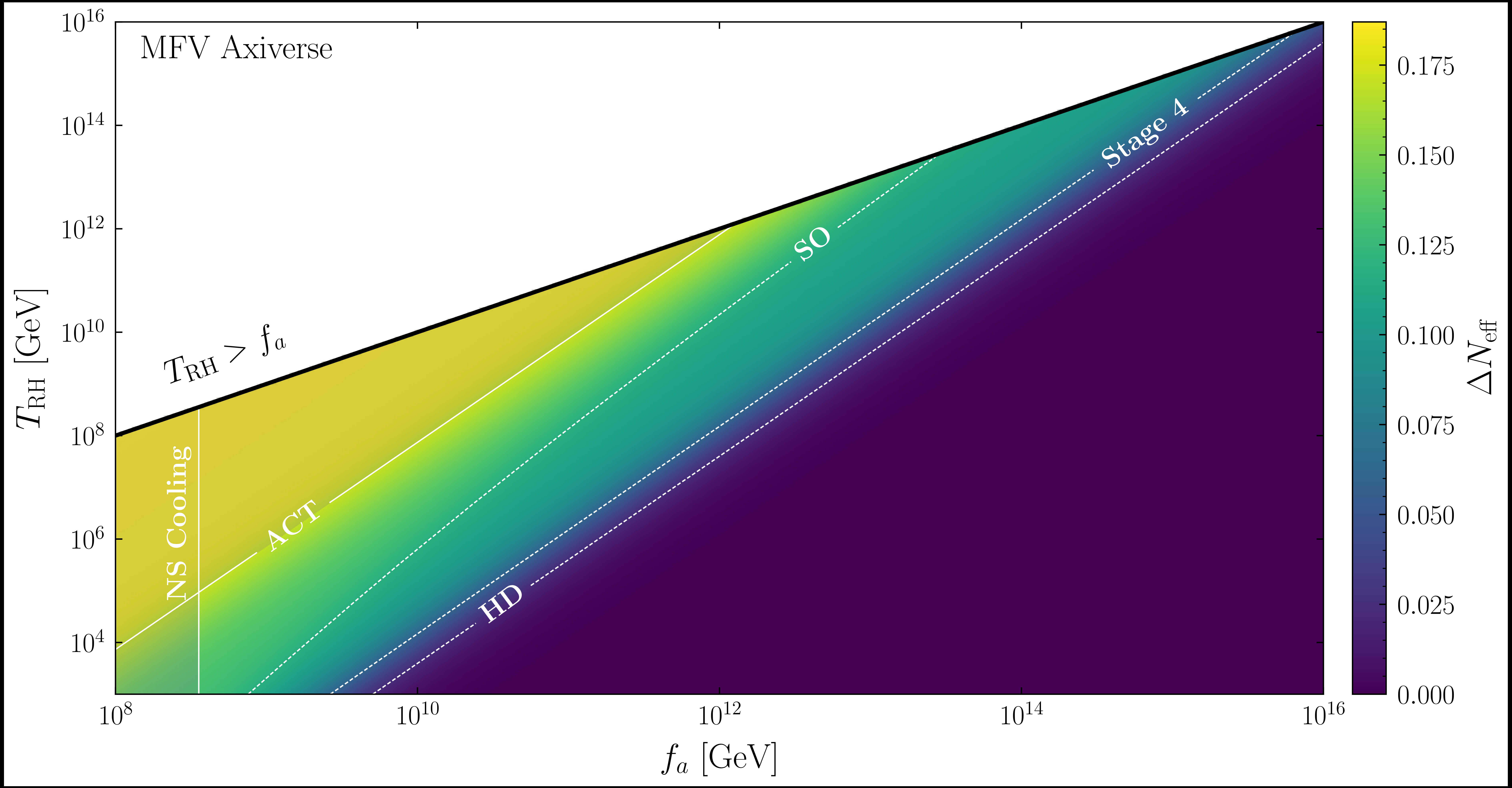
$$c_e \approx c_e^{(0)} I$$

- Only 6 axions thermalize with the SM.

MFV Axiverse



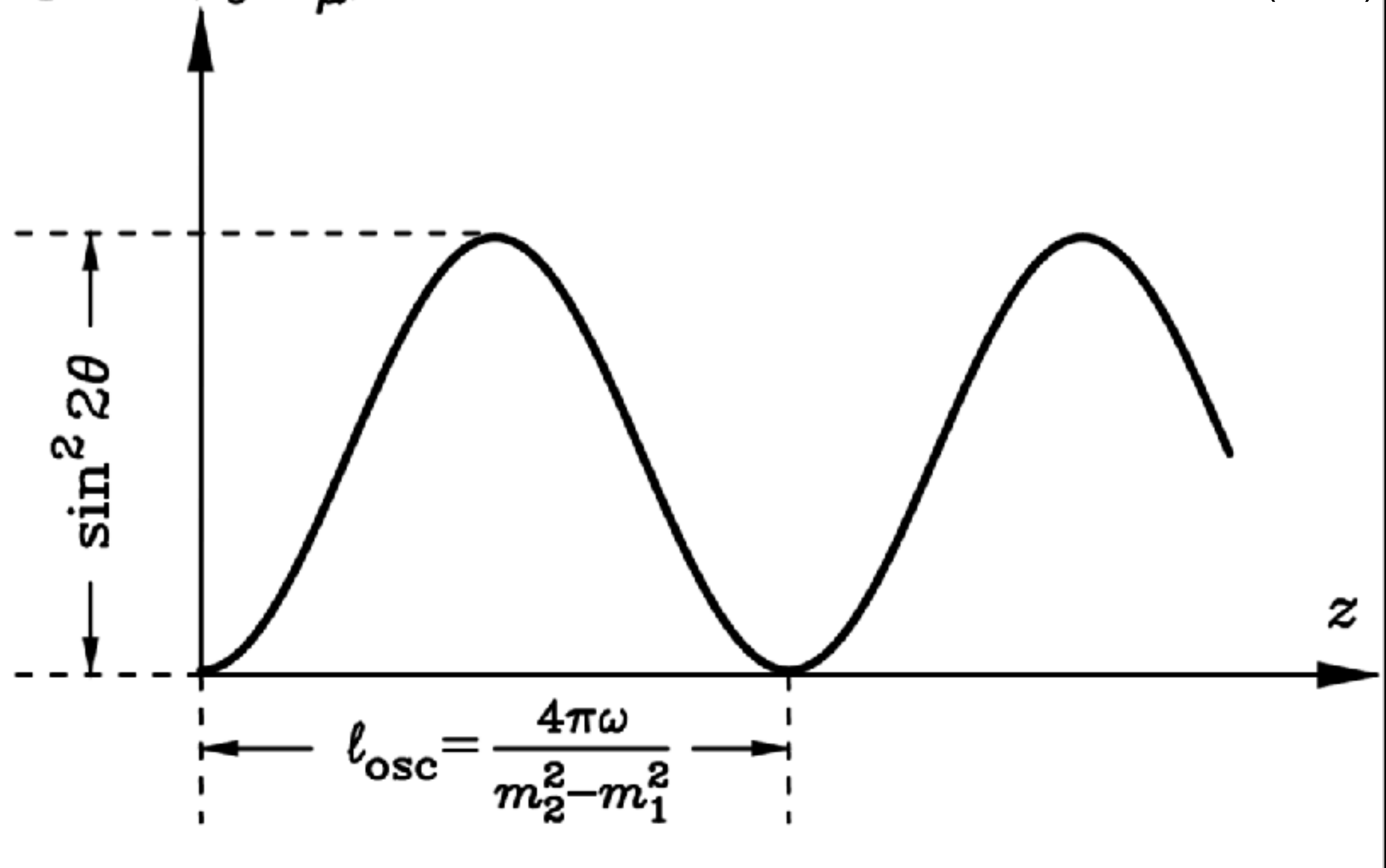
MFV Axiverse



N_{eff} from Oscillations?

- Freeze-in N_{eff} of sterile axions through mixing?
  - Analogous to Dodelson-Widrow

Stars as Laboratories for Fundamental Physics,
Raffelt (1996)



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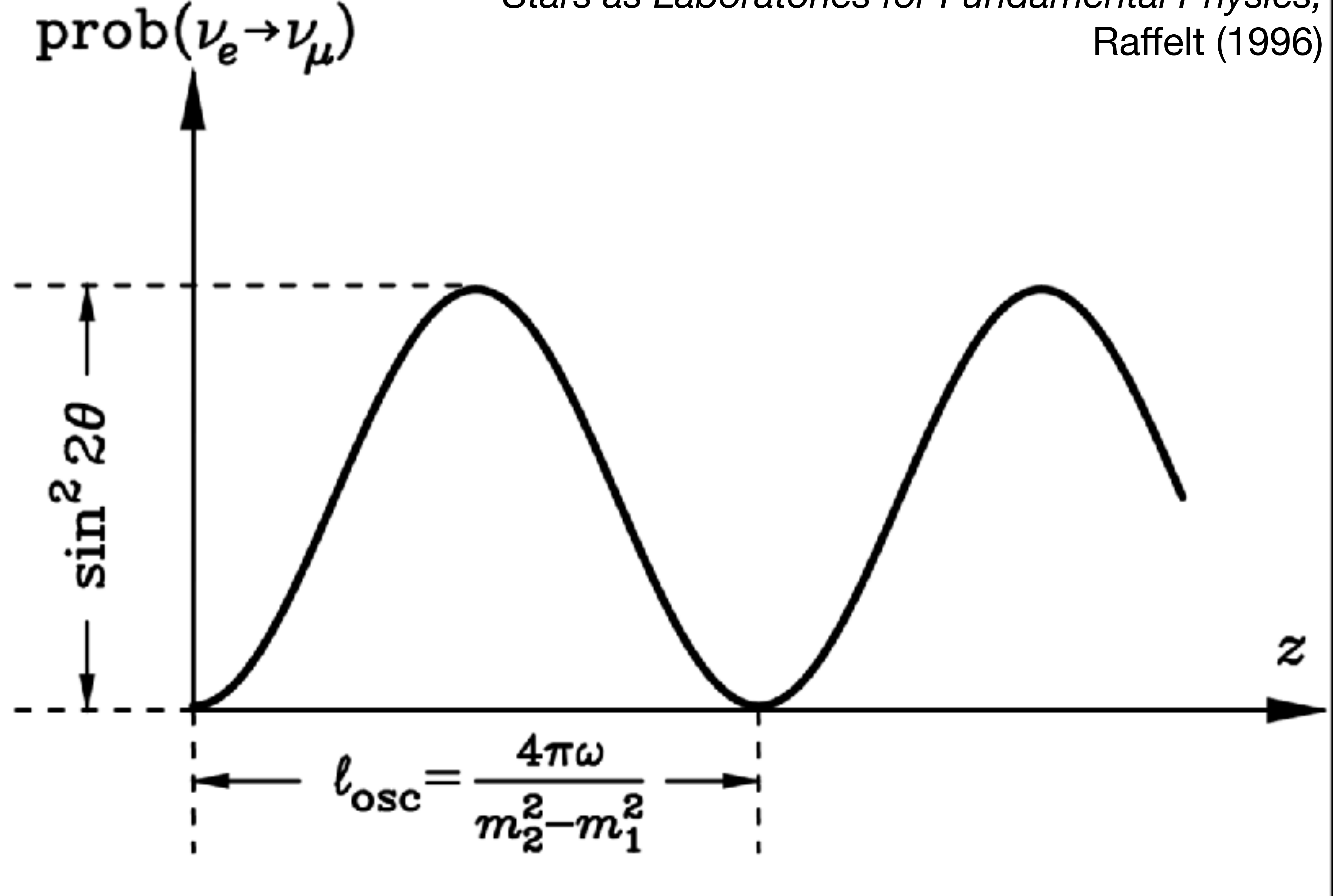
$$(\partial_t + 3H)\, n_{\nu_s} = \left[\frac{1}{2}\sin^2(2\theta)\Gamma_{\text{int}}\right] n_{\nu_a}$$



Stars as Laboratories for Fundamental Physics, Raffelt (1996)

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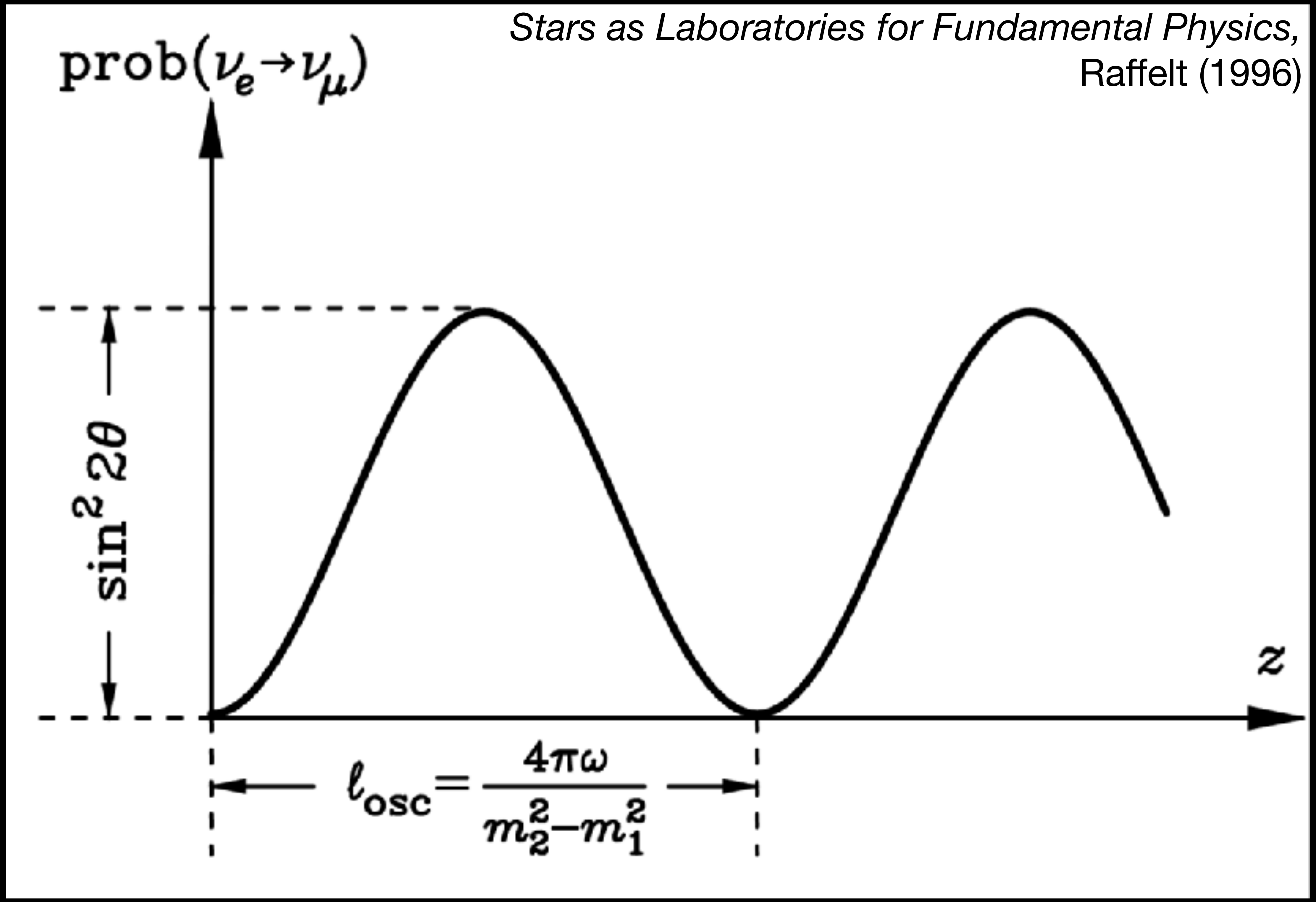
$$\int_{l_{\mathrm{osc}}} \sin^2\left(\frac{\Delta m^2}{\omega} L\right) dz$$



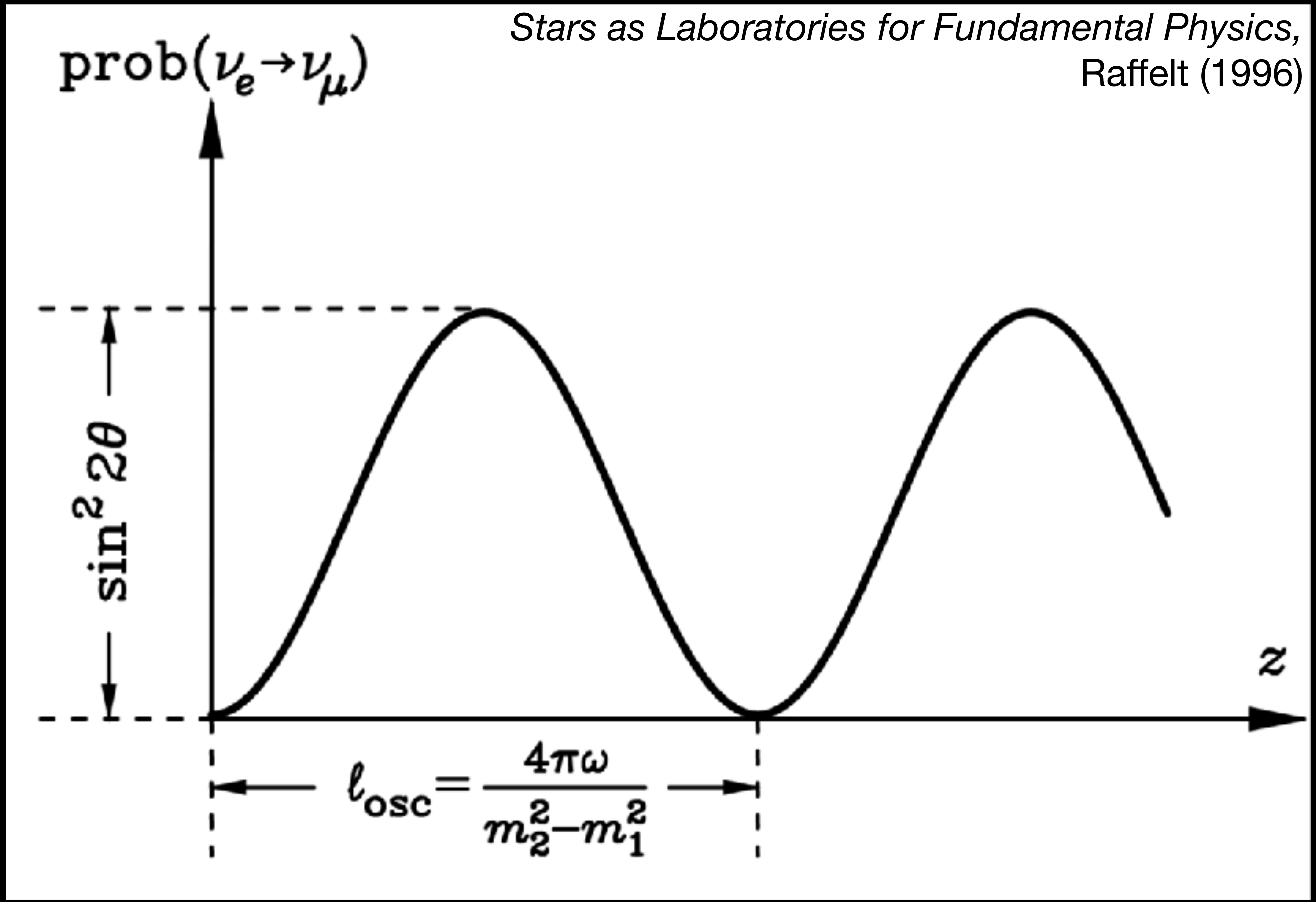
Stars as Laboratories for Fundamental Physics, Raffelt (1996)

N_{eff} from Oscillations?

- Freeze-in N_{eff} of sterile axions through mixing?
  - Analogous to Dodelson-Widrow
- Mixing important $\iff$ $\Gamma_{\text{int}} < \Gamma_{\text{mix}}$ above T_d

$$\Gamma_{\text{int}} \approx \alpha^3 \frac{T^3}{f_a^2}, \ \Gamma_{\text{mix}} \approx \frac{\Delta m^2}{T}$$

$$\implies \sqrt{\Delta m^2} \gtrsim 1 \text{ MeV} \left(\frac{f_a}{10^9 \text{ GeV}} \right)^3$$



ΔN_{eff}