Cosmology of Heavy Axions: Decaying Dark Matter & Baryogenesis

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Strong *CP* Problem

$$\mathscr{L}_{\text{SM}} \supset \frac{\alpha_3}{8\pi}\theta G\tilde{G} + Y_u \bar{Q}_L \tilde{H} u_R + Y_d \bar{Q}_L H d_R$$

- Observed $|\bar{\theta}| = |\theta + \text{arg det}(Y_u Y_d)| < 10^{-10}$
- But why so small given $\delta_{\text{CKM}} \sim \mathcal{O}(1)$?

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strong *CP* problem

- Solutions: ~~massless up quark~~, parity, *CP*, axions

lattice results

Axion Solution

Peccei, Quinn ’77
Weinberg, Wilczek ’78

- Axion solution:

$\bar{\theta}$ is a dynamical quantity

$$\mathscr{L}_{\text{SM+Axion}} \supset \frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G\tilde{G} \Rightarrow V(a) \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a} + \bar{\theta}\right)$$

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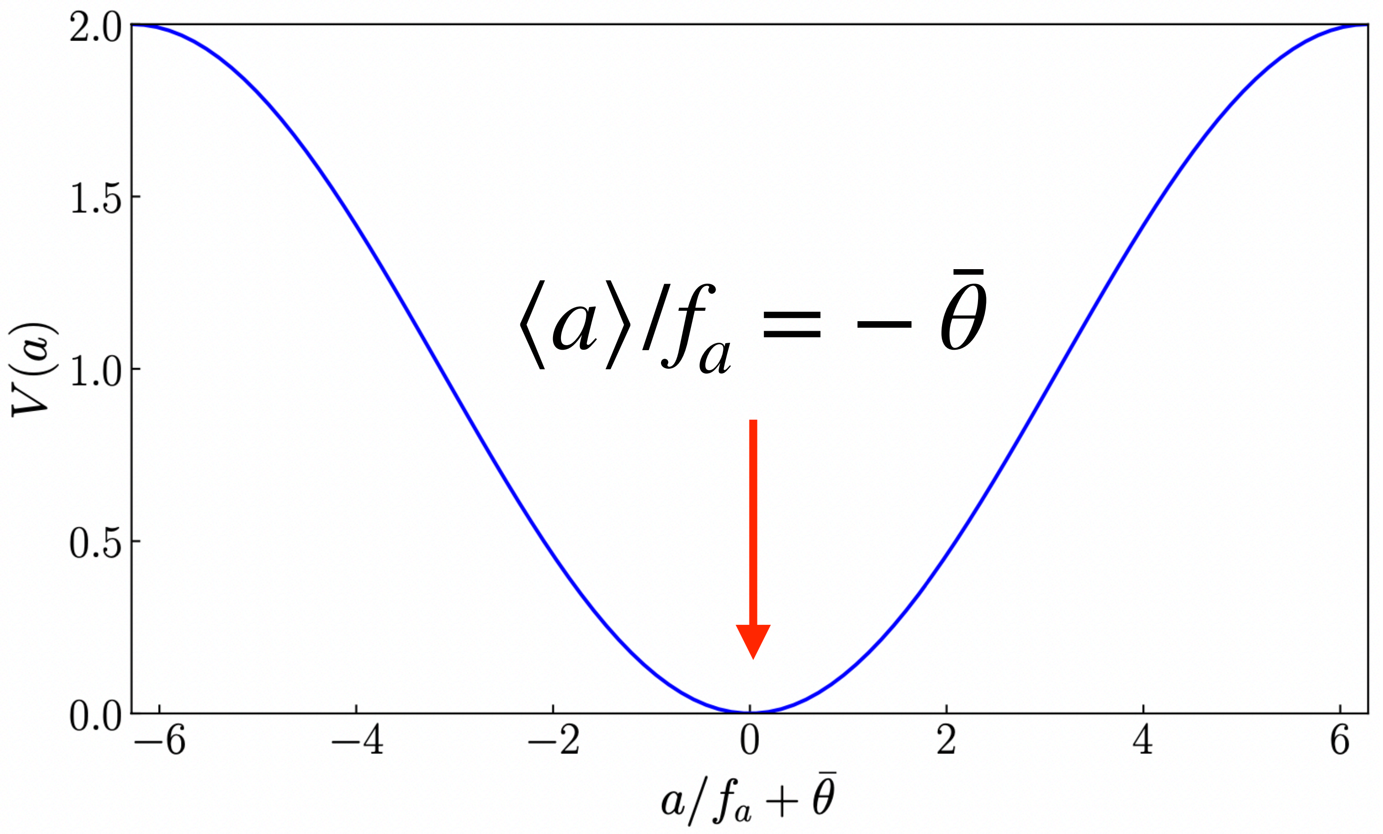

$$\bar{\theta}_{\text{eff}} = \bar{\theta} + \langle a \rangle / f_a = 0!$$

elegant solution from IR EFT point of view

Why Axions?

- strong *CP* problem [QCD Axion]
- dark matter [QCD Axion or ALPs]

Extra-
dim.
Theories

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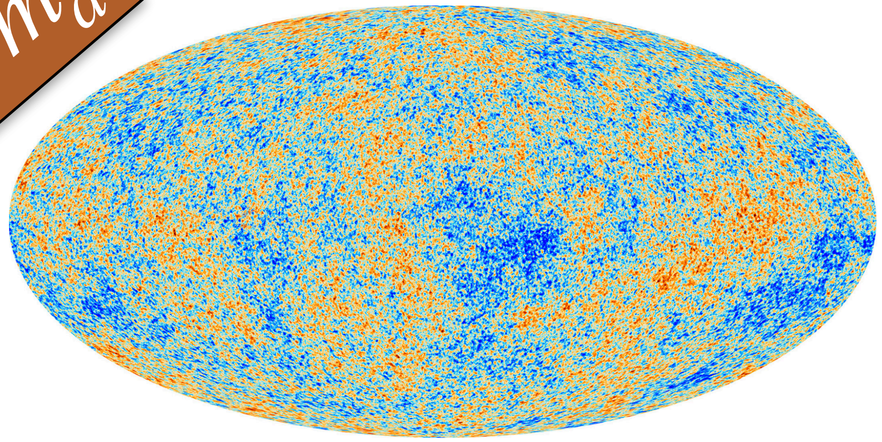
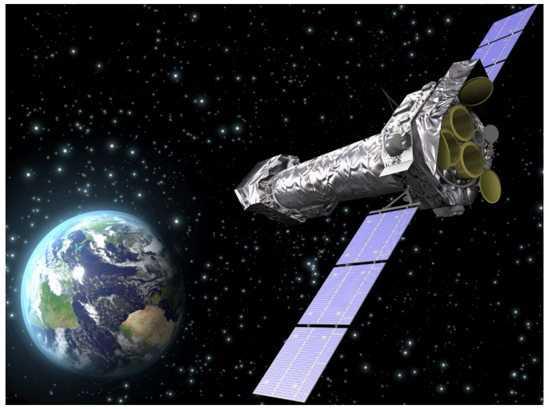
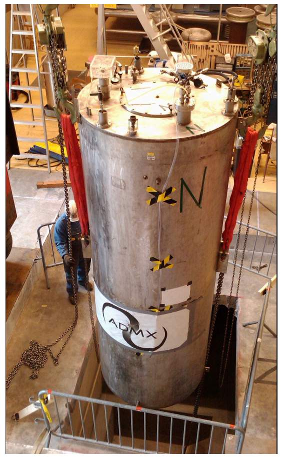
Extra-dim. Theories

Many probes for small m_a







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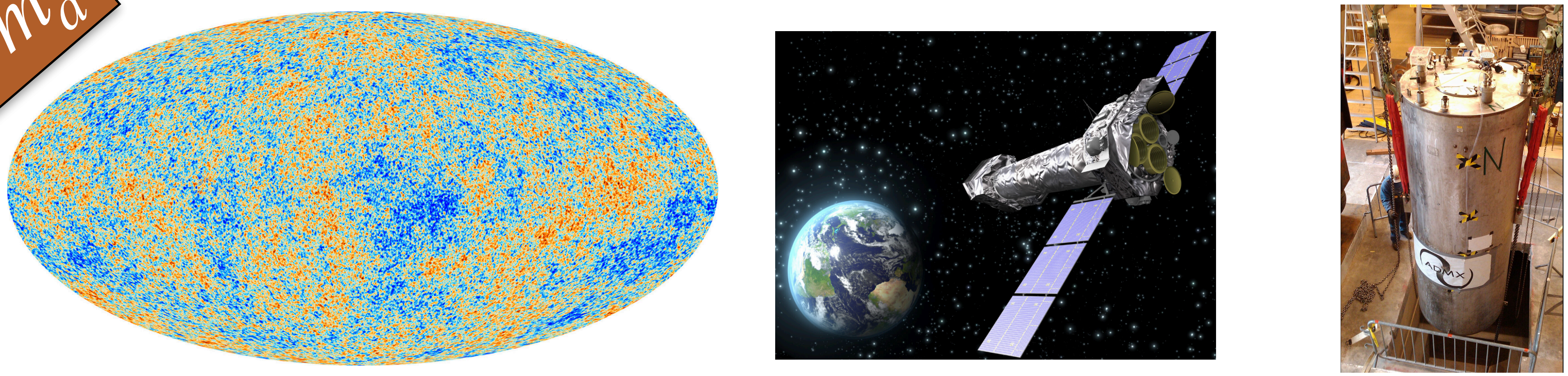


Today: heavy axions with $m_a \gg$ eV

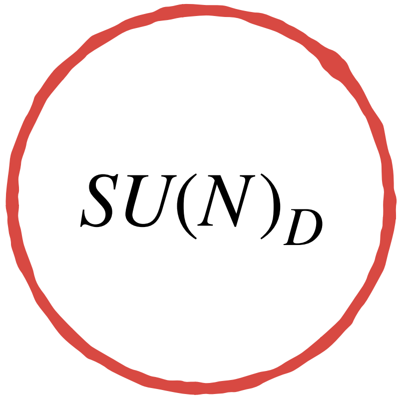
☑ quality problem

☑ strong *CP*

☑ **dark matter**

Heavy Axions

A toy model for heavy ALP†



$SU(N)_D$

$$\frac{\alpha_D}{8\pi f_a} a G_D \tilde{G}_D$$

$$m_a f_a \approx \Lambda_D^2$$

† another axion can solve the strong *CP* problem

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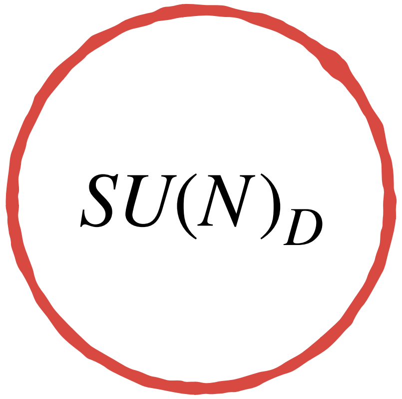

$$\frac{\alpha_D}{8\pi f_a} a G_D \tilde{G}_D$$

$$m_a f_a \approx \Lambda_D^2$$

$$\Lambda_D \gg \Lambda_{\rm QCD} \longrightarrow \frac{m_a}{m_{a,\rm QCD}} \approx \frac{\Lambda_D^2}{\Lambda_{\rm QCD}^2} \gg 1$$

[†] another axion can solve the strong *CP* problem

How Heavy?

$$m_a f_a \approx \Lambda_D^2 \gg \Lambda_{\rm QCD}^2$$

$$\Lambda_D \simeq \Lambda_{\rm UV} \exp\left(-\frac{6\pi}{11N\alpha_{\rm UV}}\right)$$

UV Scale

UV Coupling

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$$\Lambda_D \simeq \underset{\overset{\uparrow}{\text{UV Scale}}}{\Lambda_{\rm UV}} \exp\left(-\frac{6\pi}{11N\underset{\overset{\uparrow}{\text{UV Coupling}}}{\alpha_{\rm UV}}}\right)$$

$$f_a \sim \Lambda_{\rm UV} \sim 10^{16}\ \text{GeV}$$
$$\alpha_{\rm UV} \sim 1/25$$

	$SU(2)_D$	$SU(5)_D$
Λ_D	10^7 GeV	10^{12} GeV
m_a	MeV	10^8 GeV
Pheno	Dark Matter	Baryo-genesis

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Cosmology of keV-MeV axions

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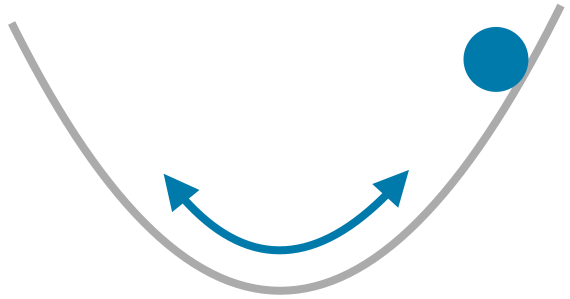
Heavy Axion DM

Axion Overclosure!



Misalignment Production

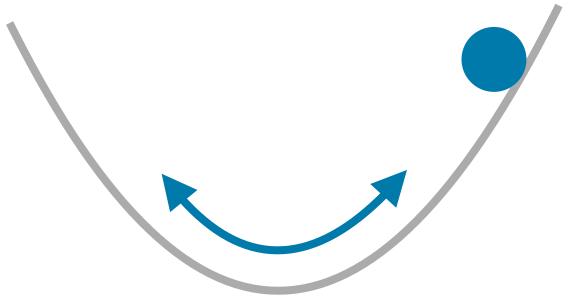
$$\boxed{\begin{array}{c} m_a \sim \text{MeV} \\ f_a \sim 10^{15}\ \text{GeV} \end{array}}$$

$\theta_i =$ misalignment angle, expected $\mathcal{O}(1)$

$$\Omega_a h^2|_{\mathrm{RD}} \approx 0.12 \left(\frac{\theta_i f_a}{2 \times 10^{13}\ \text{GeV}}\right)^2 \left(\frac{m_a}{1\ \mu\text{eV}}\right)^{\frac{1}{2}} \left(\frac{90}{g_*(T_{\mathrm{osc}})}\right)^{\frac{1}{4}}$$

$$\Omega_a \approx 10^{10} \cdot \theta_i^2 \cdot \Omega_{\mathrm{DM}}!$$ ☹

Axion Overclosure!



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Axion heavy due to $SU(N)_D$

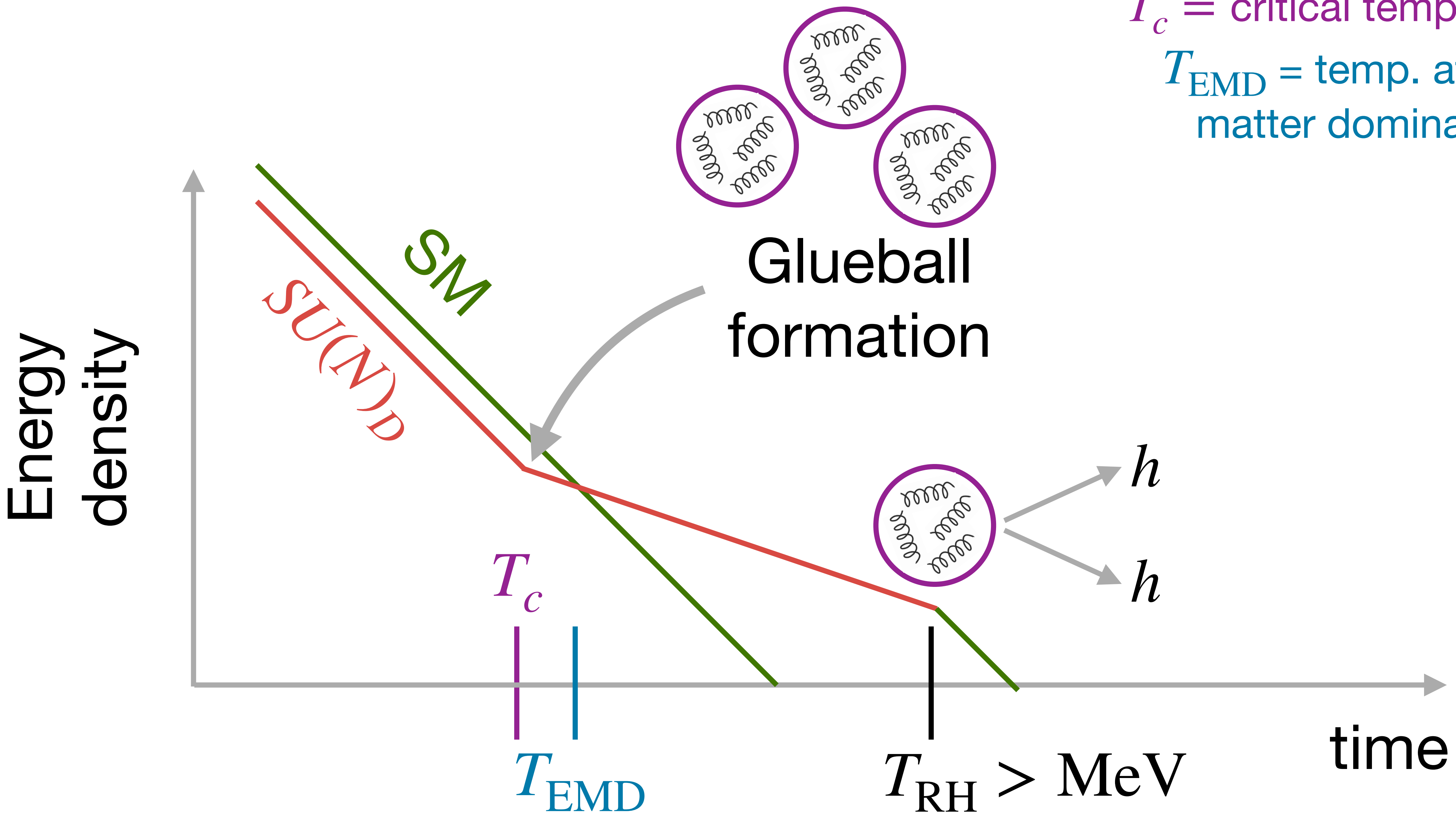
🤔

What is its cosmology?

Cosmology of a Confining $SU(N)_D$

T_c = critical temp. $\sim \Lambda_D$

T_{EMD} = temp. at early matter domination



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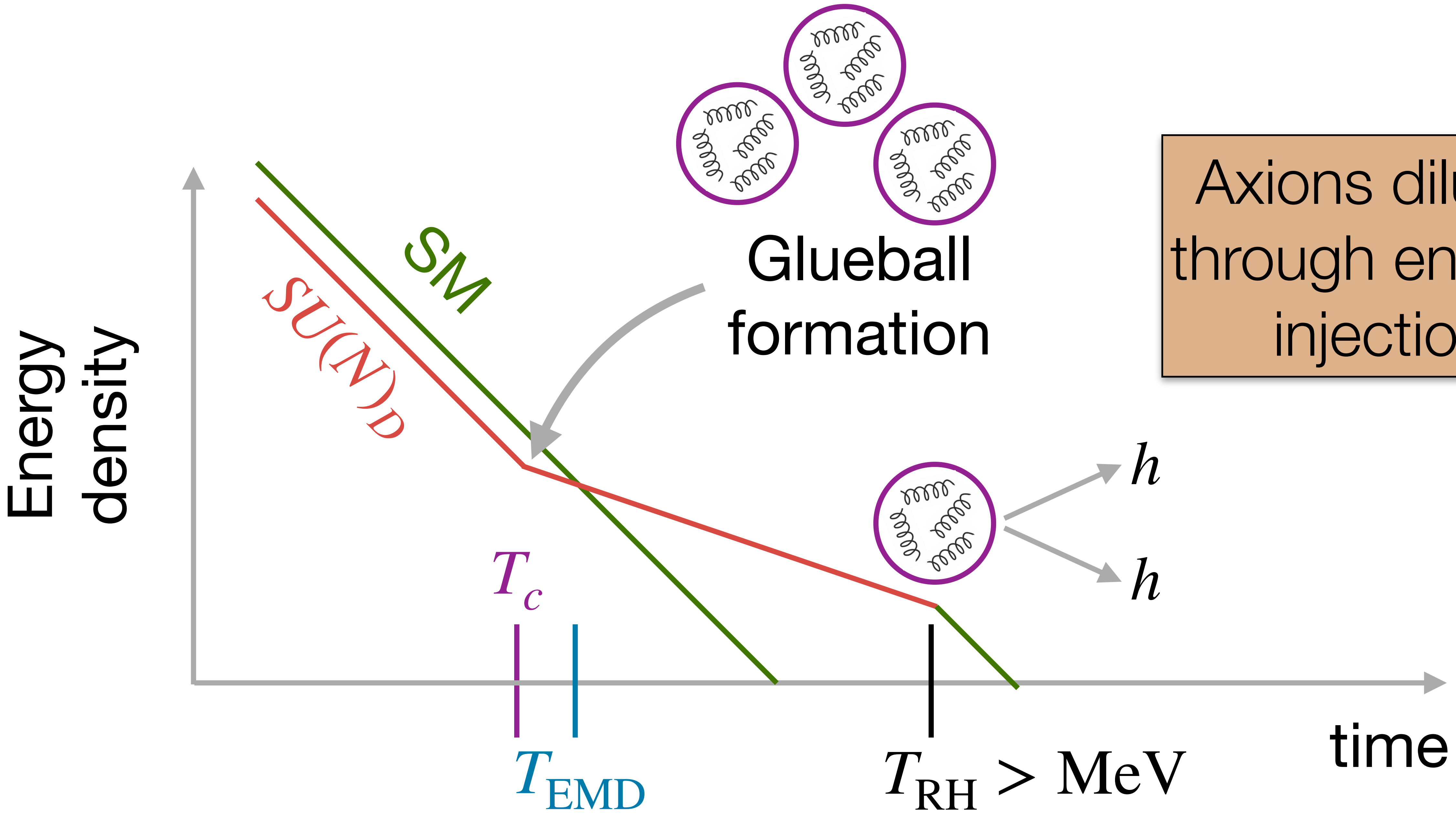
Cosmology of a Confining $SU(N)_D$



Axions diluted through entropy injection

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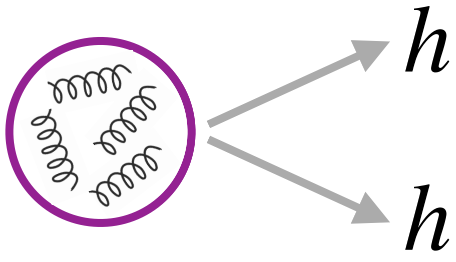
Dark Glueball Reheating and $\Omega_{\rm DM}$

Glueball Decay



$$\frac{\alpha_D}{4\pi} G_d G_d \frac{H^\dagger H}{\Lambda^2}$$

$$\boxed{\begin{matrix} m_a \sim \text{MeV} \\ f_a \sim 10^{16}\ \text{GeV} \\ \Lambda \sim 10^{14}\ \text{GeV} \end{matrix}} \Rightarrow T_{\rm RH} \sim 5\ \text{MeV}$$

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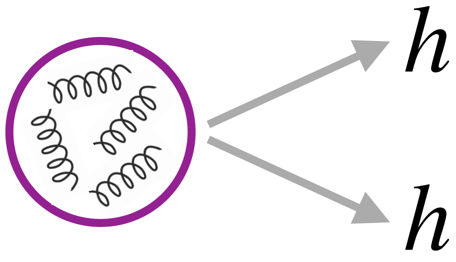

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$m_a \sim$ MeV

$f_a \sim 10^{16}$ GeV

$\Lambda \sim 10^{14}$ GeV

$\Rightarrow$ $T_{\rm RH} \sim$ 5 MeV

$$\Omega_a \approx \Omega_{\rm DM} \left(\frac{\theta_i f_a}{10^{15}\ \text{GeV}}\right)^2 \left(\frac{T_{\rm RH}}{10\ \text{MeV}}\right)$$ 🙂

correct $\Omega_{\rm DM}$ w/o fine-tuning of θ_i !

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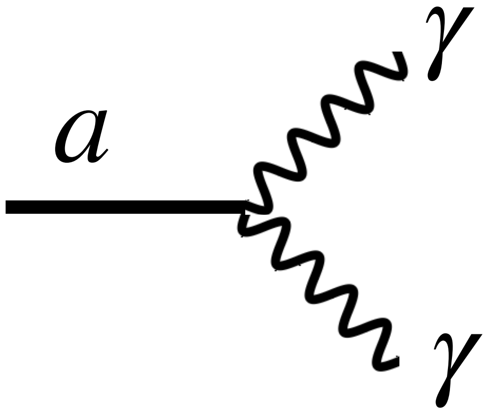
Axion Lifetime

$$\mathscr{L} \supset C_{a\gamma\gamma} \frac{\alpha_{\rm EM}}{8\pi} \frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$$



Lifetime

$$\tau_{a\to\gamma\gamma} \approx 10^{28}\ \text{s} \left(\frac{0.1}{C_{a\gamma\gamma}}\right)^2 \left(\frac{0.1\ \text{MeV}}{m_a}\right)^3 \left(\frac{f_a}{10^{15}\ \text{GeV}}\right)^2$$

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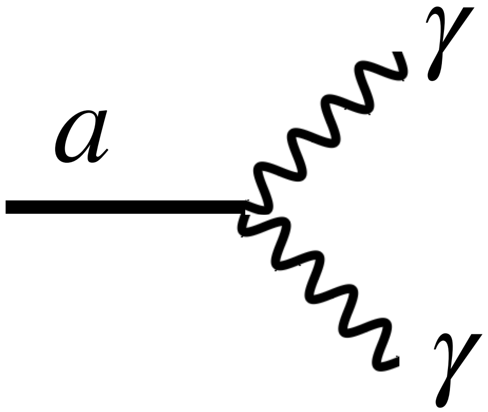

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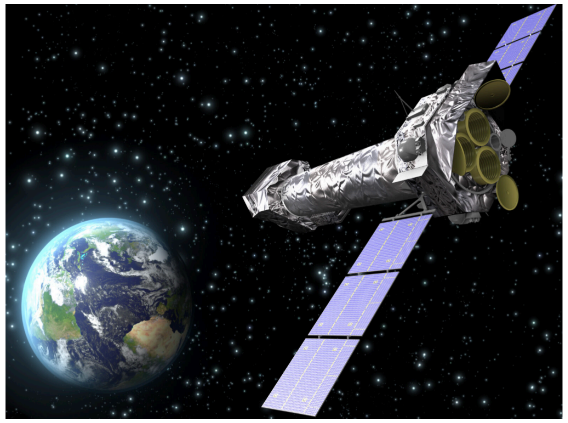
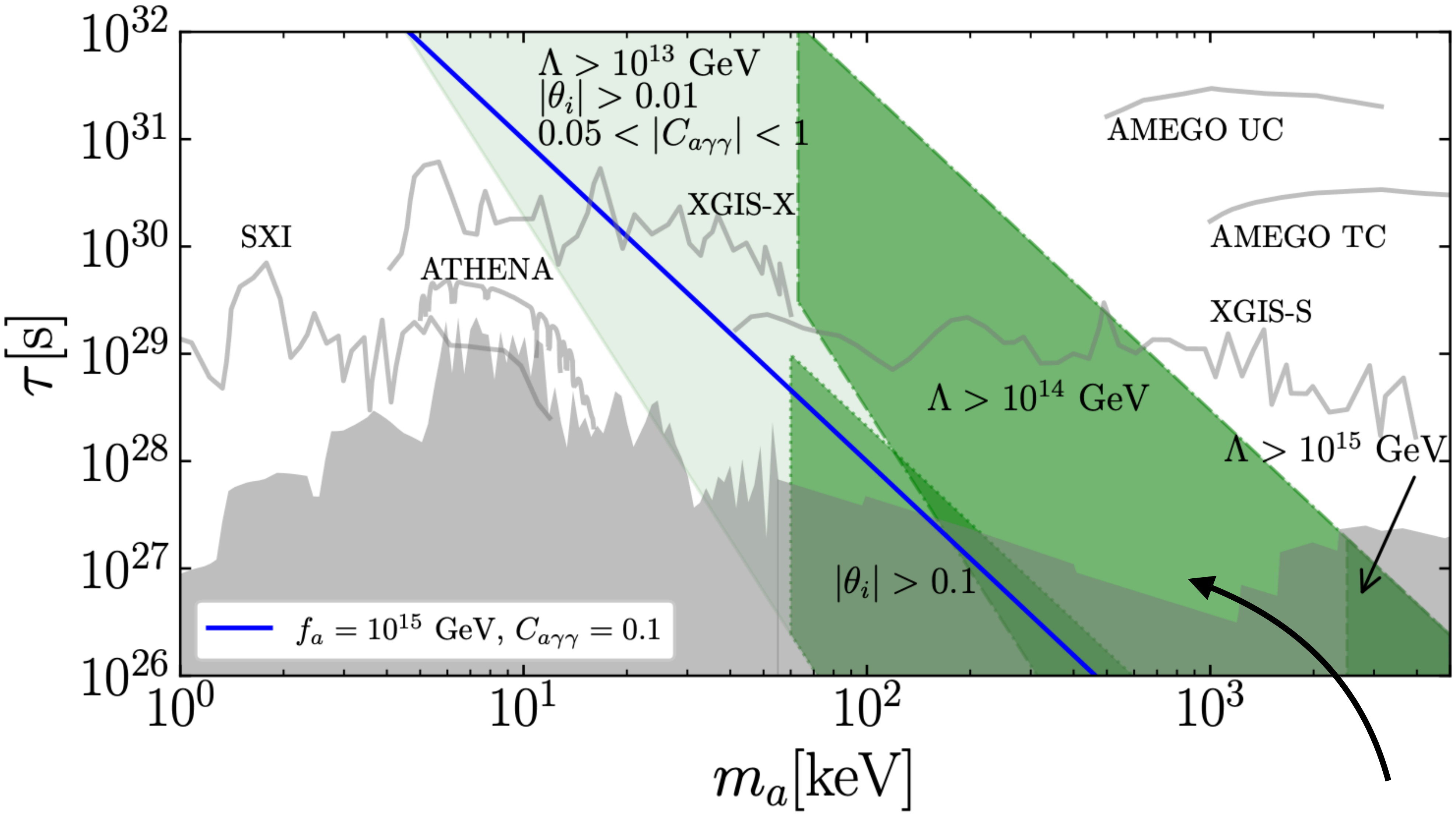
similar τ as decaying DM searches ⇨ Line signals at X-ray and γ-ray telescopes



Decaying Heavy Axion DM



$SU(2)_D$ **and $T_{\mathrm{RH}} > 5$ MeV**

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But can we explain baryon asymmetry given low T_{RH}?

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Cosmology of 10^8 GeV axions

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Spontaneous Baryogenesis

- Fermion coupling as an example:

Cohen, Kaplan '87

$$\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\psi \supset \frac{\dot{a}}{f_a}\psi^\dagger\psi$$

spontaneous *CPT* breaking

- Effective "chemical potential": fermions and anti-fermions have differing abundances
  $\Delta n_i = n_i - \bar{n}_i \approx g_i \mu_i T^2/6$ with $\mu_i \sim \dot{a}/f_a$

- Need B or L violation: asymmetry in equilibrium

- As B or L violation drops out of equilibrium, asymmetry also gets frozen out

Heavy Axion Baryogenesis

- Lepton number violation via $(HL)^2/\Lambda_W$ with scale set by neutrino mass
- Solve Boltzmann equation for the asymmetries

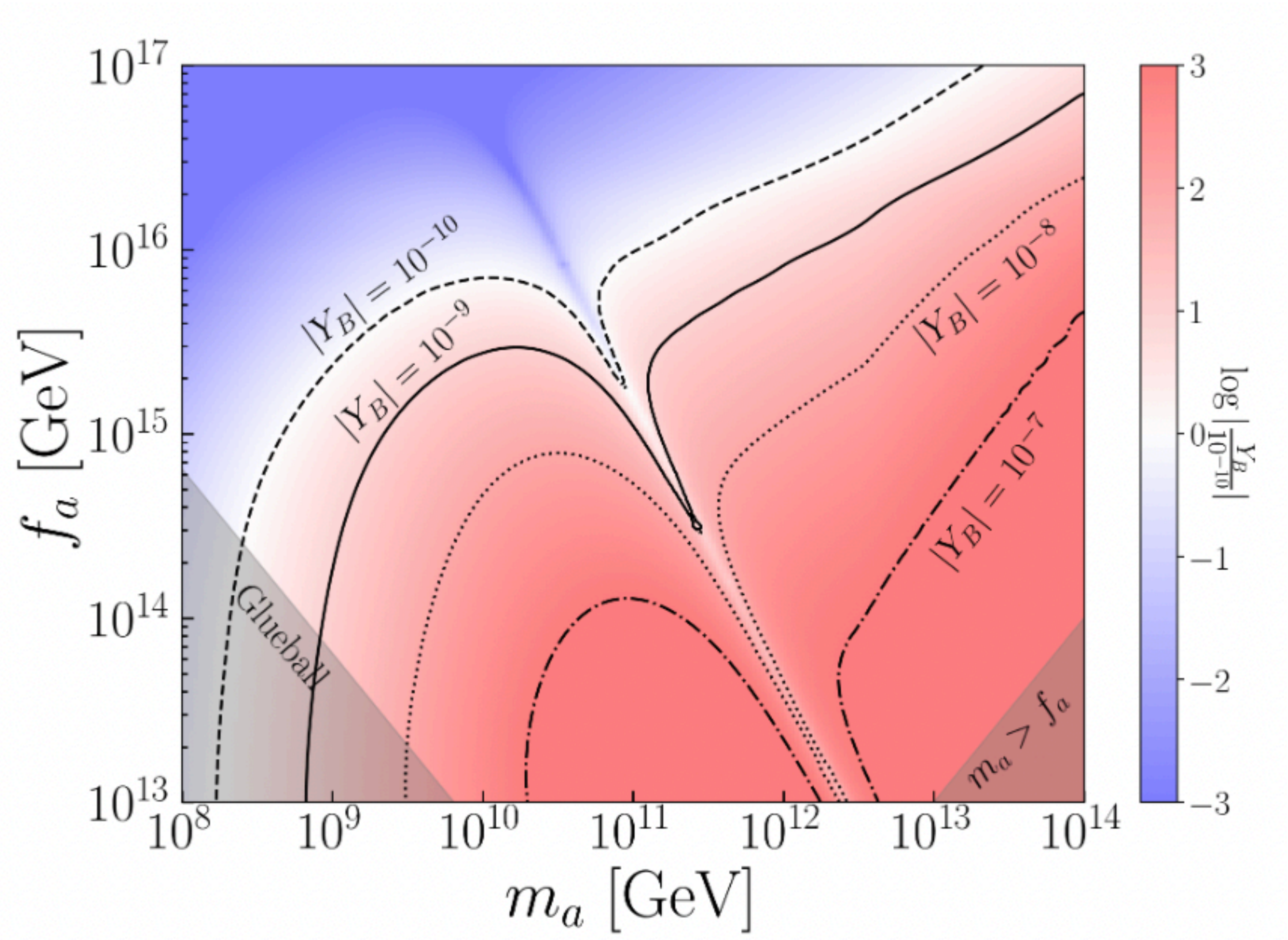
$$c_{aG}\left(\frac{\alpha_s}{8\pi f_a}aG\tilde{G}+\frac{\alpha_2}{8\pi f_a}aW\tilde{W}+\frac{\alpha_1}{8\pi f_a}aB\tilde{B}\right)+c_{af}\left(\sum_i \frac{\partial_\mu a}{f_a}J_i\right)$$

$$\frac{d}{dt}\left(\frac{\mu_i}{T}\right)=\frac{dT}{dt}\frac{1}{g_iT}\times\sum_\alpha \mathscr{C}_{i\alpha}\frac{\Gamma_\alpha}{H}\left[\sum_j\left(\frac{\mu_j}{T}\right)\mathscr{C}_{j\alpha}-n_{S\alpha}\left(\frac{\dot{a}}{f_aT}\right)\right]$$

$i=\tau, L_{12}, L_3, q_{12}, t, b, Q_{12}, Q_3, H$

α runs over weak sphaleron, strong sphaleron, tau Yukawa, top Yukawa, bottom Yukawa, and the Weinberg operator

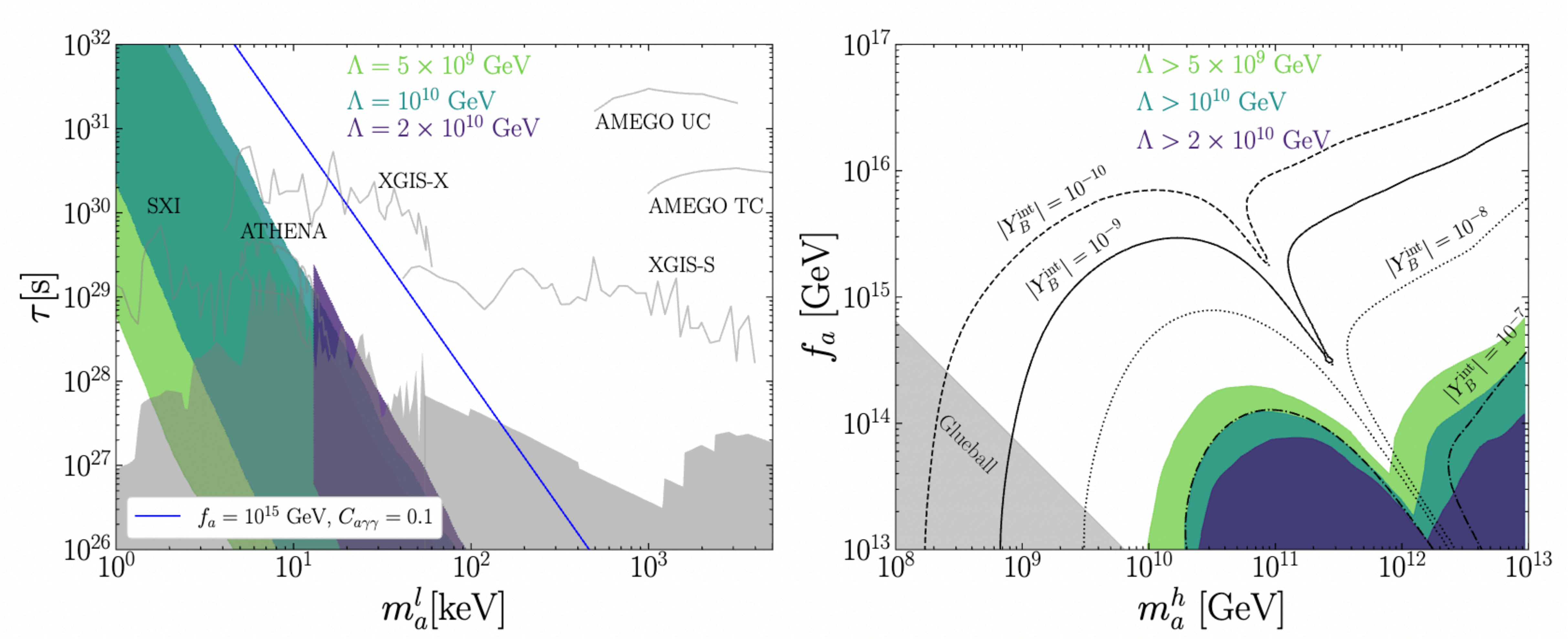
Heavy Axion Baryogenesis



Cosmological History

- Two axions - a_h with $SU(N_h)$ and a_l with $SU(N_l)$
- $H \sim m_h$: a_h starts to oscillate and generates initial baryon asymmetry
- Both cold and thermal a_h populations — they decay into SM
- Then a_l and glueballs of the light sector becomes important
- Eventually, entropy injections dilute both $\Omega_{\rm DM}$ and Ω_b

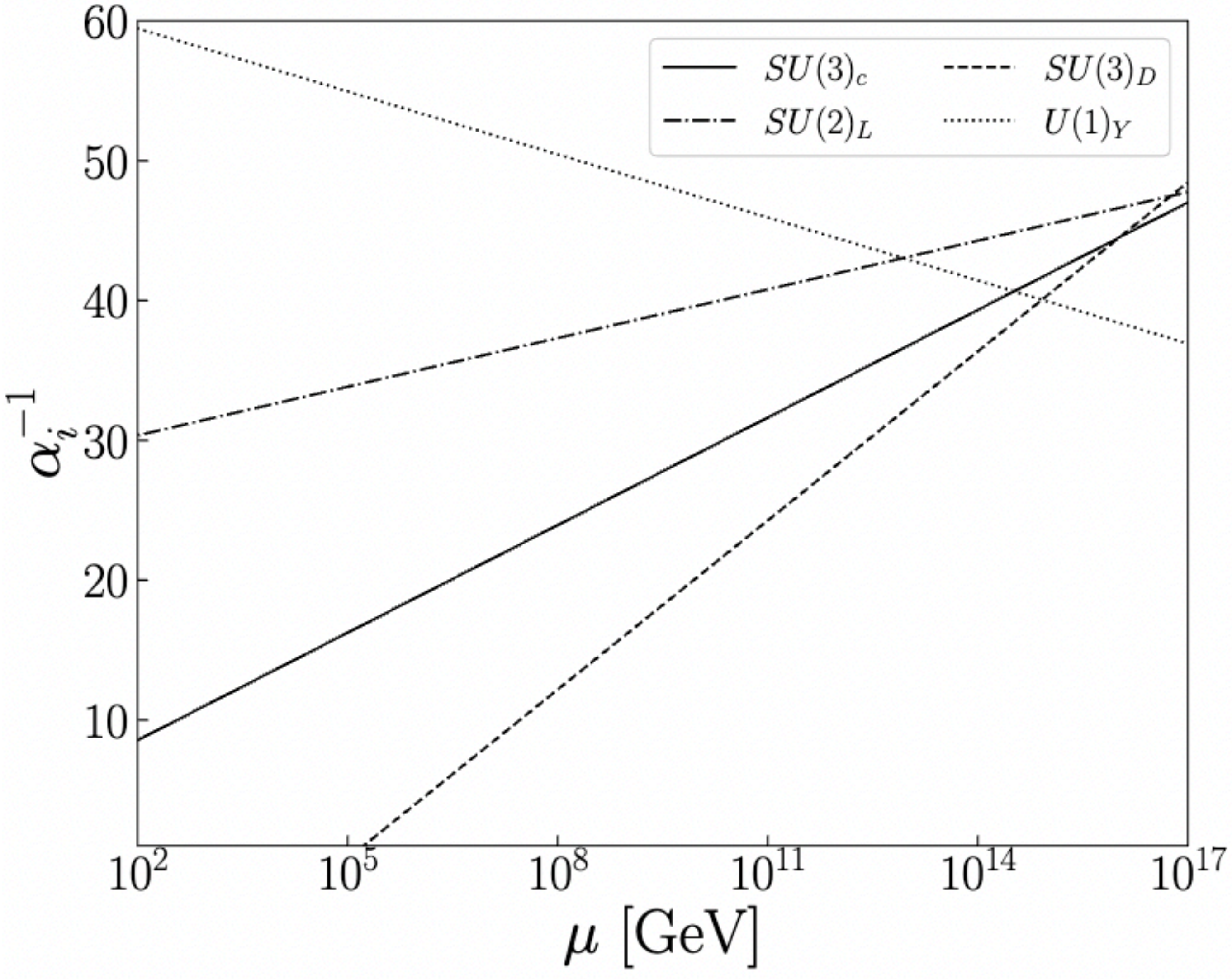
Explaining both $\Omega_{\rm DM}$ and Ω_b



Are these $SU(N)_D$ gauge groups connected to SM in a deeper way?

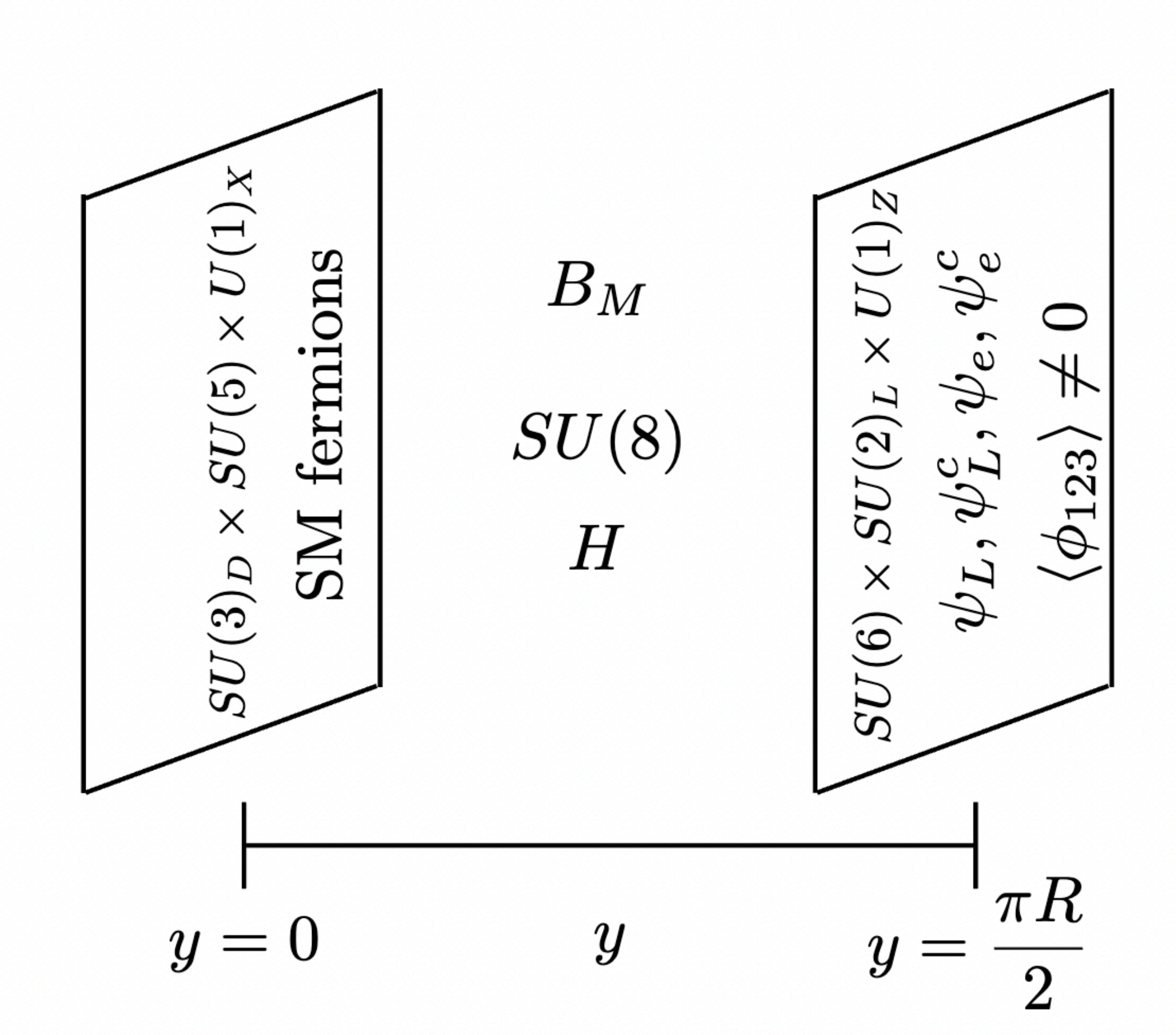
Dark Grand Unification: Running

- Small mismatch as in non-SUSY theories, but indicates unification scale $\sim 10^{16}$ GeV and $\Lambda_D \sim 10^5$ GeV



Dark Grand Unification: Construction

- Orbifold unification: extra dimensional theory with boundary conditions breaking gauge invariance
- Below the unification scale $\sim 1/R$:
  $G = G_{\rm SM} \times SU(3)_D$



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Axions from $U(1)$ Gauge Fields

- Chern-Simons interaction

$$\int d^4x \int_0^{\pi R} dy \left(\frac{1}{4g_{5B}^2} B_{MN} B^{MN} + \kappa_B \epsilon^{MNPQR} B_M \mathrm{Tr}(F_{NP} F_{QR}) \right)$$

$$\frac{\pi R}{2g_{5B}^2} (\partial_\mu B_5)^2 + 2\pi R \kappa_B B_5 G\tilde{G}$$

$$\frac{a}{32\pi^2 f_a} G\tilde{G}\,, \qquad f_a \equiv \frac{1}{64\pi^2 \sqrt{\pi R}\, \kappa_B g_{5B}}$$

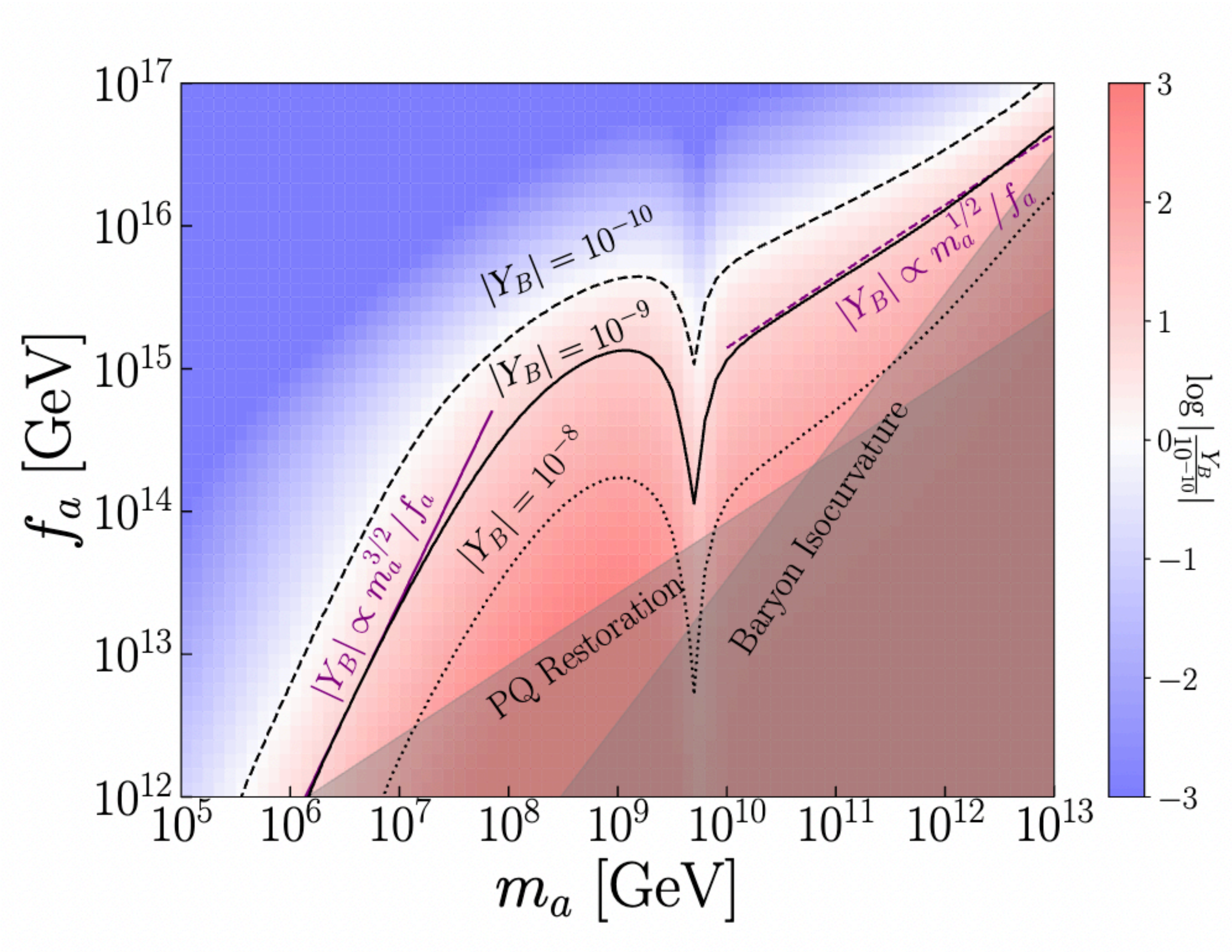
Conclusion

- Heavy axions can easily arise in UV-motivated constructions
- keV-MeV scale axions can naturally explain the DM abundance
- They also predict line signals at X-ray and gamma-ray telescopes
- It is also possible to explain baryon abundance with a heavier, second axion

Thanks for your attention!

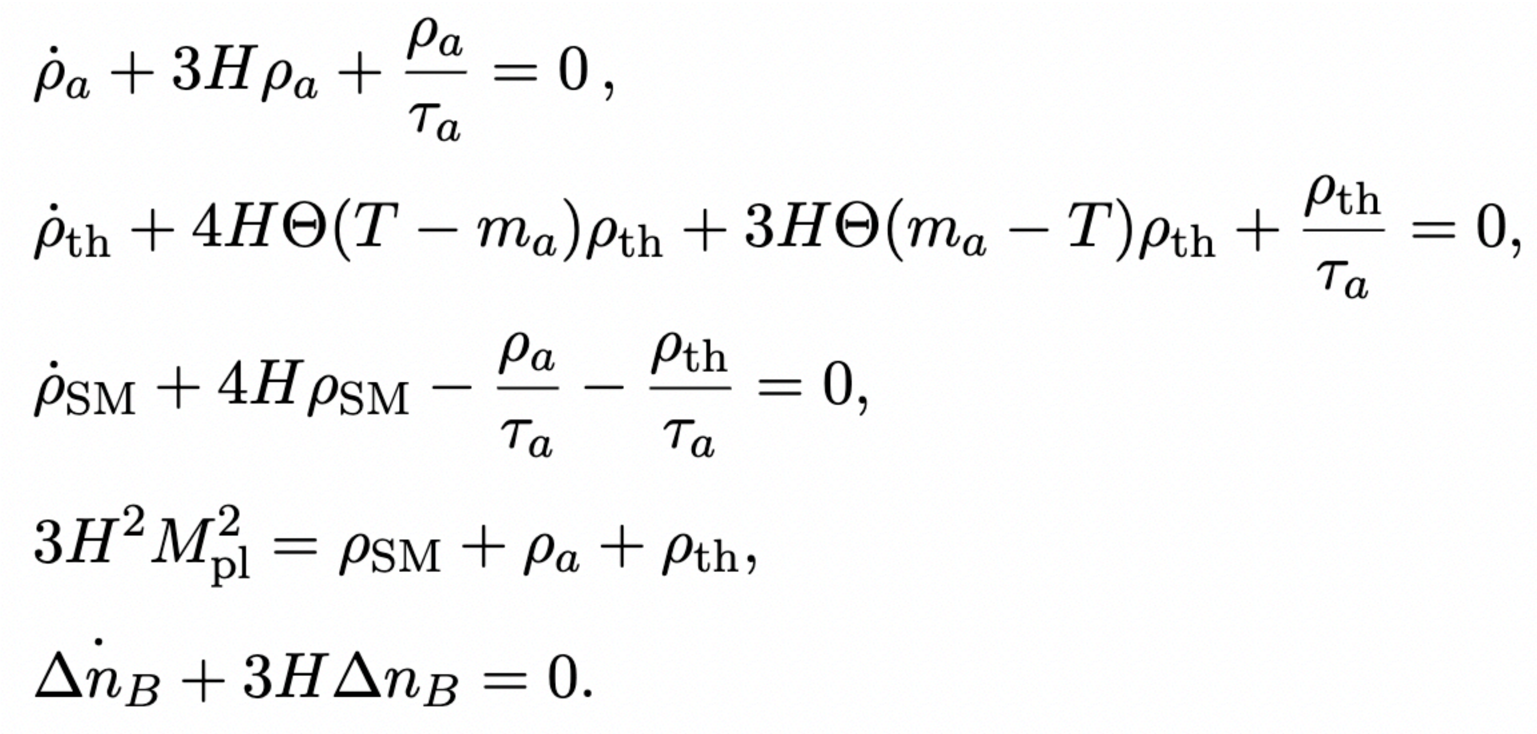
Extra Slides

Temperature Independent Mass



Temperature Independent Mass

- $\mu_{B-L} = -(\mu_\tau + 4\mu_{L_{12}} + 2\mu_{L_3}) + (12\mu_{q_{12}} + 3\mu_t + 3\mu_b + 12\mu_{Q_{12}} + 6\mu_{Q_3})/3$
- Coupled evolution equations



$$\dot{\rho}_a + 3H\rho_a + \frac{\rho_a}{\tau_a} = 0\,,$$

$$\dot{\rho}_{\rm th} + 4H\Theta(T - m_a)\rho_{\rm th} + 3H\Theta(m_a - T)\rho_{\rm th} + \frac{\rho_{\rm th}}{\tau_a} = 0,$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} - \frac{\rho_a}{\tau_a} - \frac{\rho_{\rm th}}{\tau_a} = 0,$$

$$3H^2M_{\rm pl}^2 = \rho_{\rm SM} + \rho_a + \rho_{\rm th},$$

$$\Delta\dot{n}_B + 3H\Delta n_B = 0.$$

Soubhik Kumar, Berkeley

Axions from the UV

- 5D Chern-Simons term:

$$\epsilon^{MNPQR} A_M \mathrm{Tr}(F_{NP} F_{QR}) \to (a/f_a) G\tilde{G}$$

- Similar in spirit to what happens in String Theory constructions

- In fact, with multiple extra dimensions, many ways of compactifying → many axion (-like particles) (ALPs)

- One linear combination couples to QCD → QCD axion. Rest survive as ALPs.

Axion Coupling

- Linear combination coupling to the dark gauge group

$$\mathscr{L} = \sum_i \frac{\alpha_d}{8\pi} \frac{c^i_{\mathrm{d}} a_i}{f_a} G^a_{\mathrm{d}\,\mu\nu} \tilde{G}^{\mu\nu}_{\mathrm{d}\,a}$$

- Axion potential:

$$V \approx \Lambda_D^4 \left(\sum_i \frac{c^i_{\mathrm{d}} a_i}{f_a} + \bar{\theta}_D \right)^2$$

- Coupling to SM gauge group:

$$\mathscr{L} = \sum_i \frac{\alpha}{8\pi} \frac{d^i a_i}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} = \frac{\alpha}{8\pi} \frac{d_D a_D}{\tilde{f}_a} G_{\mu\nu} \tilde{G}^{\mu\nu} + \cdots$$

$$d_D = \frac{\sum_i c^i_d d^i}{\sum_i (c^i_d)^2}$$

Axion Lifetime and Dynamics

- Into diphotons

$$\tau_{a\to\gamma\gamma} = \frac{256\pi^3}{\alpha^2 C_{a\gamma\gamma}^2}\frac{f_a^2}{m_a^3} \approx 9.6\times 10^{27}\ \text{s}\left(\frac{0.1}{C_{a\gamma\gamma}}\right)^2\left(\frac{0.1\ \text{MeV}}{m_a}\right)^3\left(\frac{f_a}{10^{15}\ \text{GeV}}\right)^2$$

- Axion abundance

$$\Omega_a = \frac{1}{2}\frac{m_a^2 f_a^2 \theta_i^2}{\rho_c}\left(\frac{R_{\text{osc}}}{R_{\text{RH}}}\right)^3\left(\frac{T_0}{T_{\text{RH}}}\right)^3\frac{g_{*S}(T_0)}{g_{*S}(T_{\text{RH}})}$$

- Critical temperature

$$\frac{T_c}{\sqrt{m_a f_a}} \approx 1.6 - \frac{0.8}{N_c^2}$$

Temperature Dependence

- T dependent mass: $m_a(T) \approx \begin{cases} m_a\left(\frac{T_c}{T}\right)^b, \; T > T_c \\ m_a, \; T \leq T_c \, , \end{cases}$

$$\frac{T_{\rm osc}}{T_c} \approx \left(\frac{3\sqrt{10}}{q_T \pi \sqrt{g_*}\left(1.6 - \frac{0.8}{N_c^2}\right)^2} \frac{M_{\rm pl}}{f_a} \right)^{\frac{1}{2+b}} \approx \begin{cases} 5.5\left(\frac{10^{15}\ {\rm GeV}}{f_a}\right)^{0.27}, \; N_c = 2 \\ 2.6\left(\frac{10^{15}\ {\rm GeV}}{f_a}\right)^{0.18}, \; N_c = 3 \end{cases}$$

$$\Omega_a h^2 \approx 0.12\,\theta_i^2 \begin{cases} \left(\frac{f_a}{10^{13}\ {\rm GeV}}\right)^{1.27}\left(\frac{T_{\rm RH}}{10\ {\rm MeV}}\right), \; N_c = 2 \\ \left(\frac{f_a}{4.3 \cdot 10^{12}\ {\rm GeV}}\right)^{1.18}\left(\frac{T_{\rm RH}}{10\ {\rm MeV}}\right), \; N_c = 3. \end{cases}$$