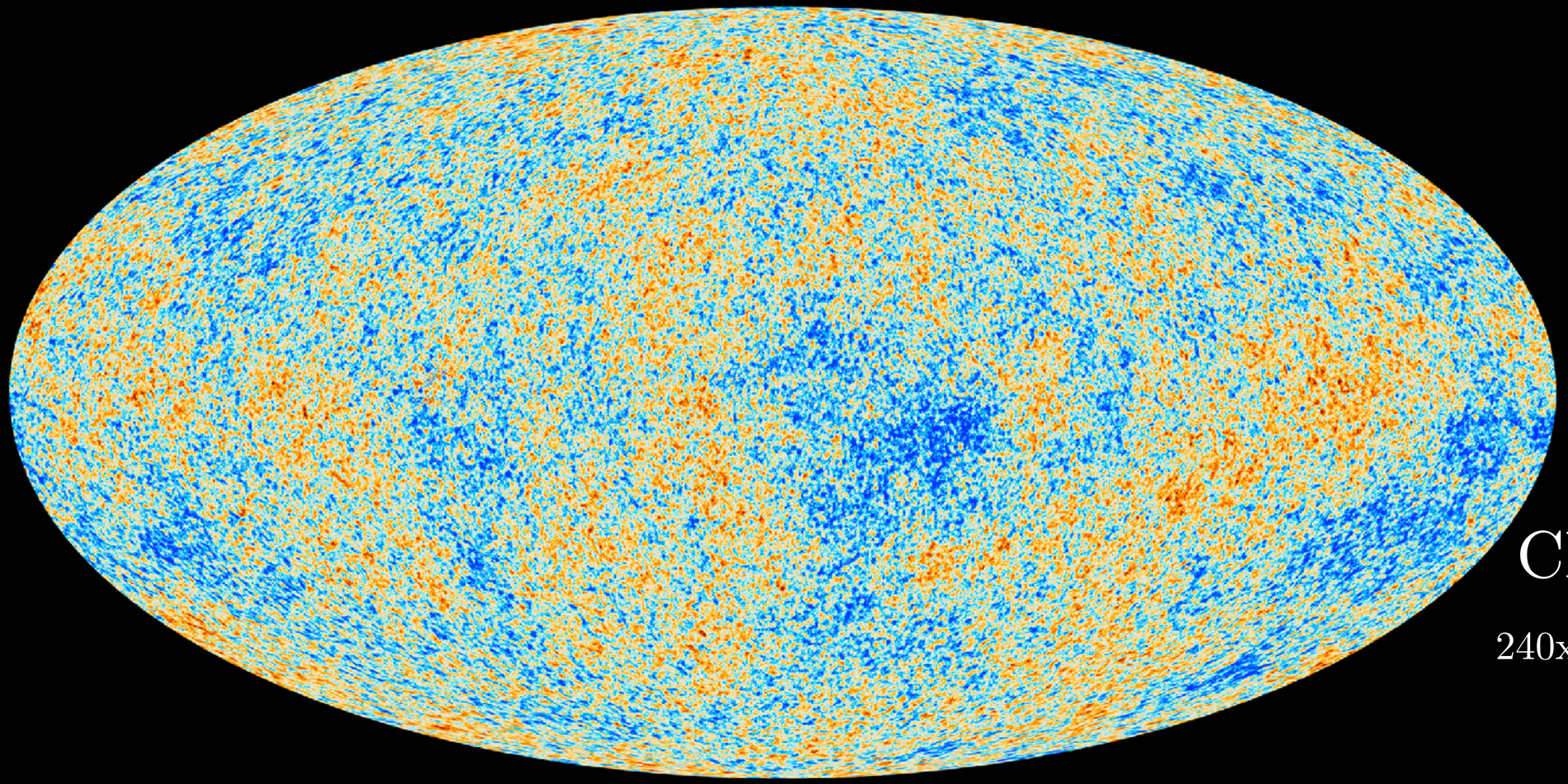
The Cosmic Axiverse Background



Christopher Dessert

240x.xxxxx w/ Ruderman, Kumar

Catch22+2

NYU FLATIRON INSTITUTE

Credits: ESA/Planck Collaboration

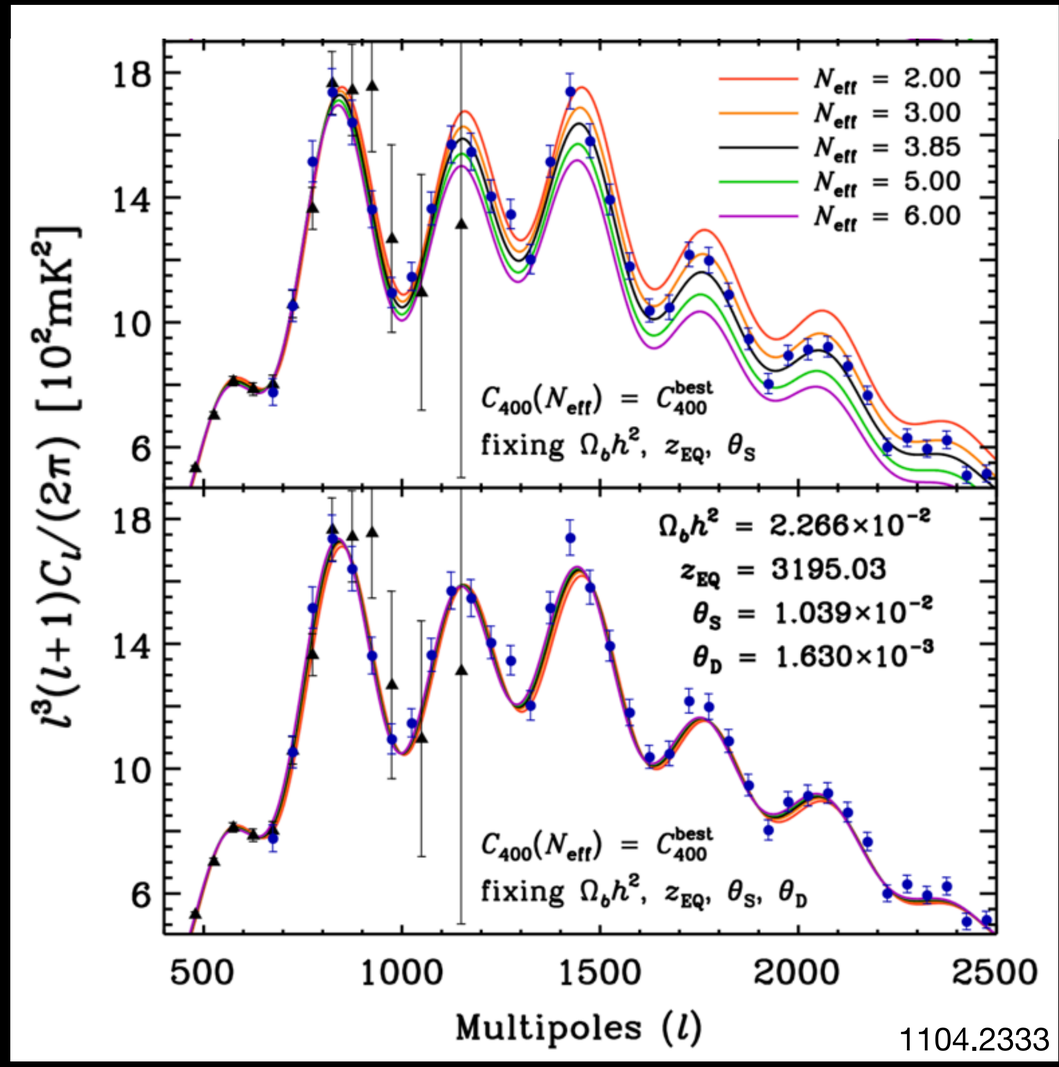
Light Relics

- Relativistic DOF at recombination contributes to $N_{\rm eff}$

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

- $N_{\rm eff,SM} = 3.044$, but enhanced by additional radiation

$$\Gamma \gtrsim H \implies \Delta N_{\rm eff} \approx 0.027 N_{\rm dof} \left(\frac{106.75}{g_{*s}(T_d)}\right)^{4/3}$$



Light Relics

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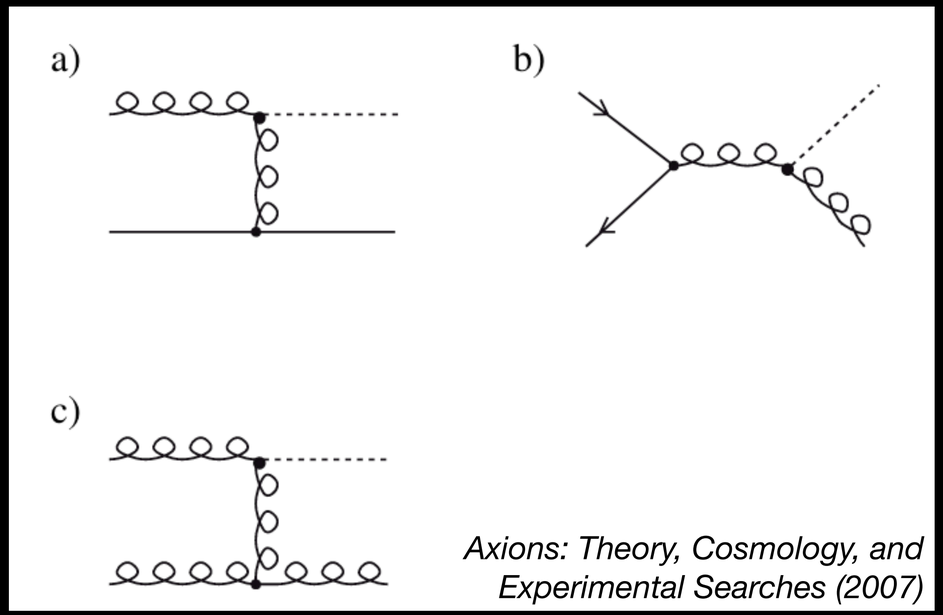
- $N_{\rm eff,SM} = 3.044$, but enhanced by axion*

$$\Gamma \gtrsim H \implies \frac{\alpha_s^3}{4\pi^2} \frac{T^3}{f_a^2} \gtrsim \frac{T^2}{M_P}$$

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

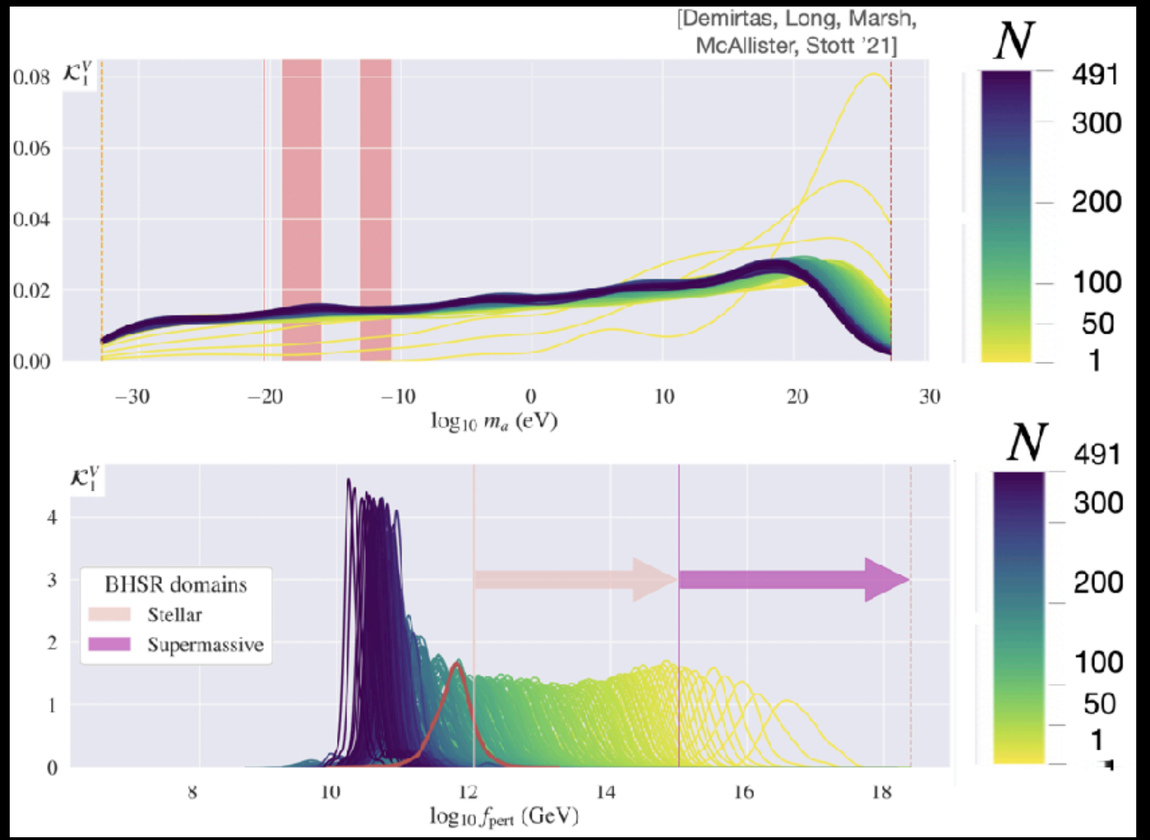


Axions: Theory, Cosmology, and Experimental Searches (2007)

*See talk by F. D'Eramo earlier today

The Axiverse

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



The Axiverse

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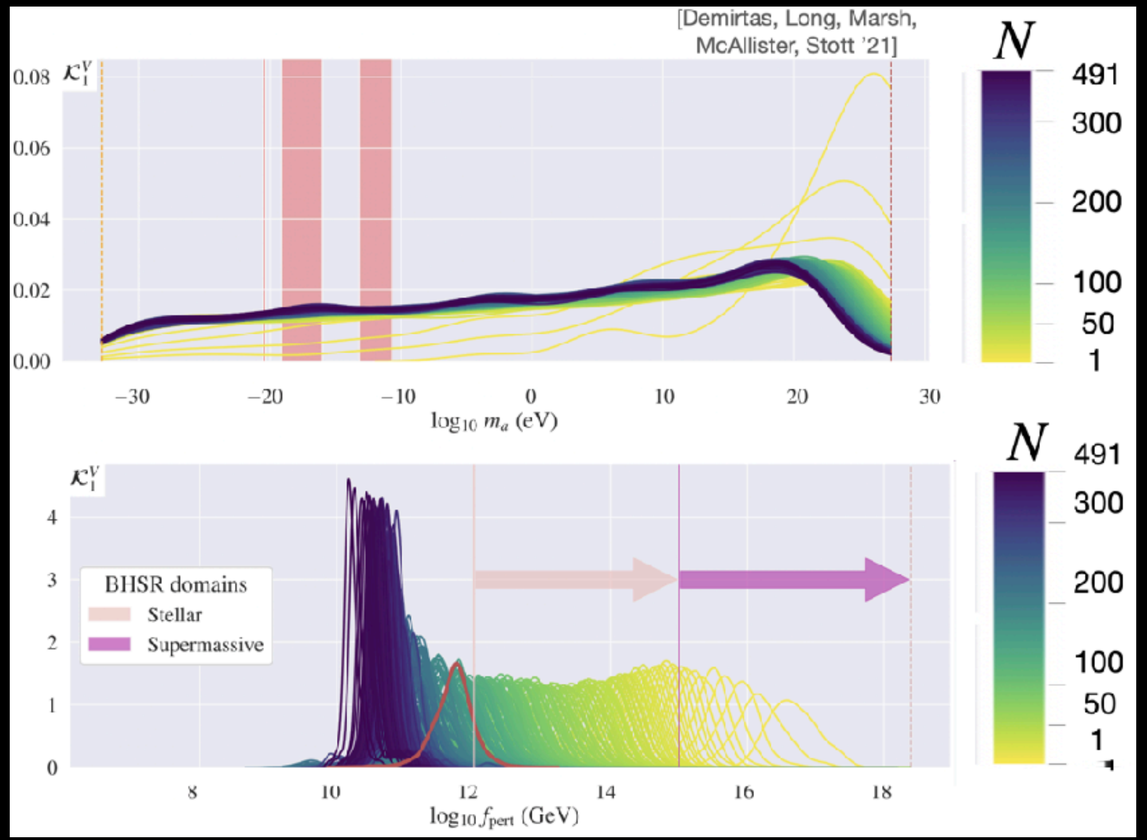
$$\Delta N_{\text{eff,Axiverse}} \stackrel{?}{=} 0.027 N_{\text{ax}}$$

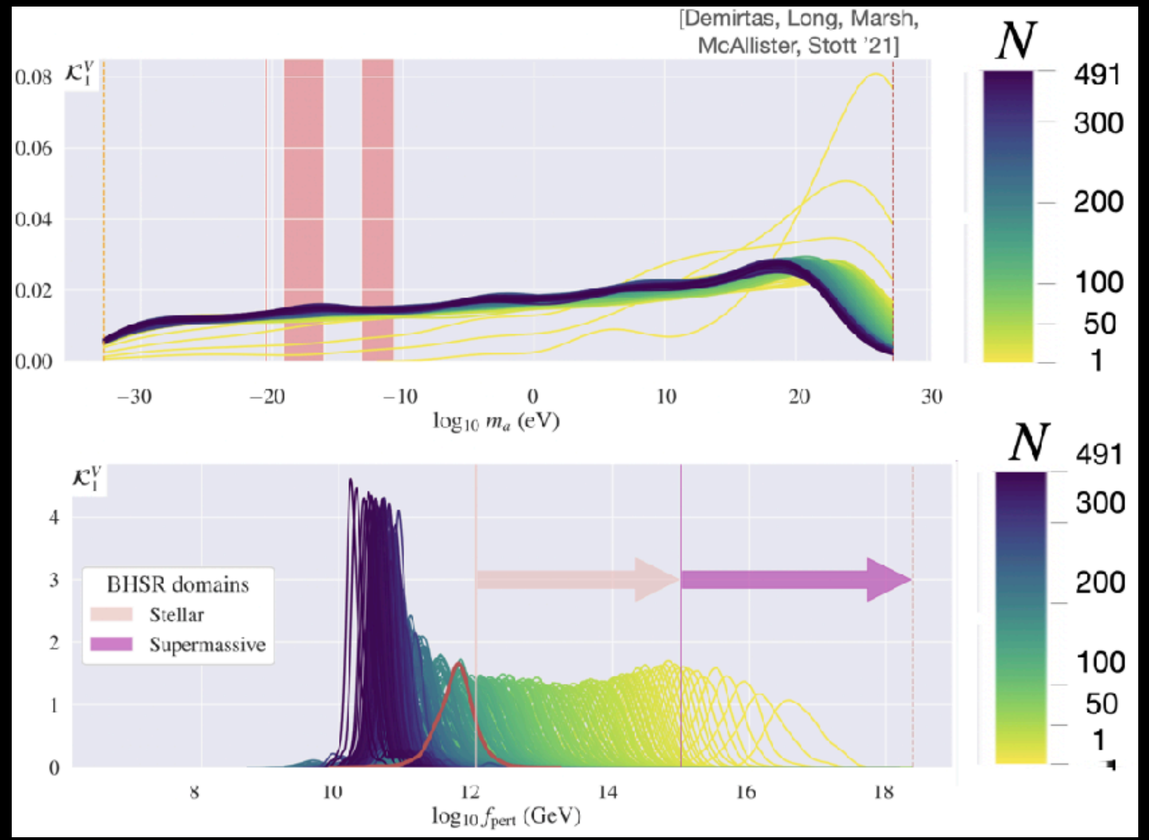


The Axiverse

- String theory $\rightarrow \mathcal{O}(100\text{s})$ axions associated with 0-modes of gauge fields
- Log-uniform masses and similar decay constants
- Toy $N_{\text{ax}} = 2$ setup

$$\mathscr{L} = -\frac{1}{2}\partial_\mu \phi_i \partial^\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i \phi_i F\tilde{F}$$

$$= -\frac{1}{2}\partial_\mu a_i \partial^\mu a_i - \frac{1}{2} a_i M_{ij}^2 a_j - g_{a\gamma\gamma} a_\gamma F\tilde{F}$$



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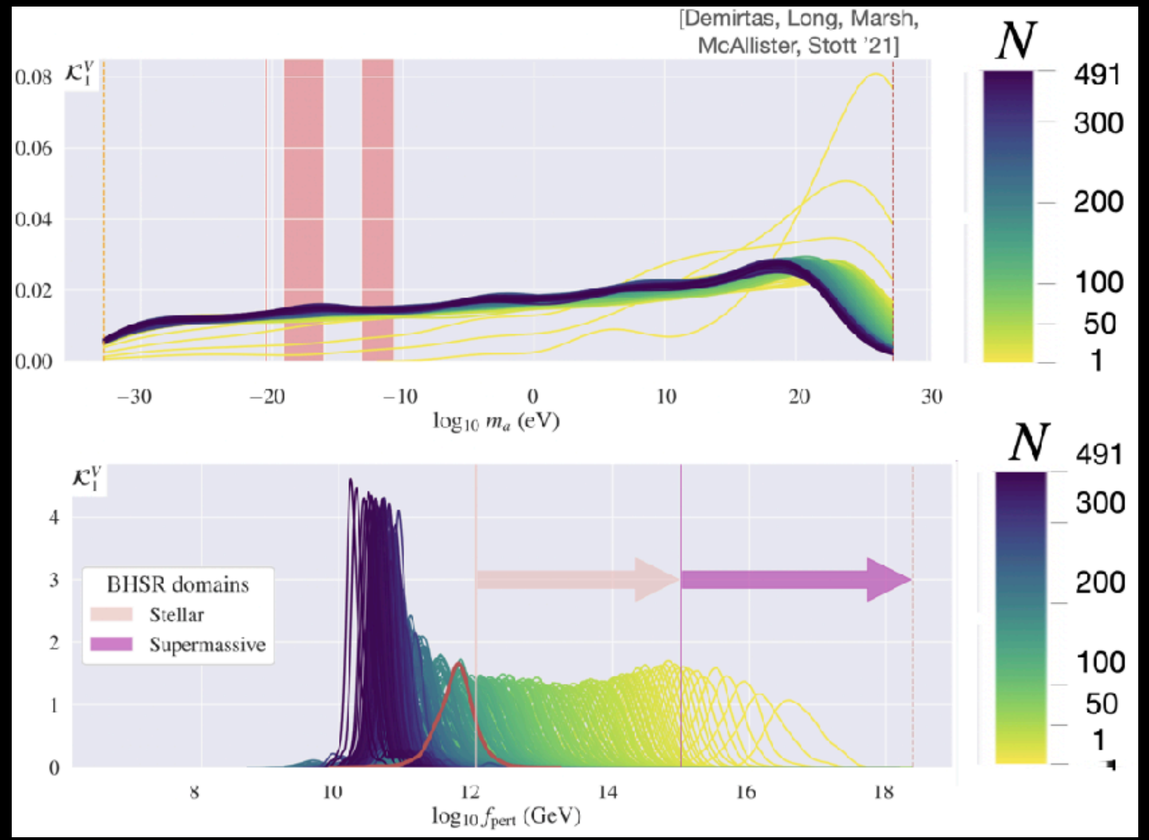
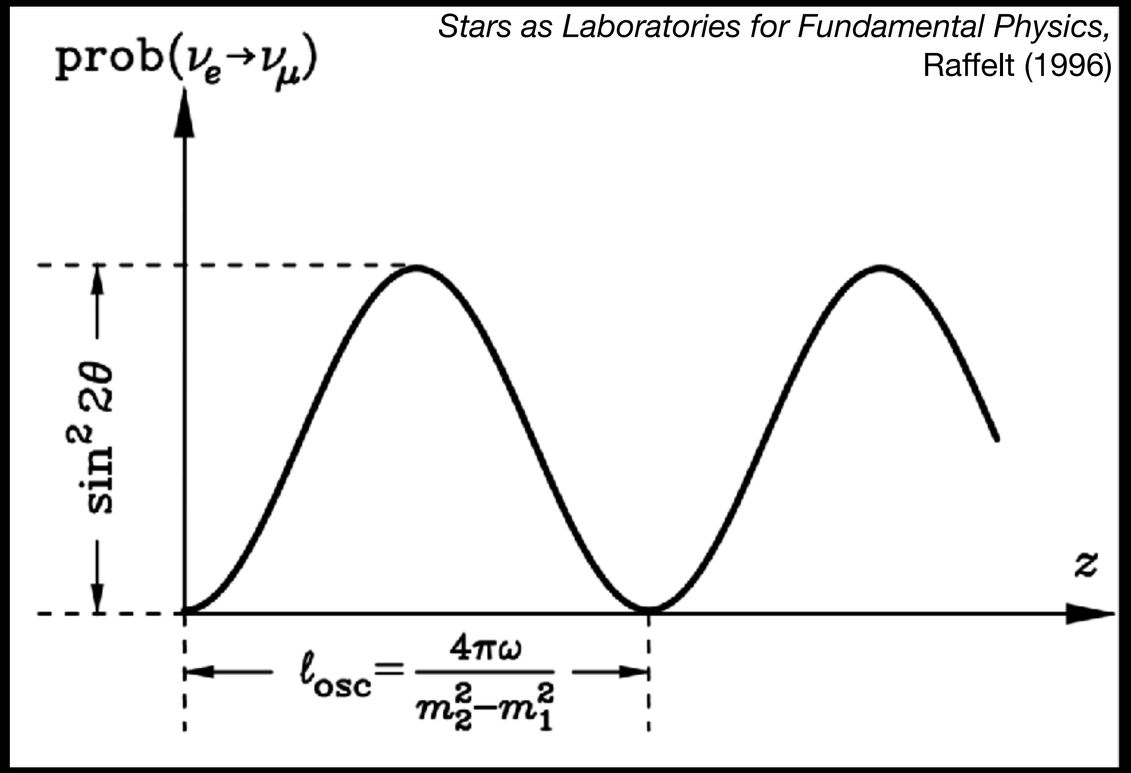
- $\Delta N_{\rm eff} = 0.027$ per $c_i \phi_i \mathcal{O}_{\rm SM} \subset \mathscr{L}$
- Planck bounds $N_{\rm ax}^{95\%} = 9$



$N_{\rm eff}$ from Oscillations?

- Does mixing lead to freeze-in $N_{\rm eff}$ of sterile axions?
  - Analogous to Dodelson-Widrow



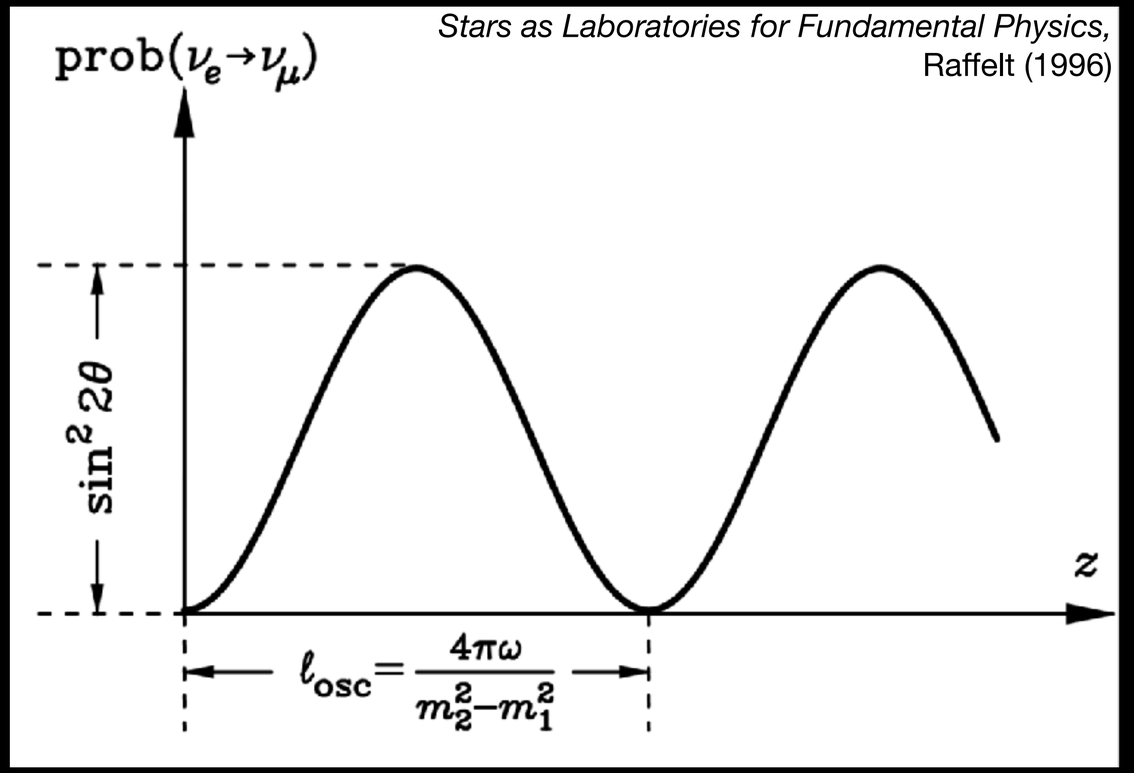
Stars as Laboratories for Fundamental Physics, Raffelt (1996)

N_{eff} from Oscillations?

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

$$\Gamma_{\text{int}} \approx \frac{\alpha^3}{4\pi^2}\frac{T^3}{f_a^2},\ \Gamma_{\text{mix}} \approx \frac{\Delta m^2}{T}$$

$$\implies \sqrt{\Delta m^2} \gtrsim 1\ \text{eV}\left(\frac{f_a}{10^8\ \text{GeV}}\right)^3$$



Stars as Laboratories for Fundamental Physics, Raffelt (1996)

$N_{\rm eff}$ from Thermalization

- Dimension-5 axiverse EFT below f_a

$$\mathscr{L}^5_{\rm int} = -\frac{1}{4}\sum_G \frac{c^G \alpha_G}{2\pi f_a} a_G G\tilde{G} + \sum_F \frac{c^F_{ij}}{2f_a}\left(\partial_\mu a^F_{ij}\right)\bar{\psi}^i_F \gamma^\mu \psi^j_F$$

$N_{\rm eff}$ from Thermalization

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- 3 axions associated with gauge bosons
- 45 axions associated with fermions/flavor
- If all were in thermal equilibrium, that would violate Planck bound!

Dimension-6 EFT

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

$$\mathscr{L}^{6}_{\text{int}} = -\frac{c^{ij}_{ah}}{f_a^2}(\partial_\mu a_i)(\partial^\mu a_j)\,|H|^2$$

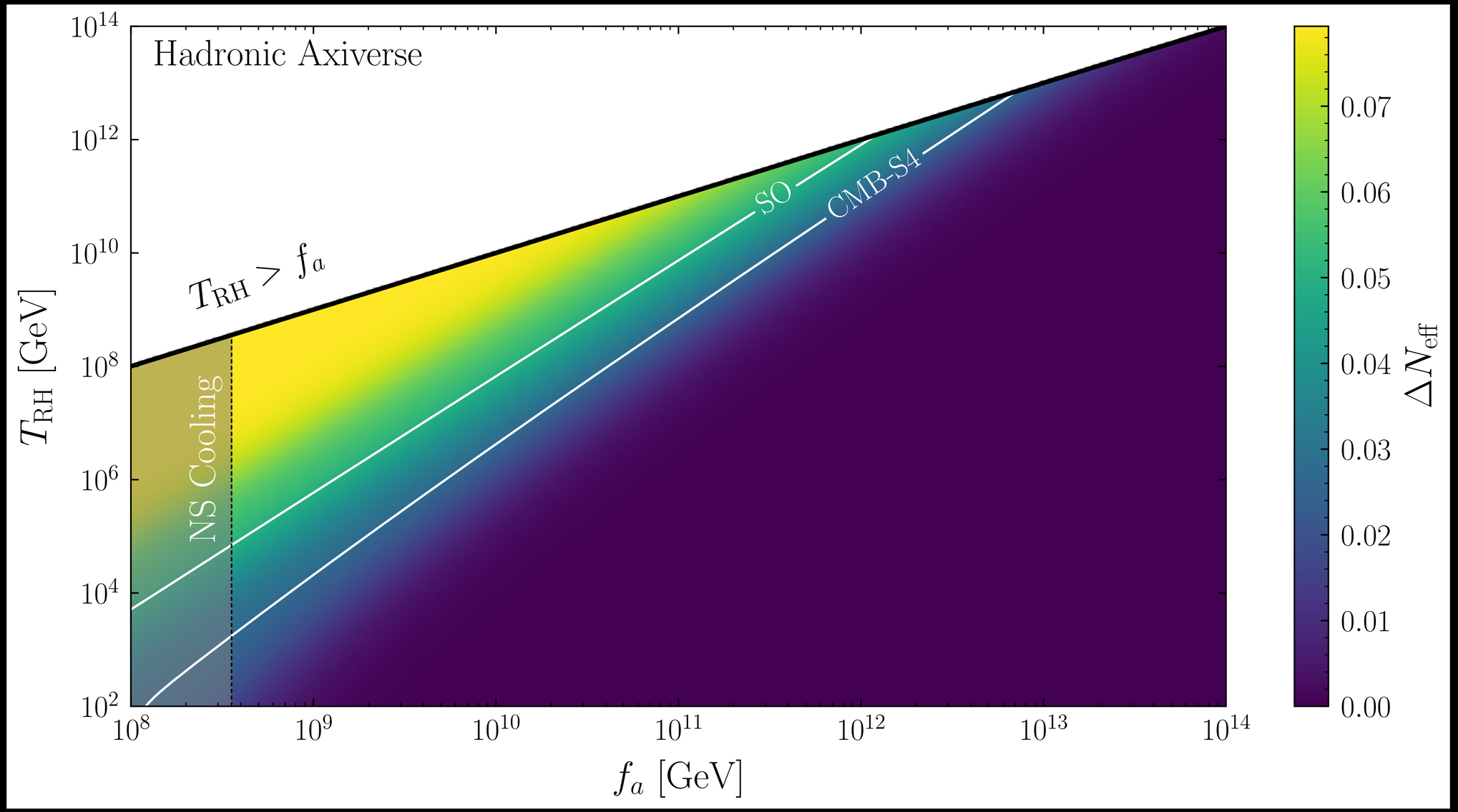
Dimension-6 EFT

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

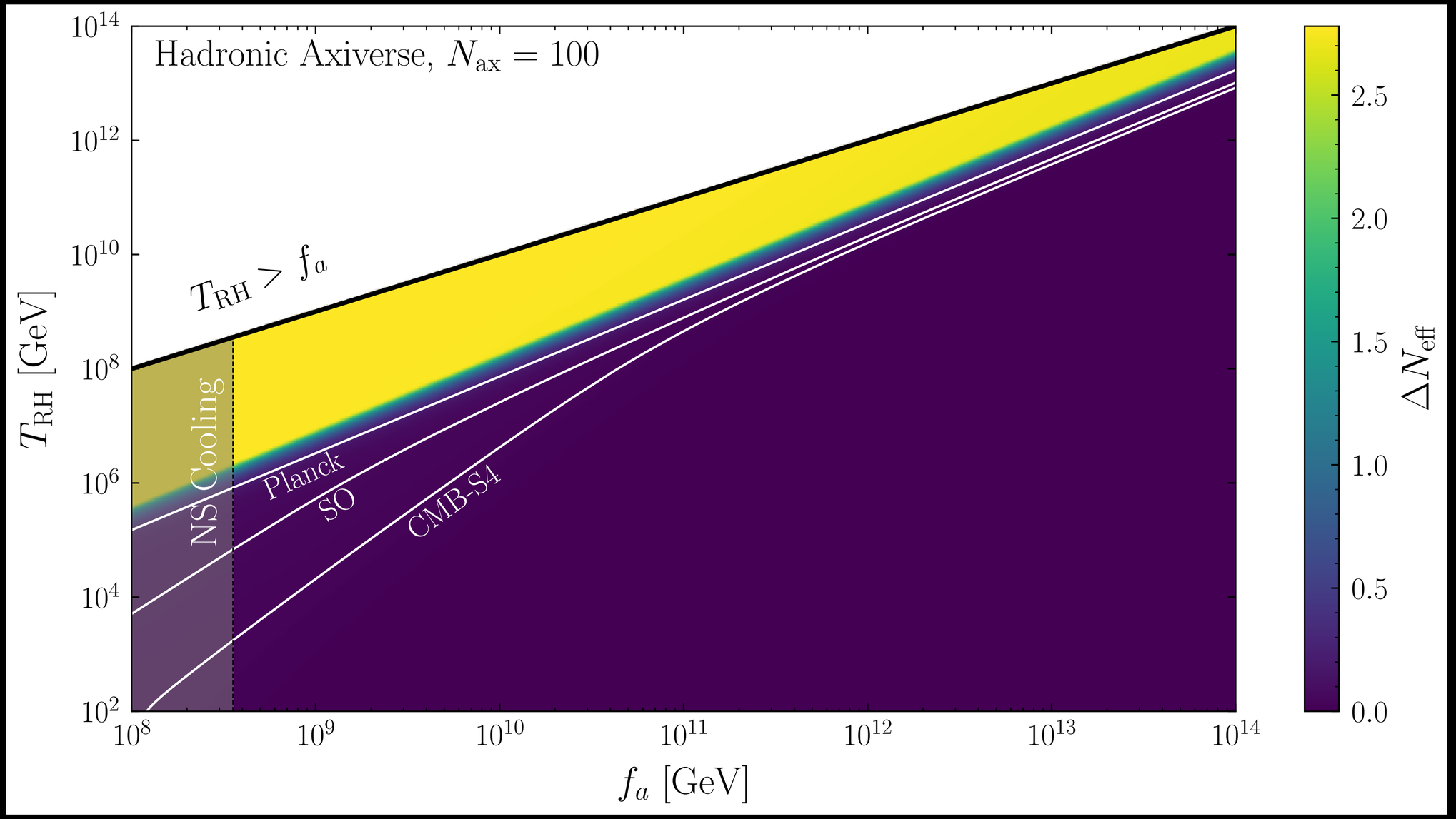
$$\mathscr{L}^{6}_{\text{int}} = -\frac{c^{ij}_{ah}}{f_a^2}(\partial_\mu a_i)(\partial^\mu a_j)\,|H|^2$$

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

Hadronic Axiverse, Dim-5

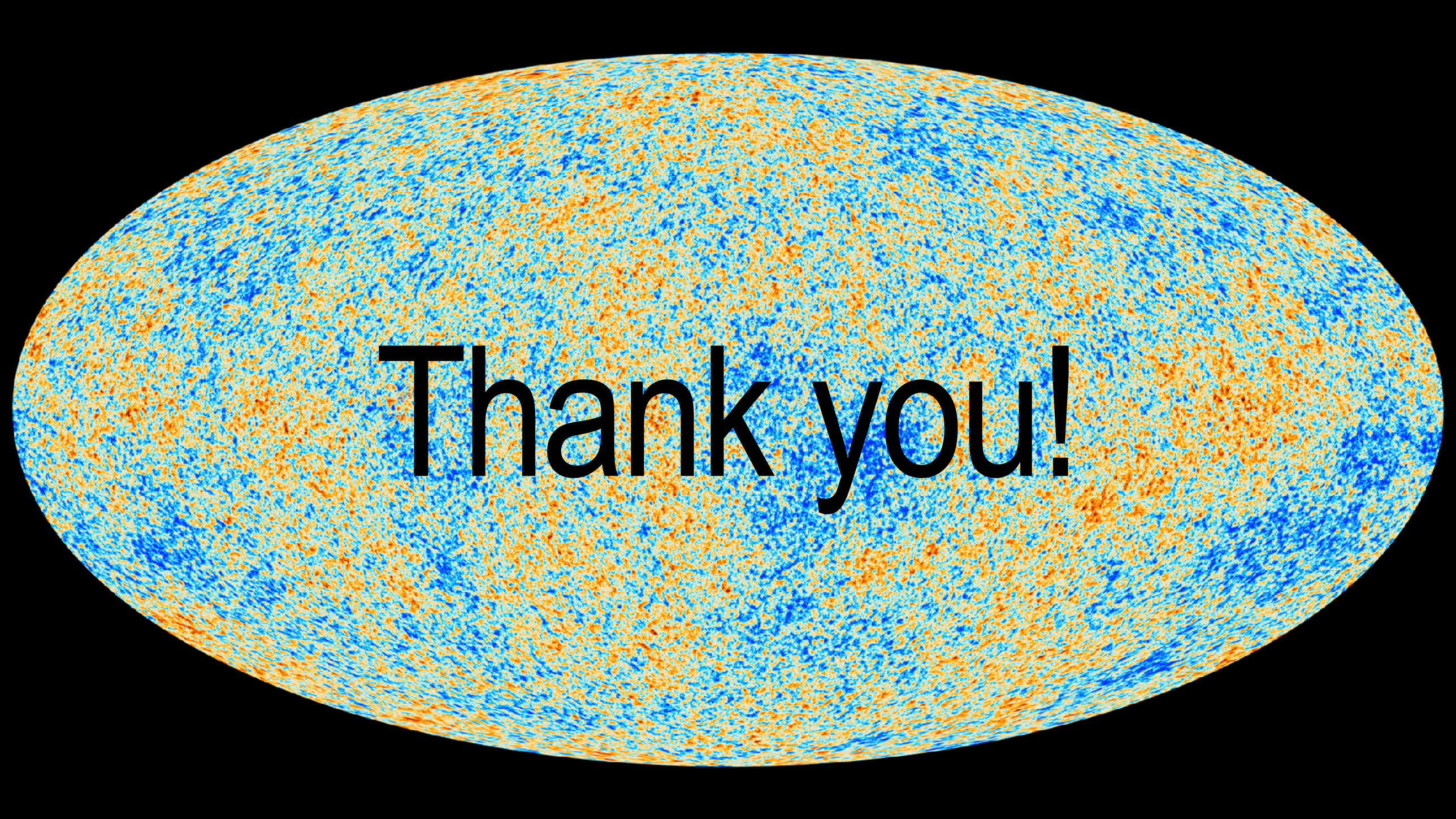


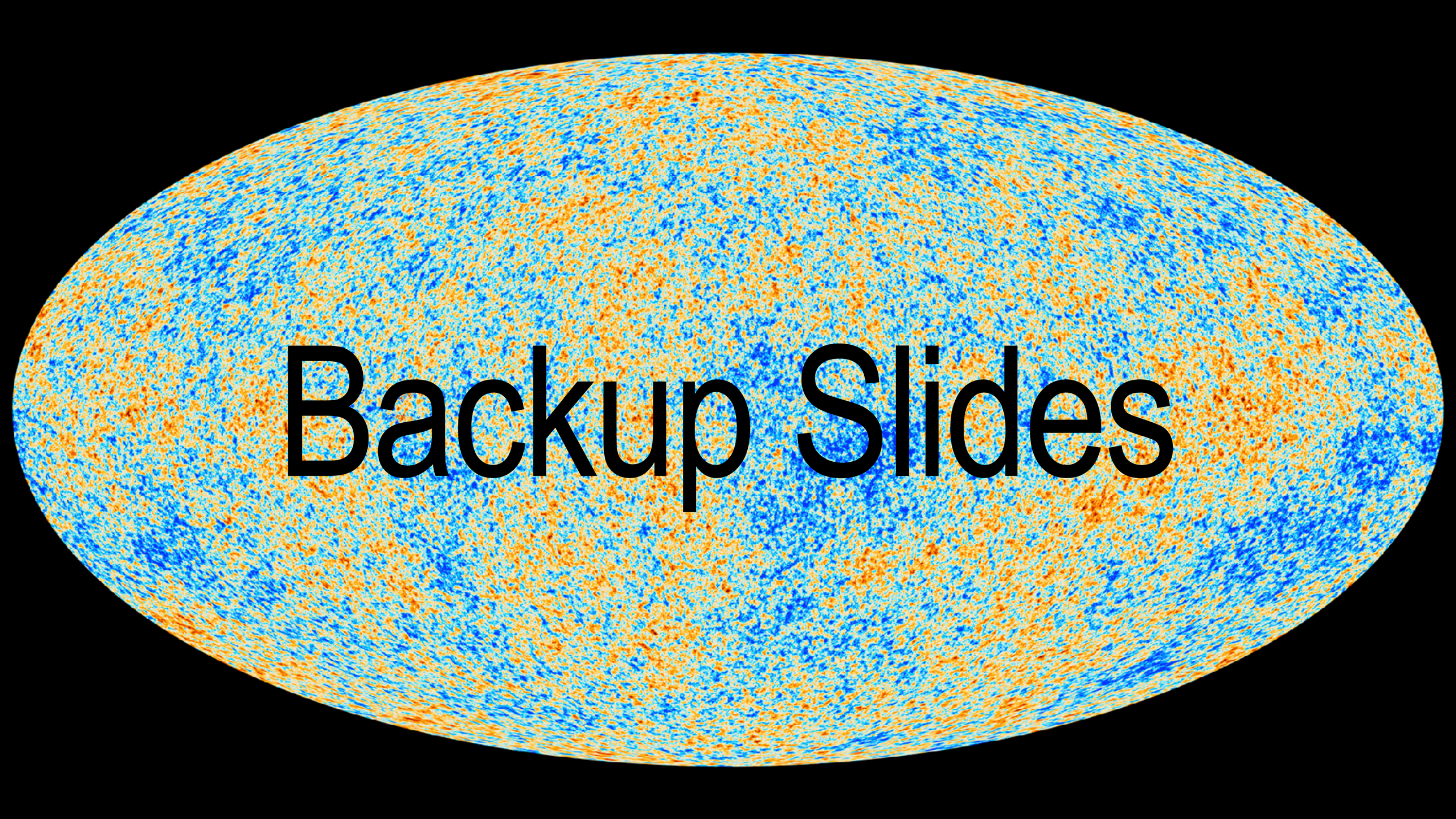
Hadronic Axiverse, Dim-6



Conclusions

- Axiverse phenomenology rich and underexplored
- May lead to large $N_{\rm eff}$ signals at ongoing CMB experiments
- Currently analyzing Axiverse thermalization from flavor operators


Thank you!


Backup Slides

Orthogonal Axiverse

- Axion EFT at dimension 5

$$\mathscr{L}^5_{\rm int} = -\frac{1}{4}\sum_G \frac{c_i^G \alpha_G}{2\pi f_a}\phi_i G\tilde{G} + \sum_F \frac{c_i^{F,jk}}{2f_a}\left(\partial_\mu \phi_i^{F,jk}\right)\bar{\psi}_F^i \gamma^\mu \psi_F^j$$

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

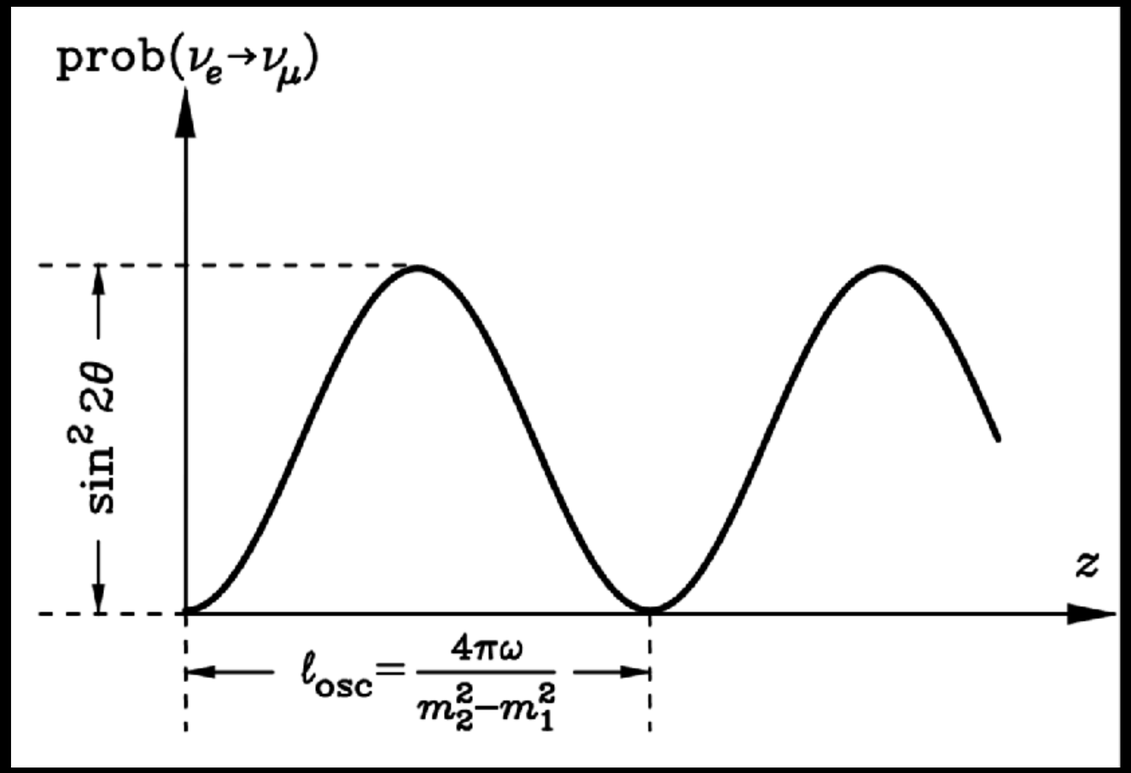
$$\mathscr{L}^5_{\rm int} = -\frac{1}{4}\frac{c_{\rm QCD}\alpha_G}{2\pi f_a} a_{\rm QCD} G\tilde{G} + [\text{couplings to all other operators}]$$

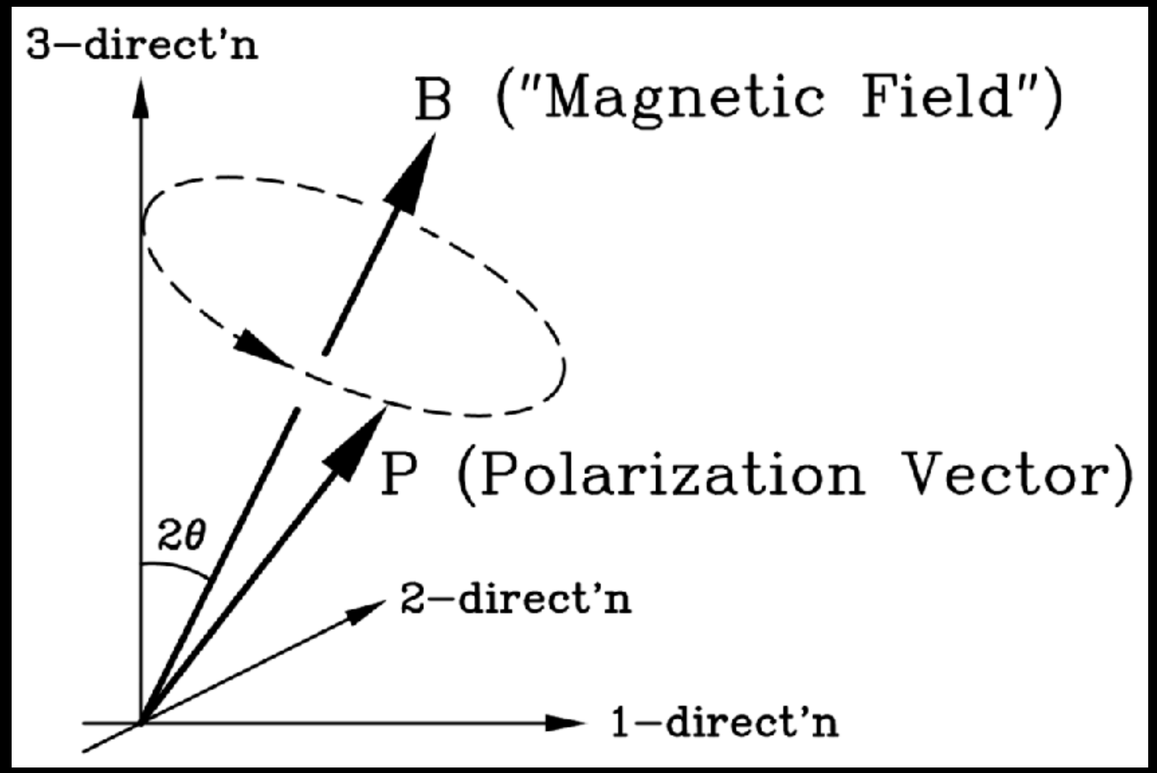
$$-\frac{1}{4}\frac{c_2\alpha_2}{2\pi f_a} a_2 W\tilde{W} + [\text{couplings to all other operators except QCD}]$$

$$+ \ldots$$

$$+ [N - N_{\rm SM} \text{ sterile axions}]$$

Axion oscillation





Stars as Laboratories for Fundamental Physics, Raffelt (1996)

What can the CMB do for us?

- Exciting time to think about the CMB:

ACT (DR6 this year)

$\Delta N_{\rm eff} \approx 0.1$

SO (now taking data)

$\Delta N_{\rm eff} \approx 0.05$

CMB-S4

Next Generation CMB Experiment

CMB-S4 (Future)

$\Delta N_{\rm eff} \approx 0.03$