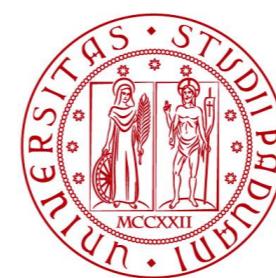


# Axions in the Early Universe

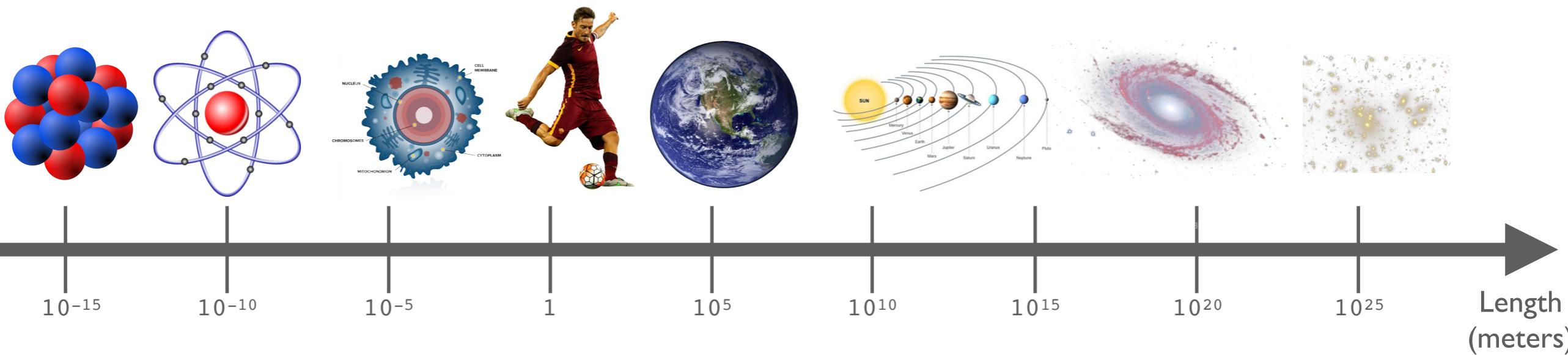
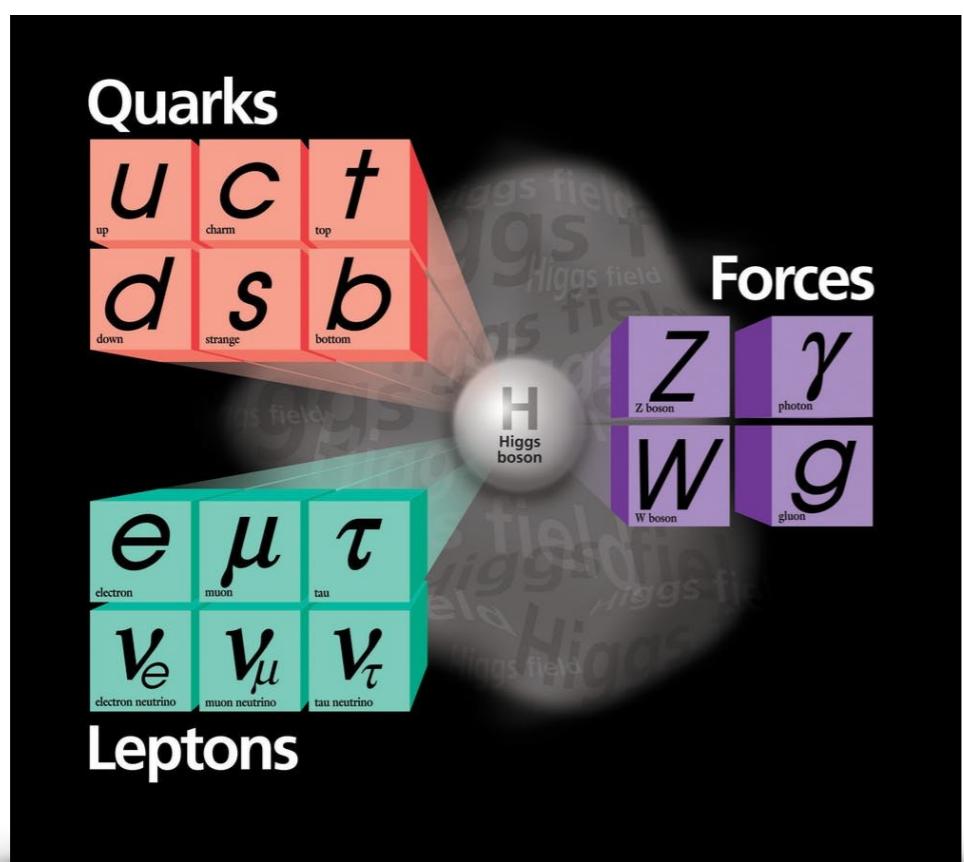
Francesco  
D'Eramo



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

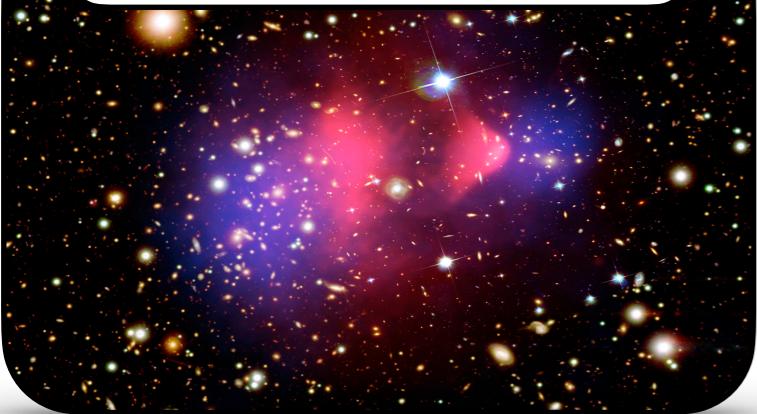


# The Standard Model

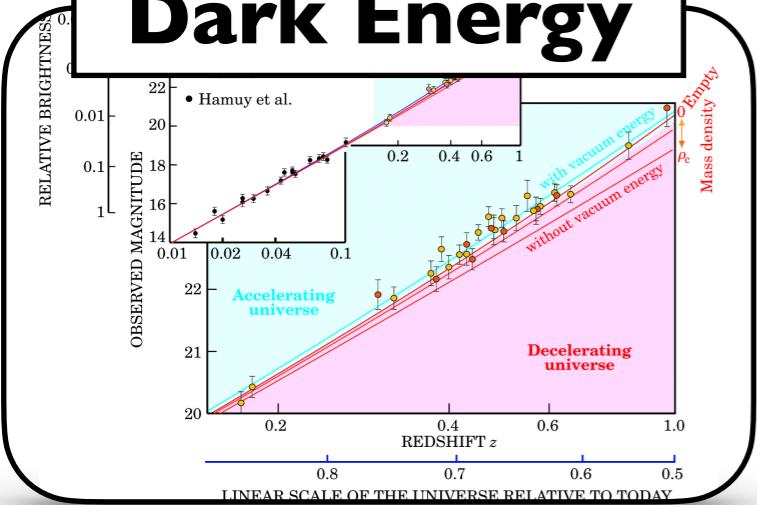


# Still Unanswered Questions...

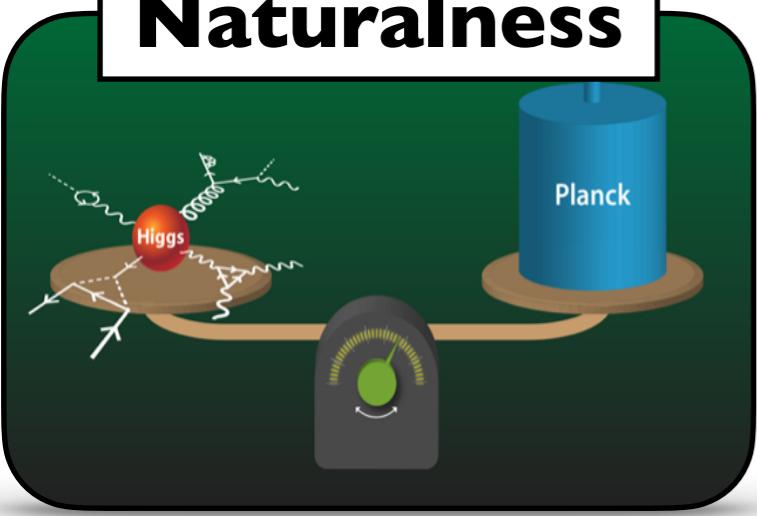
## Dark Matter



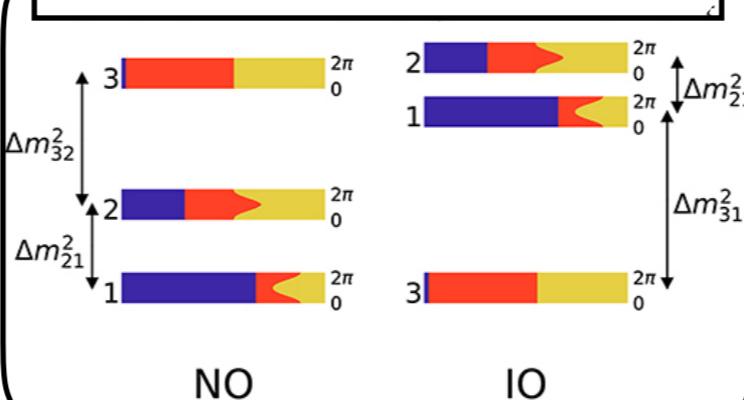
## Dark Energy



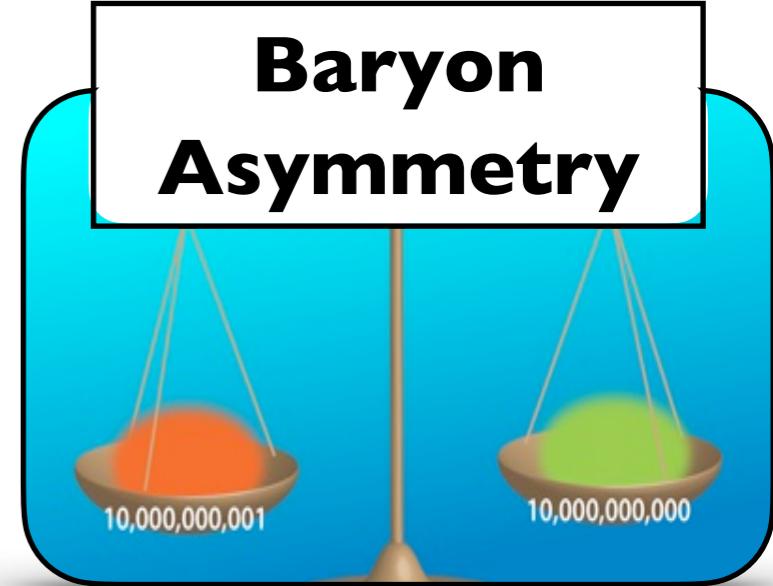
## Naturalness



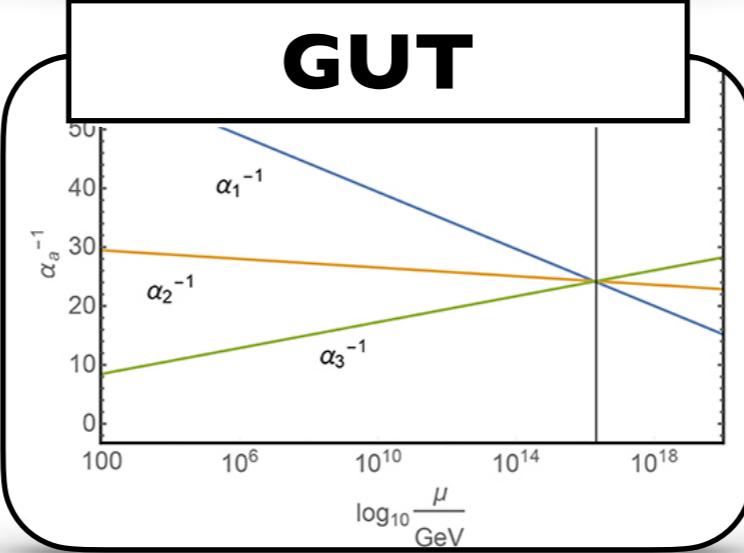
## Neutrino Mass



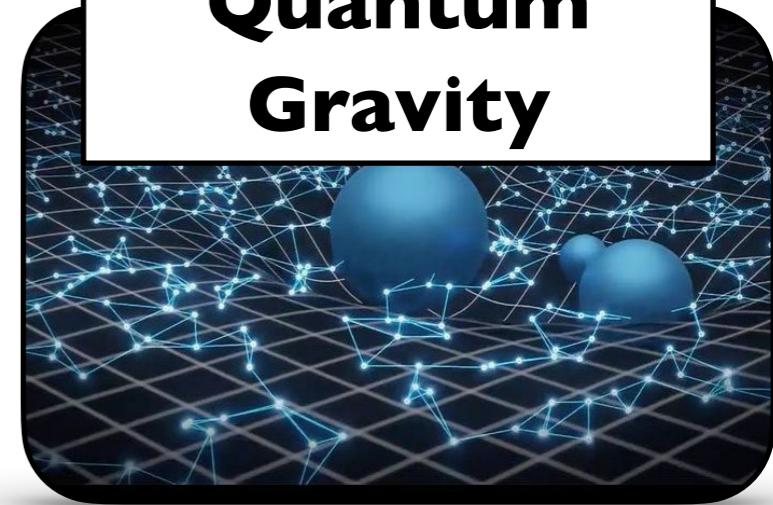
## Baryon Asymmetry



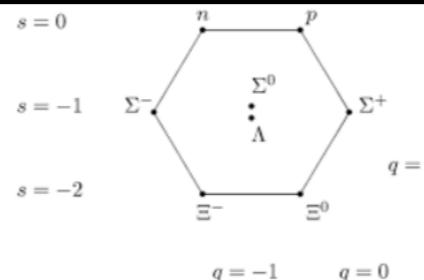
## GUT



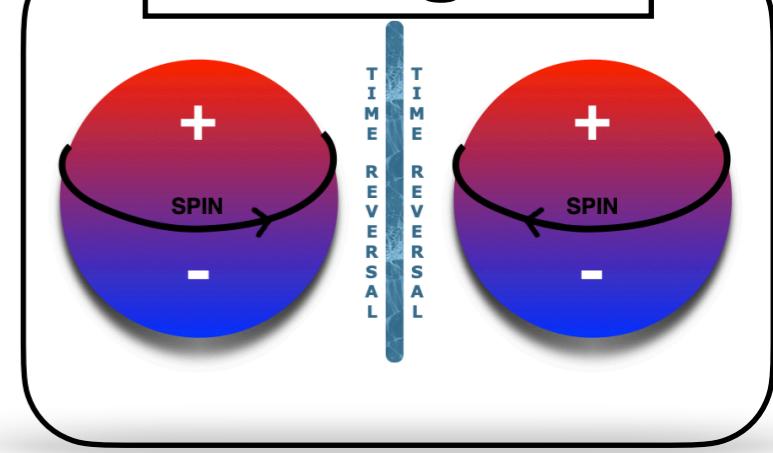
## Quantum Gravity



## Charge Quantization

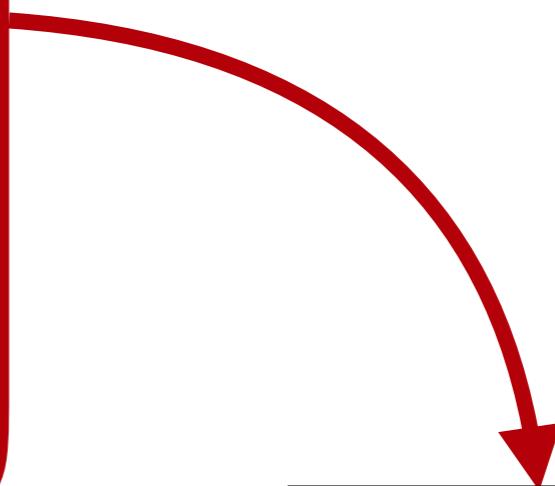


## Strong CP

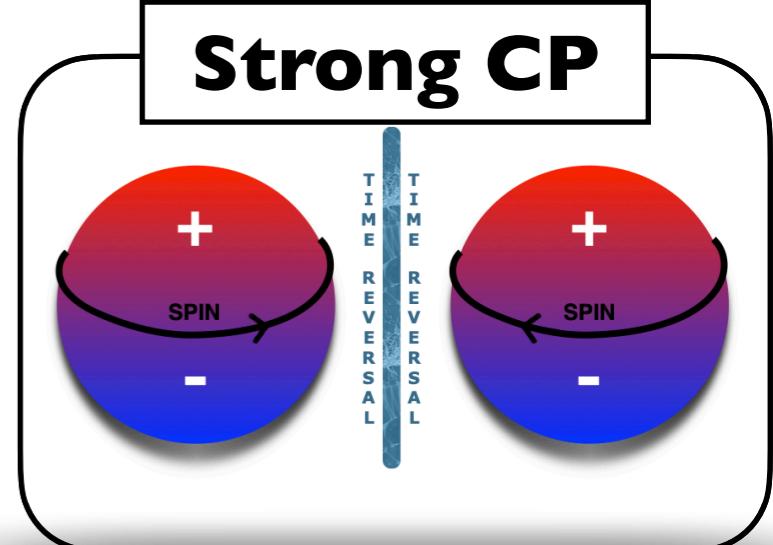


# QCD Axion: 2 Birds with 1 Stone

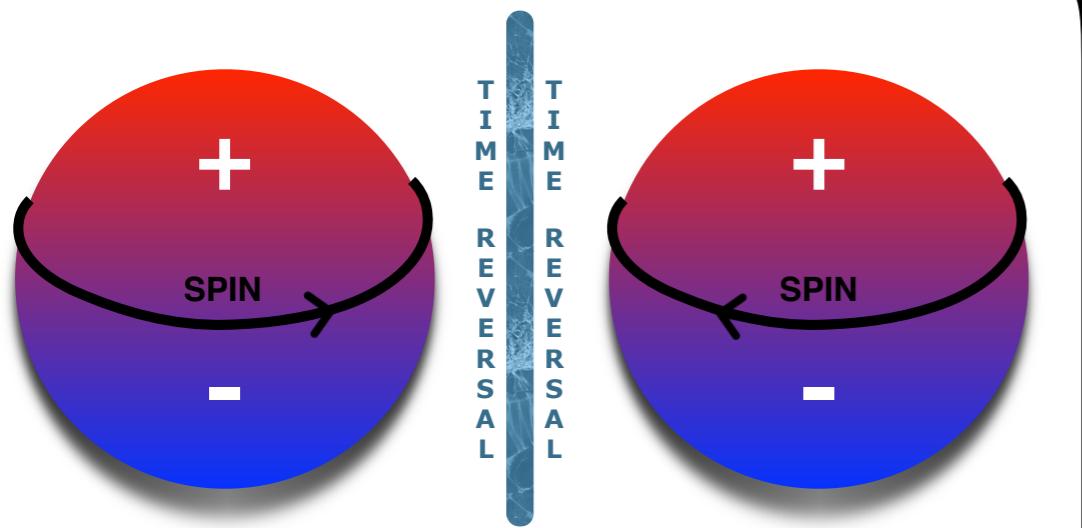
Dark Matter



Strong CP



# The Strong CP Problem



No detection of time reversal invariance violation by strong interactions



Why is the  $\theta$  parameter of the QCD Lagrangian so small?

$$|\theta| \lesssim 10^{-10}$$

# The Strong CP Problem

CP violation in Quantum Chromodynamics

$$\mathcal{L}_{\text{QCD}} \supset -\theta \frac{g_s^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu} - \sum_q \bar{q} m_q e^{-i\theta_q \gamma_5} q$$

Observable consequence:  $d_n \simeq 2.4 \times 10^{-16} \bar{\theta} \text{ e cm}$   
neutron electric  
dipole moment

$$\bar{\theta} \equiv \theta - \sum_q \theta_q$$

Crewther, Di Vecchia, Veneziano, Witten,  
PLB88 (1979) and PLB91 (1980)

Experimental Bound

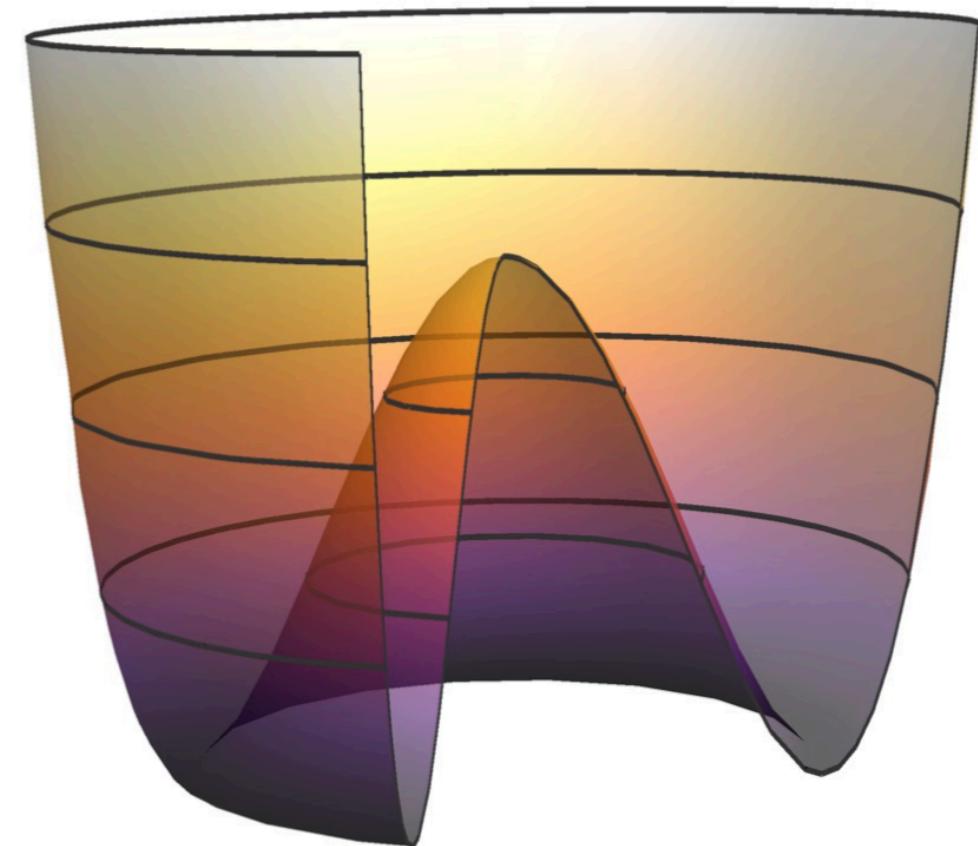
$$|\bar{\theta}| \lesssim 10^{-10}$$

# The Peccei-Quinn Mechanism

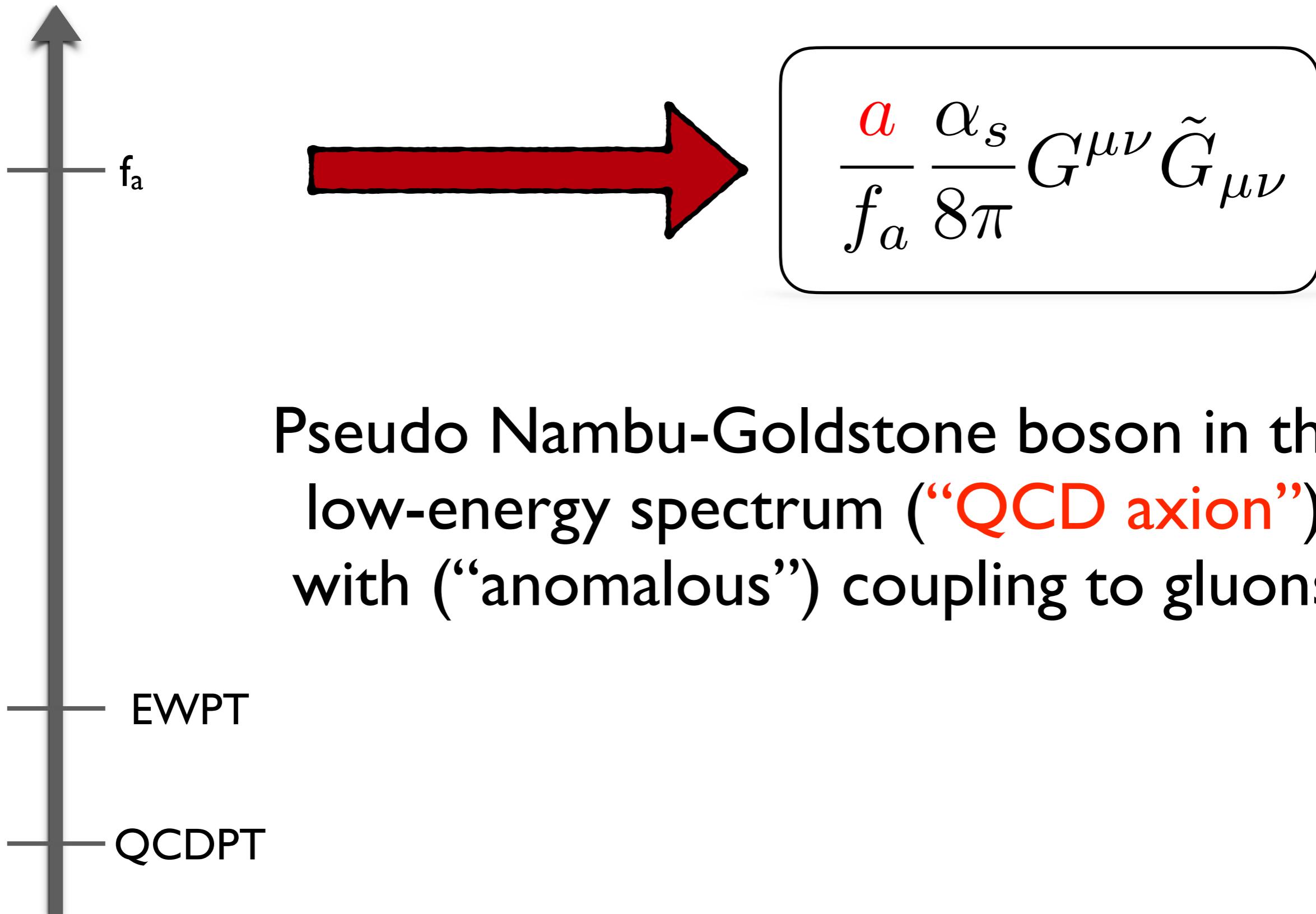
Dynamical solution to the strong CP problem

New global  $U(1)_{\text{PQ}}$  symmetry

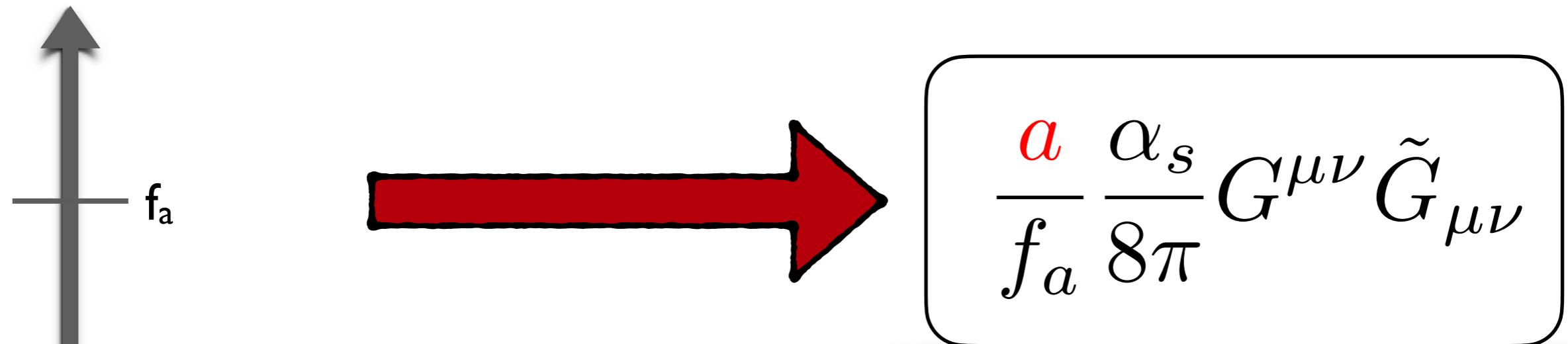
- spontaneously broken at the scale  $f_a$  (with  $f_a \gg$  weak scale)
- anomalous under strong interactions



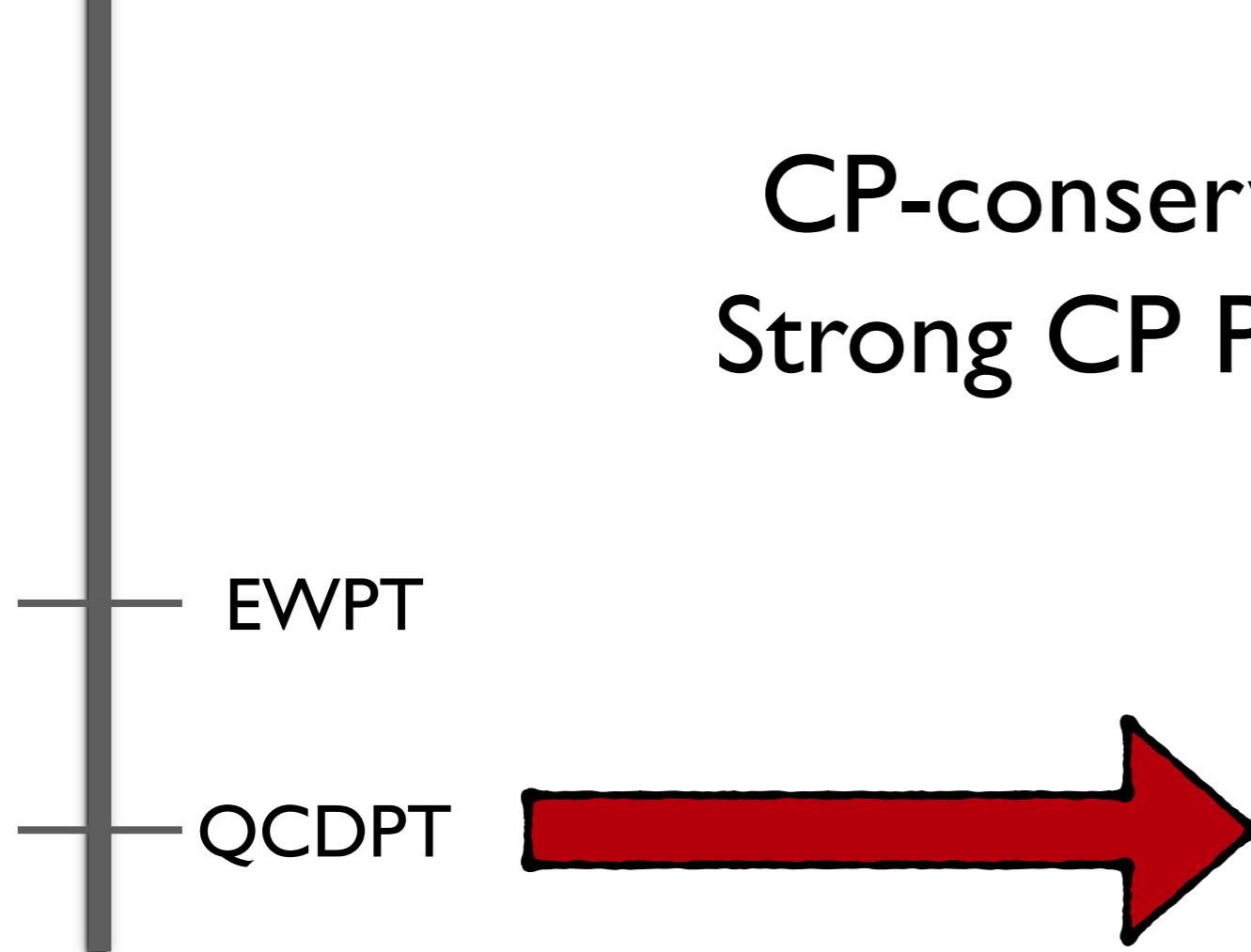
# The Peccei-Quinn Mechanism



# The Peccei-Quinn Mechanism



CP-conserving minimum!  
Strong CP Problem Solved!



# The QCD Axion

Axion (zero-temperature) mass  
from non-perturbative potential

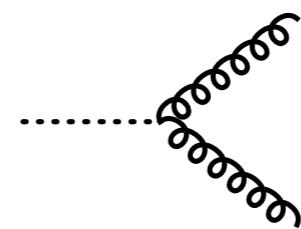
$$m_a \simeq 5.7 \left( \frac{10^9 \text{ GeV}}{f_a} \right) \text{ meV}$$

**The QCD axion is very light!**

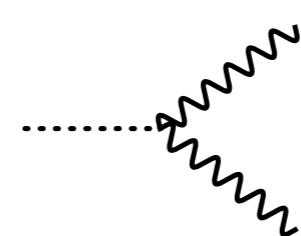
Coupling to gluons, electroweak gauge  
bosons (not mandatory), derivative  
interactions with fermions

$$\mathcal{L}_{\text{int}} = c_X \frac{\alpha}{f_a} \frac{\alpha_X}{8\pi} X^{\mu\nu} \tilde{X}_{\mu\nu} + c_\psi \frac{\partial_\mu \alpha}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

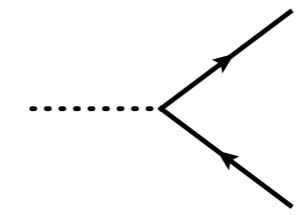
**The QCD axion is elusive!**



$$\frac{\alpha_s}{8\pi} \frac{\alpha}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$



$$c_{\gamma\gamma} \frac{\alpha_{\text{em}}}{8\pi} \frac{\alpha}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$$



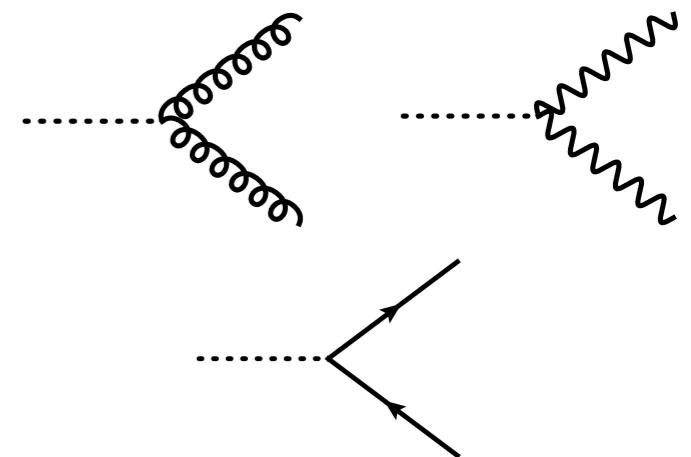
$$c_\psi \frac{\partial_\mu \alpha}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

# Axion Signals

A new light and weakly coupled particle

$$m_a \simeq 5.7 \left( \frac{10^9 \text{ GeV}}{f_a} \right) \text{ meV}$$

$$\mathcal{L}_{\text{int}} = c_X \frac{\alpha_X}{f_a} \frac{a}{8\pi} X^{\mu\nu} \tilde{X}_{\mu\nu} + c_\psi \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

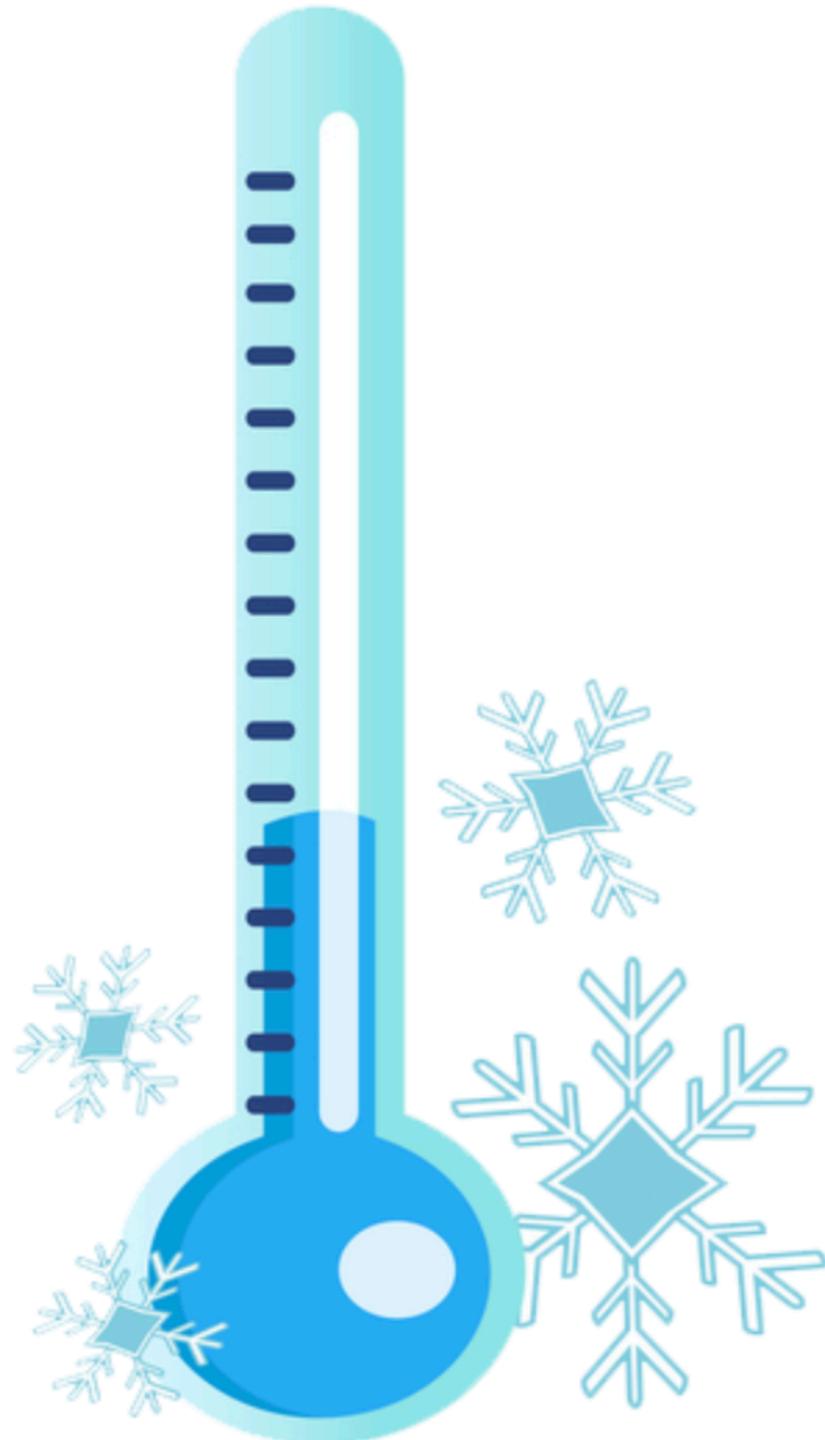


- detection challenging
- prominent role in the early universe

We will hear from  
**Claudio Gatti**  
about this soon

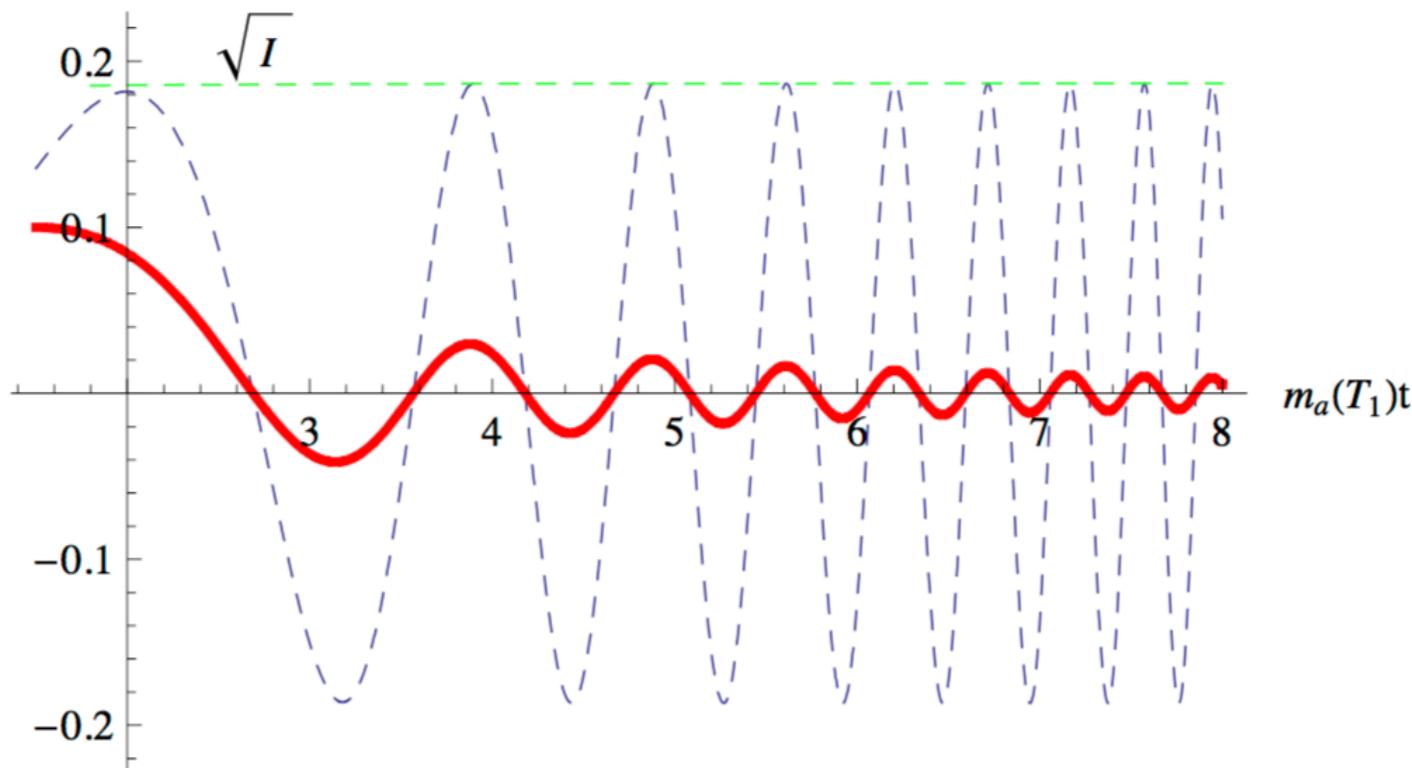
**This talk**  
will be about  
axions in the  
early universe!

# Cold Axions (Dark Matter)



# Axion Misalignment

$$\theta \equiv a/f$$



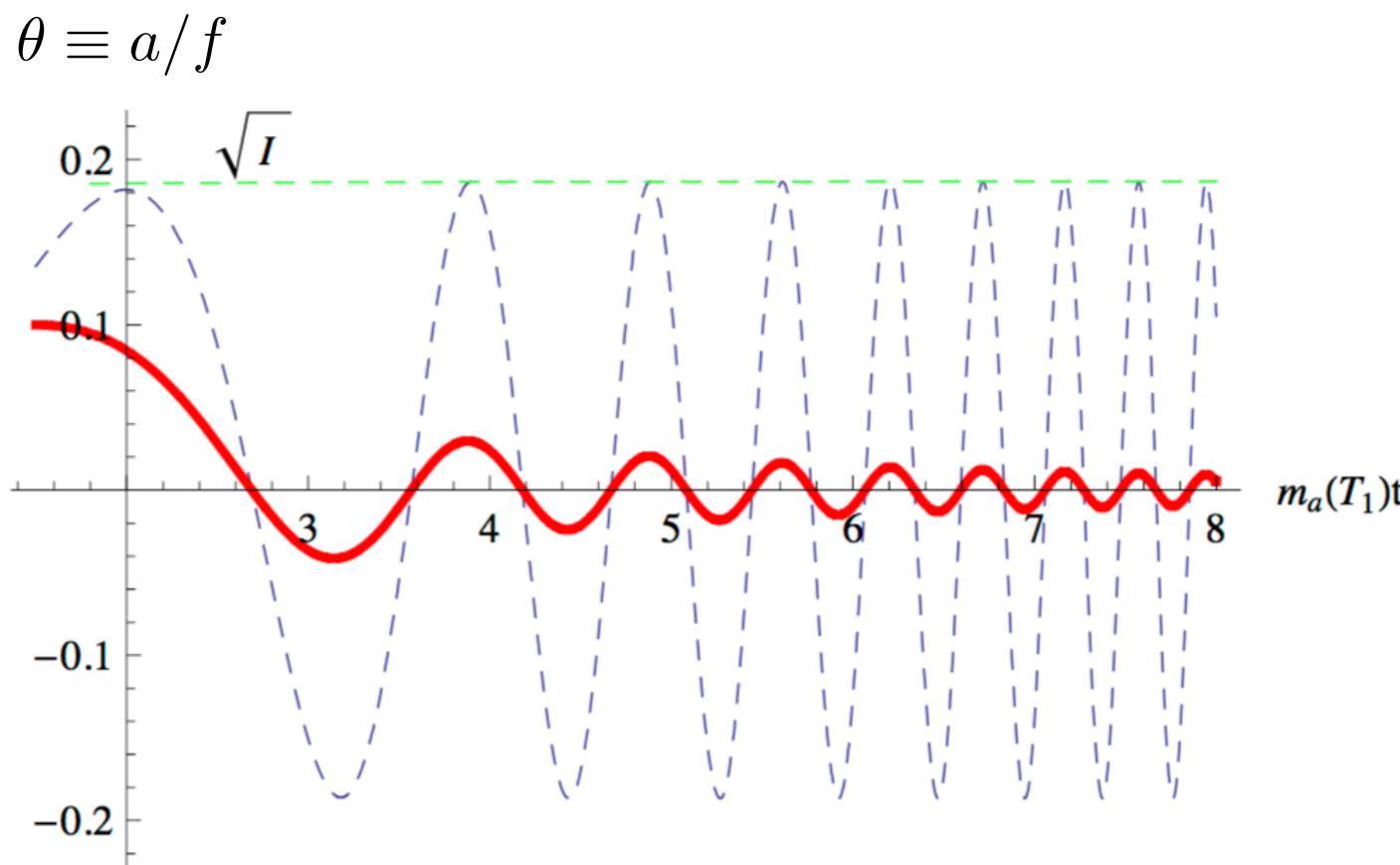
## Misalignment

$$\frac{d^2a}{dt^2} + 3H\frac{da}{dt} + m_a(T)^2a = 0$$

$$\Omega_a h^2 \simeq 0.1 \theta_i^2 \left( \frac{f_a}{10^{11} \text{ GeV}} \right)^{1.18}$$

- $3H(T) > m_a(T)$ : axion stuck by “Hubble friction”
- $3H(T) < m_a(T)$ : axion oscillates, energy density as cold matter

# Axion Misalignment



## Misalignment

$$\frac{d^2a}{dt^2} + 3H\frac{da}{dt} + m_a(T)^2a = 0$$

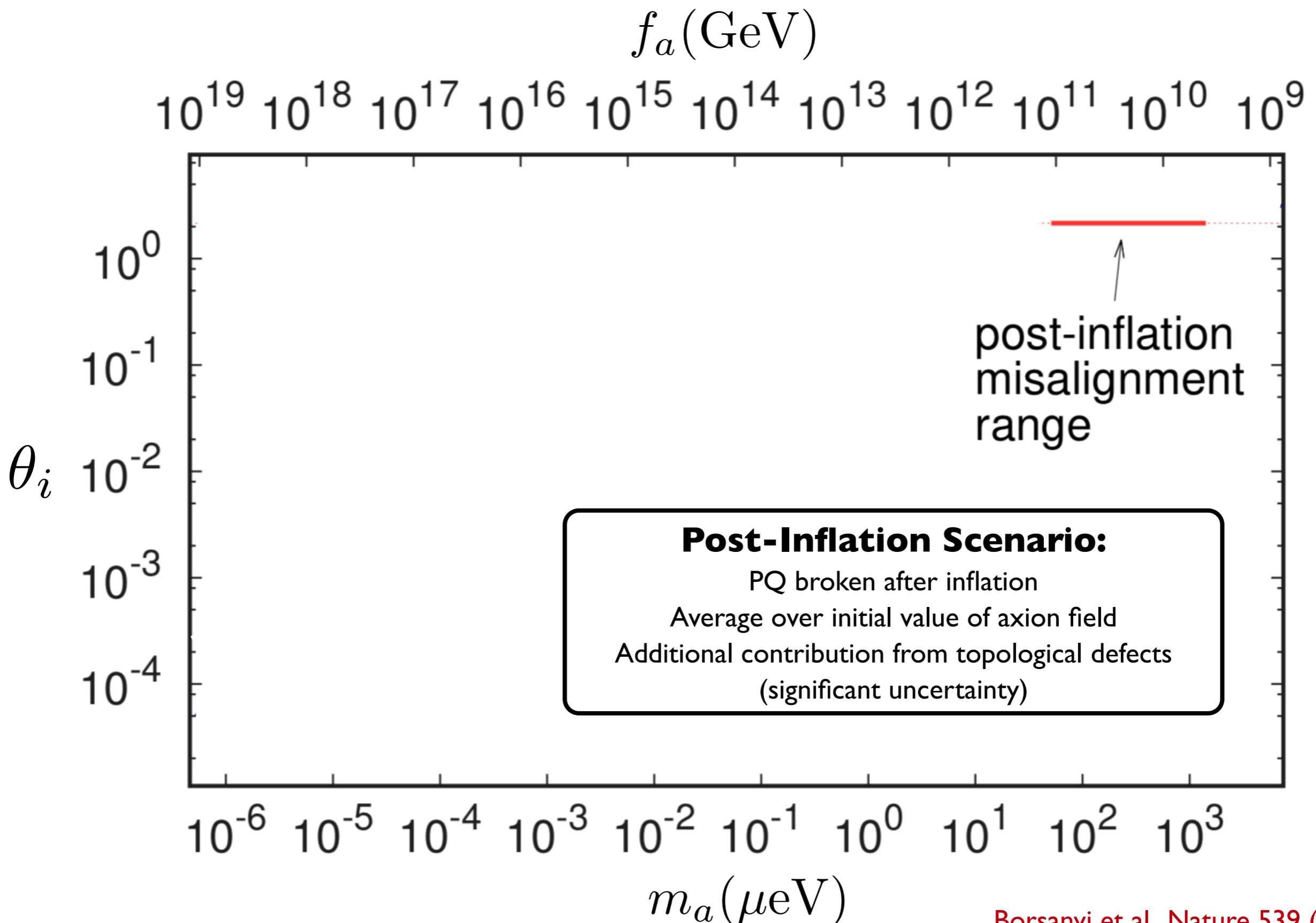
$$\Omega_a h^2 \simeq 0.1 \theta_i^2 \left( \frac{f_a}{10^{11} \text{ GeV}} \right)^{1.18}$$

Axion initial field value? It depends...

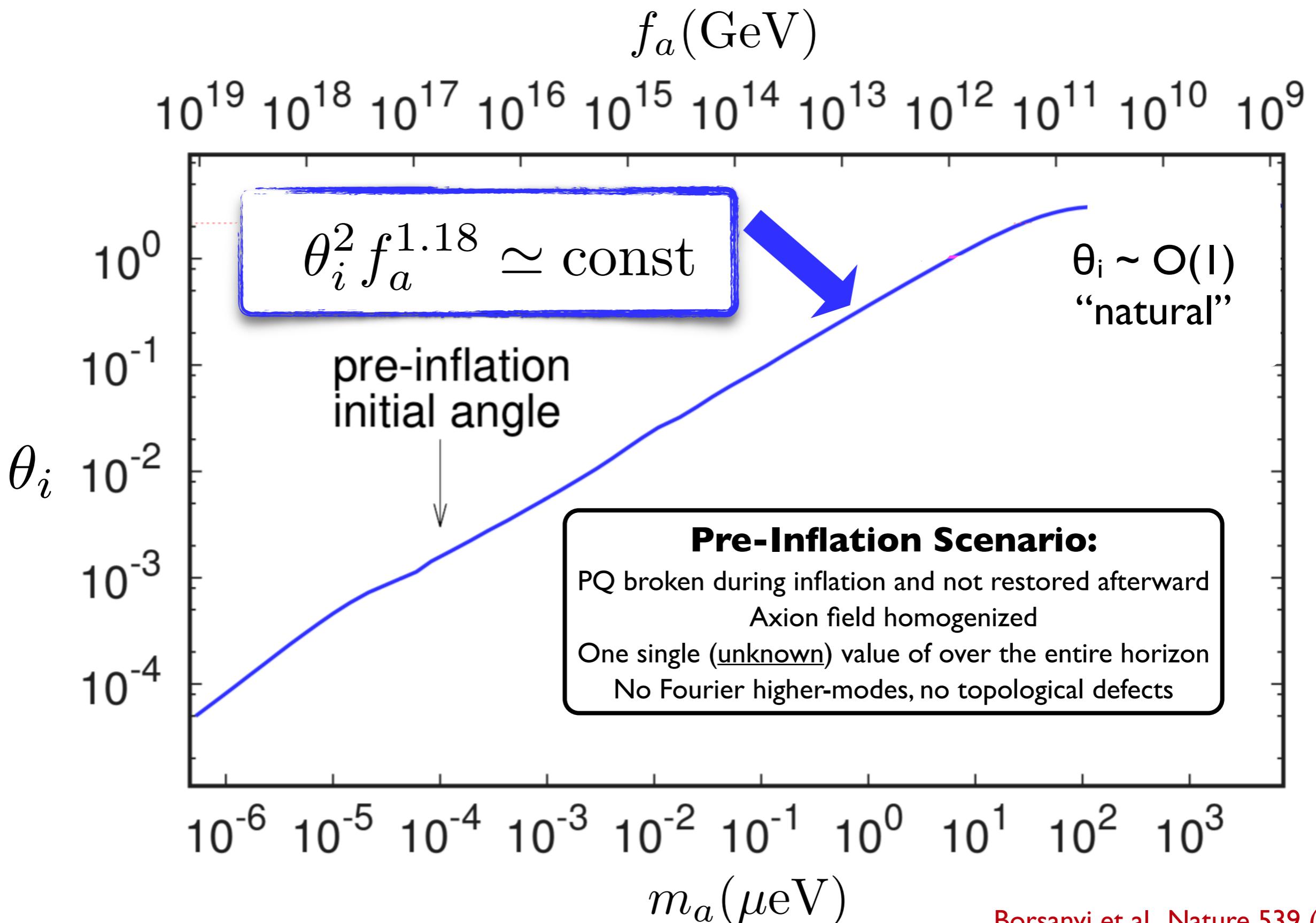
Was PQ broken during inflation?

If yes, was it restored afterwards?

# Post-Inflation Scenario



# Pre-Inflation Scenario



# QCD Axion Cold Dark Matter

## Post-Inflation

Axion cold dark matter  
from strings

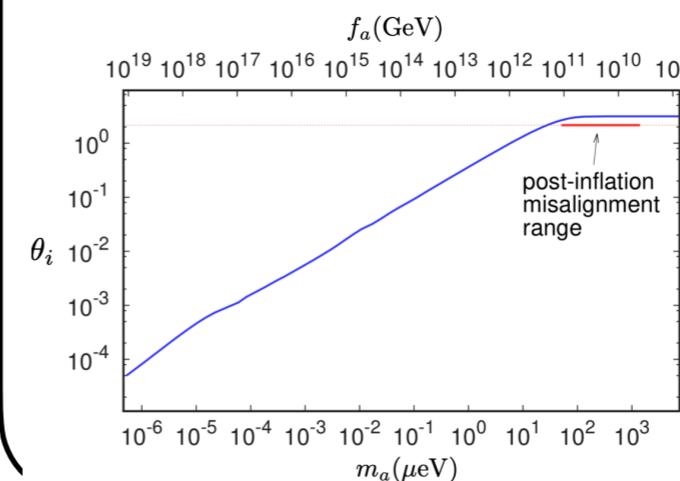
Klaer and Moore, JCAP 10 and JCAP 11 (2017)

Gorghetto, Hardy, Villadoro  
JHEP 07 (2018) and SciPost Phys.10 (2021)

Buschmann, Foster, Safdi  
PRL124 (2020) and Nature Commun. 13 (2022)

## Pre-Inflation

Finite temperature axion  
mass from lattice

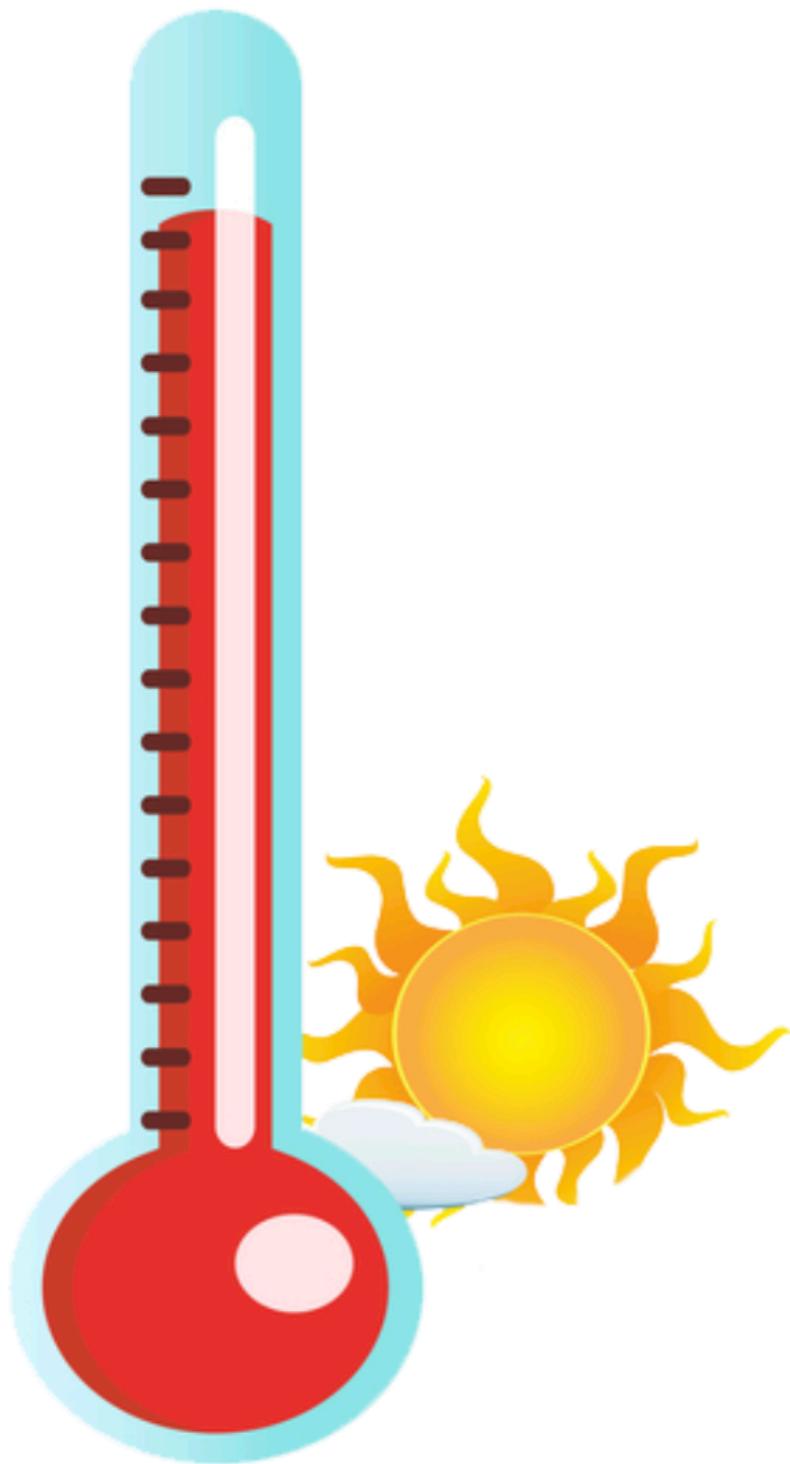


Borsanyi et al.,  
Phys.Lett.B 752 (2016)  
Nature 539 (2016)

Range for  $f_a$  (with caveats):

$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{11} \text{ GeV}$$

- Larger  $f_a$ : dilute dark matter abundance or fine-tune initial field value
- Lower  $f_a$ : axion sub-dominant dark matter component

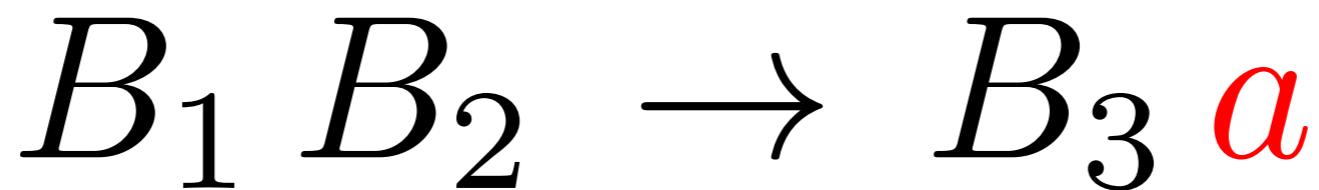


# Hot Axions

## (Dark Radiation)

# Thermal Axions

Scatterings and/or decays involving particles belonging to the primordial thermal bath  
(axion energy much higher than  $m_a$ , i.e. “hot”)



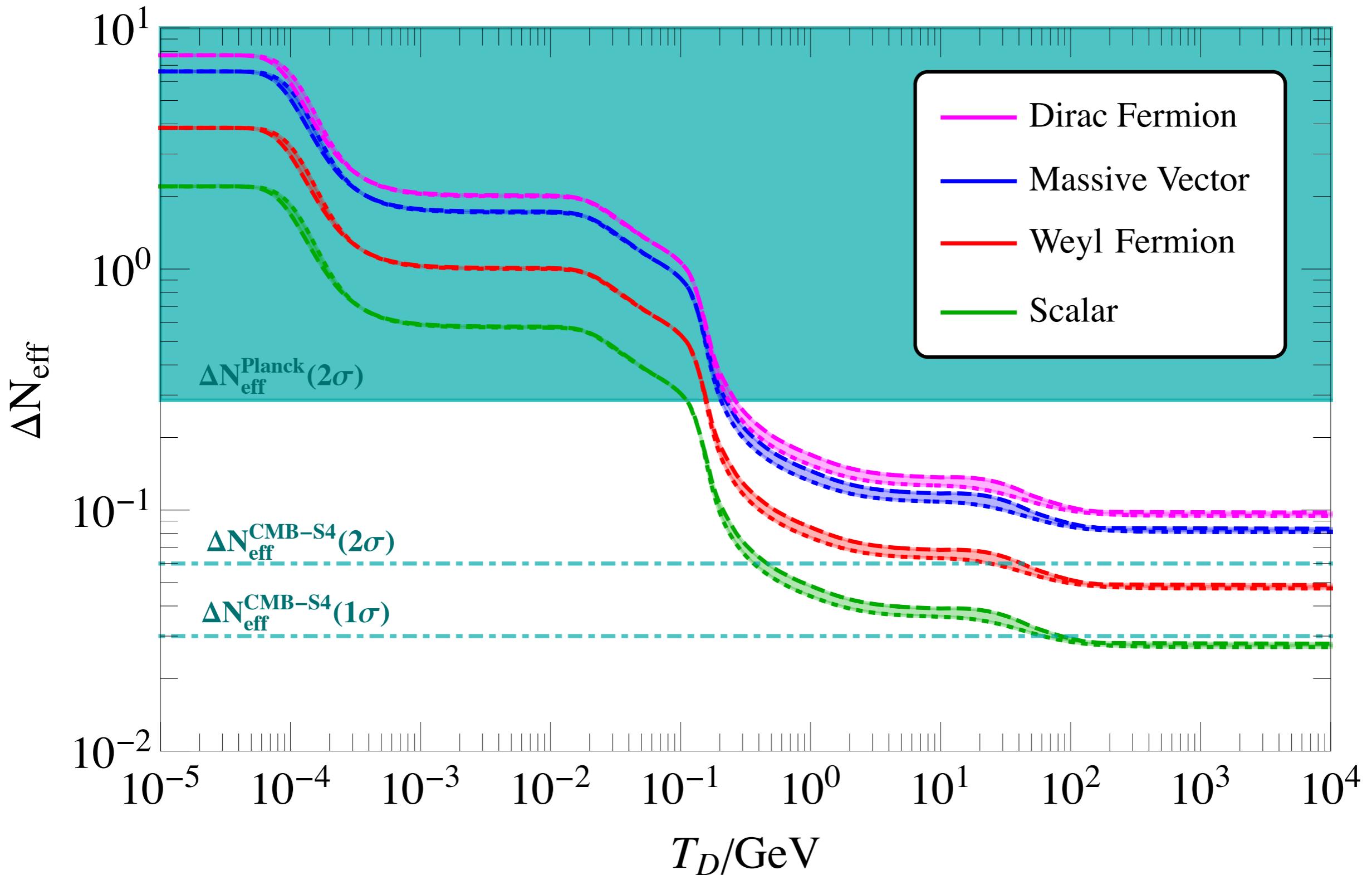
Additional radiation at:

- BBN ( $m_a \lesssim \text{MeV}$ )
- CMB formation ( $m_a \lesssim 0.3 \text{ eV}$ )

$$\rho_{\text{rad}} = \left[ 1 + \frac{7}{8} \left( \frac{T_\nu}{T_\gamma} \right)^4 N_{\text{eff}} \right] \rho_\gamma$$

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

# Dark Radiation in the CMB



# Scenarios for Hot Axions

## Single Coupling Switched On

Axion coupled to a given  
Standard Model field

Ferreira, Notari, Phys.Rev.Lett. 120 (2018)

FD et al, JCAP 11 (2018)

Arias-Aragón et al., JCAP 11 (2020) and JCAP 03 (2021)

Green et al., JCAP 02 (2022)

FD et al., Phys.Rev.Lett. 128 (2022)

## UV Completions

FD, Hajkarim, Yun, JHEP 10 (2021)

- **KSVZ Axion:** Standard Model fields are PQ-neutral and color anomaly from heavy colored and PQ-charged fermion  $\Psi$

Kim, PRL 43 (1979)

Shifman, Vainshtein, Zakharov, NPB 166 (1980)

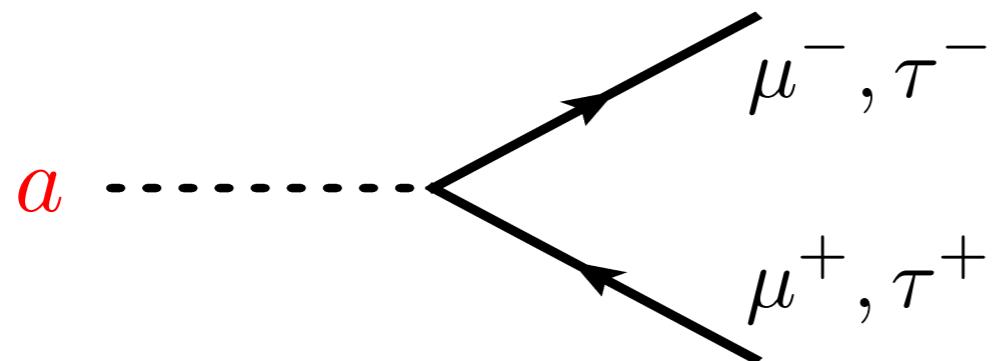
- **DFSZ Axion:** Standard Model fields charged (two Higgs doublets) and color anomaly from quarks

Zhitnitsky, SJNP 31 (1980)

Dine, Fischler, Srednicki, PLB 104 (1981)

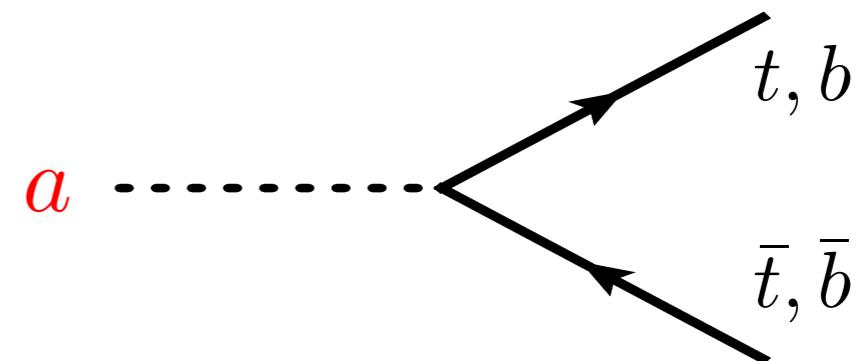
# Two Simple Scenarios

## Leptons



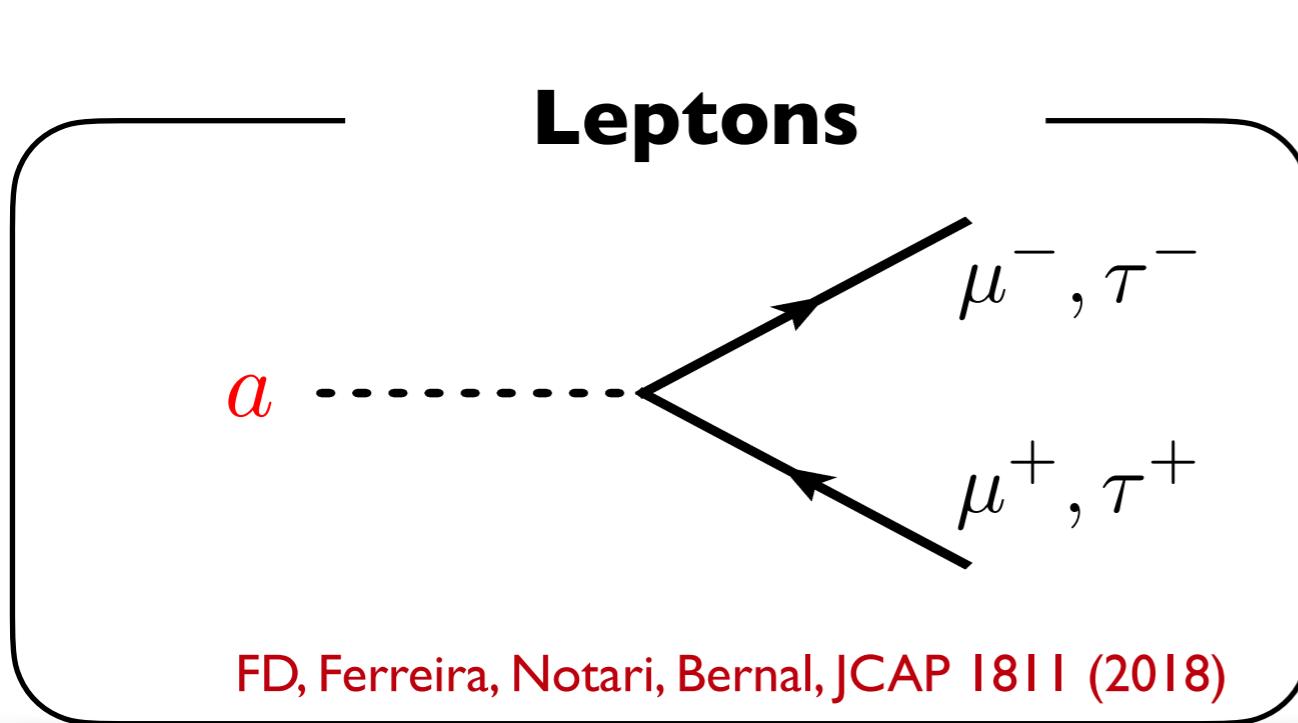
FD, Ferreira, Notari, Bernal, JCAP 1811 (2018)

## 3rd Gen. Quarks

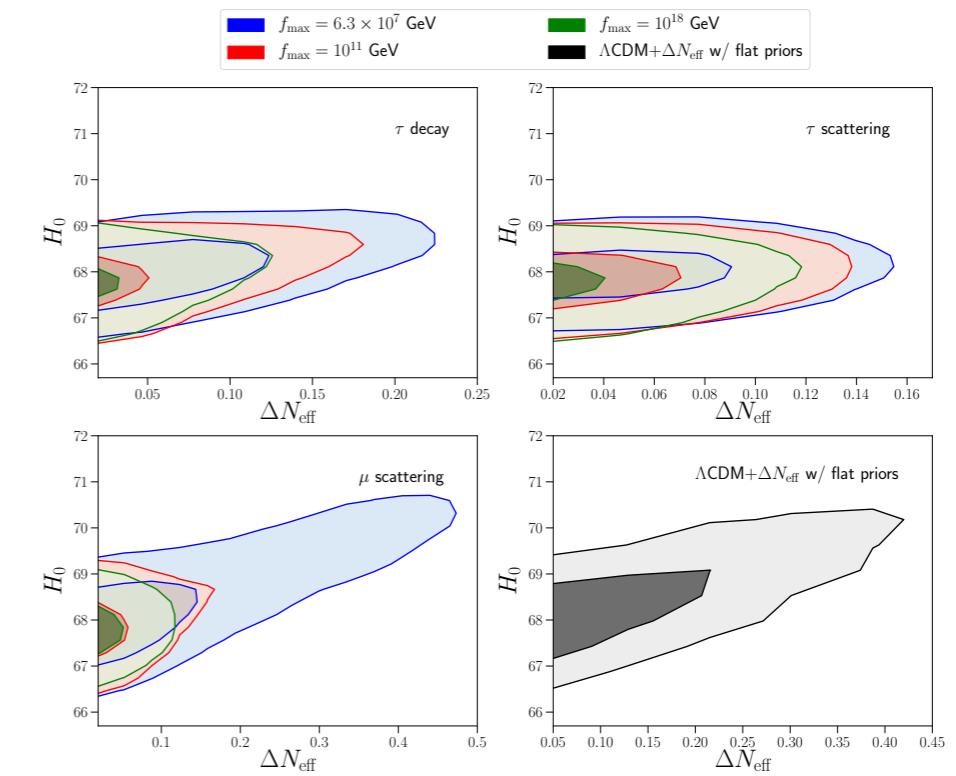
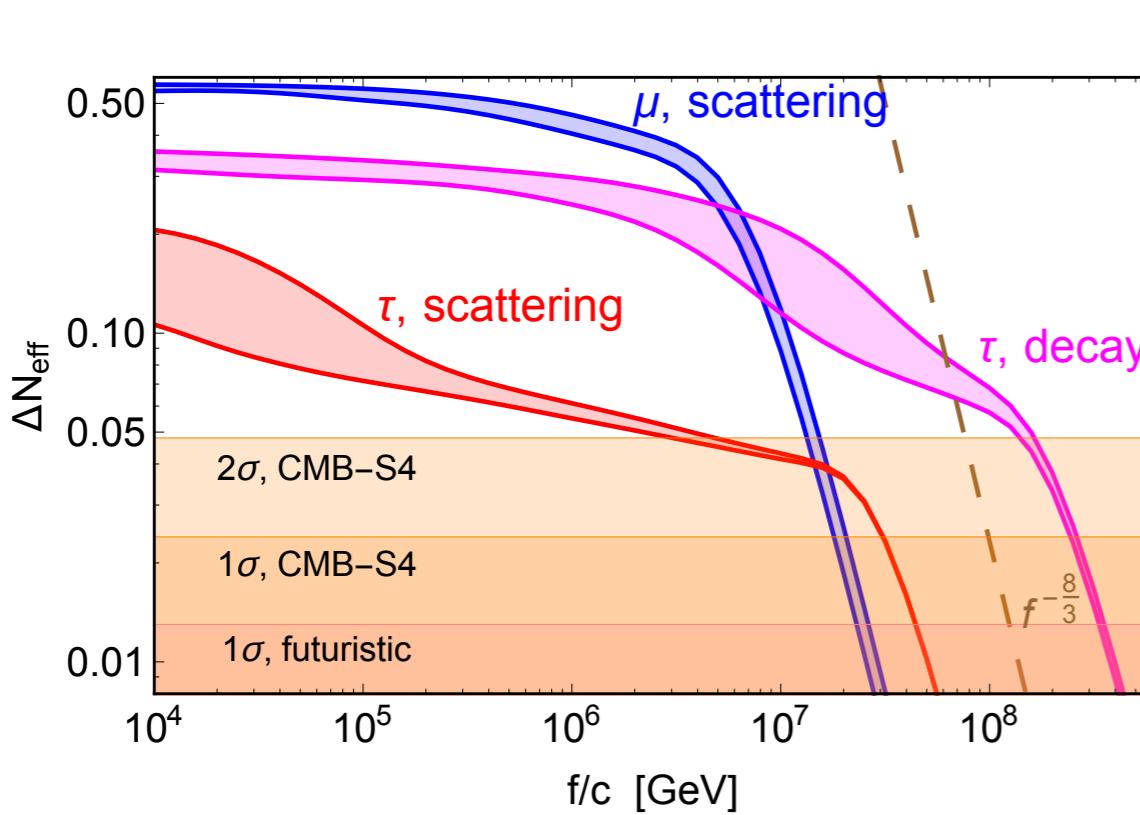


Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)

# A Leptophilic Axion



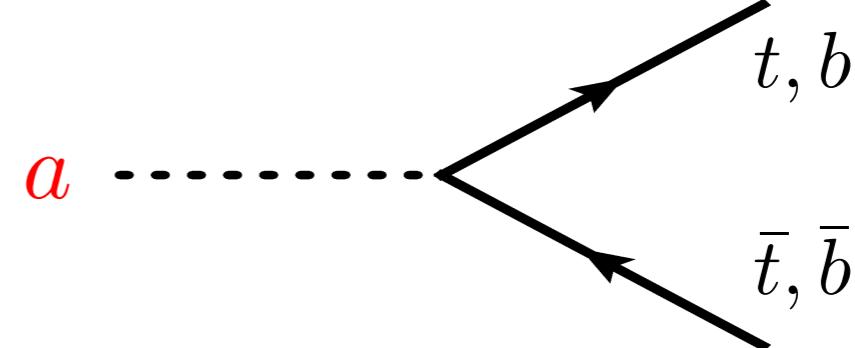
They can alleviate  
the Hubble  
tension



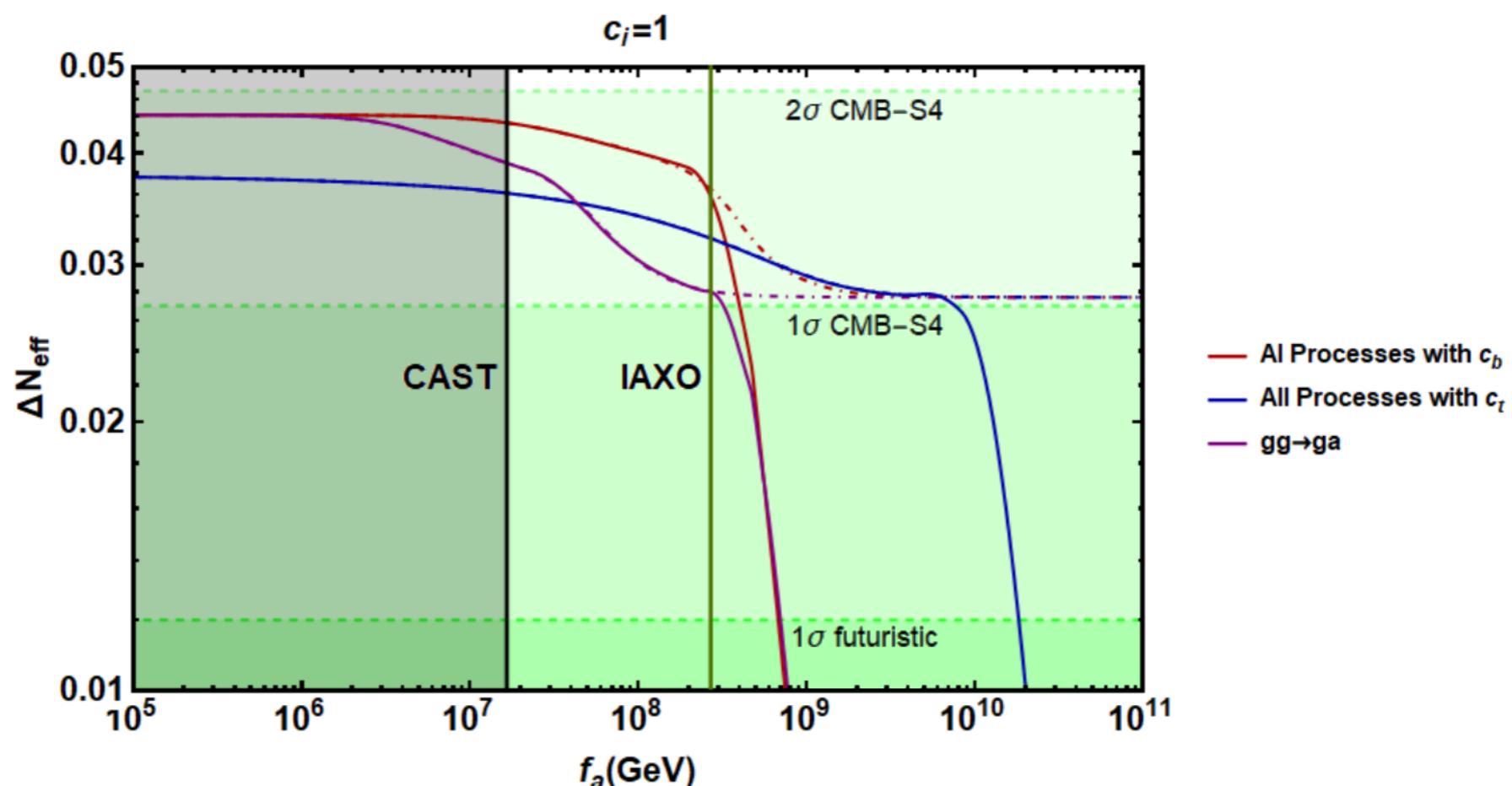
# Axion Coupled to Heavy Quarks

Smooth rate  
across EWPT,  
within reach of  
**CMB-S4**  
**surveys**

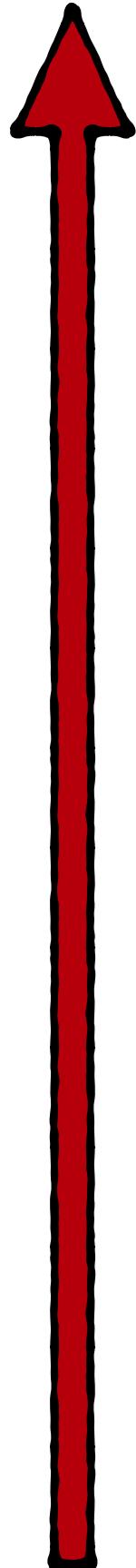
**3rd Gen. Quarks**



Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)



# KSVZ Axion – Theory



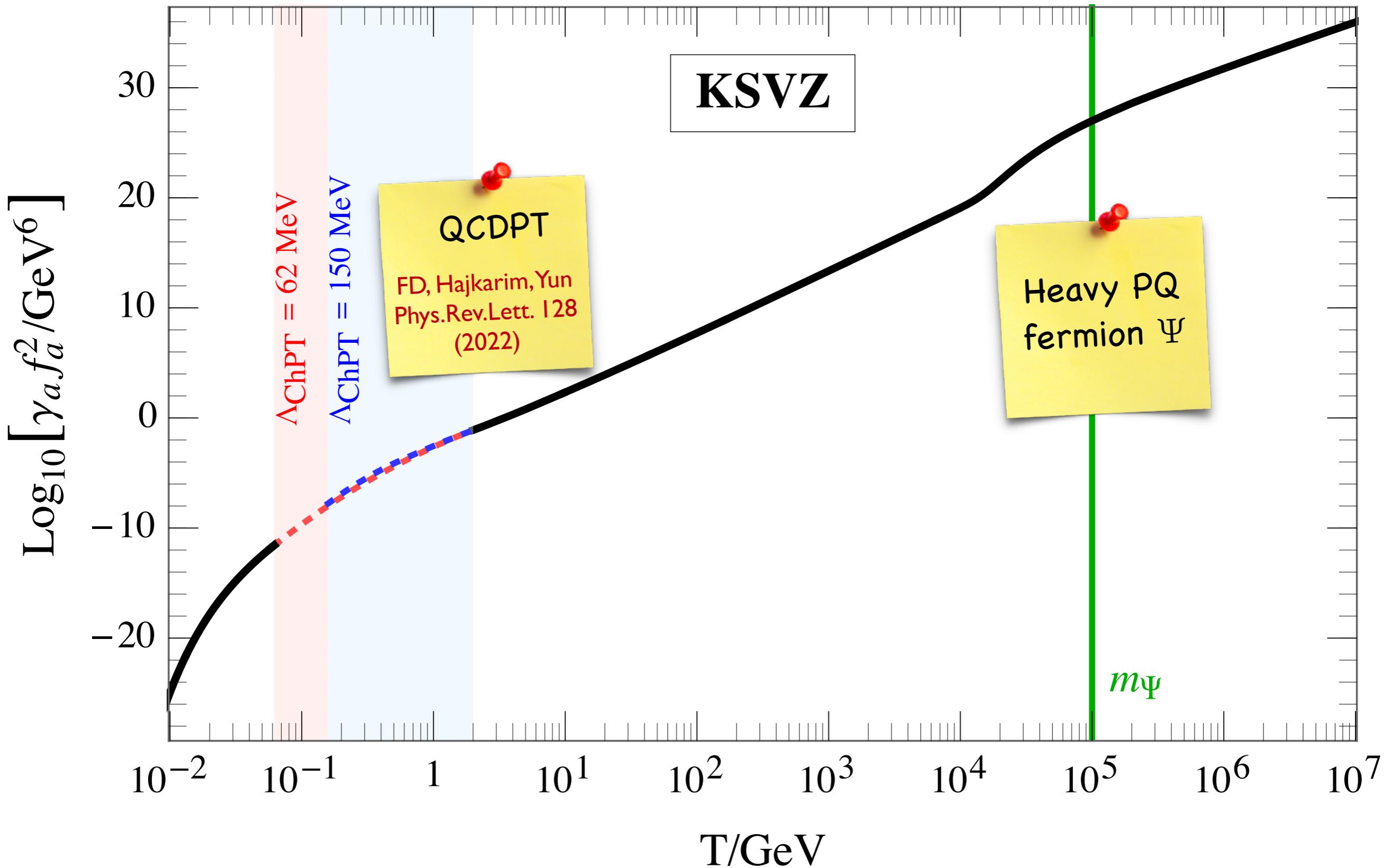
Energy

$$(\partial^\mu \varphi)^\dagger \partial_\mu \varphi + \bar{\Psi} i \not{D} \Psi - \lambda_\varphi \left( |\varphi|^2 - v_\varphi^2 / 2 \right)^2 - (y_\Psi \varphi^\dagger \bar{\Psi}_L \Psi_R + \text{h.c.})$$

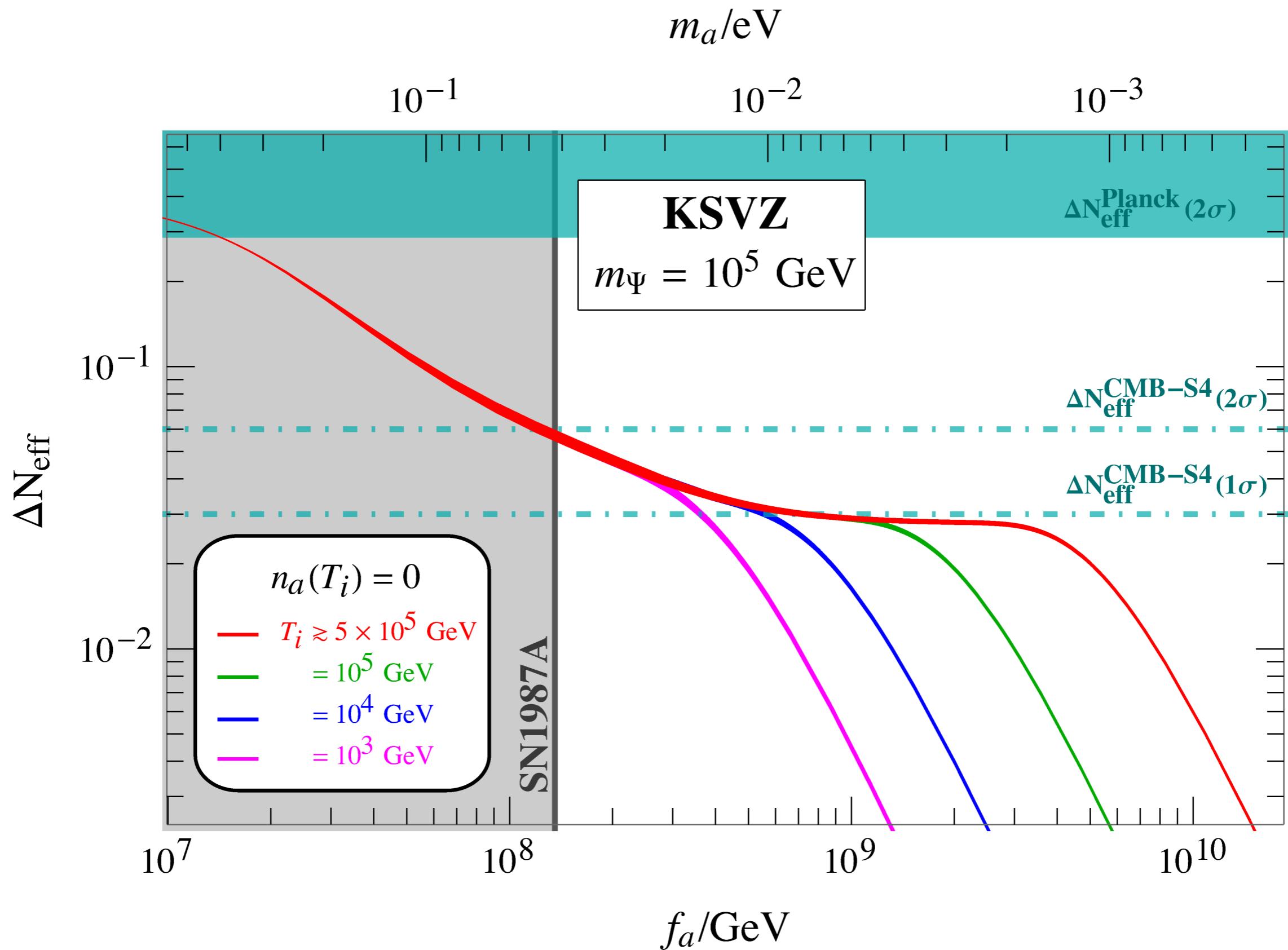
$$\frac{1}{2} \partial^\mu a \partial_\mu a + \bar{\Psi} i \not{D} \Psi - [m_\Psi e^{-ia/v_\varphi} \bar{\Psi}_L \Psi_R + \text{h.c.}]$$

$$\frac{1}{2} \partial^\mu a \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{v_\varphi} G_{\mu\nu}^A \tilde{G}^{A\mu\nu}$$

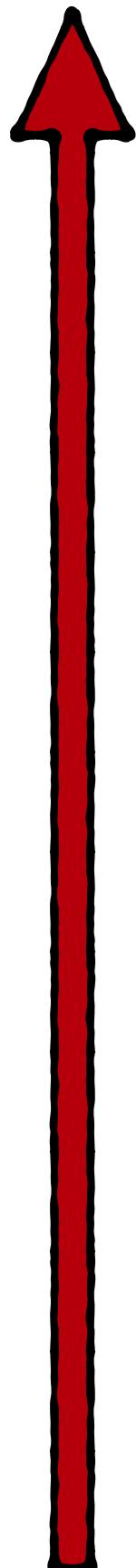
# KSVZ Axion – Production Rate



# KSVZ Axion – $\Delta N_{\text{eff}}$



# DFSZ Axion – Theory



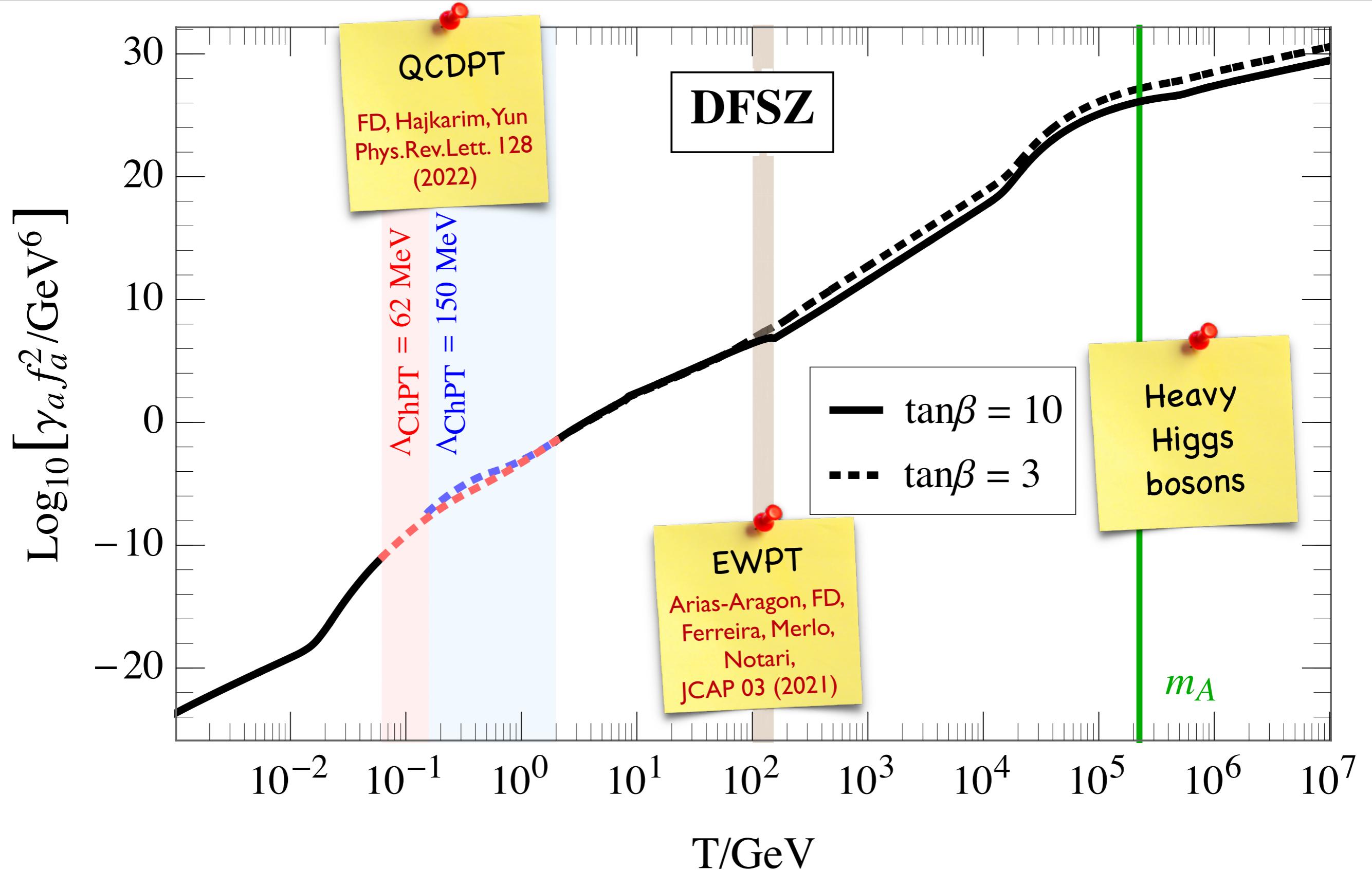
Energy

$$B \left( \frac{\varphi^\dagger}{v_\varphi / \sqrt{2}} \right)^r H_u^T i\sigma^2 H_d + \text{h.c.}$$

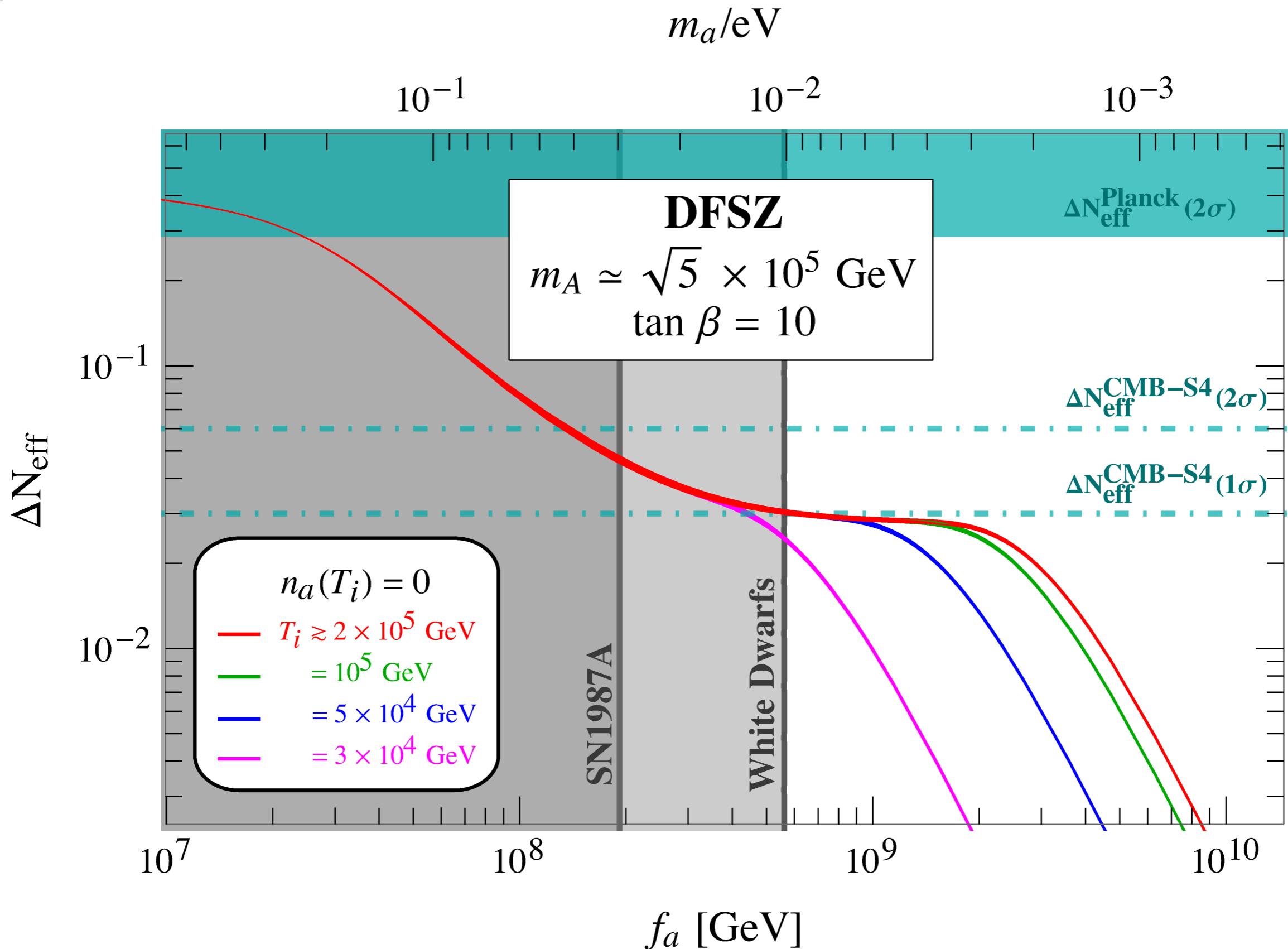
$$\frac{1}{2} \partial^\mu a \partial_\mu a - B \left[ e^{-i \frac{N_{\text{DW}}}{3} \frac{a}{v_\varphi}} H_u^T i\sigma^2 H_d + \text{h.c.} \right]$$

$$\begin{aligned} & \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{\partial_\mu a}{v_\varphi} \left[ \sum_f q_f \bar{f} \gamma^\mu f + \sum_\alpha q_{H_\alpha} H_\alpha^\dagger i \overleftrightarrow{D}^\mu H_\alpha \right] \\ & + \frac{a}{v_\varphi} \left[ N_{\text{DW}} \frac{g_s^2}{32\pi^2} G_{\mu\nu}^A \tilde{G}^{A\mu\nu} + c_W \frac{g^2}{32\pi^2} W_{\mu\nu}^I \widetilde{W}^{I\mu\nu} + c_Y \frac{g'^2}{32\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} \right] \end{aligned}$$

# DFSZ Axion – Production Rate

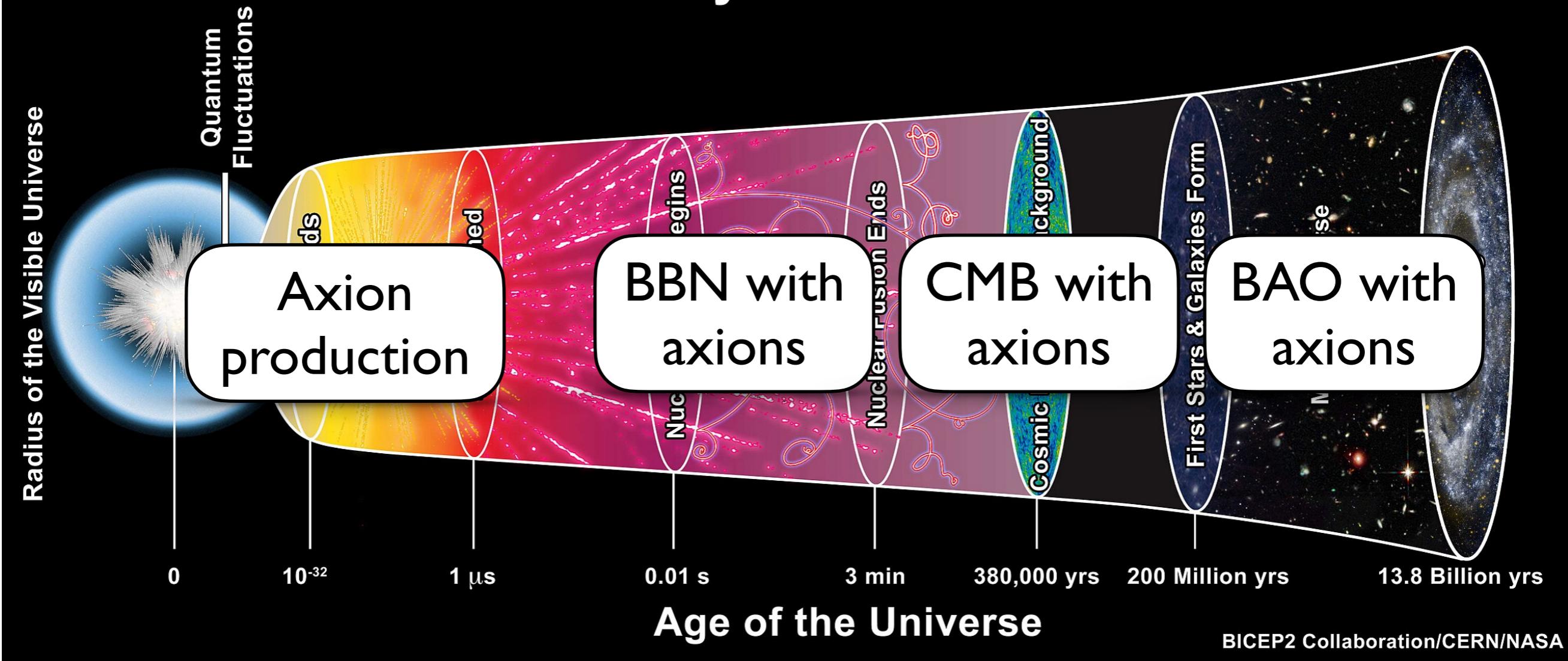


# DFSZ Axion – $\Delta N_{\text{eff}}$



# QCD Axion Mass Bound

## History of the Universe



**KSVZ**

$$m_a \leq 0.282(0.420) \text{ eV}$$

**DFSZ**

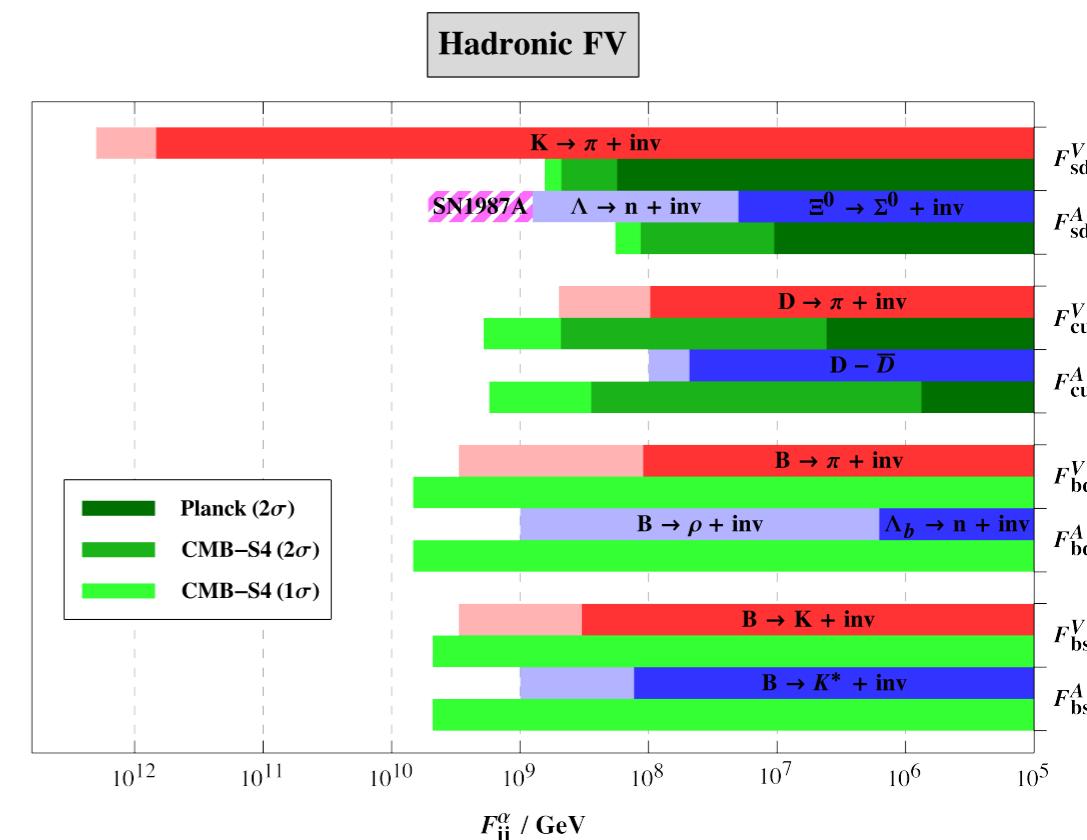
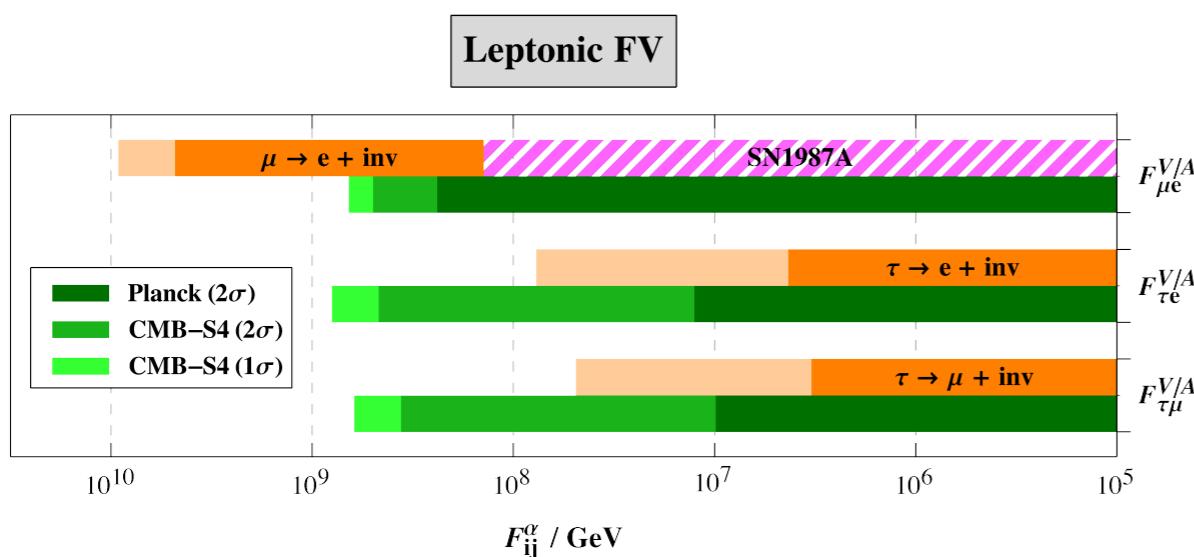
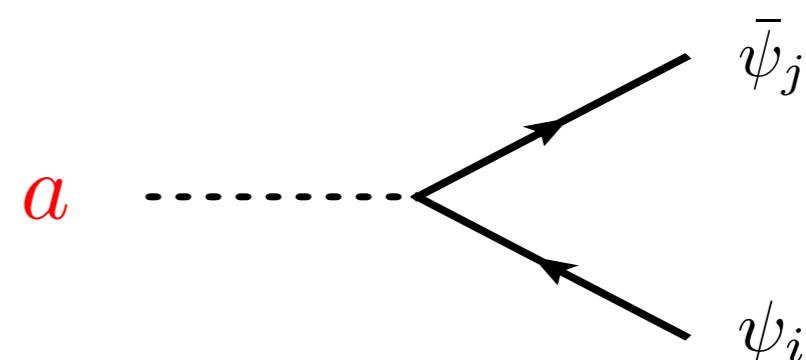
$$m_a \leq 0.209(0.293) \text{ eV}$$

# Flavor Violating Axions

Target of several terrestrial experiments

What about their role in the early universe?

$$\mathcal{L}_{\text{FV}}^{(a)} = \frac{\partial_\mu a}{2f_a} \sum_{\psi_i \neq \psi_j} \bar{\psi}_i \gamma^\mu \left( c_{\psi_i \psi_j}^V + c_{\psi_i \psi_j}^A \gamma^5 \right) \psi_j$$



Current and future cosmological bounds competitive (or sometimes even better!) than terrestrial searches

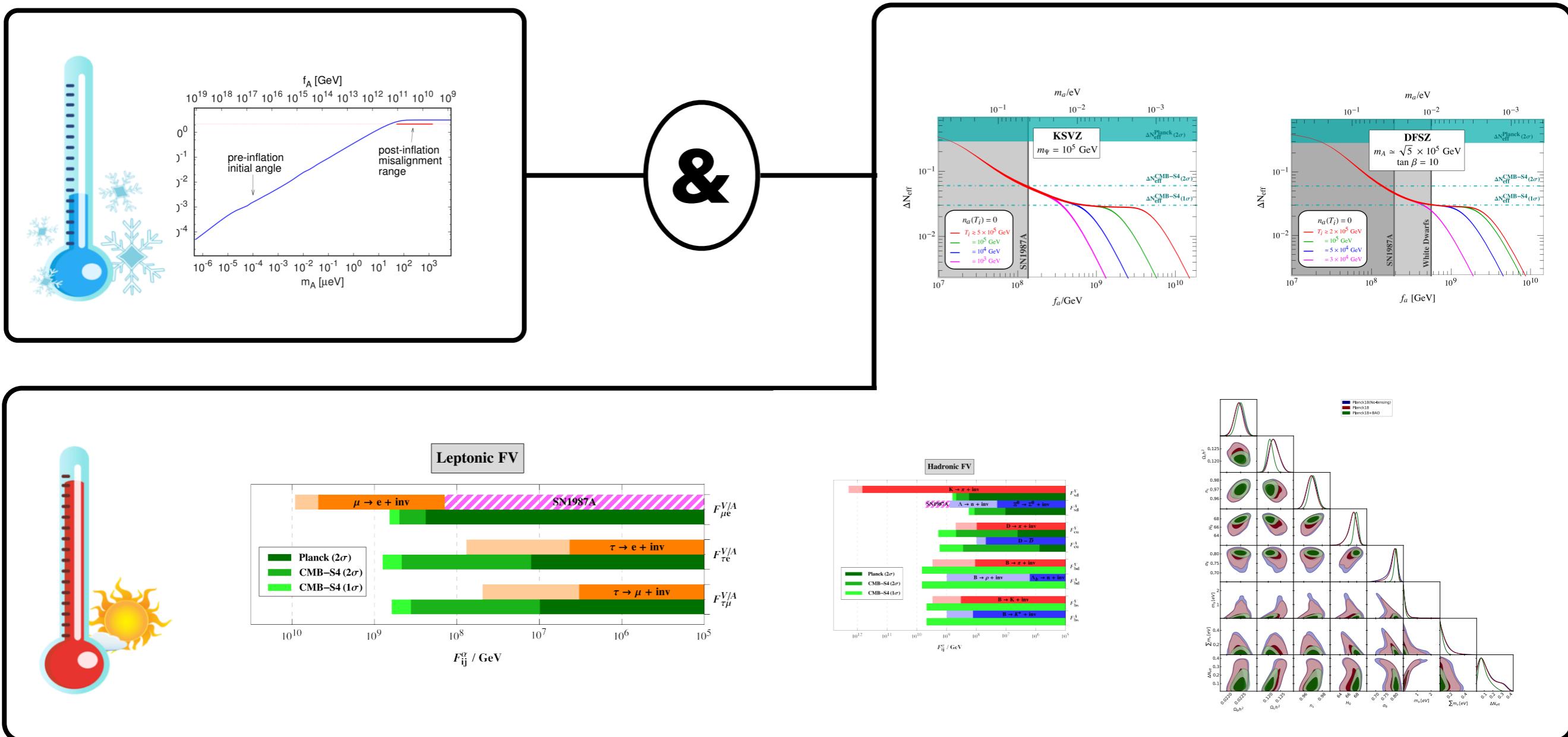
# Outlook



## Peccei-Quinn Mechanism and the QCD Axion

Motivated and testable scenario  
for physics beyond the standard model  
rich of cosmological consequences

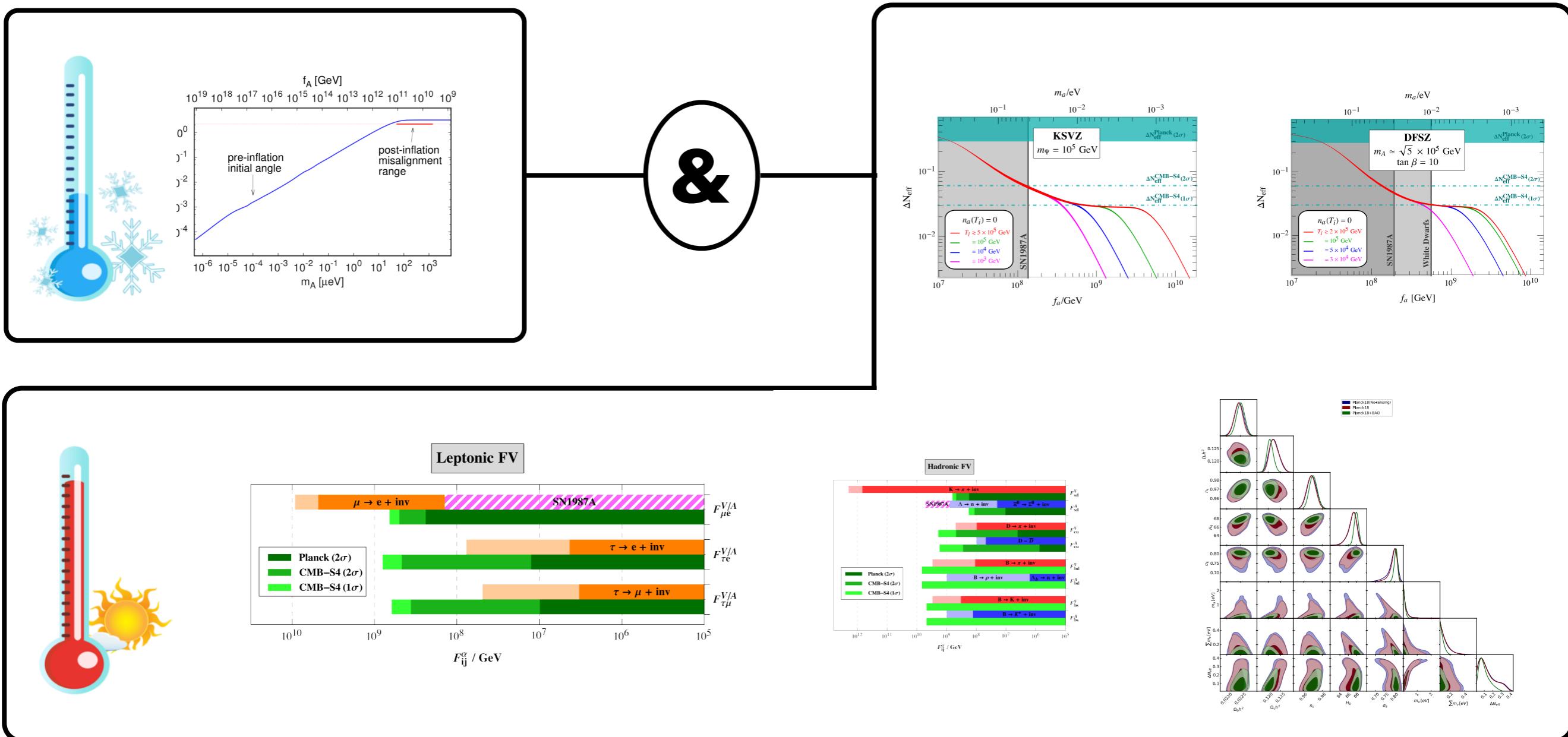
# Outlook



## Thermal Axions

Complementary to other probes of the PQ mechanism

# Outlook



THANK YOU!