Axions in the Early Universe

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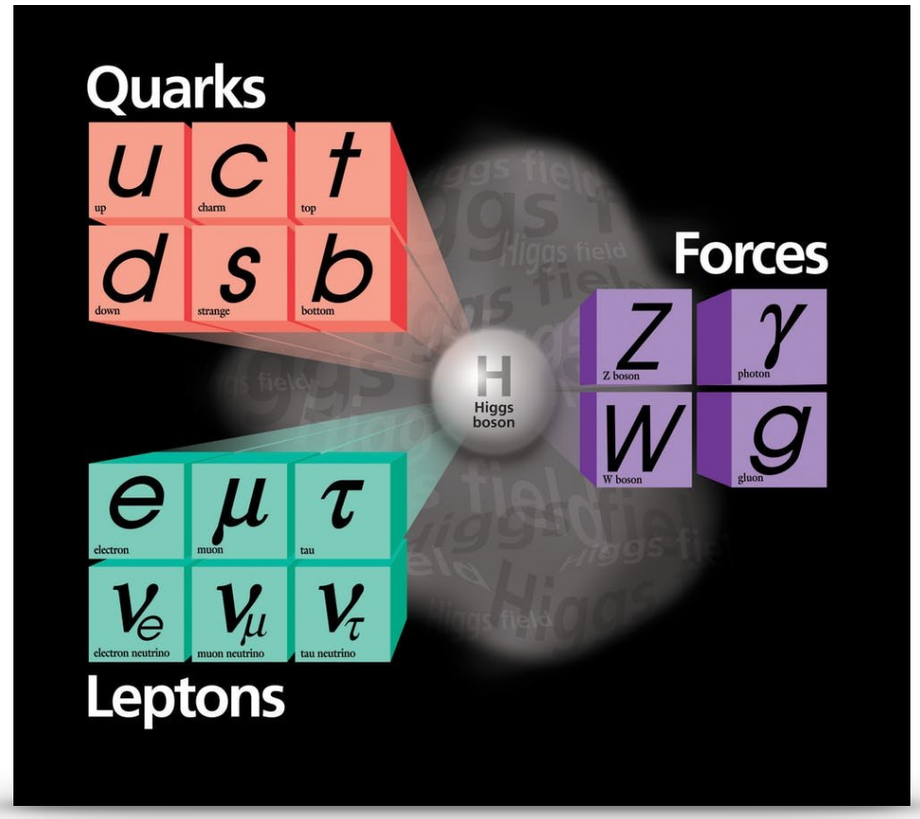
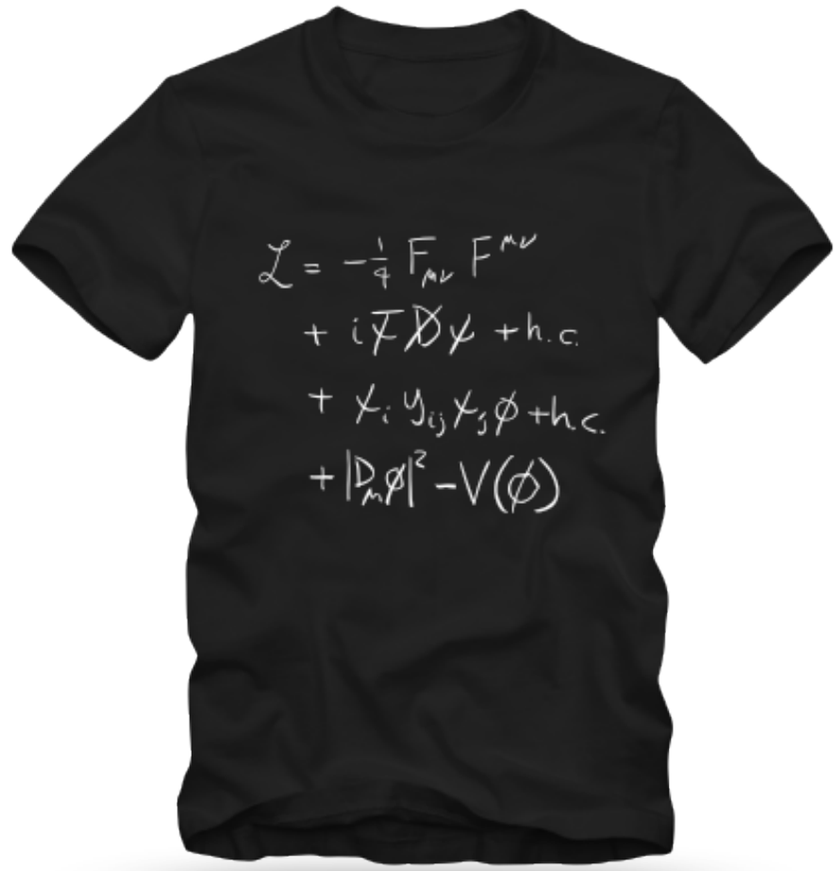
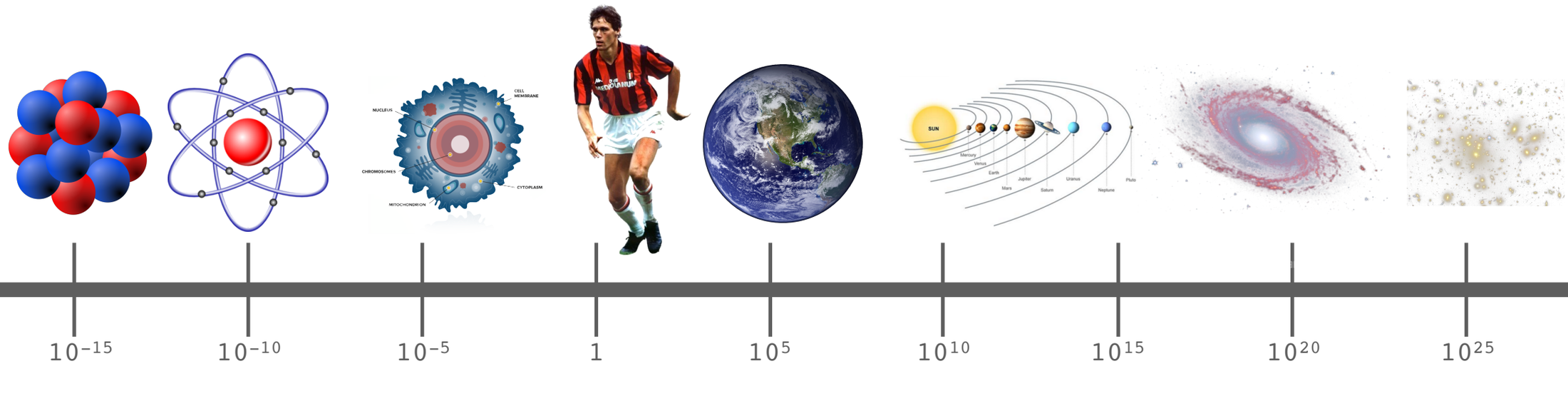
Sezione di Padova

DarkCosmoGrav: New Frontiers in Particle Physics, Gravity, and Cosmology
University of Pisa — 25 January 2023

The Standard Model



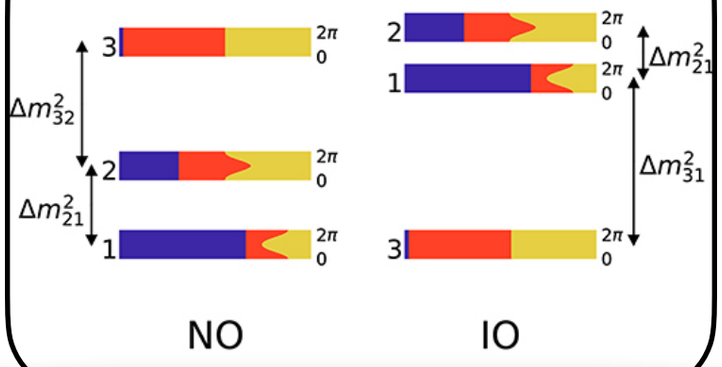




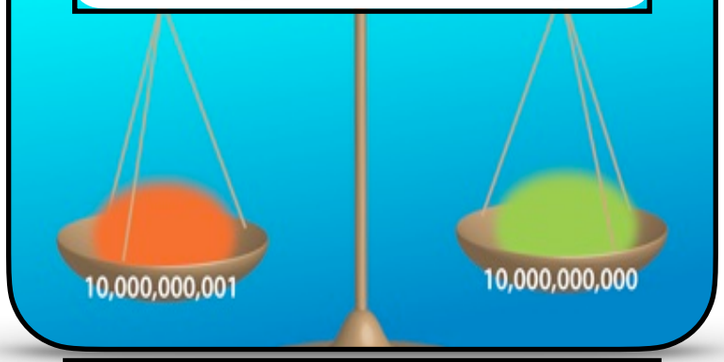
Still Unanswered Questions...

Dark Matter

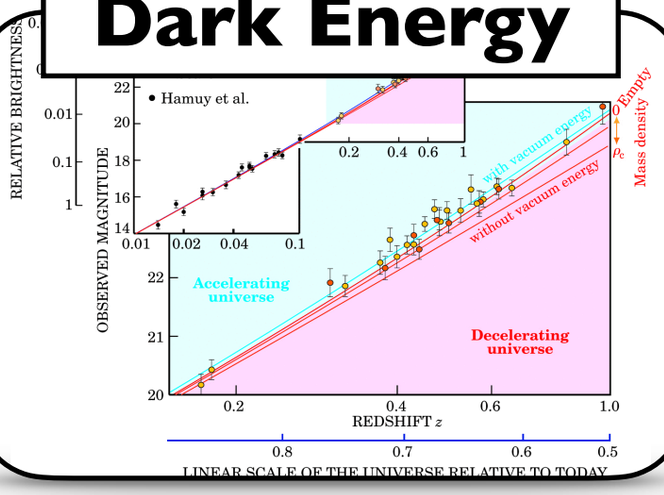
Neutrino Mass



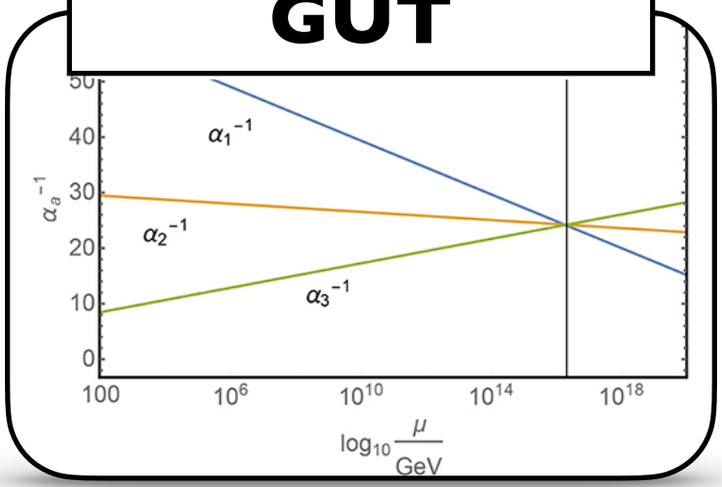
Baryon Asymmetry



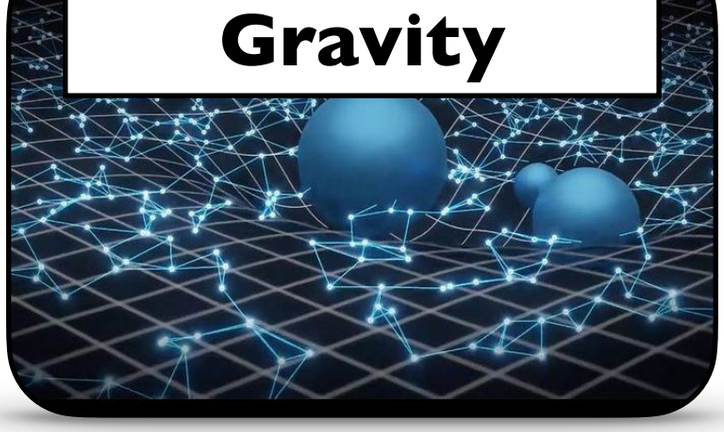
Dark Energy



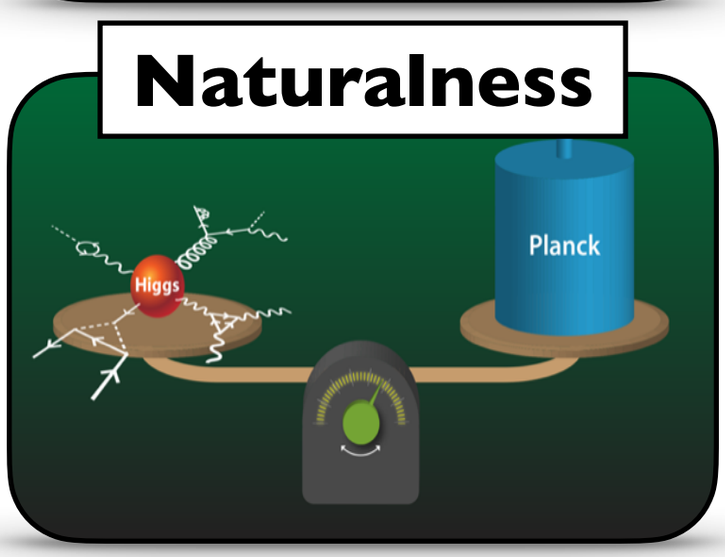
GUT



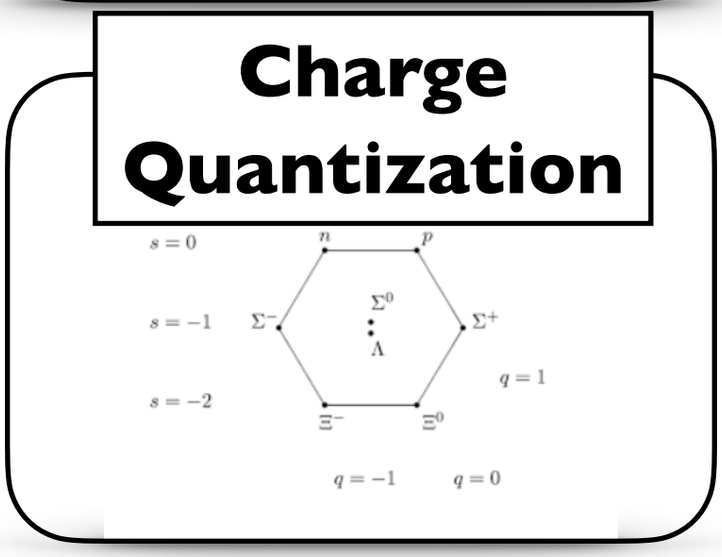
Quantum Gravity



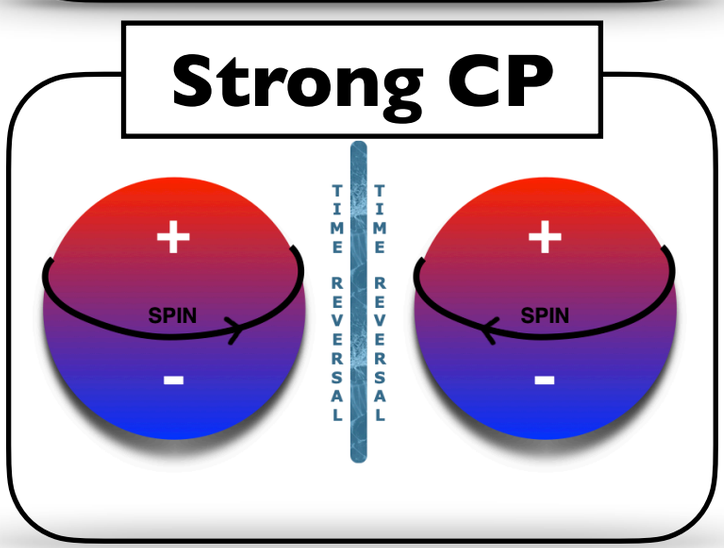
Naturalness



Charge Quantization



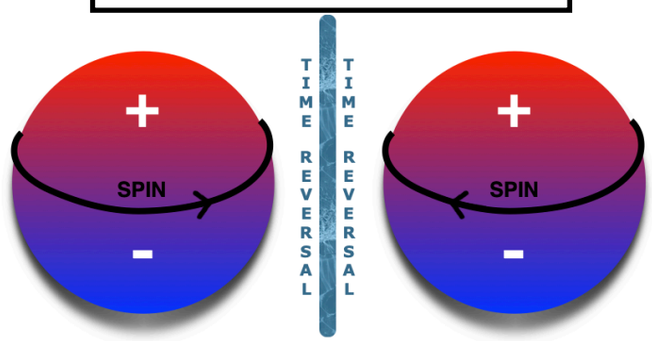
Strong CP



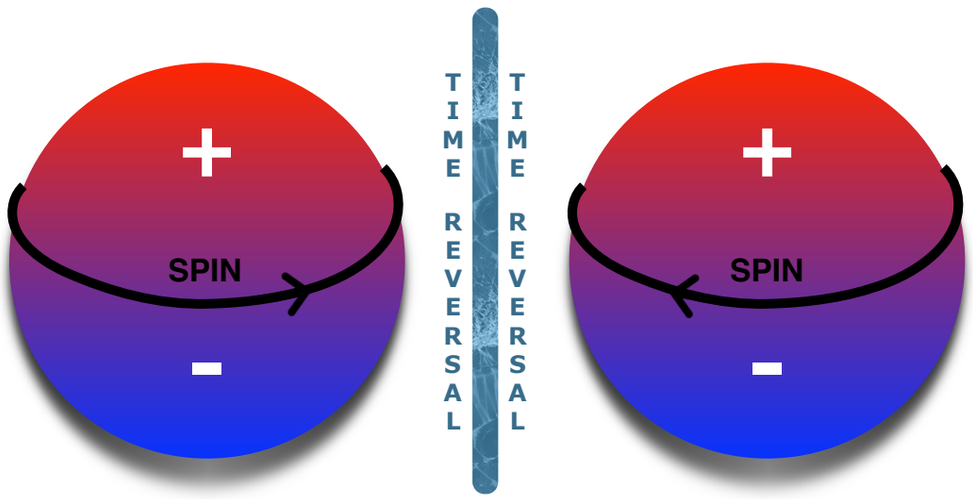
QCD Axion: 2 Birds with 1 Stone

Dark Matter

Strong CP



The Strong CP Problem



No detection of time reversal invariance violation by strong interactions

VS

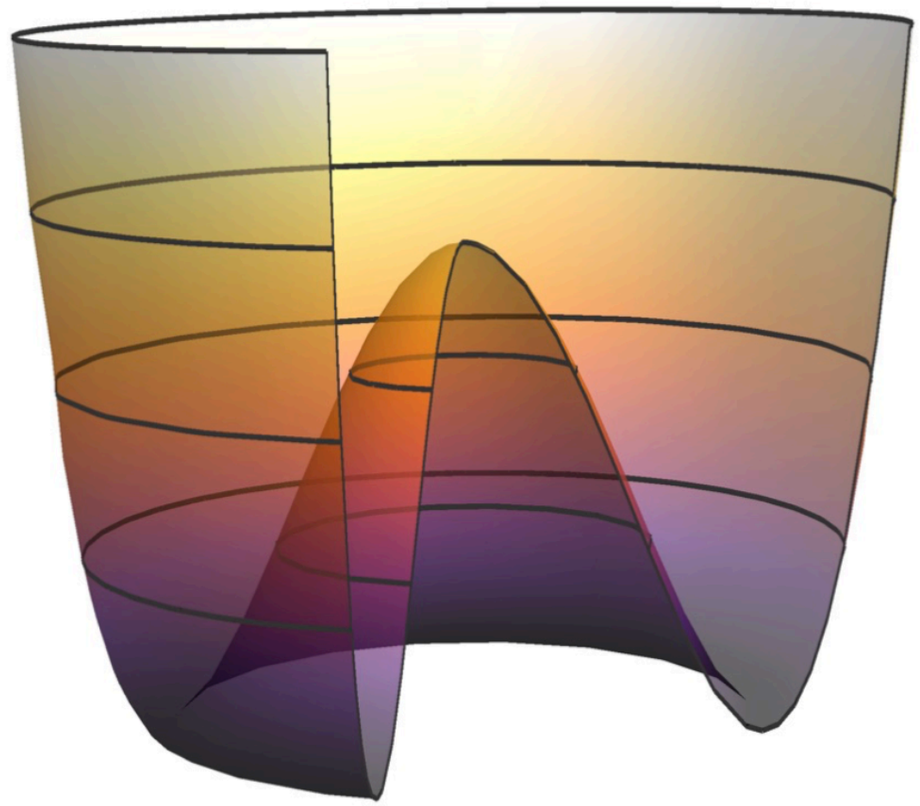
Why is the θ parameter of the QCD Lagrangian so small?

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

The Peccei-Quinn Mechanism

Dynamical solution to the strong CP problem

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



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

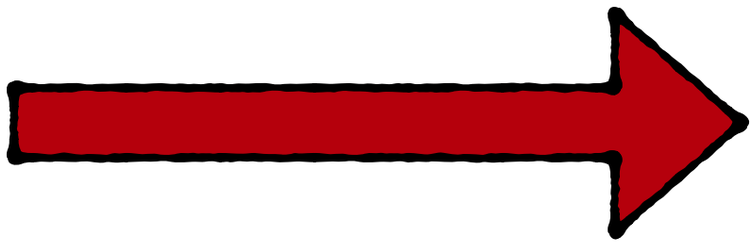
Peccei, Quinn, Phys.Rev.Lett. 38 (1977) and Phys.Rev.D 16 (1977)

The Peccei-Quinn Mechanism

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

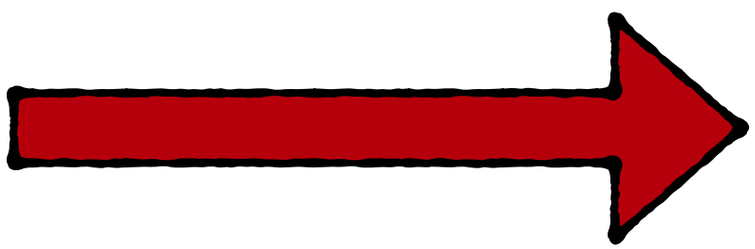
Pseudo Nambu-Goldstone boson in the low-energy spectrum ("QCD axion") with ("anomalous") coupling to gluons

The Peccei-Quinn Mechanism



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

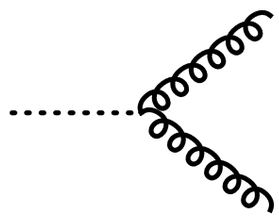
CP-conserving minimum!
Strong CP Problem Solved!



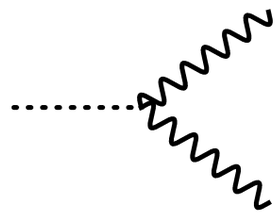
$$V(a) \simeq \frac{1}{2}m_a^2 a^2$$

The QCD Axion

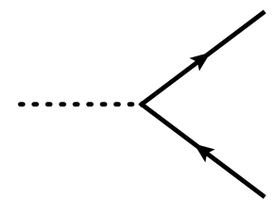
- Coupling to gluons and (not mandatory) to electroweak gauge bosons
- Derivative couplings to fermions



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



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



$$c_\psi\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$

The QCD axion is <u>elusive</u>!

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

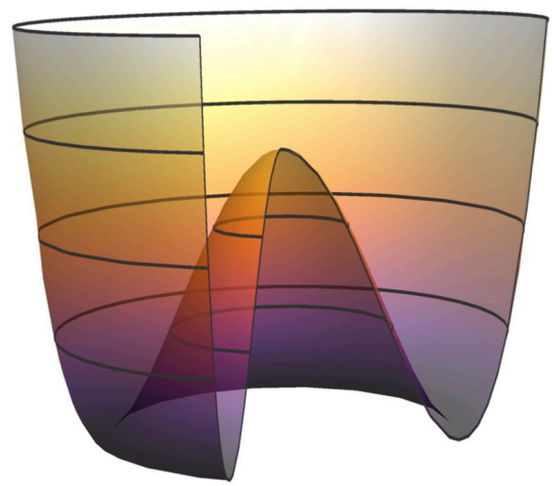
$$m_a \simeq 5.7\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)\,\mu\text{eV}$$

The QCD axion is <u>very light</u>!

Georgi, Kaplan, Randall, PLB169 (1986)

Axion-Like-Particles (ALPs)

Ubiquitous in motivated
extension of the Standard Model

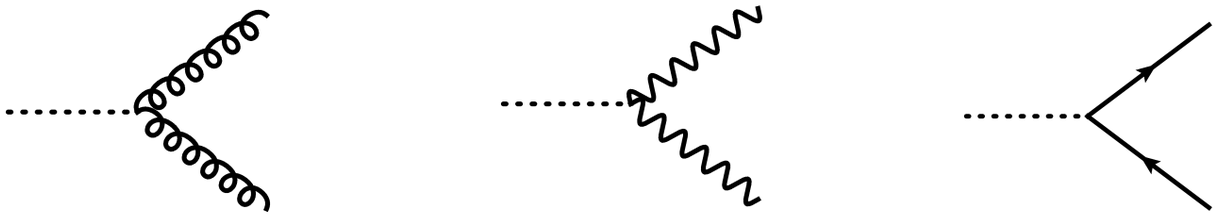


- Pseudo-Nambu-Goldstone-bosons in field theory
- Axions in string theory

$$m_a \simeq \frac{\Lambda^2}{f_a}$$

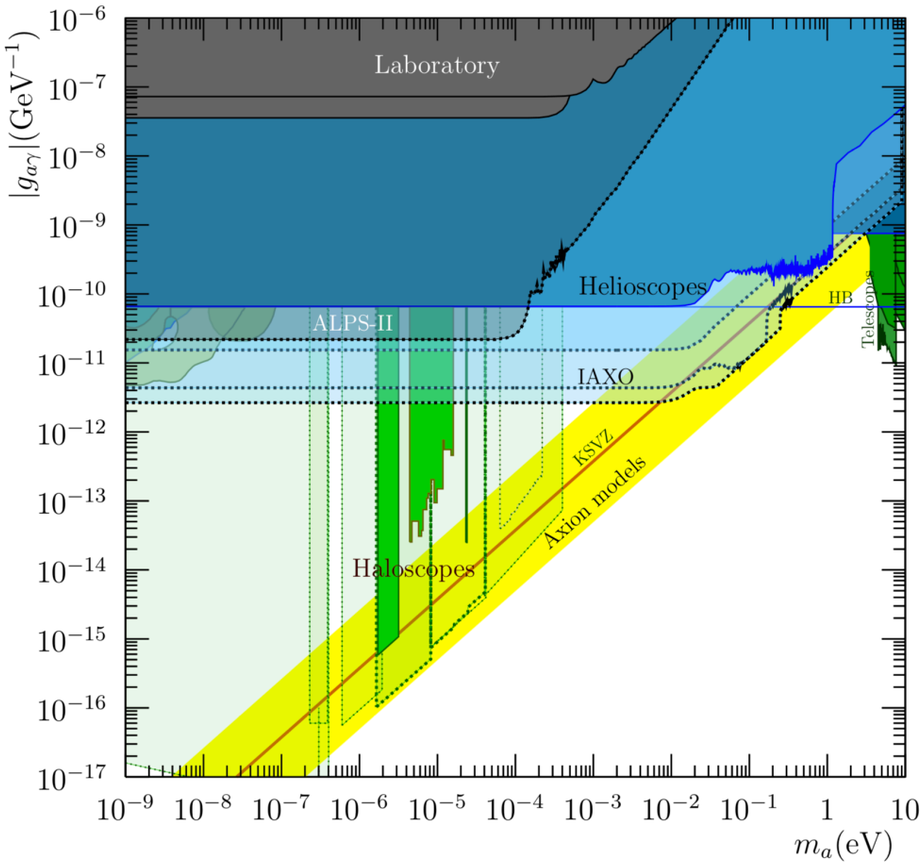
$$\mathcal{L}_{\rm int} = c_X \frac{a}{f_a} \frac{\alpha_X}{8\pi} X^{\mu\nu} \tilde{X}_{\mu\nu} + c_\psi \frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$$

Axion Signals



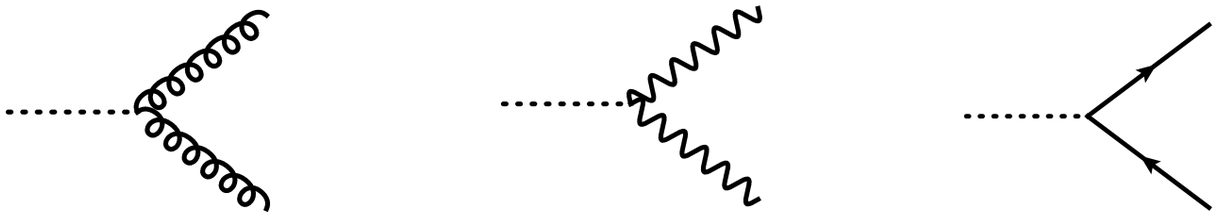
Very light and weakly coupled:

- detection challenging
- prominent role in the early universe



Irastorza and Redondo, Prog.Part.Nucl.Phys. 102 (2018)

Axion Signals



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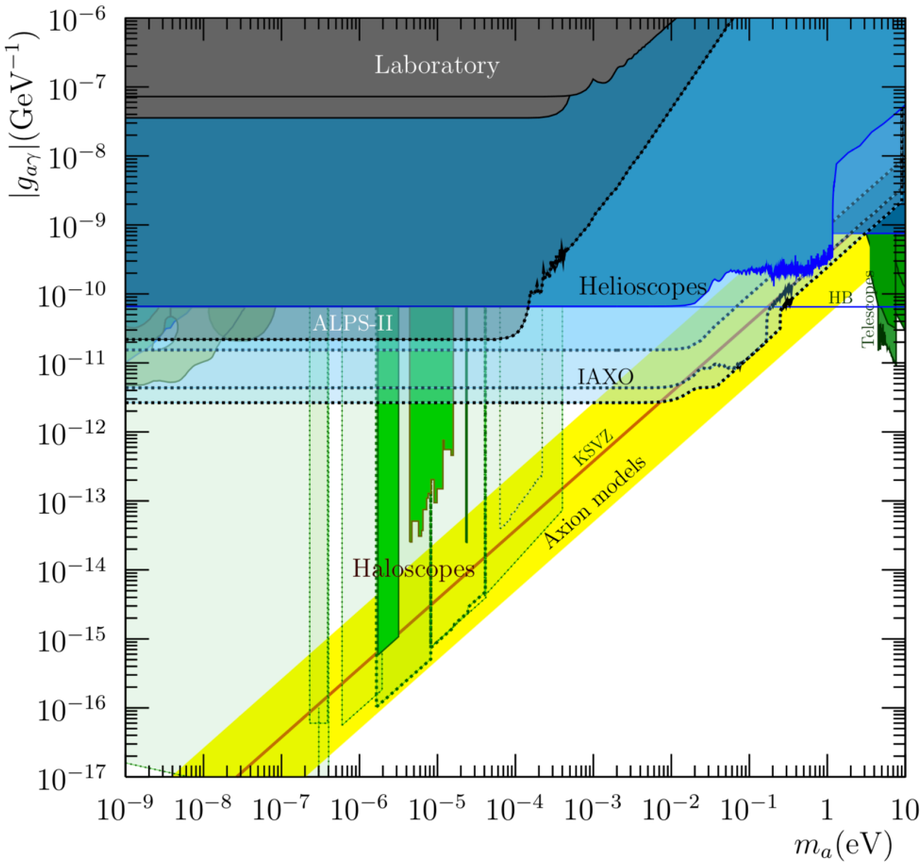
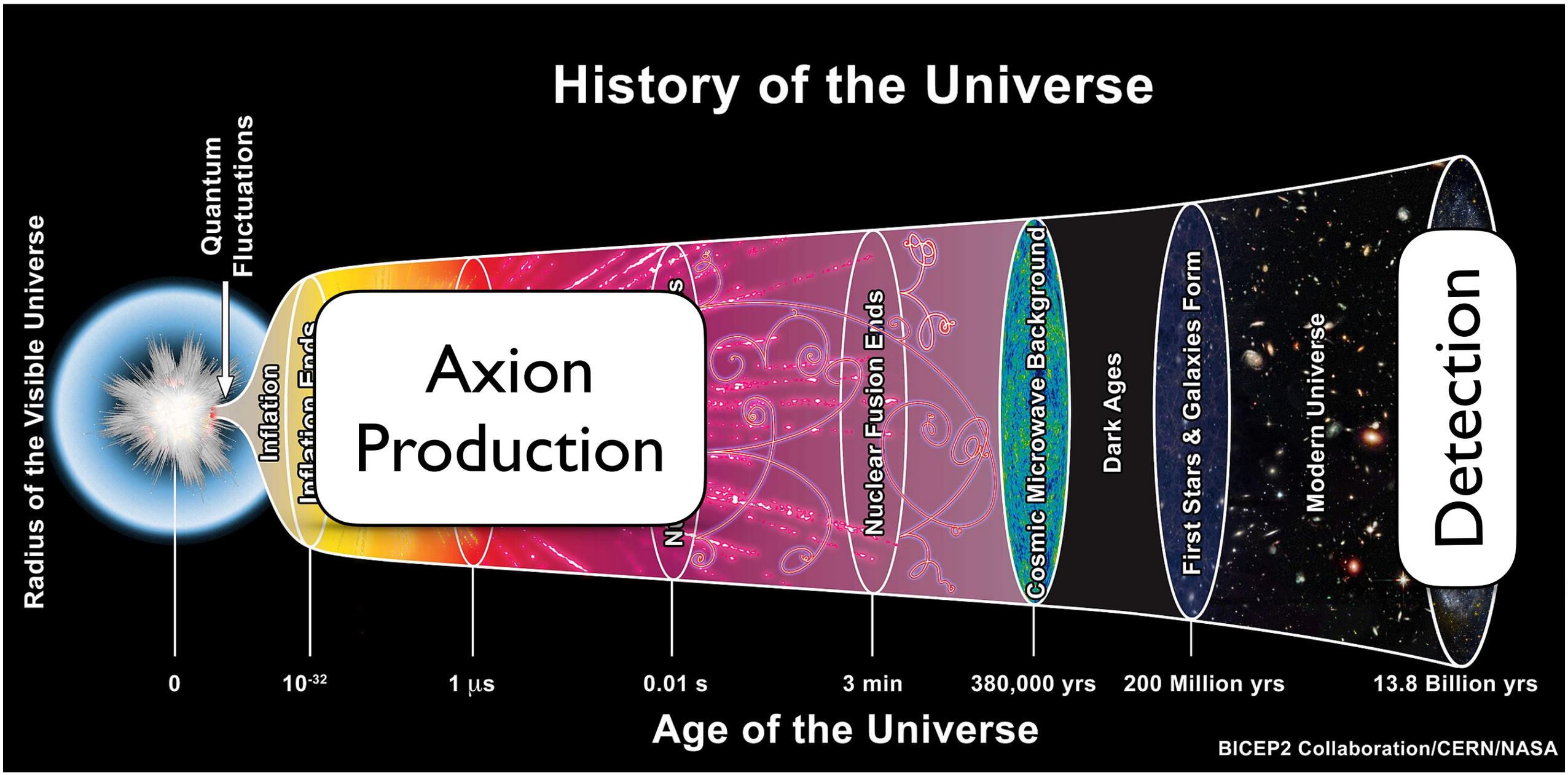


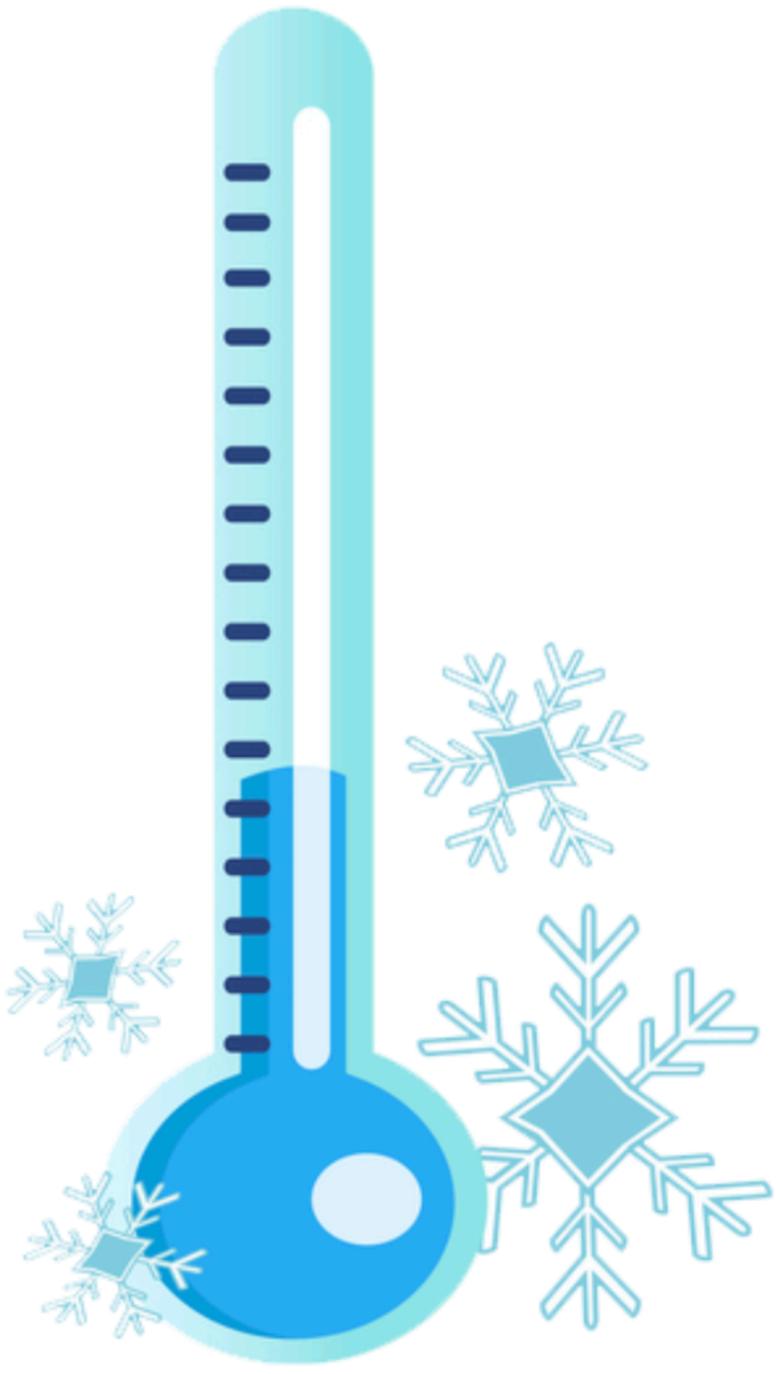
Irastorza and Redondo, Prog.Part.Nucl.Phys. 102 (2018)

In this talk:

Axions in the early universe

Axions in the Early Universe



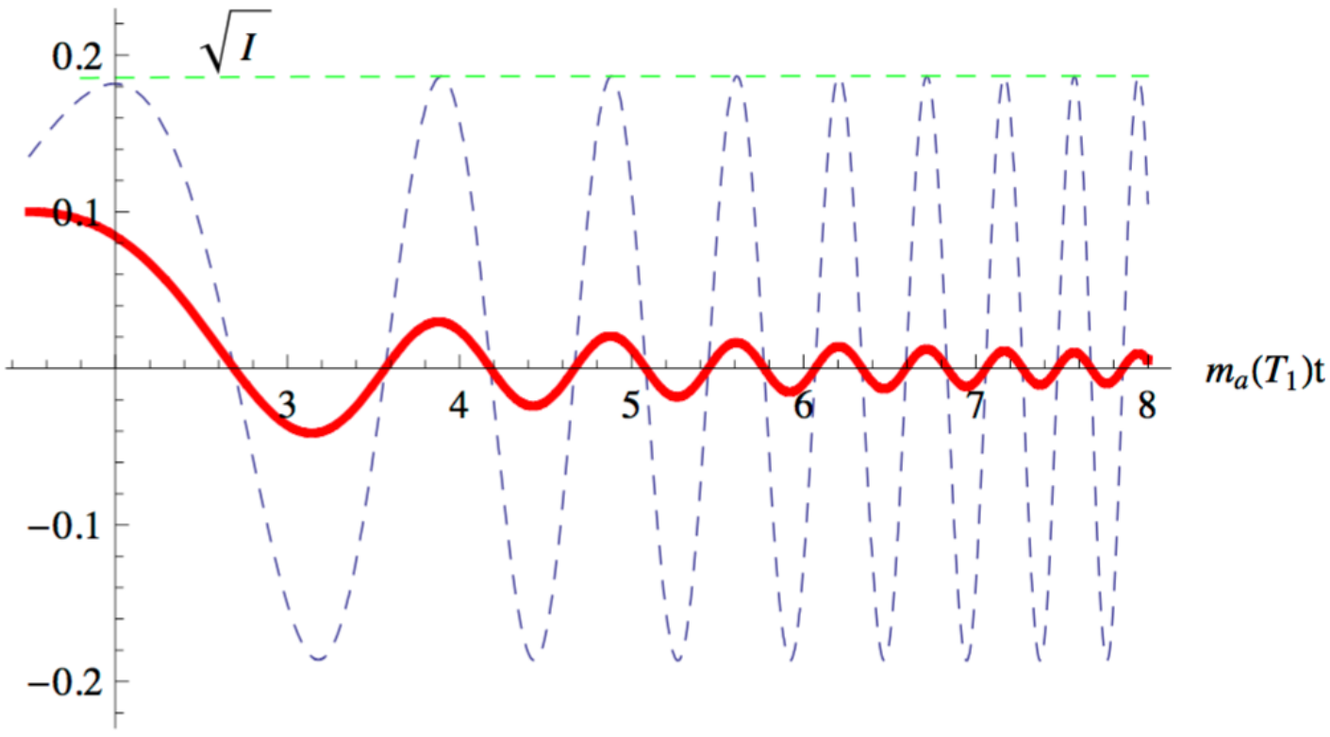


Cold Axions

(Dark Matter)

Axion Misalignment

$\theta \equiv a/f$



Misalignment

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

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

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

Bae, Huh, Kim, JCAP 0809 (2008)

Axion Misalignment

See talk by **Lingxiao Xu** in this session for a possible variation

"Axion Free-kick Misalignment Mechanism"

Misalignment

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

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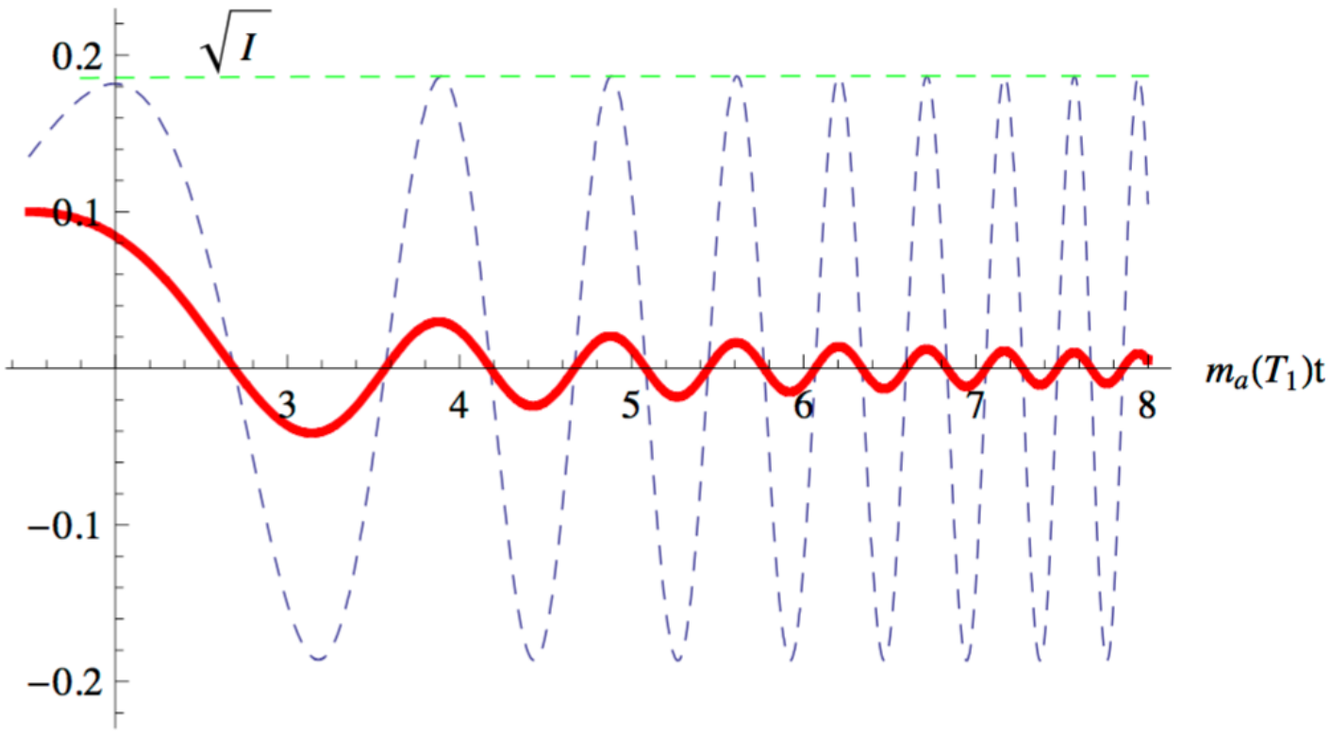

Misalignment

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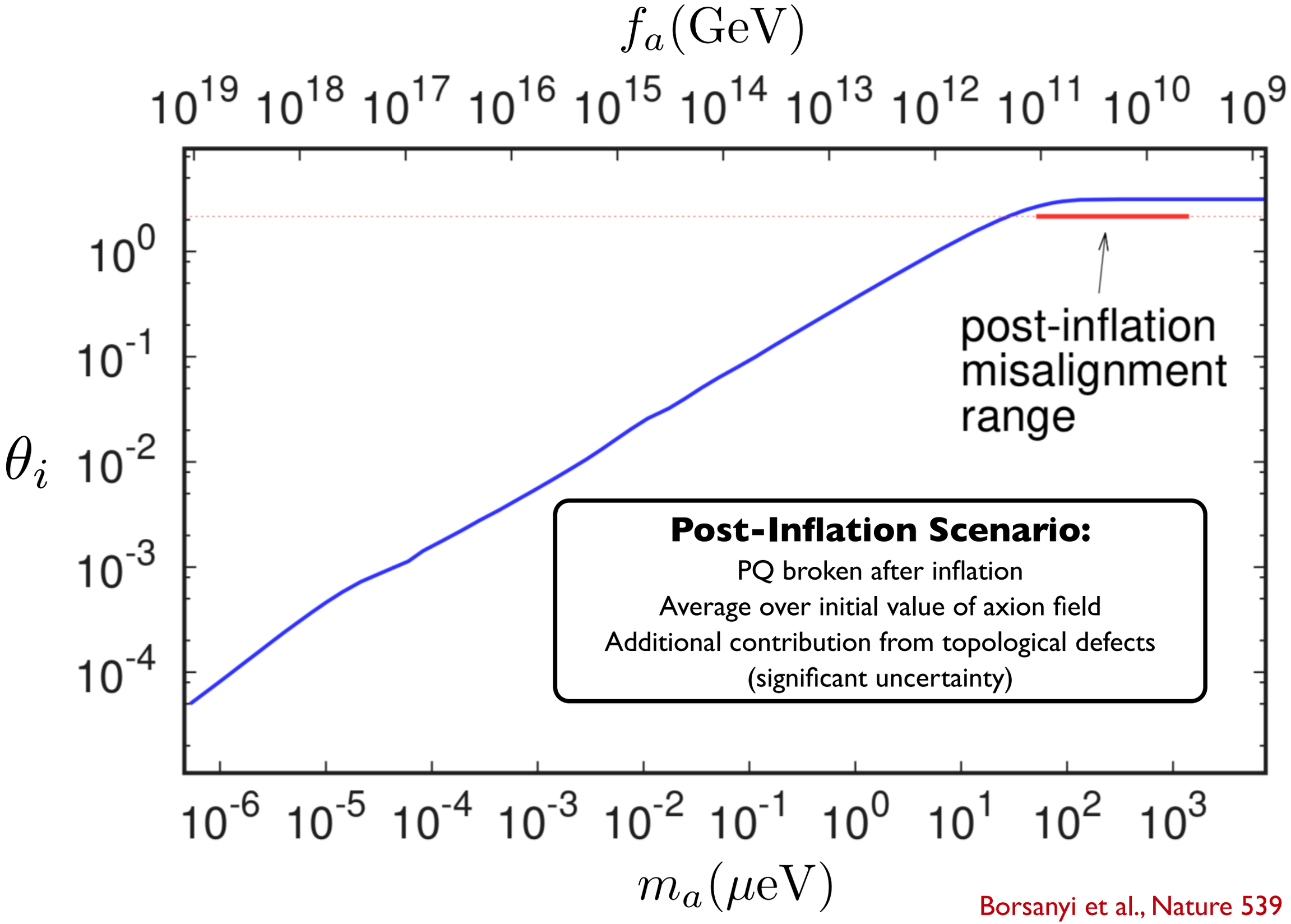
Axion initial field value? It depends…

Was PQ broken during inflation?

If yes, was it restored afterwards?

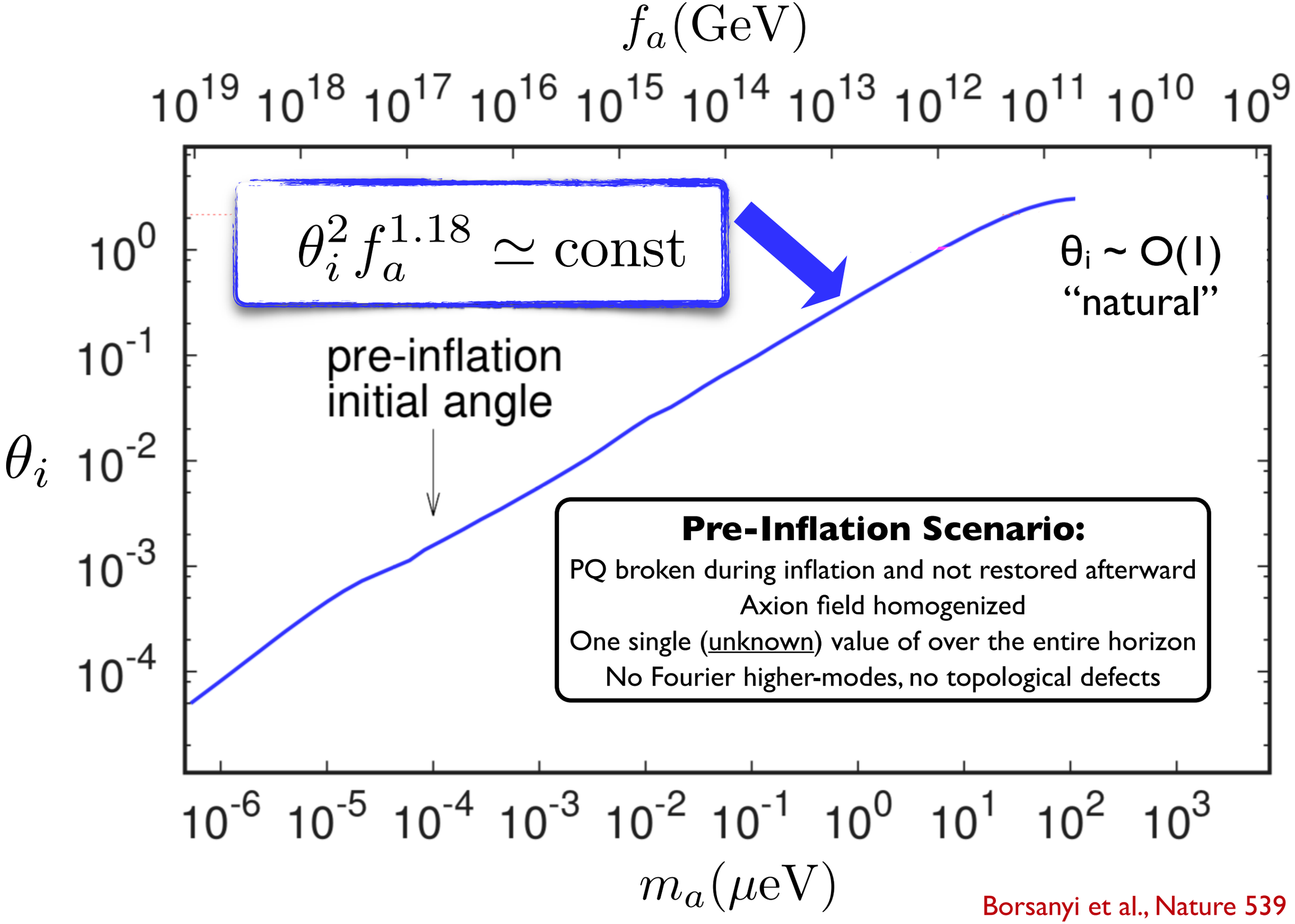
Bae, Huh, Kim, JCAP 0809 (2008)

Post-Inflation Scenario



Borsanyi et al., Nature 539 (2016)

Pre-Inflation Scenario



Pre-Inflation Scenario:

PQ broken during inflation and not restored afterward

Axion field homogenized

One single (unknown) value of over the entire horizon

No Fourier higher-modes, no topological defects

Borsanyi et al., Nature 539 (2016)

QCD Axion Cold Dark Matter

Post-Inflation

Axion cold dark matter from strings

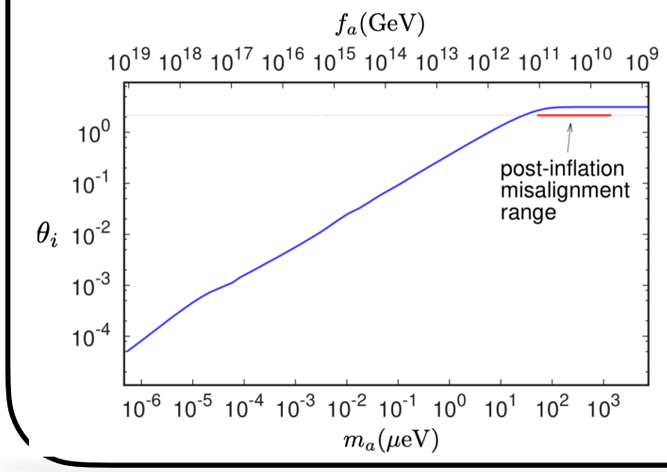
Klaer and Moore, JCAP 10 and JCAP 11 (2017)

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

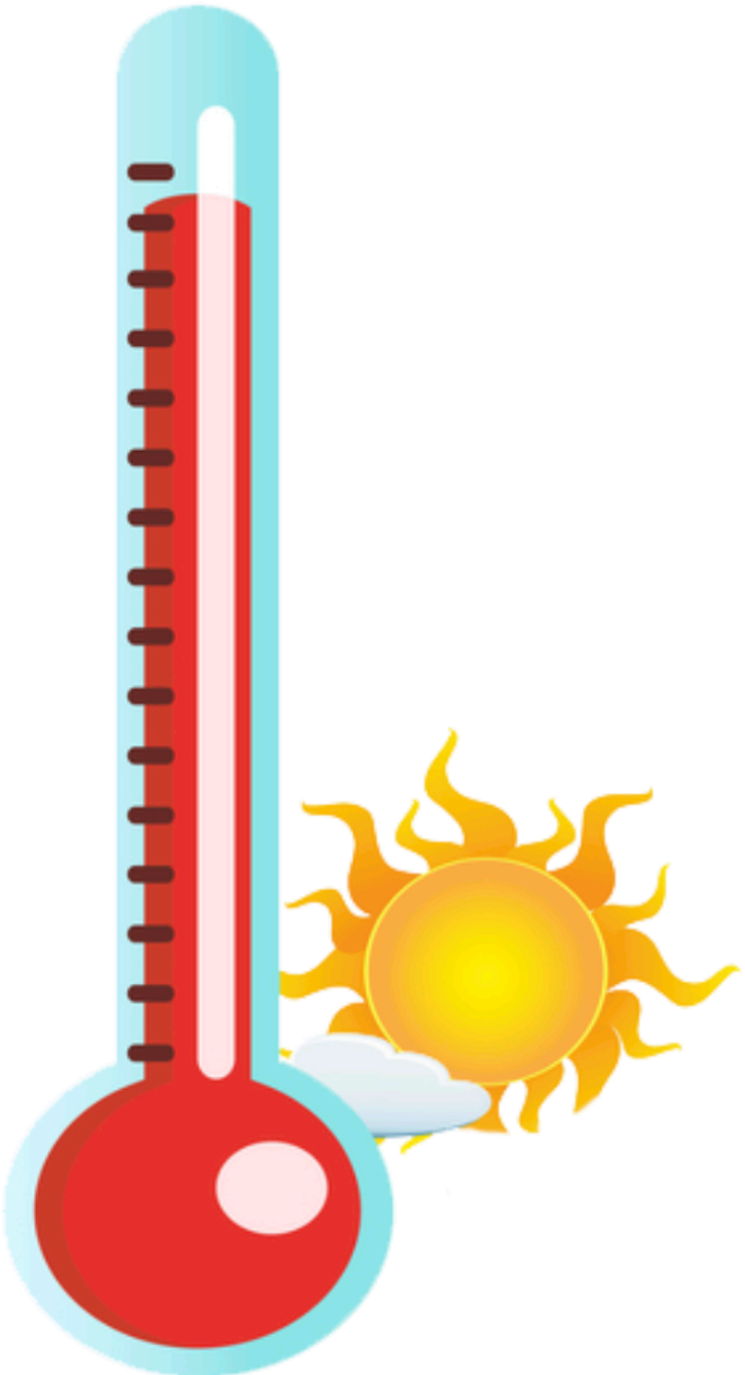


Borsanyi et al.,
Phys.Lett.B 752 (2016)
Nature 539 (2016)

Range for f_a (<u>with caveats</u>):

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

- 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")

$$B_1\, B_2 \;\rightarrow\; B_3\, a$$

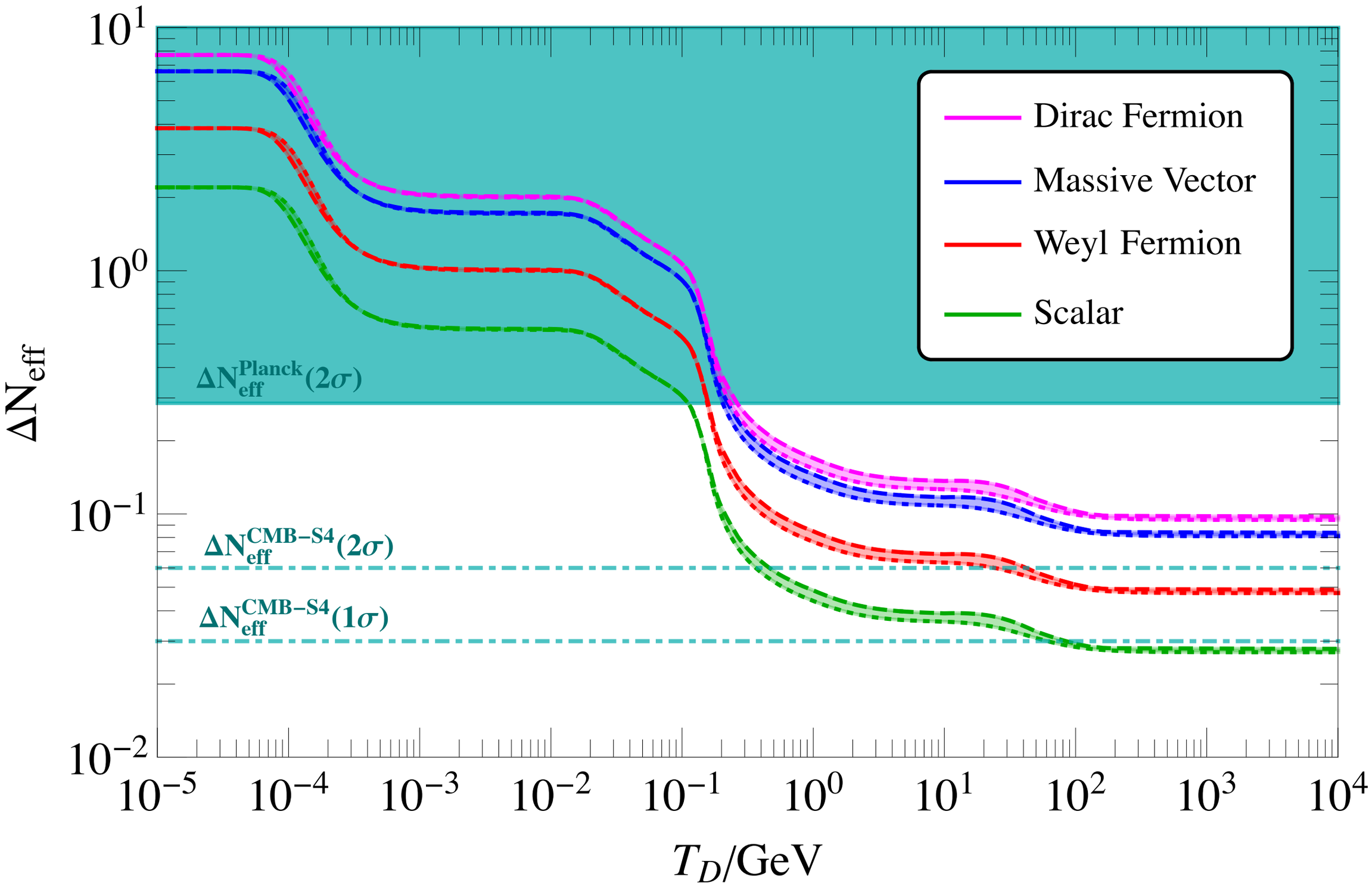
Additional radiation at:

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

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

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

Dark Radiation in the CMB

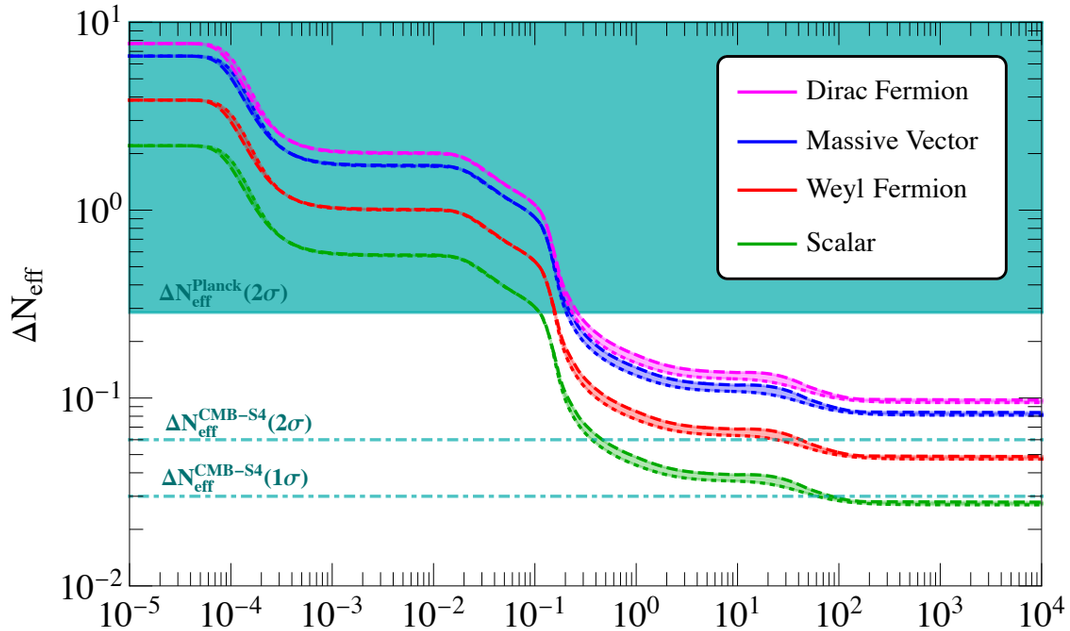


FD, Hajkarim, Yun, JHEP 10 (2021)

Predicting ΔN_{eff}

Axions may never thermalize

If they do, decoupling detail relevant
(effect larger the experimental error)



$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \gamma_\alpha$$

<u>GOAL</u>: compute the right-hand side that accounts for processes changing the number of axions

Scenarios for Thermal 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 at 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 Ψ

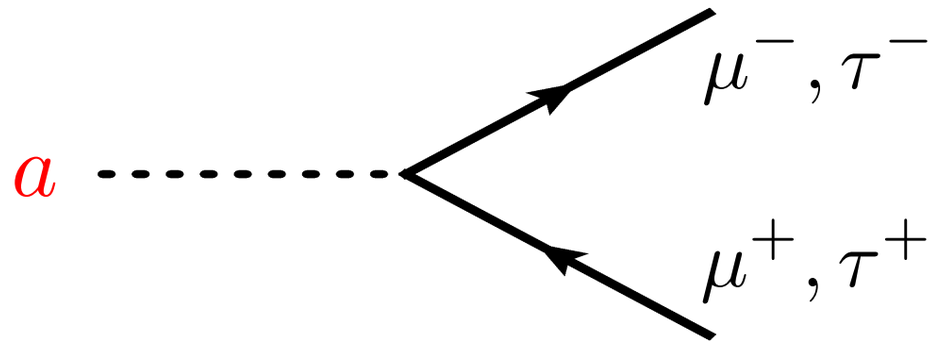
Kim, PRL 43 (1979)
Shifman, Vainshtein, Zakharov, NPB 166 (1980)

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

Zhitnitsky, SJNP 31 (1980)
Dine, Fischler, Srednicki, PLB 104 (1981)

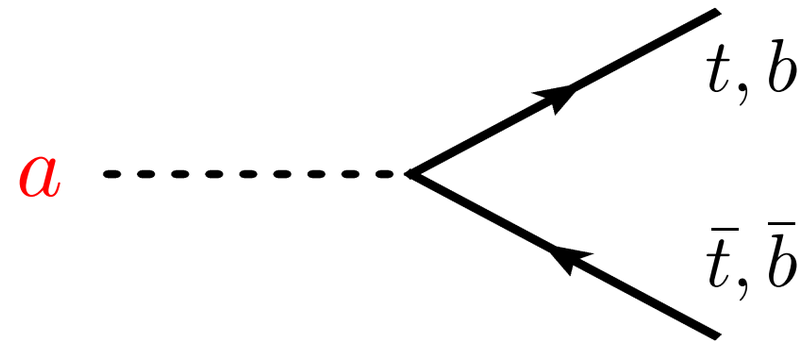
Single Coupling Switched On

Leptons



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

3rd Gen. Quarks



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

Single Coupling Switched On

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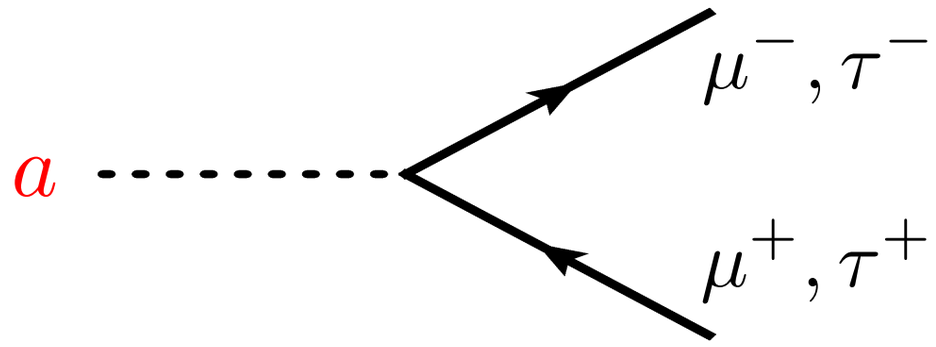

FD, Ferreira, Notari, Bernal, JCAP 1811 (2018)

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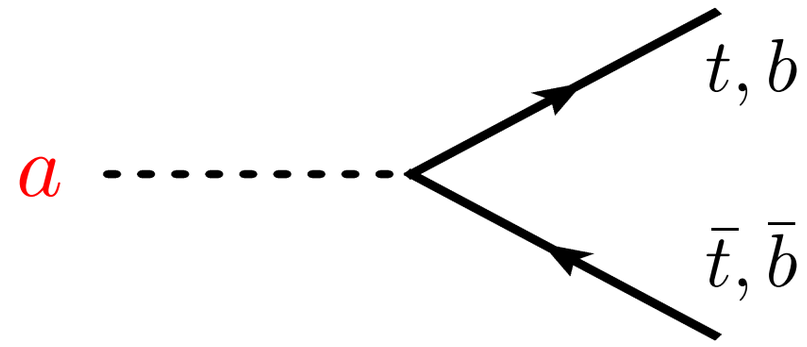
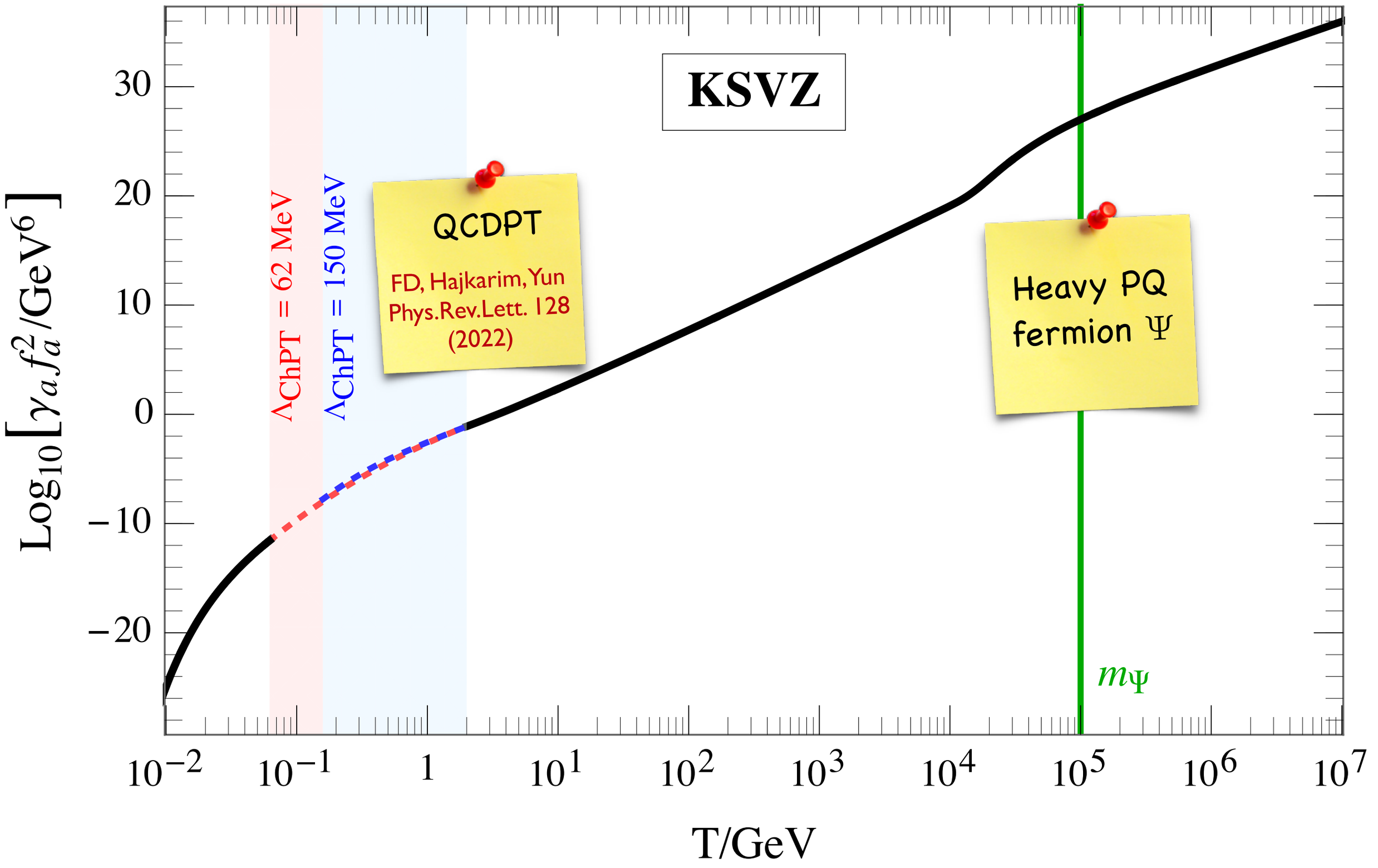


Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)

They can alleviate the Hubble tension

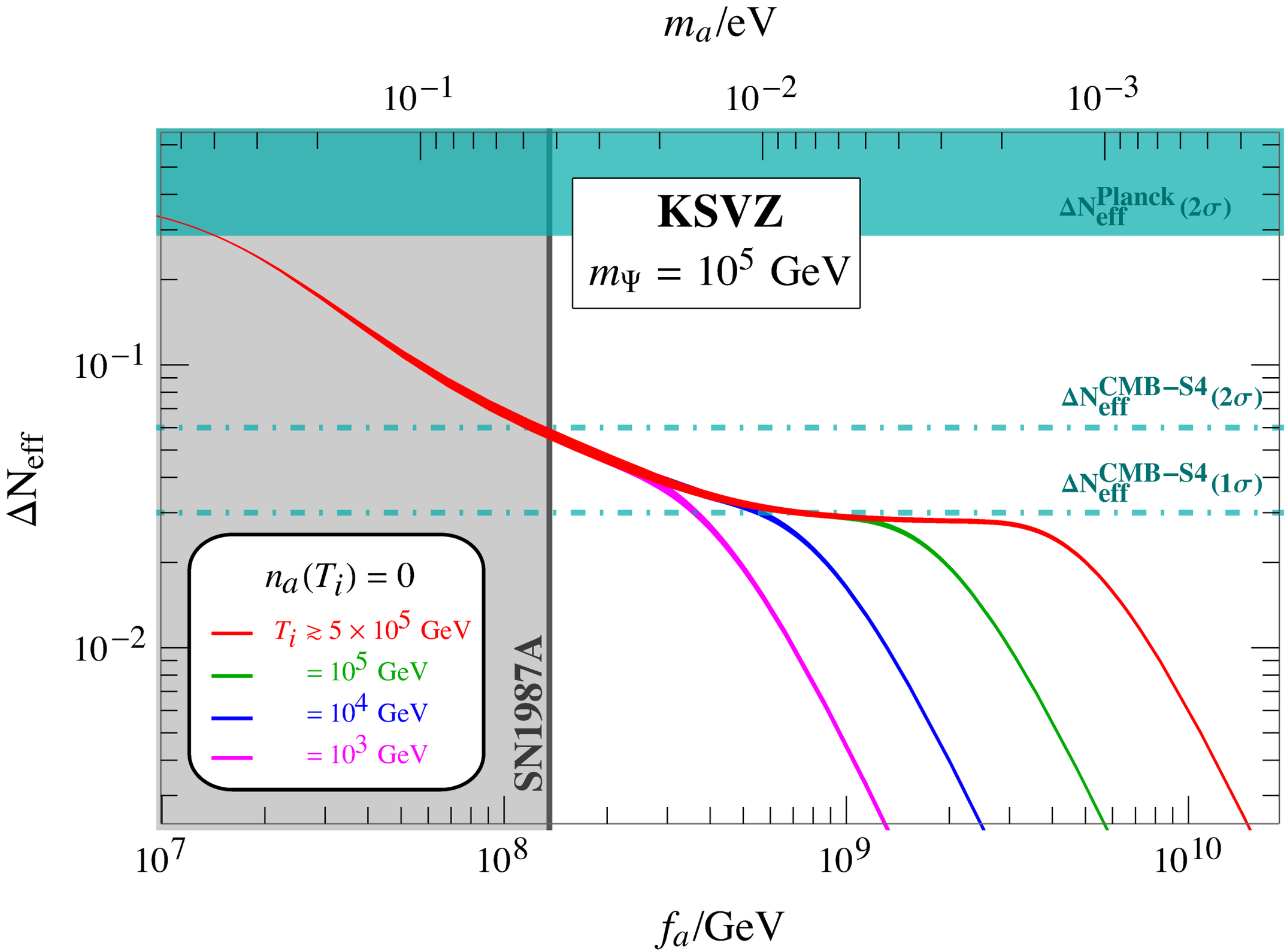
Smooth rate across EWPT, within reach of CMB-S4 surveys

KSVZ Axion — Production Rate



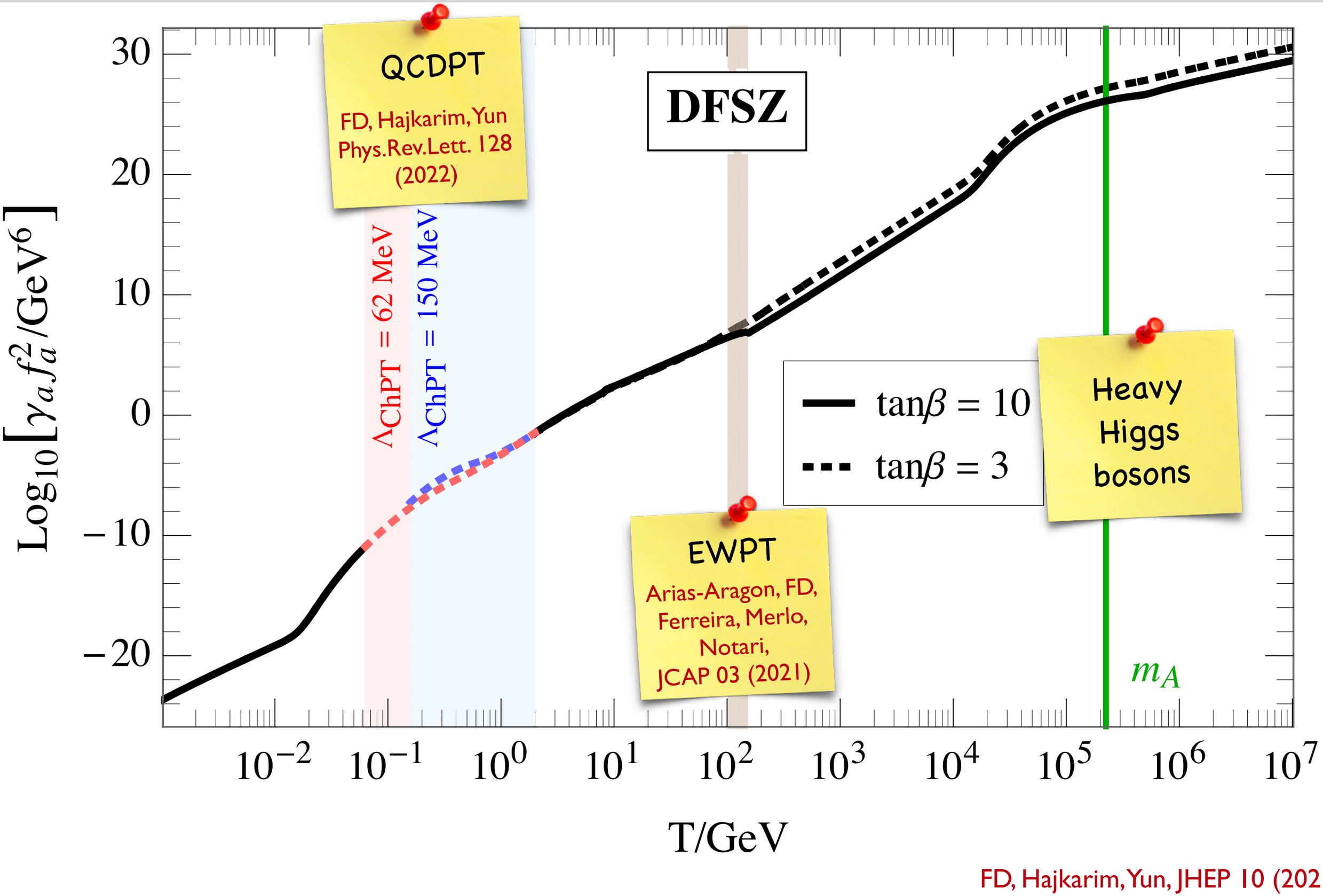
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — ΔN_{eff}



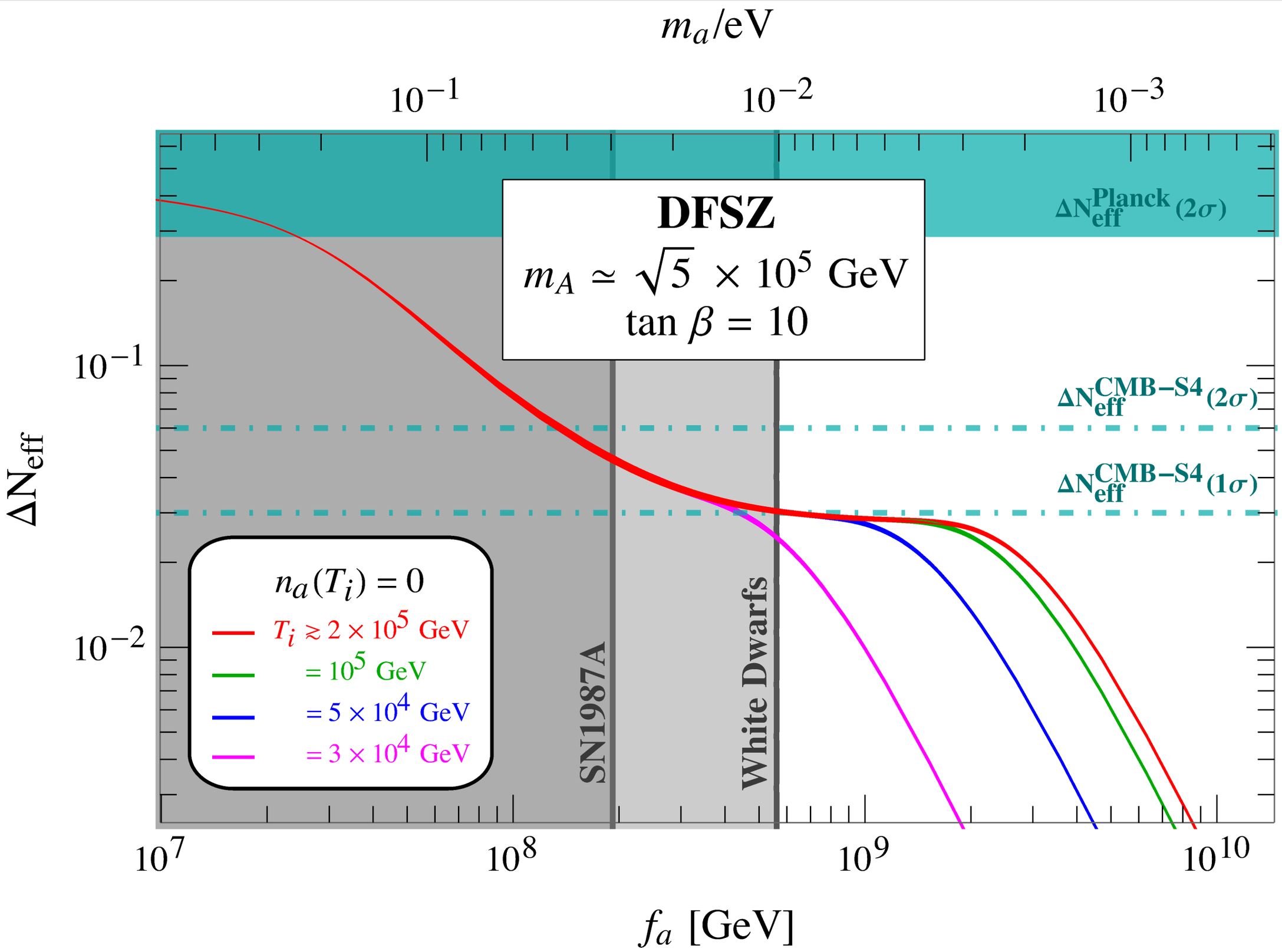
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



FD, Hajkarim, Yun, JHEP 10 (2021)

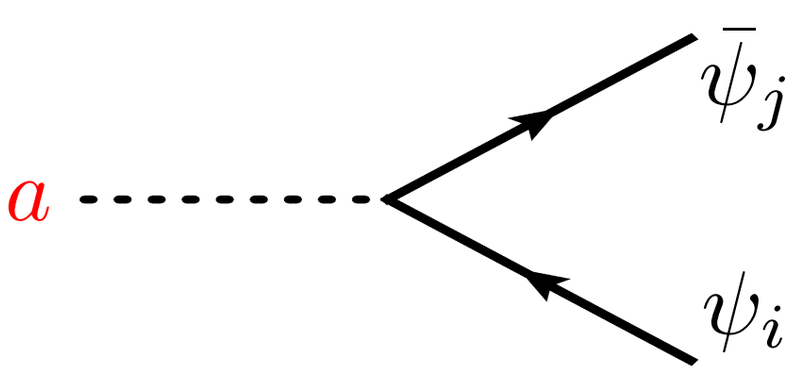
DFSZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, JHEP 10 (2021)

Flavor Violating Axions

$$\mathcal{L}_{\rm FV}^{(a)} = \frac{\partial_\mu a}{2f_a} \sum_{\psi_i \neq \psi_j} \bar{\psi}_i \gamma^\mu \left(c^V_{\psi_i \psi_j} + c^A_{\psi_i \psi_j} \gamma^5 \right) \psi_j$$



Target of several terrestrial experiments

Camalich et al., Phys.Rev.D 102 (2020)
Calibbi et al., JHEP 09 (2021)

What about their role in the early universe?

They mediate hot axion production
via <u>decays</u> and <u>scatterings</u>

FD, Yun, Phys.Rev.D 105 (2022)

Flavor Violating Axions

$$\frac{\partial_\mu a}{f_a}\bar{\psi}_i\gamma^\mu\left(c^V_{\psi_i\psi_j}+c^A_{\psi_i\psi_j}\gamma^5\right)\psi_j$$

See talk by **Clemente Smarra** in this session for an explicit construction

"The axion-flavour connection"

a ----

rget of several terrestrial experiments

Camalich et al., Phys.Rev.D 102 (2020)
Calibbi et al., JHEP 09 (2021)

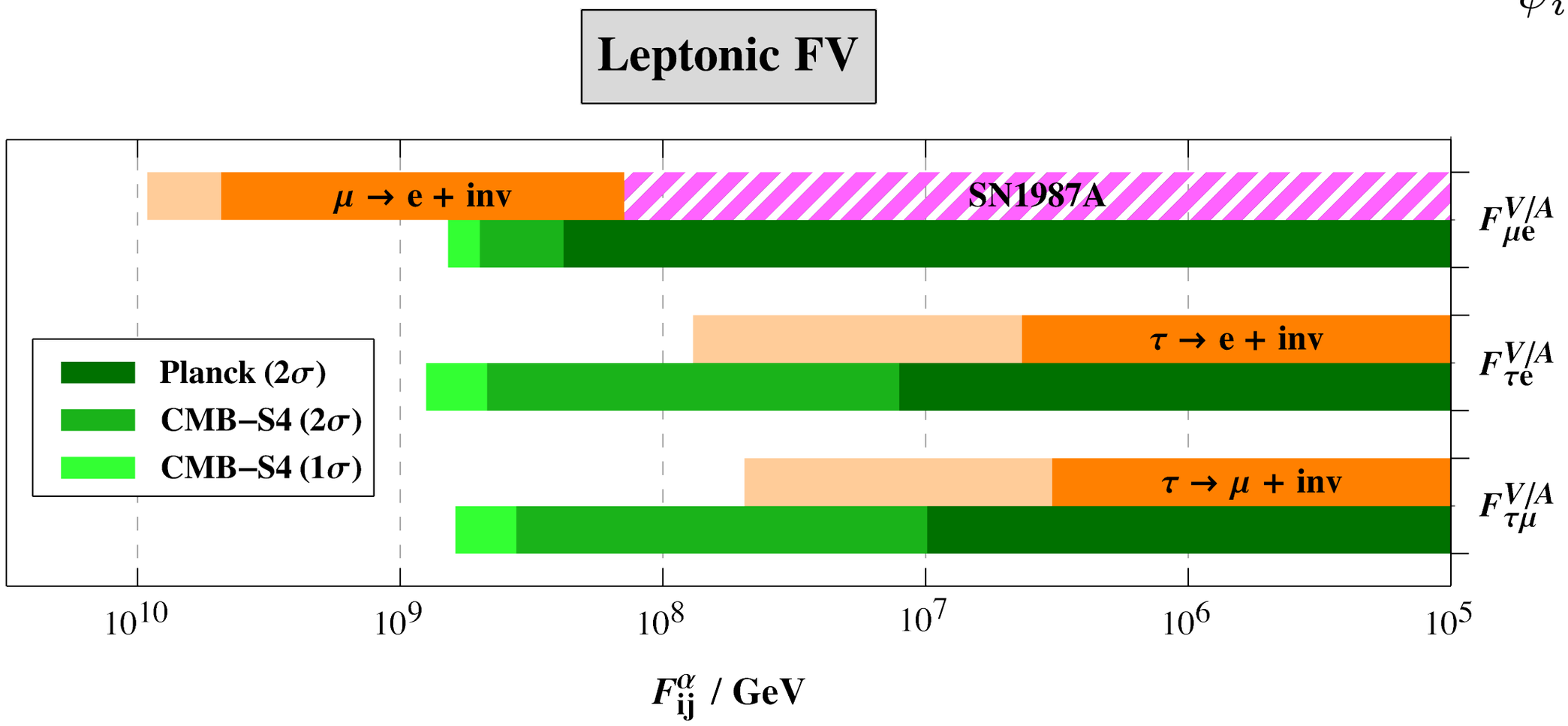
What about their role in the early universe?

They mediate hot axion production via <u>decays</u> and <u>scatterings</u>

FD, Yun, Phys.Rev.D 105 (2022)

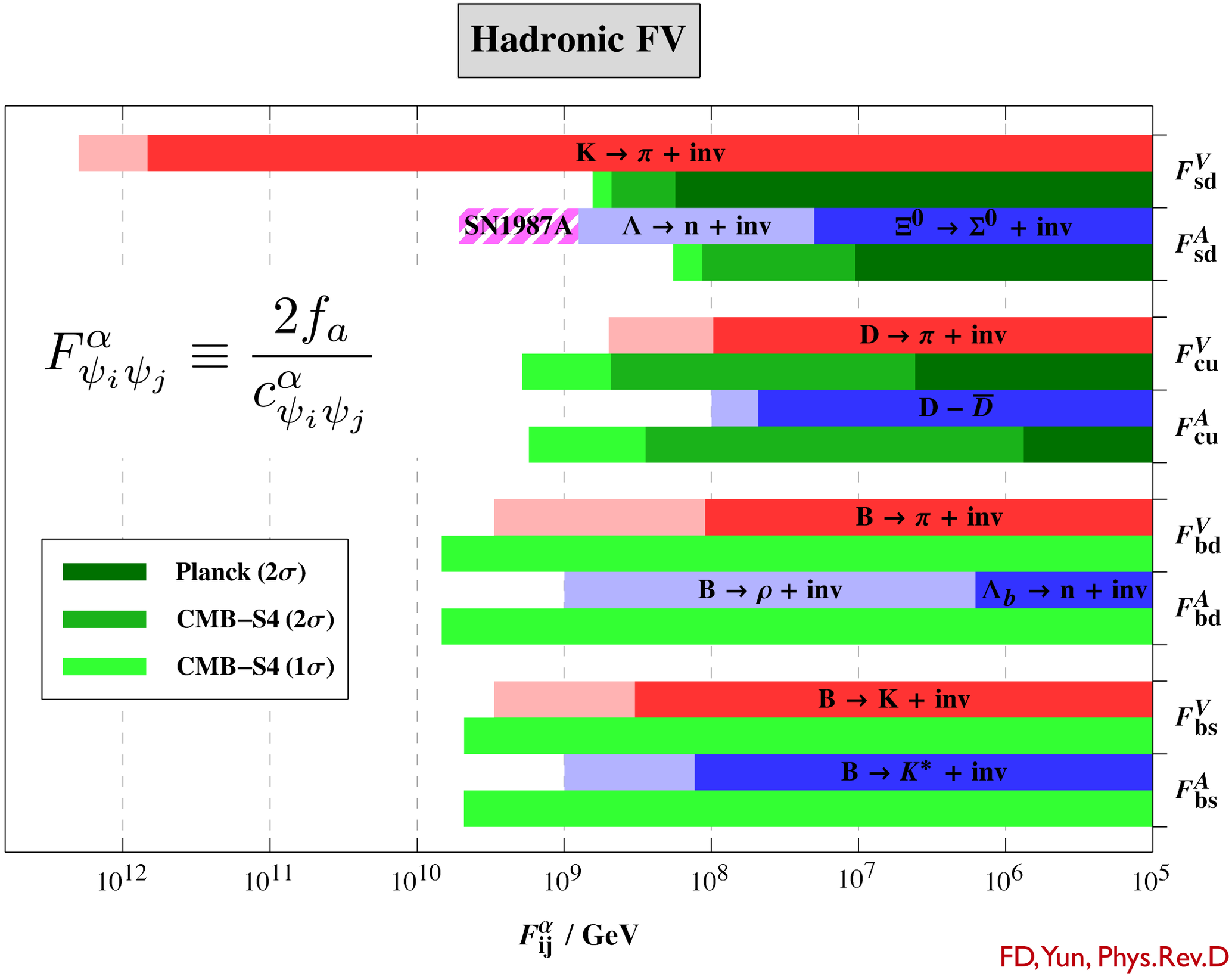
Flavor Violating Axions - Leptons

$$F^{\alpha}_{\psi_i\psi_j} \equiv \frac{2f_a}{c^{\alpha}_{\psi_i\psi_j}}$$



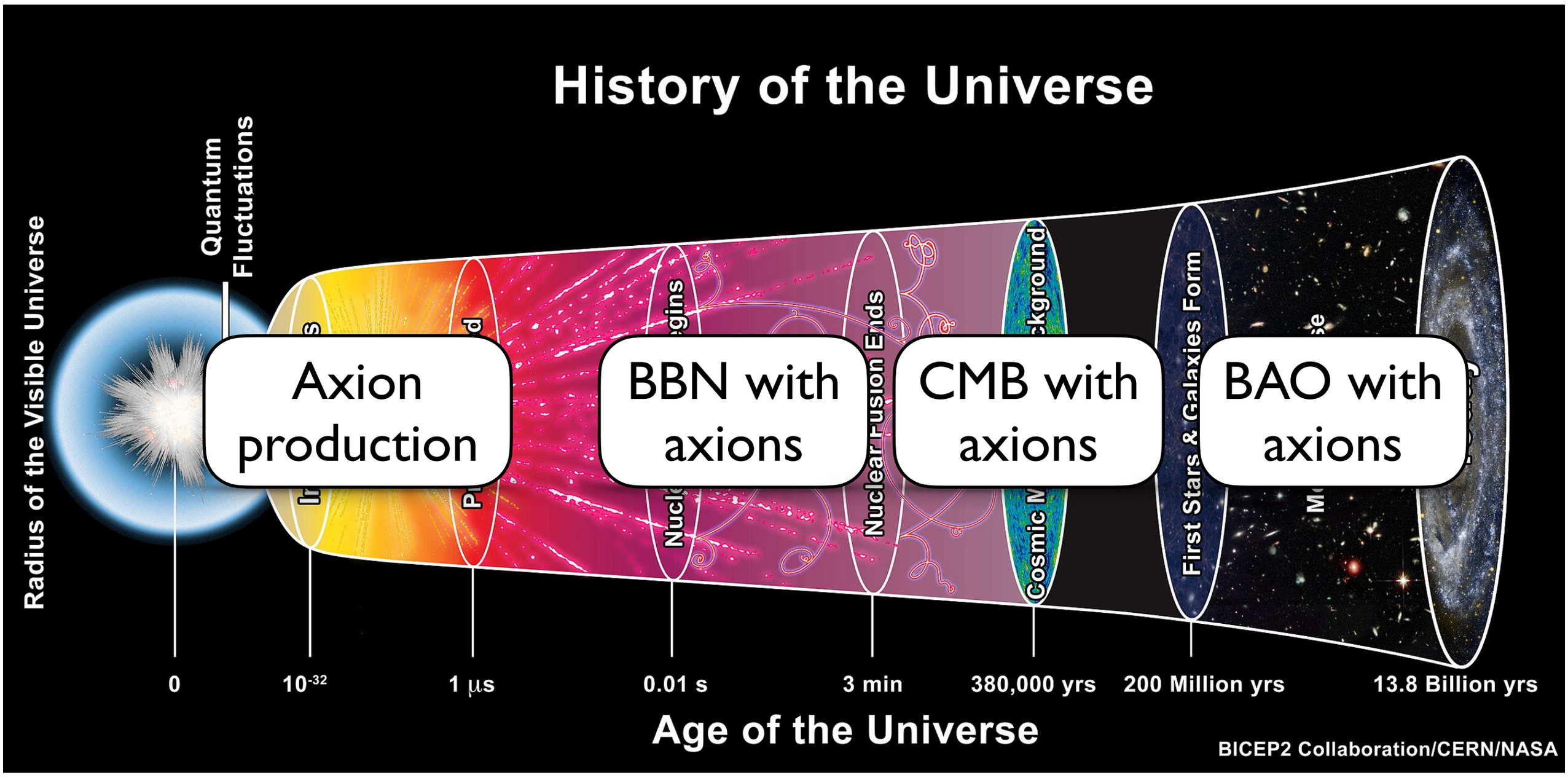
FD, Yun, Phys.Rev.D 105 (2022)

Flavor Violating Axions - Hadrons



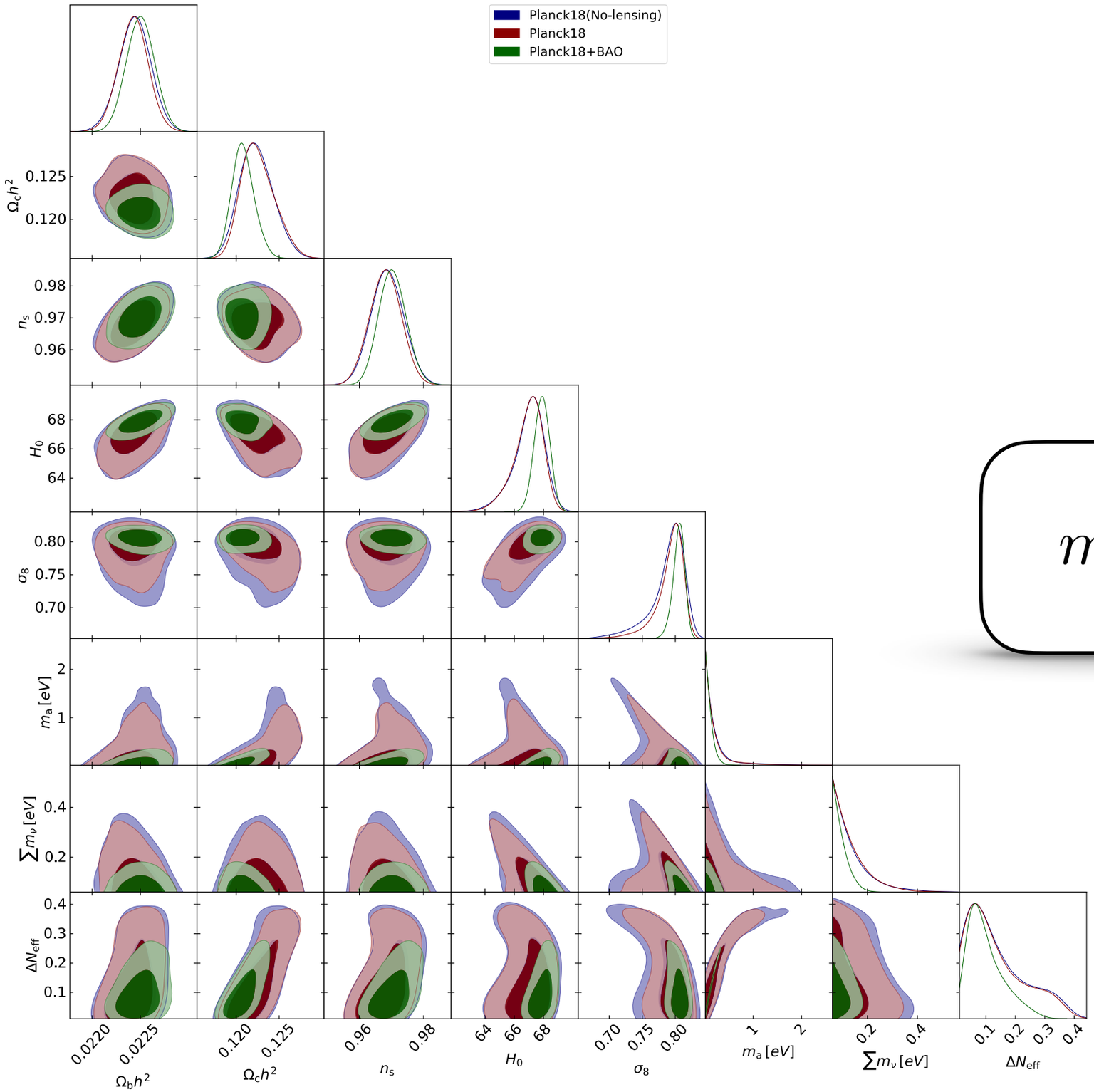
FD, Yun, Phys.Rev.D 105 (2022)

QCD Axion Mass Bound



FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, JCAP 09 (2022)

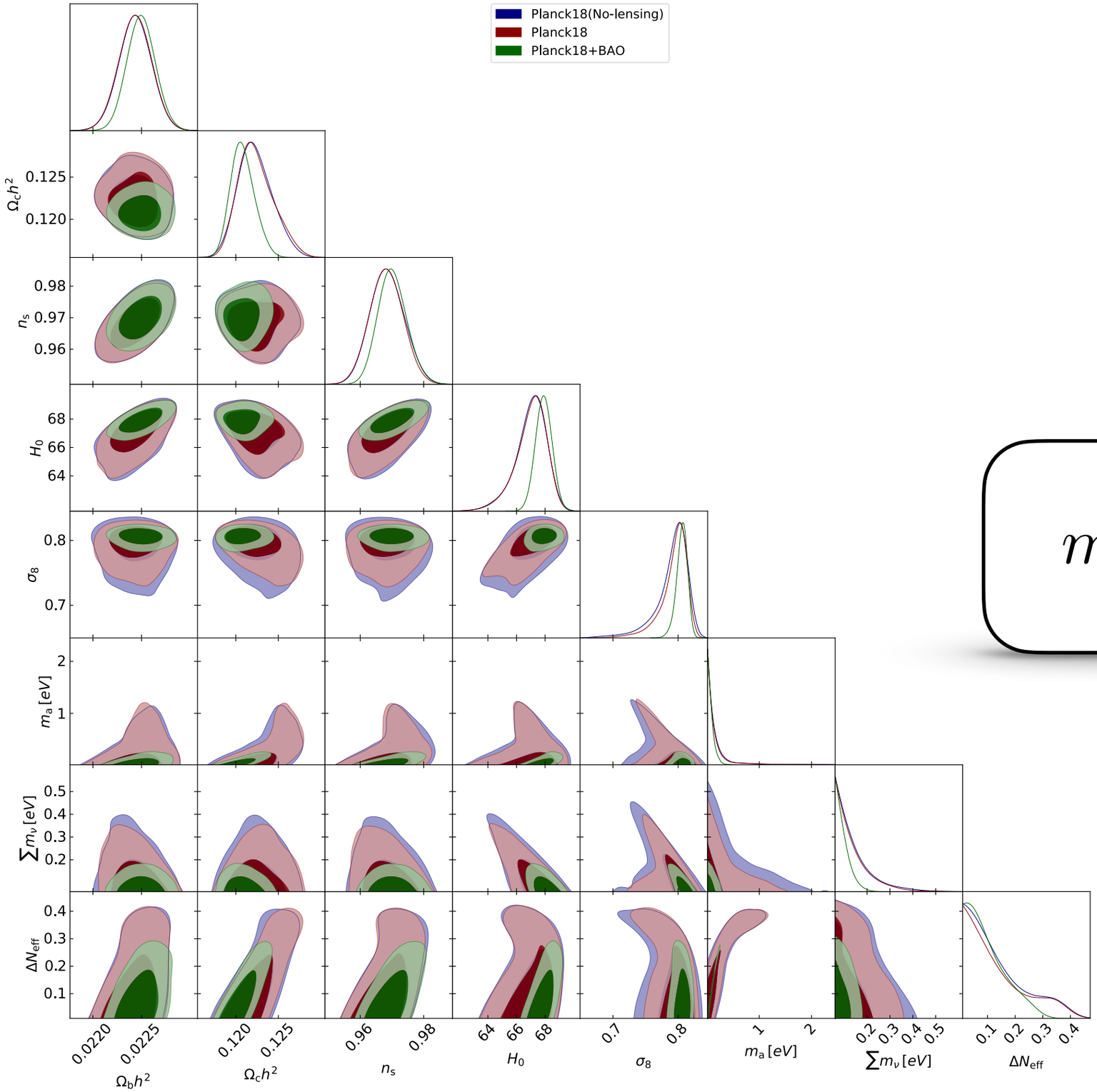
KSVZ Axion Mass Bound



$$m_a \leq 0.282(0.420)\,\mathrm{eV}$$

FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, JCAP 09 (2022)

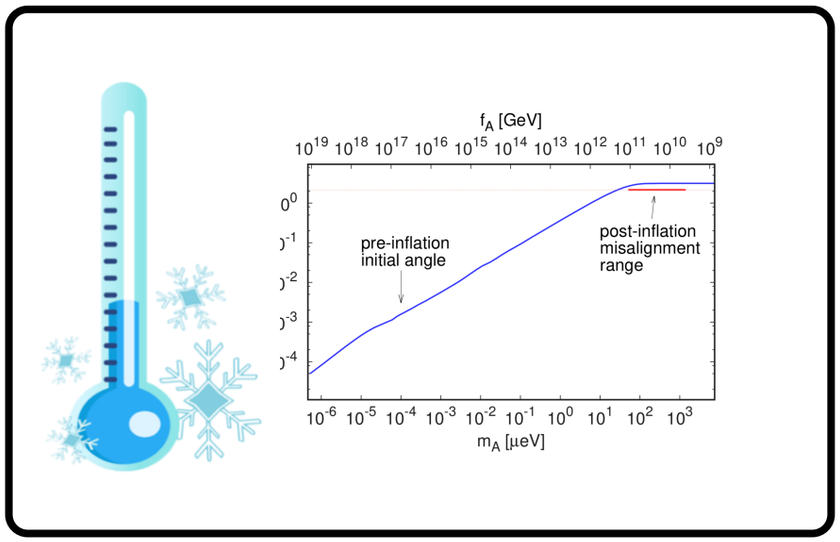
DFSZ Axion Mass Bound



$$m_a \leq 0.209(0.293)\,\mathrm{eV}$$

FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, JCAP 09 (2022)

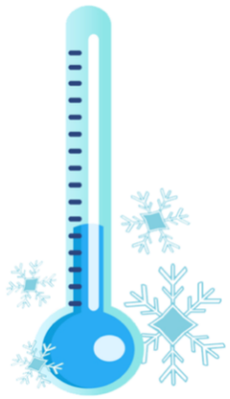
Outlook

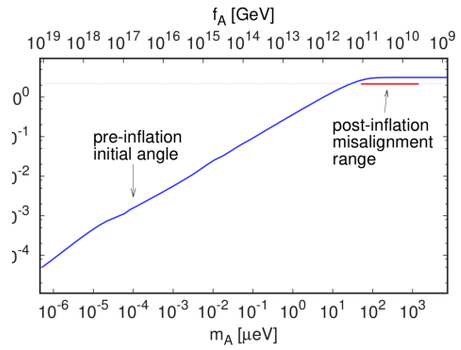


Peccei-Quinn Mechanism and the QCD Axion

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

Outlook





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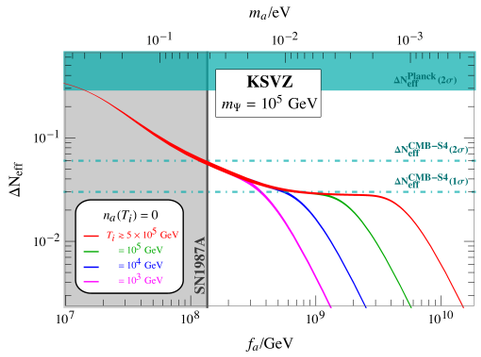
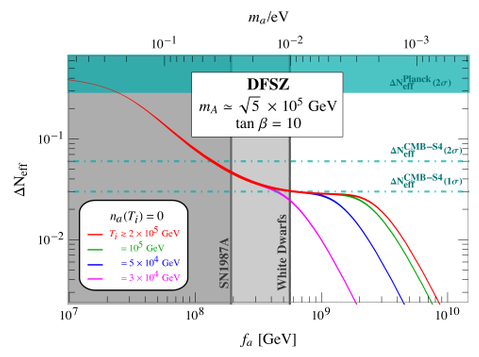
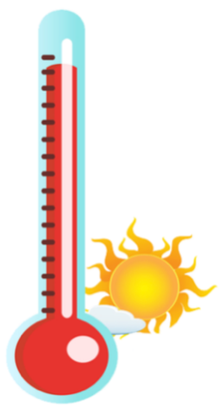
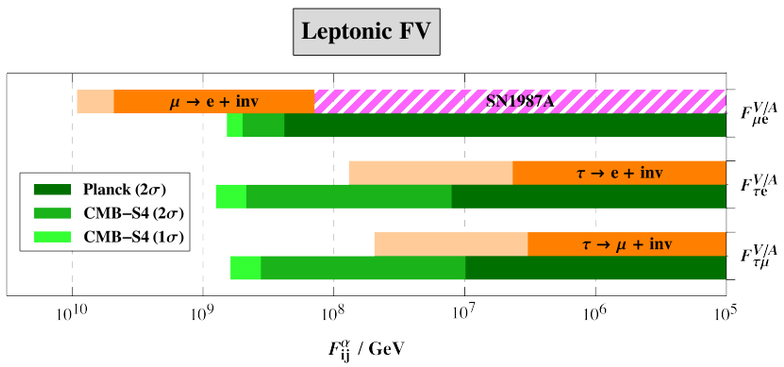
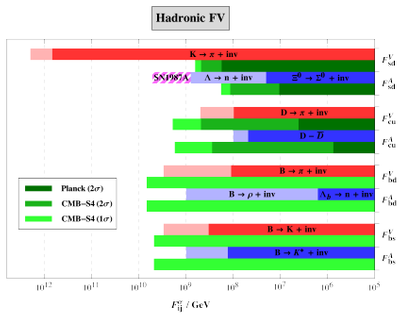
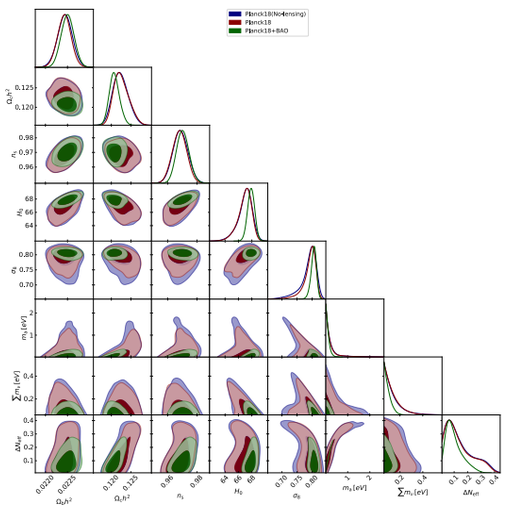








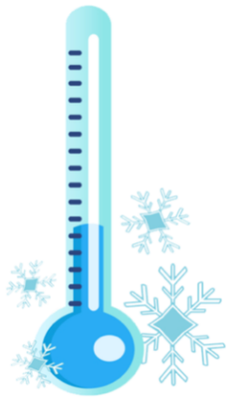


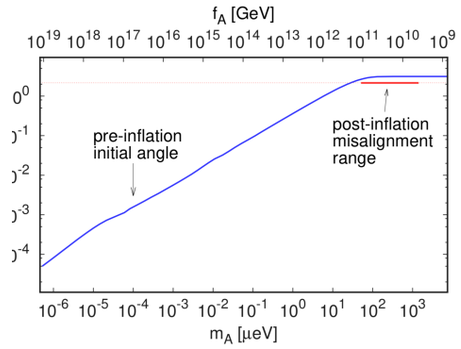


Thermal Axions

Complementary to other probes of the PQ mechanism

Outlook





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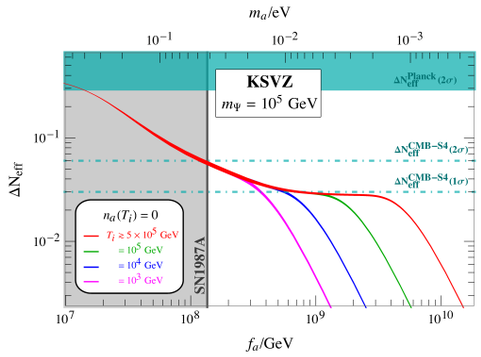

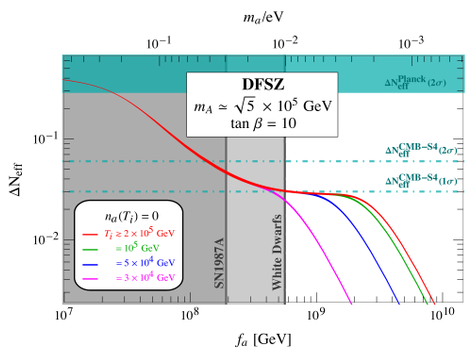

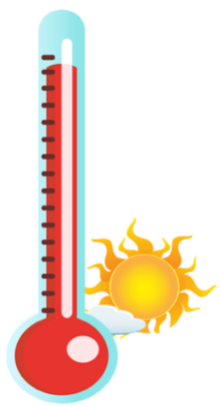

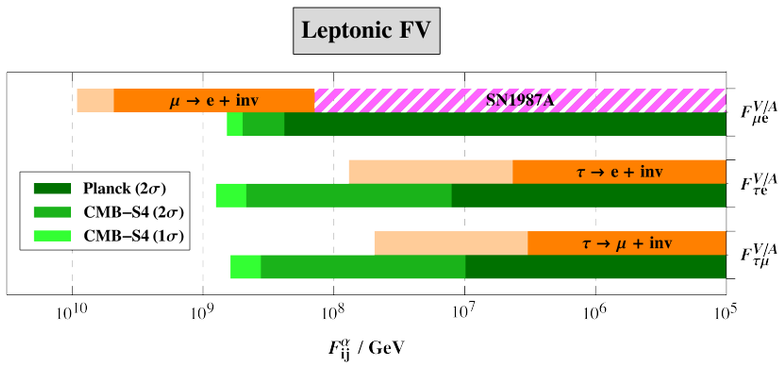

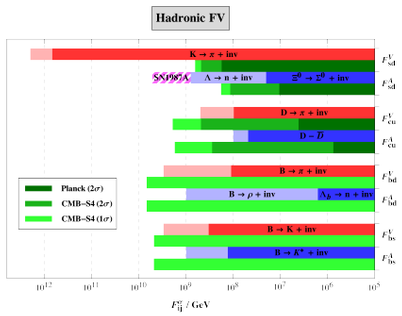

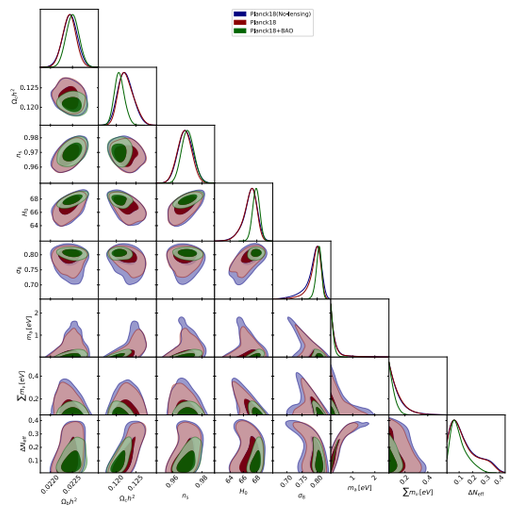

THANK YOU!