

Axions at the meV Crossroads

Francesco D'Eramo



UNIVERSITÀ DI PADOVA

Dipartimento
di Fisica e Astronomia
“Galileo Galilei”

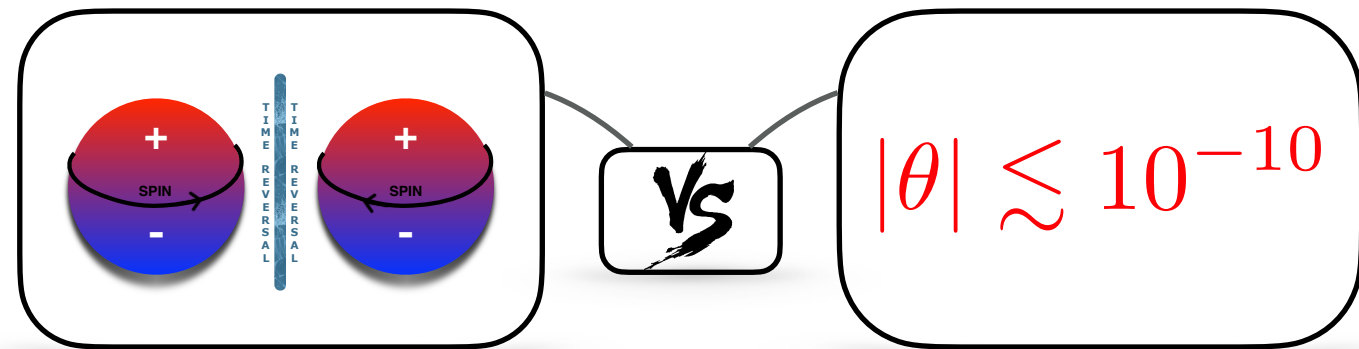


News from the Dark II

Institut de Physique Théorique (IPhT), Saclay — 29 September 2026

The QCD Axion

Peccei-Quinn (PQ) Mechanism:
Dynamical Solution to the
Strong CP problem



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

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

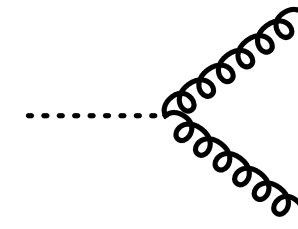
Pseudo Nambu-Goldstone boson in the
low-energy spectrum (“**QCD axion**”)
with (“anomalous”) coupling to gluons

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

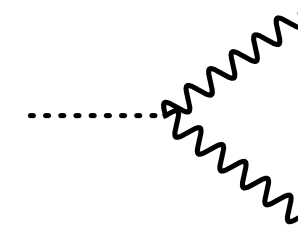
Properties of the QCD Axion

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

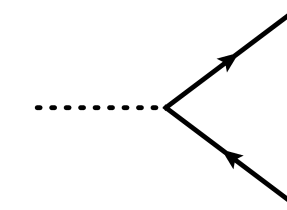
The QCD axion is elusive!



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



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



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

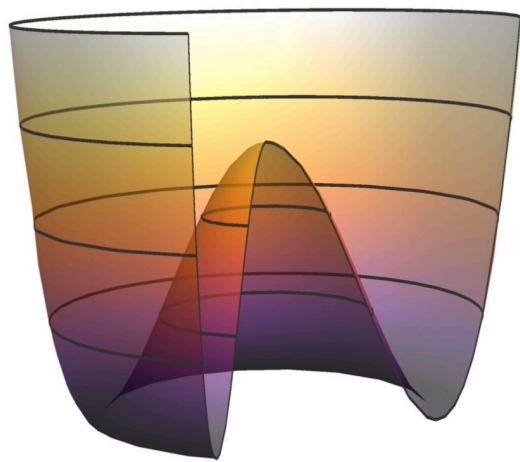
Axion (zero-temperature) mass
from non-perturbative potential

The QCD axion is very light!

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

QCD Axion vs ALPs

Axion-Like-Particles (ALPs) are ubiquitous in extensions of the Standard Model



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

QCD Axion

Coupling to gluons mandatory

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

ALPs

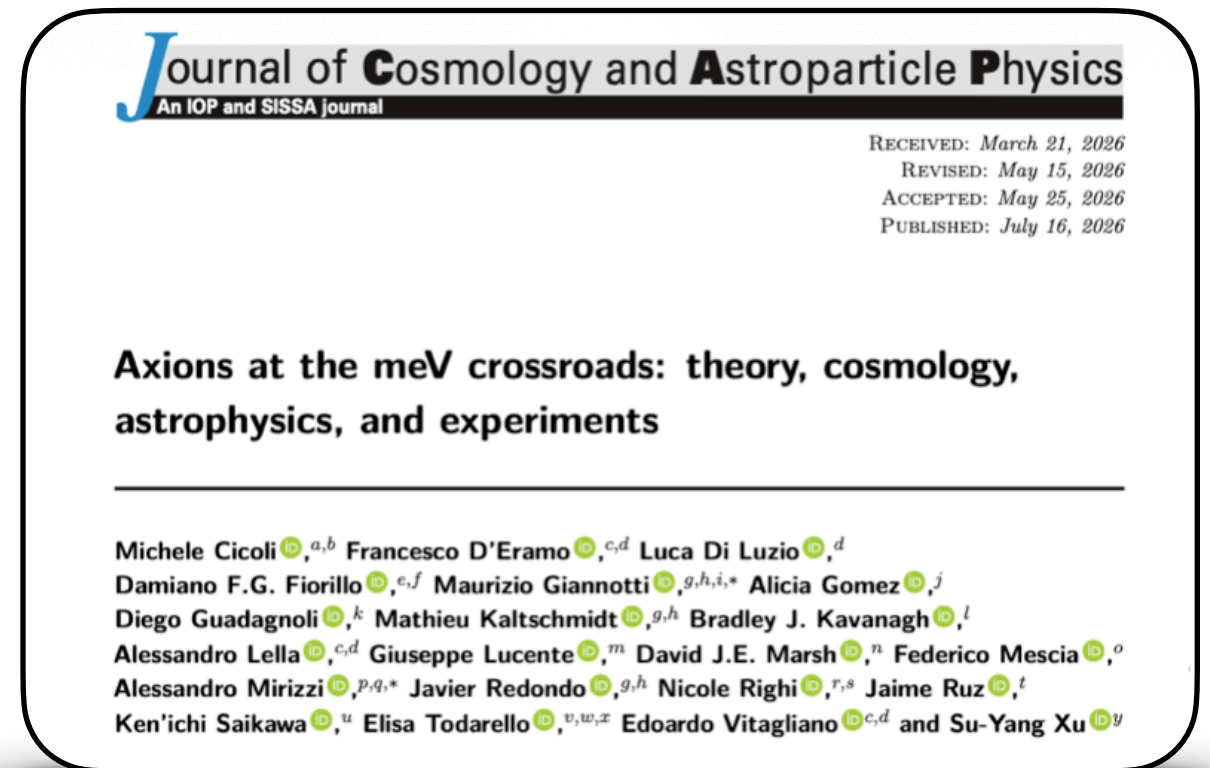
Coupling to gluons optional

$$m_a \simeq \Lambda_X^2 / f_X$$

In this talk, I will clarify which results apply specifically to the QCD axion and which extend to general ALPs

All Roads Lead to meV Axions

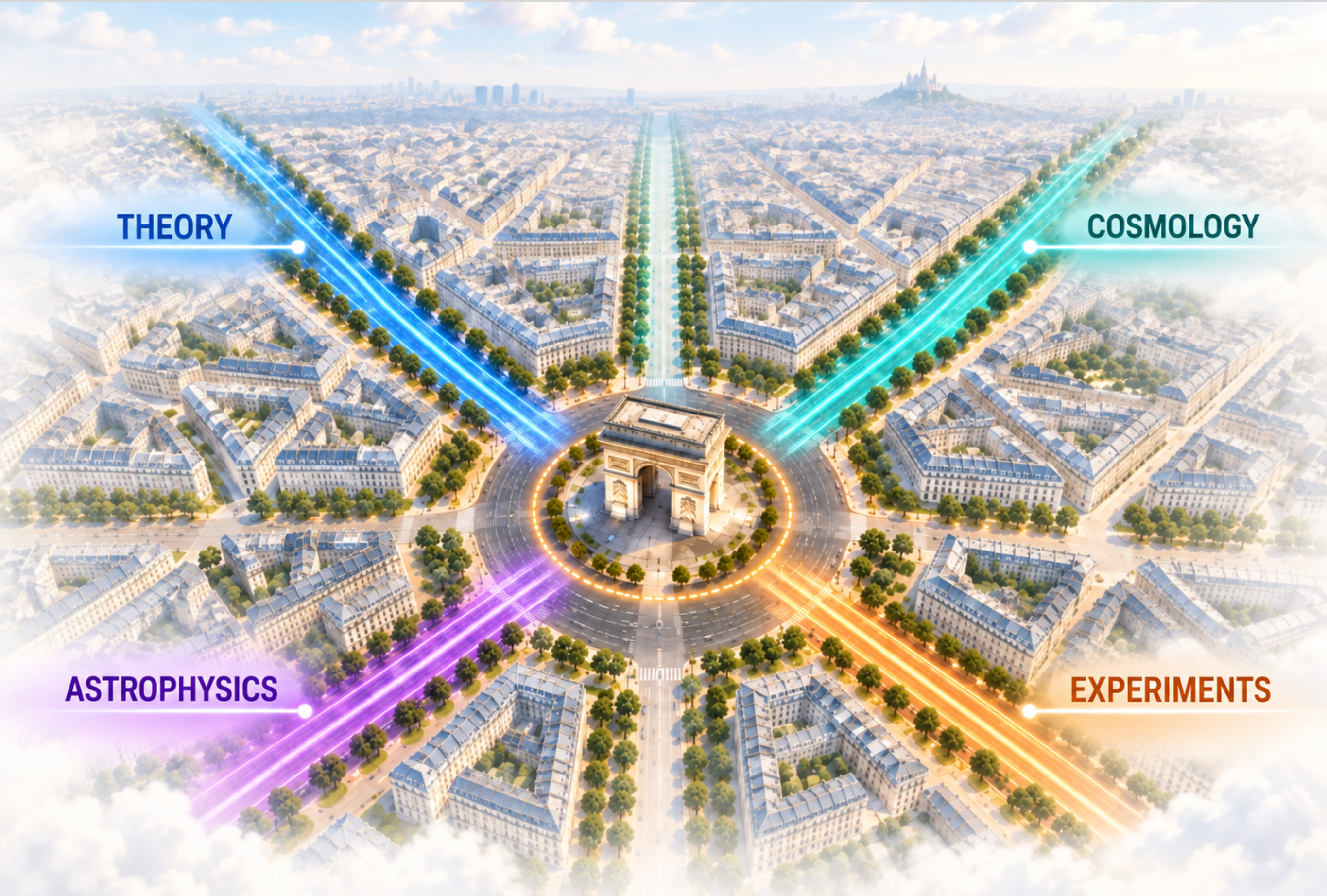
The meV is more than a mass scale, it is where **four roads** in axion physics converge



Cicoli, FD et al., JCAP 07 (2026) 060

Theory, Cosmology, Astrophysics and Experiments all provide *independent and complementary reasons* to focus on the meV scale, where theoretical expectations, observational sensitivity and experimental opportunities naturally converge

The meV Axions Crossroads



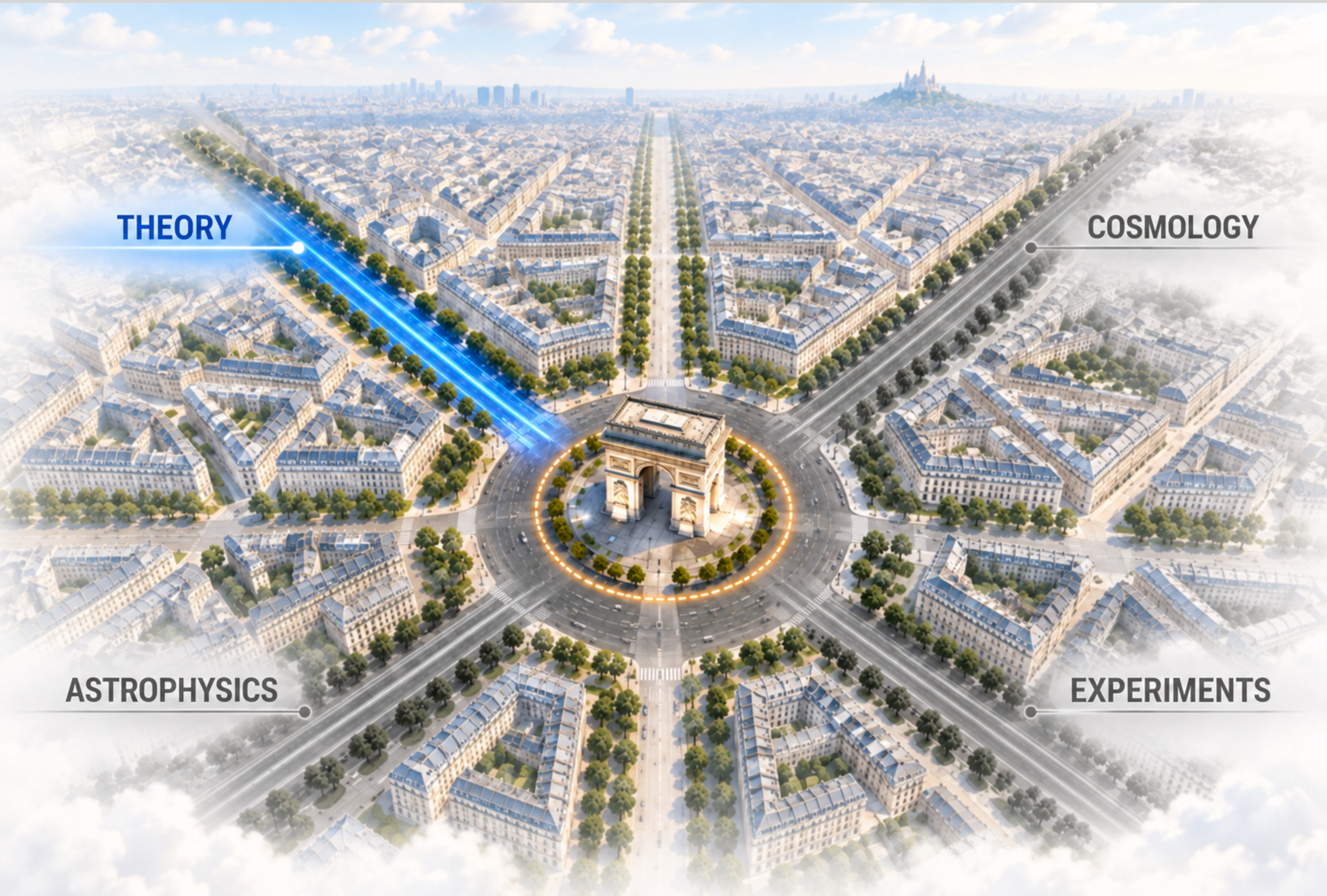
THEORY

COSMOLOGY

ASTROPHYSICS

EXPERIMENTS

Axion Models



THEORY

COSMOLOGY

ASTROPHYSICS

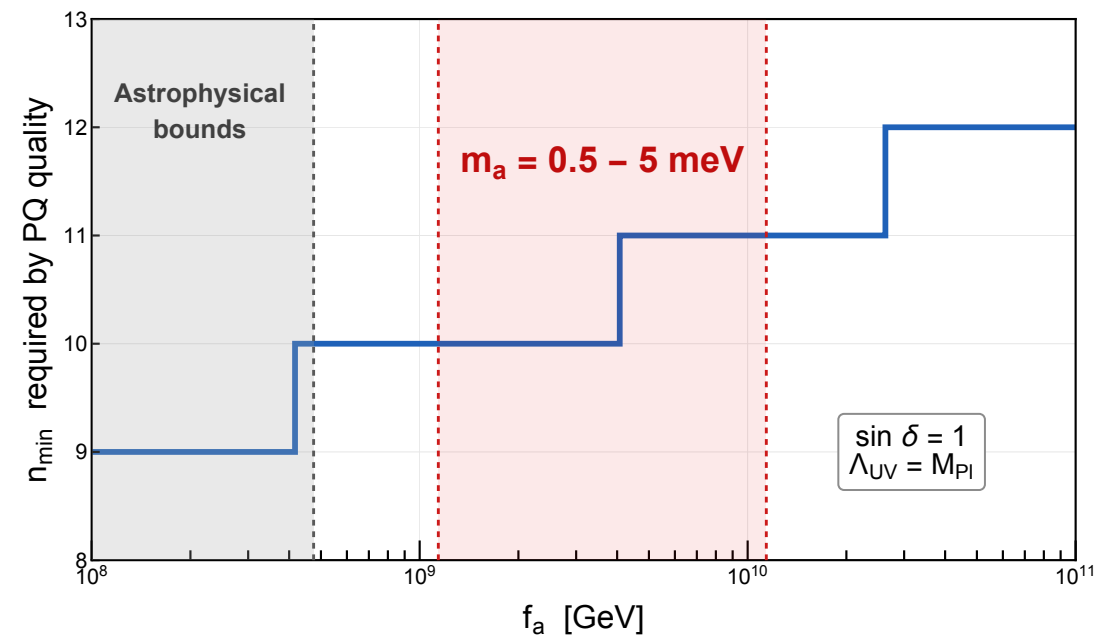
EXPERIMENTS

Why the meV mass scale?

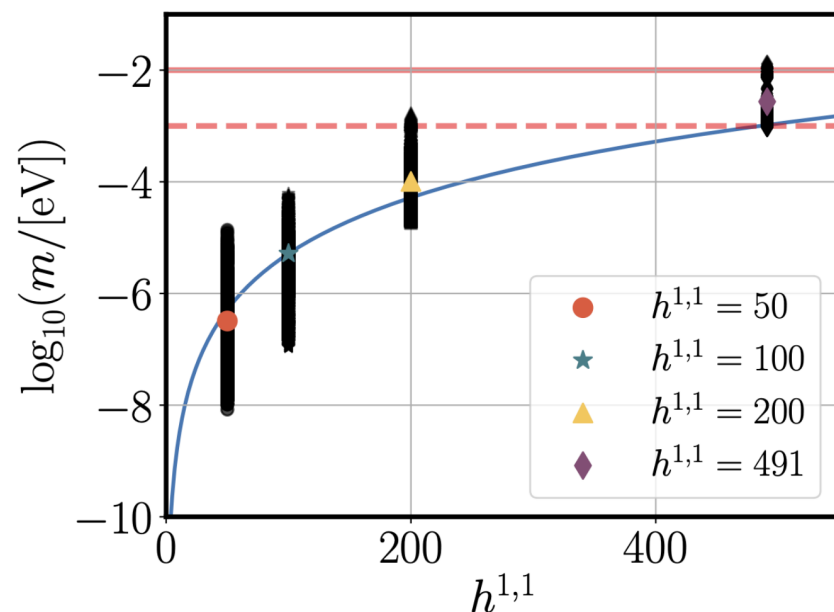
PQ Quality Points to meV Axions

$$V_{\text{PQ}} = -e^{i\delta} \frac{\Phi^n}{\Lambda_{\text{UV}}^{n-4}} + \text{h.c.}$$

$$\theta_{\text{eff}} \simeq -\frac{n \Lambda_{\text{UV}}^{4-n} f_a^n \sin \delta}{2^{n/2-1} f_a^2 m_a^2}$$



meV Axions from the UV



Large-complexity string compactifications naturally push the QCD axion toward the meV scale

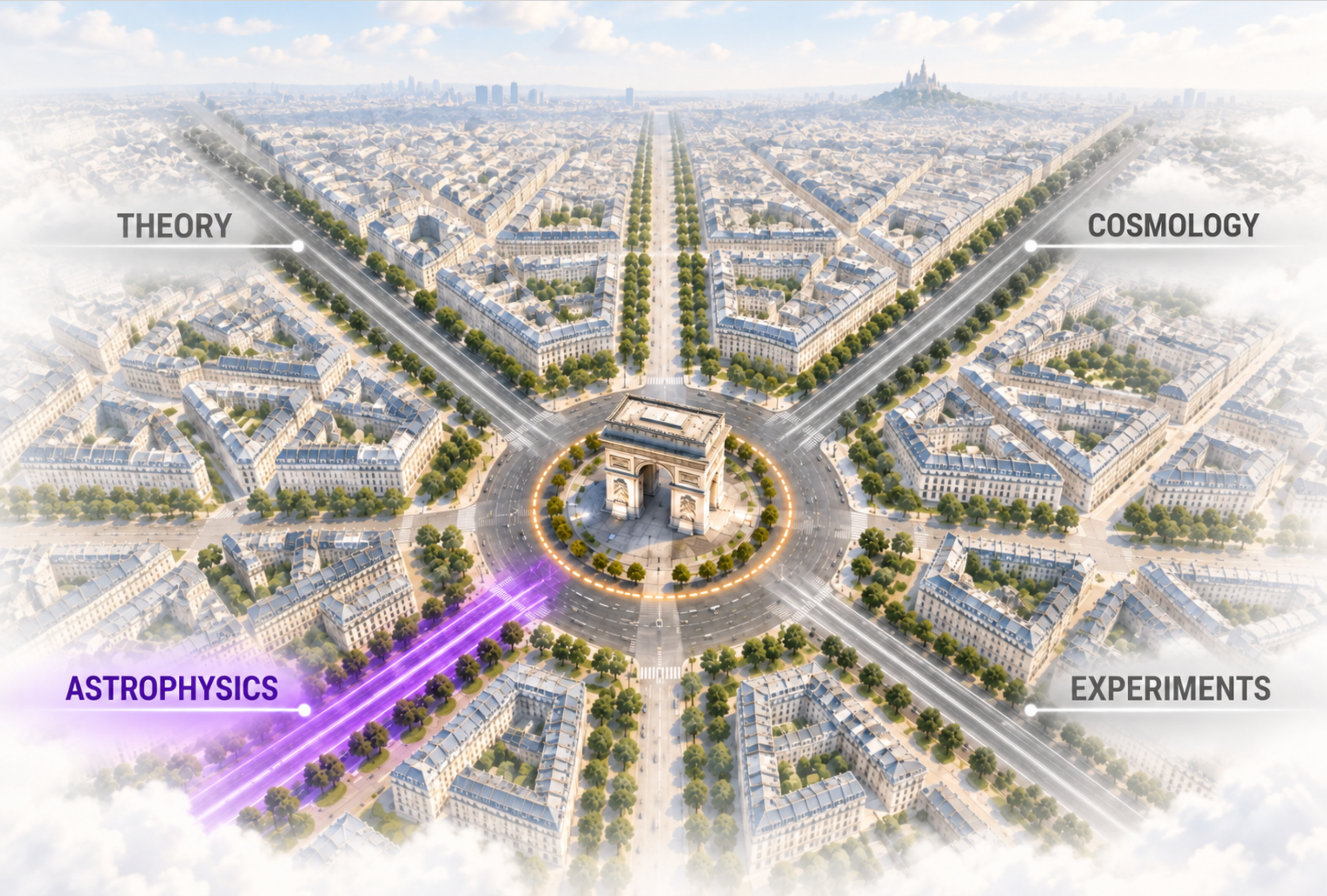
Axions in Stars

THEORY

COSMOLOGY

ASTROPHYSICS

EXPERIMENTS



Axions from Dense Nuclear Media

Already Probing meV Axions

Dense nuclear environments
are powerful axion factories
thanks to their extreme
temperatures and densities

NS Cooling: $m_a \lesssim 16 \text{ meV}$

Buschmann, Dessert, Foster,
Long and Safdi, Phys. Rev. Lett. 128 (2022)

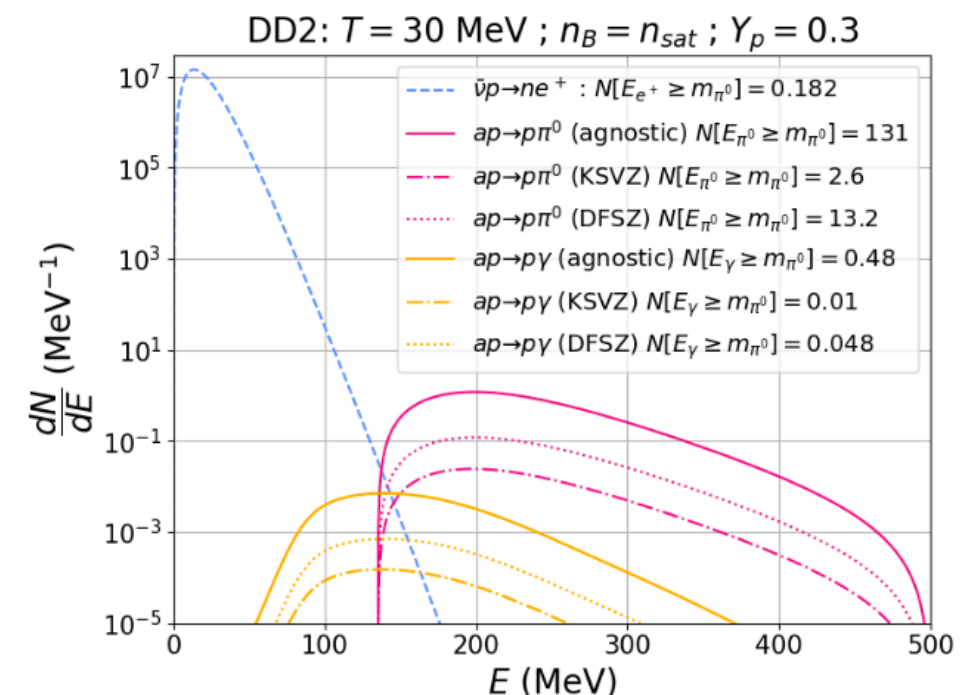
SNI987A: $m_a \lesssim 12 \text{ meV}$

Fiorillo, Gil Muyor, Janka, Raffelt, Vitagliano, JCAP 03 (2026)

Looking Ahead

The next nearby supernova ($d \approx \text{kpc}$)
could turn today's meV axion limits
into tomorrow's discovery

$$a + N \rightarrow N + \pi^0, \gamma$$



Axion Terrestrial Searches



THEORY

COSMOLOGY

ASTROPHYSICS

EXPERIMENTS

Experimental Paths to meV Axions

Helioscopes (BabyIAXO / IAXO)

Solar axions and systematic scanning of the meV mass range

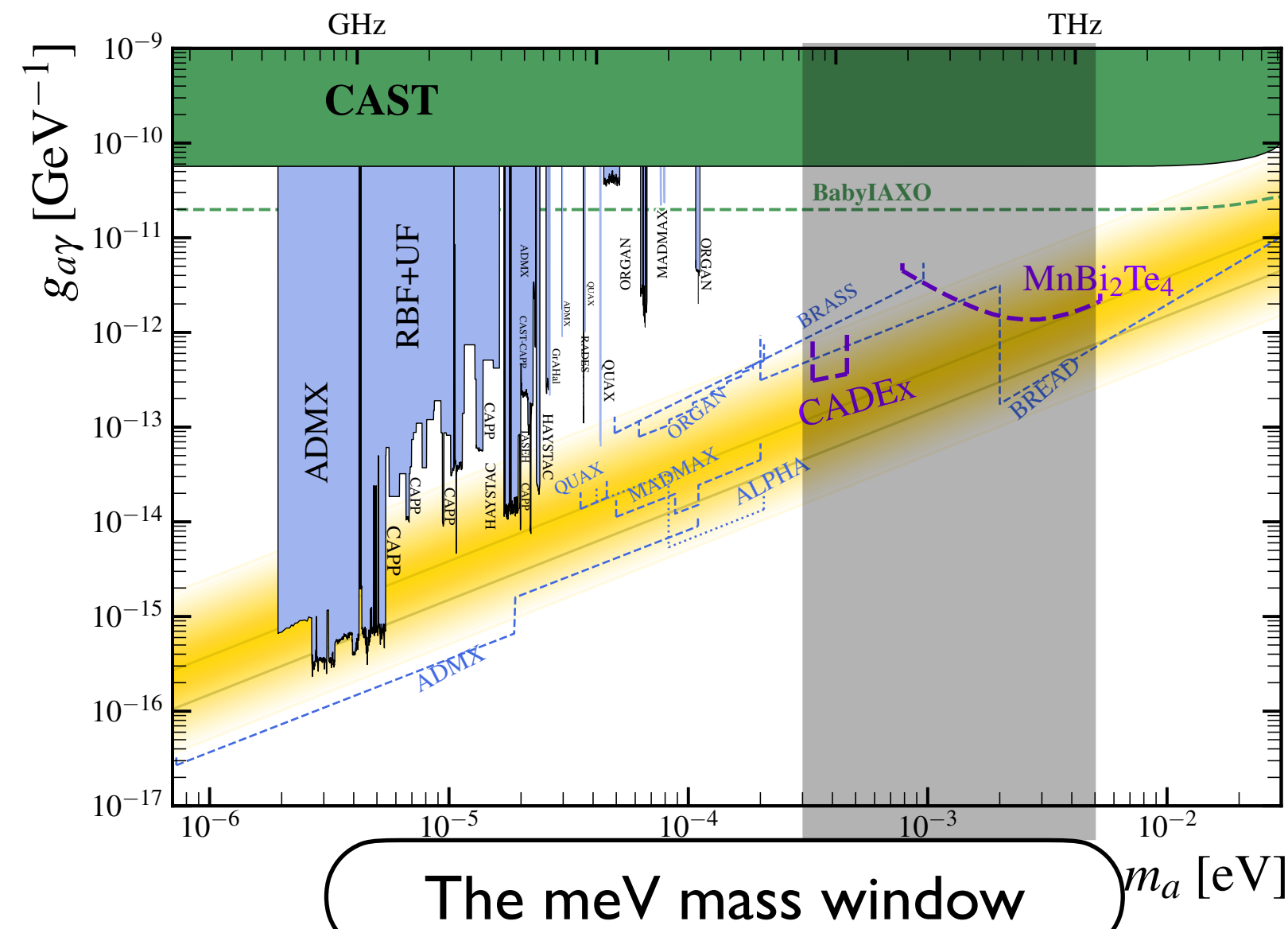
Haloscopes (CADEx)

High-frequency resonant searches pushing detection toward the meV scale

Condensed Matter

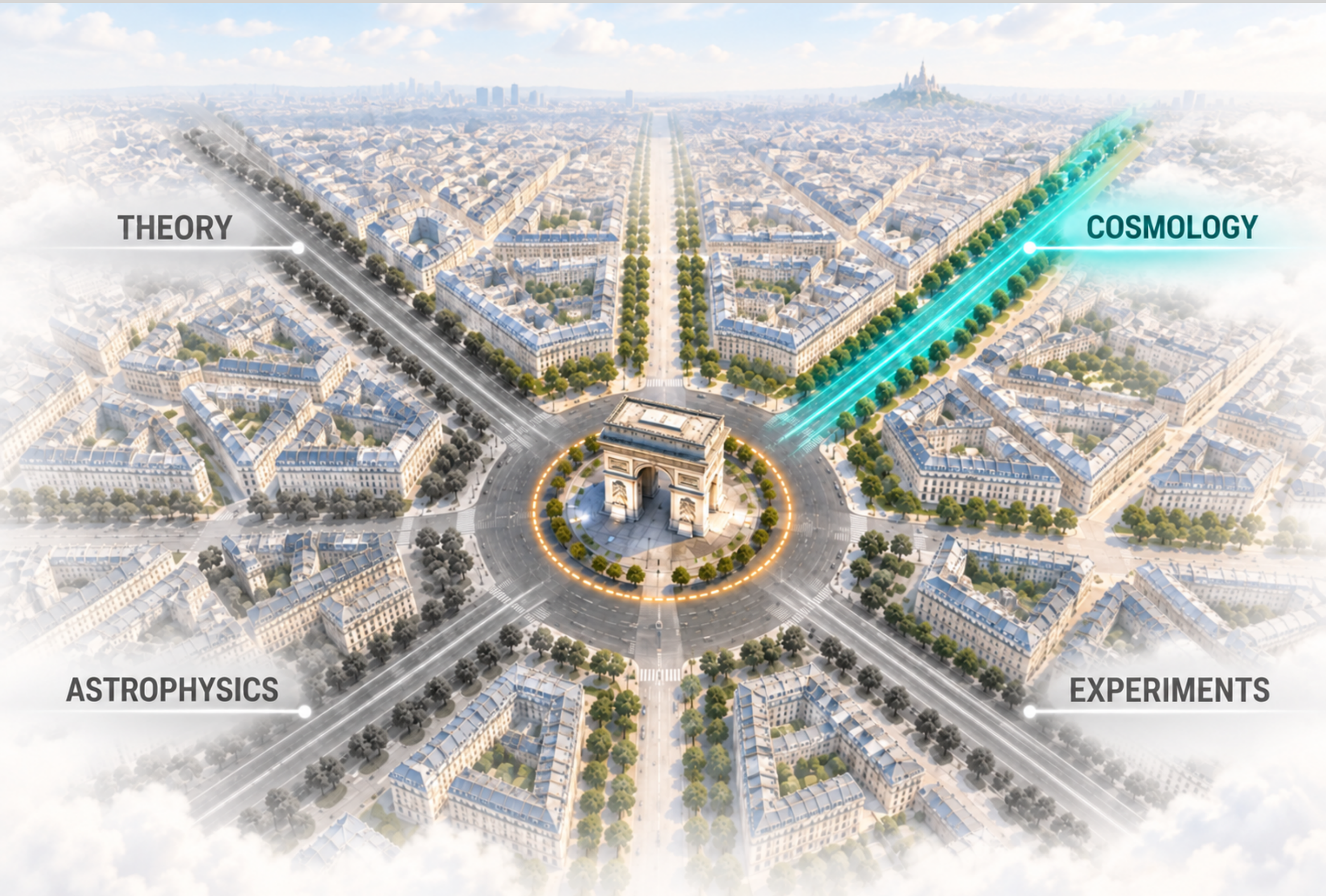
Axion quasiparticles as resonant detectors

MnBi₂Te₄: tunable resonances in the meV range



See **Raffaele Tito D'Agnolo** talk at this workshop for more experiments

Axion Cosmic Relics



THEORY

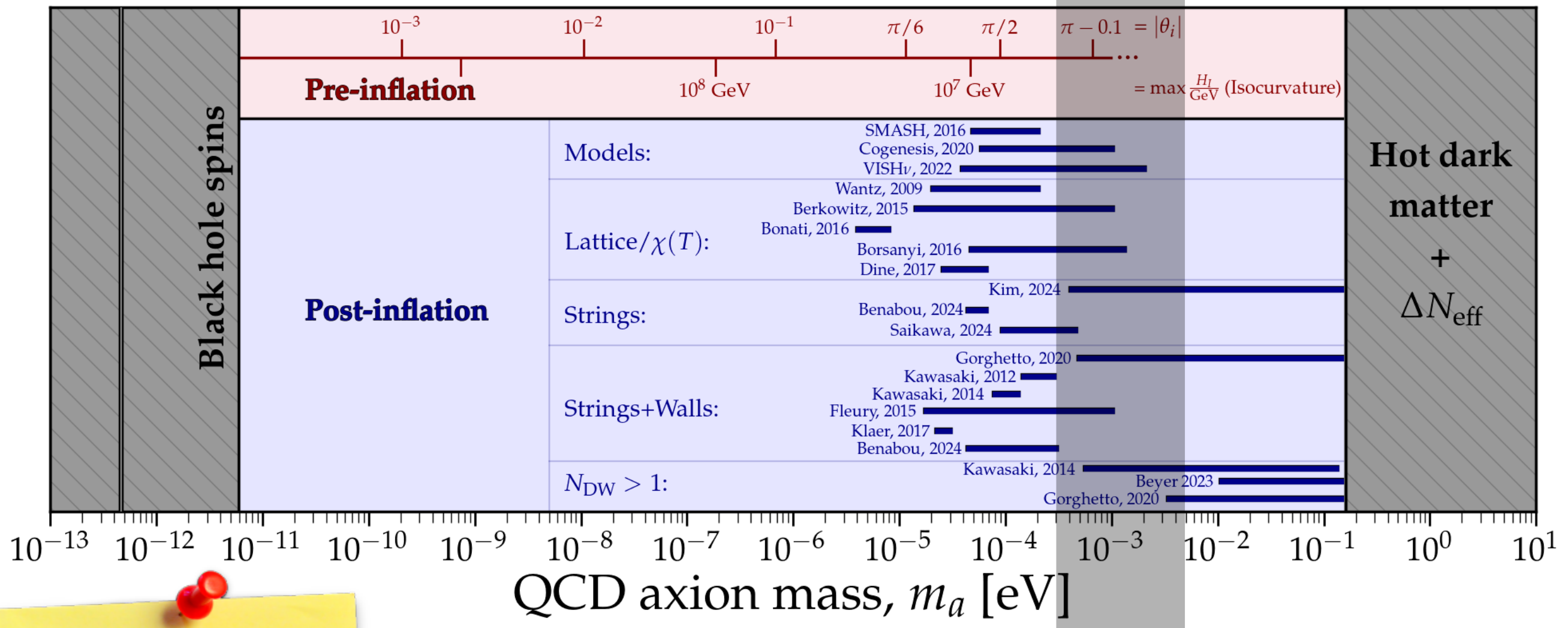
COSMOLOGY

ASTROPHYSICS

EXPERIMENTS

Cold Dark Matter and Axion Mass

The meV mass window



See **Malte Buschmann's** talk at this workshop

meV axions: large initial misalignment angle for pre-inflation whereas post-inflationary production can still yield a sizeable relic fraction

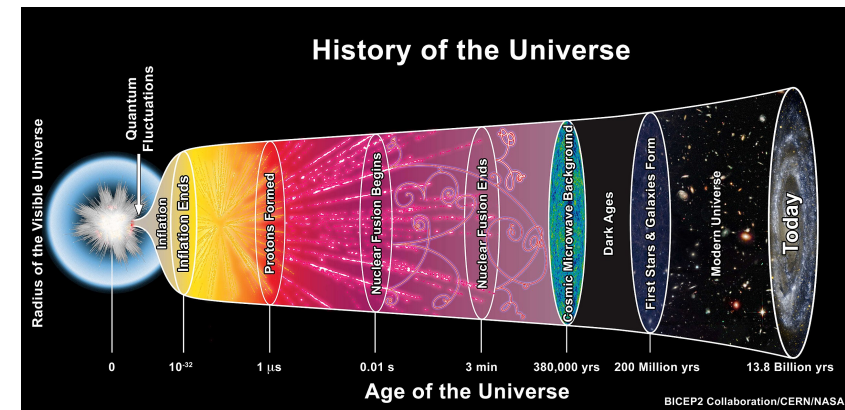
There is More than just Dark Matter

I. Axion Couplings

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

Axion interactions with all Standard Model fields, beyond the light degrees of freedom probed by astrophysics and terrestrial searches

II. Primordial Bath



Early universe filled with a thermal bath of Standard Model particles up to temperatures of approximately 1 TeV

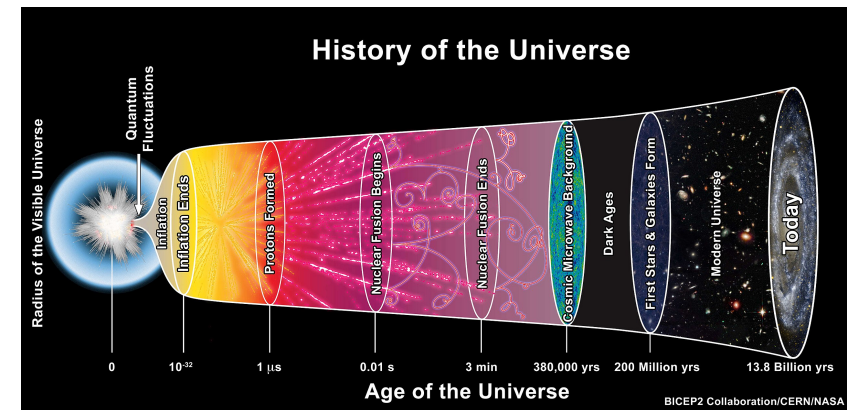
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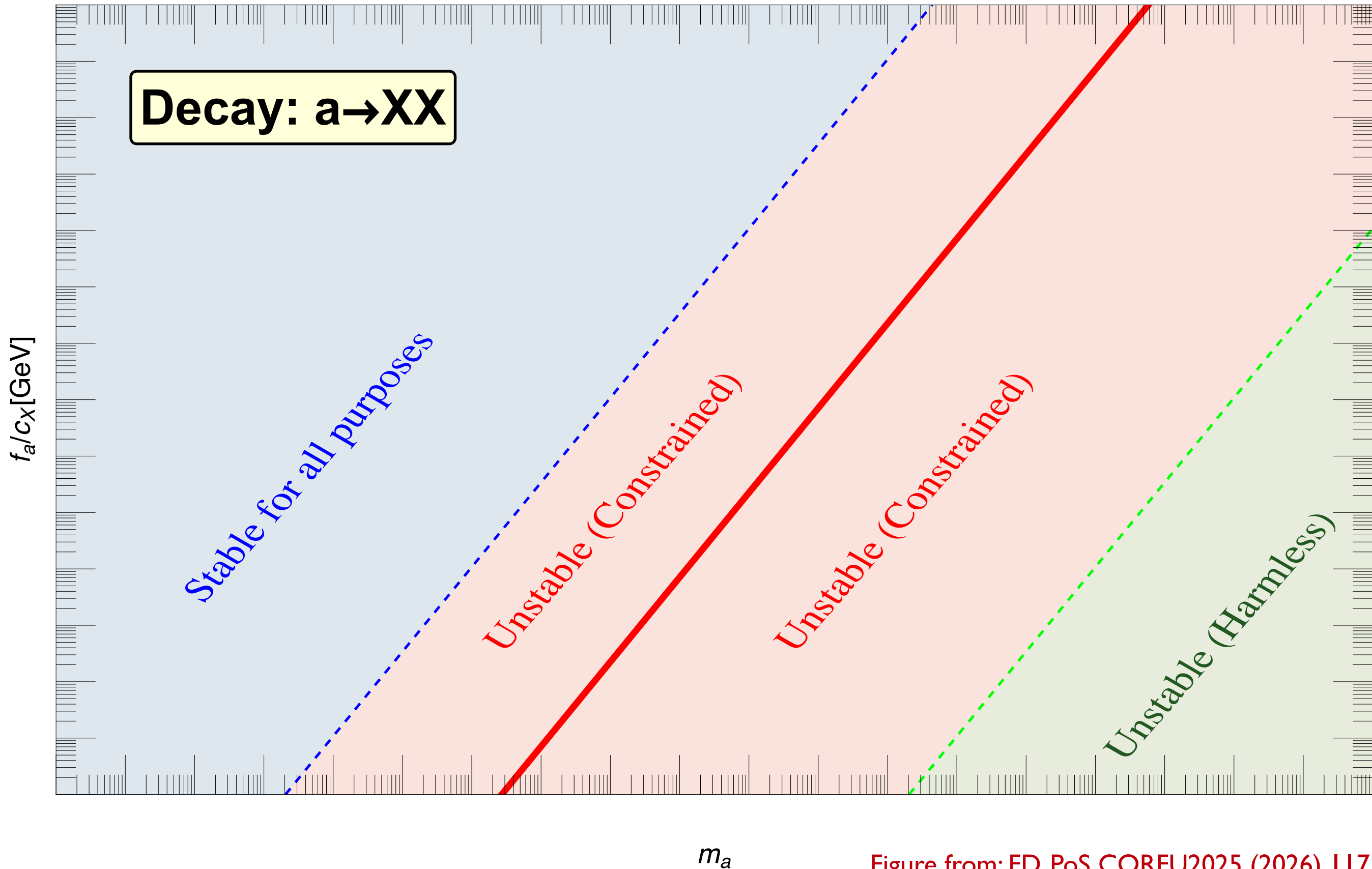
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Early universe filled with a thermal bath of Standard Model particles up to temperatures of approximately 1 TeV

**With these two ingredients,
the universe does the rest!**

Lifetime Shapes the Phenomenology



For Today: Light and Stable Axions

$f_a/c_X [\text{GeV}]$

Axion Dark Radiation
($m_a \ll 0.1 \text{ eV}$)

Axion Hot Dark Matter
Sub-Component
($m_a \sim 0.1 \text{ eV}$)

m_a

for all purposes

Constrained)

Signals also from the Other Regions

Related work includes...

**Axion decays to photons
and the 21 cm Signal
($m_a \sim 100 \text{ keV}$)**

FD, Cima, JCAP 02 (2026)

**Axions coupled to SM fermions
Warm Dark Matter
($m_a \sim 10 \text{ keV}$)**

FD, Lenoci, Dekker, Phys.Rev.D 112 (2025) 11

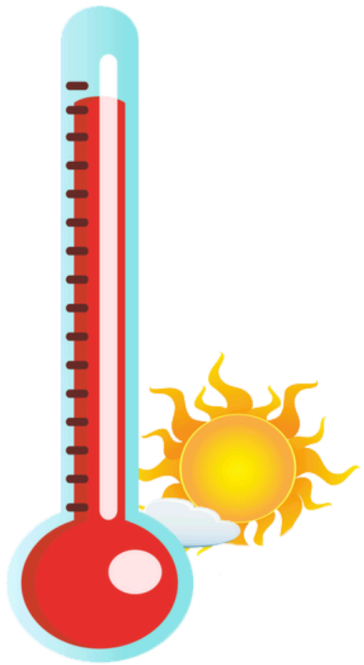
**Axion Portal to
Scalar Dark Matter
($m_a \sim \text{GeV}$)**

FD, Sassi, JHEP 07 (2025)

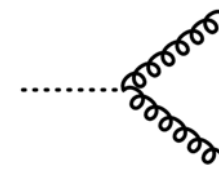
m_a

Thermal Axions

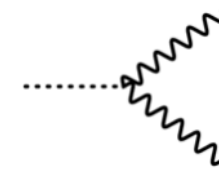
Unavoidable Production



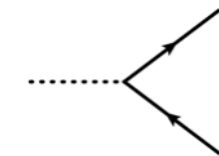
Scatterings and/or decays of thermal bath particles produce axions with kinetic energy much larger than their mass (i.e., “hot”)



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



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

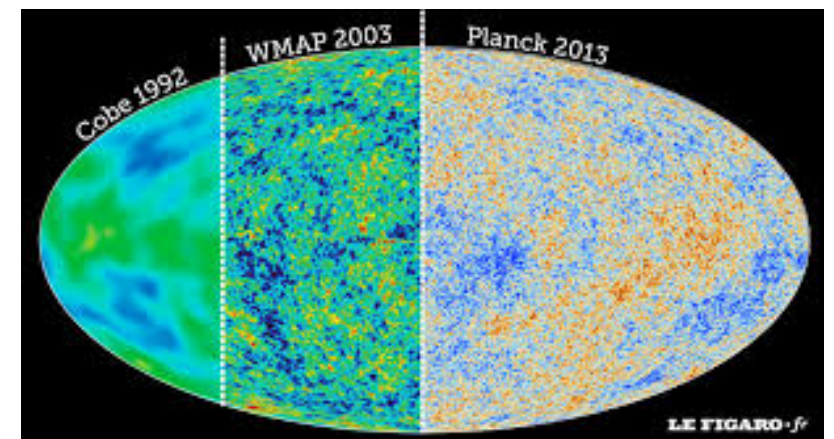


$$c_\psi \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

Signals

Additional radiation at:

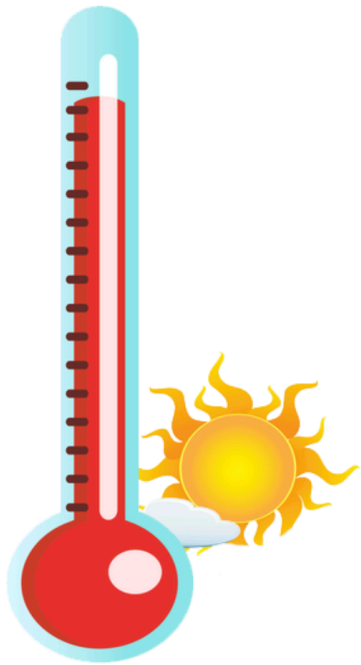
- BBN ($m_a \lesssim \text{MeV}$)
- CMB ($m_a \lesssim 0.1 \text{ eV}$)



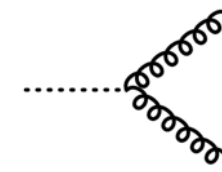
If $m_a \sim 0.1 \text{ eV}$ we have a hot dark matter component (exactly as neutrinos in the Standard Model)

Thermal Axions

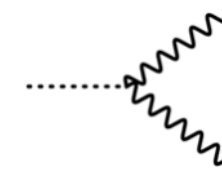
Unavoidable Production



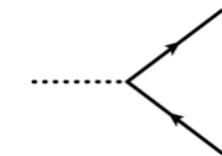
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$$c_\psi \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

Axion/fermion couplings

Baumann, Green, Wallisch, Phys.Rev.Lett. 117 (2016)

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

FD, Ferreira, Notari, Bernal, JCAP 11 (2018)

Arias-Aragón, FD, Ferreira, Merlo, Notari, JCAP 11 (2020)

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

Green, Guo, Wallisch, JCAP 02 (2022)

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

Badziak, Laletin, JHEP 02 (2025)

FD, Lenoci, Phys.Rev.D 110 (2024)

Axion/gauge boson couplings

Graf, Steffen, Phys.Rev.D 83 (2011)

Salvio, Strumia, Xue, JCAP 01 (2014)

FD, Hajkarim, Yun, JHEP 10 (2021)

FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

Caloni, Gerbino, Stengel Lattanzi, JCAP 10 (2024)

Bouzoud, Ghiglieri, JHEP 01 (2025)

Axion WDM mass bound

Ferreira, Notari, Rompineve, Phys.Rev.D 103 (2021)

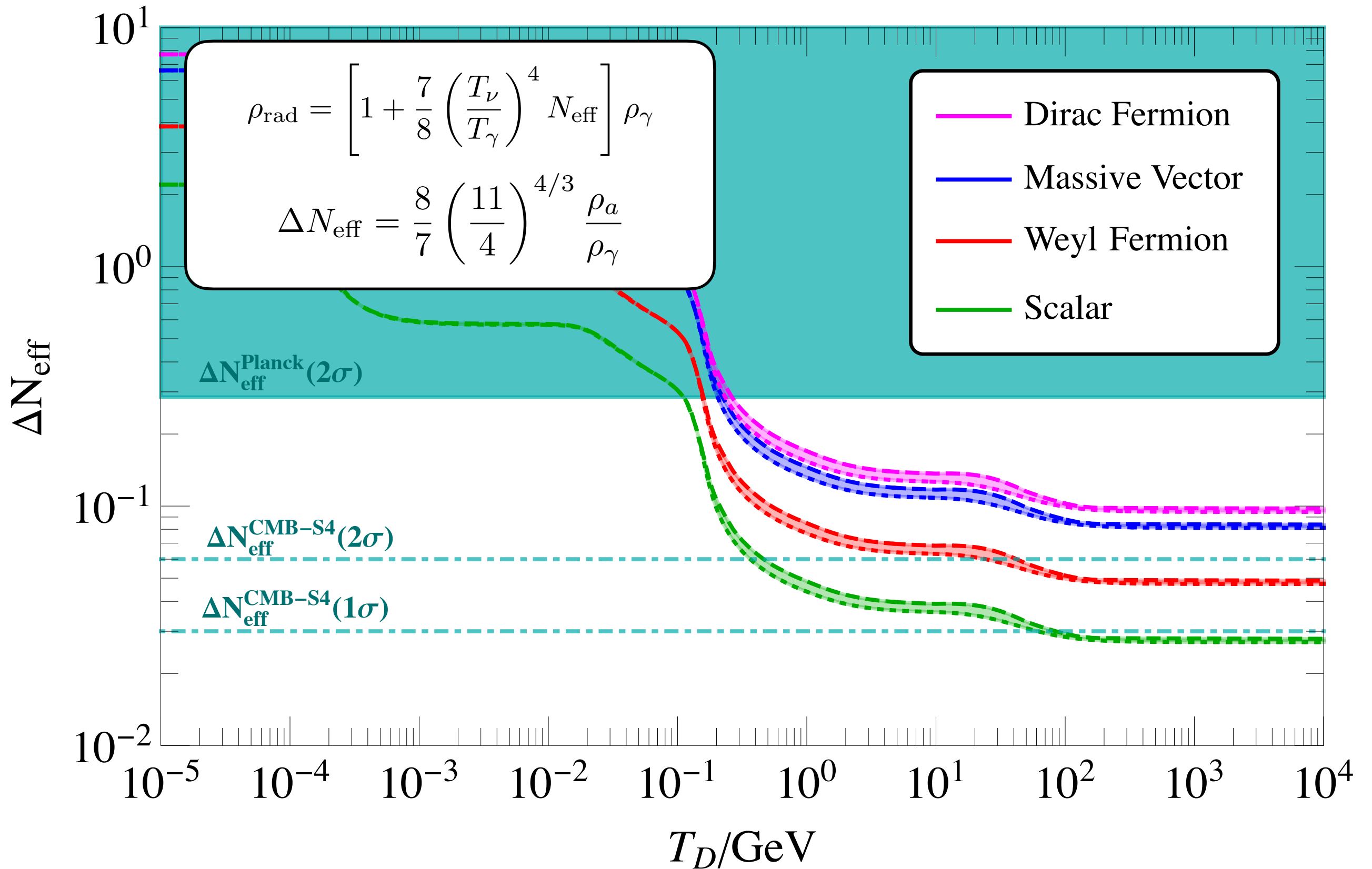
Caloni, Gerbino, Lattanzi, Visinelli, JCAP 09 (2022)

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

Notari, Rompineve, Villadoro, Phys.Rev.Lett. 131 (2023)

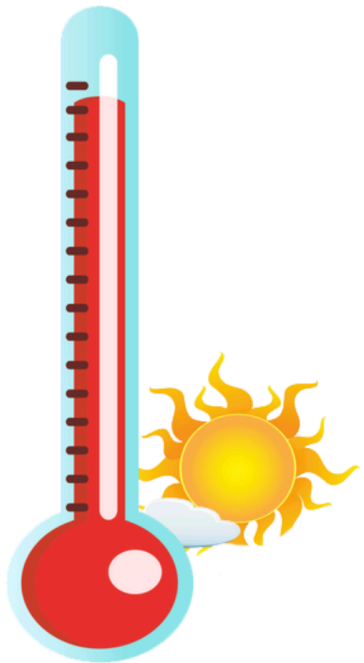
Bianchini, Grilli, Valli, Phys.Rev.D 110 (2024)

Dark Radiation in the CMB

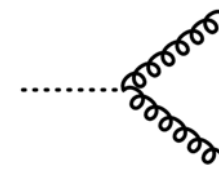


Improved Prediction for ΔN_{eff}

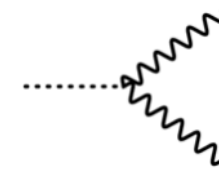
Unavoidable Production



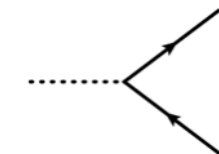
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$$\frac{\alpha_s}{8\pi} \frac{a}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$



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

Tracking the Axion Population



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

- Equilibrium thermodynamics for the conversion to energy
- Spectral distortions neglected
- Maxwell-Boltzmann statistics (i.e., no quantum effects)
- Static thermal bath (i.e., no energy exchanged)



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

Model Independent Contribution

Strong CP Problem

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

Above QCDPT

$$gg \rightarrow ga$$

$$\bar{q}q \rightarrow ga$$

$$q/\bar{q} g \rightarrow q/\bar{q} a$$

Long-range of gluon-mediated interactions
give rise to unpleasant IR behavior

Masso, Rota, Zsembinski, PRD66 (2002)

Graf, Steffen, PRD 83 (2011)

Salvio, Strumia, Xue, JCAP 01 (2014)

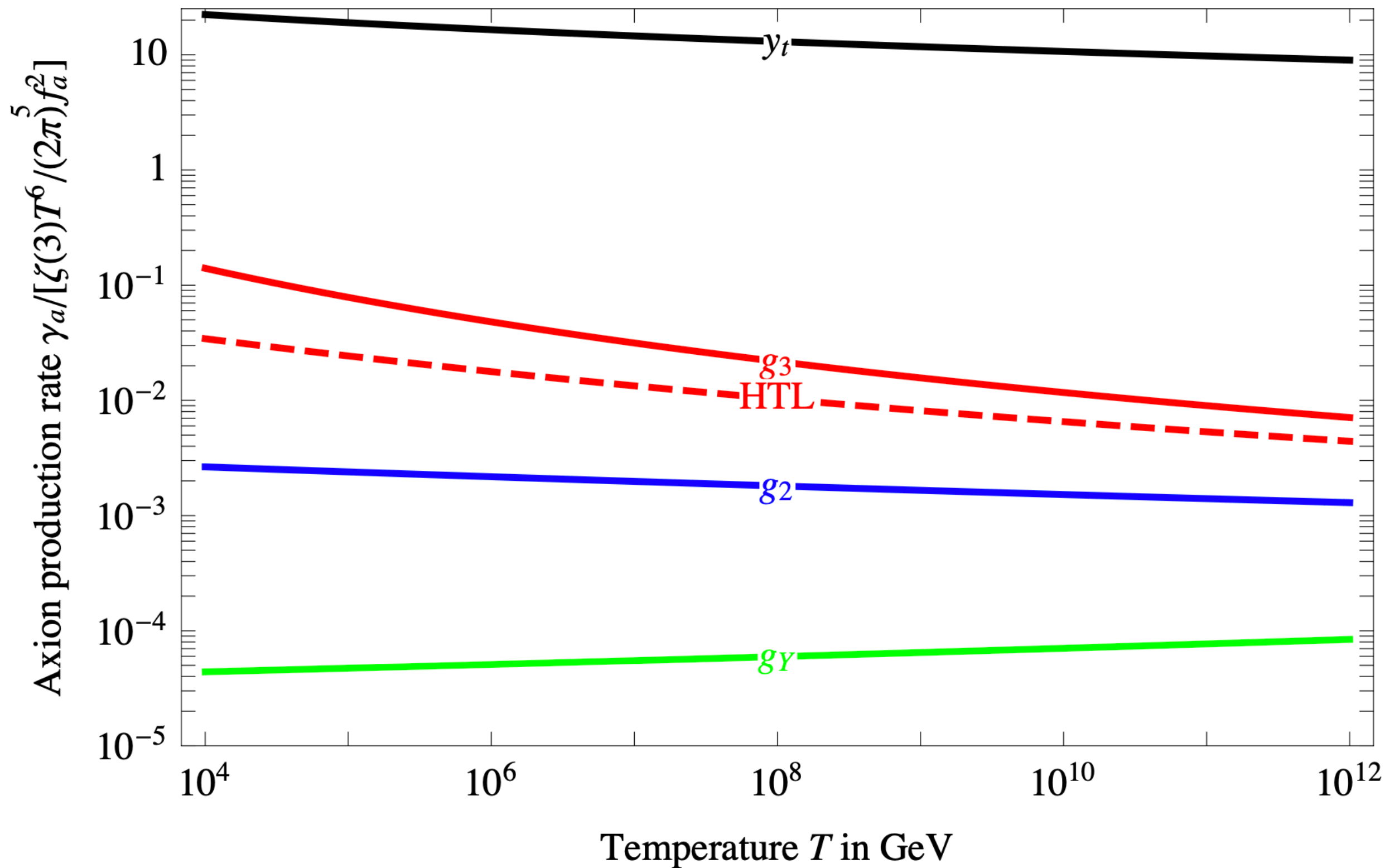
Below QCDPT

$$\pi\pi \rightarrow \pi a$$

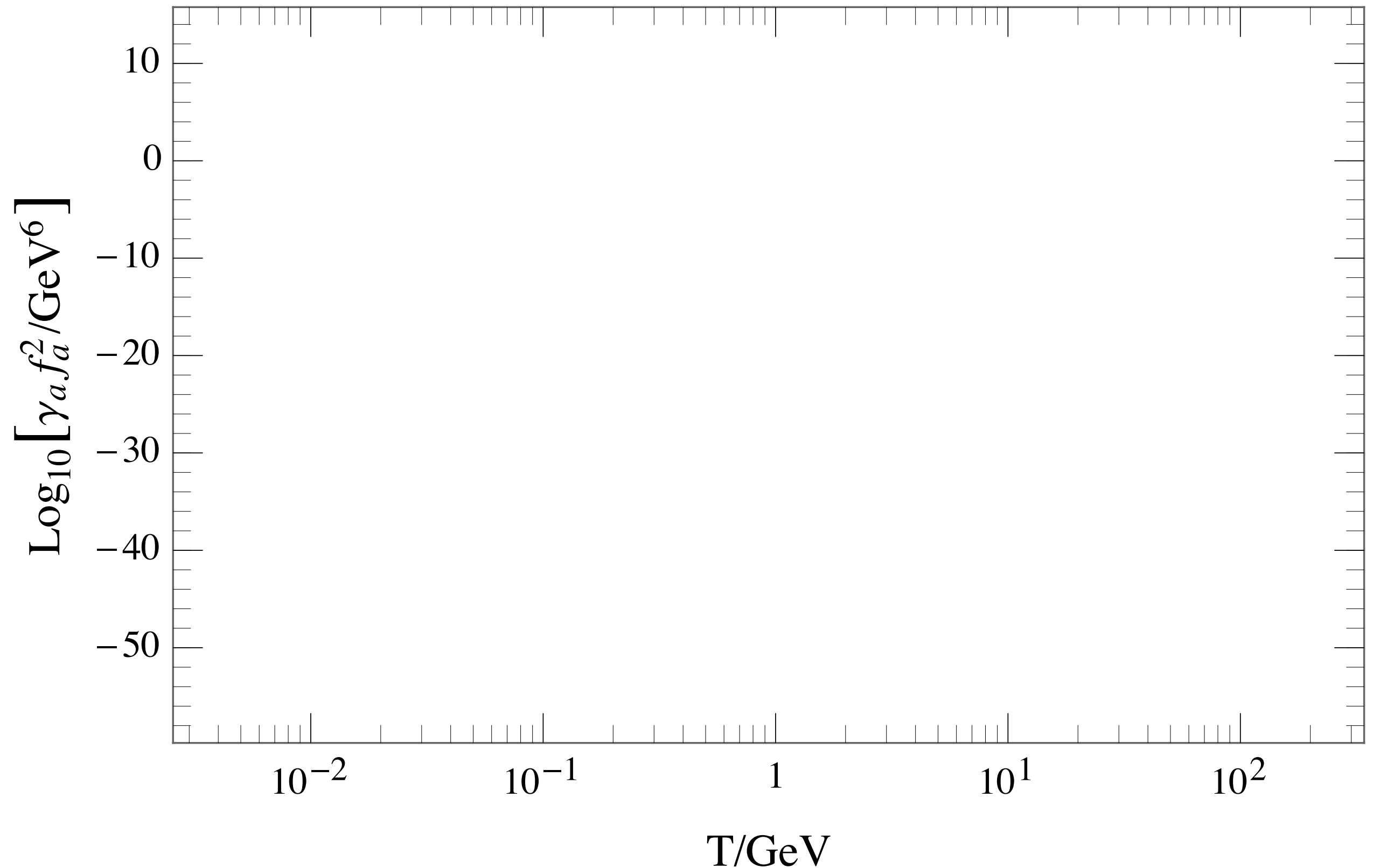
Thermalization via pion scattering
requires rather small values of f_a

Chang, Choi, PLB 316 (1993)

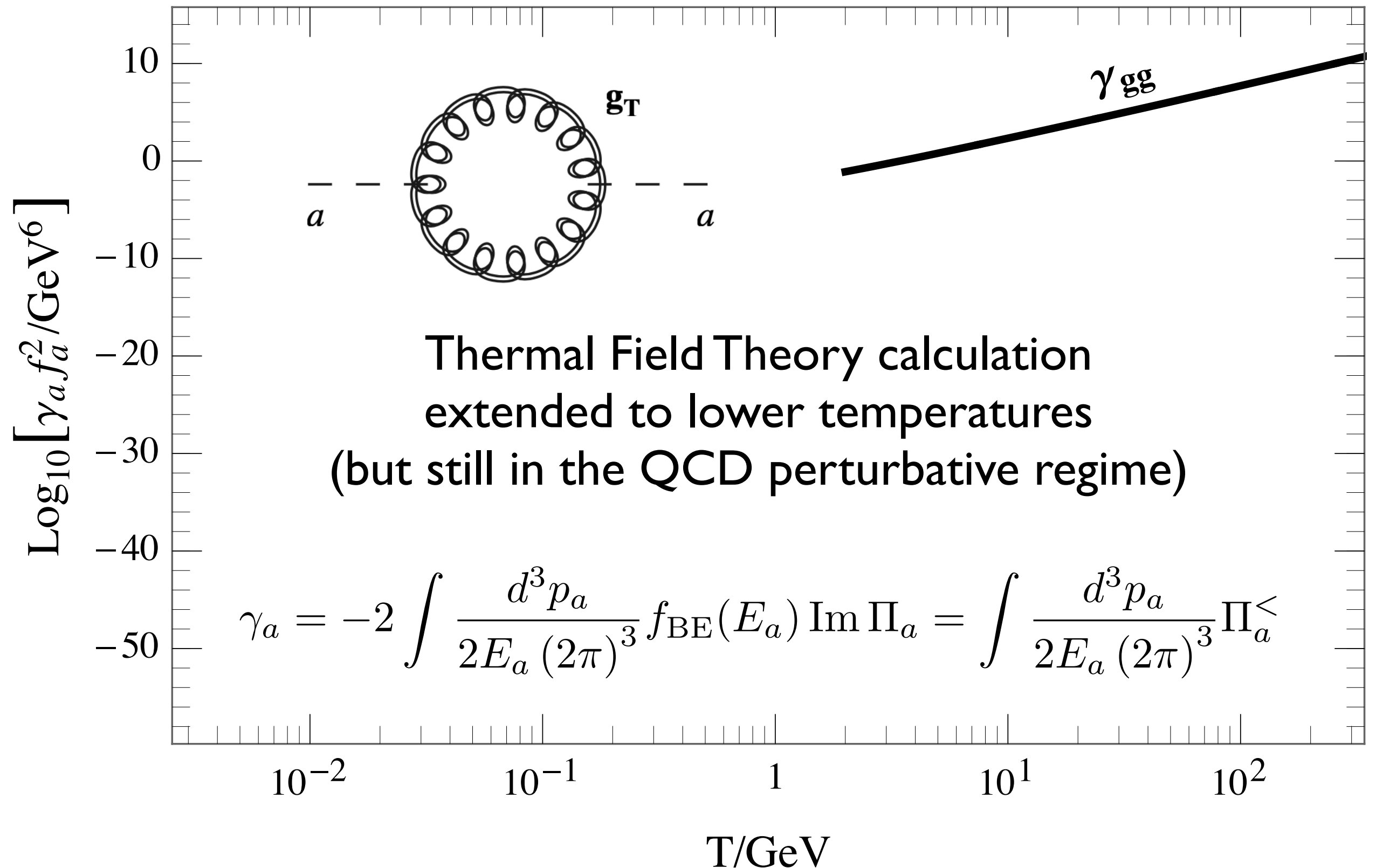
Thermal Gluon Scattering



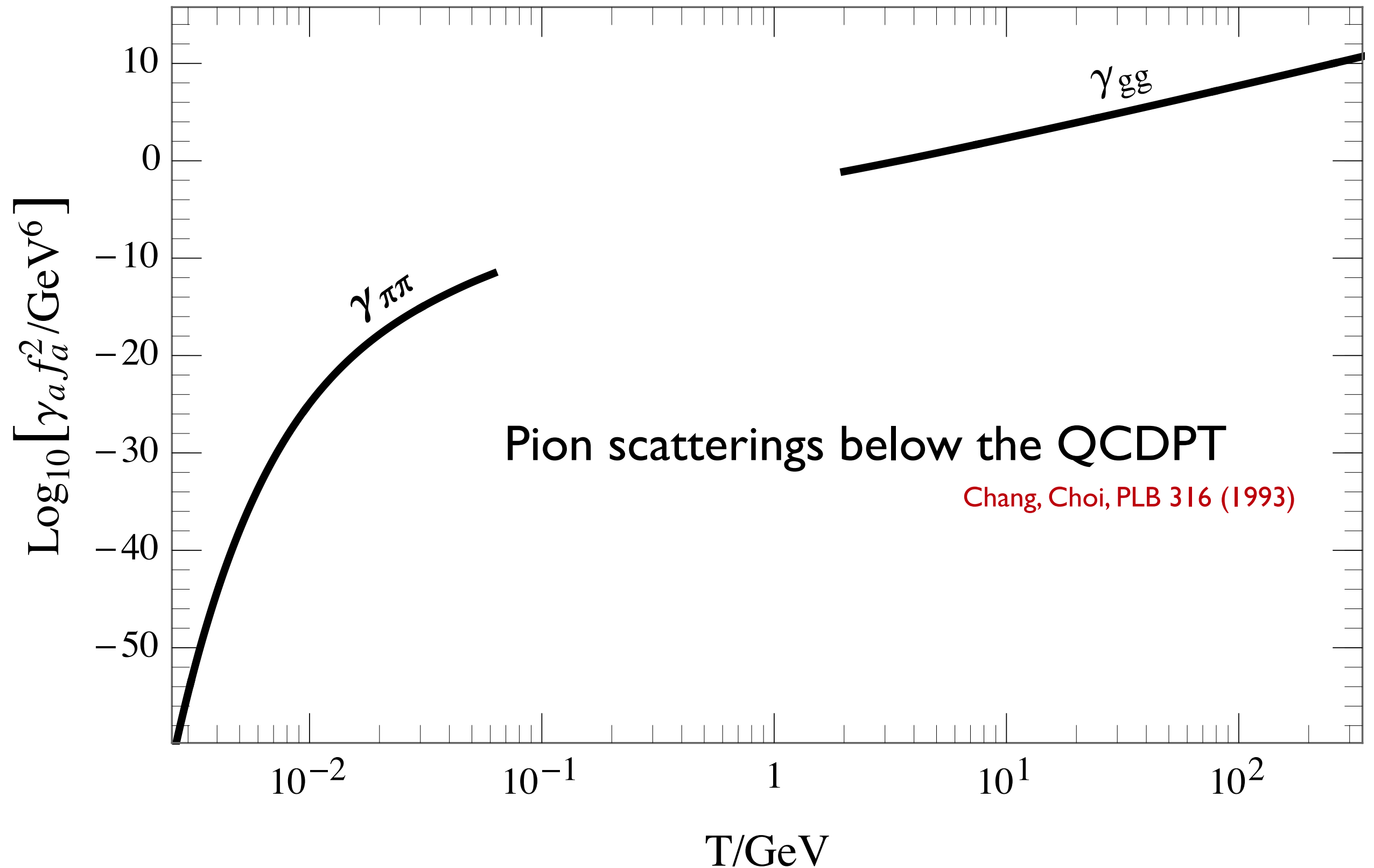
Approaching the QCD Scale



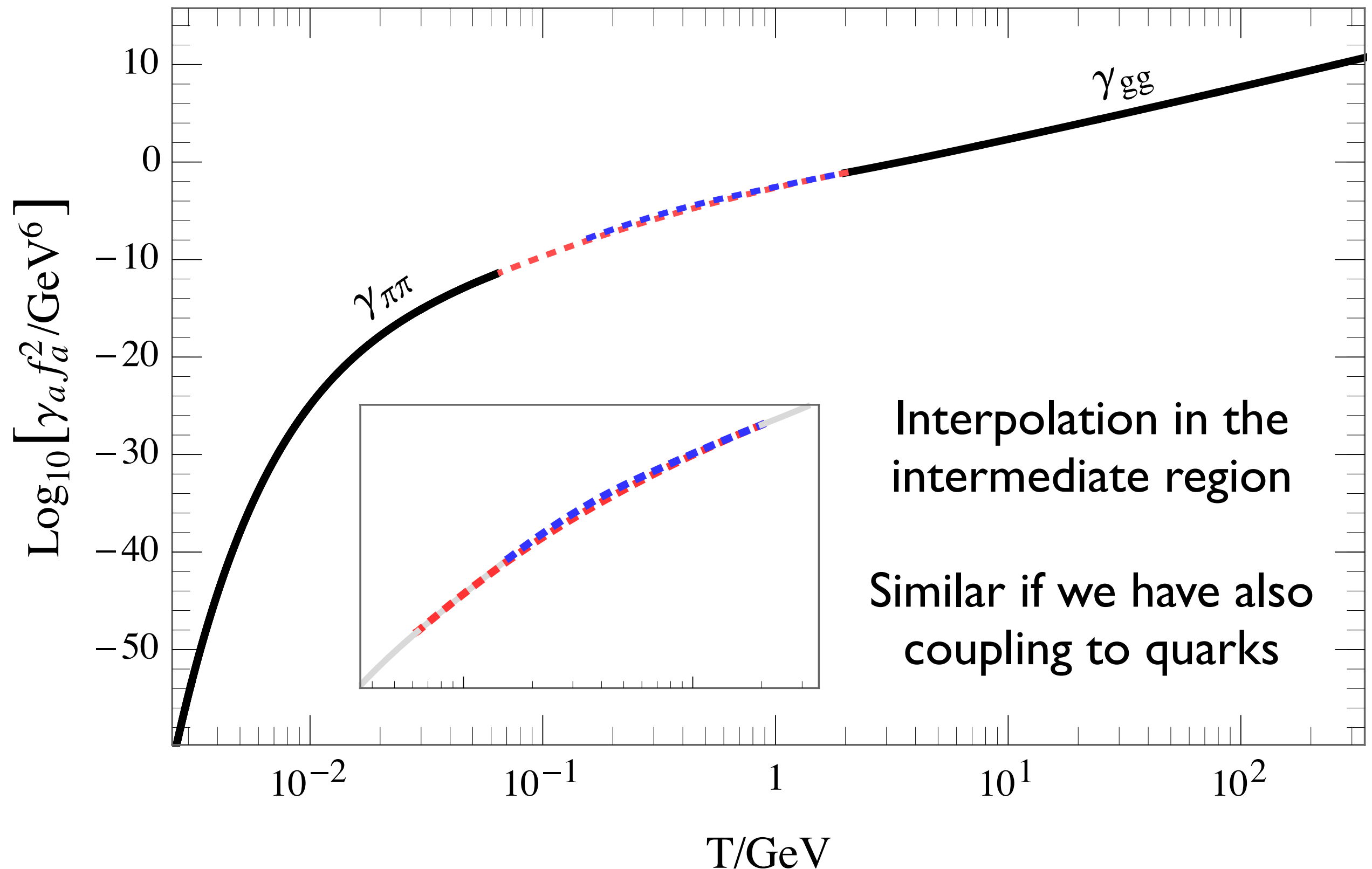
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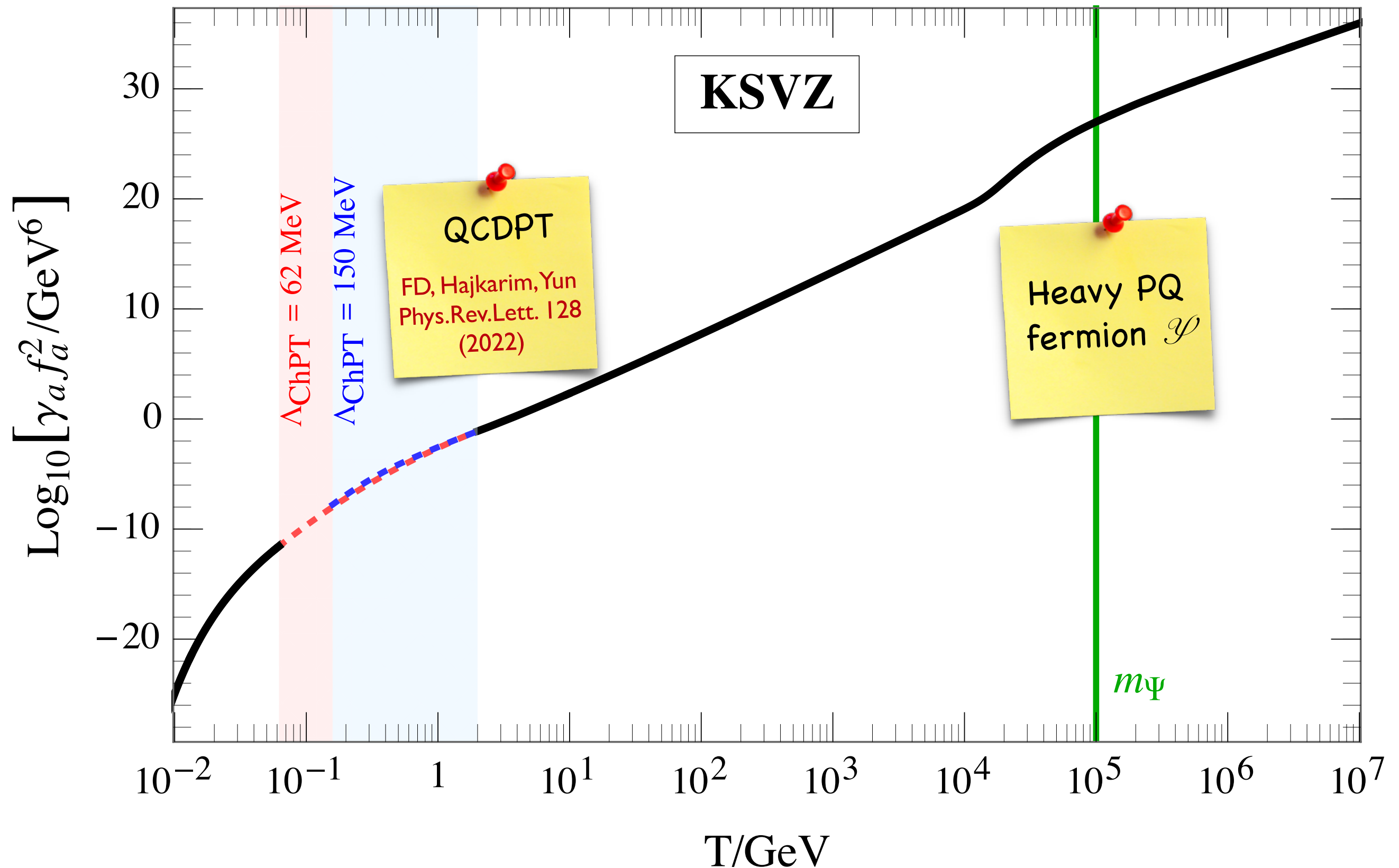
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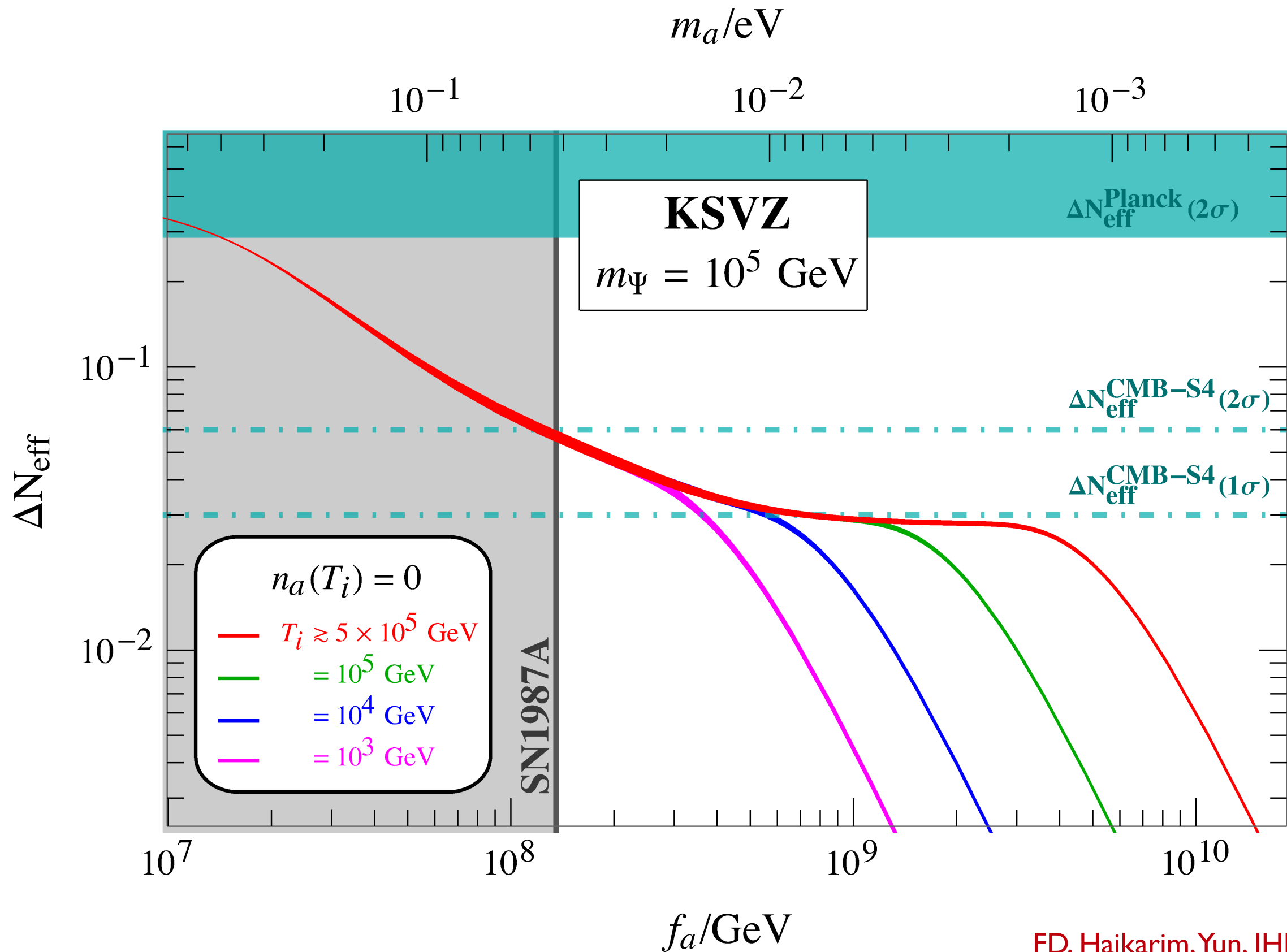
Approaching the QCD Scale



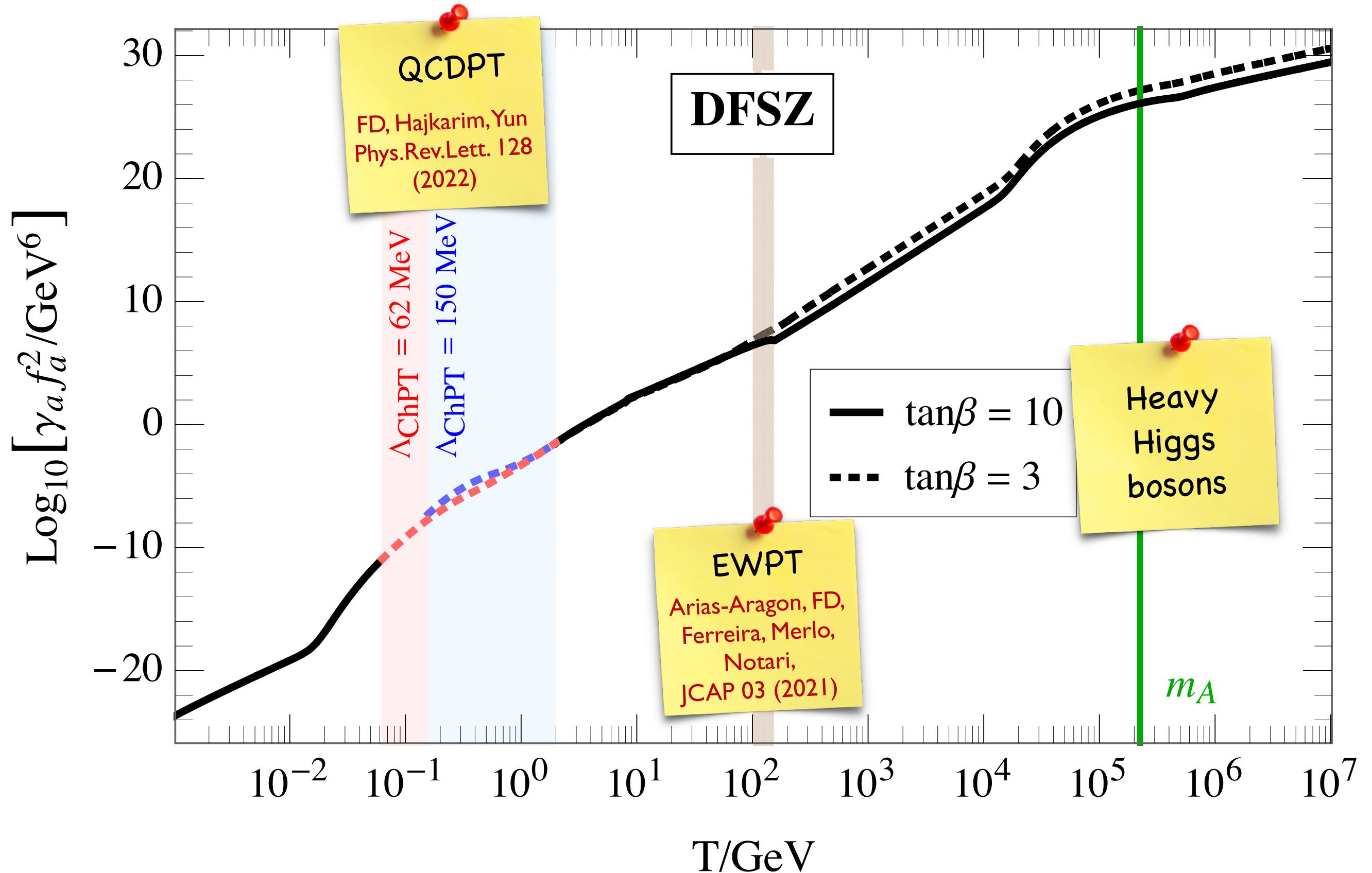
KSVZ Axion — Production Rate



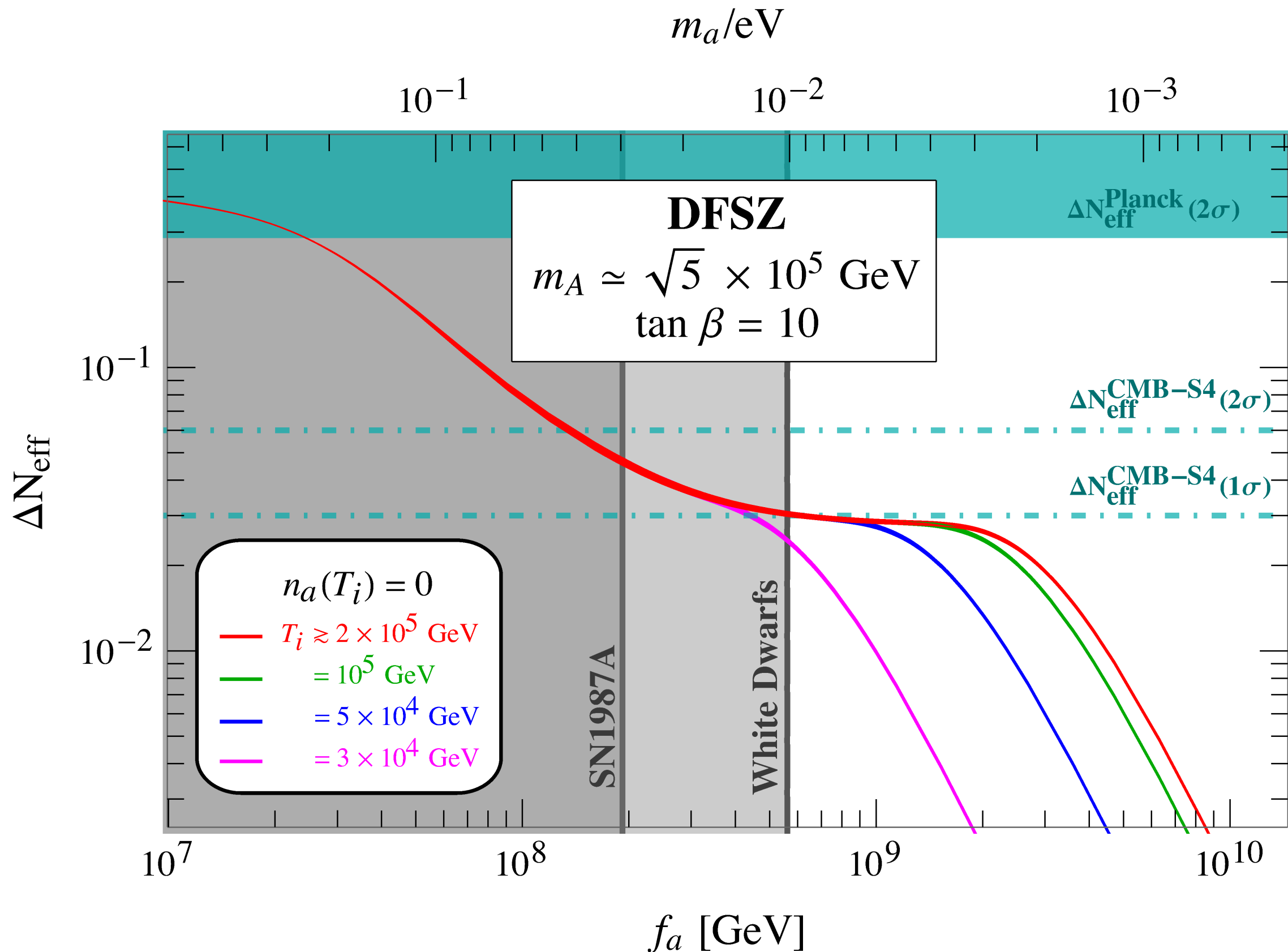
KSVZ Axion — Results for ΔN_{eff}



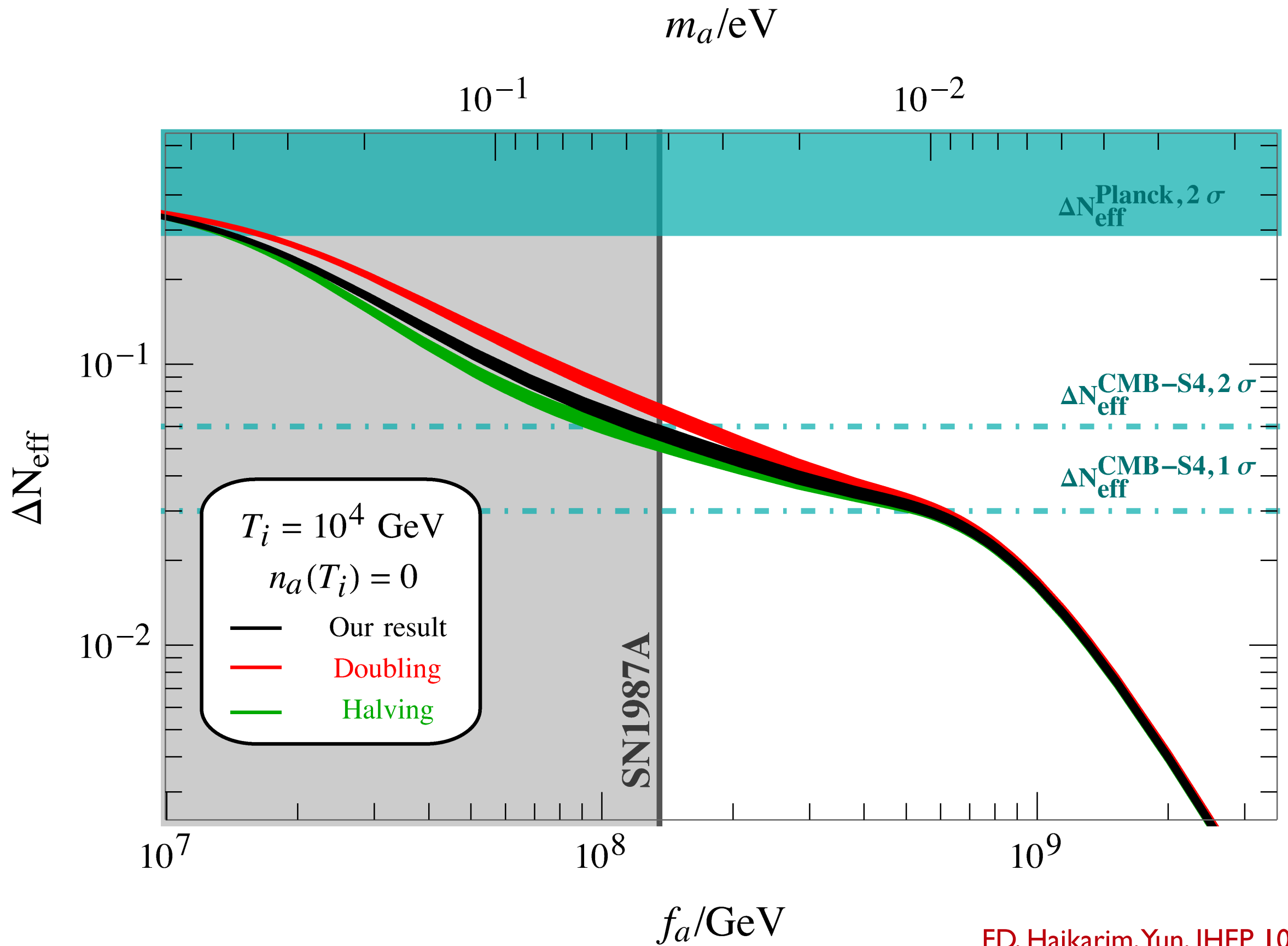
DFSZ Axion — Production Rate



DFSZ Axion — Results for ΔN_{eff}



A Worrisome Interpolation?



Finite QCD Axion Mass Effects?

Planck: tension with
astrophysics and axion
mass non-negligible

Finite axion mass

- Pion scatterings

Ferreira et al., Phys.Rev.D 103 (2021)

Notari et al., Phys.Rev.Lett. 131 (2023)

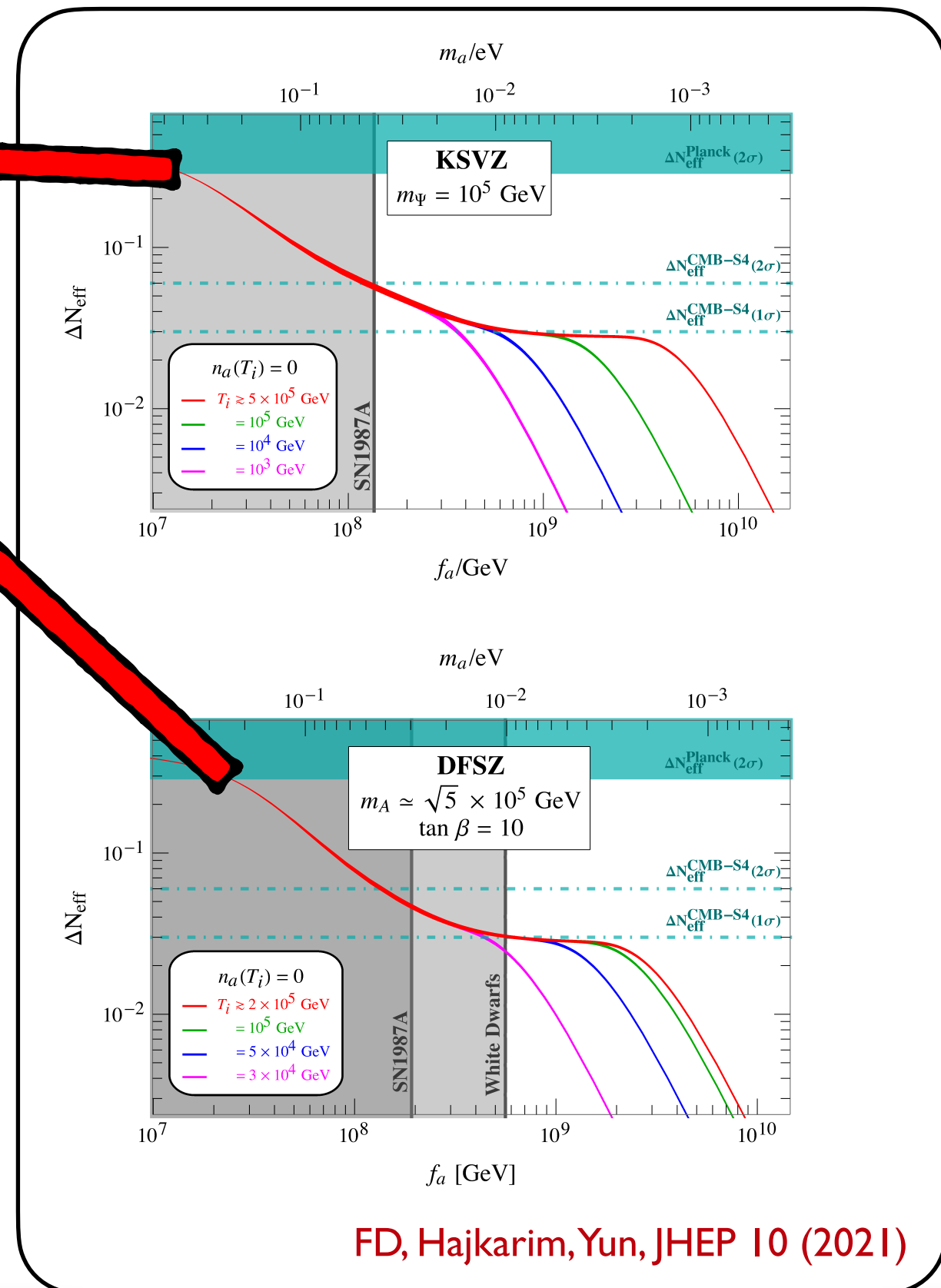
Bianchini et al., Phys.Rev.D 110 (2024)

- Gluon, photon couplings

Caloni et al., JCAP 09 (2022)

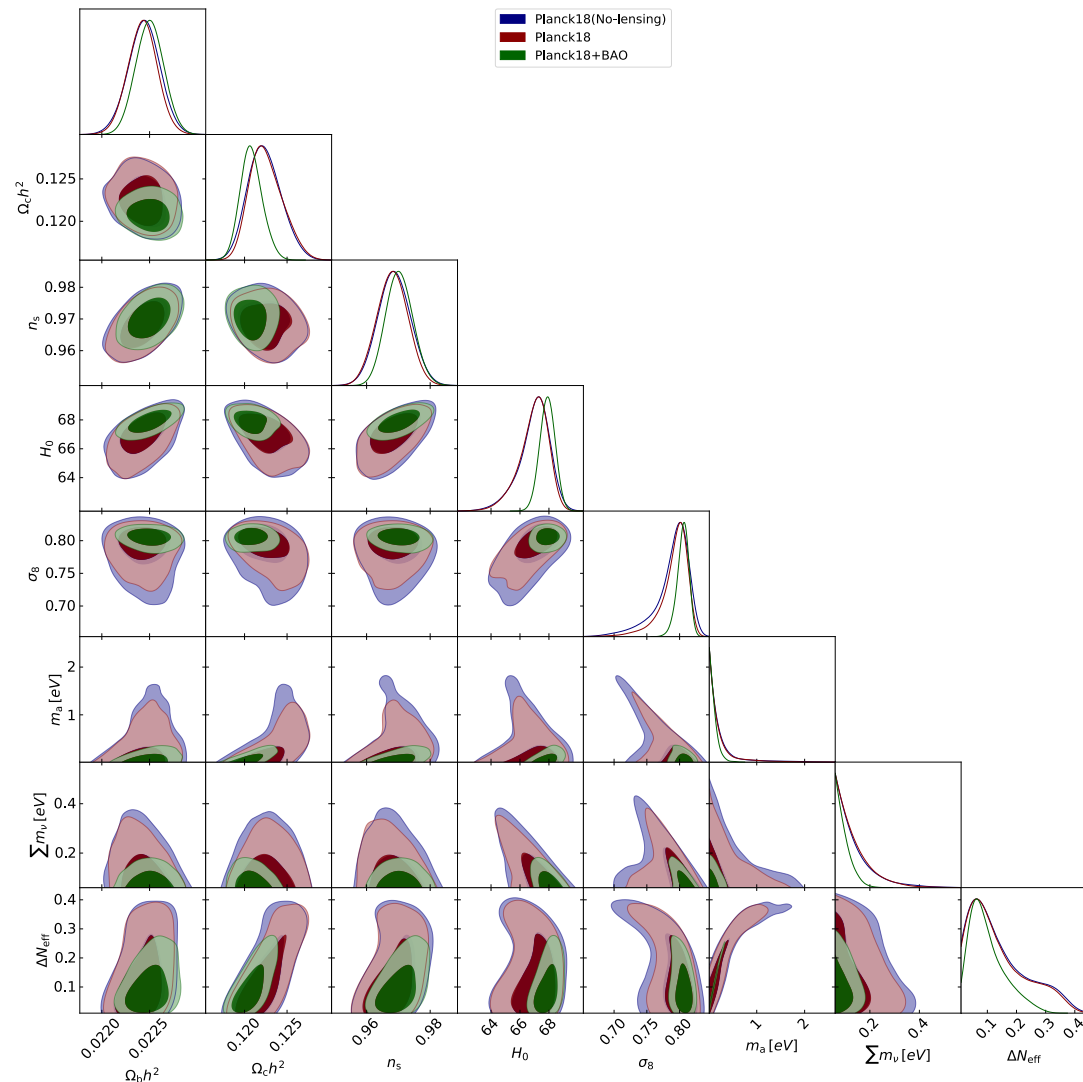
- KSVZ and DFSZ

FD et al., JCAP 09 (2022)



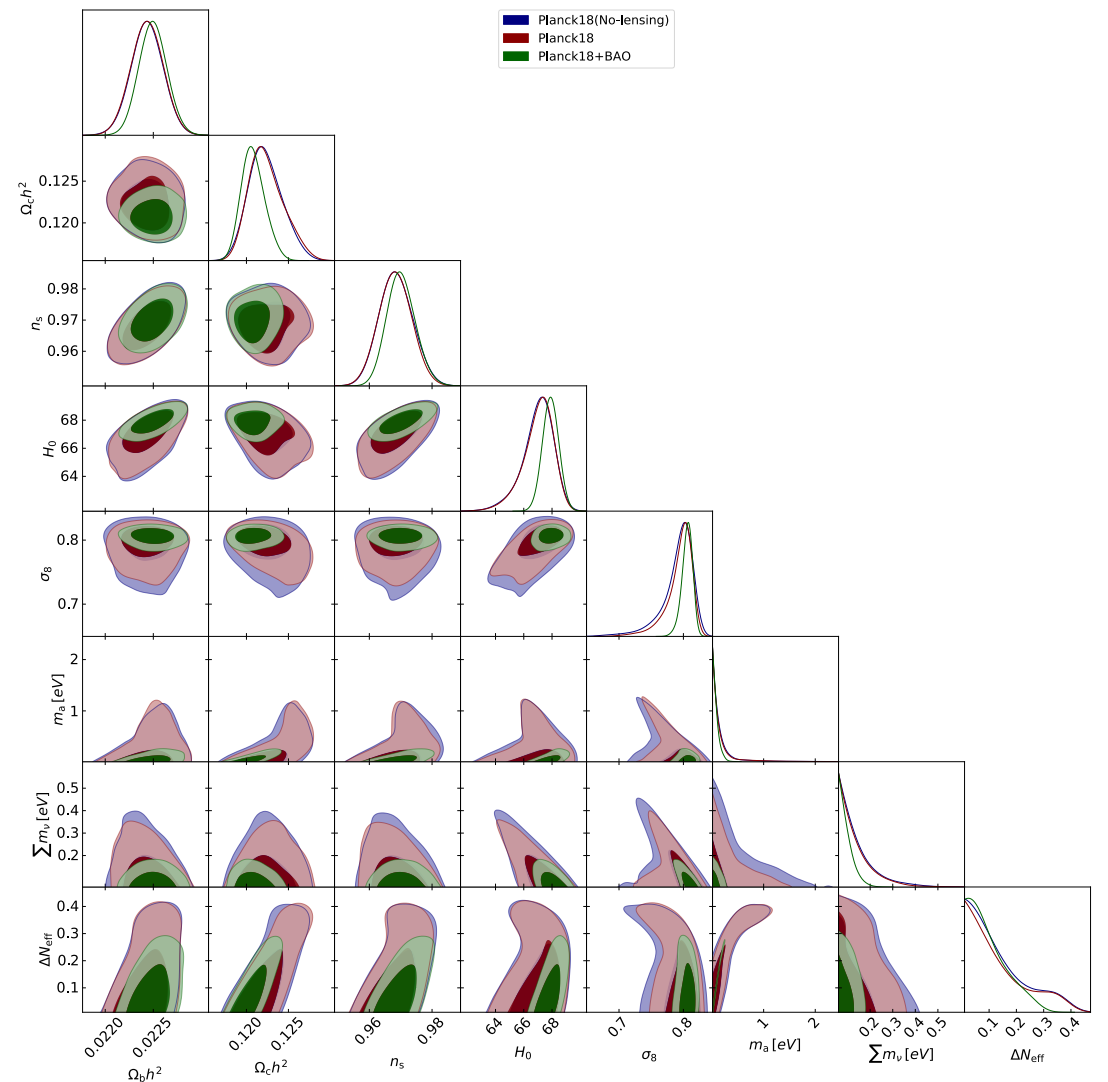
Axion Mass Bound

KSVZ



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

DFSZ



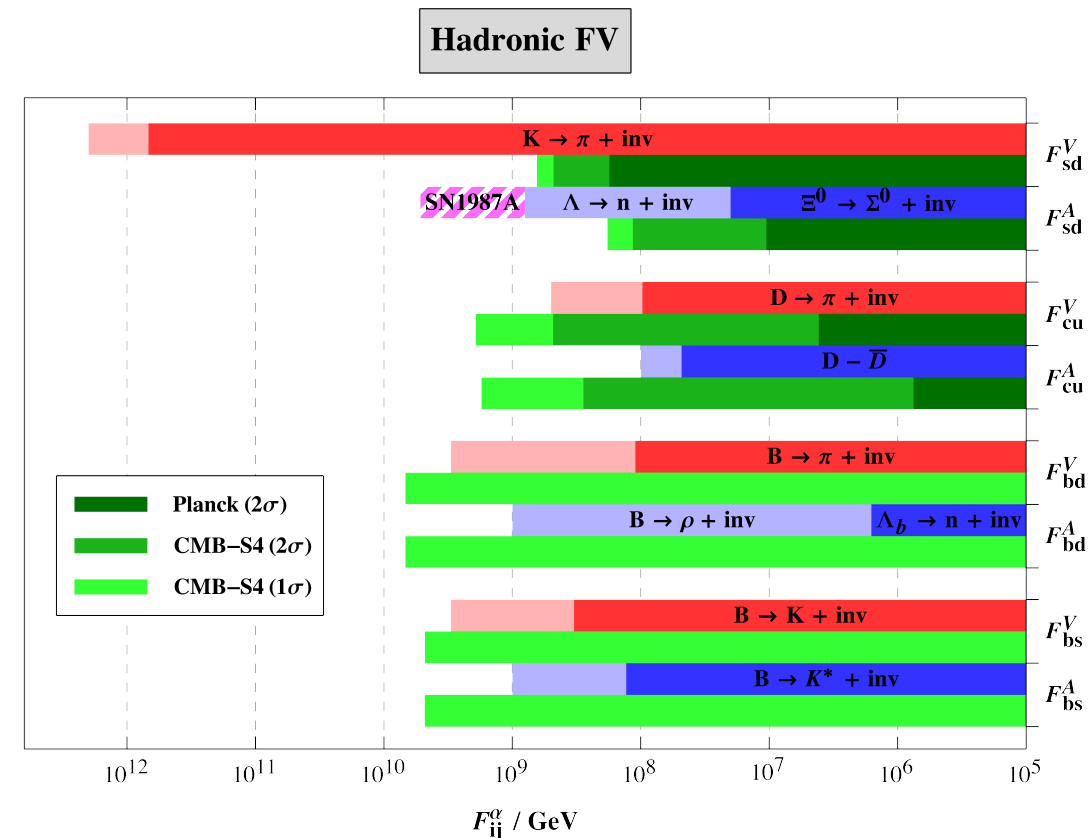
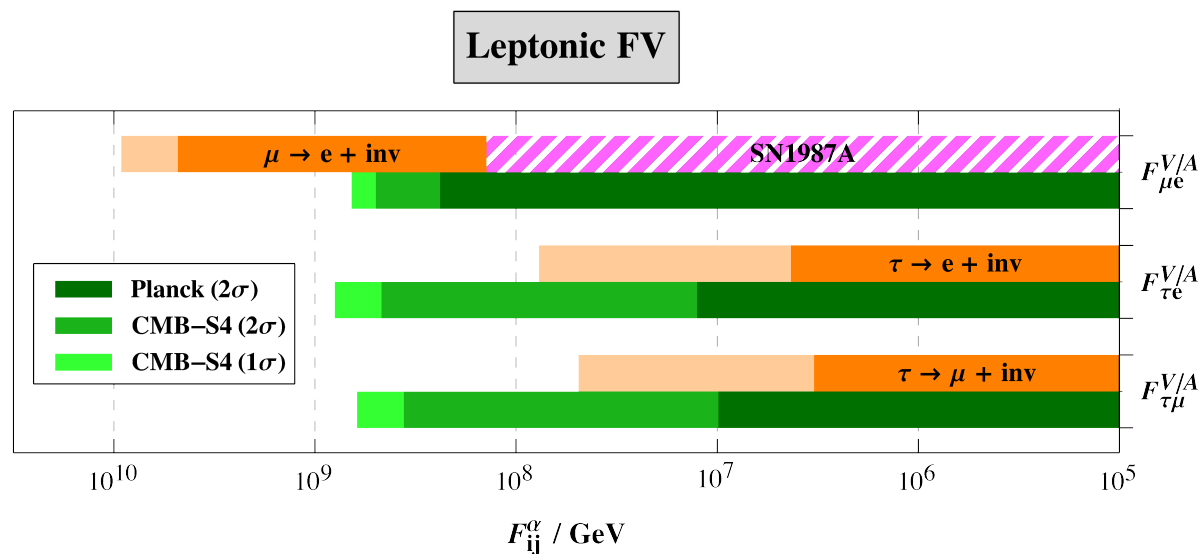
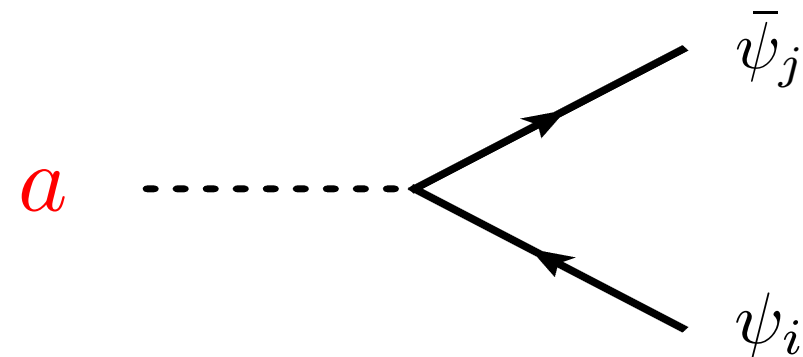
$$m_a \leq 0.209(0.293) \text{ eV}$$

A Minor Variation: FV Axions

Target of several
terrestrial experiments

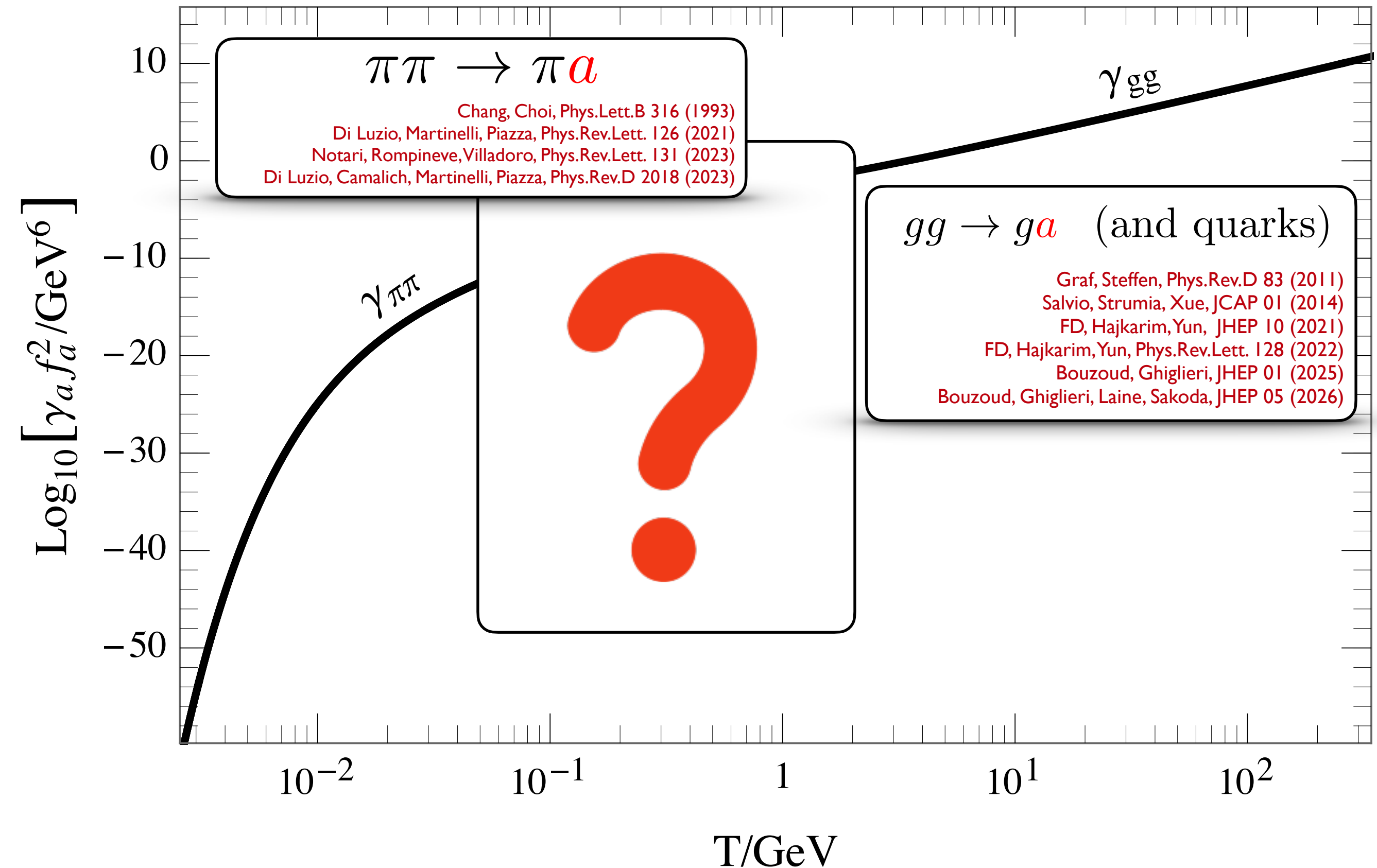
What about their role
in the early universe?

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

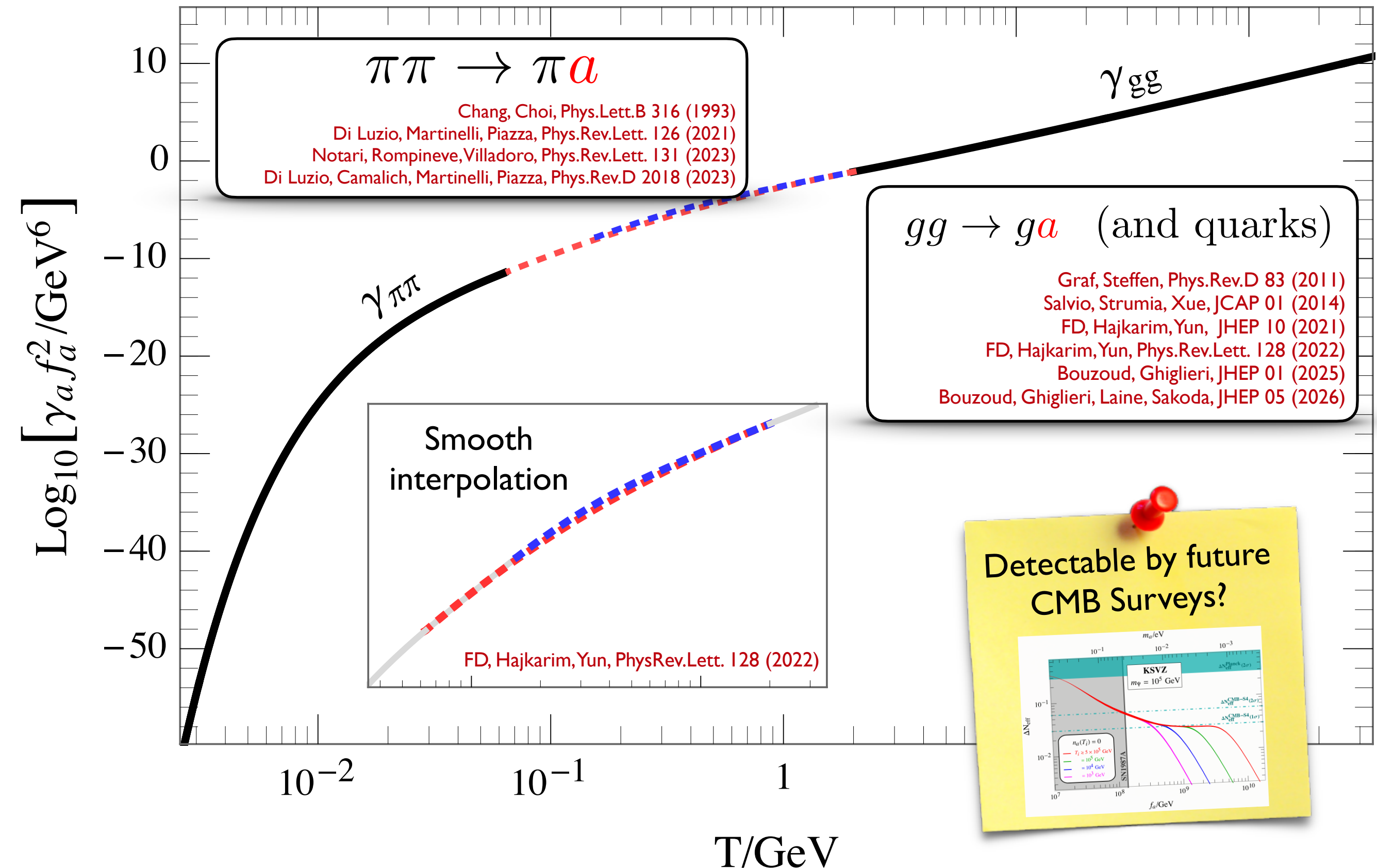


Current and future cosmological bounds
competitive (or sometimes even better!)
than terrestrial searches

Where do we stand?



Where do we stand?



What's next?

Axion production rate
across the confinement scale still unknown

$$\gamma_a = n_i n_j \times \langle \sigma_{ij \rightarrow ja} v_{\text{rel}} \rangle$$

Thermal bath

Particle Physics

1. Cross sections with other hadrons?
2. Thermal bath description between 150 MeV and a few GeV?
3. Boltzmann equation evolution and cosmological observables?

Back to the Phase Space

Axion Momentum Distribution

$$\frac{df_a(k, t)}{dt} = \mathcal{C}(k, t) \left(1 - \frac{f_a(k, t)}{f_a^{\text{eq}}(k, t)} \right)$$

Typical spectral distortions detectable in the future!

$$\mathcal{C}(k, t) = \frac{1}{2\omega} \int \prod_{i=1}^n d\Pi_i \prod_{j=n+1}^{n+m} d\Pi_j (2\pi)^4 \delta^4(P_{\text{in}} - P_{\text{fin}}) |\mathcal{M}|^2 \prod_{i=1}^n f_{\mathcal{B}_i} \prod_{j=n+1}^{n+m} (1 \pm f_{\mathcal{B}_j}) .$$

FD, Hajkarim, Lenoci, JCAP 03 (2024)

Axion/fermion couplings

Baumann, Green, Wallisch, *Phys.Rev.Lett.* 117 (2016)
Ferreira, Notari, *Phys.Rev.Lett.* 120 (2018)
FD, Ferreira, Notari, Bernal, *JCAP* 11 (2018)
Arias-Aragón, Merlo, Notari, *JCAP* 11 (2020)
Arias-Aragón, Merlo, Notari, *JCAP* 03 (2021)
Green, Guo, Wallisch, *JCAP* 02 (2022)
FD, Yun, *Phys.Rev.D* 105 (2022)
Badziak, Laletin, *JHEP* 02 (2025)
FD, Lenoci, *Phys.Rev.D* 110 (2024)

Leptons



Leptons&HeavyQuarks

Studies using a phase-space formalism are the exception

Axion/gauge boson couplings

Sraf, Steffen, *Phys.Rev.D* 83 (2011)
Salvio, Strumia, Xue, *JCAP* 01 (2014)
FD, Hajkarim, Yun, *JHEP* 10 (2021)
Hajkarim, Yun, *Phys.Rev.Lett.* 128 (2022)
Bouzoud, Ghiglieri, *JHEP* 01 (2025)

Axion WDM mass bound

Ferreira, Notari, Rompineve, *Phys.Rev.D* 103 (2021)
Caloni, Gerbino, Lattanzi, *JCAP* 09 (2022)
Giarè, Hajkarim, Melchiorri, Mena, Rompineve, Yun, *JCAP* 09 (2022)
Notari, Rompineve, Villadoro, *Phys.Rev.Lett.* 131 (2023)
Bianchini, Grilli, Valli, *Phys.Rev.D* 110 (2024)

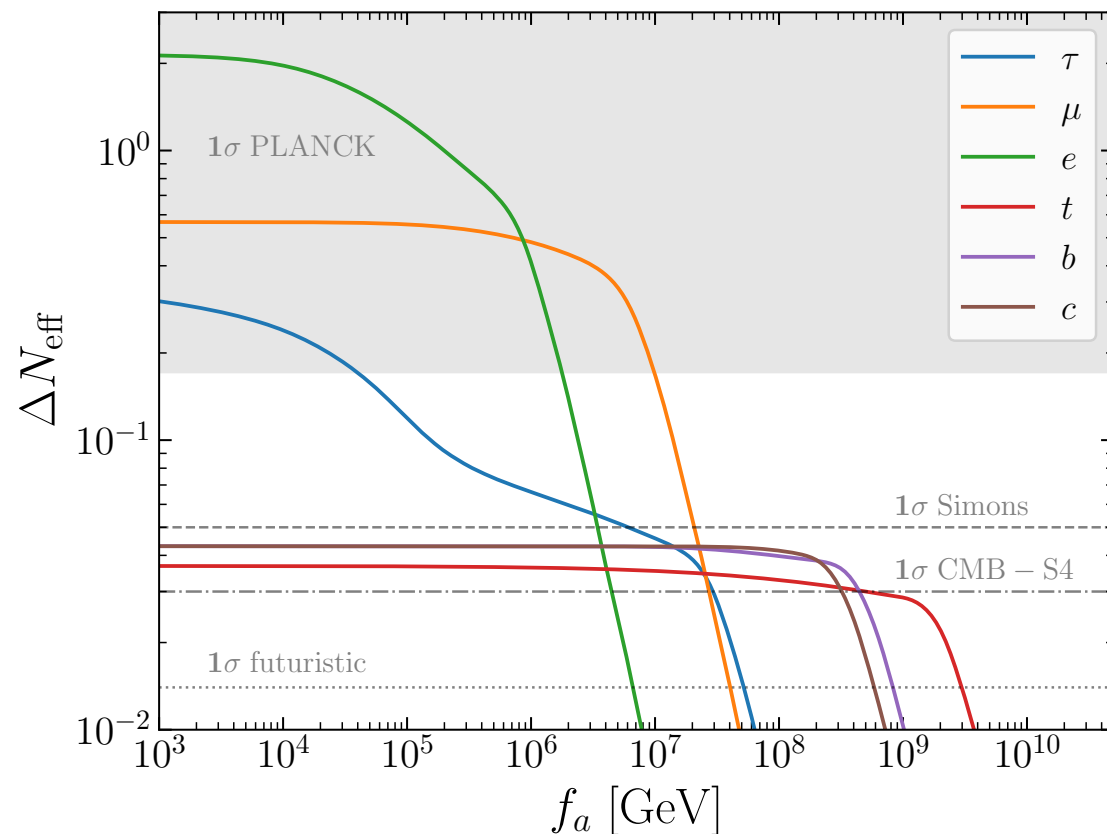
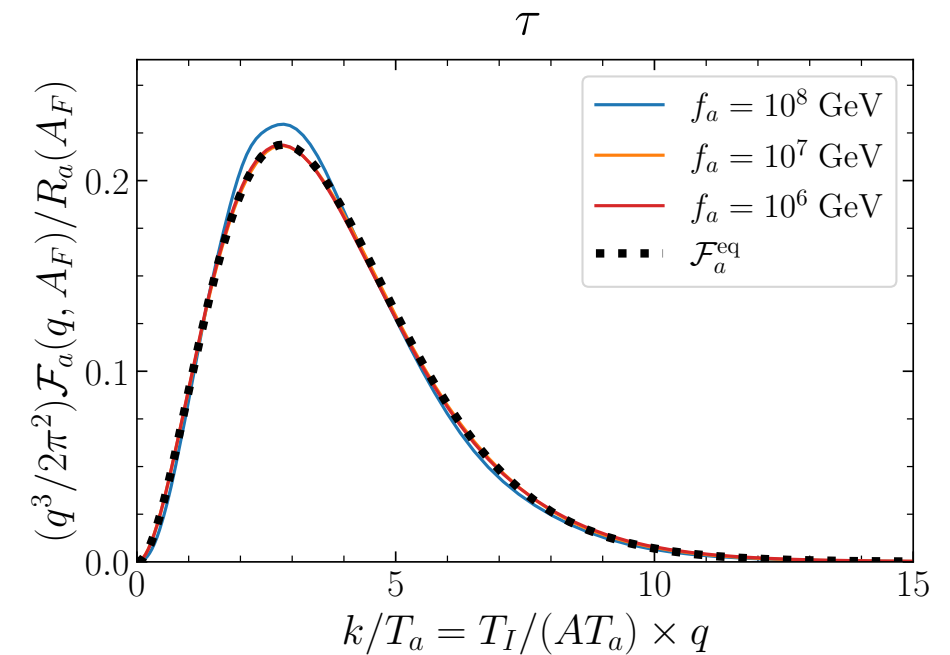
Pions



Fermion Couplings in Phase Space

$$\mathcal{L}_{\text{int}} = \frac{\partial_\mu a}{2f_a} \sum_\psi c_\psi \bar{\psi} \gamma^\mu \gamma_5 \psi$$

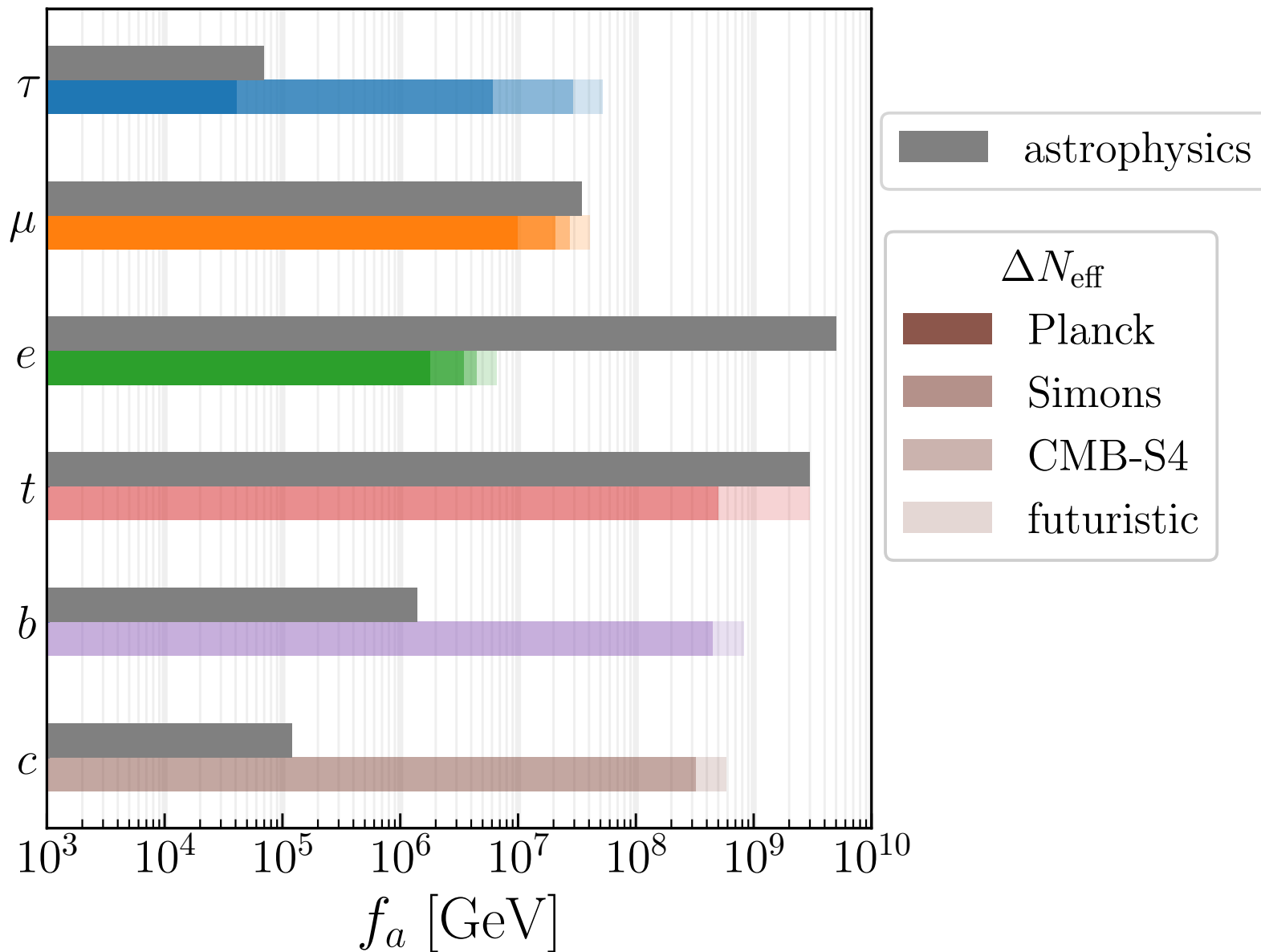
Phase space distribution
very close to a thermal
one (with a different T)
even in the *freeze-in* region



Phase space analysis matters!
Spectral distortions due to
non-instantaneous decoupling
alter the predictions

Fermion Couplings in Phase Space

$$\mathcal{L}_{\text{int}} = \frac{\partial_\mu a}{2f_a} \sum_\psi c_\psi \bar{\psi} \gamma^\mu \gamma_5 \psi$$



Comparison with
astrophysics

Future cosmological
probes will provide
stronger bounds!

Outlook

Cicoli, FD et al., “Axions at the meV
*Crossroads: Theory, Cosmology, Astrophysics,
and Experiments*”, **JCAP 07 (2026) 060**

THEORY

Theory points naturally to
the meV scale

COSMOLOGY

Thermal meV axions within
reach of future CMB surveys

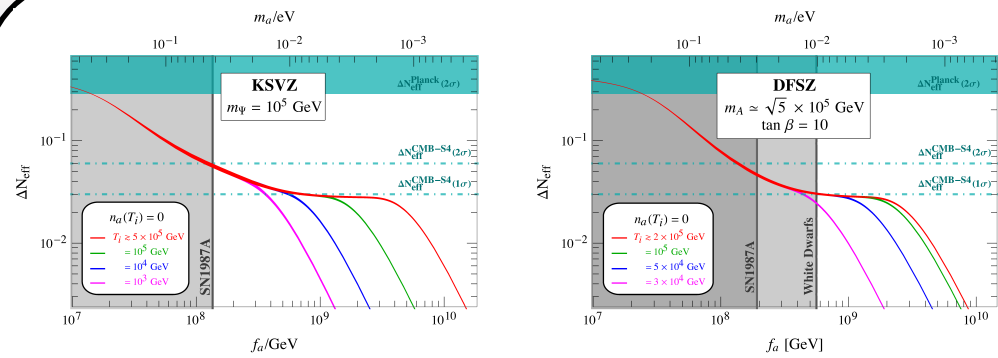
ASTROPHYSICS

We are already probing
meV axions

EXPERIMENTS

We are building ways to
discover meV axions

Outlook



ΔN_{eff} tracking the number density

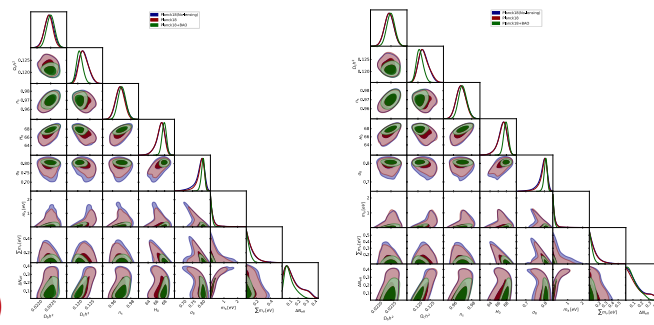
FD, Hajkarim, Yun, JHEP 10 (2021)

FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

COSMOLOGY

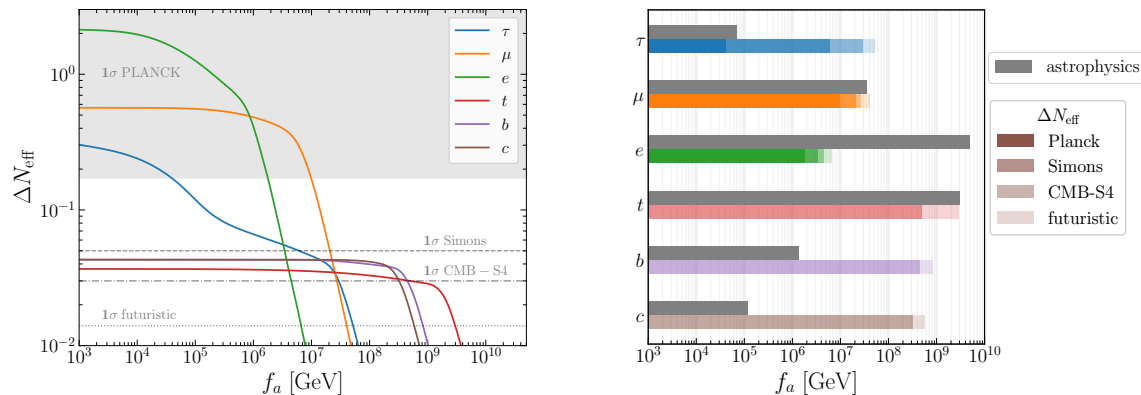
Axion cosmological mass bound

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



As cosmological data become more precise, thermal axion predictions must keep pace and challenges lie ahead!

ASTROPHYSICS



Importance of a phase space analysis

FD, Hajkarim, Lenoci, JCAP 03 (2024)

FD, Lenoci, Phys.Rev.D 110 (2024)

Outlook

Cicoli, FD et al., “Axions at the meV
Crossroads: Theory, Cosmology, Astrophysics,
and Experiments”, JCAP 07 (2026) 060

THEORY

COSMOLOGY

ASTROPHYSICS

EXPERIMENTS

