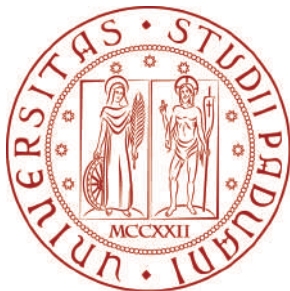


Five Lectures on Dark Matter

Fifth Lecture



UNIVERSITÀ
DEGLI STUDI
DI PADOVA



Istituto Nazionale
di Fisica Nucleare
Sezione di Padova

Francesco D'Eramo

The QCD Axion

Dark matter candidate
motivated from particle physics

Very light and weakly-coupled particle,
significantly different from WIMPs

Different production mechanisms

The Strong CP Problem

STRONG INTERACTIONS

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \bar{q}i\not{D}q - [\bar{q}_R m_q q_L + \text{h.c.}]$$

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

$$m_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

The Strong CP Problem

STRONG INTERACTIONS

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \bar{q}i\not{D}q - [\bar{q}_R m_q q_L + \text{h.c.}]$$

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

$$m_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

It conserves C, P and T (and of course CPT)

Can we conclude that we cannot have CP
(or T) violation by strong interactions?

The Strong CP Problem

CP VIOLATION

$$\mathcal{L}_{\text{QCD}}^{CPV} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu} - [\bar{q}_R m_q e^{i\theta_q} q_L + \text{h.c.}]$$

The Strong CP Problem

CP VIOLATION

$$\mathcal{L}_{\text{QCD}}^{CPV} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu} - [\bar{q}_R m_q e^{i\theta_q} q_L + \text{h.c.}]$$

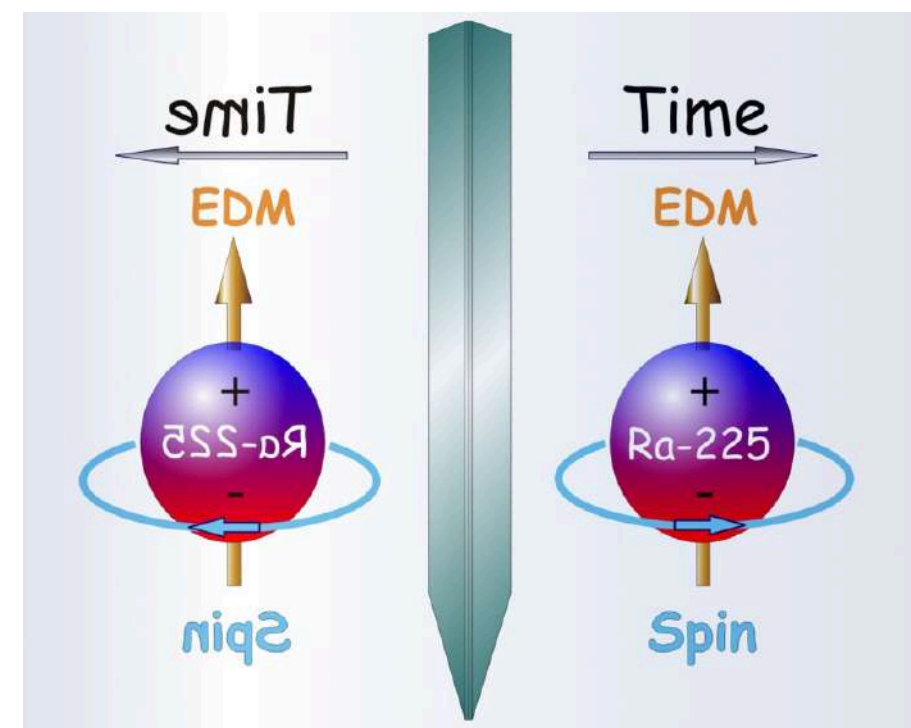
$$\bar{\theta} \equiv \theta - \sum_q \theta_q$$

OBSERVABLE CONSEQUENCES

Neutron electric dipole moment

$$d_n \simeq 2.4 \times 10^{-16} \bar{\theta} e \text{ cm}$$

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



The Strong CP Problem

CP VIOLATION

$$\mathcal{L}_{\text{QCD}}^{CPV} = \theta \frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu} - [\bar{q}_R m_q e^{i\theta_q} q_L + \text{h.c.}]$$

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

A SPECTACULAR BOUND

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

Why so small?

The Peccei-Quinn Solution

Dynamical solution to the strong CP problem

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

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

Peccei, Quinn, PRL38 (1977) and PRD16 (1977)

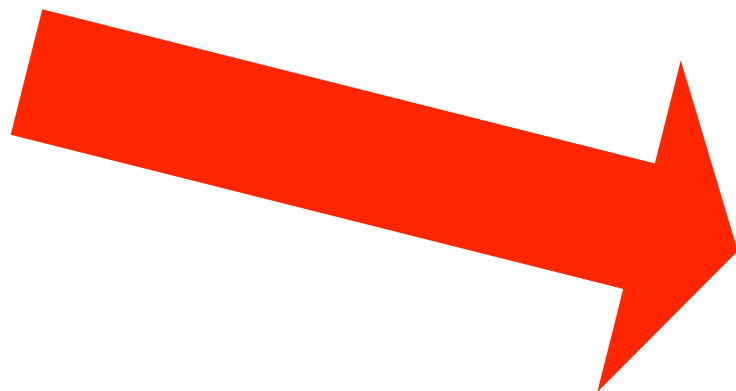
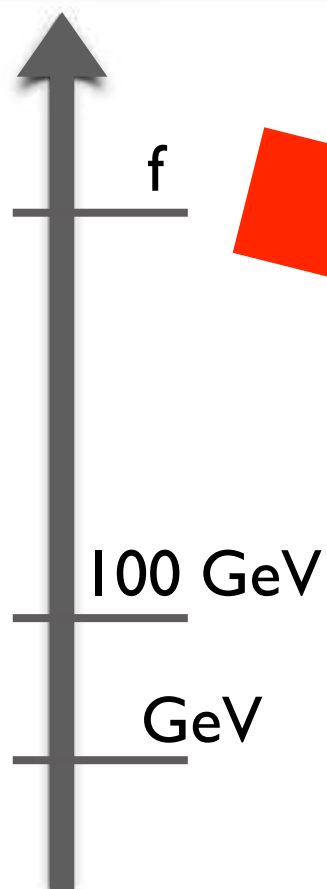
The Peccei-Quinn Solution

Dynamical solution to the strong CP problem

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

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

Peccei, Quinn, PRL38 (1977) and PRD16 (1977)



New physics at a very high energy scale
Do we have any low-energy degree of freedom?

The Peccei-Quinn Solution

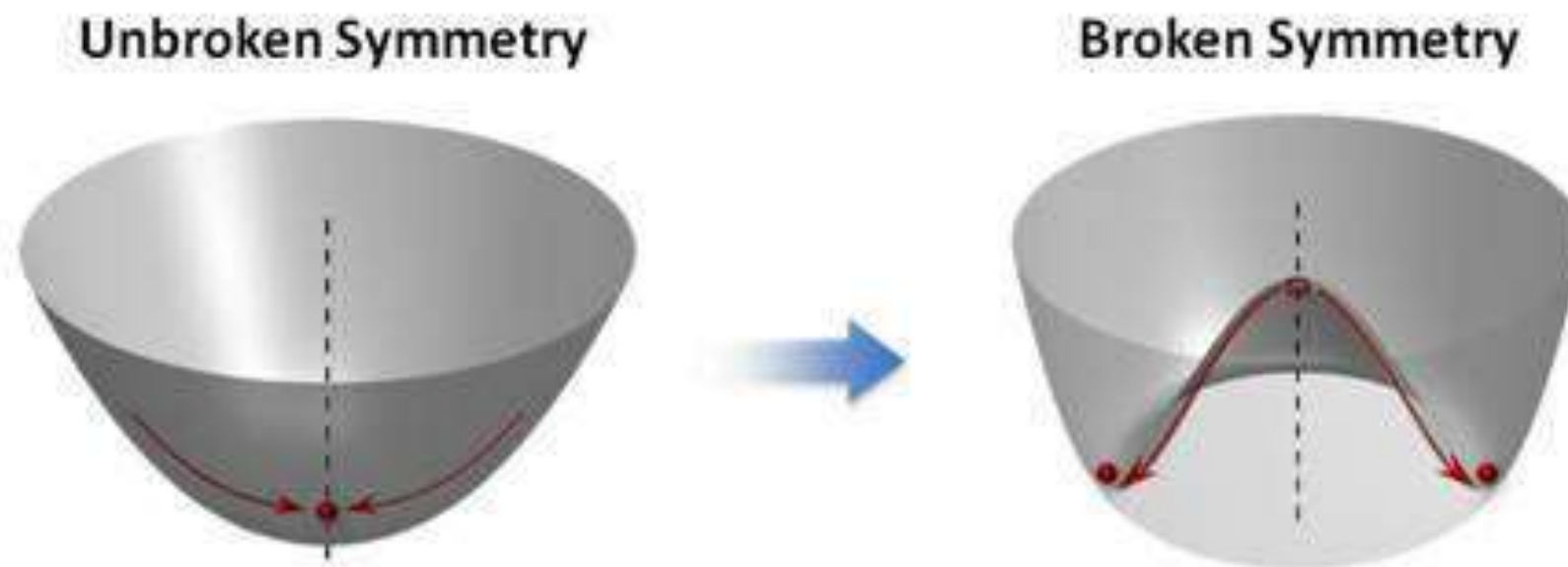
Dynamical solution to the strong CP problem

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

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

Peccei, Quinn, PRL38 (1977) and PRD16 (1977)

PROBLEM I



Pseudo Nambu-Goldstone boson in the spectrum (axion)

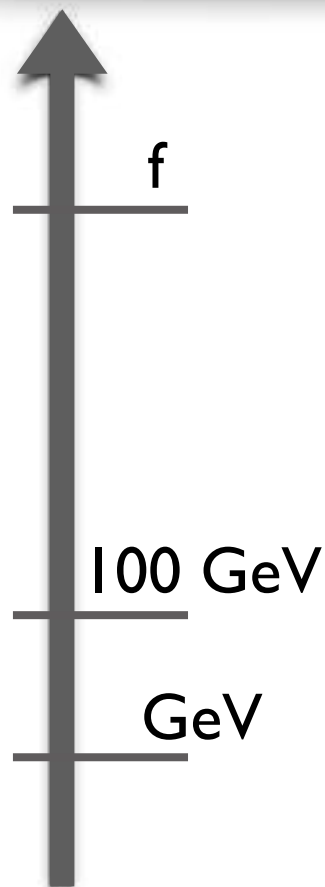
The Peccei-Quinn Solution

Dynamical solution to the strong CP problem

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

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

Peccei, Quinn, PRL38 (1977) and PRD16 (1977)



The axion has (“anomalous”) coupling to gluons

$$\mathcal{L}_{QCD} \supset \frac{a}{f} \frac{g_s^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

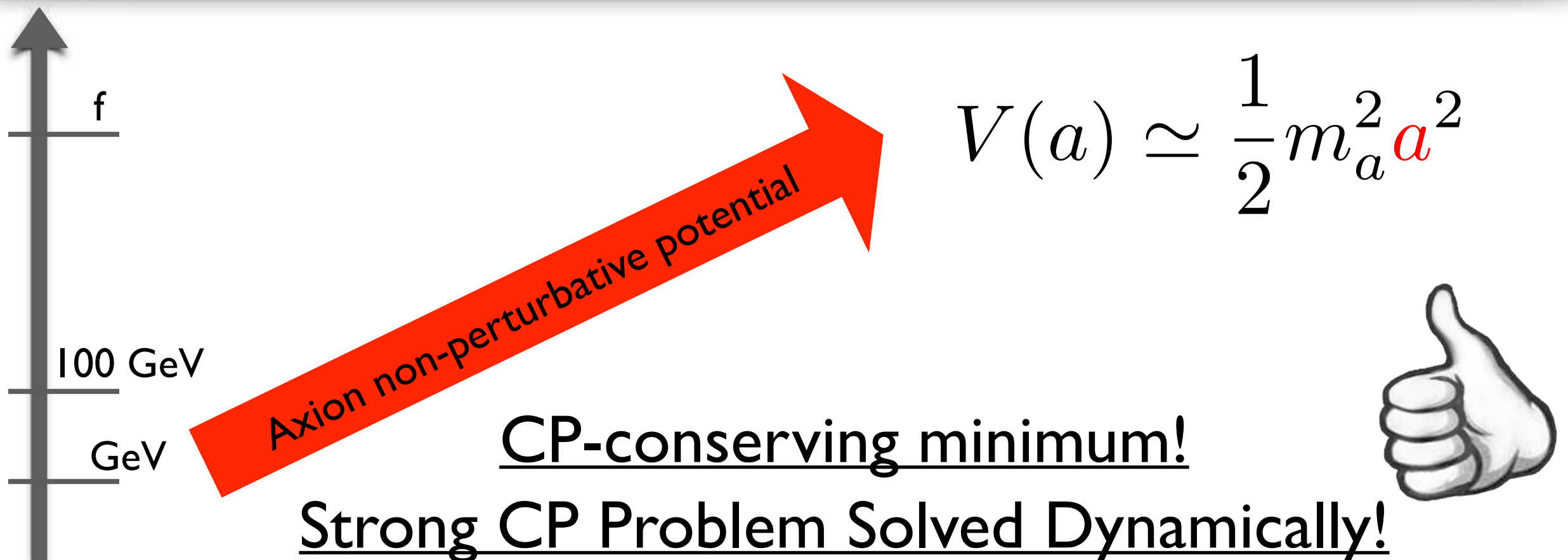
The Peccei-Quinn Solution

Dynamical solution to the strong CP problem

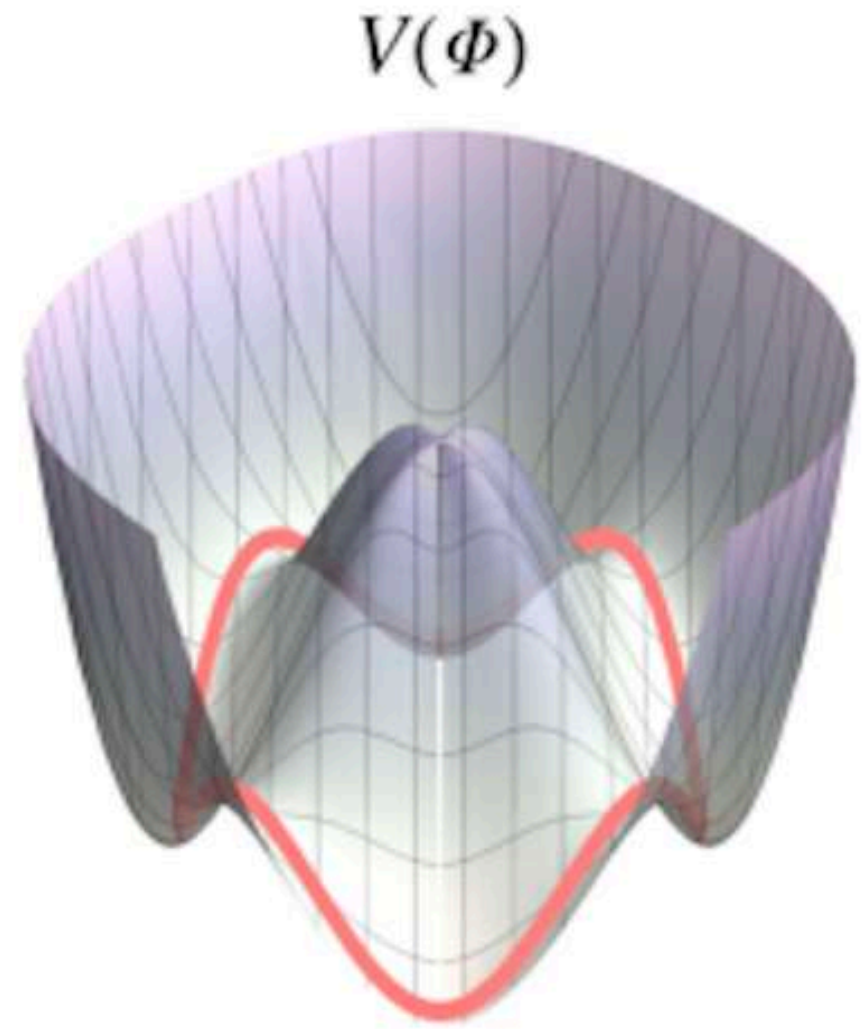
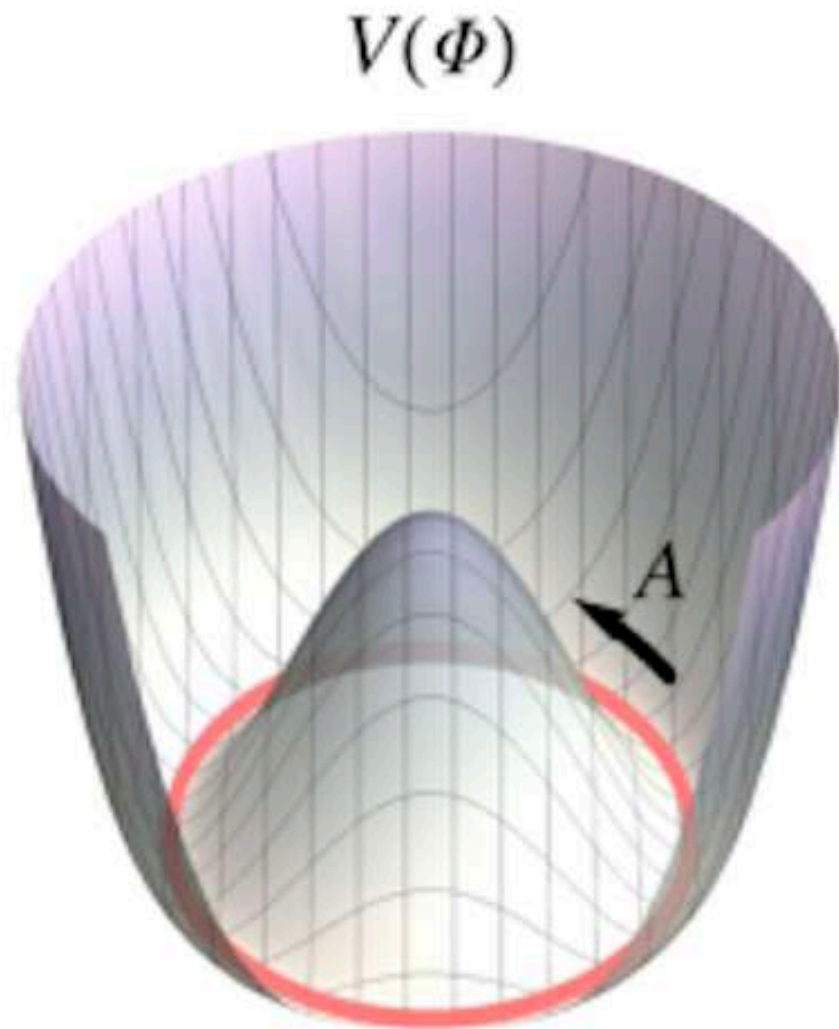
New $U(1)_{PQ}$ symmetry

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

Peccei, Quinn, PRL38 (1977) and PRD16 (1977)



The QCD Axion



Axion develops a potential below the QCDPT
(harmonic potential only good around its minimum)

The QCD Axion

Axion (zero-temperature)
mass from non-perturbative
potential ($f \geq 10^8 \text{ GeV}$)

The QCD axion is very light!

$$m_a = 5.7 \left(\frac{10^{12} \text{ GeV}}{f} \right) \mu\text{eV}$$

Georgi, Kaplan, Randall, PLB169 (1986)
Grilli di Cortona, Hardy, Vega, Villadoro, JHEP1601 (2016)

The QCD Axion

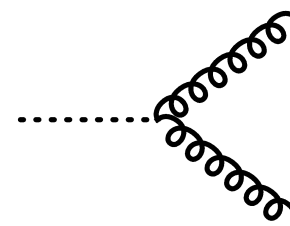
Axion (zero-temperature)
mass from non-perturbative
potential ($f \geq 10^8$ GeV)

The QCD axion is very light!

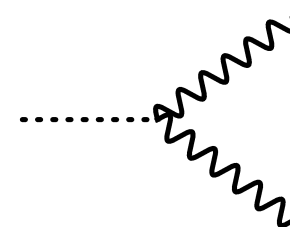
$$m_a = 5.7 \left(\frac{10^{12} \text{ GeV}}{f} \right) \mu\text{eV}$$

Georgi, Kaplan, Randall, PLB169 (1986)
Grilli di Cortona, Hardy, Vega, Villadoro, JHEP1601 (2016)

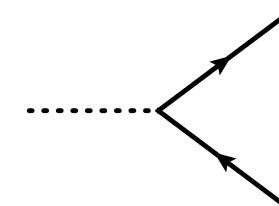
The QCD axion is extremely
weakly coupled to Standard
Model particles



$$\frac{g_s^2}{32\pi^2} \frac{a}{f} G^{\mu\nu} \tilde{G}_{\mu\nu}$$



$$c_{\gamma\gamma} \frac{e^2}{32\pi^2} \frac{a}{f} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

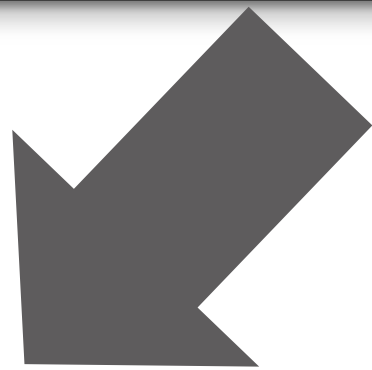
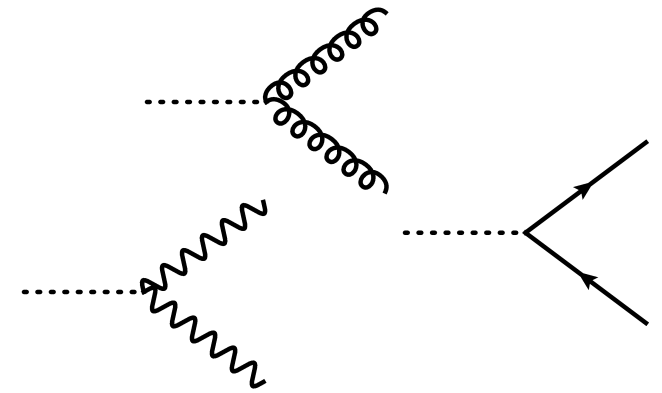


$$c_f \frac{\partial_\mu a}{f} \bar{f} \gamma^\mu \gamma^5 f$$

The QCD Axion

$$m_a = 5.7 \left(\frac{10^{12} \text{ GeV}}{f} \right) \mu\text{eV}$$

Very light and
extremely weakly
coupled



Axion detection challenging,
but several novel ideas

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



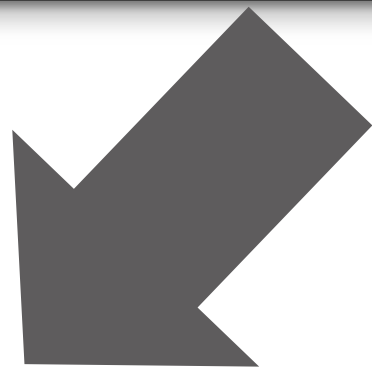
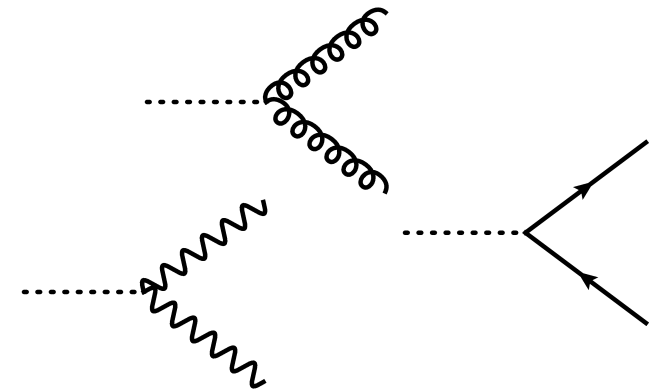
Potential prominent
role in cosmology

Wilczek, Phys.Rev.Lett.40 (1978)
Weinberg, Phys.Rev.Lett.40 (1978)

The QCD Axion

$$m_a = 5.7 \left(\frac{10^{12} \text{ GeV}}{f} \right) \mu\text{eV}$$

Very light and
extremely weakly
coupled



Axion detection challenging,
but several novel ideas

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



Potential prominent
role in cosmology

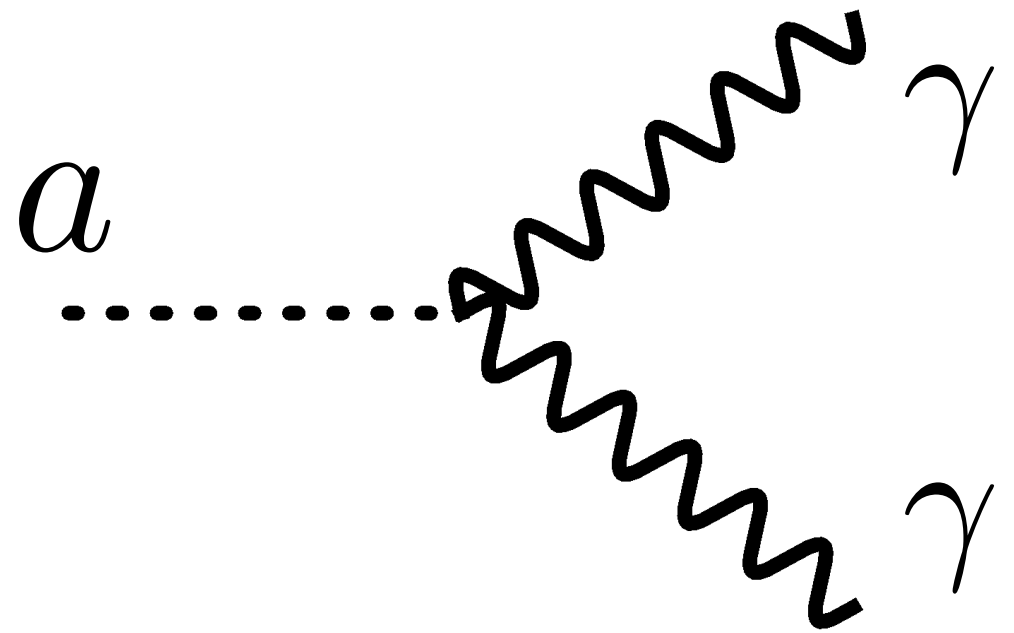
Wilczek, Phys.Rev.Lett.40 (1978)
Weinberg, Phys.Rev.Lett.40 (1978)

In this lecture:

Cosmological production of axions in the early universe

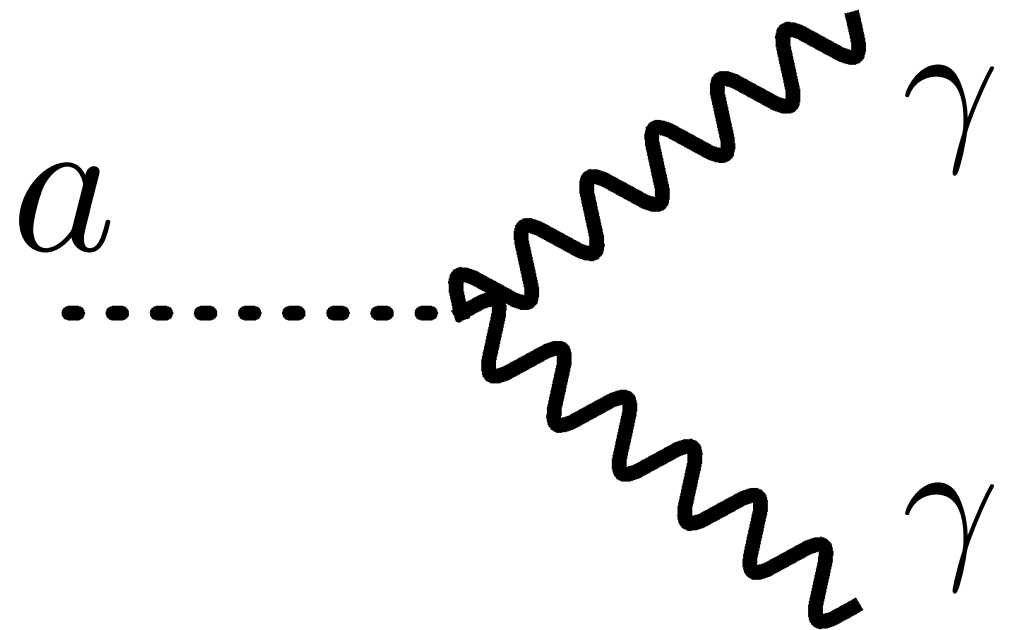
Axion Stability

Axion can decay to
two photons



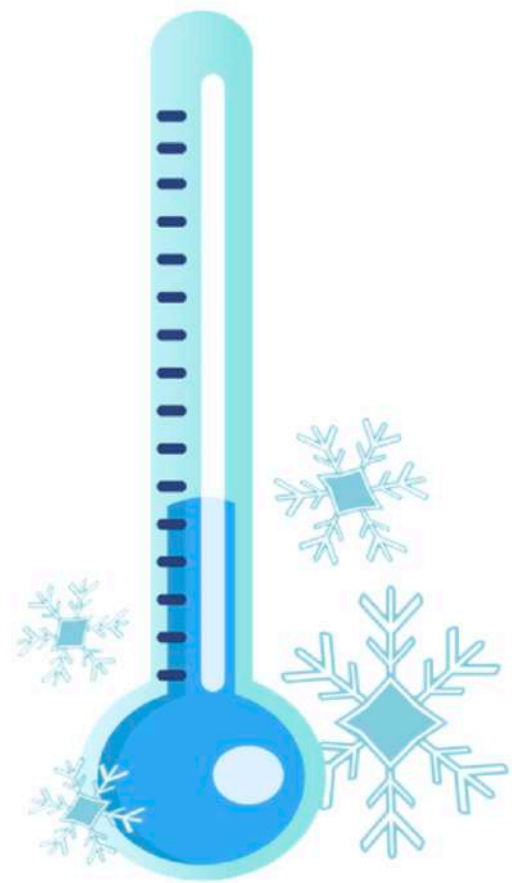
Axion Stability

Axion can decay to
two photons



PROBLEM 2

$$\tau_{a \rightarrow \gamma\gamma} \simeq 1.3 \times 10^{28} \left(\frac{f}{10^9 \text{ GeV}} \right)^5 \text{ yrs}$$



Cold Axions (Dark Matter)

Axion Field Evolution

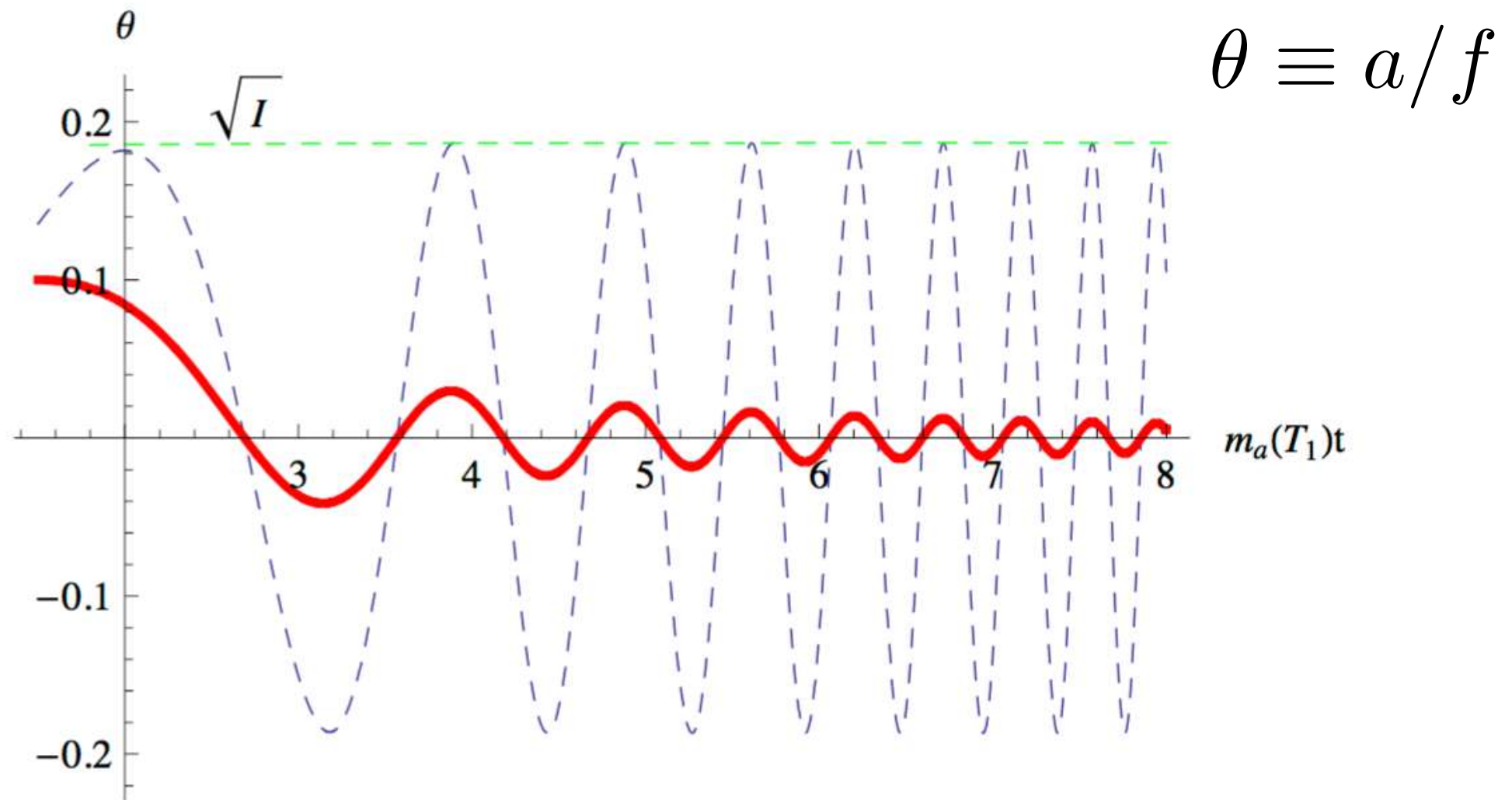
$$\frac{d^2 a}{dt^2} + 3H \frac{da}{dt} + m_a(T)^2 a = 0$$

Axion Field Evolution

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

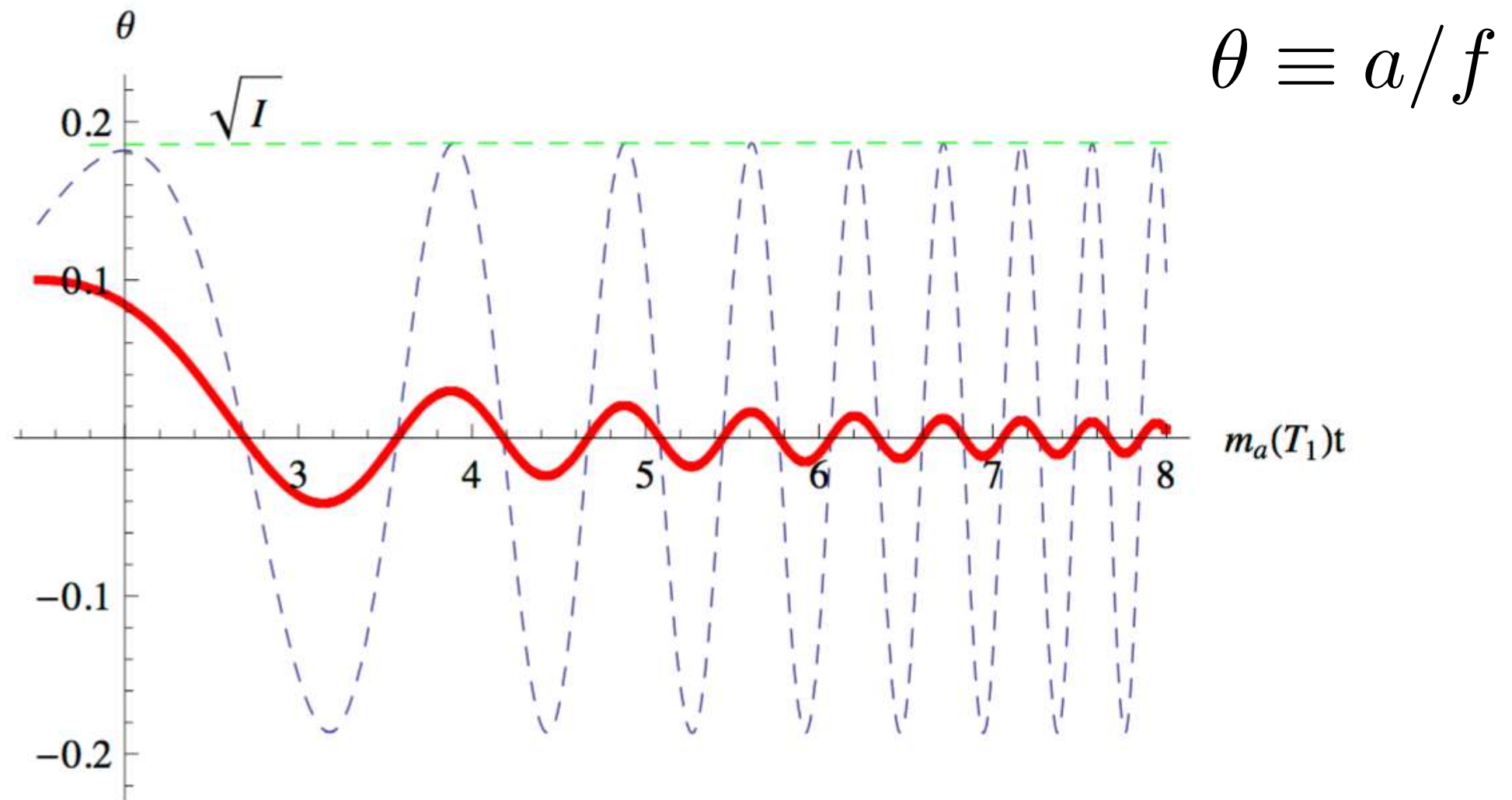
- $3H(T) > m_a(T)$: axion field stuck by “Hubble “friction
- $3H(T) < m_a(T)$: axion field oscillates, energy density stored in oscillations evolves as non-relativistic matter

Axion Cold Dark Matter



Bae, Huh, Kim, JCAP 0809 (2008)

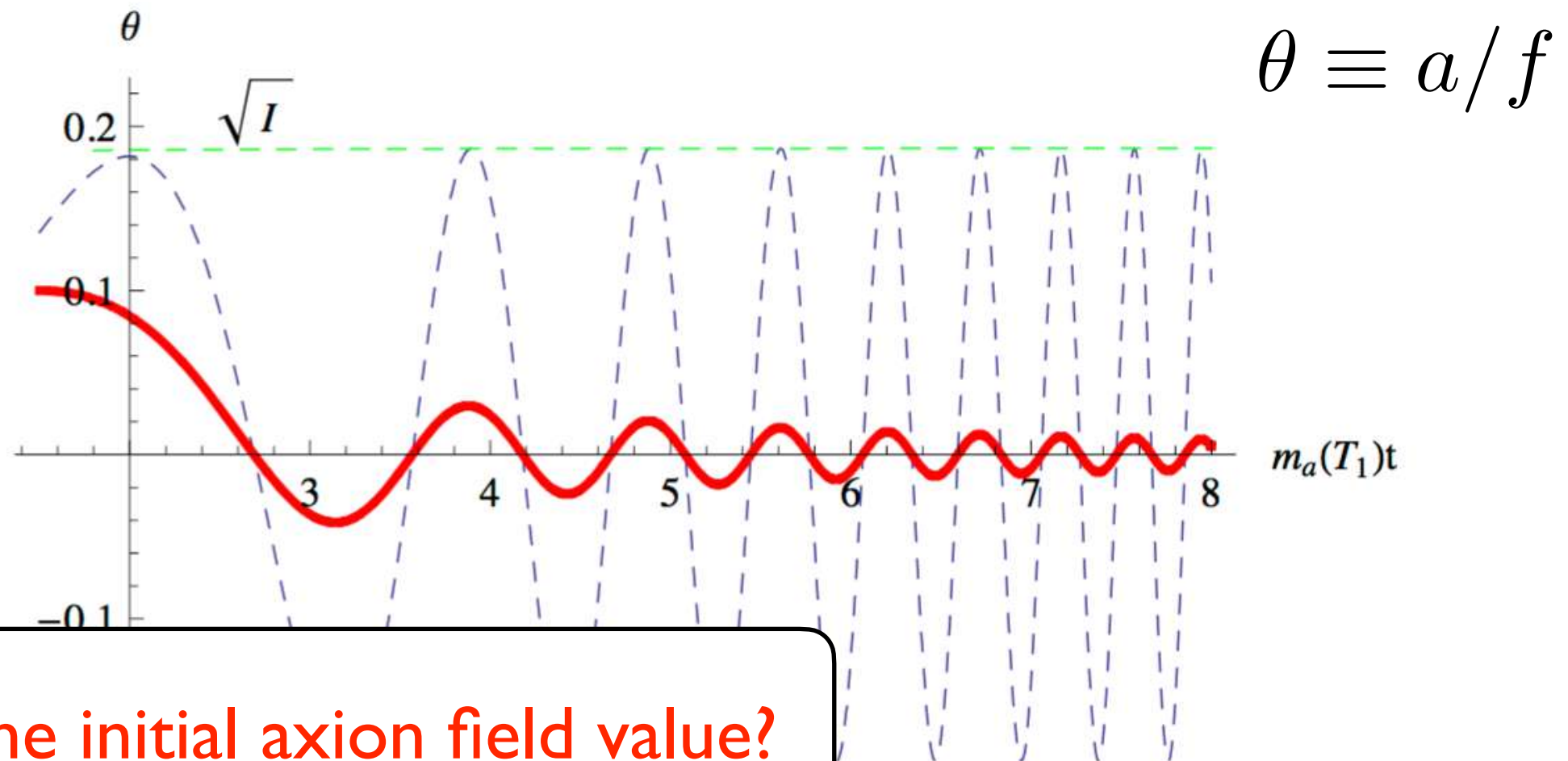
Axion Cold Dark Matter



Bae, Huh, Kim, JCAP 0809 (2008)

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

Axion Cold Dark Matter



What is the initial axion field value?
It depends...

Bae, Huh, Kim, JCAP 0809 (2008)

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

Pre vs Post Inflation

Dark matter relic density gives us
a hint about what f could be

What PQ broken during inflation?
If yes, was it restored afterward?

Pre vs Post Inflation

Dark matter relic density gives us
a hint about what f could be

What PQ broken during inflation?
If yes, was it restored afterward?

Pre-Inflation

Single initial field value

Relic density depends on f and θ_i

Misalignment only

Post-Inflation

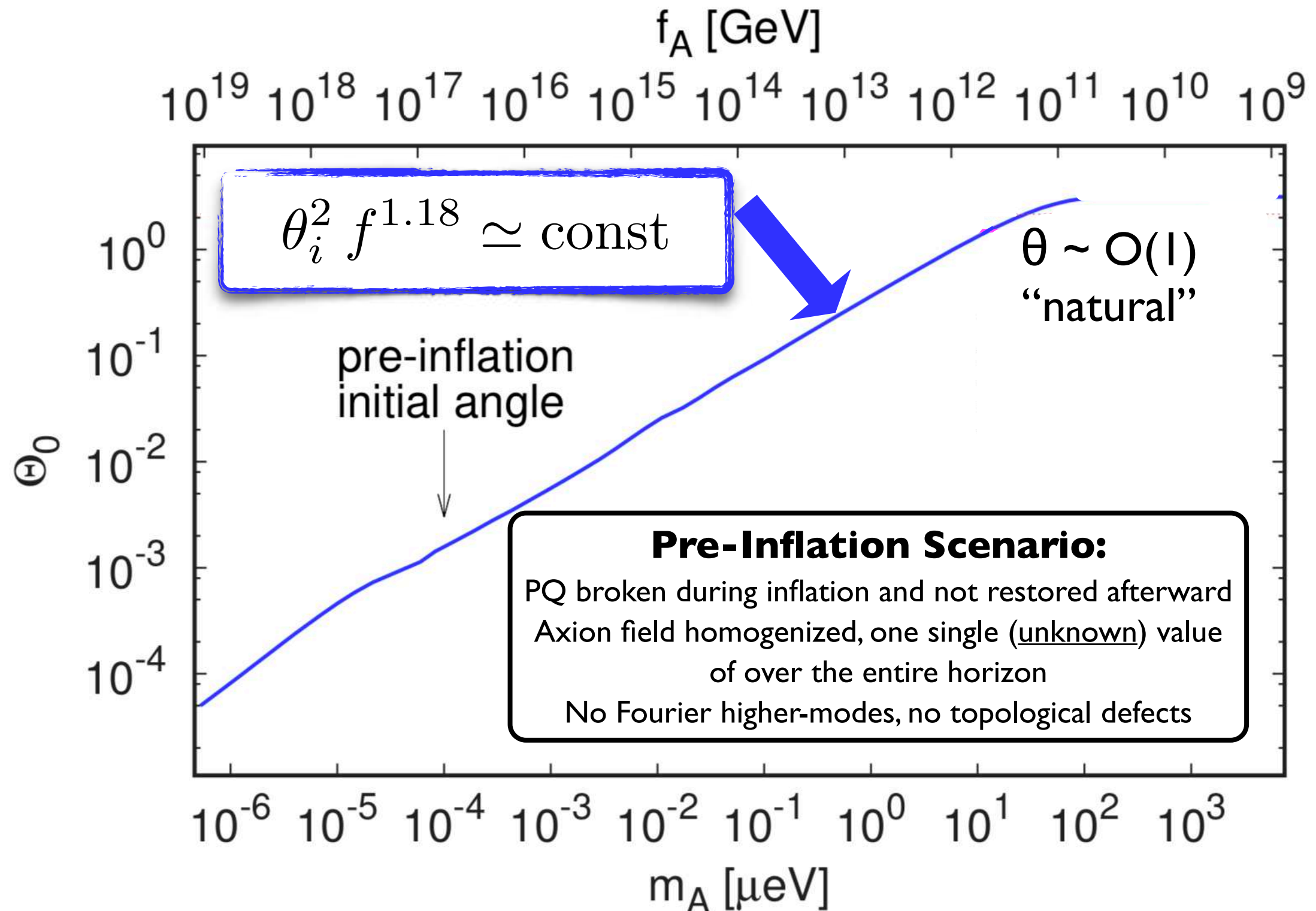
Average over initial field value

Relic density depends on f only

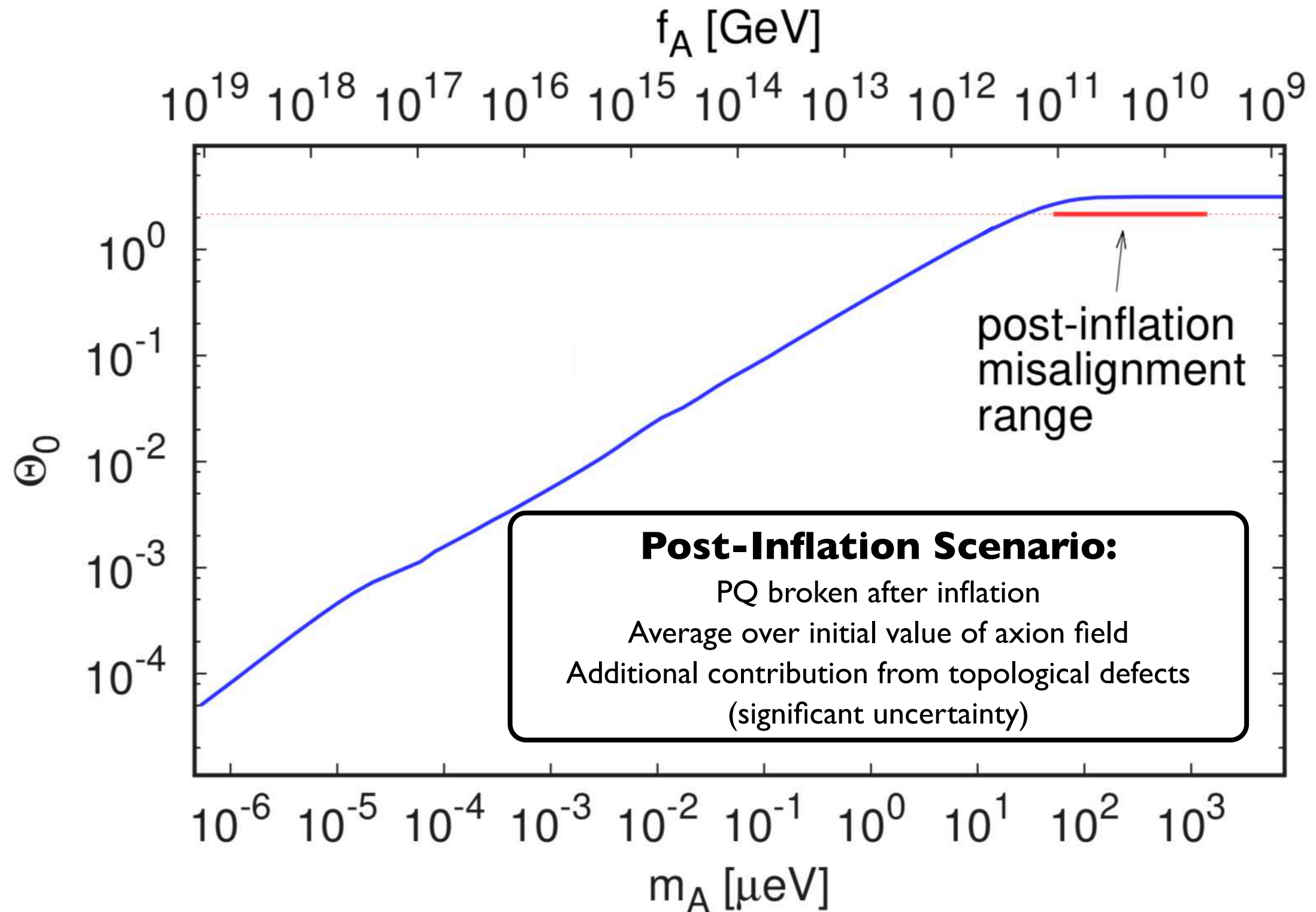
Misalignment + **Topological defects**

Gorghetto, Hardy, Villadoro, JHEP 07 (2018)

Axion CDM Summary

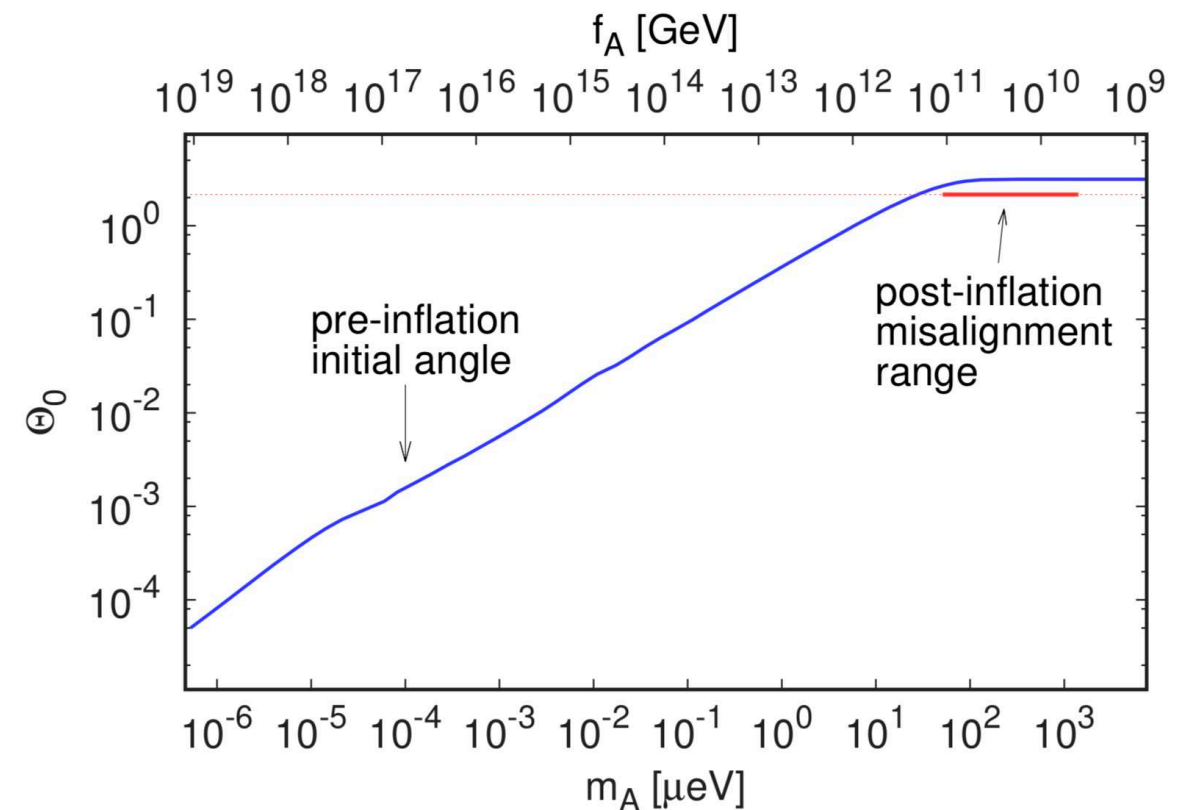


Axion CDM Summary



Axion CDM Summary

- PRE: initial field value unknown, just a relation between θ and f (i.e. m_a)
- POST: theoretical uncertainty on topological defects contribution gives a range for f (i.e. m_a)



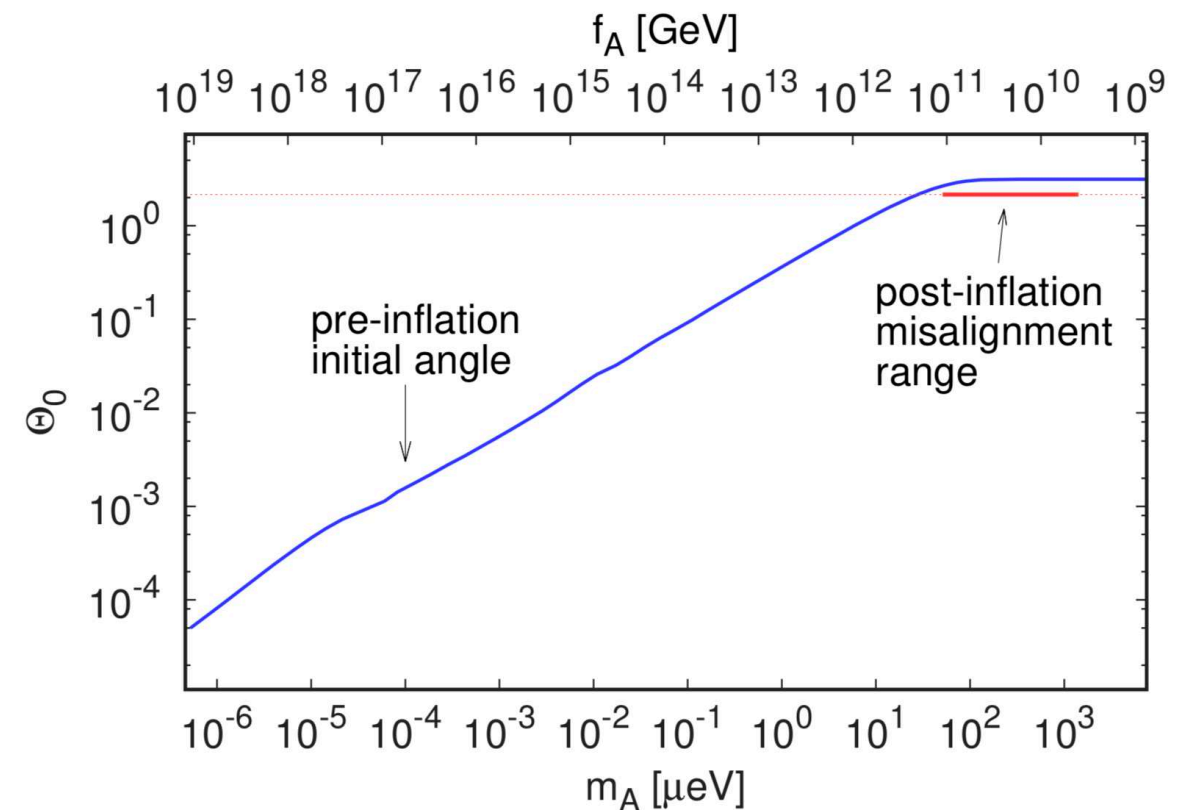
Motivated range for f (with caveats):

Correct dark matter abundance for POST, and PRE if there is a $O(1)$ initial misalignment angle

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

Axion CDM Summary

- PRE: initial field value unknown, just a relation between θ and f (i.e. m_a)
- POST: theoretical uncertainty on topological defects contribution gives a range for f (i.e. m_a)

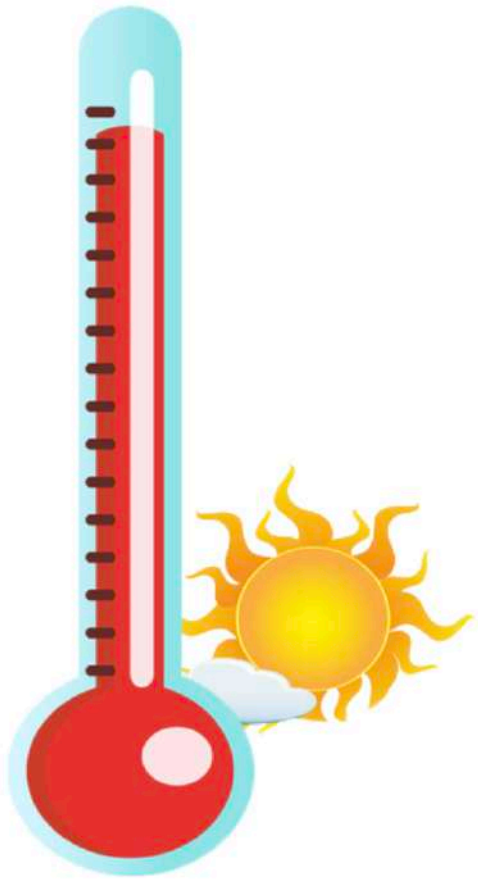


Motivated range for f (with caveats):

Correct dark matter abundance for POST, and PRE if there is a $O(1)$ initial misalignment angle

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

What about hot axions in this range?



Hot Axions (Dark Radiation)

Axion Dark Radiation

Axions produced by $2 \rightarrow 2$ processes involving particles in the primordial thermal bath (final energy much higher than m_a , i.e. “hot”)

$$B_1 B_2 \rightarrow B_3 a$$

They are still around today!
How do we unveil their presence?

Axion Dark Radiation

Axions produced by $2 \rightarrow 2$ processes involving particles in the primordial thermal bath (final energy much higher than m_a , i.e. “hot”)

$$B_1 B_2 \rightarrow B_3 a$$

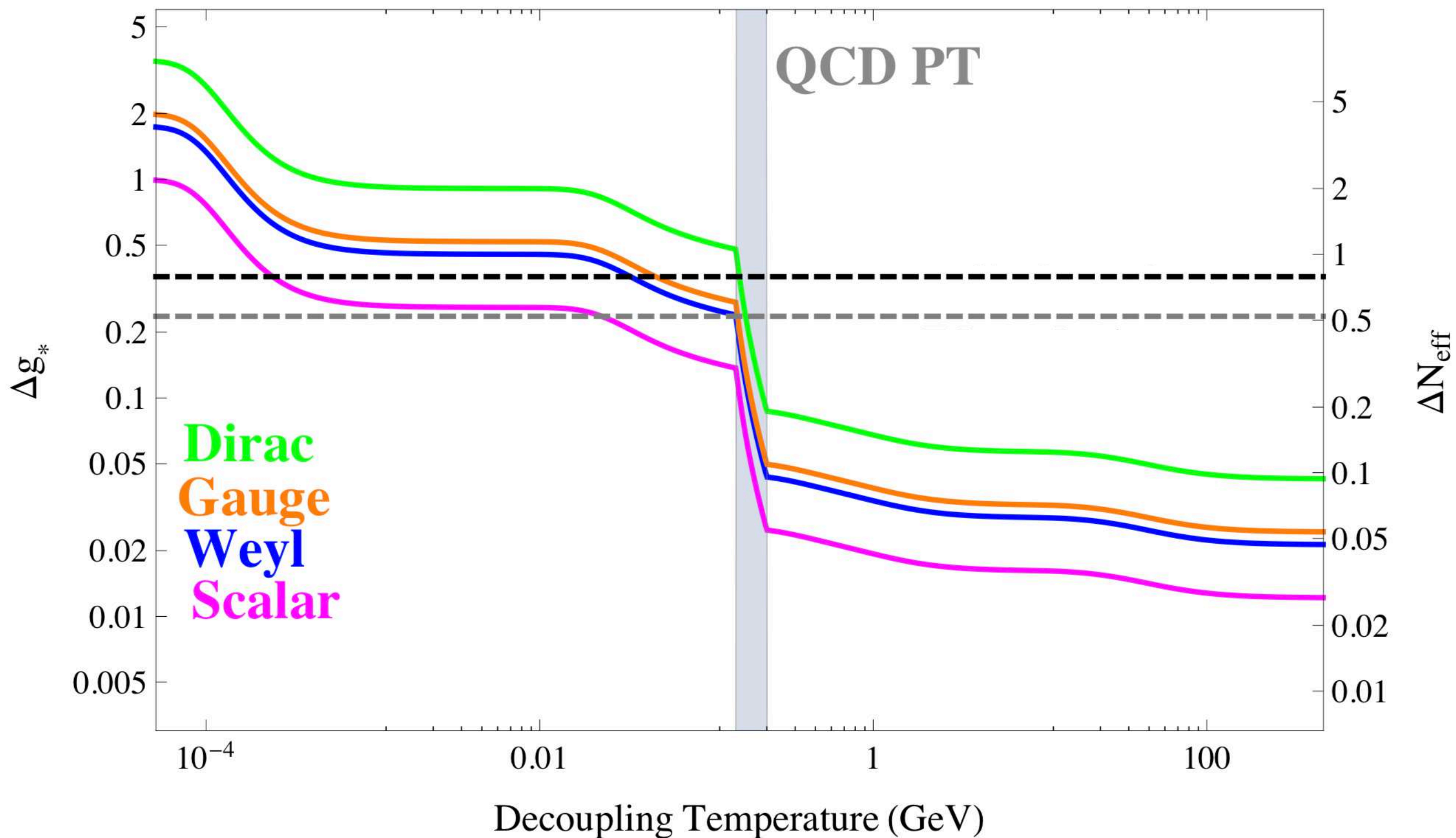
They are still around today!
How do we unveil their presence?

“Hot axions” can be inferred by studying the CMB, manifesting as additional neutrino species

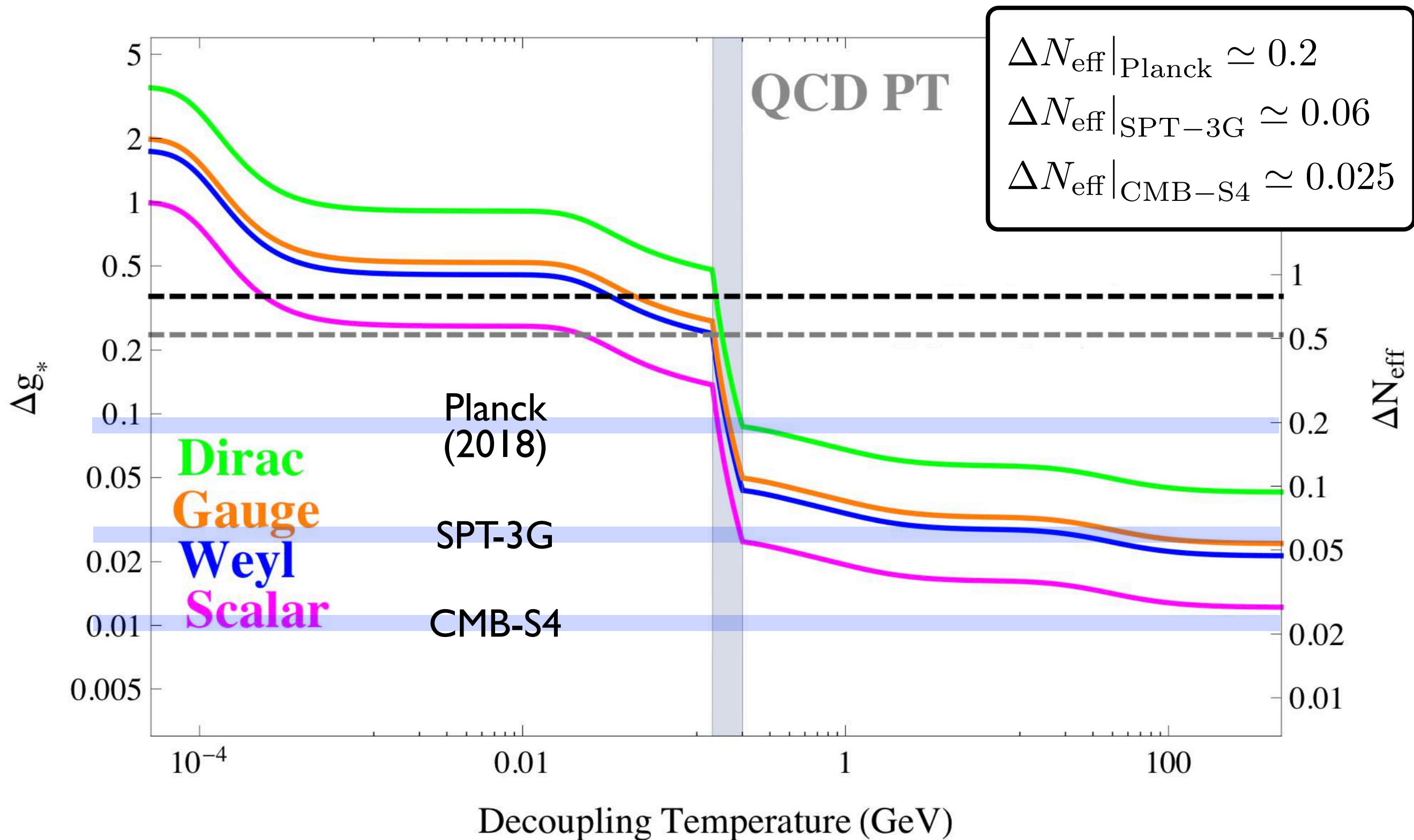
$$\rho_{\text{rad}} = \rho_\gamma + \rho_\nu + \rho_a \equiv \left[1 + \frac{7}{8} \left(\frac{T_\nu}{T_\gamma} \right)^4 N_{\text{eff}} \right] \rho_\gamma$$

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

Hot Axions and CMB



Hot Axions and CMB

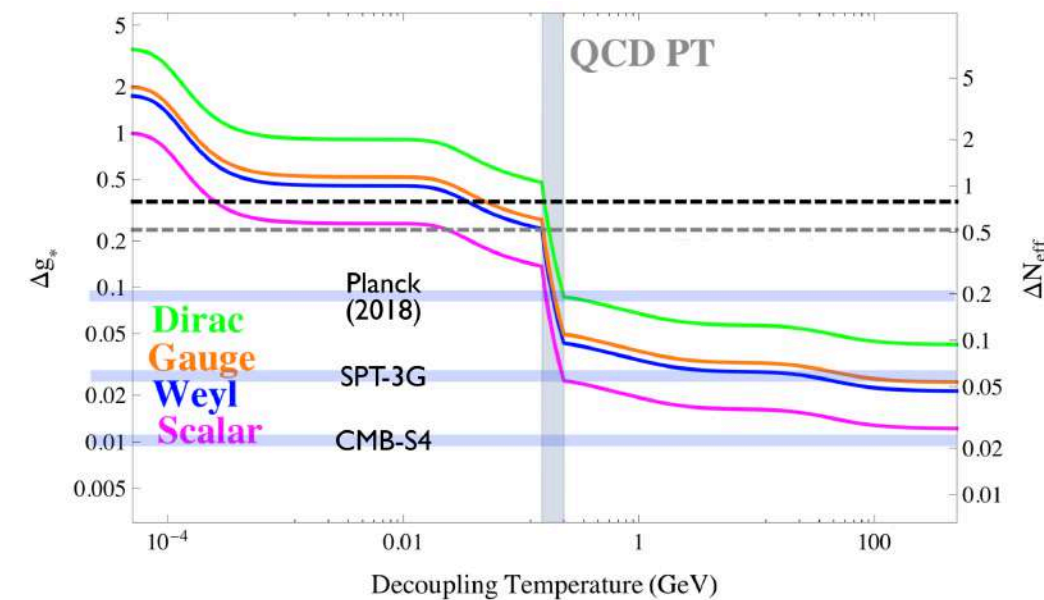


A Note on Precision

Importance of a precise calculation:

Axions may never thermalize

If they thermalize, decoupling details relevant
(i.e. effect larger the experimental error)

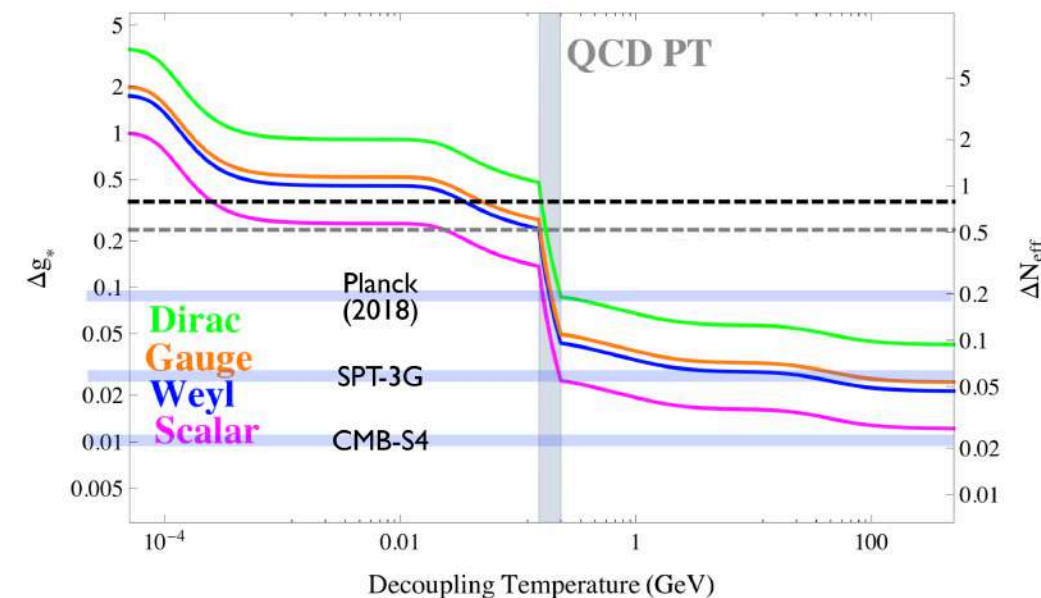


A Note on Precision

Importance of a precise calculation:

Axions may never thermalize

If they thermalize, decoupling details relevant
(i.e. effect larger the experimental error)



Tracking the axion number density

$$\frac{dn_a}{dt} + 3Hn_a = \sum_{\alpha} \mathcal{C}_{\alpha}$$

Collision operators accounting for all
processes (scattering and decays) changing
the axion number density

Collision Rates

$g g \rightarrow g a$ (and others)	$\Gamma_{\text{gauge}} \propto \alpha_s^3 \frac{T^3}{f^2}$
$f h \rightarrow f a$	$\Gamma_{\text{fermion}}^{\text{UV}} \propto y_f^2 \frac{T^3}{f^2}$
$f g \rightarrow f a$	$\Gamma_{\text{fermion}}^{\text{IR}} \propto \alpha_s m_f^2 \frac{T}{f^2}$

Collision Rates

$$g g \rightarrow g a \quad \Gamma_{\text{gauge}} \propto \alpha_s^3 \frac{T^3}{f^2}$$

(and others)

Loop suppression

$$f h \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{UV}} \propto y_f^2 \frac{T^3}{f^2}$$

Enhanced for
heavier fermions

$$f g \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{IR}} \propto \alpha_s m_f^2 \frac{T}{f^2}$$

Collision Rates

$$g g \rightarrow g a \quad \Gamma_{\text{gauge}} \propto \alpha_s^3 \frac{T^3}{f^2}$$

(and others)

$$f h \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{UV}} \propto y_f^2 \frac{T^3}{f^2}$$

$$f g \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{IR}} \propto \alpha_s m_f^2 \frac{T}{f^2}$$

Efficient at high
temperatures
(UV production)

Efficient at low temperatures
(IR production)

This has to be compared with the expansion rate $H(T) \sim T^2/M_{\text{Pl}}$

$$Y_a(T) \equiv \frac{n_a(T)}{s(T)} \simeq \Gamma(T)/H(T) \simeq M_{\text{Pl}}\Gamma(T)/T^2$$

Collision Rates

$$g g \rightarrow g a \quad \Gamma_{\text{gauge}} \propto \alpha_s^3 \frac{T^3}{f^2}$$

(and others)

$$f h \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{UV}} \propto y_f^2 \frac{T^3}{f^2}$$

$$f g \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{IR}} \propto \alpha_s m_f^2 \frac{T}{f^2}$$

ΔN_{eff} barely within reach
of future CMB surveys

Potentially large
contribution to ΔN_{eff}

This has to be compared with the expansion rate $H(T) \sim T^2/M_{\text{Pl}}$

$$Y_a(T) \equiv \frac{n_a(T)}{s(T)} \simeq \Gamma(T)/H(T) \simeq M_{\text{Pl}}\Gamma(T)/T^2$$

Collision Rates

$$g g \rightarrow g a \quad \Gamma_{\text{gauge}} \propto \alpha_s^3 \frac{T^3}{f^2}$$

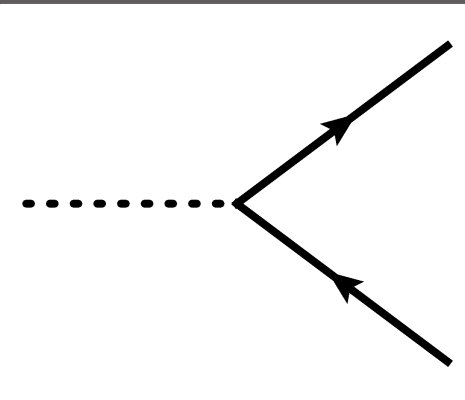
(and others)

$$f h \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{UV}} \propto y_f^2 \frac{T^3}{f^2}$$

$$f g \rightarrow f a \quad \Gamma_{\text{fermion}}^{\text{IR}} \propto \alpha_s m_f^2 \frac{T}{f^2}$$

ΔN_{eff} barely within reach
of future CMB surveys

Potentially large
contribution to ΔN_{eff}

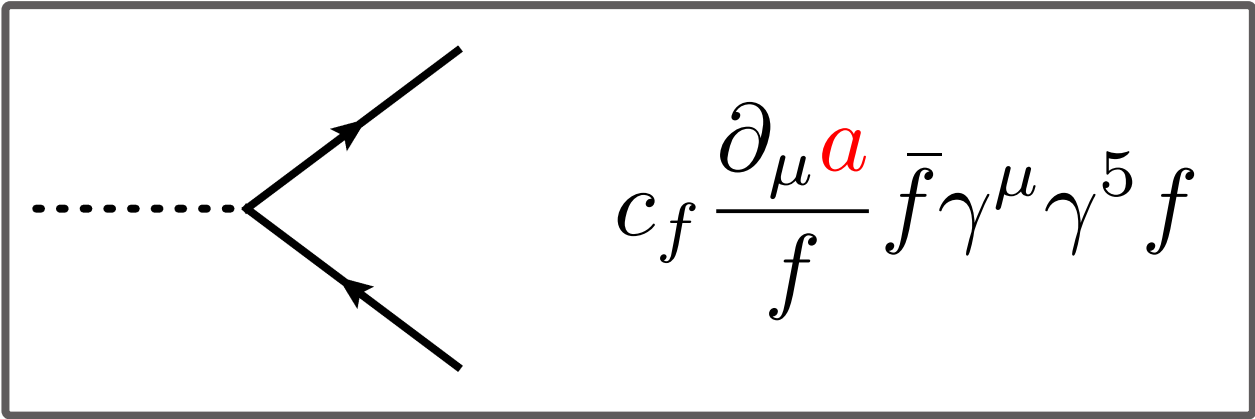


$$c_f \frac{\partial_\mu a}{f} \bar{f} \gamma^\mu \gamma^5 f$$

Axion coupling to fermions
mediate processes leading to
detectable ΔN_{eff}

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

Third Generation Quarks


$$c_f \frac{\partial_\mu a}{f} \bar{f} \gamma^\mu \gamma^5 f$$

Already studied well above
and below the EWPT

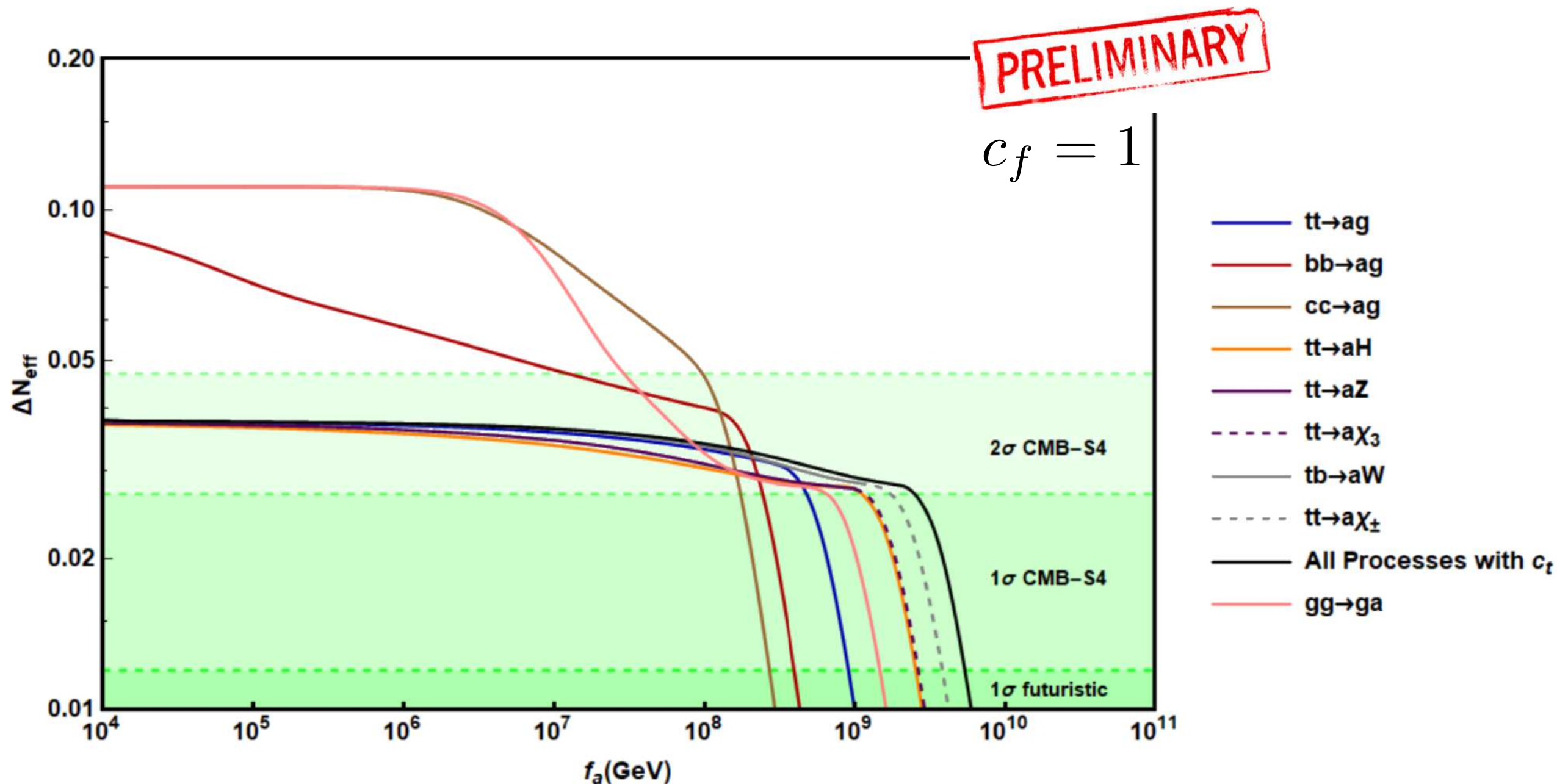
Compute axion production
mediated by coupling to
Standard Model quarks of the
third generation (t and b)

Salvio, Strumia, Xue, JCAP 1401 (2014)
Ferreira, Notari, Phys.Rev.Lett. 120 (2018)

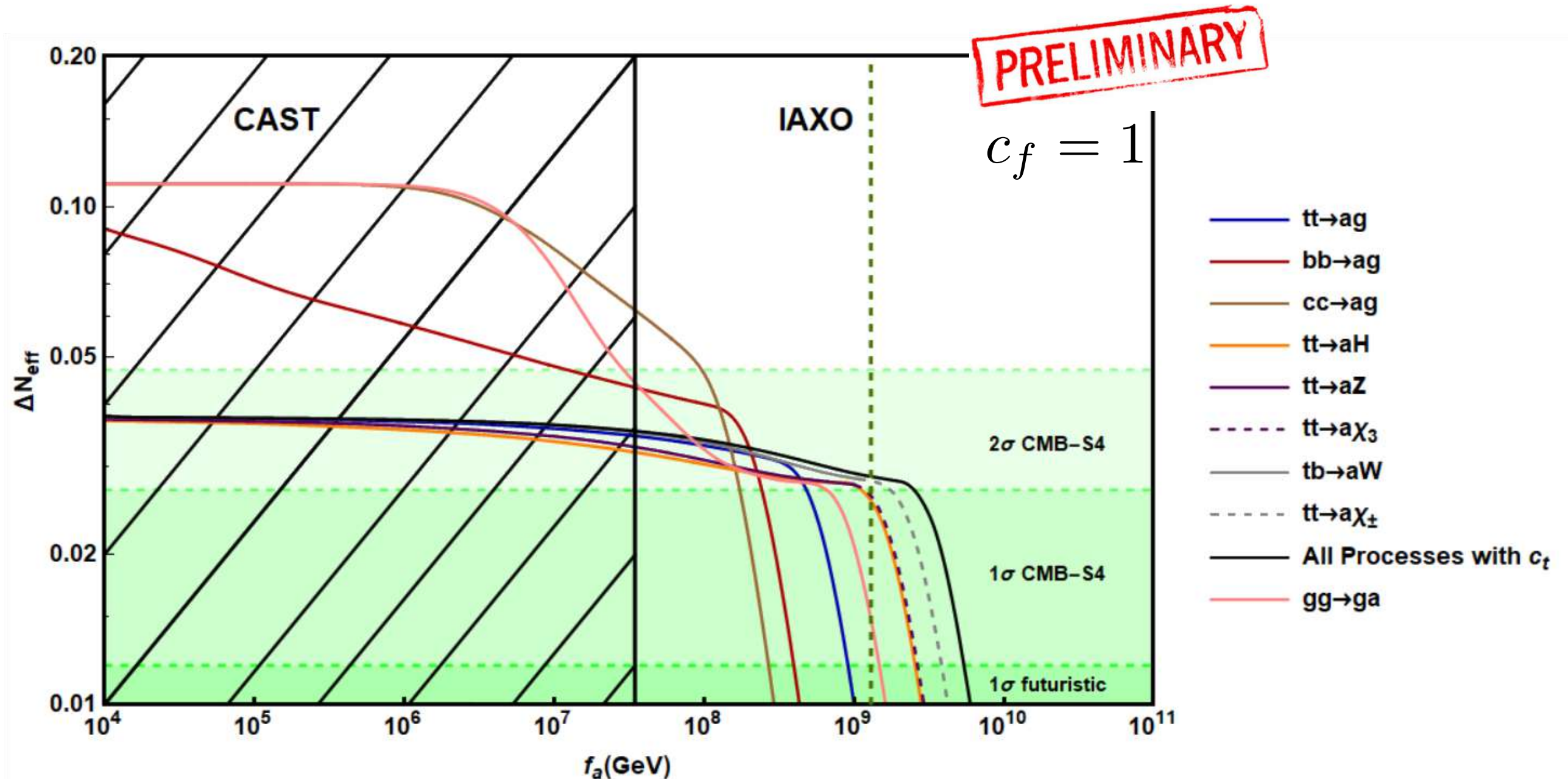
- Complete calculation by including processes with all electroweak states
- Smooth connection between above and below the EWPT (with temperature dependent Higgs vev)
- Thermal masses
- New contribution: axions from decays (for off-diagonal couplings)

Aragon, FD, Ferreira, Merlo, Notari, in preparation

Results: Scattering

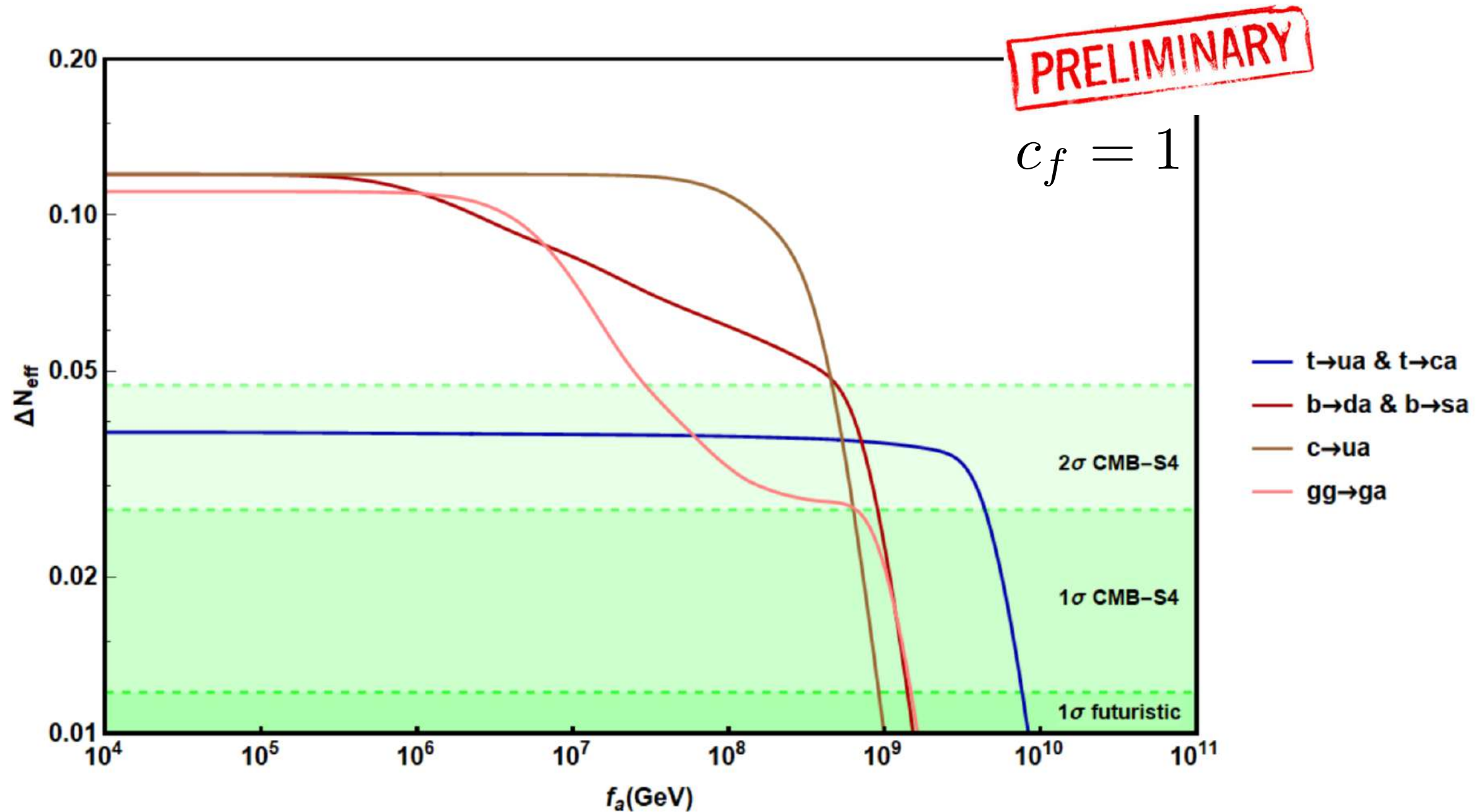


Results: Scattering

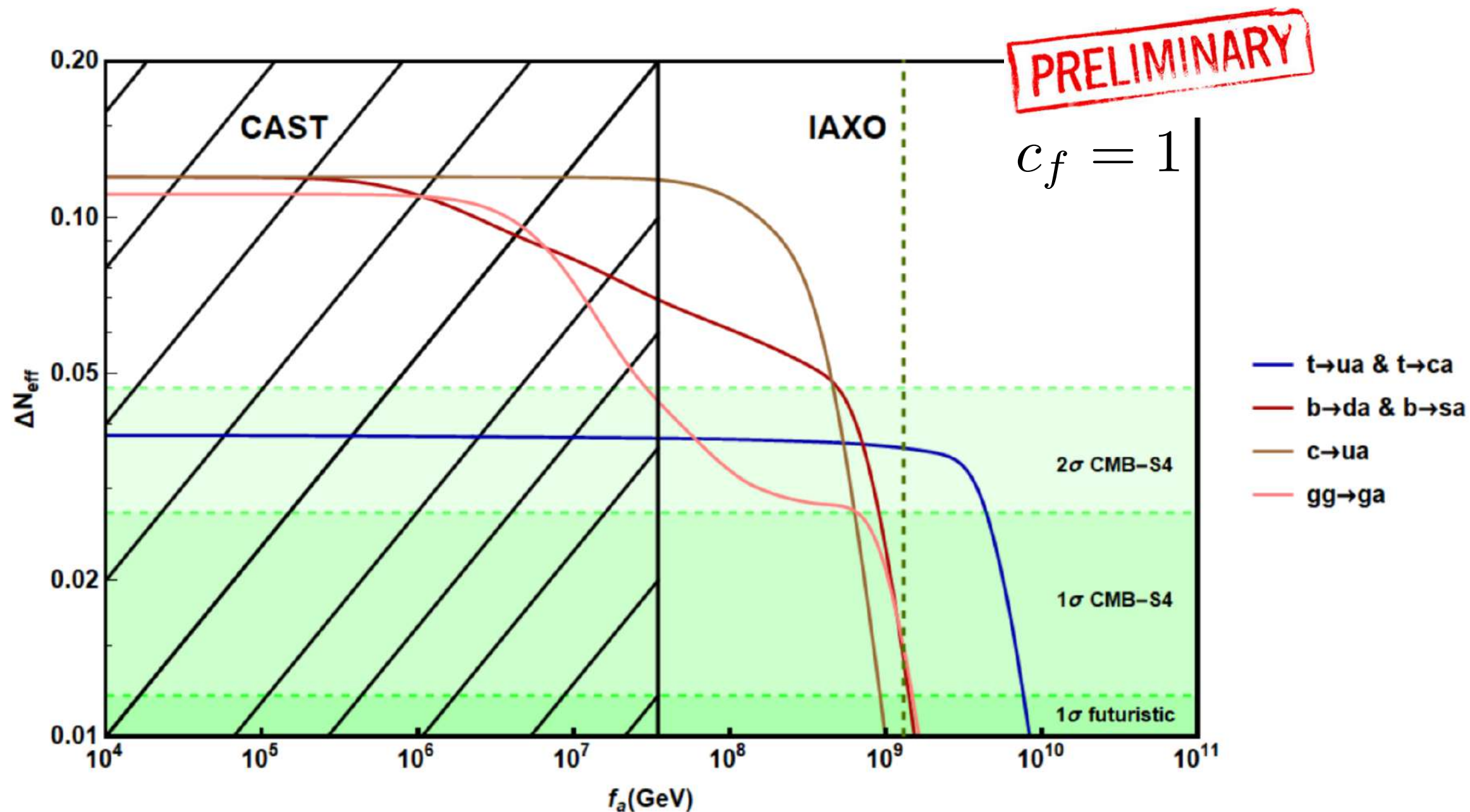


Bounds from coupling to photons (assuming order one couplings)
Region relevant to cosmology within reach of future axion terrestrial searches!

Results: Decays



Results: Decays



Bounds from coupling to photons (assuming order one couplings)
Region relevant to cosmology within reach of future axion terrestrial searches!

The H_0 Tension

Mismatch between early and late universe measurements of the Hubble constant H_0

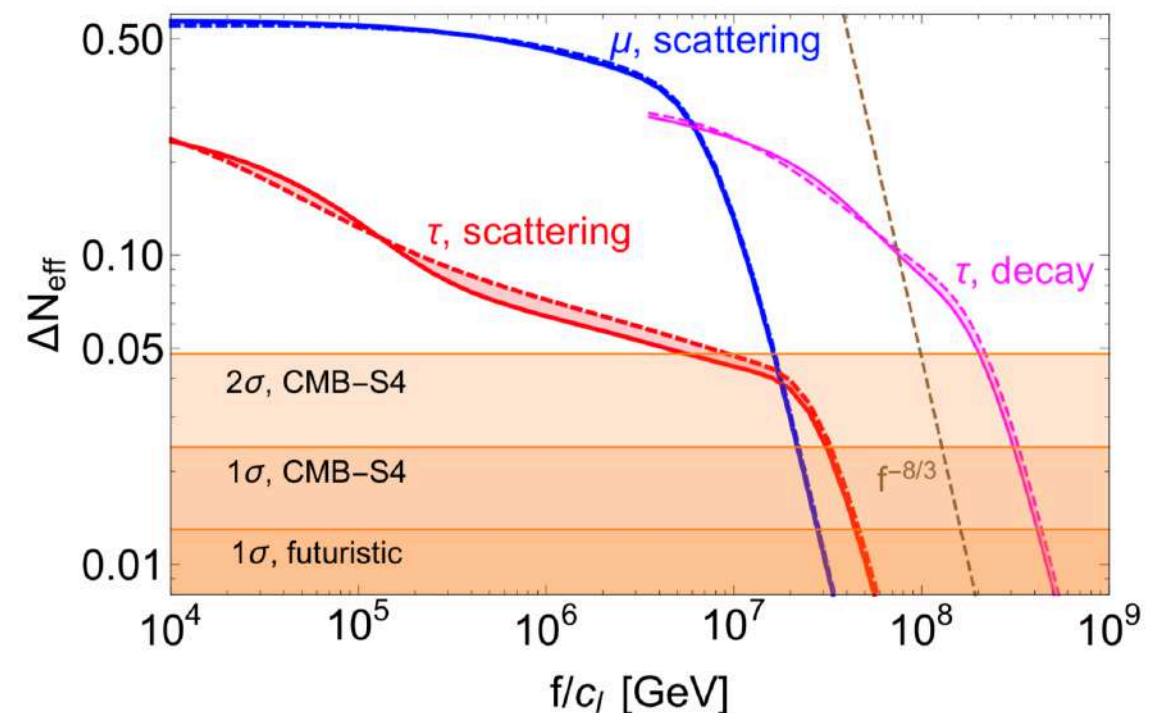
Planck Collaboration, Planck 2018 results.,arXiv:1807.06209]
A. G. Riess et al.,Astrophys.J. 861 (2018)

A substantial (~ 0.2) contribution to ΔN_{eff} can be the origin

Bernal,Verde, Riess,JCAP 1610 (2016)

Could it be from axions? Yes!

But... axion interacting with heavier lepton flavors and large couplings

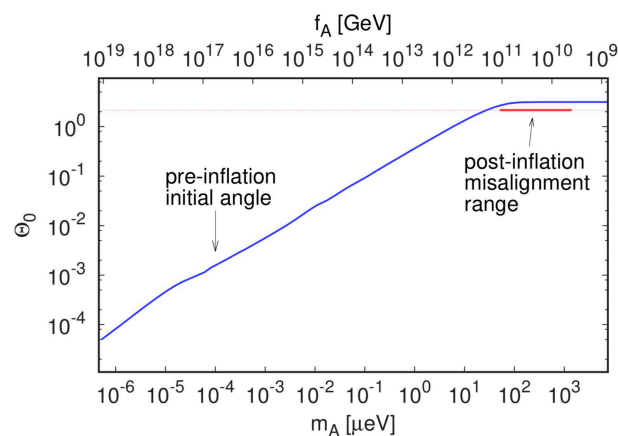
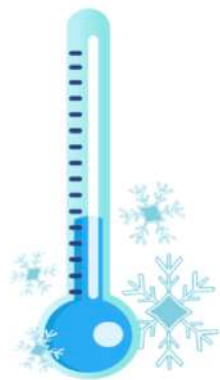


FD, Ferreira, Notari, Bernal,JCAP 1811 (2018)

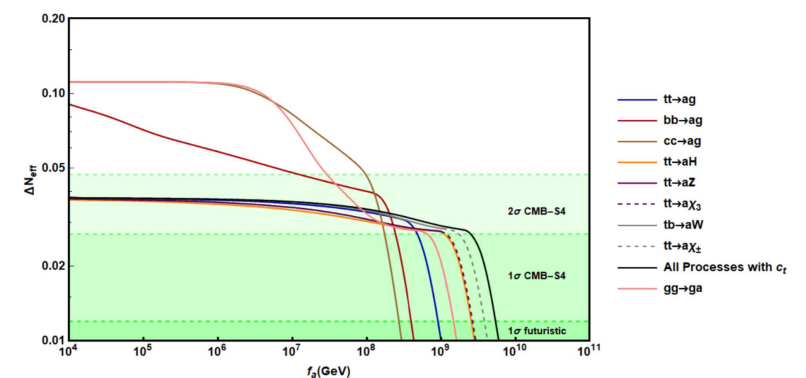
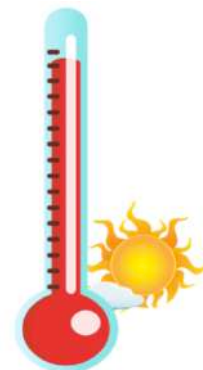
Cold and Hot Axions

QCD axion: motivated hypothetical particle with substantial cosmological consequences

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

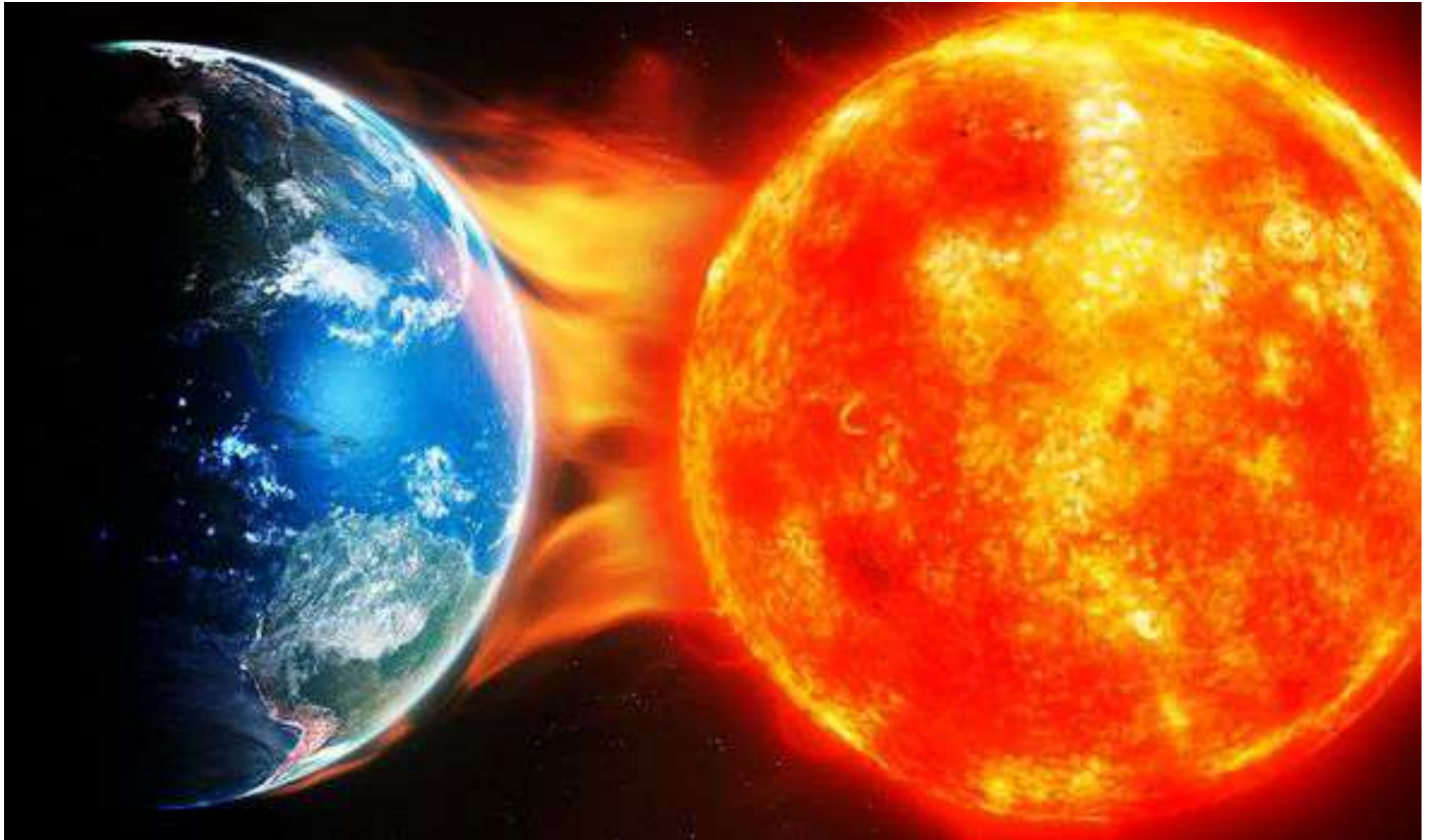


&

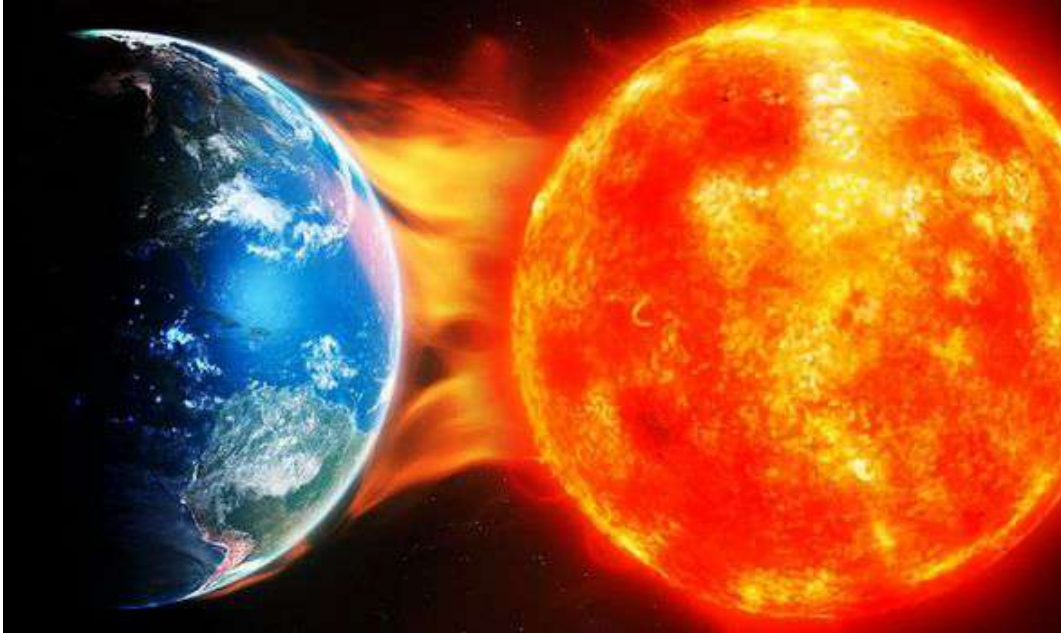


Aragon, FD, Ferreira, Merlo, Notari, in preparation

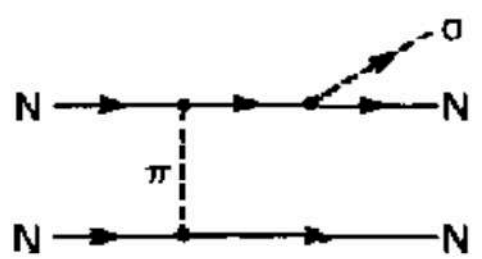
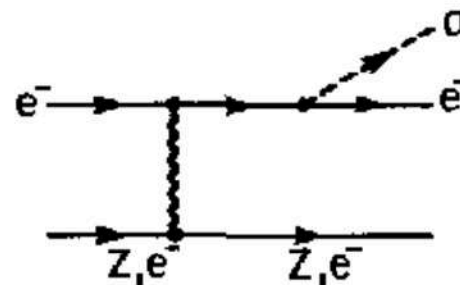
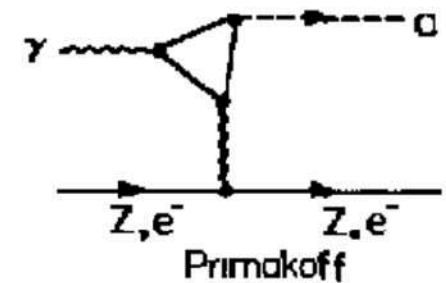
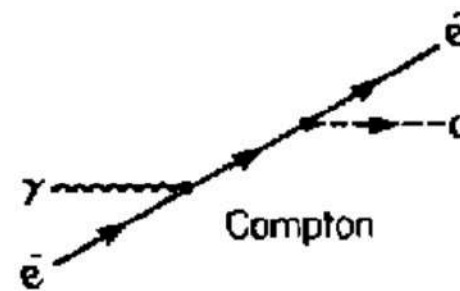
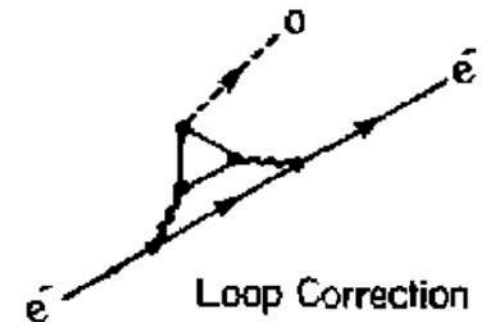
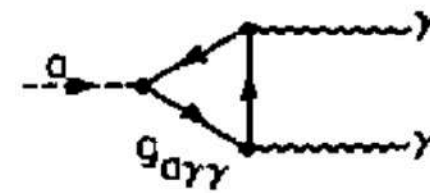
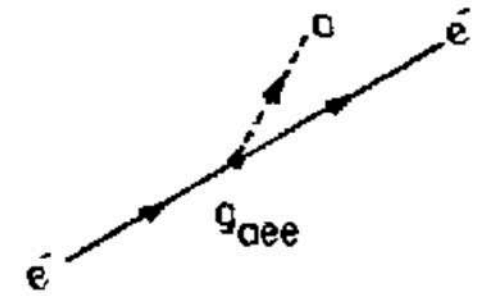
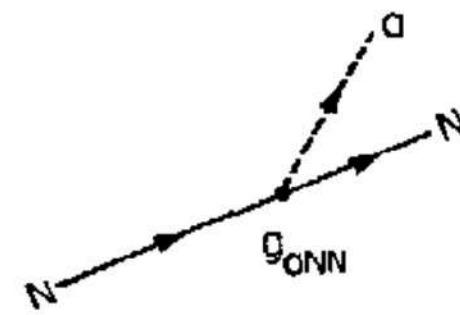
Solar Axions



Solar Axions



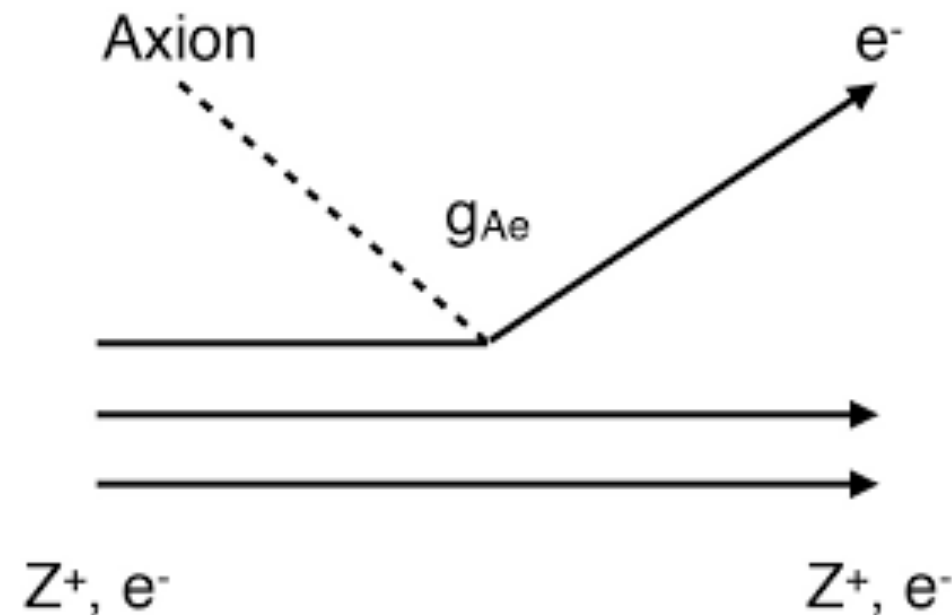
Axions can be produced in the Sun and they would escape without further interactions and with energy around the keV



Bremsstrahlung

Electron Recoil from Solar Axions

They can hit an atomic target here on Earth and ionize the atom via the axioelectric effect



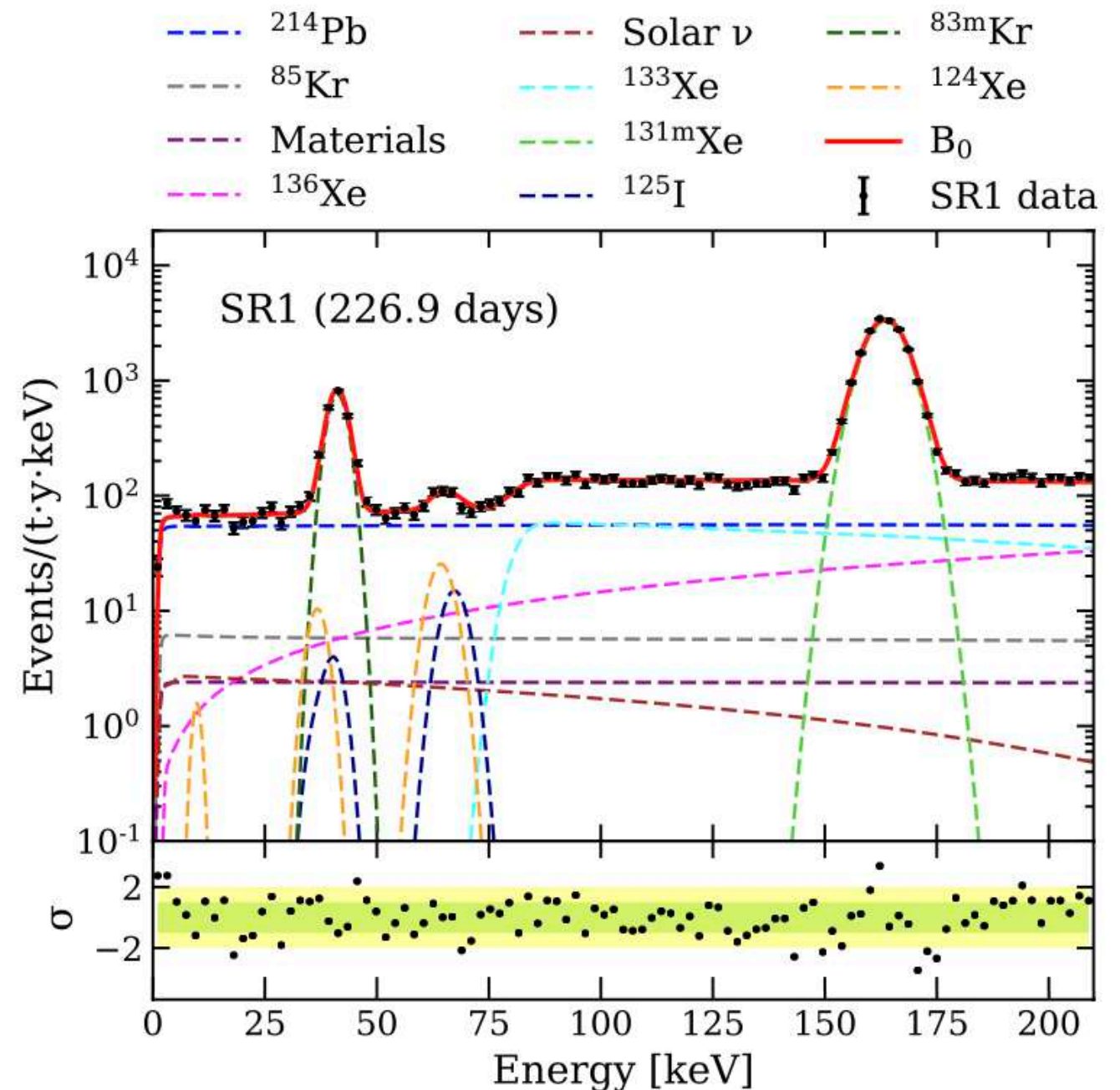
This would induce an order keV electro recoil

Can we detect it?



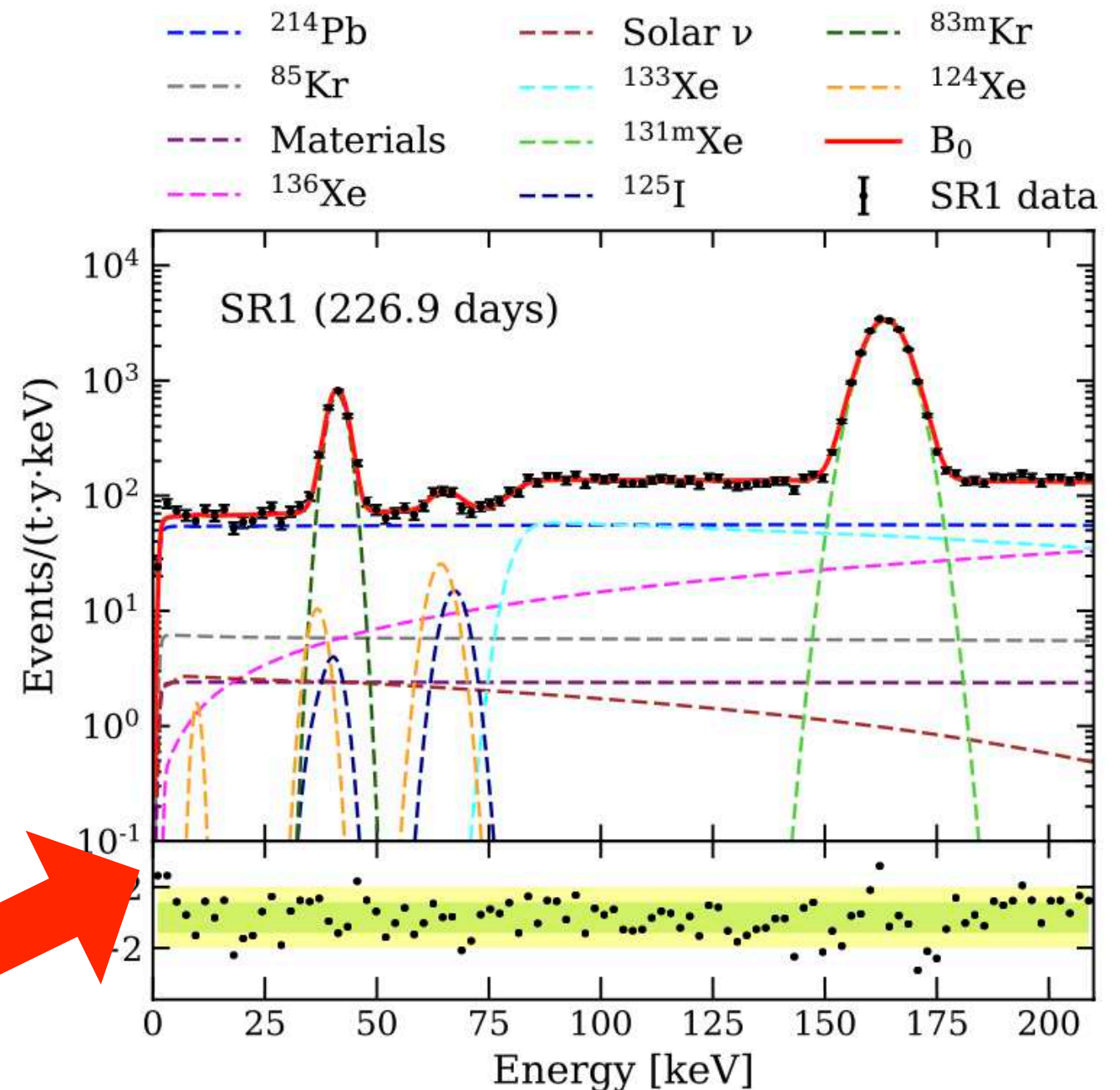
Solar Axions at XENON1T?

Observation of electron recoils over a wide range or recoil energies (1 - 210) keV



Solar Axions at XENON1T?

Observation of electron recoils over a wide range or recoil energies (1 - 210) keV



Excess at low energy?

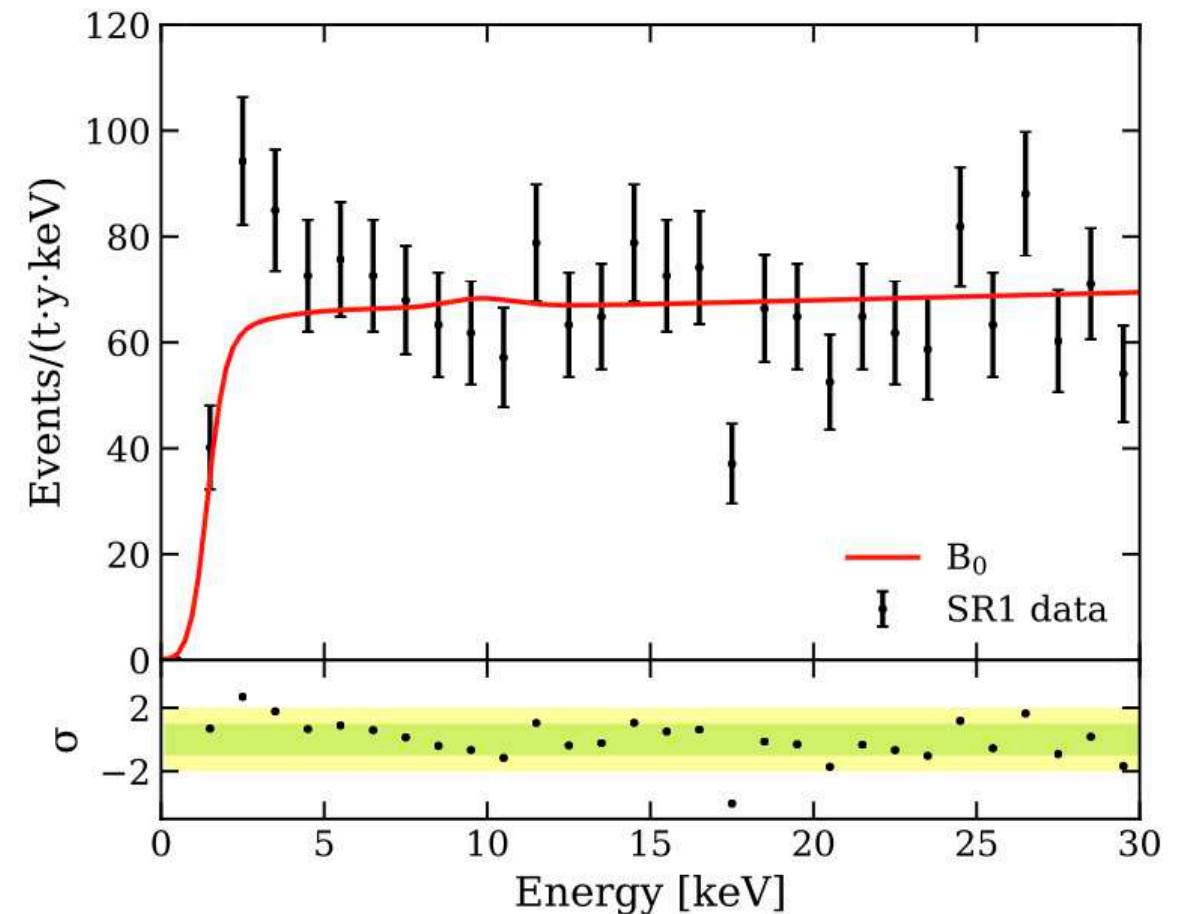
Solar Axions at XENON1T?

1–7 keV range:

285 events observed

Background expectation:

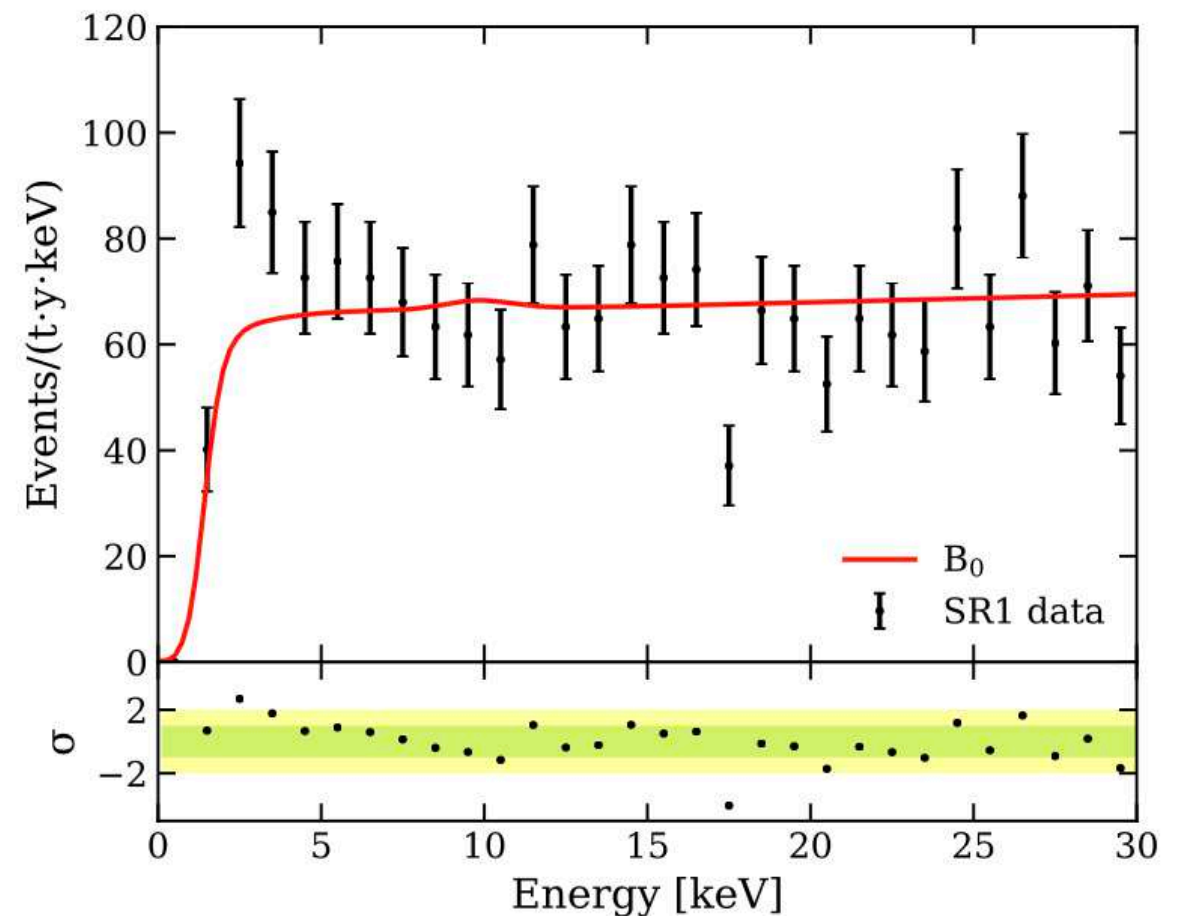
232 ± 15



Solar Axions at XENON1T?

1–7 keV range:
285 events observed

Background expectation:
 232 ± 15



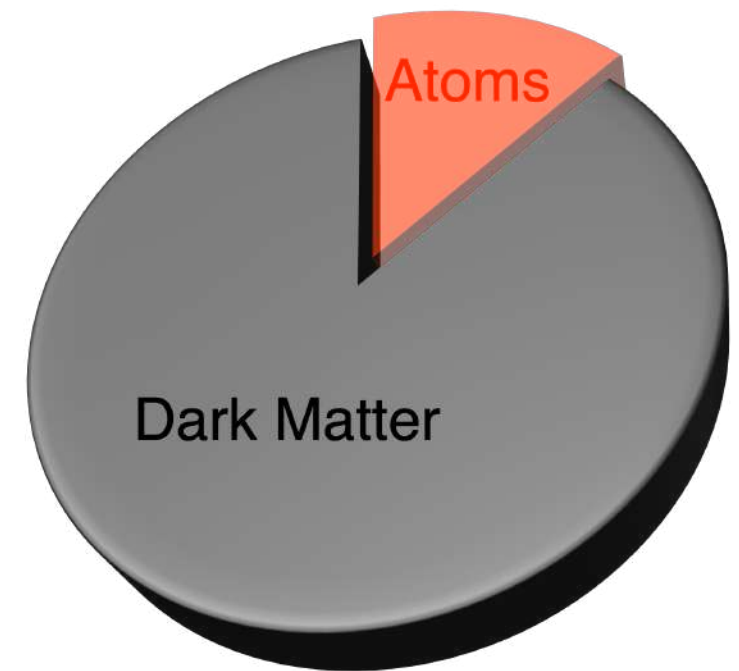
Background from tritium decay
still not completely understood

Worth keeping an eye on it!

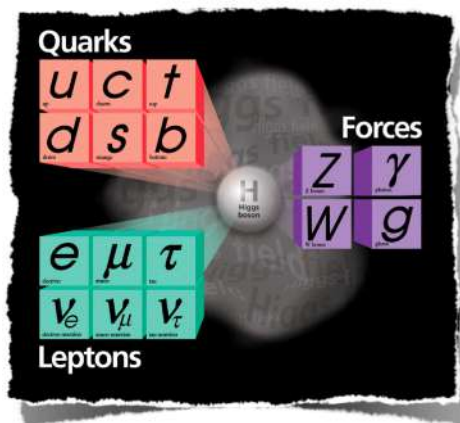
SUMMARY

Dark Matter

85% of matter of
unknown origin and composition



Standard Model



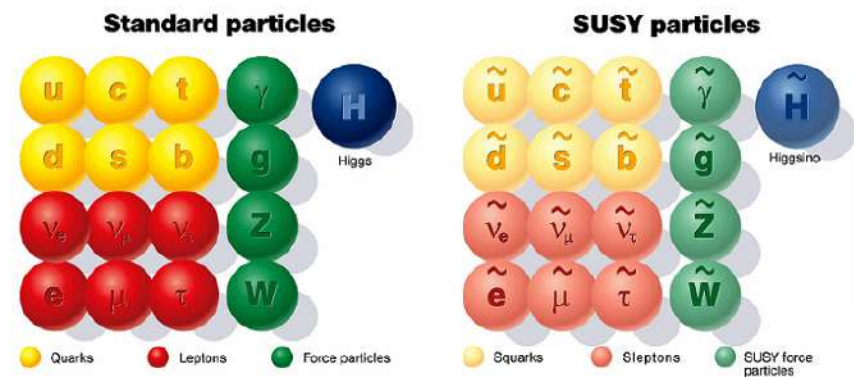
gravity

Dark Matter

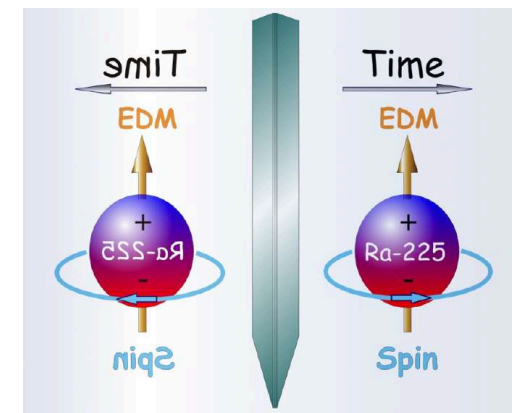


Motivated Candidates in 2020

Hierarchy Problem

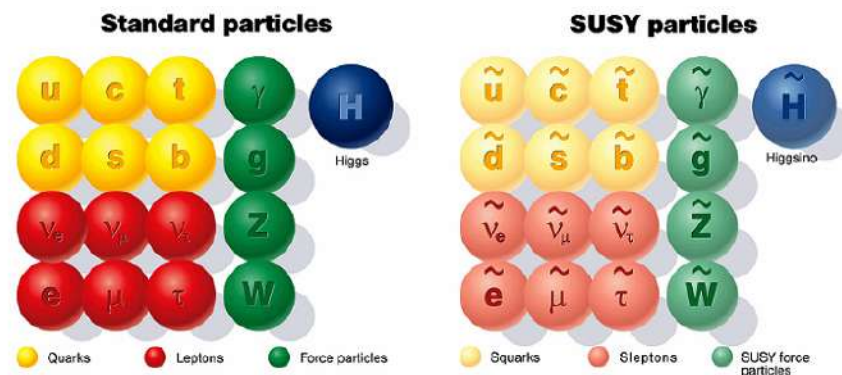


Strong CP Problem



Motivated Candidates in 2020

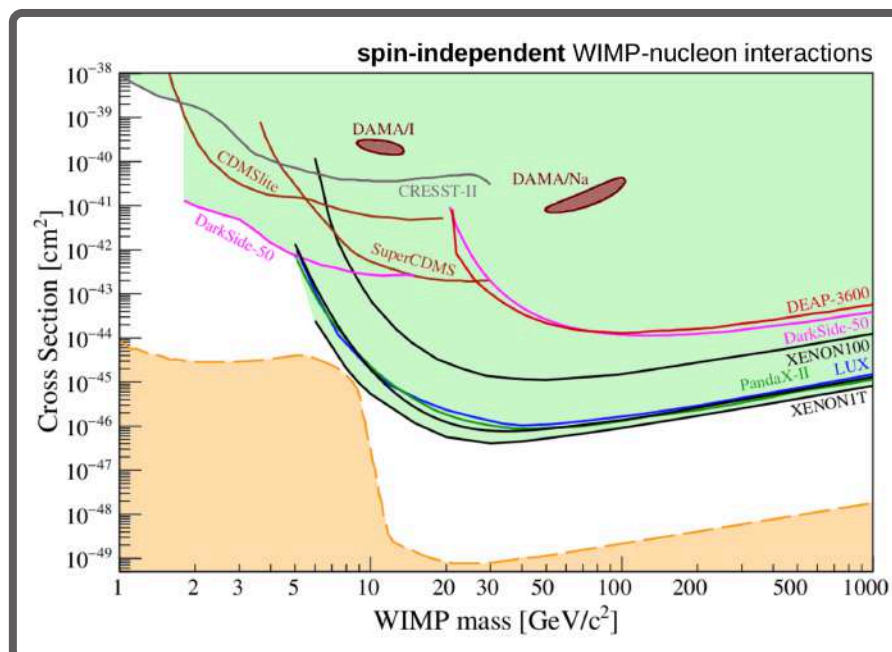
Hierarchy Problem



WIMPs

$$1 \text{ GeV} \lesssim m_{\text{WIMP}} \lesssim 10 \text{ TeV}$$

$$\sigma_{\text{WIMP}} \simeq 1 \text{ pb}$$



WIMP paradigm
challenged by decades
of negative searches

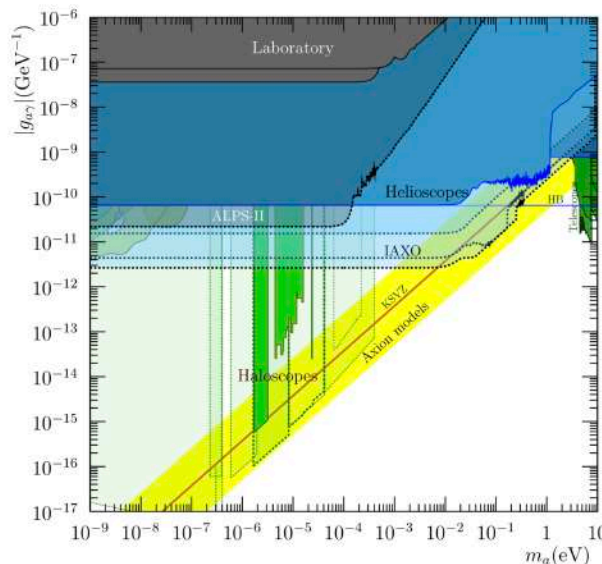
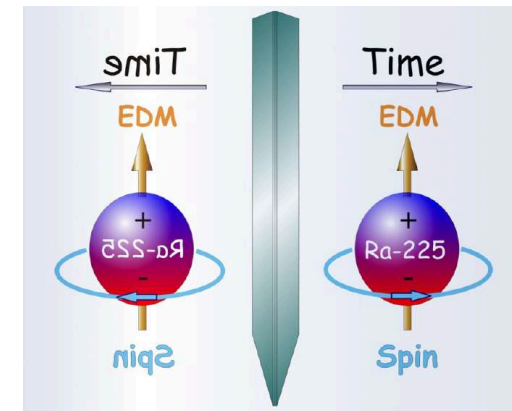
Motivated Candidates in 2020

Axion

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

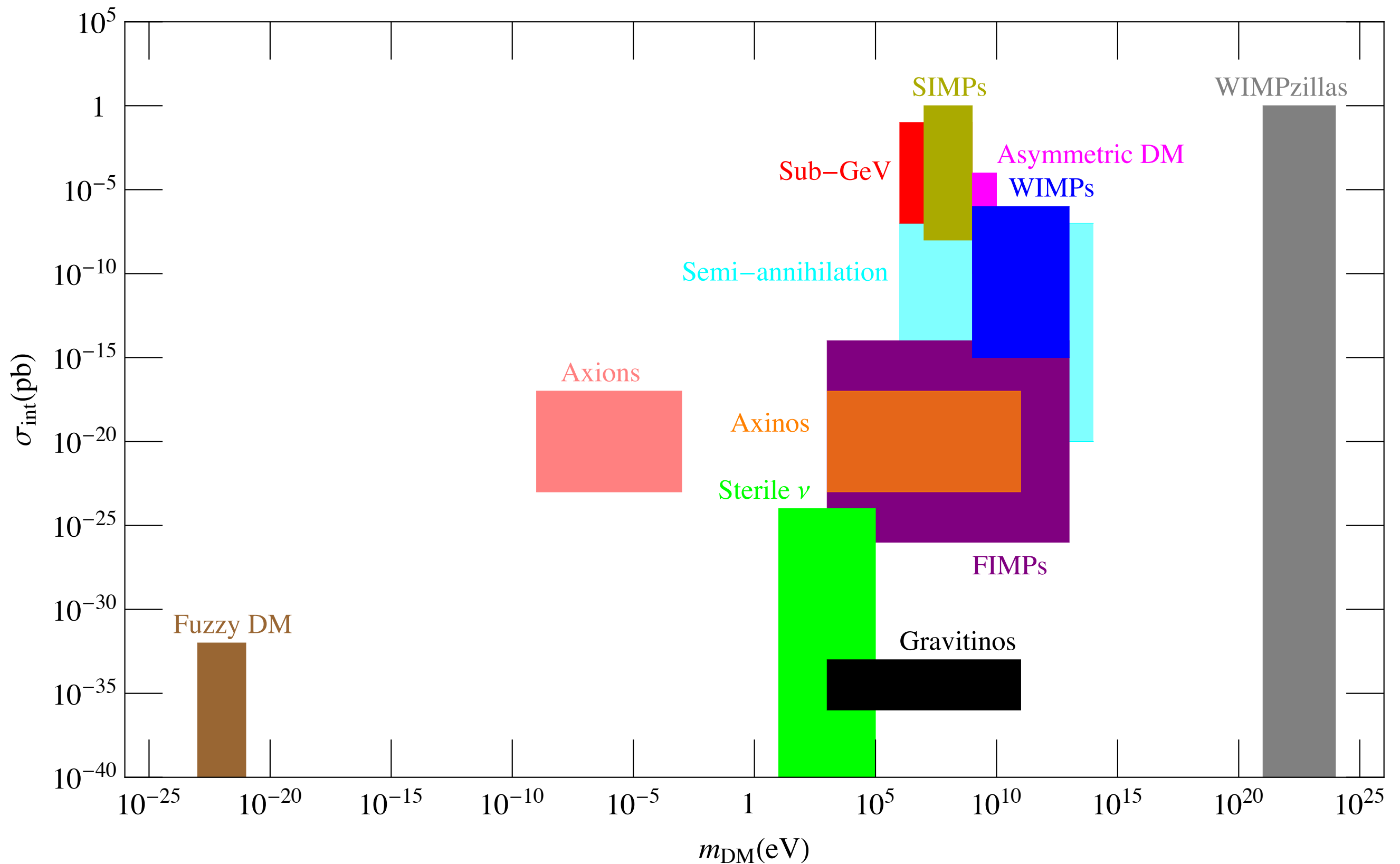
$$g_{a \text{ SM}} \propto f_a^{-1}$$

Strong CP Problem

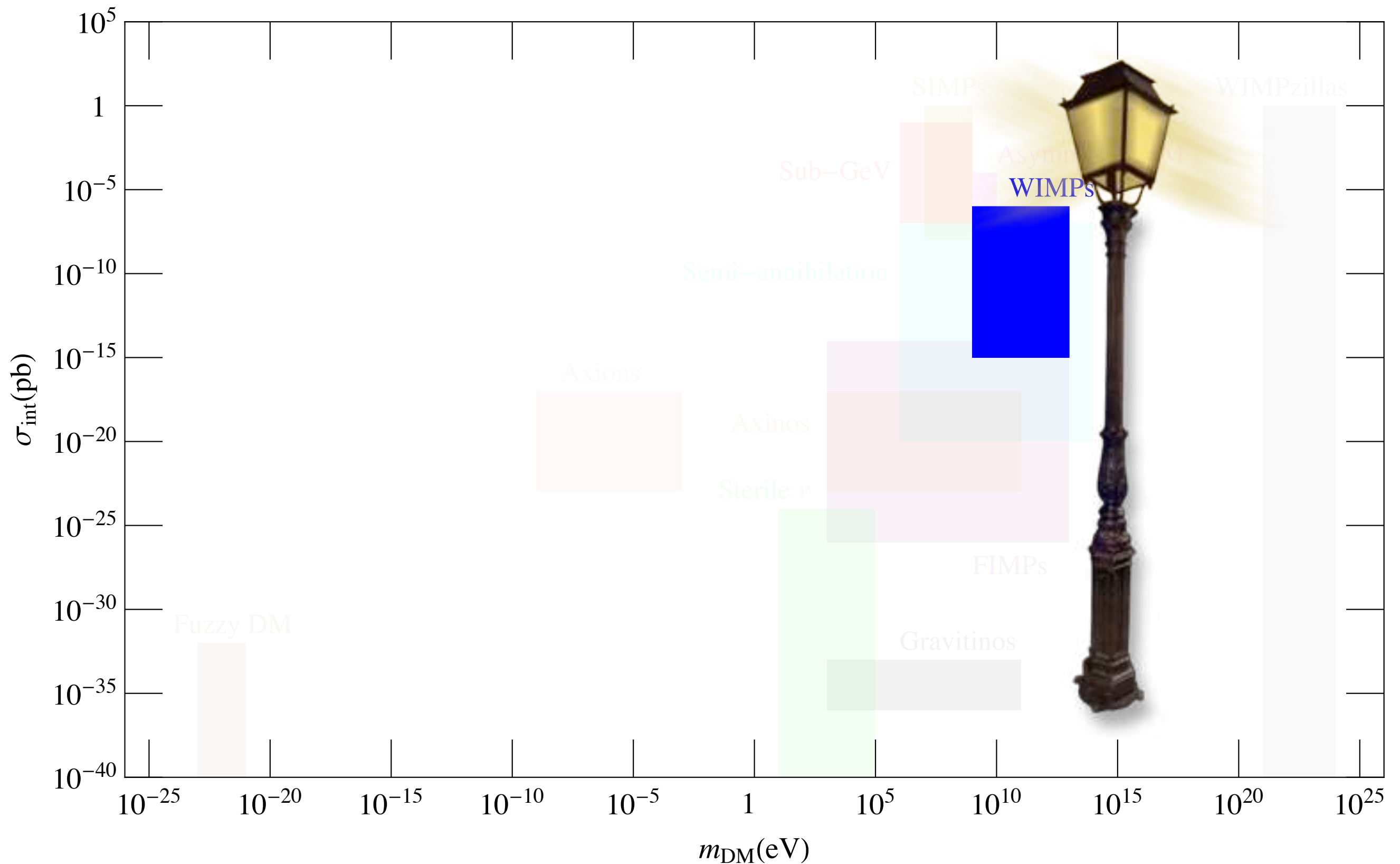


Wealth of new ideas
for axion detection

Where Are We?

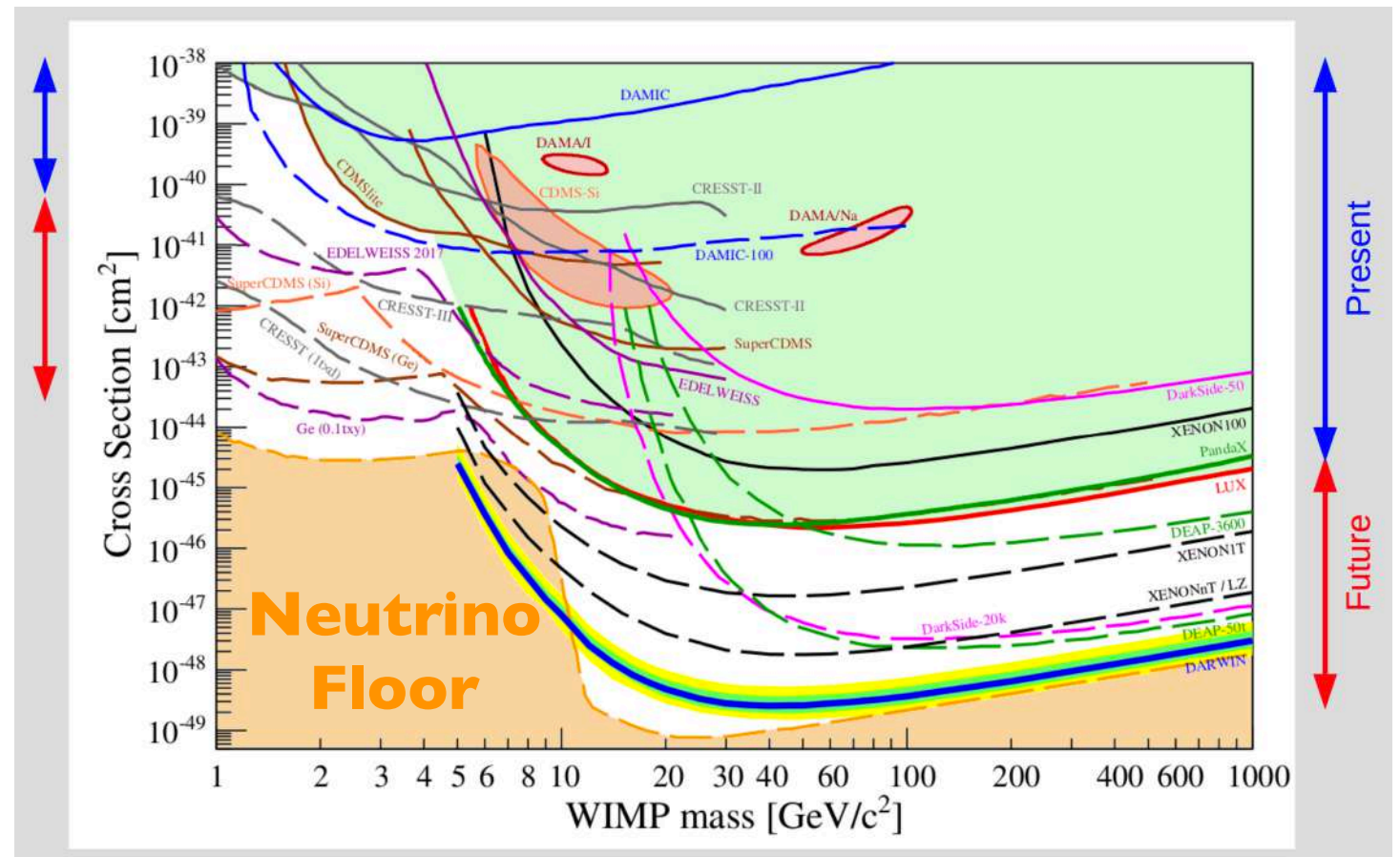


Where Are We?



Where Are We?

Direct searches:
“neutrino floor” in
the next 5-10 years

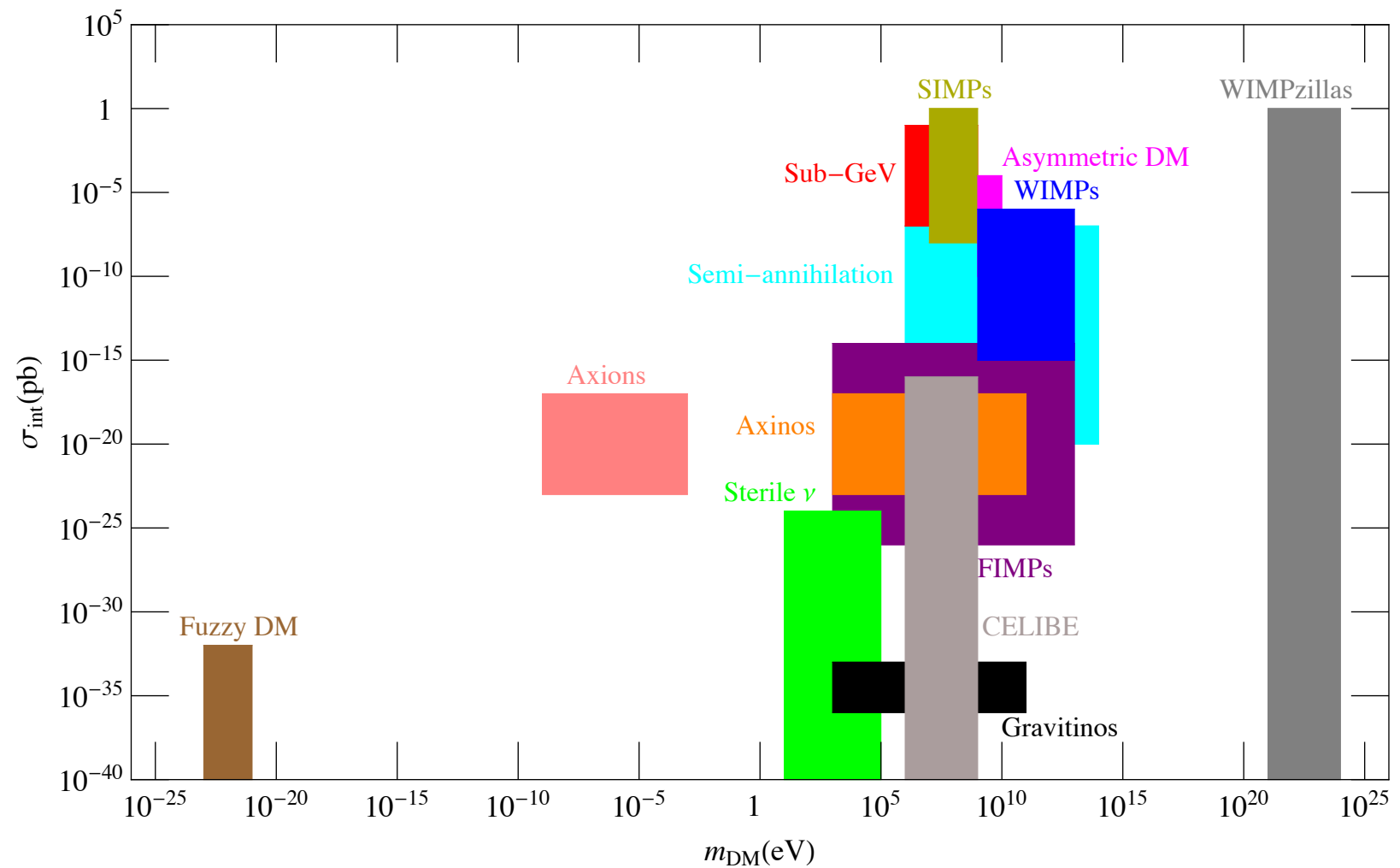
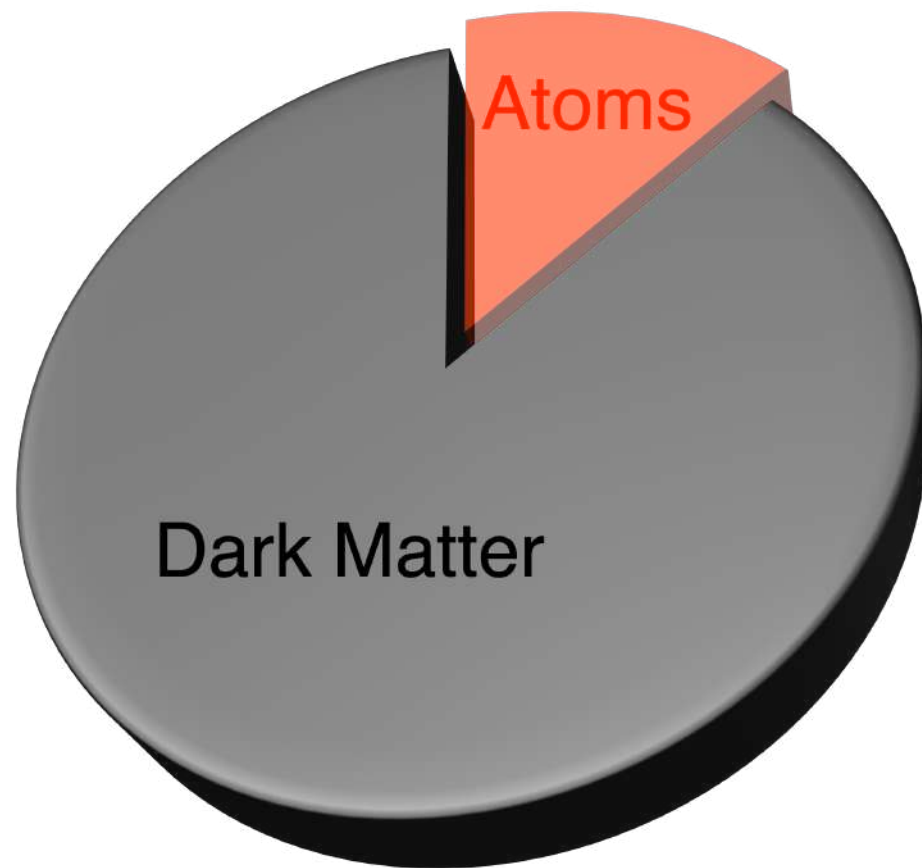


Talk by M. Schumann at TeVPA 2016

Within few years:

- WIMP discovered (herald of additional discoveries?)
- Move on with new ideas beyond the WIMP paradigm

Next Idea Could Be Yours!



THANK YOU