Probing Axions Through N_{eff}

NORDITA
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Outline

Motivation

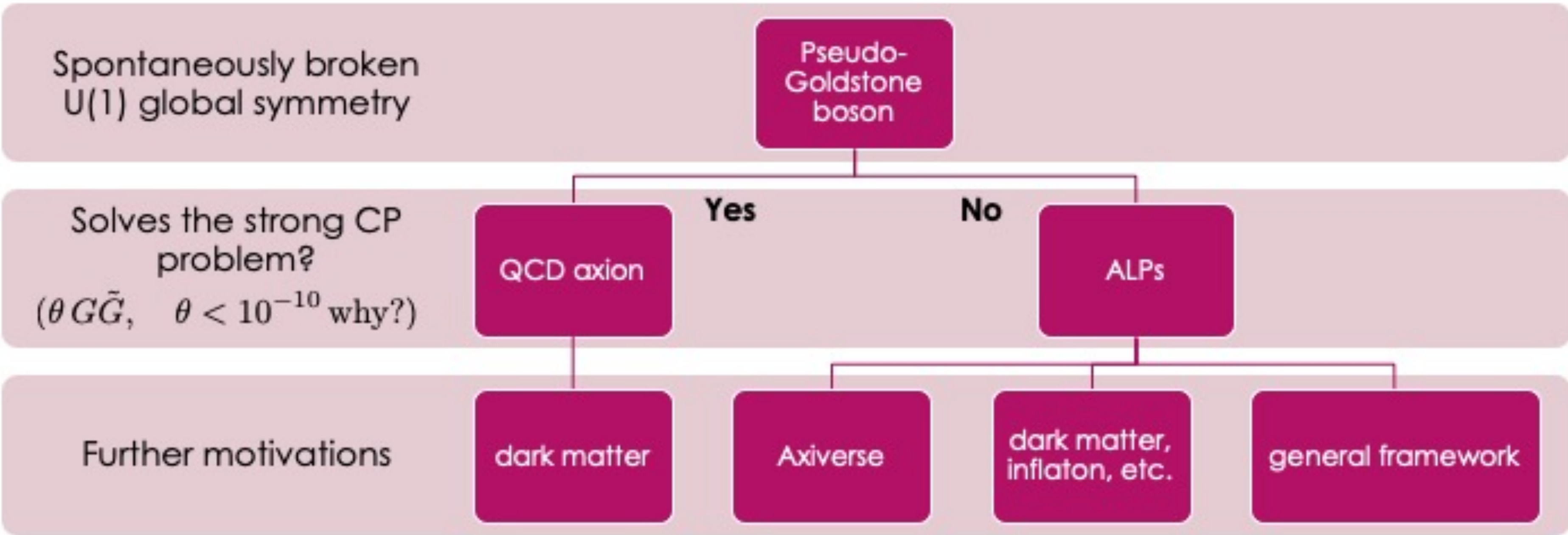
Axion EFT

Axion Searches

- Cosmological probes: Neff

H0 tension

Motivation



Spontaneously broken U(1) global symmetry
Pseudo-Goldstone boson
Solves the strong CP problem?
$(\theta G\tilde{G}, \quad \theta < 10^{-10}$ why?)
Yes
No
QCD axion
ALPs
Further motivations
dark matter
Axiverse
dark matter, inflaton, etc.
general framework

Axion EFT

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_{\rm int}^{\rm SM} + \text{extensions}\,.$$

U(1) broken at the scale f

$\Phi = \phi e^{ia/f}$

$$\mathcal{L}_{\rm int}^{\rm SM} = \frac{1}{2f}\,\partial_\mu a\, J_a^\mu + \frac{c_H}{2f}\,\partial_\mu a\left[iHD_\mu H^\dagger + h.c.\right] + \sum_{X=\{G,B,W\}} \frac{a}{f}\frac{\alpha_X}{8\pi} C_{XX} X_{\mu\nu}\tilde{X}^{\mu\nu}$$

Fermion current

$$J_a^\mu = J_a^\mu|_{\rm diag} + J_a^\mu|_{\rm off-diag}\,,$$

Axial
(vector is conserved)

Axial and vector

$$J_a^\mu|_{\rm diag} = \sum_{\ell = fermions} c_\ell\, \bar{\ell}\gamma^\mu\gamma^5\ell$$

$$J_a^\mu|_{\rm off-diag} = \sum_{\ell\neq\ell'} \bar{\ell}'\gamma^\mu\left(\mathcal{V}_{\ell'\ell} + \mathcal{A}_{\ell'\ell}\gamma^5\right)\ell + \text{h.c.}\,,$$

Axion EFT

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_{\rm int}^{\rm SM} + \text{extensions} \,.$$

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Typically the PQ charges

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_{\rm int}^{(a)} \qquad \mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_{\rm int}^{\rm SM} + \text{extensions} .$$

$$\mathcal{L}_{\rm int}^{\rm SM} = \frac{1}{2f}\,\partial_\mu a\, J_a^\mu + \frac{1}{2f}\,\partial_\mu a \left[iHD_\mu H^\dagger + h.c.\right] + \frac{a}{f}\sum_X \frac{\alpha_X}{8\pi} C_{XX} X_{\mu\nu}\tilde{X}^{\mu\nu} .$$

$$\mathcal{L}_{\rm int}^{(a)} = \frac{1}{2f}\,\partial_\mu a\, J_a^\mu + \frac{1}{2f}\,\partial_\mu a \left[iHD_\mu H^\dagger + h.c.\right] + \frac{a}{f}\sum_X \frac{\alpha_X}{8\pi} C_{XX} X_{\mu\nu}\tilde{X}^{\mu\nu} + \text{extensions}$$

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$$J_a^\mu\big|_{\rm diag} = \sum_{\ell=e,\mu,\tau} c_\ell\, \bar{\ell}\gamma^\mu\gamma^5\ell .$$

$$J_a^\mu\big|_{\rm diag} = \sum_{\ell=fermions} c_\ell\, \bar{\ell}\gamma^\mu\gamma^5\ell$$

$$J_a^\mu\big|_{\rm off-diag} = \sum_{\ell\neq\ell'} \bar{\ell}'\gamma^\mu \left(\mathcal{V}_{\ell'\ell} + \mathcal{A}_{\ell'\ell}\gamma^5\right)\ell + \text{h.c.} ,$$

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$$J_a^\mu = J_a^\mu\big|_{\rm diag} + J_a^\mu\big|_{\rm off-diag} ,$$

Benchmark models
(invisible axion)

	KFVZ	DFSZ
Axion couple to SM	through heavy quarks $\lambda_Q \Phi \bar{Q}_L Q_R + h.c. + V(\Phi)$	through Higgs sector (2 Higgs)
Coupling to SM fermions	loop-level $c_l \simeq \mathcal{O}(1/(4\pi))$	tree-level $c_l \simeq \mathcal{O}(1)$
Dominant scattering channel above QCDPT	w/ gluons	w/ fermions

Benchmark models
(invisible axion)

Axion couple to SM	$\lambda_Q \Phi \bar{Q}_L Q_R + h.c. + V(\Phi)$	
Coupling to SM fermions	$c_l \simeq \mathcal{O}(1/(4\pi))$	$c_l \simeq \mathcal{O}(1)$
Dominant scattering channel above QCDPT		

Benchmark models (invisible axion)

[Wilczek 78', Weinberg 78', Kim 79',...]

▶ KFVZ

- Axion couple to SM through heavy quarks

$$\lambda_Q \Phi \bar{Q}_L Q_R + h.c. + V(\Phi)$$

- No coupling to SM fermions at tree-level

$$c_l \simeq \mathcal{O}(1/(4\pi))$$

- Axion-gluon scattering dominate cross-sections above QCDPT

[Masso + 02', ...]

▶ DFSZ

- Axion couple to SM through the Higgs sector (there are 2 Higgses)

$$\lambda_u \bar{q}_L q_R H_u + \lambda_d \bar{q}_L d_R H_d + V(\Phi, H_u, H_d)$$

- Coupling to SM fermions is tree-level

$$c_l \simeq \mathcal{O}(1)$$

- Axion-fermion scatterings can dominate cross-sections

[Salvio+ 13', ..., **RZF**&Notari 17']

$$c_l \simeq \mathcal{O}(1)$$

$$\mathcal{L} = \lambda_Q \Phi \bar{Q}_L Q_R + h.c. + V(\Phi)$$

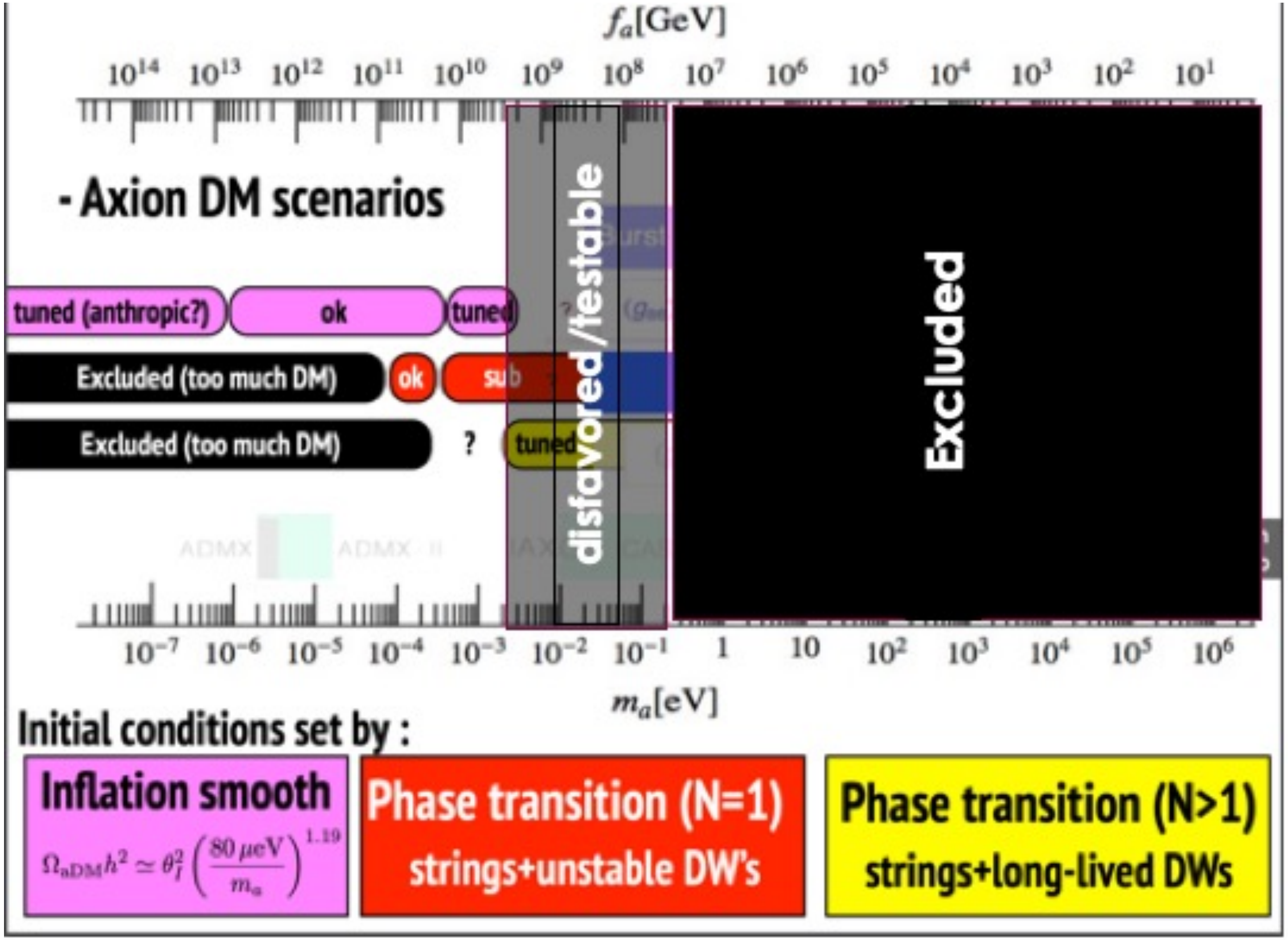
$$c_l \simeq \mathcal{O}(1/(4\pi))$$

$$\lambda_Q \Phi \bar{Q}_L Q_R + h.c. + V(\Phi)$$

$$\lambda_u \bar{q}_L q_R H_u + \lambda_d \bar{q}_L d_R H_d + V(\Phi, H_u, H_d)$$

Axion Searches

(QCD) axion window



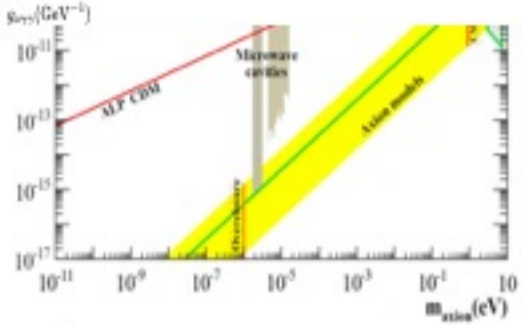
- From SN1987A cooling

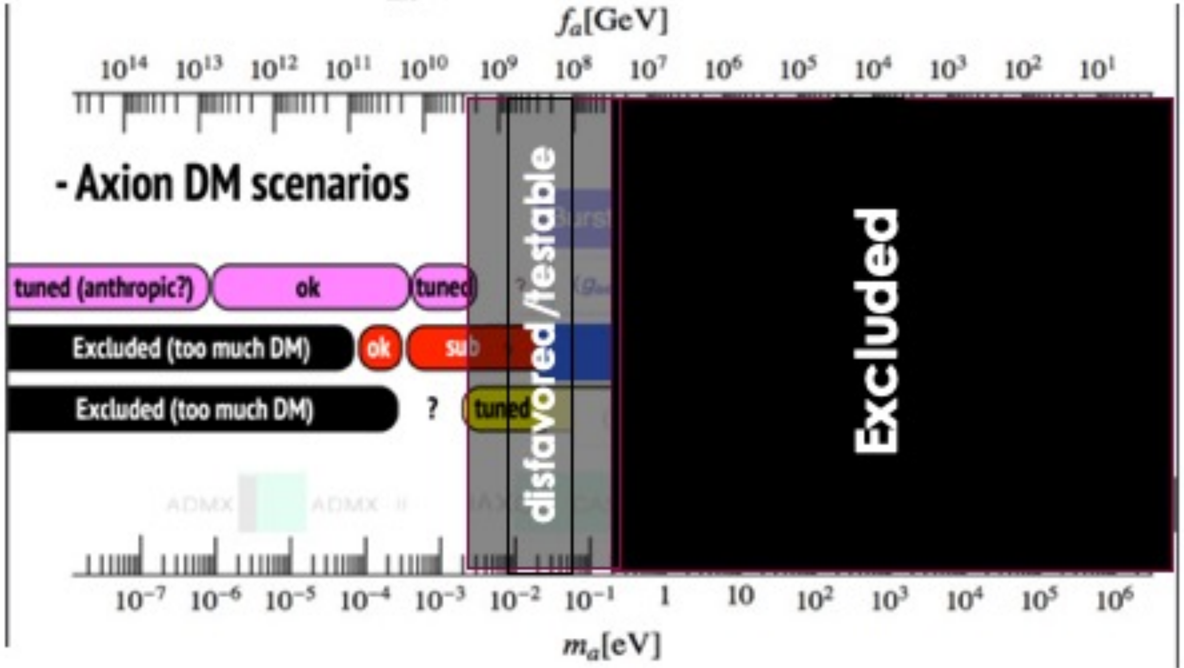
  $f \gtrsim 5 \times 10^{8}\,\mathrm{GeV}$

  but complicated astrophysics.
- Bounds also apply to ALPs but can be easily evaded in that case.

Adapted from
J. Redondo talk

(QCD) axion window





- From SN1987A cooling [PDG 16']

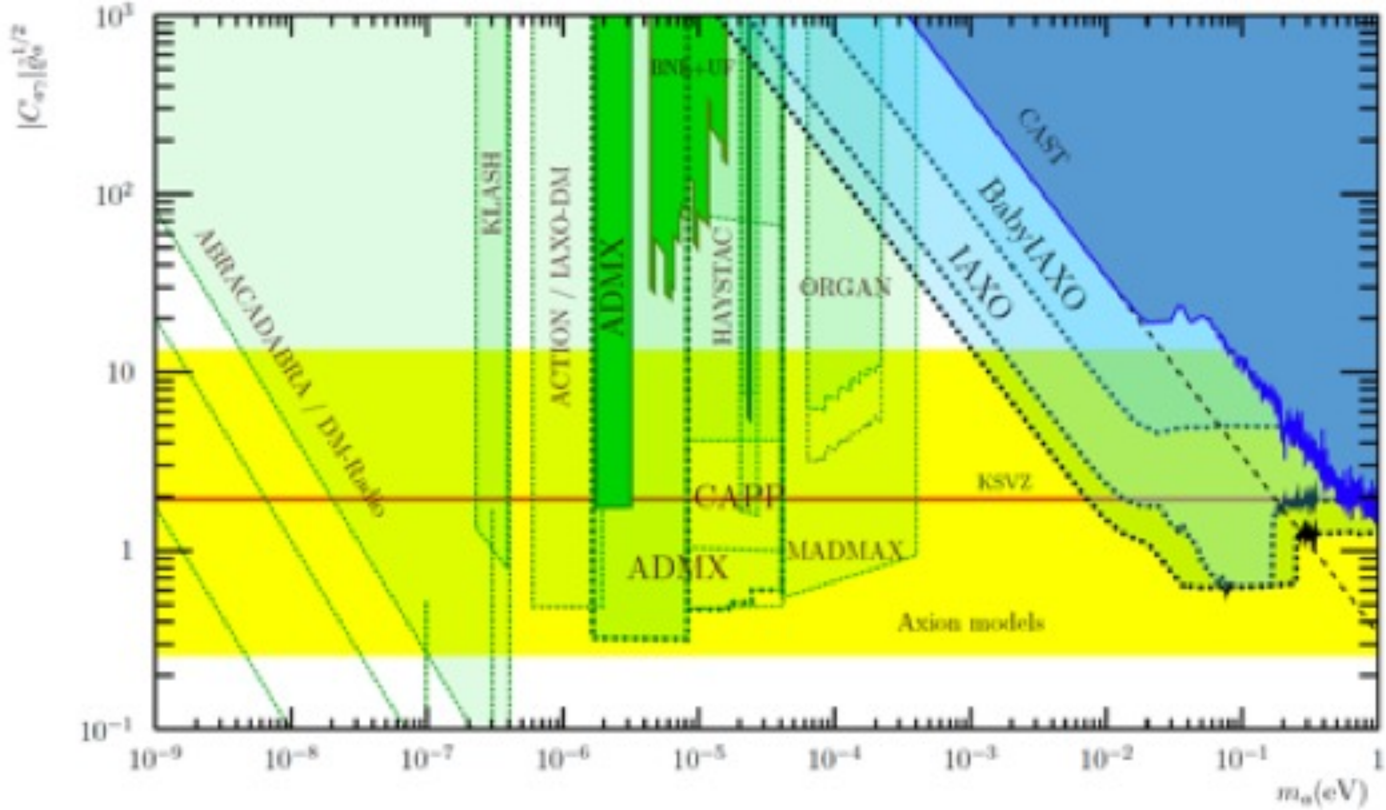
  $$f \gtrsim 5 \times 10^8 \mathrm{GeV}$$

  but complicated astrophysics.

- Experimental bounds also apply to ALPs

Adapted from J. Redondo talk

Constraints on axion-photon coupling



Taken from 1801.08127

Constraints on fermion couplings

$\Lambda_{l,l'} = 2f/c_{l,l'}$

Coupling	Bound [GeV]	Origin
Λ_{ee}	1.2×10^{10}	white dwarfs
$\Lambda_{\mu\mu}$	2.0×10^{6}	stellar cooling
$\Lambda_{\tau\tau}$	2.5×10^{4}	stellar cooling
Λ_{bb}	6.1×10^{5}	stellar cooling
Λ_{tt}	1.2×10^{9}	stellar cooling
$\Lambda^{V}_{\mu e}$	5.5×10^{9}	$\mu^+ \to e^+ \phi$
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+ \to e^+ \phi \gamma$
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^- \to e^- \phi$
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^- \to \mu^- \phi$
Λ^{A}_{cu}	6.9×10^{5}	D^0-$\bar{D}^0$
Λ^{A}_{bd}	6.4×10^{5}	B^0-$\bar{B}^0$
Λ_{bs}	6.1×10^{7}	$b \to s\phi$
Λ_{tu}	6.6×10^{9}	mixing
Λ_{tc}	2.2×10^{9}	mixing

Table taken from [Baumann+ 16']

- Constraint from the **cooling of white dwarfs.** [Hansen 15'] (Other authors see it as **hints**! [PDG 17'])
- Suppressing $c_{e,e'} \ll 1$ not necessarily fine-tuned.

Constraints on fermion couplings

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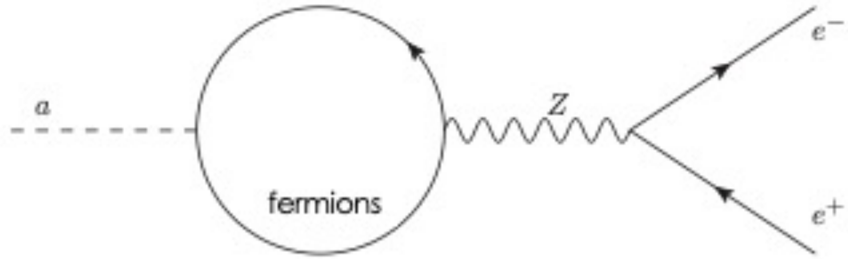
Table taken from [Baumann+ 16']

- Loop induced constraints:
  [Feng+ 98'; Bernal,D'Eramo, **RZF**, Notari 18']



$$c_e = c_e(\Lambda) - \frac{\lambda_\ell^2}{8\pi^2} c_\ell \log\left(\Lambda/m_\ell\right) \ .$$

- Model dependent, one needs to run the coupling from Λ to low energies.

Constraints on fermion couplings

$\Lambda_{l,l'} = 2f/c_{l,l'}$

Coupling	Bound [GeV]	Origin
[Bernal,D'Eramo, **RZF**, Notari 18']		white dwarfs
$\Lambda_{\mu\mu}$	200	stellar cooling
$\Lambda_{\tau\tau}$	2.5×10^4	stellar cooling
Λ_{bb}	6.1×10^5	stellar cooling
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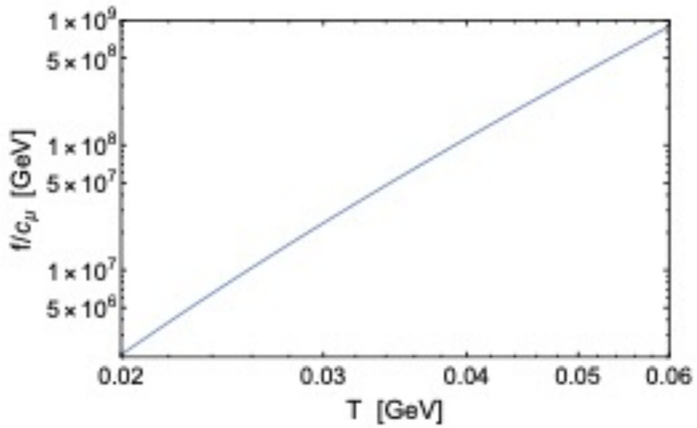
Table taken from [Baumann+ 16']

- Energy loss of SN1987A (T=20-60 MeV) into muons:
  [Brust+ 13'; Bernal,D'Eramo, **RZF**, Notari 18']
  - Assumes an initial thermal abundance of muons. **Unclear** because $T_{SN} \ll m_\mu$
  - Constraint greatly depends on T_{SN}



- Loop induce constraint is much weaker.

Constraints on fermion couplings

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Interesting cases
+ $\Lambda_{cc}, \Lambda_{ss}$

Table taken from [Baumann+ 16]

Cosmological Probes

Effects	Observables
Interact with photons	CMB blackbody spectrum, …
Affect structure formation	matter power sepctrum
Change expansion history	N_{eff} (BBN, CMB), H_0 (today)
	…

Effective Number of relativistic species (Neff)

- CMB probes energy density stored in relativistic species at recombination.

$$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff(SM)} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4 \frac{\rho_a}{\rho_\gamma} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_a}{\rho_\gamma}\,.$$
$$= 74.85\, Y_a^{4/3} \propto g_{*s,\,\text{axion-dec}}^{-4/3}$$

$$Y_a \equiv n_a/s$$

$$s = \frac{2\pi^2}{45} g_{*s} T^3$$

- Current status:

$$N_{\rm eff(SM)} = 3.046$$

$$N_{\rm eff}^{\rm Planck} = 3.27 \pm 0.15$$

[Turner 88', Brust 13', Baumann+ 16']

Future experiments

$$\sigma\left(\Delta N_{\rm eff}^{\rm CMB-S4}\right) \simeq 0.024$$

If 1 extra d.o.f thermalized above EWPT gives: $\Delta N_{\rm eff} \lesssim 0.027$

Boltzmann eq.

$$\frac{dn_a}{dt} + 3Hn_a = \left(\sum_S \overline{\Gamma}_S + \sum_D \overline{\Gamma}_D\right)\left(n_a^{\rm eq} - n_a\right)$$

$$\overline{\Gamma}_S = \frac{n_1^{\rm eq} n_2^{\rm eq}}{n_a^{\rm eq}} \langle \sigma_{B_1 B_2 \to B_3 a} v_{\rm rel} \rangle$$

$$\overline{\Gamma}_D = \frac{n_1^{\rm eq}}{n_a^{\rm eq}} \Gamma_{B_1 \to B_3 a} \frac{K_1 [m_1/T]}{K_2 [m_1/T]}$$

$$sHx\frac{dY_a}{dx} = \left(1 - \frac{1}{3}\frac{d\ln g_{*s}}{d\ln x}\right)\left(\sum_S \gamma_S + \sum_D \gamma_D\right)\left(1 - \frac{Y_a}{Y_a^{\rm eq}}\right)$$

$x \equiv m/T$ $\qquad$ $\gamma \equiv n_a^{\rm eq}\,\overline{\Gamma}$

Relevant processes

Decays

- $\ell \to \ell' a$
- $\bar{\ell} \to \bar{\ell}' a$

$$\Gamma_{l^- \to l'^- a} = \left(\mathcal{V}_{\ell'\ell}^2 + \mathcal{A}_{\ell'\ell}^2\right) \frac{m_\ell^3}{64\pi f^2} \left(1 - \frac{m_{\ell'}^2}{m_\ell^2}\right)^3$$

Scatterings

- $\ell + \bar{\ell} \to \{g, \gamma\} + a$

$$\bar{\Gamma}_S \propto \frac{e^2 c_\ell^2}{f^2} m_\ell^2 \, T \, e^{-2m_\ell/T}$$

- $\ell + \{g, \gamma\} \to \ell + a$
- $\bar{\ell} + \{g, \gamma\} \to \bar{\ell} + a$

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For gluons, $e^2 \to g_s^2 N_c$

Relevant processes

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Scatterings

$$\ell + \bar{\ell} \to \{g, \gamma\} + a$$

$$\sigma_{\ell^+\ell^- \to \gamma a}(s) = \frac{c_\ell^2 e^2}{f^2} \frac{m_\ell^2 \tanh^{-1}\left(\sqrt{1 - \frac{4m_\ell^2}{s}}\right)}{4\pi(s - 4m_\ell^2)}$$

$$\ell + \{g, \gamma\} \to \ell + a$$

$$\bar{\ell} + \{g, \gamma\} \to \bar{\ell} + a$$

$$\sigma_{\ell^\pm \gamma \to \ell^\pm a}(s) = \frac{c_\ell^2 e^2}{f^2} \frac{m_\ell^2[2s^2 \log(s/m_\ell^2) - 3s^2 + 4m_\ell^2 s - m_\ell^4]}{32\pi s^2 (s - m_\ell^2)}$$

For gluons, $e^2 \to g_s^2 N_c$

$$\ell \to \ell' a$$

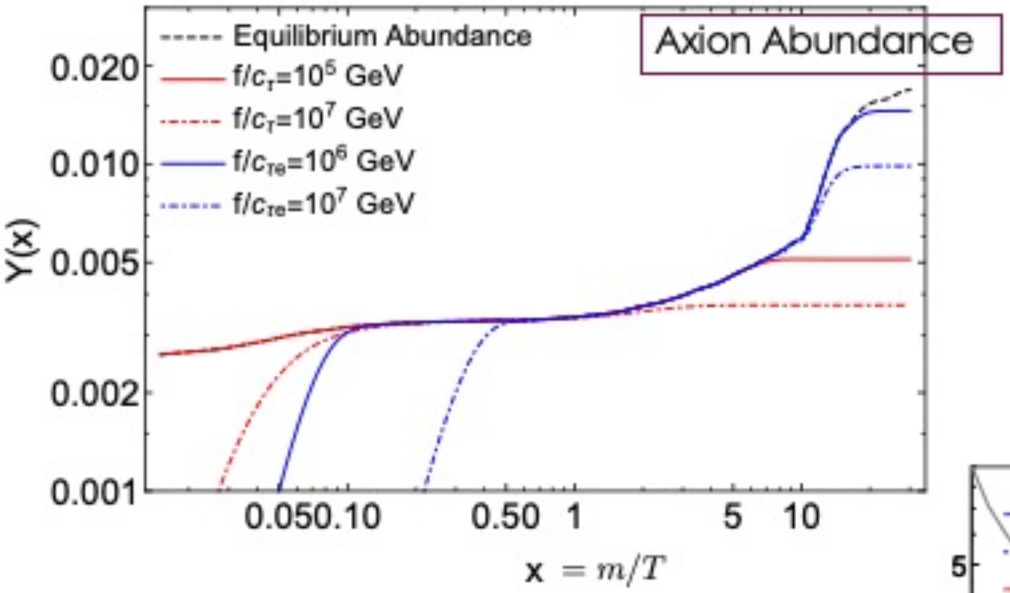
$$\bar{\ell} \to \bar{\ell}' a \qquad \bar{\ell} + \{g, \gamma\} \to \bar{\ell} + a$$

$$\ell\bar{\ell} \to ga \qquad \ell\bar{\ell} \to ga$$

$$\bar{\ell} g \to \bar{\ell} a \qquad \ell + \bar{\ell} \to \{g, \gamma\} + a$$

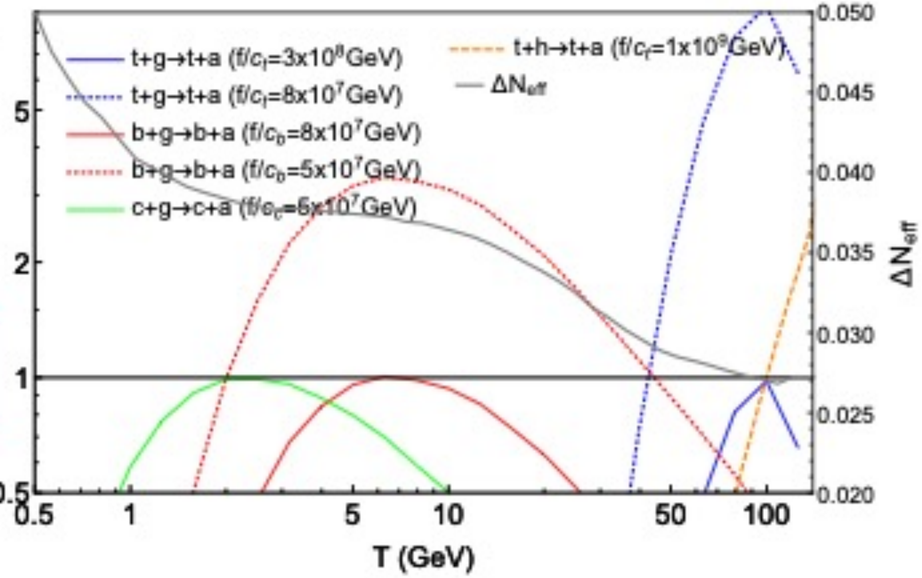
$$\ell g \to \ell a \qquad \ell + \{g, \gamma\} \to \ell + a$$

Abundances and rates



For scatterings peak production is at $T = m_l$

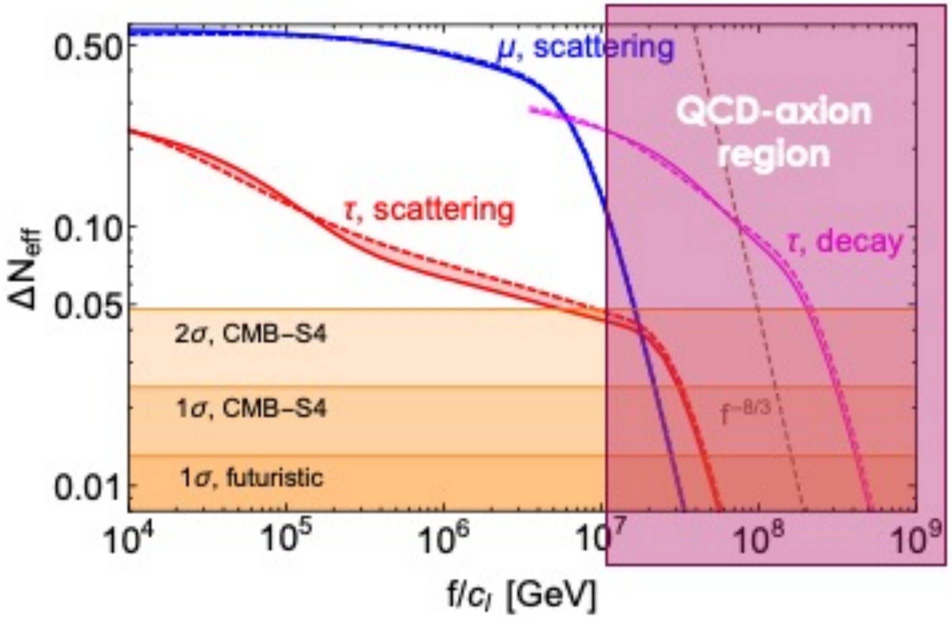
Scattering rate/Hubble



Results

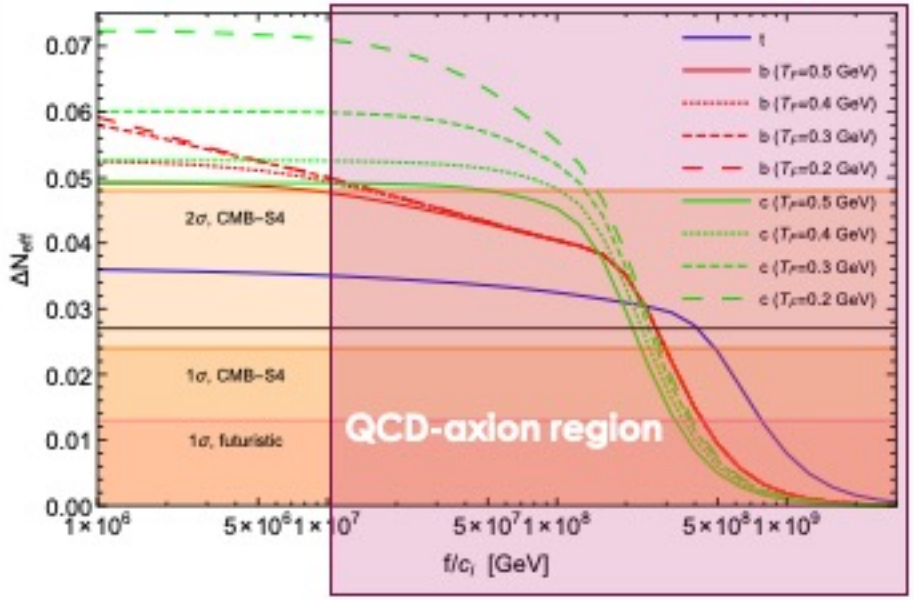
Axion – lepton - photon scatterings and decays

[Bernal, D'Eramo, **RZF**, Notari 18']



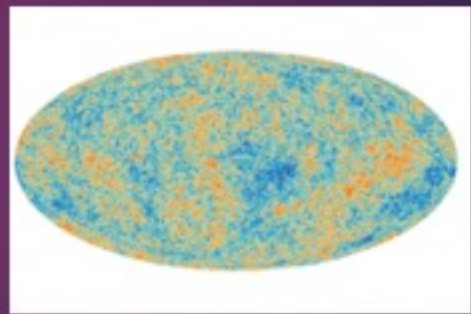
[**RZF**, Notari 18']

Axion – quarks - gluon scatterings



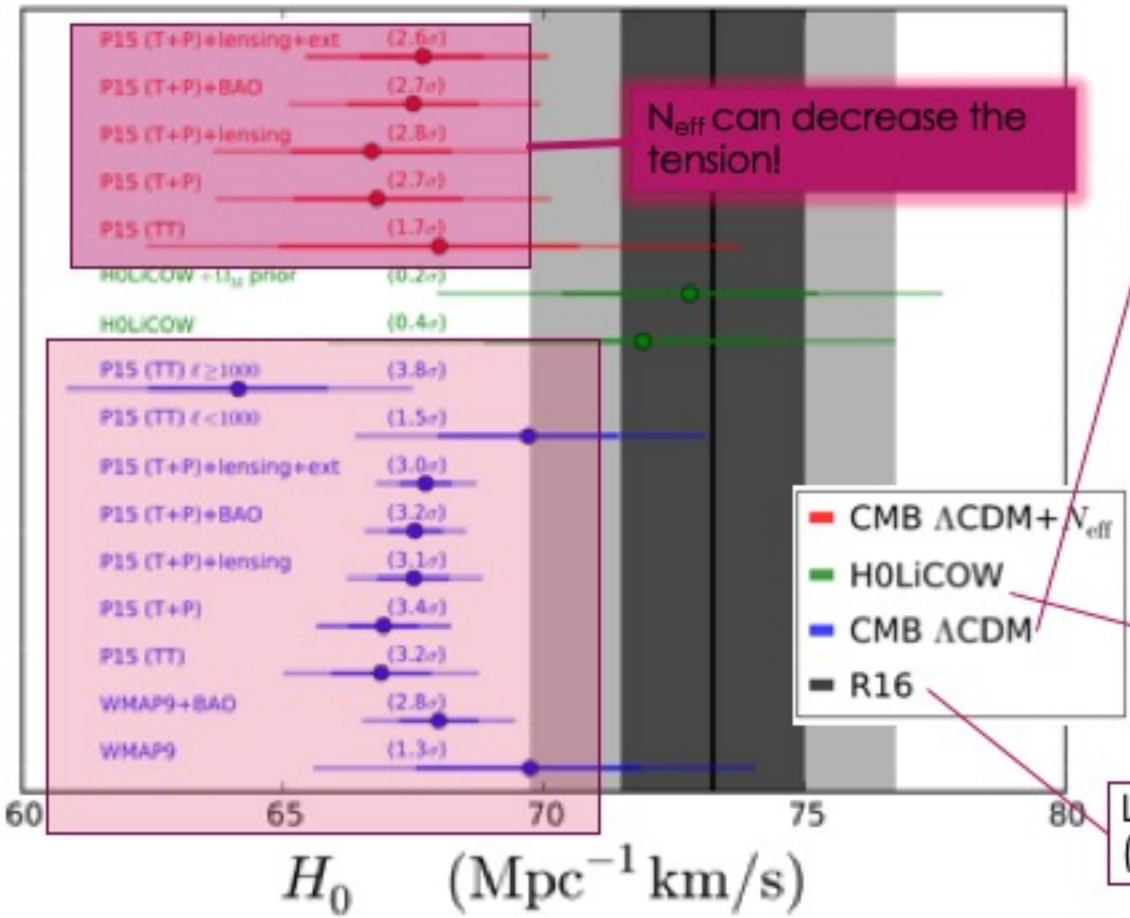
The H_0 tension

VS



H0 tension

Taken from [Bernal+ 16]



N_{eff} can decrease the tension!

and also BAO data (including Planck prior)

Smaller H0

67.3 ± 0.60 [Planck 18']

Galaxy lensing of quasars

Local measurements (supernovae, z<1)

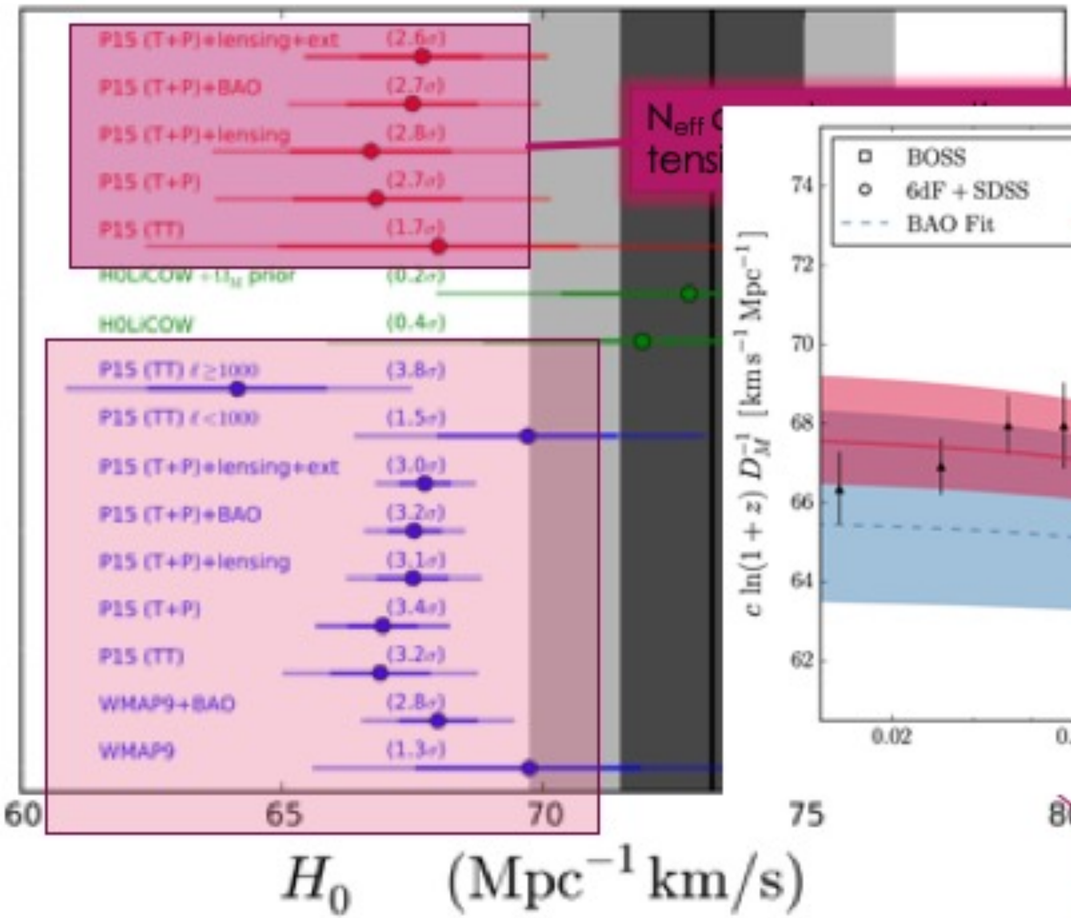
Larger H0

73.52 ± 1.62

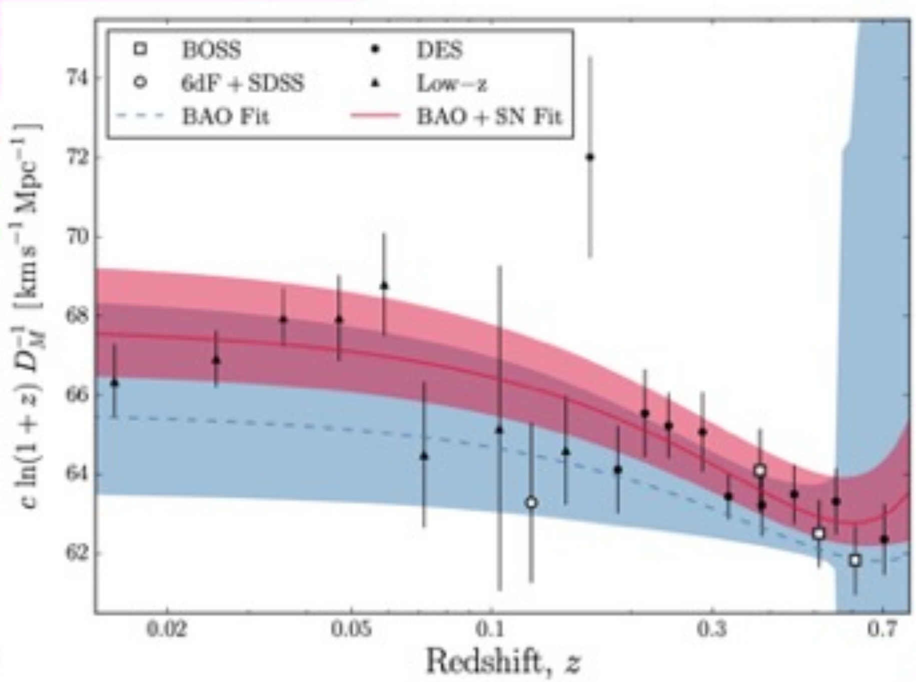
[Riess+ 18'w/ latest Gaia data]

H0 tension

Taken from [Bernal+ 16]



N_{eff} c...
tensi...



Smaller H0

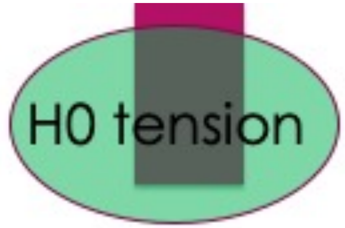
.60 [Planck 18']

Larger H0

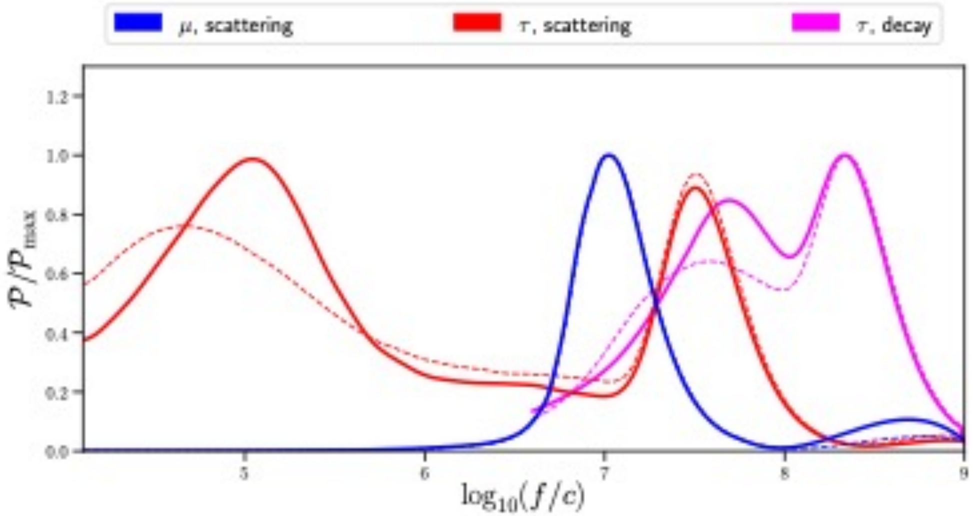
73.52 ± 1.62

[Riess+ 18'w/ latest Gaia data]

Local measurements (supernovae, z<1)



[Bernal,D'Eramo, **RZF**, Notari 18']



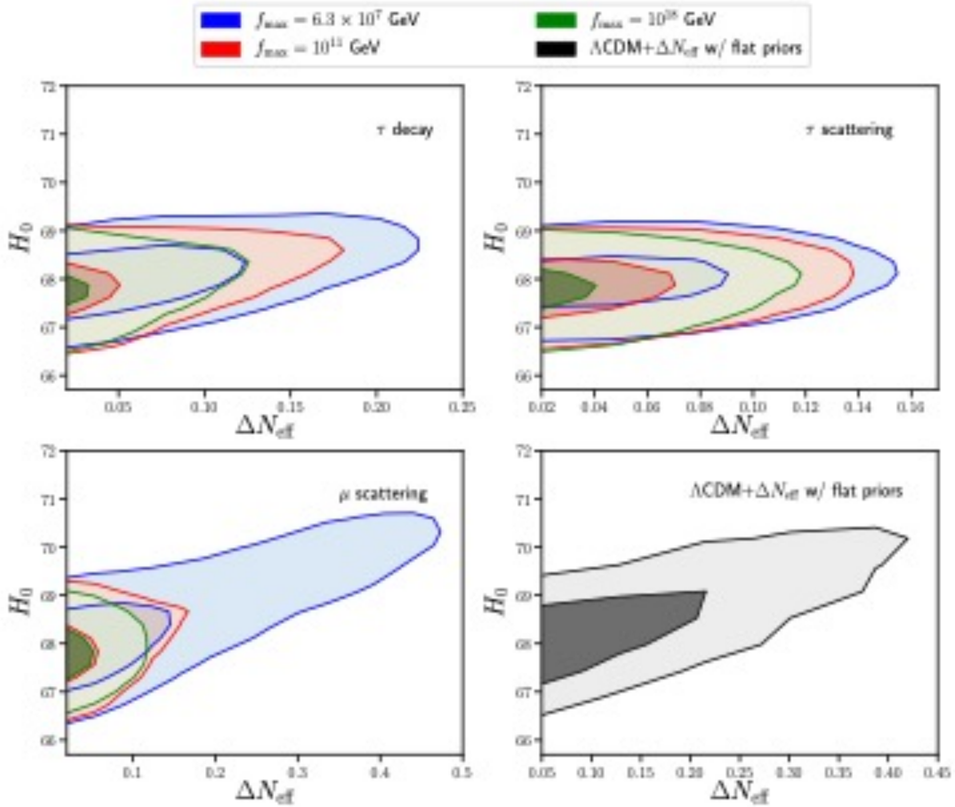
- Thermal axion production provides a physical realization

- N_{eff} in Planck is varied phenomenologically with a **flat prior**

Figure:
Posterior distribution for Λ CDM+Neff with flat priors on Neff.

Role of the Prior

Flat prior on $\log(f/c_l)$



[Bernal,D'Eramo, **RZF**, Notari 18']

- Flat prior on N_{eff} is not physically motivated in this case.
- The prior should be on f/c_l.
- We need to scan over many orders of magnitude so a linear prior in $\log\left(\frac{f}{c_l}\right)$ is more adequate.
- Tension can be **reduced to 2.7 sigma** in the case of mu-scattering!

Conclusions

- Axions are well motivated extensions of the SM. The coupling with photons is the one more probed but the coupling with fermions also provides very useful information in particular it could inform us about the UV completion.
- Cosmology, through e.g. Neff, will be able to probe an interesting region of the axion parameter space. More generically, through Neff one might be able to find indirect evidence for new (light) particles.
- In the case of an ALP coupling with leptons the change in Neff can reduce the current tension on the value of the H0 parameter.