Axion-Like-Particles, Direct Detection & Solar constraints

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[JCAP 10(2021); ArXiv 2303.06968]

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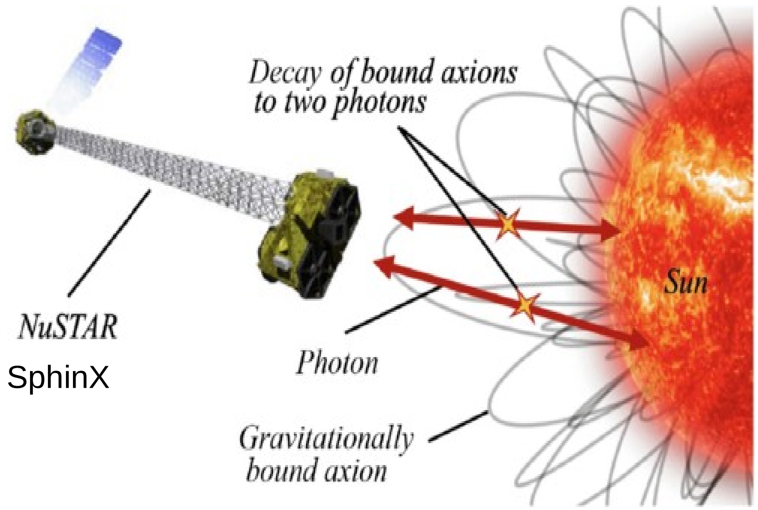
Axion-Like-Particles, Direct Detection & Solar constraints

- Axions and extra-dimensions: direct detection? [MIMAC]

- ALPs & Solar constraints

(Trapped axions)



[DeRocco et al., PRL 129 (2022)]

(Invisible) Axions, Strong CP problem and Dark Matter

[Peccei & Quin 1977; Weinberg 1978; Wilczek 1978]

- Strong CP problem: $L_{SM} = \ldots + \frac{\alpha_s}{8\pi}\theta \tilde{G}_a^{\mu\nu} G_{\mu\nu a} + \ldots$ (CP̸)

$$\Rightarrow \quad d_n = 2.4 \times 10^{-16}\,\theta \;\; e\,cm < 2.9 \times 10^{-26} \quad \Rightarrow \quad \theta < 10^{-10}$$

- Axion: Pseudo-Nambu-Goldstone-Boson of a global $U(1)_{PQ}$, broken spontaneously at f_a

QCD: $V(a) \sim \Lambda_{QCD}^4\,[1 - \cos(a/fa)]$

$$L_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\xi_s \frac{\alpha_s}{8\pi}\theta \tilde{G}_a^{\mu\nu} G_{\mu\nu a} + \frac{a}{f_a}\xi_{em}\frac{\alpha}{8\pi}\tilde{F}^{\mu\nu}F_{\mu\nu} \quad \Rightarrow \quad L_{eff} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{g_{a\gamma\gamma}}{4} a\,\tilde{F}^{\mu\nu}F_{\mu\nu} + g_{af}\frac{\partial_\mu a}{2m_f}\bar{f}\gamma^\mu\gamma^5 f + \ldots$$

$$m_a \simeq 6\,\mu eV \left(\frac{10^{12}\,GeV}{f_a}\right) \qquad g_{a\gamma\gamma}(f_a, \xi_{em}) \qquad g_{ae}(f_a, \xi_{em})$$

Models:

- DFSZ: $H_u\ (1,2,-1/2) + H_d\ (1,2,1/2) + \Phi\ (1,1,0)$
- KSVZ: $Q\ (3,1,0) + \Phi\ (1,1,0) \quad [g_{ae} \simeq 0]$

Parameter: $f_a \Leftrightarrow m_a$

[Dine-Fischler-Srednicki-Zhitnitsky] [Kim-Shifman-Vainshtein-Zakharov]

(Invisible) Axions, Strong CP problem and Dark Matter

[Preskill, Wise, Wilczek 1993; Dine & Fischler 1083; Abott & Sikivie 1983]

- Axions as Dark Matter: misalignment mechanism

$$L_{eff} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 + \frac{g_{a\gamma\gamma}}{4} a \tilde{F}^{\mu\nu} F_{\mu\nu} + \dots$$

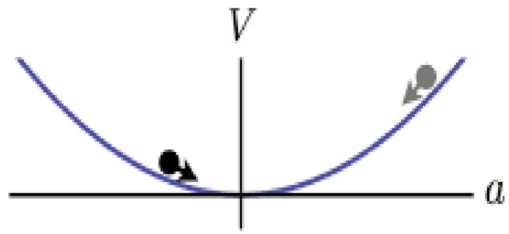
T >> GeV ➡ ma =0

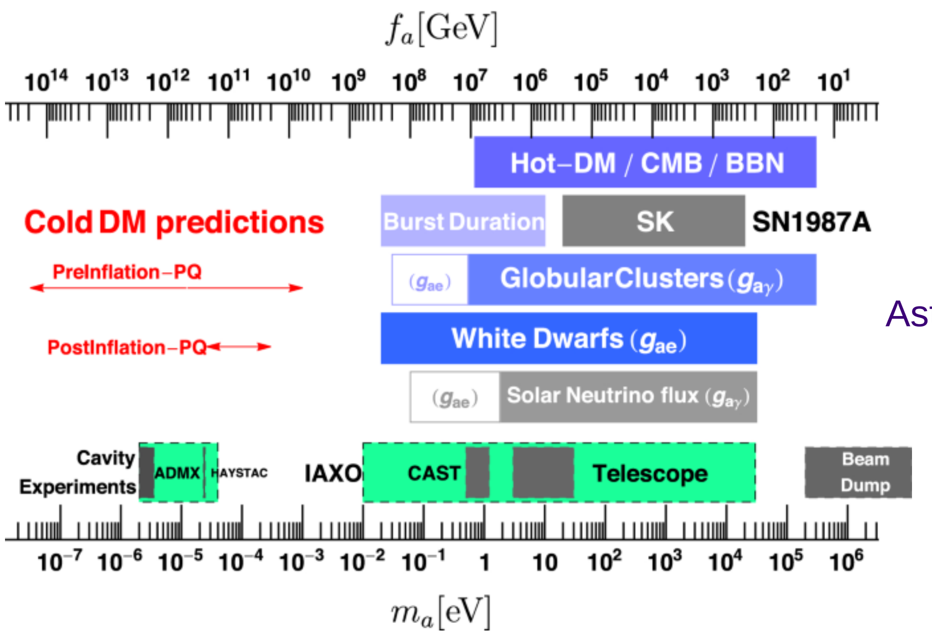
T < GeV (QCD) ➡ ma(T) > 0

Value of the field “frozen” until H(t) <ma(T), when it starts oscillating

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$ H(t)= Hubble rate

Energy density of the oscillating field behaves as **NR matter**





[Raffelt et. Al, EPJC 2019]

Cosmology $\Omega_{DM} h^2 \leq 0.120\,h$ $\rho_{DM} \propto f_a^{7/8}\,\theta_0^2$

Astrophysics

$$10^8 \ \mathrm{GeV} \leq f_a \leq 10^{12} \ \mathrm{GeV}$$

Experiments

(model dependent)

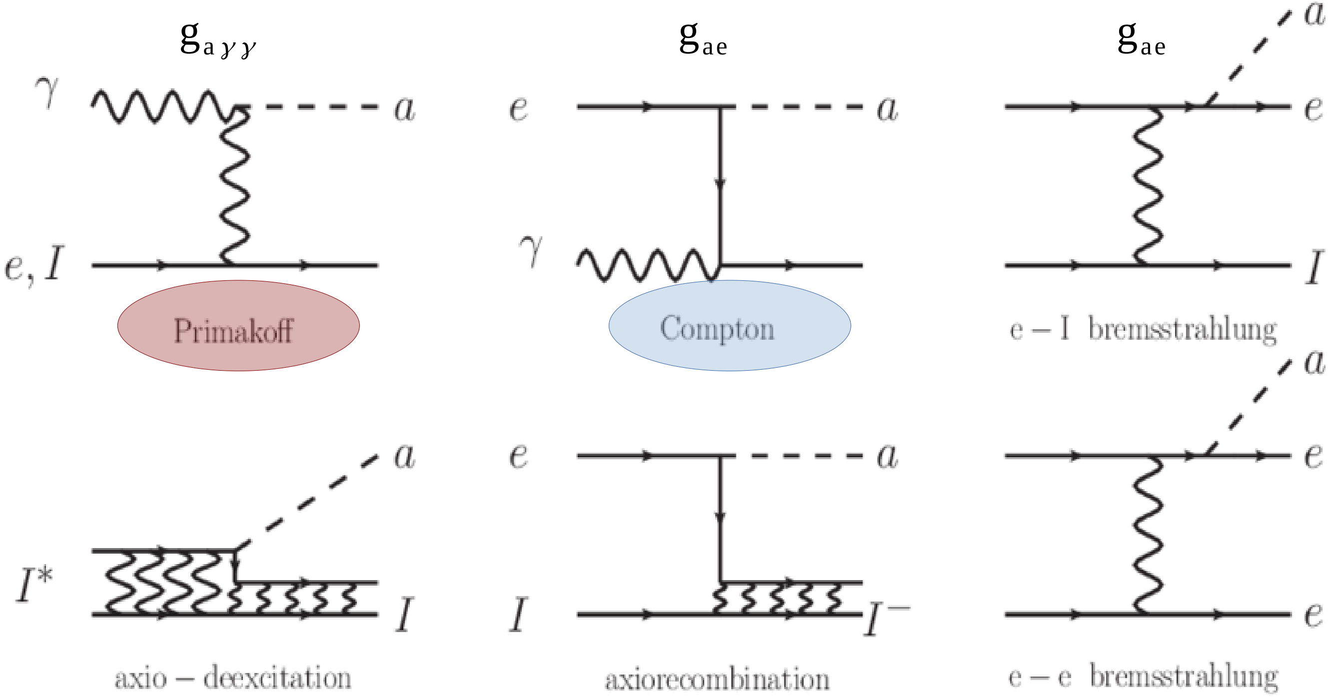
Axion-Like-Particles

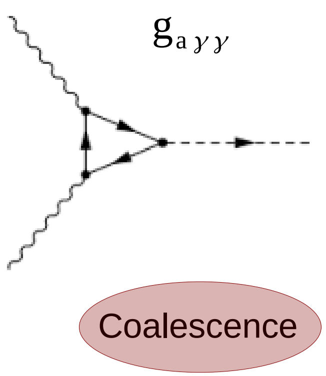
Pseudo-Nambu-Goldstone-Boson of a weakly broken global symmetry

$$L_{eff} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 + \frac{g_{a\gamma\gamma}}{4} a \tilde{F}^{\mu\nu} F_{\mu\nu} + g_{af} \frac{\partial_\mu a}{2 m_f} \bar{f} \gamma^\mu \gamma^5 f + \dots$$

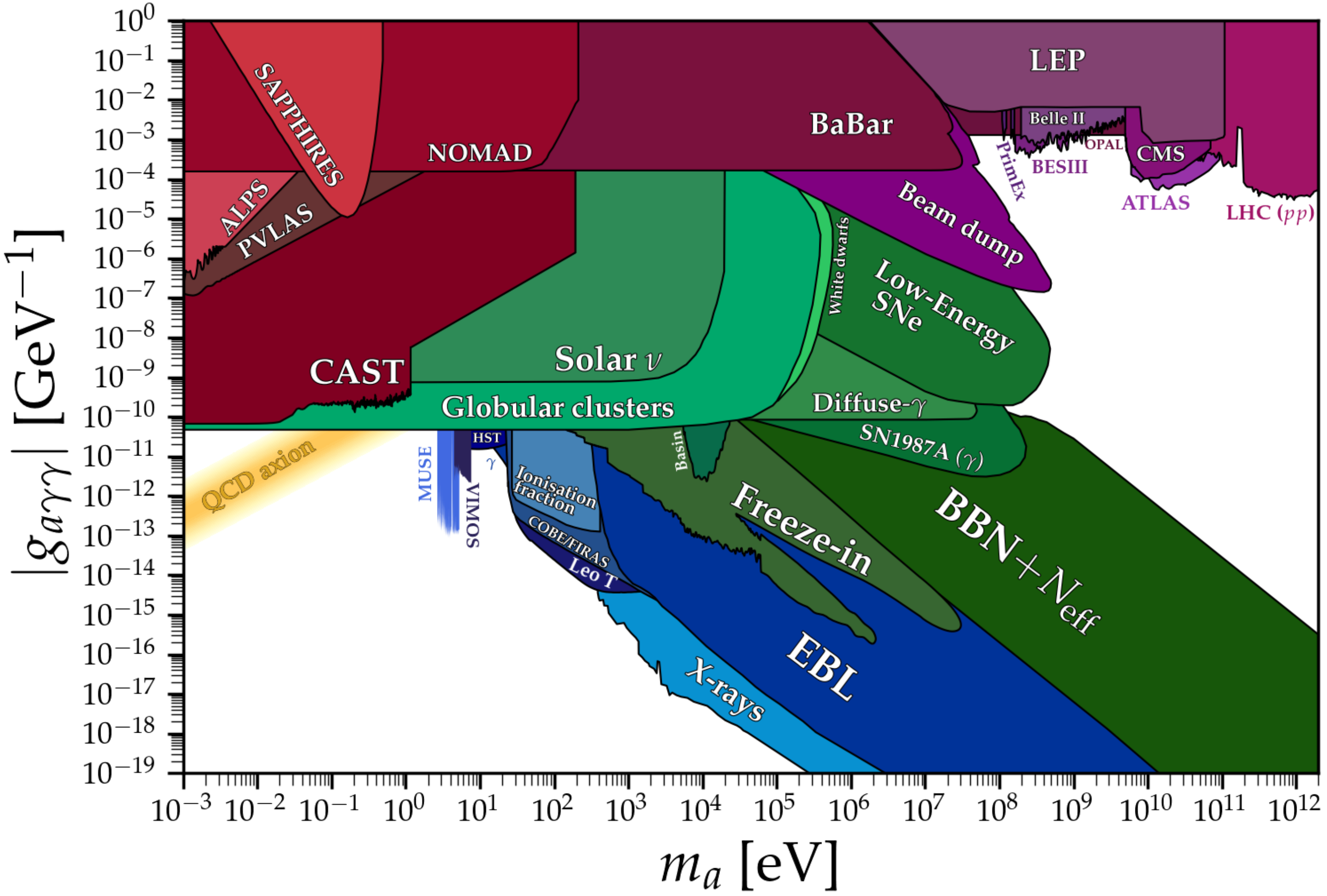
Parameters: m_a . $g_{a\gamma\gamma}[\mathrm{GeV}^{-1}]$, g_{ae}

- ALP production (estellar objects)





Axion-Like-Particles



Helioscopes, Haloscopes [CAST, ALPs]

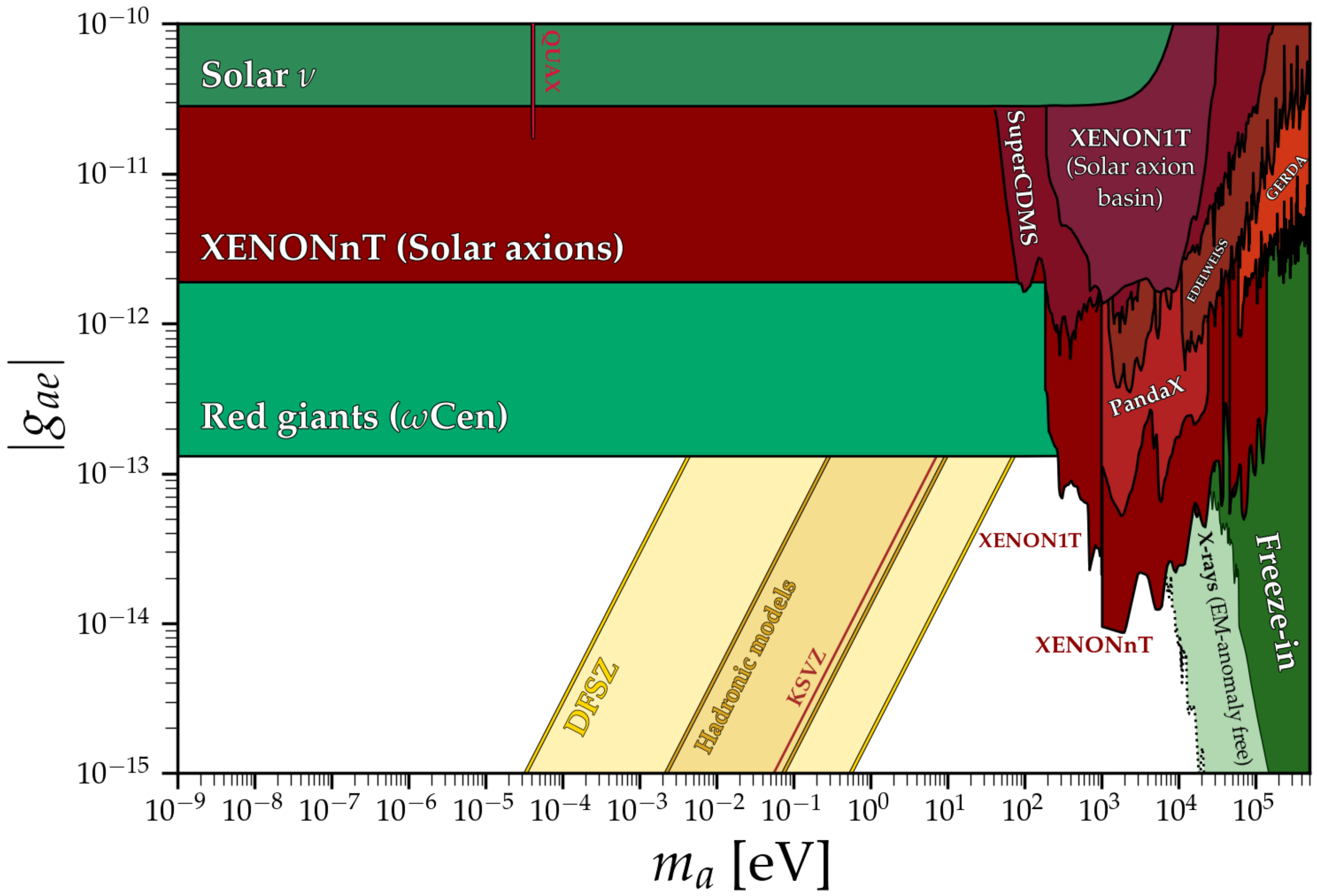
Astrophysical / Cosmology

Astro+ DM

Colliders

[https://cajohare.github.io/AxionLimits]

Axion-Like-Particles

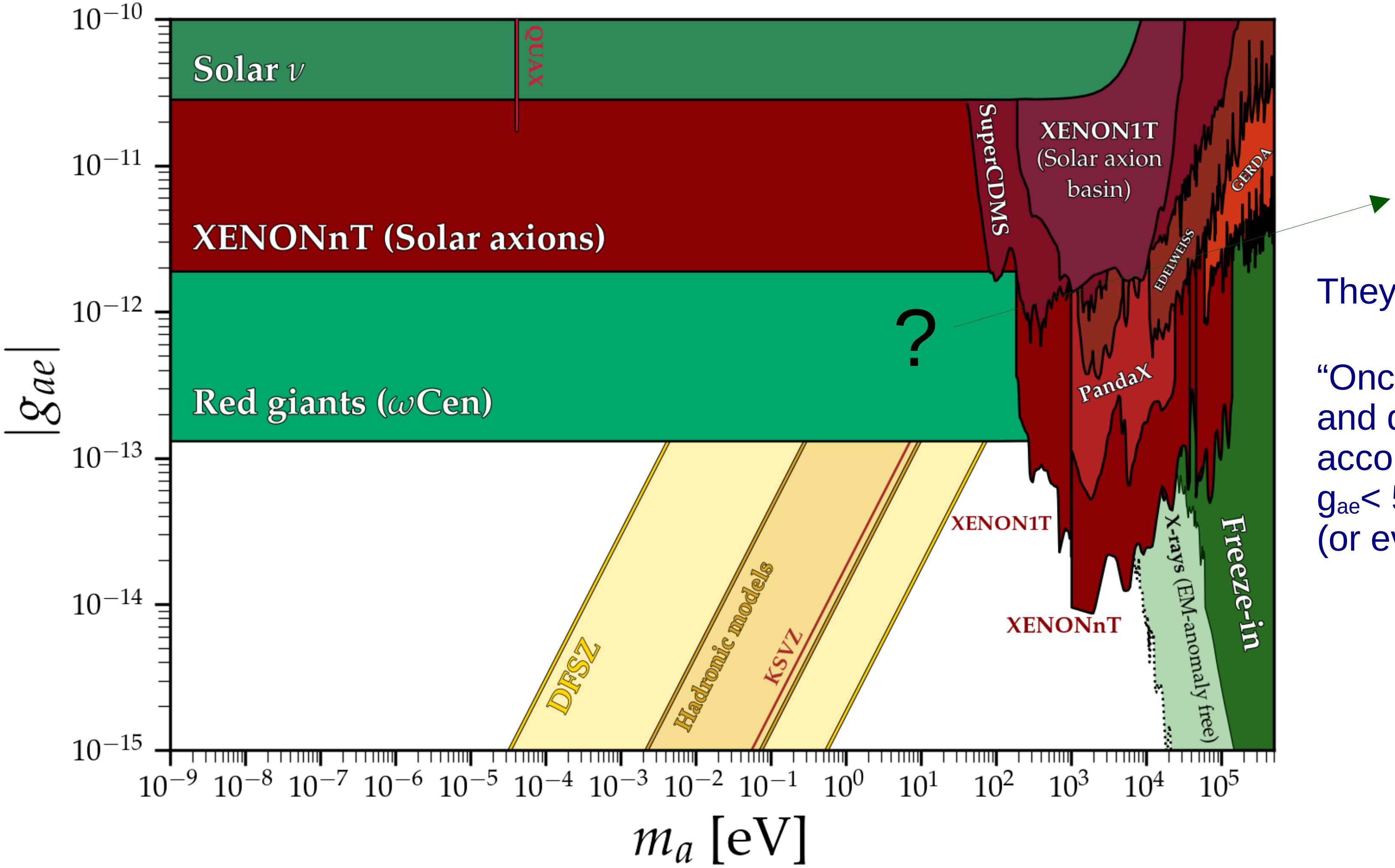


Astrophysical

Underground detectors

[https://cajohare.github.io/AxionLimits]

Axion-Like-Particles



ArXiv 2305.03113

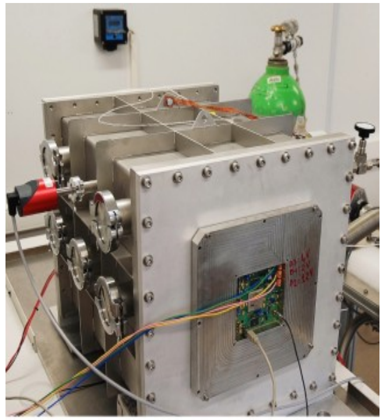
They question this limit.

"Once stellar uncertainties and degeneracies are accounted for, $g_{ae} < 5\times10^{-13}$ is not excluded" (or even larger couplings...)

[https://cajohare.github.io/AxionLimits]

Axion-Like-Particles: Direct detection

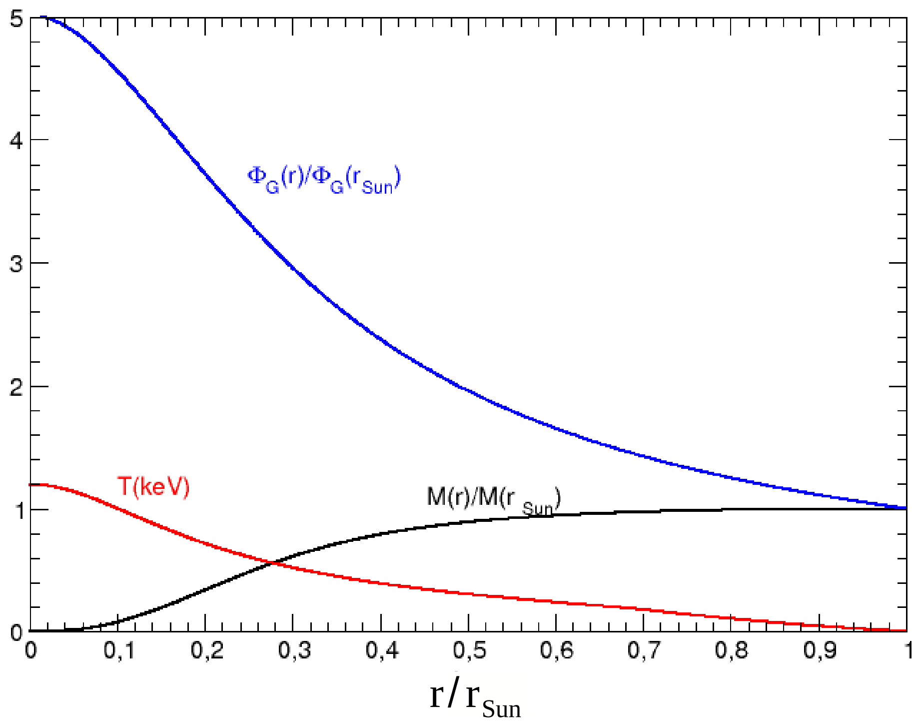
MIMAC



- **Light scalar m~ O(keV)**
- Direct detection through the **decay** into 2 γ's   (identical photons), instead of **recoil**

➡ Collab with **MIMAC** group (LPSC, Grenoble)
[MIcro-tpc MAtrix of Chambers] [**Directional DM detection**] [3D Track reconstruction]

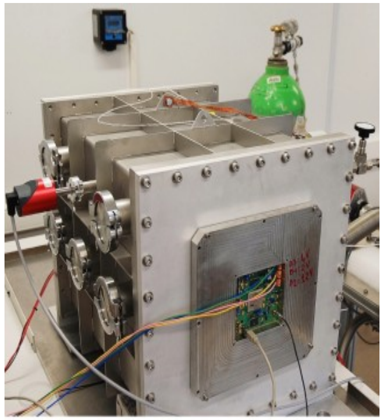
- "Look" at the **sun** as a source of potential candidates (~upto keV masses)



[Saclay Solar Model]

Axion-Like-Particles: Direct detection

MIMAC



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- "Look" at the **sun** as a source of potential candidates (~upto keV masses)

  - **Axion :**

  Flux of axions produced in the Sun may be detected with "axion telescopes" (CAST, IAXO), but they are too light for "standard" direct detection

  - **Axion + large extra dimensions** → **axion + KK modes** $m_a \sim m_{PQ}, \quad m_{KK} \simeq \frac{n}{R}$

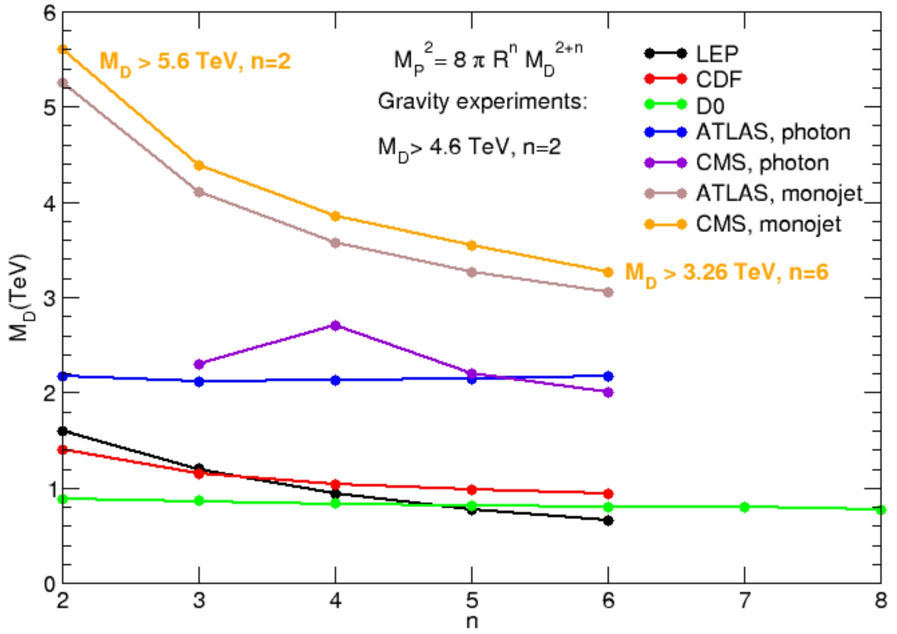
$$L_{eff} = \frac{1}{2}\sum_{n=0}(\partial_\mu a_n)^2 - \frac{1}{2}m_a^2 a_0^2 - \frac{1}{2}\sum_{n>0}\frac{n^2}{R^2}a_n^2 + \frac{g_{a\gamma\gamma}}{4}\sum_{n=0} a_n \tilde{F}^{\mu\nu}F_{\mu\nu} + \dots$$

m_a long lived, DM candidate, m_{KK} may decay in the detector $a \to \gamma + \gamma$

Size of the extra dimension R > keV^{-1} → m_{KK} ~ O(keV) → no. extra dim $\delta \leq 3$

[Di LeLLa et al PRD62 '00: Di Lella & Zioutas Astropart. Phys. 19 '03] [Morgan et al. Astropart. Phys. 23 '05]

Experimental limits on LED

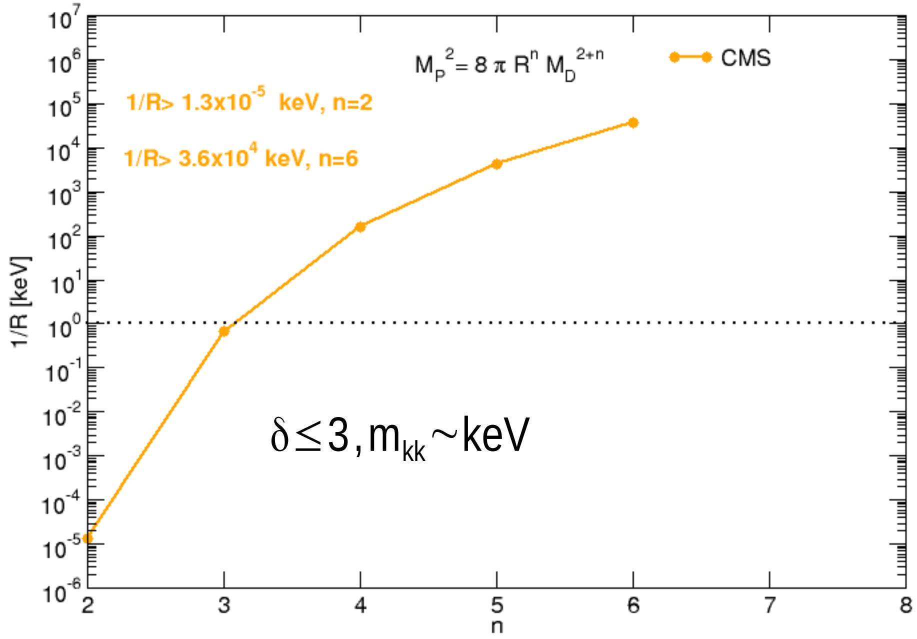


[D. M. Gingrich, arXiv: 1210.5923]

$$M_P^2 = 8\pi R^n M_D^{n+2}$$

4D Planck scale

nD Fundamental scale



KK axions and solar flux $(g_{ae}=0)$

- Flux due to Primakoff and Coalescence:

$$\frac{d\Phi^P}{dE}=4.2\,x\,10^{10}\ \ cm^{-2}\ \ s^{-1}\ \ keV^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\right)^2\frac{E\,p^2}{e^{E/1.1}-0.7}(1+0.02\,m)$$

$$\frac{d\Phi^C}{dE}=1.68\,x\,10^{9}\ \ cm^{-2}\ \ s^{-1}\ \ keV^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\right)^2 m^4\,p\left(1+0.0006\,E^3+\frac{10}{0.2+E^2}\right)e^{-E}$$

- Event rate in a detector of volume V:

density of states $\rho(m)=\frac{2\pi^{\delta/2}}{\Gamma[\delta/2]}(Rm)^{\delta}m^{-1}$

$$R(\delta)\simeq\int d\,\omega\underbrace{\int dm\,\rho(m)}_{\text{KK-tower}}\ \Gamma_{a\gamma\gamma}\ \ m\ \ V\int_{\omega+m^2/4\omega}dE\frac{2}{p^2}\frac{d\Phi}{dE}$$

KK-tower

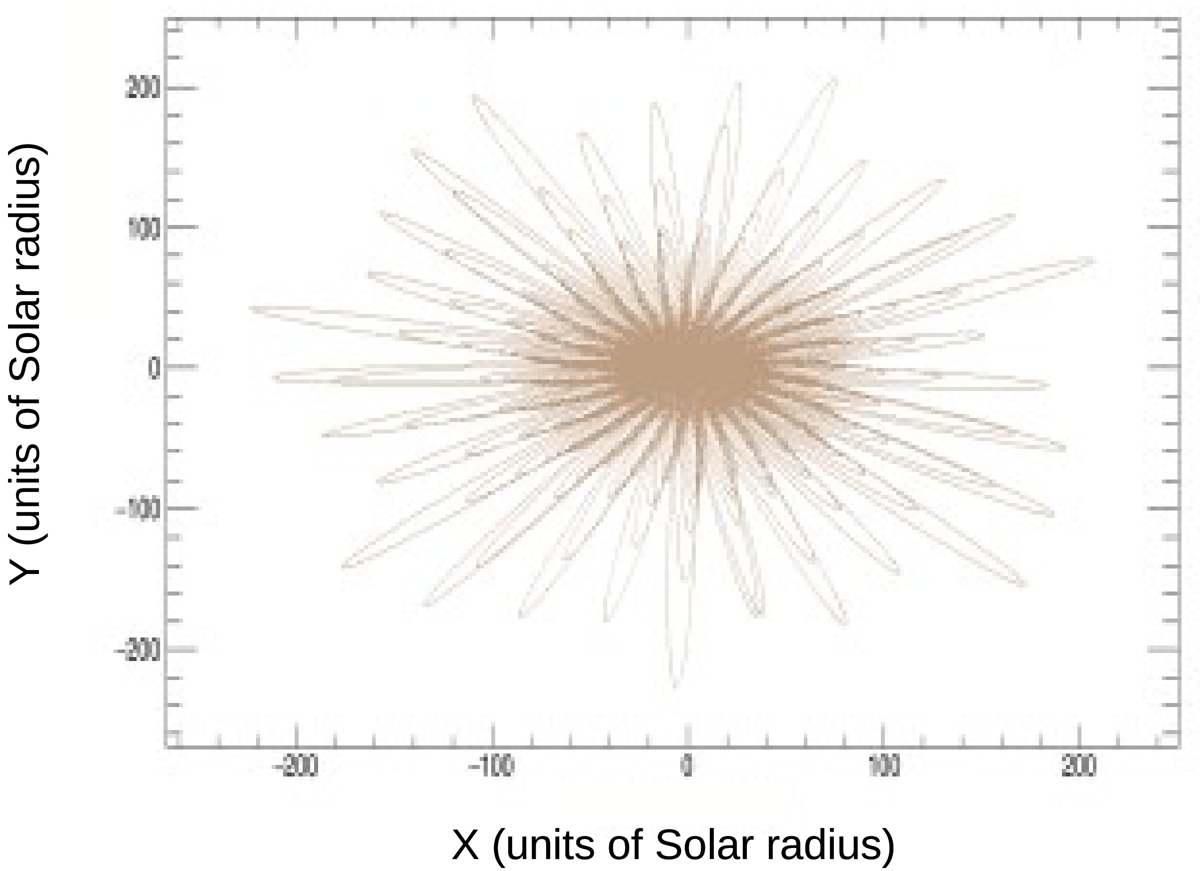
$$R(\delta)\sim10^{-3(7-\delta)/2}\left(\frac{g_{a\gamma\gamma}}{10^{-12}GeV^{-1}}\right)^4\left(\frac{R}{keV^{-1}}\right)^{\delta}$$

no. of events per day per cubic m

Too small!!

KK axions and solar flux (g_{ae}=0): “trapped” axions

- KK axions produced with a small $\mathbf{E_{kin}}$ (small p) are “**trapped**” in the sun gravitational field (bounded orbits)



D_{ST} =215.7 R_{sun}

KK axions and solar flux (g_{ae}=0): “trapped” axions

- KK axions produced with a small $\mathbf{E_{kin}}$ (small p) are “**trapped**” in the sun gravitational field (bounded orbits)

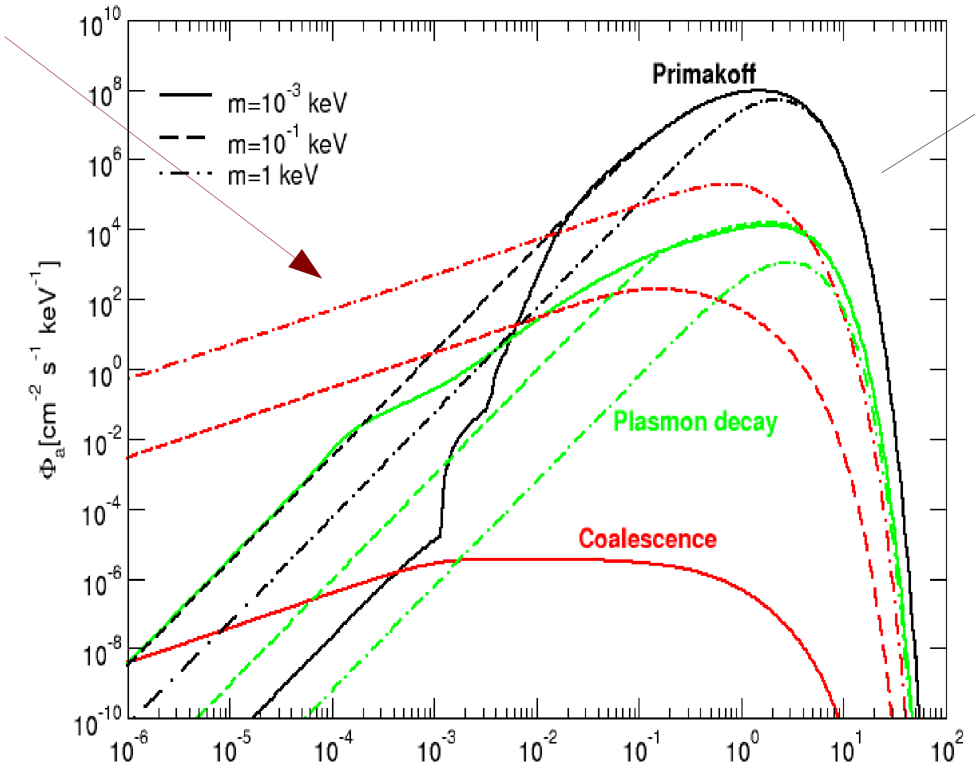
“trapped”

Coalescence

Primakoff ~ v_a^2

Plasmon decay ~ v_a^2

Fluxes



“Normal”

Primakoff

[MBG, C. Beaufort, D. Santos JCAP10 ‘21]

KK axions and solar flux (g_{ae}=0): “trapped” axions

- **no. density of trapped (non-relativistic) axions:**

$$\frac{d n_a^T}{dt} = S_a^T - \Gamma_{a\gamma\gamma} n_a^T$$

Decay

“Source” (Coalescence):

$$S_a^T = \frac{m^3}{(2\pi)^3} \int_{Sun} dV \int dv\, 2\pi v^2 N_\delta \delta(f_T(v)) \Gamma_{a\gamma\gamma} f_a^{eq}(m/T)$$

Solar Model (Saclay Solar Model)

Velocity constraint for trapped axions

$$\sqrt{2(\bar{\Phi}_G - 1/\bar{r})}/(2\pi\bar{r}^4)$$

$$\bar{\Phi}_G = \left(\frac{GM}{R_{sun}}\right)^{-1} \Phi_G$$ Sun grav. Pot.

$$\bar{r} = r/R_{sun}$$

- Summing over the KK-tower

$$n_{KK}^T \simeq \frac{2.2\,x\,10^{14}\,cm^{-3}}{2\pi\bar{r}^4} g_{10}^2 \int dm\, \rho(m) m^6 \frac{(1-e^{-\Gamma_{a\gamma\gamma} t_{sun}})}{\Gamma_{a\gamma\gamma} t_{sun}} \int \bar{r}_0^2 d\bar{r}_0 f_a^{eq} \sqrt{2(\bar{\Phi}_G - 1/\bar{r})}$$

$$[g_{10} = g_{a\gamma\gamma} 10^{10}\, GeV]$$

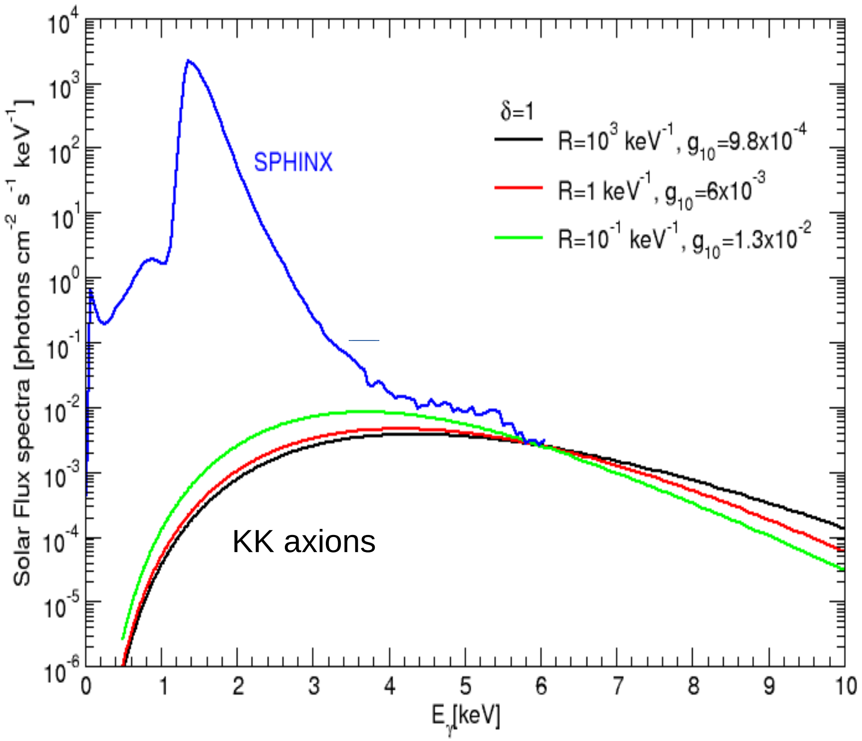
[MBG, C. Beaufort, D. Santos JCAP10 ‘21]

KK axions and solar flux (g_{ae}=0): “trapped” axions

- They will contribute to the **solar luminosity**

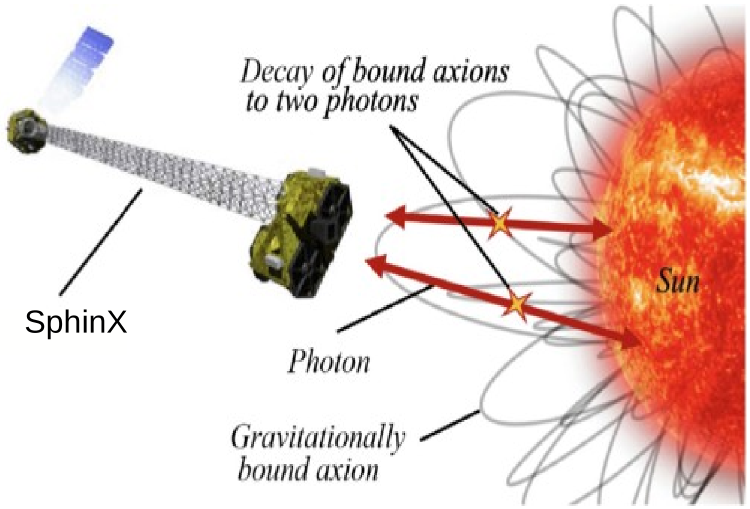
Flux of photons that enters the FoV of the detector:

$$\frac{dF}{dE_\gamma}=2\rho(m)\Gamma_{a\gamma\gamma}\int_{FoV} dr^3 \frac{r^2}{4\pi D^2} n_a^T(r,m)$$



[SPHINX: Sylwester et al., 1203.6809; 1912.030823]

(Trapped axions)



When compared to recent limits by SPHINX on the solar luminosity, this sets an upper limit on the axion-photon coupling

- **Even rate in a detector on Earth:**

$$R \simeq 3\times10^{-7}\, day^{-1}\, m^{-3}$$

Too small!!

$$[R \propto g^4_{a\gamma\gamma}]$$

KK axions and solar flux (g_{ae}=0): “trapped” axions

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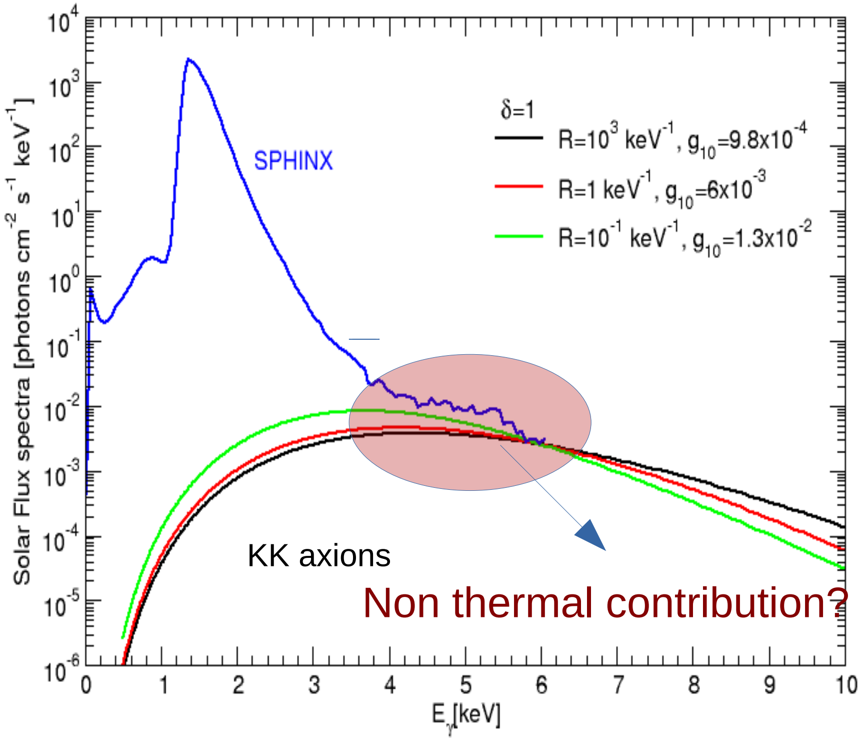

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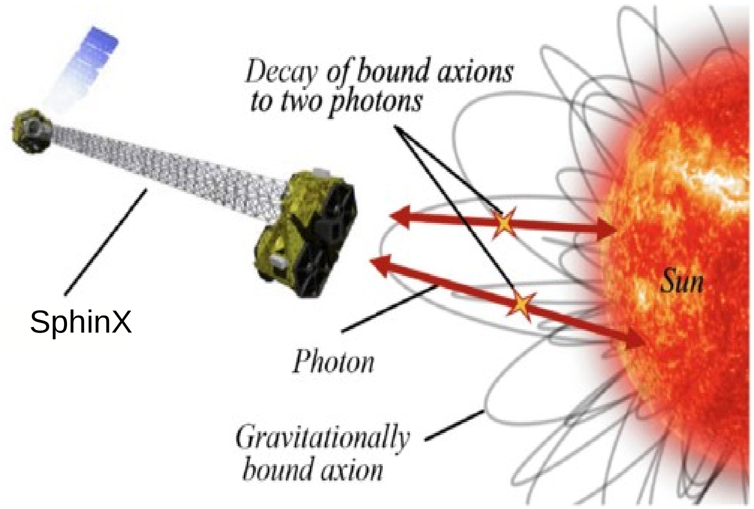

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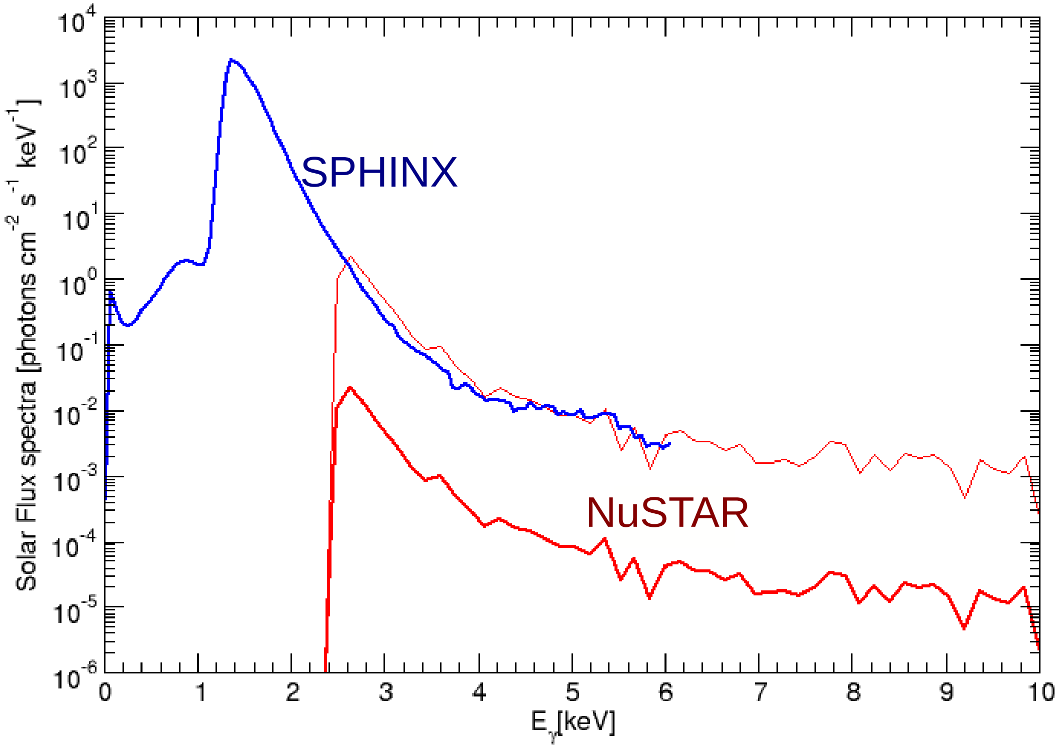
$$[R \propto g^4_{a\gamma\gamma}]$$

Solar constrains on ALPs couplings to photons and electron

[Van Tilburg PRD104 (2021); DeRocco et al., PRL 129 (2022)]

[MBG et al, arXiv:2303.06968]

- ALP with masses ~ keV produced in the Sun, and “trapped” in its gravitational field
- They decay and contribute to the Solar luminosity observed by SPHINX and NuStar (during period of low solar activity)
- They may/may not account for the DM



[SPHINX: Sylwester et al., 1203.6809; 1912.030823]

[NuSTAR: Harrison et al. Astrophys. J. 770 (2013)]

Different FoV:

SPHINX: 120x120 arcmin

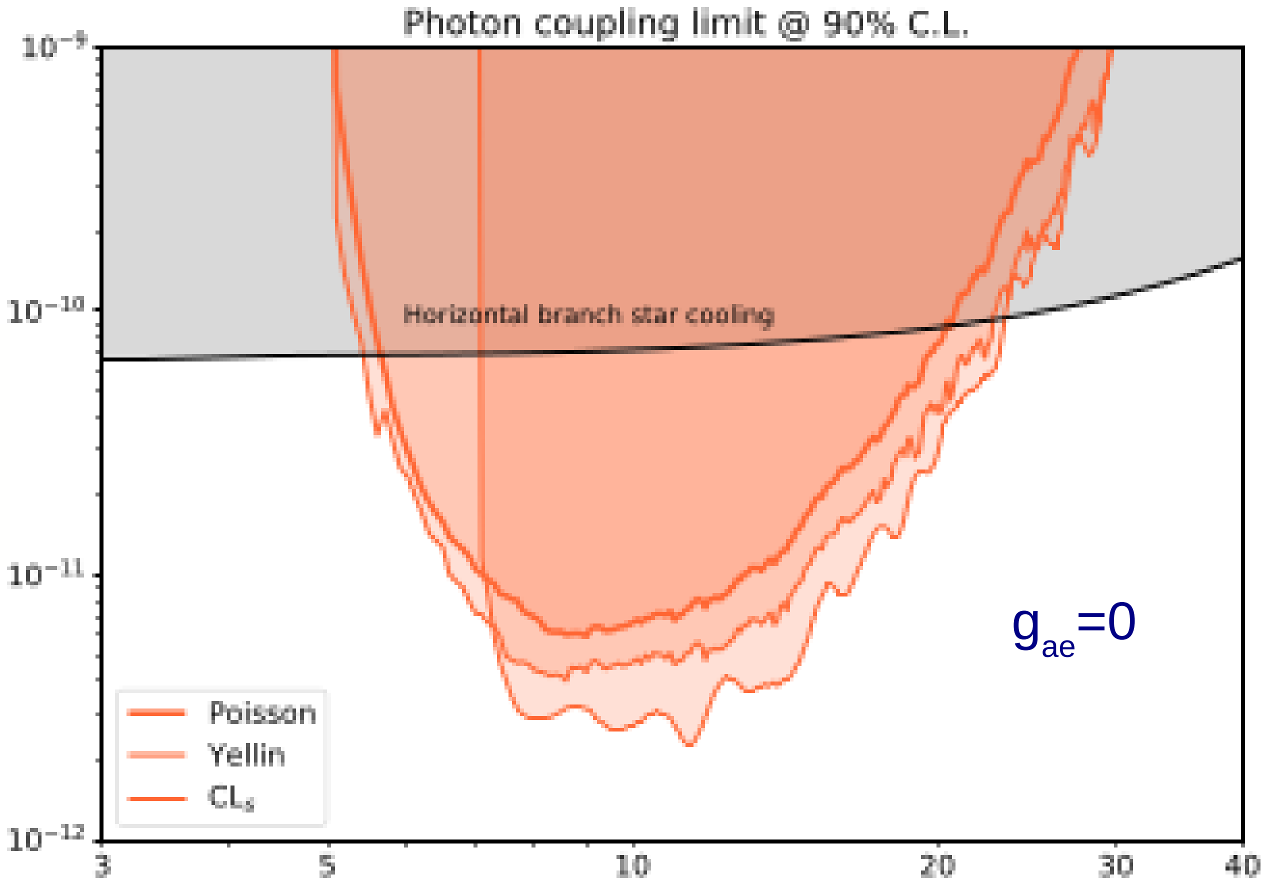
NuSTAR: 12x12 arcmin

Solar constrains on ALPs couplings to photons

DeRocco et al., PRL 129 (2022)

- **Production**: Primakoff, only suppressed by $v_e^2 \sim 3T/m_e$ when taking into account thermal effects
- **Solar data:** NuStar

$m \simeq 10\,\mathrm{keV}, g_{a\gamma\gamma} \simeq 2 \times 10^{-12}\,\mathrm{GeV}^{-1}$



$g_{a\gamma\gamma}\,[\mathrm{GeV}^{-1}]$

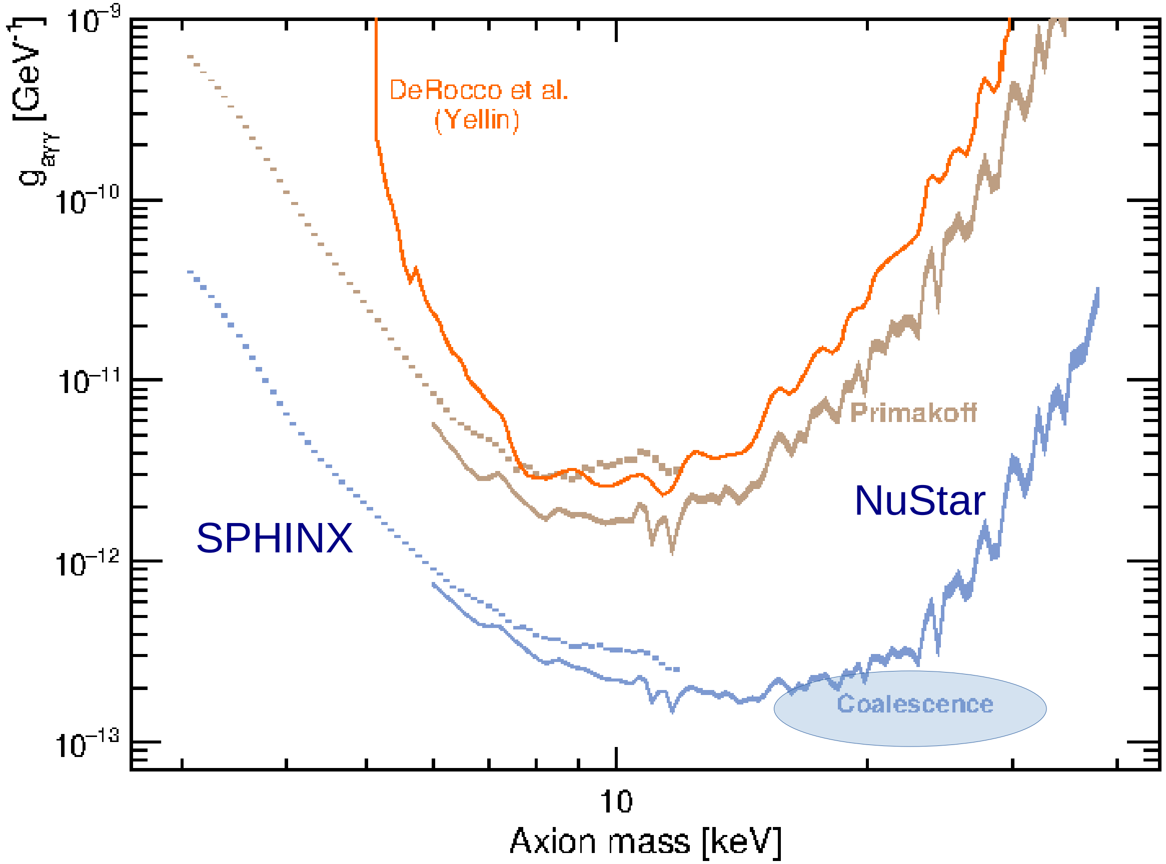
axion mass [keV]

$g_{ae}=0$

Solar constrains on ALPs couplings to photons

- **Coalescence** production still dominant: lower limit ~ one order of magnitude
- **Solar data**: NuStar + SPHINX
- Limits on photon coupling when $g_{ae}=0$

$$m \simeq 10\,\mathrm{keV},\ g_{a\gamma\gamma} \simeq 2 \times 10^{-13}\,\mathrm{GeV}^{-1}$$



Solar constrains on ALPs couplings to photons and electrons

- **Compton will dominate when** $g_{ae} \sim 10^{-13}$ $\qquad \gamma + e \rightarrow a + e$

- Axions in bounded orbits can be "re-absorbed" by (inverse) Compton $\qquad a + e \rightarrow \gamma + e$

- No. density of trapped axions:

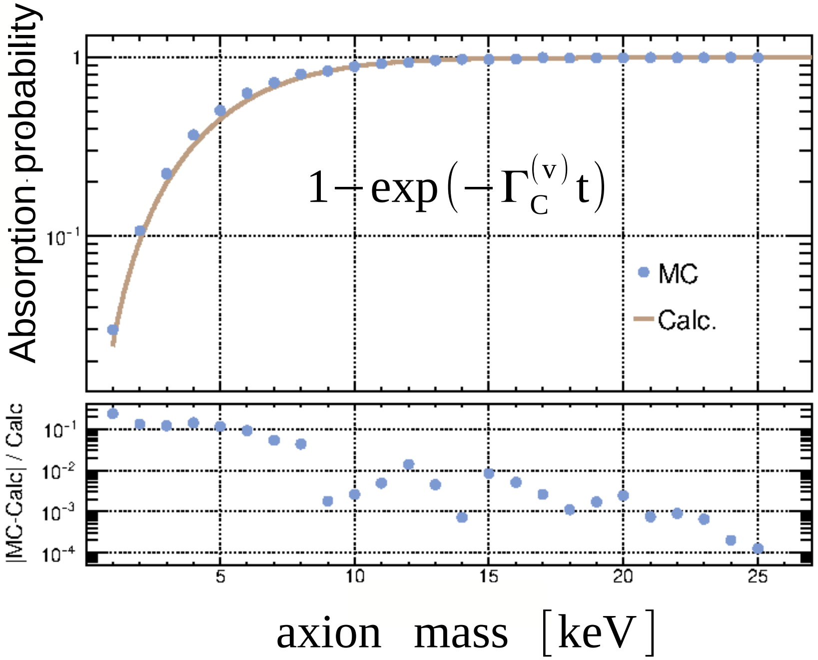
$$\frac{d n_a^T}{d t} = S_a^T - \left(\Gamma_{a\gamma\gamma} + \Gamma_C^{(v)}\right) n_a^T$$

"Source"

Decay

Compton absorption rate, velocity dependent

$$\Gamma_C^{(v)} = \frac{\int d\bar{r}\, \bar{r}^2 \Gamma_C \bar{v} P_T(\bar{v})}{\int d\bar{r}\, \bar{r}^2 \bar{v} P_T(\bar{v})}$$



- Velocity distribution: comparing with the MonteCarlo

$$P_T(\bar{v}) \simeq \Phi_L(\bar{v}, \mu, \sigma)$$

Landau Distrib.

$$\mu \simeq 0.08,\ \sigma \simeq 0.1 - 0.2$$

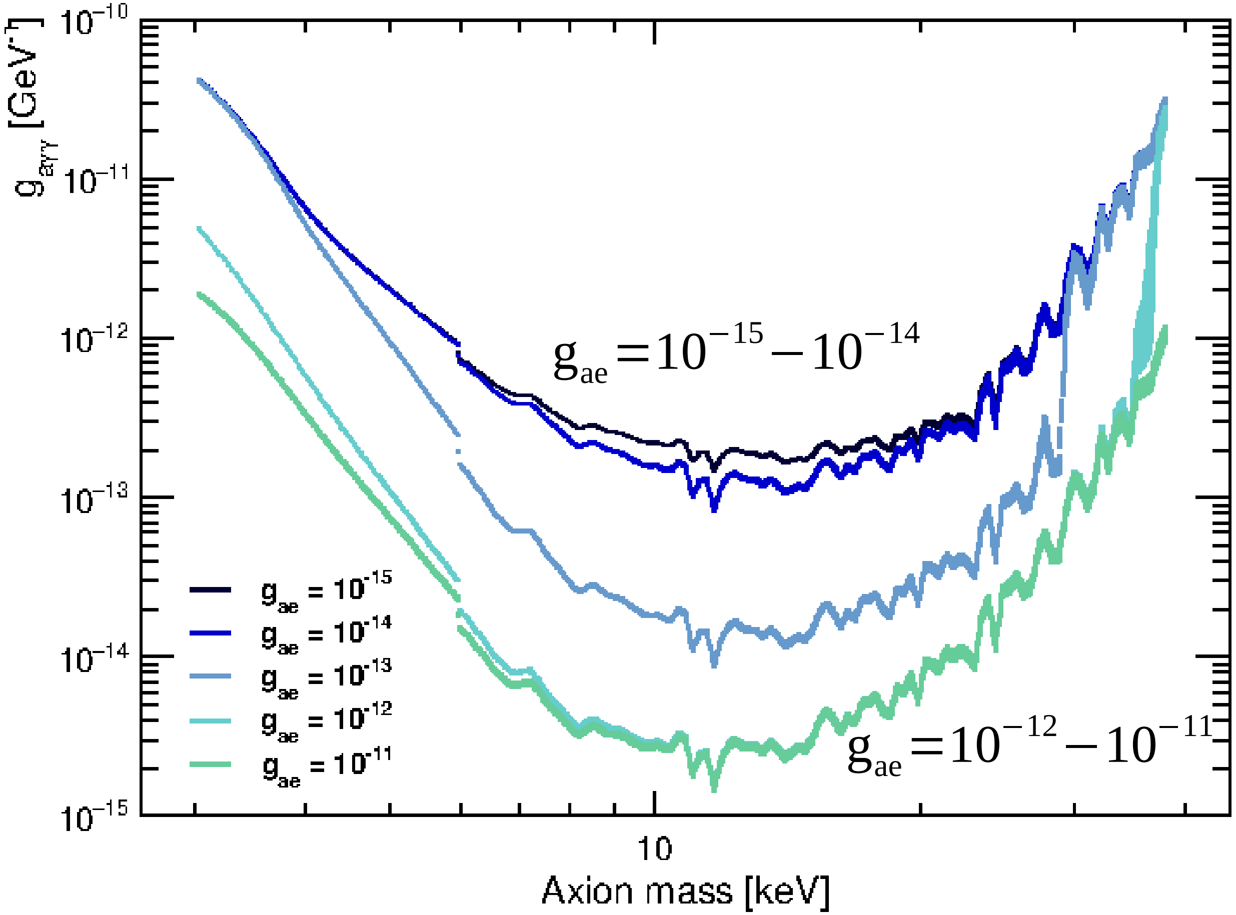
$$n_a^T \sim S_a^T \frac{\left(1 - e^{-t\left(\Gamma_{a\gamma\gamma} + \Gamma_C^{(v)}\right)}\right)}{\Gamma_{a\gamma\gamma} + \Gamma_C^{(v)}}$$

Solar constrains on ALPs couplings to photons and electrons

- Primakoff, Coalescence: $n_a^T \propto g_{a\gamma\gamma}^4 \frac{\left(1-e^{-\left(\Gamma_{a\gamma\gamma}+\Gamma_C^{(v)}\right)}\right) t_{Sun}}{\left(\Gamma_{a\gamma\gamma}+\Gamma_C^{(v)}\right) t_{Sun}}$
- Compton, Bremss.: $n_a^T \propto g_{a\gamma\gamma}^2 g_{ae}^2 \frac{\left(1-e^{-\left(\Gamma_{a\gamma\gamma}+\Gamma_C^{(v)}\right) t_{Sun}}\right)}{\left(\Gamma_{a\gamma\gamma}+\Gamma_C^{(v)}\right) t_{sun}}$

$g_{ae} \gg 10^{-13}$ ⟶ $n_a^T \propto g_{a\gamma\gamma}^2$

Compton Prod/Absorp balance each other



Solar constrains on ALPs couplings to photons and electrons

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$g_{ae} \gg 10^{-13}$ →

Compton Prod/Absorp balance each other

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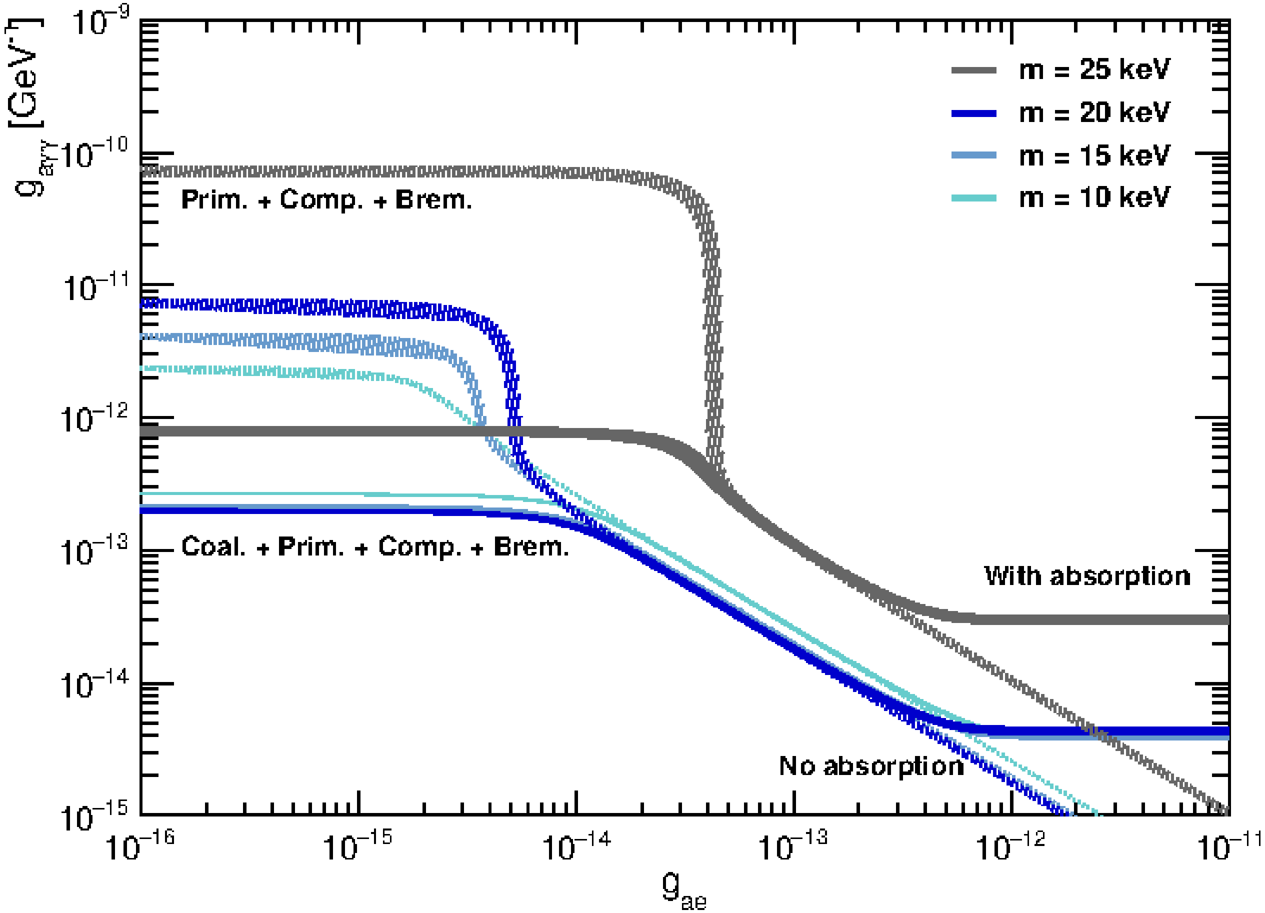

Irreducible ALP background

Langhoff, Outmezguine & Rodd arXiv:2209.06216

- ALPs may be produced by different mechanism in the Early Universe (pre BBN)
- Although their final abundance is model dependent, there is an **irreducible abundance** due to their coupling to photons and electrons

$$\frac{dn_a}{dt} + 3Hn_a = S_a - \Gamma_{a\gamma\gamma} n_a$$

Source: coalescence, Primakoff, Compton-like

- Freeze-in mechanism: no previous ALP no. density, start the integration just before BBN at T= 5 MeV (radiation dominated universe, this sets the Hubble parameter H)
- Their decay into photons give rise to a signal in X-rays (decaying DM)
- To compare with data, one assumes that the ALP energy density distribution is the same than the local DM density distribution

Irreducible ALP background

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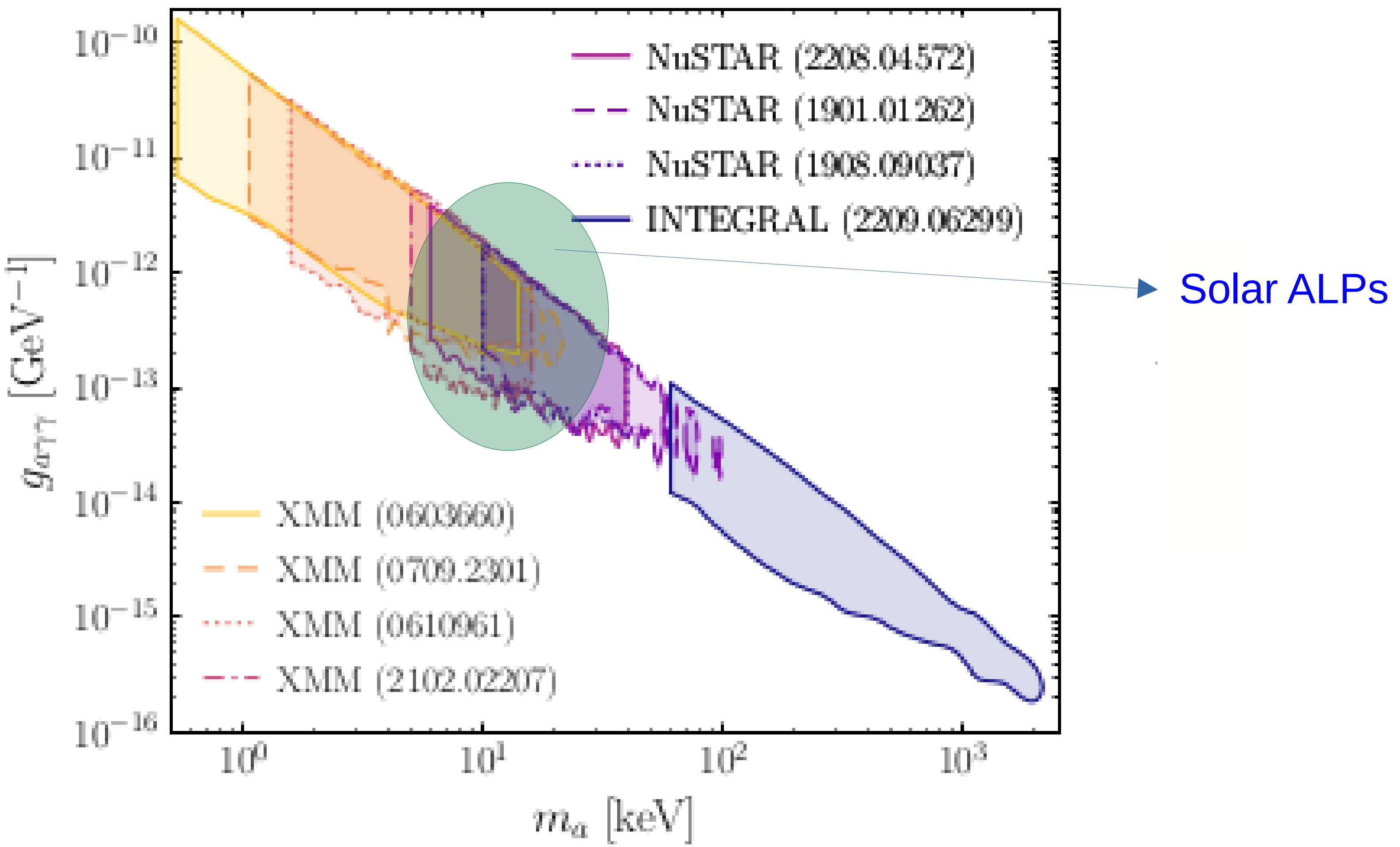
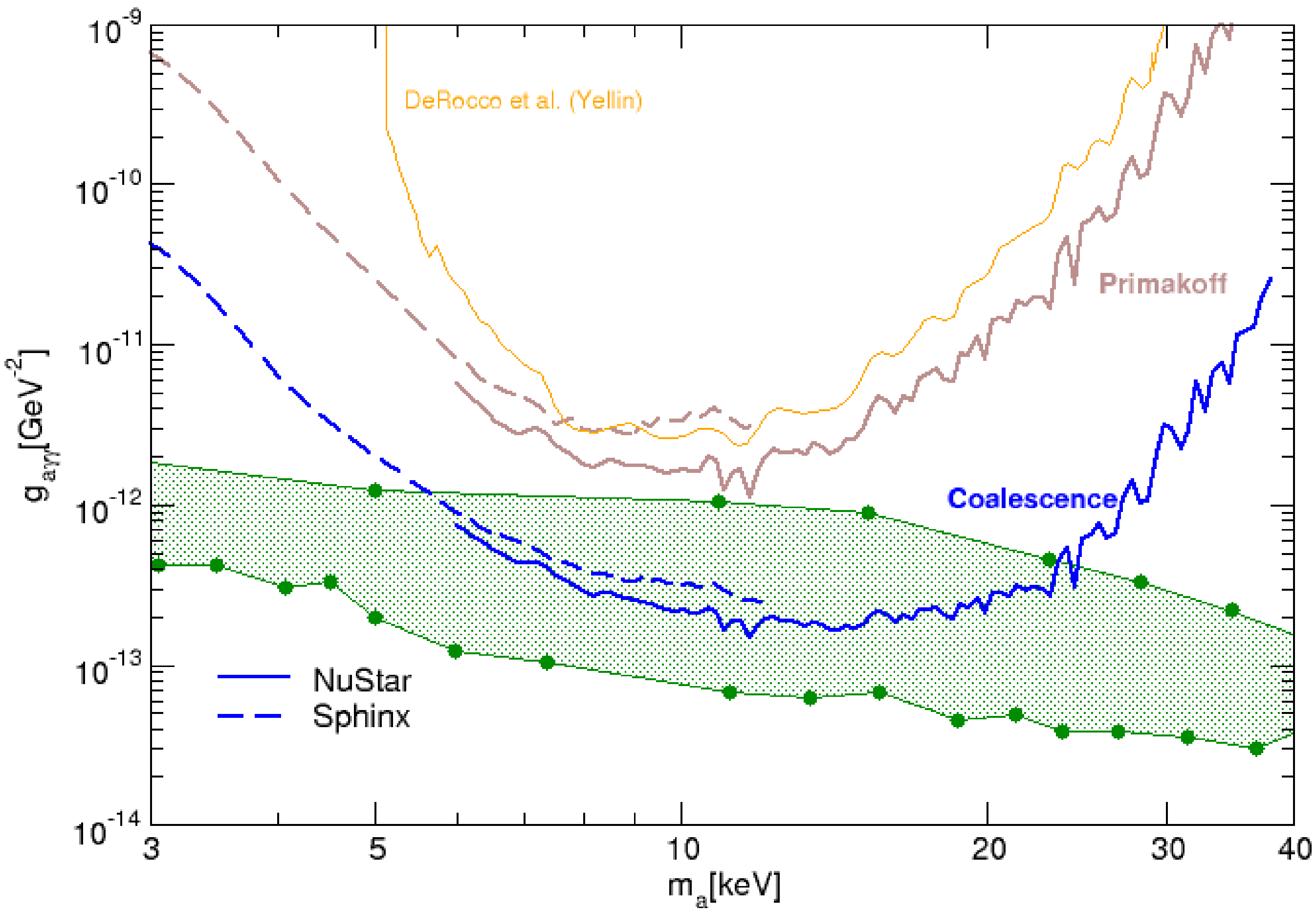


Irreducible ALP background

Langhoff, Outmezguine & Rodd arXiv:2209.06216

[MBG et al, arXiv:2303.06968]

Similar limit on $g_{a\gamma\gamma}$ for m_a~ 10 keV



Summary

- Axions/ALP are PNGB associated to the breaking of a global U(1) symmetry: they are good candidates for cold DM

  Axions (QCD) $m_a \simeq 6\mu eV \left(\frac{10^{12} GeV}{f_a}\right)$ ALP: $m_a \sim [10^{-12} eV, 10^3 TeV],\ f_a$

- Rich phenomenology, and different direct/indirect constraints on their couplings to photons and electrons

- Sun can efficiently produced ALPs (and axions) with masses upto ~ keV
  (“Solar Telescopes” like CAST, IAXO looking for them...)

- Direct detection: directional detection experiments, like MIMAC, could detect ALPs with m_a ~ keV through the **decay** into 2 γ's (identical photons)

- KeV ALPs are “trapped” by the Sun gravitational field, and produced dominantly by **Coalescence** (inverse decay) instead of **Primakoff**, but the detection rate is too low

- Even if no detectable in DD experiments, their decay will contribute to the Solar luminosity, and must be below current limits by SPHINX and NuSTAR: **constraints** on $g_{a\gamma\gamma}$ and g_{ae}

- Small values of $g_{ae}<10^{-13}$: Coalescence production dominates and set the limit on the coupling to photons

- Large values of $g_{ae>}10^{-13}$: Compton production dominates, but it is counter-balanced by Compton absorption
  Limit on the coupling to photons independent on the limit to electrons