TOHOKU UNIVERSITY

Axion dark matter as an explanation for XENON1T excess

@Less-traveled-path of dark matter, ICTS

Nov. 12, 2020

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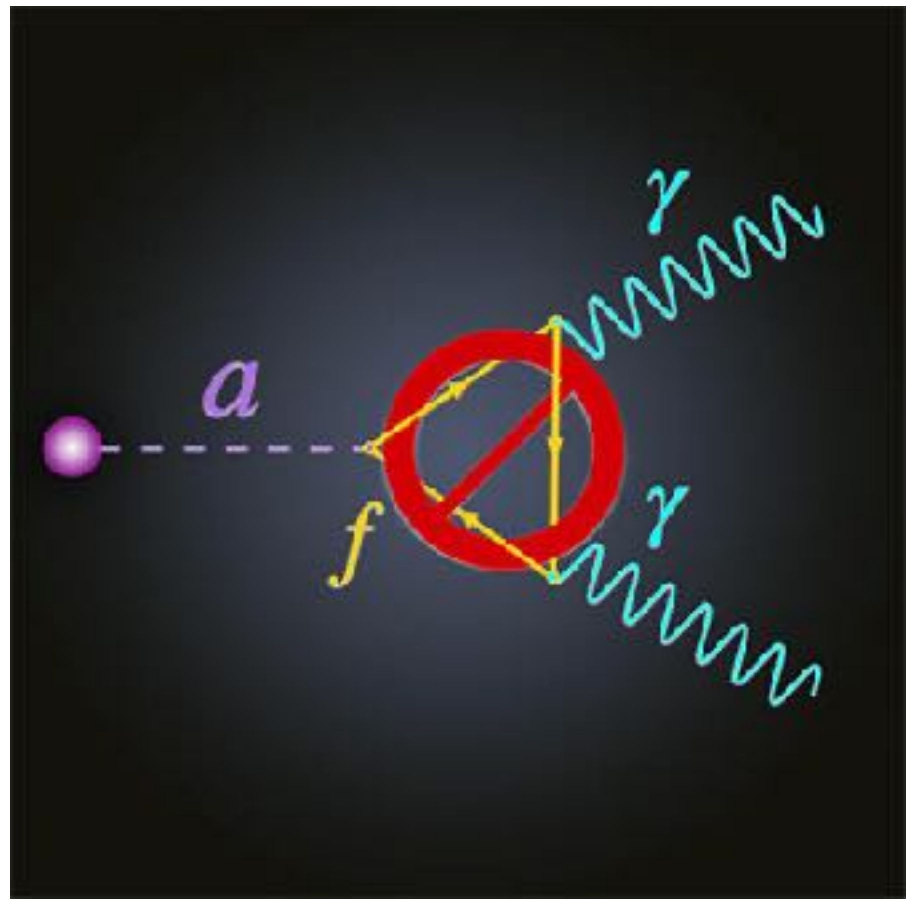
ArXiv:2006.10035 [PRL 125, 161801 (2020)] with Masaki Yamada and Wen Yin

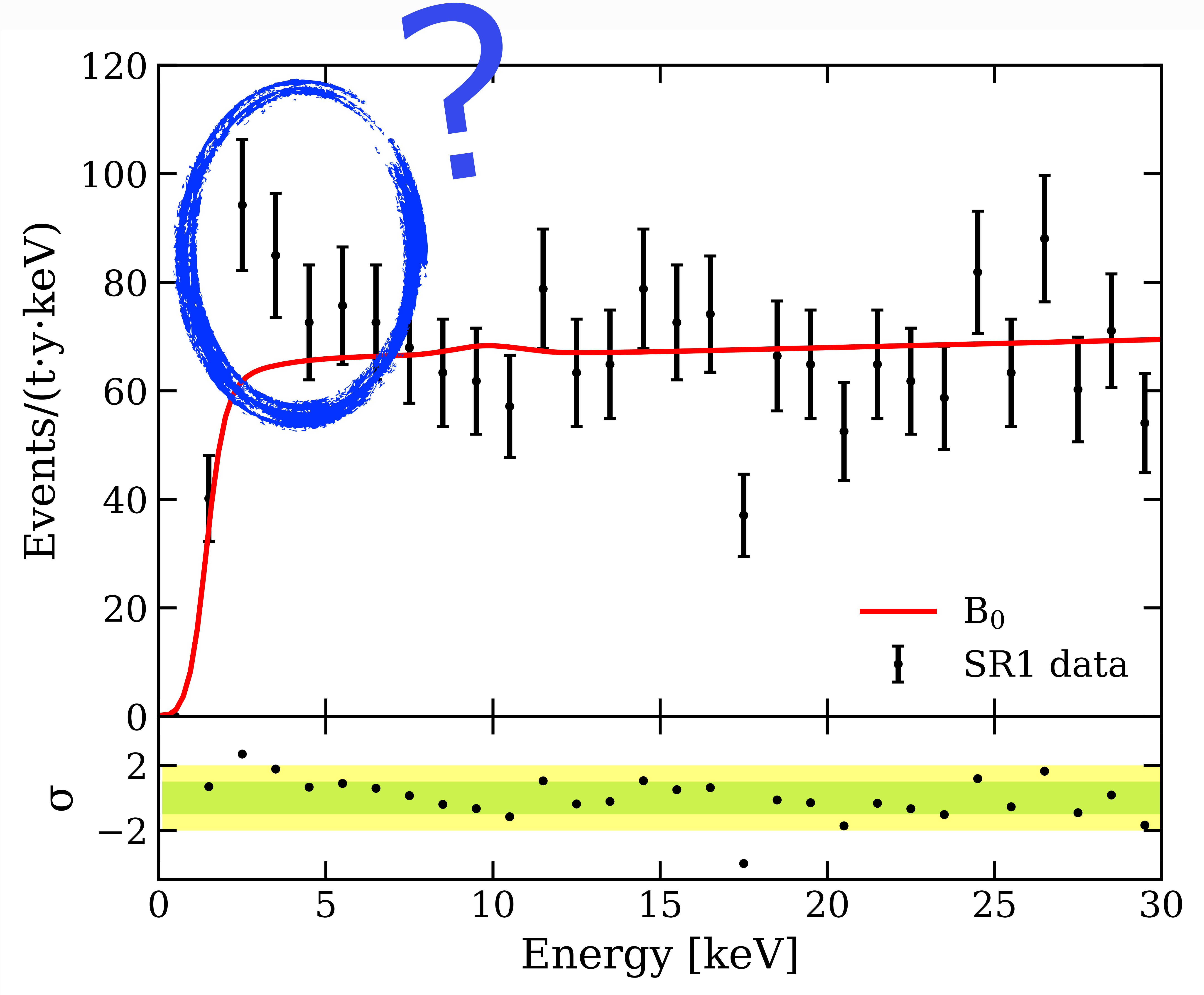
Content

1. (Incomplete) review of theoretical models explaining XENON1T
2. Anomaly-free axion dark matter
3. Summary



Electron recoil events in XENON1T

XENON1T, arXiv:2006.09721



Interpretations in terms of new physics

1. Solar axions
2. Neutrino magnetic moment
3. KeV-scale bosonic DM
   a) Axion (ALP)
   b) Dark photon
4. Others

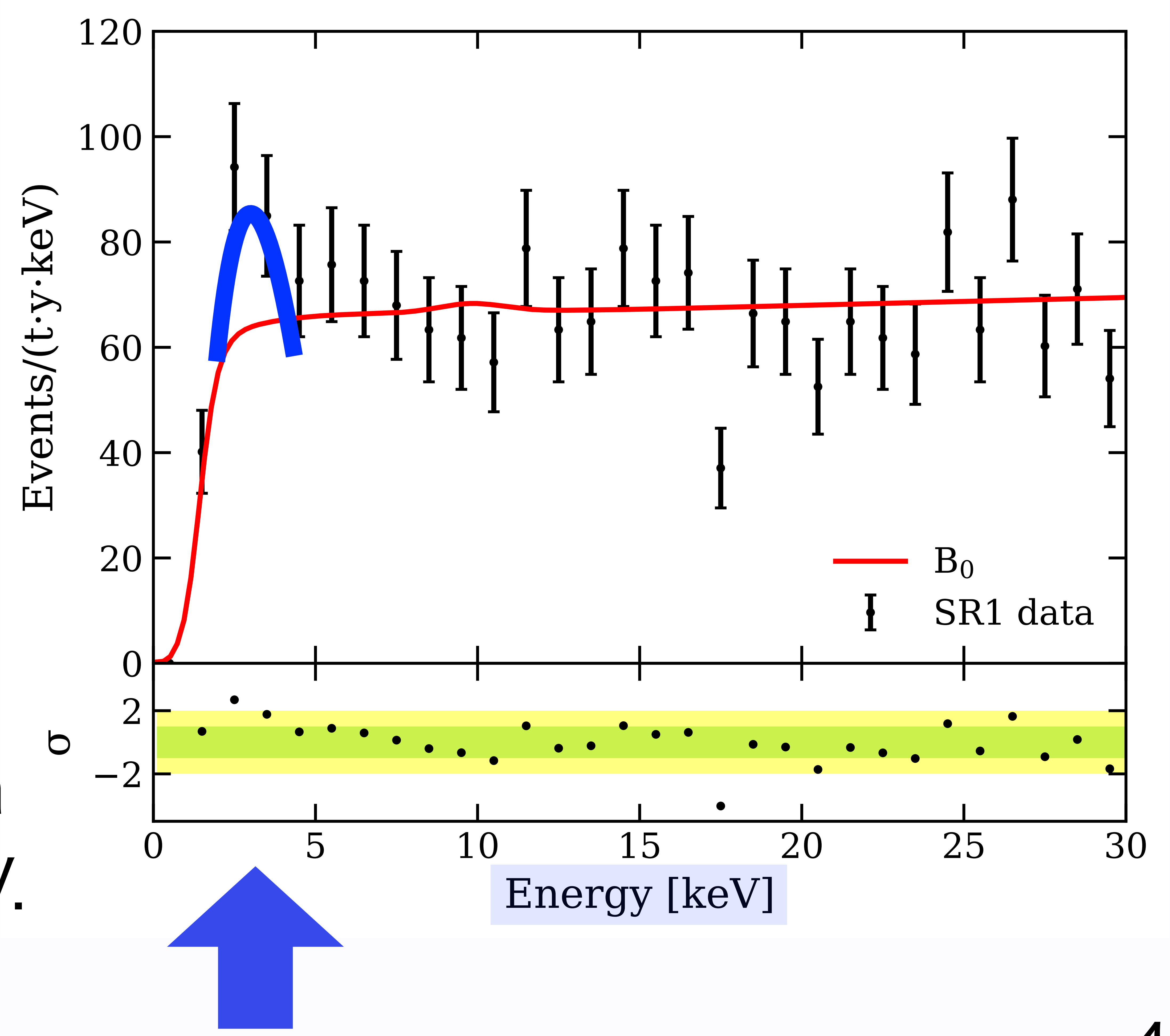
To explain the excess in terms of new physics, we need

1. Energy transfer of O(keV)

Something must sneak into the XENON1T detector and somehow passe keV energy to electrons.

2. Number of events and spectral shape

The electron recoil energy spectrum has a pronounced peak at a few keV.



The points to be explained by theory are

• **What is the particle?**	Related to DM or not
• **What is the interaction?**	Electron or photon, absorption or scattering
• **Other bounds satisfied?**	Model-dependent. If not, give up the model or extend it.

The points to be explained by theory are

- What is the particle? — Related to DM or not
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- Other bounds satisfied? — Model-dependent. If not, give up the model or extend it.

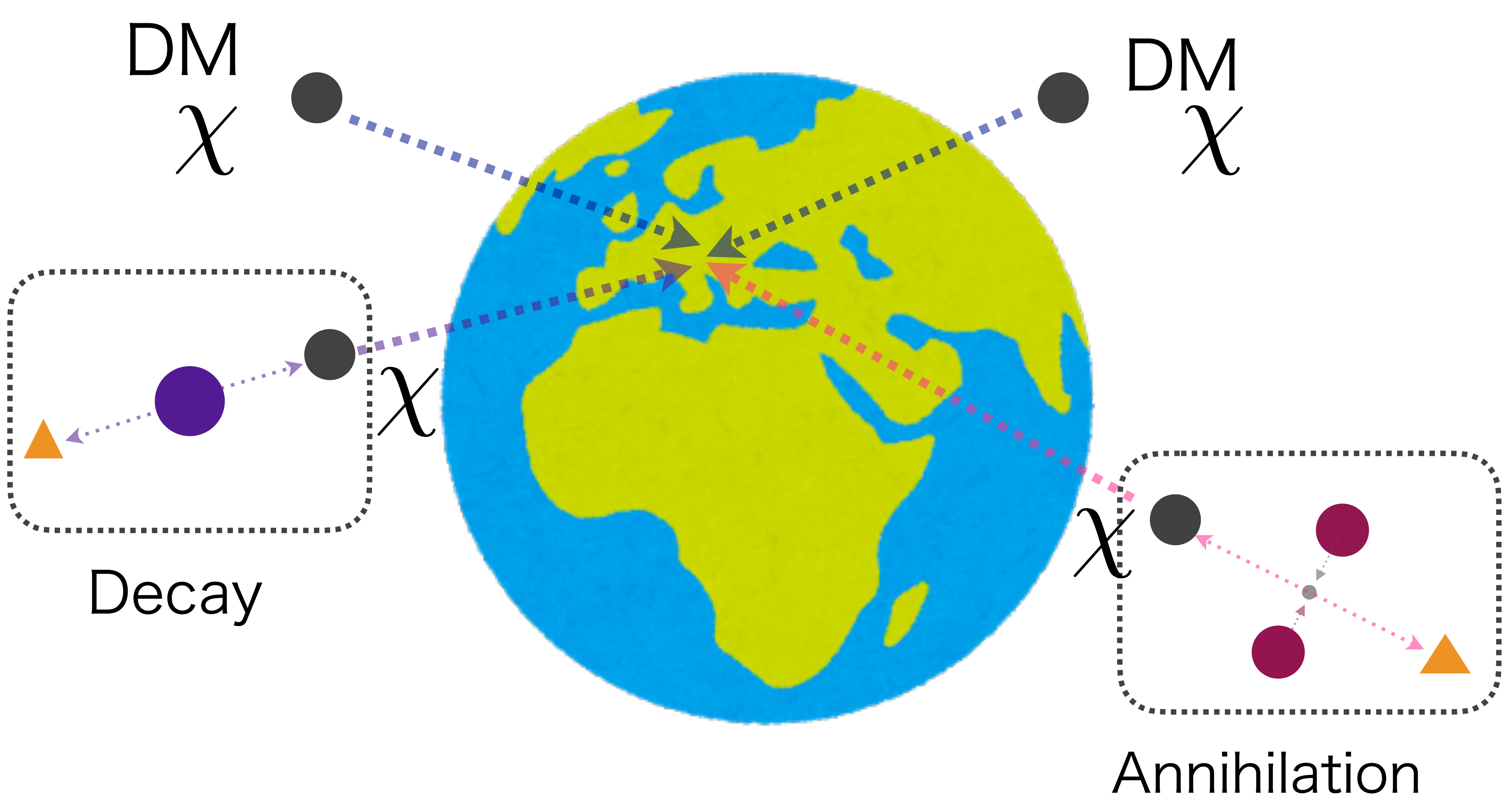
\+

- Why keV? Why this much excess? — Preferable if the energy and strength of the interaction are determined for other reasons.
- Any predictions? If so, is it within future experiments? — Refutable models!

The origin of the particle

Related to DM

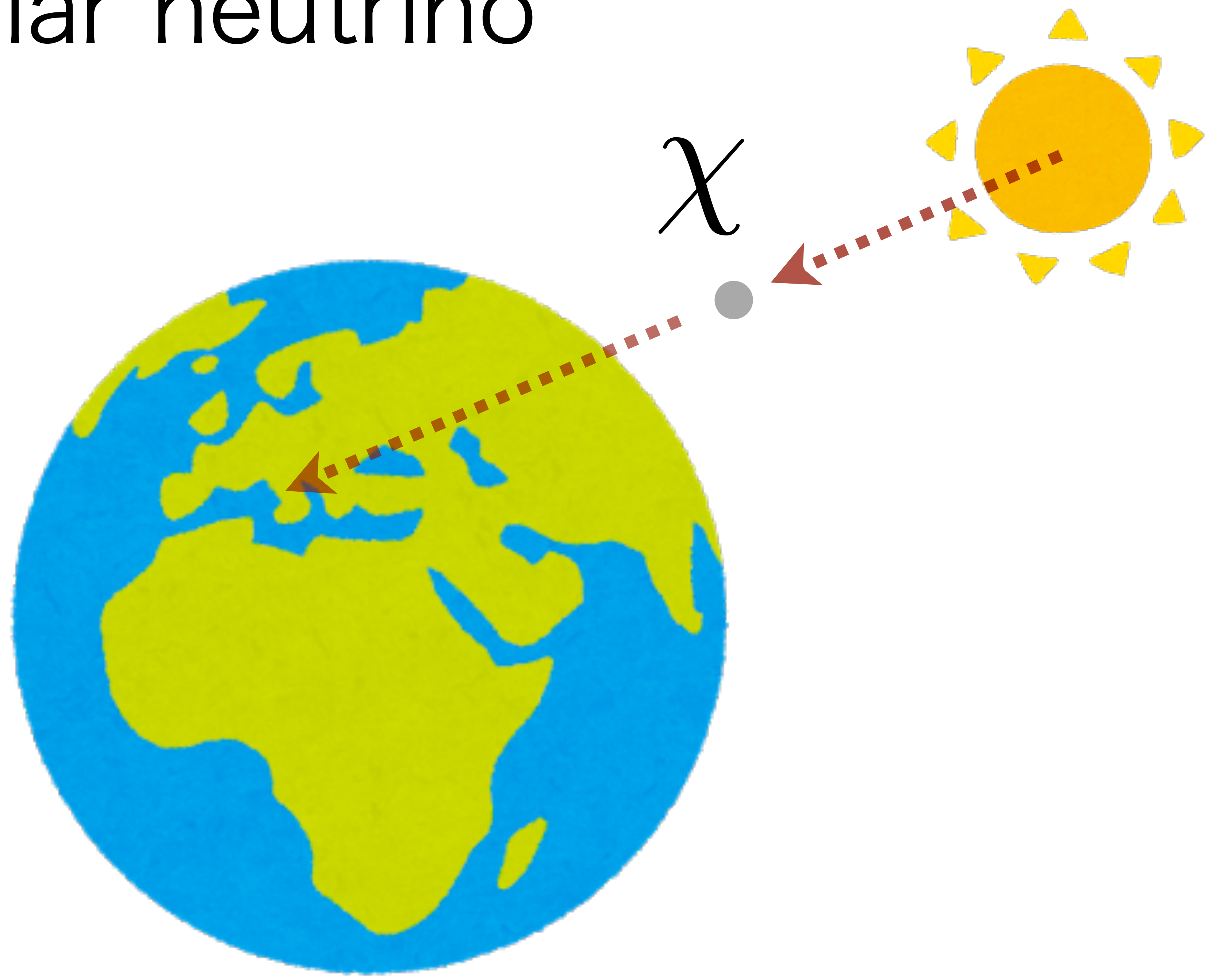
- DM itself
- Particles created by DM annihilation or decay



Unrelated to DM

e.g. It is created in the center of the sun and it propagates to us.

solar axion, solar dark photon, solar neutrino



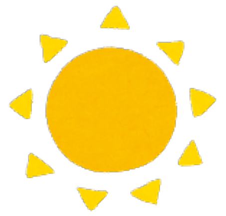
How to realize the electronic recoil?

Two ways to pass energy to electrons:

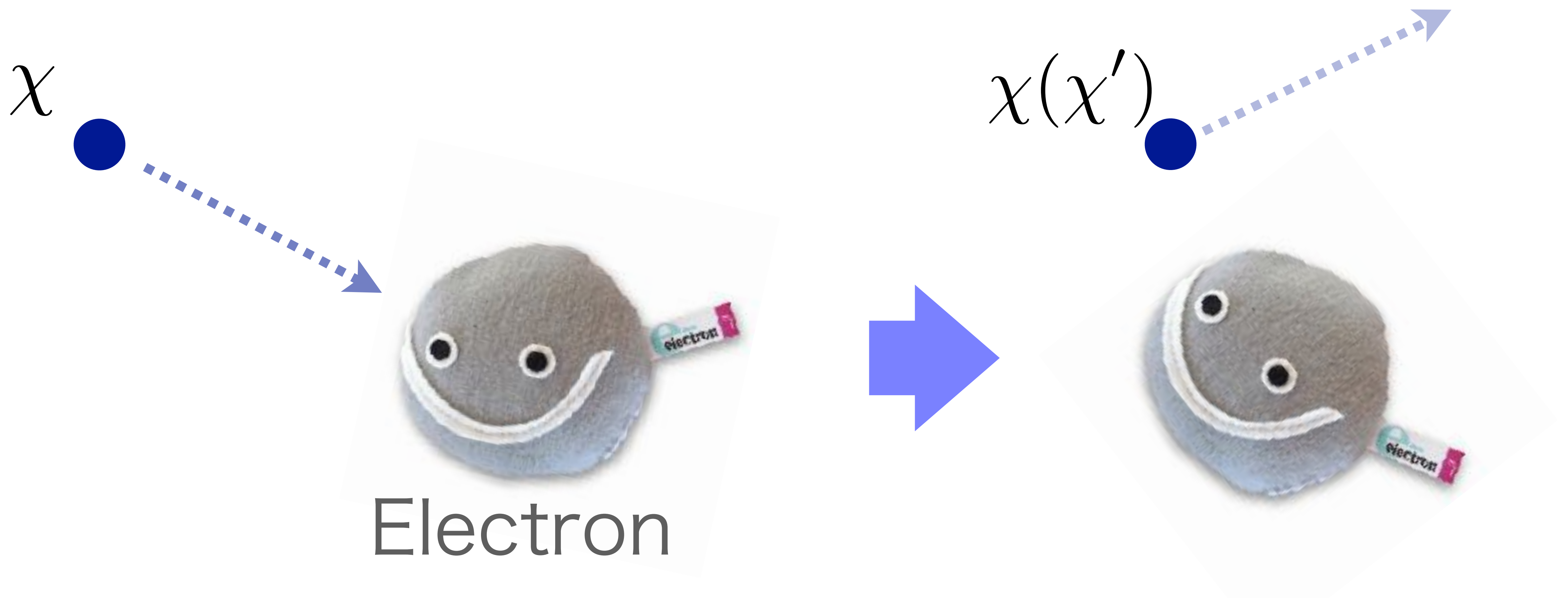
Absorption

- The total energy becomes the recoil E
- If non-relativistic, the mass is of keV
- Kinetic energy is of keV if relativistic

The origin of keV kinetic energy?

The sun? 

Scattering



$$E_R \sim \mathrm{keV} \sim \frac{\mu^2 v^2}{m_e} \lesssim m_e v^2 \qquad \mu = \frac{m_\chi m_e}{m_\chi + m_e}$$

$$\therefore v \gtrsim 0.1c \gg v_{\mathrm{local}} \simeq 220\mathrm{km/sec}$$

Galactic escape velocity $v_{\mathrm{escape}}(r_\odot) \simeq 580\mathrm{km/sec} \sim 0.002c$

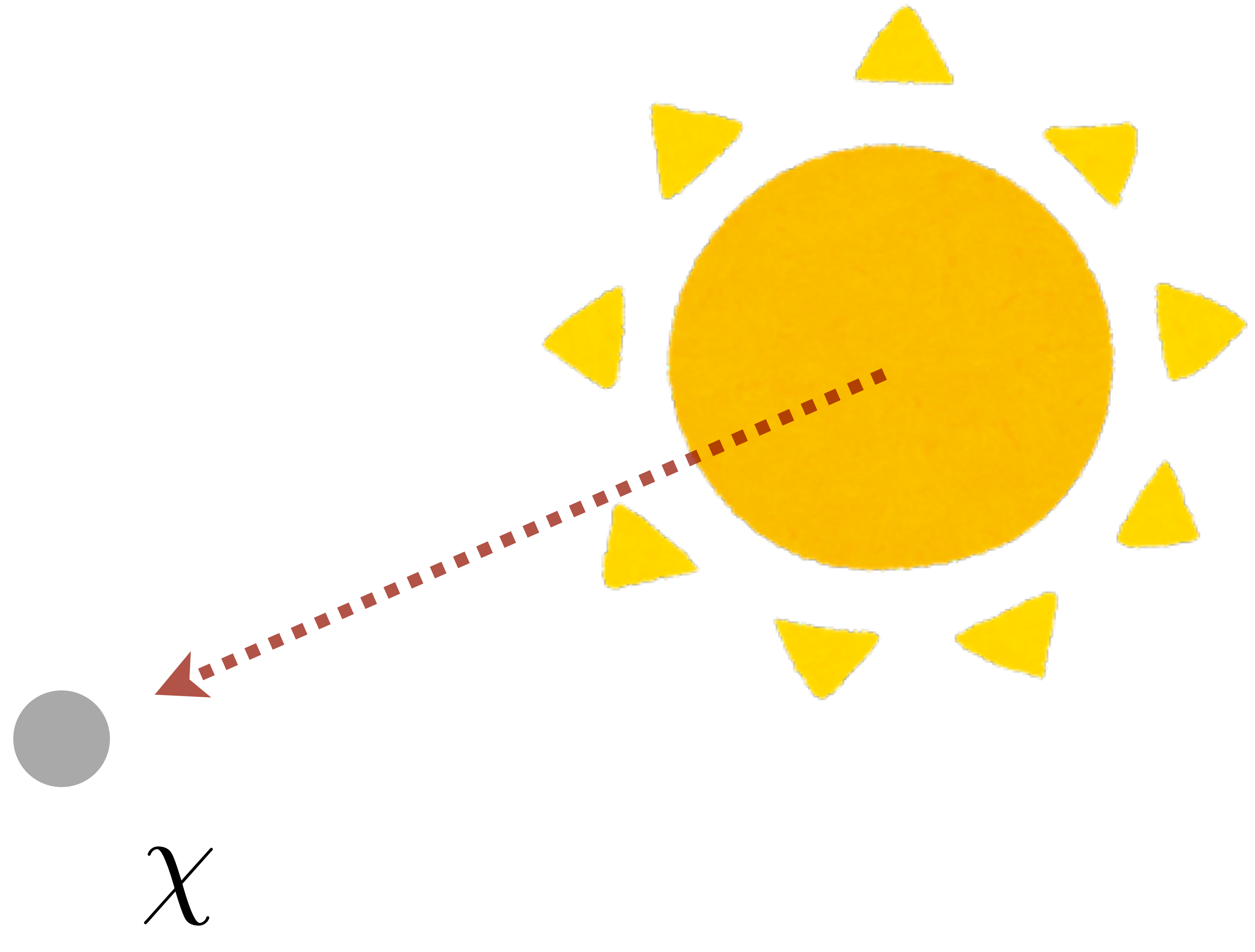
Need an acceleration mechanism

DM decay, (semi)annihilation, CR-boosted DM
exothermic DM

Y. Jho, J. C. Park, S. C. Park and P. Y. Tseng, 2006.13910
H.M. Lee 2006.13183

Any other bounds?

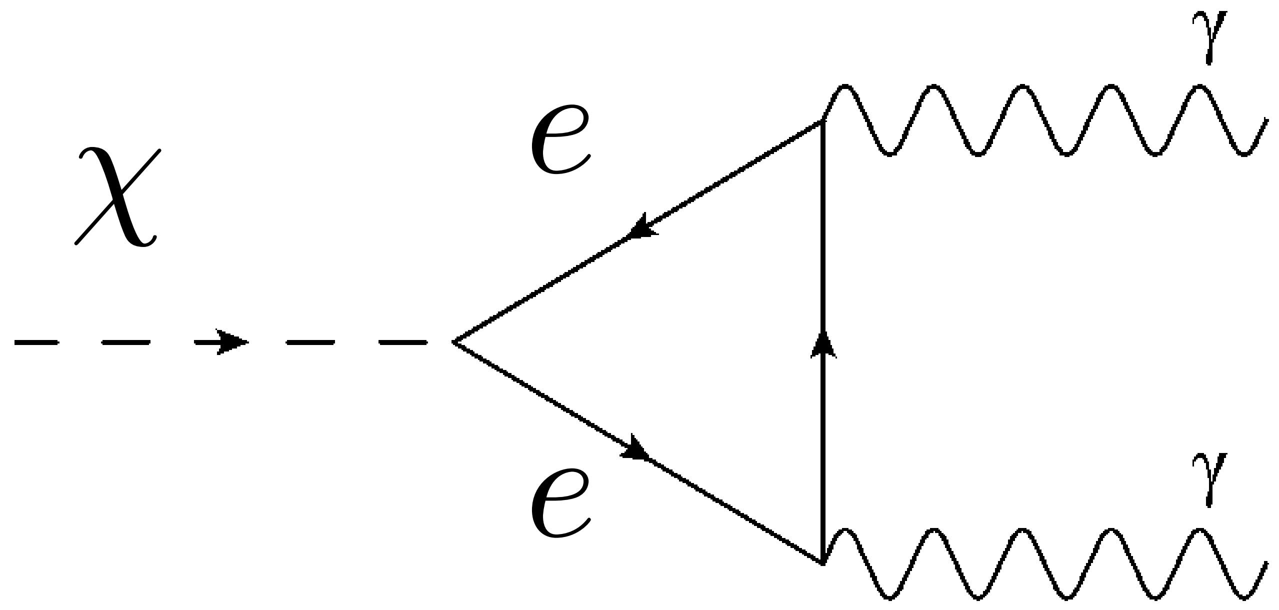
- Light and weakly interacting particles are produced inside stars, and they carry away energy which affect the **stellar evolution**.



e.g. the Sun: $L_\chi \lesssim L_\odot$

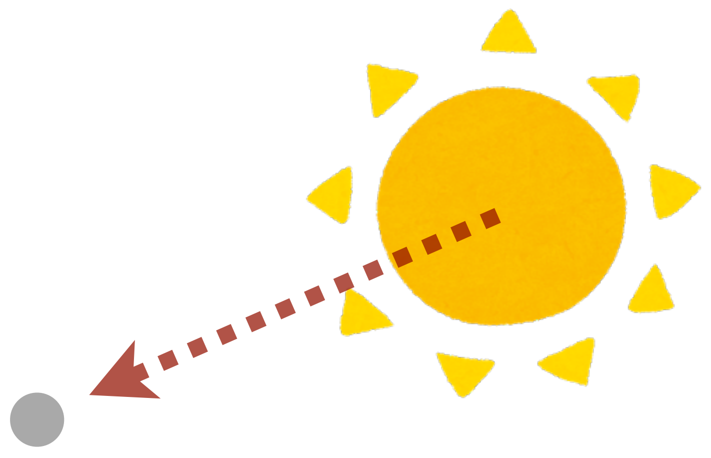
Other bounds from white dwarfs (WD), red giants (RG) and horizontally branched stars (HB).

- Alternatively, the decay of keV-mass DM into photons is constrained by the **X-ray obs**.



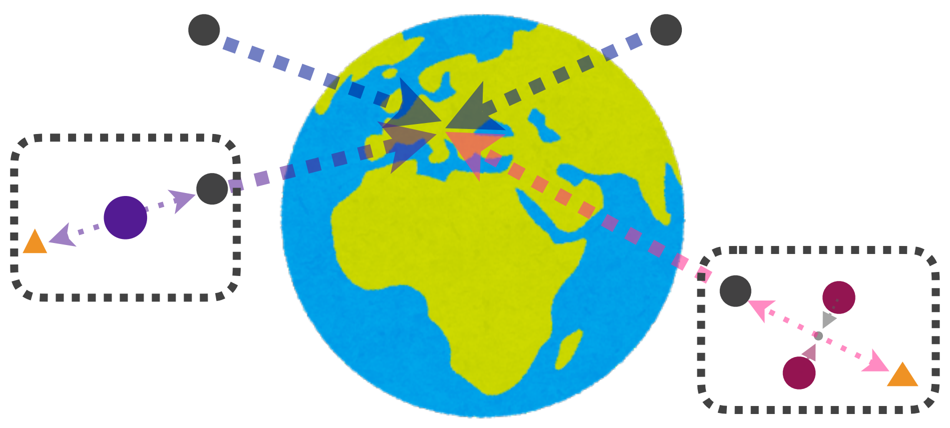
- Other limits from **BBN**, **structure formation**, etc.

Various models



- Solar axion/hidden(dark) photon
- Solar neutrinos + extra interactions (e.g. magnetic moment, vector portal)

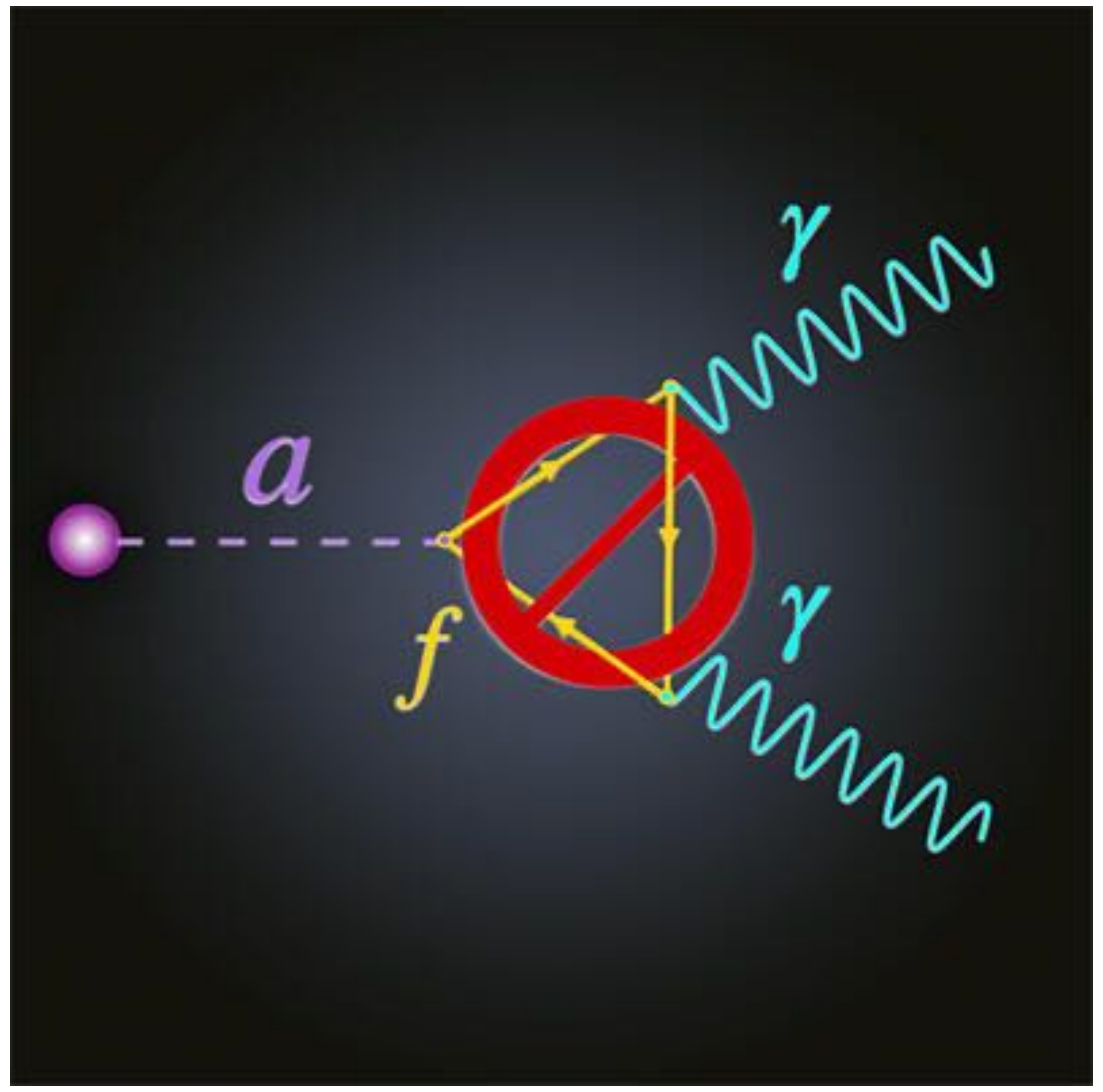
- Axion/hidden photon DM
- Boosted DM (Two-component DM, semi-annihilation, self-annihilation (3→2), Nearby DM clump, CR-boosted DM)



- Exothermic DM
- etc.

- Many interesting ideas on production or boosting DM (e.g. Sun-/CR-heated DM, stellar basin), avoiding the stellar cooling bounds, and implications for other experiments…

2. Anomaly-free ALP DM



ALP = axion-like particle

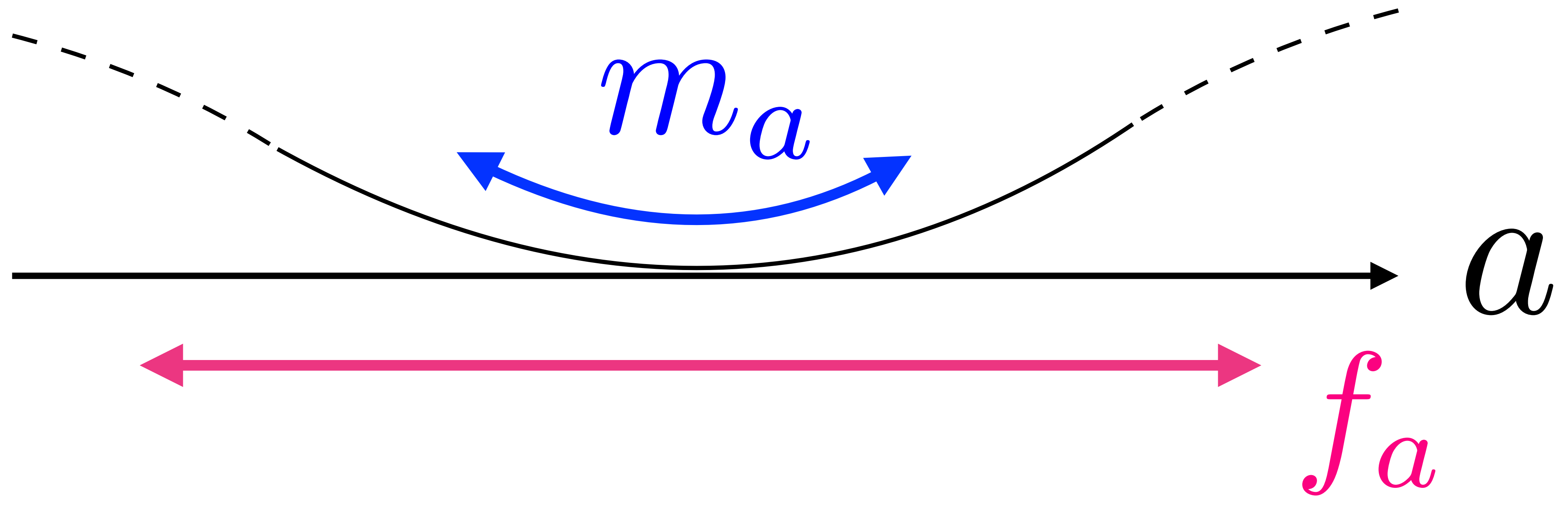
ArXiv:2006.10035 [PRL 125, 161801 (2020)]

FT, Masaki Yamada and Wen Yin

Axion (ALP) DM

Mass m_a and decay constant f_a

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

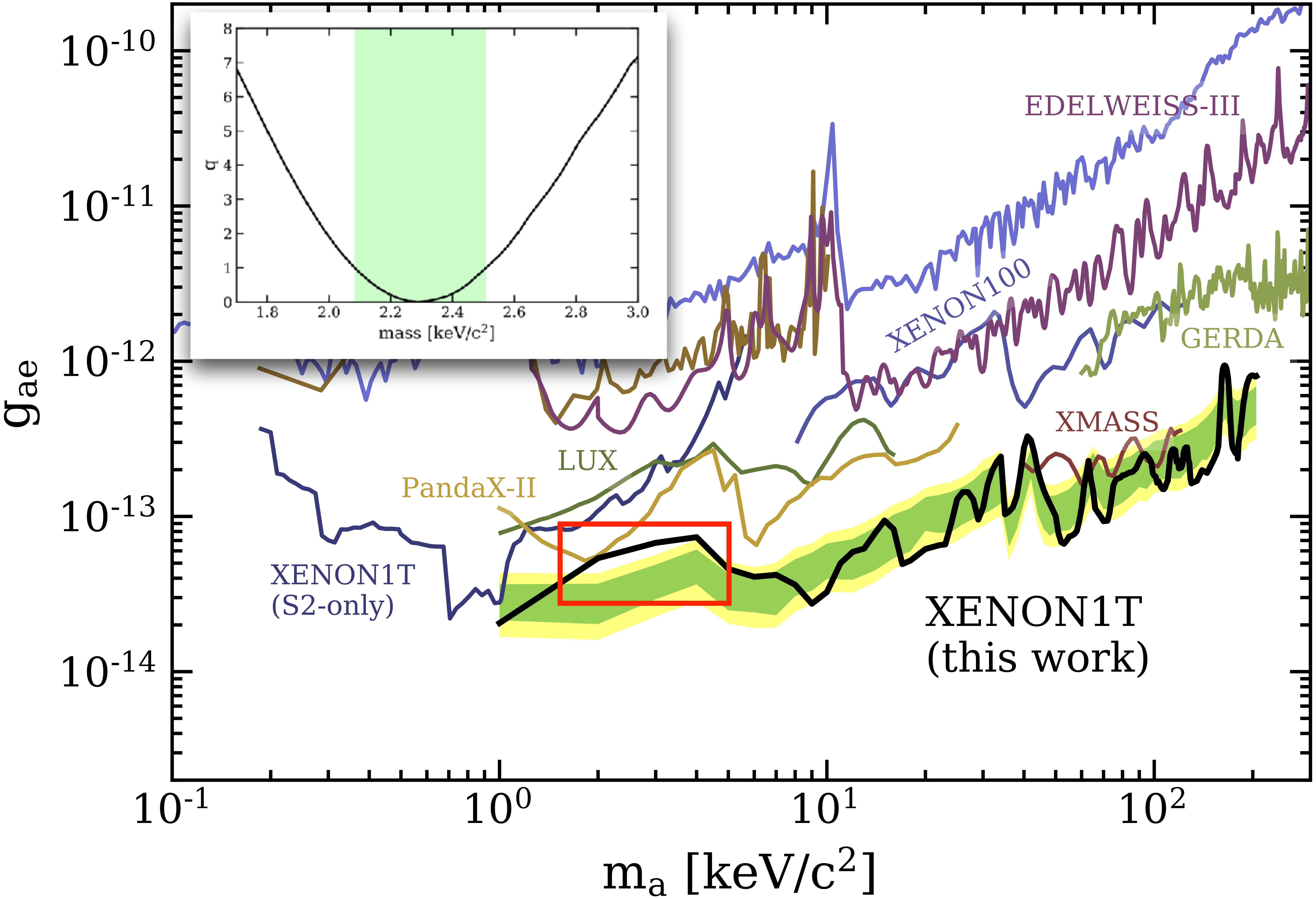


Interactions with the SM particles:

- Photons $\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}_{\mu\nu} = -g_{a\gamma\gamma}\, a\, \vec{E} \cdot \vec{B}$
- Electrons $\mathcal{L}_{aee} = \frac{C_e}{2f_a} \partial_\mu a \left(\bar{\Psi}_e \gamma^\mu \gamma_5 \Psi_e\right) = -i g_{aee} a \left(\bar{\Psi}_e \gamma_5 \Psi_e\right) + \cdots$
- Nucleons $\mathcal{L}_{aNN} = \sum_{N=p,n} \frac{C_N}{2f_a} \partial_\mu a \left(\bar{\Psi}_N \gamma^\mu \gamma_5 \Psi_N\right)$

$$g_{aee} \equiv \frac{C_e m_e}{f_a}$$

Direct DM search bounds on g_{ae}



$$\mathcal{L} = i g_{ae} a \bar{\Psi}_e \gamma_5 \Psi_e$$

The excess favors a mono-energetic peak at

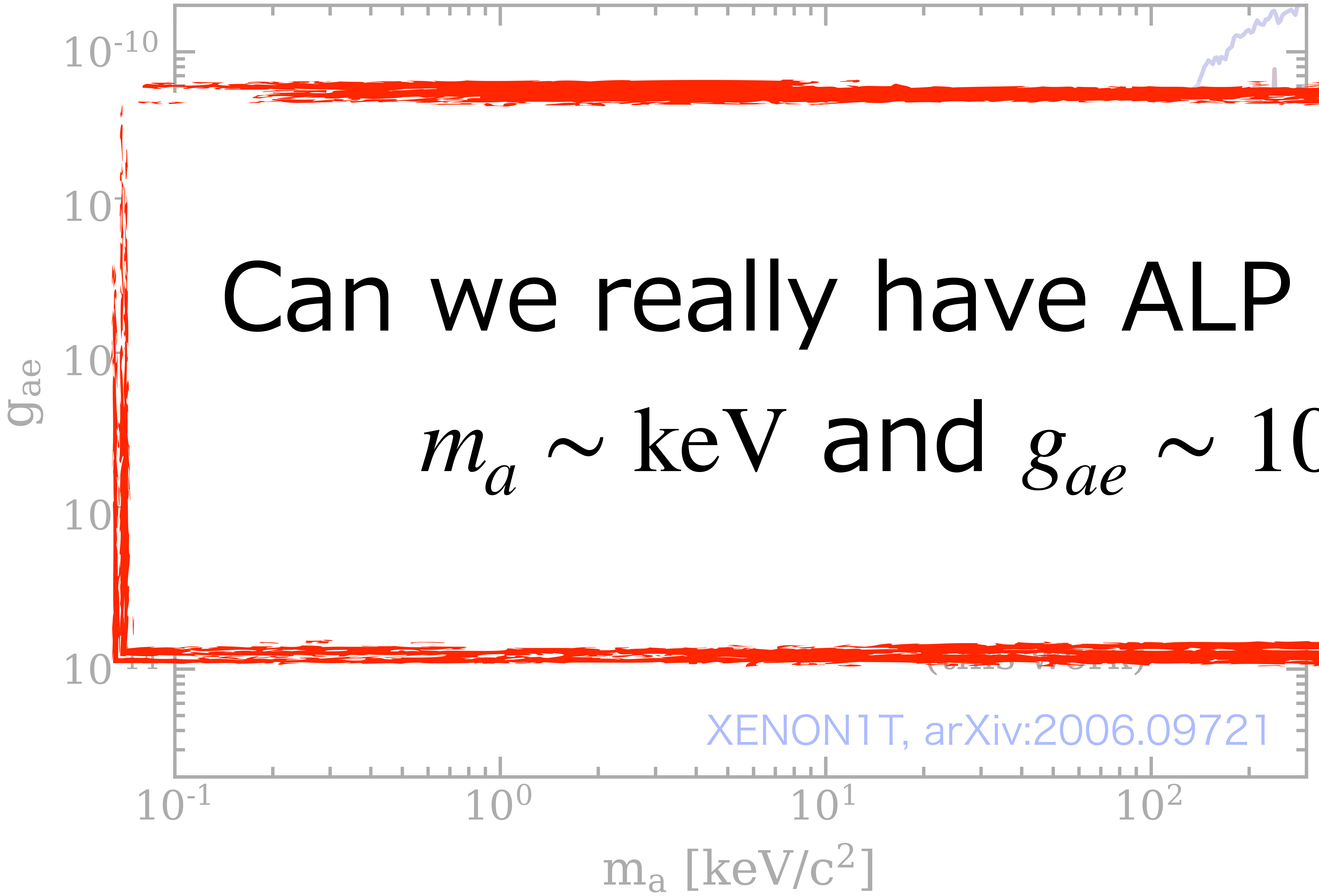
$m_a = 2.3 \pm 0.2\,\mathrm{keV}$

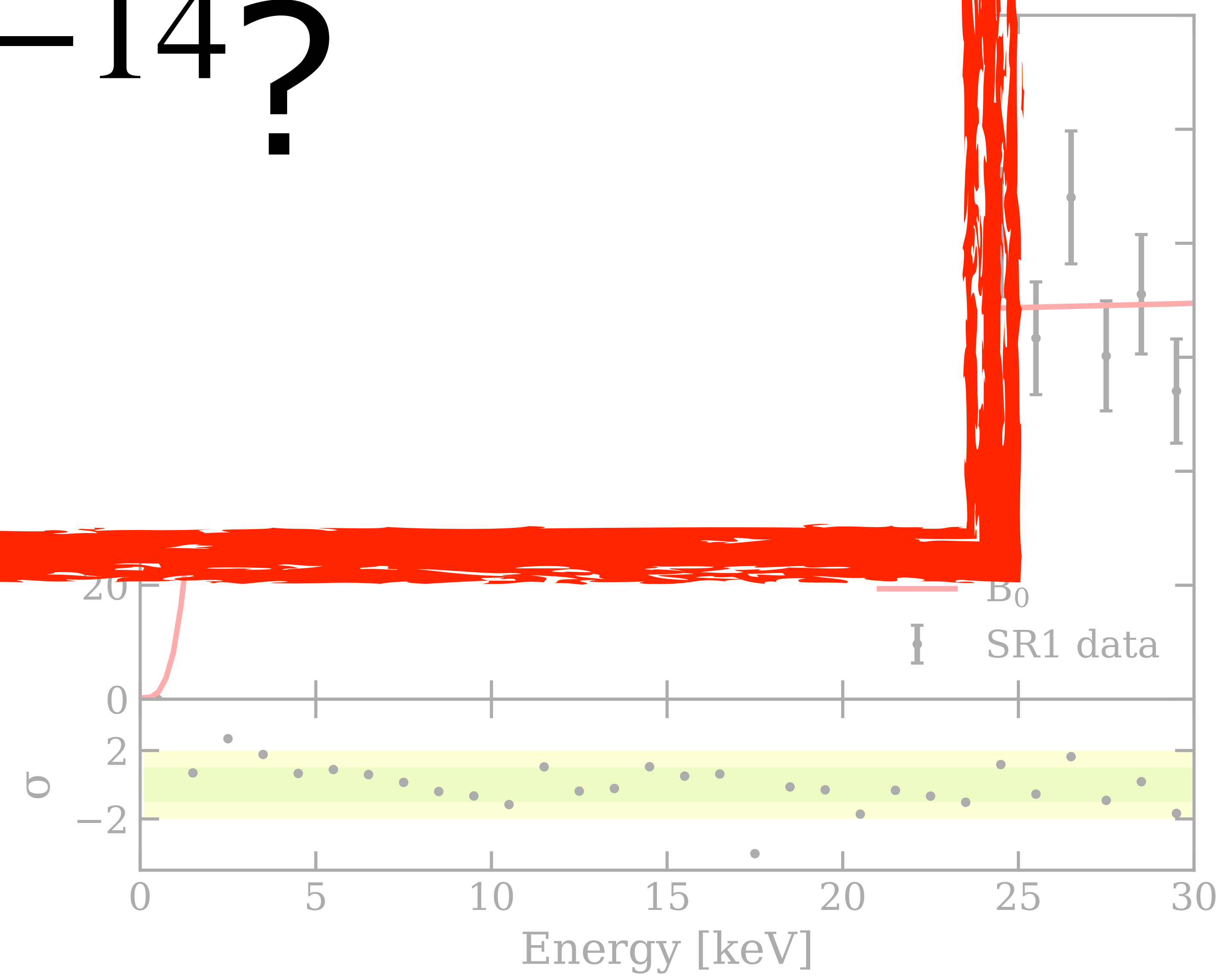
$g_{ae} \approx 3 \times 10^{-14}$

with 3σ significance over background.

XENON1T, arXiv:2006.09721

Direct DM search bounds on g_{ae}





Can we really have ALP DM with

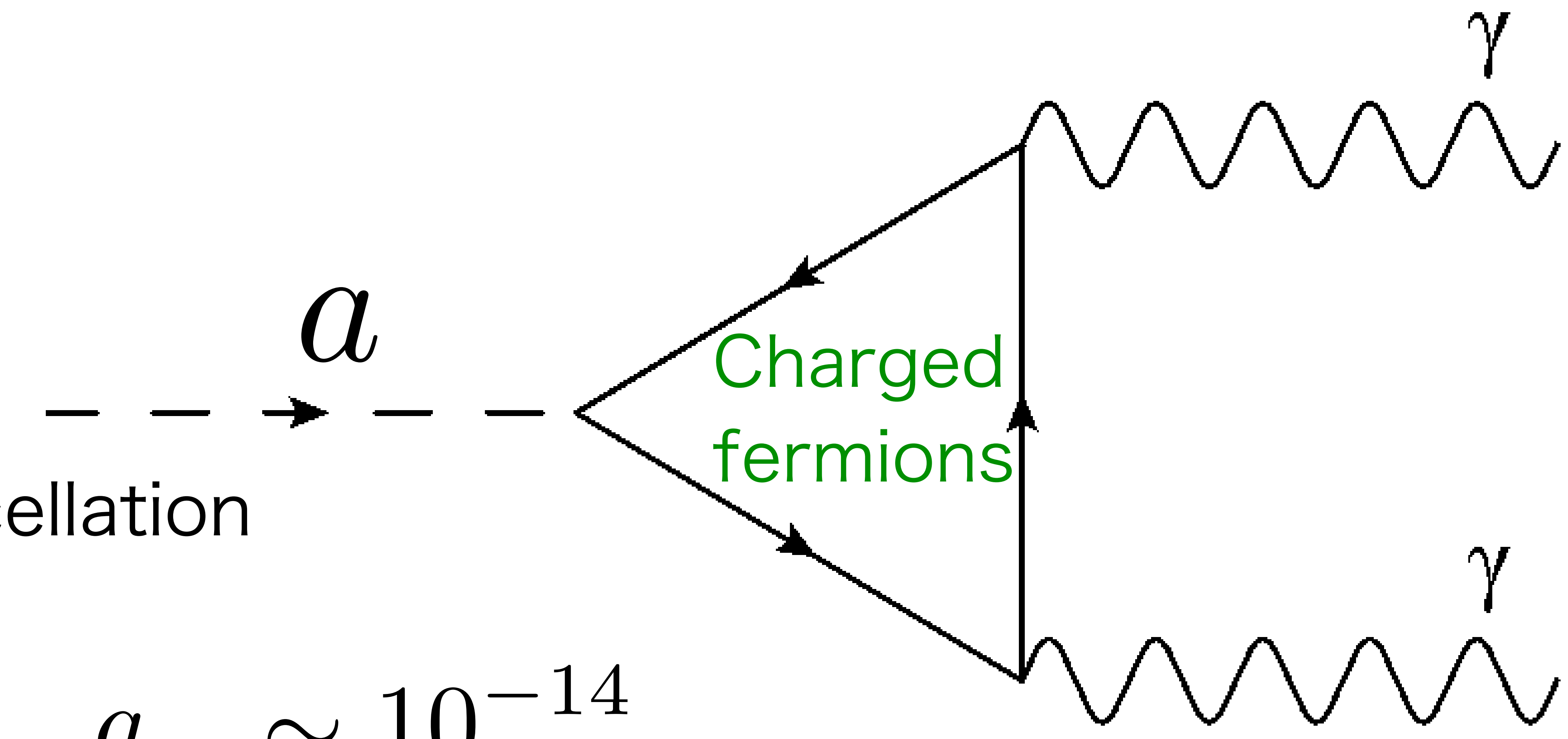
$m_a \sim \mathrm{keV}$ and $g_{ae} \sim 10^{-14}$?

Anomaly-free ALP DM

FT, Yamada,Yin 2006.10035
Nakayama, FT, Yanagida 1403.7390
see also Pospelov, Ritz, Voloshin 0807.3279

The axion generically has an anomalous coupling to photons

$$\mathcal{L} = \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



w/o cancellation

$$g_{a\gamma} \sim \frac{\alpha}{2\pi f_a}(C_e + \cdots) \sim \frac{\alpha g_{ae}}{2\pi m_e}$$

$$g_{aee} \equiv \frac{C_e m_e}{f_a}$$

$g_{ae} \sim 10^{-14}$
suggested by XENON1T

$$\Gamma_{a\to\gamma\gamma} \simeq \frac{\alpha_{\rm em}^2 g_{ae}^2}{256\pi^3}\frac{m_a^3}{m_e^2} \simeq \frac{1}{2\times 10^{21}\,\sec}$$

for $m_a = 2.3\,\mathrm{keV},\ g_{ae} \approx 3\times 10^{-14}$

The X-ray obs. constrains the lifetime to be longer than 10^{28} sec.

See e.g. Arias, Cadamuro, Goodsell, Jaeckel, Redondo and Ringwald, arXiv:1201.5902

Anomaly-free ALP DM

FT, Yamada,Yin 2006.10035
Nakayama, FT, Yanagida 1403.7390
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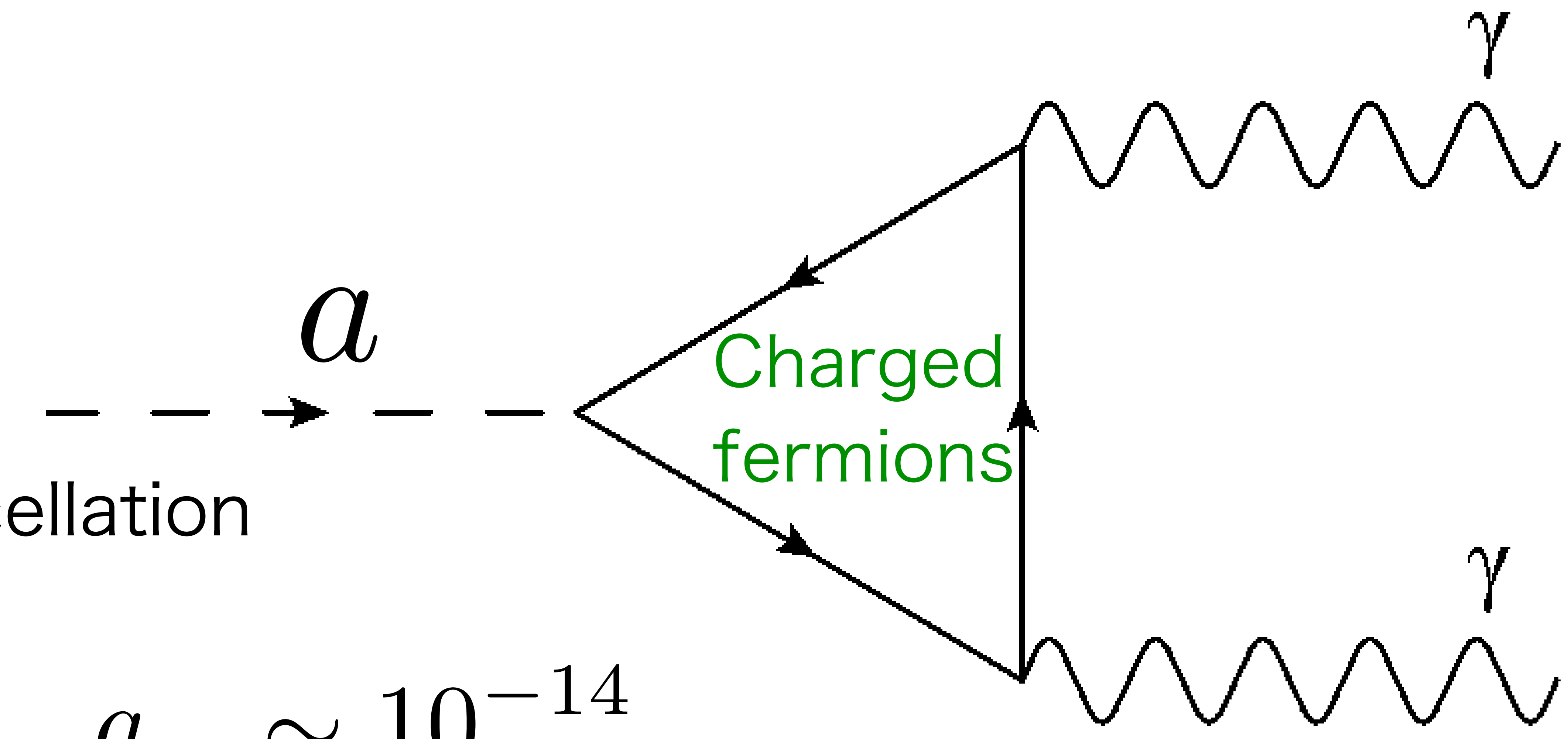


w/o cancellation

$$g_{a\gamma} \sim \frac{\alpha}{2\pi f_a}\left(C_e + \cdots\right) \sim \frac{\alpha g_{ae}}{2\pi m_e}$$

$(C_e + \cdots) = 0$

$$g_{aee} \equiv \frac{C_e m_e}{f_a}$$

$g_{ae} \sim 10^{-14}$
suggested by XENON1T

The X-ray observations tightly constrain the axion-photon coupling in the keV range, and we would need $g_{ae} \lesssim \mathcal{O}(10^{-18})$!!

Thus, we are led to consider the anomaly-free ALP DM.

Anomaly-free ALP DM

FT, Yamada,Yin 2006.10035
Nakayama, FT, Yanagida 1403.7390
see also Pospelov, Ritz, Voloshin 0807.3279

Integrating out electrically charged SM fermions, we obtain

$$\mathcal{L}_{\rm eff} \simeq -(C_e + C_\mu + \cdots)\frac{\alpha_{em}}{4\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha}{48\pi f_a}\left(\frac{C_e}{m_e^2} + \frac{C_\mu}{m_\mu^2} + \cdots\right)\left((\partial^2 a)F_{\mu\nu}\tilde{F}^{\mu\nu} + 2aF_{\mu\nu}\partial^2\tilde{F}^{\mu\nu}\right)$$

$= 0$

$$\simeq \frac{\alpha C_e}{48\pi f_a}\frac{m_a^2}{m_e^2} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

assuming on-shell ALP and photon.

threshold corrections
(dominated by **electron**)

$$\Gamma_{a\to\gamma\gamma} \simeq \frac{\alpha_{\rm em}^2 C_e^2}{9216\pi^3}\frac{m_a^7}{m_e^4 f_a^2} = \frac{\alpha_{\rm em}^2 g_{ae}^2}{9216\pi^3}\frac{m_a^7}{m_e^6}$$

cf. Anomalous ALP:

$$\Gamma_{a\to\gamma\gamma} \simeq \frac{\alpha_{\rm em}^2 g_{ae}^2}{256\pi^3}\frac{m_a^3}{m_e^2}$$

The decay into photons is significantly suppressed, satisfying the bound.
Also, the rate is **universal** for various anomaly-free ALP DM models.

Anomaly-free ALP DM

FT, Yamada, Yin 2006.10035
Nakayama, FT, Yanagida 1403.7390
see also Pospelov, Ritz, Voloshin 0807.3279

EM anomaly and color anomaly should vanish:

PQ charge

$$\sum_i C_i q_i^2 = 0 \quad \text{and} \quad \sum_{i \in \text{color}} C_i = 0$$

EM charge

(for avoiding mixing with π^0)

e.g.

- Leptophilic ALP: $C_e = -C_\mu$ or C_τ $C_{\text{others}} = 0$
- DFSZ-like ALP (based on type-I 2HDM, PQ = hypercharge)

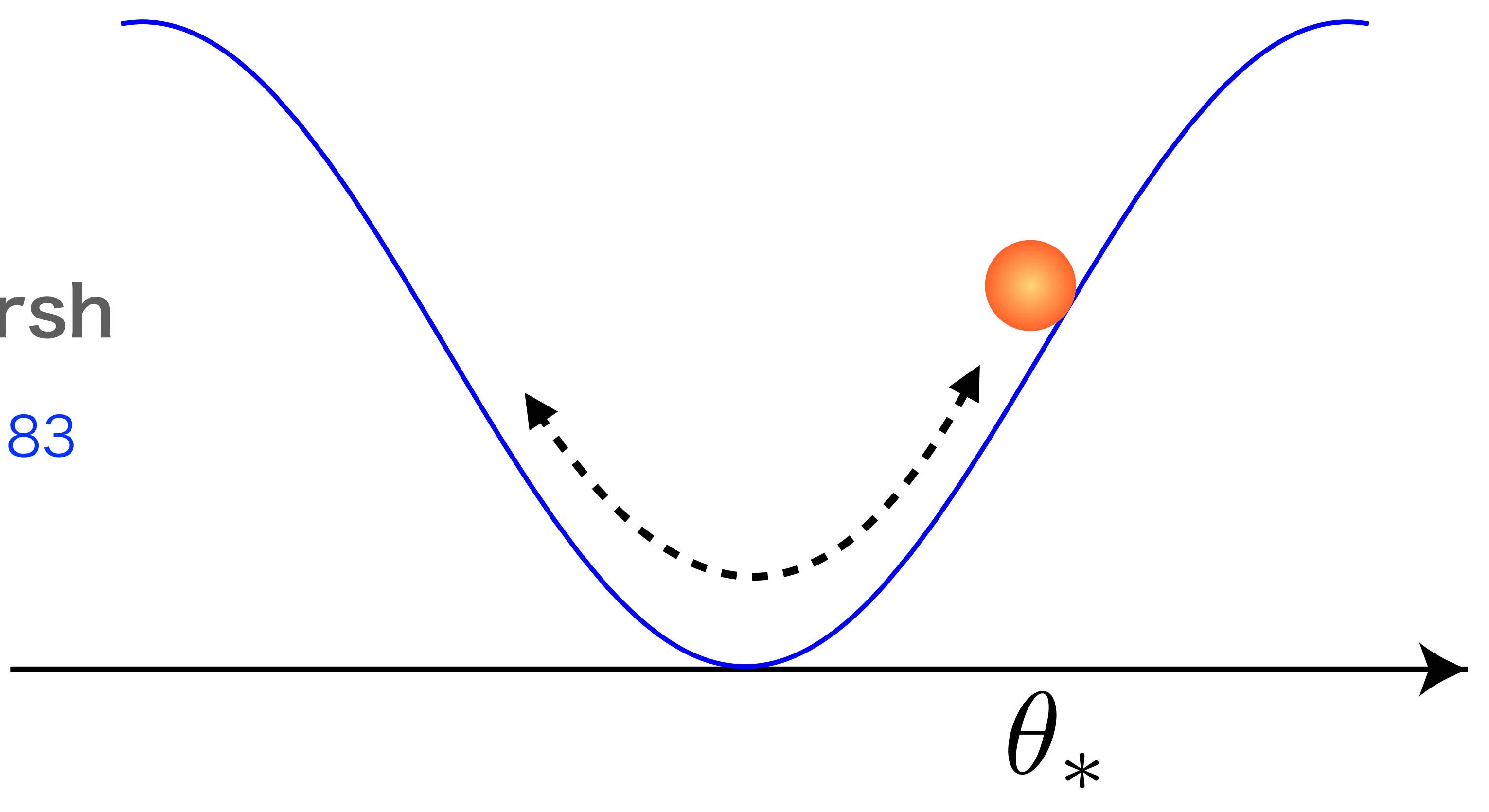
A general UV model is given by only derivative couplings
$\mathscr{L} = (\partial_\mu a/f_a) J^\mu_{\text{PQ}}$, where there is no SM anomaly (in a certain basis).

ALP production

- **Misalignment mechanism**

See also lecture by D. Marsh

Preskill, Wise, Wilczek \`83, Abbott, Sikivie, \`83, Dine, Fischler, \`83



$$\Omega_{\rm ALP}^{\rm (mis)} h^2 \sim 0.1 \left(\frac{\theta_*}{2}\right)^2 \left(\frac{C_e}{4}\right)^2 \left(\frac{f_a/C_e}{10^{10}~{\rm GeV}}\right)^2$$

$$\times \begin{cases} \left(\frac{T_R}{10^6~{\rm GeV}}\right) & \text{for} \quad T_R \lesssim T_{\rm osc} \\ \left(\frac{m_a}{2~{\rm keV}}\right)^{1/2} & \text{for} \quad T_R \gtrsim T_{\rm osc} \end{cases}$$

$$T_{\rm osc} \sim 10^6~{\rm GeV} \left(\frac{m_a}{2~{\rm keV}}\right)^{1/2}$$

ALP is cold and can explain all DM.

- We need $T_{\rm RH} \gtrsim 10^6 {\rm GeV}$ to get the right abundance for $C_e = O(1)$.
- For $T_{\rm RH} \lesssim 10^6 {\rm GeV}$ we need to invoke the clockwork to get $C_e \gg 1$ or use the anharmonic effect.

ALP production

- <u>Thermal production</u>

cf. Salvio, Strumia and Xue, arXiv:1310.6982

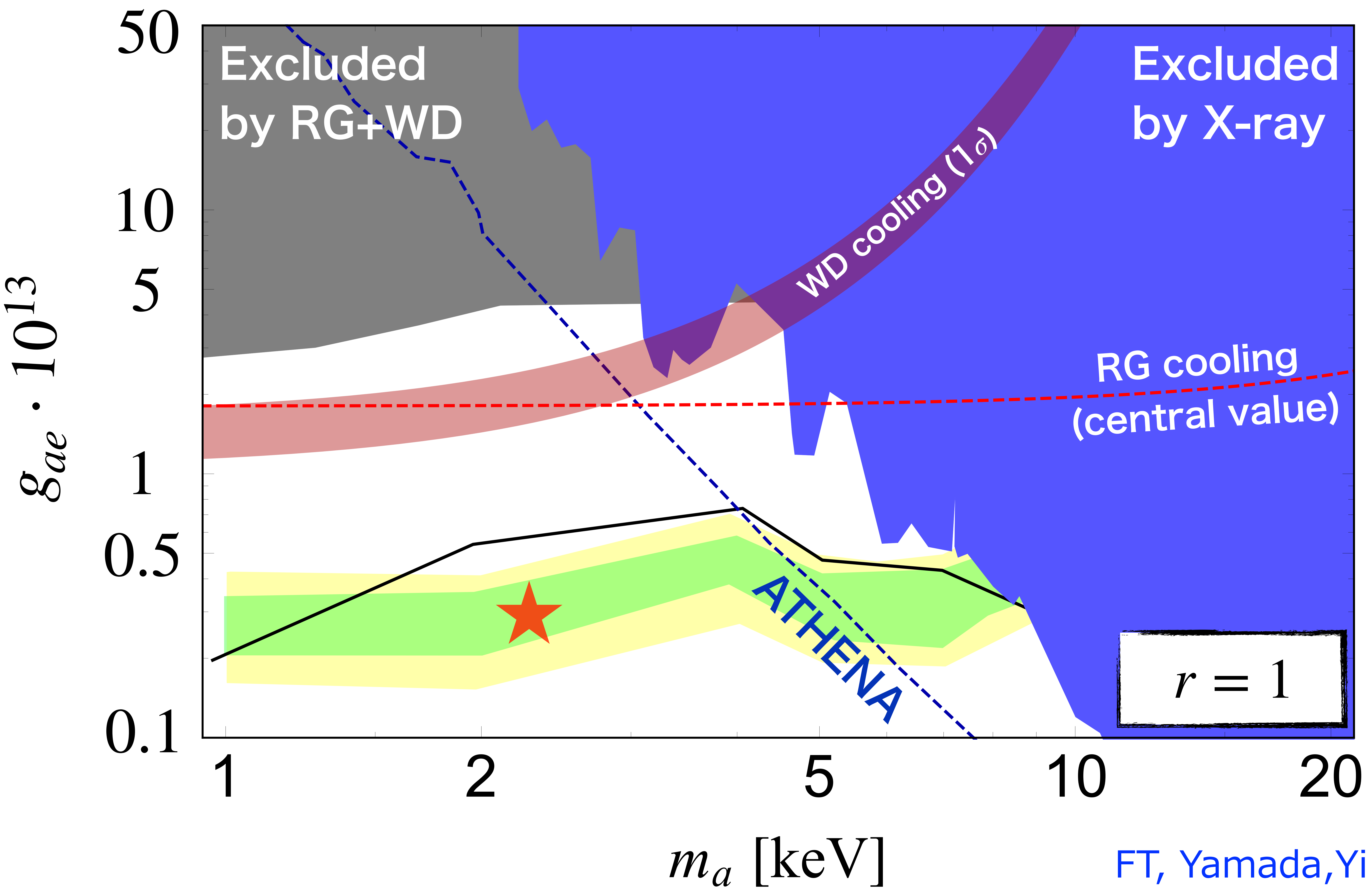
$$\Omega_{\rm ALP}^{\rm (th)} h^2 \sim 0.01 \left(\frac{T_R}{3 \times 10^5 \ {\rm GeV}} \right) \left(\frac{m_a}{2 \ {\rm keV}} \right) \times \left(\frac{f_a/C_e}{10^{10} \ {\rm GeV}} \right)^{-2} \sum_f \left(\frac{C_f m_f / C_e}{1 \ {\rm GeV}} \right)^2$$

ALP is warm DM and can explain about 10% of DM (or less).

The reheating should be low if the ALP is coupled to heavy fermions.
If the ALP is coupled to only e and mu, it can be as high as 10^8 GeV.

Results

$$r \equiv \Omega_a/\Omega_{\rm DM} = 1$$



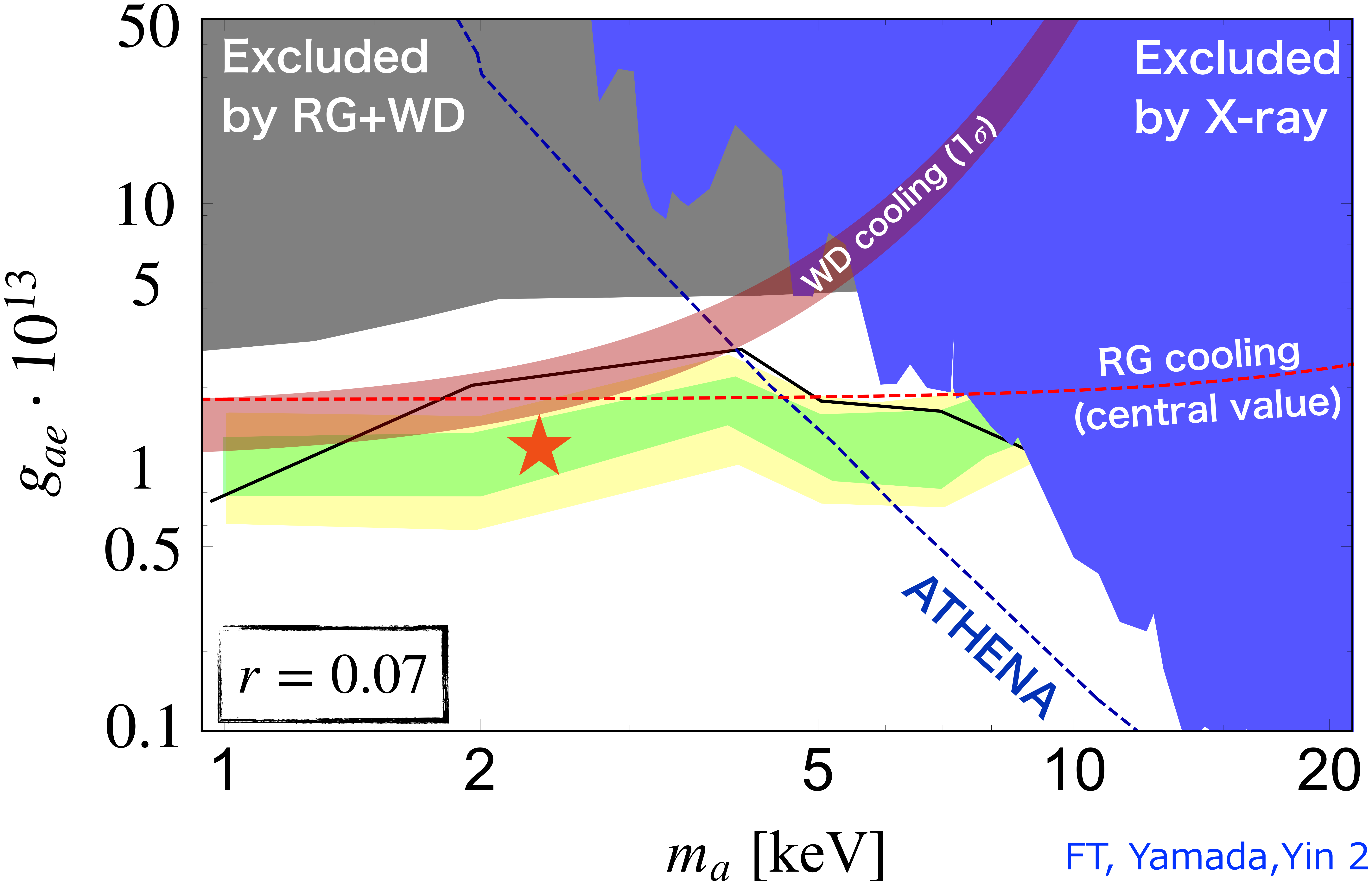
WD cooling hint:
Miller-Bertolami et al `14

RG cooling hint:
Viaux et al `13

FT, Yamada,Yin 2006.10035

Results

$$r \equiv \Omega_a/\Omega_{\rm DM} = 0.07$$



cf. $g_{an} \simeq 4 \times 10^{-10}$

from neutron star (CasA) cooling.

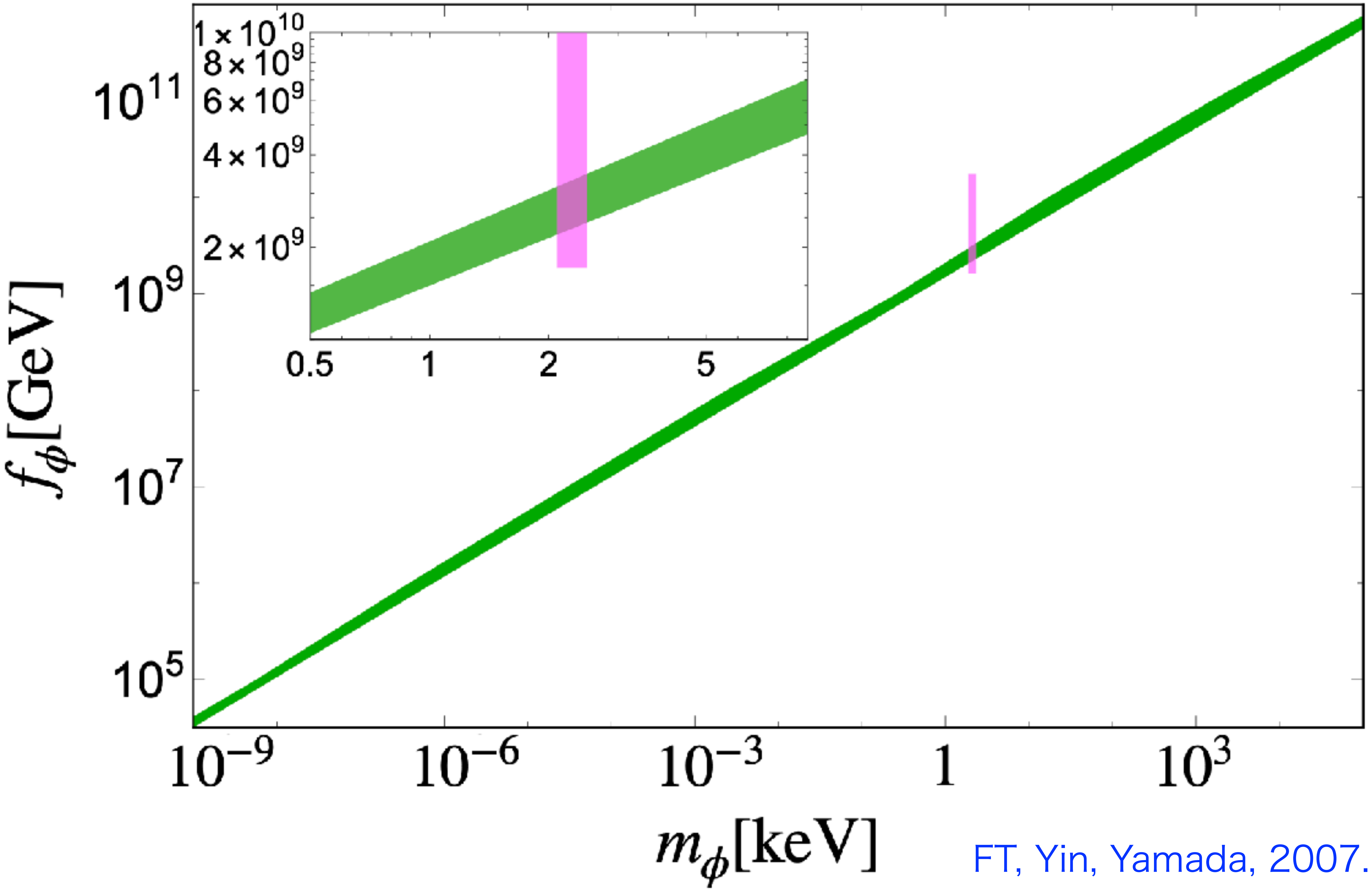
Leinson `14, see however Hamaguchi et al `18

FT, Yamada,Yin 2006.10035

ALP = DM = inflaton ?

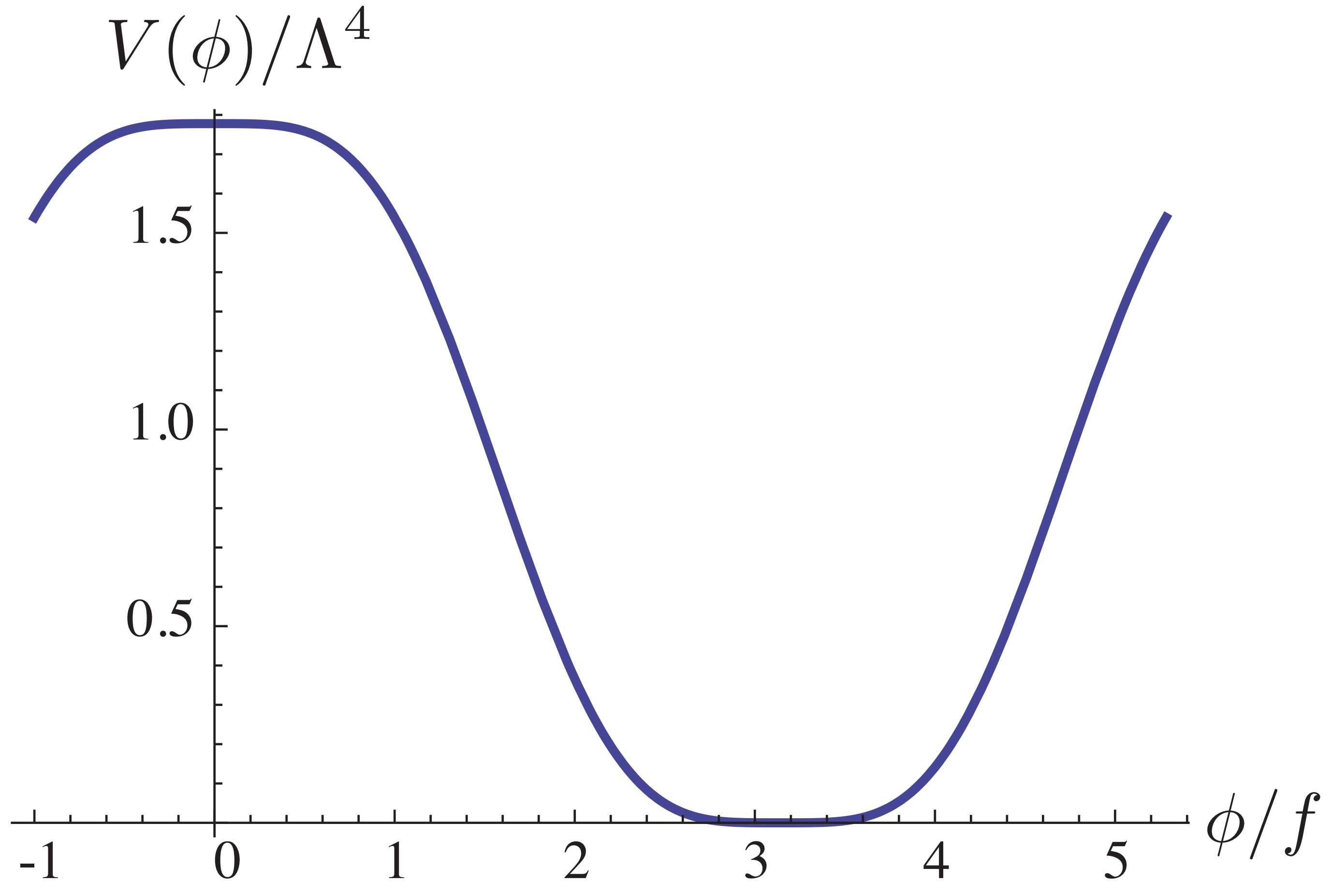
Daido, FT, and Yin 1702.03284, 1710.11107
FT and Yin,1903.00462, FT, Yin, Yamada, 2007.10311

The mass and coupling hinted by XENON1T and stellar cooling anomaly are consistent with the prediction of the ALP inflaton model !



FT, Yin, Yamada, 2007.10311

$$f_\phi \sim 10^3\sqrt{m_\phi M_p}$$



$$V_{\rm inf}(\phi) = \Lambda^4\left(\cos\left(\frac{\phi}{f}+\theta\right) - \frac{\kappa}{n^2}\cos\left(\frac{n\phi}{f}\right)\right) + \text{const.}$$

$$= V_0 - \lambda\phi^4 - \theta\frac{\Lambda^4}{f}\phi + (\kappa-1)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots$$

Summary

✓ Many interesting ideas to explain the XENON1T excess.

- Related to DM or not
- Absorption or scattering
- Various bounds: stellar cooling, direct/indirect DM search, BBN, etc.
- Why keV? Why this much excess? Any testable prediction?

✓ **Anomaly-free axion DM** is a viable candidate since it has only **suppressed coupling to photons**. It predicts an X-ray line with a definite strength due to threshold corr. from electron.

✓ The electron coupling is close to values favored by the stellar cooling of WD and RG. The agreement is even better if the axion is only a fraction of DM.

✓ **ALP DM = inflaton?** $f_\phi \sim 10^3 \sqrt{m_\phi M_p}$