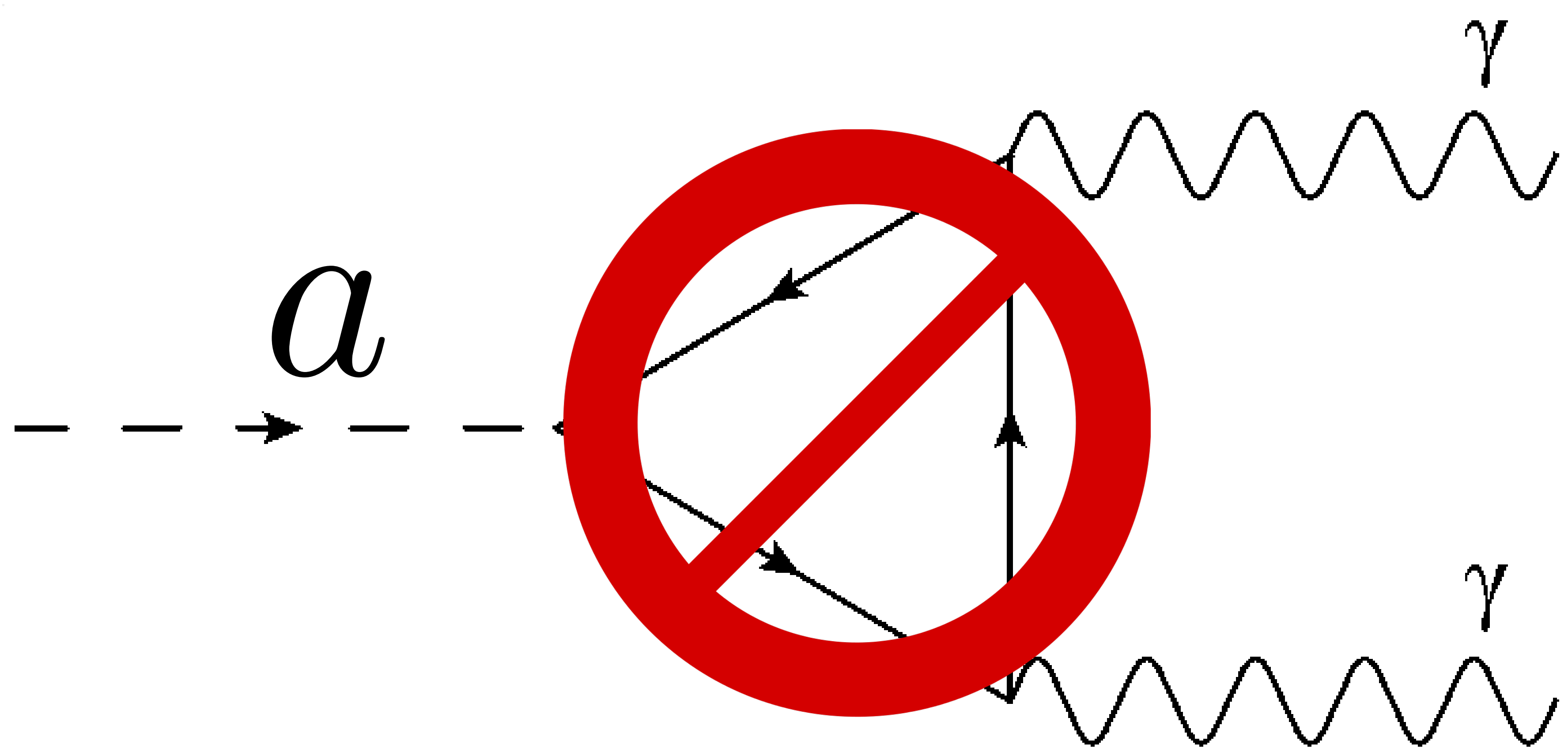
29, June, 2020, Theoretical interpretations of the Xenon anomaly, On-line “Newton 1665” seminars

XENON1T anomaly from Anomaly-free ALP DM



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Based on 2006.10035 with Fuminobu Takahashi, Masaki Yamada (Tohoku Univ.)

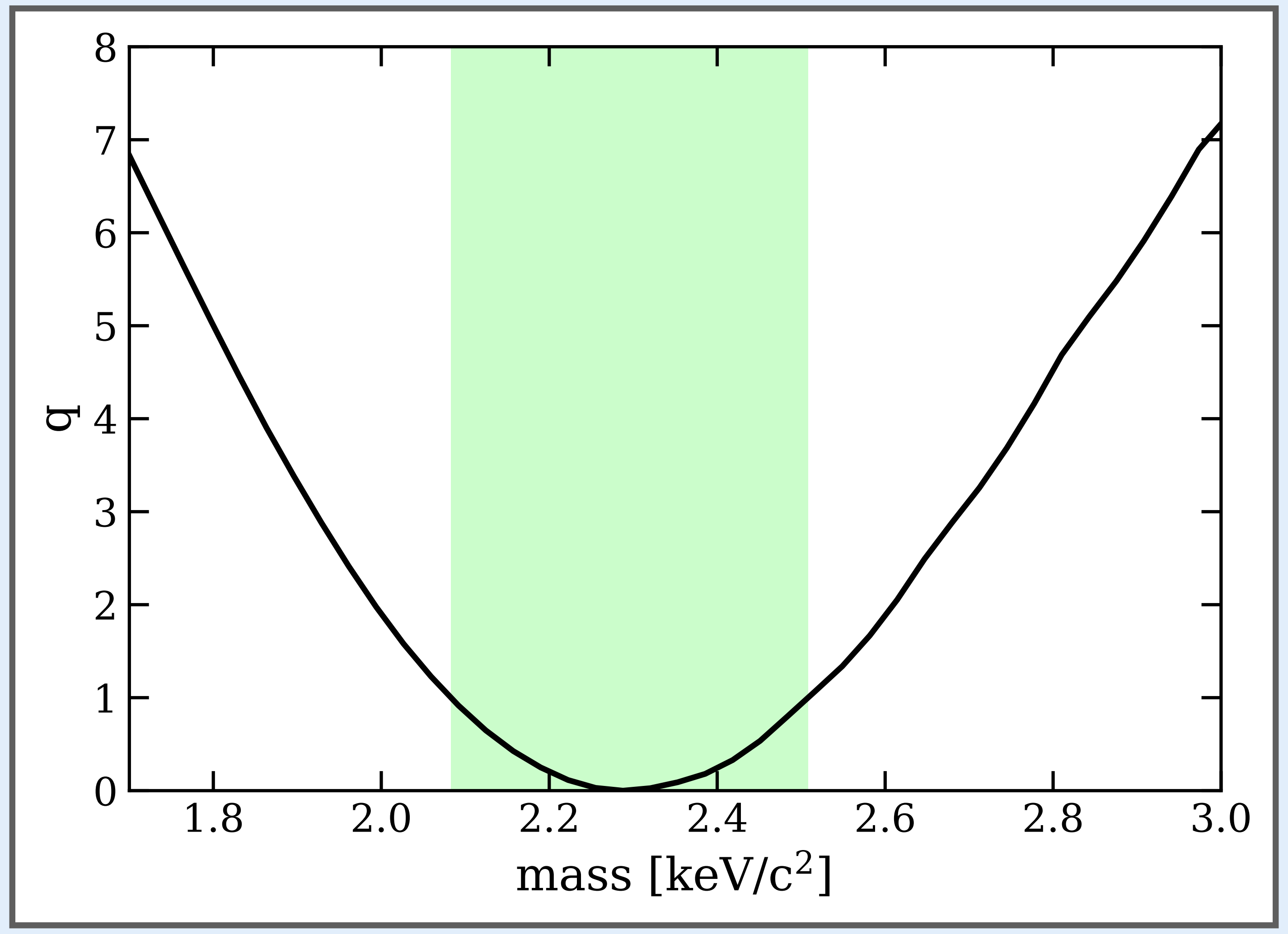
ALP DM explanation of Xenon1T excess.

Bosonic dark matter

XENON Dark Matter Project

Fitting a mono-energetic peak to the excess:
2.3 +/- 0.2 keV

$$q = -2\ln\frac{L(m_a,\theta)}{L(\hat{m}_a,\hat{\theta})}$$



Best fit: ~60 events/tonne/year
4.0 σ local significance
3.0 σ (global).

ALP DM

$$\mathscr{L} \supset i g_{ae} a \bar{\Psi}_e \gamma_5 \Psi_e$$

$$g_{ae} \equiv q_e \frac{m_e}{f_a}$$

q_e :“PQ” charge of e.

favored region
3.0σ (global significance)

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

60 events/tonne/year $\rightarrow$ $g_{ae} \approx 3 \times 10^{-14}$

From seminar on 26th June
by M. Galloway for XENONE1T

ALP DM explanation of Xenon1T excess.

Bosonic dark matter

XENON Dark Matter Project

ALP DM

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

Is ALP DM with $m_a \sim \mathrm{keV}$ and $g_{ae} \sim 10^{-14} - 10^{-13}$ consistent with cosmology/astronomy?

4.0 σ local significance
3.0 σ (global).

Taken from Galloway's slide.

What I will be talking about

Takahashi, Yamada, WY 2006.10035

1. ALP must be $U(1)_{''\mathrm{PQ}''}$-$U(1)_{\mathrm{EM}}$-$U(1)_{\mathrm{EM}}$ anomaly-free.
   Model-independent X-ray line signal predicted.

2. Close to the stellar cooling hint,
   and better agreement if ALP is subdominant DM.

3. The DM abundance naturally obtained by misalignment.
   (Thermal production is also natural for subdominant DM.)

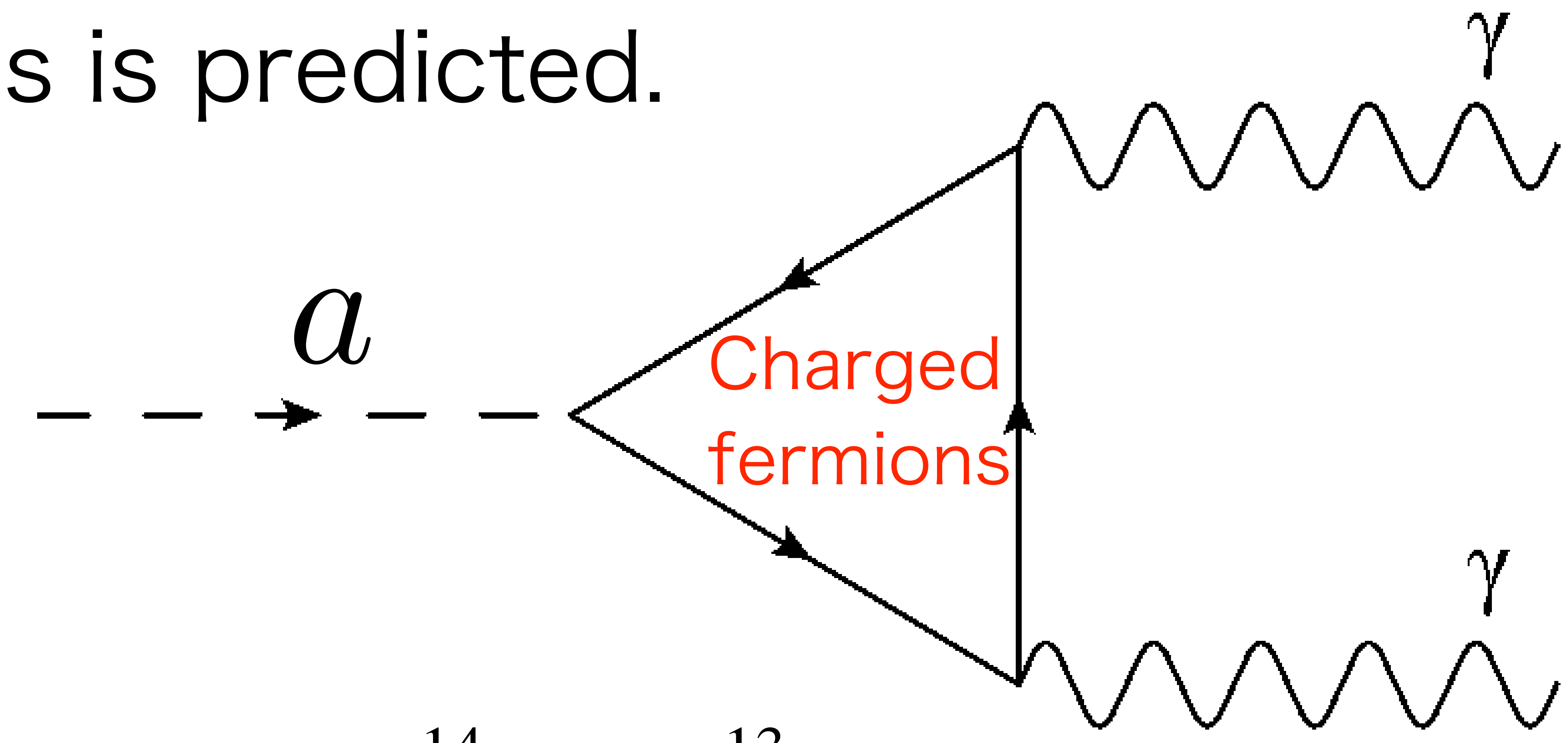
ALP DM coupled to electron

If the axion is *only coupled* to electron,
an anomalous coupling to photons is predicted.

$U(1)_{''\mathrm{PQ}''}\mathrm{U}(1)_{\mathrm{EM}}\mathrm{U}(1)_{\mathrm{EM}}$ anomaly:

$$\mathscr{L} = \frac{g_{a\gamma}}{4} a F \tilde{F}$$

$$g_{a\gamma} \approx \frac{\alpha}{2\pi f_a} = \frac{\alpha g_{ae}}{2\pi m_e}.$$



$g_{ae} \sim 10^{-14} - 10^{-13}$
favored by XENON1T

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

Anomaly-free ALP DM

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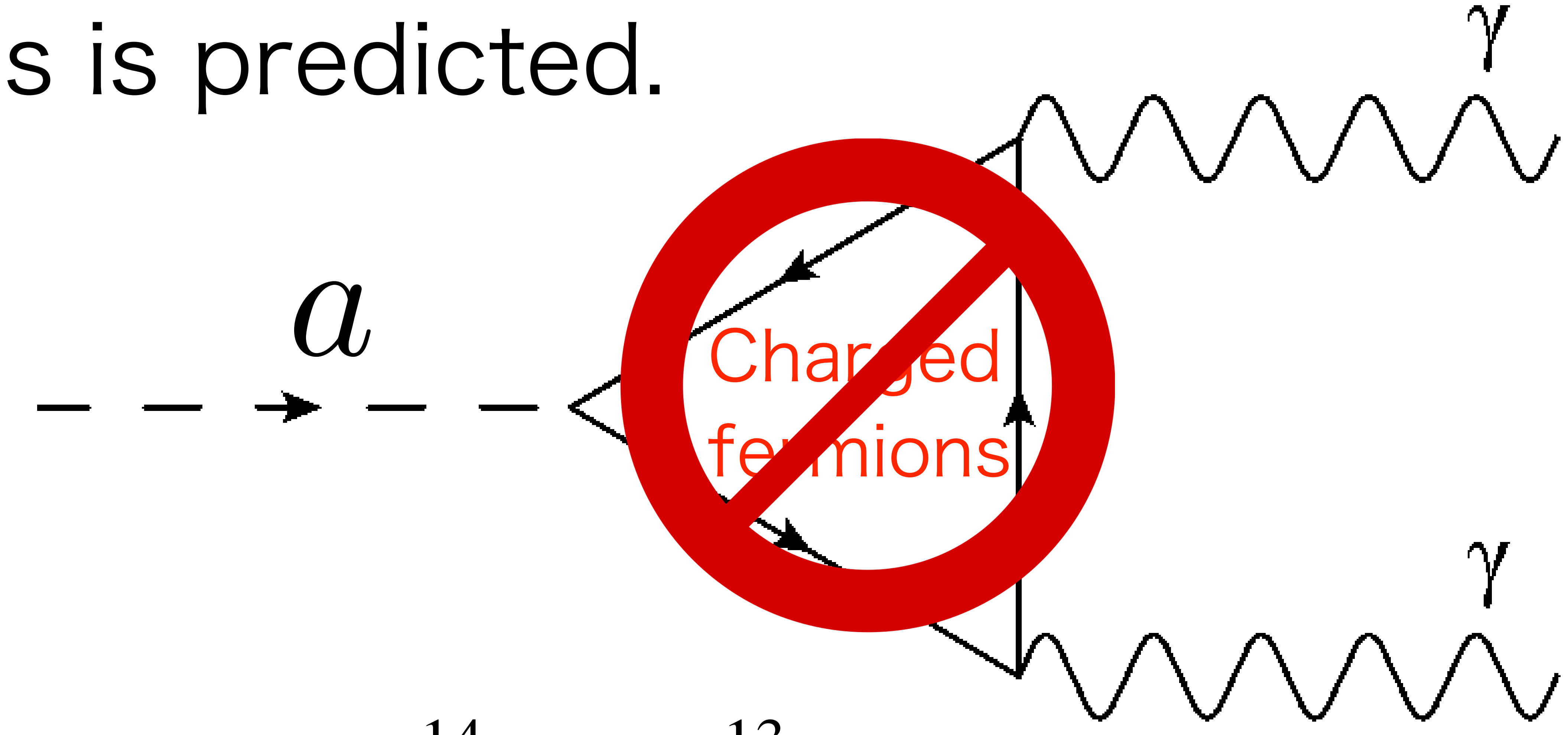

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However, the X-ray observations tightly constrain the axion-photon coupling in the keV range, and we need $g_{ae} \lesssim \mathcal{O}(10^{-18})$!!

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

Anomaly-free ALP DM

Takahashi, Yamada, WY, 2006.10035
Nakayama, Takahashi, Yanagida 1403.7390
(See also Pospelov, Ritz, Voloshin, 0807.3279)

Since the axion of keV mass is lighter than any (electrically charged) SM fermions, we can integrate them out to obtain

$$\mathcal{L}_{\rm eff} \simeq -\underbrace{(q_e + q_\mu + \cdots)}_{=0} \frac{\alpha_{em}}{4\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha}{48\pi f_a}\left(\frac{q_e}{m_e^2} + \frac{q_\mu}{m_\mu^2} + \cdots\right)\left((\partial^2 a)F_{\mu\nu}\tilde{F}^{\mu\nu} + 2aF_{\mu\nu}\partial^2\tilde{F}^{\mu\nu}\right)$$

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

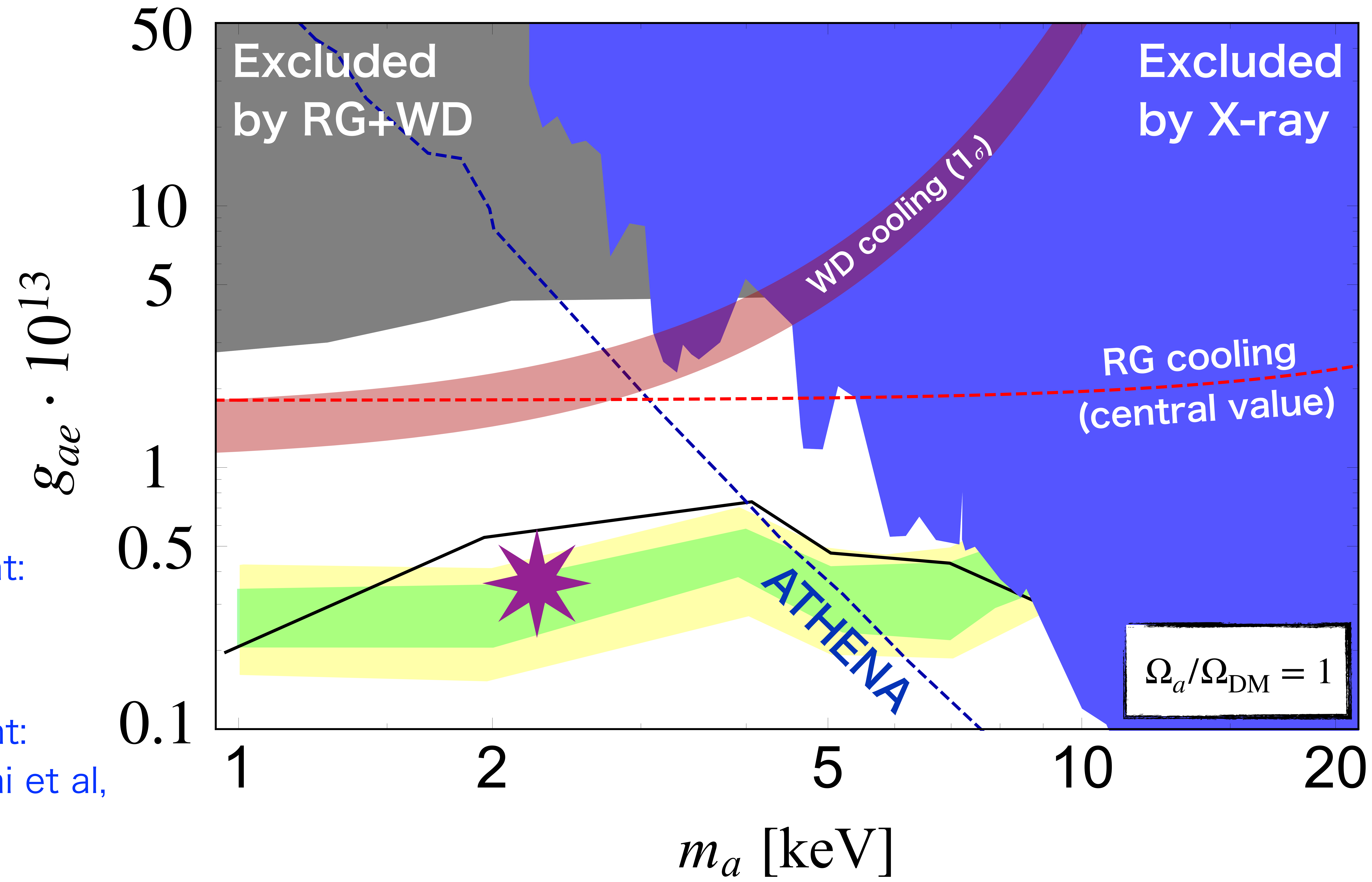
threshold corrections dominated by electron.

assuming on-shell ALP and photon.

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

The decay into photons is significantly suppressed, and moreover, the rate is universal for various anomaly-free ALP DM models.

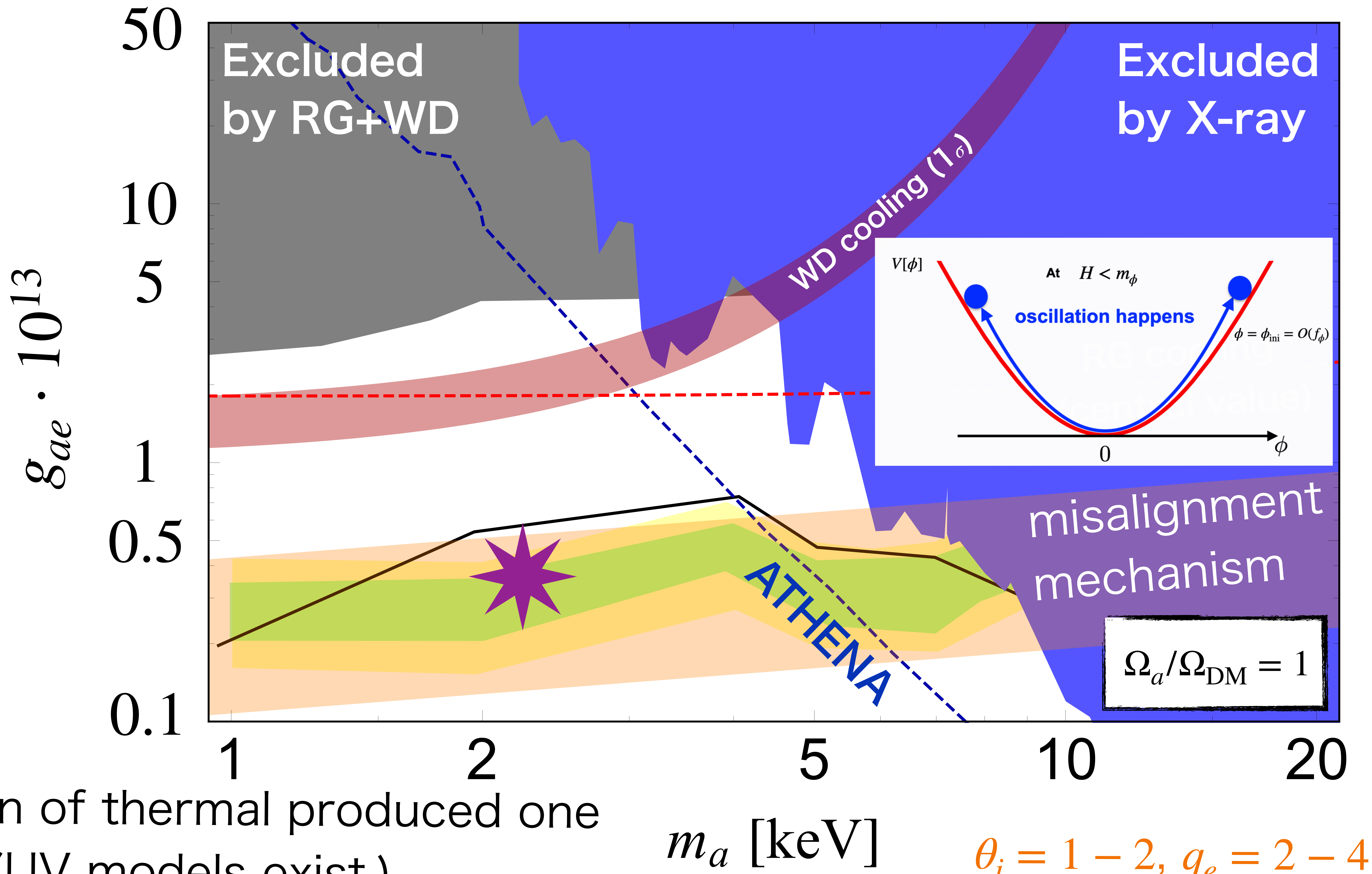
Parameter region of anomaly-free ALP DM



RG cooling hint:
Viaux et al,
1311.1669

WD cooling hint:
Miller-Bertolami et al,
1406.7712

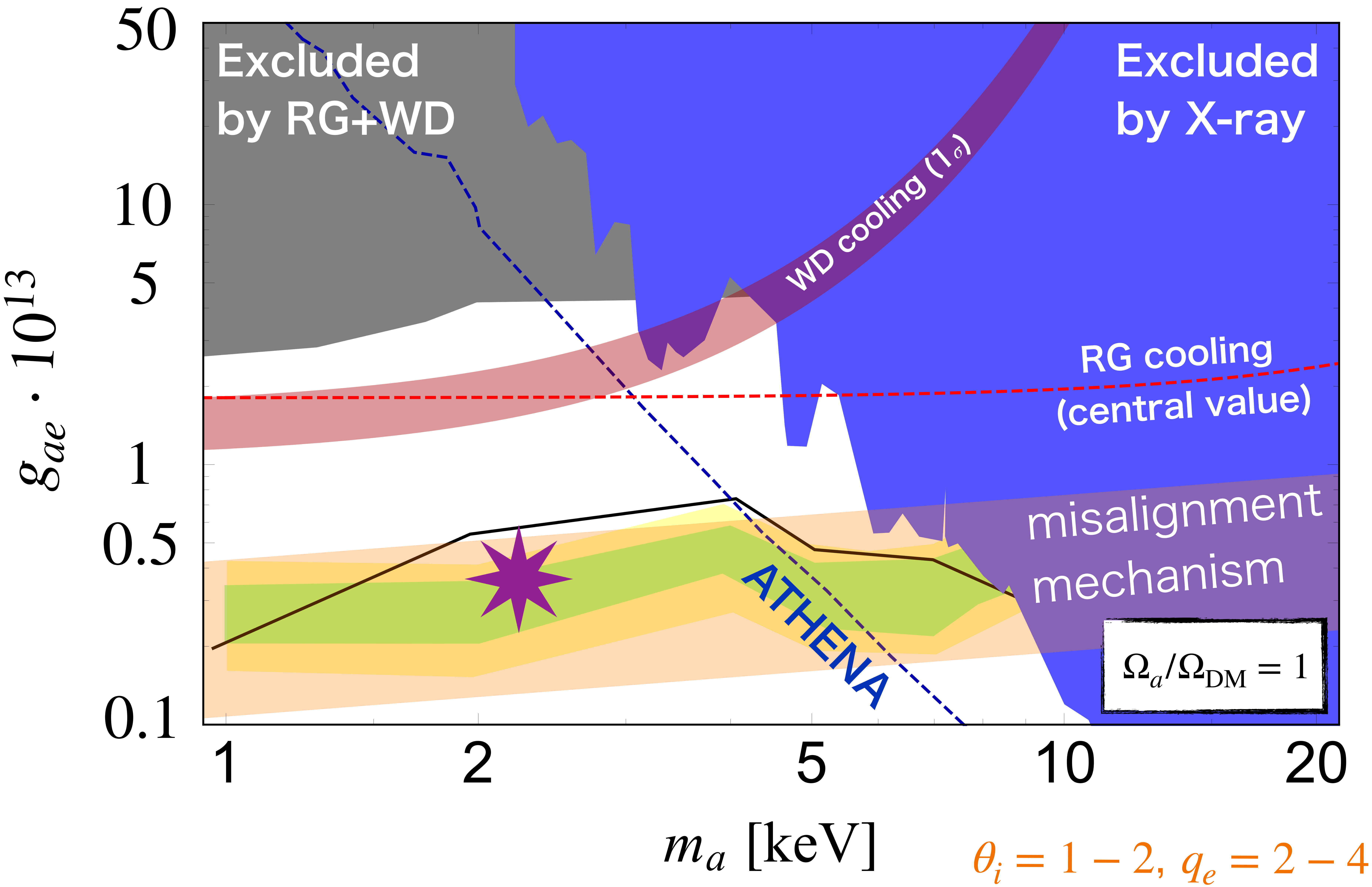
Consistent DM abundance with $q_e = O(1), \theta_i = O(1)$



Suppression of thermal produced one is needed. (UV models exist.)

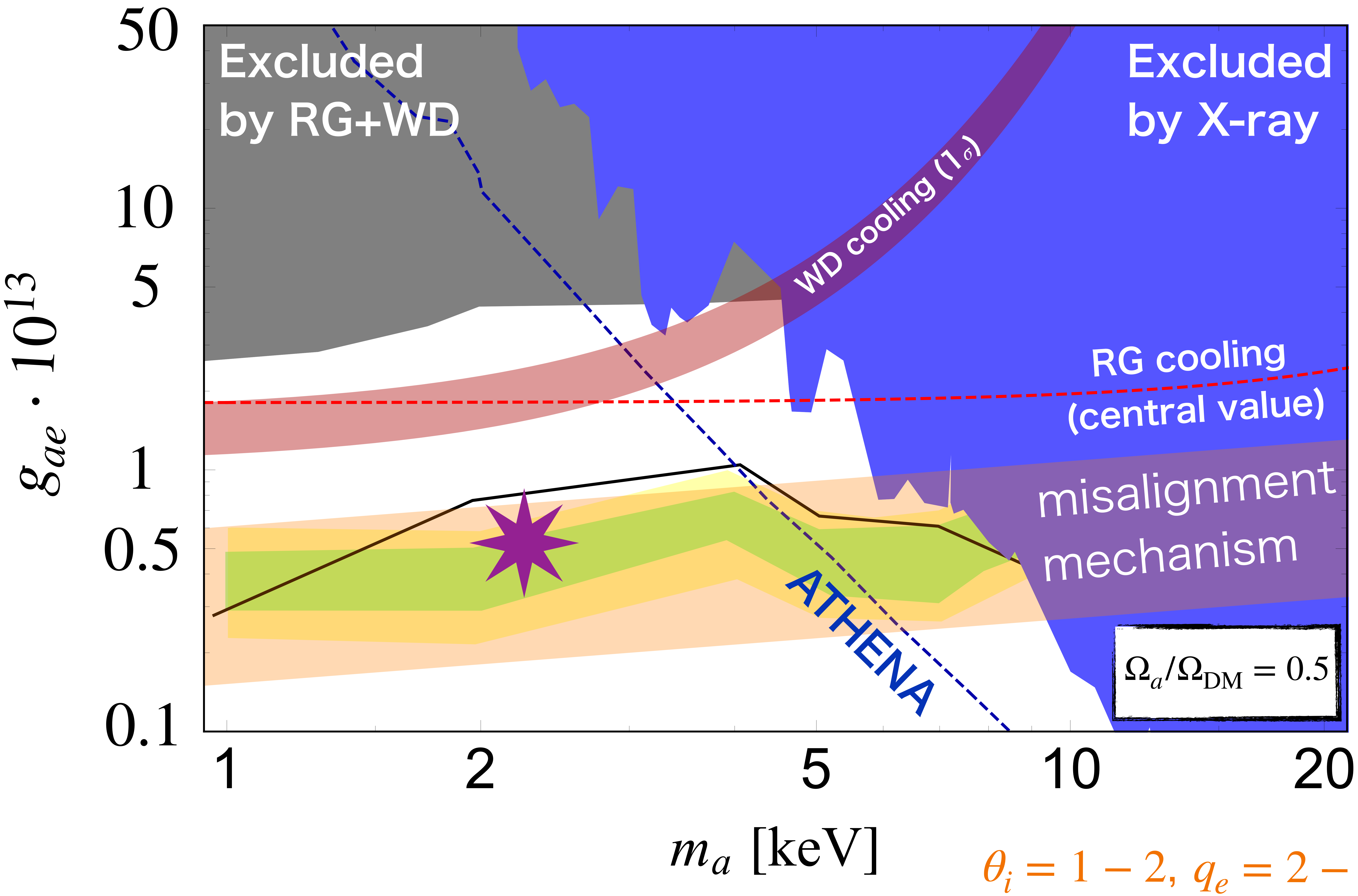
$\theta_i = 1 - 2,\ q_e = 2 - 4.$

Ω_a–dependence: $\Omega_a/\Omega_{DM} = 1$



$\theta_i = 1 - 2,\ q_e = 2 - 4.$

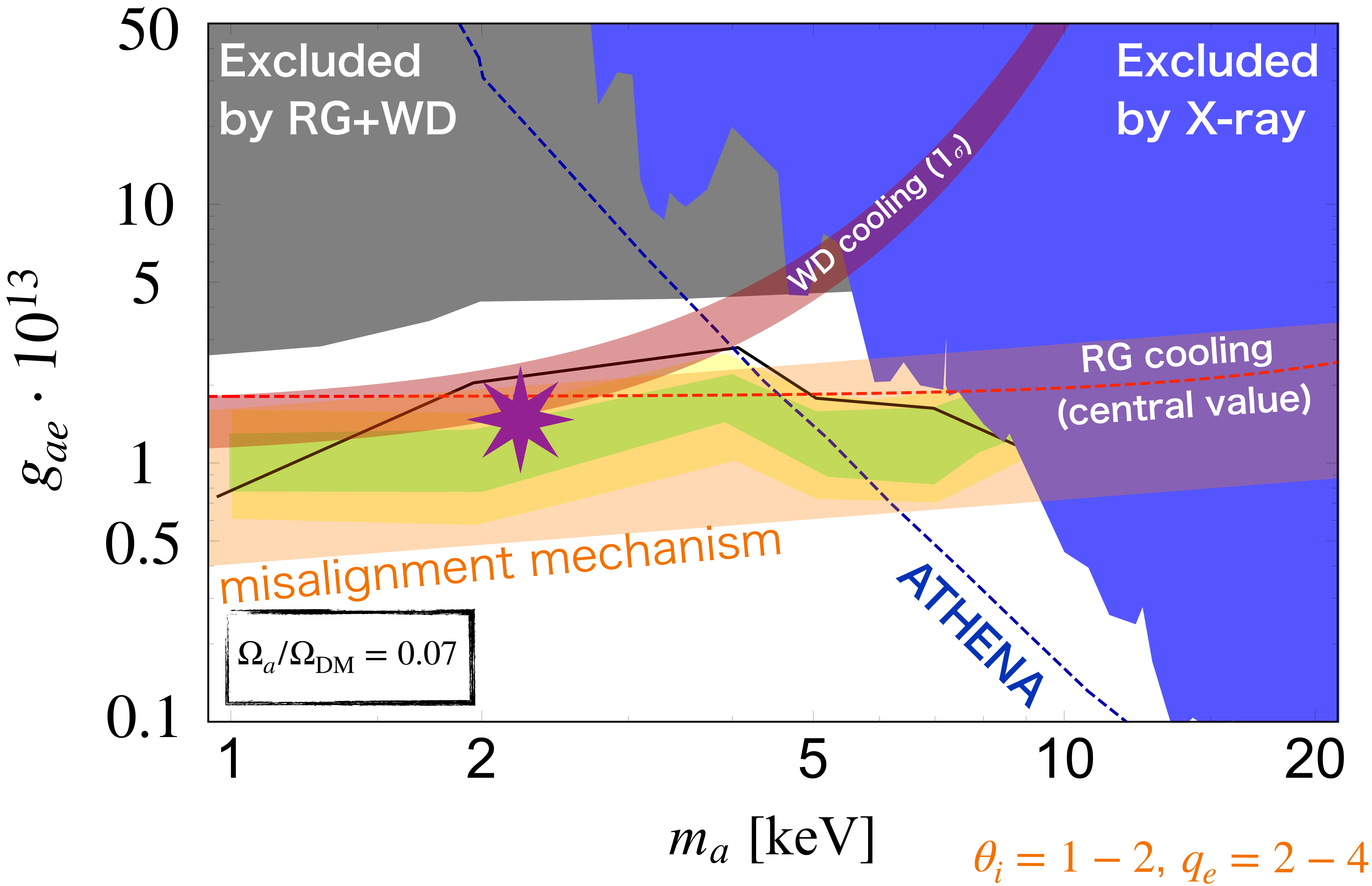
Ω_a−dependence: $\Omega_a/\Omega_{DM} = 0.5$



$\theta_i = 1 - 2,\ q_e = 2 - 4.$

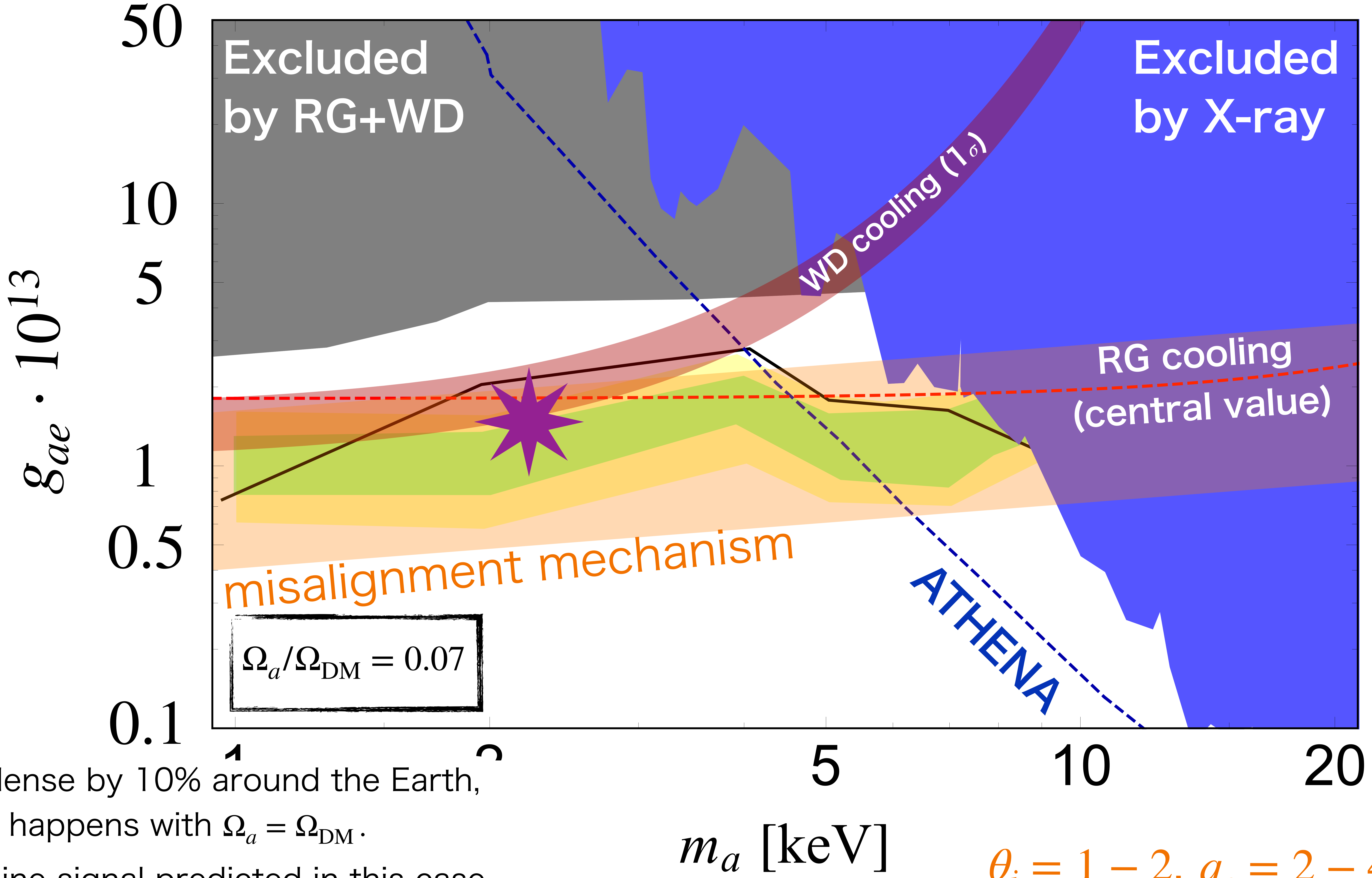
Ω_a–dependence:

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



$\theta_i = 1 - 2,\ q_e = 2 - 4.$

Favored region, cooling hints, and misalignment prediction coincide if $\Omega_a = O(1-10)\,\%\,\Omega_{\rm DM}$



If DM is under-dense by 10% around the Earth, the coincidence happens with $\Omega_a = \Omega_{\rm DM}$.

Stronger X-ray line signal predicted in this case.

$\theta_i = 1-2,\ q_e = 2-4.$

Conclusions

Takahashi, Yamada, and WY, 2006.10035

Xenon1T anomaly indicates

Anomaly-free ALP DM with

$$f_a \simeq \mathcal{O}(10^{10})\sqrt{\frac{\Omega_a}{\Omega_{\rm DM}}}\ \mathrm{GeV}, \quad m_a \simeq O(1)\,\mathrm{keV}\,.$$

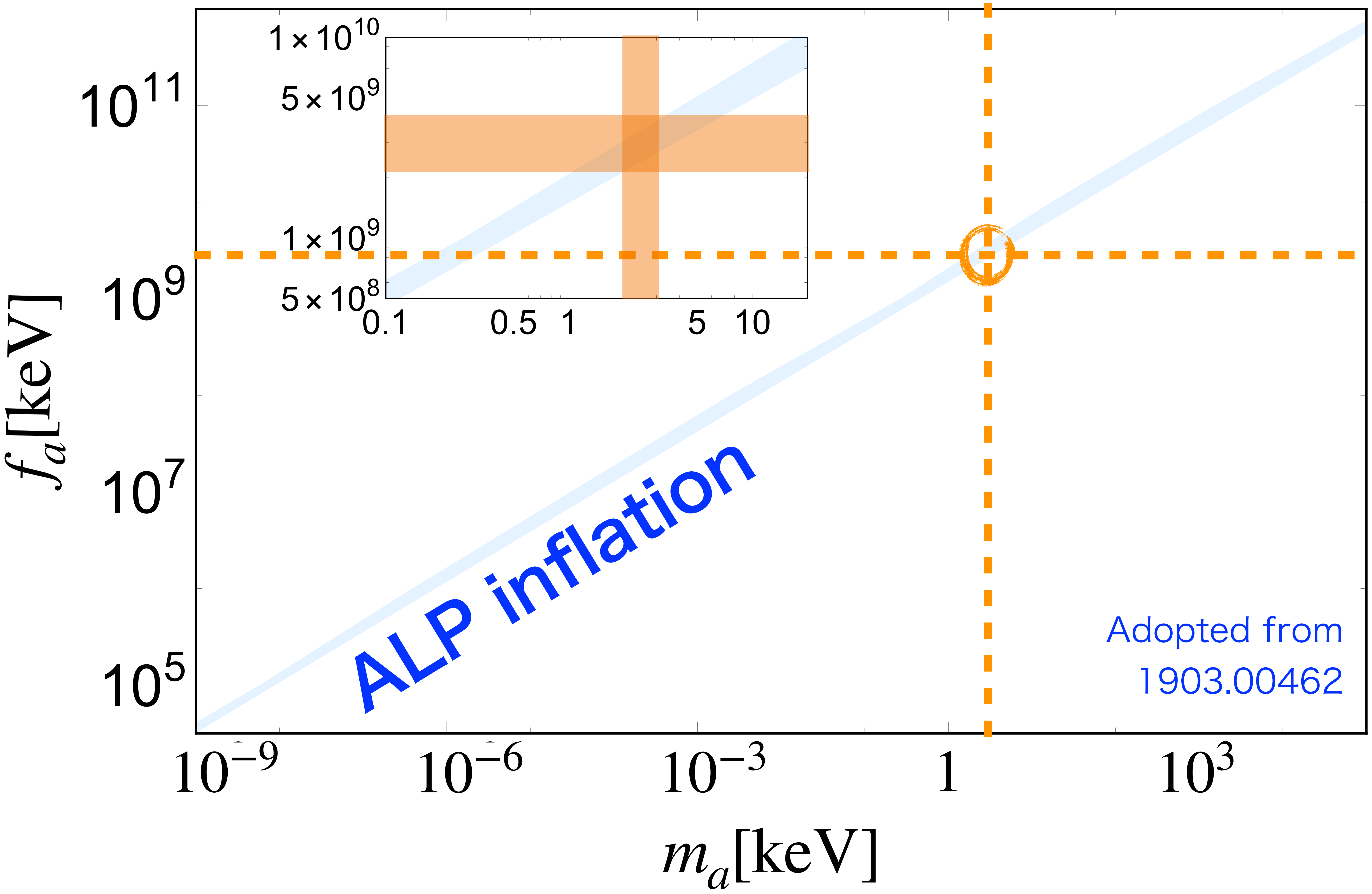
- Robust prediction on X-ray line signal.
- Naturally explains DM abundance.
- Close to the stellar cooling anomaly, better agreement if ALP is subdominant.

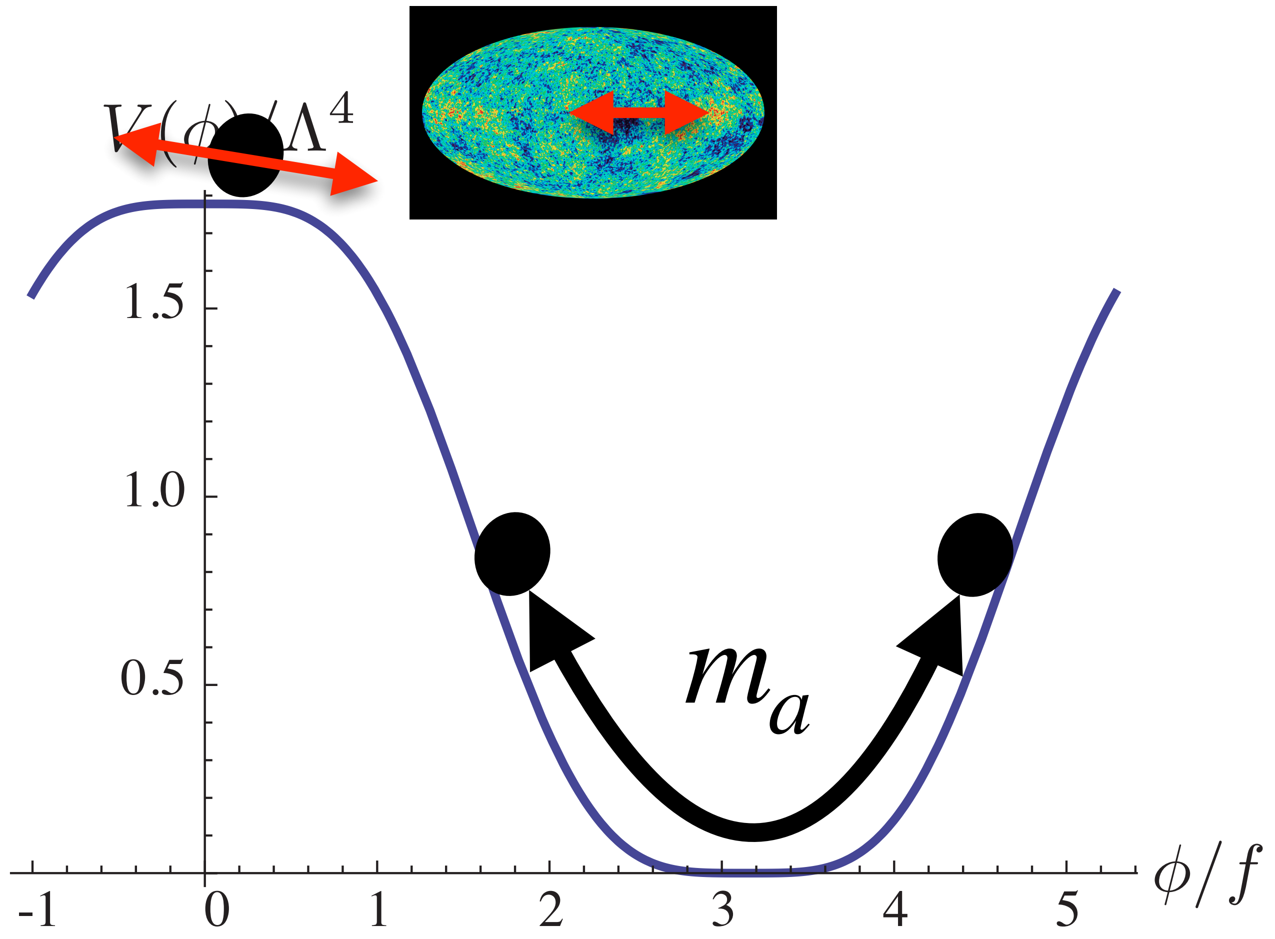
(Thermal production is also natural to get subdominant DM.)

Anomaly-free ALP DM=Inflaton?

Daido, Takahashi, and WY 1702.03284, 1710.11107
Takahashi and WY 1903.00462

The mass and coupling hinted by XENON1T and stellar cooling anomaly are exactly on the line predicted by the ALP inflation model !





$$m_a \simeq 2 - 3\,\mathrm{keV}$$

$$\to f_a \simeq (2-4)\times 10^9\,\mathrm{GeV}$$

Takahashi, Yamada, and WY, to appear

Back-up slides

“Pion decay problem”

Sutherland, 67; Veltman 67; Bell, Jackiw 69; Adler 69; Fujikawa 79
See also Weinberg, The Quantum Theory of Fields, Volume2.

In the mid-1960s, the theoretical estimation of $\pi \to \gamma\gamma$ decay rate was much smaller than the observed value. **If shift (chiral) symmetry is only broken by** $O(m_\pi^2)$ $(\propto m_u + m_d)$,

$$\mathscr{L}_{\rm eff} \sim \frac{m_\pi^2}{m_N^2}\frac{\pi}{f_\pi}F\tilde{F} \quad \longrightarrow \quad \Gamma_{\pi\to 2\gamma} \sim \frac{\alpha^2 m_\pi^7}{4\pi^3 m_N^4 f_\pi^2} \sim 10^{13}\, s^{-1}$$

The puzzle was solved by the discovery of a chiral anomaly by Bell and Jackiw:
the shift symmetry is not only broken by m_π but also by **anomaly**

$$\mathscr{L}_{\rm eff} \sim \frac{\pi}{f_\pi}F\tilde{F} \quad \longrightarrow \quad \Gamma_{\pi\to 2\gamma} \sim \frac{\alpha^2 m_\pi^3}{4\pi^3 f_\pi^2} \sim 10^{16}\, s^{-1}$$

cf. observed $\Gamma_{\pi\to\gamma\gamma} \sim 10^{16} s^{-1}$

General anomaly-free ALP model:

The shift symmetry of a is only broken by its potential from hidden sector.

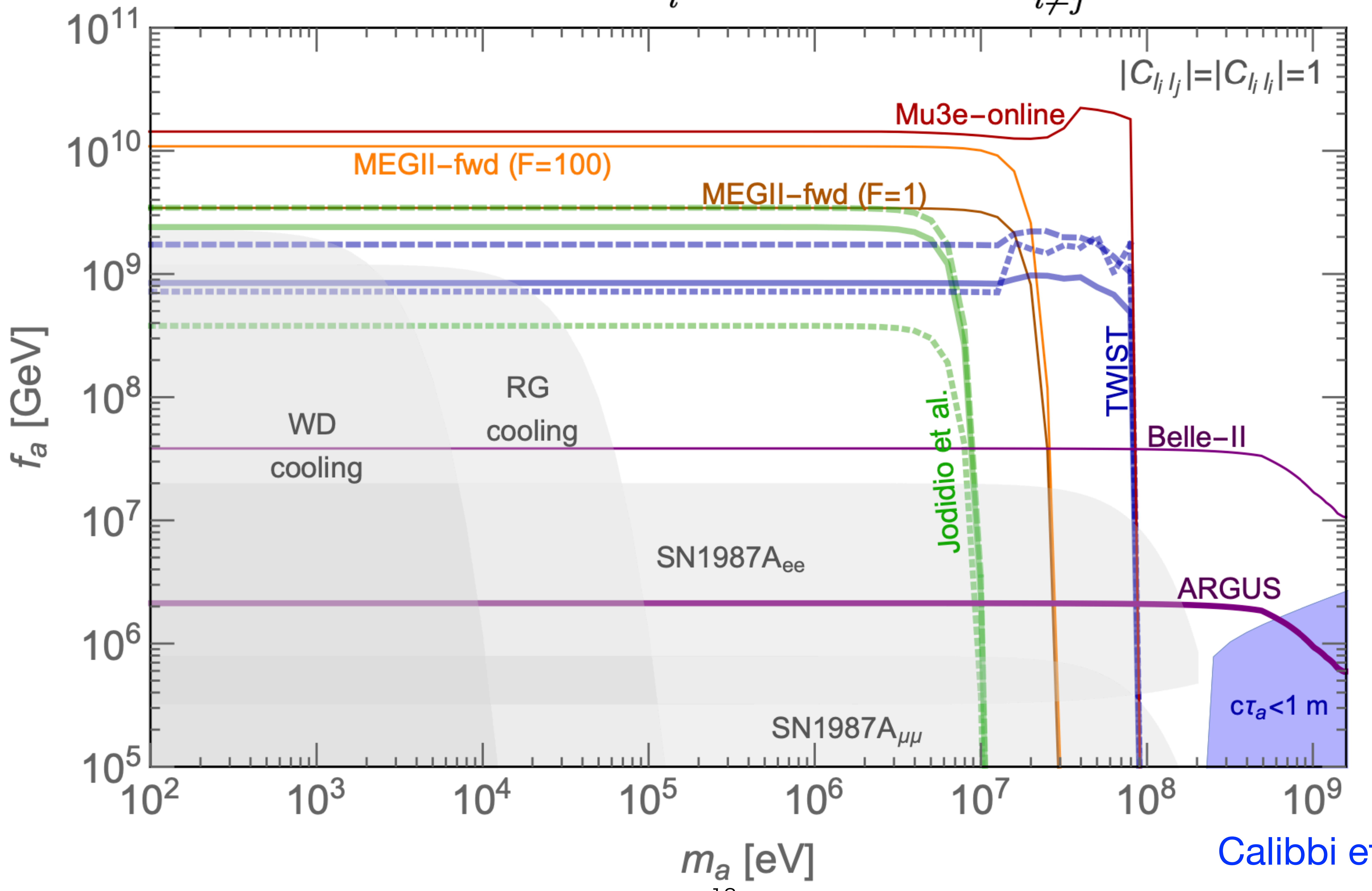
$$\mathcal{L}_{\rm eff}^{\rm int} = C_{ij}\frac{\partial_\mu a}{2f_a}\bar{\Psi}^i_{\rm SM}\hat{P}_L\gamma^\mu\Psi^j_{\rm SM} + \mathcal{O}(1/f_a^2), \qquad V_{\rm eff}^{\rm hidden}(\phi) \supset \frac{m_a^2}{2}a^2$$

Since this is a general effective theory, any UV completion can be reduced to this form with certain field-redefinition.

(Strictly speaking: the anomalous couplings to W,Z boson are OK to avoid the X-ray constraints. Color anomaly should be avoided, since there would be π-a mixing leading to photon coupling.)

In the effective theory, there is generally flavor-violation.
This may be confirmed from $\mu \to ea$.

$$\mathcal{L}_{\rm eff} = \sum_i \frac{\partial_\mu a}{2f_a}\bar\ell_i C^A_{\ell_i\ell_i}\gamma_5\ell_i + \sum_{i\neq j}\frac{\partial_\mu a}{2f_a}\bar\ell_i\gamma^\mu(C^V_{\ell_i\ell_j} + C^A_{\ell_i\ell_j}\gamma_5)\ell_j\,,$$



Calibbi et al, 2006.04795

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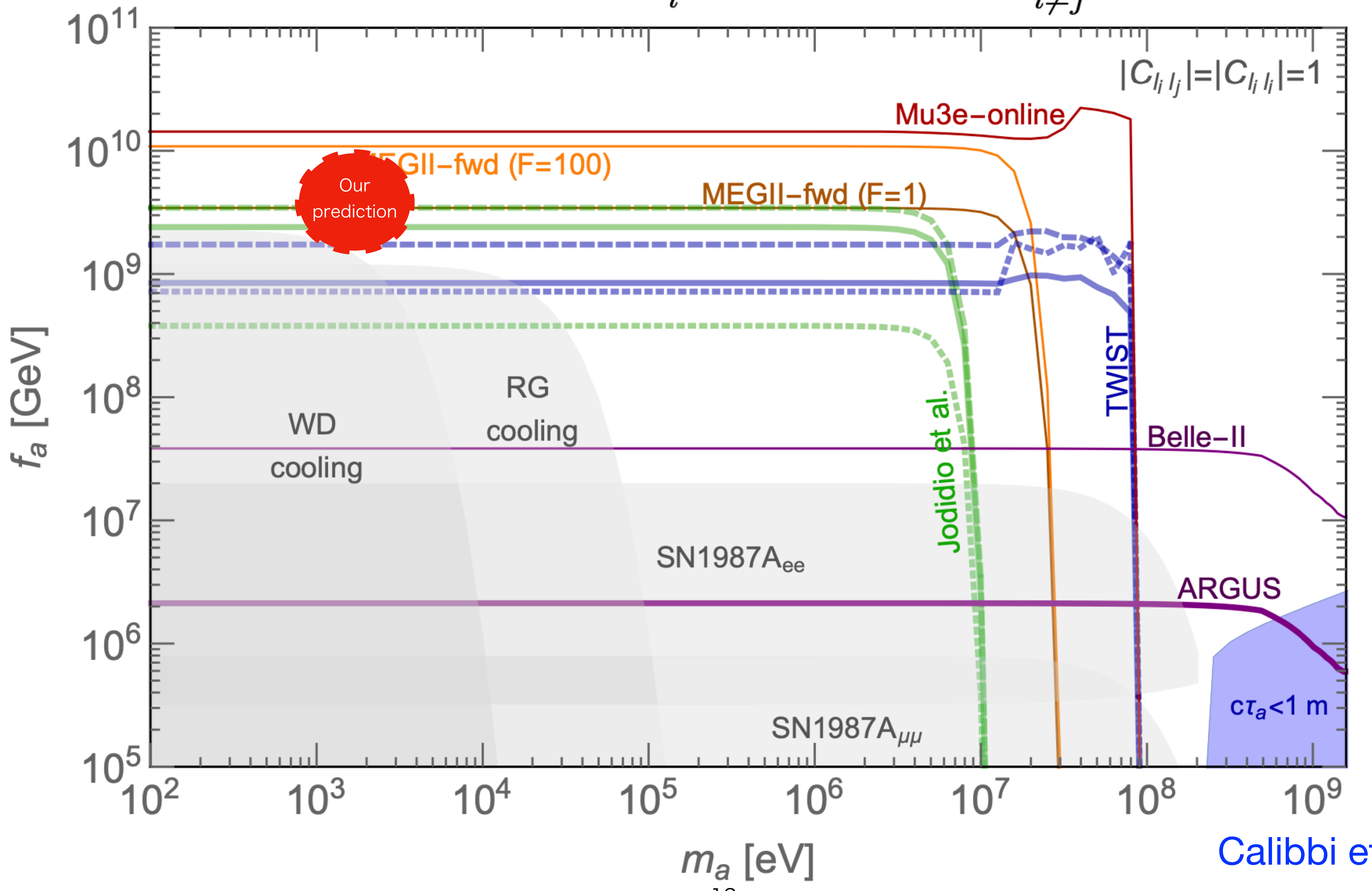


Calibbi et al, 2006.04795

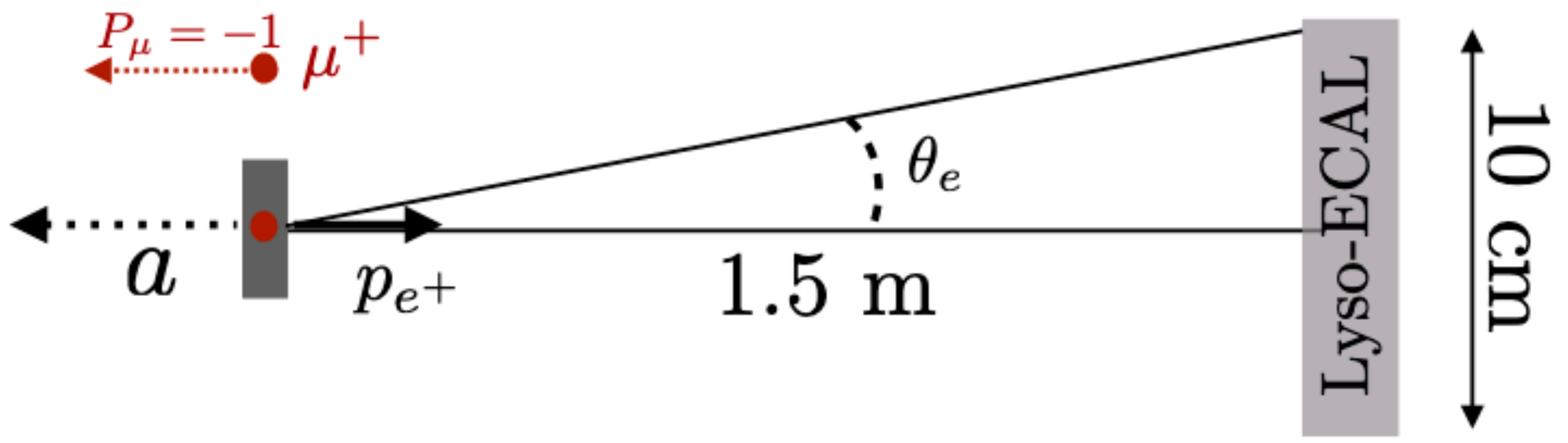
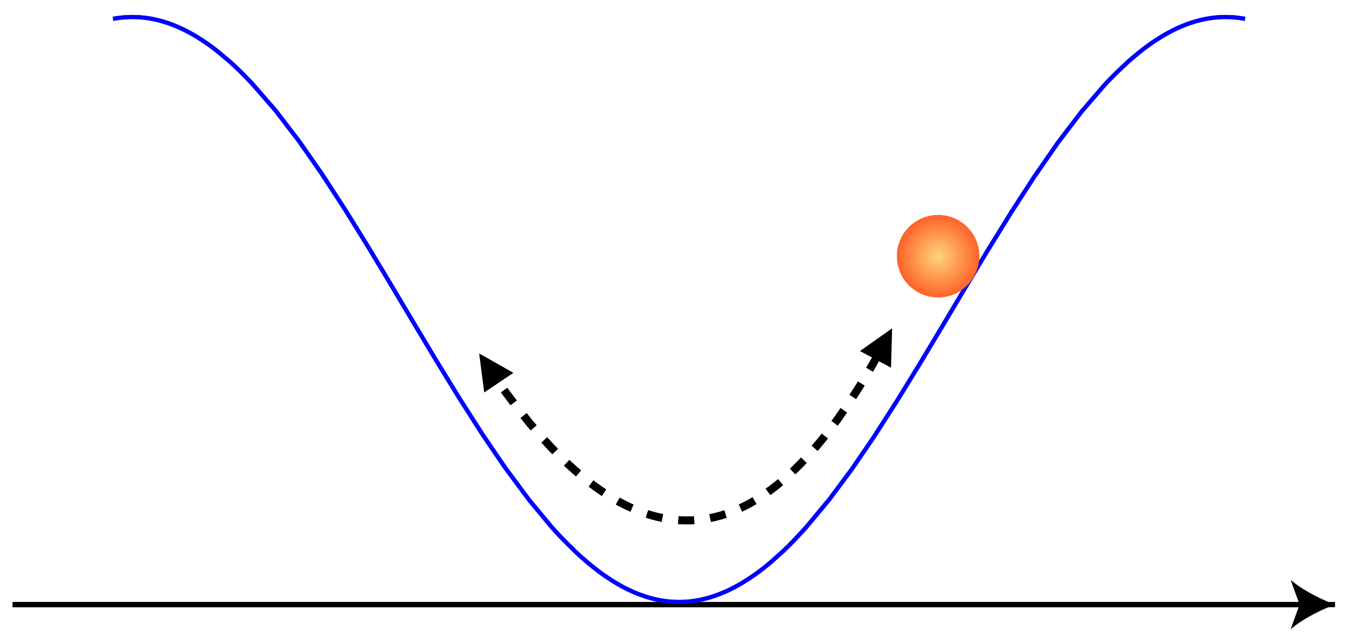


Figure 5. The proposed MEGII-fwd set-up. A Lyso-ECAL detector of 10 cm in diameter is placed along the muon beam line 1.5 m downstream from the stopping point. The muon polarization P_μ is in the opposite direction than the detected positron.

Calibbi et al, 2006.04795

ALP production

- Misalignment mechanism



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

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

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

ALP is cold and can explain all DM.

We need $T_{\rm RH} \gtrsim 10^6 {\rm GeV}$ to get the right abundance for $q_e = O(1)$.

For $T_{\rm RH} \lesssim 10^6 {\rm GeV}$ we need to invoke the clockwork to get $q_e \gg 1$.

From Fumi' slide

ALP production

- Thermal production

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

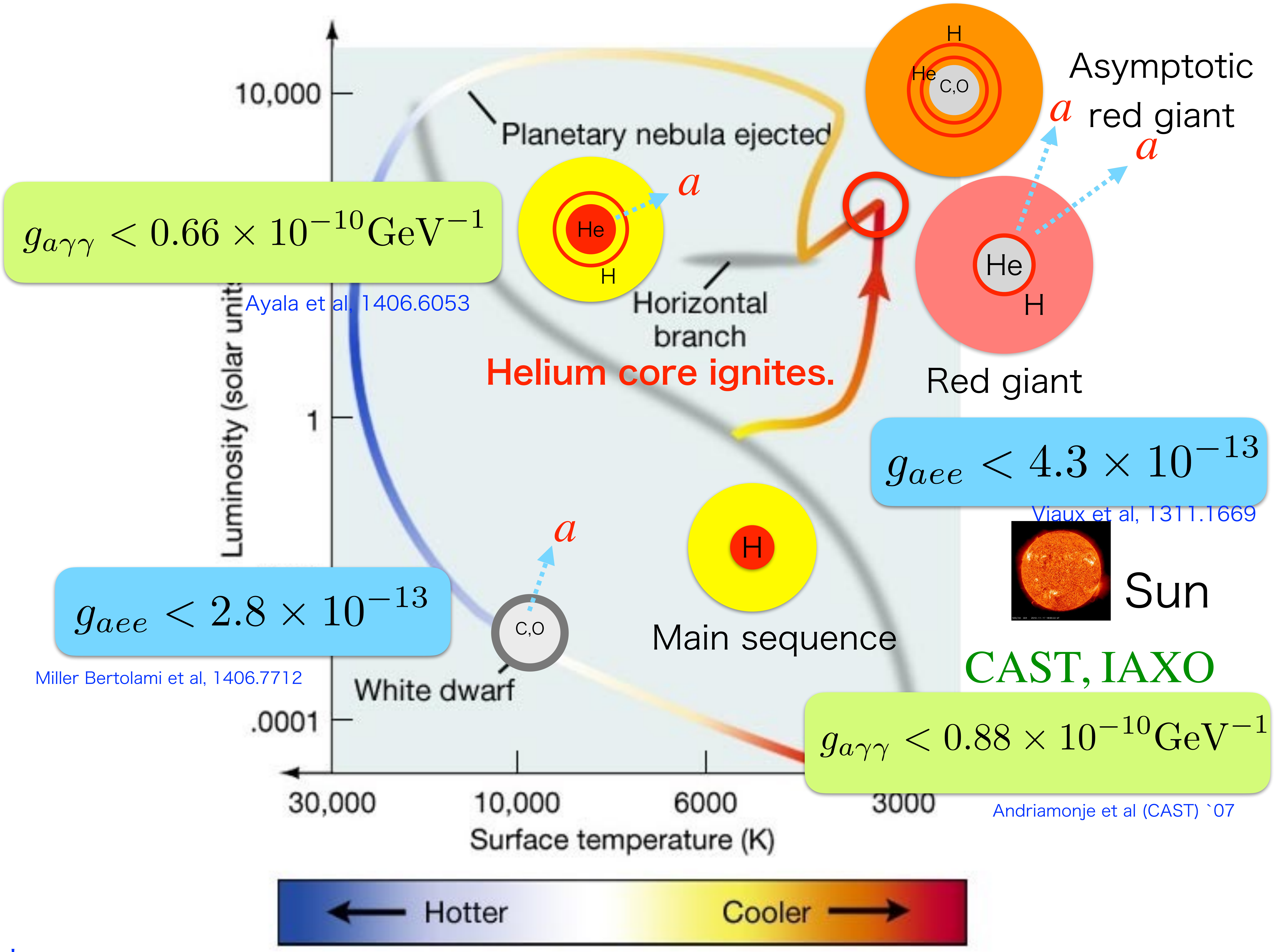
ALP is warm DM and can explain only about 10% of DM.

The reheating should be low if the ALP is coupled to heavy fermions.

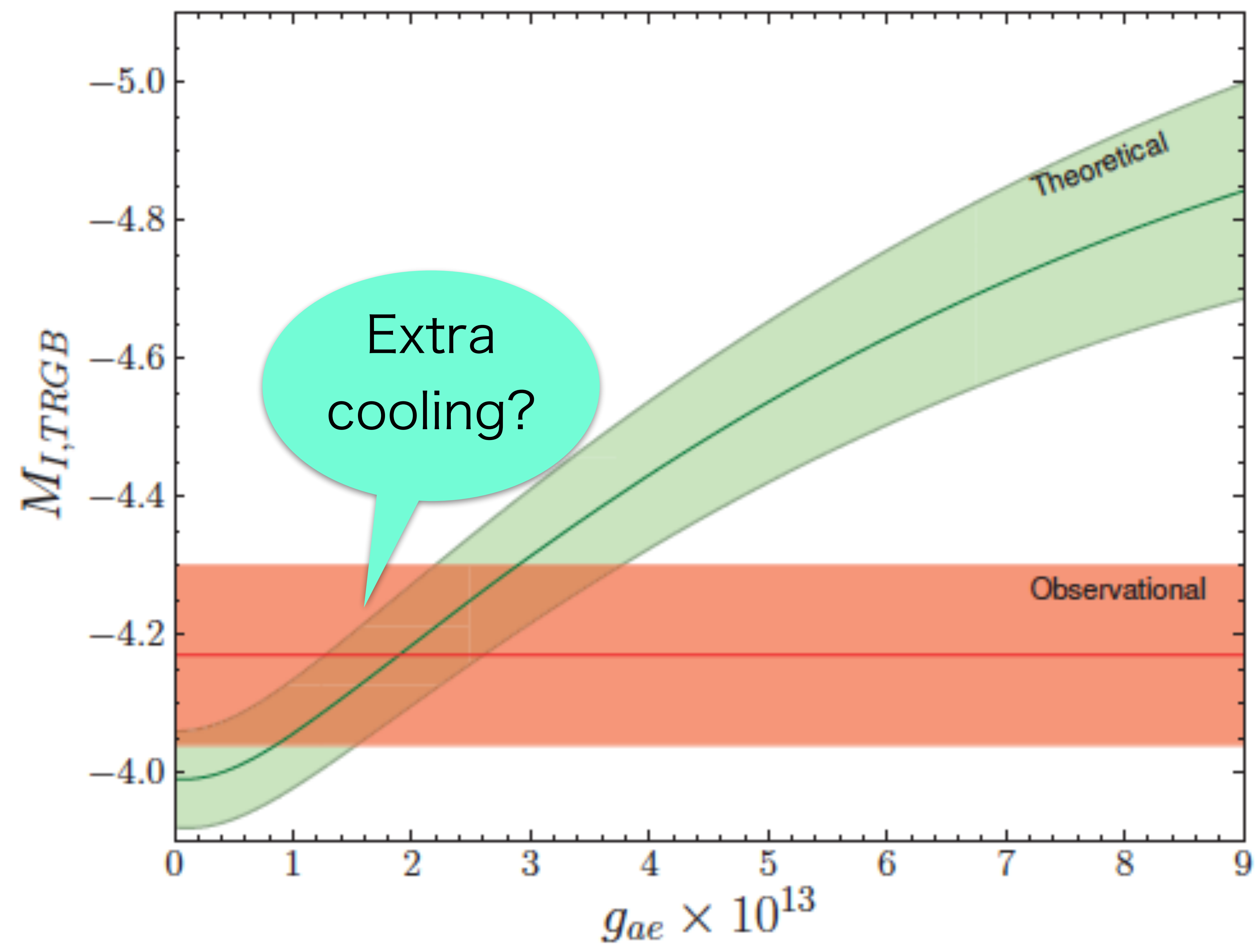
If the ALP is coupled to only e and mu, it can be as high as 10^8 GeV.

From Fumi' slide

(τ, b contribution in the broken phase is also of this order.)

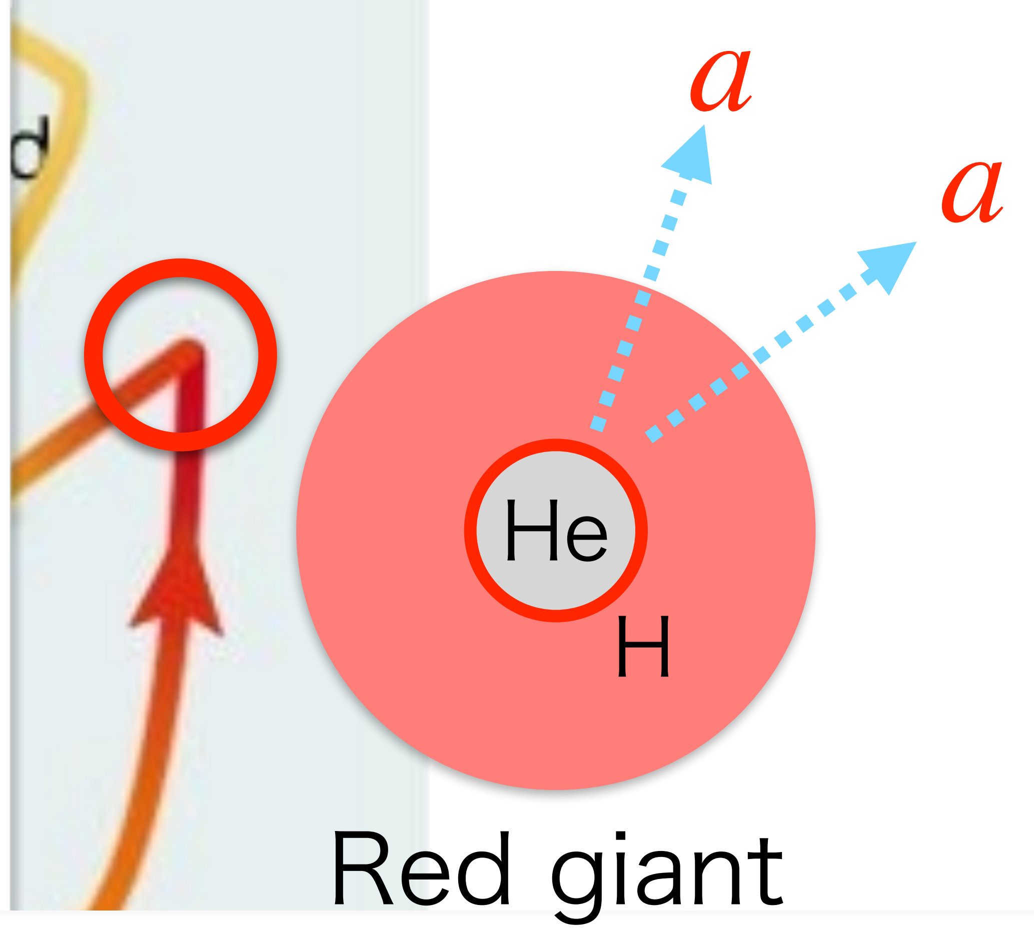


From Fumi’ slide



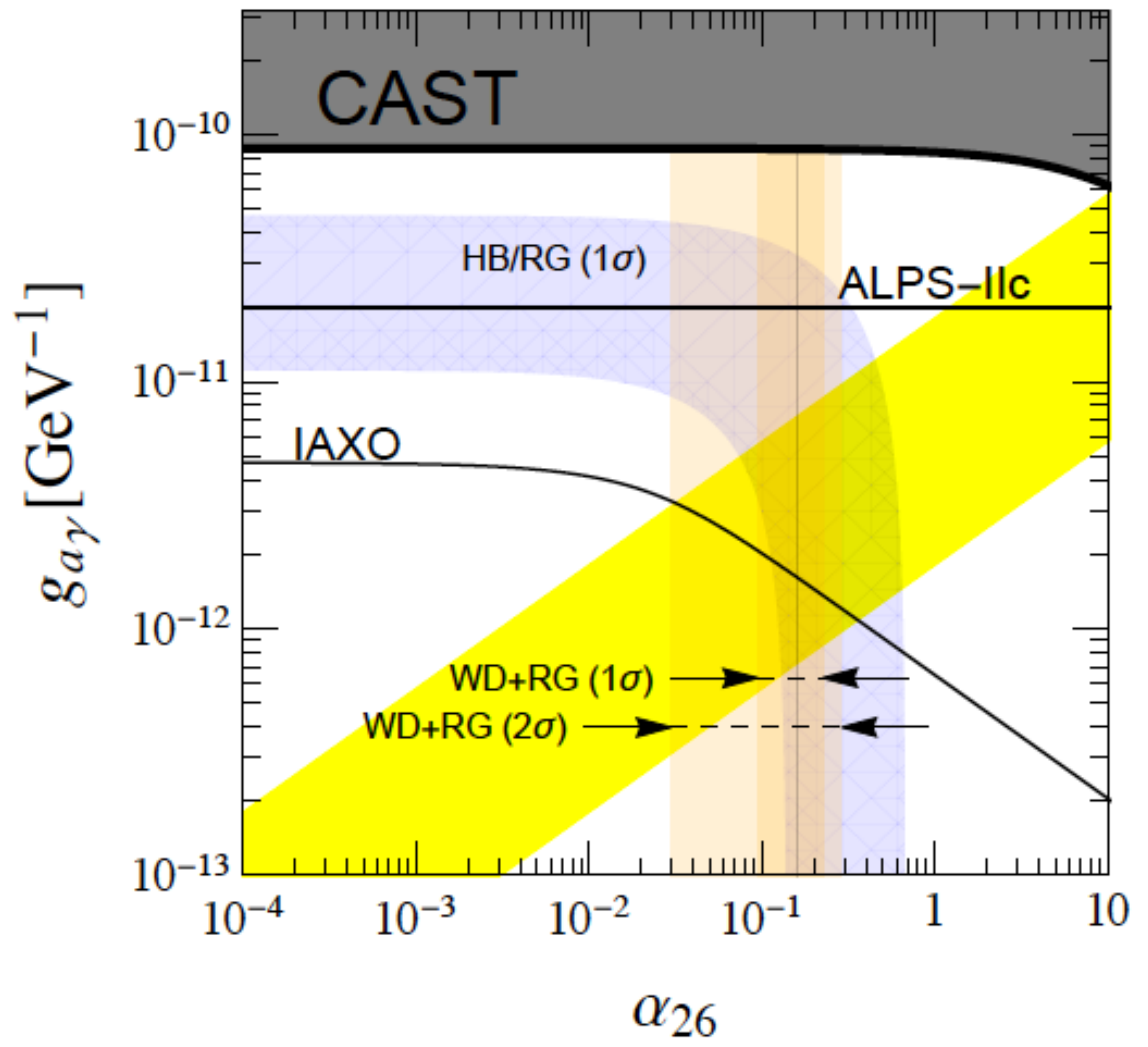
Viaux et al, 1311.1669

FIG. 2. Absolute *I*-band brightness of TRGB in cluster M5. *Red band:* Observations with 1σ error, dominated by distance. *Green band:* Theoretical prediction, depending on the axion-electron coupling, with 1σ systematic error, dominated by the bolometric correction.



From Fumi' slide

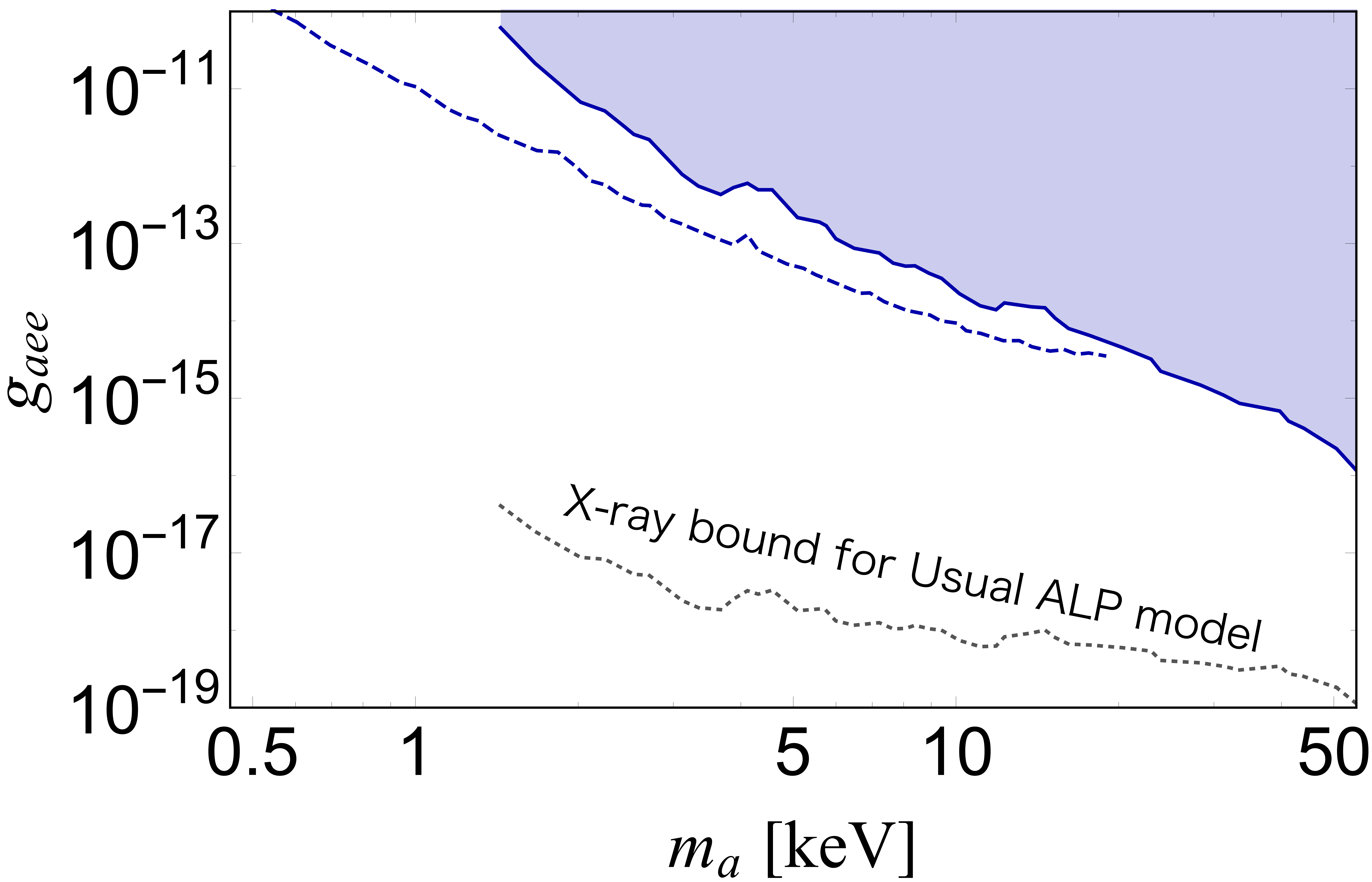
Hints for extra cooling?



Giannotti et al, 1512.08108

Those hints for extra cooling can be explained by axion (ALP) with couplings within the reach of future experiments.

From Fumi' slide



10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
g_{aee}
X-ray bound for Usual ALP model
0.5
1
5
10
50
m_a [keV]