Dark Photon and Stellar Cooling

Po-Yan Tseng (Yonsei U.)

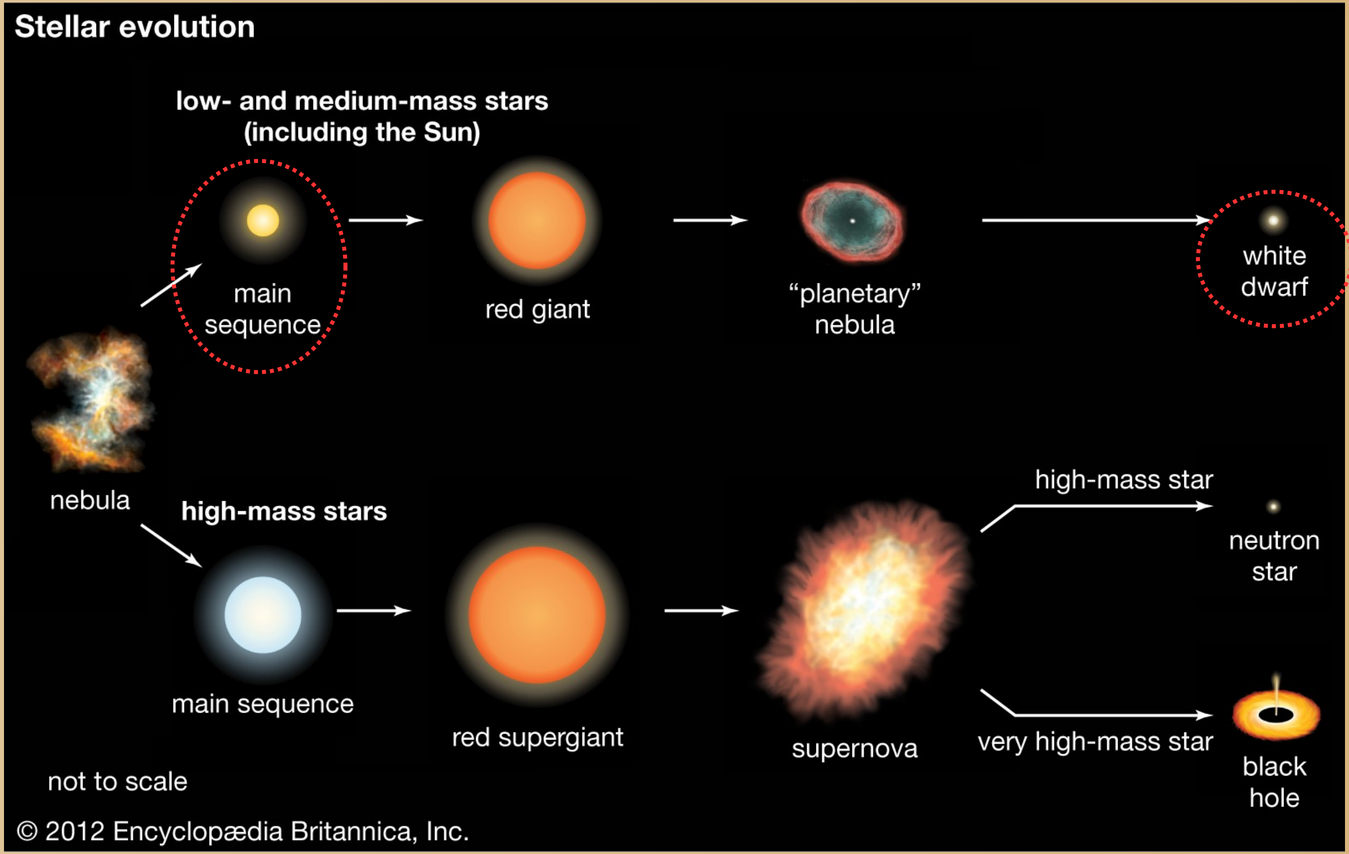
References:
Wai-Yee Keung, Danny Marfatia: arXiv-2009.04444

The 17th Saga-Yonsei partnership program of HEP,
7-8, 21-22, Jan. 2021

Life of Stellar

- Stellar evolution:

Stellar evolution: Encycloadia Britannica, Inc.



Outline

- Stellar cooling & White Dwarf luminosity function.
- Dark Photon production from stellar
- XENON1T
- Inelastic DM
- Summary

Stellar Cooling

- Neutrino emission dominates the stellar cooling, if $T \gtrsim 5 \times 10^7$ K ~ keV.

$$\boxed{\varepsilon_\nu = 1.40 \times 10^{15}\ \lambda^9 \gamma^6 e^{-\gamma}(f_T + f_L)\ \mathrm{erg\ g^{-1}\ s^{-1}}}$$

$$\lambda = 1.69 \times 10^{-3}\ T_7, \qquad \gamma = \frac{28}{T_7},$$

$$f_T = 2.4 + 0.6\gamma^{1/2} + 0.51\gamma + 1.25\gamma^{3/2}, \qquad f_L = \frac{8.6\gamma^2 + 1.35\gamma^{7/2}}{225 - 17\gamma + \gamma^2}$$

- Photon emission dominates, when $T \lesssim 10^7$ K.

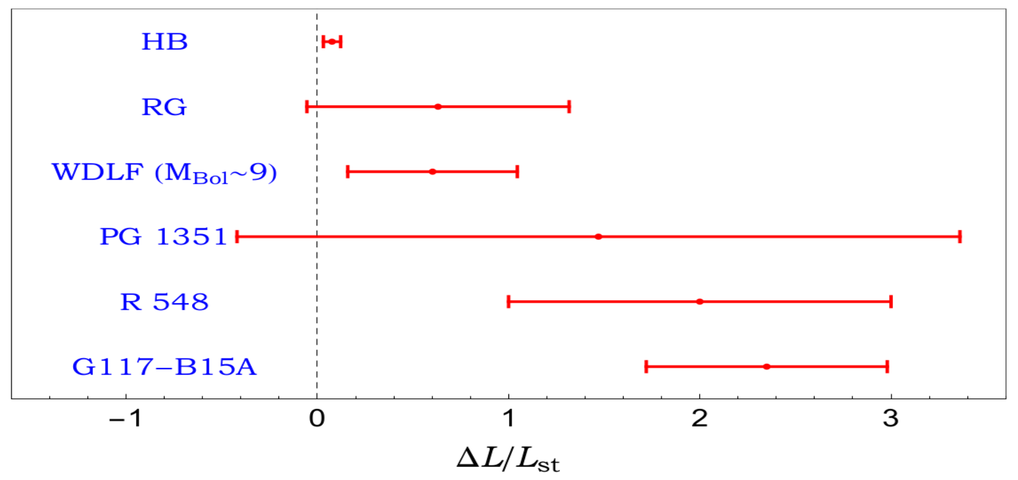
$$\boxed{\varepsilon_\gamma = 3.29 \times 10^{-3}\ T_7^{7/2}\ \mathrm{erg\ g^{-1}\ s^{-1}}}$$

L.Ubaldi: 1310.5073

Stellar Cooling

- Neutrino emission dominates the stellar cooling, if $T \gtrsim 5 \times 10^7$ K ~ keV.
- Photon emission dominates, when $T \lesssim 10^7$ K.
- Deviation from SM expectation where found in diverse stellar systems:

M.Giannotti, I.Irastorza, J.Redondo, A.Ringwald: 1512.08108



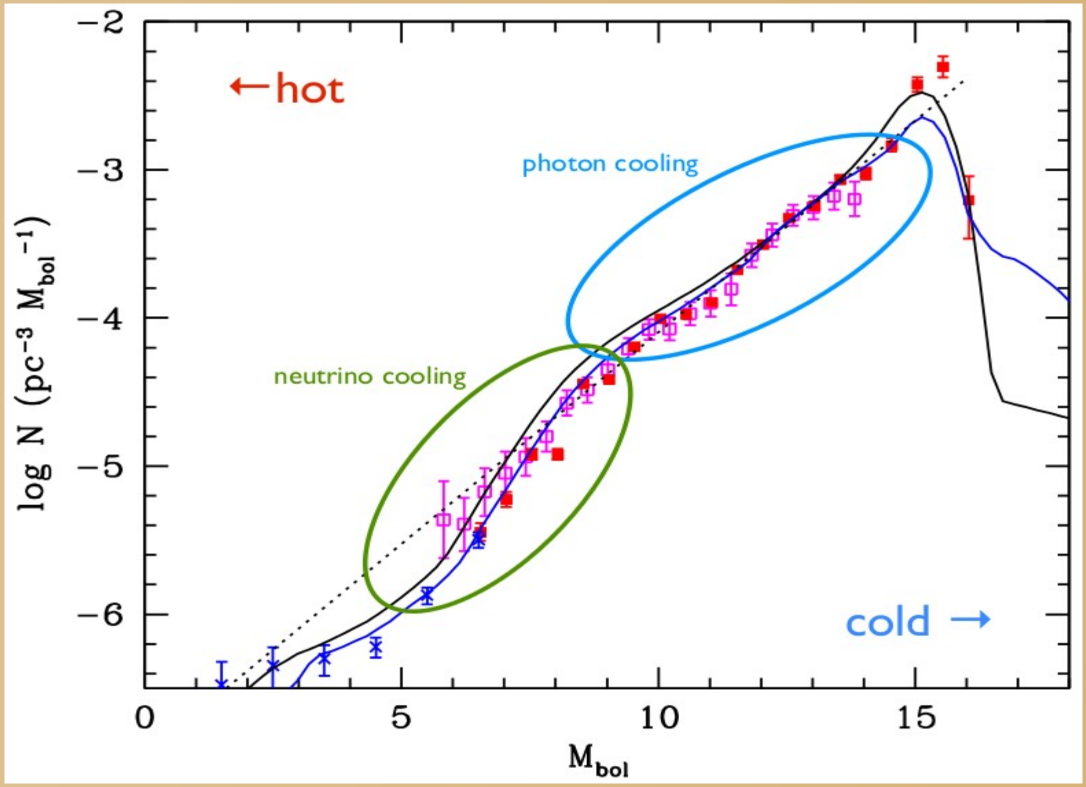
WDLF

- **White Dwarf Luminosity Function(WDLF):** number density distribution of WD per luminosity or brightness(bolometric magnitude $M_{\rm bol}$) bin.

$$\frac{dN}{dM_{\rm bol}} = -B\frac{dU}{dM_{\rm bol}}\frac{1}{L_\gamma + L_\nu + L_x}$$

$$M_{\rm bol} = -2.5\log_{10}(L/L_\odot) + 4.74$$

L.Ubaldi: 1310.5073



Stellar Cooling

- Massive **Dark photon(DP)** with mass lighter than few keV.
- **DP** has transverse and longitudinal modes, and photon can oscillate into DP w/o an external magnetic or electric field. Turn out more efficient cooling.

M.Giannotti, I.Irastorza, J.Redondo, A.Ringwald: 1512.08108

- The **DP** *thermal production rate* from *thermal plasma* is related to imaginary part of *self-energy* in the medium.

$$\Gamma_{\mathrm{prod}} = -\frac{\mathrm{Im}\,\Pi}{\omega\left(e^{\omega/T}-1\right)}$$

J.Redondo, G.Raffelt: 1305.2920,
H.An, M.Pospelov, J.Pradler: 1302.3884.

Stellar Cooling

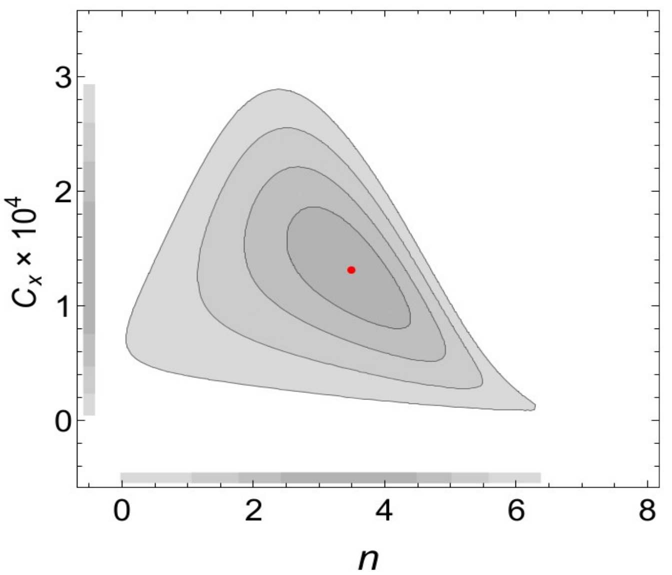
- Massive **Dark photon(DP)** with mass lighter than few keV.

- For colder WD $7.75 \lesssim M_{\rm bol} \lesssim 14.25$, where neutrino cooling is negligible Used the *model-independent* exotic cooling rate $L_x = C_x L_\odot T_7^n$. They found 4-sigma significance of additional cooling.

M.Giannotti, I.Irastorza, J.Redondo, A.Ringwald: 1512.08108

Stellar Cooling

- Massive **Dark photon(DP)** with mass lighter than few keV.



$$\boxed{L_X \simeq 3.13 \times 10^{32}\ \mathrm{GeV/s}}$$

$$L_\odot = 2.39 \times 10^{36}\ \mathrm{GeV/s}$$

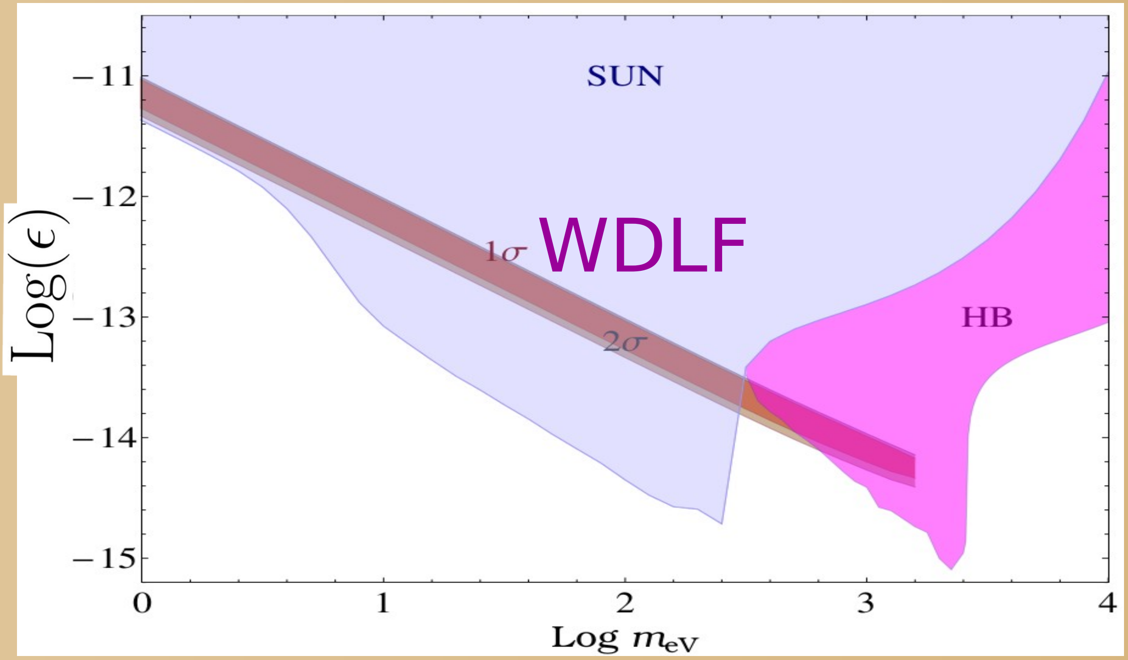
Figure 2. Contours of the 1, 2, 3 and 4 σ C.L. in the n and C_x parameter space, defined in Eq. (3.2). The red dot refers to the best fit value: $n_{\rm best} = 3.49$, $C_{x,\rm best} = 1.31 \times 10^{-4}$. The analysis is based on the data in [9] for $7.75 \lesssim M_{\rm bol} \lesssim 14.25$.

M.Giannotti, I.Irastorza, J.Redondo, A.Ringwald: 1512.08108

Stellar Cooling

- Massive **Dark photon(DP)** with mass lighter than few keV.

$$\mathcal{L}_{A'} \supset (\epsilon e)(\bar{\ell}\gamma^{\mu}\ell)A'_{\mu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$



M.Giannotti, I.Irastorza, J.Redondo, A.Ringwald: 1512.08108

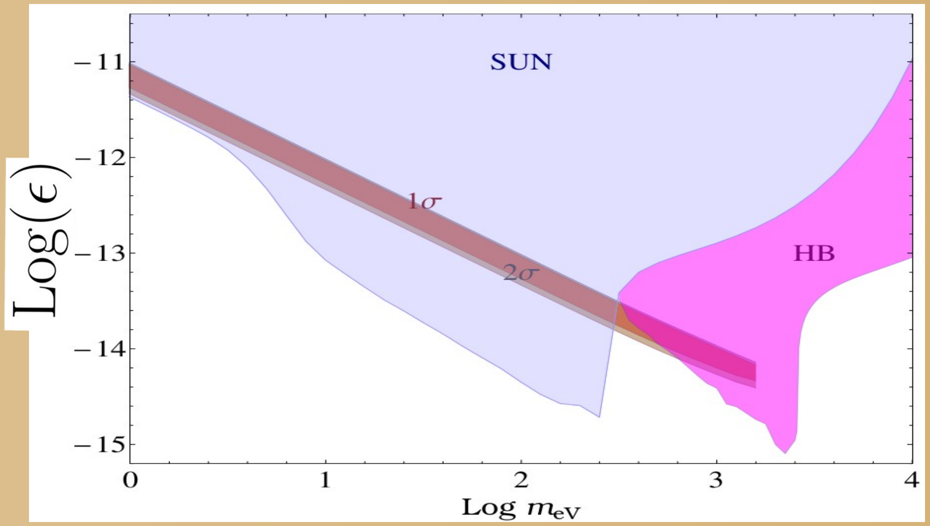
Dark Photon production from Stellar

- **DP** can be produced from **photon conversion**, **bremsstrahlung** and **Compton scattering** from **thermal plasma** inside stellar.
- The plasma frequency $\omega_p = (n_e e^2/m_e)^{\frac{1}{2}}$

$$\text{Sun: } \omega_p \simeq 0.3 \text{ keV}$$

$$\text{HB: } \omega_p \simeq 2 \text{ keV}$$

$$\text{WD: } \omega_p \simeq 30 \text{ keV}$$



Dark Photon production from Stellar

- Emission rate of **DP** longitudinal mode from stellar:

$$\left.\frac{d^2\Gamma^{\odot}_{A'}}{dV\,d\omega}\right|_L = \frac{1}{\pi^2}\frac{\omega\sqrt{\omega^2-m_{A'}^2}}{e^{\frac{\omega}{T_\odot}}-1}\frac{\epsilon^2 m_{A'}^2\omega^2\Gamma_L}{(\omega^2-\omega_p^2)^2+(\omega\Gamma_L)^2},$$

$$\Gamma_L = \frac{8\pi\alpha^3 n_e \sum_{i=H,He} Z_i^2 n_{Z_i}}{3\sqrt{2\pi T_\odot}\, m_e^{3/2}\omega^3} F\left(\frac{\omega}{T_\odot}\right) + \frac{8\pi\alpha^2 n_e}{3m_e^2}\sqrt{1-\frac{\omega_P^2}{\omega^2}},$$

$$F(\omega) = (1-e^{\omega})\int_0^\infty dx x e^{-x^2}\int_{\sqrt{x^2+\omega}-x}^{\sqrt{x^2+\omega}+x}\frac{t^3 dt}{(t^2+y^2)^2},\quad y = k_s/\sqrt{2m_e T},\ k_s \text{ a screening scale}$$

H.An, M.Pospelov, J.Pradler,1302.3884. J.Redondo,G.Raffelt:1305.2920

- Longitudinal mode dominates if $m_{A'} \ll \omega_p$.

Dark Photon production from Stellar

- Emission rate of **DP** transverse mode from stellar:

$$\left.\frac{d^2\Gamma^{\odot}_{A'}}{dV\,d\omega}\right|_T = \frac{1}{\pi^2}\frac{\omega\sqrt{\omega^2-m^2_{A'}}}{e^{\frac{\omega}{T_\odot}}-1}\frac{\epsilon^2 m^4_{A'}}{(\omega_p^2-m^2_{A'})^2+(\omega\Gamma_T)^2}\Gamma_T\,,$$

$$\Gamma_T = \frac{16\pi^2\alpha^3}{3m_e^2\omega^3}\sqrt{\frac{2\pi m_e}{3T_\odot}}\,n_e\sum_{i=H,He} Z_i^2 n_{Z_i}\bar{g}_i(1-e^{-\frac{\omega}{T_\odot}}) + \frac{8\pi\alpha^2}{3m_e^2}n_e$$

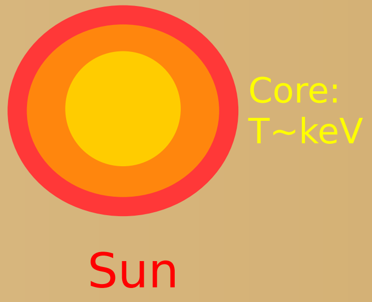
J.Redondo,JCAP 0807,008(2008): 0801.1527

- Transverse mode dominates if $m_{A'} \simeq \omega_p$ and $m_{A'} \gtrsim \omega_p$.

- The $\bar{g}_i$ is a Boltzmann averaged Gaunt factor.

Dark Photon production from Stellar

- **KeV DP** flux produced from thermal plasma of *core* our **Sun** could be one interpretation.
- We did **NOT** assume **DP** is DM relic.
- The **DP** flux from the Sun,
- For $T_\odot = 1.15\ \mathrm{keV}$ and $R_{\mathrm{core}}/R_\odot \simeq 0.18$:



$$\boxed{\frac{d\Phi^\odot_{A'}}{d\omega} = \frac{1}{4\pi \mathrm{D}^2_{\mathrm{SE}}} \int dV \frac{d^2\Gamma^\odot_{A'}}{dV\, d\omega}}$$

$$\boxed{\frac{dR}{d\omega} \simeq N_T \sigma_{A'} \frac{d\Phi^\odot_{A'}}{d\omega}}$$

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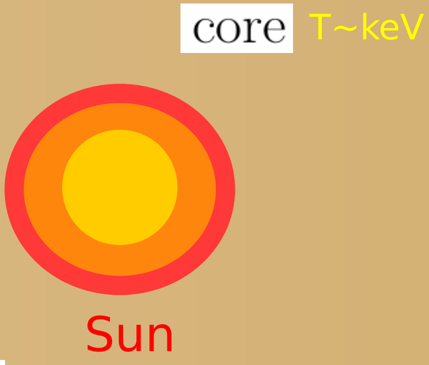

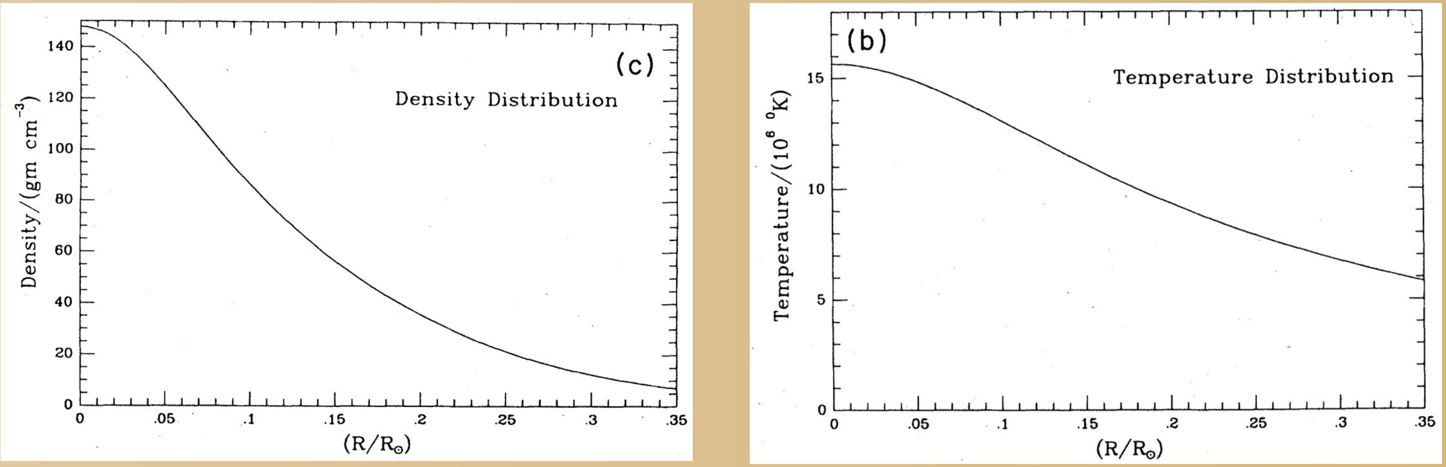

John Bahcall, Roger Ulrich, Rev.Mod.Phy 60.297

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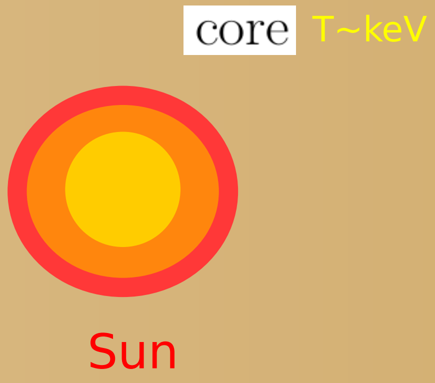

$$\boxed{\frac{d\Phi^\odot_{A'}}{d\omega} = \frac{1}{4\pi \mathrm{D}^2_\mathrm{SE}} \int dV \frac{d^2\Gamma^\odot_{A'}}{dV\, d\omega}}$$

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Events at XENON1T

- **KeV DP** flux produced from thermal plasma of *core* our **Sun** could be one interpretation.

- We did **NOT** assume **DP** is DM relic.

- Then **DP** contributes to XENON1T event through absorption by bounded electron: $A'e \to e$

$$\sigma_{A'} \begin{cases} \simeq \left(\frac{m_{A'}}{\omega}\right)^2 \epsilon^2 \sigma_\gamma \left(\frac{c}{v_{A'}}\right) & \text{for longitudinal } A'\,, \\ = \epsilon^2 \sigma_\gamma \left(\frac{c}{v_{A'}}\right) & \text{for transverse } A' \text{ [25]}\,, \end{cases}$$

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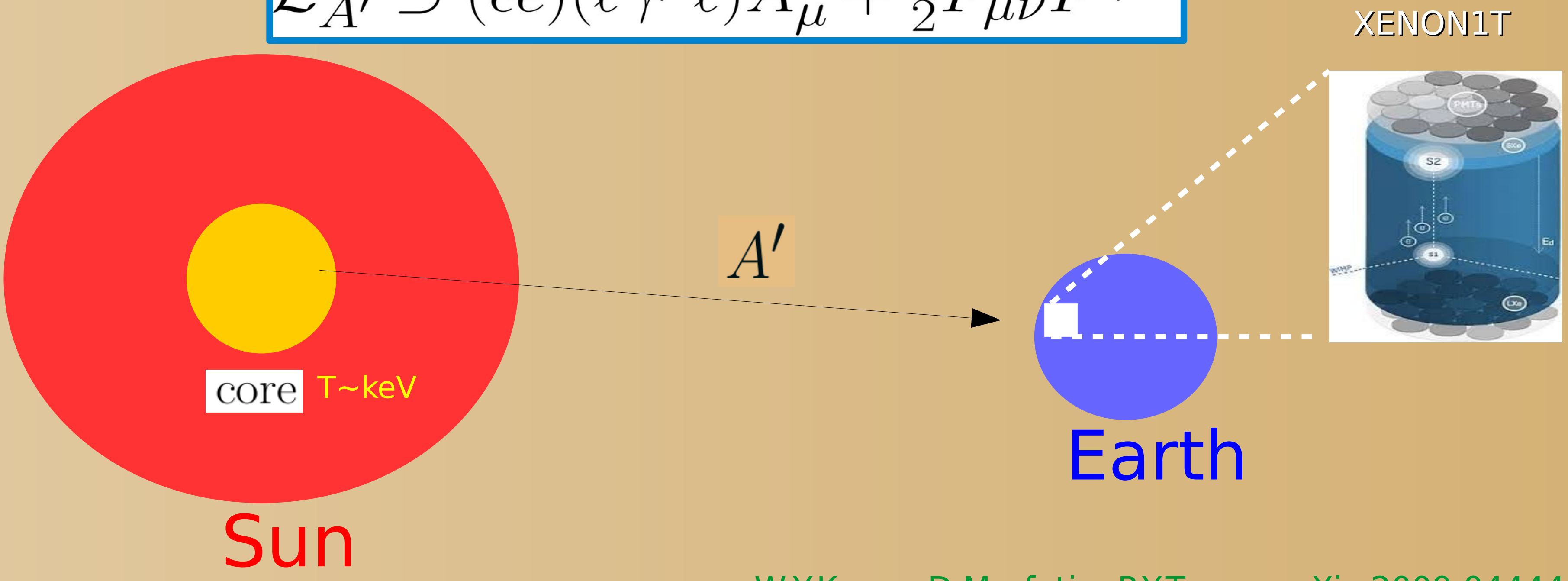
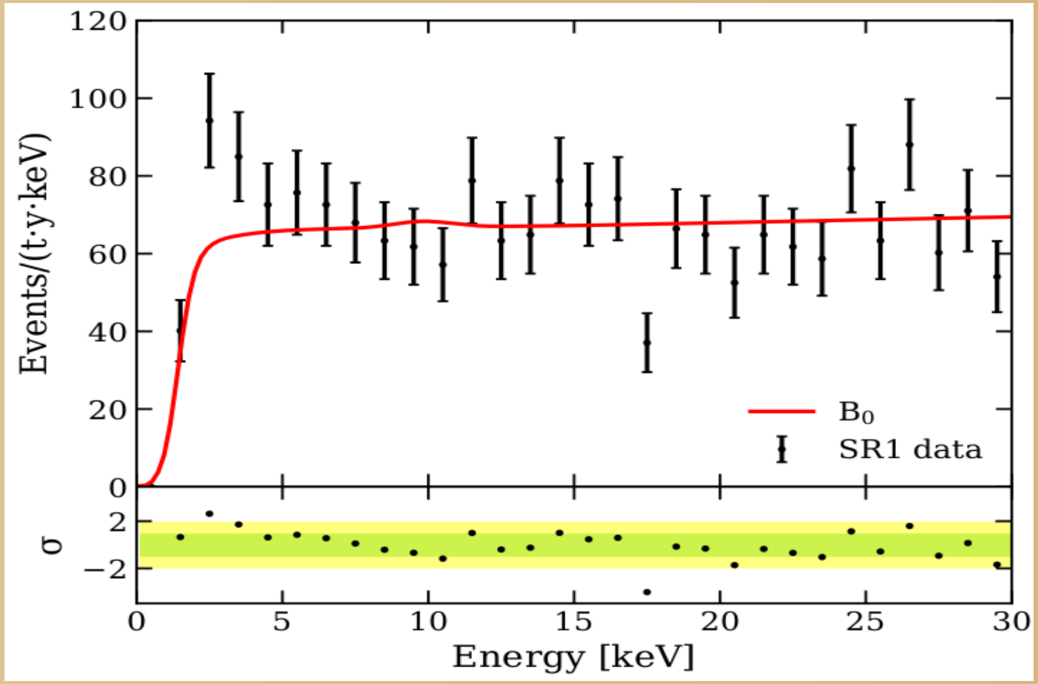
$$\mathcal{L}_{A'} \supset (\epsilon e)(\bar{\ell}\gamma^{\mu}\ell)A'_{\mu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$



W.Y.Keung,D.Marfatia, P.Y.Tseng, arXiv:2009.04444

Events at XENON1T

- XENON1T experiment reported 3-sigma excess in the electron recoil spectrum between 2-3 keV.



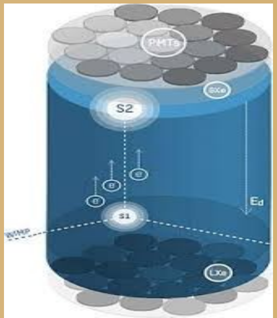
XENON Collaboration, PRD 102.072004, arXiv:2006.09721

Events at XENON1T

- **KeV DP** flux produced from thermal plasma of *core* our **Sun** could be one interpretation.
- The event rate at XENON1T detector :

$$\boxed{\frac{dR}{d\omega} \simeq N_T \sigma_{A'} \frac{d\Phi^{\odot}_{A'}}{d\omega}}$$

XENON1T



- The $N_T \simeq 4.52 \times 10^{27}$ is the number of Xe atoms per ton.

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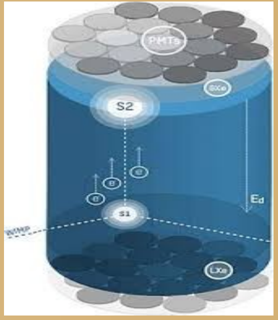

XENON1T

- The absorption cross section $A'e \to e$:

$$\sigma_{A'} \begin{cases} \simeq \left(\frac{m_{A'}}{\omega}\right)^2 \epsilon^2 \sigma_\gamma \left(\frac{c}{v_{A'}}\right) & \text{for longitudinal } A', \\ = \epsilon^2 \sigma_\gamma \left(\frac{c}{v_{A'}}\right) & \text{for transverse } A' \text{ [25]}, \end{cases}$$

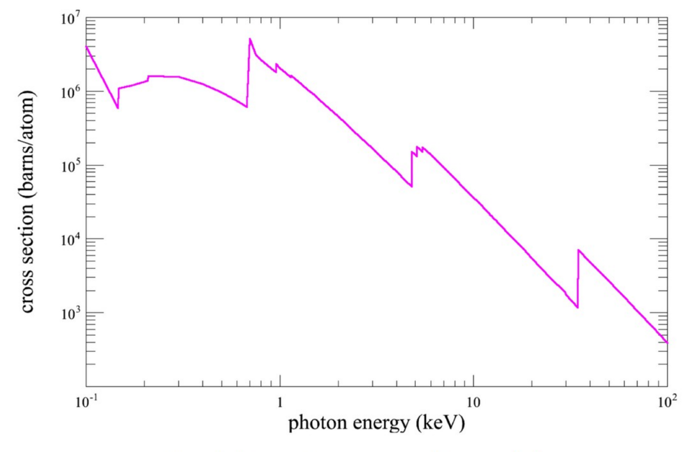

Figure 1: Photo-electric cross section on Xenon atom [27].

K. Arosala et al., 1209.3810

Events at XENON1T

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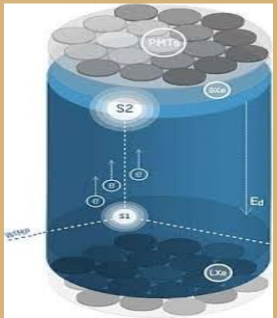
- The event rate at XENON1T detector :

$$\frac{dR}{d\omega} \simeq N_T \sigma_{A'} \frac{d\Phi^{\odot}_{A'}}{d\omega}$$

$$\Rightarrow \frac{dT}{dE} = N_T \int \left(\sigma_{A'} \frac{d\Phi^{\odot}_{A'}}{d\omega} \right) Res(E,\omega) d\omega$$

XENON1T



- The energy resolution by Gaussian smearing:

$$\frac{\sigma_{\rm det}}{E_R} = \frac{a}{\sqrt{E_R/{\rm keV}}} + b$$

$$Res(E, E_R) = \frac{1}{\sqrt{2\pi\sigma^2_{\rm det}}} e^{-\frac{(E-E_R)^2}{\sigma^2_{\rm det}}} \alpha(E)$$

$a = 0.3171 \pm 0.0065$ and $b = 0.0015 \pm 0.0002$.

J.Bramante, N.Song, 2006.14089

Events at XENON1T

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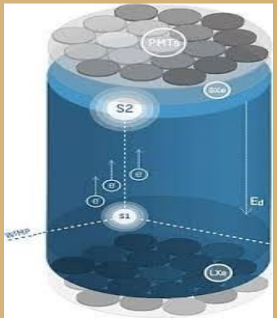
XENON1T



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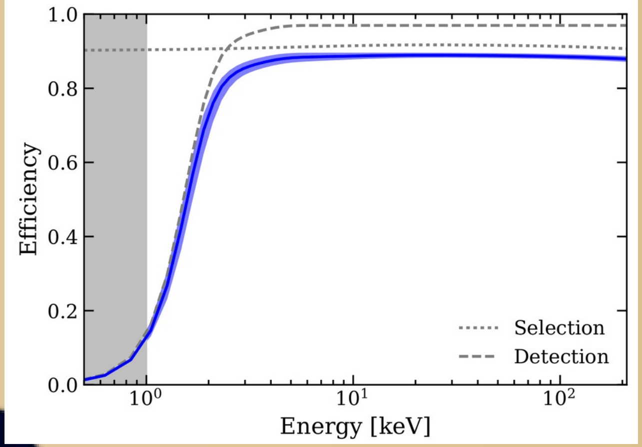
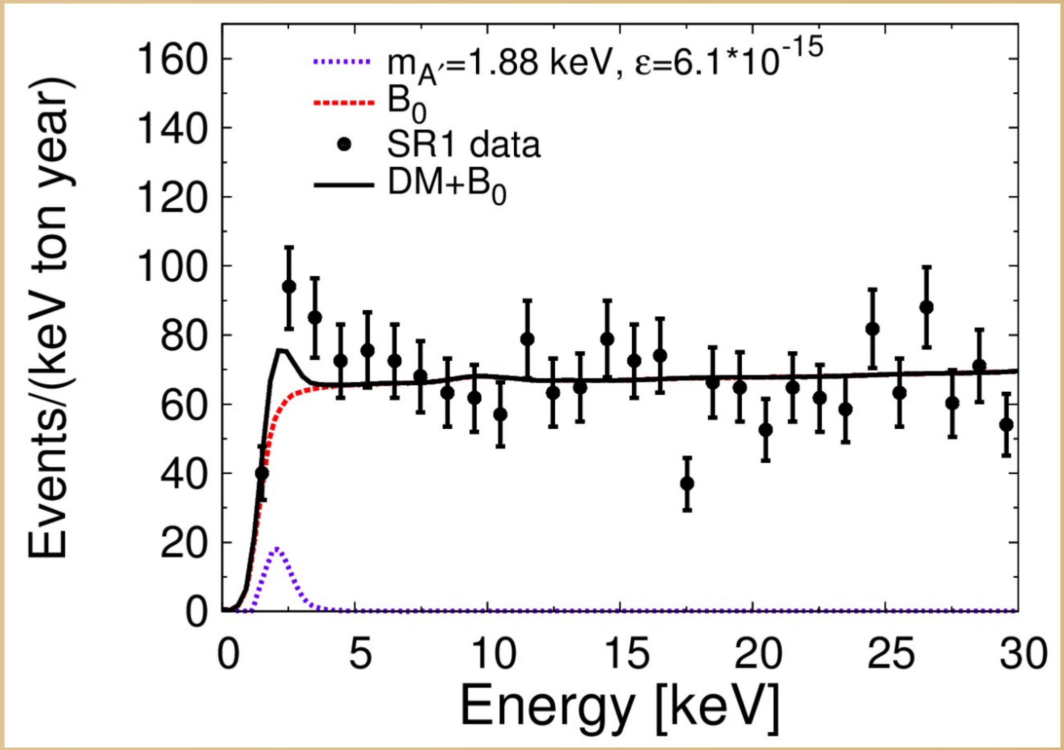


$$Res(E, E_R) = \frac{1}{\sqrt{2\pi\sigma^2_{\rm det}}} e^{-\frac{(E-E_R)^2}{\sigma^2_{\rm det}}} \alpha(E)$$

XENON1T collaboration, 2006.09721

Events at XENON1T

- **KeV DP** flux produced from thermal plasma of *core* our **Sun** could be one interpretation.
- The **DP** flux from the Sun and XENON1T event rate:



WDLF Anomaly

- **KeV DP** contribute additionally emission for WD cooling.
- Using the approximation in the limit $m_{A'} \ll \omega_p$

$$\frac{d^2\Gamma^{\rm WD}_{A'}}{dV\,d\omega} = \frac{1}{4\pi}\frac{\epsilon^2 m_{A'}^2\omega^2}{e^{\omega/T}-1}\delta(\omega-\omega_p)$$

- Additional luminosity from **KeV DP**:

$$L_X = \int dV \int d\omega\, \omega \frac{d^2\Gamma^{\rm WD}_{A'}}{dV\,d\omega} = \left(\frac{4}{3}\pi R^3_{\rm WD}\right)\frac{1}{4\pi}\frac{\epsilon^2 m^2_{A'}\omega_p^3}{e^{\omega_p/T_{\rm WD}}-1}\,,$$

i.e., $\underline{\epsilon\, m_{A'} \simeq 10^{-14}\,\mathrm{keV}.}$

$$L_X \simeq 3.13 \times 10^{32}\ \mathrm{GeV/s}$$

WDLF Anomaly

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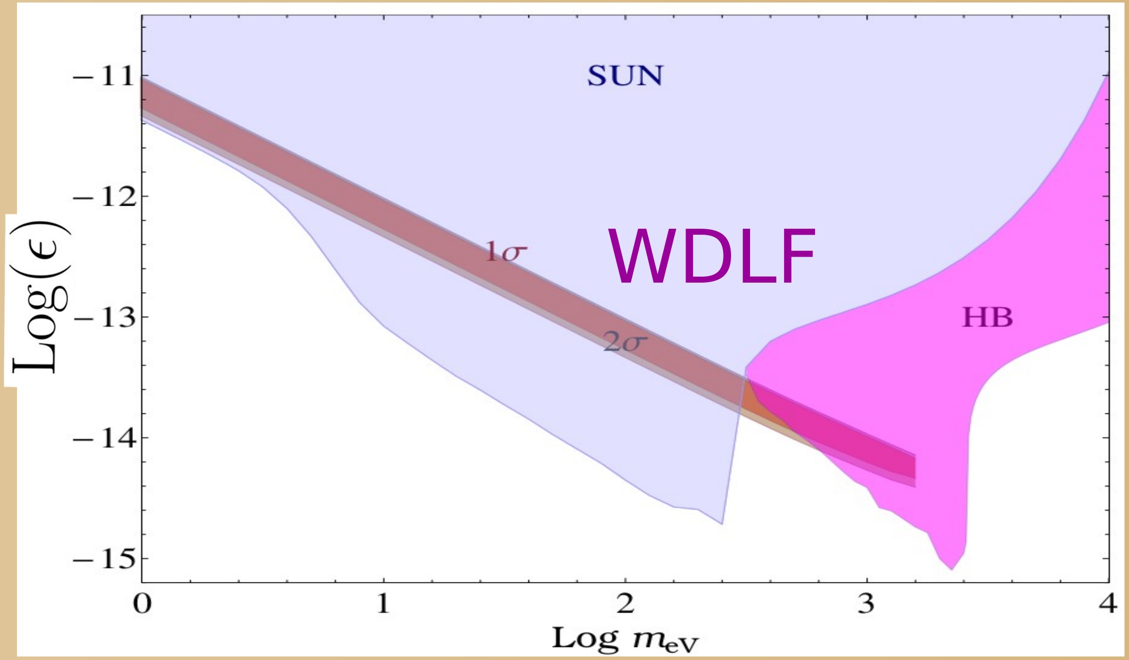
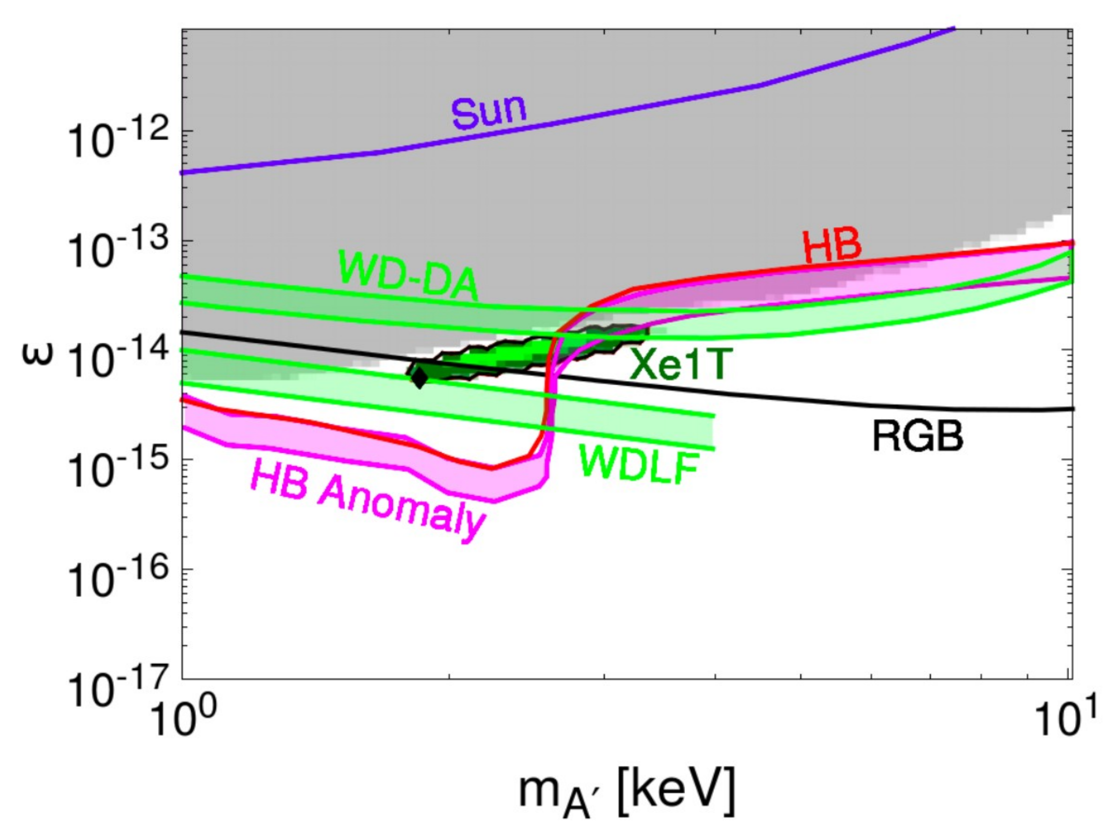


XENON1T and WDLF

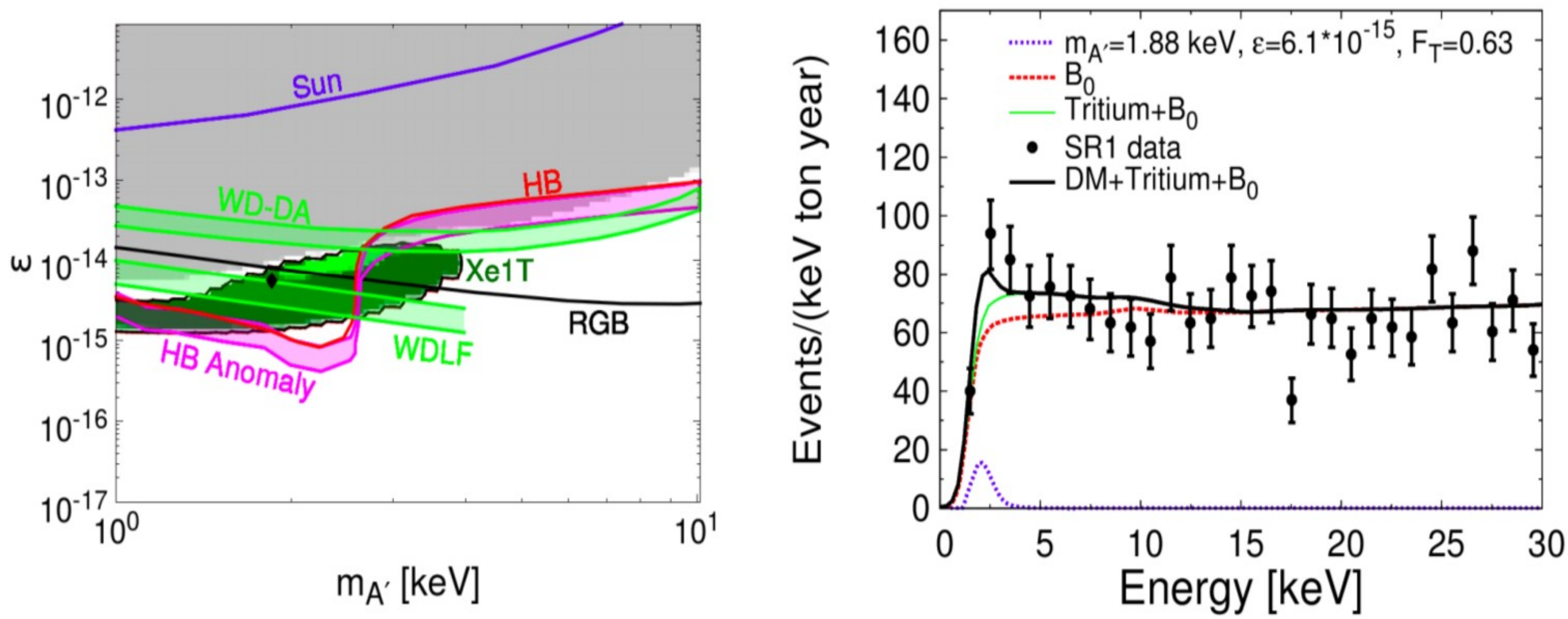
- Comparing to stellar cooling constraints:



W.Y.Keung,D.Marfatia, P.Y.Tseng, arXiv:2009.04444

XENON1T and WDLF

- Including **Tritium** contribution to XENON1T:



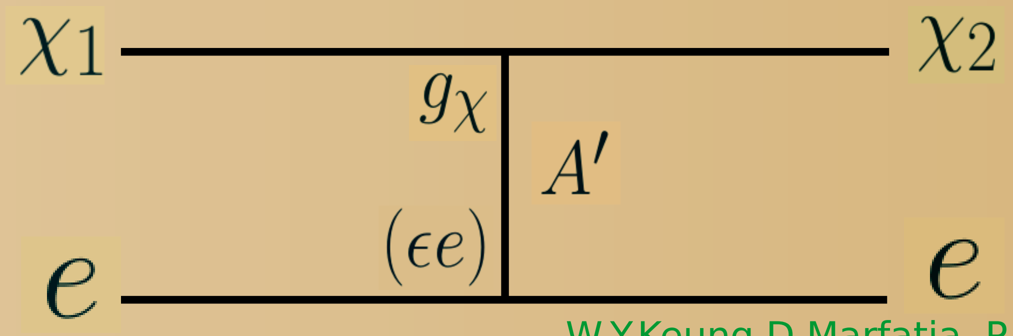
W.Y.Keung,D.Marfatia, P.Y.Tseng, arXiv:2009.04444

Inelastic DM

- If **DP** is much heavier than keV, it cannot be thermally produced from the Sun.
- We consider **DP** as a mediator between ***MeV Inelastic DM*** and electron.

$$\boxed{\mathcal{L} \supset (\epsilon e) A'_\mu (\bar{e}\gamma^\mu e) + \left(\frac{i\, g_\chi}{2} A'_\mu (\bar{\chi_2}\gamma^\mu \chi_1) + \text{h.c.} \right)}$$

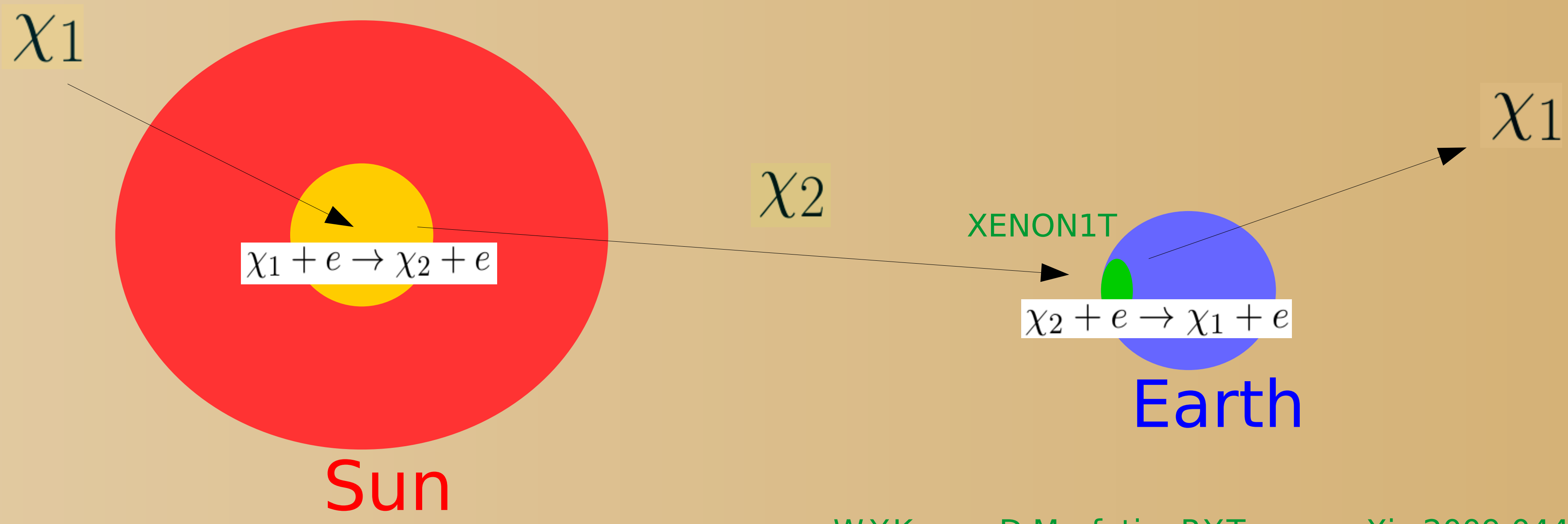
$$\Delta m_\chi \equiv m_{\chi_2} - m_{\chi_1} \approx \text{keV}$$



W.Y.Keung,D.Marfatia, P.Y.Tseng, arXiv:2009.04444

Inelastic DM

- If DM relic is mainly composed by χ_1. When DM wind cross the Sun, χ_1 is excited into χ_2. Then χ_2 propagate to Earth, down scattering at XENON1T.



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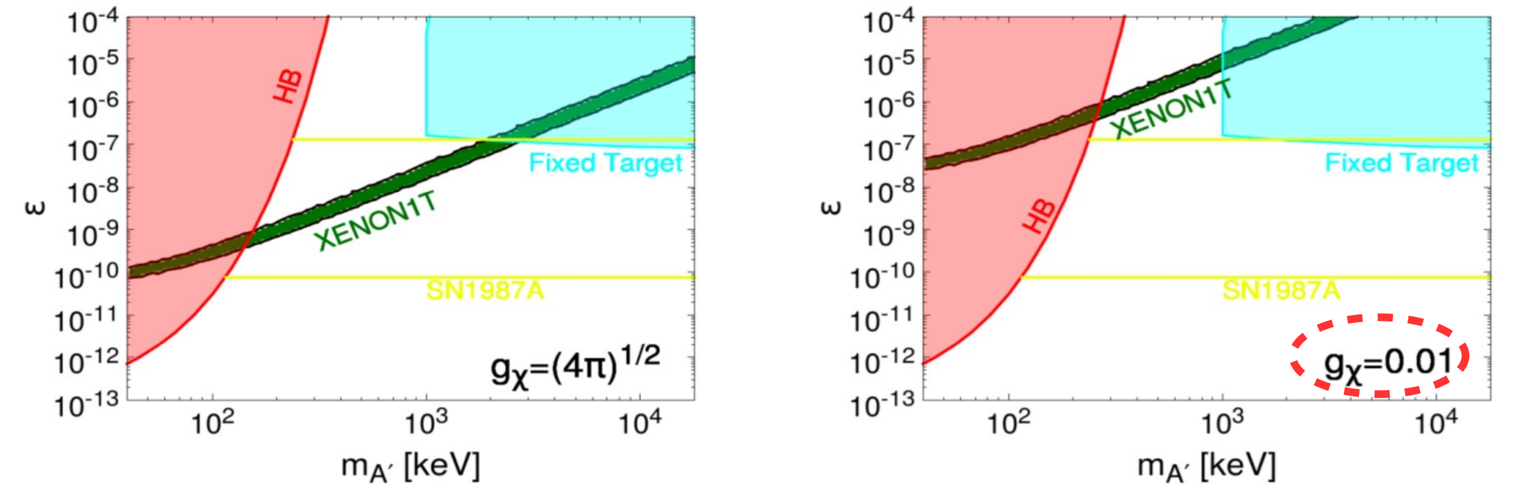

Figure 2. $m_{A'} > \Delta m_\chi$. The 2σ XENON1T allowed regions for $g_\chi = \sqrt{4\pi}$ and $g_\chi = 0.01$. The constraints from HB stars [13, 14], fixed-target experiments [23] and an approximate constraint from SN 1987A [24] are also shown.

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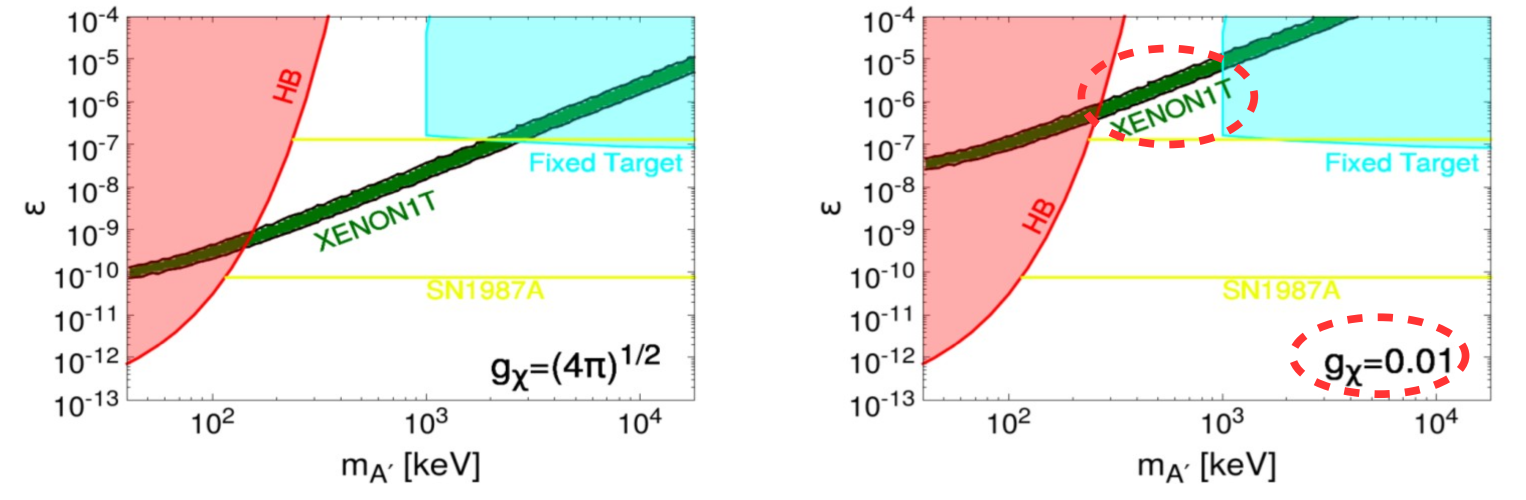

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W.Y.Keung, D.Marfatia, P.Y.Tseng, arXiv:2009.04444

Inelastic DM

- The $\chi 2$ population after freeze out. The inter-conversion process:

$$\boxed{\chi 2\chi 2 \rightarrow \chi 1\chi 1}$$

J.Barmante, N.Song: , arXiv:2006.14089

- The ratio of number density is given by:

$$\frac{n_{\chi 2}}{n_{\chi 1}} \sim e^{-\frac{\Delta m_\chi}{T_{co}}} \Rightarrow n_{\chi 2} \ll n_{\chi 1}$$

$$T_{co} = \left(\frac{\sqrt{\pi g_*}}{\alpha_\chi^2} \frac{m_{A'}^4}{M_{pl}} \right)^{1/3}$$

- The $\chi 1$ dominates DM relic.

Summary

- **Stellar cooling** is sensitive to *microscopy* physics and *particles lighter than keV*.

- We performed the computation of **keV dark photon** *thermal production* from *thermal plasma* of stellar systems, and event rate at XENON1T detector.

- The **keV dark photon** could be simultaneous explanation of the **WDLF** cooling anomaly and XENON1T excess by including the **Tritium** contribution.

Summary

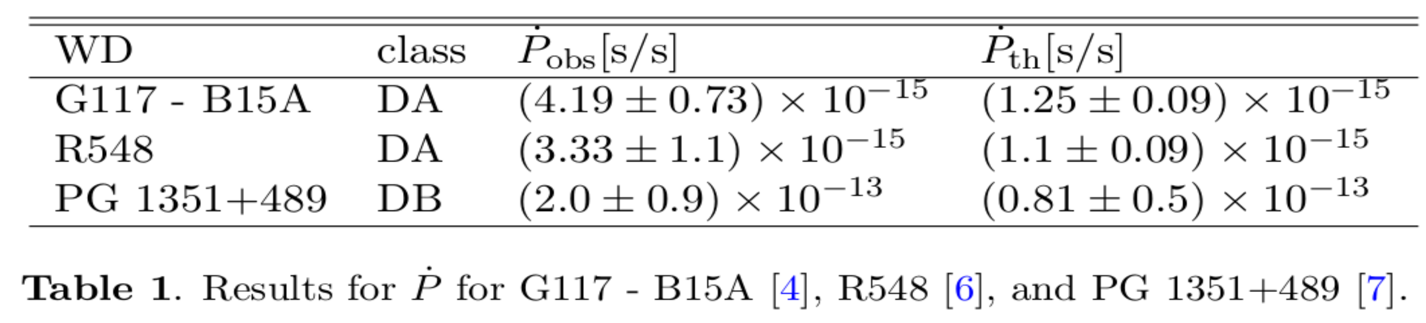
- For ***inelastic DM*** with heavy mediator: **thermal electrons** inside the **Sun** provide a power source to excite $\chi_1 + e \to \chi_2 + e$. After propagate to Earth, it contribute to XENON1T signal via down scattering $\chi_2 + e \to \chi_1 + e$.

Thank You!

Back Up

Stellar Cooling

- Observation of ***period decreasing rate*** of type DA pulsating WD



WD	class	$\dot{P}_{\mathrm{obs}}[\mathrm{s/s}]$	$\dot{P}_{\mathrm{th}}[\mathrm{s/s}]$
G117 - B15A	DA	$(4.19 \pm 0.73) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$
R548	DA	$(3.33 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$
PG 1351+489	DB	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$

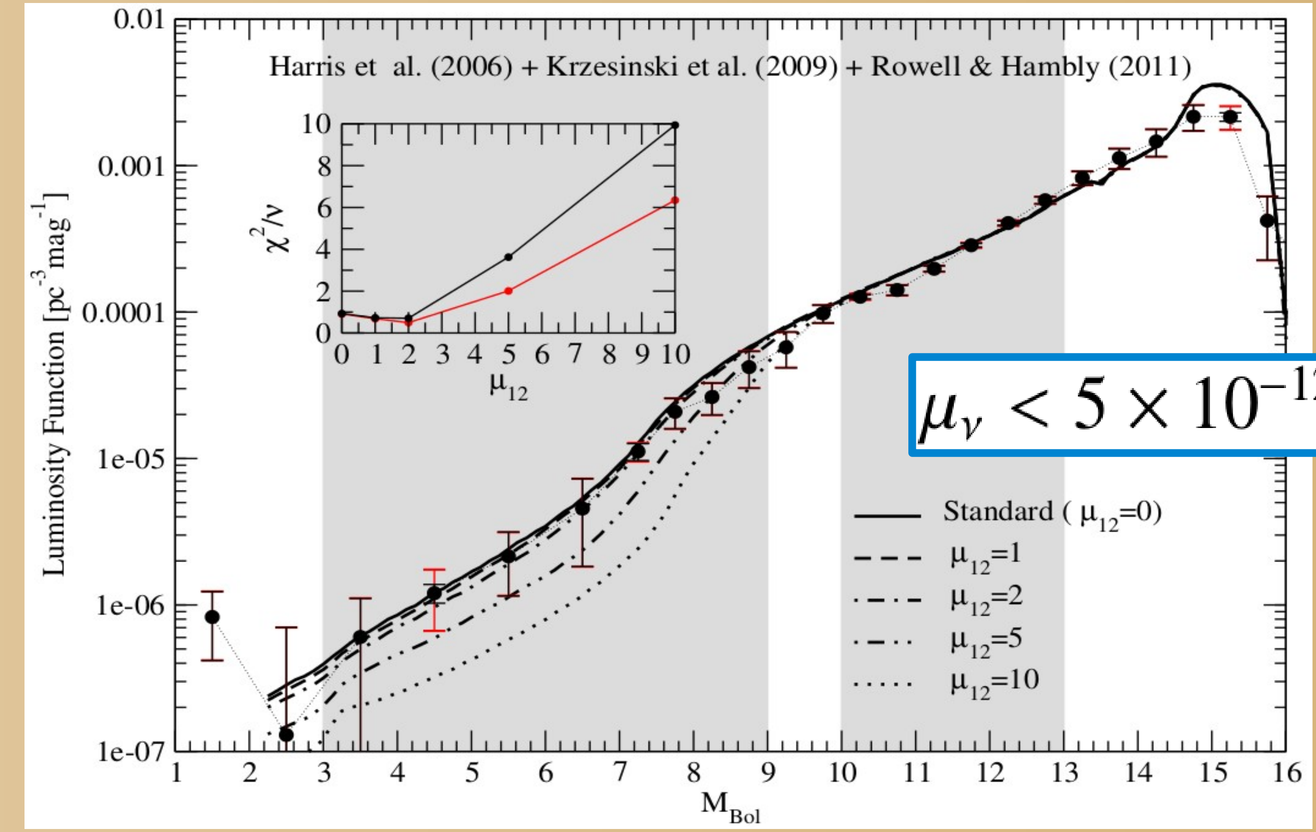
Table 1. Results for $\dot{P}$ for G117 - B15A [4], R548 [6], and PG 1351+489 [7].

M.Giannotti, I.Irastorza, J.Redondo, A.Ringwald: 1512.08108

- ***Period decreasing rate*** is proportional to ***cooling rate***.

WDLF

- The additional coolings may due to the Axion-Like particle(ALP) or neutrino magnetic moment.

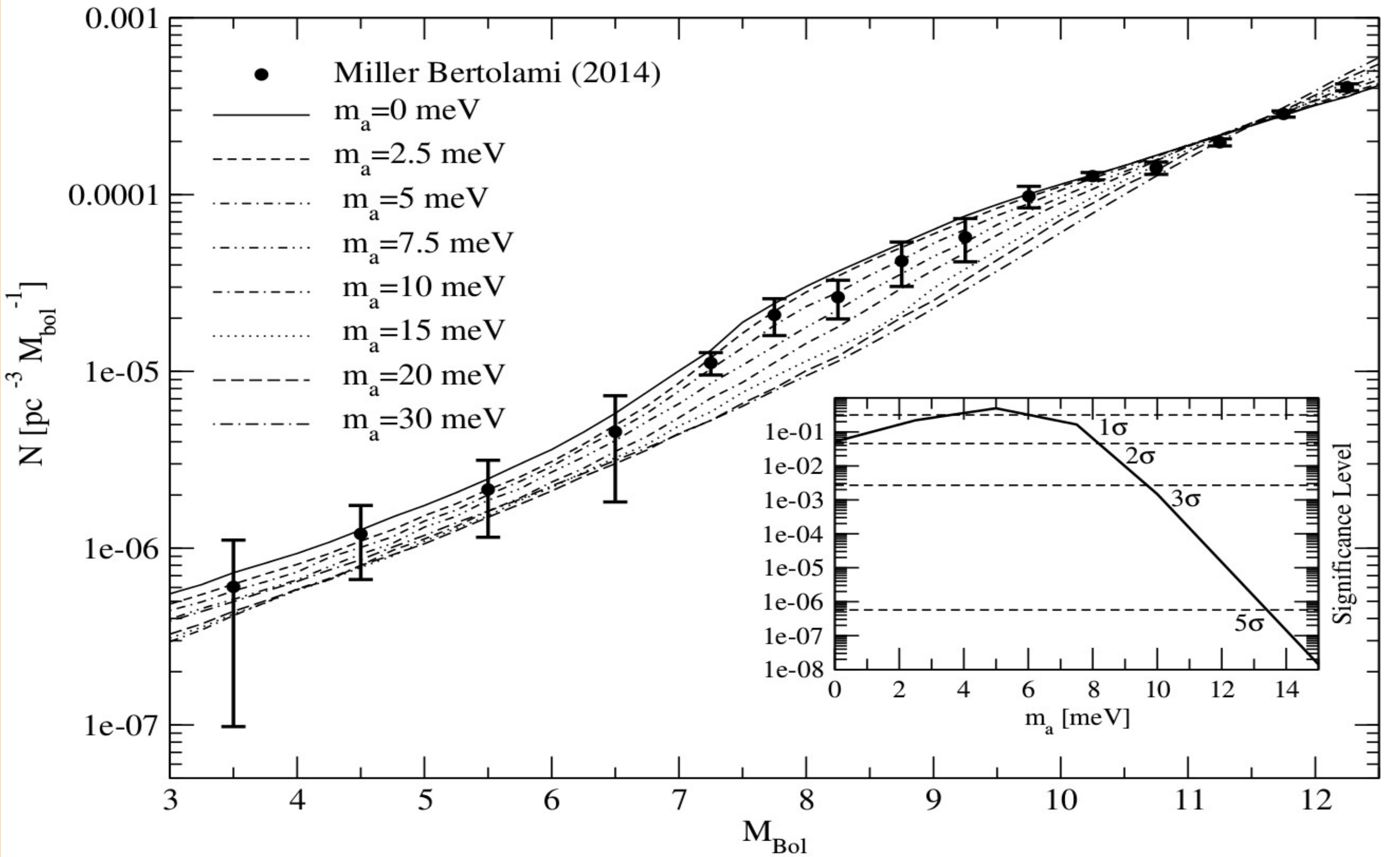


$$\boxed{\mu_\nu < 5 \times 10^{-12}\, e\hbar/(2m_e c)}$$

M.M.M. Bertolami: 1407.1404

WDLF

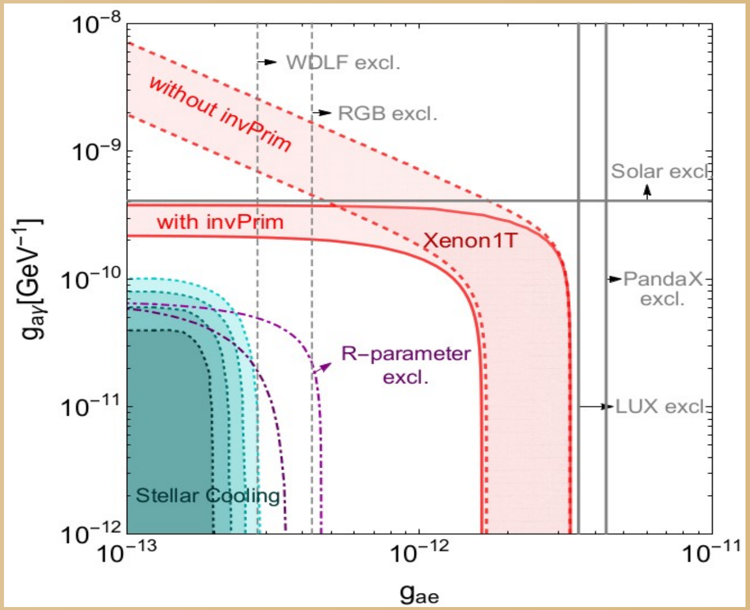
- The additional coolings may due to the Axion-Like particle(ALP) or neutrino magnetic moment.



M.M.M. Bertolami, B.E.Melendez, L.G.Althaus, J.Isern: 1406.7712

XENON1T Anomaly

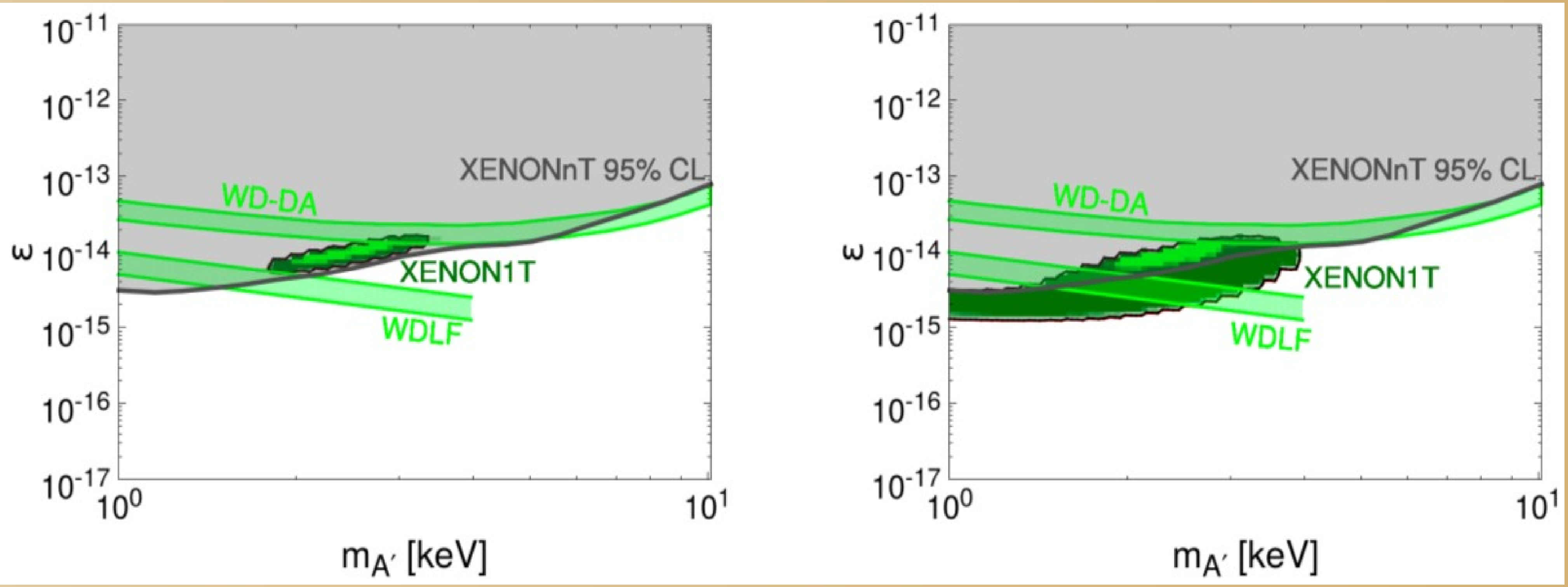
- XENON1T experiment reported 3-sigma excess in the electron recoil spectrum between 2-3 keV.
- Axion interpretation is not well consistent with constraints from stellar cooling



C.Gao, J.Liu,L.T.Wang, X.P.Wang, W.Xue, Y.M. Zhong :2006.14598

XENONnT

- XENONnT project limit:



W.Y.Keung,D.Marfatia, P.Y.Tseng, arXiv:2009.04444