XVI Patras Workshop on Axions, WIMPs and WISPs
Trieste, 14-18 June 2021

Supernova bounds on axion-like particles coupled with nucleons and electrons

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Based on
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In preparation

OUTLINE

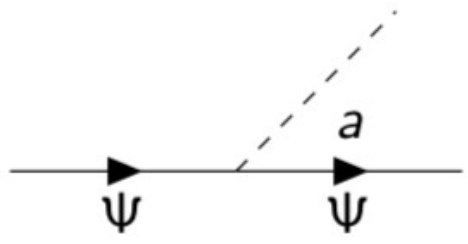
- Introduction
- Constraining strategies for ALPs from Supernovae
- The 511 keV X-ray line and ALP bounds from (Extra)Galactic Supernovae
- Conclusions

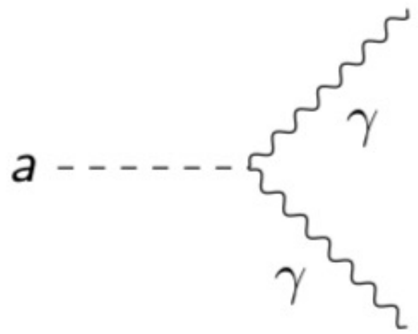
AXION-LIKE PARTICLES

Axion-like particles (ALPs) are pseudoscalar particles introduced in UV completions of Standard Model (SM).

Possible interactions with SM particles

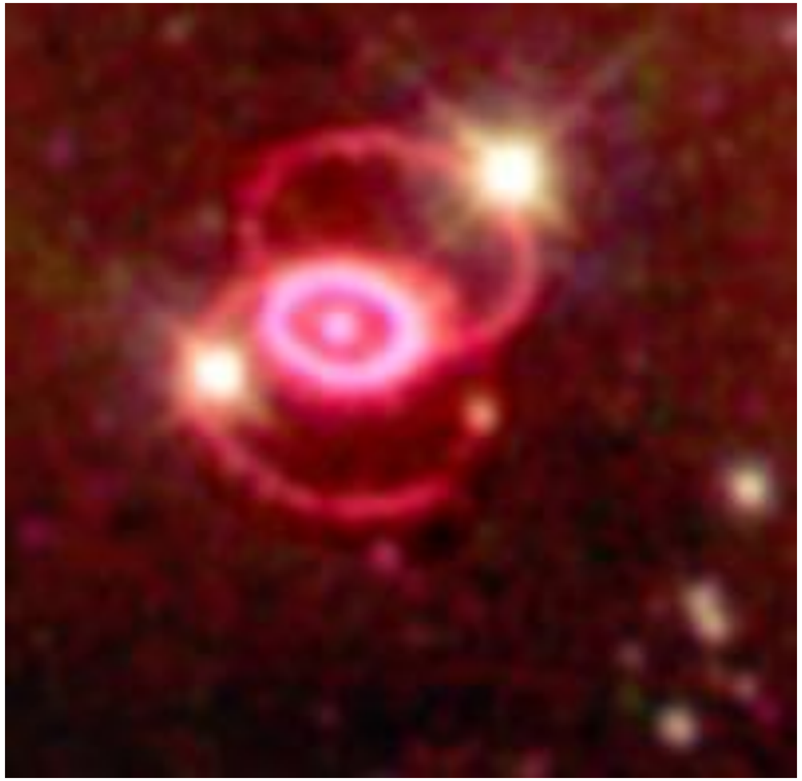
$$\mathcal{L}_{int} = \sum_{\psi=e,p,n} \frac{g_{a\psi}}{2\, m_{\psi}} (\bar{\psi}\gamma^{\mu}\gamma^{5}\psi)\partial_{\mu}a - \frac{1}{4} g_{a\gamma}\, \tilde{F}^{\mu\nu}\, F_{\mu\nu}\, a$$





SUPERNOVAE

Core-collapse SN corresponds to the terminal phase of a massive star [M $\gtrsim$ 8 $M_{\odot}$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.



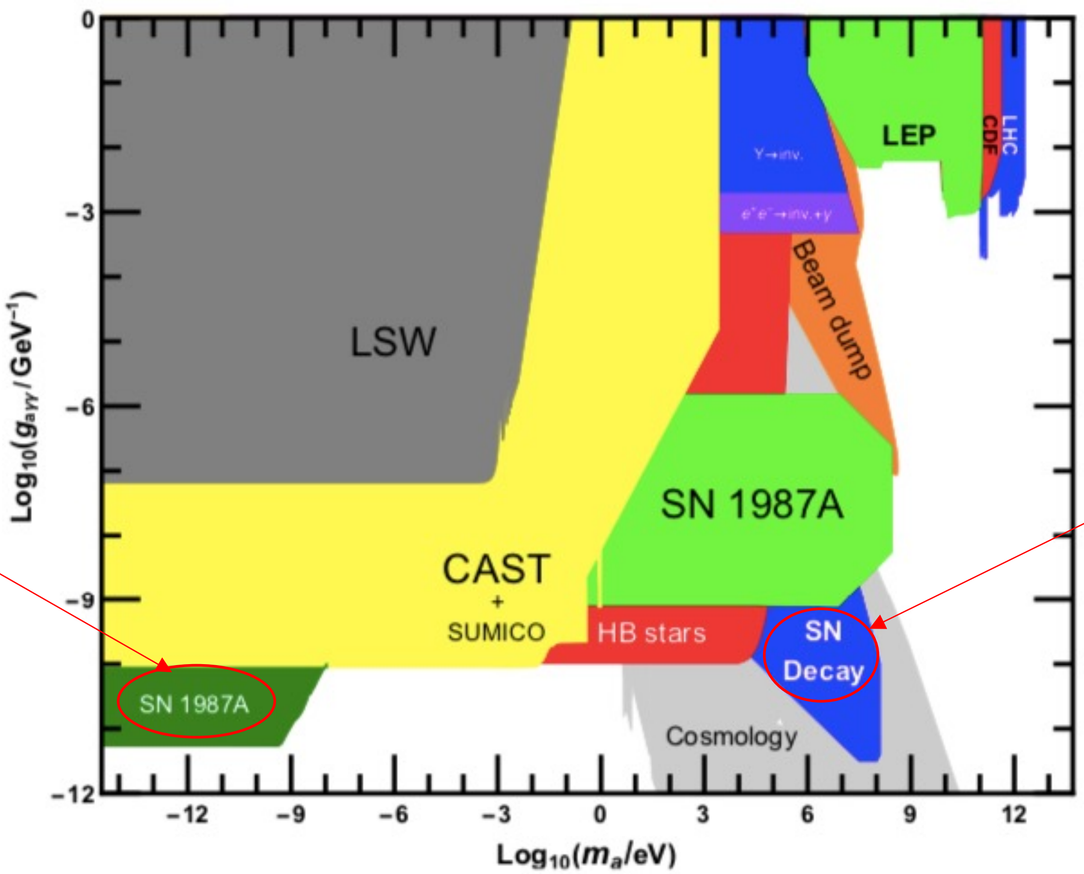
- **ENERGY SCALES:** 99% of the released energy ($\sim 10^{53}$ erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies $E \sim 15$ MeV.
- **TIME SCALES:** Neutrino emission lasts ~ 10 s.
- **EXPECTED:** 1-3 SN/century in our galaxy ($d \approx O(10)$ kpc)
- Standard picture confirmed by SN 1987A.

DIRECT SIGNATURE

Constraining strategy: search for a direct signature of the SN ALP flux.

- $g_{a\gamma}$: main production channel Primakoff effect.
- Non-observation of a gamma-ray signal in coincidence with SN 1987A neutrino-burst → ALP bound

$m_a \lesssim 10^{-9}$ eV:
ALP conversion $a \to \gamma$
in the galactic magnetic field
[Payez et al., *JCAP* 02 (2015)]

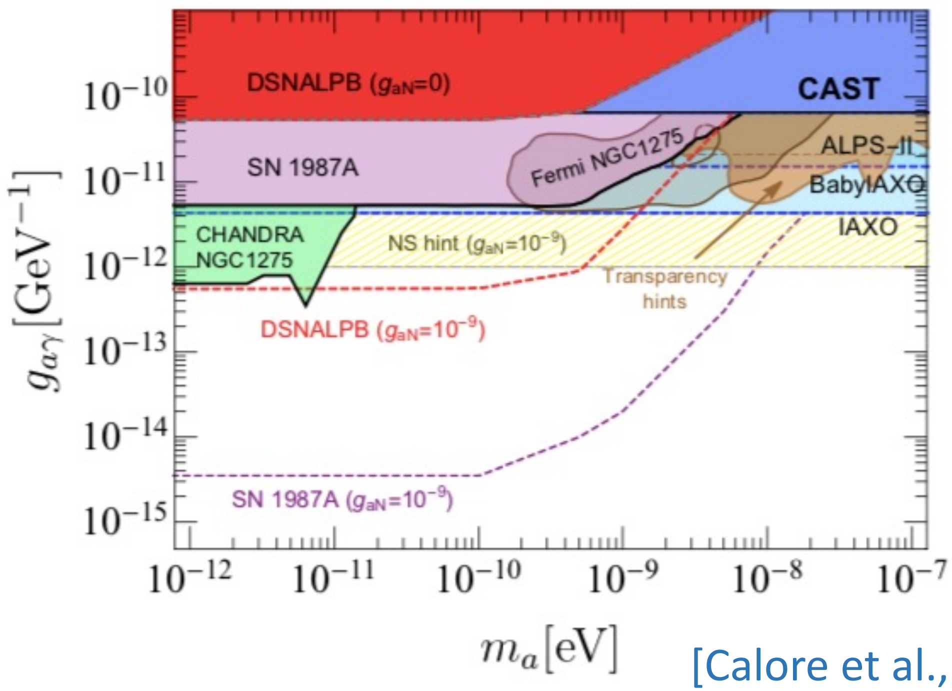


$0.1 \lesssim m_a \lesssim 100$ MeV:
ALP decay $a \to \gamma\gamma$
[Jaeckel et al., *PRD* 98 (2018)]

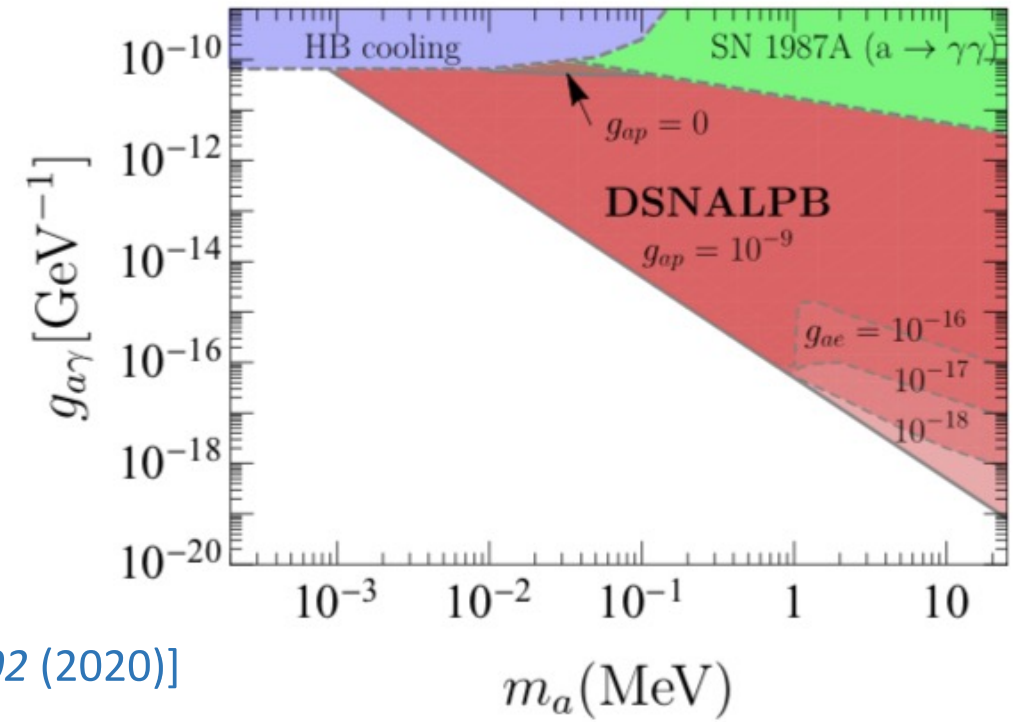
SIMULTANEOUS COUPLING

- $g_{a\gamma} - g_{ae}$: Sun [Jaeckel & Thormaehlen, *JCAP 03* (2019)] and Globular-Clusters [Giannotti et al., *JCAP 10* (2017)]
- $g_{aN} - g_{a\gamma}$: Supernova bounds are strengthened [Calore et al., *PRD 102* (2020)]

Ultralight ALPs



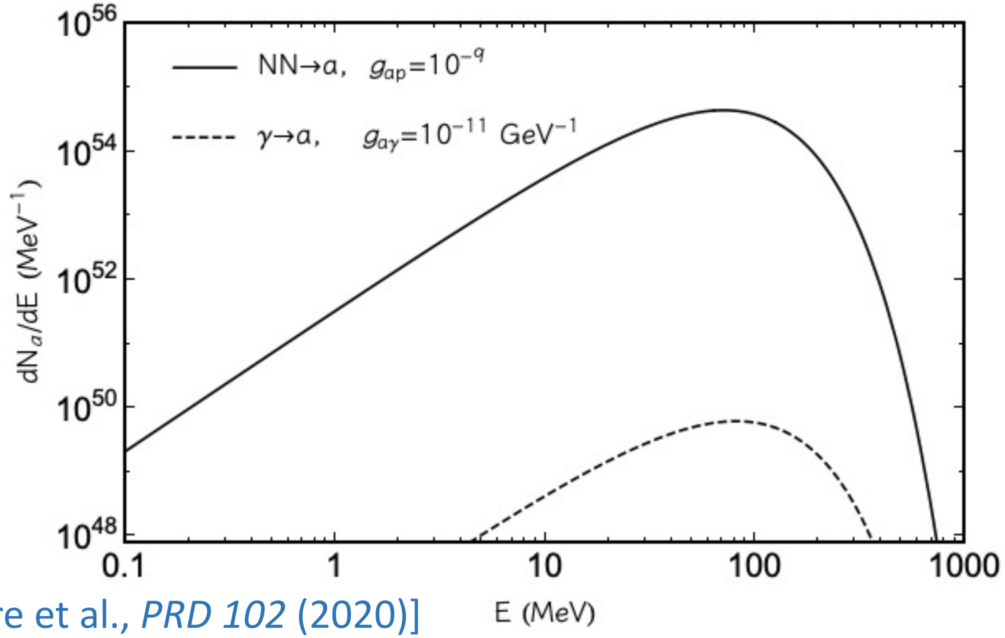
Massive ALPs



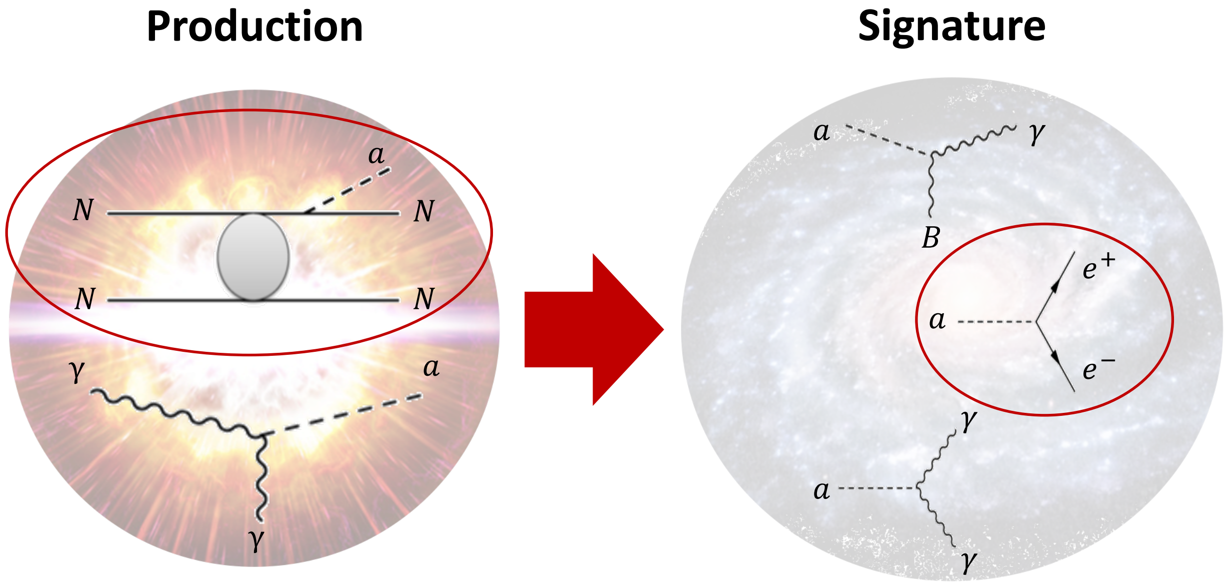
[Calore et al., *PRD 102* (2020)]

ALP PROCESSES WITH DIFFERENT COUPLINGS

- Main production channel in a SN: nucleon bremsstrahlung.
- $m_a > 1$ MeV: possible decays into photons and electron-positron pairs.



[Calore et al., *PRD 102* (2020)]

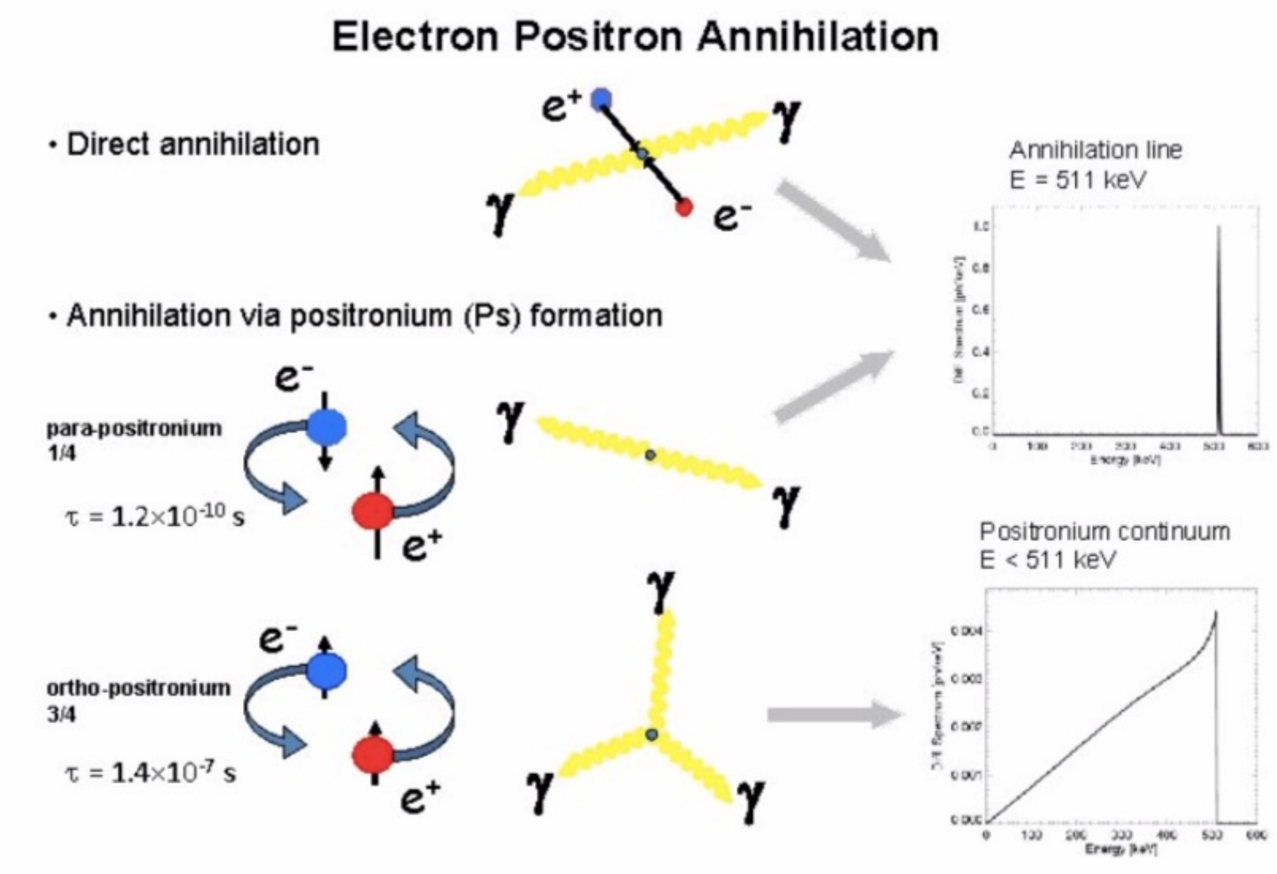


We consider the case in which the ALP decay in photons is negligible

$$\frac{BR(a \to \gamma\gamma)}{BR(a \to e^+e^-)} = \frac{l_e}{l_\gamma} \sim 10^{-5}\left(\frac{m_a}{10\text{ MeV}}\right)^2\left(\frac{10^{-13}}{g_{ae}}\right)^2\left(\frac{g_{a\gamma}}{10^{-13}\text{ GeV}^{-1}}\right)^2 \ll 1$$

ELECTRON-POSITRON ANNIHILATION

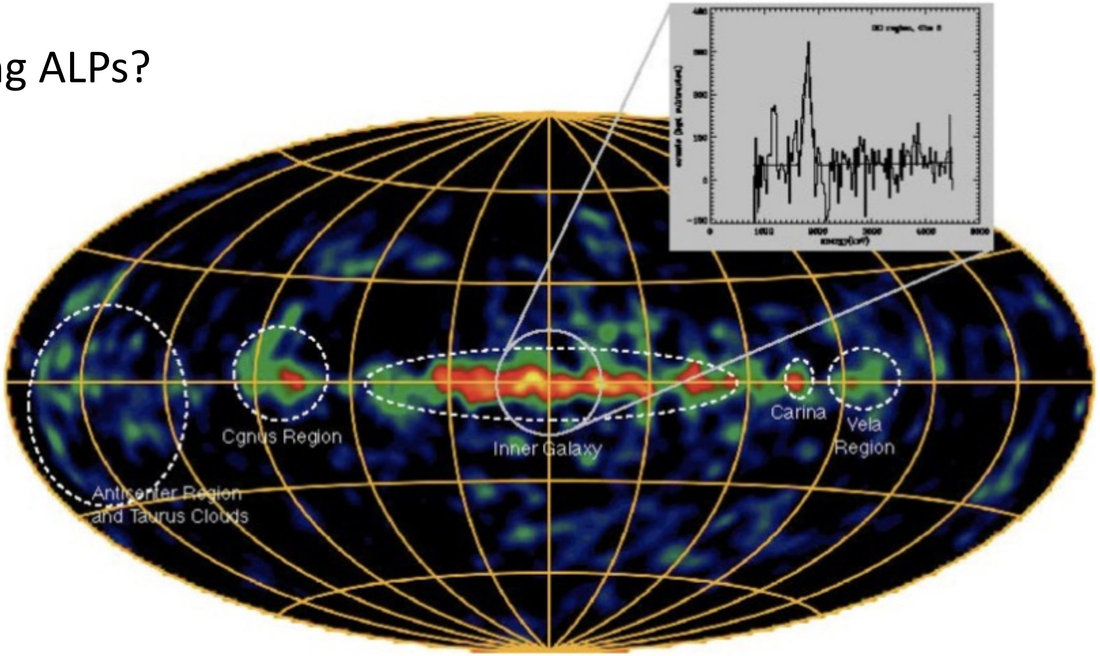
Positrons lose energy and annihilate in $10^3 - 10^6$ yrs.



THE 511 keV LINE

[Prantzos et al., *Rev. Mod. Phys. 83* (2011)]

- Strong flux of 511 keV photons $\sim 10^{-3}\ \mathrm{ph\ cm^{-2}\ s^{-1}}$ from the galactic buldge.
- SPI measurements: positron annihilation (production) rate $\sim 10^{43}\ \mathrm{s}^{-1}$.
- Constraints on Dark Photons [De Rocco et al., *JHEP* 02 (2019)], Primordial Black Holes [Laha et al., *PRD* 101 (2020)], decaying Dark Matter [Cai et al., *JCAP* 03 (2021)]
- Can we constrain decaying ALPs?



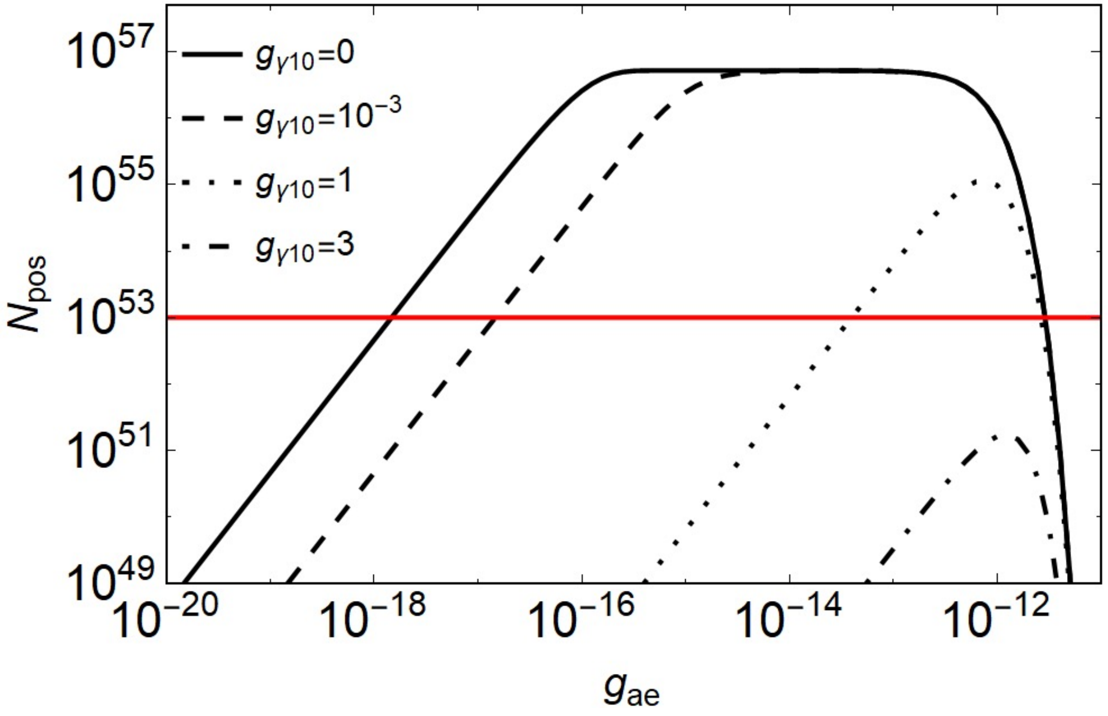
SN POSITRON PRODUCTION

ALPs must escape the SN photosphere and remain in the Galaxy.

$$N_{pos} = \int dE \frac{dN_a}{dE} e^{-r_{esc}/l_e}\left(1 - e^{-r_G/l_e}\right)$$

If $g_{a\gamma}$ increases, less ALPs decay into e^+e^- pairs.

$$g_{\gamma 10} = \frac{g_{a\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}$$



Number of positrons for $g_{ap} = 10^{-9}$ and $m_a = 30$ MeV

ALP-ORIGINATED 511 keV PHOTON SIGNAL

Positrons trapped by $B \sim O\ (\mu G)$: 511 keV photons generated not far from the ALP decay region.

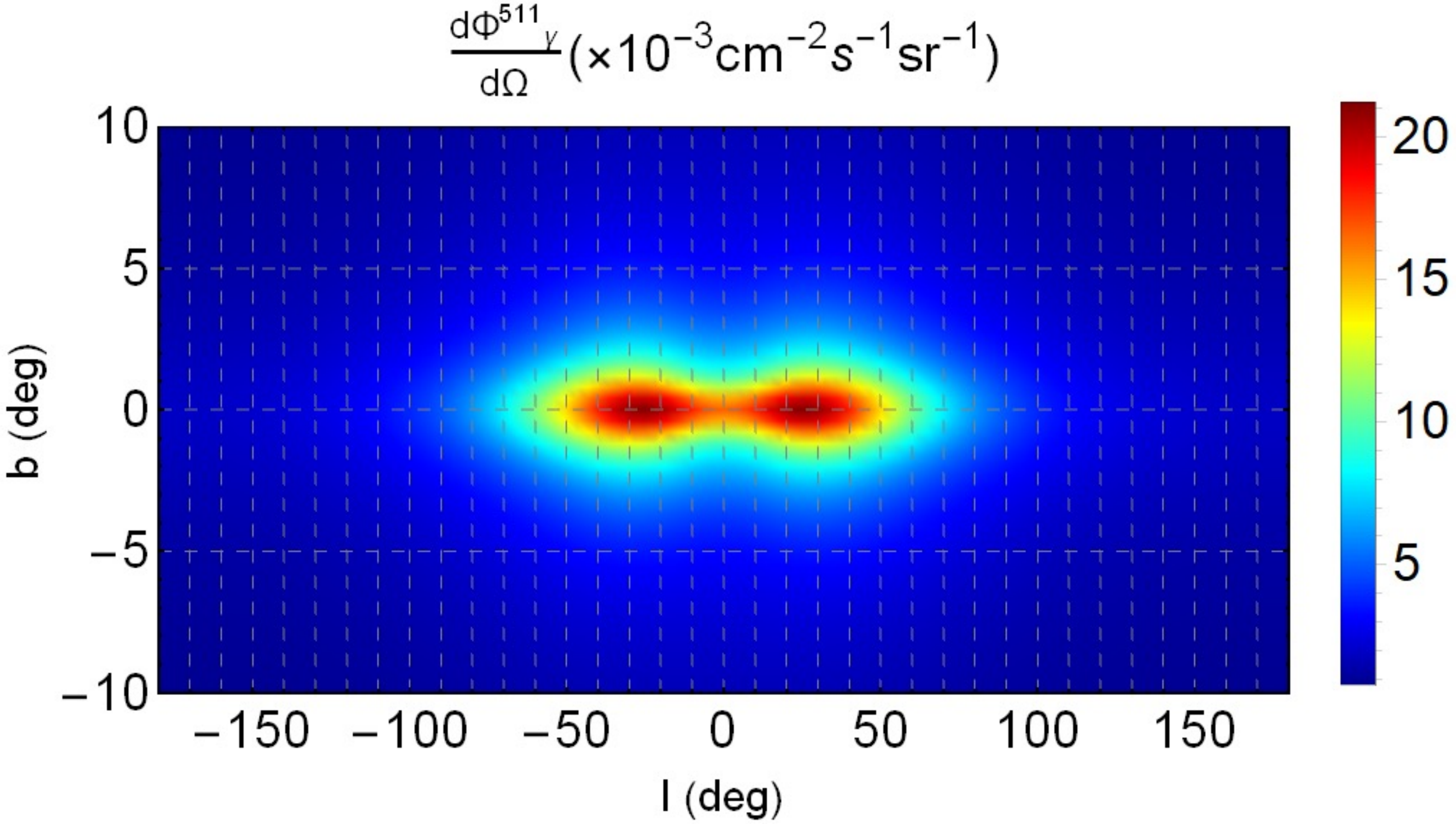
Angular distribution of the 511 keV line photon signal from e^+e^- annihilation ($\tau_e \gtrsim 10^3$ yrs):

$$\frac{d\phi_\gamma^{511}}{d\Omega} = 2k_{ps}N_{pos}\Gamma_{cc}\int ds\ s^2 \frac{n_{cc}}{4\ \pi\ s^2}$$

Where

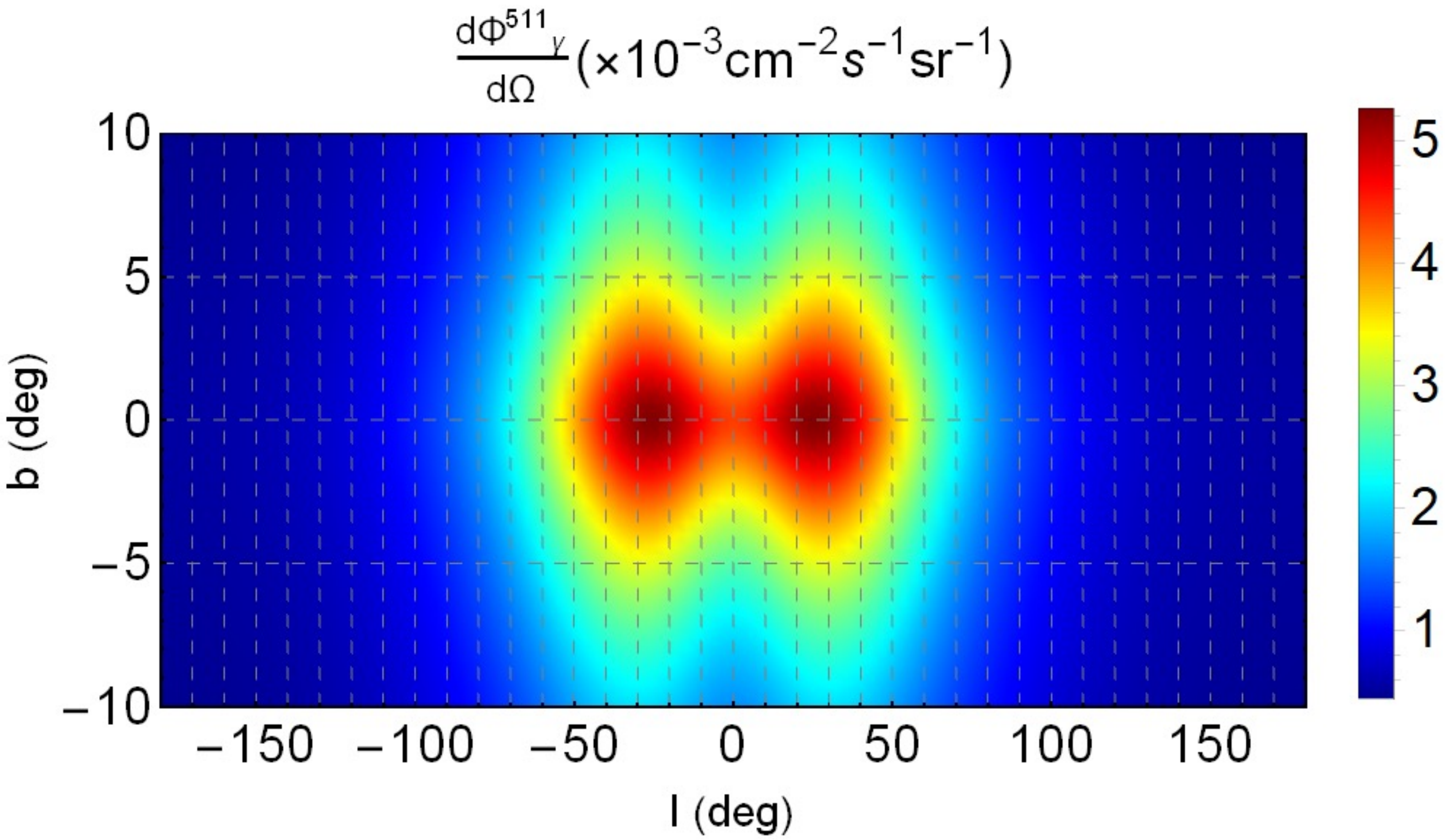
- $k_{ps} = \frac{1}{4}$ (parapositronium formation)
- $\Gamma_{cc} = 2$ SNe/century Galactic SN explosion rate
- n_{cc} normalized SN volume distribution [Mirizzi et al., *JCAP* 0605 (2006)]

511 keV PHOTON SKY-MAP FOR $g_{ae} = 3.5\times10^{-12}$



ALPs decay close to the SN: the photon signal follows the SN distribution.

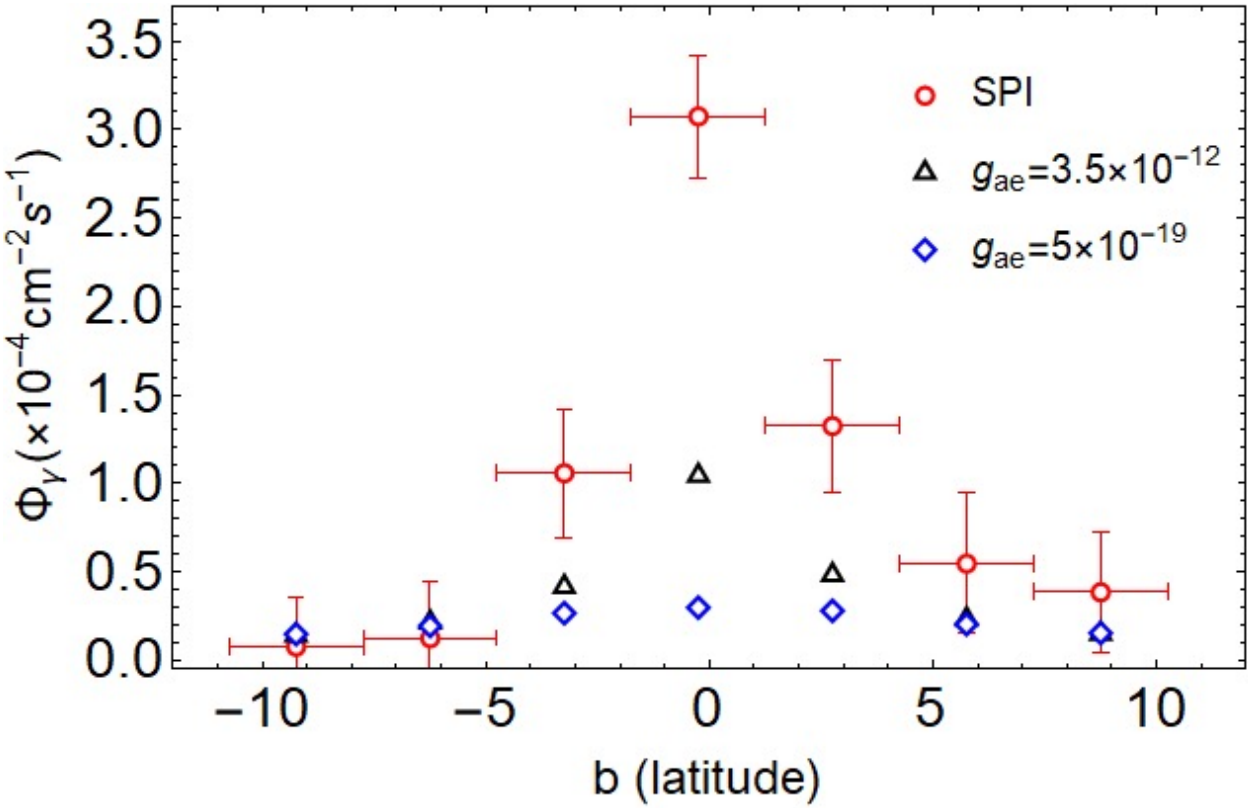
511 keV PHOTON SKY-MAP FOR $g_{ae} = 5\times10^{-19}$



ALPs decay far from the SN: smeared distribution.

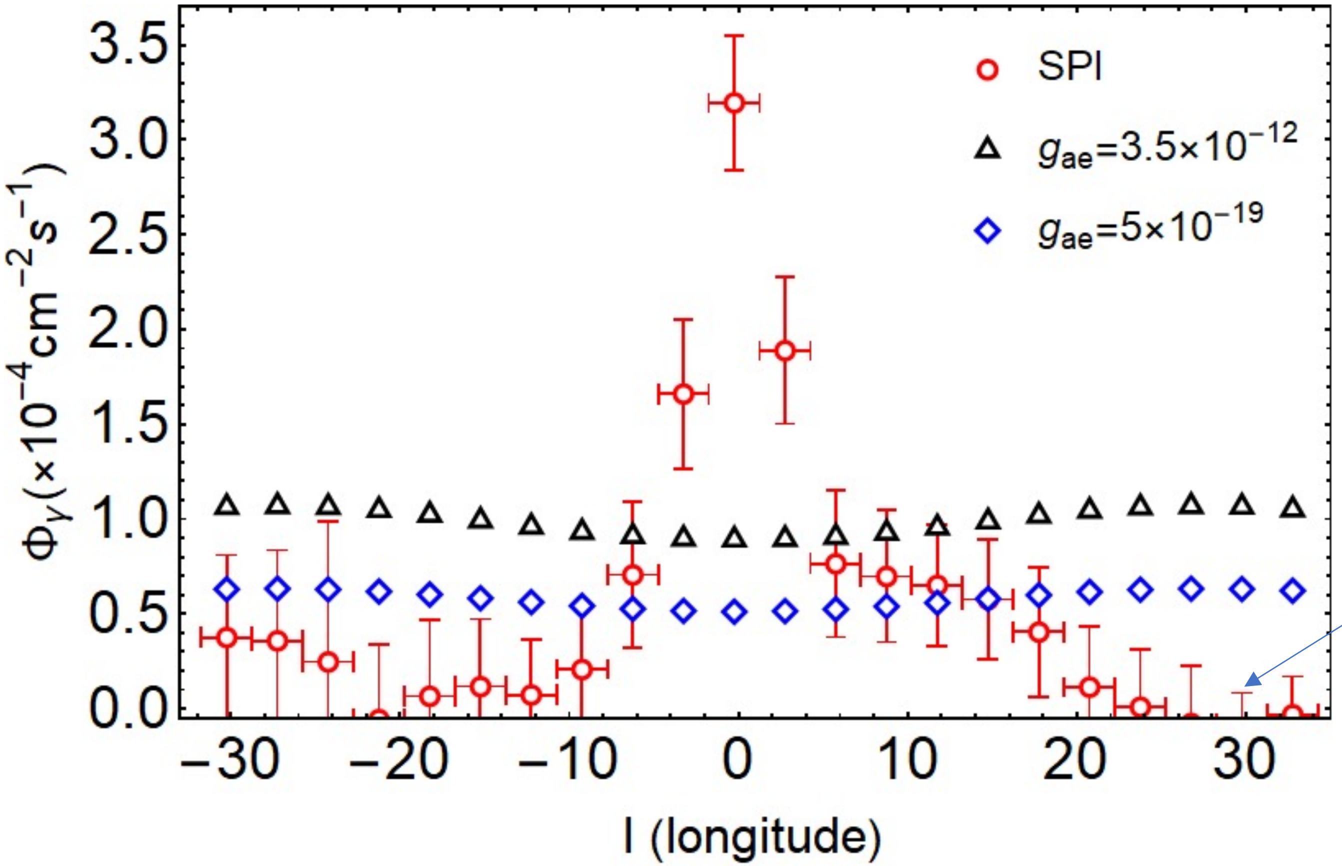
LATITUDE DISTRIBUTION

- Comparison with SPI data. [Siegert et al., *Astron. Astrophys.* 627 (2019)]
- Peak at $b = 0°$ for both the signals.
- Larger coupling: ALP-signal shape closer to the observed 511 keV photon flux.



LONGITUDE DISTRIBUTION

Dip at $l = 0°$ and peaks at $l \approx \pm 30°$: ccSN-mechanism does not explain the 511 keV line.

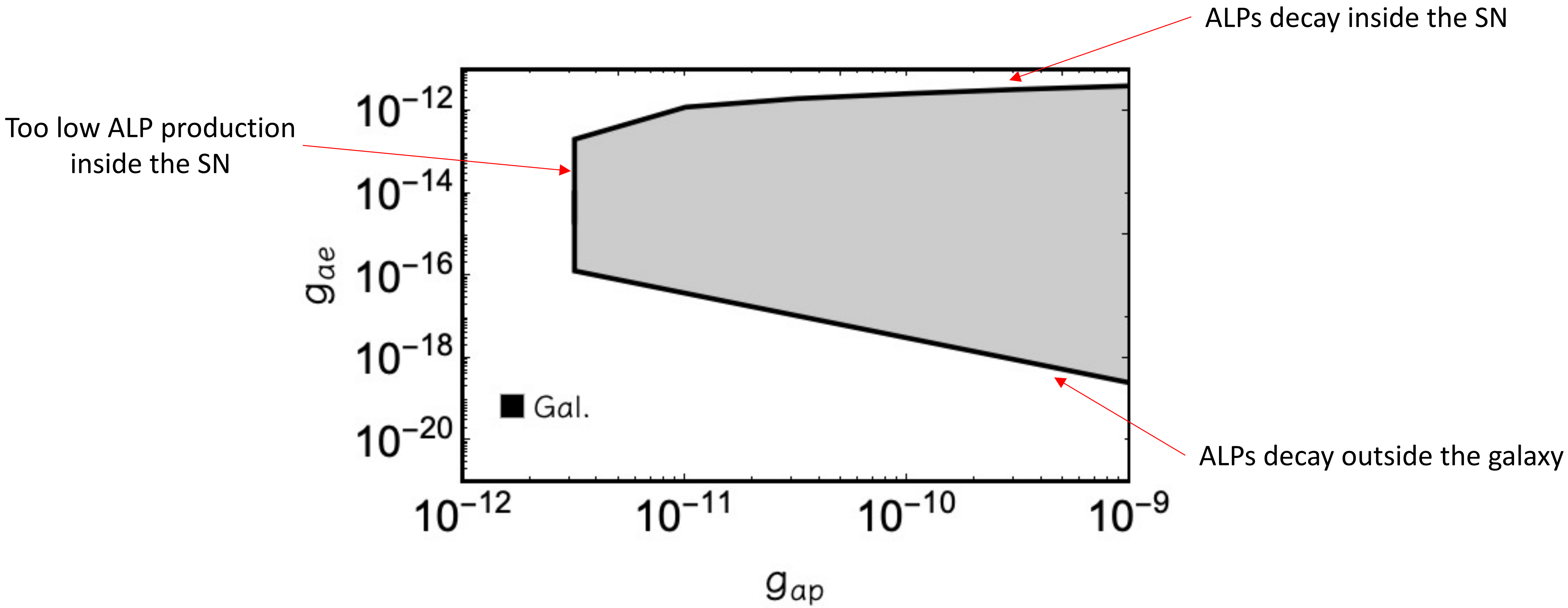


The most constraining bin $l \in [28.25°, 31.25°]$

Bound: the ALP signal must not exceed the data at 2σ.

BOUND IN THE $g_{ae} - g_{ap}$ PLANE

Bound obtained for $m_a = 30$ MeV, rather insensitive for $10 \lesssim m_a \lesssim 40$ MeV.



EXTRA-GALACTIC SUPERNOVAE

In the extra-galactic medium $B \sim O(nG)$: positrons annihilate in $\sim 10^{10}$ yr and photons are redshifted.

Cumulative energy flux of escaping ALPs from past core-collapse supernovae, and decaying into e^+e^- in the redshift interval between $[z_d : z_d - dz_d]$ [Raffelt et al., *PRD 84* (2011)]

$$\left(\frac{d^2\phi_a(E_a)}{dE_a dz_d}\right)_{dec} = \int_{z_d}^{\infty} (1+z) \frac{dN_a\big(E_a(1+z)\big)}{dE_a} [R_{SN}(z)] \frac{e^{-\frac{z-z_d}{H_0 l_e}}}{H_0 l_e} \left[\left|\frac{dt}{dz}\right| dz\right]$$

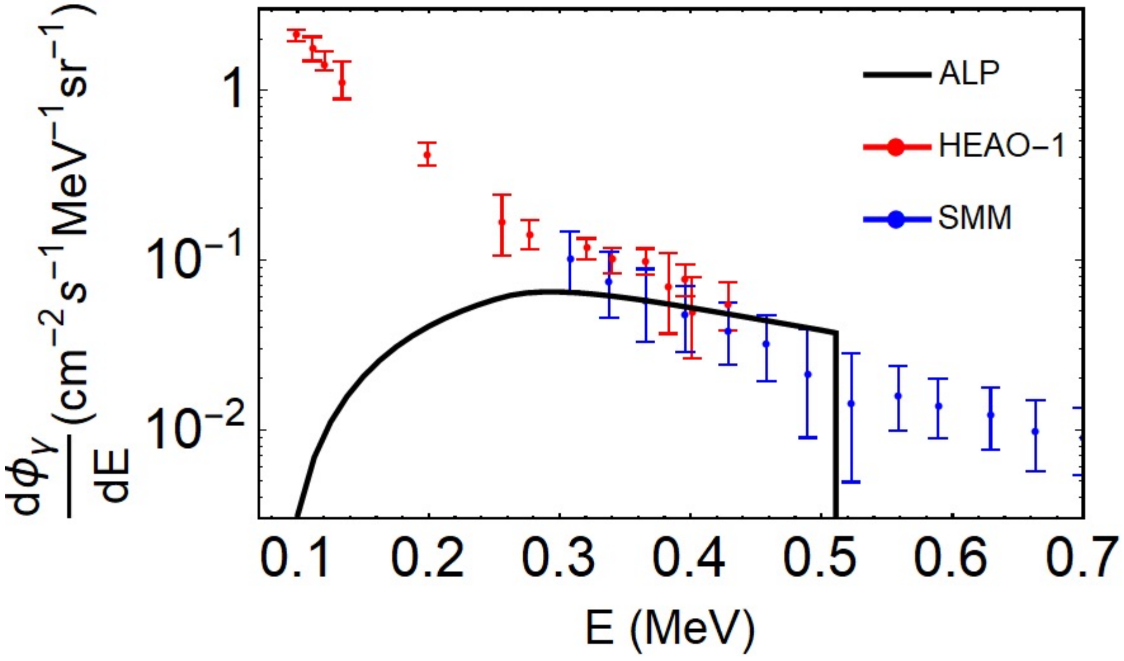
Where

- $\frac{dN_a}{dE_a}$ is the SN ALP flux
- R_{SN} is the SN cosmological rate [Priya & Lunardini, *JCAP 1711* (2017)]
- $\frac{dt}{dz}$ depends on the cosmological parameters [Planck Collaboration, *Astron. Astrophys. 641* (2020)]

EXTRA-GALACTIC X-RAY DIFFUSE FLUX

Redshift: no 511 keV line. ➡ Contribution to Cosmic X-ray background (CXB).

$$\frac{d\phi_\gamma}{dE} = 2k_{ps}\frac{m_e}{E^2}\int_{m_a}^{\infty} dE_a \left(\frac{d^2\phi_a(E_a)}{dE_a dz_d}\right)_{dec}$$

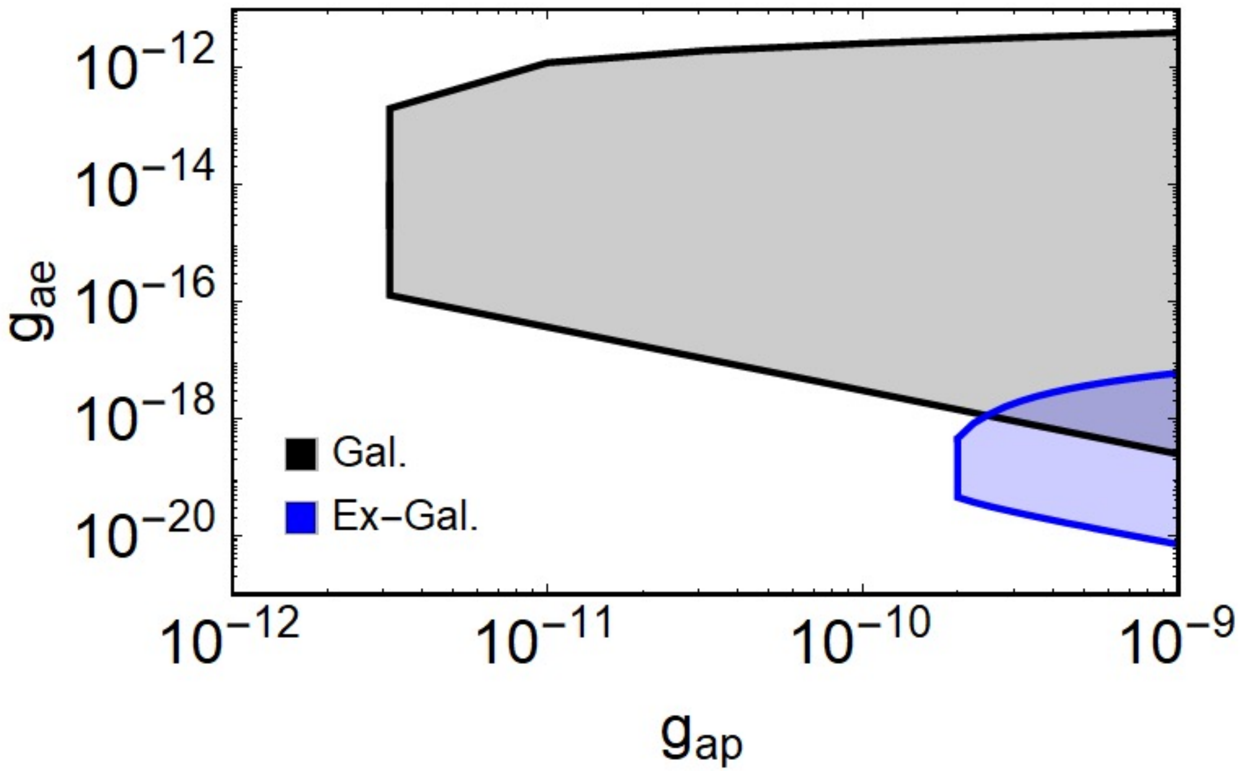


$m_a = 30$ MeV
$g_{ap} = 10^{-9}$
$g_{ae} = 3\times10^{-21}$

Bound: The photon flux from ALP decays must not exceed the measured CXB by more than 2σ.

EXCLUSION PLOT

- Galactic bound improved by ~ 1 order of magnitude for $g_{ap} \approx 10^{-9}$.
- Many orders of magnitude ecluded: $10^{-20} \lesssim g_{ae} \lesssim 10^{-12}$ for $g_{ap} \approx 10^{-9}$.



CONCLUSIONS

- Supernovae are efficient cosmic laboratories to probe ALPs. We considered ALP production by $NN \to NNa$ process and decay $a \to e^+e^-$ outside the SN.
- The 511 keV photon signal produced by the positron annihilation with environmental electrons can be compared with the SPI data.
- Galactic and extra-galactic SNe: bound on a currently unexplored region of (g_{aN}, g_{ae}).
- Further improvement from future observations and more accurate analysis.

Thanks for your attention

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Back-up slides

ALP DECAYS IN $e^+ e^-$ PAIRS

The ALP decay into photons is negligible when

$$\frac{BR(a \to \gamma\gamma)}{BR(a \to e^+e^-)} = \frac{l_e}{l_\gamma} \sim 10^{-5} \left(\frac{m_a}{10\ \mathrm{MeV}}\right)^2 \left(\frac{10^{-13}}{g_{ae}}\right)^2 \left(\frac{g_{a\gamma}}{10^{-13}\ \mathrm{GeV}^{-1}}\right)^2 \ll 1$$

Condition satisfied for a typical pseudo-Goldstone boson with universal decay constant f, where

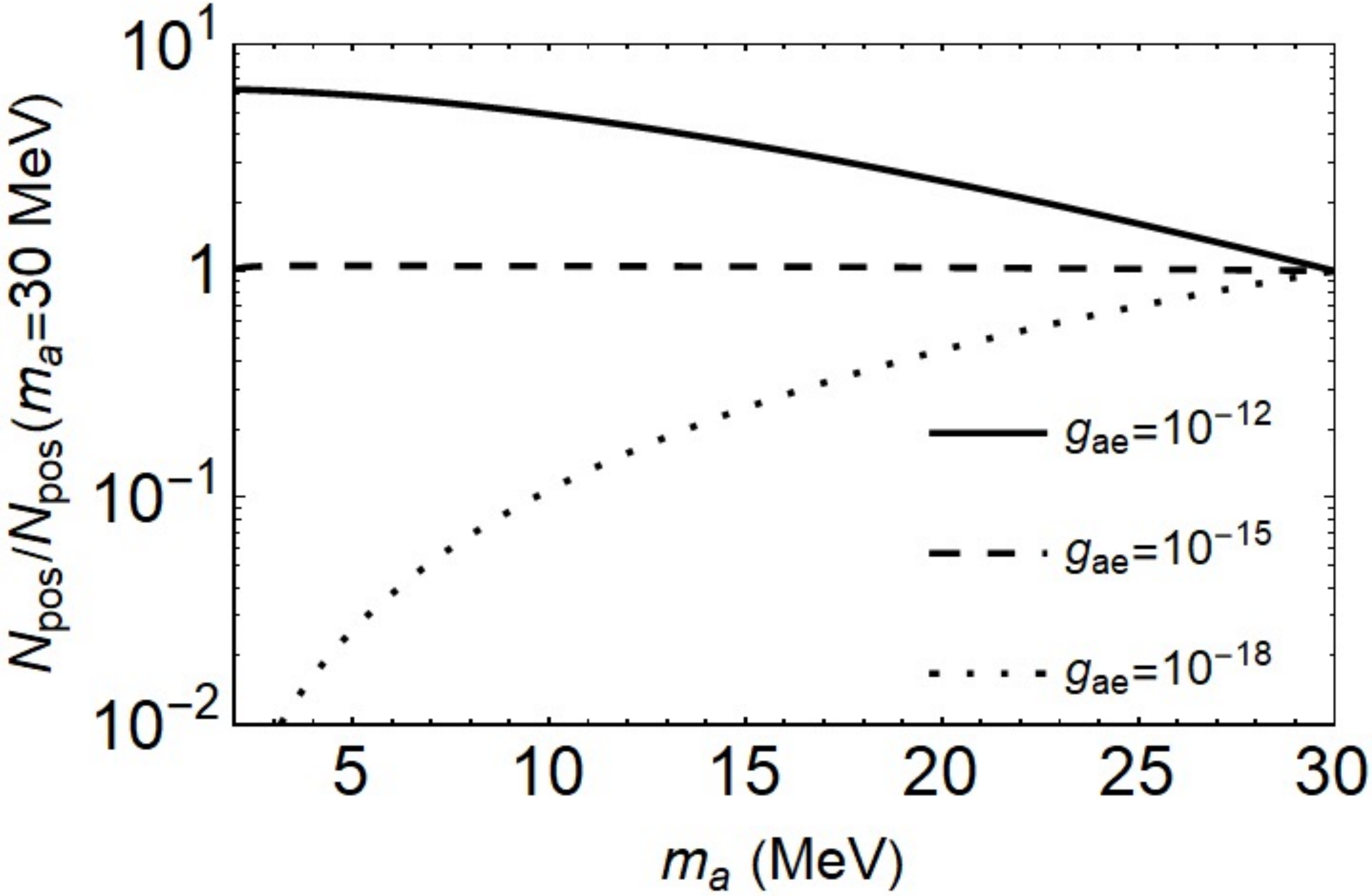
$$g_{ae} \sim \frac{m_e}{f} \sim 10^{-13} \left(\frac{10^{10}\ \mathrm{GeV}}{f}\right) \qquad g_{a\gamma} \sim \frac{\alpha}{4\pi f} \sim 10^{-13}\ \mathrm{GeV}^{-1} \left(\frac{10^{10}\ \mathrm{GeV}}{f}\right) \qquad g_{aN} \sim O(1)\frac{m_N}{f} \sim 10^{-10} \left(\frac{10^{10}\ \mathrm{GeV}}{f}\right)$$

Loop generated photon coupling from the nucleon coupling [Bauer et al., *JHEP 12* (2017)]

$$g_{a\gamma} \sim \frac{\alpha}{6\pi}\frac{m_a^2}{m_N^3}\, g_{aN} \sim 4 \times 10^{-18}\ \mathrm{GeV}^{-1} \left(\frac{m_a}{10\ \mathrm{MeV}}\right)^2 \left(\frac{g_{aN}}{10^{-10}}\right)$$

For $g_{ae} \sim O(10^{-18})$ some tuning may be required to eliminate $g_{a\gamma}$.

ALP MASS EFFECT ON N_{pos}



DETAILS ON SMEARING

The normalized SN distribution [Mirizzi et al., *JCAP* 0605 (2006)]

$$n_{cc} = \sigma_{cc}(r) R_{cc}(z) \ \mathrm{kpc}^{-3}$$

$\sigma_{cc}(r)$ normalized Galactic surface density of cc-SNe
$R_{cc}(r)$ vertical distribution

The smeared SN distribution is given by

$$\sigma'_{cc}(r) = \int_0^{\infty} ds \ \sigma_{cc}(s) \frac{e^{-\frac{|s-r|}{\lambda}}}{2\lambda}$$

$$R'_{cc}(z) = \int_{-\infty}^{+\infty} ds \ R_{cc}(s) \frac{e^{-\frac{|s-r|}{\lambda}}}{2\lambda}$$

Where $\lambda = \min(l_e, r_G)$, with $r_G = 1$ kpc (scale height of the galactic disk) to stay inside the galaxy in all the directions.