Constraining axion-like particles coupled to electrons with gamma rays from recent supernova events

Jorge García García (IAA-CSIC and UGR**)**

In collaboration with

Dr. Marina Cermeño Gavilán (IFT UAM-CSIC)

Dr. Miguel A. Sánchez-Conde (IFT UAM-CSIC)

IAA INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

EXCELENCIA SEVERO OCHOA

UNIVERSITAS · GRANATENSIS · 1531 · PLUS ULTRA

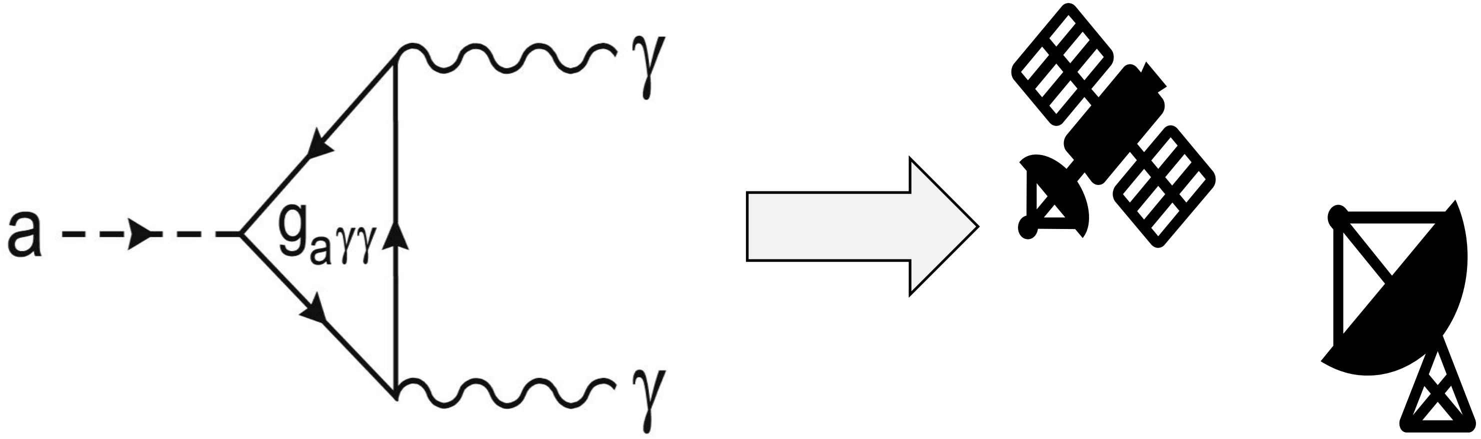
UNIVERSIDAD DE GRANADA

SUPRISE 2025

13 March 2025, IFT Madrid

Motivation

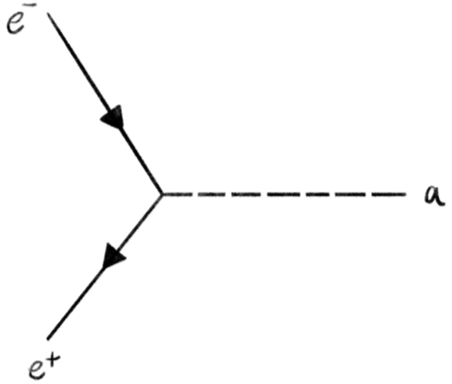
Axion-like particles (ALPs) **coupled to electrons** with masses $m_a \sim 0.1 - 250$ MeV created within the first seconds of core-collapse supernovae (SNe) can decay into gamma-rays

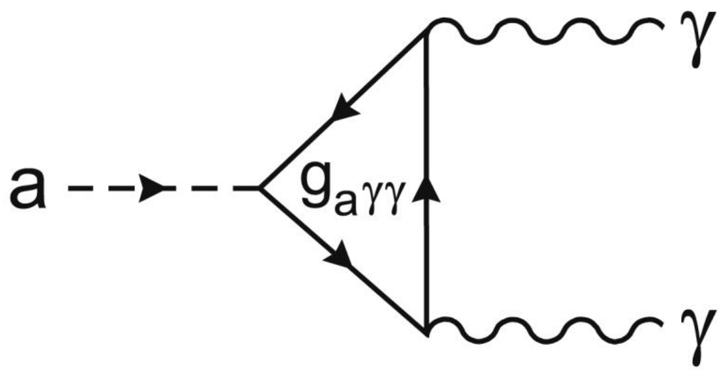


Such process enables searches of ALP-electron couplings with gamma-ray telescopes.
Even if no signal is detected, it will be possible to derive constraints on the relevant parameter space

Motivation

Axion-like particles (ALPs) **coupled to electrons** with masses $m_a \sim 0.1 - 250$ MeV created within the first seconds of core-collapse supernovae (SNe) can decay into gamma-rays





$$\boldsymbol{\mathcal{L}_{ae} = \hat{g}_{ae}\bar{\psi}_e\gamma^\mu\gamma^5\psi_e(\partial_\mu a)}$$

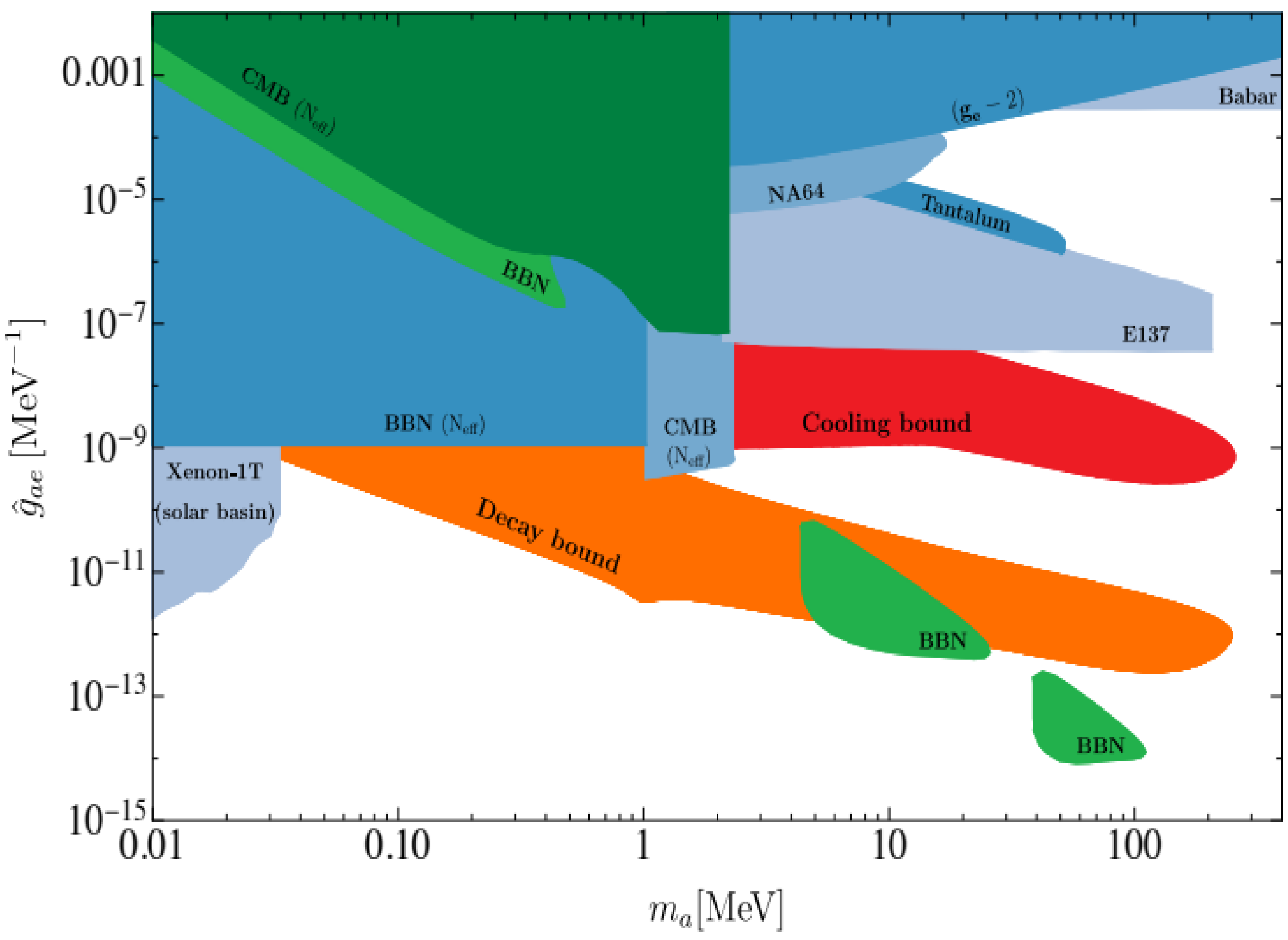
g_{ae}	ALP-e^- coupling
ψ_e	e^- field
a	ALP field
γ^μ, γ^5	Dirac matrices
m_e	e^- mass

$$\boldsymbol{\mathcal{L}_{a\gamma} = -1/4\, g_{a\gamma}F_{\mu\nu}\bar{F}^{\mu\nu}a}$$

$g_{a\gamma}$	ALP-γ coupling
$F_{\mu\nu}$	EM field tensor

$$\boxed{\boldsymbol{\hat{g}_{ae}}} \rightarrow \boxed{\boldsymbol{g_{a\gamma} = \frac{2\alpha}{\pi}\hat{g}_{ae}}}$$

Current ALP-electron bounds



Ferreira, David Marsh and Müller, JCAP 11 (2022) 057

Supernova 2023ixf

- Located in Pinwheel Galaxy at $6.85\ \mathrm{Mpc}$
- Coordinates (l, b) = (101.9º , 59.8º)
- Location allowed measurements in optical range
- The progenitor star had a mass $M{\sim}11.2M_{\odot}$
- Observed by Fermi-LAT in 2023, but not detected
- Fermi-LAT fluence sensitivity for upper limits

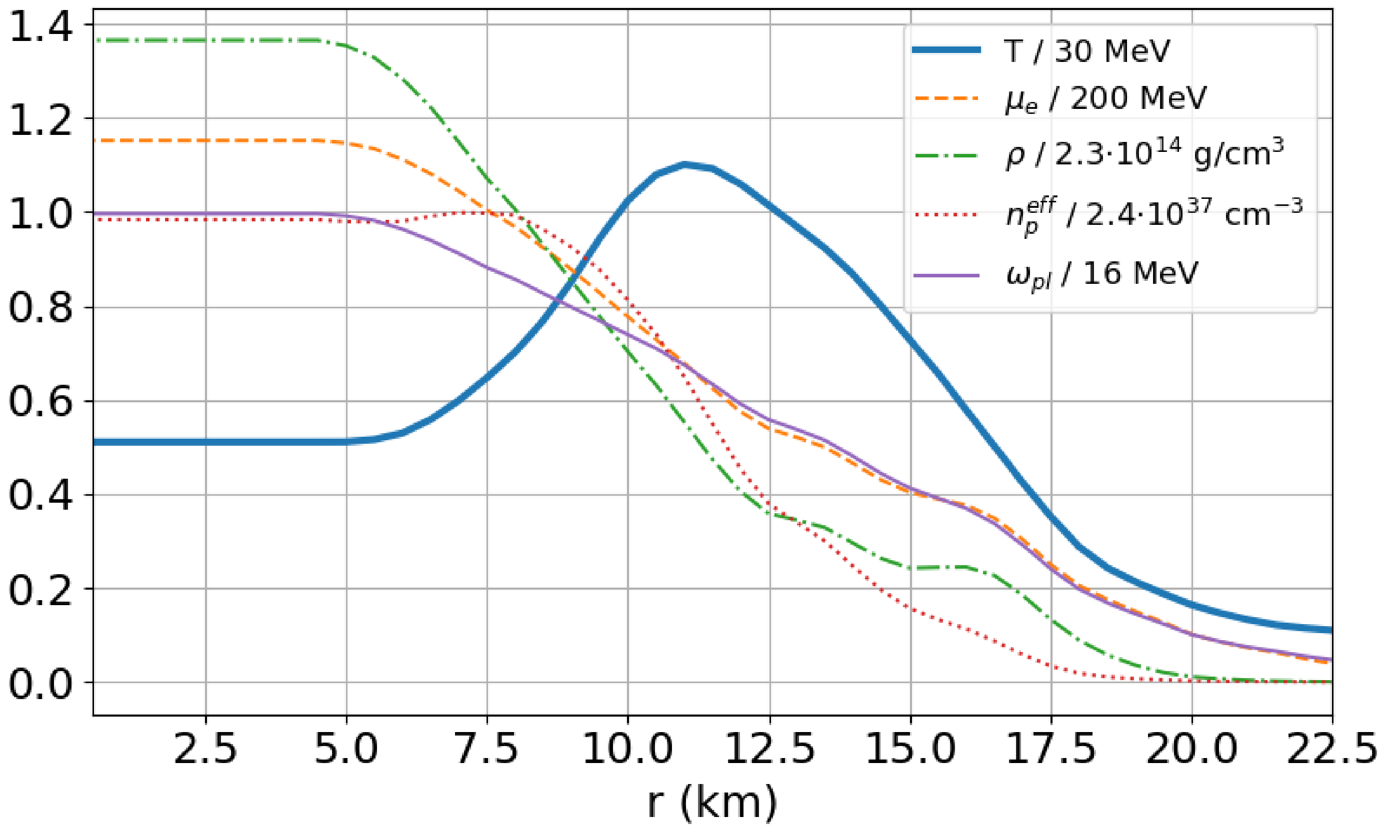
  Sensitivity data taken from Fermi-LAT Performance (SLAC Stanford, accessed: March 2025)

Gemini North Observatory

Supernova conditions

- In the first seconds after explosion, SN cores reach extremely high temperatures T and densities ρ → ALPs could be produced

- In the following 10 s, the proto-neutron star core cools down significantly due to neutrino emission → Inefficient ALP production



OUTPUT

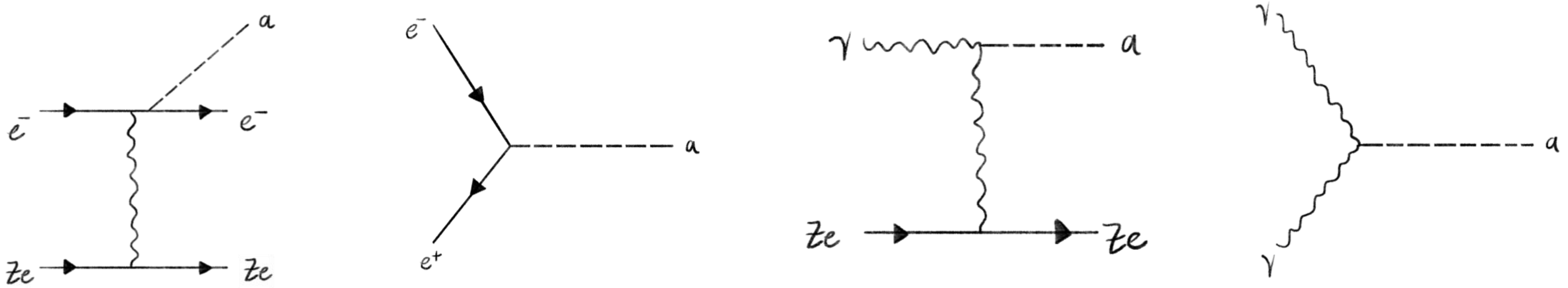
ALP Production Rates

$$n_p{}^{\mathrm{eff}} = 2\int \frac{d^3p}{(2\pi)^3} f_p(1-f_p)$$

$t = 1$ s after bounce, $M_{prog} = 10.8 M_\odot$

Fischer, Tobias, et al. A&A 517, A80 (2010)

ALP production rate in SN



(a) Bremsstrahlung (b) Electron positron fusion (c) Primakoff (d) Photon coalescence

G. G. Raffelt, Phys. Rept. 198, 1 (1990)

$$\frac{d^2n}{d\omega dt} = \left[\prod_i \int \frac{d^3\vec{p}_i}{(2\pi)^3 2E_i} f_i(E_i)\right]\left[\prod_{j\neq a} \int \frac{d^3\overrightarrow{p'}_j}{(2\pi)^3 2E'_j}\left[1 \pm f_j(E'_j)\right]\right] \times (2\pi)^4 \delta^{(4)}\left(\sum_i P_i - \sum_j P'_j\right)\frac{|\vec{p}_a|}{4\pi^2}|\overline{M}|^2$$

$P_i, E_i, \vec{p}_i, P_j', E_j', \vec{p}_j{}'$ four-momentum, energy and tri-momentum of incoming particle i and outgoing particle j

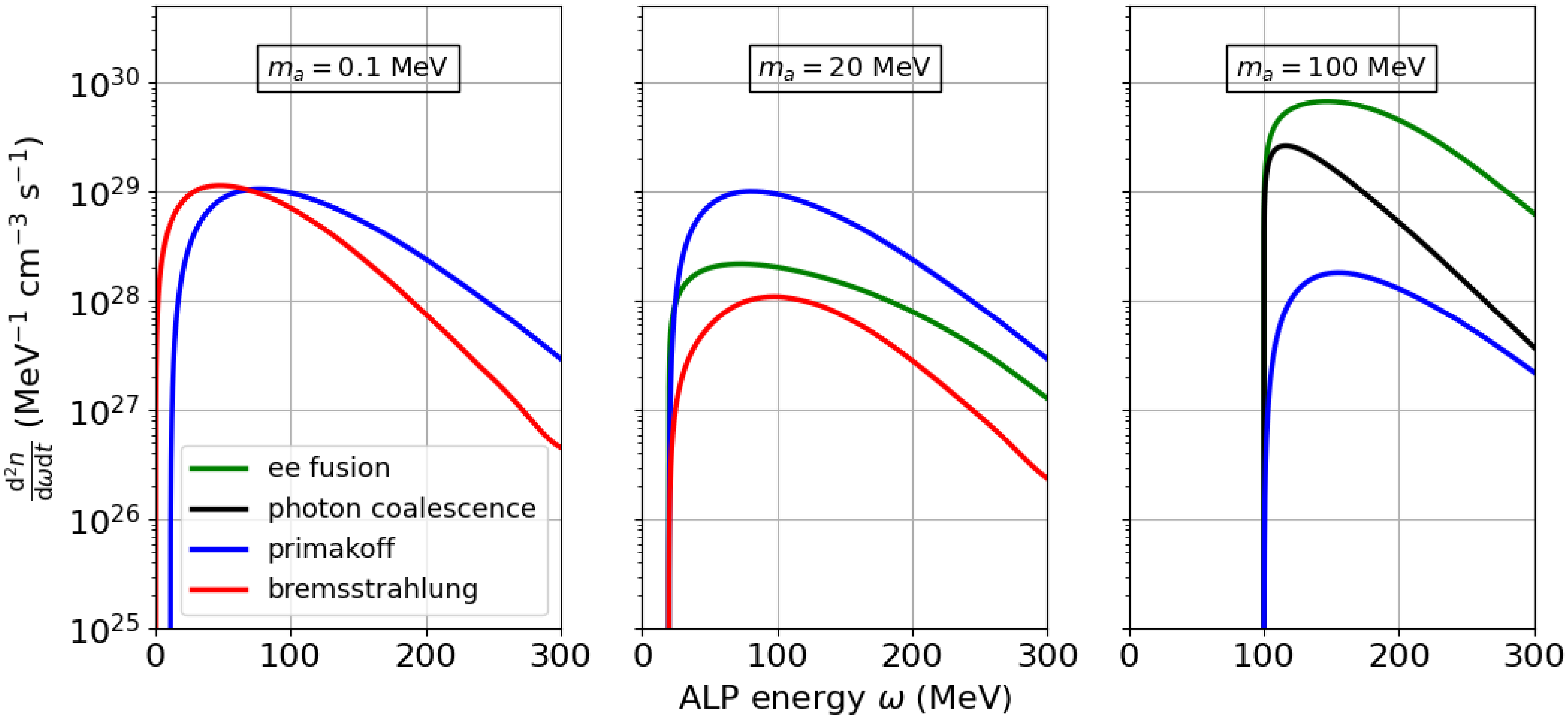
$P'_a, \omega, \vec{p}_a$ ALP four-momentum, energy and tri-momentum

$|\overline{M}|^2$ Feynman amplitude averaged over initial and final states

f_i Fermi-Dirac distribution function for fermions with chemical potential μ_F or Bose-Einstein distribution function for bosons (ALP, γ)

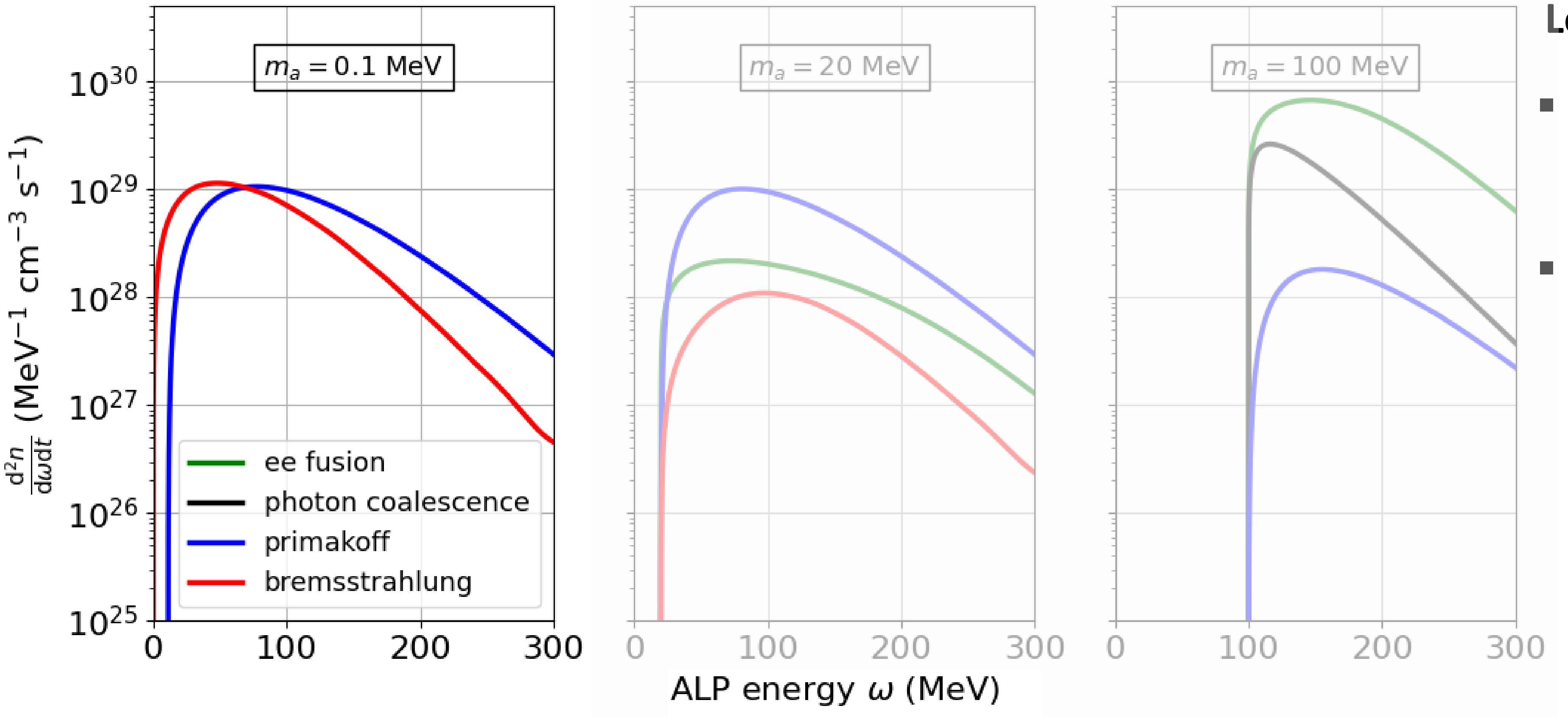
ALP production rate

$t = 1$ s, $\hat{g}_{ae} = 10^{-12}$ MeV^{-1}, $g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}$ for $r \approx 10.5$ km, $T \approx 30$ MeV



ALP production rate

$t = 1$ s, $\hat{g}_{ae} = 10^{-12}$ MeV^{-1}, $g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}$ for $r \approx 10.5$ km, $T \approx 30$ MeV

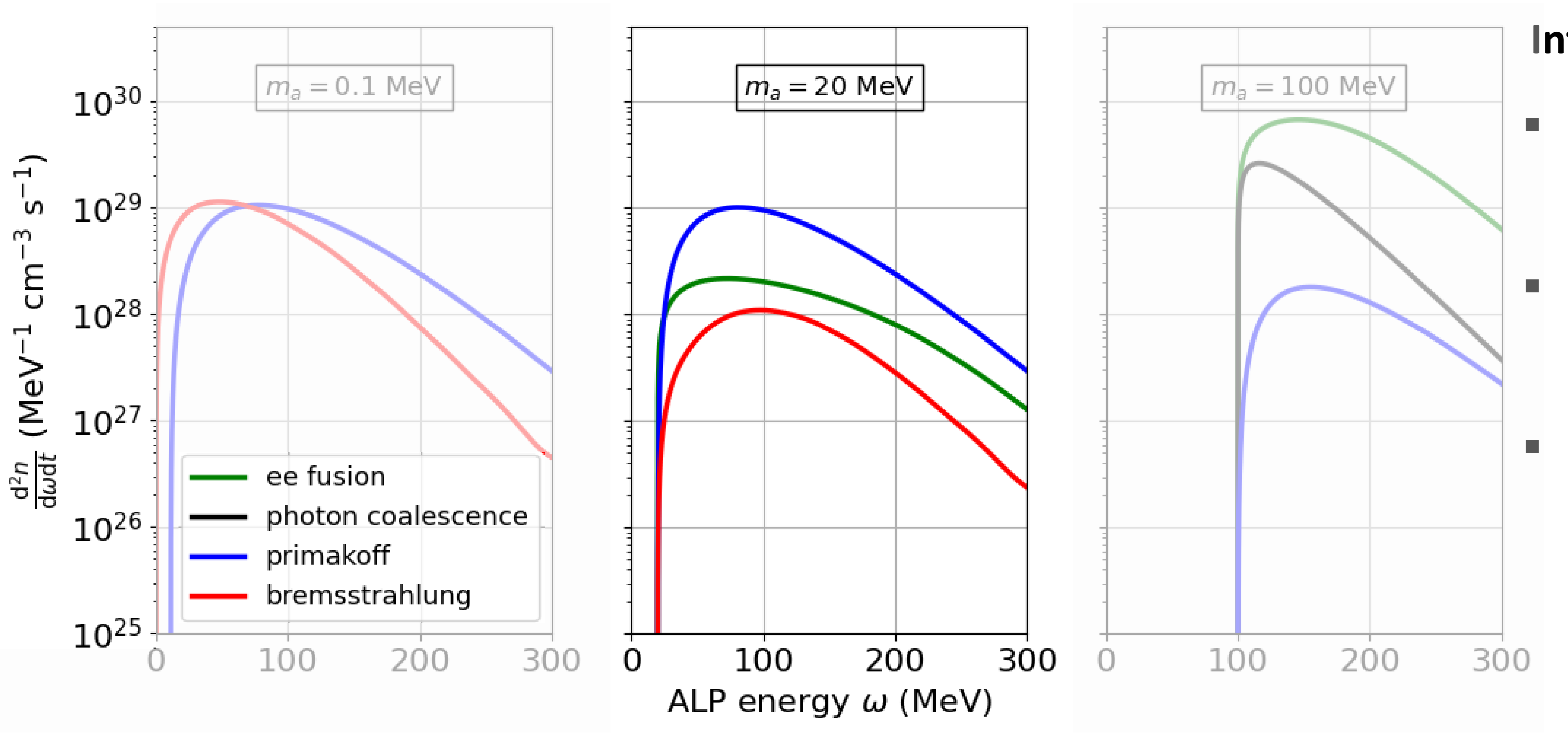


Low ALP masses:

- Only Primakoff and Bremsstrahlung allowed
- Inverse decay processes kinematically forbidden

ALP production rate

$t = 1$ s, $\hat{g}_{ae} = 10^{-12}$ MeV^{-1}, $g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}$ for $r \approx 10.5$ km, $T \approx 30$ MeV

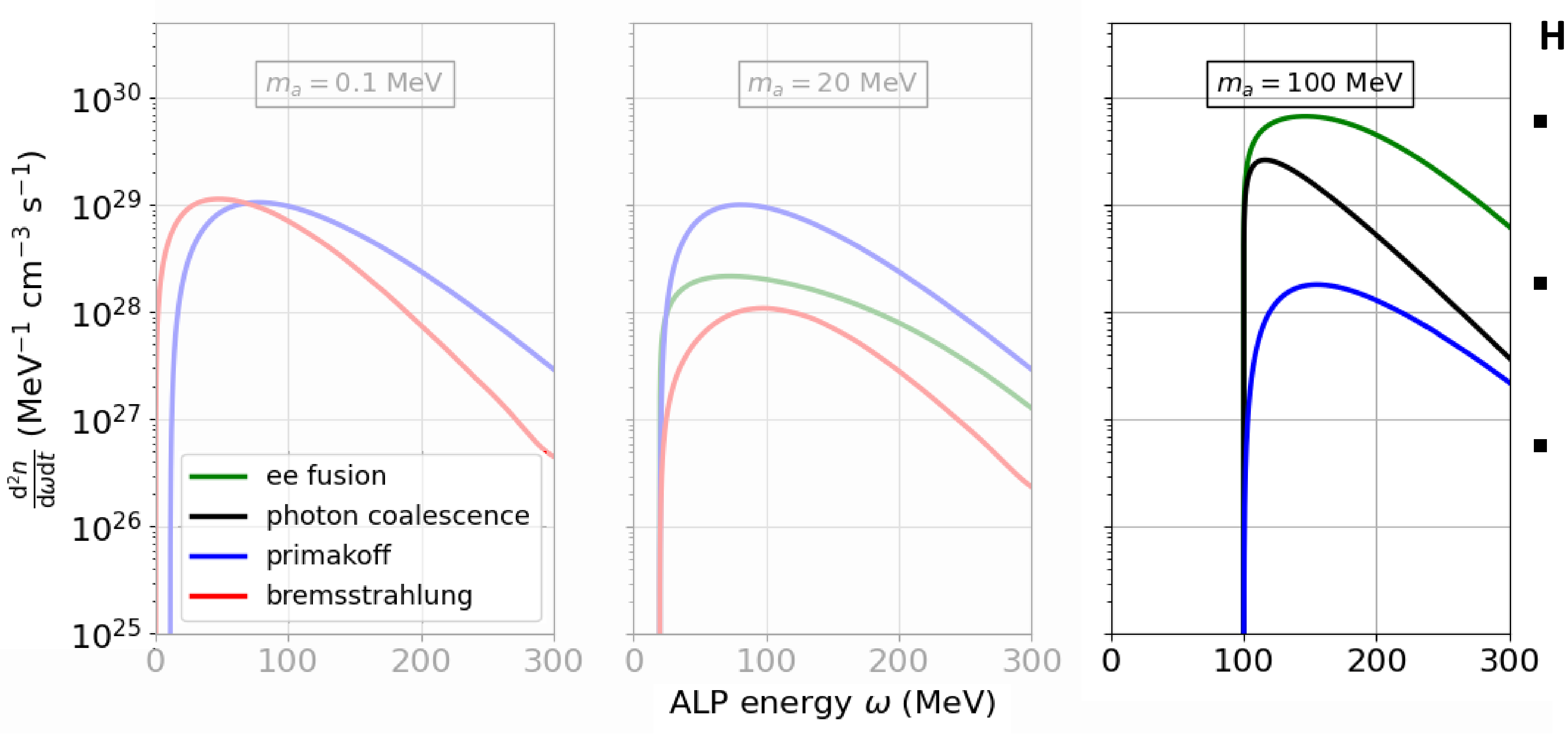


Intermediate ALP masses:

- Inverse decay processes allowed
- e^+e^- fusion and Primakoff dominate
- Bremsstrahlung at least one order of magnitude below most important process for $m_a > 22$ MeV

ALP production rate

$t = 1$ s, $\hat{g}_{ae} = 10^{-12}$ MeV^{-1}, $g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}$ for $r \approx 10.5$ km, $T \approx 30$ MeV

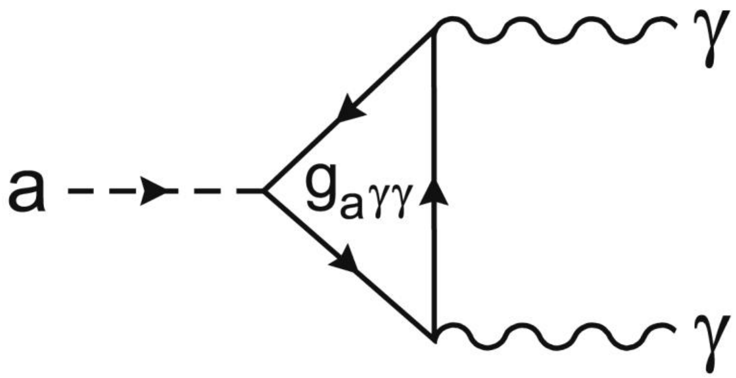


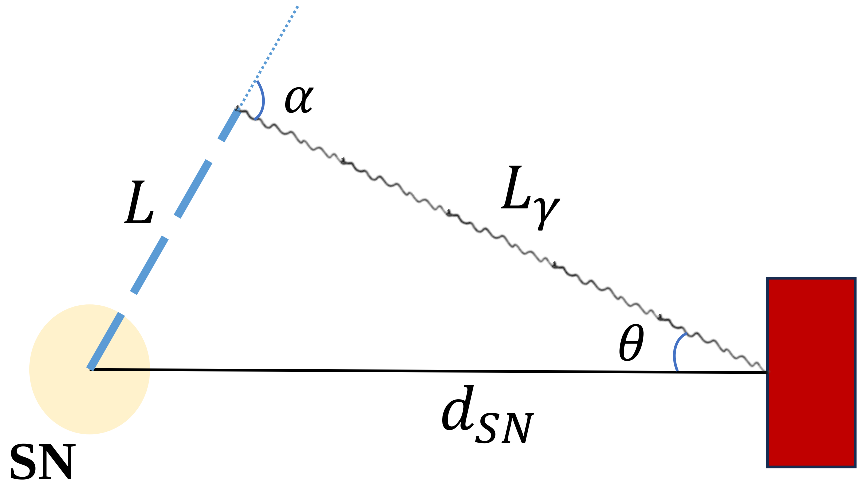
Heavy ALP masses:

- Electron positron fusion most relevant
- Primakoff now the least efficient one.
- Not enough free energy available inside the SN plasma to create ALPs with $m_a > 250$ MeV

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays



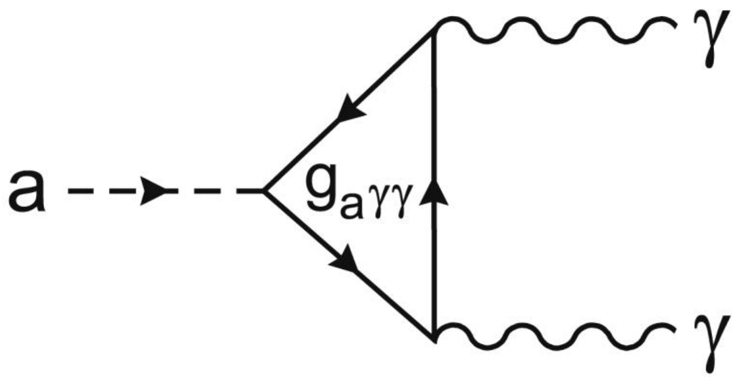


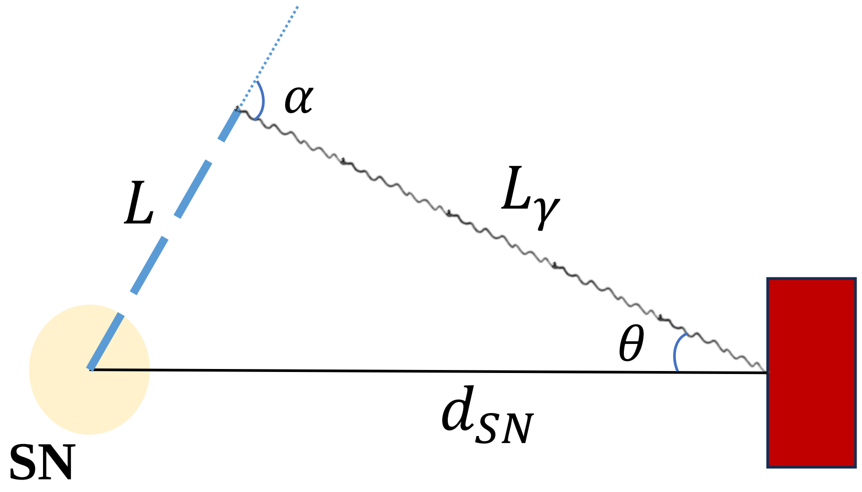
Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

$$\mathrm{d}F_\gamma = 2\,\mathrm{BR}_{a\to\gamma\gamma}\,\frac{\mathrm{d}N/\mathrm{d}\omega}{4\pi {d_{SN}}^2}\,\mathrm{d}\omega\; f_{c_\alpha}(\omega, c_\alpha)\mathrm{d}c_\alpha\;\frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\,\mathrm{d}L\;\Theta_{\mathrm{cons}}(\omega, c_\alpha, L)$$

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays





Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

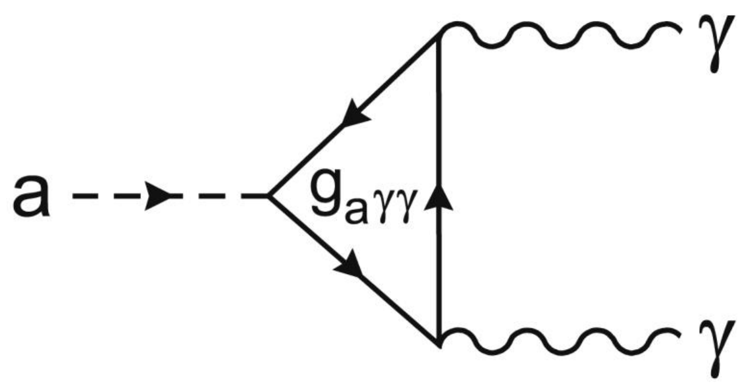
$$\mathrm{d}F_\gamma = 2\,\mathrm{BR}_{a\to\gamma\gamma}\,\frac{dN/d\omega}{4\pi {d_{SN}}^2}\mathrm{d}\omega\, f_{c_\alpha}(\omega, c_\alpha)\mathrm{d}c_\alpha\,\frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\mathrm{d}L\,\Theta_{\mathrm{cons}}(\omega, c_\alpha, L)$$

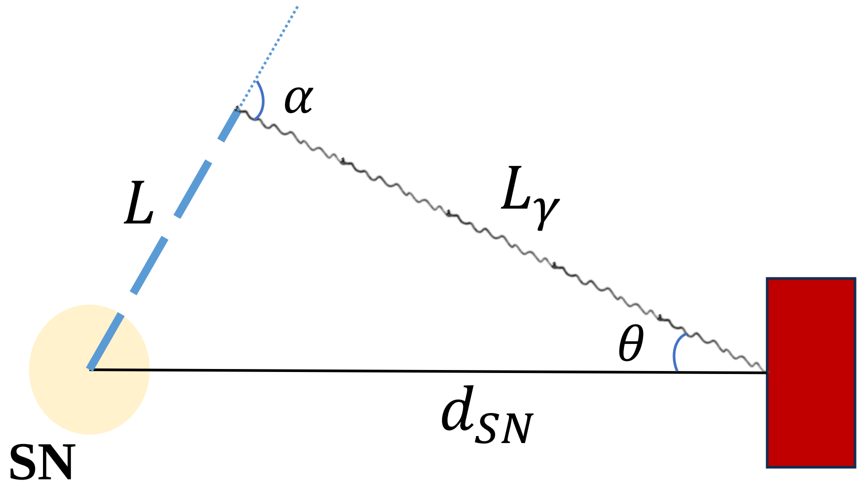
Spectral fluence of ALPs that come from isotropic production spectrum

$$\frac{\mathrm{dN}}{\mathrm{d}\omega}(\omega) = \int_0^{R_{max}} \mathrm{dr}4\pi r^2 \int_{t_{min}}^{t_{max}} \mathrm{dt}\,\frac{\mathrm{d}^2 n}{\mathrm{d}\omega\mathrm{dt}}(r,t,\omega)\Bigg|_{\substack{R_{max}=23\text{ km}\\ t_{min}=0.5\text{ s}\\ t_{max}=2\text{ s}}}$$

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays





Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

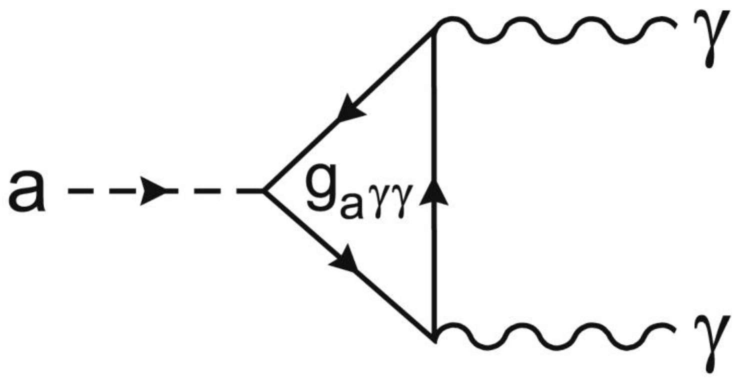
$$dF_\gamma = 2\,\mathrm{BR}_{a\to\gamma\gamma}\,\frac{dN/d\omega}{4\pi {d_{SN}}^2}\,d\omega\,\boldsymbol{f_{c_\alpha}(\omega, c_\alpha)}\,dc_\alpha\,\frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\,dL\,\Theta_{\mathrm{cons}}(\omega, c_\alpha, L)$$

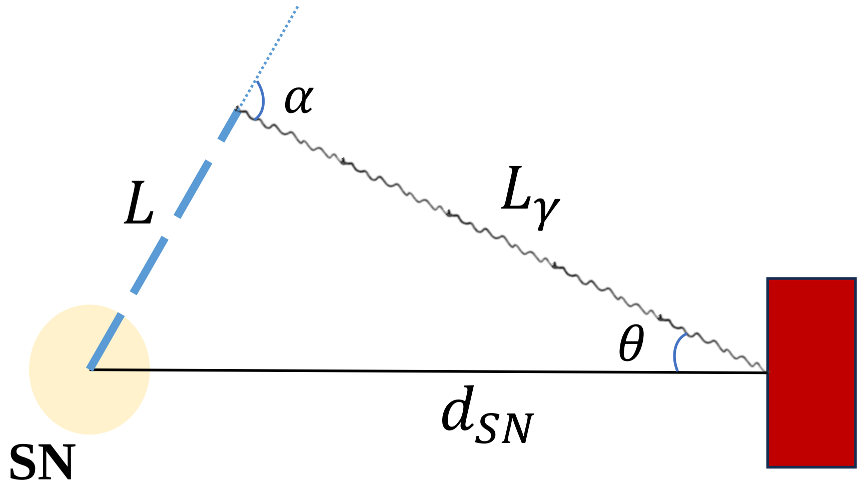
Distribution function of the angle $\boldsymbol{\alpha}$

$$f_{c_\alpha}(\omega, c_\alpha) = \frac{m_a^2}{2\omega^2(1 - c_\alpha \cdot \beta_a)^2}, \quad \beta_a = \sqrt{1 - \left(\frac{m_a}{\omega}\right)^2}$$

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays





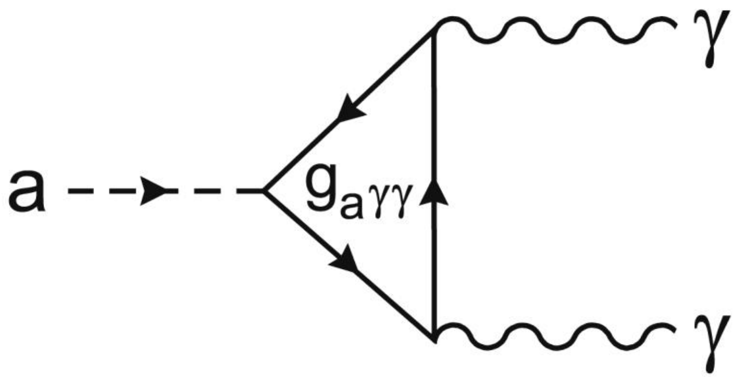
Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

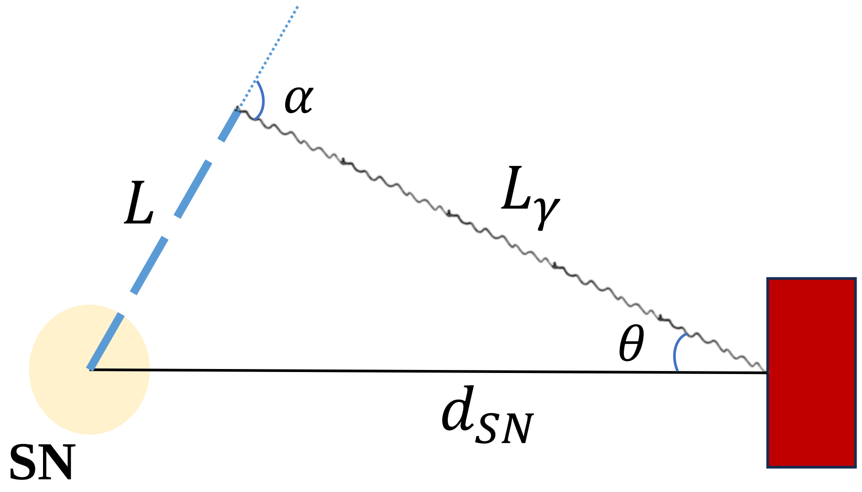
$$\mathrm{d}F_\gamma = 2\ \mathrm{BR}_{a\to\gamma\gamma} \frac{\mathrm{d}N/\mathrm{d}\omega}{4\pi {d_{SN}}^2} \mathrm{d}\omega\ f_{c_\alpha}(\omega, c_\alpha)\mathrm{d}c_\alpha \frac{\boldsymbol{\exp[-L/l_a(\omega)]}}{\boldsymbol{l_a(\omega)}} \mathrm{d}L\ \Theta_{\mathrm{cons}}(\omega, c_\alpha, L)$$

Probability of the ALP to decay at L to $L + \mathrm{d}L$, $l_a(\omega)$ decay length of the ALP

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays





Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

$$\mathrm{d}F_\gamma = 2\,\mathrm{BR}_{a\to\gamma\gamma}\,\frac{\mathrm{d}N/\mathrm{d}\omega}{4\pi {d_{SN}}^2}\,\mathrm{d}\omega\; f_{c_\alpha}(\omega, c_\alpha)\mathrm{d}c_\alpha\;\frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\,\mathrm{d}L\;\boldsymbol{\Theta}_{\mathbf{cons}}(\boldsymbol{\omega}, \boldsymbol{c_\alpha}, \boldsymbol{L})$$

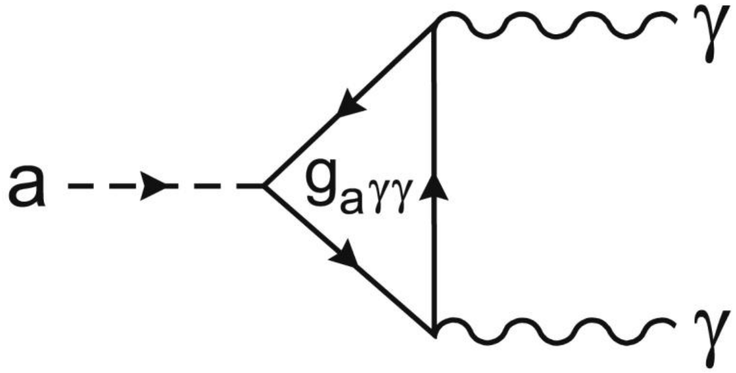
$$\boldsymbol{\Theta}_{\mathbf{cons}}(\boldsymbol{\omega}, \boldsymbol{c_\alpha}, \boldsymbol{L}) \equiv \Theta(L - R_*)\,\Theta(c_\theta(c_\alpha, L) - c_\alpha)\,\Theta(c_\theta(c_\alpha, L))$$
$$\Theta(\omega_\gamma(c_\alpha, \omega) - 50\text{ MeV}),$$

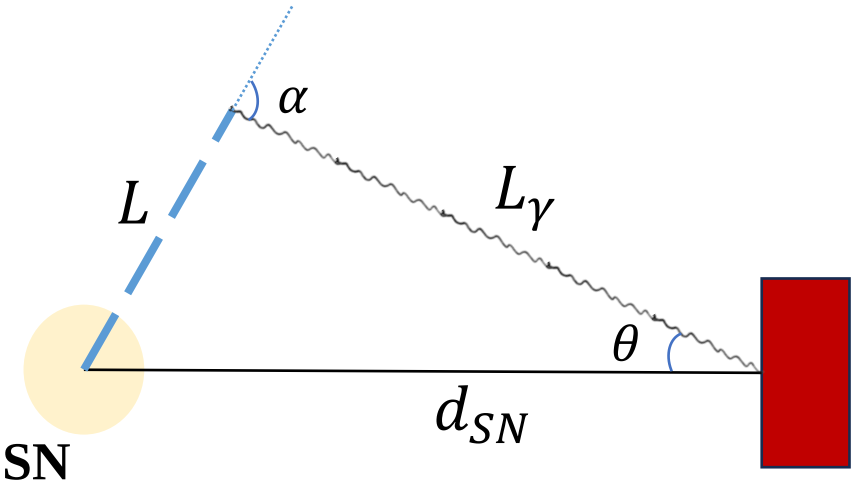
$R_* \approx 3\;10^8$ km radius of SN2023ixf including surrounding plasma

Joshua N. Benabou, Claudio Andrea Manzari et. al., [arXiv:2412.13247]

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays





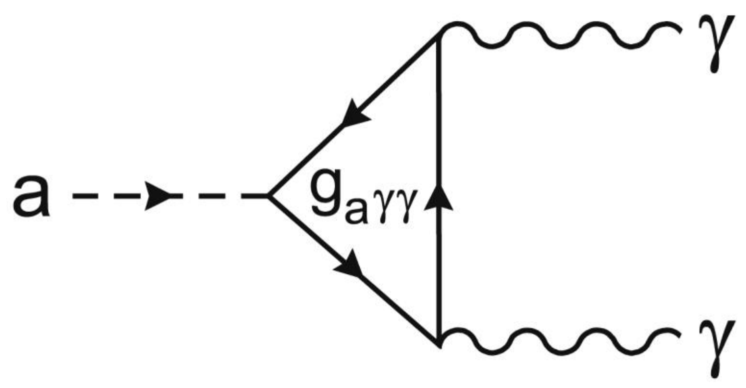
Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

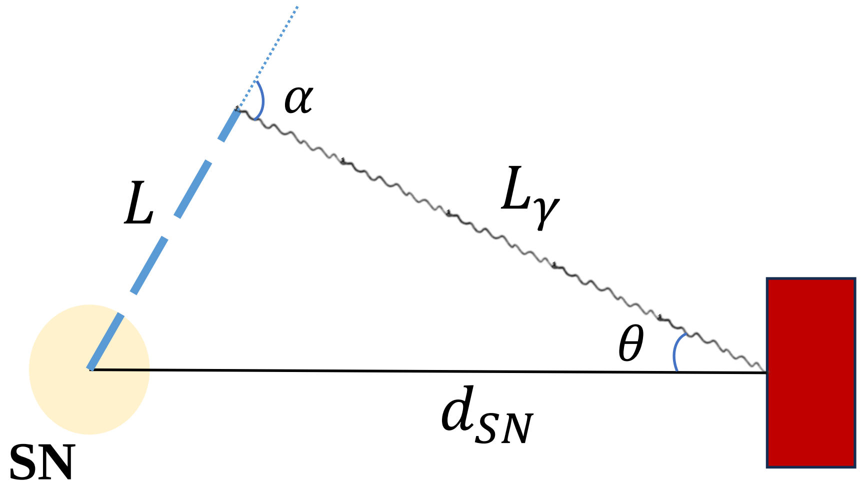
$$\mathrm{d}F_\gamma = \mathbf{2}\ \mathrm{BR}_{a\to\gamma\gamma}\ \frac{\mathrm{d}N/\mathrm{d}\omega}{4\pi {d_{SN}}^2}\mathrm{d}\omega\ f_{c_\alpha}(\omega, c_\alpha)\mathrm{d}c_\alpha\ \frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\mathrm{d}L\ \Theta_{\mathrm{cons}}(\omega, c_\alpha, L)$$

Number of photons produced in one decay

Photon fluence from ALP decay

ALPs generated in the SN leave the core and decay into two gamma rays





Photon fluence expected on Earth (at a distance d_{SN} from the SN): *Ferreira, David Marsh and Müller, JCAP 11 (2022) 057*

$$\mathrm{d}F_\gamma = 2\,\mathbf{BR}_{a\to\gamma\gamma}\,\frac{\mathrm{d}N/\mathrm{d}\omega}{4\pi {d_{SN}}^2}\mathrm{d}\omega\; f_{c_\alpha}(\omega, c_\alpha)\mathrm{d}c_\alpha\,\frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\mathrm{d}L\;\Theta_{\mathrm{cons}}(\omega, c_\alpha, L)$$

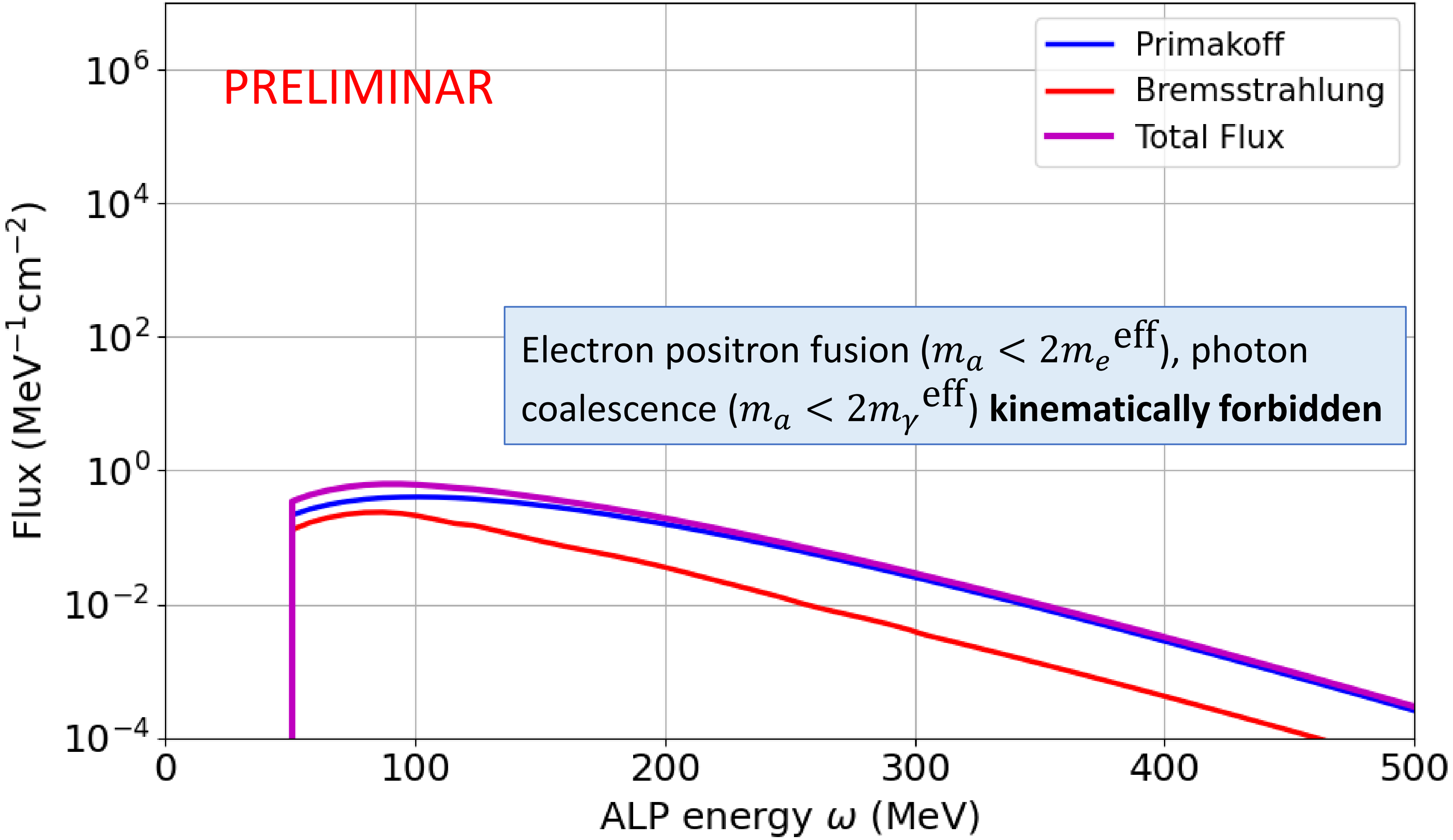
Fraction of ALPs that decay into photons

$$BR_{a\to\gamma\gamma} = \frac{\Gamma_0^{a\to\gamma\gamma}}{\Gamma_0^{a\to\gamma\gamma} + \Gamma_0^{a\to e^- e^+}}$$

$\Gamma_0^{a\to\gamma\gamma}, \Gamma_0^{a\to e^- e^+}$ are the decay widths of ALP-photon decay and ALP-electron decay

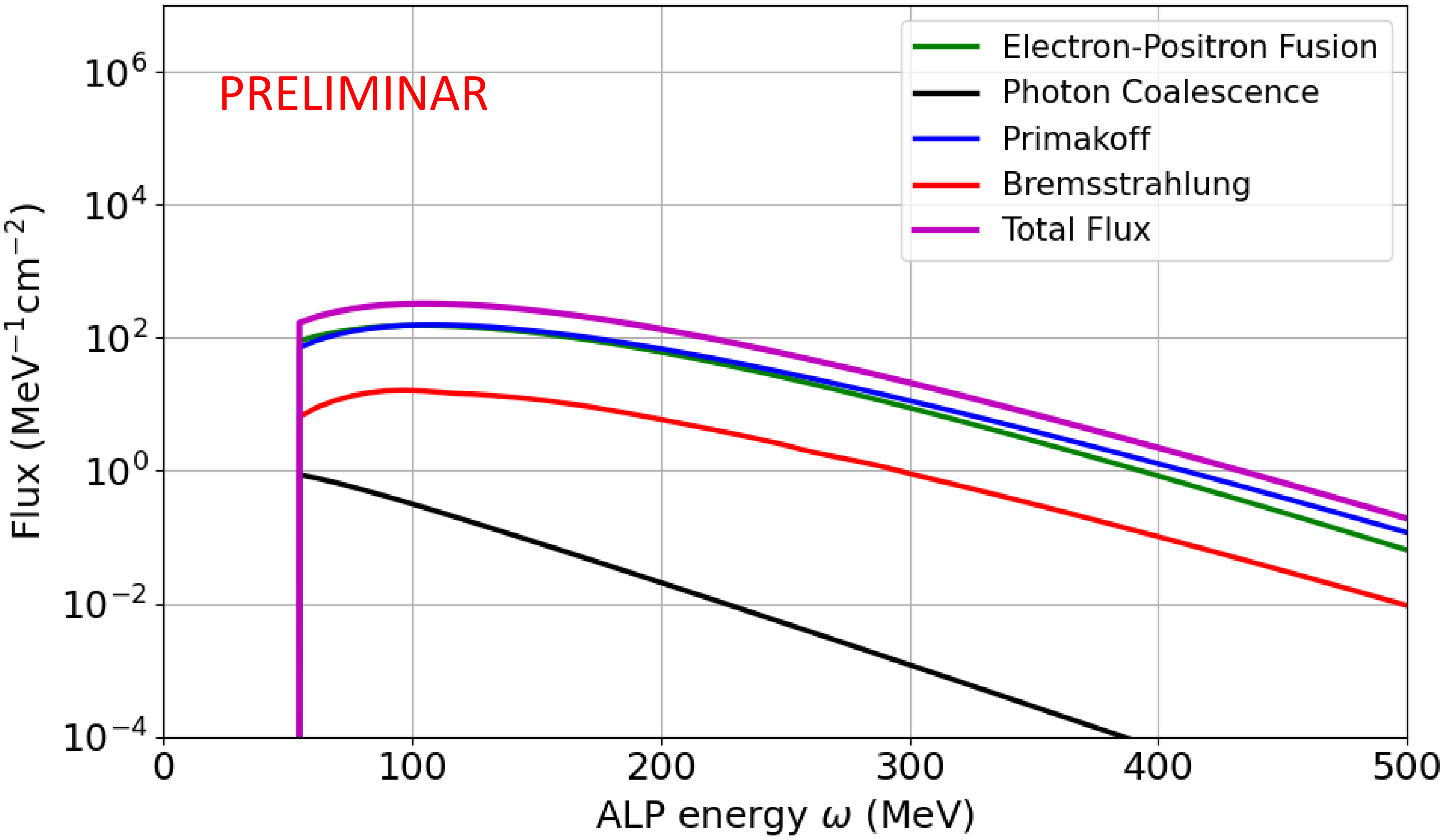
Expected fluence with energy

$$\hat{g}_{ae} = 10^{-12}\ \text{MeV}^{-1},\ g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}\ ,\ \boldsymbol{m_a} = \mathbf{0.1\ MeV}$$



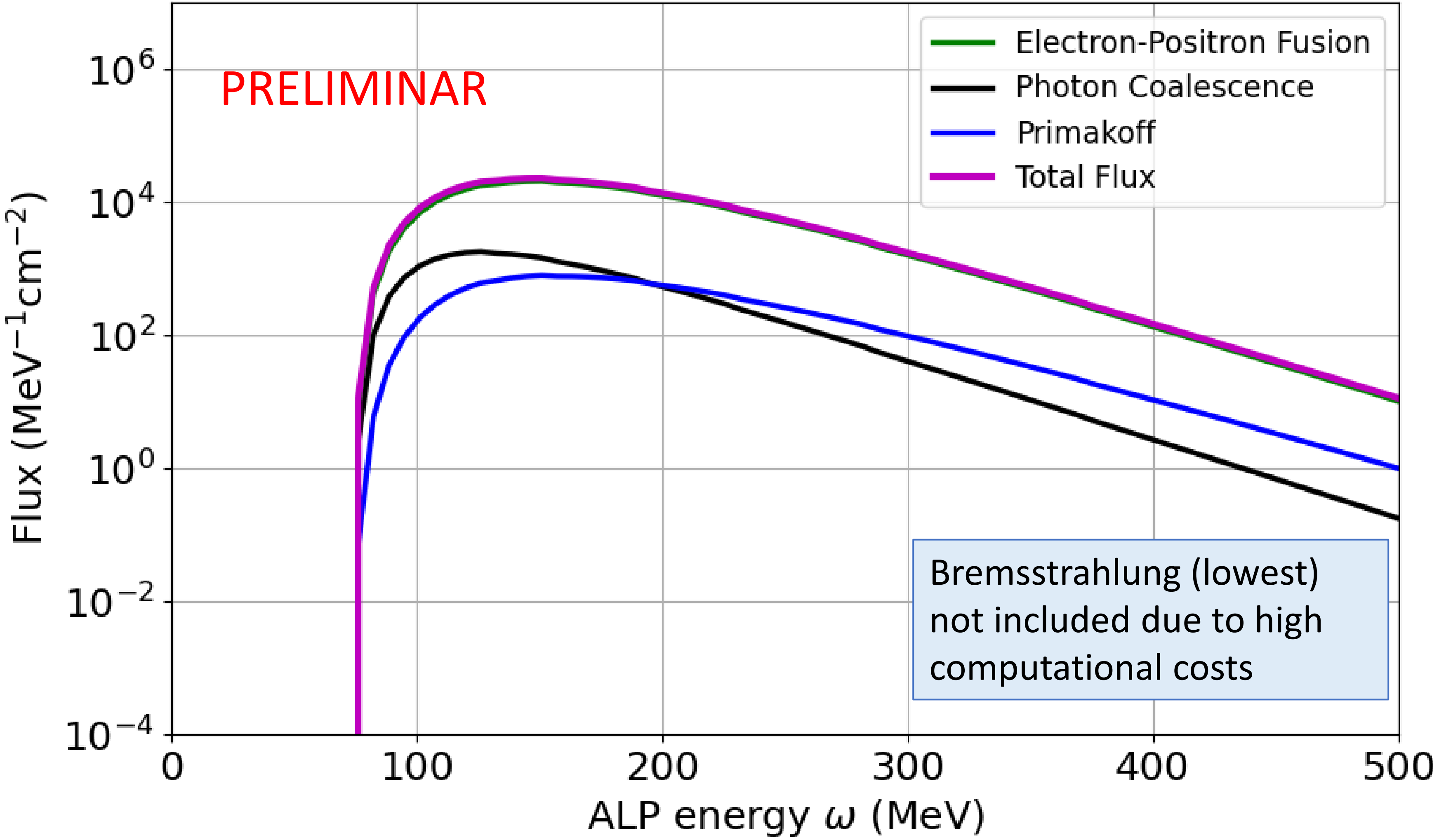
Expected fluence with energy

$\hat{g}_{ae} = 10^{-12}\ \text{MeV}^{-1}$, $g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}$, $\boldsymbol{m_a} = \mathbf{20\ MeV}$



Expected fluence with energy

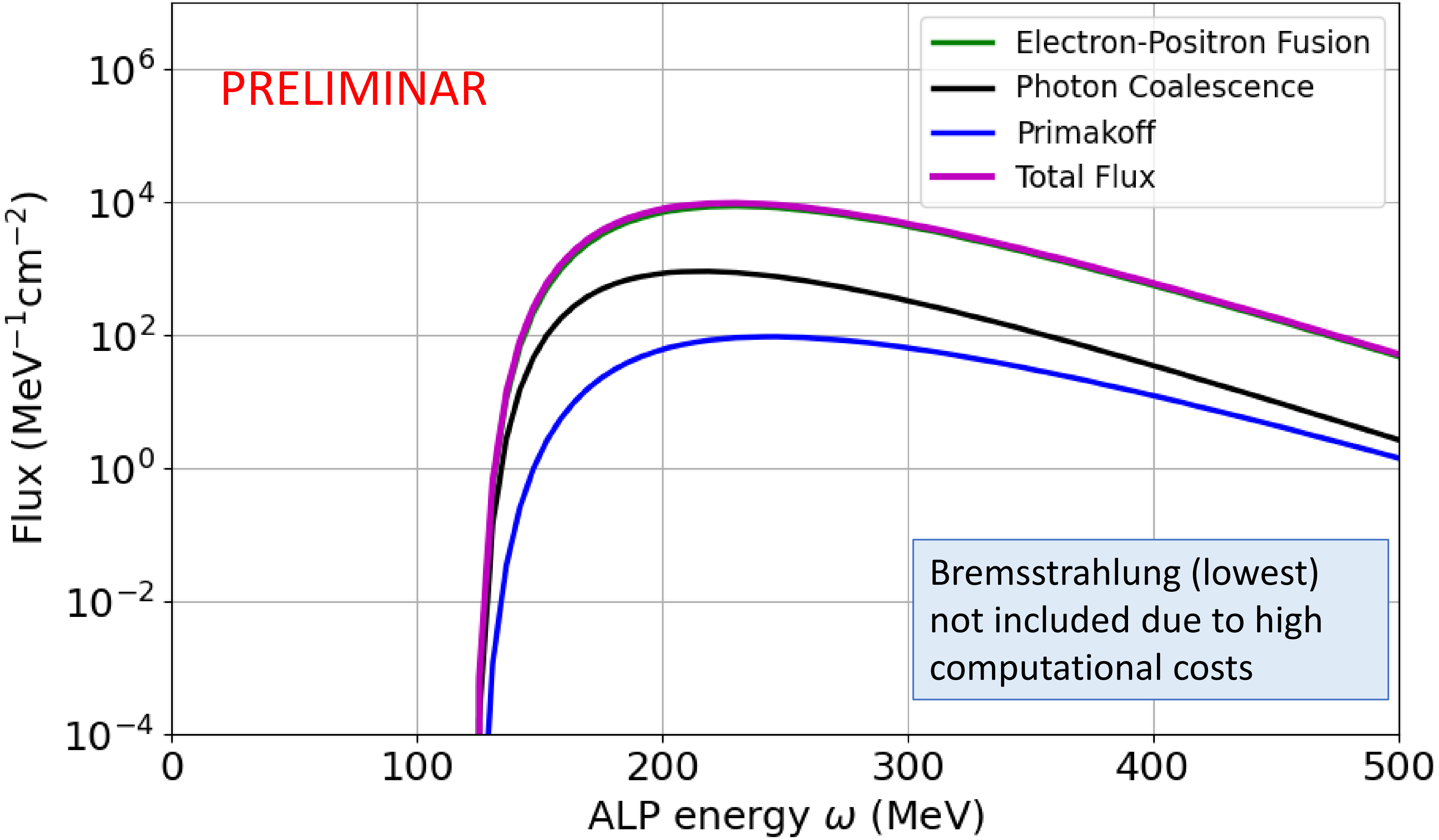
$$\hat{g}_{ae} = 10^{-12}\ \mathrm{MeV}^{-1},\ g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}\ ,\ \boldsymbol{m_a} = \mathbf{70\ MeV}$$



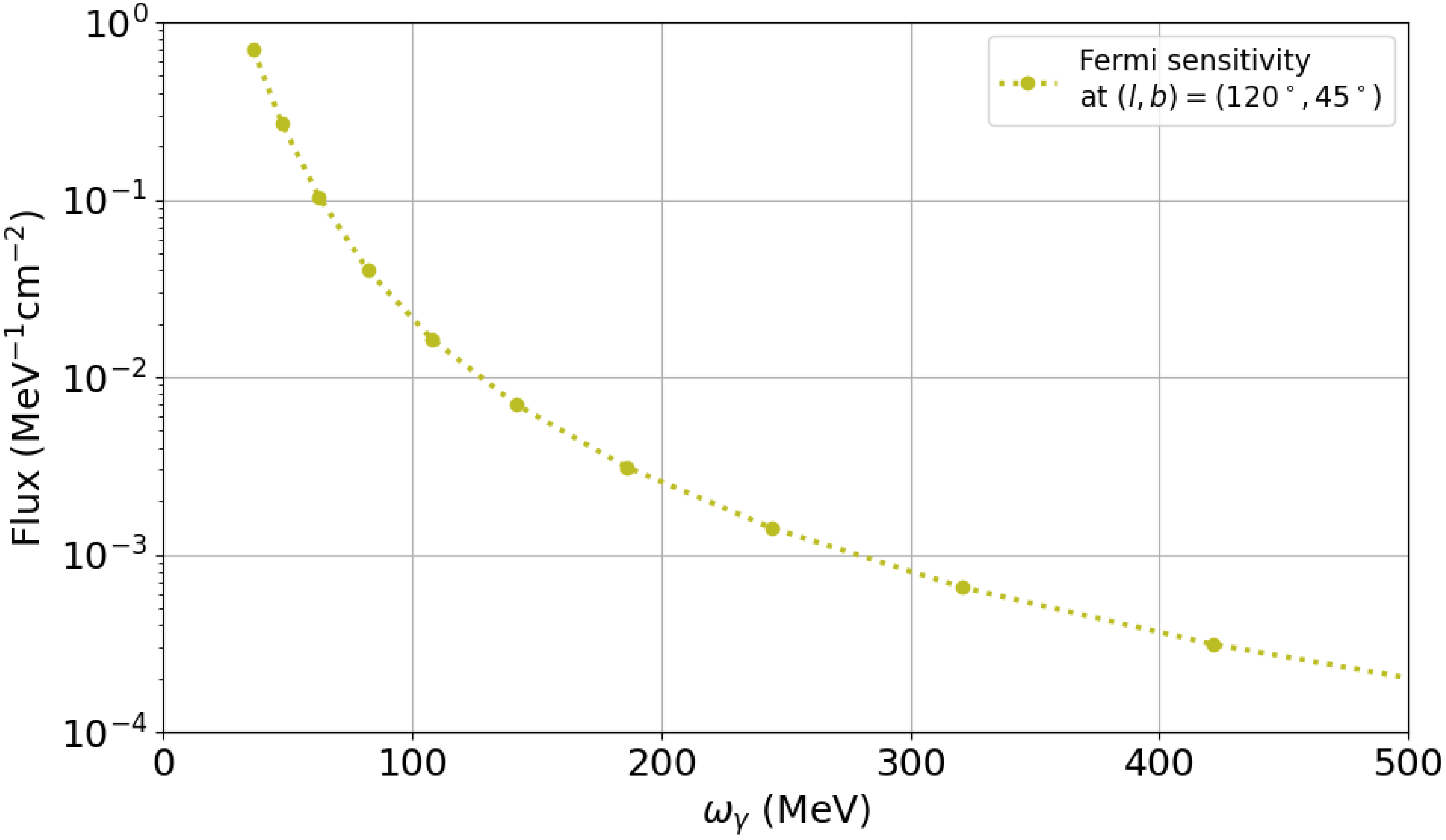
Bremsstrahlung (lowest) not included due to high computational costs

Expected fluence with energy

$$\hat{g}_{ae} = 10^{-12}\ \text{MeV}^{-1},\ g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}\ ,\ \boldsymbol{m_a} = \mathbf{120\ MeV}$$



Fermi-LAT fluence sensitivity



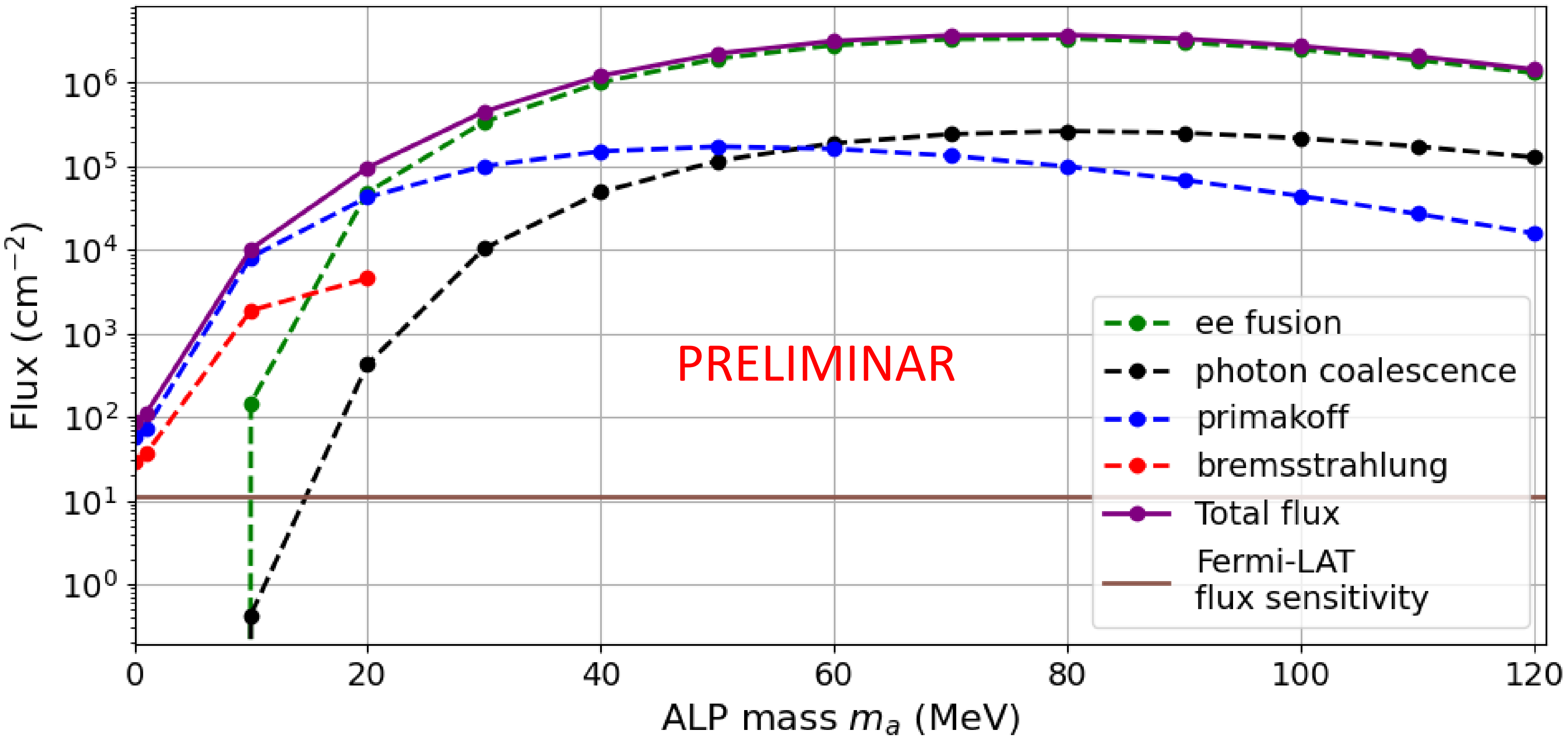
10 years calibration data

$$\boxed{F_\gamma \leq 11.42\ \mathrm{cm}^{-2}}$$

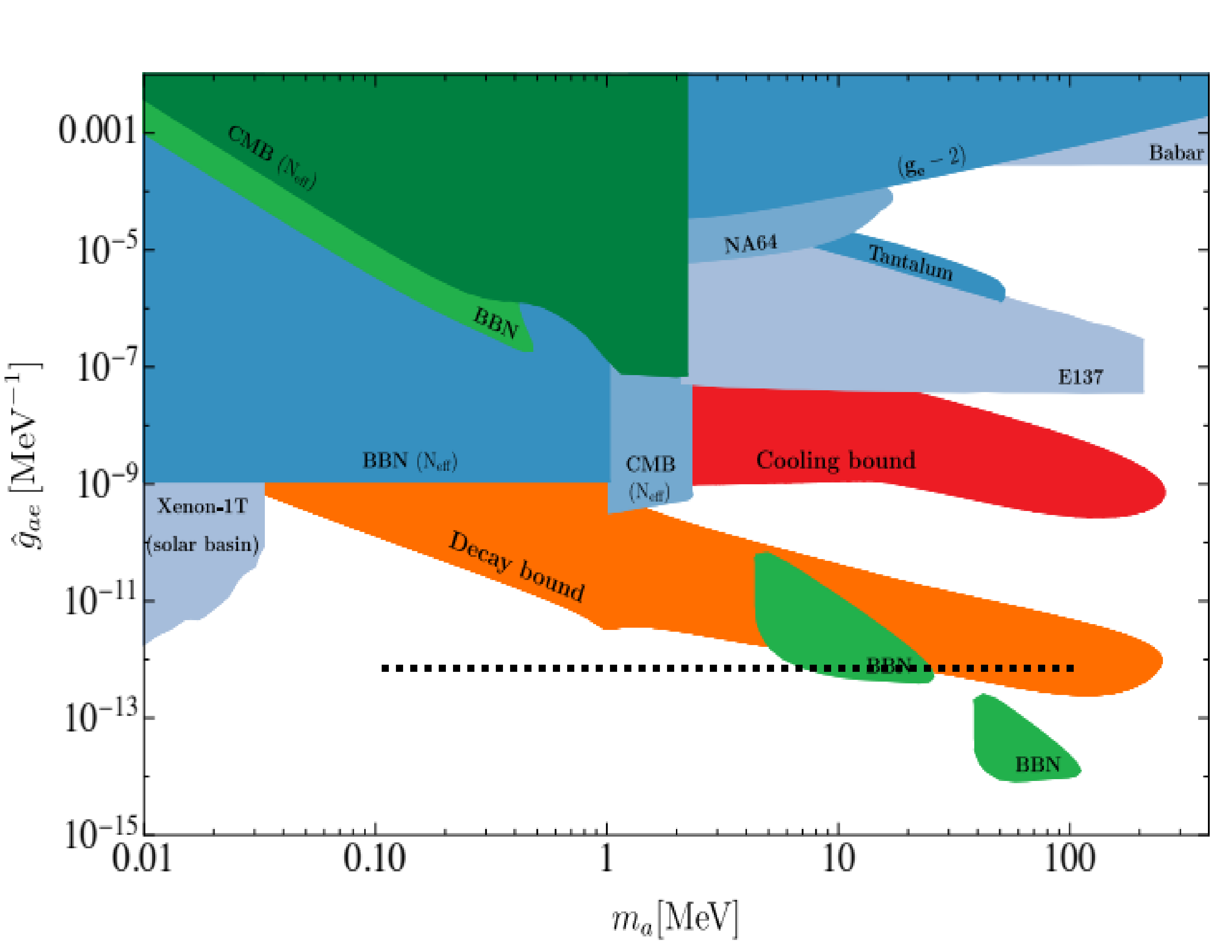
Decay bound

Expected flux

$\hat{g}_{ae} = 10^{-12}$ MeV^{-1}, $g_{a\gamma} = 2\alpha/\pi\hat{g}_{ae}$, TOTAL FLUX



The path for new exclusion regions



PRELIMINAR

Ferreira, David Marsh and Müller, JCAP 11 (2022) 057

Conclusions and next steps

1. Calculation of the ALP production rate in core-collapse SN for ALP coupled to electrons via electron positron fusion, photon coalescence, Primakoff and Bremsstrahlung in first seconds after explosion

2. For masses below 20 MeV, only Primakoff and Bremsstrahlung allowed, whereas for heavier ALPs , e^+e^- fusion dominates, whereas Primakoff and Bremsstrahlung least efficient

3. The computed fluence exceeds the flux sensitivity of Fermi-LAT in some regions of the ALP parameter space that have not yet been excluded.

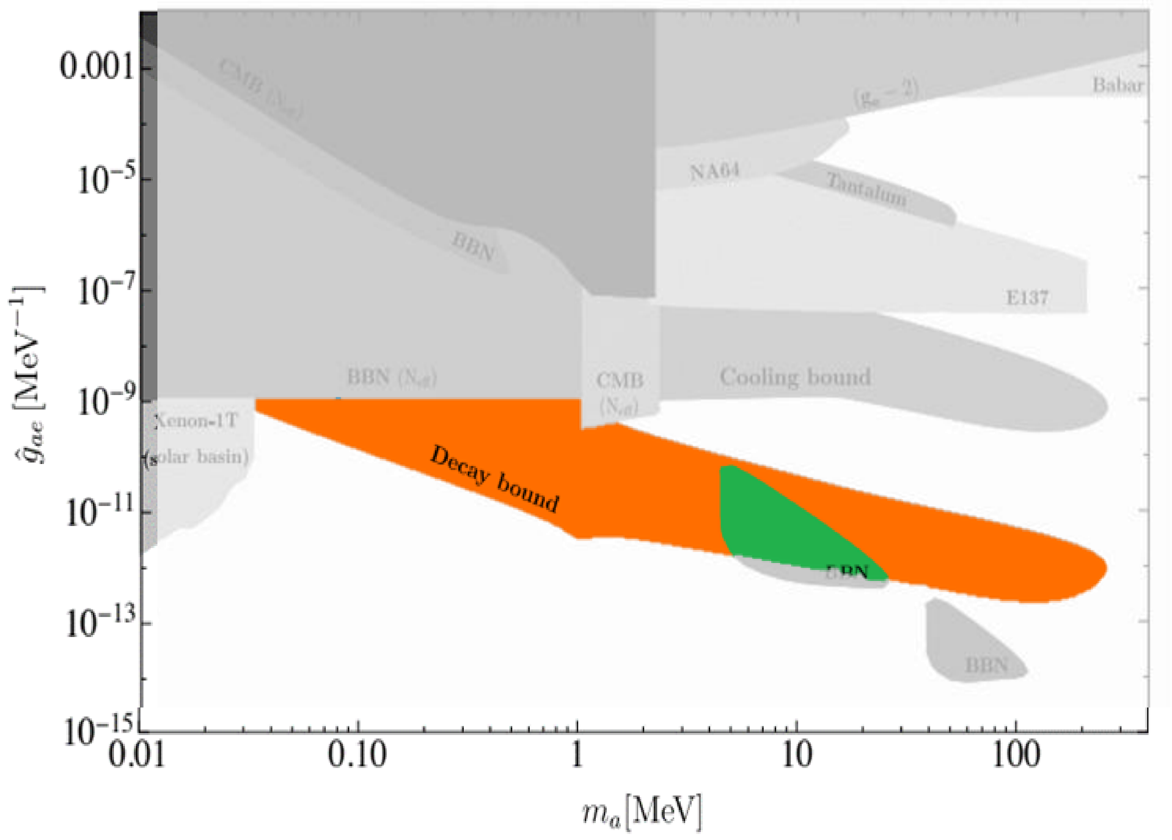
4. Now working on the implementation of new exclusion regions

Thank you!

BACKUP

Exclusion regions electron-ALP coupling vs ALP mass

ALP coupling to electrons at tree level and to photons at one loop level for SN 1987A

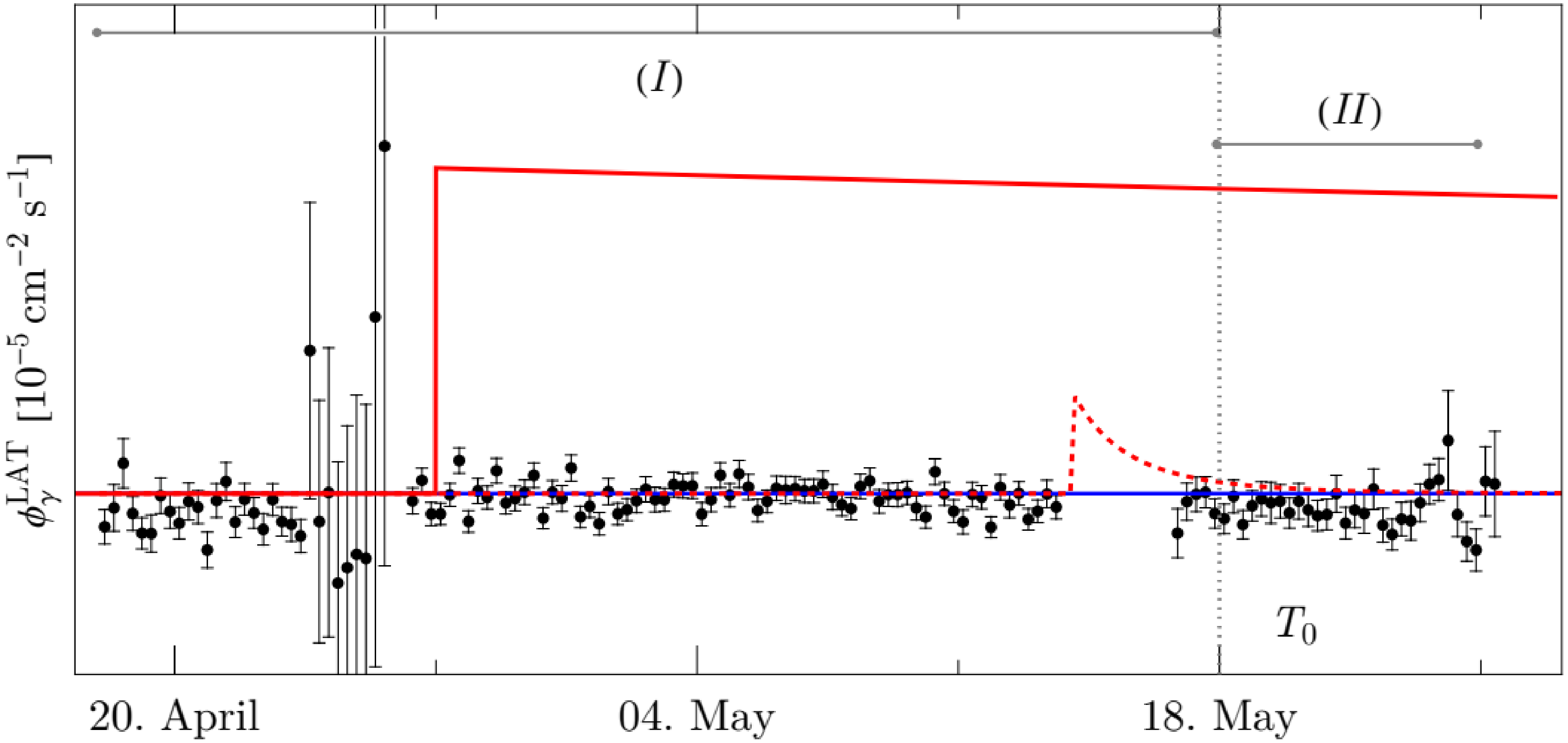


Ferreira, David Marsh and Müller, JCAP 11 (2022) 057

Decay bound

- Exclusion of expected fluence $F_\gamma > 1.78\ \mathrm{cm}^{-2}$
- Below lower limit, not enough ALP production to surpass the background gamma fluence
- Over upper limit, electron coupling so big that ALPs get trapped inside the SN
- ALPs with mass $m_a > 250$ MeV cannot be produced inside the SN

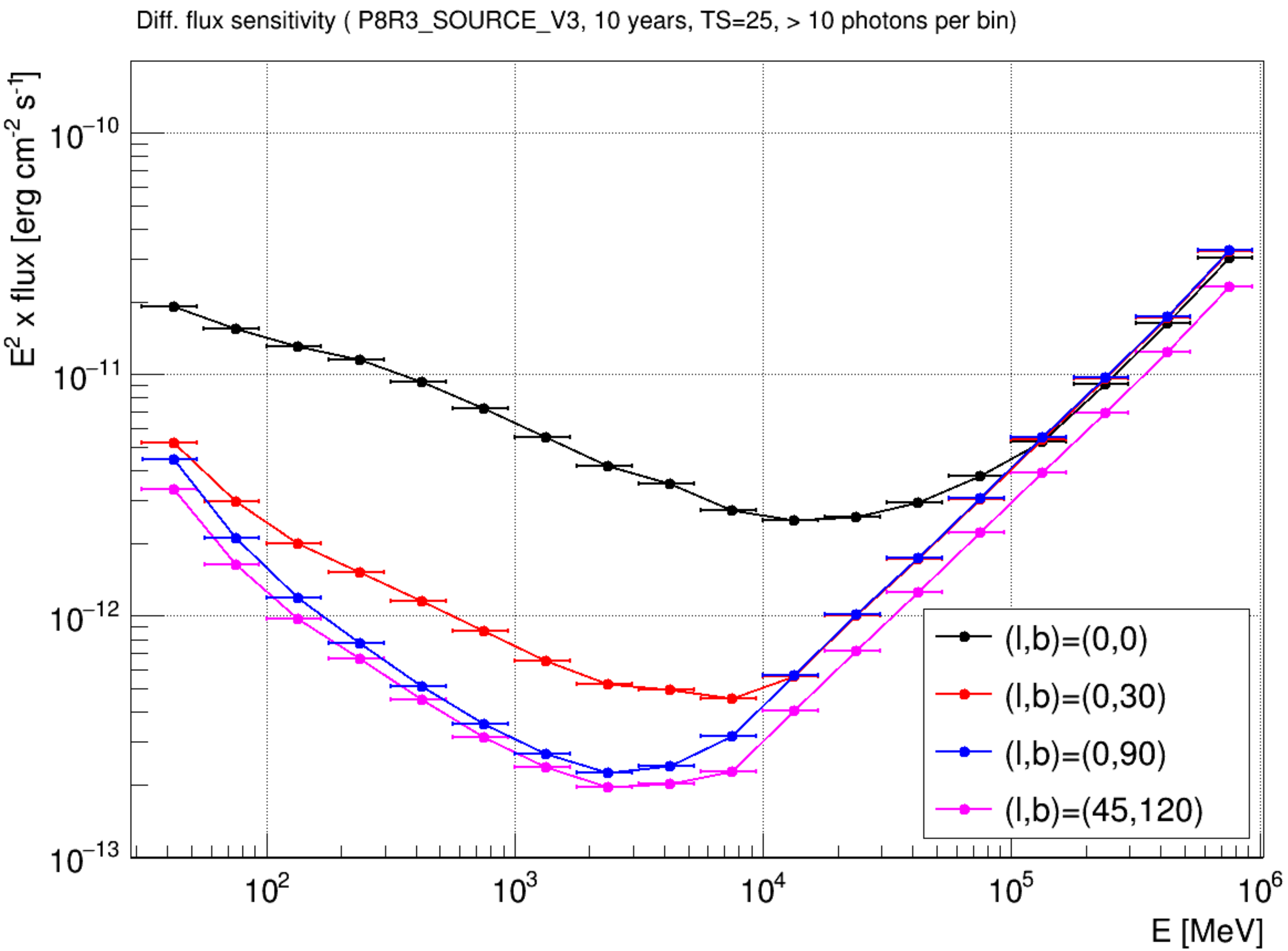
Fermi-LAT and SN2023ixf



Eike Ravensburg et. al., Phys.Rev.D 109 (2024) 2, 023018

Parameter	opt.	cons.	Unit
distance R_{SN}	6.70	7.00	Mpc
mass M	13	9	$M_\odot$
radius R_*	400	420	$R_\odot$
spectral normalization C	17.9	1.36	$10^{48}\,\mathrm{MeV}^{-1}$
average energy ω_0	87.0	71.2	MeV
spectral index β	2.43	2.86	1
observed flux	1.57	1.47	$10^{-5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
flux upper limit $\Delta\phi_\gamma$	3.98	9.10	$10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Fermi-LAT Sensitivity

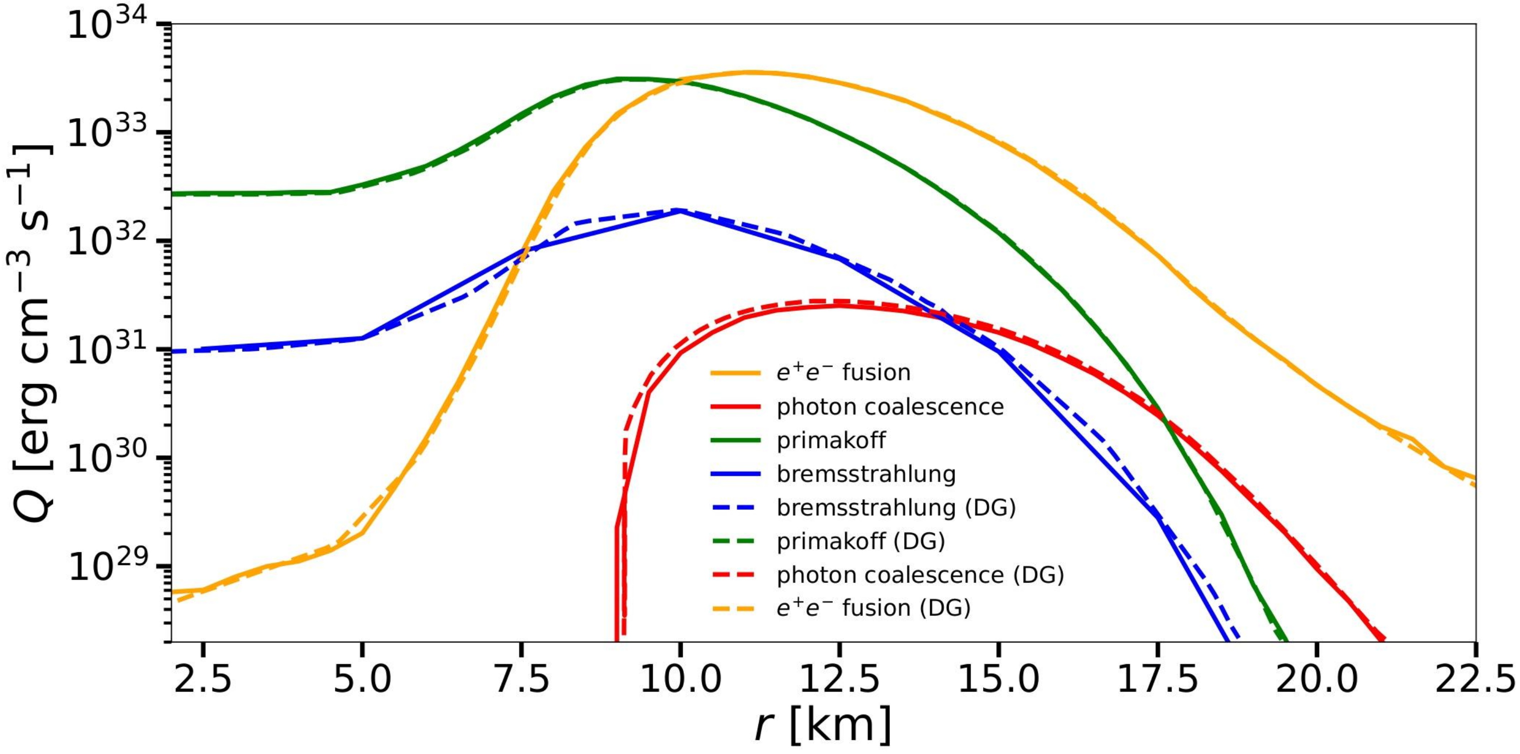


Comparison of emissivity Q for SN1987A

$$Q = \int_{m_a}^{\infty} \omega \mathrm{d}\omega \frac{\mathrm{d}^2 n}{\mathrm{d}\omega \mathrm{d}t}$$

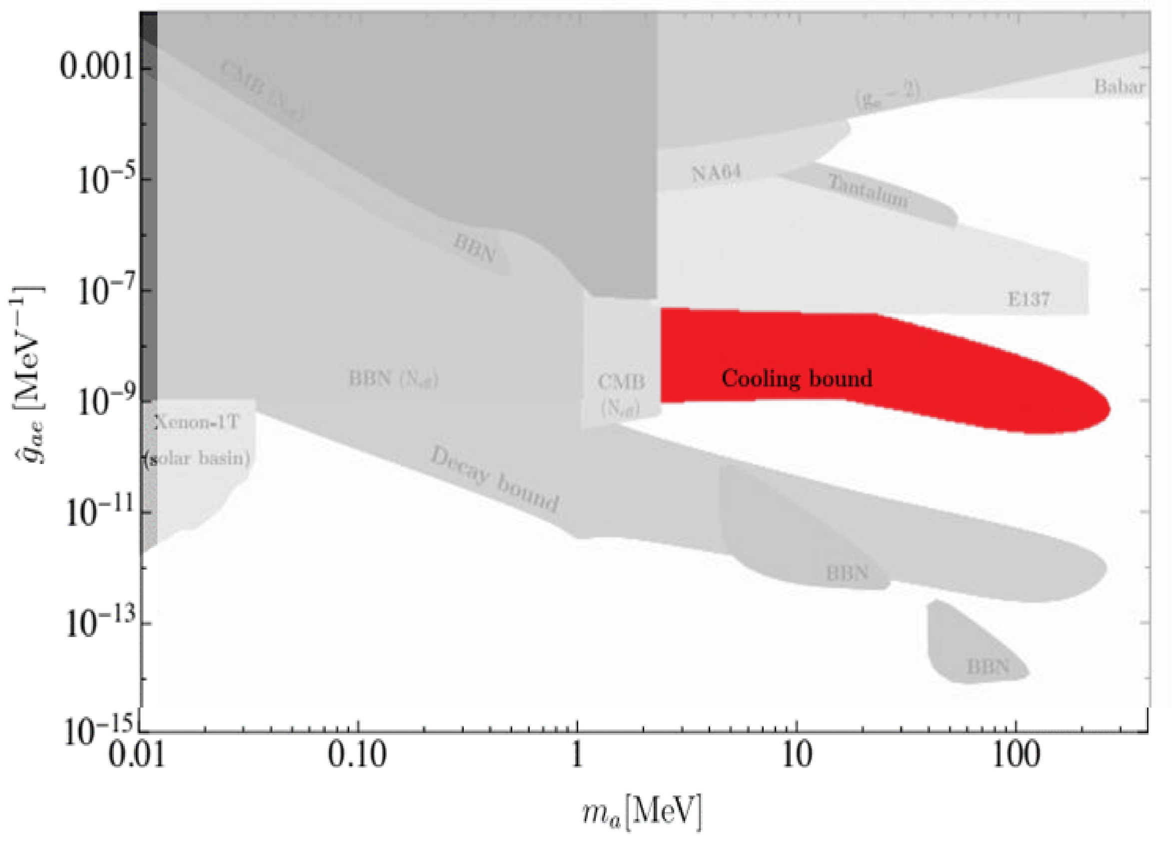
Comparisons with results of *Ferreira, David Marsh and Müller, JCAP 11(2022)057*

$m_a = 25$ MeV, $\hat{g}_{ae} = 10^{-9}$ MeV^{-1}, $g_{a\gamma} = 2\alpha/\pi \hat{g}_{ae}$ at $t = 1$ s after bounce



Exclusion regions electron-ALP coupling vs ALP mass

ALP coupling to electrons at tree level and to photons at one loop level for SN 1987A



Ferreira, David Marsh and Müller, JCAP 11 (2022) 057

Cooling bound

- Exclusion of ALP luminosity $L_a > 3\ 10^{52}$ erg/s
- Below lower limit, not enough ALP production to shorten neutrino burst
- Over upper limit, electron coupling so big that ALPs get trapped inside the SN
- ALPs with mass $m_a > 250$ MeV cannot be produced inside the SN

The Fermi Large Area Telescope

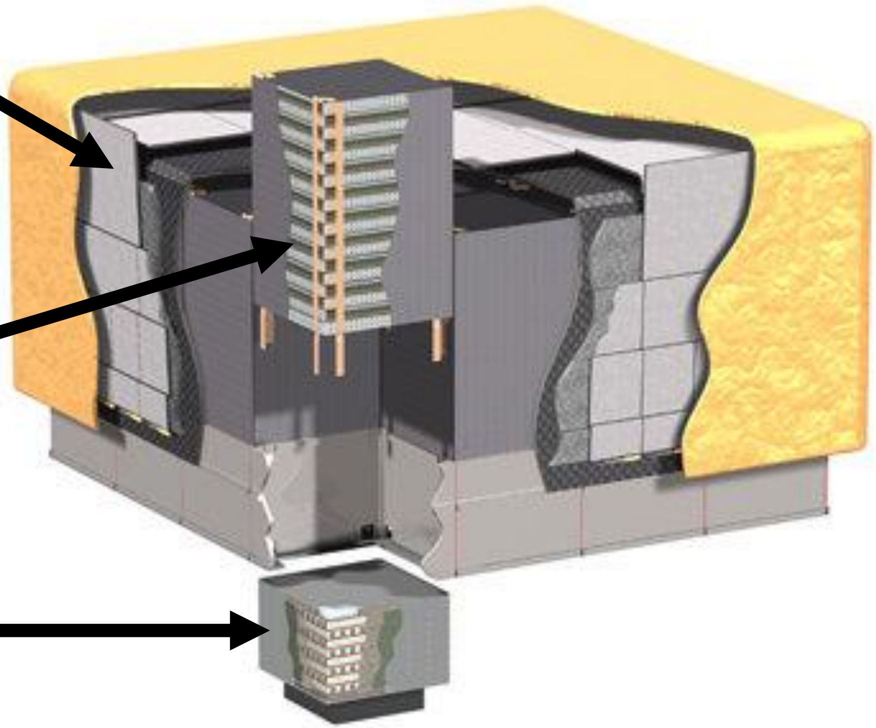
Launched in June 2008

[1.8m x 1.8m x 0.7 m]

Anti-Coincidence Detector:
Background rejection

Si-Strip Tracker:
Convert γ -> e^+e^-
Reconstruct γ 3D trajectory

CsI Calorimeter:
Measure γ energy



The Fermi-LAT collaboration:
~400 Scientific Members,
NASA/DOE& International Contributions

Sky Survey:
2.5 sr field-of-view
Covers the whole sky every 3 hours

Trigger and Filter:
Reduces datatake from ~100kHz to 300-500 Hz

Our objective: to use LAT observations to constraint ALPs models if no gamma-ray signal detected from these SNe

Public Data Release:
All γ-ray data is made public in 24 hours or less