Probing axion-like and other feebly interacting particles with high-energy astrophysics

KCL TPPC online seminar — 16/03/2022

Francesca Calore (CNRS/LAPTh)

Outline

- Stars as laboratories of ALPs and other FIPs
- Signatures of ALP-photon coupling
  - Search for gamma-ray *core collapse SNe*
  - Searches for *spectral irregularities* in gamma and X rays
- Conclusion and outlook

Feebly interacting particles (FIPs)

The mystery of dark matter?

The matter-antimatter asymmetry in the universe?

The strong CP problem?

Feebly interacting particles

- Light particles (sub-GeV masses)
- Extremely suppressed interactions between new particles and SM bosons and/or fermions
- Interactions with SM mediated by (pseudo)scalar, fermion or vector particles (*portals*)
- Examples are **dark photons**, **sterile neutrinos**, **axions** and **axion-like particles**
- Offer good and viable **dark matter candidates**

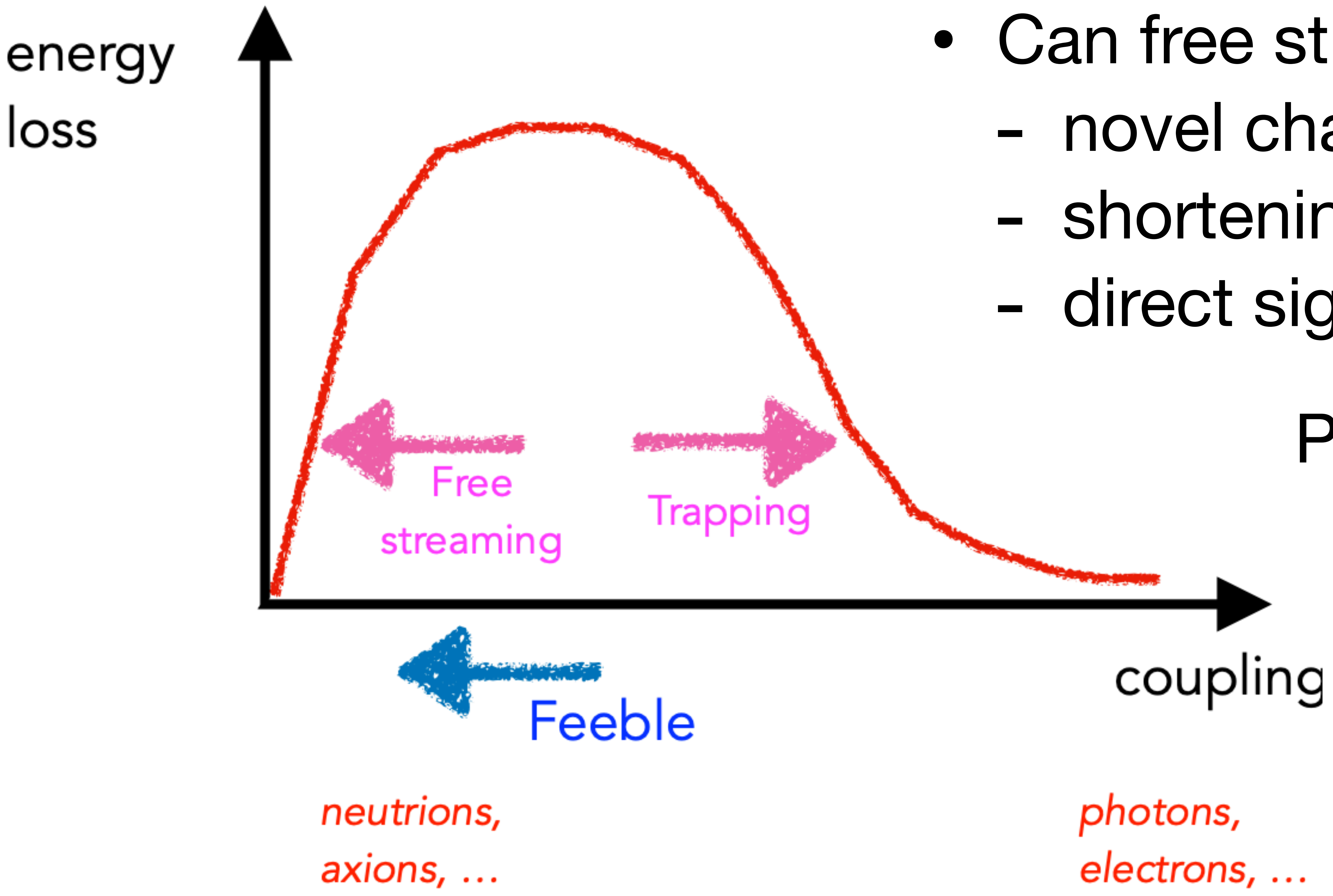
[See also maturation of the experimental programs searching for new physics with sizeable couplings at the LHC]

Agrawal+ Eur.Phys.J. C'21

Stars as laboratories of FIPs

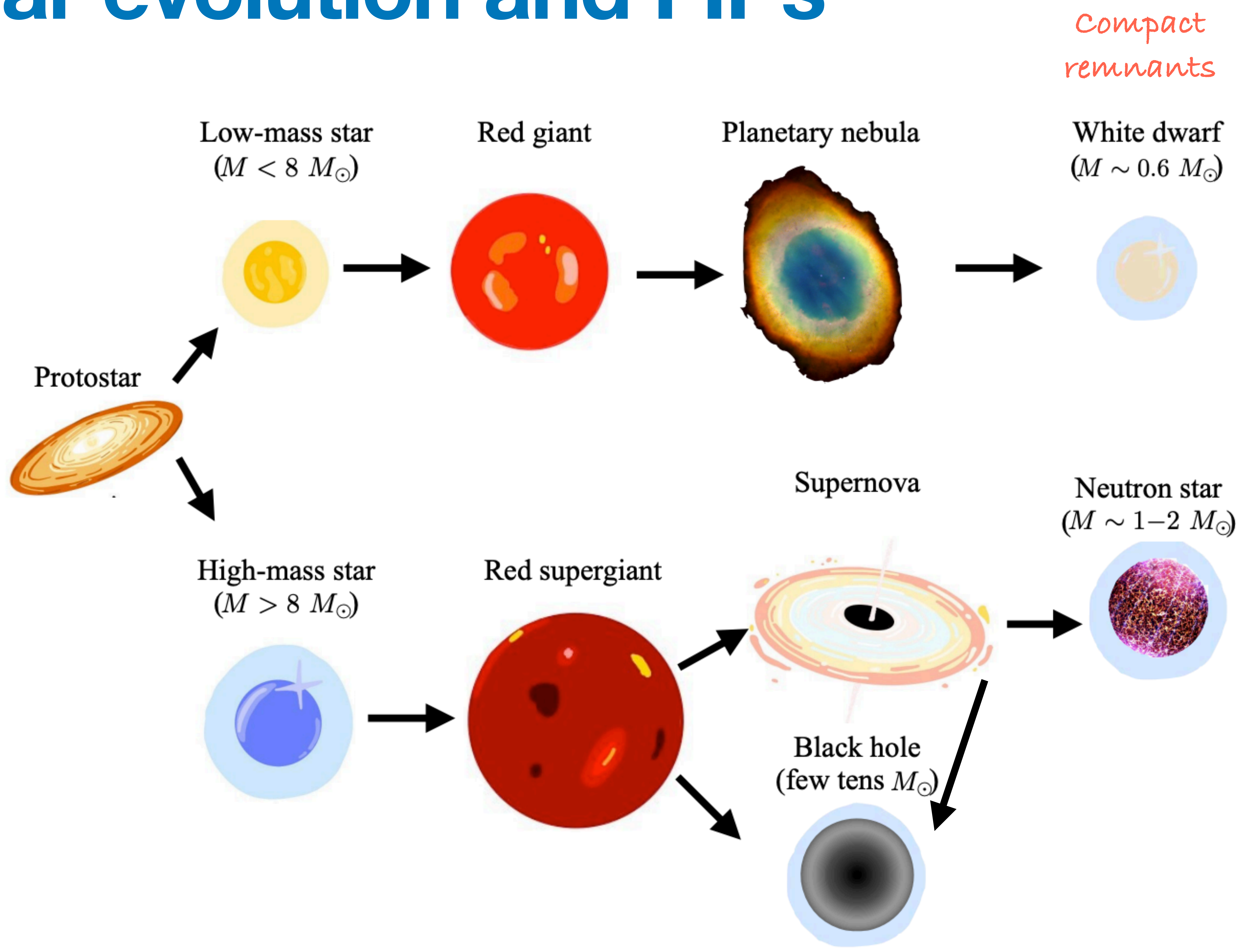
- Light particles (up to ~100 MeV) can be efficiently thermally produced in stellar cores
- Can free stream and escape from the core inducing
  - novel channel of energy-loss
  - shortening the duration of the neutrino burst
  - direct signatures in cosmic backgrounds

Paradigmatic example: **neutrinos**



Credit: Giannotti @ FIPs2020

Stellar evolution and FIPs



EuCAPT Whitepaper 2110.10074

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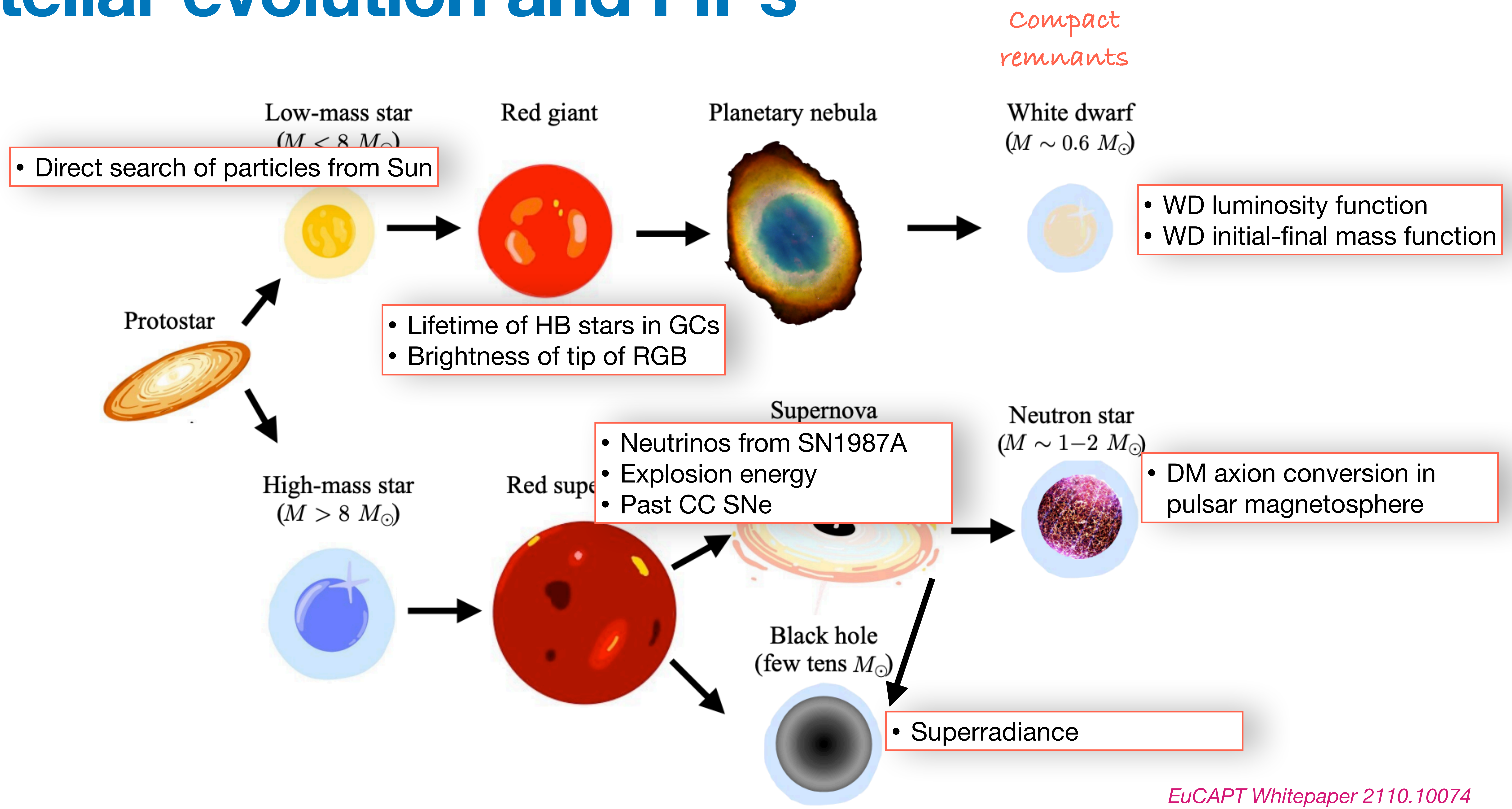


EuCAPT Whitepaper 2110.10074

Axion & Axion-like particles

- Axion as pseudo-Nambu Goldstone boson predicted by the Peccei-Quinn mechanism

  Peccei Journal of Korean Physical Society 1996

- ALPs as generalization of the QCD axion
  - Very light pseudo-scalar bosons predicted by multiple extensions of the Standard Model

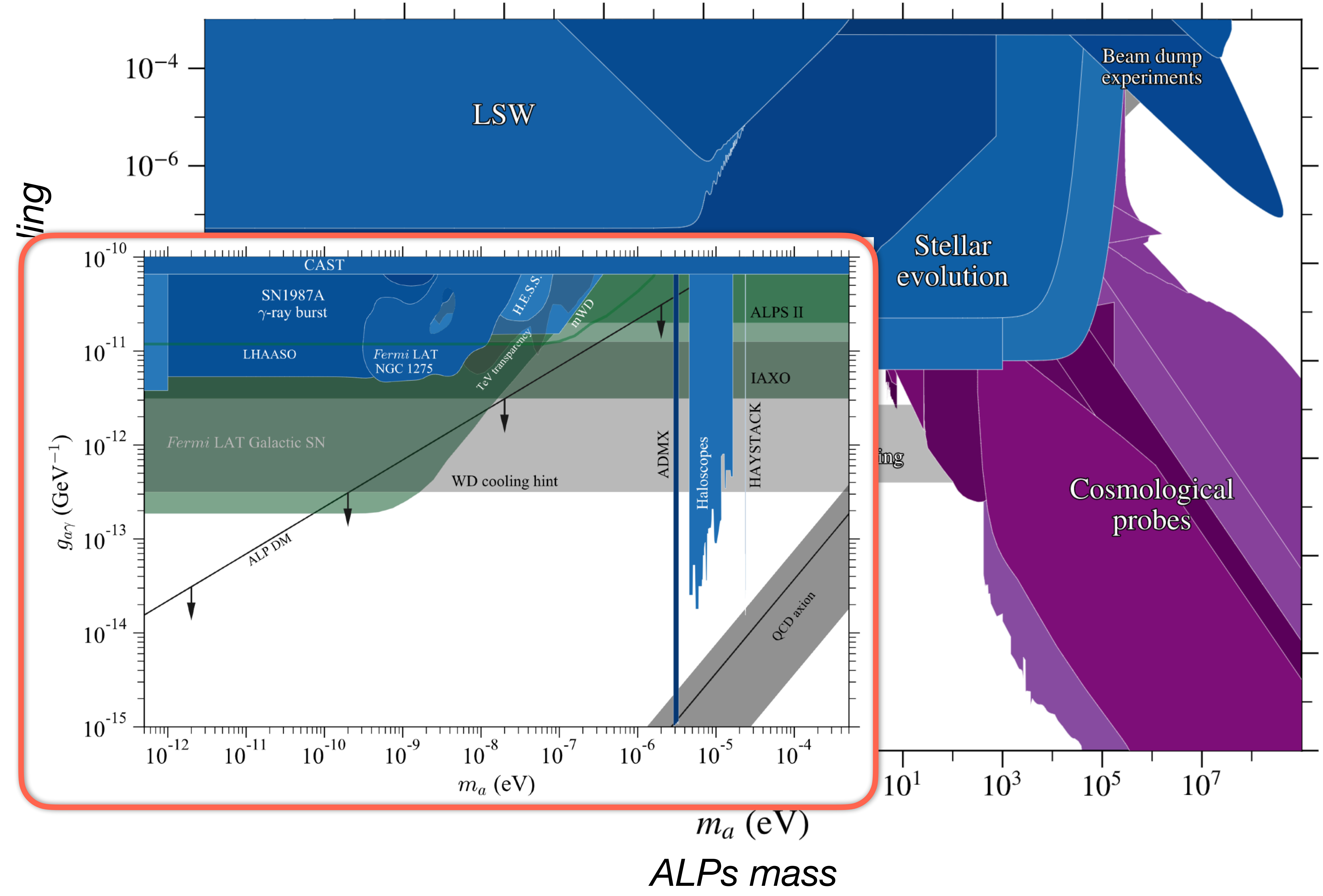
    Chang+ PRD 2000; Turok PRL 1996; Arvanitaki+ PRD'10

  - The mass and the coupling constant of ALPs are completely independent parameters
  - They represent weakly interacting slim (ultralight) particles (**WISPs**)
  - They can be cold dark matter candidates for certain values of mass and coupling

    Preskill+ PLB 1983; Sikivie International Journal of Modern Physics '10

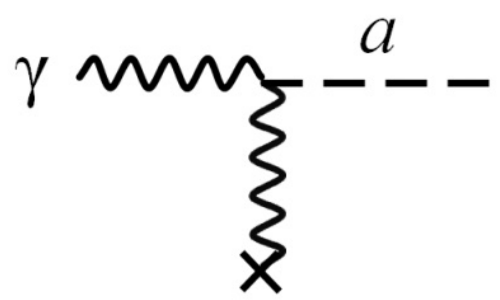
The ALP-photon coupling landscape

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$



Credit: M. Meyer @ https://github.com/me-manu/gammaALPsPlot/

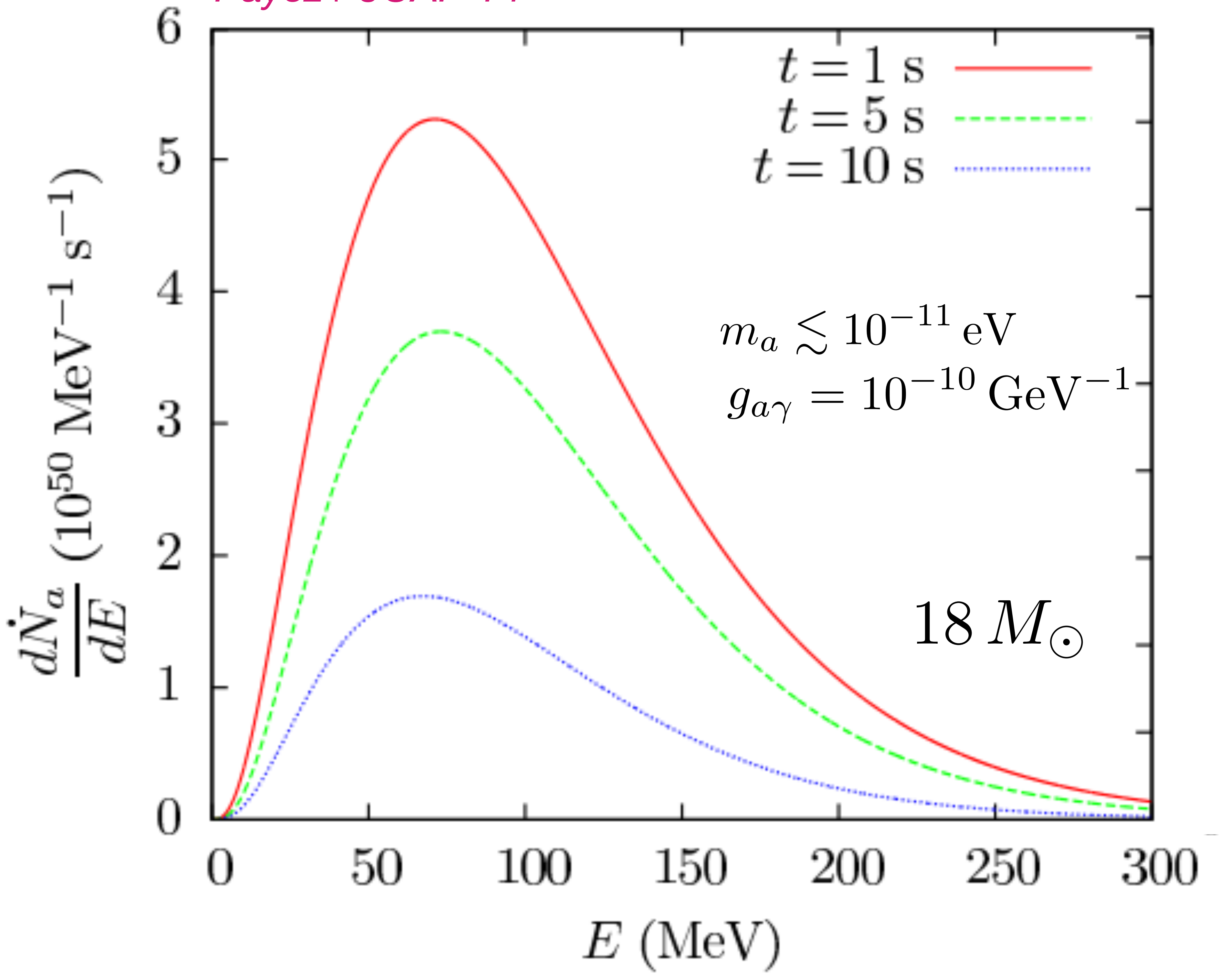
ALPs production in CC SNe



Production of ALPs in the SNe mainly by **Primakoff effect**

$$\gamma + Ze \to Ze + a$$

Payez+ JCAP'14



[Inclusion of alpha particles and gravitational redshift induce 15%-20% spectral variations, see Caputo+ PRD'22; Calore+ 2110.03679v2; Caputo+ 2201.09890]

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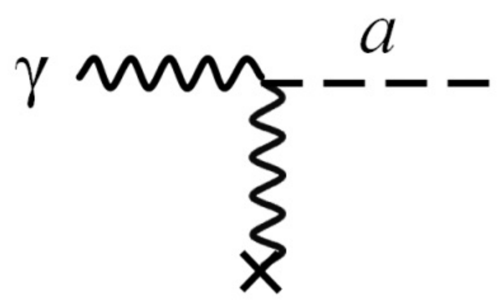

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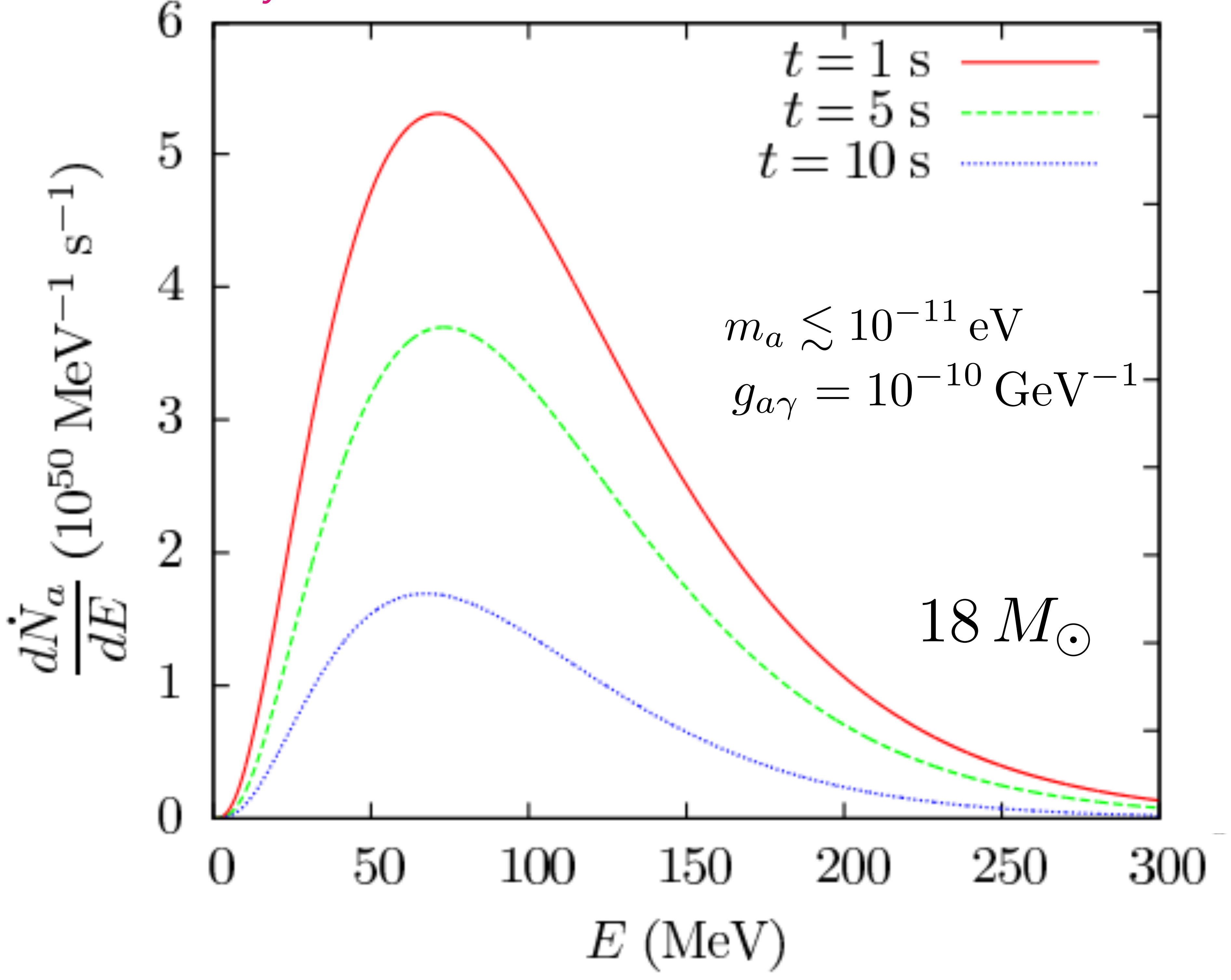
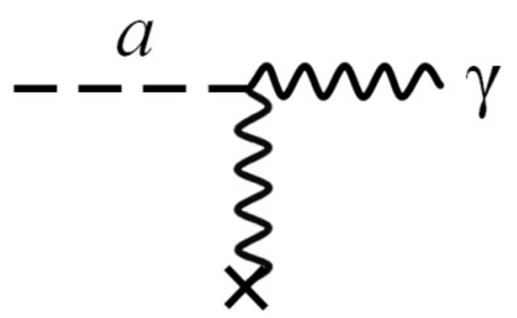


For Galactic SNe

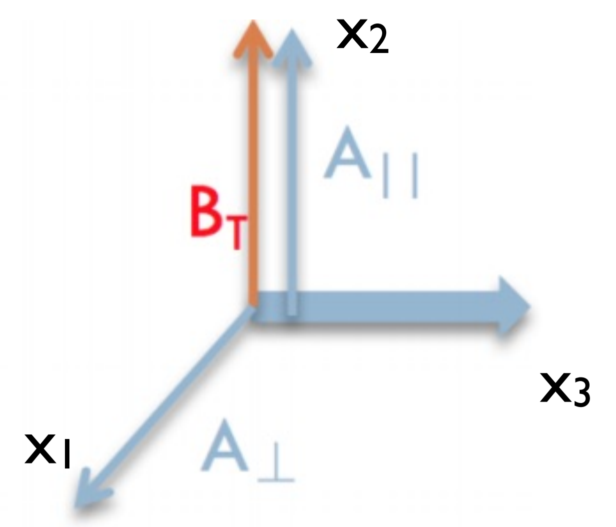
$$\frac{d\Phi_a}{dE} = \frac{1}{4\pi d^2} \frac{d\dot{N}_a}{dE}$$

[Inclusion of alpha particles and gravitational redshift induce 15%-20% spectral variations, see *Caputo+ PRD'22; Calore+ 2110.03679v2; Caputo+ 2201.09890*]

ALP-photon Galactic conversion



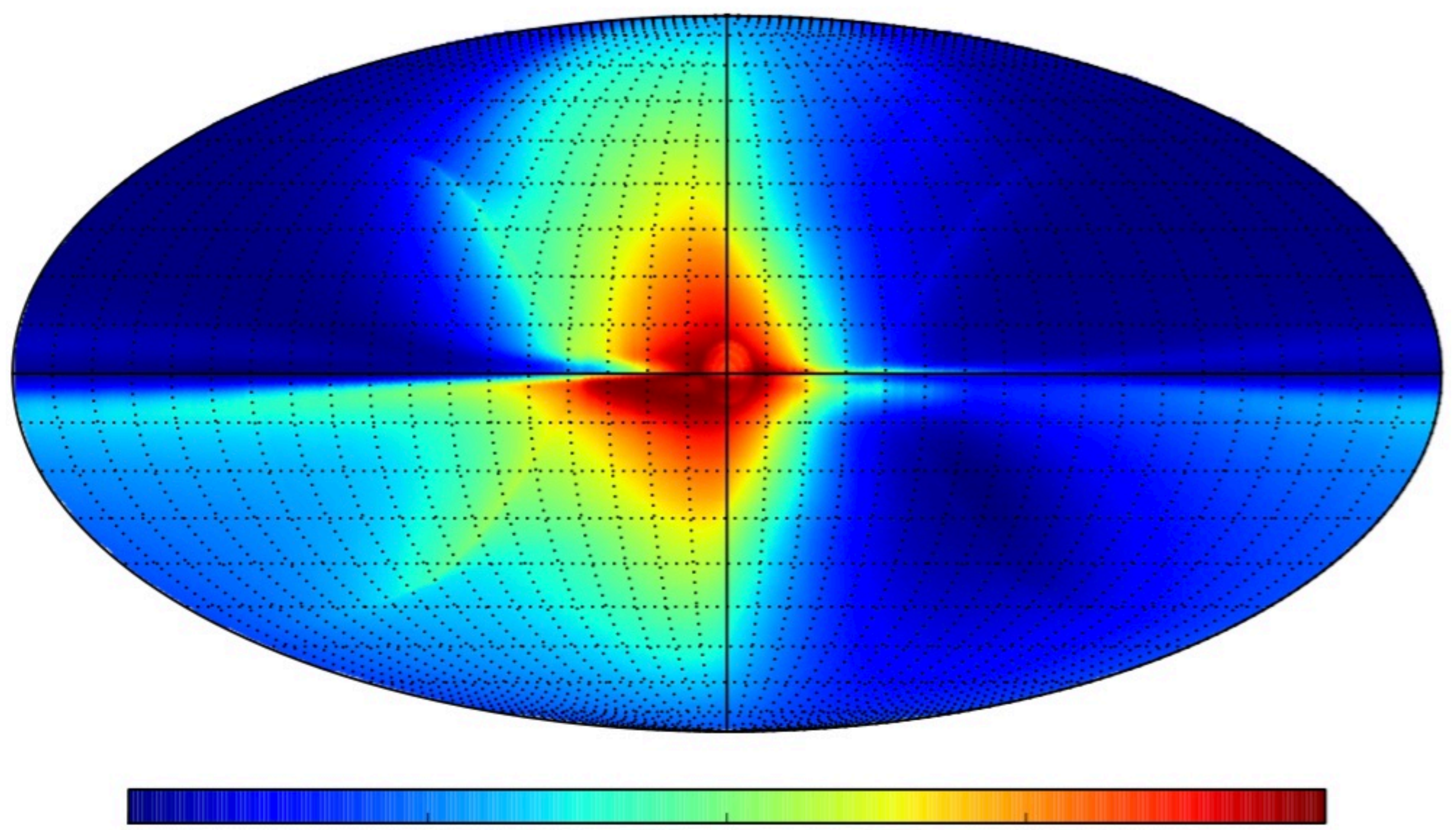
For a **monochromatic photon-ALP beam** of energy E propagating along the x_3 axis in a cold plasma within a **homogeneous magnetic field B**



$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B_T}{2}\right)^2 d^2$$

$$\sim 0.015\left(\frac{g_{a\gamma}}{10^{-11}\,\mathrm{GeV}}\right)^2\left(\frac{B_T}{10^{-6}\,\mathrm{G}}\right)\left(\frac{d}{\mathrm{kpc}}\right)^2$$

Raffelt & Stodolsky PRD'88; Horns+PRD'12; and others

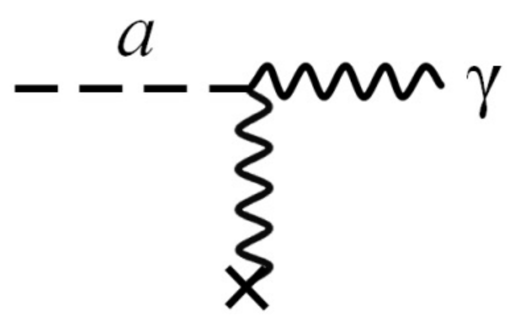


$g_{a\gamma} = 5 \times 10^{-11}$ GeV^{-1}
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

ALP searches sensitive to the product $\mathbf{g_{a\gamma}\, B_T}$

Good knowledge of B-field is required!

ALPs gamma-ray flux from CC SNe



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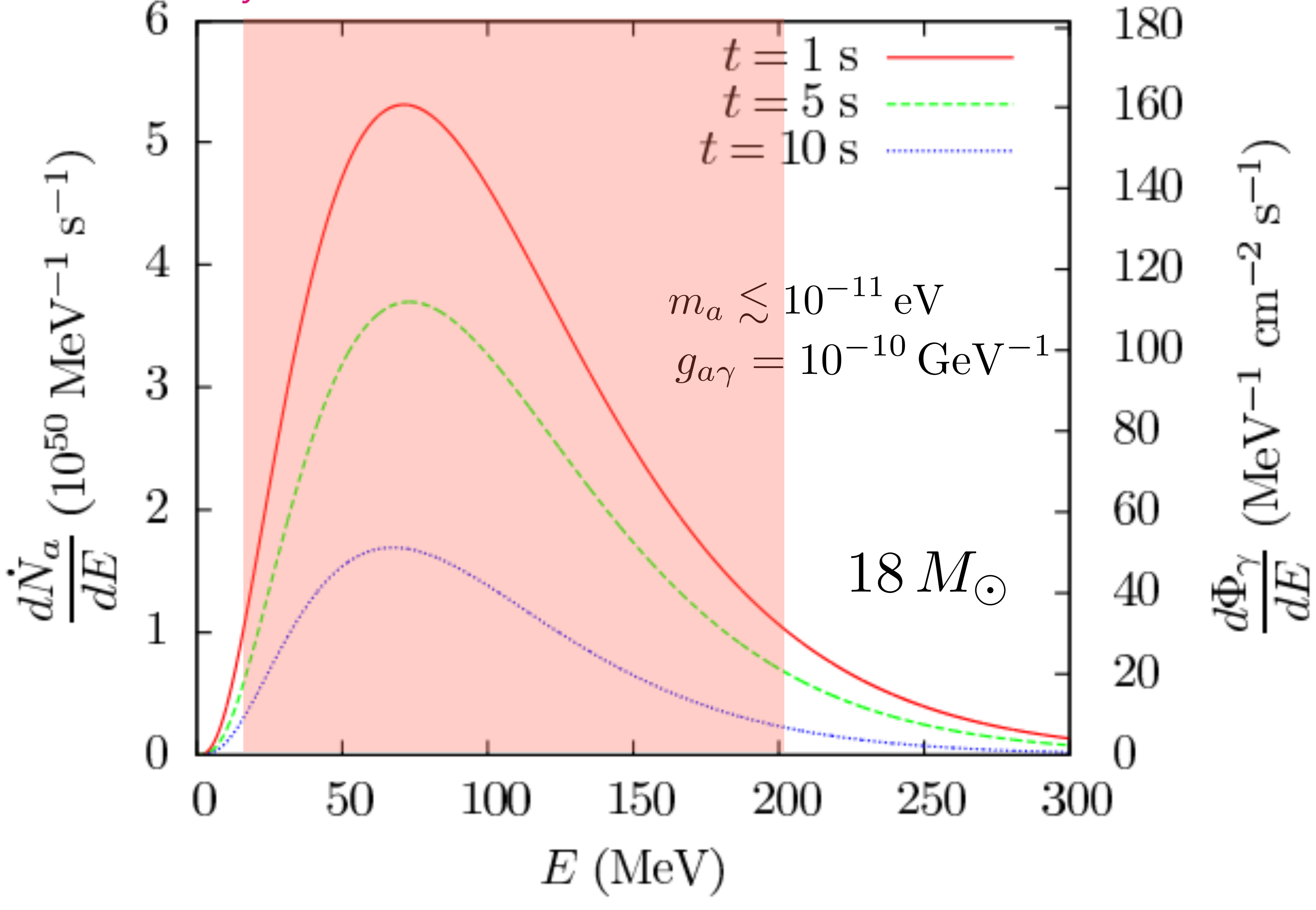


For Galactic SNe

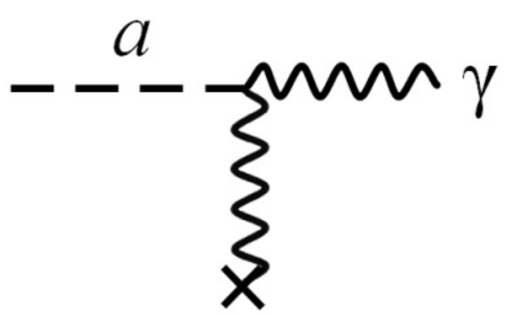
$$\frac{d\Phi_a}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}$$

$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}P_{a\gamma}(E)$$

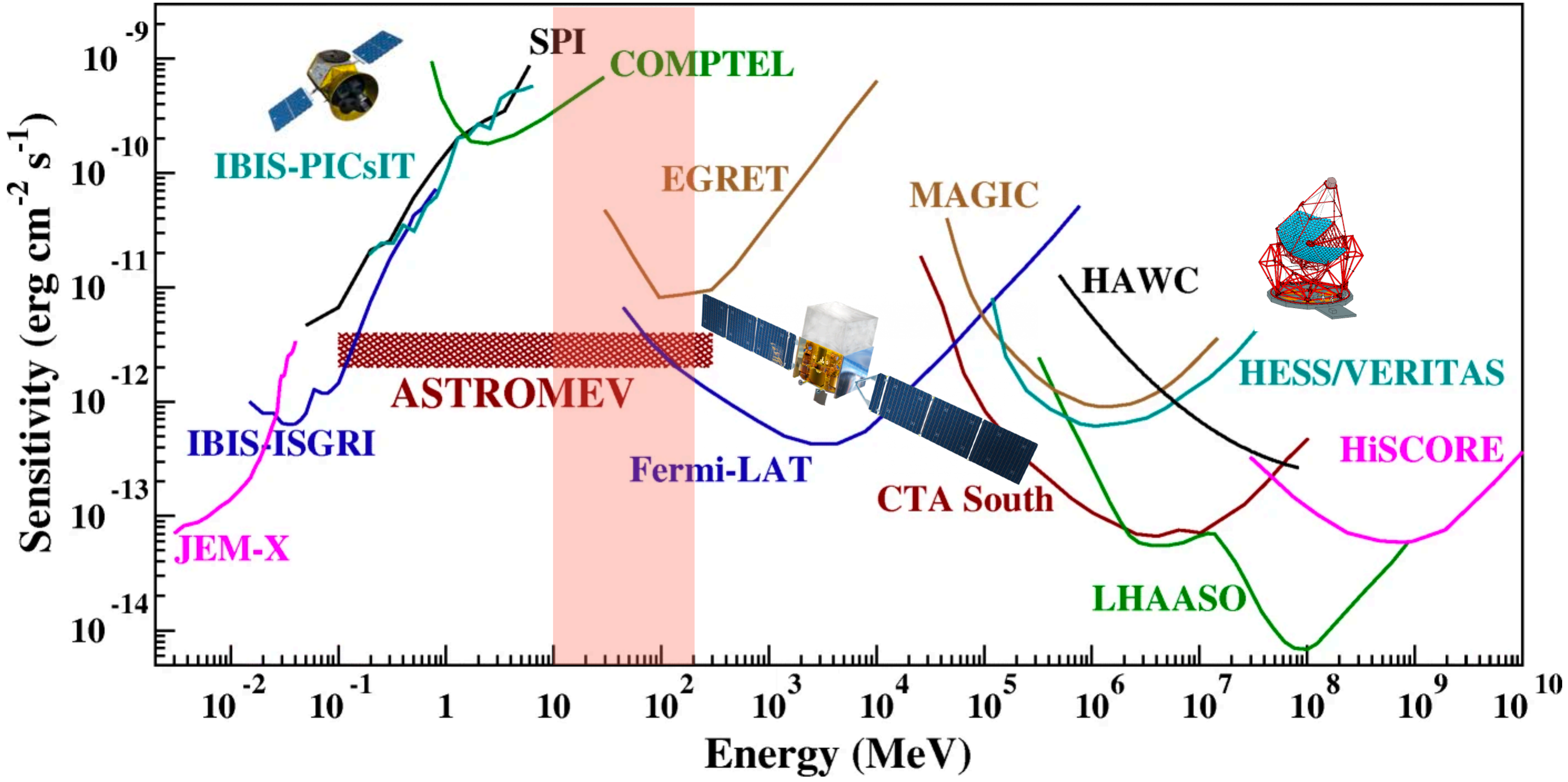
For massless ALPs, one-to-one correspondence between ALPs and photon energy

[Inclusion of alpha particles and gravitational redshift induce 15%-20% spectral variations, see *Caputo+ PRD'22; Calore+ 2110.03679v2; Caputo+ 2201.09890*]

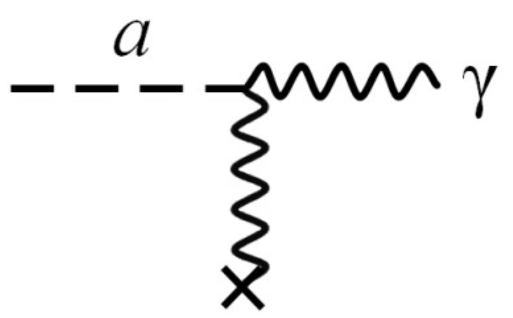
Gamma-ray astrophysics



DeAngelis+ Voyage 2050 '21



Gamma-ray bursts from CC SNe



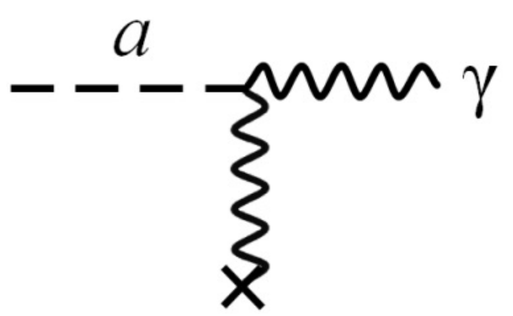
Production of ALPs in the SNe mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

ALPs produced in **O(10) sec bursts**, with an energy spectrum peaked at **60-80 MeV**

➡ Specific **time dependent** and **spectral** signatures

➡ Chance to see a Galactic SN depends on SN rate (~3/century) and field-of-view of telescope

Gamma-ray bursts from CC SNe



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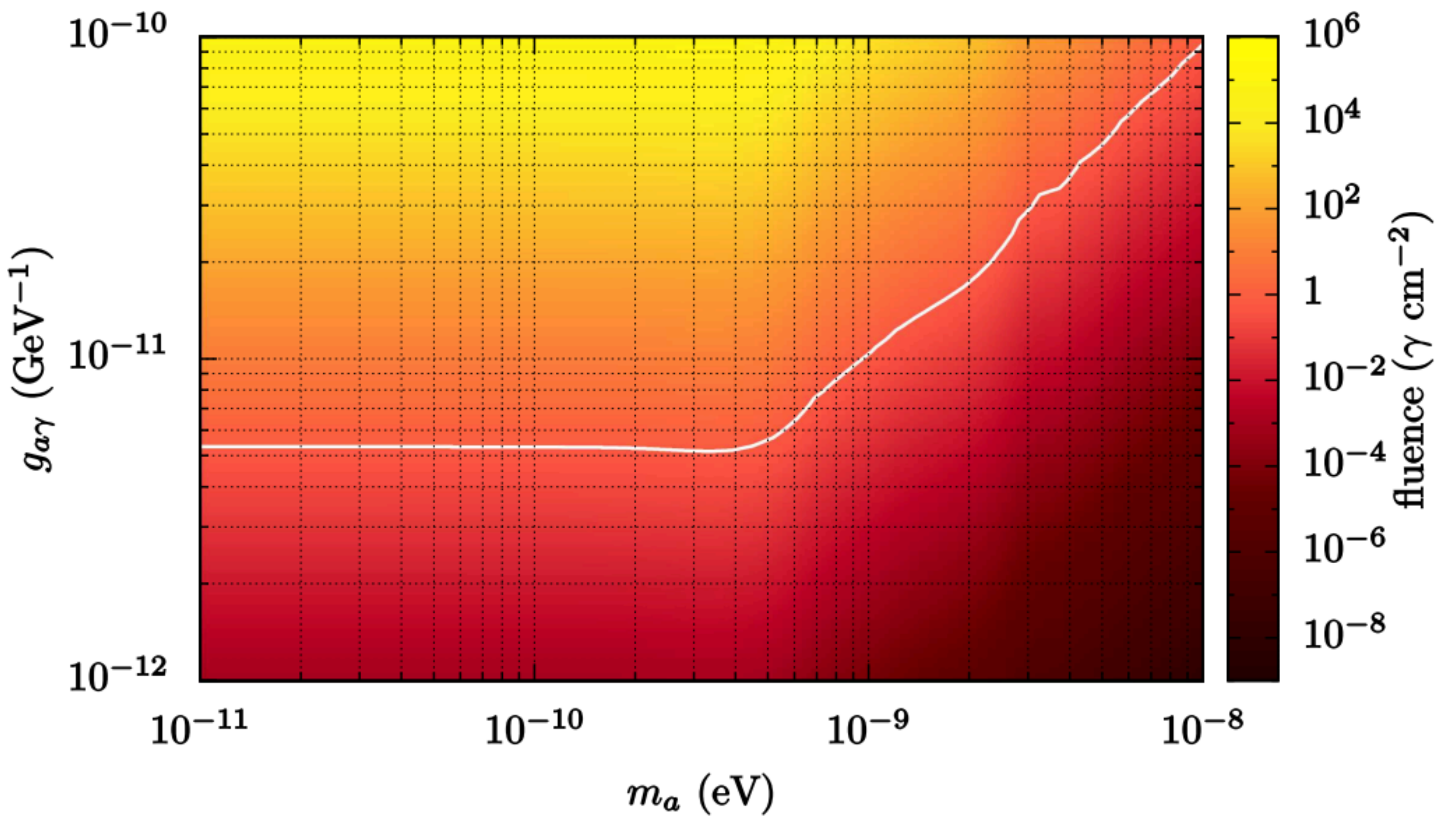
- **SN1987A**: Lack of gamma-ray burst in the Gamma-Ray Spectrometer (GRS) of the Solar Maximum Mission (SMM)

$$g_{a\gamma} \lesssim 5.3 \times 10^{-12}\ \mathrm{GeV}^{-1}, \quad \text{for} \quad m_a \lesssim 4.4 \times 10^{-10}\ \mathrm{eV}$$

Payez+ JCAP'14



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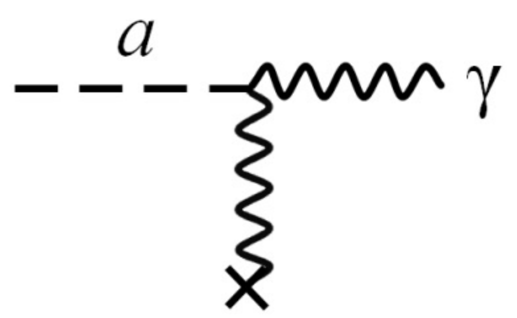

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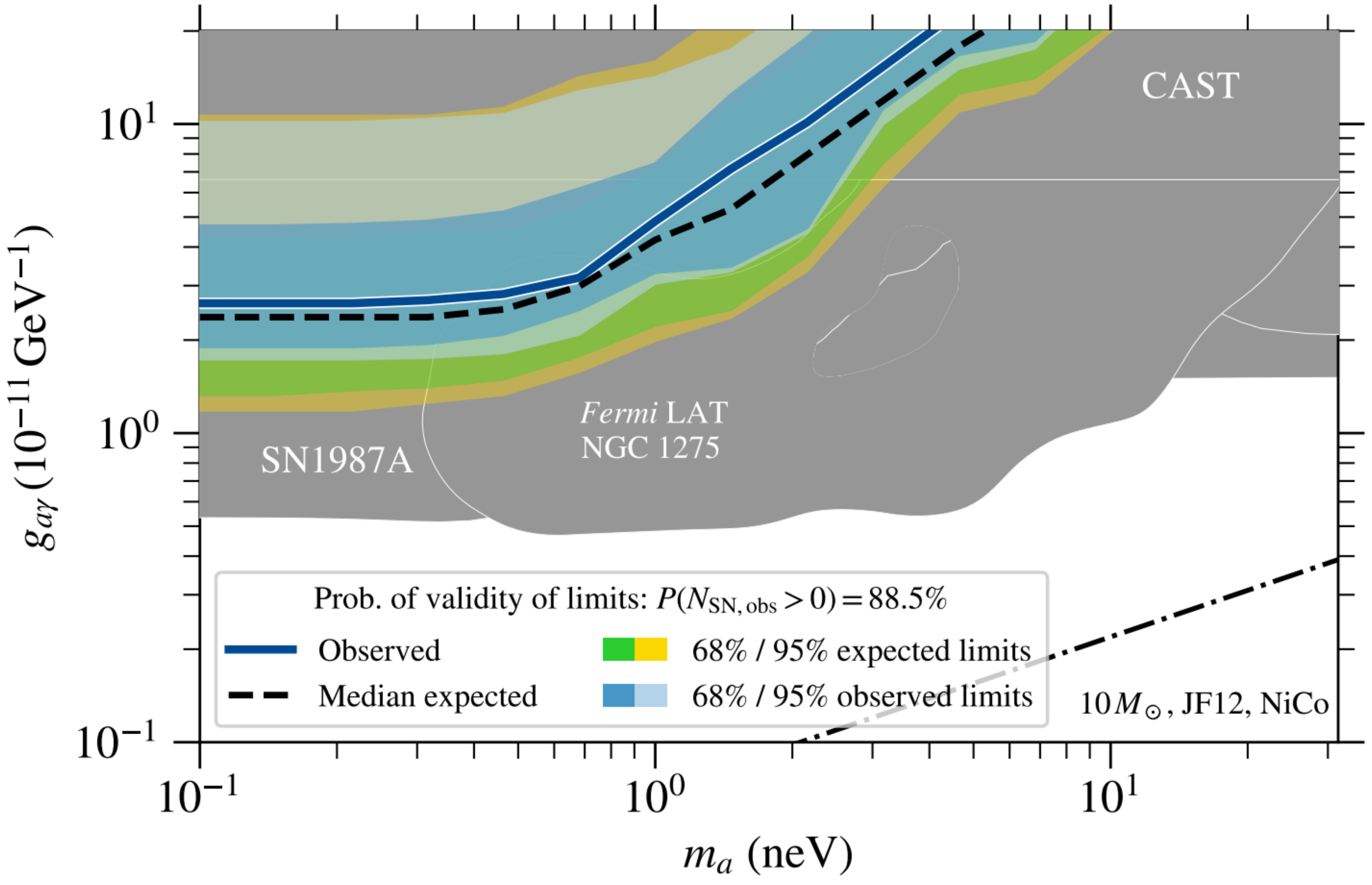
Payez+ JCAP'14

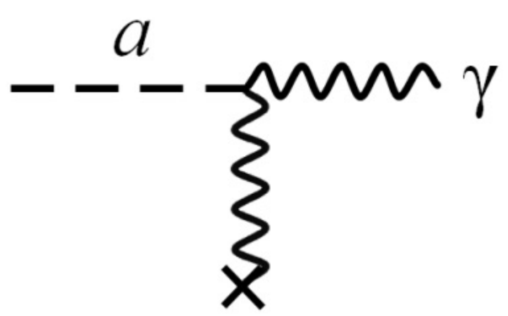
- **Extragalactic SNe**: Search for gamma-ray burst at the time and direction of 20 optically characterised SNe

Meyer & Petrushevska PRL'20

Crnogorcevic+ PRD'21



The diffuse SN ALP background

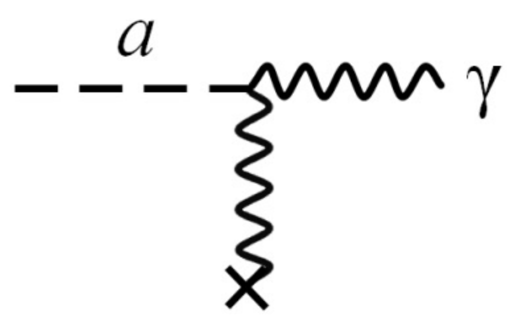


DSNALPB

- The cumulative **axion** emission from past core-collapse SNe in the Universe would lead to a diffuse axion flux comparable with that of neutrinos ⟶ Gamma-ray signal suppressed by Galactic conversion *Raffelt+ PRD'11*
- The same **cumulative contribution** can be considered for **ALP production in SNe** ⟶ Significant regions in the parameter space where we can have a large ALP production and sizeable photon conversions

FC+ PRD'20, 2110.03679

The diffuse SN ALP background



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FC+ PRD'20, 2110.03679

$$\frac{d\phi_a(E_a)}{dE_a} = \int_0^\infty (1+z) \frac{dN_a(E_a(1+z))}{dE_a} [R_{SN}(z)] \left[\left| c \frac{dt}{dz} \right| dz \right]$$

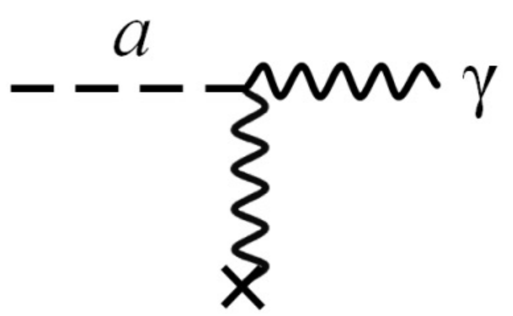
Beacom, Ann. Rev. Nucl. Part. Sci.'10

Time-integrated CC SNe ALPs spectrum from past events

CC SNe rate density at redshift z

Yuksel et al. ApJ Letters'08

Time-integrated DSNALPB spectrum



Evolution of CC SNe from numerical simulations with progenitor ZAMS masses:

- **CCSN explosion: 8.8, 11.2, 18, 25** M⊙
- **Failed CCSN explosion: 40, 70** M⊙

Fischer+ A&A'10; Kotake+ ApJ'18; Kuroda+ MNRAS'18

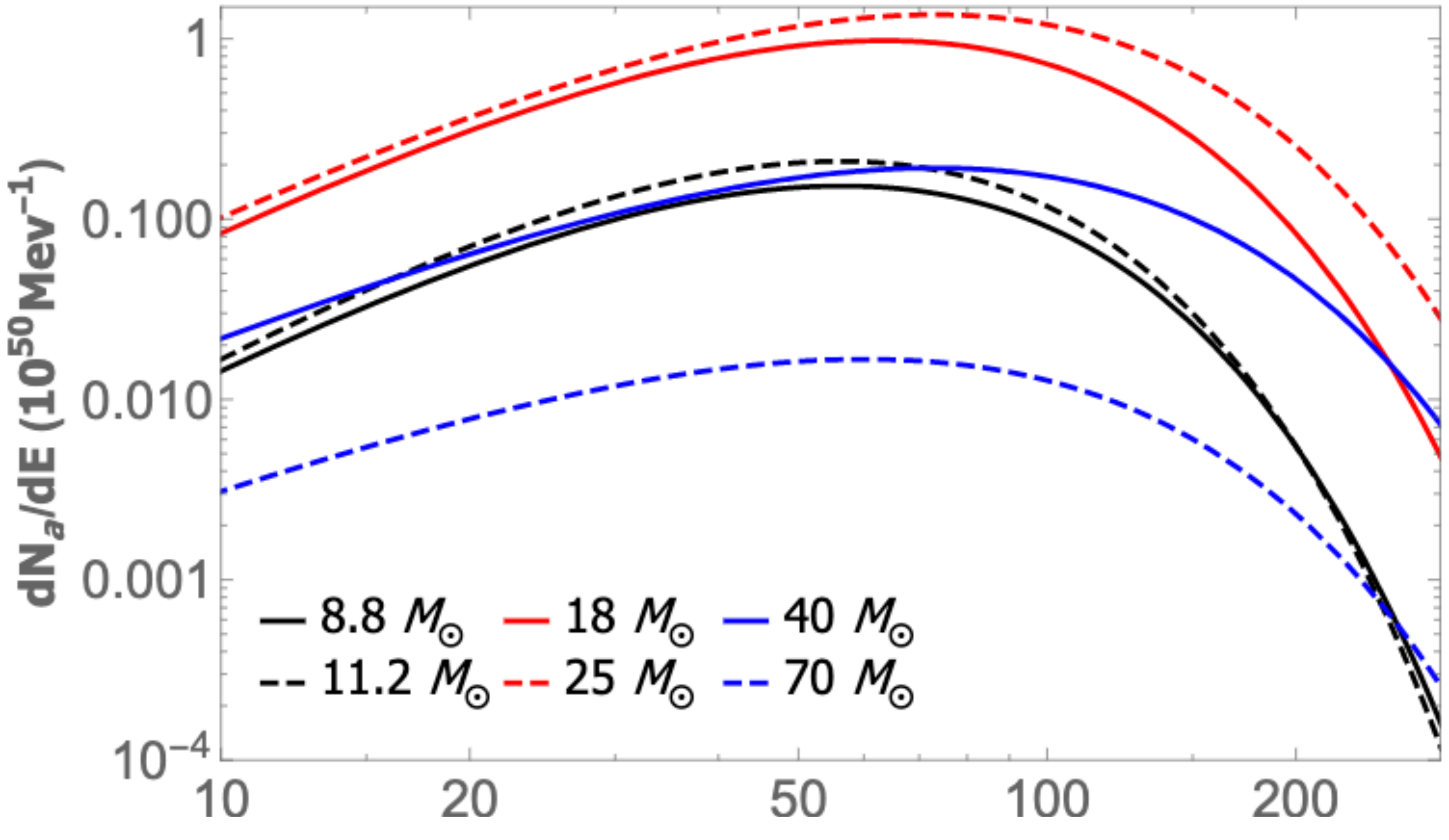
Time-integrated spectrum weighted by initial mass function over the range 8-125 M⊙,

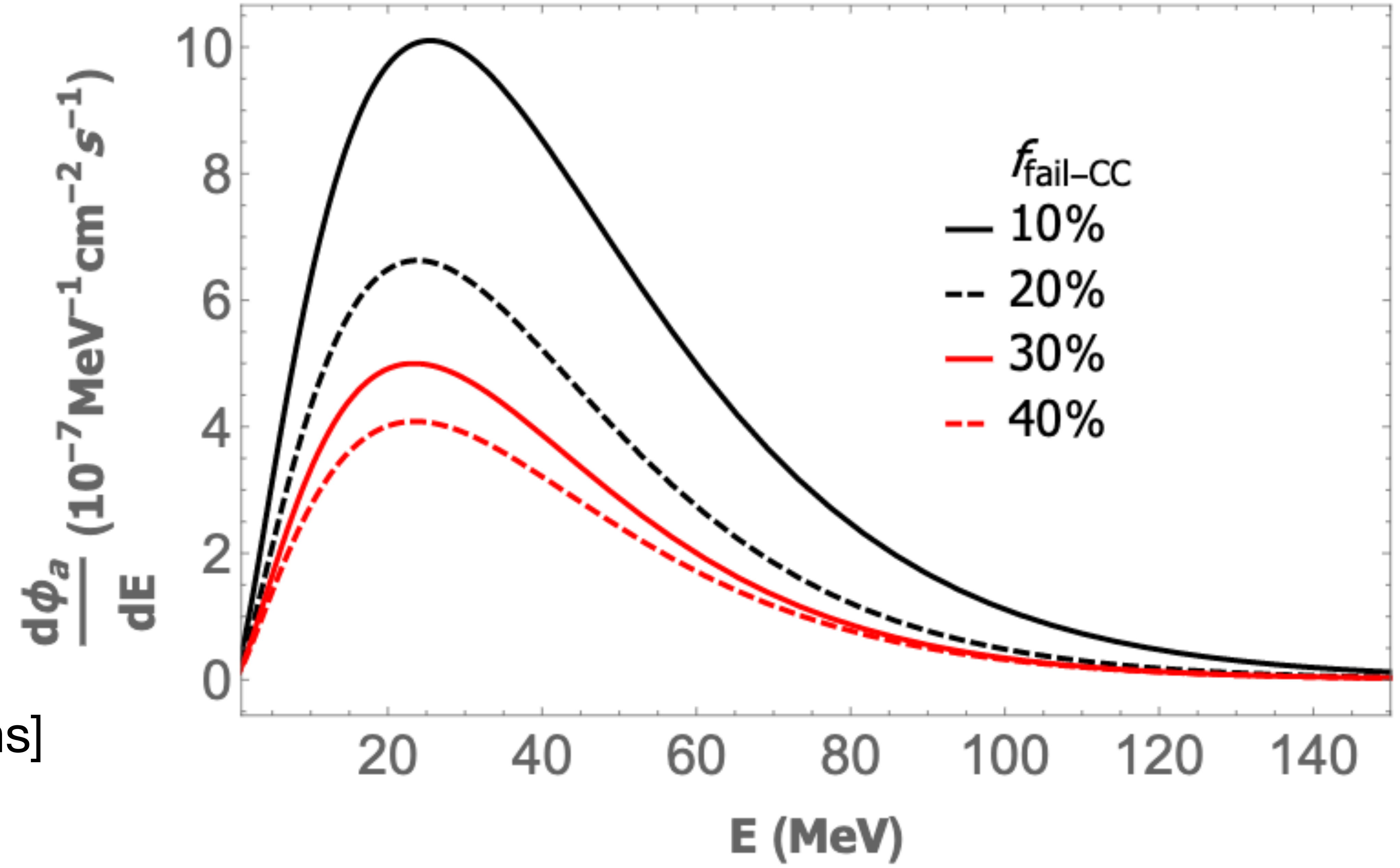
$$\frac{dN_a^{CC}}{dE_a} = \frac{\int_{\Lambda_{\rm expl-CC}} dM \phi(M) \frac{dN_a}{dE}(M) + \int_{\Lambda_{\rm fail-CC}} dM \phi(M) \frac{dN_a}{dE}(M)}{\int_{8M_\odot}^{125M_\odot} dM \phi(M)}$$

$$f_{\rm fail-CC} = \frac{\int_{\Lambda_{\rm fail-CC}} dM \phi(M)}{\int_{8M_\odot}^{125M_\odot} dM \phi(M)}$$

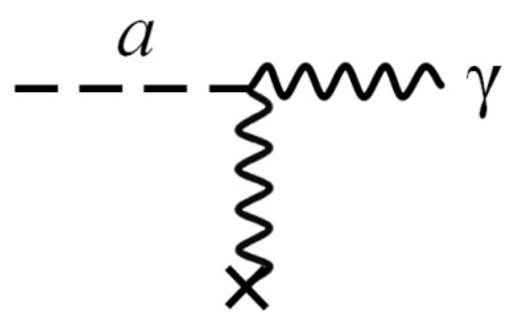
[Other source of uncertainty: initial mass function and SN rate parameterisations]

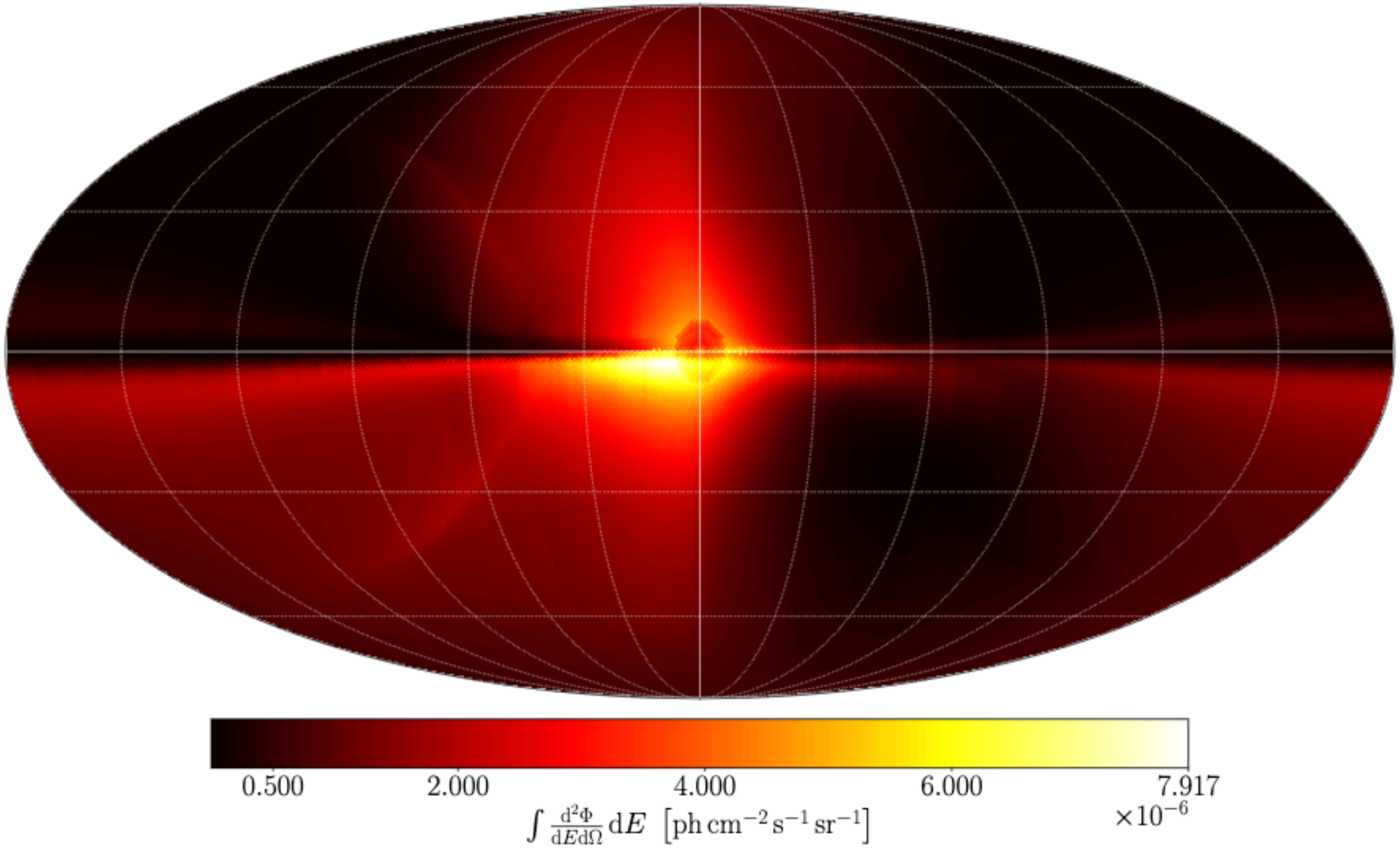
FC+ 2110.03679





Gamma-ray DSNALPB signal





Conversion in Jansson & Farrar Galactic magnetic field model updated to Planck data

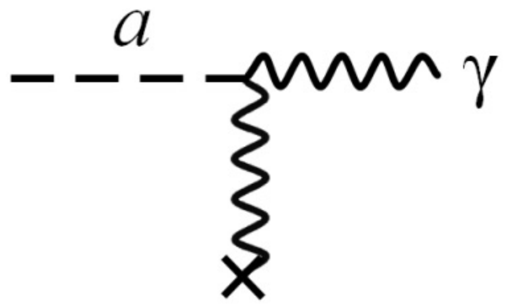
Integrated ALPs signal between 50 and 200 MeV

$$g_{a\gamma} \sim 4 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

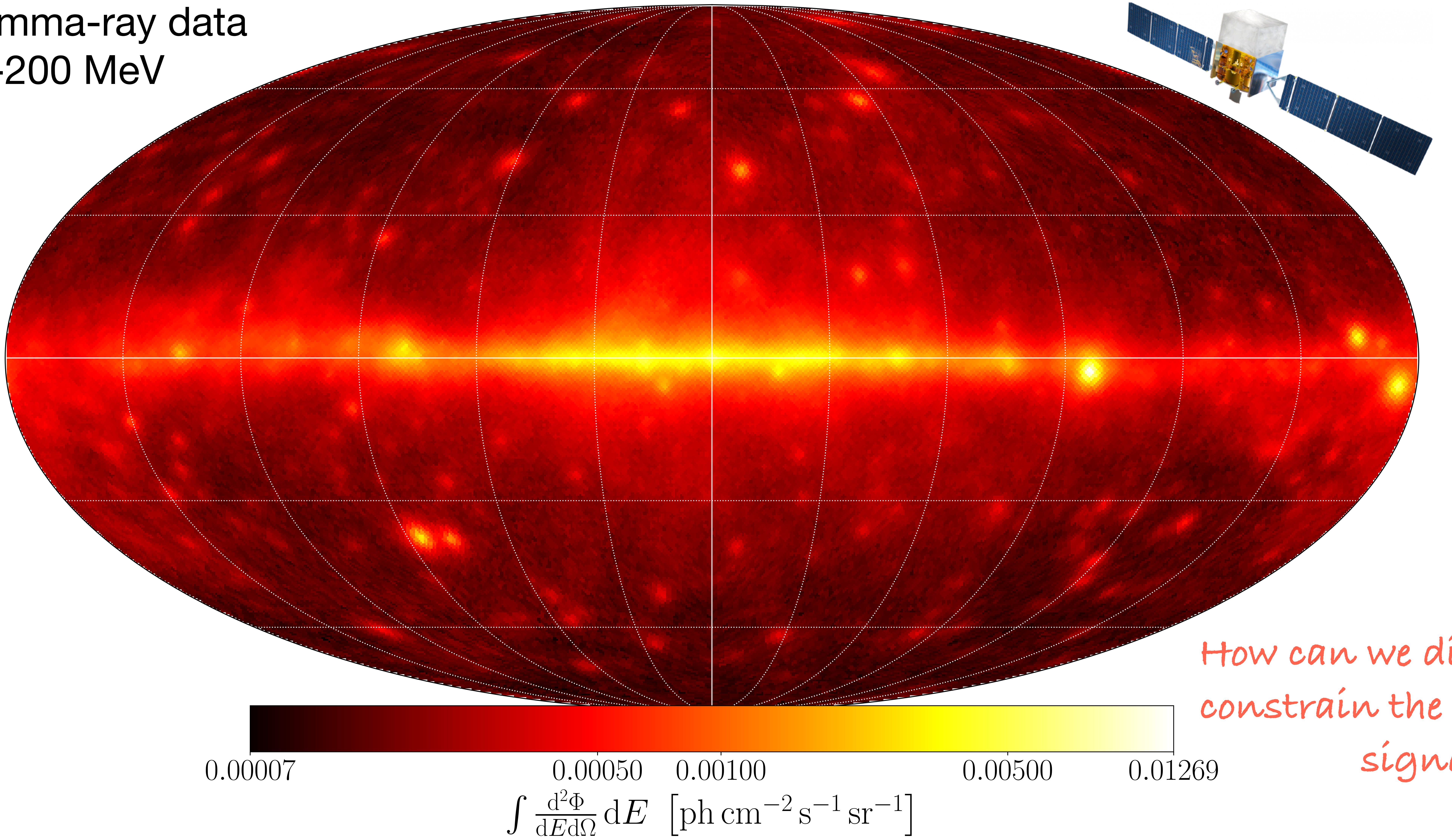
$$m_a \lesssim 10^{-11}\,\mathrm{eV}$$

All-sky diffuse signal
With specific extended spatial features

The Fermi-LAT gamma-ray sky

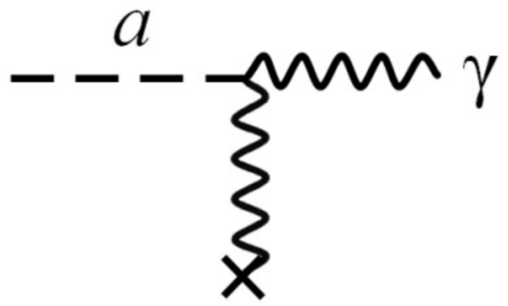


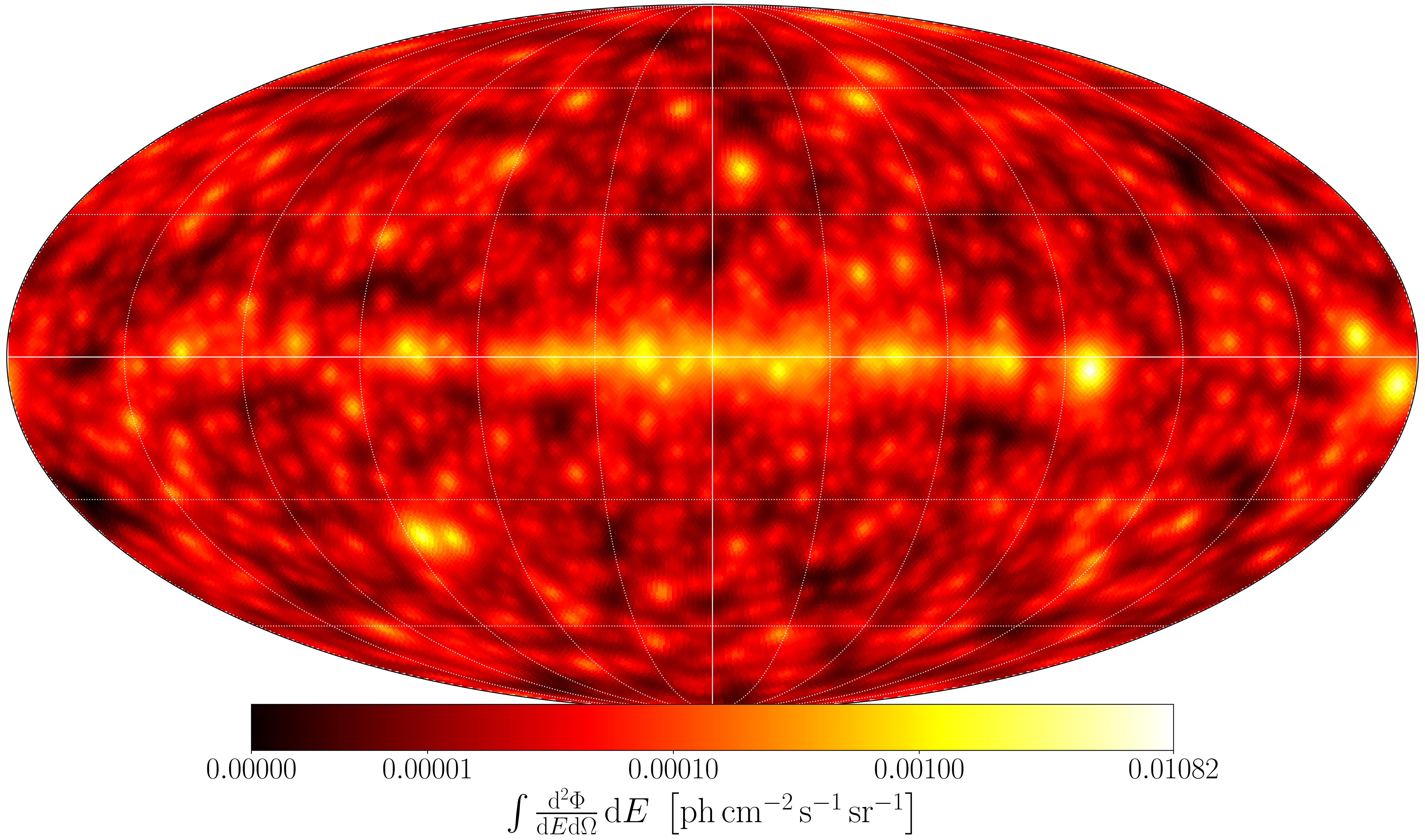
12yr gamma-ray data
50-200 MeV



How can we disentangle/ constrain the faint ALPs signal?

The gamma-ray sky components

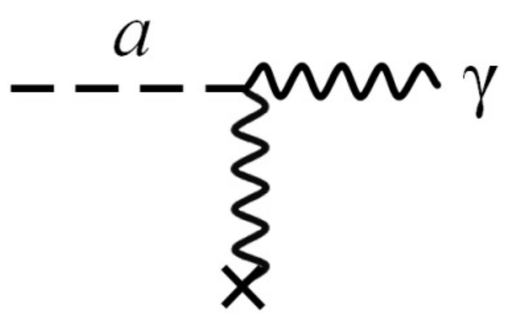


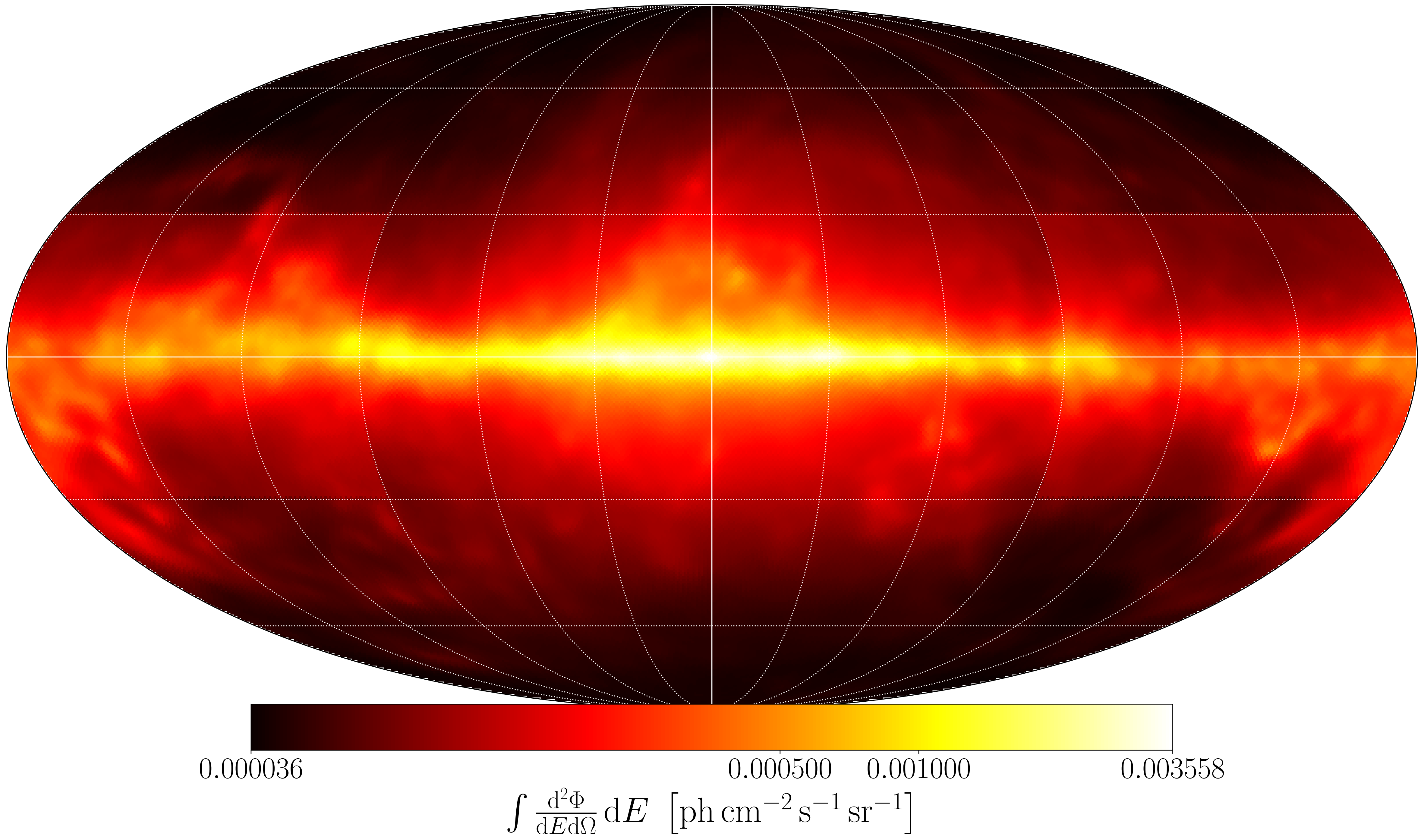


- ***Detected sources*** (point-like and extended) ~5000 objects

Fermi-LAT Collab. ApJS'20

The gamma-ray sky components





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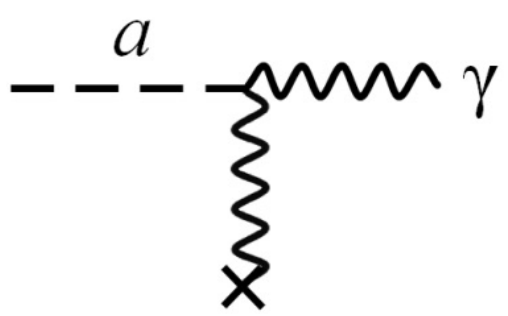
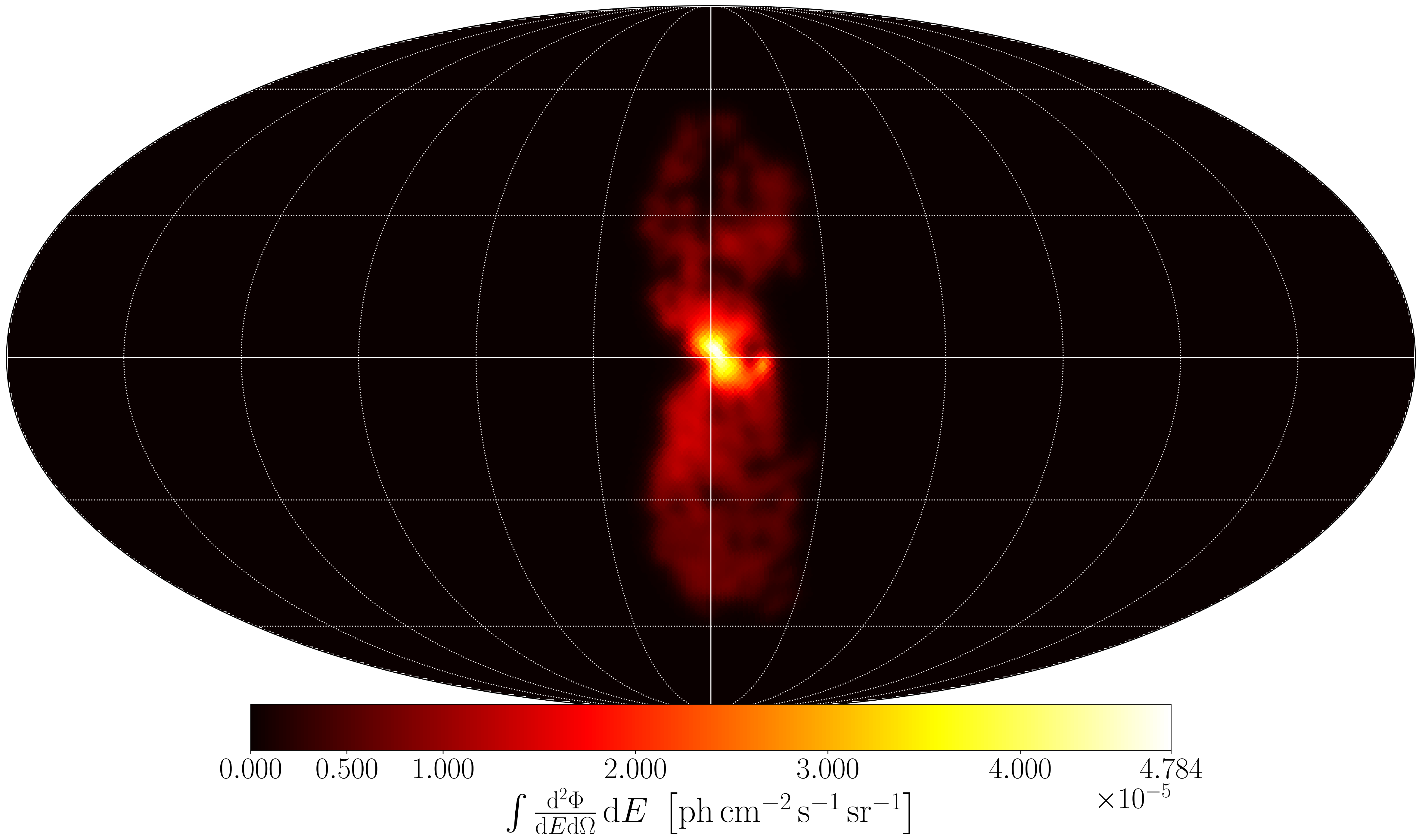




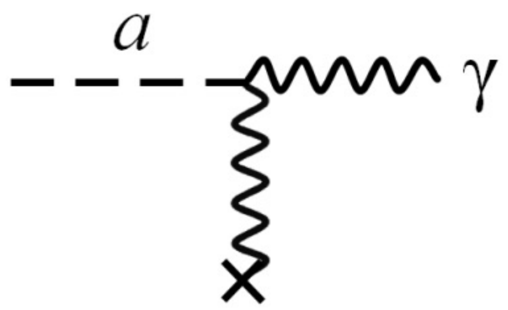
- ***Detected sources*** (point-like and extended) ~5000 objects

Fermi-LAT Collab. ApJS'20

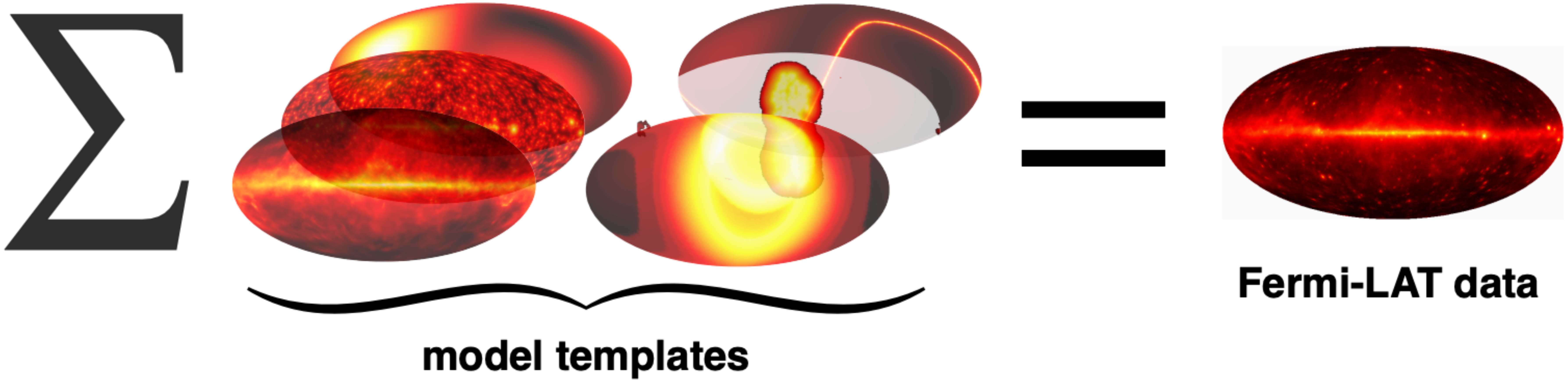
- ***Galactic diffuse emission*** from cosmic-ray interactions with gas and radiation
- Other large scale structures, e.g. ***Fermi bubbles*** — yet of unknown origin

Su+ ApJ'10

Fermi-LAT 3D template-based fit



New: Dedicated **template-based analysis** of 12yr Fermi-LAT data

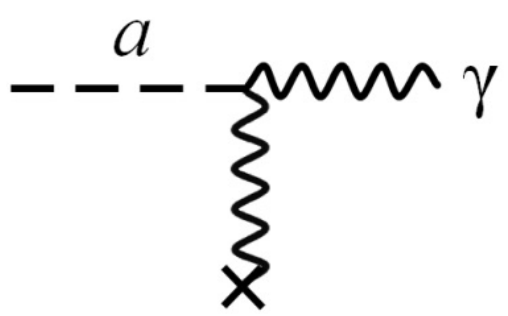


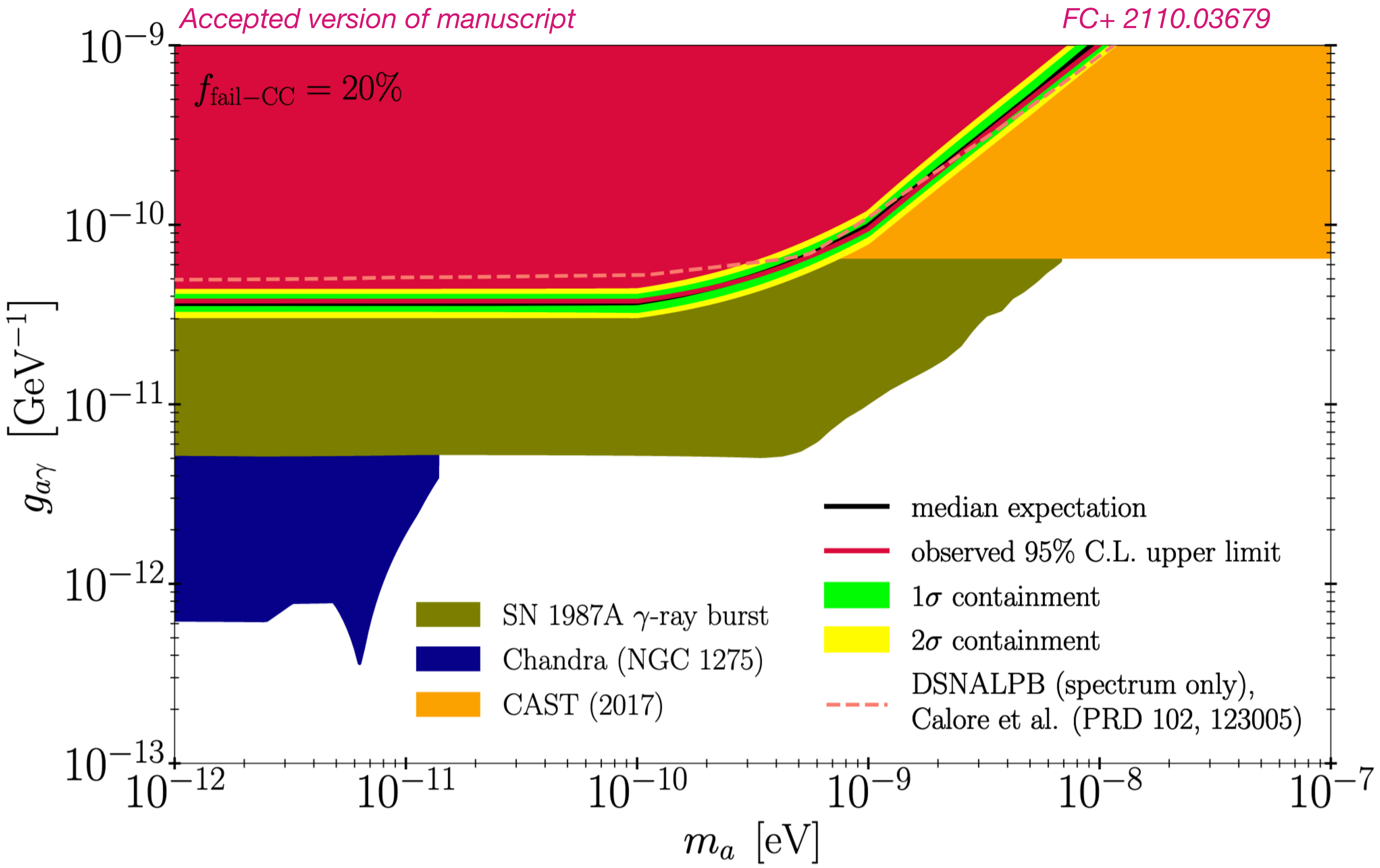
How to beat systematic uncertainties?

- *Interstellar model emission iterative fitting* procedure to reduce effect of background mis-modelling
- *ROI optimisation* to guarantee best consistency between model and data (high-latitude South)
- Statistical inference is based on a *weighted Poisson* log-likelihood function
- Extended LAT data sample down to *50 MeV*

FC+ 2110.03679

DSNALPB gamma-ray constraints





$$g_{a\gamma} \lesssim 3.7 \times 10^{-11}\,\mathrm{GeV}^{-1}\,,\ 95\%\ \mathrm{CL}$$

$$m_a \ll 10^{-11}\,\mathrm{eV}$$

source of uncertainty	relative [%]
$f_{\mathrm{fail-CC}}$	51.1
IMF	7.2
SNR	10.4
IEM	13.8
GMF model	38.8
total	124

Going beyond photon-only couplings

Production of ALPs in the SNe

ALP-photon coupling

Primakoff production $\gamma + Ze \to Ze + a$

ALP-electron coupling

Electron bremsstrahlung $e + Ze \to Ze + e + a$

$$\mathcal{L}_{\text{int}} = \sum_{\psi=e,p,n} \frac{g_{a\psi}}{2m_\psi}(\bar{\psi}\gamma_\mu\gamma_5\psi)\partial^\mu a - \frac{1}{4} g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

ALP-nucleon coupling

NN bremsstrahlung $N_1 + N_2 \longrightarrow N_3 + N_4 + a$

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$g_{ae} < 2.6 \times 10^{-13}$ → ALPs production suppressed by small coupling

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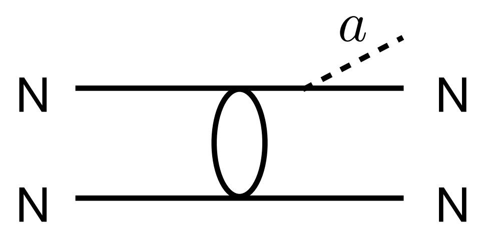
ALP-nucleon coupling

NN bremsstrahlung $N_1 + N_2 \longrightarrow N_3 + N_4 + a$

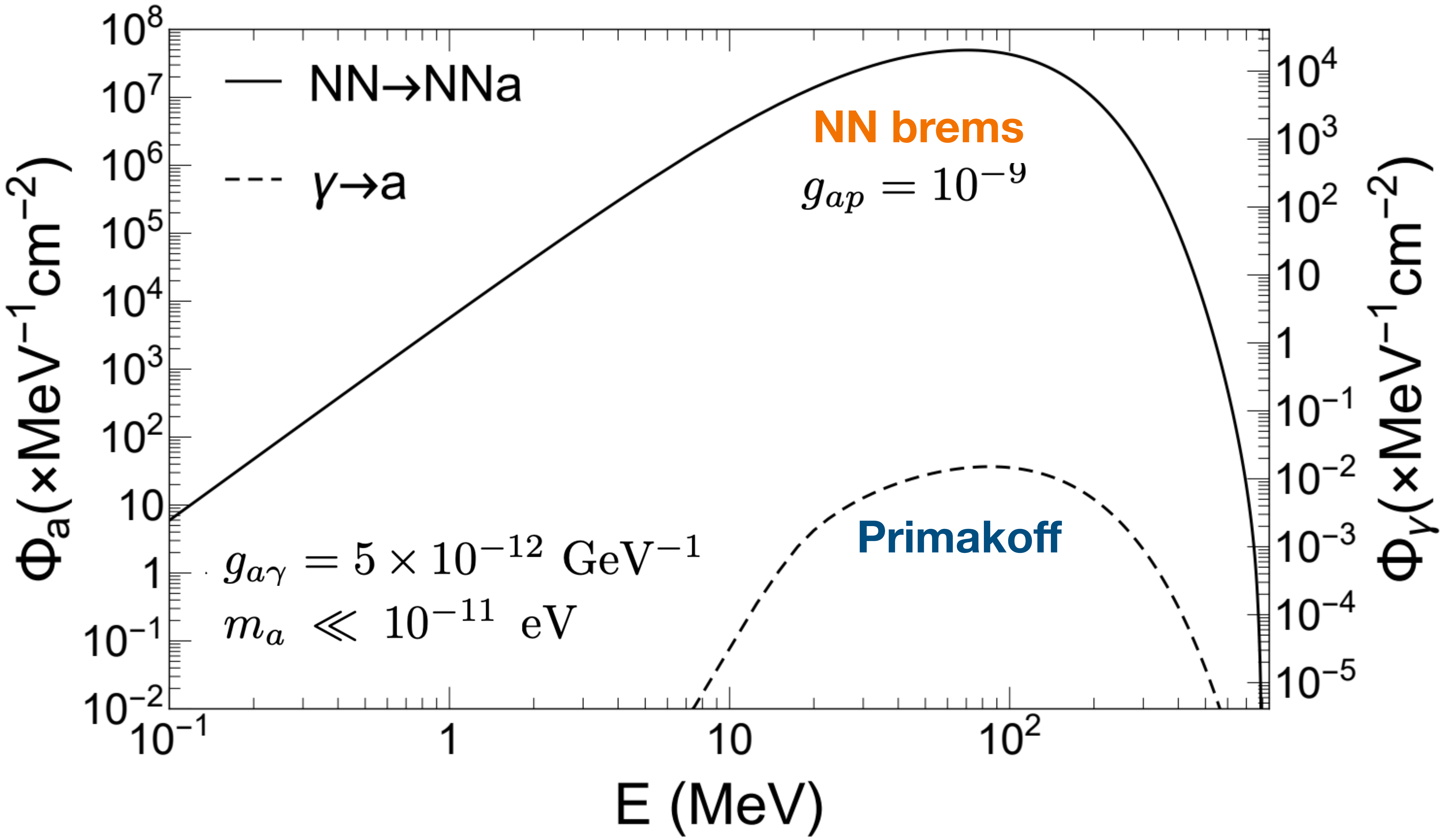
$g_{ap} < 0.9 \times 10^{-9}$
$g_{an} < 0.8 \times 10^{-9}$ → Copious ALPs production

Coupling with photons and nucleons

NN bremsstrahlung from SN1987A and DSNALPB



FC+ PRD'20



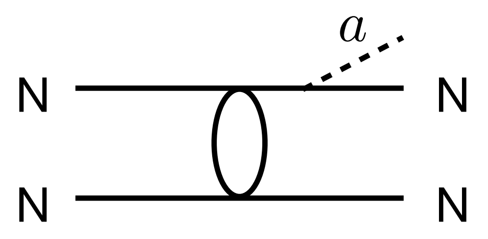
ALPs flux at Earth and gamma-ray flux for **SN1987A**

- NN brems. enhances the ALPs production and final gamma-ray flux

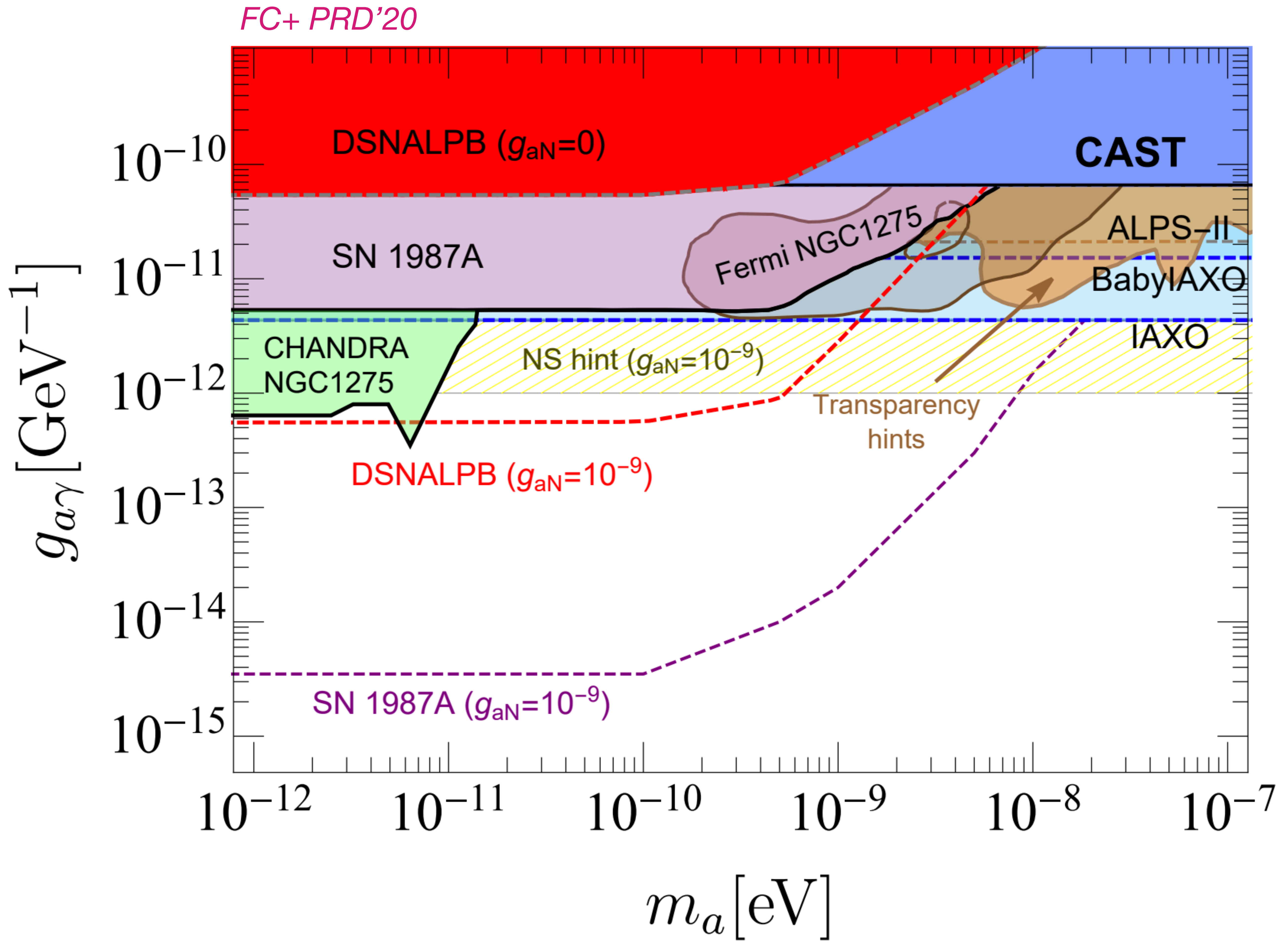
➡New limits from SN1987A

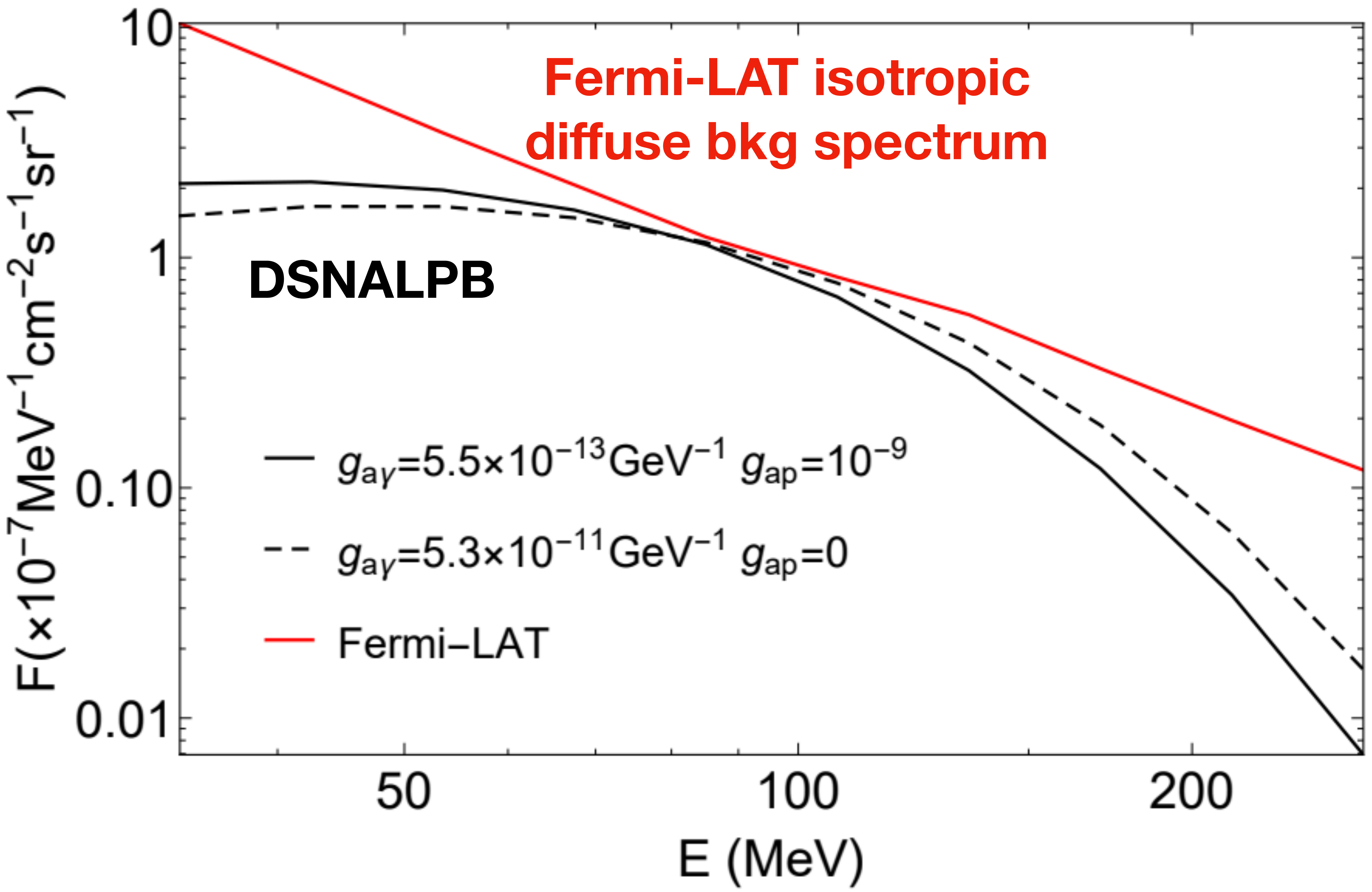
➡New constraints from DSNALPB

Constraints from enhanced NN brems

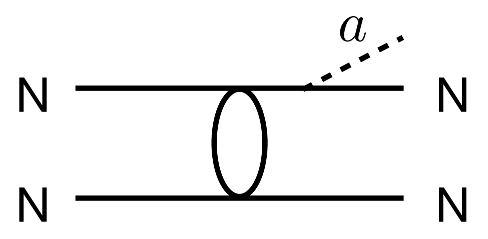


ALPs-photon conversion



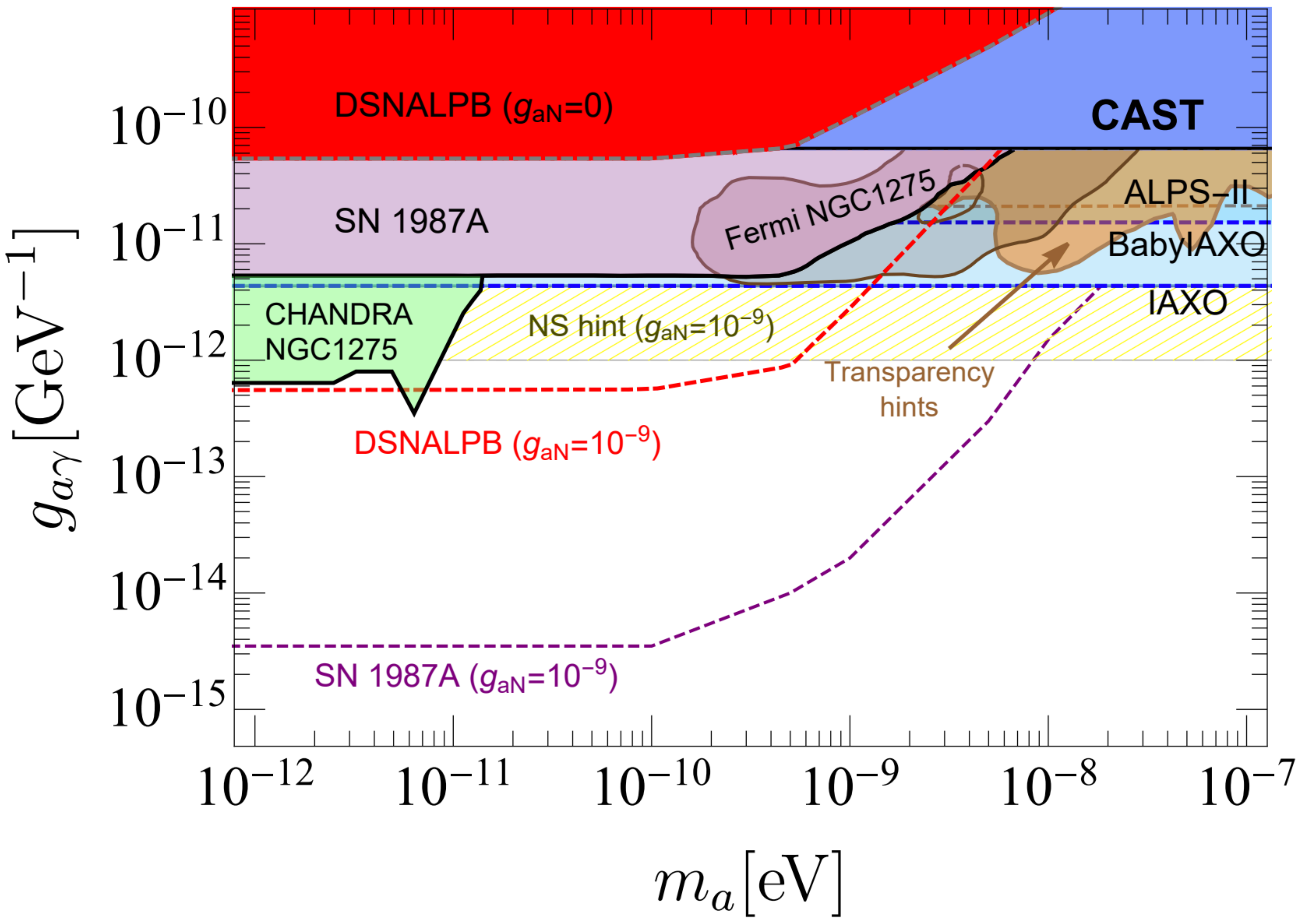


Constraints from enhanced NN brems



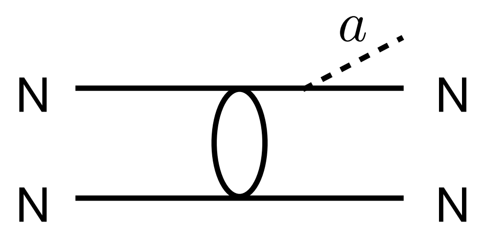
ALPs-photon conversion

FC+ PRD'20



- If coupling w/ **nucleons**, DSNALPB constraint:
  - ✓ Competitive w/ IAXO sensitivity
- If coupling w/ **nucleons**, SN1987A constraint:
  - ✓ Improves by $O(10^3)$

Constraints from enhanced NN brems



Heavy ALPs decay

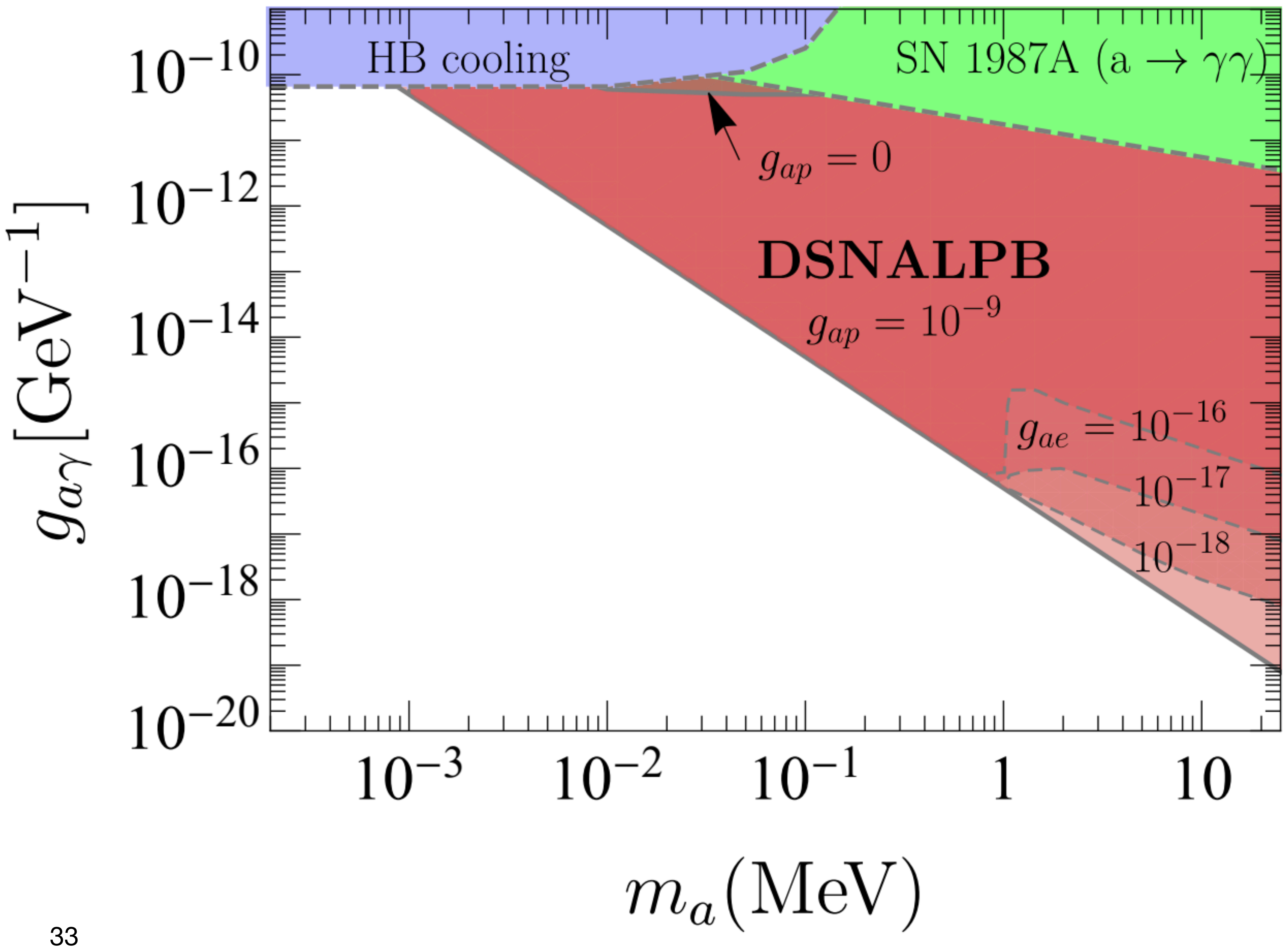
Using **COMPTEL** data (< 30 MeV), strong constraints on heavy *decaying* ALPs (10 - 100 keV) from gamma-ray decay

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

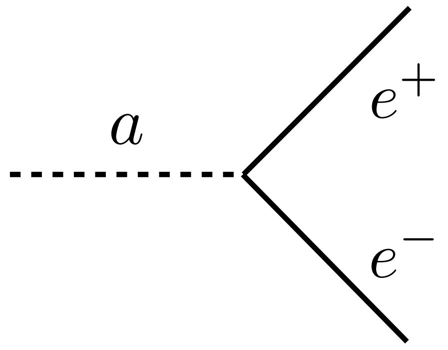
The decay into e+e- pairs tends to reduce the decay length as well as the total number of photons produced from ALP decays

[See also *Caputo+ 2201.09890*]

FC+ PRD'20



Coupling with nucleons and electrons



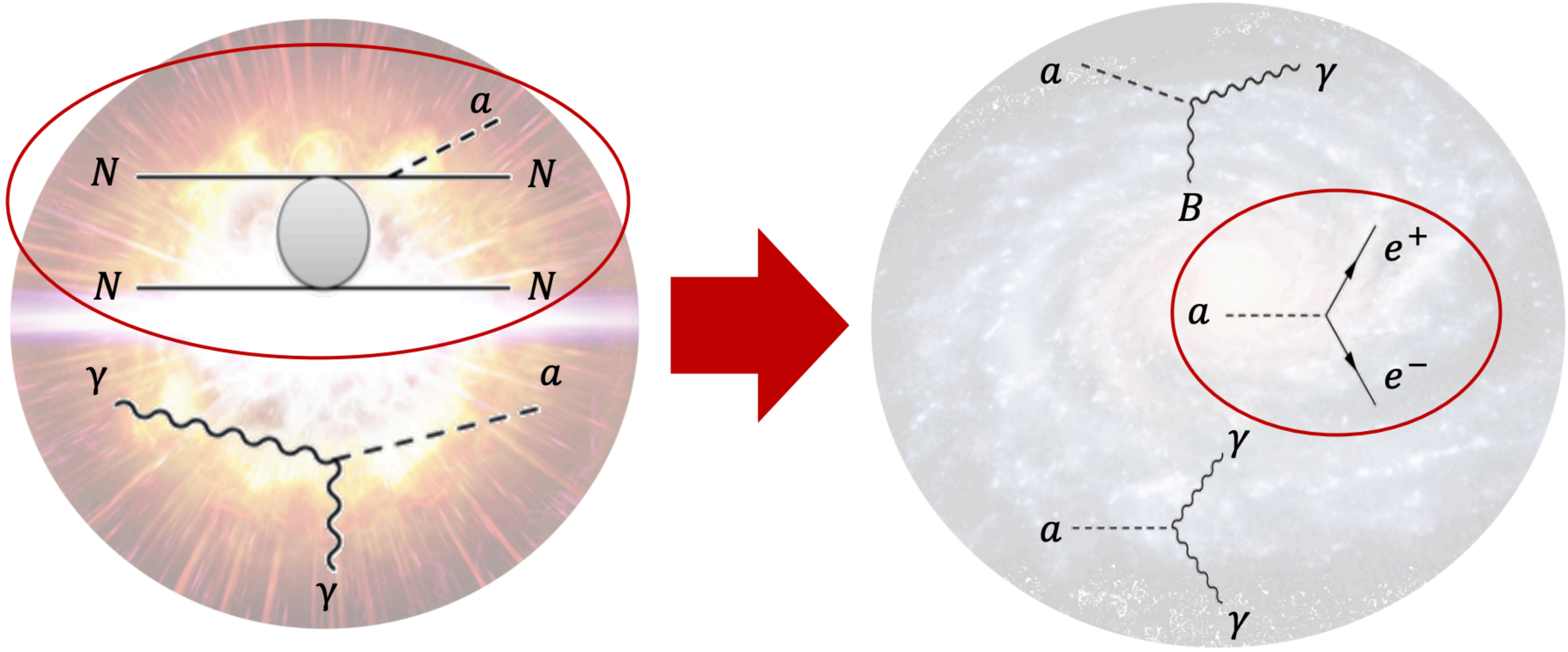
Heavy ALPs decay

- Production through **nucleon bremsstrahlung** in CC SNe
- For **m > MeV**, conversion suppressed but possible decays into **photons** and **electron-positron pairs**

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

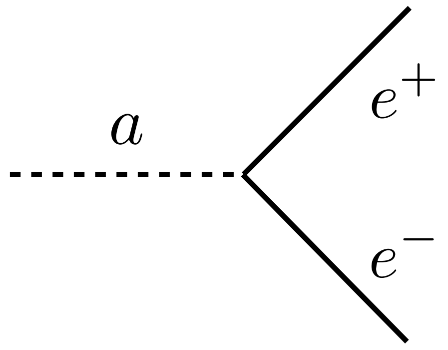
FC+ PRD'21

Production **Signature**



Credit: G. Lucente

Coupling with nucleons and electrons

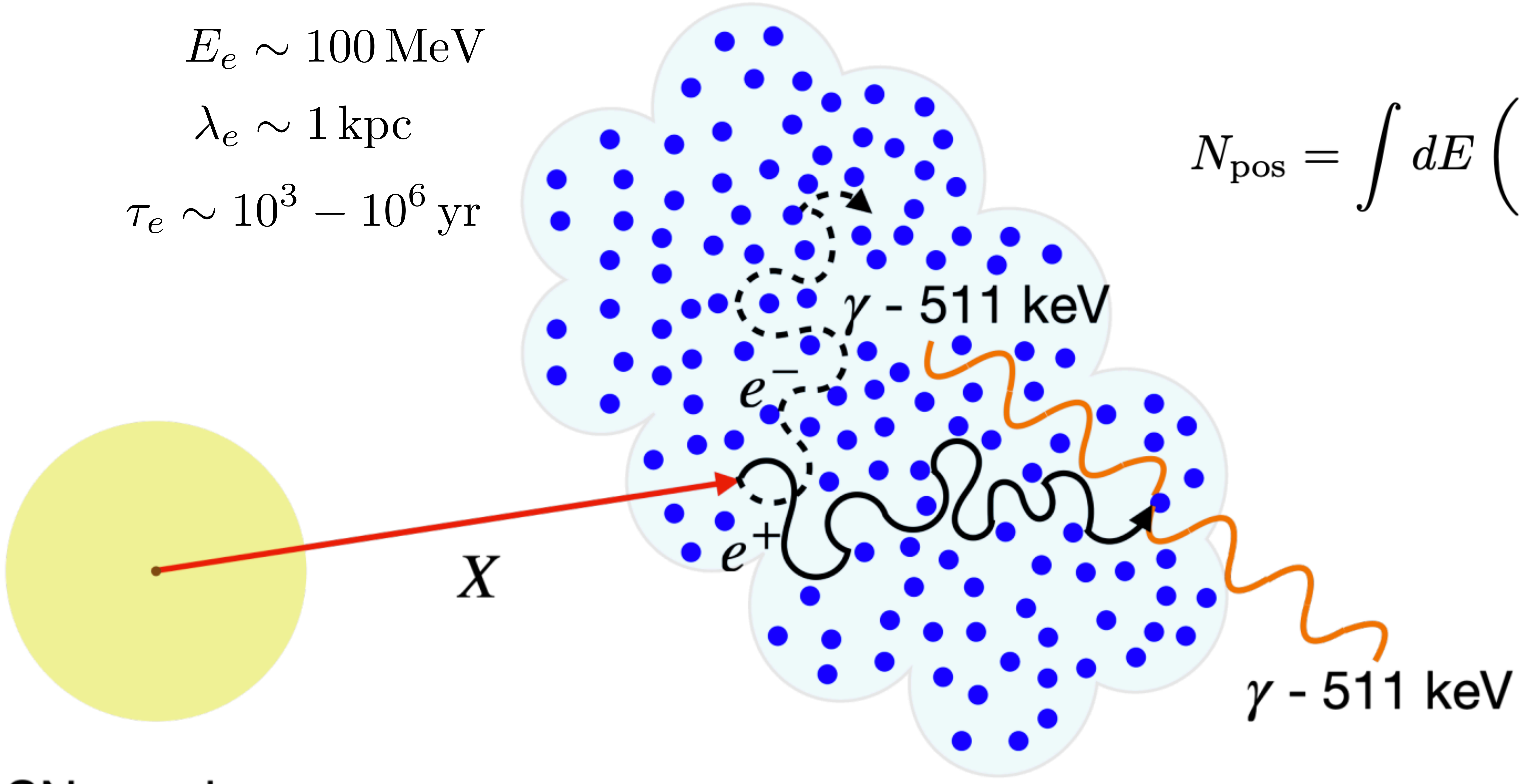


Positron production and annihilation

$$E_e \sim 100\,\mathrm{MeV}$$

$$\lambda_e \sim 1\,\mathrm{kpc}$$

$$\tau_e \sim 10^3 - 10^6\,\mathrm{yr}$$



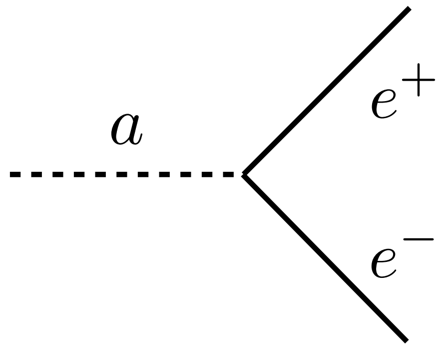
$$\left(\frac{dN_a^p}{dE}\right)_{\rm esc} = \frac{dN_a^p}{dE} \times \exp\left(-\frac{r_{\rm esc}}{l_e}\right)$$

In the Galaxy

$$N_{\rm pos} = \int dE \left(\frac{dN_a^p}{dE}\right)_{\rm esc} \left[1 - \exp\left(-\frac{r_{\rm G}}{l_e}\right)\right] \times BR_{\rm pos}$$

$$r_G = 1\,\mathrm{kpc}$$

Coupling with nucleons and electrons



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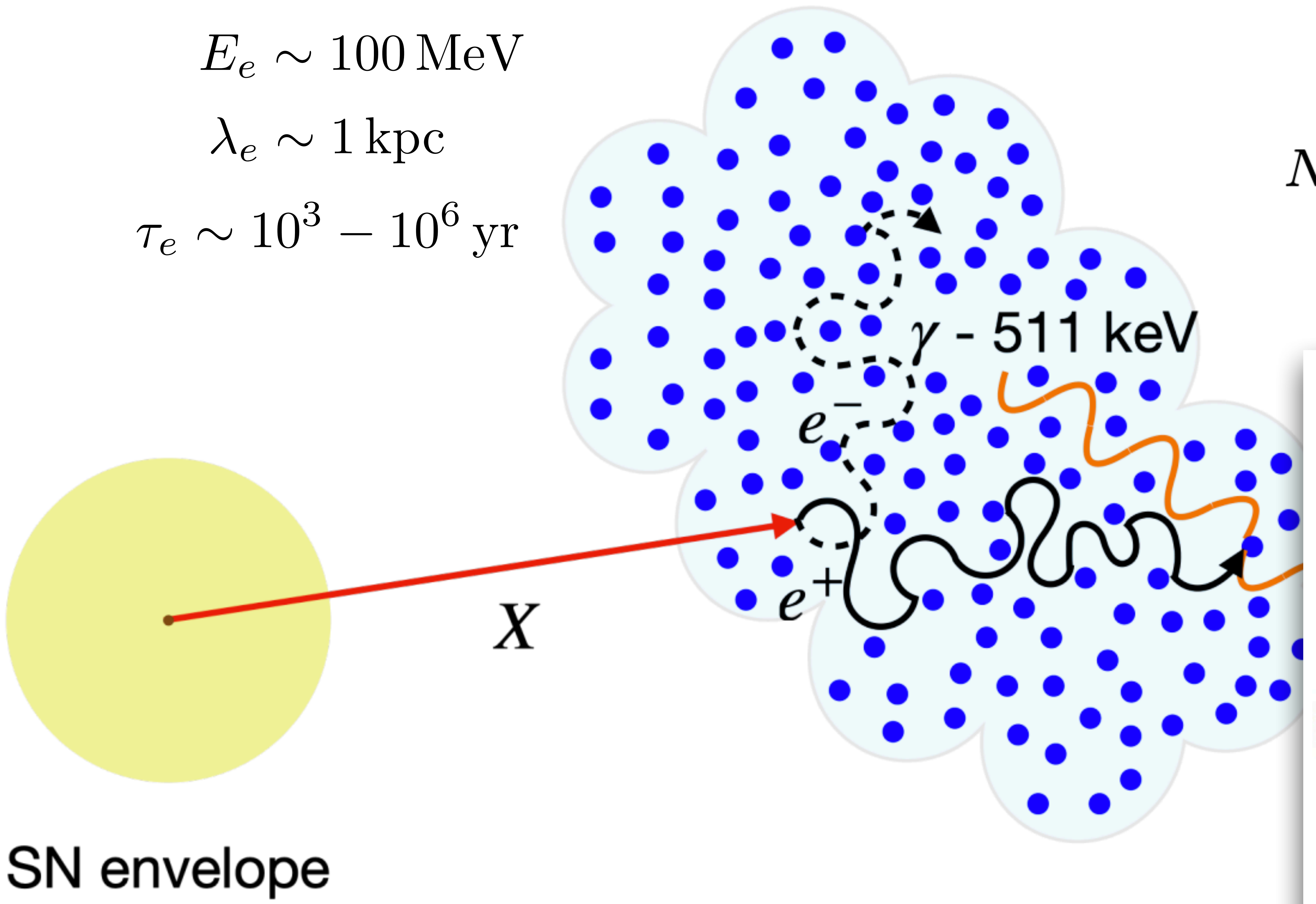

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In the Galaxy

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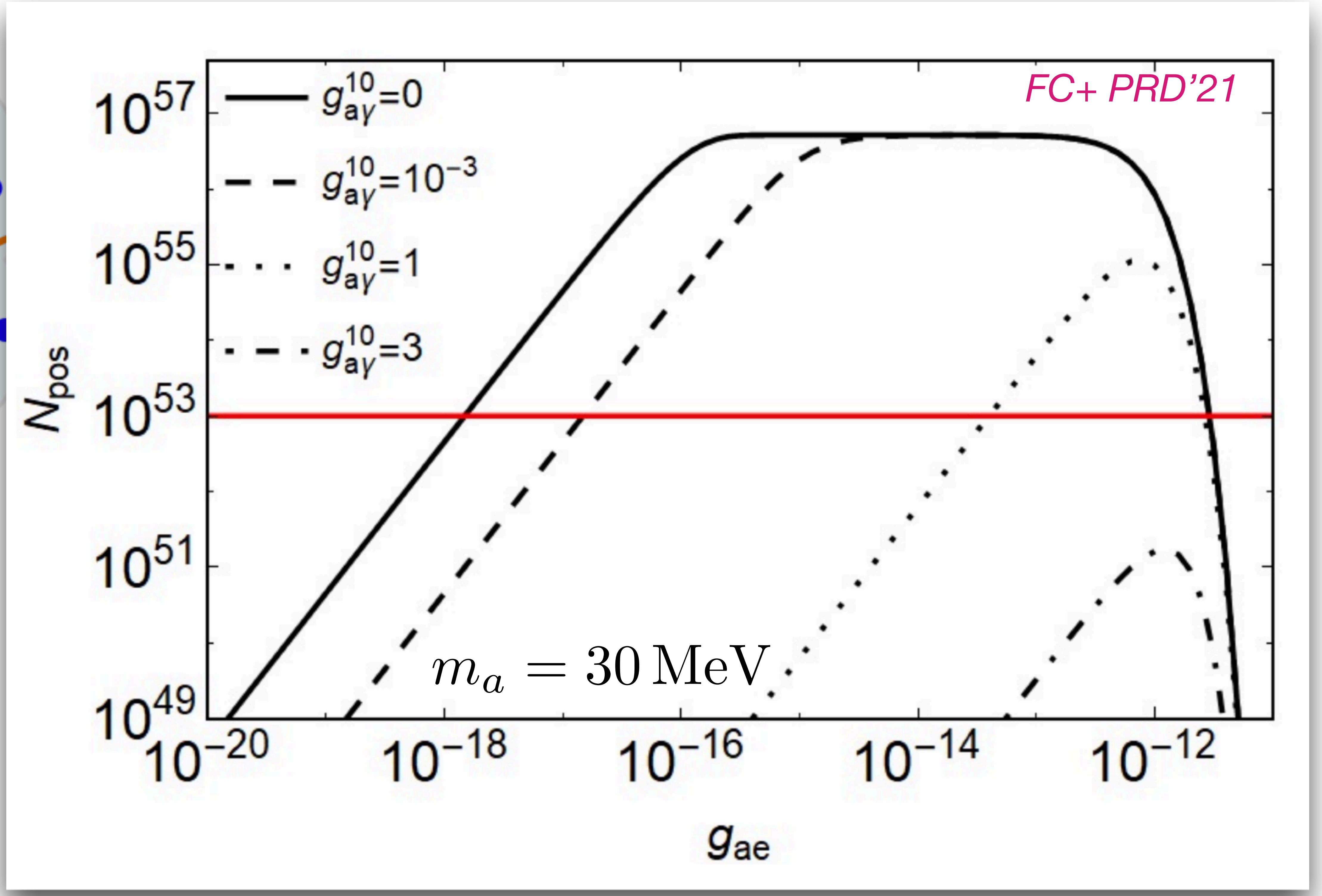
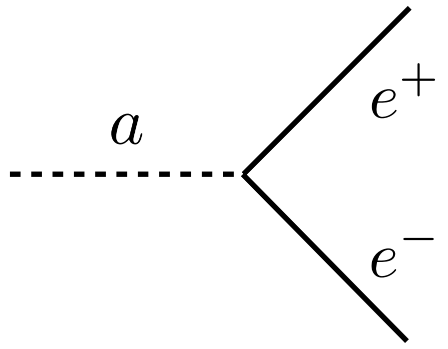
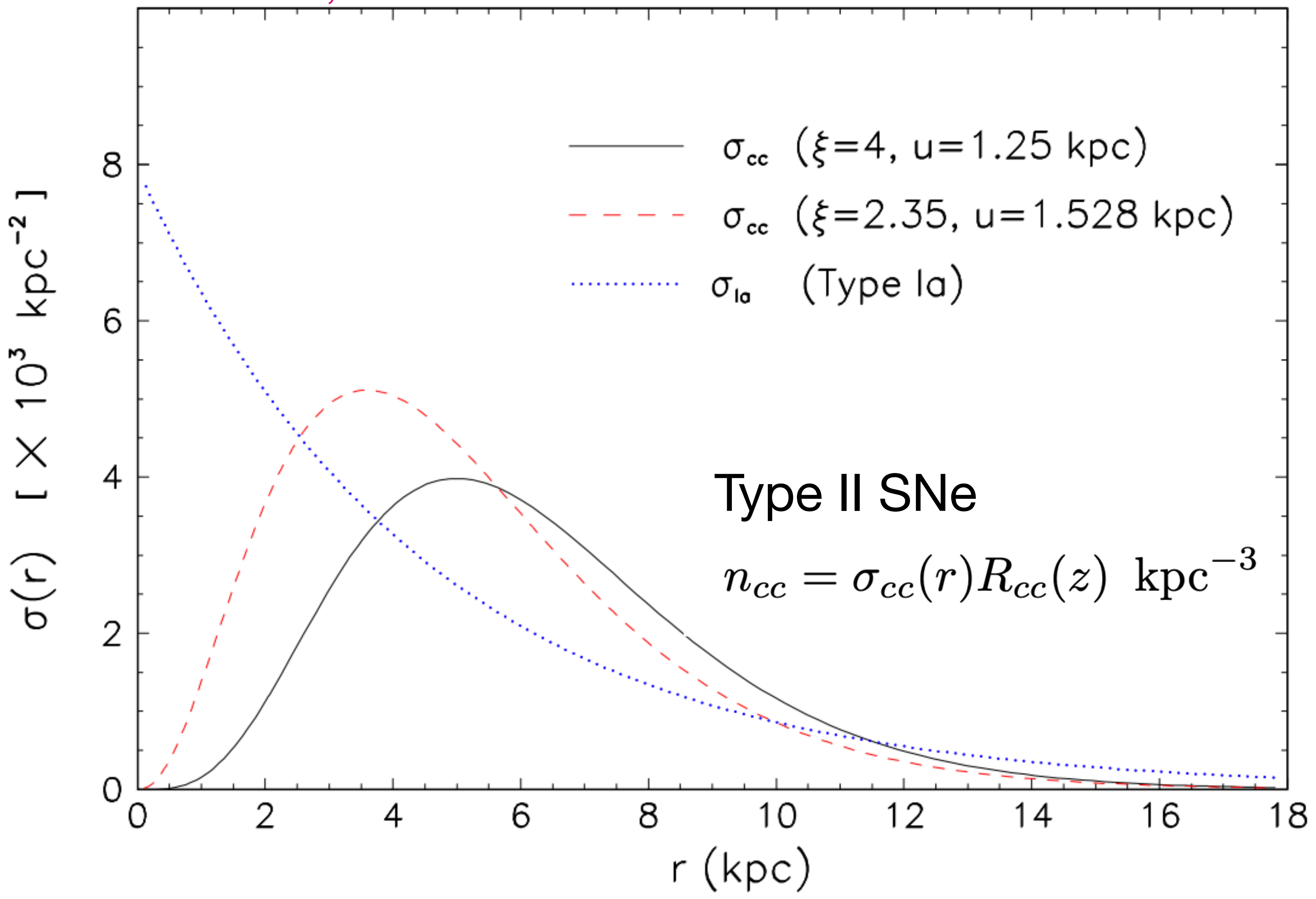


Coupling with nucleons and electrons



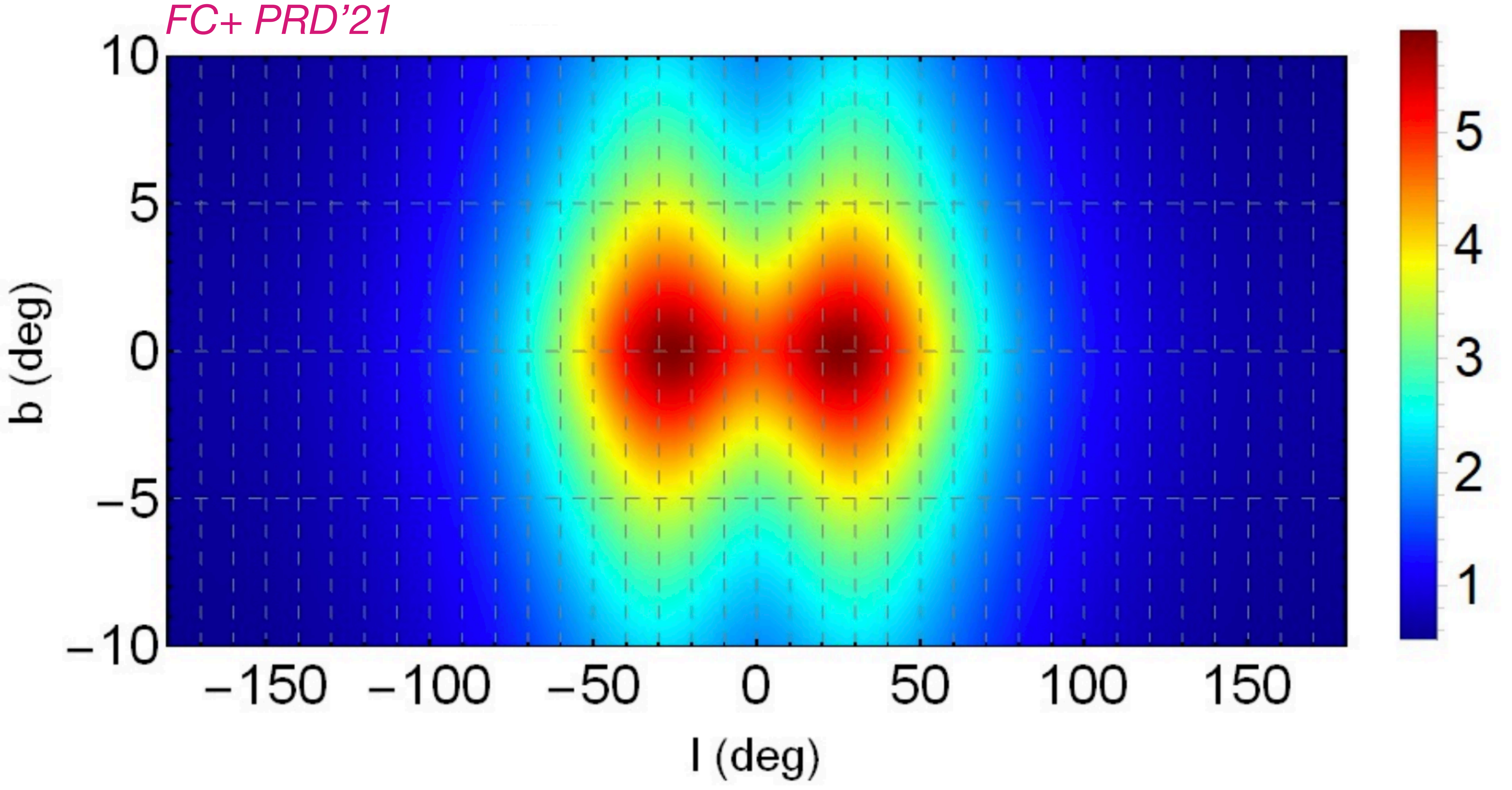
511 keV line from Galactic CC SNe population

Mirizzi et al., JCAP'06



$$\frac{d\phi_\gamma^{511}}{d\Omega} = 2k_{ps}N_{\rm pos}\Gamma_{cc}\int ds\, s^2\,\frac{n_{cc}[r(s,b,l)]}{4\pi s^2}$$

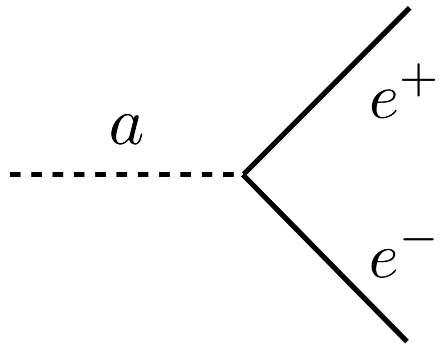
FC+ PRD'21



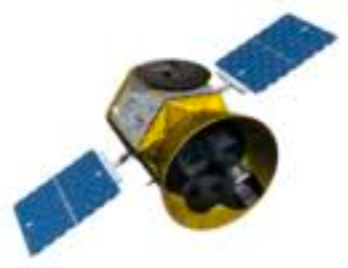
Smearing from decay length & positrons propagation

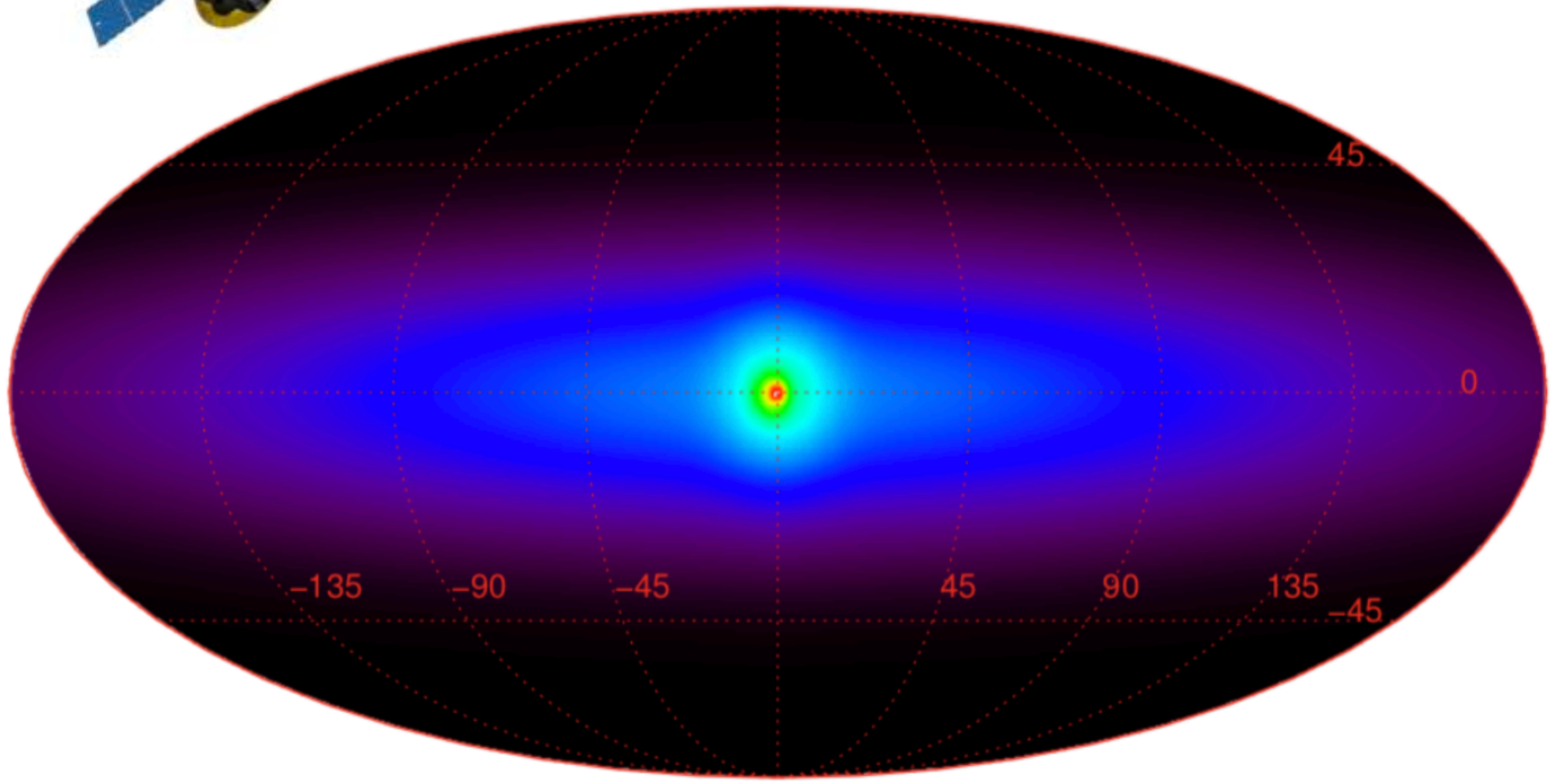
Jean et al., Astron. Astrophys. 445 (2006)

Coupling with nucleons and electrons



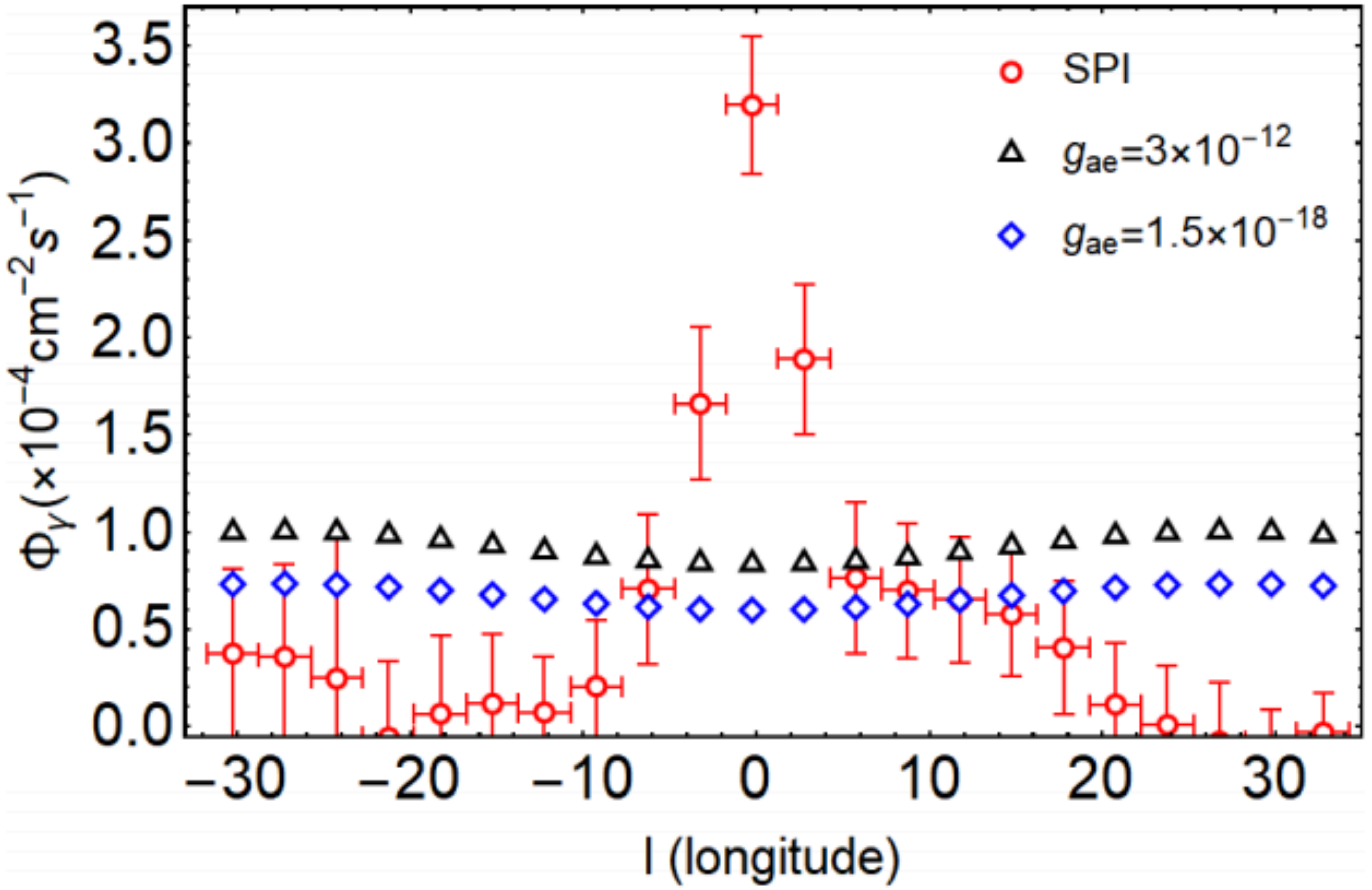
Limits from Integral/SPI 511 keV line observation



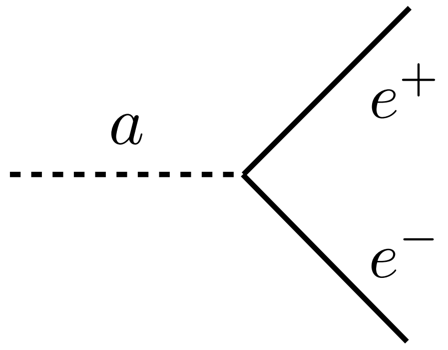


Siegert et al., Astron. Astrophys. 586 (2016)

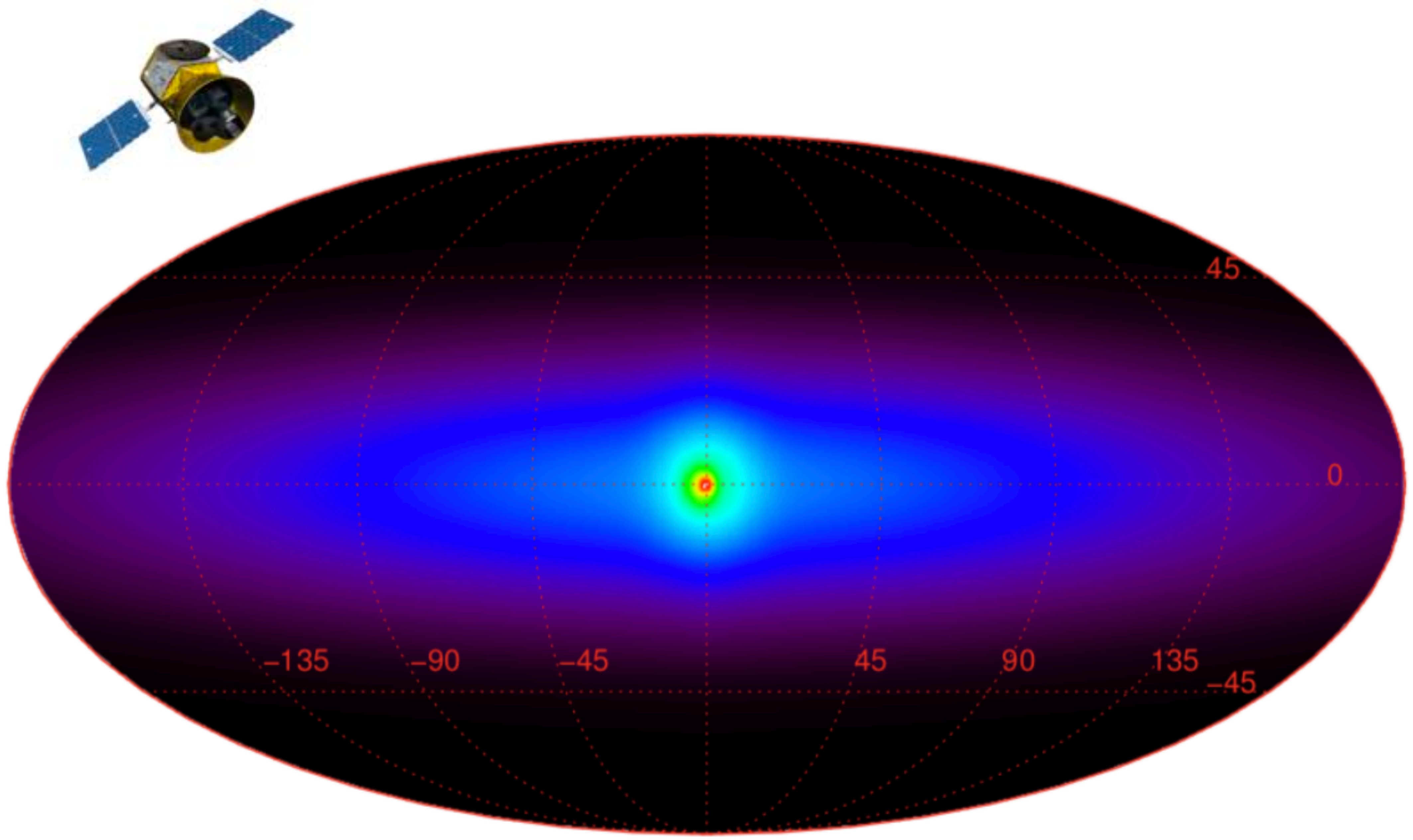
Siegert et al., Astron. Astrophys. 627 (2019)



Coupling with nucleons and electrons



Limits from Integral/SPI 511 keV line observation

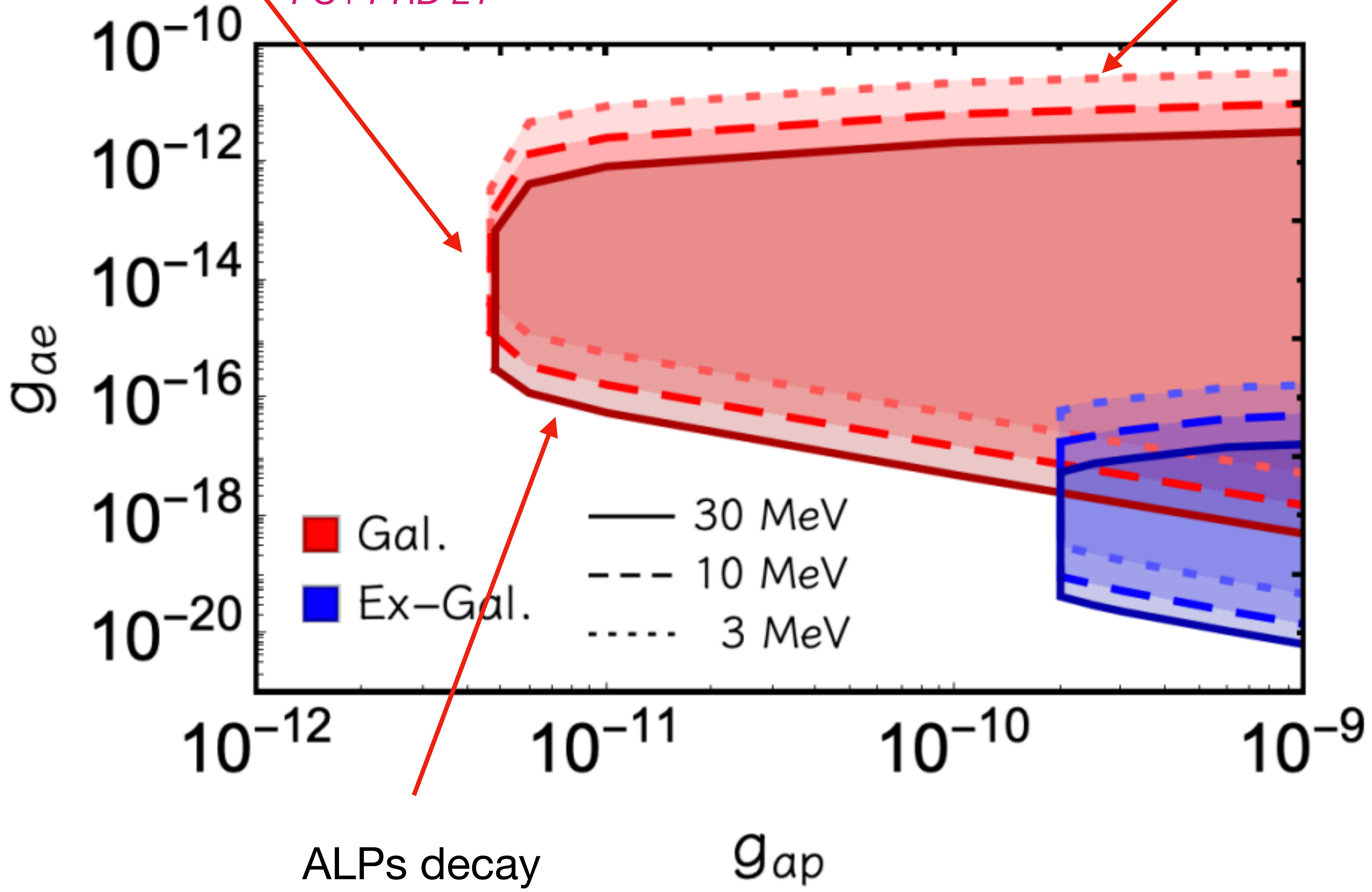


Siegert et al., Astron. Astrophys. 586 (2016)

Too few ALPs produced

ALPS decay inside SN

FC+ PRD'21

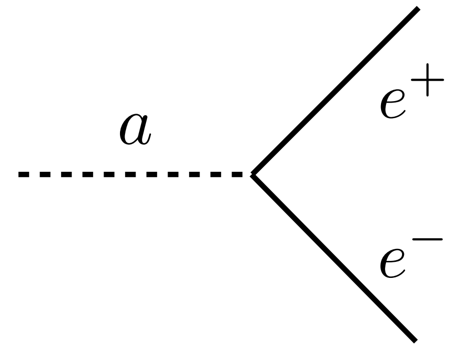


ALPs decay outside the Galaxy

[Theory uncertainties from positron propagation and progenitor mass]

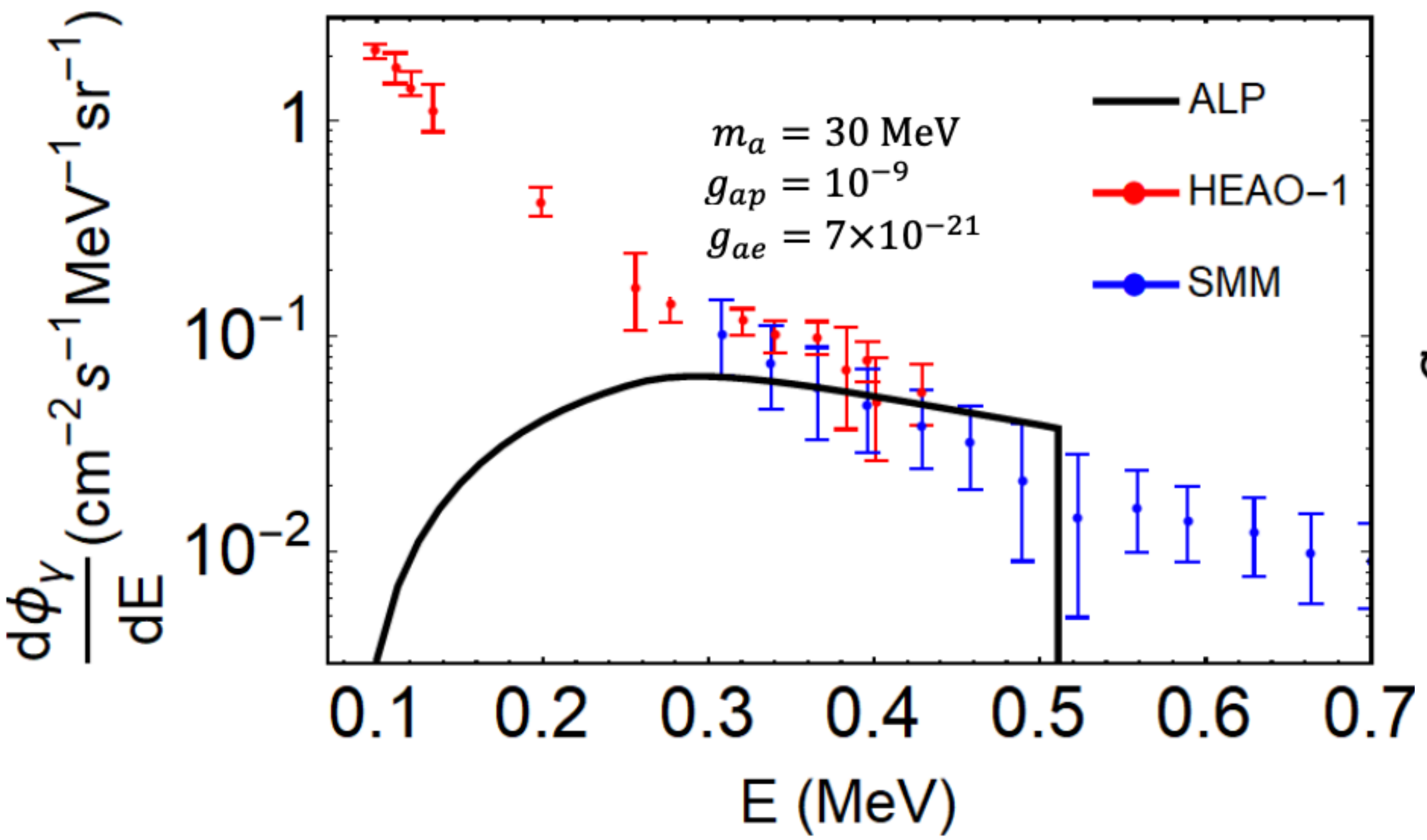
Coupling with nucleons and electrons

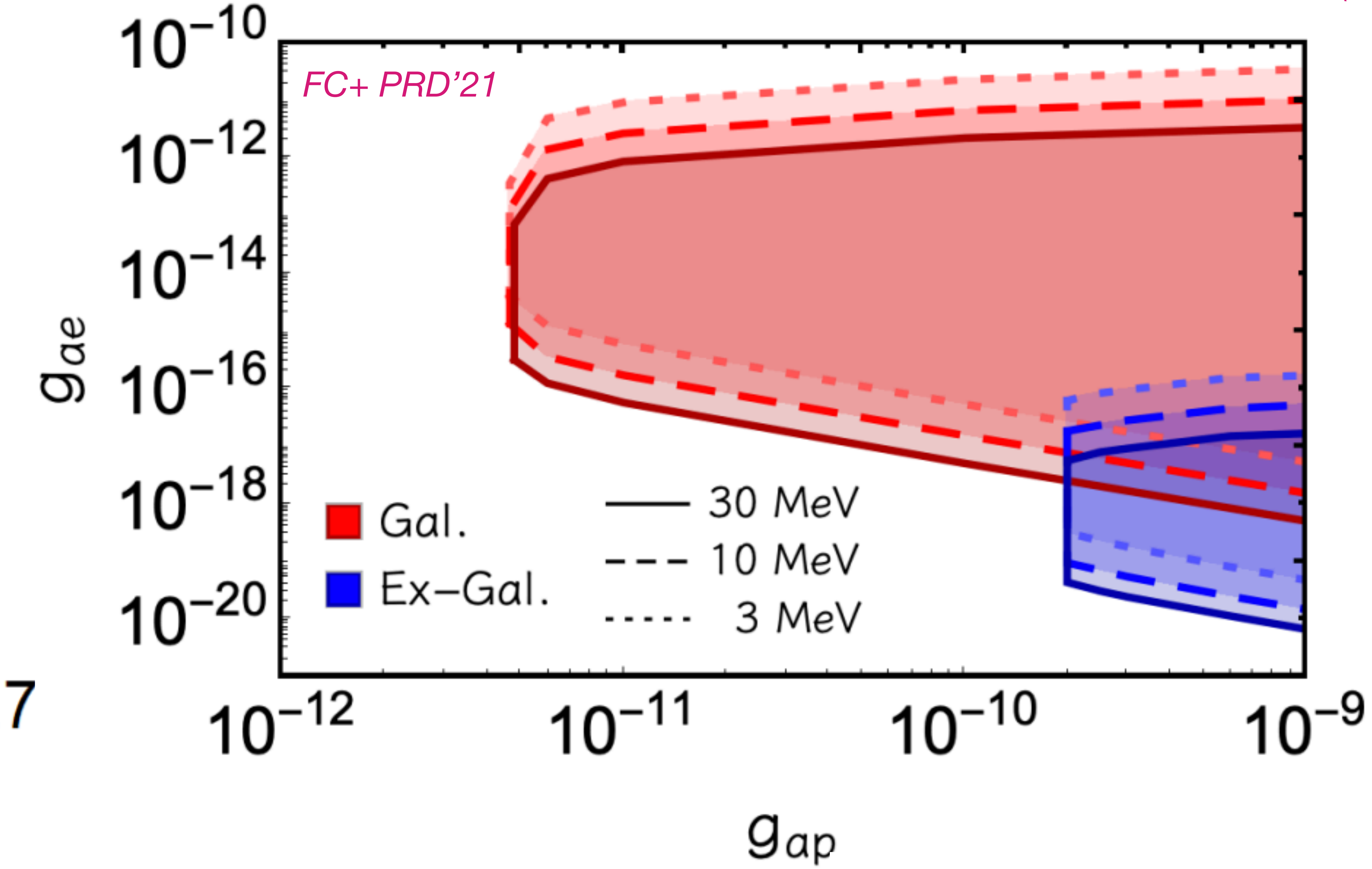
The cosmic X-ray background



Extragalactic CC SNe => **Redshifted** 511 keV line signal, from escaping ALPs from past CC SNe

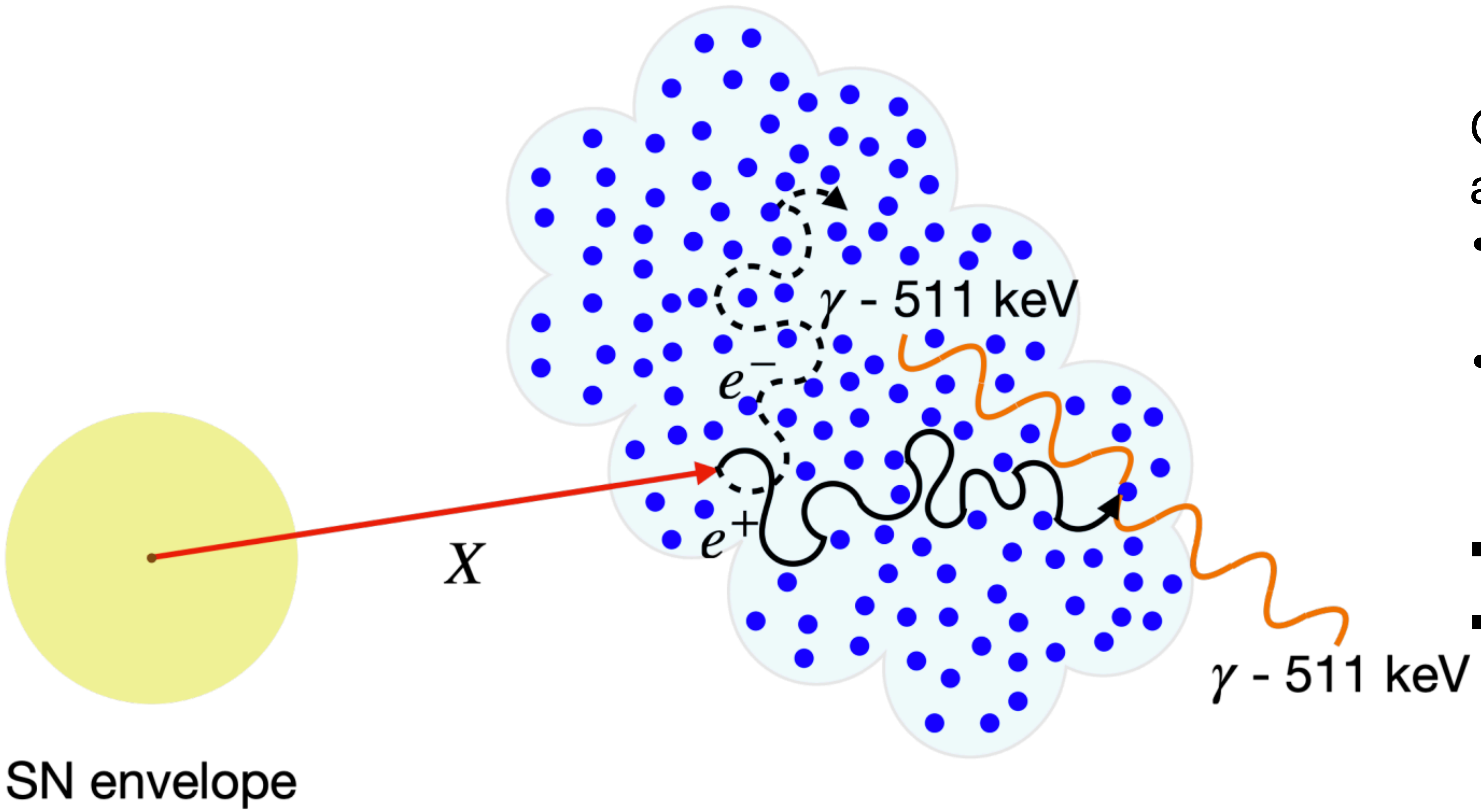
Raffelt et al., PRD 84 (2011)





Galactic and extra-galactic SNe: bound on a currently unexplored region (g_{aN}, g_{ae})

Constraints on FIPs from CC SNe



General rationale can be applied to all FIPs that:

- Can be produced through mixing with SM particles
- Have decay channels with positrons in the final state

➡ Limits on **sterile neutrinos**

➡ Limits on **dark photons**

FC+ 2112.08382

Dar+ PRL 1987; DeRocco+ JHEP’19

Constraints on FIPs from CC SNe

The case of dark photons

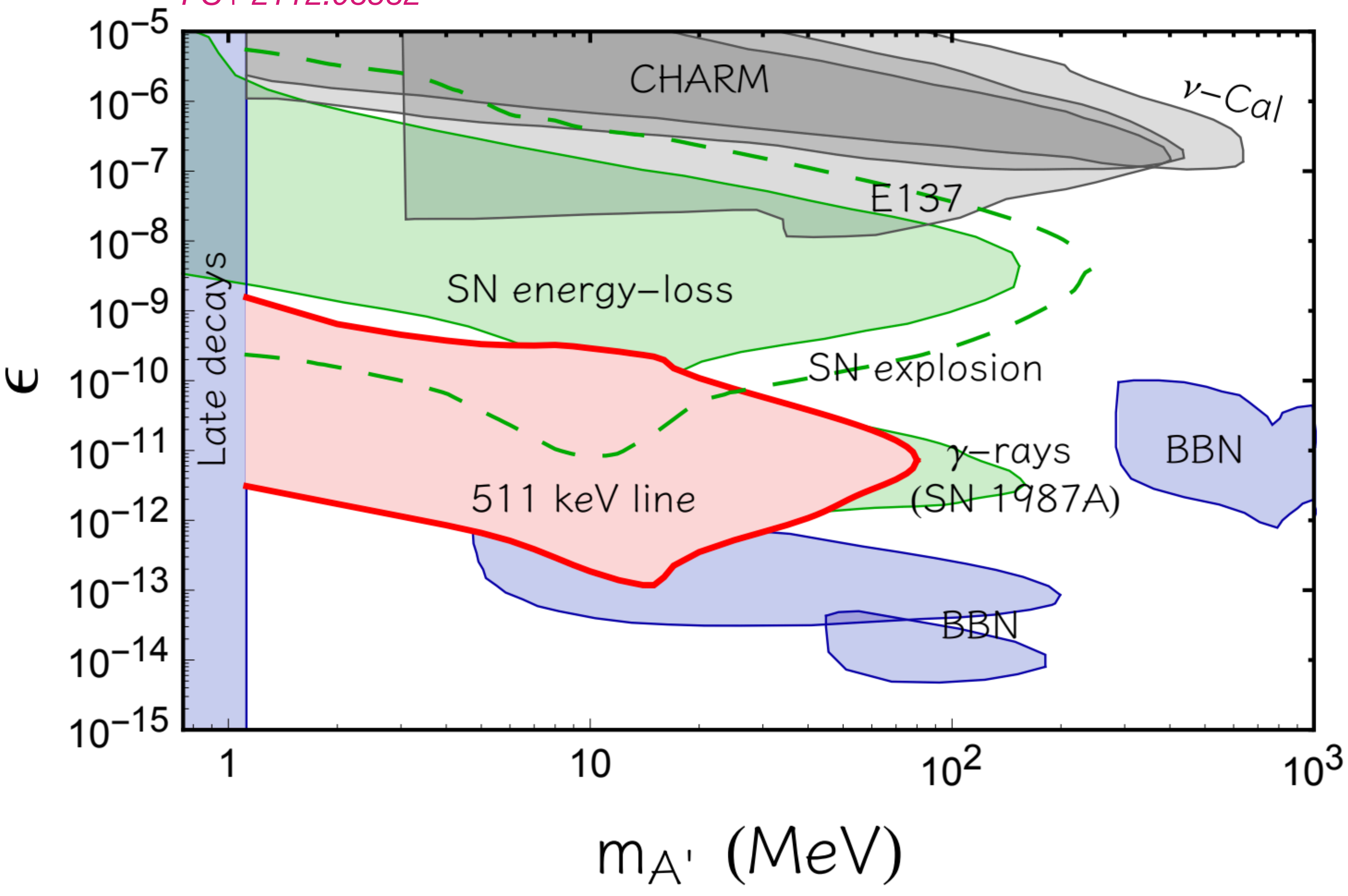
The **dark photon** (DP) is a $U(1)_0$ gauge boson kinetically mixed with the SM photon

$$\mathcal{L} = \frac{1}{2} m_{A'} \, A'_\mu \, A'^\mu - \frac{1}{4} F'_{\mu\nu} \, F'^{\mu\nu} - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

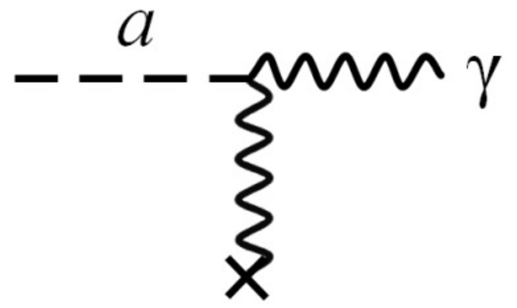
Transverse and longitudinal d.o.f can be produced in SN core

Chang+ JHEP'17

FC+ 2112.08382



Future gamma-ray bursts from CC SNe



Production of ALPs in the SNe mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

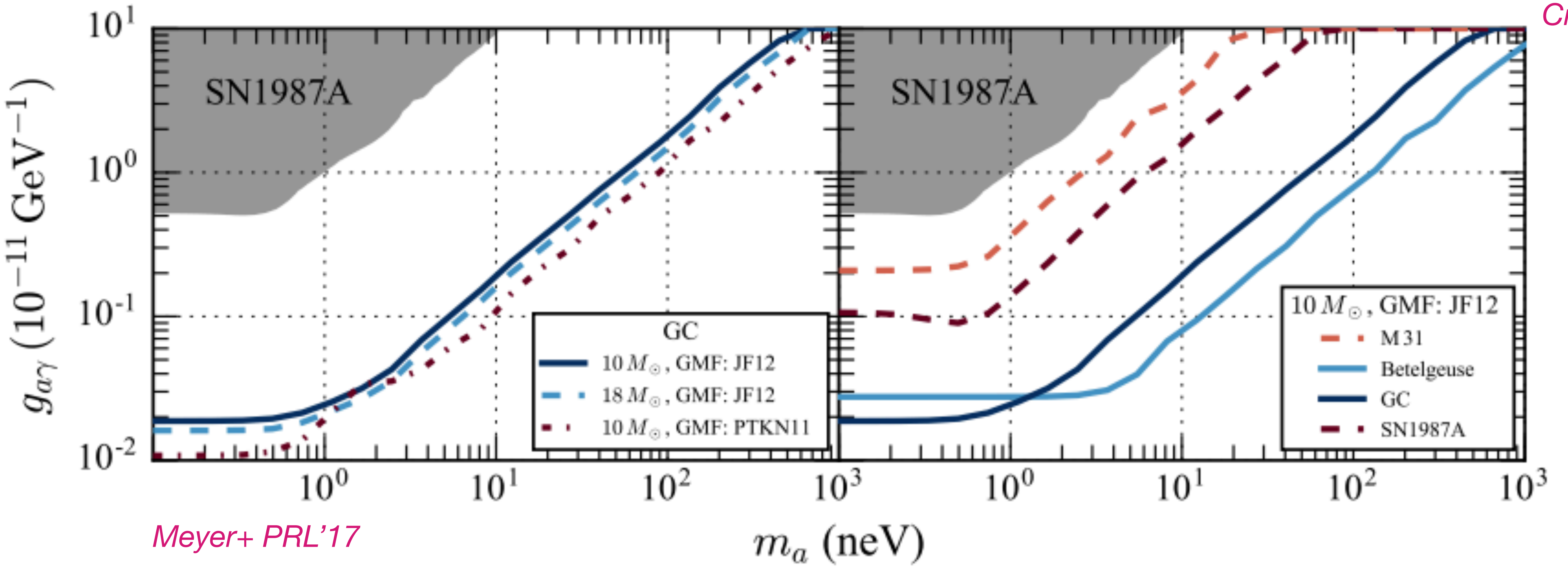
ALPs produced in **O(10) sec bursts**, with an energy spectrum peaked at **60-80 MeV**

➡ Specific **time dependent** and **spectral** signatures

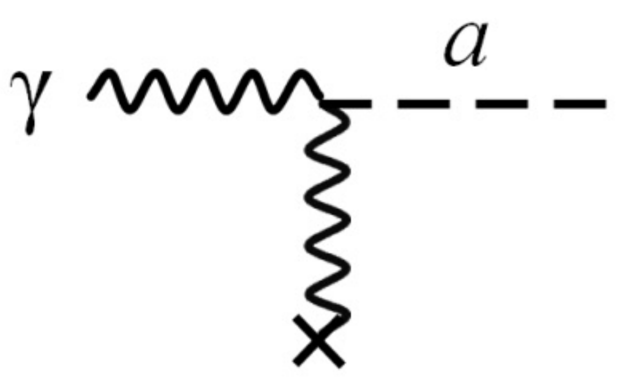
➡ 3% chance to see a Galactic SN with the LAT over the next 7 years

- **Future Fermi-LAT Galactic SN**: Projected constraints from observation of short gamma-ray burst from SN explosion with the LAT from time-dependent signal

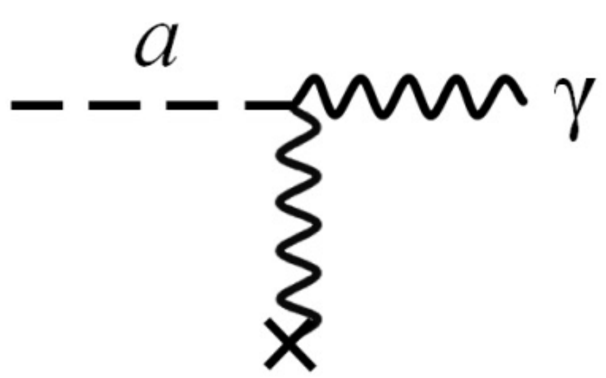
Meyer+ PRL'17
Crnogorcevic+ PRD'21

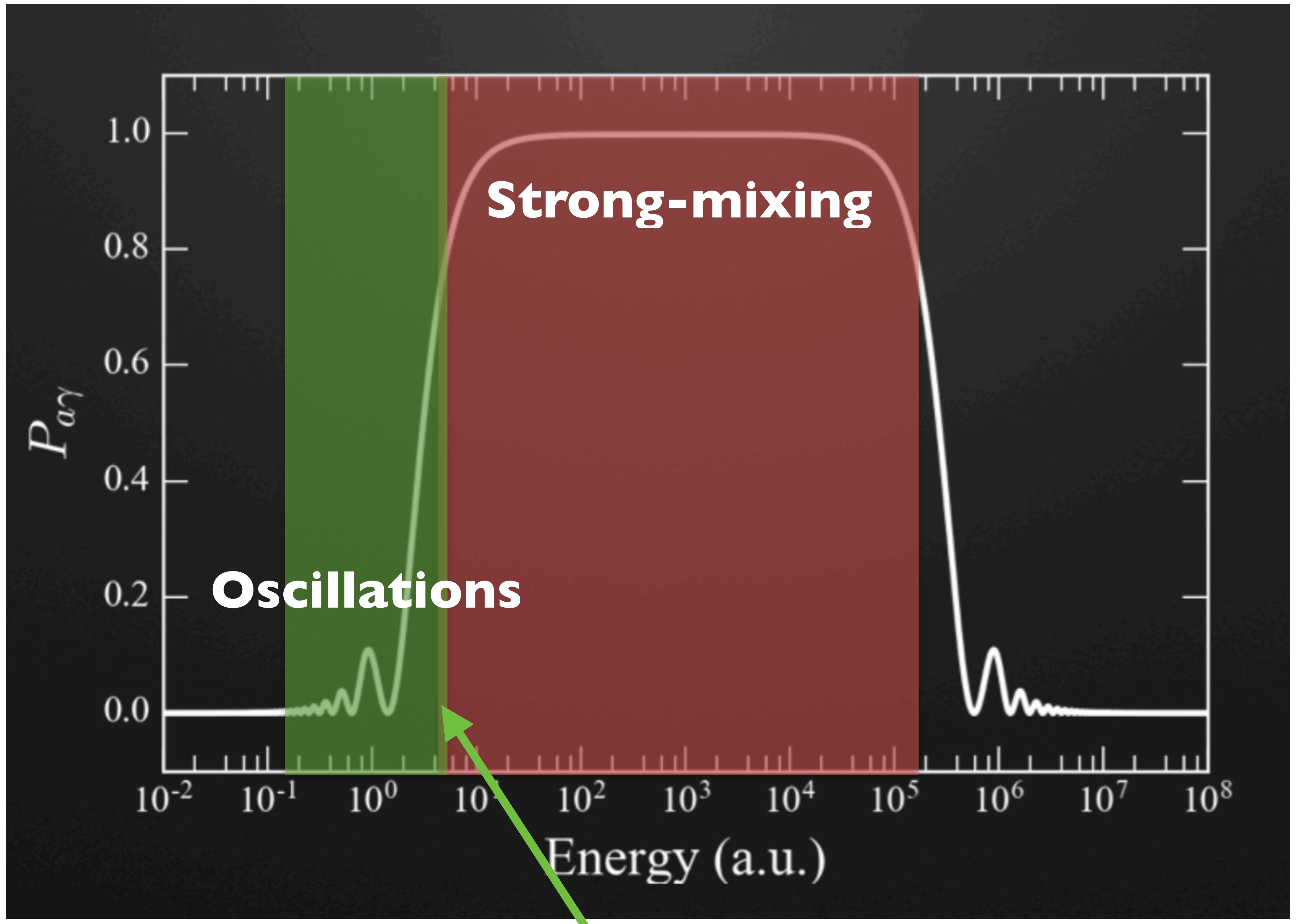


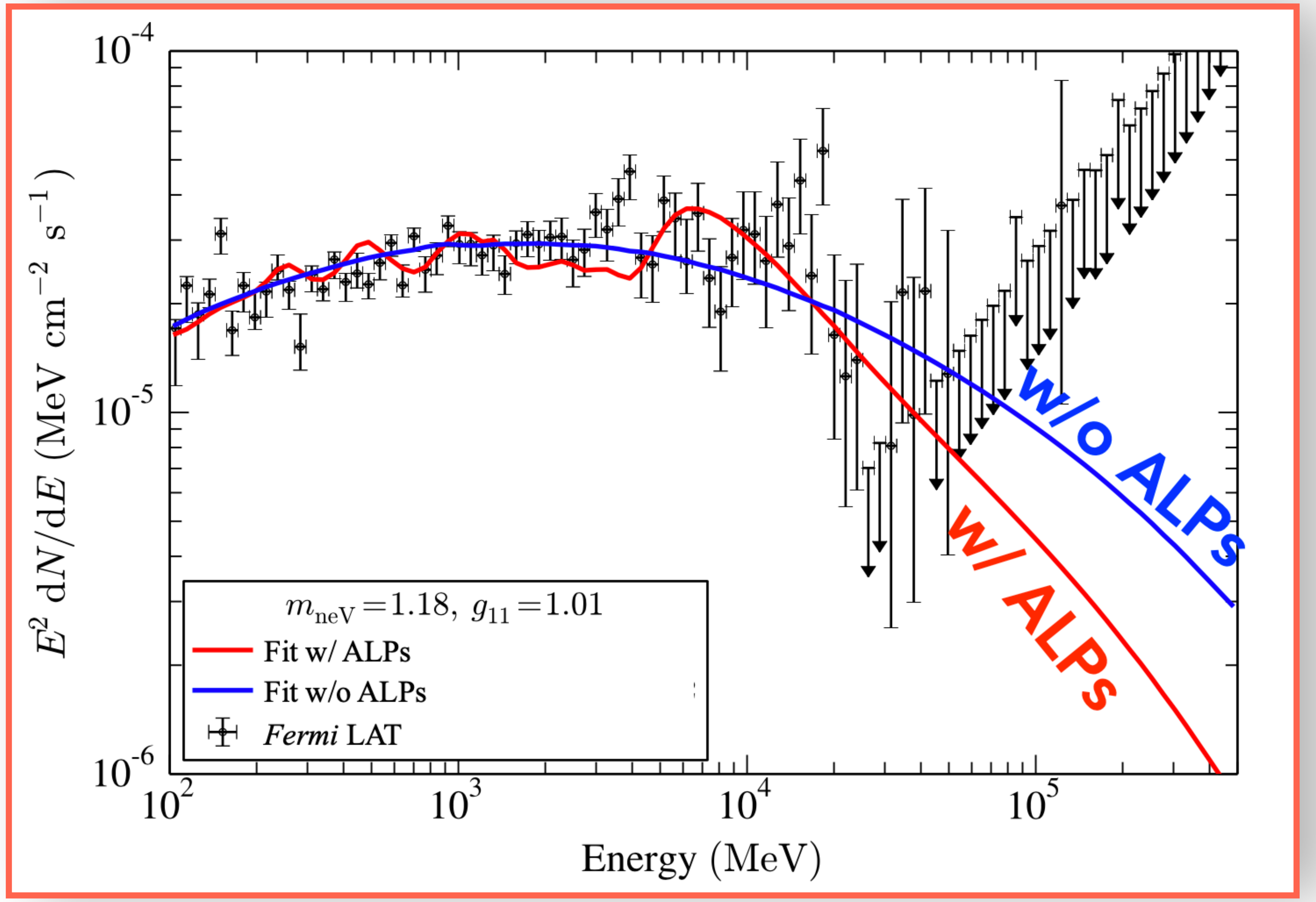
Meyer+ PRL'17



Searches for spectral irregularities

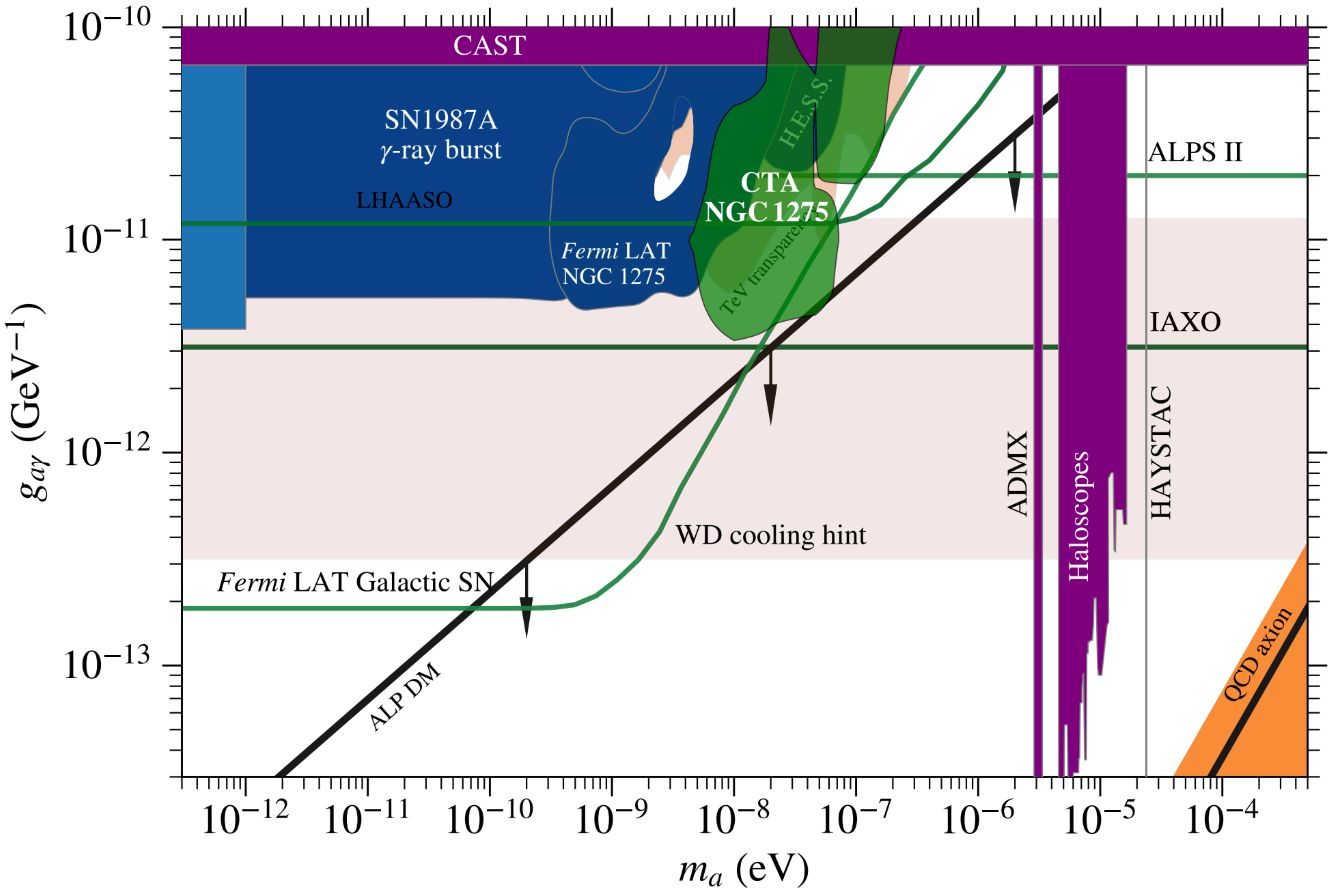






$$E_c \simeq 2.5\ \mathrm{GeV}\frac{|m_a^2-\omega_{Pl}^2|}{1\,\mathrm{neV}}\left(\frac{B_\perp}{\mu\mathrm{G}}\right)^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^{-1}$$

What future for gamma-ray searches?



- DSNALB, SNe and pulsars constraints would benefit by **future MeV missions**, able to **better resolve the diffuse gamma-ray background** and provide **accurate spectra in the MeV** energy range
- Galaxy clusters (e.g. NGC1275) limits would be improved by **CTA** touching ALP DM region

CTA Consortium 2010.01349
Batkovic+ Universe Review'21

- Search for SNe bursts opens exciting complementarity with **optical transient facilities (Rubin, ZTF, TESS)**.

Meyer+ PRL'17
Crnogorcevic+ PRD'21

Conclusions & Outlook

- Probes for axion/ALP-photon coupling, and for FIPs in general, in astrophysics are truly **multi-wavelength** (radio, X-rays, gamma rays)
- HE gamma-ray astrophysics **strongly constraint ALPs** coupling with photons, nucleons and electrons
- Next generation gamma-ray telescopes at high and low energies — **CTA**, **HAWC, future MeV missions** — will improve by far the sensitivity to ALPs in the neV to μeV mass range

Thank you for the attention!