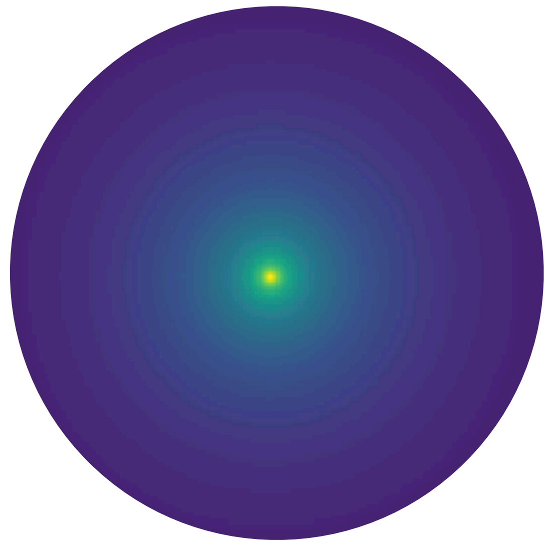
Probing ALPs and other light particles with high-energy astrophysics


Théorie, Univers et Gravitation (TUG) — 10/10/2023

Francesca Calore (CNRS/LAPTh)

Feebly interacting particles (FIPs)

The mystery of dark matter?

The matter-antimatter asymmetry in the universe?

The strong CP problem?

Agrawal+ Eur.Phys.J. C'21

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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]

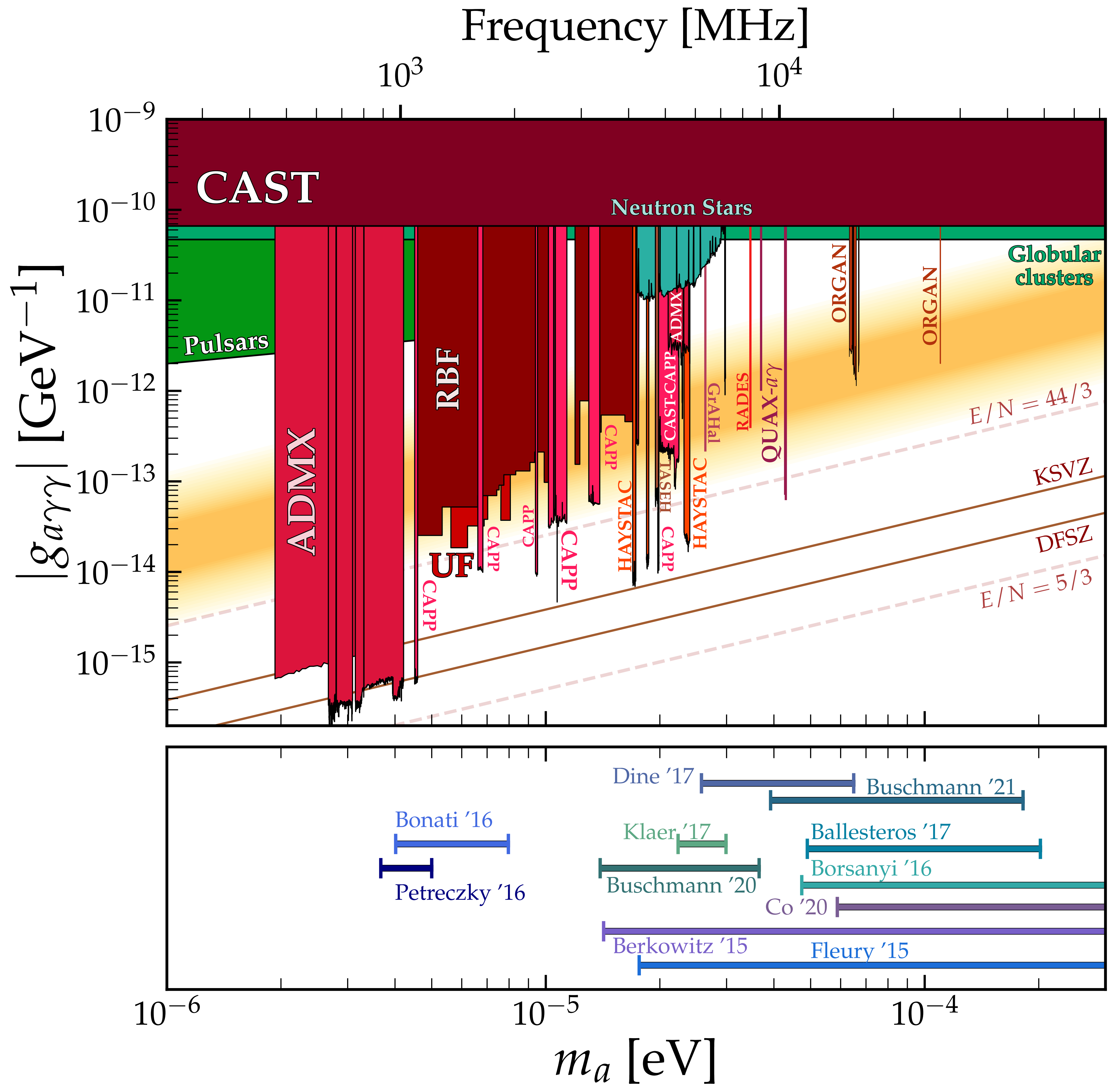
Agrawal+ Eur.Phys.J. C'21

The QCD axion

Quick ID: 10^{-12} — 0.01 eV, minimal coupling with photons

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

$$f_a \approx 10^{10}\,\mathrm{GeV} \left(\frac{0.6\mathrm{meV}}{m_a} \right)$$



https://github.com/cajohare/AxionLimits

A diversified search program:

- **Haloscopes**: DM axion conversion in B field (ADMX, HAYSTAC, DMRadio, etc) $\sim g_{a\gamma}^2 \rho_{\mathrm{DM}}$
- **Helioscopes**: Solar axion conversion in B field (CAST, IAXO) $\sim g_{a\gamma}^4$
- **Pulsars**: DM axion conversion in pulsar magnetosphere (Green Bank Telescope)

Foster+ PRL'22

Several detection methods are systematically probing QCD axions

Broadening the landscape
Axion-like particles

Axion-like particles: (pseudo-)scalar particles, masses as low as ZeV, very weak couplings with SM, coupled with photons as QCD axions

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

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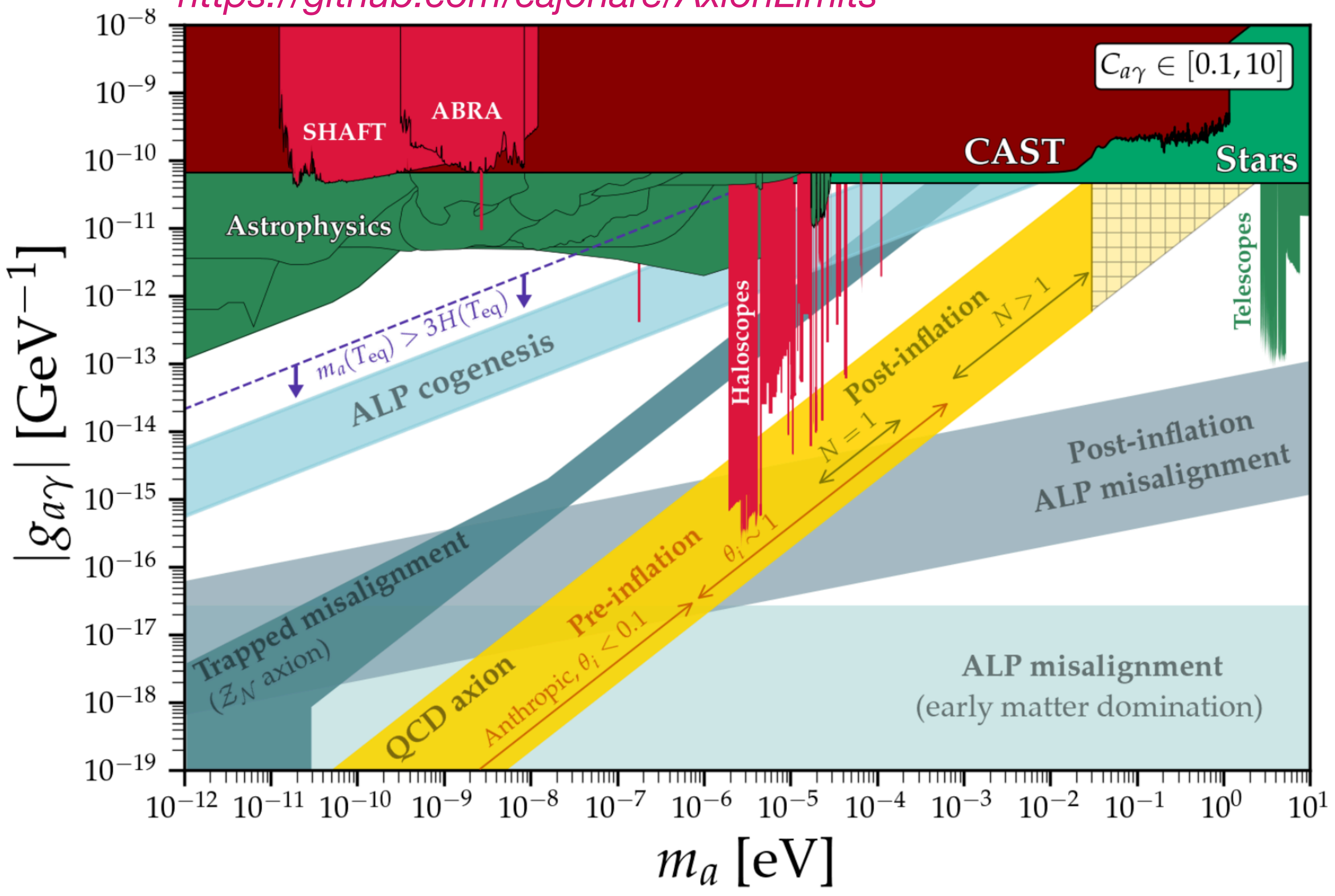


Quick ID:

- **Common** in many **extensions of the SM** from the spontaneous breaking of approximate global symmetries
- **Mass** is **not determined** by QCD effects
- They do **not solve** the **strong CP problem**

[Wave-like DM is even broader: more generally, light scalars or vectors]

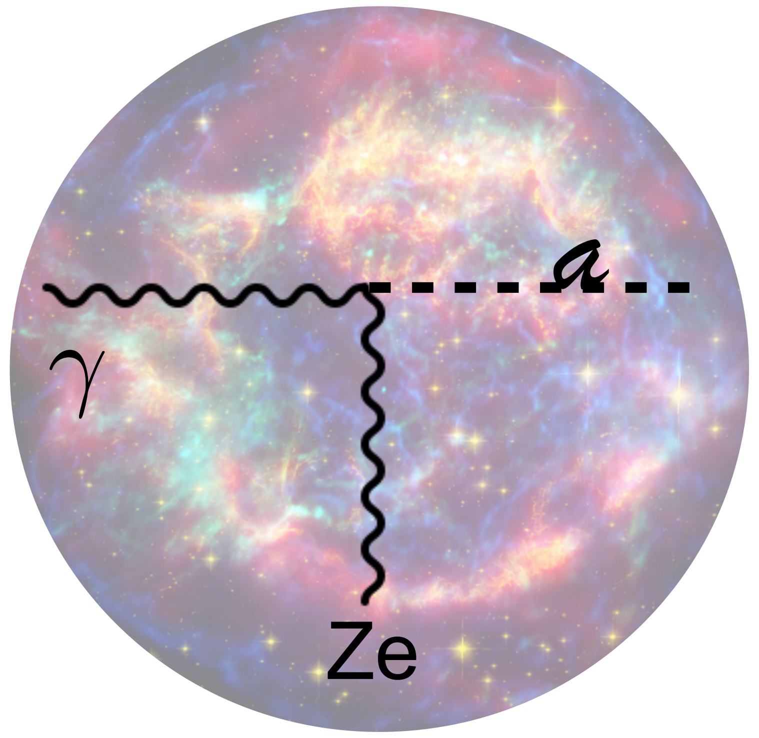
Signatures from ALPs?

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

Focus **High-energy gamma rays**

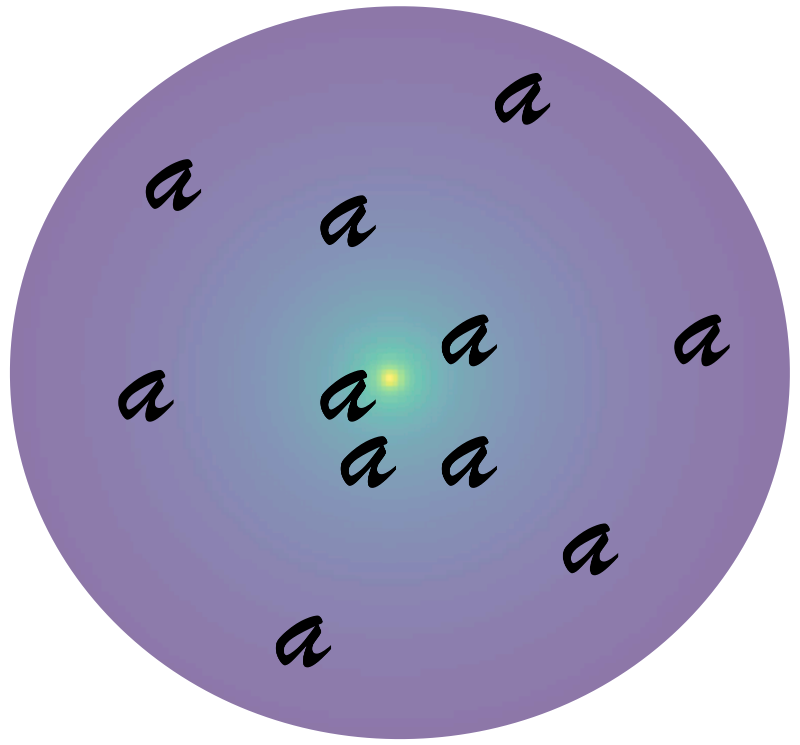
Gamma rays from ALPs?

Source



cc-SNe Primakoff

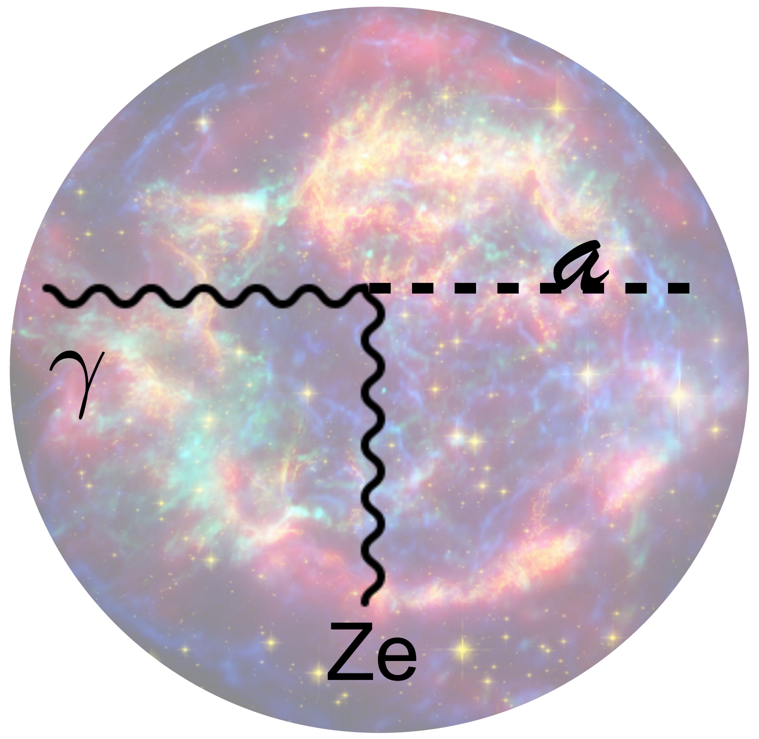
Photons in source B field



Dark matter

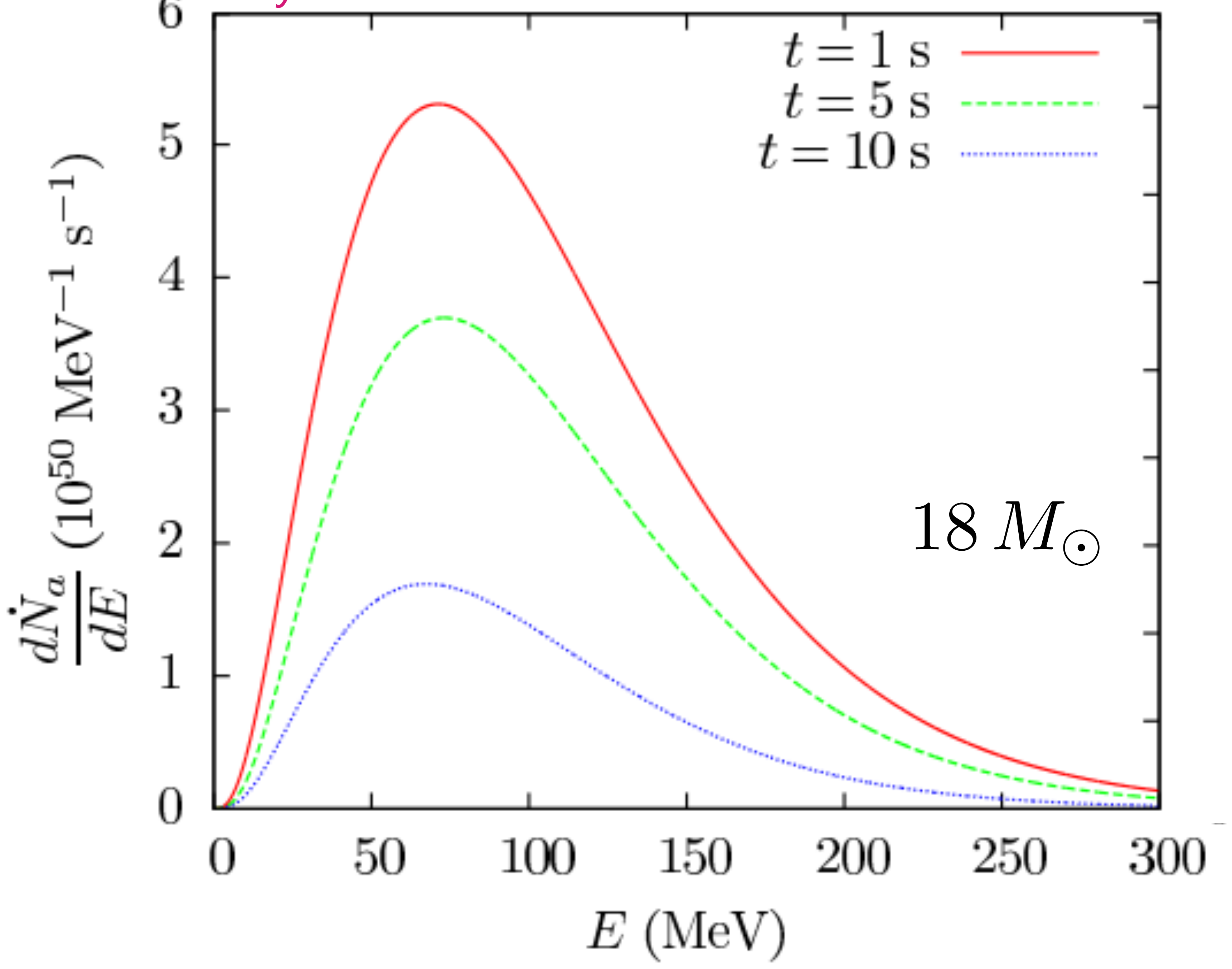
Source: Core-collapse supernovae

Source



cc-SNe Primakoff

Payez+ JCAP'14



For Galactic SNe

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

[Not only cc-SN: proto-neutron stars, mains-sequence stars, white dwarfs, etc]

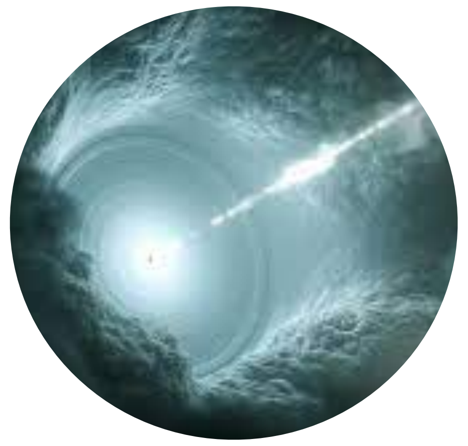
Source: High-energy gamma-ray emitters

Source

Photons in *source* B field

Extragalactic gamma-ray emitters

- AGNs jets
- Star-forming and star-burst galaxies
- Galaxy clusters



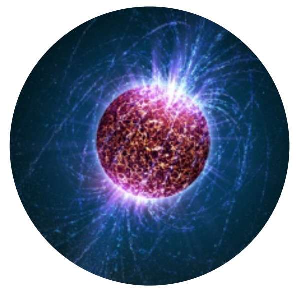
In-situ photon spectrum through hadronic (pp and pg) or leptonic interactions

$$\left(\frac{dN_\gamma}{dE}\right)_{\mathrm{P}}$$

In-situ conversion into ALPs

* Interstellar medium
* Intergalactic radiation fields
* Magnetic field strength and coherence length

$$\left(\frac{dN_a}{dE}\right)_{\mathrm{S}} \propto P_{\mathrm{S}}(\gamma \to a) \times \left(\frac{dN_\gamma}{dE}\right)_{\mathrm{P}}$$

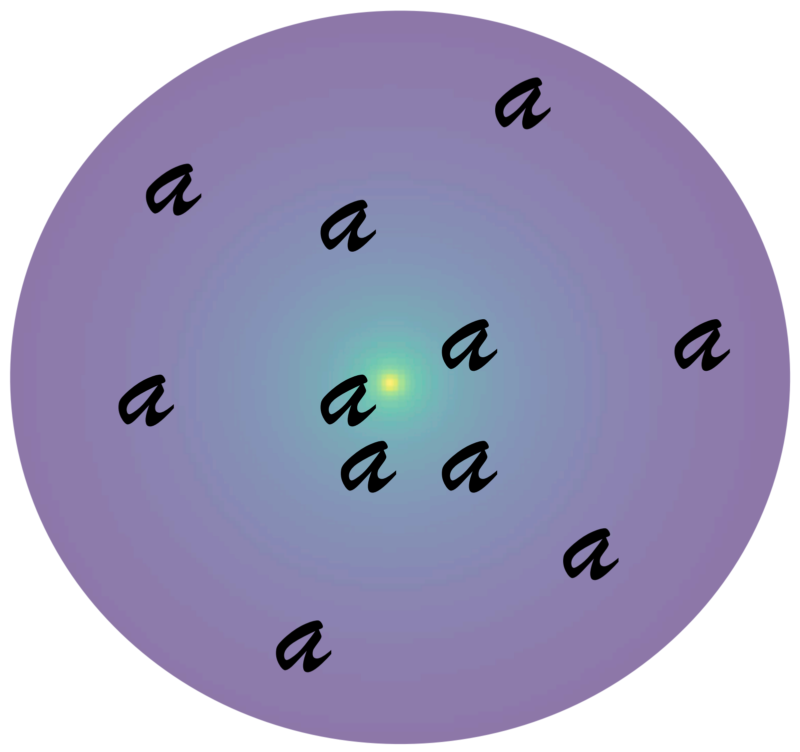


[Also photons from **Galactic objects** like pulsars and SNRs sourced by electric and magnetic fields]

Prabhu PRD'21

Source: Dark matter

Source

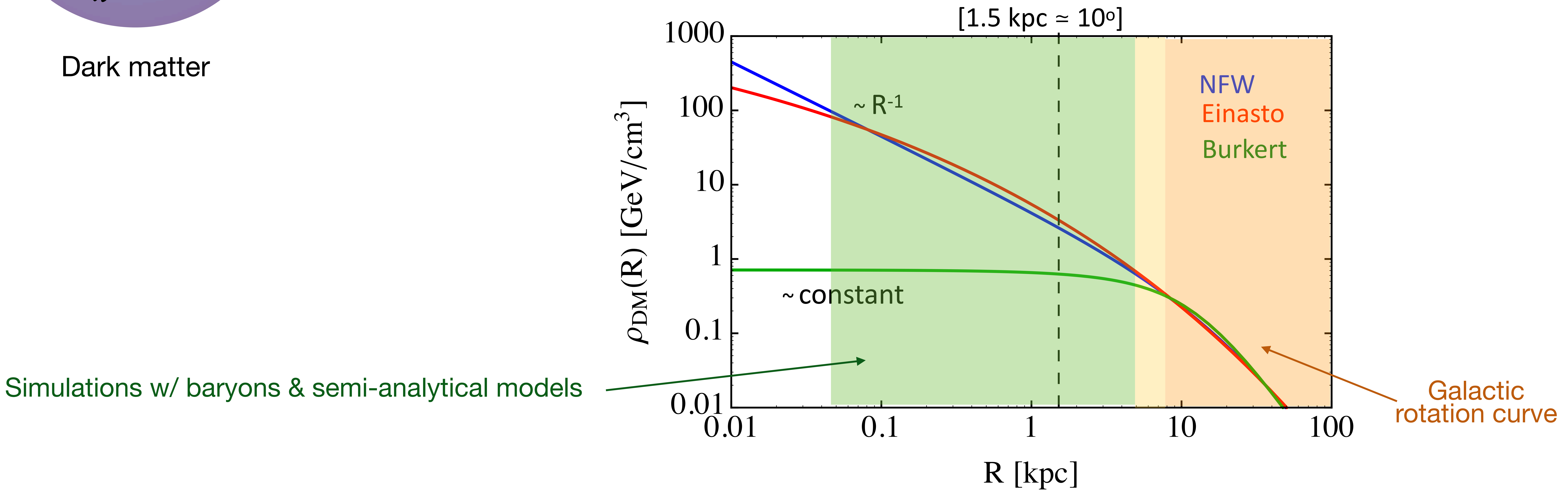


Dark matter

- ALPs can be good DM candidates in some portions of the parameter space

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

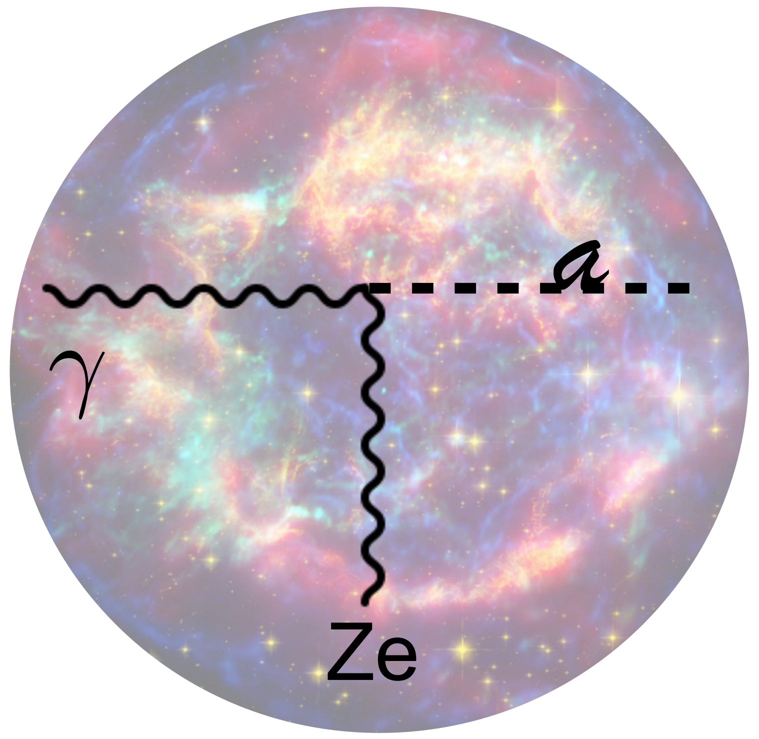
- If DM, ALPs distributed in galaxies according standard DM density distributions (e.g. NFW)



[All profiles normalised by measure of **local DM density** at $\mathbf{R_{Sun}}$]

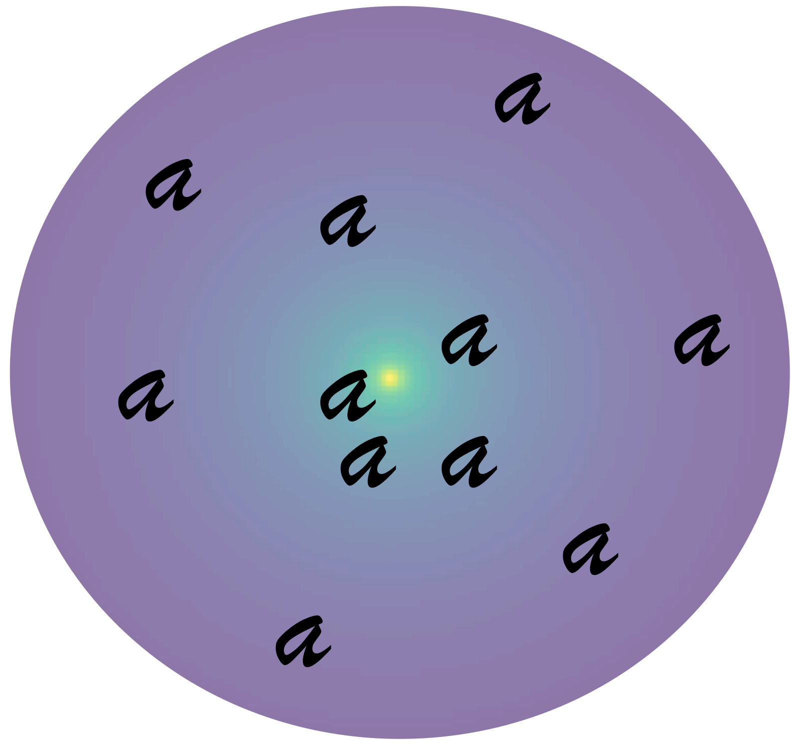
ALPs travelling in the Galaxy

Source



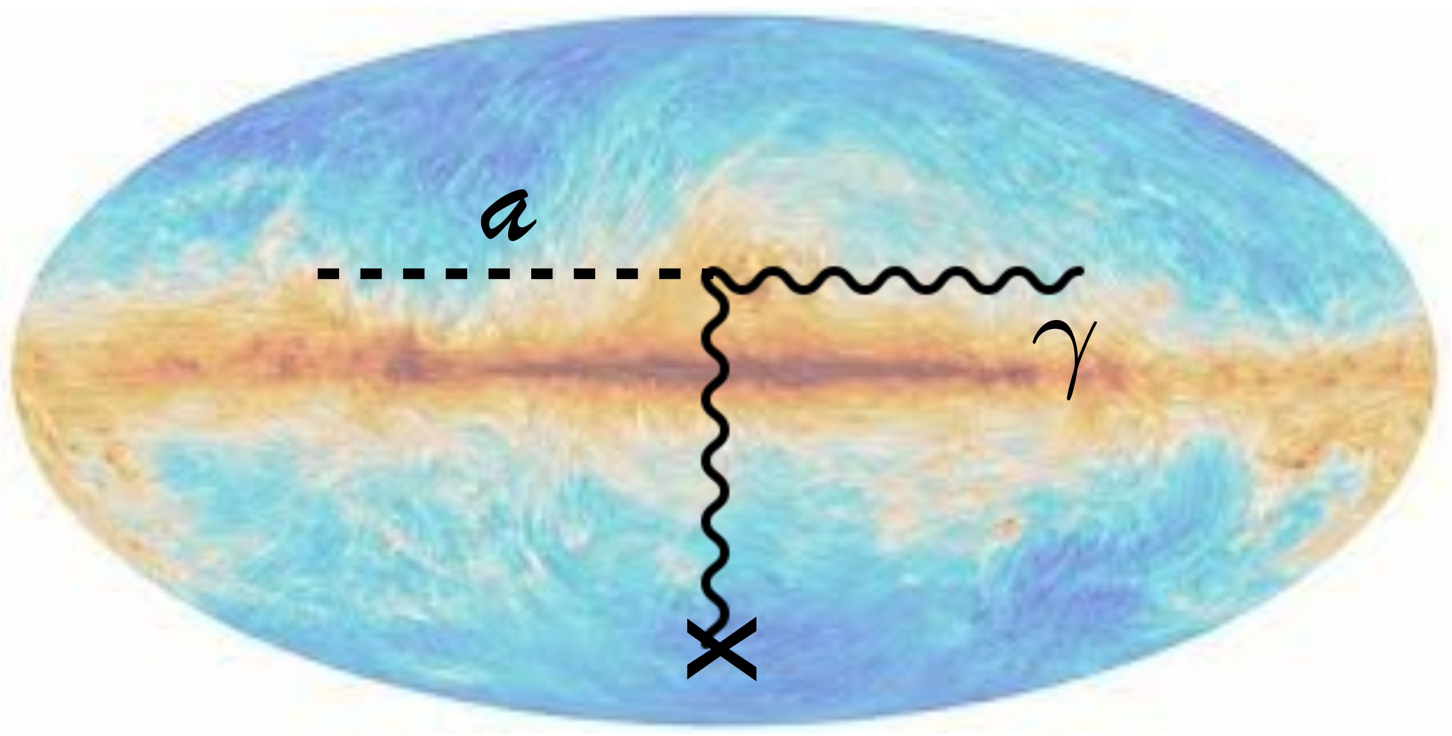
cc-SNe Primakoff

Photons in source B field

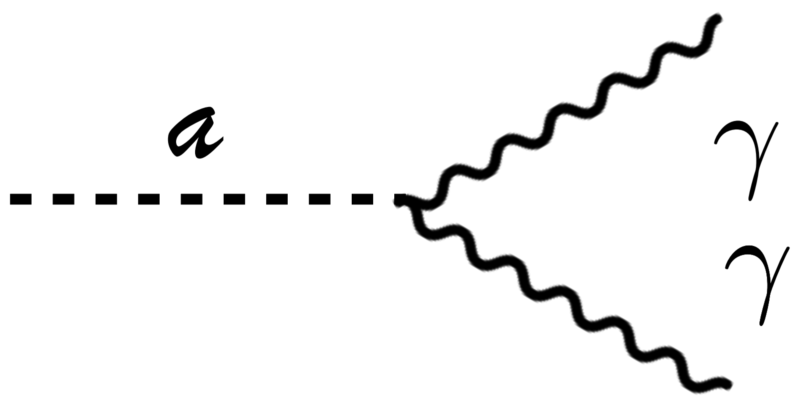


Dark matter

Galaxy



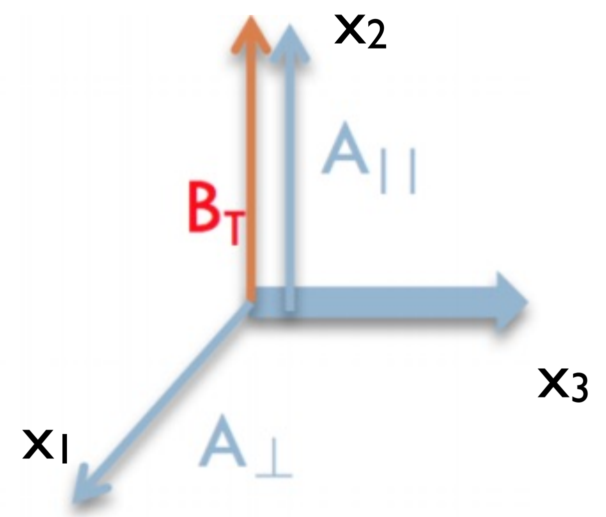
Conversion in Galactic B field



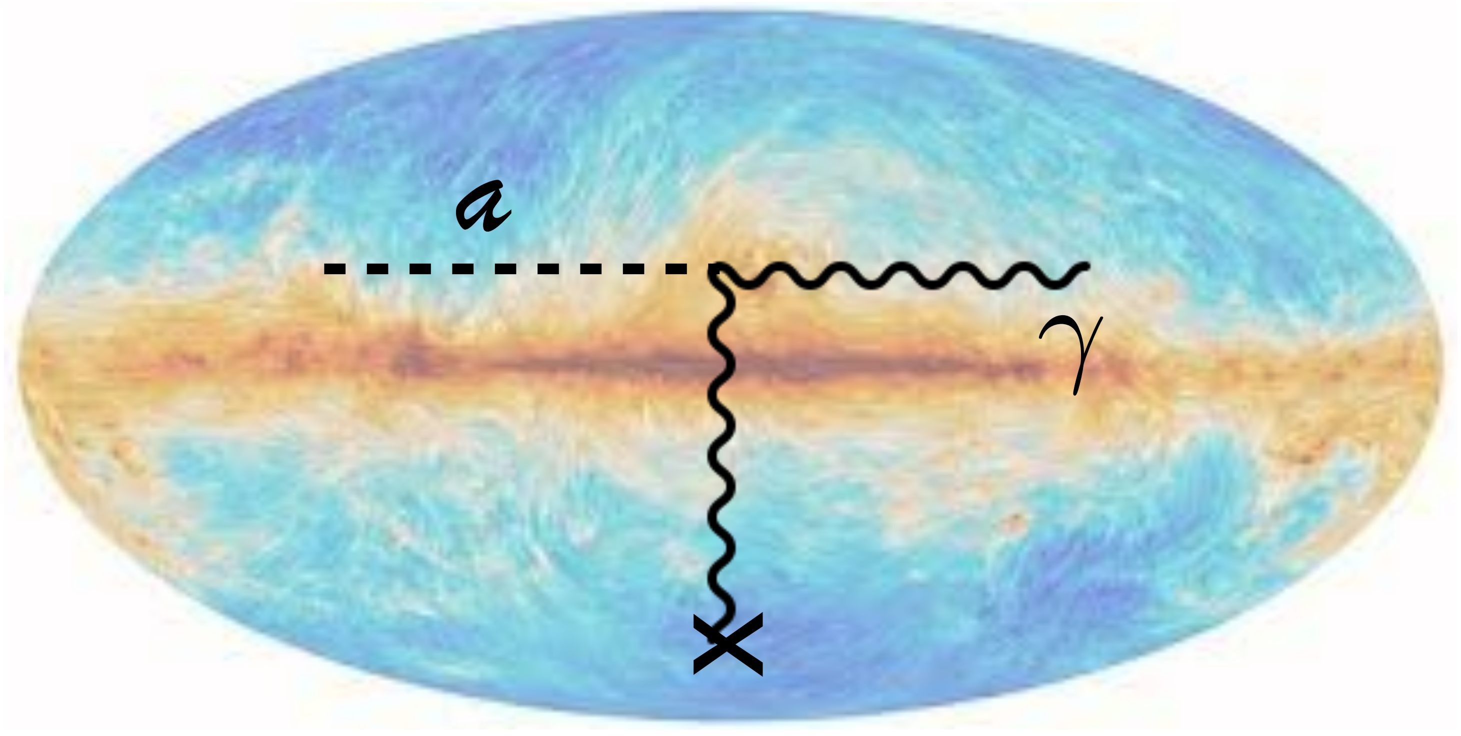
Spontaneous decay

[Conversion in intergalactic magnetic fields is not efficient]

Galaxy: Conversion



Galaxy



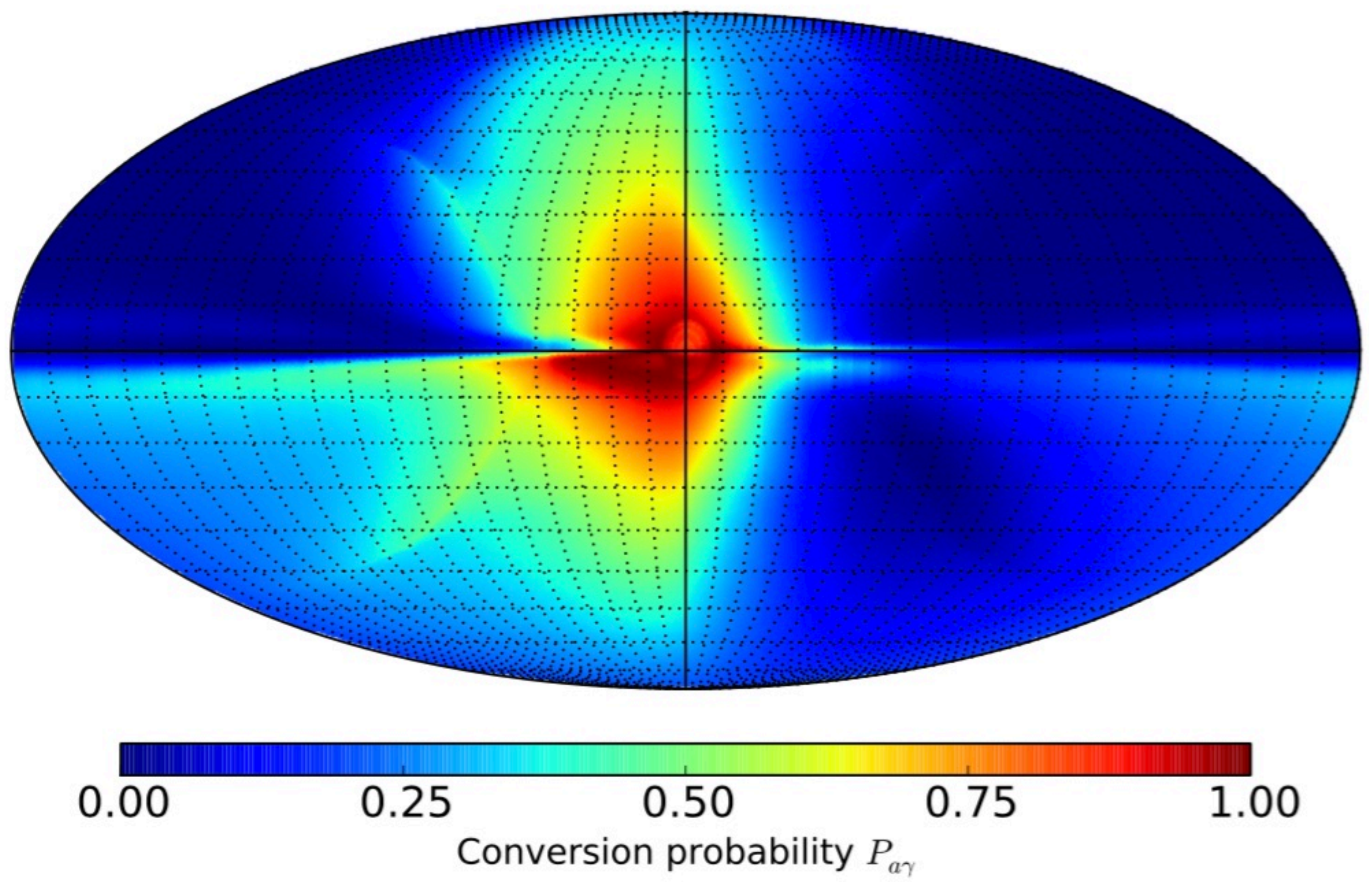
Conversion in Galactic B field

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**

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

$$P_{a\gamma} = (\Delta_{a\gamma} L)^2 \frac{\sin^2(\Delta_{\rm osc} L/2)}{(\Delta_{\rm osc} L/2)^2}$$

$$\Delta_{\rm osc} \equiv \left[(\Delta_a - \Delta_{\rm pl})^2 + 4\Delta_{a\gamma}^2\right]^{1/2} = \left[\frac{(m_a - \omega_{\rm pl})^2}{4E^2} + (g_{a\gamma} B_T)^2\right]^{1/2}$$

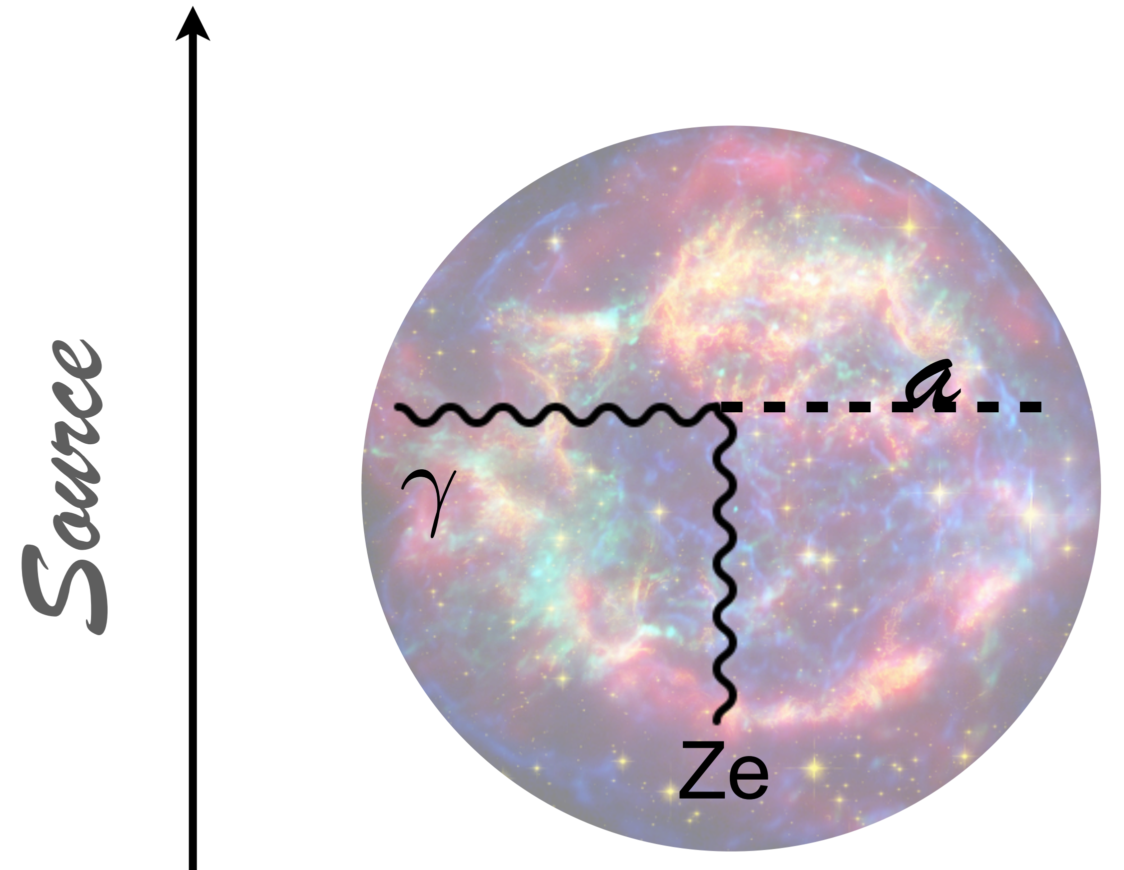


=> For massless ALPs and sufficiently low couplings: energy-independent conversion probability

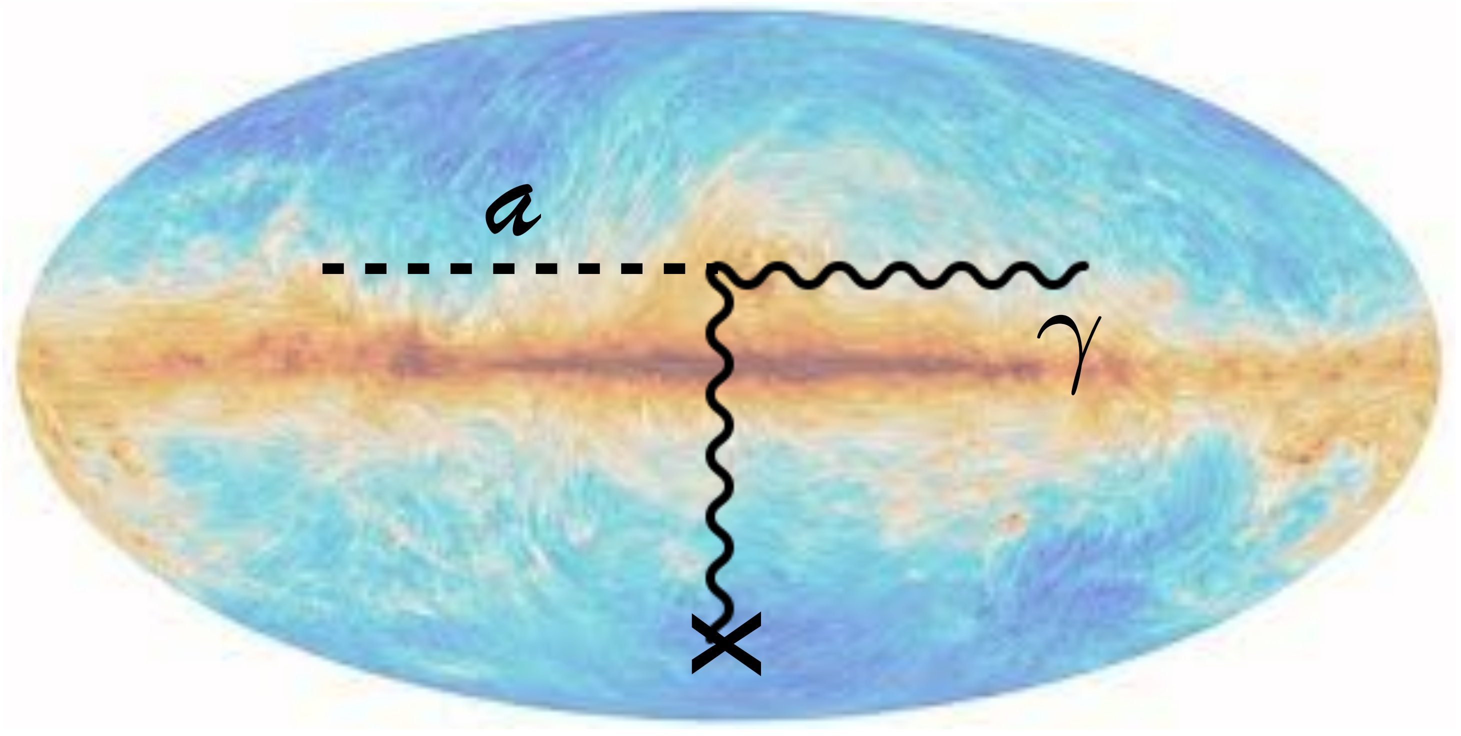
$$P_{a\gamma} \simeq (\Delta_{a\gamma} L)^2 = \left(\frac{g_{a\gamma} B_T}{2}\right)^2 L^2$$

$$\Delta_{a\gamma} L \ll 1$$

Galaxy: Conversion of cc-SNe ALPs



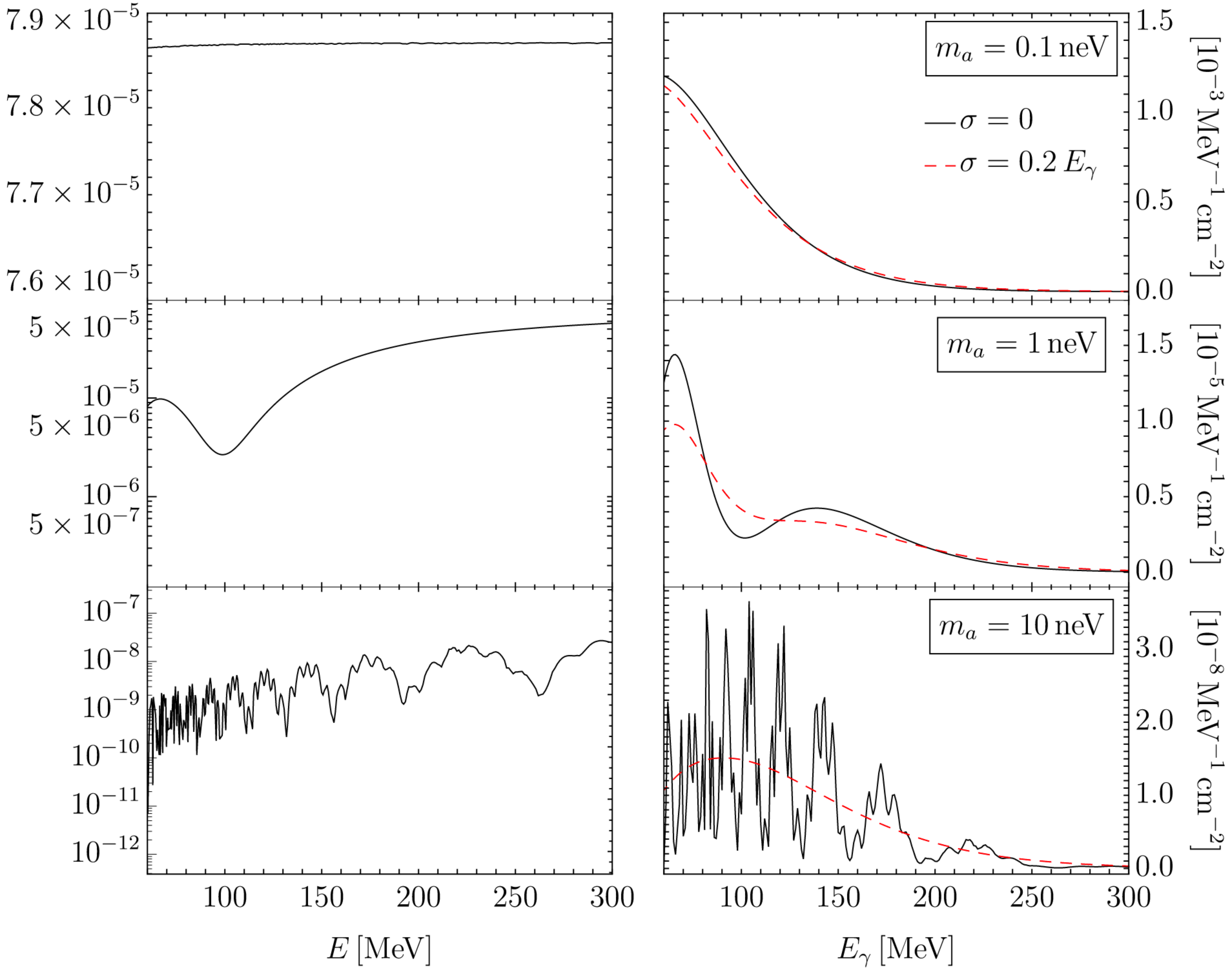
cc-SNe Primakoff



Conversion in Galactic B field

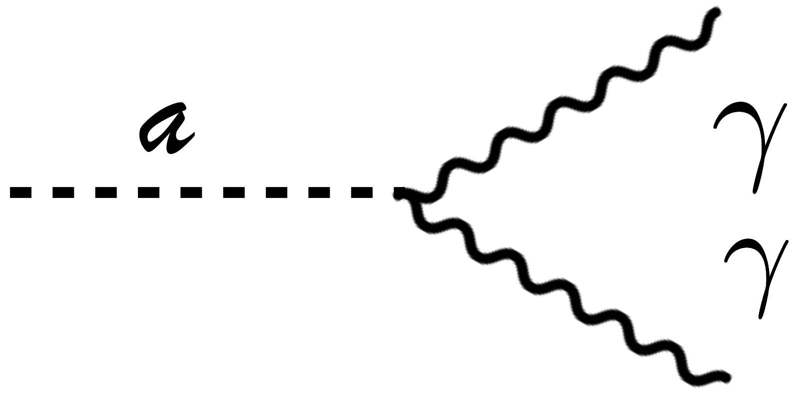
$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}P_{a\gamma}(E)$$

FC+ 2306.03925



Galaxy: Dark matter decay

Galaxy



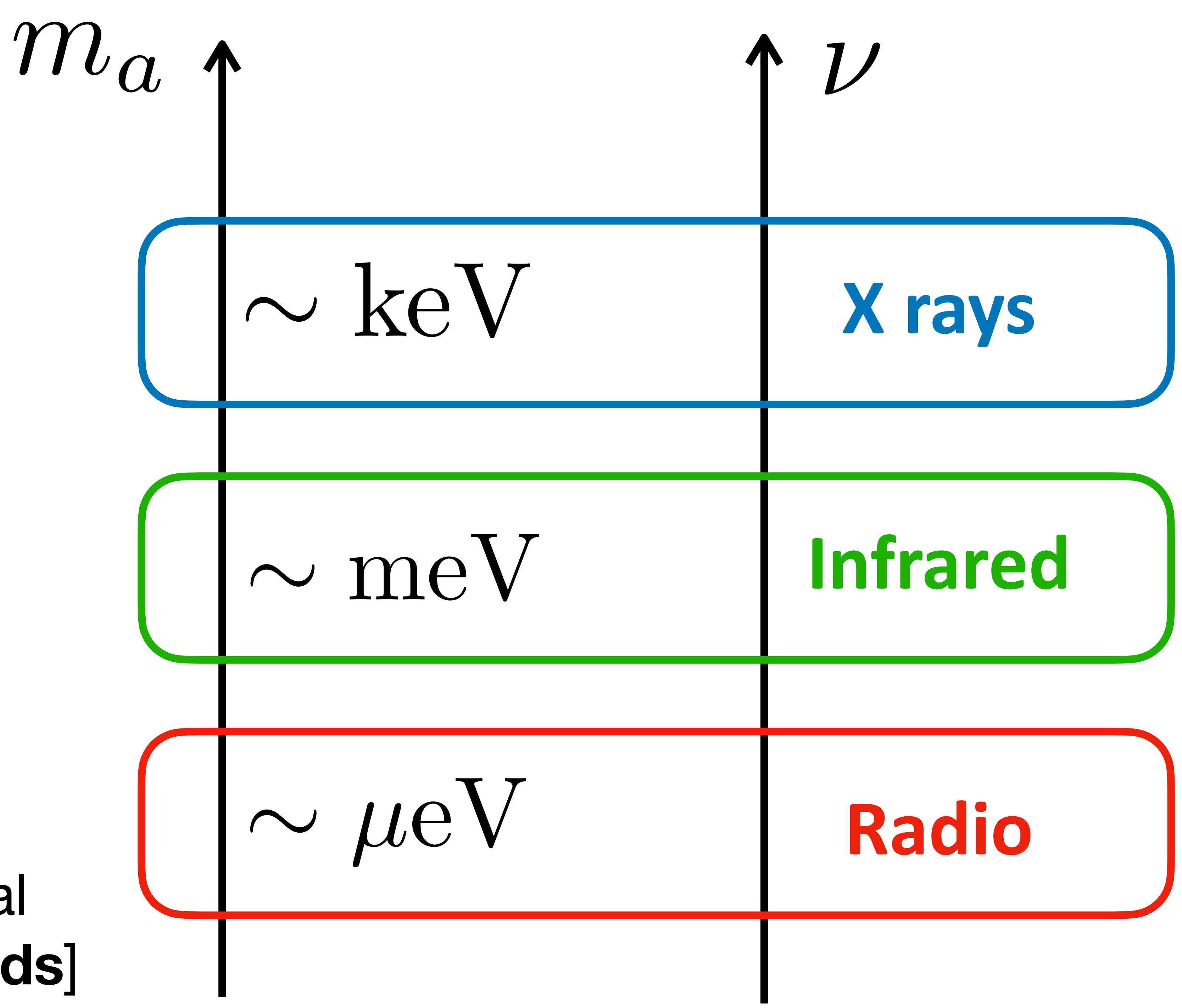
Spontaneous decay

$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\rm decay} = \frac{\Gamma(a \to \gamma\gamma)}{4\pi m_a}\left(\frac{dN_\gamma}{dE}\right)_{\rm decay} \times \int_{\rm l.o.s.} \rho_a(\ell) d\ell$$

$$m_a \lesssim \text{MeV} \qquad E_\gamma = \frac{m_a}{2}$$

Narrow line signal

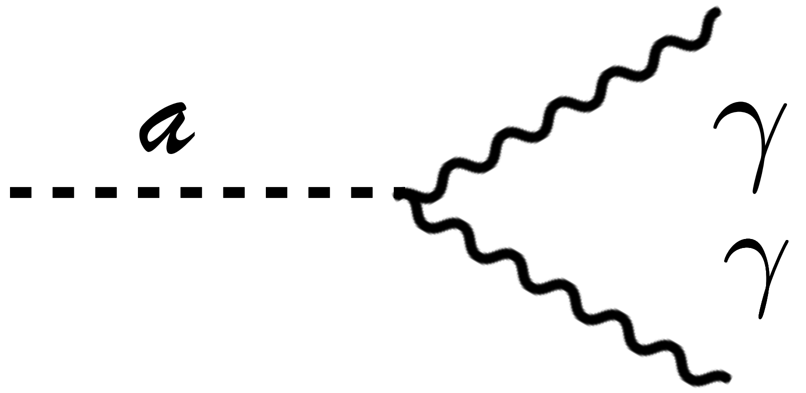
@ energy scale of the DM mass



[Contribution from all galaxies in the universe: redshifted line and integral over star-formation history => contribution to **extragalactic backgrounds**]

Galaxy: Dark matter decay

Galaxy



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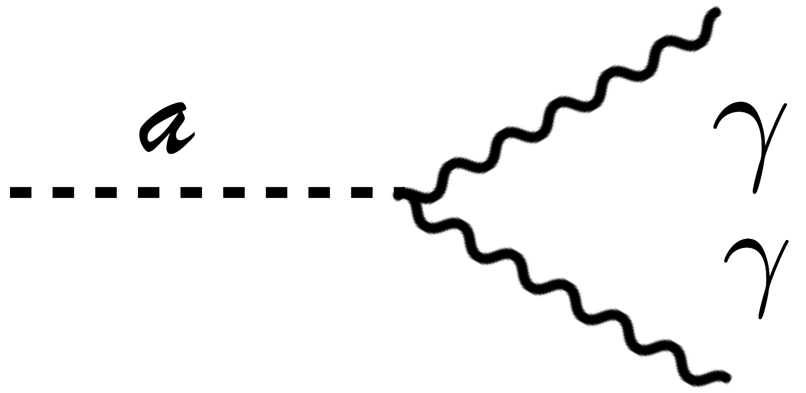
$$\tau_a = \frac{64\pi}{m_a^3 g^2}$$

=> Rate not-negligible for heavy (> keV) ALPs, where conversion is suppressed

Galaxy: Dark matter decay

Galaxy



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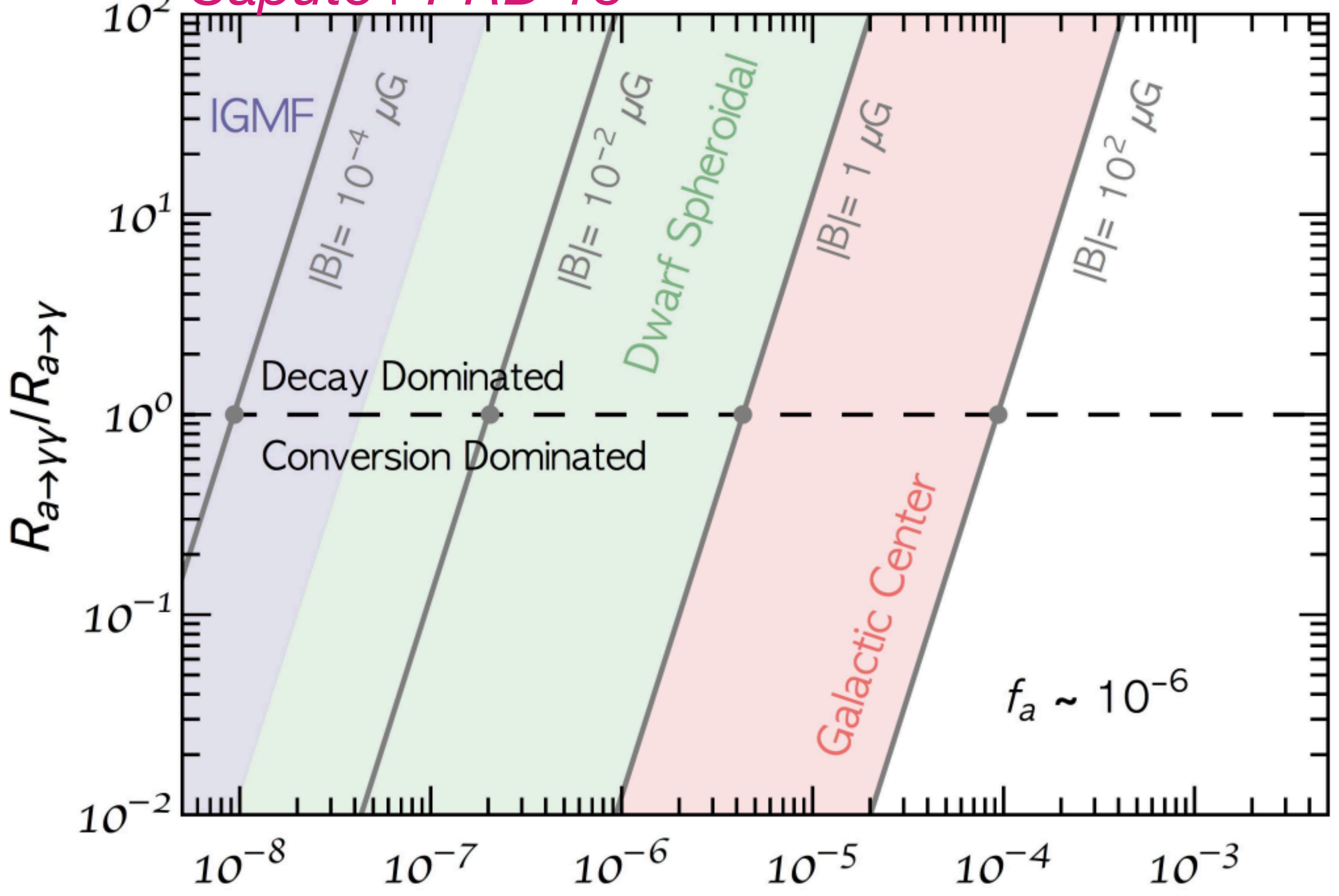
Stimulated decay can occur in the presence of non-relativistic ambient radiation (e.g. CMB)

Caputo+ PRD'18; JCAP'19; Battye+ PRD'20

Caputo+ PRD'18



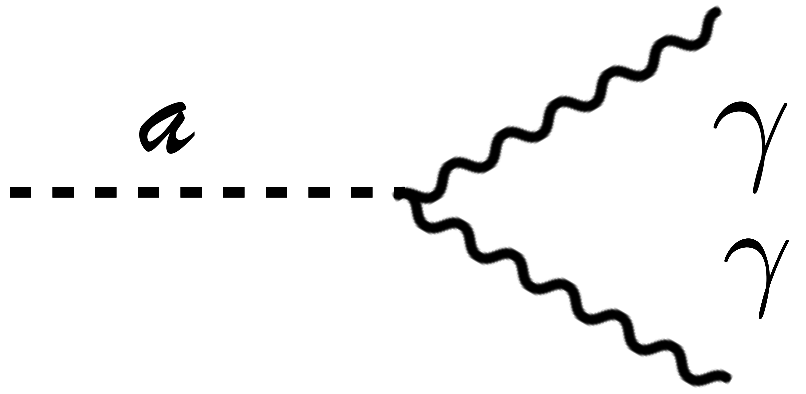
=> In large-scale astro environments with low B-field, stimulated decay dominates also for masses in the 10^{-6} eV mass range

[Same effect also onto photons emitted by high-energy sources, such as pulsars or SNR, creating an ALPs-induced *echo* in the source opposite direction]

Ghosh+ 2008.02729; Sun+ PRD'22, 2310.03788

Galaxy: Dark matter decay

Galaxy



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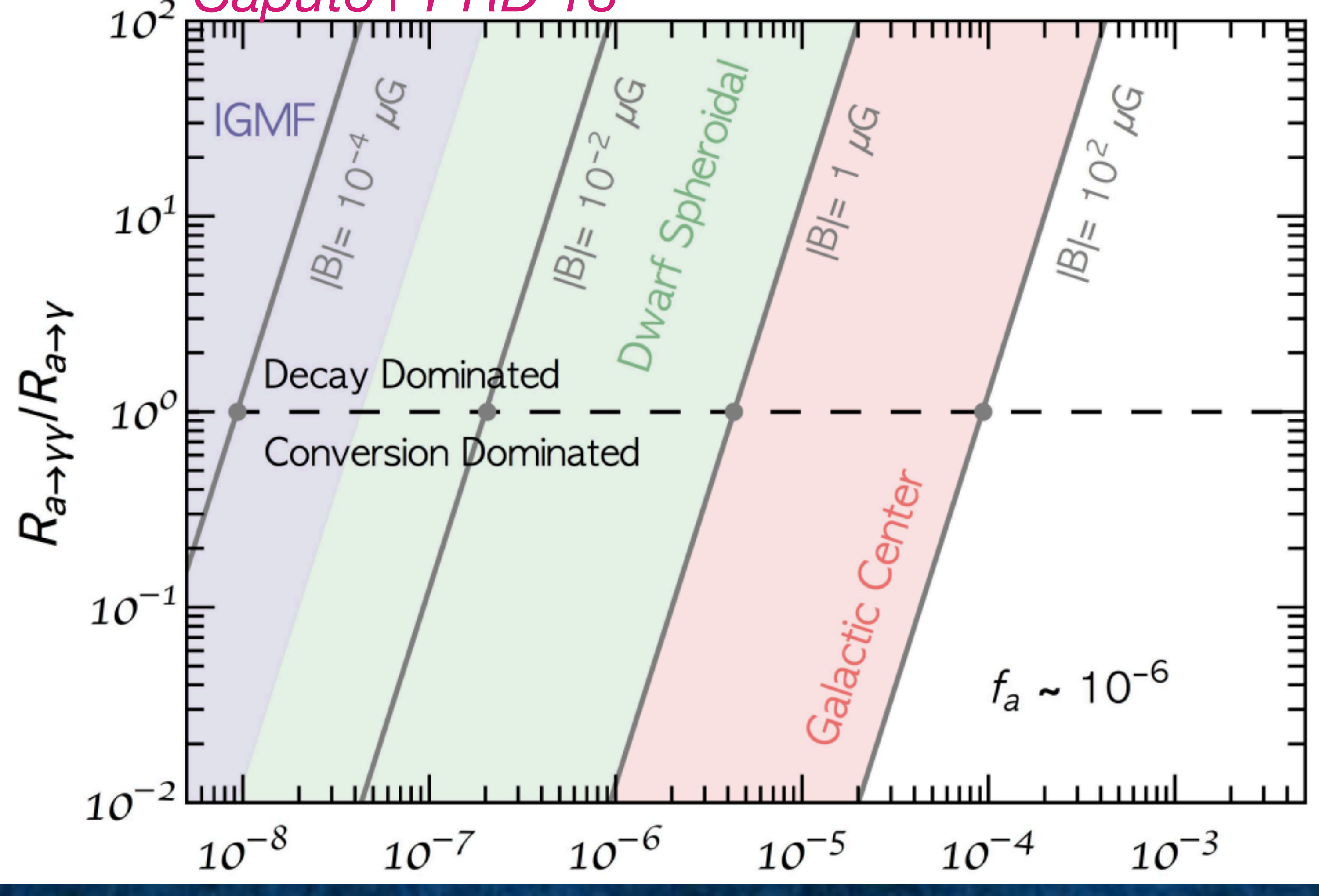

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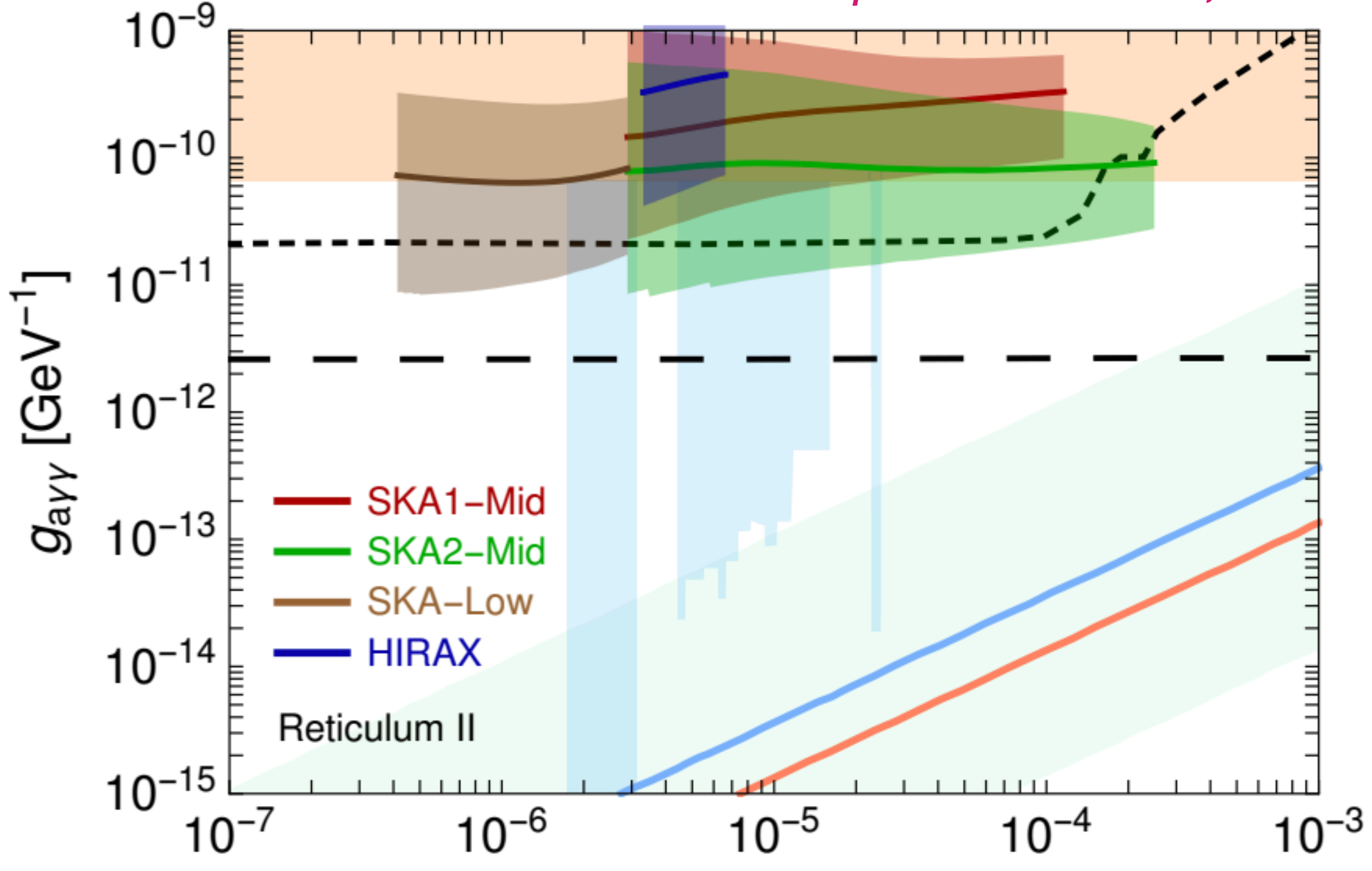
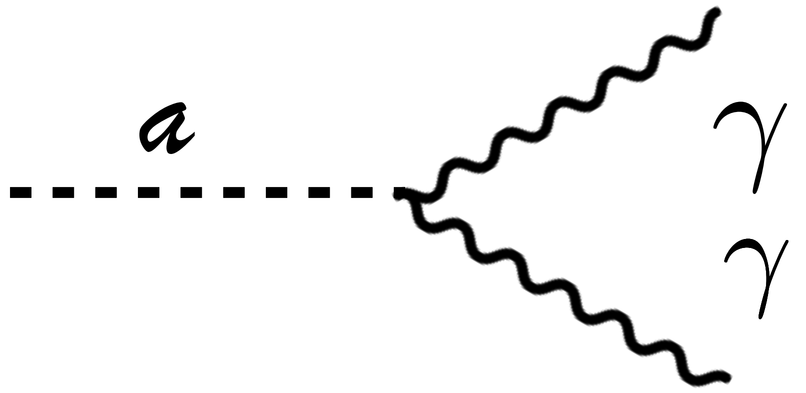


Caputo+JCAP'19

Galaxy: Dark matter resonant conversion

Galaxy



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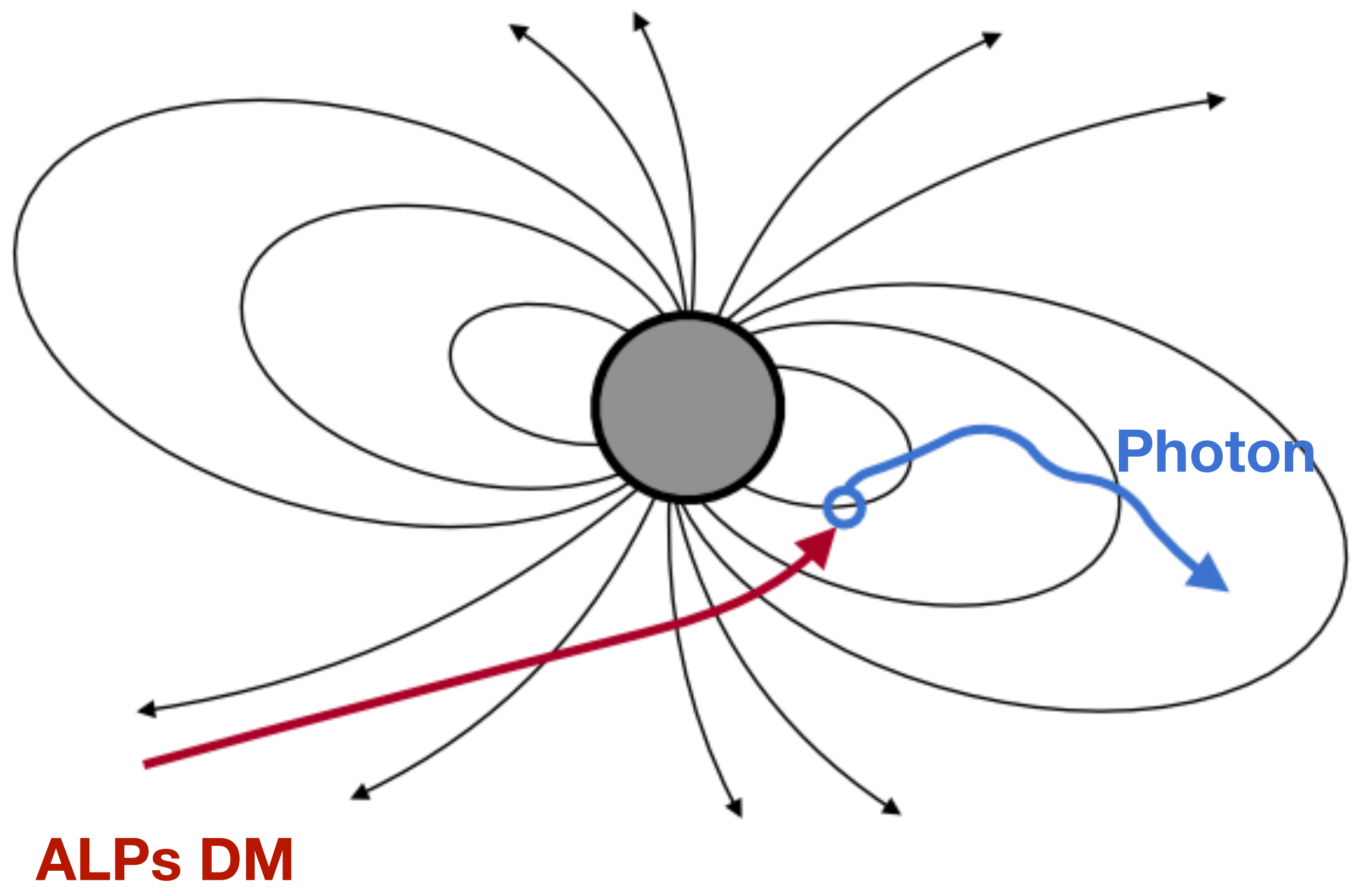
- Monochromatic radio emission (MHz - GHz) from **DM axion/ALP-photon conversion**:
  - *Resonant* conversion from highly magnetised neutron stars (NSs), or white dwarf stars

    Pshirkov JETP'09; Huang+2018; Hook+PRL'18
  - *Non-resonant* transitions in the Galactic center and/or of discrete astrophysical objects

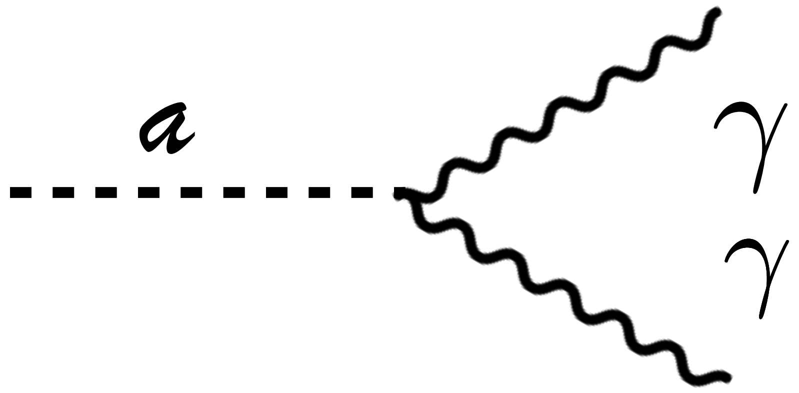
    Kelley&Quinn ApJ'17; Sigl PRD'17
  - Still large **limitations** in **model predictions**

    Leroy+ PRD'20; Witte+ PRD'21; Battye+ JHEP'21; Millar+JCAP'21



Galaxy: Dark matter resonant conversion

Galaxy



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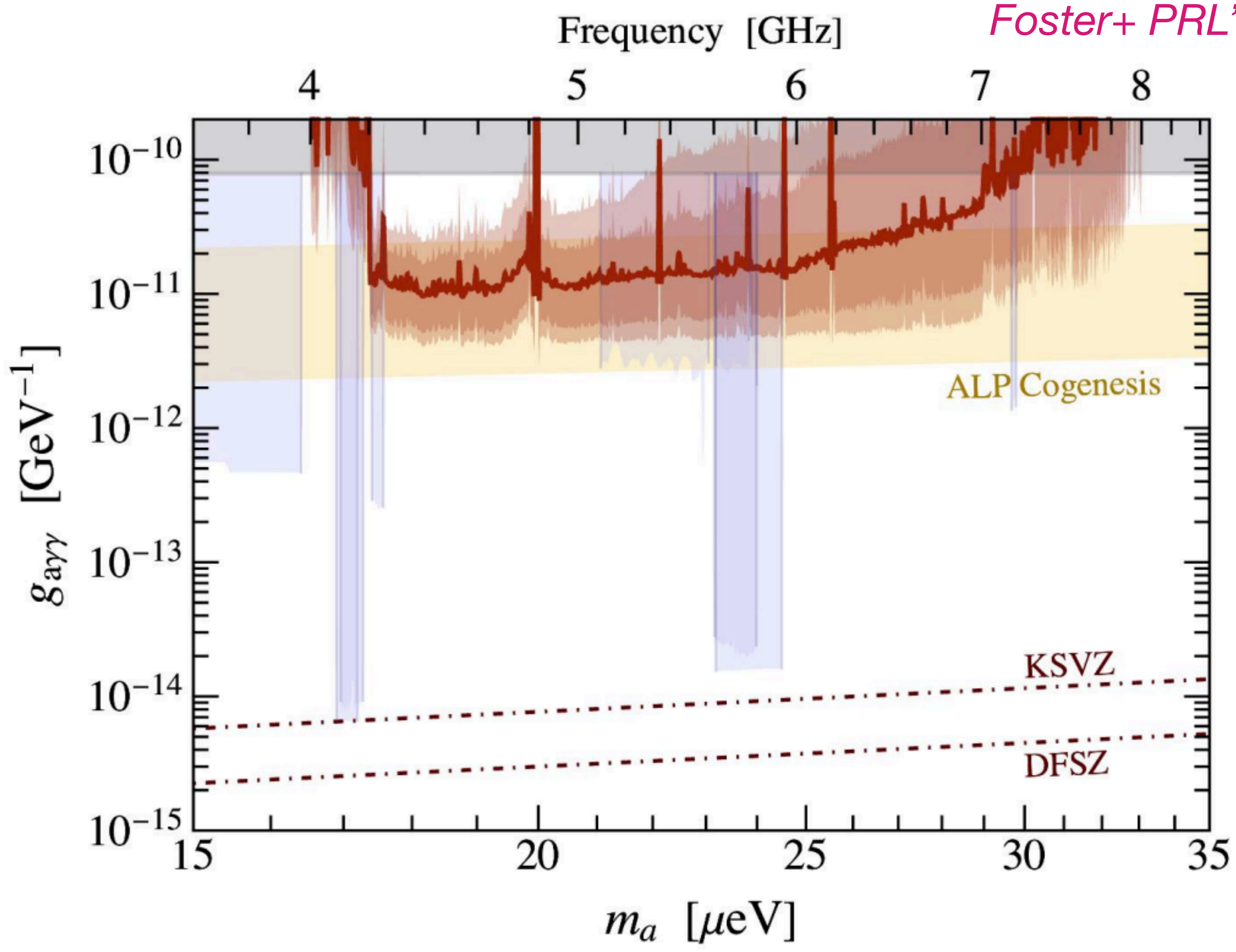
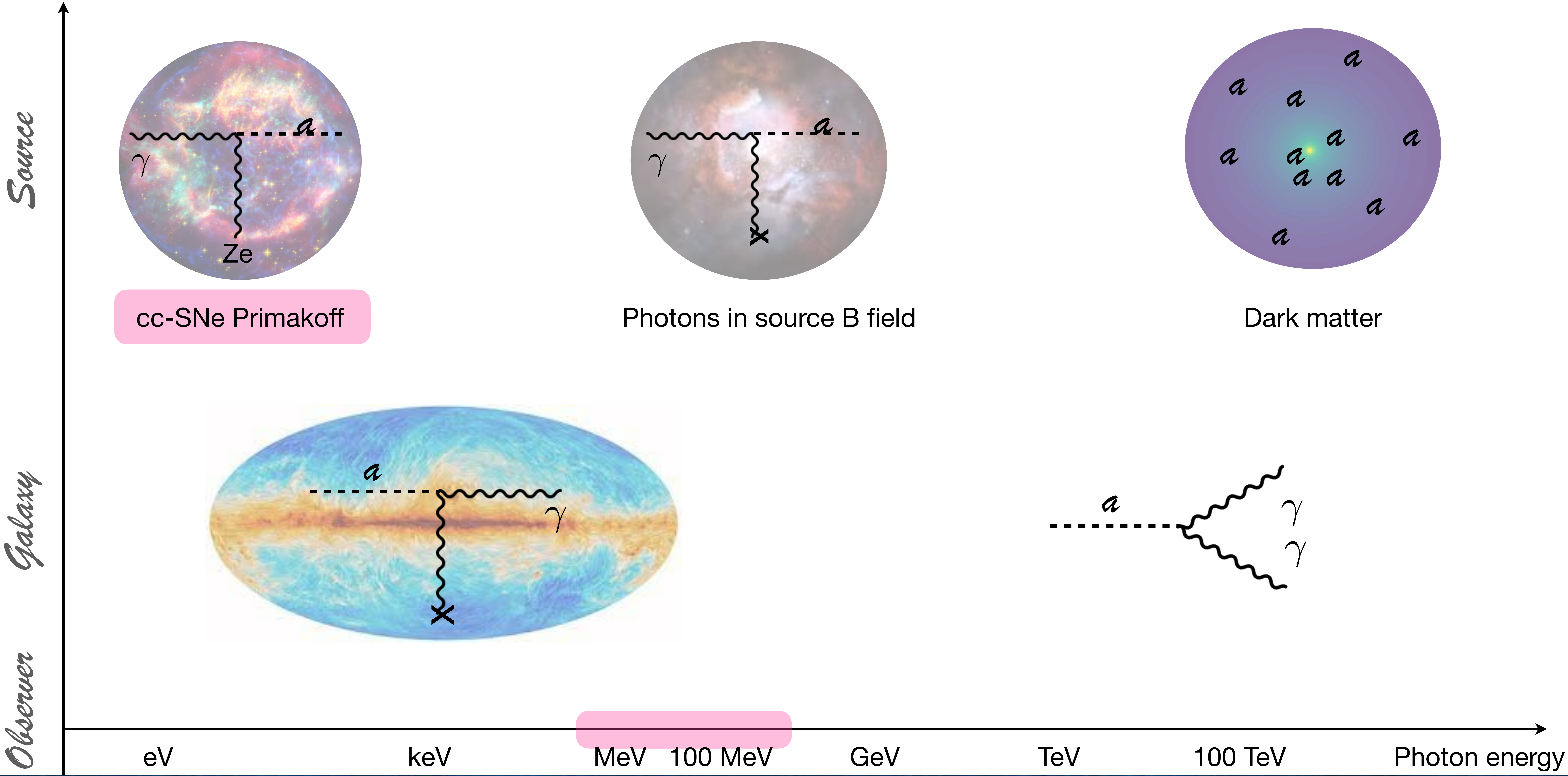
Foster+ PRL'22



What photon energies?



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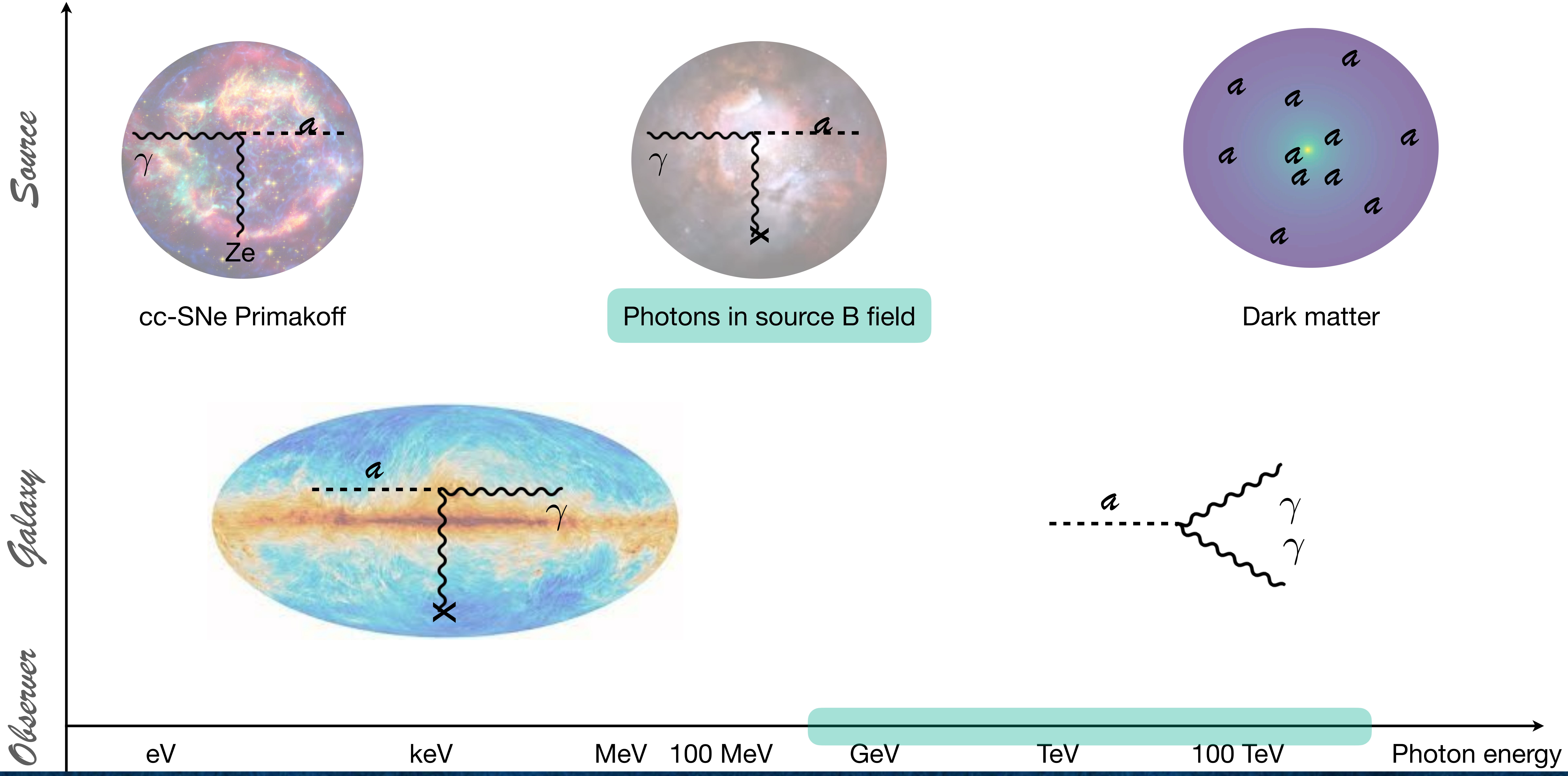

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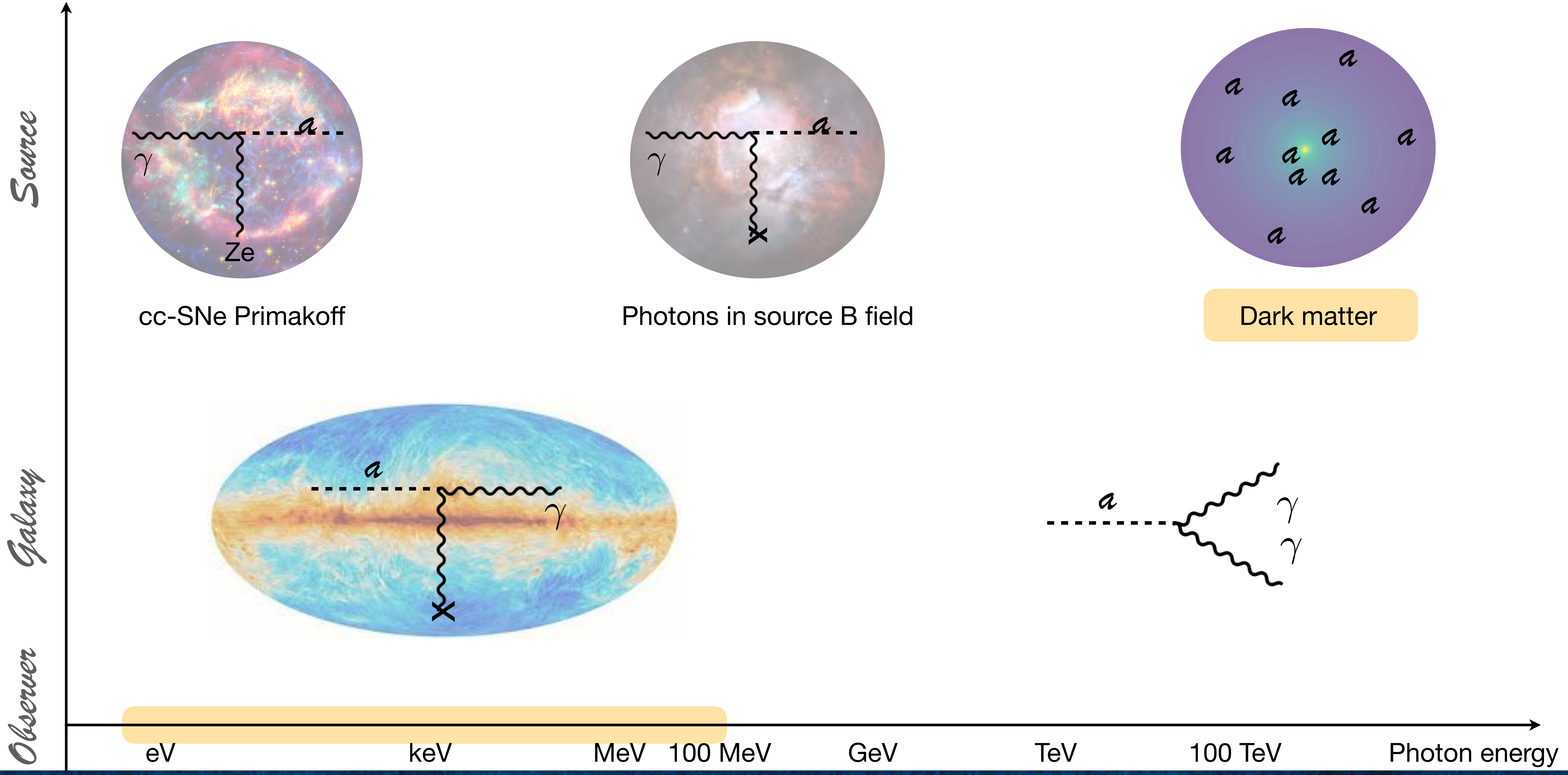
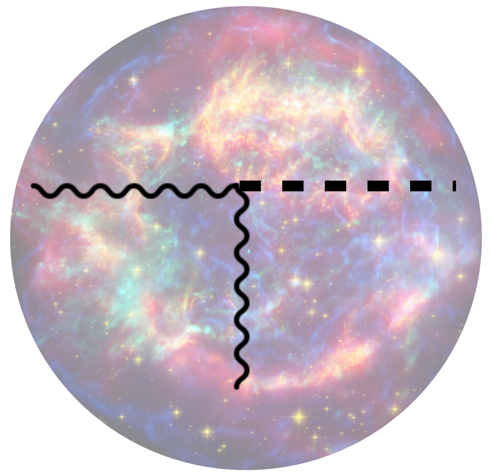
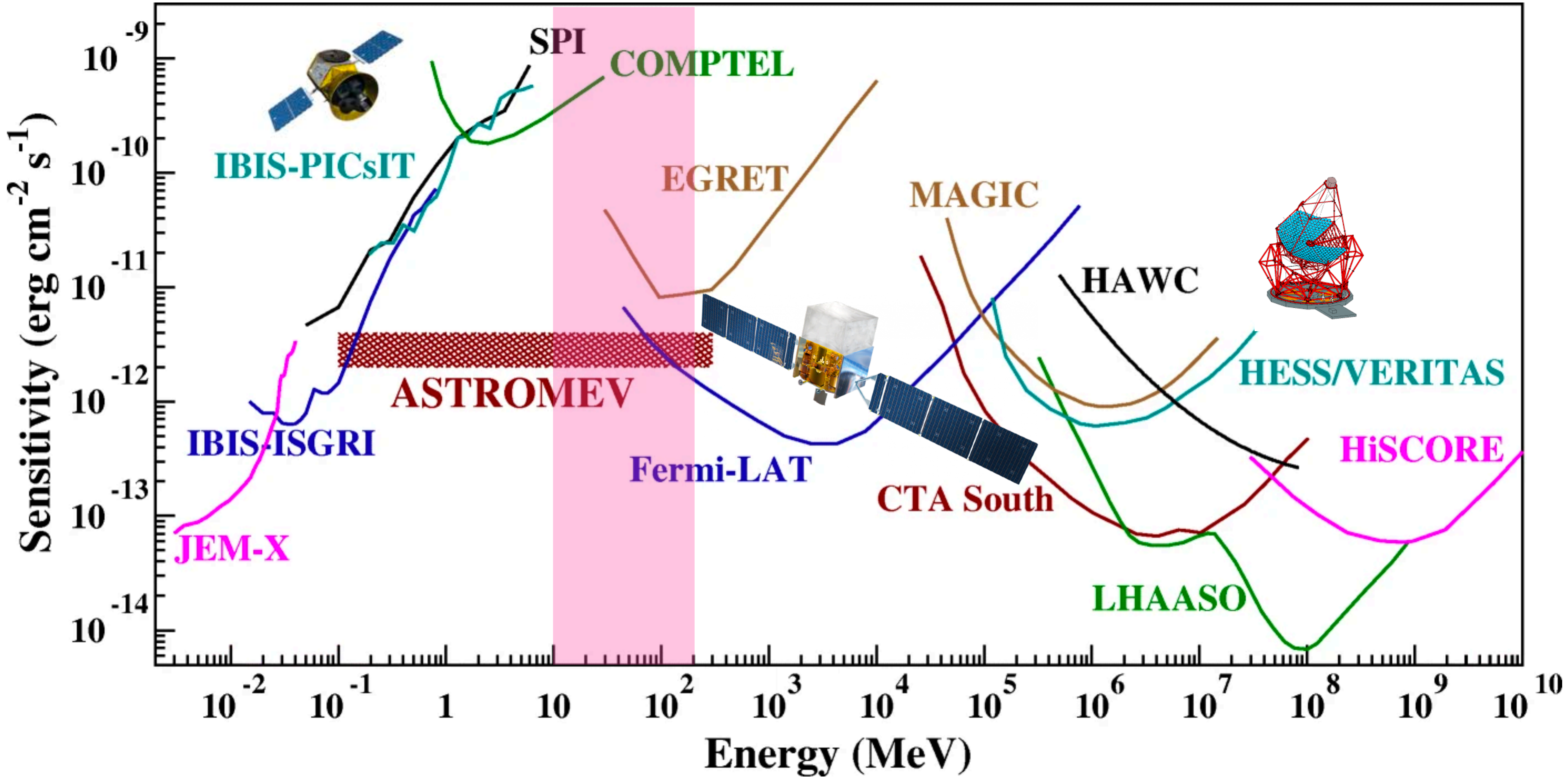
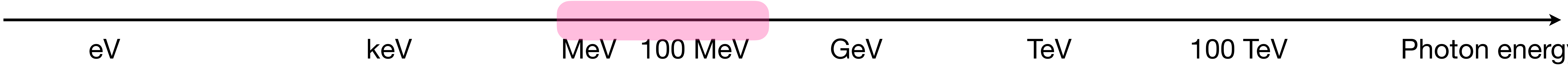


Gamma-ray data landscape



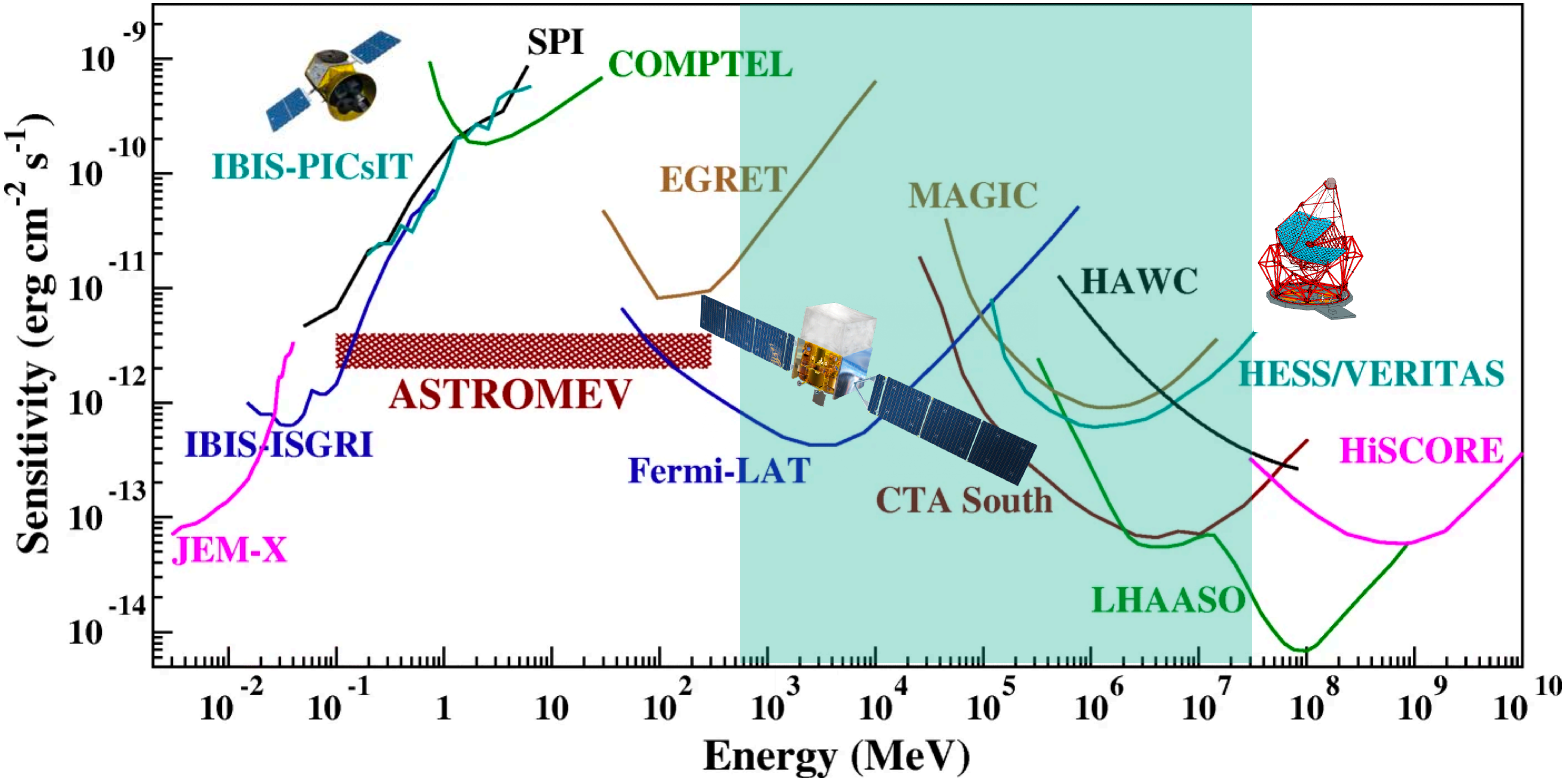
DeAngelis+ Voyage 2050 ‘21

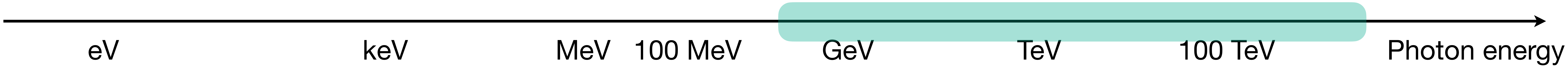




Gamma-ray data landscape

DeAngelis+ Voyage 2050 '21





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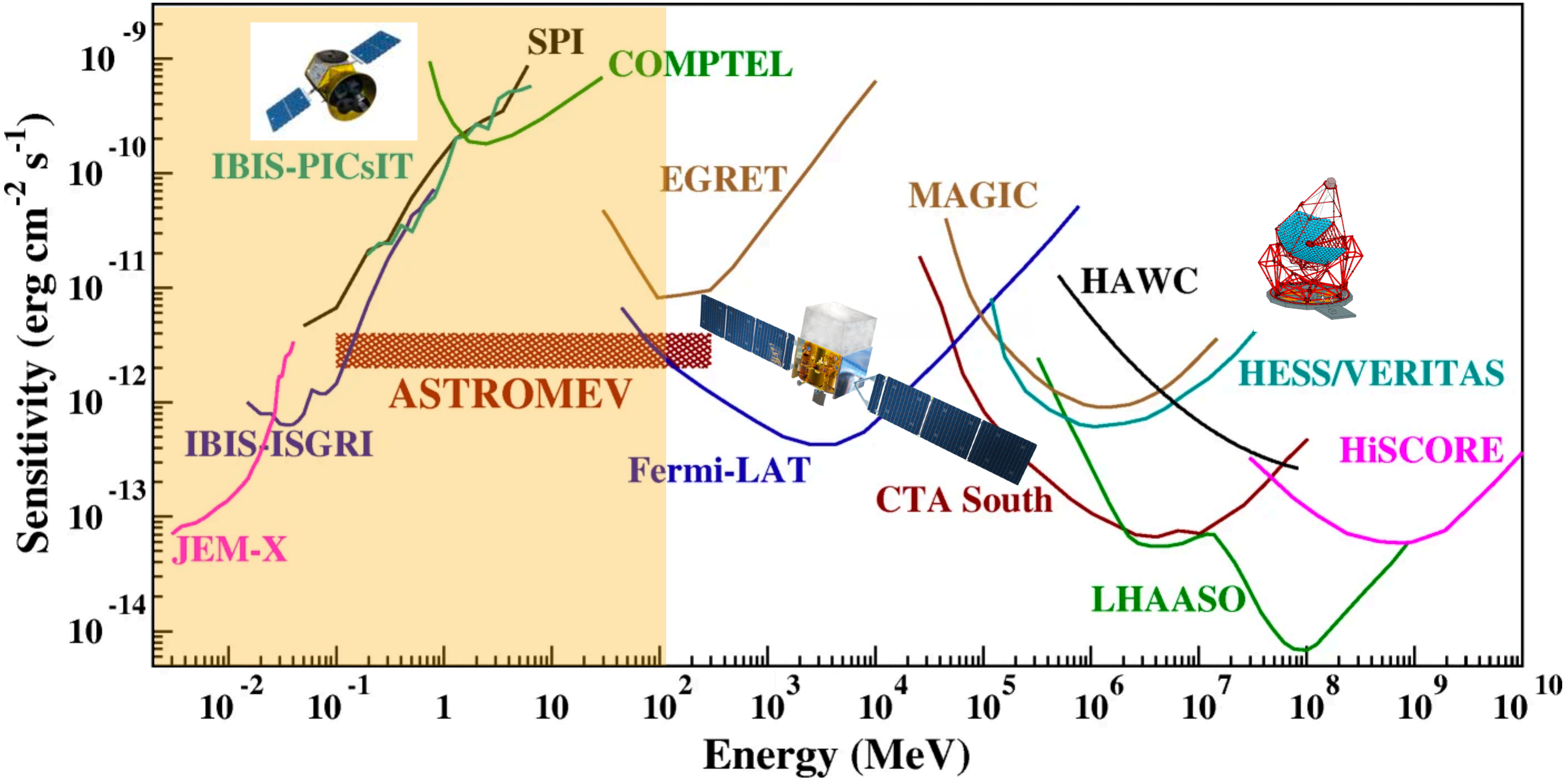
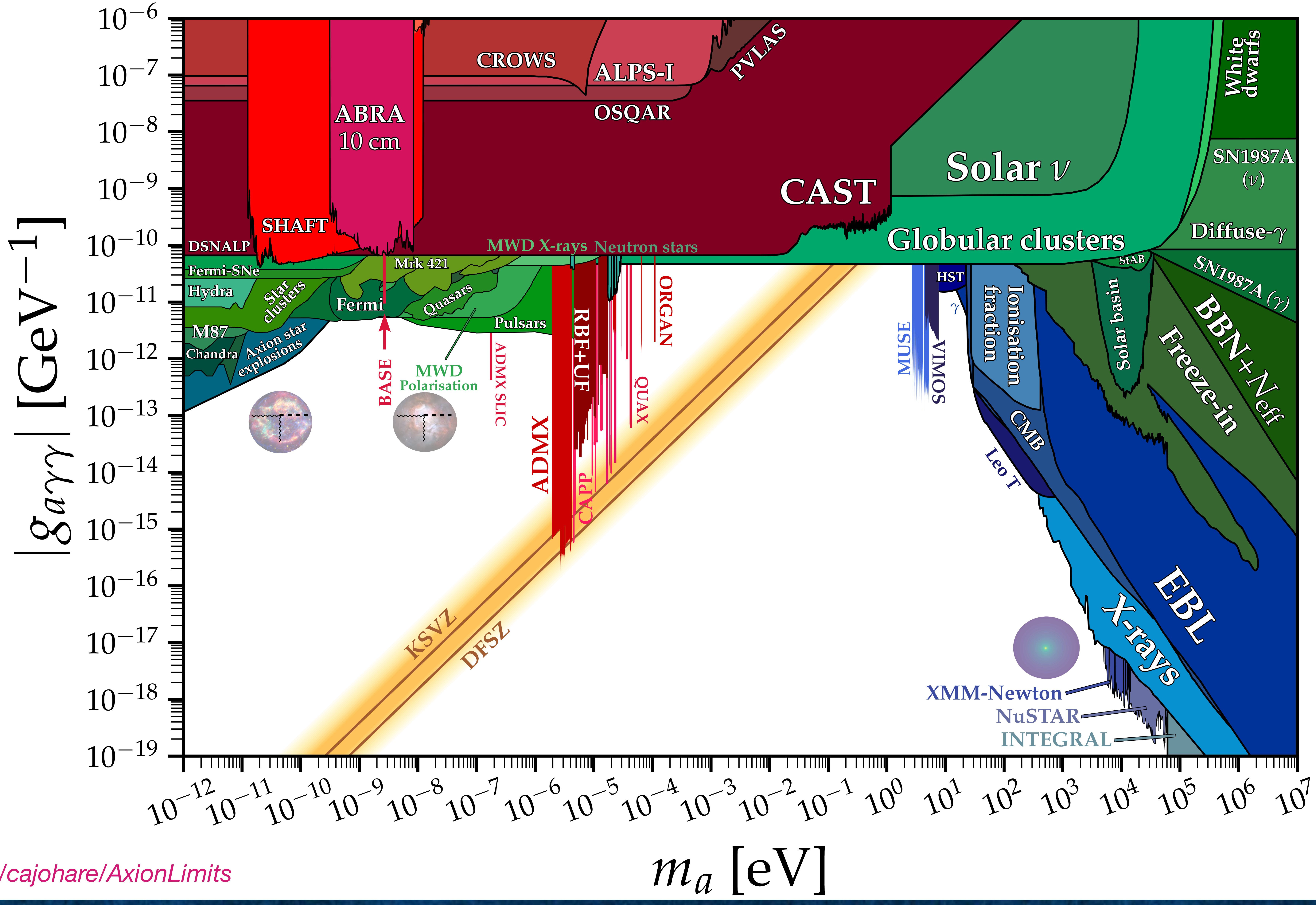


eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

Constraints on ALP-photon mixing



https://github.com/cajohare/AxionLimits

Constraints on ALP-photon mixing

Core-collapse SNe

- Searches for **single SNe** events or cumulative flux from **all past SNe**

Payez+ JCAP'14; Meyer & Petrushevska PRL'20; Crnogorcevic+ PRD'21

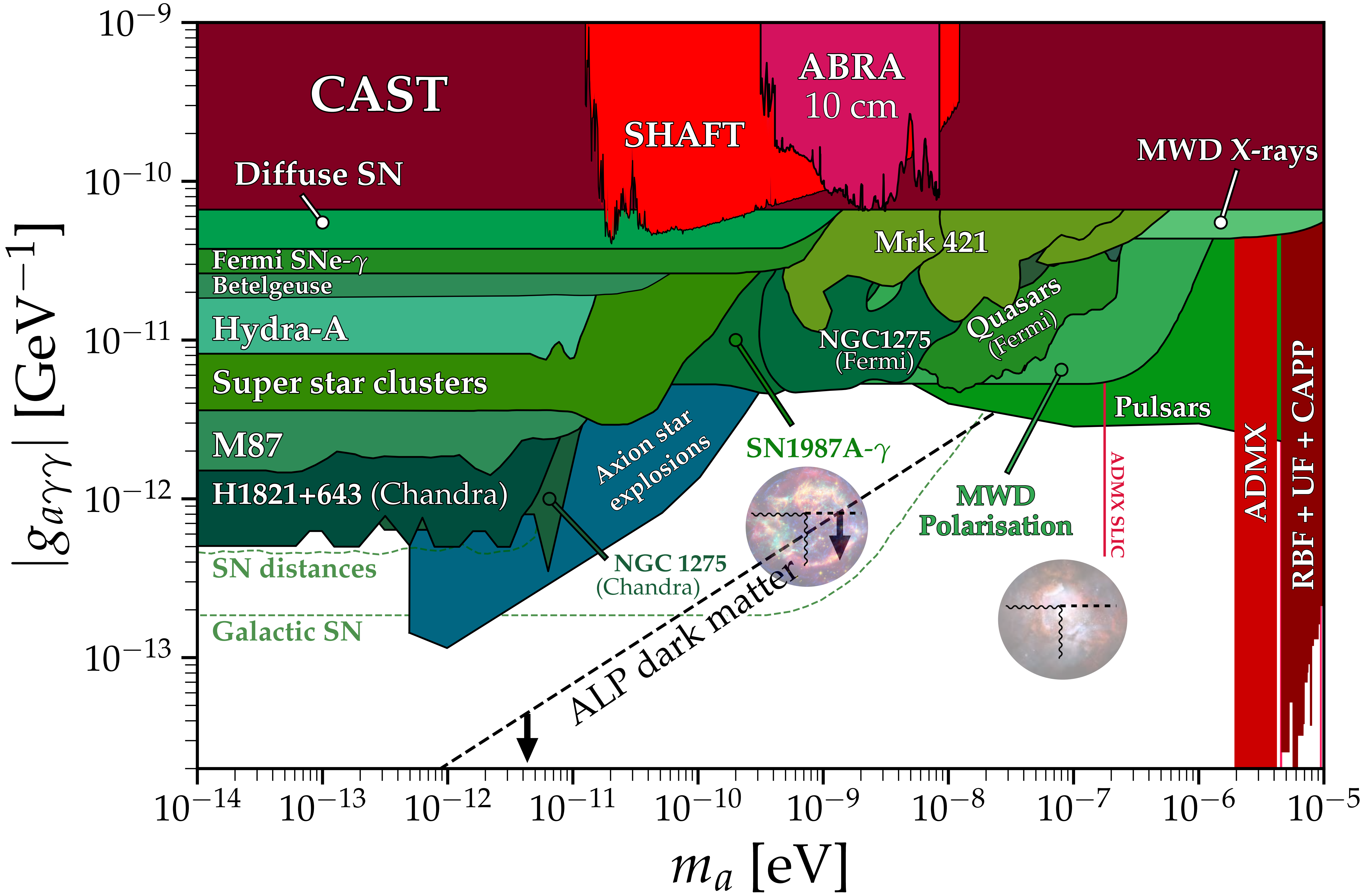
FC+ PRD'20, Eckner, FC+PRD'22, FC+ 2306.03925

- MeV to GeV cosmic backgrounds offer a unique window on this production mechanism

High-energy gamma-ray sources

- Search for **spectral distortion** of high-energy Galactic and extra-galactic sources from X- to gamma rays (e.g. NGC1275, Mrk421) *Davies+ PRD'23*
- Search for **photons appearance** from photon-ALPs *in source* conversion (HAWC blazars, sub-PeV Gal.)

Jacobsen+JCAP'23; Eckner&FC PRD'22



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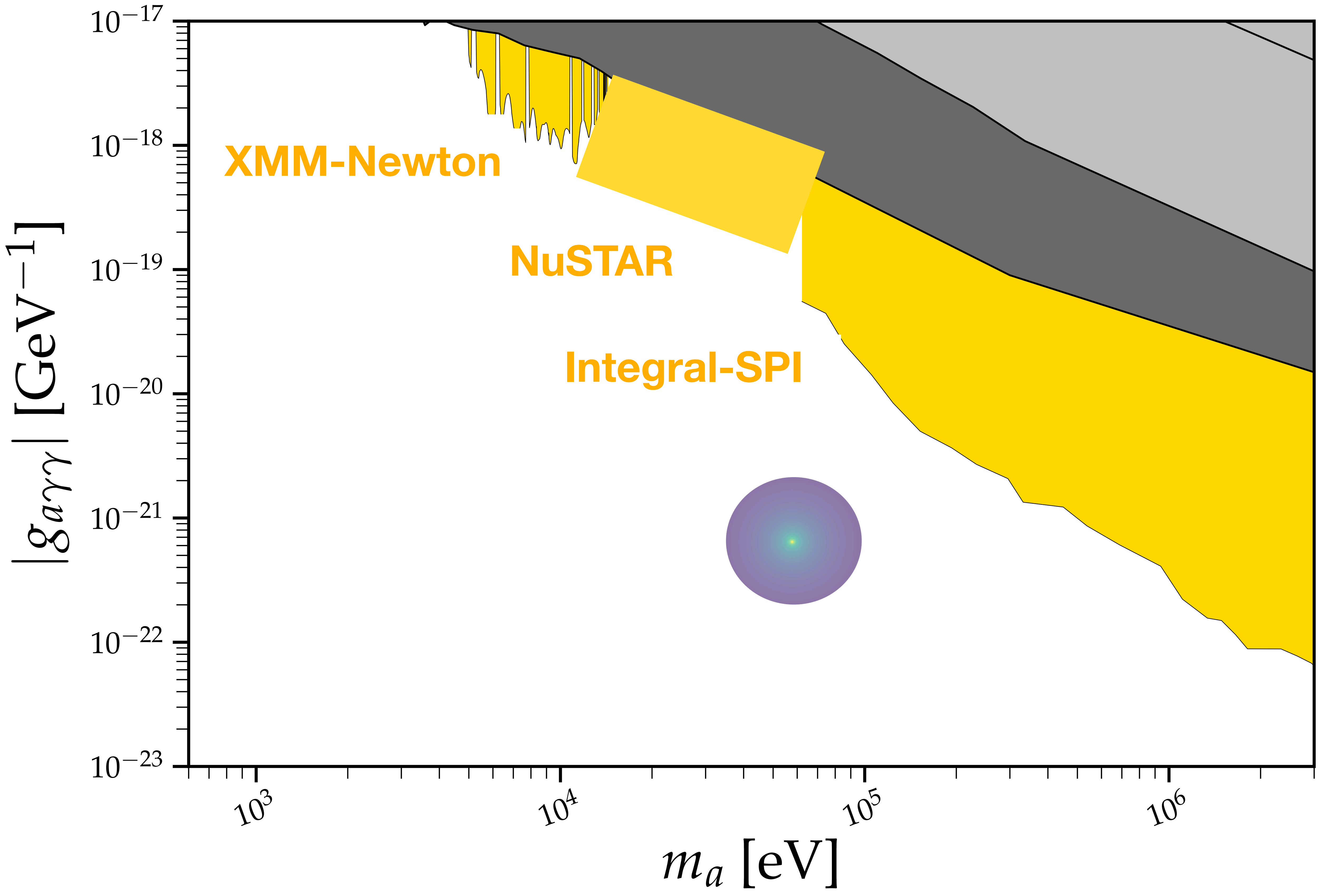
Constraints on ALP-photon mixing

Heavy ALPs DM decay

- Search for narrow lines in X and gamma-ray data
- XMM-Newton: 5-16 keV, archival data => No evidence found for unassociated X-ray lines *Foster+ PRL'21*
- NuSTAR: 7-Ms/detector deep blank-sky exposures *Roach+ PRD'23*
- Integral-SPI: new analysis of 16yr data with dedicated search for DM component in continuum Galactic emission *Berteaud, FC+PRD'22; FC+ MNRAS'22*

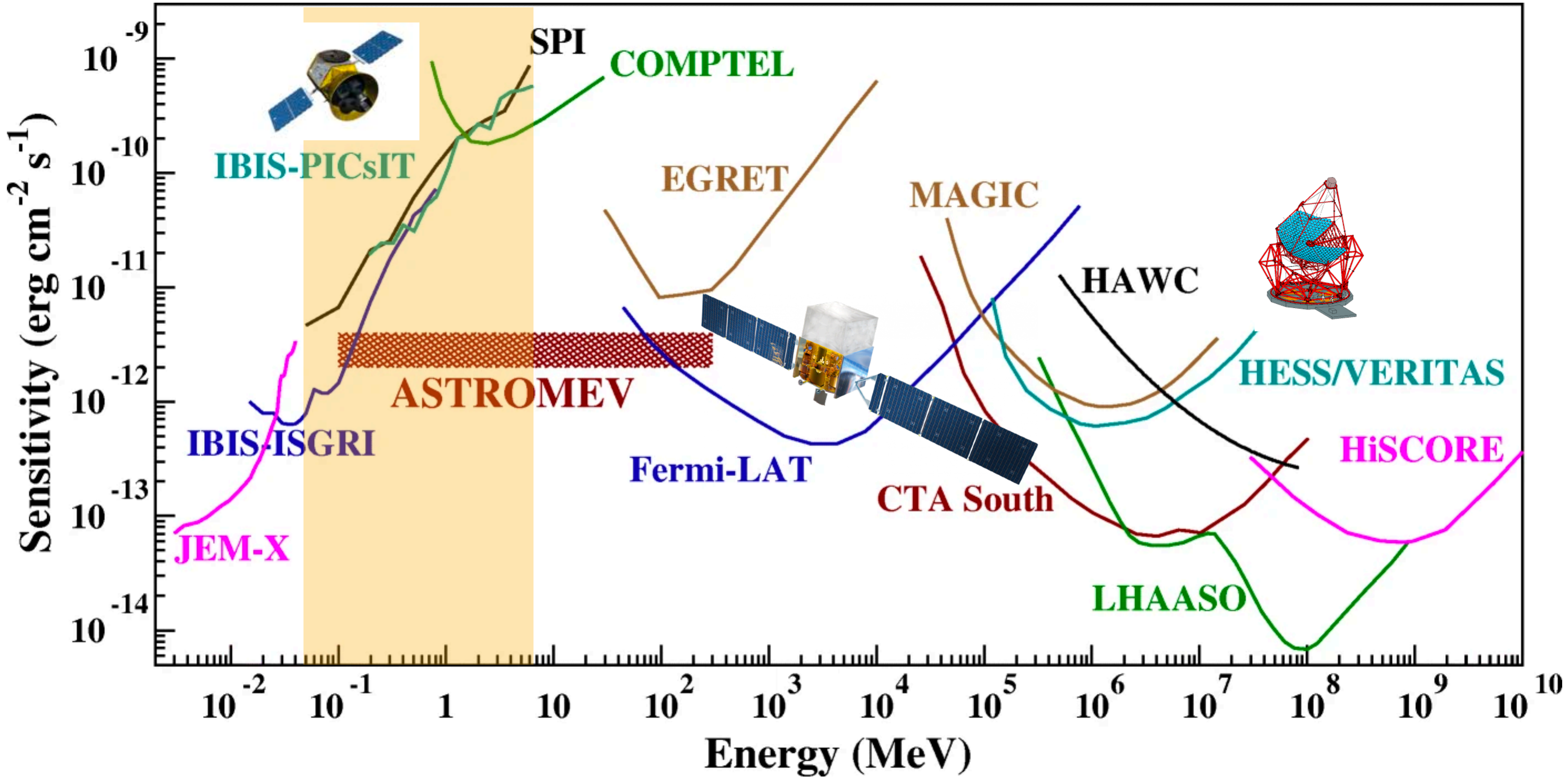


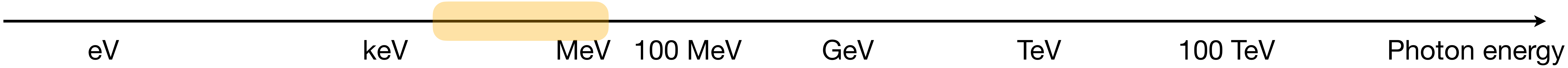
https://github.com/cajohare/AxionLimits

One recent highlight

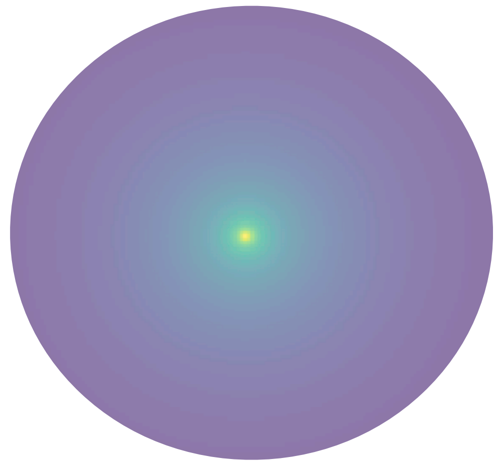
Gamma-ray data landscape: hard X rays

DeAngelis+ Voyage 2050 ‘21

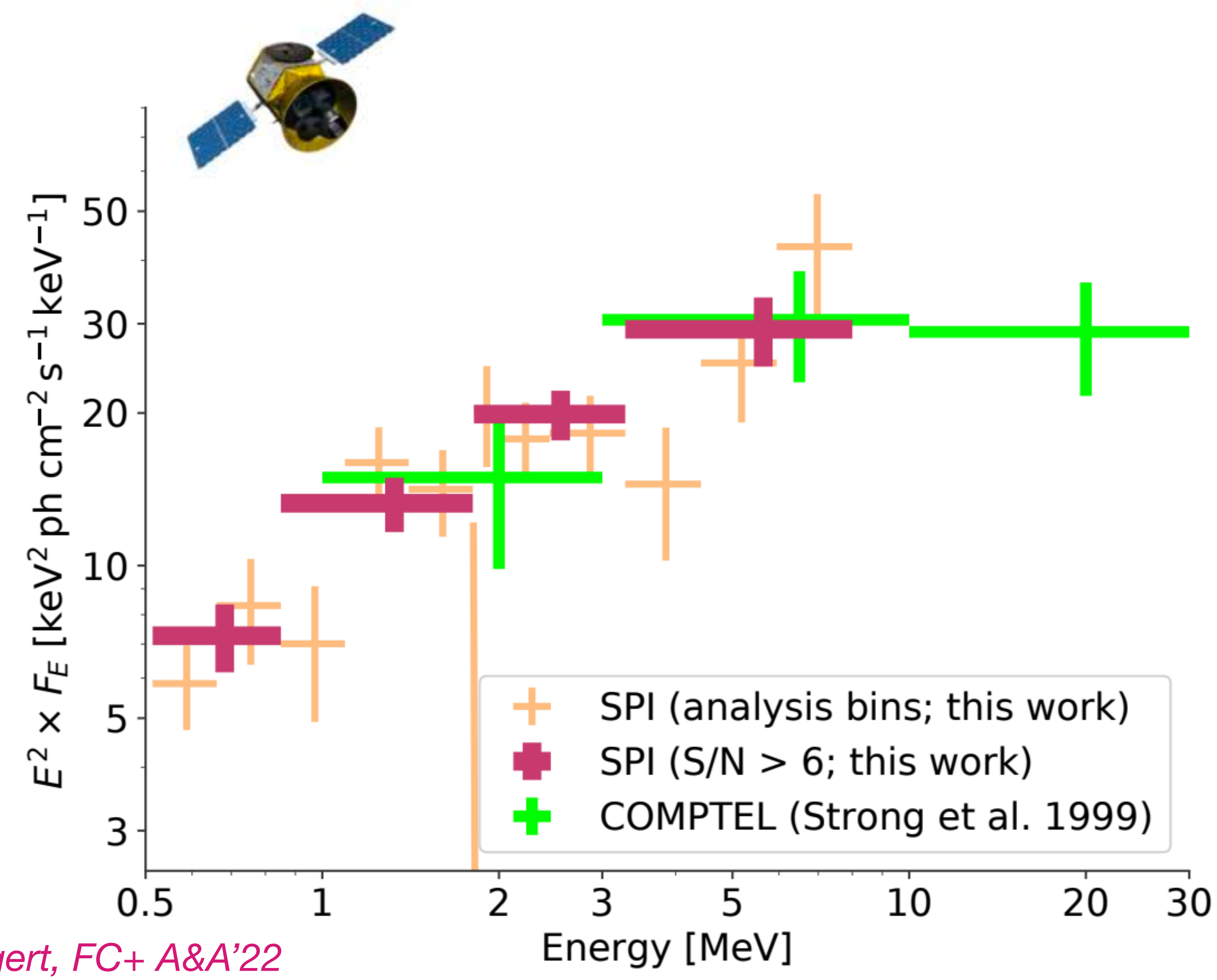




The gamma-ray Galactic diffuse emission



Soft gamma rays: Integral/SPI



Siegert, FC+ A&A'22

Constraints on **cosmic-ray transport** at MeV energy but also on **exotic emission mechanisms**: particle and non-particle dark matter

Berteaud, FC+ PRD'22 ; FC+ MNRAS'23

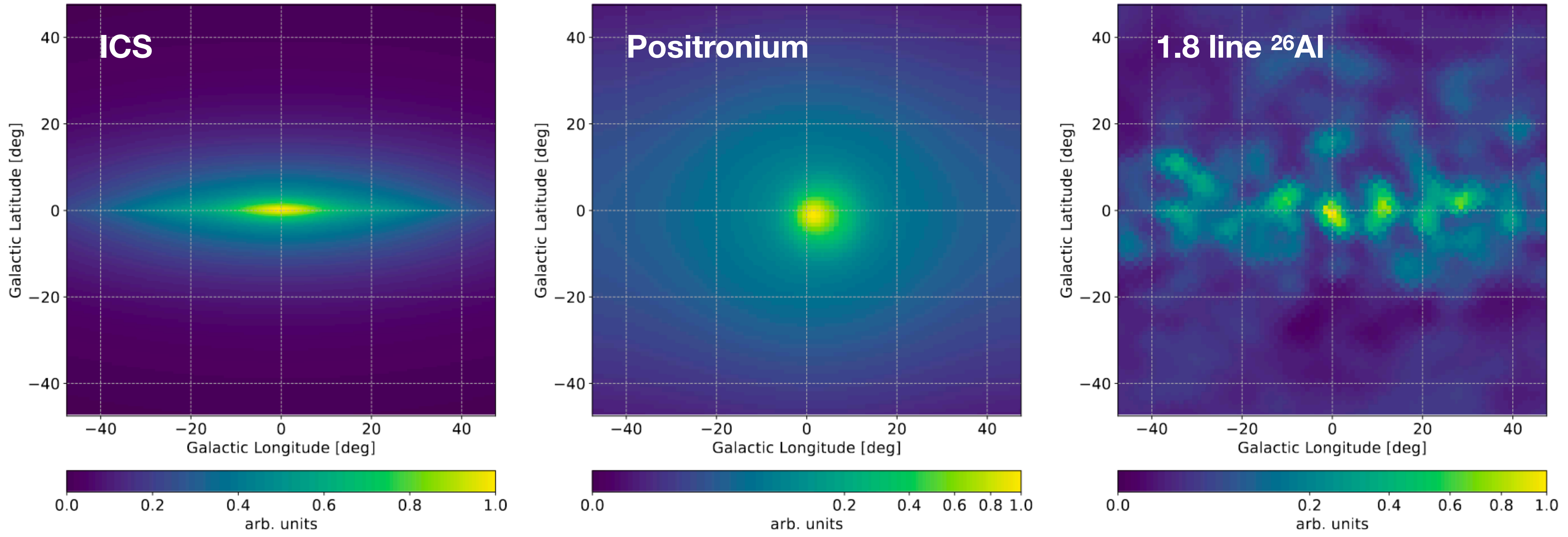
New analysis of 16yr-data from SPI
30 keV — 8 MeV

The gamma-ray Galactic diffuse emission

Soft gamma rays: astrophysical contributions

Modelled spatial templates (30 keV — 8 MeV)

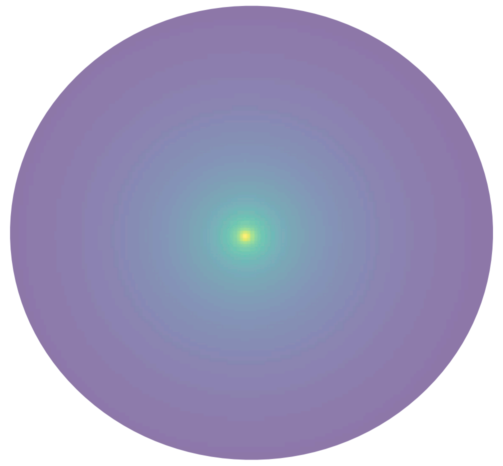
- **Inverse Compton scattering** of electrons off the interstellar radiation field $e^{\pm}_{CR} + \gamma \longrightarrow e^{\pm} + \gamma_{MeV}$
- Unresolved sources (<100 keV)
- Nuclear lines
- Positronium annihilation line+continuum



Berteaud, FC+ PRD'22

The gamma-ray Galactic diffuse emission

Soft gamma rays: dark matter signals?



Modelled **spatial templates** (30 keV — 8 MeV)

- **Inverse Compton scattering** of electrons off the interstellar radiation field $\mathrm{e}^{\pm}_{\mathrm{CR}} + \gamma \longrightarrow \mathrm{e}^{\pm} + \gamma_{\mathrm{MeV}}$
- Unresolved sources (<100 keV)
- Nuclear lines
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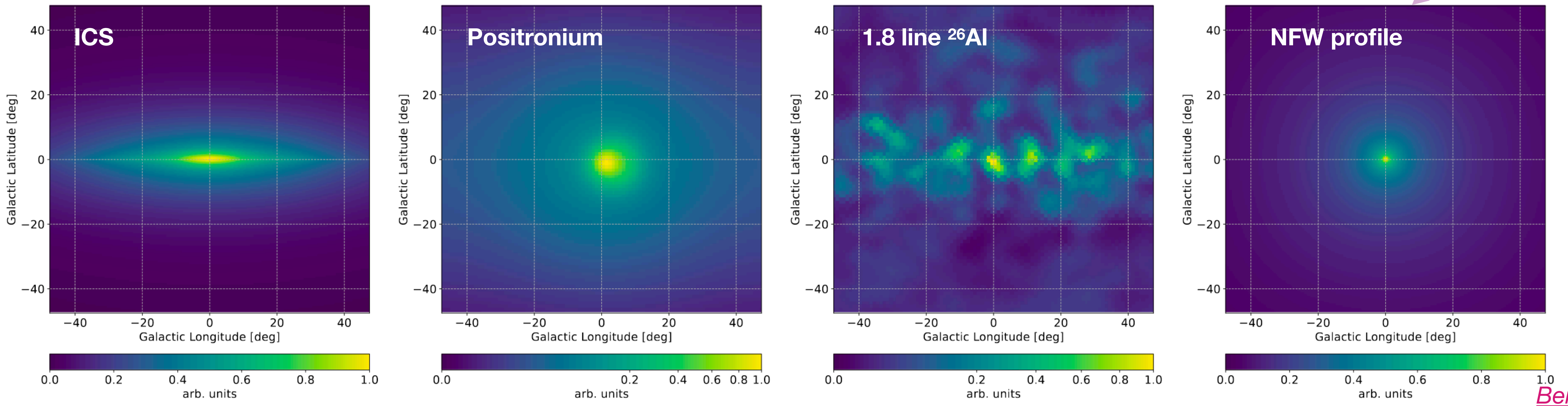
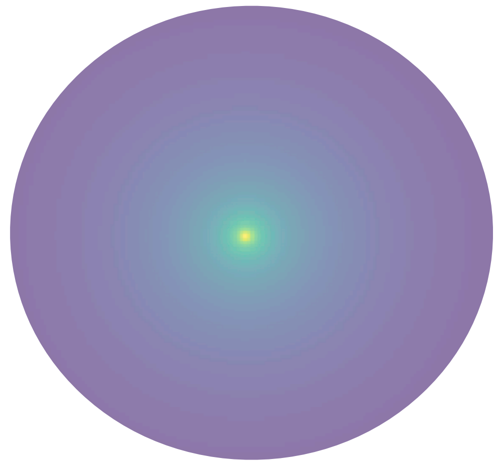
- Additional **decaying DM signal**?

$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\mathrm{decay}} = \frac{\Gamma(a \to \gamma\gamma)}{4\pi m_a} \left(\frac{dN_\gamma}{dE}\right)_{\mathrm{decay}} \times \int_{\mathrm{l.o.s.}} \rho_a(\ell) d\ell$$



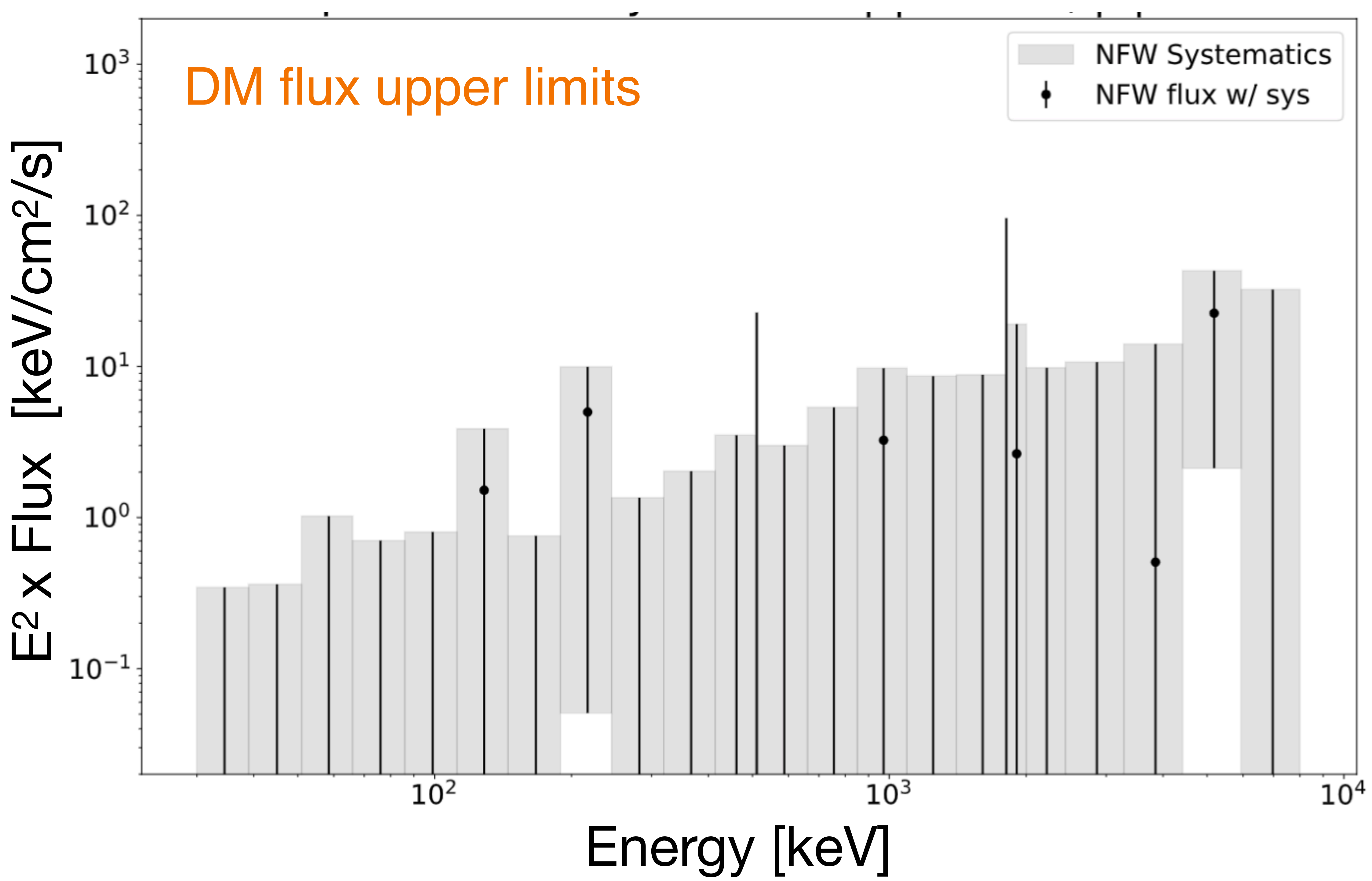
Berteaud, FC+ PRD'22

The gamma-ray Galactic diffuse emission



Soft gamma rays: constraints on dark matter

No signal detected

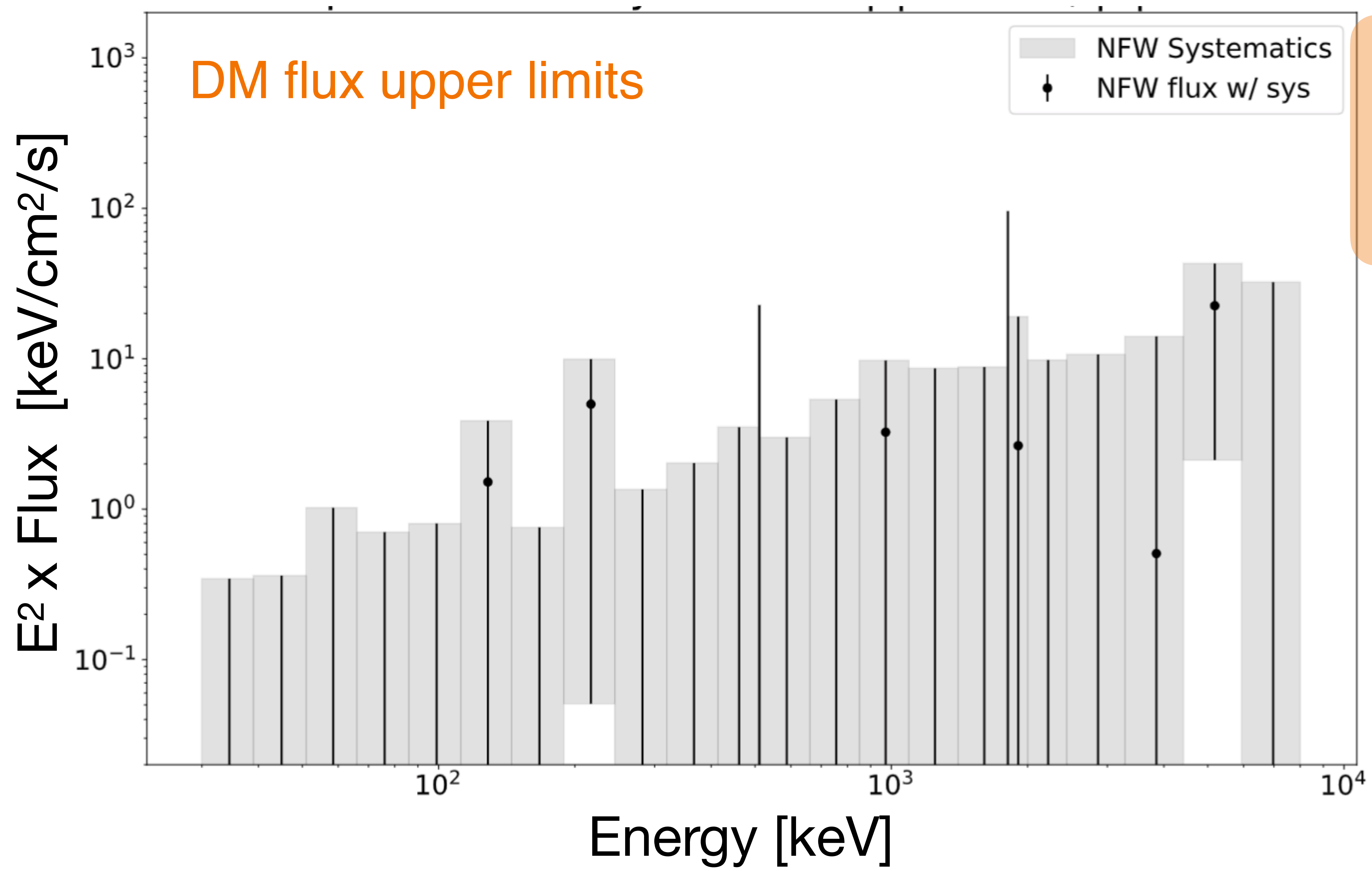


https://zenodo.org/record/6505275

The gamma-ray Galactic diffuse emission

Soft gamma rays: constraints on dark matter

No signal detected



$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\rm decay} = \frac{\Gamma(a\to\gamma\gamma)}{4\pi m_a}\left(\frac{dN_\gamma}{dE}\right)_{\rm decay} \times \int_{\rm l.o.s.} \rho_a(\ell)\, d\ell$$

$$\left(\frac{dN_\gamma}{dE}\right)_{\rm decay} = 2\delta\left(E - \frac{m_a}{2}\right)$$

ALPs decay rate into 2 photons

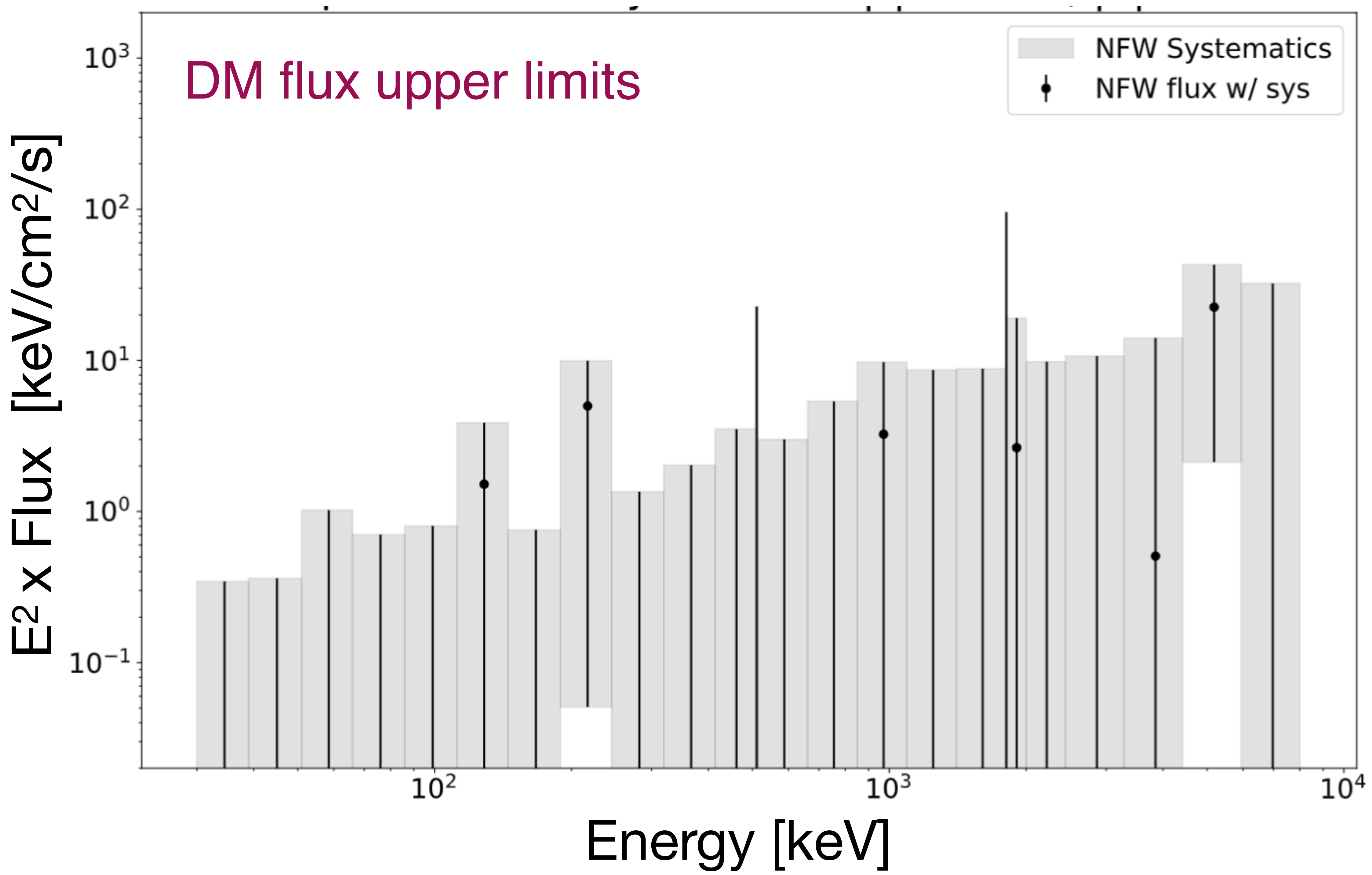
$$\Gamma_{2\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 0.755\times 10^{-30}\left(\frac{g_{a\gamma\gamma}}{10^{-20}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{m_a}{100\,\mathrm{keV}}\right)^3 \mathrm{s}^{-1}$$

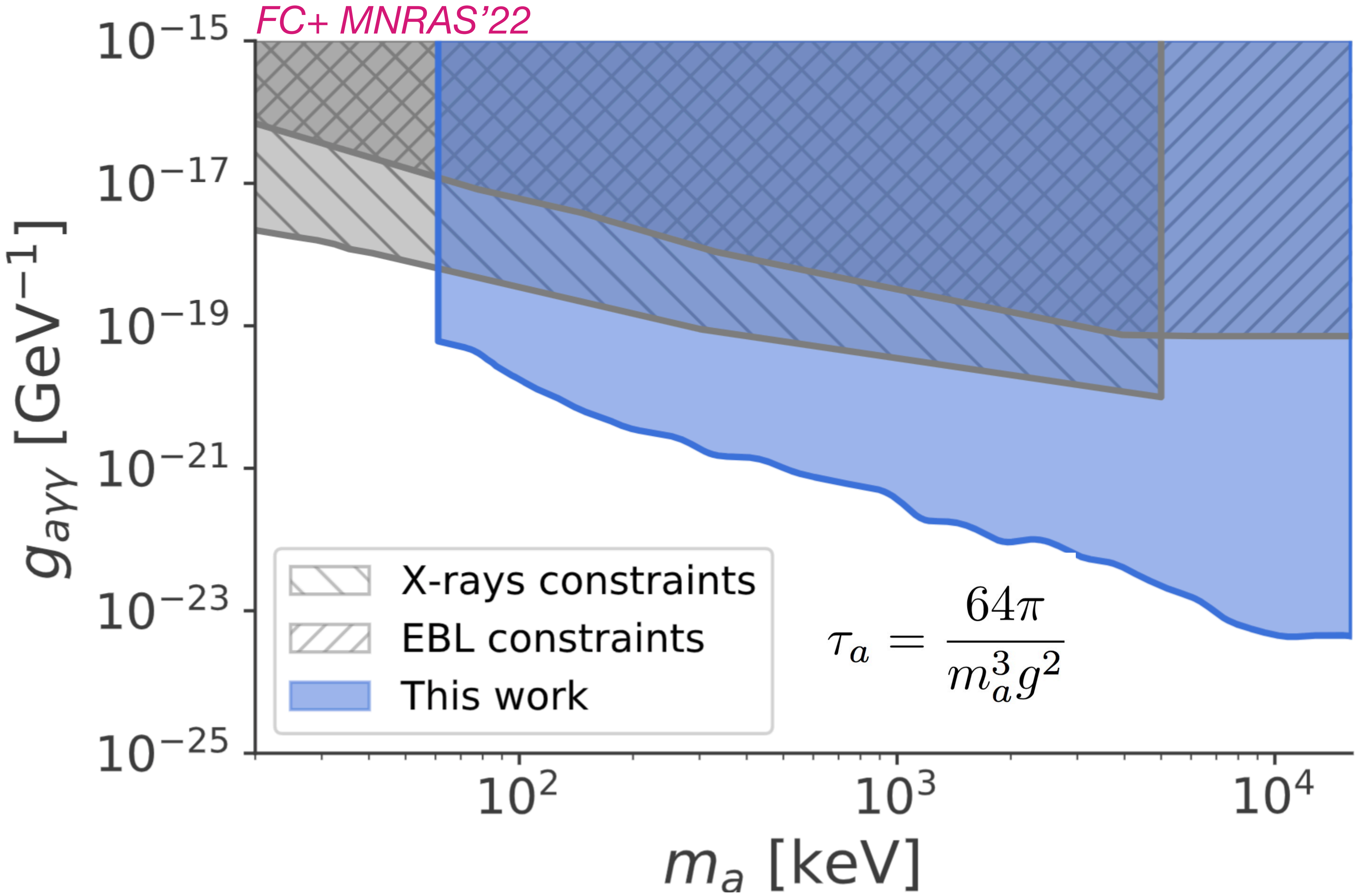
https://zenodo.org/record/6505275

The gamma-ray Galactic diffuse emission

Soft gamma rays: constraints on dark matter

No signal detected → Upper limits on **ALPs coupling**





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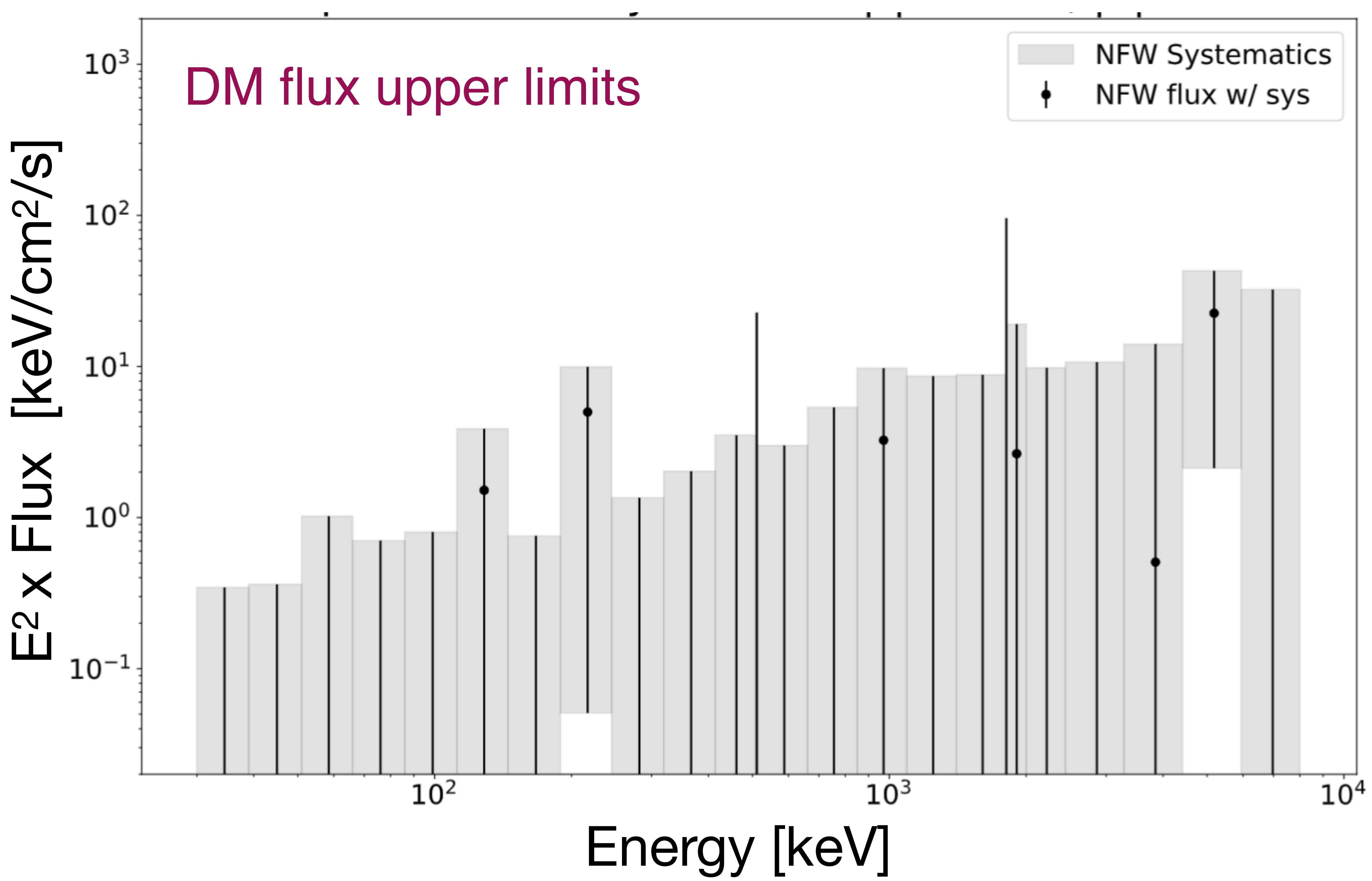
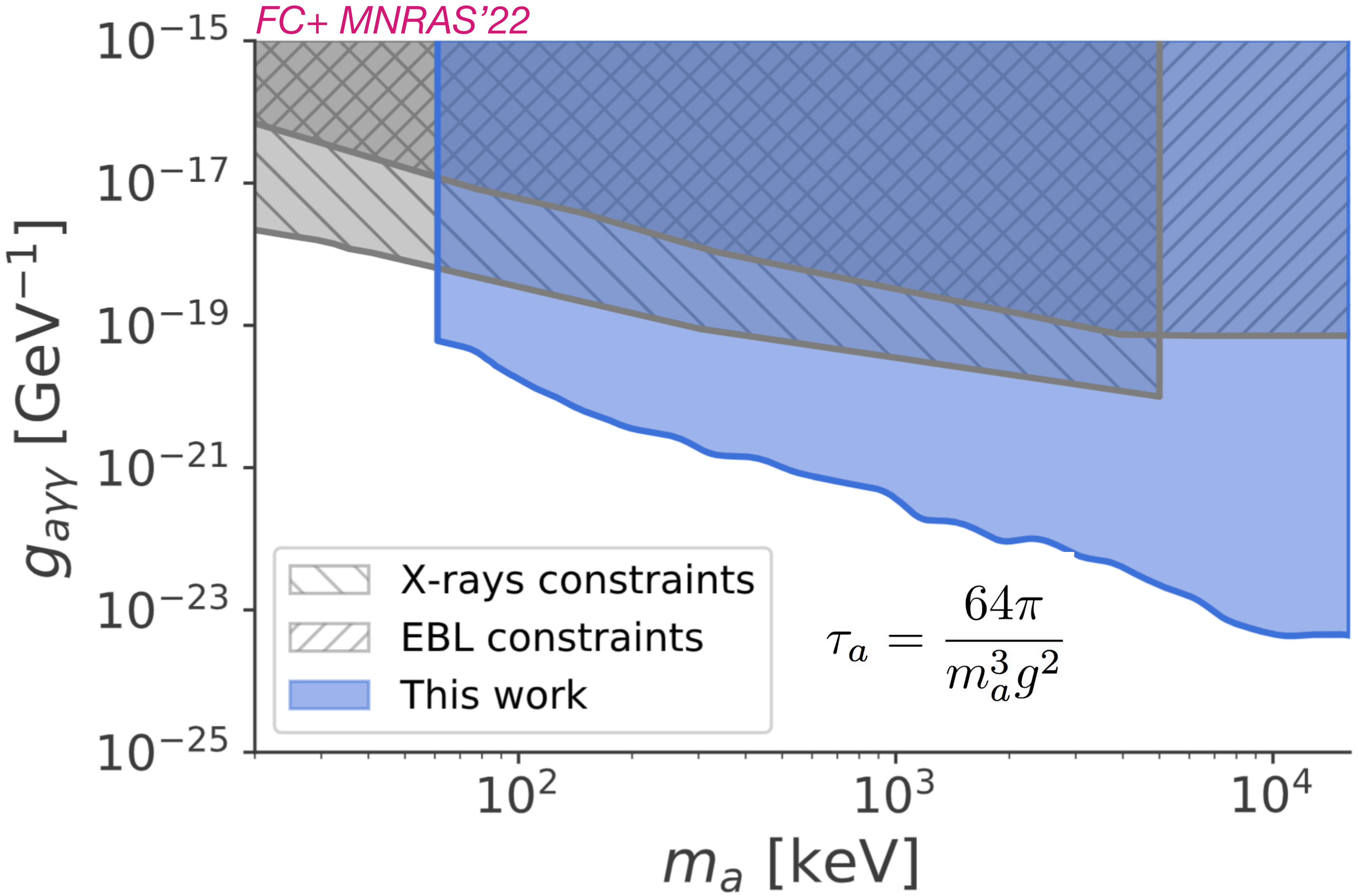


→ Upper limits on **ALPs coupling**



Re-analysis of Integral/SPI data provides the **strongest constraints** on (light) particle and non-particle DM (PBH)

Conclusions & Outlook

- Probes for axion/ALP-photon coupling in astrophysics are truly **multi-wavelength** (radio, X-rays, gamma rays)
- HE gamma-ray astrophysics **strongly constrains 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

Apply to join the WGs on the Action webpage
https://www.cost.eu/actions/CA21106/

Conclusions & Outlook

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COSMIC WISPERS
CA 21106

Apply to join the WGs on the Action webpage
https://www.cost.eu/actions/CA21106/

Thank you for the attention!

Backup slides

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 $e + Ze \to Ze + e + a$

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

ALP-nucleon coupling

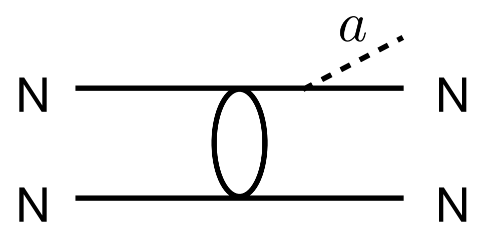
NN bremsstrahlung $N_1 + N_2 \longrightarrow N_3 + N_4 + a$

$g_{ap} < 0.9 \times 10^{-9}$

$g_{an} < 0.8 \times 10^{-9}$

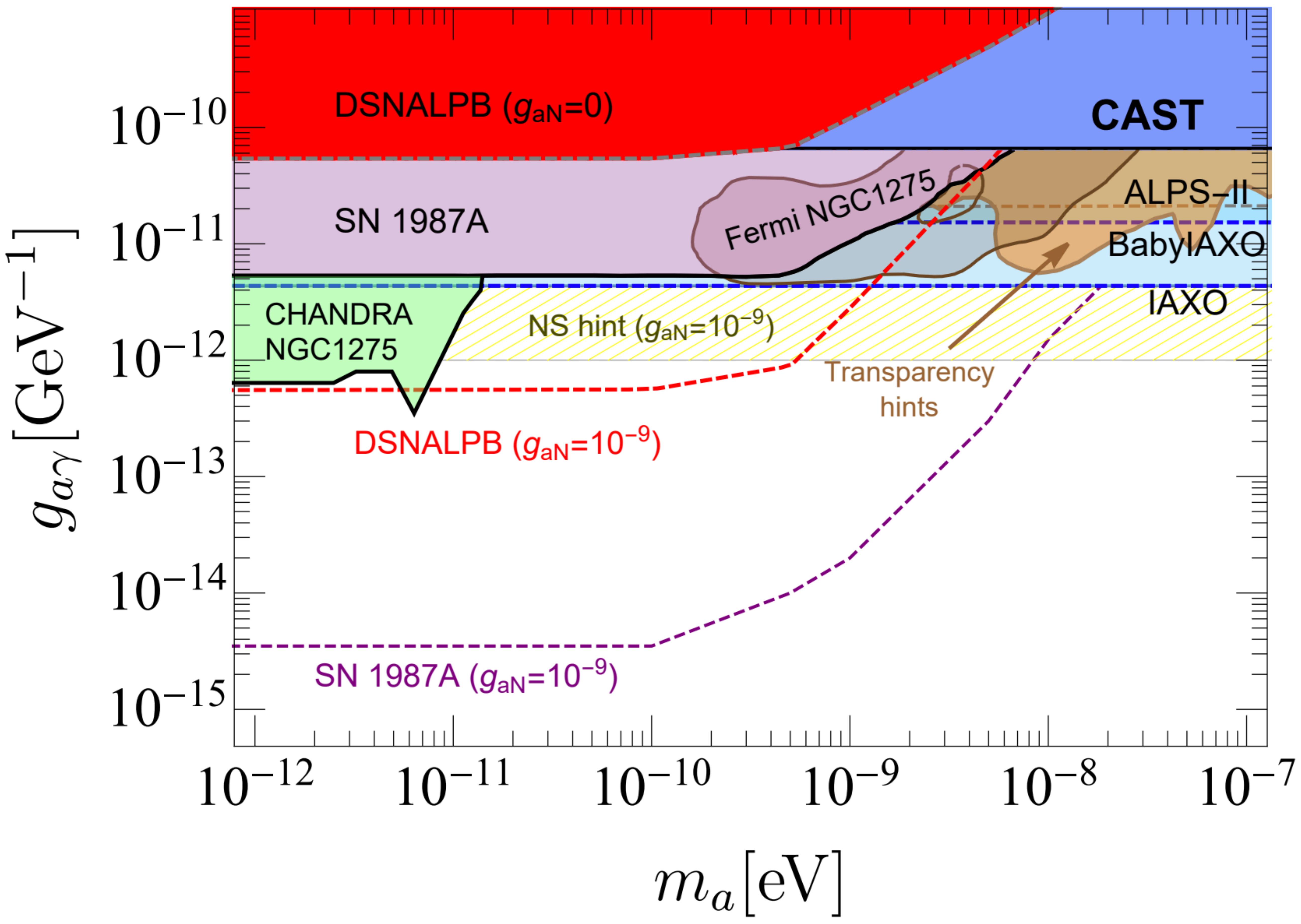
→ Copious ALPs production

Constraints from enhanced NN brems



NN bremsstrahlung from SN1987A and DSNALPB

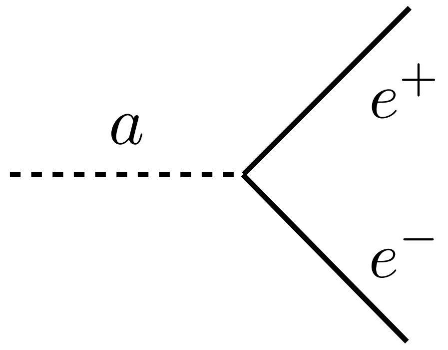
FC+ PRD'20



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

Coupling with nucleons and electrons

Heavy ALPs decay

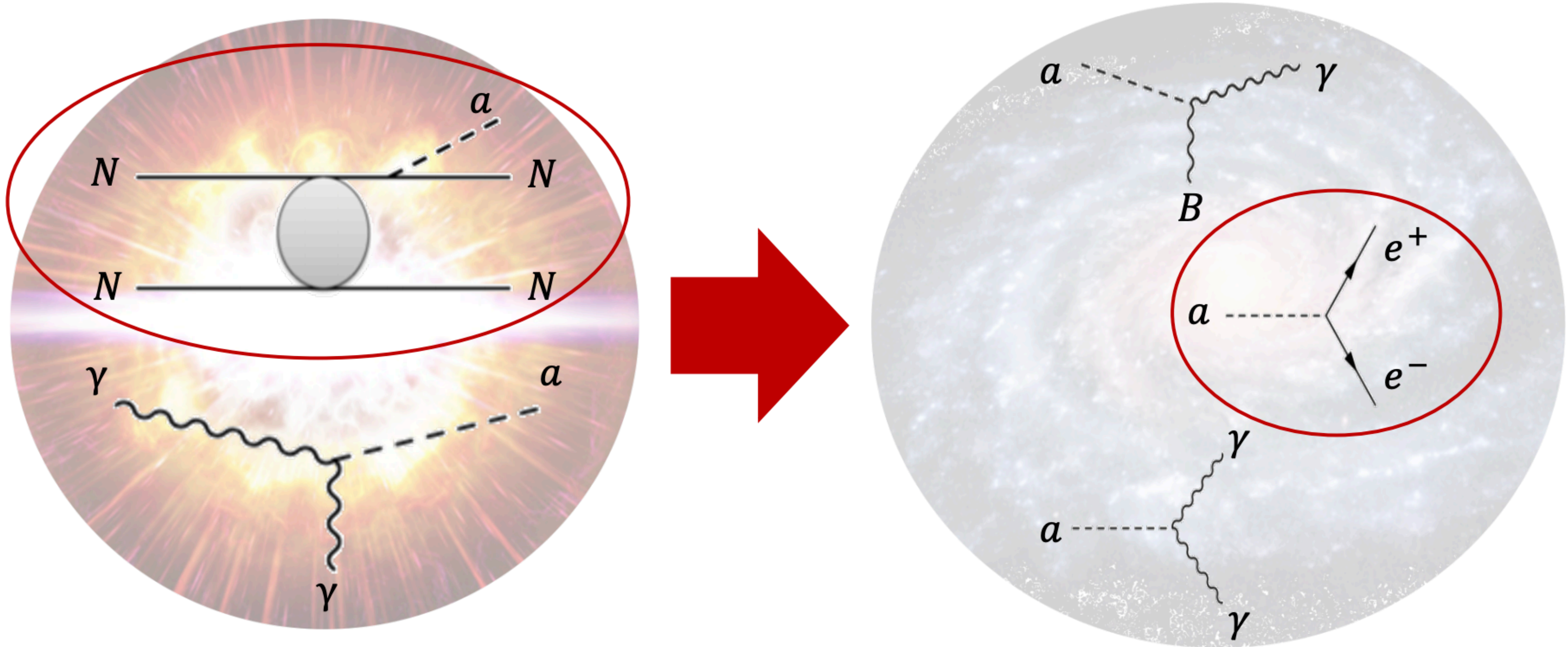


- Production through **nucleon bremsstrahlung** in CC SNe
- For **m > MeV**, conversion suppressed but possible decays into **photons** and **electron-positron pairs**

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

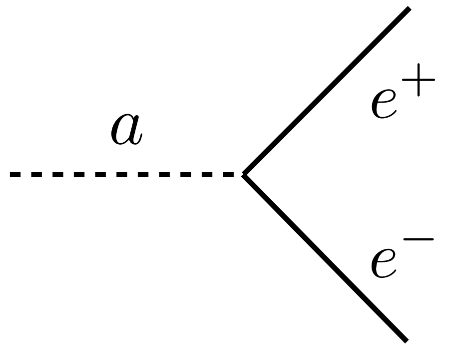
FC+ PRD'21

Production | **Signature**



Credit: G. Lucente

Coupling with nucleons and electrons

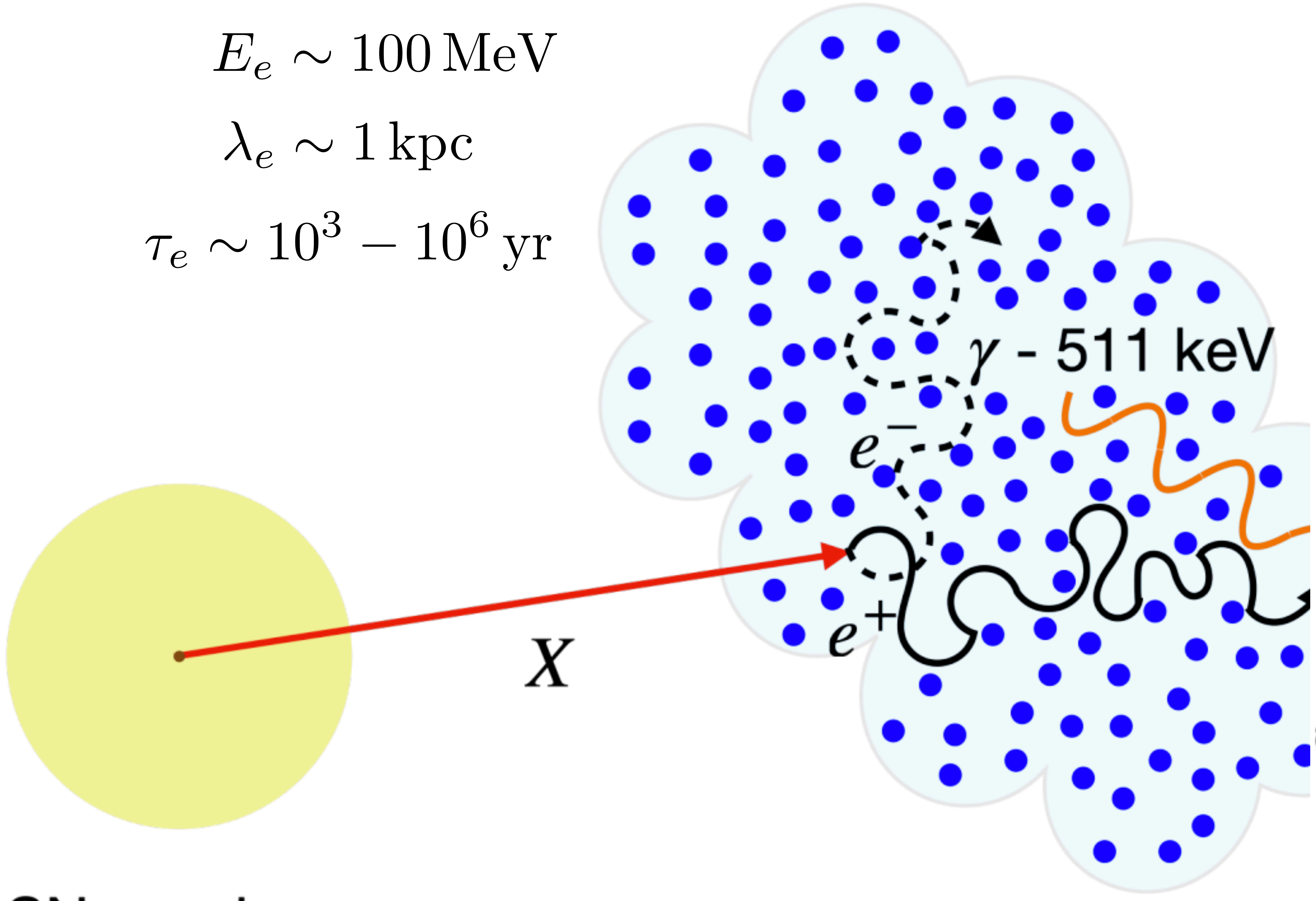


Positron production and annihilation

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

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

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

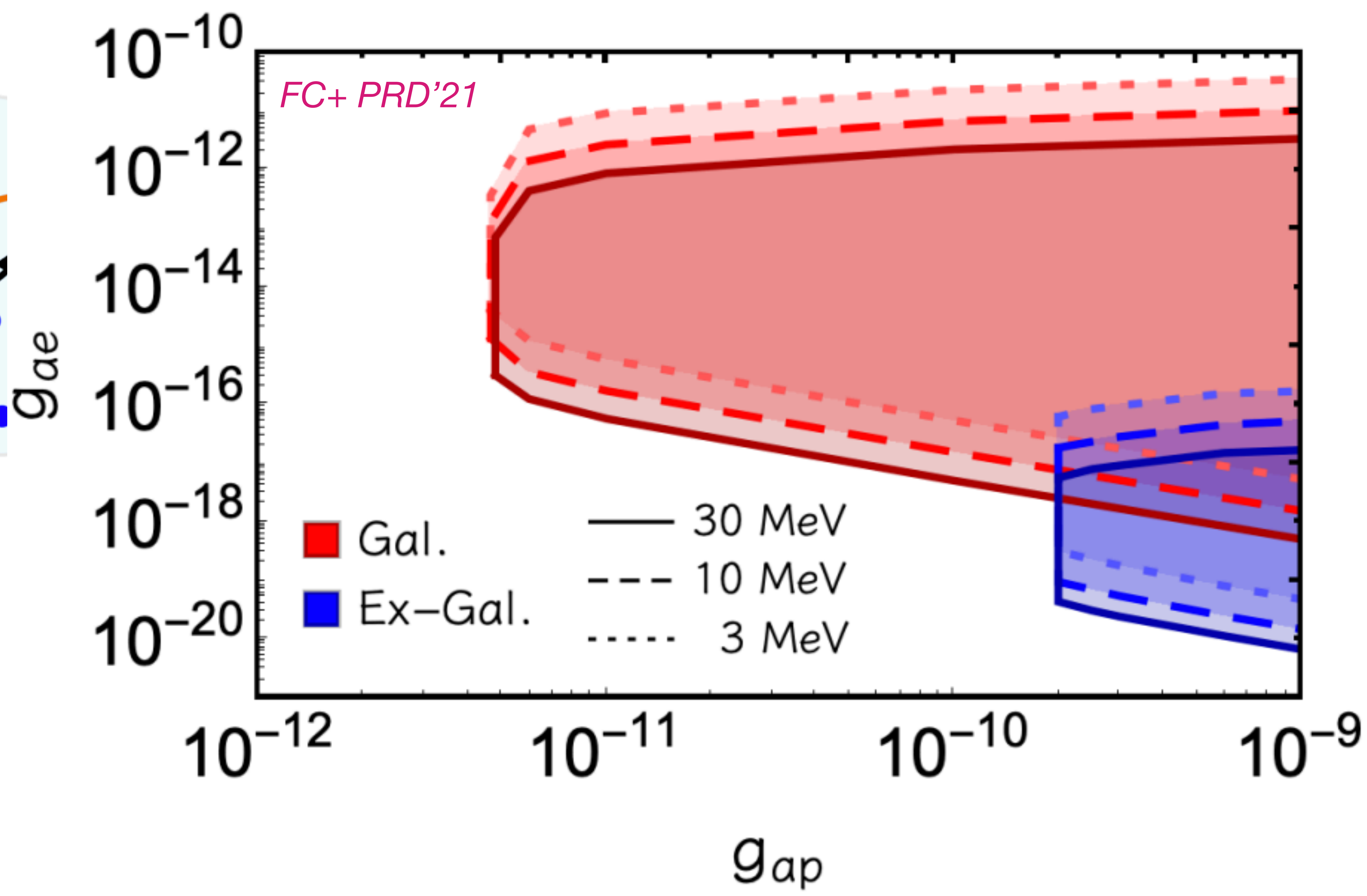


SN envelope

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

In the Galaxy

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



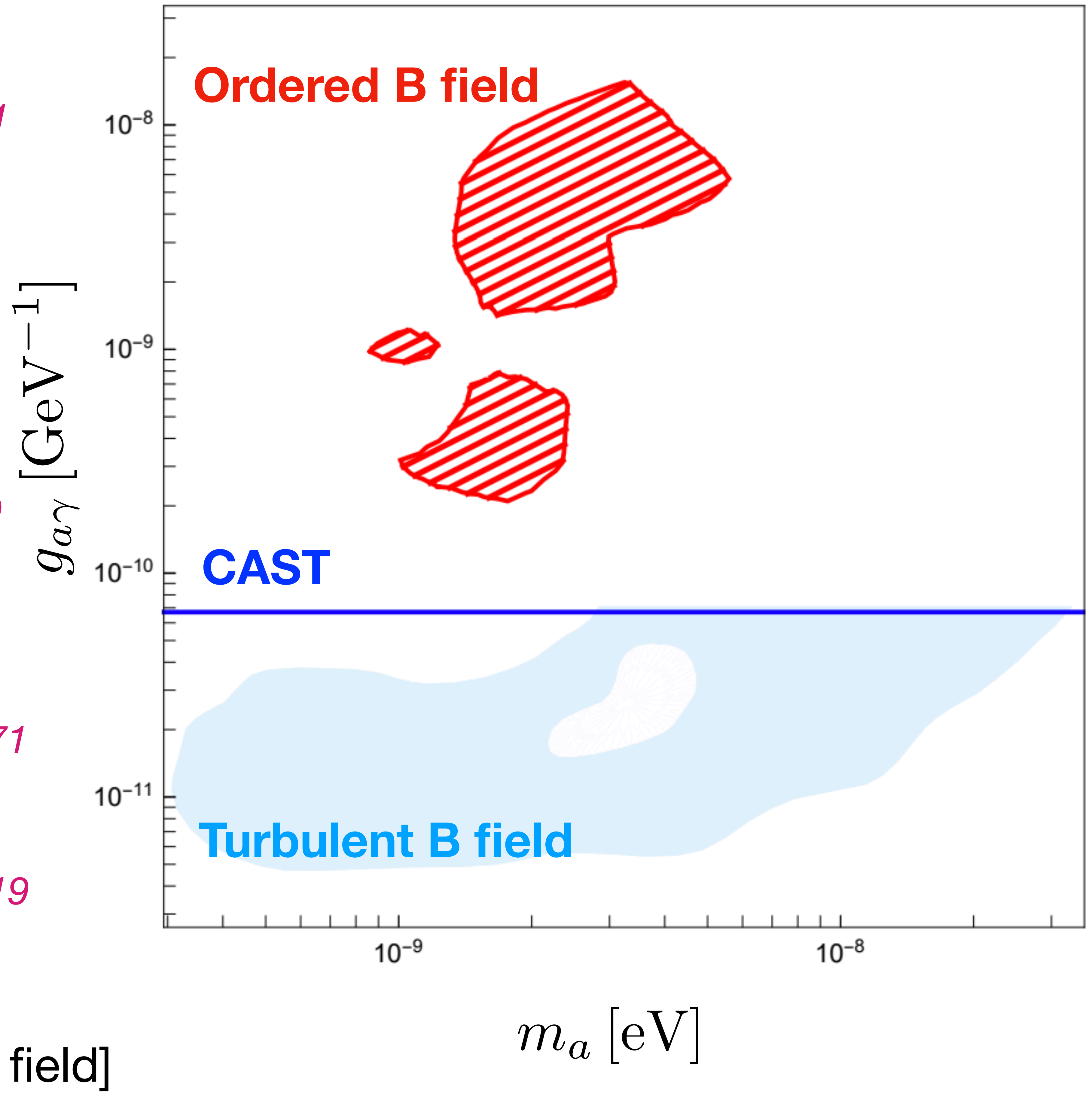
Constraints on ALP-photon mixing

Search for spectral irregularities in extragalactic targets

No evidence for ALP-photon mixing ⟶ Strong but **not very robust upper limits**

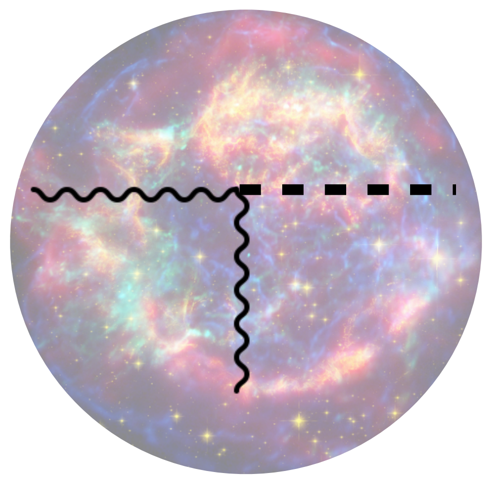
- Analysis of radio galaxy **NGC1275** (Perseus cluster) with **Fermi-LAT** and **MAGIC** *Ajello+PRL'16, Malyshev+1805.04388, Cheng+ PLB'21*
  - ✓ Limits very sensitive to modelling of intra-cluster B field
  - ✓ Typically, only turbulent component is modelled
  - ✓ But, there is evidence for large scale ordered component (better match to Faraday rotation measure and others) *Libanov &Troitsky PLB'20*
  - ✓ With a purely ordered B field limits almost vanish
- Analysis of nearby blazar **PKS 2155-304** with **Fermi-LAT** and **HESS** *Abramowski+ PRD'13, Zhang+ PRD'18; Guo+:2002.07571*
  - ✓ Only turbulent component of the intra-cluster B field
  - ✓ Intergalactic B field RMS usually overestimated *Jedamzik & Saveliev, PRL'19*
  - ✓ Limits can be significantly weakened

[See also *Carenza+ PRD'21, Kachelriess+ JCAP'22* for impact of turbulent Galactic B field]



Libanov &Troitsky PLB'20

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

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

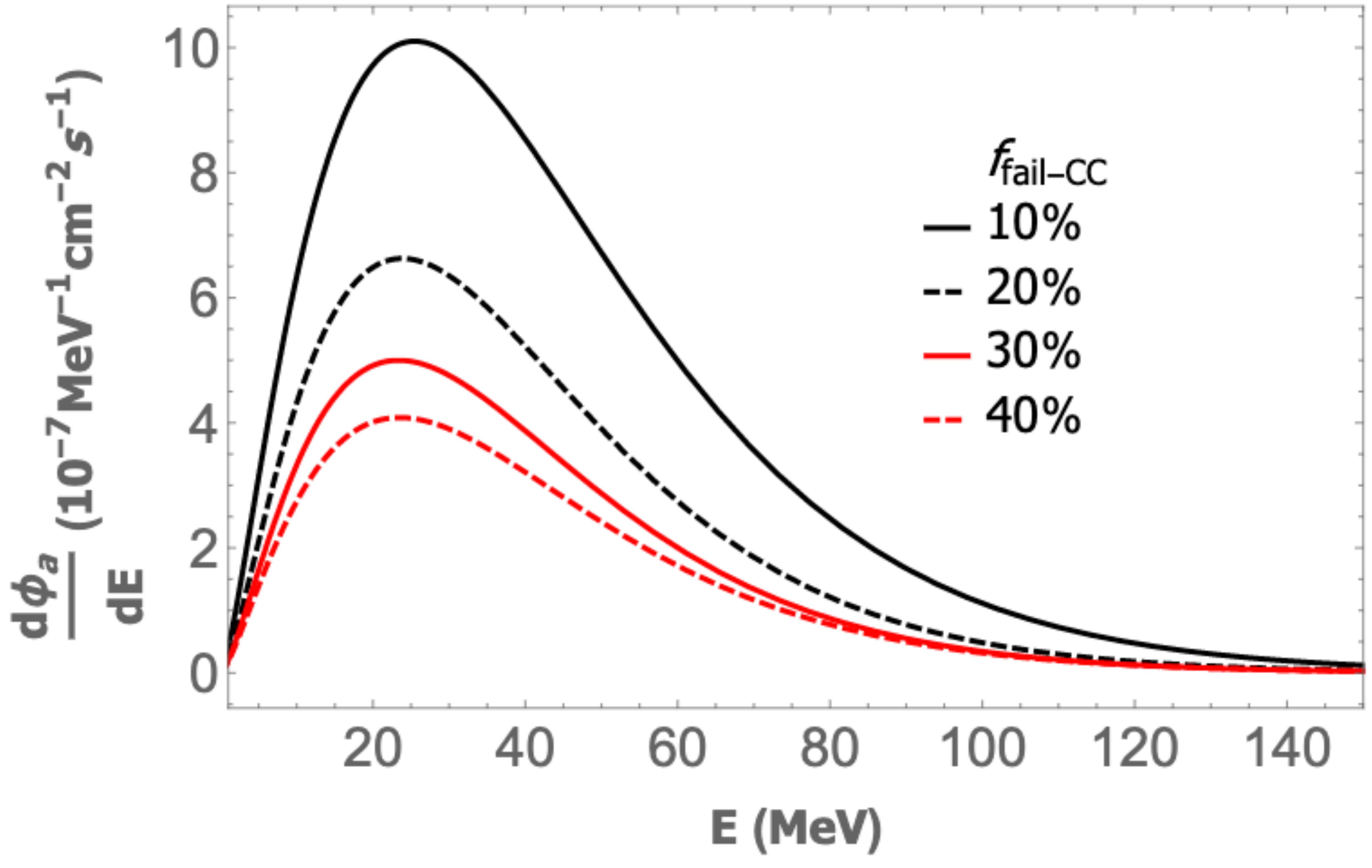
Beacom, Ann. Rev. Nucl. Part. Sci.'10

Time-integrated CC SNe ALPs spectrum from past events

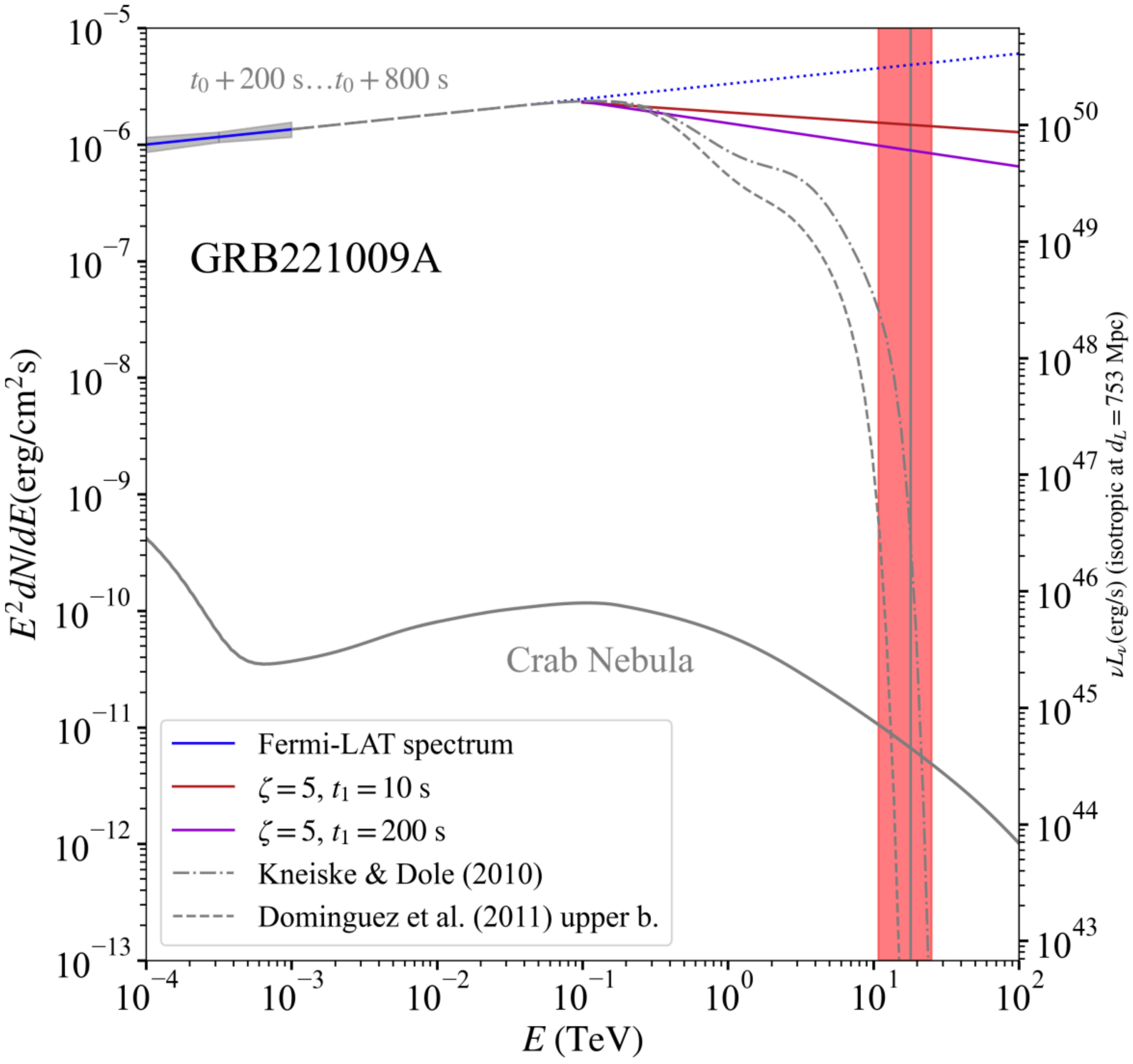
Time-integrated spectrum weighted by initial mass function over the range 8-125 $M_\odot$

CC SNe rate density at redshift z

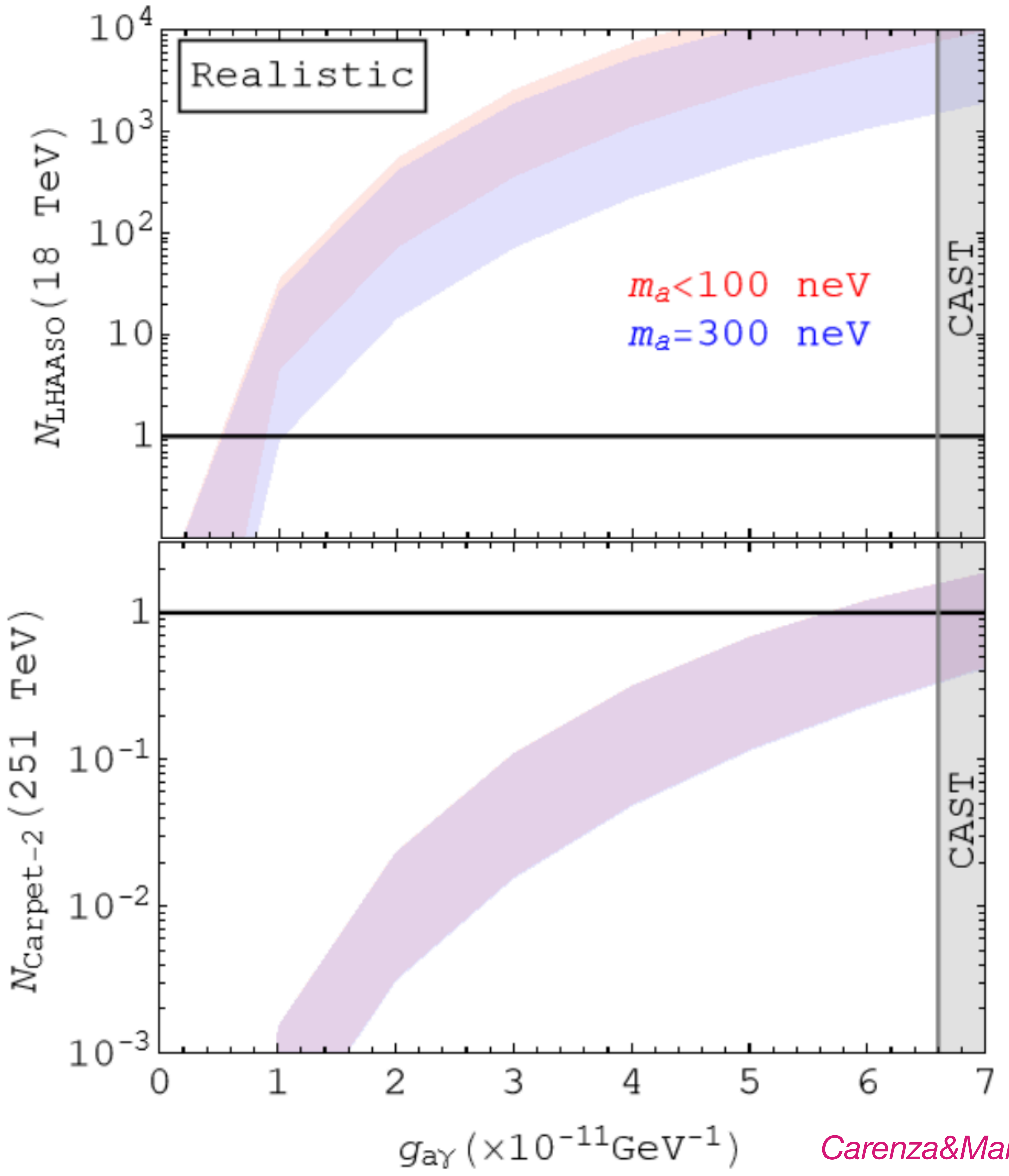
Yuksel et al. ApJ Letters'08



The GRB221009A



Batkash+ JCAP'23



Carenza&Marsh 2022