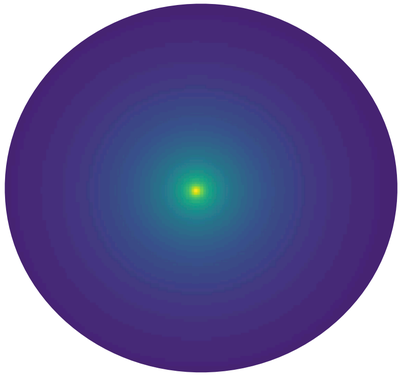




Axion signatures in gamma-ray fluxes

5th YoungSt@rs @ MITP — 07/10/2022

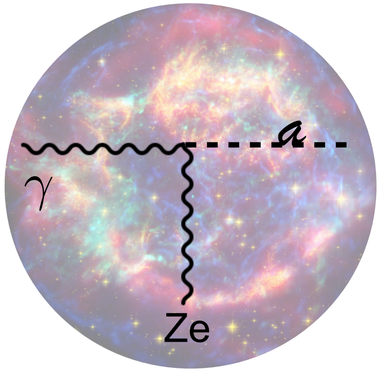
Francesca Calore (CNRS/LAPTh)

Gamma rays from ALPs?

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

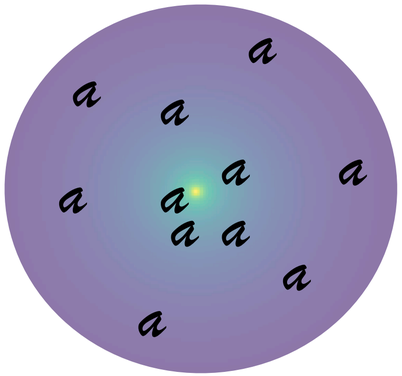
Gamma rays from ALPs?

Source



cc-SNe Primakoff

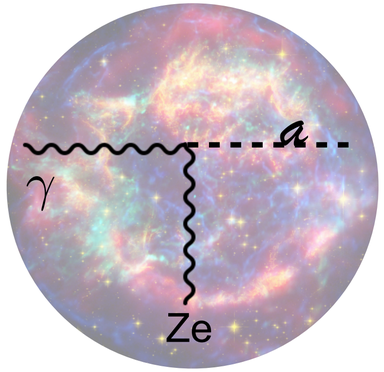
Photons in source B field



Dark matter

Source: Core-collapse supernovae

Source



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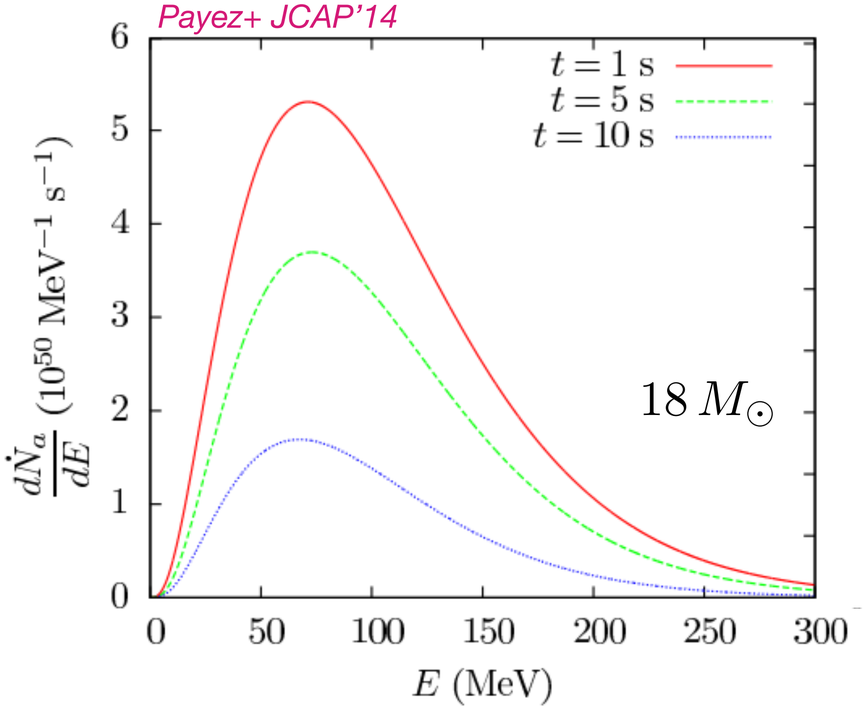
Payez+ JCAP'14



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*]

Source: High-energy gamma-ray emitters

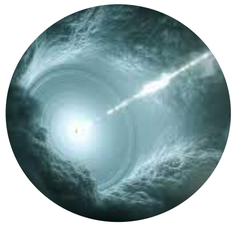
Source

Photons in *source* B field

C. Eckner talk

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

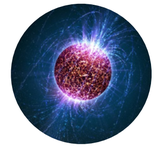
$$\left(\frac{dN_\gamma}{dE}\right)_{\mathrm{P}}$$

In-situ conversion into ALPs

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

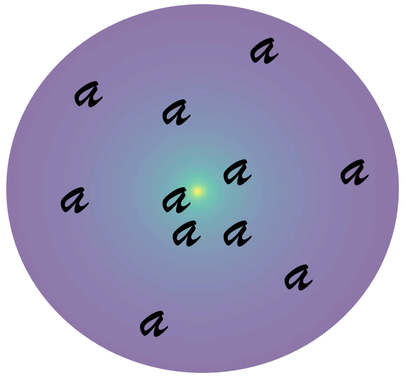
$$\left(\frac{dN_a}{dE}\right)_{\mathrm{S}} \propto P_{\mathrm{S}}(\gamma \to a) \times \left(\frac{dN_\gamma}{dE}\right)_{\mathrm{P}}$$

[Also photons from **Galactic objects** like pulsars and SNRs with conversion in Galactic magnetic field]



Source: Dark matter

Source

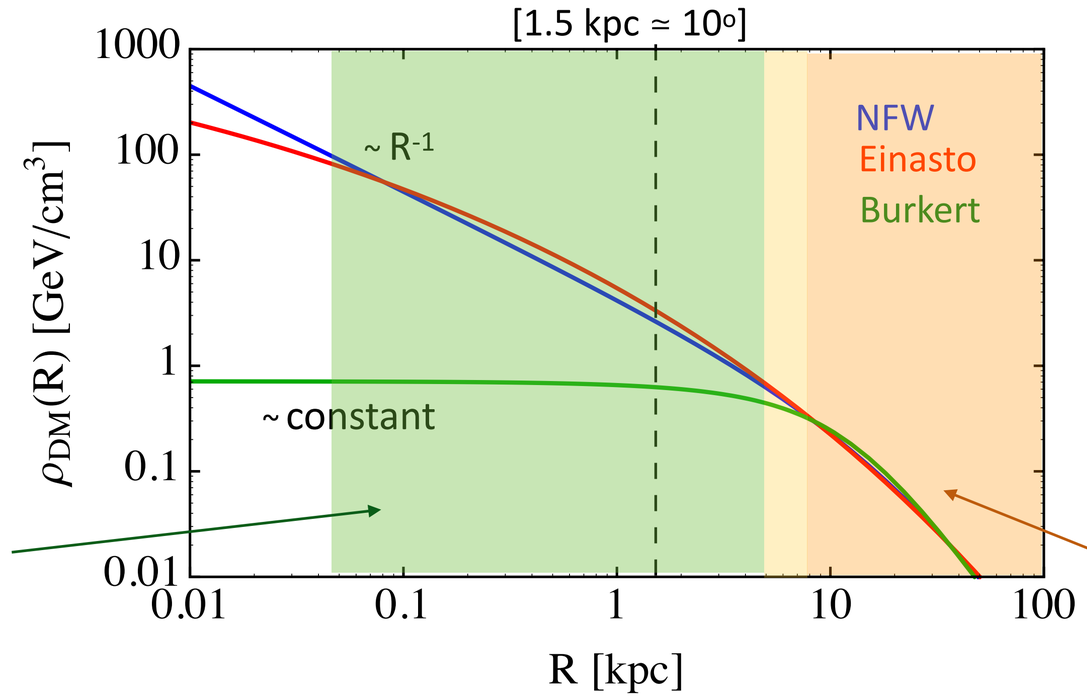


Dark matter

- 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)



Simulations w/ baryons & semi-analytical models

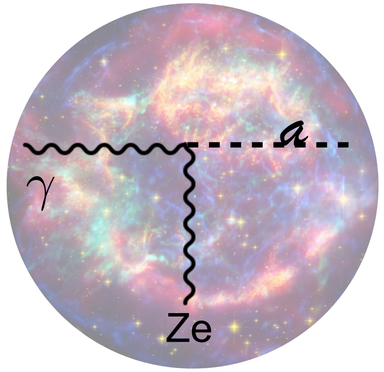
Galactic rotation curve

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

ALPs travelling in the Galaxy

Source

Galaxy



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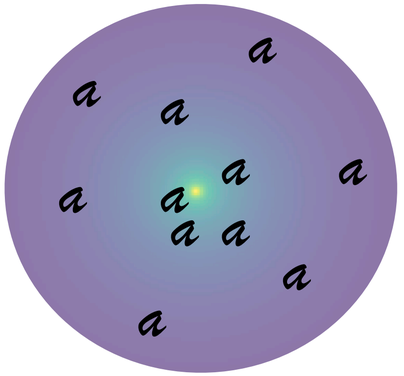
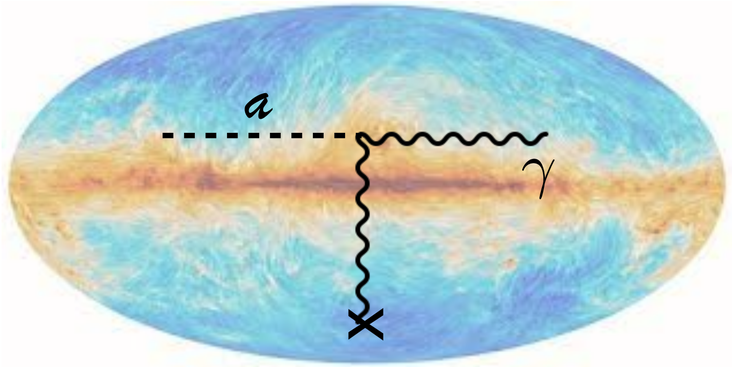
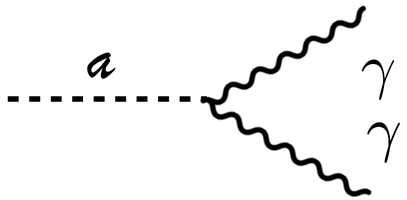
Photons in source B field



Dark matter



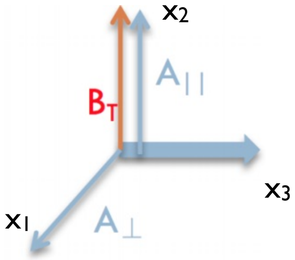
Conversion in Galactic B field



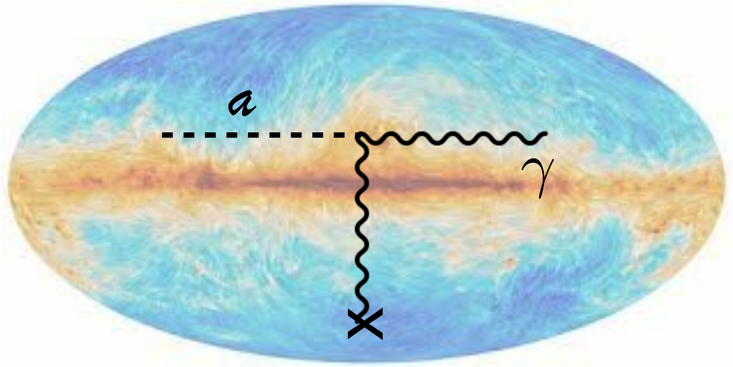
Spontaneous decay

[Conversion in intergalactic magnetic fields is not efficient]

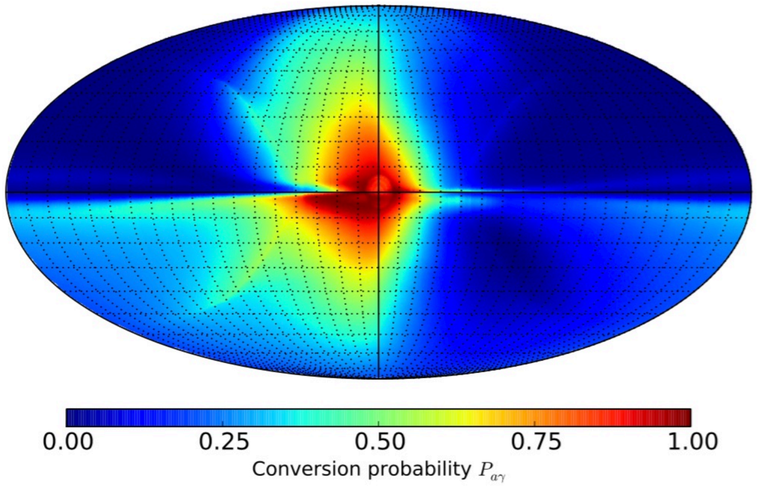
Galaxy: Conversion



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**

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

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

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

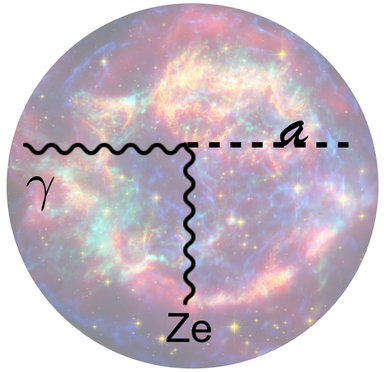
$g_{a\gamma} = 5 \times 10^{-11}\ \mathrm{GeV}^{-1}$
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

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

Good knowledge of B-field is required!

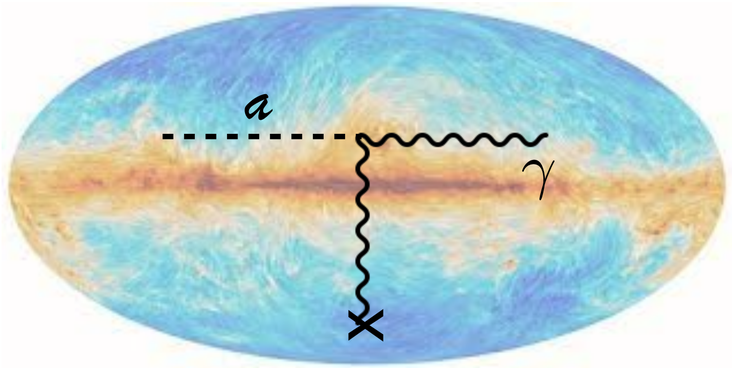
Galaxy: Conversion of cc-SNe ALPs

Source



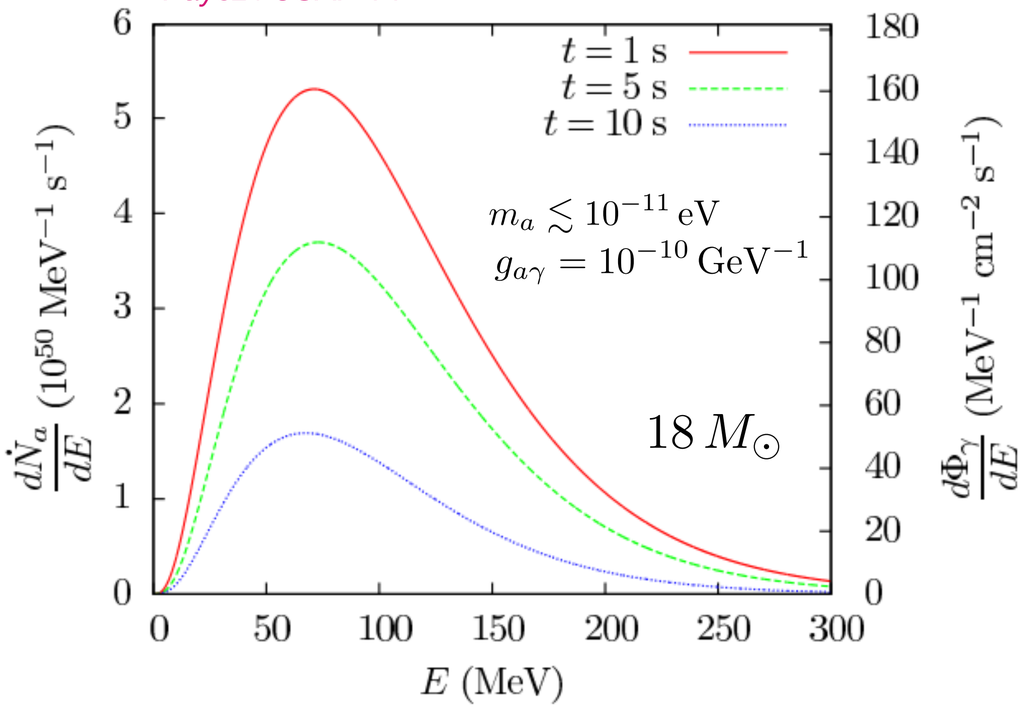
cc-SNe Primakoff

Galaxy



Conversion in Galactic B field

Payez+ JCAP'14



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

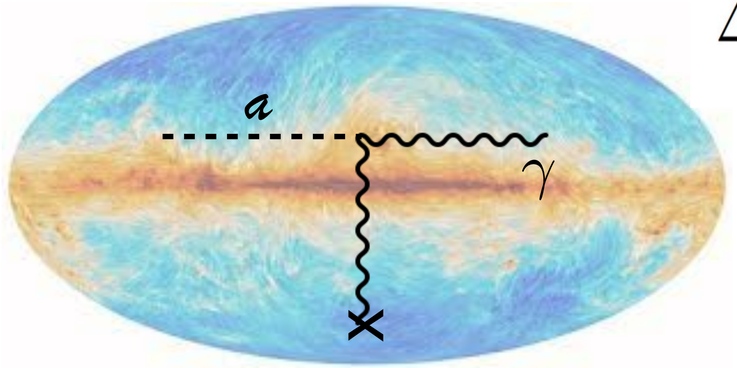
For massless ALPs, one-to-one correspondence between ALPs and photon energy

Galaxy: Conversion of/to photons

Source

Photons in *source* B field

Galaxy



Conversion in Galactic B field

ALPs or photons from high-energy astrophysical sources will undergo conversion in the Galactic magnetic field

$$P_{a\to\gamma}(E) = \left(\frac{g_{a\gamma}B_T}{2}\right)^2 d^2 \times \frac{\sin^2(\Delta_{\rm osc}d/2)}{\Delta_{\rm osc}d/2}$$

$$\Delta_{\rm osc} = 2\Delta_{a\gamma}\sqrt{1+\left(\frac{E_{\rm c}}{E}\right)^2}$$

$E \gg E_c$ → $\Delta_{\rm osc} \simeq 2\Delta_{a\gamma}$ **Strong mixing regime**

$E \simeq E_c$ → **Oscillation regime**

e.g. Mirizzi & Montanino JCAP'09

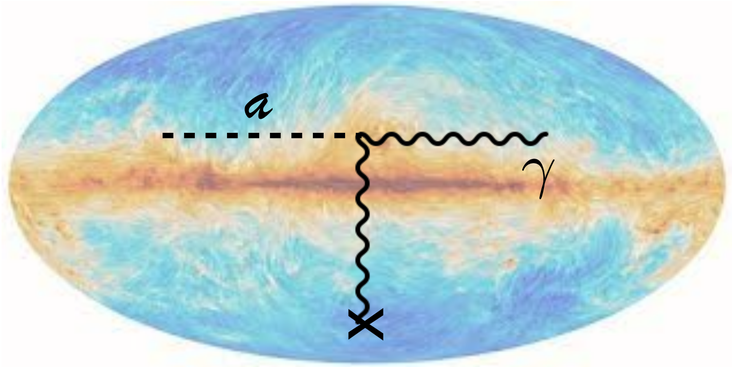
$$E_c \simeq 2.5\ \text{GeV}\,\frac{|m_a^2-\omega_{Pl}^2|}{1\,\text{neV}}\left(\frac{B_\perp}{\mu\text{G}}\right)^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \text{GeV}^{-1}}\right)^{-1}$$

Galaxy: Conversion of/to photons

Source

Photons in *source* B field

Galaxy



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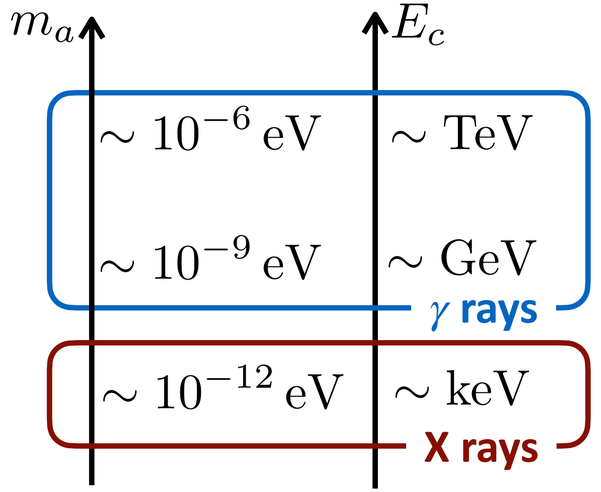
$n_e \sim 0.01\,{\rm cm}^{-3}$

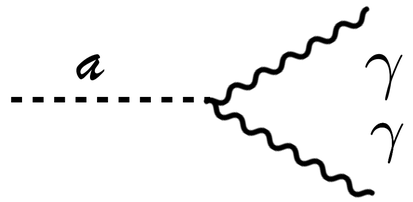
$B_0 \sim 1-10\,\mu{\rm G}$

Wouters & Brun ApJ'13;
Conlon+ JCAP'17



Galaxy: Dark matter decay

Galaxy



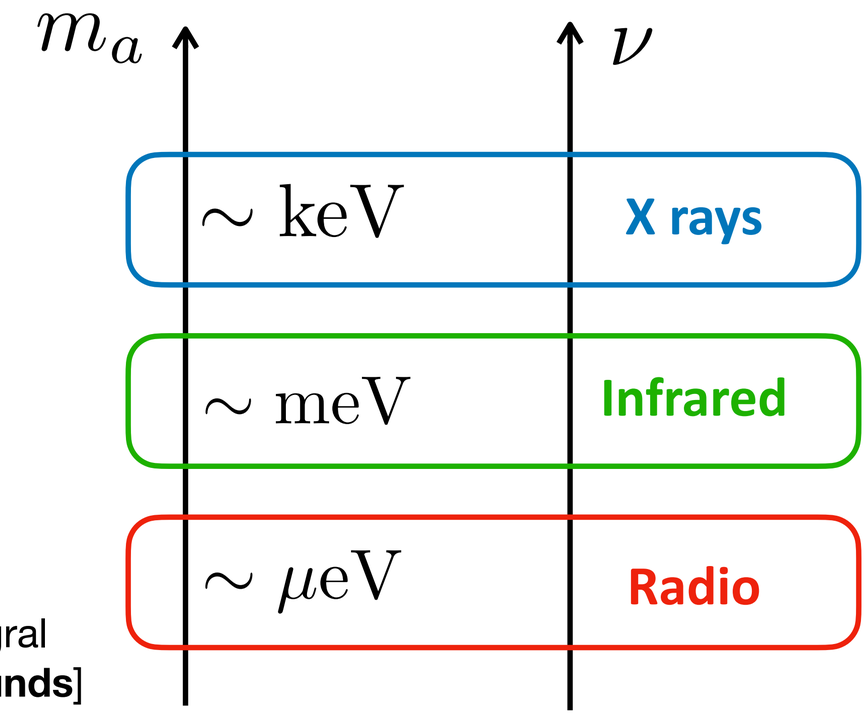
$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\rm decay} = \frac{\Gamma(a\to\gamma\gamma)}{4\pi m_a}\left(\frac{dN_\gamma}{dE}\right)_{\rm decay} \times \int_{\rm l.o.s.} \rho_a(\ell) d\ell$$

Spontaneous decay

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

Narrow line signal

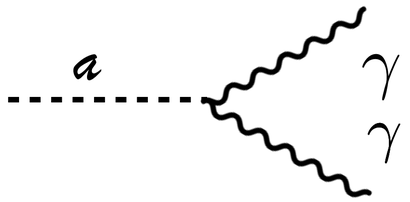
@ energy scale of the DM mass



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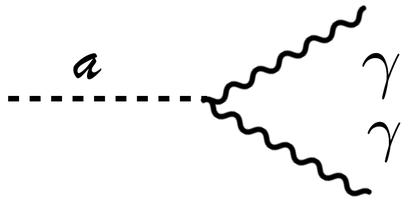
$$\tau_a = \frac{64\pi}{m_a^3 g^2}$$

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

Galaxy: Dark matter decay

Galaxy



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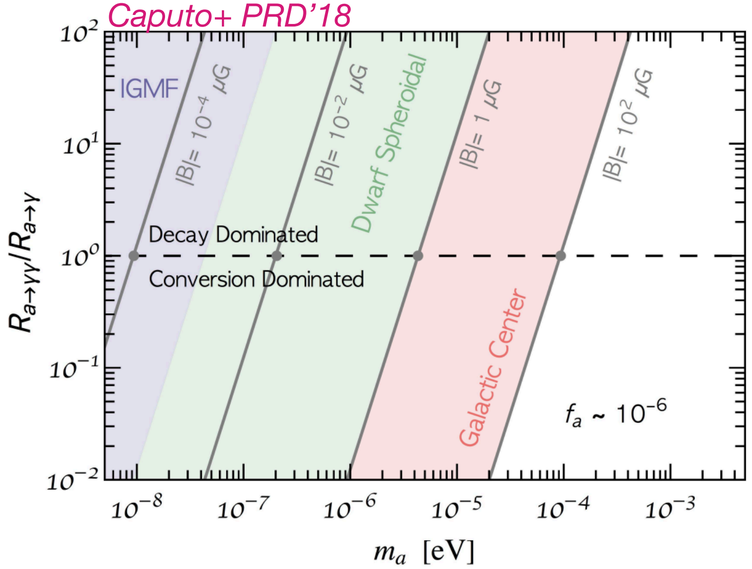
Stimulated decay can occur in the presence of non-relativistic ambient radiation (e.g. CMB)

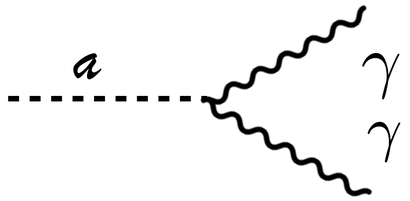
Caputo+ PRD'18; JCAP'19; Battye+ PRD'20



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

Galaxy: Dark matter decay

Galaxy



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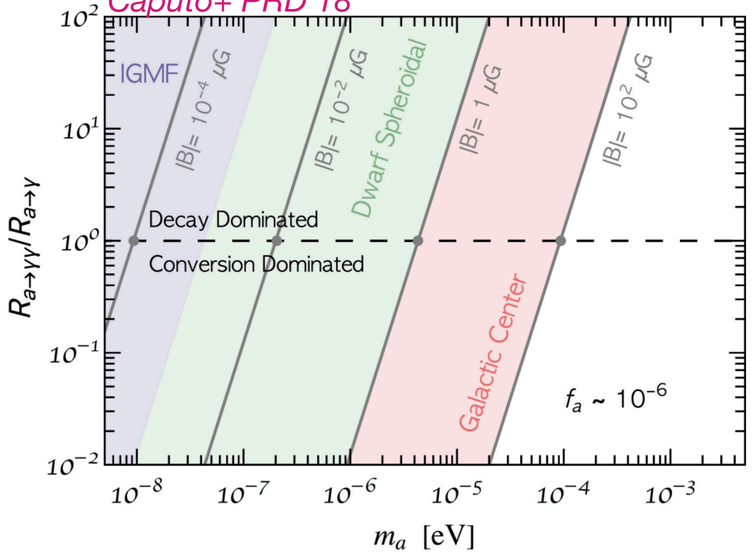

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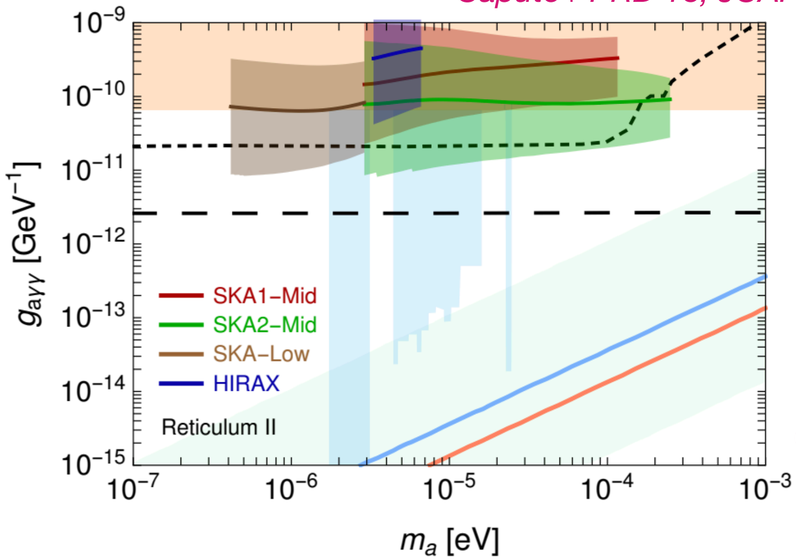
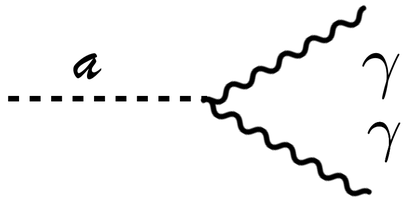


Caputo+JCAP'19

Galaxy: Dark matter resonant conversion

Galaxy



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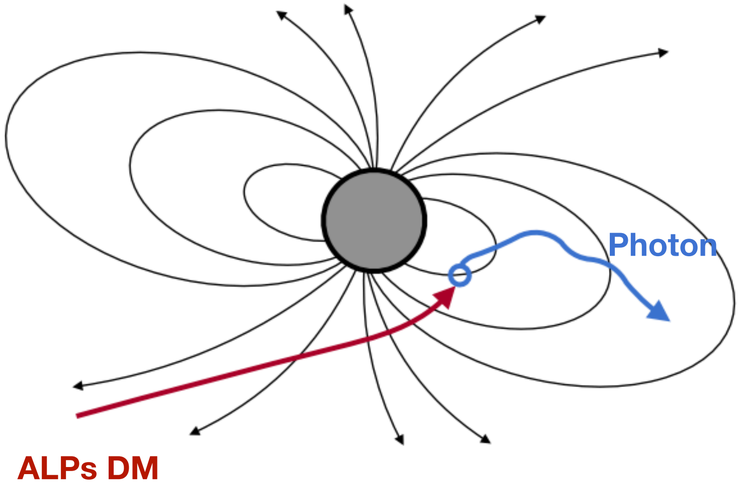
- Monochromatic radio emission (MHz - GHz) from **DM axion/ALP-photon conversion**:
  - *Resonant* conversion from highly magnetised neutron stars (NSs), or white dwarf stars

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

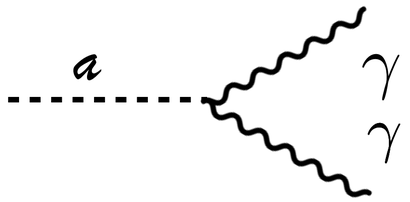
    Kelley&Quinn ApJ'17; Sigl PRD'17
  - Still large **limitations** in **model predictions**

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



Galaxy: Dark matter resonant conversion

Galaxy



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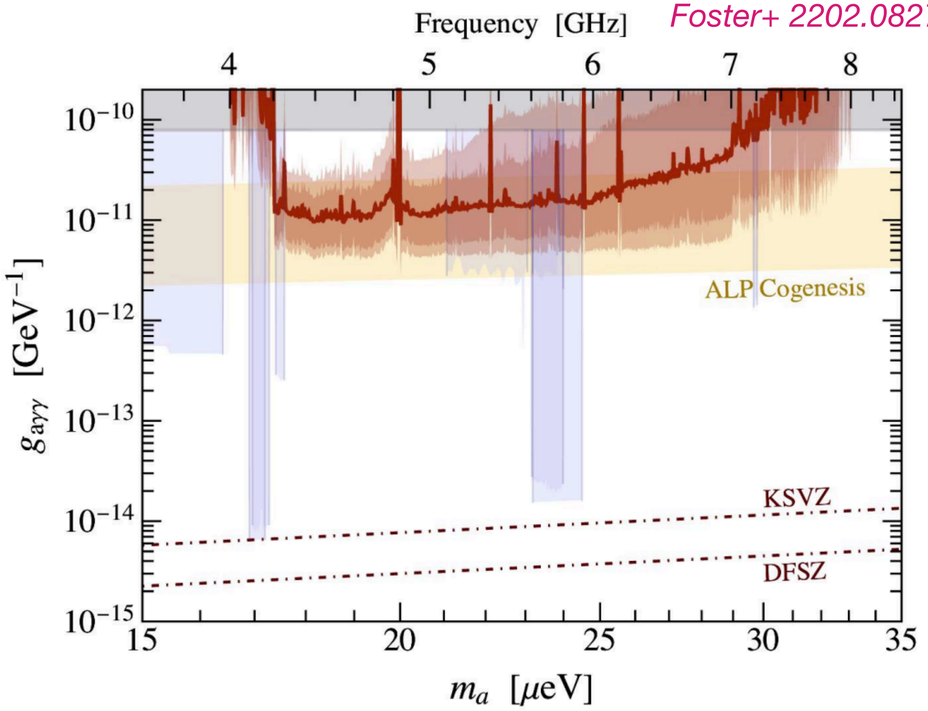
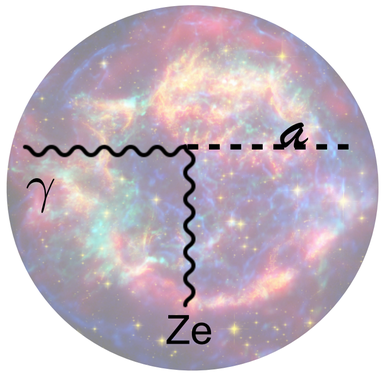
Foster+ 2202.08274



What photon energies?



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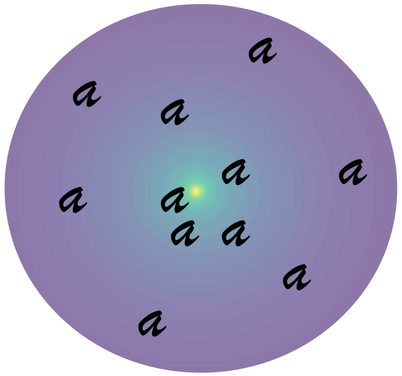
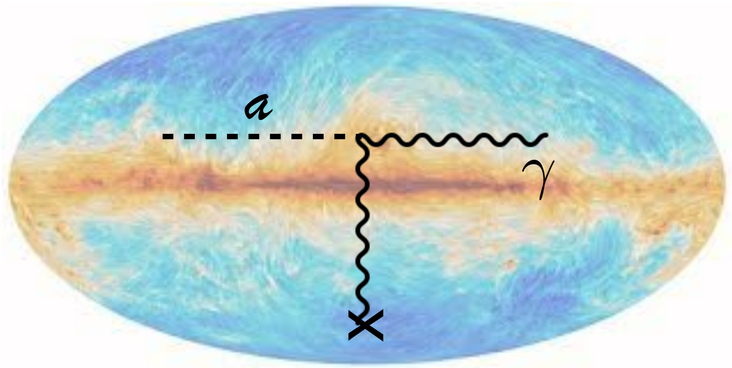
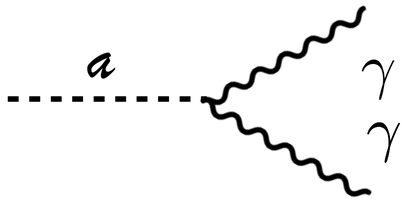
Photons in source B field



Dark matter





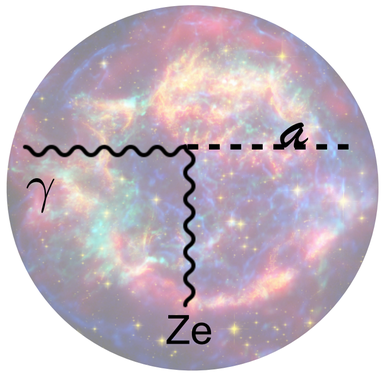
Source

Galaxy

Observer

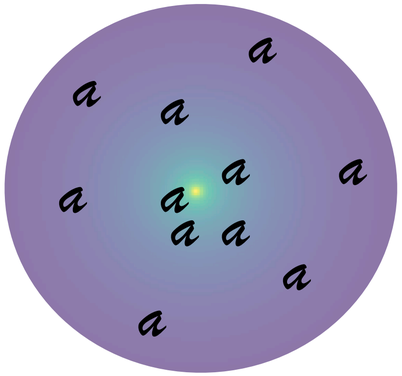
eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

What photon energies?

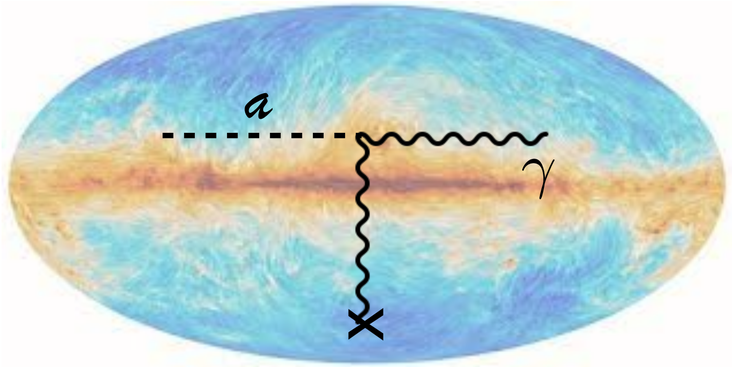


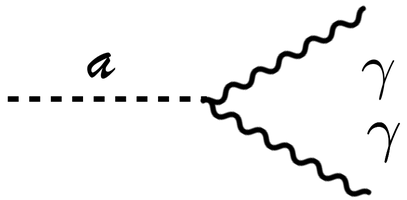
cc-SNe Primakoff

Photons in source B field



Dark matter





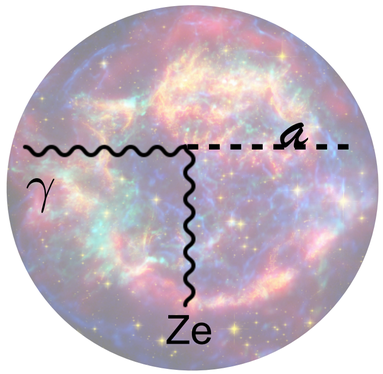
Source

Galaxy

Observer

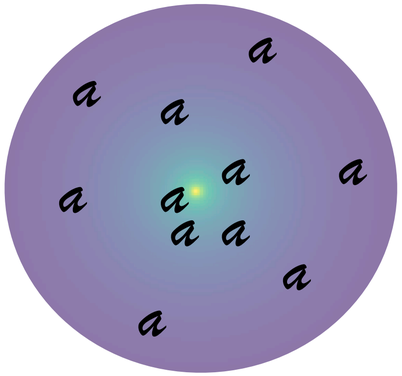
eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

What photon energies?



cc-SNe Primakoff

Photons in source B field



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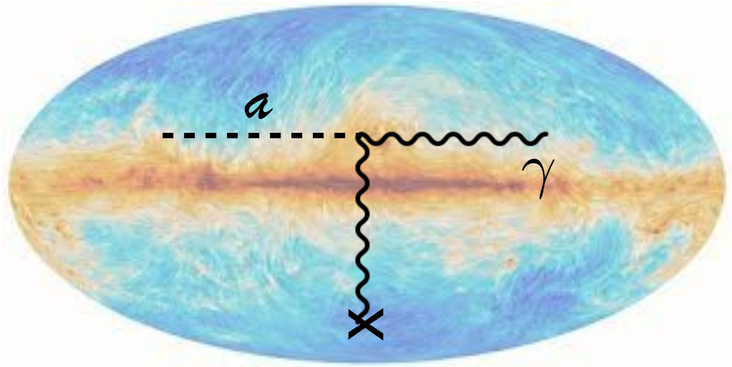

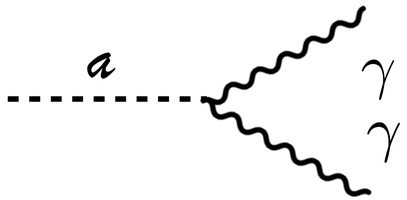

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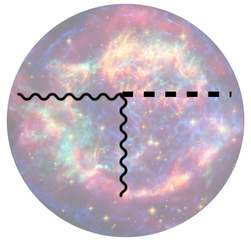
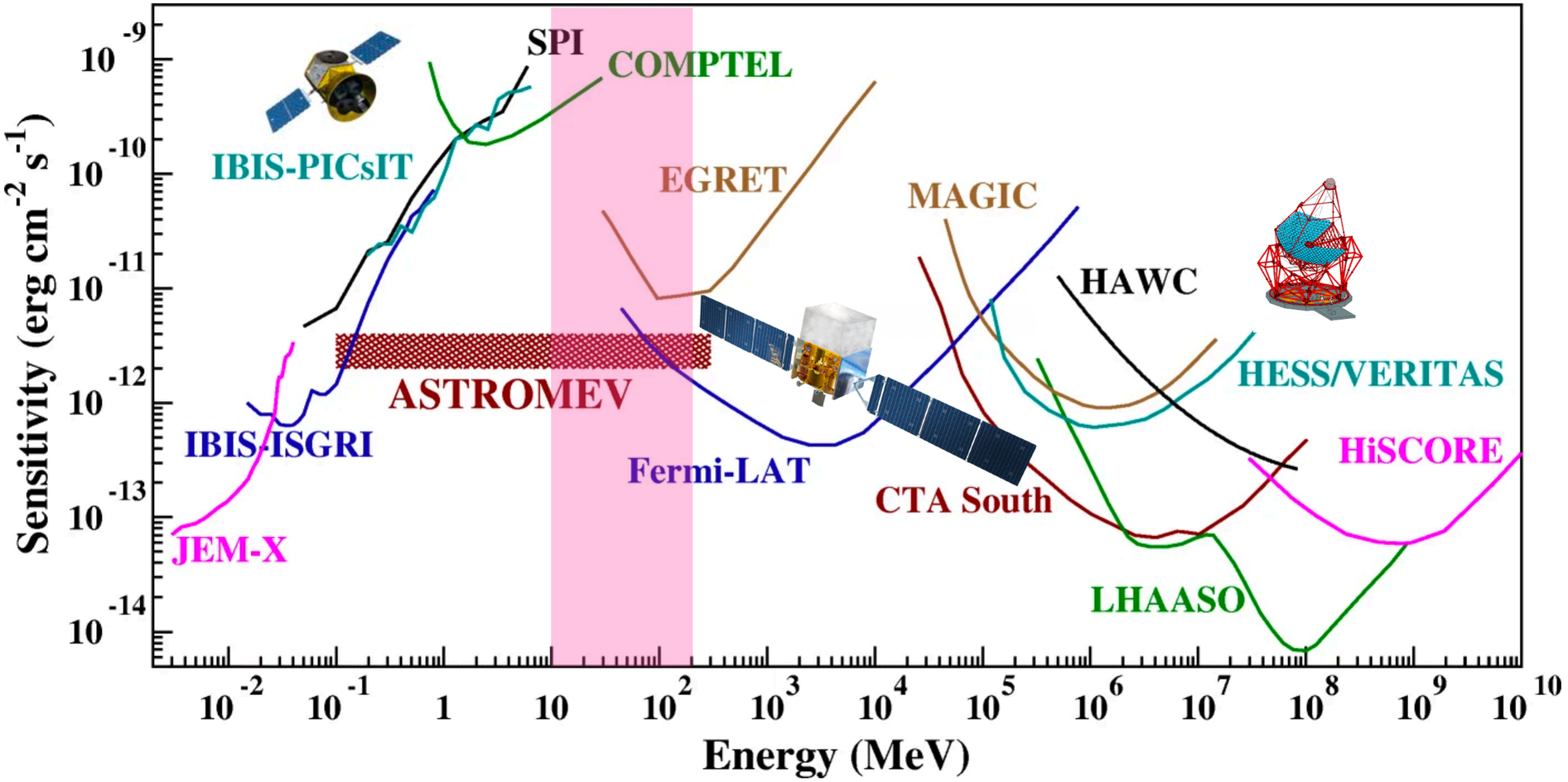
Gamma-ray data landscape



DeAngelis+ Voyage 2050 '21



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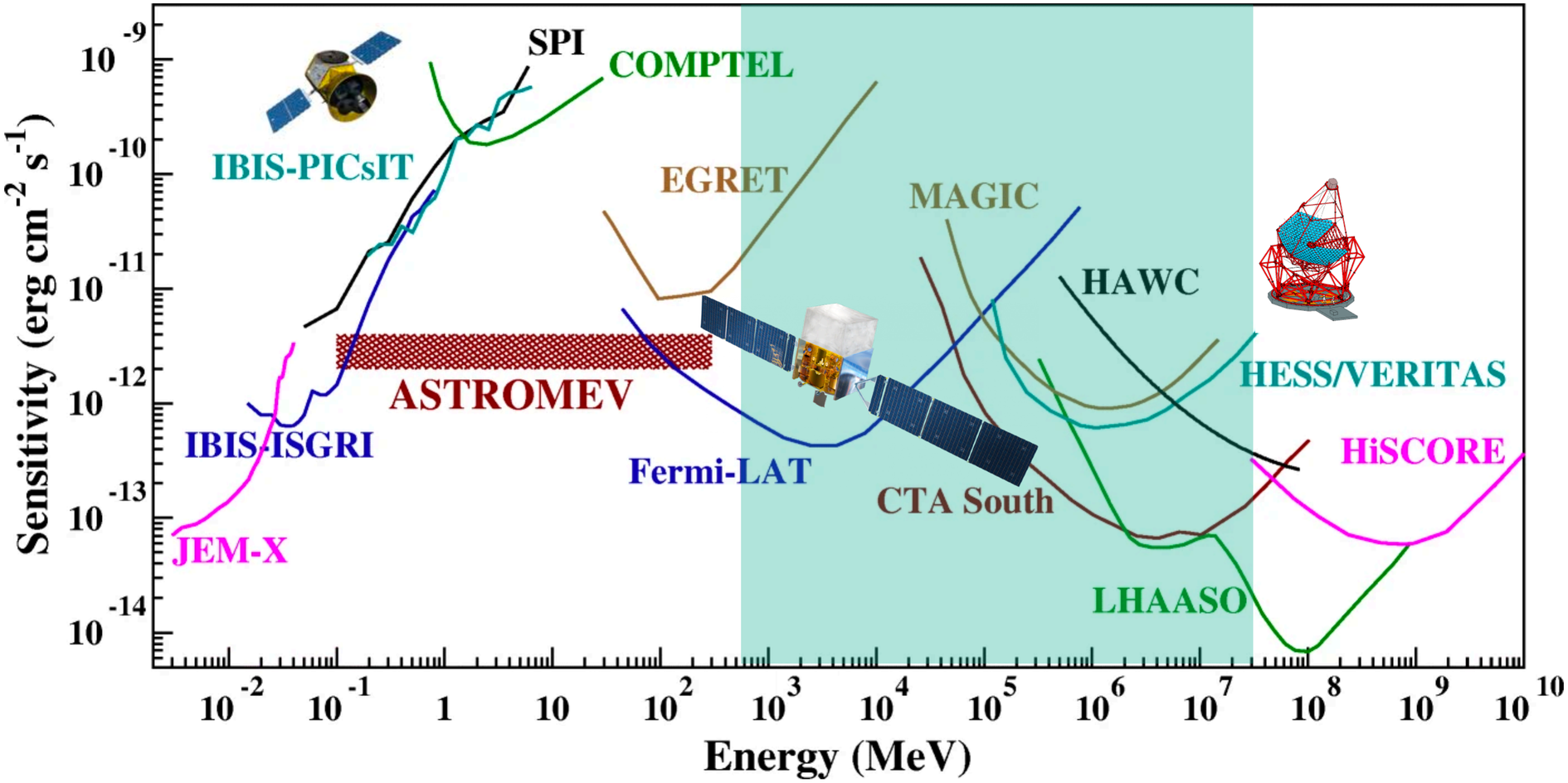
Gamma-ray data landscape

DeAngelis+ Voyage 2050 '21



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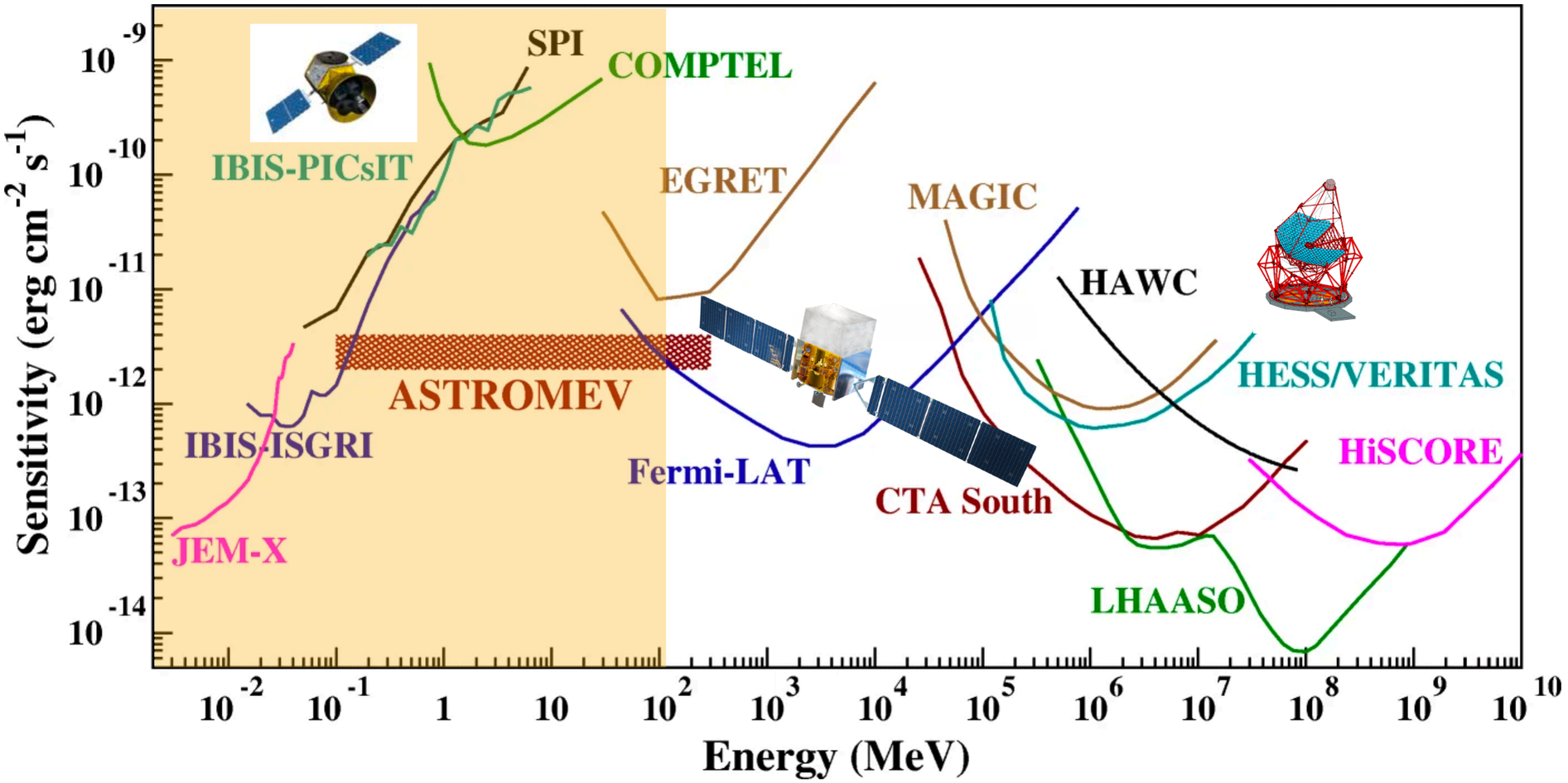
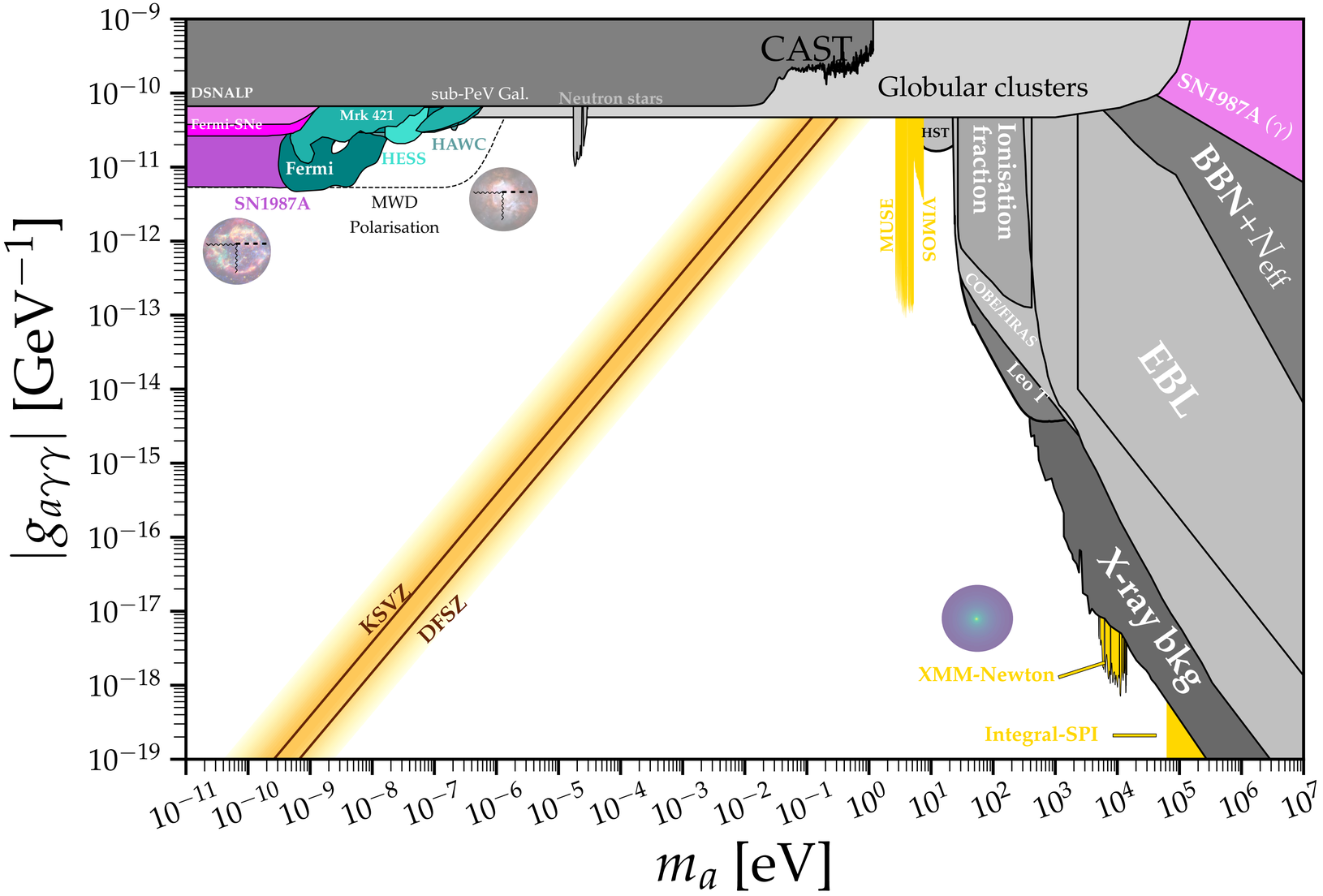


eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

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**

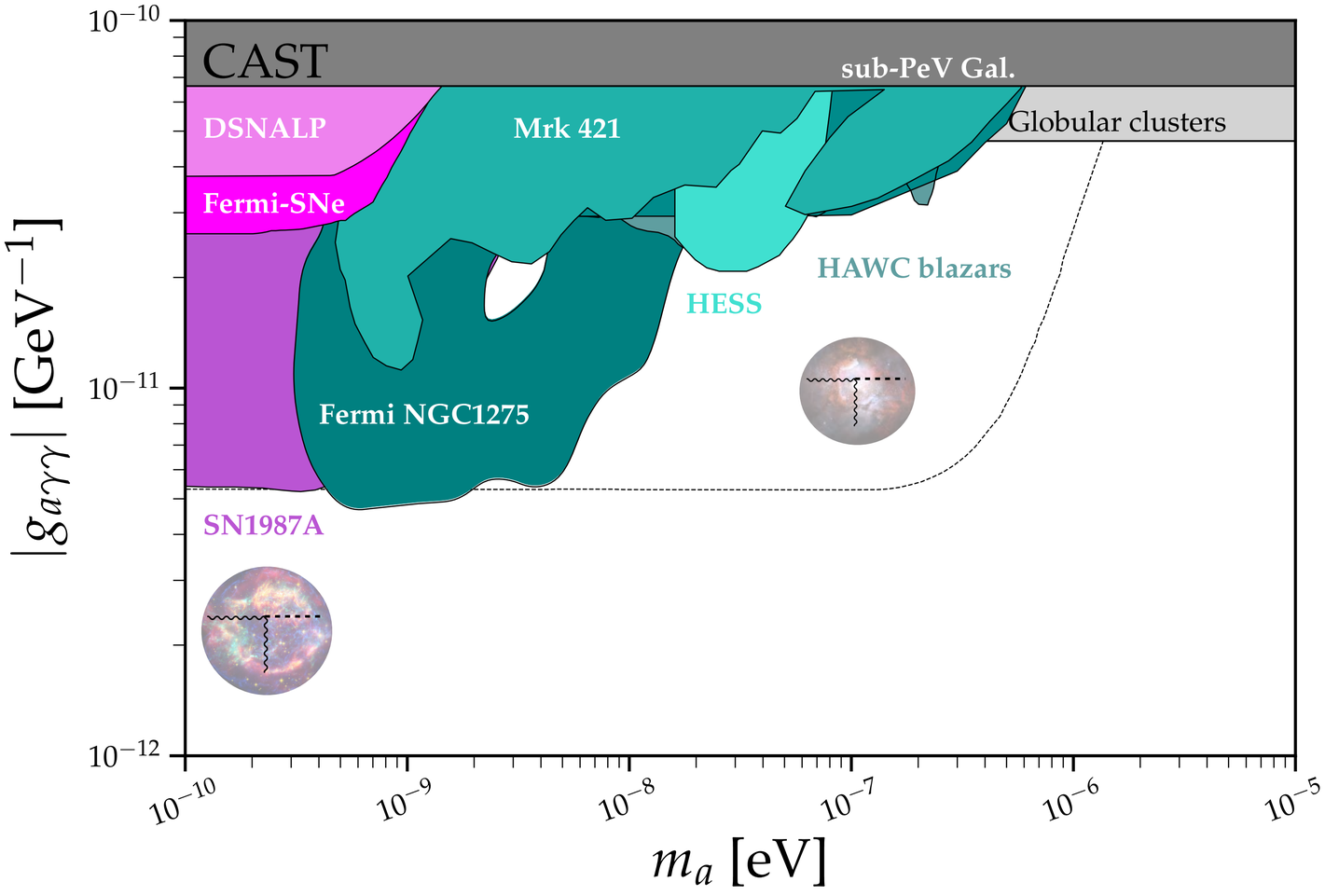
Payez+ JCAP'14; Meyer & Petrushevska PRL'20; Crnogorcevic+ PRD'21 FC+ PRD'20, Eckner, FC+PRD'22

- 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)
- Search for **photons appearance** from photon-ALPs *in source* conversion (HAWC blazars, sub-PeV Gal.)

Jacobsen+2203.04332; Eckner&FC PRD'22



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Constraints on ALP-photon mixing

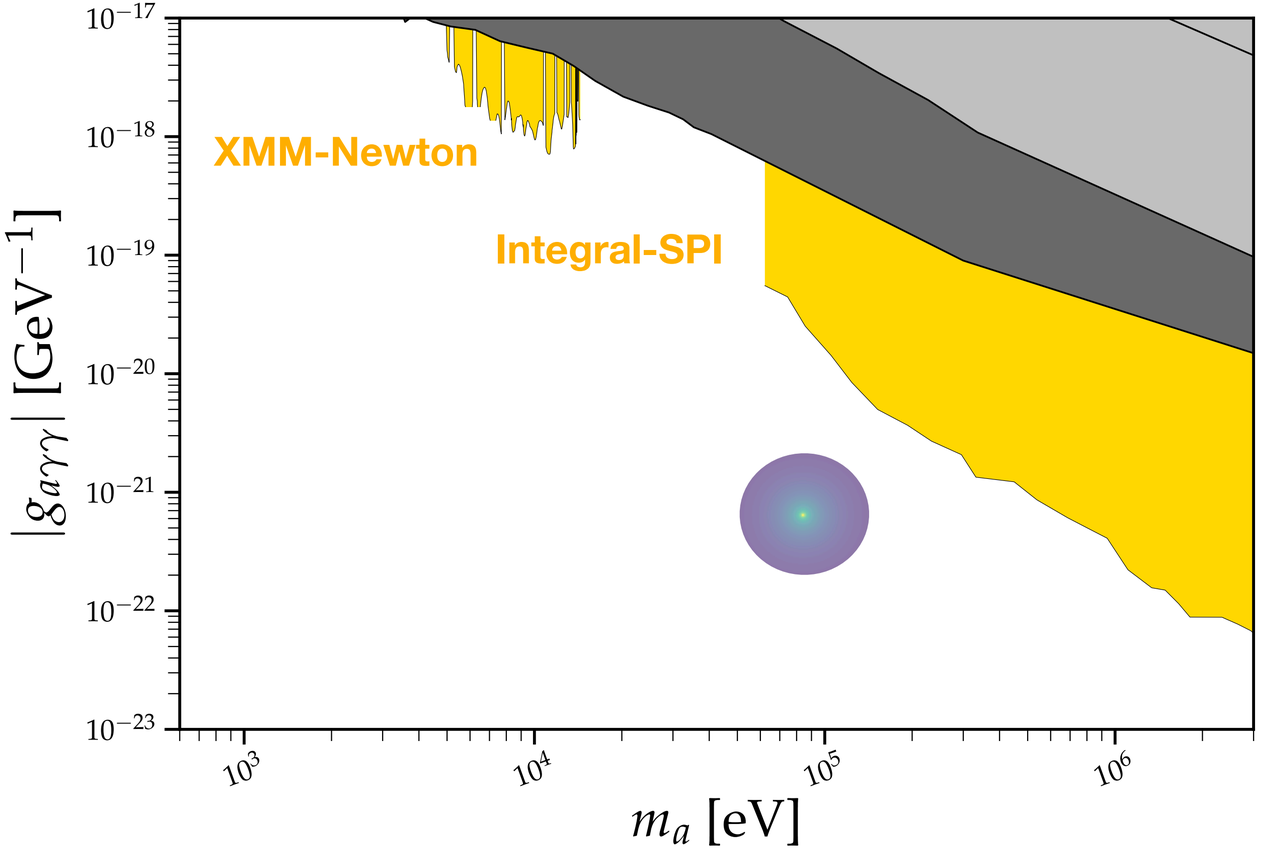
Heavy ALPs DM decay

- 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

- **Integral-SPI**: new analysis of 16yr data with dedicated search for DM component in continuum Galactic emission

Berteaud, FC+PRD'22; FC+'22 arXiv:2209.06299



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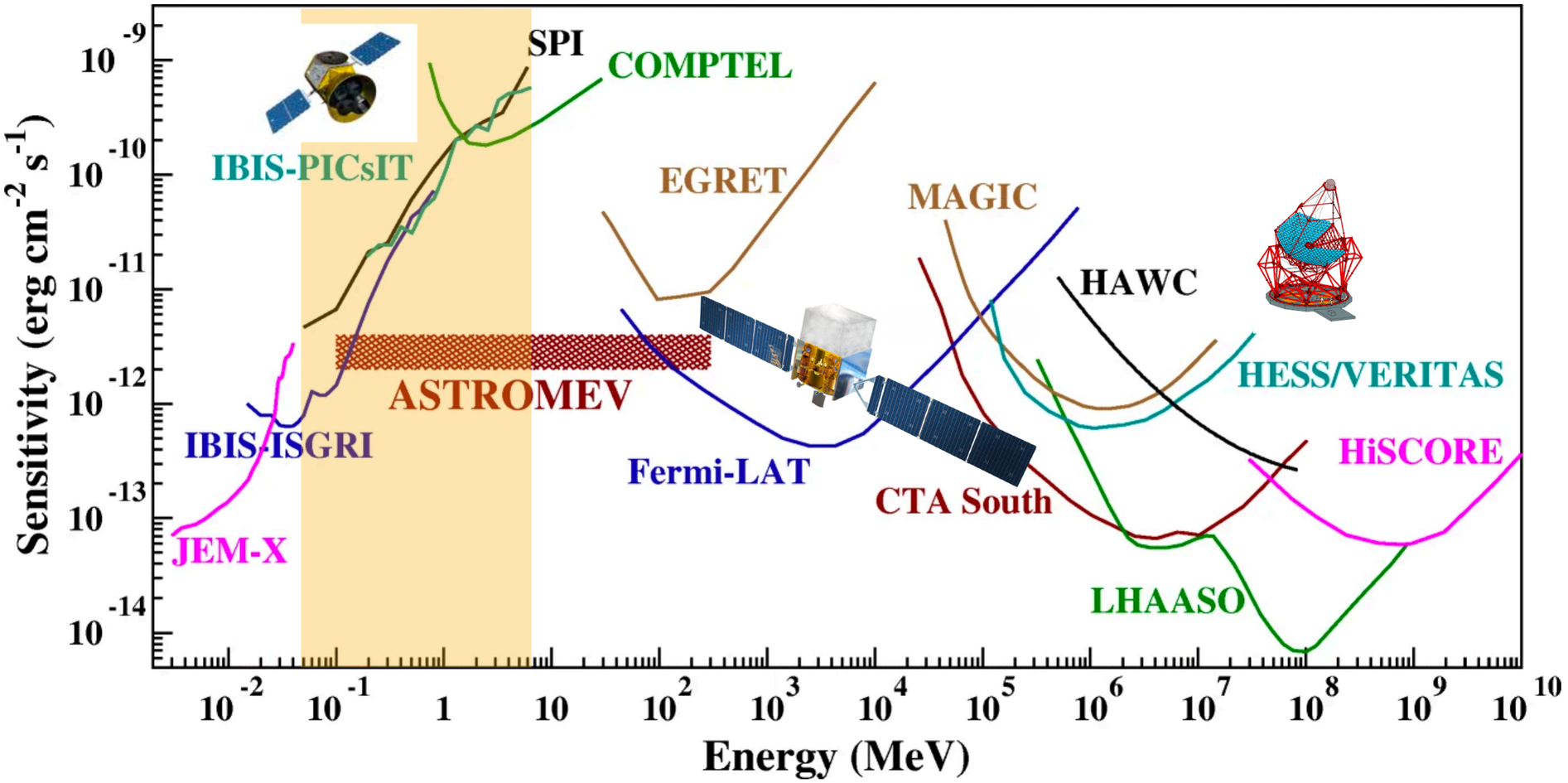
One recent highlight

Gamma-ray data landscape: hard X rays

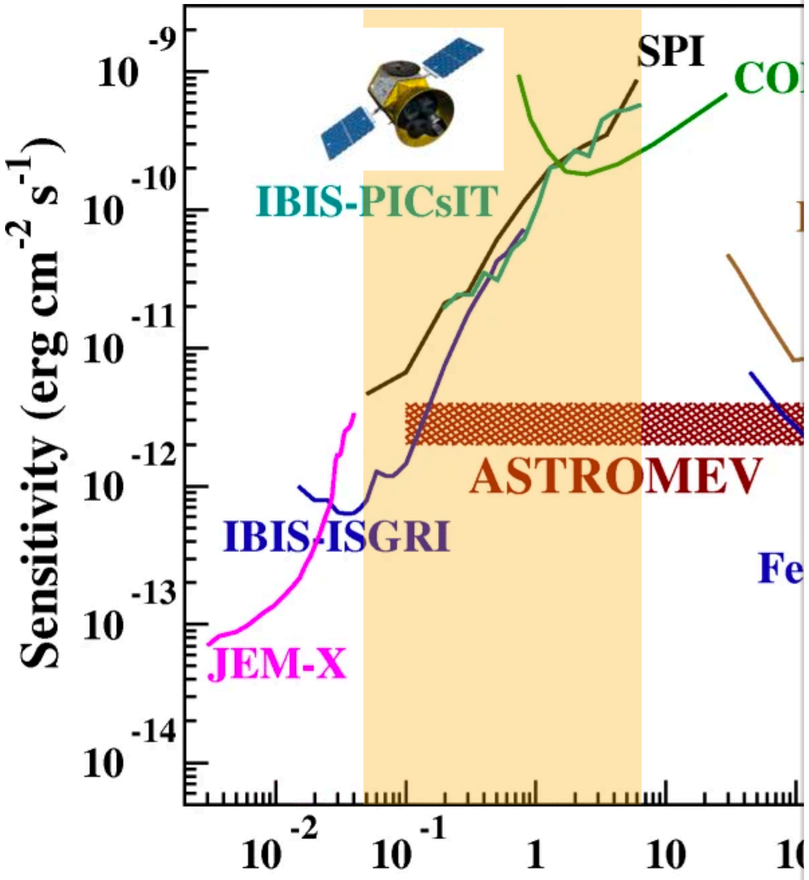
DeAngelis+ Voyage 2050 '21

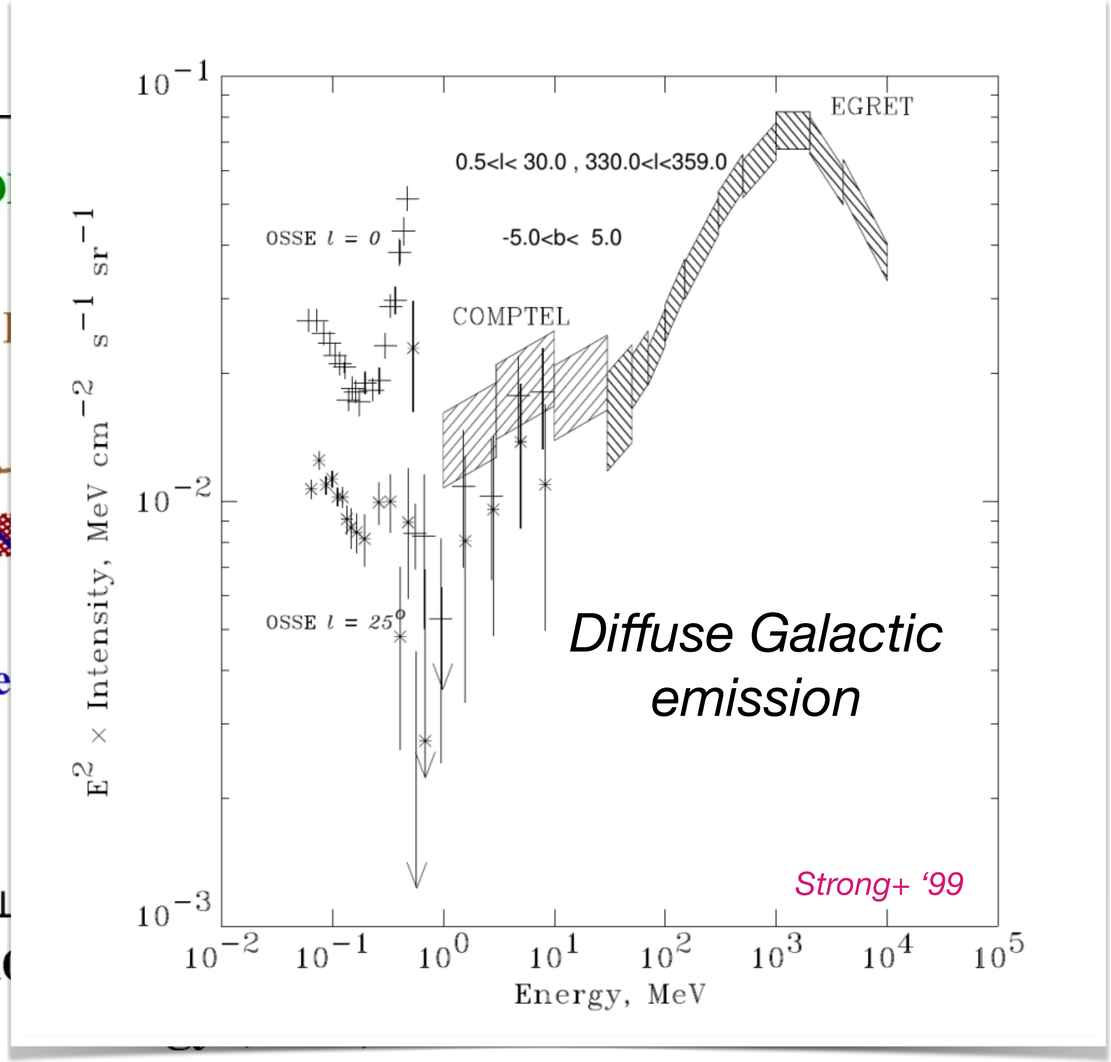


eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

Gamma-ray data landscape: hard X rays

DeAngelis+ Voyage 2050 ‘21

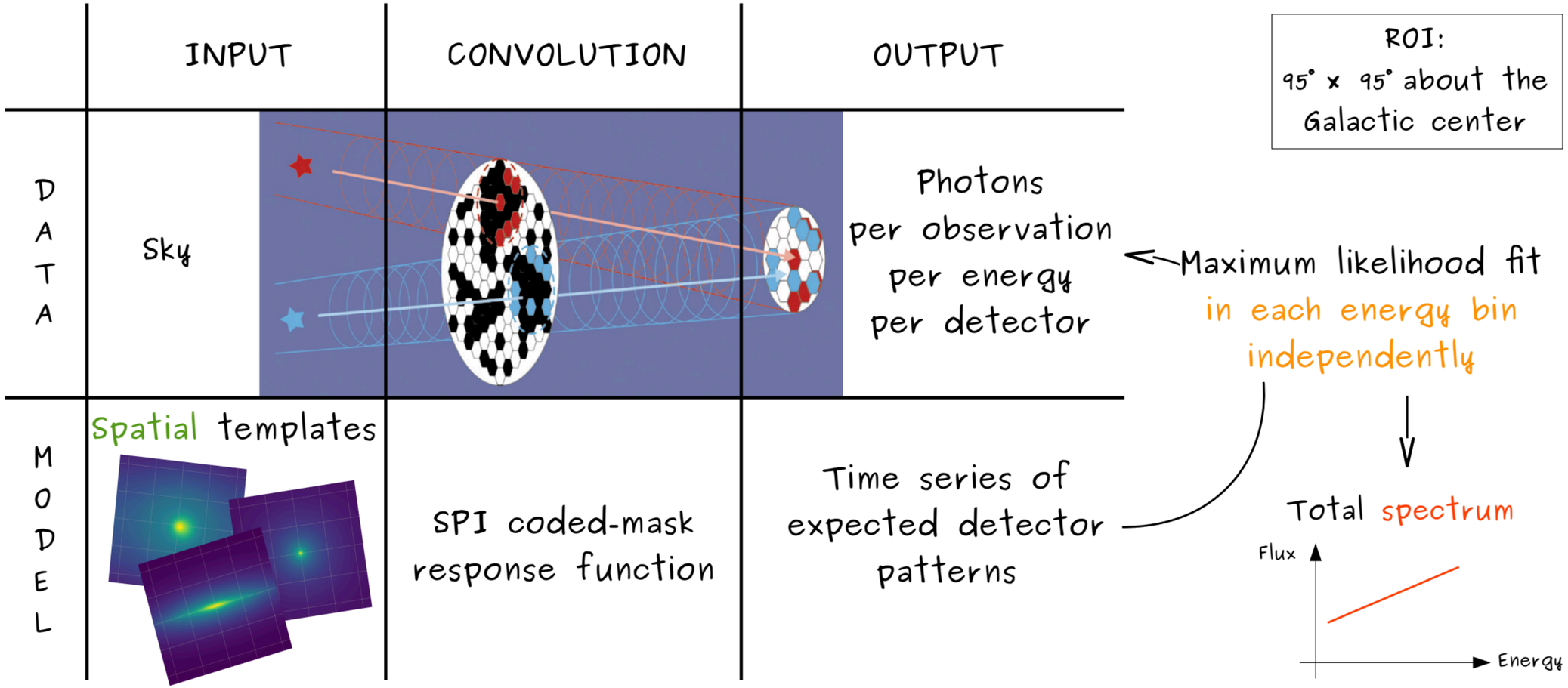




eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

An old instrument, a new analysis

Diffuse Galactic emission spectrum with SPI 16yr data



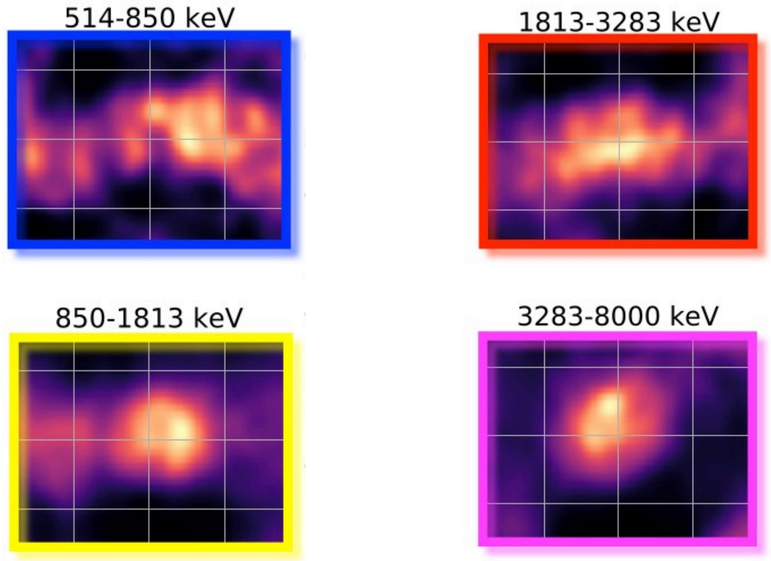
Credit: J. Berteaud, RICAPP'22

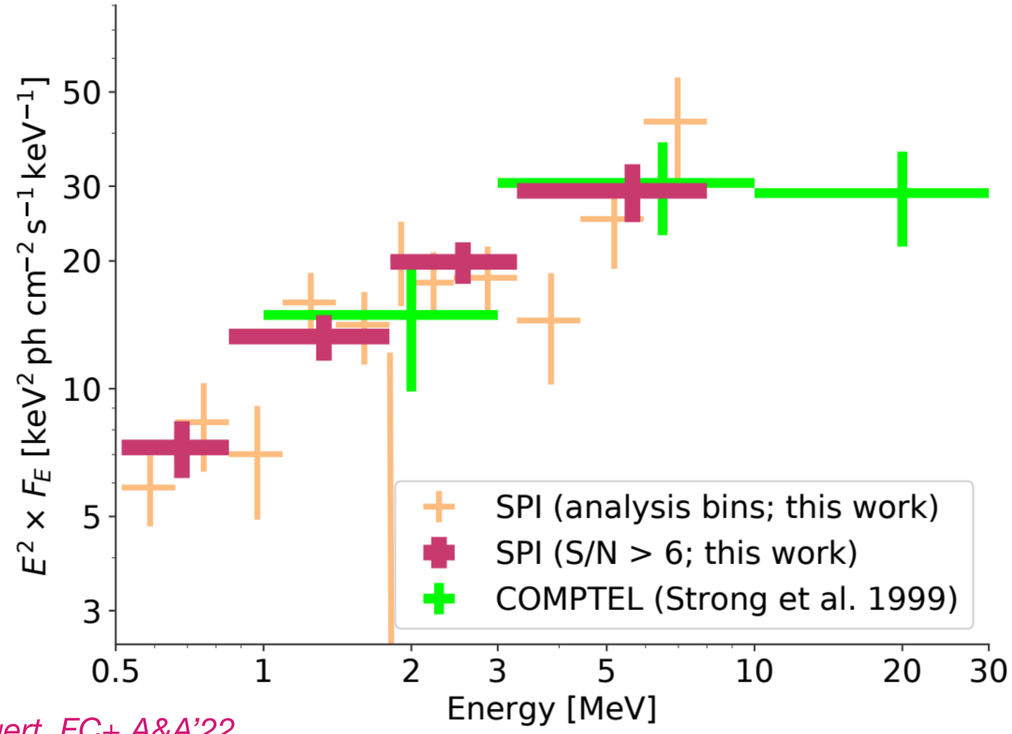
An old instrument, a new analysis

Diffuse Galactic emission spectrum with SPI 16yr data

Modeled **spatial templates**

- **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
- Nuclear lines
- Positronium annihilation line



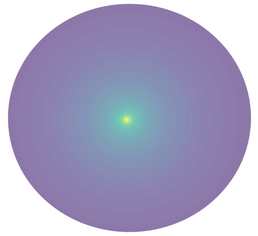


Siegert, FC+ A&A'22

Integral picture of the month, March 2022

MeV Galactic diffuse emission

Is there evidence for an additional dark matter component?



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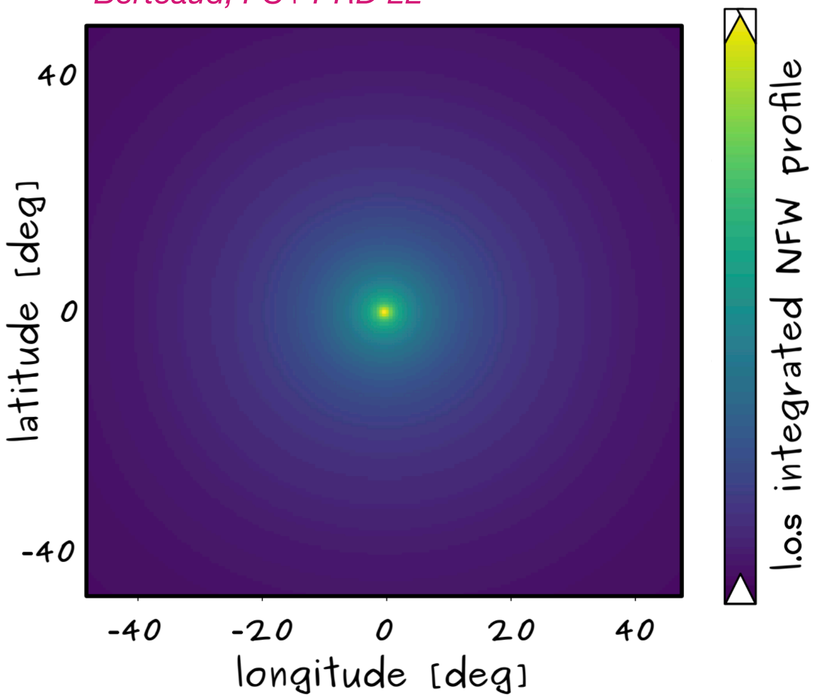
$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\mathrm{decay}} = \frac{\Gamma(a \to \gamma\gamma)}{4\pi m_a}\left(\frac{dN_\gamma}{dE}\right)_{\mathrm{decay}} \times \int_{\mathrm{l.o.s.}} \rho_a(\ell) d\ell$$

Berteaud, FC+ PRD'22



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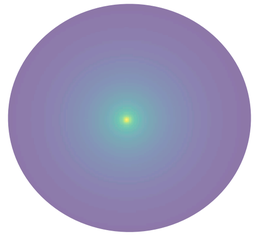

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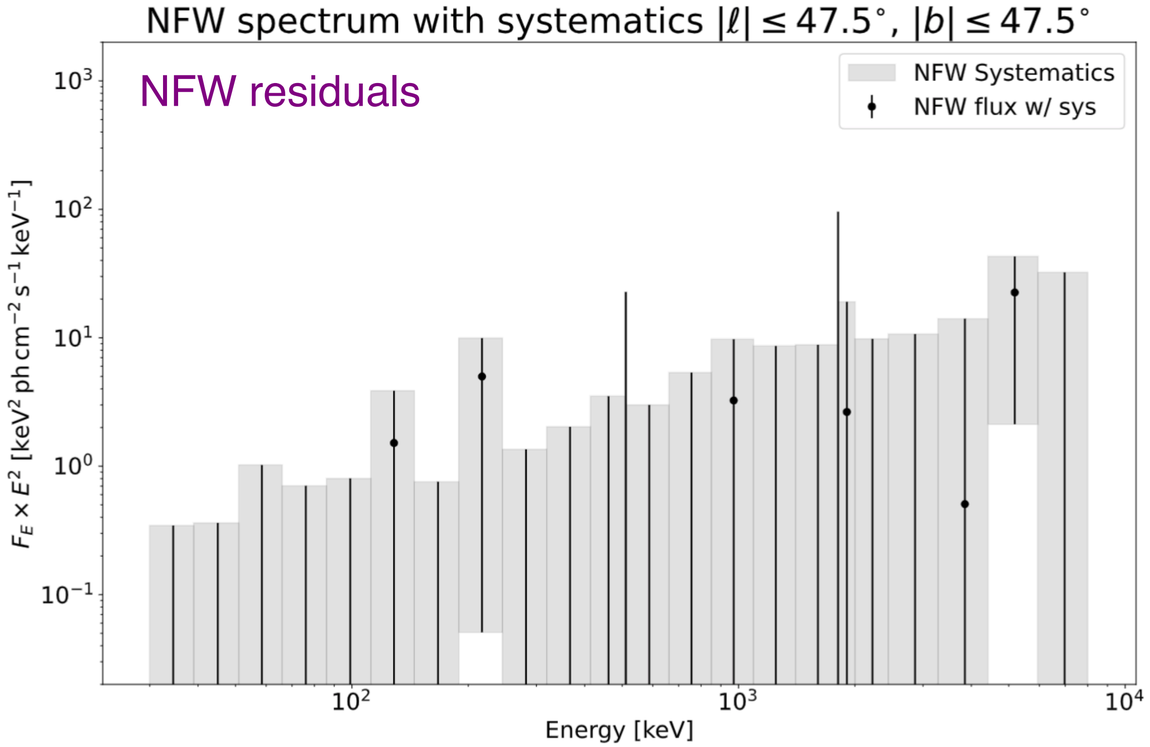
No signal detected

=> Upper limits on NFW decay flux



Limits on light decaying dark matter

Decaying dark matter and Galactic diffuse emission

Modeled **spectral components** — MCMC fit

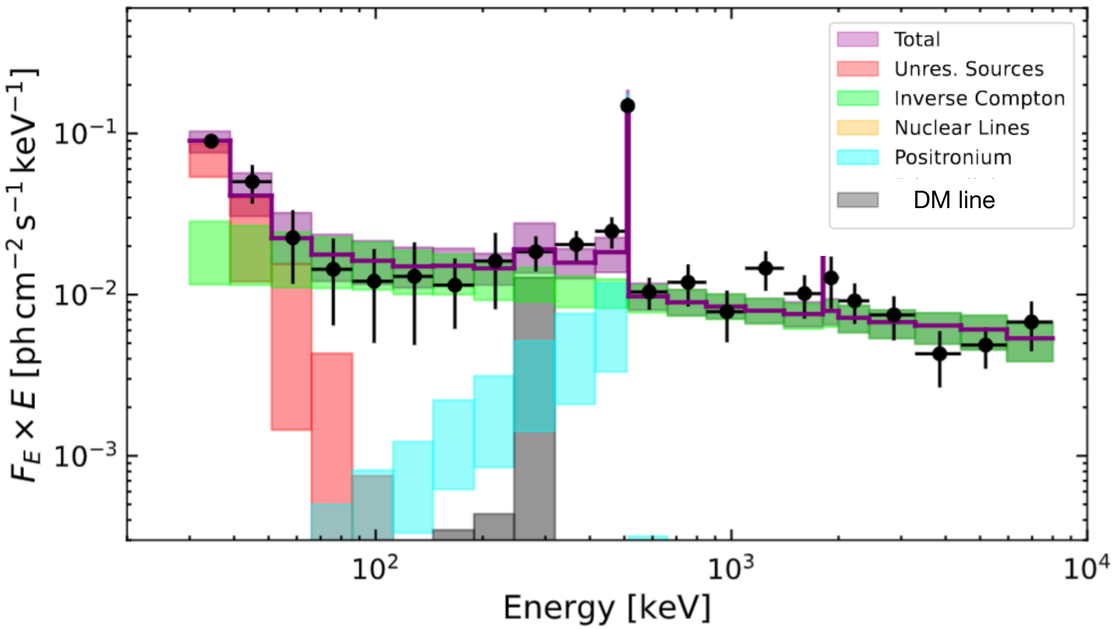
- Inverse Compton: power law
- Unresolved sources: cutoff power law
- Nuclear lines: narrow gaussians
- Positronium annihilation: line + continuum
- **Decaying dark matter**: line at half DM mass

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

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

=> Upper limits on **decay rate** into 2 photons

$$\mathrm{DM} \to \gamma + \gamma$$



Dekker, FC+'22 arXiv:2209.06299

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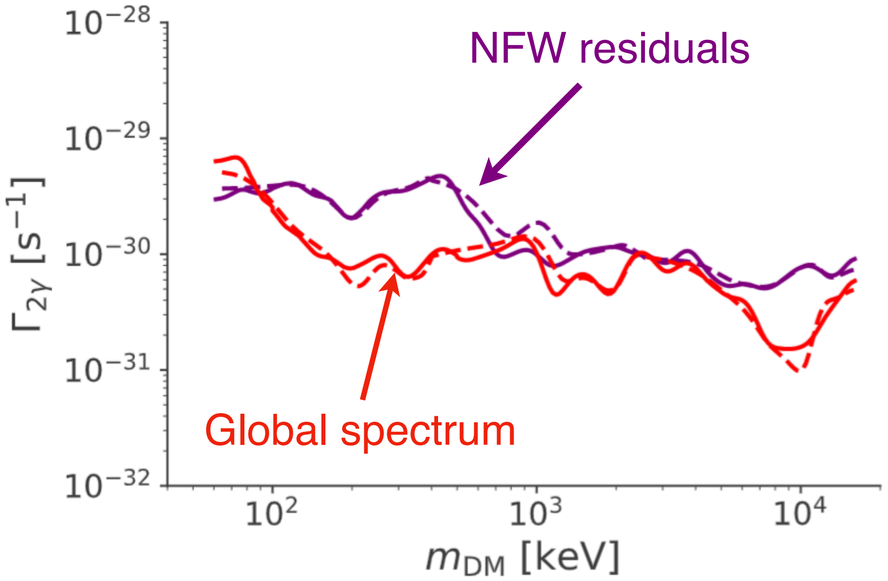


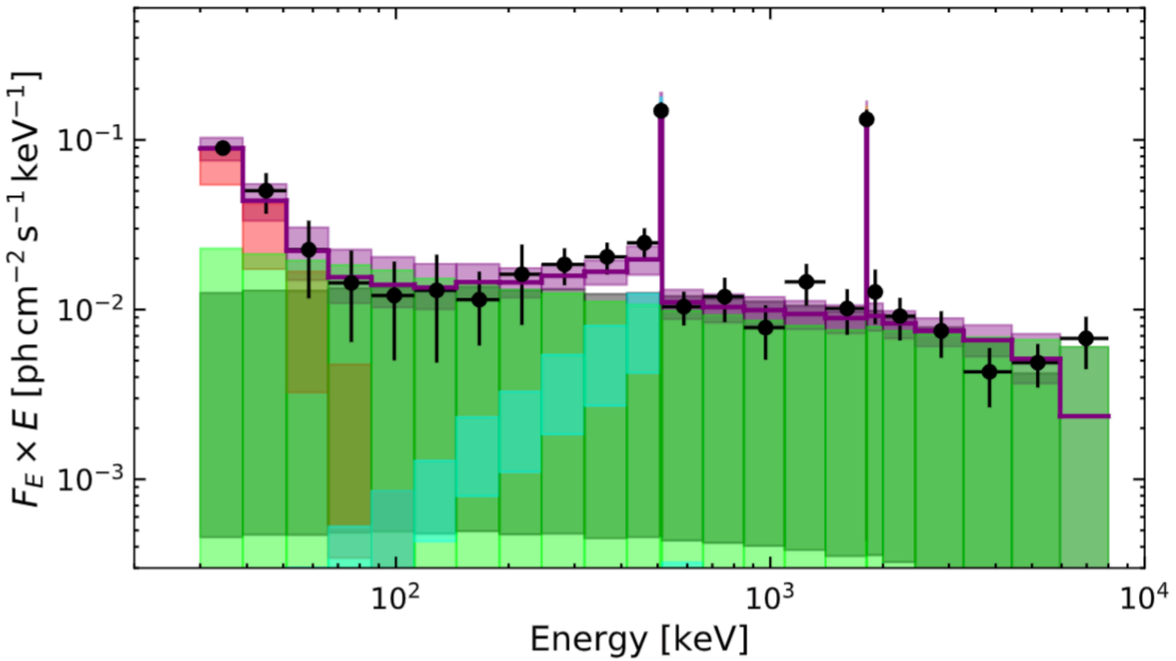
Dekker, FC+'22 arXiv:2209.06299

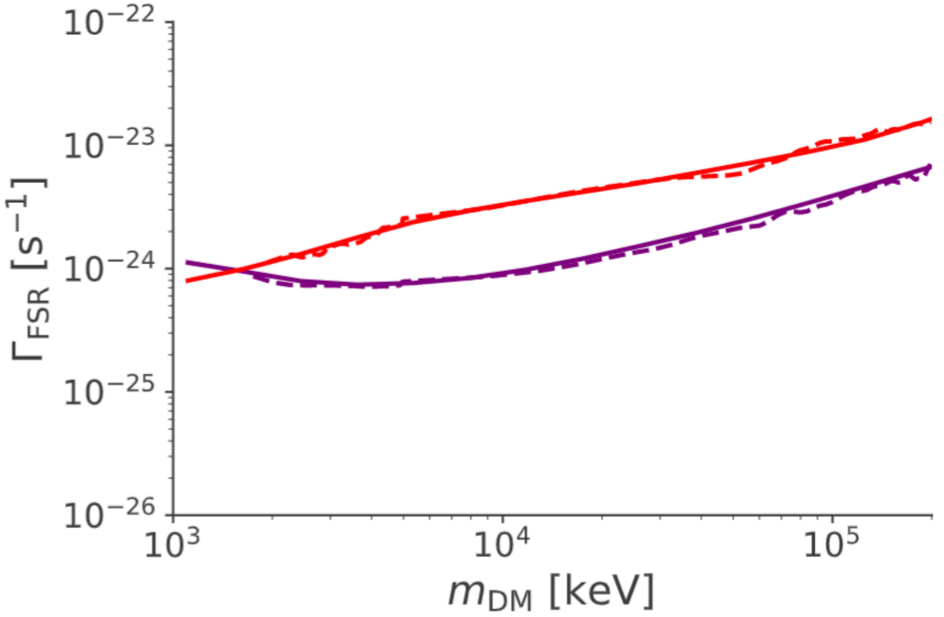
Limits on light decaying dark matter

General limits of final state radiation

$$\mathrm{DM} \to e^+ + e^- + \gamma$$

$$\frac{\mathrm{d}N_{\mathrm{decay}}}{\mathrm{d}E} \simeq \frac{\alpha}{2\pi}\left[\frac{m_{\mathrm{DM}}^2 + (m_{\mathrm{DM}} - 2E)^2}{m_{\mathrm{DM}}^2 E}\ln\left(\frac{m_{\mathrm{DM}}(m_{\mathrm{DM}} - 2E)}{m_e^2}\right)\right]$$





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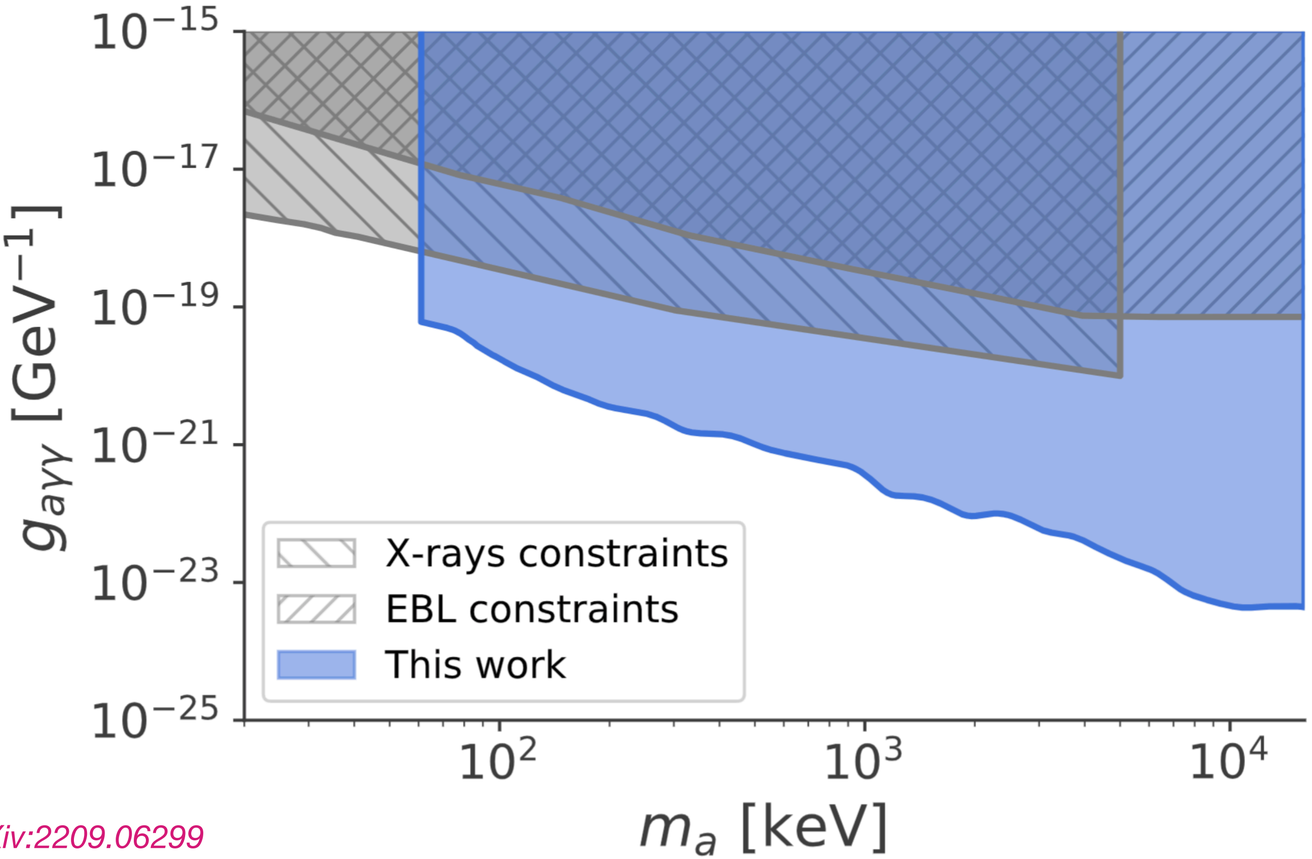
Limits on light decaying dark matter

The case of axion-like particles

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



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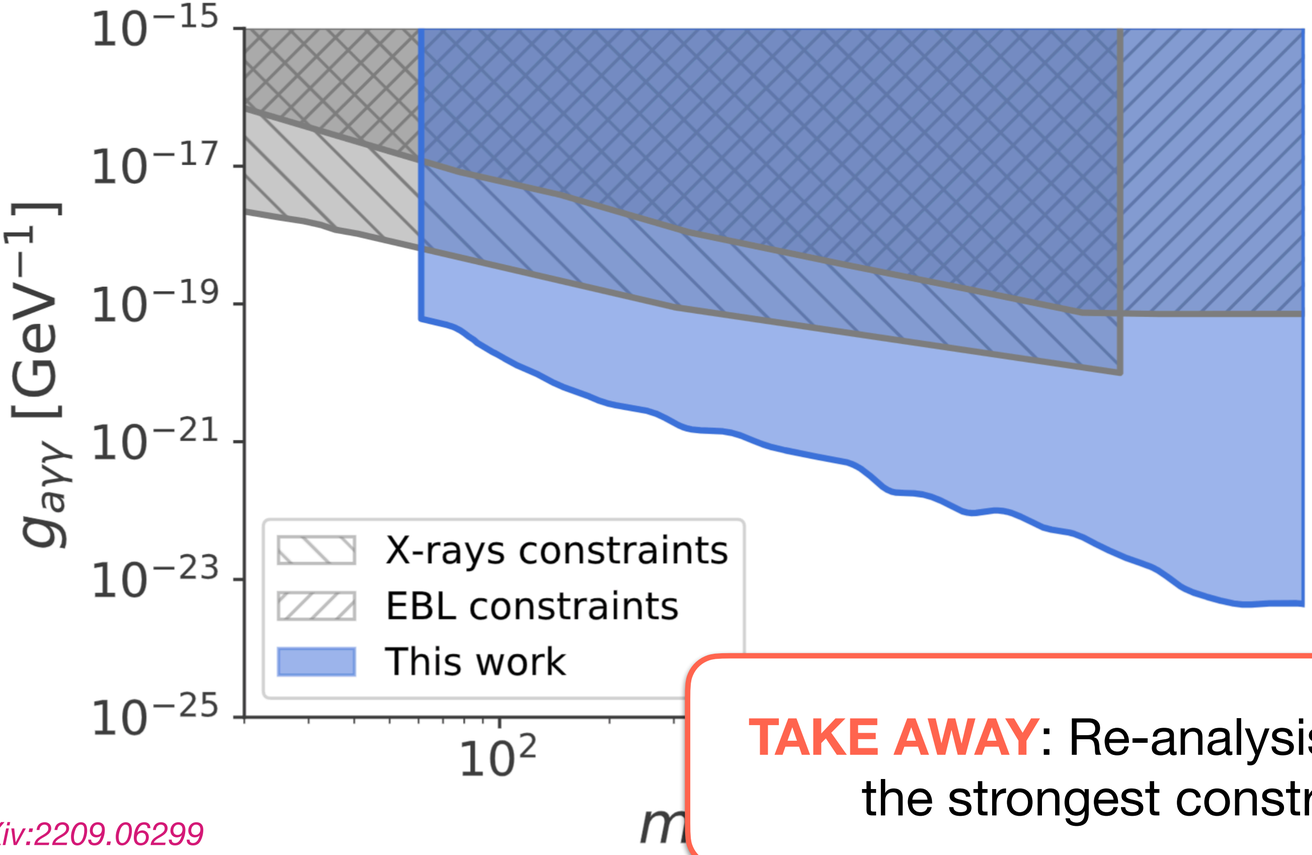
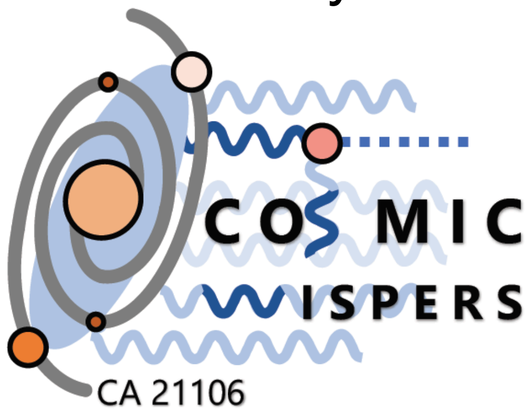


Dekker, FC+'22 arXiv:2209.06299

TAKE AWAY: Re-analysis of INTEGRAL data provides the strongest constraints on ALPs ~100 keV

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/

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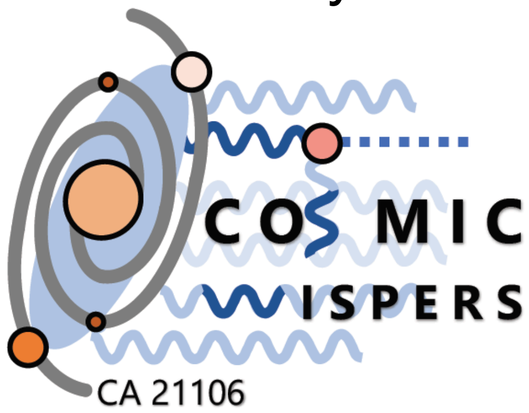

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Thank you for the attention!

Backup slides

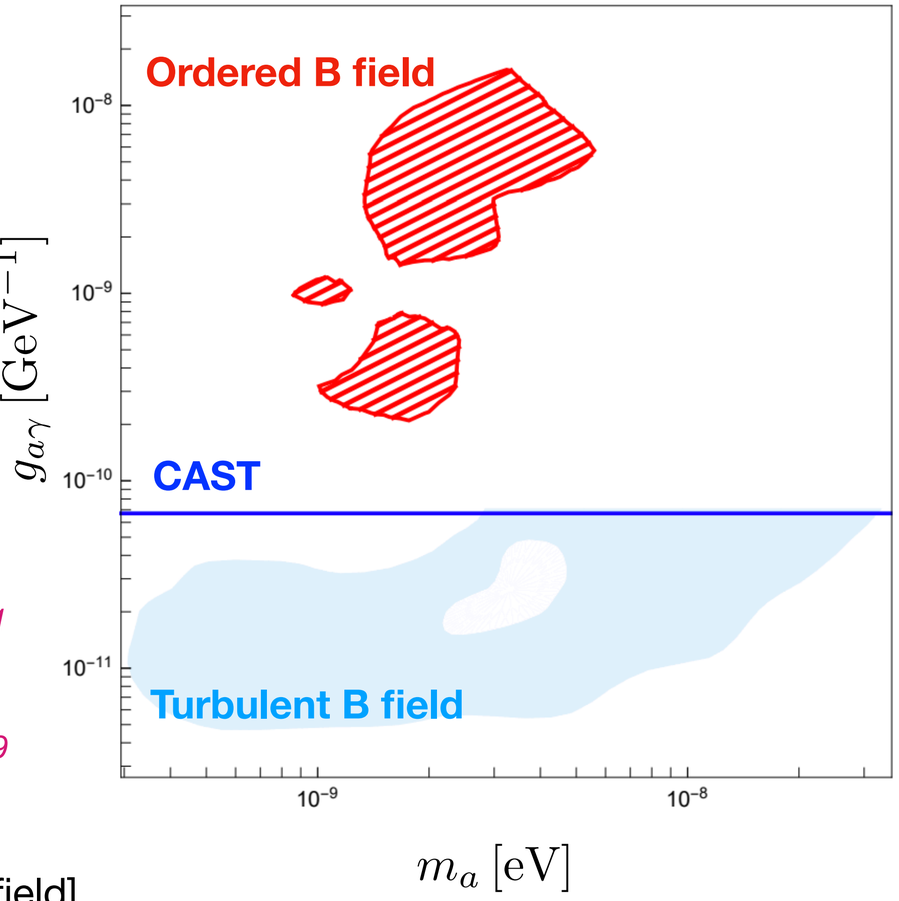
Constraints on ALP-photon mixing

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

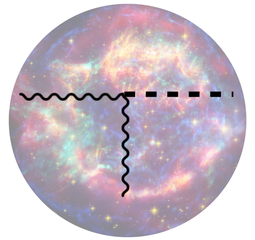
[See also *Carenza+ PRD'21, Kachelriess+ JCAP'22* for impact of turbulent Galactic B field]



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

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

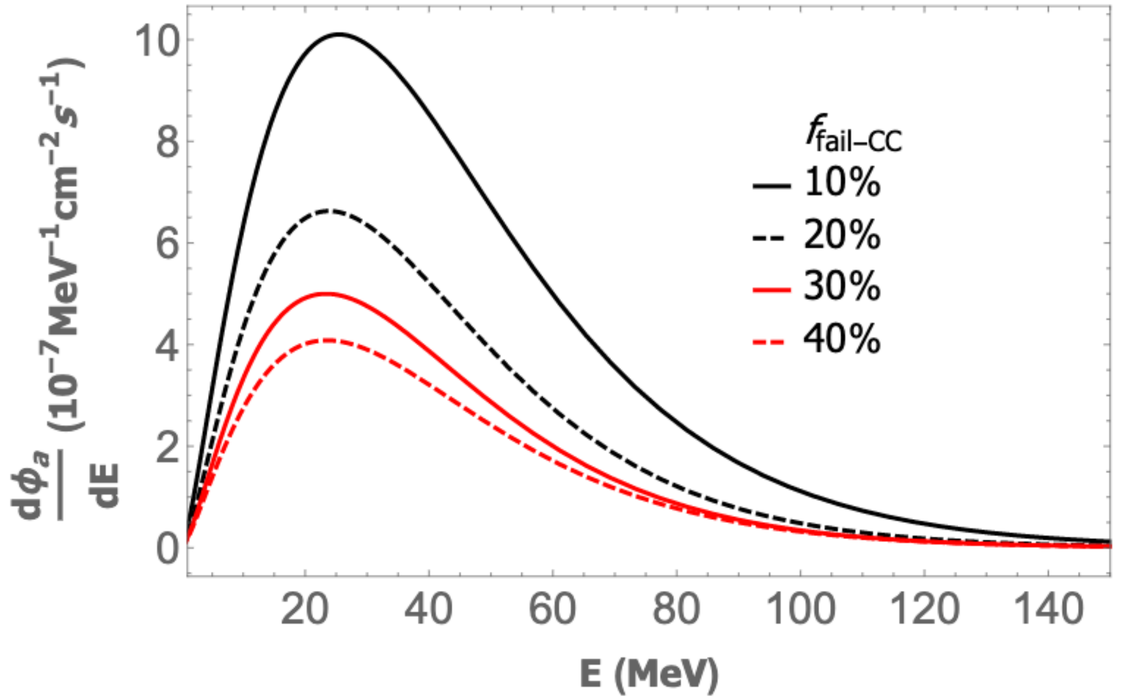
Beacom, Ann. Rev. Nucl. Part. Sci.'10

Time-integrated CC SNe ALPs spectrum from past events

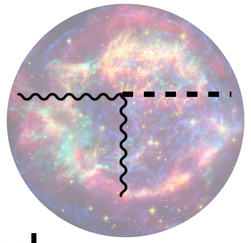
Time-integrated spectrum weighted by initial mass function over the range 8-125 $M_\odot$

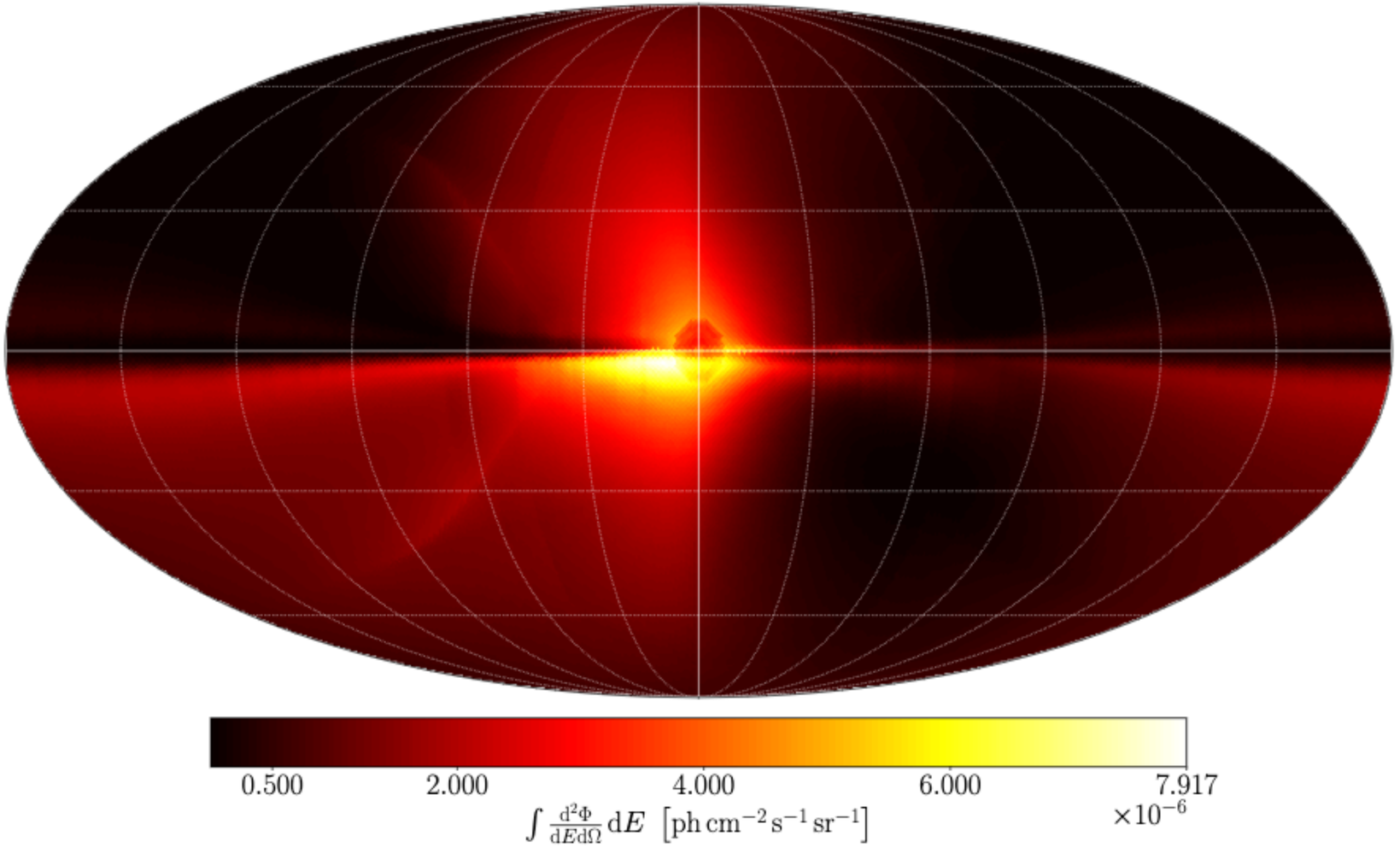
CC SNe rate density at redshift z

Yuksel et al. ApJ Letters'08



Gamma-ray DSNALPB signal





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

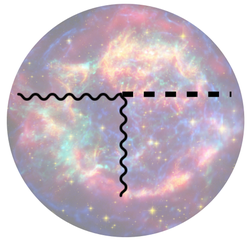
Integrated ALPs signal between 50 and 200 MeV

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

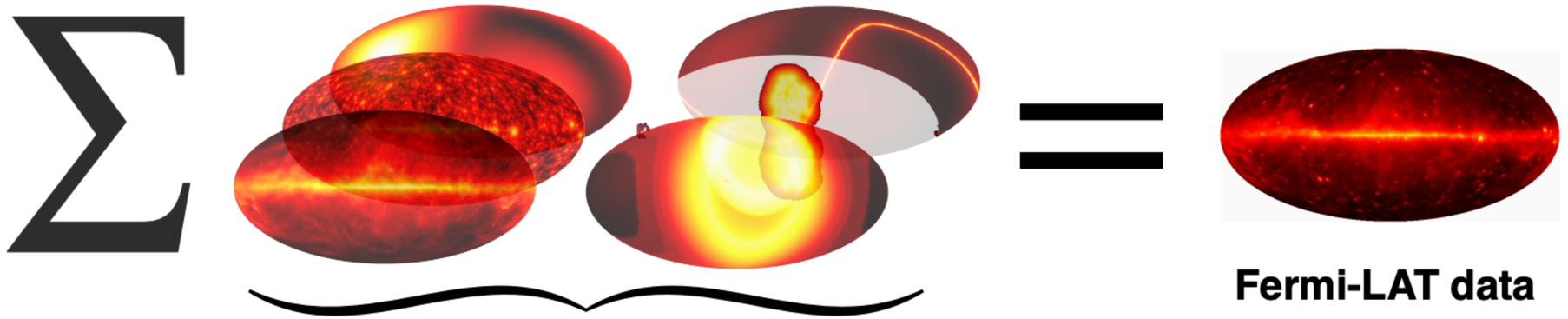
$$m_a \lesssim 10^{-11}\,\mathrm{eV}$$

All-sky diffuse signal
With specific extended spatial features

Fermi-LAT 3D template-based fit



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

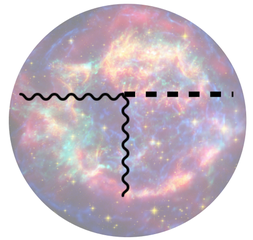


How to beat systematic uncertainties?

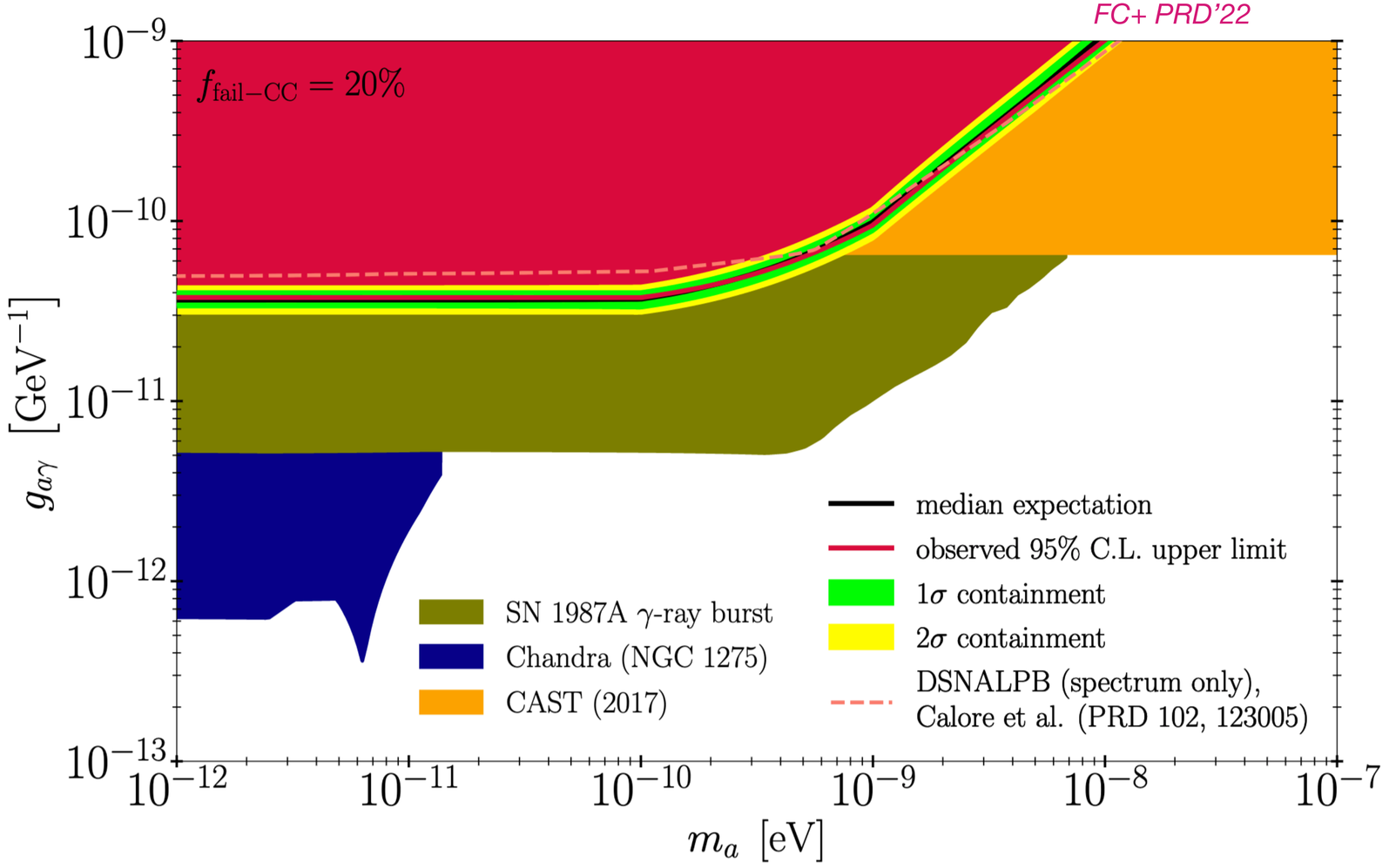
- *Interstellar model emission iterative fitting* procedure to reduce effect of background mis-modelling
- *ROI optimisation* to guarantee best consistency between model and data (high-latitude South)
- Statistical inference is based on a *weighted Poisson* log-likelihood function
- Extended LAT data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

FC+ PRD'22

DSNALPB gamma-ray constraints



FC+ PRD'22



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

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

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