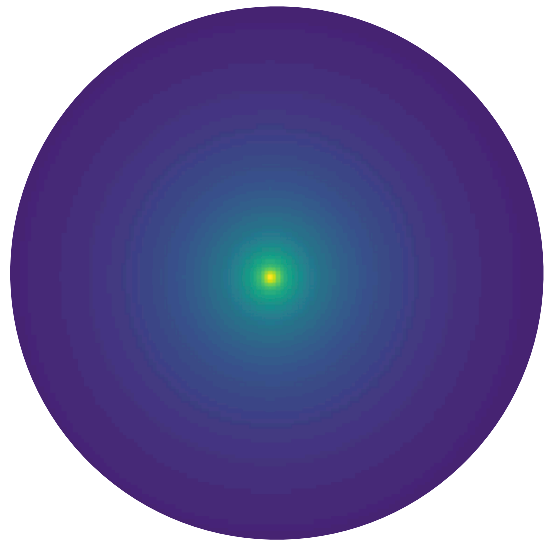
WISPs in high-energy astrophysics

II Training School COST Action COSMIC WISPers
Ljubljana, 11/06/2024

Francesca Calore (CNRS/LAPTh)


Who am I?

Francesca Calore is a staff researcher at the French National Center for Scientific Research (CNRS) at the Annecy-le-Vieux Theoretical Physics Laboratory (LAPTh). After completing a joint Ph.D. at the University of Hamburg, Germany, and the University of Turin, Italy, she has held a postdoctoral position at the Center of Excellence for Gravitation and Astroparticle Physics (GRAPPA) at the University of Amsterdam, Netherlands. She is an expert in dark matter searches with astroparticle experiments and high-energy astrophysics.

APS Physics

Plan of the lectures

I. A short introduction to high-energy astrophysics

II. A short introduction to axions and alike

III. High-energy signatures of ALP-photon conversion from different ALPs sources

IV. High-energy signatures of ALPs (and other light particles) decay

Disclaimer: What I do not cover here:

- Deep theoretical motivations and derivations
- Production of WISPs in the early universe and connection with dark matter
- Bounds from stellar evolution and alike
- Bounds from strongly magnetised objects (pulsars)

Axions and 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

A poor phenomenologist perspective

- From a fundamental theory or more EFT approaches couplings with SM and new particles induce specific phenomenological signatures
- We are interested here in **signatures of light, weekly coupled particles in high-energy astrophysics**

What I consider as HE astro?

- Emission of **astrophysical sources** from X (~keV) to gamma rays (PeV)
- Astrophysical **diffuse backgrounds** at multiple wavelengths

What is a signature?

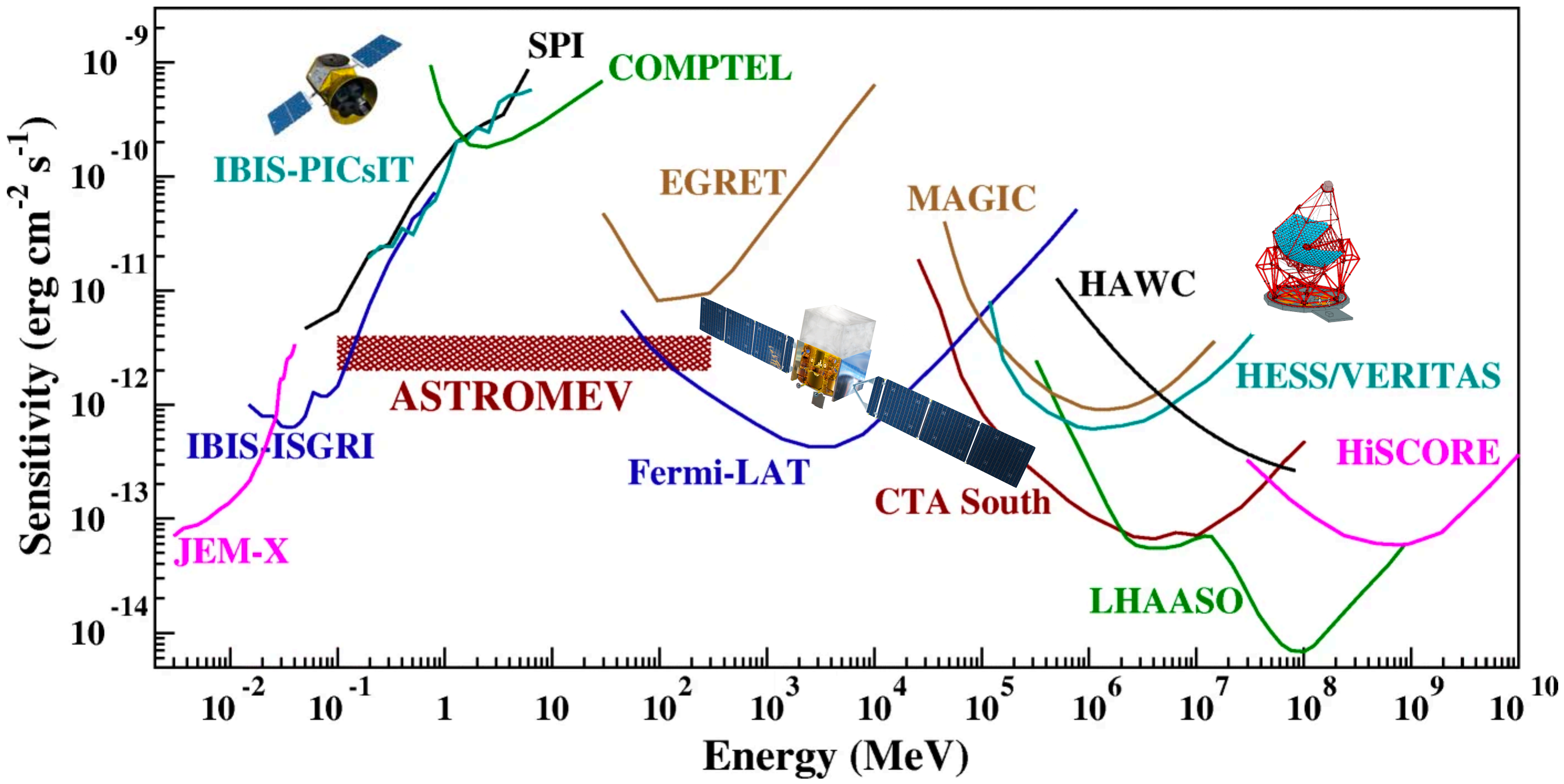
- It is a **sizeable modification** of *standard* astrophysical signals
- Modification of spectral and spatial distributions of event counts, and/or polarisations

Detection vs constraints

A short introduction to high-energy astrophysics

High-energy astrophysical data landscape

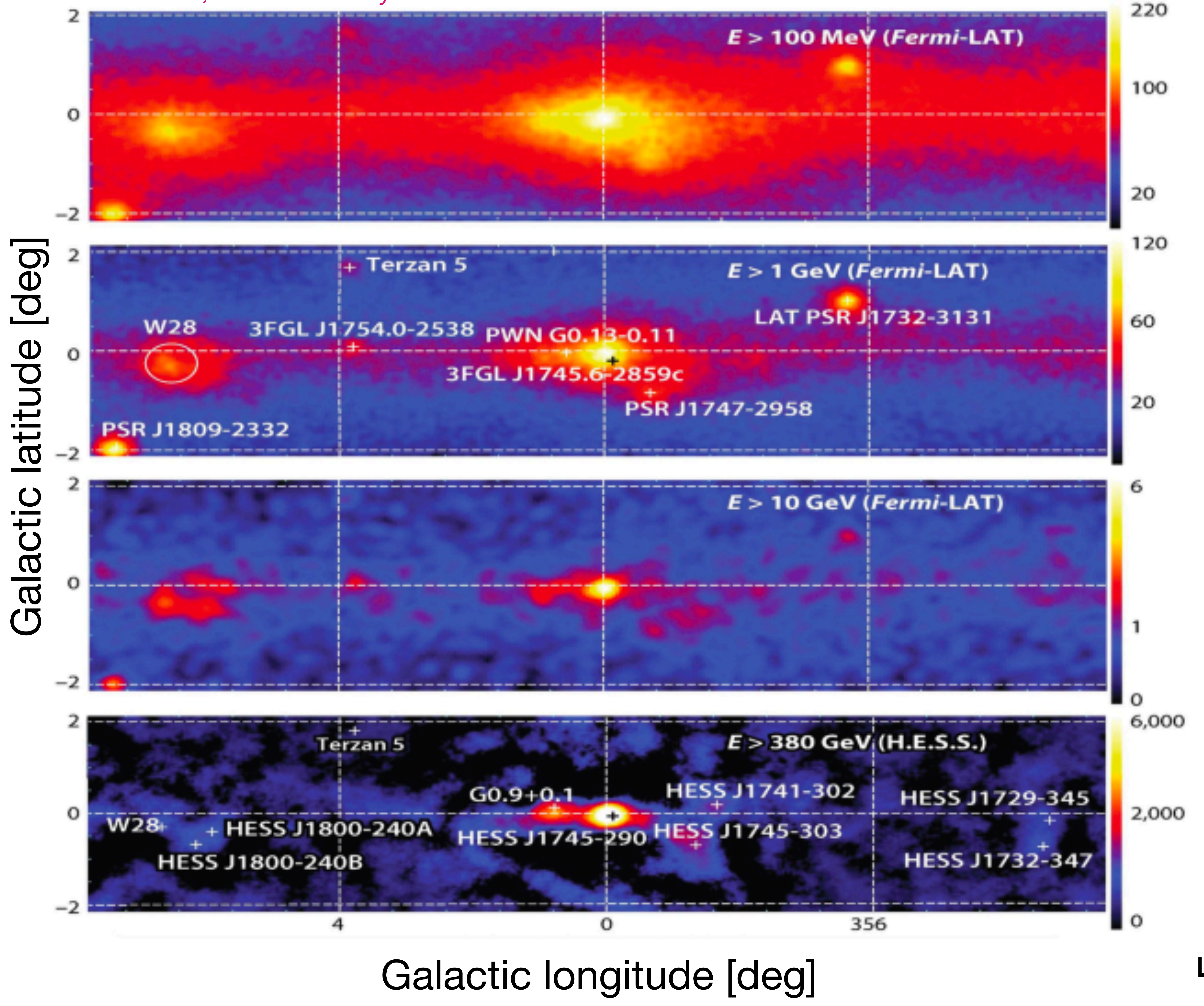
DeAngelis+ Voyage 2050 '21



eV keV MeV 100 MeV GeV TeV 100 TeV Photon energy

High-energy cosmic radiation

Beckman, MM Astronomy '21



Integral/SPI: 100 keV — 8 MeV
Siegert, FC, PDS+ A&A'22

***Fermi*-LAT**: ~30 MeV — 1 TeV

HESS: ~200 GeV — 30 TeV
Abramowski+ PRD'14

HAWC: 300 GeV — 100 TeV
Abeysekara+ PoS ICRC2021

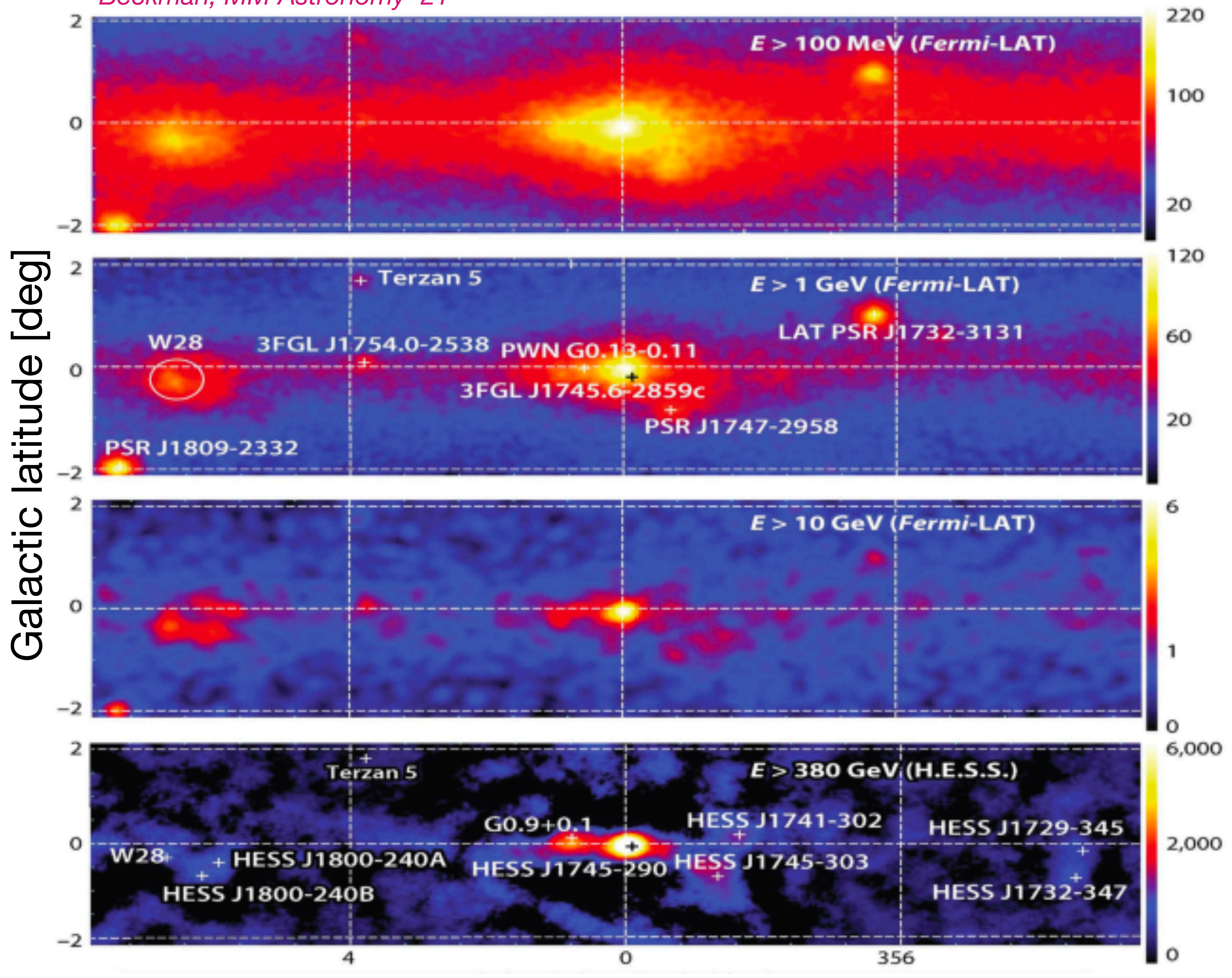
LHAASO: 10 TeV — 1 PeV
Cao+ 2305.05372

Tibet ASg: 100 TeV — 500 TeV
Amenomori+ PRL'21

Energy

High-energy cosmic radiation

Beckman, MM Astronomy '21



Total emission is a sum of guaranteed contributions and possibly exotic ones

$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{diffuse}} + \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{PS}} + \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{new physics}}$$

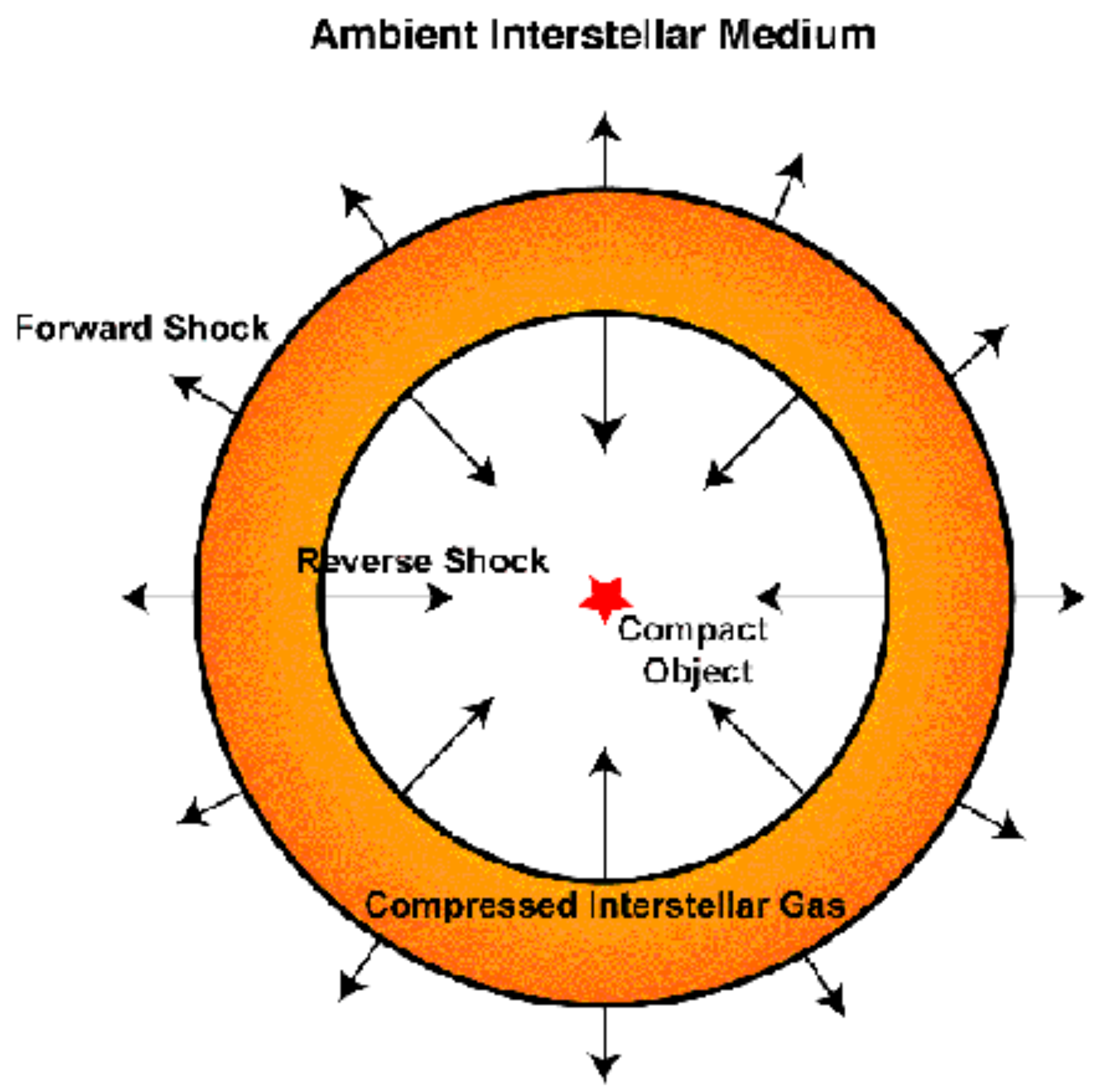
Challenge: Understanding the contribution of diffuse cosmic-ray processes as well as point sources

⟶ Crucial MM connection

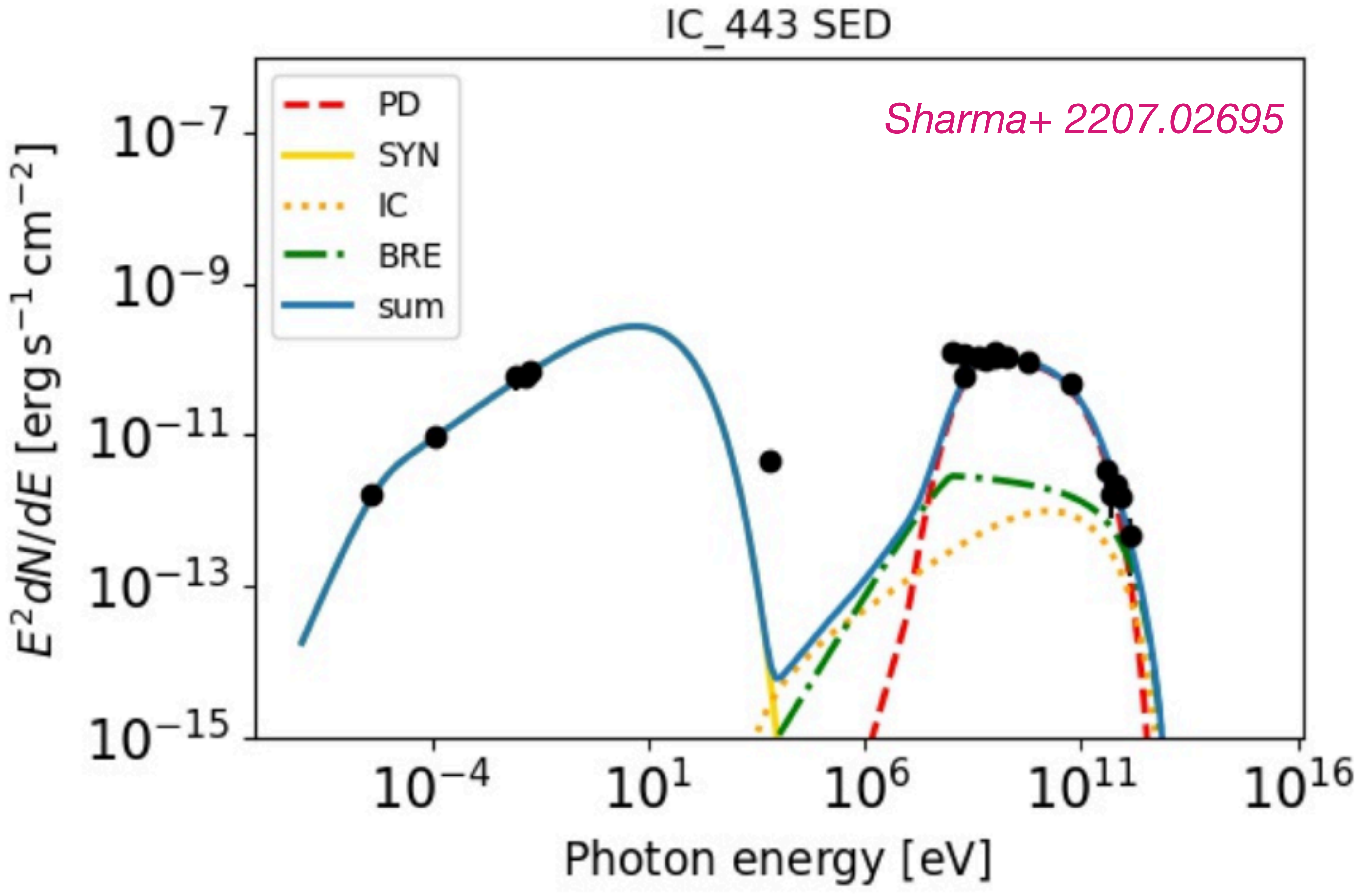
e.g. De La Torre Luque+ Front.Astron.Space Sci.'22, A&A'23

Main astrophysical sources

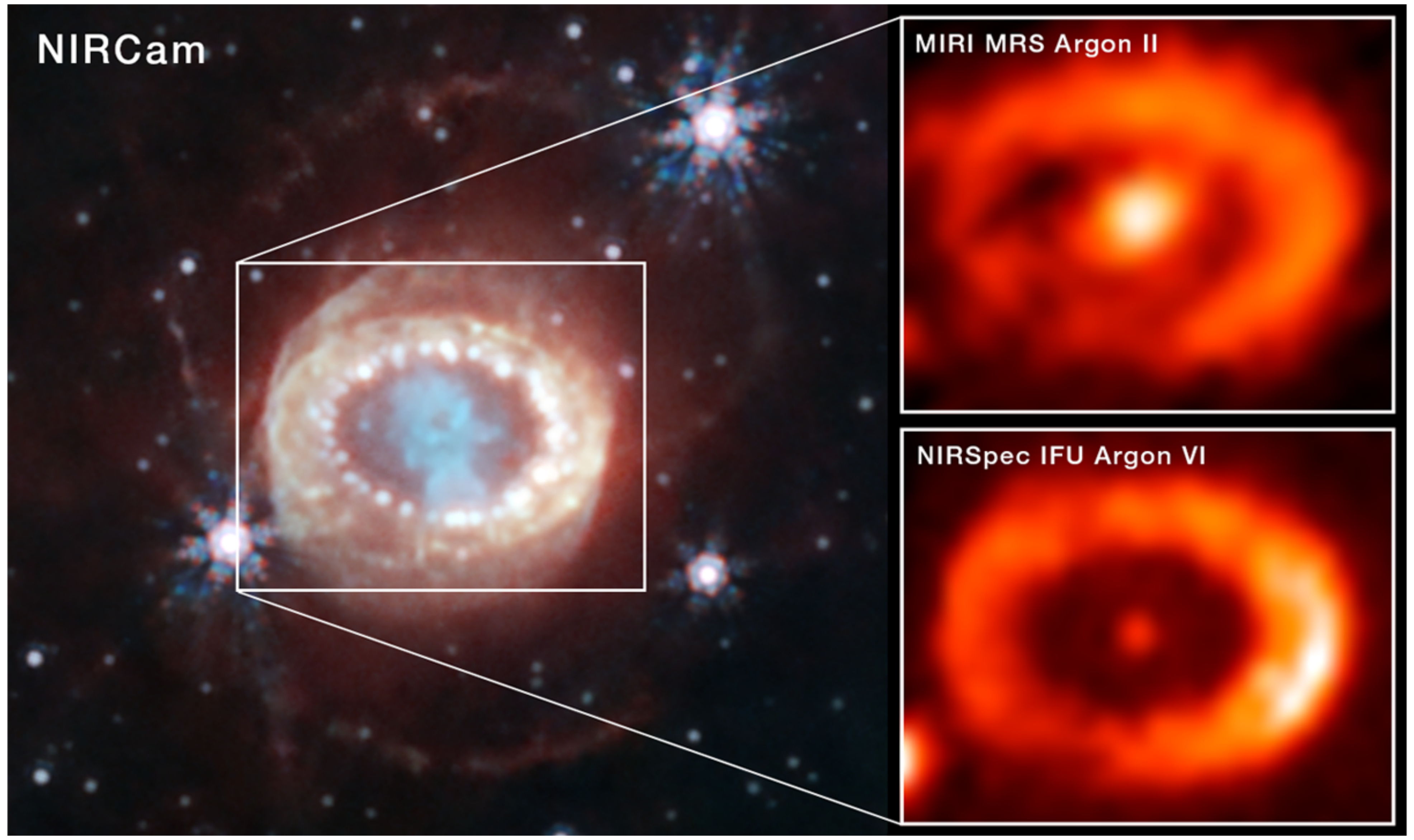
Supernova remnants



- Structure resulting from the explosion of a star in a SN of type I (white-dwarf accretion) or II (core-collapse)
- Expanding material ejected in the explosion and shocking the ISM along the way
- Strongly magnetised shocks 25 — 1000 μG

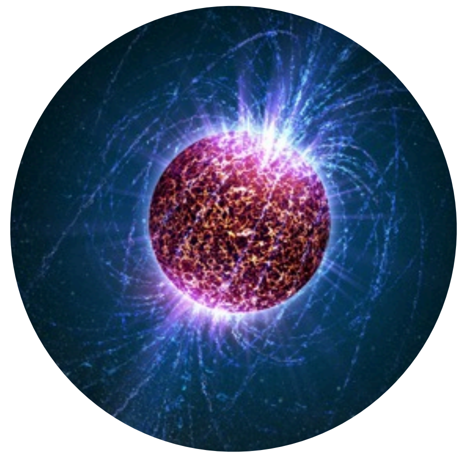


Webb's evidence of neutron star in SN1987A

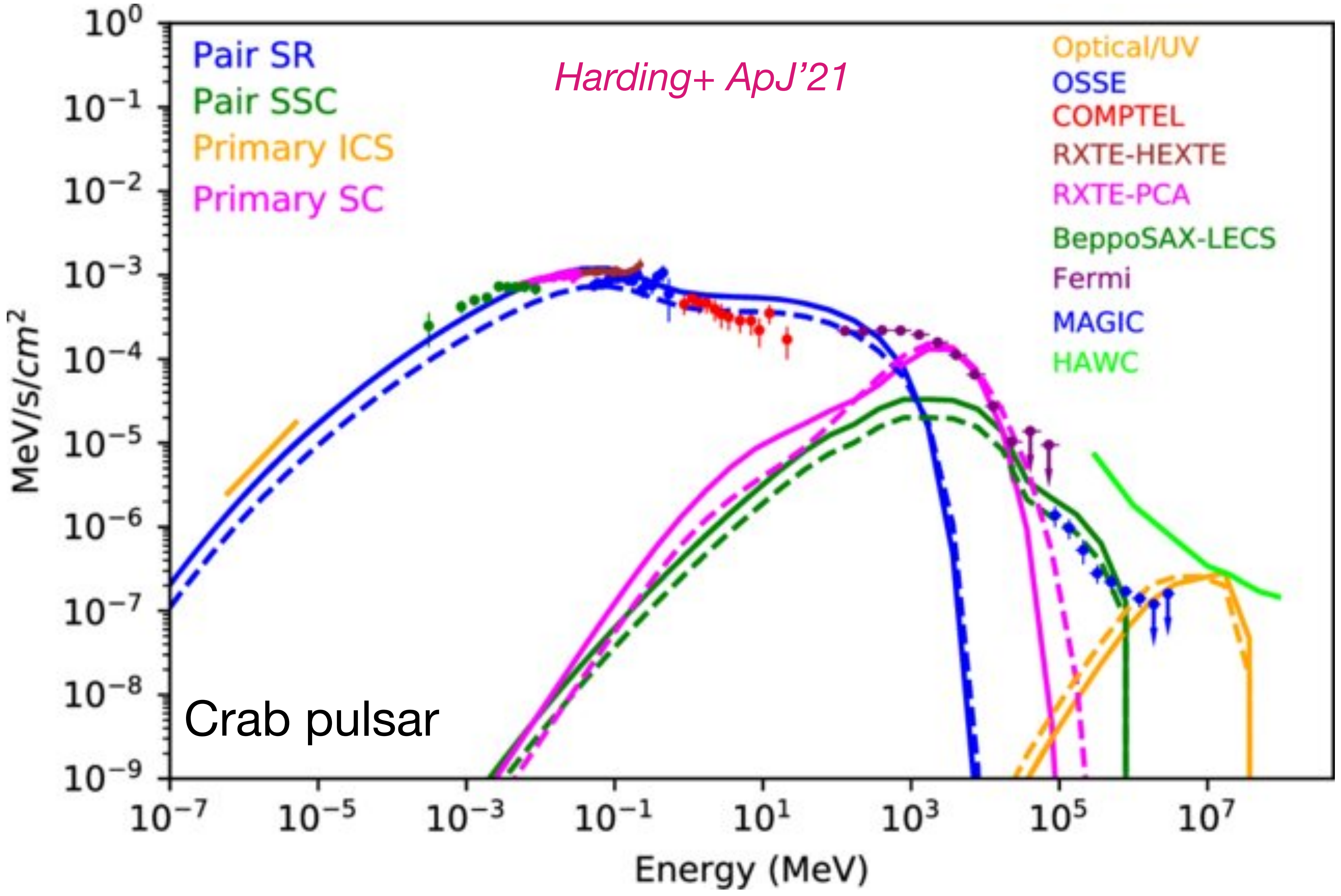


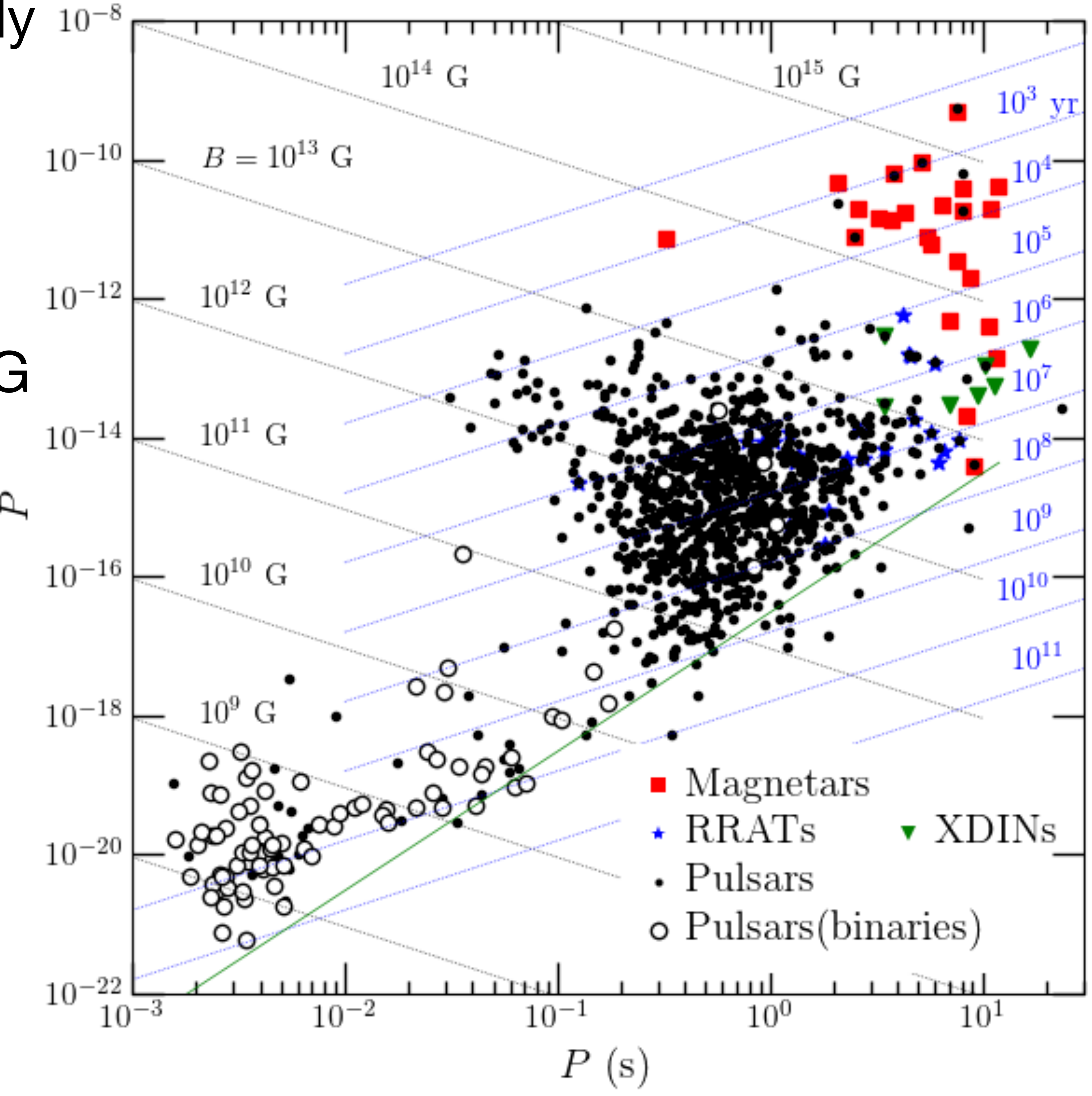
Main astrophysical sources

Pulsars and pulsar wind nebulae



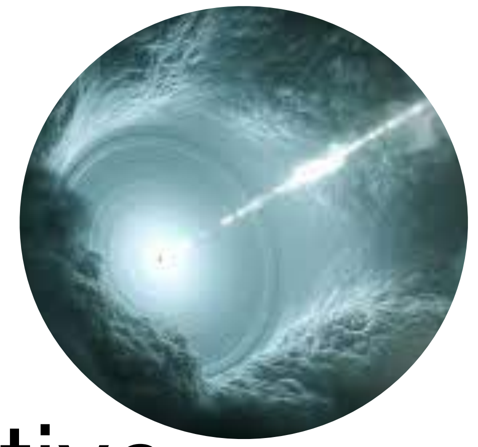
- Pulsars are rapidly rotating neutron stars with extremely high densities
- Emit beams of electromagnetic radiation (radio, X-ray, gamma-ray) from their magnetic poles through synchrotron and curvature radiation
- Dipolar magnetic field with strengths from 10^8 to 10^{15} G

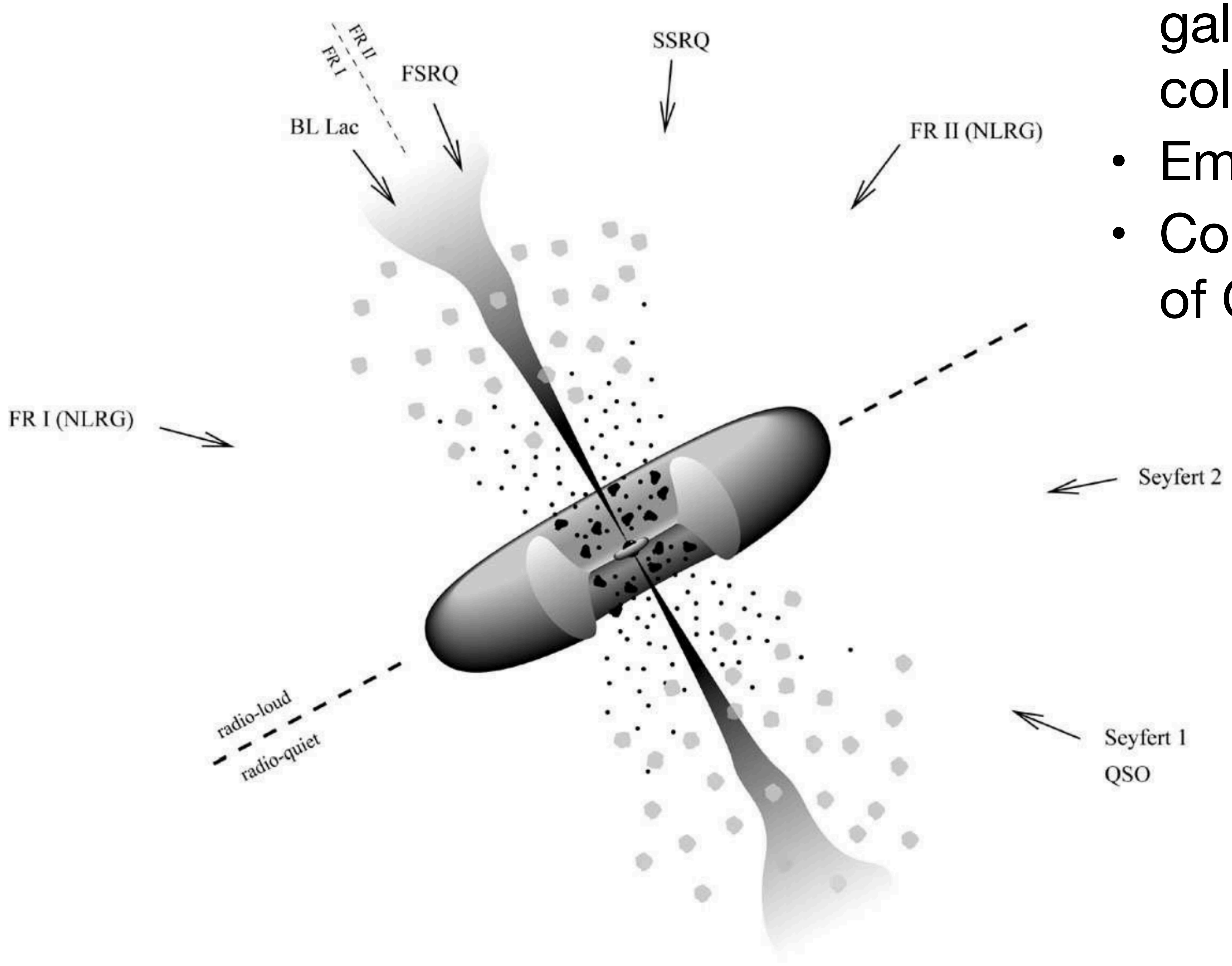




Main astrophysical sources

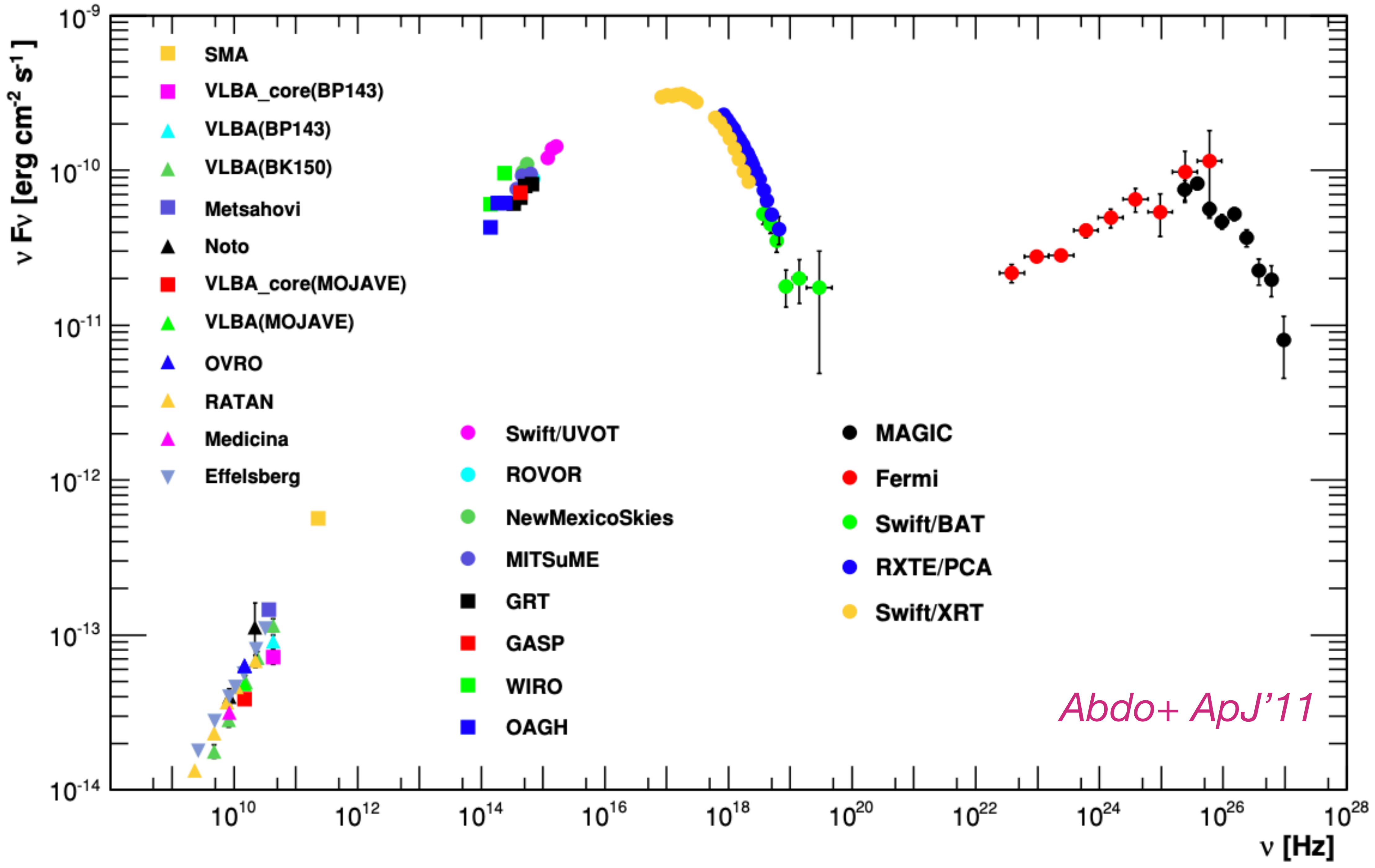
Active galactic nuclei





- Large fraction of the total luminosity of an active galaxy is non-thermal (accretion disk and collimated jet)
- Emitted by the nuclei of the galaxy
- Complex B fields structure (poloidal and toroidal) of O(10^3 G)

SED of Mrk 421



Main astrophysical sources

Star-forming and star-burst galaxies

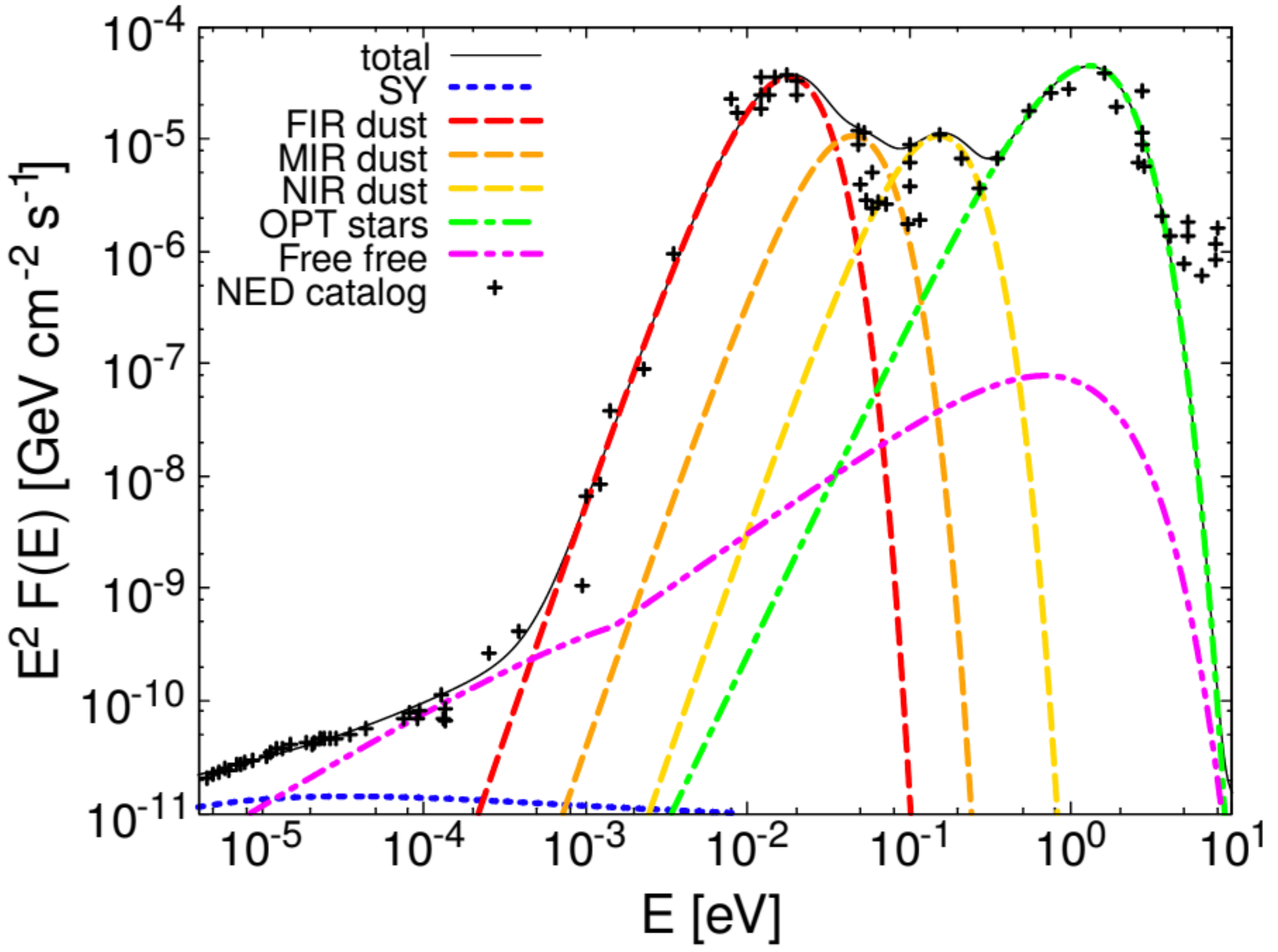
- Galaxies characterised by high rates of star-formation in star-forming and/or star-burst regions
- Large scale B fields from few μG up to 100 of μG

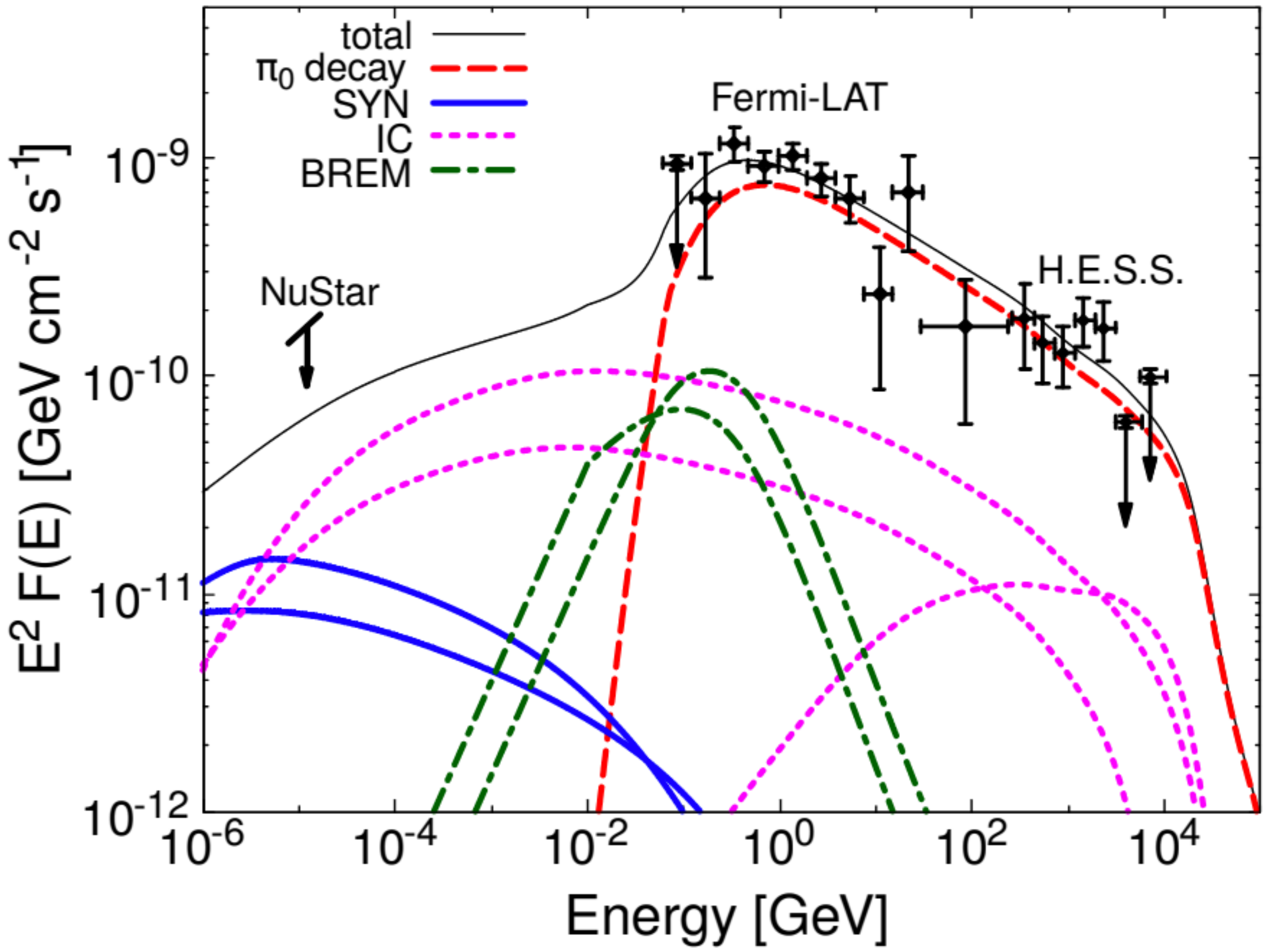
Galaxy clusters

- Galaxy clusters are the largest gravitationally bound structures in the universe, containing hundreds to thousands of galaxies
- The intracluster medium (ICM) is filled with hot, X-ray emitting, highly ionised gas
- Magnetic fields in galaxy clusters are typically weak, ranging from 0.1 to a few μG
- B field structure is often tangled and chaotic due to turbulence within the ICM + ordered large-scale fields
- Coherence lengths of magnetic fields in galaxy clusters range from 10 to 100 kpc

Spectrum of NGC253

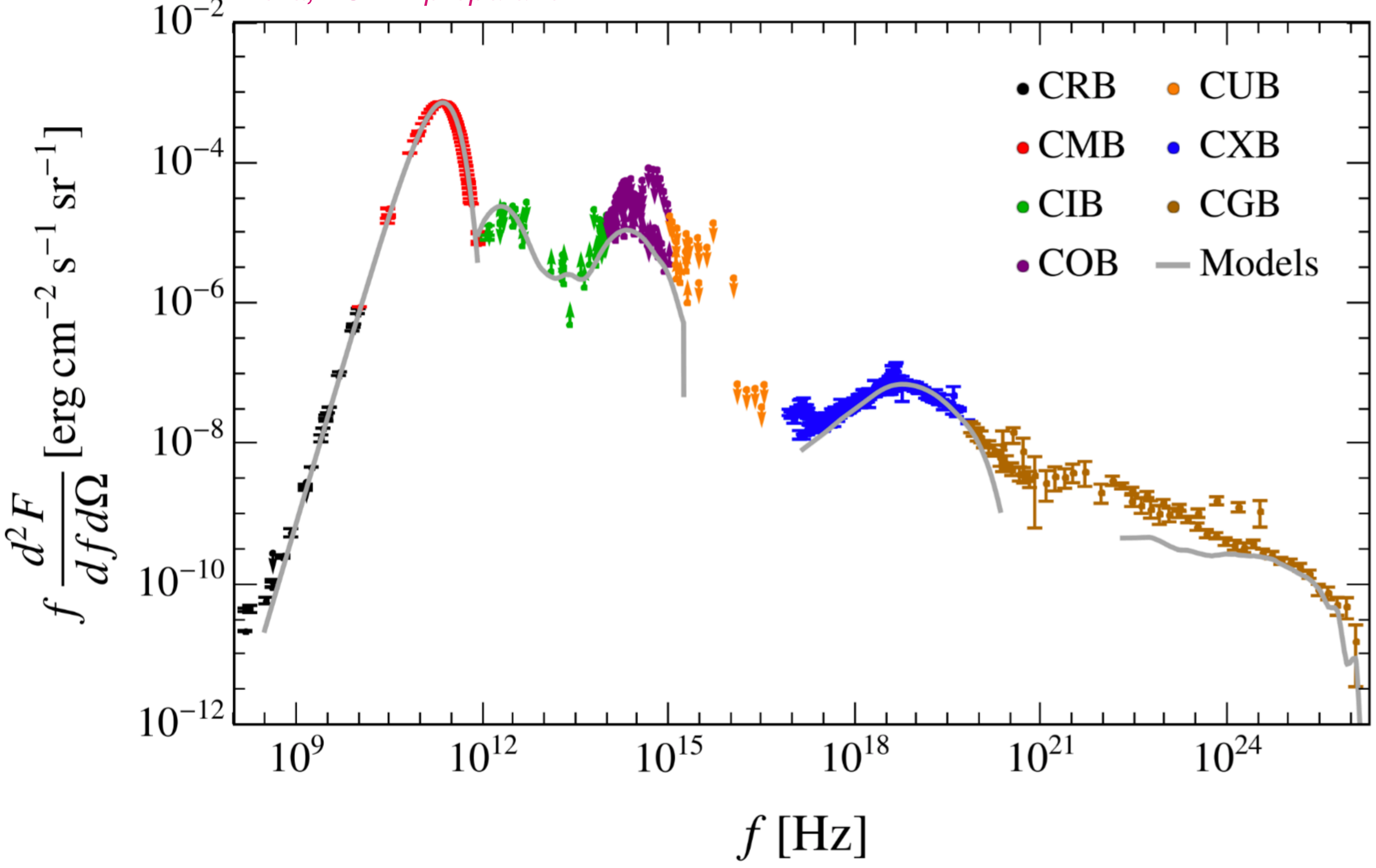
Peretti+ MNRAS'19





The cosmic photon backgrounds

Lella, FC+ In preparation



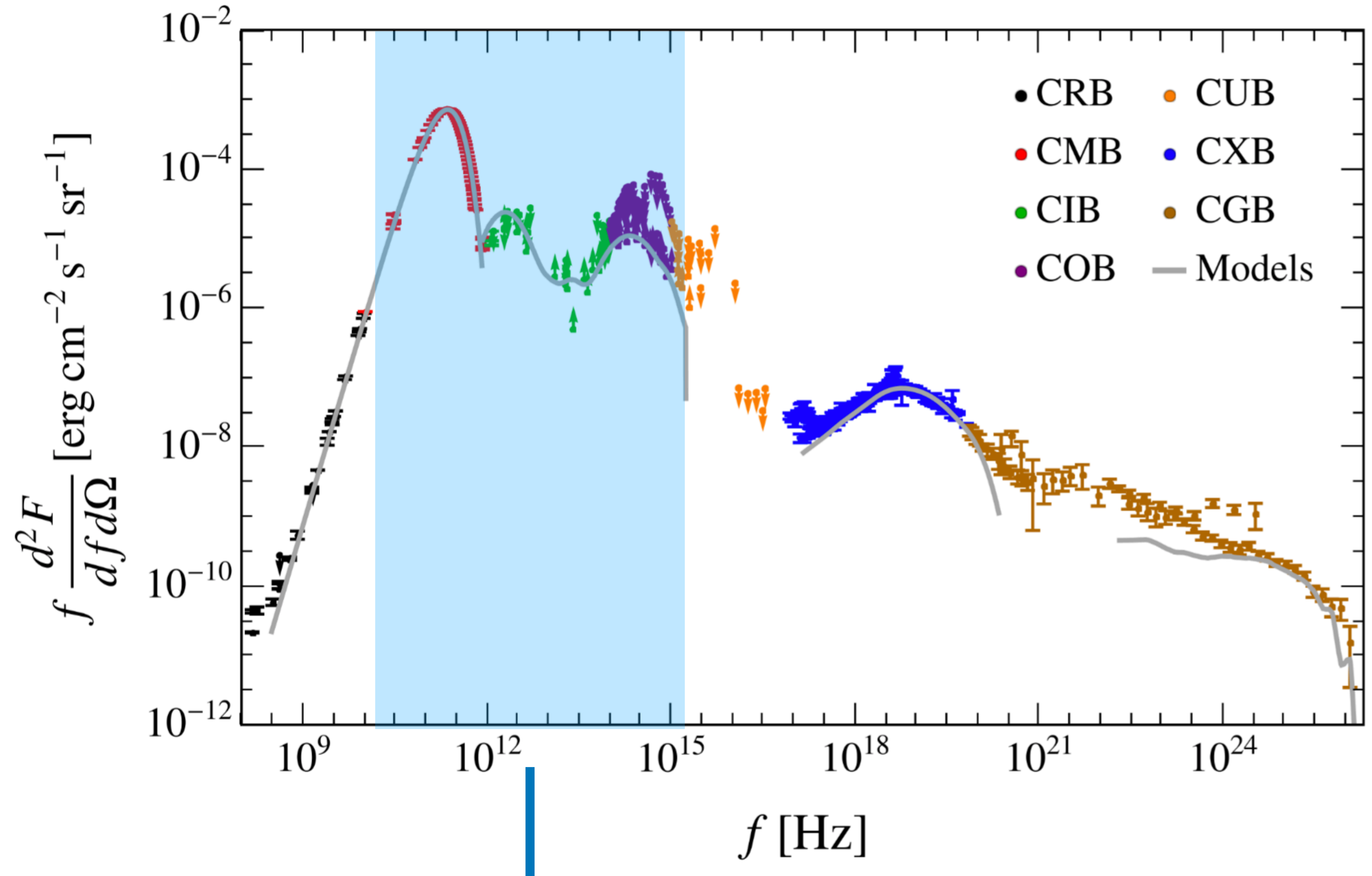
[For a review see: *Hill+ App. Spectrosc.'18*]

- **CRB** & **CMB**: Primordial background subtracted by Galactic foregrounds @ 2.7255 K
- **CIB**: Emission of dust heated by stars within unresolved galaxies, difficult to clean from Galactic foregrounds
- **COB**: Emission from stars, difficult to clean from Galactic foregrounds
- **CUB**: From all sources of ionising photons such as star-forming galaxies and quasars
- **CXB**: Dominate by bremsstrahlung in the hot accretion disks around AGNs
- **CGB**: Superposition of several source classes (AGNs, star-forming galaxies) and Galaxy emission

Common element: Mostly of extra-galactic origin, as superposition of faint photon emitters

EBL absorption of VHE photons

- At higher energies diffuse emission detected by HESS, HAWC Tibet ASg, and LHAASO
- Mostly of Galactic origin because of intrinsic horizon of VHE photons (absorption)



Extragalactic Background Light (EBL)

$$\sim 400\,\mathrm{ph/cm^3}$$
$$\sim 1\,\mathrm{ph/cm^3}$$

Pair-production

$$\gamma_{\rm VHE} + \gamma_{\rm EBL} \to e^+ + e^-$$

From invariance of *s*, COM energy

$$E'_\gamma \geq \frac{m_e^2}{\epsilon'}$$

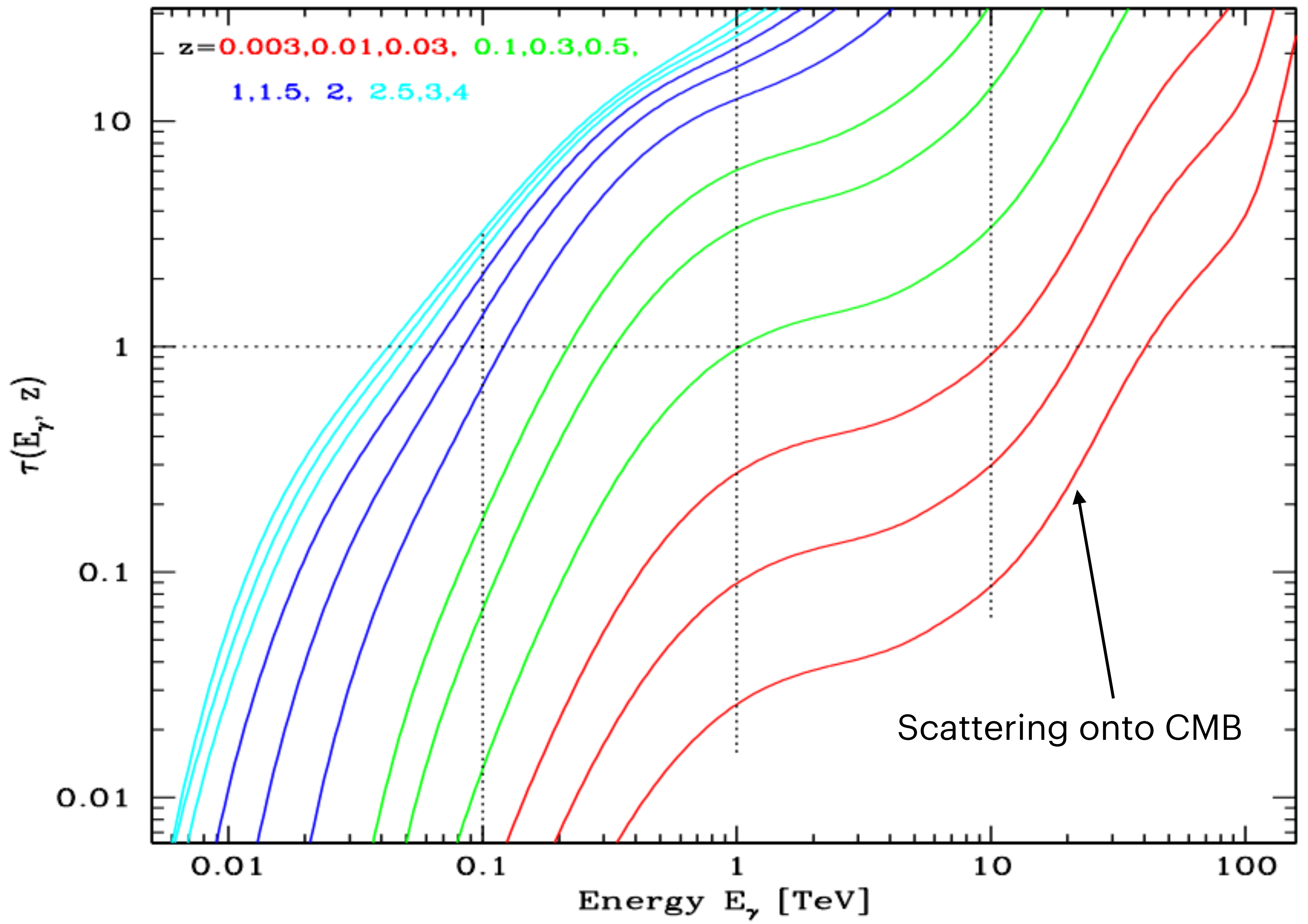
in cosmological coving frame

EBL absorption of VHE photons

Optical depth ~ # interactions along the l.o.s

$$\tau(E_\gamma, z_s) = \mathcal{F}(n_\gamma(\epsilon', z), d_L(z), \sigma_{\gamma\gamma}(E_\gamma, \epsilon'))$$

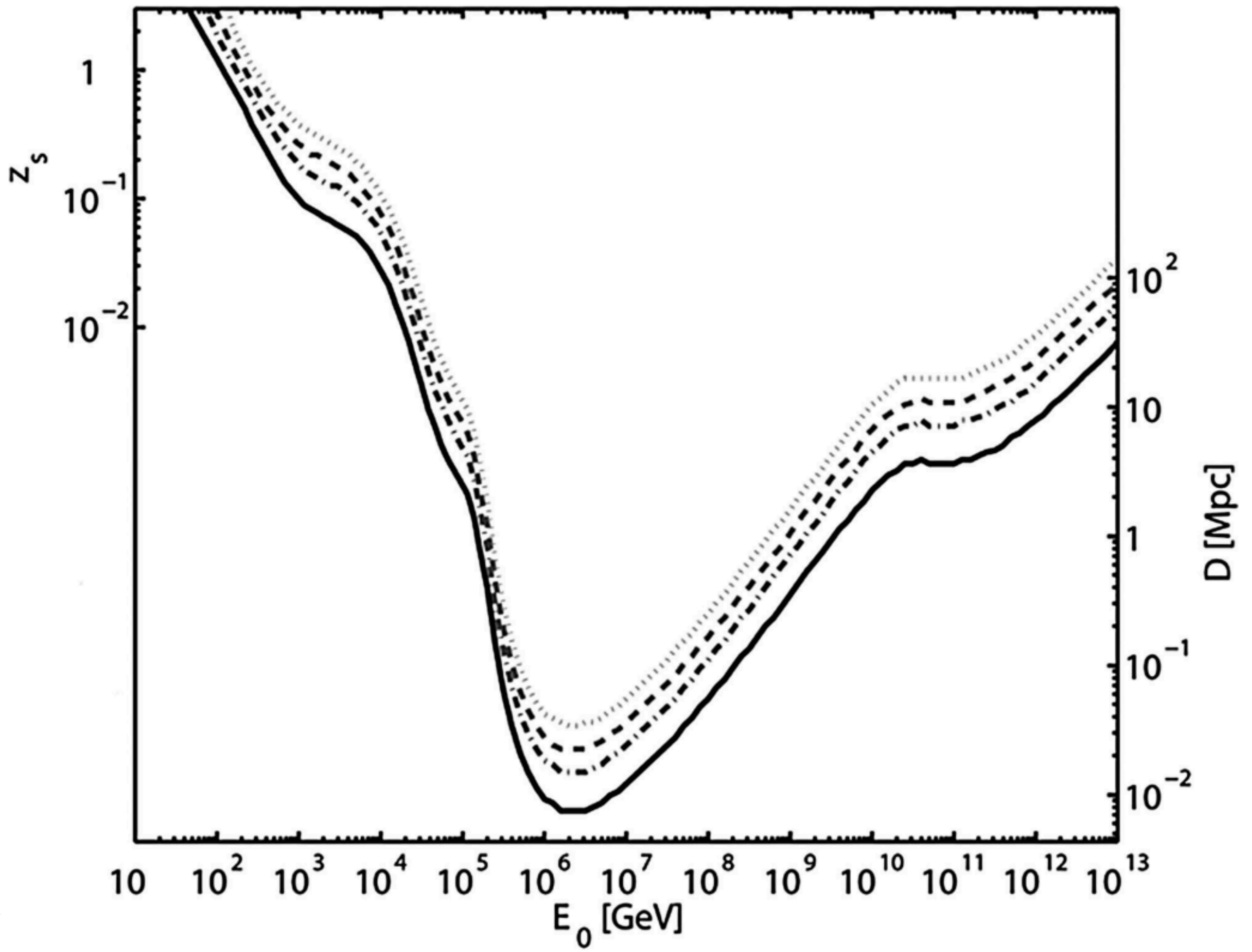
Franceschini Universe'21



Gamma-ray cosmic horizon

$$\tau(E_\gamma, z_s) = 1$$

De Angelis+MNRAS'13

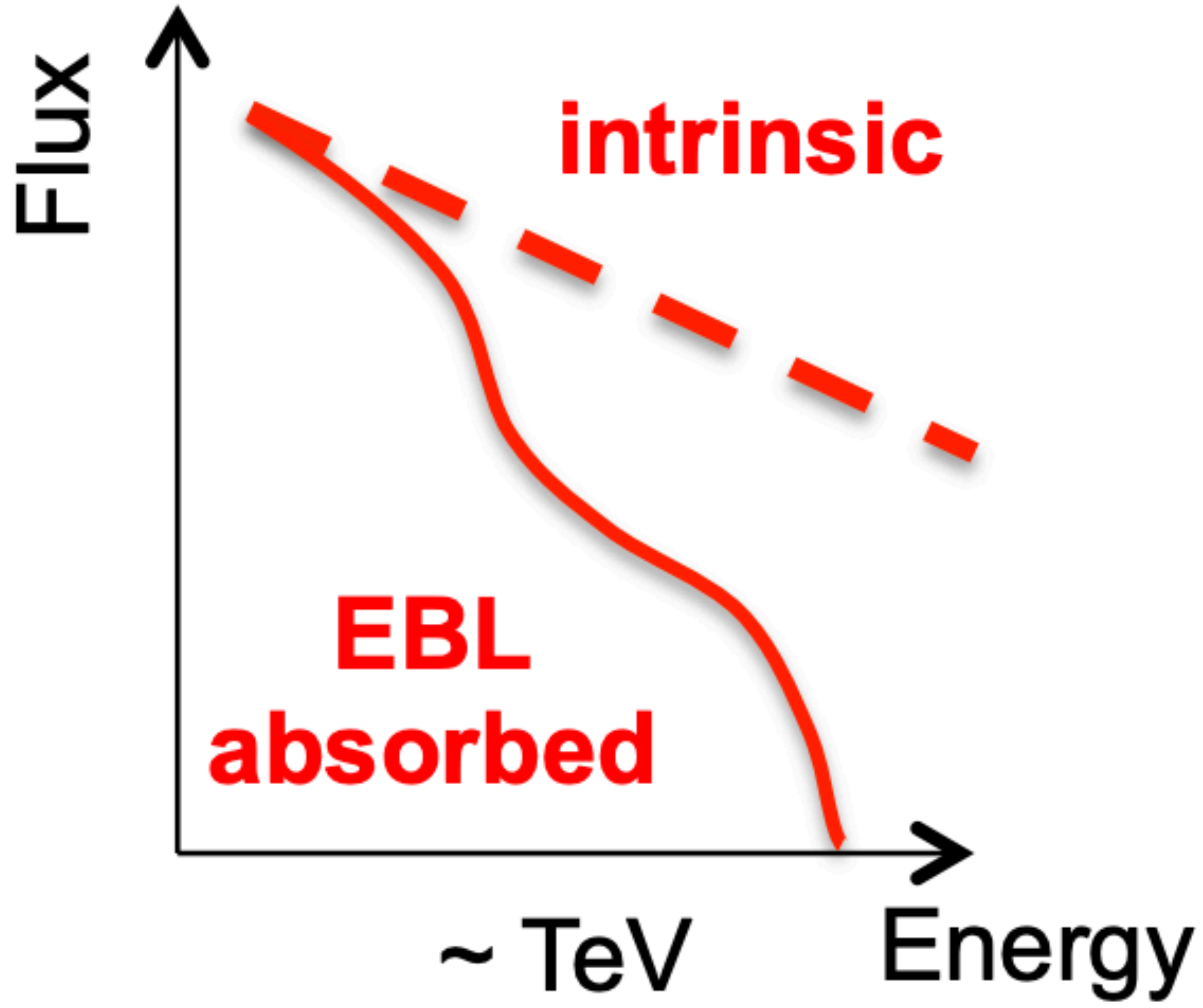


EBL absorption of VHE photons

Photon survival probability

$$P_{\gamma\gamma}(E_\gamma, z_s) \equiv e^{-\tau(E_\gamma, z_s)}$$

Also called transfer function $T_\gamma(E, L)$



$$\Phi(E_\gamma, z_s) = \Phi(E_\gamma) \times e^{-\tau(E_\gamma, z_s)}$$

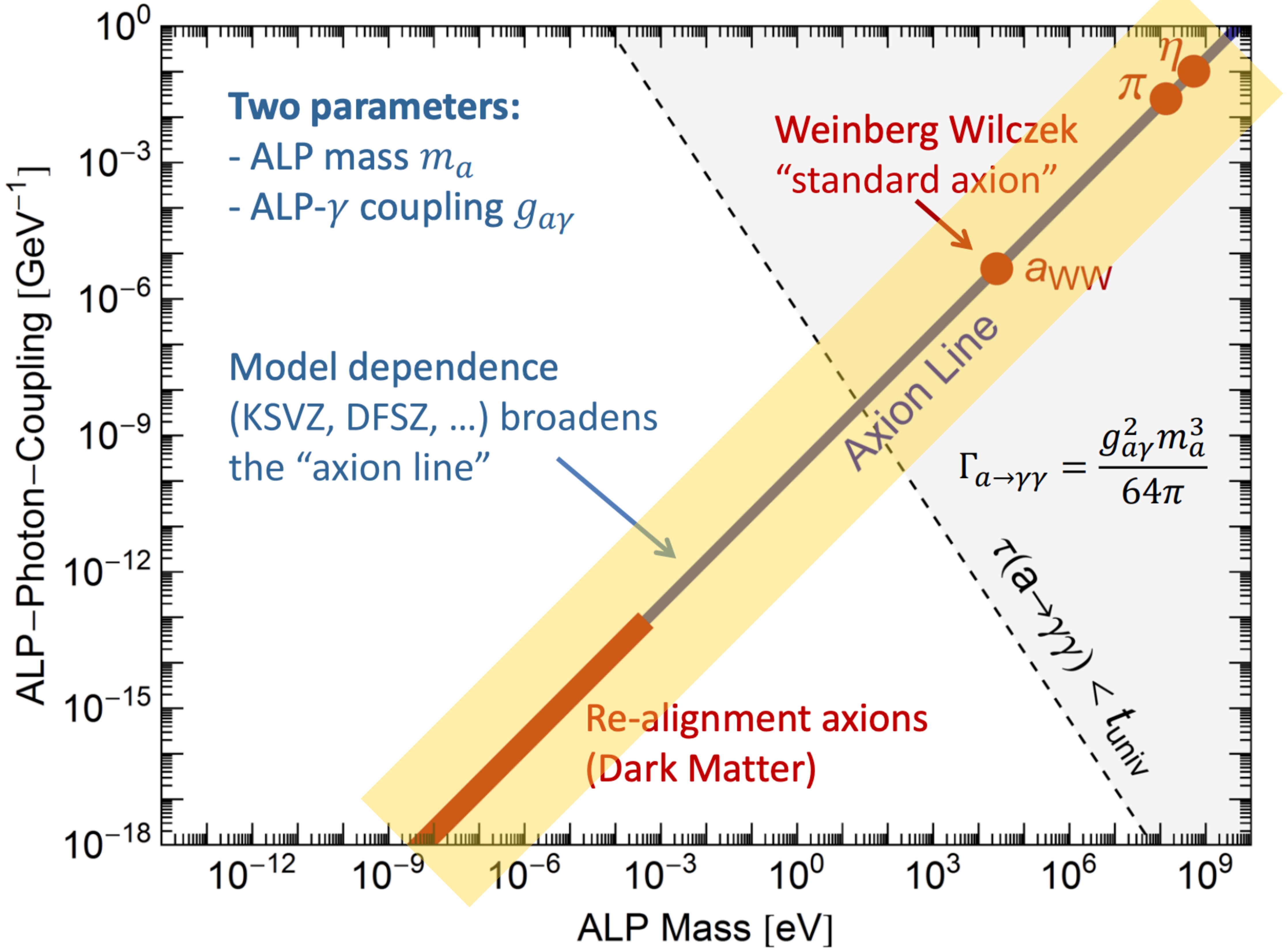
Differential (in energy) photon flux shows a characteristic EBL cutoff at about

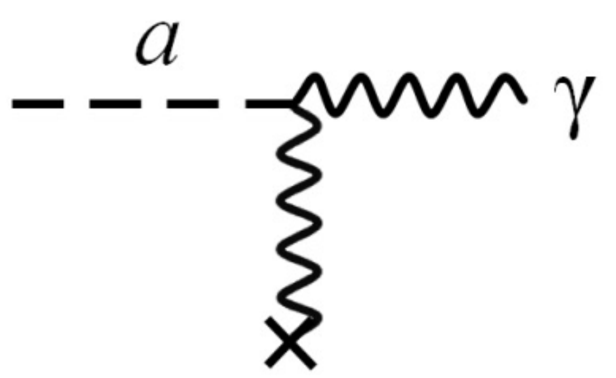
$$E_{\gamma,\mathrm{cutoff}}(z_s) \sim 800\,(1+z_s)^{-2.4}\,\mathrm{GeV}$$

A short introduction to the QCD axion and alike

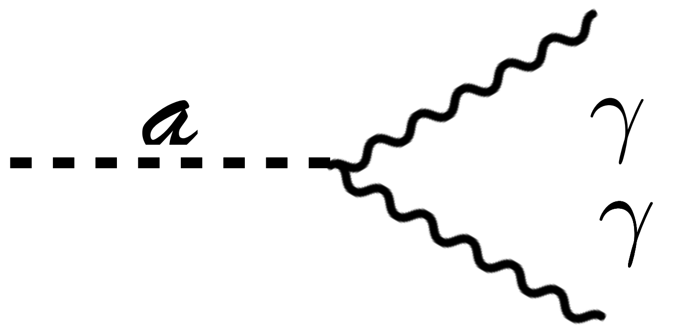
The QCD axion

Credit: G. Raffelt





Primakoff conversion



Decay

Quick ID:

- **Light** pseudo-scalar particle
- Minimal coupling with **gluons** to solve the strong CP problem
- Production through Peccei-Quinn symmetry breaking at the energy scale

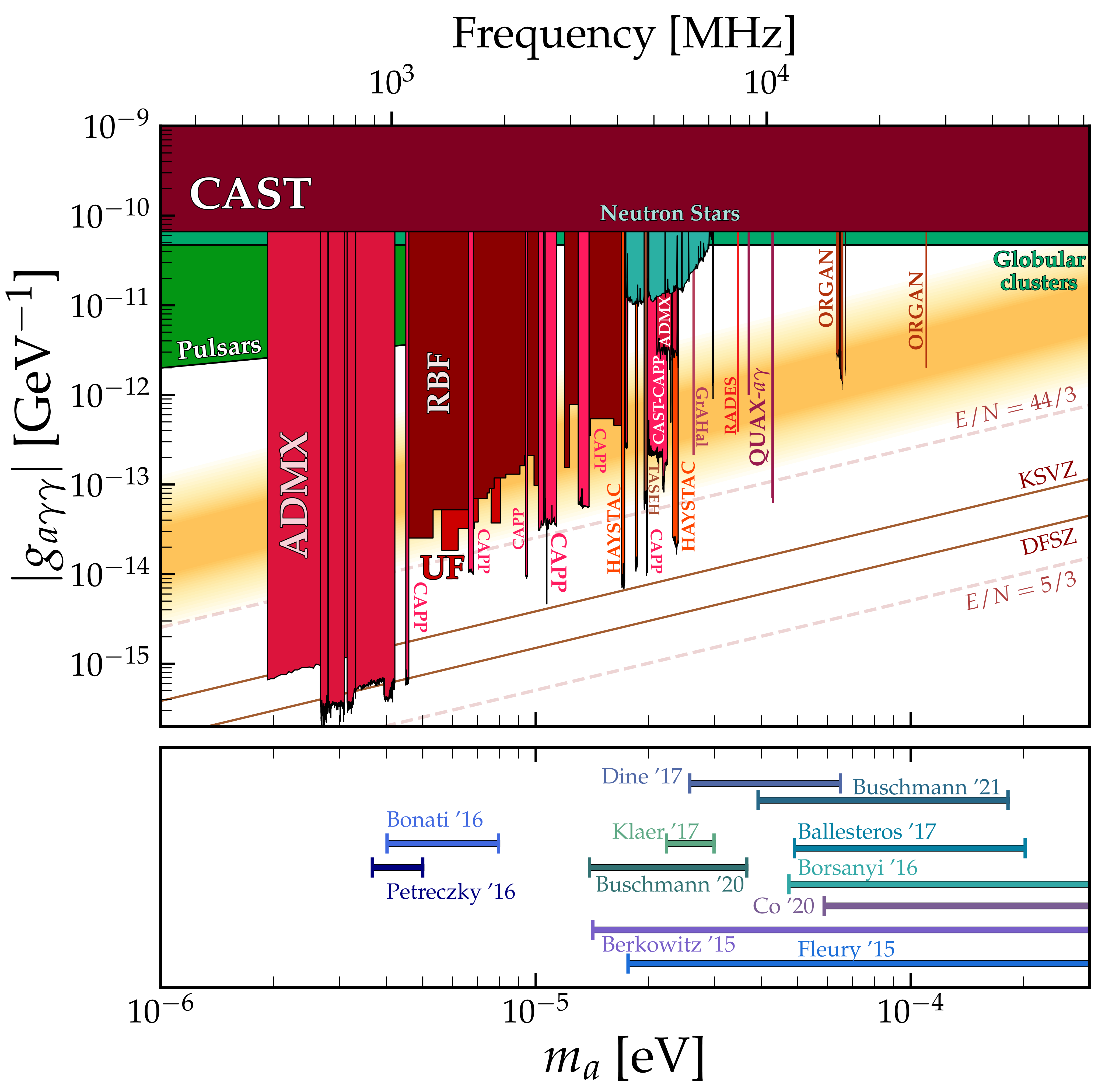
$$f_a \approx 10^{10}\,\mathrm{GeV}\left(\frac{0.6\mathrm{meV}}{m_a}\right)$$

- Viable **cold dark matter candidate** over a large mass range
- Induced coupling with **photons**

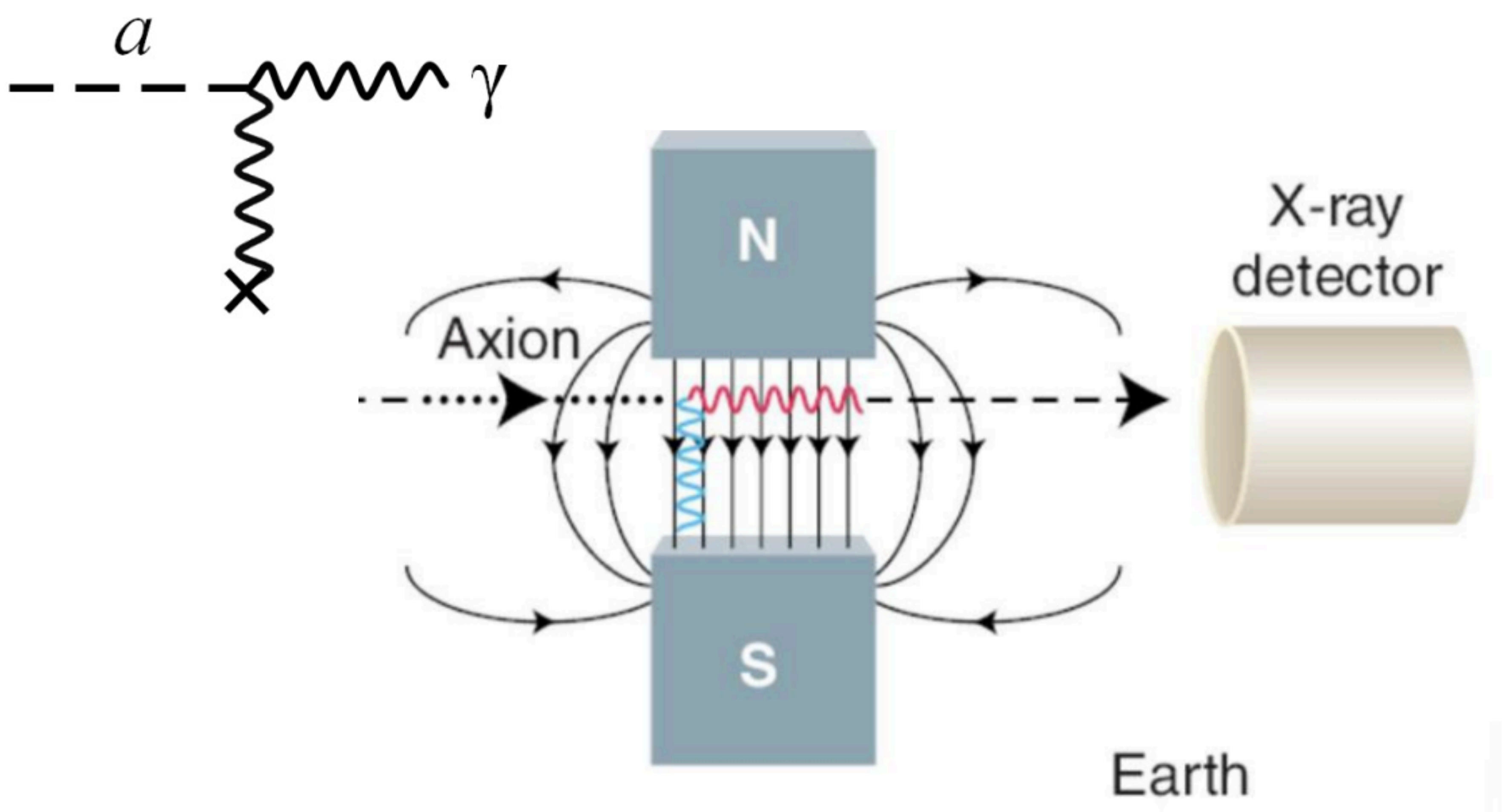
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}a$$

$$g_{a\gamma} = \frac{\alpha_{\mathrm{em}}}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$

The QCD axion



https://github.com/cajohare/AxionLimits



Sikivie PRL'83

A diversified LAB-search program:

- **Haloscopes**: Dark matter axion conversion in B field (ADMX, HAYSTAC, DMRadio, etc) $\sim g_{a\gamma}^2 \rho_{\rm DM}$
- **Helioscopes**: Axions from the Sun converting in B field (CAST, IAXO) $\sim g_{a\gamma}^4$

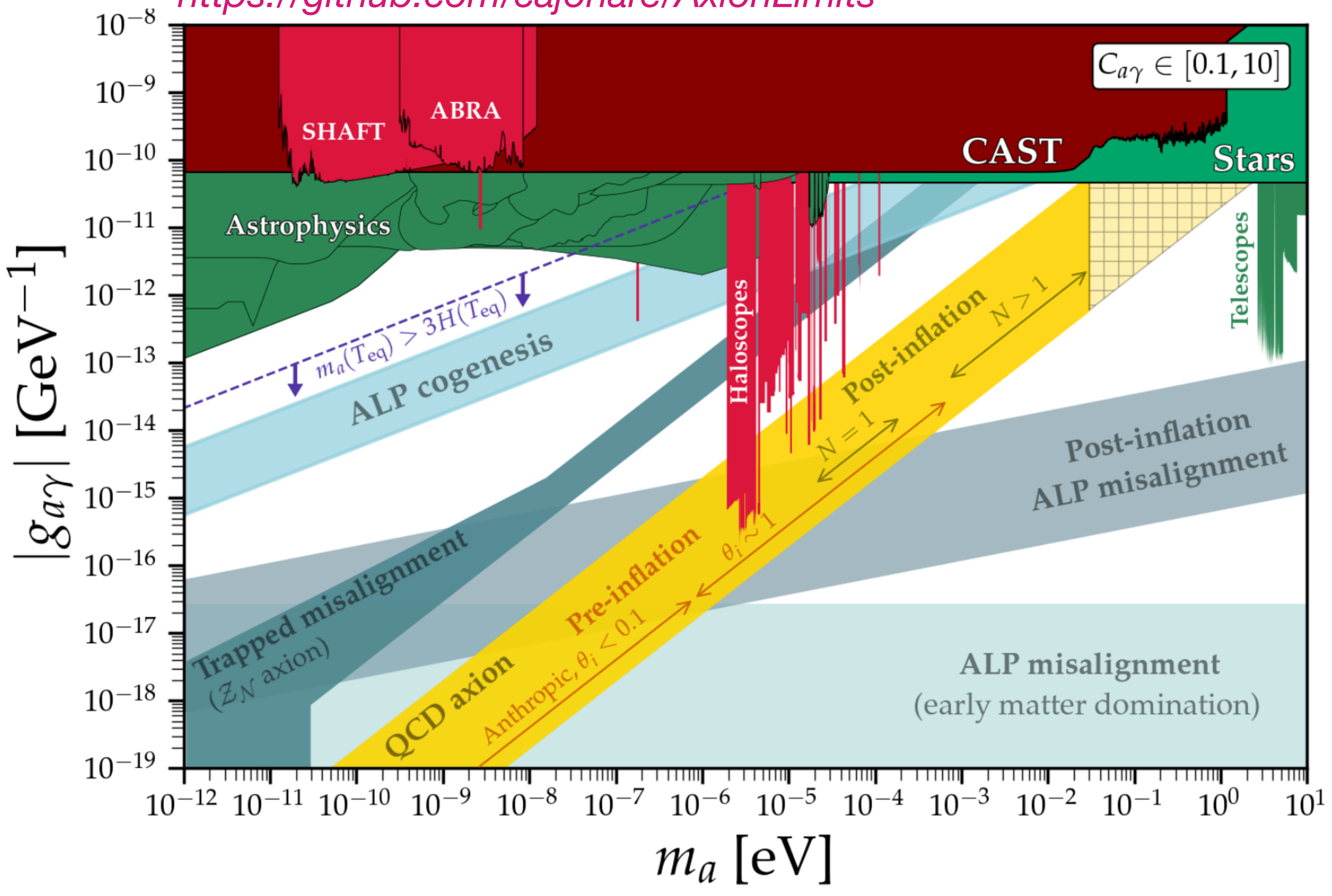
Several detection methods are systematically probing QCD axions

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

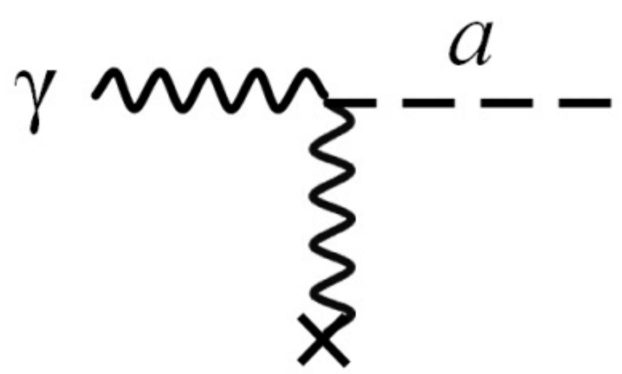
https://github.com/cajohare/AxionLimits



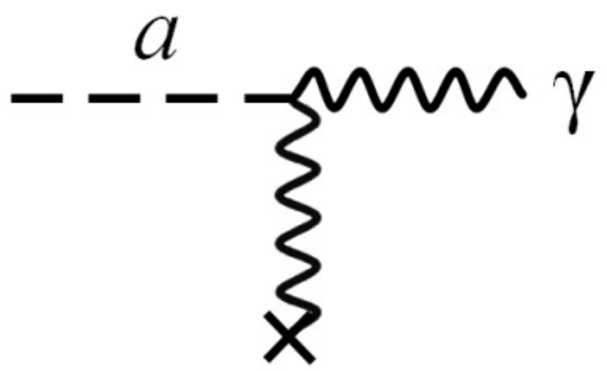
Quick ID:

- **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**
- They can be **viable dark matter candidates**

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



The ALP-photon mixing



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**:

$$\left(i\frac{\mathrm{d}}{\mathrm{d}x_3} + E + \mathcal{M}_0\right)\begin{pmatrix} A_1(x_3) \\ A_2(x_3) \\ a(x_3) \end{pmatrix} = 0$$

Schrödinger-like equation of motion

$$\mathcal{M}_0 = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_{||} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_\perp \equiv \Delta_{\rm pl} + \Delta_\perp^{\rm CM} + \Delta_{\rm CMB} \qquad \Delta_{||} \equiv \Delta_{\rm pl} + \Delta_{||}^{\rm CM} + \Delta_{\rm CMB}$$

$$\Delta_{\rm QED} = |\Delta_\perp^{\rm CM} - \Delta_{||}^{\rm CM}| \propto B_T^2$$

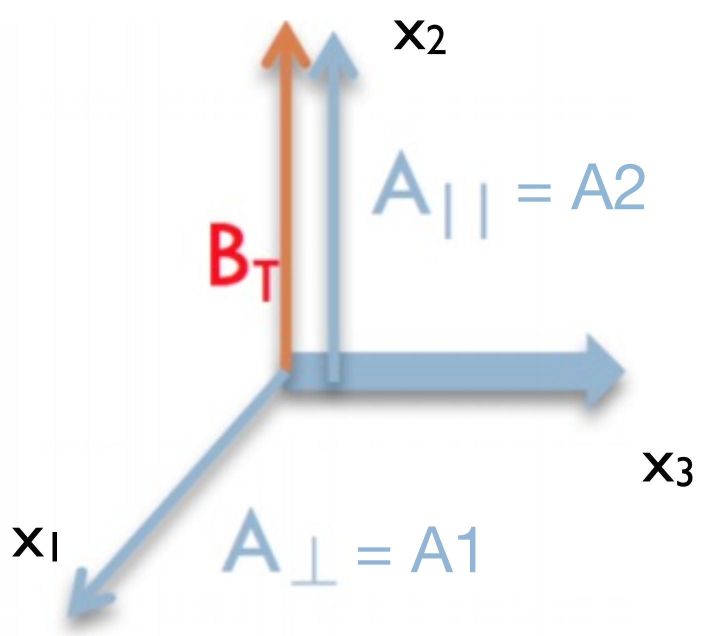
$$\Delta_{a\gamma} \simeq 1.5 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-9}\,\mathrm{G}}\right)\mathrm{Mpc}^{-1},$$

$$\Delta_a \simeq -3.2 \times 10^{1} \left(\frac{m_a}{2\times 10^{-8}\mathrm{eV}}\right)^2\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\mathrm{Mpc}^{-1},$$

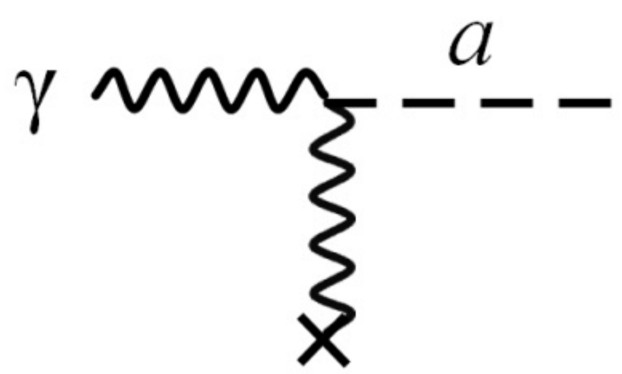
$$\Delta_{\rm pl} \simeq -1.1 \times 10^{-7} \left(\frac{E}{\mathrm{TeV}}\right)^{-1}\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)\mathrm{Mpc}^{-1},$$

$$\Delta_{\rm QED} \simeq 4.1 \times 10^{-9} \left(\frac{E}{\mathrm{TeV}}\right)\left(\frac{B_T}{10^{-9}\,\mathrm{G}}\right)^2\mathrm{Mpc}^{-1},$$

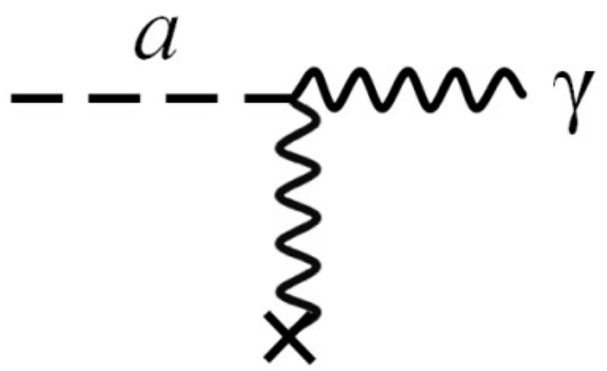
$$\Delta_{\rm CMB} \simeq 0.80 \times 10^{-1} \left(\frac{E}{\mathrm{TeV}}\right)\mathrm{Mpc}^{-1}\ .$$



Raffelt & Stodolsky PRD'88; Horns+PRD'12; Montanino+ PRL'17



The ALP-photon mixing



Considering the propagation of **purely polarised photon beam** ($A_{\parallel}$) in a **single magnetic domain L** with a **coherent B-field**, the propagation equations reduce to a 2-dimensional problem:

$$\frac{1}{2}\tan(2\theta) = \frac{\Delta_{a\gamma}}{\Delta_{||} - \Delta_a}$$

Rotation angle to diagonalise mixing matrix

In analogy with neutrino oscillations:

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

Probability for purely polarised photon beam ($A_{\parallel}$) to oscillate into an ALP after distance d

e.g. Mirizzi & Montanino JCAP'09

$$\Delta_{a\gamma} \gg \Delta_{||} - \Delta_a$$

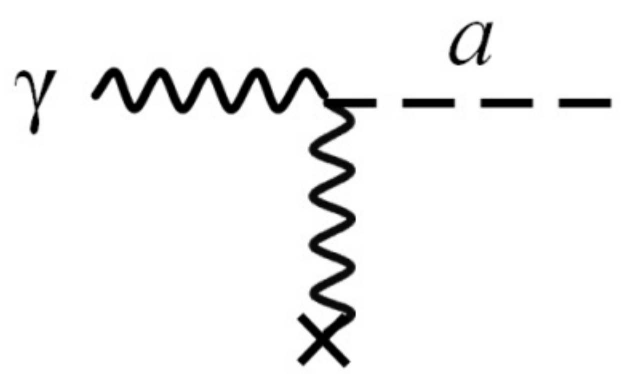
Mixing is maximum **Strong mixing regime**

$$\Delta_{a\gamma} \ll \Delta_{||} - \Delta_a$$

Either plasma effects or CMB dominate suppressing the probability

$$\Delta_{\rm osc} \equiv \left[(\Delta_{||} - \Delta_a)^2 + 4\Delta_{a\gamma}^2\right]^{1/2}$$

Oscillation regime



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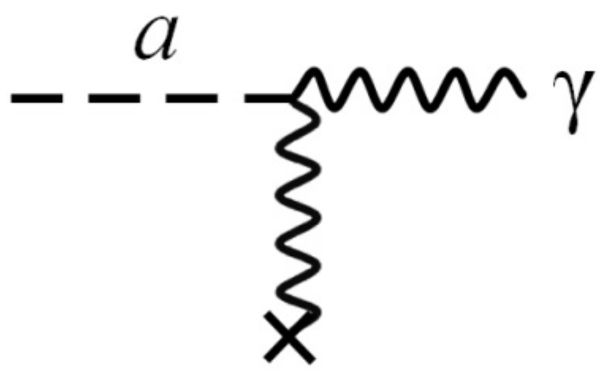

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$$P_{a\gamma} = (\Delta_{a\gamma} L)^2 \frac{\sin^2(\Delta_{\rm osc} L/2)}{(\Delta_{\rm osc} L/2)^2}$$

For low-energies, massless ALPs and sufficiently low couplings

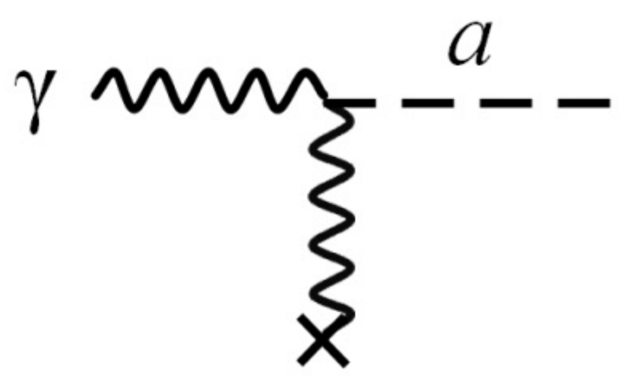
$$\Delta_{a\gamma} \equiv \frac{g_{a\gamma} B_T}{2}$$

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

$$\omega_{\rm pl}^2 = \frac{4\pi\alpha n_e}{m_e}$$

Oscillation wave number

$$L_{\rm osc} = \frac{2\pi}{\Delta_{\rm osc}}$$



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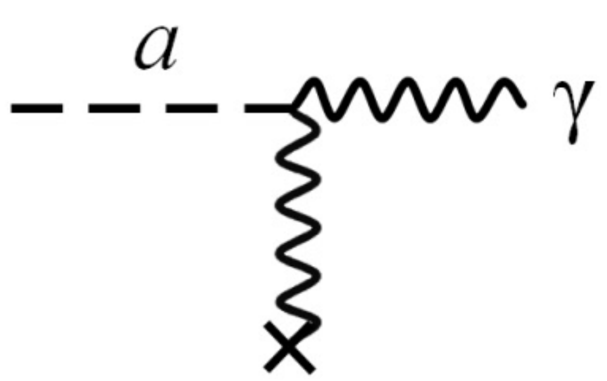

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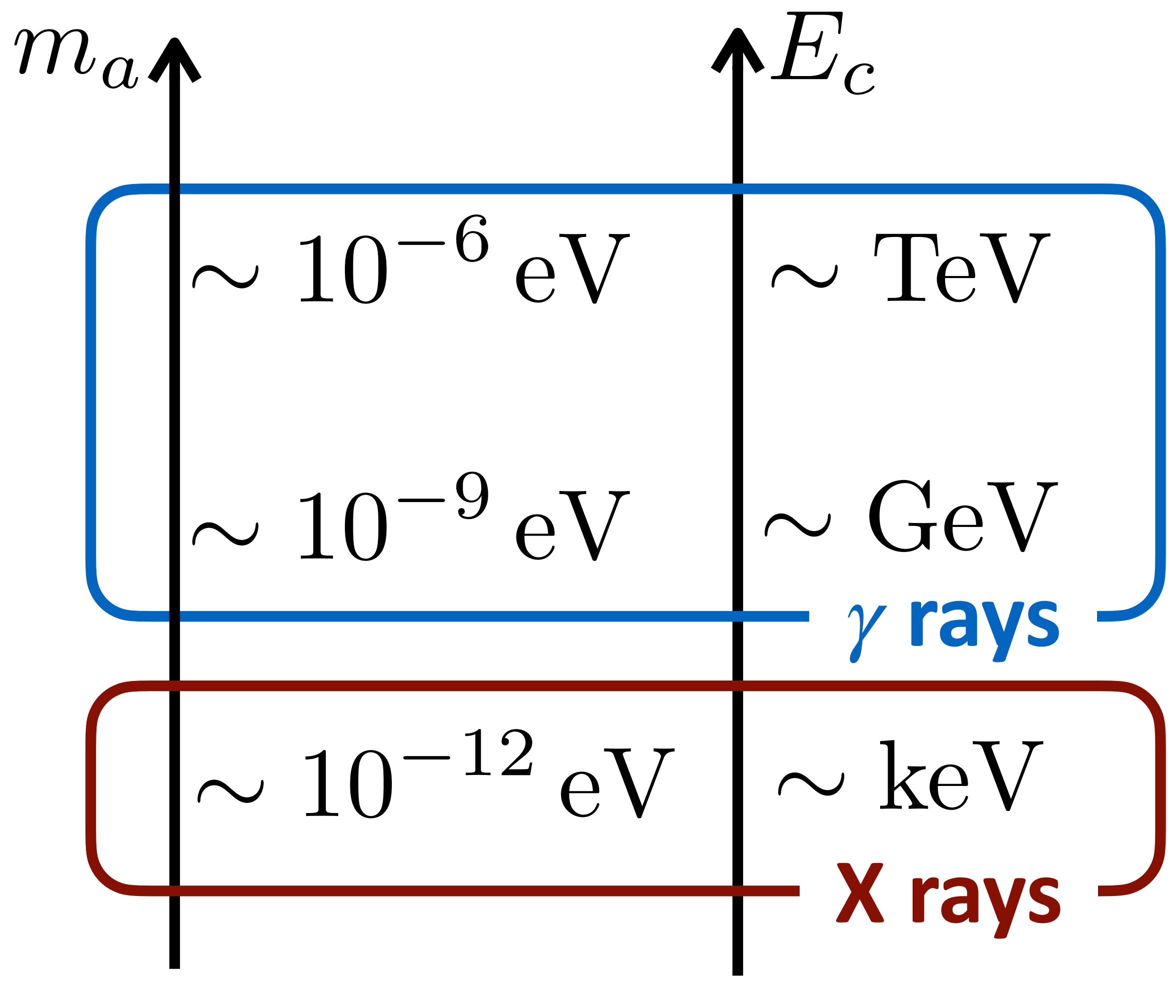
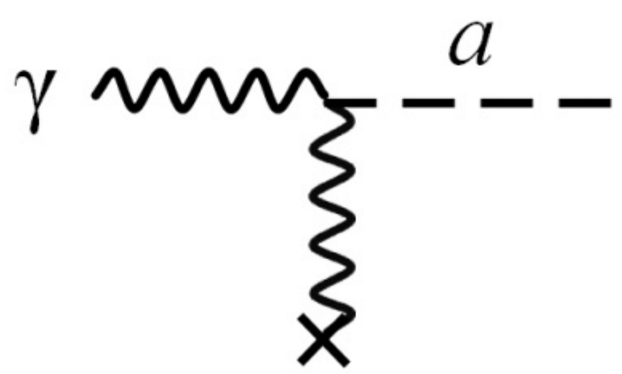
For low-energies, massless ALPs and sufficiently low couplings

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

$$E_c = 2.5\,{\rm GeV}\left(\frac{{\rm m}_a^2 - \omega_{\rm pl}^2}{1\,{\rm neV}^2}\right)\left(\frac{1\,\mu{\rm G}}{{\rm B_T}}\right)\left(\frac{10^{-11}\,{\rm GeV}^{-1}}{{\rm g}_{a\gamma}}\right)$$

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





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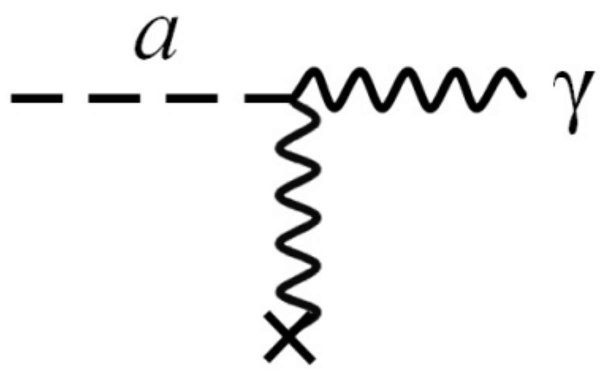

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$$\Delta_{\rm osc} = 2\Delta_{a\gamma}\sqrt{1 + \left(\frac{E_c}{E}\right)^2}$$

For low-energies, massless ALPs and sufficiently low couplings

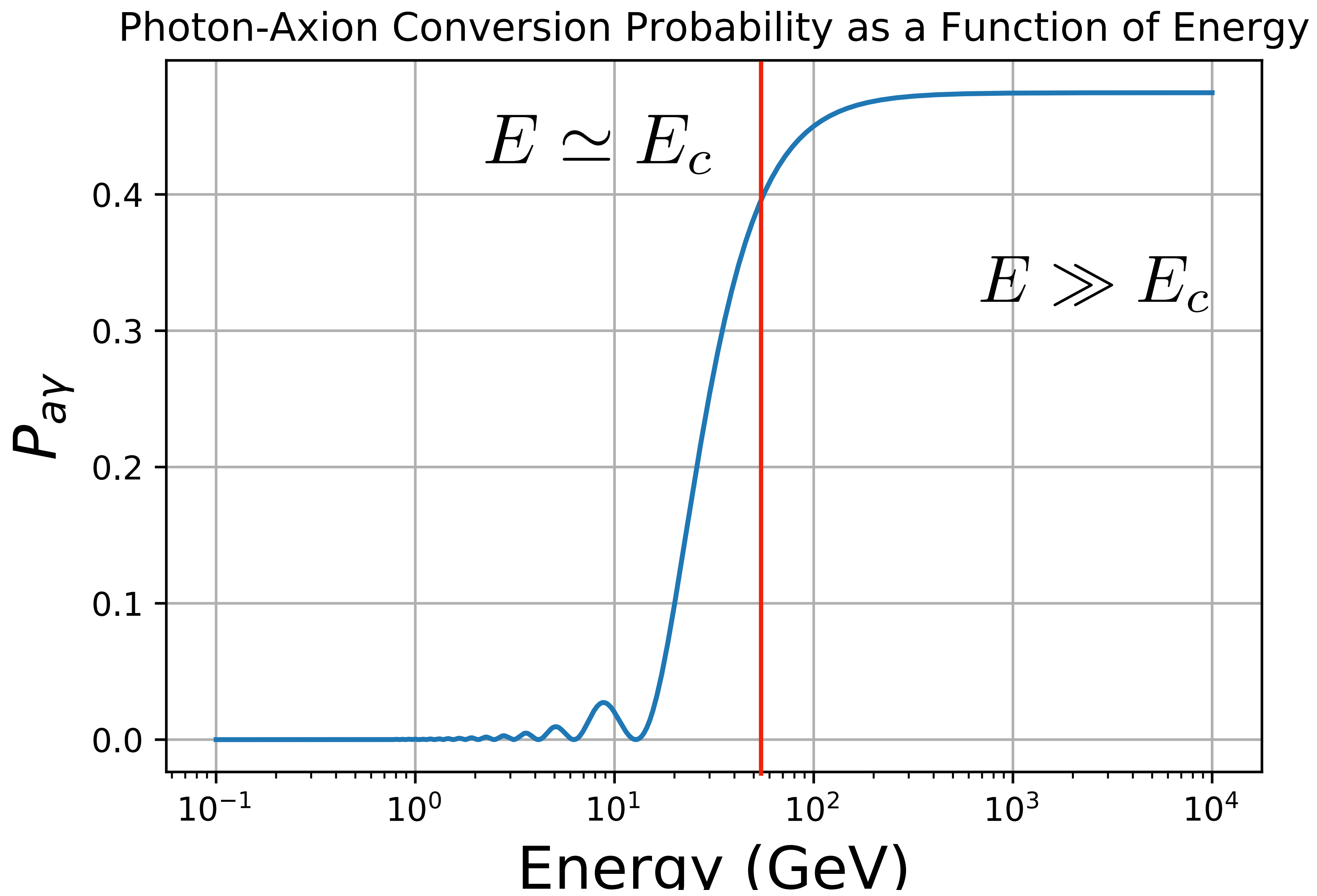
$E \gg E_c$ →

$\Delta_{\rm osc} \simeq 2\Delta_{a\gamma}$ **Strong mixing regime**

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

$E \simeq E_c$ →

Oscillation regime

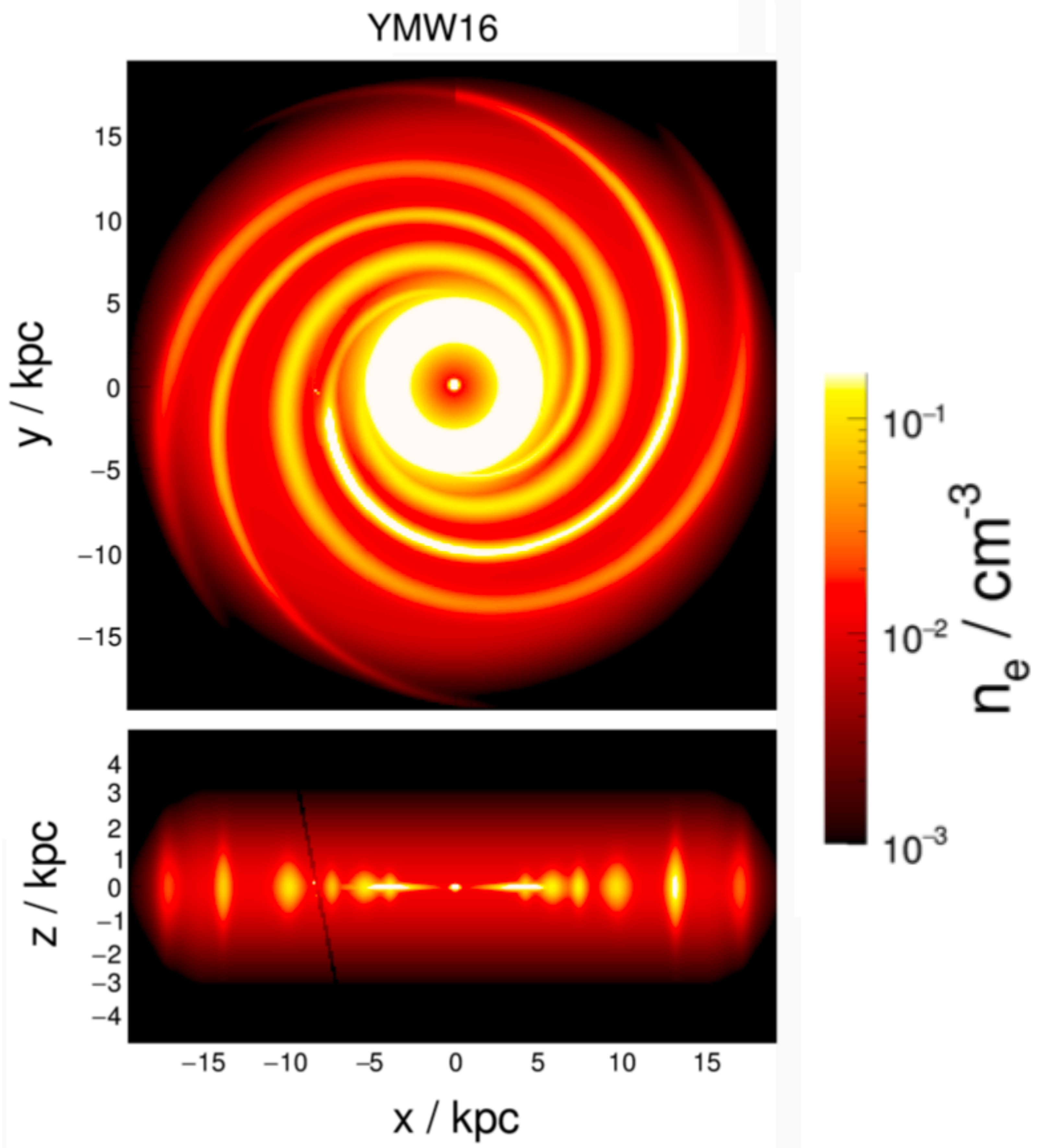


Going beyond the ideal case

- Fluctuations in the free electron density
- Stochasticity of the turbulent B-field component**
- Limitations of domain-like approximation
- Photon absorption at the highest energies**

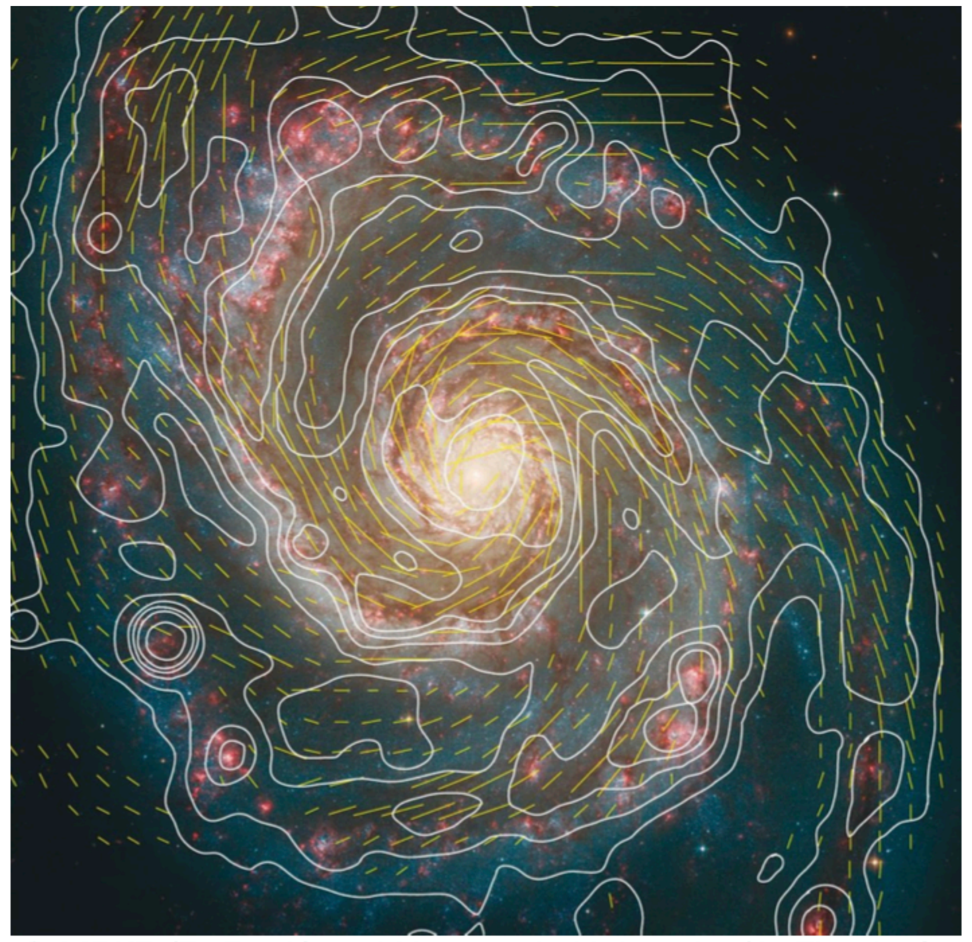
(…)

In all cases, **realistic models of magnetic field configurations** are required



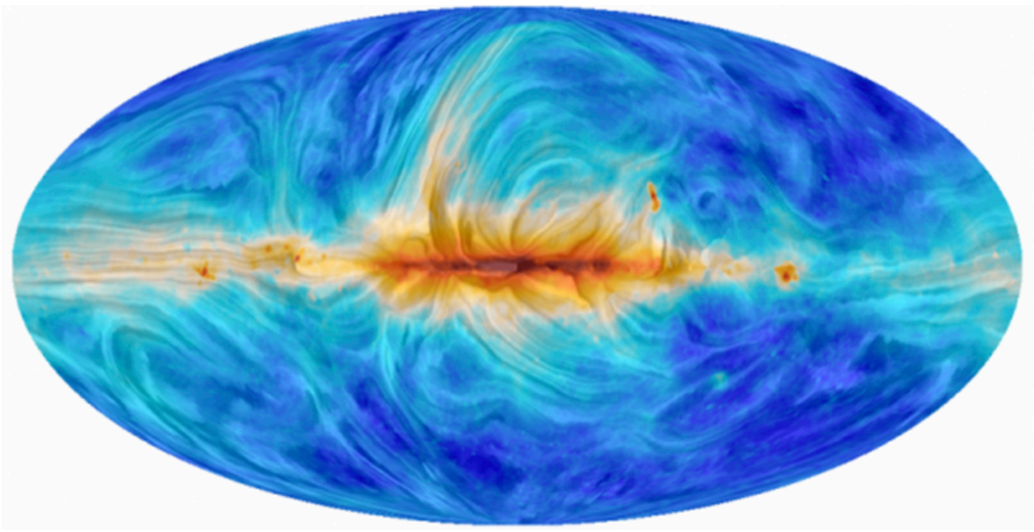
The Galactic magnetic field

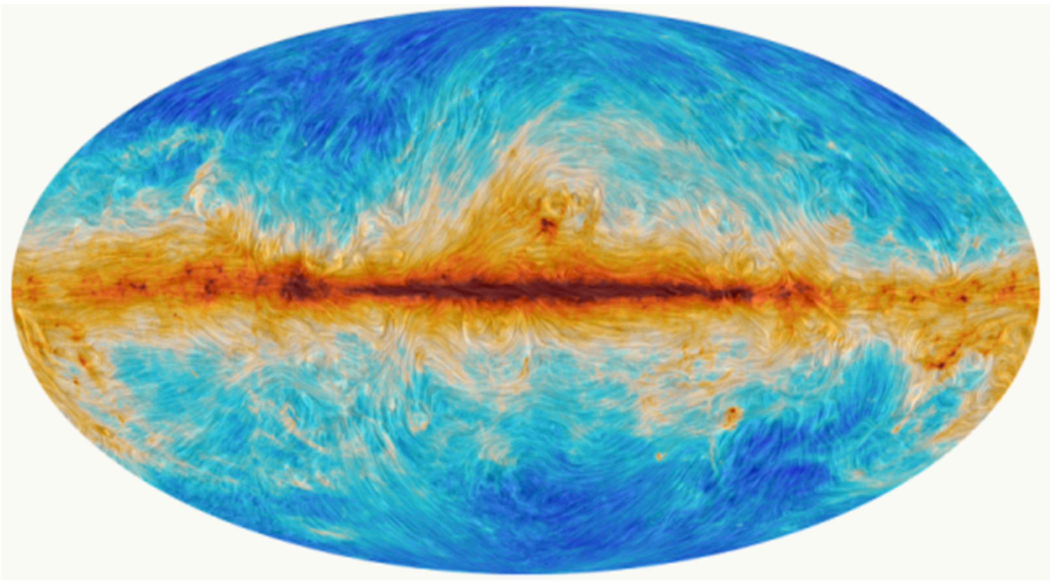
Observables


© MPIfR (R. Beck) and Newcastle University (A. Fletcher)

In external galaxies:

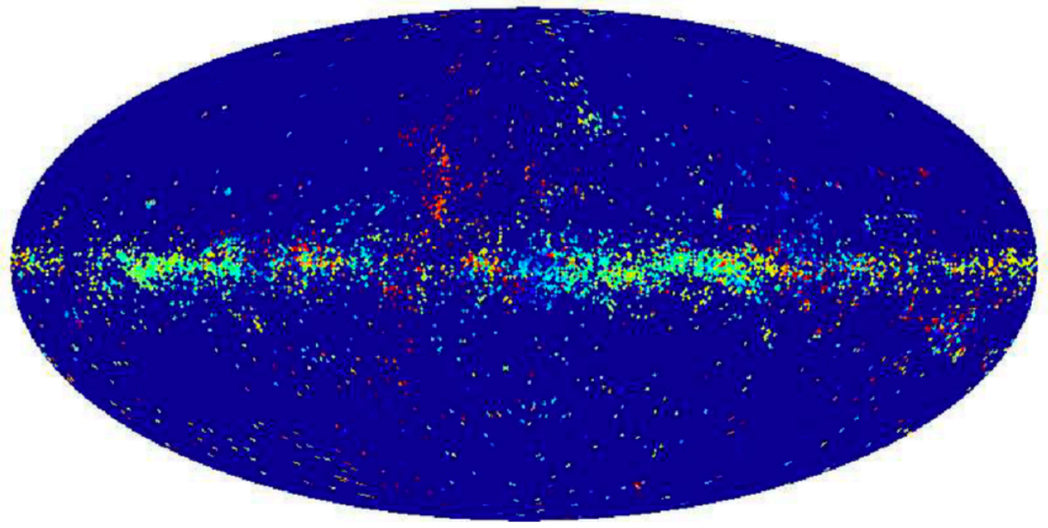
- Magnetic fields aligned with matter spiral structure
- Evidence for vertical fields

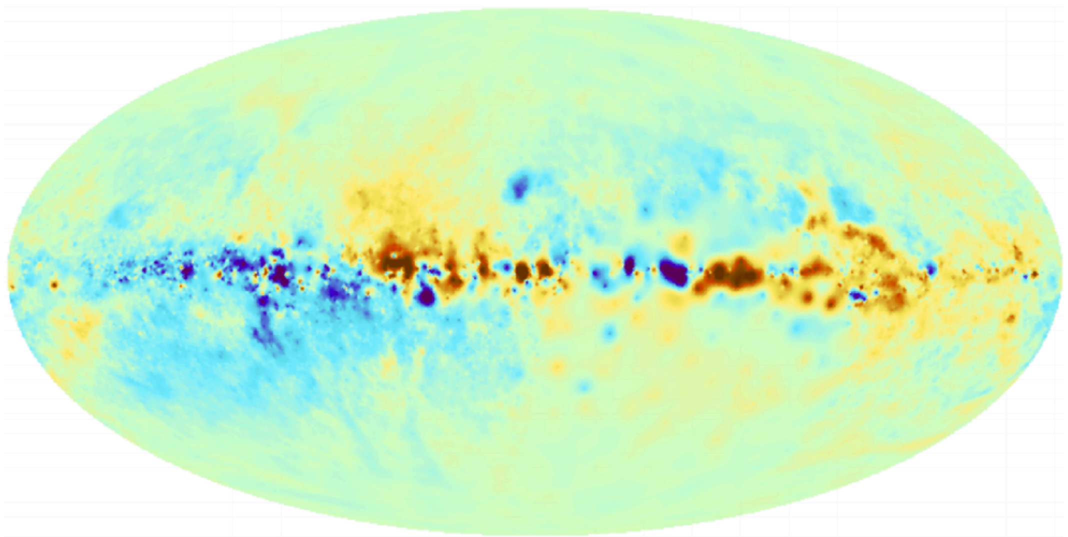




We can access the Milky-Way B-field through:

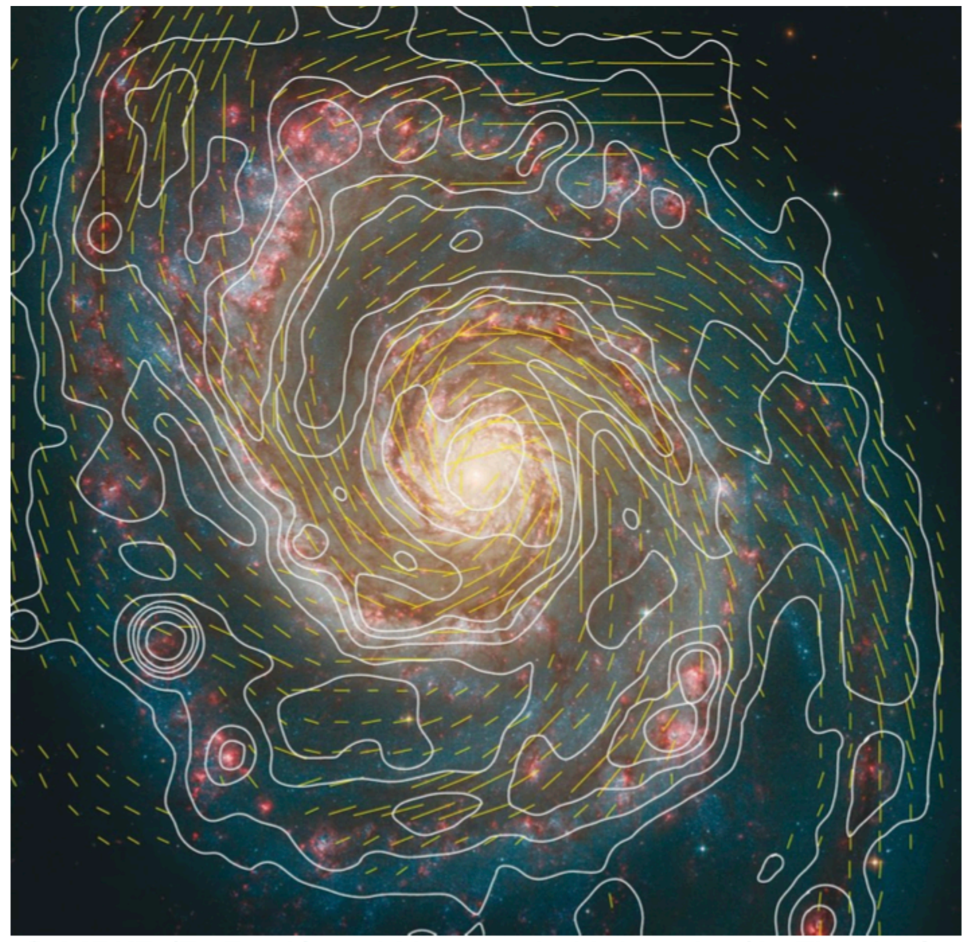
- Polarised synchrotron emission (radio to μ-waves)
- Polarised dust emission (sub-mm)
- Starlight polarisation
- Faraday rotation





The Galactic magnetic field

Observables



© MPIfR (R. Beck) and Newcastle University (A. Fletcher)

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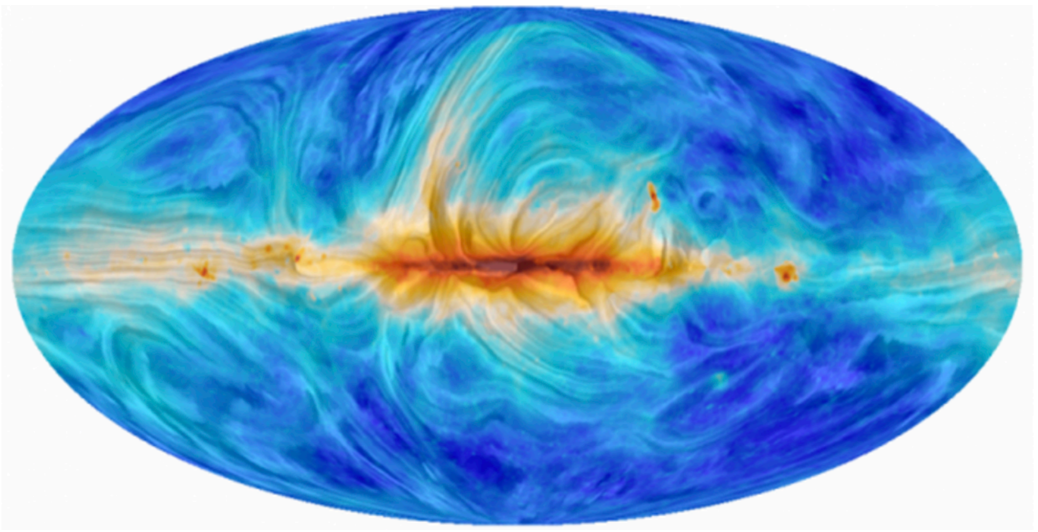

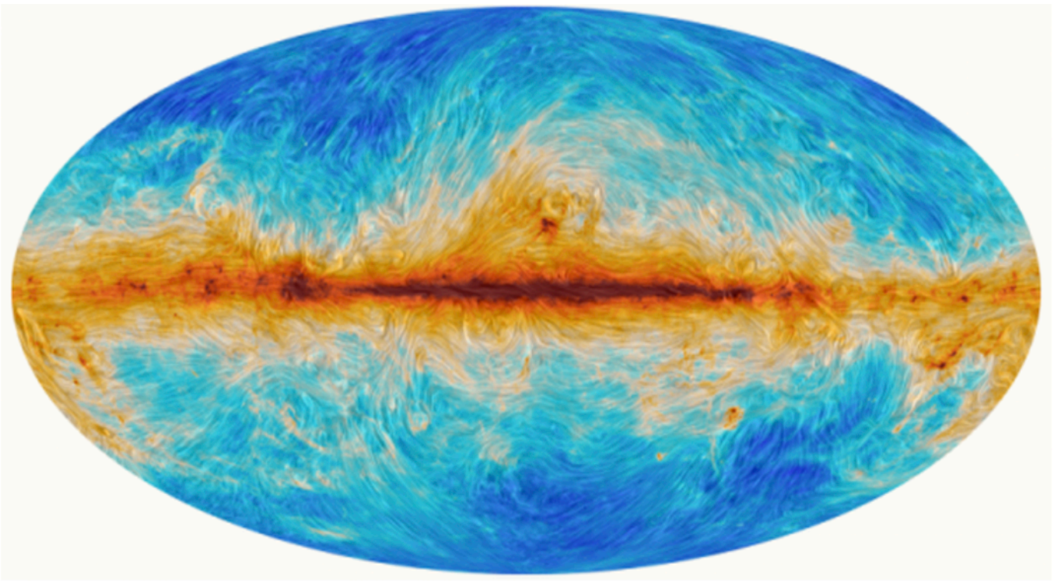

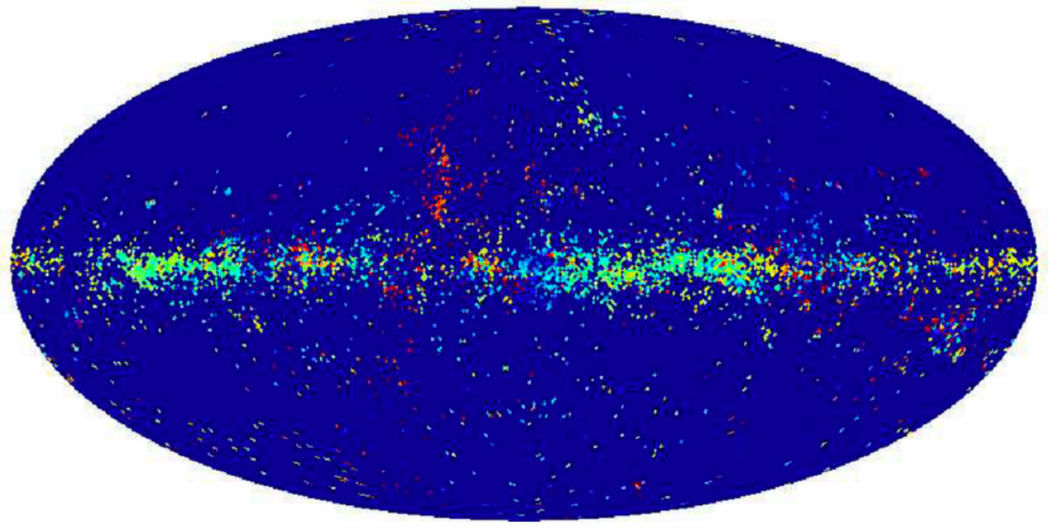

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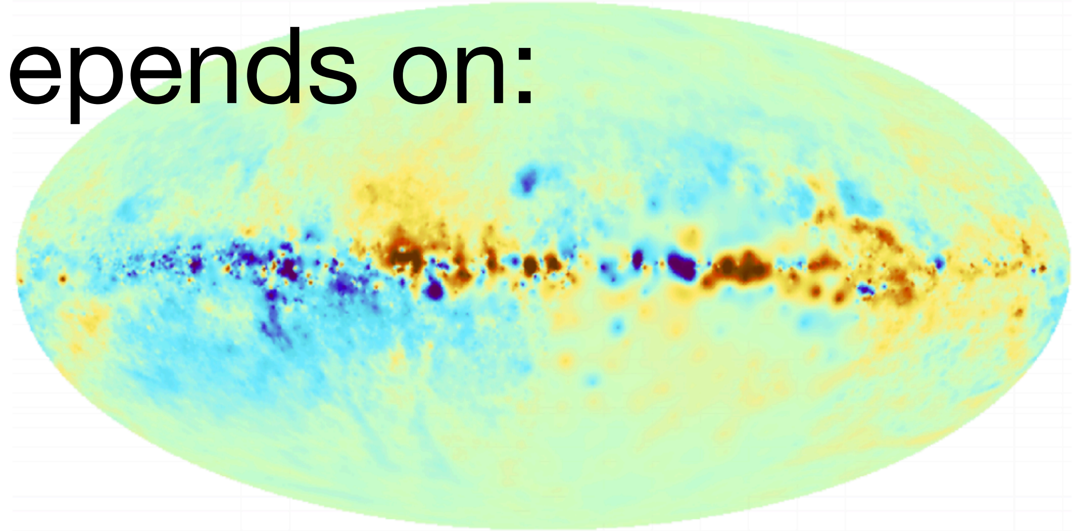
- Faraday rotation

Sensitivity to B perpendicular to l.o.s

Challenge: Reconstruction depends on:

- CR spatial distribution
- CR spectral distribution

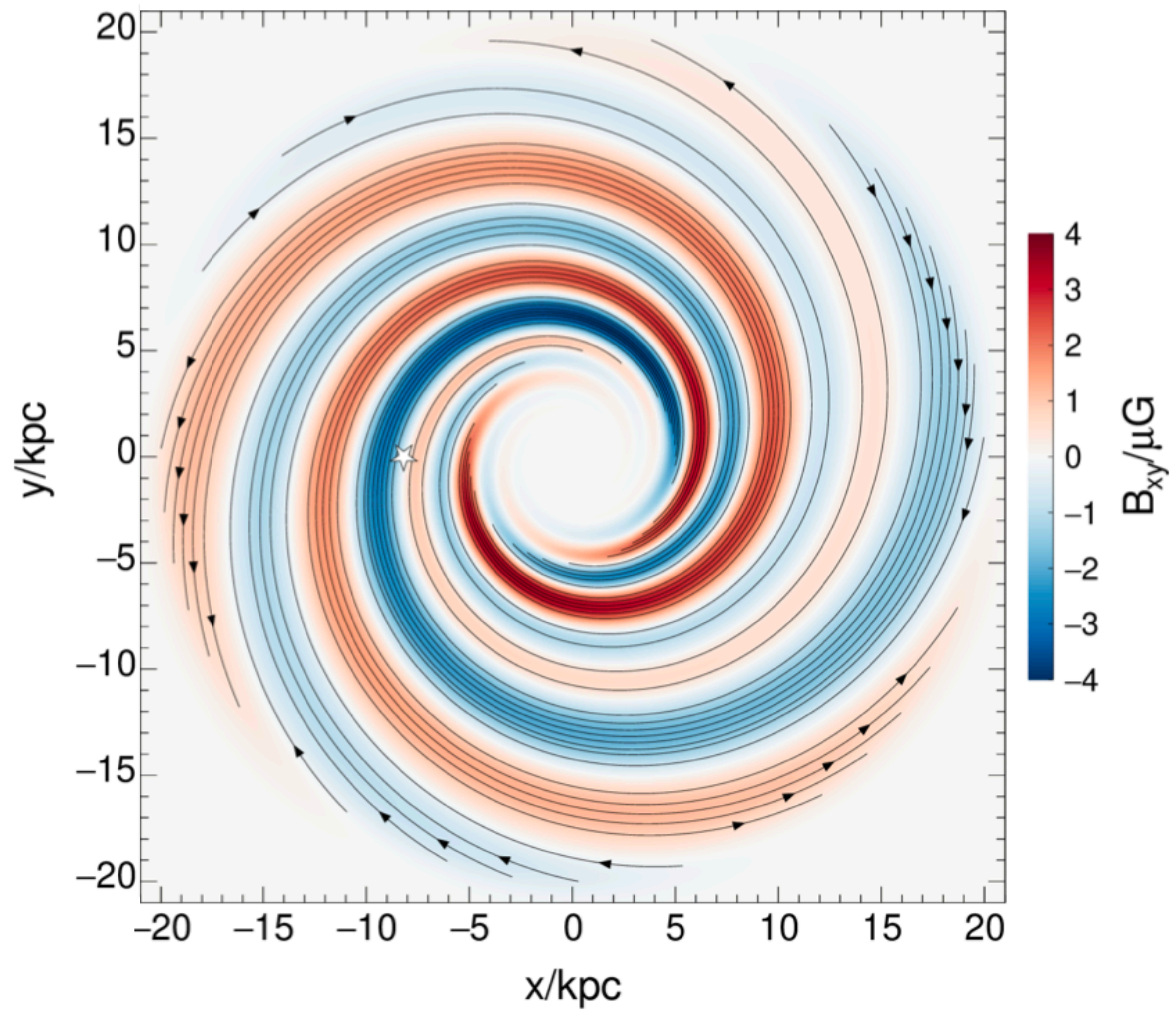


The Galactic magnetic field

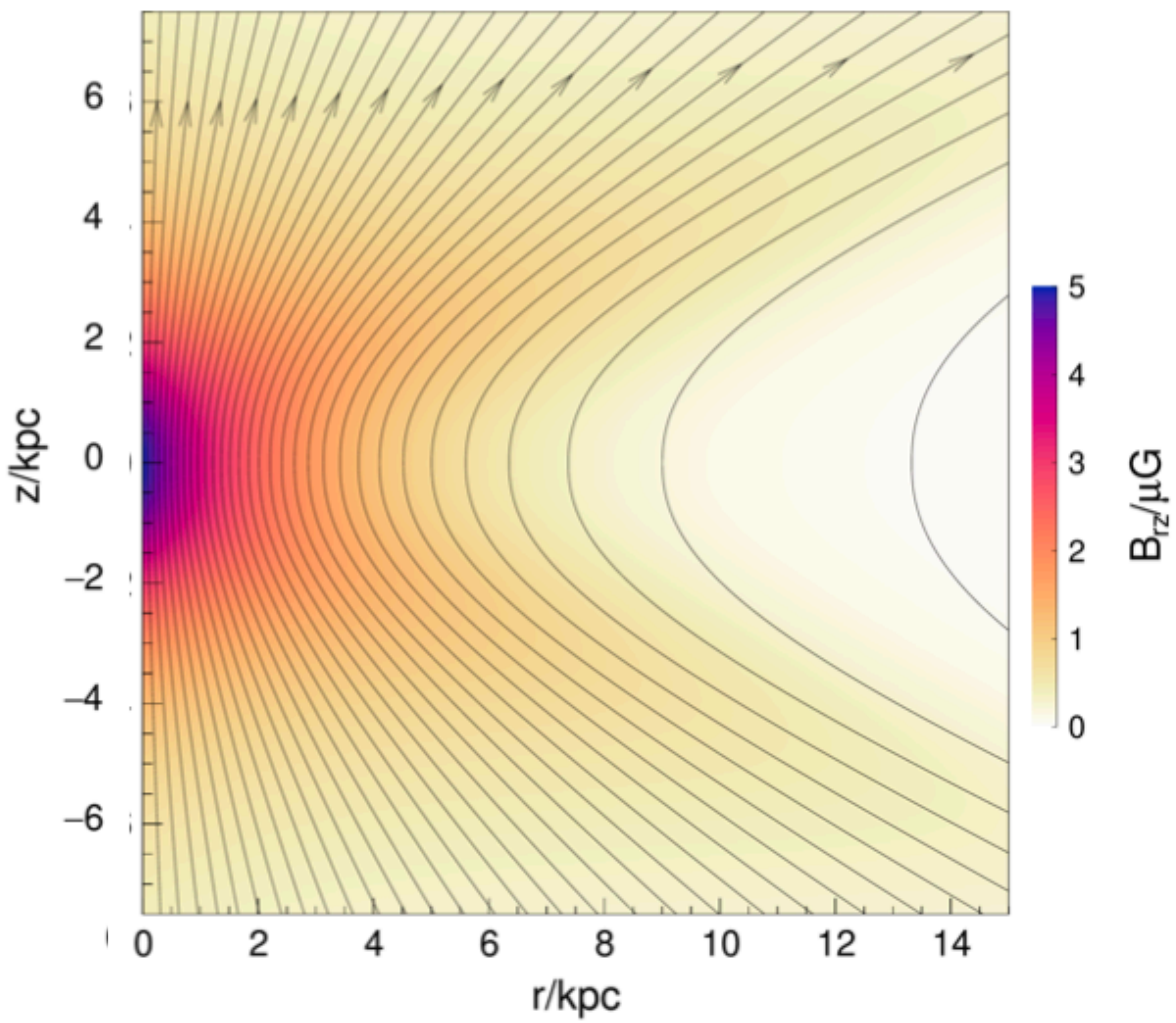
Components of regular, ordered field

Unger & Farrar ApJ'23

Disk, spiral arms structure

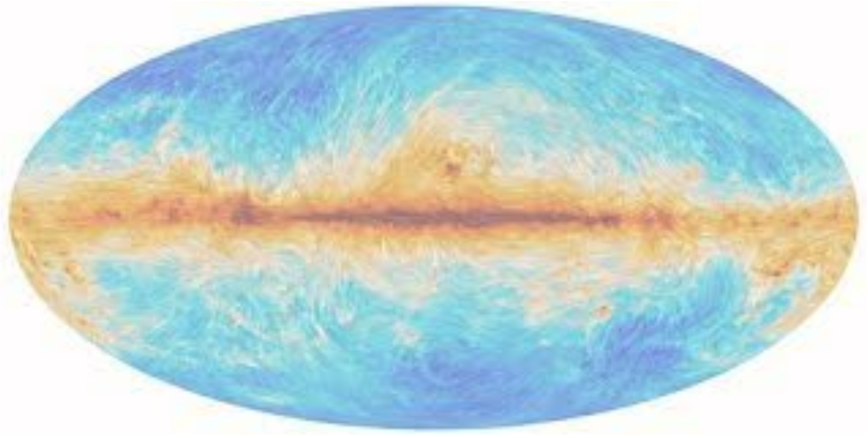


Toroidal and poloidal halo components

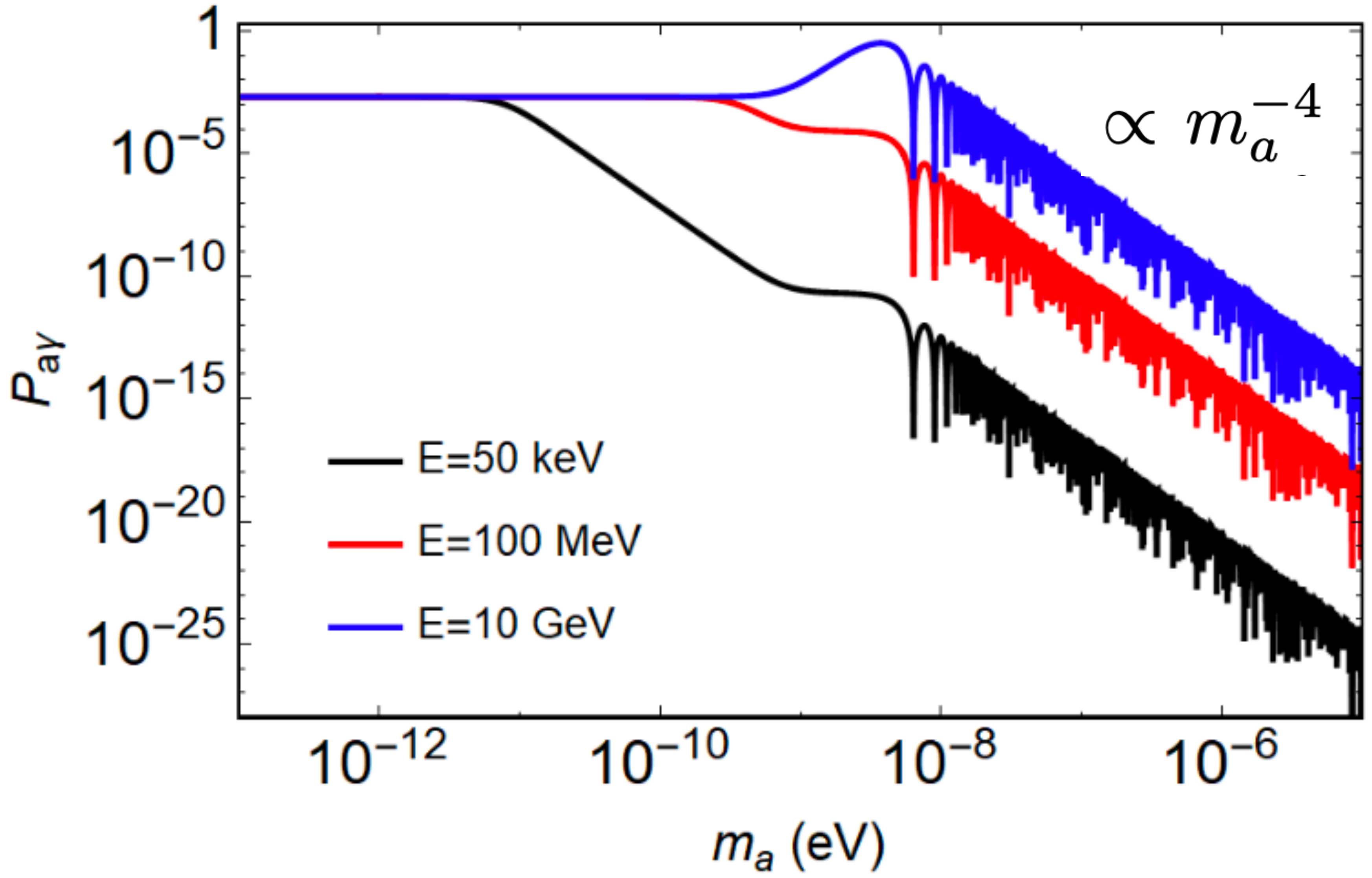


Turbulent, random field: Similar strengths but ℓ_{corr} ~20-200 pc

The Galactic conversion

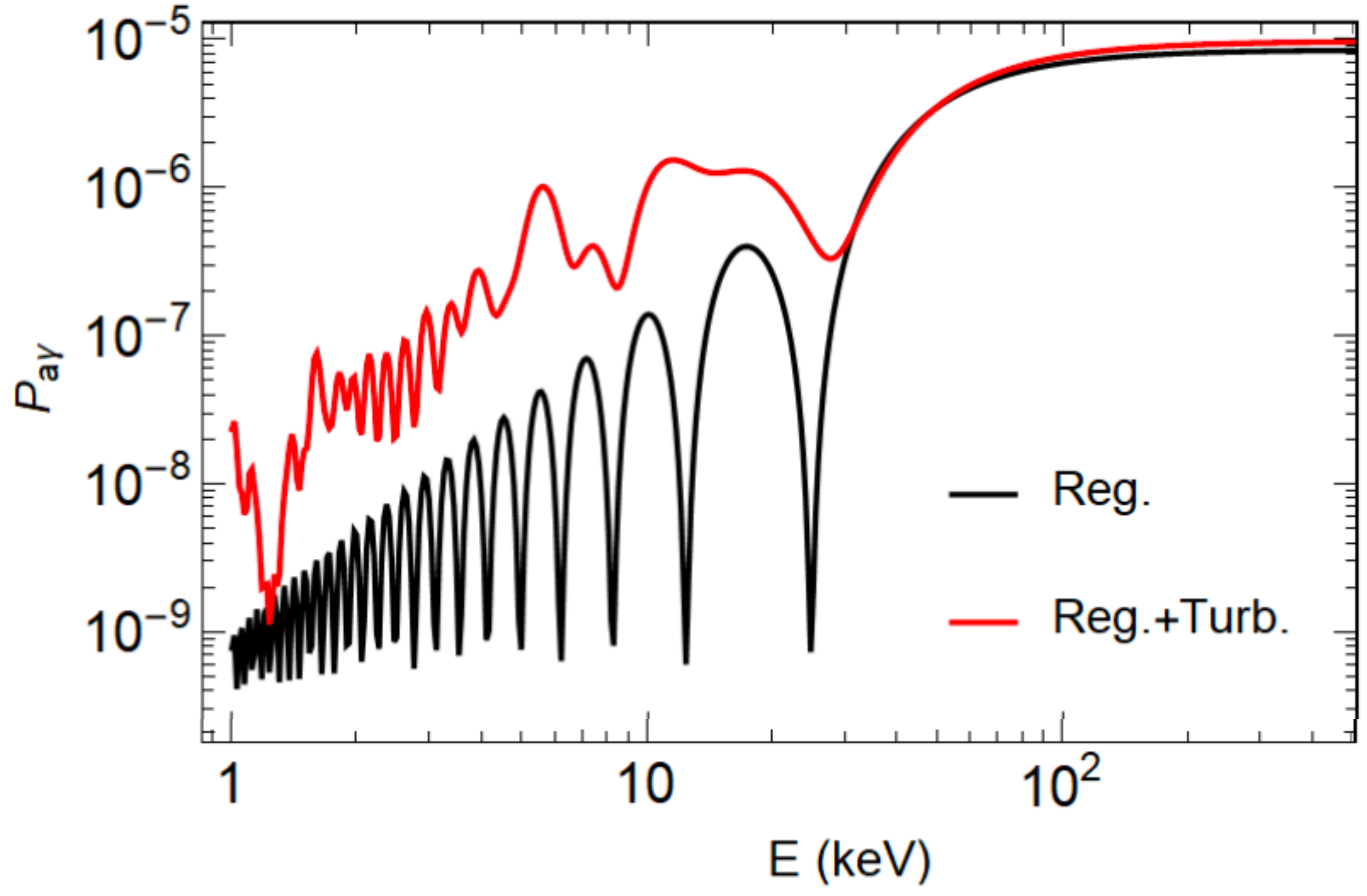


Conversions in the regular magnetic field



$$r = 1 \text{ kpc}$$
$$B_T = 3\ \mu\text{G}$$
$$g_{a\gamma} = 10^{-11}\text{GeV}^{-1}$$

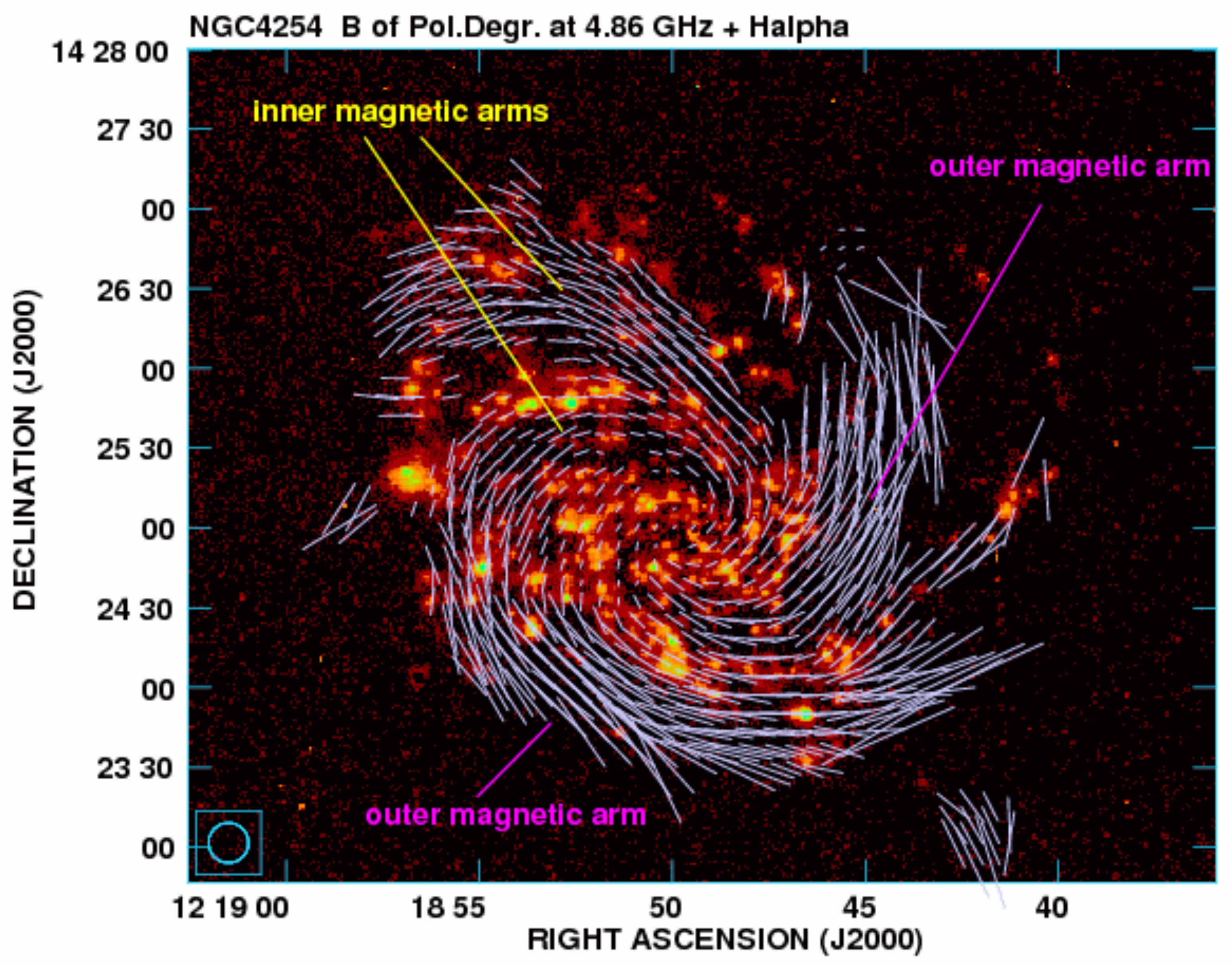
Relevance of turbulent component



$$B_{\rm rms} = 1\ \mu\text{G}$$
$$l_{\rm corr} = 10 \text{ pc}$$
$$l_{\rm osc} > l_{\rm corr}$$

Carenza+ PRD'21

The intra-cluster conversion

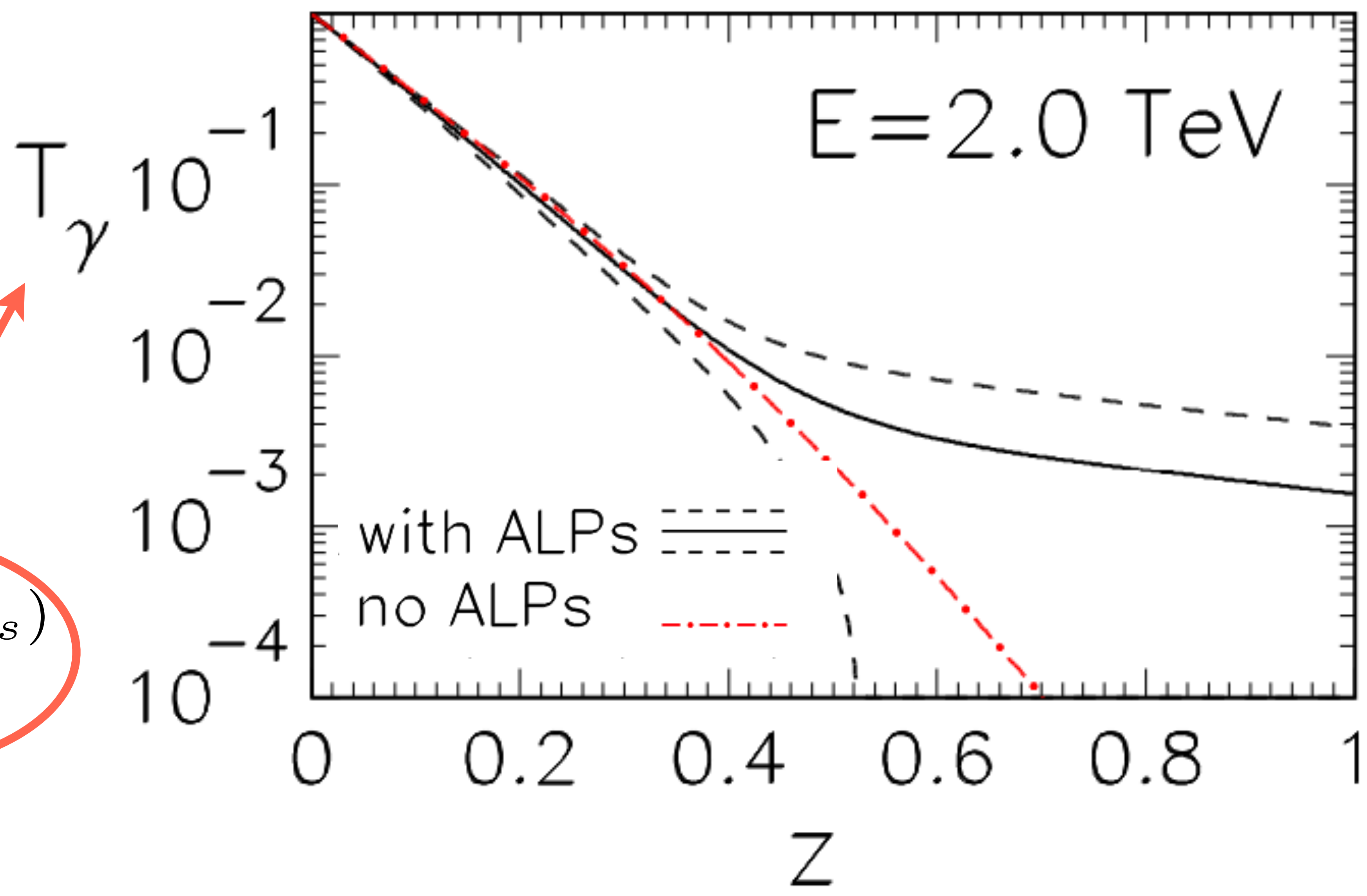


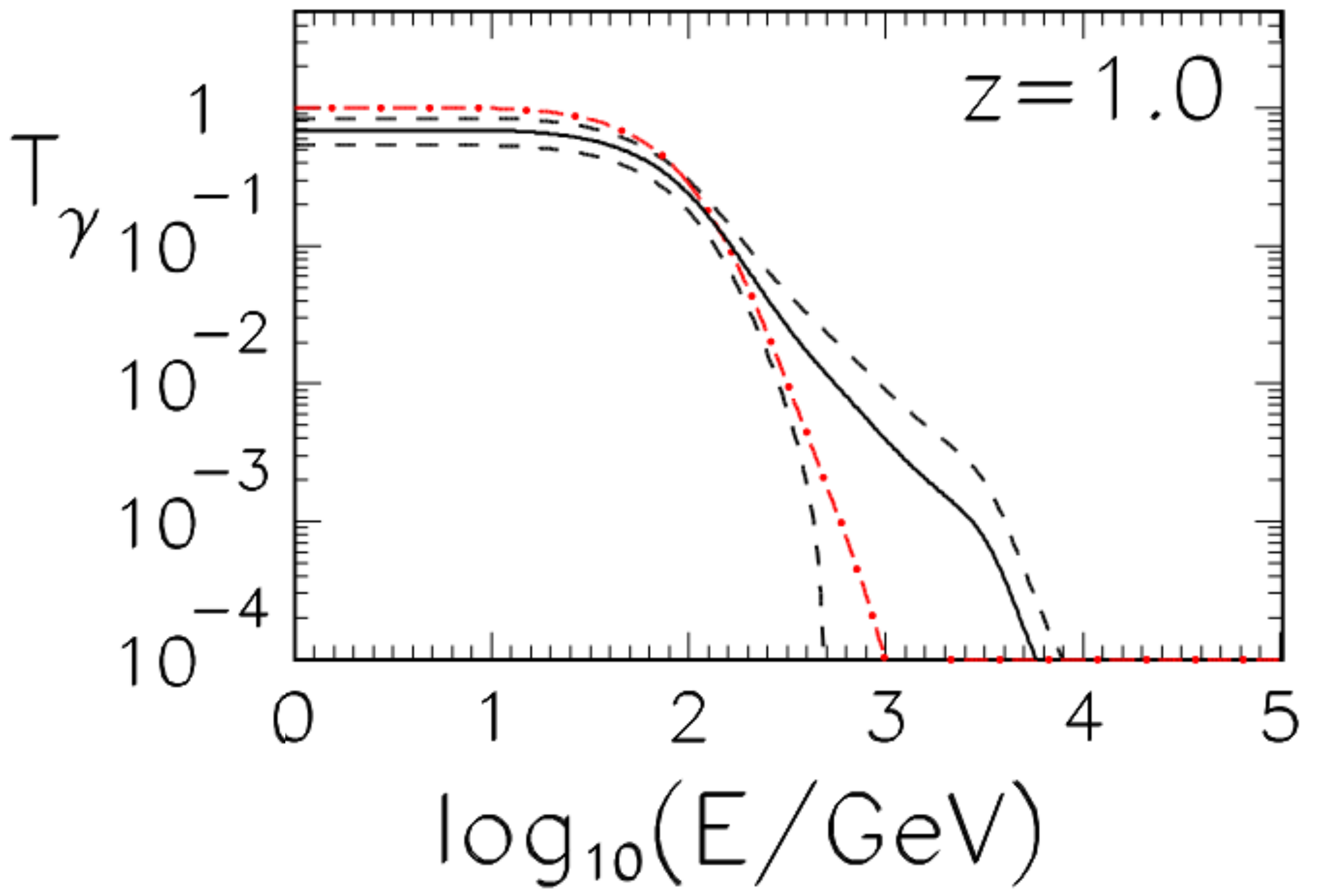
- **Turbulent fields** have a random configuration, constant over magnetic domains
- An **ensemble average** over all possible realisations is required on the N domains
- In absence of absorption the maximum of the transfer function is 2/3
- However, **large variance** of transfer function's values

Mirizzi & Montanino JCAP'09

Effect on the **transparency** of VHE photons

$$\Phi(E_\gamma, z_s) = \Phi(E_\gamma) \times e^{-\tau(E_\gamma, z_s)}$$

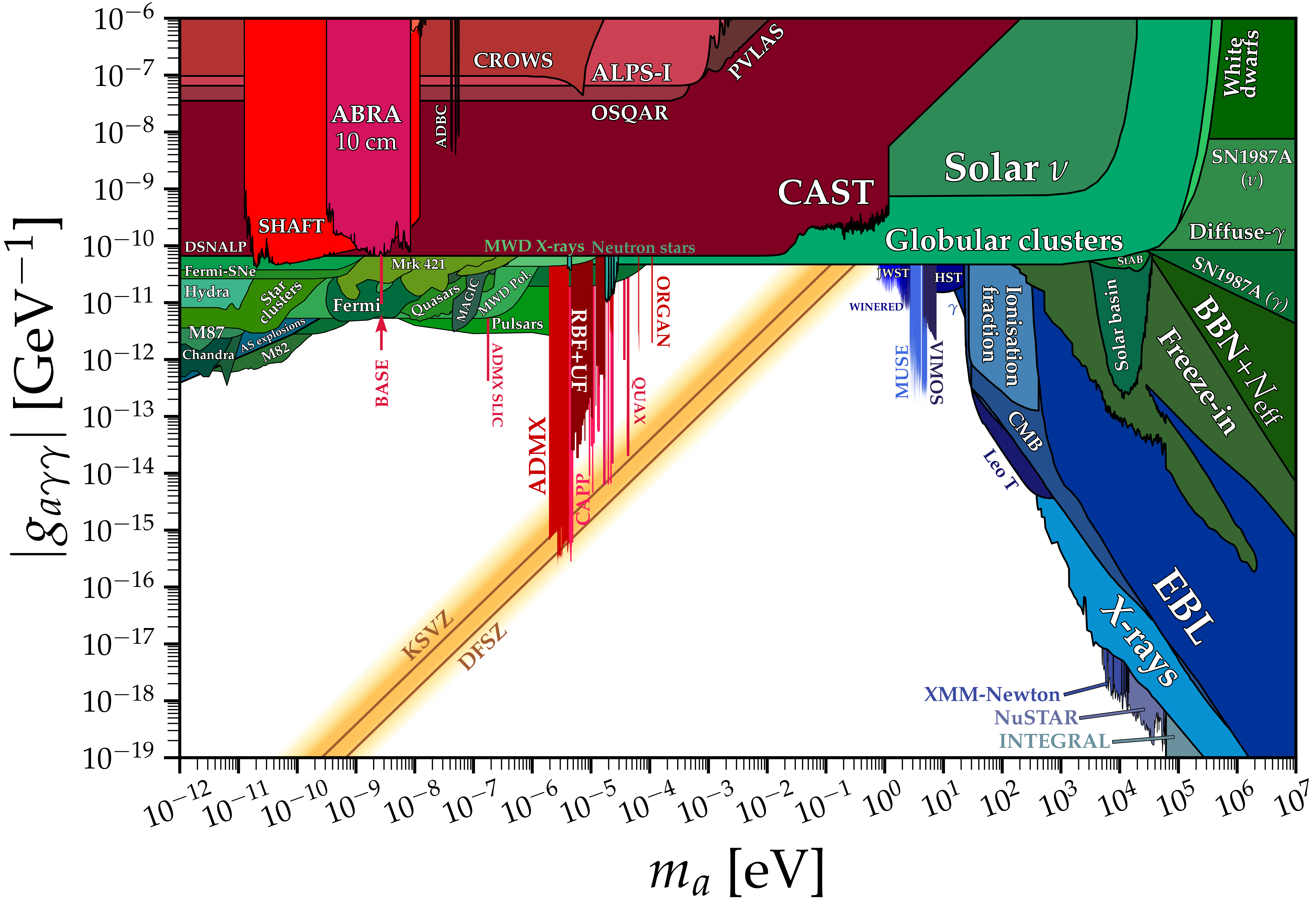




Signatures of ALP-photon conversion from different ALPs sources

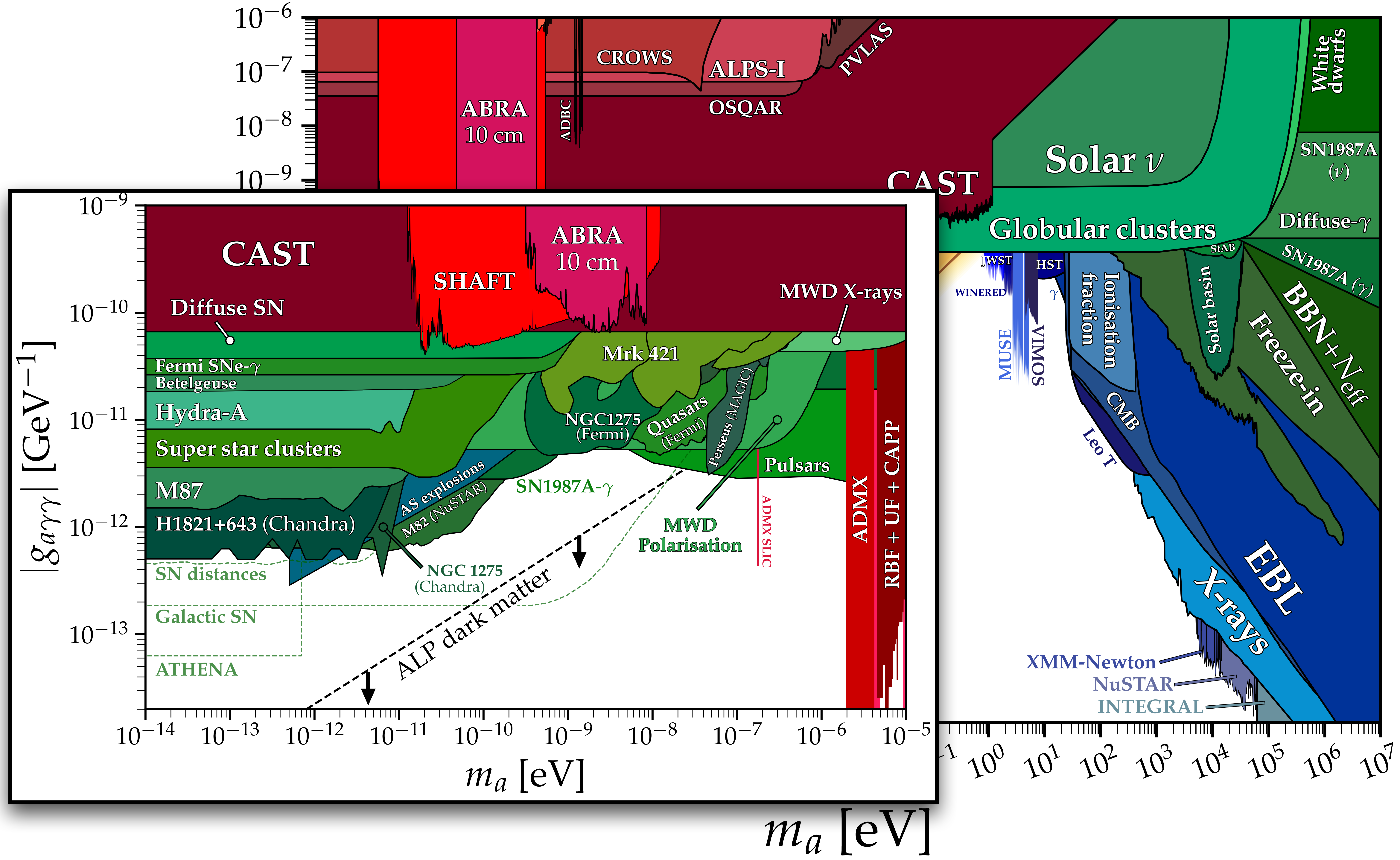
- ➡ **ALPs sources**
- ➡ **Photon production mechanism**
- ➡ **Signal modelling**
- ➡ **Analysis**

Constraints on ALP-photon mixing



https://github.com/cajohare/AxionLimits

Constraints on ALP-photon mixing



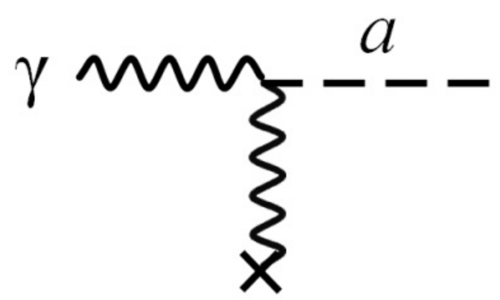
https://github.com/cajohare/AxionLimits

Signatures from ALPs?

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

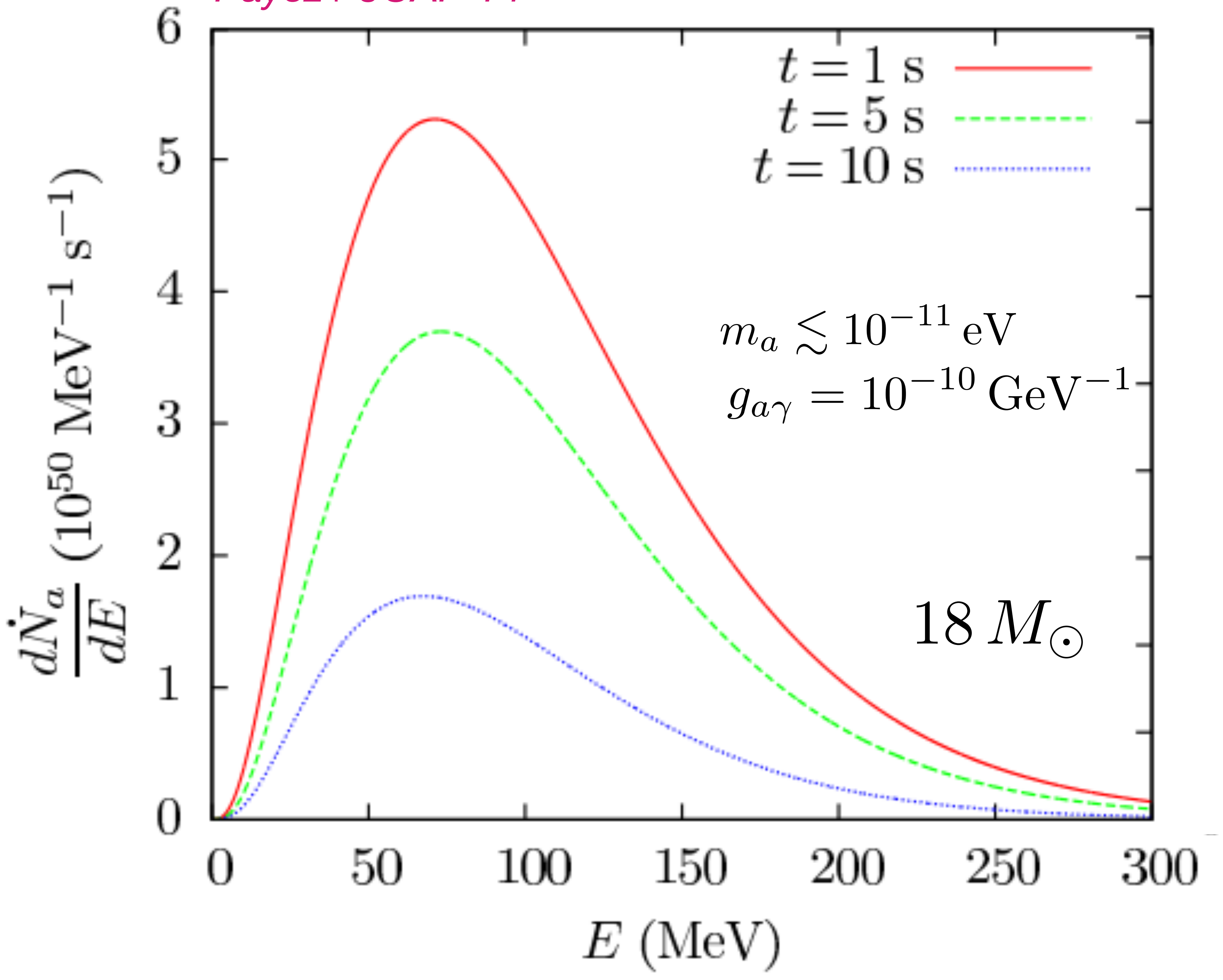
Focus **High-energy photons (X to gamma rays)**

ALPs production in CC SNe



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

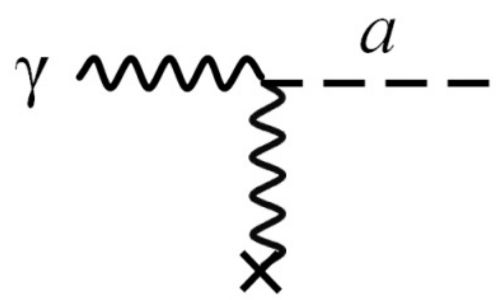
Payez+ JCAP'14



- ALPs produced from thermal photons in the fluctuating electromagnetic fields of the stellar plasma
- Dominant process for MS stars (like Sun) or HB stars

[Not only cc-SN: proto-neutron stars, mains-sequence stars, white dwarfs, etc; If present NN bremsstrahlung dominates]

ALPs production in CC SNe



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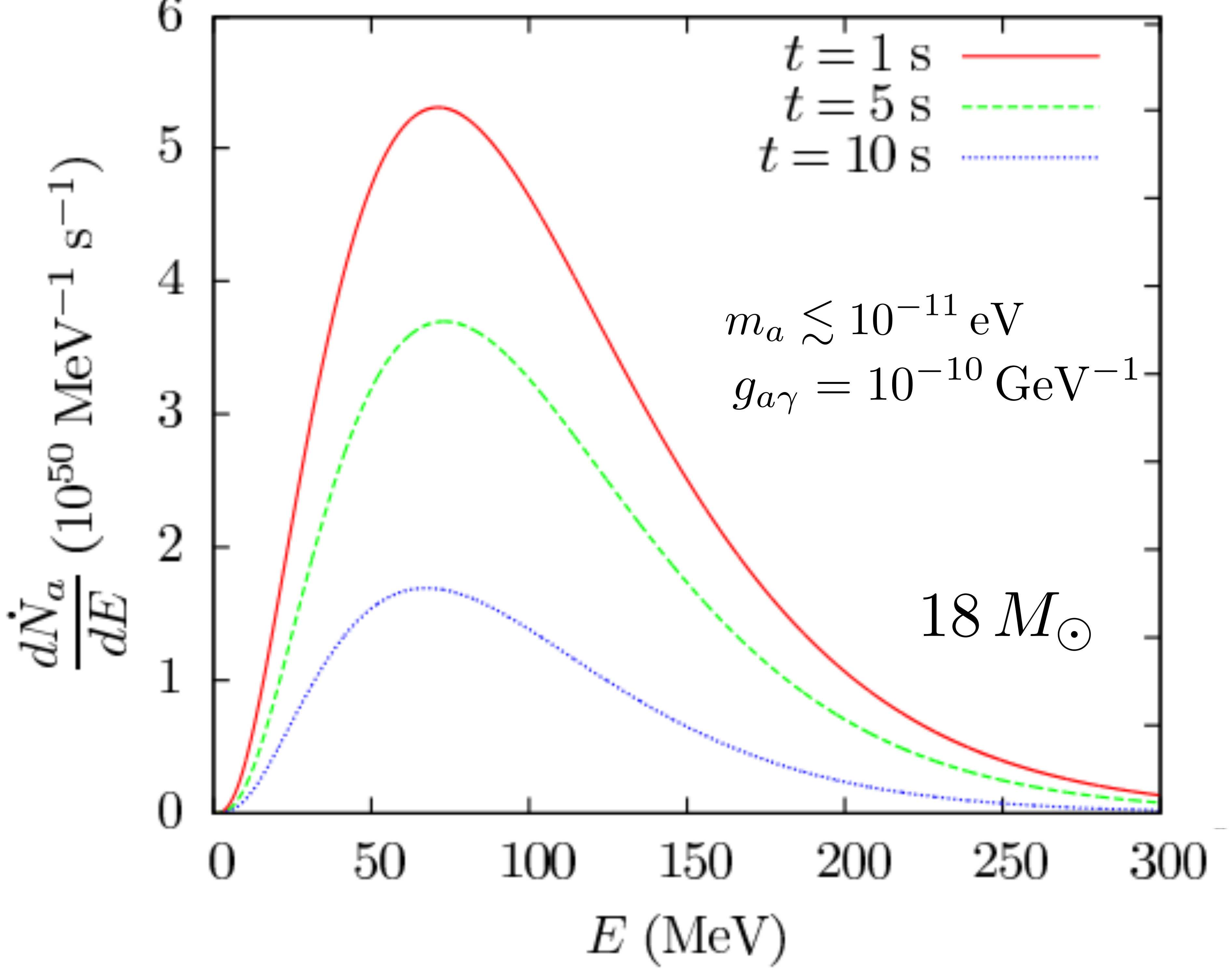
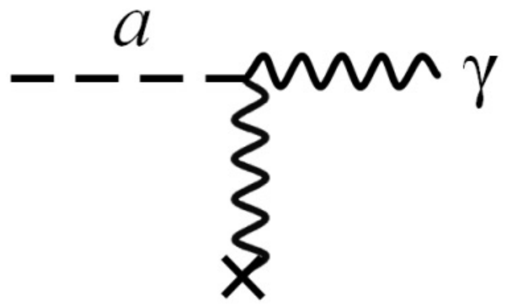


For Galactic SNe

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

[Not only cc-SN: proto-neutron stars, mains-sequence stars, white dwarfs, etc; If present NN bremsstrahlung dominates]

ALPs gamma-ray flux from CC SNe



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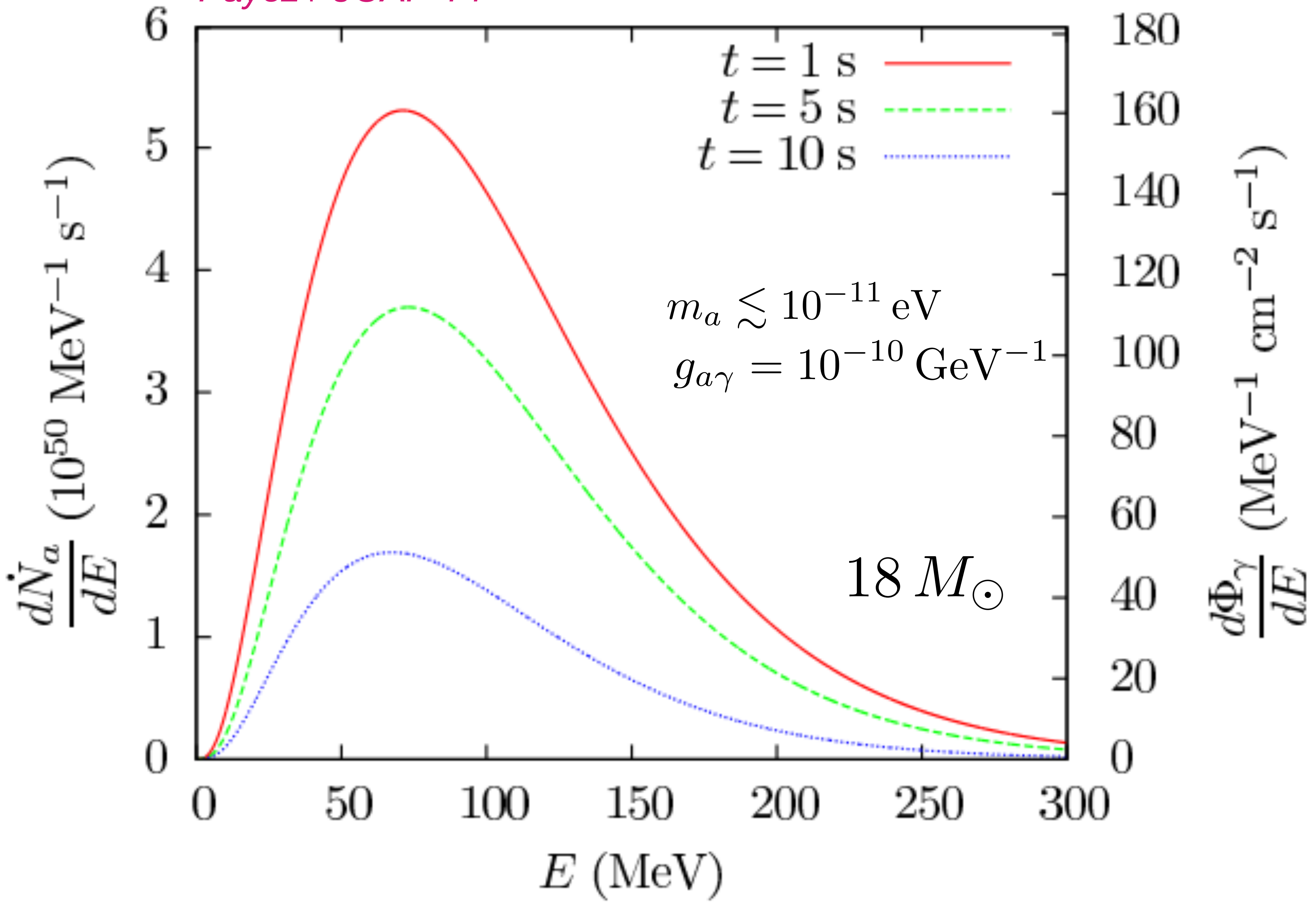

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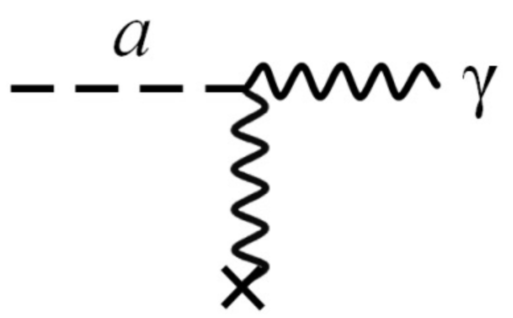
$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}P_{a\gamma}(E)$$

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

[Not only cc-SN: proto-neutron stars, mains-sequence stars, white dwarfs, etc; If present NN bremsstrahlung dominates]

ALPs gamma-ray flux from CC SNe



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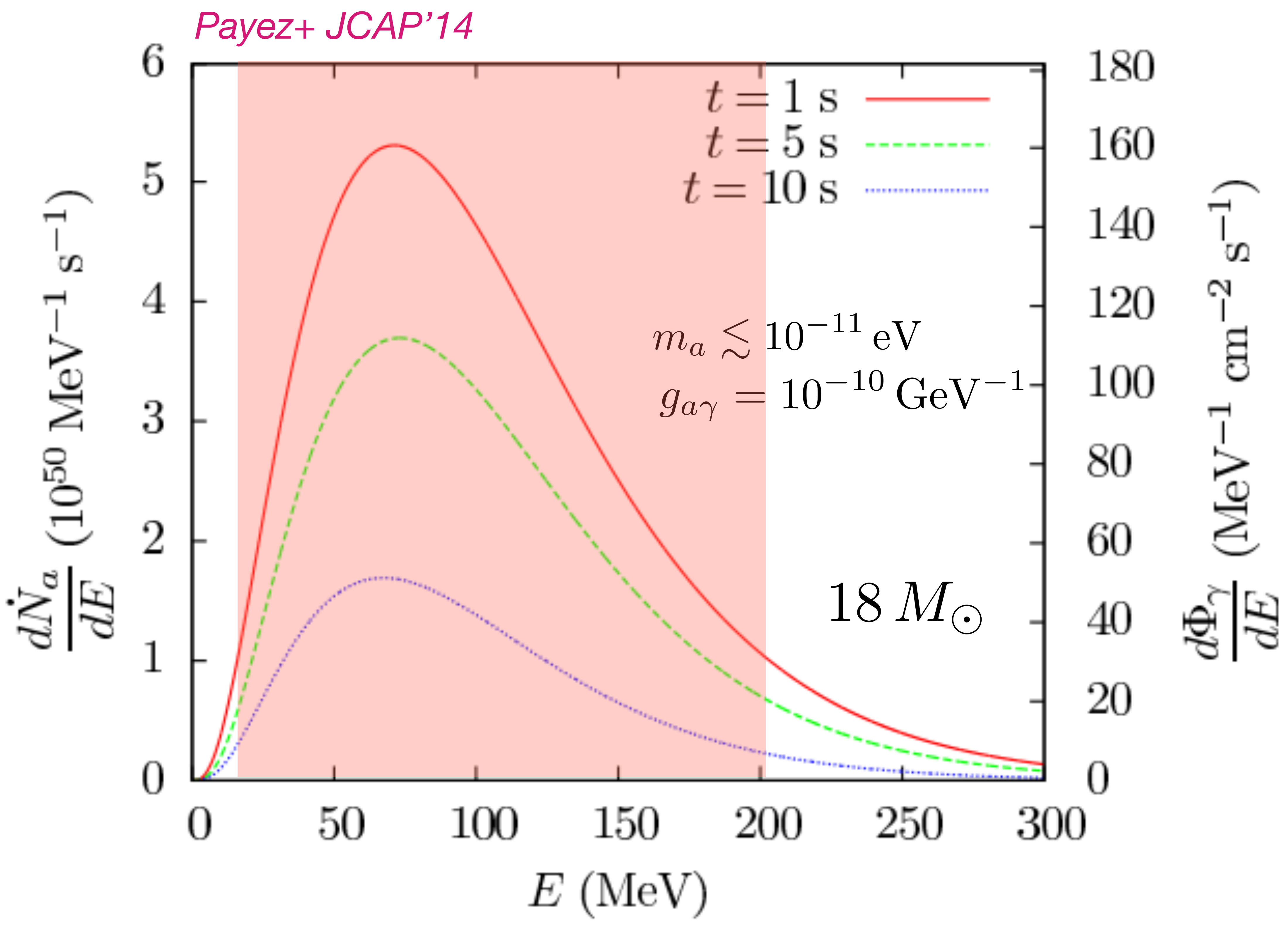

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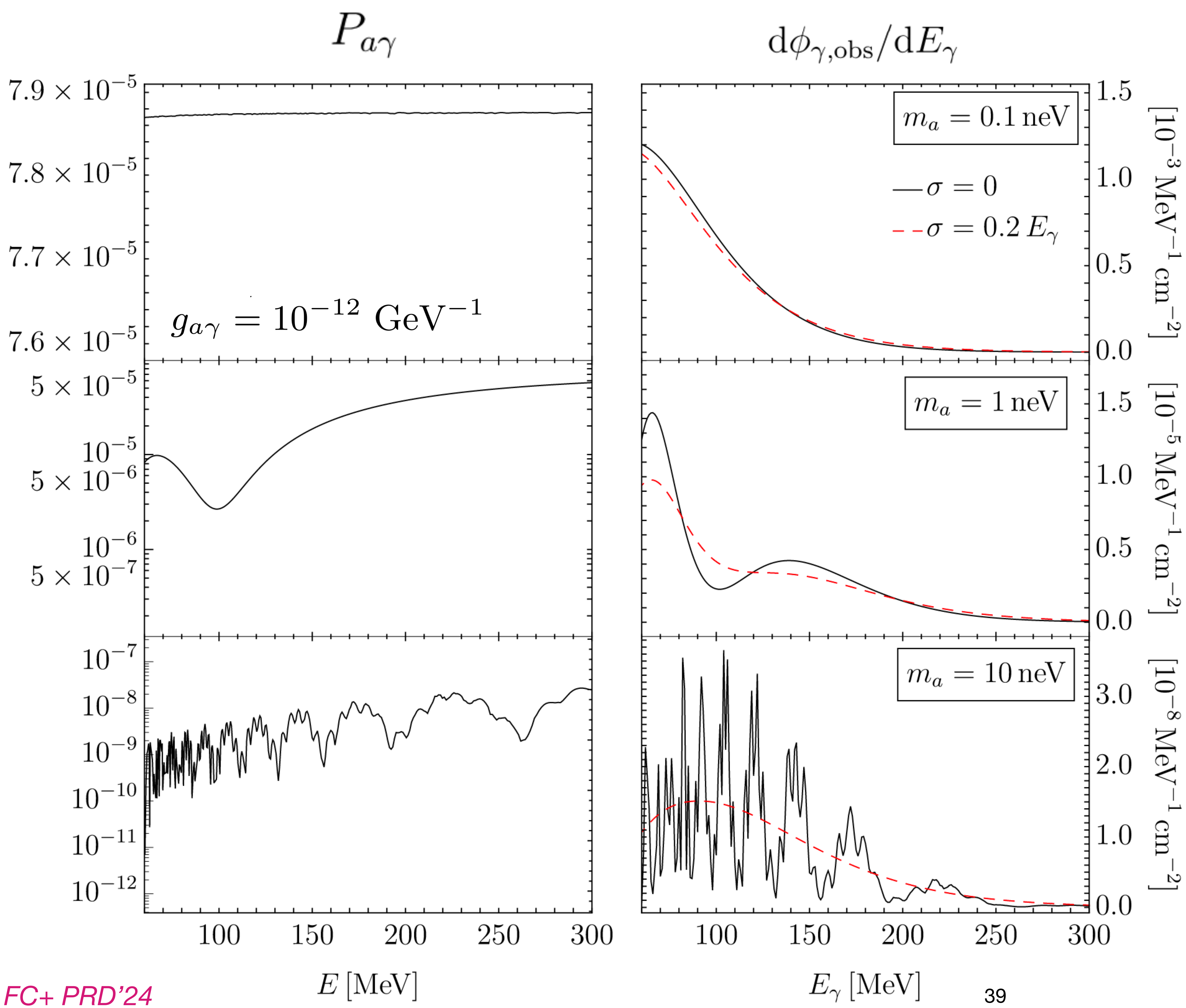


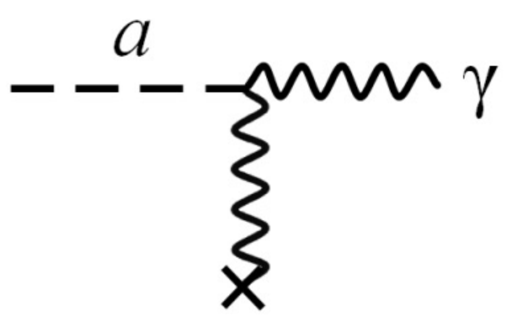
$$\frac{d\phi_\gamma}{dE} = \frac{1}{4\pi L^2}\frac{dN_a}{dE}P_{a\gamma}(E)$$

- Mass dependence induces variation in the spectrum
- Spectral irregularities may be detectable, depending on instrumental E resolution

$$\frac{d\phi_{\gamma,\mathrm{obs}}}{dE_\gamma} = \int_{-\infty}^{+\infty} \eta(E, E_\gamma)\frac{d\phi_\gamma}{dE}(E)dE$$

FC+ PRD'24

Gamma-ray bursts from CC SNe



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

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

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

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

Payez+ JCAP'14

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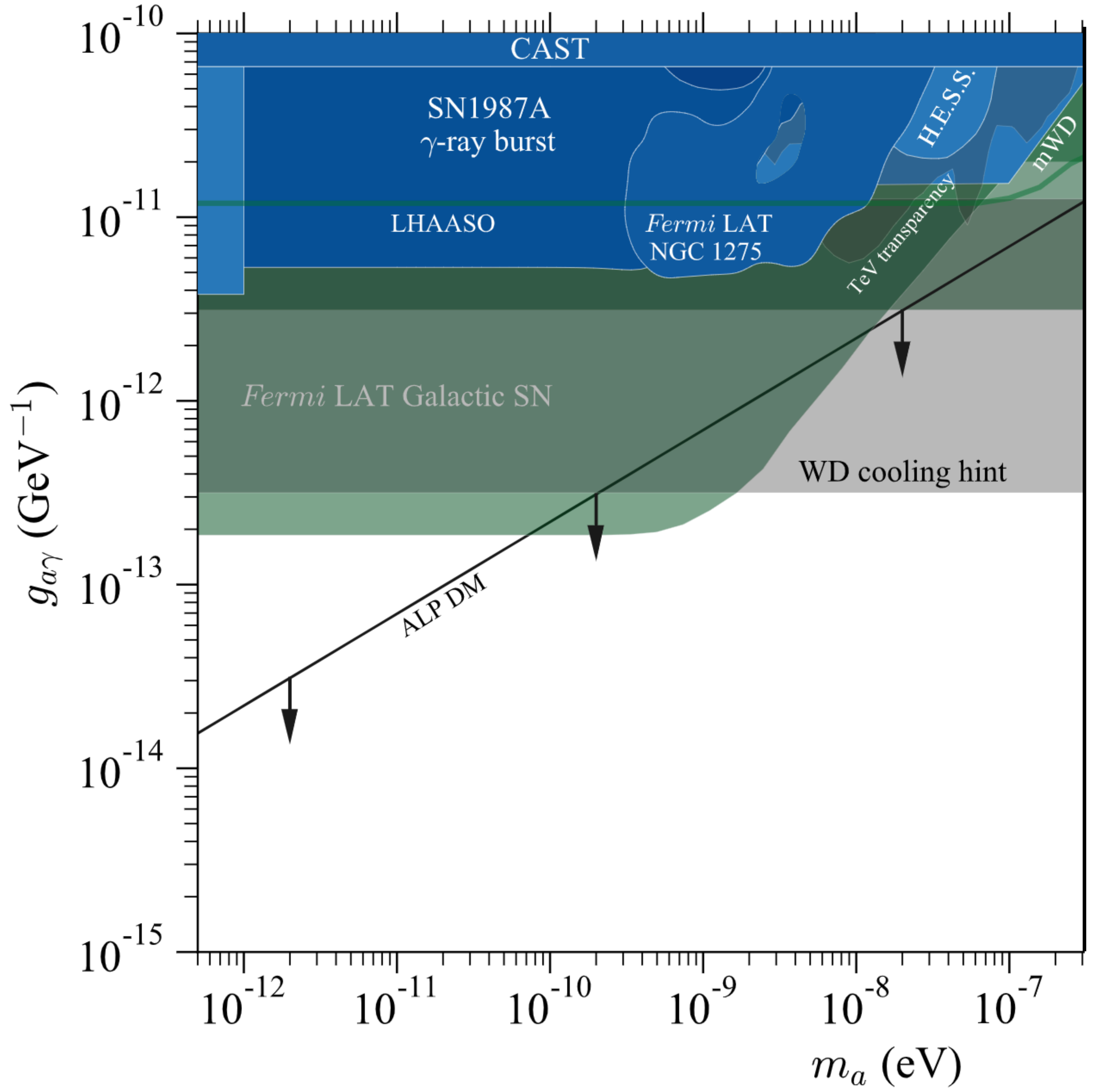
Meyer & Petrushevska PRL'20
Crnogorcevic+ PRD'21

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

Meyer+ PRL'17; FC+PRD'24



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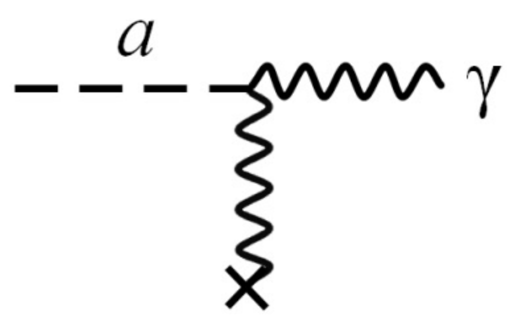

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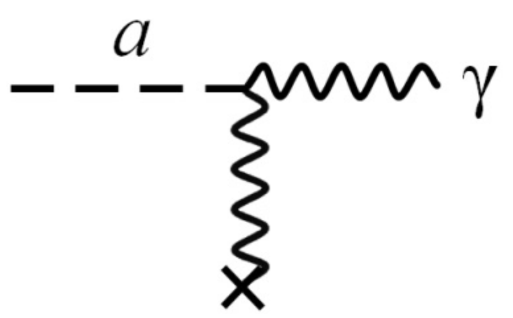

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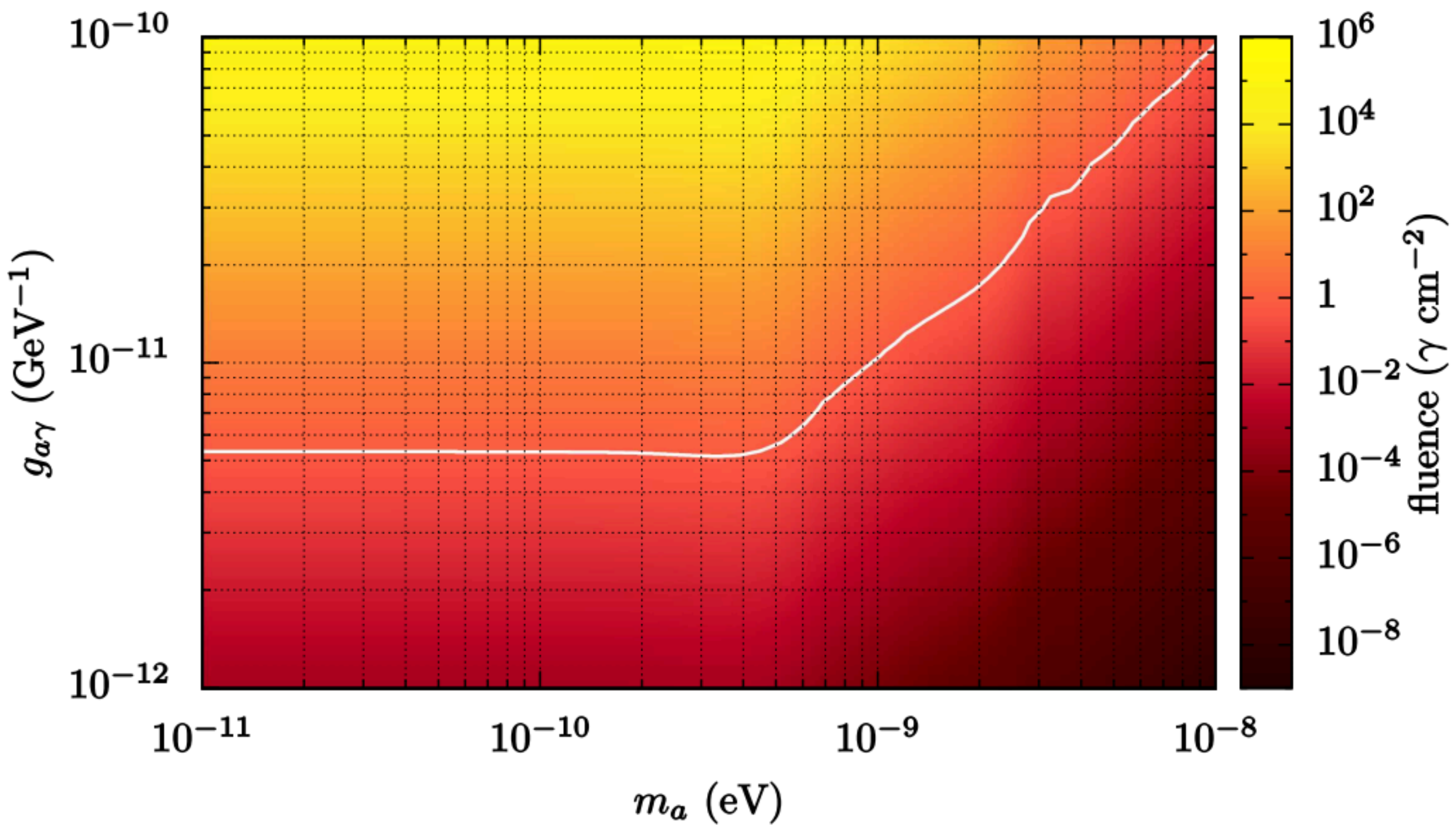
Payez+ JCAP'14



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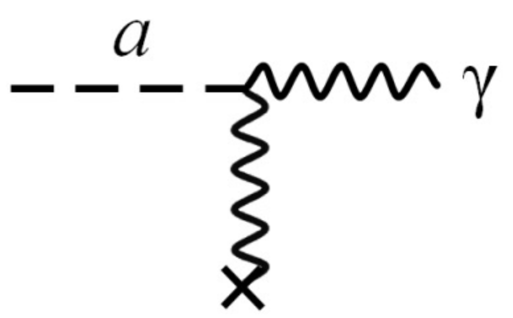

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Payez+ JCAP'14

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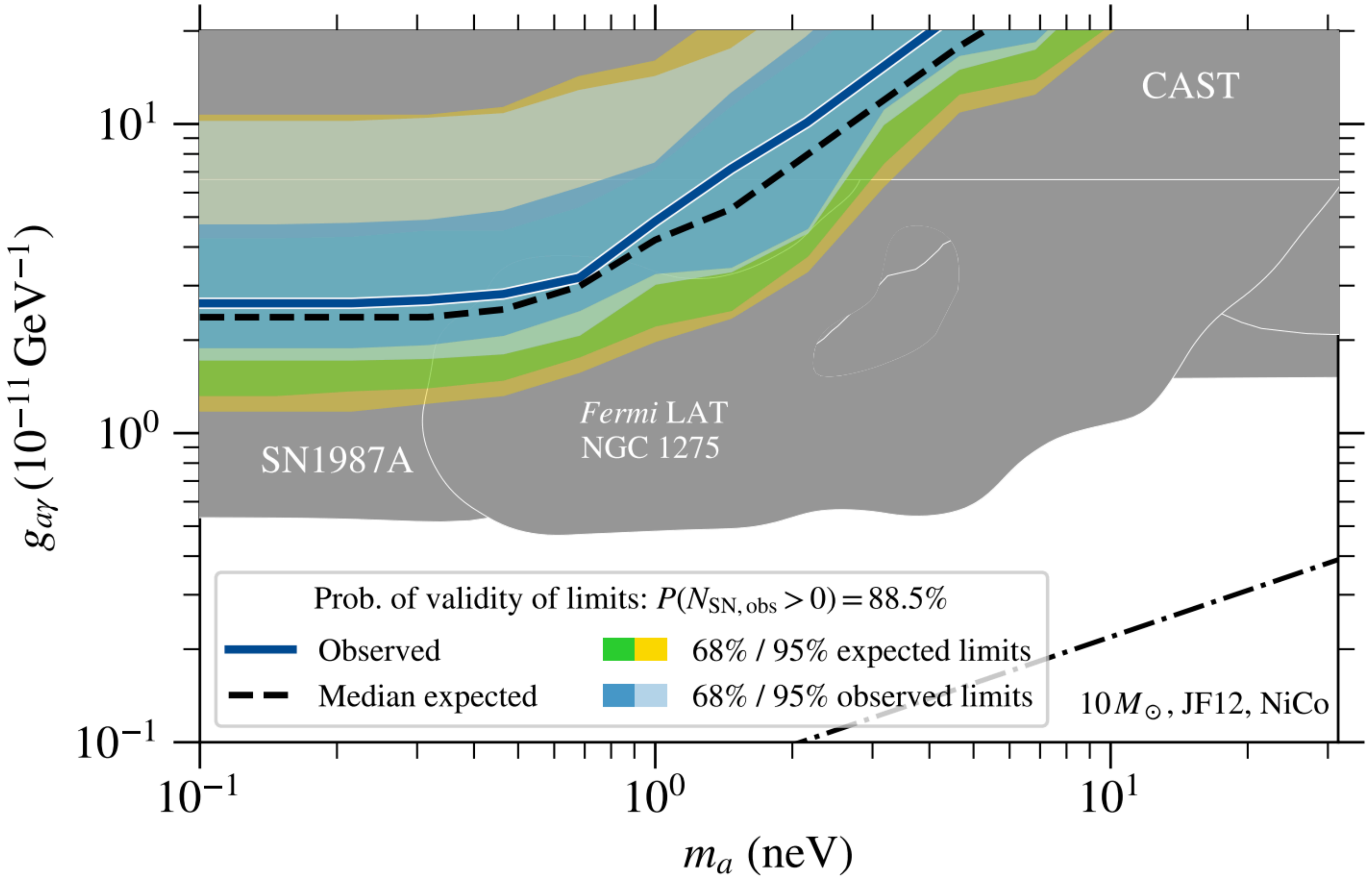
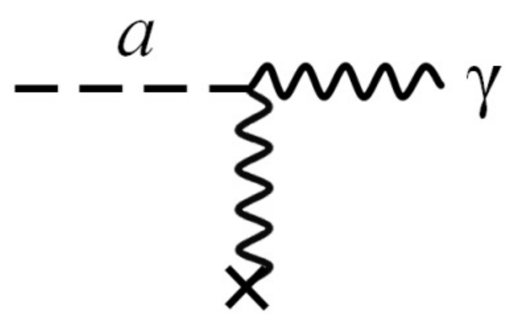


Future gamma-ray bursts from CC SNe



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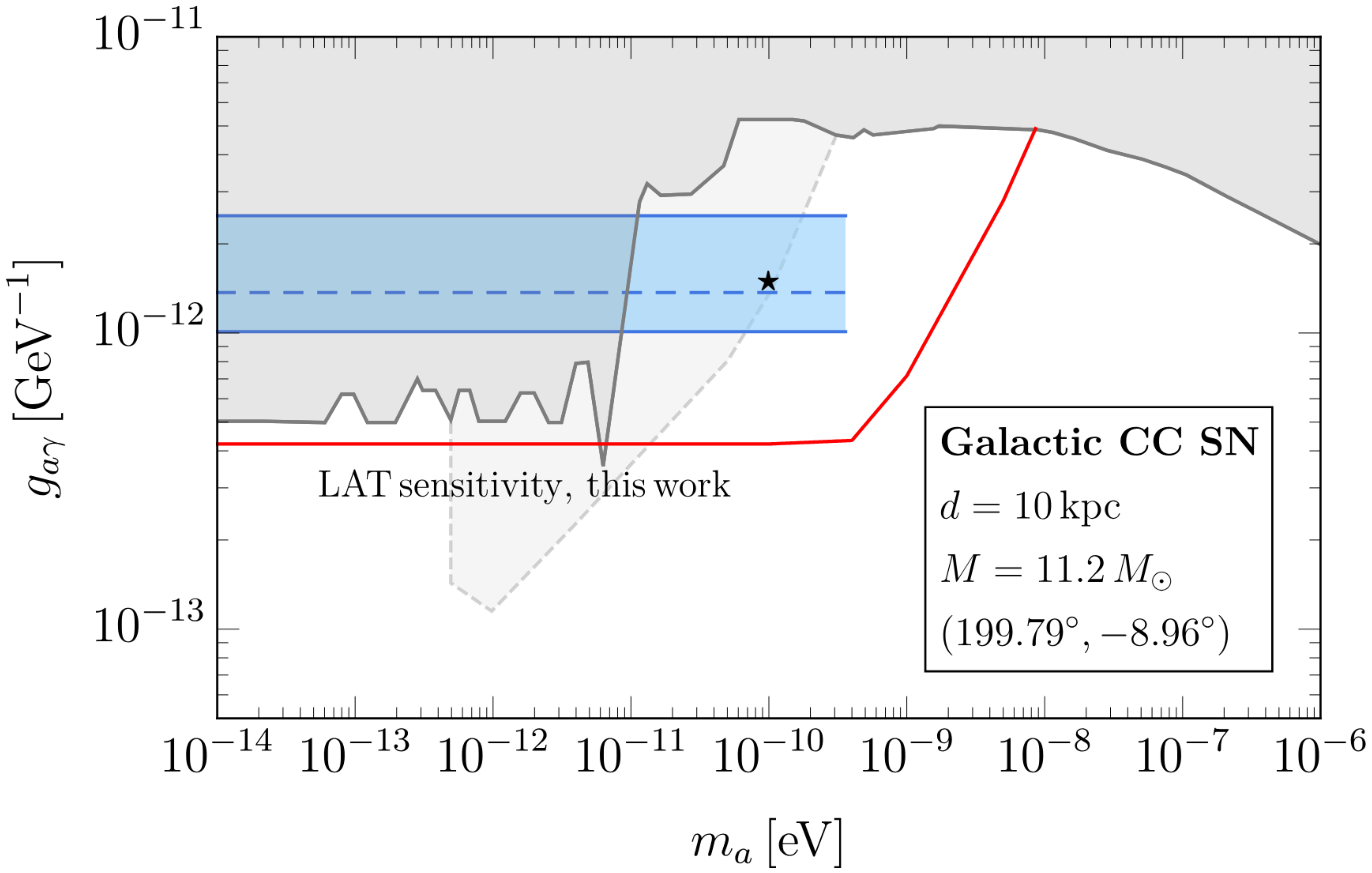
➡ Specific **time dependent** and **spectral** signatures

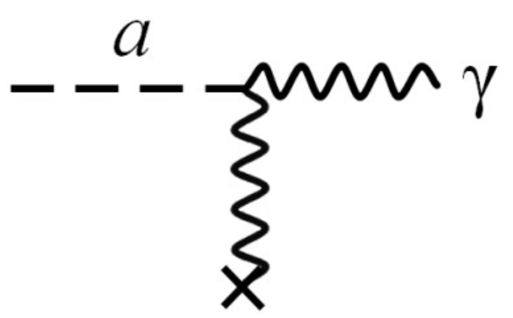
➡ 3% chance to see a Galactic SN with the LAT over the next 7 years

- **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
FC+PRD'24



The diffuse SN ALP background



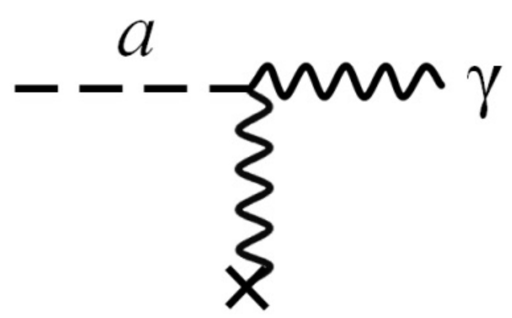
DSNALPB

- 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

DSNALPB



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FC+ PRD'20, 2110.03679

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

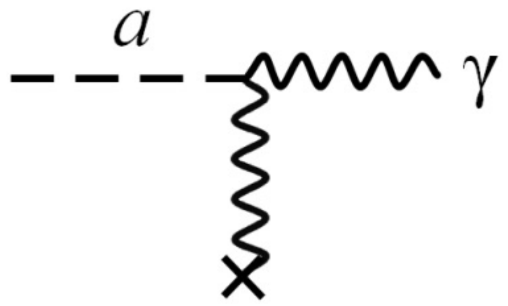
Beacom, Ann. Rev. Nucl. Part. Sci.'10

Time-integrated CC SNe ALPs spectrum from past events

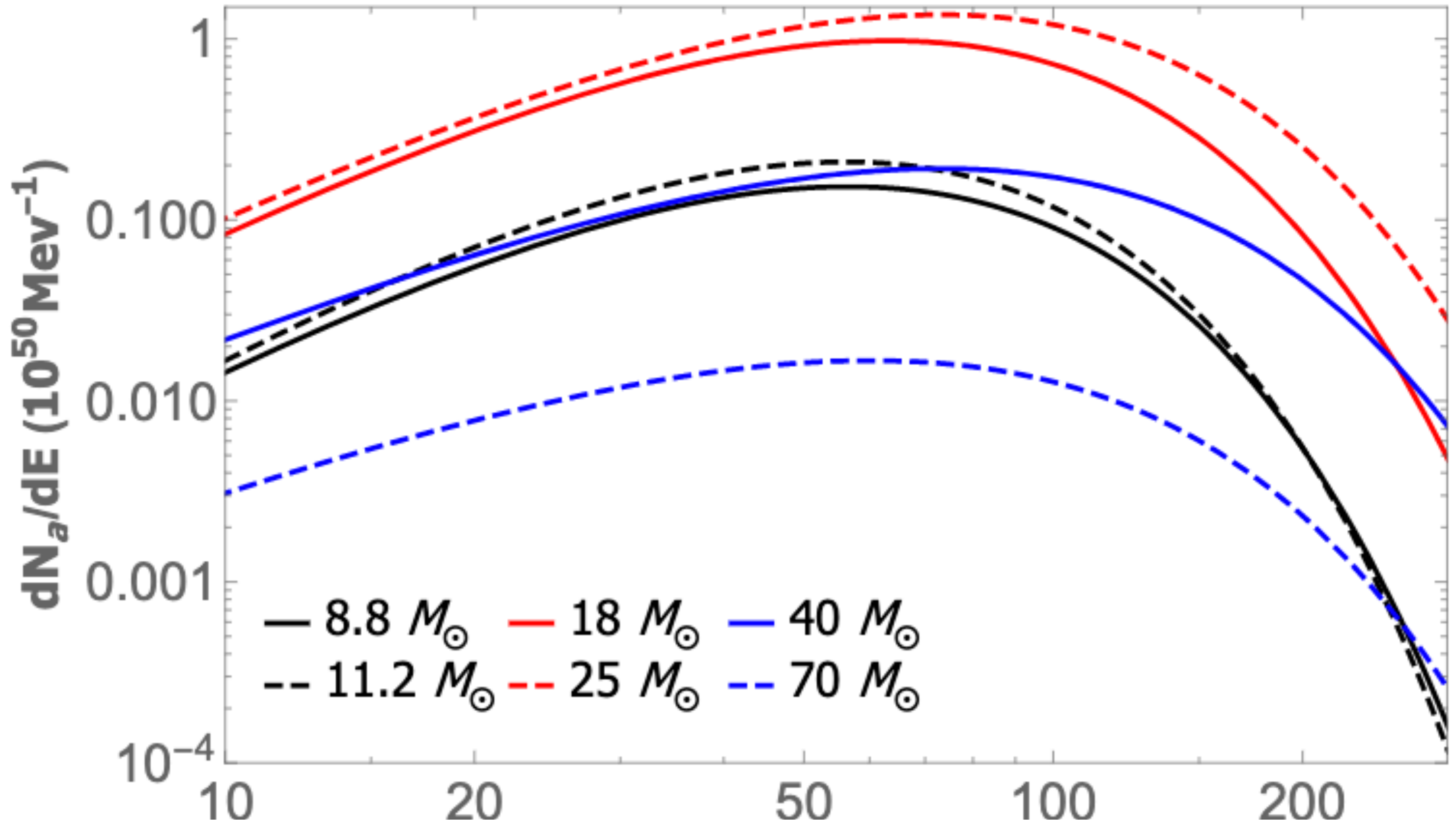
CC SNe rate density at redshift z

Yuksel et al. ApJ Letters'08

Time-integrated DSNALPB spectrum



FC+ 2110.03679



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

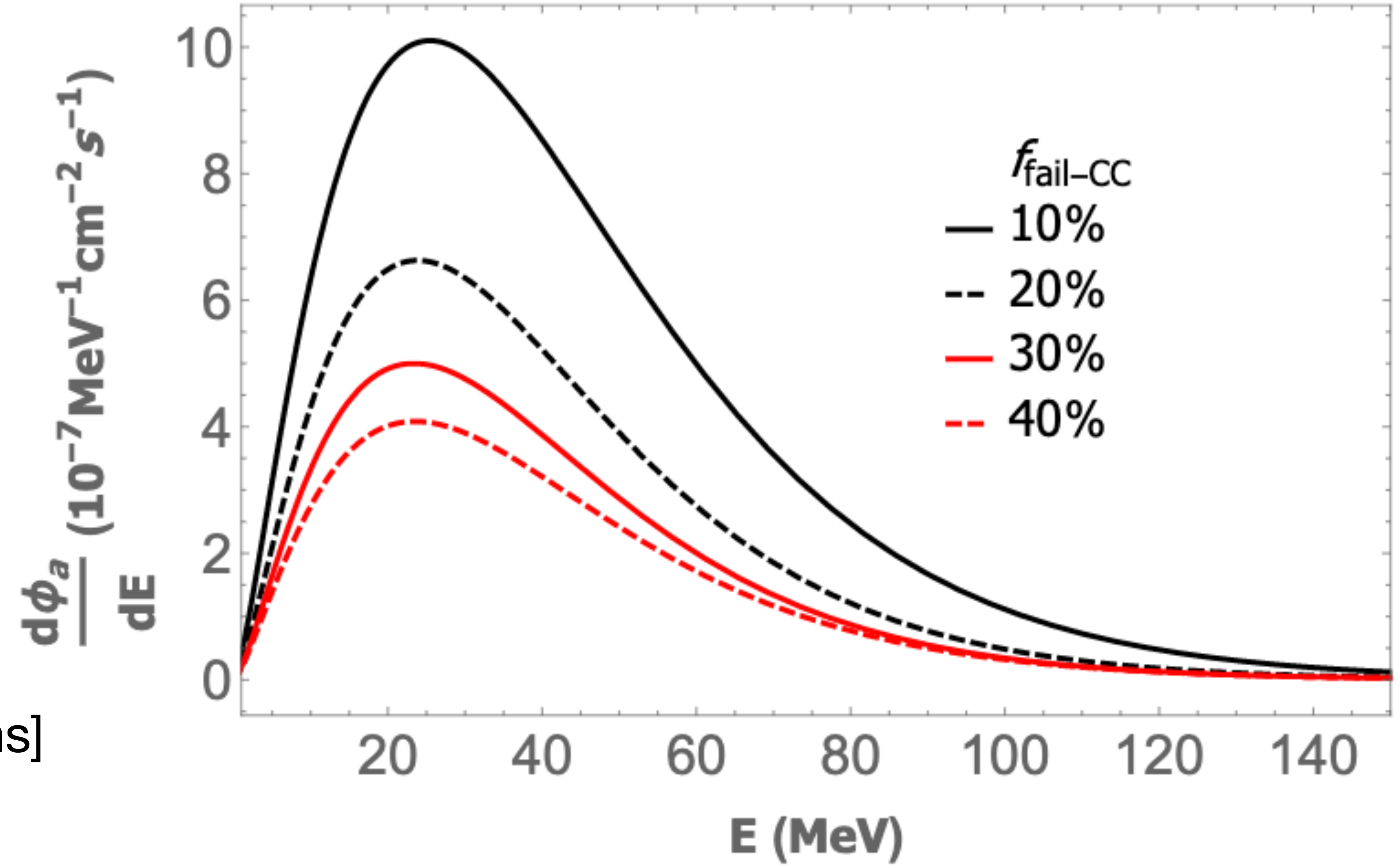
- **CCSN explosion: 8.8, 11.2, 18, 25** M$_\odot$
- **Failed CCSN explosion: 40, 70** M$_\odot$

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

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

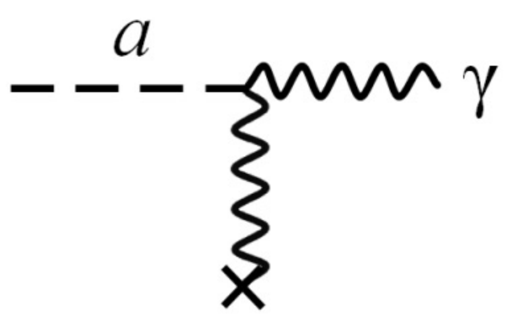
$$\frac{dN_a^{CC}}{dE_a} = \frac{\int_{\Lambda_{\mathrm{expl-CC}}} dM \phi(M) \frac{dN_a}{dE}(M) + \int_{\Lambda_{\mathrm{fail-CC}}} dM \phi(M) \frac{dN_a}{dE}(M)}{\int_{8M_\odot}^{125M_\odot} dM \phi(M)}$$

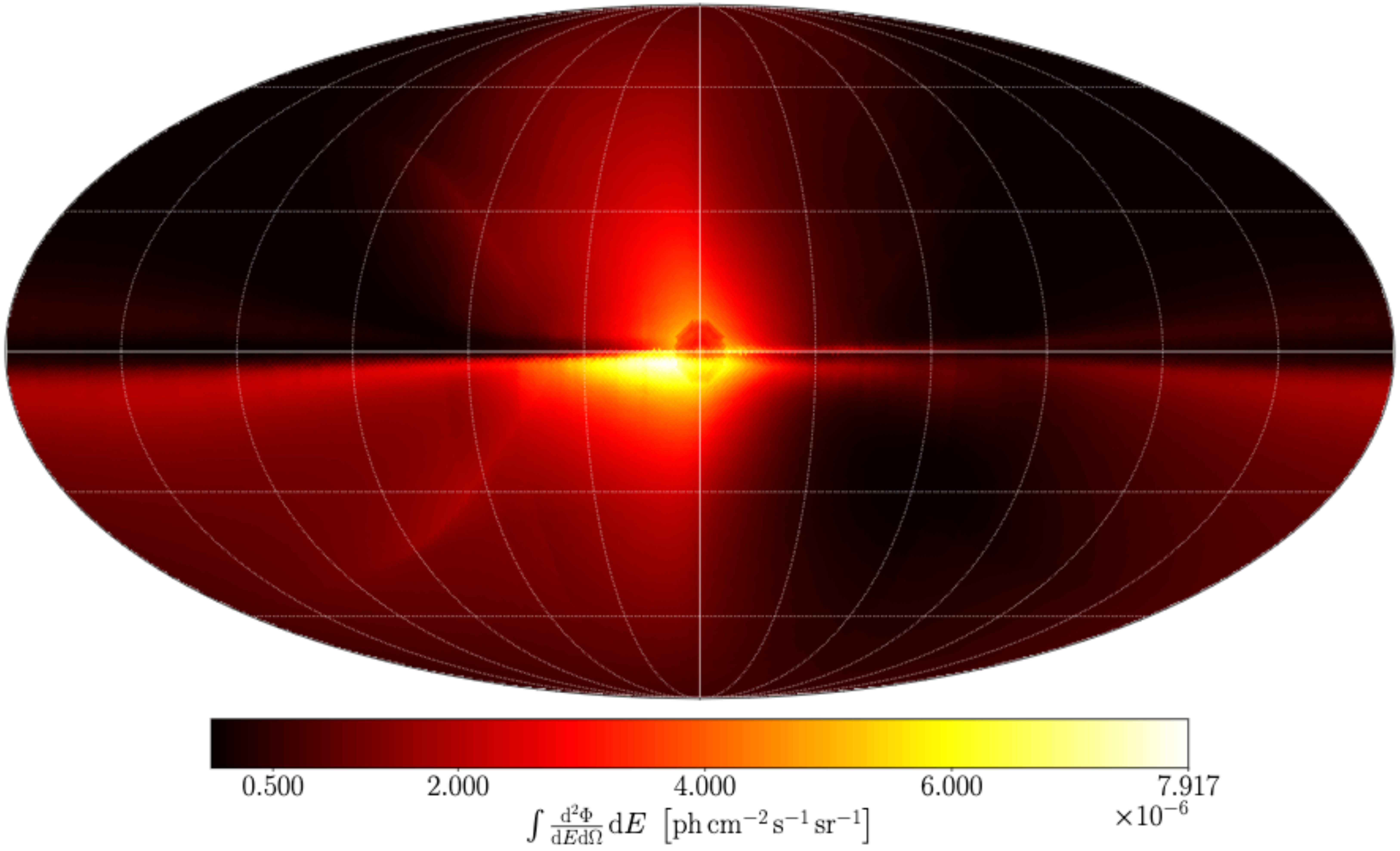
$$f_{\mathrm{fail-CC}} = \frac{\int_{\Lambda_{\mathrm{fail-CC}}} dM \phi(M)}{\int_{8M_\odot}^{125M_\odot} dM \phi(M)}$$



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

Gamma-ray DSNALPB signal





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

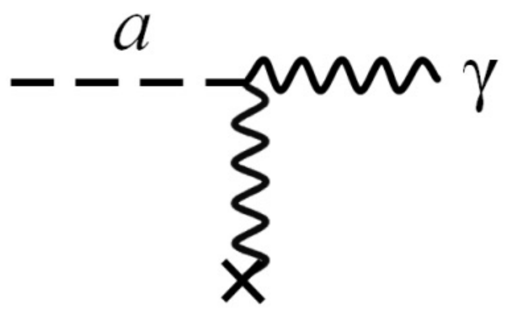
Integrated ALPs signal between 50 and 200 MeV

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

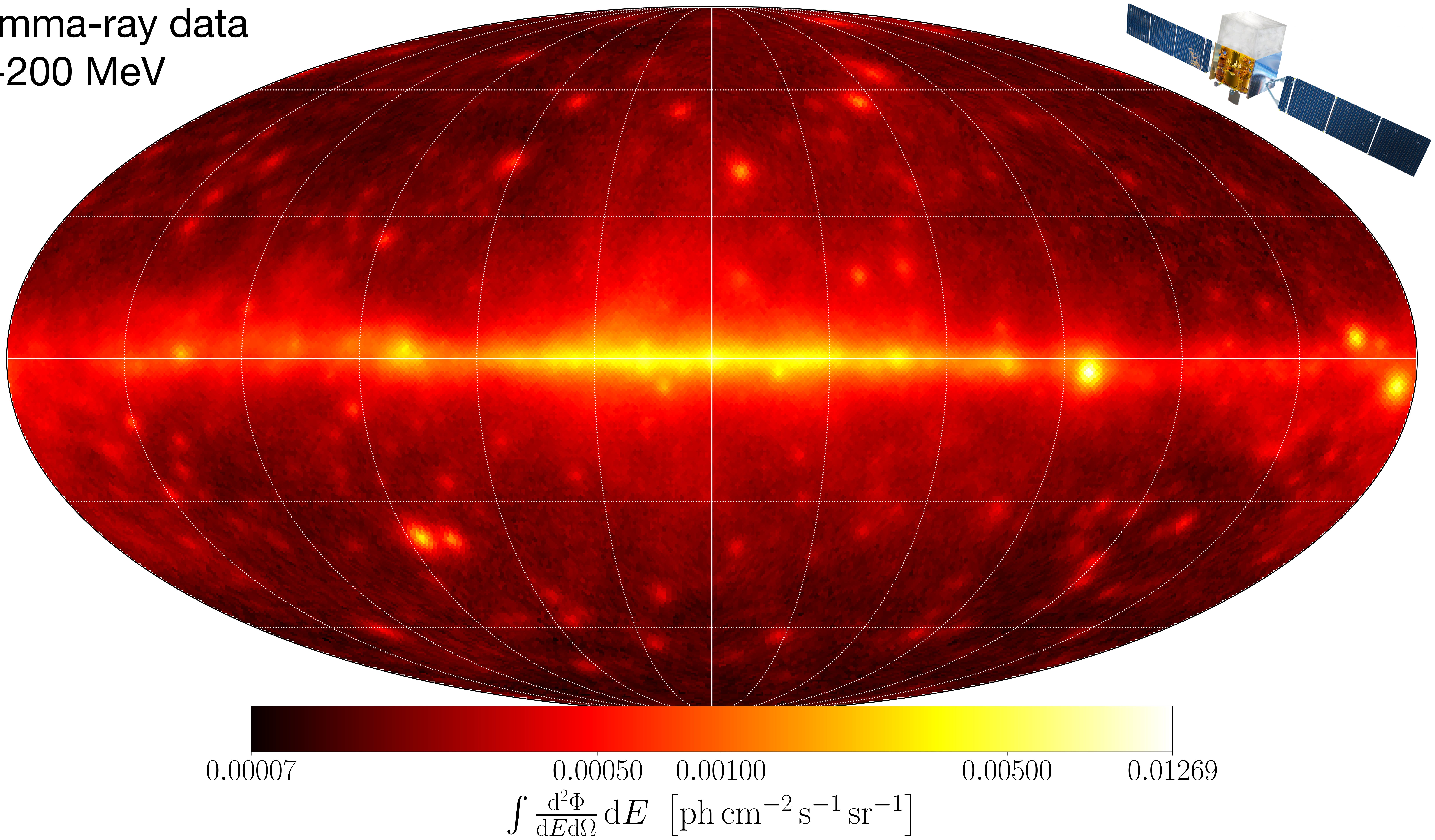
$$m_a \lesssim 10^{-11}\, \mathrm{eV}$$

All-sky diffuse signal
With specific extended spatial features

The Fermi-LAT gamma-ray sky



12yr gamma-ray data
50-200 MeV



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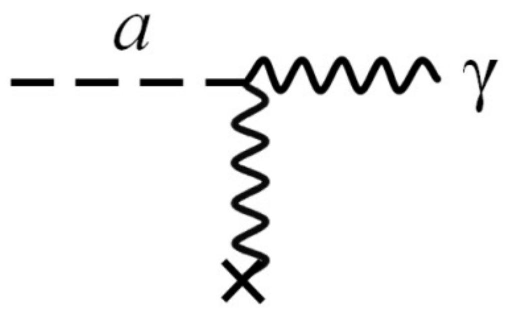

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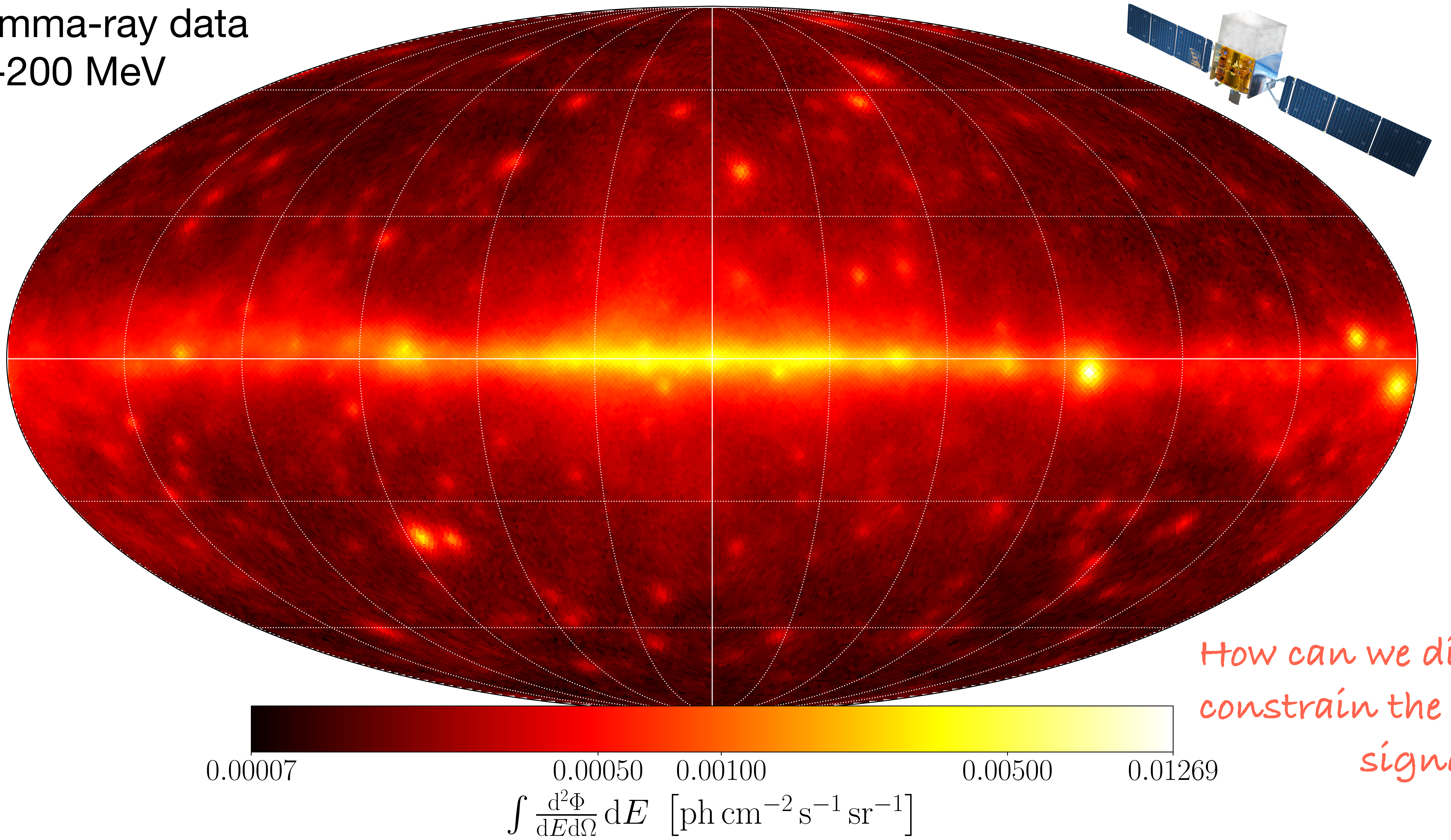
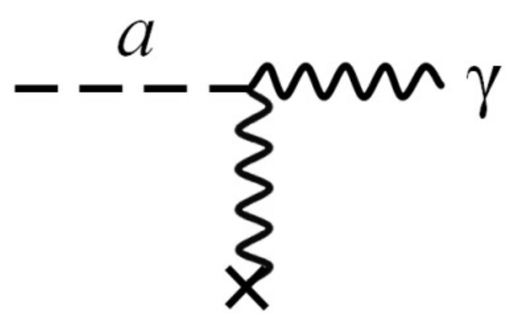
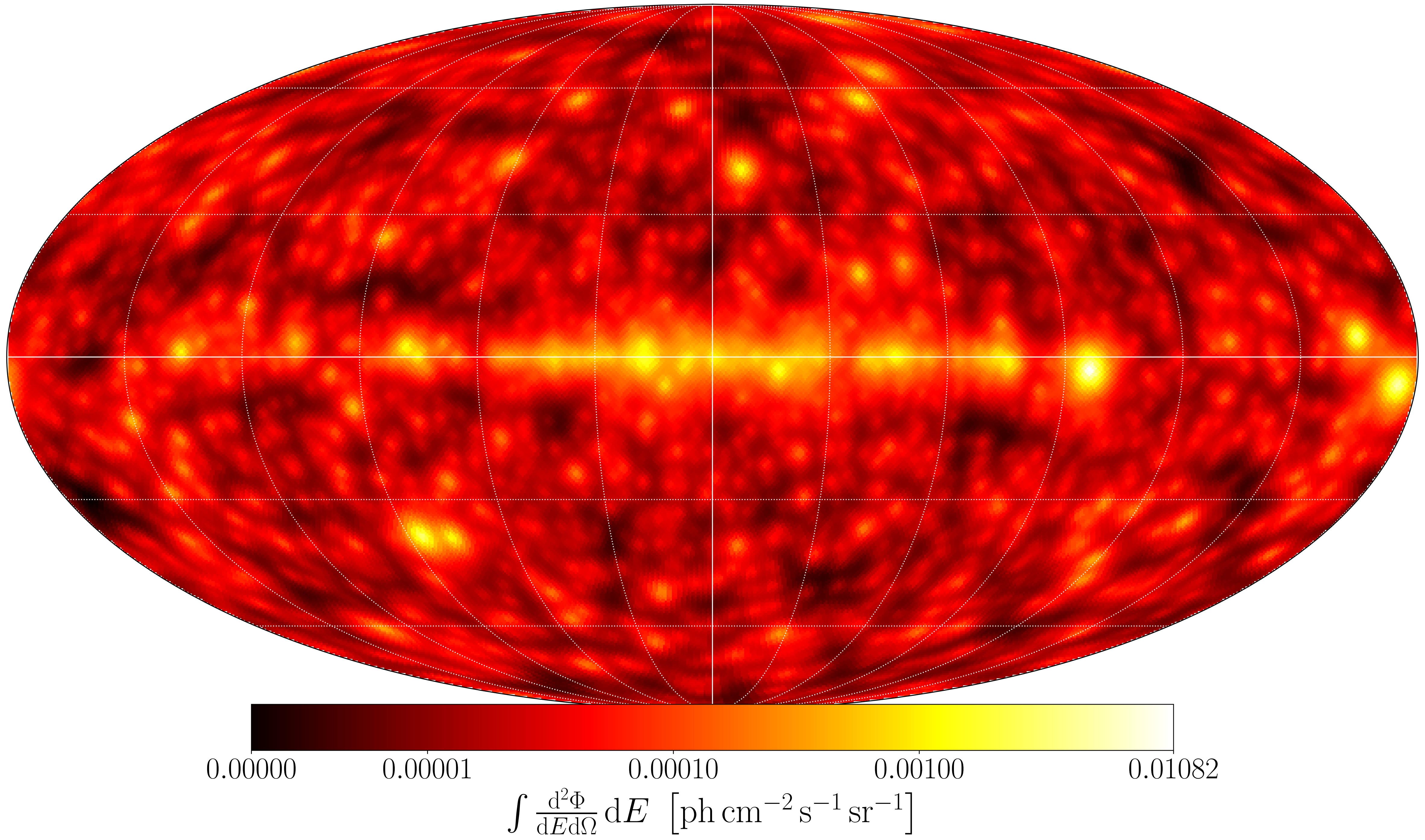


How can we disentangle/ constrain the faint ALPs signal?

The gamma-ray sky components

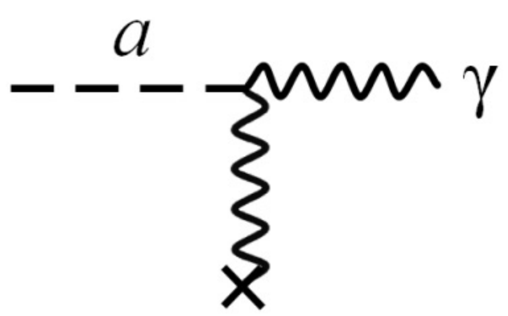


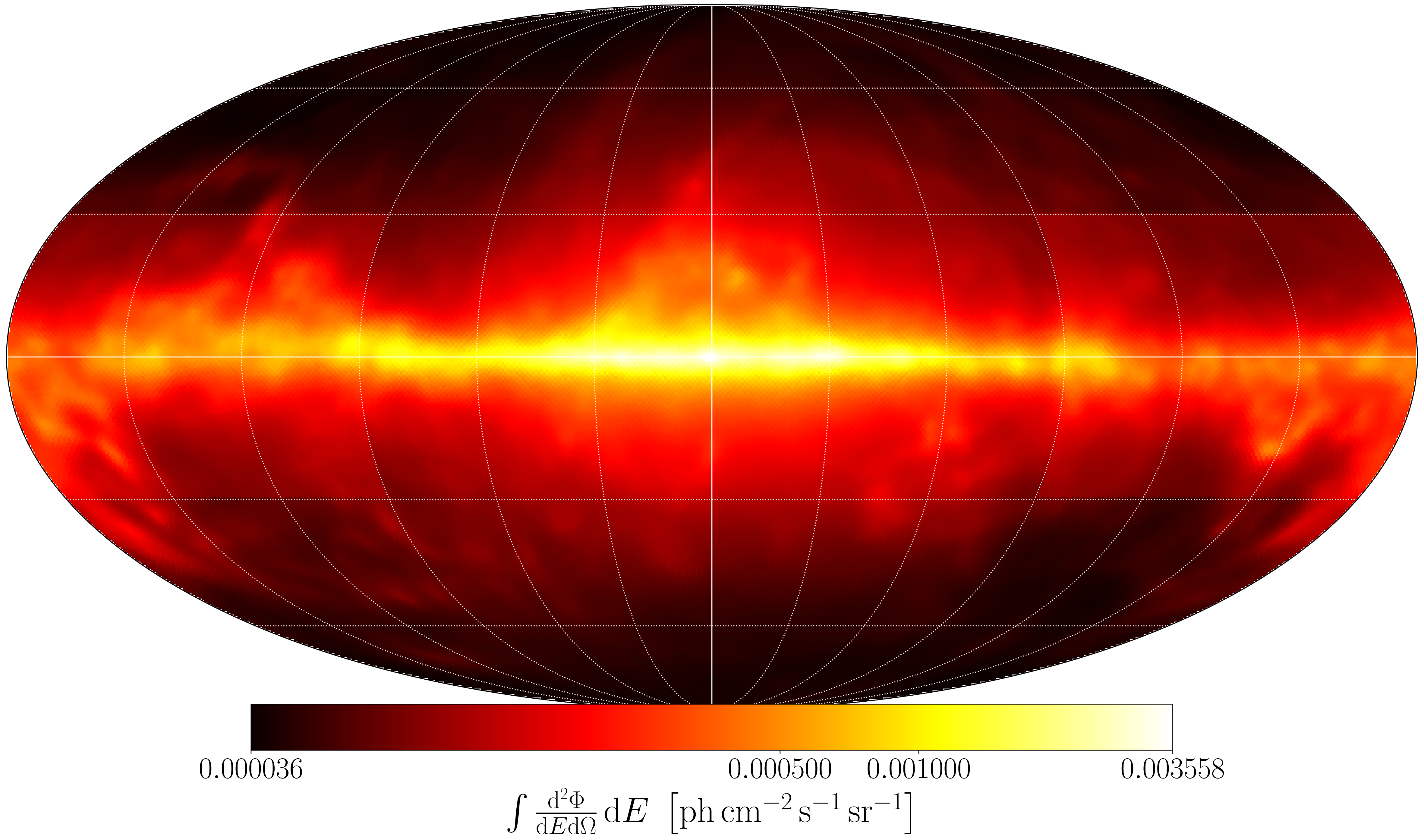


- ***Detected sources*** (point-like and extended) ~5000 objects

Fermi-LAT Collab. ApJS'20

The gamma-ray sky components





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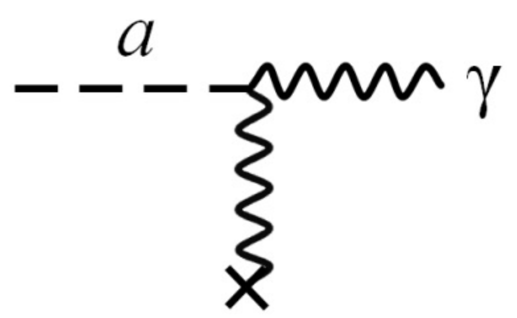
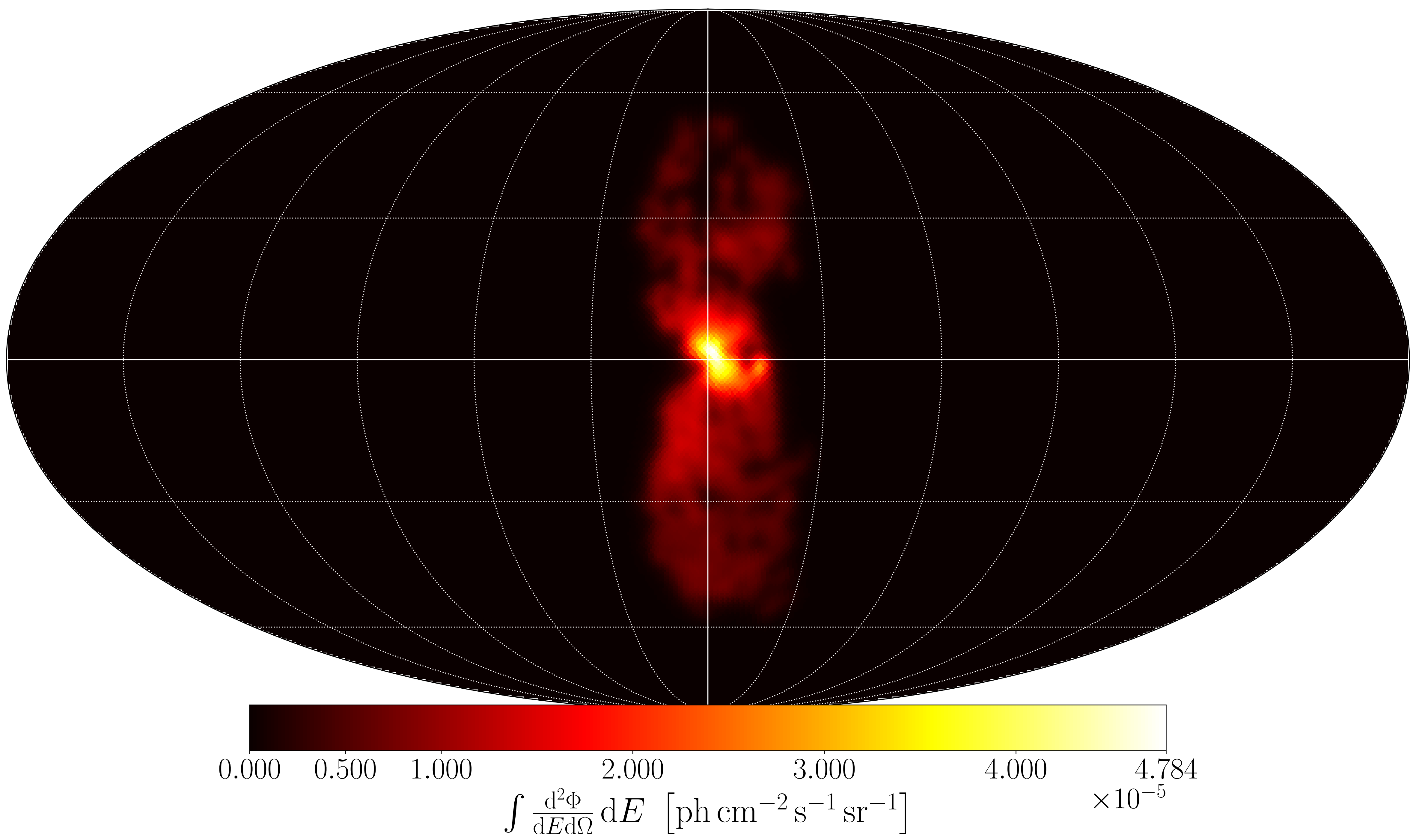
Fermi-LAT Collab. ApJS'20

- ***Galactic diffuse emission*** from cosmic-ray interactions with gas and radiation

The gamma-ray sky components





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

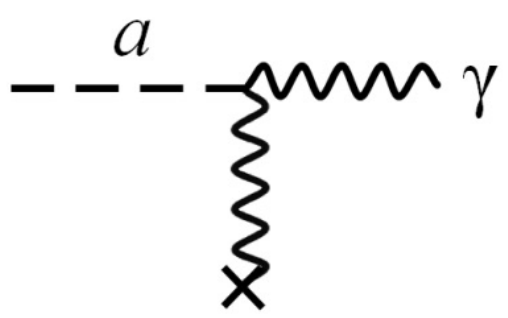
Fermi-LAT Collab. ApJS'20

- ***Galactic diffuse emission*** from cosmic-ray interactions with gas and radiation

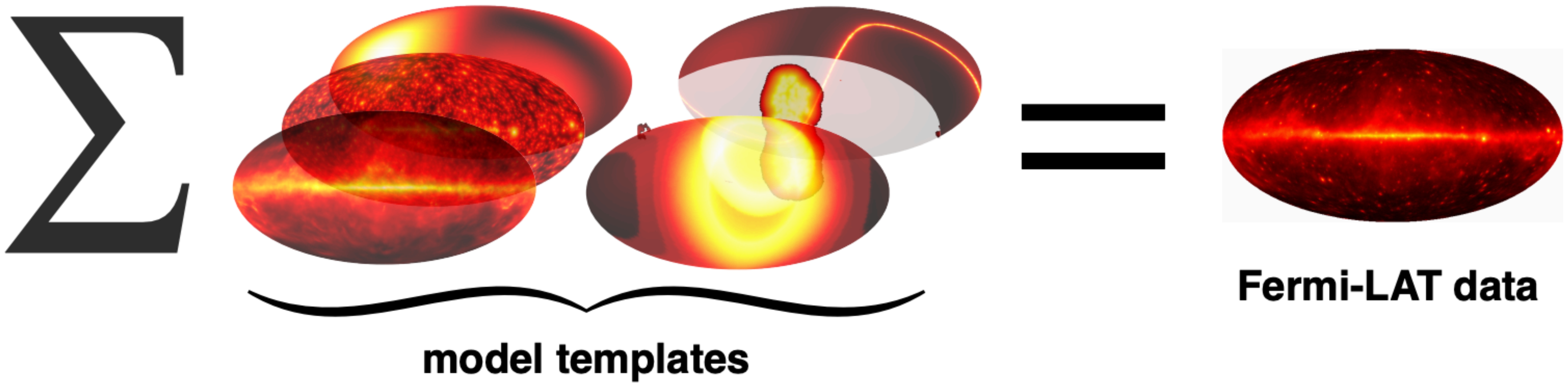
- Other large scale structures, e.g. ***Fermi bubbles*** — yet of unknown origin

Su+ ApJ'10

Fermi-LAT 3D template-based fit



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

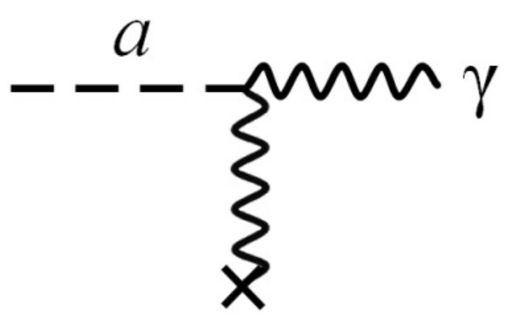


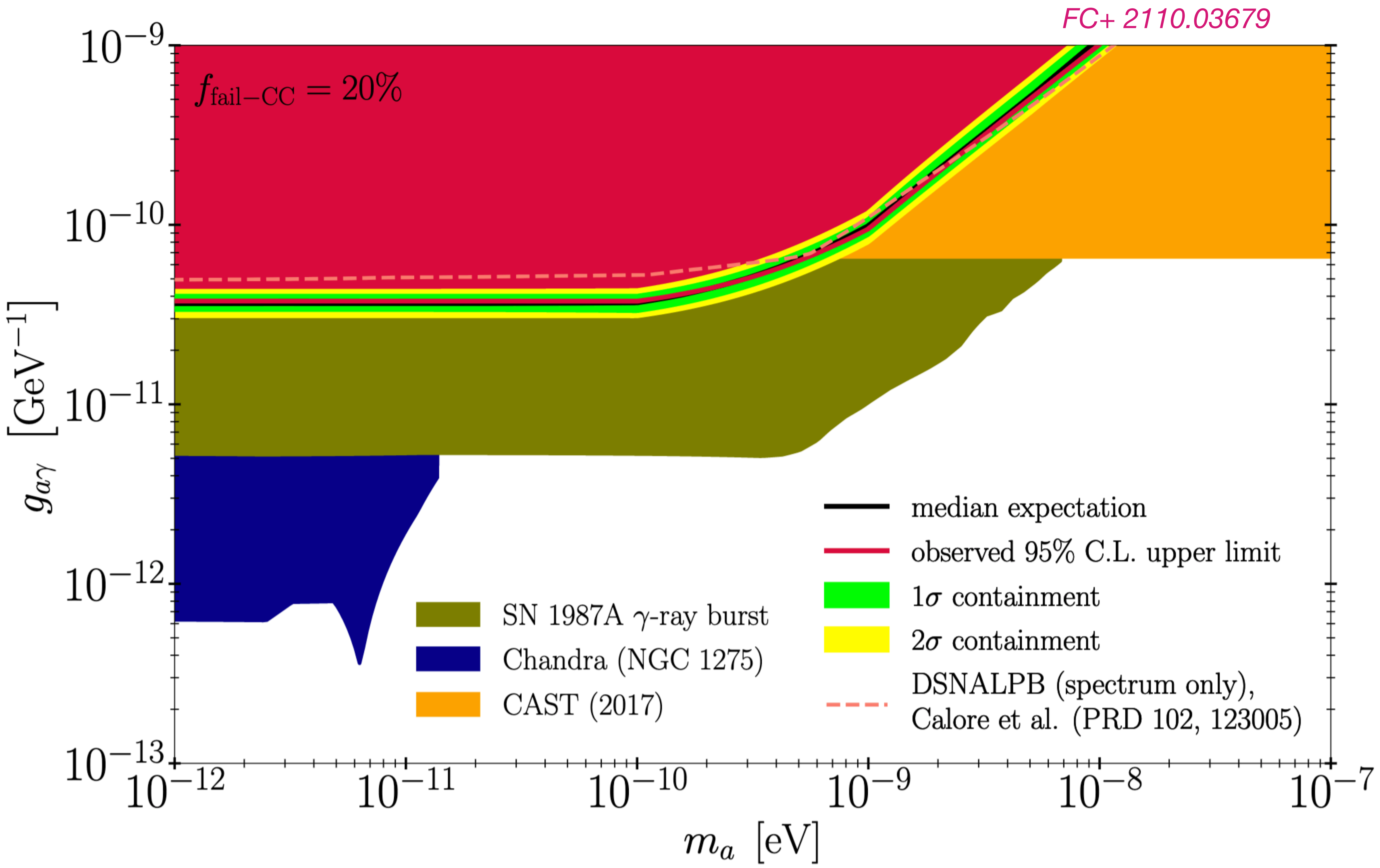
How to beat systematic uncertainties?

- *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 $e + Ze \to Ze + e + a$

ALP-nucleon coupling

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

- Important for nuclear plasma
- Dominant for neutron stars and supernova

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

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

- Important for nuclear plasma
- Dominant for neutron stars and supernova

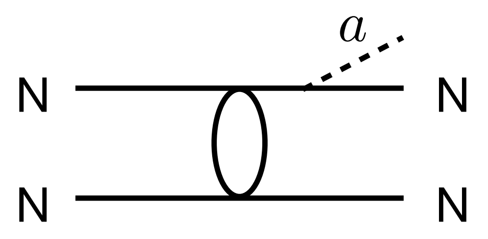
$g_{ap} < 0.9 \times 10^{-9}$

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

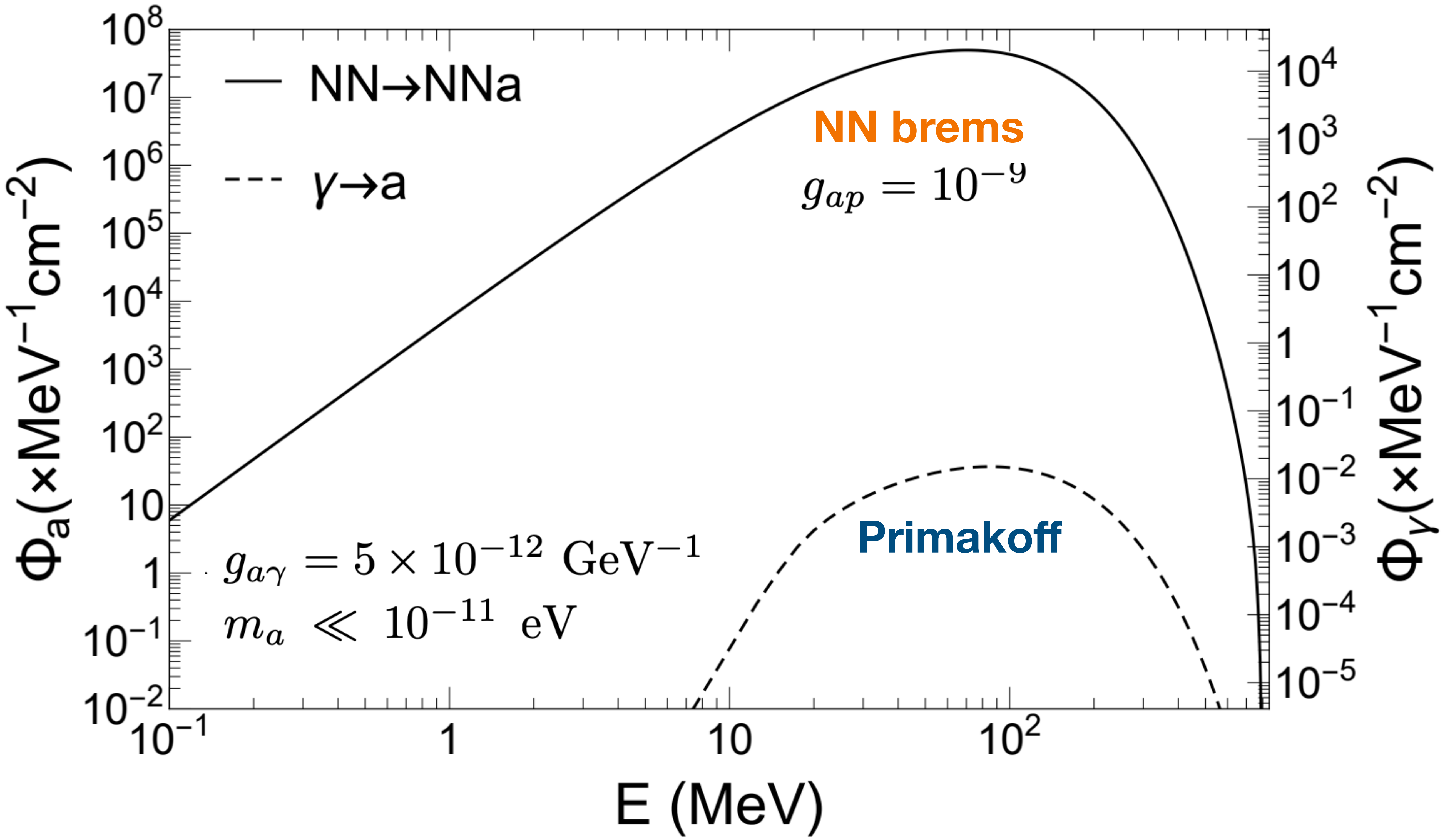
→ Copious ALPs production

Coupling with photons and nucleons

NN bremsstrahlung from SN1987A and DSNALPB



FC+ PRD'20



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

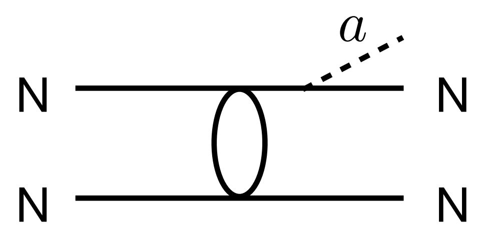
- NN brems. enhances the ALPs production and final gamma-ray flux

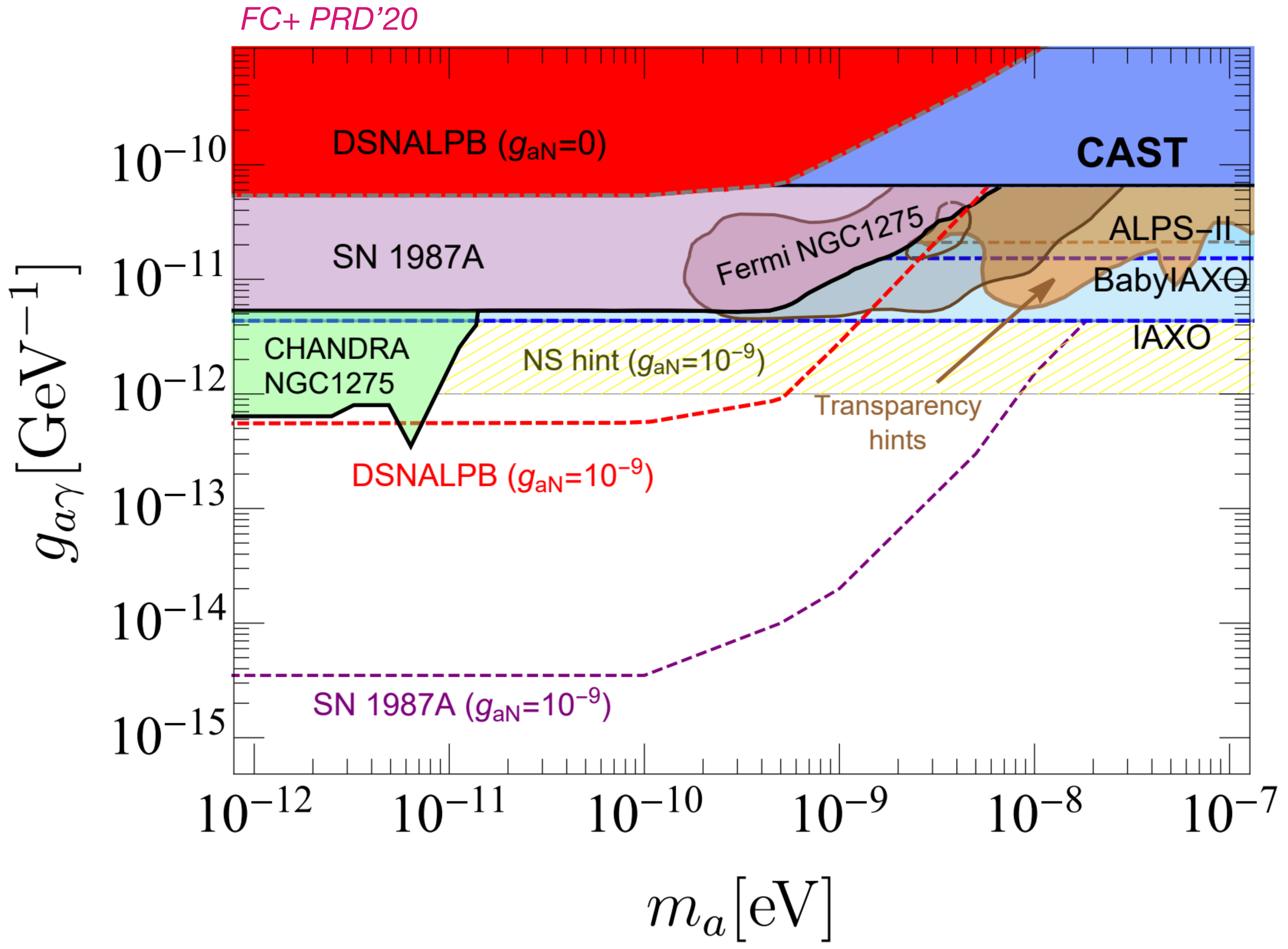
➡New limits from SN1987A

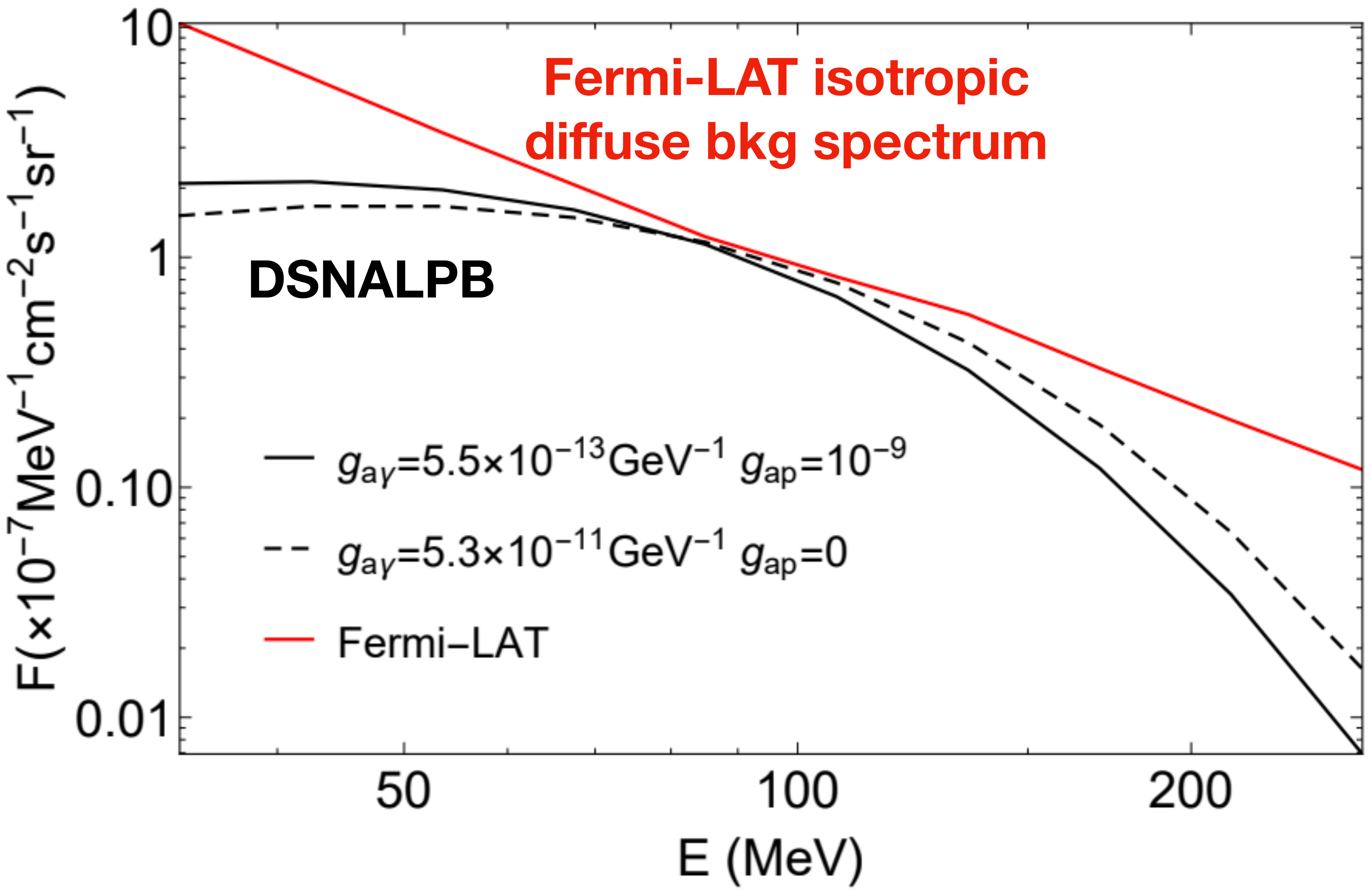
➡New constraints from DSNALPB

Constraints from enhanced NN brems

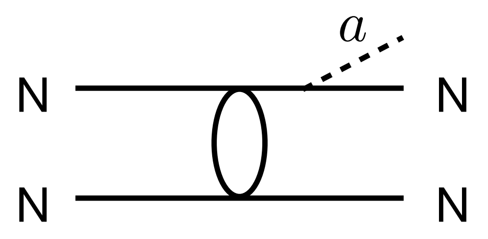
ALPs-photon conversion



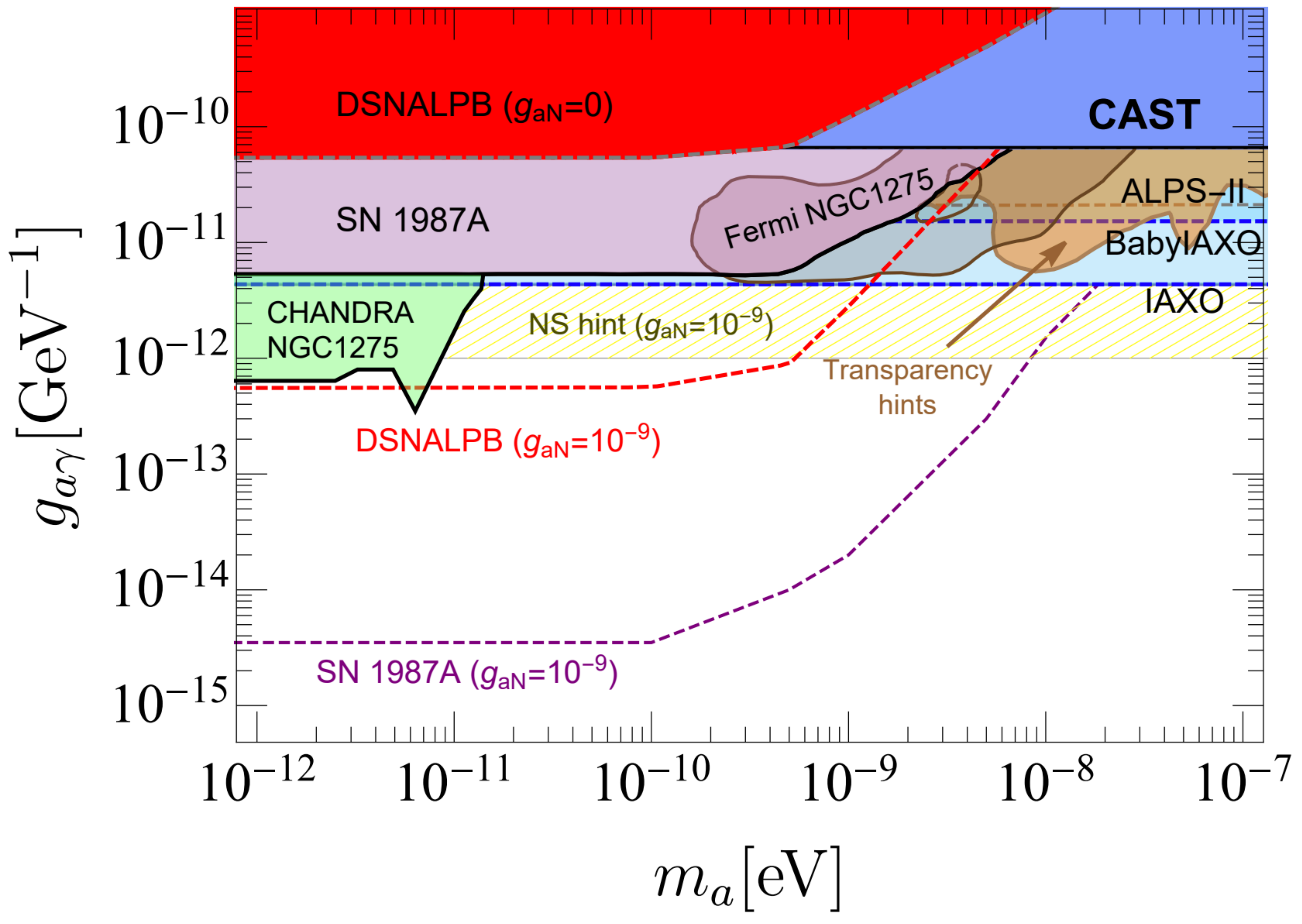




Constraints from enhanced NN brems



ALPs-photon conversion



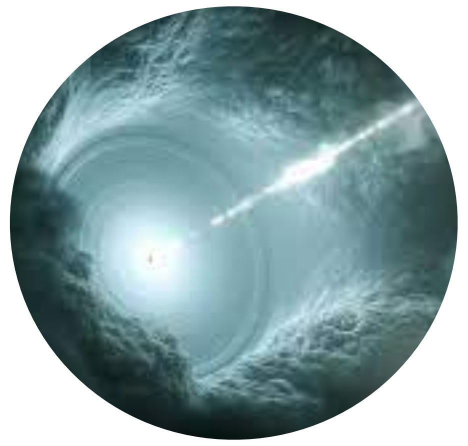
- If coupling w/ **nucleons**, DSNALPB constraint:
  - ✓ Competitive w/ IAXO sensitivity
- If coupling w/ **nucleons**, SN1987A constraint:
  - ✓ Improves by $O(10^3)$

High-energy gamma-ray emitters

Photons in *source* B field

Extragalactic gamma-ray emitters

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



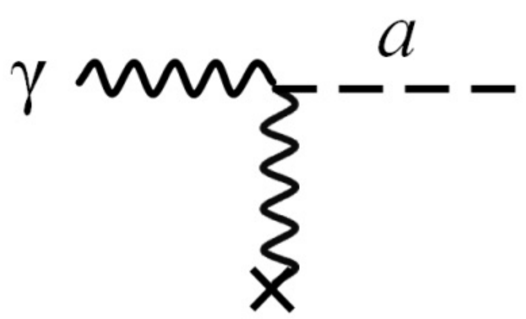
In-situ photon spectrum through hadronic (pp and pg) or leptonic interactions

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

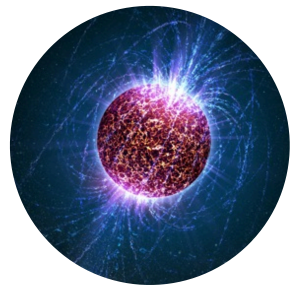
In-situ conversion into ALPs

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

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

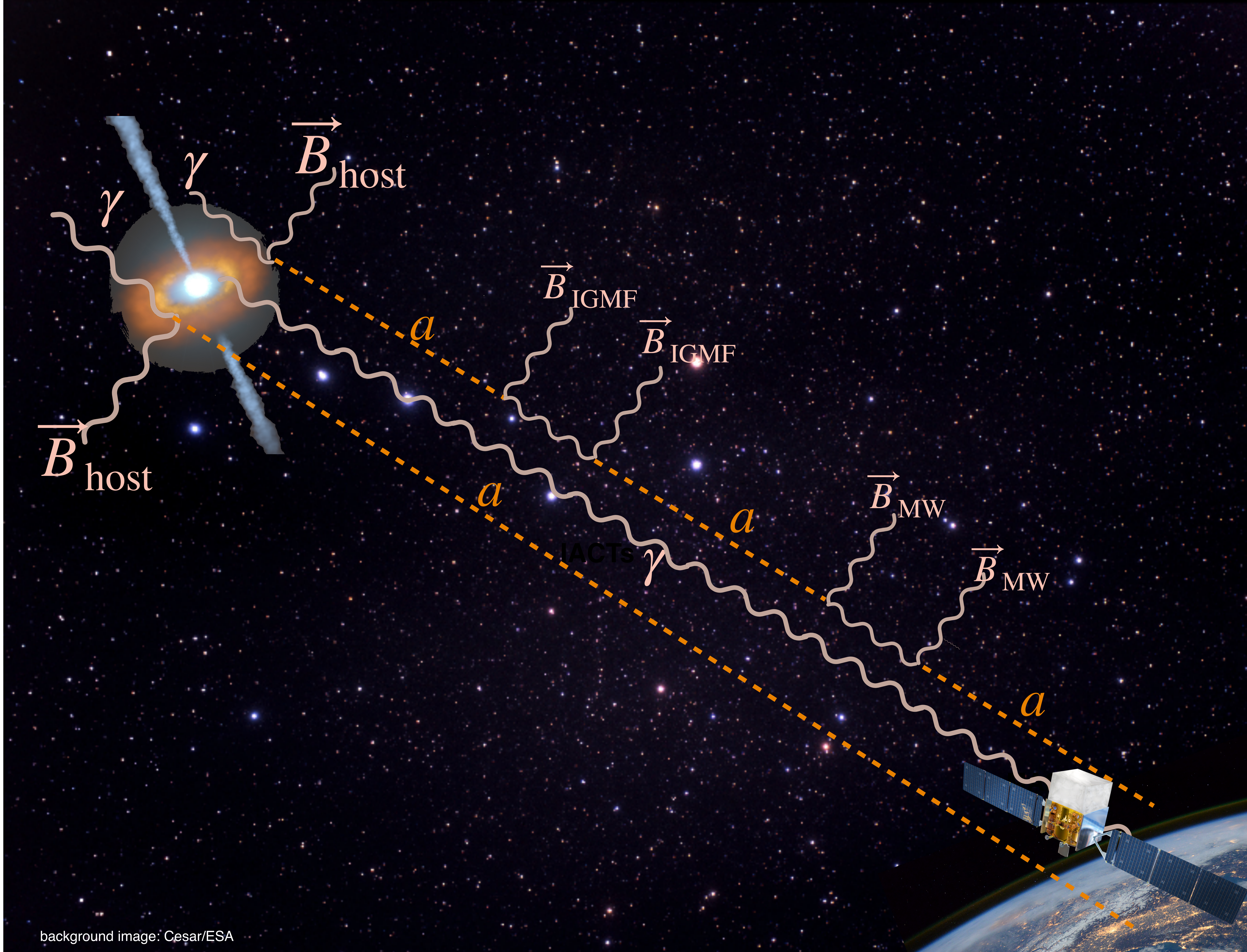


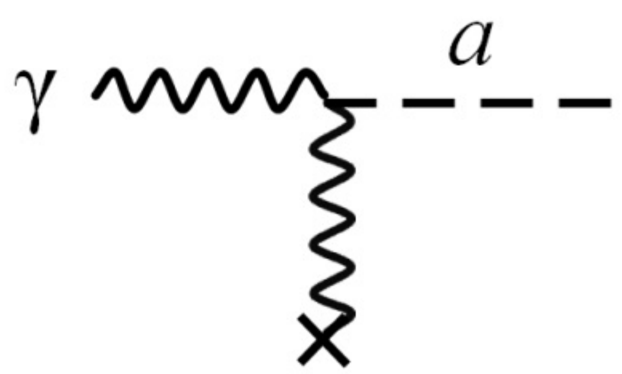
[Also photons from **Galactic objects** like pulsars and SNRs sourced by electric and magnetic fields]



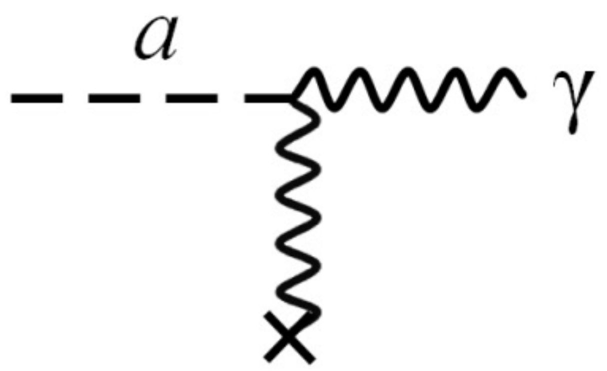
Prabhu PRD'21

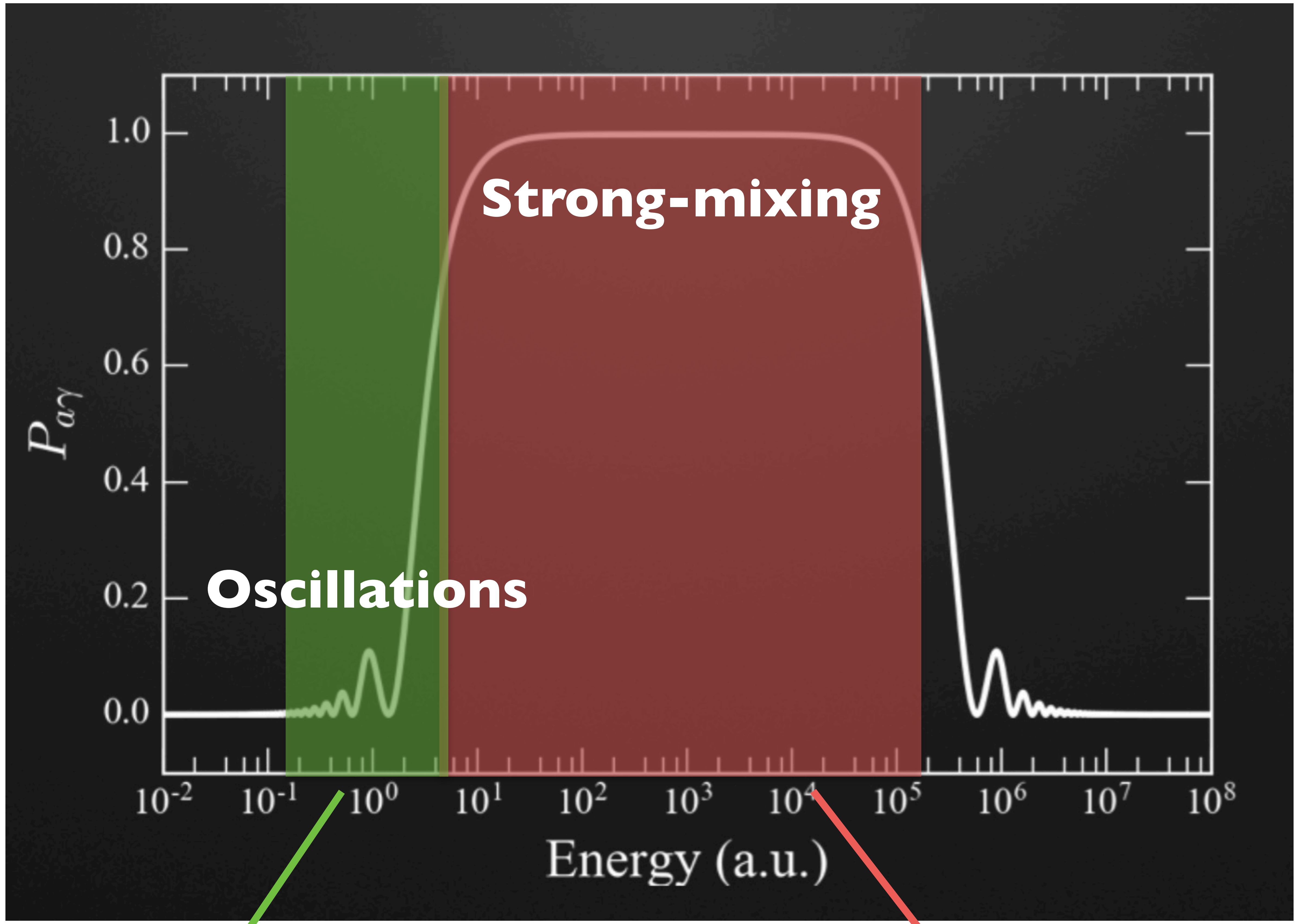
Conversion in extragalactic environments





The ALP-photon mixing





I. Spectral irregularities at $\sim E_c$

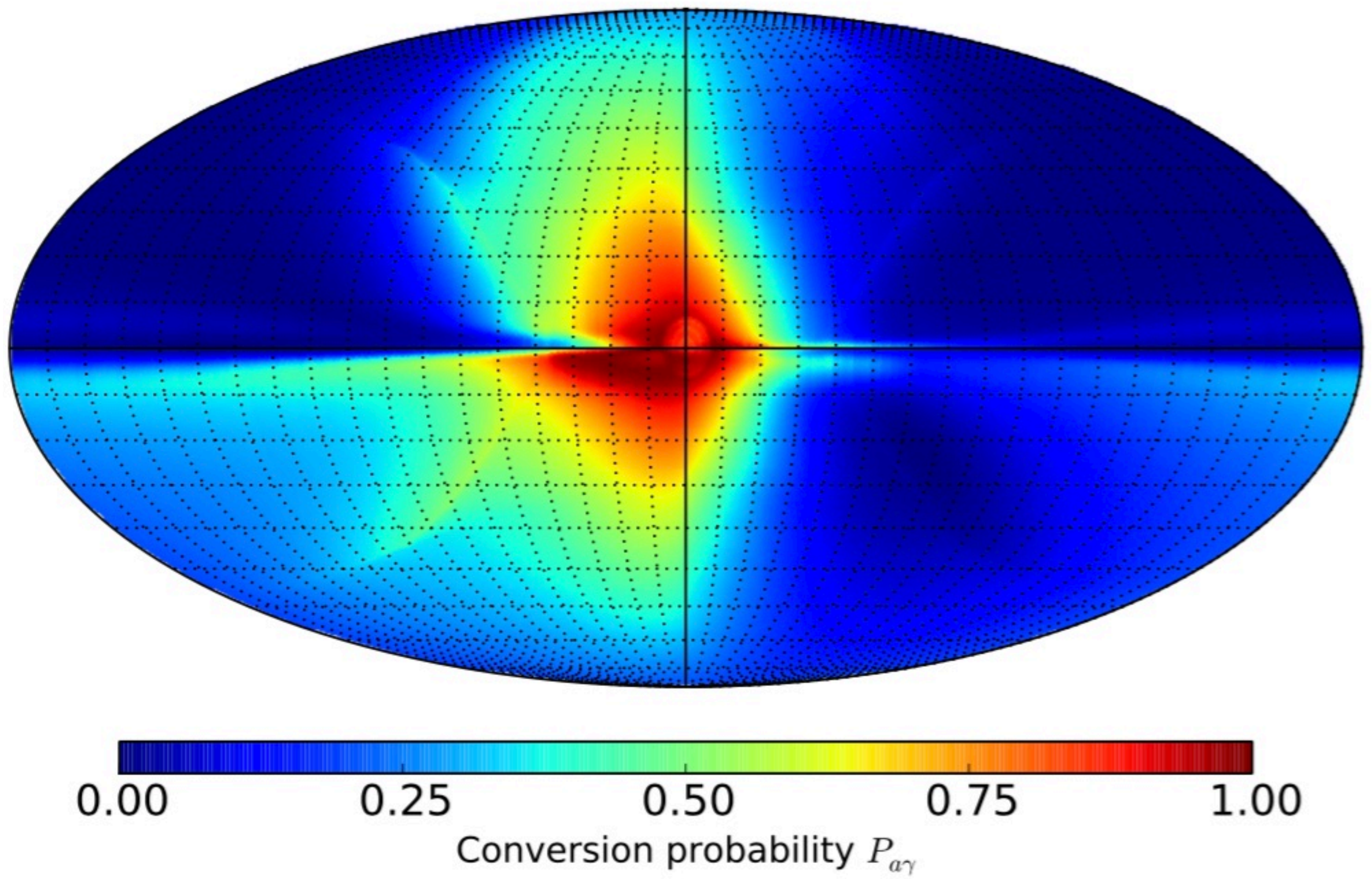
II. ALPs do not get absorbed, enhancing the photon flux

Searches for spectral irregularities

High-energy gamma rays

Some basic requirement:

- Very **bright gamma-ray sources** ⟶ High statistics for a good spectral determination
- Sources far enough and in the **direction of strong transversal B-fields**, e.g. behind or within a galaxy cluster
- Good knowledge of B-field! As ALP searches are sensitive to the product $\mathbf{g_{a\gamma}\,B_T}$, the constraint on $g_{a\gamma}$ is only as good as the knowledge of B_T.

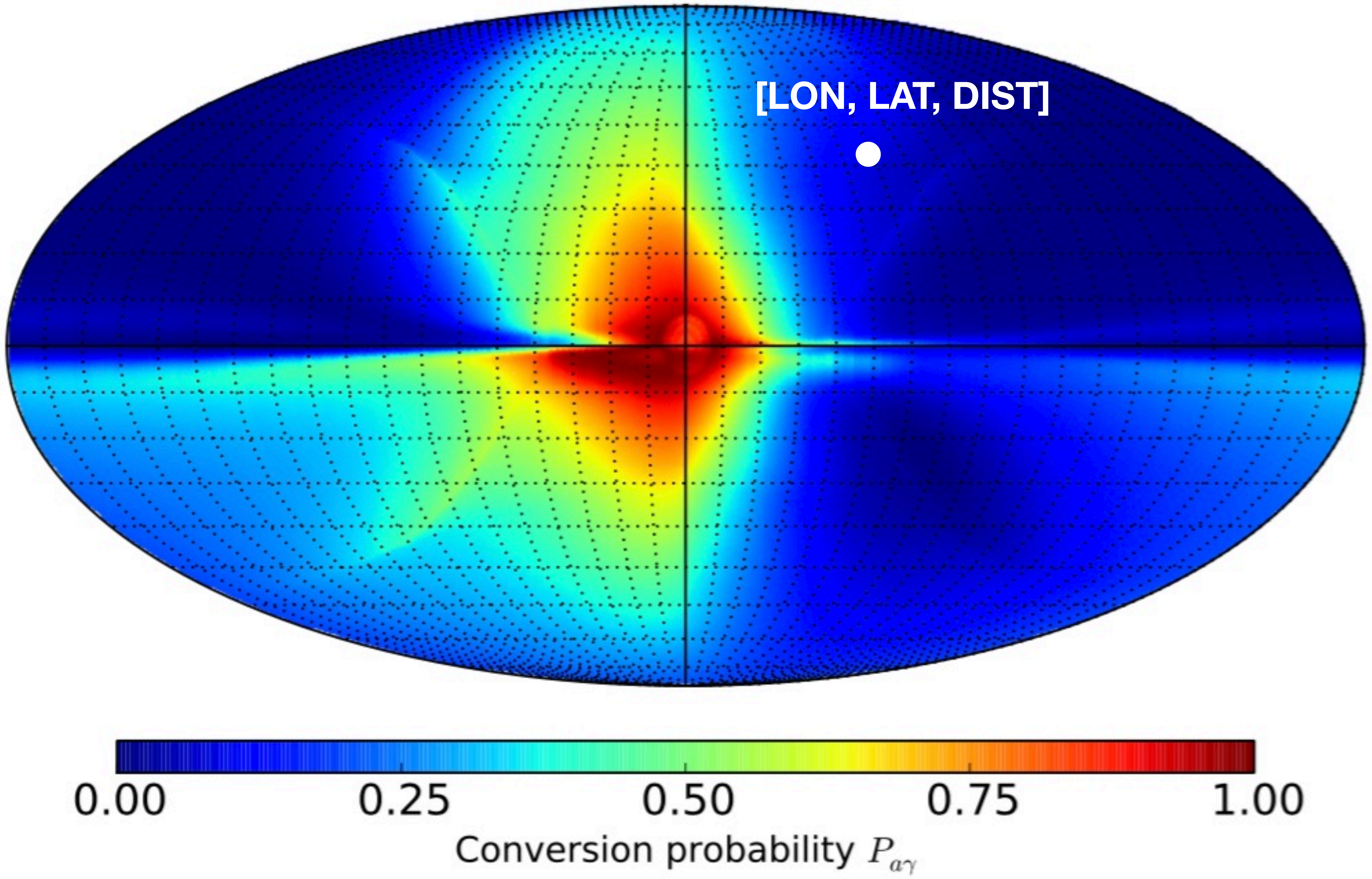


Conversion probability in Galactic B-field

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

Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

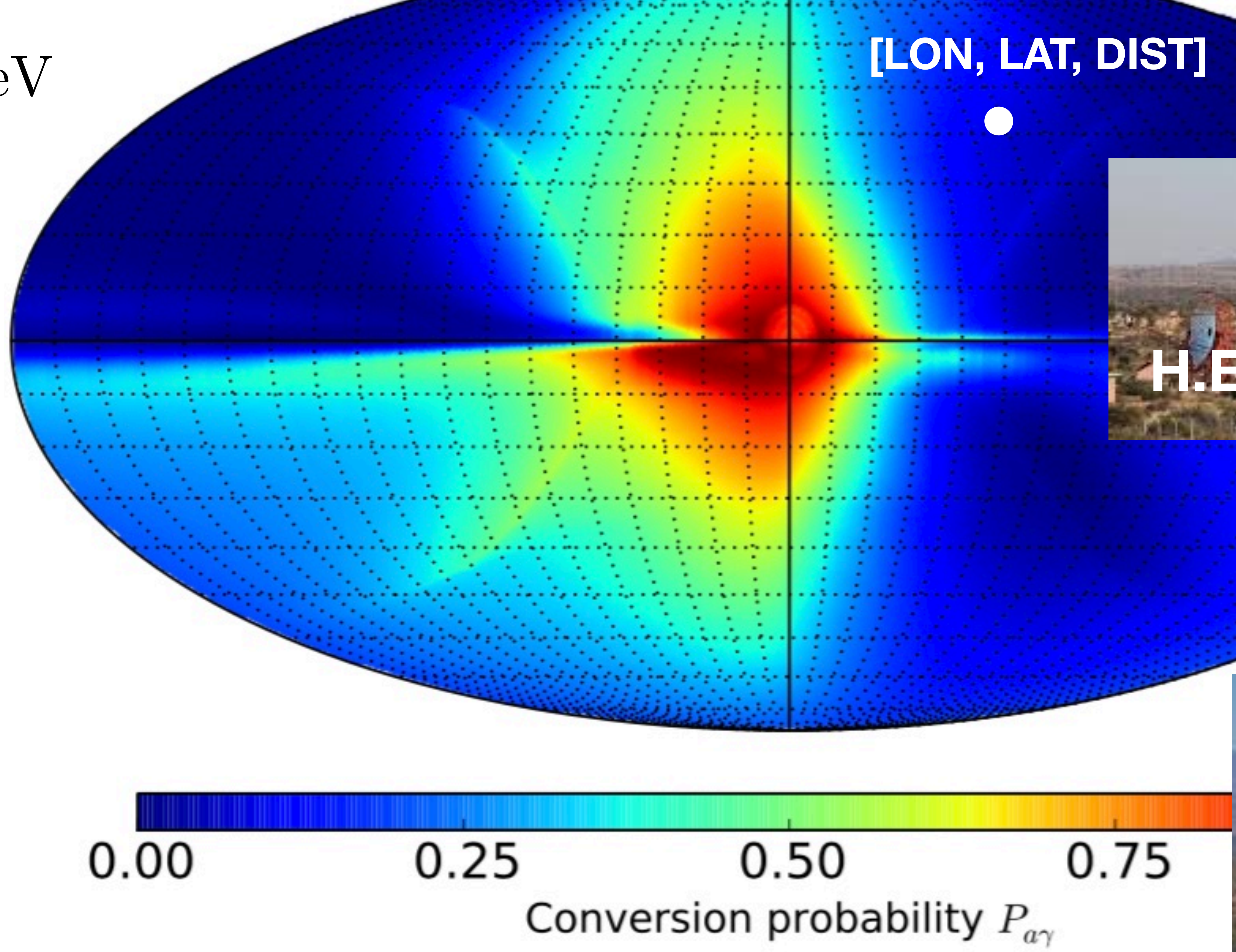


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Fermi Large Area Telescope (LAT)

$30\,\mathrm{MeV} \lesssim \mathrm{E}_\gamma \lesssim 1\,\mathrm{TeV}$

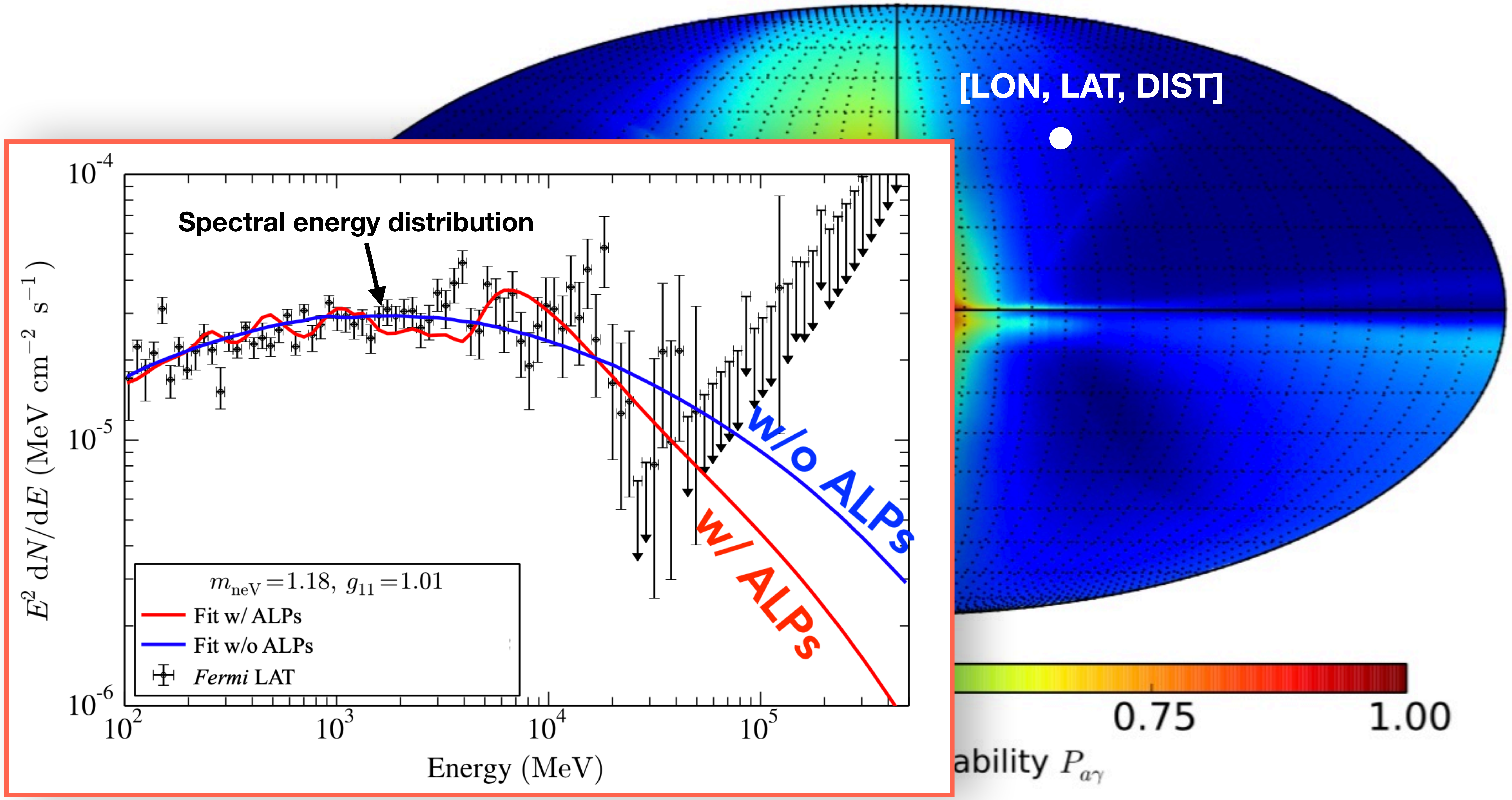


Imaging Air Cherenkov Telescopes

$50\,\mathrm{GeV} \lesssim \mathrm{E}_\gamma \lesssim 100\,\mathrm{TeV}$

Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

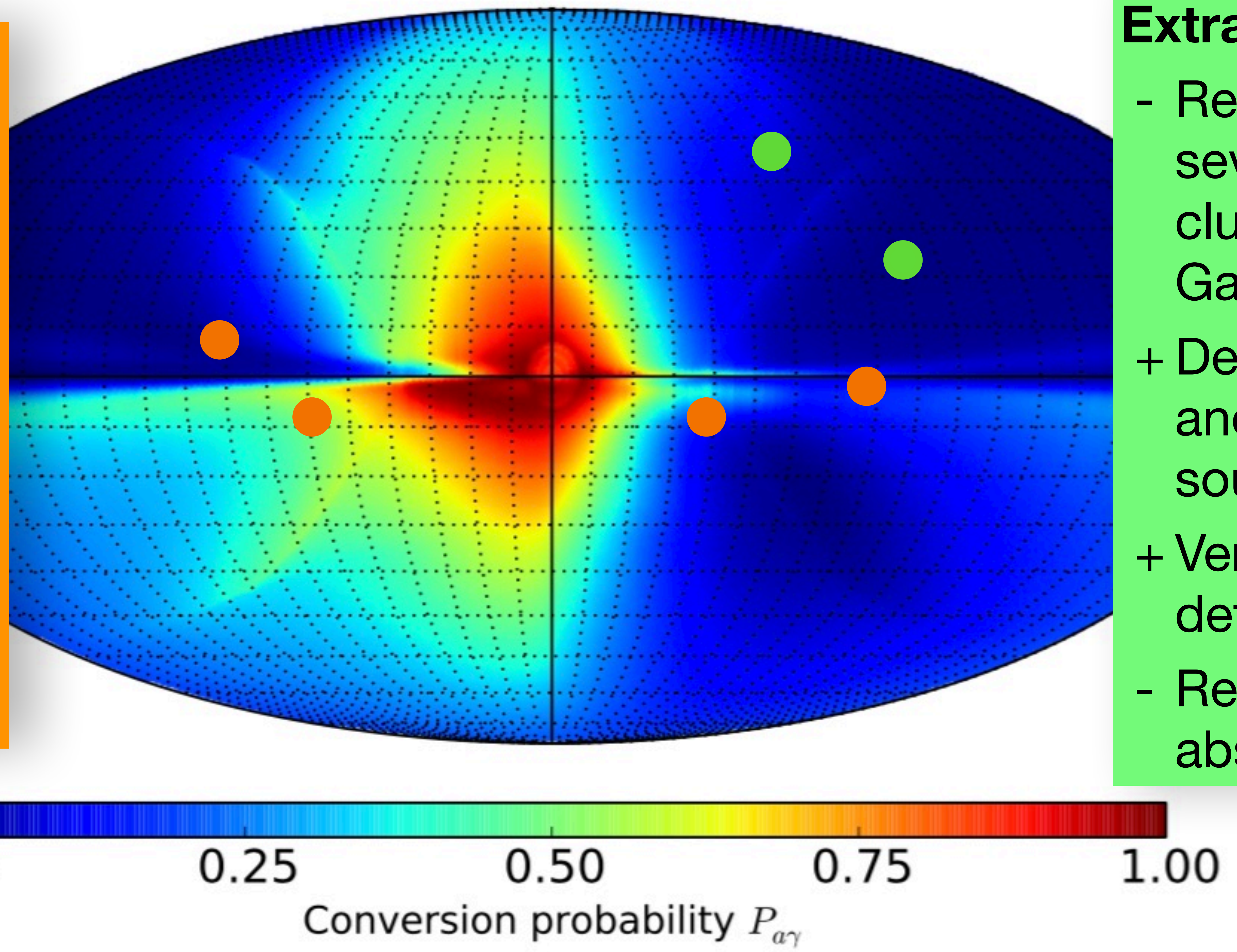


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Galactic targets:

- + Require only modelling of Galactic B field
- - Strength of the conversion depends on position in the Galaxy (e.g. beyond spiral arms)
- - Larger systematics on spectral determination due to gamma-ray diffuse emission foreground



Extragalactic targets:

- - Require modelling of several B fields (intra-cluster, intergalactic, Galactic)
- + Depends only on latitude and longitude of the sources
- + Very accurate spectral determination
- - Require modelling of EBL absorption

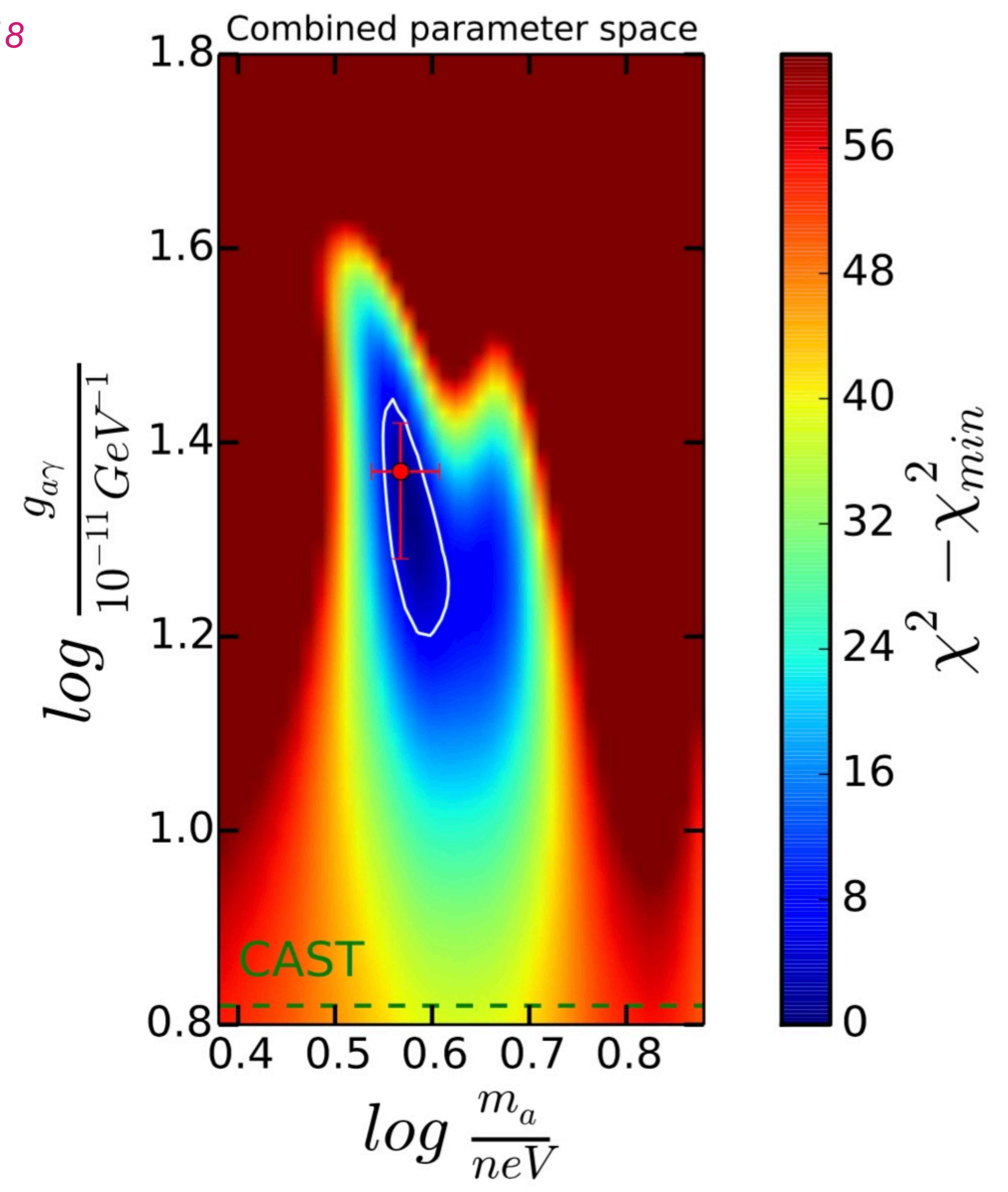
Signal hints for ALP-photon mixing

Search for spectral irregularities in Galactic targets

- Analysis of **6 bright pulsars** with **Fermi-LAT** *Majumdar, FC & Horns JCAP'18*
  - ✓ **4.6σ** significance for common ALP-photon mixing

$$m_a = (3.6^{+0.5_{\rm stat.}}_{-0.2_{\rm stat.}} \pm 0.2_{\rm syst.})\ {\rm neV} \qquad g_{a\gamma\gamma} = (2.3^{+0.3_{\rm stat.}}_{-0.4_{\rm stat.}} \pm 0.4_{\rm syst.}) \times 10^{-10}\ {\rm GeV}^{-1}$$

  - ✓ 20%-40% spectral variation vs ~3% experimental systematic uncertainty
  - ✓ Systematic theoretical uncertainties on transverse B field and distances
- Analysis of **3 bright SNRs** with **Fermi-LAT** and **HESS/MAGIC/VERITAS** *Xia+ PRD'19*
  - ✓ **3σ** significance for only one source (IC443)
  - ✓ Large systematic due to GeV-TeV data calibration
- Analysis of **10 SNRs and pulsars** *Liang+ JCAP'19*
  - ✓ No evidence for common ALP-photon mixing

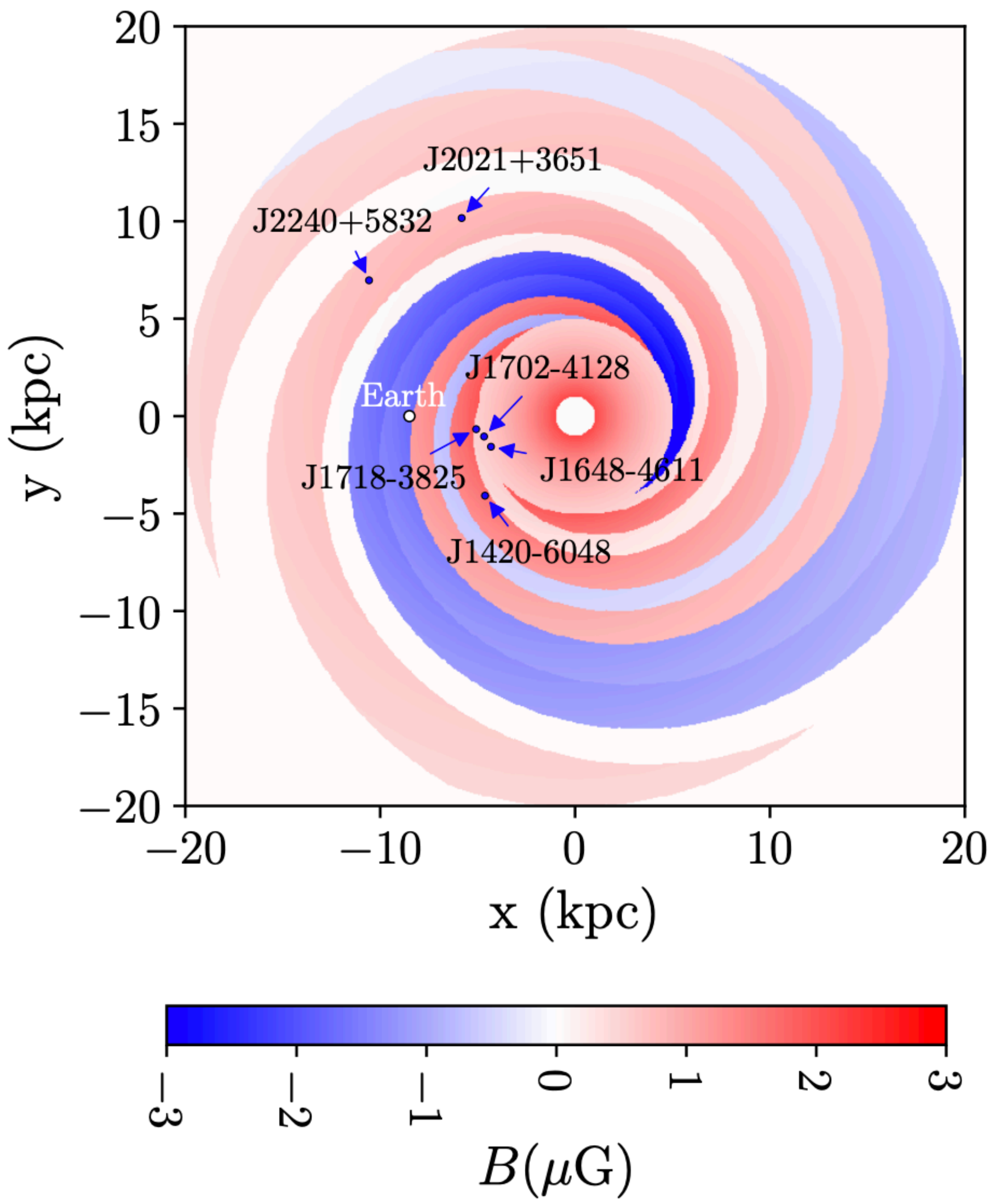


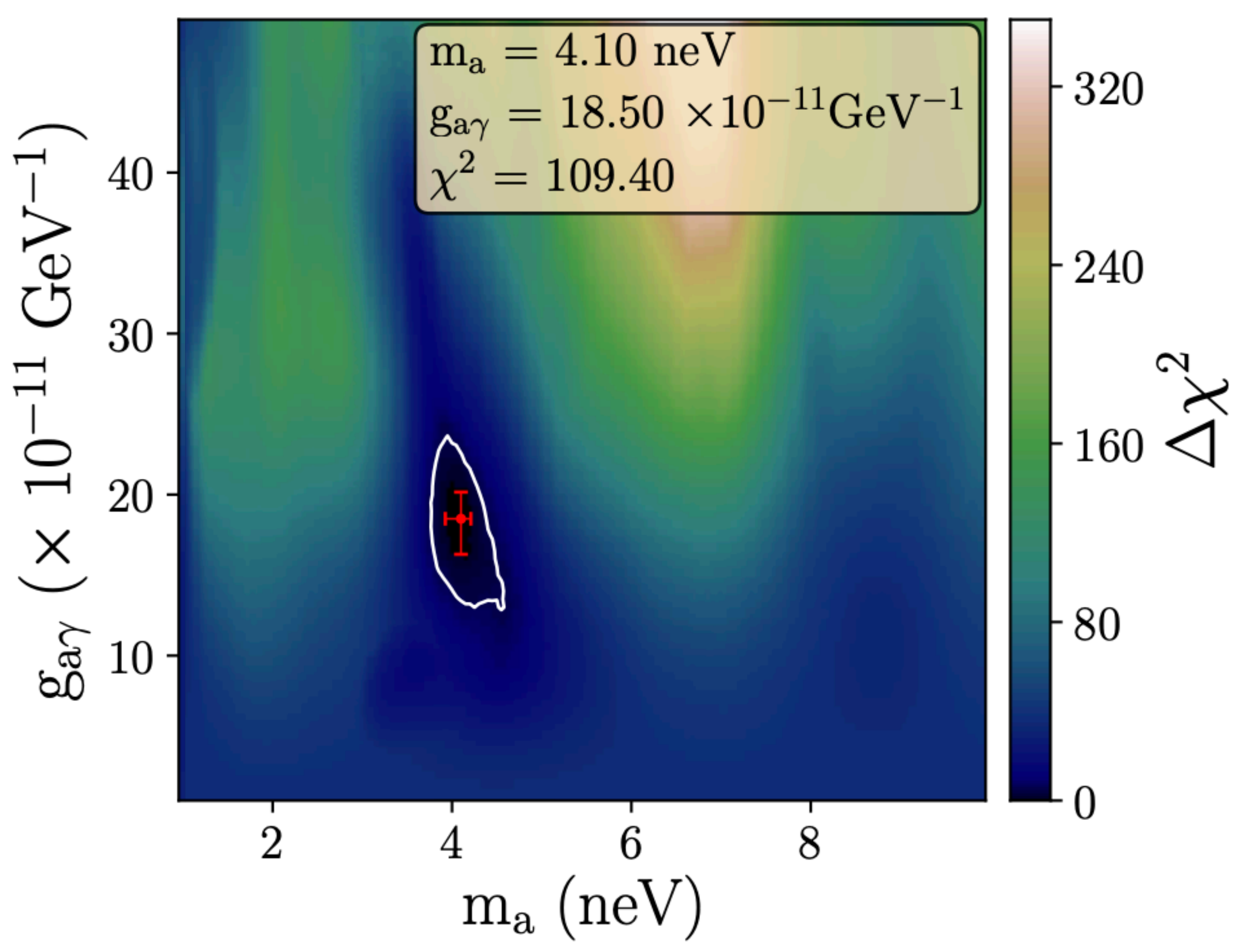
Signal hints for ALP-photon mixing

A recent update of PSR signal region

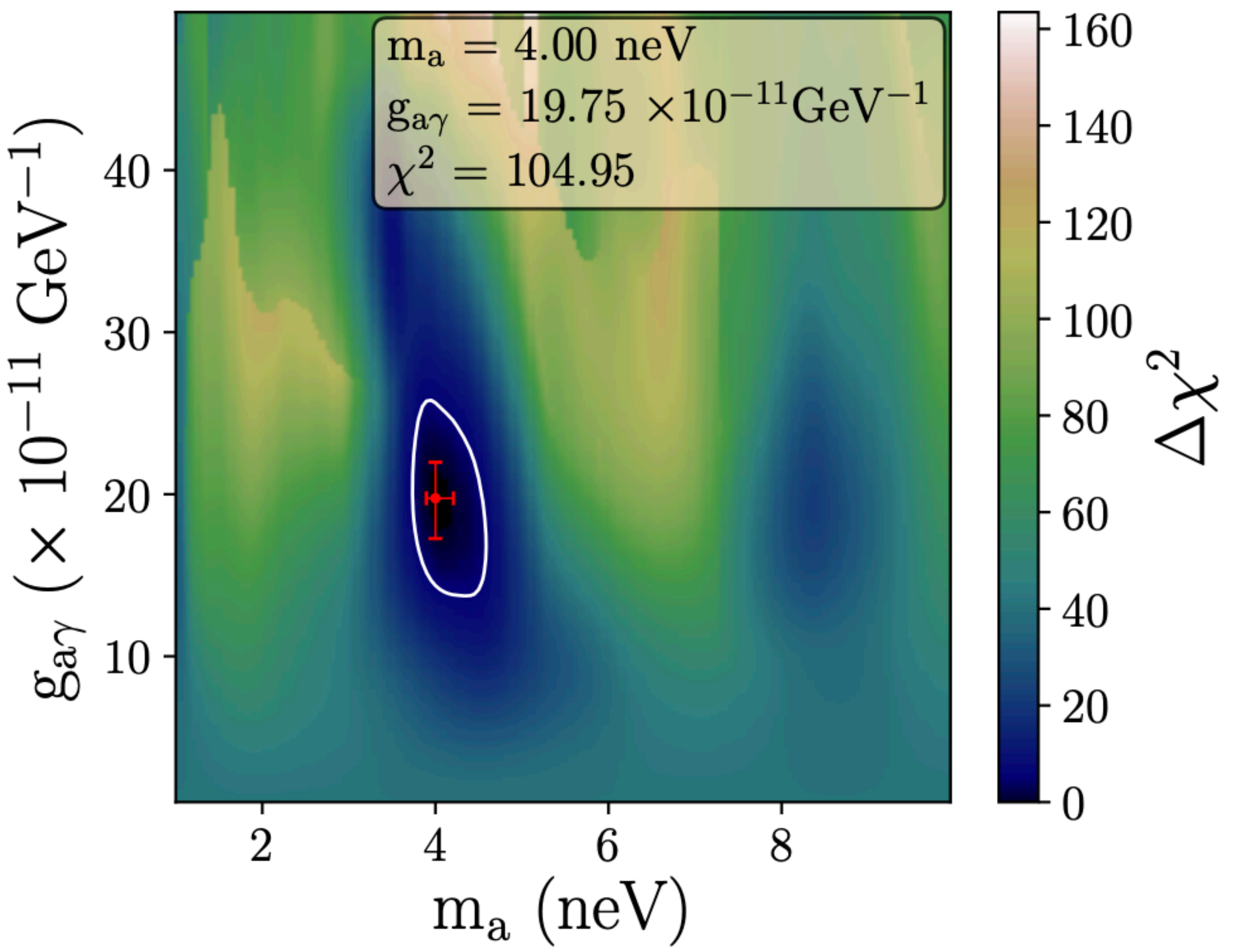
Adamane Pallathadka, FC+ 2008.08100

- Re-analysis of **6 bright pulsar sample**
- Updated B field model (Planck results) and distance measurements
- **Profiling** of the likelihood over **distance and B field uncertainties** adding penalised likelihood terms





Distance uncertainty



B-field uncertainty

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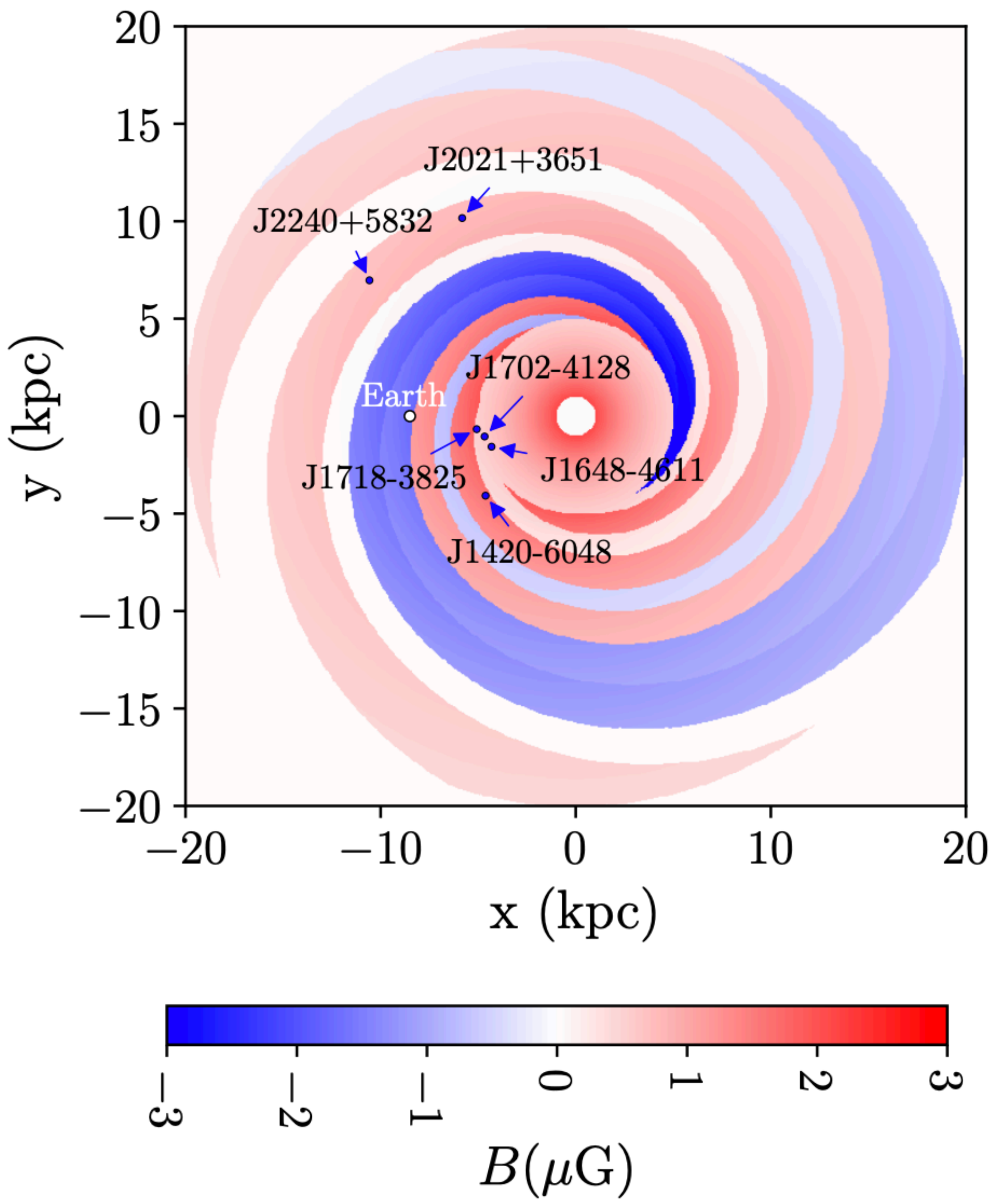
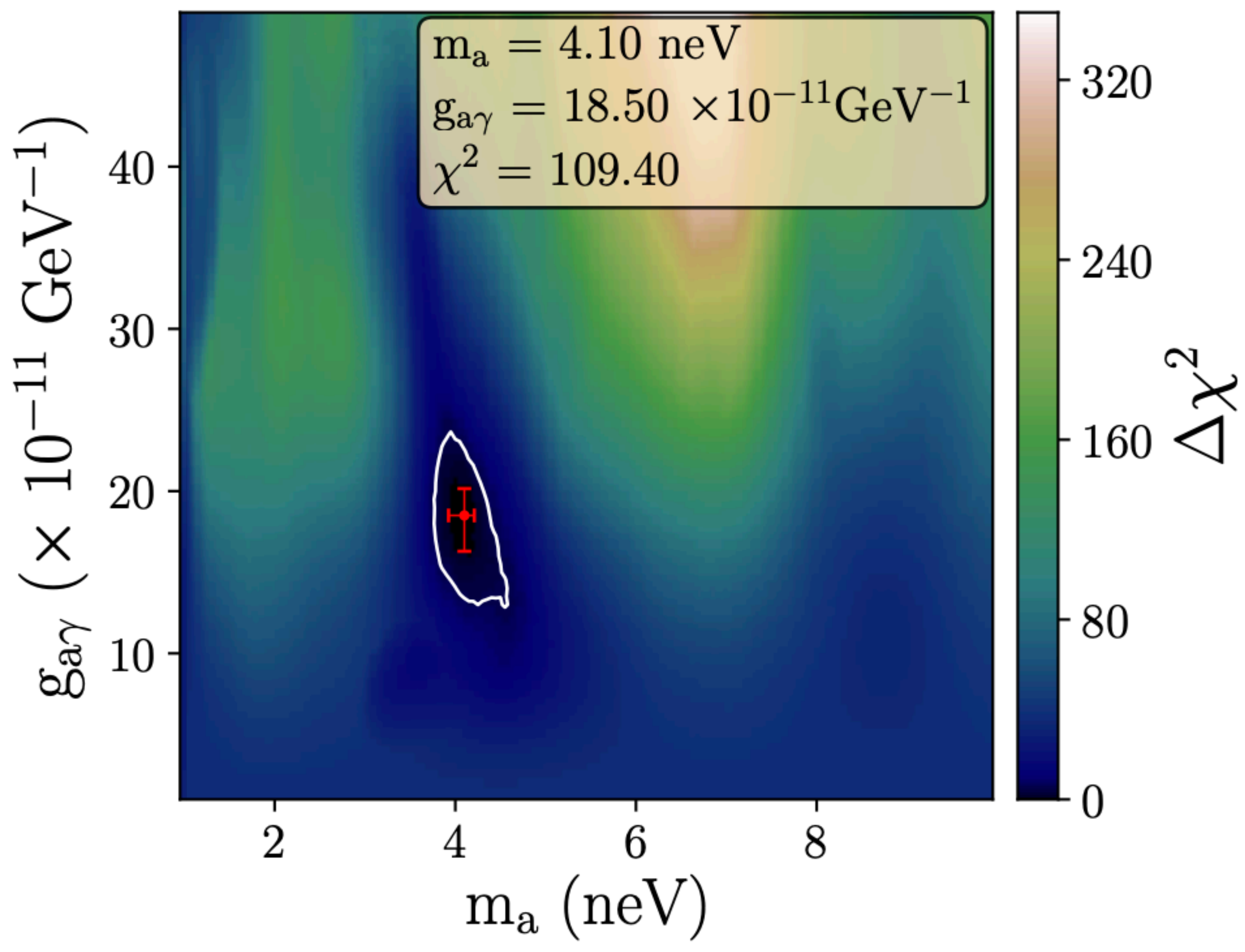
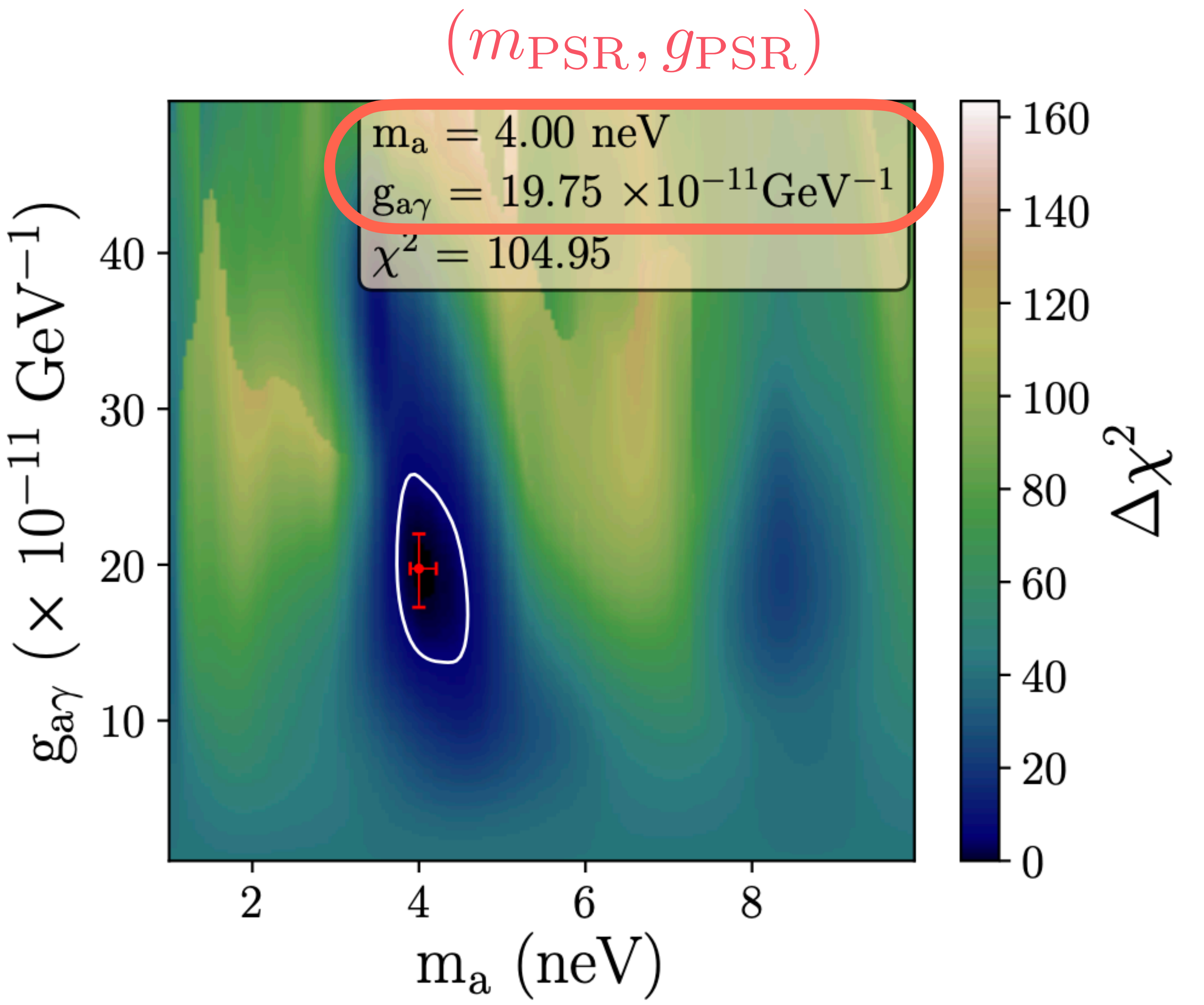




Distance uncertainty



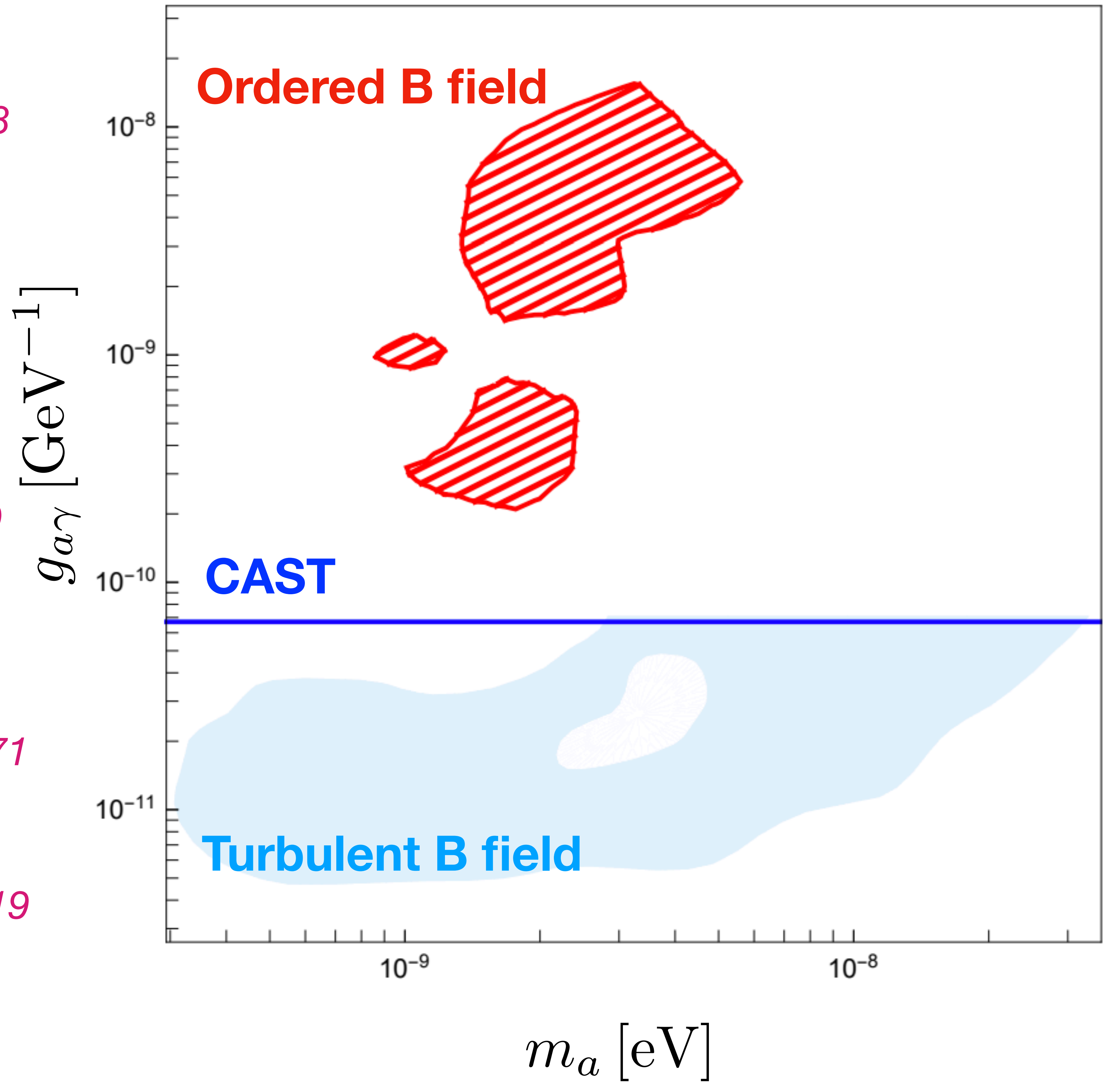
B-field uncertainty

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**

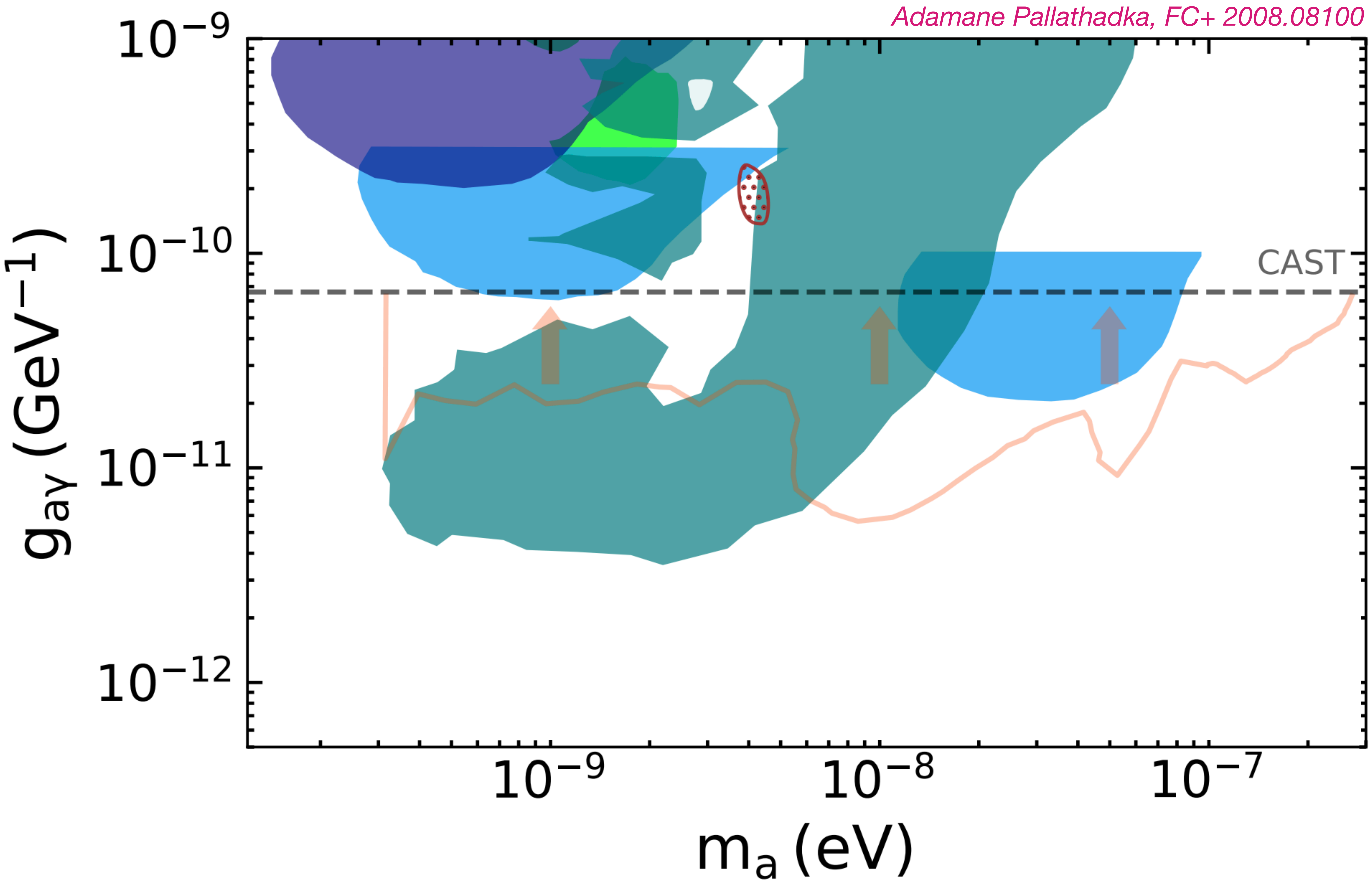
- Analysis of radio galaxy **NGC1275** (Perseus cluster) with **Fermi-LAT** and **MAGIC** *Ajello+PRL'16, Malyshev+1805.04388*
  - ✓ Limits very sensitive to modelling of intra-cluster B field
  - ✓ Typically, only turbulent component is modelled
  - ✓ But, there is evidence for large scale ordered component (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



Libanov &Troitsky PLB'20

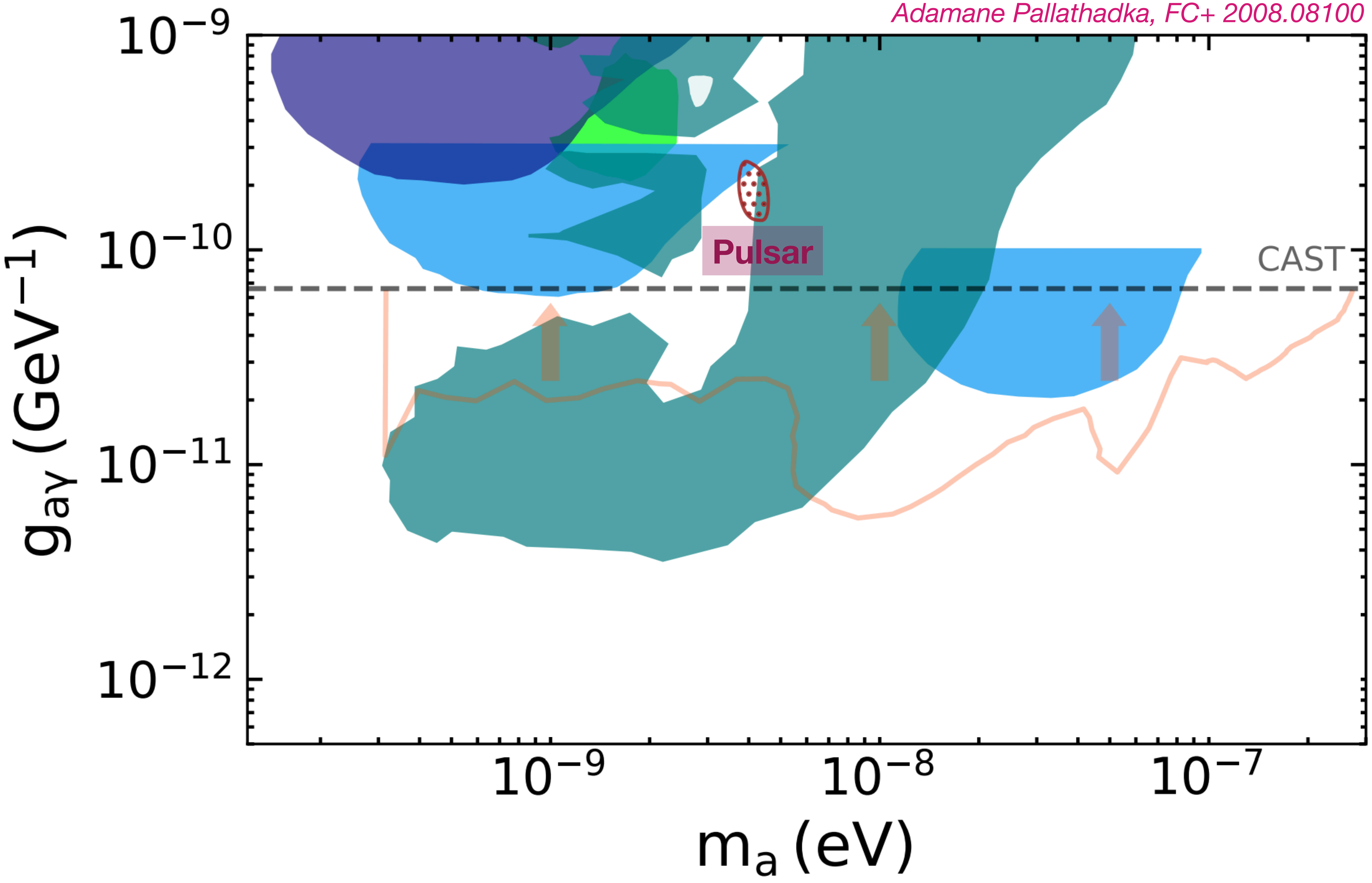
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



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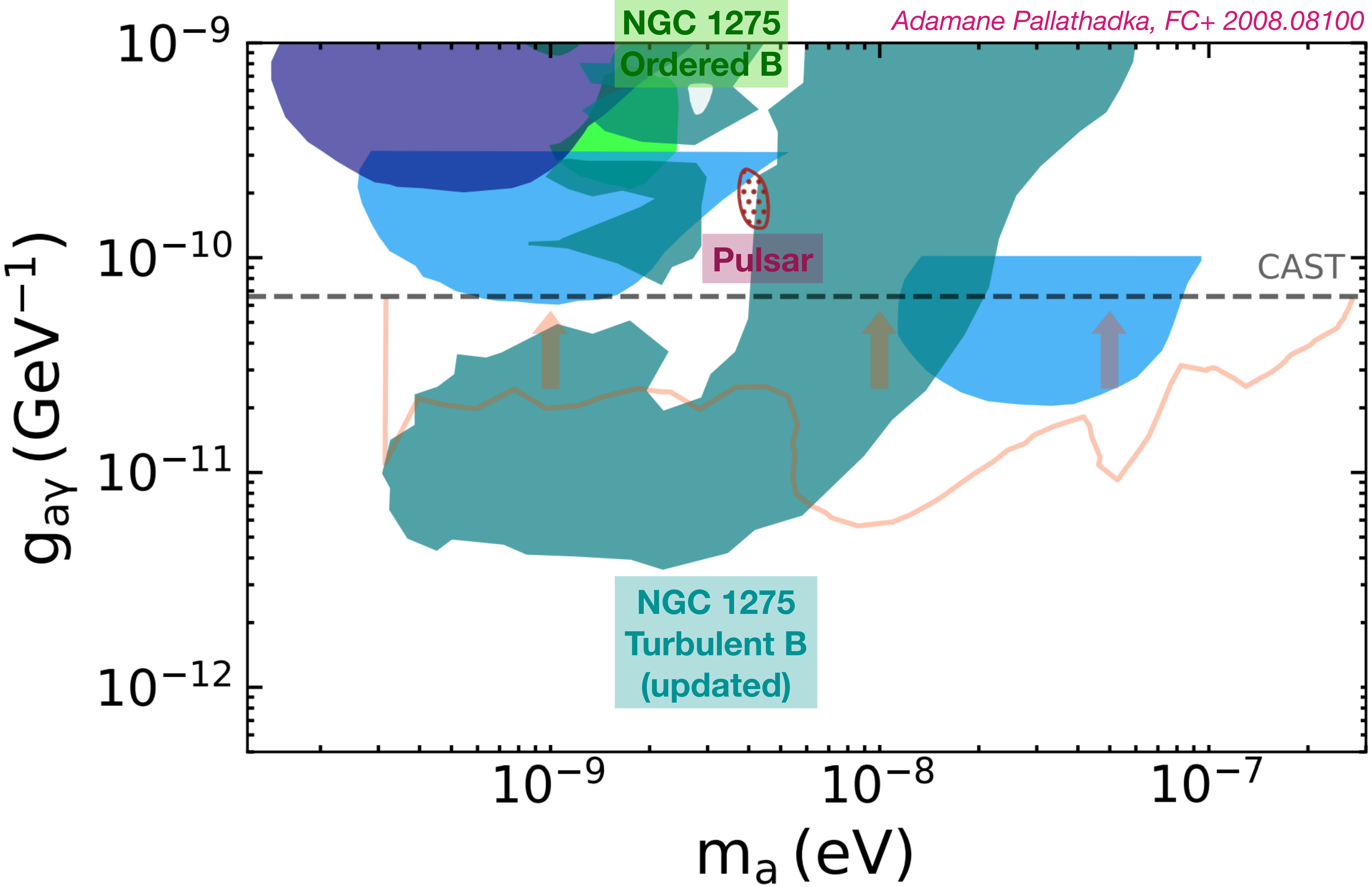
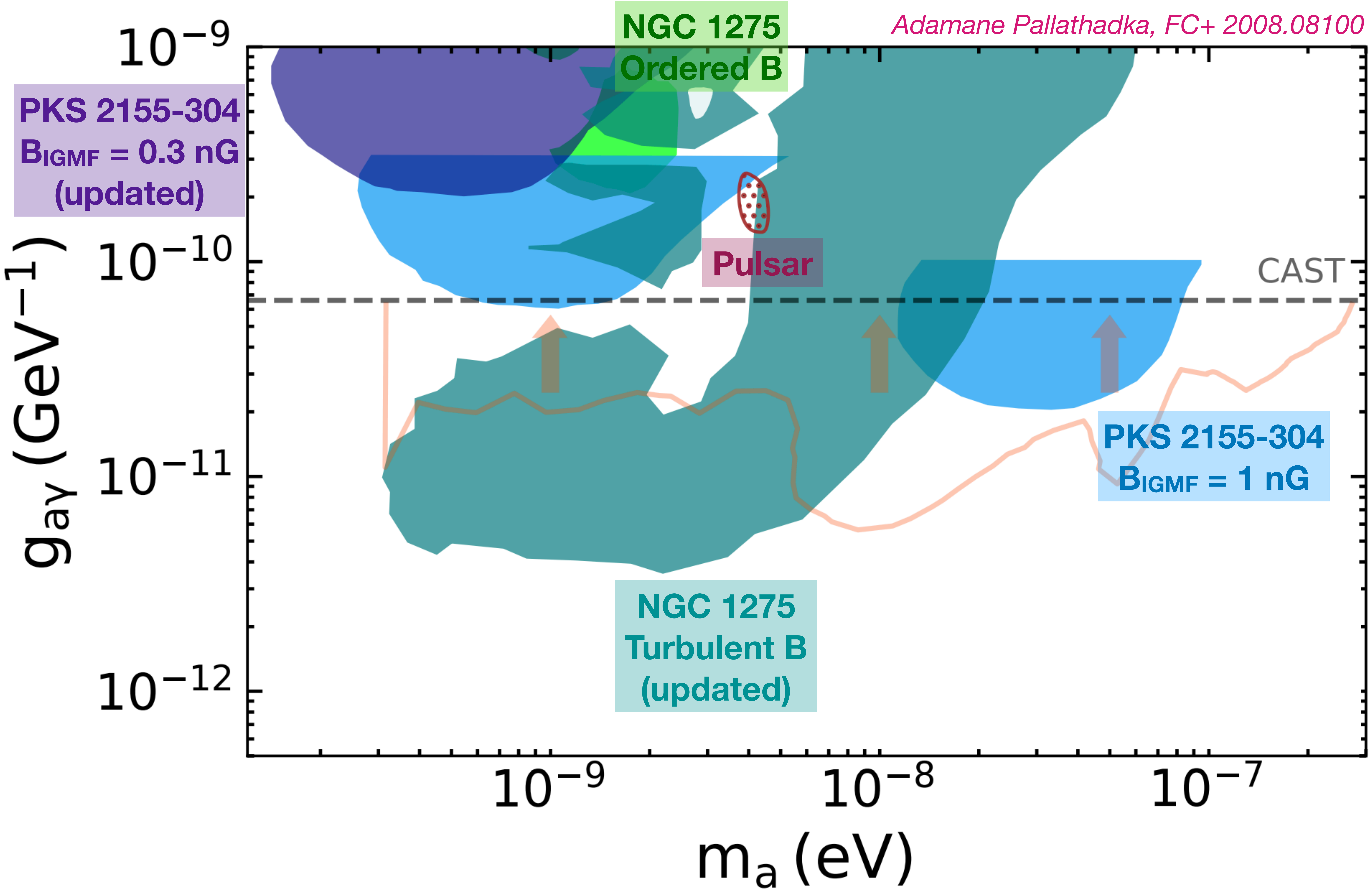


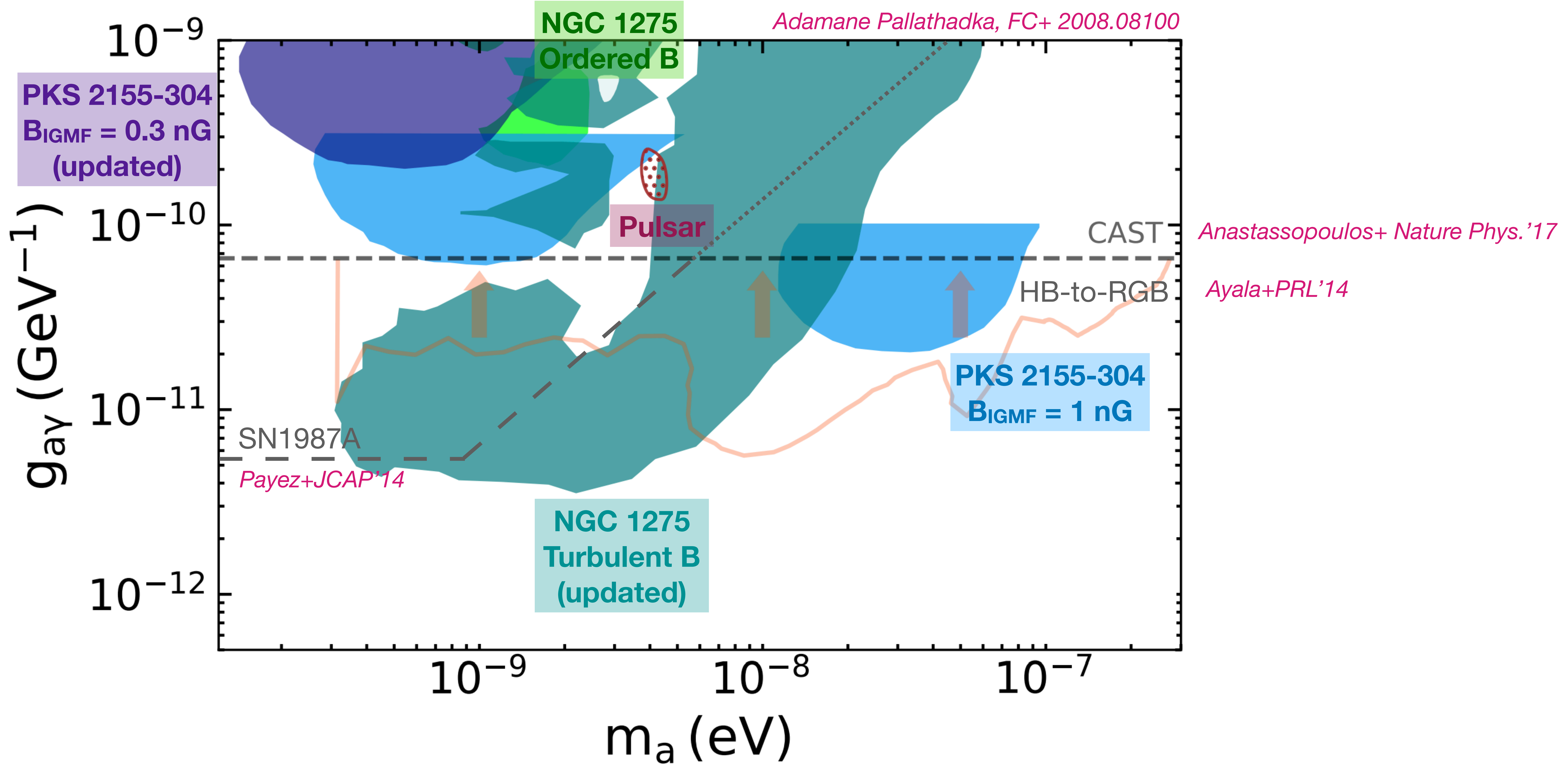
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



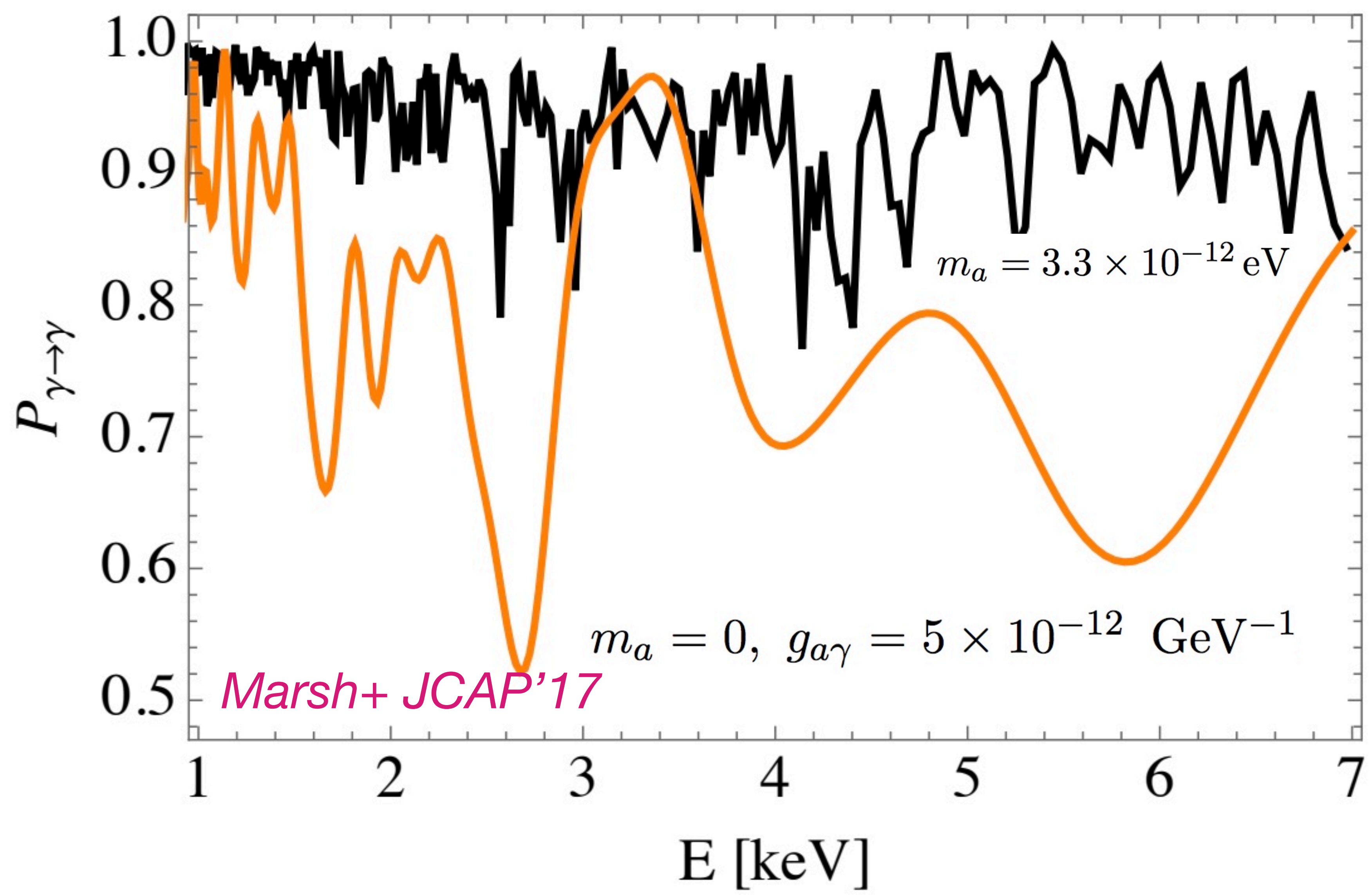
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



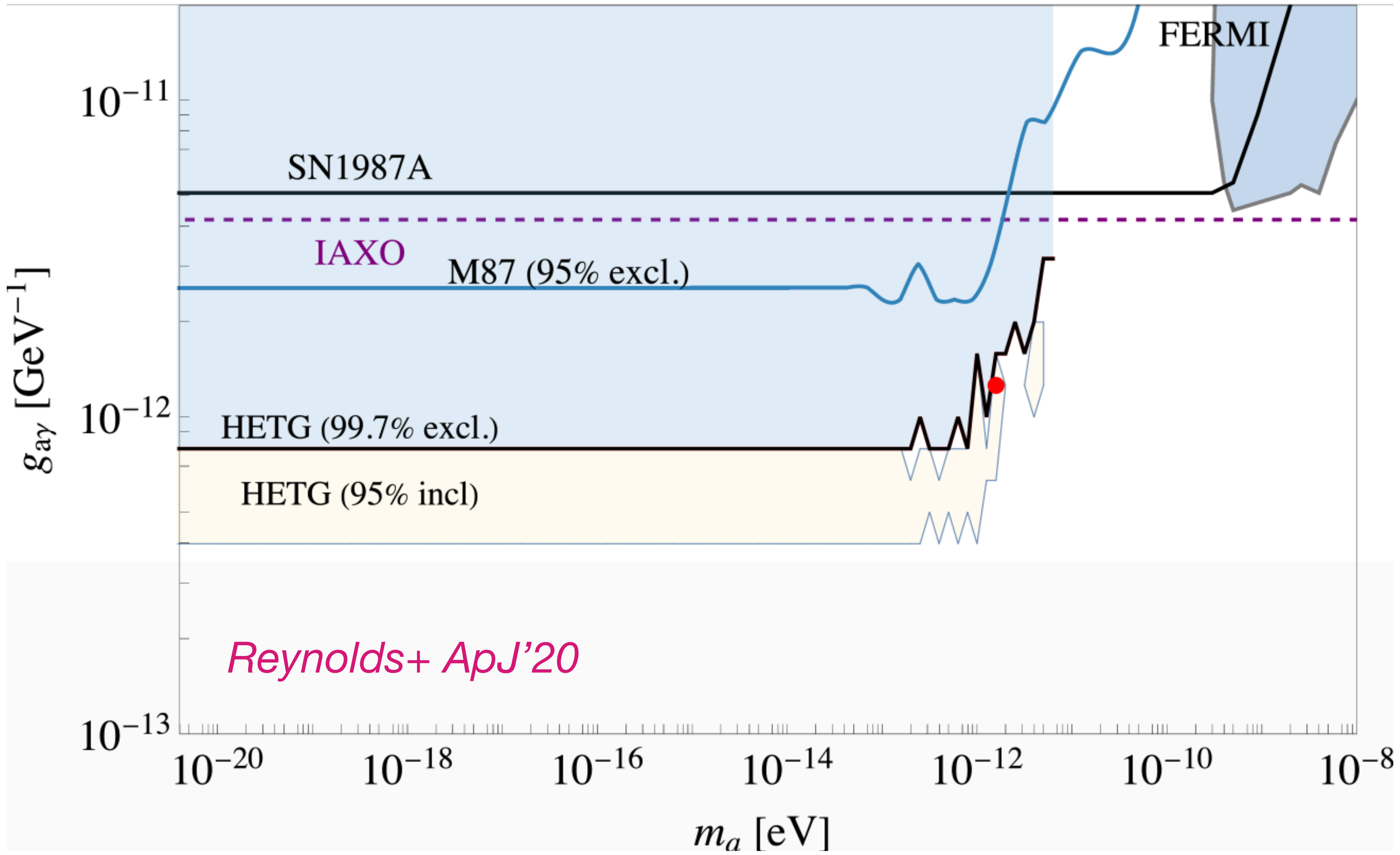
Searches for X-ray spectral irregularities

- **Hydra A galaxy cluster**: z = 0.052, 240ks *Chandra* observation *Wouters&Brun ApJ'13*
- **NGC1275** in **Perseus cluster**: *Chandra* and *XMM Newton* observations *Berg+ ApJ'17; Reynolds+ ApJ'20*
- **M87** AGN in the **Virgo cluster** *Marsh+ JCAP'17*
- **7 Quasars/AGN** behind/within **nearby clusters**: *Chandra* archival data *Conlon+ JCAP'17*



➡ All spectra consistent with absorbed power laws

➡ X rays strong emission in low-mass regime **$m_a \sim 10^{-12}$eV**, where the ALP mass is below the plasma frequency of galaxy clusters



[See also: *Schlederer&Sigl JCAP'16; Conlon+PRD'16*]

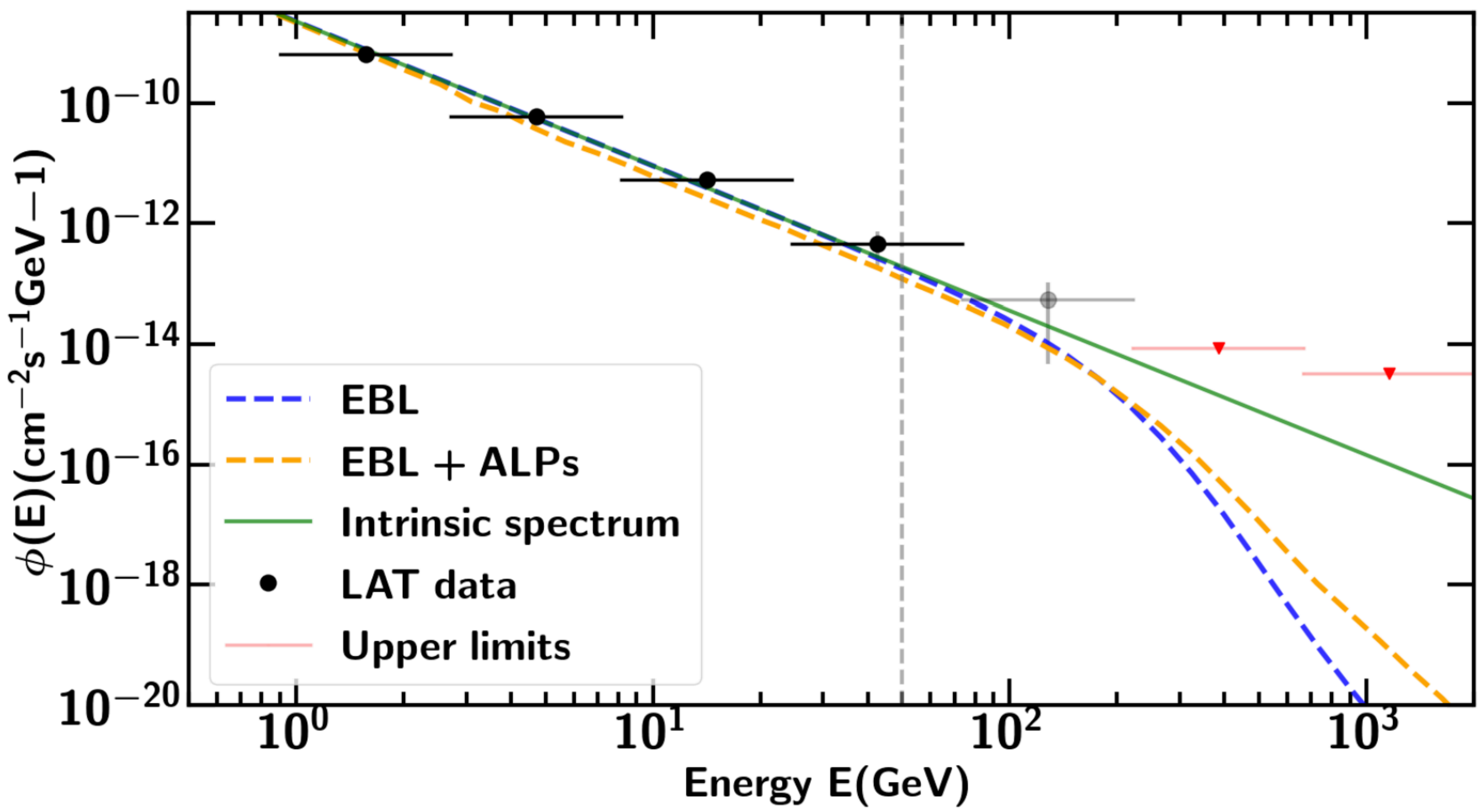
ALPs and the opacity of the Universe

- **VHE photons** from distant sources are **attenuated** by pair production onto the **Extragalactic Background Light (EBL)**

$$\phi_{obs}(E) = \phi_{int}(E) \cdot \exp\left[-\tau(E,z)\right] \qquad \tau = \frac{d}{n(E)\sigma(\gamma\gamma \to e^+e^-)}$$

- The flux of very distant sources and at very high energies should be exponentially suppressed
- In the past, indications of **anomalous cosmic trasparency** from gamma-ray studies interpreted as possible signs of ALPs *De Angelis et al. (2009,2011,2015); Essey & Kusenko (2012); Horns & Meyer (2012); Rubtsov & Troitsky (2014); etc*
- Latest data **consistent with EBL expectations**

Biteau&Williams+ApJ'15; Dominguez&Ajello ApJL'15



➡ Search for ALPs-induced anomalous EBL absorption

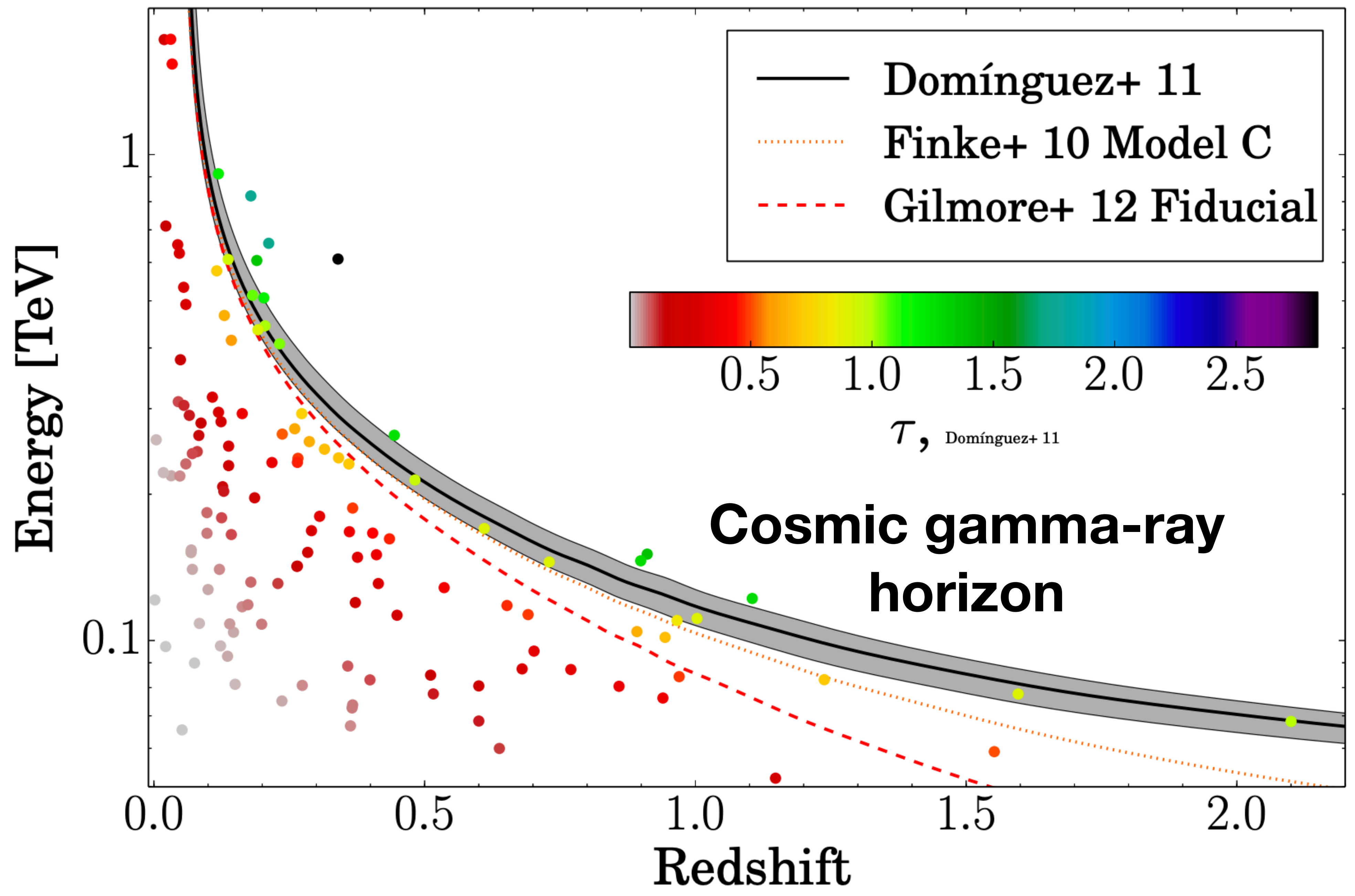
Buehler+ 2004.09396

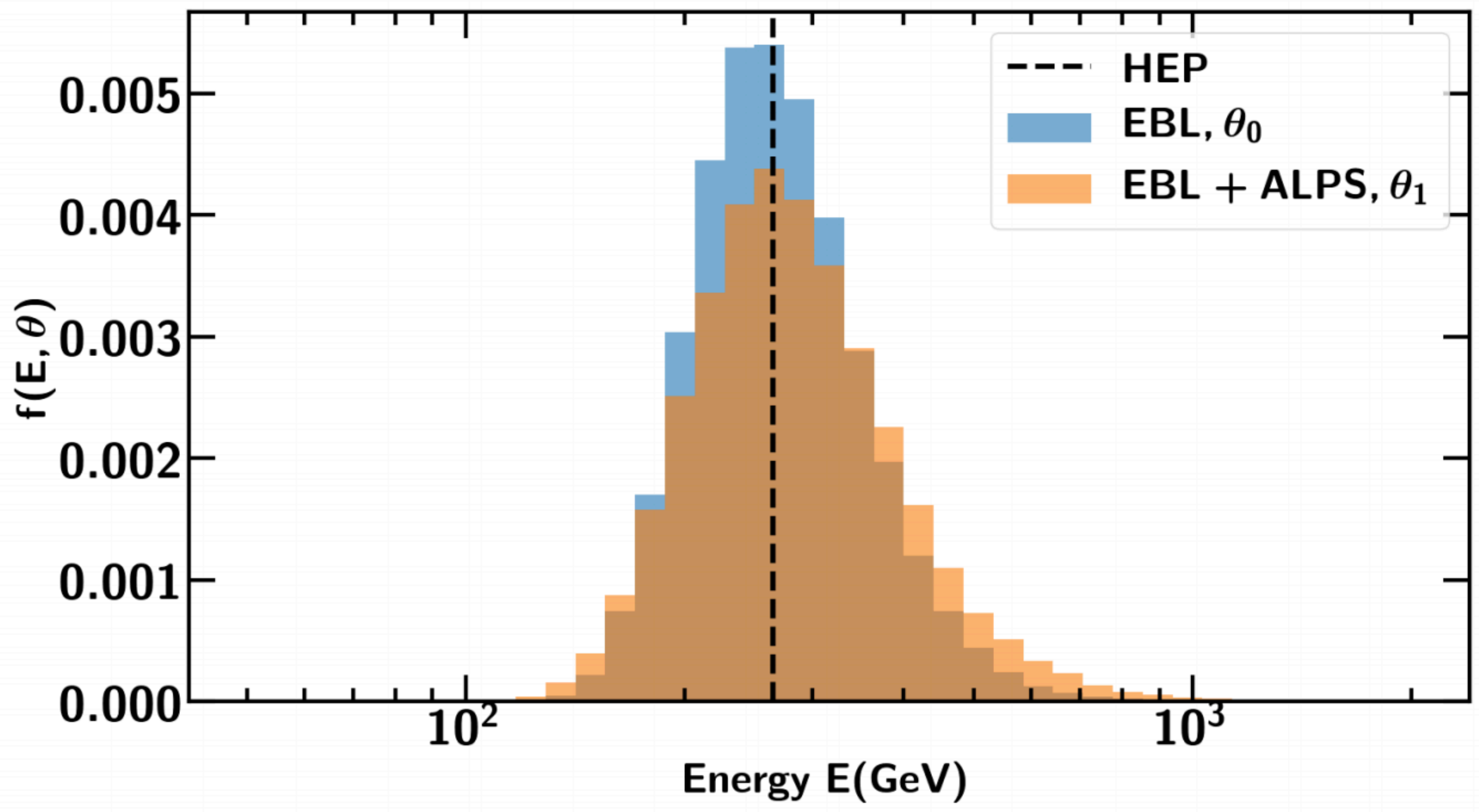
ALPs and the opacity of the Universe

Constraints from the cosmic gamma-ray horizon

Buehler+ 2004.09396

- Search for the imprint of ALPs in the **highest-energy photons** of hard gamma-ray blazars
- No evidence for an increased γ-ray transparency due to ALPs





Distribution of observed highest-energy photons (z ≥ 0.1) vs theoretical predictions in the presence of ALPs

ALPs and the opacity of the Universe

Constraints from the cosmic gamma-ray horizon

Buehler+ 2004.09396

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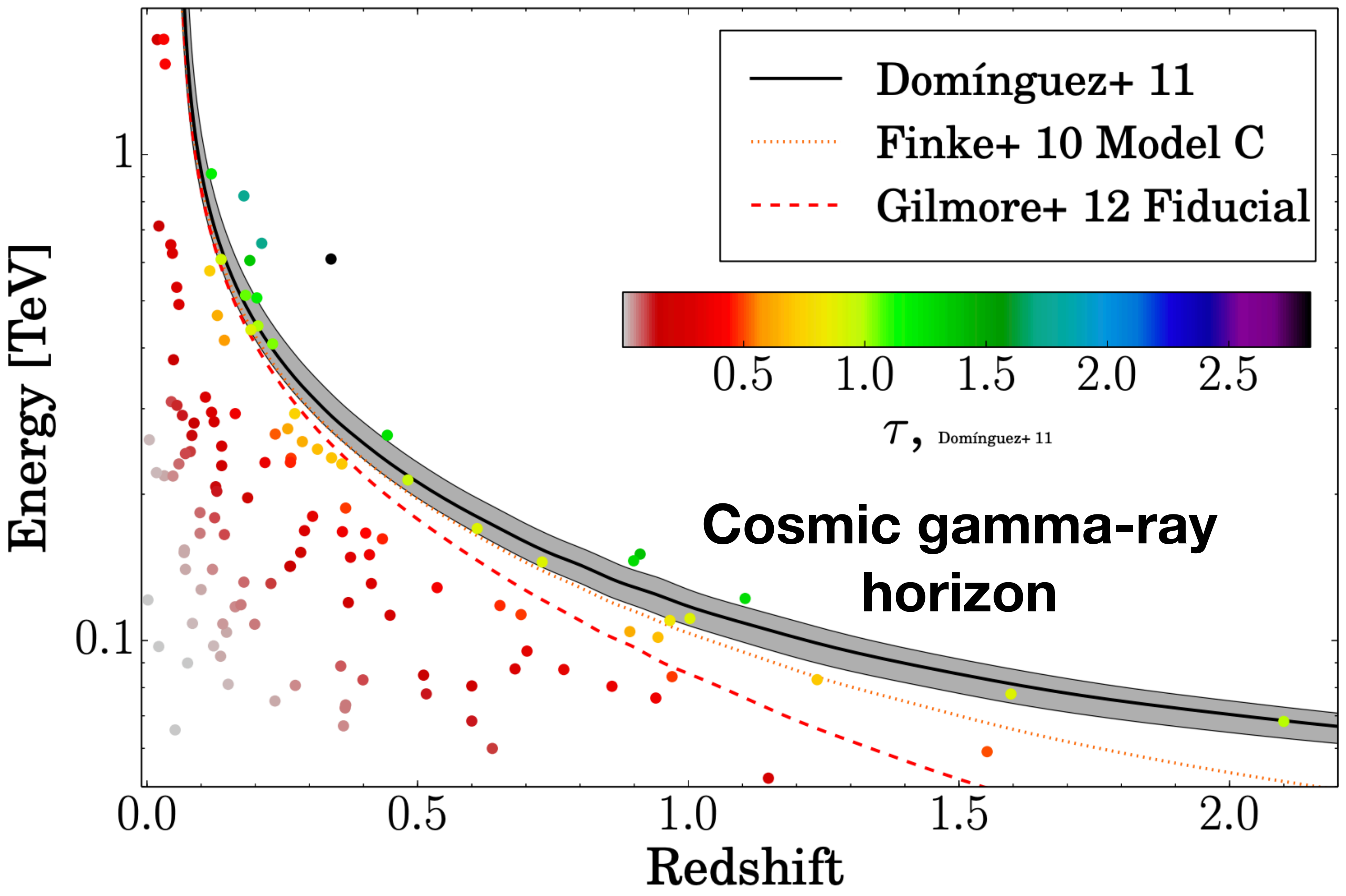
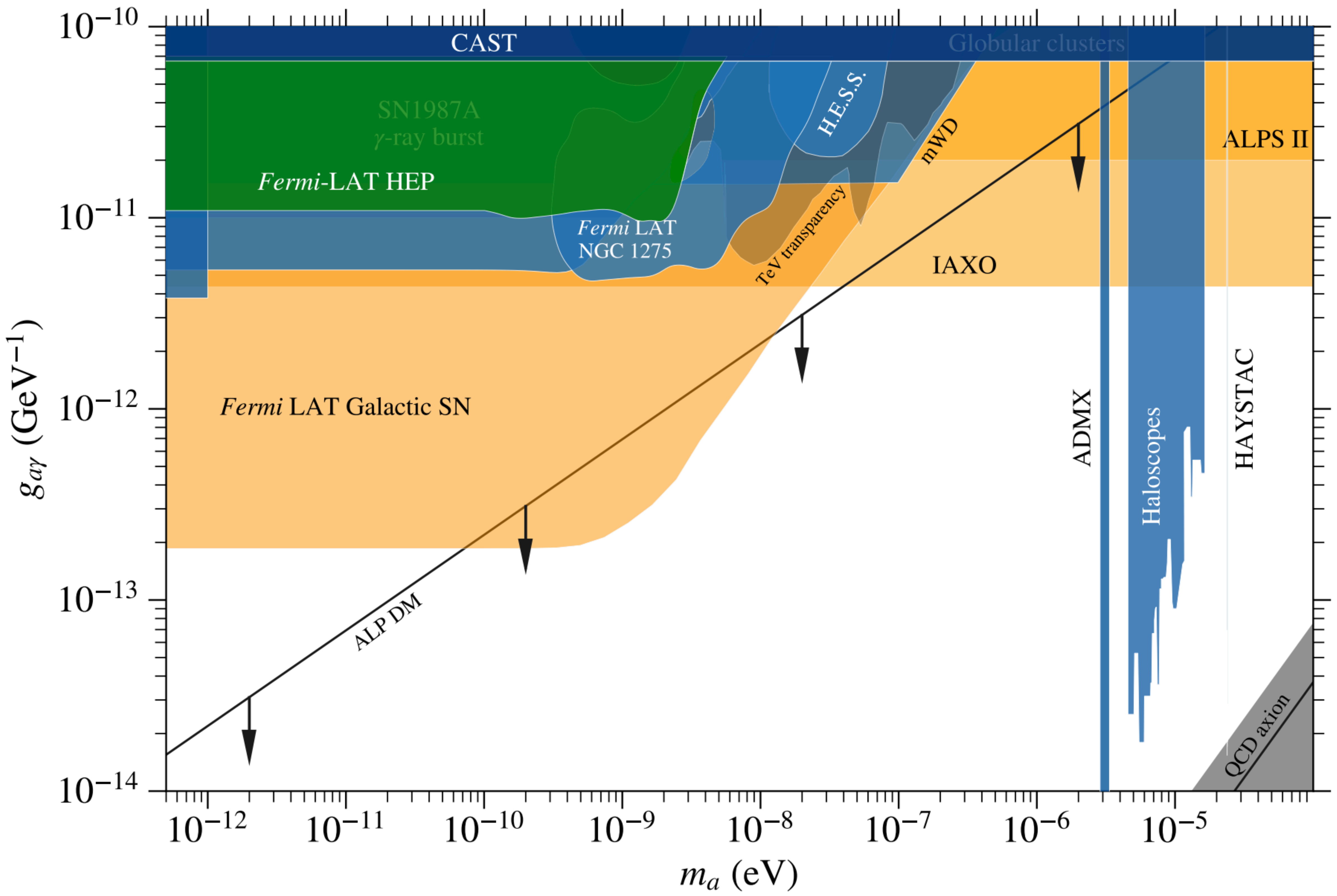
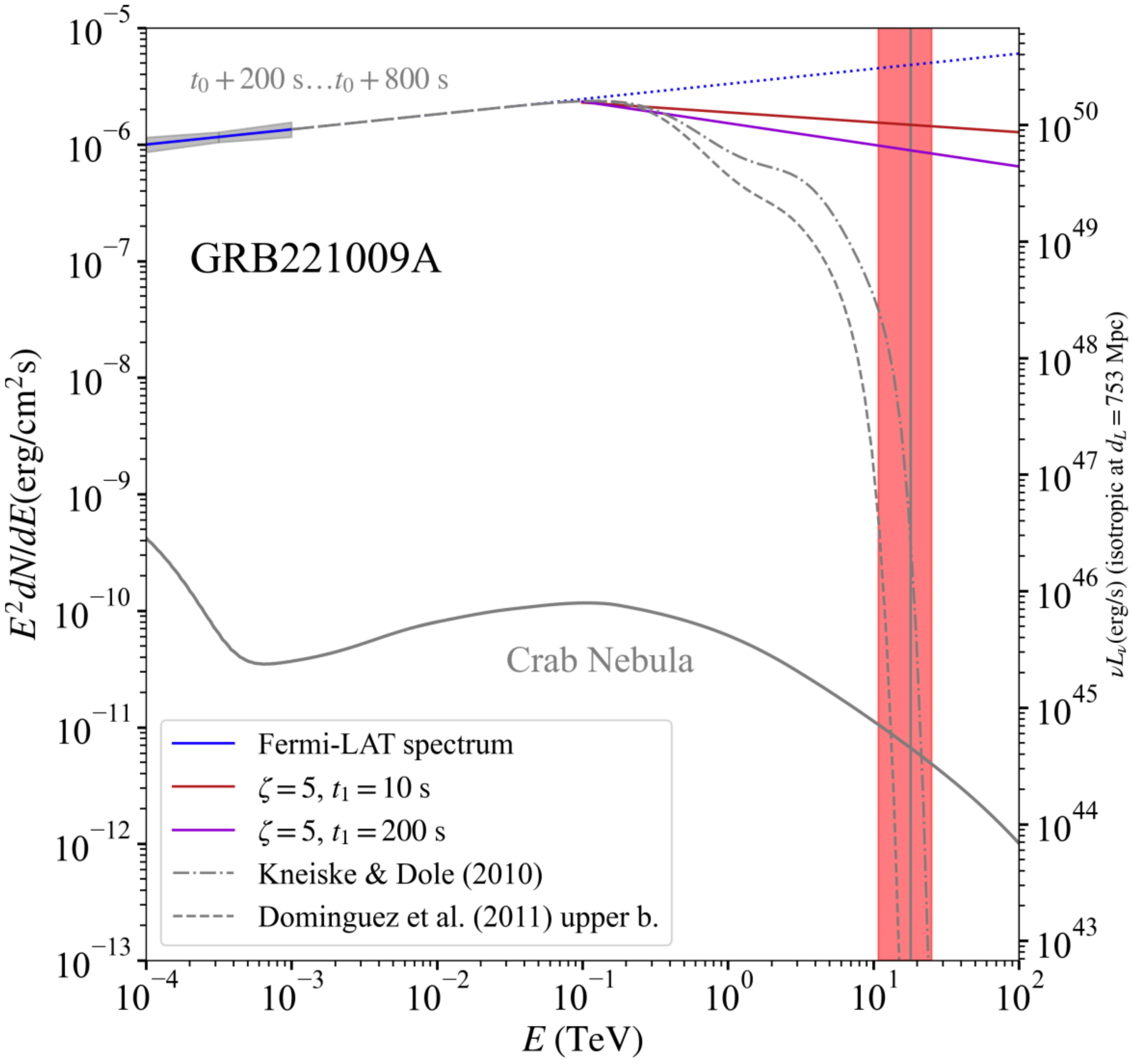
- No evidence for an increased γ-ray transparency due to ALPs

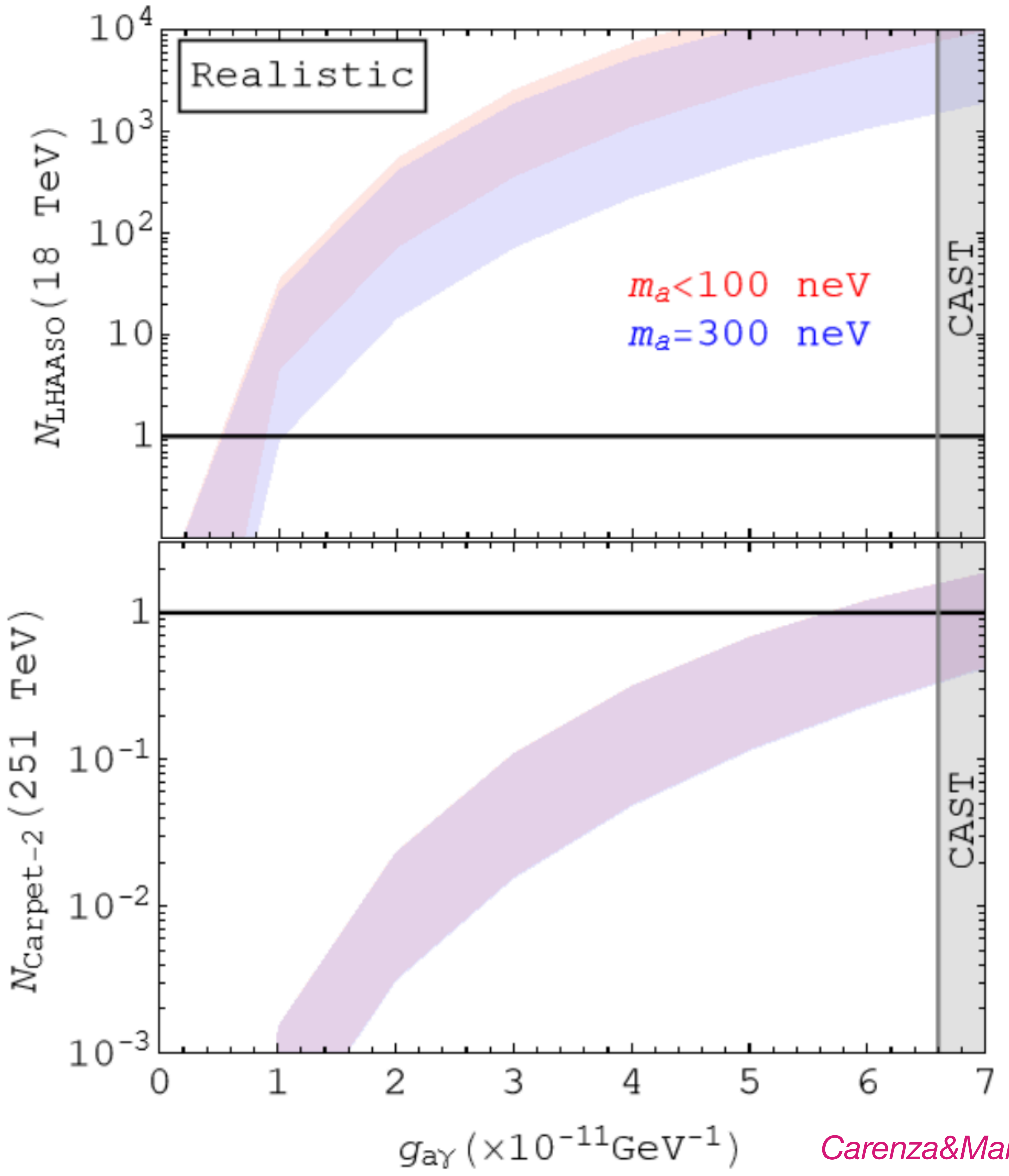




The GRB221009A



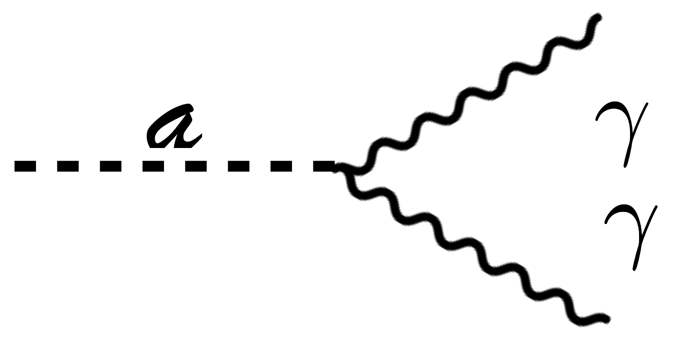
Batkash+ JCAP'23



Carenza&Marsh 2022

Signatures of ALPs (and other FIPs) decay

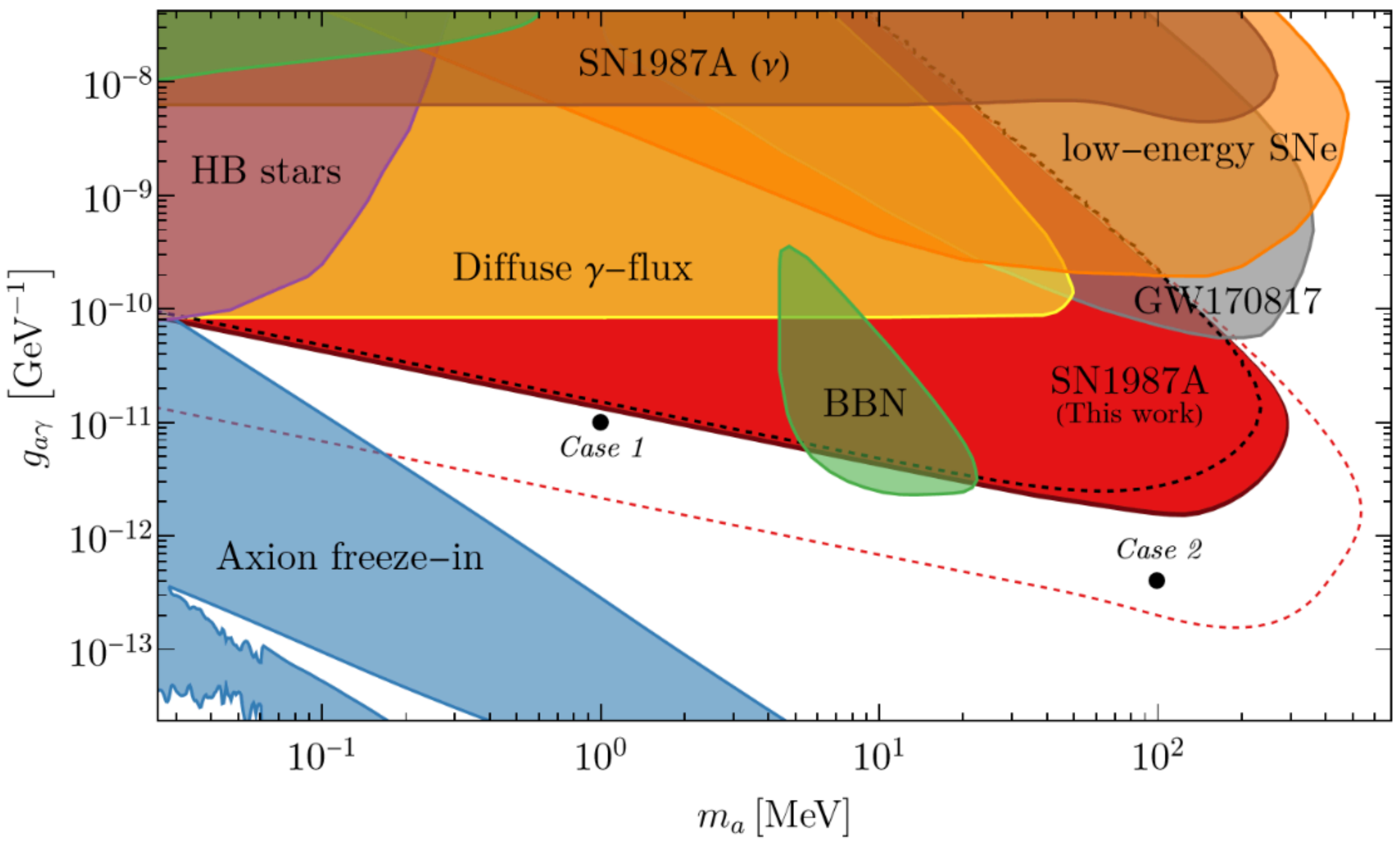
ALPs decay



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

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

Müller+ JCAP'23



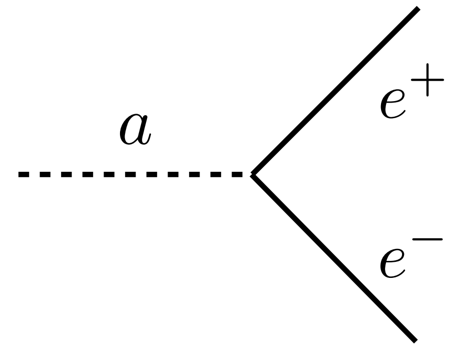
- Constraints on heavy ALPs produced in cc SNe

Caputo+ PRD'22, Müller+ JCAP'23

- Strong bound from low-energy SN, and diffuse gamma-ray flux
- Dominant constraint from SN1987A
- Sensitivity to a future nearby SN

Coupling with nucleons and electrons

Heavy ALPs decay

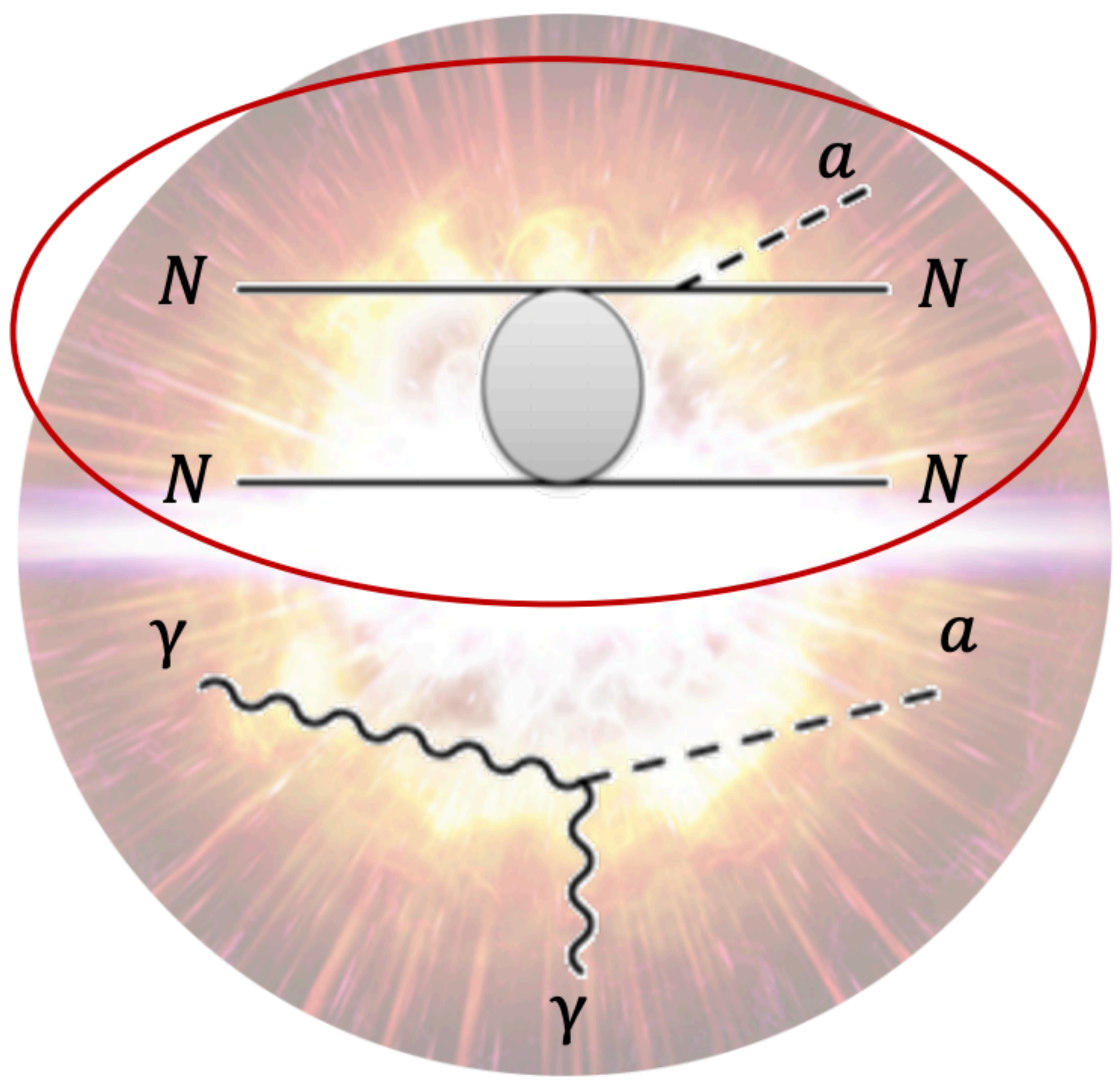


- Production through **nucleon bremsstrahlung** in CC SNe
- For **m > MeV**, conversion suppressed but possible decays into **photons** and **electron-positron pairs**

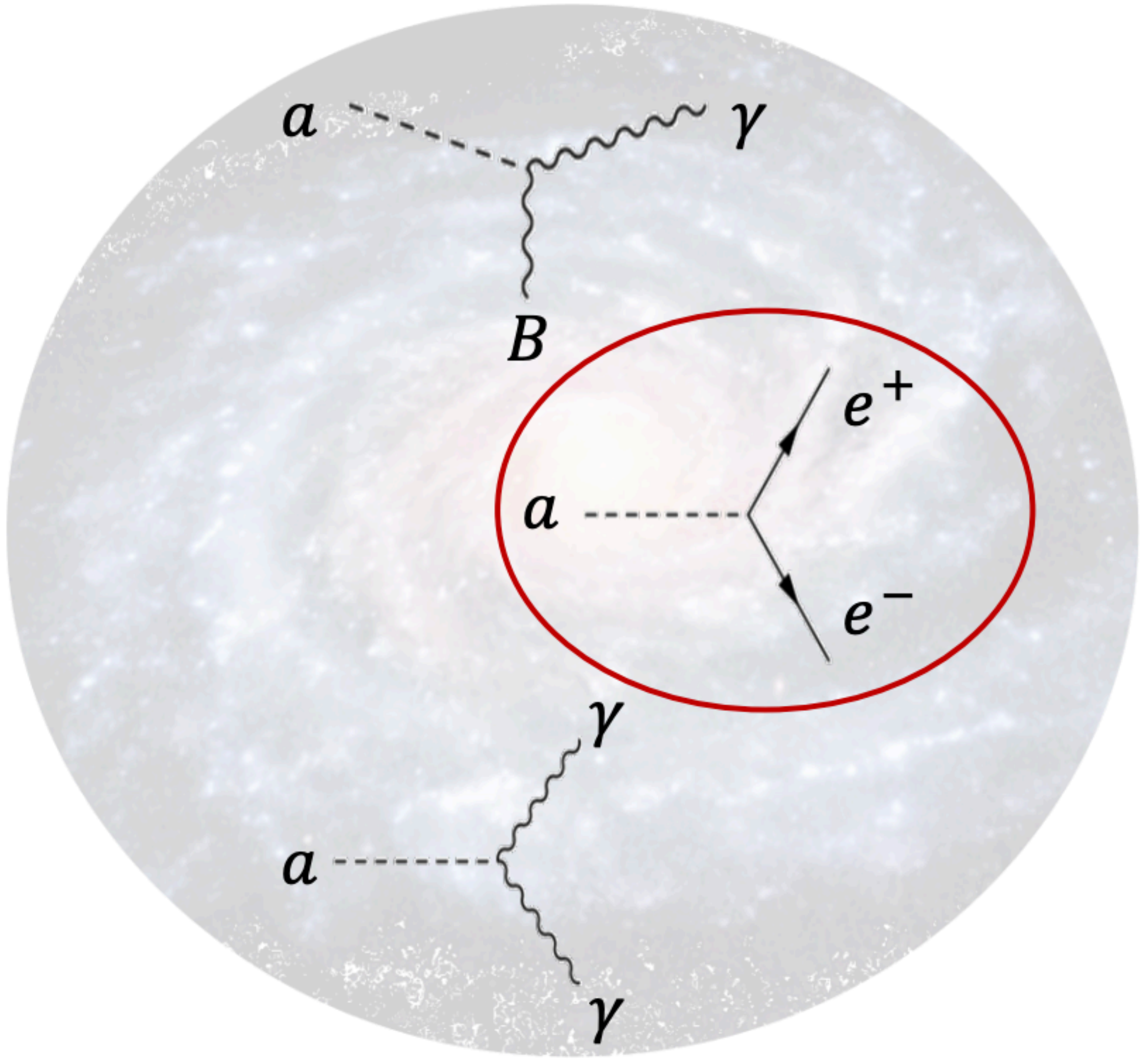
$$\frac{BR(a \to \gamma\gamma)}{BR(a \to e^+e^-)} = \frac{l_e}{l_\gamma} \sim 10^{-5} \left(\frac{m_a}{10\ \mathrm{MeV}}\right)^2 \left(\frac{10^{-13}}{g_{ae}}\right)^2 \left(\frac{g_{a\gamma}}{10^{-13}\ \mathrm{GeV}^{-1}}\right)^2 \ll 1$$

FC+ PRD'21

Production

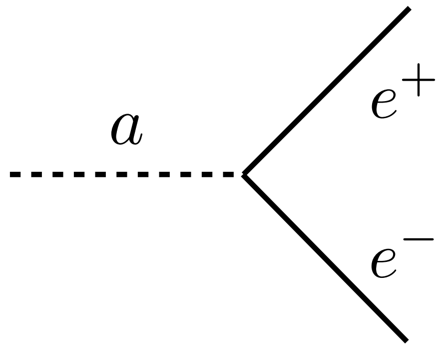


Signature



Credit: G. Lucente

Coupling with nucleons and electrons

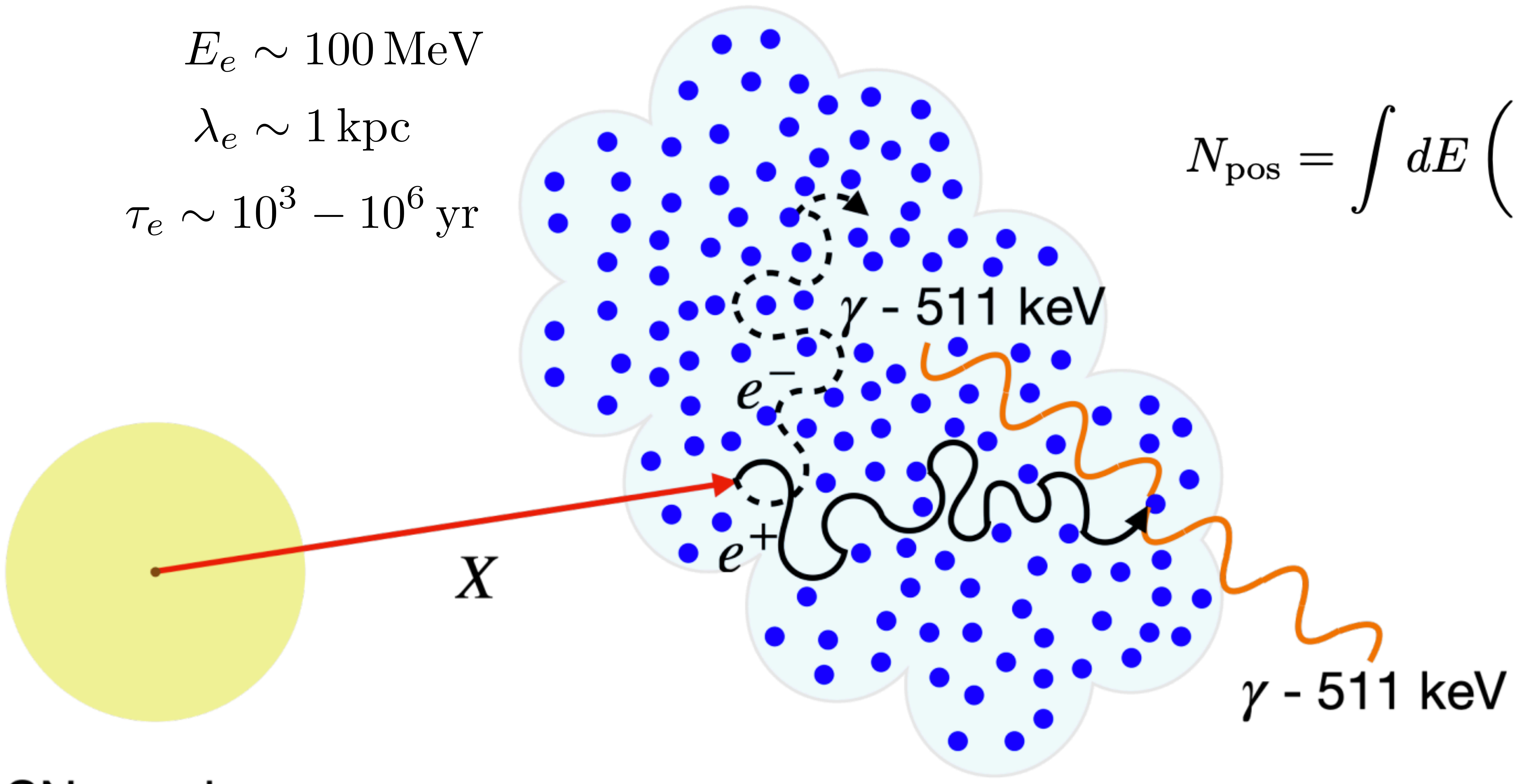


Positron production and annihilation

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

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

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



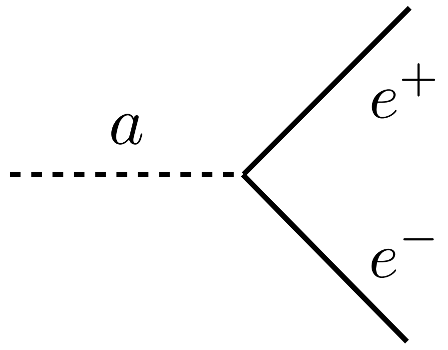
$$\left(\frac{dN_a^p}{dE}\right)_{\mathrm{esc}} = \frac{dN_a^p}{dE} \times \exp\left(-\frac{r_{\mathrm{esc}}}{l_e}\right)$$

In the Galaxy

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

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

Coupling with nucleons and electrons



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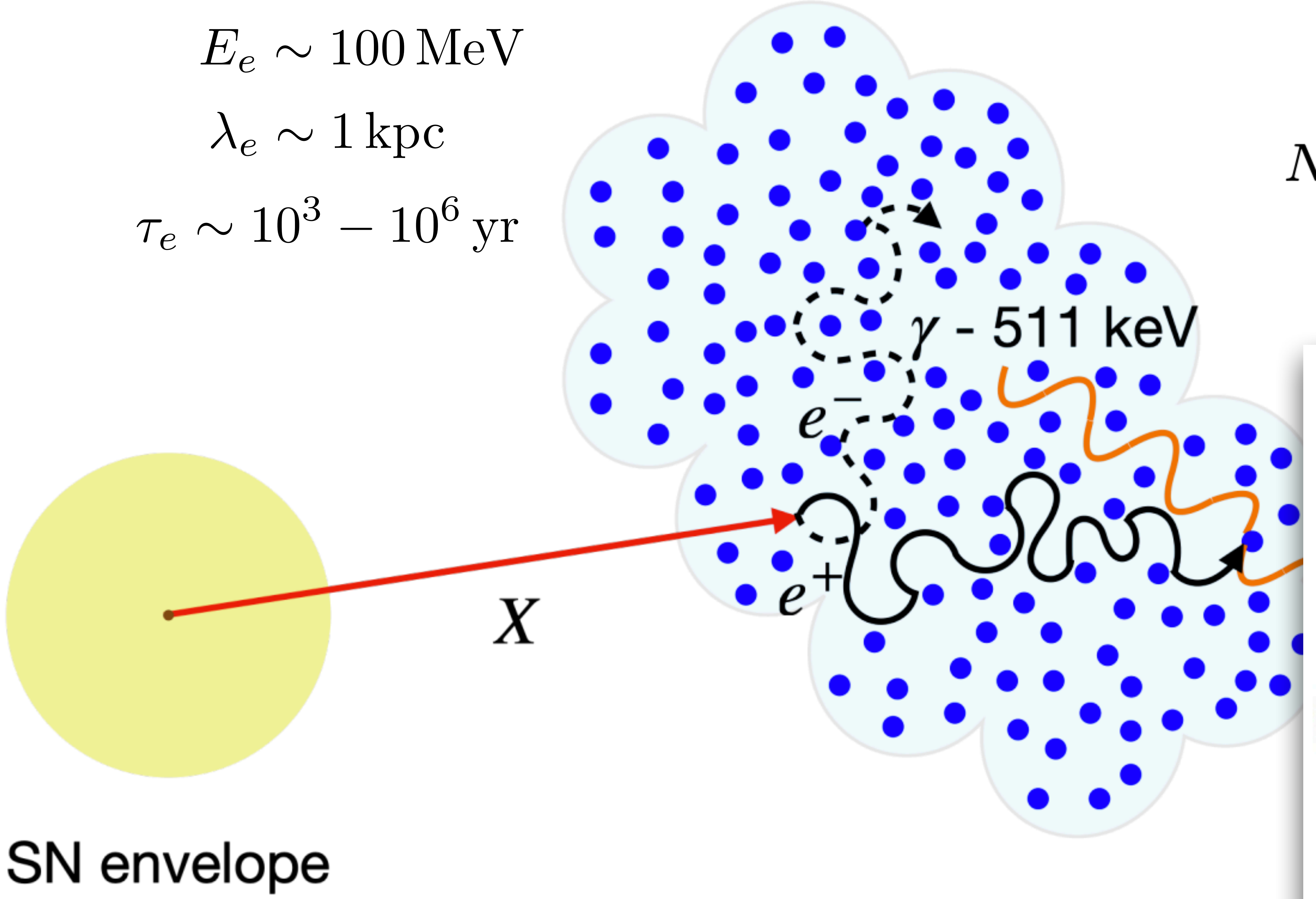

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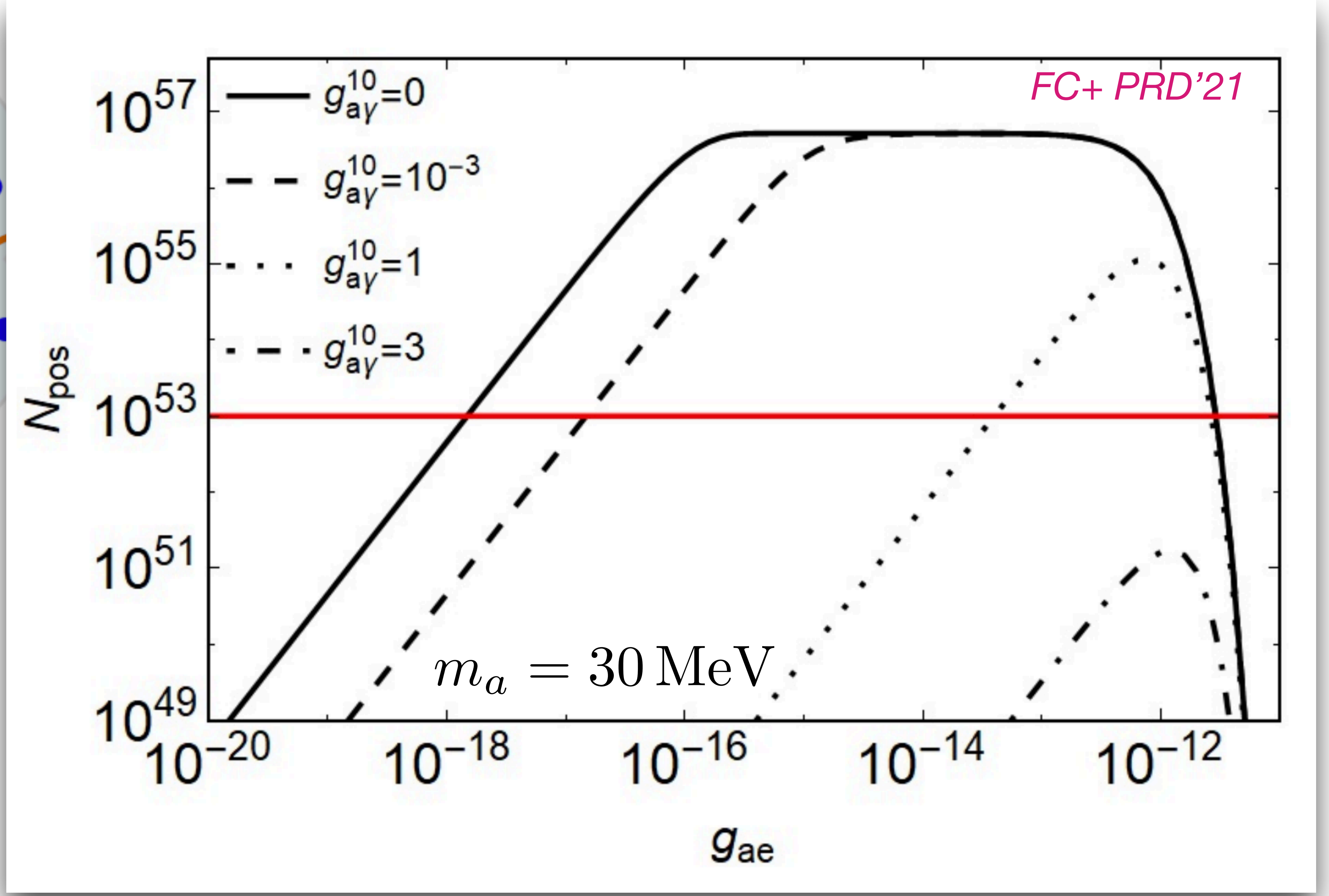
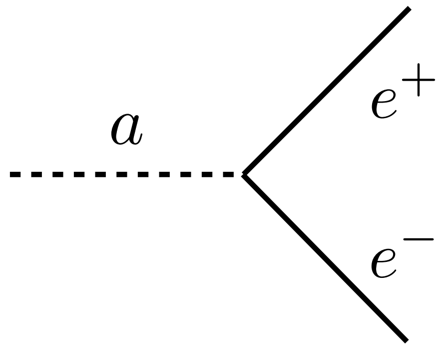
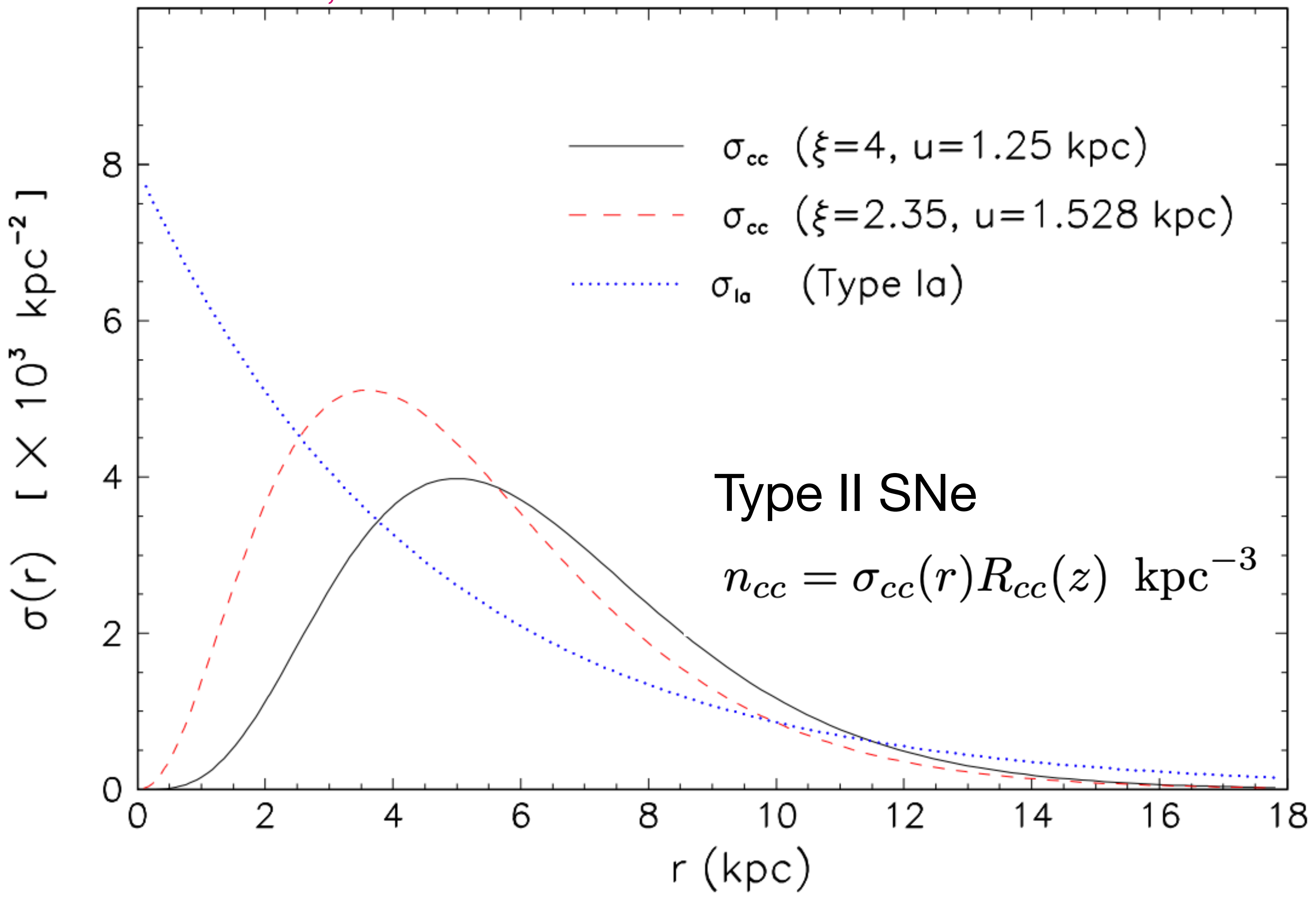


Coupling with nucleons and electrons



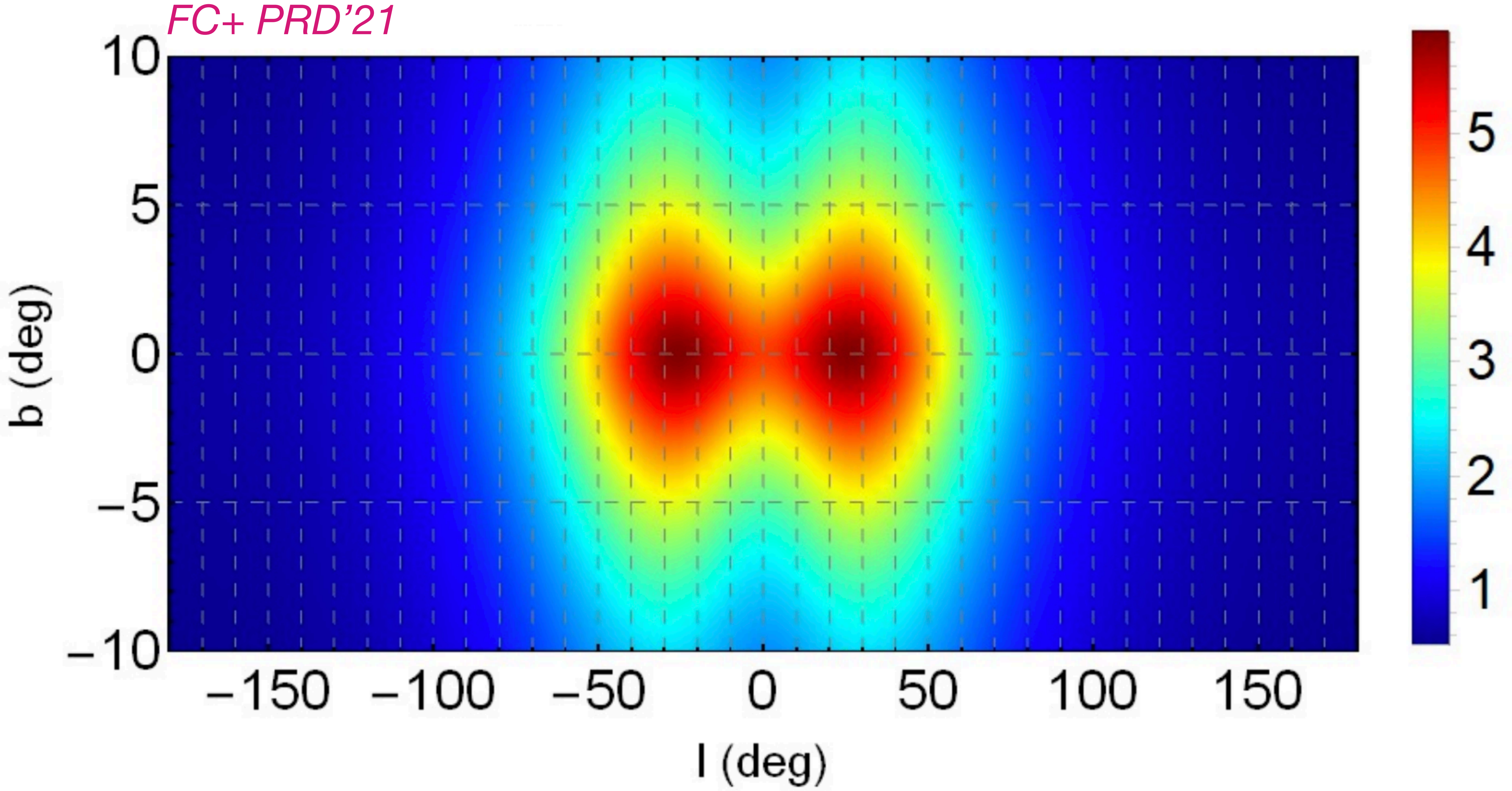
511 keV line from Galactic CC SNe population

Mirizzi et al., JCAP'06



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

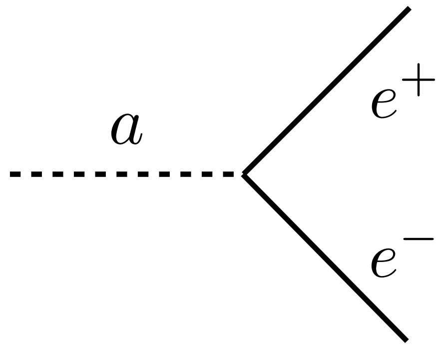
FC+ PRD'21



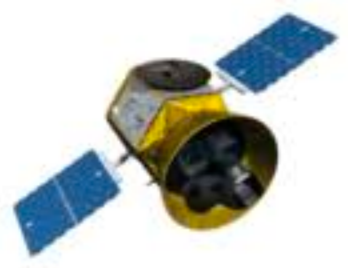
Smearing from decay length & positrons propagation

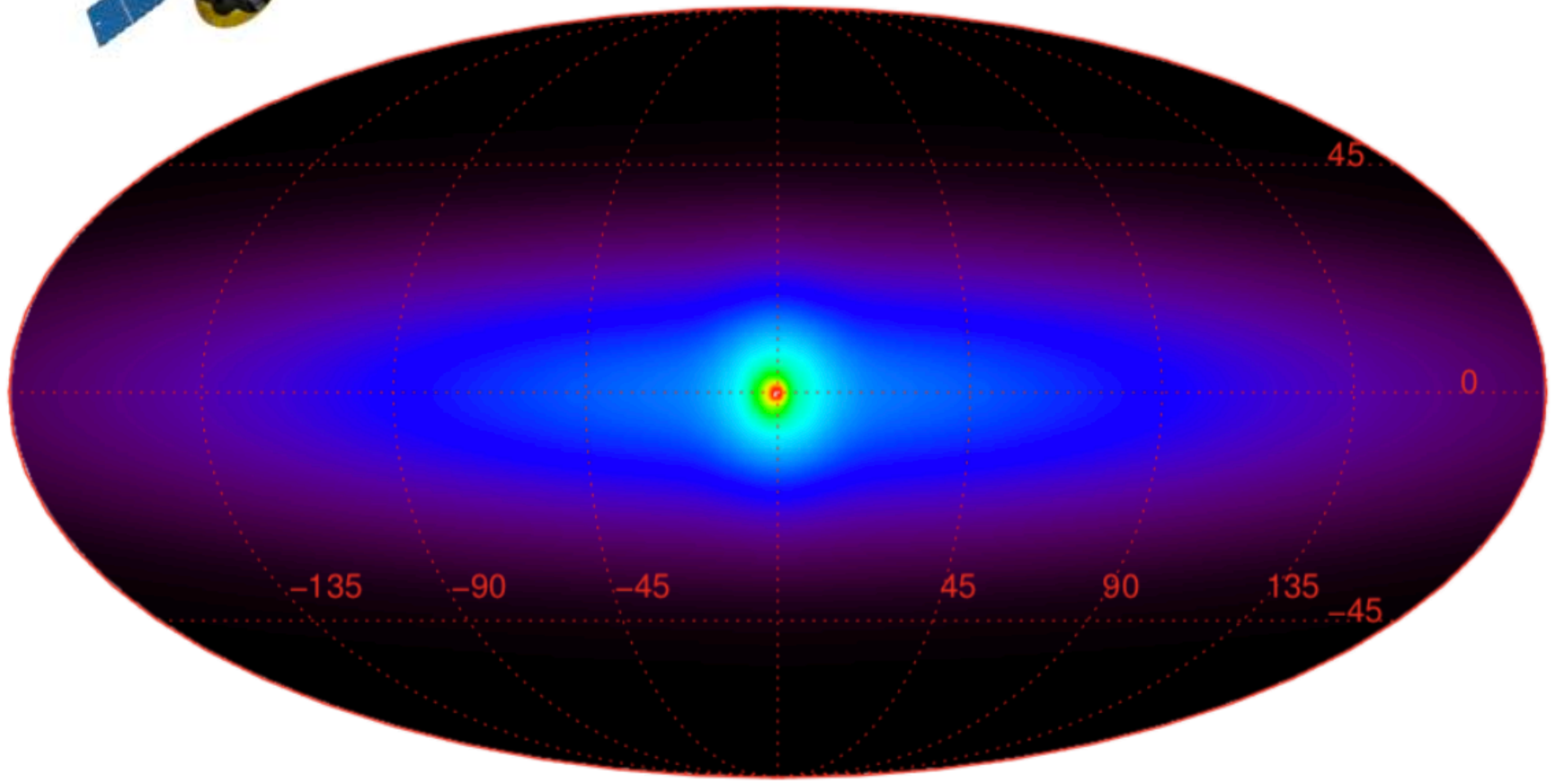
Jean et al., Astron. Astrophys. 445 (2006)

Coupling with nucleons and electrons



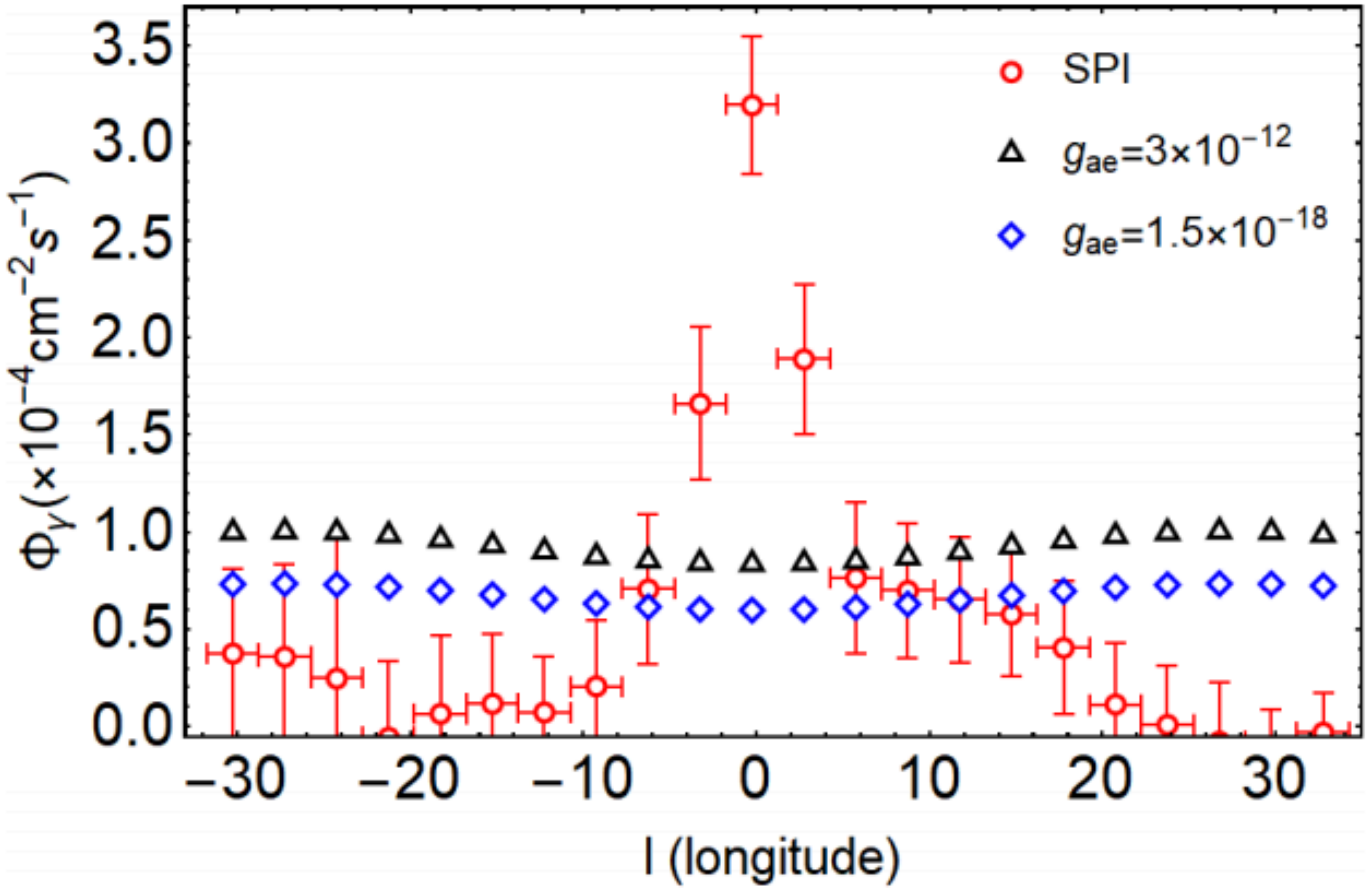
Limits from Integral/SPI 511 keV line observation



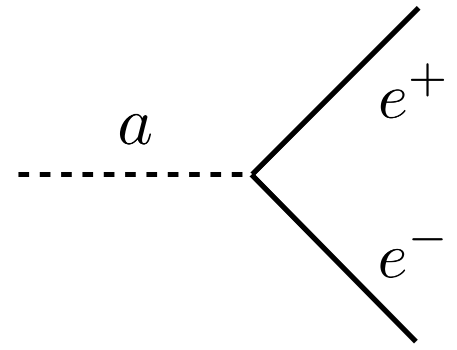


Siegert et al., Astron. Astrophys. 586 (2016)

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



Coupling with nucleons and electrons



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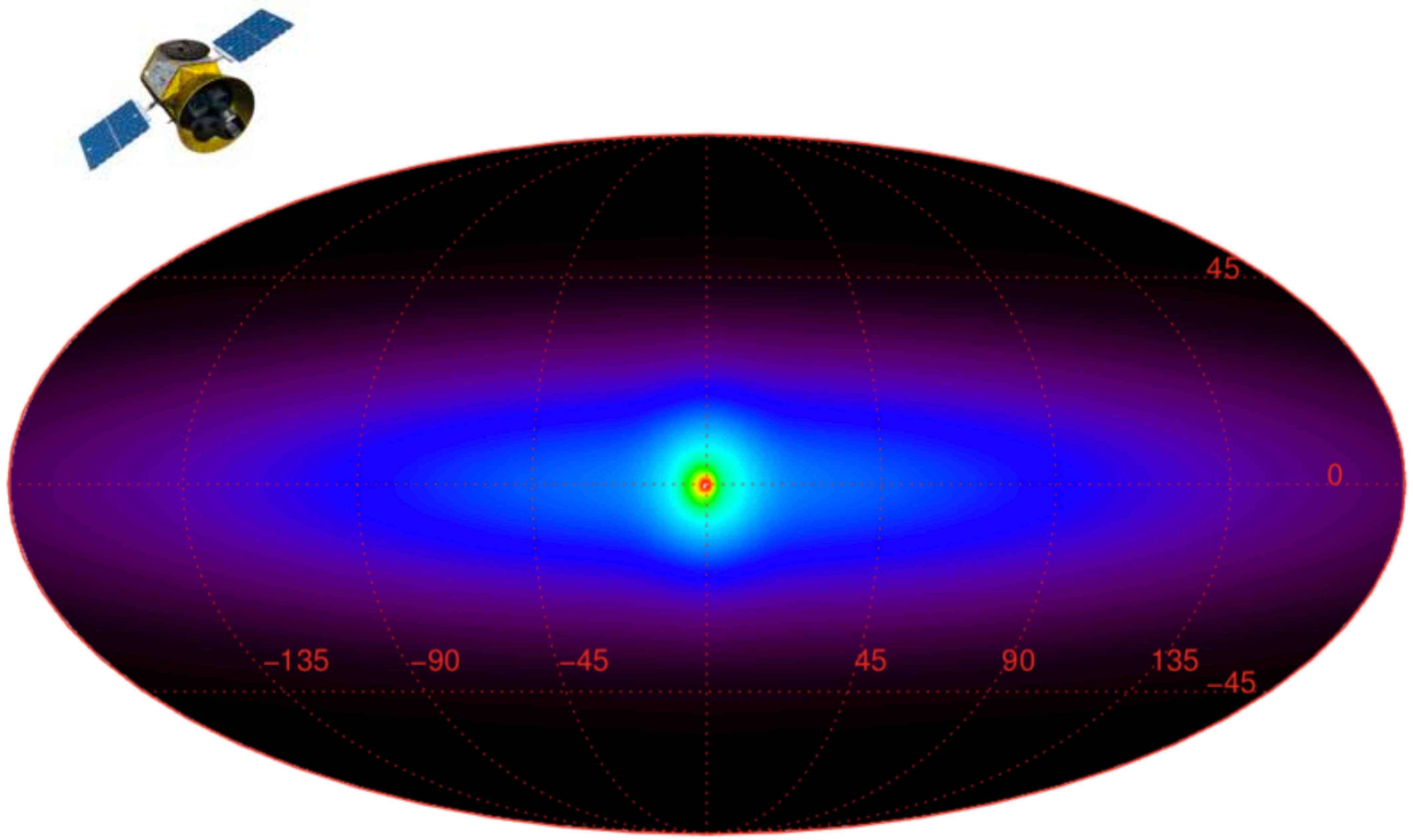
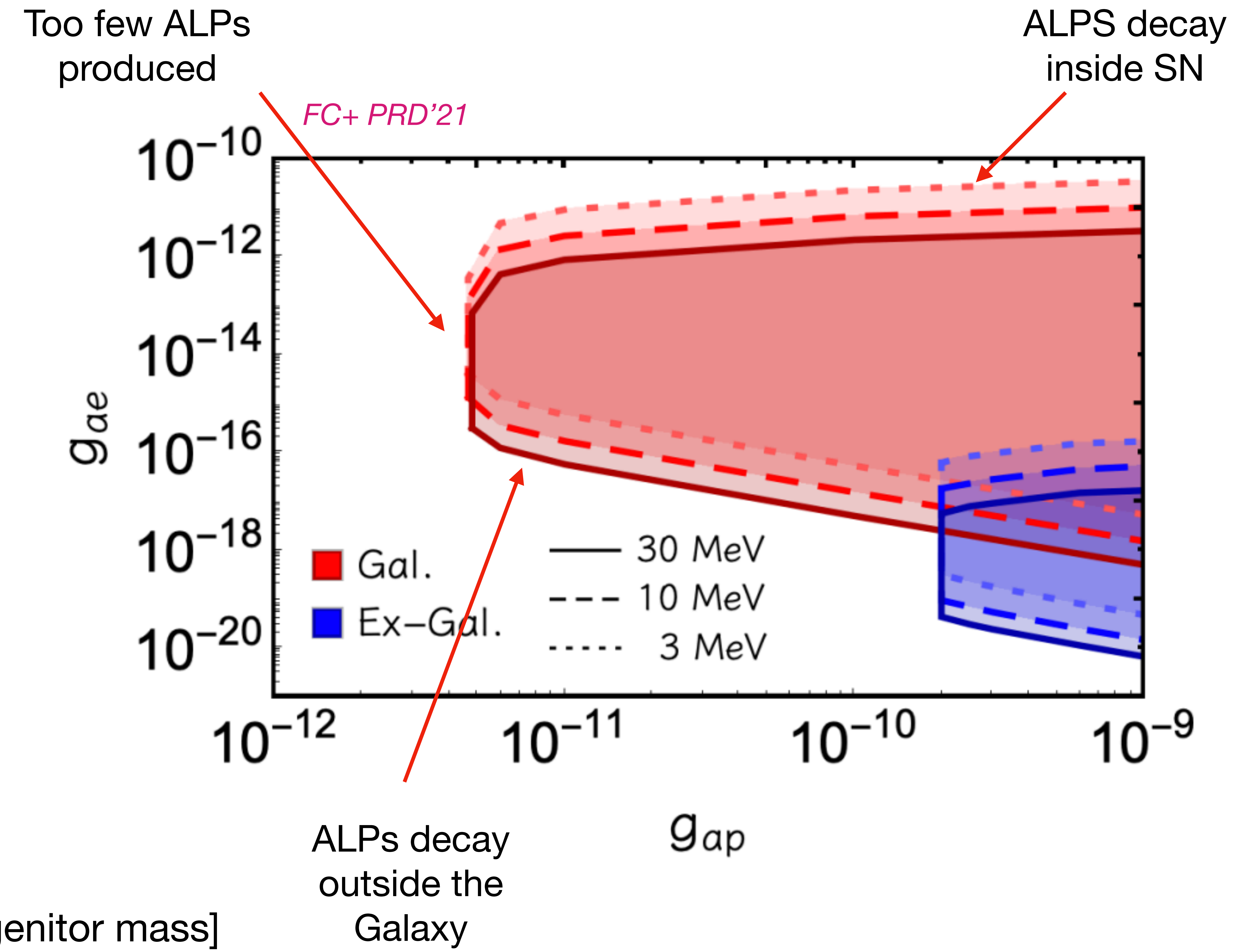


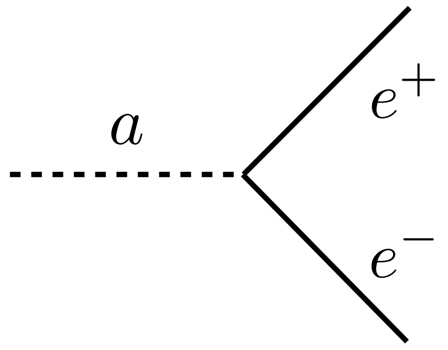
Siegert et al., Astron. Astrophys. 586 (2016)



[Theory uncertainties from positron propagation and progenitor mass]

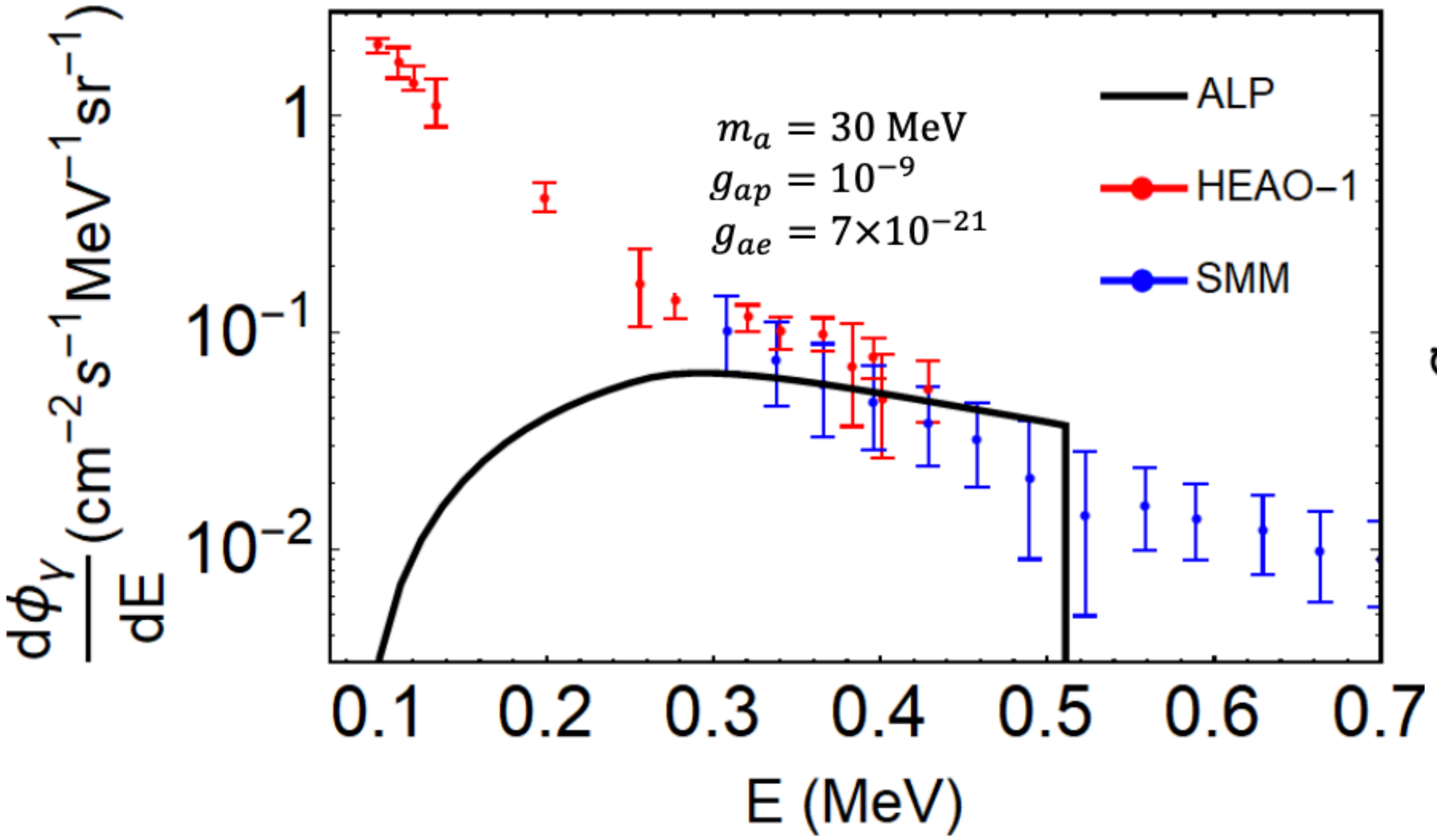
Coupling with nucleons and electrons

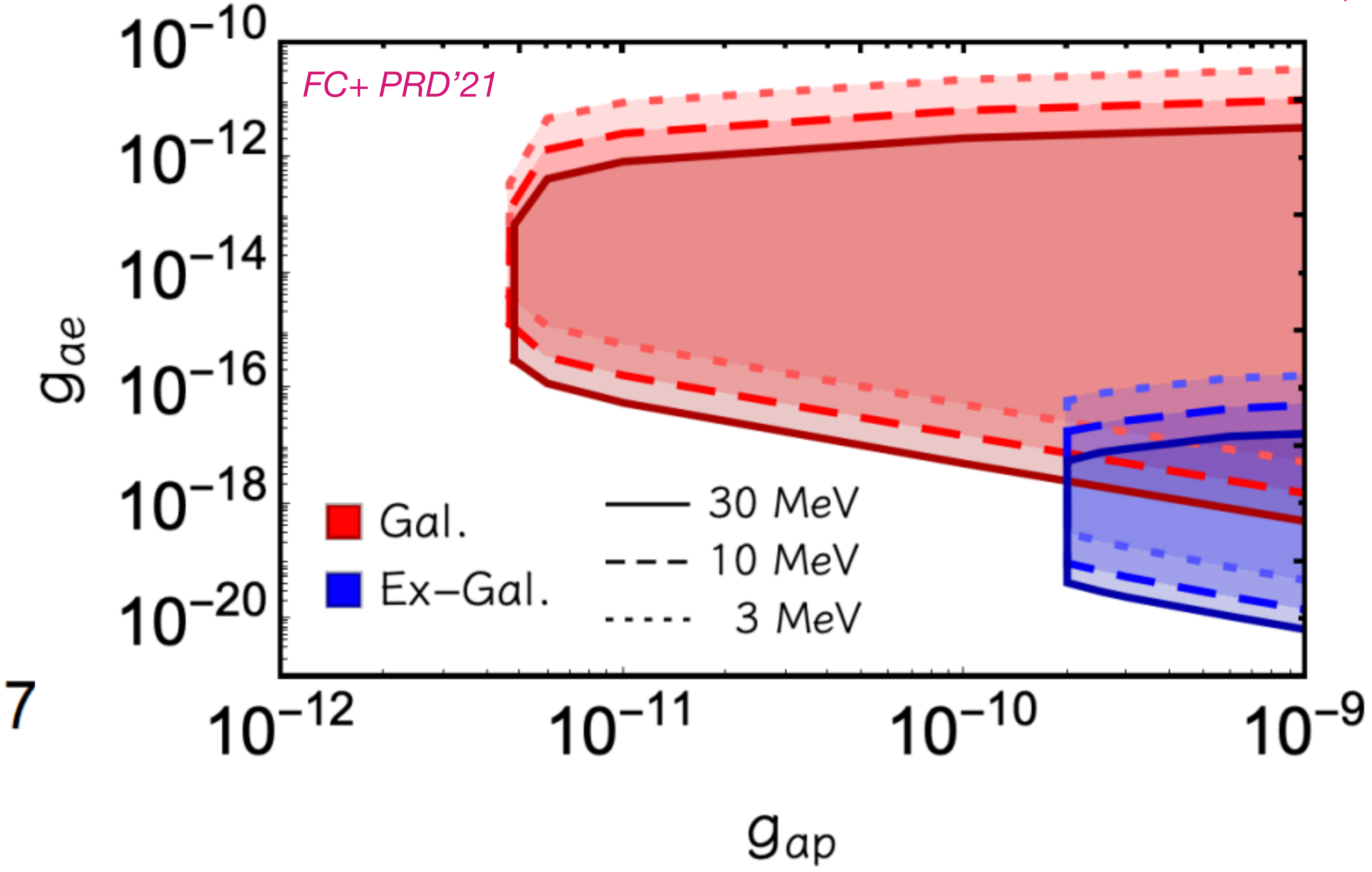
The cosmic X-ray background



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

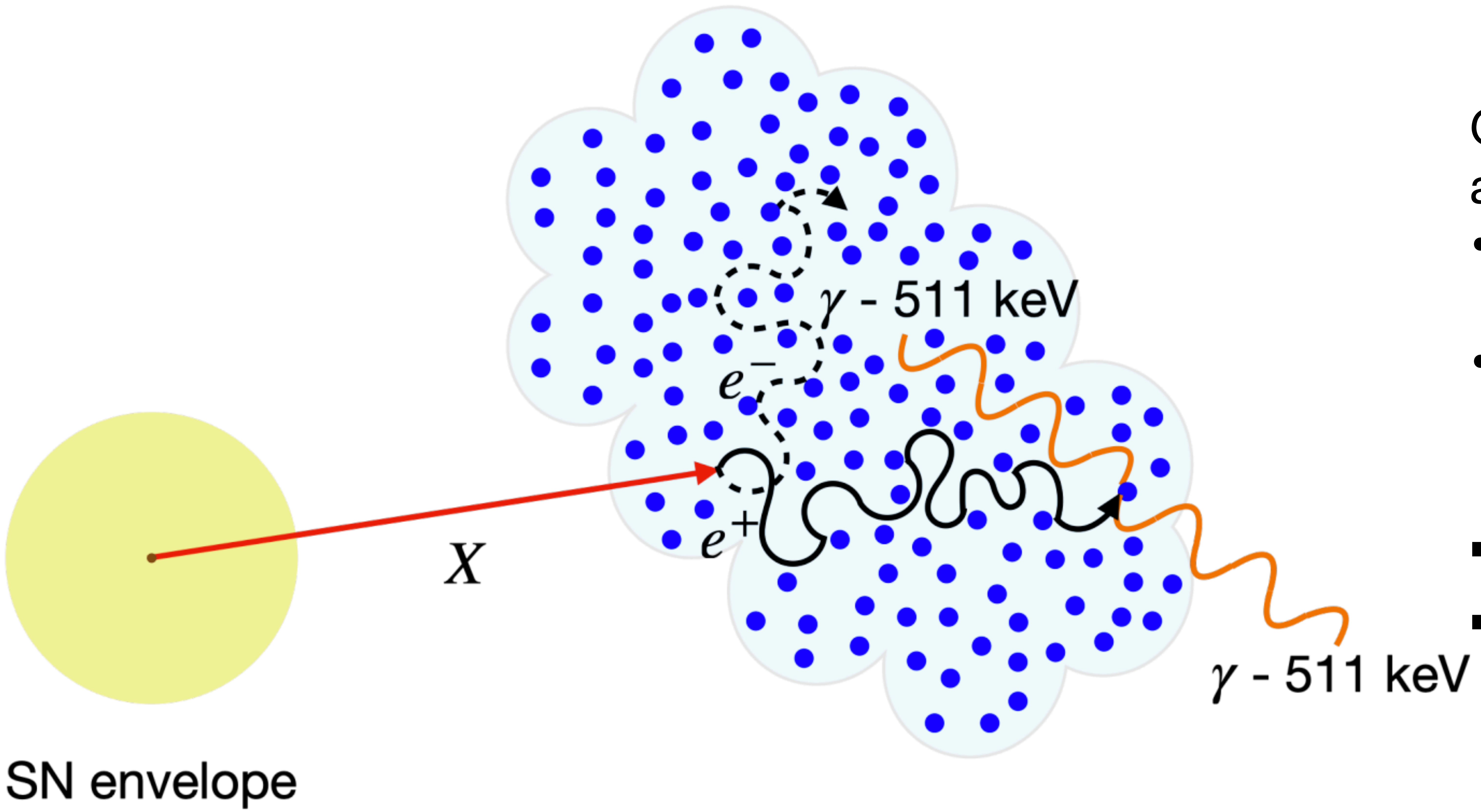
Raffelt et al., PRD 84 (2011)





Galactic and **extra-galactic** SNe: bound on a currently unexplored region c(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**

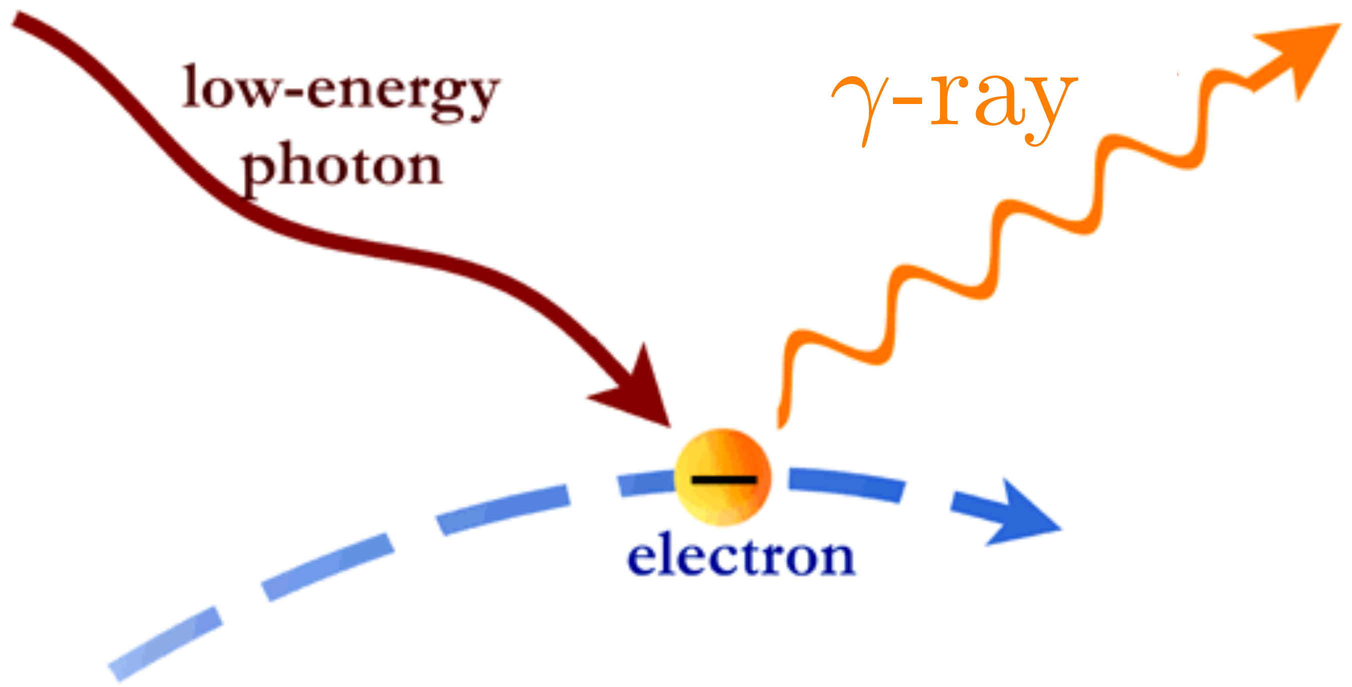
➡ Limits on **dark photons**

FC+ 2112.08382

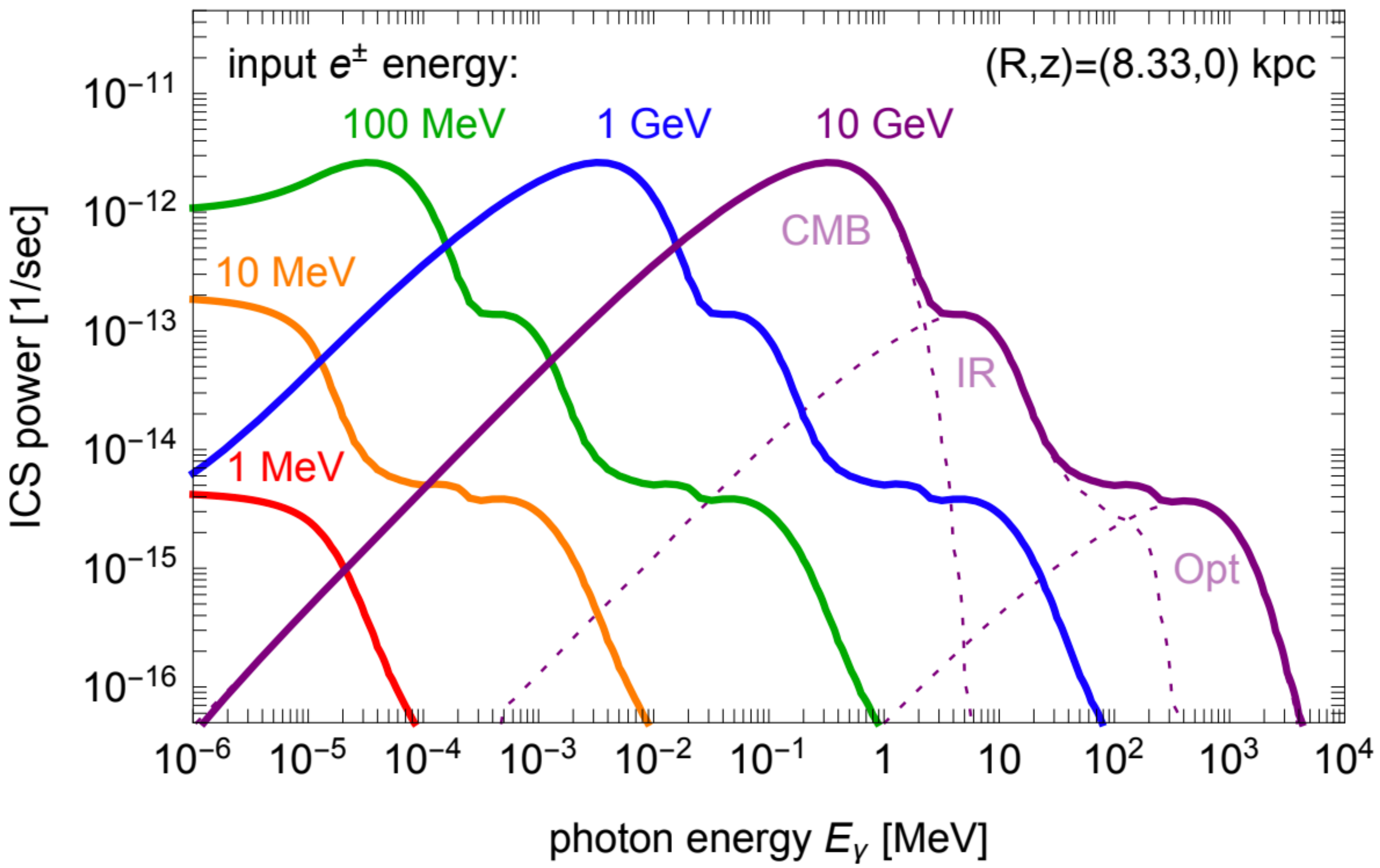
Dar+ PRL 1987; DeRocco+ JHEP’19
De La Torre Luque+2307.13731

Secondary photon production

Inverse Compton scattering



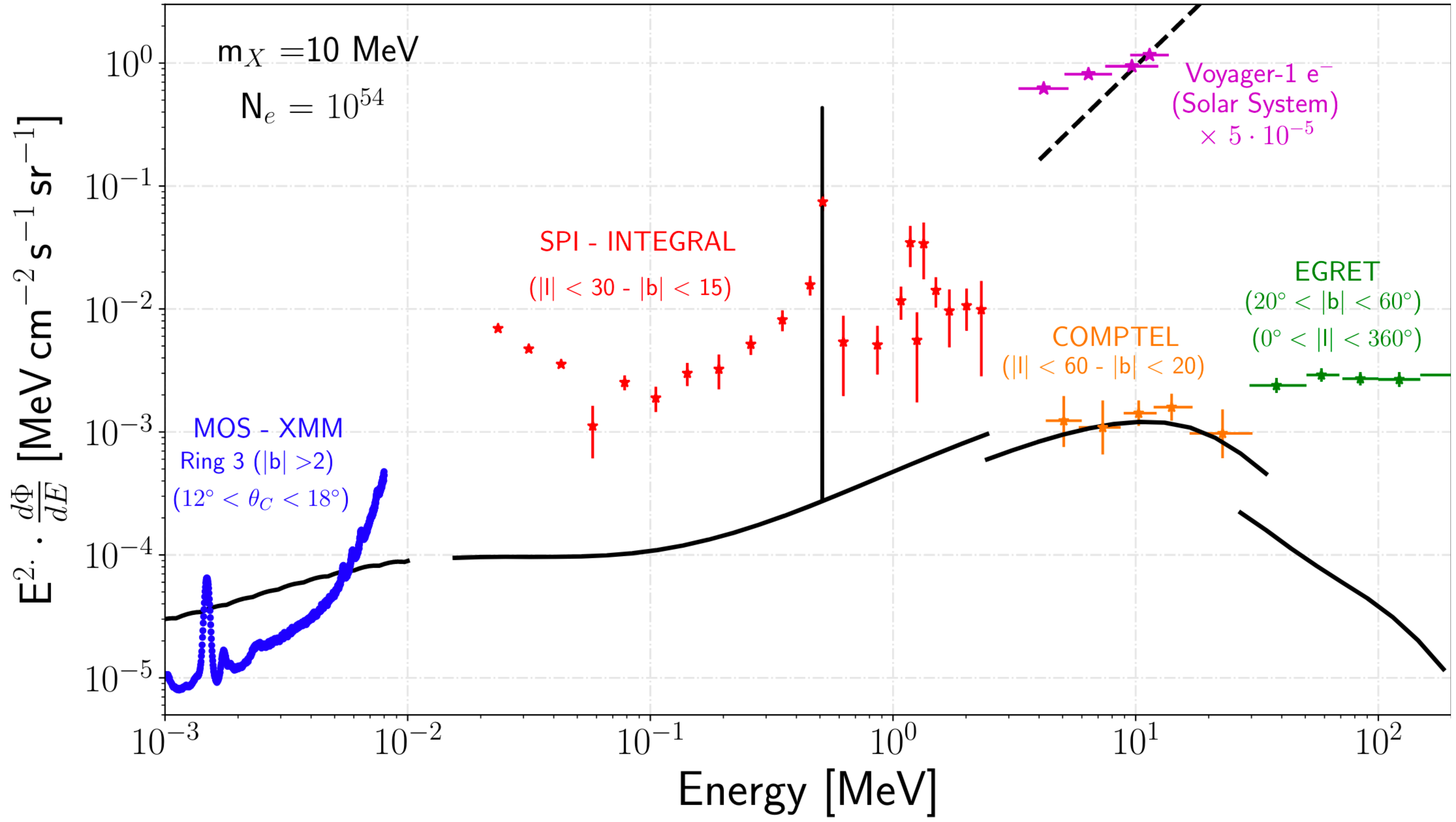
$$\epsilon_f \simeq \gamma^2 \epsilon_i = 30 \left(\frac{\epsilon_i}{\text{eV}}\right)\left(\frac{E_e}{\text{GeV}}\right)^2 \text{ MeV}$$

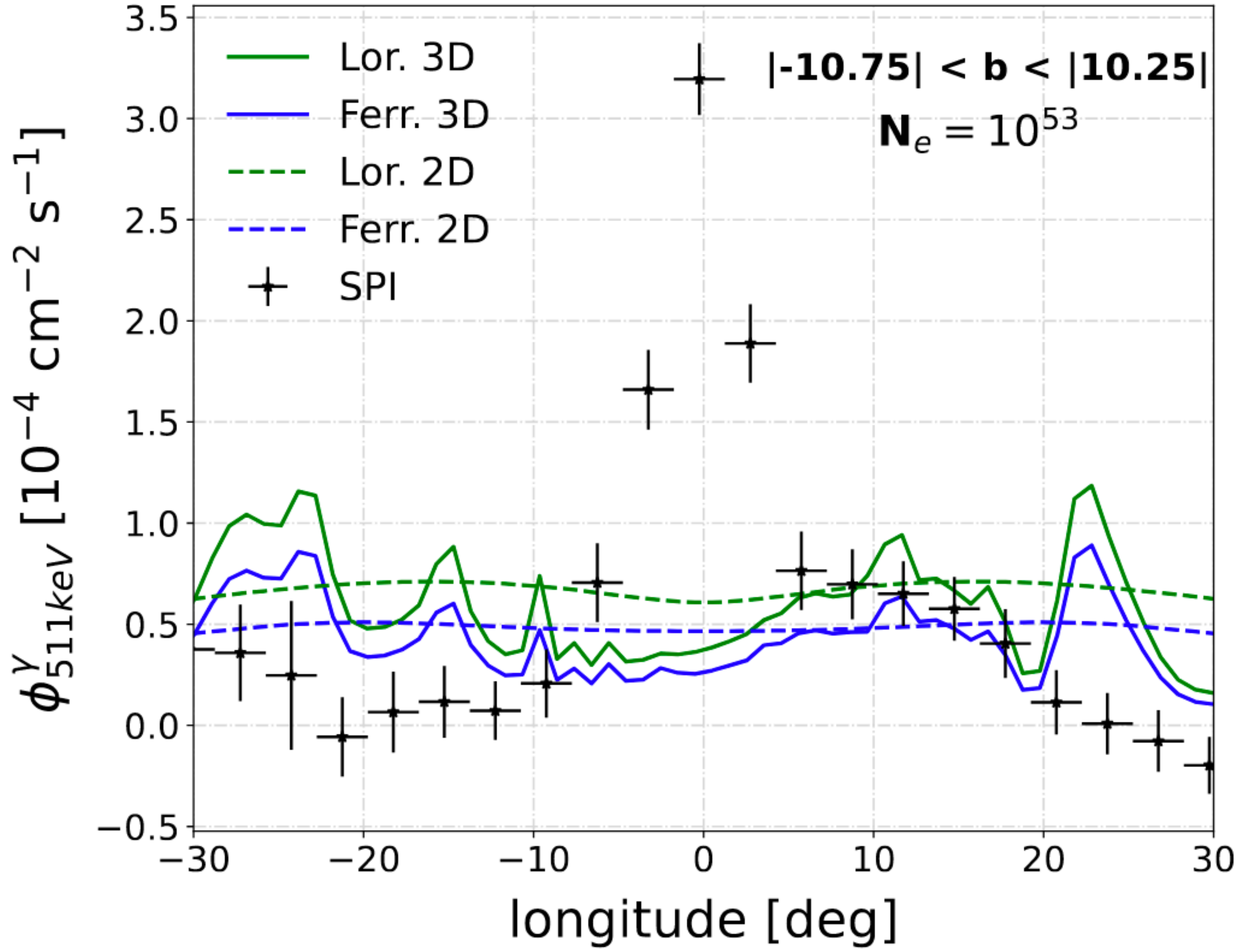


Secondary emission processes allow us to probe DM at much higher masses than prompt energy scales

Broad band emission from cc SNe

De La Torre Luque+ 2312.04907, 2307.13728

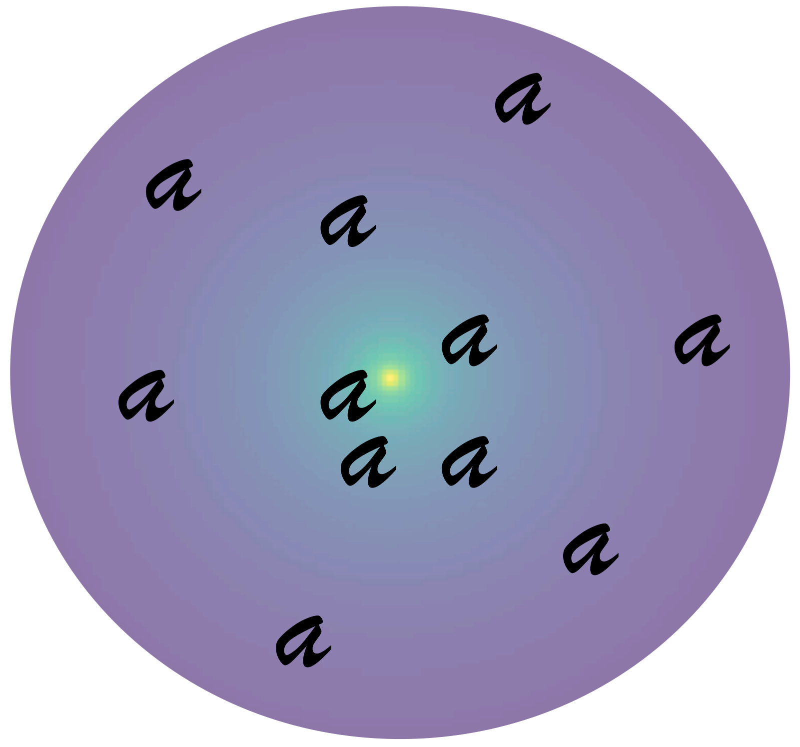




Injection morphology: Spiral arms Galactic structure

Can constrain injection rate of electrons and positrons, as well as the ALPs couplings

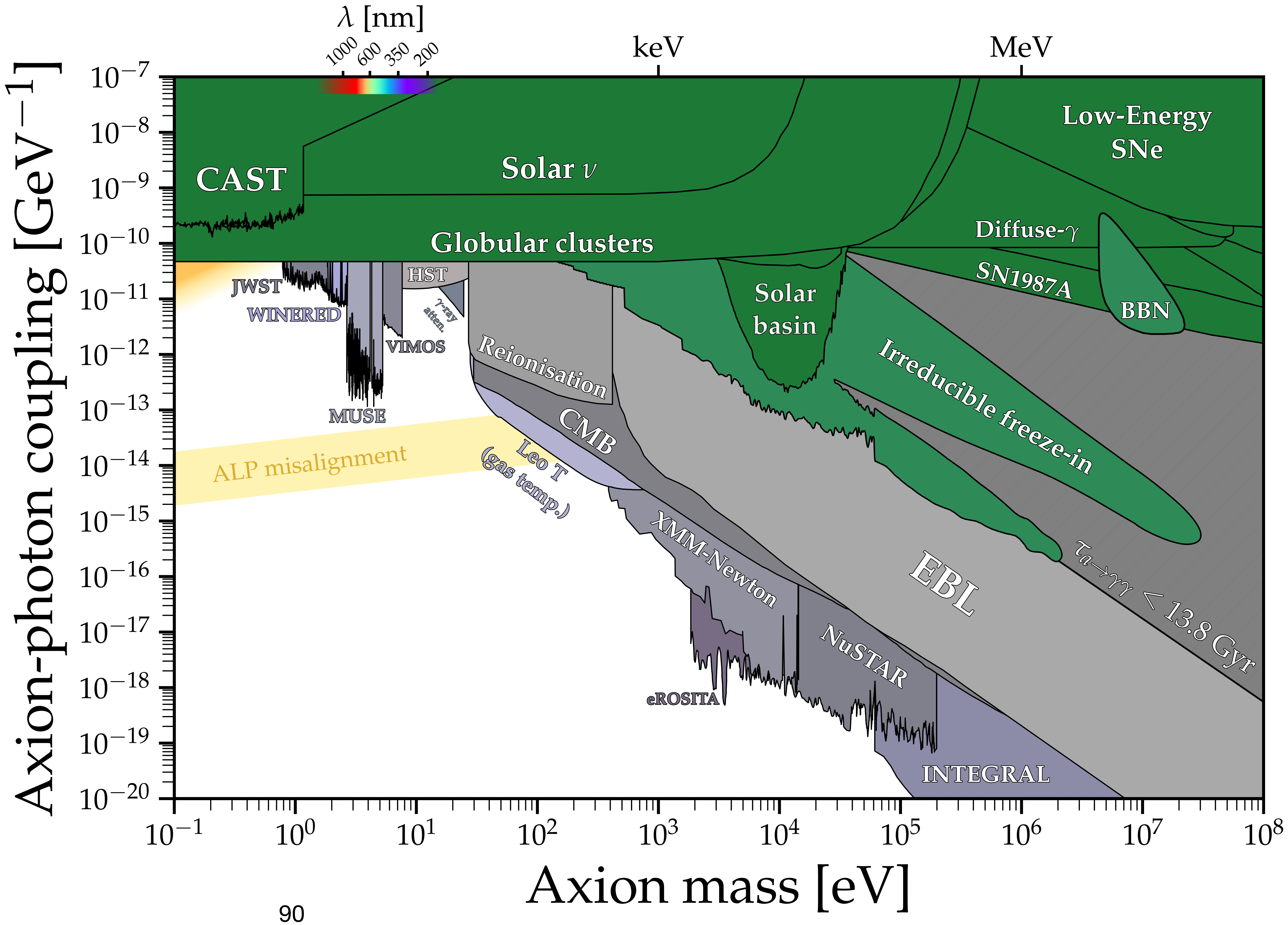
ALPs dark matter



- If DM, ALPs distributed in galaxies according standard DM density distributions (e.g. NFW)
- Search for narrow lines in DM-rich environments

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

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



Common astrophysical ingredients

$$\Phi_{\rm DM} \propto n_{\rm DM}$$

Flux proportional to DM number density

$$\rho_{\rm DM} \equiv n_{\rm DM} \times m_{\rm DM}$$

DM energy density for *non-relativistic* particles (CDM)

$$v_c = (218 - 246)\,{\rm km/s}$$

Local circular velocity

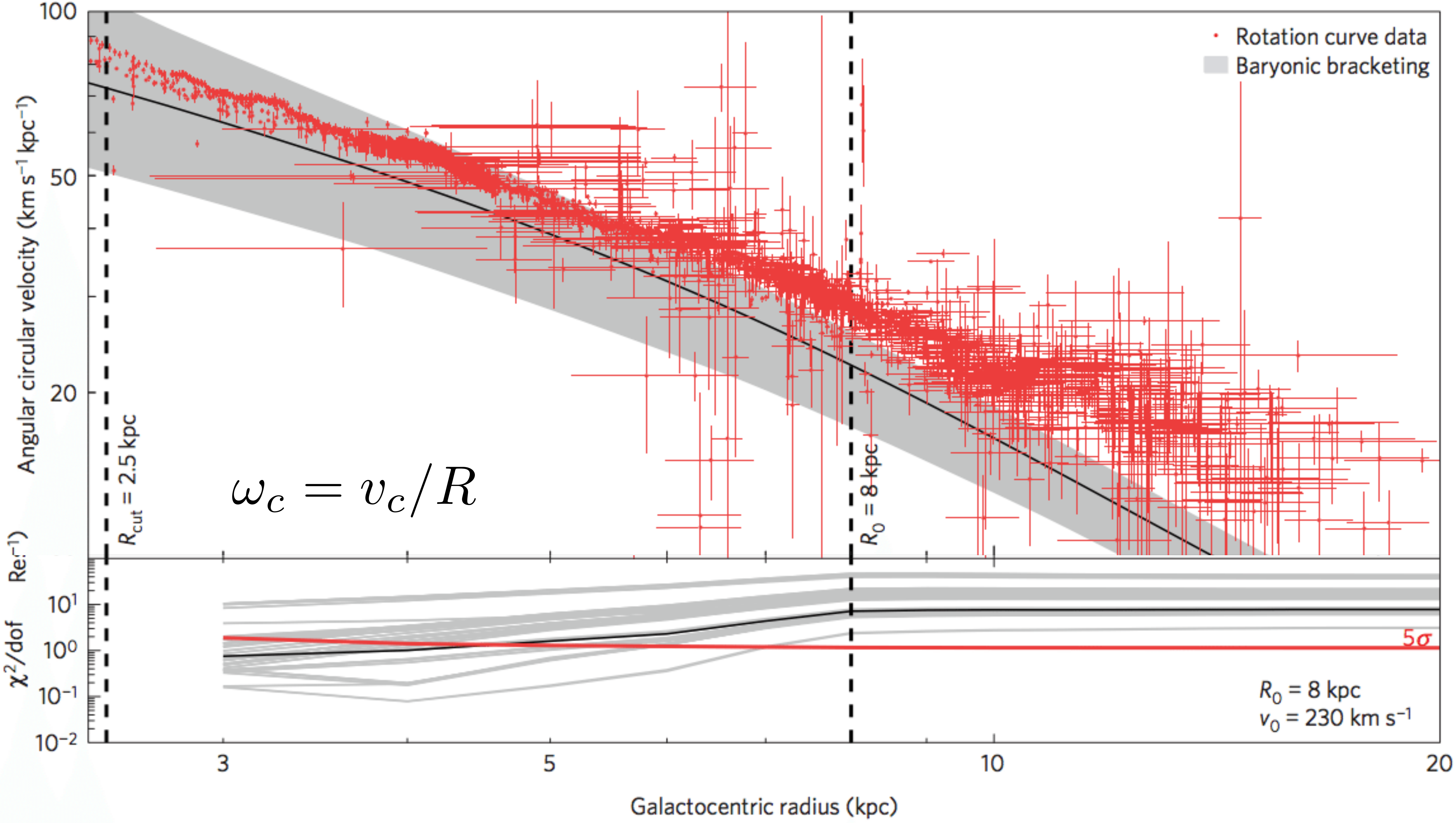
$$\sigma_v = \sqrt{3/2}\,v_c$$

DM velocity dispersion (Maxwell-Boltzmann distribution)

=> Decay (or, in general, self-interactions) of DM in the halo of galaxies at z=0 occur at rest

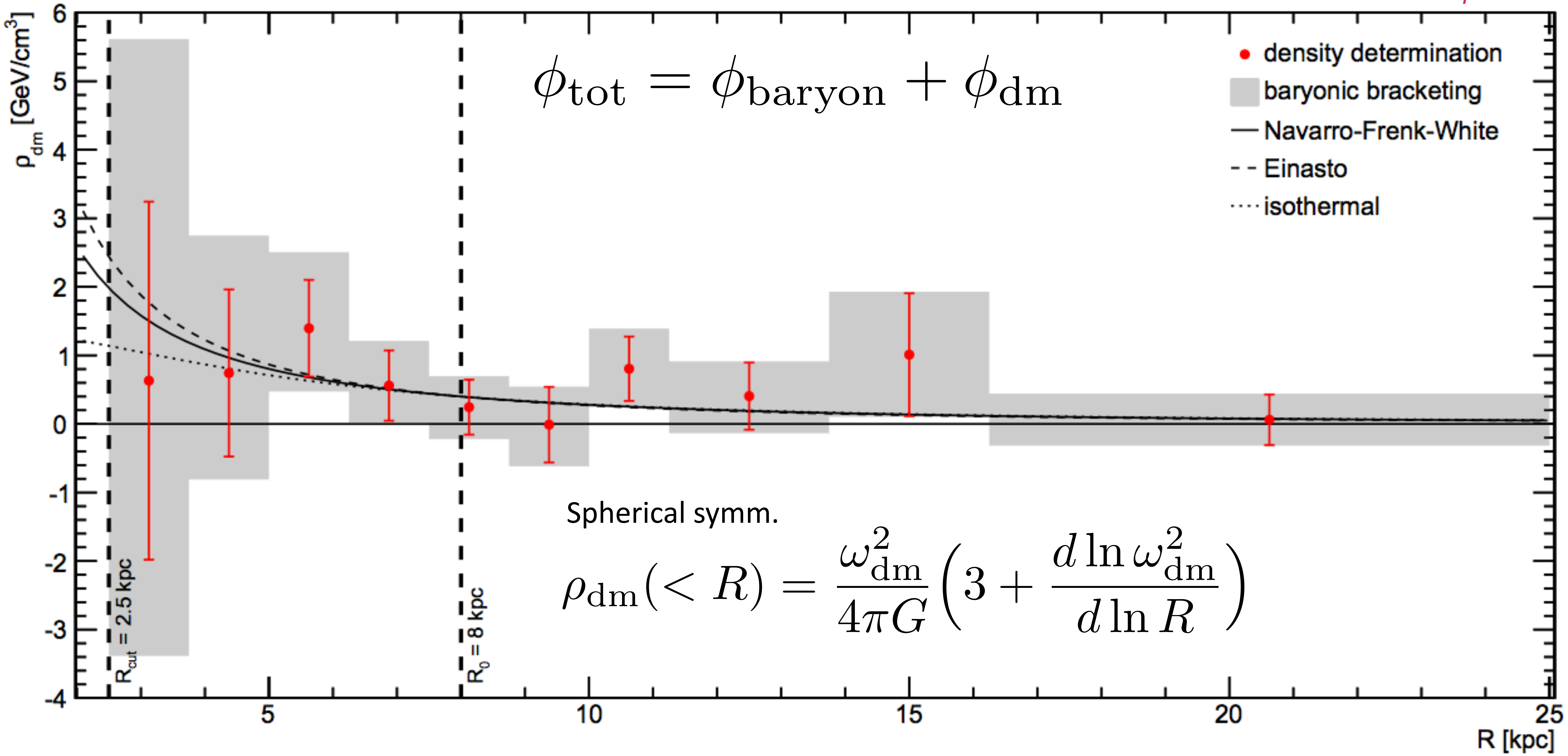
Milky Way rotation curve

Iocco+ Nature Physics'15



$$\omega_c = v_c / R$$

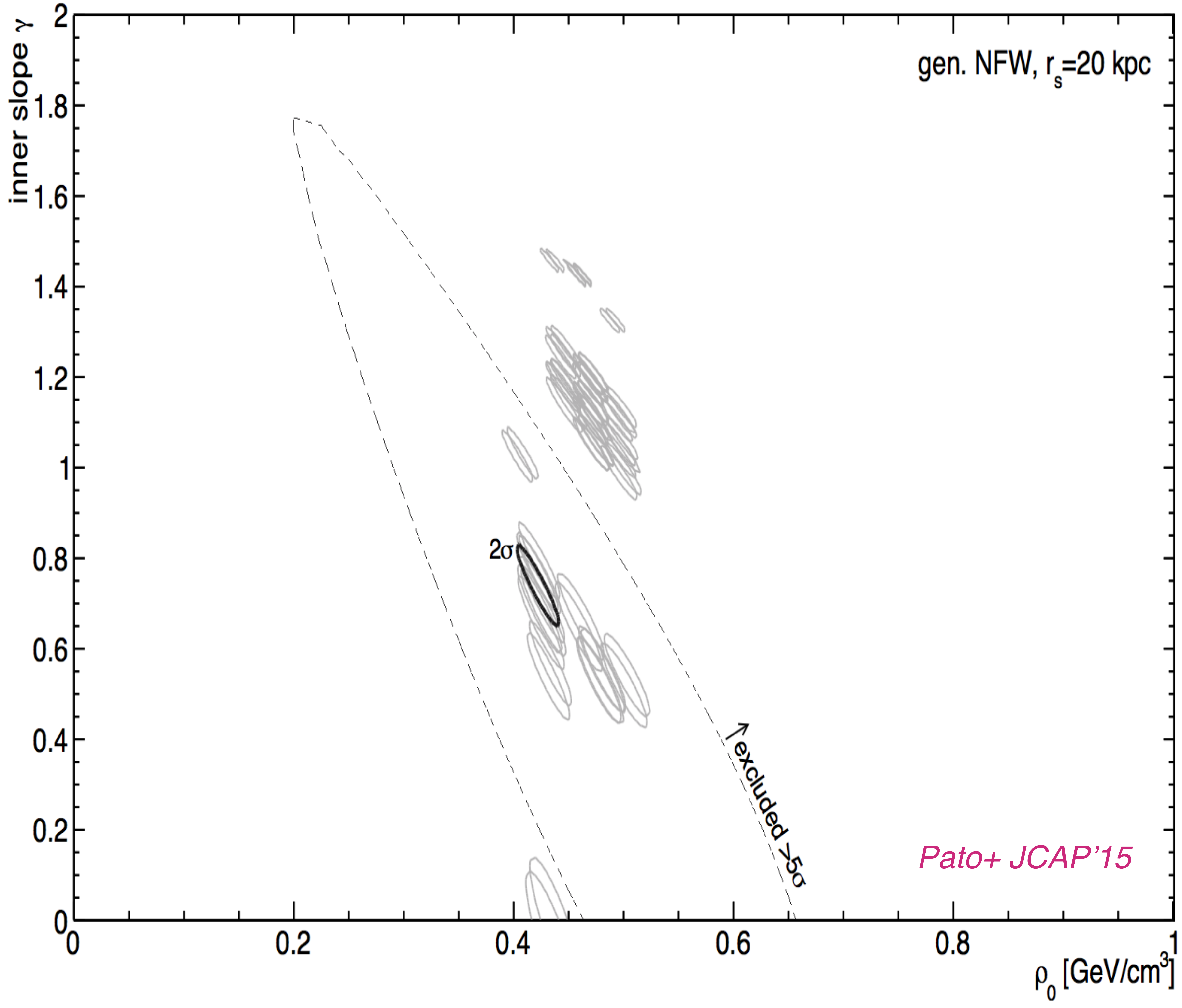
Milky Way DM density

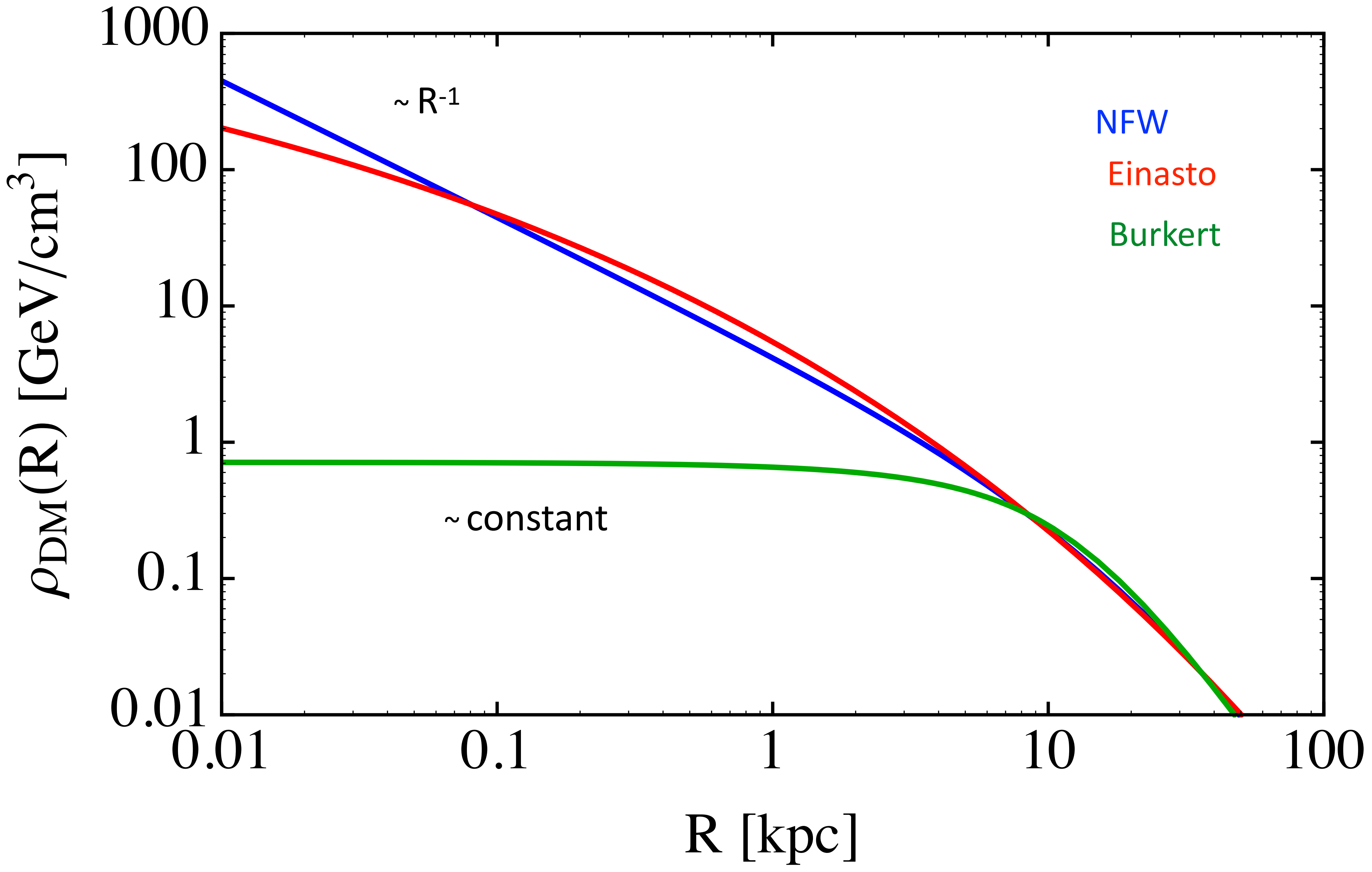


Non-parametric reconstruction: approach free of profile assumptions, but uncertainties are large and hinder discrimination power between different radial behaviours.

Pato&Iocco+ ApJ'15; Salucci+A&A'10

Milky Way DM density



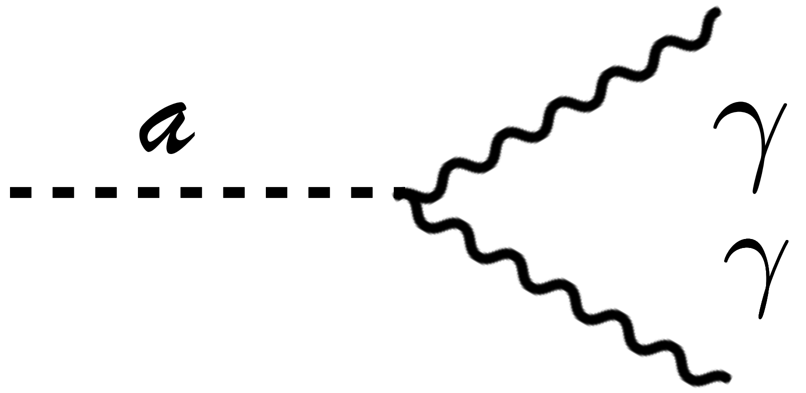


Parametric reconstruction: strong profile assumptions, "global" method to derive local DM density.

e.g: Pato+ JCAP'15; McMillan+ MNRAS'16; Iocco&Benito PDU'17

Main theoretical uncertainty!!

Dark matter decay: spectrum



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

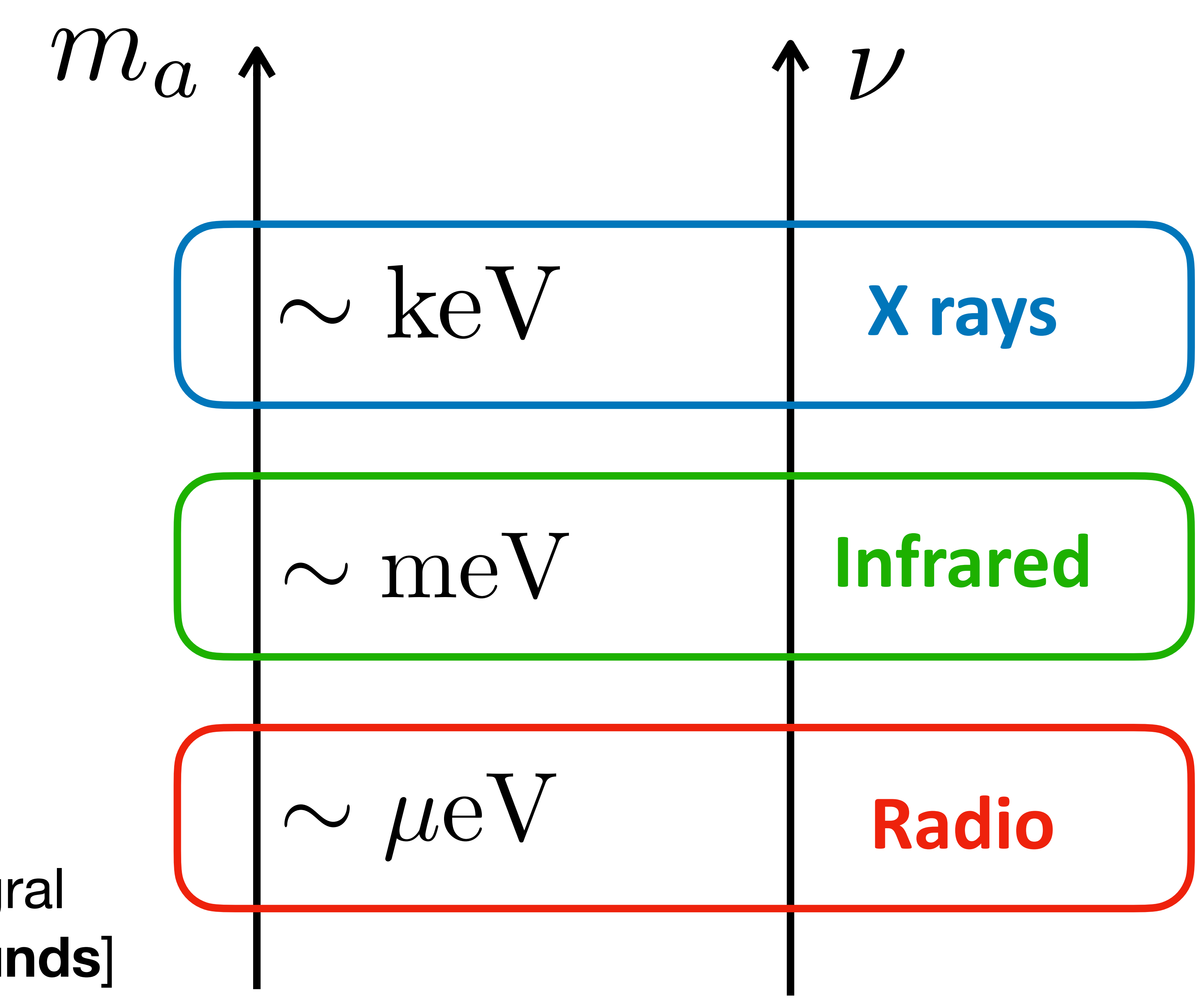
Spontaneous decay

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

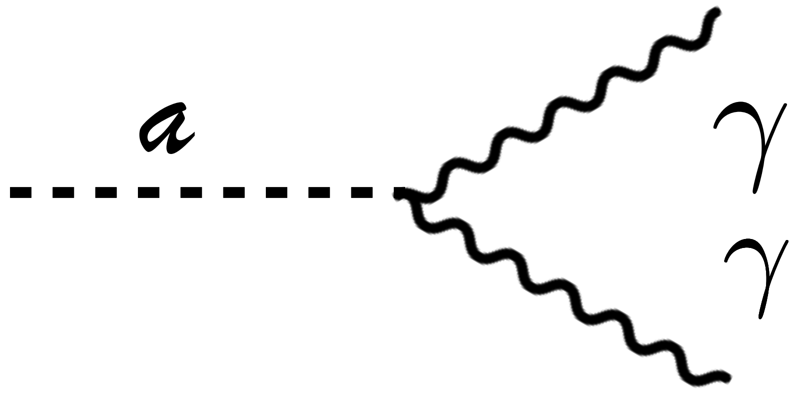
Narrow line signal

@ 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**]

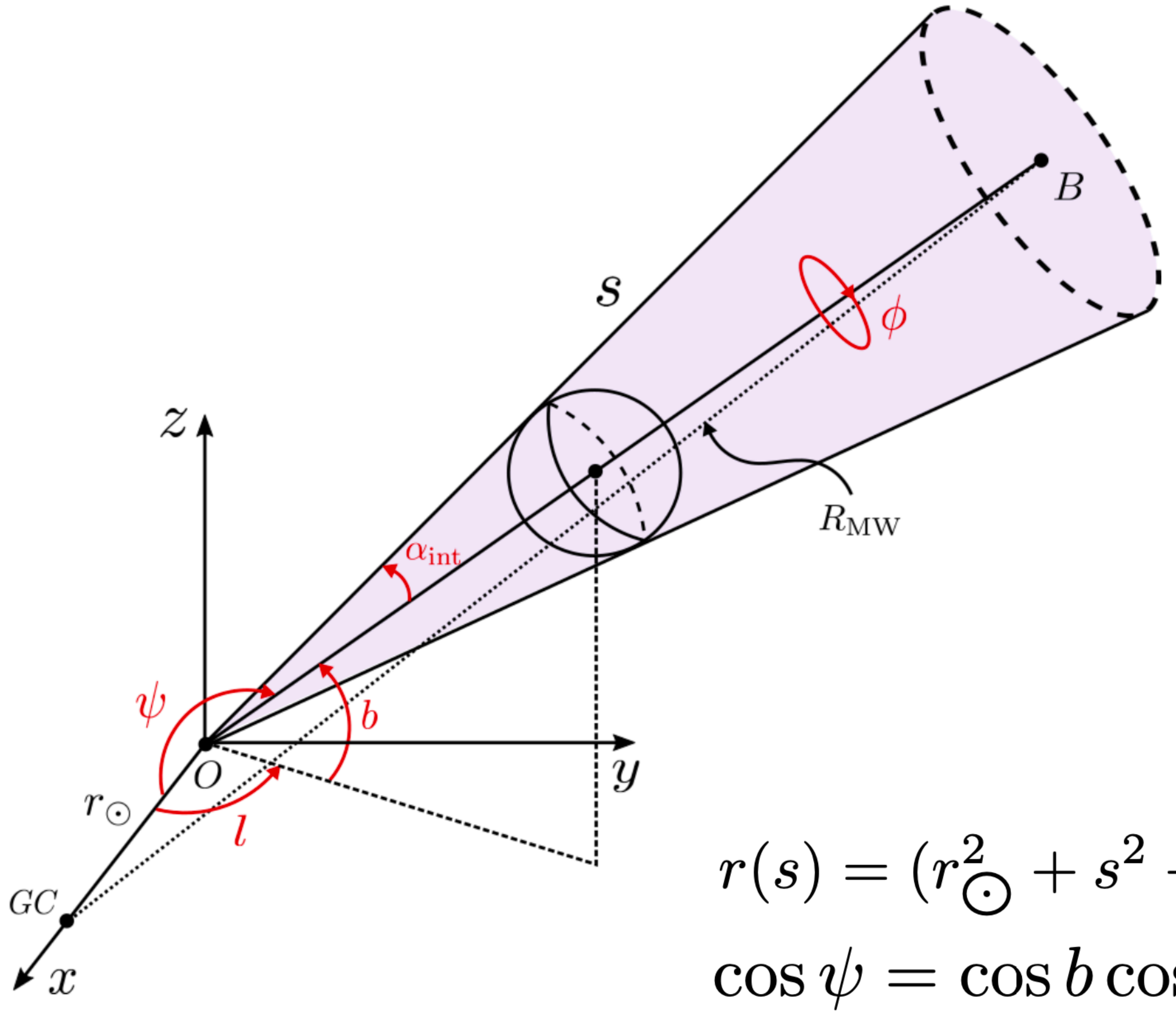


Dark matter decay: spatial distribution

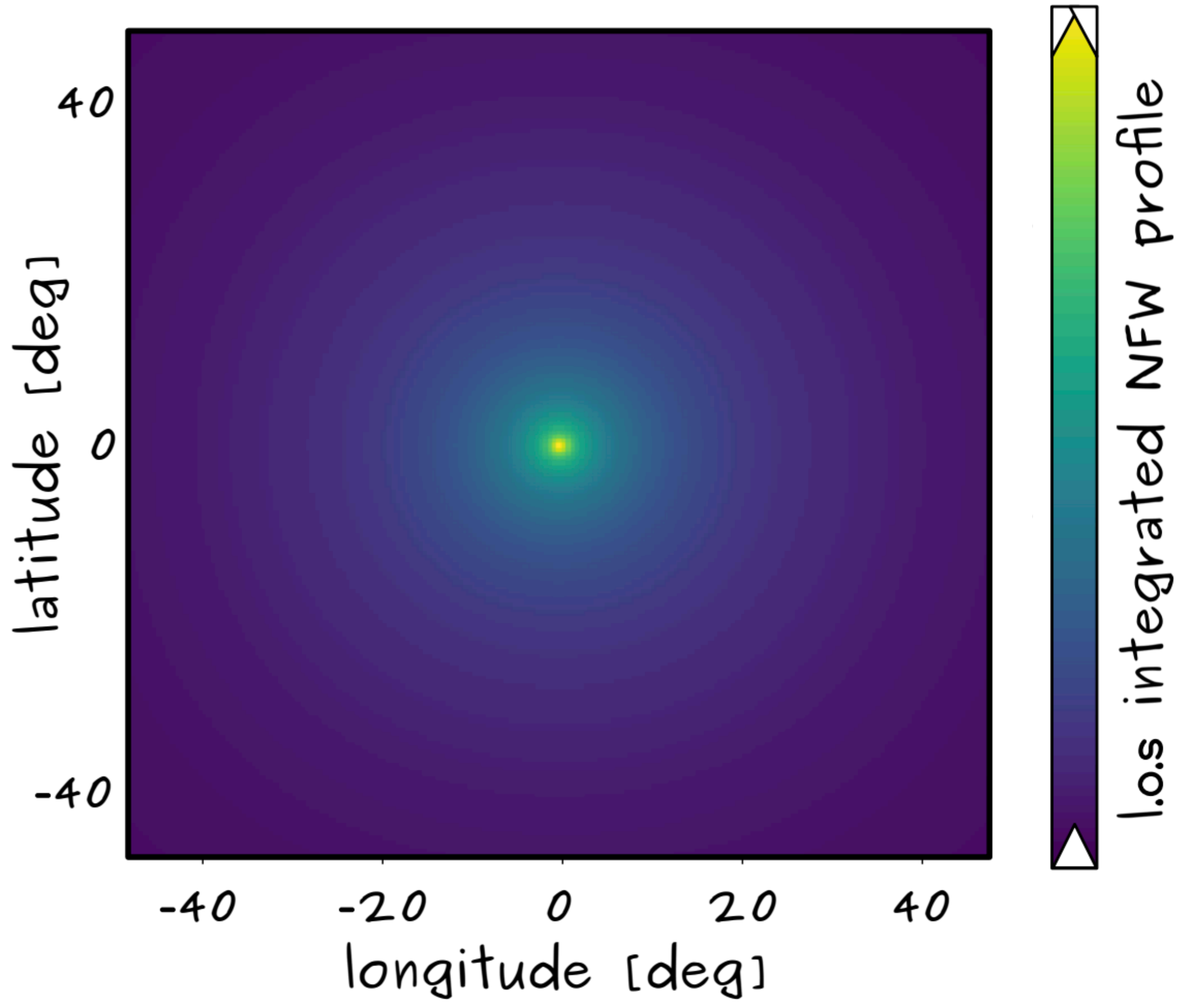


D-factor

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

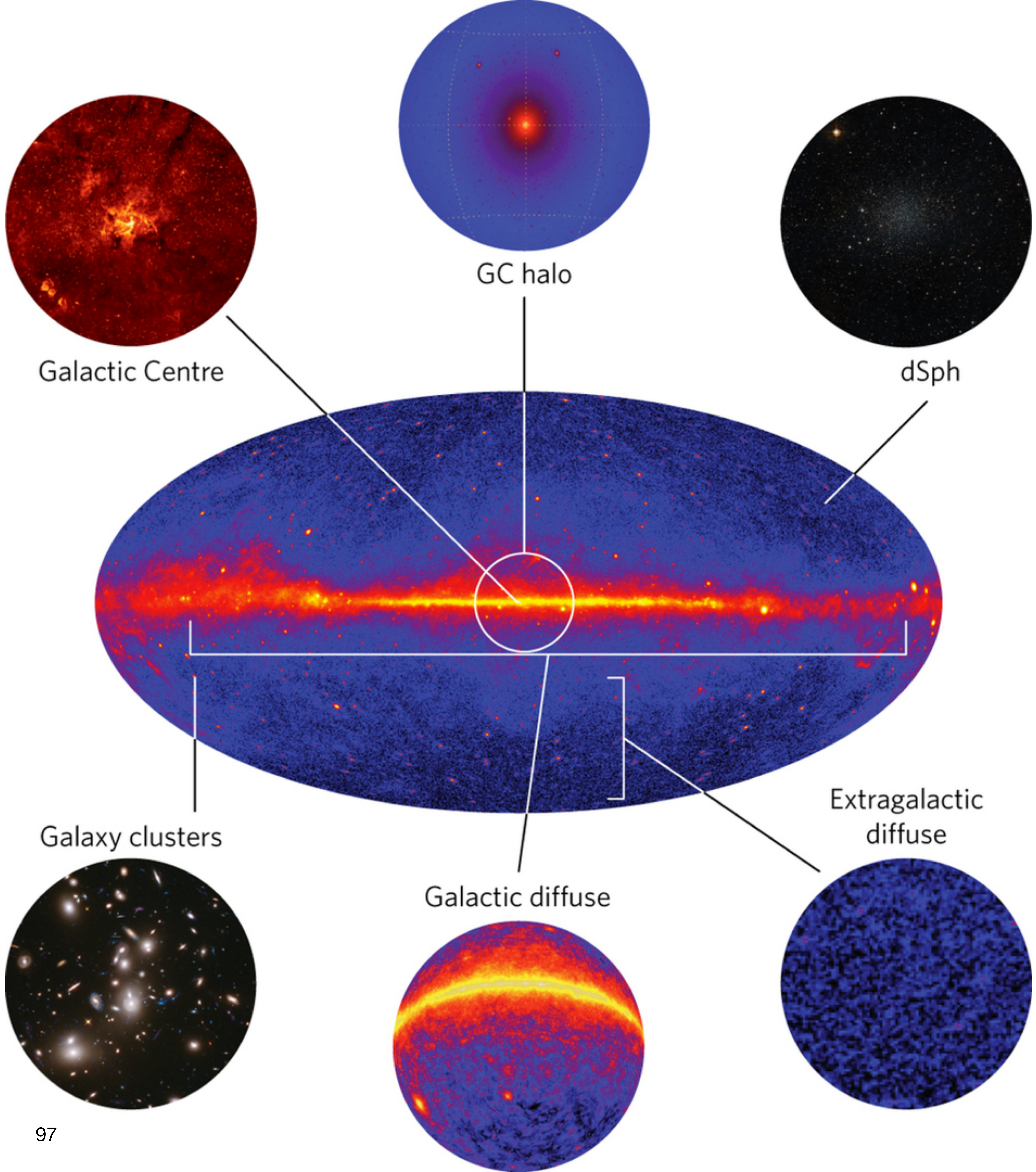


$$r(s) = (r_\odot^2 + s^2 - 2r_\odot s\cos b\cos l)^{1/2}$$
$$\cos\psi = \cos b\cos l$$



Dark matter decay: targets

- **DM-rich** and **background-free** environment
- Optimisation of **S/N** based of evaluation of D-factor
- Careful **subtraction of** astrophysical **backgrounds** can improve sensitivity



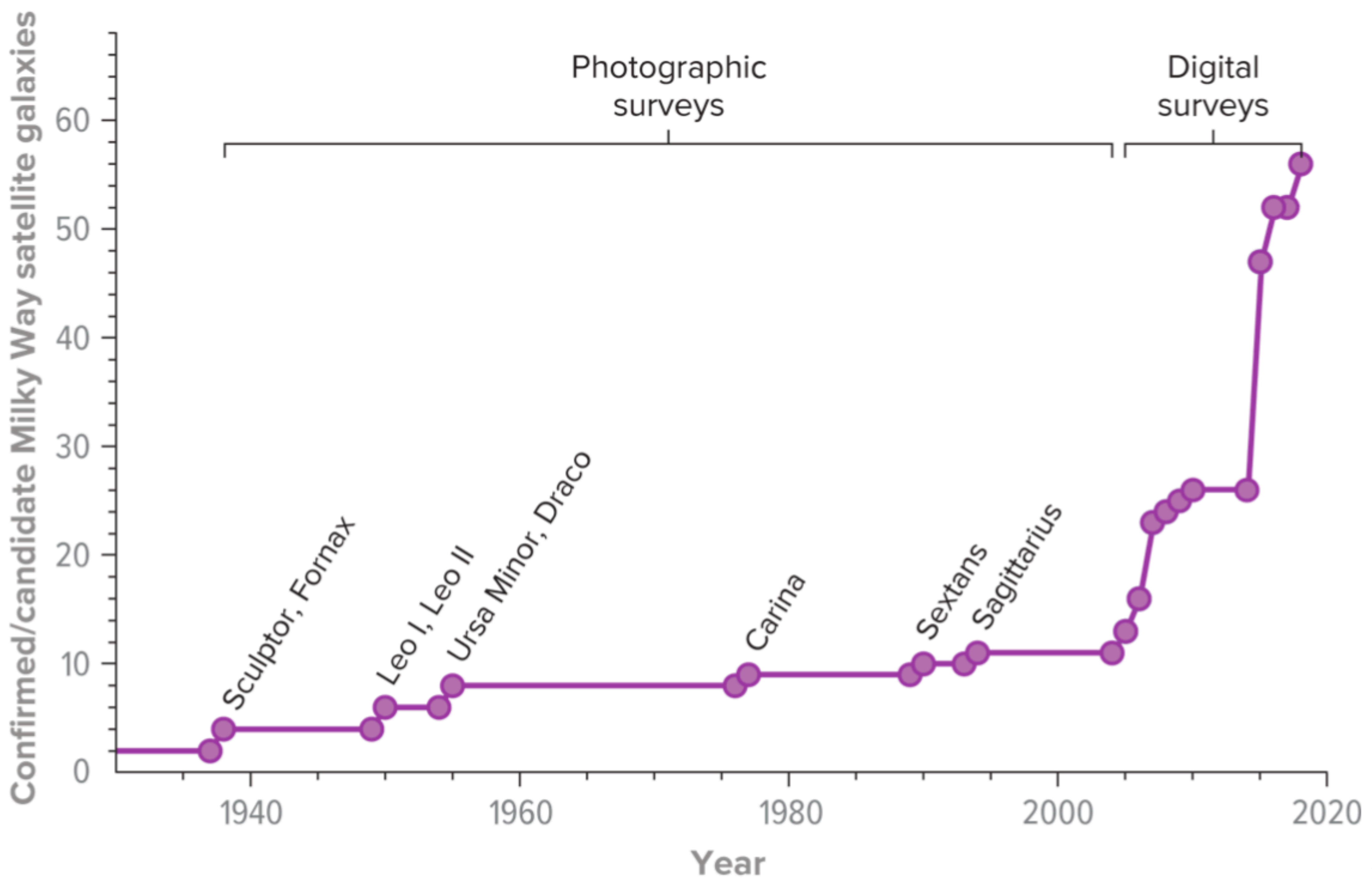
Conrad & Reimer Nature Phys. 13 (2017)

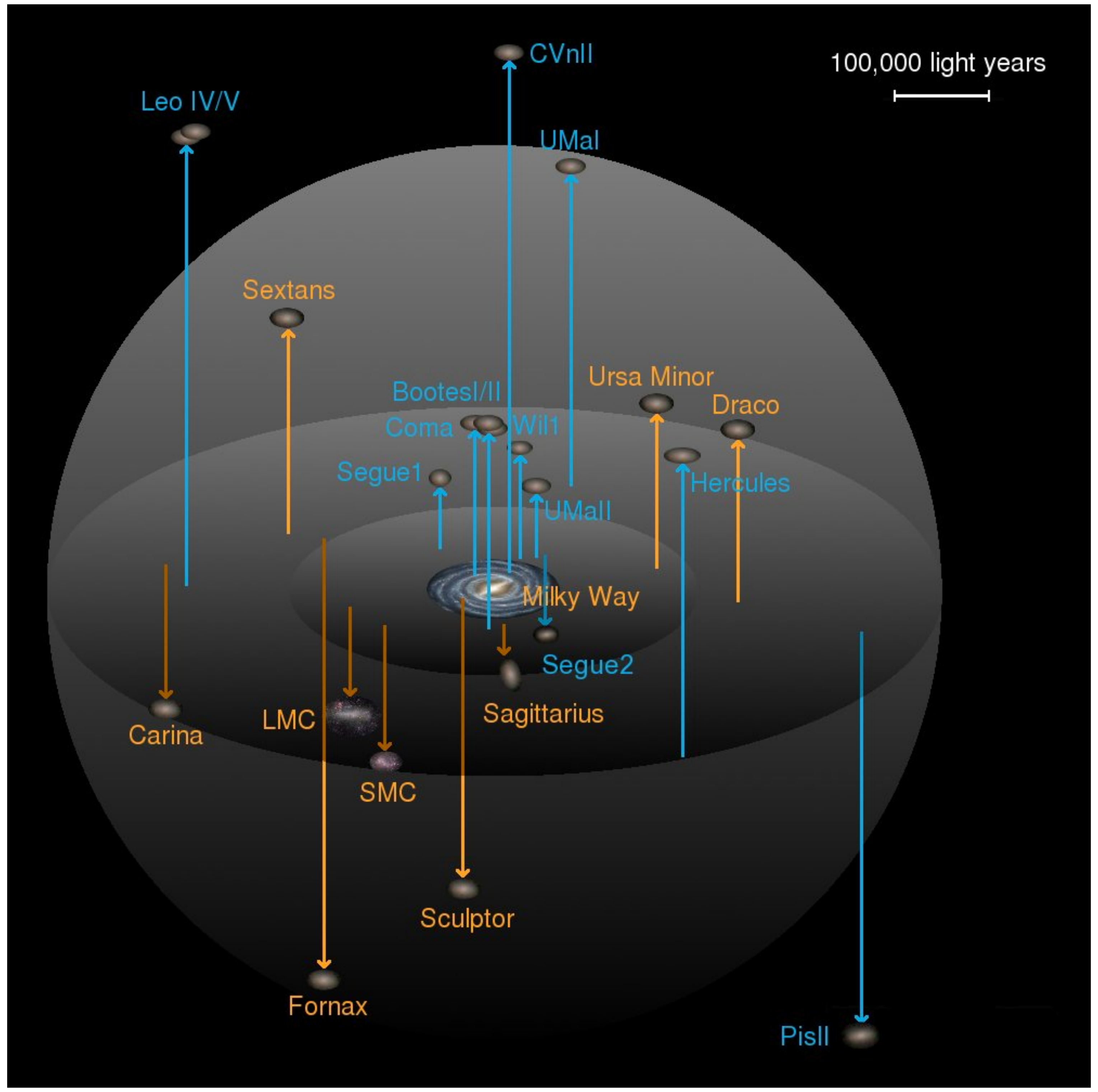
Dwarf spheroidal galaxies

Known satellites of the Milky Way at ~100 kpc from Earth

“Clean” target for DM searches, high mass-to-light ratio and little astrophysical emission

Winter+ ApJ’16





A growing Galactic crowd
> 50 satellites
(SDSS, PanSTARRS, DES)

Credit: J.D. Simon / AR Astronomy and Astrophysics

Constraints on eV ALPs

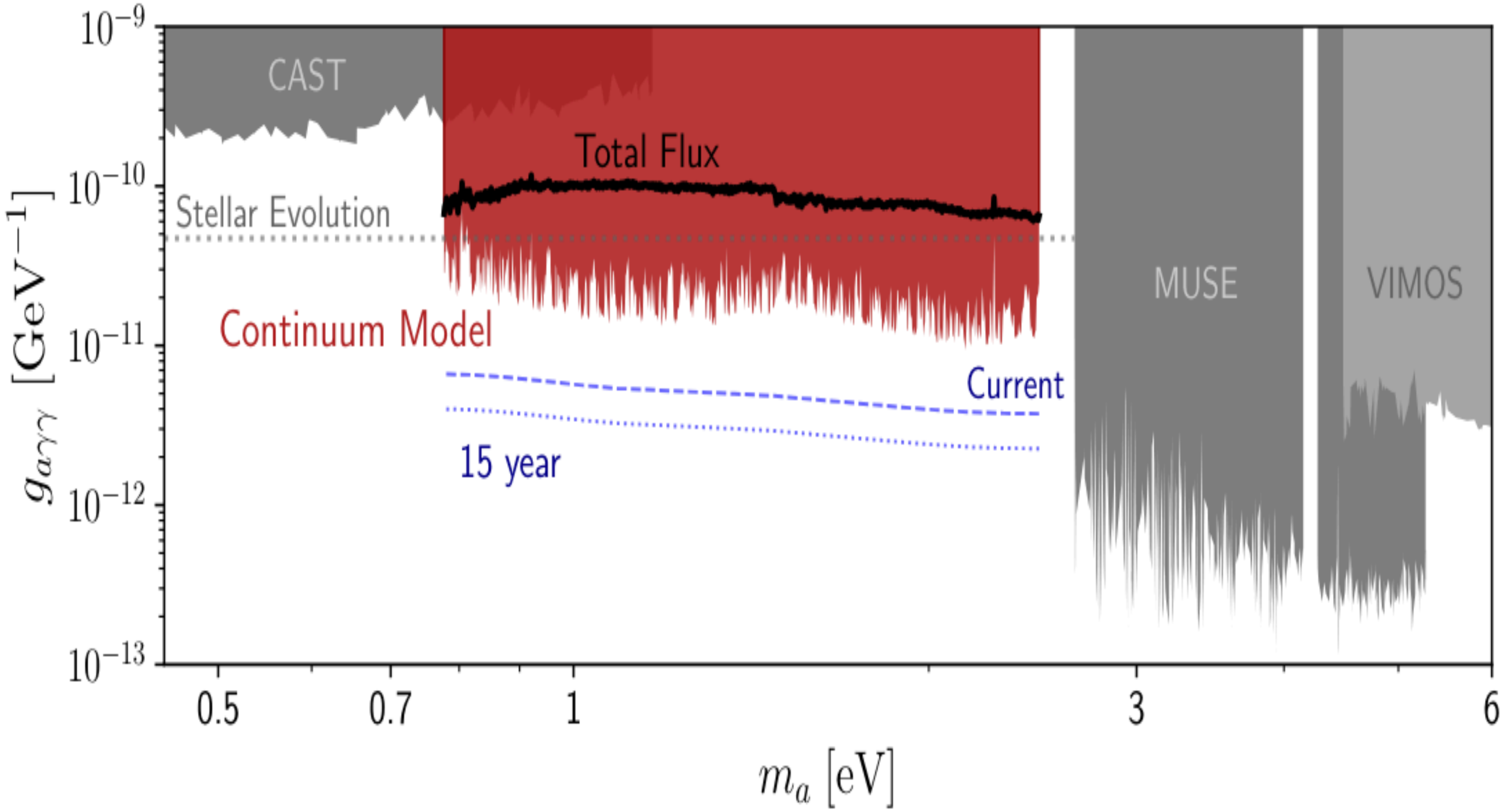
IR - optical wavelengths

Search for **narrow lines** in IR and optical data

- **MUSE**: search in the direction of 5 known dwarf galaxies
  Todarello+ JCAP'24
- **VIMOS (Visible Multi-Object Spectrograph)**: galaxy clusters Abell 2667 and 2390
  Grin+ PRD'06
- **JWST:** public blank sky observations from the NIRSpec IFU

Janish & Pinetti 2310.15395

Janish & Pinetti 2310.15395



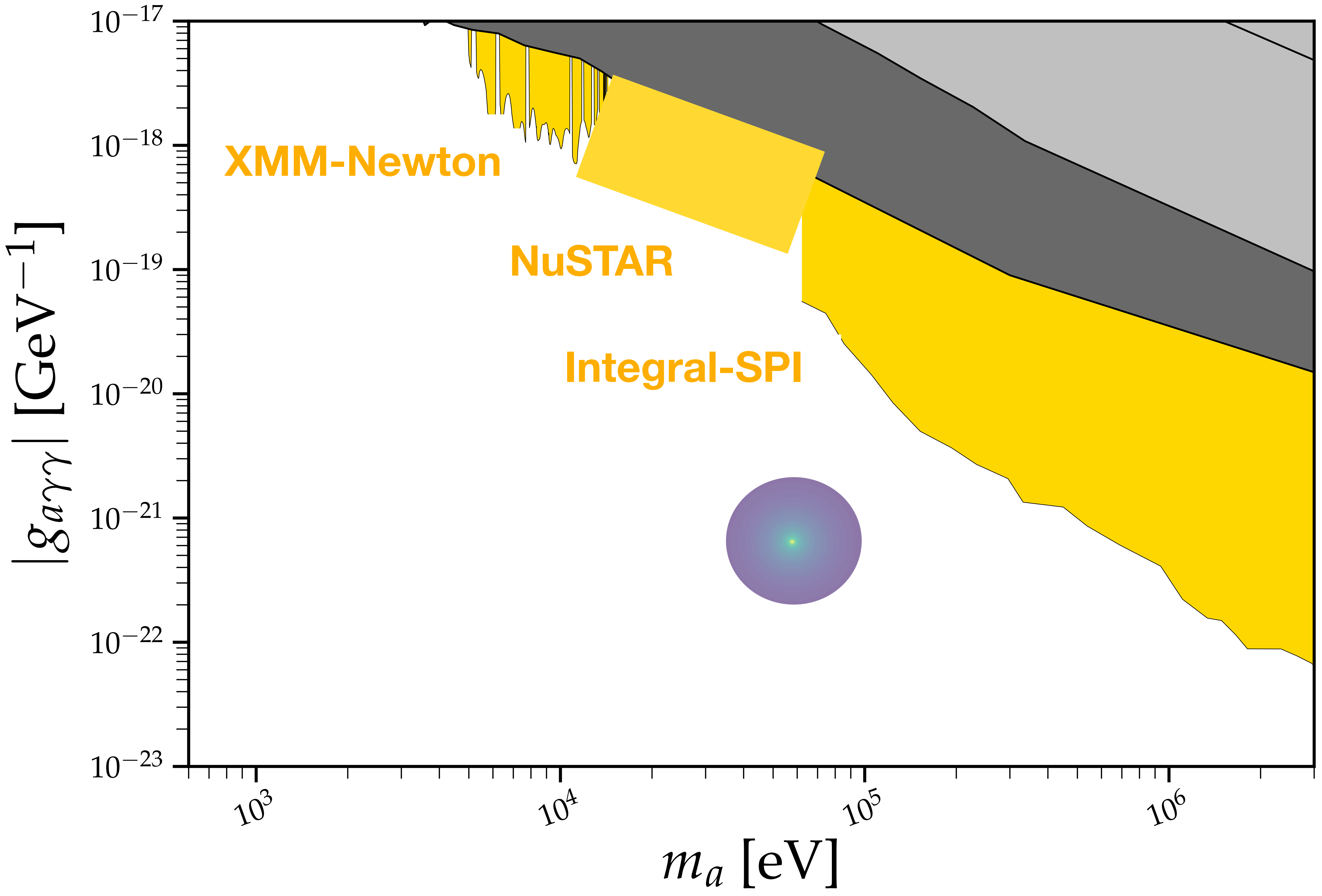
Constraints on keV - MeV ALPs

X-ray and soft gamma rays energies

Heavy ALPs DM decay

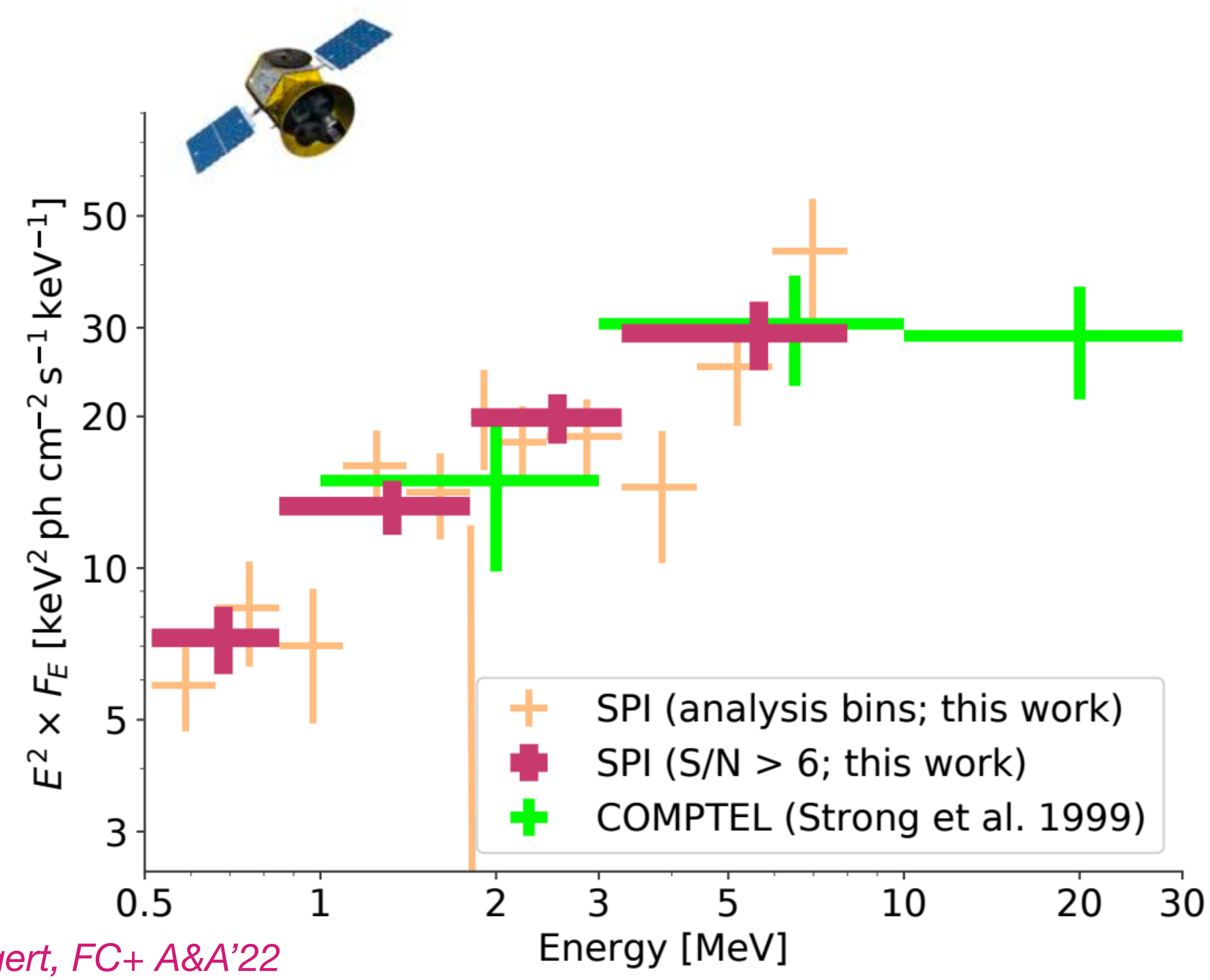
Search for **narrow lines** in X and gamma-ray data

- 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'23*



https://github.com/cajohare/AxionLimits

The MeV diffuse Galactic emission



Siegert, FC+ A&A'22

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

Constraints on **cosmic-ray transport** at MeV energy but also on **exotic emission mechanisms** for the first-time in a **self-consistent framework**

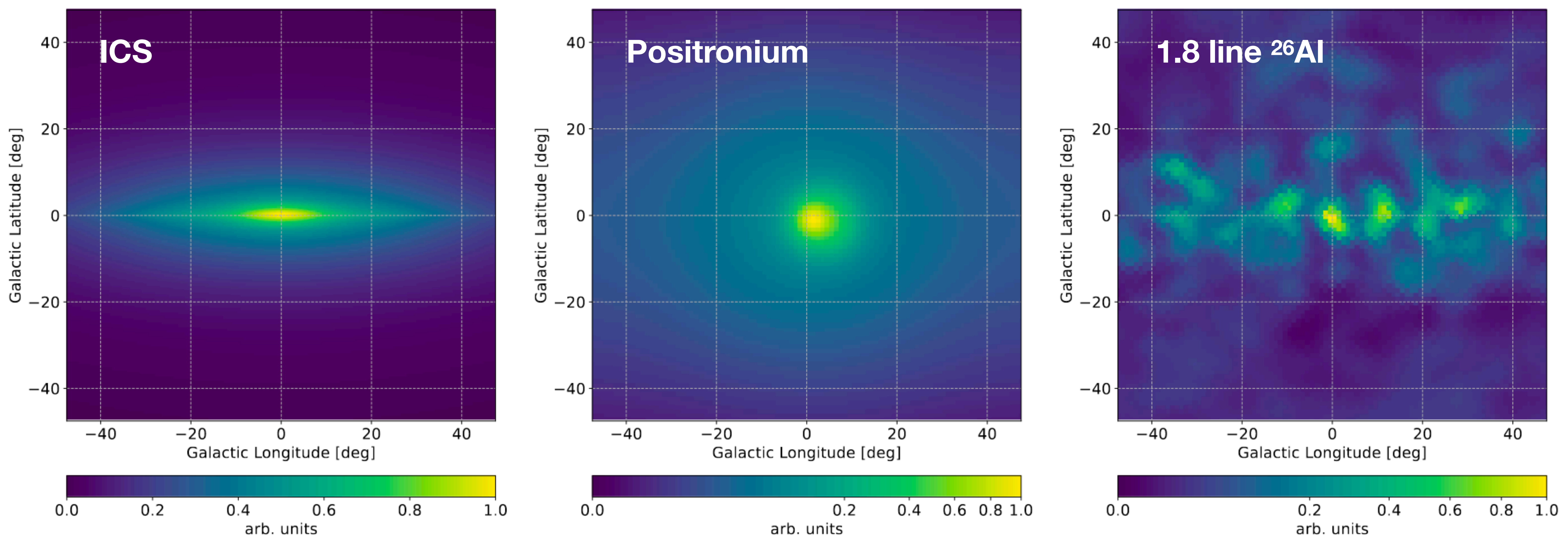
Berteaud, FC+ PRD'22 ; FC+ MNRAS'23

Extraction of the Galactic diffuse emission

Astrophysical contributions

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
- Positronium annihilation line+continuum



Berteaud, FC+ PRD'22

Extraction of the Galactic diffuse emission

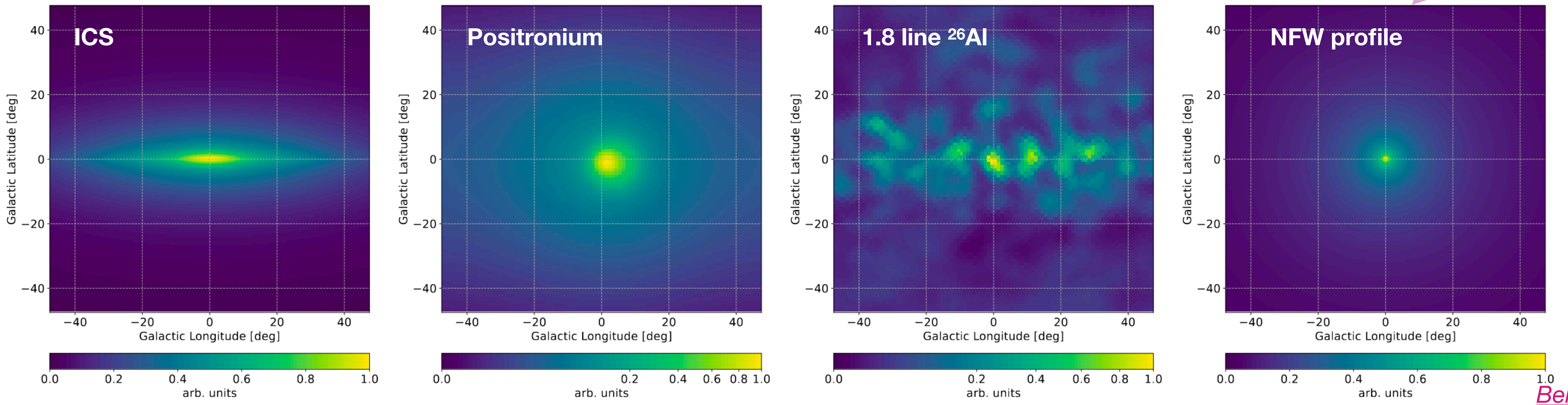
ALPs decay signal?

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

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

- Additional **ALPs decay signal**?

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



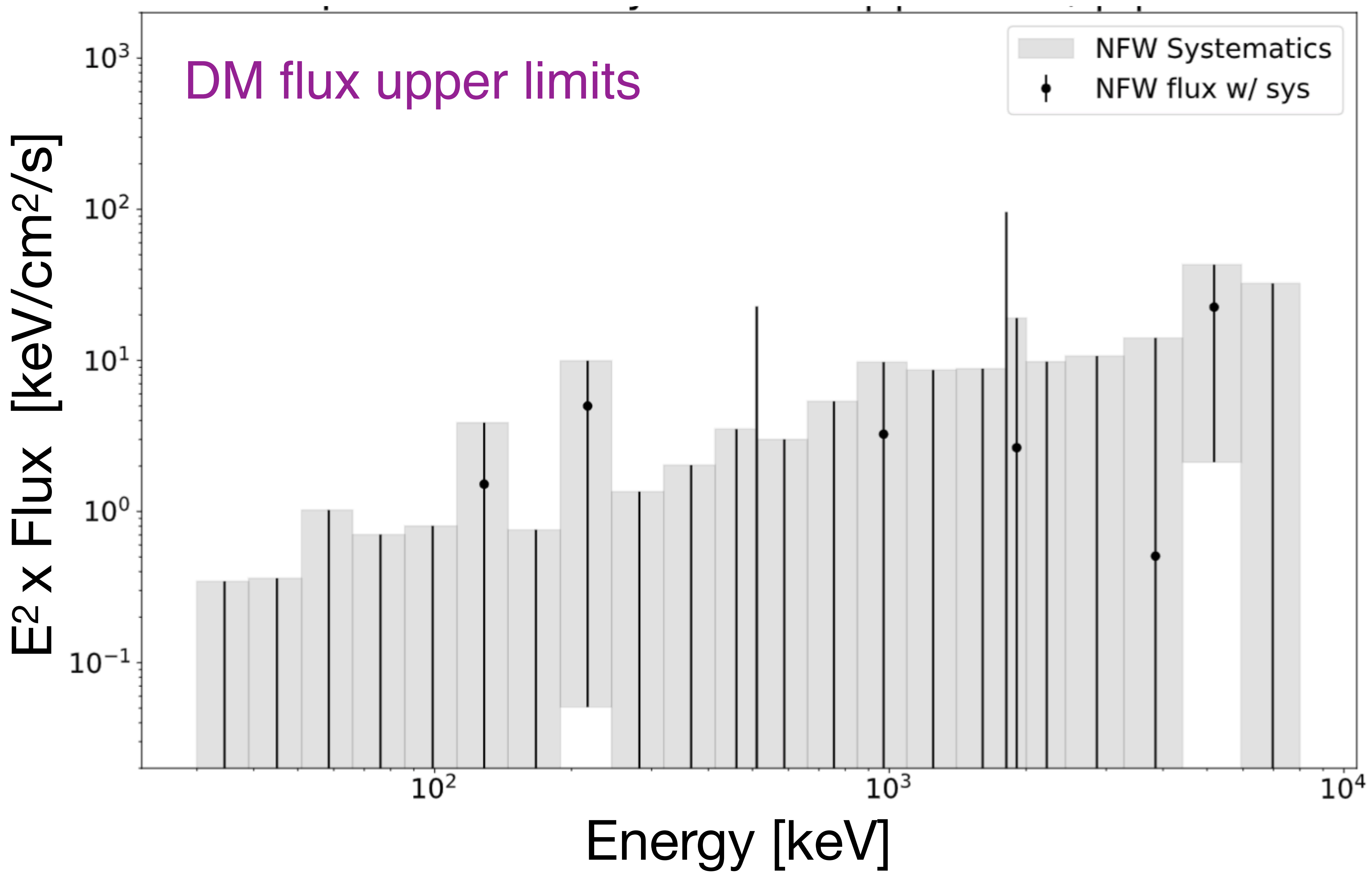
Berteaud, FC+ PRD'22

Constraints on decaying dark matter

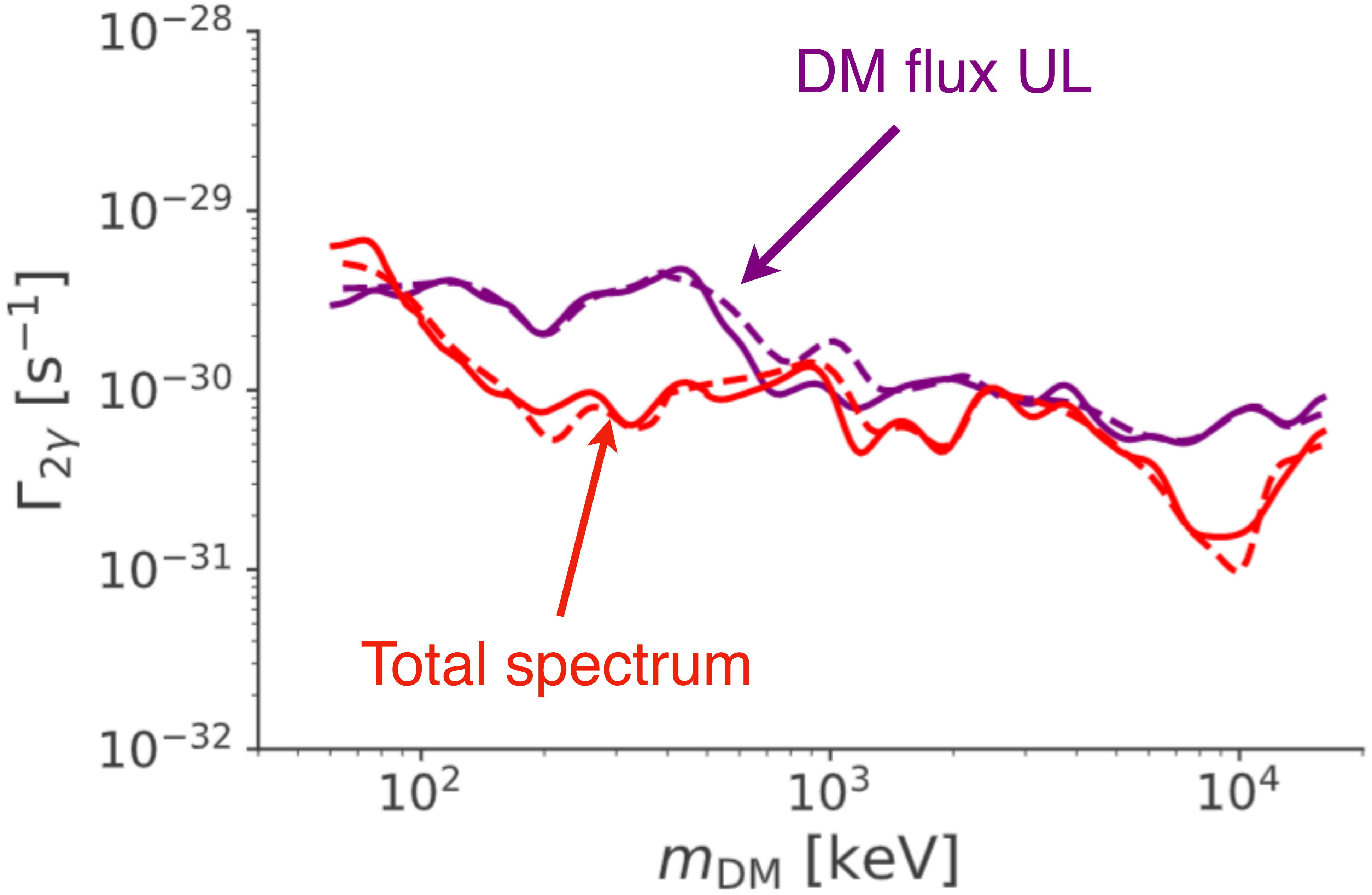
Decay into two photons (line-like spectrum)

FC+ MNRAS'23

No signal detected



⟶ Upper limits on **decay rate** into 2 photons, $\Gamma_{2\gamma}$

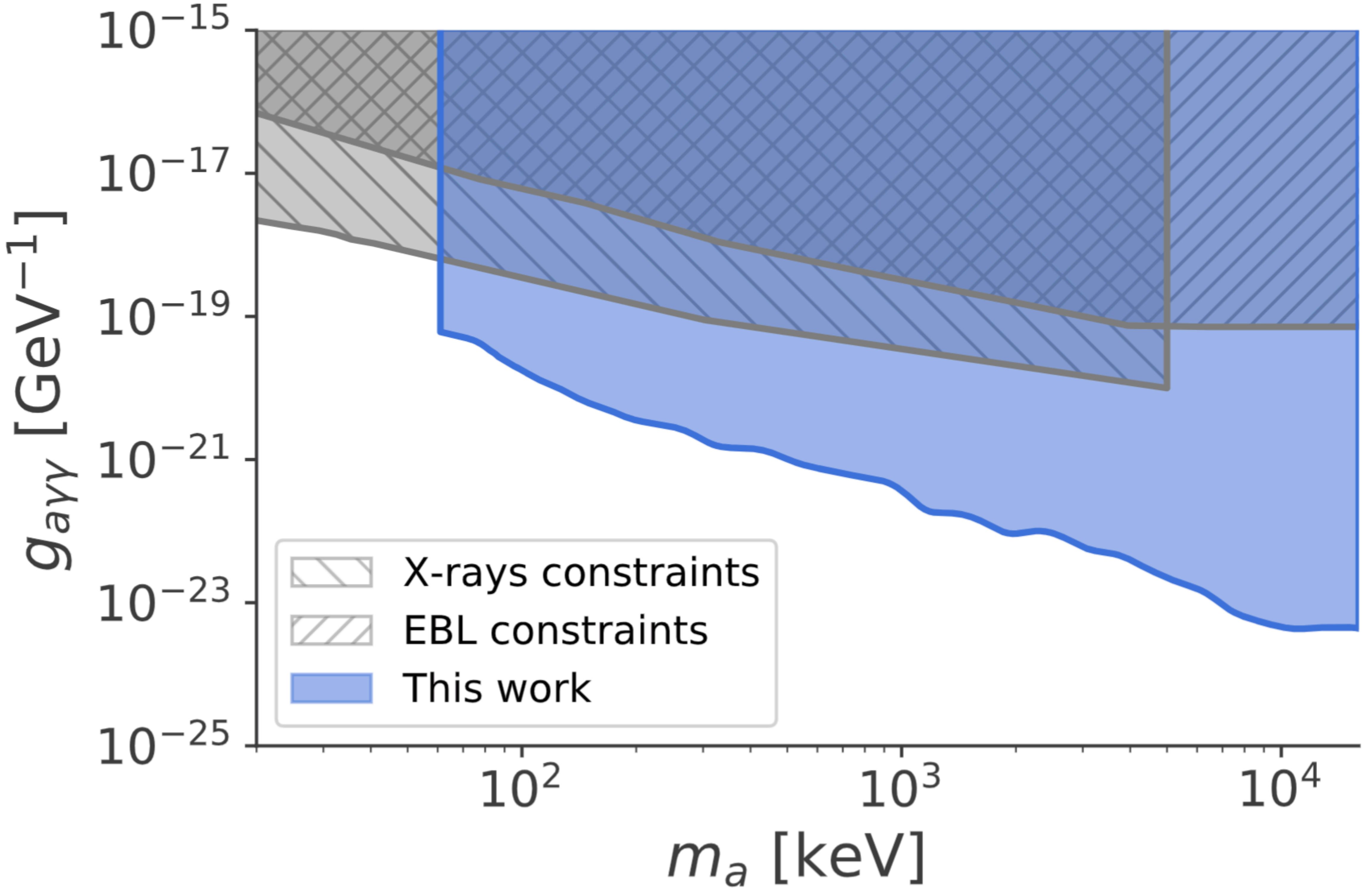


$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\mathrm{decay}} = \frac{\Gamma(a \to \gamma\gamma)}{4\pi m_a}\left(\frac{dN_\gamma}{dE}\right)_{\mathrm{decay}} \times \int_{\mathrm{l.o.s.}} \rho_a(\ell)d\ell \qquad \frac{dN_\gamma}{dE} = 2\delta\left(E - \frac{N m_{\mathrm{DM}}}{2}\right)$$

https://zenodo.org/record/7984451

Constraints on ALPs dark matter

FC+ MNRAS'23



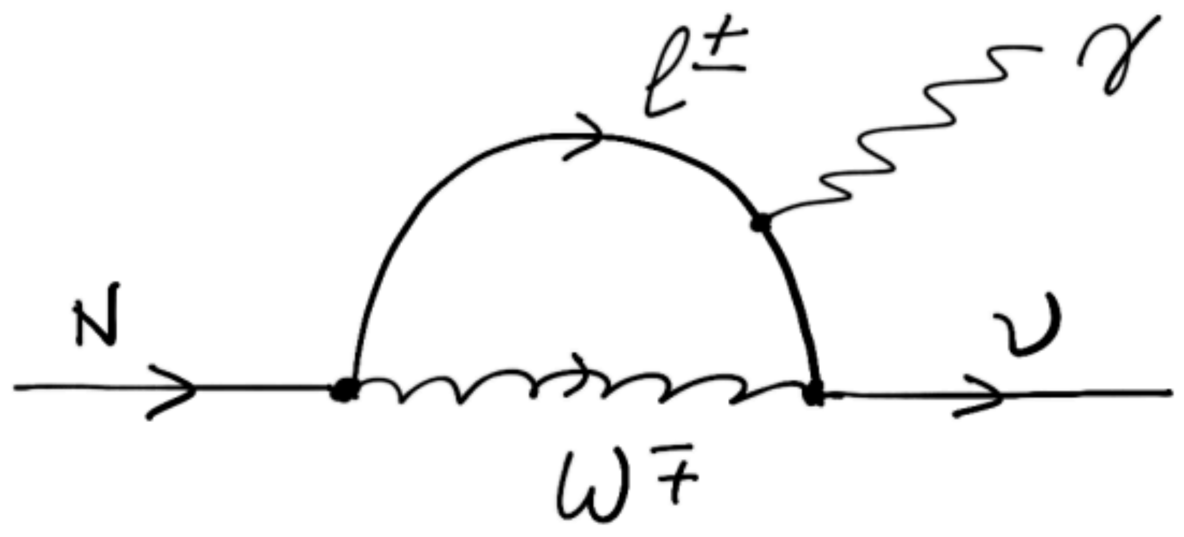
$$\tau_a = \frac{64\pi}{m_a^3 g^2}$$

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

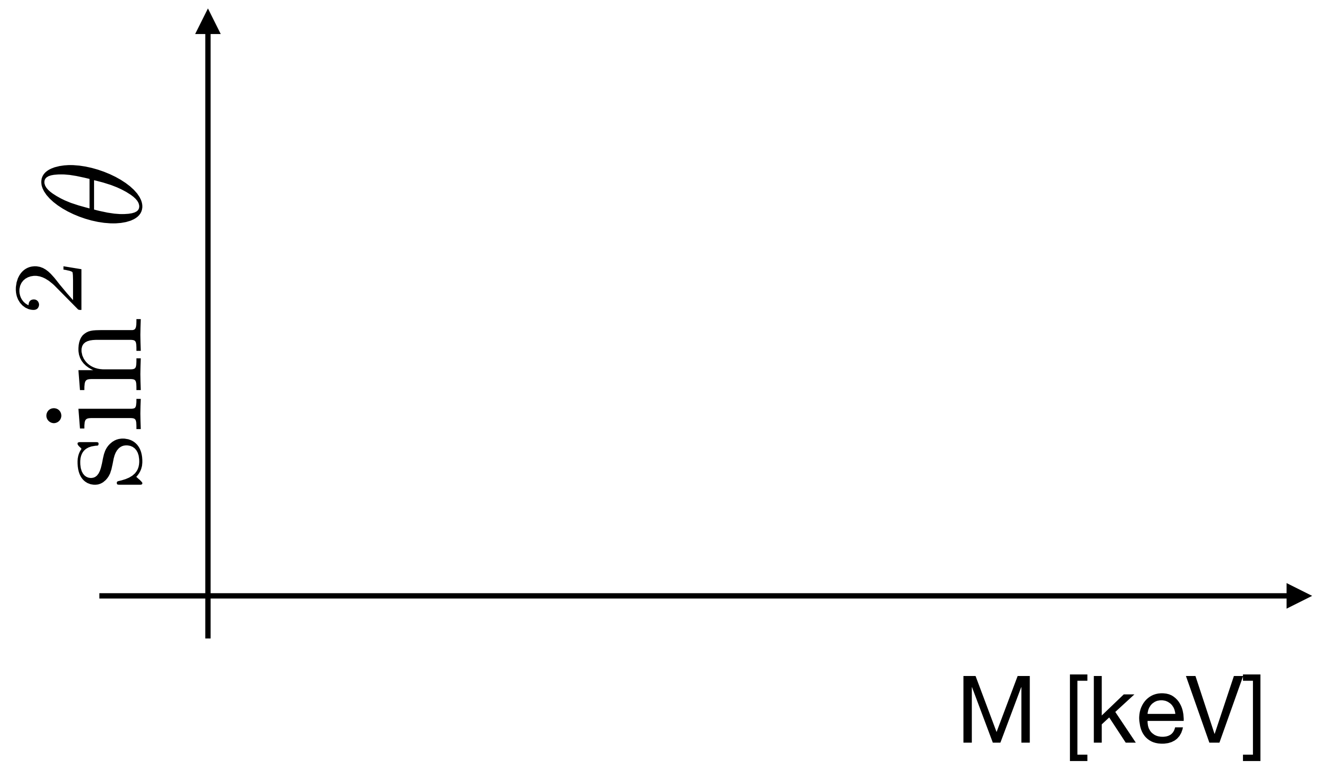
Re-analysis of Integral/SPI data provides the **strongest constraints** on (light) particle and non-particle DM

Sterile neutrinos X-ray lines
Model prediction

- X-ray lines for **sterile neutrinos** in the keV to MeV mass range
- Loop mediated radiative decay



$$\Gamma_N \approx 10^{-29}\,\mathrm{s}^{-1}\left[\frac{\sin^2(2\theta)}{10^{-7}}\right]\left(\frac{\mathrm{M}}{1\mathrm{keV}}\right)^5$$



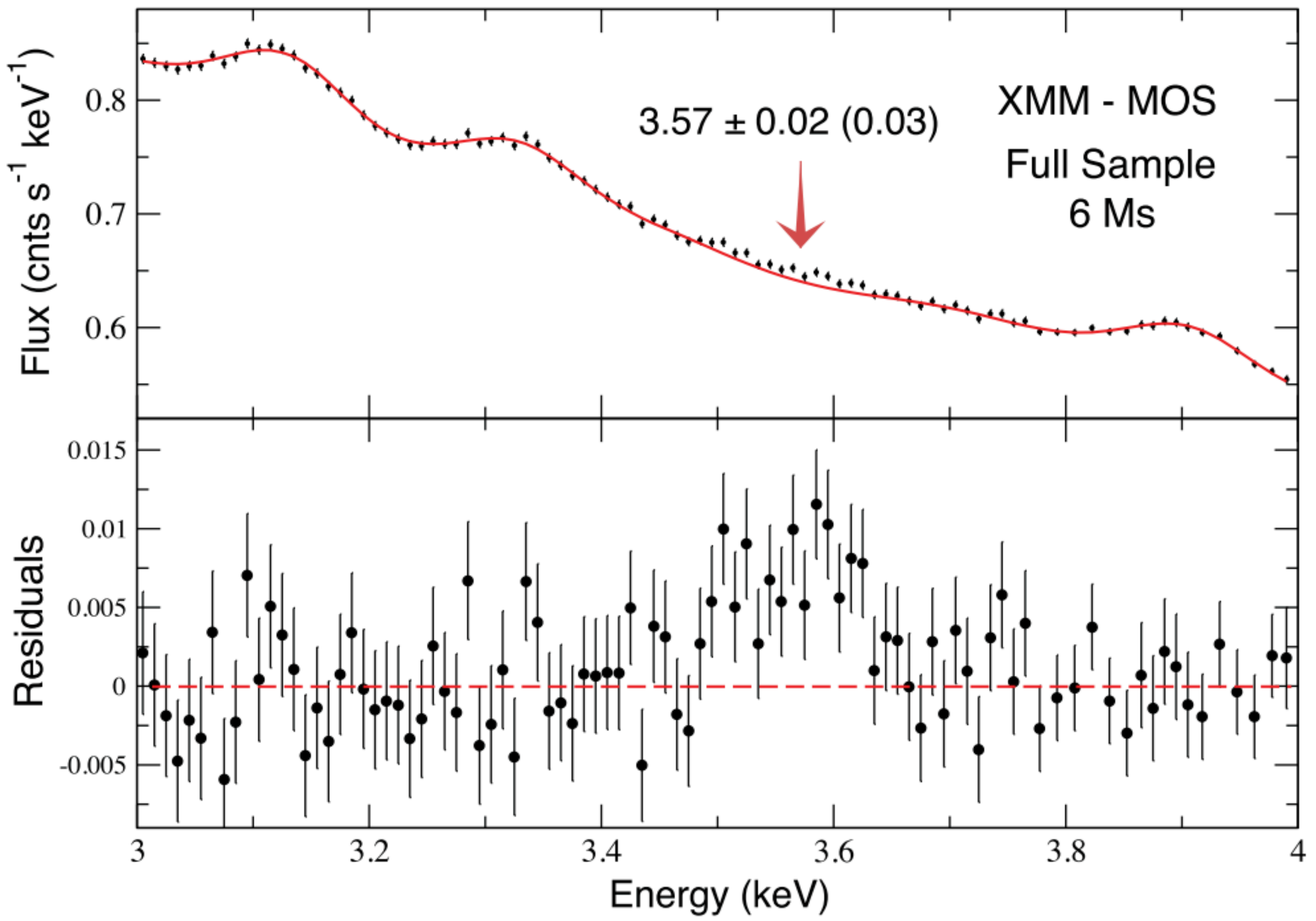
Review: *K. N. Abazajian, Phys. Rept. 711-712, 1 (2017)*

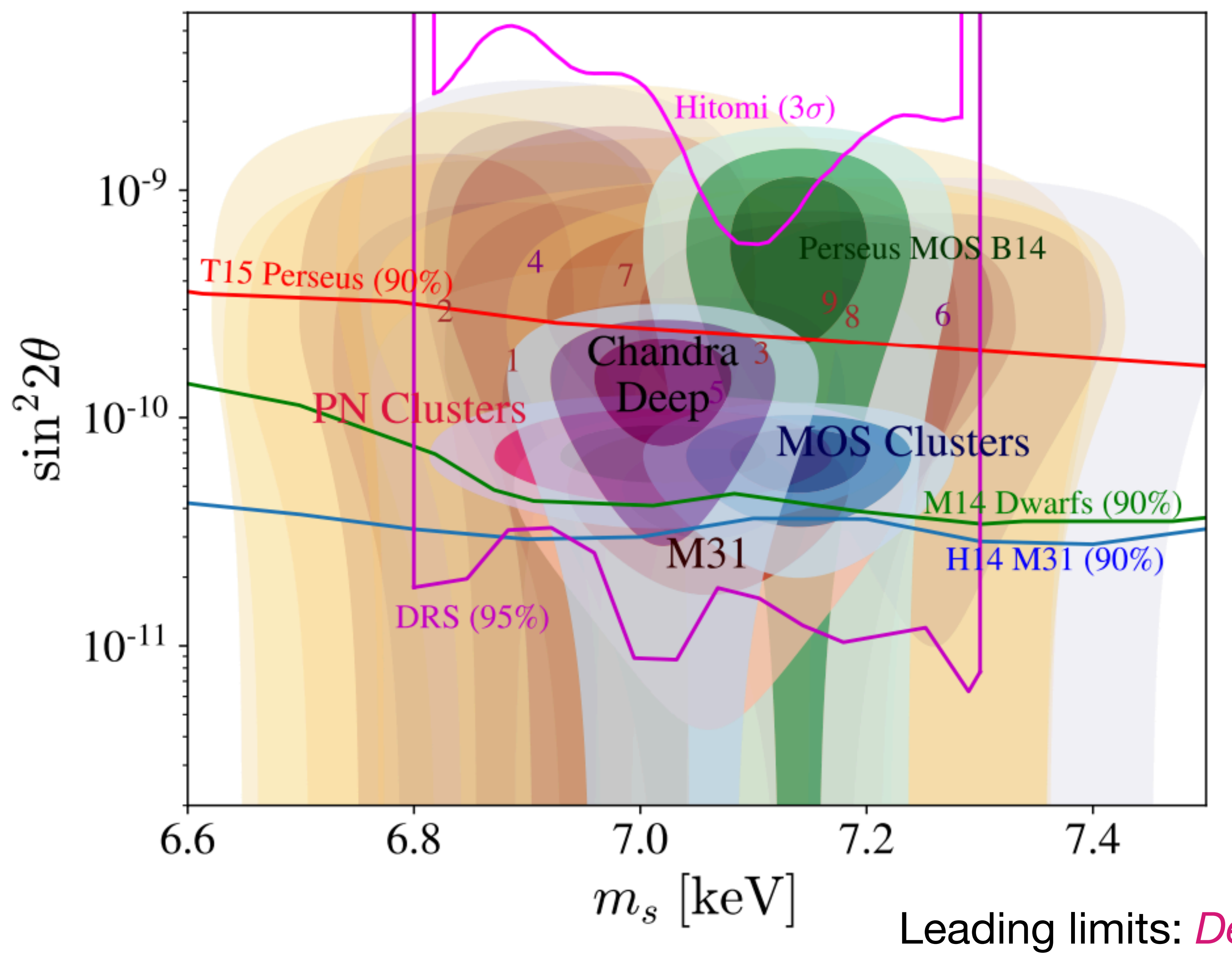
Sterile neutrinos X-ray lines

X-ray telescopes and spectral analysis

Starting from early 2014:

- **Detection** of an unidentified line at **3.5 keV**: XMM-Newton (6 Ms) & *Chandra*, Perseus cluster; XMM-Newton, M31; Suzaku, Perseus; etc
- **Constraints** from *Chandra* M31; XMM-Newton/Chandra 80 galaxies; blank field pointings Chandra and XMM-Newton, etc

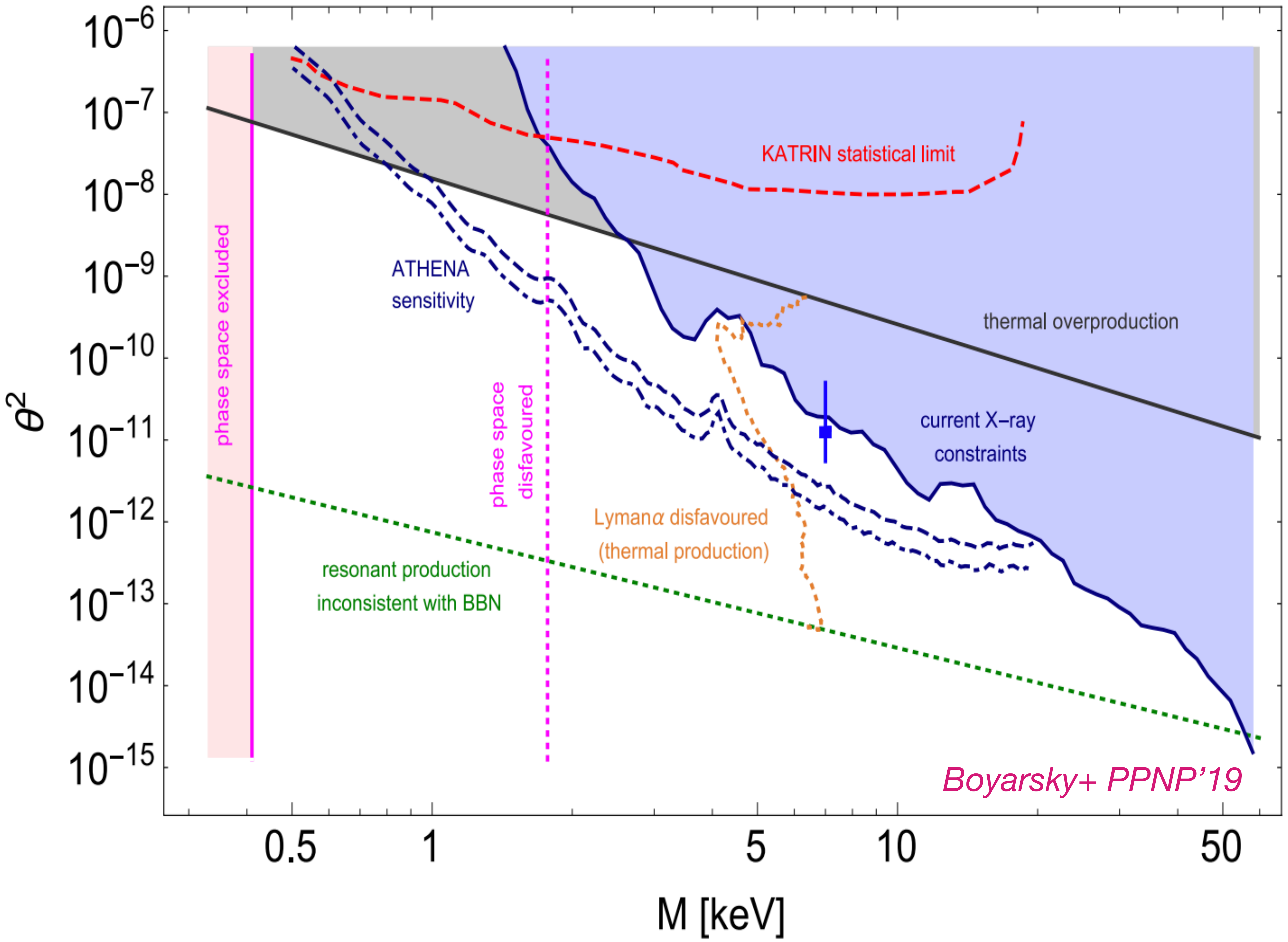




Leading limits: *Dessert+ Science' 20*

Sterile neutrinos X-ray lines

Constraints on parameter space



Future progresses with eROSITA, XARM (ex-Hitomi), Linx, and Athena+

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

- Next generation gamma-ray telescopes at high and low energies — **CTA, future MeV missions** — will improve the sensitivity to ALPs in the neV to μeV mass range

COSMIC WISPERS
CA 21106

https://www.cost.eu/actions/CA21106/

Conclusions & Outlook

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COSMIC WISPERS
CA 21106

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Thank you for the attention!

Supplemental material

Axion thermal production

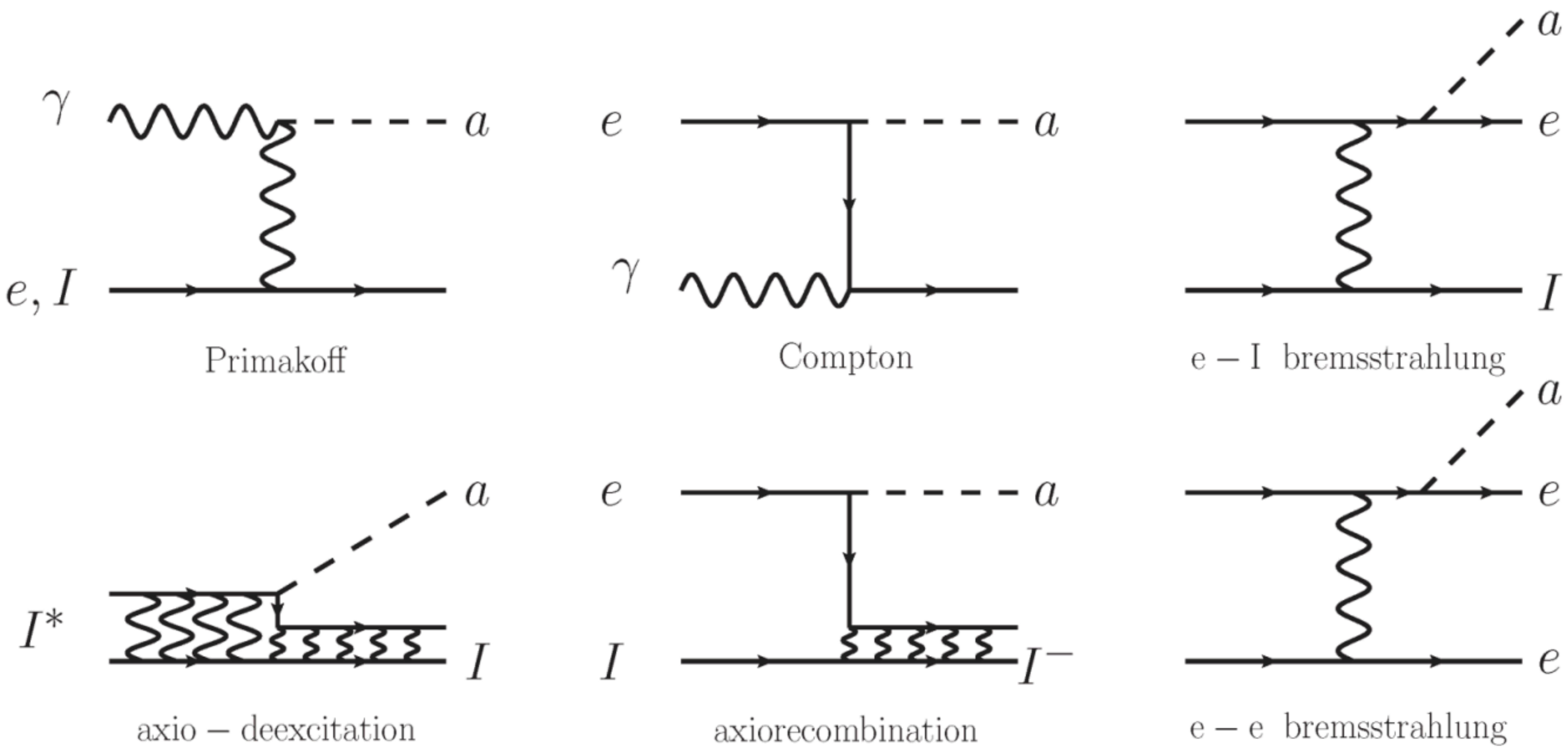
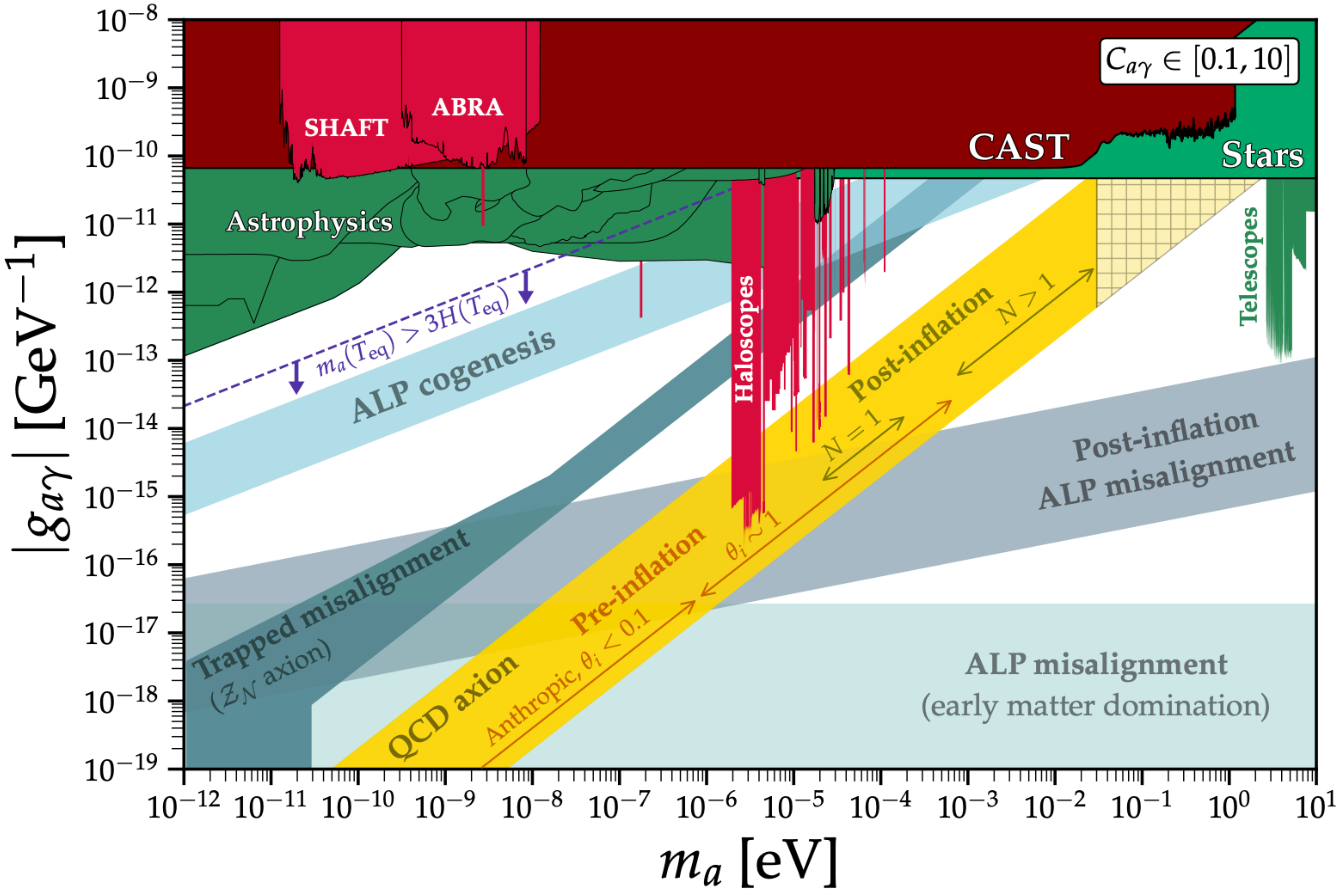


Figure 1. ABC reactions responsible for the solar axion flux in non-hadronic axion models.

Redondo 1310.0823

Non-standard axion/ALP post-dictions



- QCD axion with a non-standard mass,
  → e.g. [2102.01082]
- ALP with a temperature-independent mass
  → e.g. [2112.05117]
- Axions in non-standard cosmologies
  → e.g. [1911.07853]
- Variants of misalignment mechanism: axion rotations, parametric resonance etc.
  → e.g. [2006.04809]

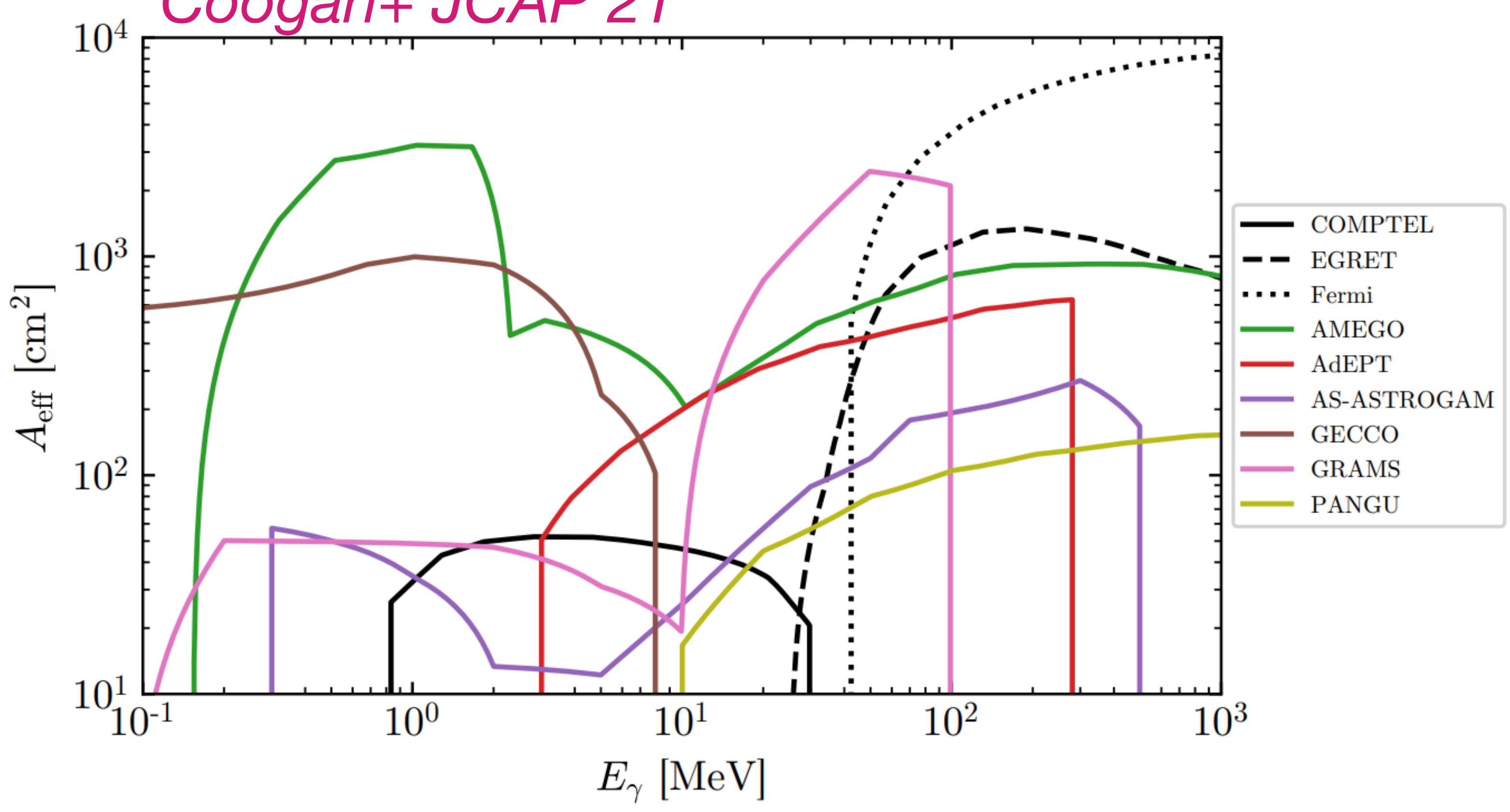
github.com/cajohare/AxionLimits

Credit: C. O'Hare

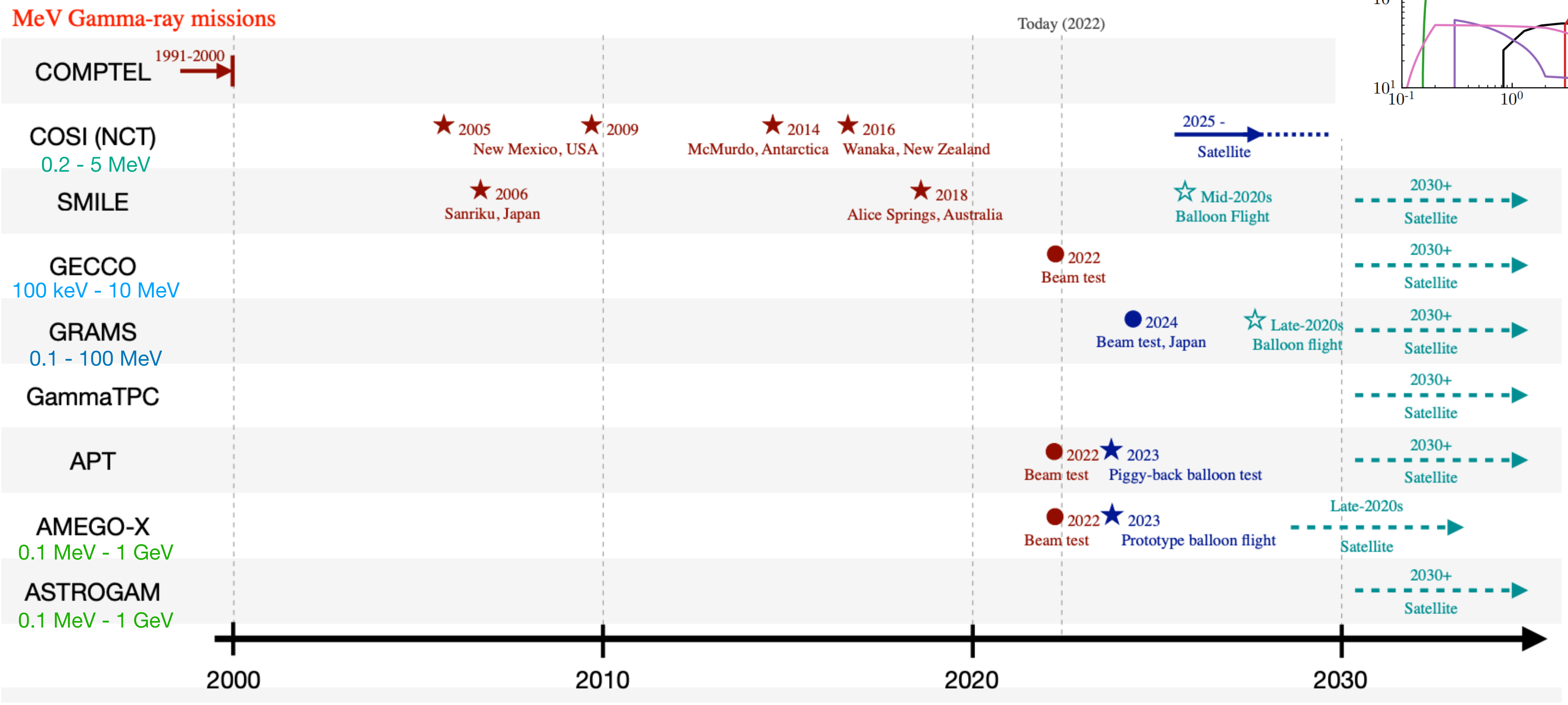
Future: MeV Galactic diffuse emission

Covering the MeV sensitivity gap

Coogan+ JCAP'21



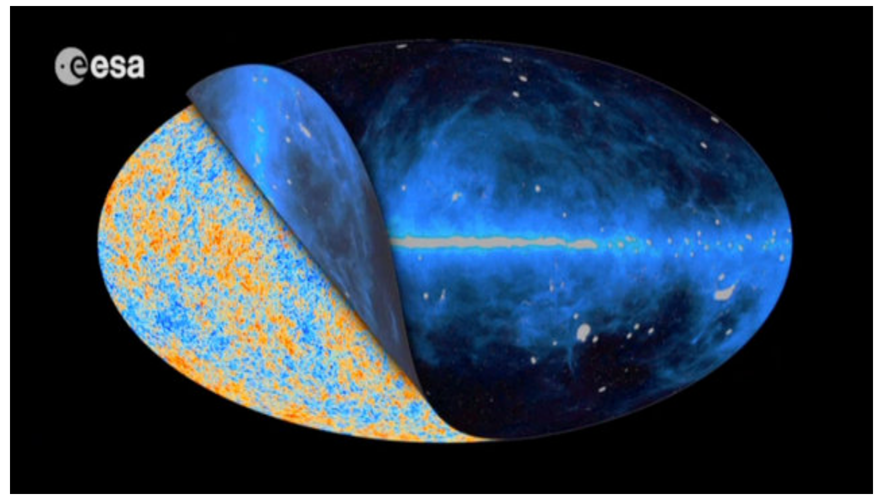
$$N_\gamma = T_{\text{obs}} \int_{E_{\min}}^{E_{\max}} \mathrm{d}E\, A_{\text{eff}} \frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}$$



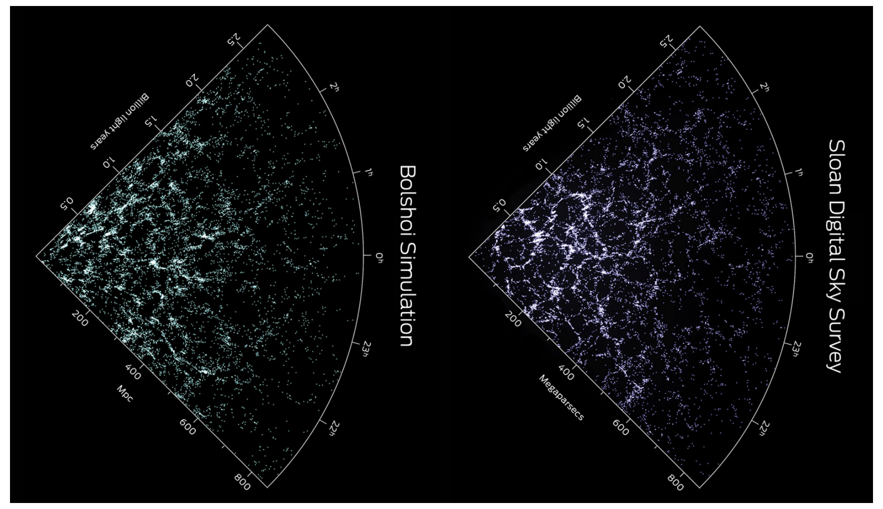
Aramaki+ Snowmass'21 CF

Dark matter astro/cosmo evidence

Cosmic microwave background



Large Scale Structures



Galaxy clusters

Galaxies

~Gpc

~Mpc

~kpc (10^{19} m)

Astro/cosmo observations at multiple scales are instrumental in showing that an unknown ingredient of matter in the universe exists

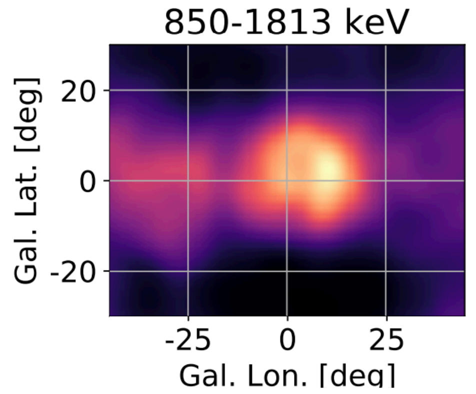
Precise measurement of how much DM is present at cosmological scales (CMB)

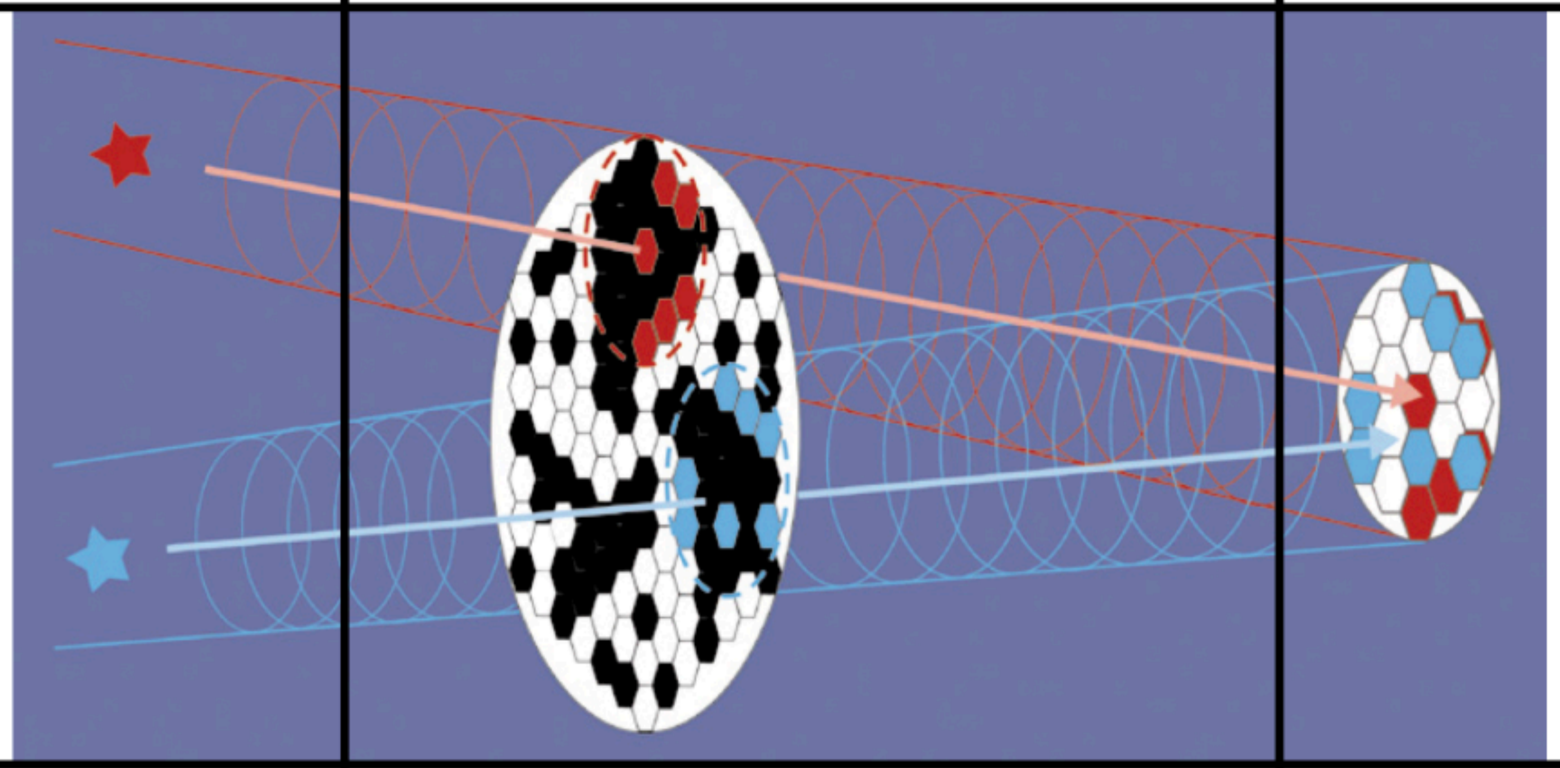
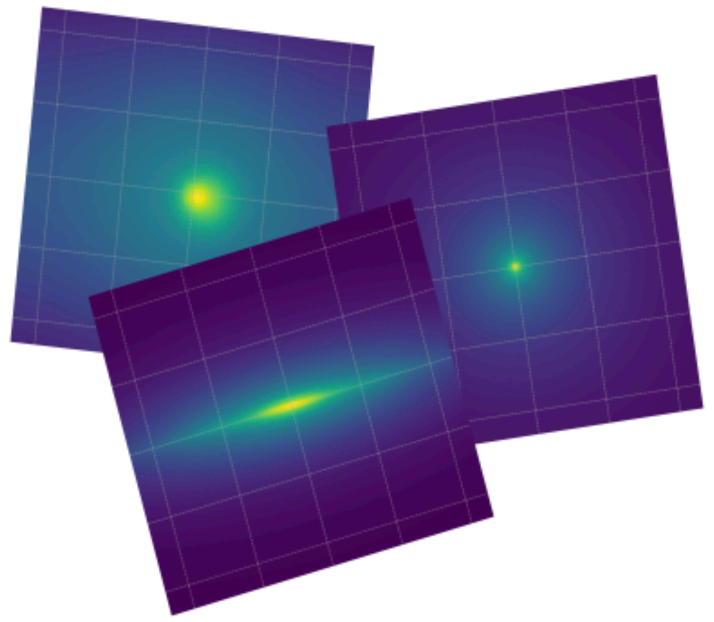
$$\Omega_{\rm CDM} \sim 0.26$$ Planck 2018, 68% CL

Inferred properties that DM should possess point to **new physics** beyond standard theories

Continuum gamma-ray emission

How do we measure the Milky Way diffuse emission?

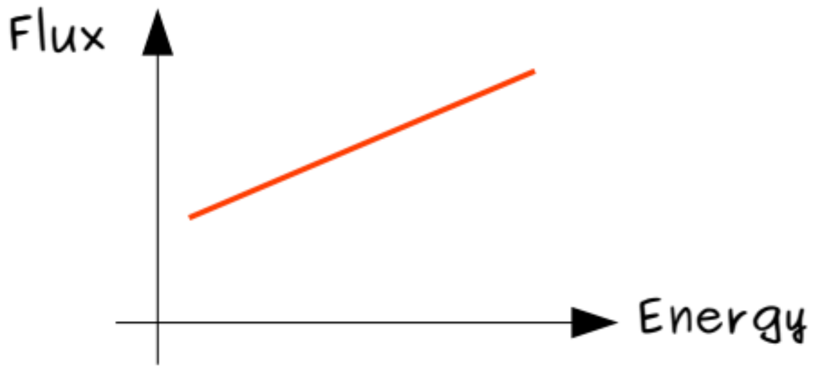


	INPUT	CONVOLUTION	OUTPUT
DATA	Sky		Photons per observation per energy per detector
MODEL	Spatial templates 	SPI coded-mask response function	Time series of expected detector patterns

ROI:
95° x 95° about the Galactic center

← Maximum likelihood fit in each energy bin independently

Total spectrum

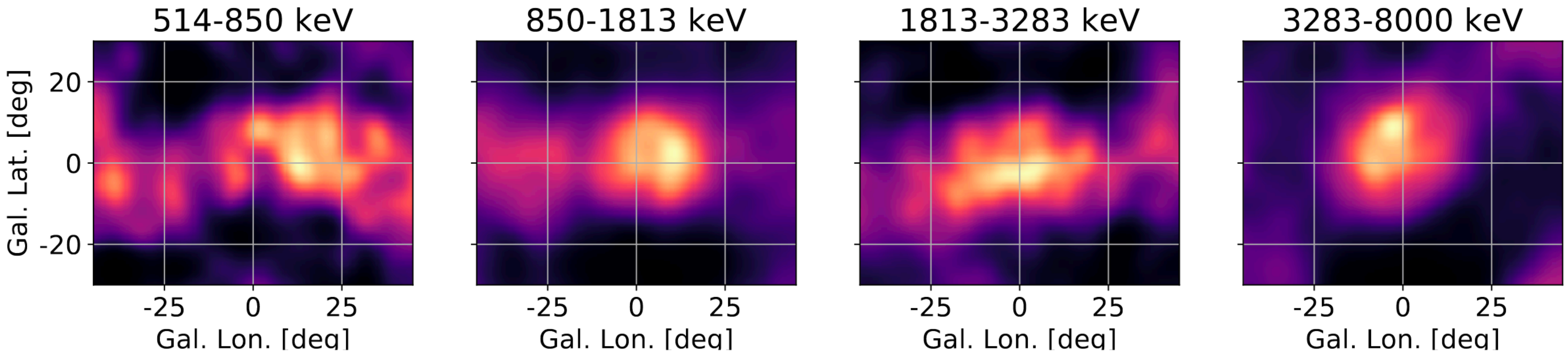


Credit: J. Berteaud, RICAPP'22

Continuum gamma-ray emission

Siegert, FC+ A&A'22

Residual emission after bgk-only model fit



Instrumental CR-induced background dominates by far the SPI detected counts

Residuals from bkg-only fit reveal the presence of correlated large-scale emission, around the Galactic plane