Indirect probes of dark matter

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ISAPP 2024: Particle candidates for dark matter
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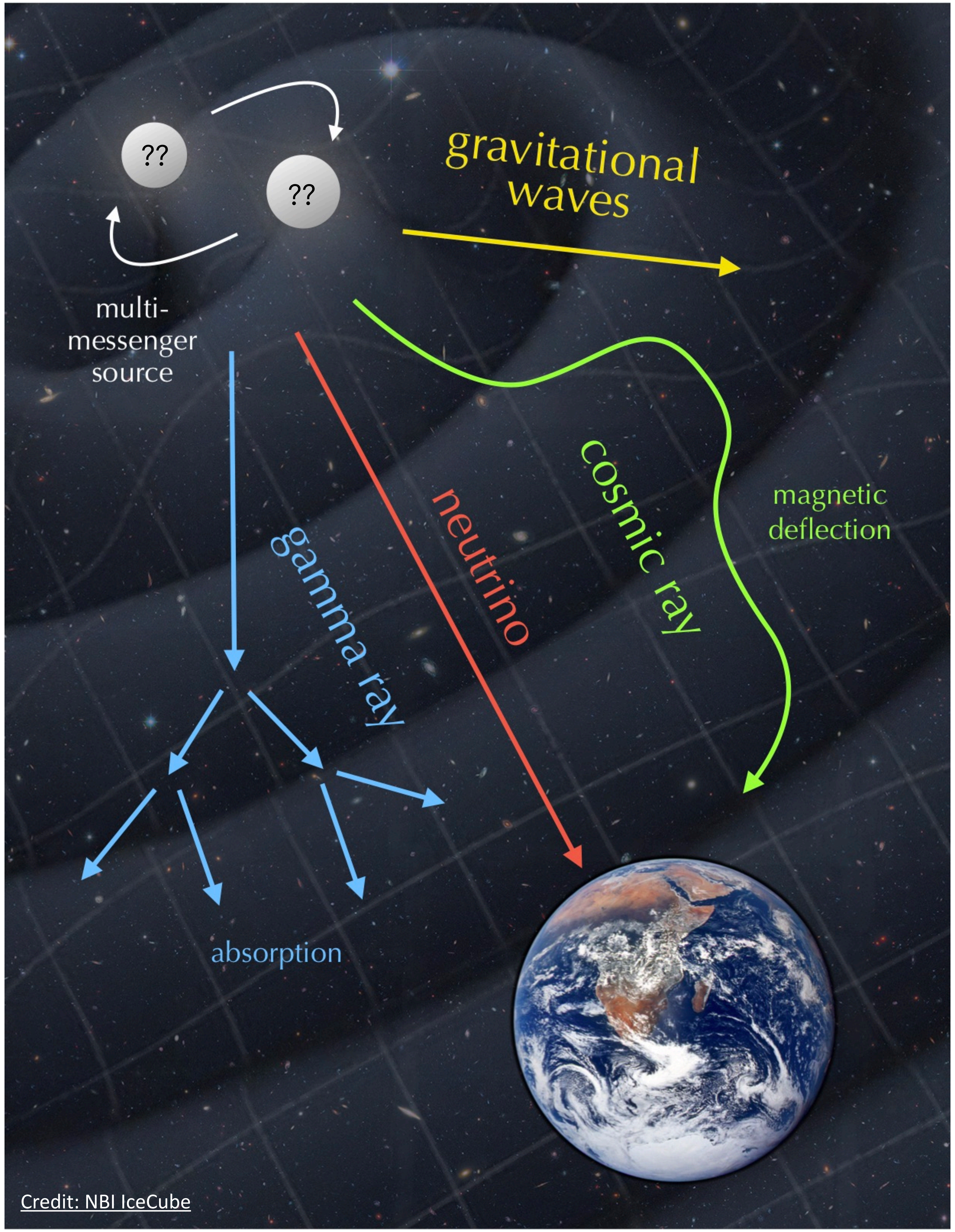
Plan of the lectures

- **Lecture 1**: Particles from the sky: **charged cosmic rays**, **gamma rays** (and **neutrinos**)
  - Basics and jargon
  - Production mechanisms
- **Lecture 2**: Sources of cosmic particles
  - Standard astrophysics
  - Generalities of dark matter searches
- **Lecture 3**: Probing **dark matter** with astroparticle observations
  - **Particle** dark matter
  - **Primordial black holes**
  - Anomalies and **excesses**



Some reading material

M. Longair, *High energy astrophysics*, Cambridge Univ. Press (2012)
V. S. Berezinskii et al., *Astrophysics of cosmic rays*, Amsterdam: North-Hollans (1990)
G. Sigl, *Astroparticle Physics: Theory and Phenomenology*, Atlantis Press Paris (2017)
G. Ghisellini, *Radiative processes in high-energy astrophysics*, Lect. Notes Phys. (2013)
Very good lectures notes: *Foundations of cosmic-ray astrophysics*, Varenna (2022)

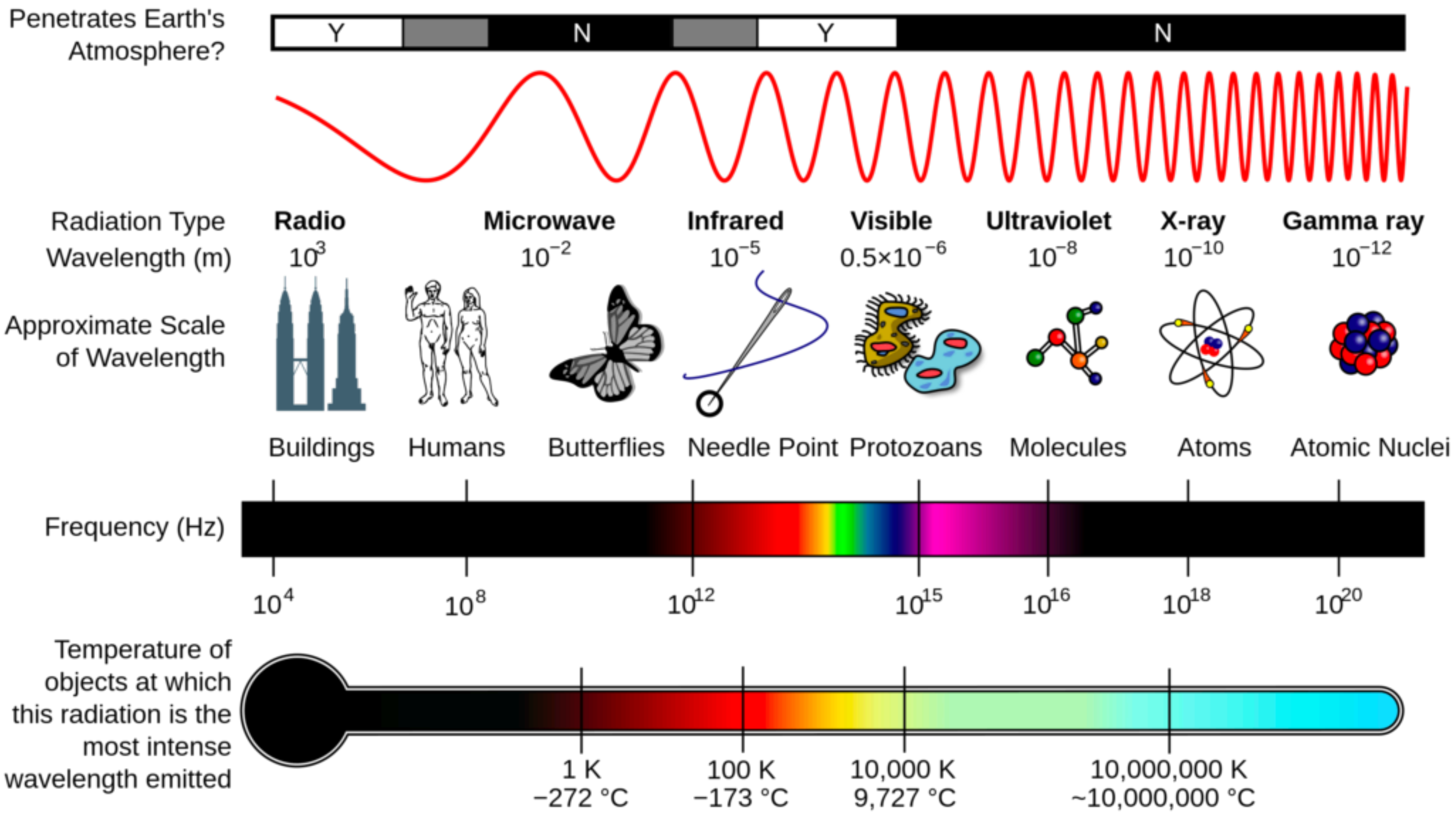
EuCAPT White Paper, *Opportunities and Challenges for Theoretical Astroparticle Physics in the Next Decade*, *arXiv:2110.10074*

EuCAPT

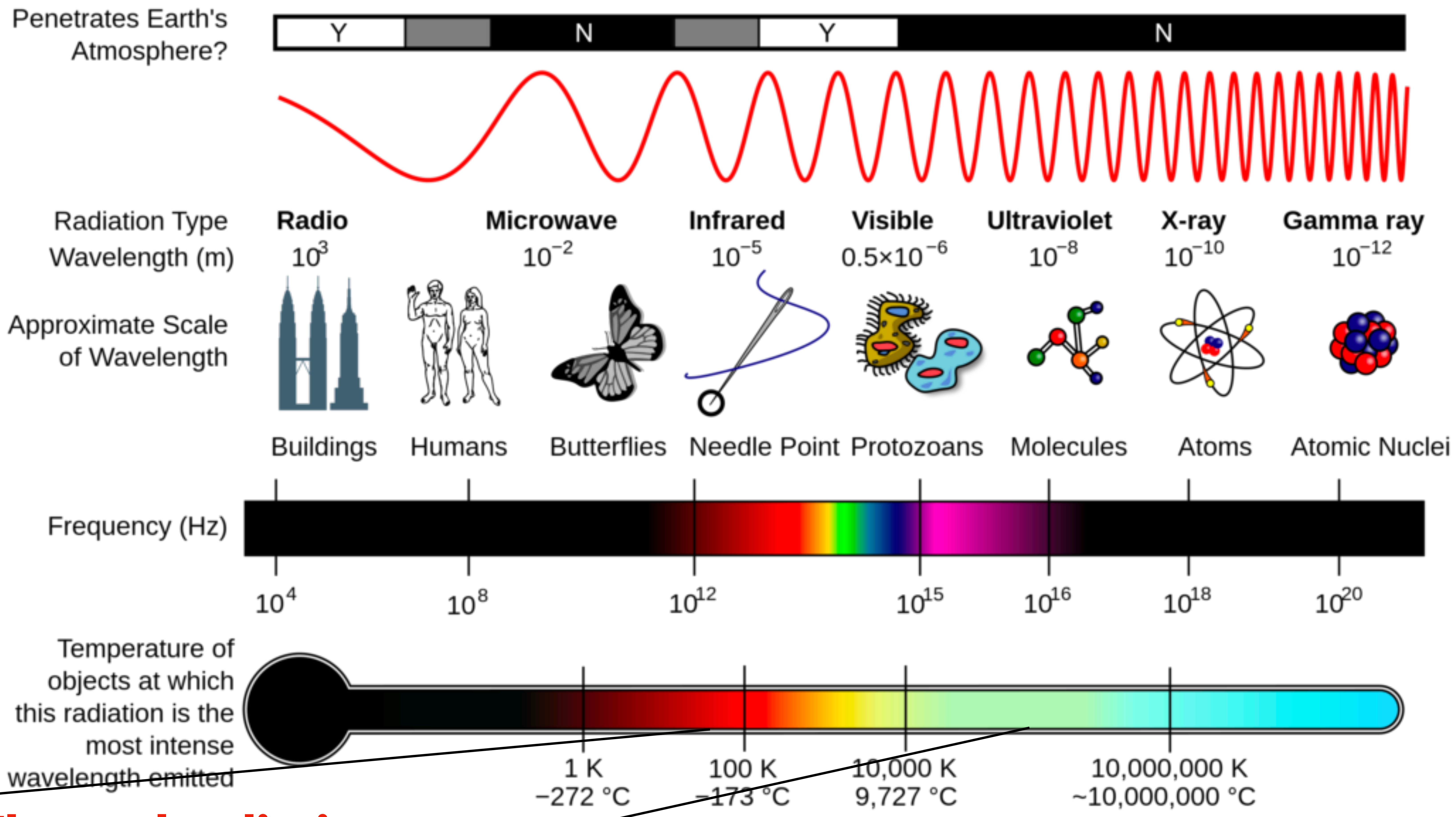
Feel free to email me at calore@lapth.cnrs.fr!

Prolegomena

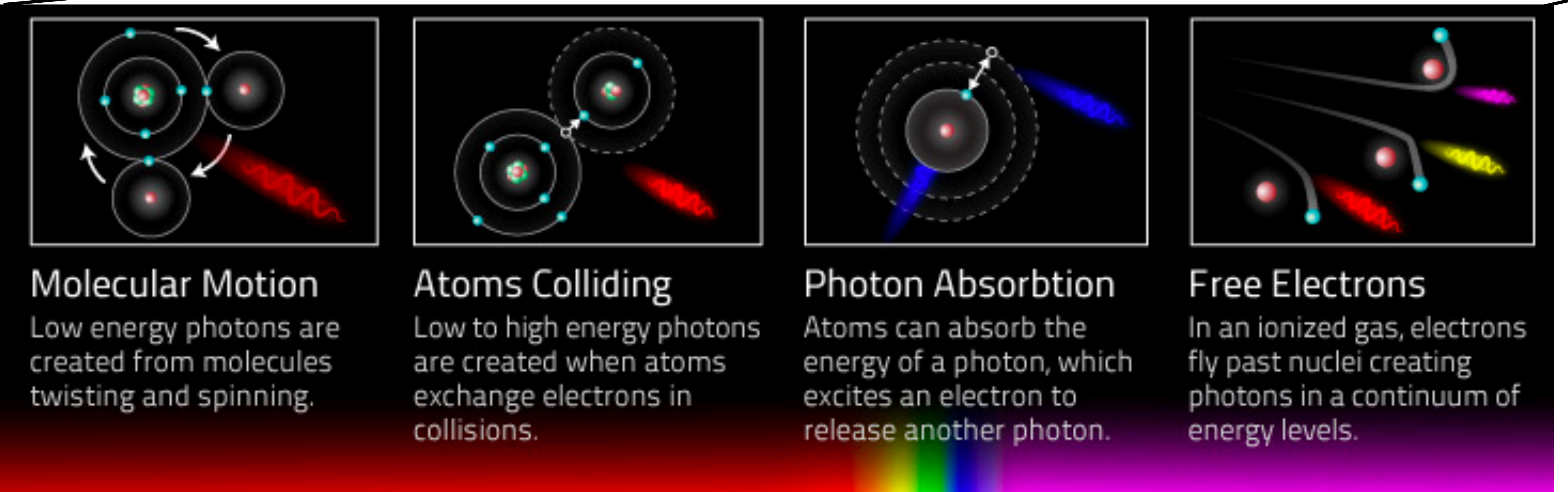
The MW spectrum



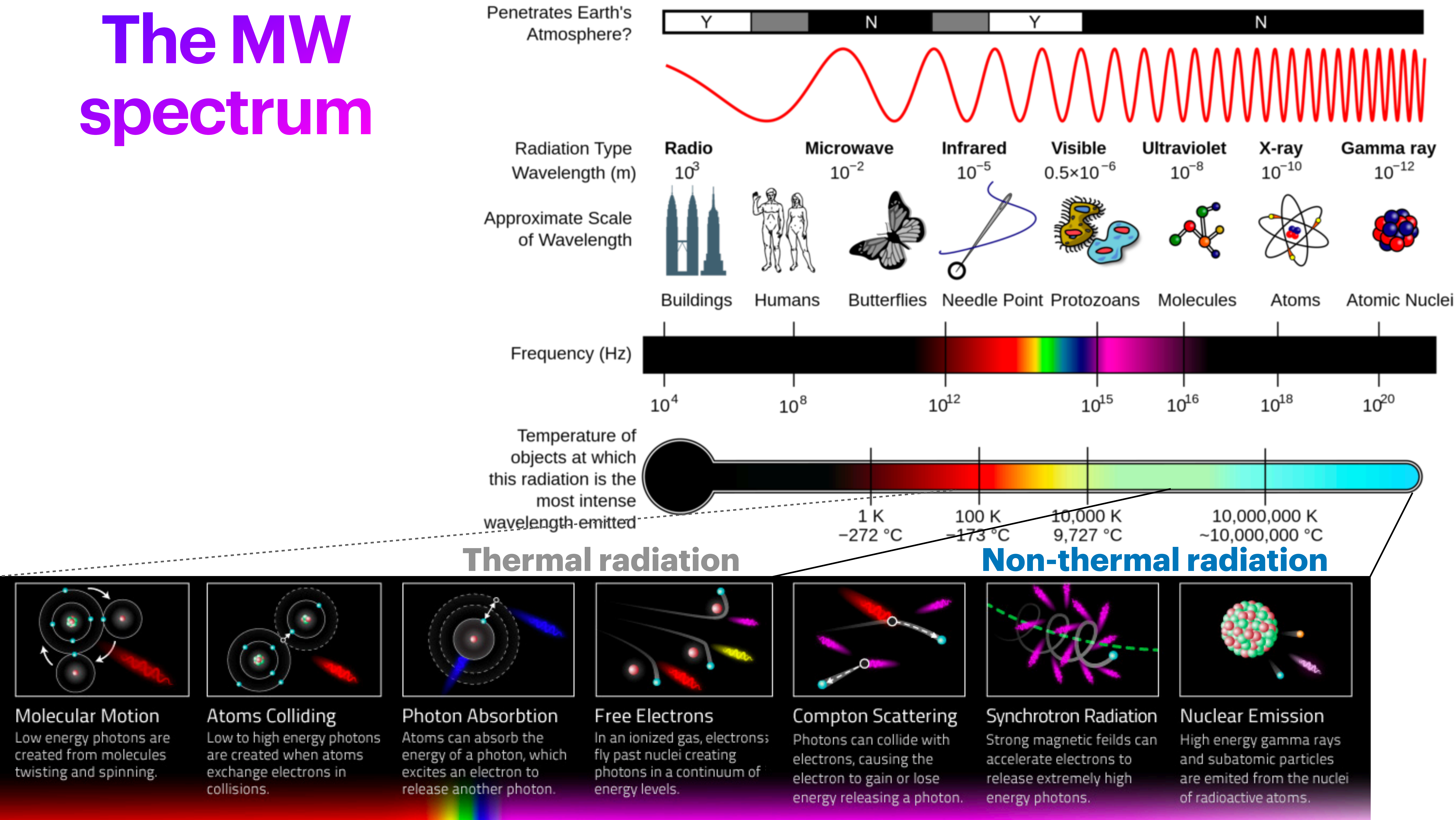
The MW spectrum



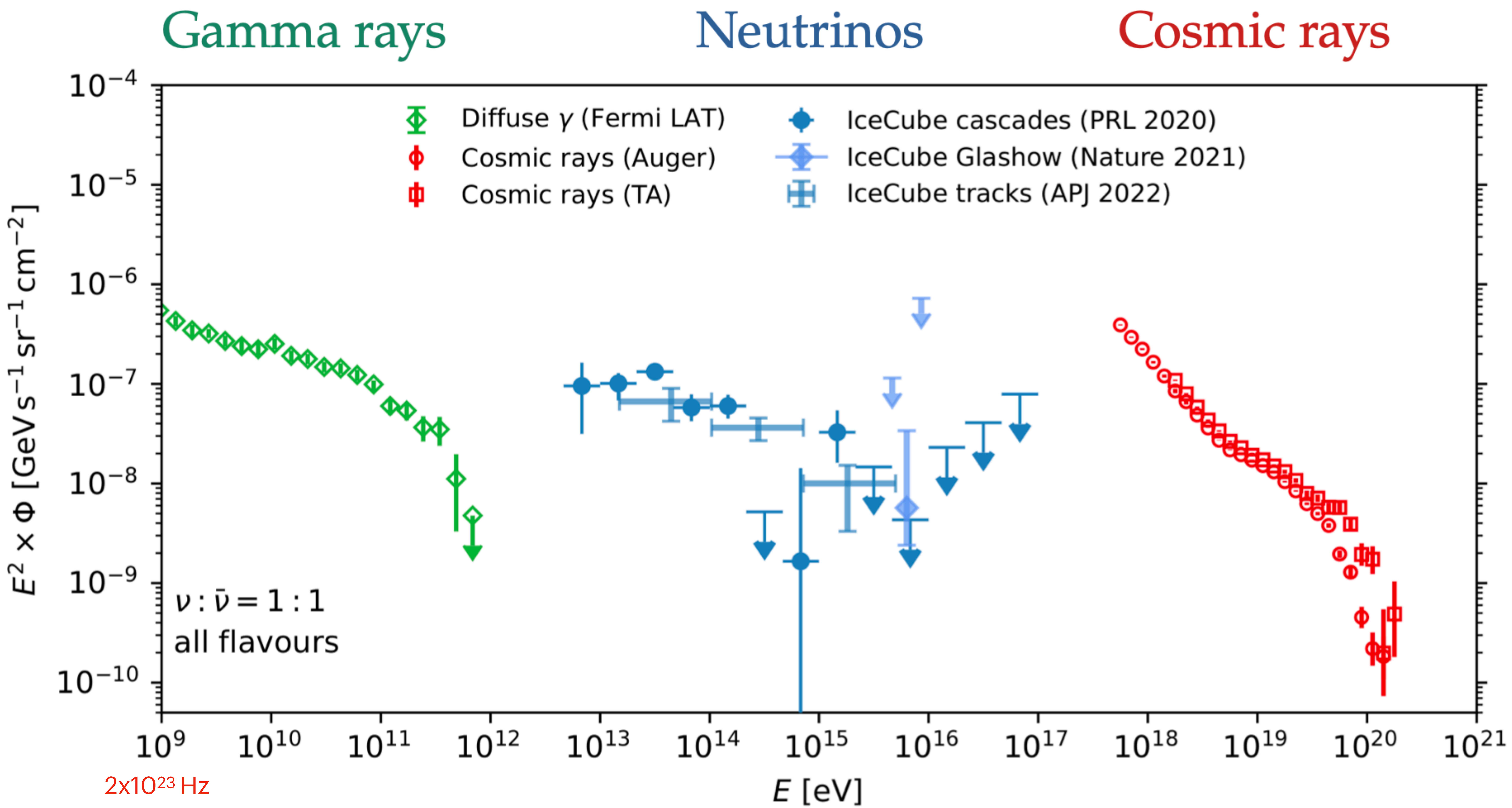
Thermal radiation



The MW spectrum



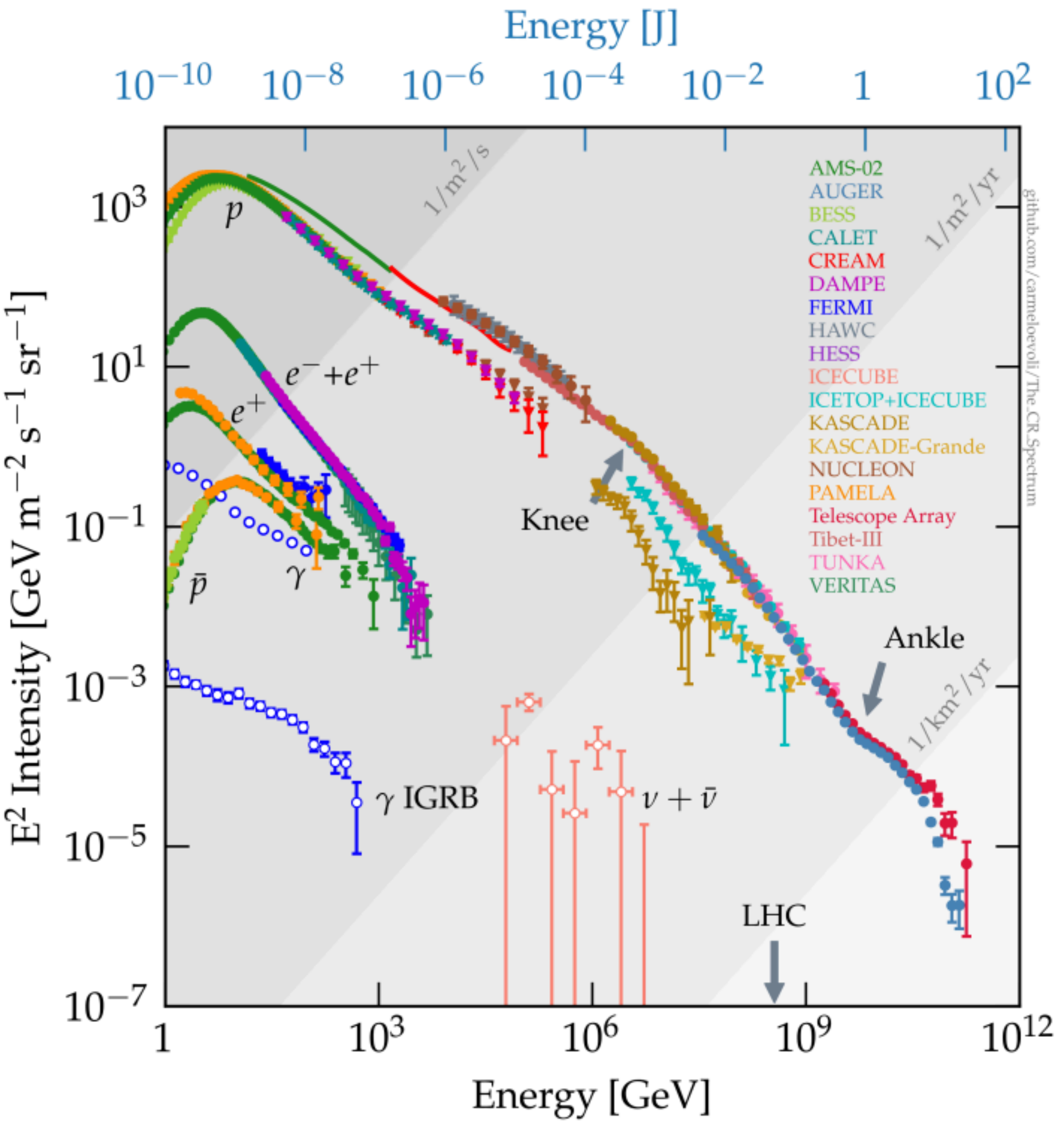
Radio Continuum (408 MHz)
Atomic Hydrogen
Radio Continuum (2.4 - 2.7 GHz)
Molecular Hydrogen
Mid Infrared
Mid Infrared
Near Infrared
Visible
X-Ray
Gamma Ray



M. Ackermann et al., JHEAp 35, 55 (2022) [2203.08096]

Fundamental physics questions

- What is the **origin of charged particles** over this broad energy and flux range?
- How do **particles travel** in inter-stellar and inter-galactic media?
- What is the **nature of cosmic** particle **diffuse fluxes** (photons and neutrinos)?
- Are there **signatures of exotic physics** in astroparticle observations?



Galactic and extragalactic environments

$\lesssim 1\,\mathrm{cm}^{-3}$

Several kpc

~230 Myr
one solar orbit

$1 - 10\,\mu\mathrm{G}$

Extremely rarefied densities of matter

Very large distances and spatial scales

Very long timescales

Magnetised environments

Radiation fields

$\lesssim 10^{-6}\,\mathrm{cm}^{-3}$

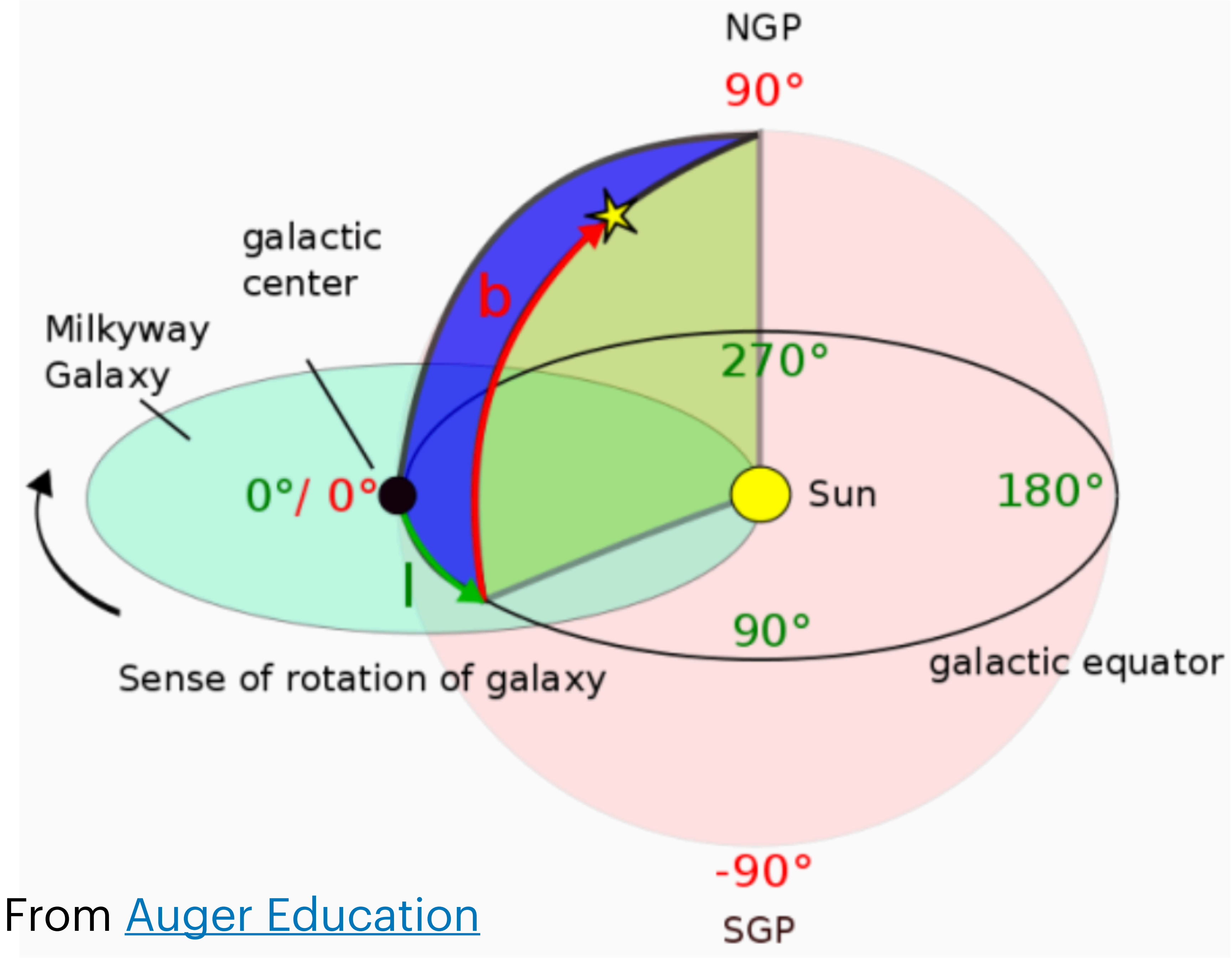
100s Mpc or Gpc

~14 Gyr
age of the universe

$2 - 4\,\mathrm{nG}$

$$1\,\mathrm{pc} \simeq 3.26\,\mathrm{lyr} \simeq 3.086 \times 10^{16}\,\mathrm{m}$$

Galactic coordinate system



From [Auger Education]

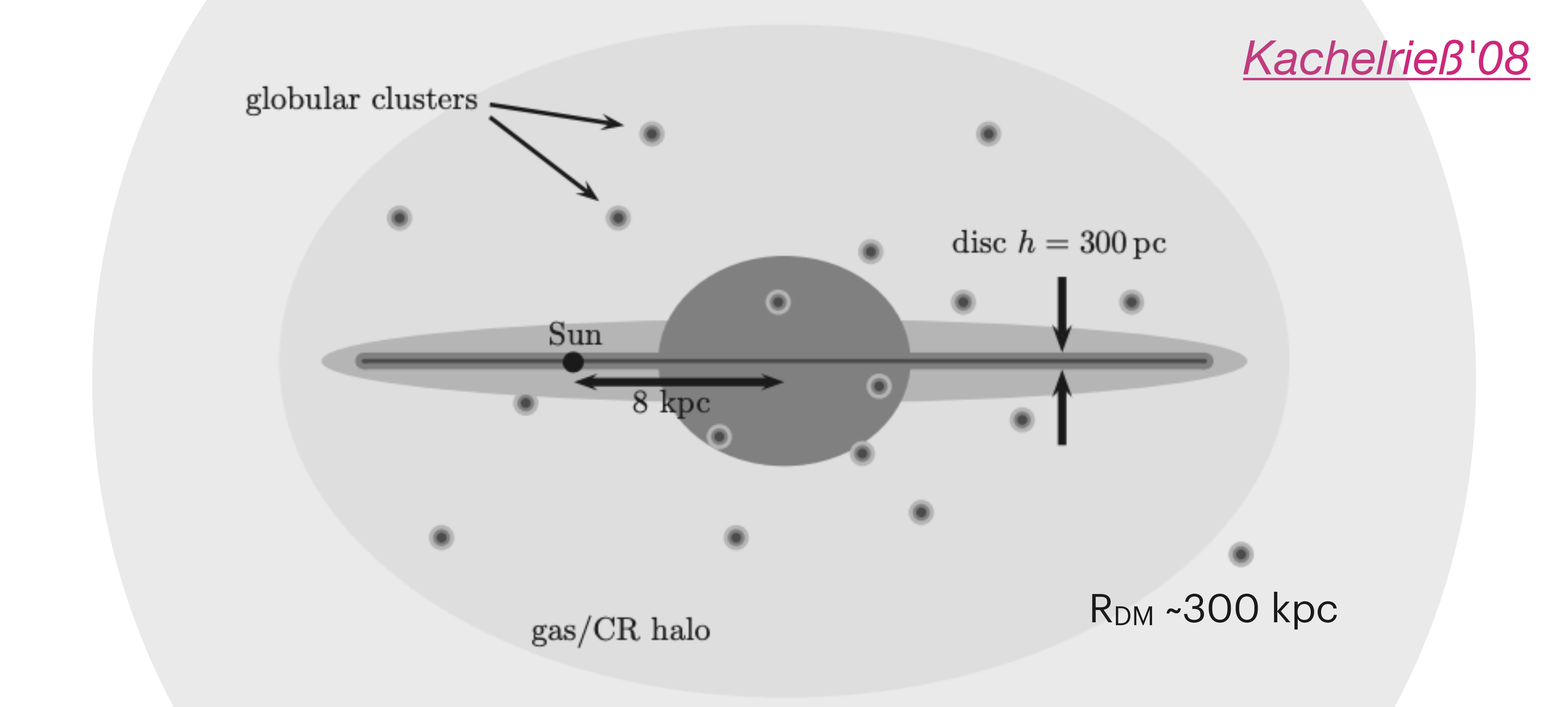


Figure 1.2: Schematic picture of the Milky Way with a gas and dust disc, an extended halo of gas and cosmic rays, surrounded by globular clusters. Everything is immersed in a halo of dark matter.

MILKY WAY ID:

Stars ~ 10^{11} => ~5 x 10^{10} M_{Sun}

Gas ~10% => ~5 x 10^{9} M_{Sun}

Total Mass => ~2 x 10^{12} M_{Sun}

[Conversion algorithms in Astropy]

Some basics: Mean free path

Particle interactions w/ associated **cross—section**

$$\ell = \frac{1}{\sigma\, n}, \quad \Gamma = \sigma\, \beta\, n = \frac{\beta}{\ell}$$

Mean-free path
Avg distance travelled in the medium of density *n* before interacting

Particle **velocity**

Cross-section of the interaction process

Collision rate

Optical depth $\tau = \frac{R}{\ell}$

Some basics: Energy losses

$\frac{d\sigma}{dE}$ Energy transferred in a radiative process

$$\tau_{\text{loss}} \equiv \frac{E}{-\mathrm{d}E/\mathrm{d}t}$$

Loss timescale ← τ_{loss}

$-\mathrm{d}E/\mathrm{d}t$ → **Loss rate** per unit time

Catastrophic losses: Particle disappears or energy transferred to other particle is seizable

$$\tau_{\text{loss}} \sim \Gamma^{-1} \qquad d_{\text{loss}} \sim \text{mfp}$$

Continous losses: Primary particle retains most of its energy and nature

$$\tau_{\text{loss}} \gg \Gamma^{-1} \qquad d_{\text{loss}} \gg \text{mfp}$$

G. Ghisellini, *Radiative processes in high-energy astrophysics*, Lect. Notes Phys. (2013)

Some basics: Energy flux and emissivity

$$S = \frac{dE}{dAdt} \qquad [\frac{\mathrm{erg}}{\mathrm{cm^2 s}}]$$

Energy flux (all rays)

$$I_\nu = \frac{dE}{dAdtd\Omega d\nu} \qquad [\frac{\mathrm{erg}}{\mathrm{cm^2 s\, sr\, Hz}}]$$

Specific intensity

$$j_\nu = \frac{dE}{dV\, dtd\Omega d\nu}$$

Spontaneous emission coefficient

$$j = \frac{P}{4\pi}$$

For isotropic emitter
P = radiated power per unit time, volume [erg/s/cm^3]

$$\epsilon = \frac{dE}{\rho dV\, dt}\,\frac{4\pi}{d\Omega}$$

Angle integrated emissivity

Some basics: Energy and particle flux

$$S(\vec{r}, l, b) = \frac{1}{4\pi}\, \epsilon(\vec{r}, l, b)\, \rho(\vec{r})\, ds\, d\Omega$$

Or

$$S(\vec{r}, l, b) = \frac{1}{4\pi}\, P(\vec{r}, l, b)\, ds\, d\Omega$$

Energy flux

Radiation ⟶ **Particle emission**

$$F(\vec{r}, l, b) = \frac{1}{4\pi}\, q(\vec{r}, l, b)\, ds\, d\Omega$$

Particle (local) emissivity q [#/cm³/s] = production rate/volume element

$$\frac{F(l,b)}{d\Omega} = \frac{1}{4\pi} \int_{los} q(\vec{r}(s), l, b)\, ds$$

$$\boxed{\frac{F(E,l,b)}{d\Omega dE} = \frac{1}{4\pi} \int_{los} \tilde{q}(E, \vec{r}(s), l, b)\, ds}$$

Some basics: Energy and particle flux

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Energy flux

Or

$$S(\vec{r}, l, b) = \frac{1}{4\pi}\,P(\vec{r}, l, b)\,ds\,d\Omega$$

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$$\frac{F(E,l,b)}{d\Omega dE} = \frac{1}{4\pi}\int_{los} \tilde{q}(E, \vec{r}(s), l, b)\,ds$$

Particles and radiation: production mechanisms

Collisional effects & radiative processes

- Photons interactions w/ radiation (**MW connection**) — *Photons*
- Leptons interactions w/ radiation (**MW/MM connection**) — *Photons*
  - ➡ Inverse Compton scattering
  - ➡ Synchrotron radiation
- Leptons interactions w/ matter (Ionisation/bremsstrahlung) — *Photons*
- Hadrons interactions w/ radiation (**MW/MM connection**, extragalactic) — *Photons, neutrinos*
- Hadrons interactions w/ matter (**MW/MM connection**, Galactic) — *Photons, neutrinos*

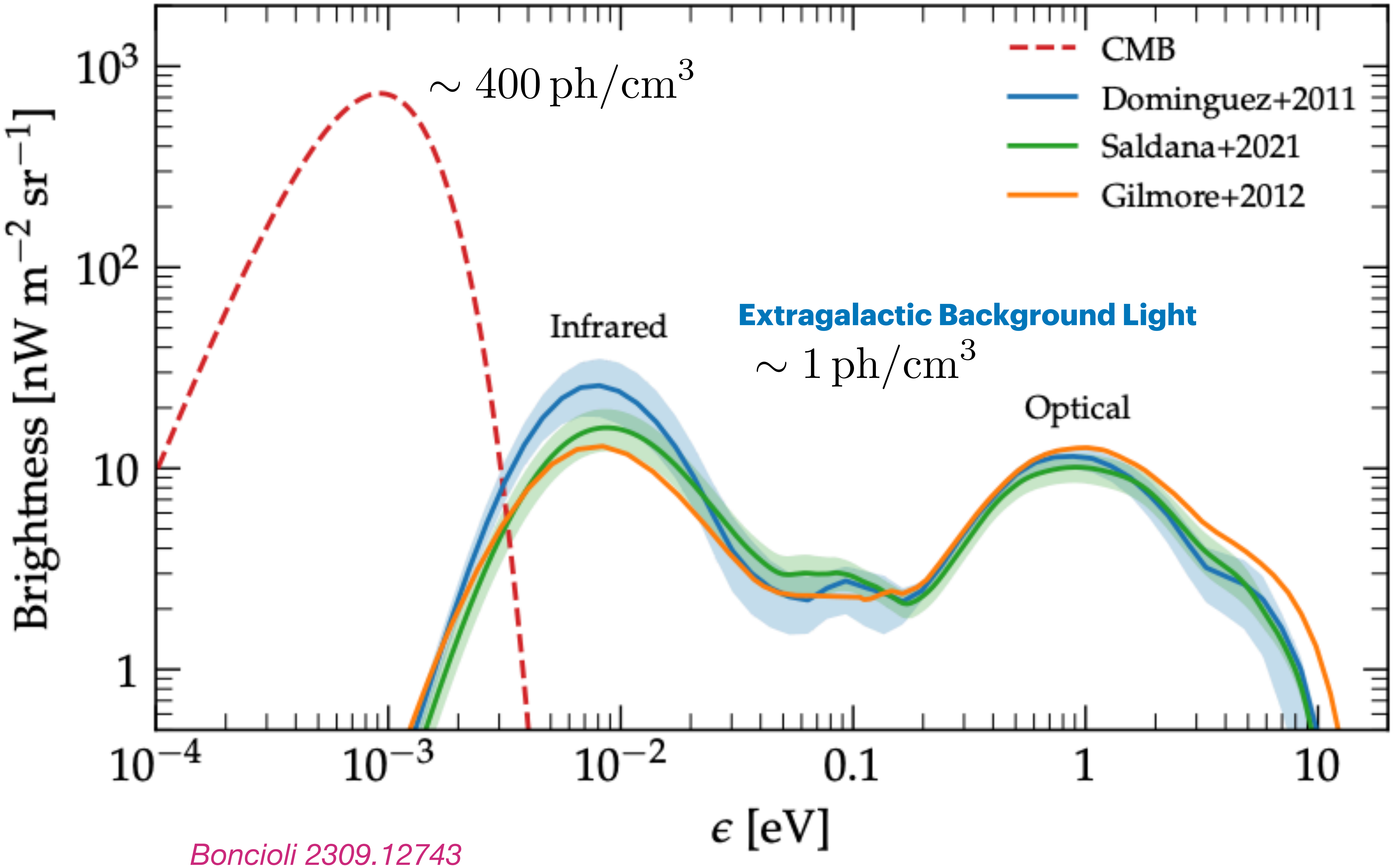
Collisional effects & radiative processes

* Galactic CR
  - prop. timescale ~ Myr
  - $n_{matter} \sim 1/cm^3$
  - CR proton $E = \gamma m_p$ sees photons w/ $E_\gamma \sim \gamma E_\gamma$ ← photon energy in its rest frame → preventing inelastic processes

* Extragal. CR
  - prop. timescale ~ Gyr
  - $n_{matter} \sim 10^{-7}\, n_{matter}^{gal}$
  - $\gamma \gtrsim 10^9$ → interesting kinemat. cal thresholds open up → inelastic processes

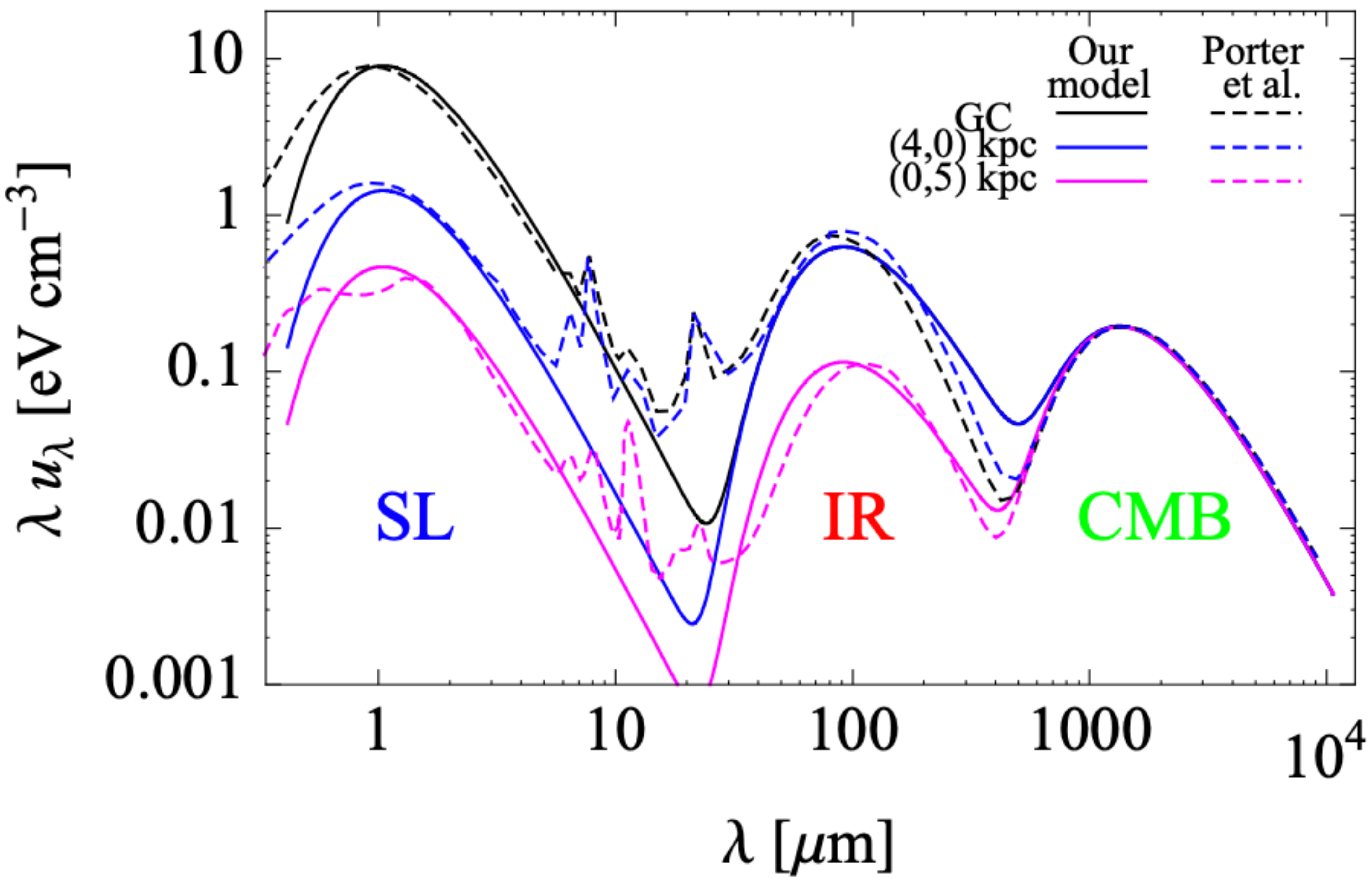
Extragalactic radiation backgrounds

$$\nu I_\nu \equiv \frac{c}{4\pi}\epsilon^2\frac{dn}{d\epsilon}$$



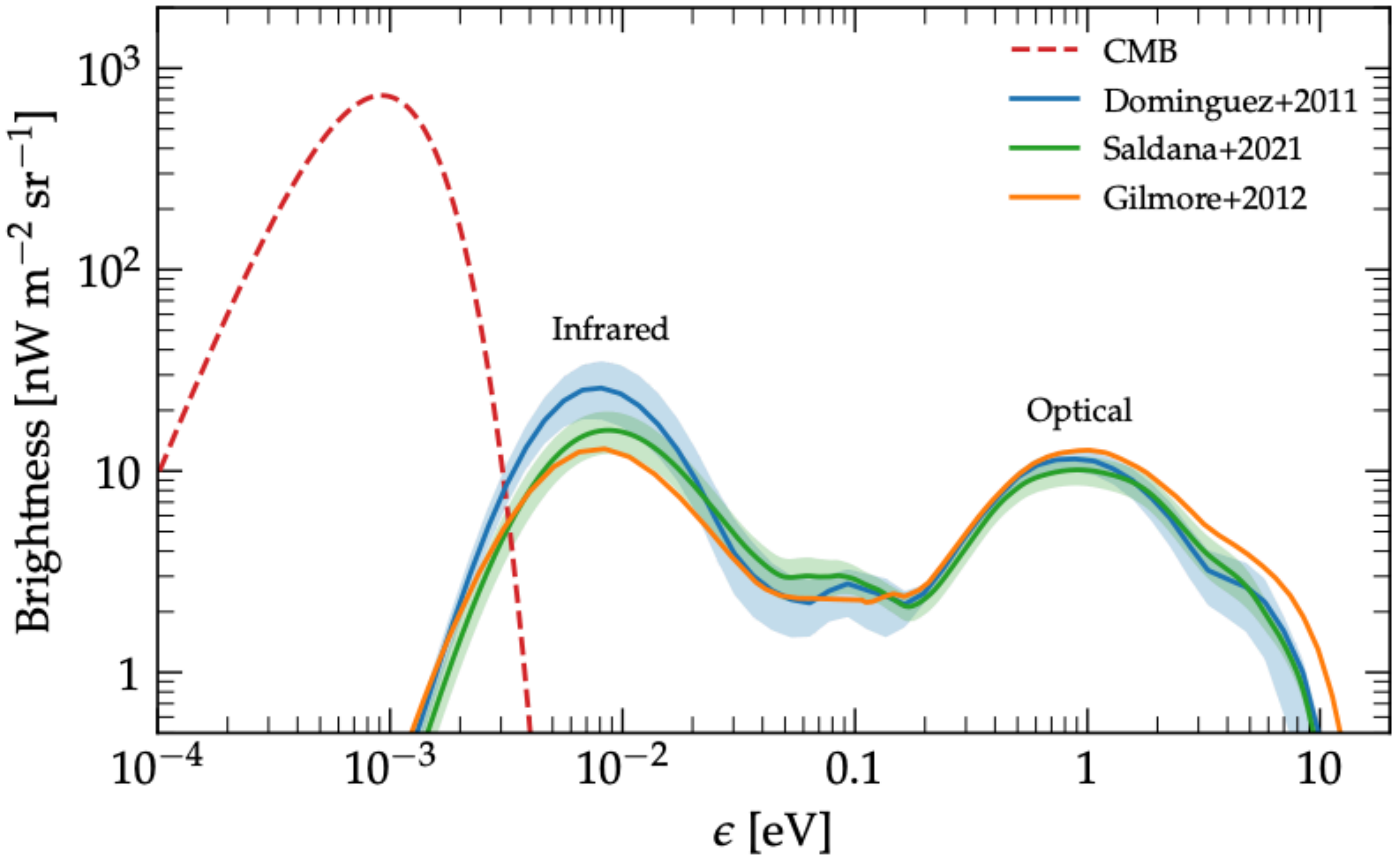
Boncioli 2309.12743

Galactic radiation backgrounds



Cirelli & Panci 0904.3830

Pair production



Pair-production

$$\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{EBL}} \rightarrow e^+ + e^-$$

From invariance of *s*, COM energy

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

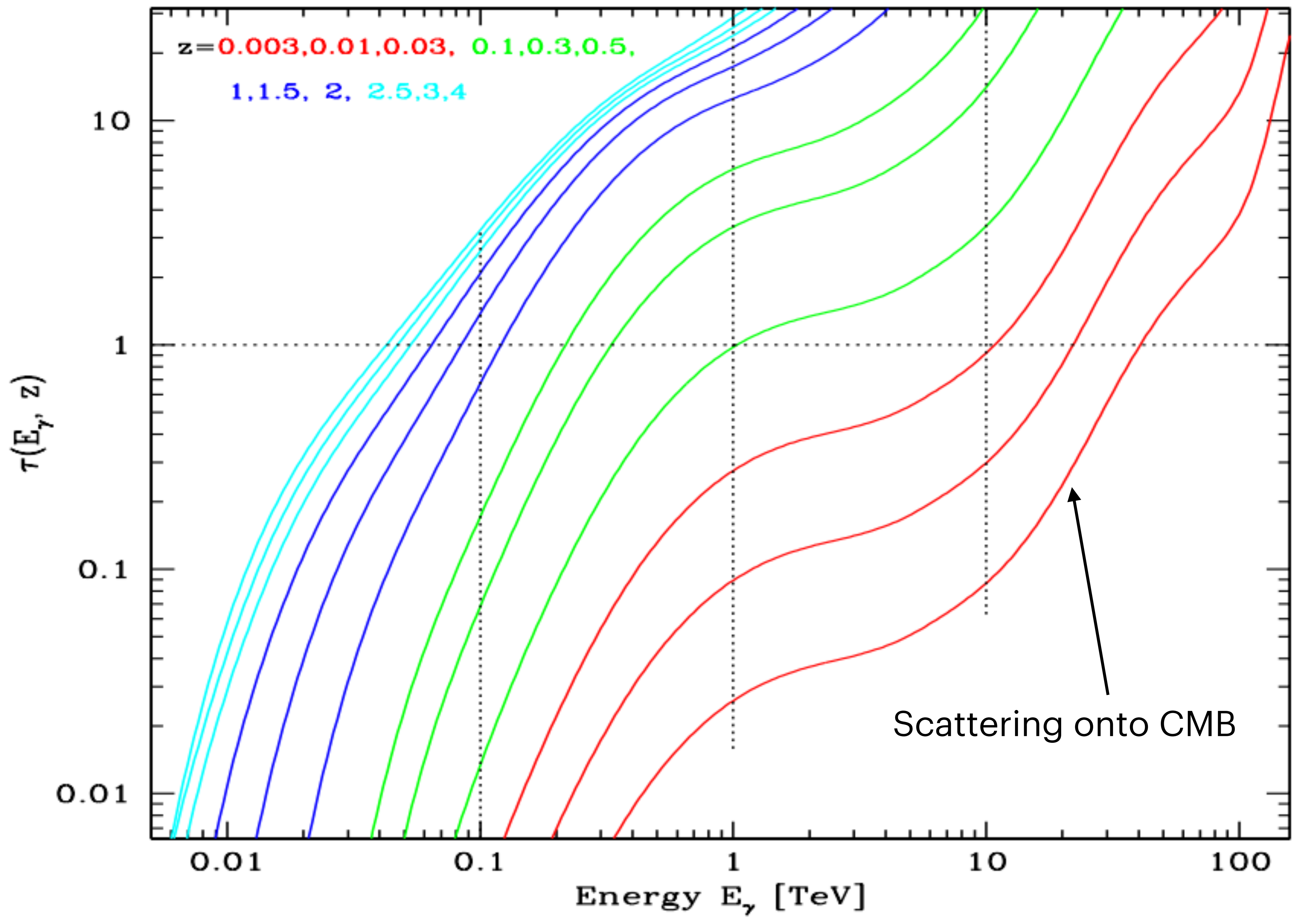
in cosmological coving frame

EBL absorption of VHE photons

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

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

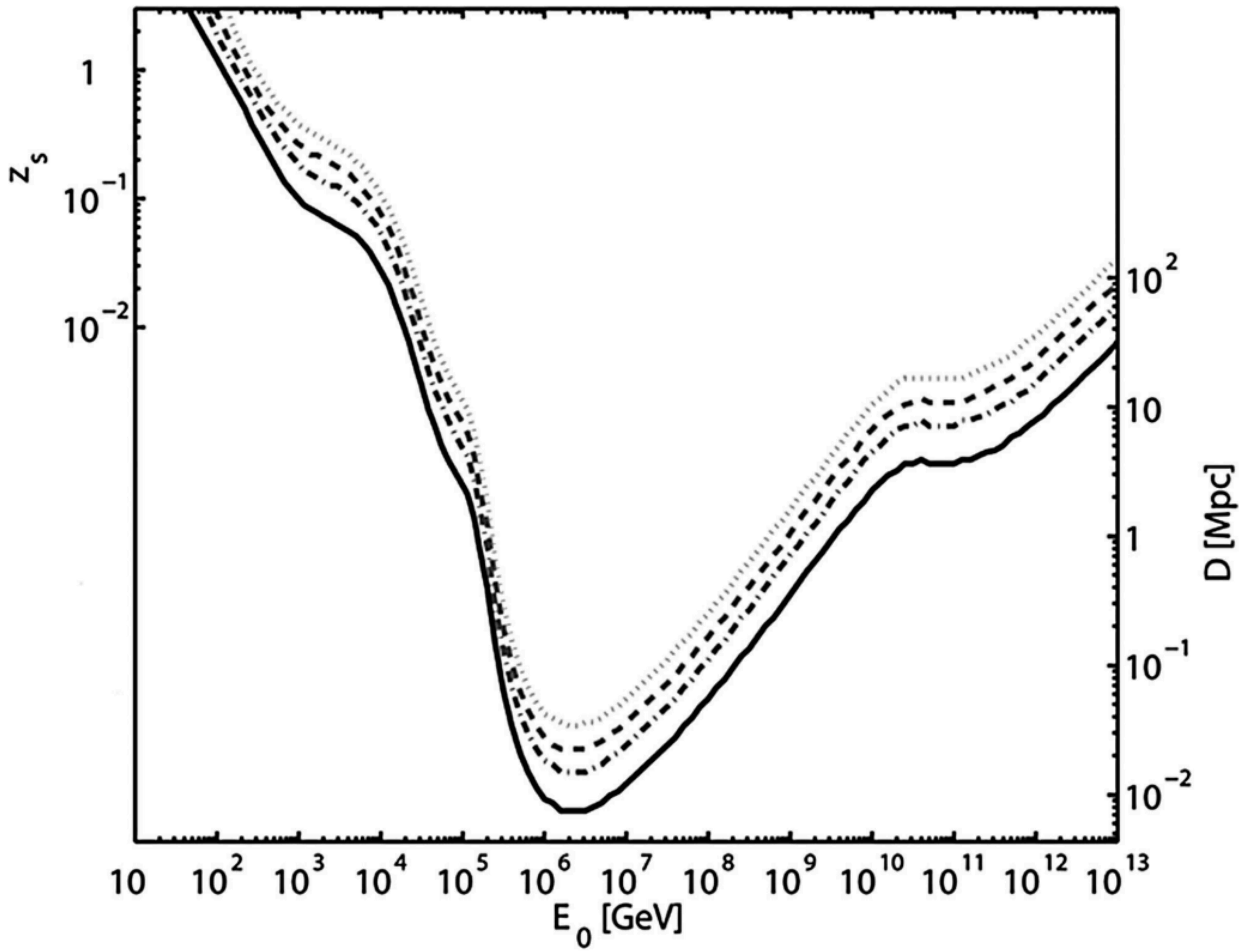
Franceschini Universe'21



Gamma-ray cosmic horizon

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

De Angelis+MNRAS'13

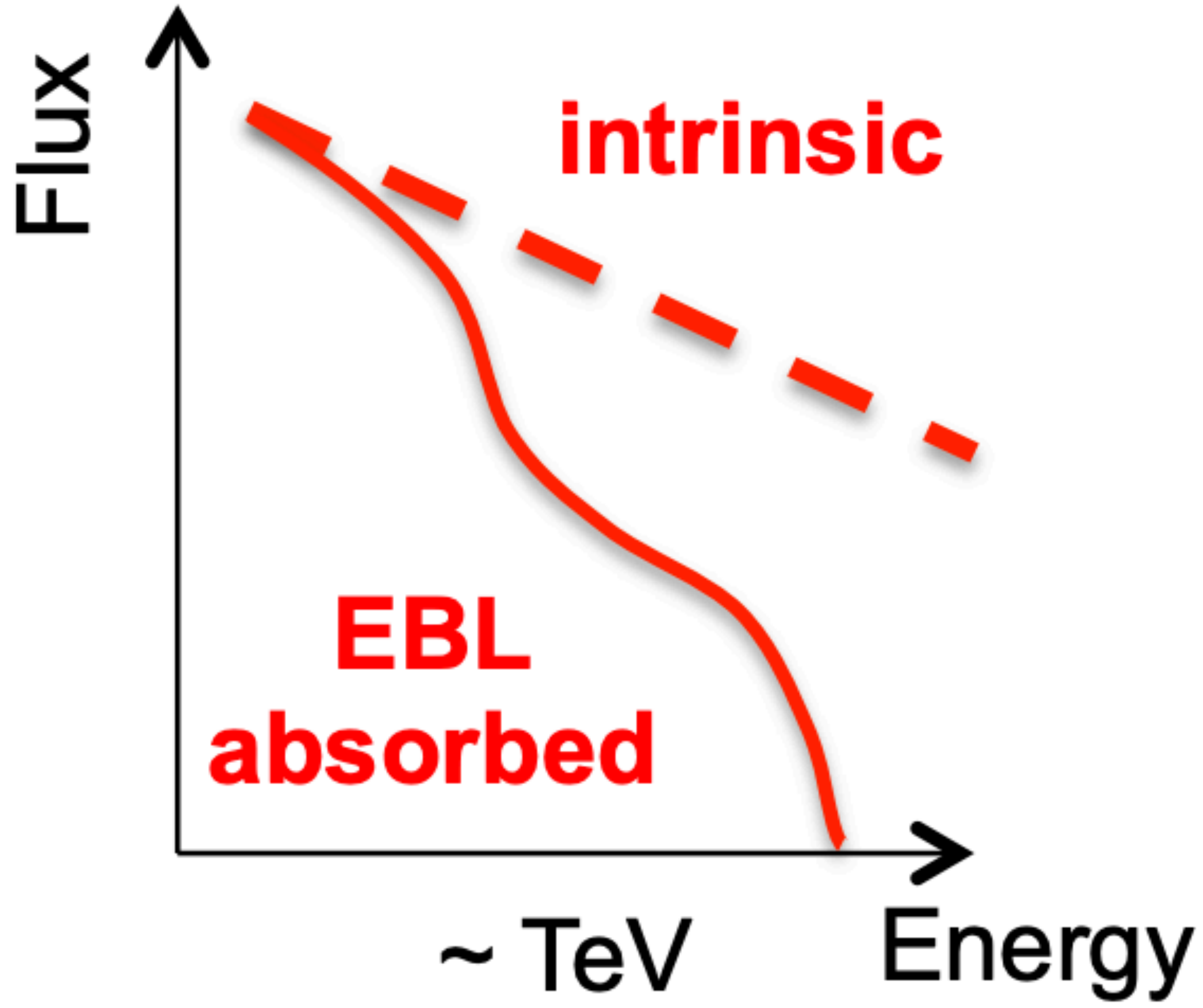


EBL absorption of VHE photons

Photon survival probability

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

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

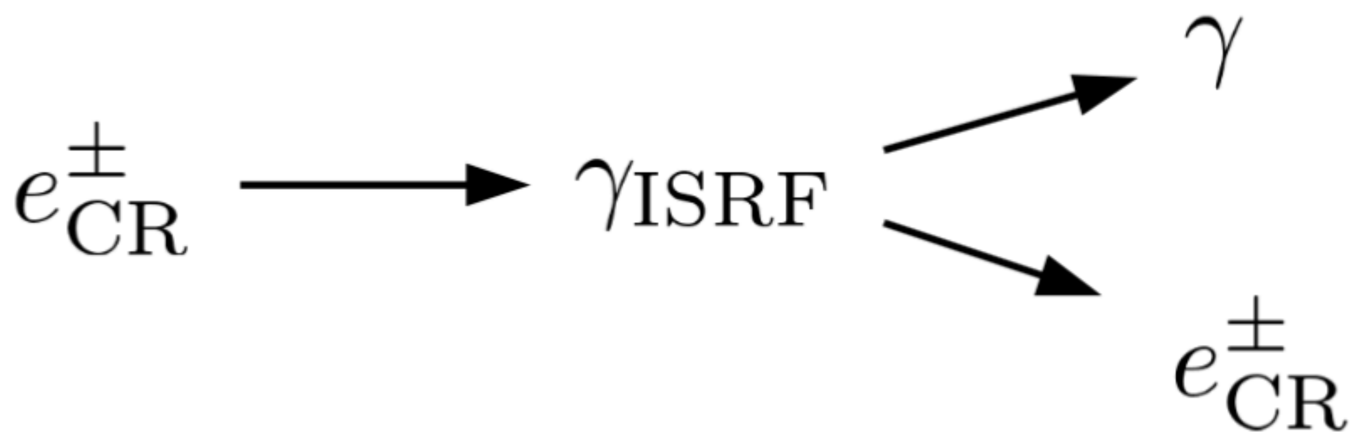


$$\Phi(E_\gamma, z_s) = \Phi(E_\gamma) \times e^{-\tau(E_\gamma, z_s)}$$

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

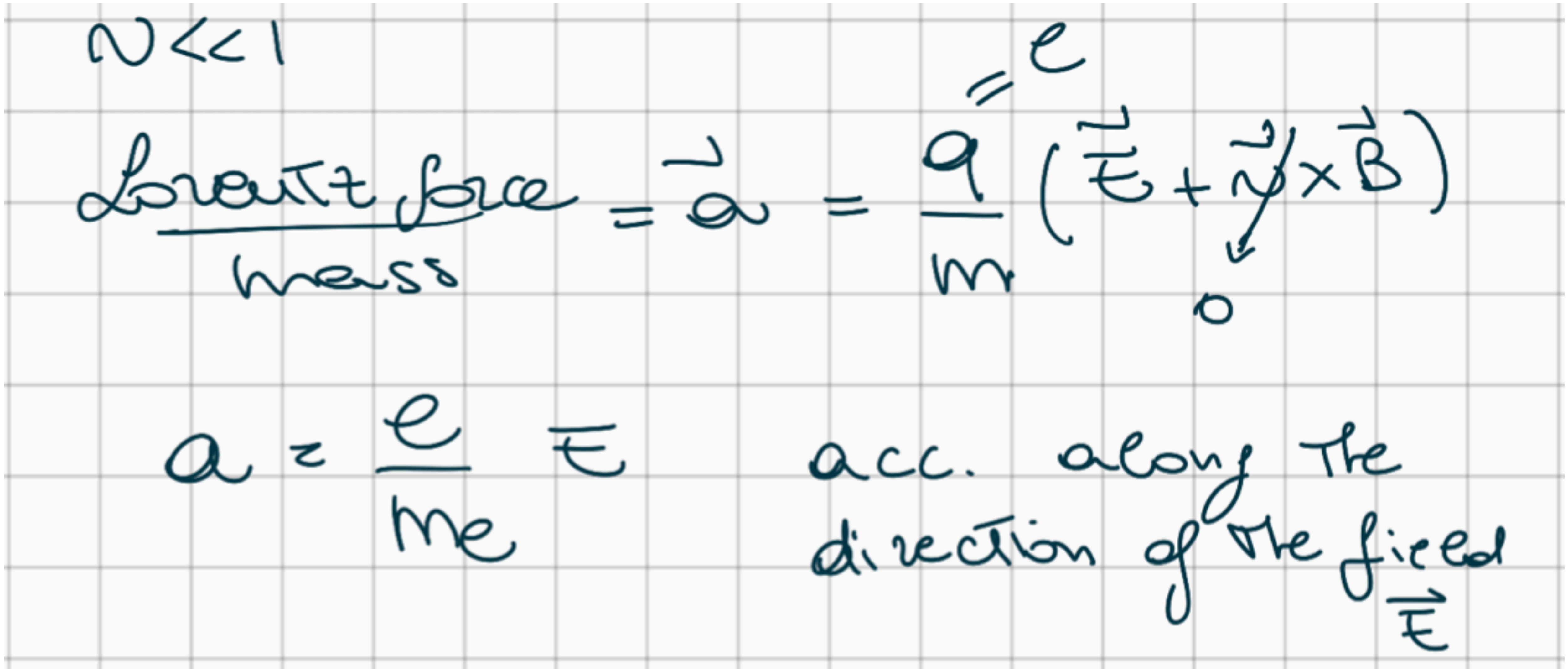
$$E_{\gamma,\mathrm{cutoff}}(z_s) \sim 800\,(1 + z_s)^{-2.4}\,\mathrm{GeV}$$

Inverse Compton scattering

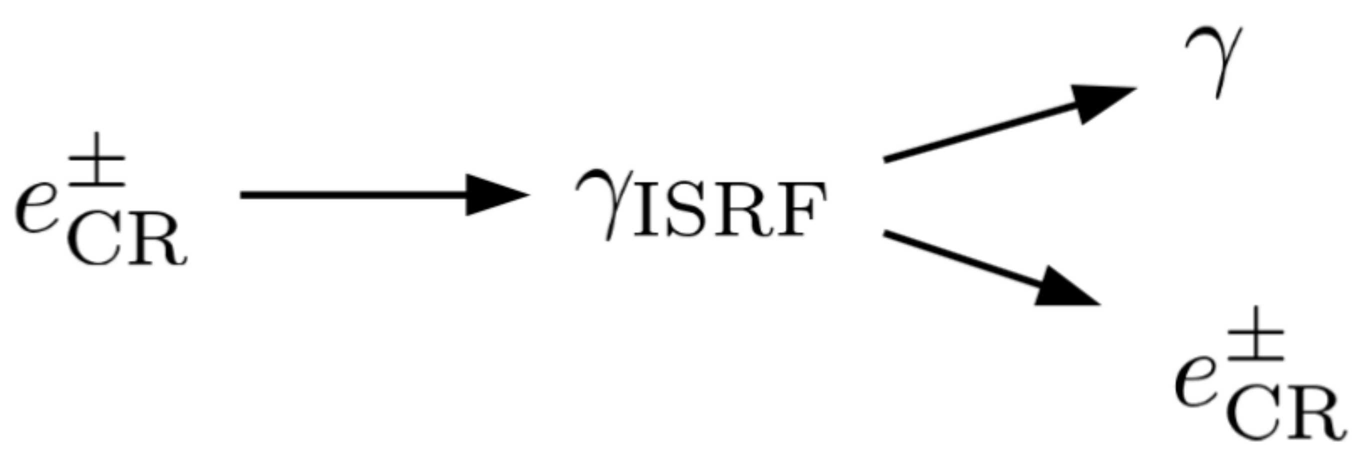


Classical treatment: Interaction of an e.m. wave w/ charged particles

- Electron subject to incoming e.m. wave is accelerated



Inverse Compton scattering



Classical treatment: Interaction of an e.m. wave w/ charged particles

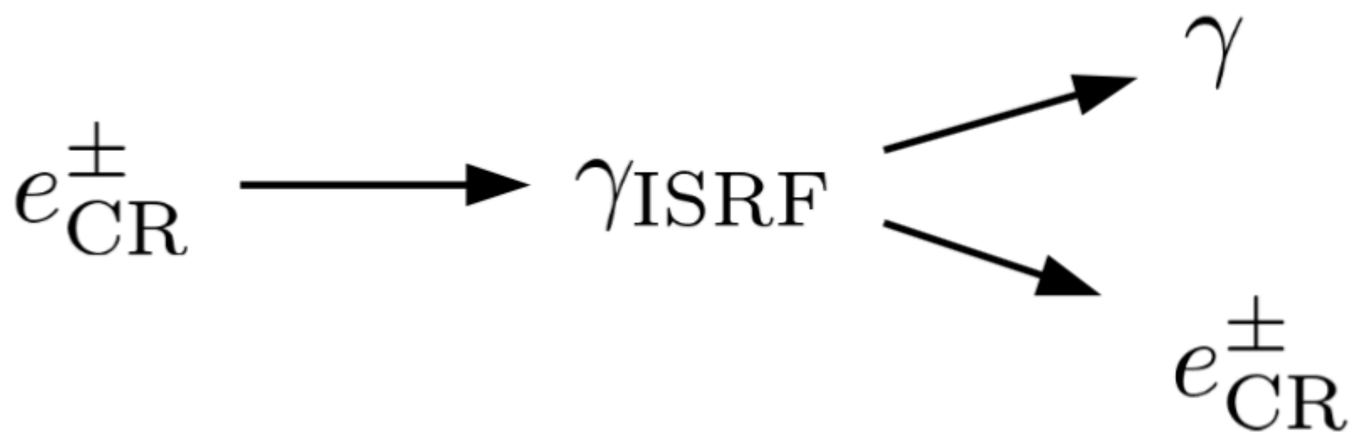
- Power re-emitted by the electron is described by the **Larmor formula**

$$\langle P \rangle = \frac{2}{3}\frac{e^4}{m_e^2}\frac{E_0^2}{2}$$

$\langle P \rangle$ ↓ Time averaged

[NB: Inefficient for nuclei]

Inverse Compton scattering



Classical treatment: Interaction of an e.m. wave w/ charged particles

- **Cross-section** in the **Thomson limit**

$$\epsilon_{\rm ph} \ll m_e$$

$\sigma \equiv \sigma_T$ Thomson cross-section $\sim 6.65 \cdot 10^{-25}$ cm^2

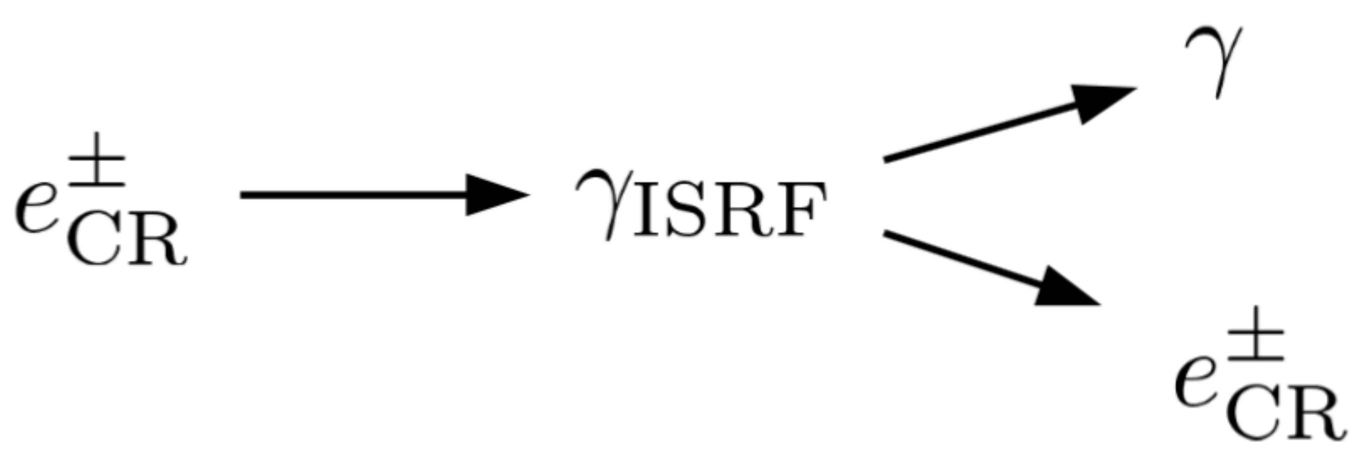
- **Energy-loss rate** (per particle) or **total IC power** is

$$P_{IC} = \frac{4}{3} \sigma_T c \beta^2 \gamma^2 u_{\rm rad}$$

$$[P_{IC}] = \text{erg/s}$$

[NB: Same for synchrotron with magnetic energy density]

Inverse Compton scattering



Classical treatment: Interaction of an e.m. wave w/ charged particles

- **Energetics** of outgoing photons

$$E_\gamma \simeq \gamma^2 \varepsilon \quad ; \quad \varepsilon E_e \ll m_e^2$$

$$E_\gamma \simeq 30 \left(\frac{\varepsilon}{eV}\right)\left(\frac{E_e}{GeV}\right)^2 \ MeV$$

typical photon fields in the Galaxy

- CMB $\varepsilon \sim 2.35 \cdot 10^{-4}$ eV
- IR $\varepsilon \sim 3.45 \cdot 10^{-3}$ eV
- OPT $\varepsilon \sim 0.3$ eV

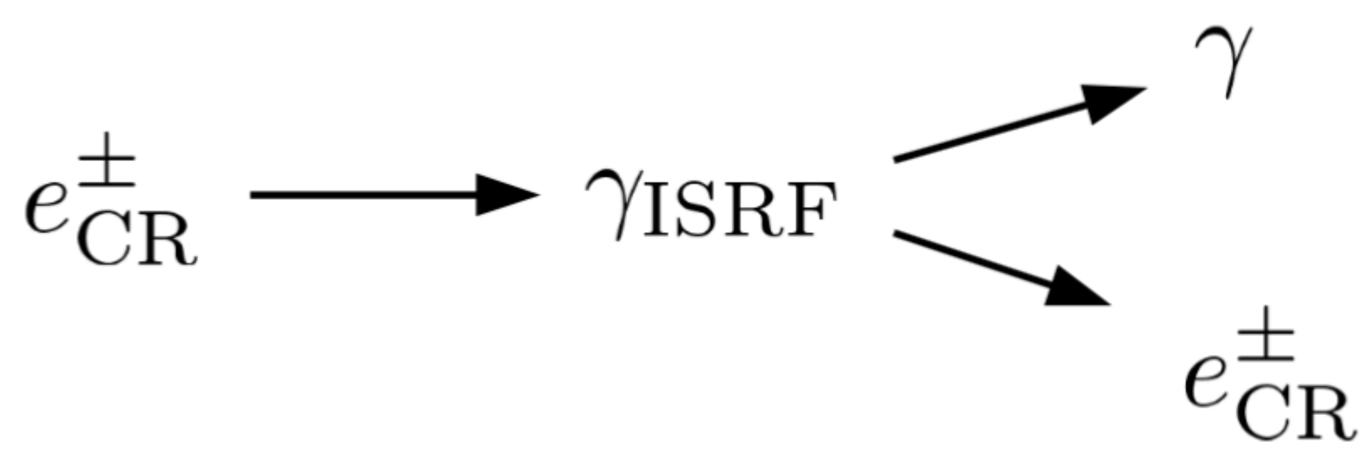
$\Rightarrow$ $E_\gamma^{CMB} \sim 7 \cdot 10^{-3}$ MeV $\sim$ keV

$E_\gamma^{IR} \sim 0.1$ MeV

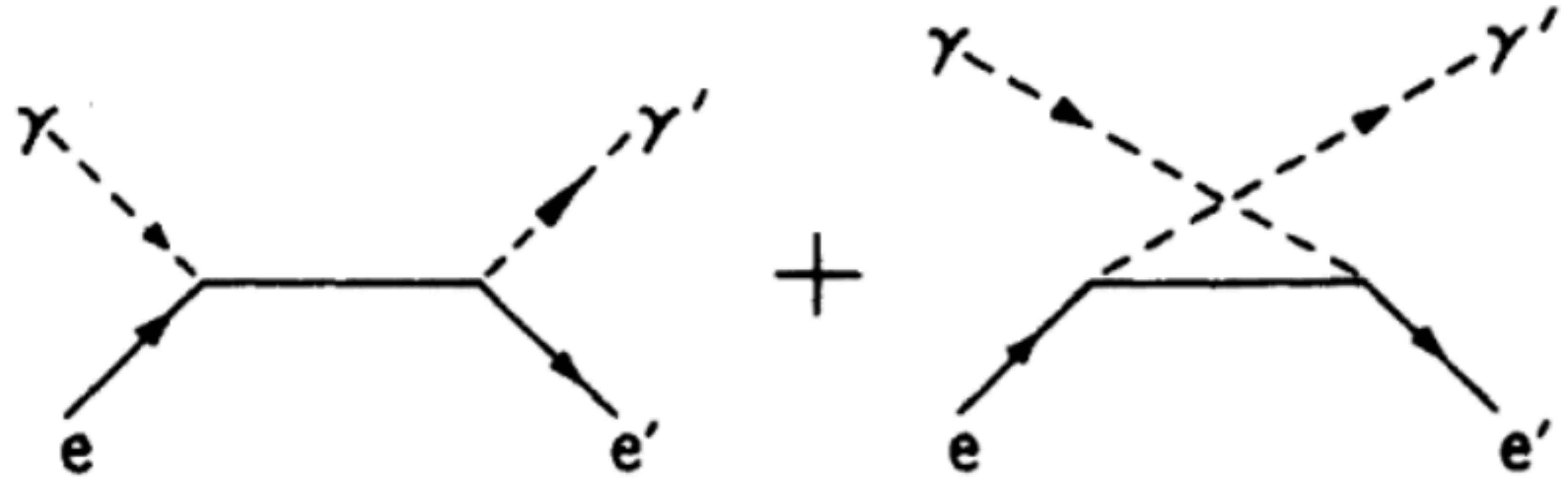
$E_\gamma^{OPT} \sim 9$ MeV

scattering probability : $\sigma(\varepsilon)$

Inverse Compton scattering



Fully relativistic treatment

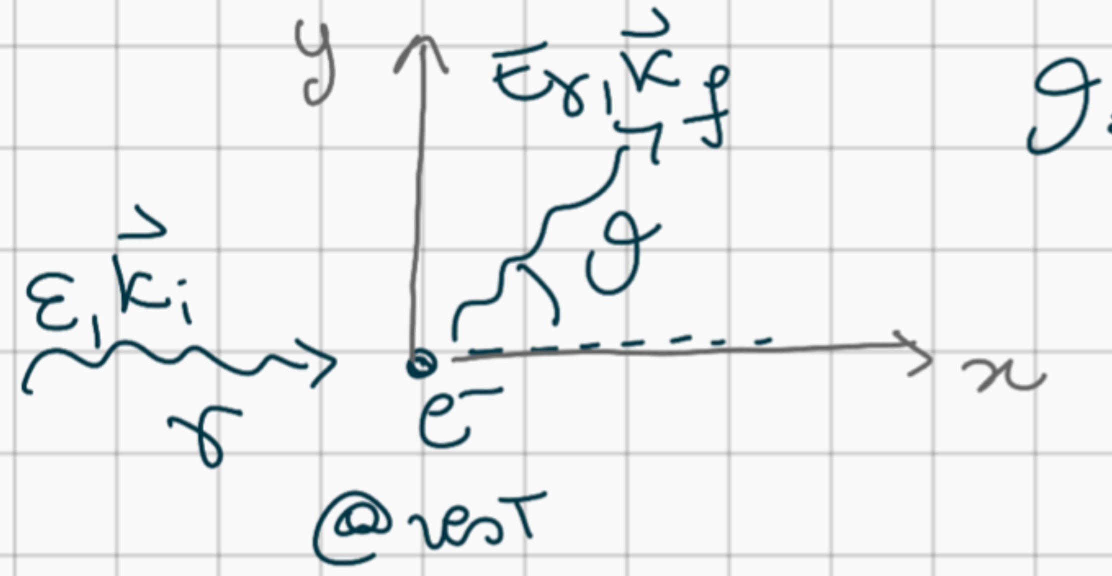


Klein-Nishina process: tree-level electron photon scattering in QED

$$\frac{d\sigma}{d\Omega} = \frac{3}{16\pi}\sigma_T\left(\frac{E_\gamma}{\varepsilon}\right)^2\left[\frac{\varepsilon}{E_\gamma} + \frac{E_\gamma}{\varepsilon} - \sin^2\vartheta\right]$$

$$\sigma = 2\pi\int_0^\pi \frac{d\sigma}{d\Omega}\sin\vartheta\, d\vartheta \equiv \sigma_{KN}(x)$$

$$x \equiv \frac{\varepsilon}{m_e}$$



$$\vartheta = \vartheta(\varepsilon, E_\gamma)$$

Galactic Inverse Compton emission

Dominant production mechanism of photons ~MeV - GeV energies

$$\tilde{q}(\vec{r}, E_\gamma) = 4\pi \int d\varepsilon \, \frac{dn}{d\varepsilon}(\varepsilon, \vec{r}) \times \int dE_e \, \frac{d\sigma_{IC}}{dE_\gamma}(E_e, \varepsilon, E_\gamma) \times \Phi_e(E_e, \vec{r})$$

$\tilde{q}(\vec{r}, E_\gamma)$ = local emissivity $\left[\frac{1}{\mathrm{cm}^3 \, \mathrm{erg} \, \mathrm{s}}\right]$

Galactic Inverse Compton emission

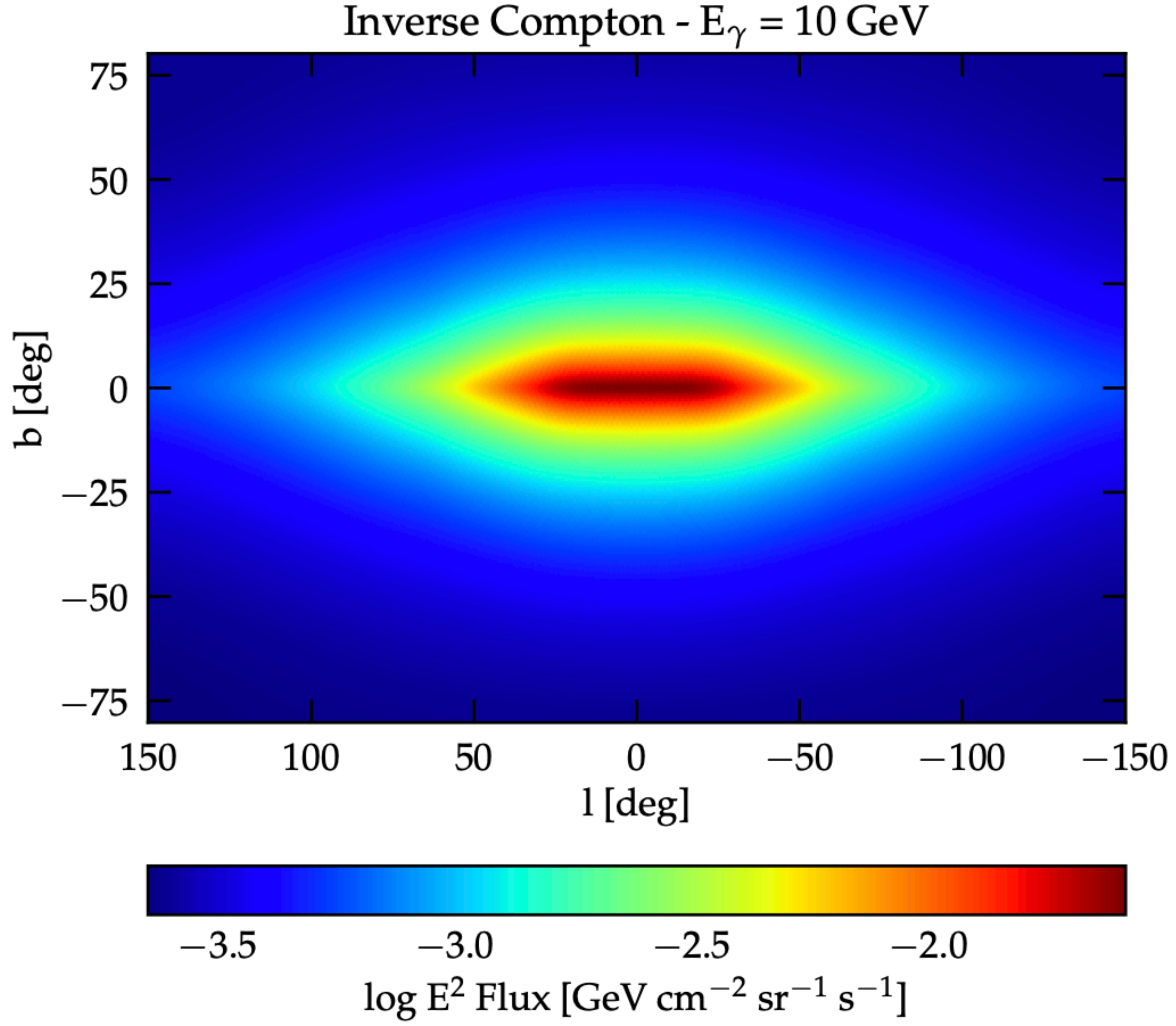
Dominant production mechanism of photons ~MeV - GeV energies

$$\tilde{q}(\vec{r}, E_\gamma) = \frac{1}{E_\gamma} \int \tilde{P}_{IC}(\epsilon, E_\gamma, E_e, \vec{r}) \, \Phi_e \, dE_e$$

$$\left[\frac{1}{s}\right] = \tilde{P}_{IC} = \frac{dP_{IC}}{dE_\gamma}$$ differential IC power

Galactic Inverse Compton emission

Dundovic+ A&A'22



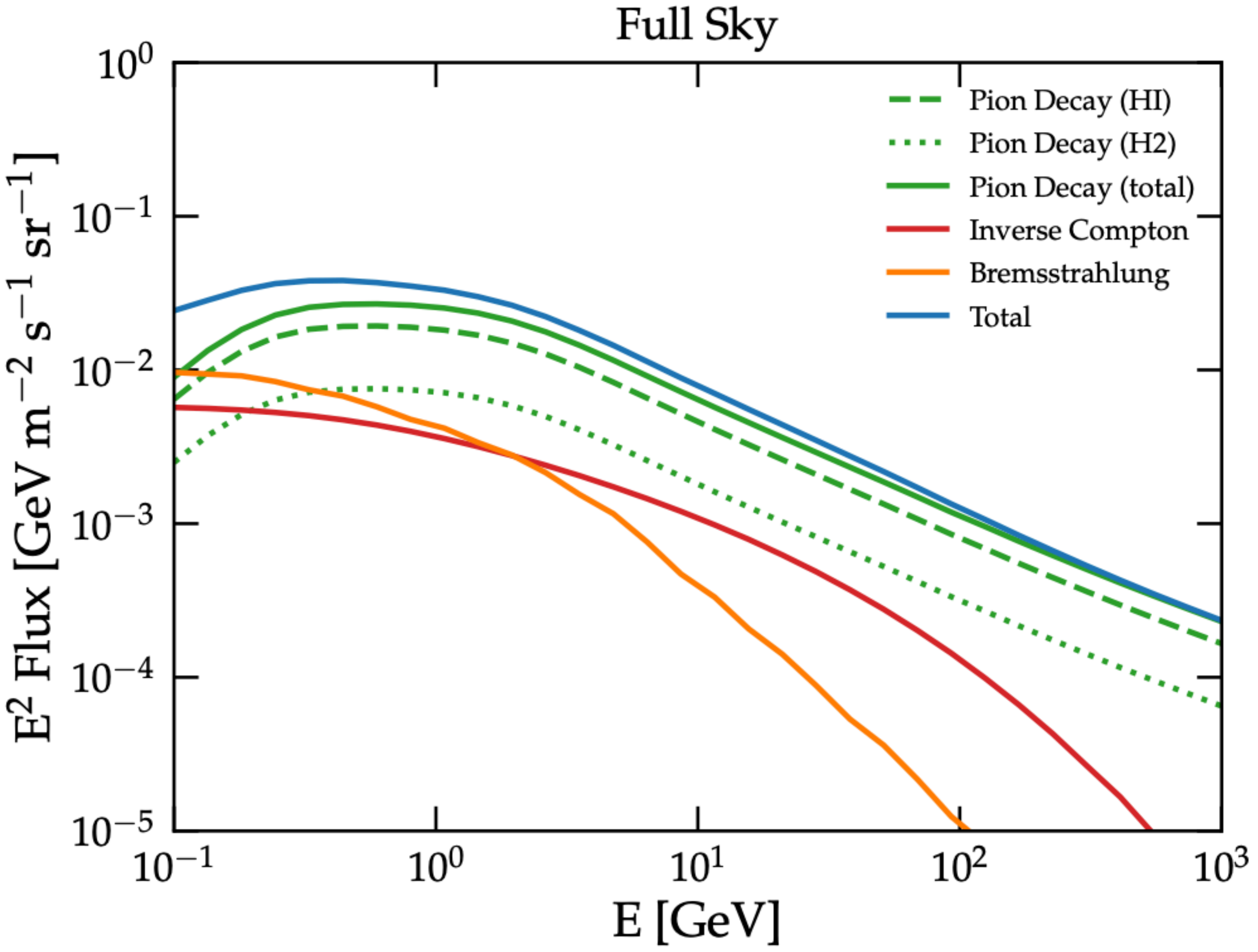
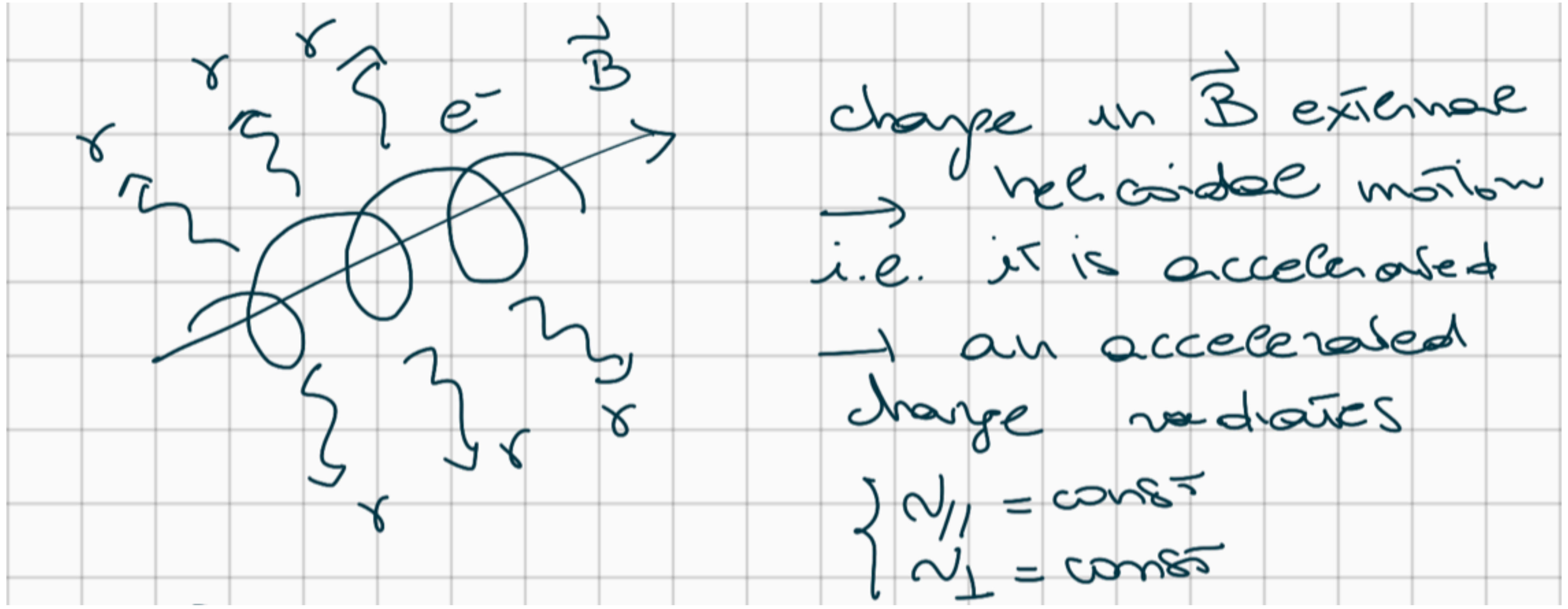


Fig. 7. Cartesian projection in Galactic coordinates of the IC gamma-ray flux at E_γ = 10 GeV.

Synchrotron radiation



$$r_L = \frac{m\gamma v_\perp}{qB}$$

Larmor radius [pc]

$$-\frac{dE}{dt} = \frac{4}{3}\sigma_T c u_B \gamma^2$$

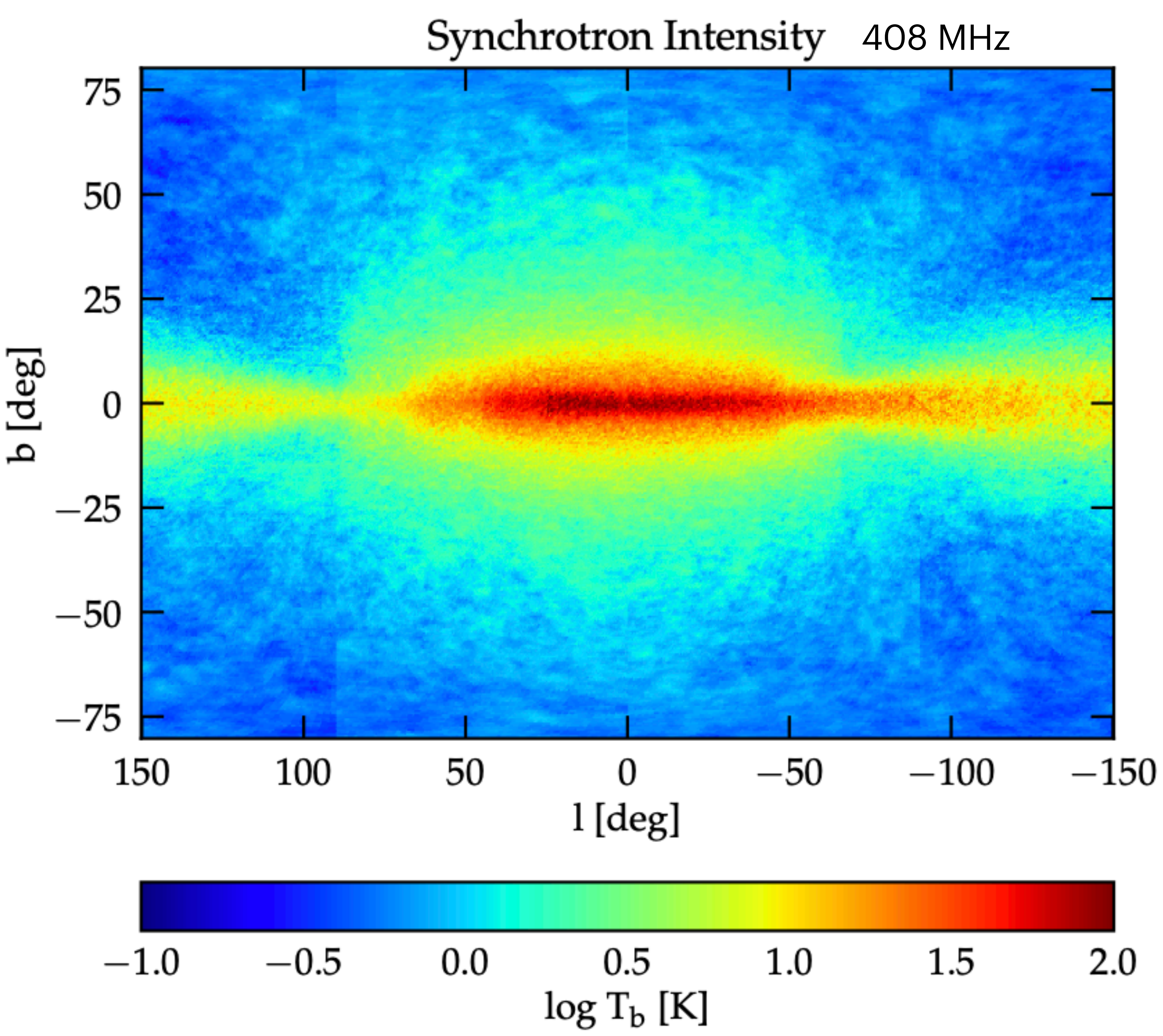
Average energy-loss rate

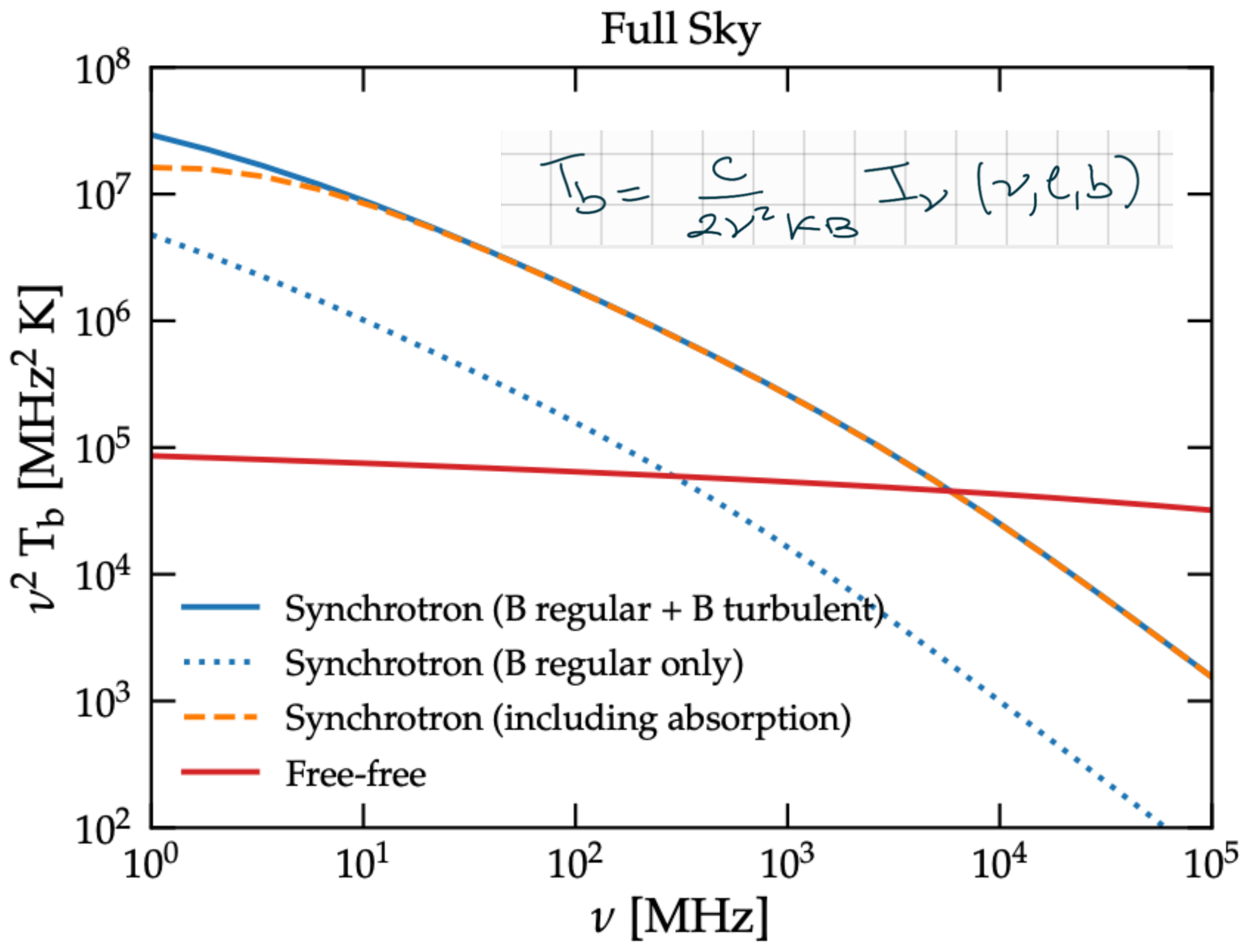
$$u_B = \frac{B^2}{2\mu_0}$$

$$E_s \simeq 500\,\mu\mathrm{eV}\frac{B}{\mu G}\left(\frac{E_e}{\mathrm{GeV}}\right)^2$$

Energy of radiation for a CR electron

Galactic synchrotron radiation





Dundovic+ A&A'22

Peculiarity: The synchrotron radiation of ultra-relativistic electrons in a uniform magnetic field is expected to be **highly polarised**

Hadrons interactions with radiation

- **Elastic scattering** is suppressed

$$\sigma_{\gamma N} \propto \frac{Z^4}{A^2}\sigma_T$$

- **Inelastic scattering** is the most efficient channel of E-loss for UHE CRs

Collisional effect, catastrophic E loss mechanism

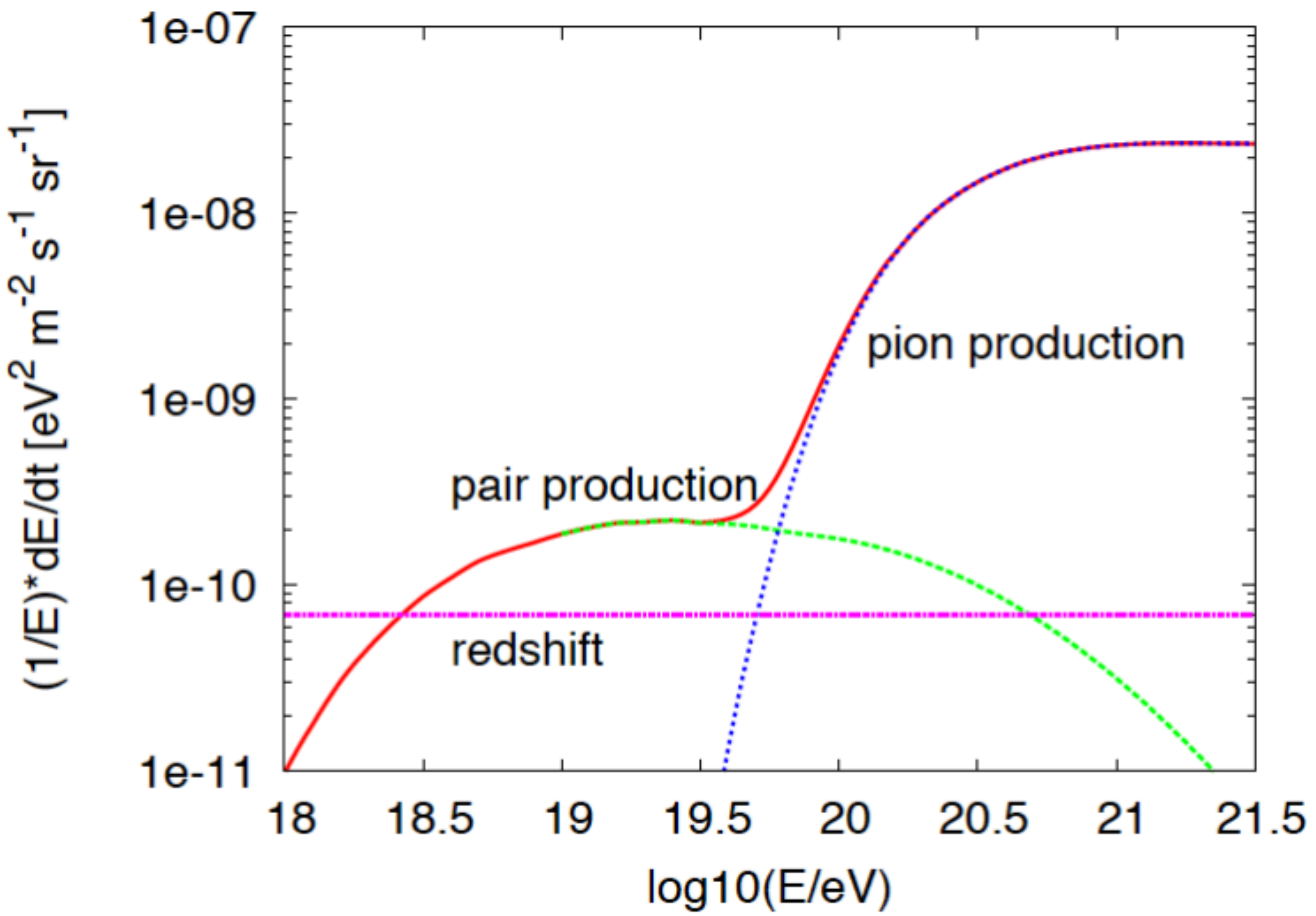
Inelasticity: $k \sim \langle \frac{E_{\rm in} - E_{\rm out}}{E_{\rm in}} \rangle$

Pair production

$$p_{\rm UHE} + \gamma_{\rm bkg} \to p + e^+ + e^-$$

Photo-pion production

$$p_{\rm UHE} + \gamma_{\rm bkg} \to p(n) + \pi^0(\pi^+)$$



Hadrons interactions with matter

Inelastic proton-proton collisions

- Main E-loss mechanism for Galactic CR protons

$$p_{\rm CR} + p_{\rm ISM} \rightarrow p + p(n) + \pi^0(\pi^+)$$

- Main production mechanism of photons at GeV energies: **Neutral pion decay**

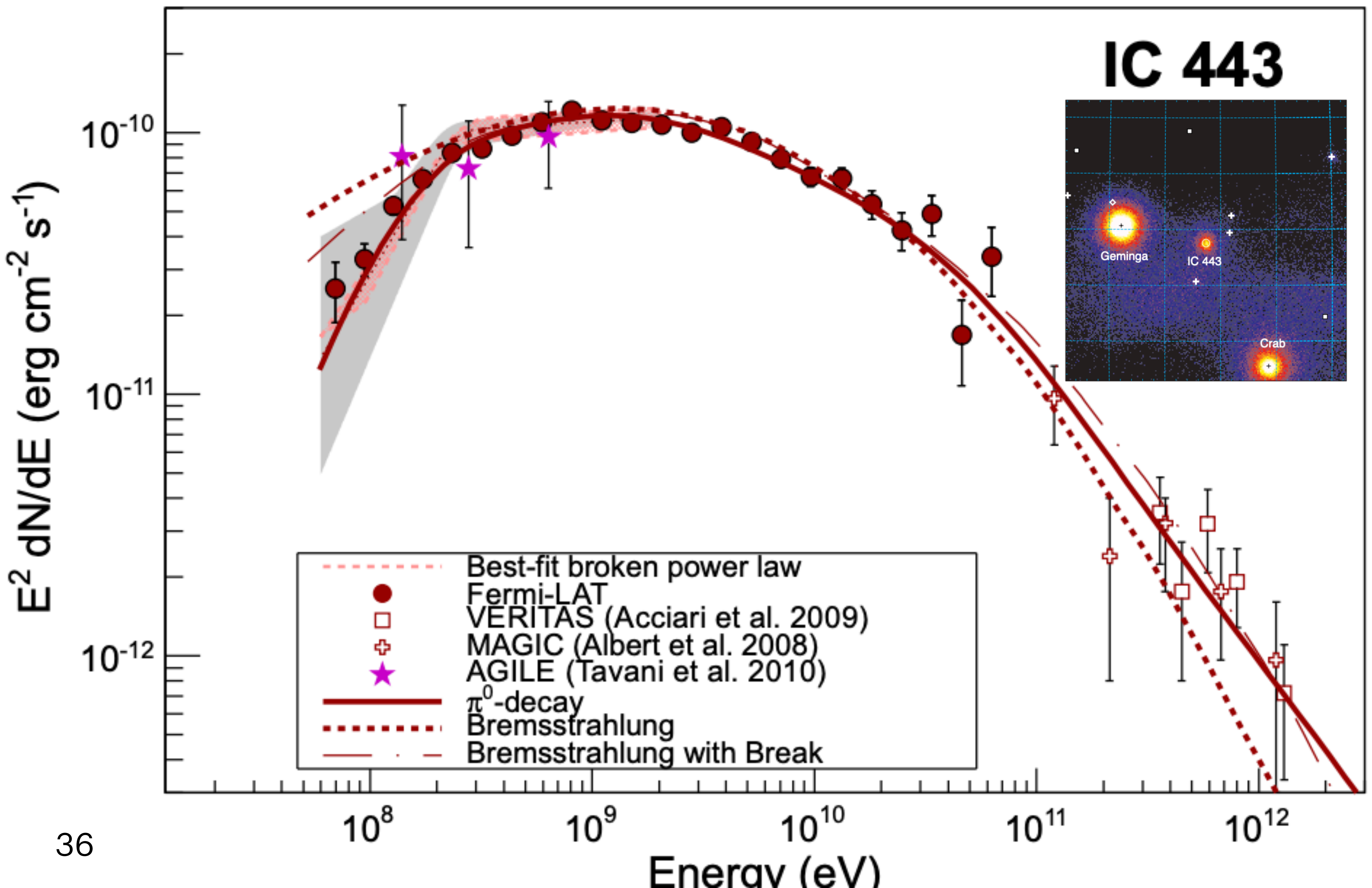
$$\pi_0 \rightarrow \gamma\gamma$$

$$E'_\gamma = \frac{m_{\pi^0}}{2} \simeq 67.5\ \mathrm{MeV}$$

Flat spectrum between E_{min}, E_{max}, always centred at the same energy regardless of pion energy

Pion bump

Ackermann+ Science'13



Galactic photons from neutral pion decay

$$\tilde{q}_\pi(E_\pi) = 4\pi n_H \int dE_p\, \delta(E_\pi - k_\pi E_p) \times \frac{d\sigma_{pp\to\pi}}{dE_\pi}(E_p)\, \Phi_p(E_p)$$

pion emissivity
pions/dNdEdt

$$= 4\pi n_H \frac{d\sigma_{pp\to\pi}}{dE_\pi}\left(\frac{E_\pi}{k_\pi}\right) \cdot \Phi_p\left(\frac{E_\pi}{k_\pi}\right)$$

Neutral pion spectrum has the same shape of the parent protons, shifted at lower energies

$$E_{\pi^0} \sim 0.17 E_p$$

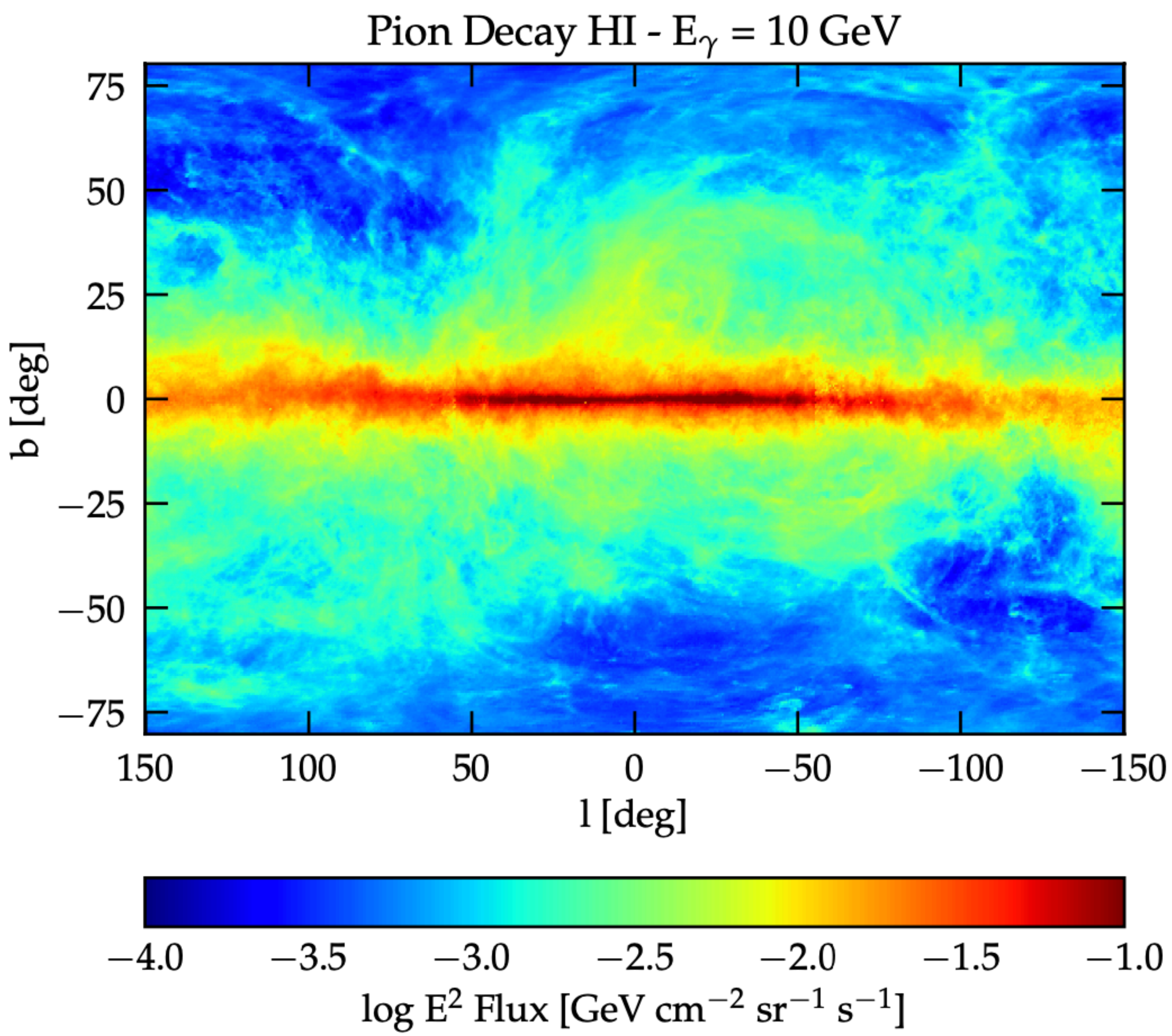
$$\tilde{q}_\gamma(E_\gamma) = \int_{E_\pi^{min}(E_\gamma)} dE_\pi \frac{dN_\gamma}{dE_\gamma}\, \tilde{q}_\pi(E_\pi)$$

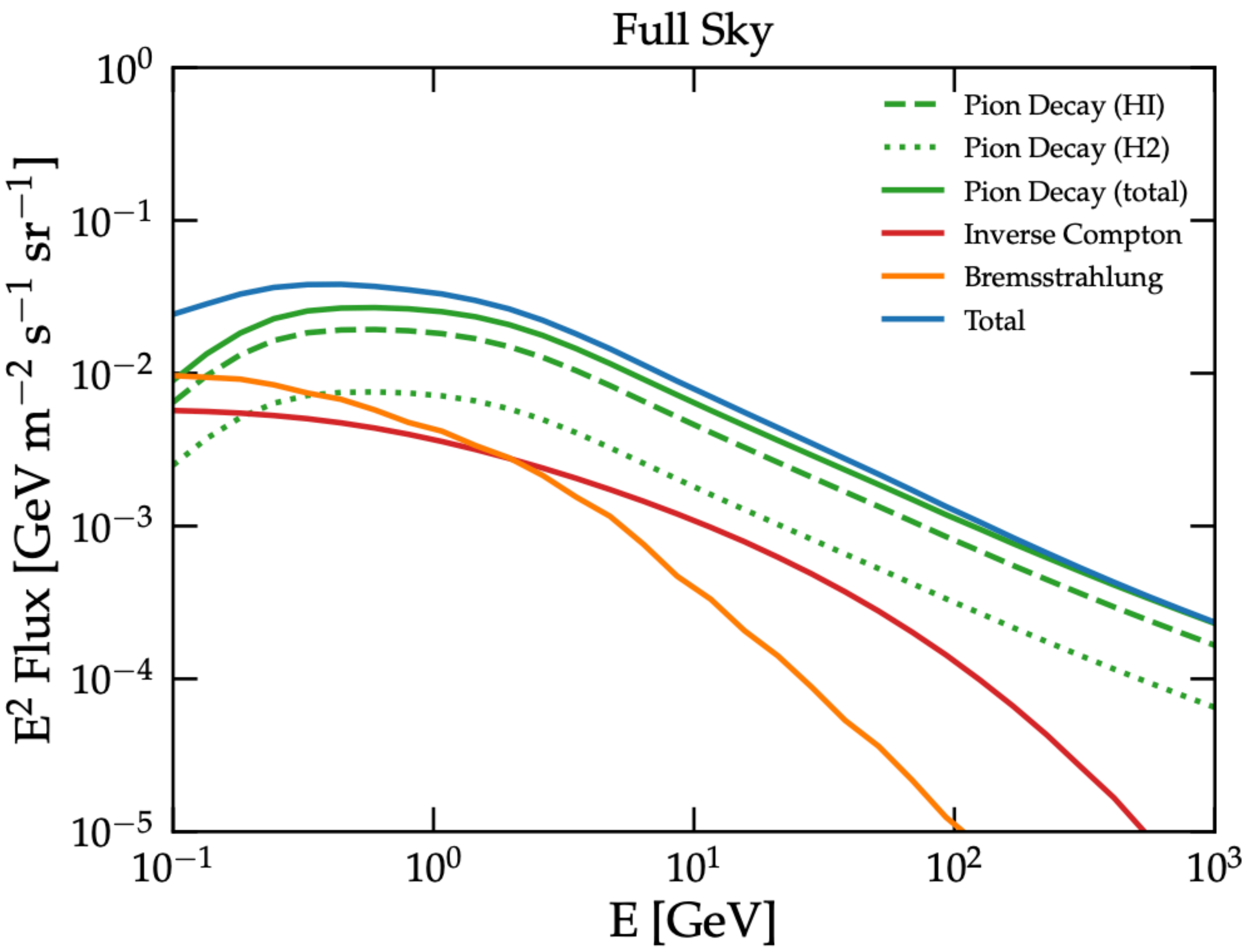
[1/erg cm^3 s]

Gamma-ray spectrum at energies above the pion bump follows the parent proton distribution shifted by

$$E_\gamma \sim \frac{1}{2} 0.17 E_p \sim \frac{E_p}{10}$$

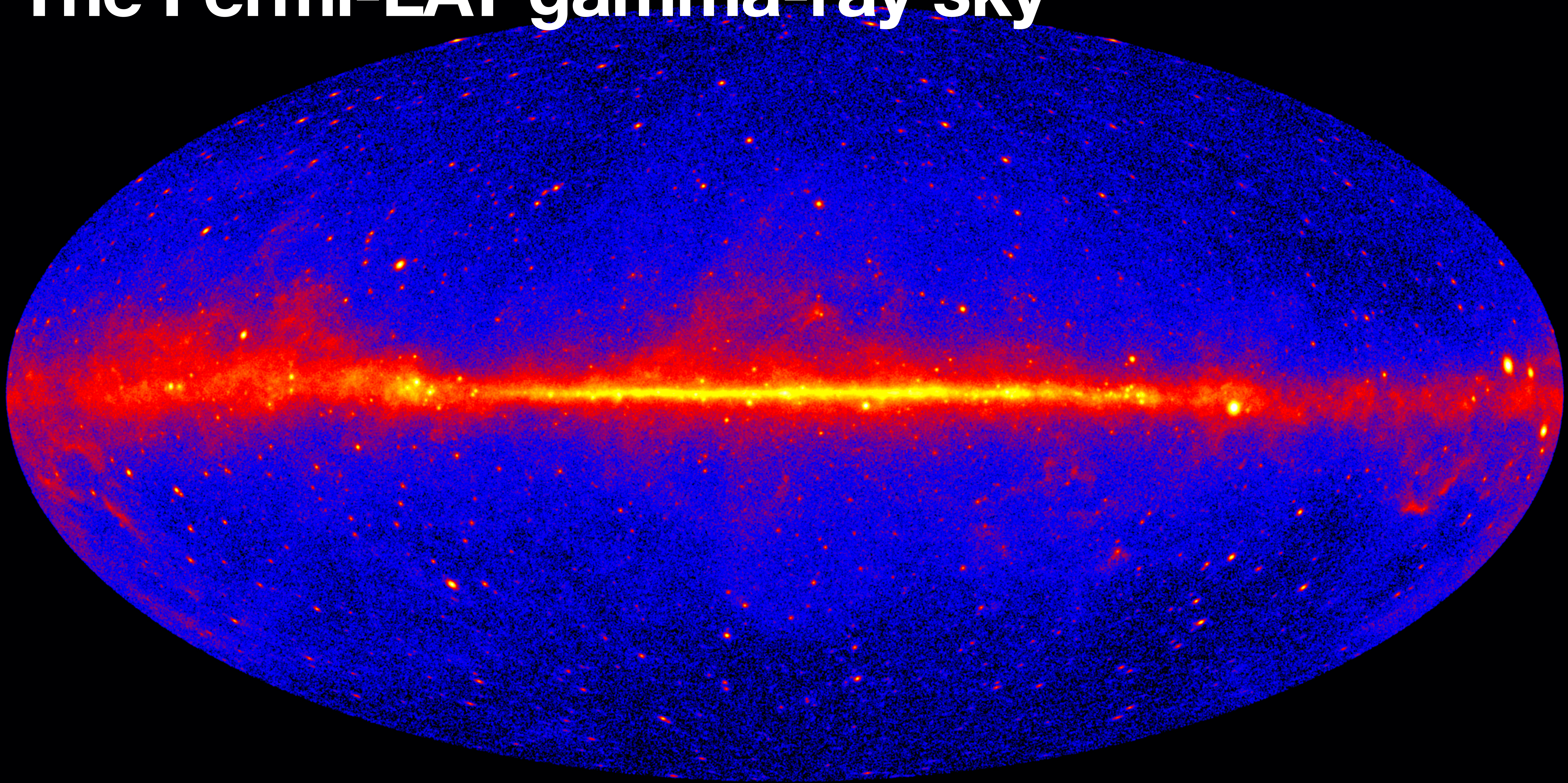
Galactic photons from neutral pion decay





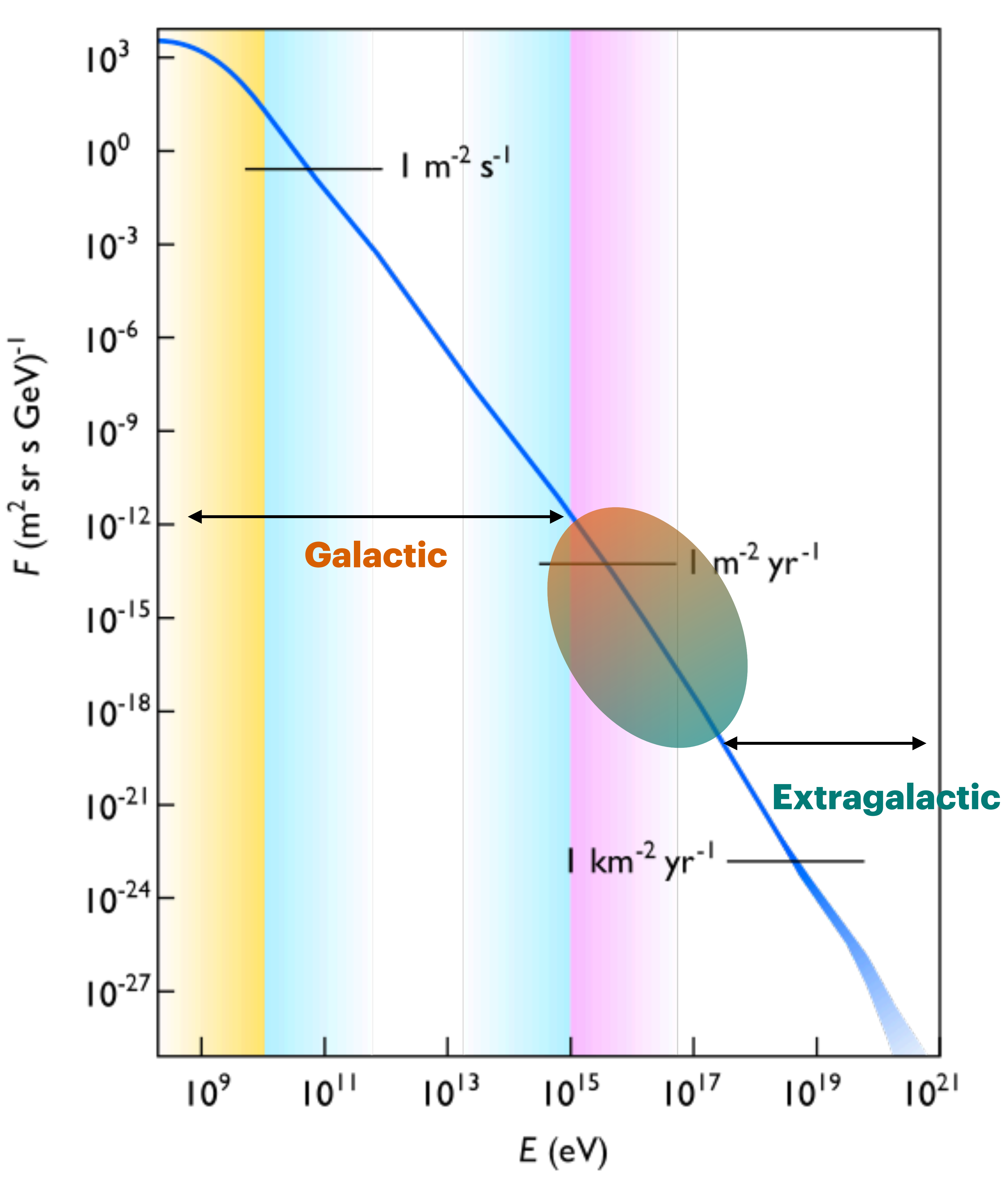
Dundovic+ A&A'22

The Fermi-LAT gamma-ray sky



Sources of cosmic particles: Standard astrophysics

Cosmic-ray sources: Galactic or extragal?



In the Galaxy we **observe** (in gamma rays)
CR factories up to
1 TeV = 10^{12} eV (HESS, VERITAS, MAGIC)
1 PeV = 10^{15} eV (LHAASO)

SNR, pulsars & neutron stars, binary, stellar clusters, PWN

AGN & jets, galaxy clusters, galaxies

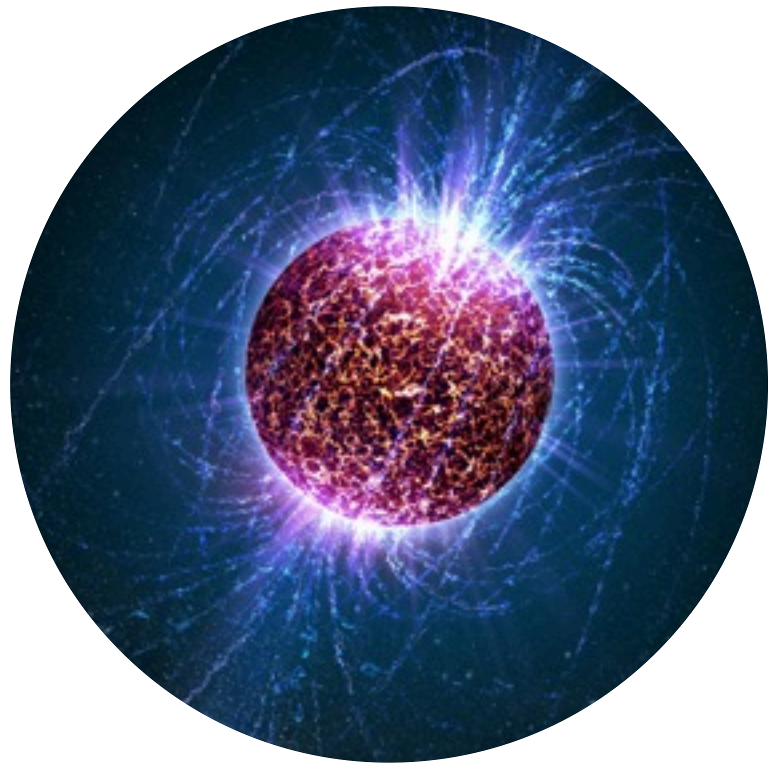
Open questions:

1. What is the maximal energy CR are accelerated?
2. Where does the Gal-extragal transition occur?

How to accelerate CRs?

Some **requirements**:

1. Energetics:
   - Kinetic Energy (translational in SNRs, rotational in pulsars)
   - Gravitational Energy (accretion disks)
   - Magnetic (solar flares)
2. Mechanism for Energy Transfer: how to transfer energy from macroscopic objects into the (microscopic) acceleration of particles? (electromagnetic)
3. Confinement: particles must stay in the accelerator for the time needed to accelerate them
4. No significant E-losses



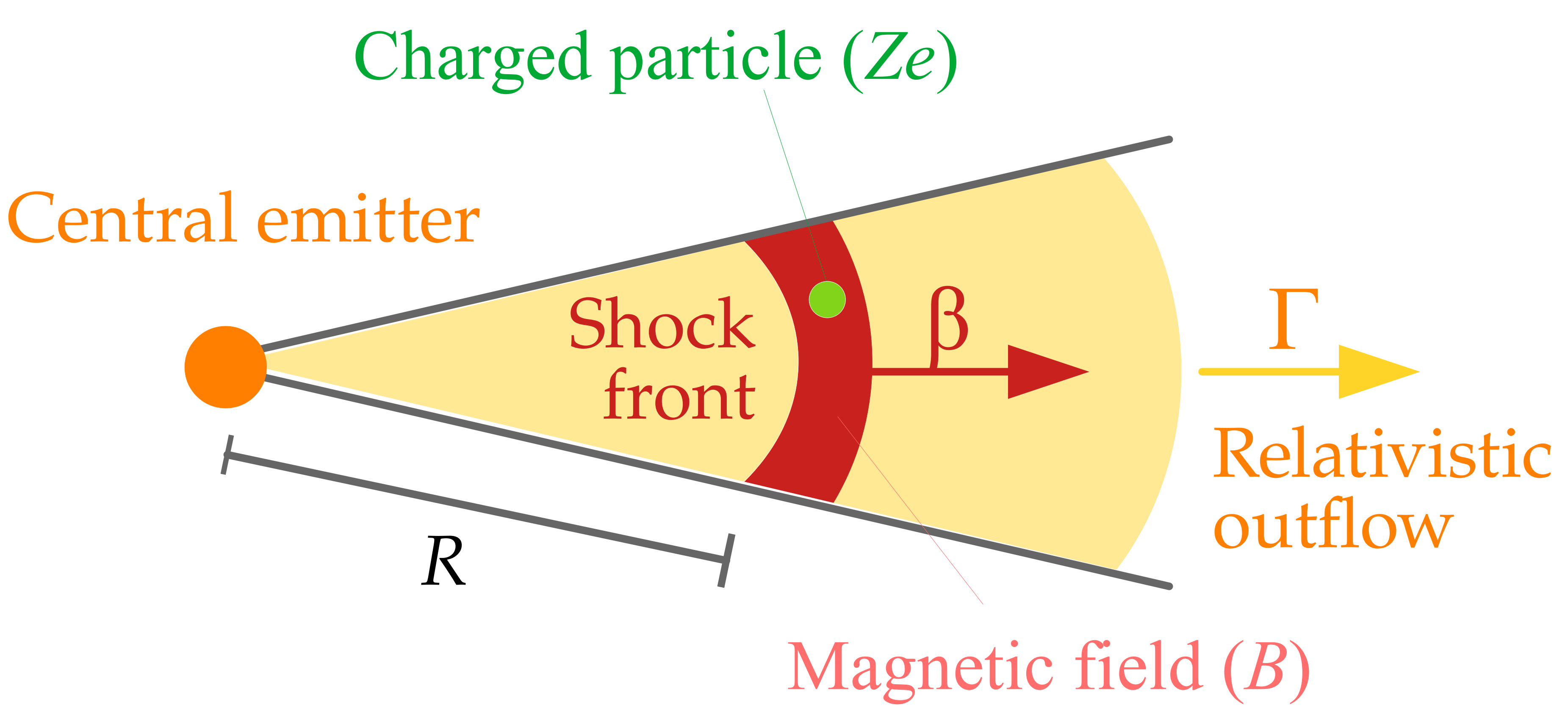
We need electric fields to accelerate particles!
They are generated by moving magnetic fields in the plasma
e.g. fast rotating B-field in pulsars, shock waves

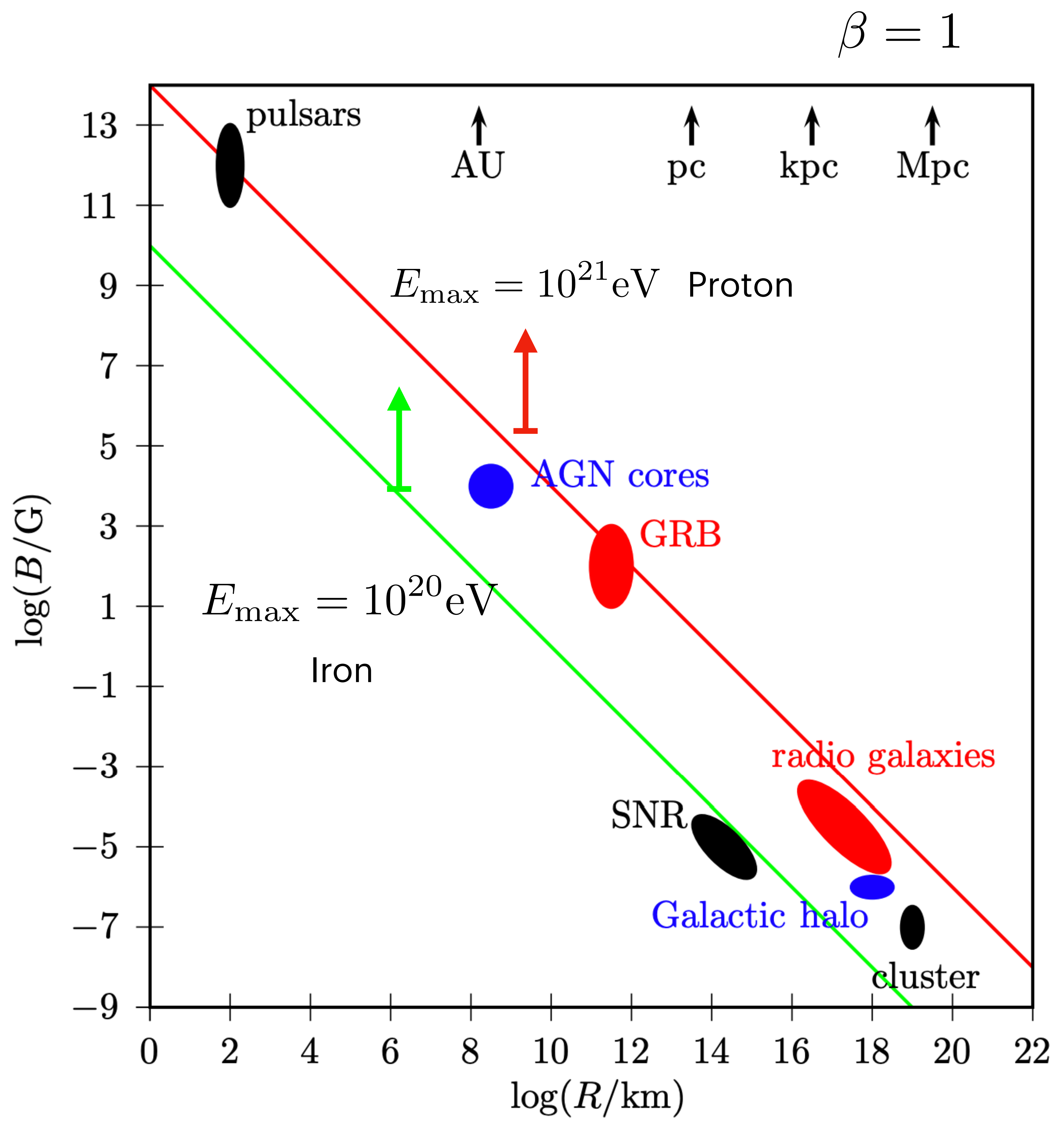
Confinement condition

Necessary condition for acceleration:

The system must be able to contain the particle

$$r_L \lesssim R$$



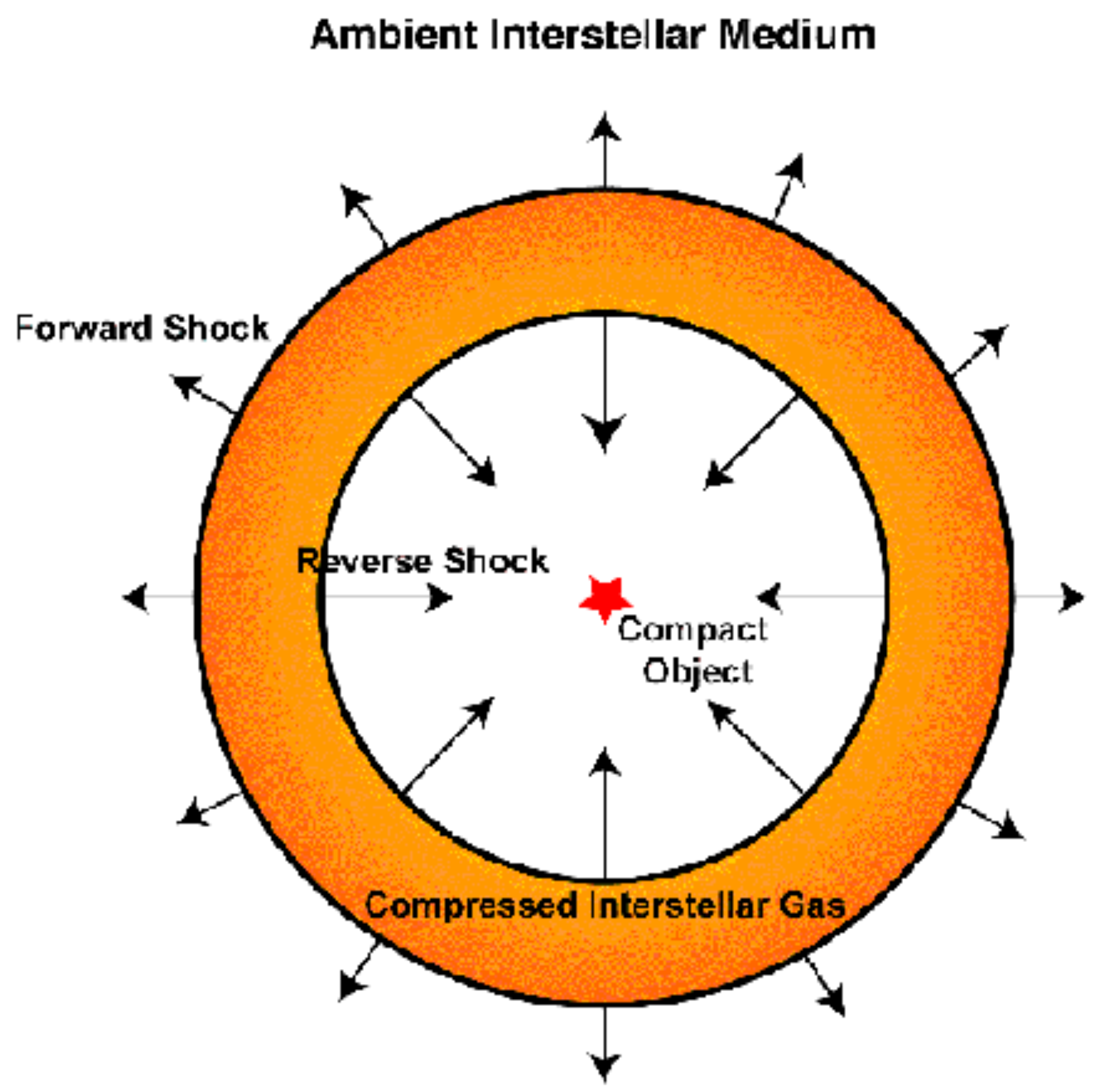


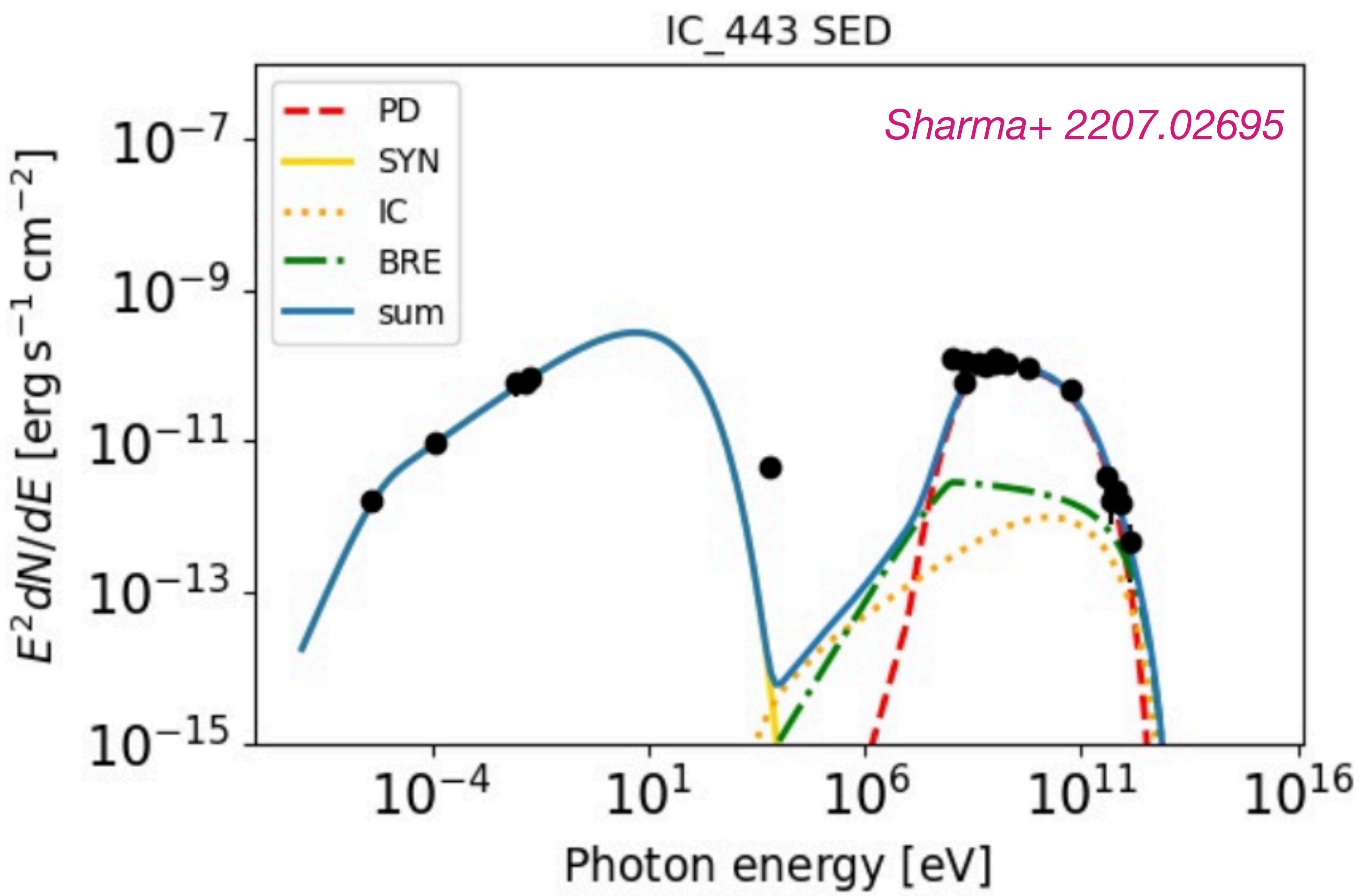
Hillas Plot $E_{\rm max} \propto RB$

$$r_L = \gamma r_g = \sqrt{1-\mu^2}\,\frac{\mathcal{R}}{B_0} \simeq 10^{-6}\sqrt{1-\mu^2}\,\frac{\mathcal{R}}{\rm GV}\,\frac{\mu{\rm G}}{B_0}\,{\rm pc}$$

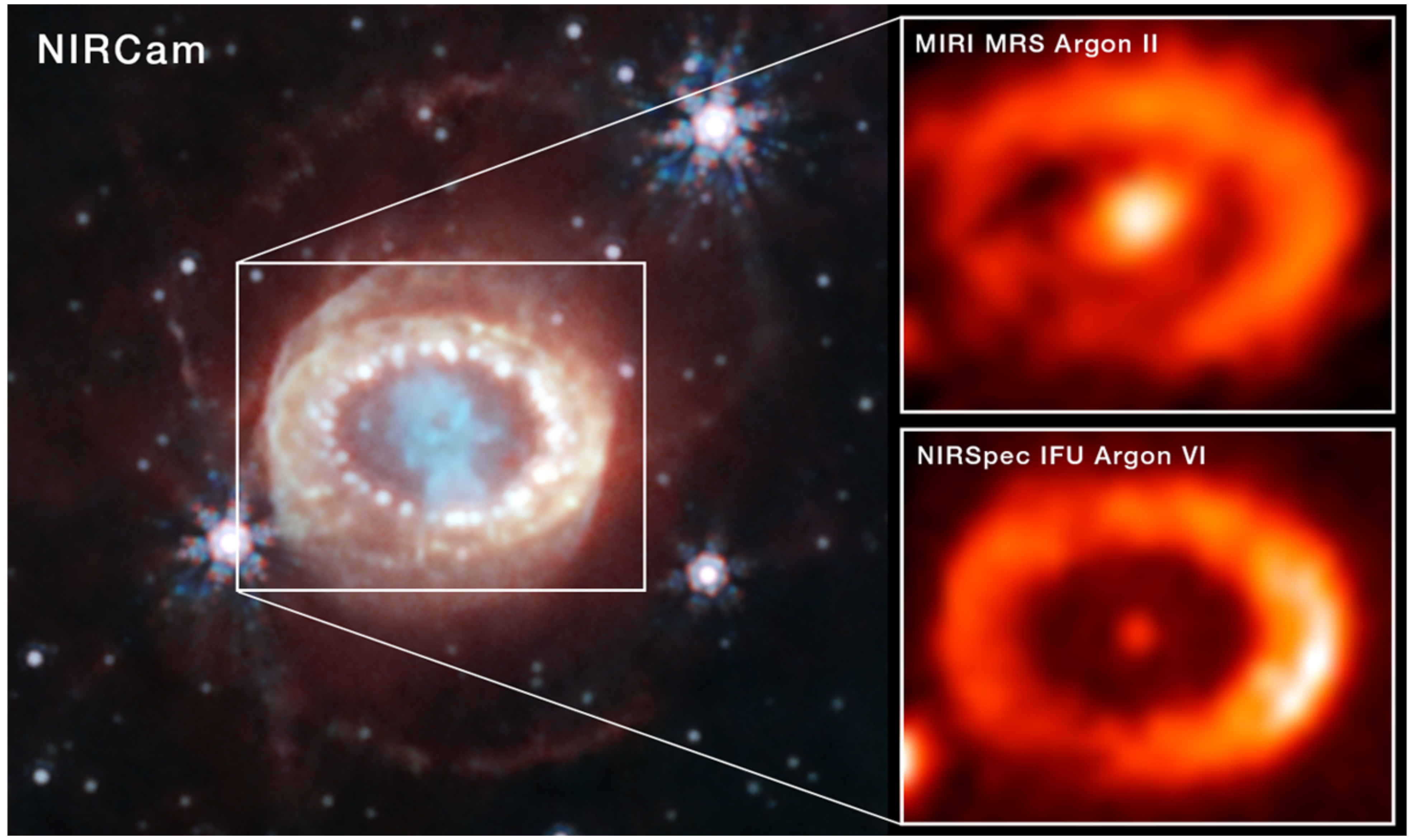
Supernova remnants

- 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

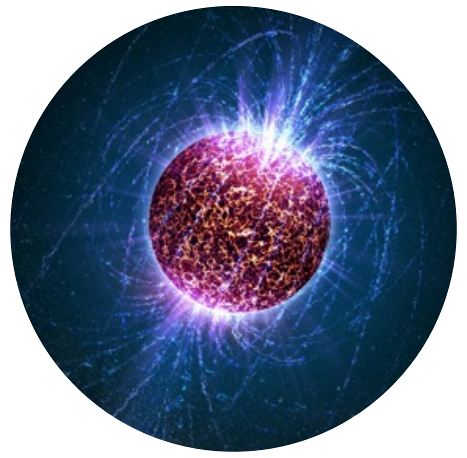




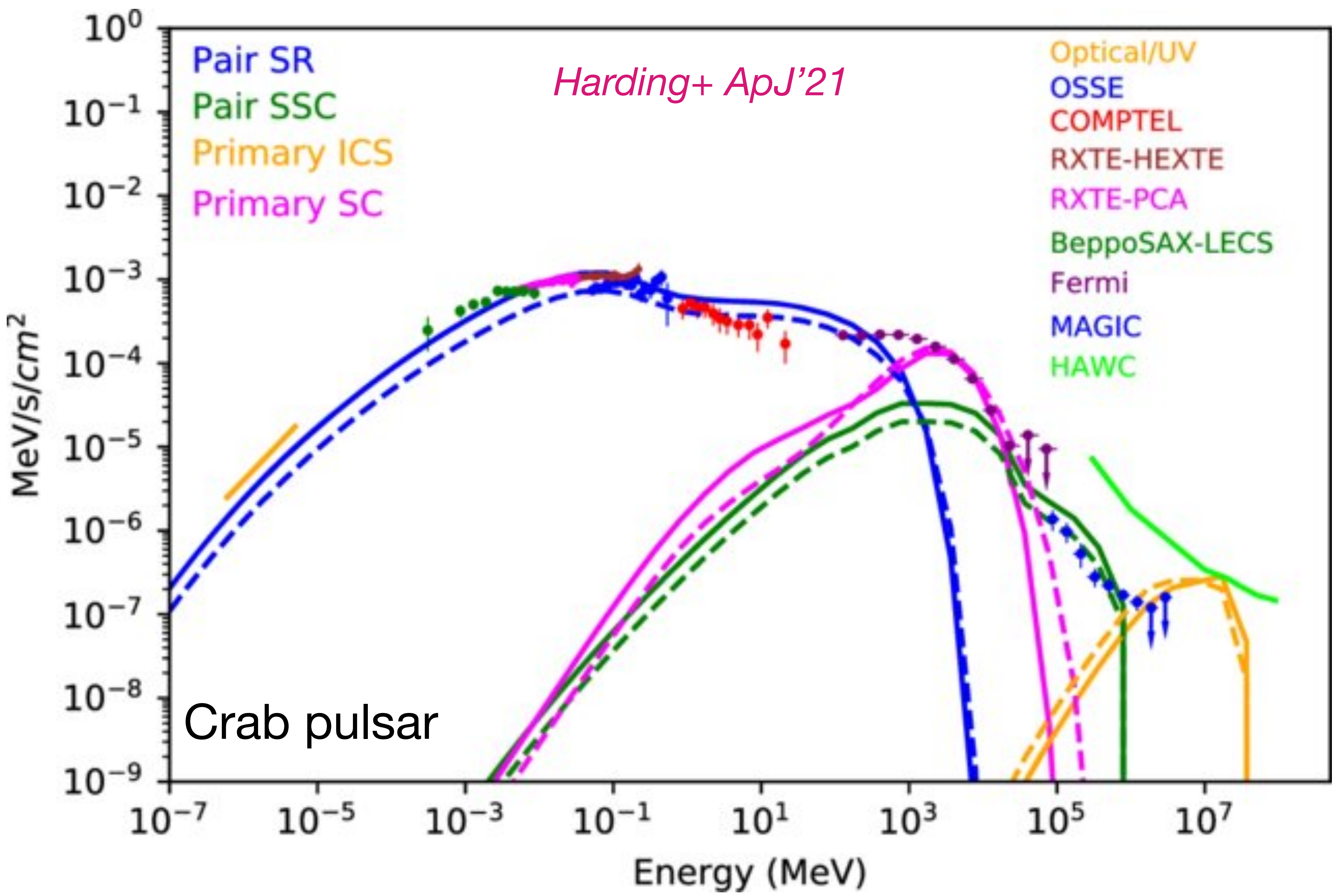
Webb's evidence of neutron star in SN1987A

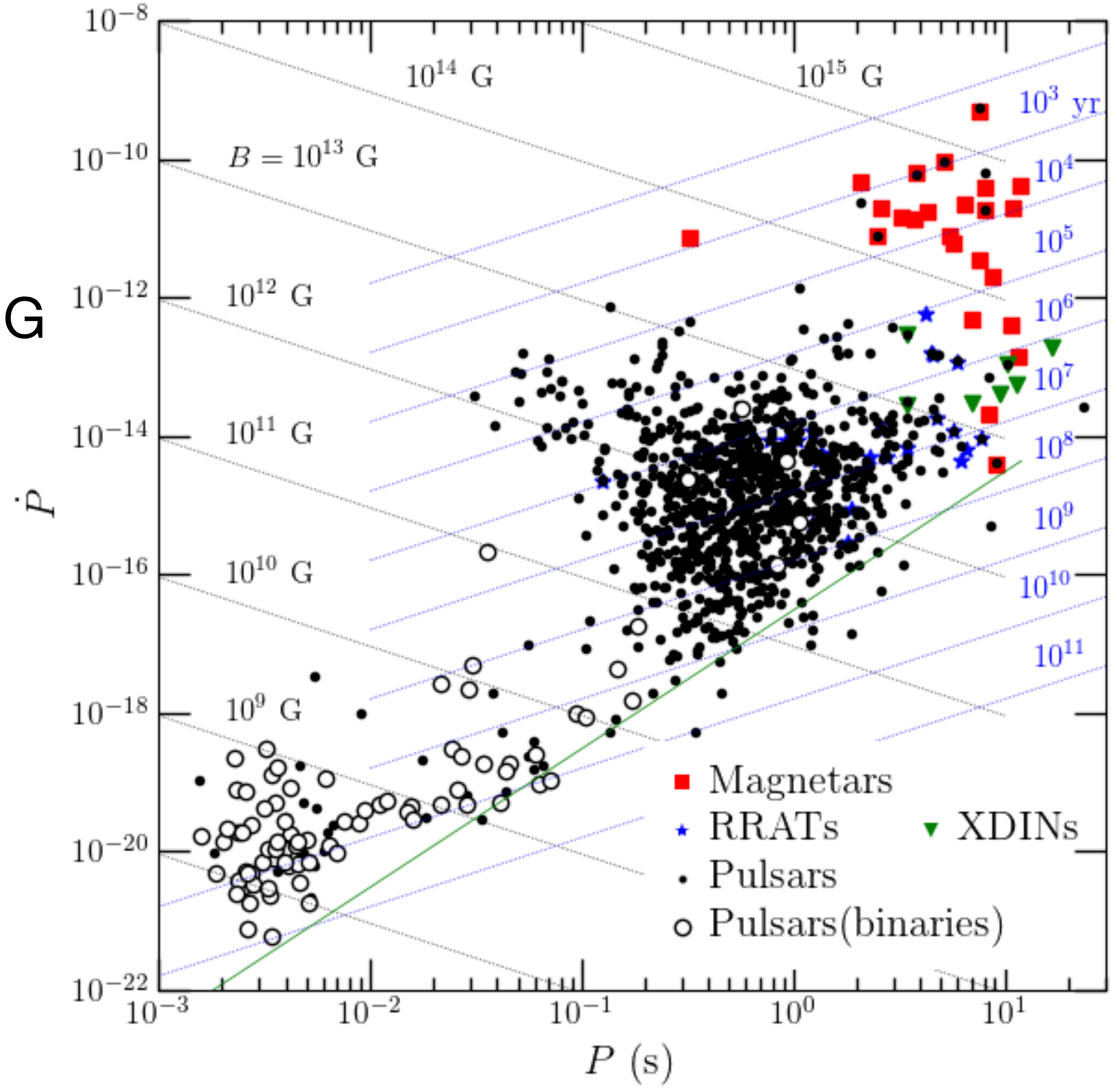


Pulsars and PSR wind nebulae

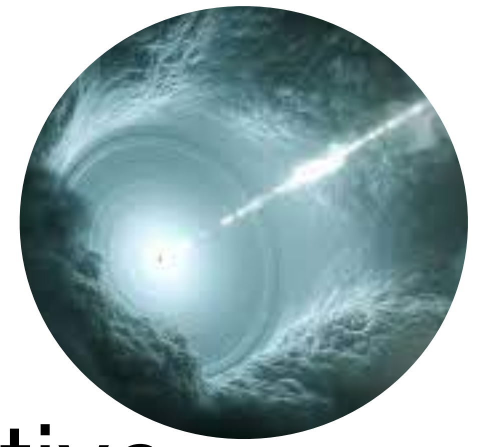


- Pulsars are rapidly rotating neutron stars with extremely high densities
- Emit beams of electromagnetic radiation (radio, X-ray, gamma-ray) from their magnetic poles through synchrotron and curvature radiation
- Dipolar magnetic field with strengths from 10^8 to 10^{15} G

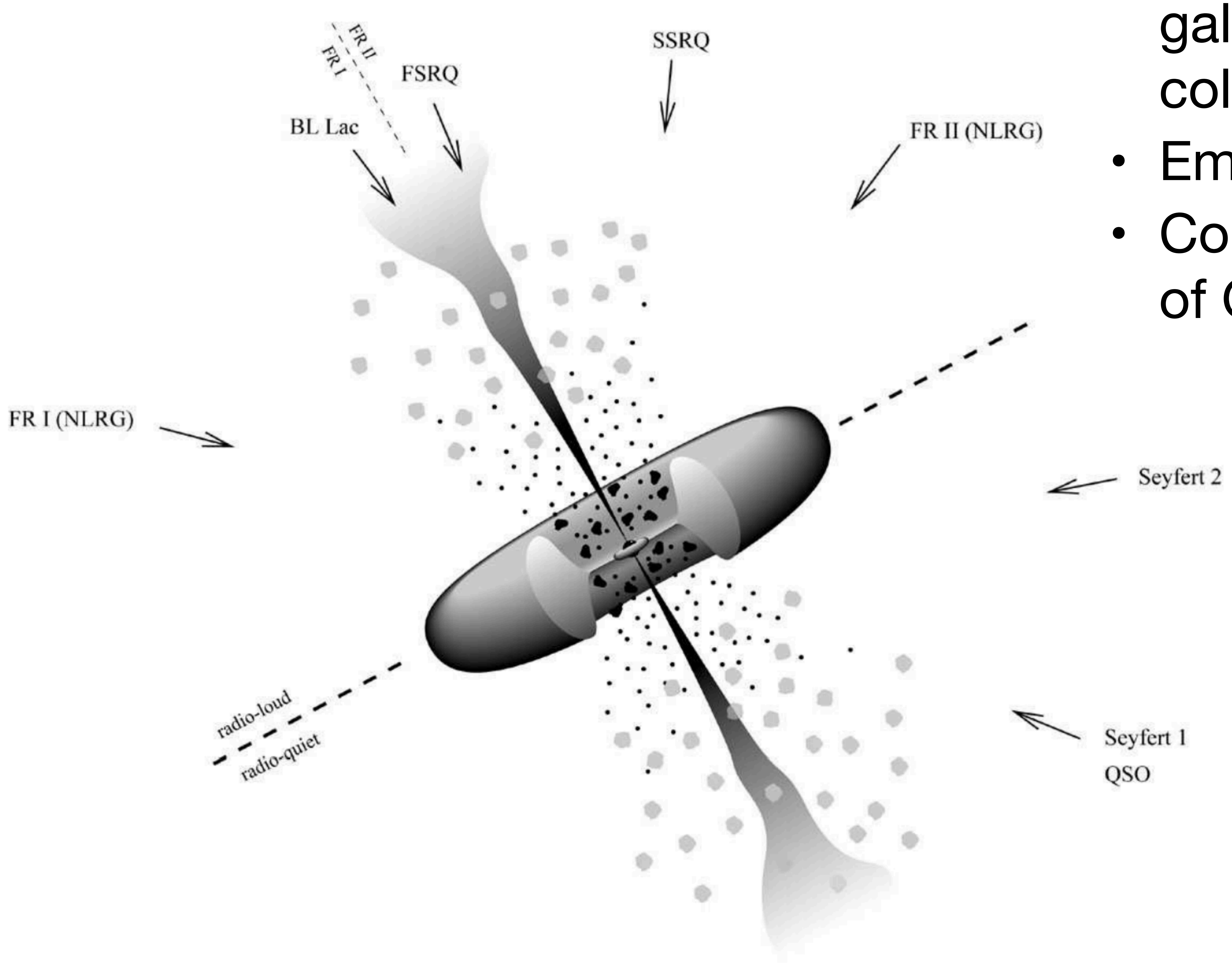




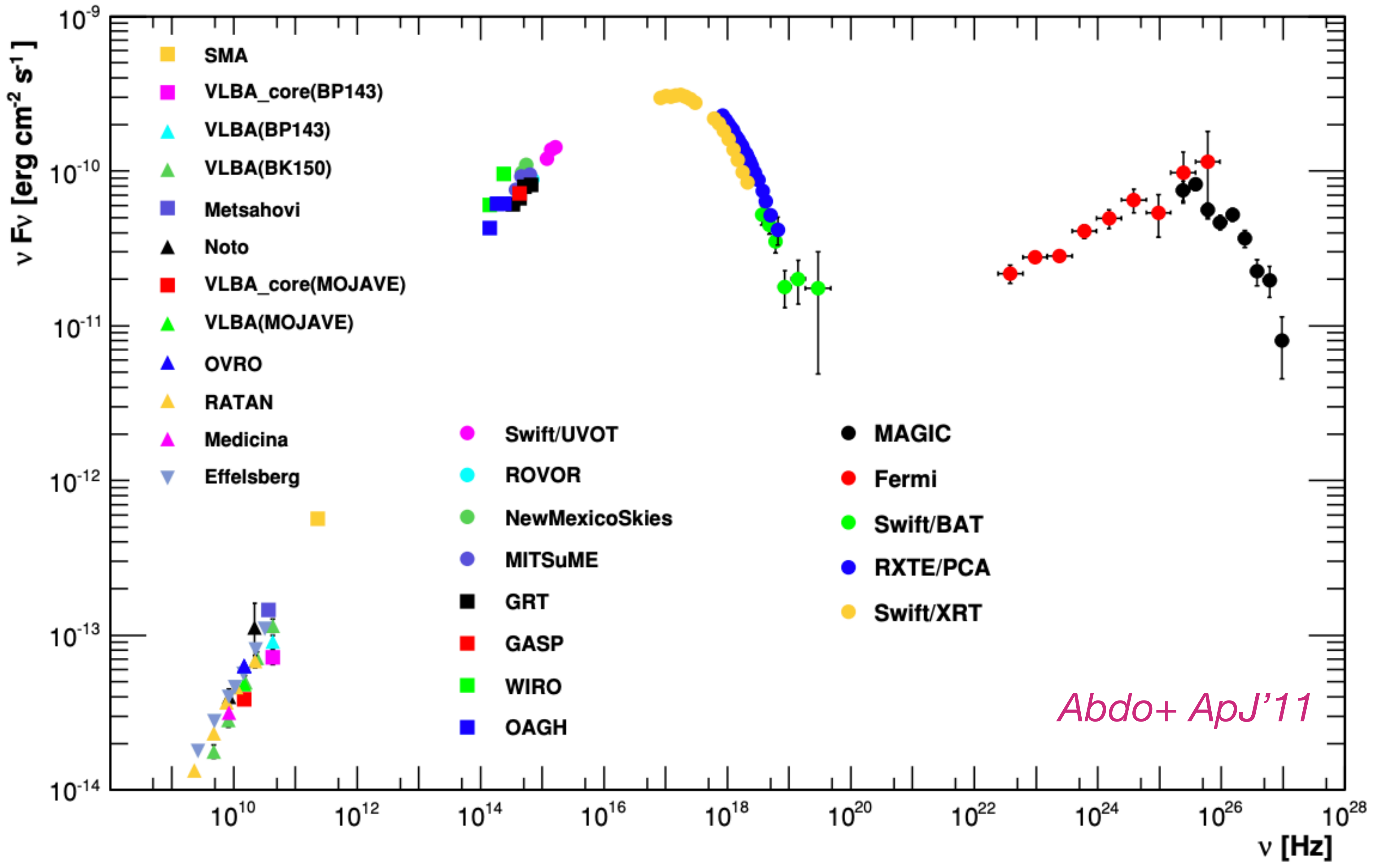
Active galactic nuclei



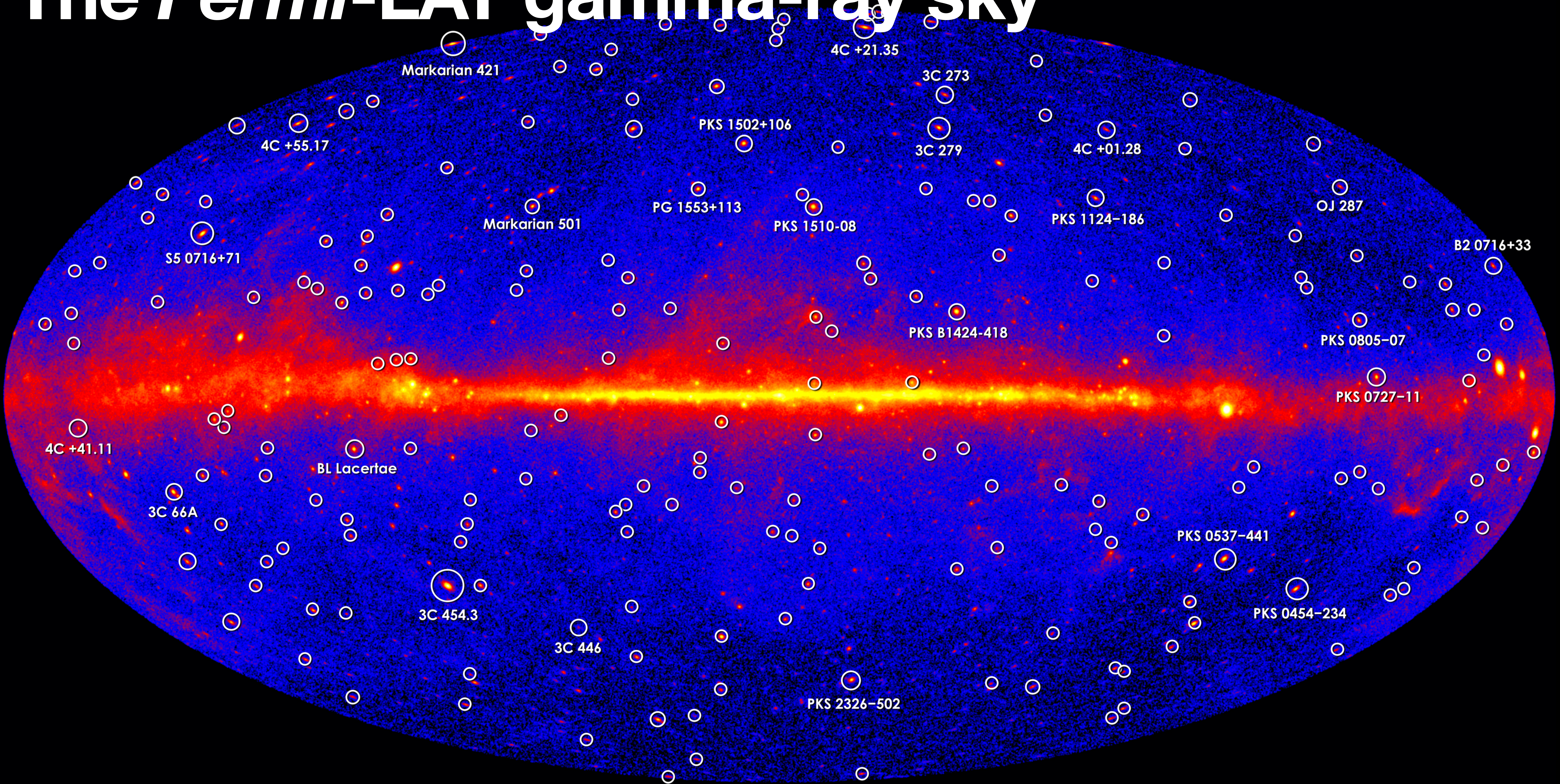
- Large fraction of the total luminosity of an active galaxy is non-thermal (accretion disk and collimated jet)
- Emitted by the nuclei of the galaxy
- Complex B fields structure (poloidal and toroidal) of O(10^3 G)



SED of Mrk 421

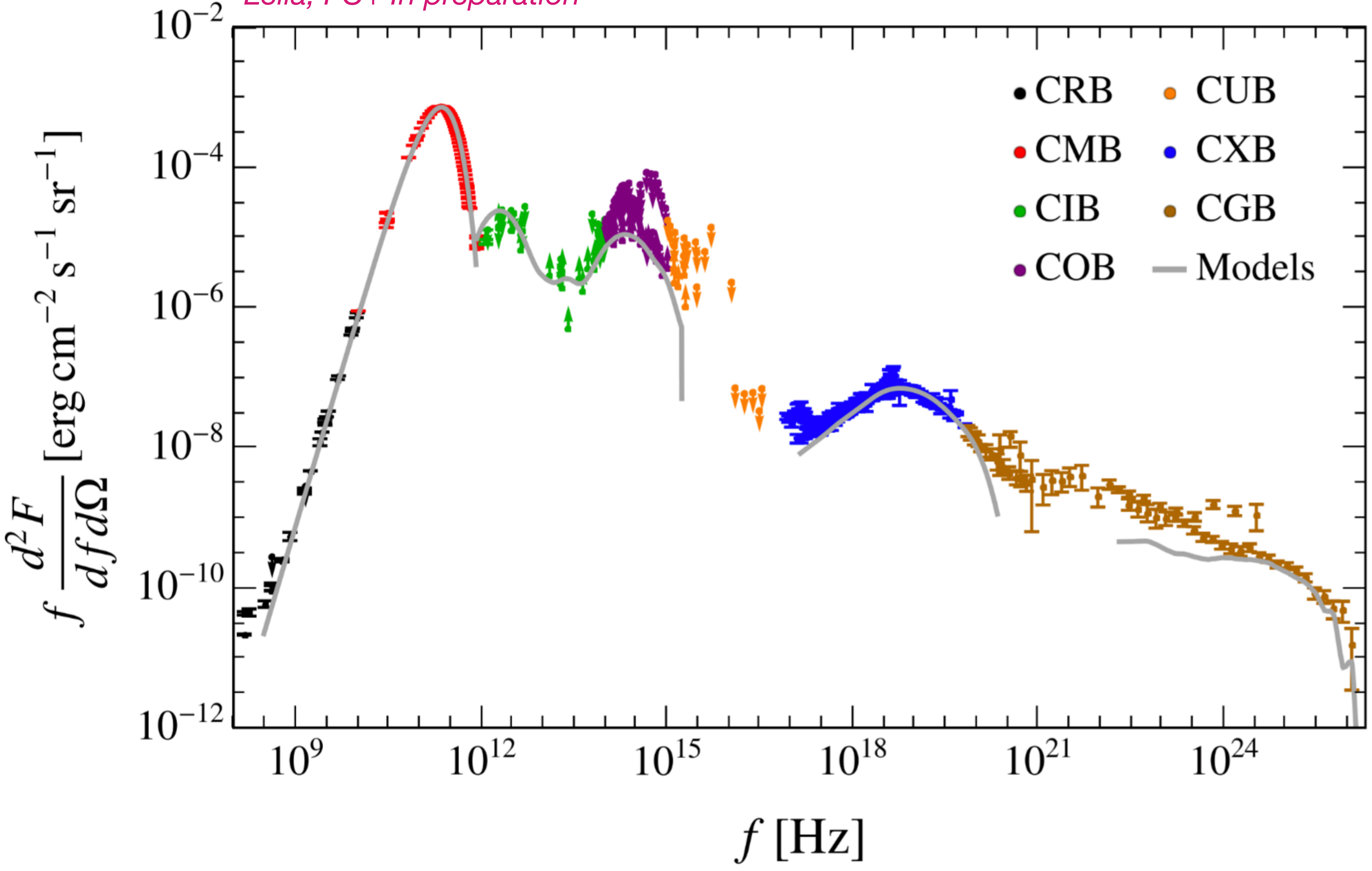


The *Fermi*-LAT gamma-ray sky



Cosmic photon background

Lella, FC+ In preparation



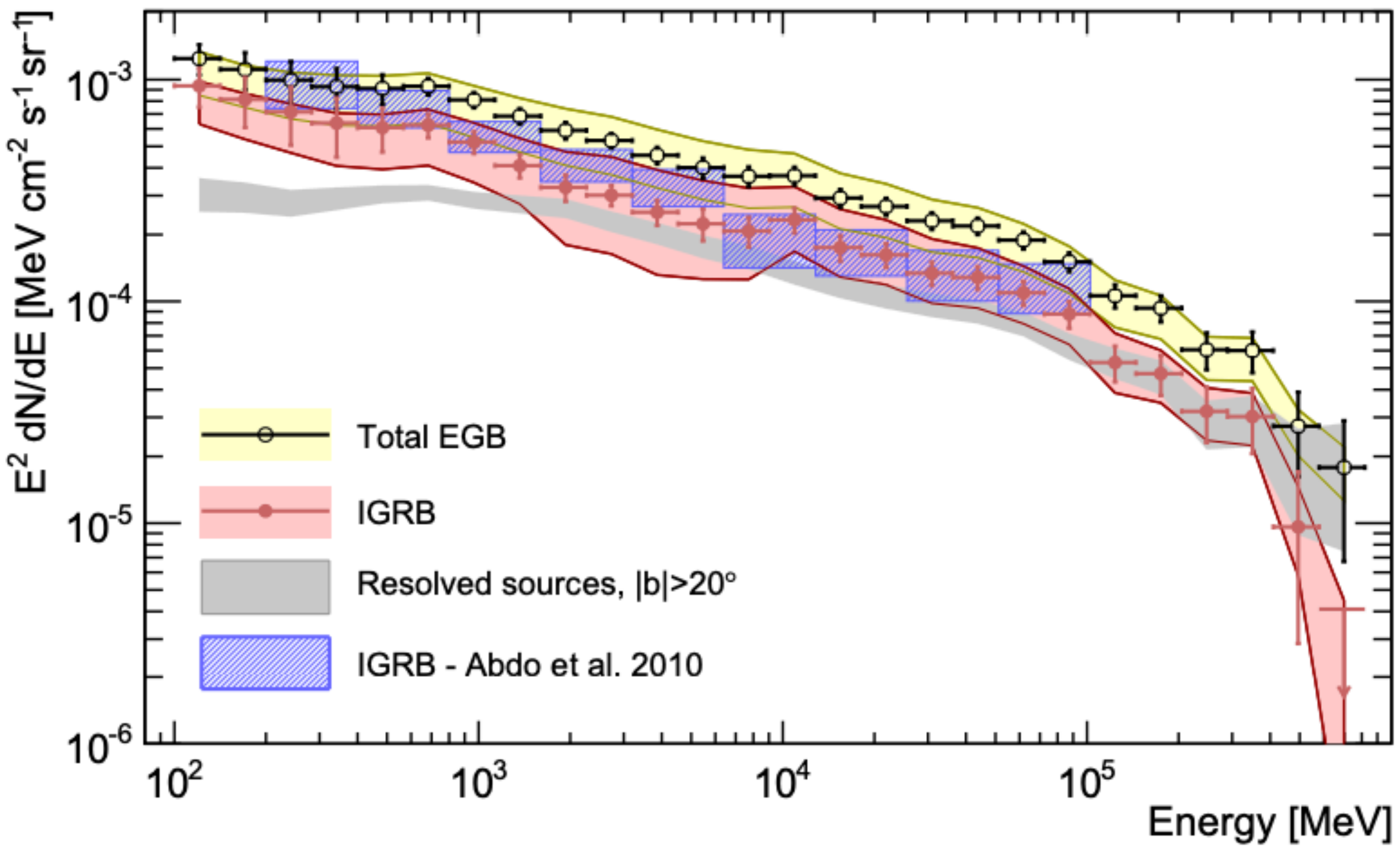
[For a review see: *Hill+ App. Spectrosc.'18*]

- **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

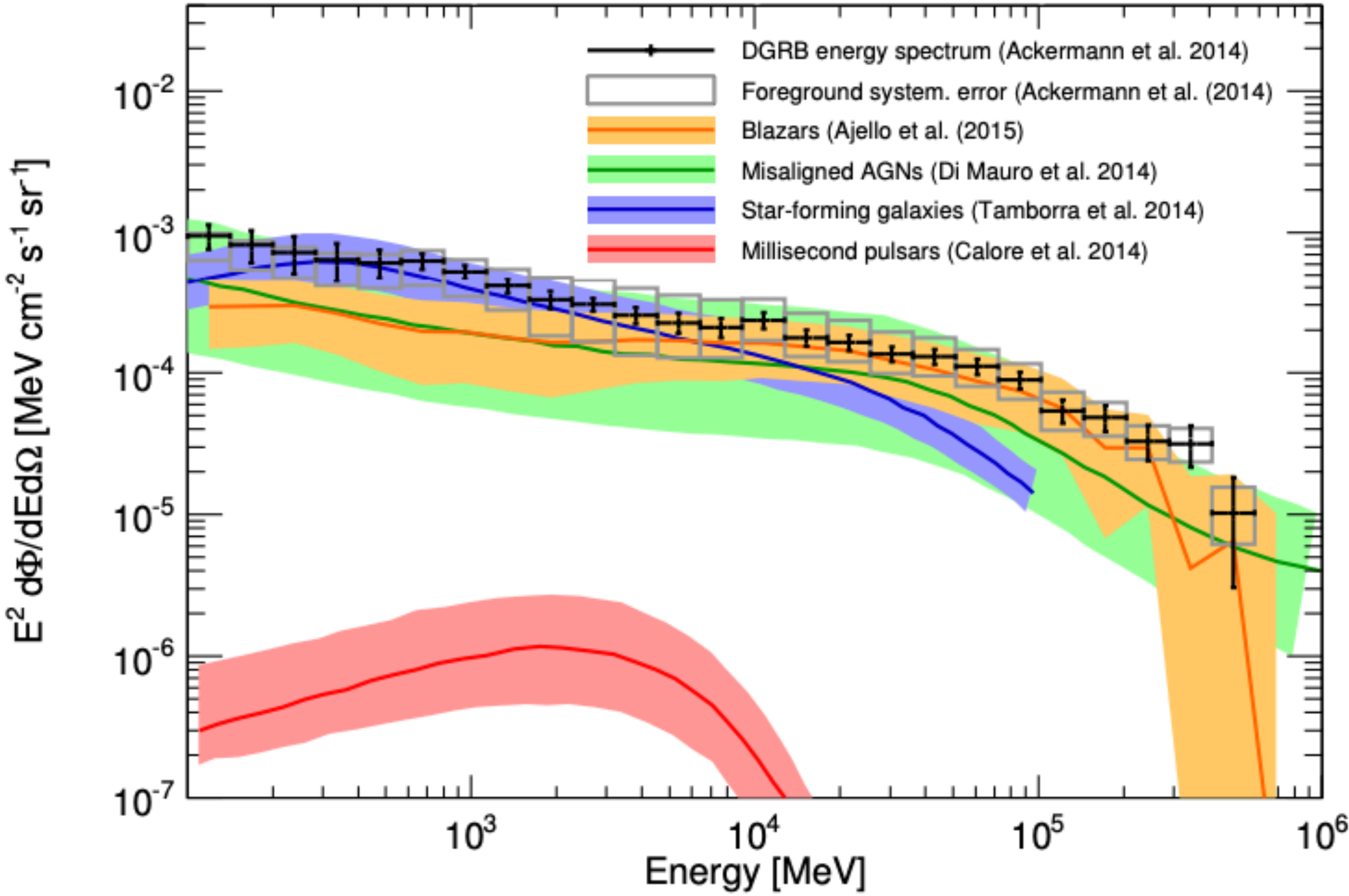
Common element: Mostly of extra-galactic origin, as superposition of faint photon emitters

Unresolved sources and the Fermi IGRB

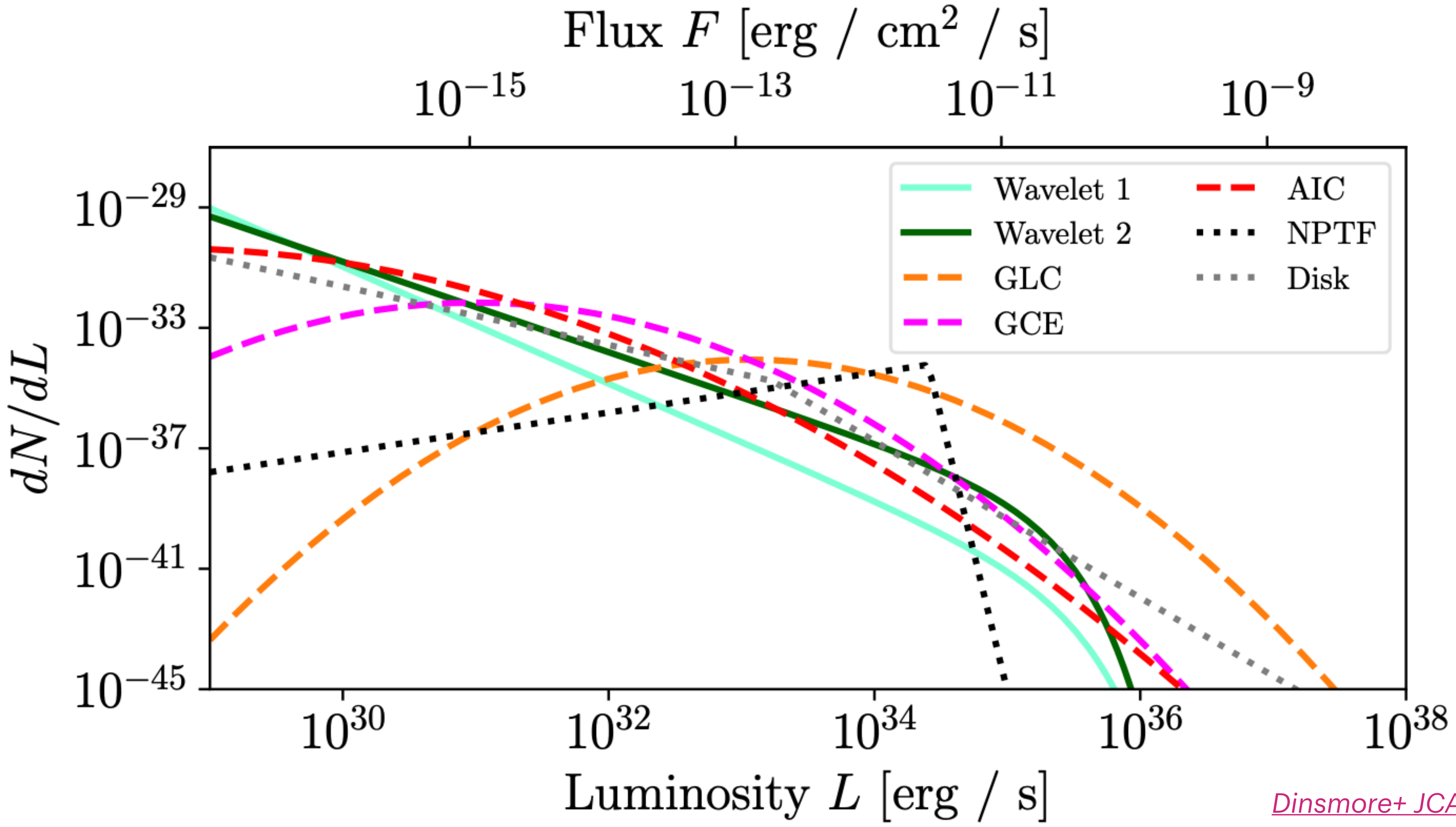
Ackermann+ ApJ'15



Fornasa & Sanchez-Conde Phys. Rep'15

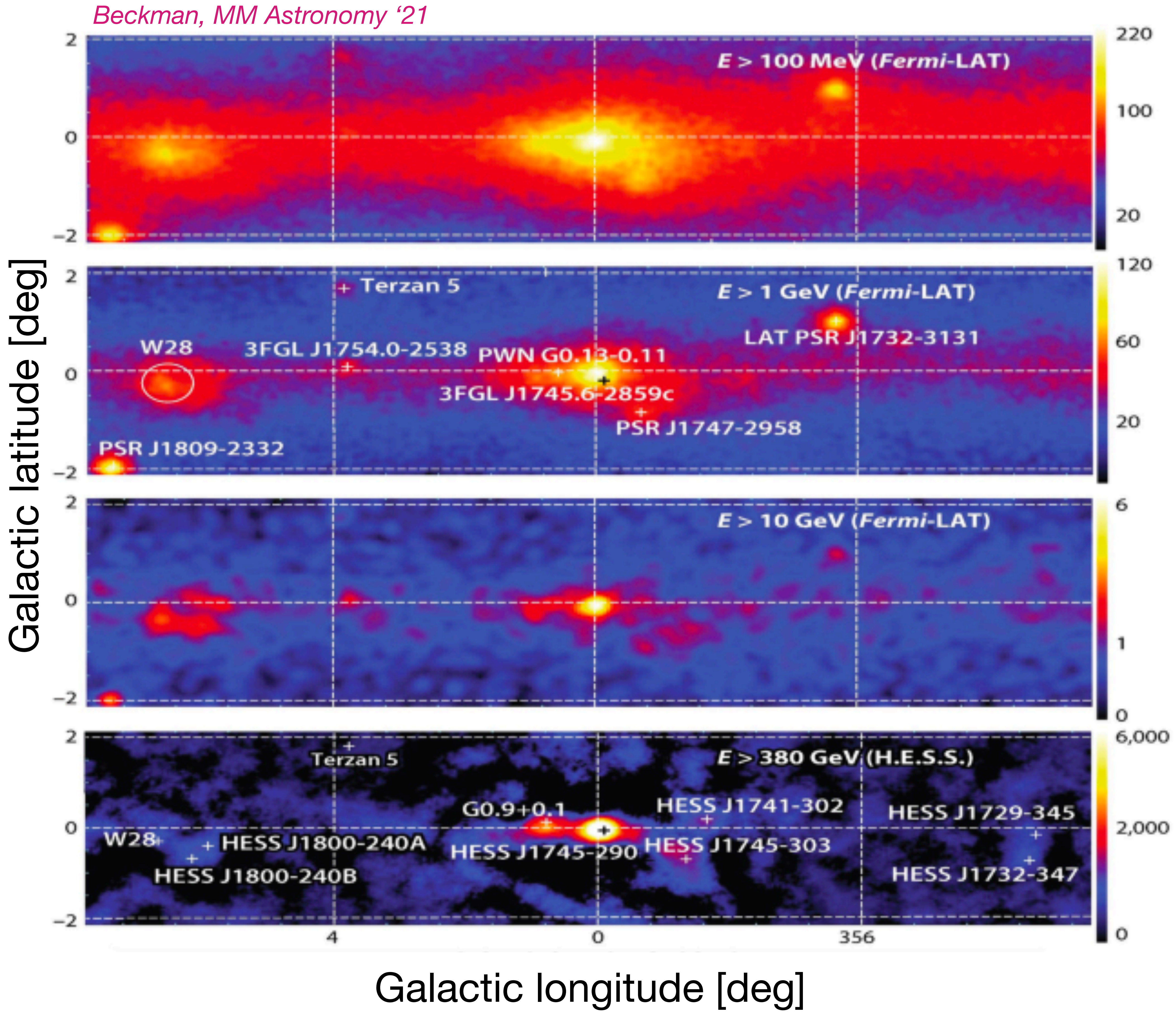


Galactic unresolved sources



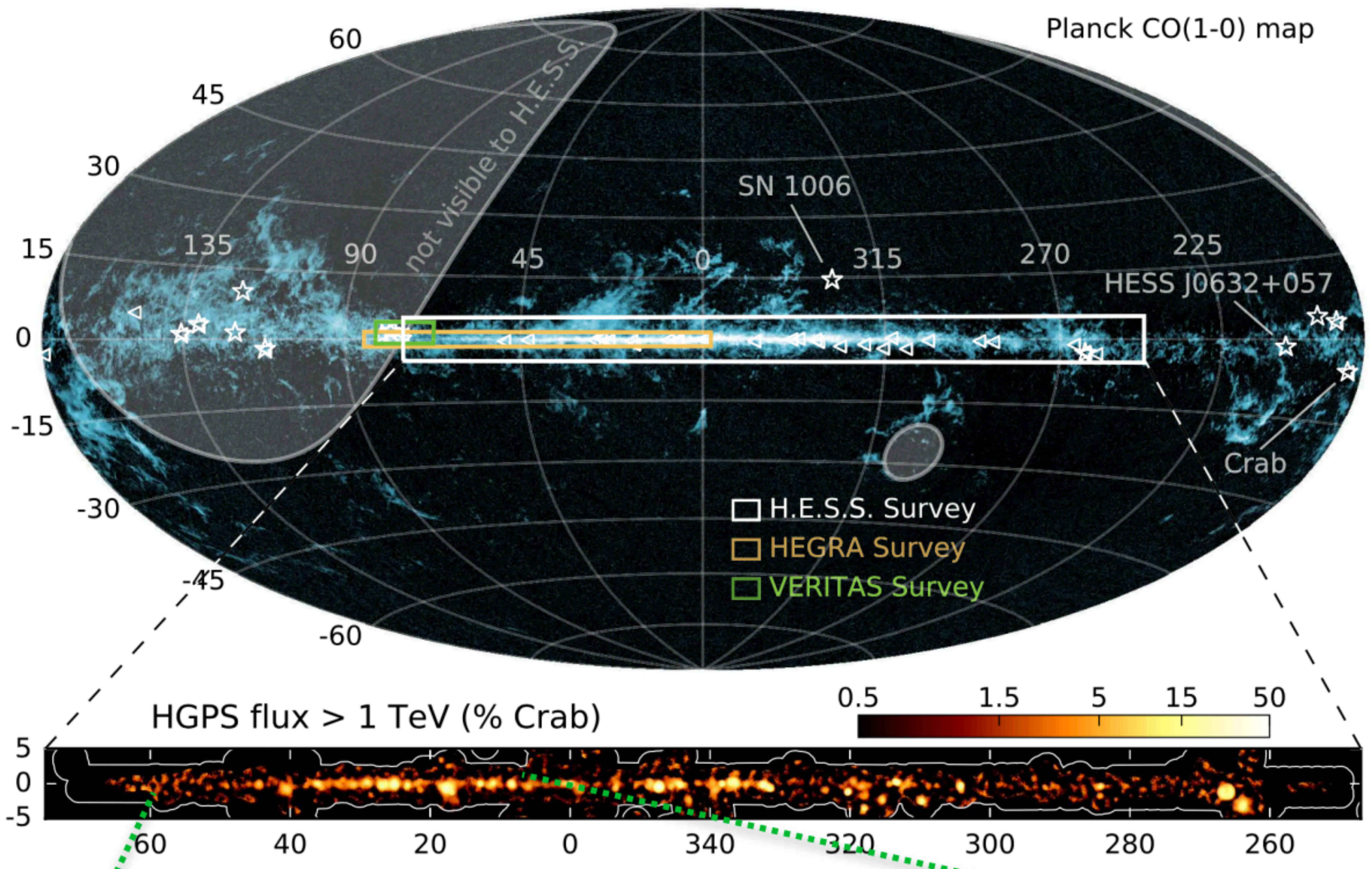
Dinsmore+ JCAP'22

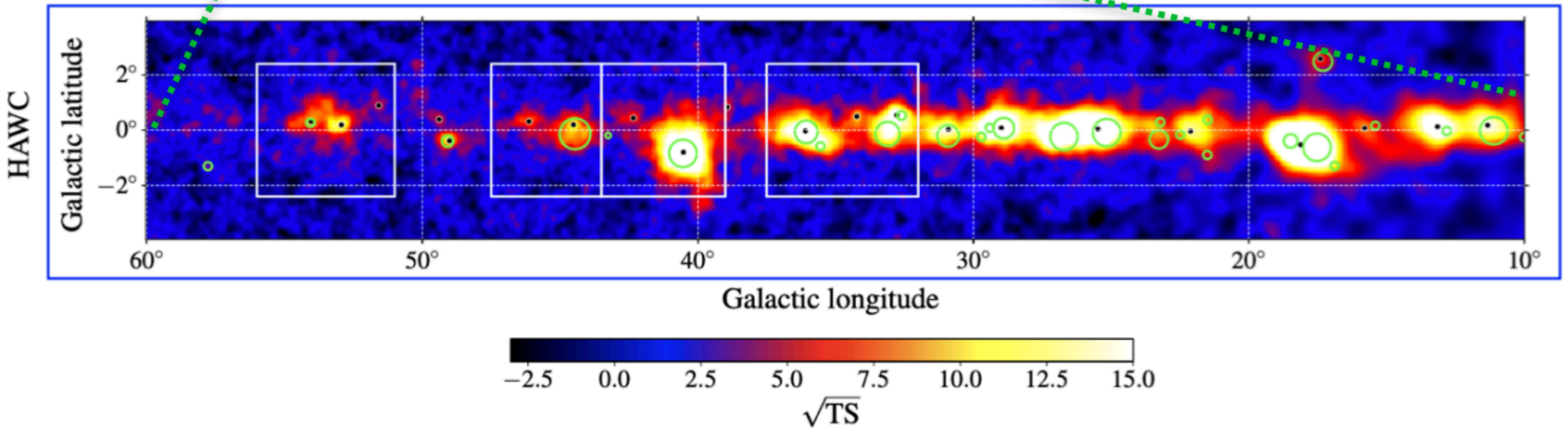
Diffuse emission from TeV to sub-PeV

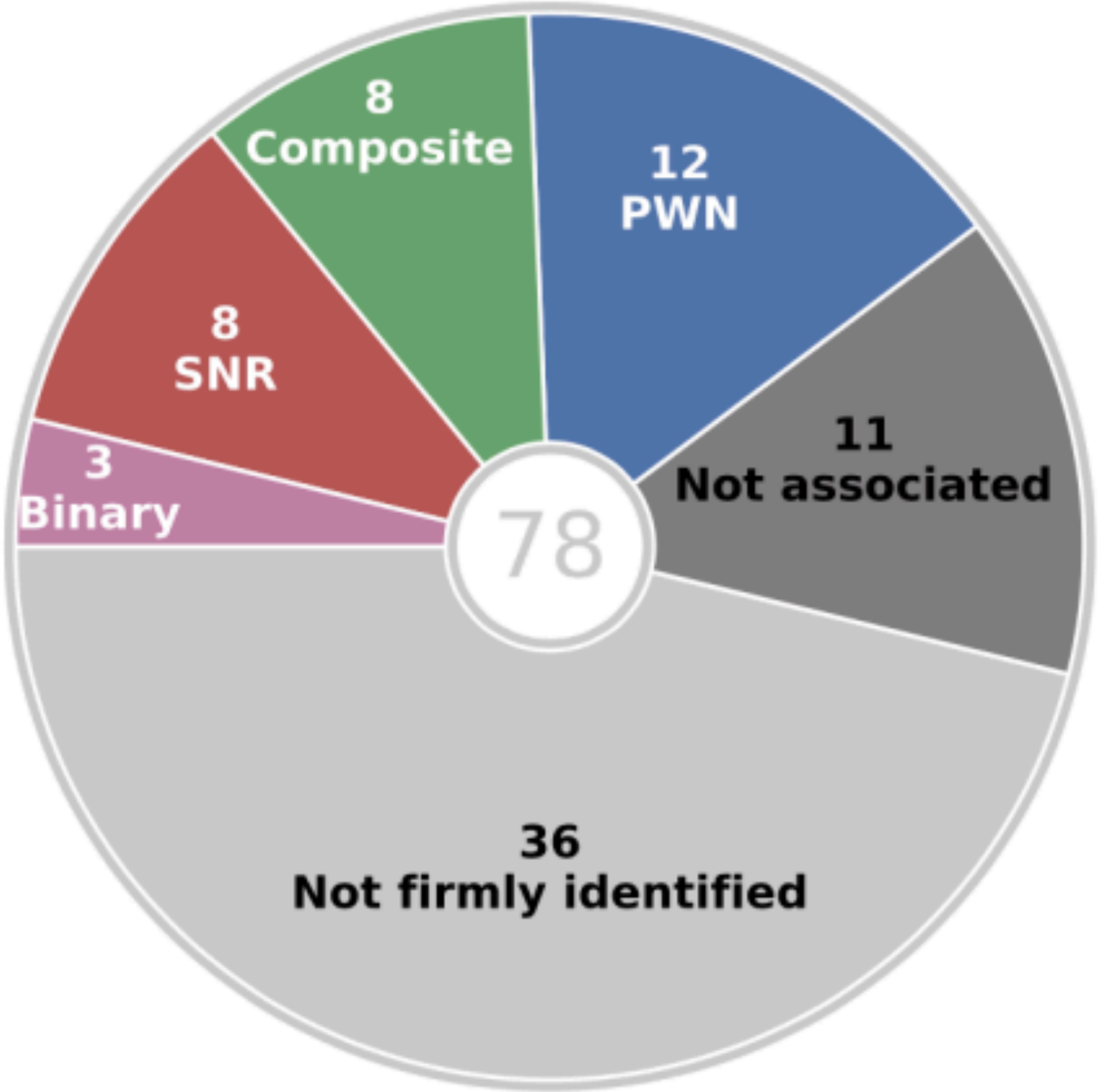


Point sources at TeV energies

Despite small FoV IACTs can perform effective surveys



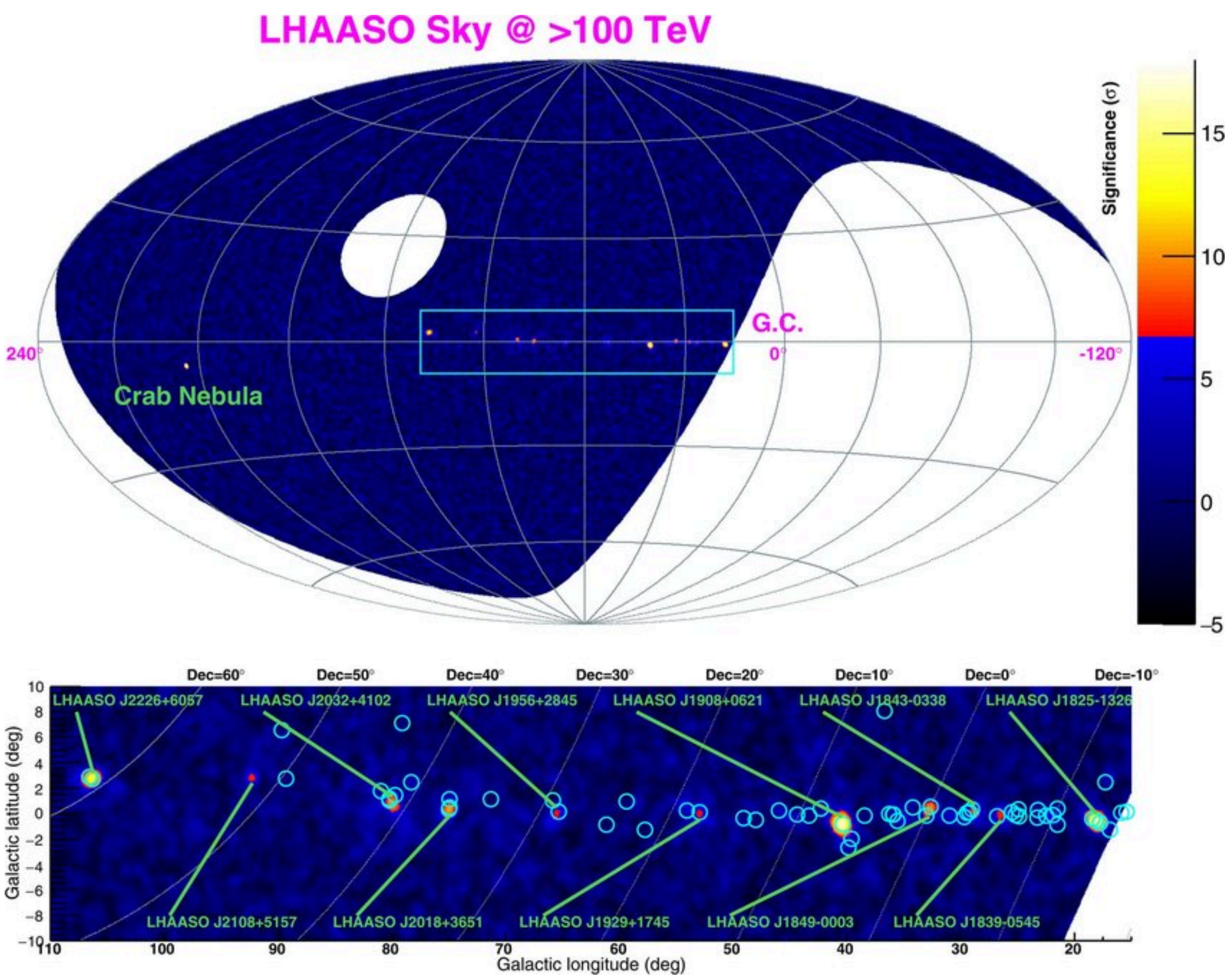


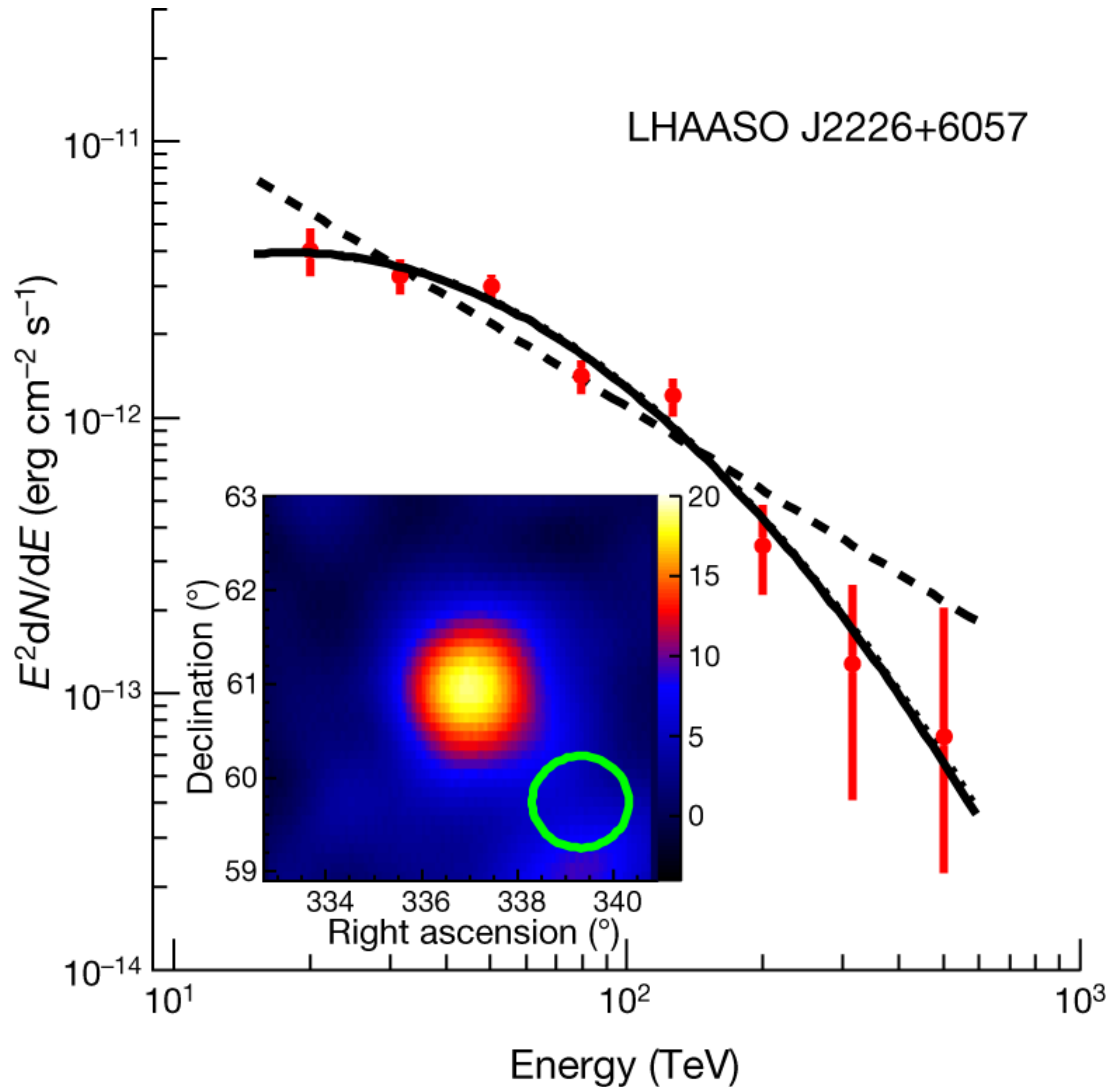


Galactic plane full of TeVatrons!

HAWC: Sources up to 100 TeV!

Point sources at sub-PeV energies





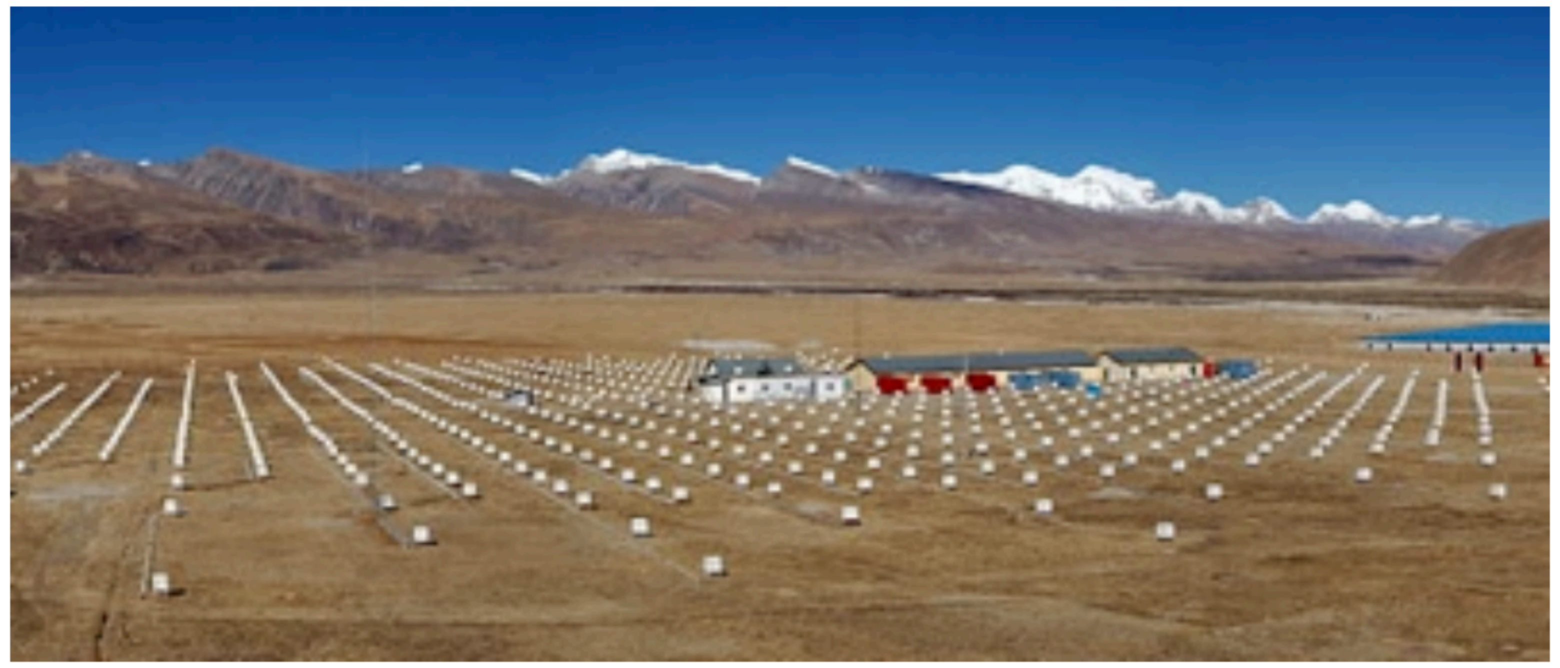
12 PeVatrons

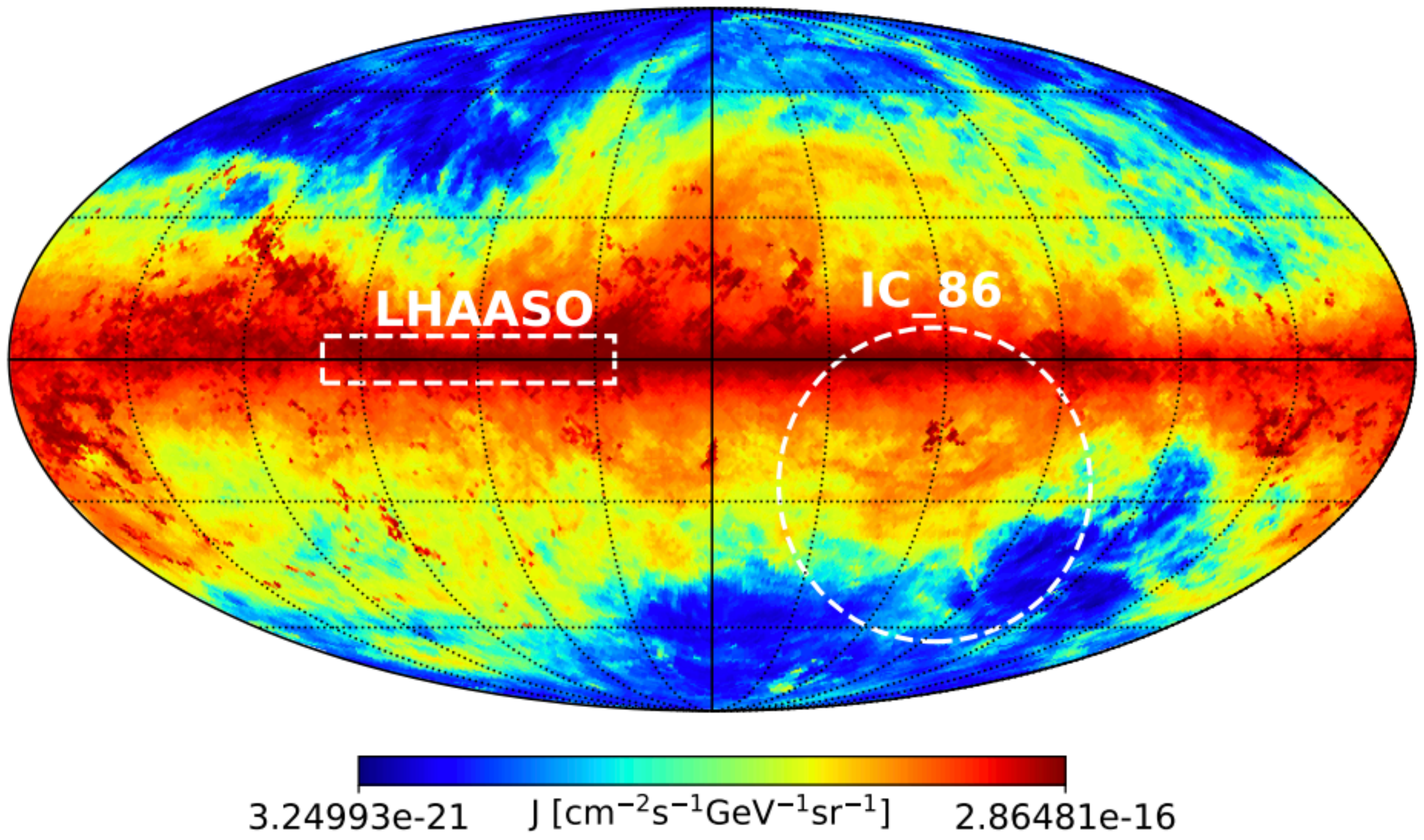
Diffuse emission: from TeV to sub-PeV


First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

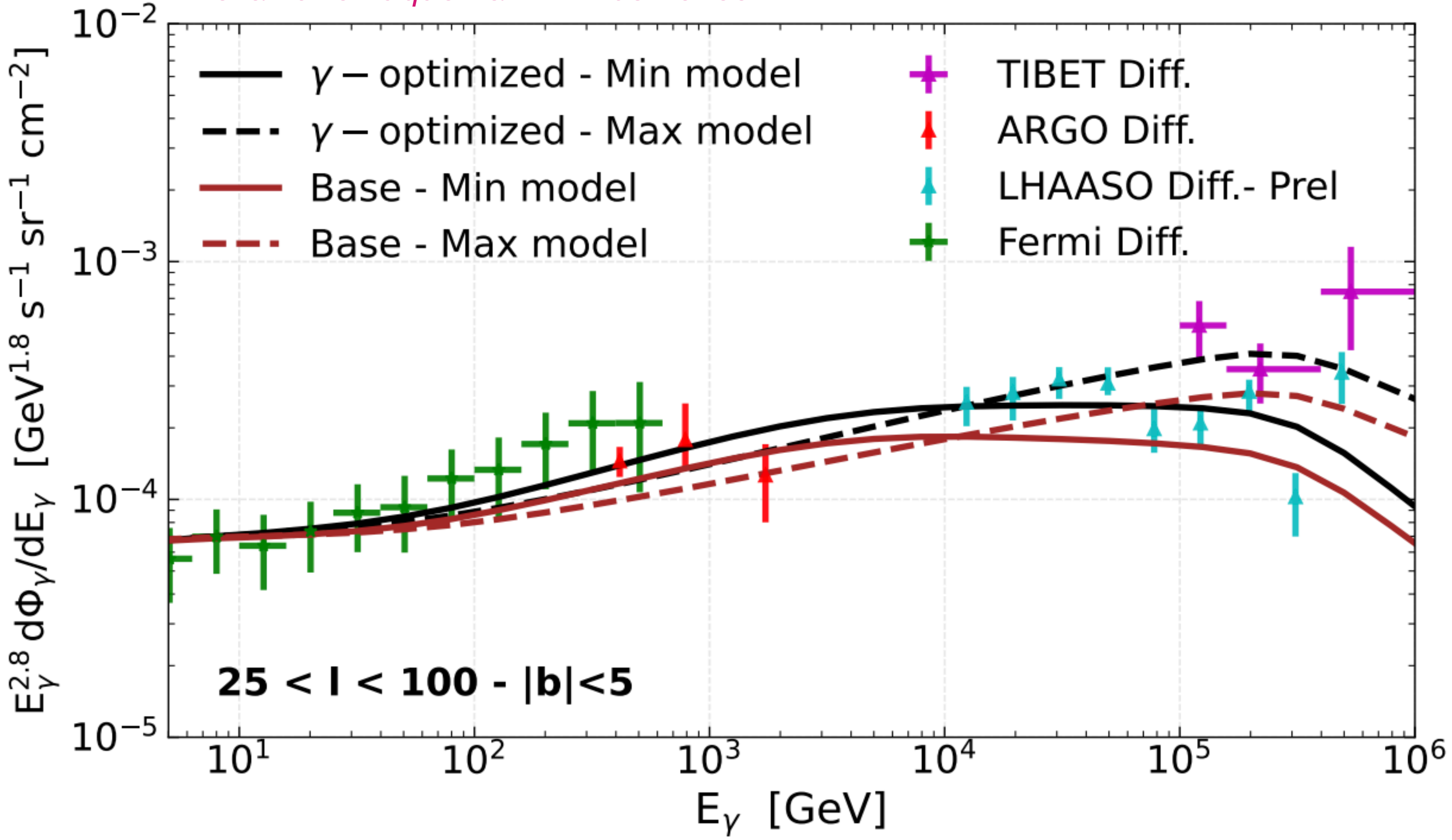
M. Amenomori *et al.* (Tibet AS_γ Collaboration)

Phys. Rev. Lett. **126**, 141101 – Published 5 April 2021





De la Torre Luque+ arXiv:2203.15759



Sources of cosmic particles: Exotic (astro)physics

Why do we want to look for new physics?

1. Physics BSM is strongly motivated
2. It already happened in the past to find some surprise in astro data which led to major discoveries (e.g. neutrino oscillations)
3. Anomalies in astroparticle observables do exist and BSM physics may be the answer
4. You expect astrophysical signatures of BSM physics. If you don't find them you can set constraints onto the relevant parameter space

Astroparticle observables can be either a **discovery** tool or a **constraint-setting** one

Challenges

Unusual scales of density, temperature, size, time, energy… if compared with what achievable in Earth laboratories!

Conceivable that some physics extrapolations may fail, highlighting new phenomena/regimes

We do not control the **environment**. This requires effort to understand astrophysics to devise ‘robust’ new physics **signatures** and validation tests

Main goal: Help you to schematise some research direction in **dark matter/BSM** searches

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 dark matter 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

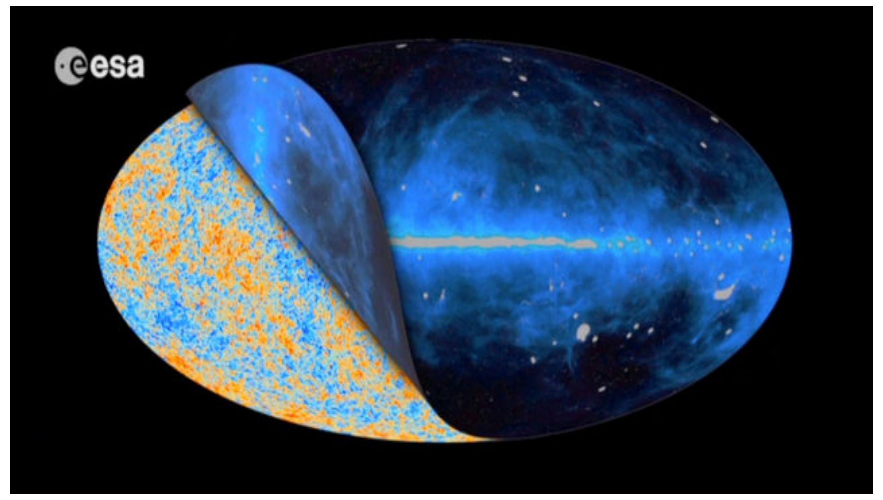
What is a signature?

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

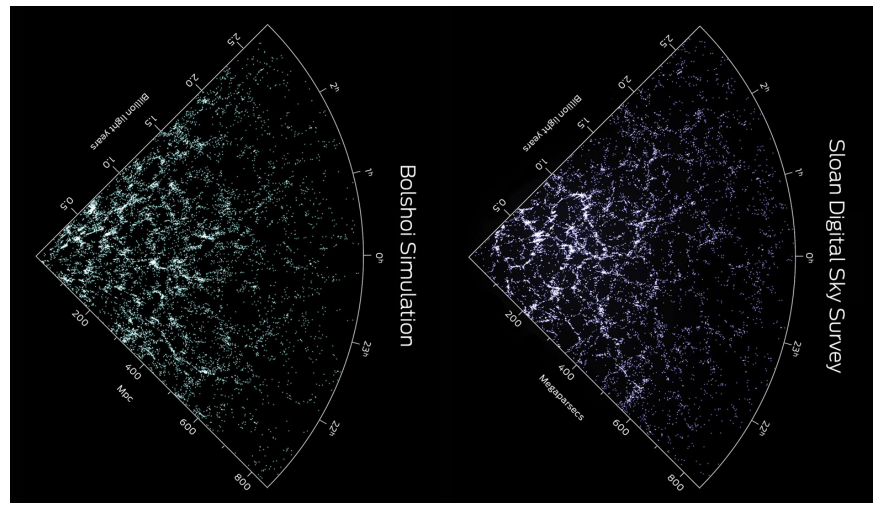
Detection vs constraints

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

The dark matter landscape

Vast parameter space in mass and interaction strength

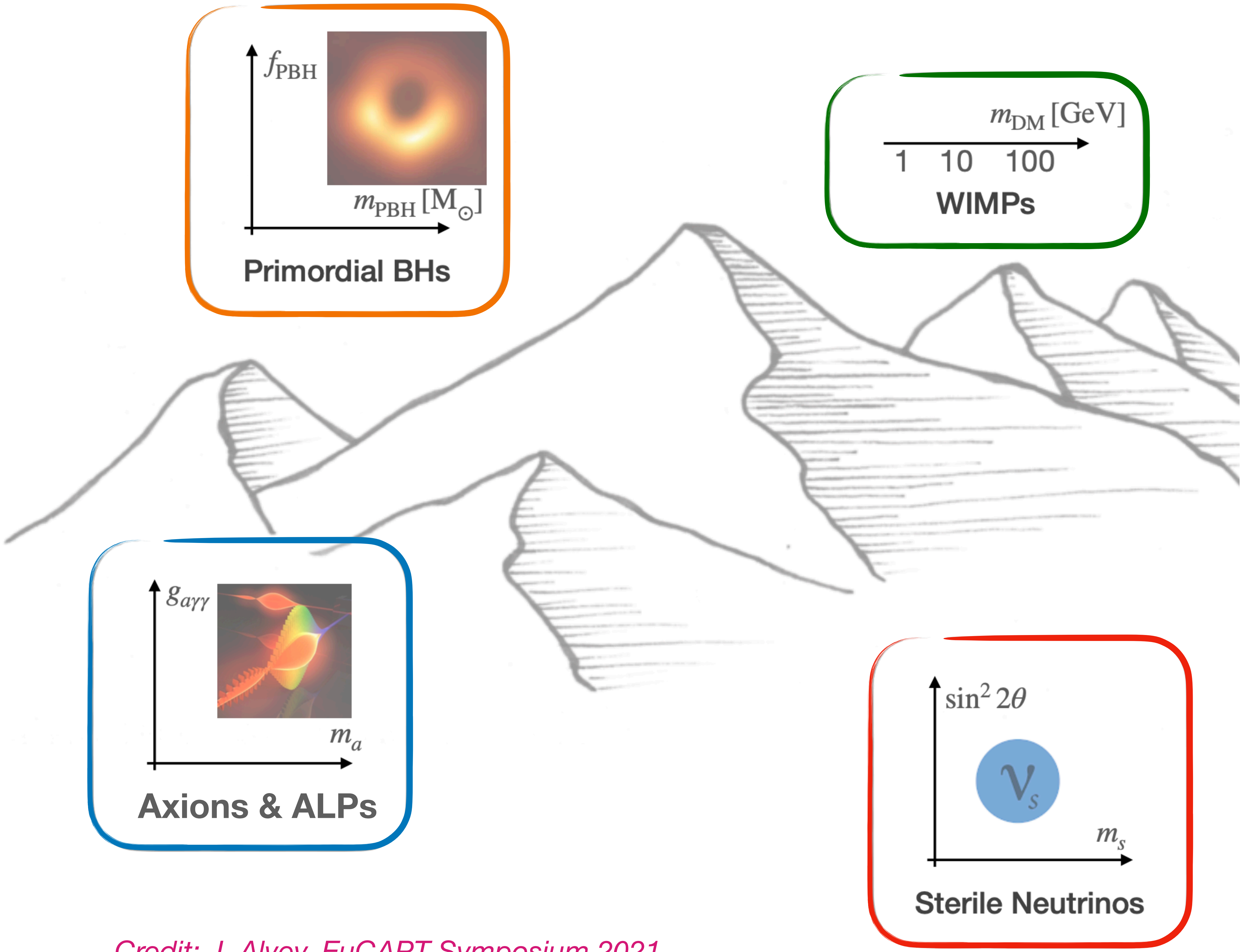
The dark matter landscape

The dark matter landscape

10^{-19} eV | μeV | 0.1 eV | keV | MeV | GeV | 10^2 TeV | $10^{-16}\,M_\odot$ | $10\,M_\odot$ | $10^3\,M_\odot$

Fuzzy DM | QCD axion/ALPs | Sterile ν | WIMPs | Primordial BHs

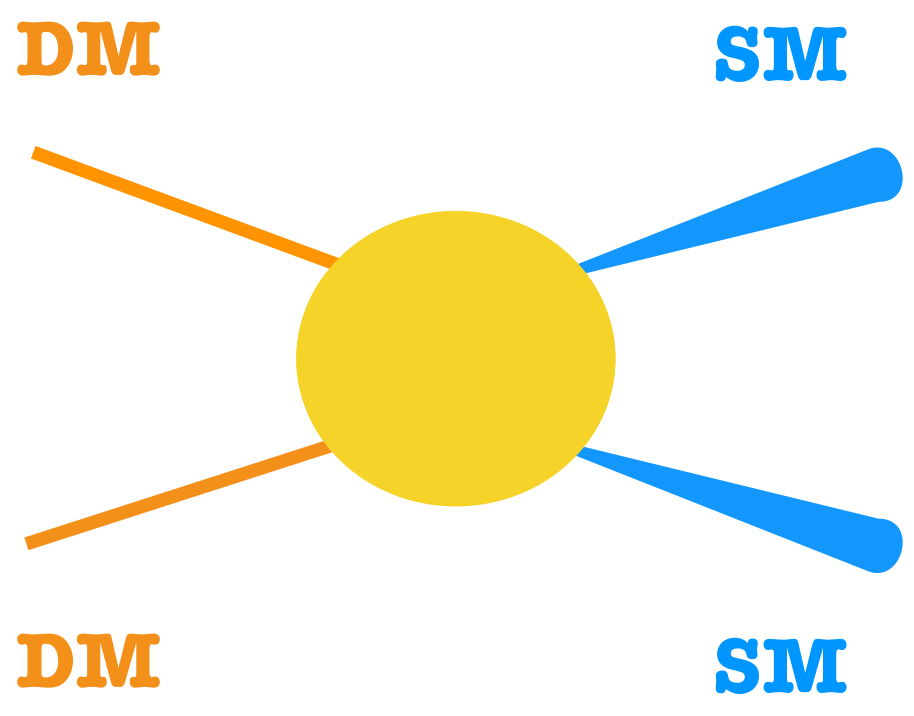
- Identification strategies are necessarily (more or less) **model dependent**
- The **theoretical prejudice** in dark matter searches is also set by what we can probe with available data
- You always need some sort of signature of your model!



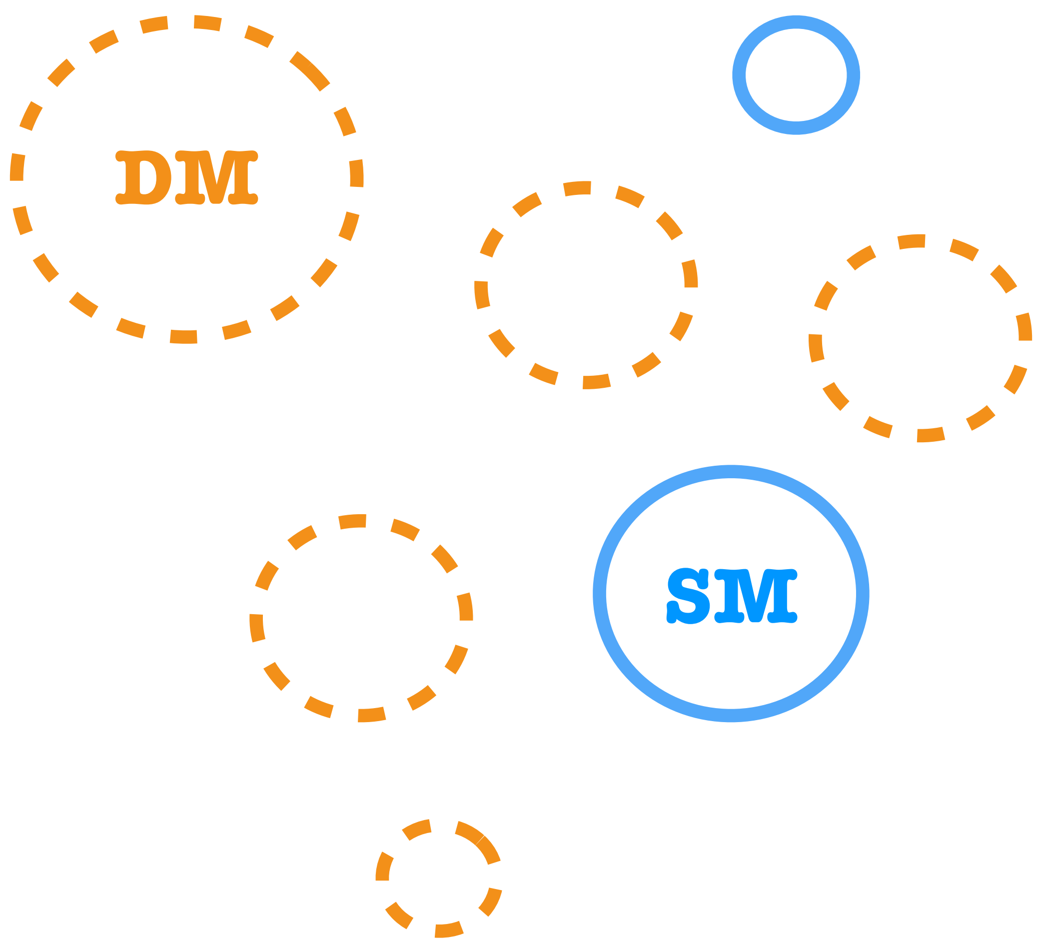
Credit: J. Alvey, EuCAPT Symposium 2021

Dark matter indirect detection

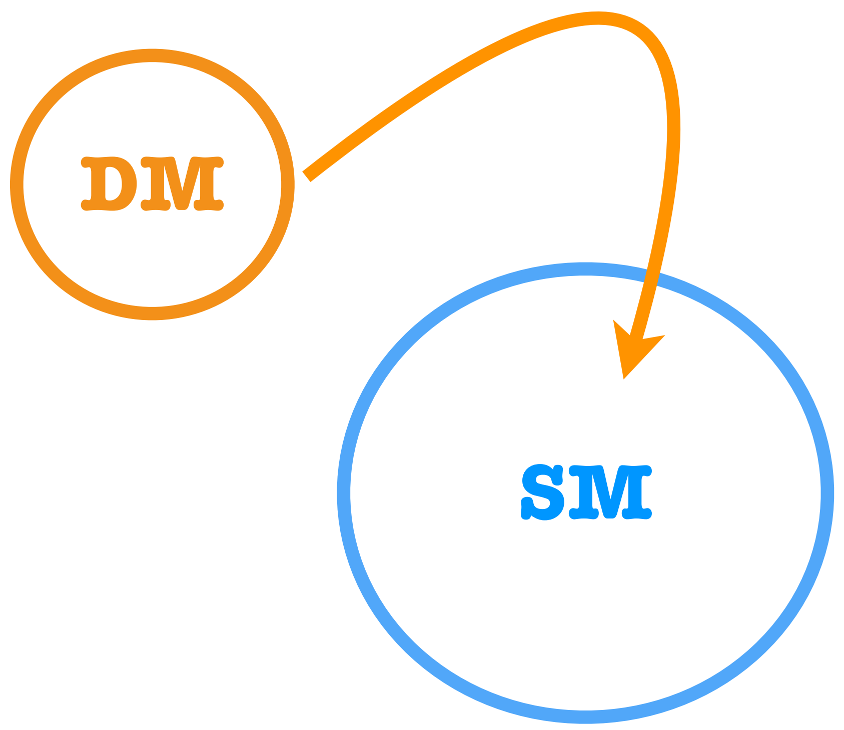
What dark matter does



Energy/particle injection



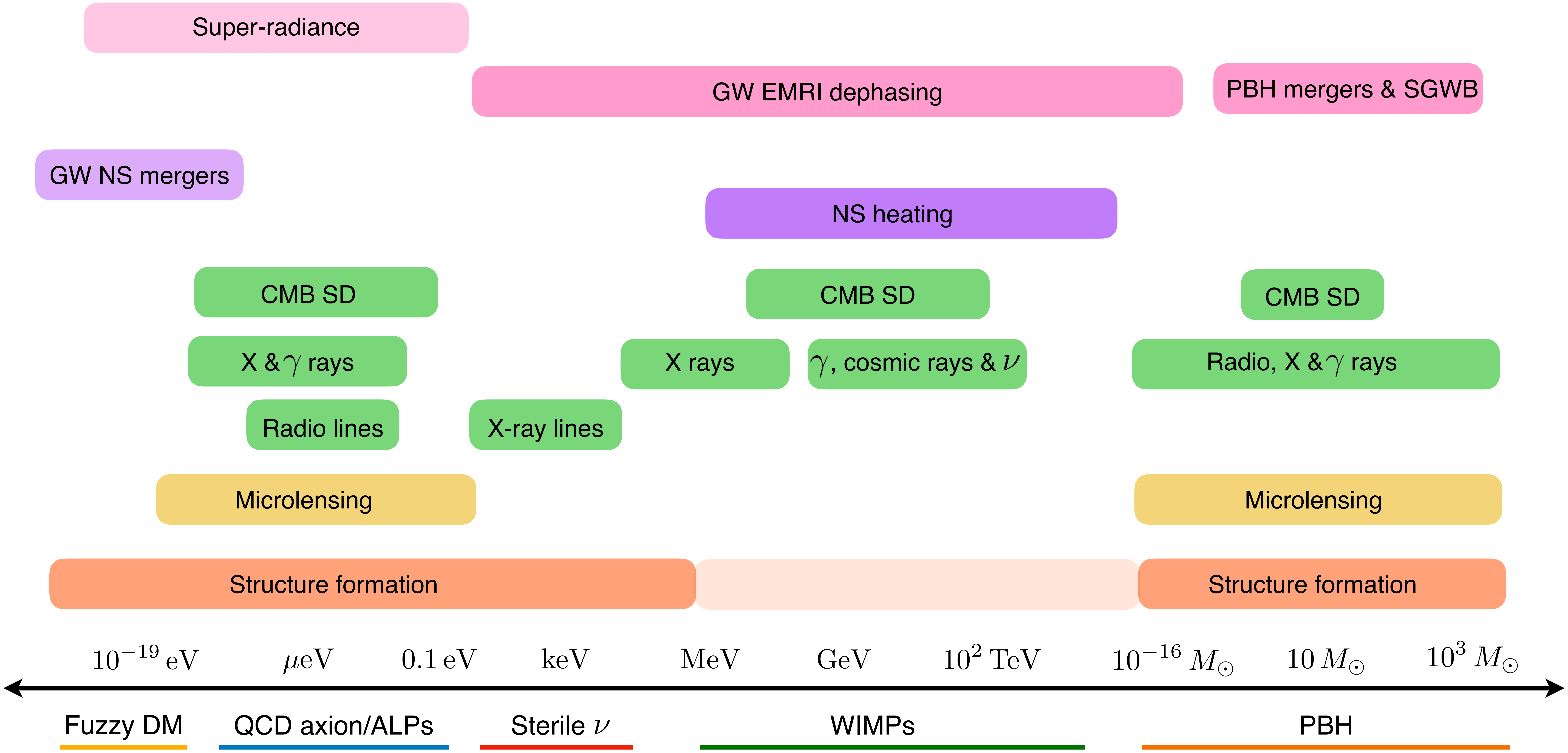
Gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

Astroparticle observables for dark matter

EuCAPT White Paper, arXiv:2110.10074



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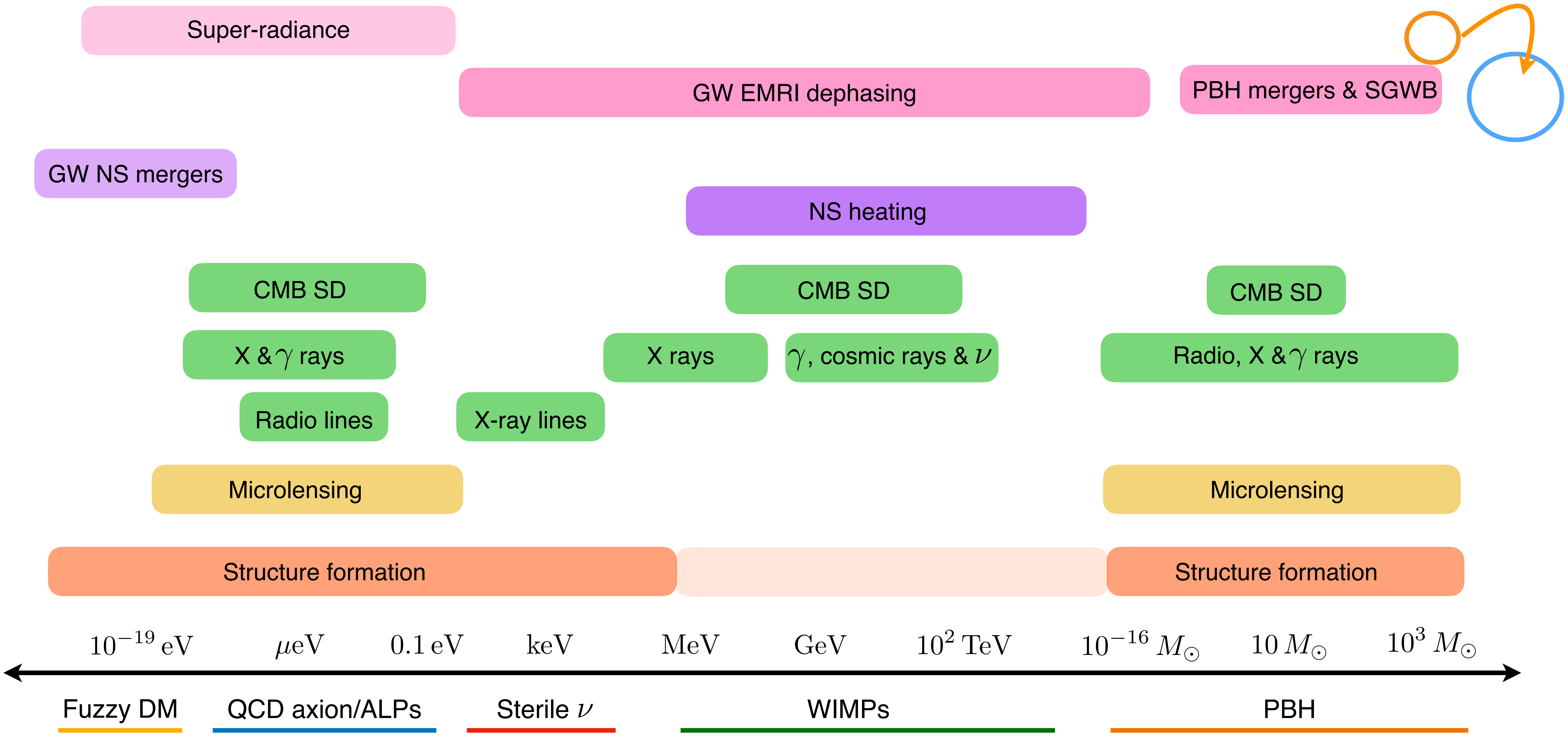

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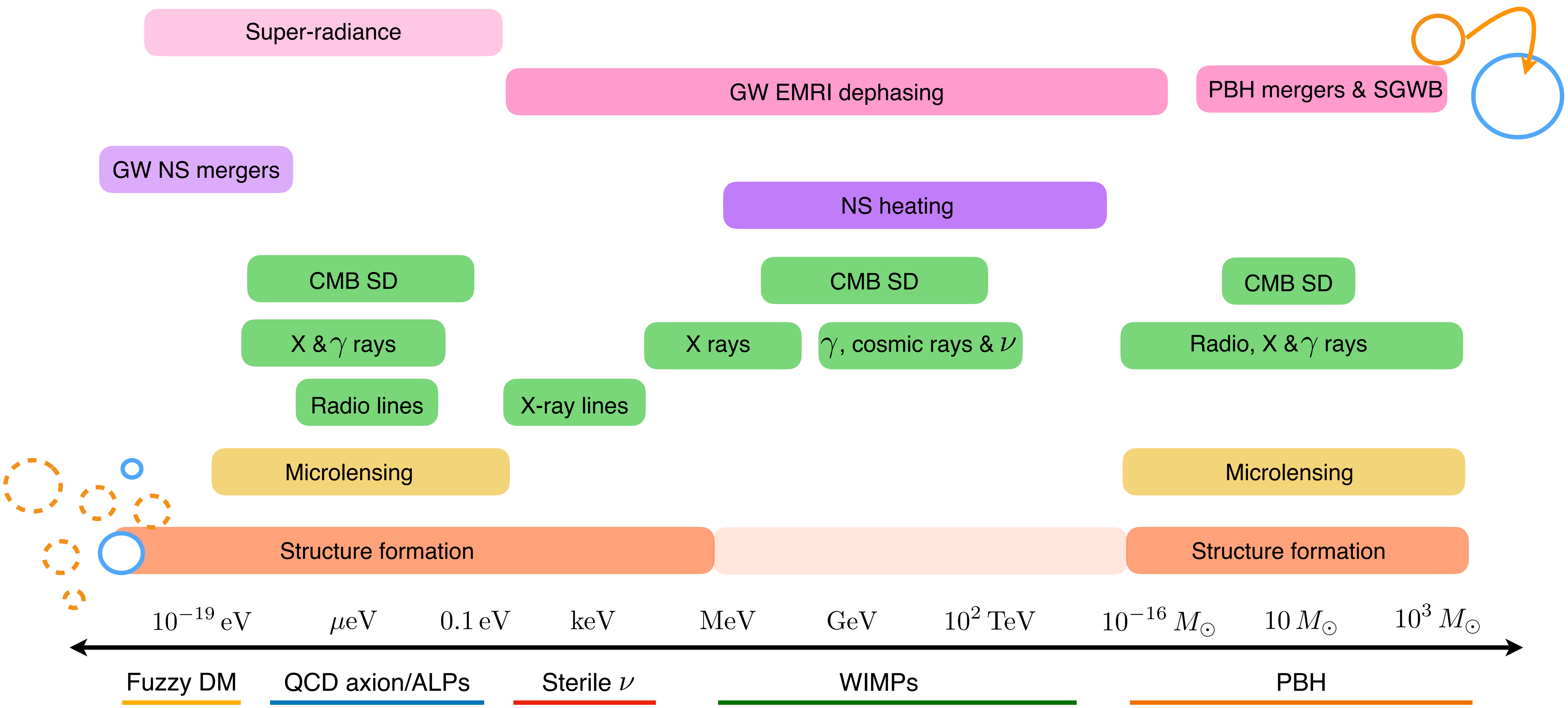

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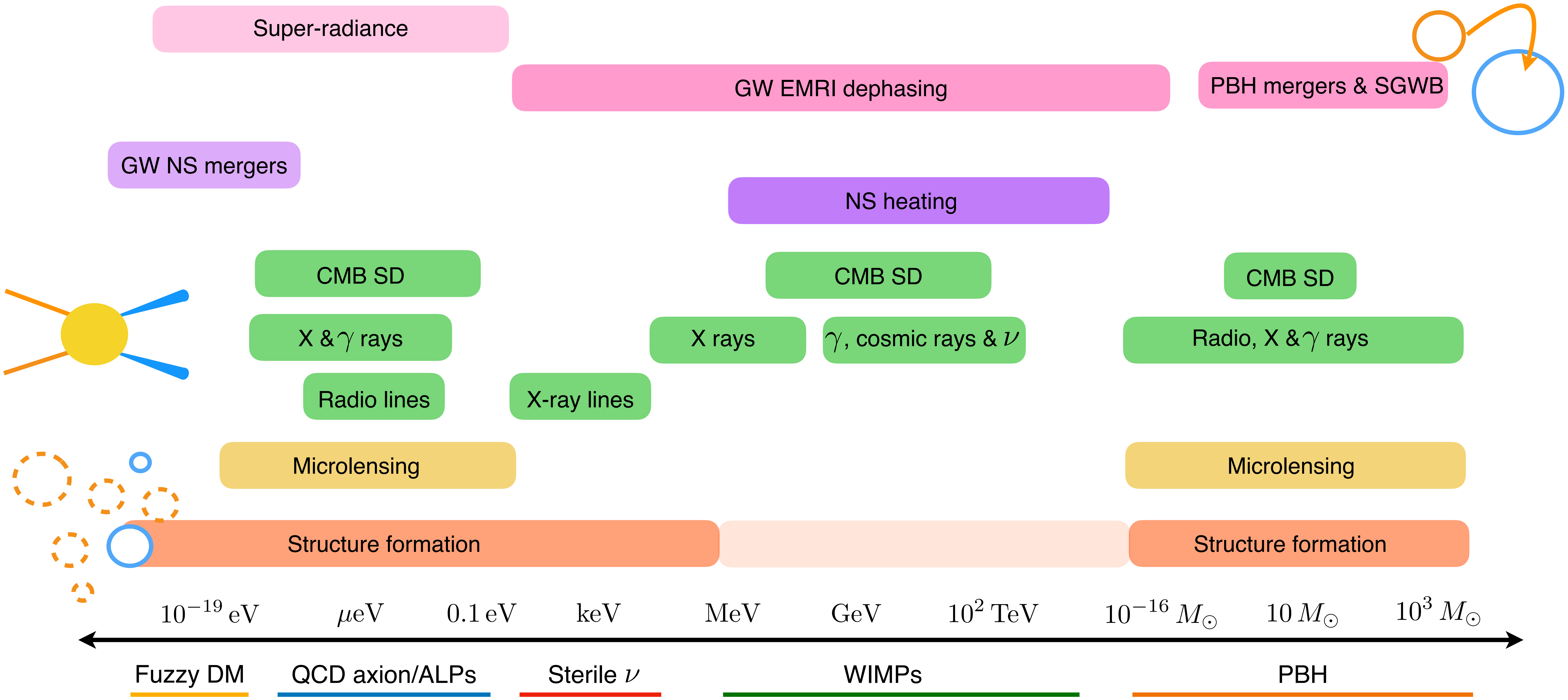
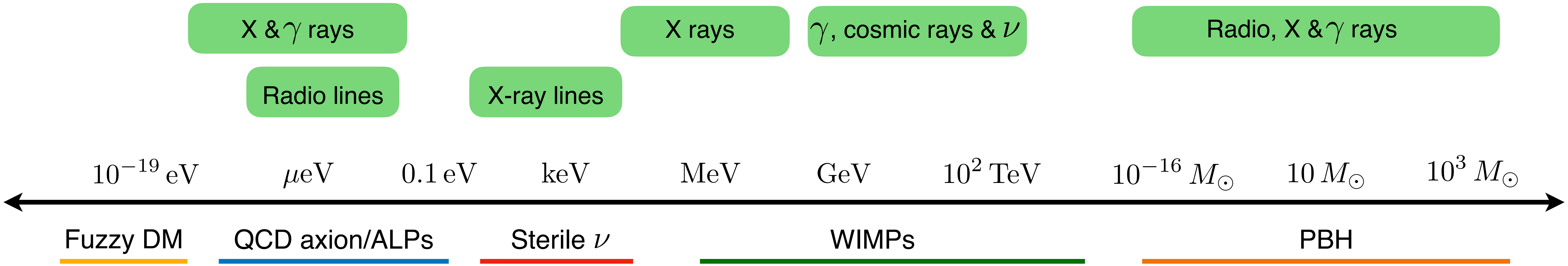


Travelling messengers



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

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

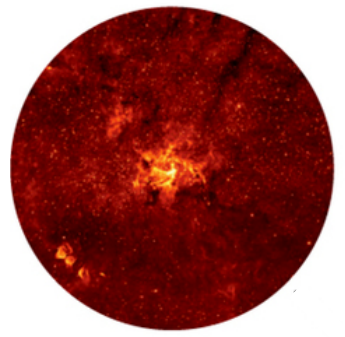
DM velocity dispersion (Maxwell-Boltzmann distribution)

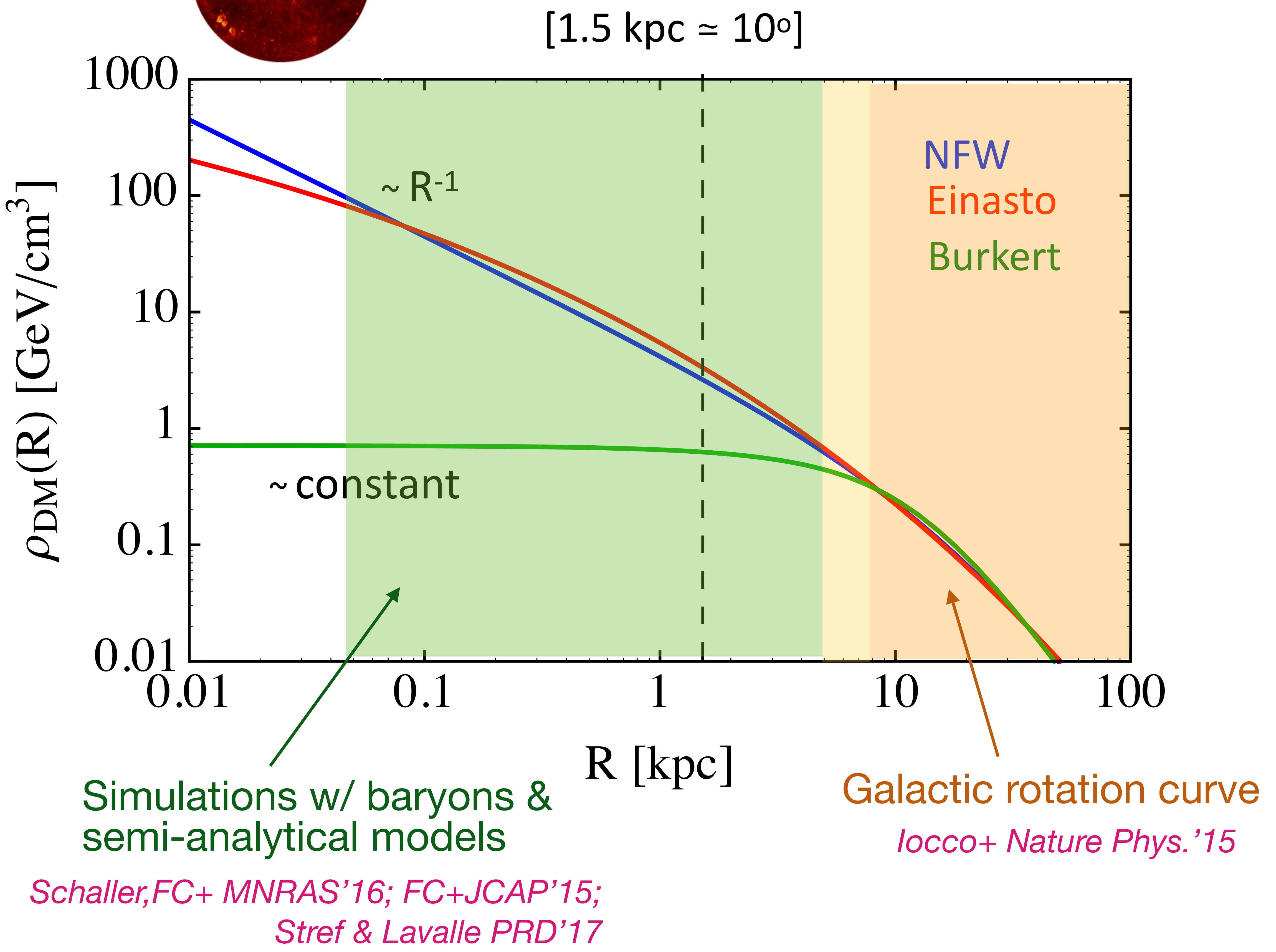
=> Decay or self-interactions of DM in the halo of galaxies at z=0 occur at rest

Common astrophysical ingredients

Halo dark matter density

- The distribution of DM in galaxies is affected by large uncertainties
- **Unavoidable modelling uncertainty** to account for when deriving constraints on DM models
- Rely on simulations of galaxy formation to get small-scale density profile and sub-halo distribution
- Less of an issue in dwarf galaxies

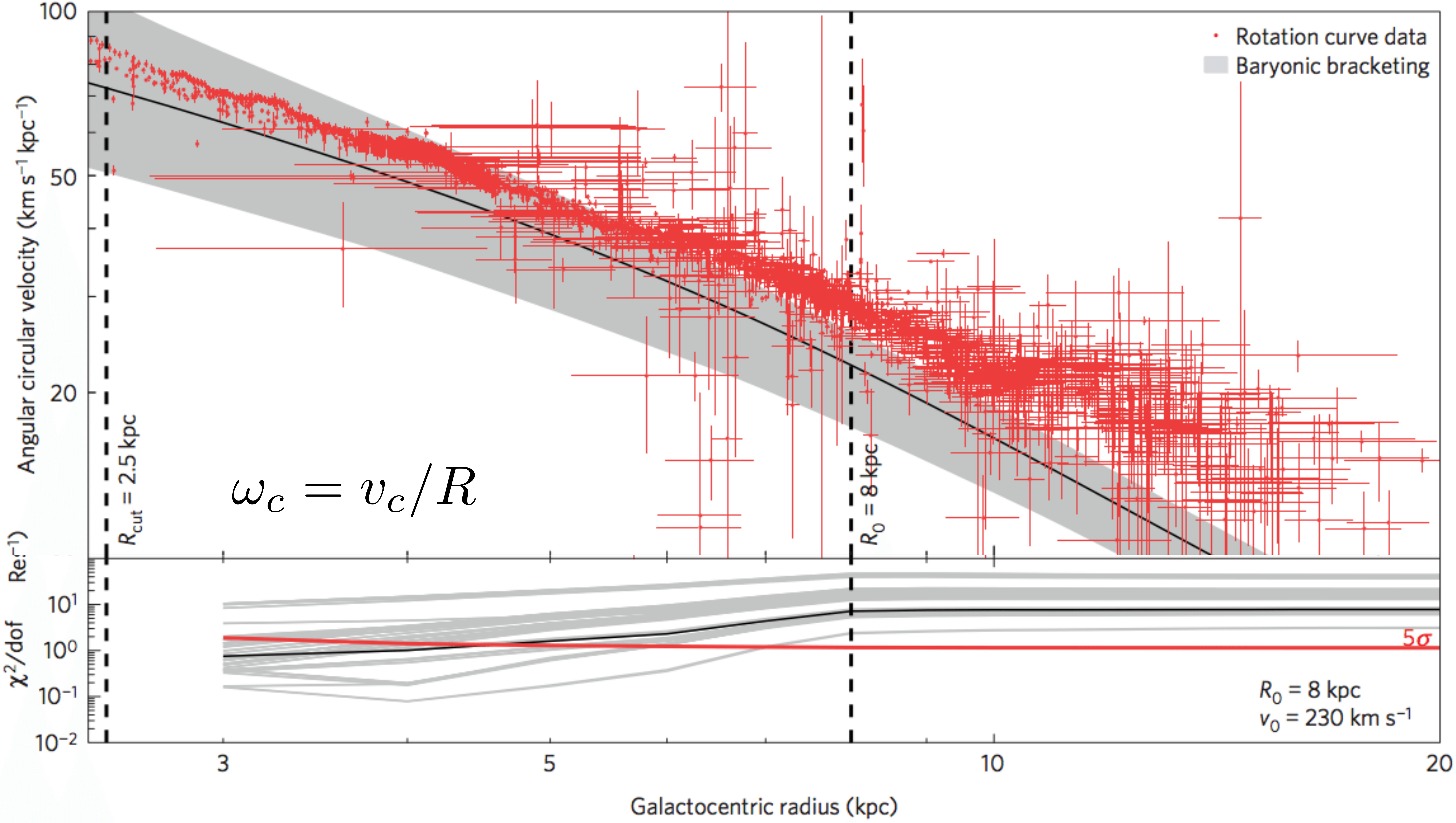




[All profiles normalised by measure of **local DM density** at **R_{Sun}**]

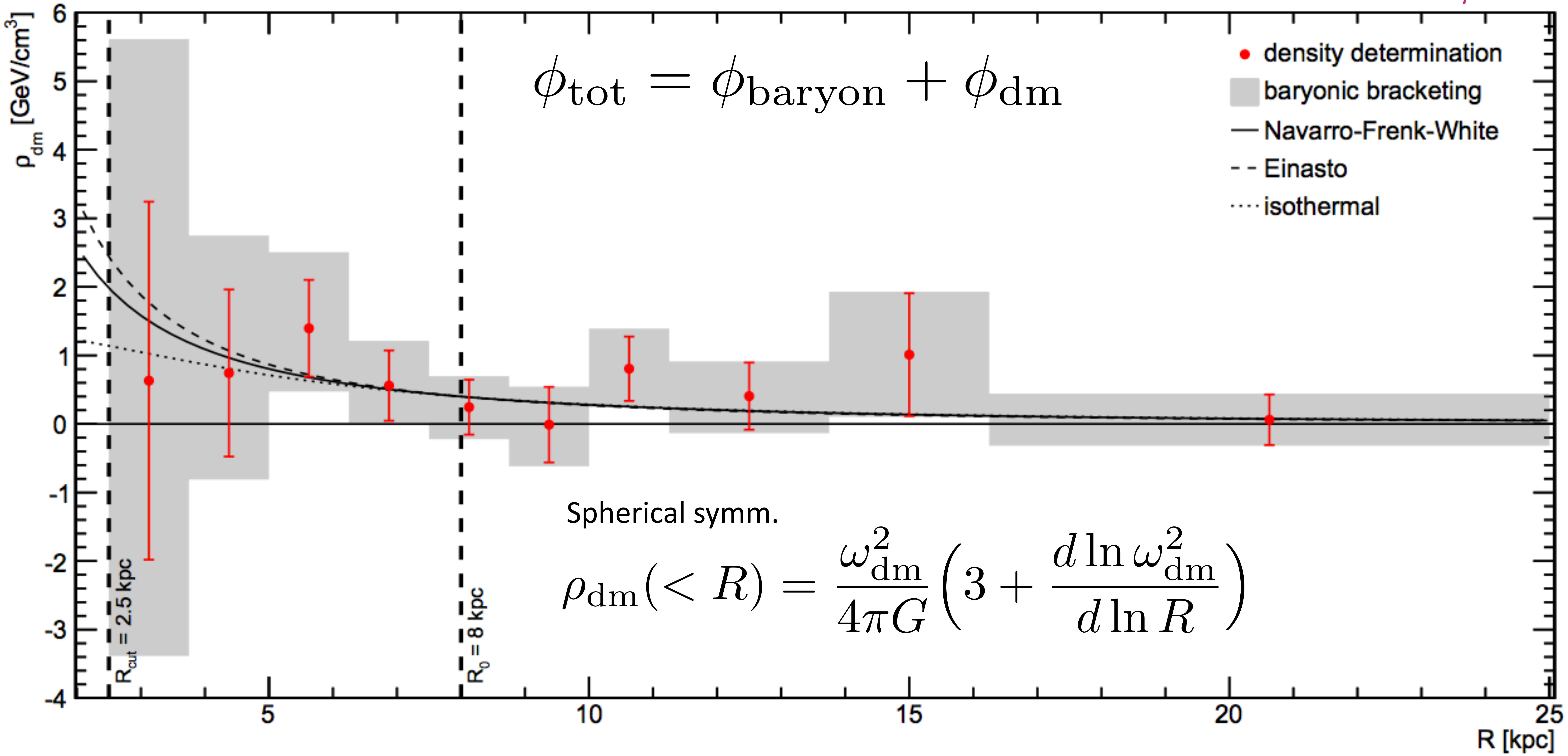
Milky Way rotation curve

Iocco+ Nature Physics'15



Milky Way DM density

Pato&Iocco+ ApJ'15



$$\phi_{\rm tot} = \phi_{\rm baryon} + \phi_{\rm dm}$$

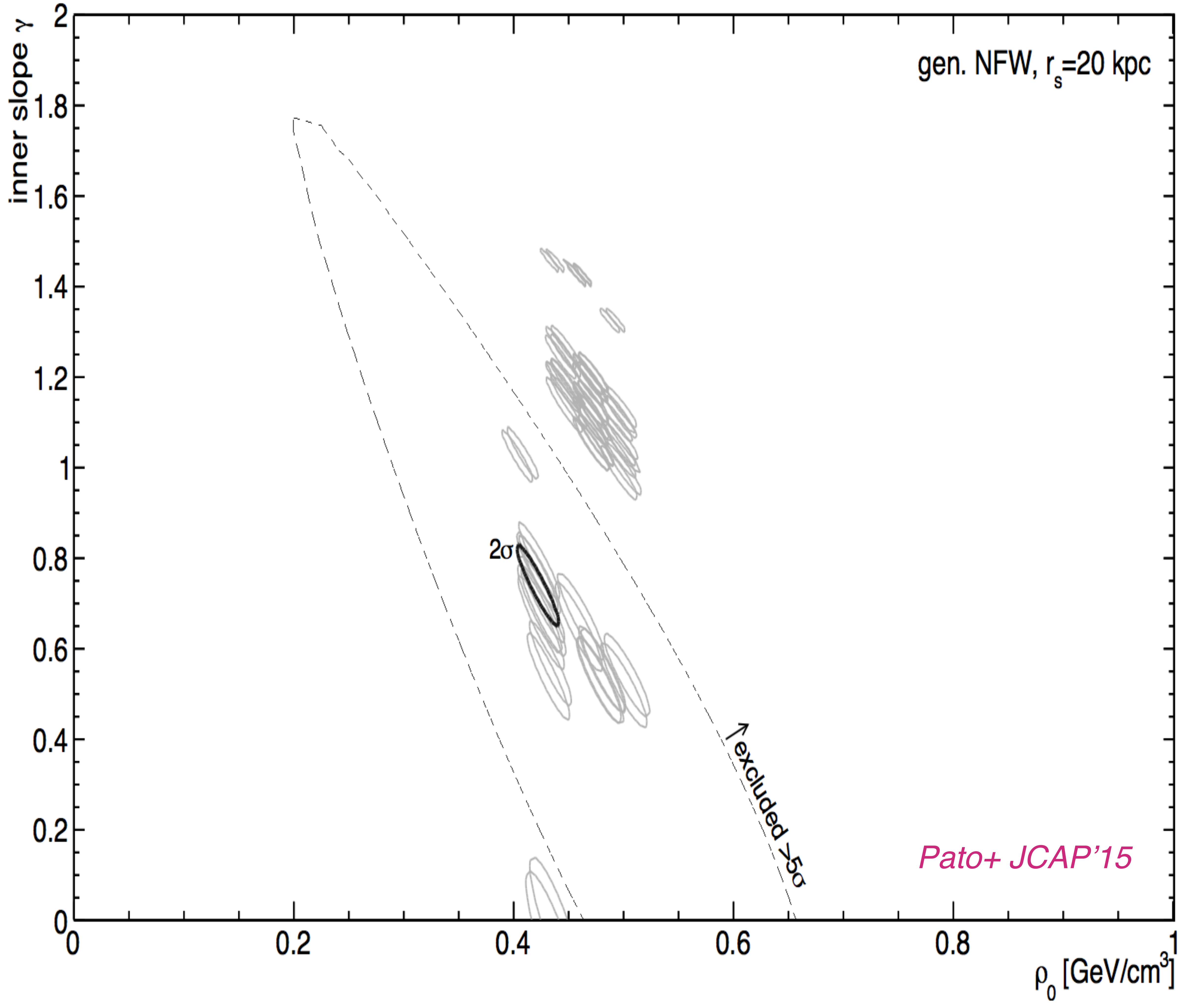
Spherical symm.

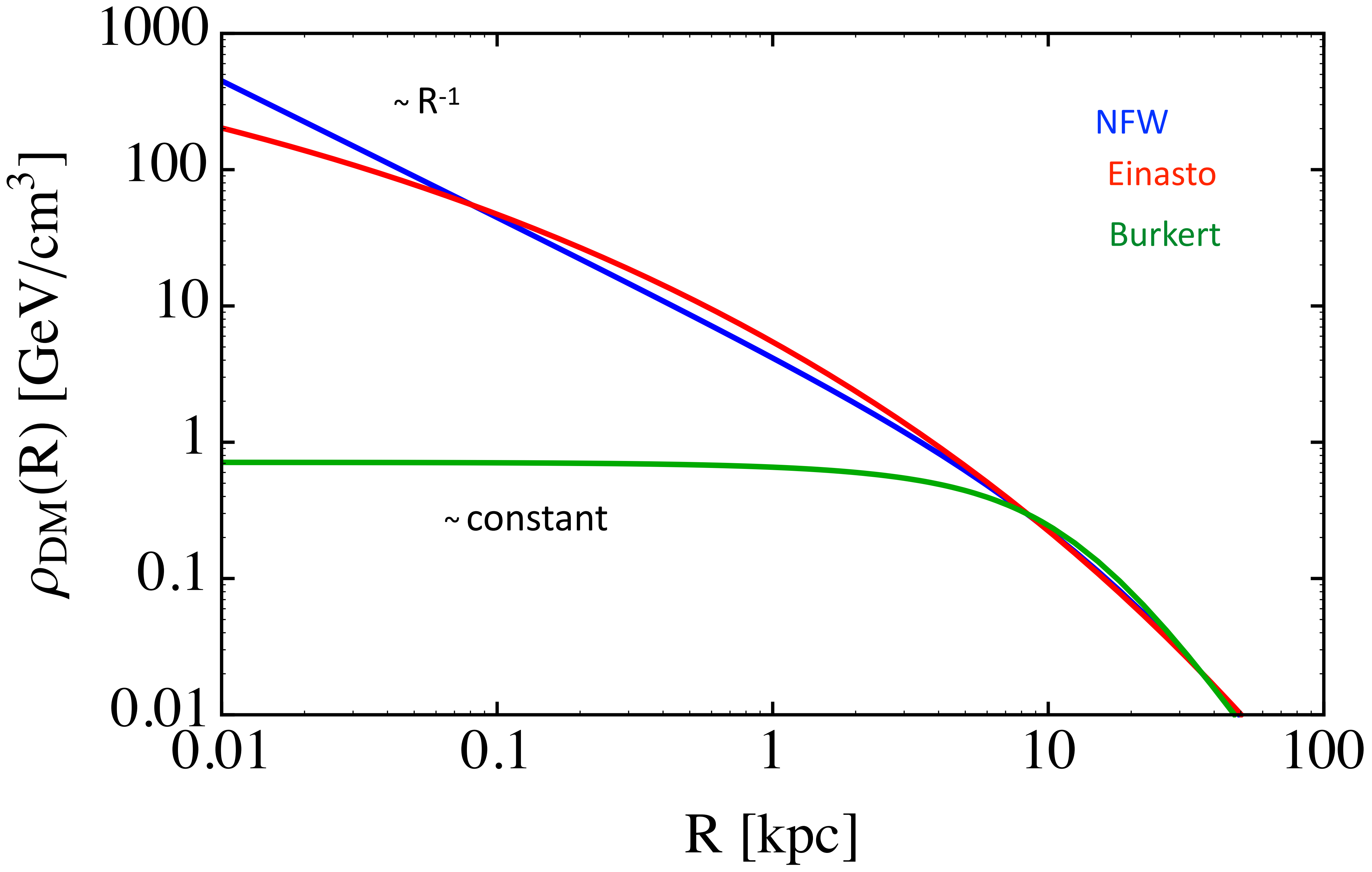
$$\rho_{\rm dm}(< R) = \frac{\omega_{\rm dm}^2}{4\pi G}\left(3 + \frac{d\ln\omega_{\rm dm}^2}{d\ln R}\right)$$

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

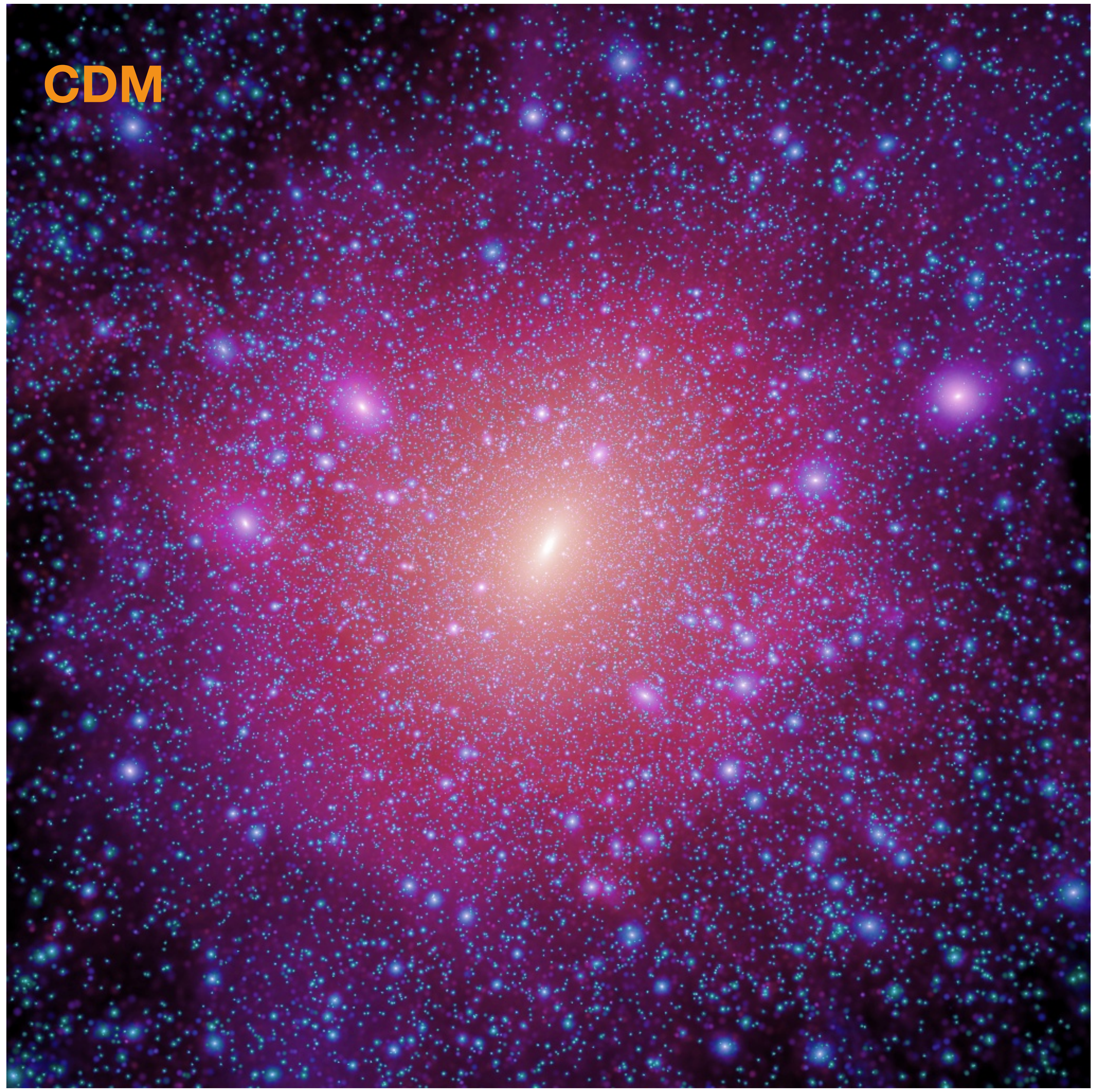




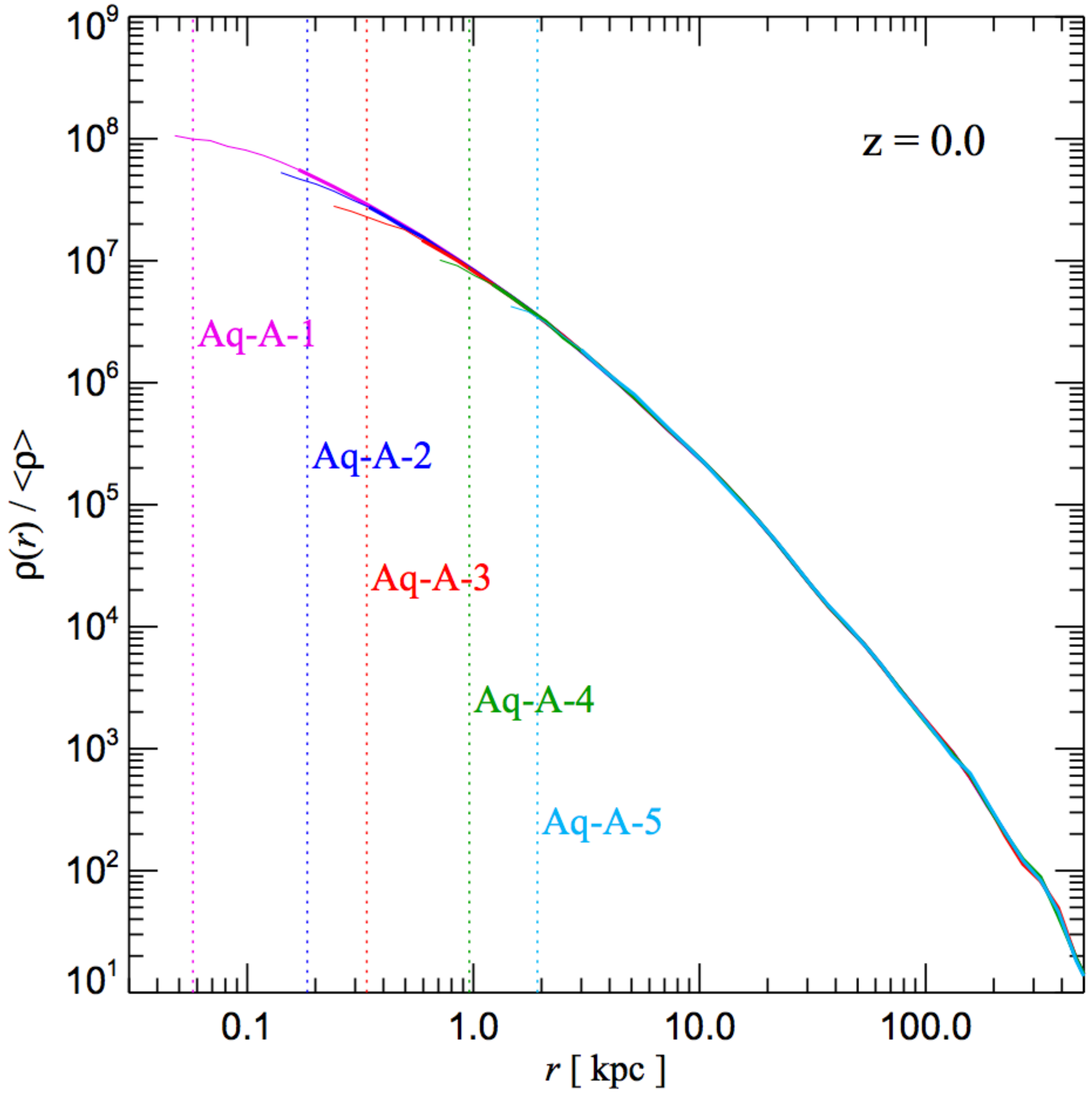
Parametric reconstruction: strong profile assumptions, "global" method to derive local DM density.

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

DM density in haloes



Springel+ MNRAS'08

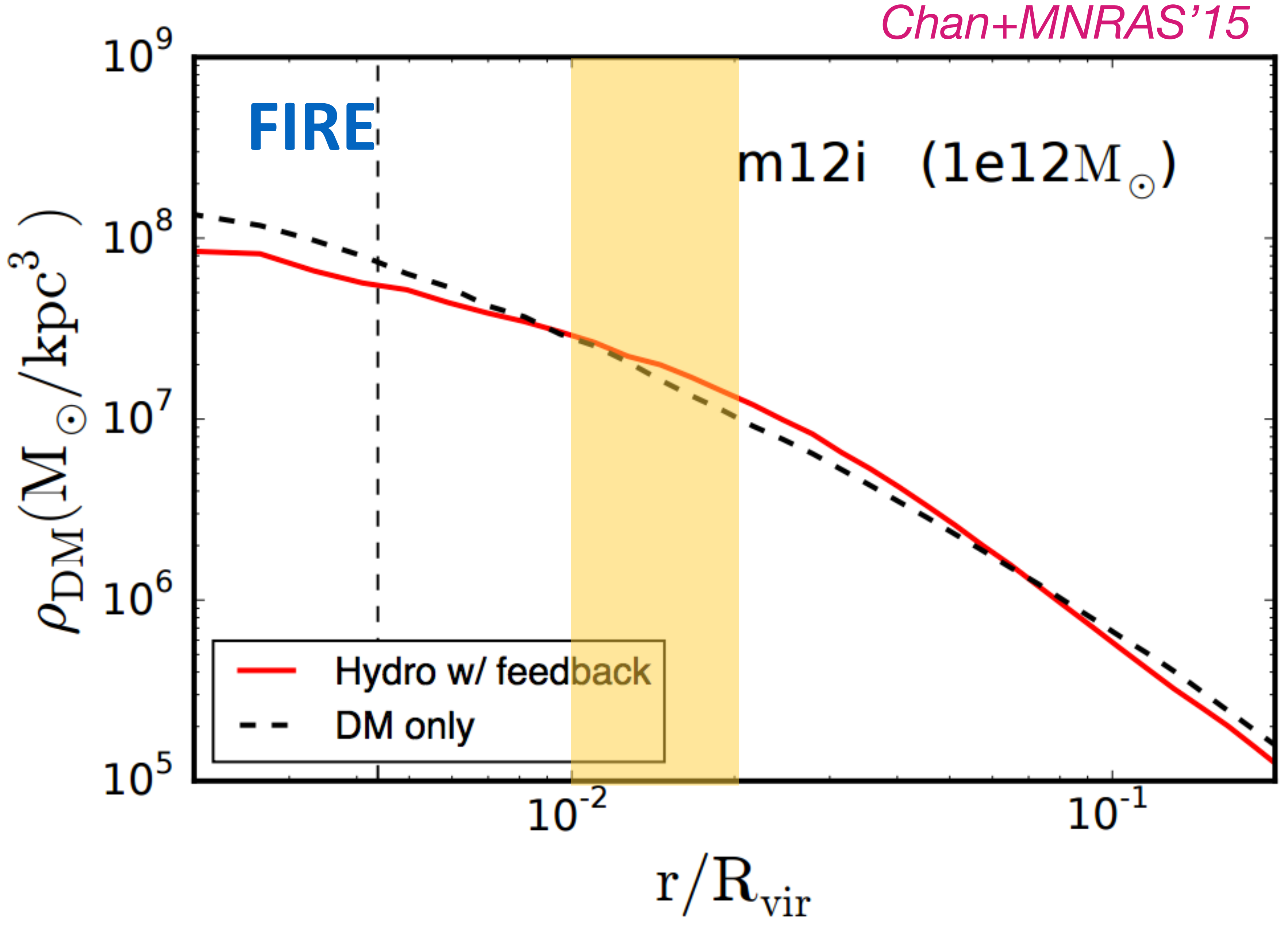


$$\rho_{\rm tot}(R) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{R}{r_s}\right)^{\alpha} - 1\right]\right\}$$

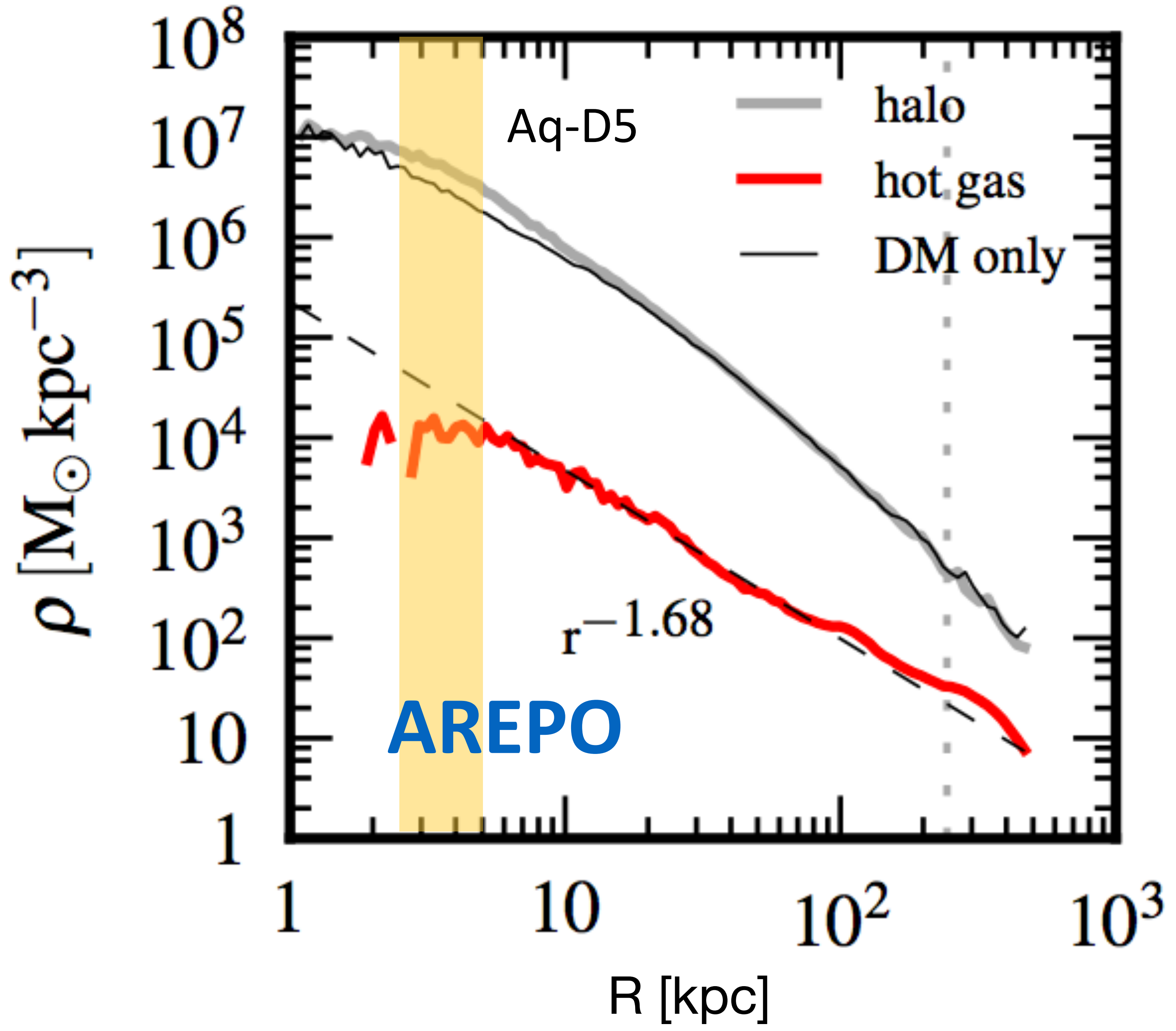
Common astrophysical ingredients

Halo dark matter density: Inner galaxy

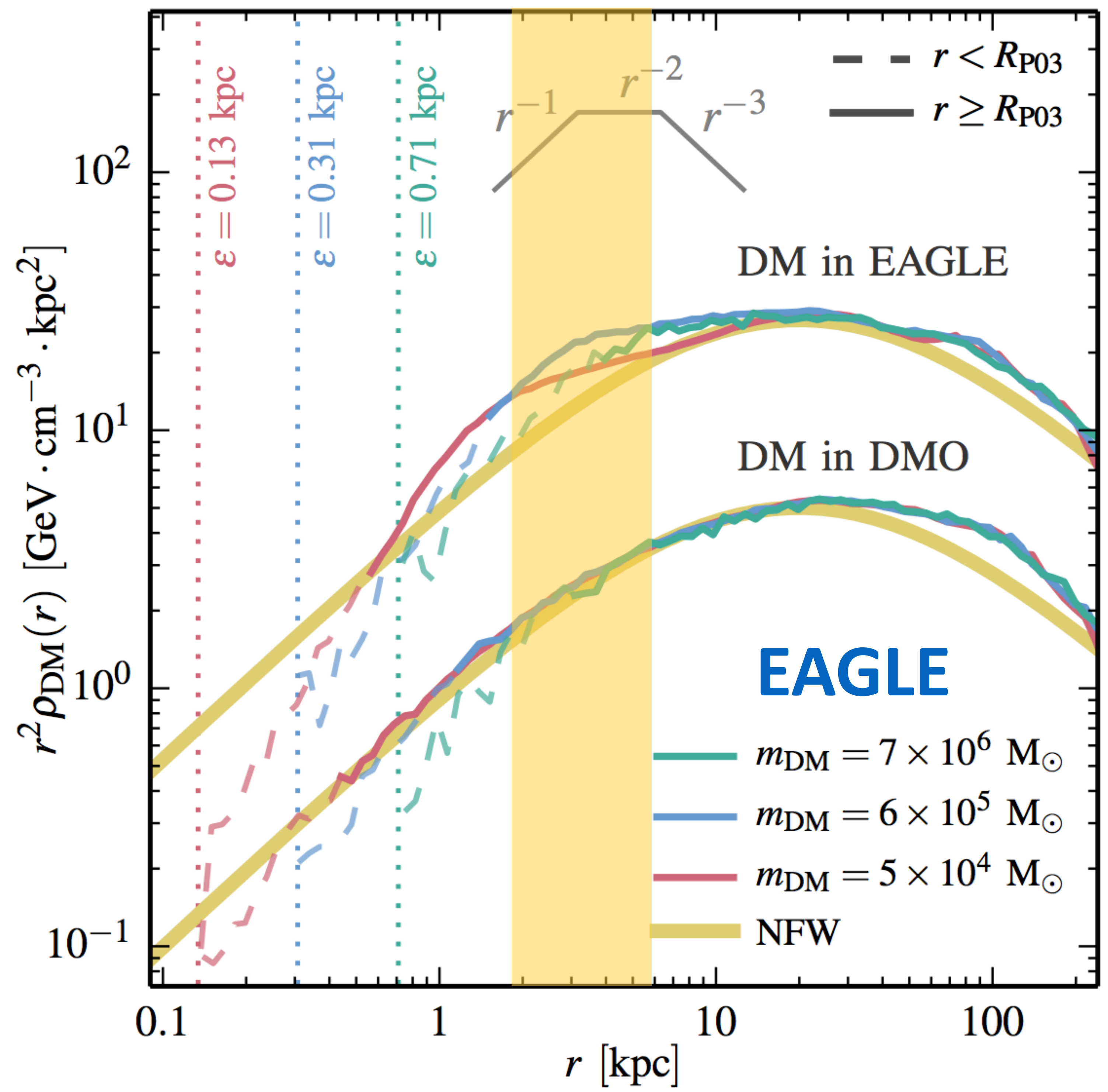
Chan+MNRAS'15



Marinacci+MNRAS'14



Schaller, FC+MNRAS'16



Challenges

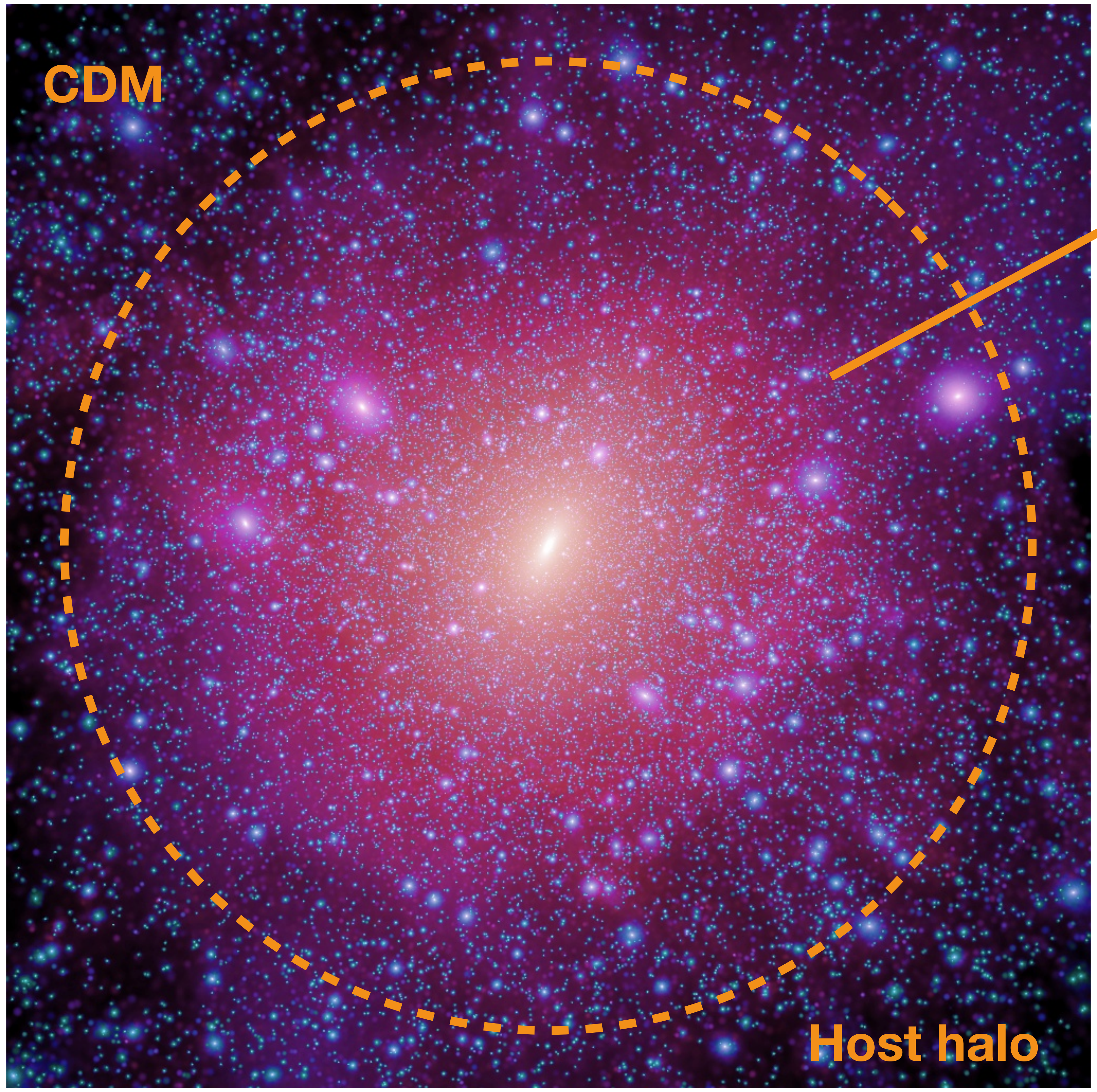
How to select a good MW halo candidate?

How to extrapolate the profile down to smaller scales?

Wang+MNRAS'12; Gottloeber+2010; FC+JCAP'15

Common astrophysical ingredients

Dark matter substructures



Springel+ MNRAS’08

Dark matter sub-haloes or sub-structures

- Low-mass DM haloes, do not trigger star formation => do not contain stars (**dark haloes**)
- Their **mass distribution** depends on fundamental properties of DM (warm vs cold)
- CDM predicts abundance down to Earth-sized objects (10^{-6} M_{Sun})*
- Their distribution leads to specific **angular signatures** of the DM signal (sub-halo searches, anisotropies, x-correlation)

Grand & White MNRAS’21

* In WIMP and non-thermal axion models

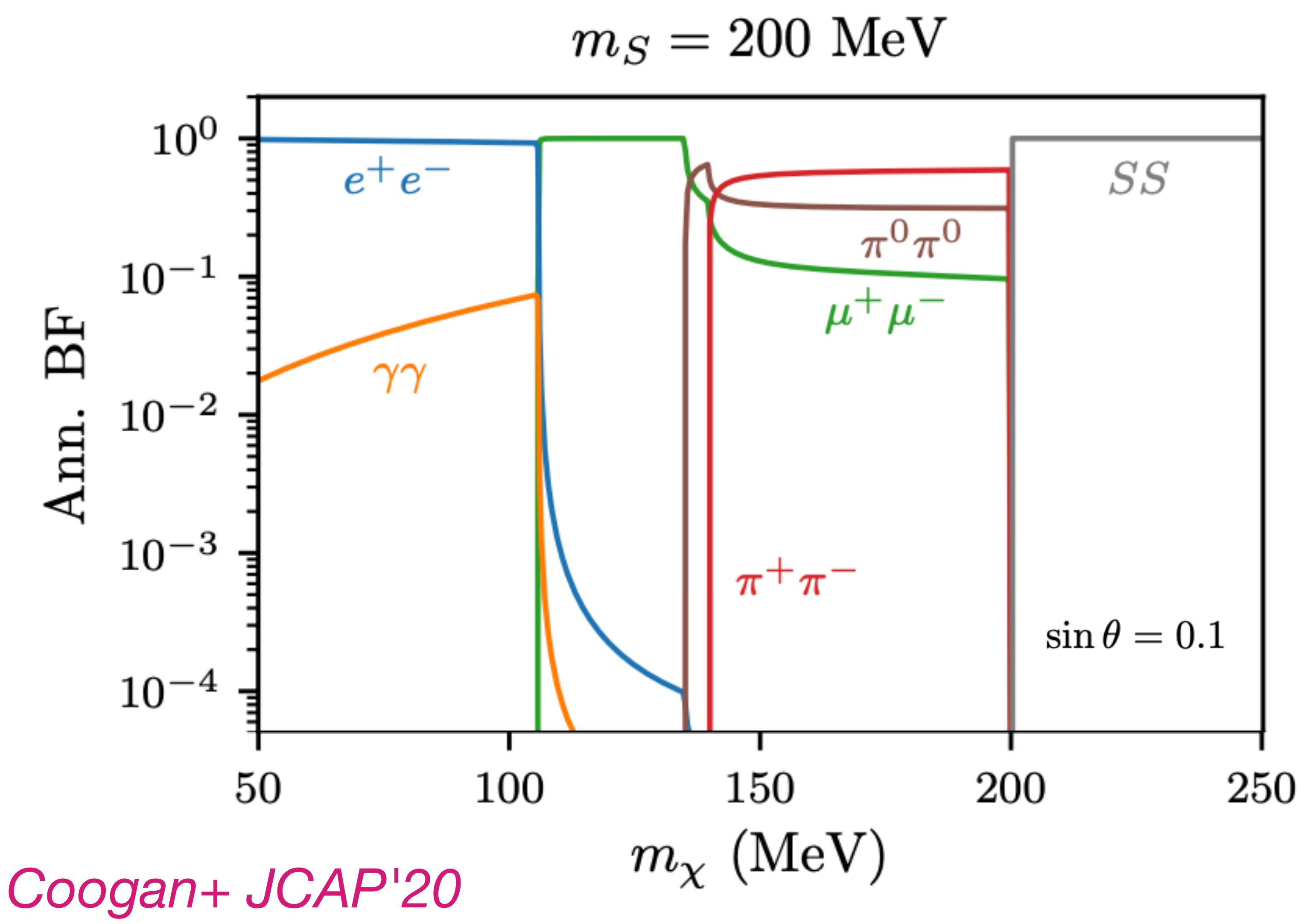
Particle dark matter

Particle dark matter emission

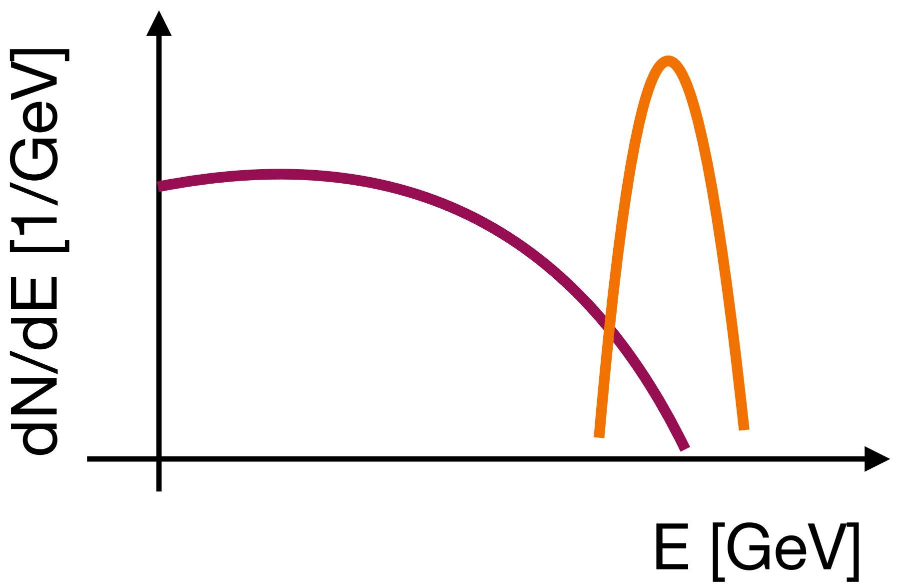
$$(DM)\, DM \to SM\, SM$$

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ (\text{decay}),\ 2\ (\text{annih})$$

Centre of mass energy $\simeq$ Signal energy



Coogan+ JCAP'20



$m_{\rm DM} \lesssim$ MeV

$$E_\gamma = \frac{N m_{\rm DM}}{2}$$

Narrow line signal

$$\frac{dN_\gamma}{dE} = 2\delta\left(E - \frac{N m_{\rm DM}}{2}\right)$$

$m_{\rm DM} \gtrsim$ MeV

Broader energy distribution

$$\frac{dN_\gamma}{dE} = \left(\frac{dN_\gamma}{dE}\right)_{\gamma\gamma} + \left(\frac{dN_\gamma}{dE}\right)_{\rm sec} + \left(\frac{dN_\gamma}{dE}\right)_{\rm FSR}$$

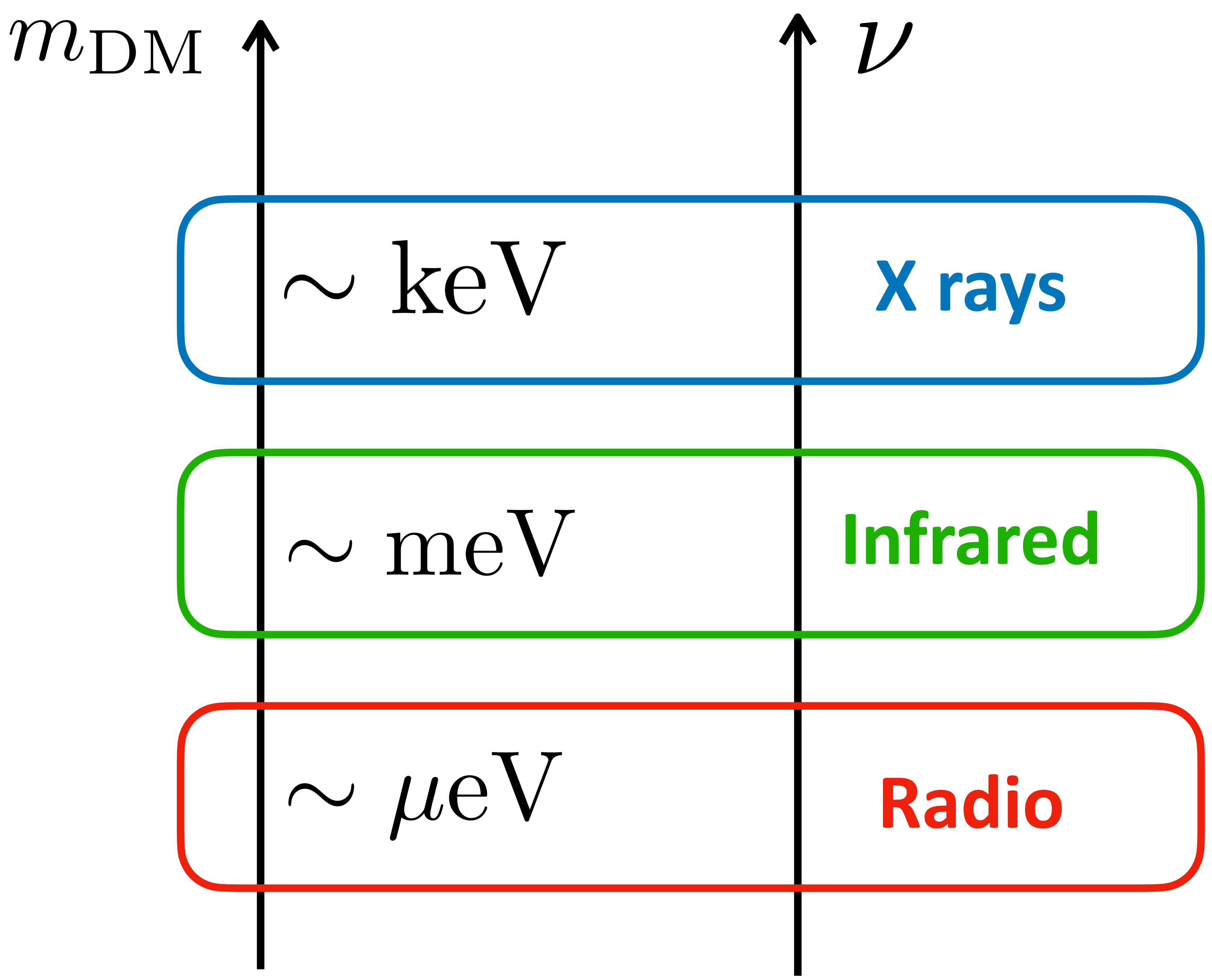
Light dark matter decay: lines

$$m_{\rm DM} \lesssim {\rm MeV}$$

Only allowed final state is into photons emitted back-to-back

$$E_\gamma = \frac{m_{\rm DM}}{2}$$

Narrow line signal @ energy scale of the DM mass



Light dark matter decay: Emissivity and flux

$$Q_\gamma^{\rm dec}(r,E) = \Gamma_\gamma \times n(r) \times \frac{dN_\gamma}{dE}(E)$$

$$n(r) = \frac{\rho(r)}{m}$$

Local emissivity per unit energy and volume

$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-3}]$

$$\frac{Q_\gamma(r,E)}{4\pi}$$

Emissivity per sr (isotropic emission)

$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-3}\mathrm{sr}^{-1}]$

$$\Phi_\gamma(E) \equiv \frac{d\Phi_\gamma}{dE} = \int_{\Delta\Omega} d\Omega(\ell,b) \int_{\rm l.o.s} ds \frac{Q_\gamma(r(s,\ell,b),E)}{4\pi}$$

Gamma-ray (or neutrino) differential energy flux

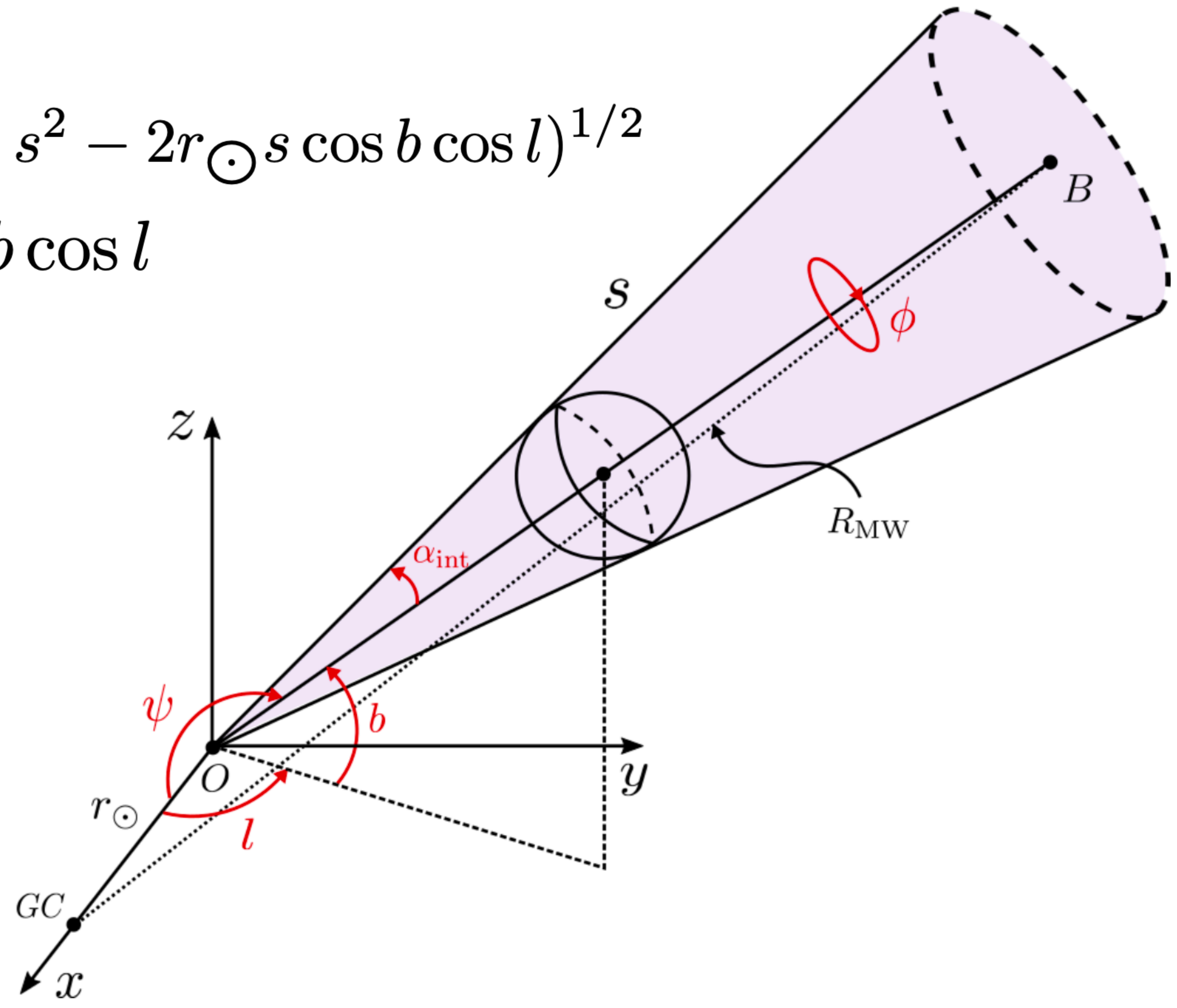
$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}]$

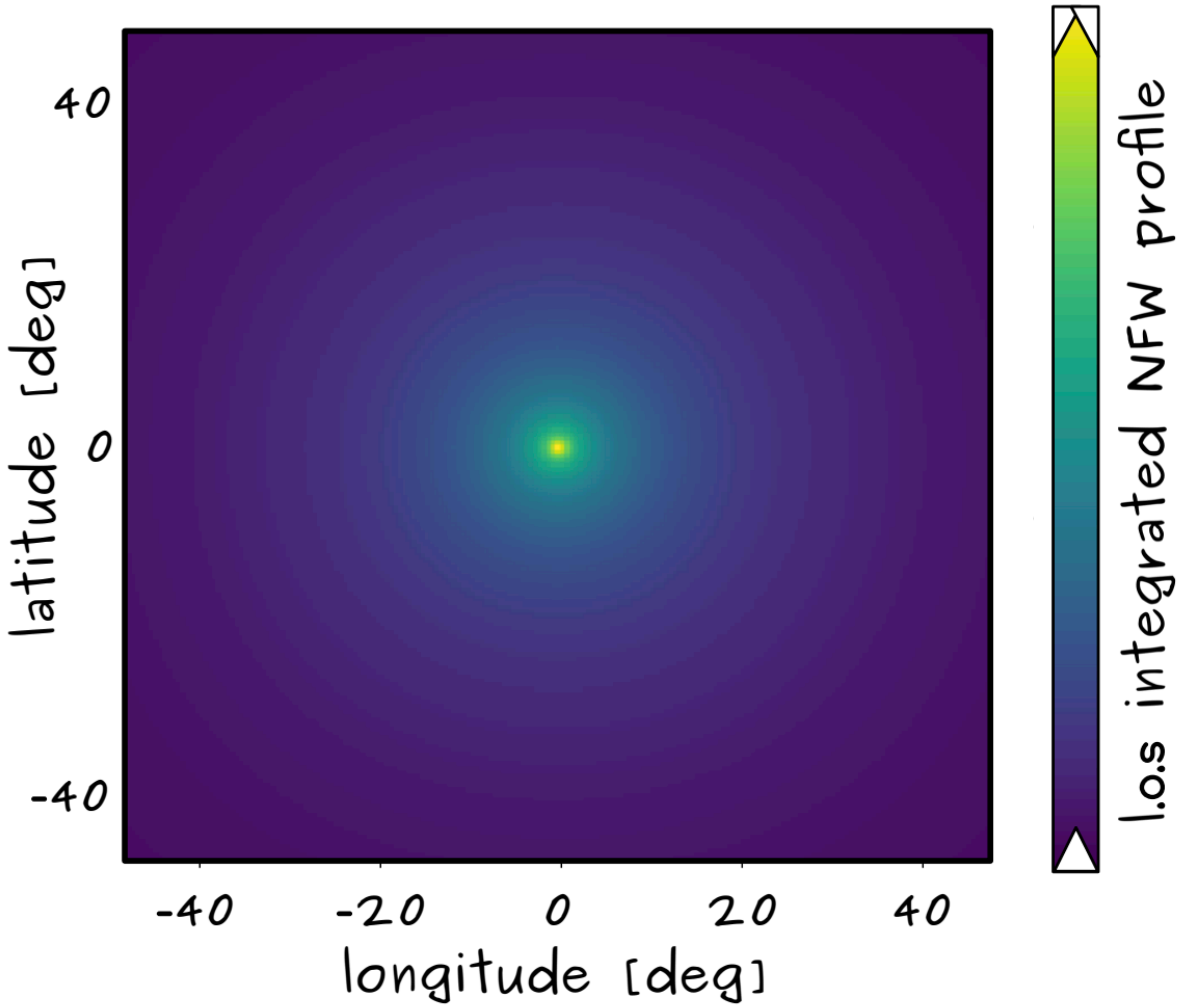
Light dark matter decay: Flux

$$\frac{d\Phi_\gamma}{dE} = \frac{\Gamma(\mathrm{DM}\to\gamma\gamma)}{4\pi m_{\mathrm{DM}}}\frac{dN_\gamma}{dE} \times \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\ell)d\ell$$

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

$$\cos\psi = \cos b\cos l$$



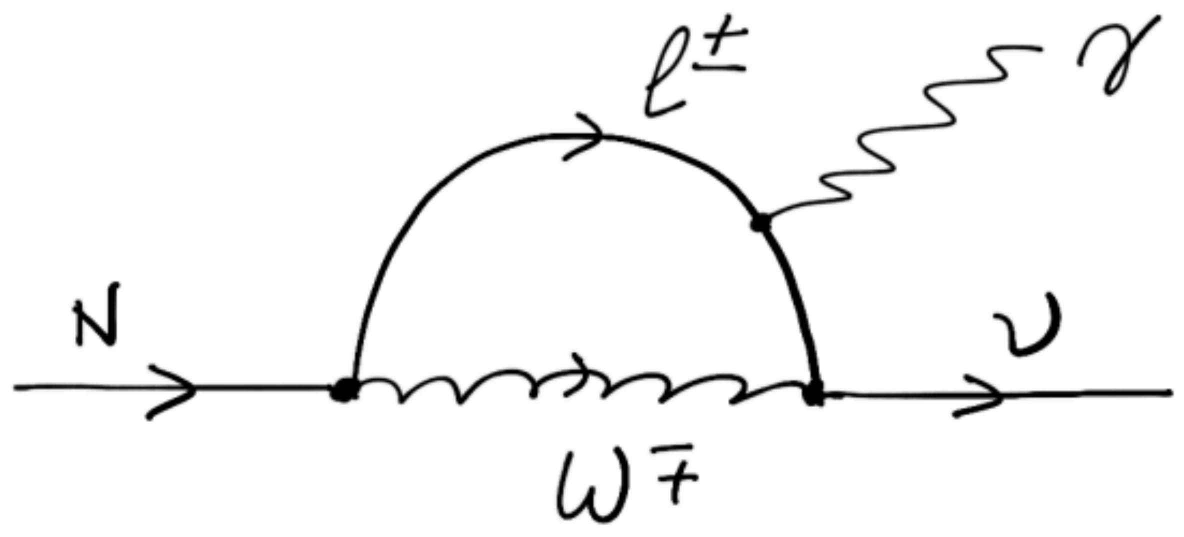


Flux from all galaxies: you need to integrate over redshift and galaxies' redshift distribution

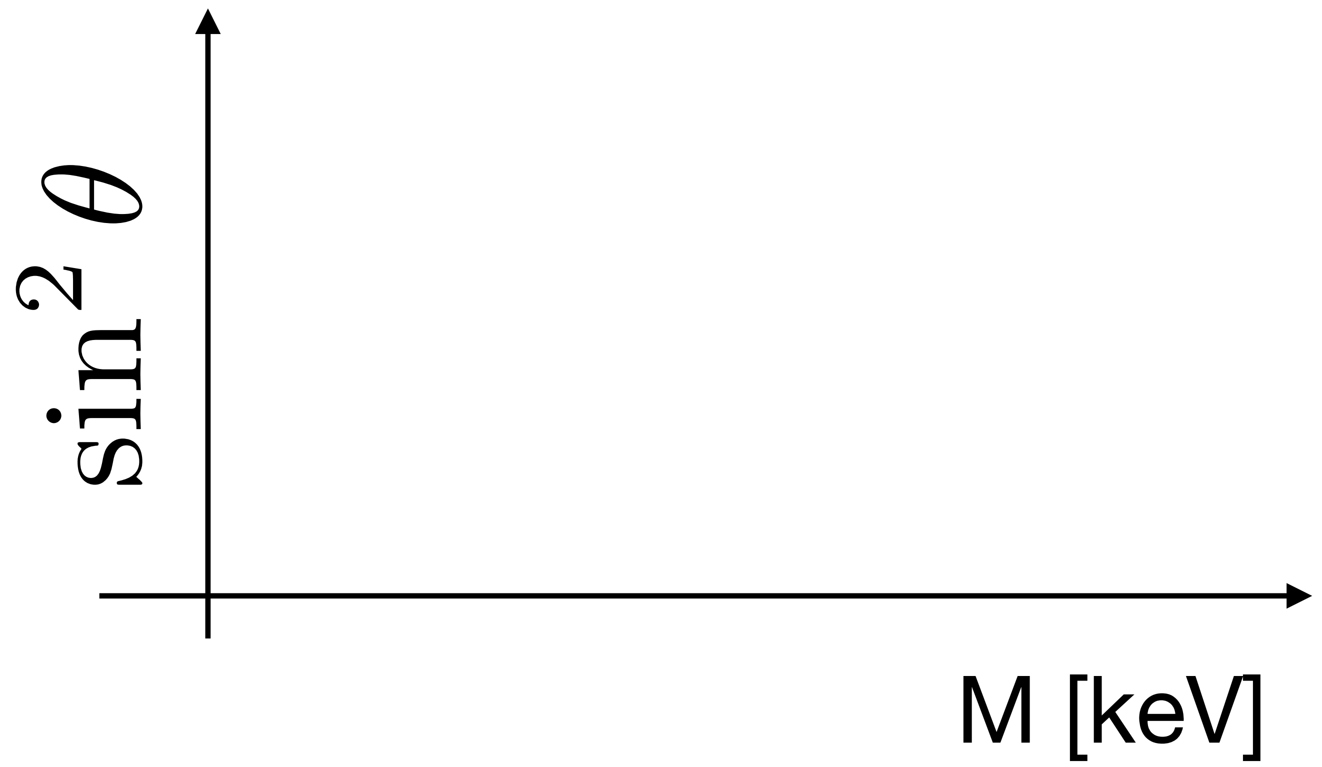
Sterile neutrinos X-ray lines

Model prediction

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



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



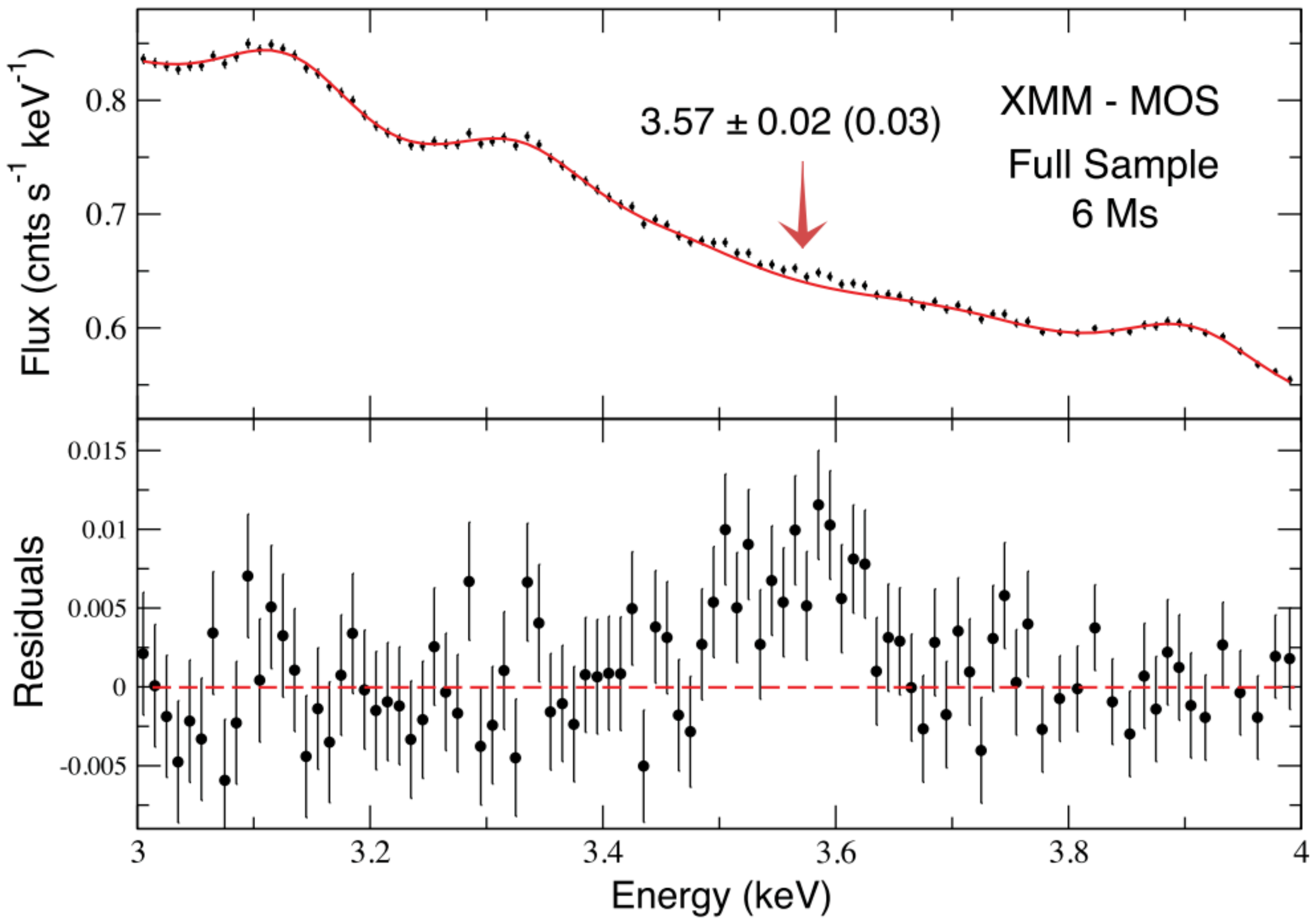
Review: K. N. Abazajian, Phys. Rept. 711-712, 1 (2017)

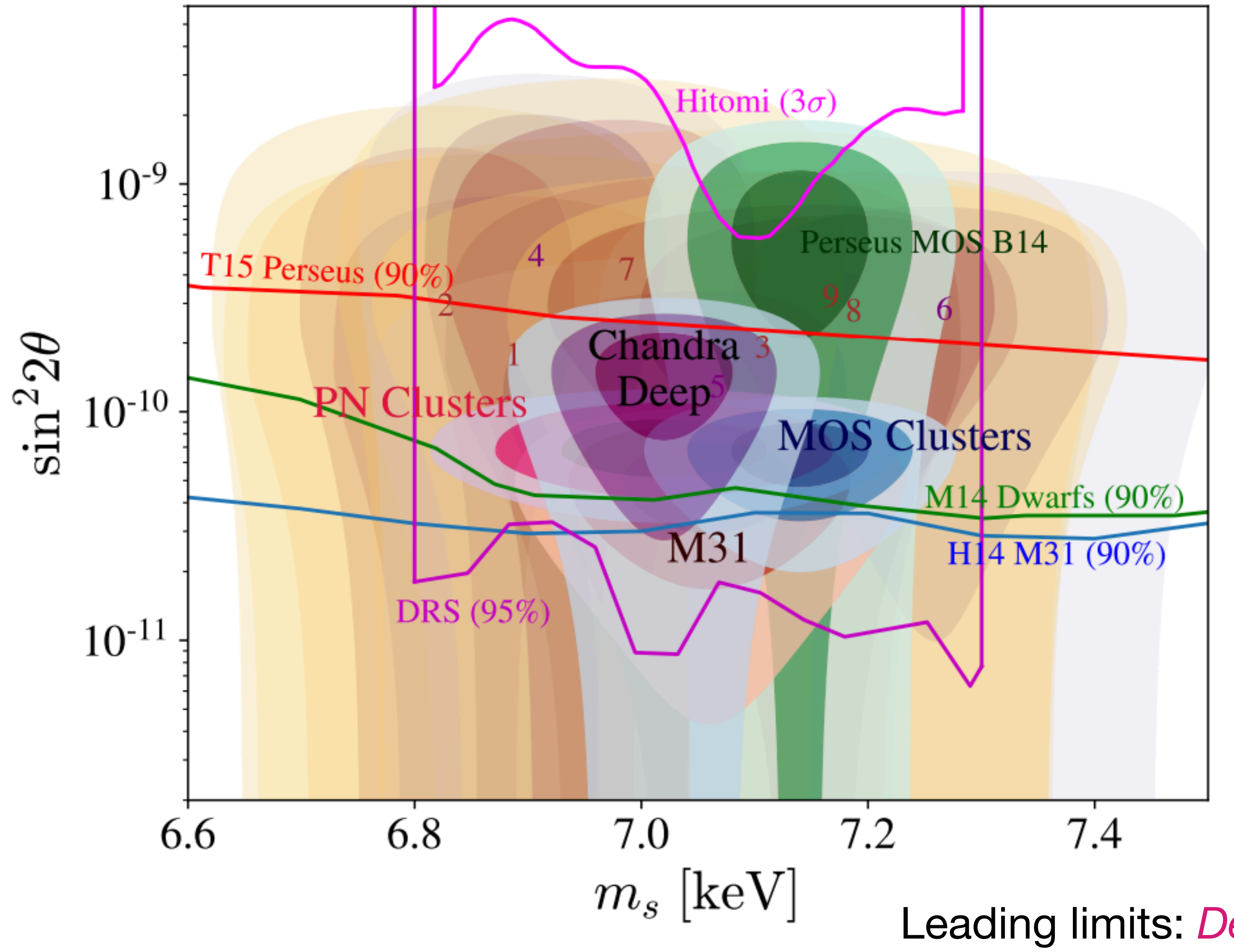
Sterile neutrinos X-ray lines

X-ray telescopes and spectral analysis

Starting from early 2014:

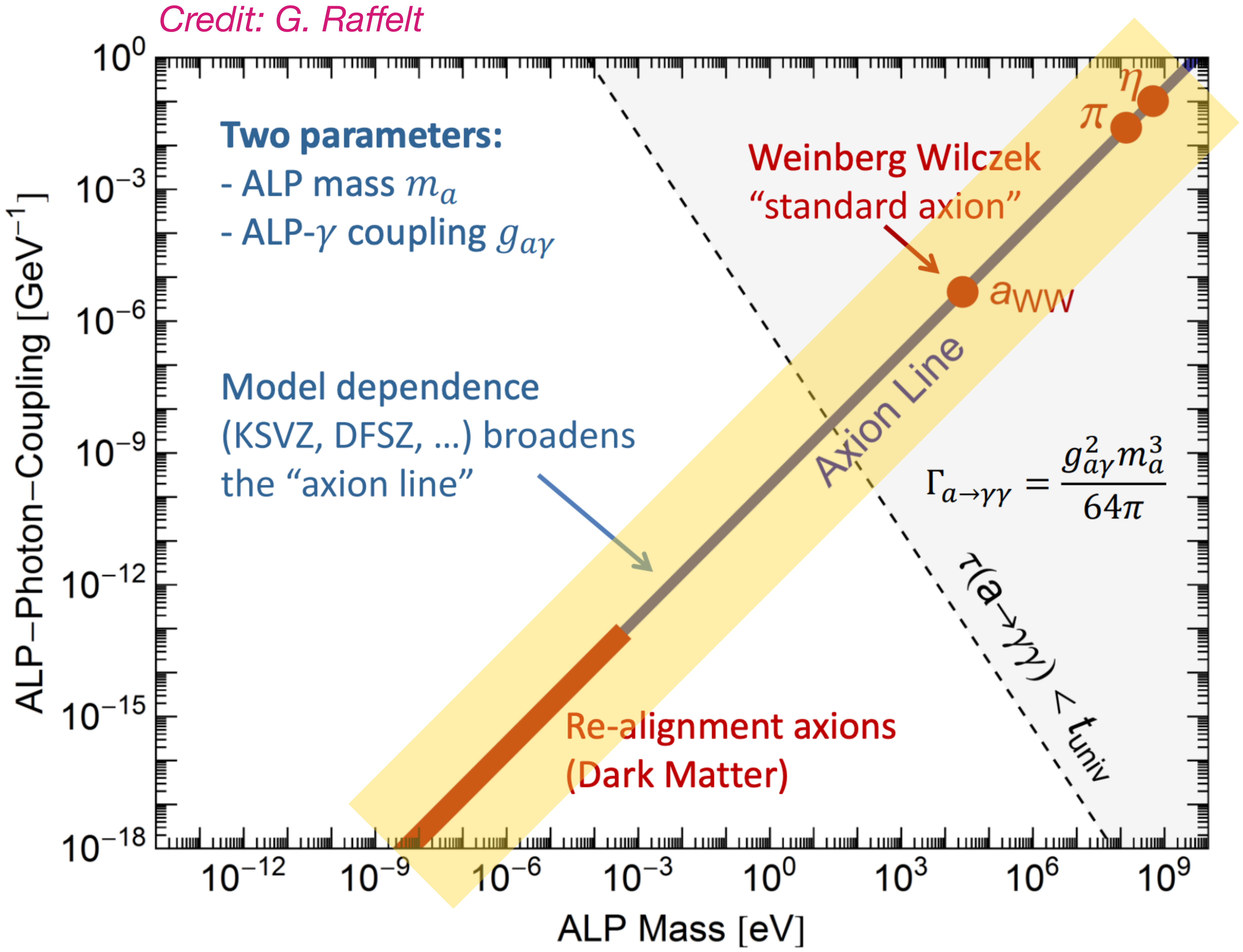
- **Detection** of an unidentified line at **3.5 keV**: XMM-Newton (6 Ms) & *Chandra*, Perseus cluster; XMM-Newton, M31; Suzaku, Perseus; etc
- **Constraints** from *Chandra* M31; XMM-Newton/Chandra 80 galaxies; blank field pointings Chandra and XMM-Newton, etc

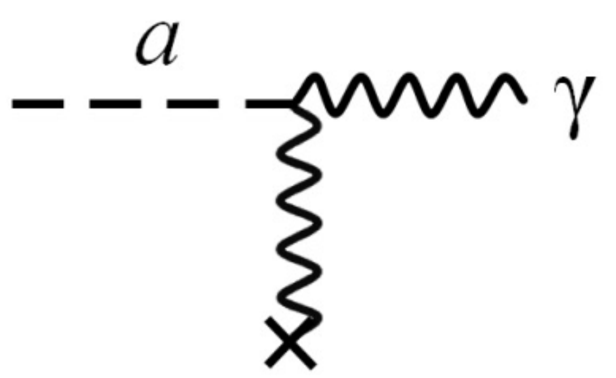




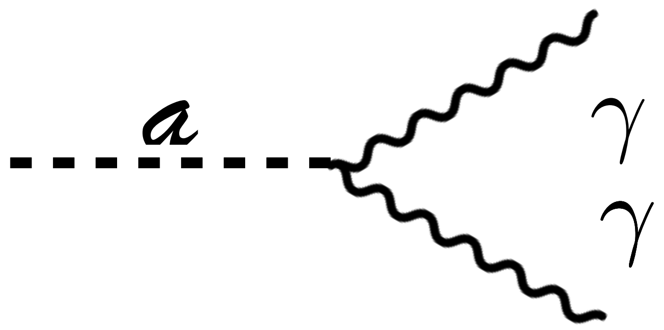
Leading limits: *Dessert+ Science' 20*

The QCD axion





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**

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

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

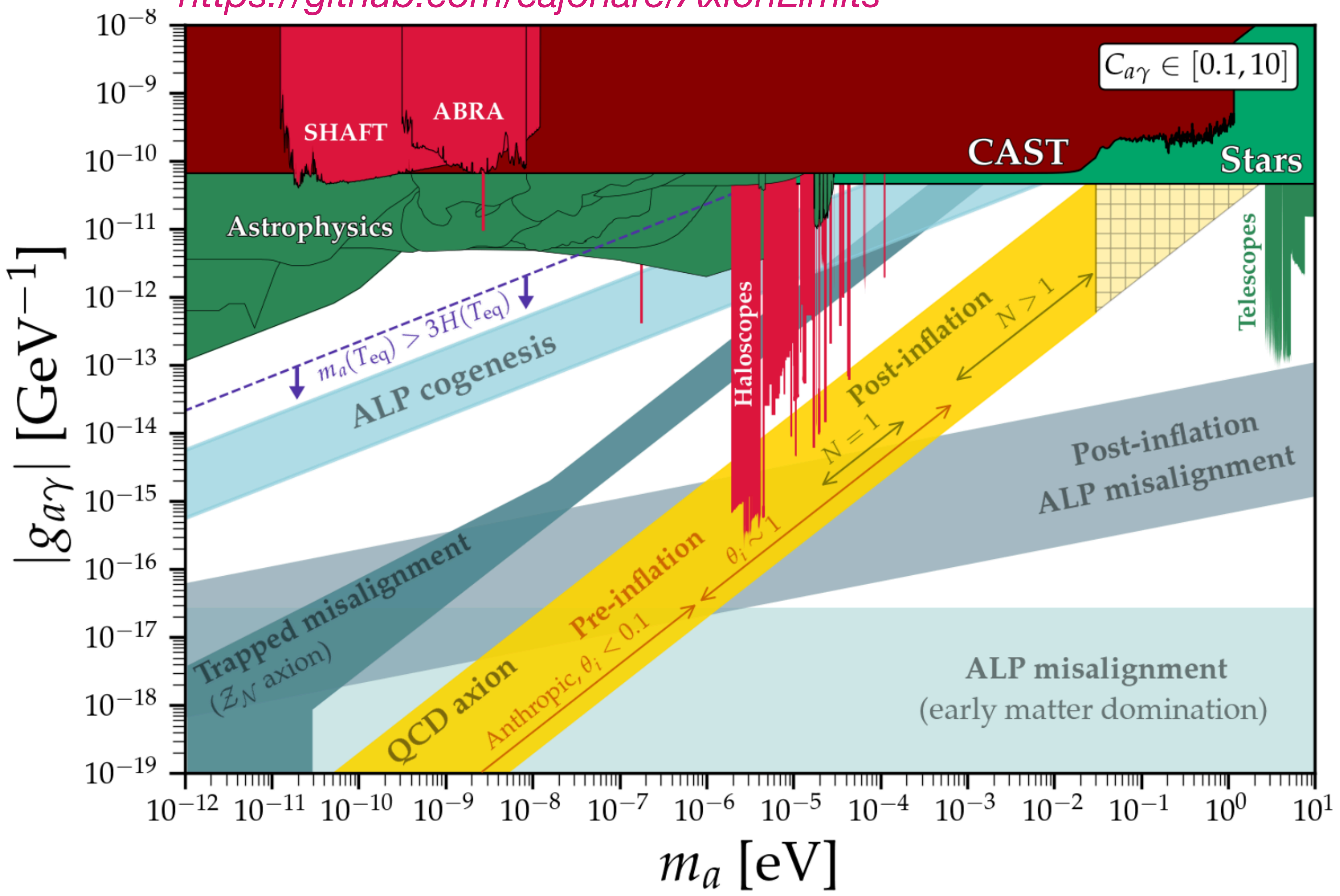
Broadening the landscape

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

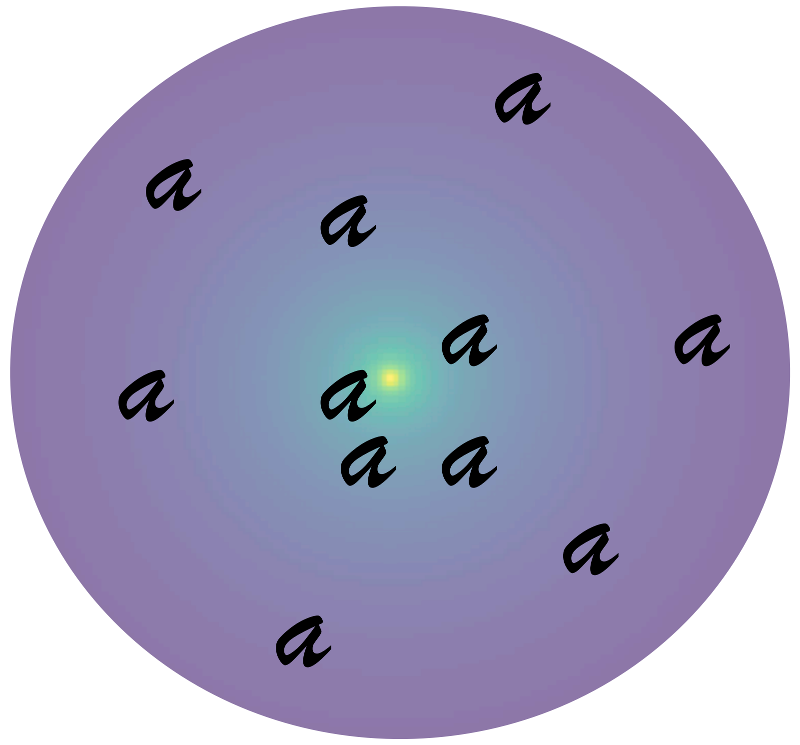


Quick ID:

- **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]

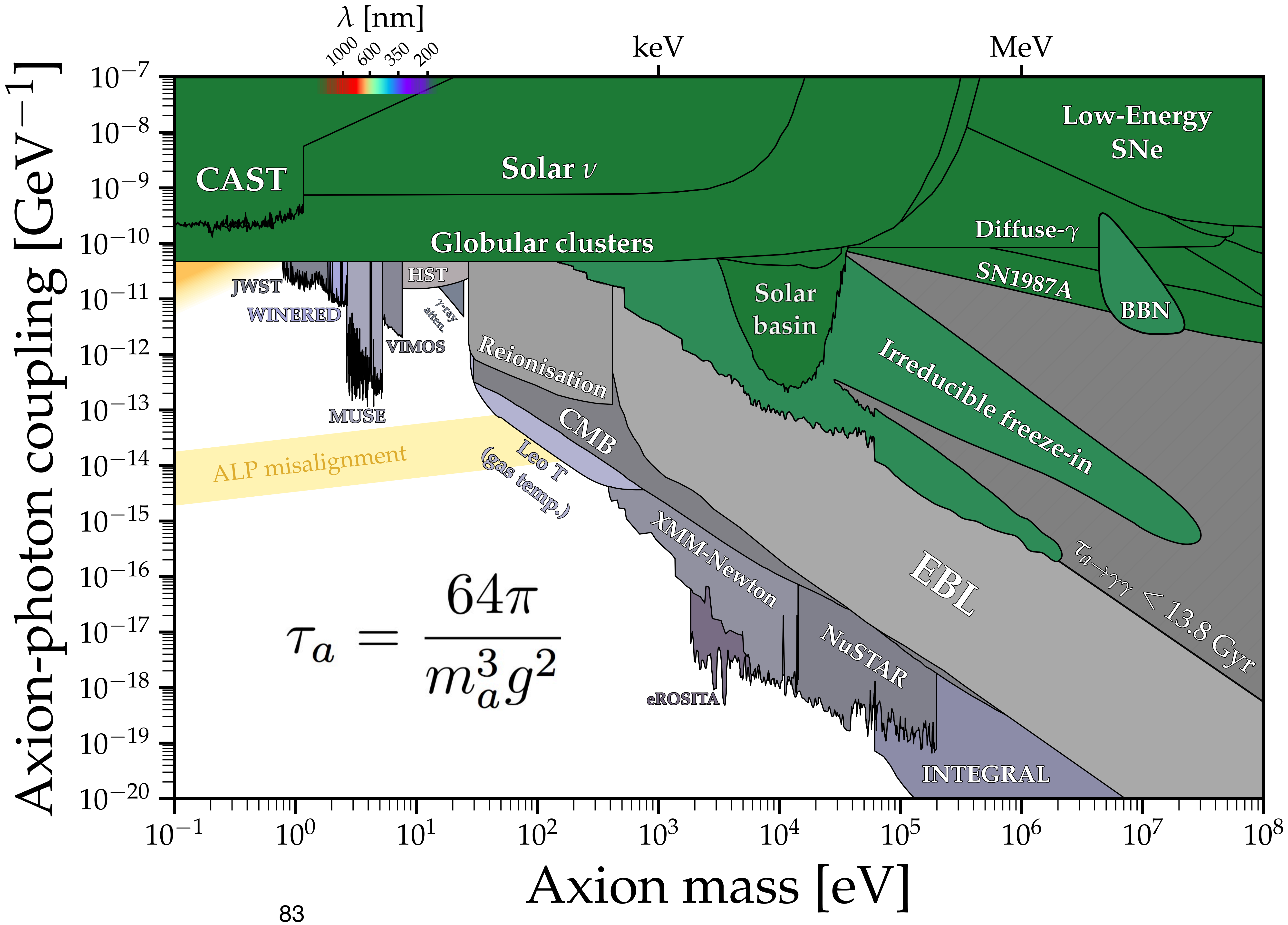
ALPs dark matter



- 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



Constraints on eV ALPs

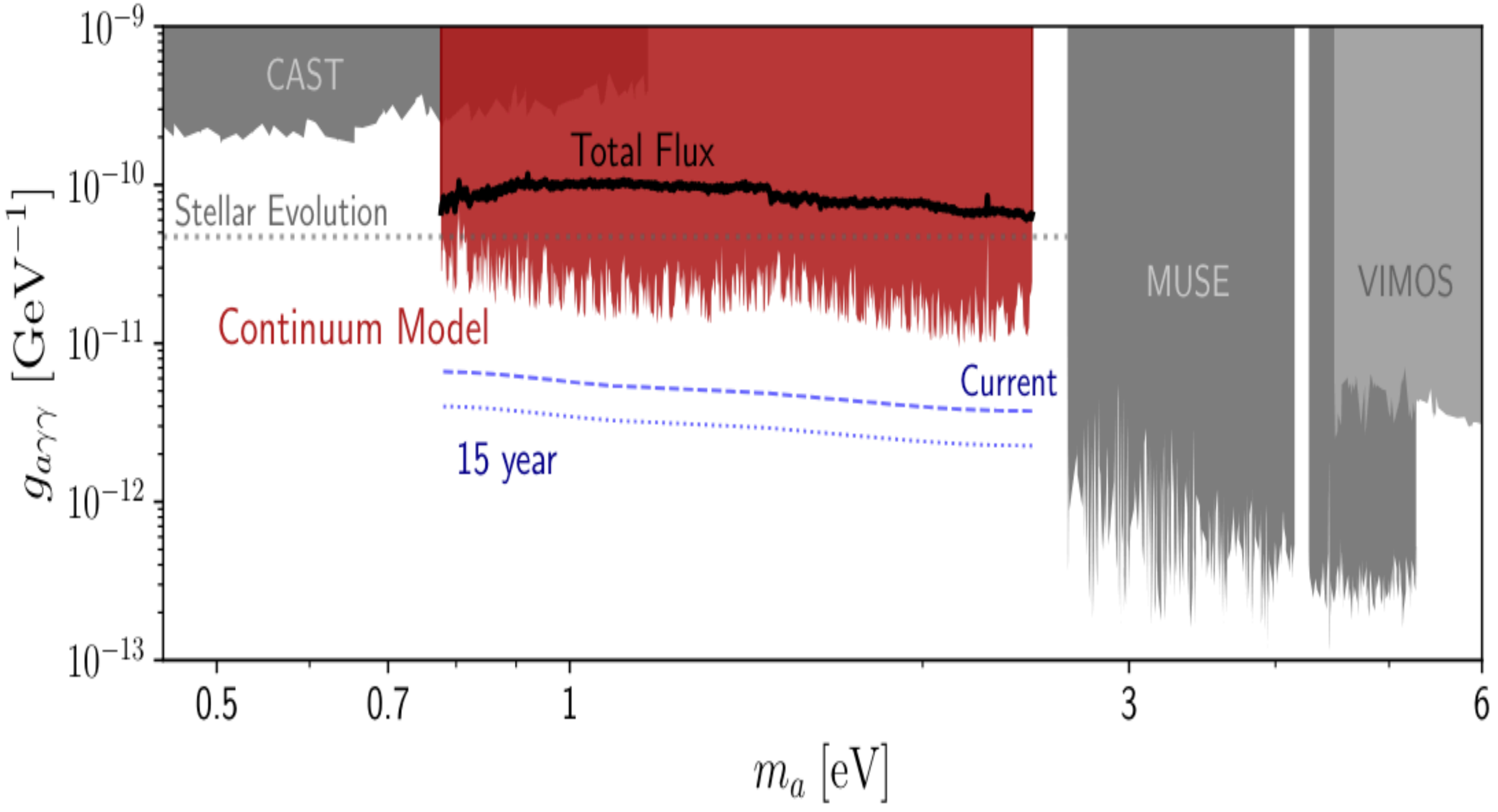
IR - optical wavelengths

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



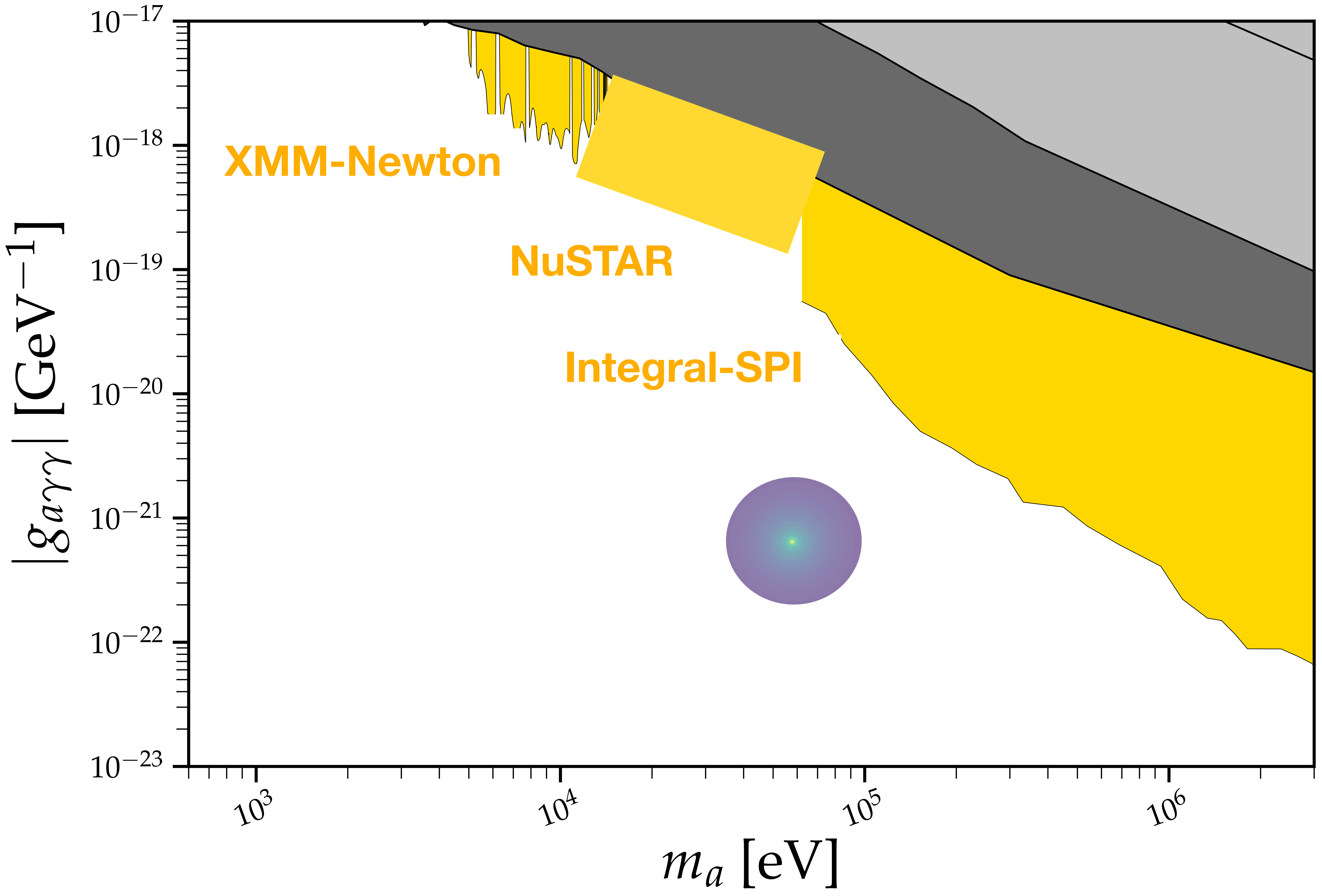
Constraints on keV - MeV ALPs

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

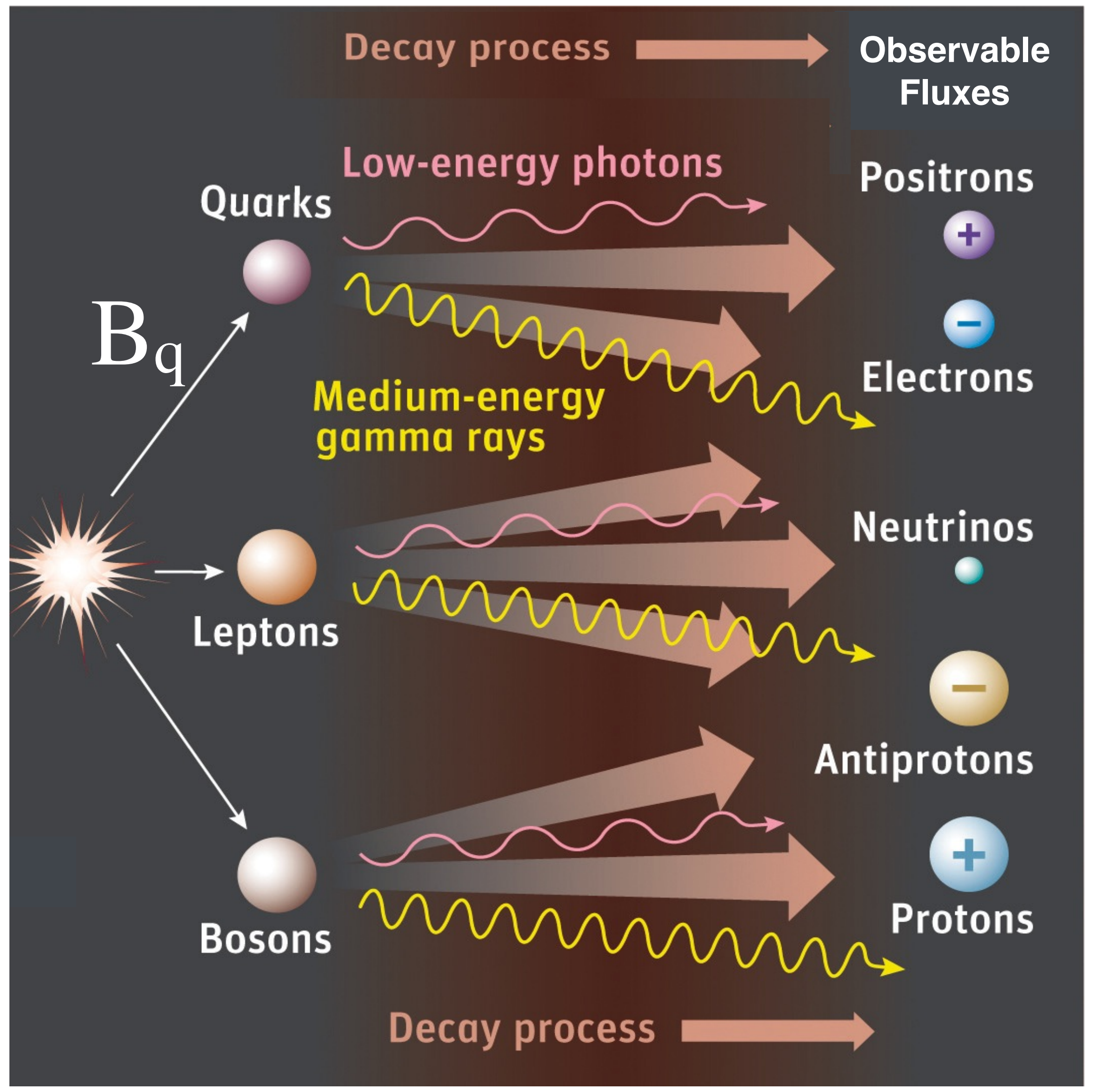
Particle dark matter emission*

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

Centre of mass energy $\simeq$ Signal energy

$m_{\rm DM} \gtrsim {\rm MeV}$

DM annihilation/decay



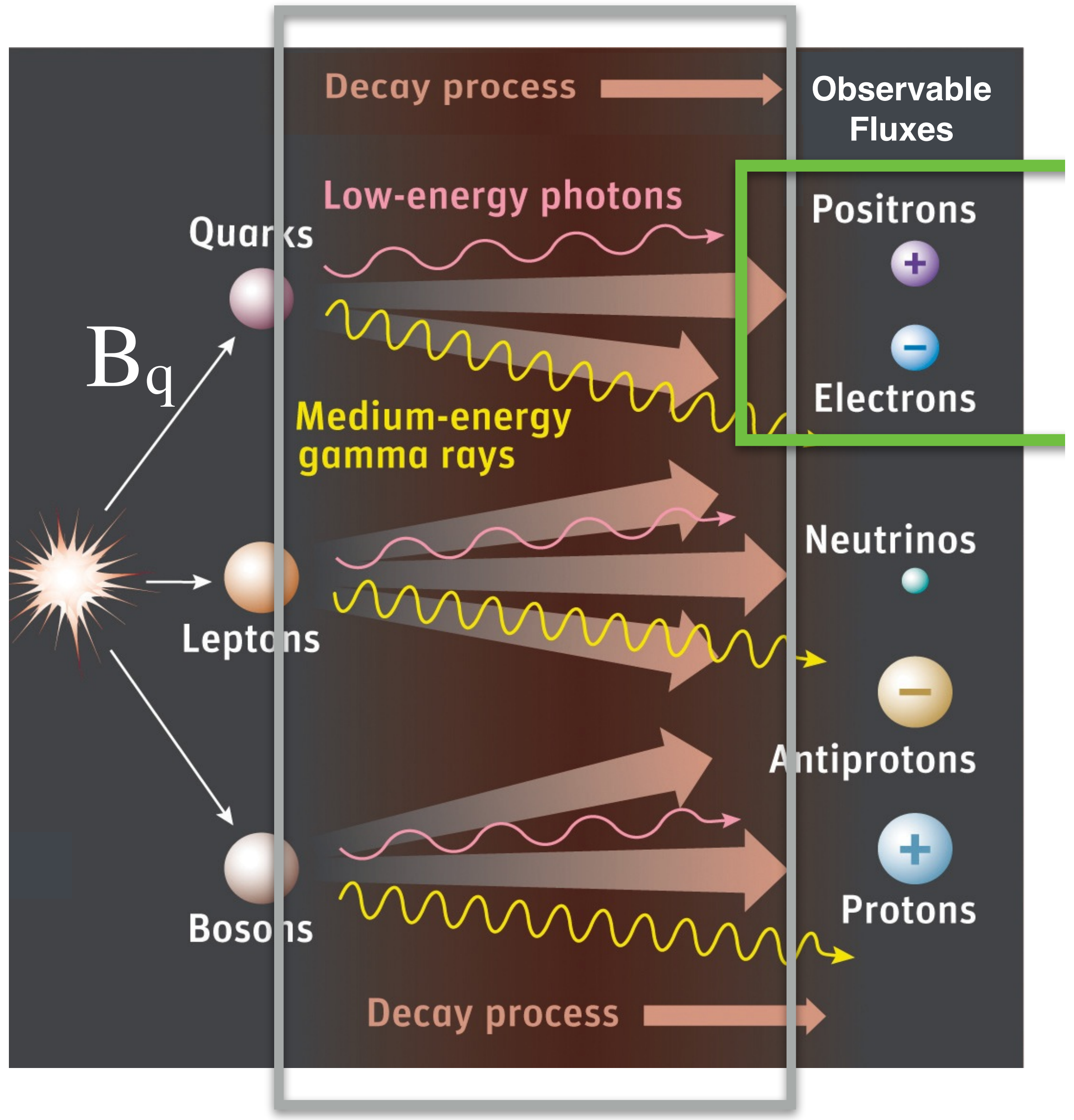
[*Dark matter = Weakly interacting massive particles, **WIMPs**]

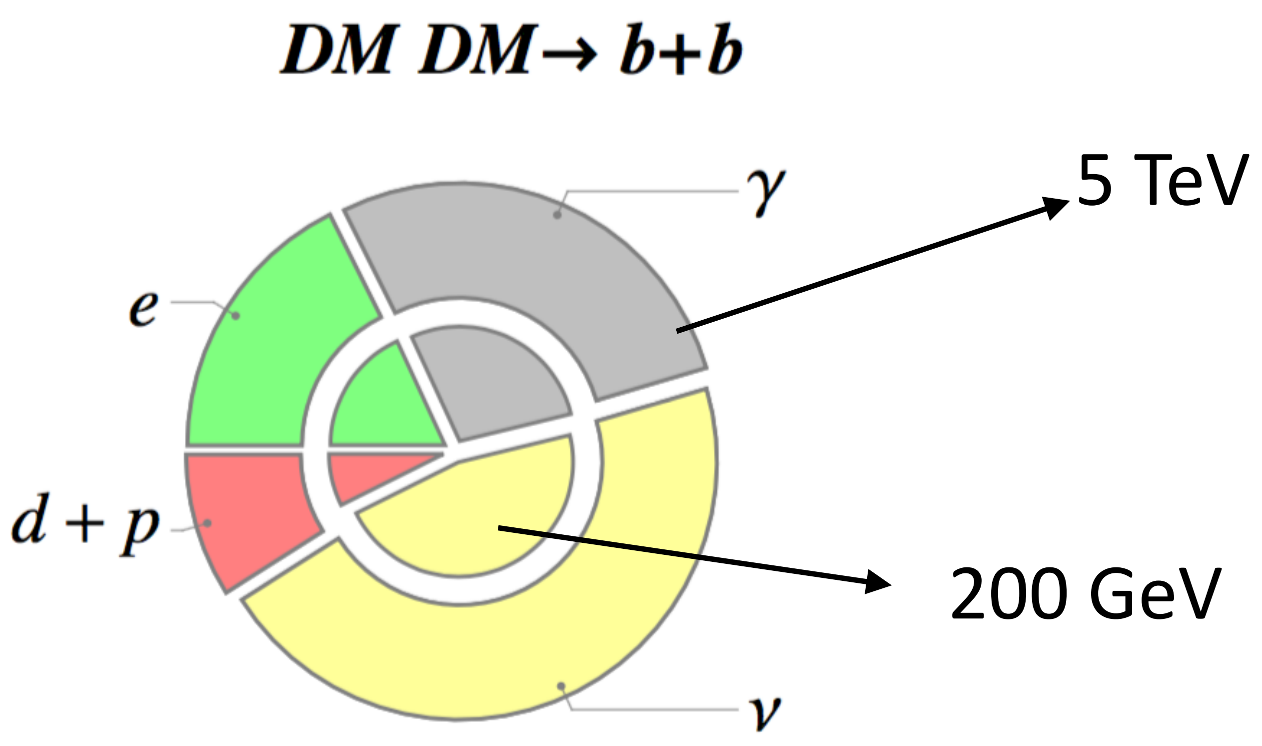
Particle dark matter emission

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

Centre of mass energy $\simeq$ Signal energy

DM annihilation/decay





$E_{\gamma+e}/E_{\rm tot} = 0.462\ (0.454)$

$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$

Prompt emission of observable particles *i*

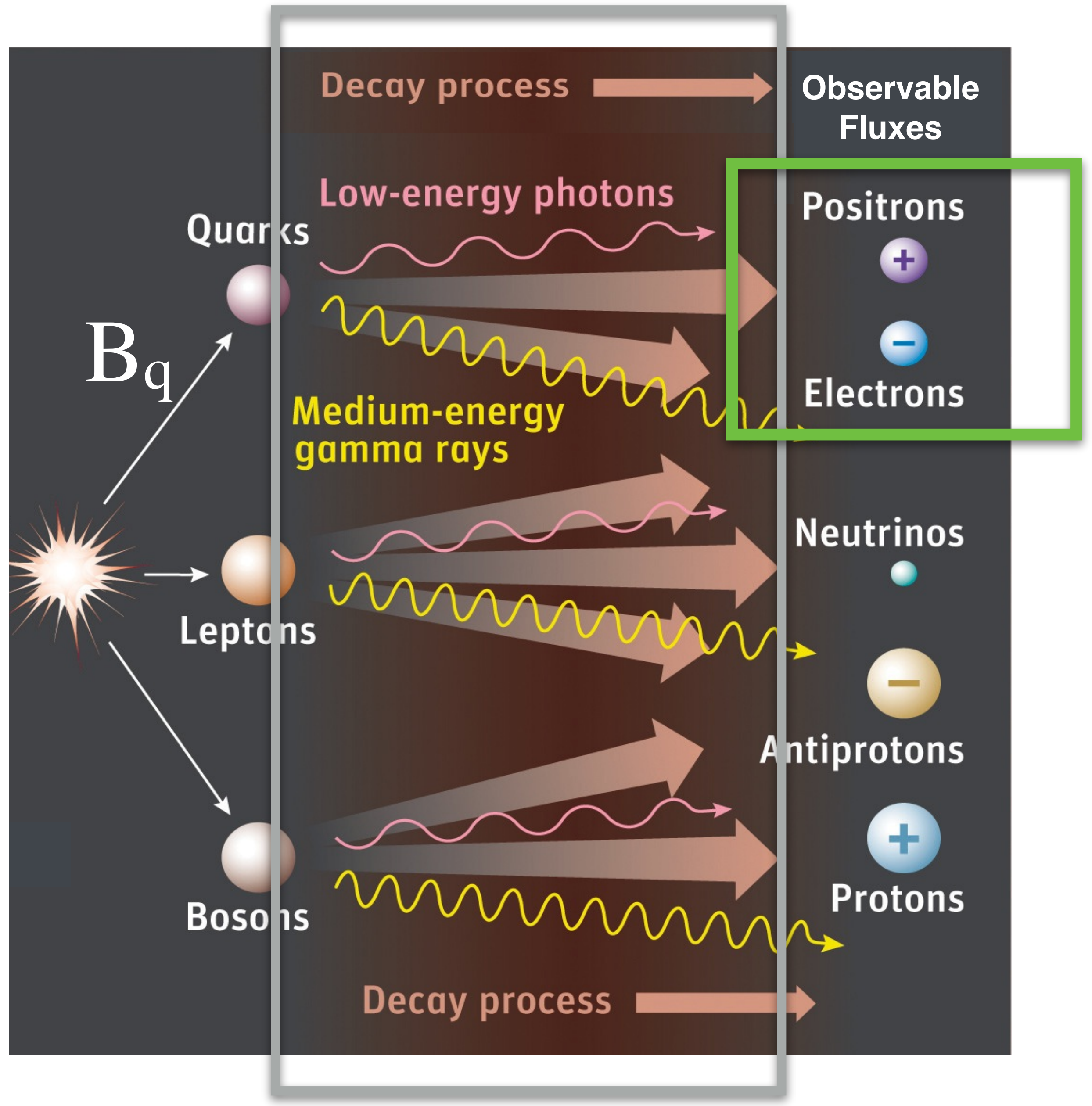
$$\sum_f B_f \frac{dN_i^f}{dE}(E)$$

Particle dark matter emission

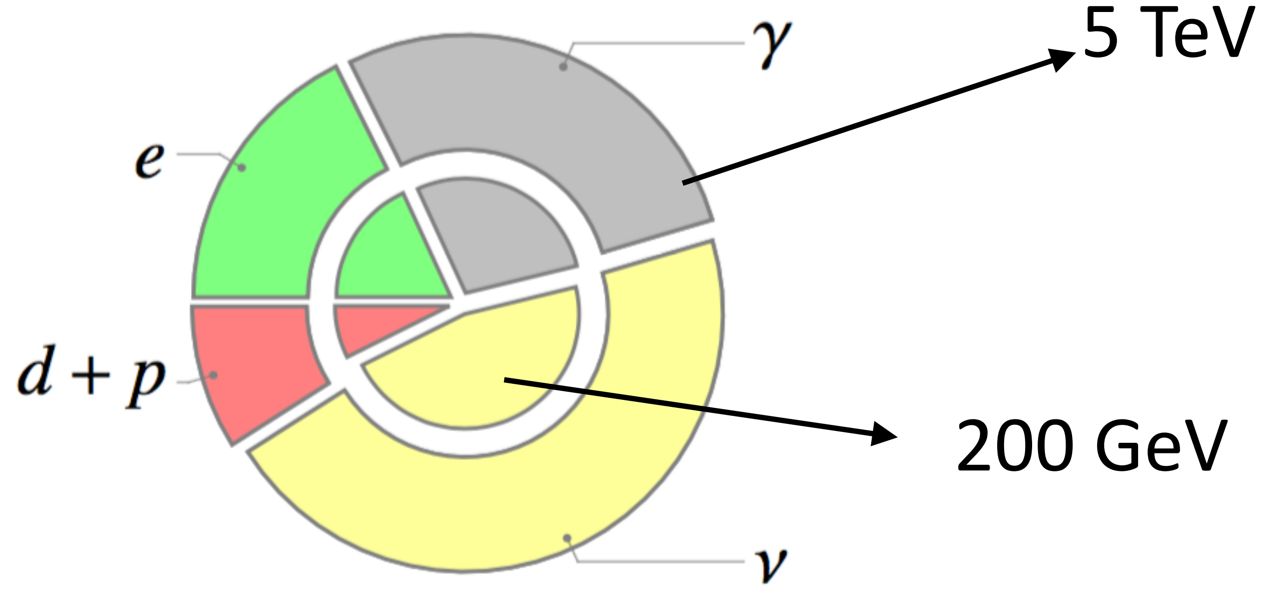
$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

Centre of mass energy $\simeq$ Signal energy

DM annihilation/decay



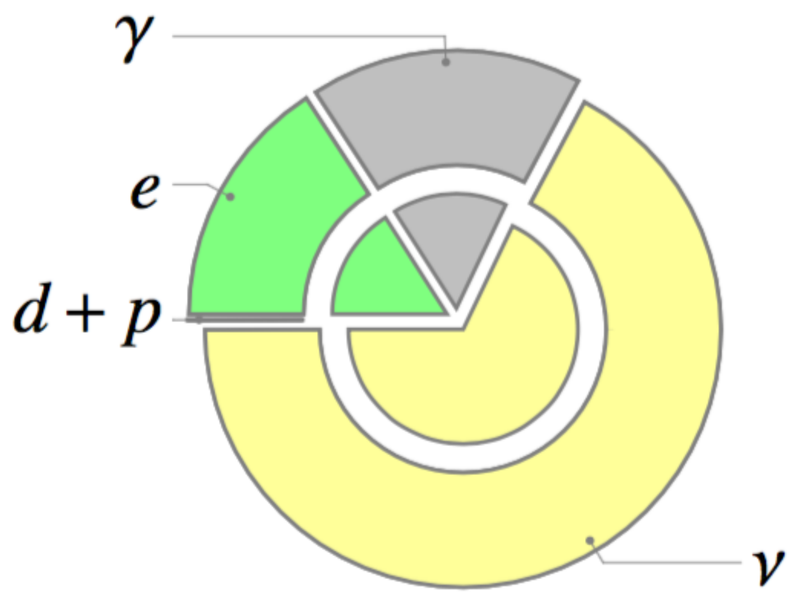
DM DM→ b+b



$E_{\gamma+e}/E_{\rm tot} = 0.462\ (0.454)$

$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$

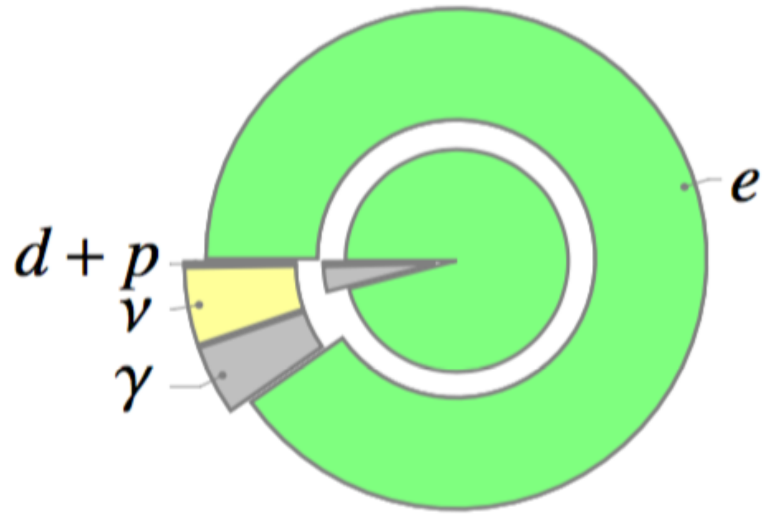
DM DM→ $\tau_R^- + \tau_R^+$



$E_{\gamma+e}/E_{\rm tot} = 0.321\ (0.328)$

$E_{p+d}/E_{\gamma+e} = 0.000\ (0.001)$

DM DM→ $e_L^- + e_L^+$



$E_{\gamma+e}/E_{\rm tot} = 0.996\ (0.948)$

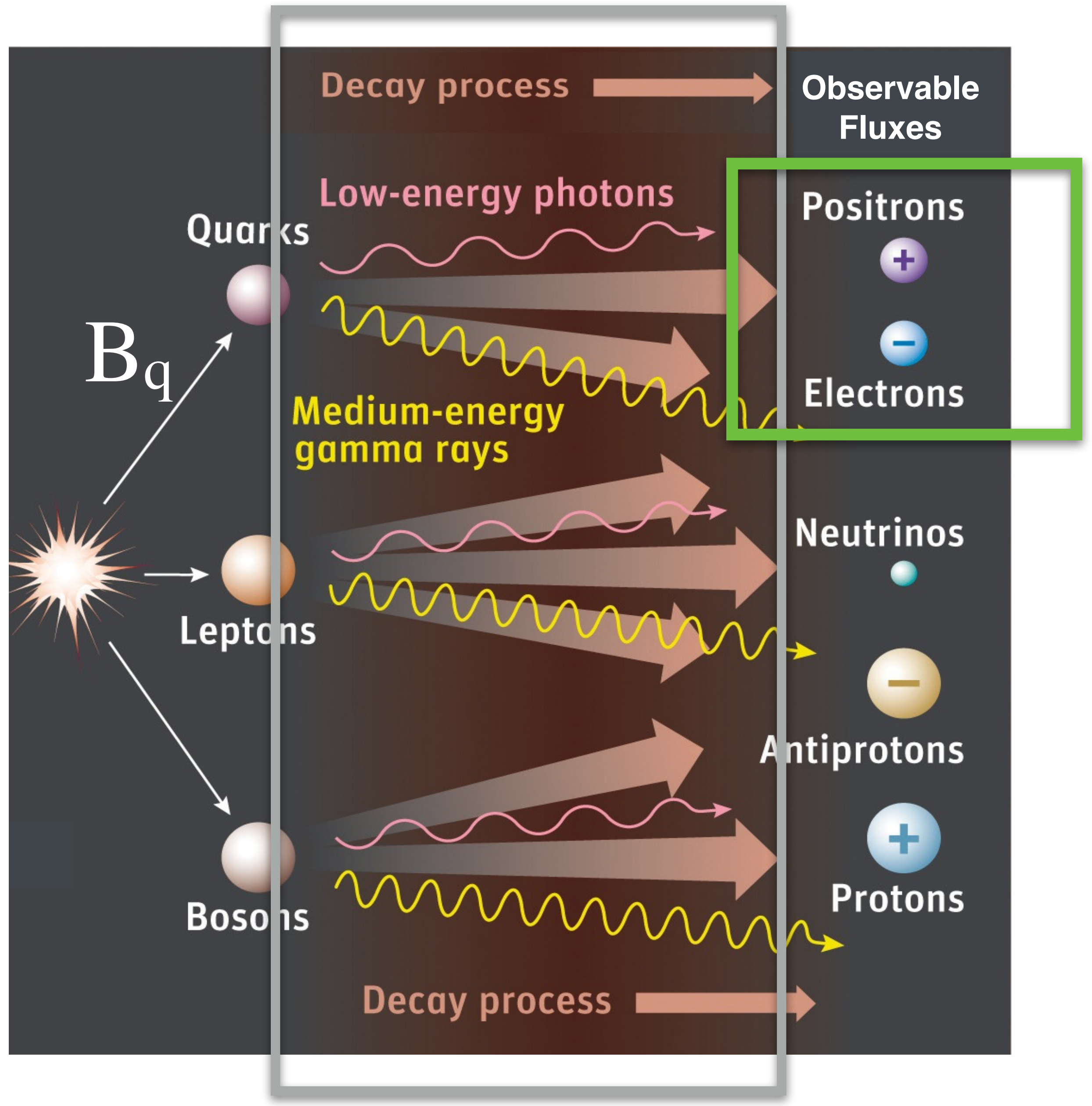
$E_{p+d}/E_{\gamma+e} = 0.000\ (0.002)$

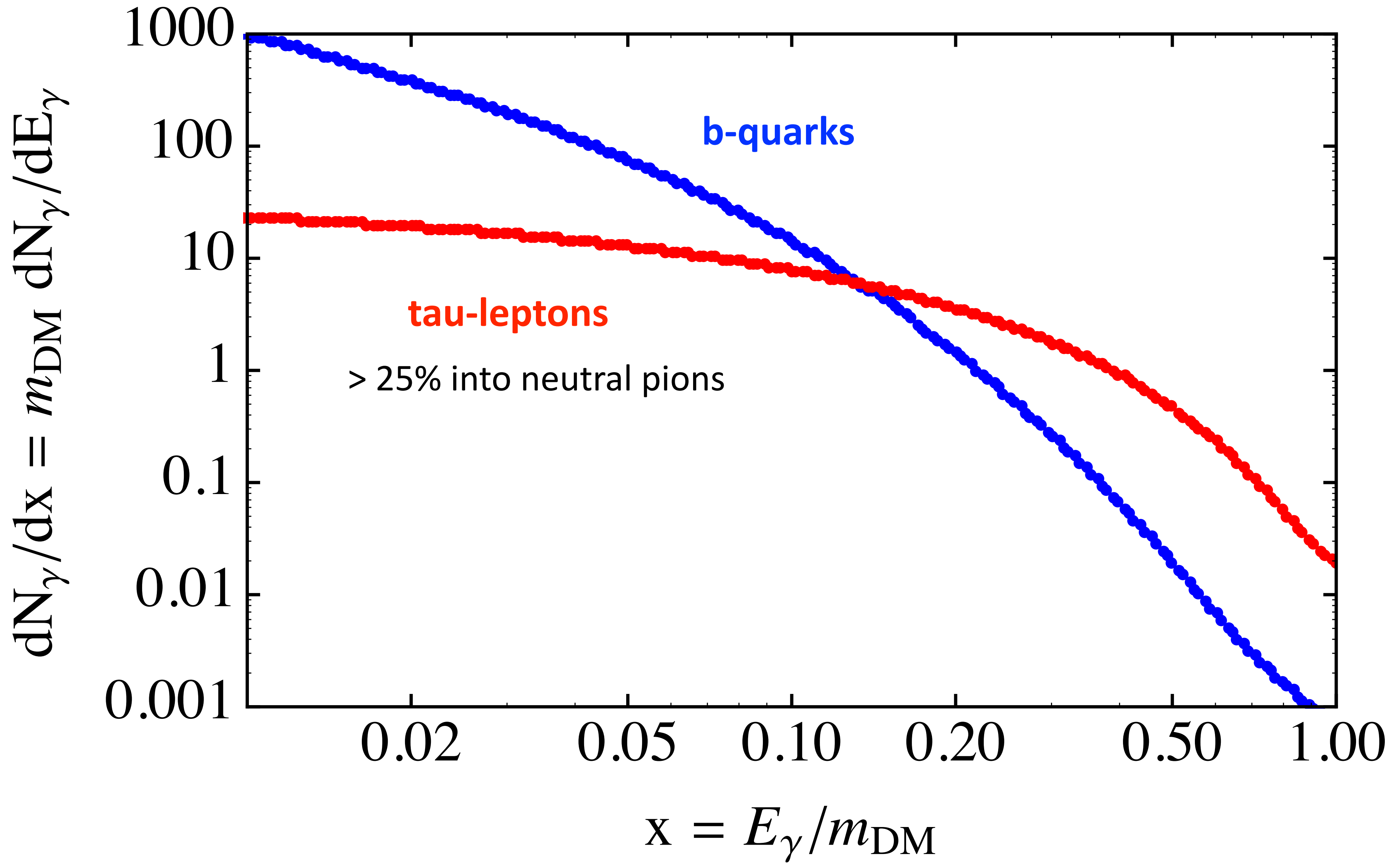
Particle dark matter emission

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

Centre of mass energy $\simeq$ Signal energy

DM annihilation/decay

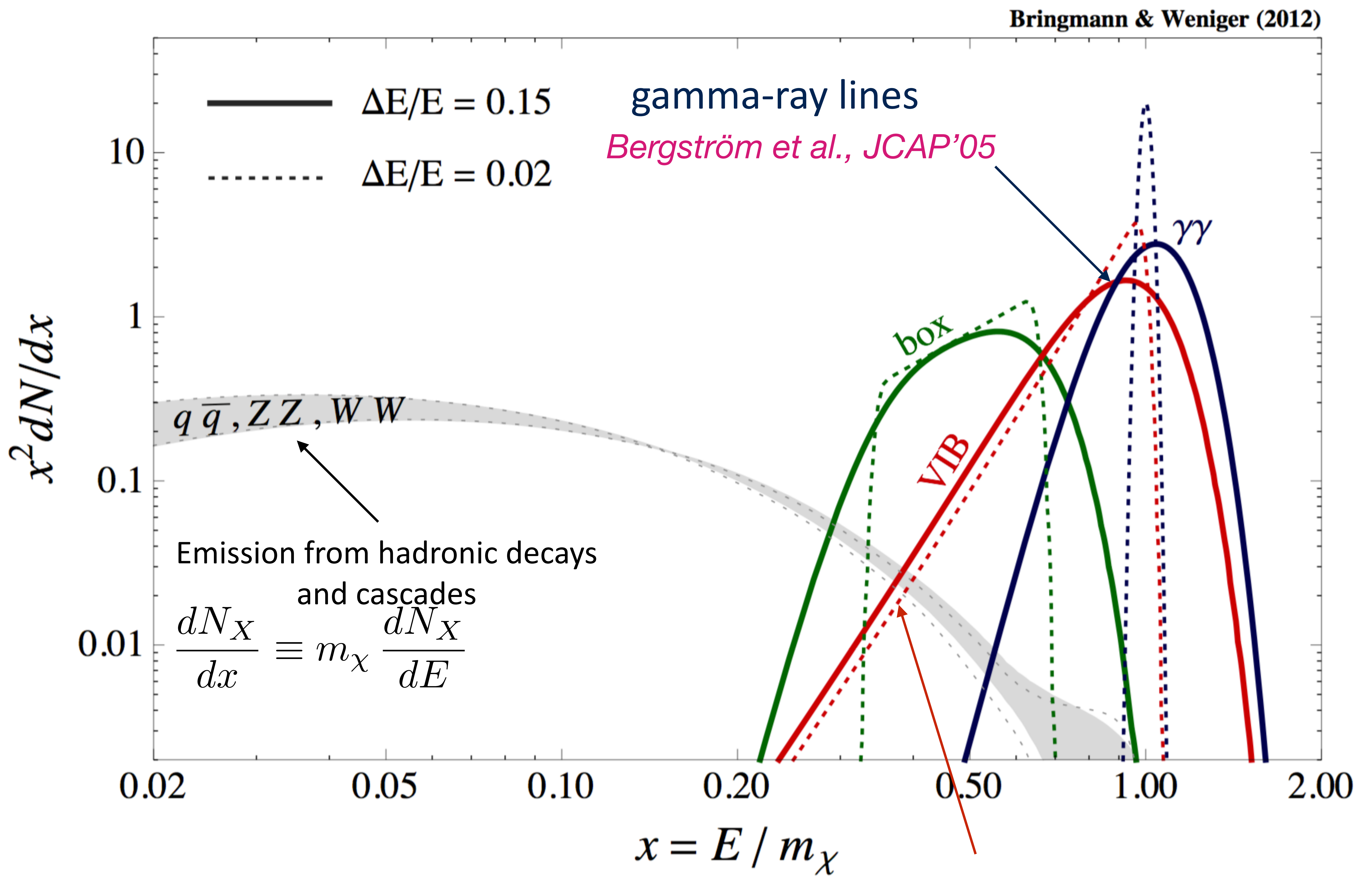




$$x \equiv \frac{E_X}{m_\chi}$$

$$\frac{dN_X}{dx} \equiv m_\chi \frac{dN_X}{dE}$$

Dark matter spectrum: prompt photons



EM and EW corrections

Bringmann, FC+ JHEP'08; Ciafaloni+ JCAP'11; Bringmann&FC PRL'14

Numerical codes for computation of DM spectra:

DarkSUSY http://www.fysik.su.se/~edsjo/darksusy/
Gondolo+ JCAP'04

MicrOMEGAs https://lapth.cnrs.fr/micromegas/
Belanger+ JCAP'05

PPC 4 DM ID http://www.marcocirelli.net/PPPC4DMID.html
Cirelli+ JCAP 2012

Analytical fitting functions:
Fornengo, Pieri, Scopel, PRD 2004
Cembranos et al., PRD 2011

For dependence on event Monte Carlo generators see, e.g.,
Cembranos+ JHEP'13

Dark matter annihilation: Rate and flux

$$Q_\gamma^{\rm ann}(r,E) = \langle\sigma v\rangle \times n_{\rm pairs}(r) \times \sum_f B_f \frac{dN_\gamma^f}{dE}(E)$$

Emissivity per unit energy and volume
$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-3}]$

$$n_{\rm pairs}(r) = s \times \frac{\rho^2(r)}{m^2}$$

$$s = \left\{\frac{1}{2}, \frac{1}{4}\right\}$$

Majorana ($\frac{1}{2}$), Dirac ($\frac{1}{4}$)

$$\frac{d\Phi_\gamma}{dE} = s\frac{\langle\sigma v\rangle}{4\pi m_{\rm DM}^2}\sum_f B_f \frac{dN_\gamma^f}{dE} \times \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho_{\rm DM}^2(\ell)d\ell$$

Gamma-ray (or neutrino) differential energy flux
$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}]$

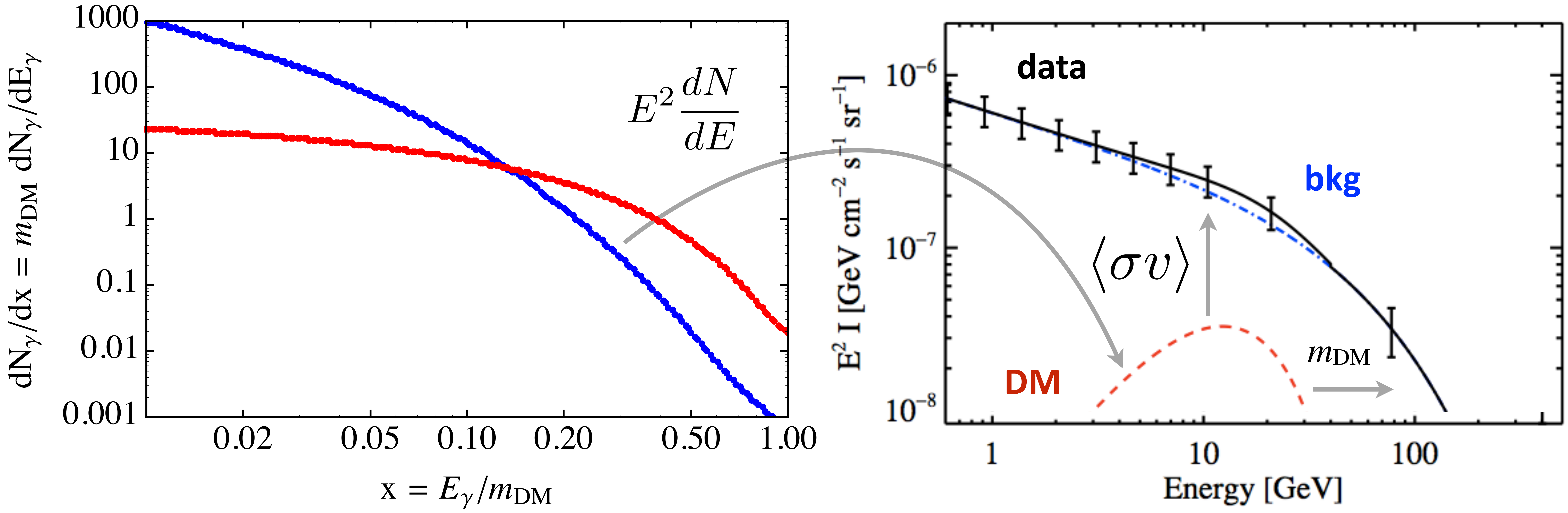
Be careful! This equation holds in the s-wave approximation, i.e. of velocity dependent cross-section

$$\langle\sigma v\rangle = a + bv^2 + \mathcal{O}(v^4),\ v/c \sim 10^{-3}$$

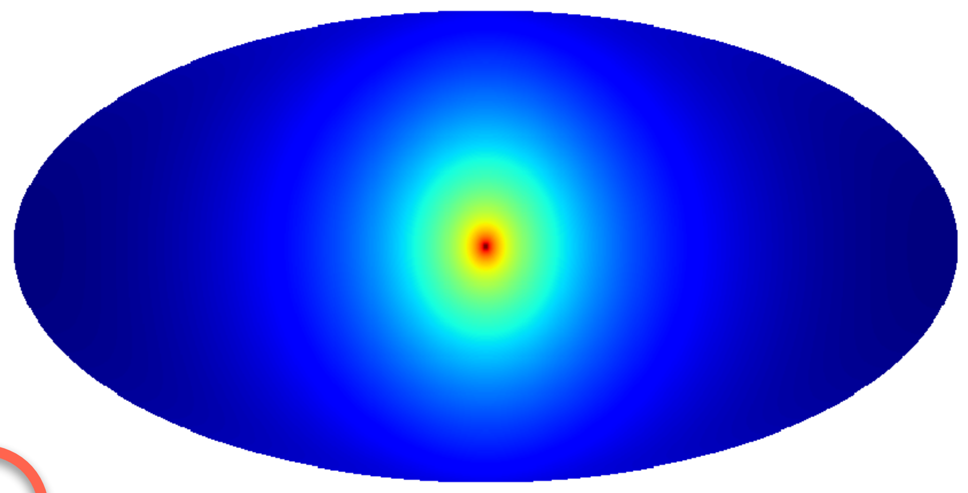
Non-relativistic regime: if present, s-wave is dominant

Dark matter annihilation flux

$$\frac{d\Phi_\gamma}{dE} = s\frac{\langle\sigma v\rangle}{4\pi m_{\rm DM}^2}\sum_f B_f \frac{dN_\gamma^f}{dE} \times \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho_{\rm DM}^2(\ell)d\ell$$

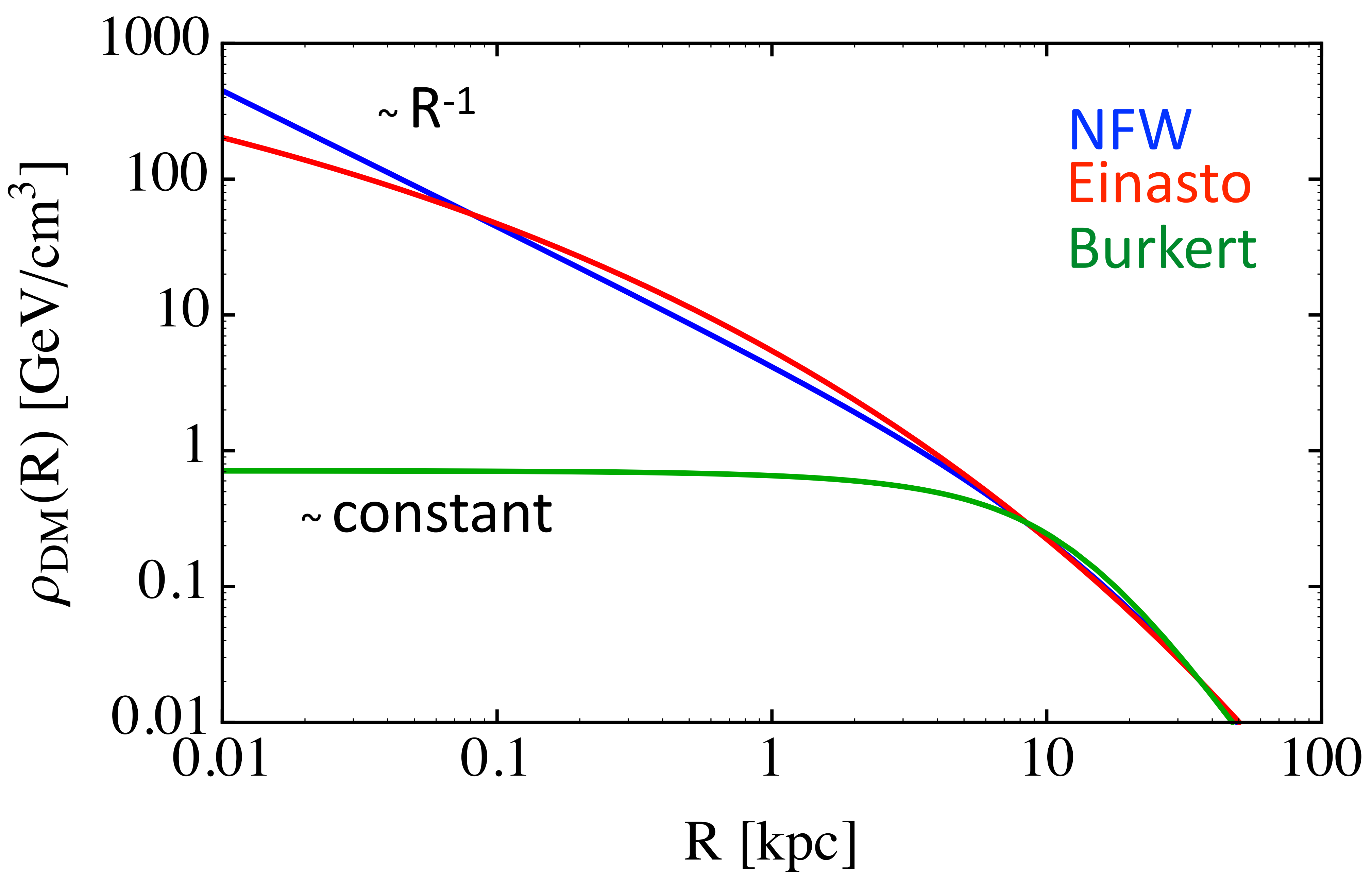


Dark matter annihilation flux

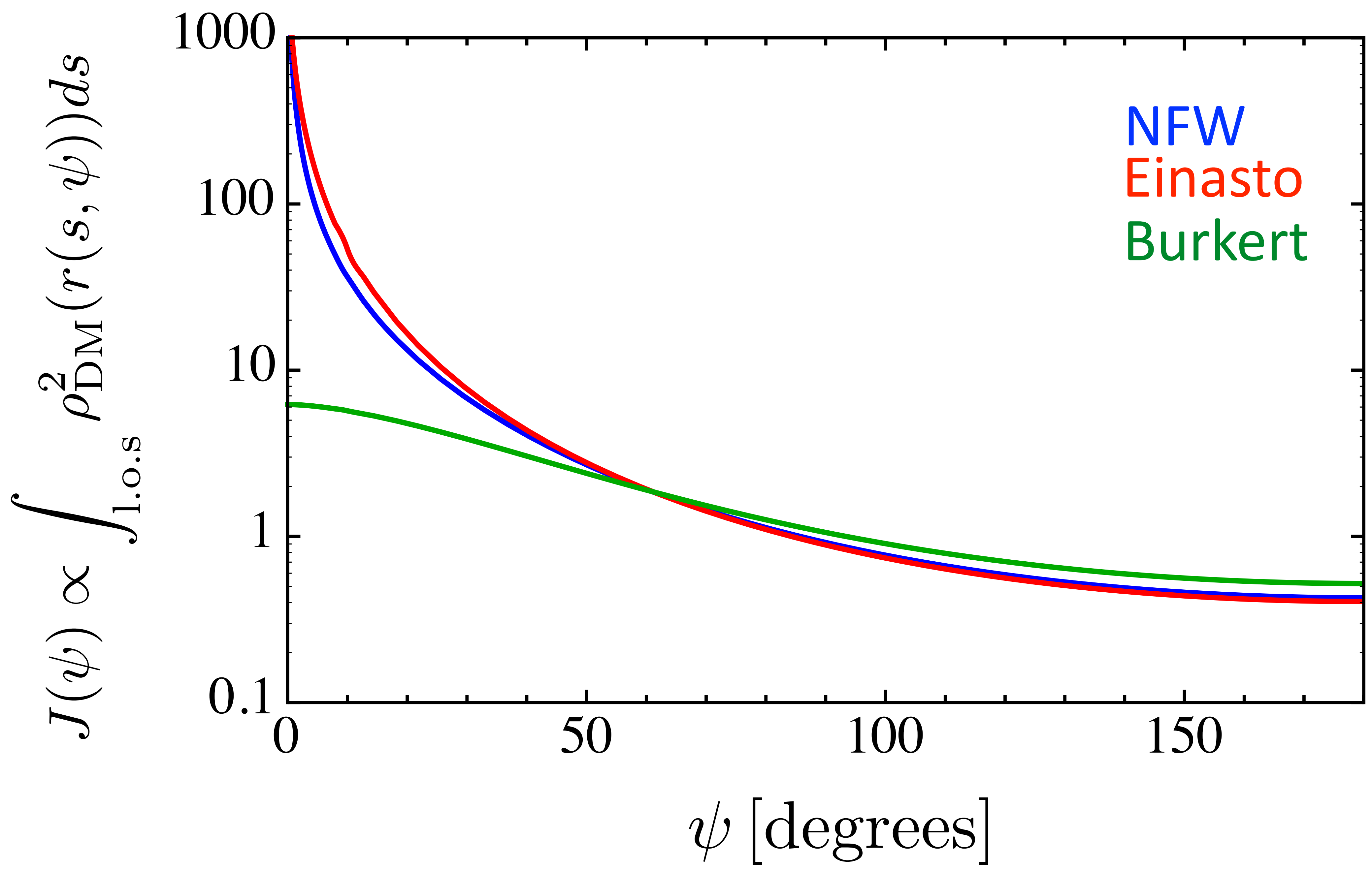


$$\frac{d\Phi_\gamma}{dE} = s\frac{\langle\sigma v\rangle}{4\pi m_{\rm DM}^2}\sum_f B_f \frac{dN_\gamma^f}{dE} \times \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho_{\rm DM}^2(\ell)d\ell$$

Dark matter density profiles

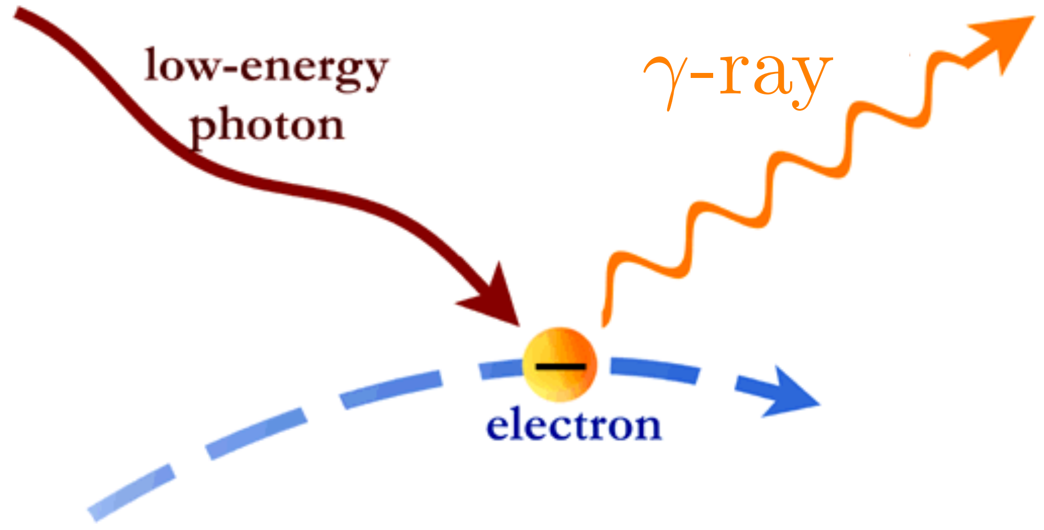


Spatial distribution of the signal



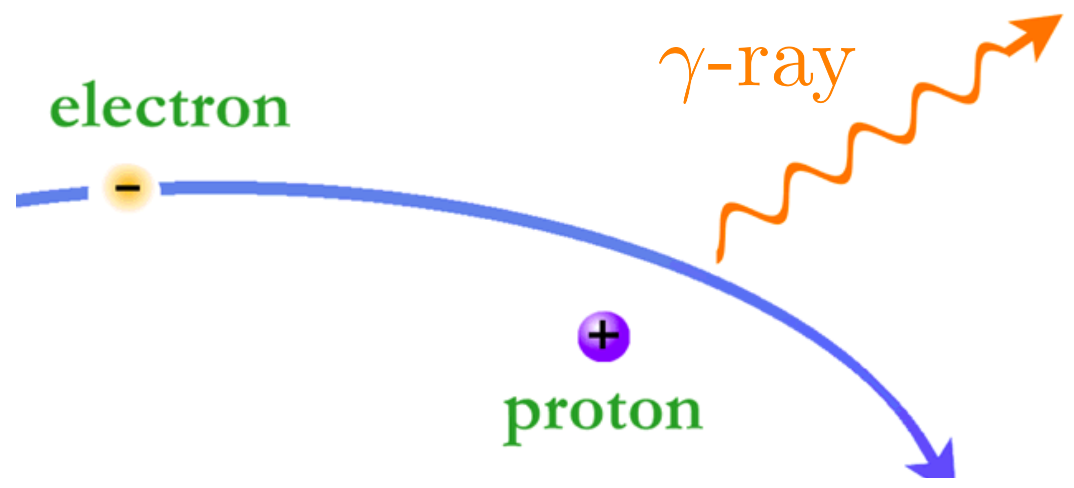
Radiative emission from leptons

$$\chi\chi \rightarrow \left\{ \begin{array}{r} ZZ,\, W^+W^-,\, \gamma\gamma \\ q\bar{q},\, l^+l^-,\, \nu\bar{\nu} \end{array} \right\} \xrightarrow[\text{decays}]{\text{hadronization}} \gamma,\, e^{\pm},\, \mu^{\pm},\, p/\bar{p},\, \pi^{\pm},\, \nu/\bar{\nu},\, \ldots$$



Inverse Compton scattering

on CMB, star-light, infrared-light



Bremsstrahlung

onto gas of interstellar medium

Synchrotron radiation

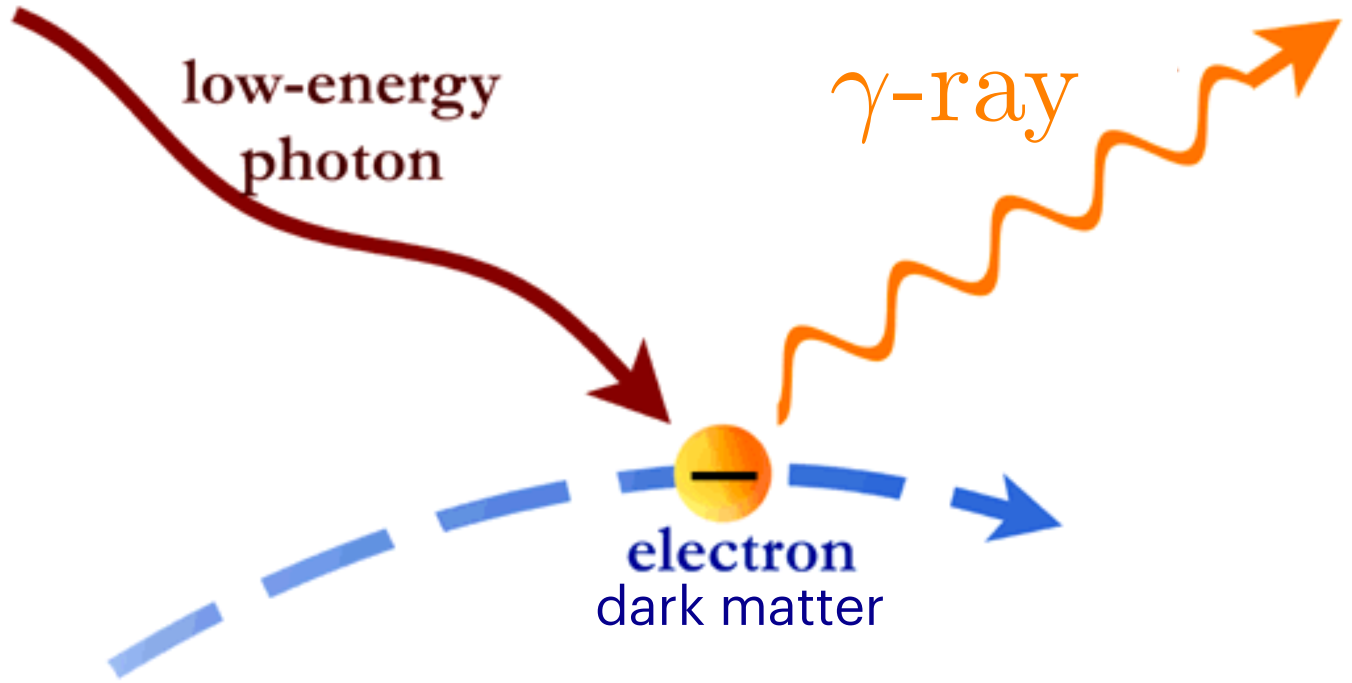
magnetic field muG for GeV-TeV electrons

=> MHz-GHz radio signal

G. Rybicki and A.P. Lightman, 1979, 'Radiative Processes in Astrophysics', John Wiley & Sons Inc.; M. S. Longair, 2011, 'High Energy Astrophysics', Cambridge University Press.

Radiative emission from leptons

Inverse Compton scattering

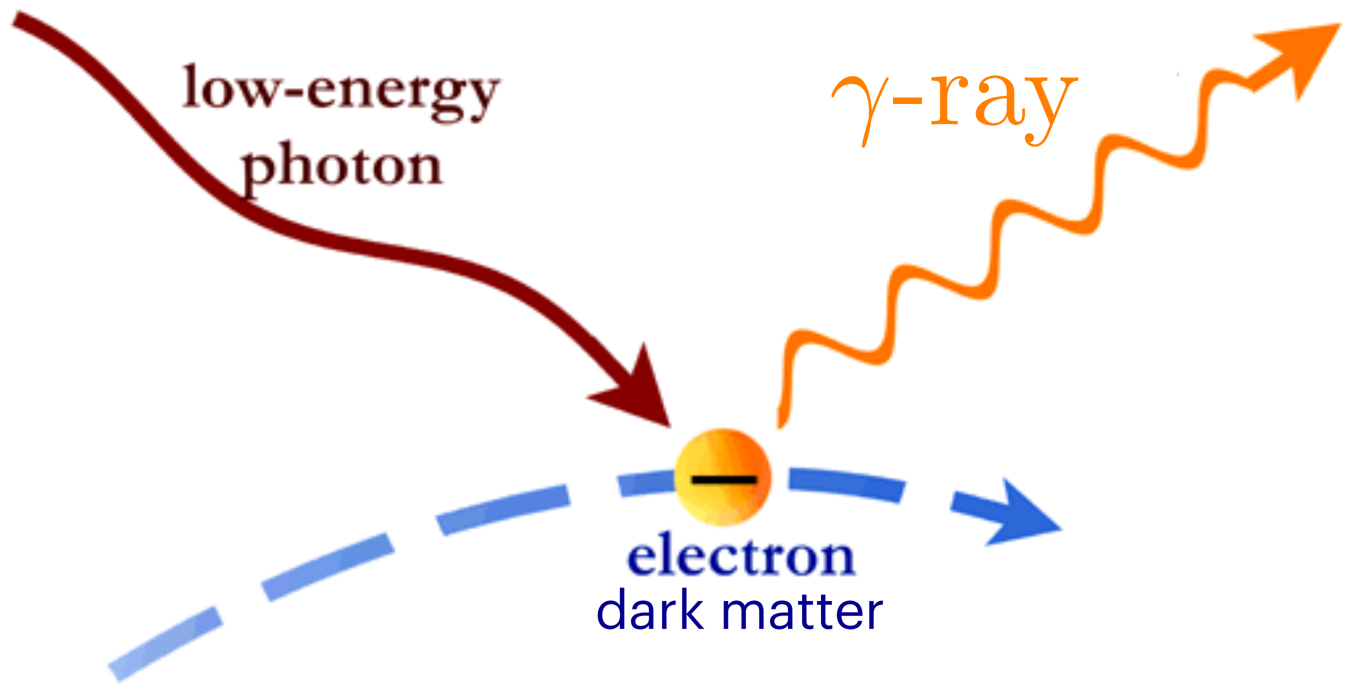


$$E_\gamma \simeq \gamma^2 \varepsilon \quad ; \quad \varepsilon E_e \ll m_e^2$$

$$E_\gamma \simeq 30 \left(\frac{\varepsilon}{\mathrm{eV}}\right)\left(\frac{E_e}{\mathrm{GeV}}\right)^2 \ \mathrm{MeV}$$

Radiative emission from leptons

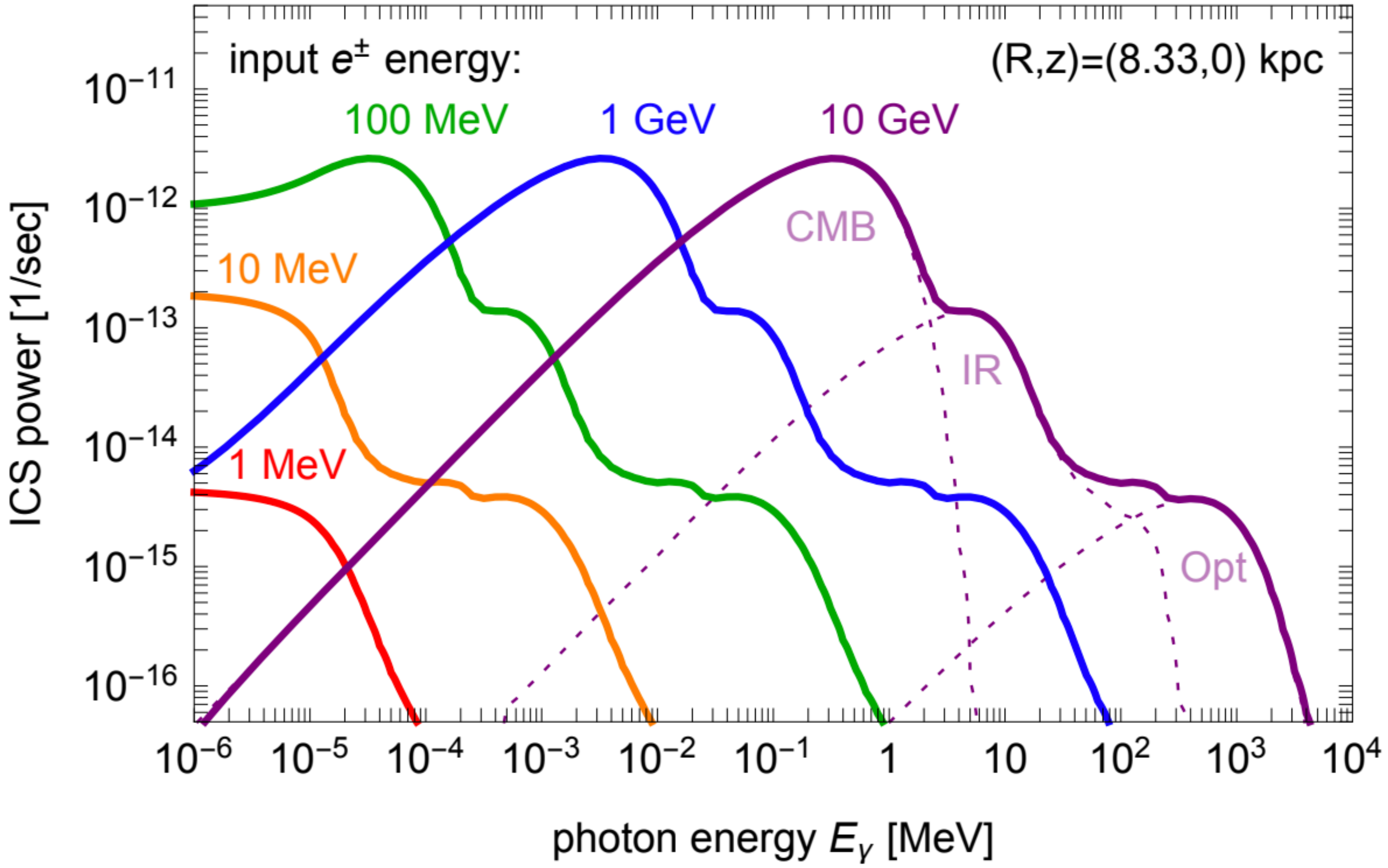
Inverse Compton scattering



$$E_\gamma \simeq \gamma^2 \varepsilon \quad ; \quad \varepsilon E_e \ll m_e^2$$

$$E_\gamma \simeq 30 \left(\frac{\varepsilon}{eV}\right)\left(\frac{E_e}{GeV}\right)^2 \text{ MeV}$$

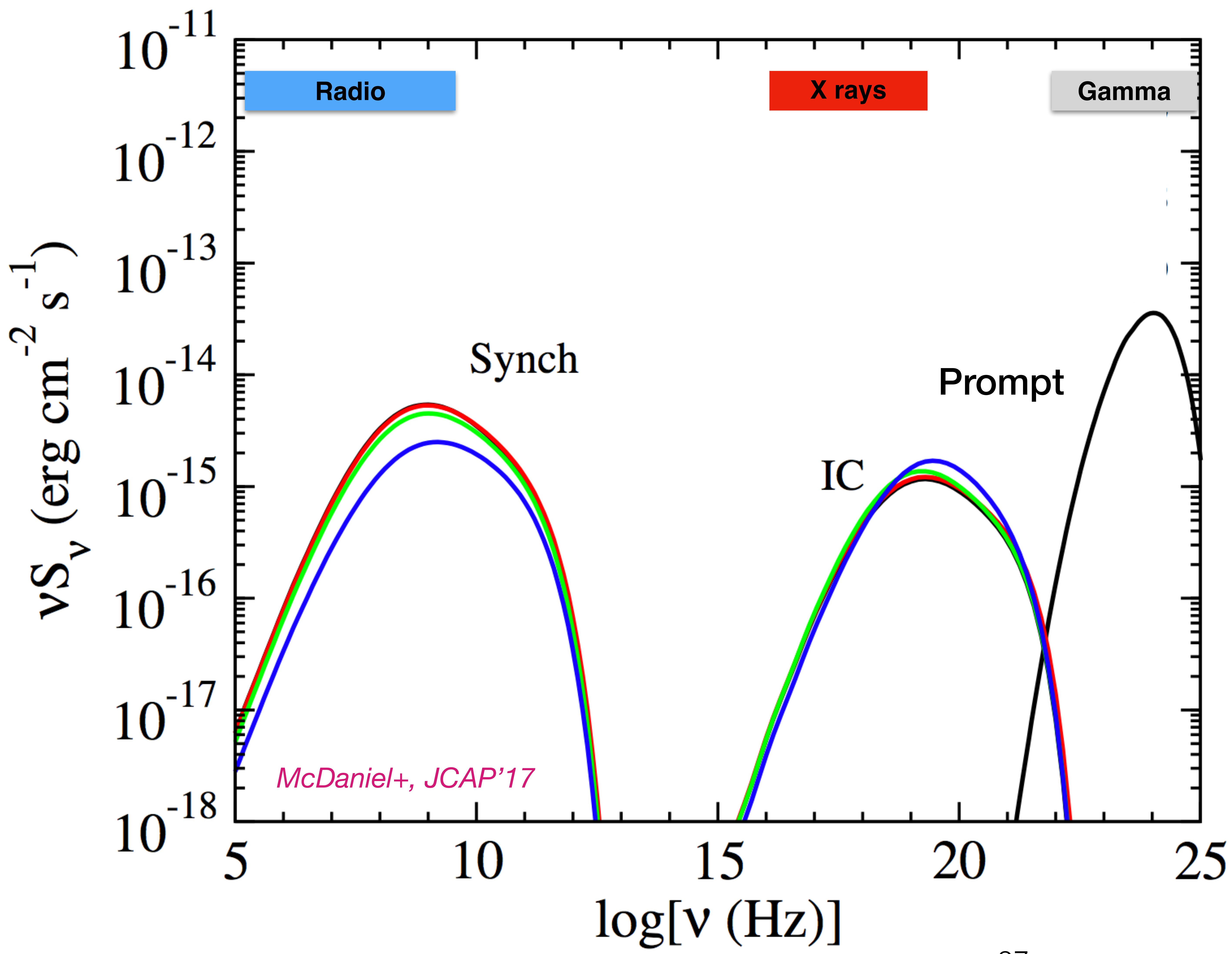
Cirelli+ PRD' 21



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

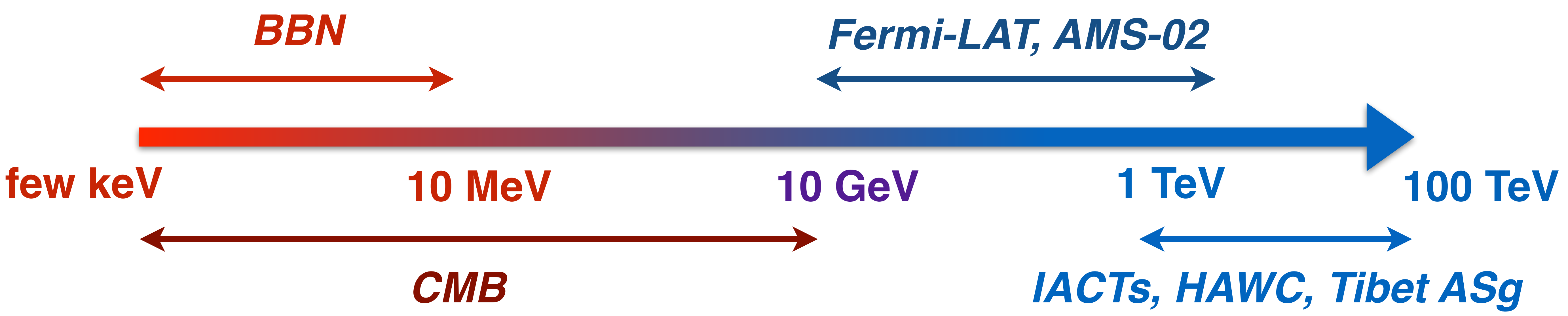
Multi-wavelength particle DM emission

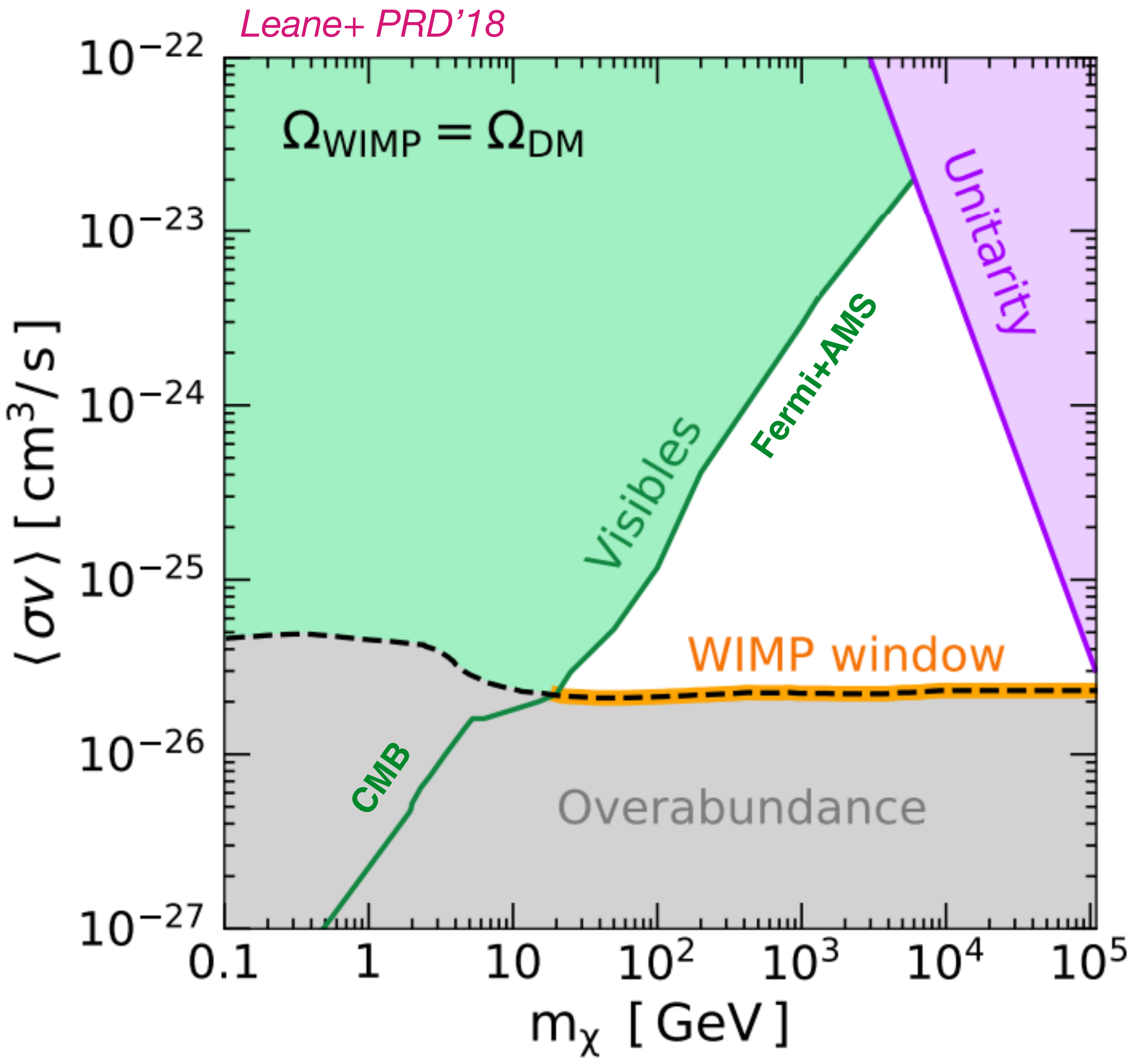
"Secondary" radiative emission induced by leptonic particles interacting with the environment



Example: Annihilation into b-quarks; m_{DM} = 100 GeV

WIMP annihilation window



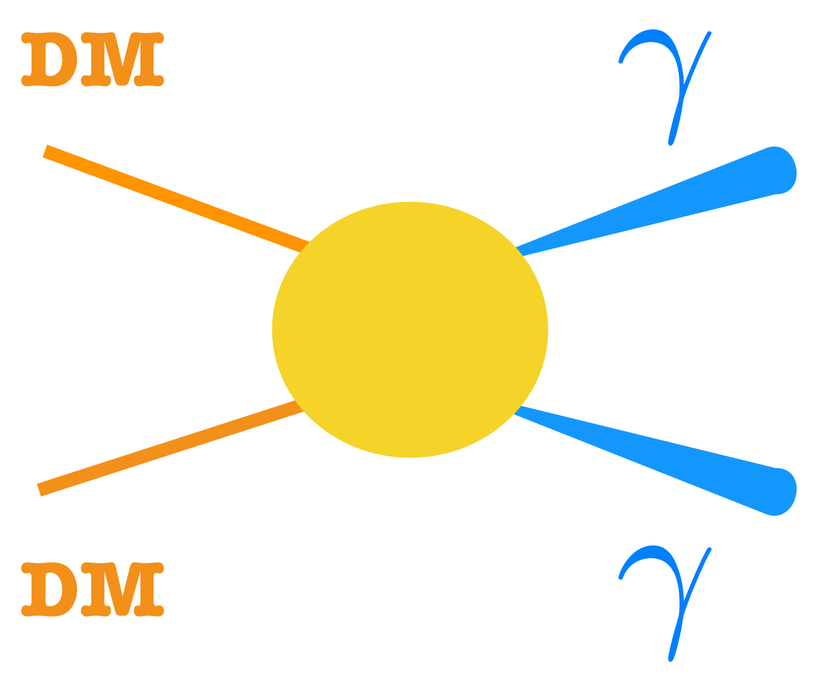


- **Total cross-section** sets **relic abundance**
- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

→ Consistent and conservative interpretation of the data in the context of the generic thermal WIMP

[Low DM masses constrained by energy injection at early times and CMB observations *Slatyer & Wu, PRD'17*]

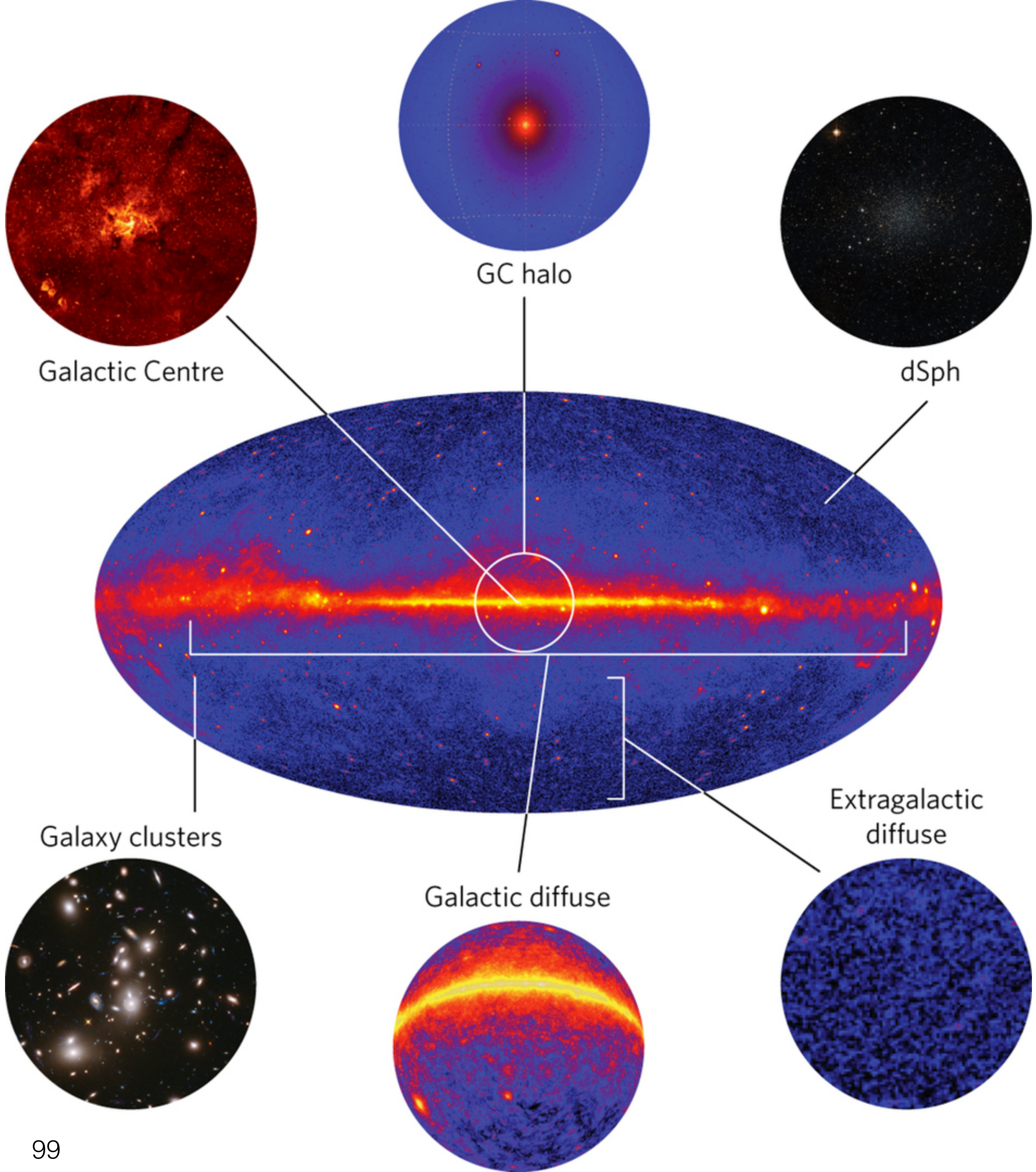
Targets for WIMP gamma-ray searches



$$J \propto \int d\ell\, \rho\, [r(\ell,\psi)]^2$$

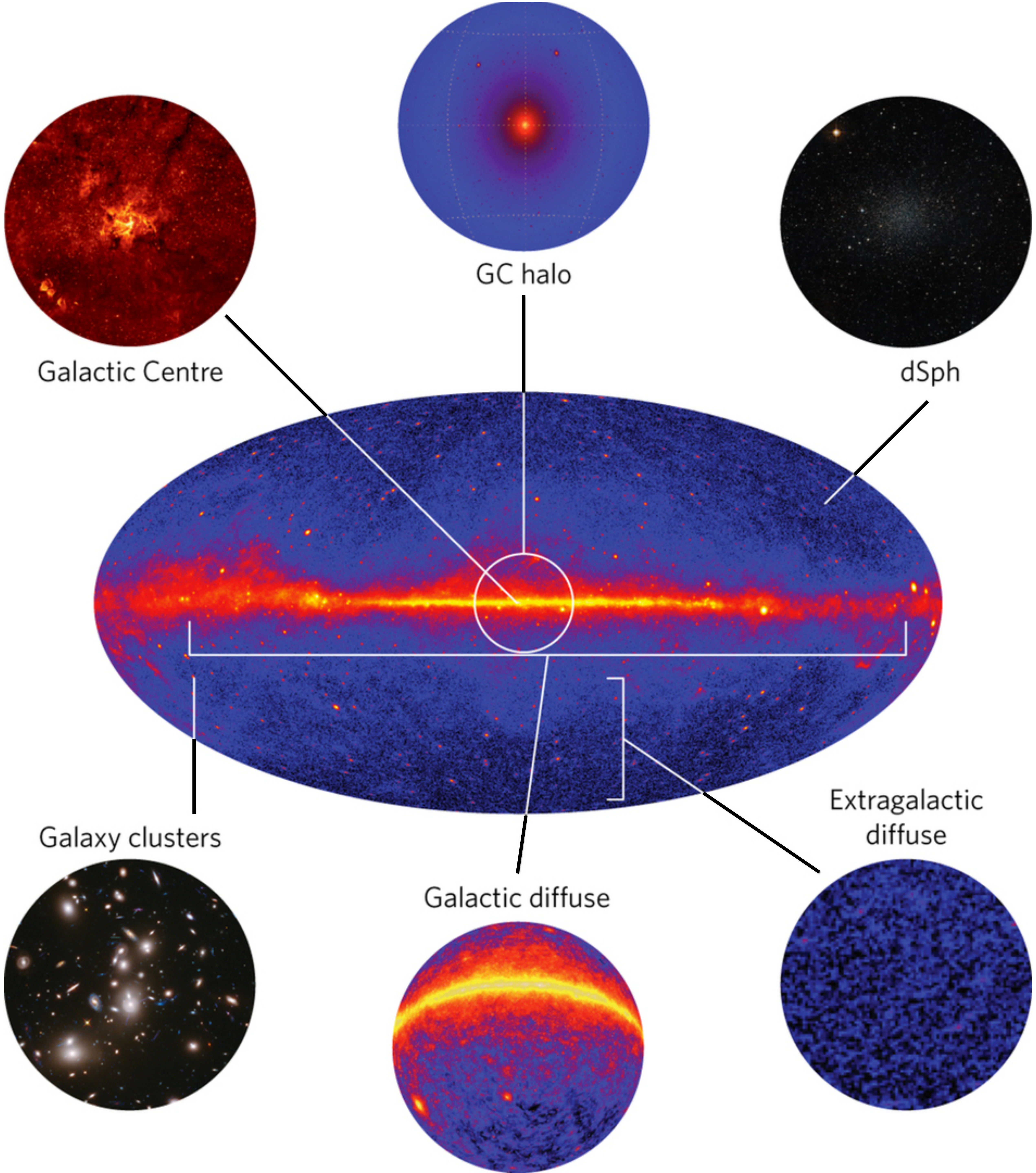
+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)

Conrad & Reimer Nature Phys. 13 (2017)



Astrophysical Backgrounds

- **Guaranteed gamma-ray emission** from astrophysical sources and cosmic-ray interactions with gas and ambient photons
- **Modelling uncertainty** from cosmic-ray propagation conditions and target distributions (gas, radiation fields)
- Careful assessment is S/B and systematic modelling uncertainties



Feature-based searches

Different WIMP searches leverage on different WIMP (generic) features

- Generally, the signal looks like a smooth bump (from decay/hadronization products) from the main, smooth, Galactic halo => Importance of astrophysical background modelling
- Spectral features: look for sharp (or less sharp) features at the high-end of the energy spectrum
- Spatial (angular) features: look for specific DM-dominated targets and/or for angular correlations in the sky (anisotropies/cross-correlation)

=> Example: Searches for DM towards dwarf spheroidal galaxies

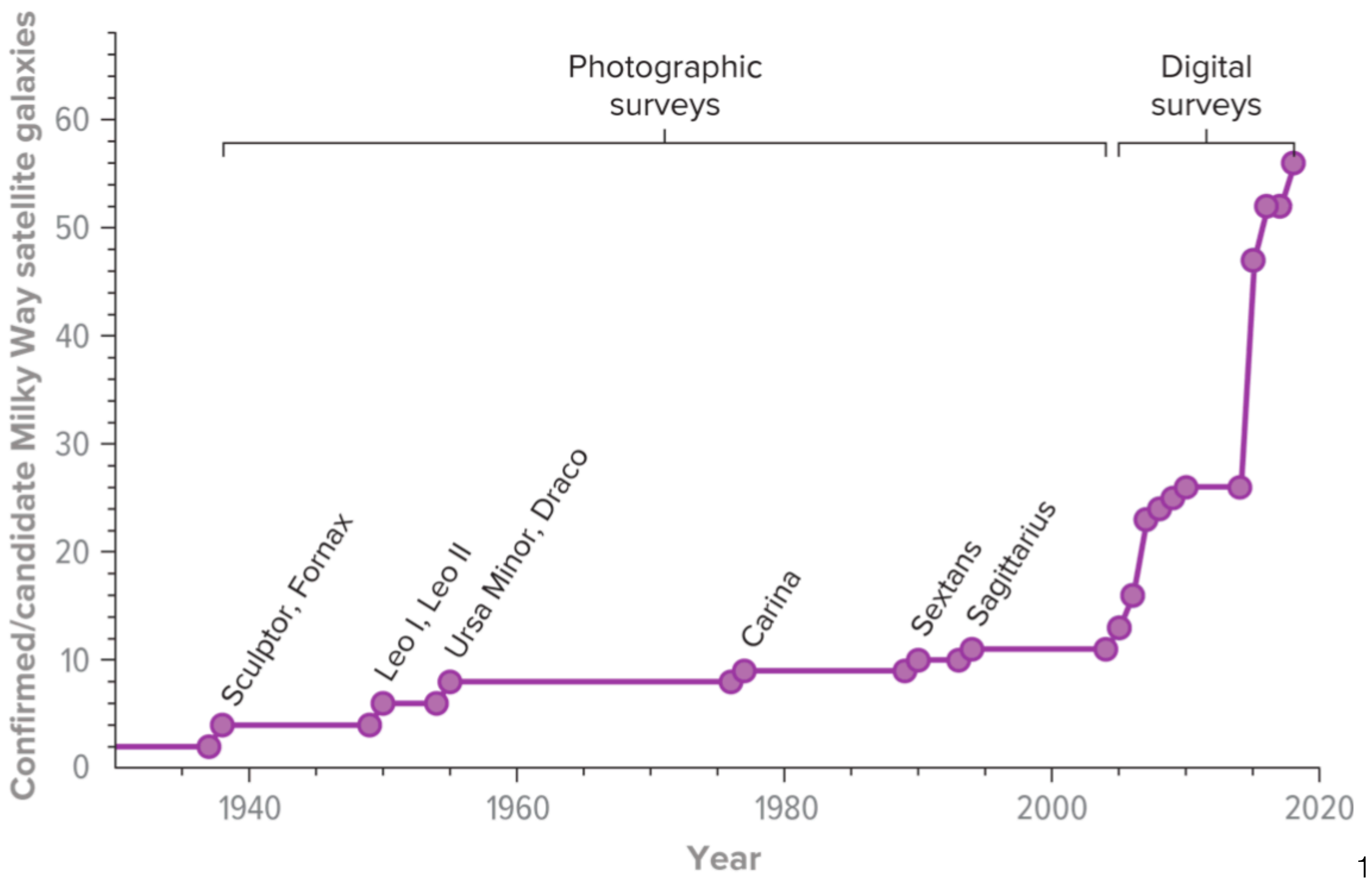
[NB: Models are predictive => can link different observables (direct/indirect/collider) and break degeneracies]

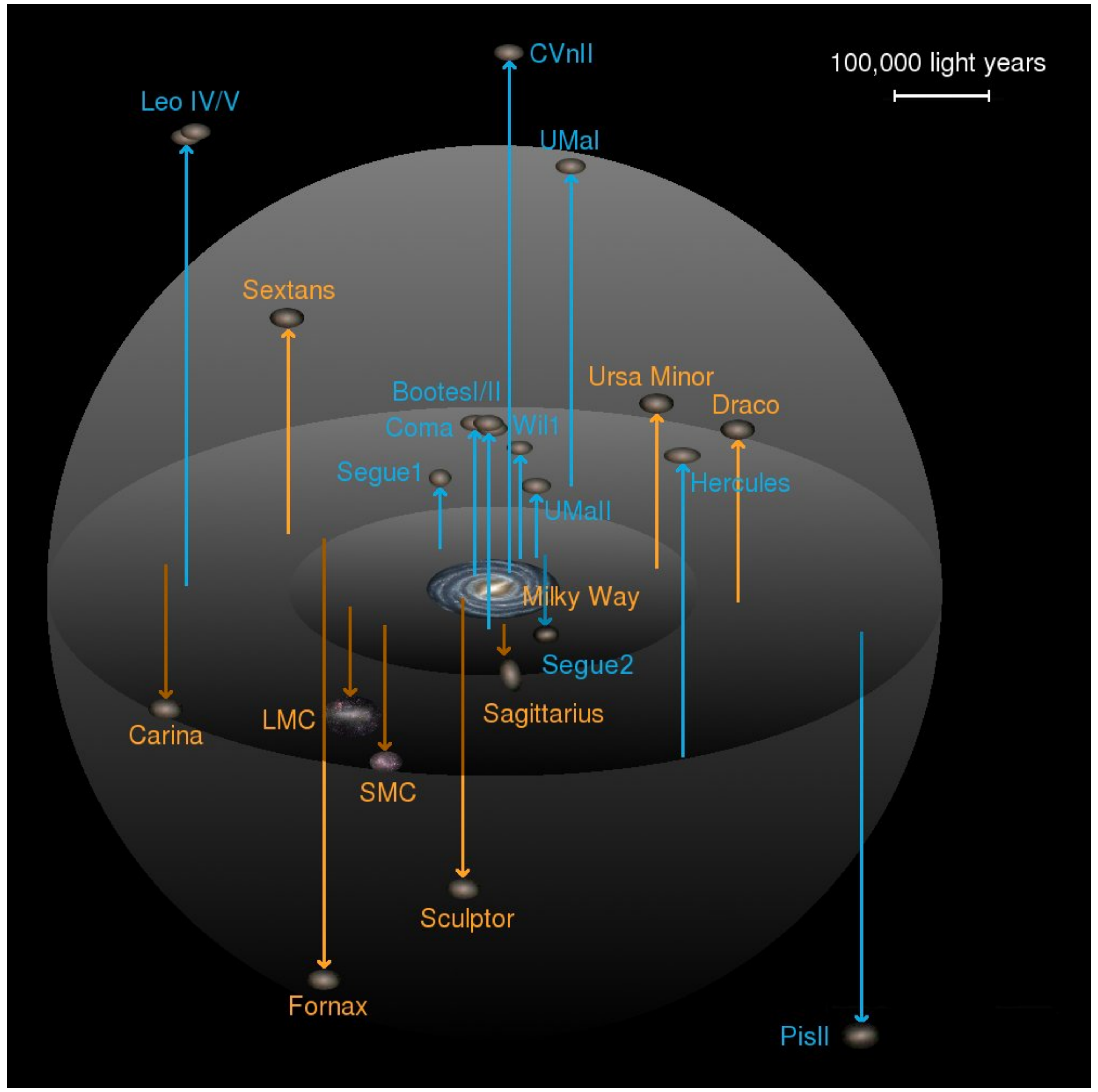
Dwarf spheroidal galaxies

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

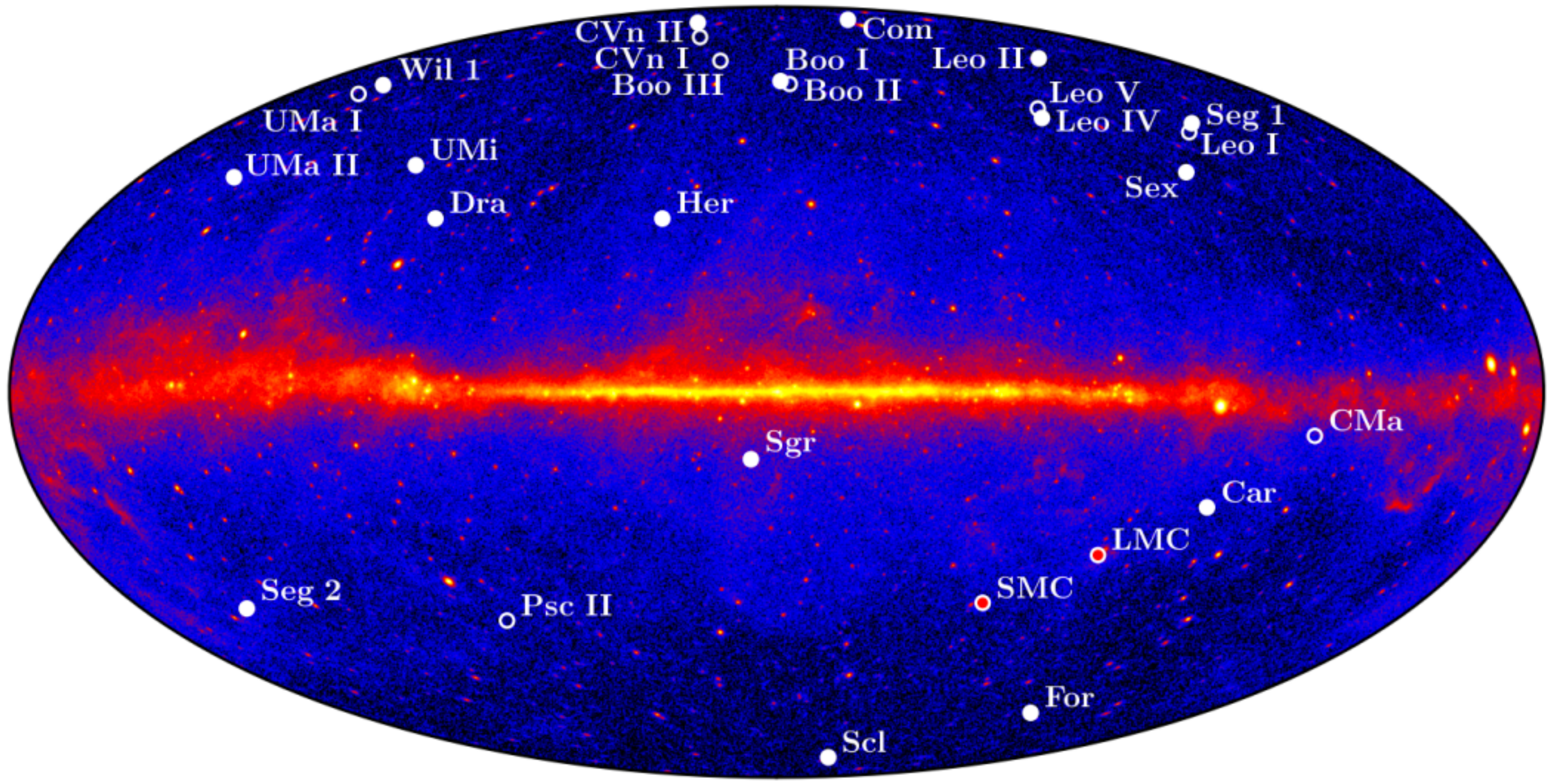




A growing Galactic crowd
> 50 satellites
(SDSS, PanSTARRS, DES)

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

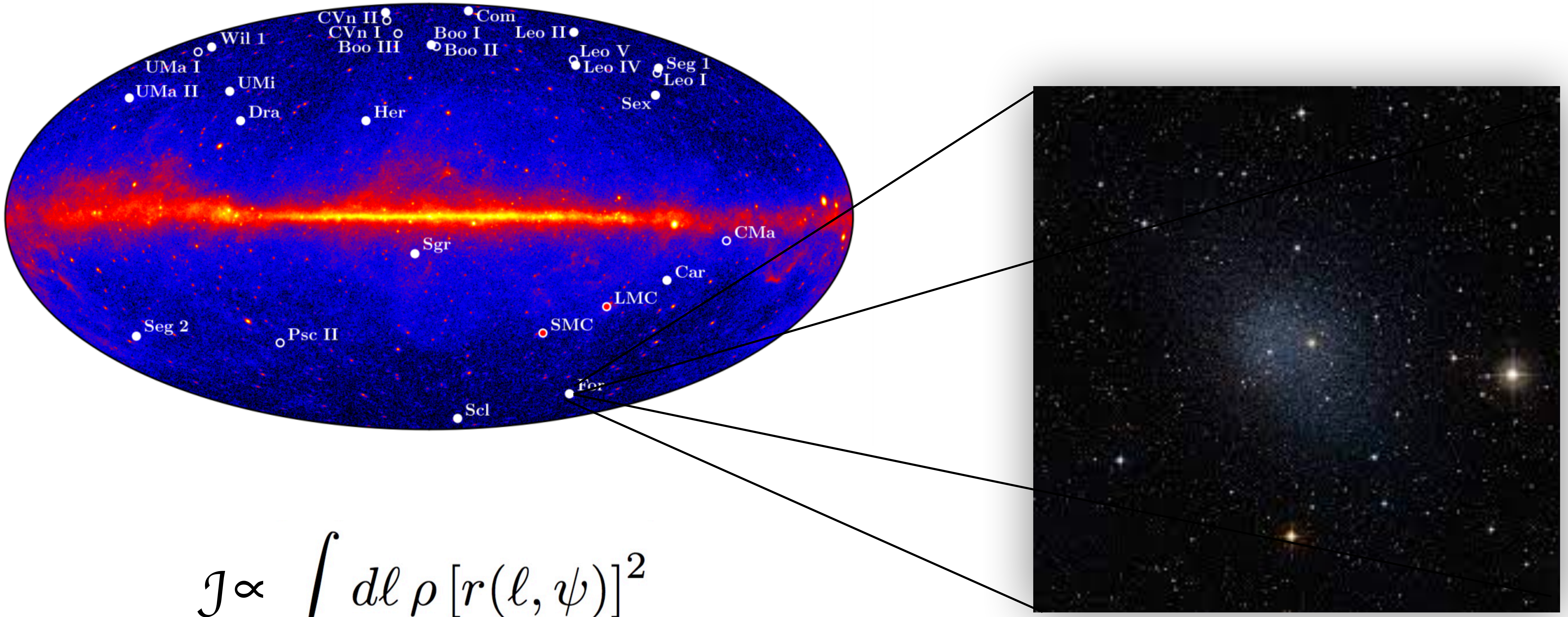
Limits from dwarf spheroidal galaxies



$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell,\psi)\right]^2$$

Fermi-LAT Collaboration, PRL'11

Limits from dwarf spheroidal galaxies

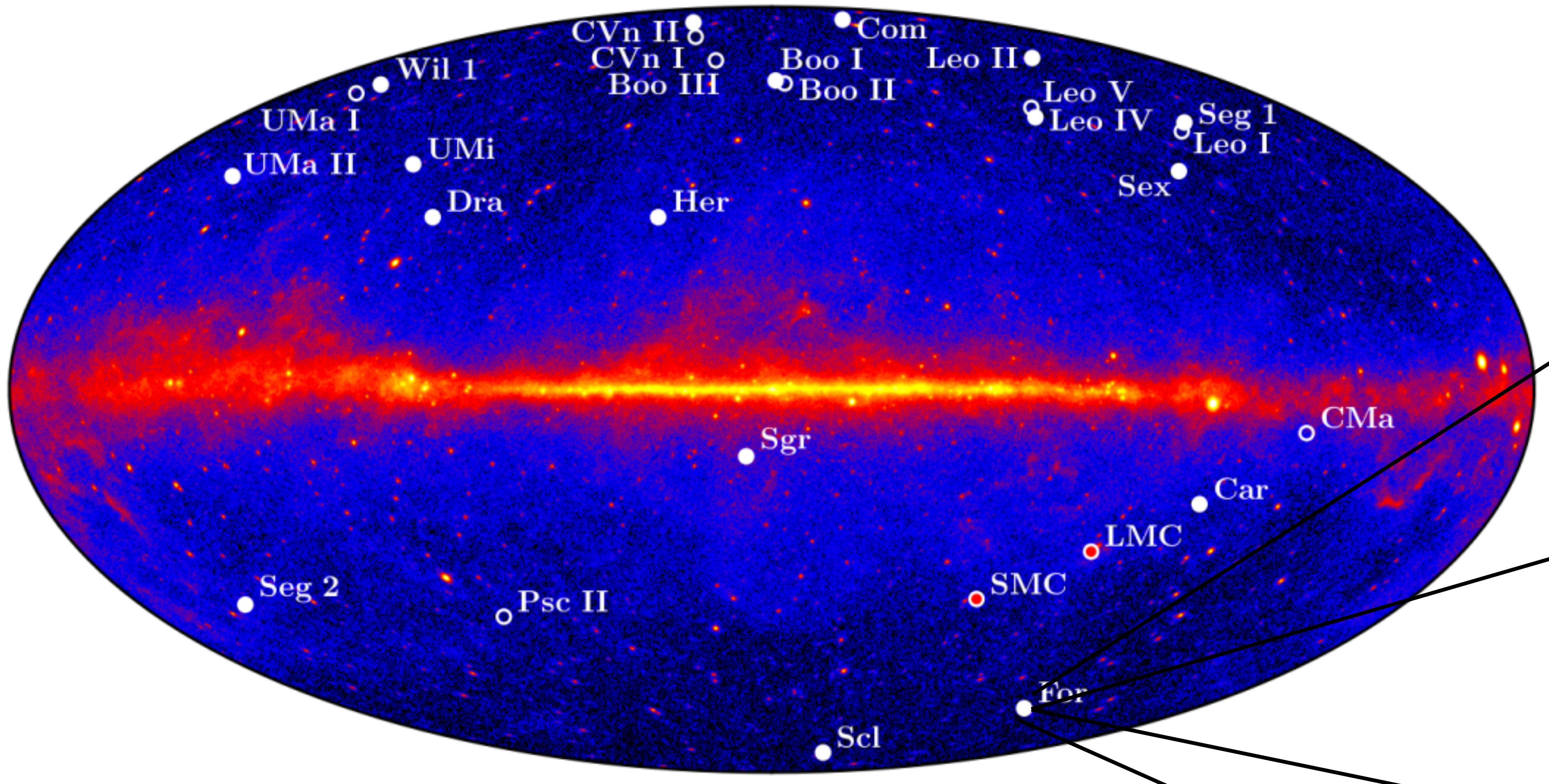


$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

Fermi-LAT Collaboration, PRL'11

Credit: ESO/Fornax galaxy

Limits from dwarf spheroidal galaxies



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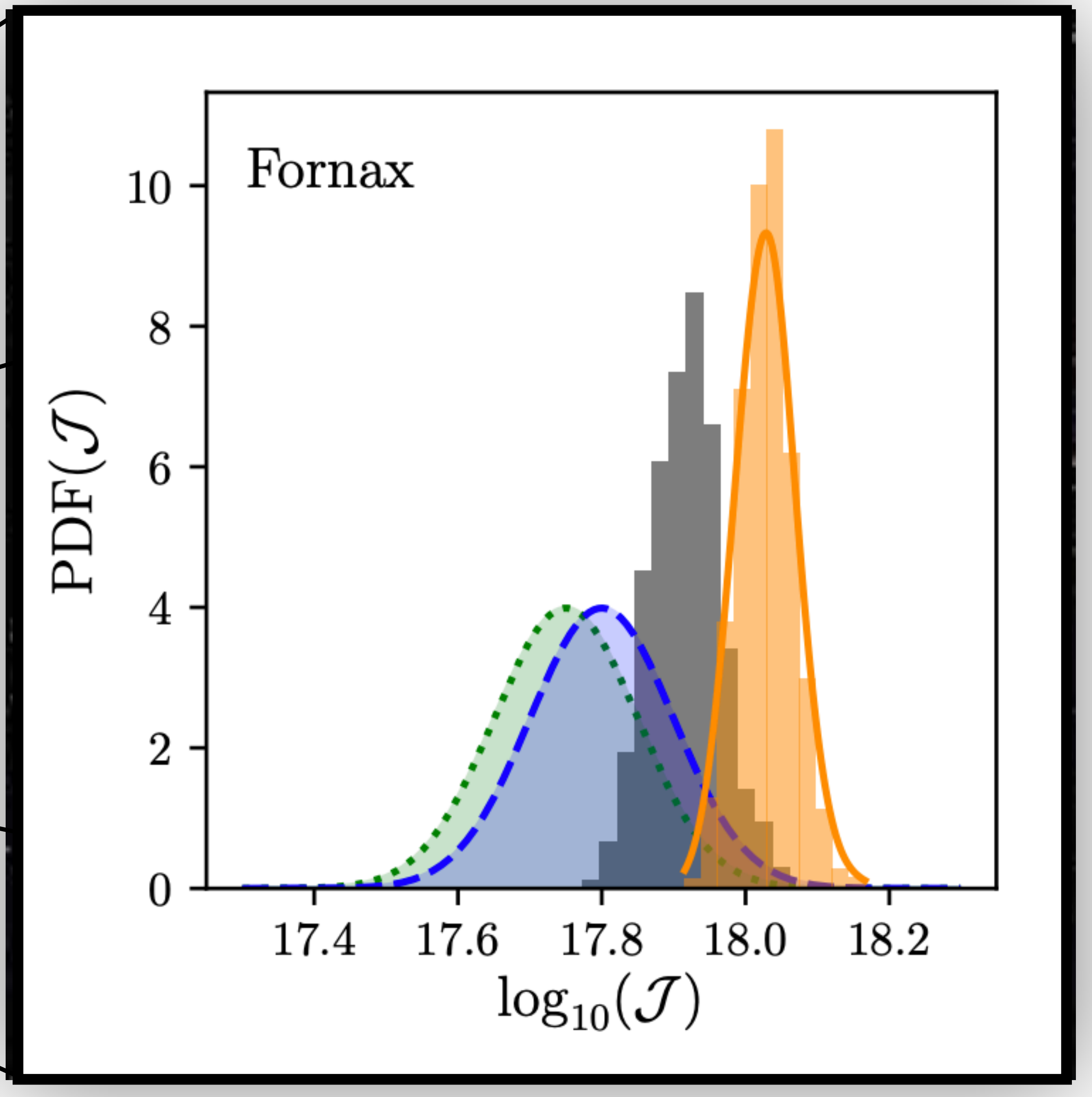
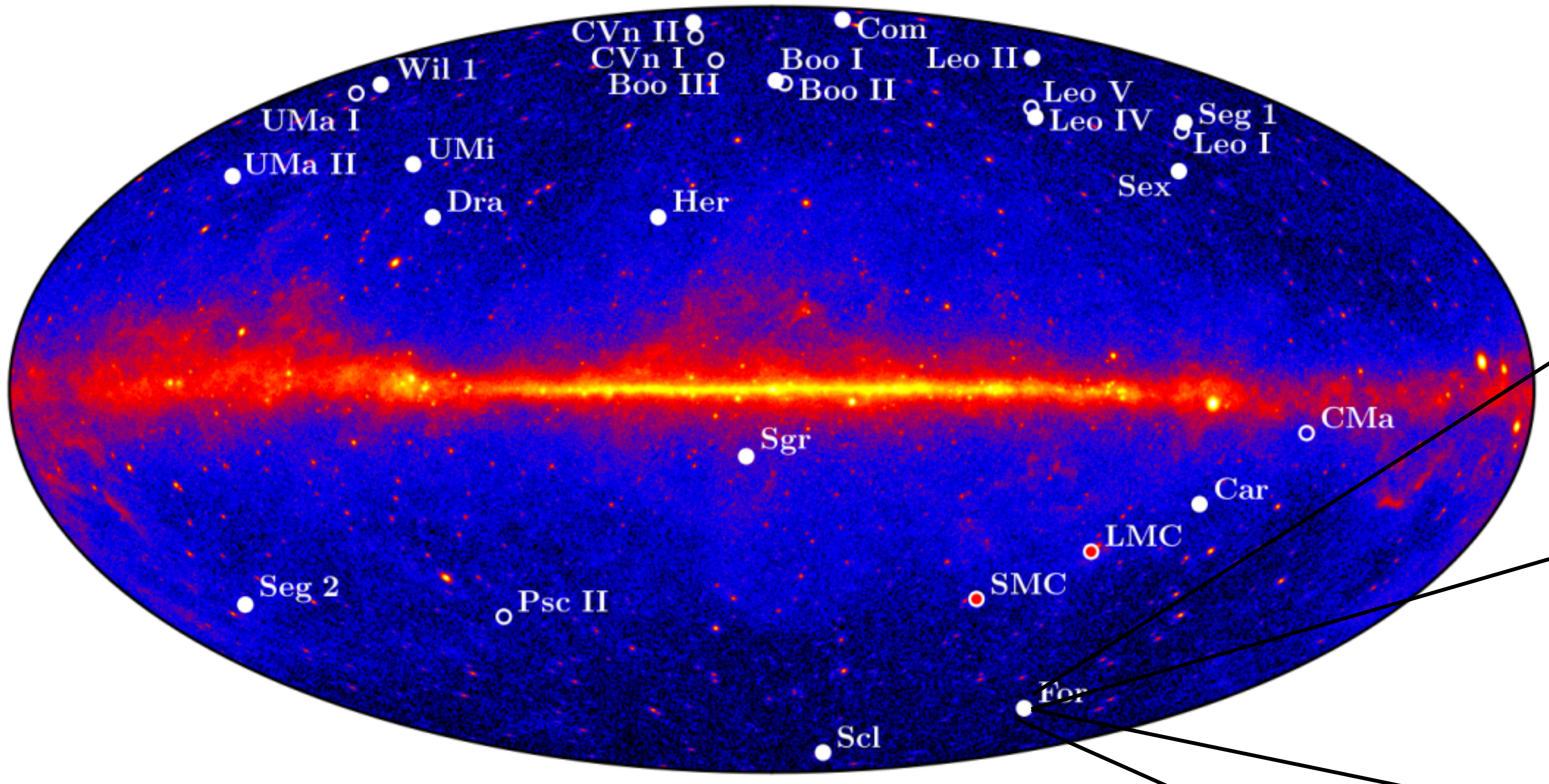
Fermi-LAT Collaboration, PRL'11



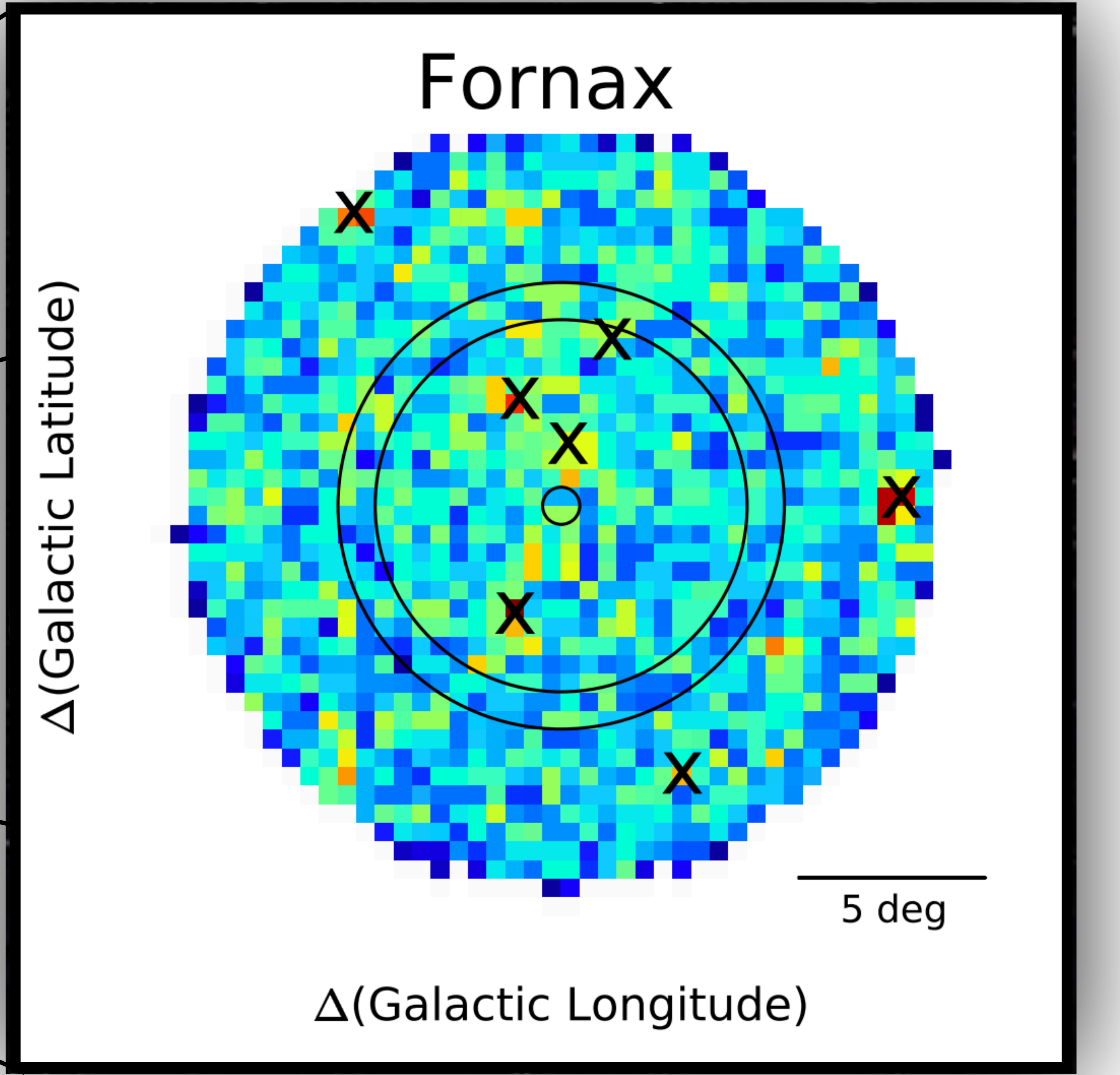
GRAVSPHERE
Alvarez, FC+ JCAP'20

Limits from dwarf spheroidal galaxies



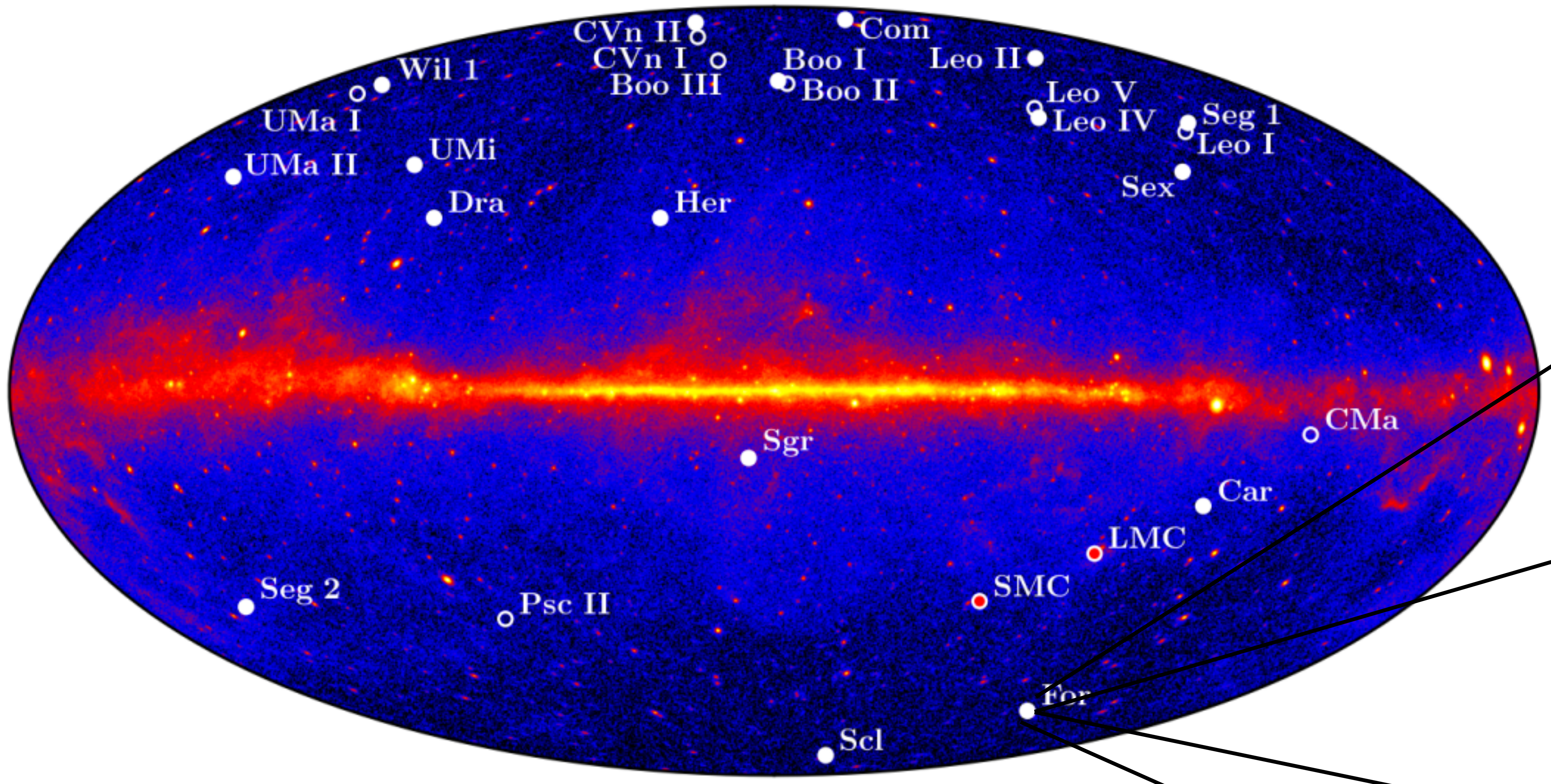
$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

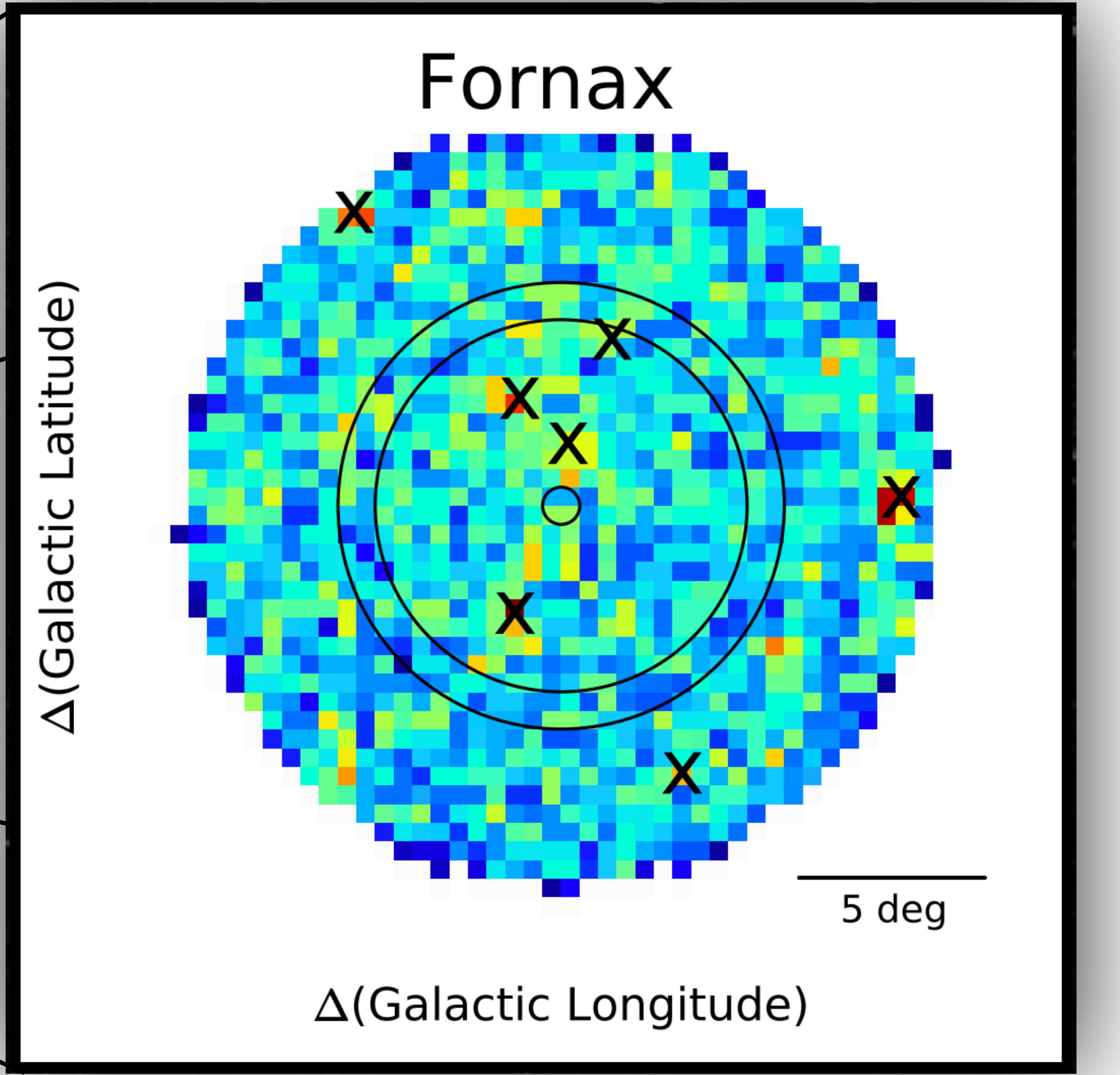
Fermi-LAT Collaboration, PRL'11



Mazziotta+Astrop. Phys.'12

Limits from dwarf spheroidal galaxies





$$\mathcal{J} \propto \int d\ell\, \rho \left[r(\ell,\psi)\right]^2$$

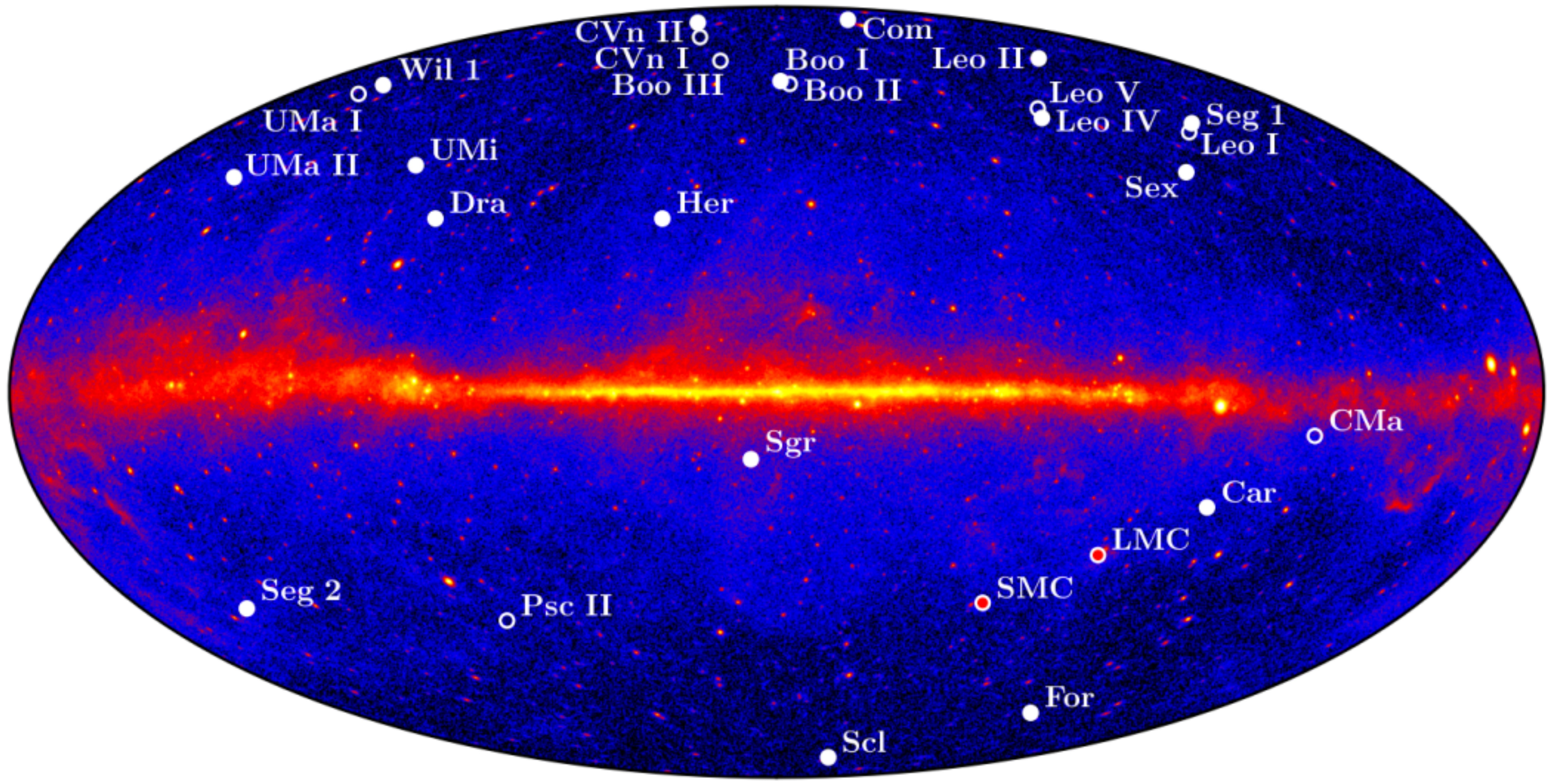
Fermi-LAT Collaboration, PRL'11

Mazziotta+Astrop. Phys.'12

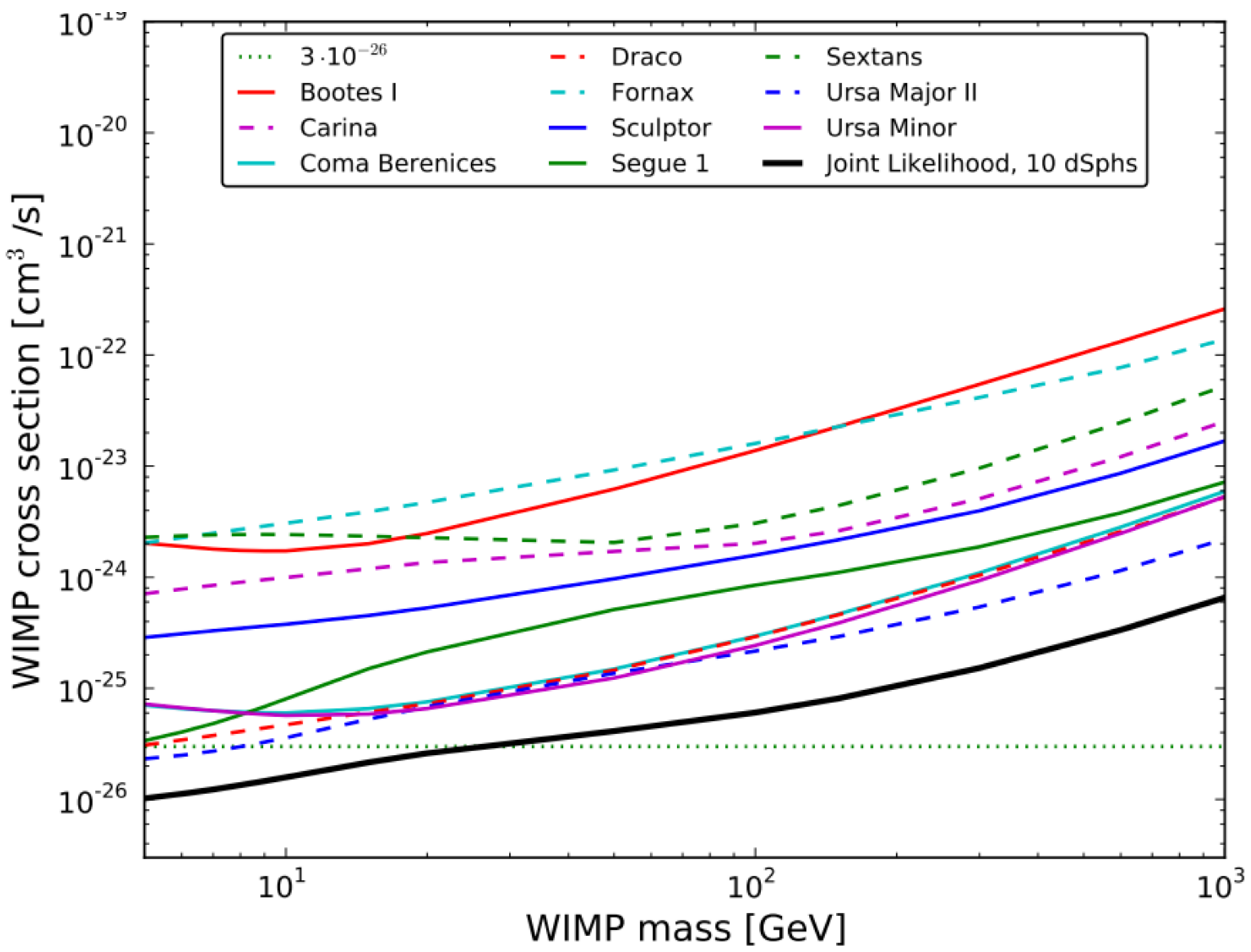
Evidence for additional **DM signal**?

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

Limits from dwarf spheroidal galaxies



$$L(D|\mathbf{pw},\{\mathbf{p}\}_i) = \prod_i L_i^{\mathrm{LAT}}(D|\mathbf{pw},\mathbf{p}_i) \times \frac{1}{\ln(10)\, J_i \sqrt{2\pi}\sigma_i} e^{-\left[\log_{10}(J_i) - \overline{\log_{10}(J_i)}\right]^2/2\sigma_i^2}$$



Analysing dSphs as a group results in sensitivity competitive with other targets => **Stacking technique**

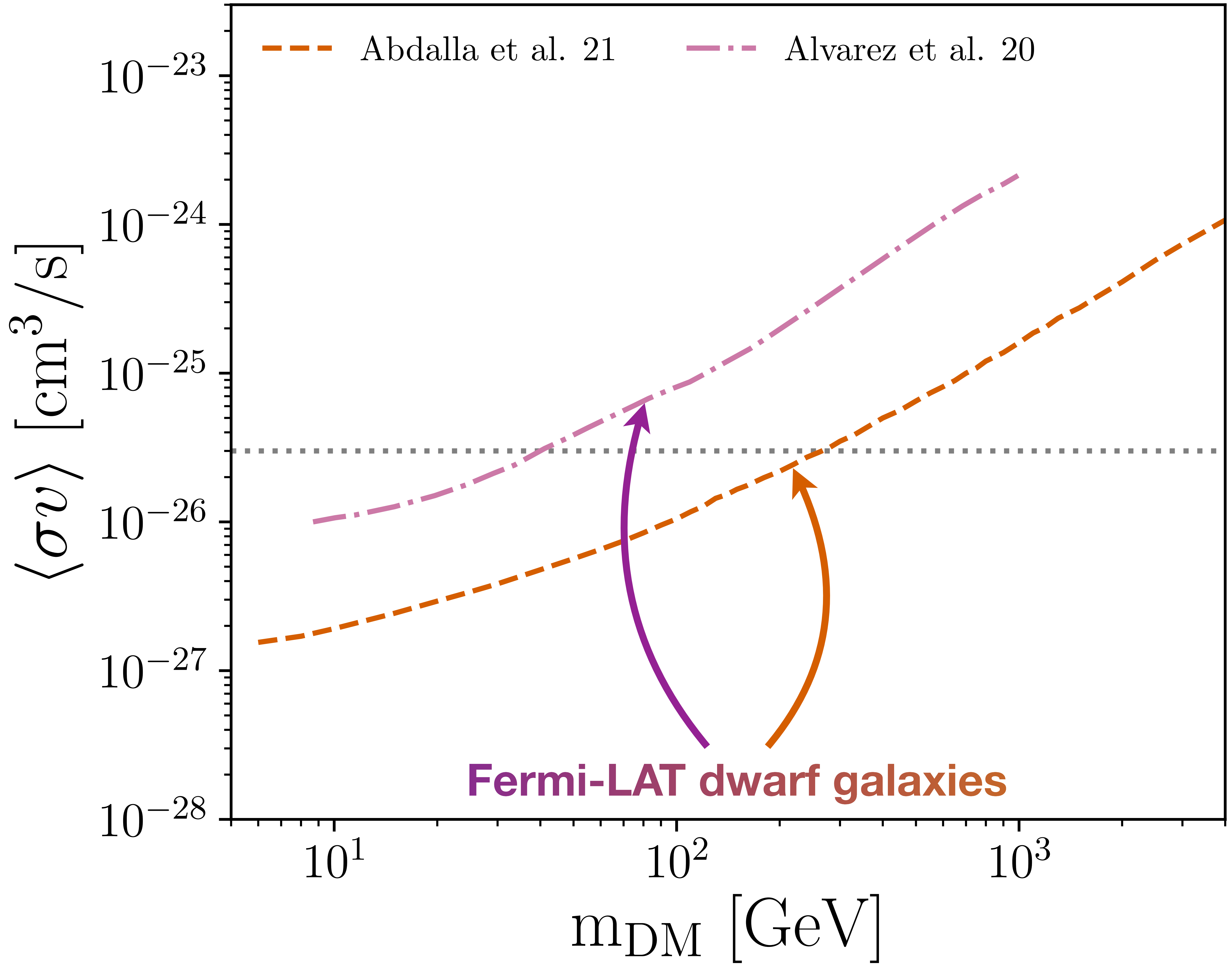
Fermi-LAT Collaboration, PRL'11

$$\mathcal{J} \propto \int d\ell\, \rho\left[r(\ell,\psi)\right]^2$$

Limits on annihilating WIMPs

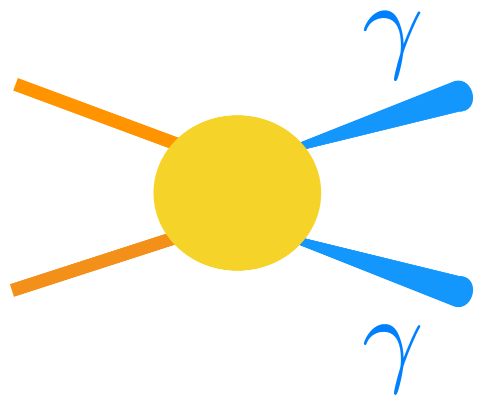
Gamma rays: Dwarf spheroidal galaxies

~ a few GeV — few TeV

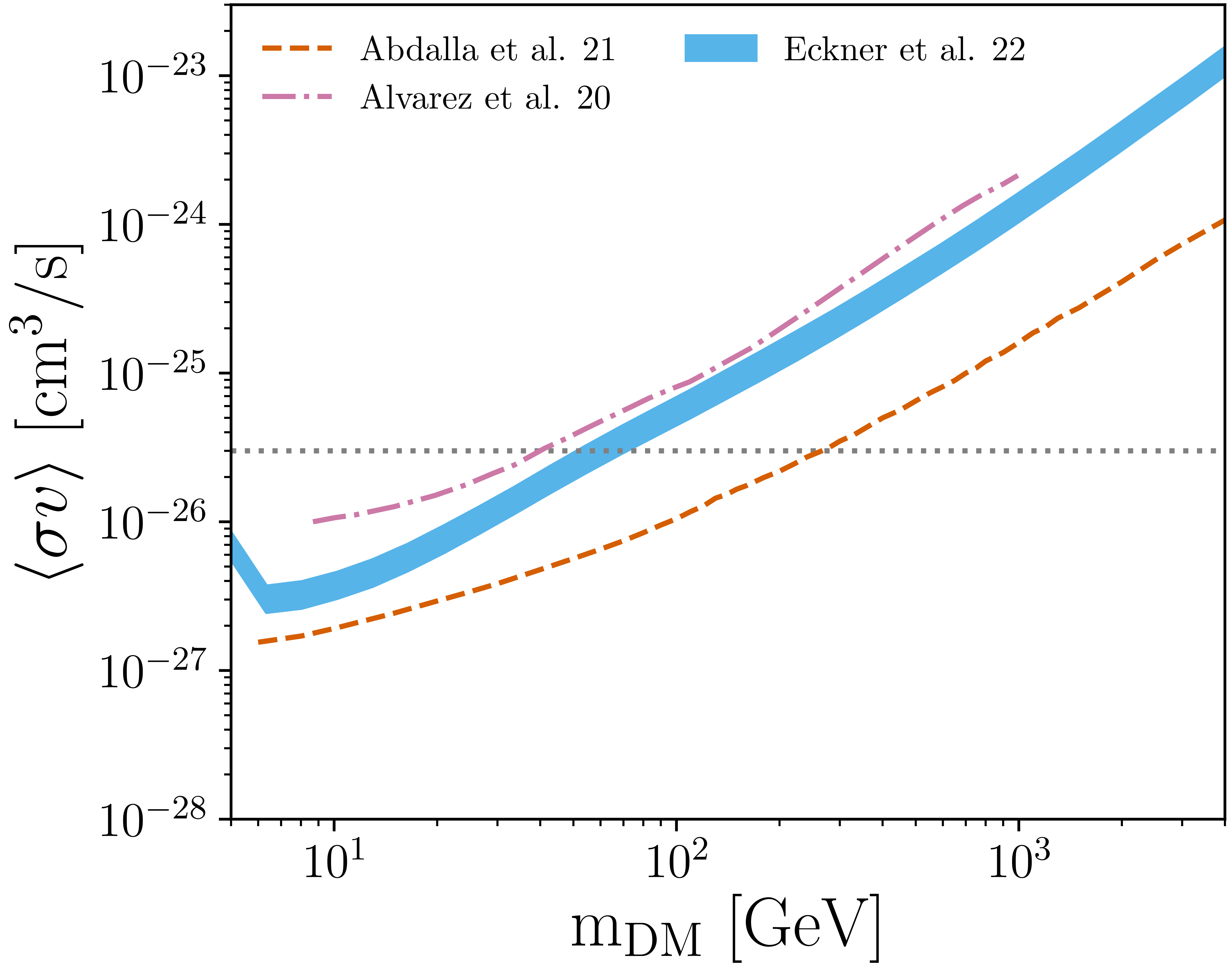


Limits on annihilating WIMPs

Gamma rays: High-latitude MW halo

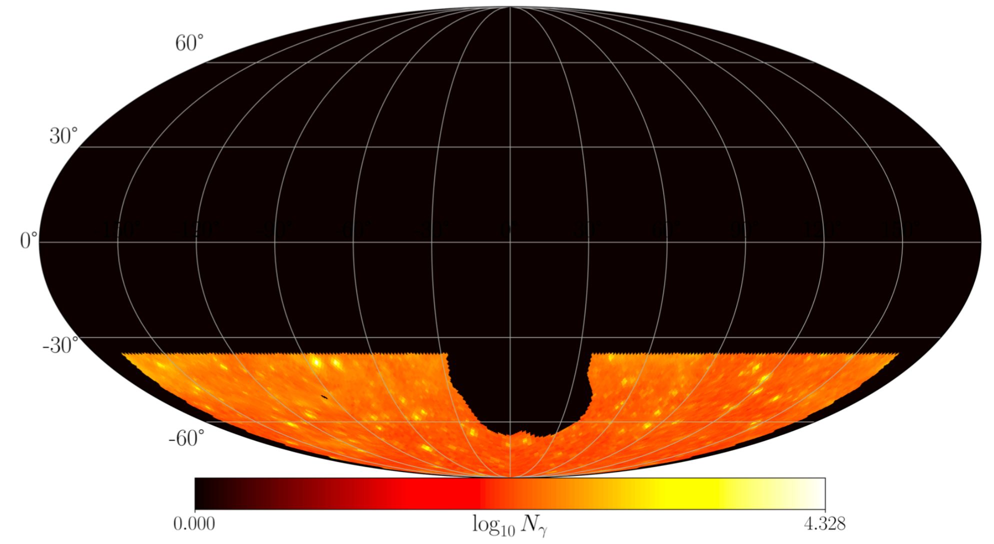


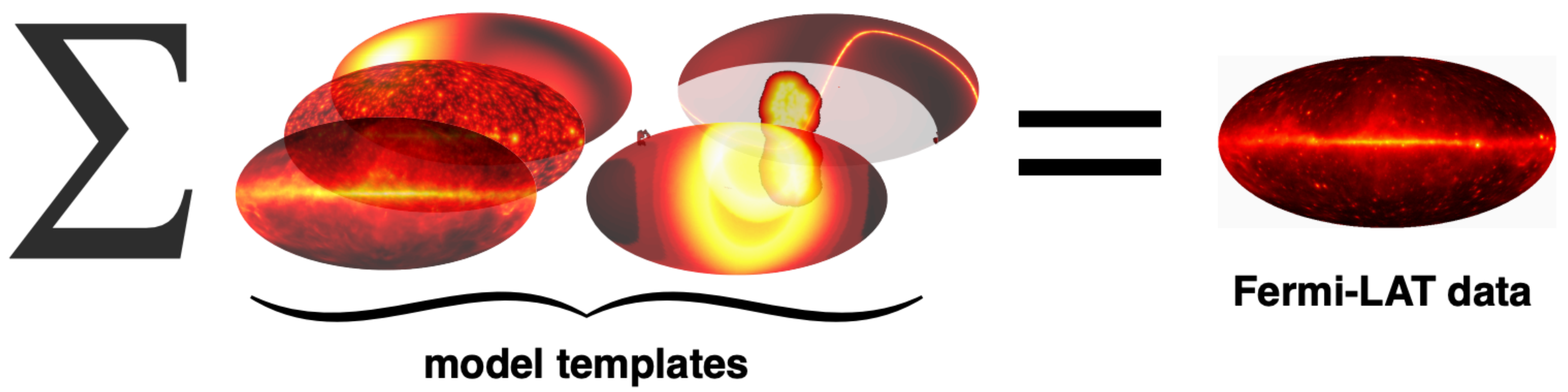
~ a few GeV — few TeV



High-latitude Fermi-LAT sky

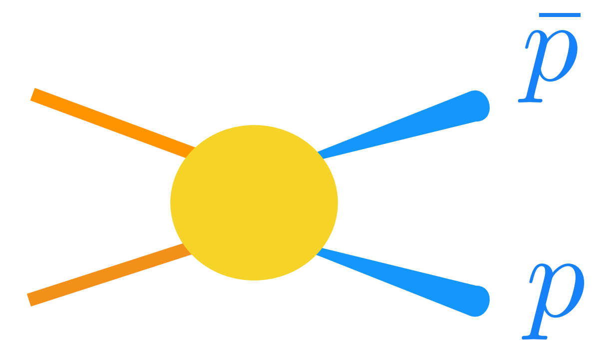
Eckner, FC+ MNRAS'22
Zechlin+ PRD'18
Chang+ PRD'18



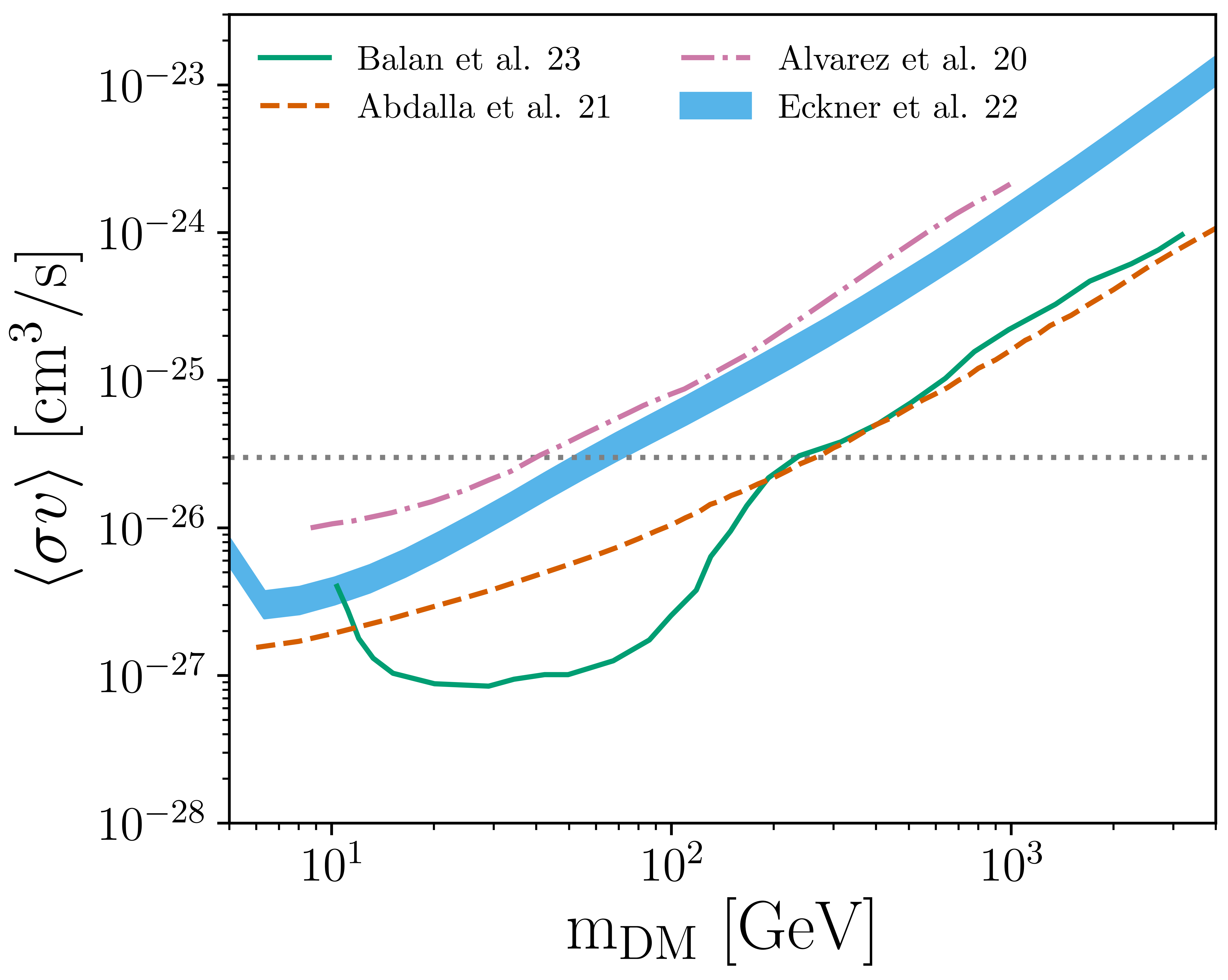


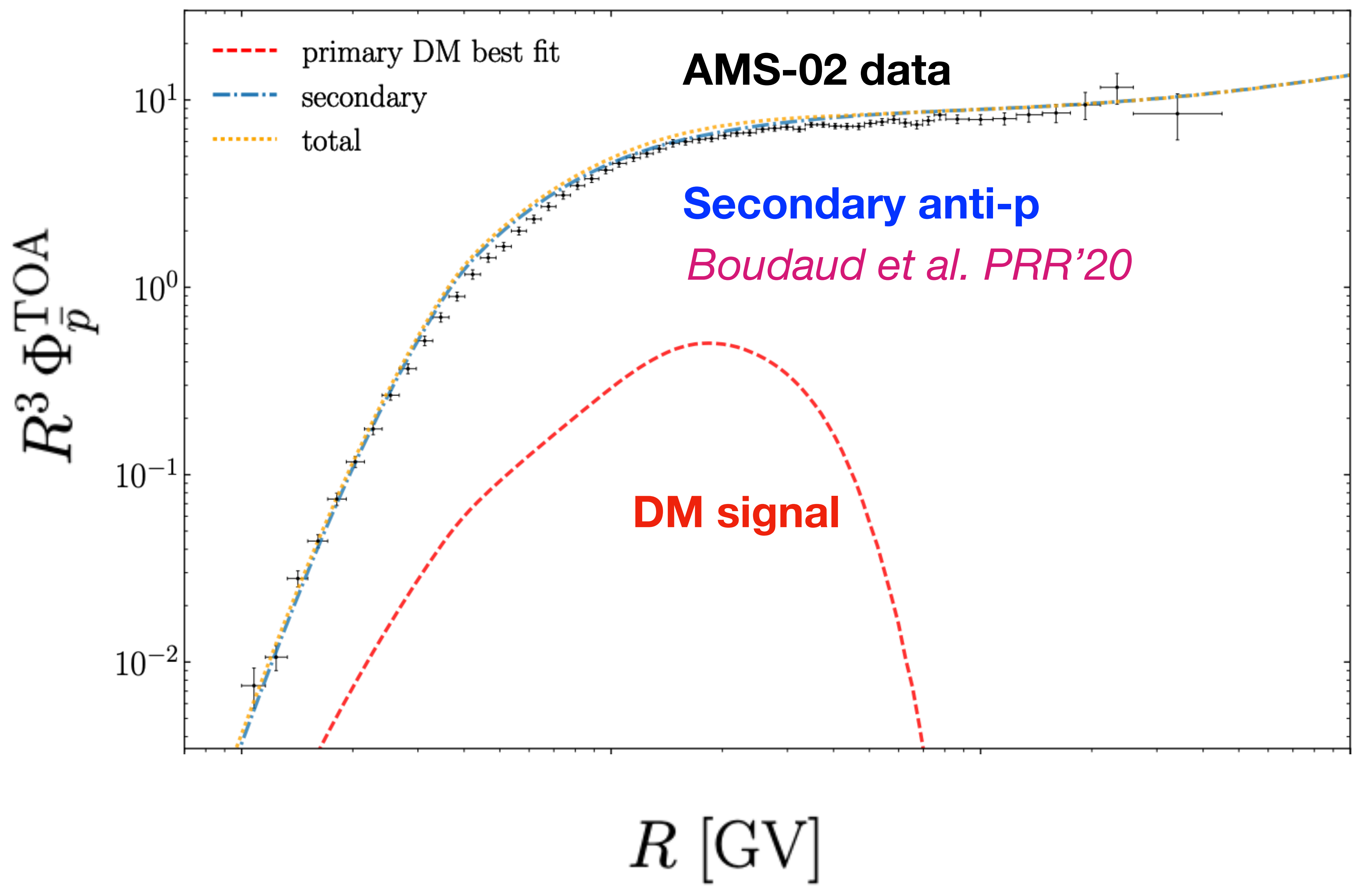
Limits on annihilating WIMPs

Anti-protons flux from the MW



~ a few GeV — few TeV





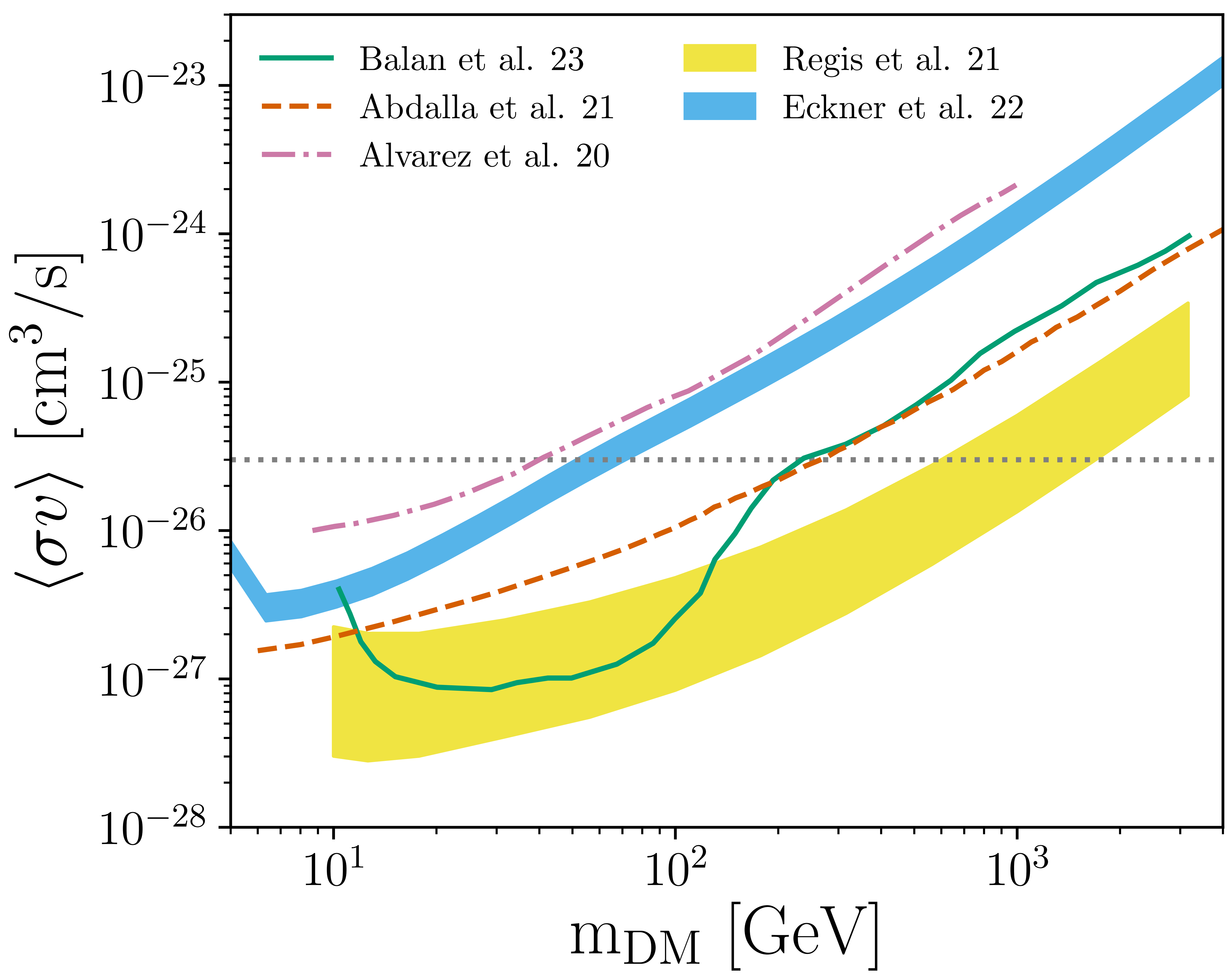
Anti-protons

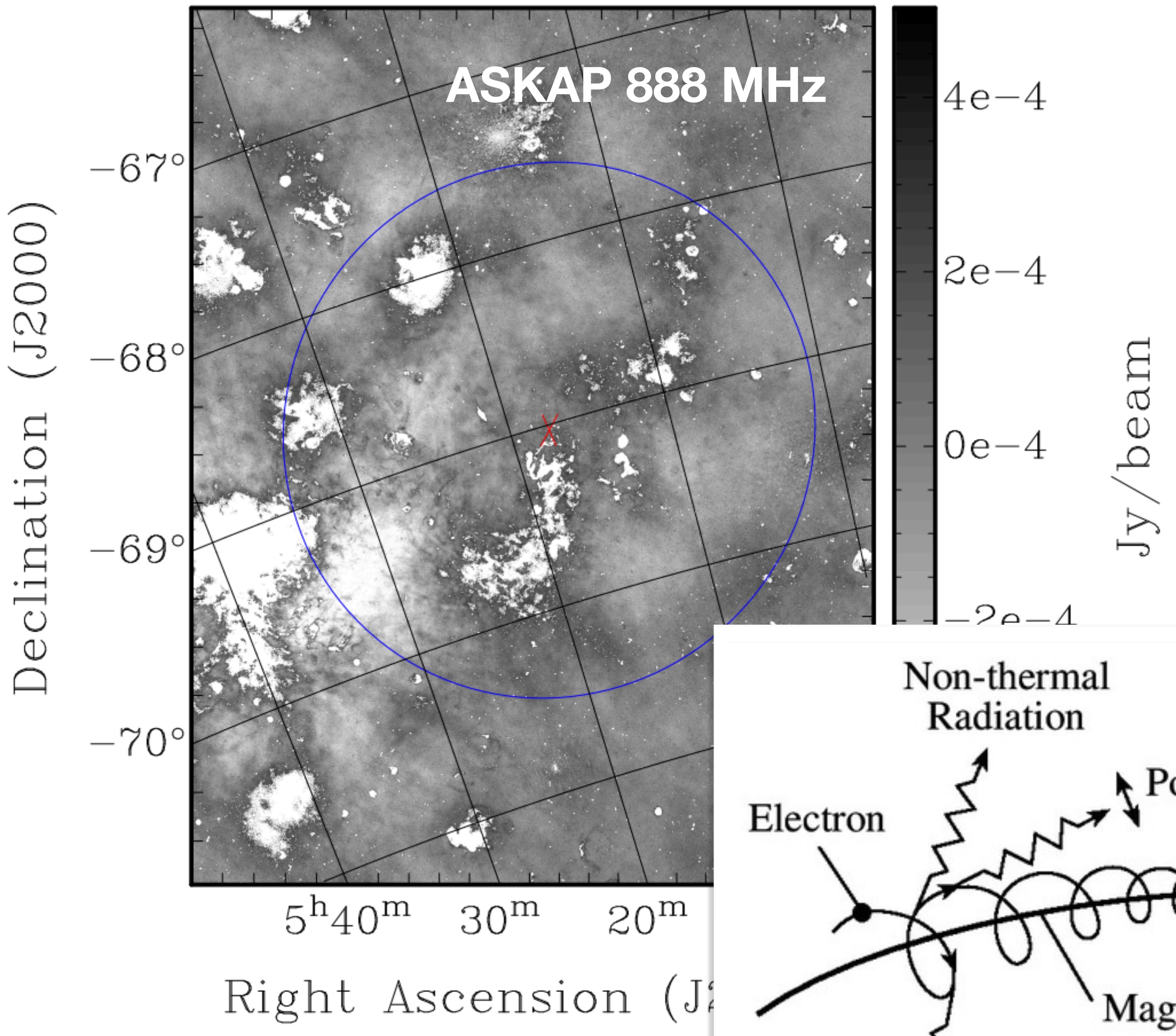
Balan+ arXiv:2303.07362
Di Mauro+ PRD'21,
FC+ SciPost'22

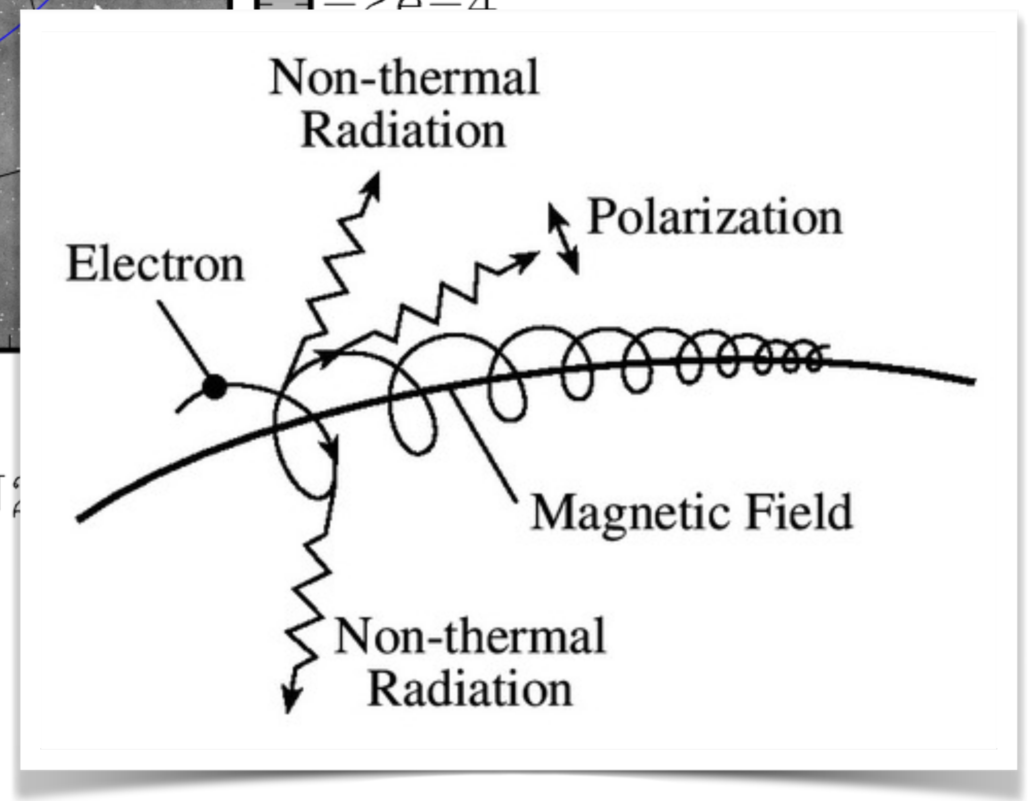
Limits on annihilating WIMPs

Synchrotron emission in the Large Magellanic Cloud

~ a few GeV — few TeV







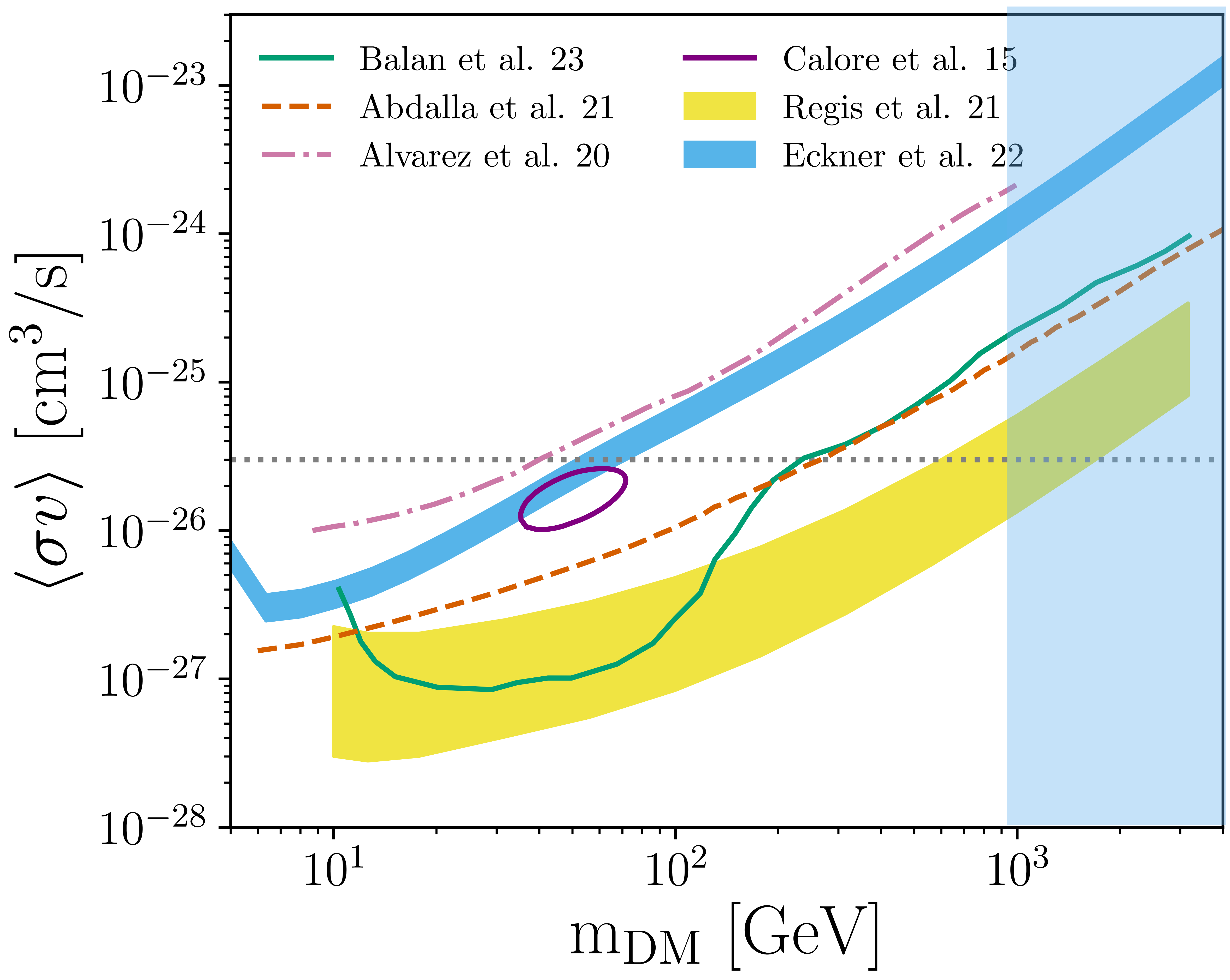
Radio LMC

Regis+ JCAP'21

Limits on annihilating WIMPs

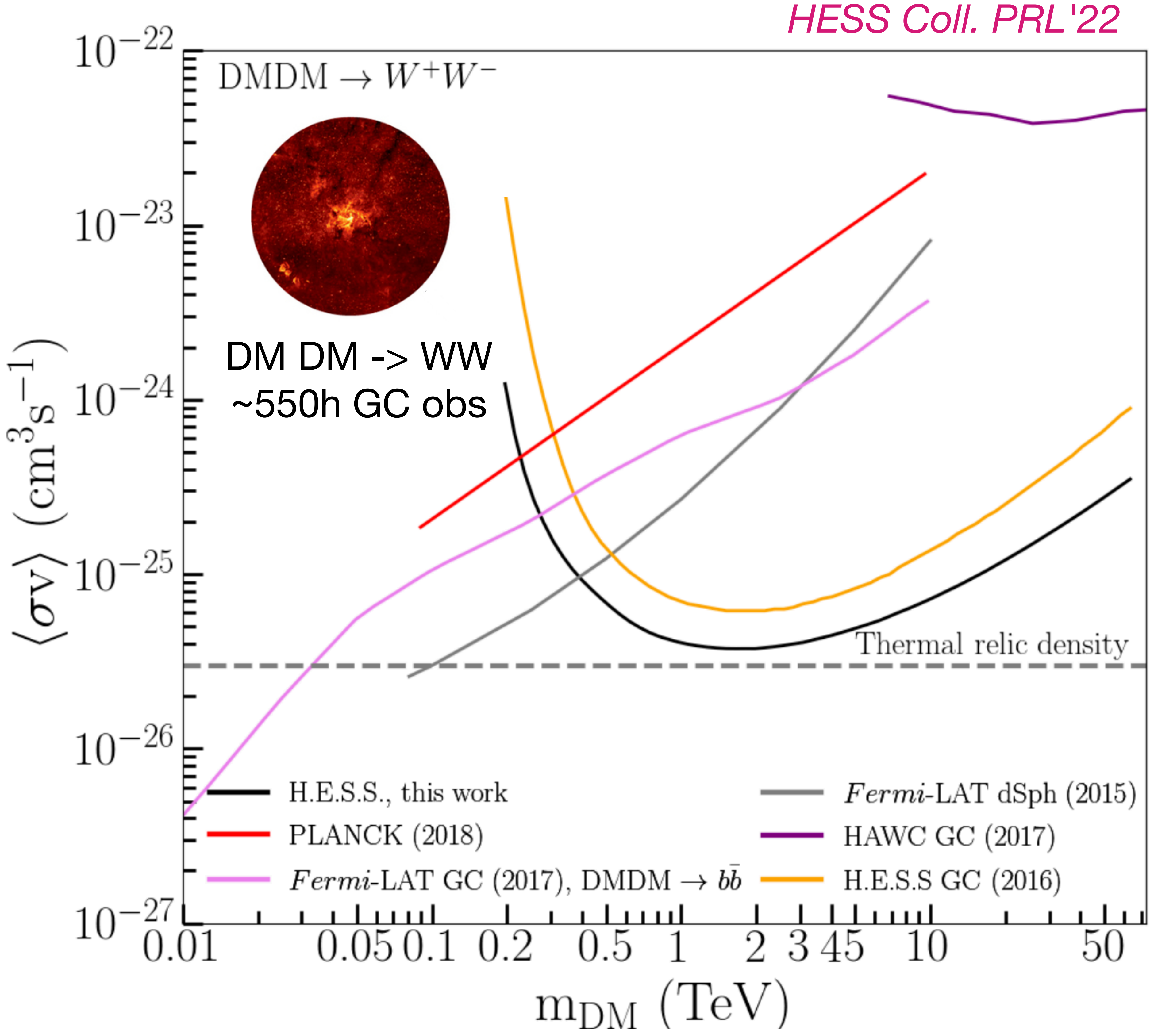
Summary of multi-targets and MW constraints

~ a few GeV — few TeV



0.2 TeV — 50 TeV

HESS Coll. PRL'22

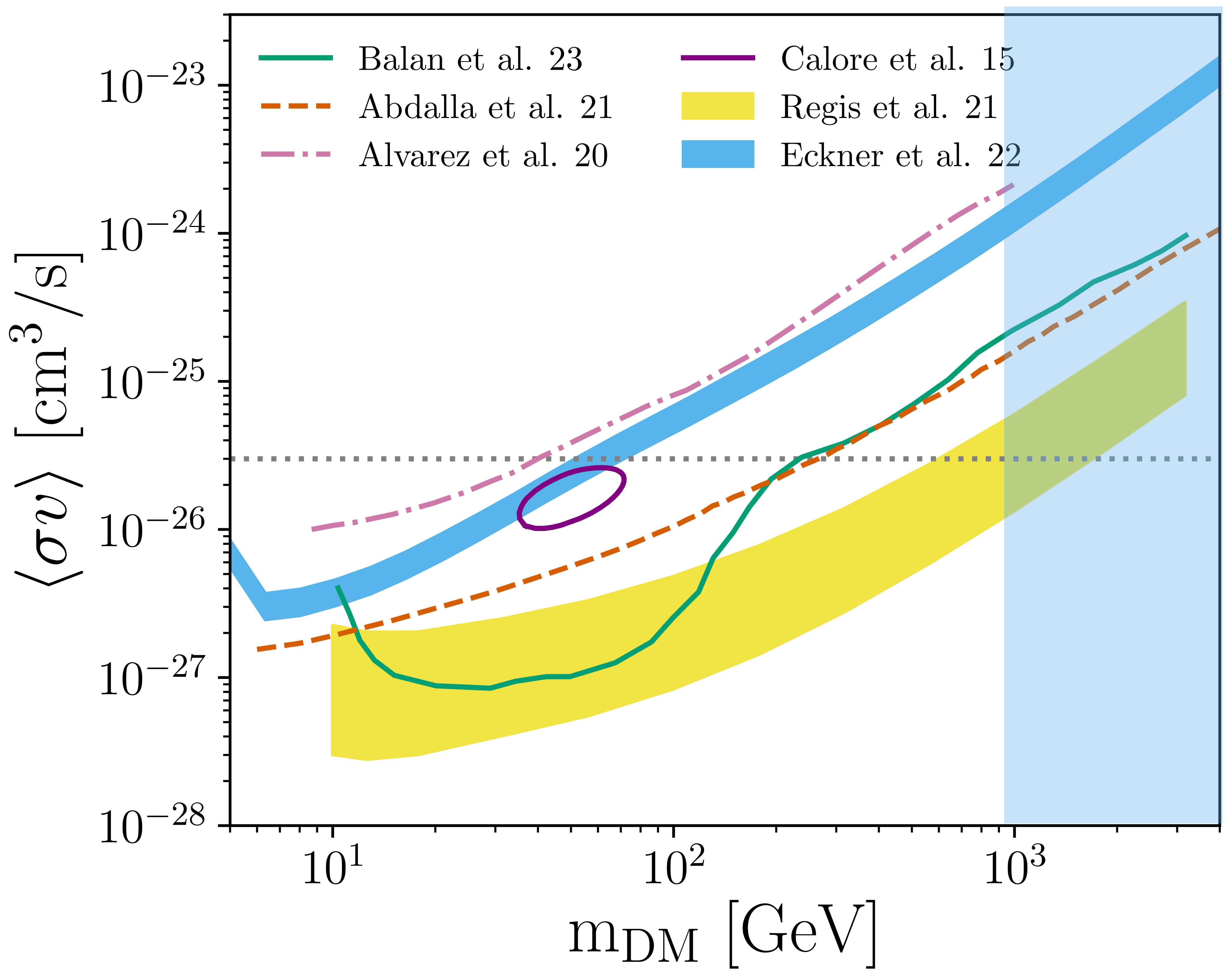


HAWC High Altitude Water Cherenkov Gamma-Ray Observatory H.E.S.S. MAGIC VERITAS

Prospects and opportunities

Extending the energy/mass scale

~ a few GeV — few TeV



Sub-PeV frontier

LHAASO,Tibet ASg

- Cannot be thermally produced (WIMpy) DM, since you hit the unitarity bound

Griest & Kamiomkowski, PRD' 90

- Viable production mechanisms for PeV DM exist, e.g. inflation decay in low-scale reheating scenarios

Harigaya+ 1402.2846

- The signal should come through decay and should appear in neutrino fluxes even before gamma rays

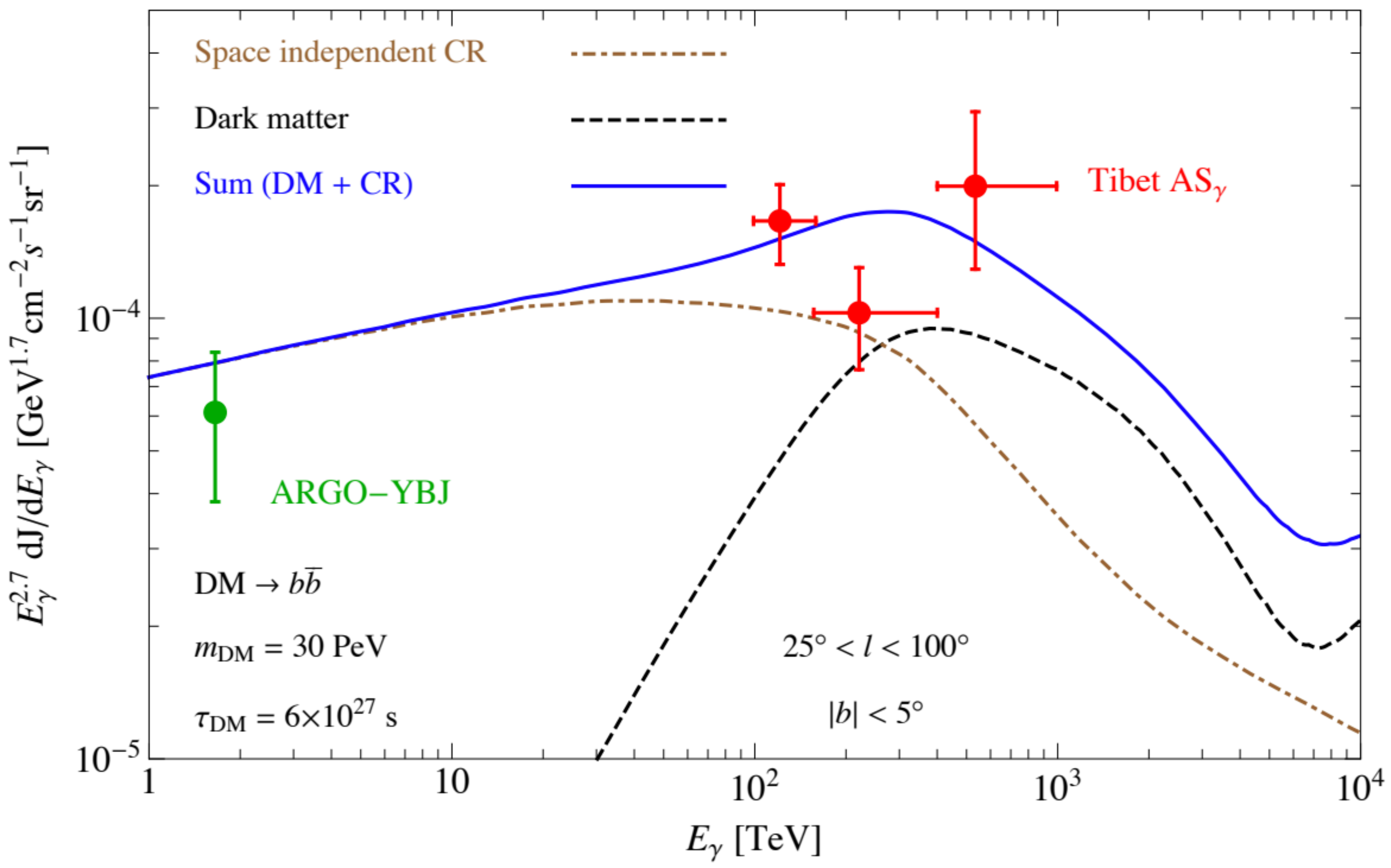
Feldstein+ PRD'13; Esmaili & Serpico, JCAP'13;
Chianese+ arXiv:2108.01678

→ These data often provide *best bounds* to heavy DM lifetime

Esmaili & Serpico, PRD'21; *Chianese+ arXiv:2108.01678*

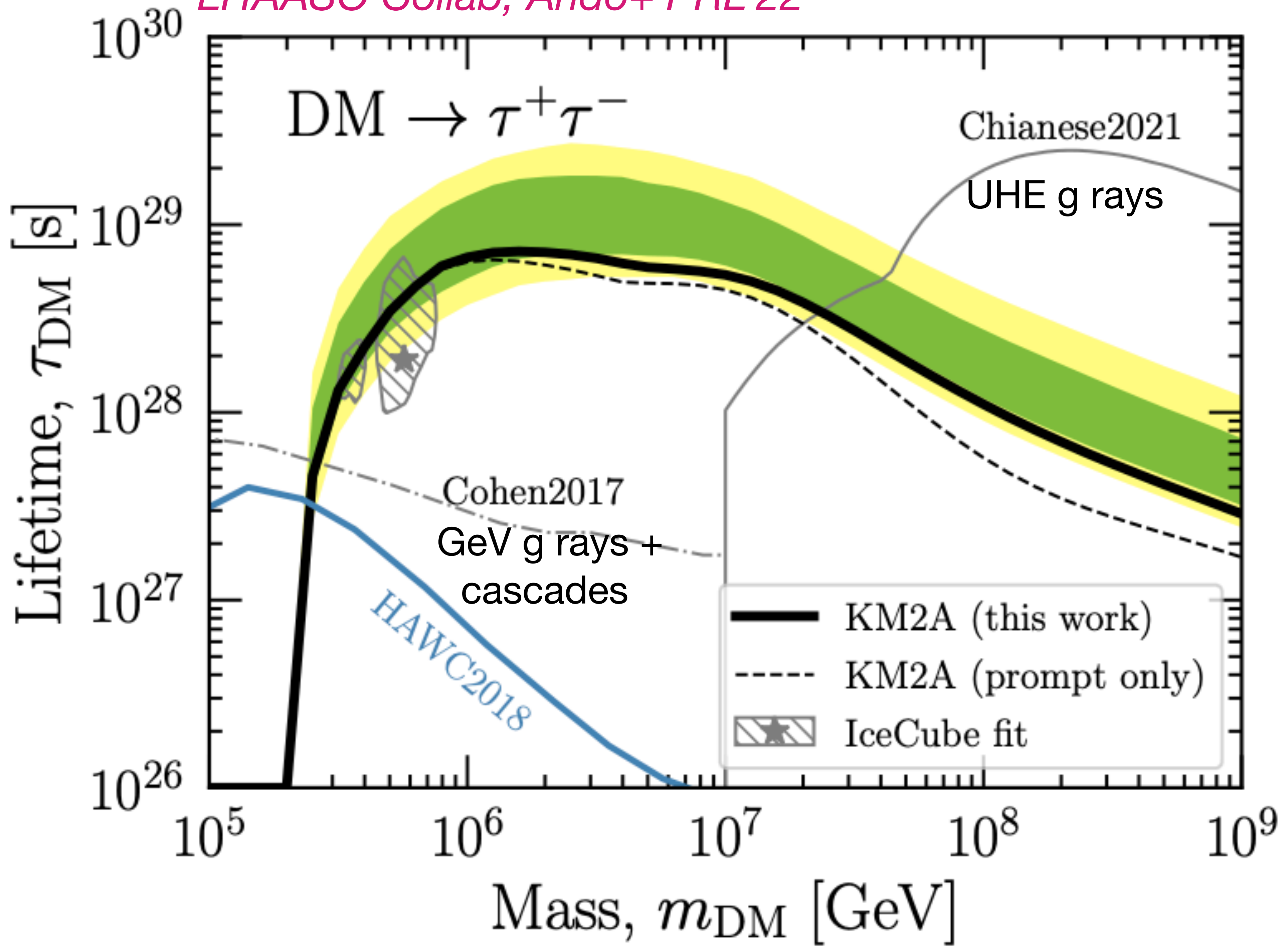
VHE gamma rays: PeV dark matter

Esmaili & Serpico, PRD Letters'21



Important degeneracies broken by **angular distribution of arrival photon directions**

LHAASO Collab, Ando+ PRL'22



Dedicated LHAASO DM **search** at slightly higher latitudes ⟶ Strongest constraints on PeV DM

Challenges: 1. Production and propagation of UHE gamma rays; 2. DM spectra at production for E_{CM} >> E_{LHC}

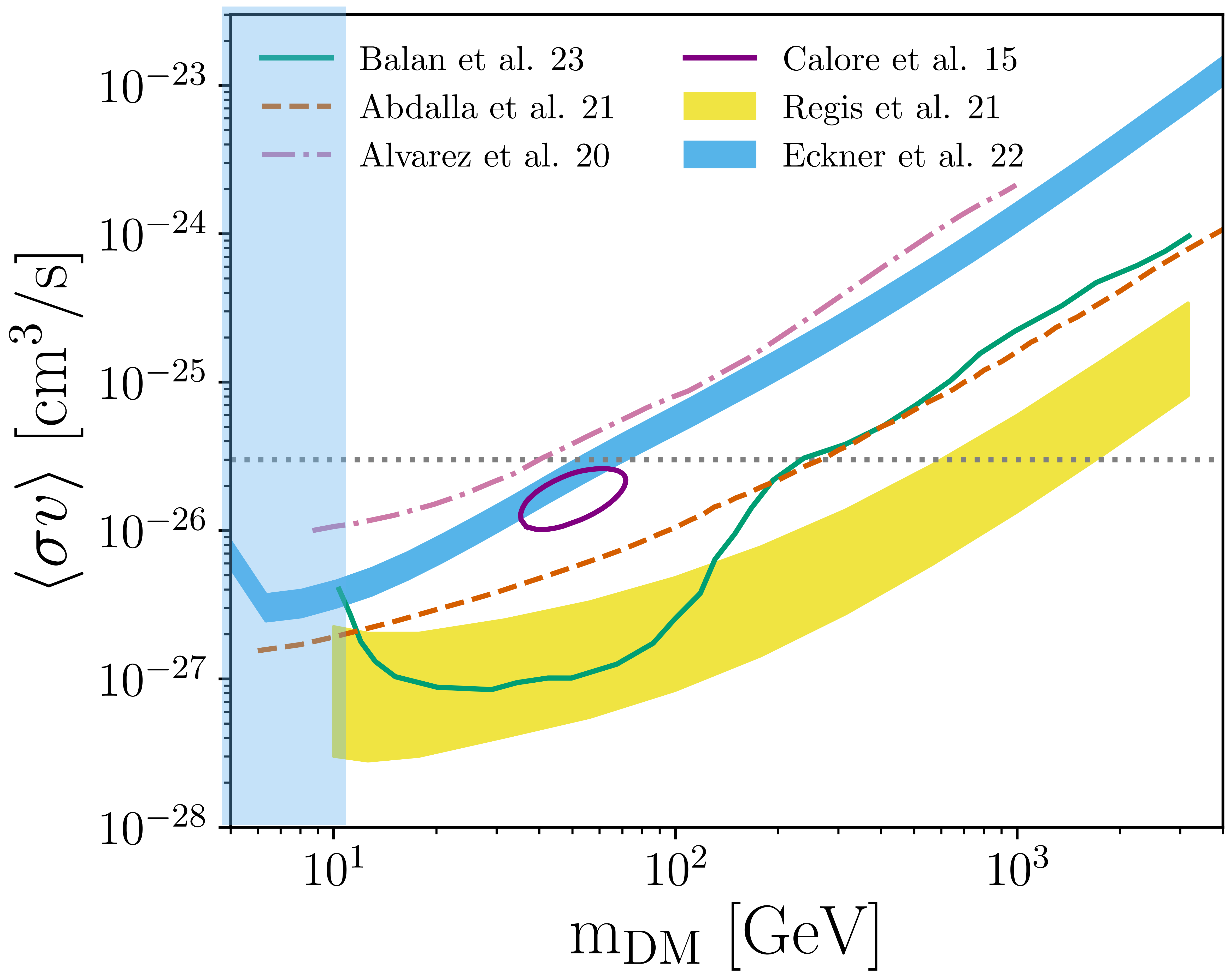
Bauer+ JHEP'21

Application to **ALPs** in HE neutrino sources *Eckner, FC+ PRD'22; Mastrototaro+ Eur.Phys.J.C'22*

Prospects and opportunities

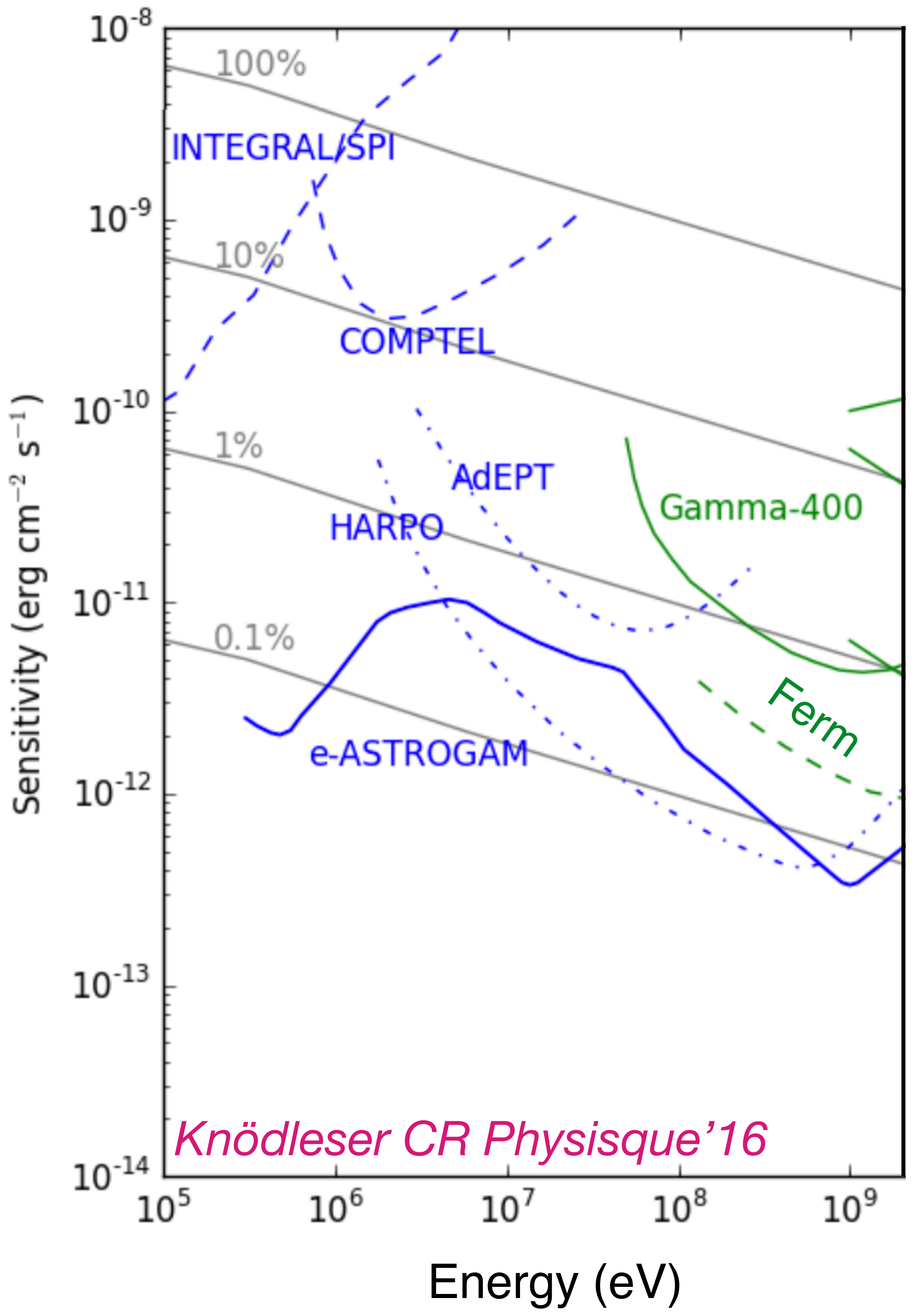
Extending the energy/mass scale

~ a few GeV — few TeV



MeV sensitivity gap

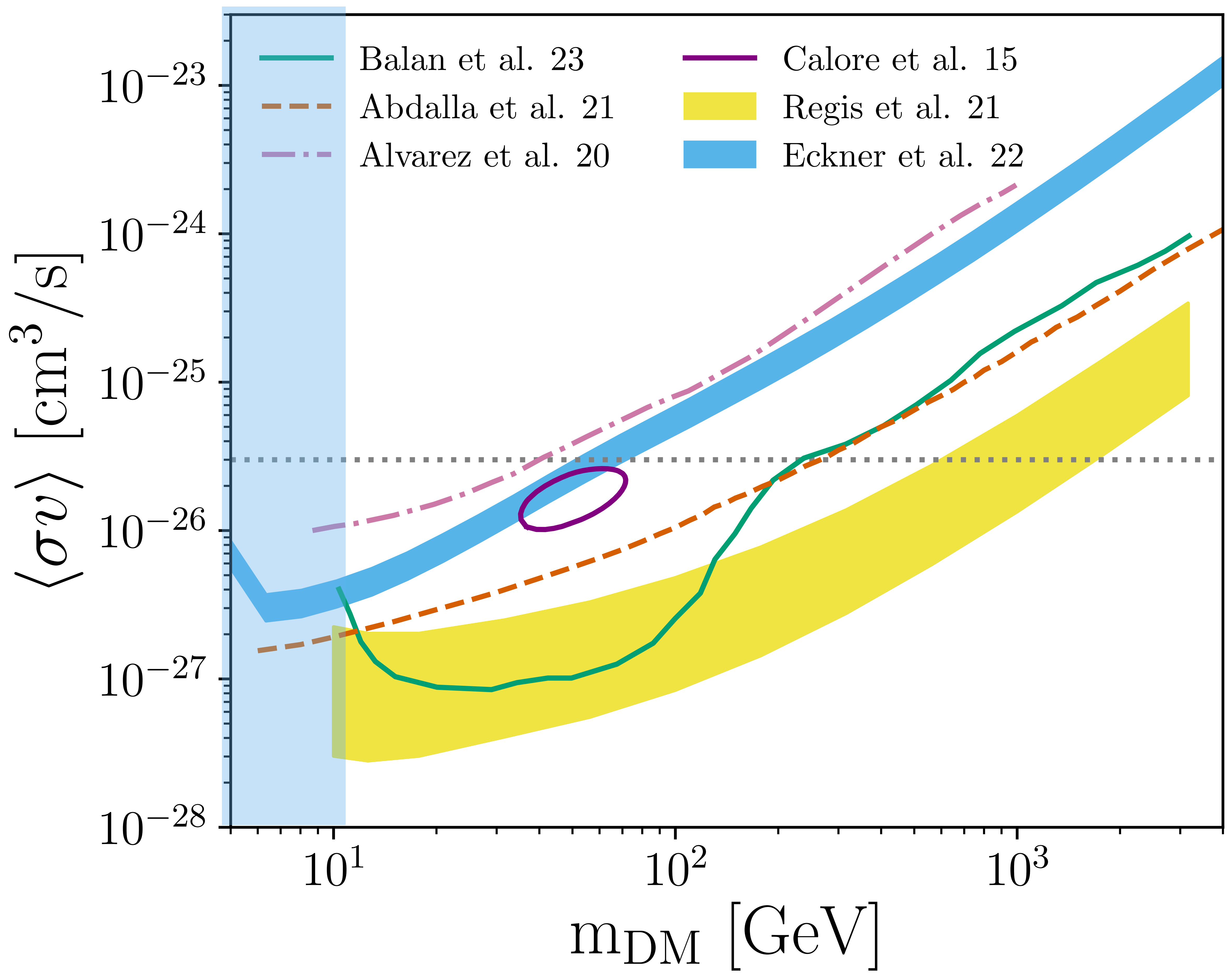
Amego, e-ASTROGAM, GECCO, GRAMS, COSI, MeVCube, etc



Prospects and opportunities

Extending the energy/mass scale

~ a few GeV — few TeV



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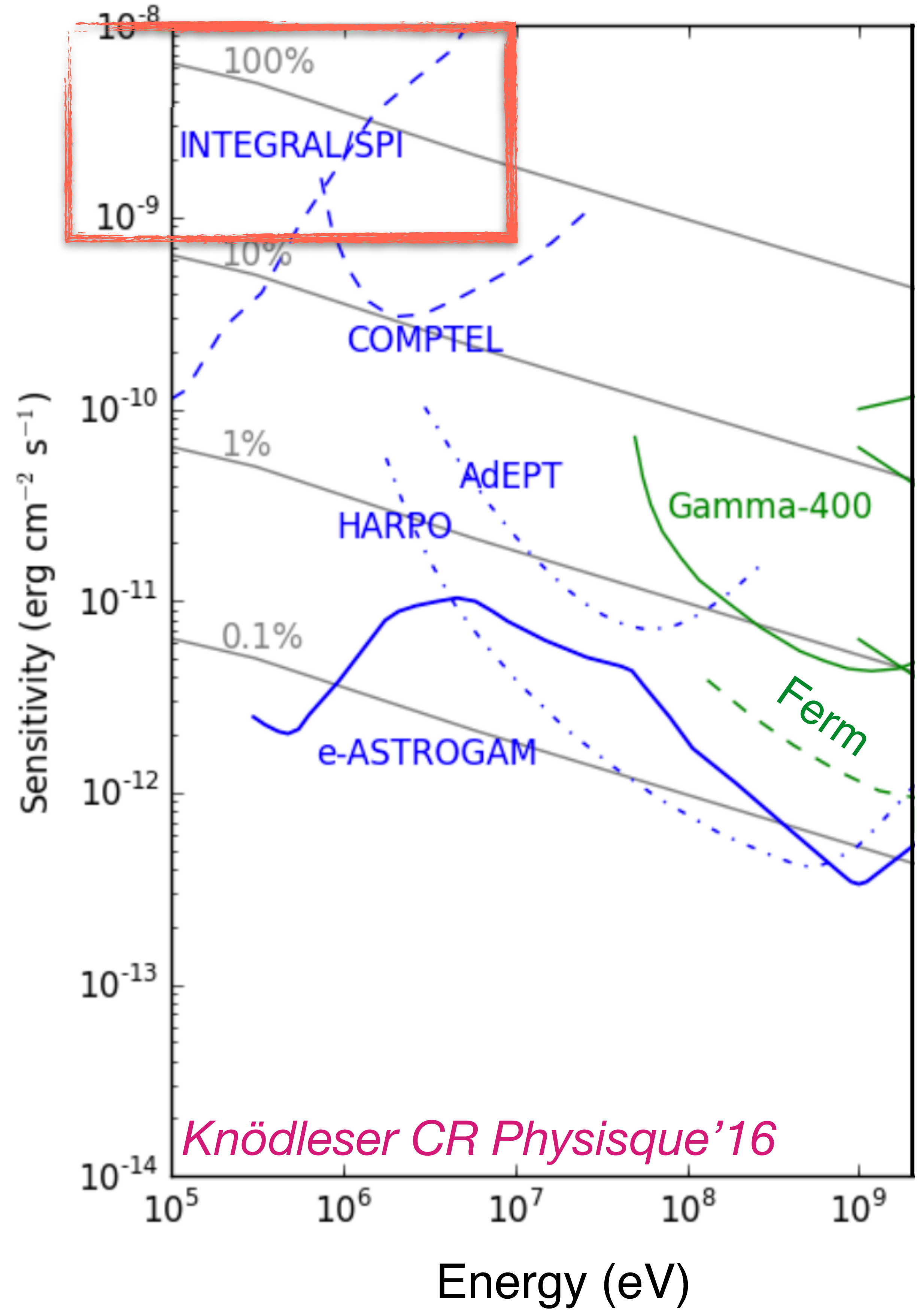
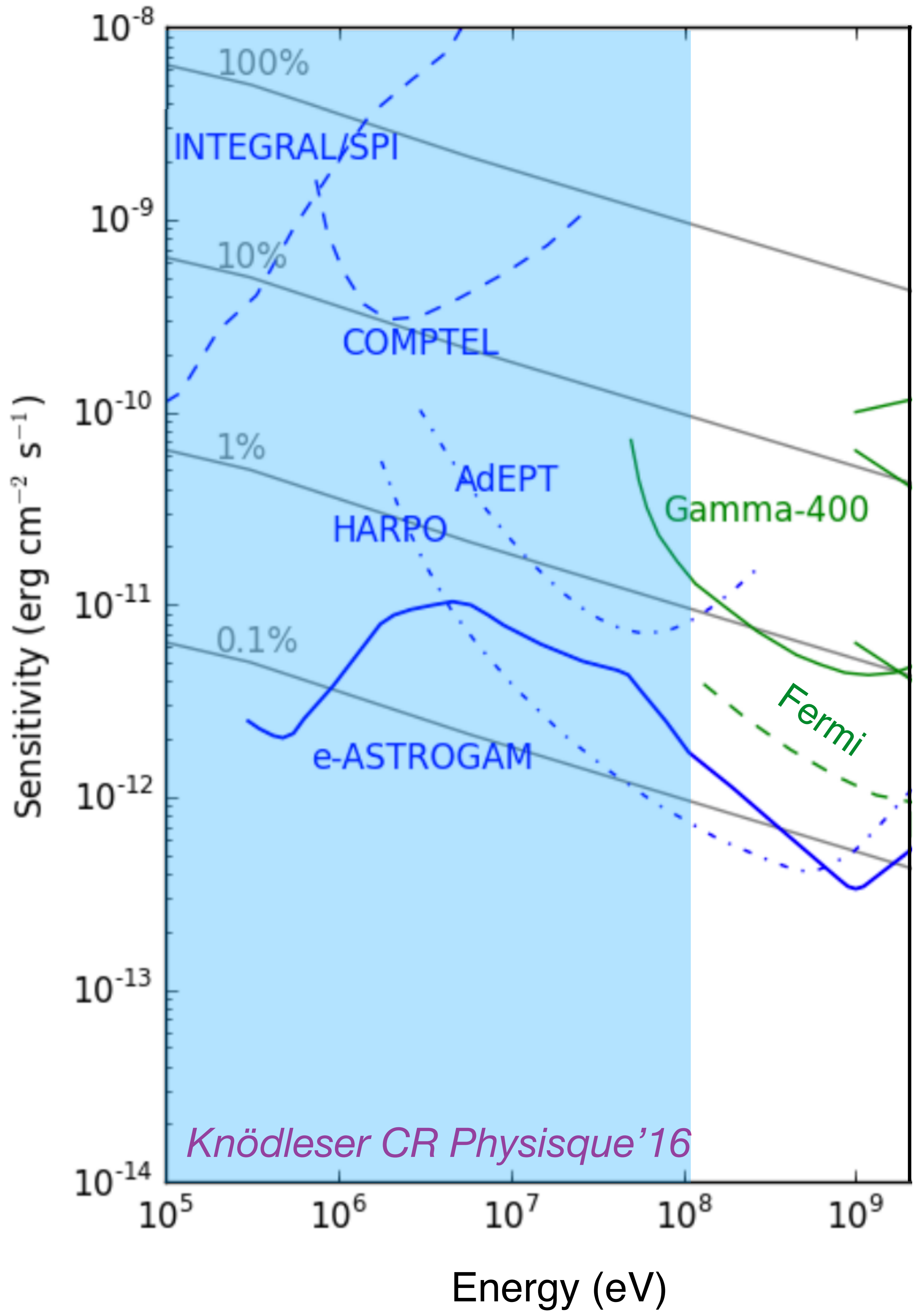


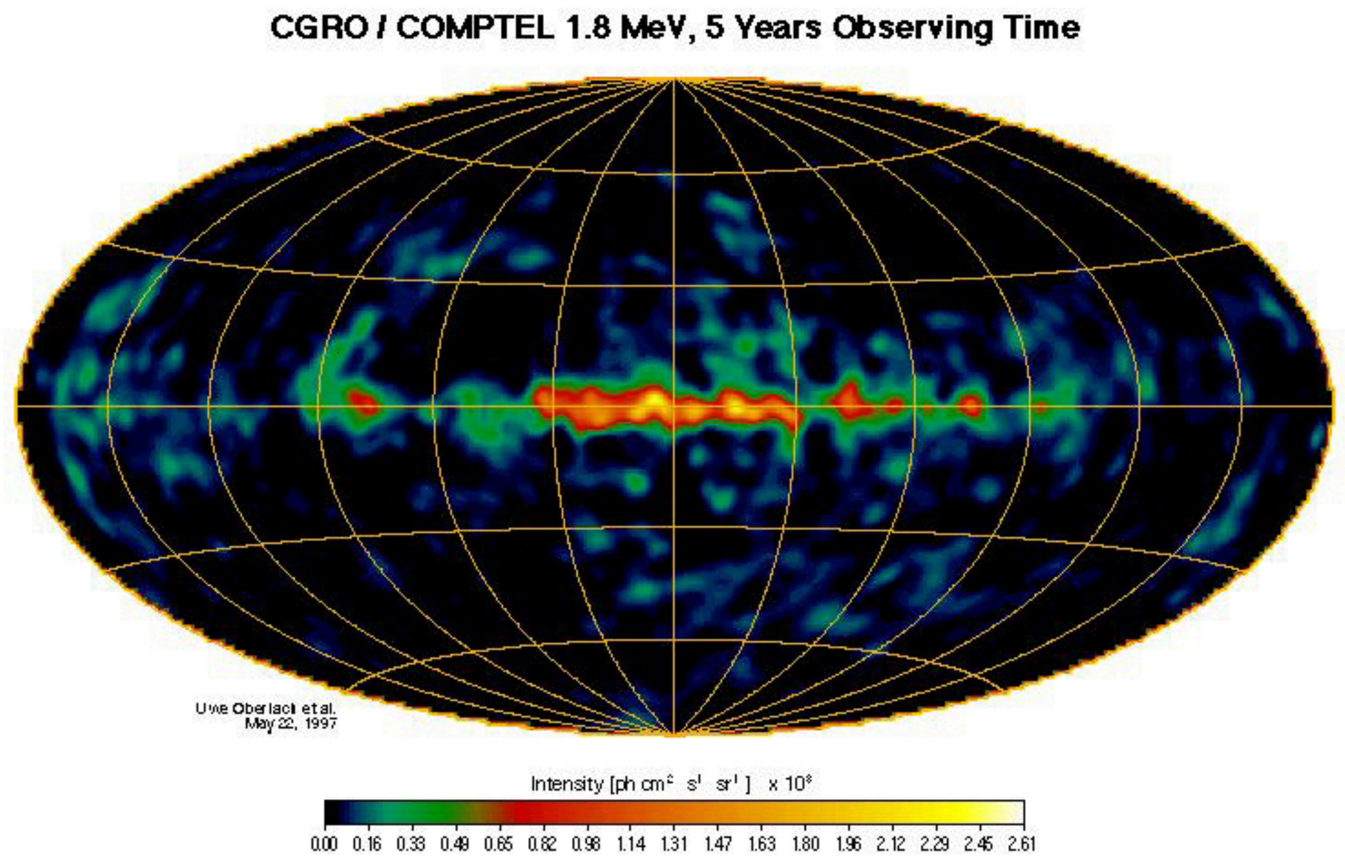
The data landscape

Hard X rays and gamma-ray sky



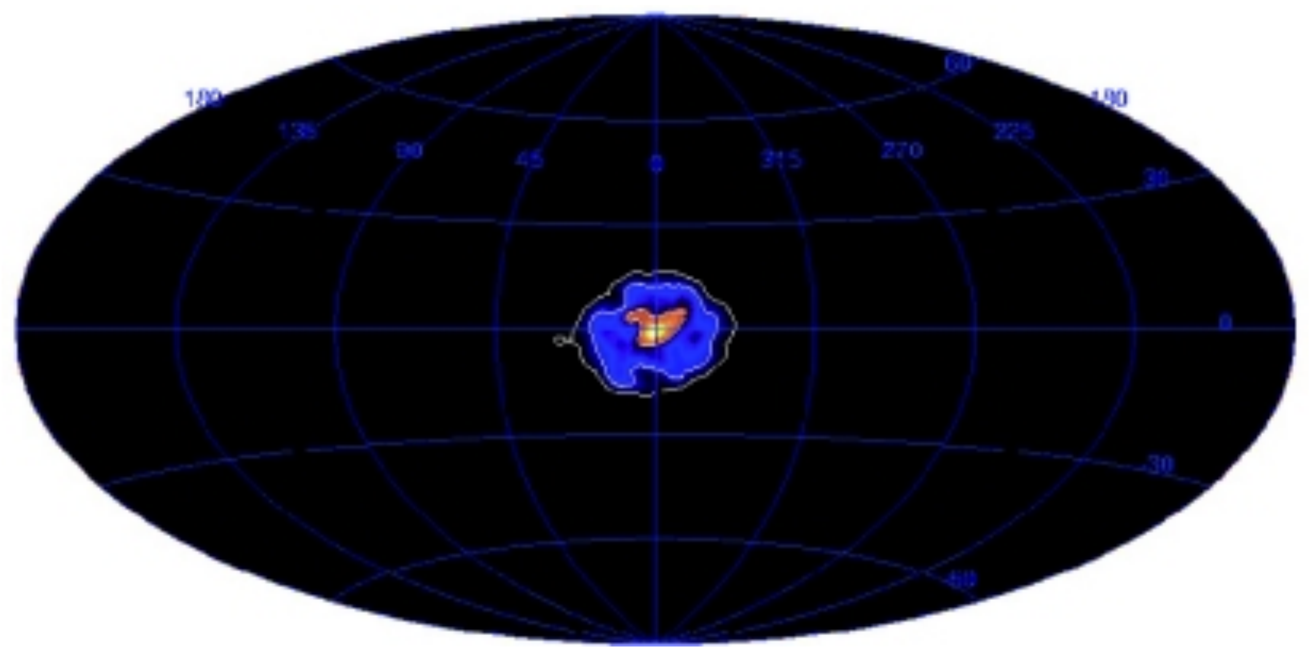
CGRO Compton Telescope (COMPTEL)

Lifetime: 1991 — 2000
Energy: 0.8 MeV - 30 MeV
Large FoV: 1 sr
Angular res: 1 deg



INTEGRAL Spectrometer (SPI)

Lifetime: 2002 — present
Energy: 20 keV - 8 MeV
Good energy res
Angular res: 2.5 deg



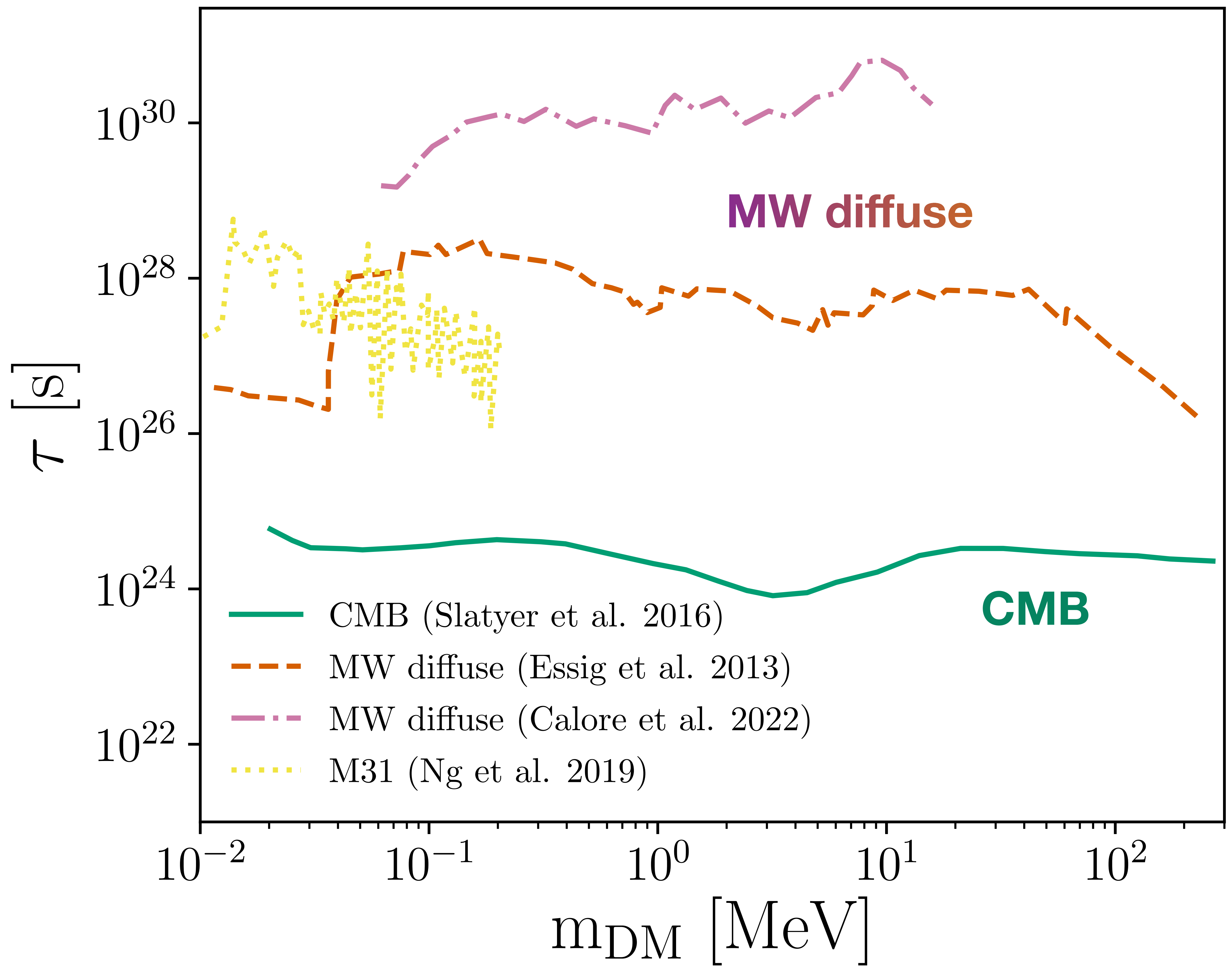
511 keV electron-positron line

Constraints on sub-GeV dark matter

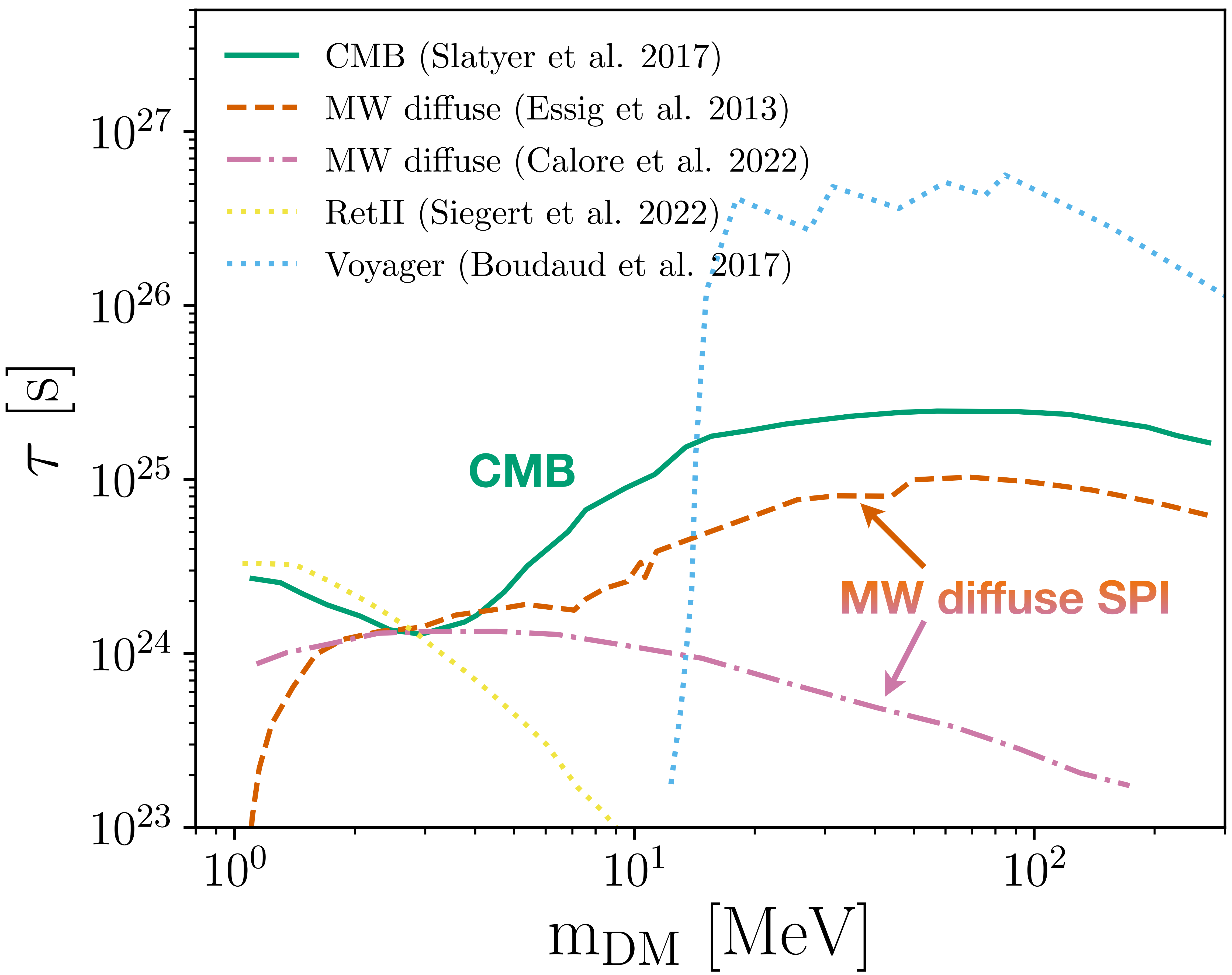
Summary: decay

FC FIPs2022 Proceedings

Two photons



e+e-

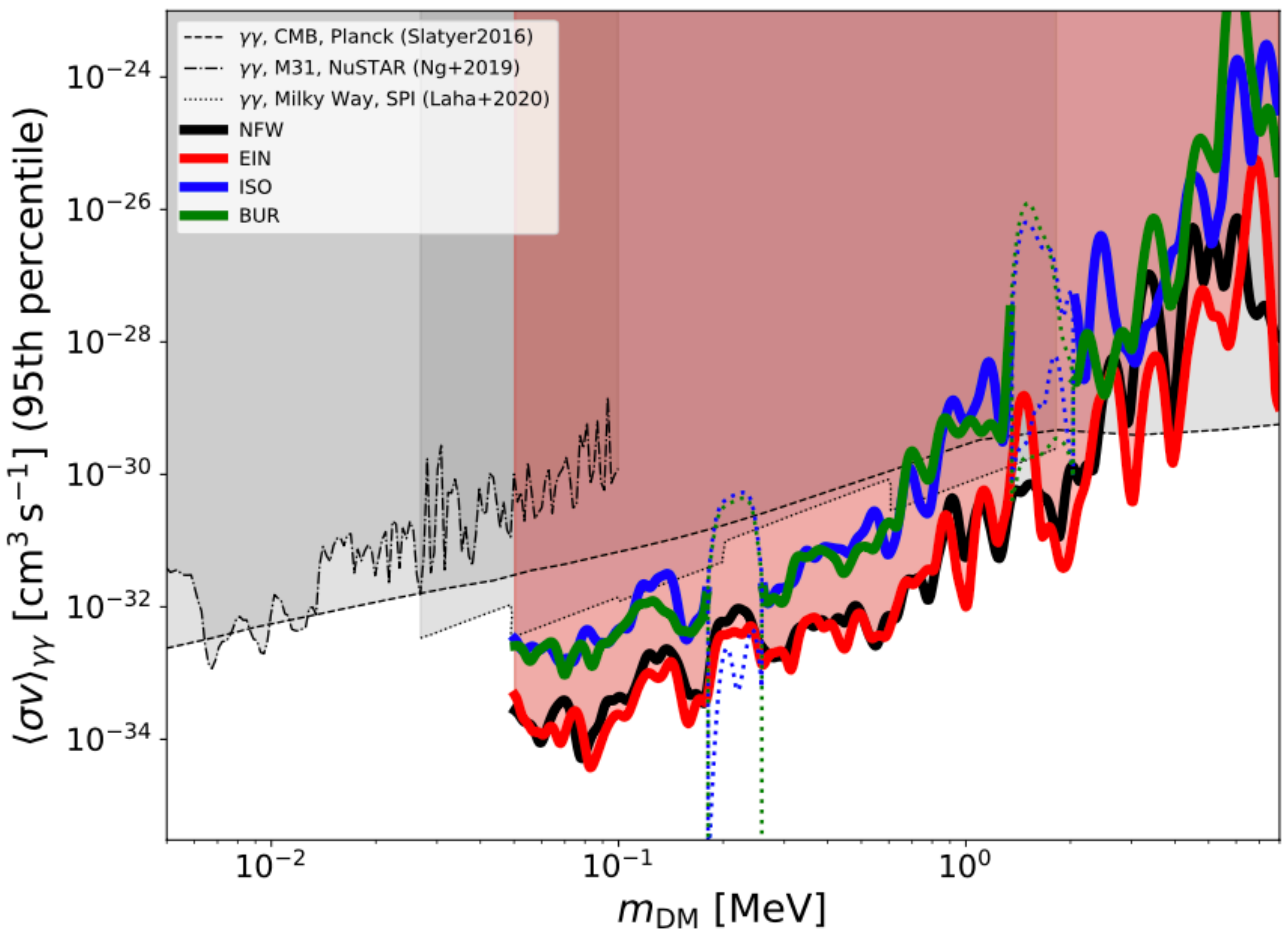


For e+e- channel, very relevant limits from Voyager 1 data *Boudaud+ PRL'17*

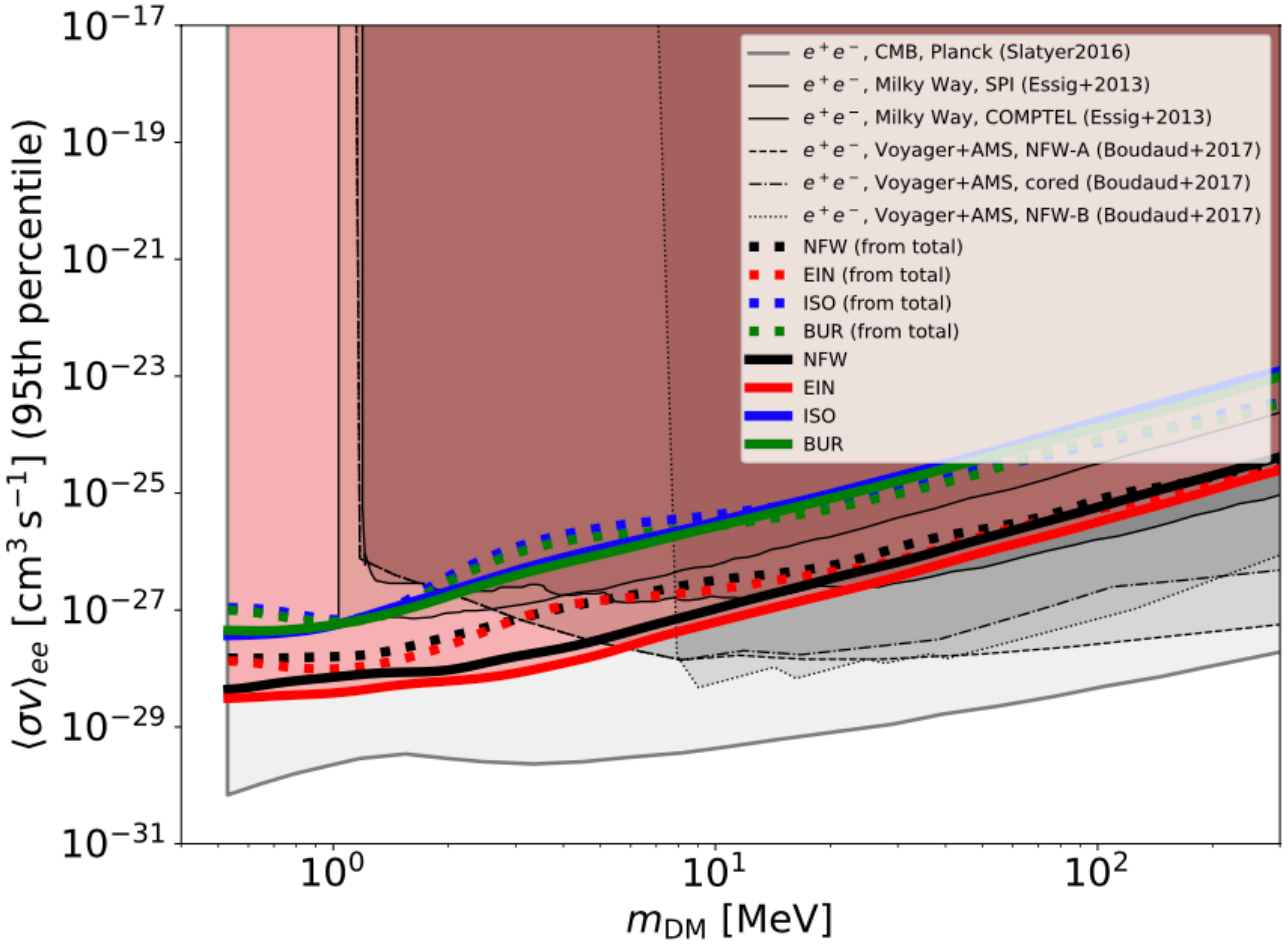
Constraints on annihilating dark matter

Summary from prompt emission

Two photons



e+e-

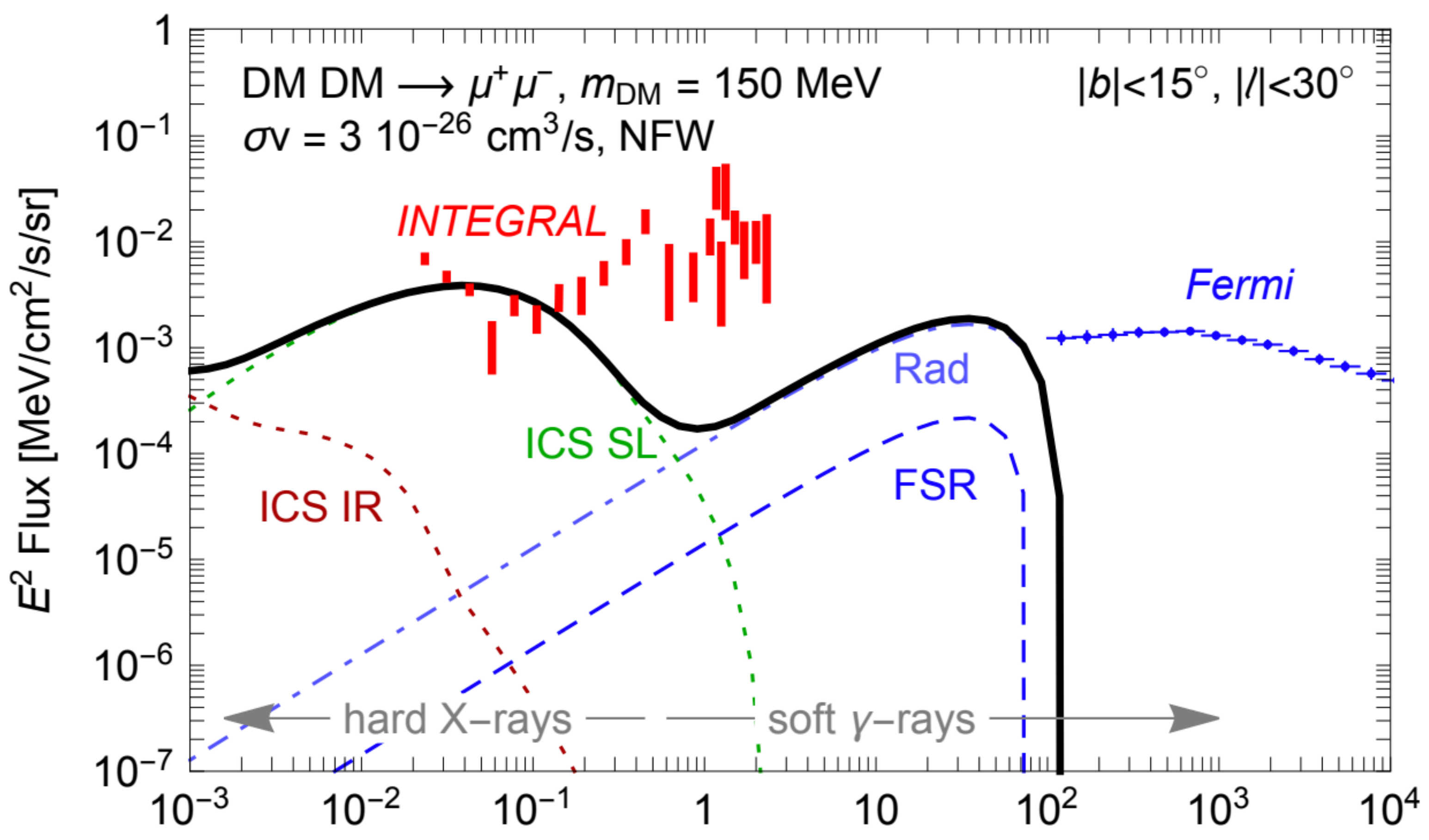


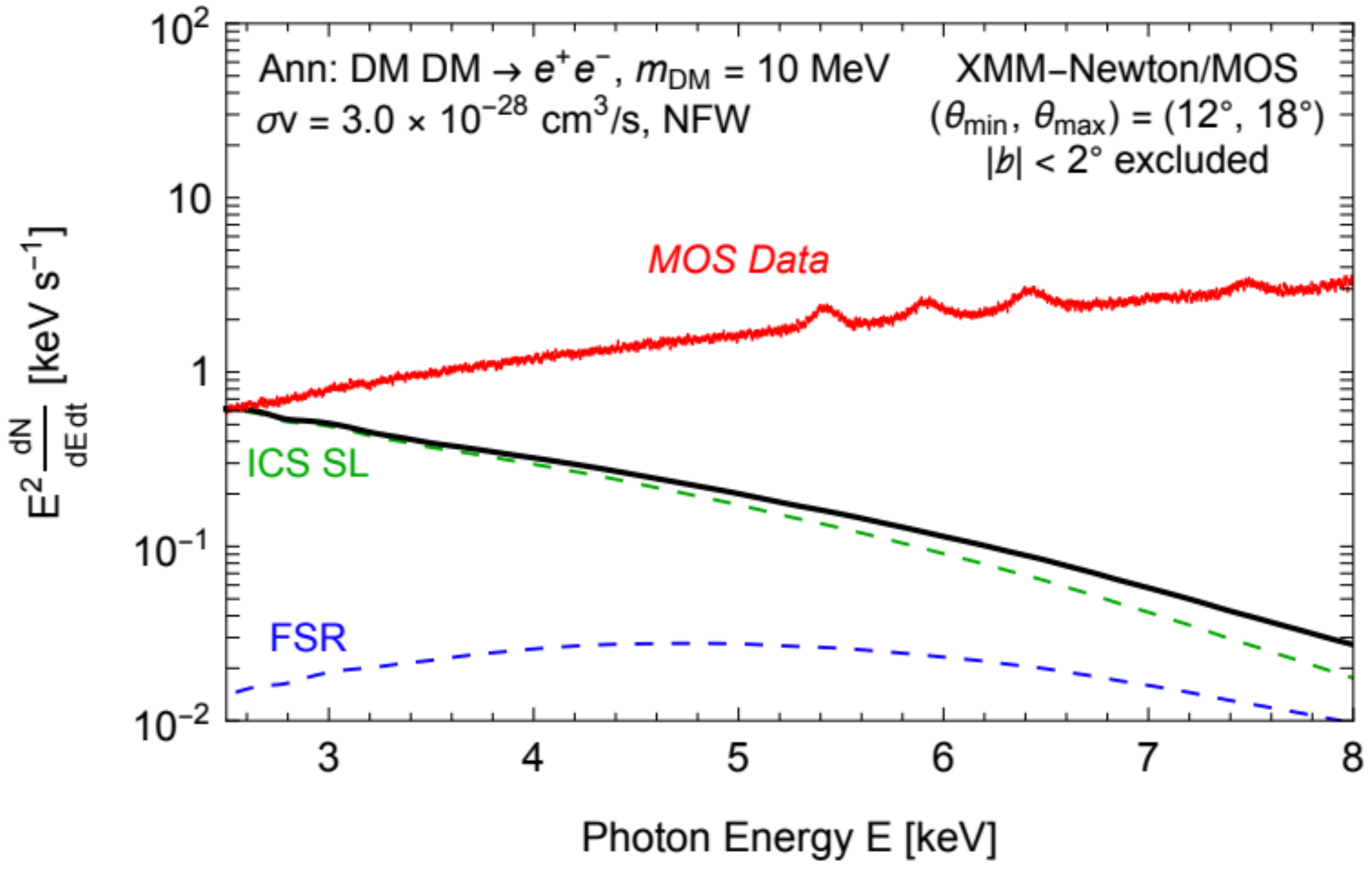
For e+e- channel, very relevant limits from Voyager 1 data *Boudaud+ PRL'17*

Constraints on annihilating dark matter

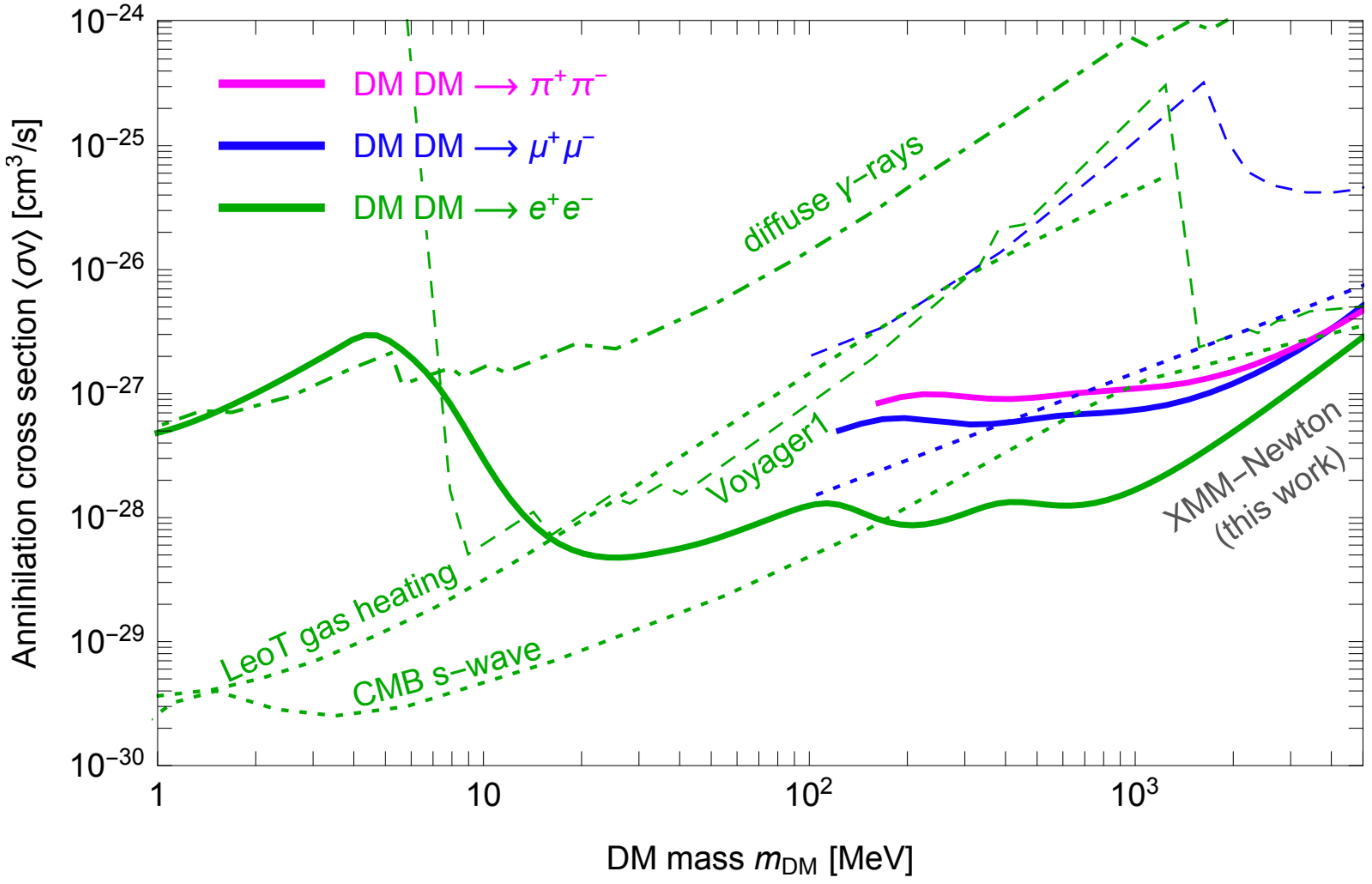
Constraining higher dark matter masses with inverse Compton

Cirelli+ PRD' 21





Cirelli+ 2303.08854



Limits on IC induced gamma-ray emission from
XMM-Newton blank-sky observations

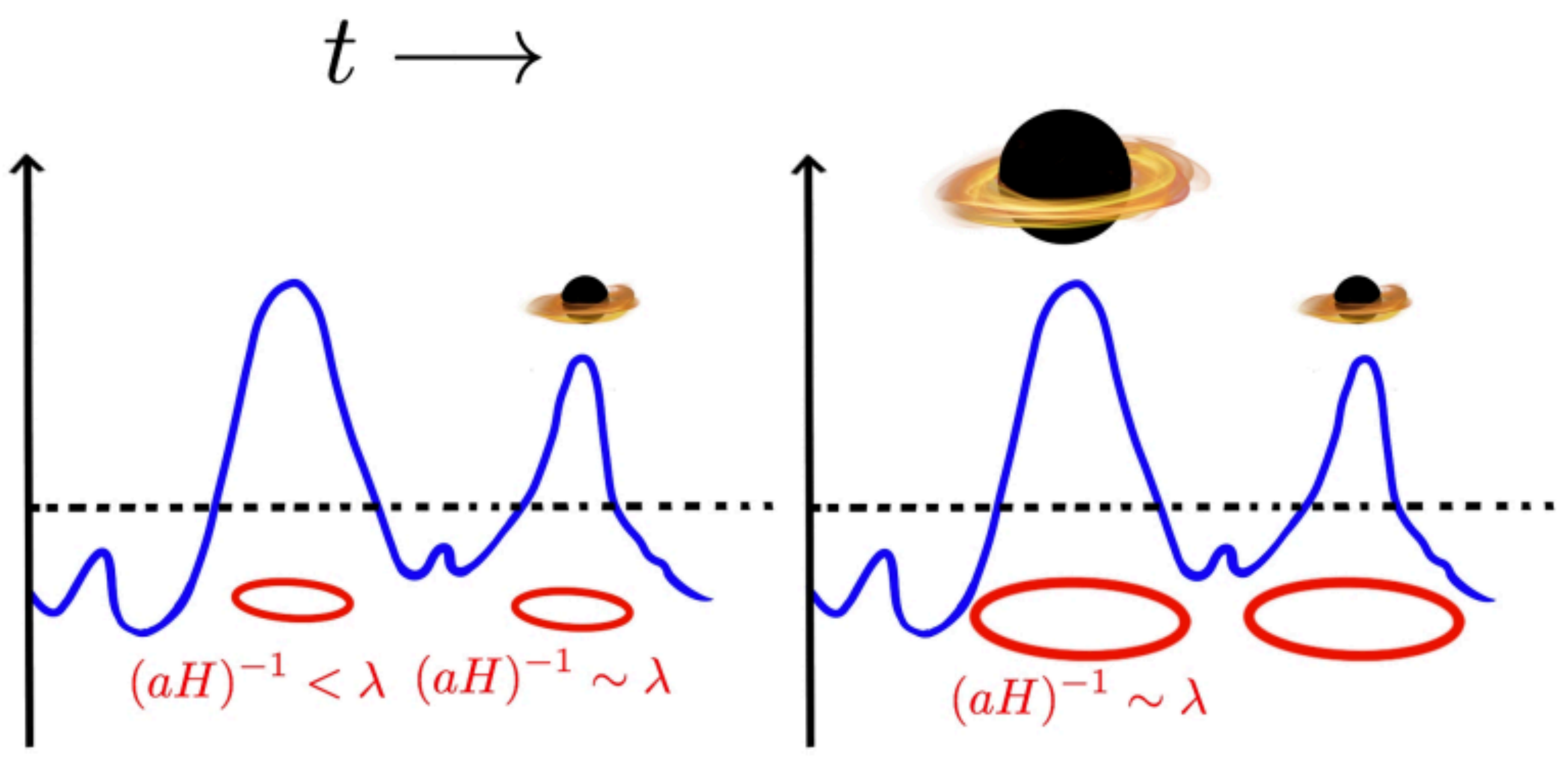
Supplemental material

(Primordial black holes)

PBH: non-particle DM candidates

Black holes formed via the **collapse of large overdensities from inflation** in the early universe, before matter-radiation equality

Review & Refs in Carr+PRD'16, Green & Kavanagh J. Phys. G'21



Villanueva-Domingo+ FrASS'21

Quick ID:

- PBHs evaporate through Hawking radiation

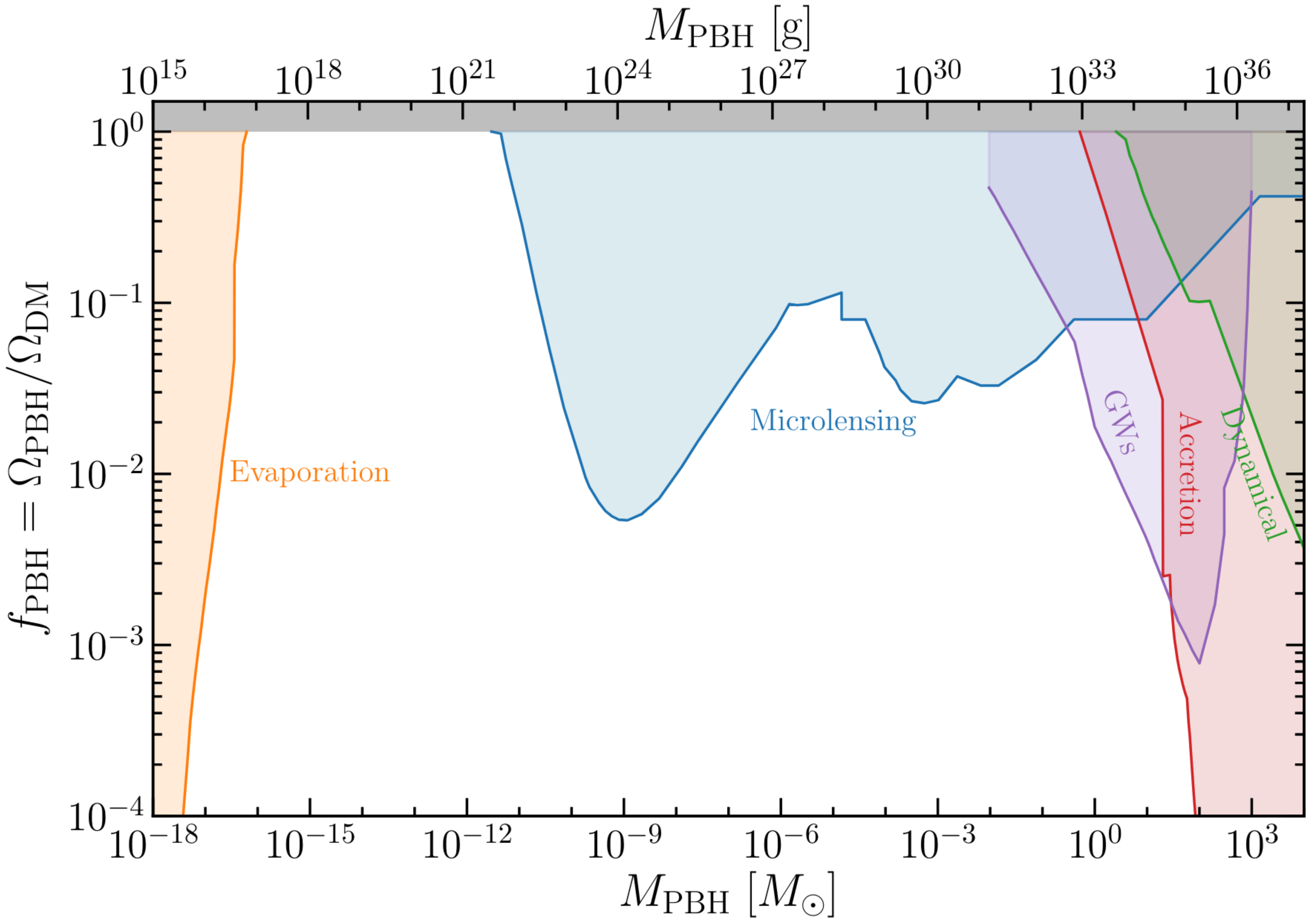
Page & Hawking ApJ'76

$$\frac{dM_{\rm BH}}{dt} \propto \frac{1}{(GM_{\rm BH})^2} \longrightarrow \tau \propto (GM_{\rm BH})^3$$

- If M > 10^{14} g, PBHs have a lifetime longer than the age of the universe
- On cosmological scales PBH DM behaves like **cold** particle DM
- Granularity observable at galactic scales

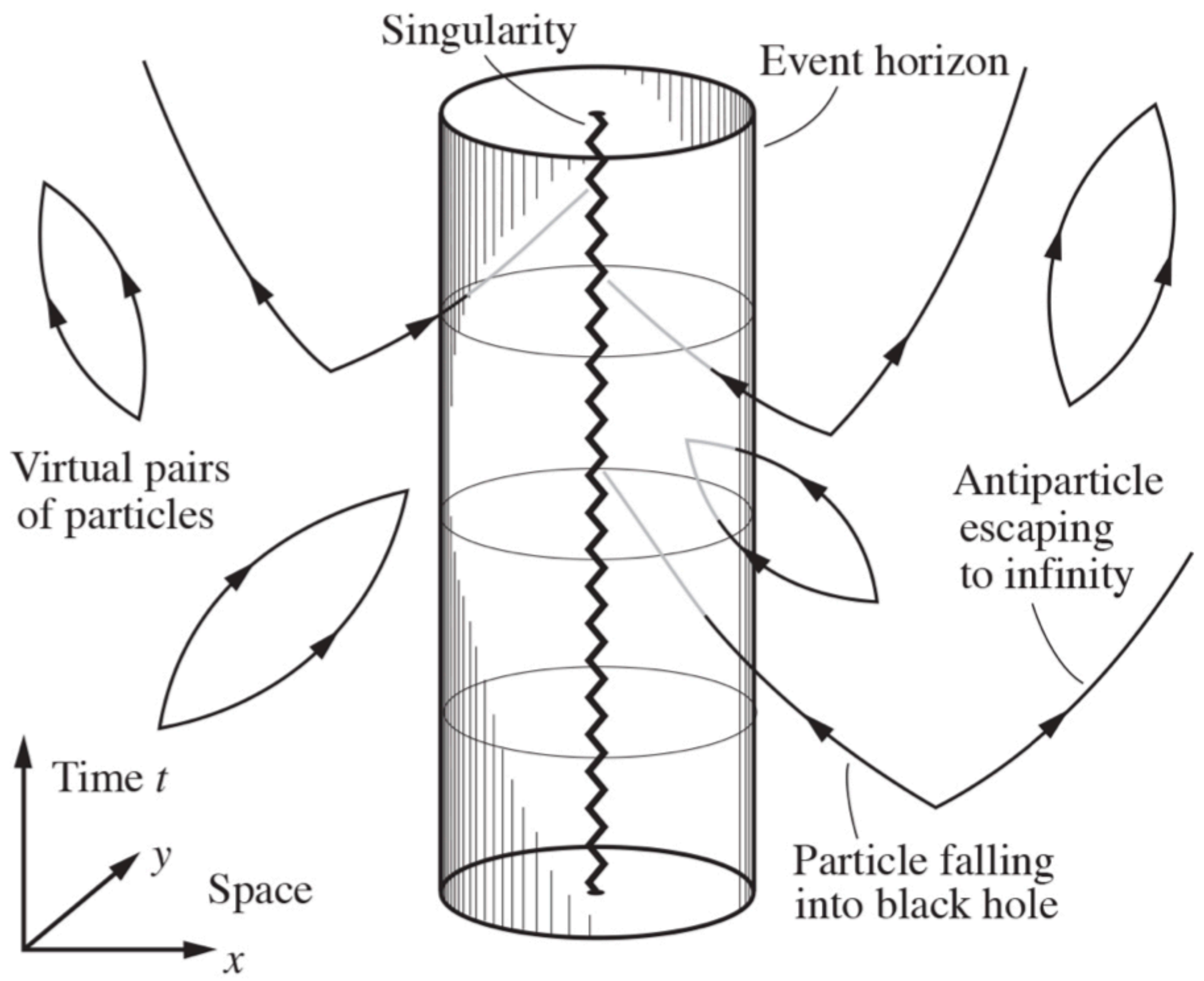
[Intermediate between unitarity bound and Planck scale: ultra-heavy dark matter]

Limits on primordial black holes



Green & Kavanagh J. Phys. G'19

Particle emission from primordial BHs



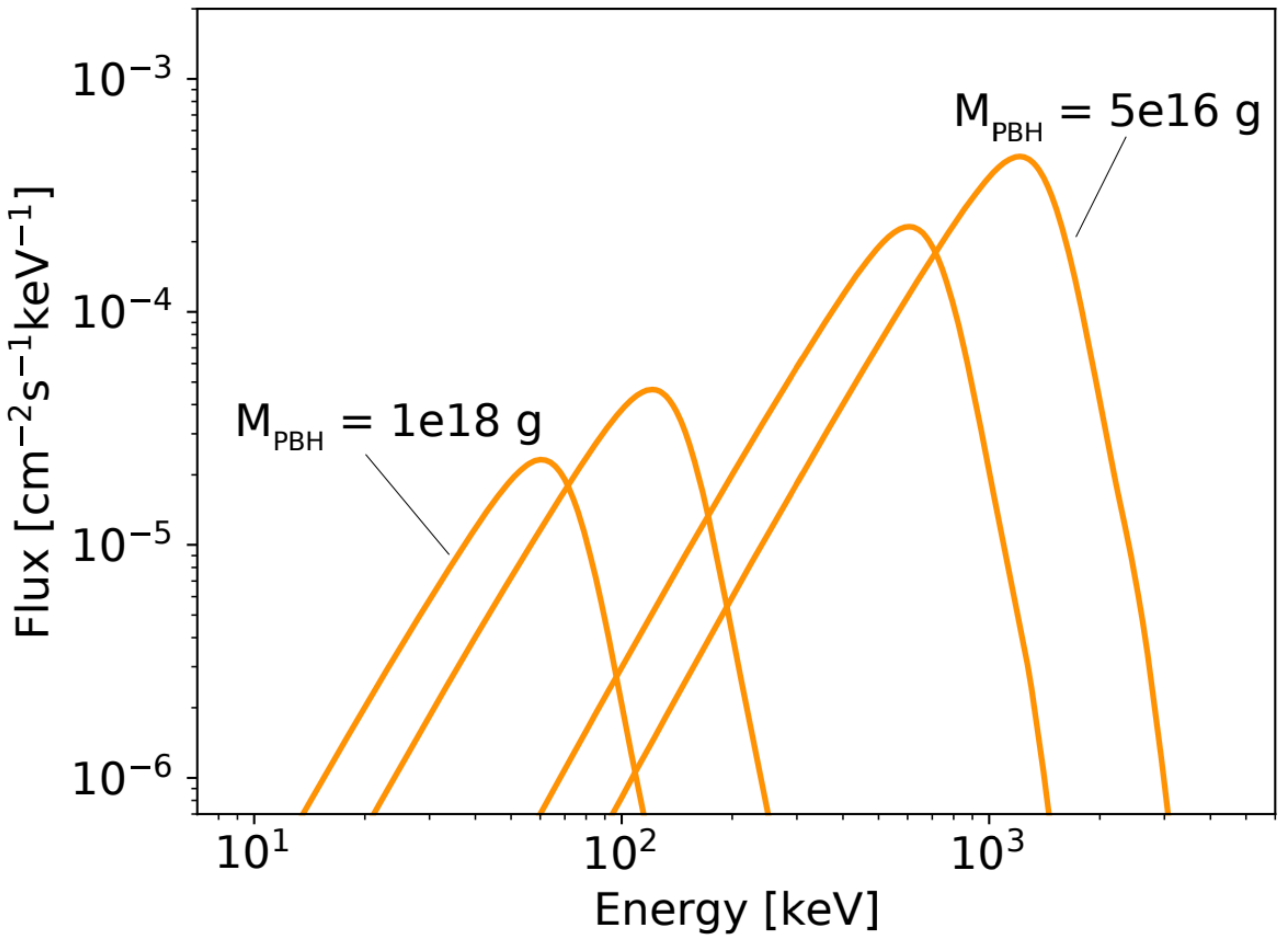
Hawking radiation

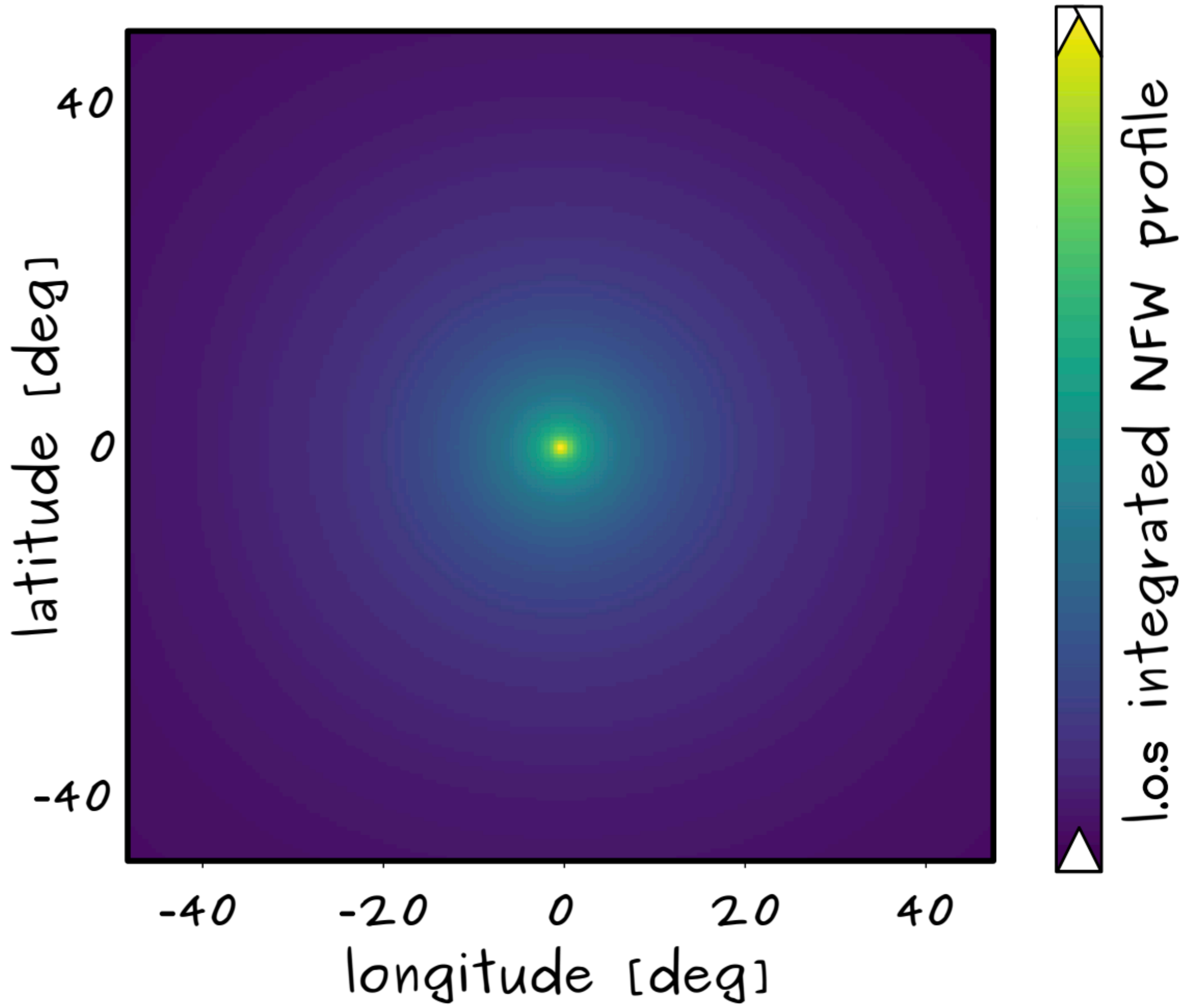
$$\frac{d^2N}{dEdt} = \frac{1}{2\pi}\frac{\Gamma(E, M_{BH})}{\exp(E/T_{BH}) - (-1)^{2S}}$$

$$T_{BH} = \frac{1}{k_B}\frac{\hbar c^3}{8\pi G M_{BH}}$$

Photons from PBHs

$$\frac{d\Phi_\gamma}{dE}(l,b) = \frac{f_{\rm PBH}}{4\pi M_{\rm PBH}} \frac{d^2 N_\gamma}{dE dt} \int_{\rm l.o.s.} ds\, \rho(r(s,l,b))$$

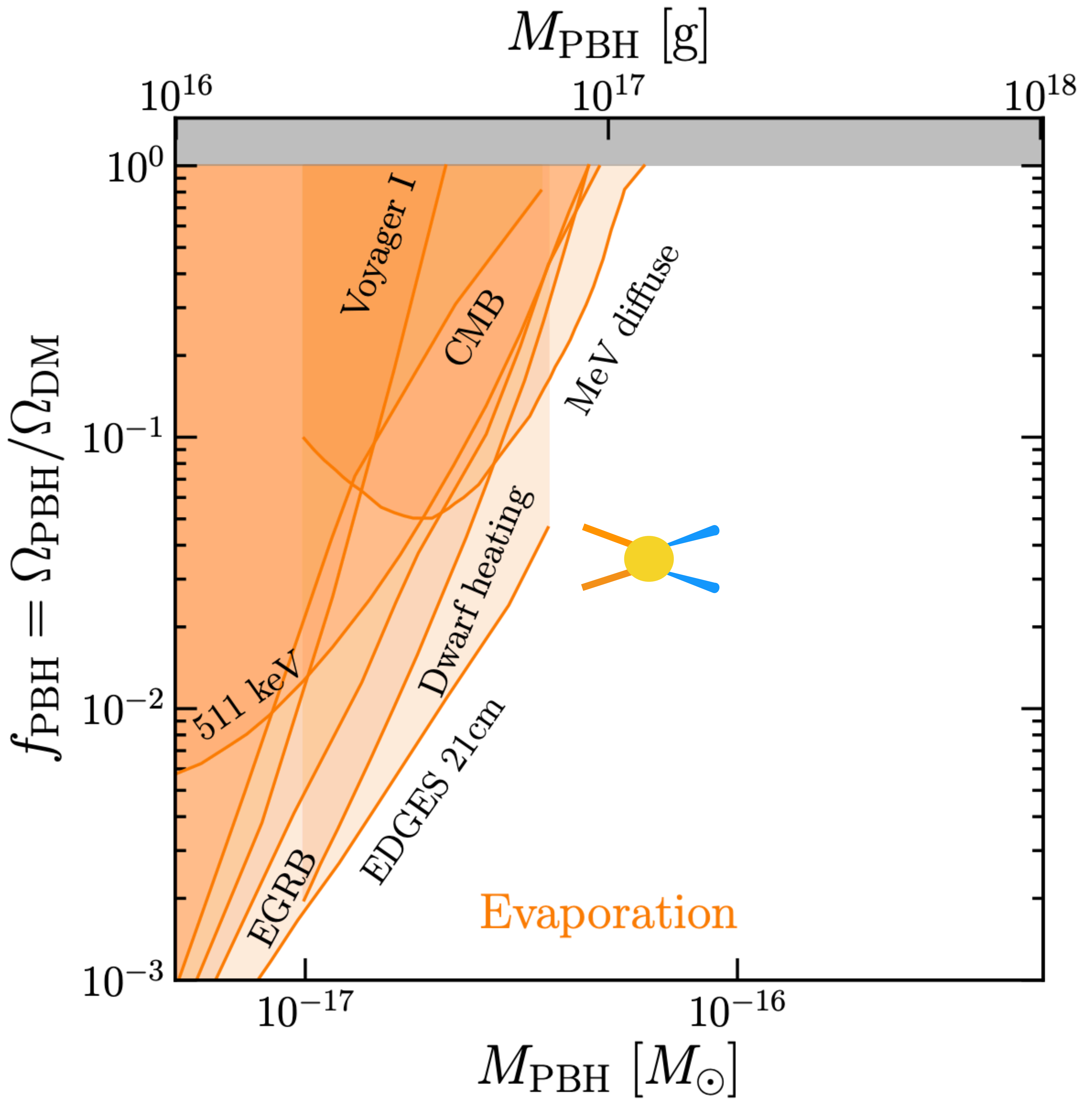




Berteaud, FC+ PRD'22

Limits on primordial black holes

Evaporation of PBH and cosmic backgrounds



Green & Kavanagh J. Phys. G'19

- Dominant limits from Galactic MeV diffuse emission from INTEGRAL/SPI

  Berteaud, FC+ PRD'22

- Photon contribution to the extragalactic gamma-ray and X-ray backgrounds

  Carr+ PRD'10; Ballesteros+ PLB'20; Iguaz+ PRD'21

- Unconstrained mass range ~10^{17} — 10^{22} g, the so-called *asteroid mass gap* where f_{PBH} can be 1

Anomalies and excesses

Low-energy excess in antiproton data?

Signal:

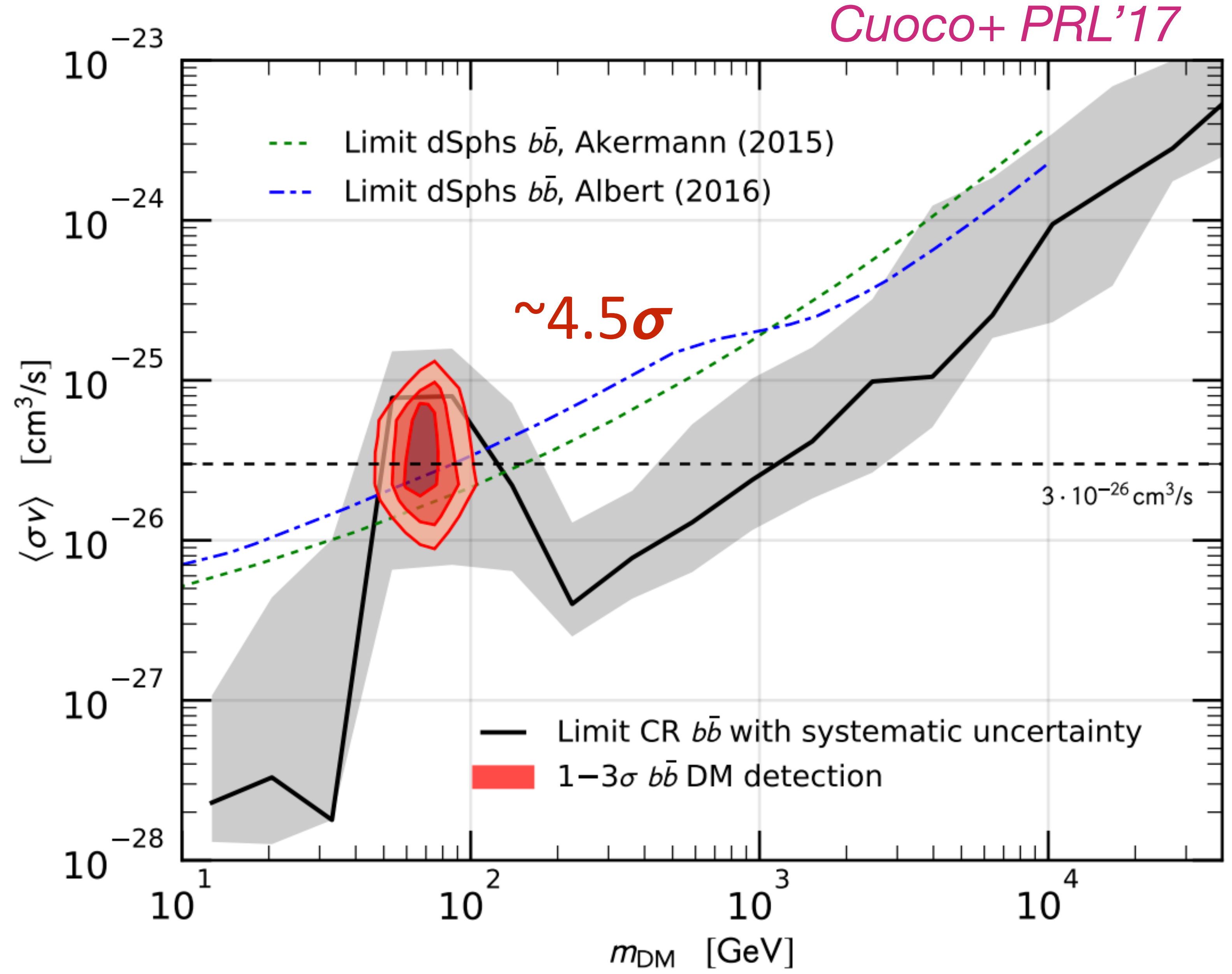
- Excess in AMS-02 cosmic-ray antiprotons @ 10 — 20 GeV *Cuoco+ PRL'17; Cui+ PRL'17; Cholis+ '17*
- Accounting for covariance of various systematics the significance drops < 2σ *Reinert&Winkler JCAP'18; Boschini+ ApJ'17*

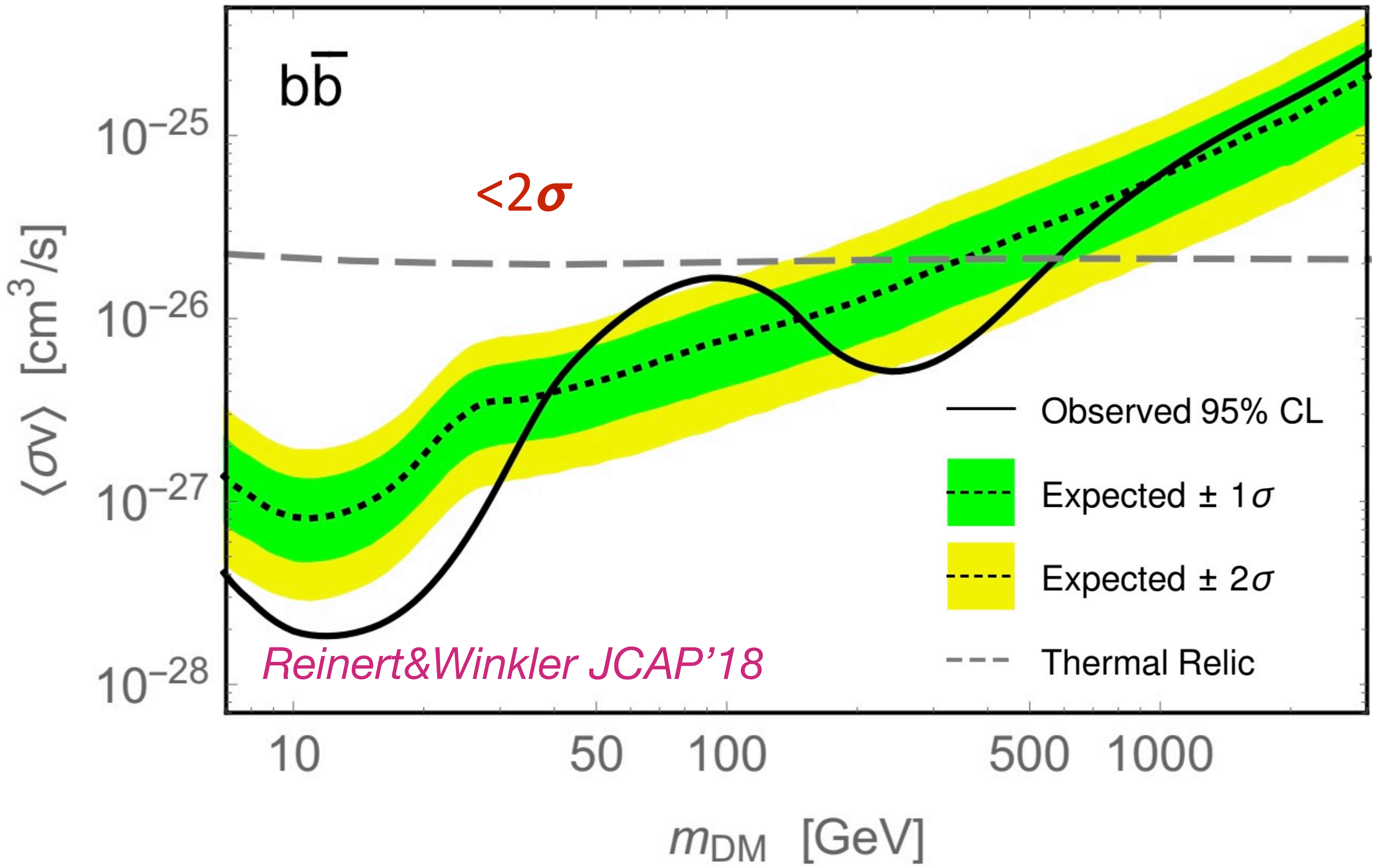
Interpretations:

- Dark matter annihilation with mass ~ 40 — 130 GeV (consistent with GeV excess) *Cuoco+ JCAP'17*
- However, simple propagation scenarios cannot explain *all* CR data
- Syst. uncertainties still large: pbar production cross section? Effects of solar modulation? Cosmic-ray propagation models?

➡Refined treatment of uncertainties is needed!

Cuoco+ PRL'17

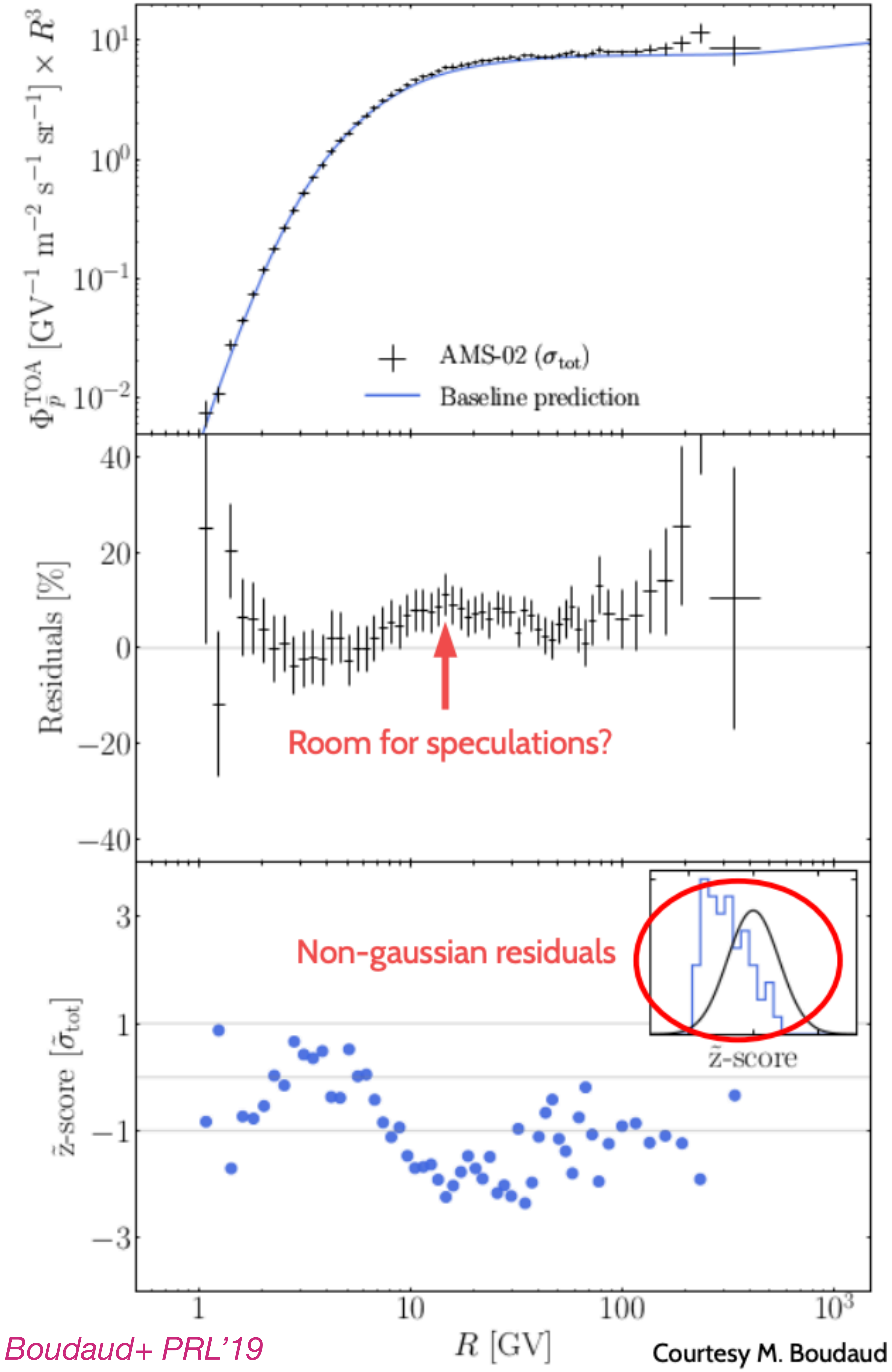




Antiproton uncertainties

Data: AMS02 antiproton from 2016
Model: semi-analytical
Comparison with data => discrepancy ~ few 10GV

New Physics?
Or sys uncertainties?



Boudaud+ PRL'19

Courtesy M. Boudaud

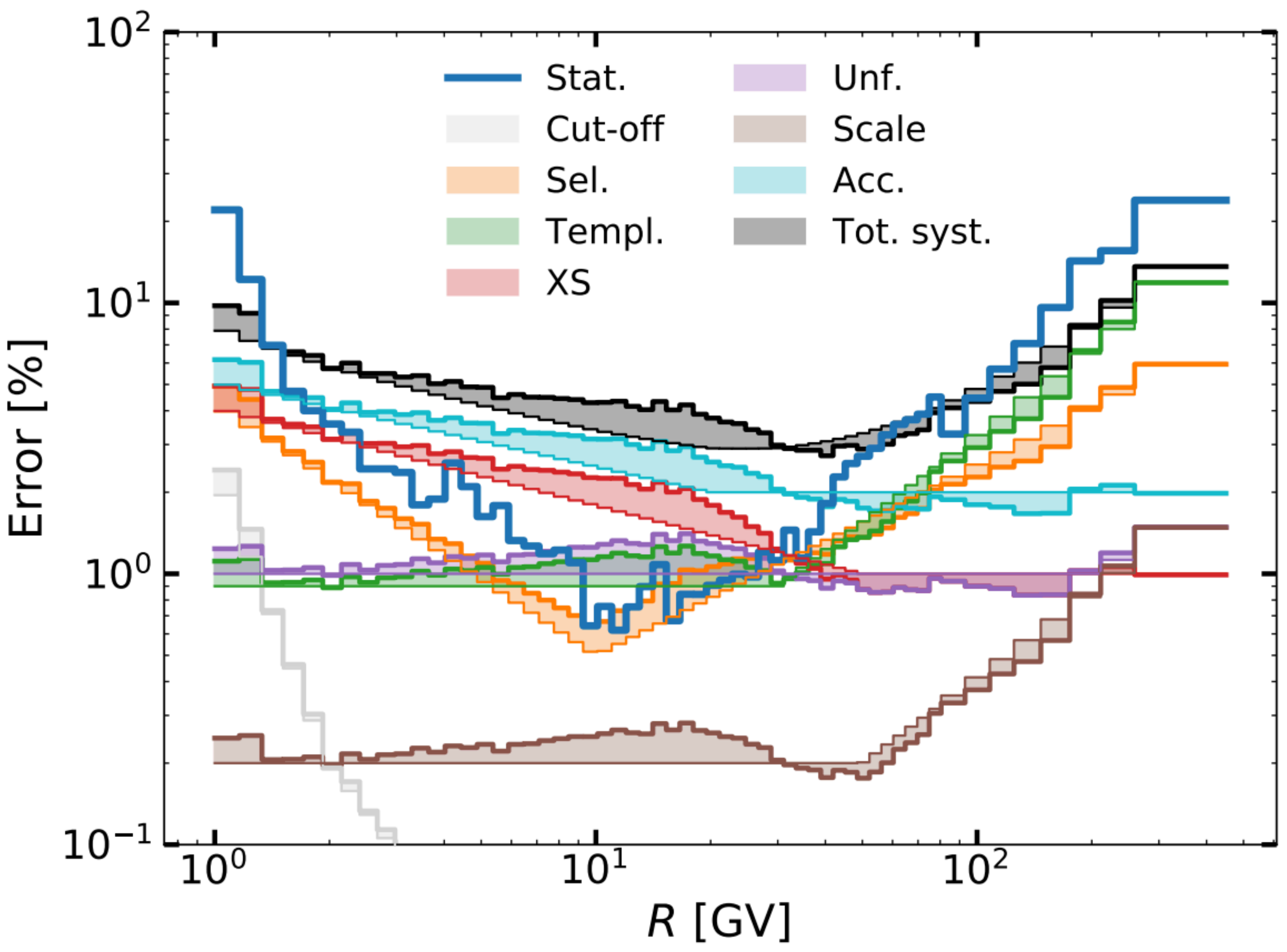
Antiproton uncertainties

Data: AMS02 antiproton from 2016
Model: semi-analytical
Comparison with data => discrepancy ~ few 10GV

New Physics?
Or sys uncertainties?

Errors on the **data**: Covariance matrix estimated from detector info
Errors on the **model**:

1. Pbar production cross-sections → Updated parameterisation and uncertainties
2. Transport → Updated transport models and uncertainties
3. Parents → Updated fit and contribution of high-Z elements



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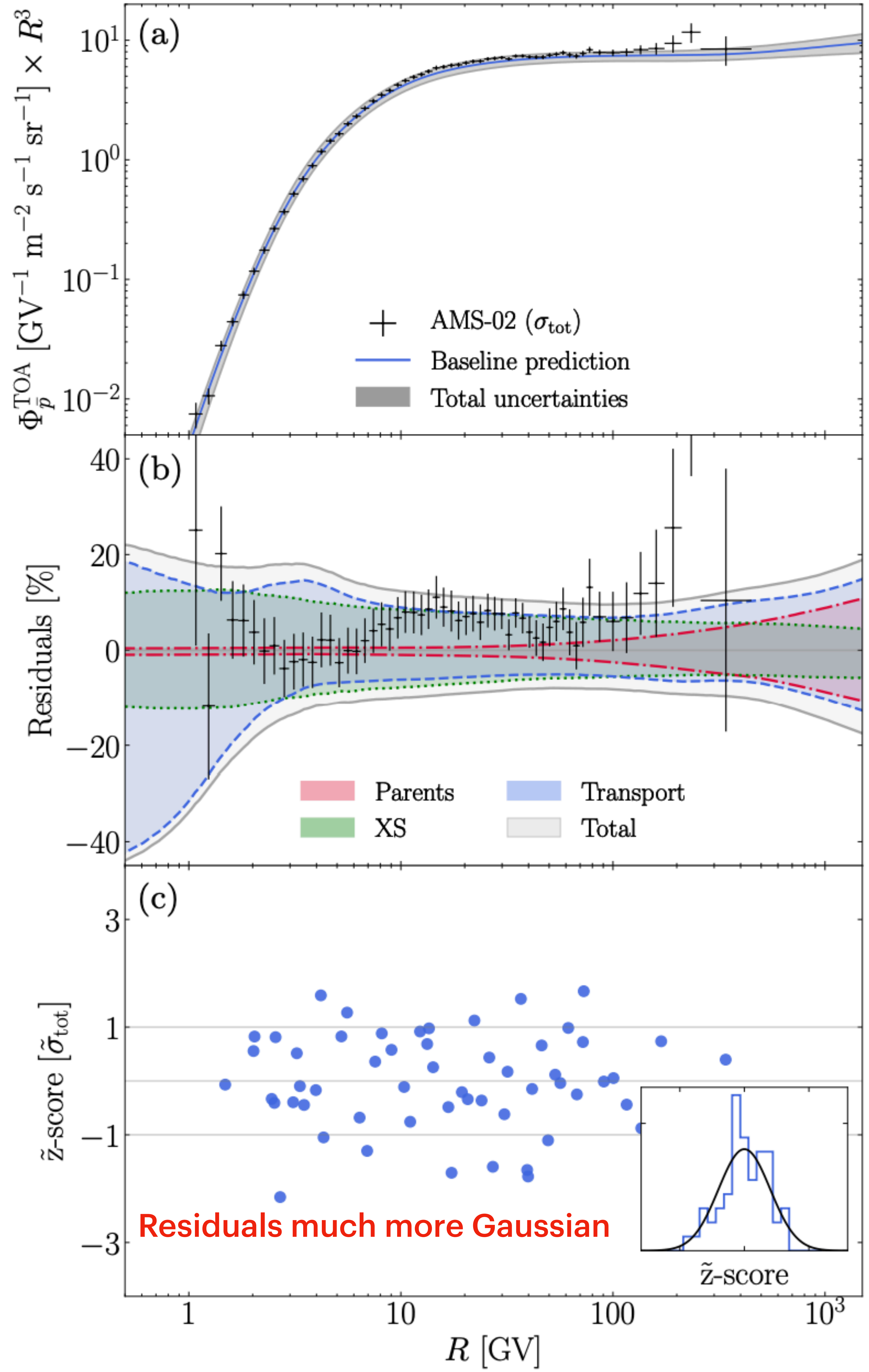
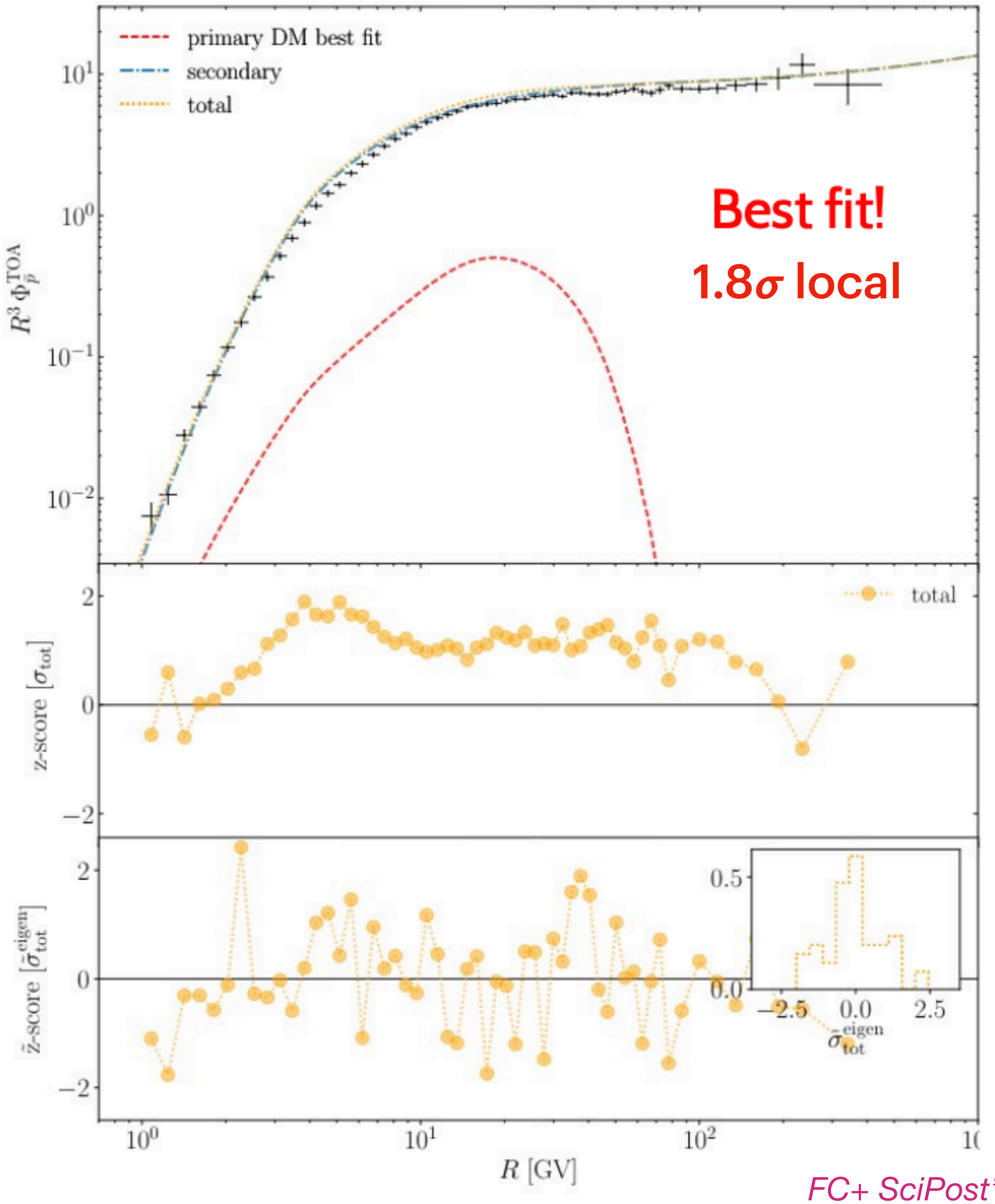
New Physics?
Or sys uncertainties?

AMS-02 antiprotons are consistent with a secondary astrophysical origin

$$\chi^2 = (\text{data}-\text{model})^T (\mathcal{C}^{\text{model}} + \mathcal{C}^{\text{data}})^{-1} (\text{data}-\text{model})$$



No room for dark matter



FC+ SciPost'22

Likelihood ratio:

$$LR(\mu_0) = -2\ln \frac{\sup_{\lambda\in\Lambda} \mathcal{L}(\lambda, \mu_0)}{\sup_{\{\lambda,\mu\}\in\Lambda\cup M} \mathcal{L}(\lambda, \mu)}$$

CR-specific parameters vs DM-specific ones

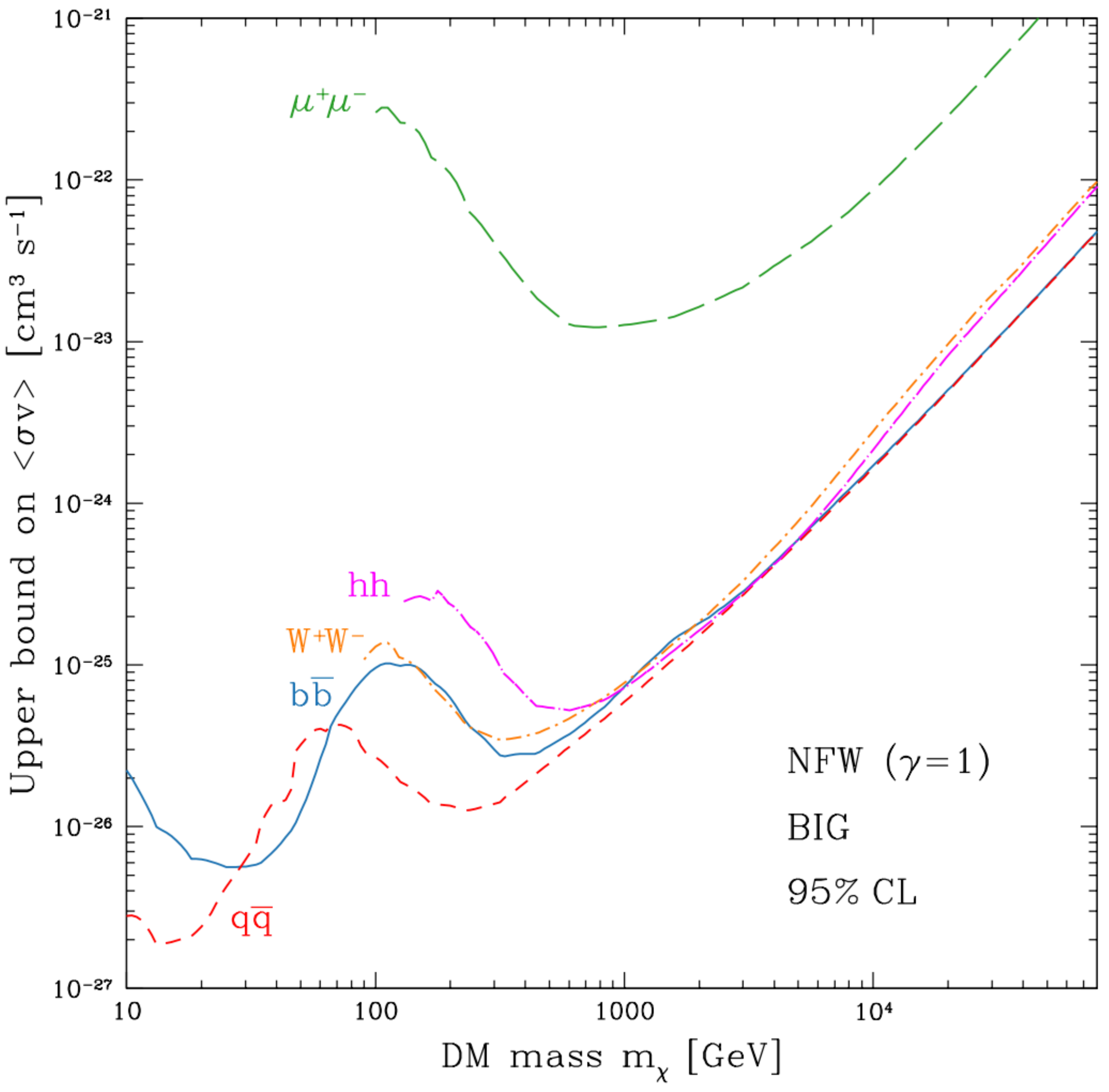
$$-2\ln \mathcal{L}(\lambda, \mu) \equiv \chi^2_{\rm LiBeB}(\lambda) + \chi^2_{\bar{p}}(\lambda, \mu)$$

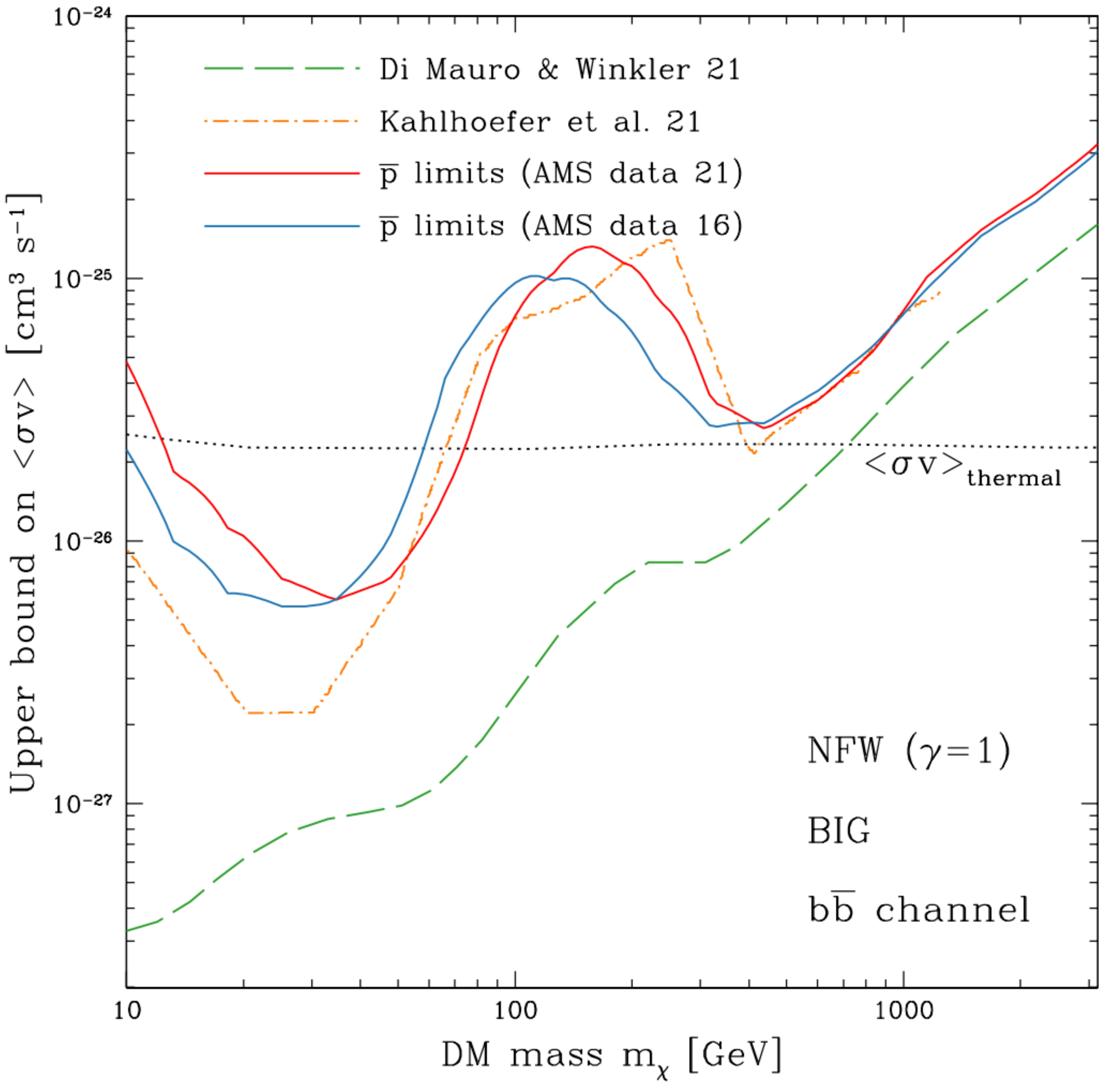
1. CR parameters derived from LiBeB, are good for anti-protons
2. DM does not alter best-fit for propagation parameters since subdominant
3. Uncertainty on primary antiproton flux dominated by the size of the diffusive halo, L

$$-2\ln \mathcal{L}(\lambda, \mu) \equiv -2\ln \mathcal{L}(L, \mu) = \left\{\frac{\log L - \log \hat{L}}{\sigma_{\log L}}\right\}^2 + x_i(\mathcal{C}^{-1})_{ij}x_j$$

Antiproton constraints on WIMPs

FC+ SciPost'22

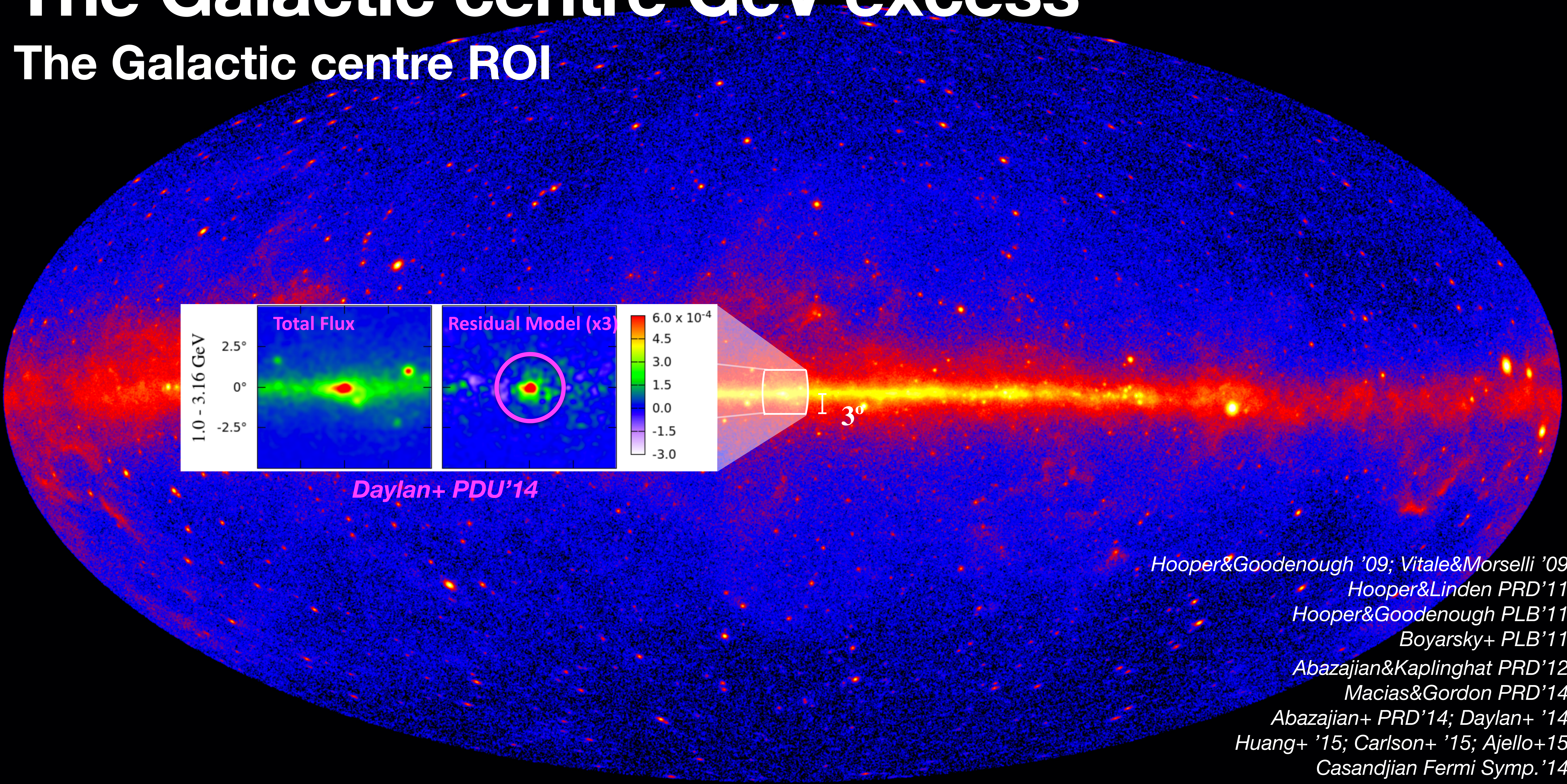




The Fermi-LAT GeV excess

The Galactic centre GeV excess

The Galactic centre ROI



Daylan+ PDU'14

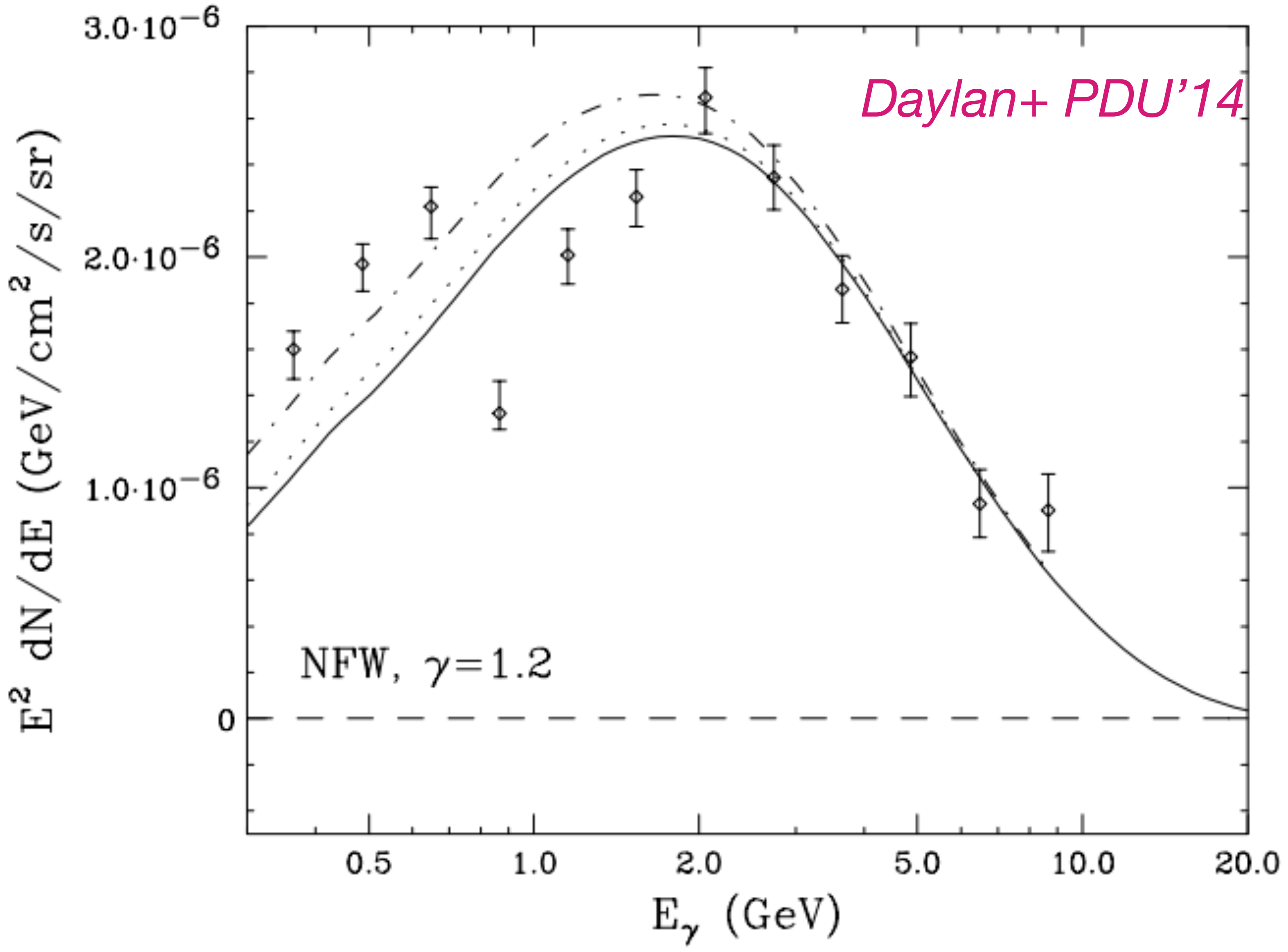
Hooper&Goodenough '09; Vitale&Morselli '09; Hooper&Linden PRD'11; Hooper&Goodenough PLB'11; Boyarsky+ PLB'11; Abazajian&Kaplinghat PRD'12; Macias&Gordon PRD'14; Abazajian+ PRD'14; Daylan+ '14; Huang+ '15; Carlson+ '15; Ajello+15; Casandjian Fermi Symp.'14; de Boer+'16; Macias+'16; etc.

The GeV excess

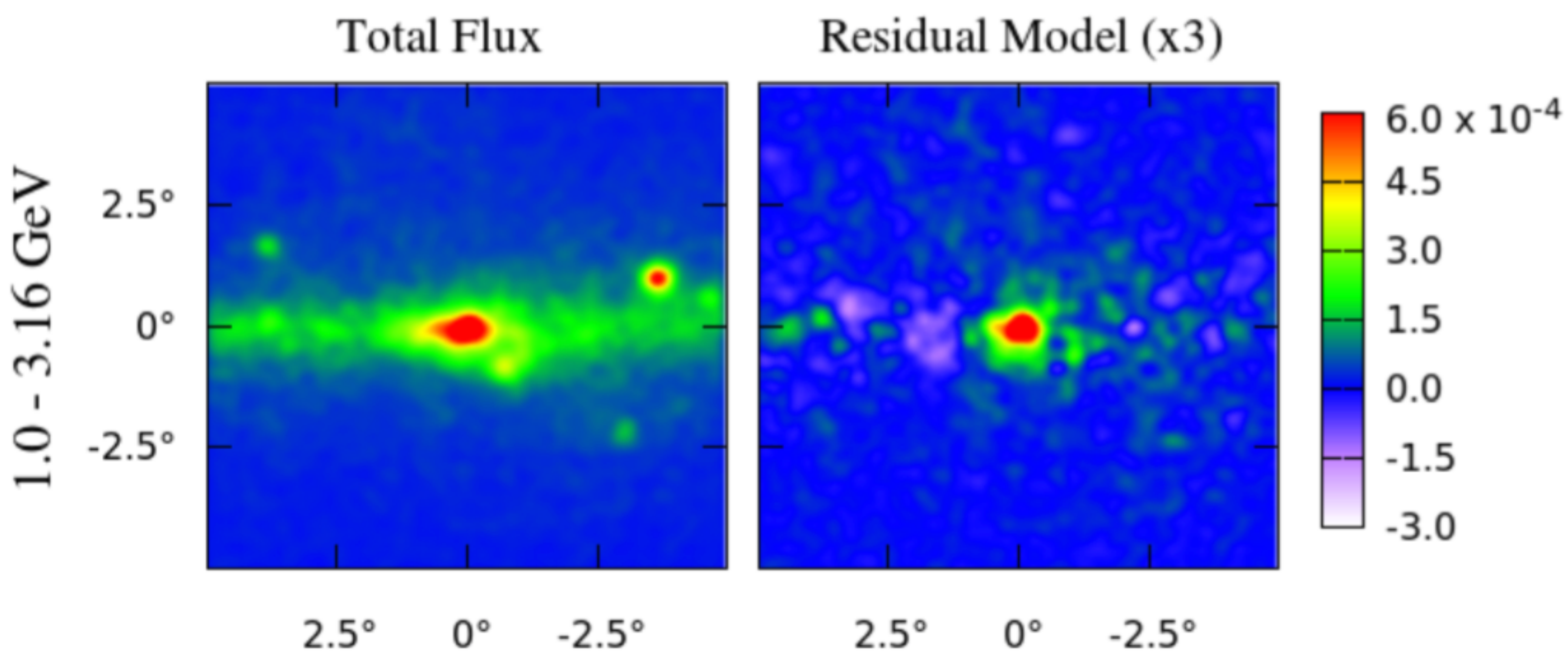
Galactic centre characterisation

$|\ell|, |b| \lesssim 2^\circ$

Spectrum



Morphology



- ✓ **Extended excess emission** above: model for diffuse emission, Sgr A* and other point sources
- ✓ The **spectrum** might strongly suffer from **background modelling**
- ✓ Compatible to be **spherically symmetric** about the Galactic centre
- ✓ Connection with HESS TeV GC ridge

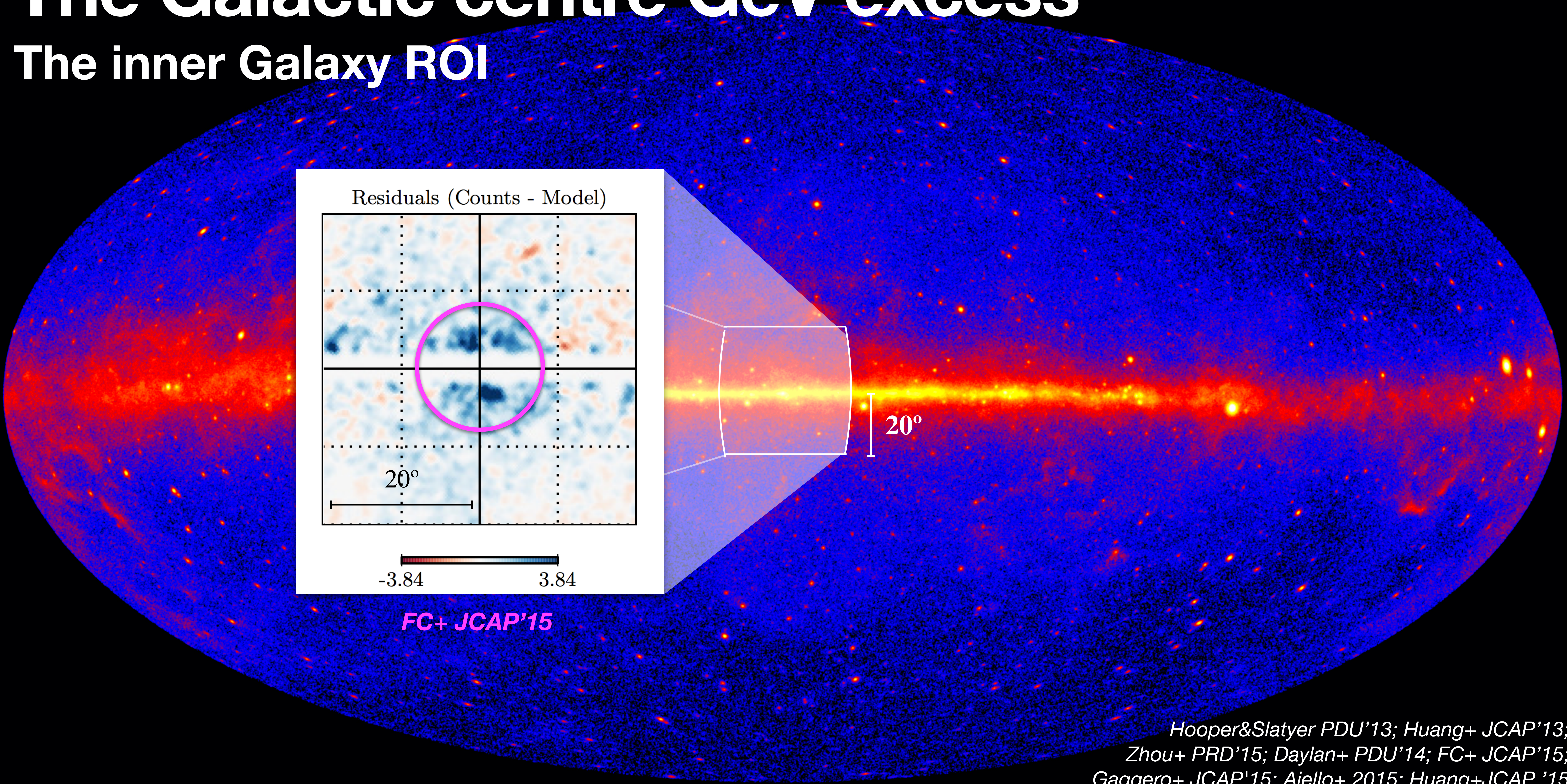
Abazjian+ PRD'14

$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.6$$

Macias&Gordon PRD'14; Macias+ MNRAS'15

The Galactic centre GeV excess

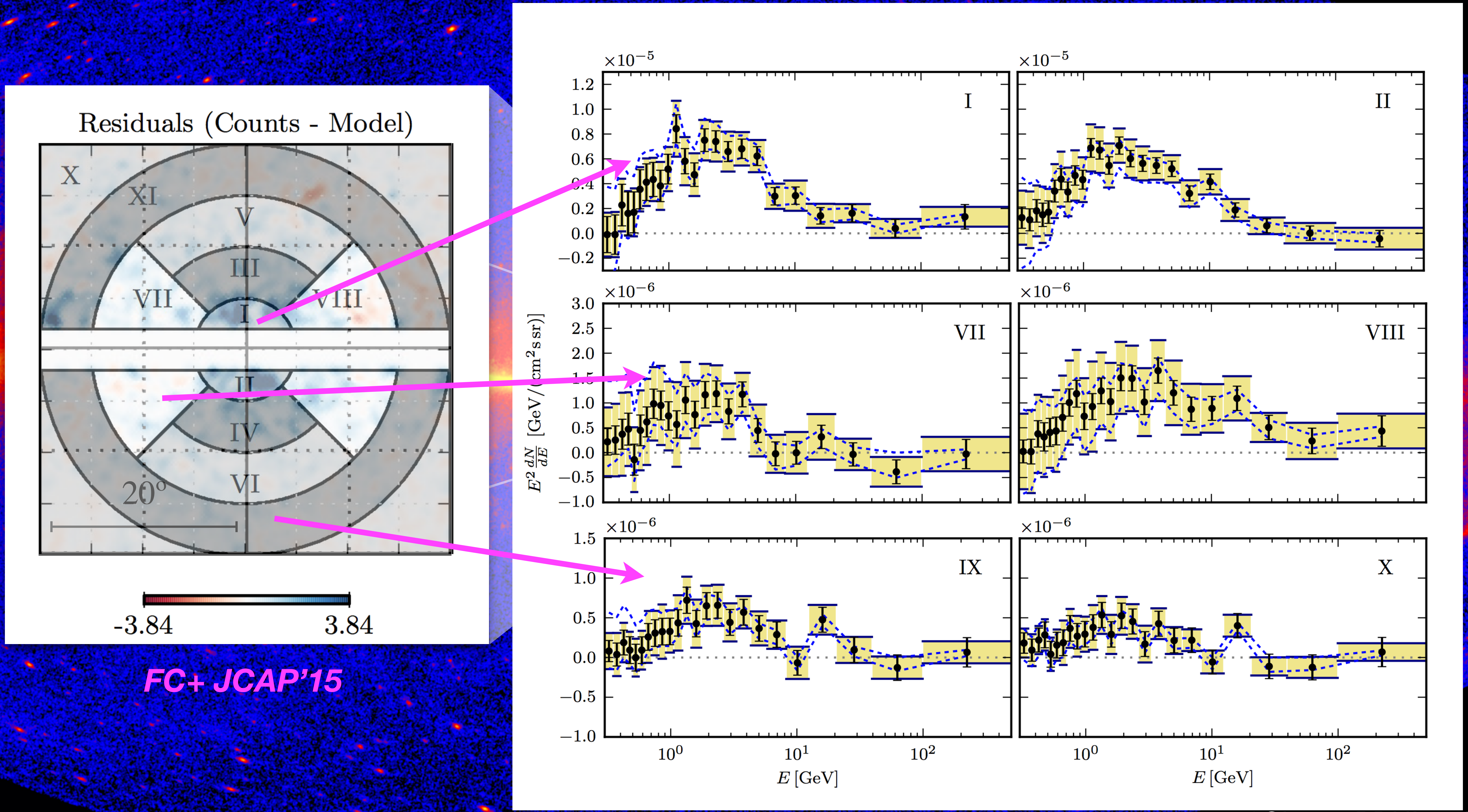
The inner Galaxy ROI



Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ PDU'14; FC+ JCAP'15; Gaggero+ JCAP'15; Ajello+ 2015; Huang+JCAP '15 Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; etc.

The Galactic centre GeV excess

The inner Galaxy ROI

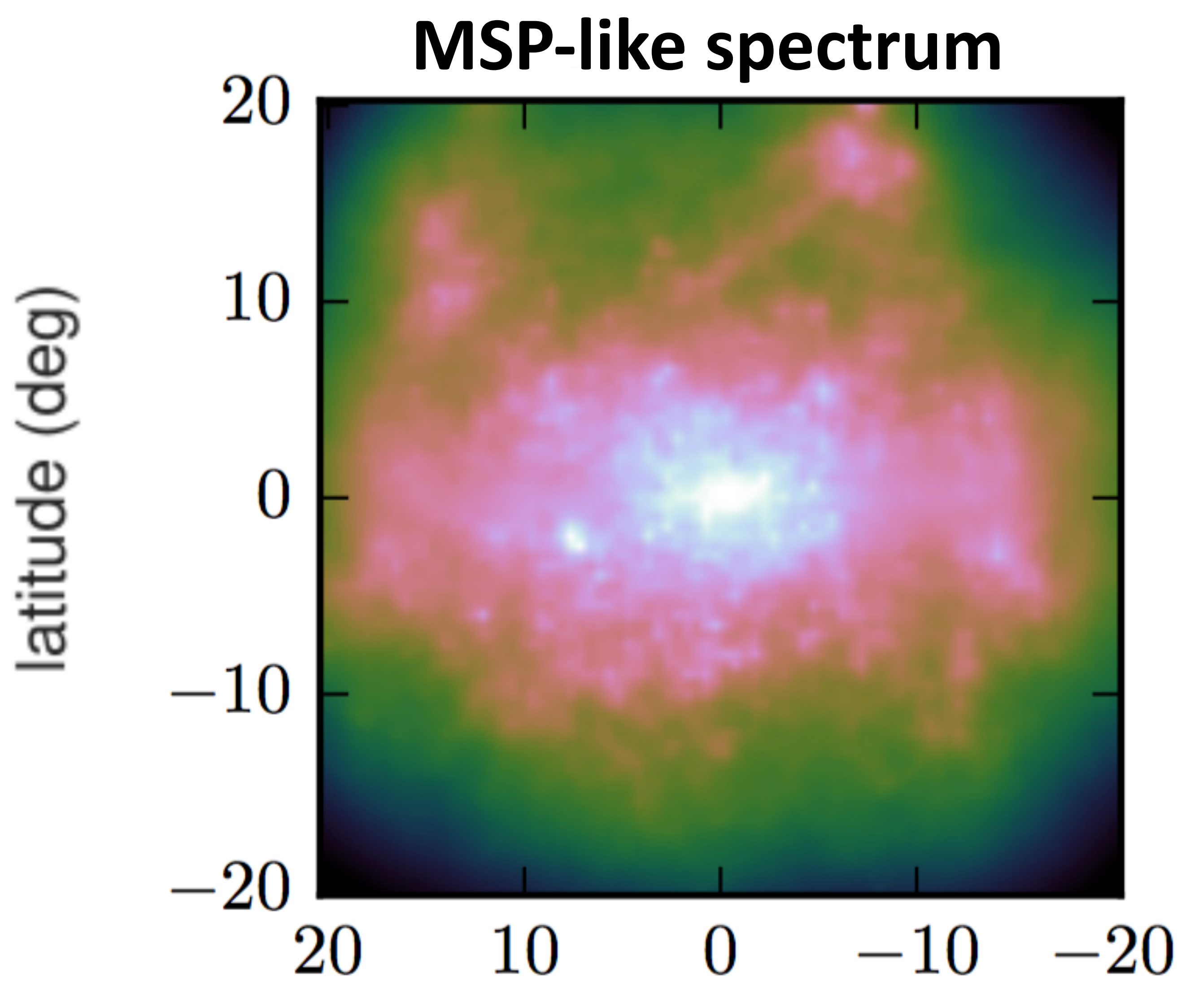


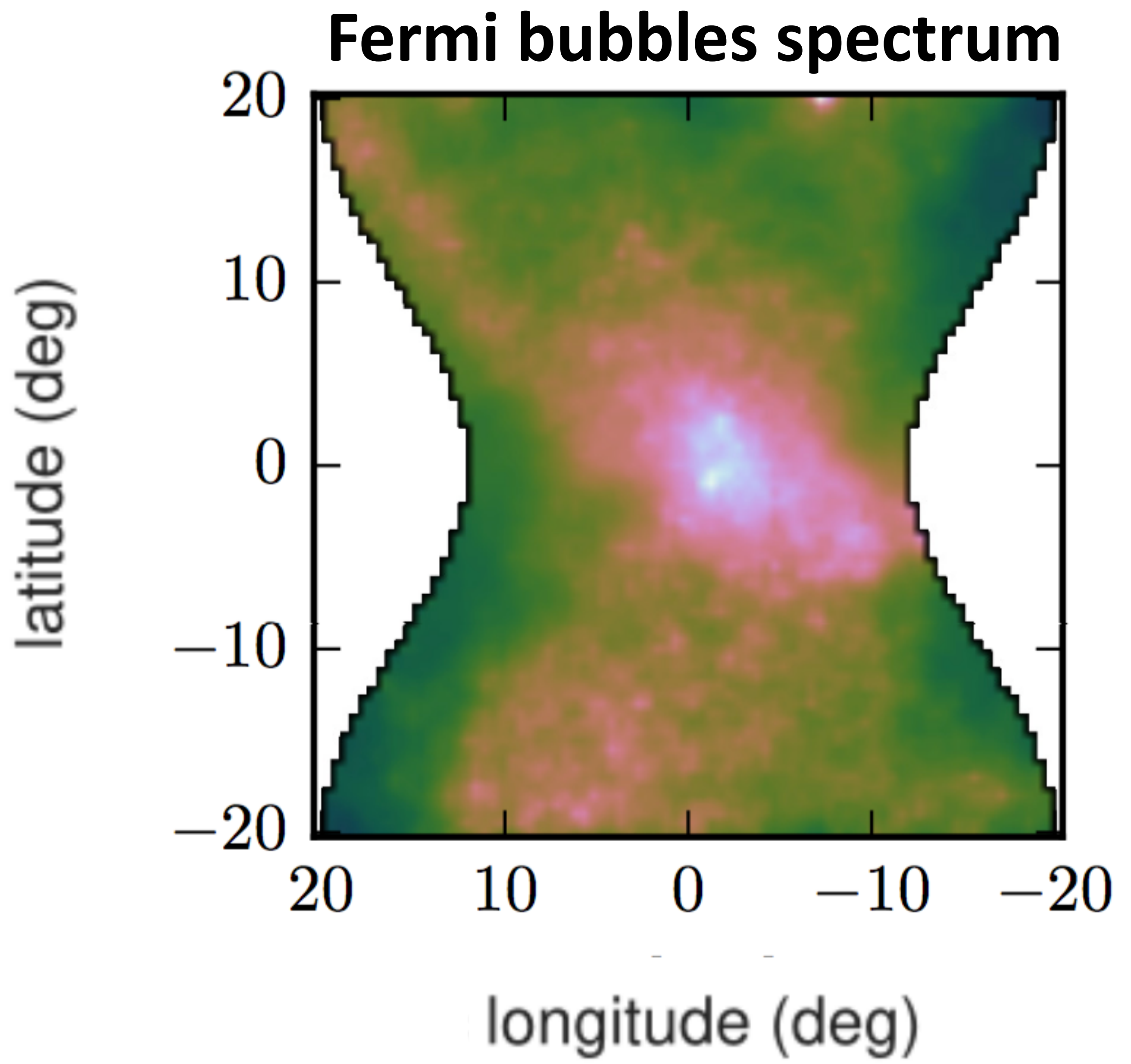
FC+ JCAP’15

1. Almost uniform spectrum peaked at ~2 GeV
2. Extended at least up to 10 degrees

Hooper&Slatyer PDU’13; Huang+ JCAP’13; Zhou+ PRD’15; Daylan+ PDU’14; FC+ JCAP’15; Gaggero+ JCAP'15; Ajello+ 2015; Huang+JCAP ’15 Linden+PRD’16; Horiuchi+’16; Ackermann+ApJ’17; Ackermann+2017; etc.

The GeV excess emission





- Established evidence for an excess emission above **known** astrophysical backgrounds (diffuse emission + point-like sources)
- **Several independent techniques** find analogous results (template fitting, spectral decomposition, image reconstruction)

Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; FC+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15; etc

Selig+ A&A'14; Huang+ JCAP'16; de Boer+'16

Storm, Weniger & FC JCAP'17

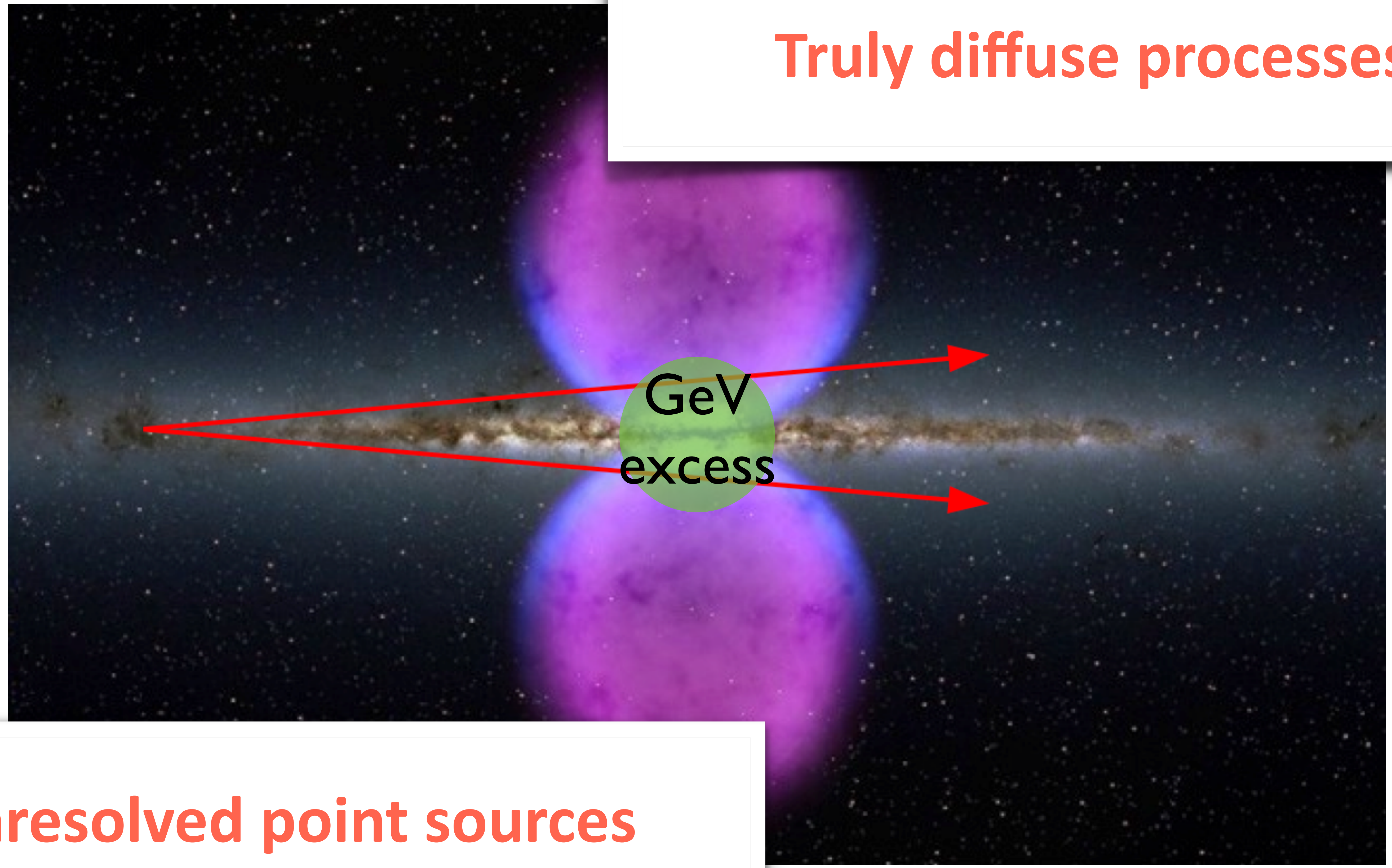
- **Template fitting - image reconstruction hybrid approach** (SKYFACT) has been proved very powerful in disentangling gamma-ray emission components

Storm, Weniger & FC JCAP'17

- **Residuals reduced significantly** when (realistic) nuisance parameters are included in the fit

What is the origin of the GeV excess?

Possible interpretations



Truly diffuse processes

Unresolved point sources

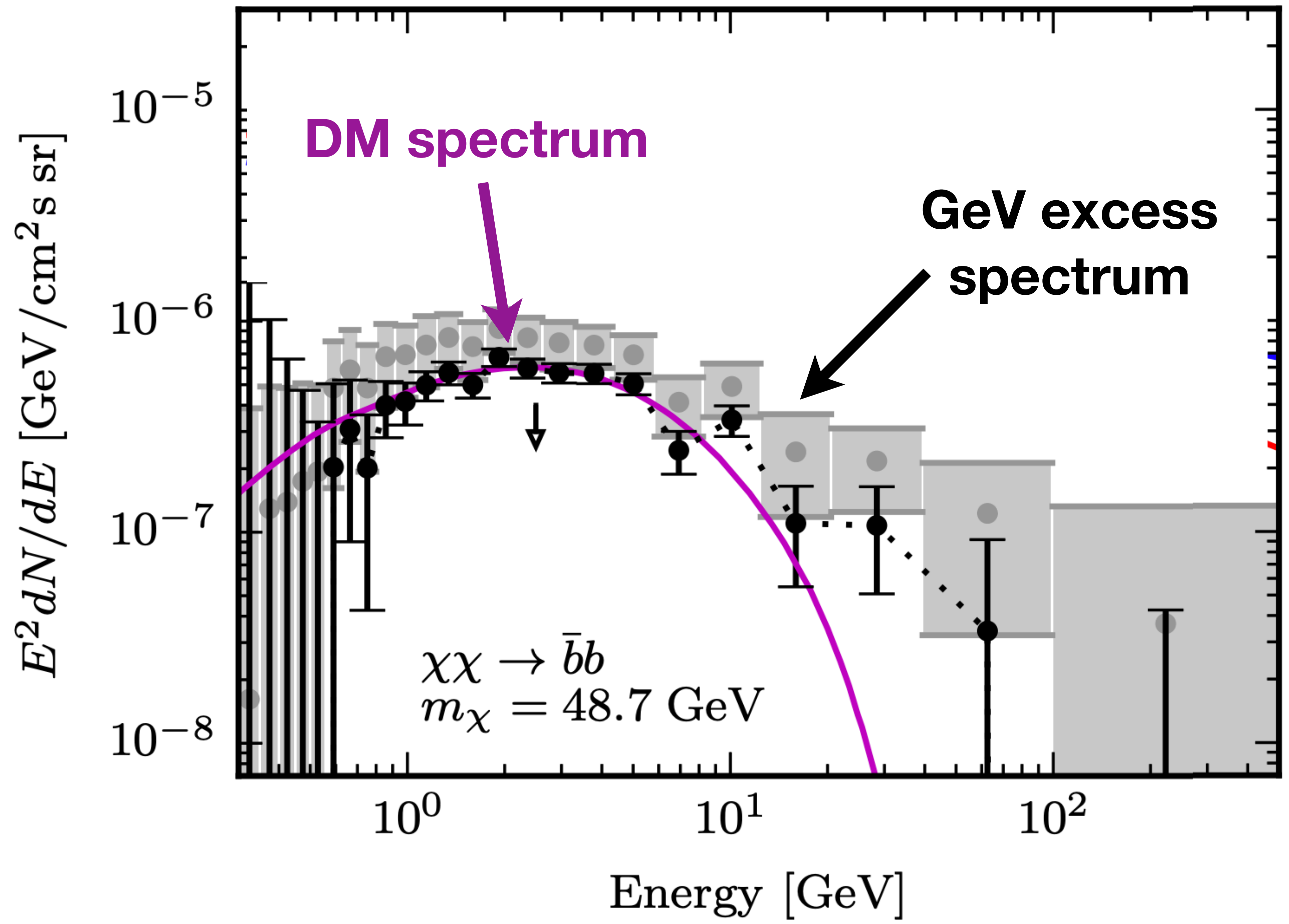
Constraints:

(a) Spectrum & Morphology of the excess? (b) Emission in other wavelengths?

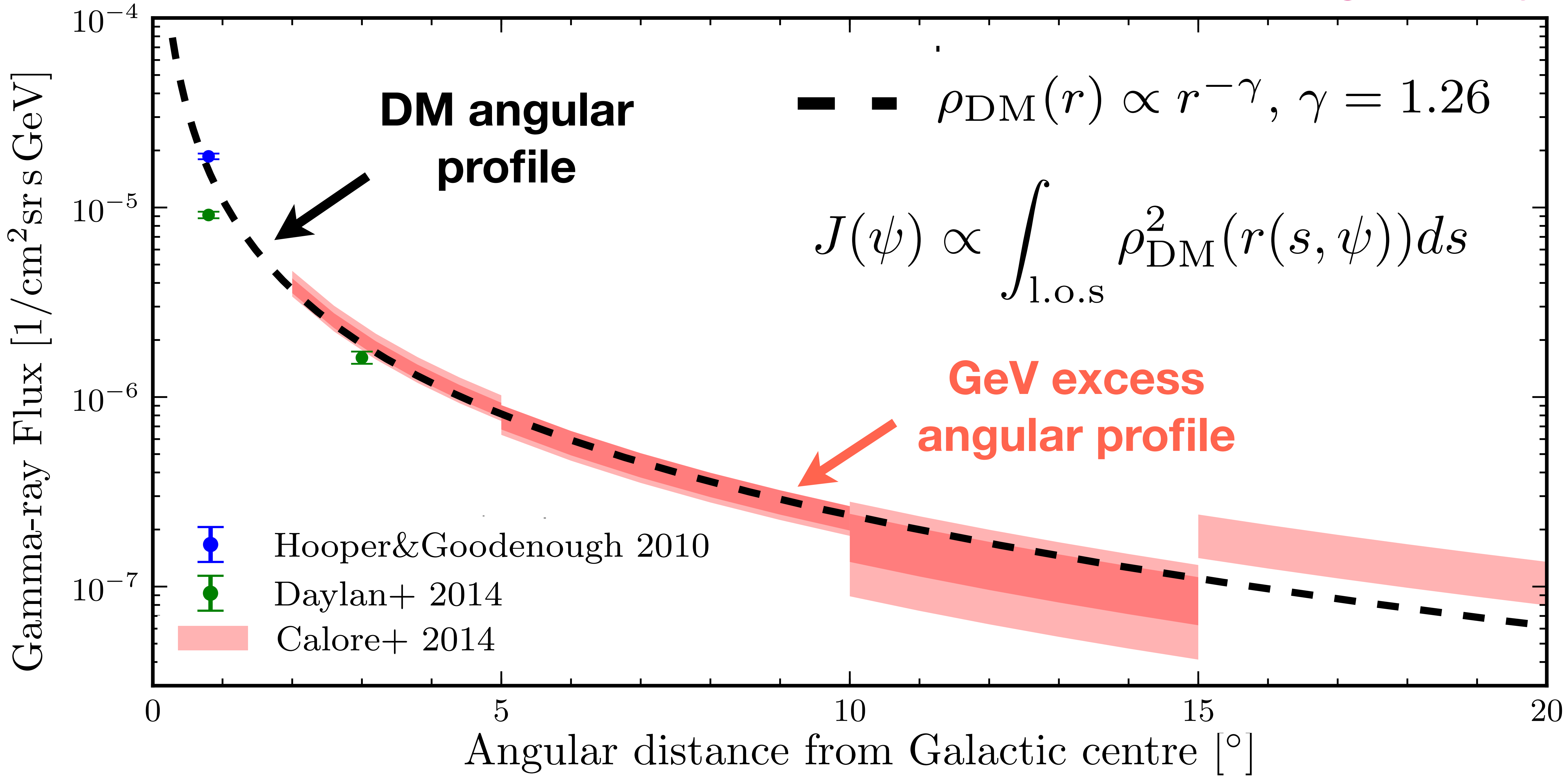
Diffuse processes I

Gamma rays from dark matter (DM) annihilation

- **Decay/Annihilation** of DM particles would lead to the production of **final gamma rays** with specific energy and spatial distribution



FC+PRD'15



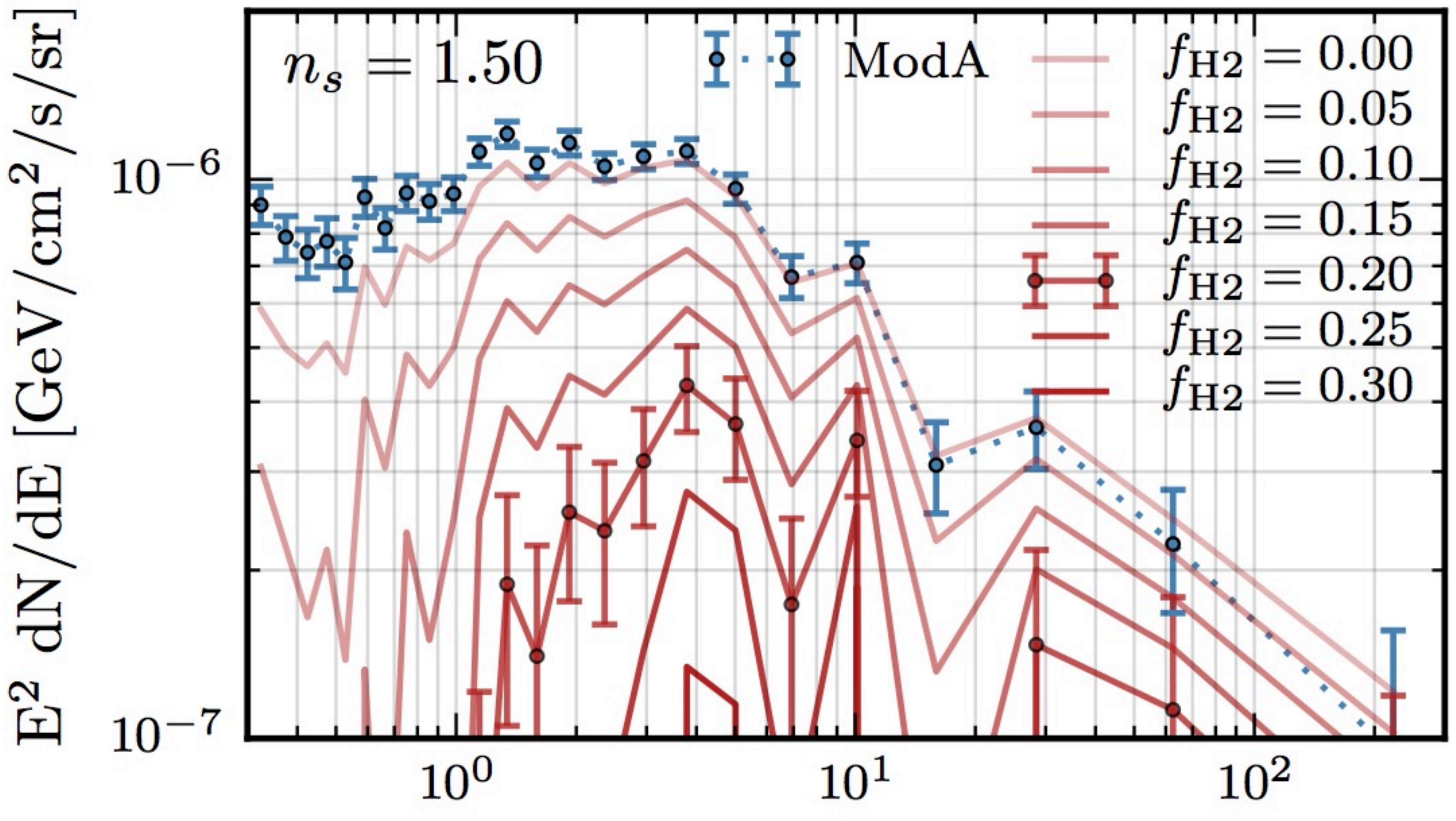
Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; O(>100) papers

Diffuse processes II

Cosmic rays in the GC

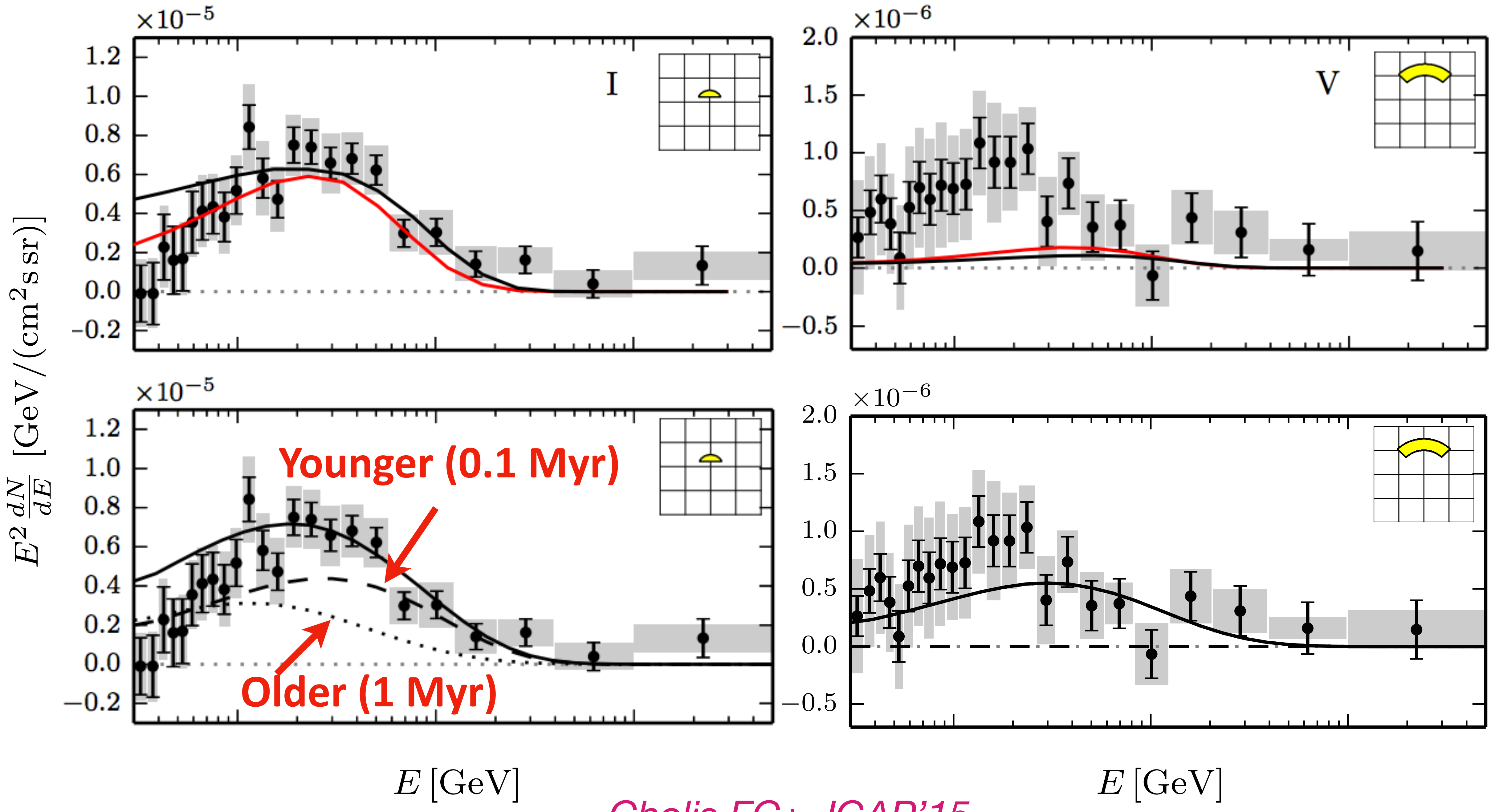
- **New population** of **cosmic rays** injected at the GC (electrons mostly)
- **Steady state** (from star formation in CMZ) and/or **time-dependent** (from outburst activity of the GC) source term

Gaggero+JCAP'15; Carlson+ PRD'16, PRL'16
Petrovic+ JCAP'14; Cholis,FC+ JCAP'15



Carlson+ PRD'16

Additional CR injection at the GC, accounting for enhanced SFR traced by H2 regions (5-10% of total SFR)

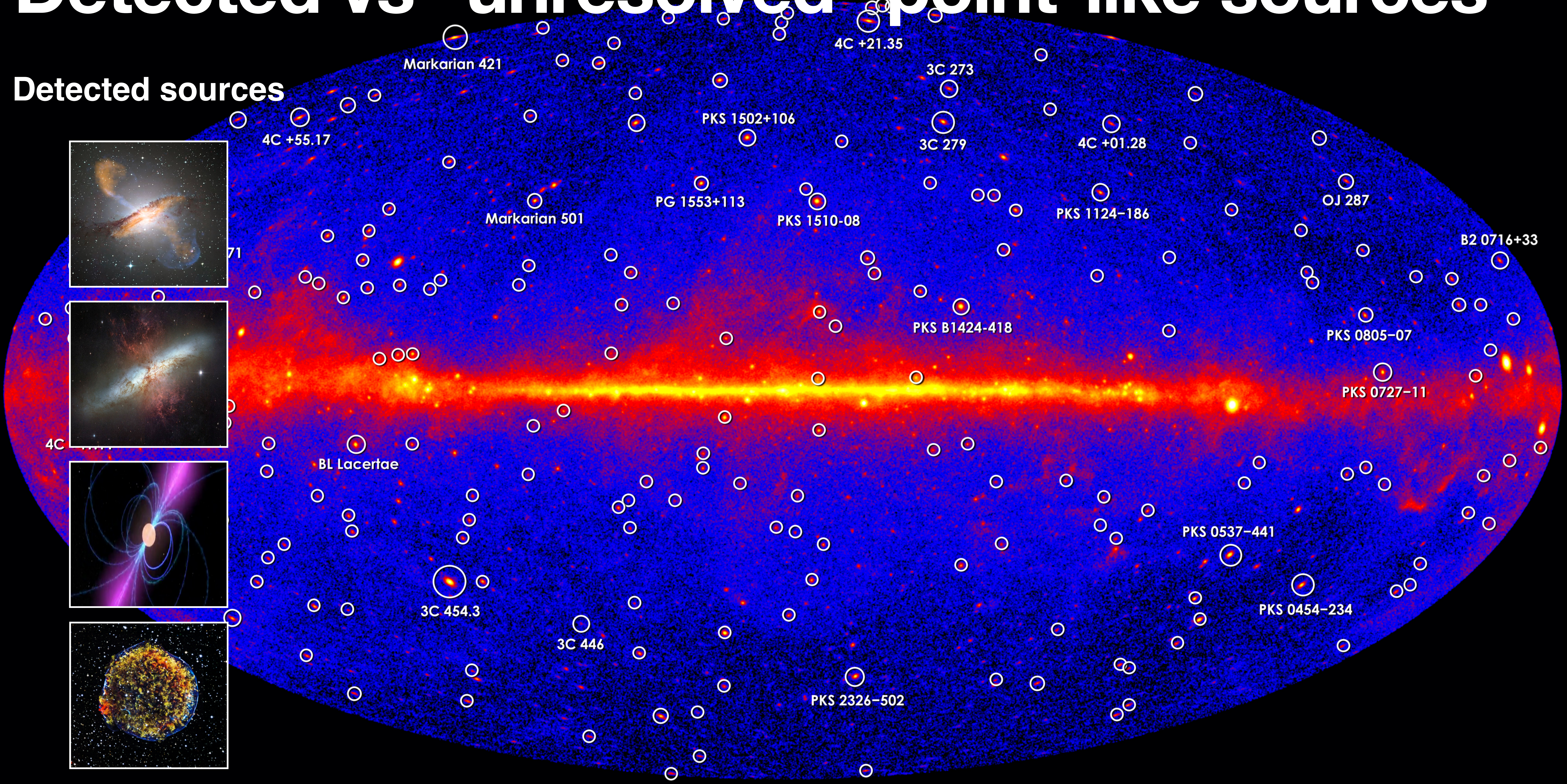


Cholis,FC+ JCAP'15

Time-dependent (burst) injection of leptons at the GC, and tuning of burst parameters (age, duration, injection spectrum, propagation parameters)

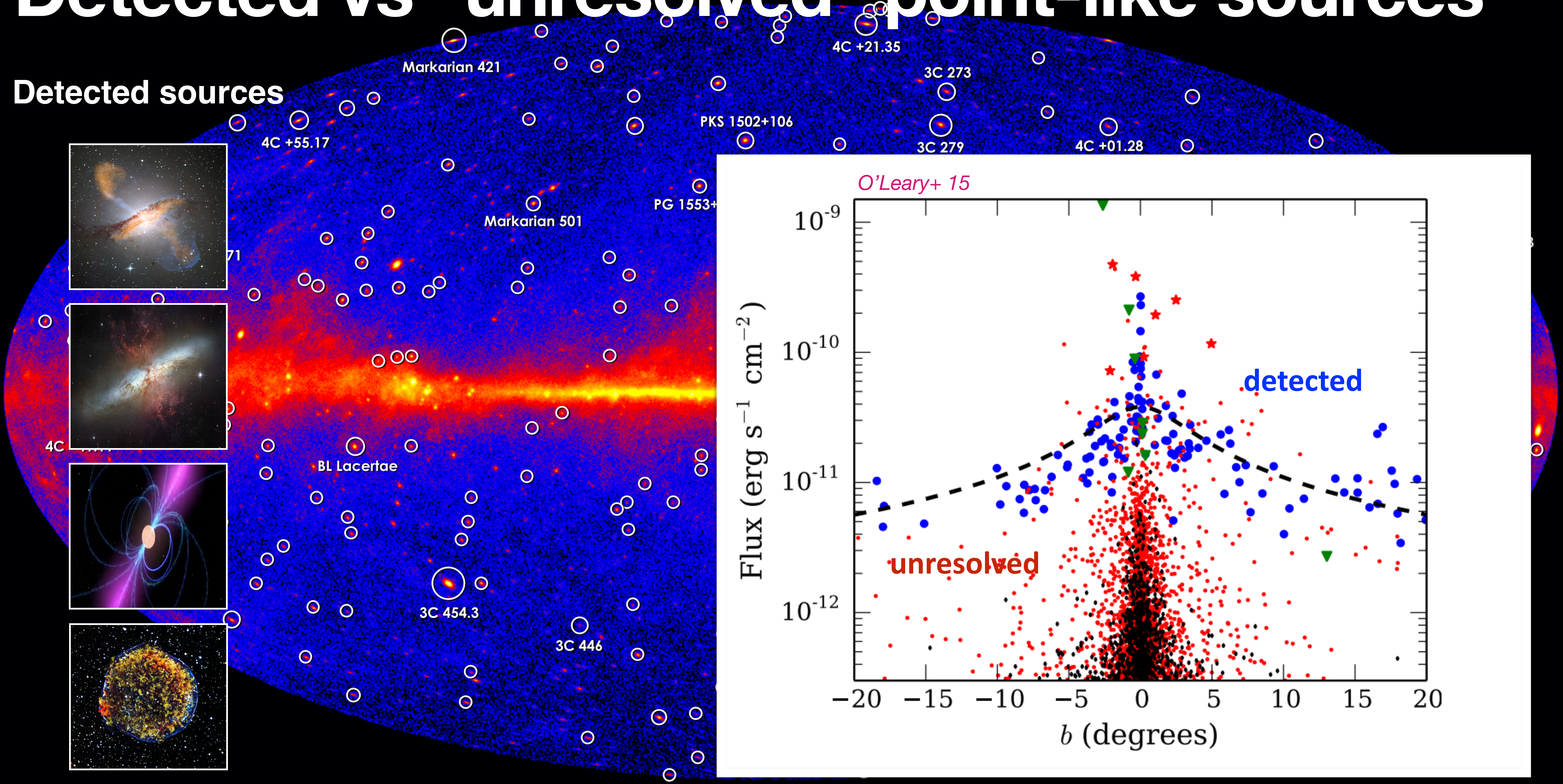
Detected vs “unresolved” point-like sources

Detected sources



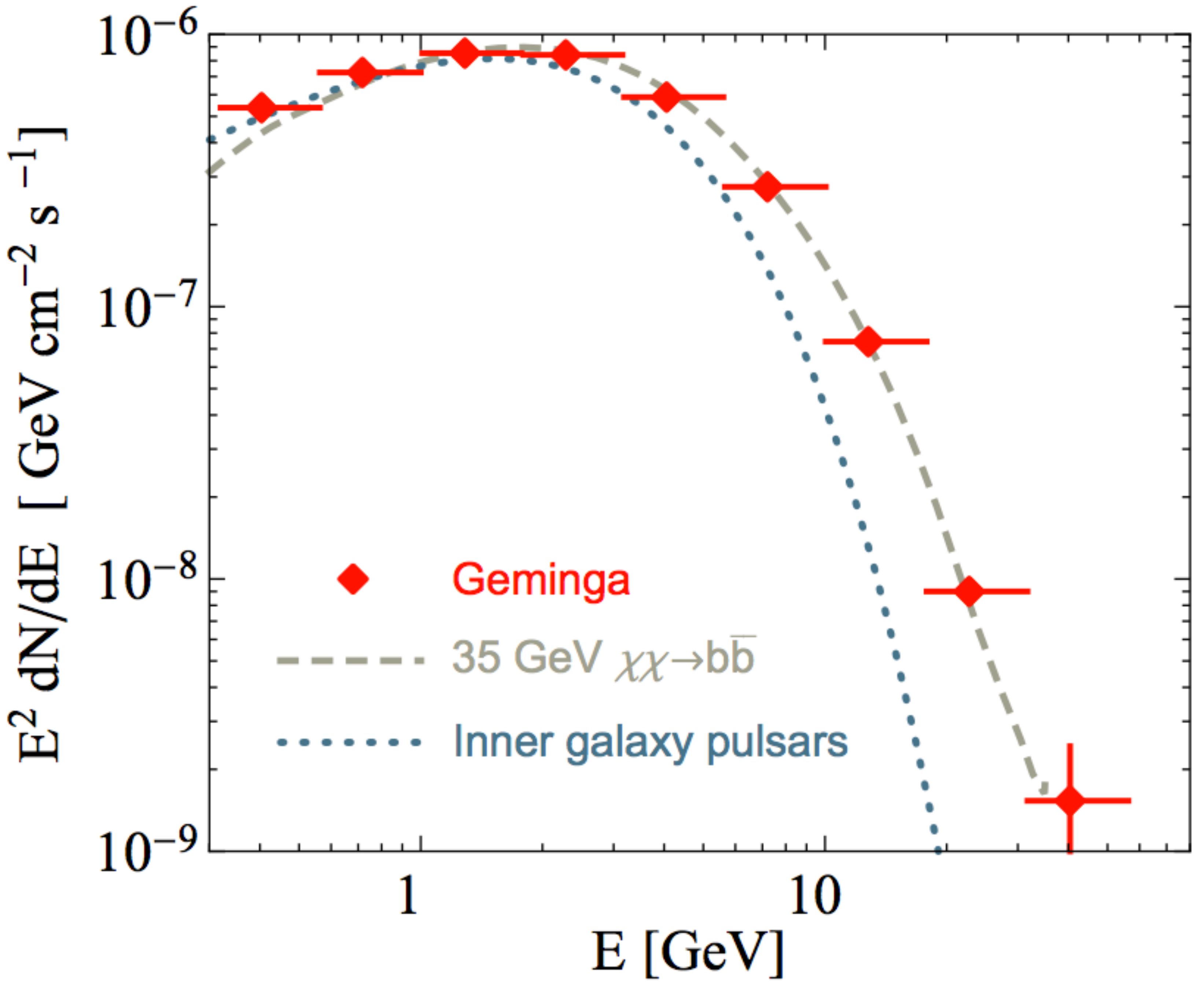
Detected vs “unresolved” point-like sources

Detected sources



Unresolved sources: PSR and MSPs

Spectrum



✓ Excess spectrum compatible with observed **millisecond pulsars** (MSPs), and marginally **young pulsars**

Abazaijan&Kaplinghat'12

Morphology

$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$

$$\Gamma = 2.5 \quad R_{\rm cut} = 3\,{\rm kpc}$$

✓ Proposed population of **MSPs in the bulge** (vs disc)

Hooper+PRD'14; Petrovic+ JCAP'15; Yuang+ MNRAS'14;

✓ **Young pulsars** from SF in the CMZ, but difficult to explain spatial extent and observed bright ones

O'Leary+ '15; Linden PRD'16

✓ **Bulge MSPs** from tidally disrupted globular clusters

Brandt&Kocsis ApJ'15; Abbate et al. 2017; Fragione et al. 2017; Arca-Sedda et al. 2017; Macias+JCAP'19

✓ Issues in luminosity function of observed MSP and LMXB-to-MSP ratio

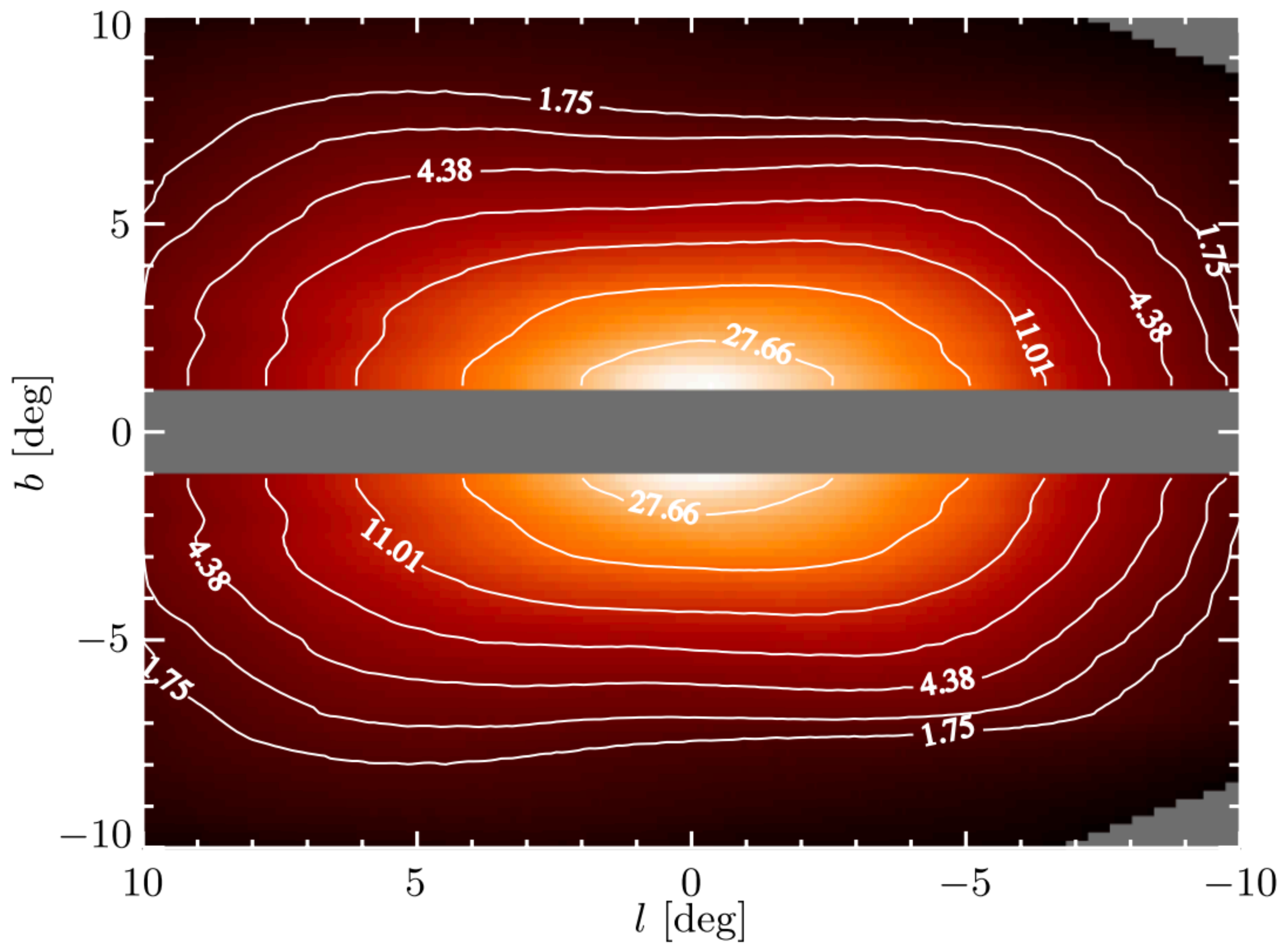
Cholis+'14; Hooper+'15; Hooper&Linden JCAP'16; Haggard+ JCAP'17; Ploeg+ JCAP'17

Going beyond dark matter templates

Stellar distribution in the bulge

Boxy bulge

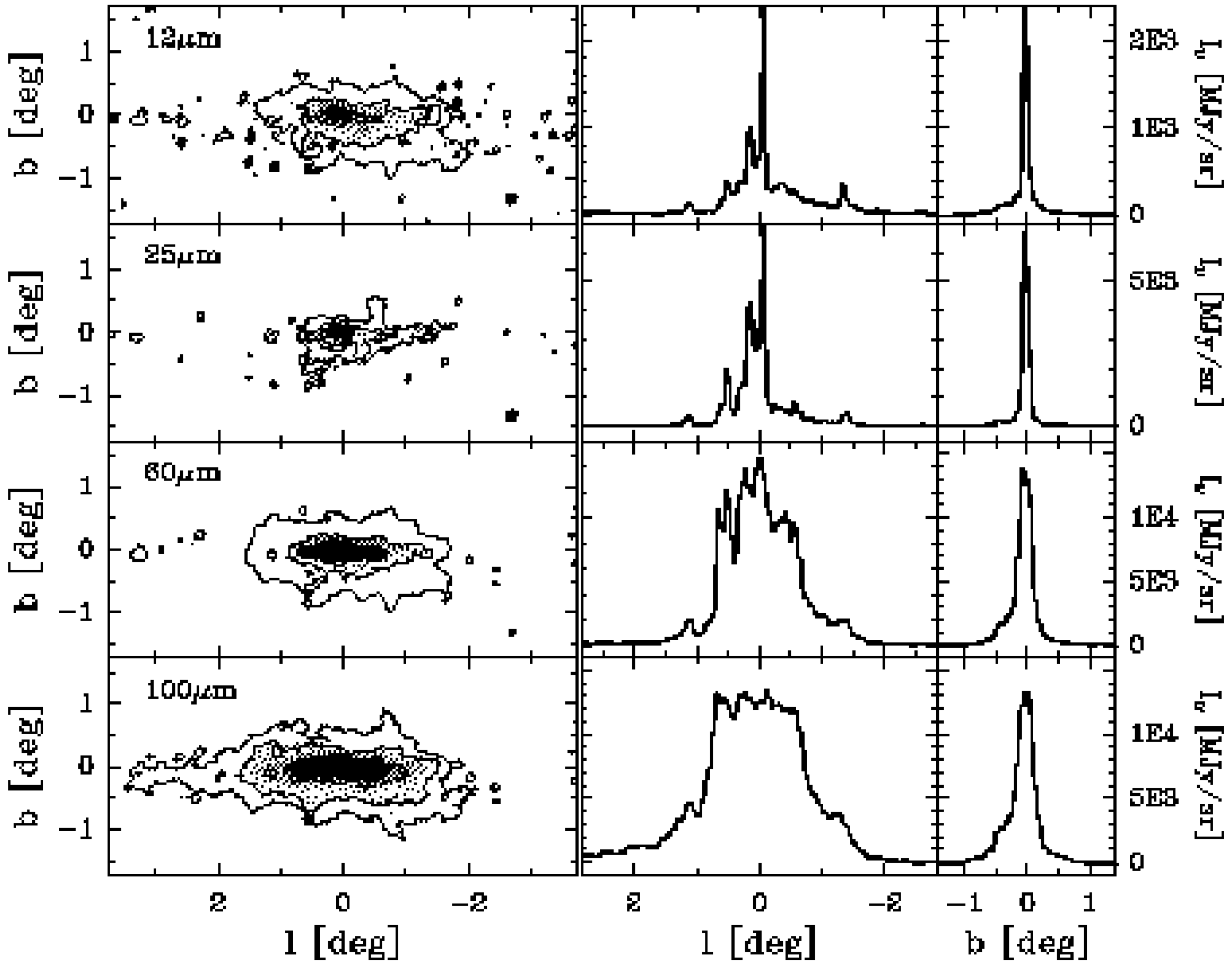
$0.9 \times 10^{10}\, M_\odot$



Wegg & Gerhard MNRAS'12

Nuclear bulge

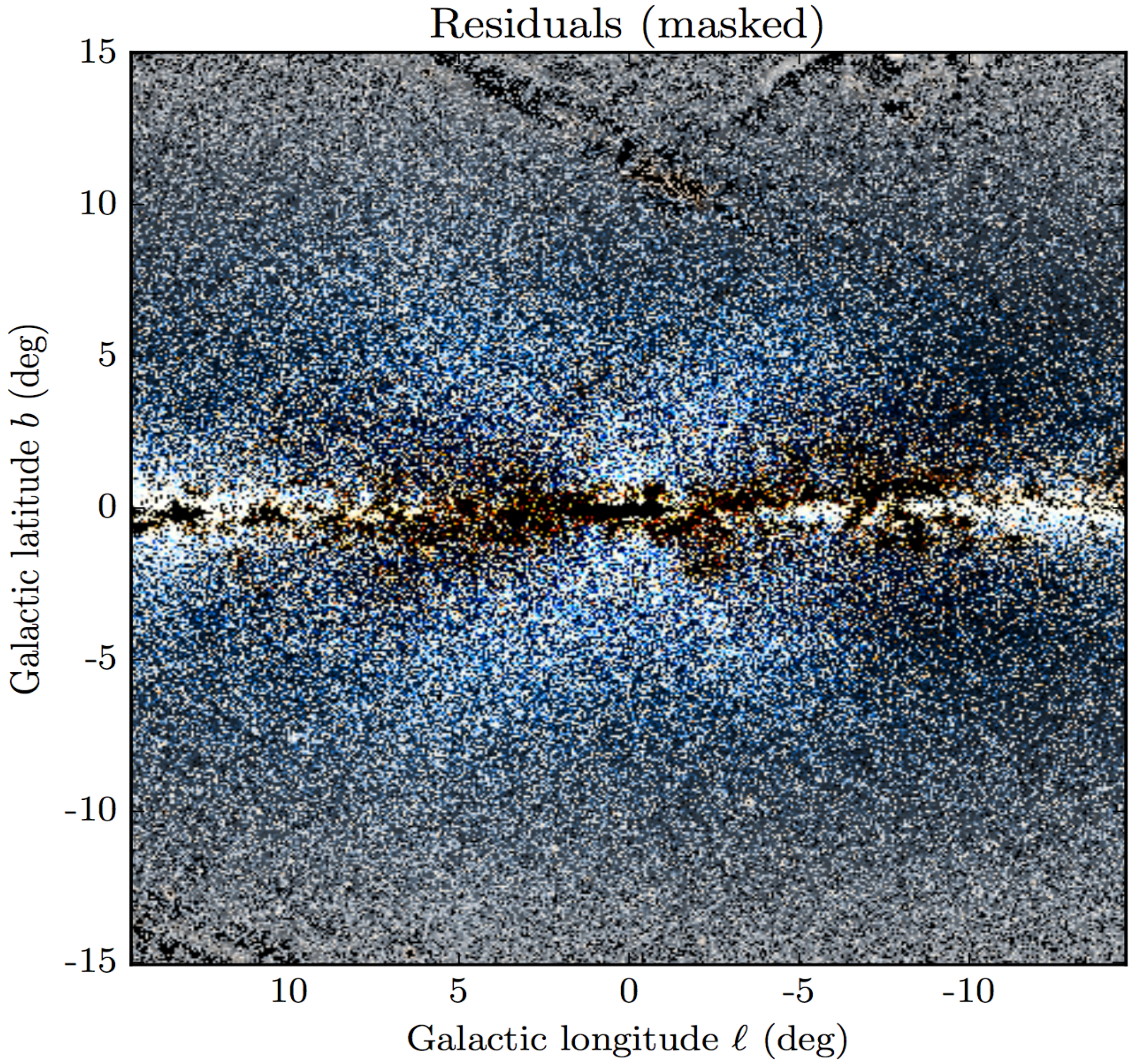
$1.4 \times 10^{9}\, M_\odot$



Launhardt+A&A'02

X-shaped bulge

~20% BB mass



Ness&Lang AJ'16

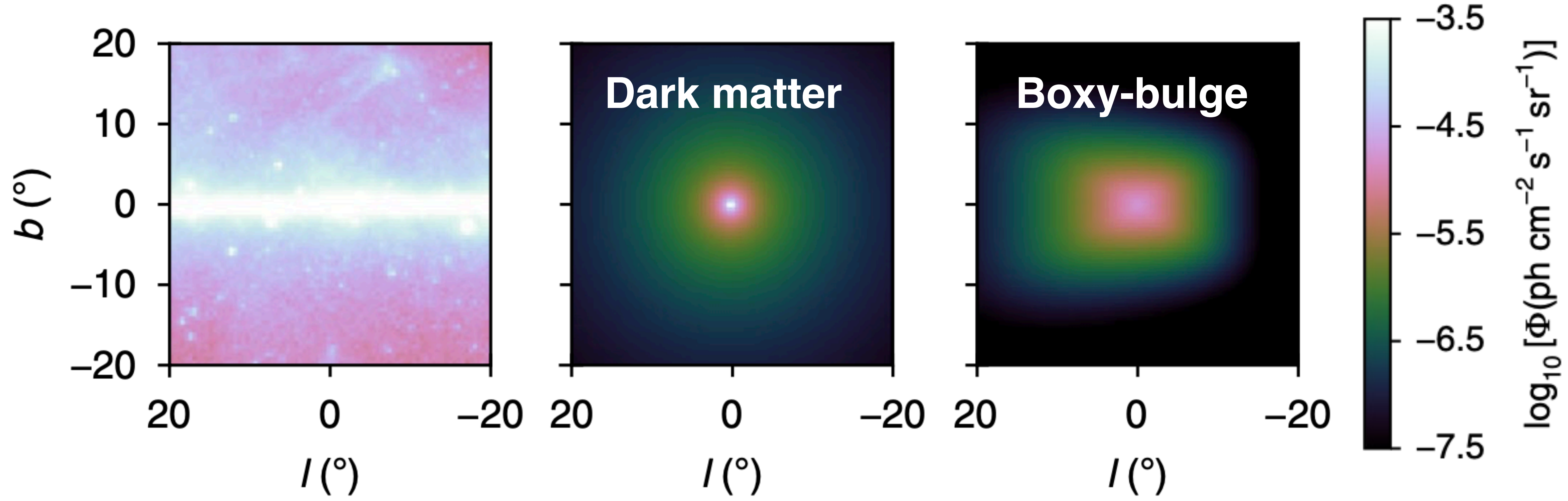
- **Red Clump stars** (near-IR) used to characterise the **three-dimensional density structure** of the BB
- Most recent non-parametrically deconvolved bulge model w/ VISTA Variables in the Via Lactea (VVV) data *Coleman+ MNRAS'20*
- X-shaped structure characteristic of boxy/peanut like morphology (extragalactic studies of barred galaxies and simulations)

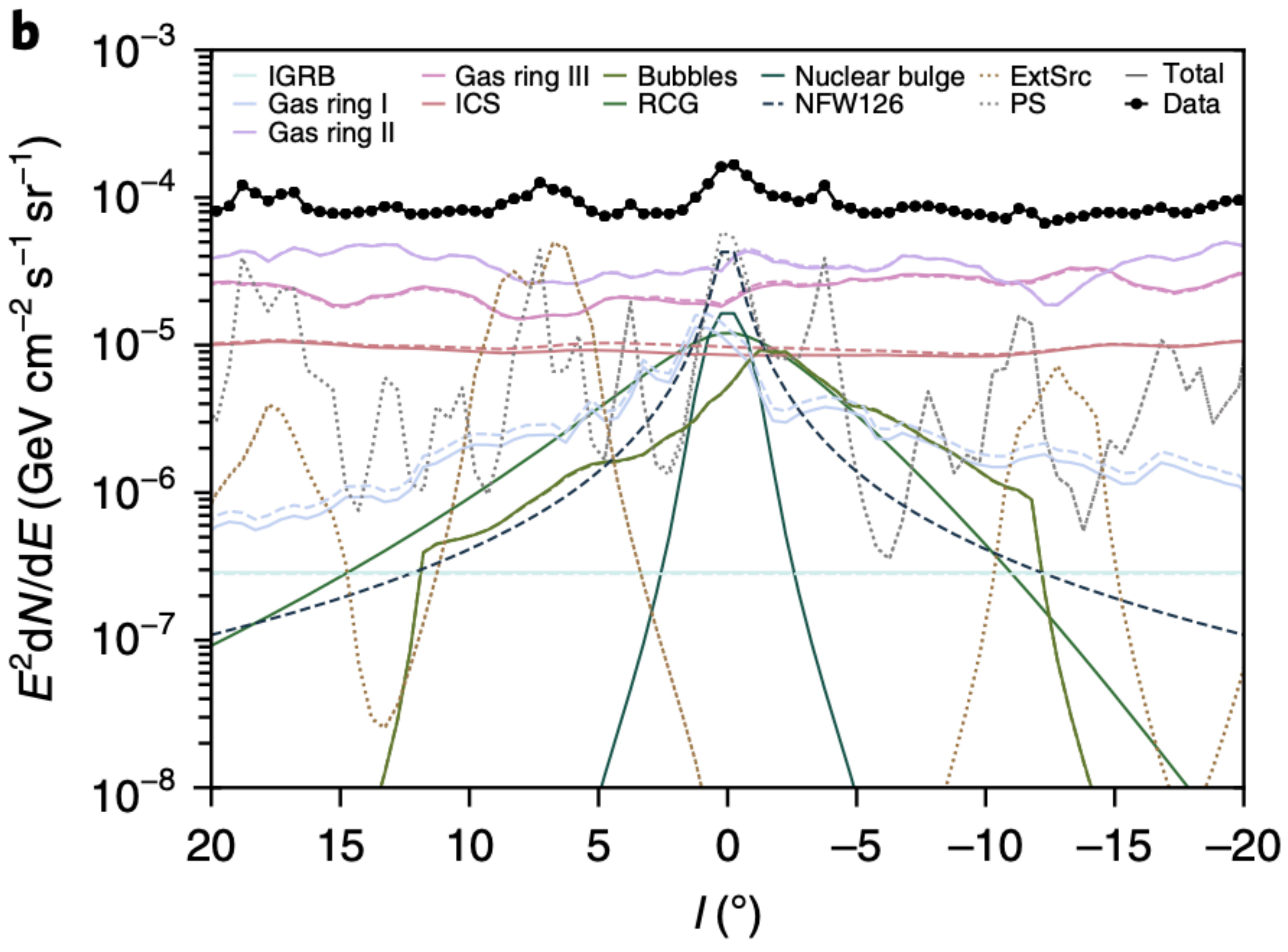
Evidence for the stellar bulge GeV emission

nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-018-0531-z

The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

Richard Bartels[1]*, Emma Storm[1], Christoph Weniger[1] and Francesca Calore[2]





- ✓ **Stellar bulge model**: **Boxy bulge** as traced by red-clump giants + **nuclear bulge**

  Cao+MNRAS'13; Launhardt+ A&A'02

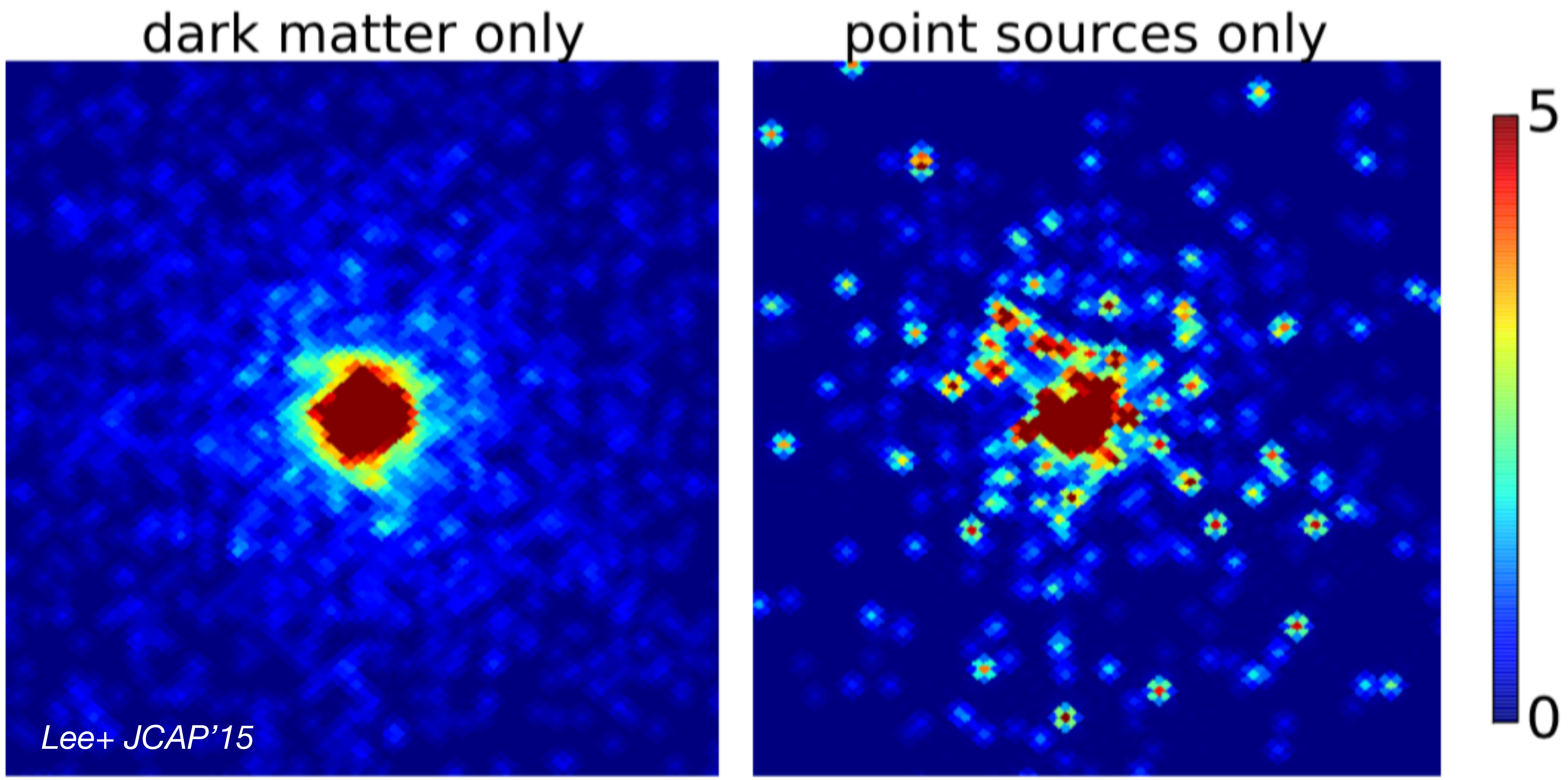
- ✓ Strong evidence for additional **stellar bulge model** (16σ); no evidence for additional **DM model** (< 3σ)

- ✓ Discriminating feature: Asymmetry at ~10 deg longitude => **Morphology** of the GCE **more oblate** than what found before

Macias+ Nature Astronomy'18; Macias+ JCAP'19

Statistics of photon counts

How to discriminate diffuse vs point-like emission

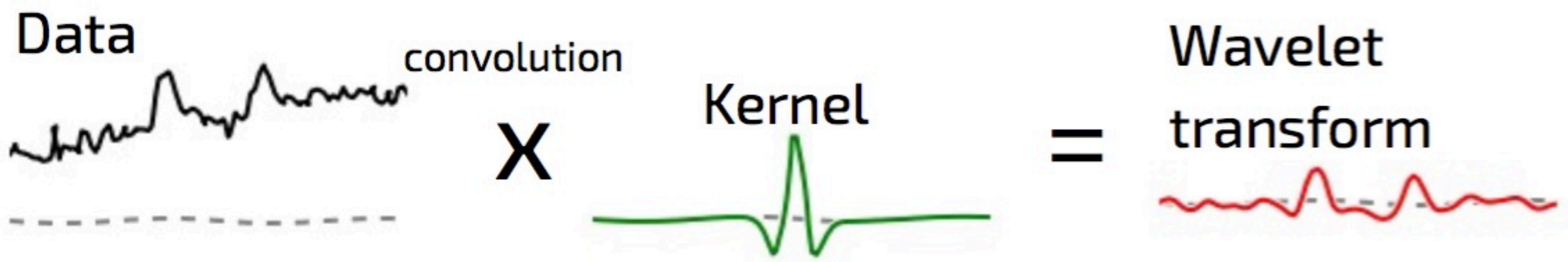


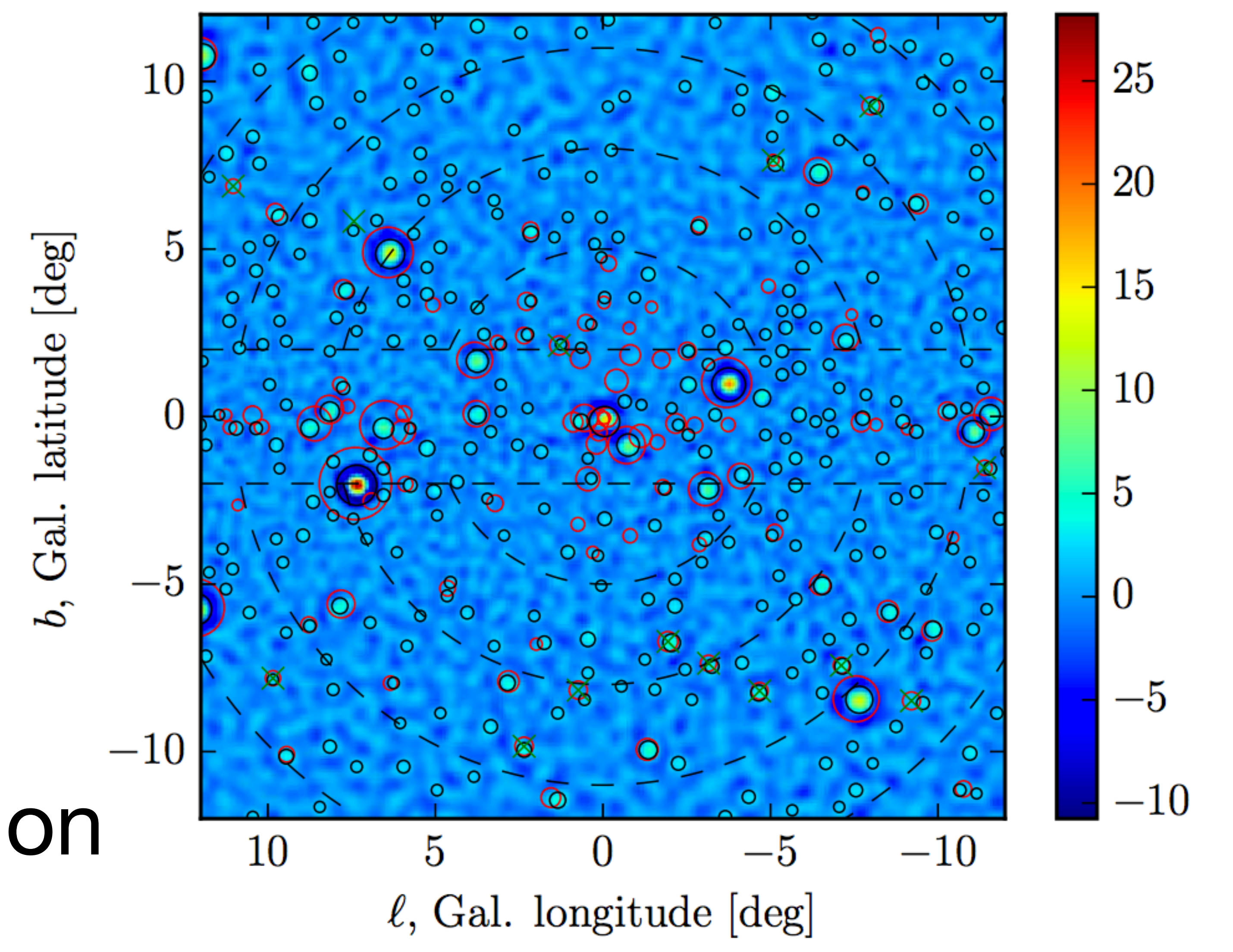
Differences in the **statistics of the photon counts** can be quantified and used for model comparison

Support for unresolved point sources (PS)

Local maxima of normalised wavelet transform

Bartels+ PRL'16

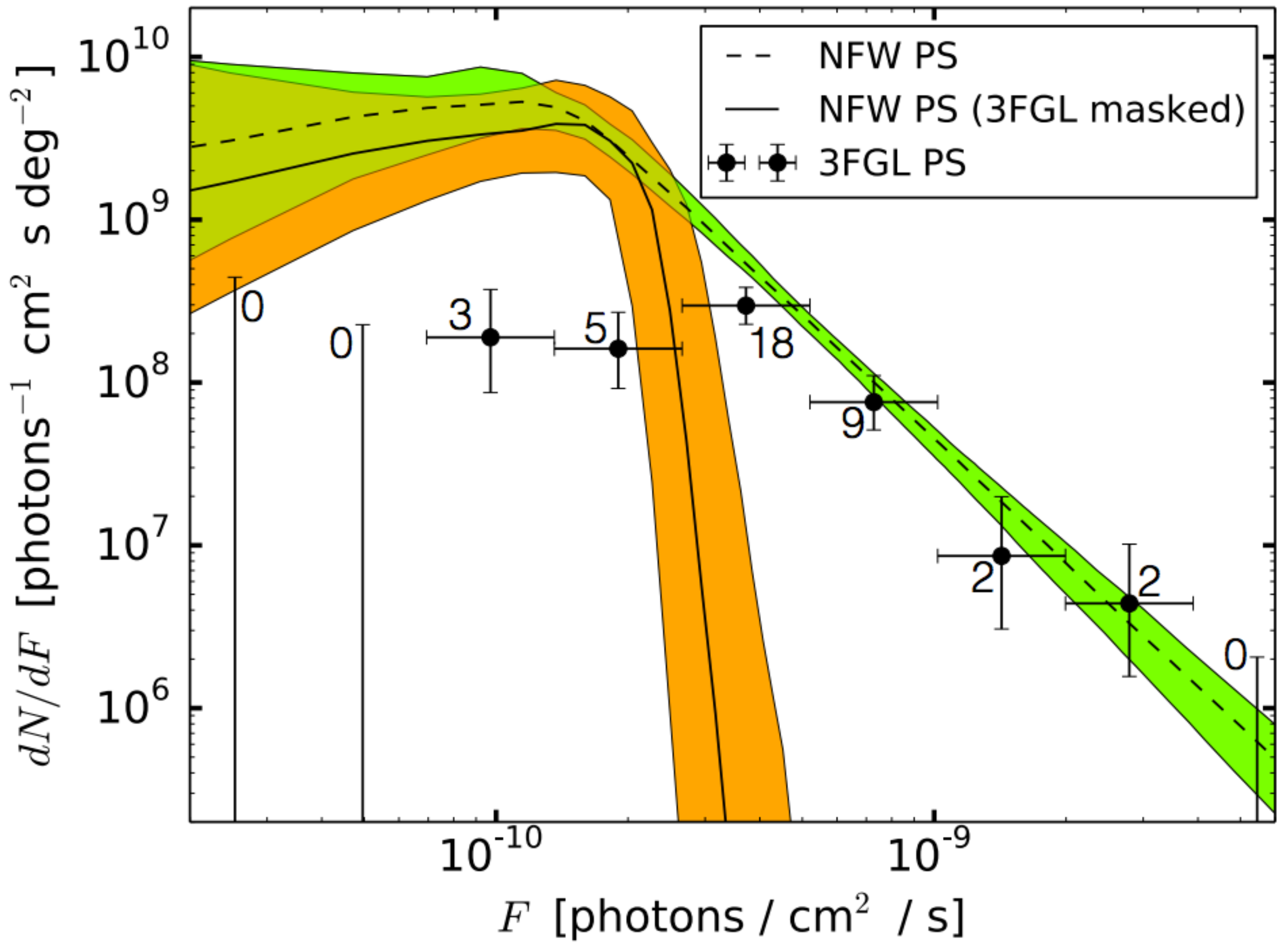


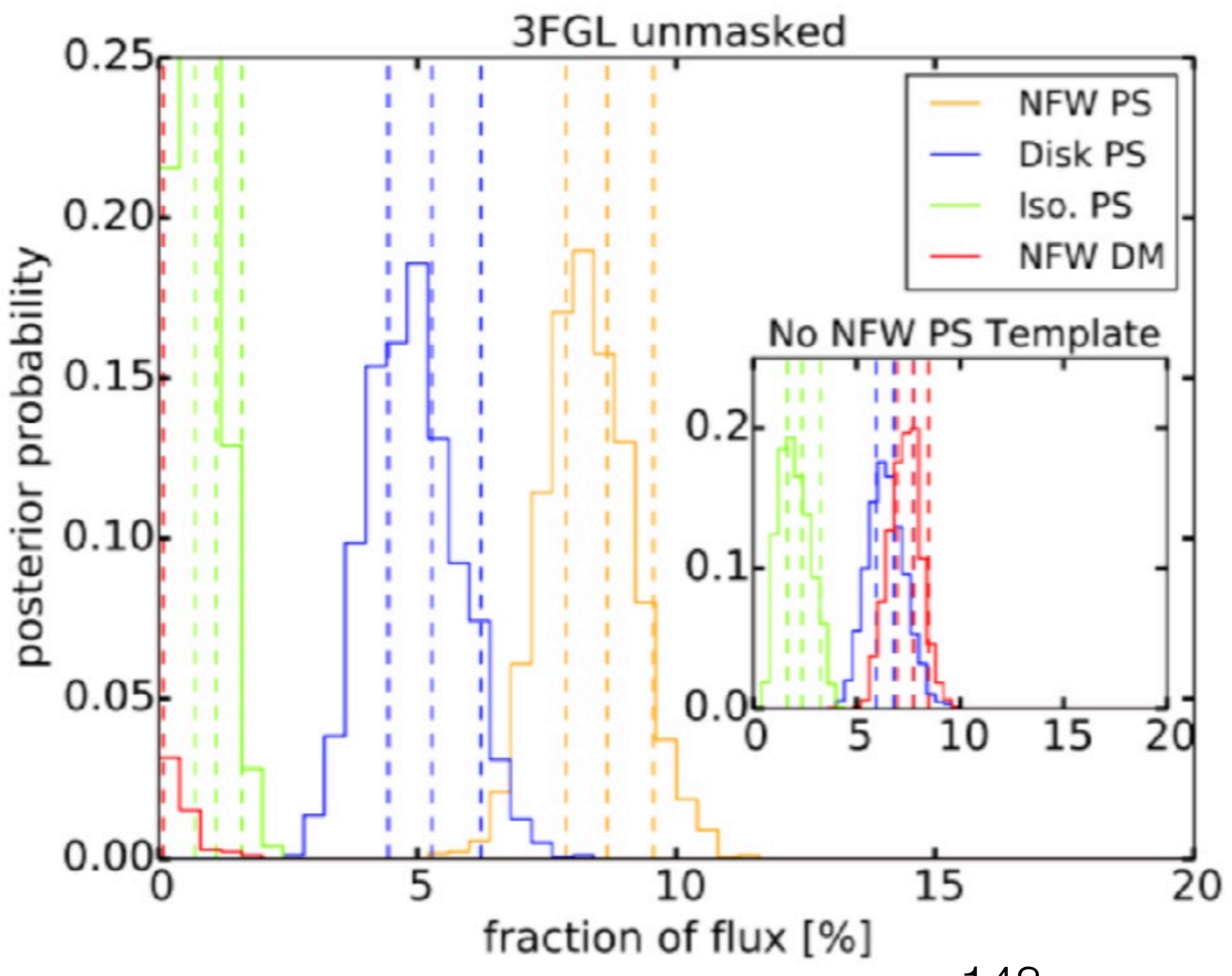


- Wavelet transform to look for **peaks** in data
- Enough peaks were found to explain the cumulative excess emission
- Evidence for unresolved PS population and constraints on luminosity function
- No modelling of diffuse emission required

Non-Poissonian template fitting

Lee+ PRL'16

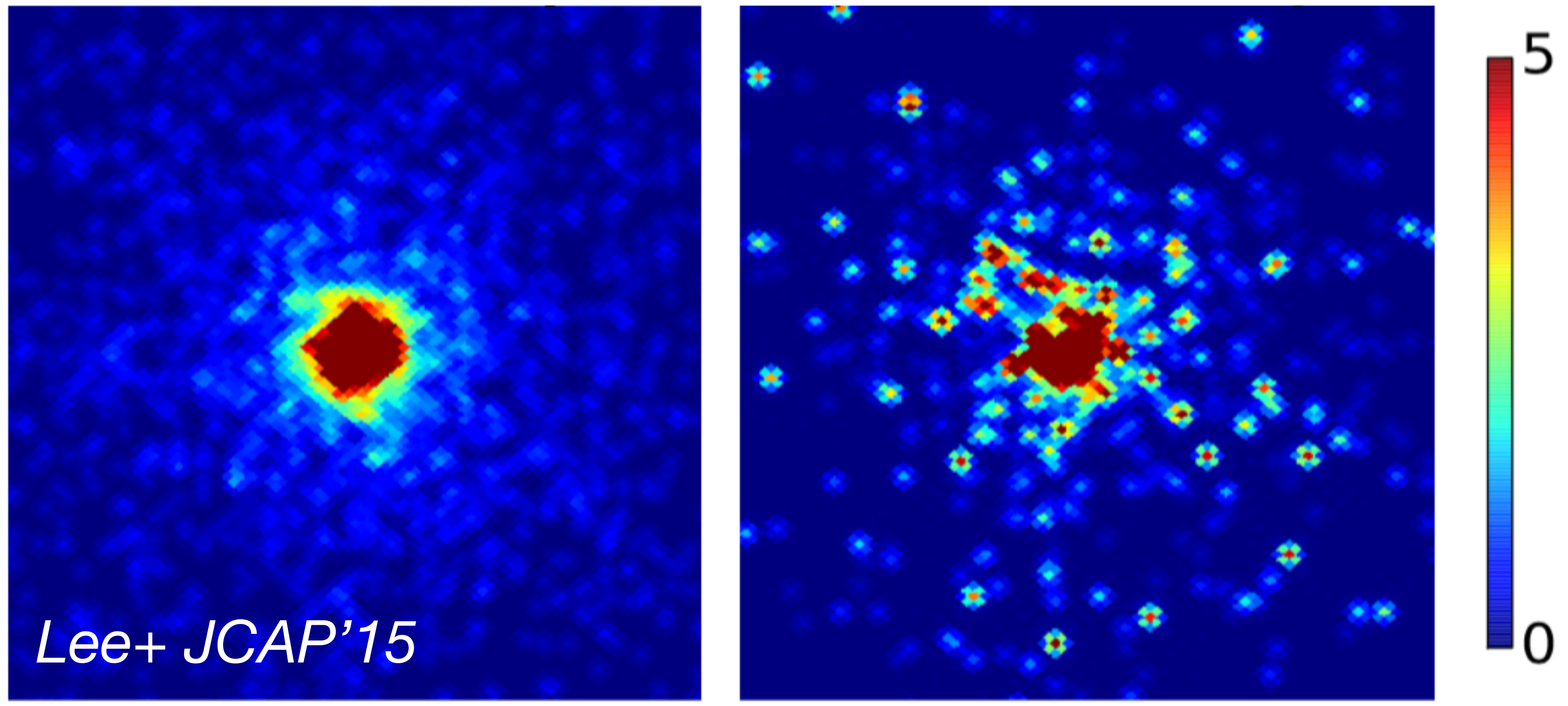




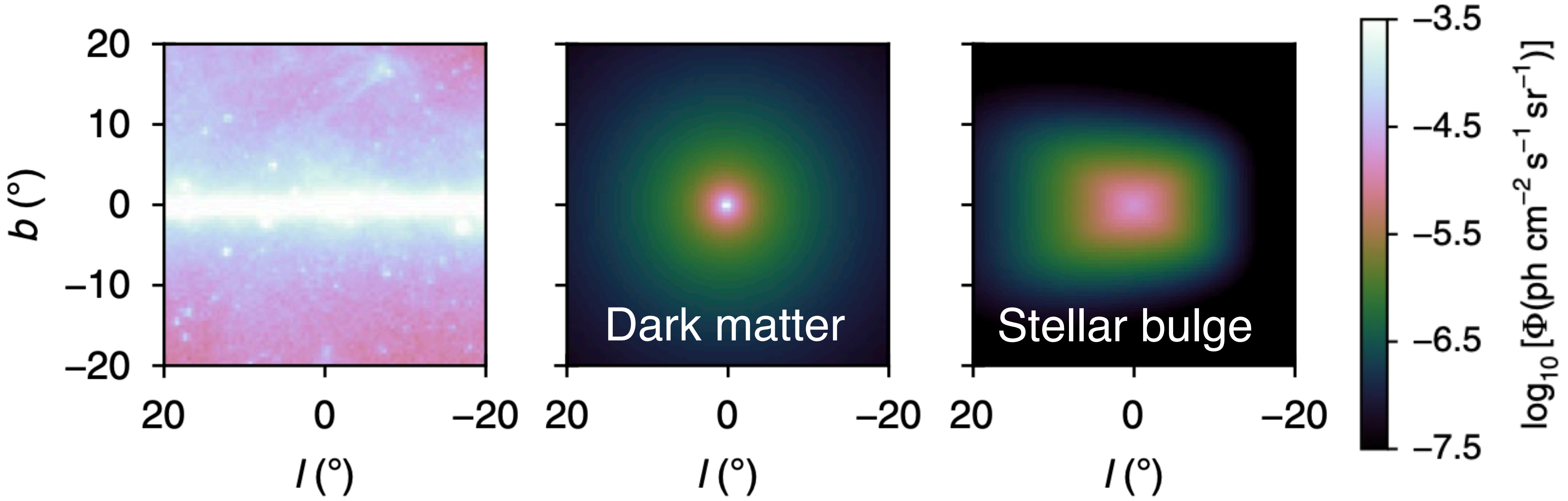
- Exploits difference in photon statistics: smooth signal (DM) vs larger variance across pixels (PS)
- PS fluctuations follow non-Poissonian statistics
- Sensitivity to spatial distribution and luminosity function of PS
- Required modelling of diffuse emission

The GeV excess nature

The gamma-ray perspective



Truly diffuse   Unresolved sources



- Difference in **statistics of photon counts** can be quantified and used for model comparison

Bartels+ PRL'16; Lee+PRL'16

- **Strong bias** from mis-modelling of foreground diffuse emission and controversial results

Zhong+PRL'19; Leane&Slatyer PRL'20, PRD'20; Chang+ PRD'20, Buschmann+PRD'20

- Nonetheless: **evidence for unresolved point sources** is there with different, independent, methods

Buschmann+PRD'20; FC+ PRL'21; List+ PRL'21

- **Stellar bulge morphology preferred over DM** also when modelling faint point sources

FC+ PRL' 21; Manconi, FC+ PRD'24

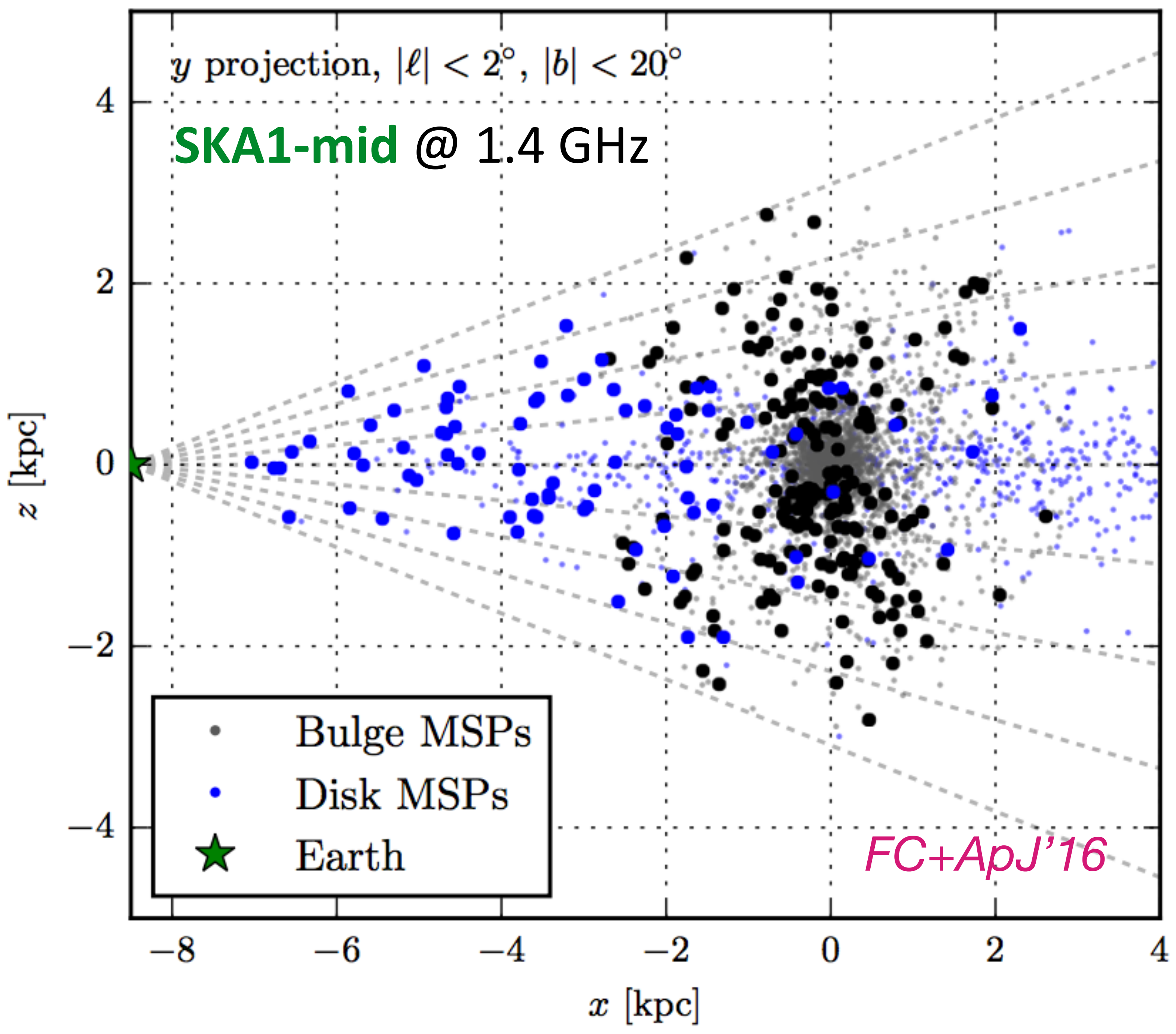
Macias+ Nature Astronomy'18; Macias+ JCAP'19

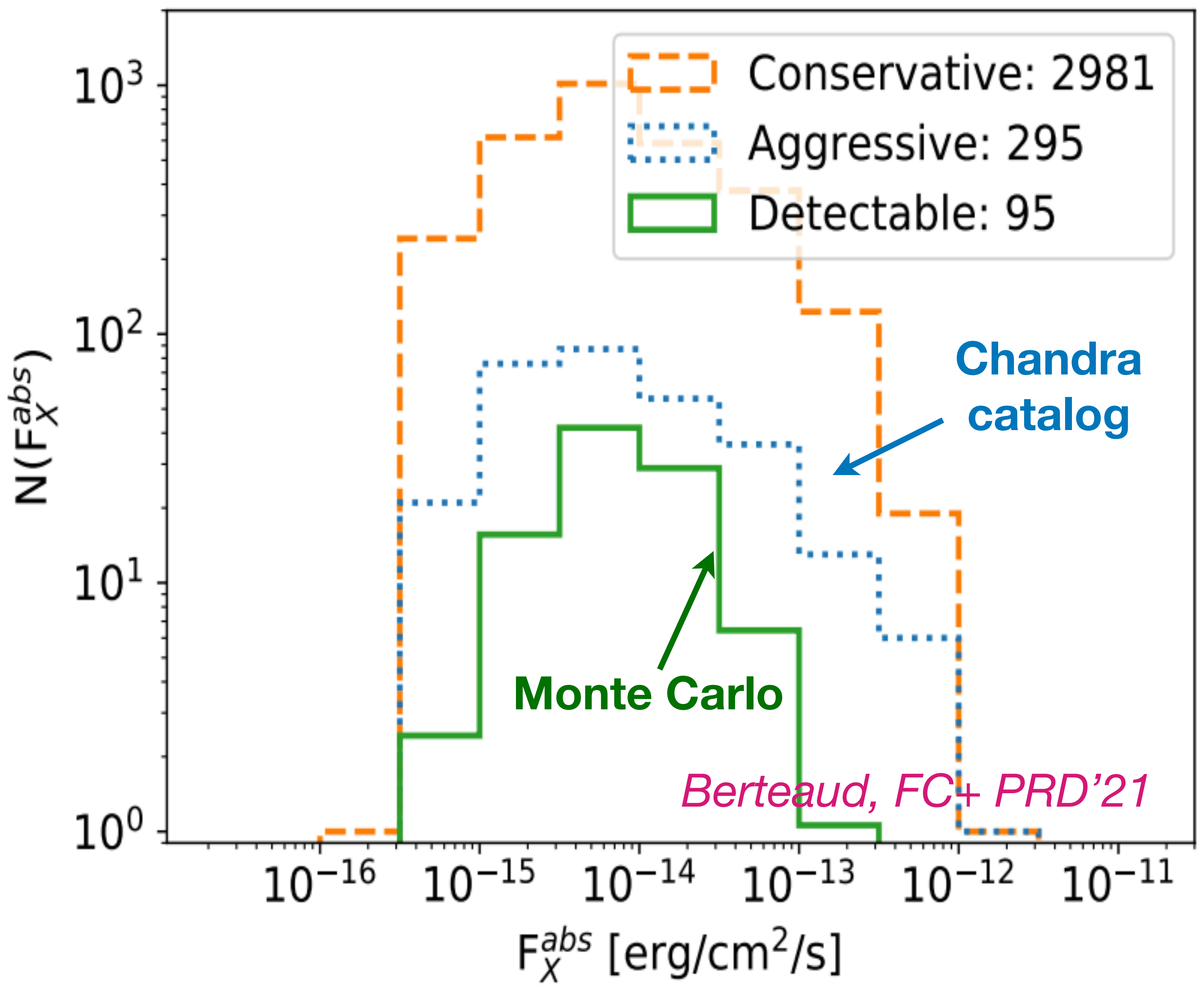
An (at least) partial **stellar origin of the GeV excess** seems to be confirmed

Multi-messenger tests of the GeV excess

Complementary techniques and **multi-wavelength searches** to test the excess nature:

- ✴ Radio, X-ray, and (future) gravitational waves searches *FC+ApJ'16; FC+PRL'19; Berteaud, FC+ PRD'21*

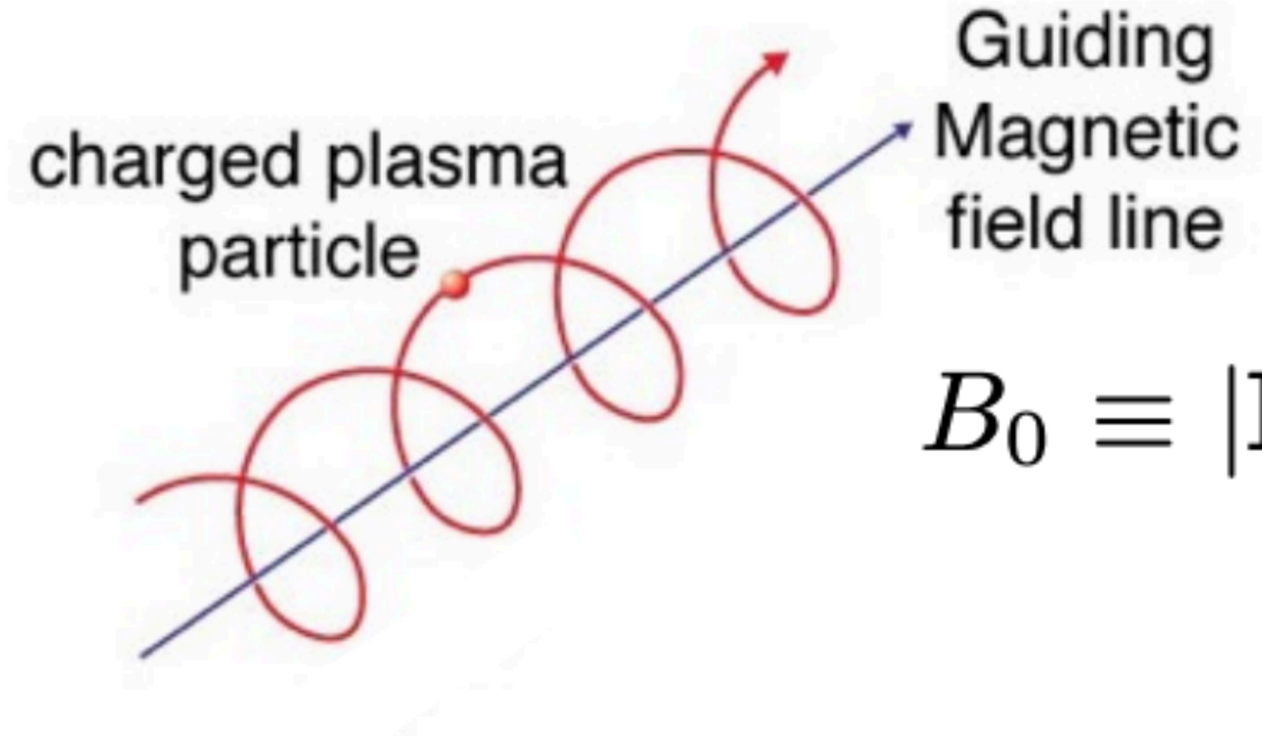




- ✴ Very high-energy photons with CTA *Macias+ MNRAS'21*
- ✴ DM constraints from gamma rays (dwarf galaxies) and cosmic-ray antiprotons *Di Mauro & Winkler PRD'21*

Cosmic-ray in regular B-field

$$\frac{\mathrm{d}\mathbf{p}}{dt} = q\mathbf{E} + q\frac{\mathbf{v}}{c} \times \mathbf{B}$$



$$B_0 \equiv |\mathbf{B}_0|$$

Solutions (no electric field):

$$p_z = \mathrm{const}$$
$$v_x = v_0 \cos(\Omega \mathrm{t})$$
$$v_y = v_0 \sin(\Omega \mathrm{t})$$

$$r_L = \gamma r_g = \sqrt{1-\mu^2}\frac{\mathcal{R}}{B_0} \simeq 10^{-6}\sqrt{1-\mu^2}\frac{\mathcal{R}}{\mathrm{GV}}\frac{\mu\mathrm{G}}{B_0}\mathrm{pc}$$

Larmor radius

$$\Omega = \frac{qB_0}{E} \simeq 10^{-2}\frac{B_0}{\mu\mathrm{G}}\frac{\mathrm{GeV}}{E}\,\mathrm{rad/s}$$

Larmor frequency

$$\mu = p_z/p \qquad \mathcal{R} = p/q\,[\mathrm{GV}]$$

Cosmic-ray in perturbed B-field

Small-scale stochastic perturbations

$|\delta \mathbf{B}| \ll |\mathbf{B}_0|$ and $\delta \mathbf{B} \perp \mathbf{B}_0$

$$\frac{\mathrm{d}\mathbf{p}}{dt} = q\frac{\mathbf{v}}{c} \times (\mathbf{B} + \delta\mathbf{B})$$

Changes x and y component of the momentum

Changes only the direction of p_z

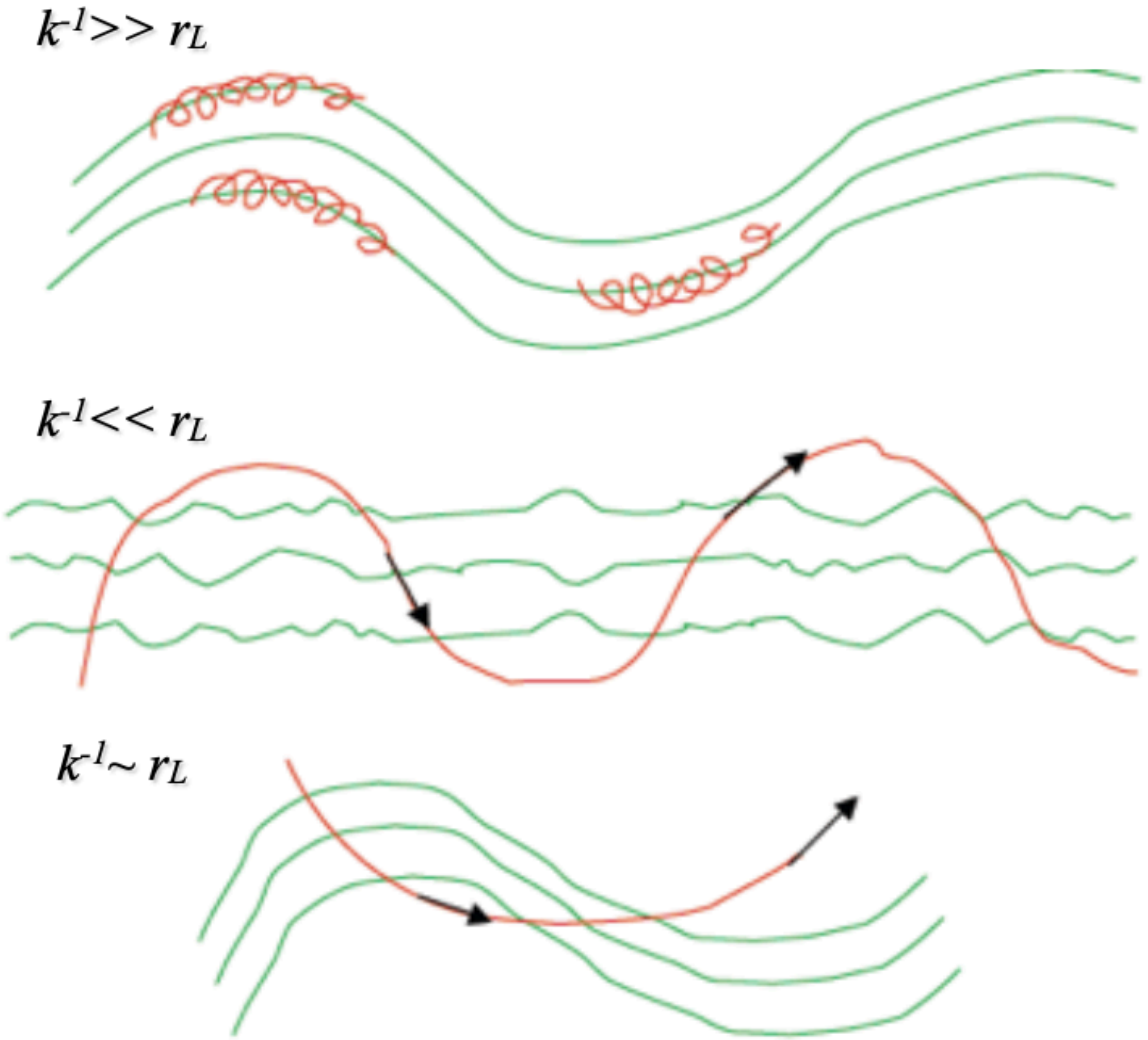
$\mu = p_z/p$

Diffusive process

Cosmic-ray in perturbed B-field

Small-scale (k) stochastic perturbations

$$|\delta \mathbf{B}| \ll |\mathbf{B}_0| \text{ and } \delta \mathbf{B} \perp \mathbf{B}_0$$



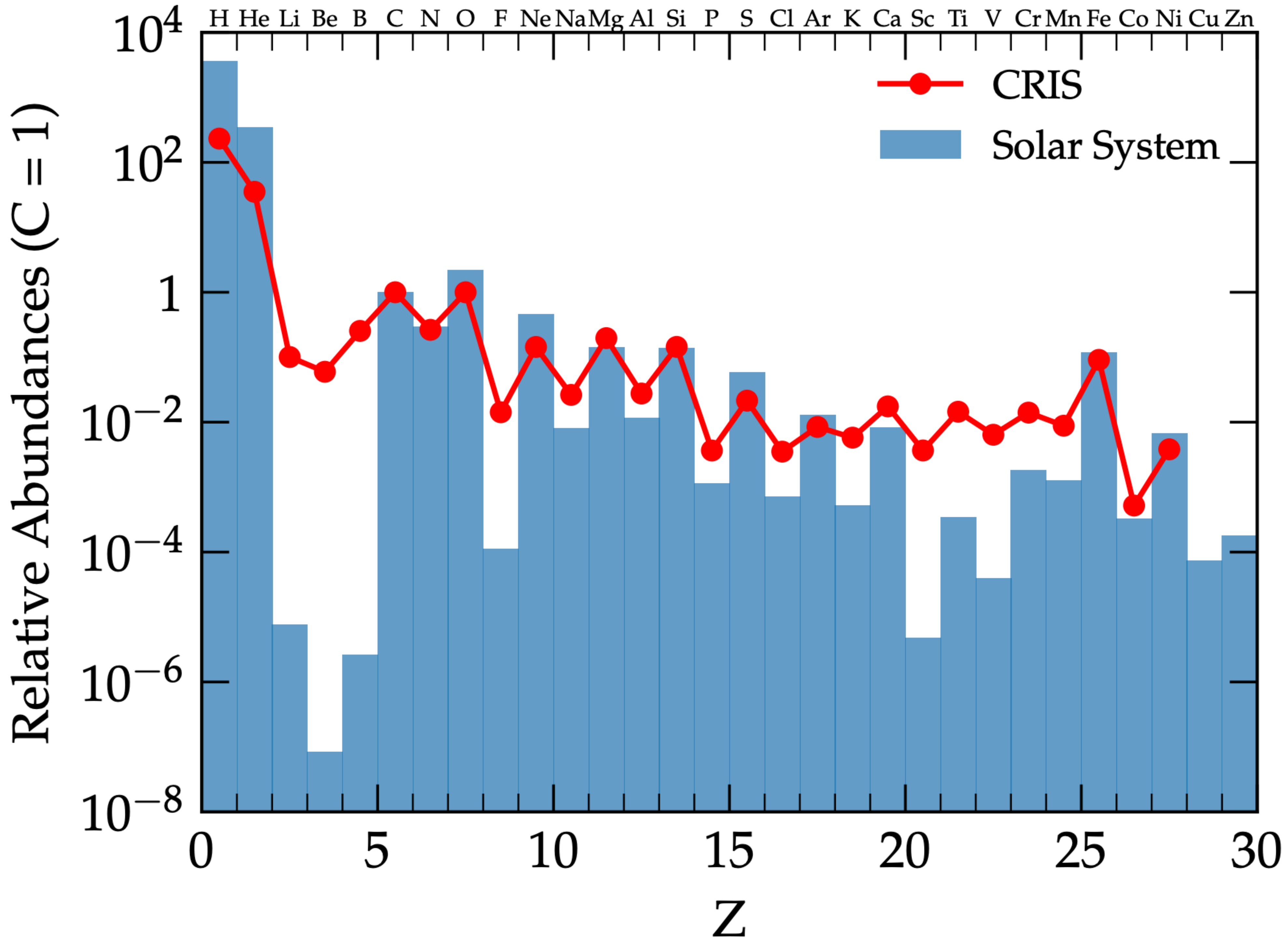
Credit: P.D.Serpico

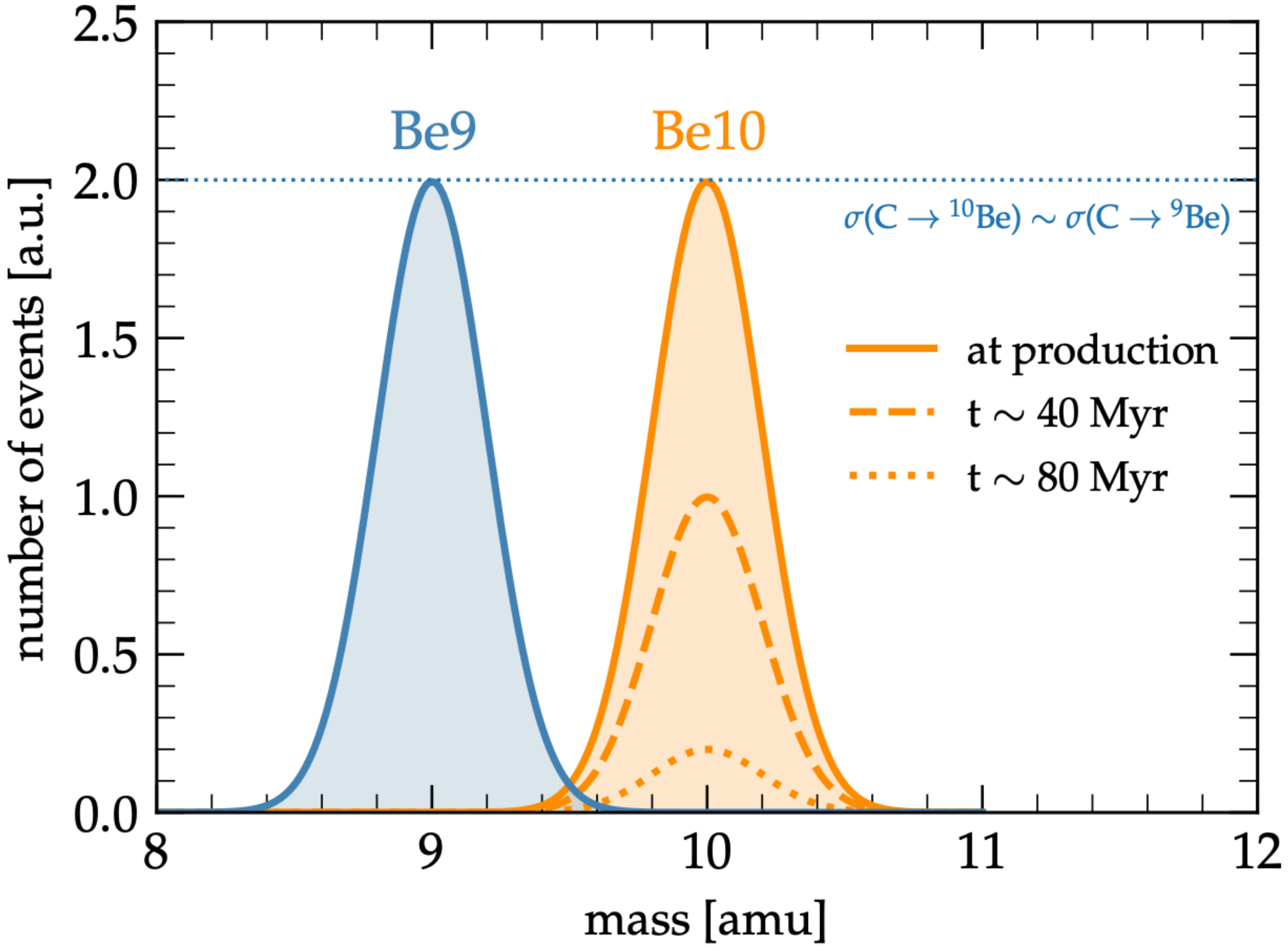
Collisionless Diffusion
[i.e. scattering on inhomogeneities of the magnetic field]

Diffusion coefficient K
Describes the random change of the pitch angle

Composition of Galactic CR

Basic indicators of diffuse transport





STABLE ELEMENTS

Besides primary species, produced in stellar nucleosynthesis, the average interstellar medium hosts a population of secondary particles produced by **primary fragmentation** during propagation (spallation)

UNSTABLE ELEMENTS

^{10}B is beta unstable with half-life time of 1.5 Myr
Production rate similar to other stable nuclei (^{9}Be)
The ratio ^{9}Be/^{10}Be can be used as a CR clock => residence time in the Galaxy of O(100) Myr => **DIFFUSIVE** propagation

Particle DM: v-dependent x-section

$$\langle \sigma v \rangle = a + bv^2 + \mathcal{O}(v^4),\ v/c \sim 10^{-3}$$

Non-relativistic regime:
if present, **s-wave** is dominant

- S-wave can be suppressed (e.g. helicity suppression) or models may allow for v-dependent cross sections (long-range interactions for TeV scale dark matter)
- The connection between Early Universe and today annihilation is altered in a non-trivial way

$$\langle \sigma v \rangle \equiv S(v/c) \times \langle \sigma v \rangle_0$$

$$S(v/c) = (v/c)^n$$

- n=-1: **Sommerfeld**-enhanced annihilation in the Coulomb limit
- n=0: **s-wave** velocity-independent annihilation
- n=2: **p-wave** annihilation. This scenario is relevant if DM is a Majorana fermion, which annihilates to Standard Model fermion/antifermion pairs

Particle DM: v-dependent x-section

Gamma-ray flux

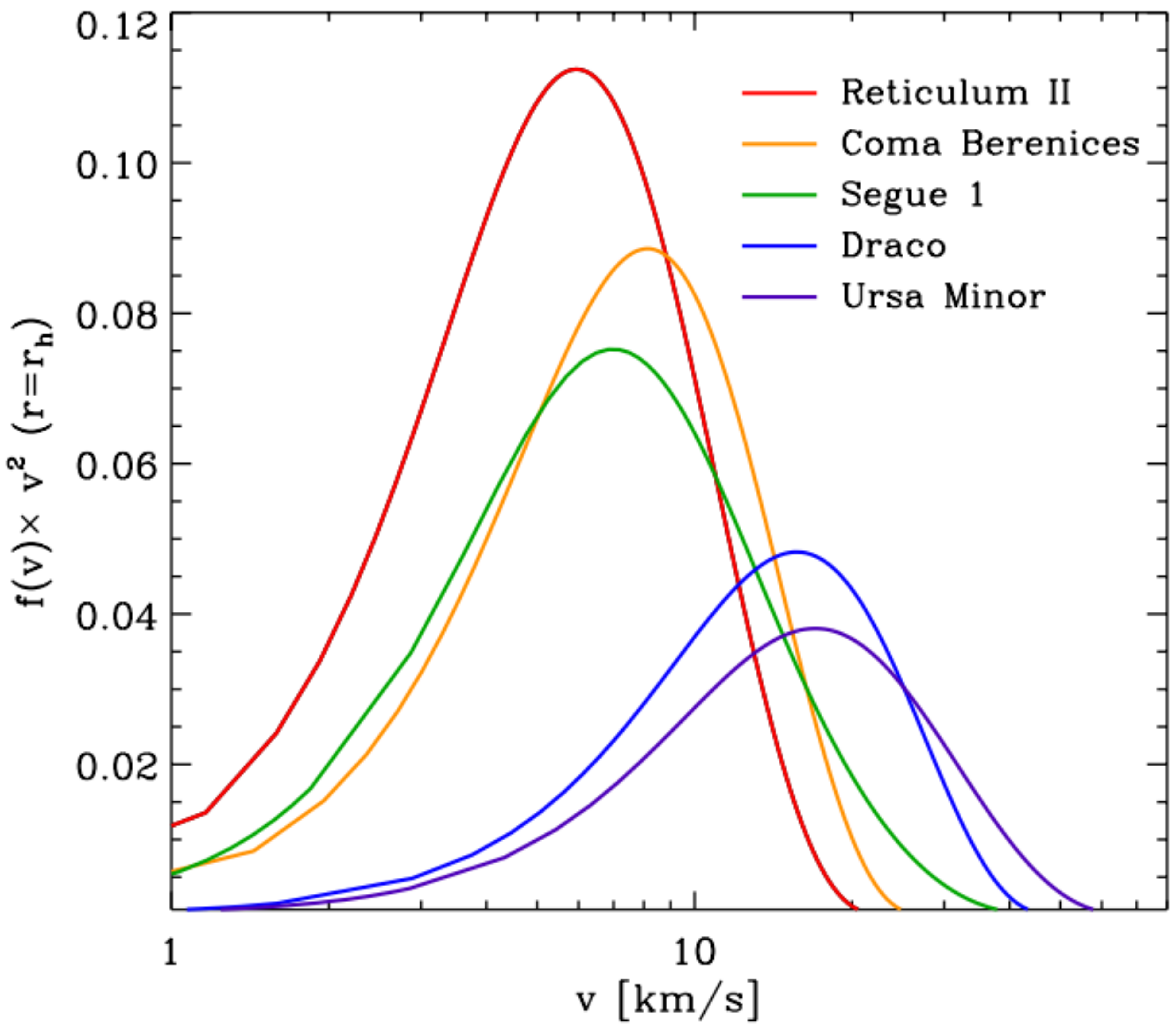
$$\langle \sigma v \rangle \equiv S(v/c) \times \langle \sigma v \rangle_0$$

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle \sigma v \rangle_0}{2 m_{\rm DM}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \times \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} ds \int d^3 v_1 f(r(s,\Omega), \mathbf{v}_1) \int d^3 v_2 f(r(s,\Omega), \mathbf{v}_2) S(|\mathbf{v}_1 - \mathbf{v}_2|/c)$$

DM phase-space distribution

$$\rho(r) \equiv \int f(r, \mathbf{v}) d^3 v$$

$$f(\mathbf{v}) \equiv \int f(r, \mathbf{v}) dr$$



Boddy et al., Phys. Rev. D 95, 123008 (2017) [1702.00408]

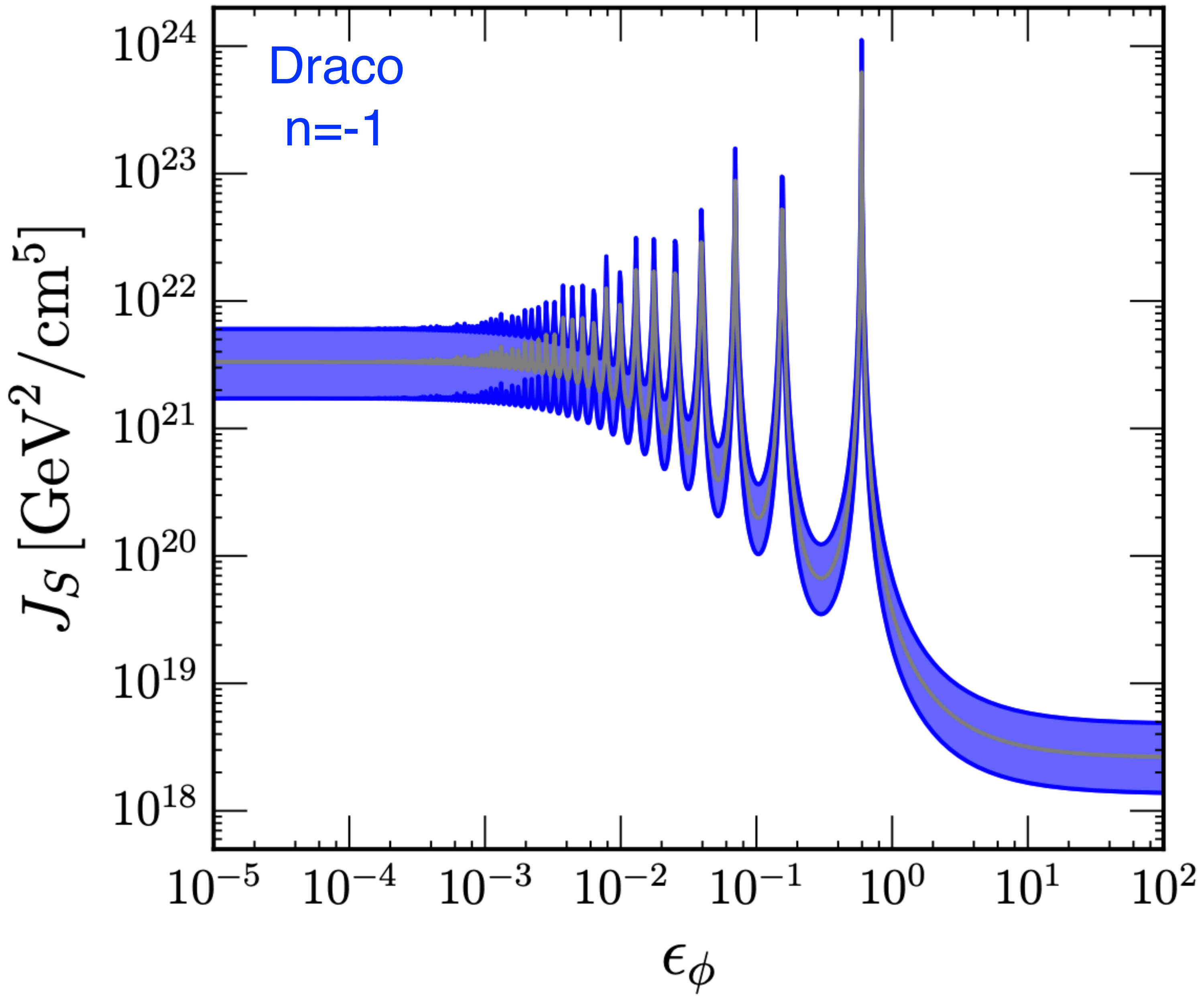
Particle DM: v-dependent x-section

Gamma-ray flux

$$\langle \sigma v \rangle \equiv S(v/c) \times \langle \sigma v \rangle_0$$

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle \sigma v \rangle_0}{2 m_{\rm DM}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \times \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} ds \int d^3 v_1 f(r(s,\Omega), \mathbf{v}_1) \int d^3 v_2 f(r(s,\Omega), \mathbf{v}_2) S(|\mathbf{v}_1 - \mathbf{v}_2|/c)$$

$$J_S(\Delta\Omega) \overset{\text{S=1}}{\rightarrow} J(\Delta\Omega) \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho(r(s,\Omega)) \times \rho(r(s,\Omega))\, ds$$

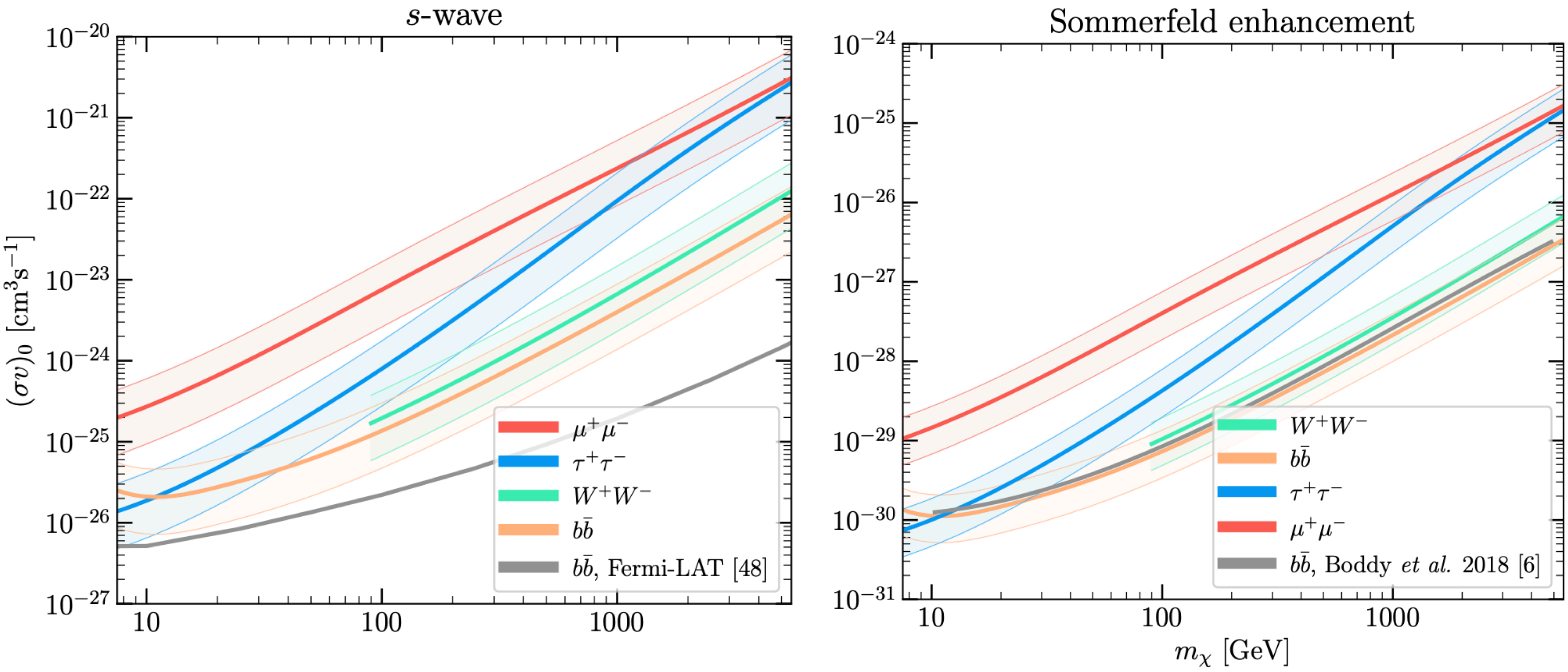


v-dependence of xsec can be translated in v-dependence of J-factors, allowing an easier **recasting** of limits under s-wave assumptions

Boddy et al., Phys. Rev. D 95, 123008 (2017) [1702.00408]
Boddy et al., Phys. Rev. D 102, 023029 (2020) [1909.13197]

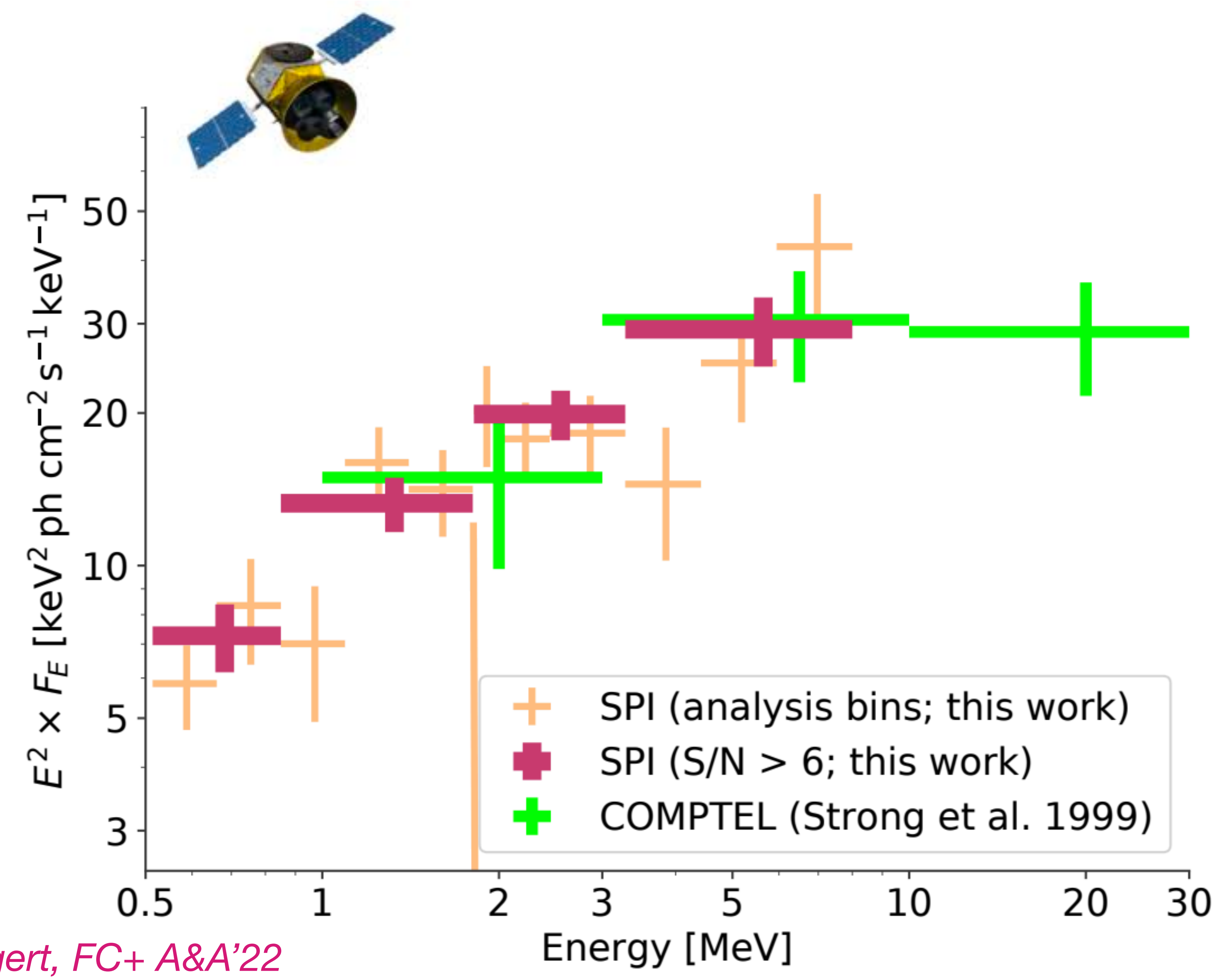
Particle DM: v-dependent x-section

Impact on DM limits



Boddy et al., Phys. Rev. D 102, 023029 (2020) [1909.13197]

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**

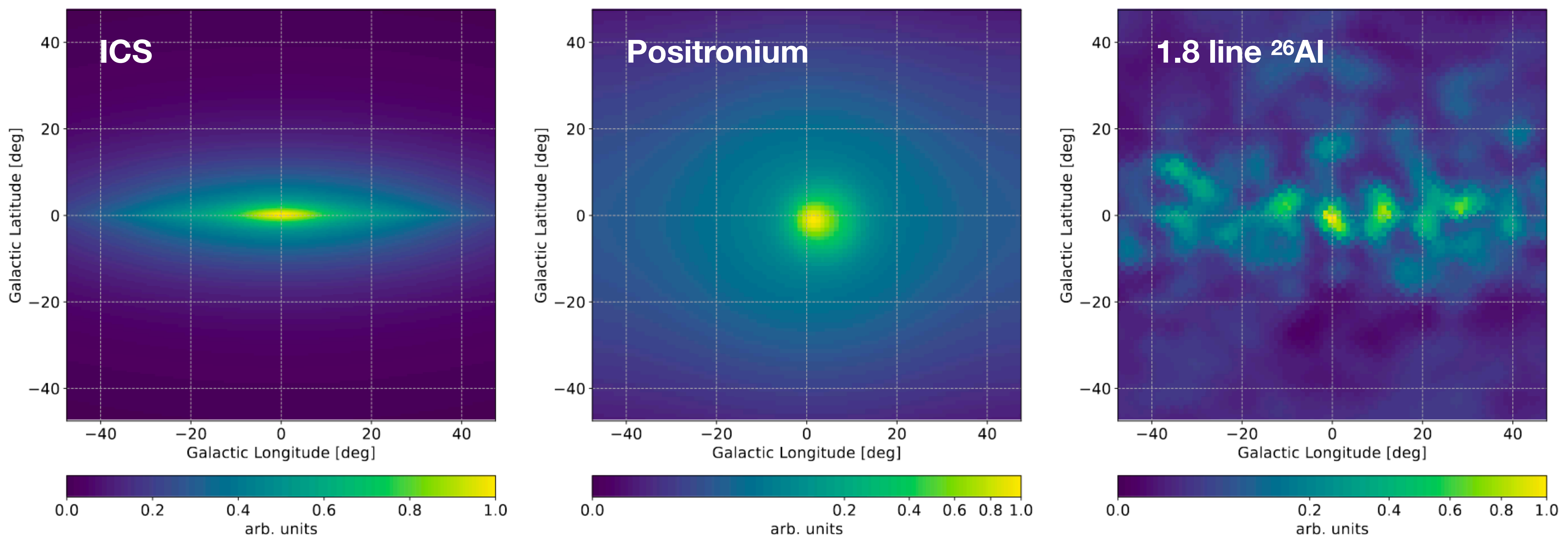
Berteaud, FC+ PRD'22 ; FC+ MNRAS'23

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 $e^{\pm}_{CR} + \gamma \longrightarrow e^{\pm} + \gamma_{MeV}$
- Unresolved sources (<100 keV)
- Nuclear lines
- Positronium annihilation line+continuum



Berteaud, FC+ PRD'22

Extraction of the Galactic diffuse emission

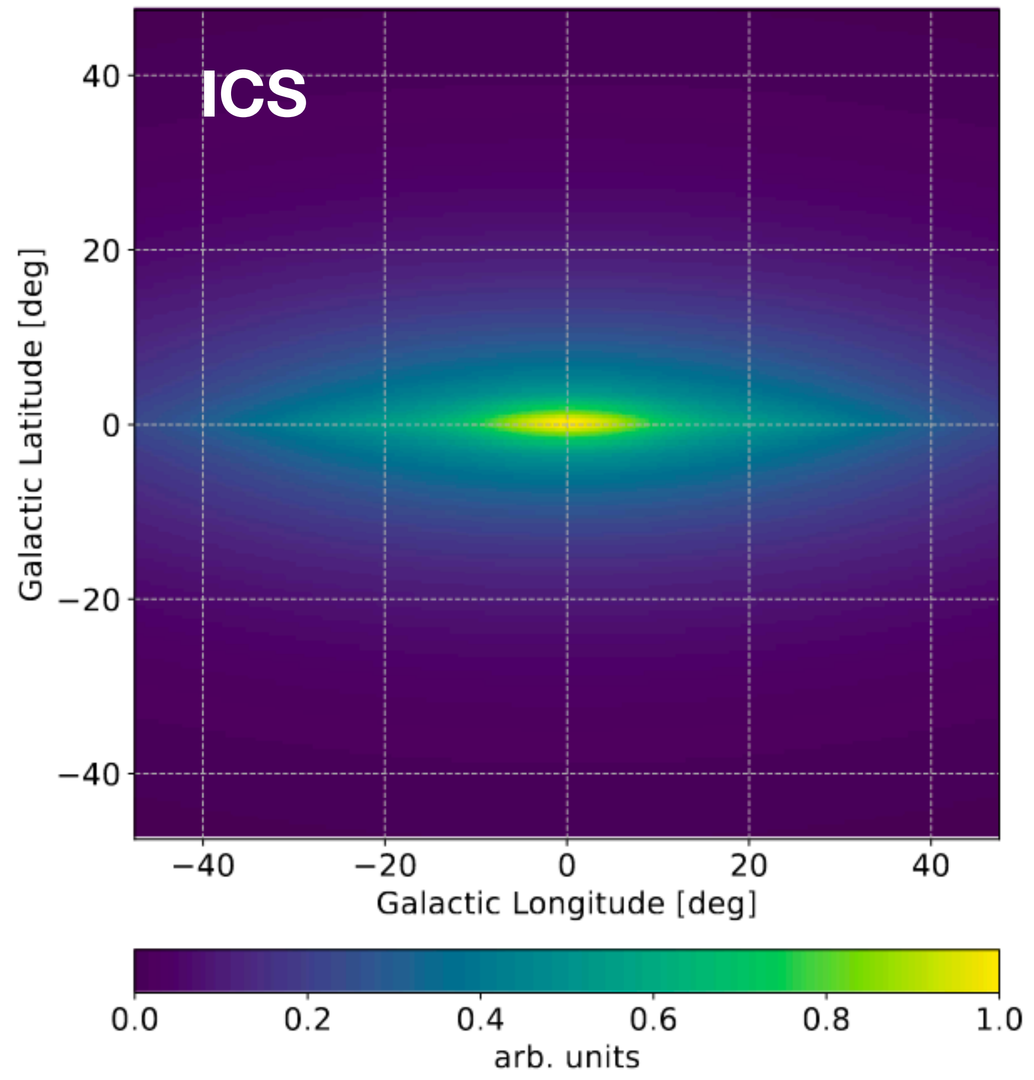
ALPs decay signal?

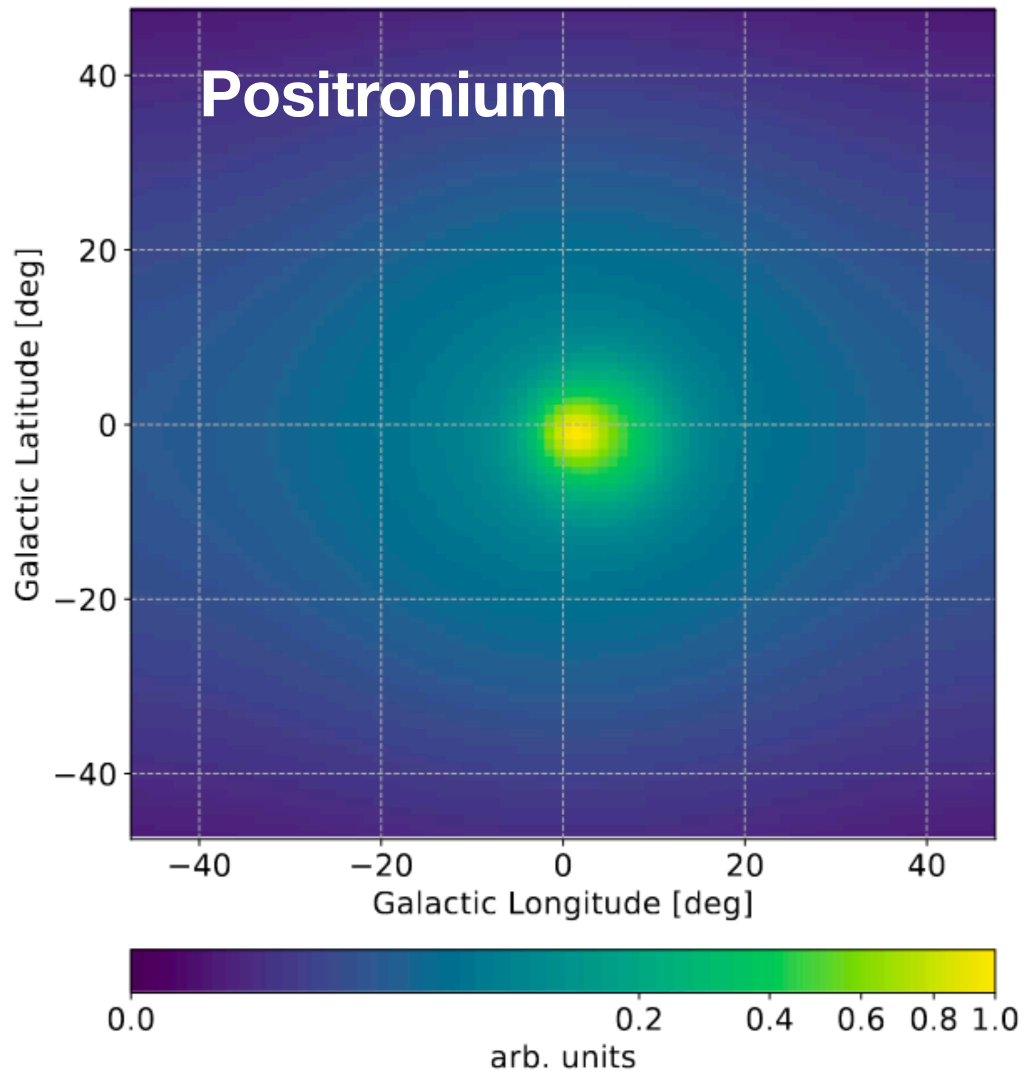
Modelled **spatial templates** (30 keV — 8 MeV)

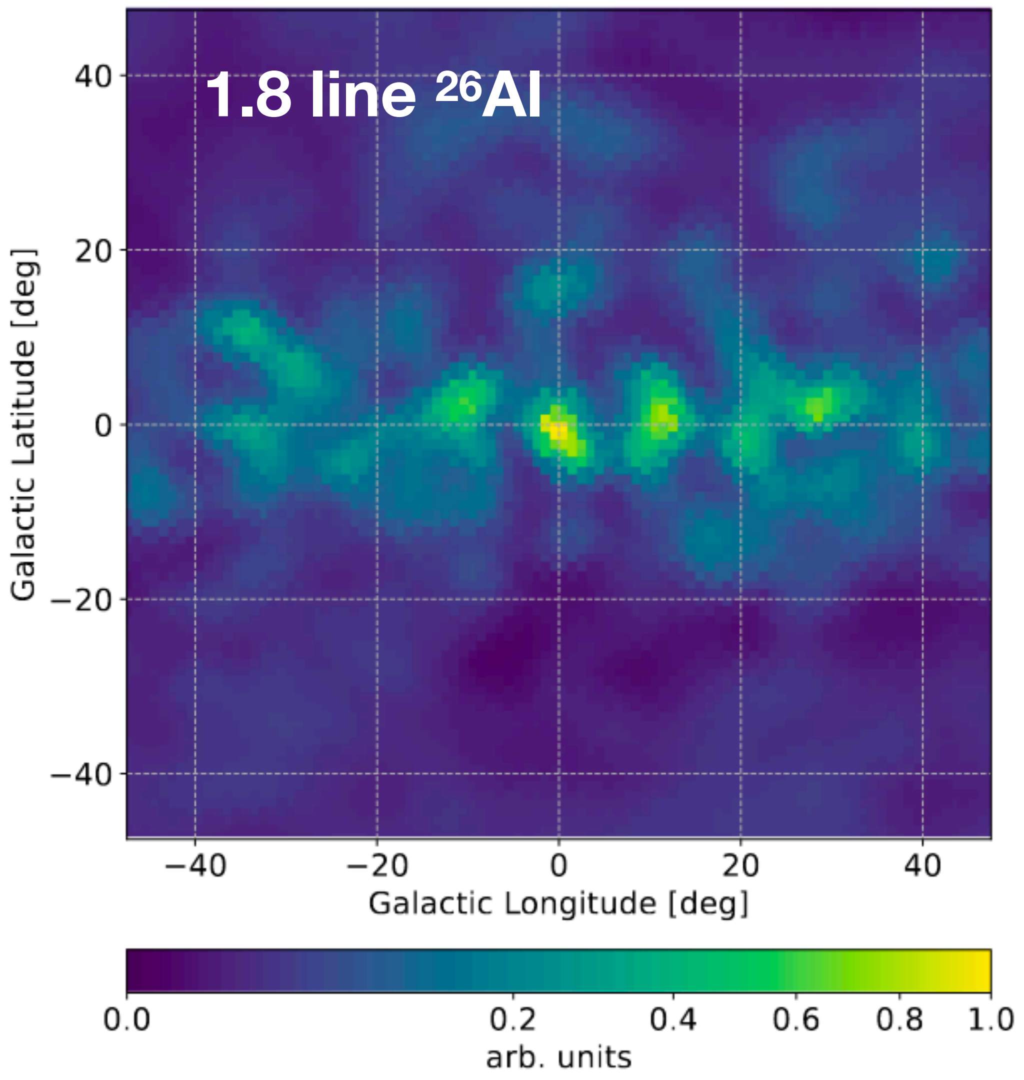
- **Inverse Compton scattering** of electrons off the interstellar radiation field $e^{\pm}_{CR} + \gamma \longrightarrow e^{\pm} + \gamma_{MeV}$
- Unresolved sources (<100 keV)
- Nuclear lines
- Positronium annihilation line+continuum

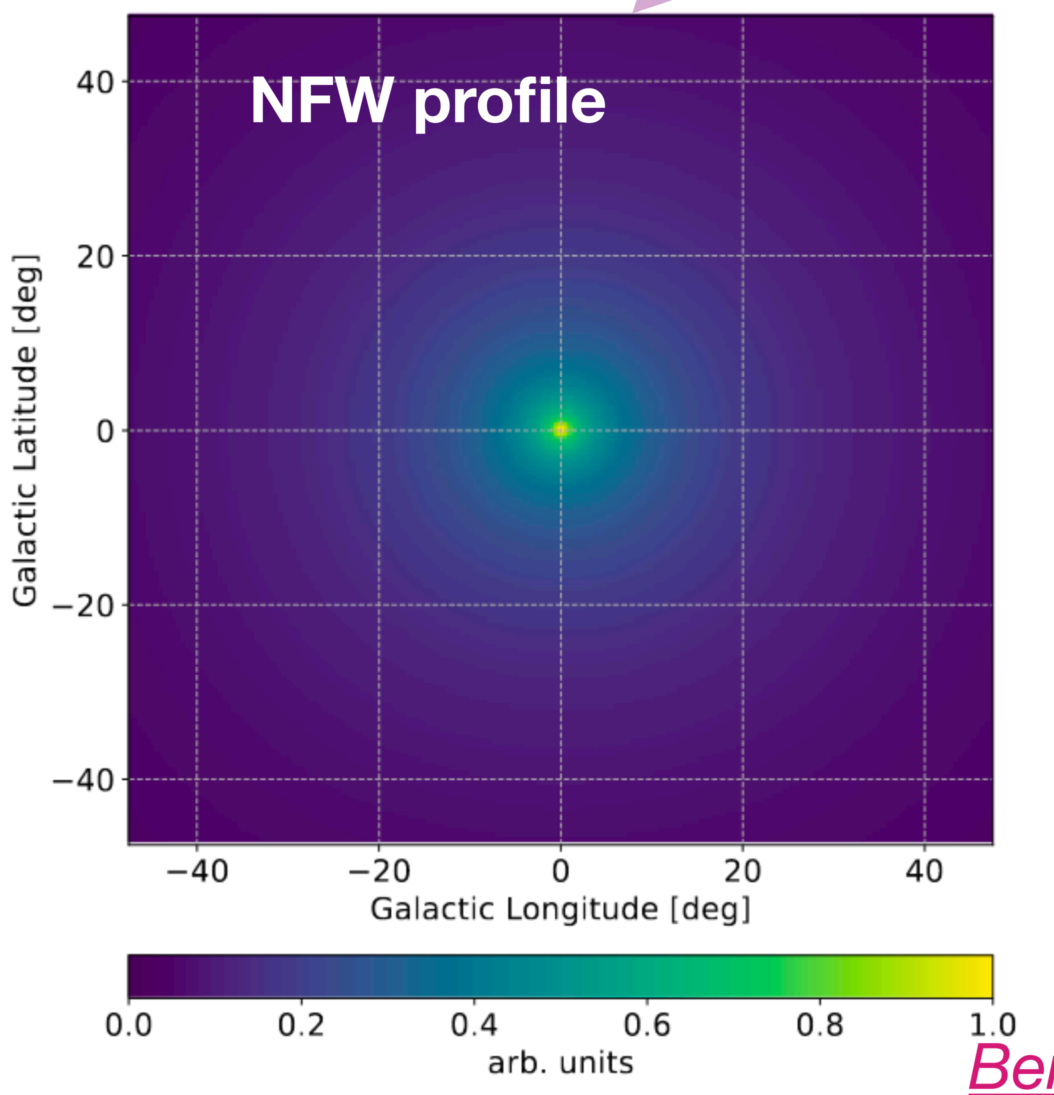
- Additional **ALPs decay signal**?

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









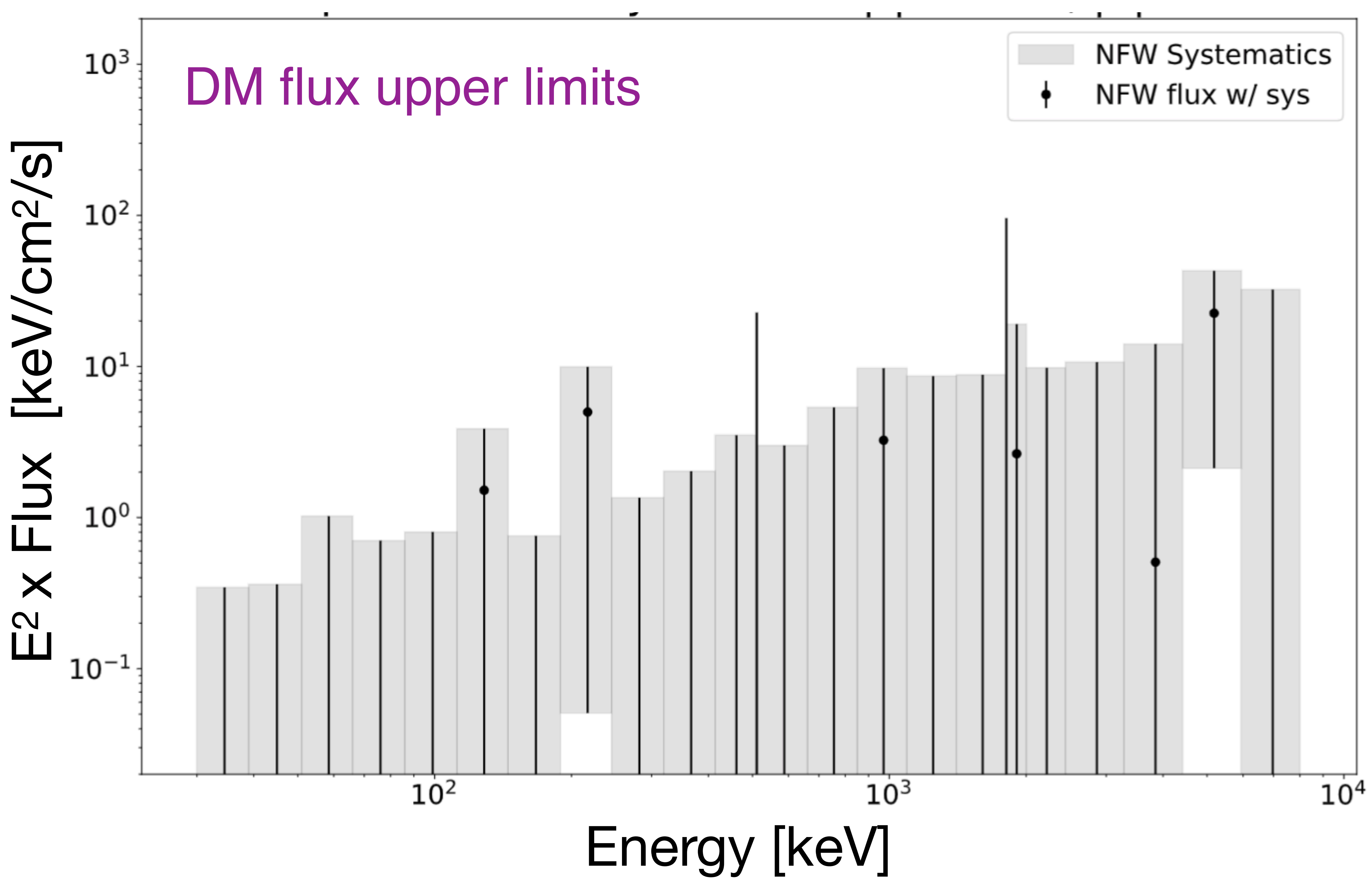
Berteaud, FC+ PRD'22

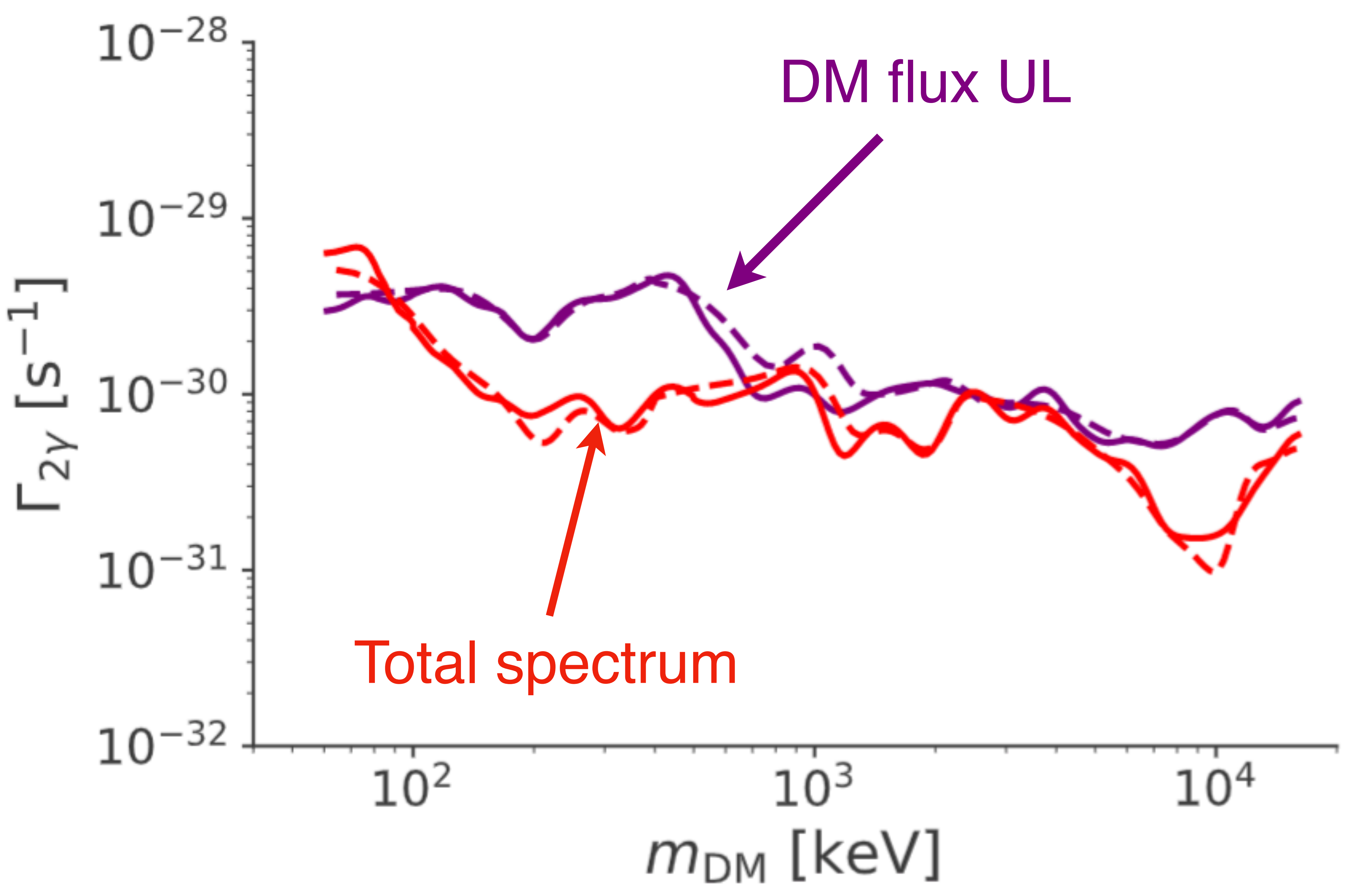
Constraints on decaying dark matter

Decay into two photons (line-like spectrum)

FC+ MNRAS'23

No signal detected → Upper limits on **decay rate** into 2 photons, $\Gamma_{2\gamma}$



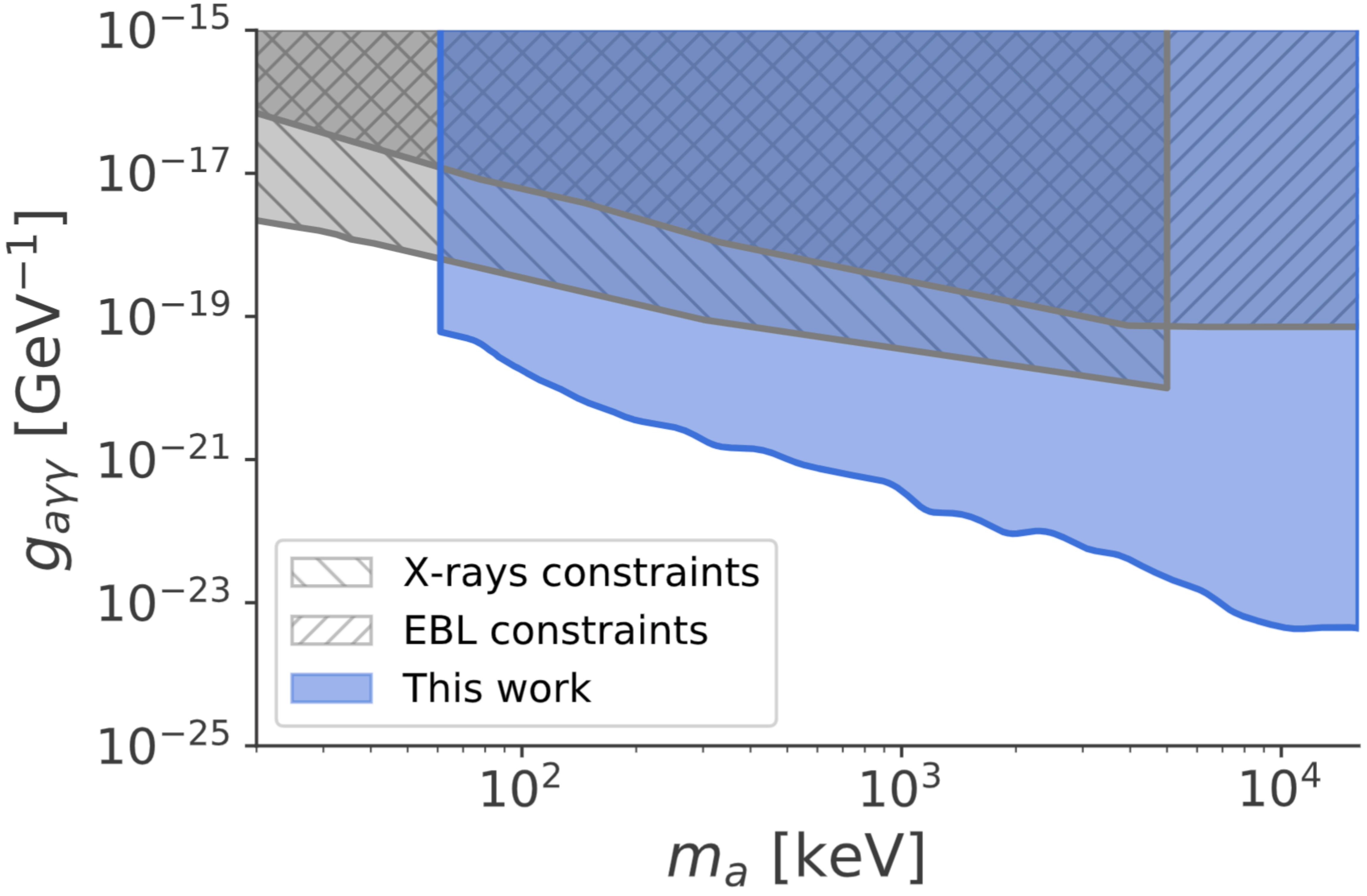


$$\left(\frac{d\Phi_\gamma}{dE}\right)_{\rm decay} = \frac{\Gamma(a\to\gamma\gamma)}{4\pi m_a}\left(\frac{dN_\gamma}{dE}\right)_{\rm decay} \times \int_{\rm l.o.s.} \rho_a(\ell)d\ell \qquad \frac{dN_\gamma}{dE} = 2\delta\left(E - \frac{Nm_{\rm DM}}{2}\right)$$

https://zenodo.org/record/7984451

Constraints on ALPs dark matter

FC+ MNRAS'23



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

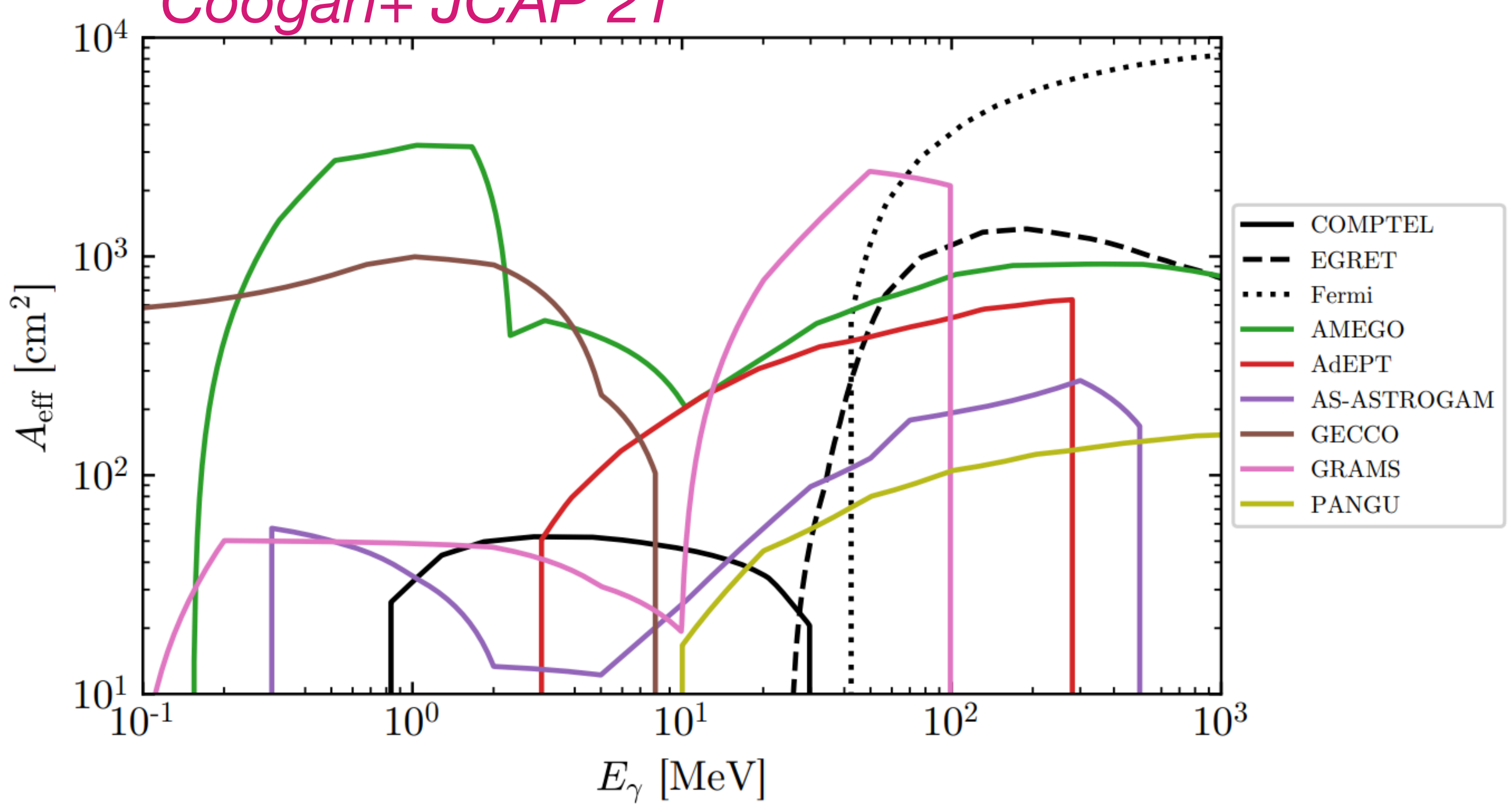
$$\Gamma_{2\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 0.755 \times 10^{-30} \left(\frac{g_{a\gamma\gamma}}{10^{-20}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{100\,\mathrm{keV}}\right)^3 \mathrm{s}^{-1}$$

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

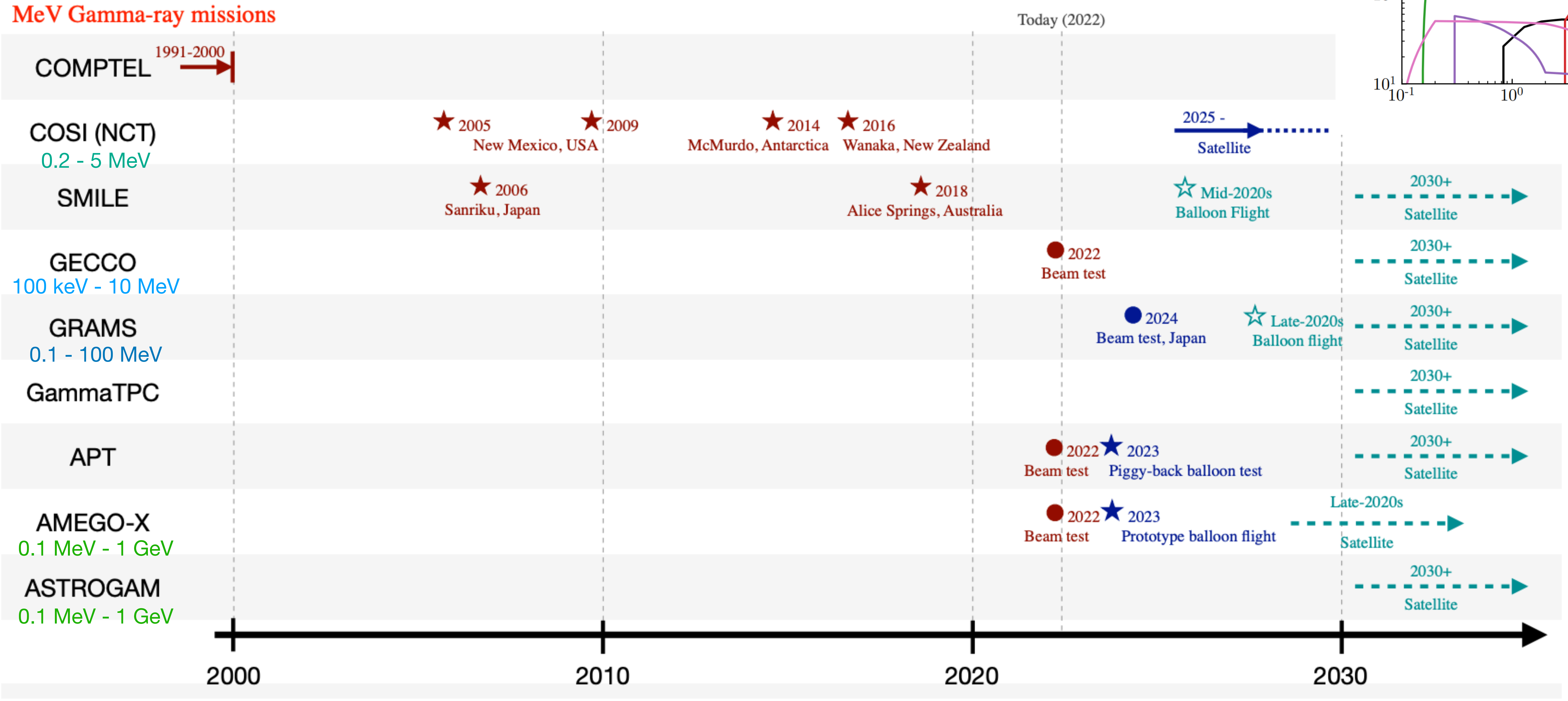
Future: MeV Galactic diffuse emission

Covering the MeV sensitivity gap

Coogan+ JCAP'21

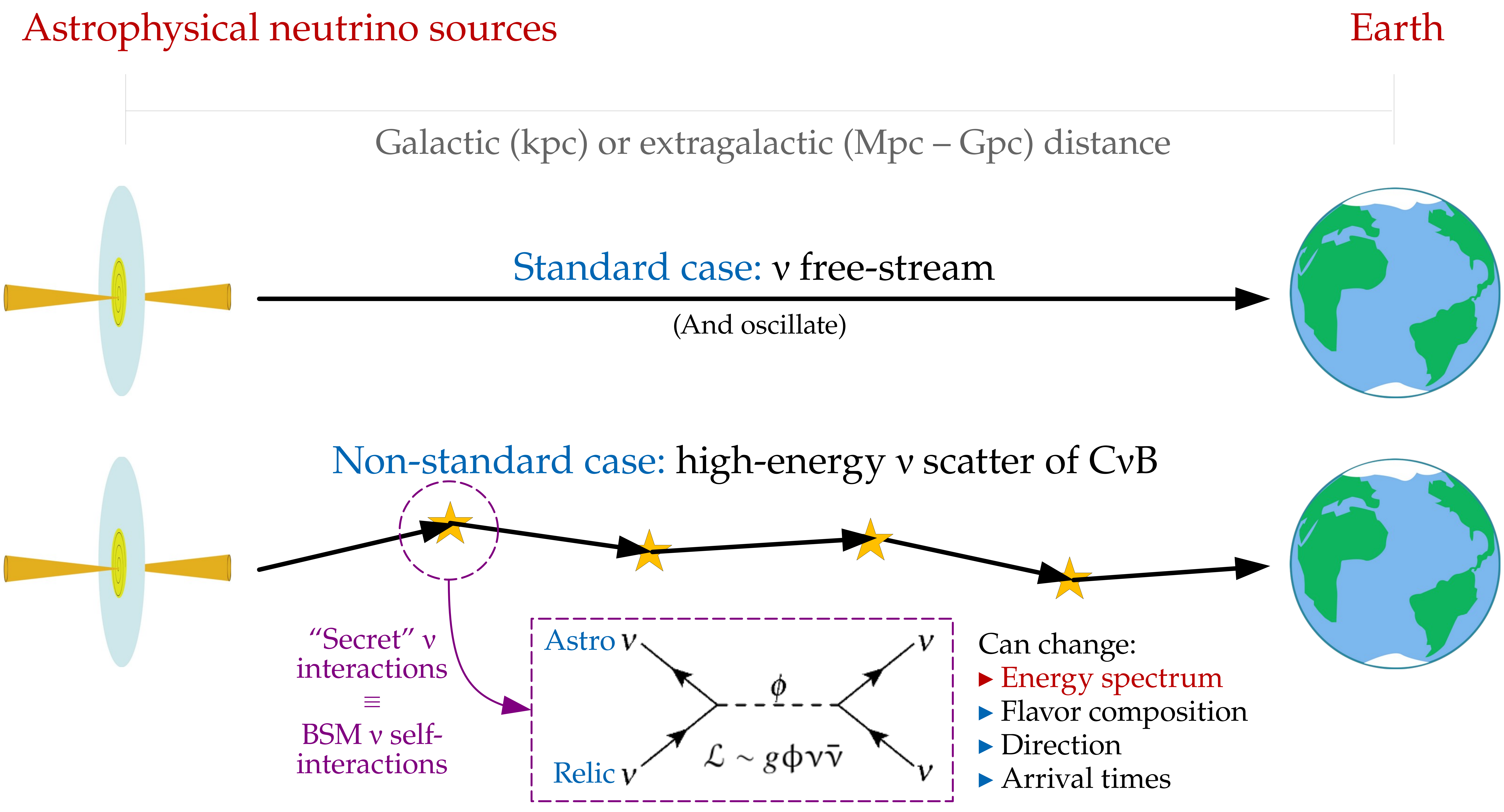


$$N_\gamma = T_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} \mathrm{d}E\, A_{\rm eff} \frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}$$



Aramaki+ Snowmass'21 CF

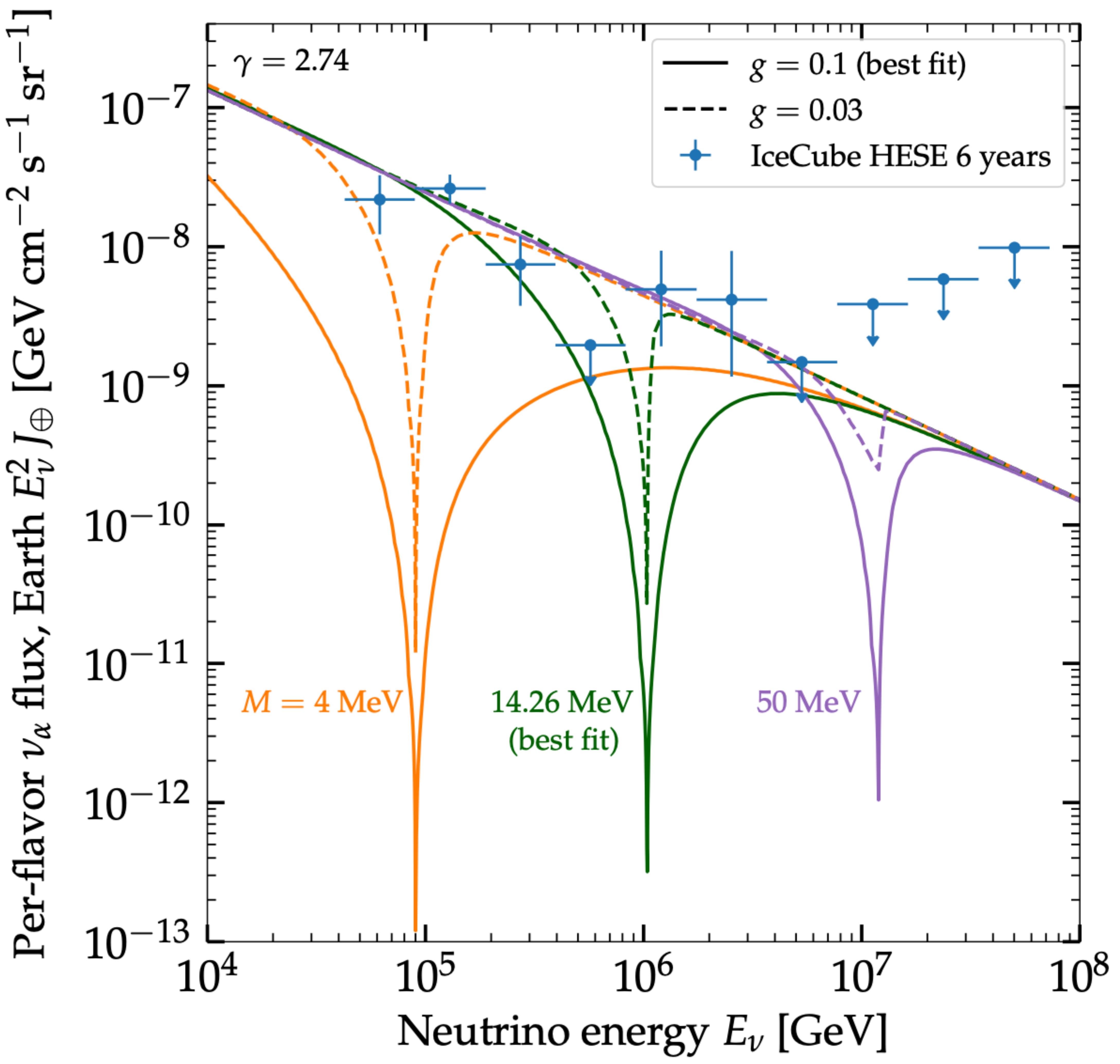
Anomalous propagation effects

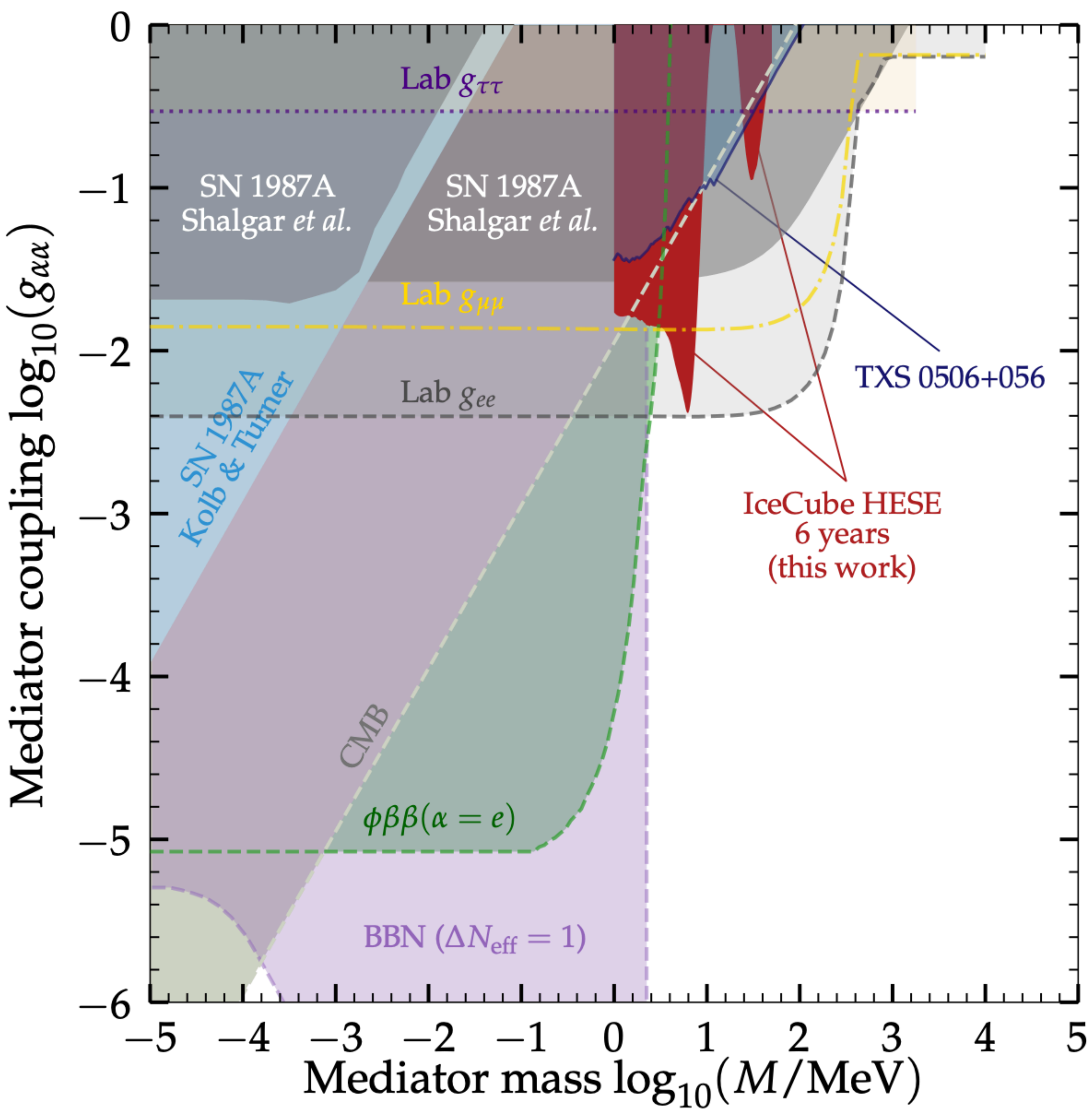


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

Neutrino spectrum and bounds

Bustamante+ PRD'20





No statistically significant evidence for νSI in the 6-year HESE sample

Tests of LIV

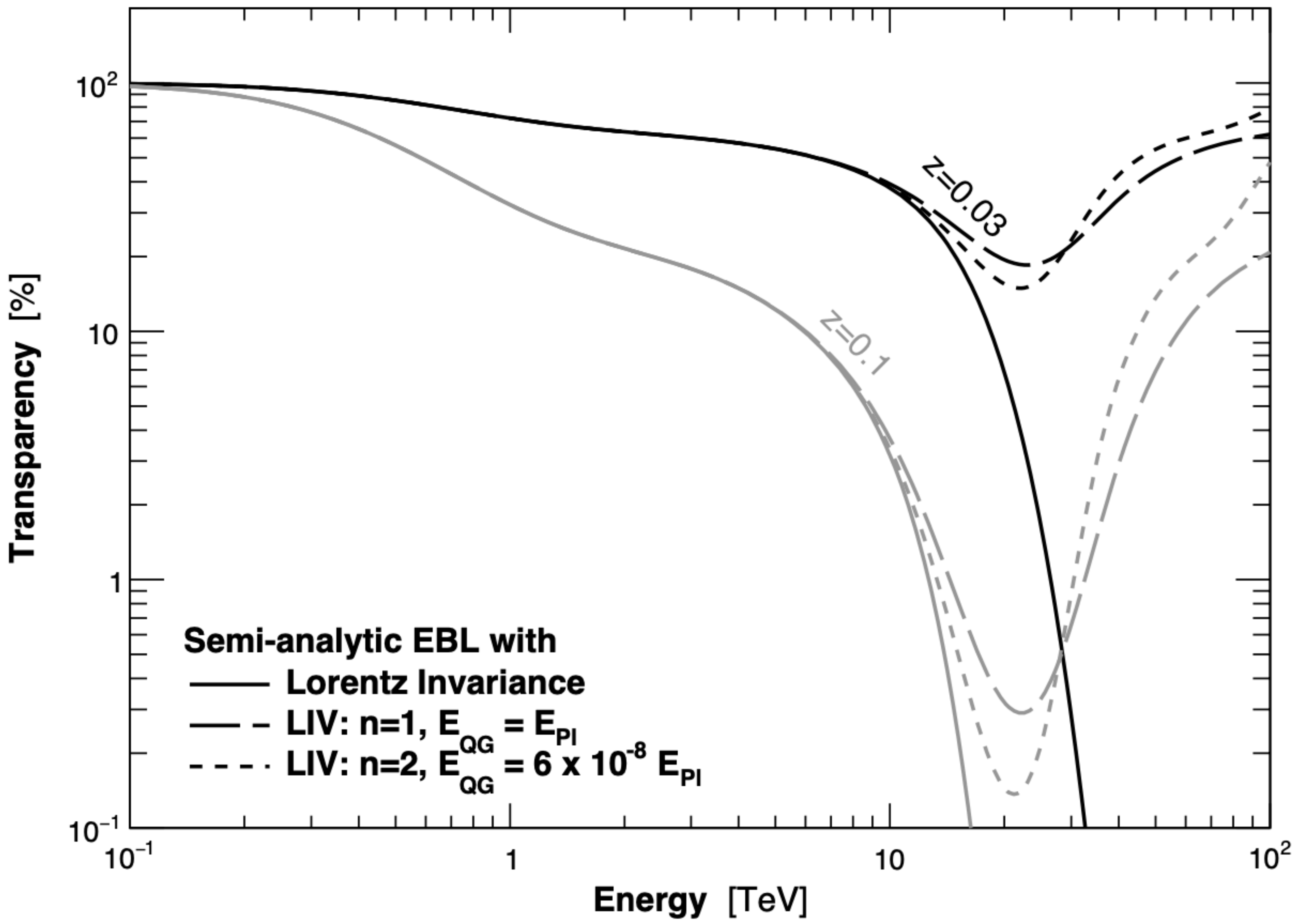


Figure 7.8: Attenuation factor, in percent, as a function of gamma-ray energy on Earth, for sources located at $z = 0.03$ and $z = 0.1$, following the semi-analytical EBL model of Gilmore et al. (2012) and the LIV formalism of Jacob and Piran (2008). Both linear ($n = 1$) and quadratic ($n = 2$) modifications of the pair-creation threshold are shown, at the Planck scale for $n = 1$, and at an ad-hoc energy scale of $6 \times 10^{-8}\, E_{\rm Pl}$ for $n = 2$, resulting in a similar effect.

Tests of LIV

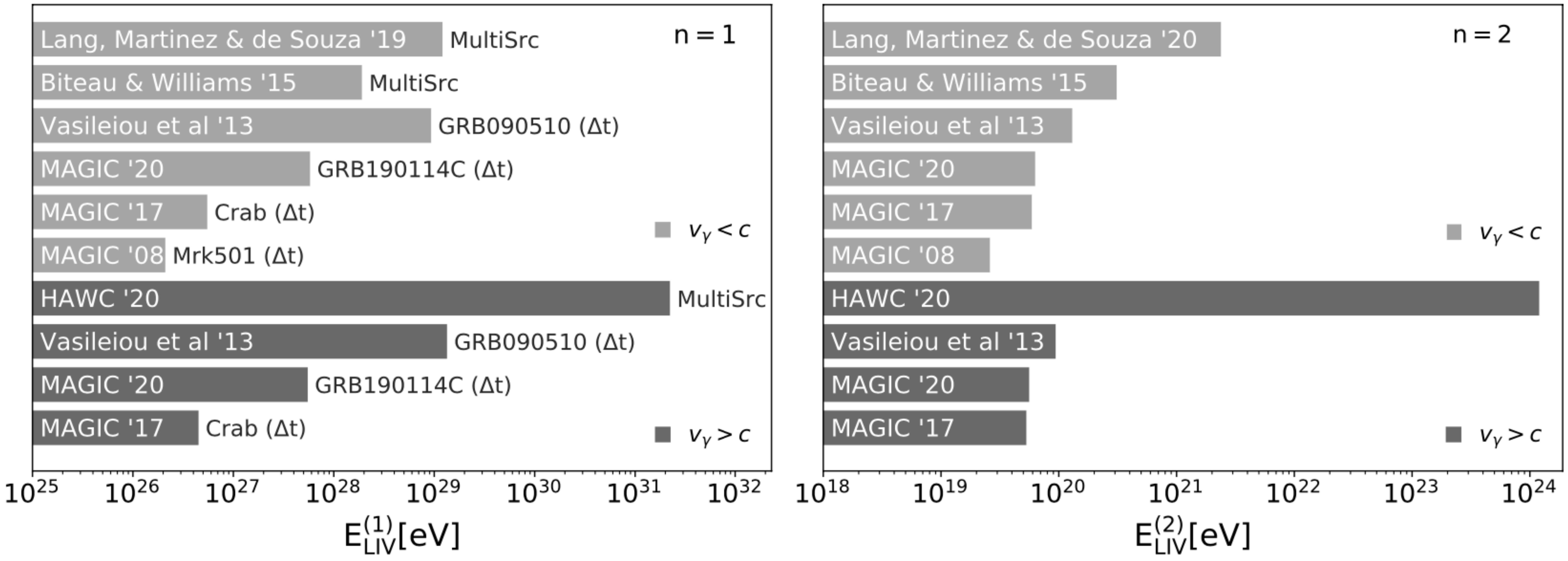


Figure 7.10: Summary of the lower limits on the energy scale of LIV, E_{LIV}. The left panel shows the limits on the linear term, the right panel on the quadratic term. Light grey bars assume a subluminal modification, while dark grey bars assume a superluminal modification. Credit: Humberto Martínez-Huerta, adapted from Martínez-Huerta et al. (2020).