Fundamental physics with multi-wavelength (and multi-messengers) observations

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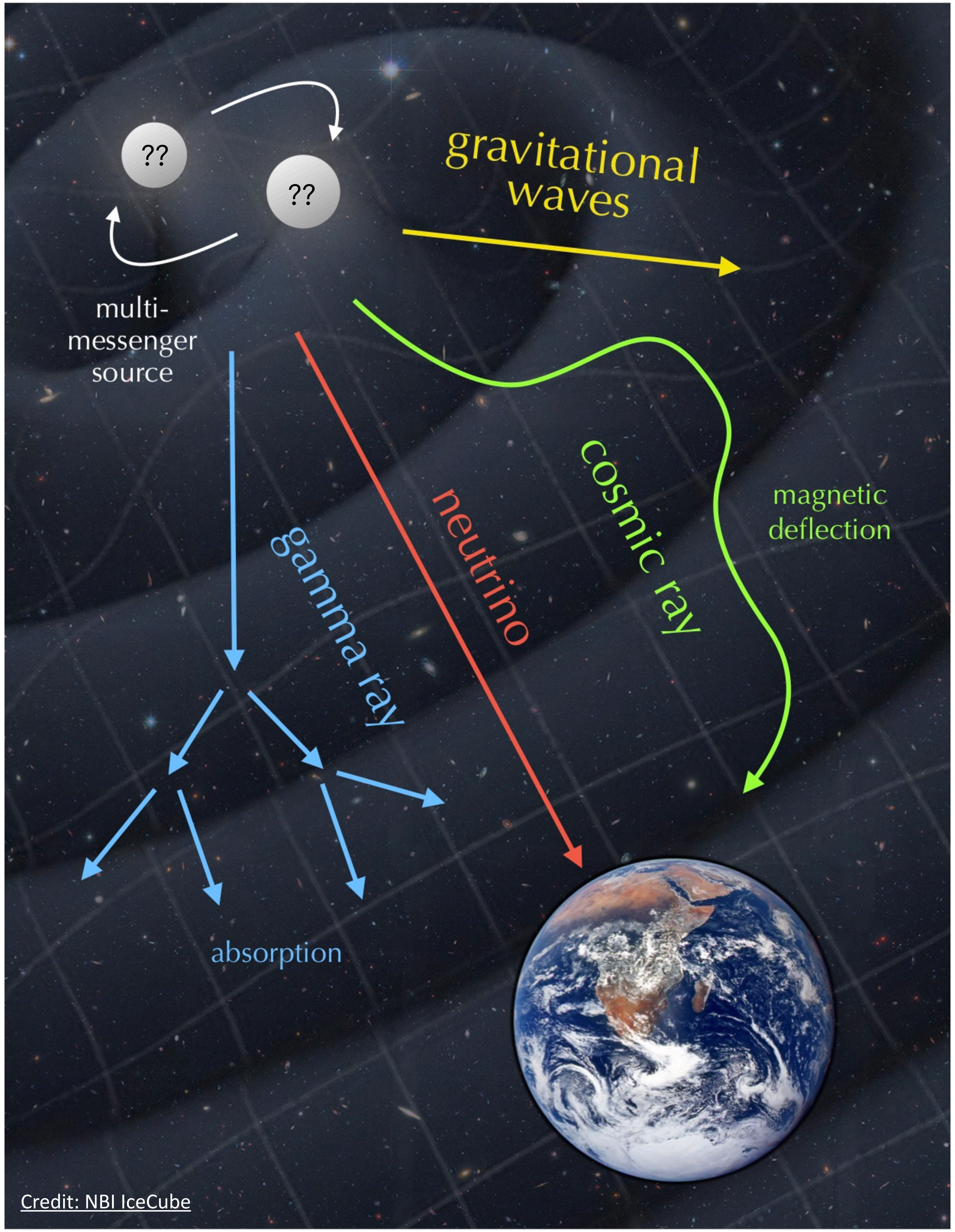
Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation
2024 Mar 11 — 16, Galileo Galilei Institute (IT)

Plan of the lectures

- Prolegomena: basic concepts
- Particles interactions w/ matter and radiation
- MW/MM connections: Gamma rays & neutrinos
- Astrophysical sources of CRs and radiation
- Exotic sources of CRs and radiation
- Generalities of dark matter searches
- Anomalous propagation of CRs/radiation



Credit: NBI IceCube

Prolegomena

Some reading material

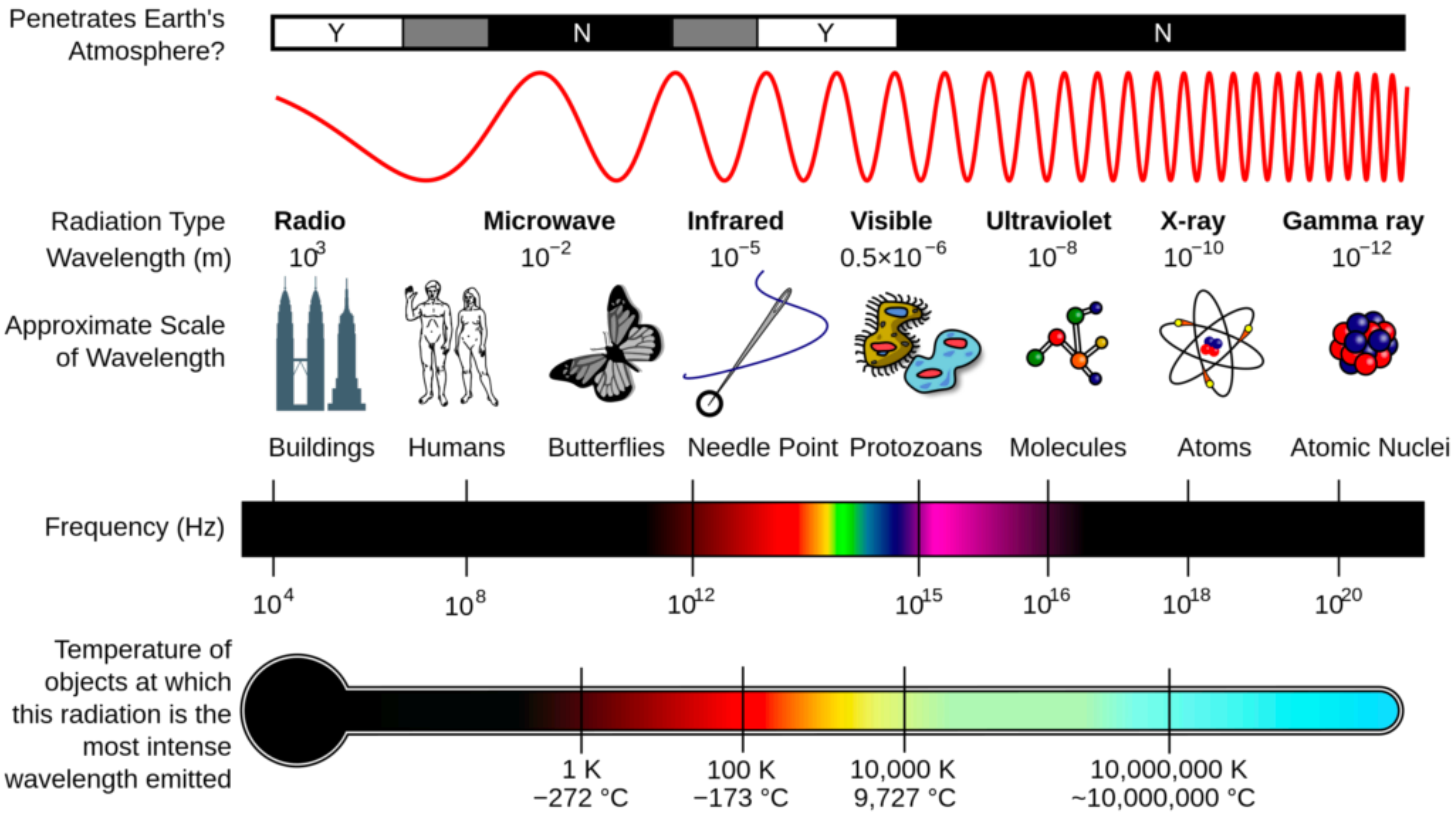
M. Longair, *High energy astrophysics*, Cambridge Univ. Press (2012)
V. S. Berezinskii et al., *Astrophysics of cosmic rays*, Amsterdam: North-Hollans (1990)
G. Sigl, *Astroparticle Physics: Theory and Phenomenology*, Atlantis Press Paris (2017)
G. Ghisellini, *Radiative processes in high-energy astrophysics*, 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*

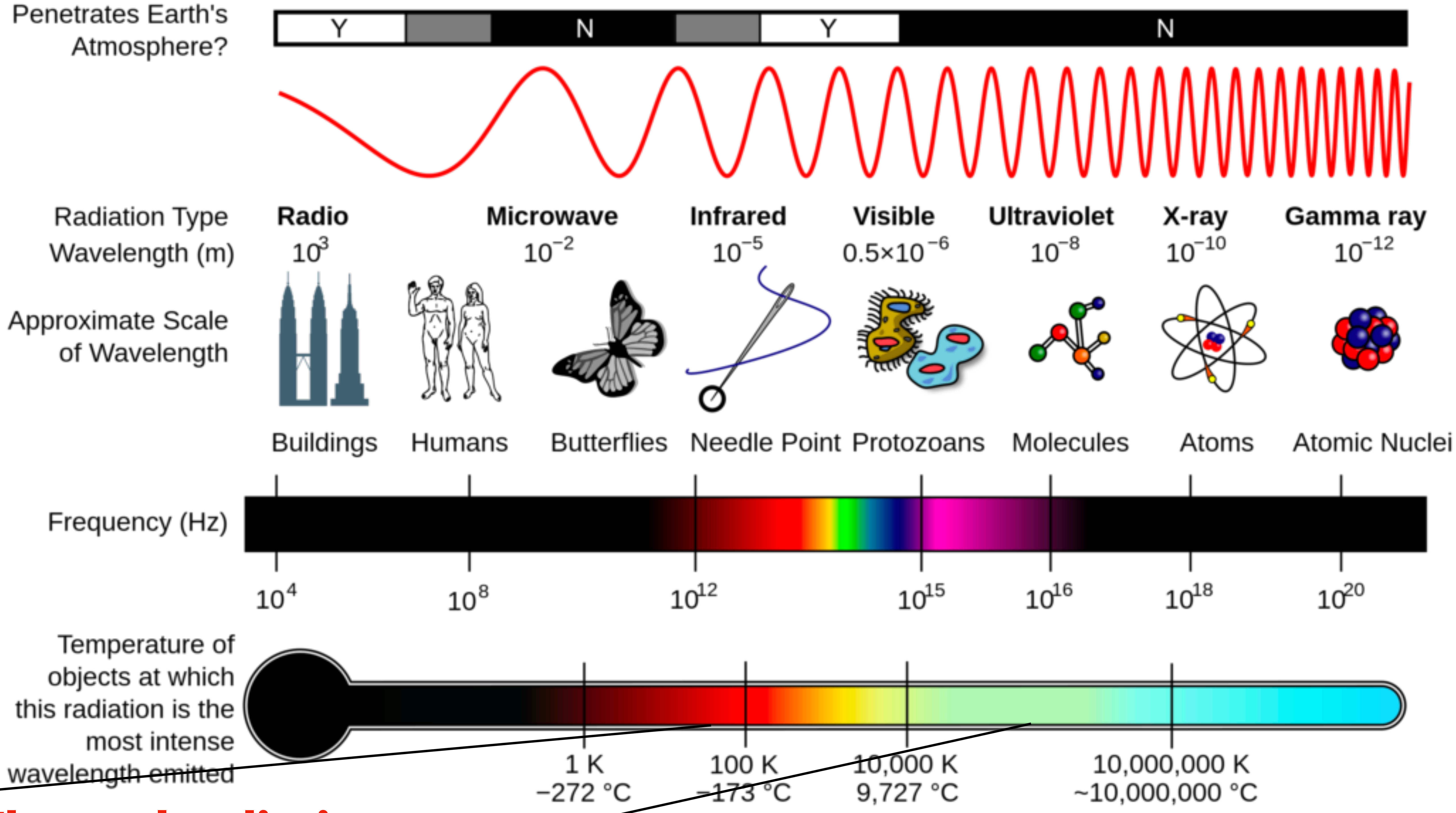
EuCAPT

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

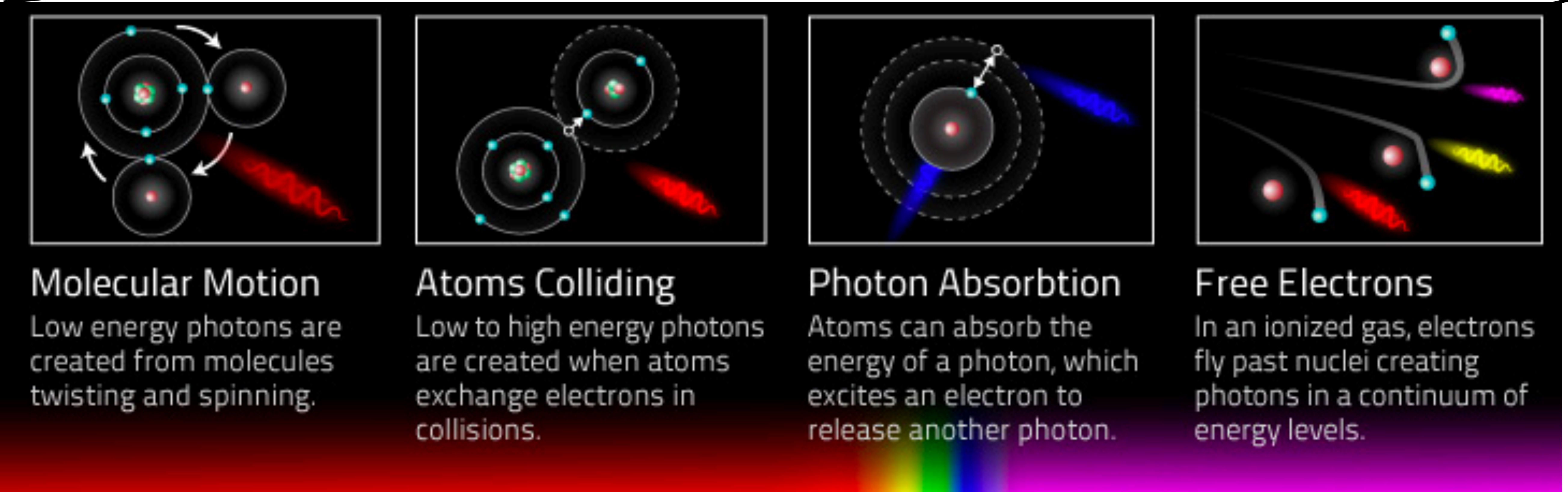
The MW spectrum



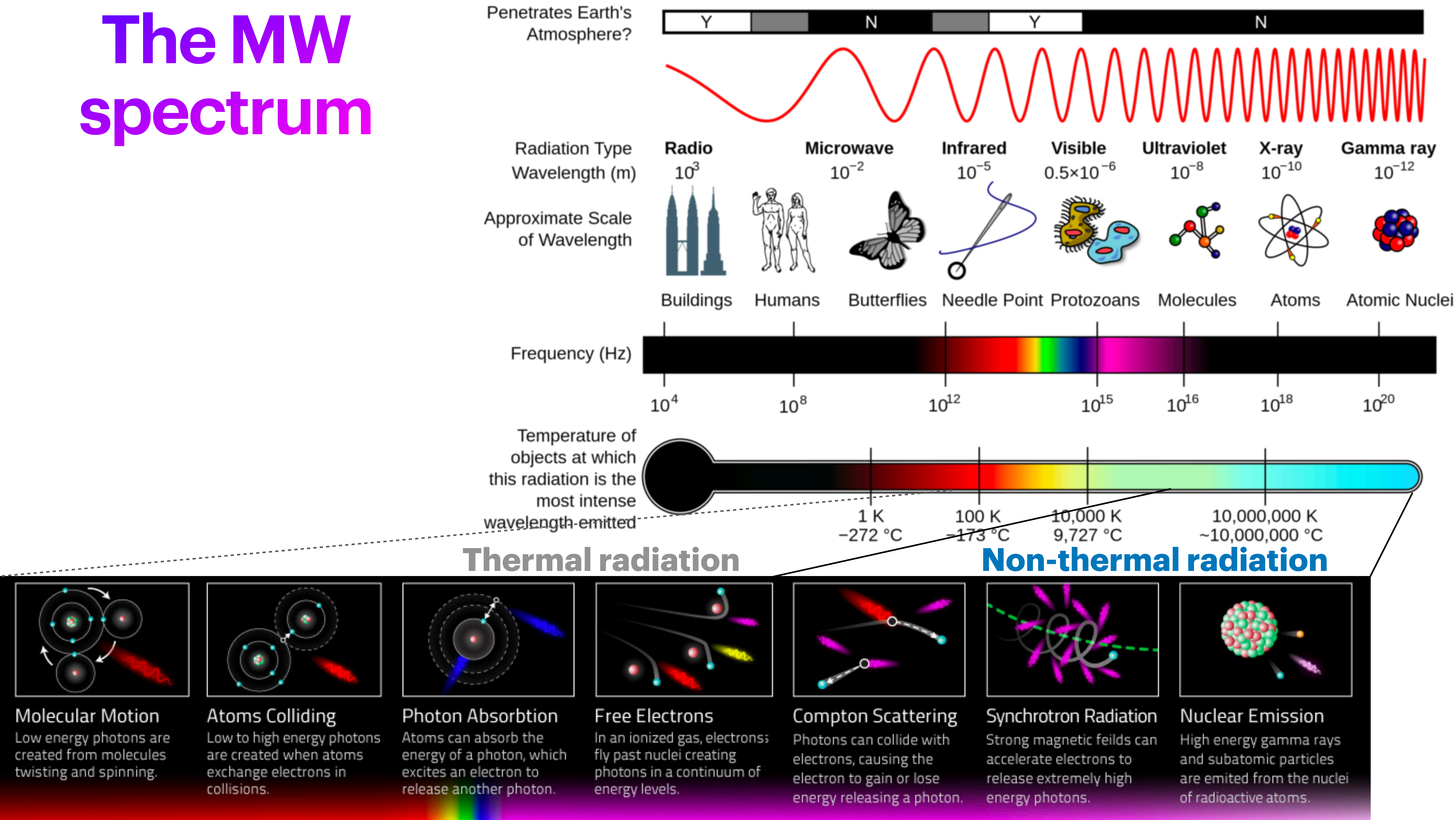
The MW spectrum



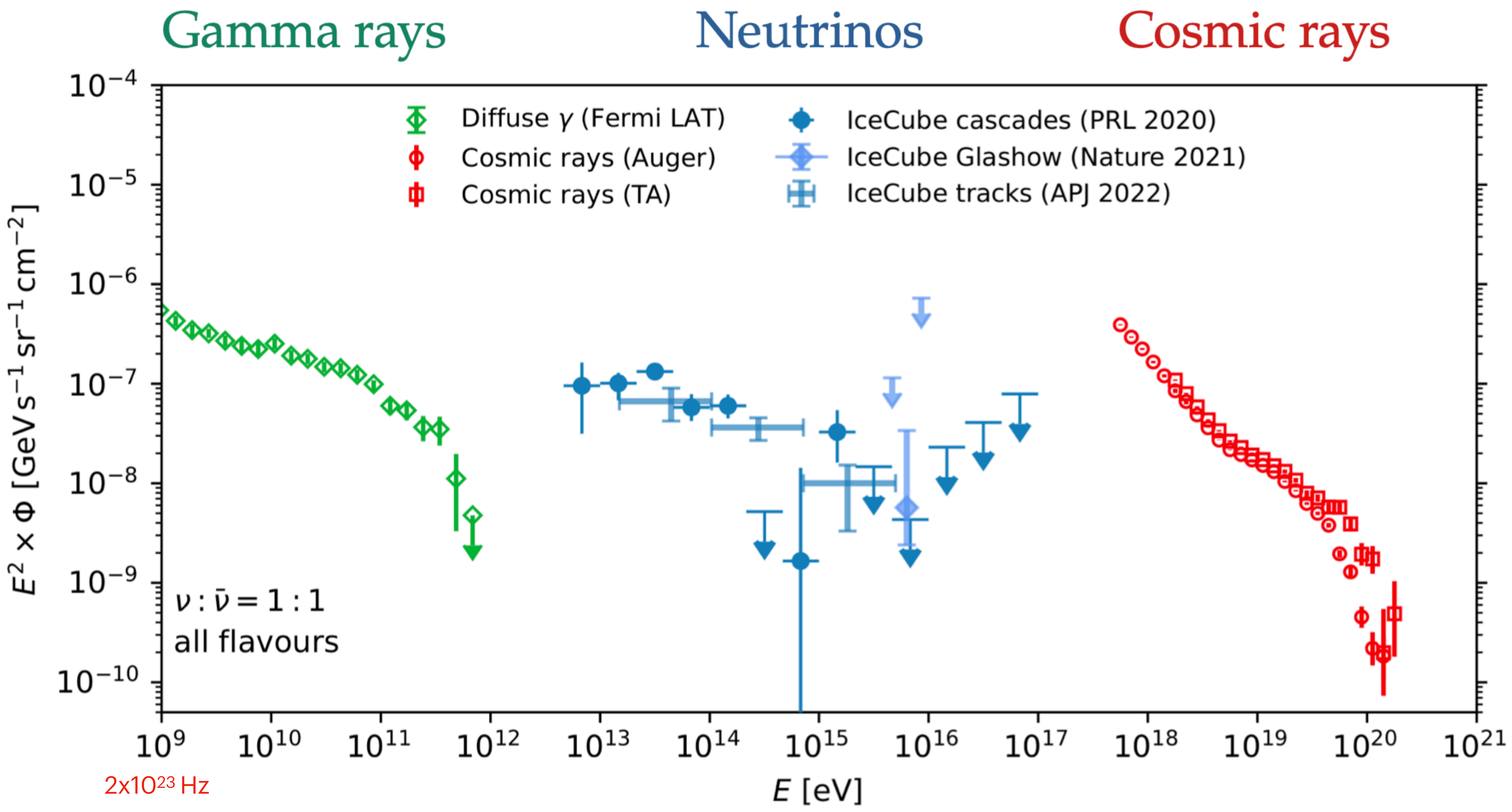
Thermal radiation



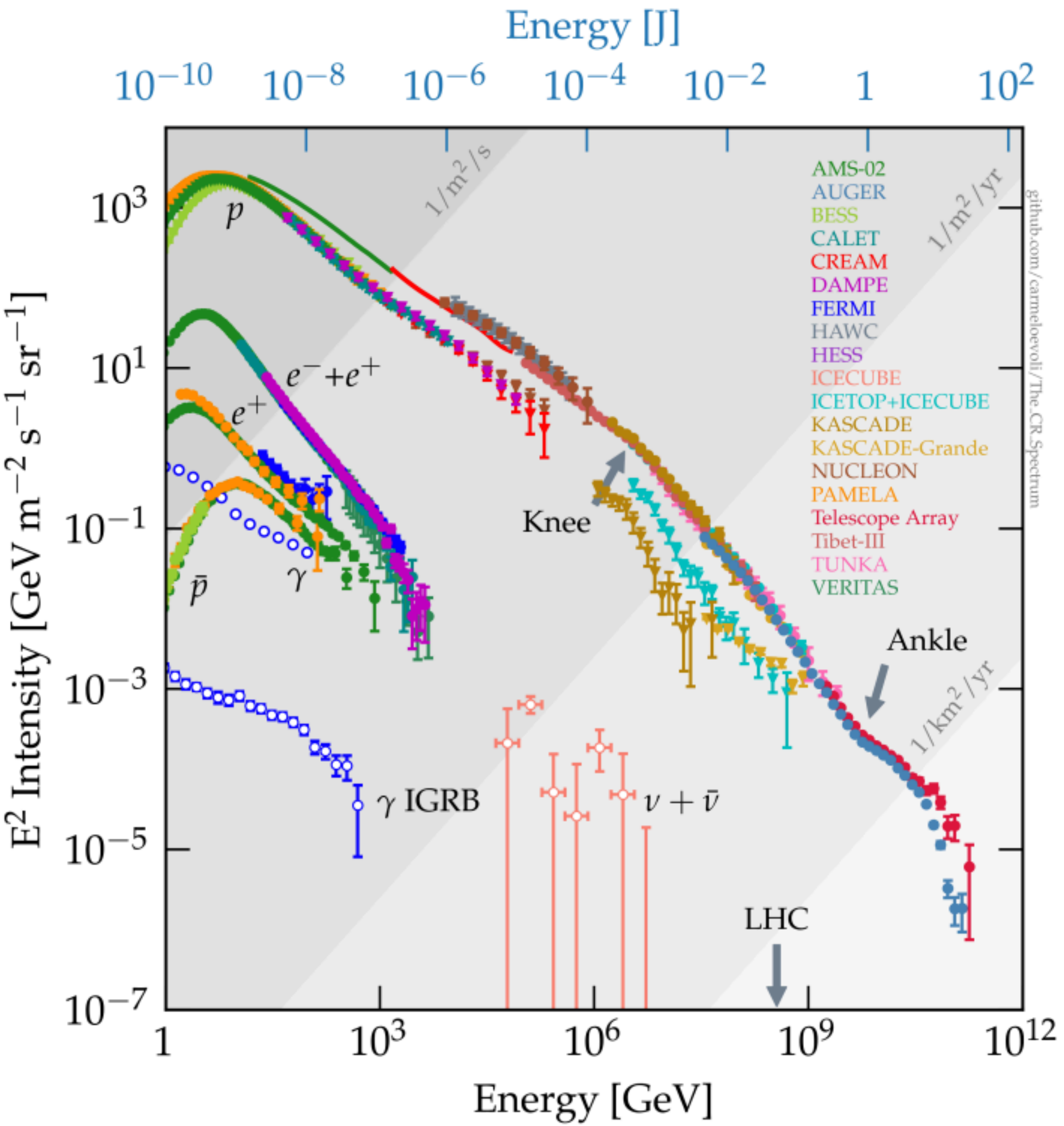
The MW spectrum



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]



Energy [J]
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}
E^2 Intensity [GeV m^{-2} s^{-1} sr^{-1}]
10^{3} 10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7}
Energy [GeV]
1 10^{3} 10^{6} 10^{9} 10^{12}
$1/m^2/s$
$1/m^2/yr$
$1/km^2/yr$
p
e^-+e^+
e^+
$\bar{p}$
γ
γ IGRB
$\nu+\bar{\nu}$
Knee
Ankle
LHC
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS
github.com/carmeloevoli/The_CR_Spectrum

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

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

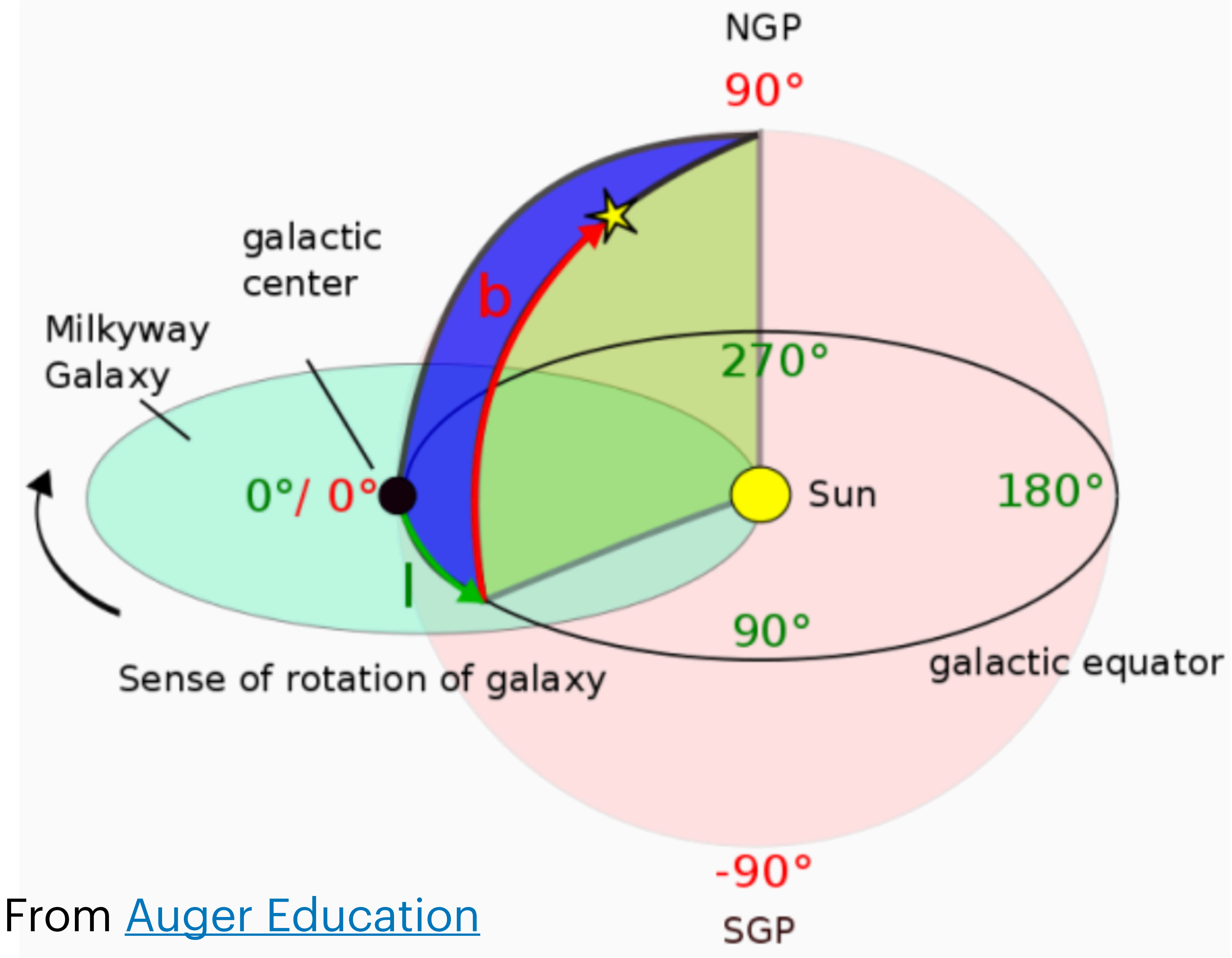
100s Mpc or Gpc

~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

Kachelrieß'08

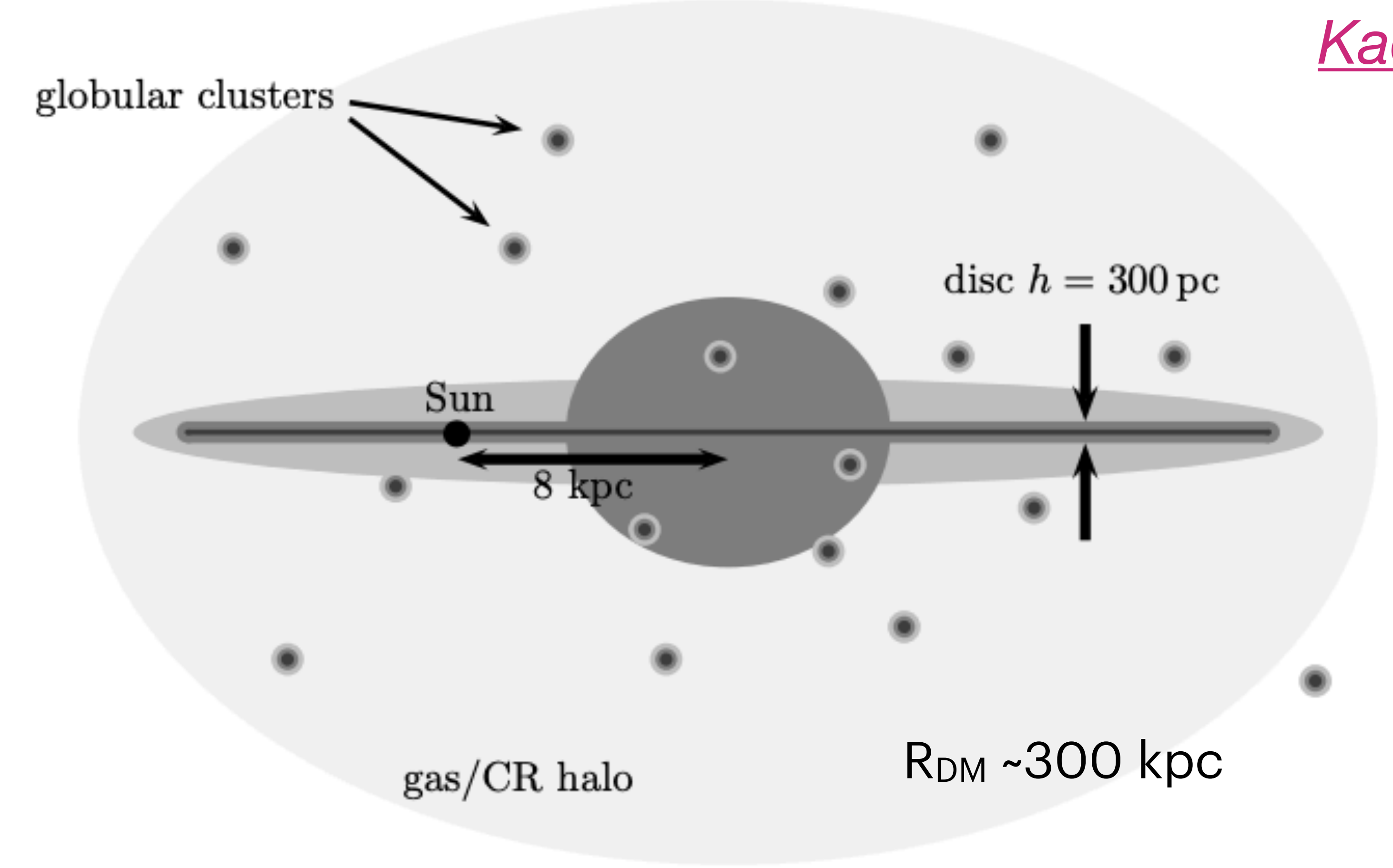


Figure 1.2: Schematic picture of the Milky Way with a gas and dust disc, an extended halo of gas and cosmic rays, surrounded by globular clusters. Everything is immersed in a halo of dark matter.

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]

Basic concepts/jargon

Natural units

Relavistic kinematics

Useful invariants

Mean free path

Energy losses

Luminosity [erg/s]

Flux [erg/cm^2/s]

Intensity [erg/cm^2/s/sr]

=> Blackboard

Charged particle motion in B field

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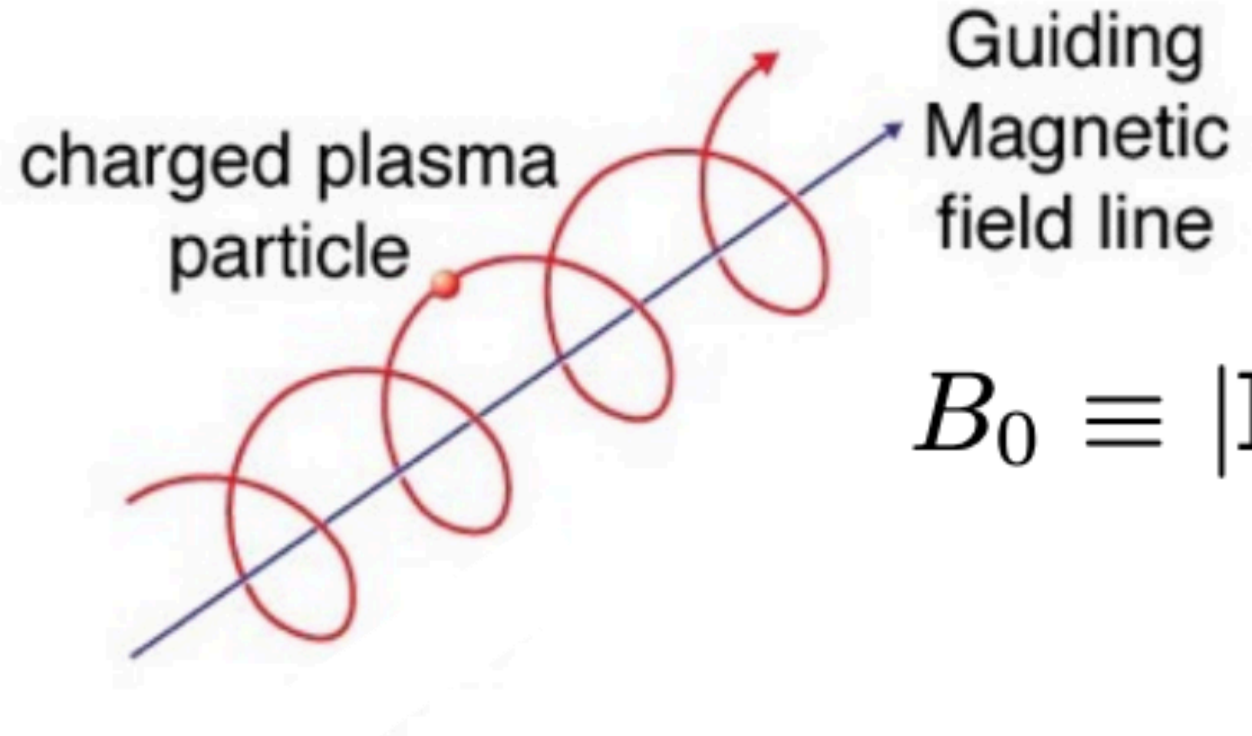
$$\frac{d\mathbf{p}}{dt} = q\mathbf{E} + q\frac{\mathbf{v}}{c} \times \mathbf{B}$$



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

Solutions (no electric field):

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

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

Larmor radius

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

Larmor frequency

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

Radiation field

=> Blackboard

$$P = \frac{2}{3} q^2 a^2$$

Larmor equation for a single accelerated charge

Particle interactions w/ matter and radiation

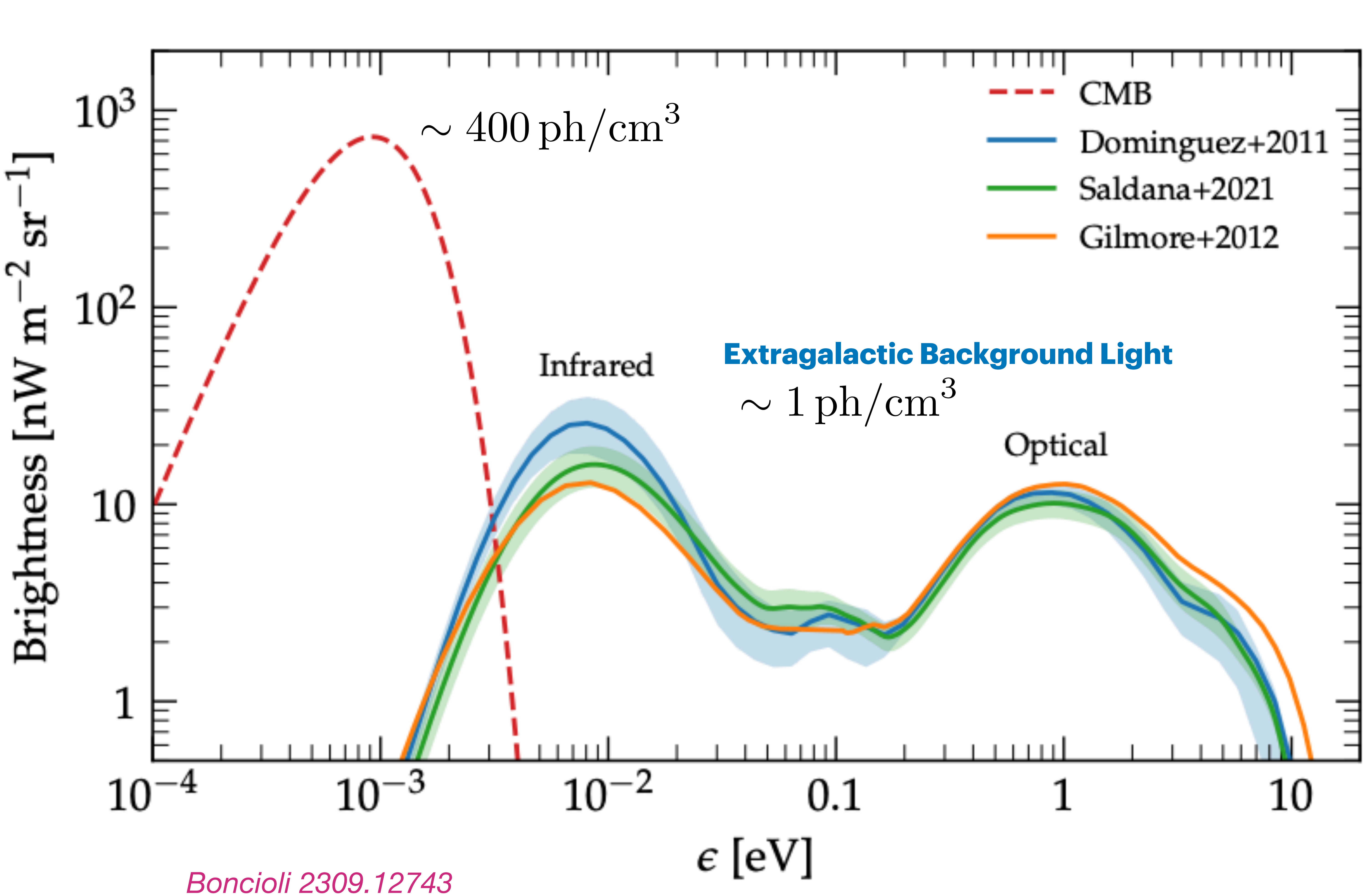
Collisional effects & radiative processes

• 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)	
• Hadrons interactions w/ radiation (**MW/MM connection**, extragalactic)	*Photons*, *neutrinos*
• Hadrons interactions w/ matter (**MW/MM connection**, Galactic)	*Photons*, *neutrinos*

[*Not covered*: Lepton interactions w/ matter]

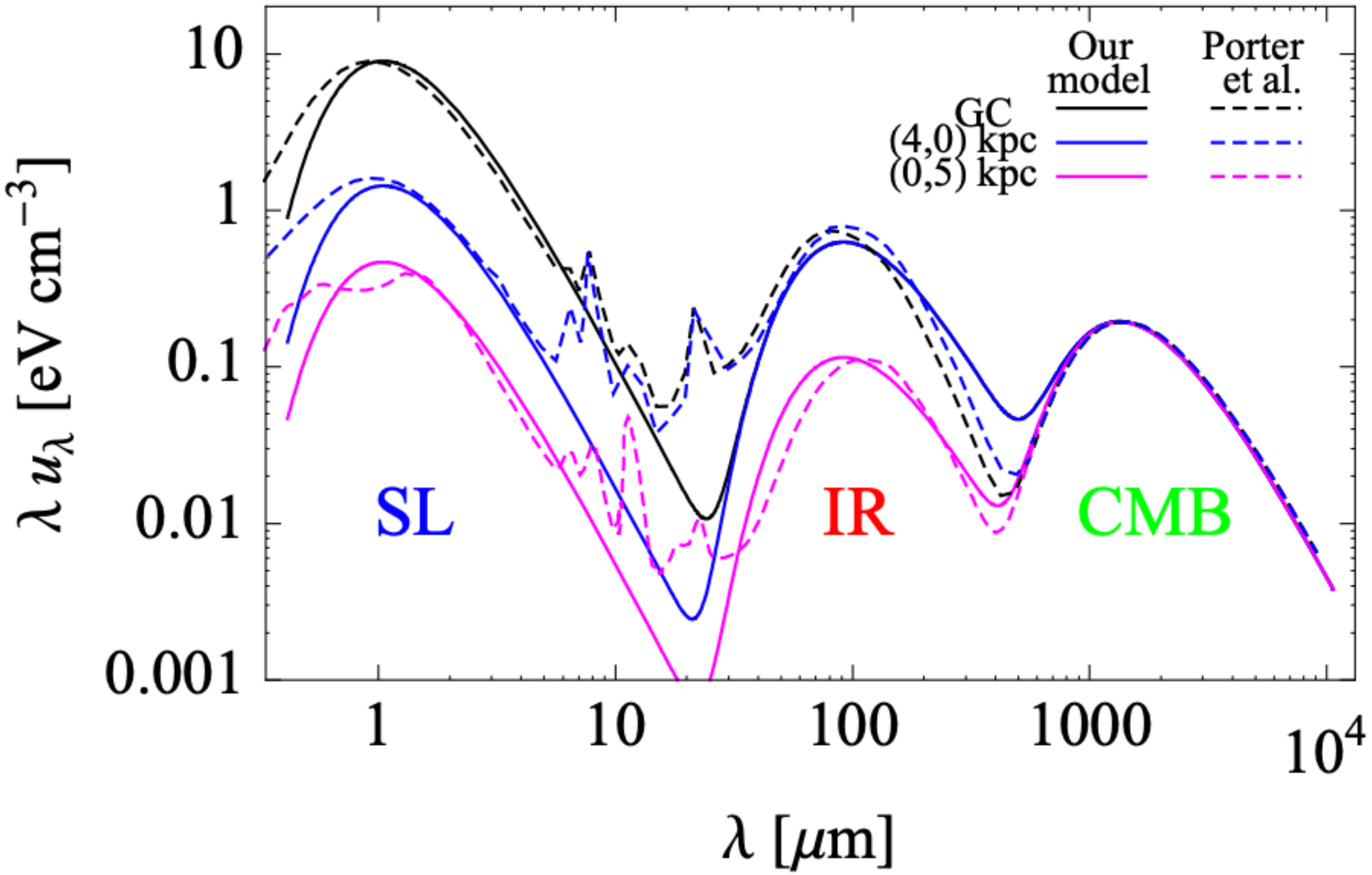
Extragalactic radiation backgrounds

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



Boncioli 2309.12743

Galactic radiation backgrounds



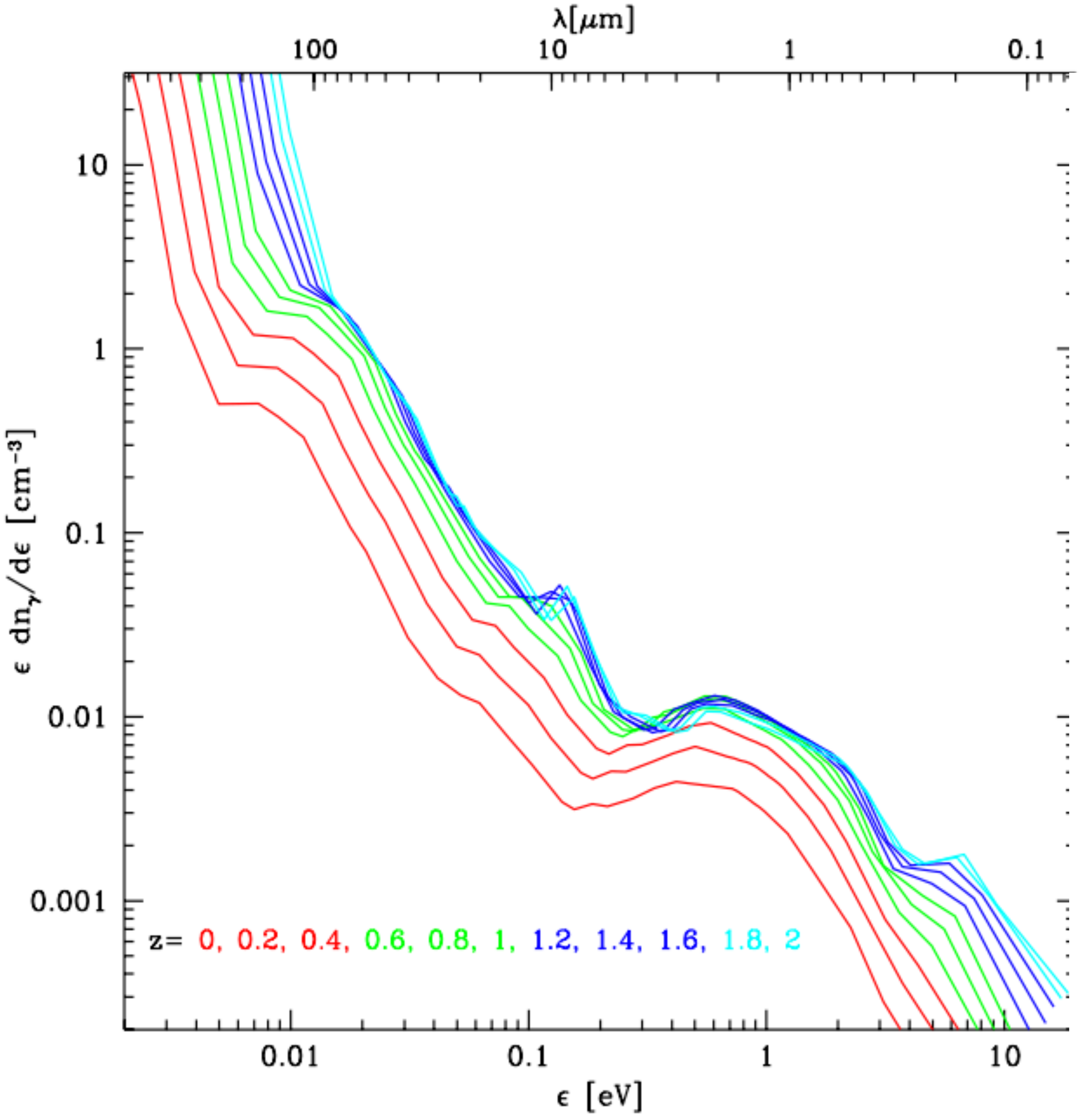
Cirelli & Panci 0904.3830

Pair production: gamma-ray horizon

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

=> Blackboard

Pair production: gamma-ray horizon



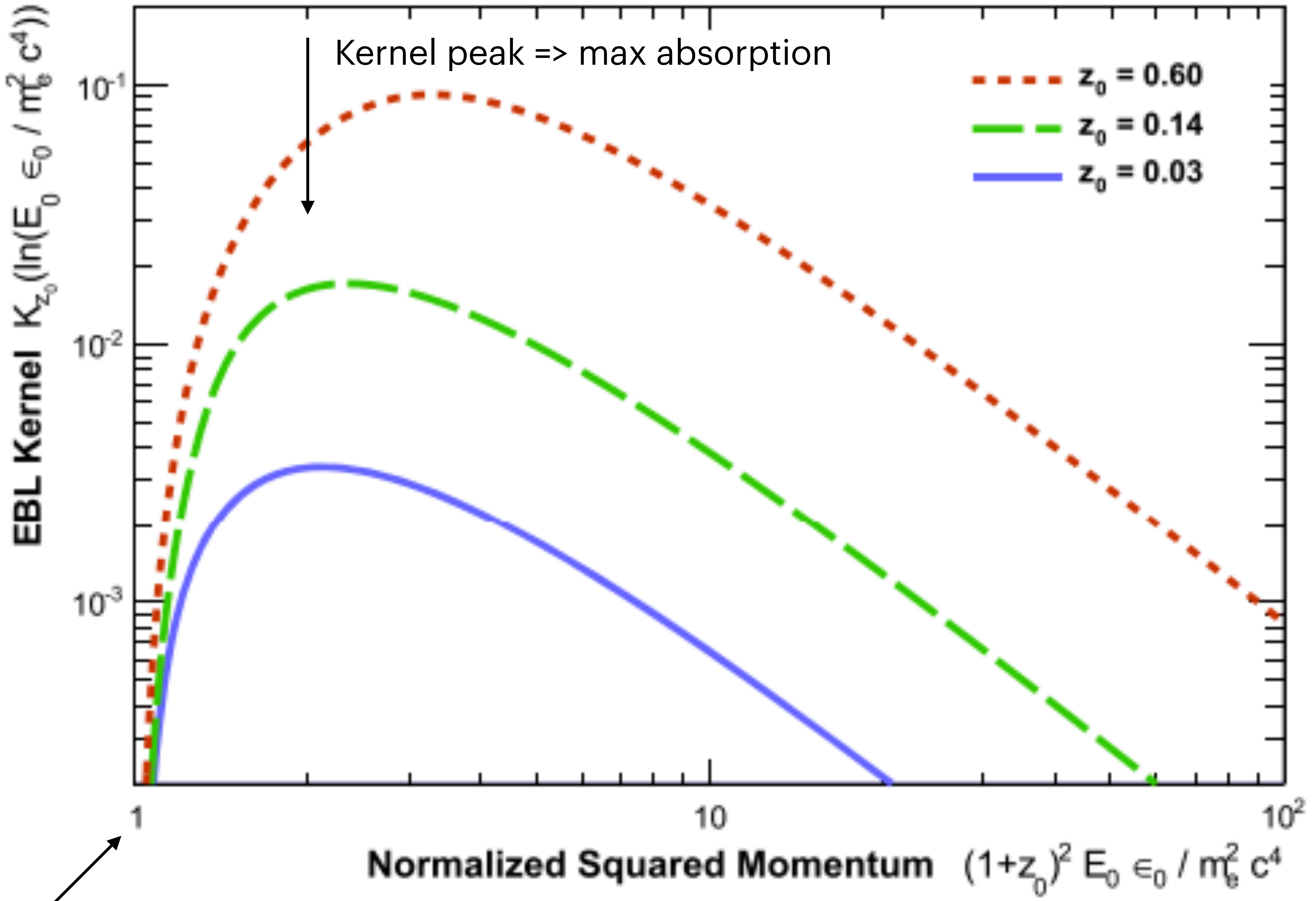


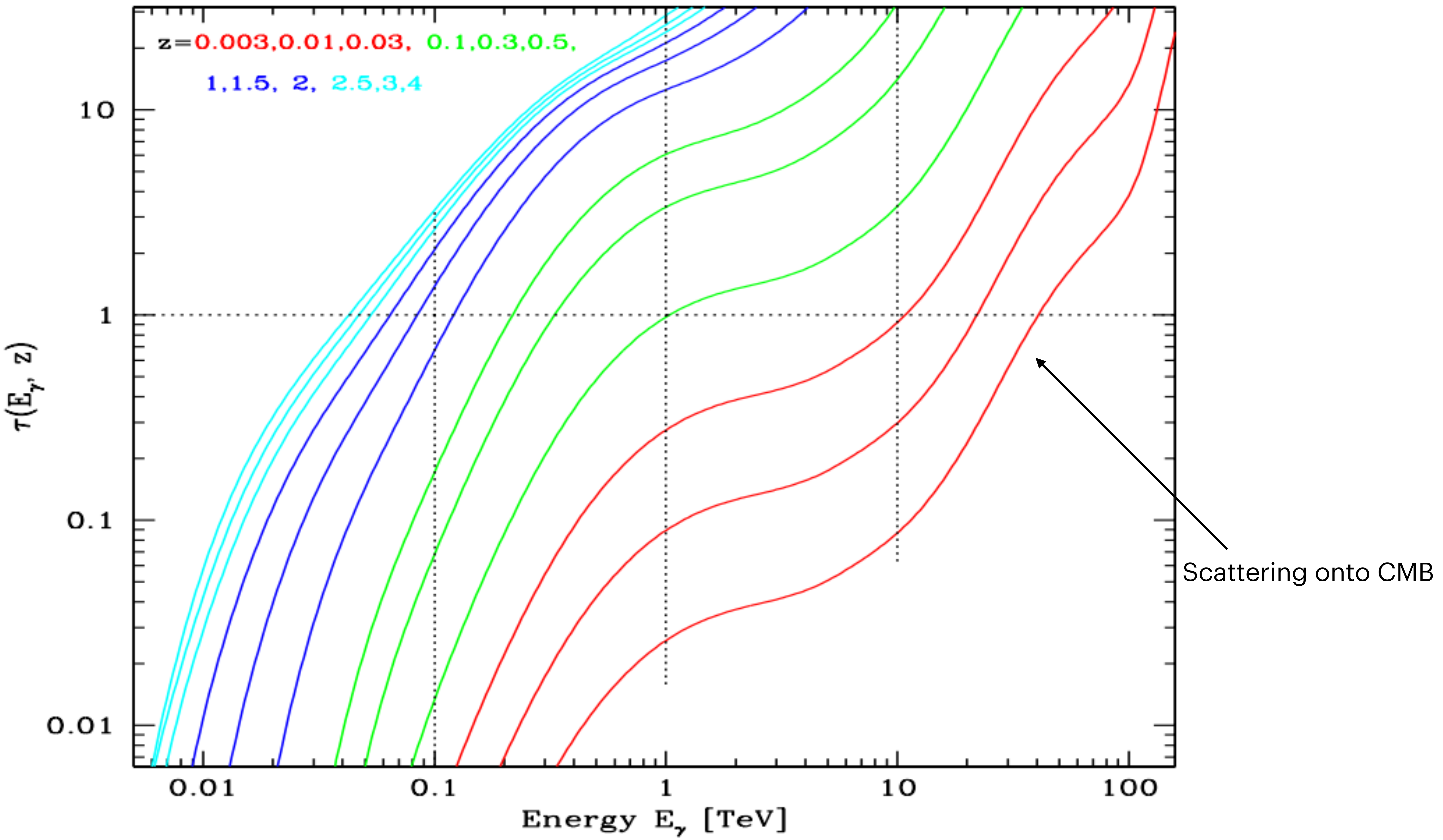
Figure 1. EBL kernel, which yields the gamma-ray optical depth after convolution with the EBL intensity, as a function of the product of gamma-ray and EBL-photon energies in electron-mass units, in the lab frame.

Threshold condition

Franceschini Universe'21

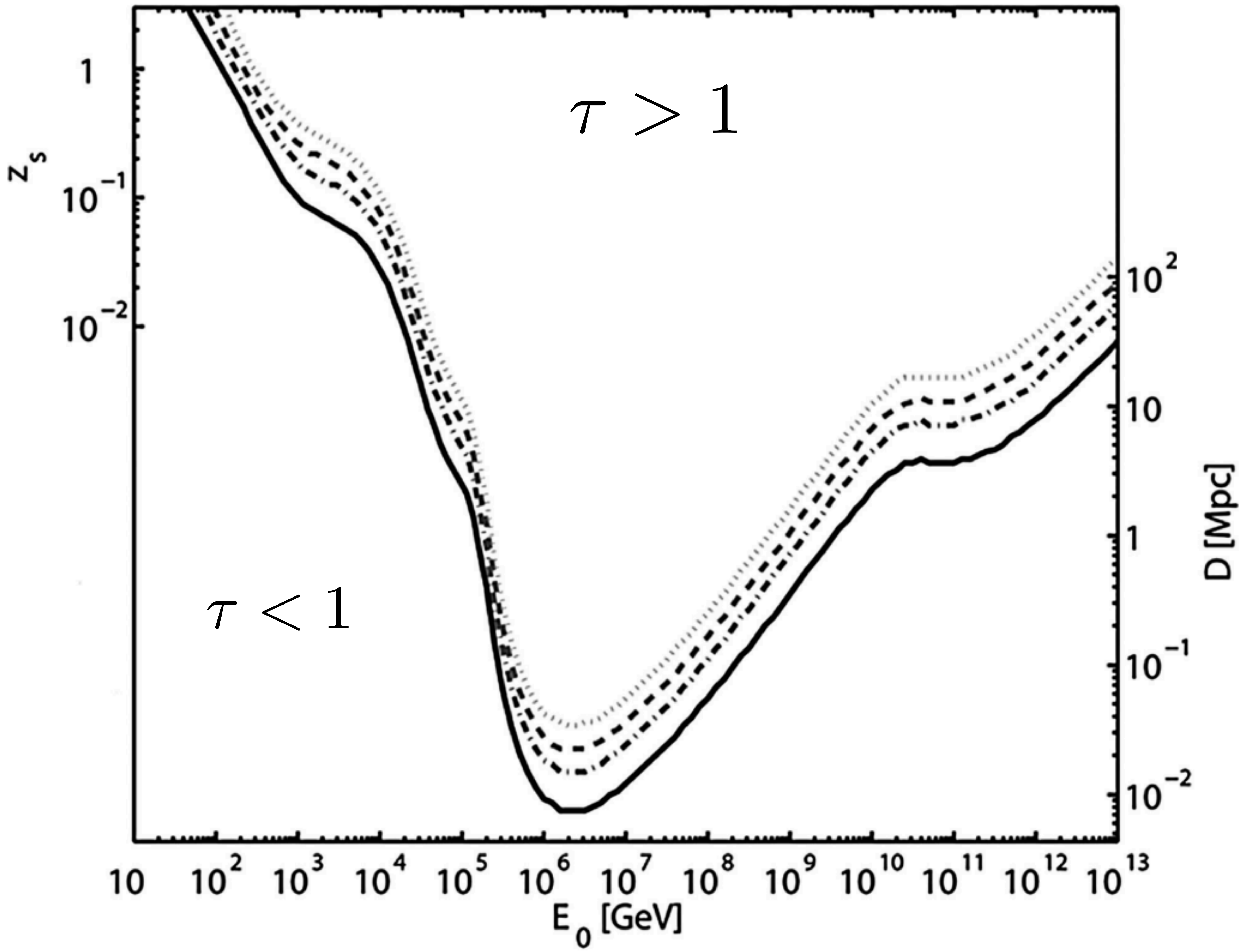
Biteau & Williams ApJ'15

Pair production: gamma-ray horizon



Franceschini Universe'21

Pair production: gamma-ray horizon



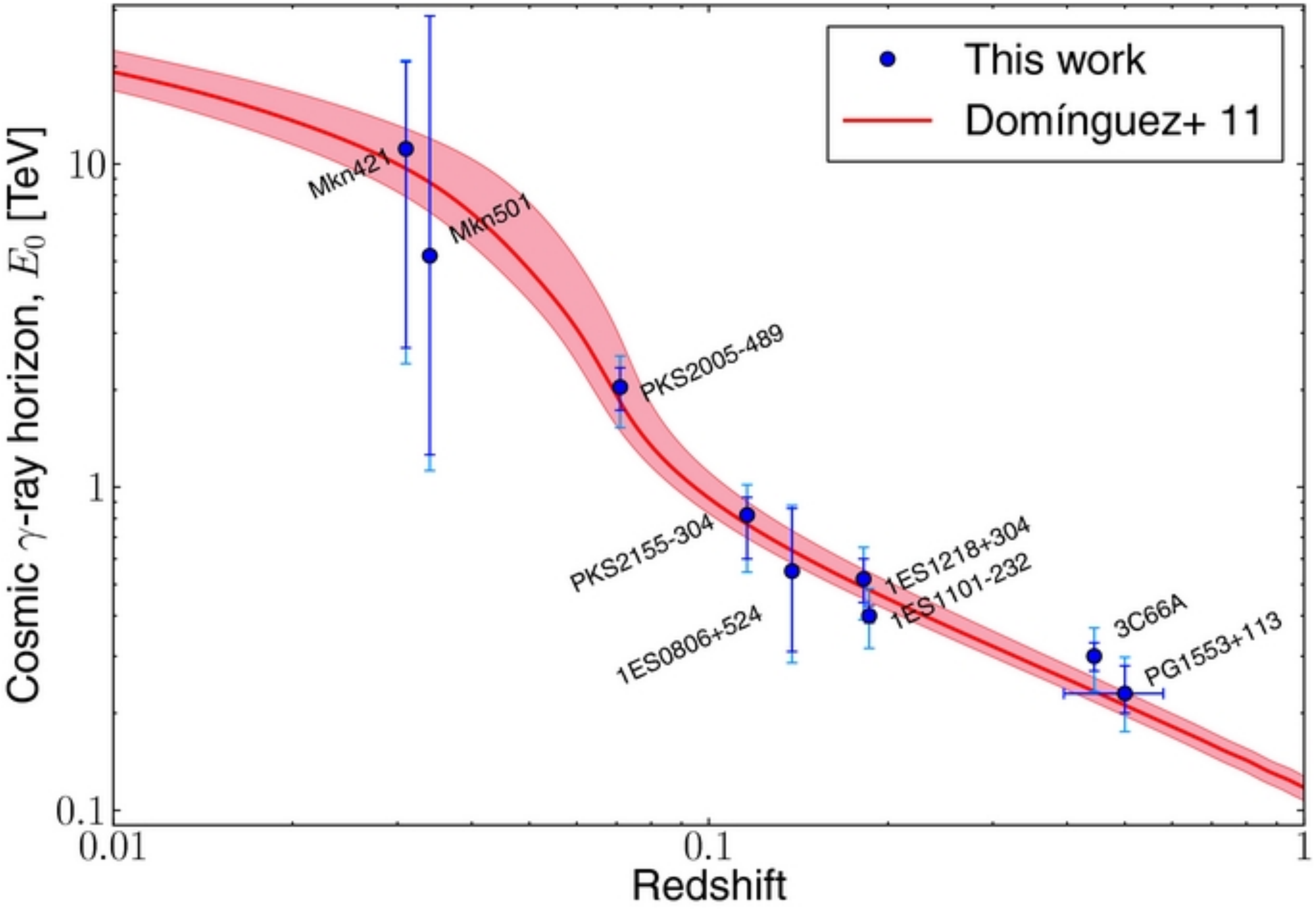
De Angelis+MNRAS'13

Figure 1. Source redshifts z_s at which the optical depth takes fixed values as a function of the observed hard photon energy E_0; the y-scale on the right side shows the distance in Mpc for nearby sources. The curves from bottom to top correspond to a photon survival probability of $e^{-1} \simeq 0.37$ (the horizon), $e^{-2} \simeq 0.14$, $e^{-3} \simeq 0.05$ and $e^{-4.6} \simeq 0.01$. For $D < 8$ kpc the photon survival probability is larger than 0.37 for any value of E_0.

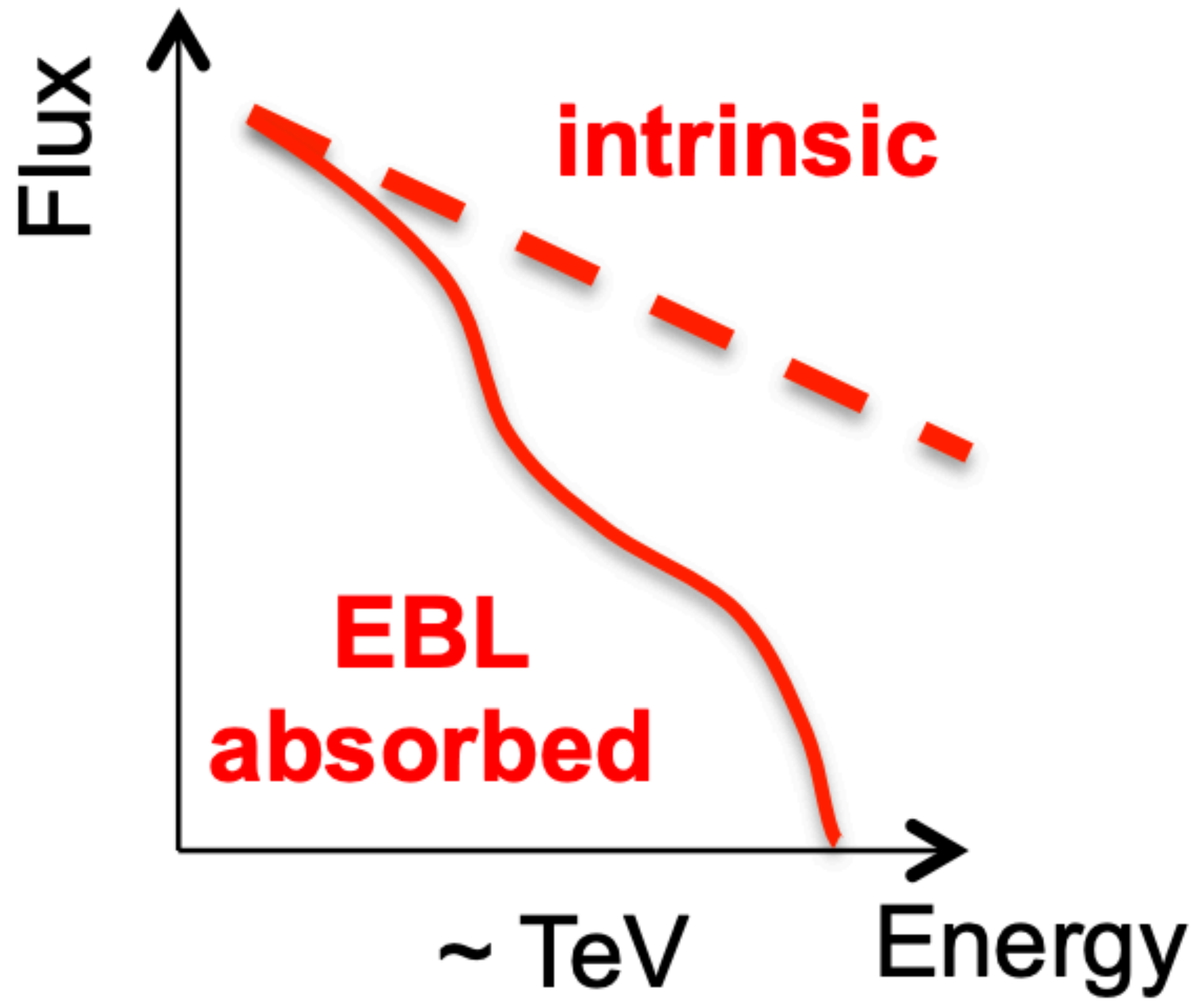
$$z_s \equiv z_0$$

$$D \equiv D_s$$

Pair production: gamma-ray horizon



Dominguez+ ApJ'13



[*MW signature*: E.m. cascades initiated by e+e-]

Inverse Compton scattering

$$\gamma_{\mathrm{LE}} + e \rightarrow \gamma_{\mathrm{HE}} + e$$

=> Blackboard

[Collisional effect, continuous E loss mechanism]

Inverse Compton scattering

[Dundovic+ A&A'22](#)

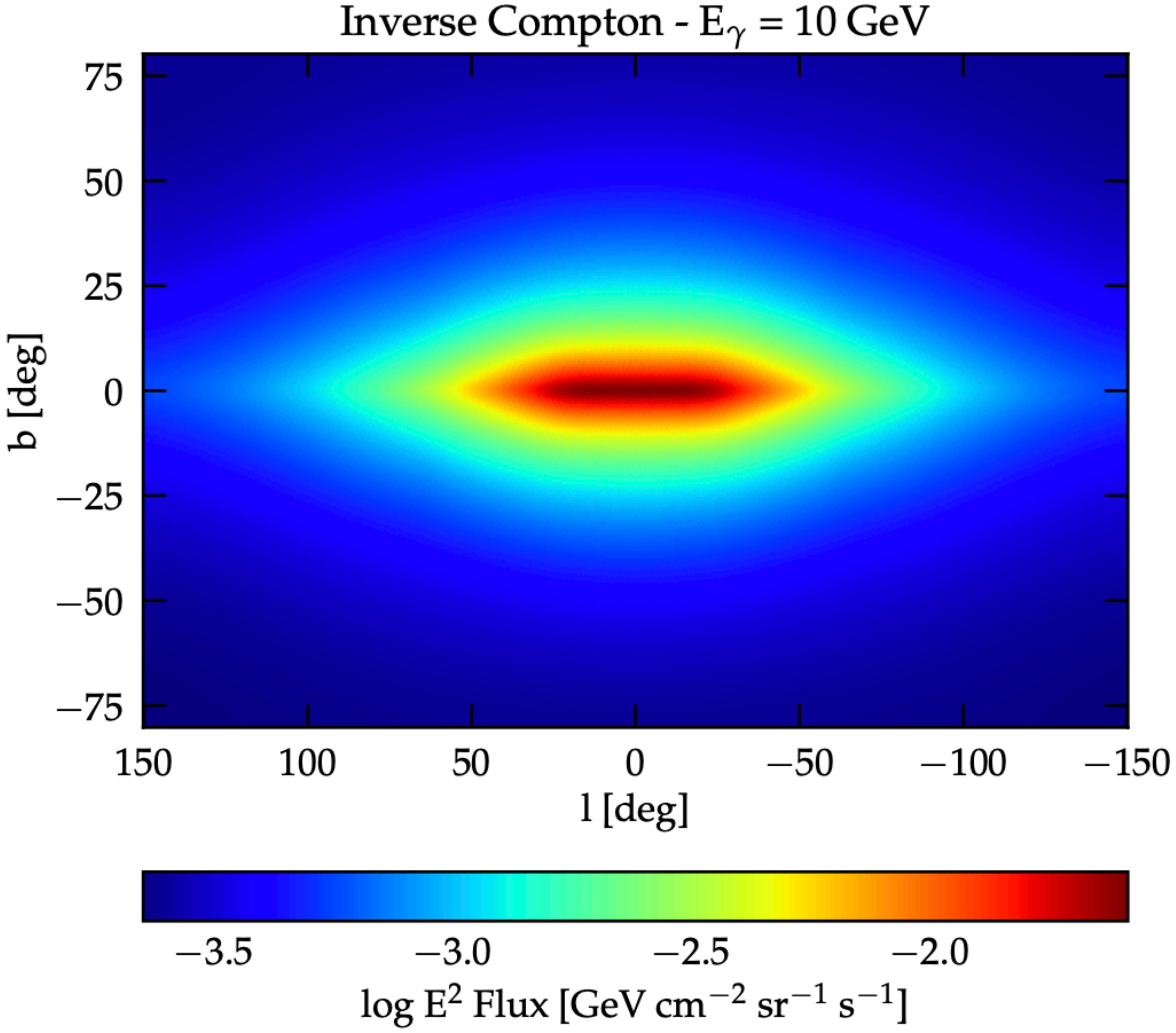
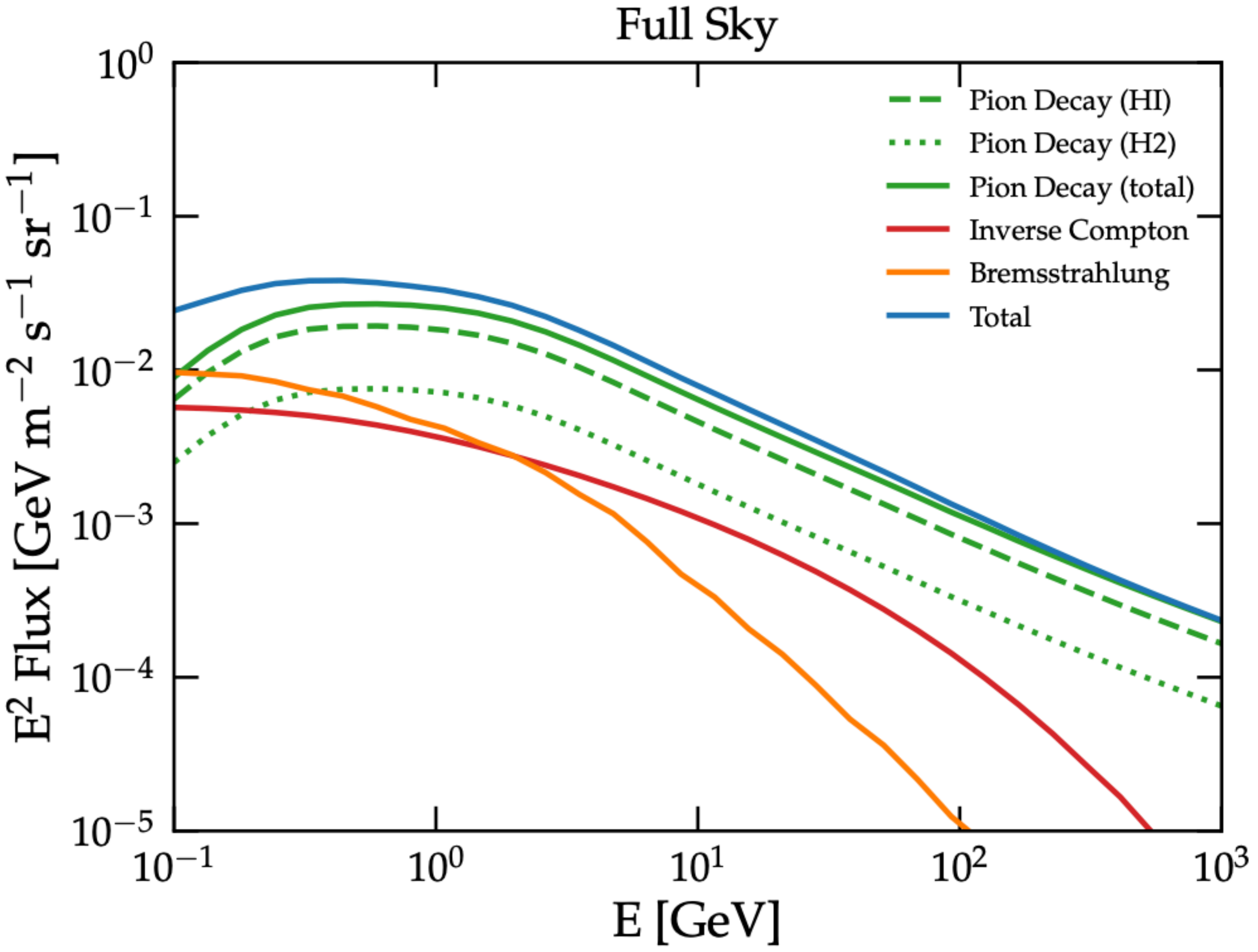
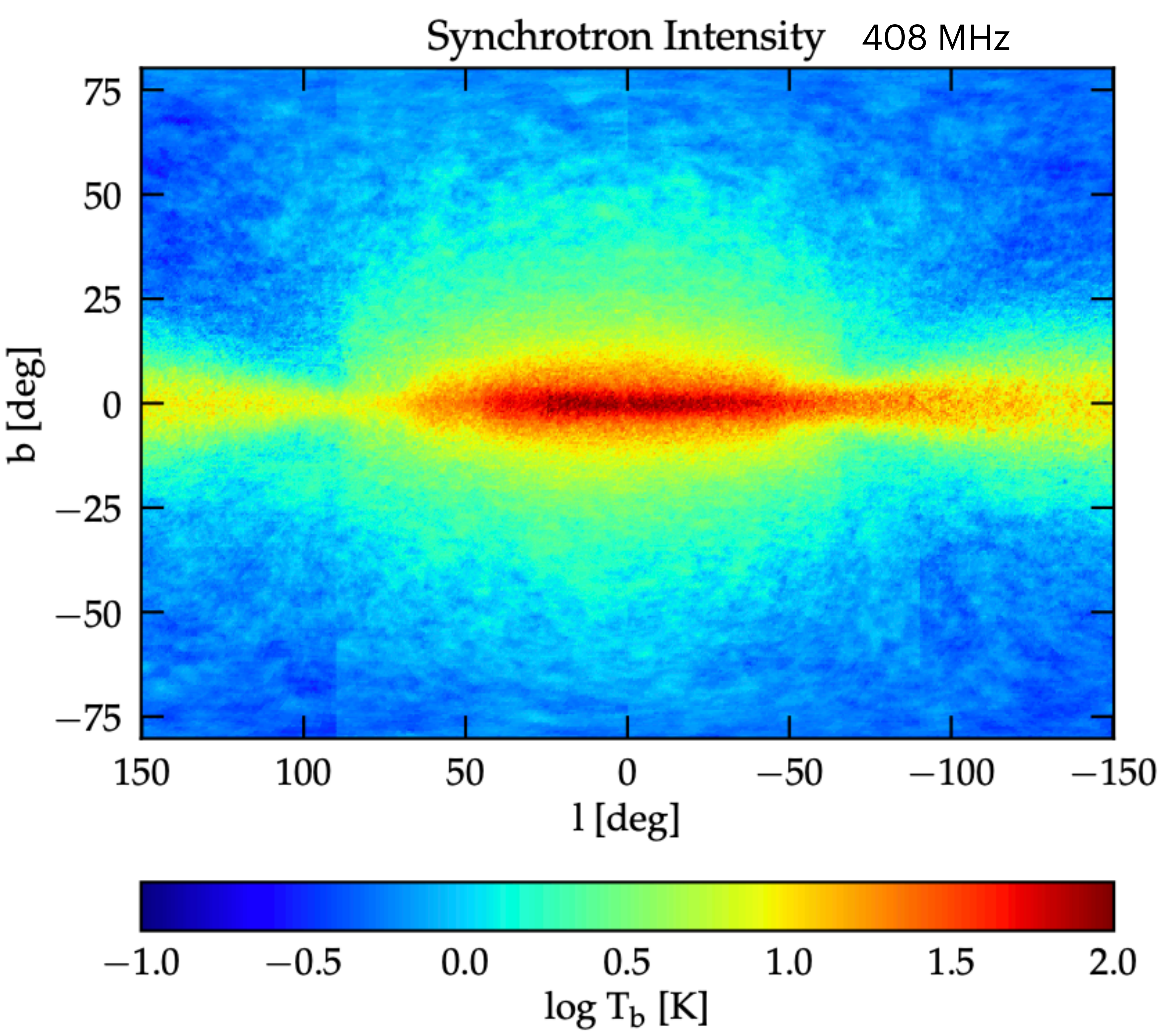
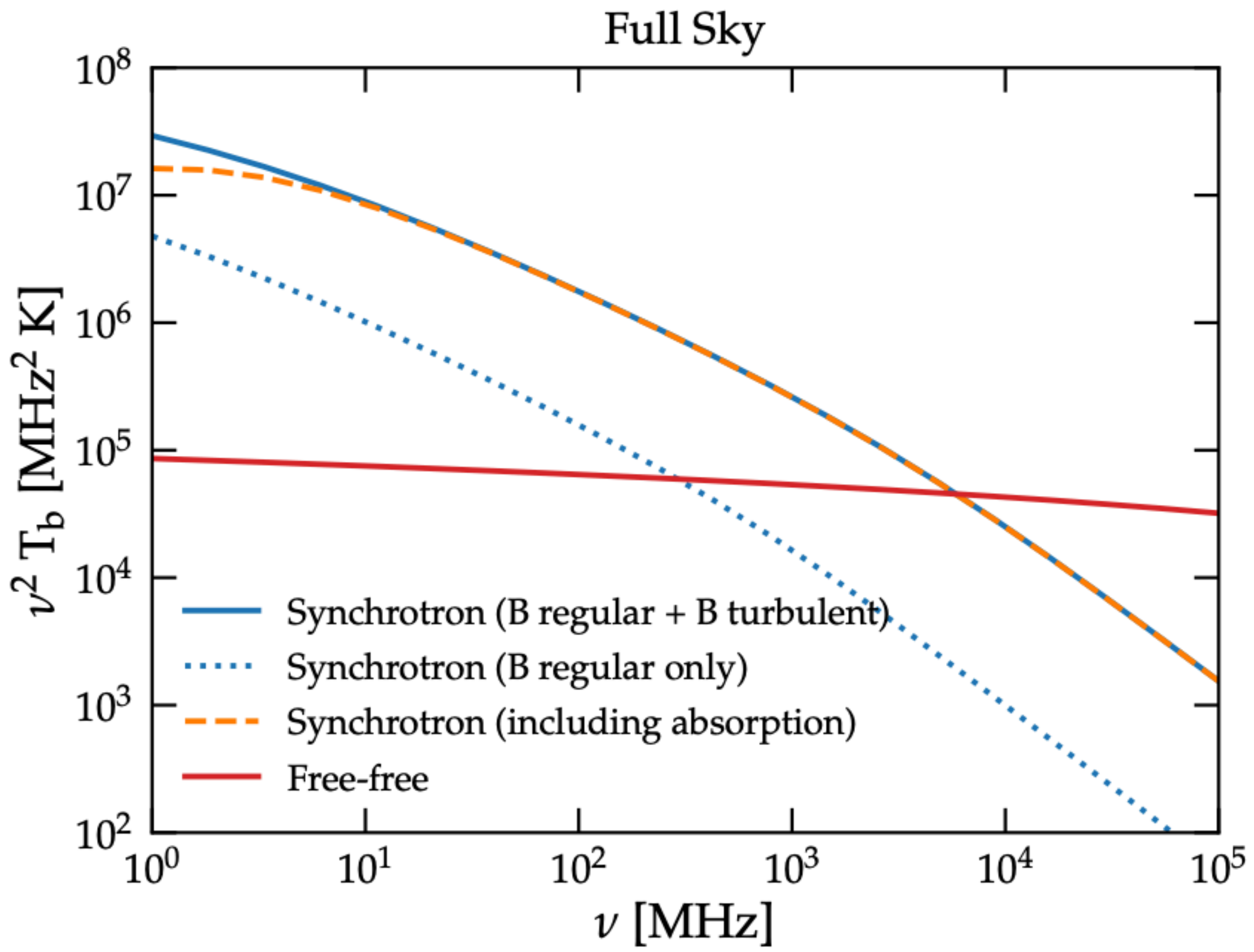


Fig. 7. Cartesian projection in Galactic coordinates of the IC gamma-ray flux at E_γ = 10 GeV.



Synchrotron radiation => Blackboard





Dundovic+ A&A'22

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

Proton-photon interactions

Collisional effect, catastrophic E loss mechanism

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

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

Photo-pion production

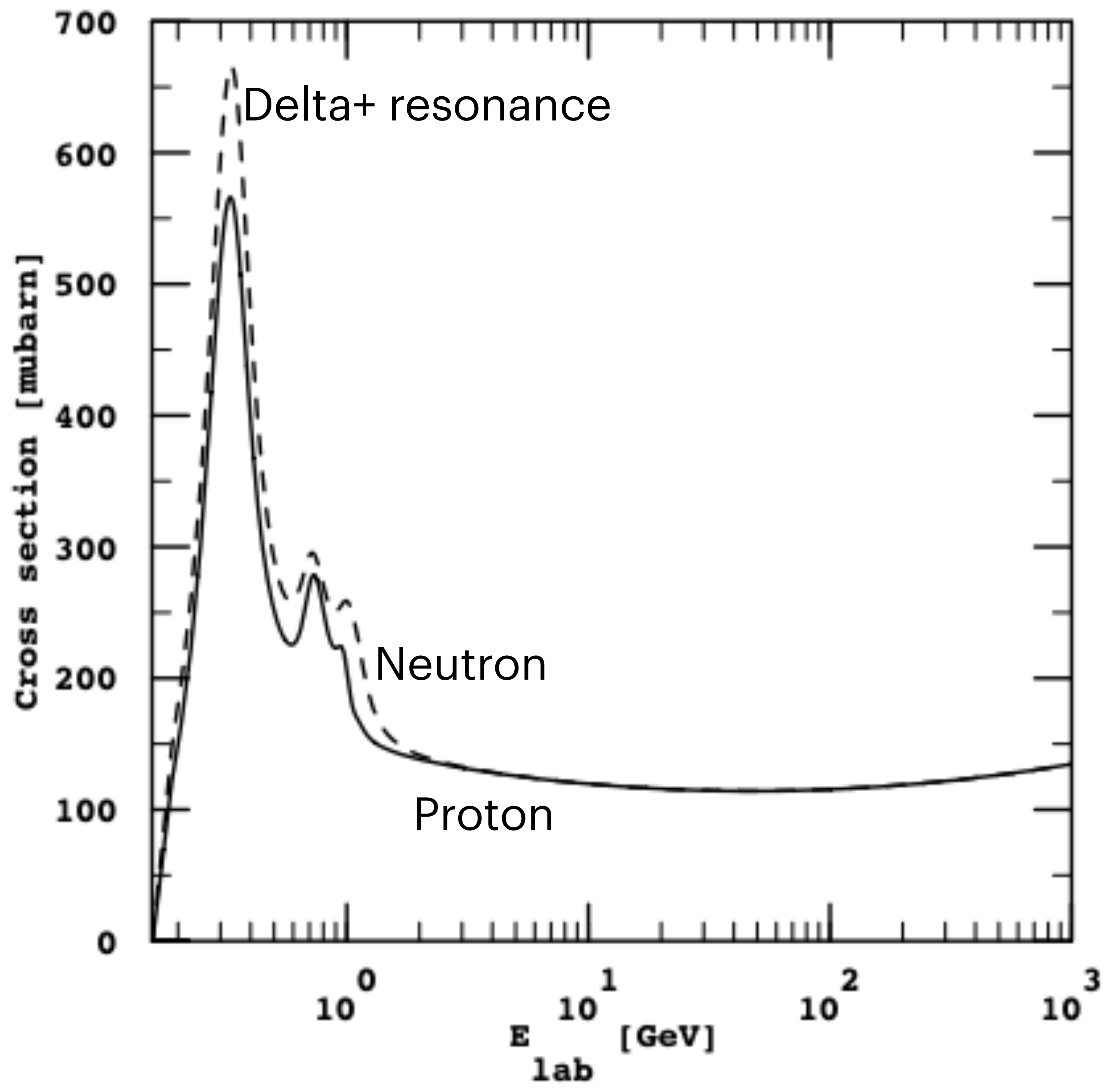
$$p_{\rm UHE} + \gamma_{\rm bkg} \to p + e^+ + e^-$$

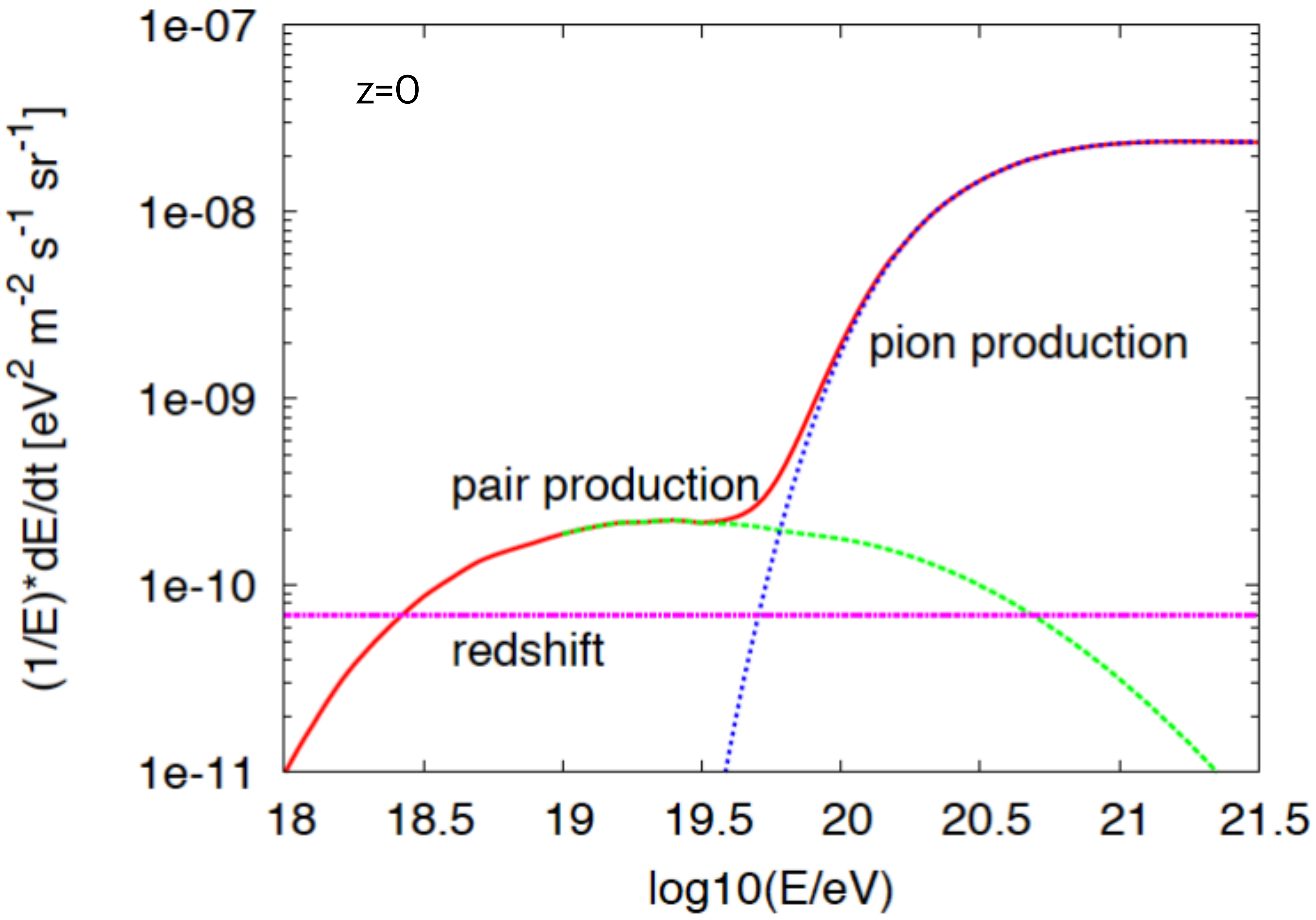
Pair production

=> Blackboard

Proton-photon interactions

Photo-pion production



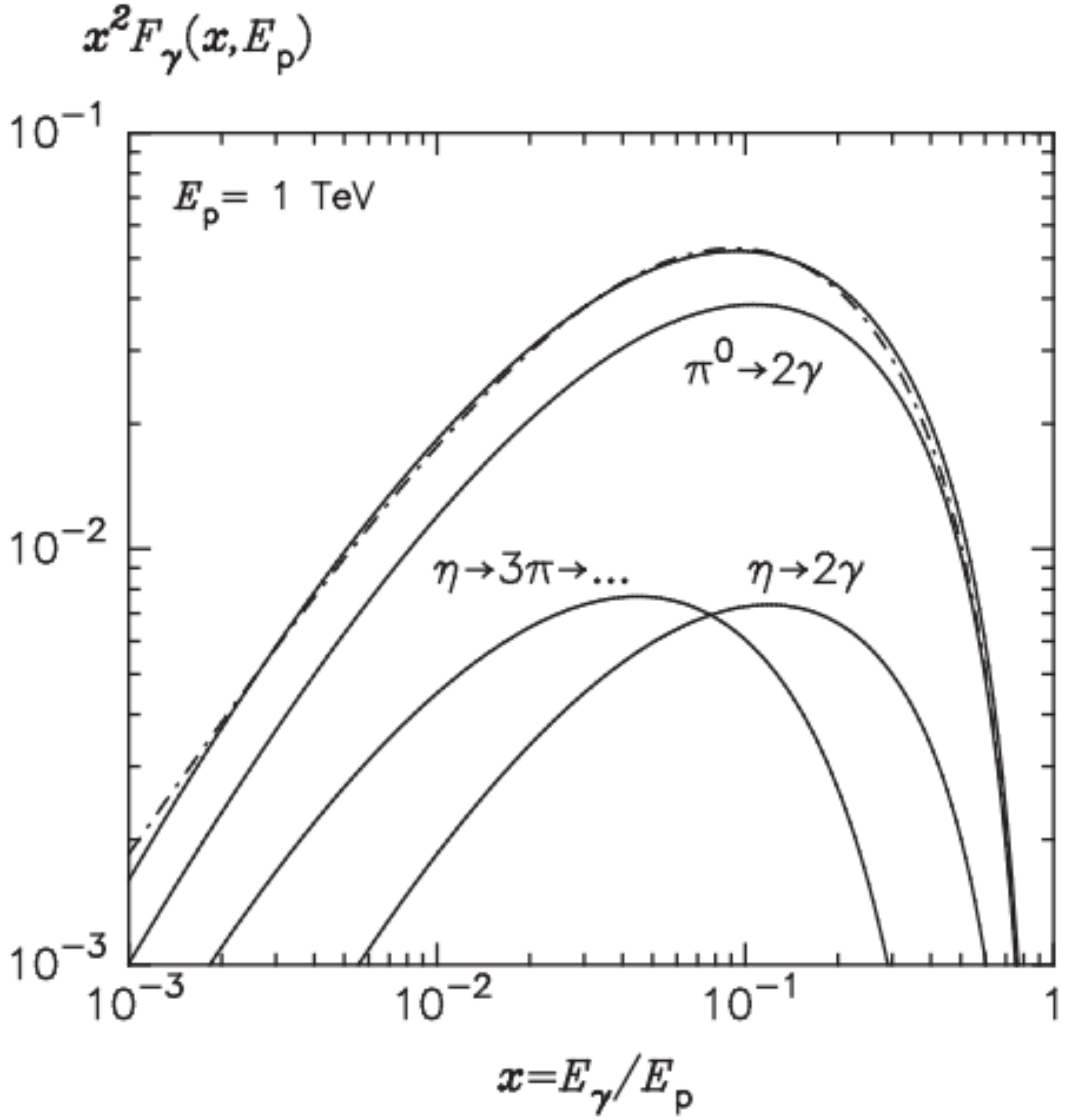


MW/MM connections

Photons from neutral pion decay

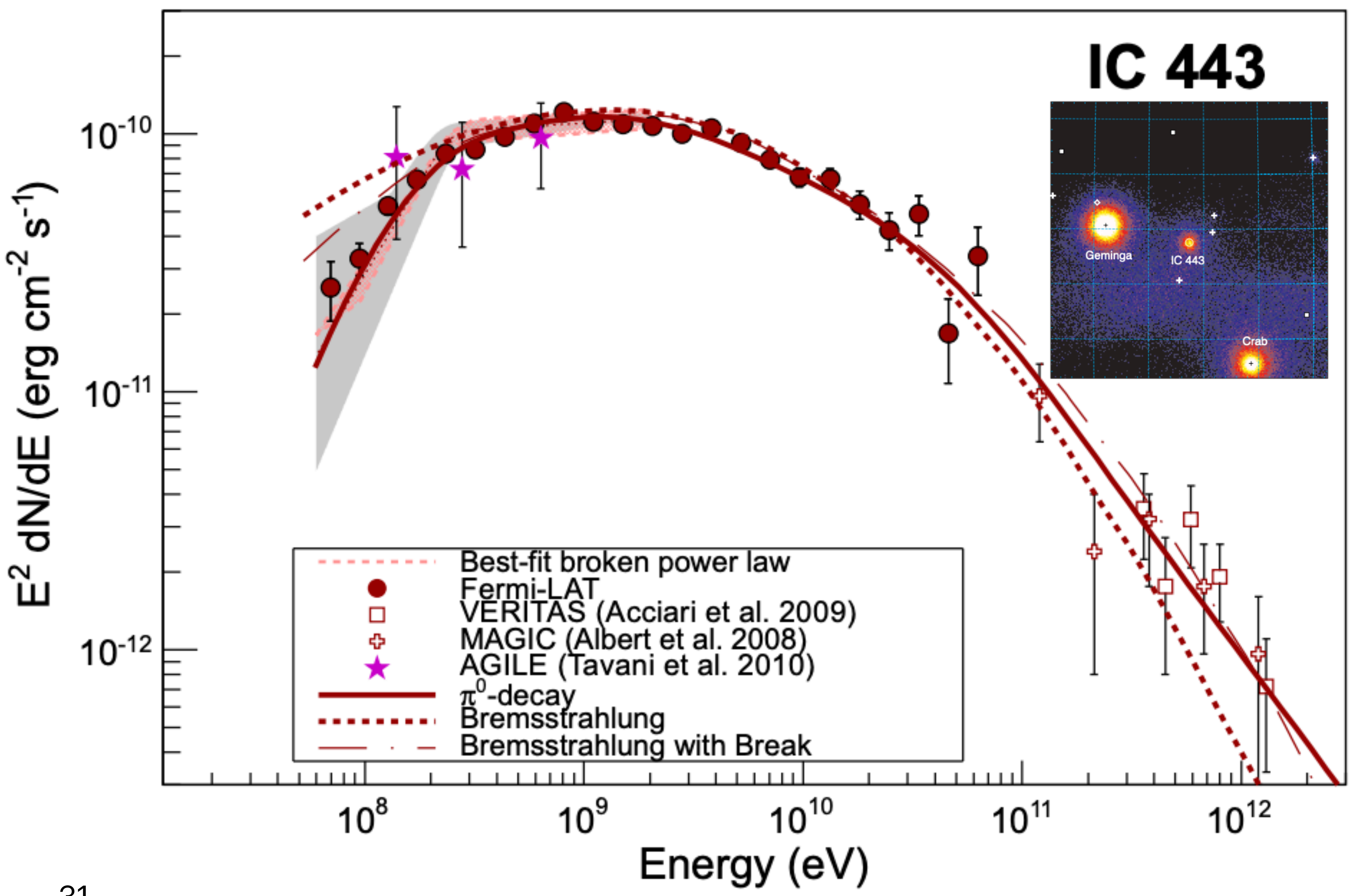
$$\pi_0 \to \gamma\gamma$$

=> Blackboard

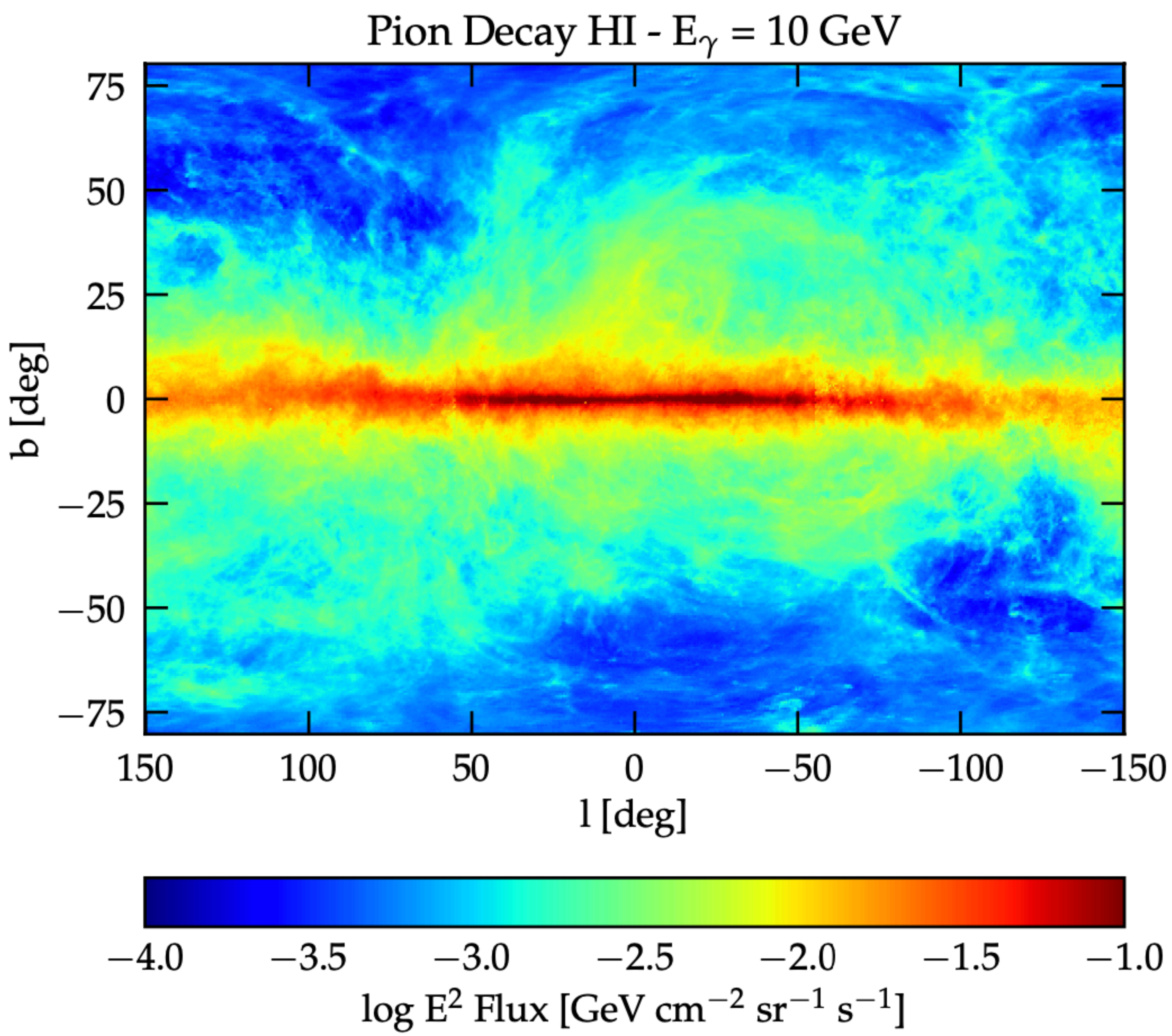


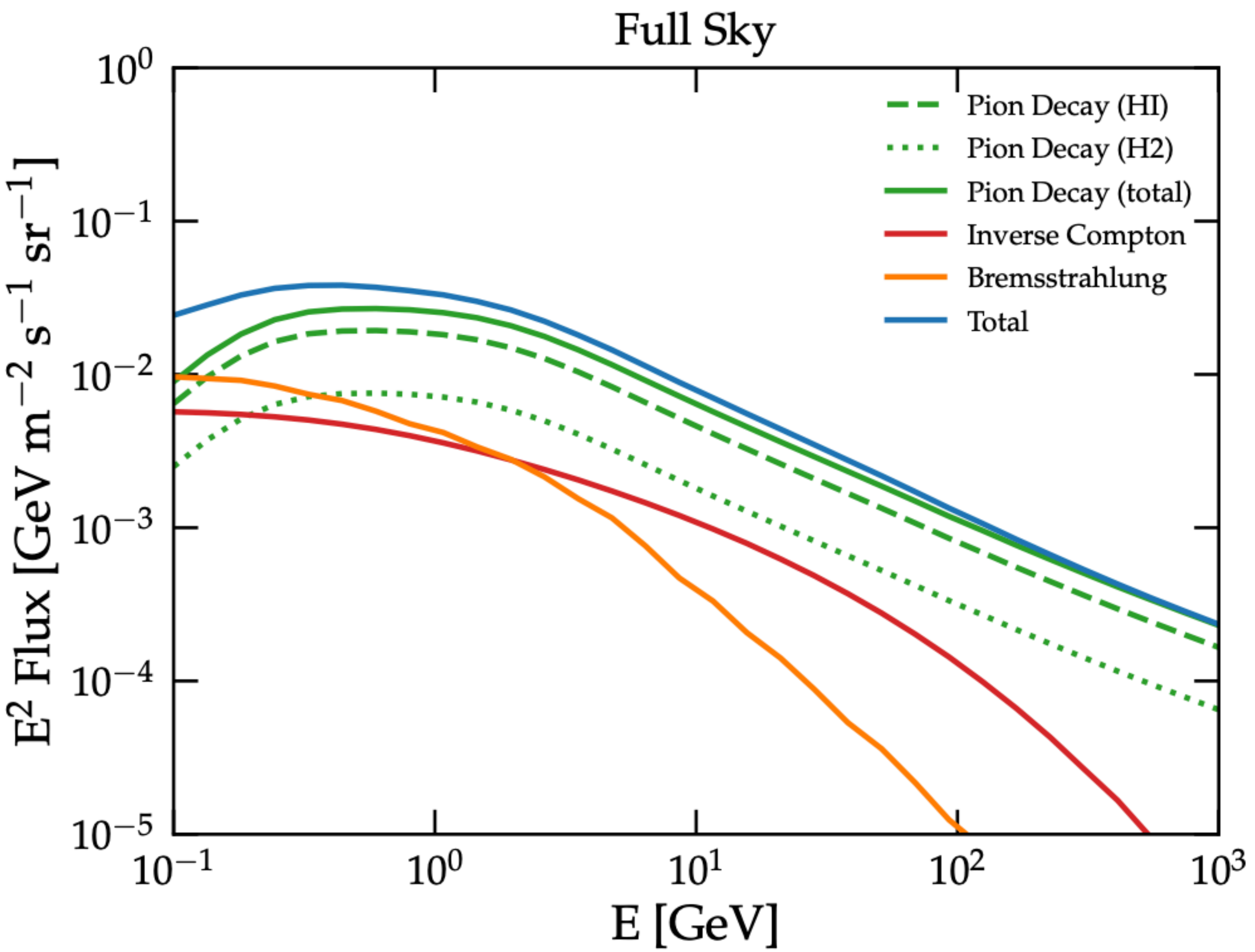
Kelner+ PRD'09

Ackermann+ Science'13



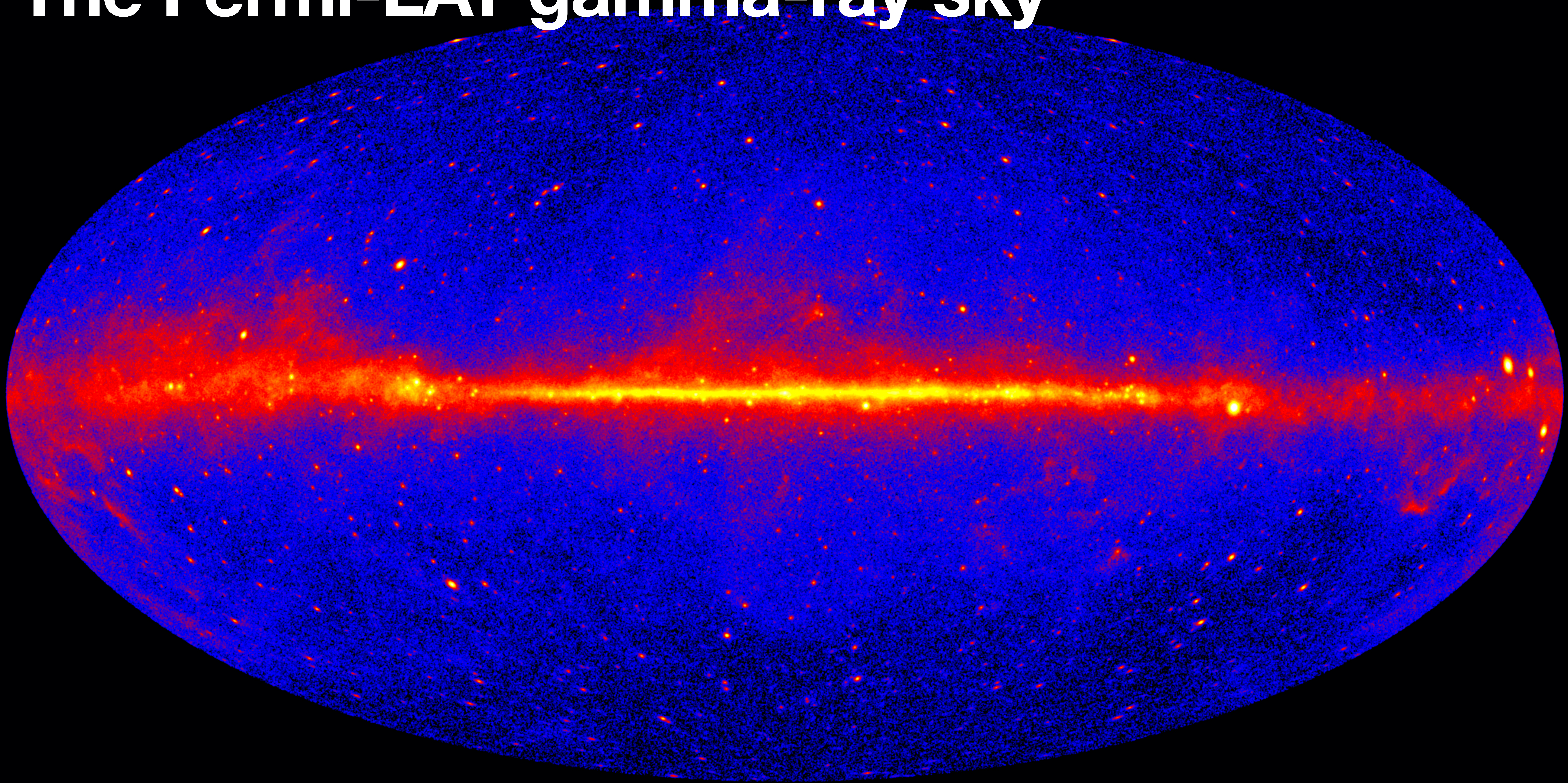
Photons from neutral pion decay





Dundovic+ A&A'22

The Fermi-LAT gamma-ray sky



Neutrinos from charged pions

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

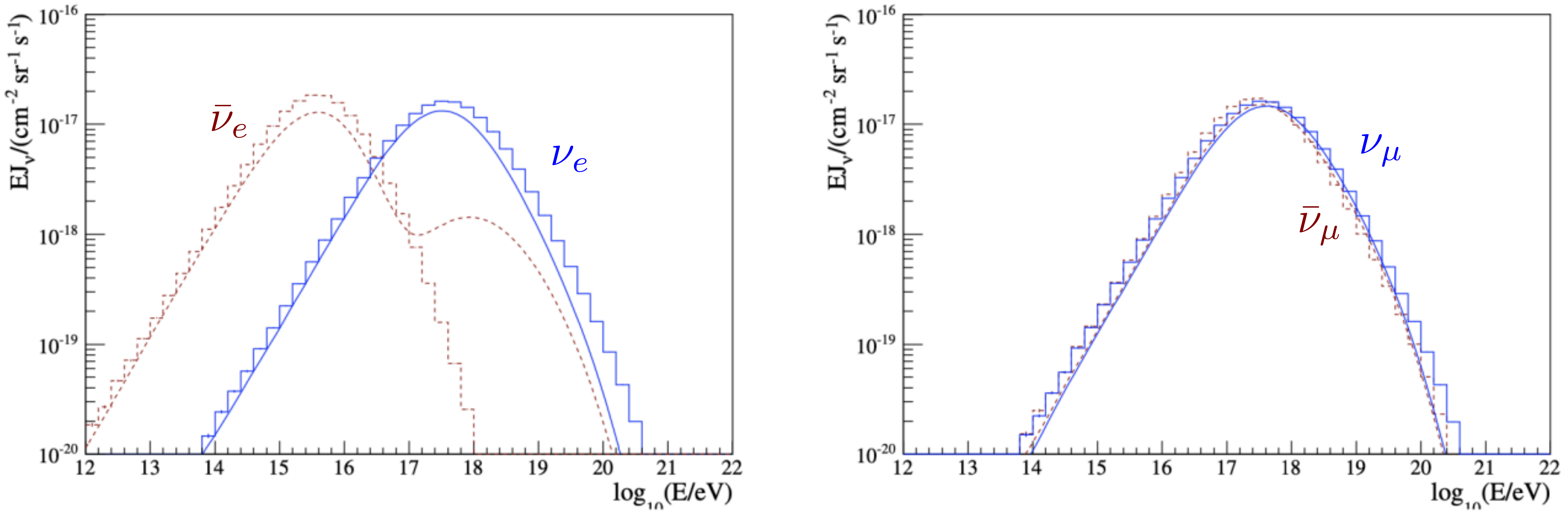


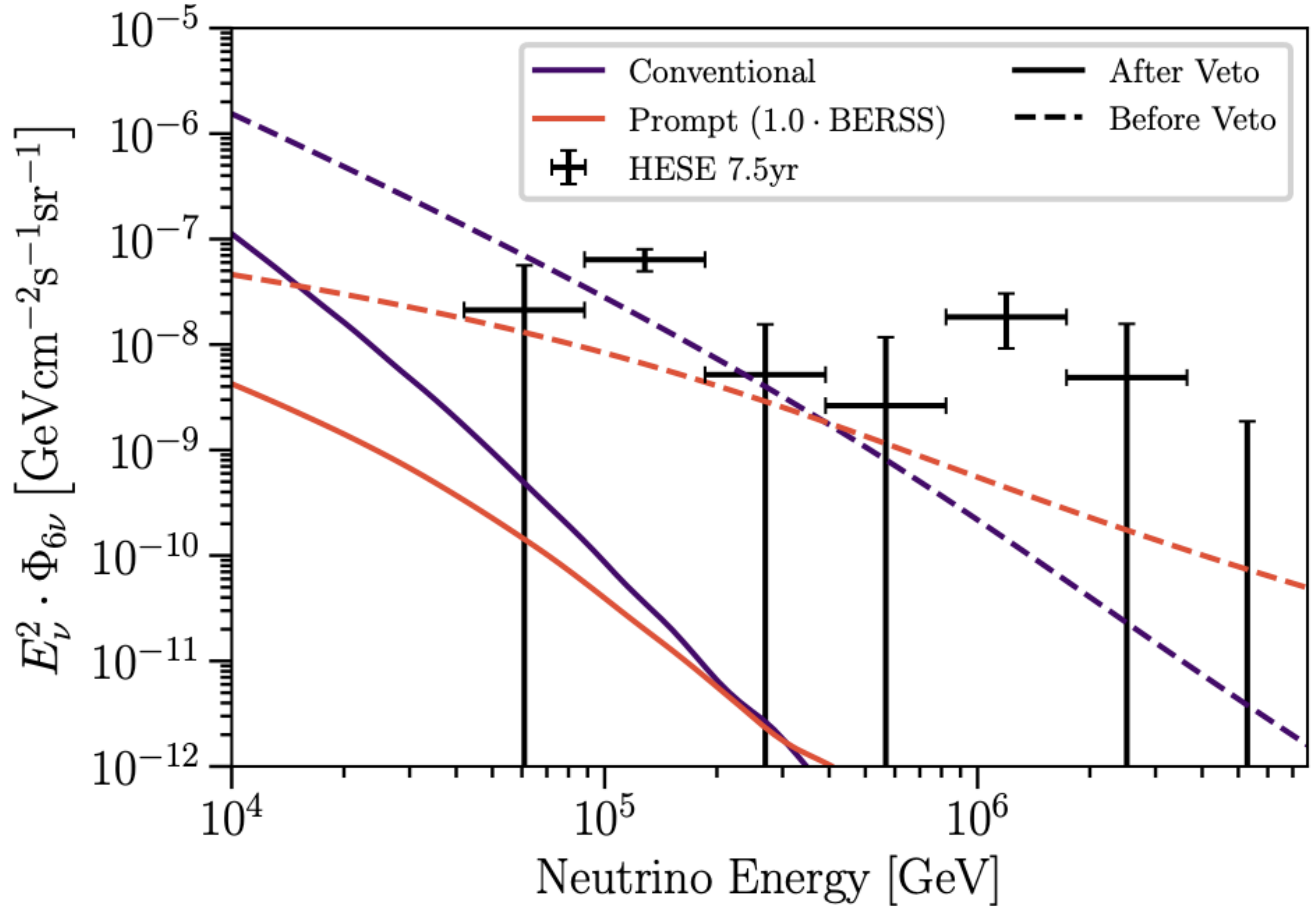
Fig. 14. – Left panel: fluxes of electron (blue solid line) and anti-electron (red dashed line) neutrinos generated in propagation of protons through CMB. Right panel: fluxes of muon (blue solid line) and anti-muon (red dashed line) neutrinos. The histograms are obtained from *SimProp* simulations, while the lines are taken from [48]. Reproduced with permission from [49].

Boncioli 2309.12743

High-energy astrophysical neutrinos

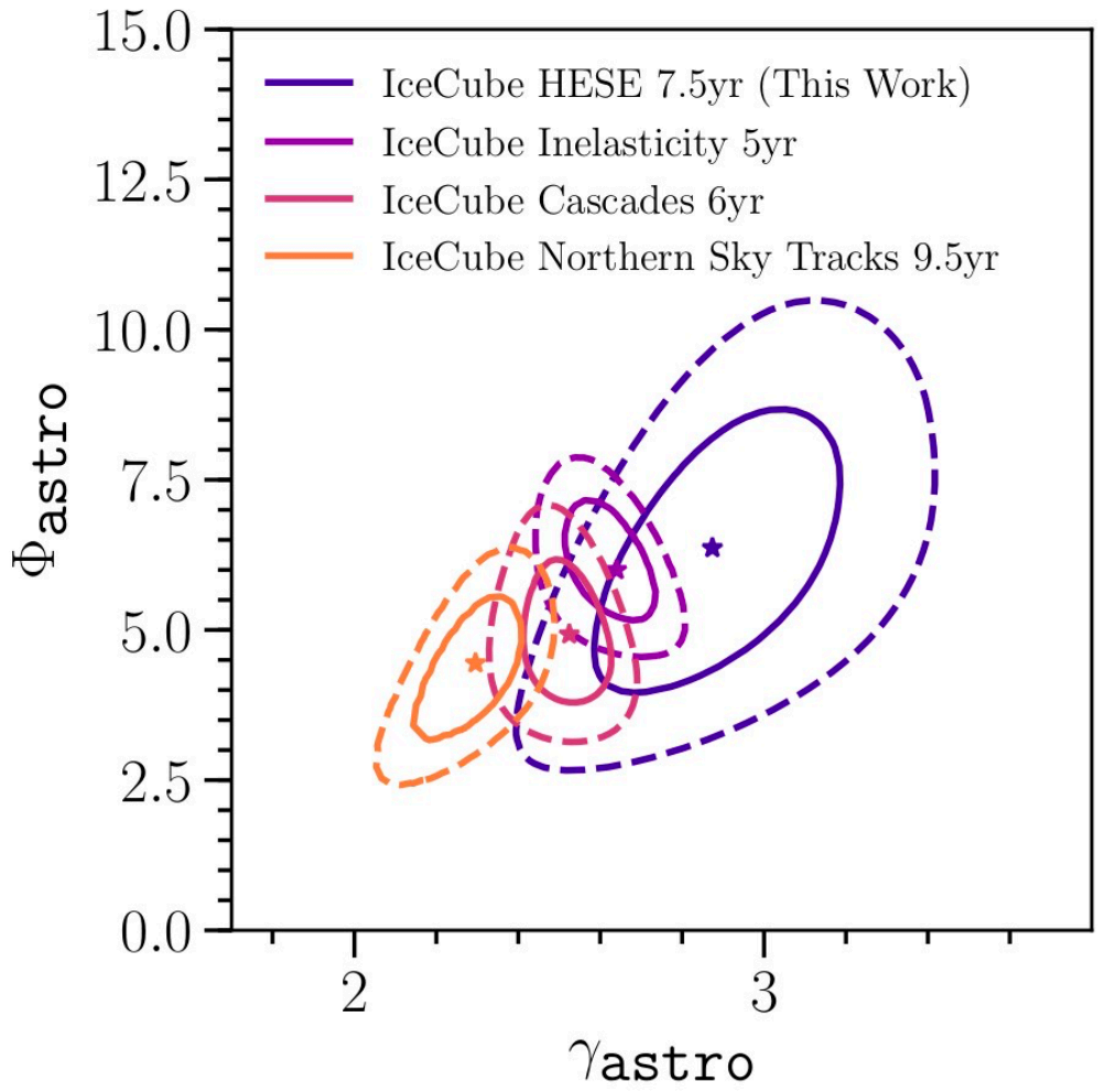
Energy spectrum

IceCube Collab. PRD'21



Data is fit well by a single power law:

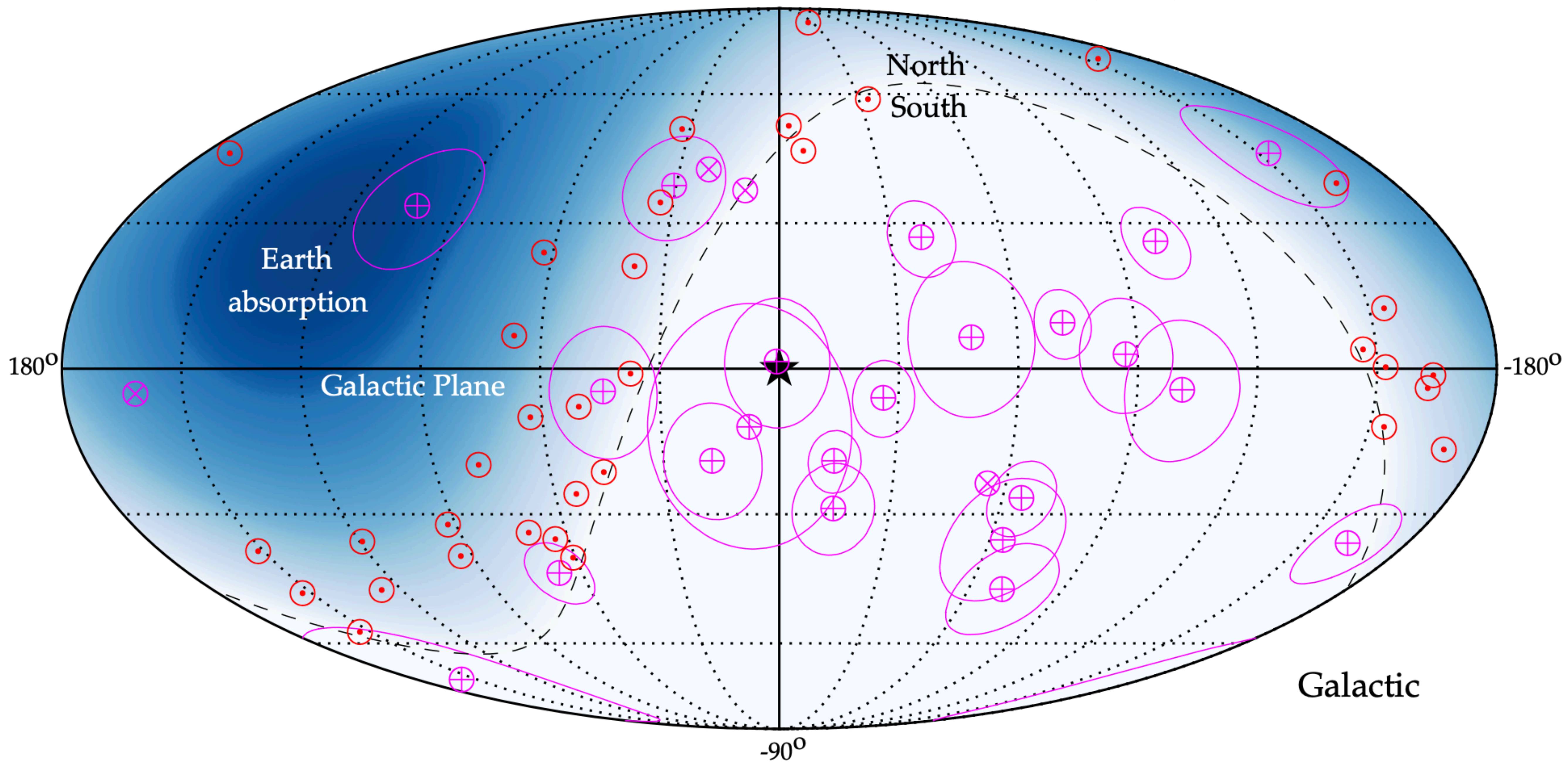
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-\gamma_{\rm astro}} \cdot 10^{-18}\ \rm GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$$



High-energy astrophysical neutrinos

Arrival directions

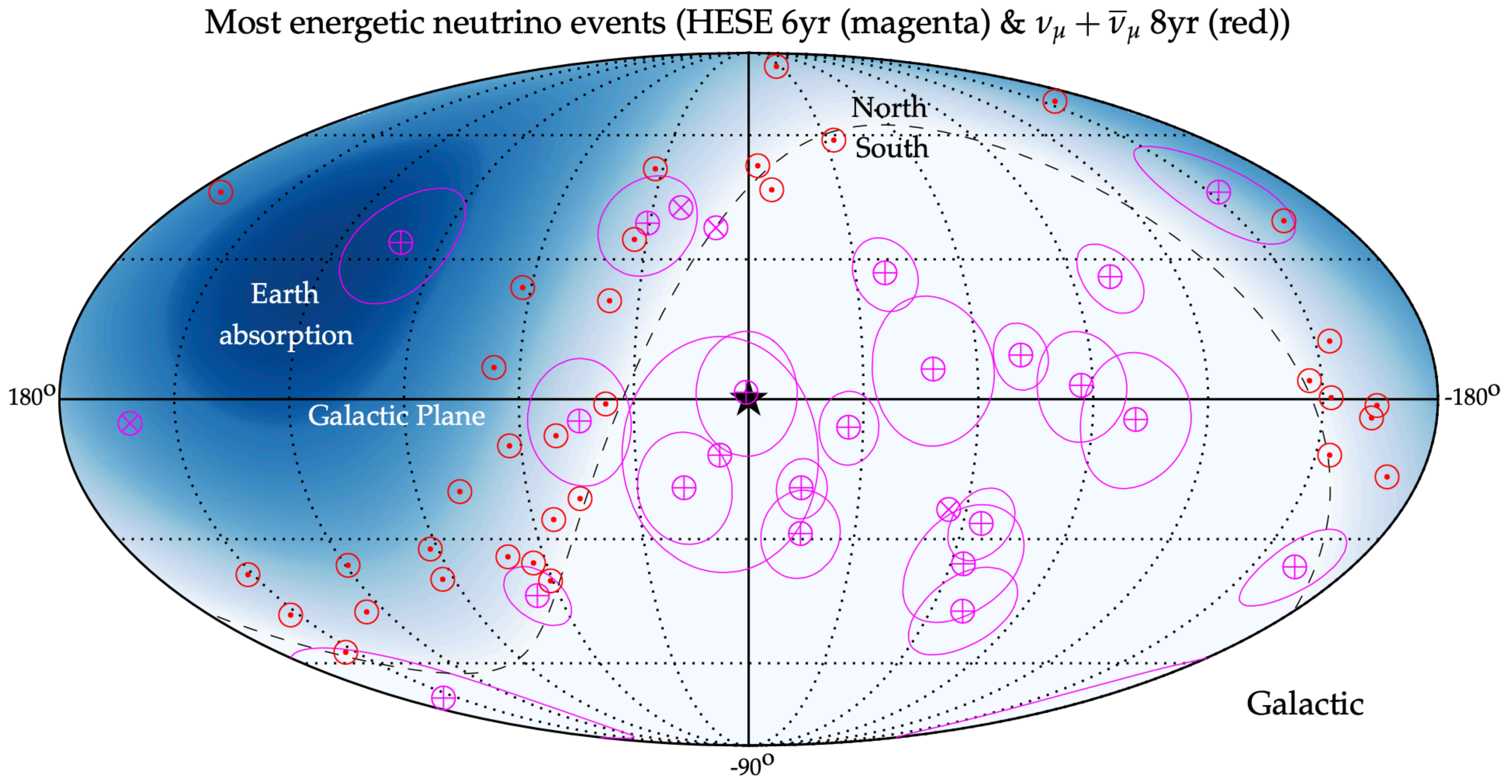
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red))

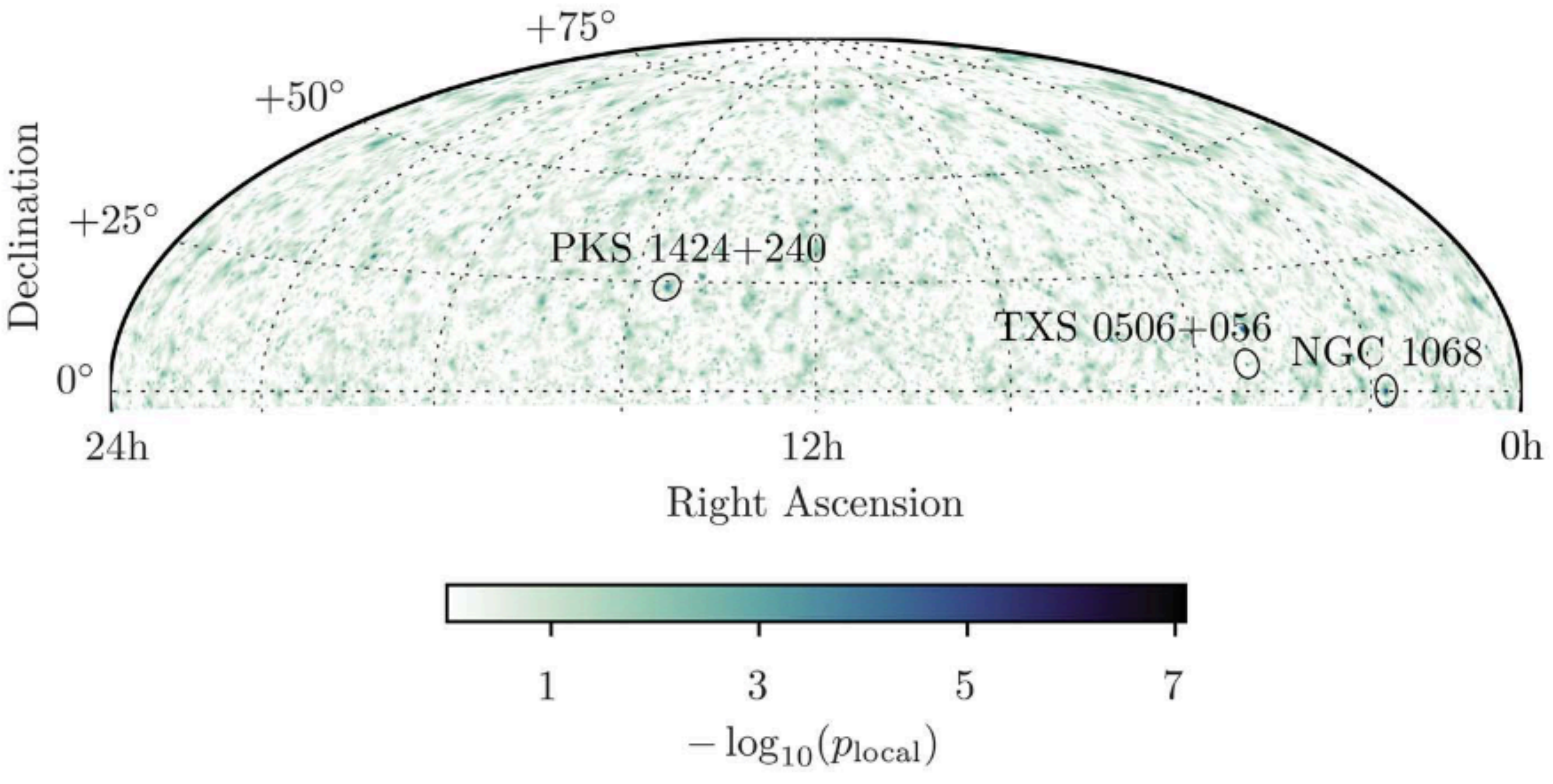


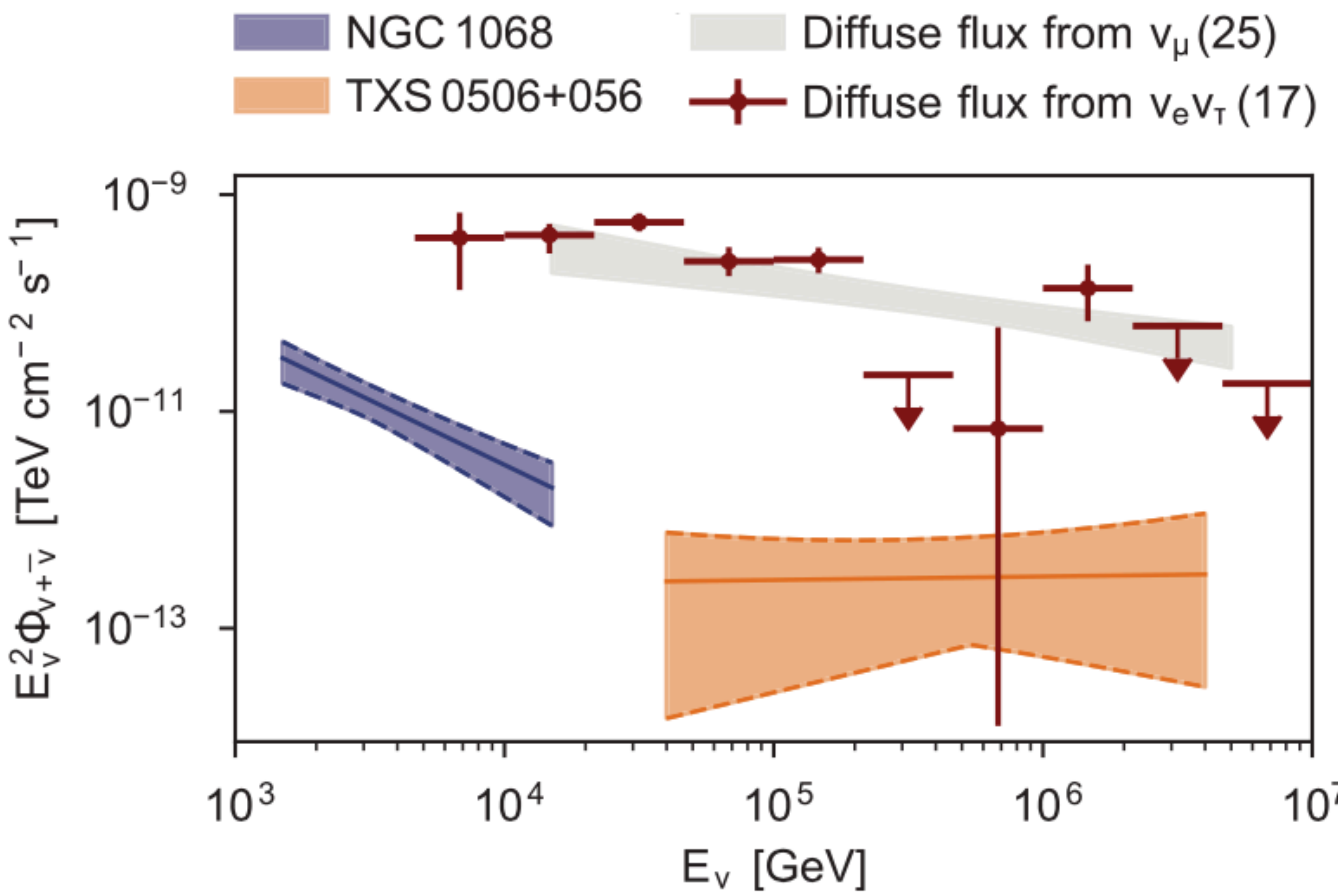
High-energy astrophysical neutrinos

Arrival directions: point sources

IceCube Collab., Science 378, 538 (2022)



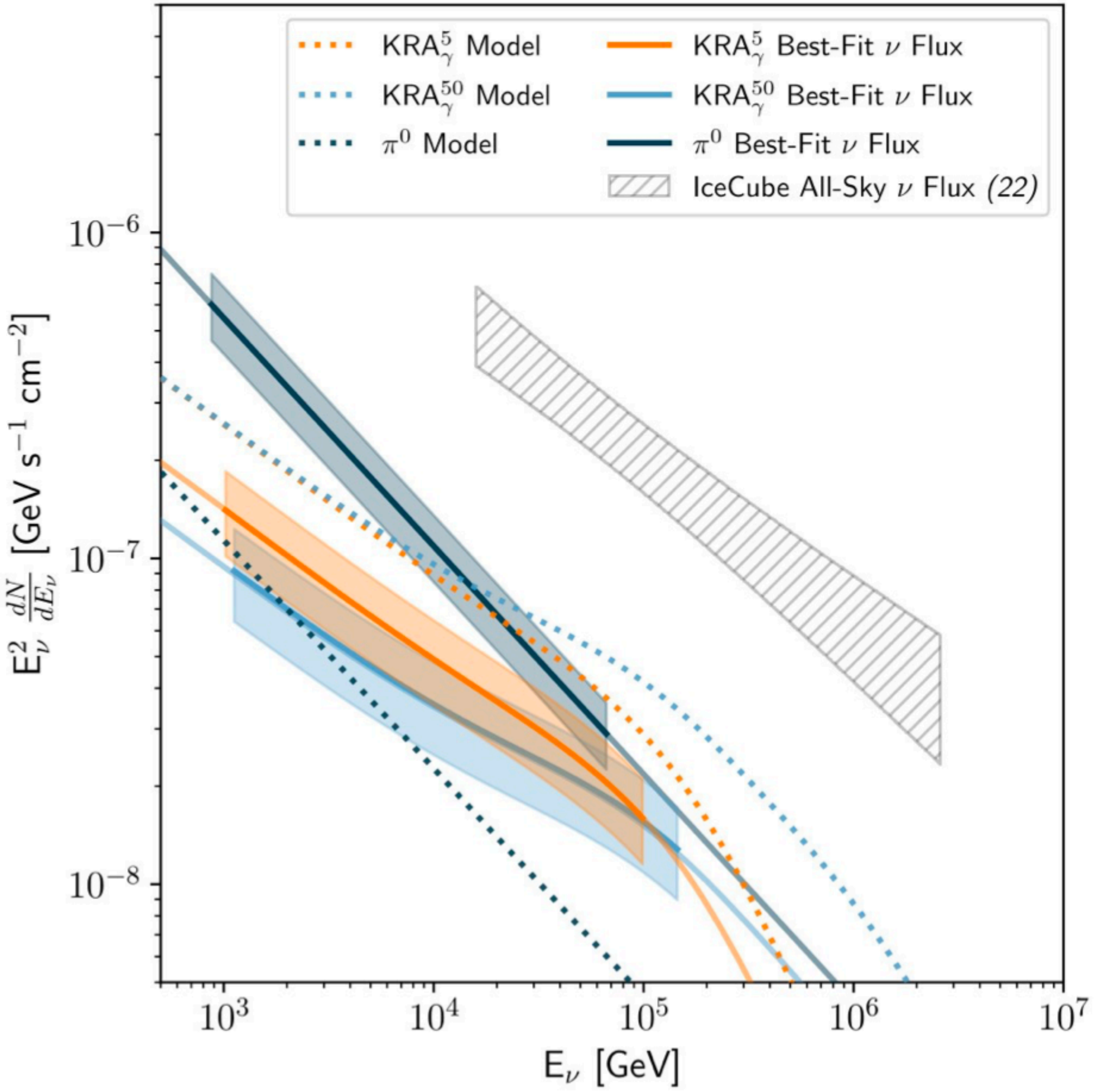




High-energy astrophysical neutrinos

Arrival directions: Galactic events

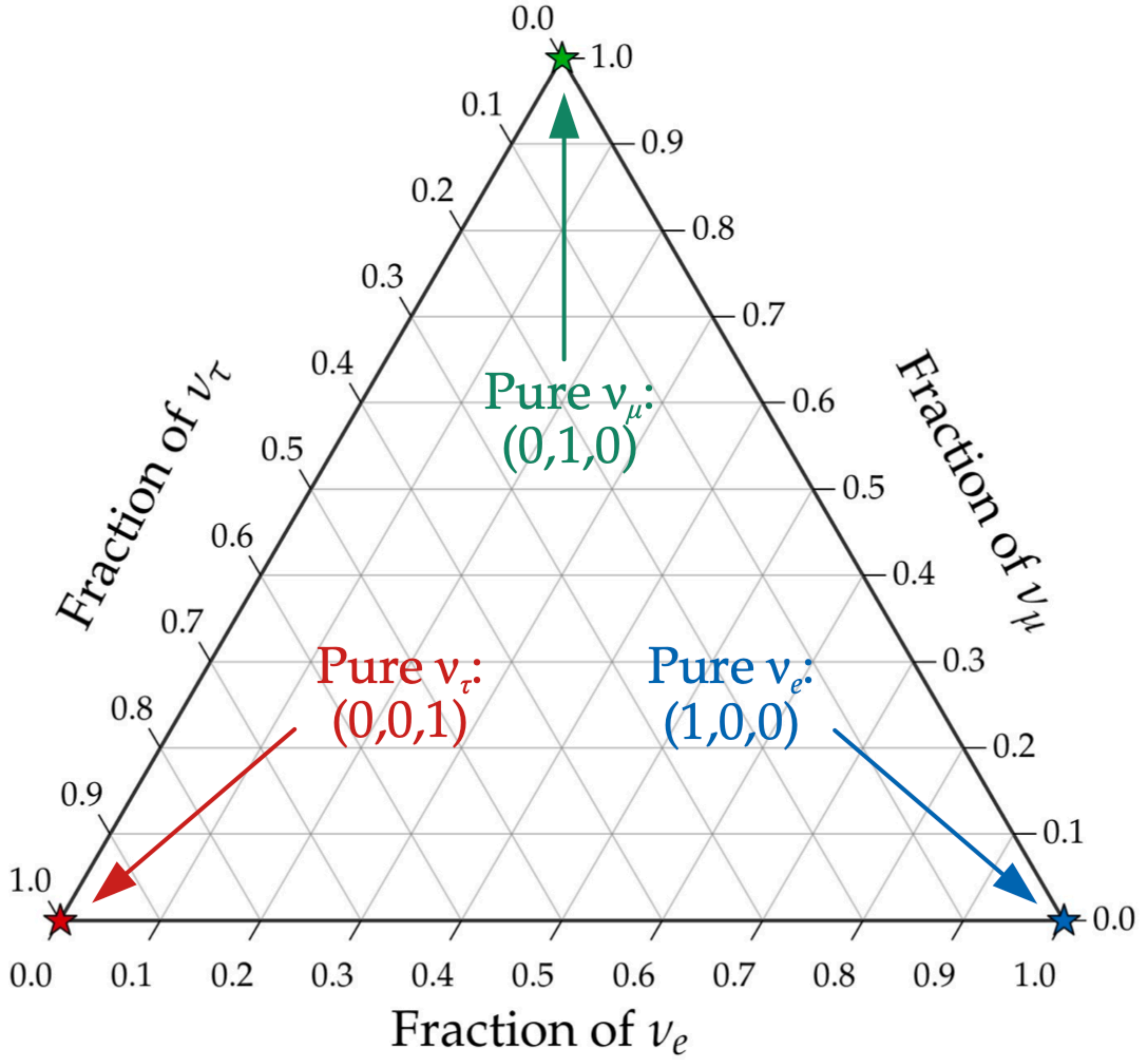
IceCube Collab., Science 2023

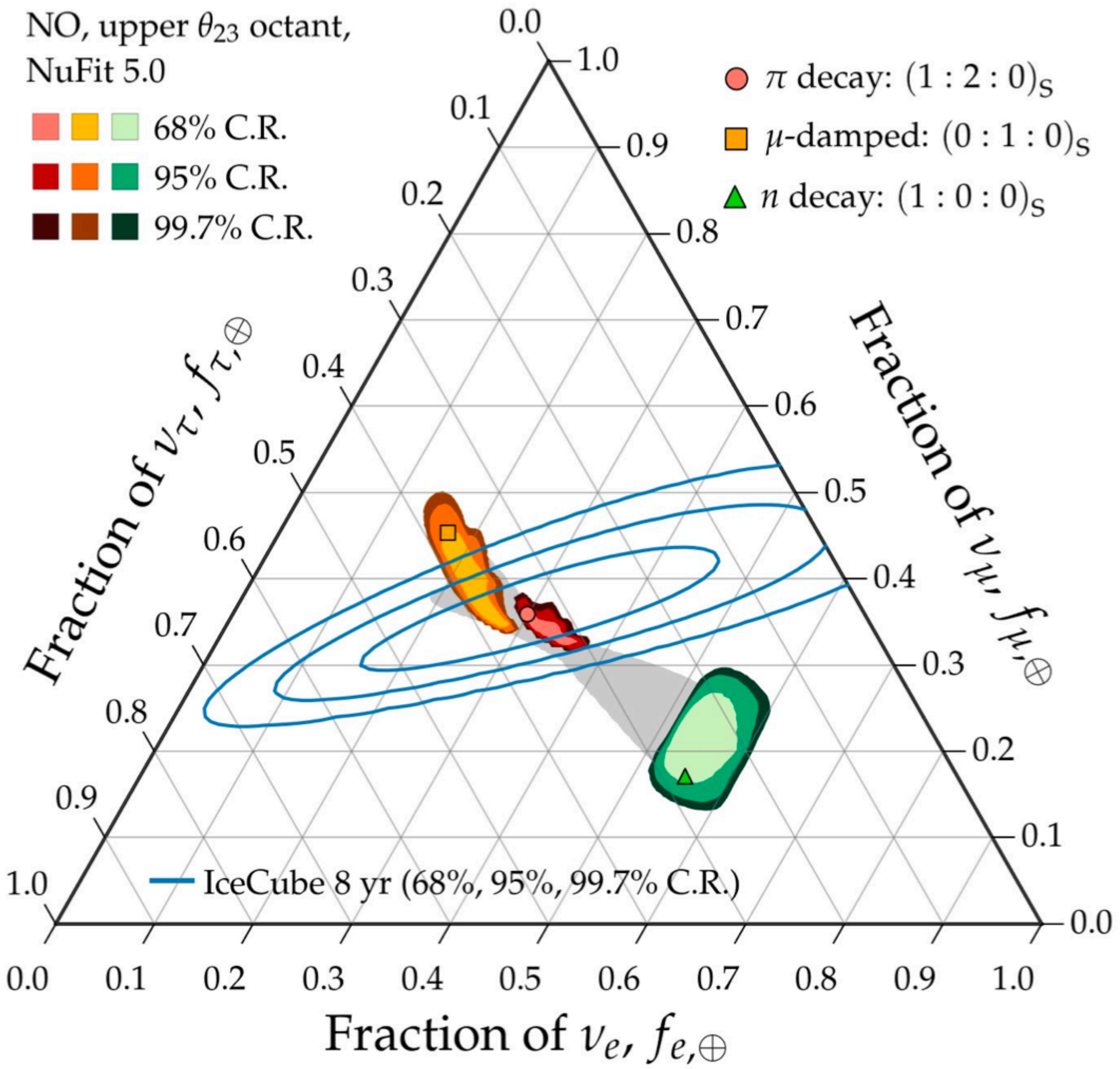


- None of the models matched data — but they are quite simple models
- **No Galactic** neutrino **source** is identified — likely som of diffuse + source [*Fang & Murase, 2307.02905*]
- Galactic plane flux is **6–13% of all-sky** at 30 TeV

High-energy astrophysical neutrinos

Flavor composition

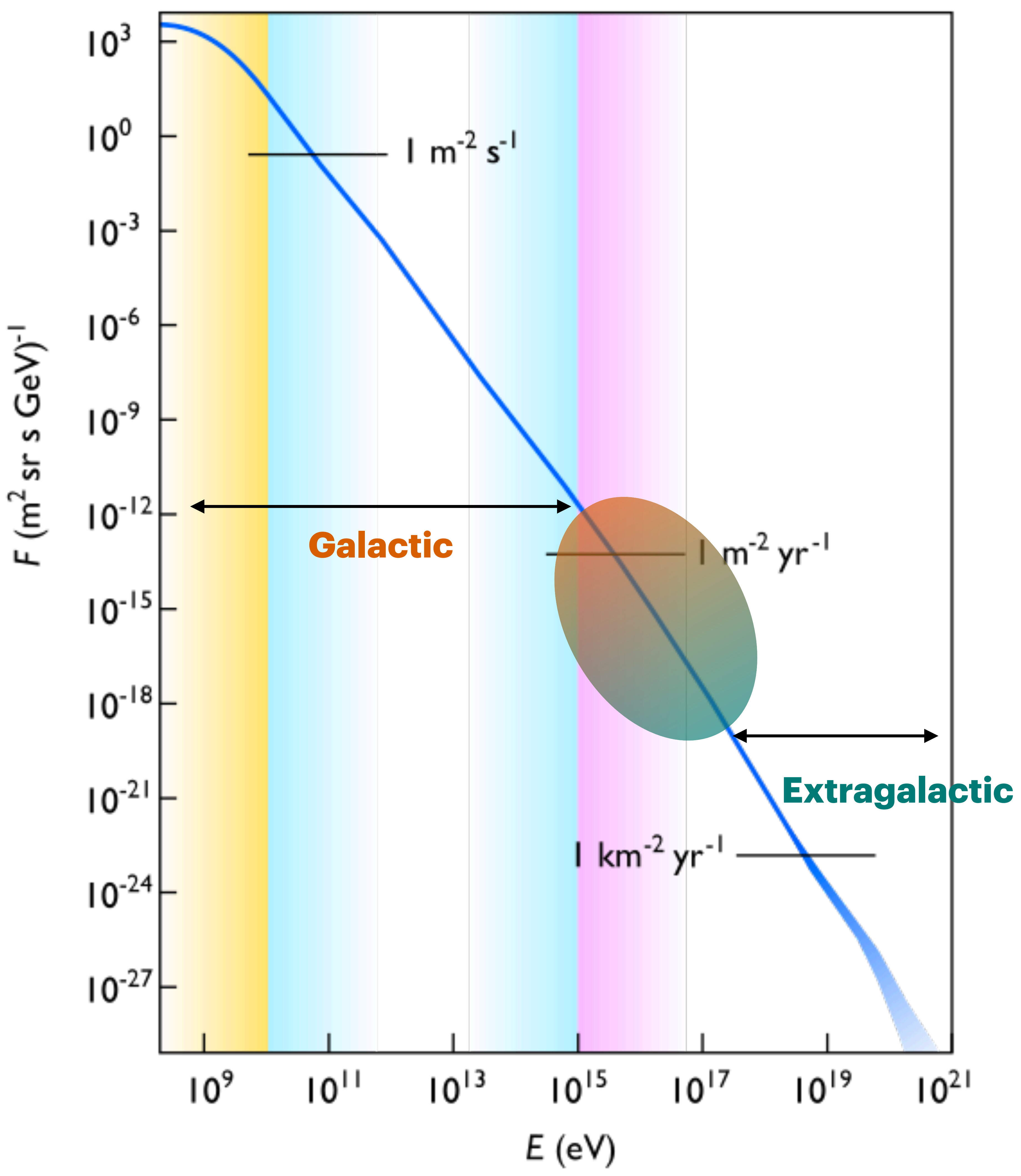




Song+ JCAP 2021

Sources
astro & exotic

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

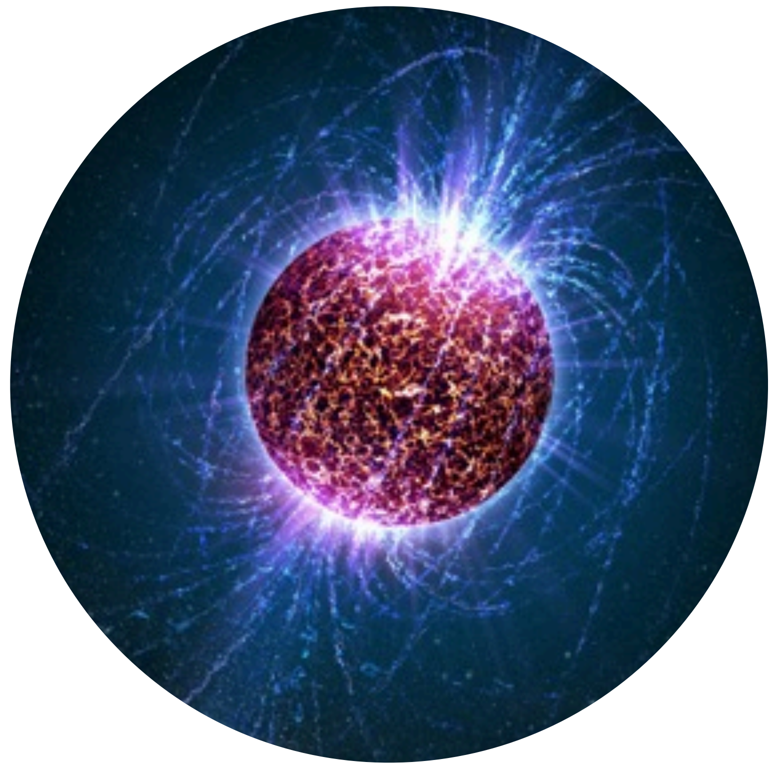
Open questions:

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

Particle acceleration

=> Blackboard

Non-thermal emission refers to source injection...

"The word [**non-thermal**] is conventionally taken to mean continuum radiation from particles, the energy spectrum of which is **not Maxwellian**. [...] If it cannot be accounted for by the spectrum of thermal bremsstrahlung or black-body radiation"

M. Longair

Queen of the non–thermal particle distribution: Power law

$$N(E) = N_0 E^{-p}$$

$$N(\gamma) = K\gamma^{-p} \qquad \gamma = 1/(1-\beta^2)^{1/2}$$ Relativistic particles

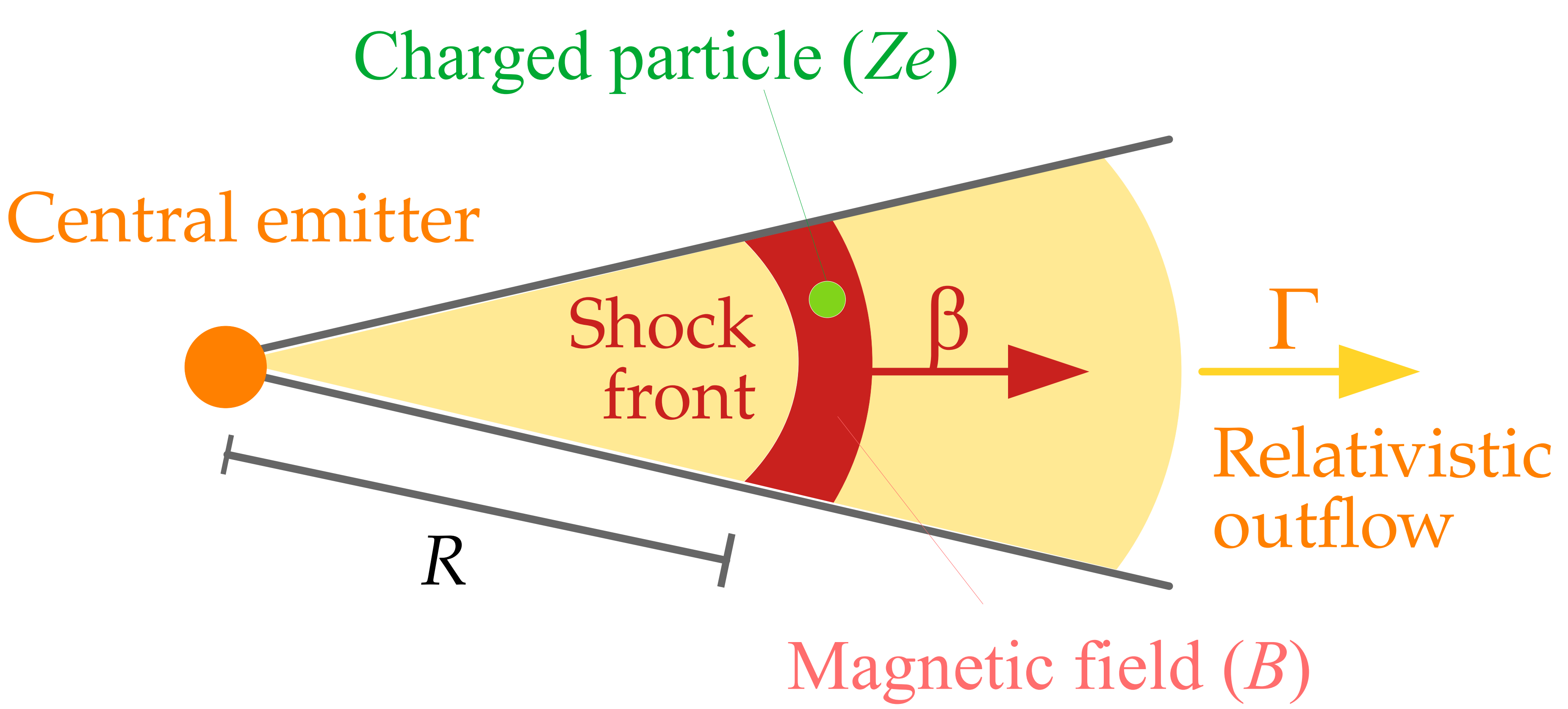
The main acceleration process leading to a power–law distribution (but not the only one) is **shock acceleration** $p \sim 2$

Confinement condition

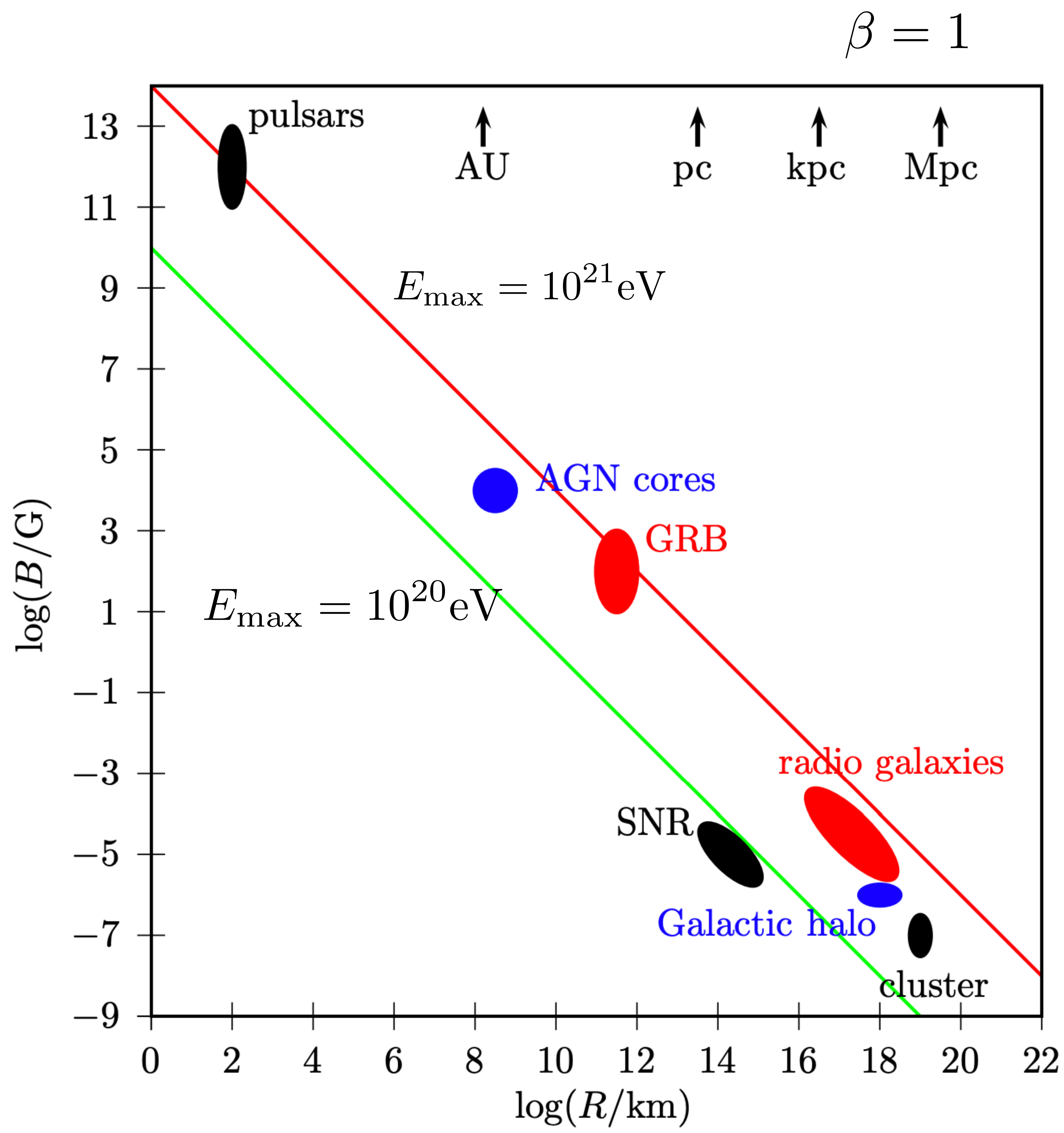
Necessary condition for acceleration:

The system must be able to contain the particle

$$r_L \lesssim R$$



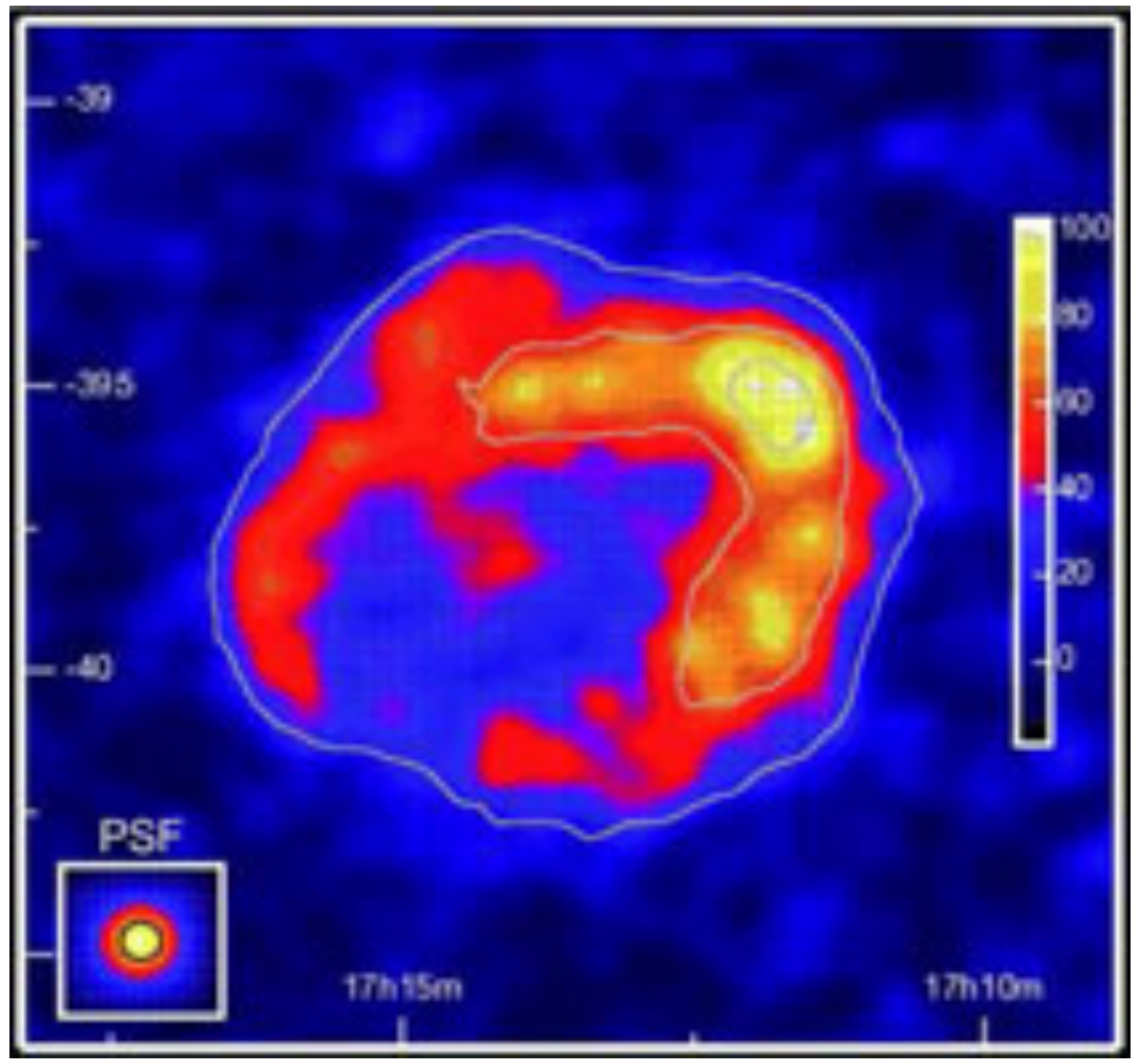
Hillas Plot



CR accelerators: Supernova remnants

Maximum energy

v_{sh} ~ 10^3 km/s, B ~few mG => Emax ~ 10^{17} eV

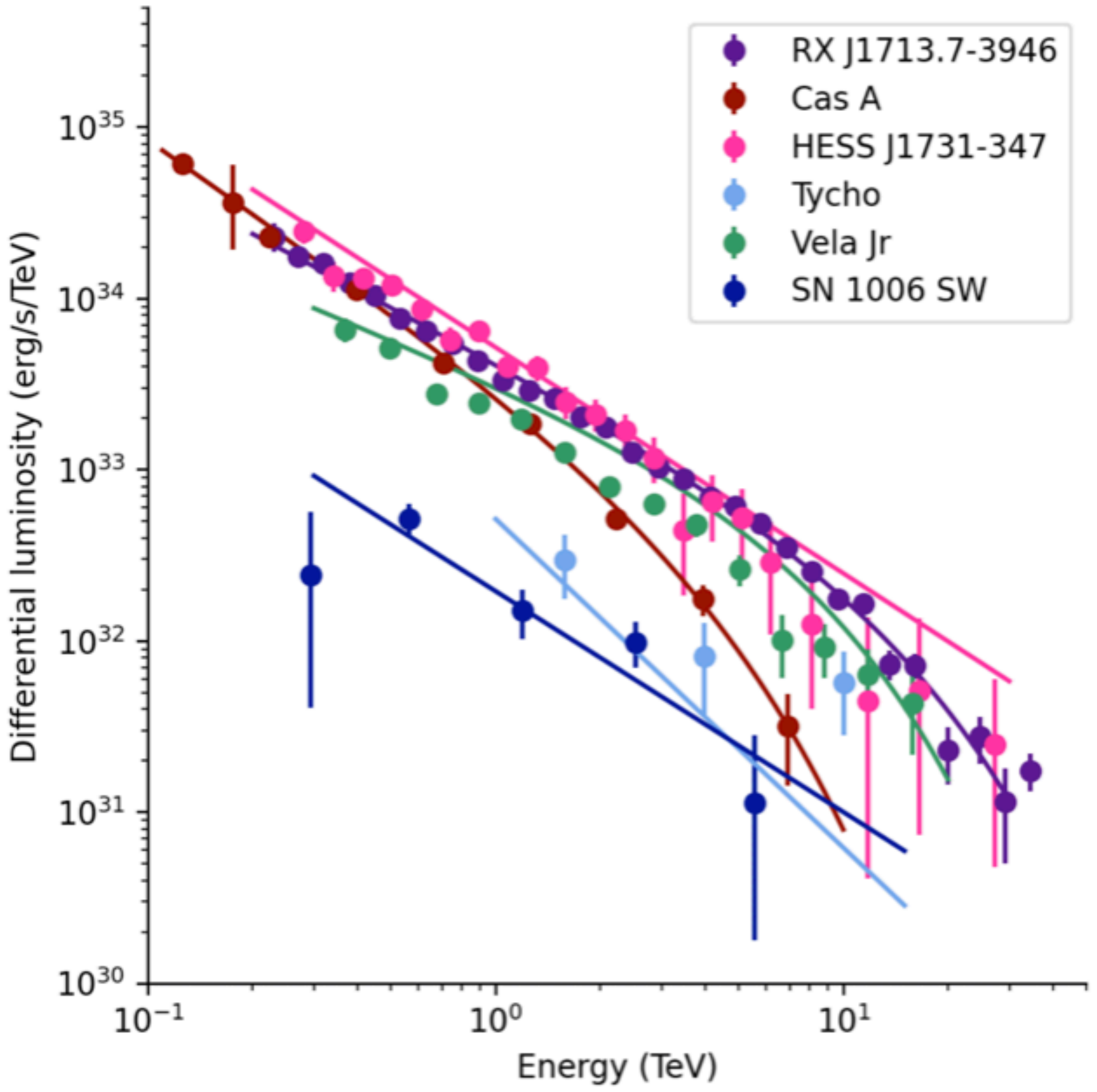


Aharonian+ A&A'07

We see **pion bump** at GeV energies (**proton** acceleration)

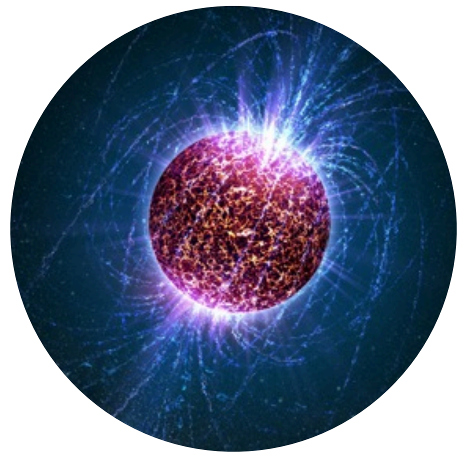
We see TeV shells (e.g. HESS)

We do not see PeV accelerated particles from SNR



[Others: stellar clusters, no indication of a TeV cutoff so far]

Pulsars



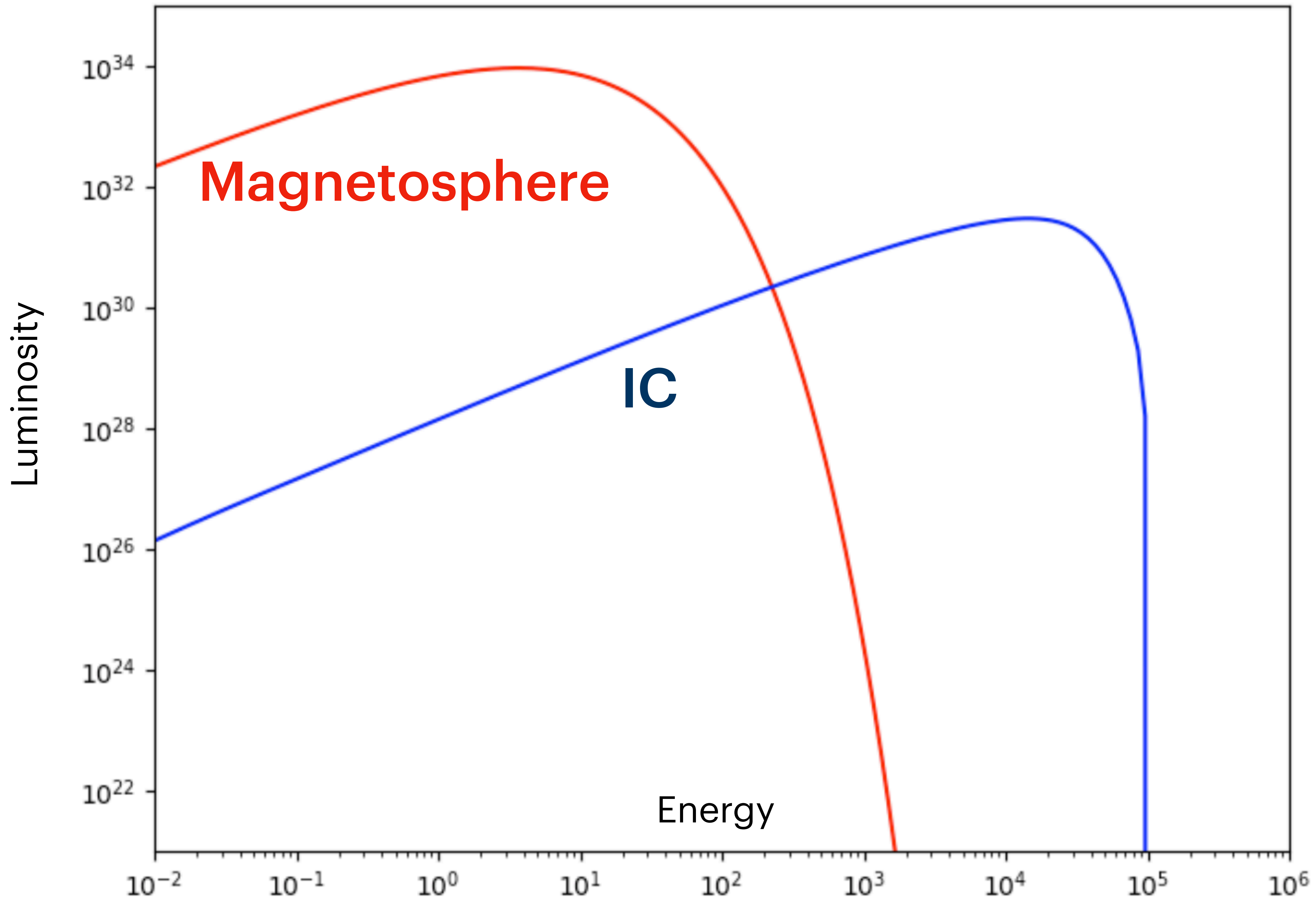
GeV — TeV emitters

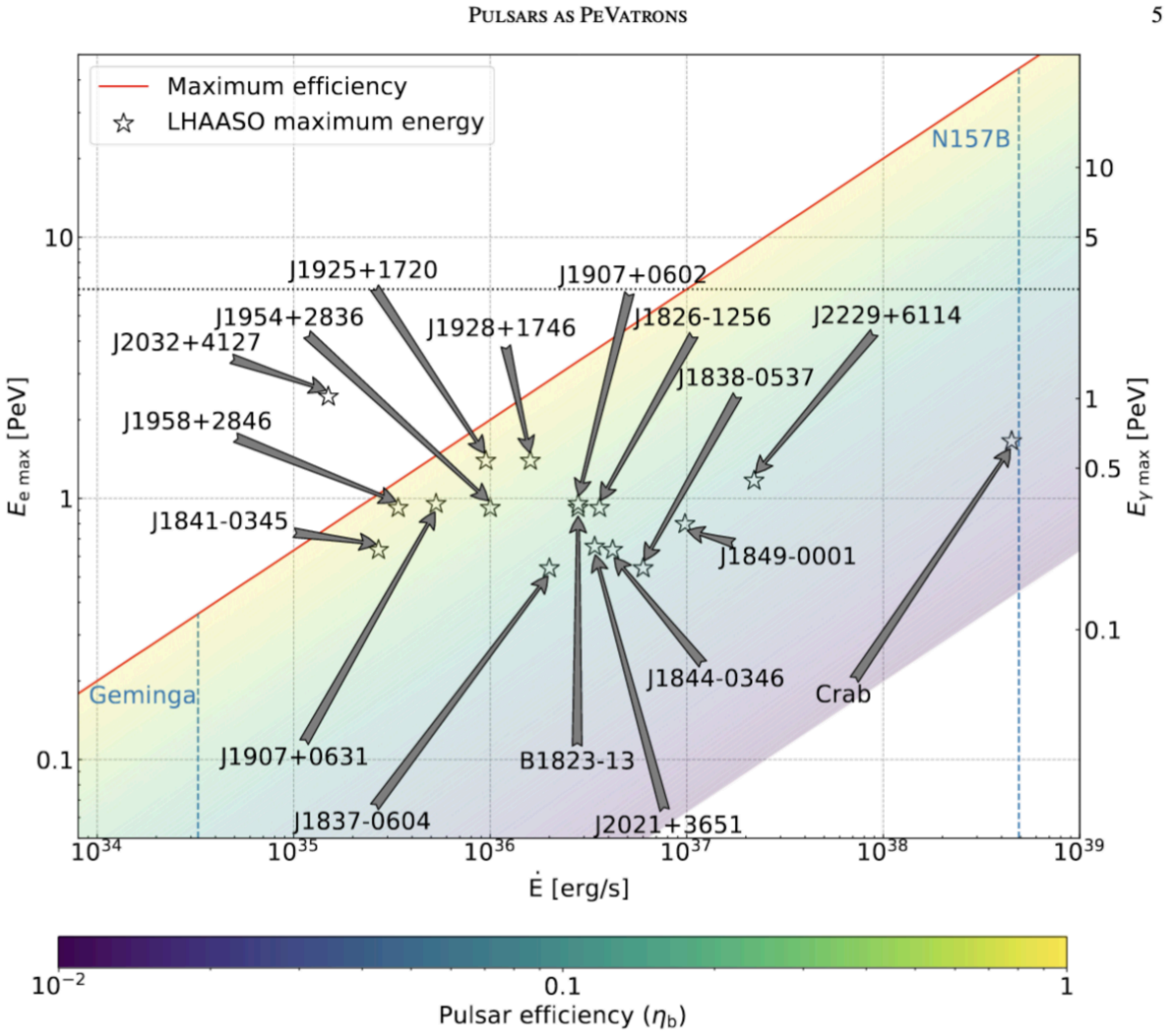
HE: curvature radiation from acceleration in magnetosphere

VHE: IC on low-energy target photons

LHAASO observed ~10 PeVatrons

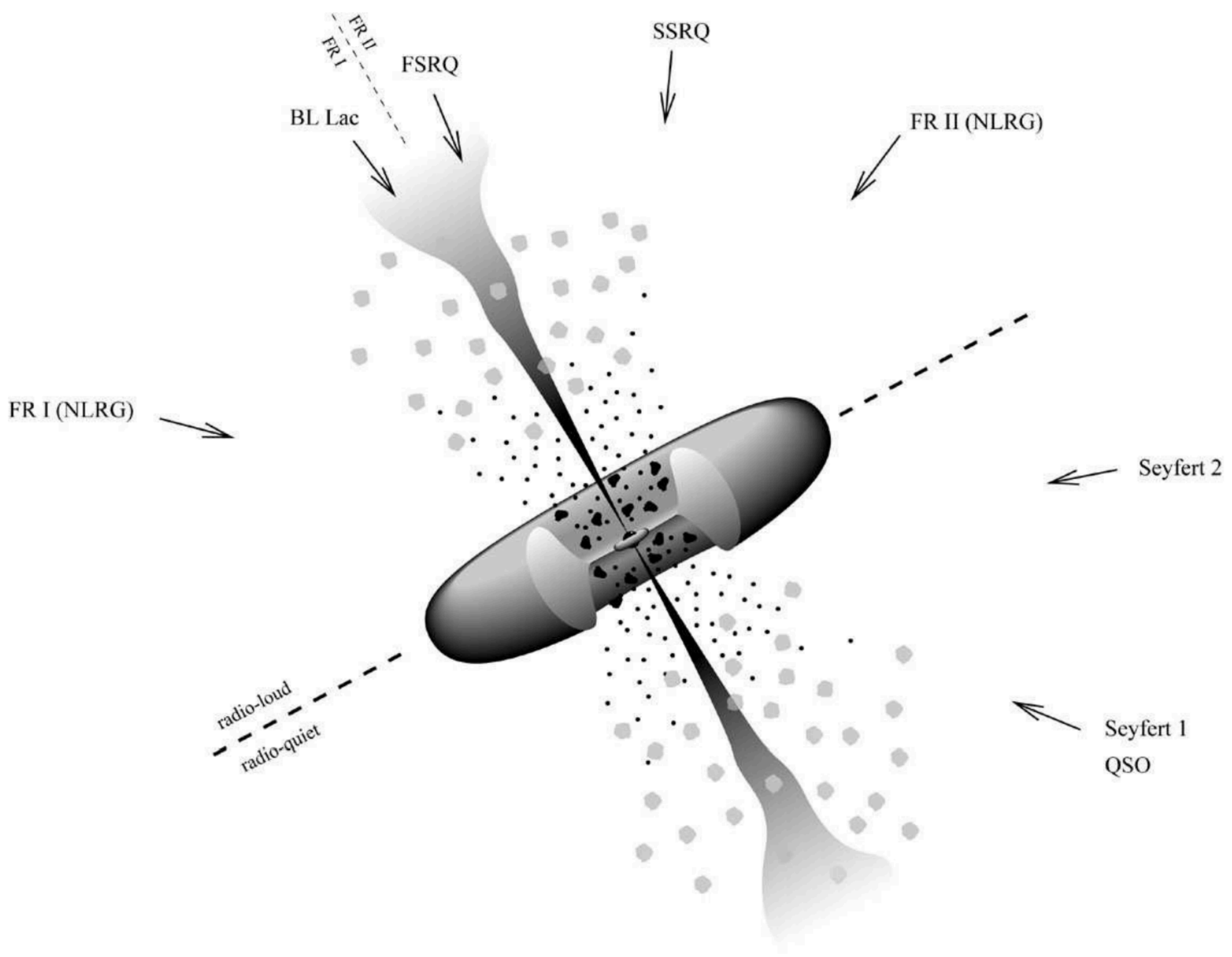
9 have a bright pulsars associated





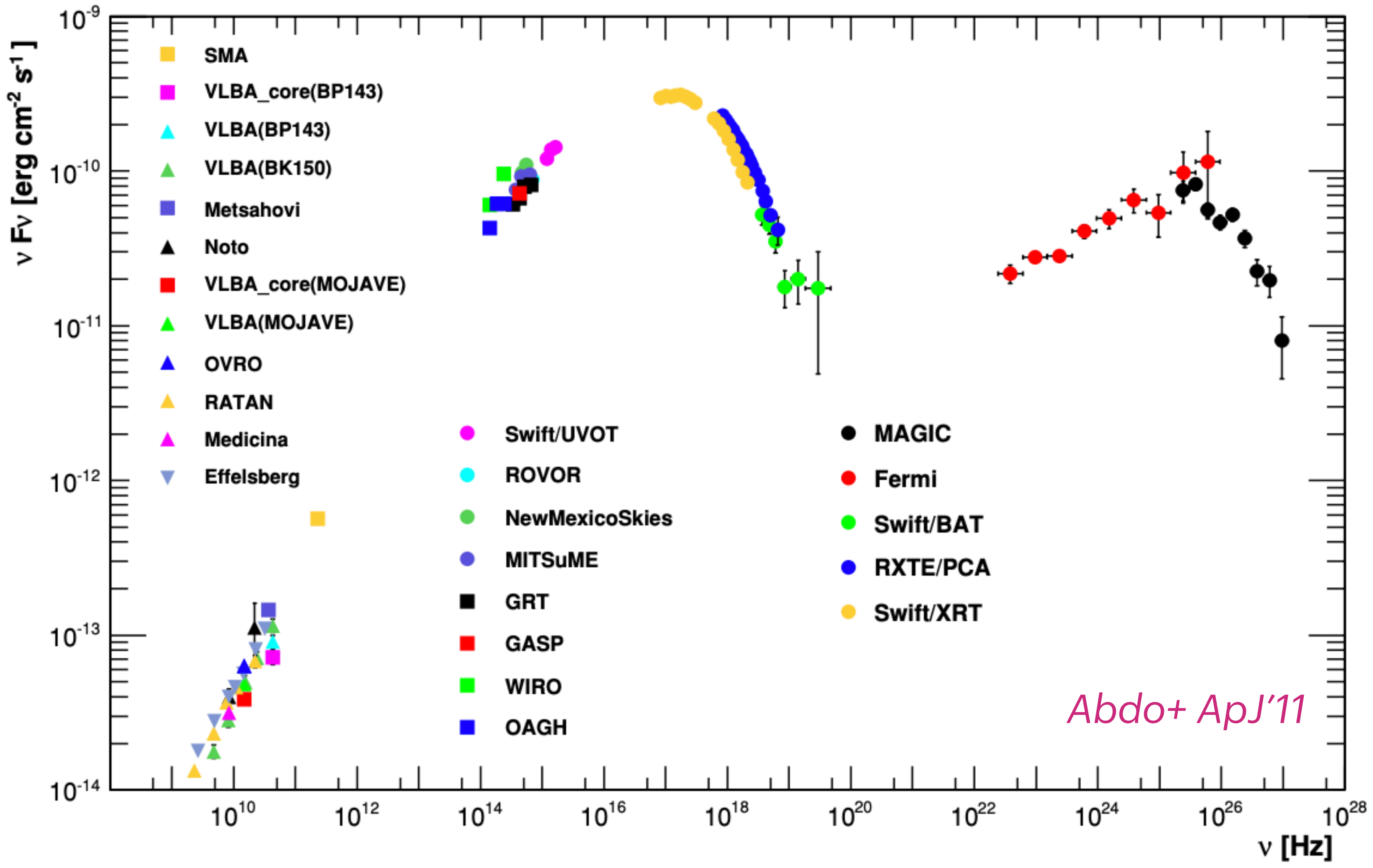
[Others: compact objects in binary systems (high-energy binaries, novae, micro quasars)]

Active galaxies

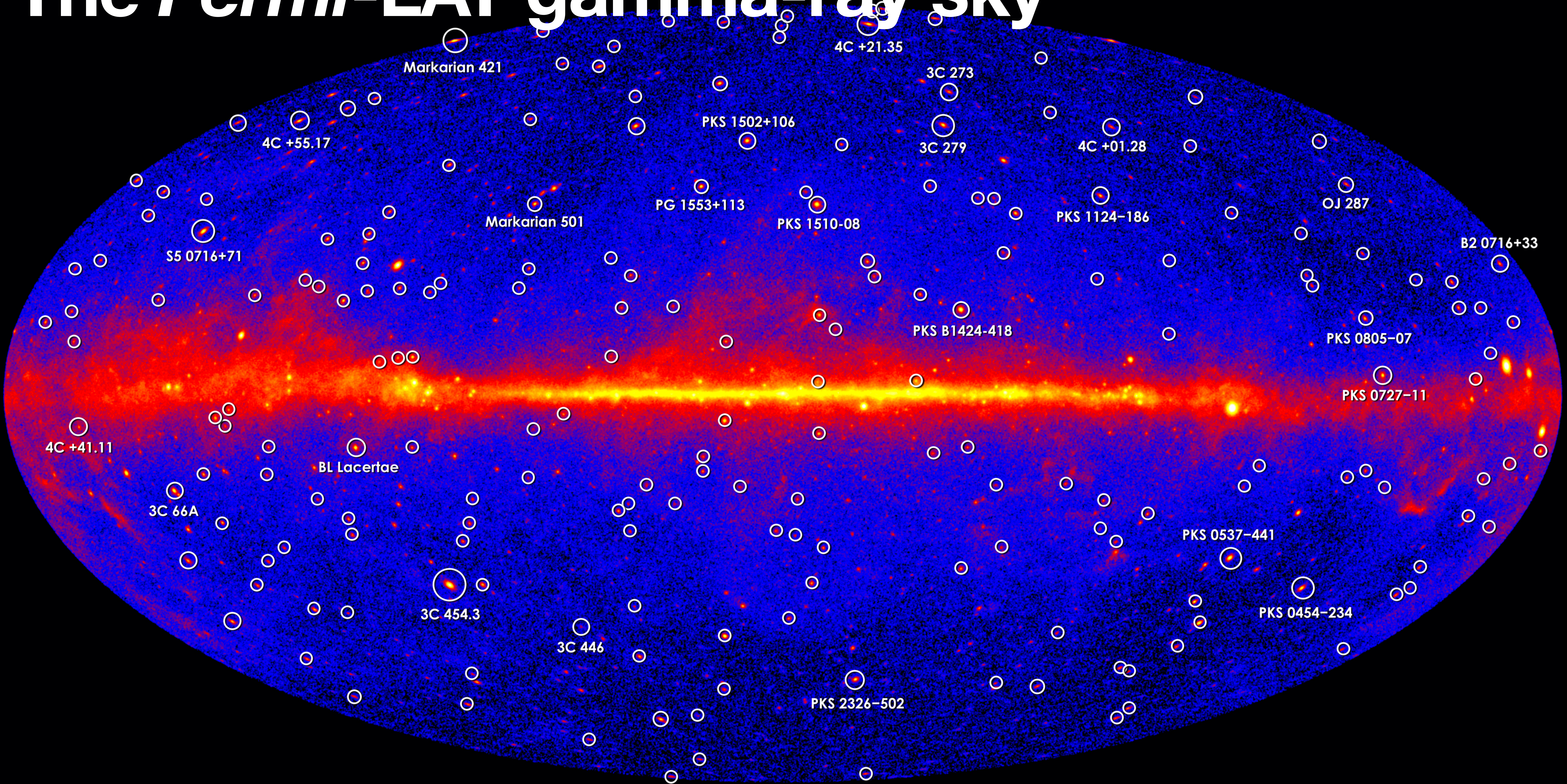


- Large fraction of the total luminosity of an active galaxy is non-thermal
- Emitted by the nuclei of the galaxy
- Energy generating mechanism: accretion on the SMBH in their center

SED of Mrk 421

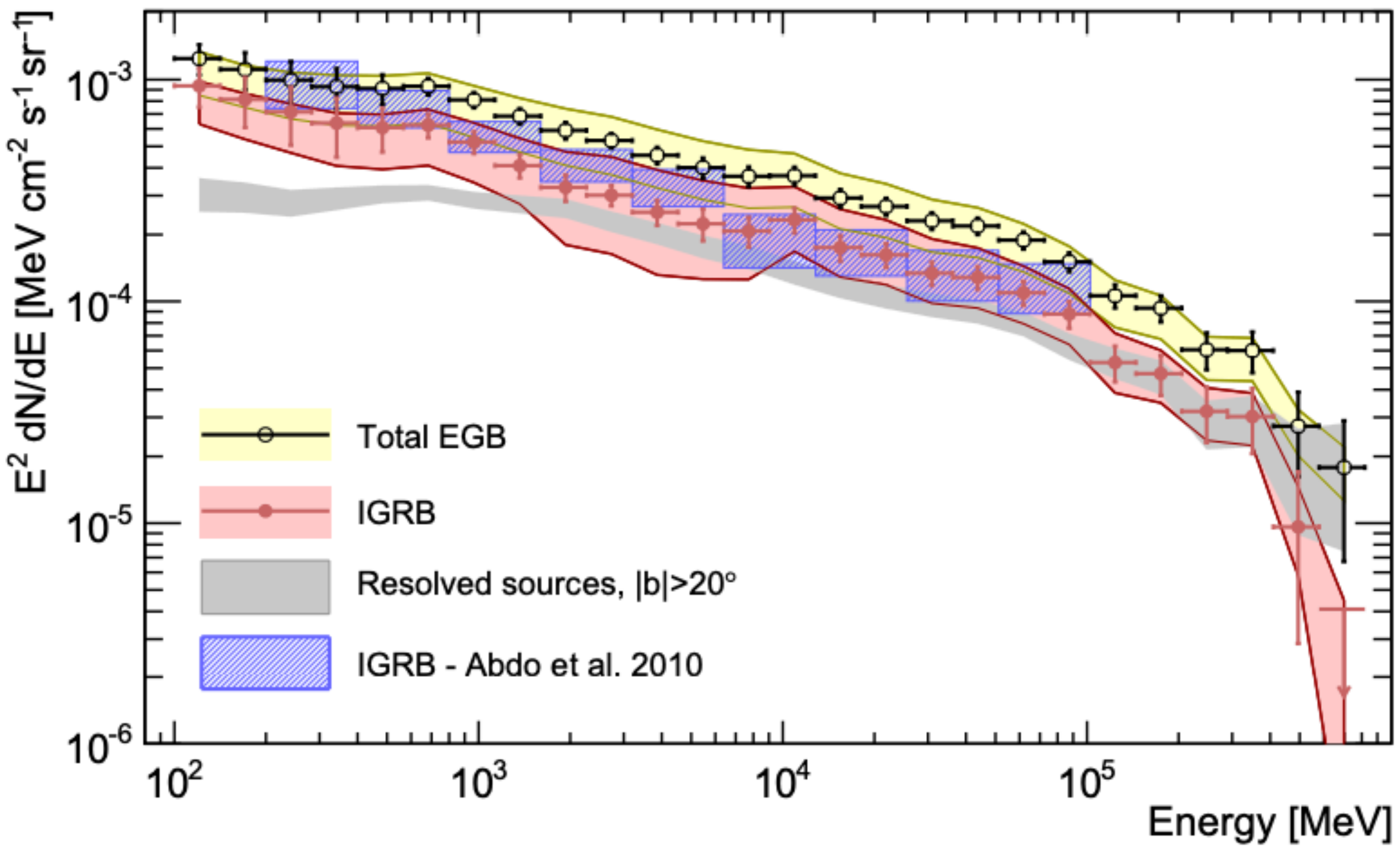


The *Fermi*-LAT gamma-ray sky

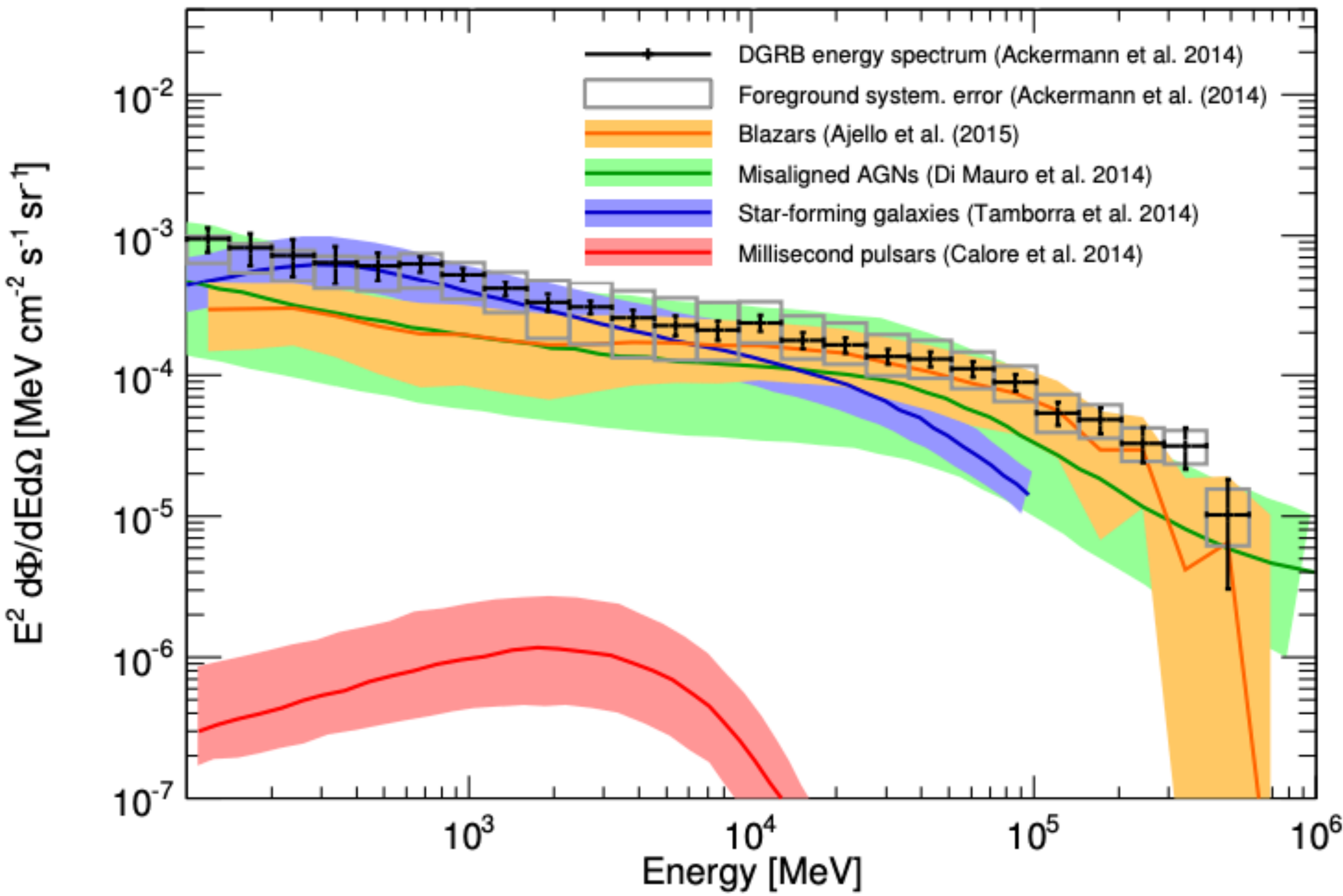


Unresolved sources and the Fermi IGRB

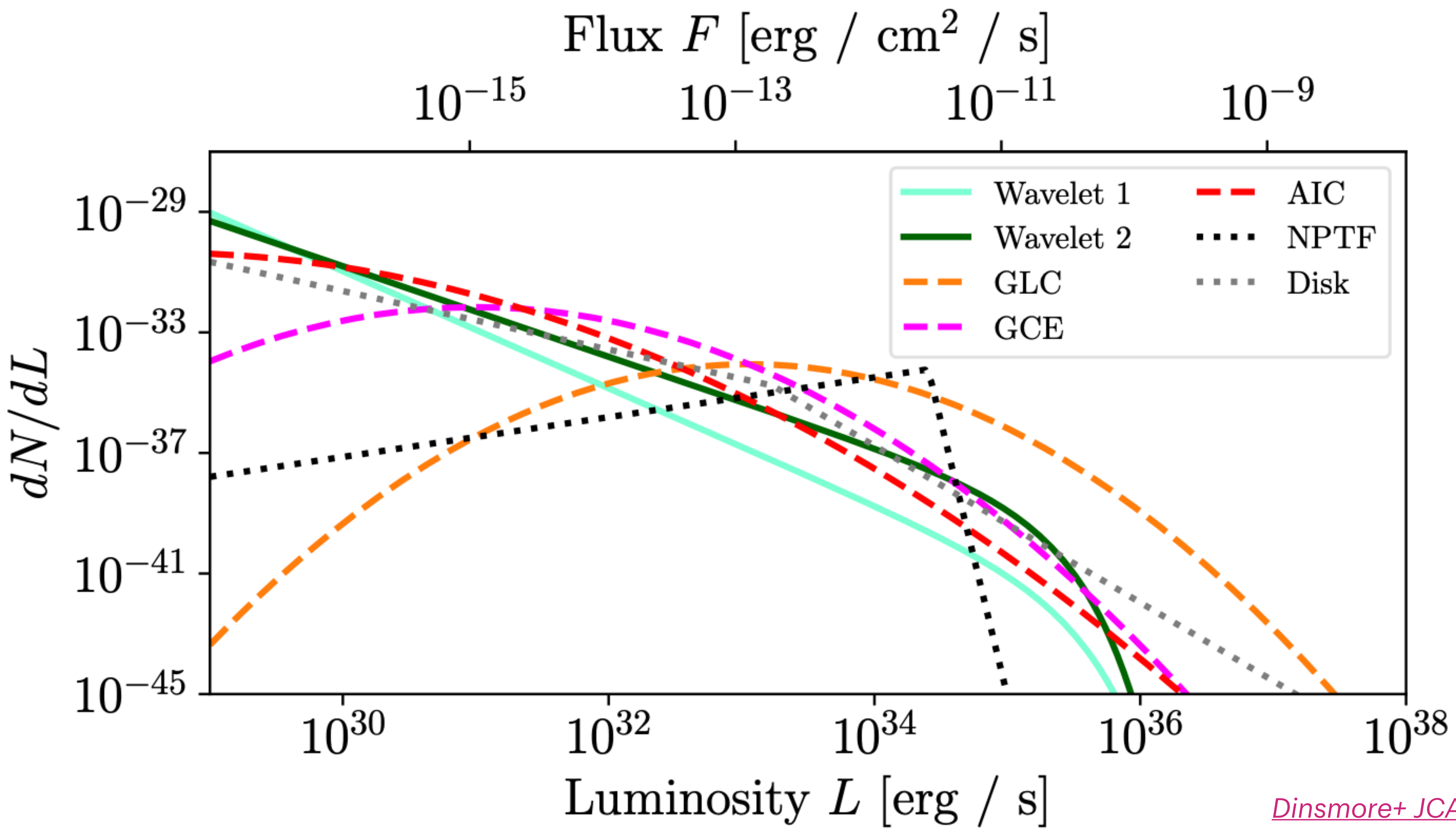
Ackermann+ ApJ'15



Fornasa & Sanchez-Conde Phys. Rep'15

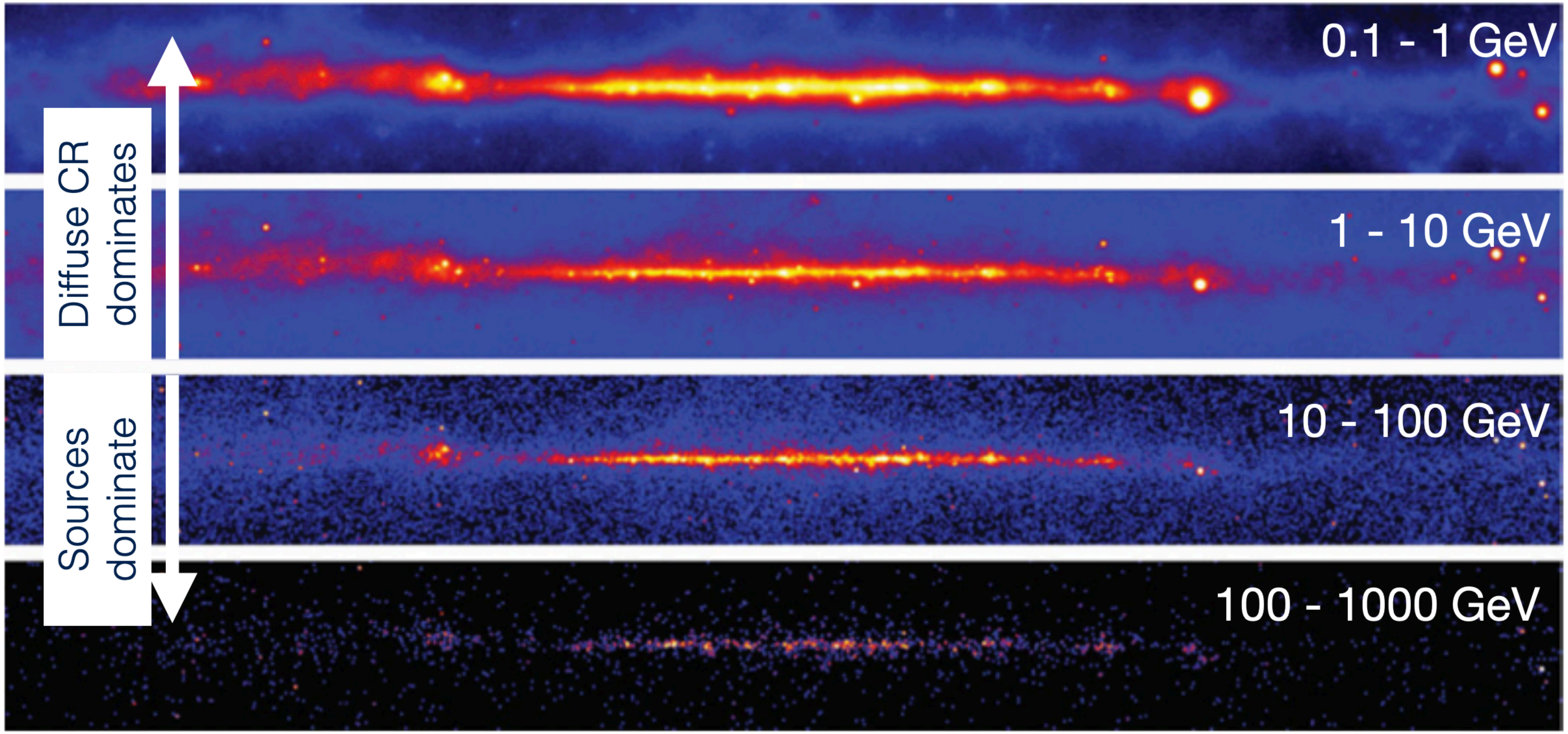


Galactic unresolved sources



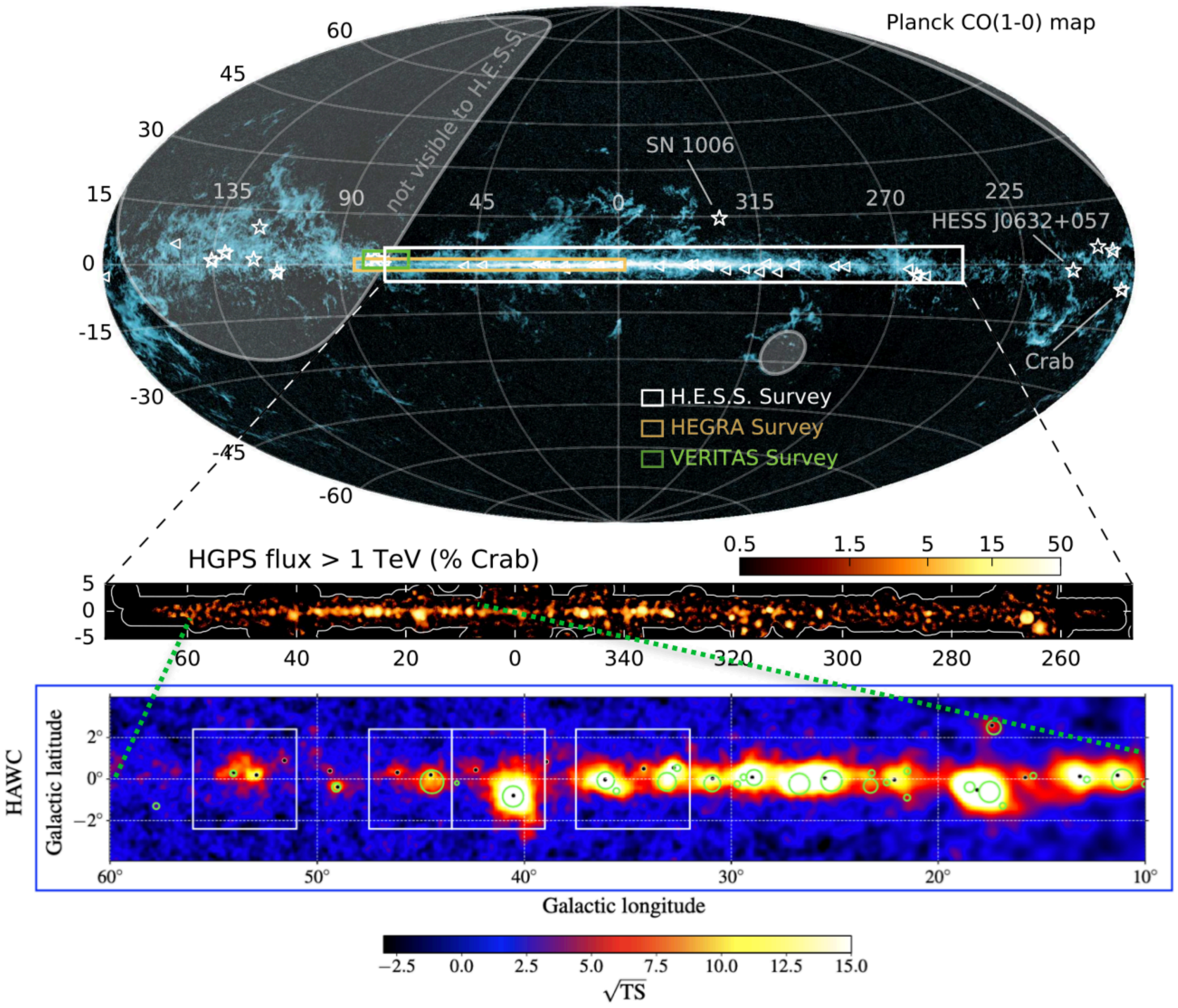
Dinsmore+ JCAP'22

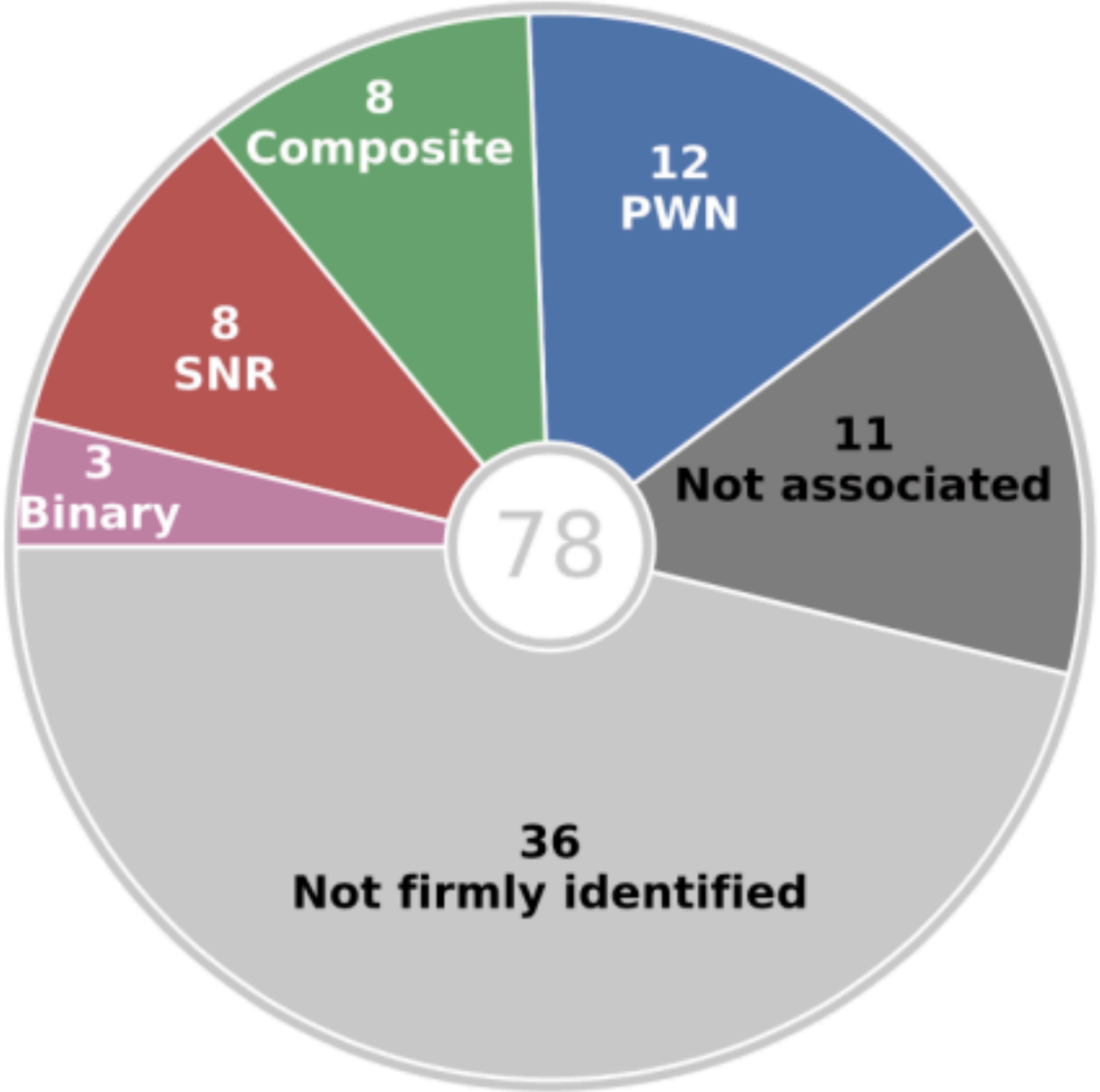
Diffuse emission from TeV to sub-PeV



Point sources at TeV energies

Despite small FoV IACTs can perform effective surveys

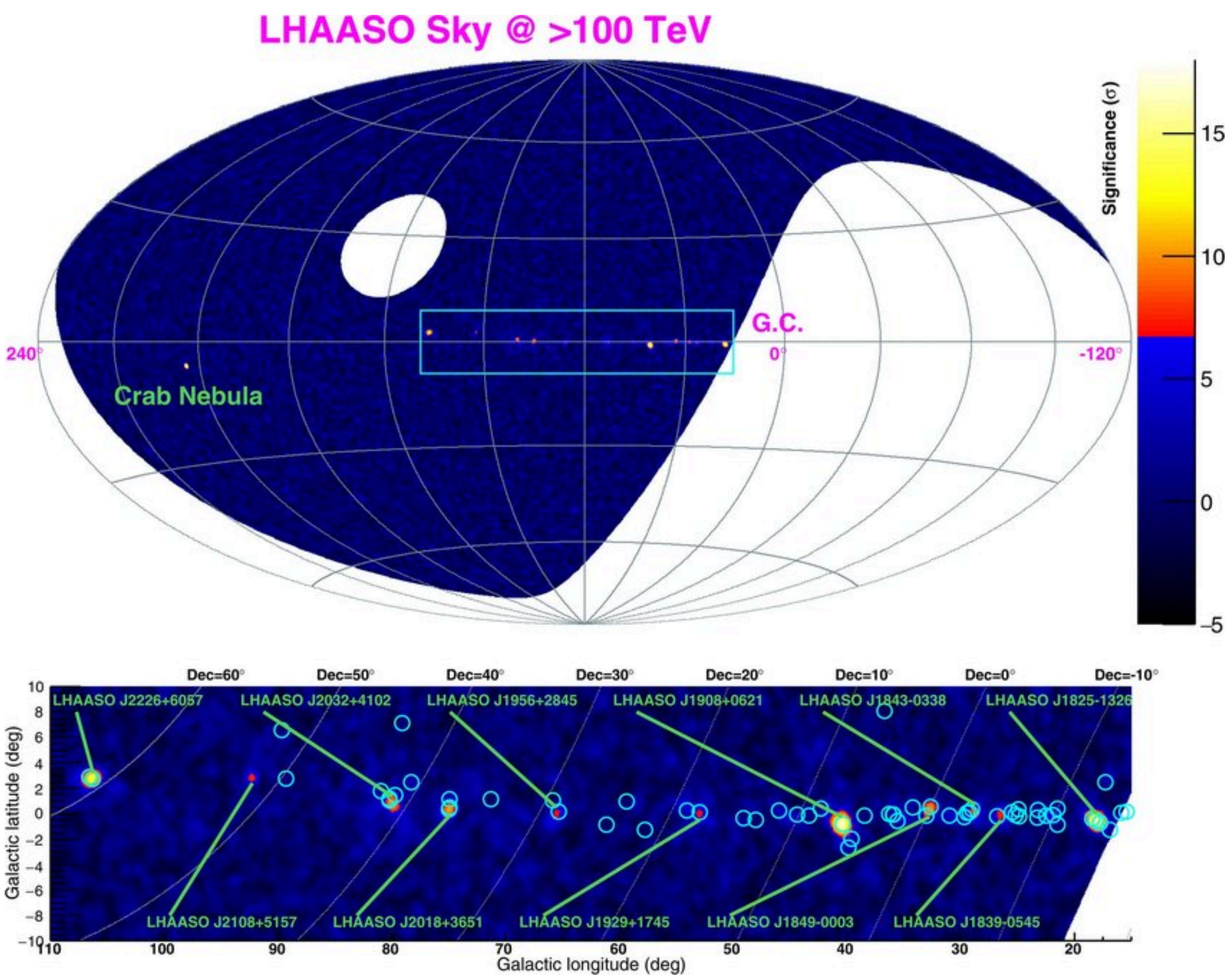


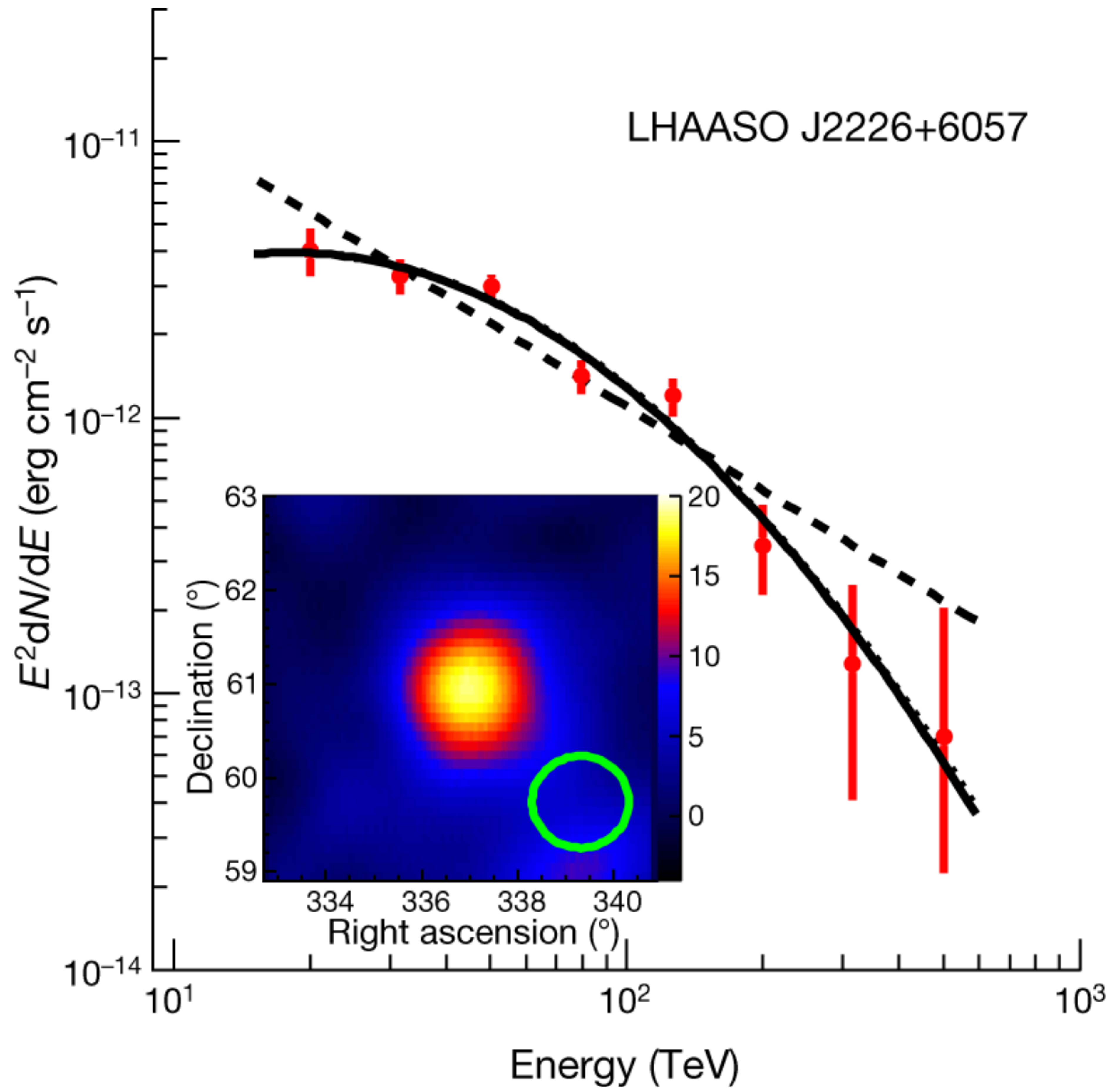


Galactic plane full of TeVatrons!

HAWC: Sources up to 100 TeV!

Point sources at sub-PeV energies





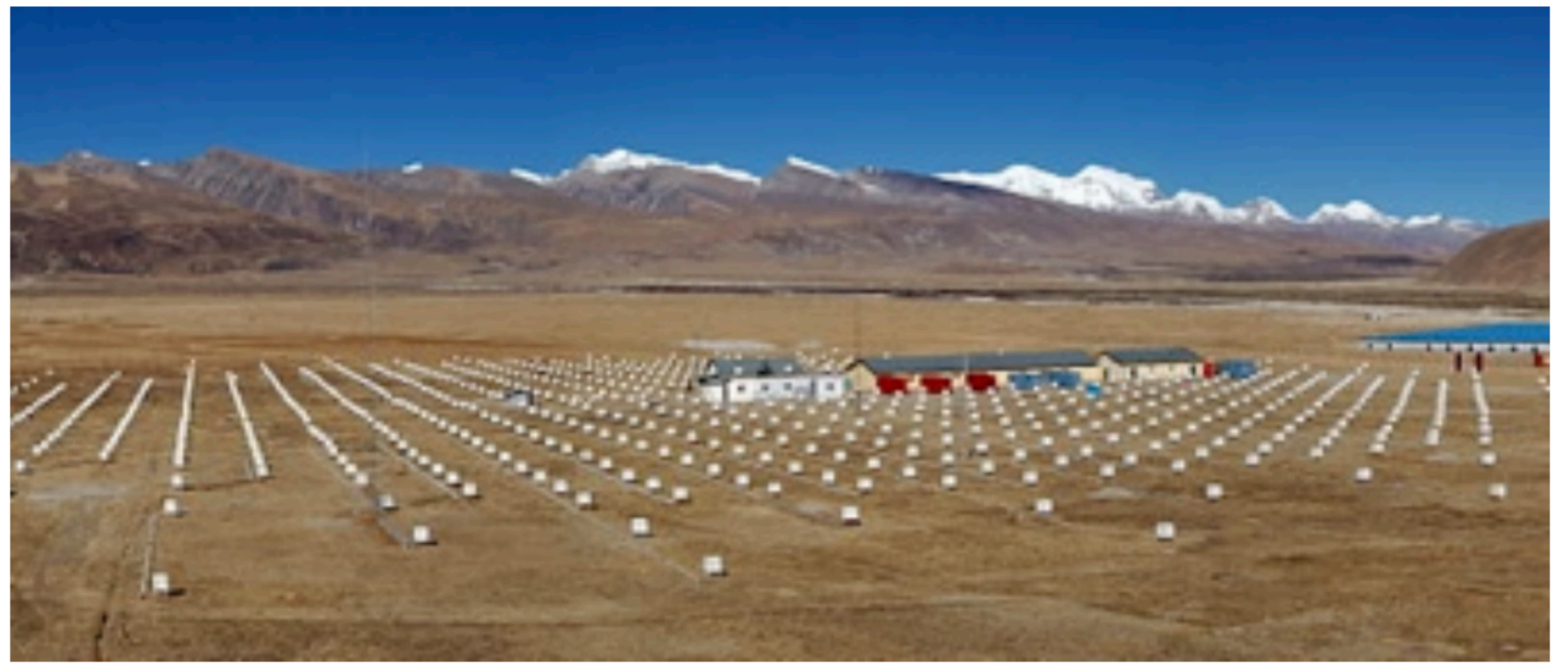
12 PeVatrons

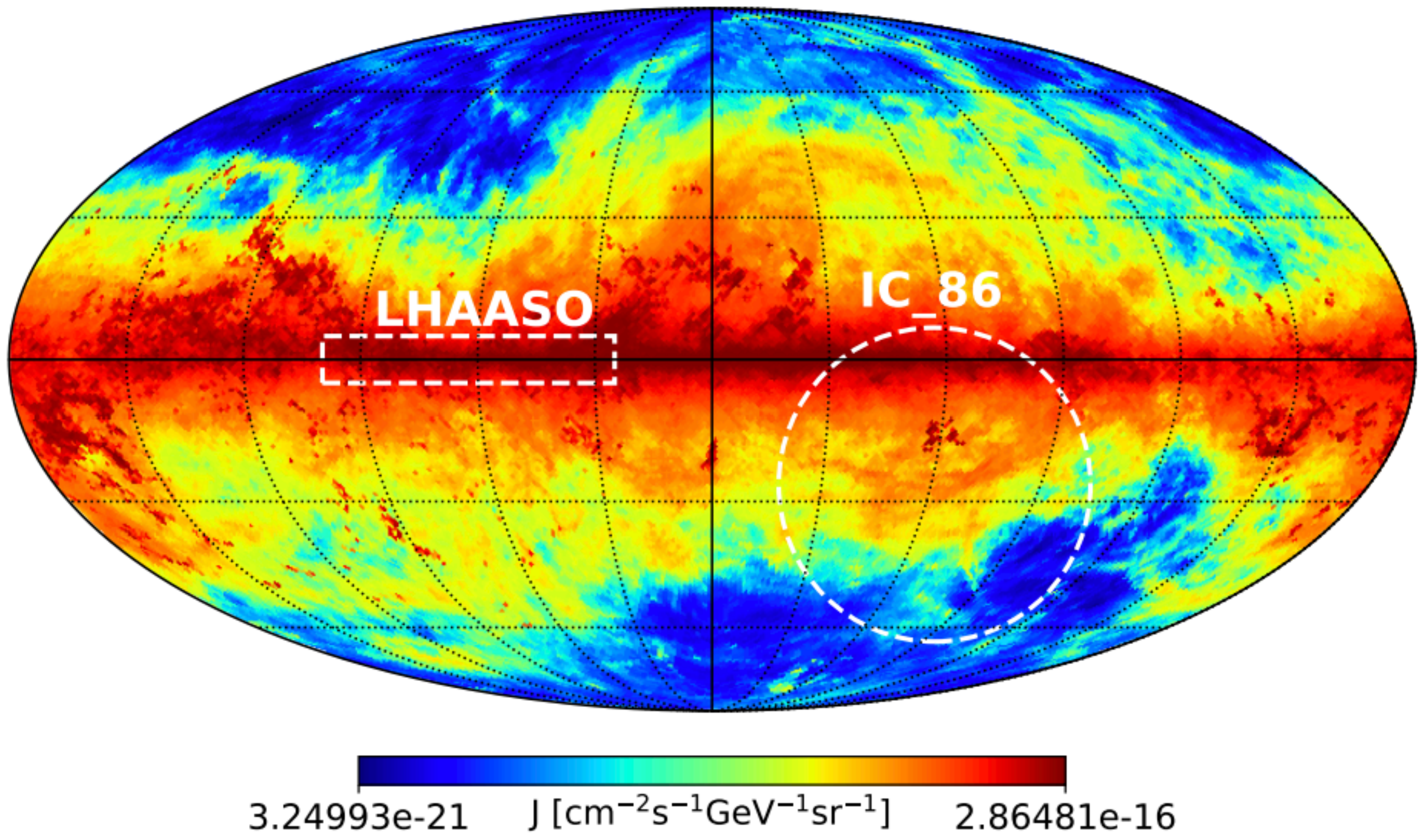
Diffuse emission: from TeV to sub-PeV

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

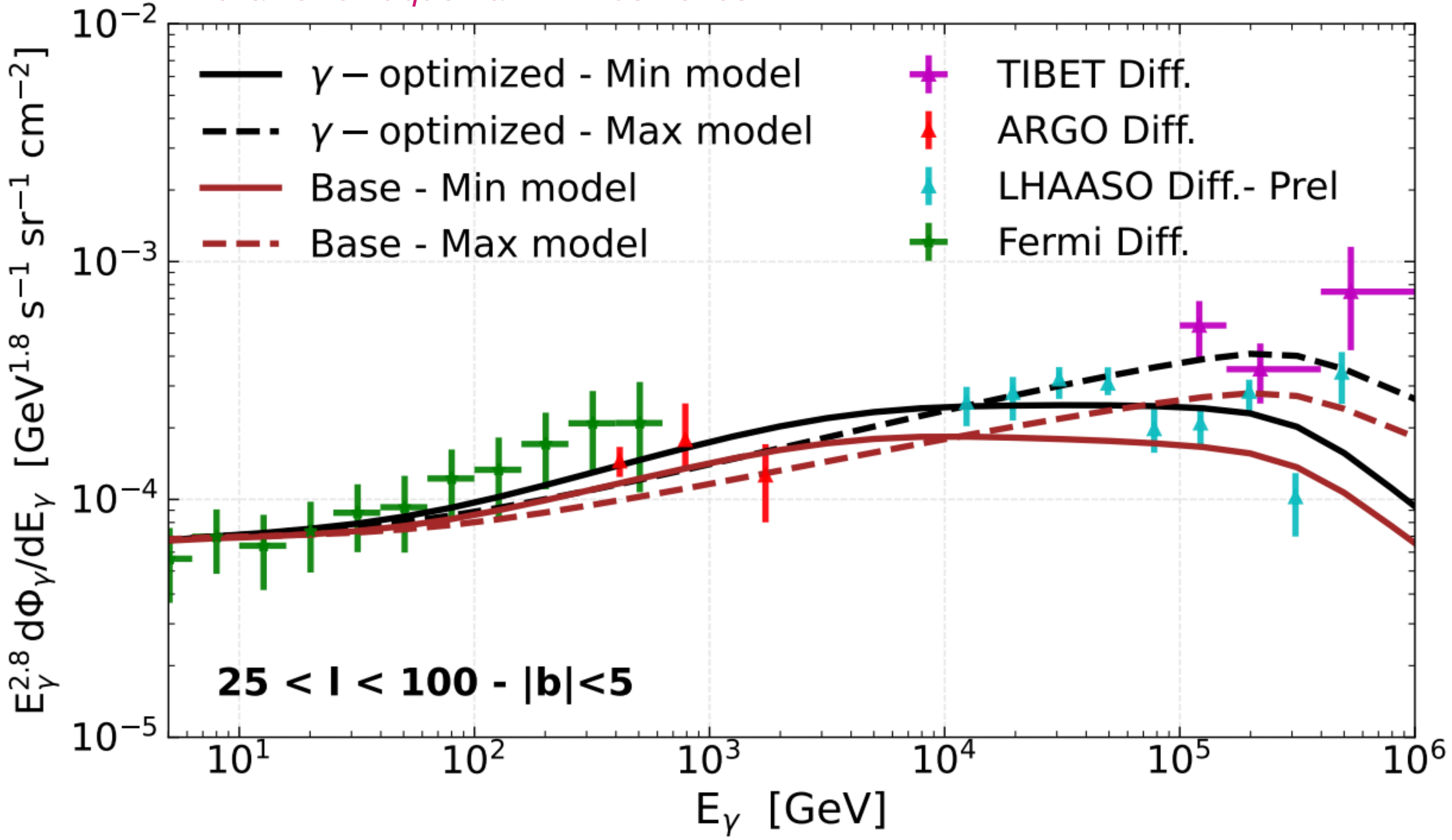
M. Amenomori *et al.* (Tibet AS_γ Collaboration)

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





De la Torre Luque+ arXiv:2203.15759



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. If there, 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

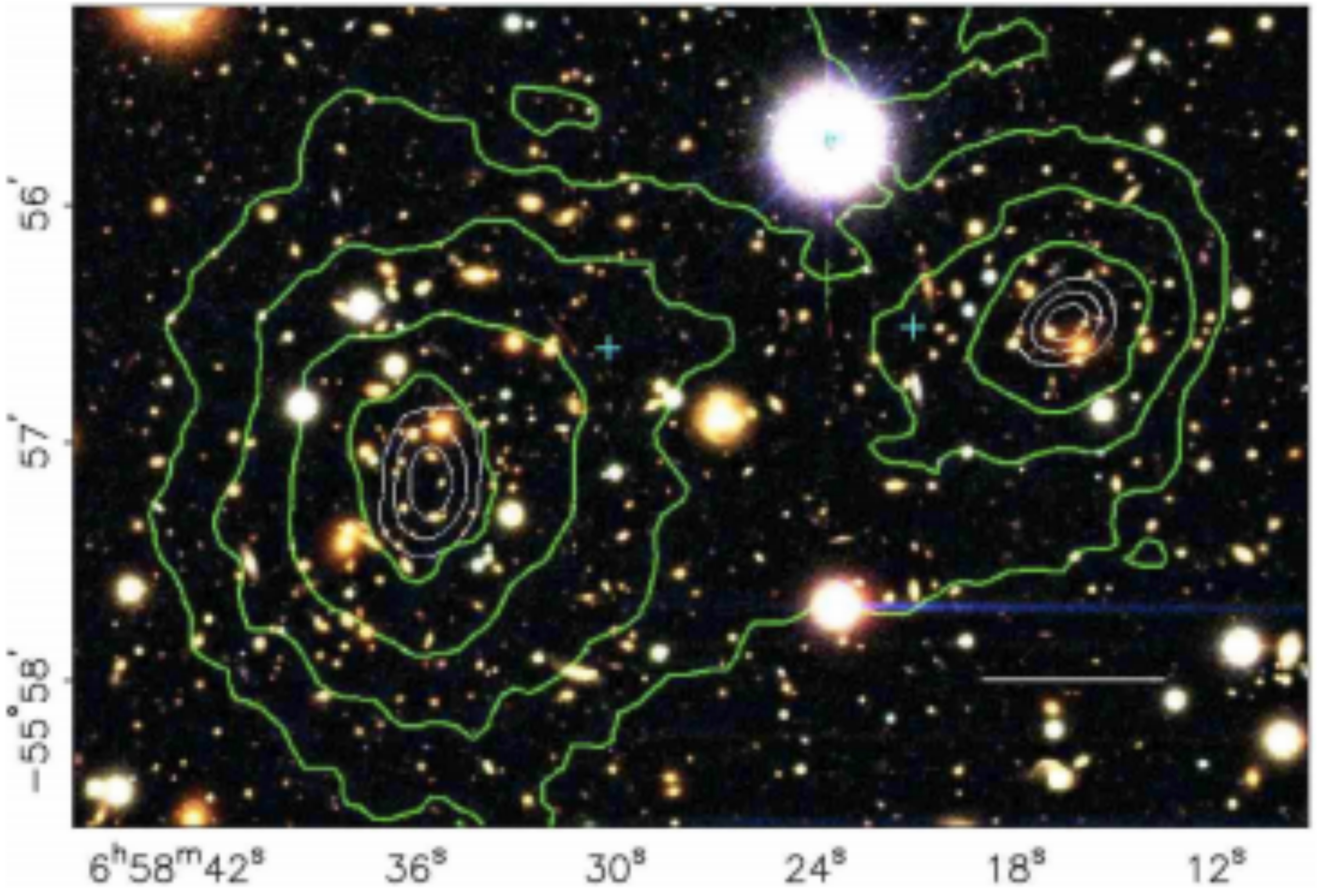
We do not control the **environment**. This requires effort to understand astrophysics to devise 'robust' new physics **signatures** and validation tests

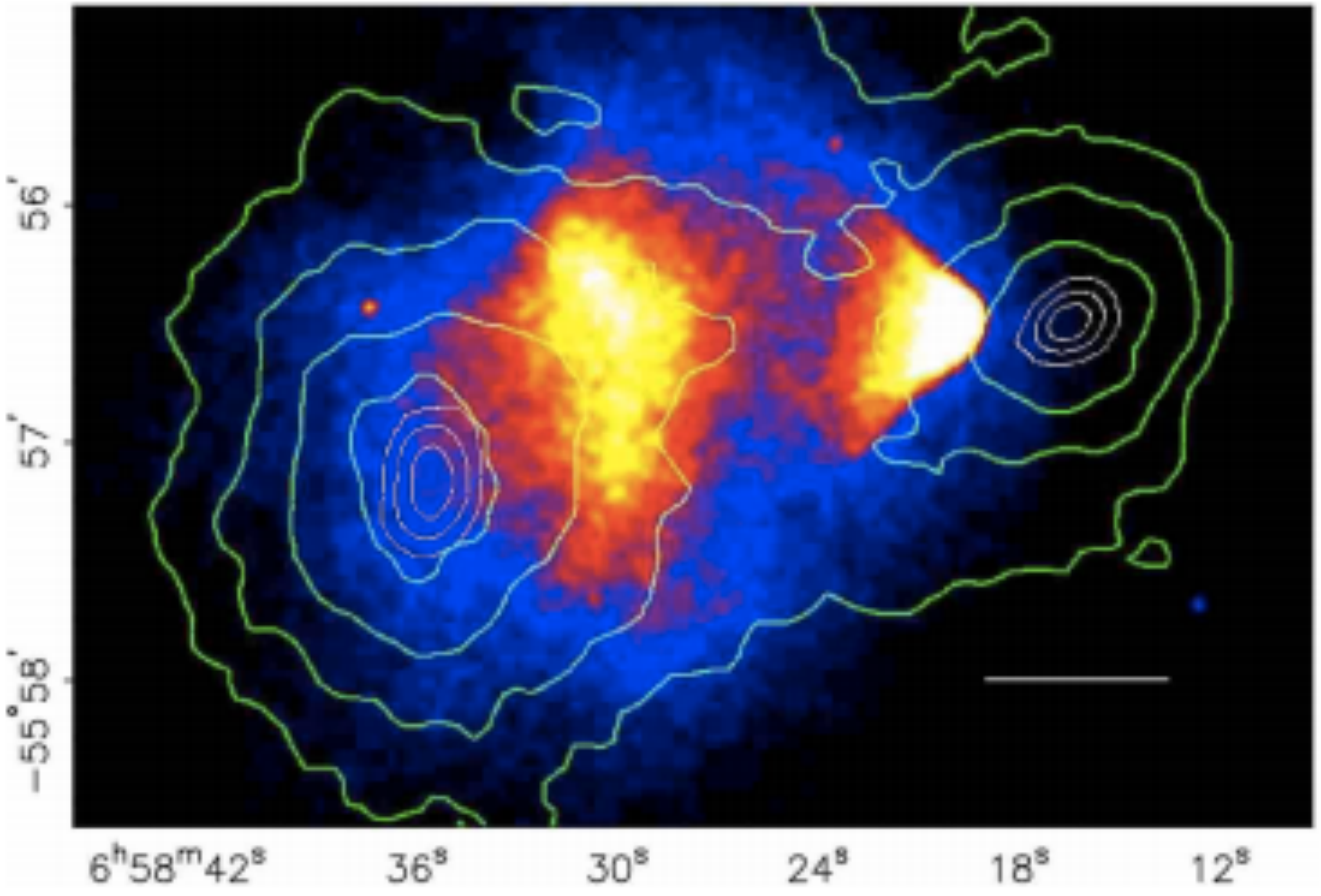
Main goal: Help you to schematise some research direction in **dark matter/BSM** searches

Dark matter in the sky

Collisionless matter

Bullet Cluster (1E 0657-56)



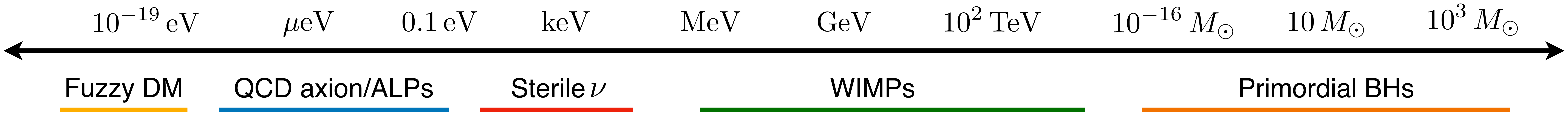


The dark matter landscape

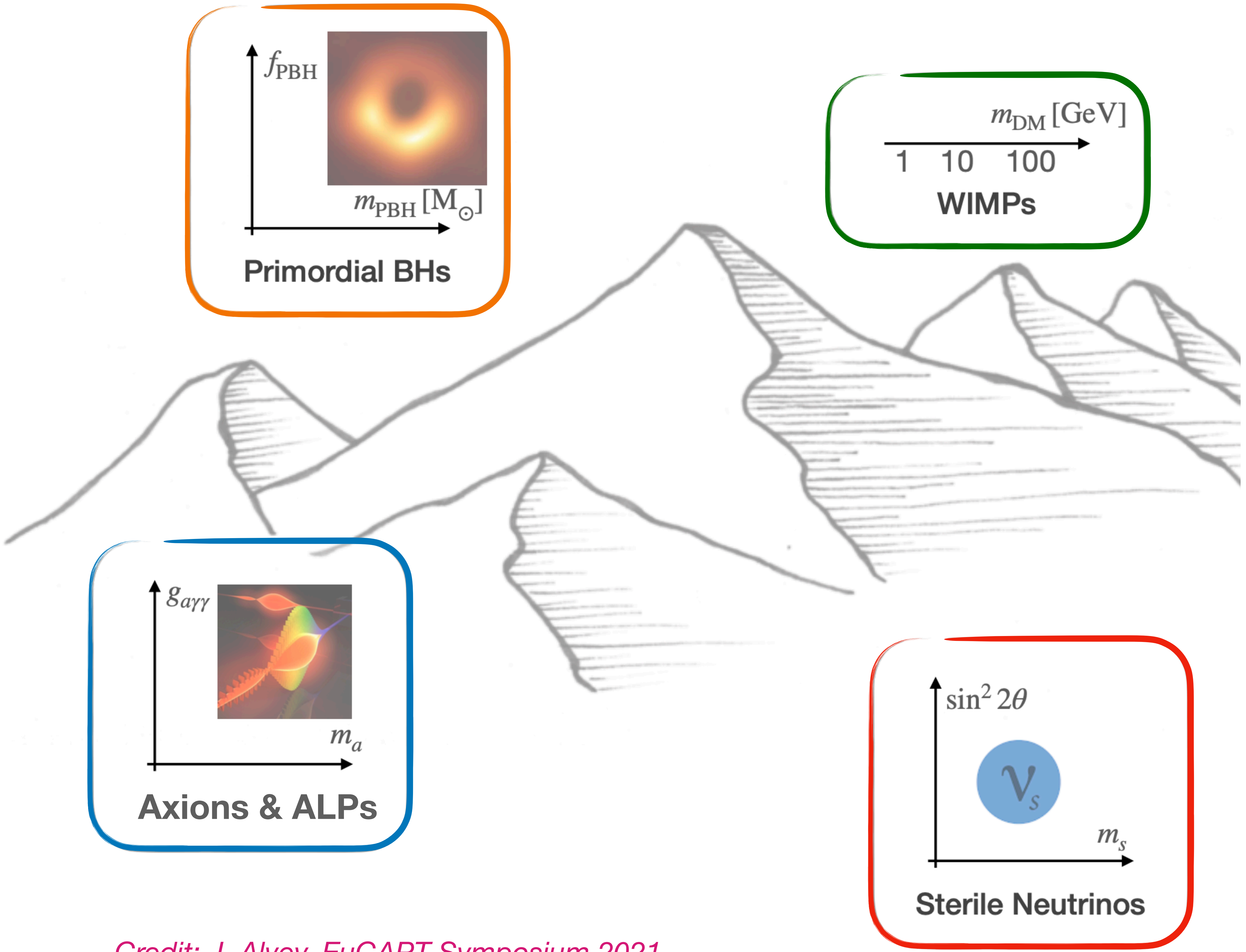
Vast parameter space in mass and interaction strength

The dark matter landscape

The dark matter landscape



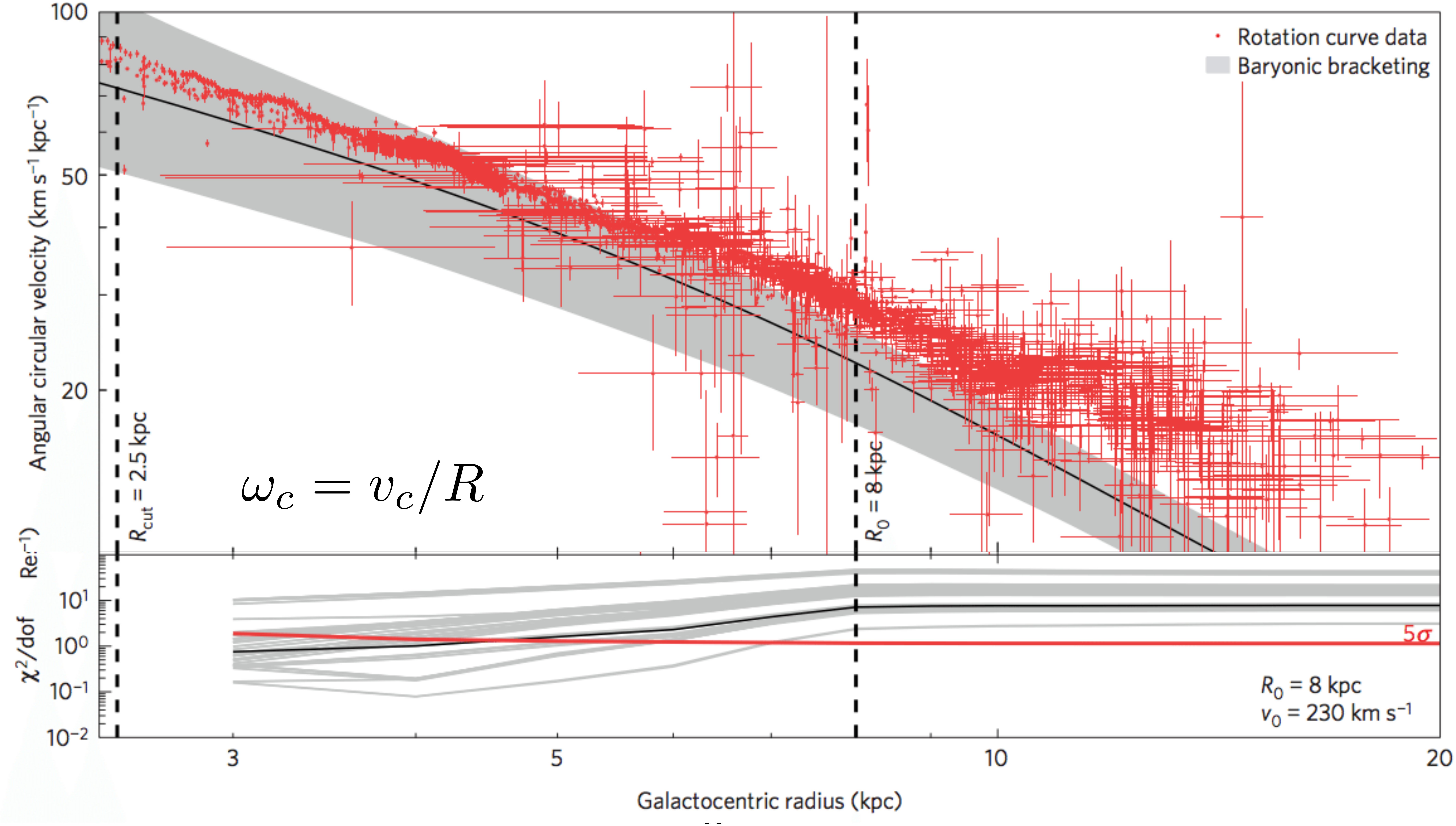
- Identification strategies are necessarily (more or less) **model dependent**
- The **theoretical prejudice** in dark matter searches is also set by what we can probe with available data
- You always need some sort of signature of your model!



Credit: J. Alvey, EuCAPT Symposium 2021

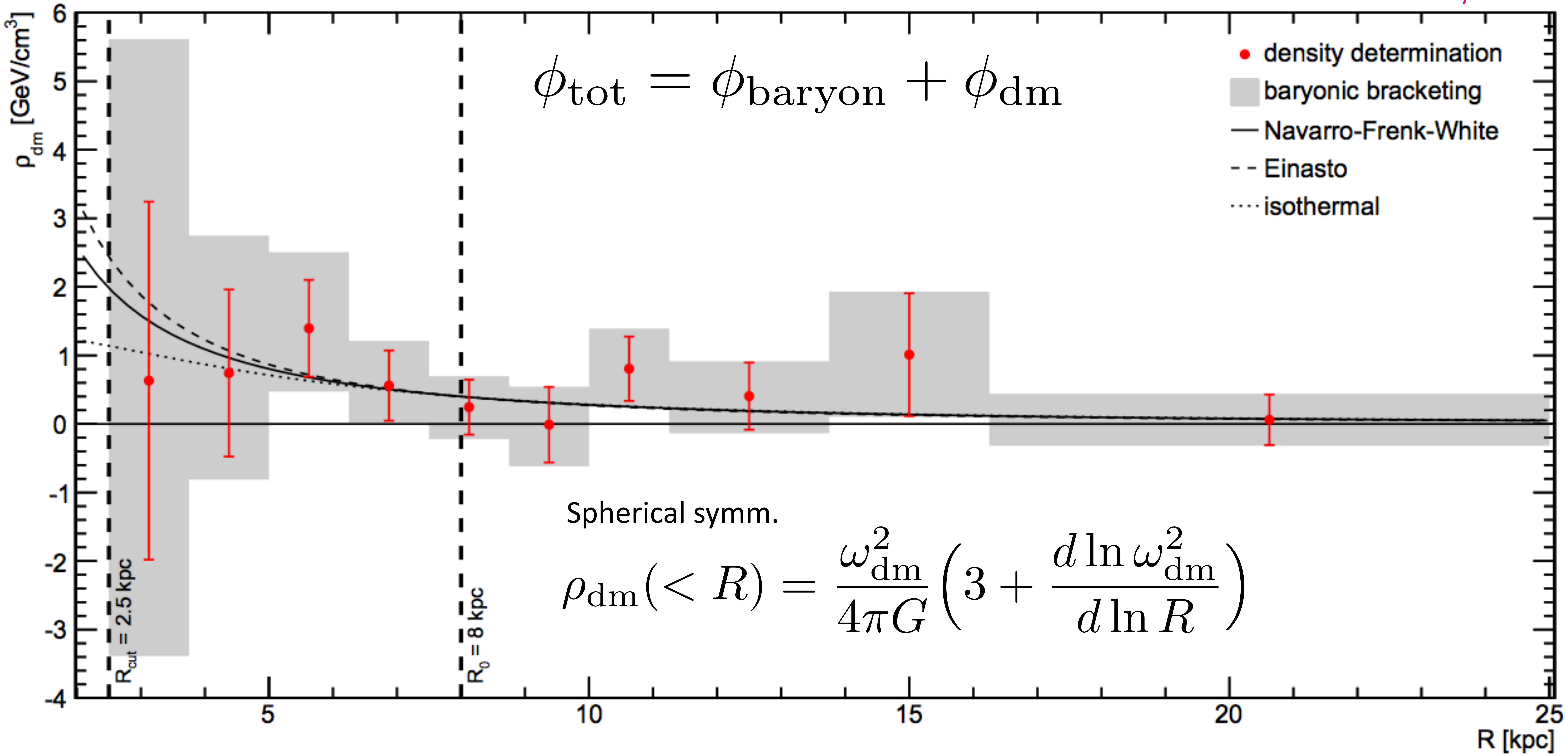
Milky Way rotation curve

Iocco+ Nature Physics'15



Milky Way DM density

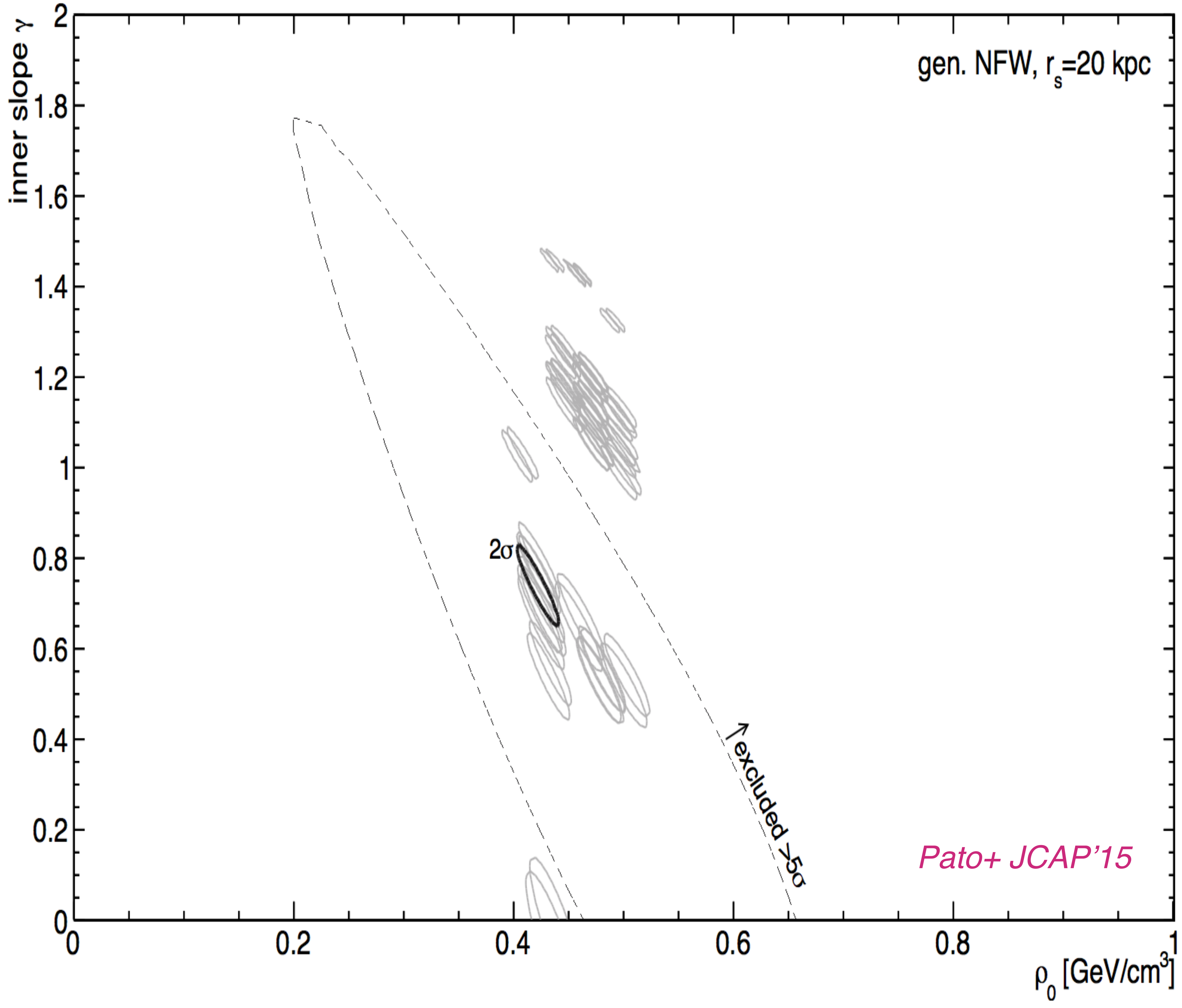
Pato&Iocco+ ApJ'15

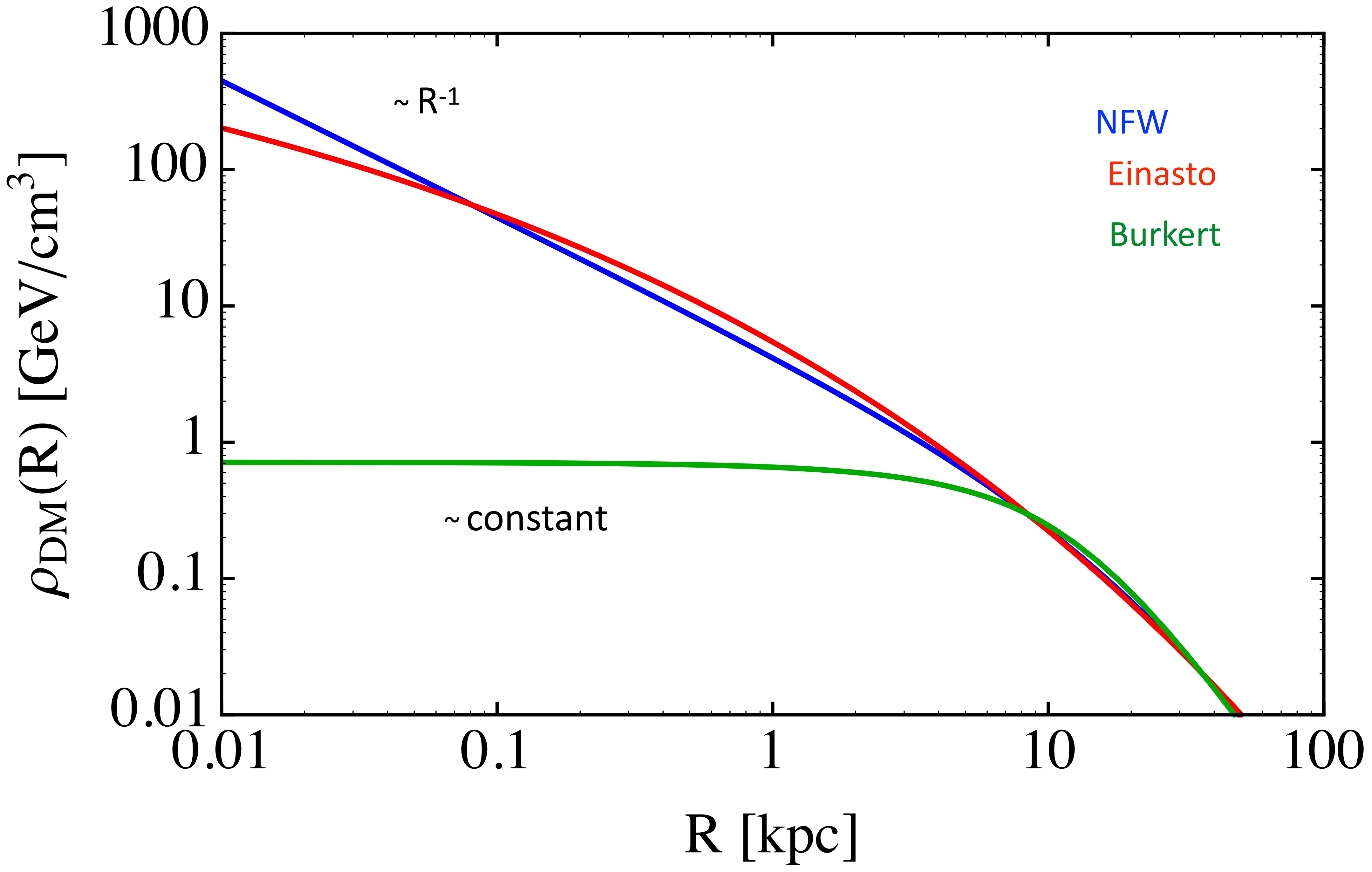


Non-parametric reconstruction: approach free of profile assumptions, but uncertainties are large and hinder discrimination power between different radial behaviours.

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

Milky Way DM density

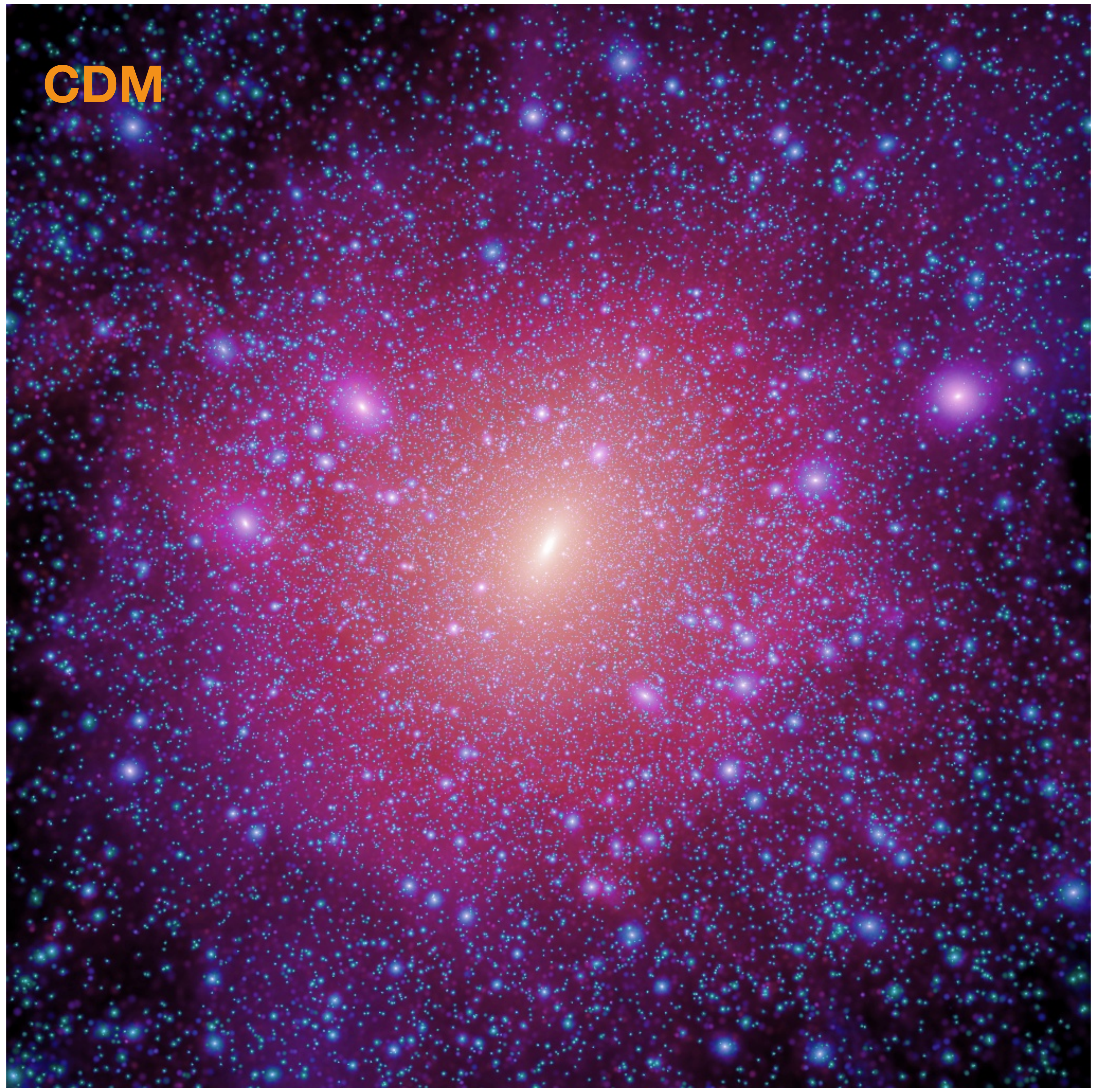




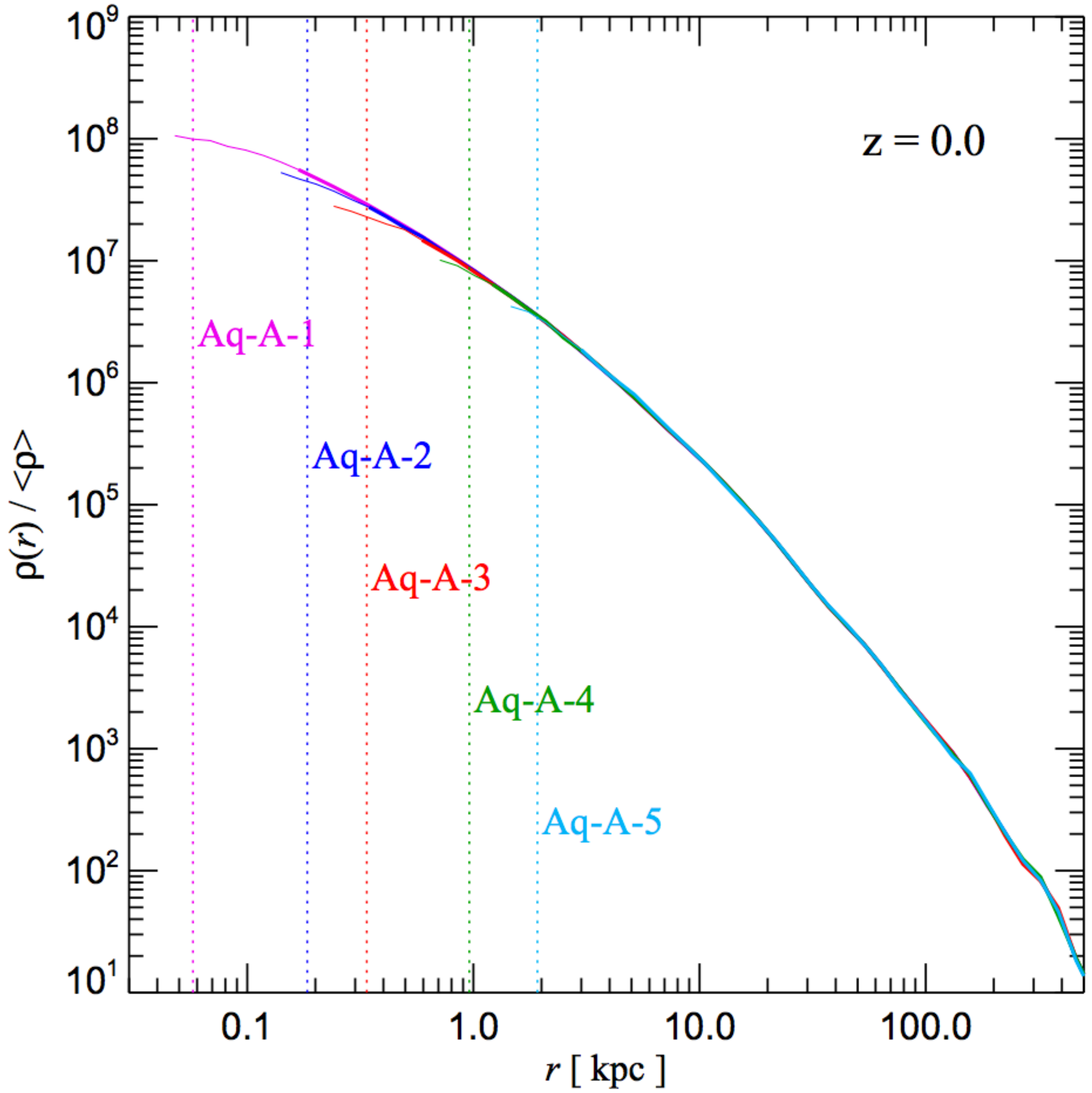
Parametric reconstruction: strong profile assumptions, "global" method to derive local DM density.

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

DM density in haloes



Springel+ MNRAS'08

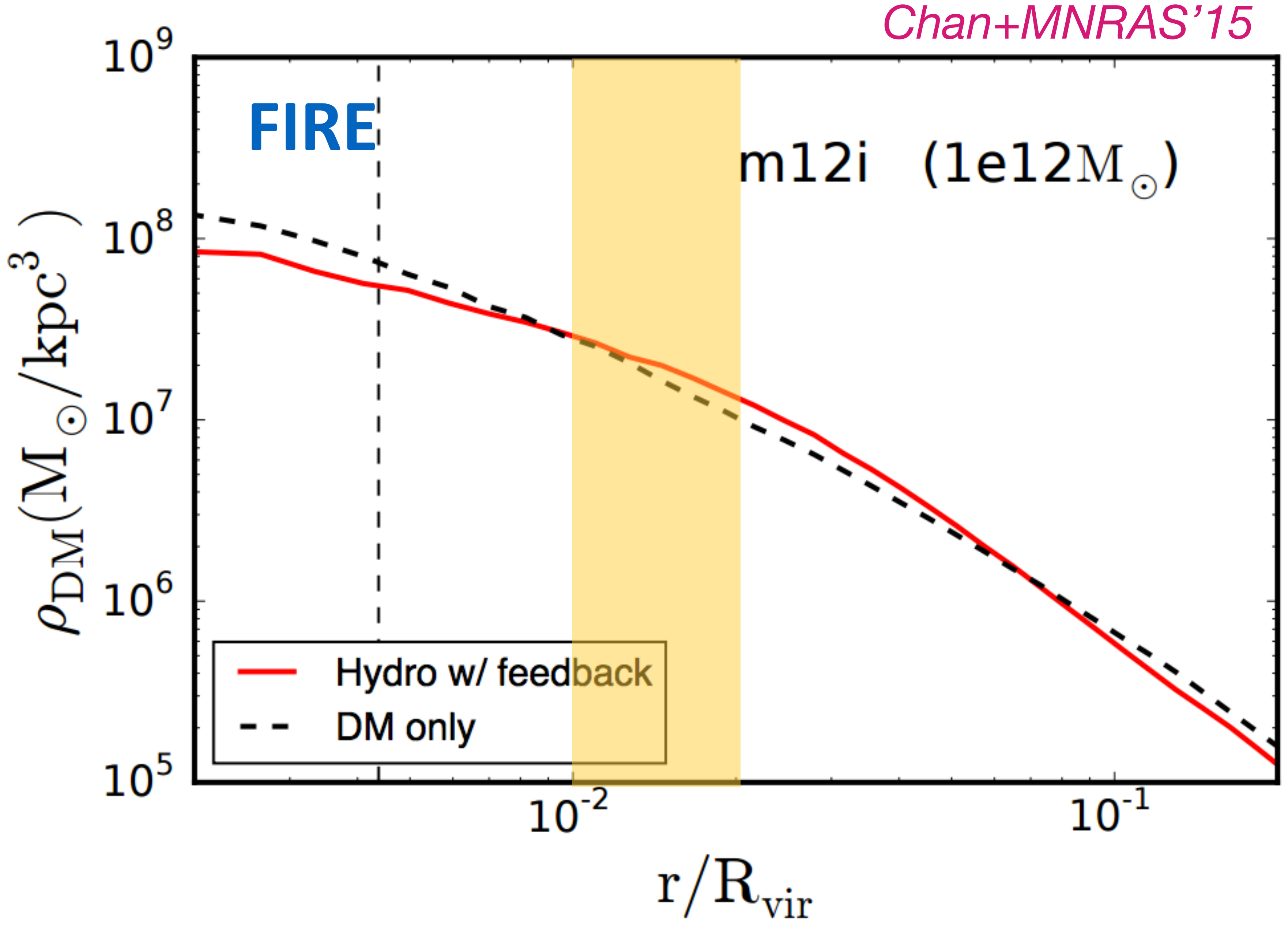


$$\rho_{\rm tot}(R) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{R}{r_s}\right)^{\alpha} - 1\right]\right\}$$

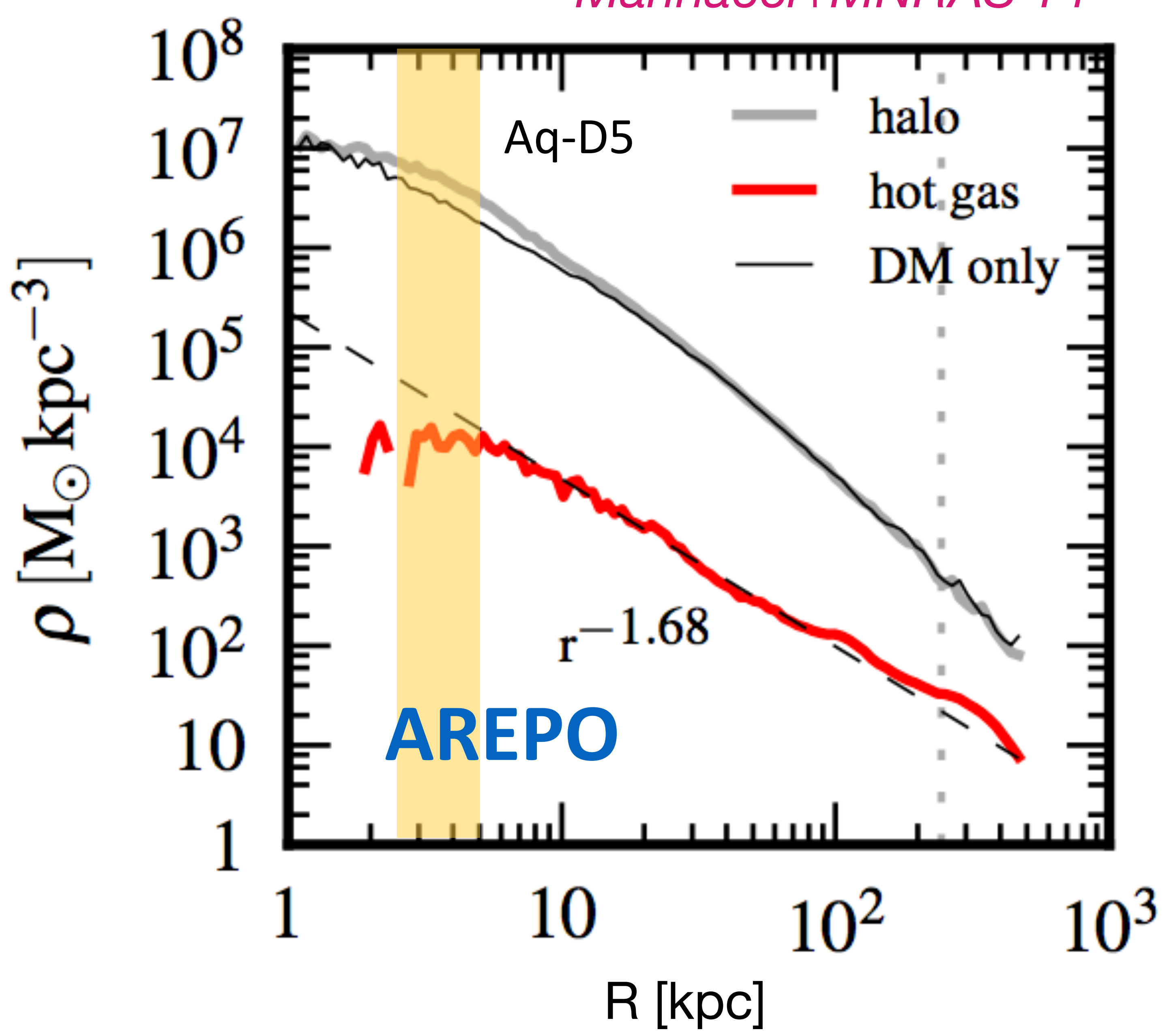
DM density in haloes

Inner galaxy

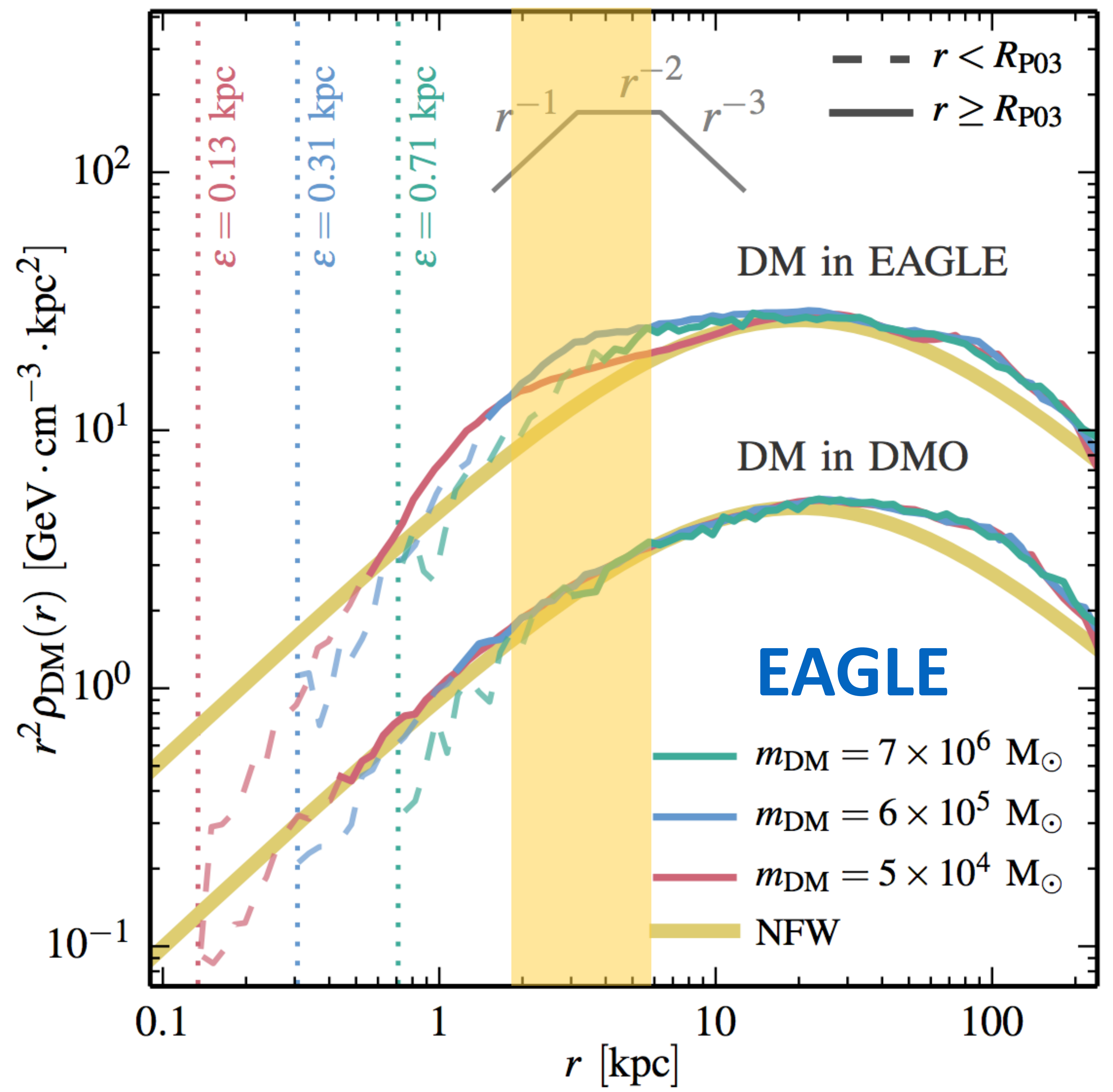
Chan+MNRAS'15



Marinacci+MNRAS'14



Schaller, FC+MNRAS'16



Challenges

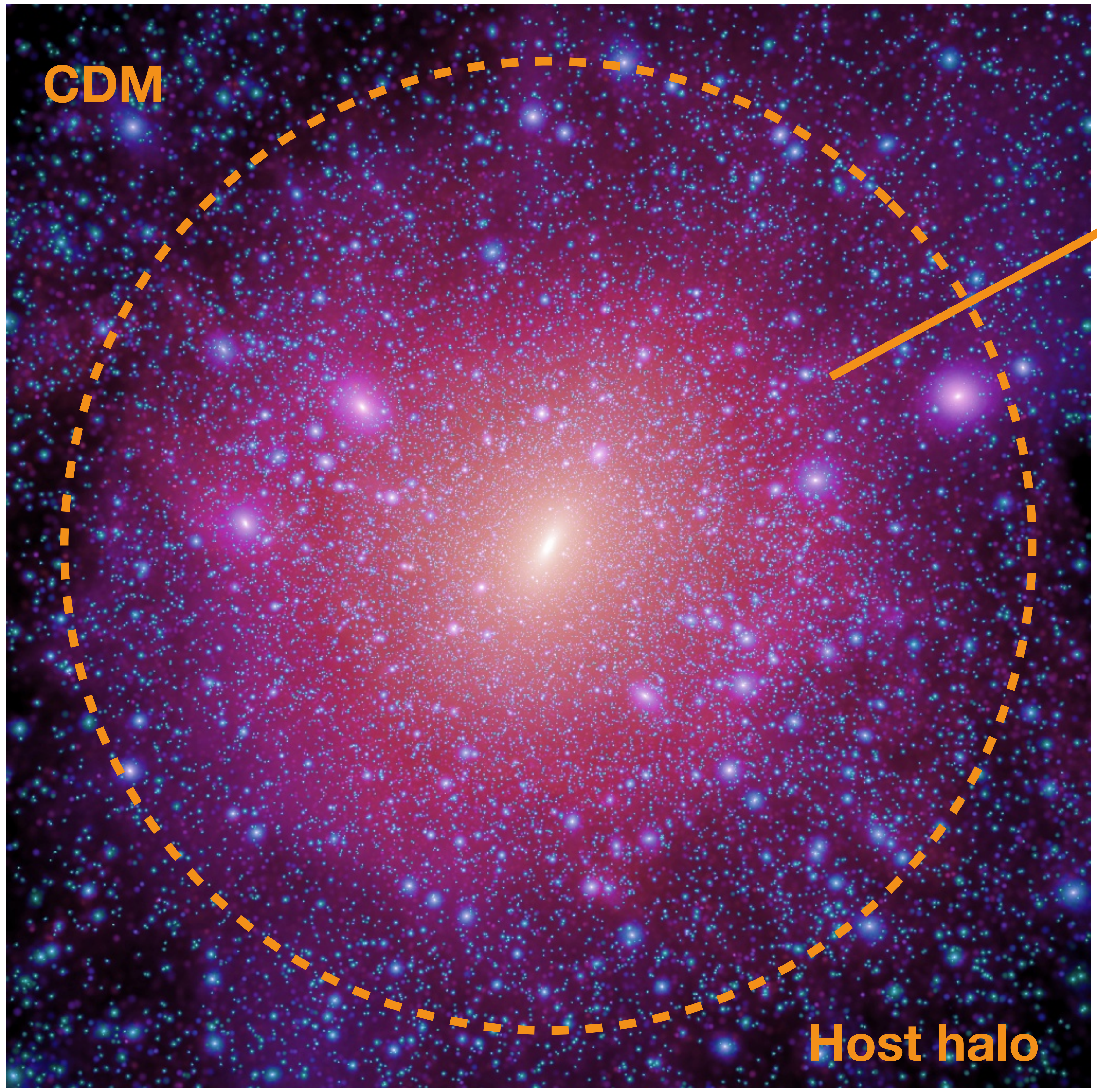
How to select a good MW halo candidate?

How to extrapolate the profile down to smaller scales?

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

DM density in haloes

Substructures and subhaloes



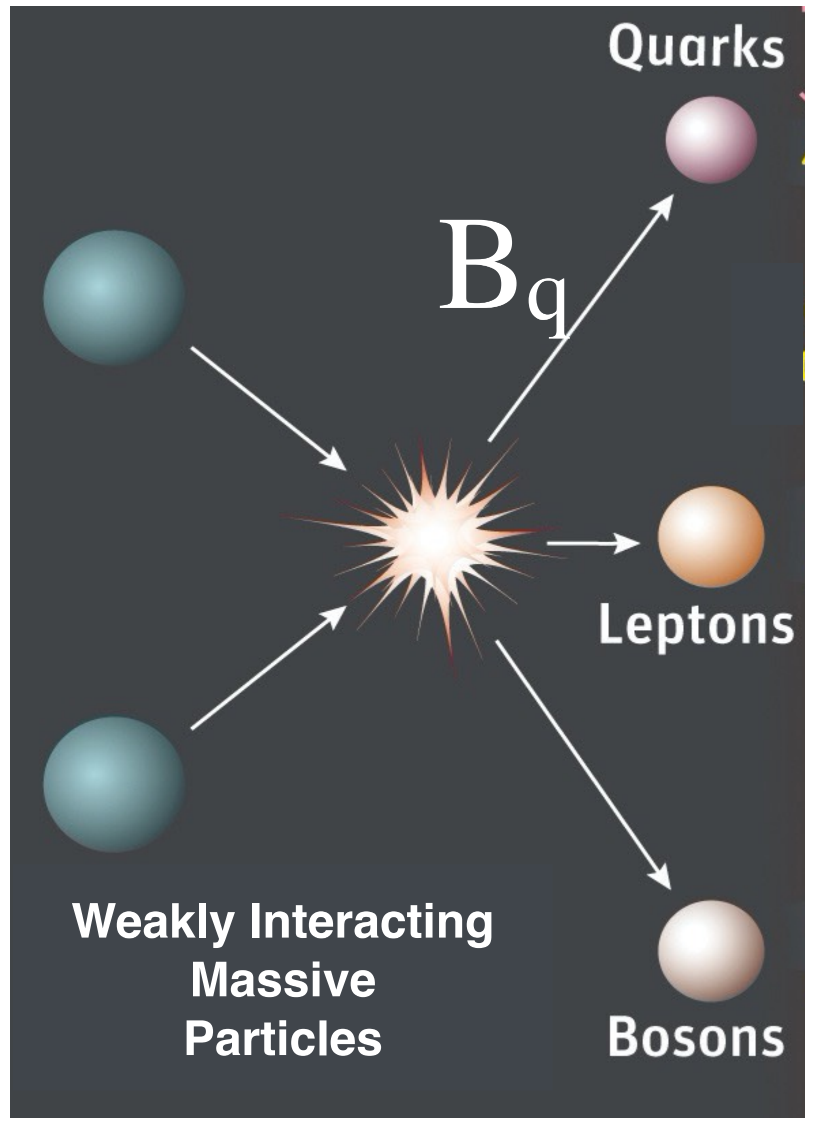
Springel+ MNRAS'08

- 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)

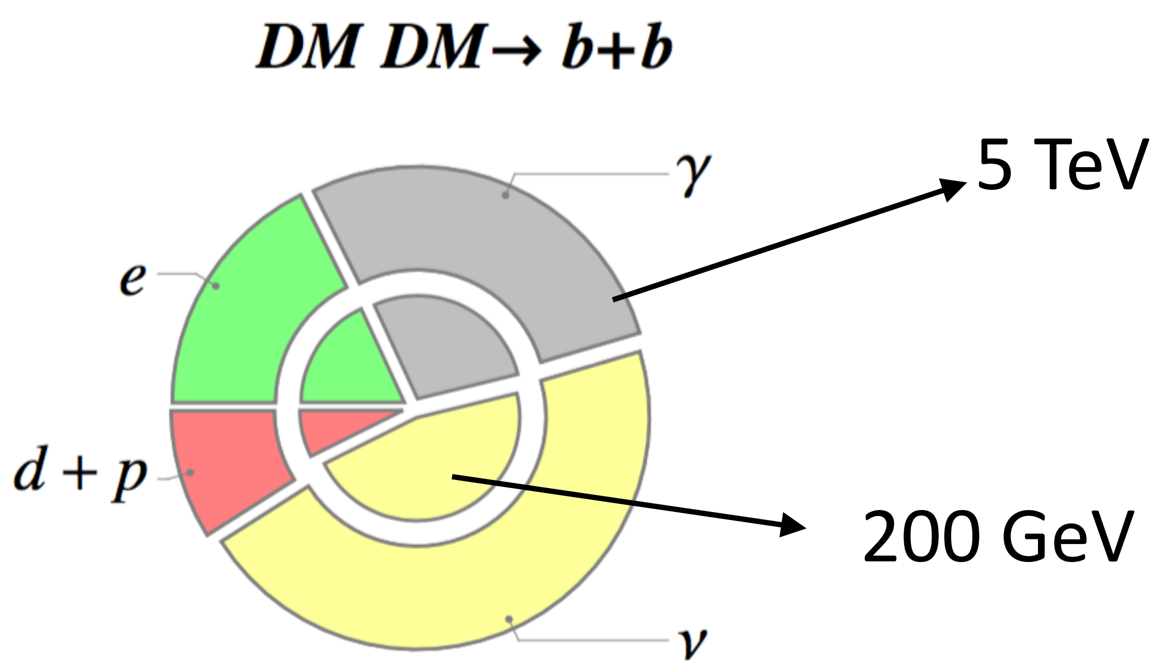
Grand & White MNRAS'21

* In WIMP and non-thermal axion models

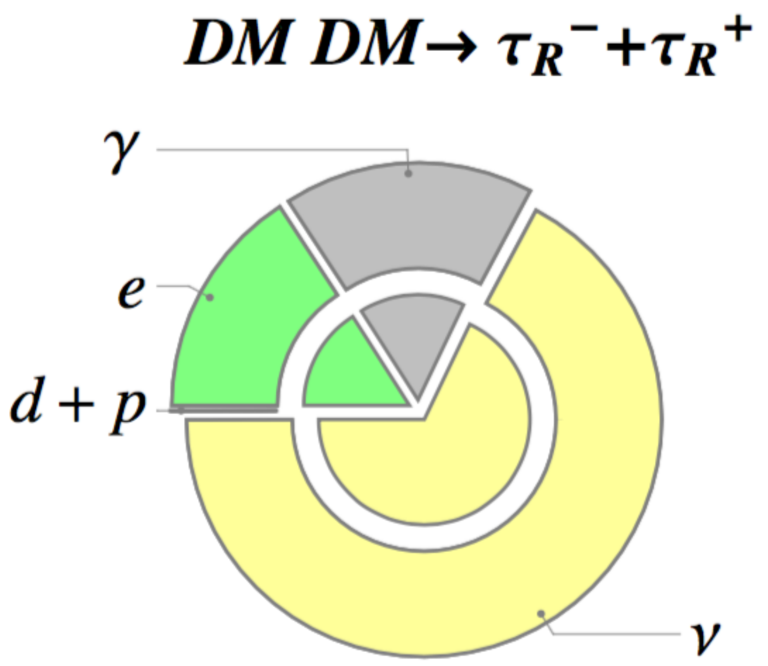
Final states energy distribution



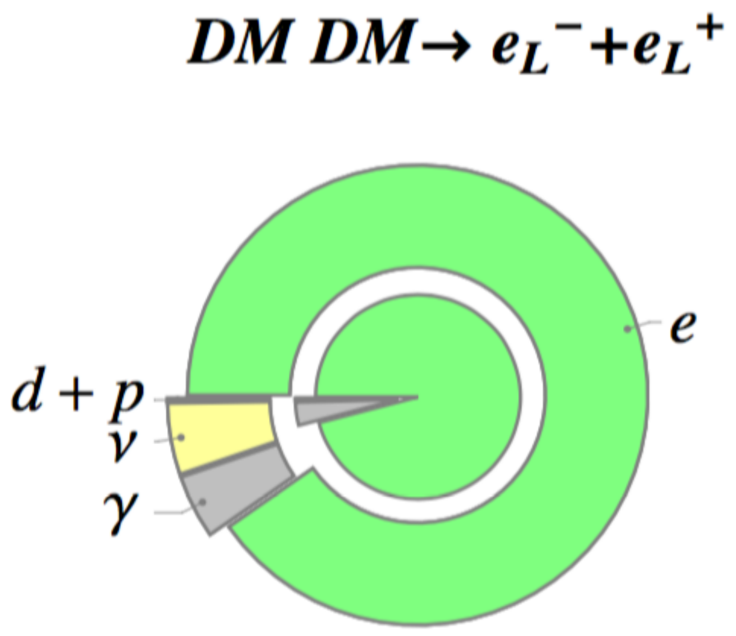
$\mathrm{DM\,DM} \rightarrow \mathrm{SM\,SM}$



$E_{\gamma+e}/E_{\rm tot} = 0.462\ (0.454)$
$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$



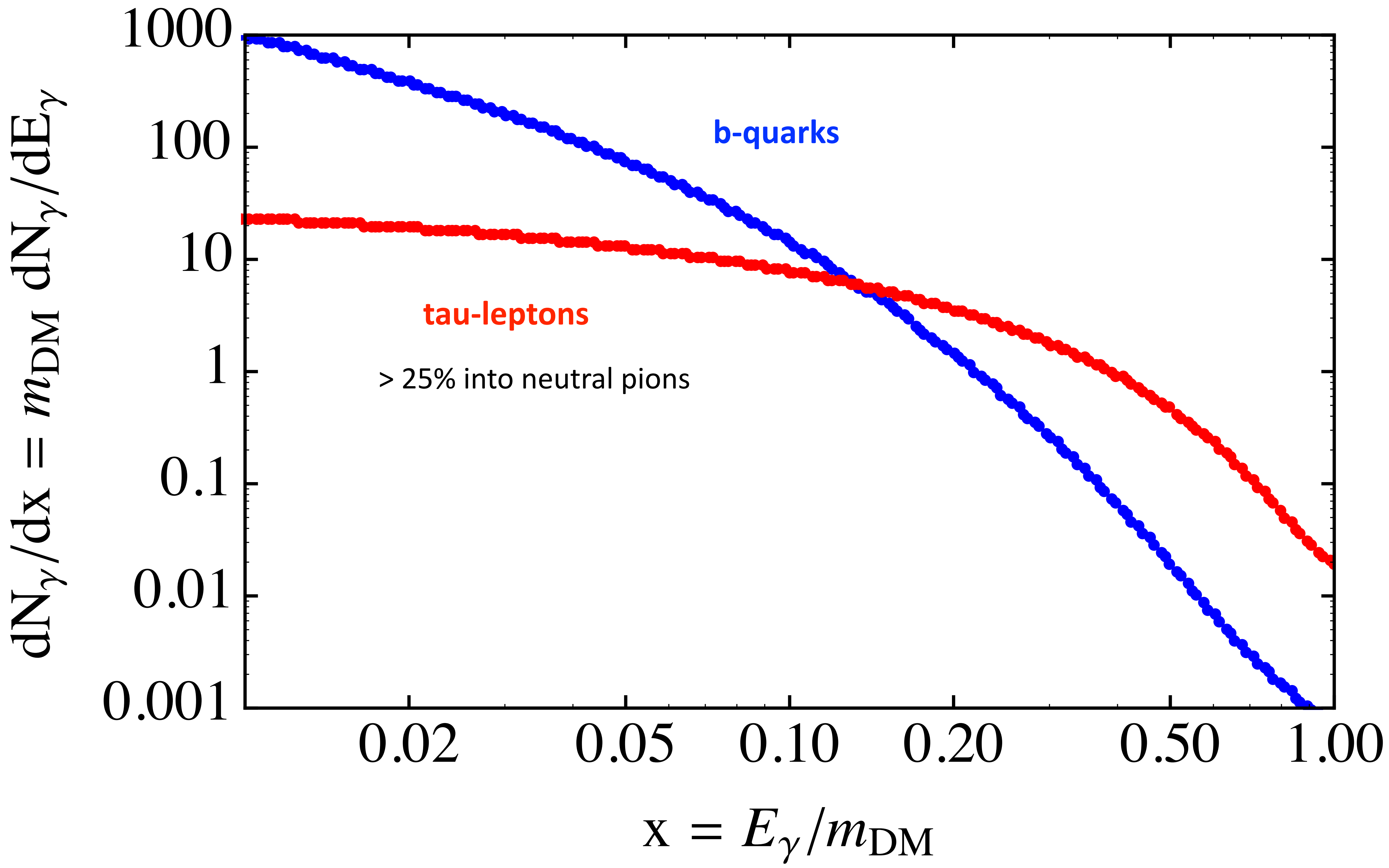
$E_{\gamma+e}/E_{\rm tot} = 0.321\ (0.328)$
$E_{p+d}/E_{\gamma+e} = 0.000\ (0.001)$



$E_{\gamma+e}/E_{\rm tot} = 0.996\ (0.948)$
$E_{p+d}/E_{\gamma+e} = 0.000\ (0.002)$

- Energy fraction going into photons and electrons (±) with respect to the total.
- Energy fraction into hadronic final states with respect to photons and electrons.

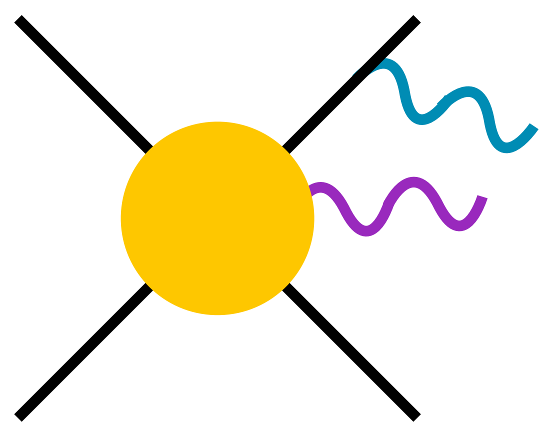
Prompt photon spectrum



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

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

Radiative corrections to photon spectrum



$\chi\chi \to f\bar{f}\gamma$

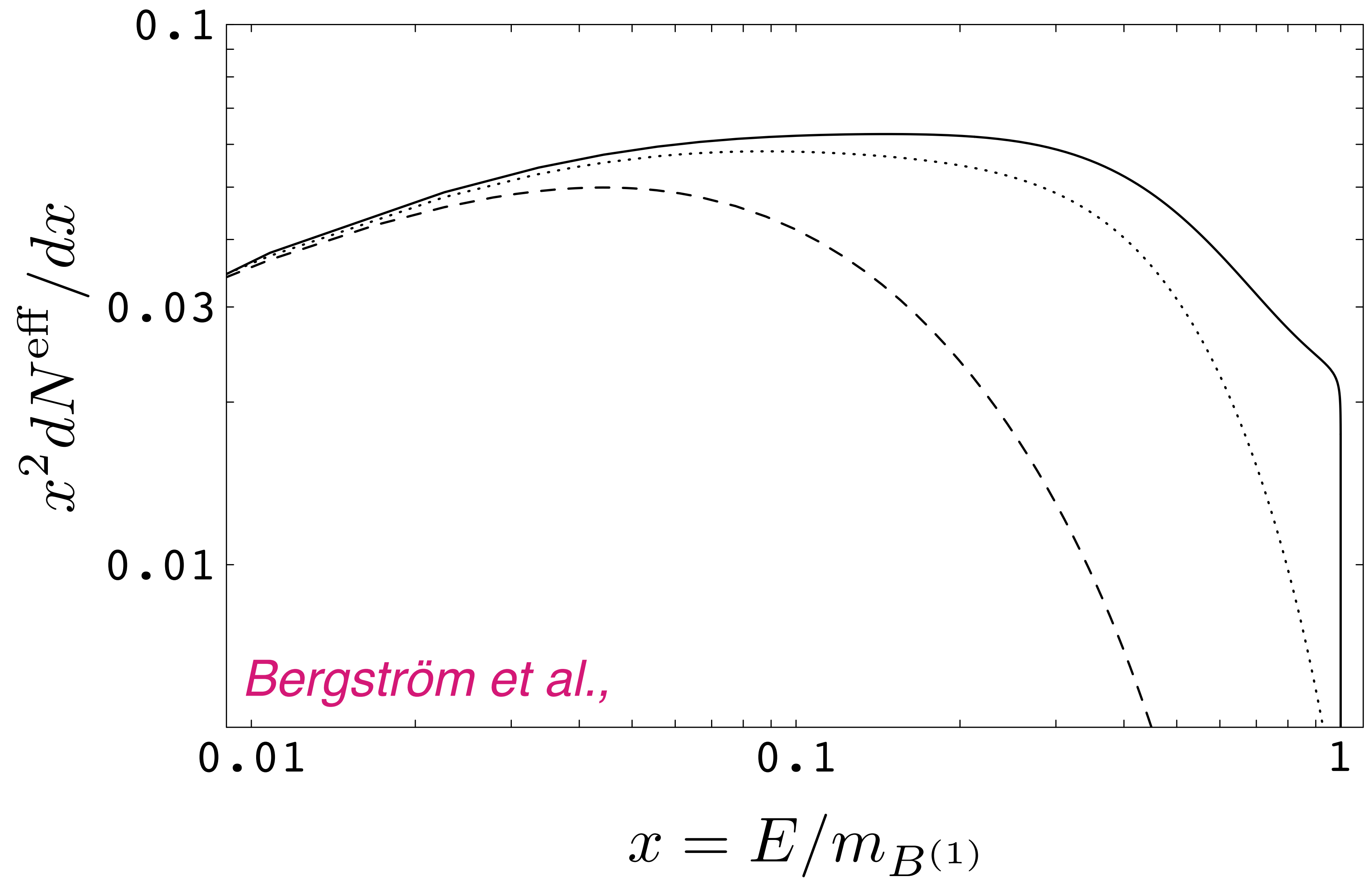
- **FSR**: logarithmic enhancement of soft collinear photons (fermion on-shell) => **model-independent** spectrum

  Birkedal et al., hep-ph/0507194

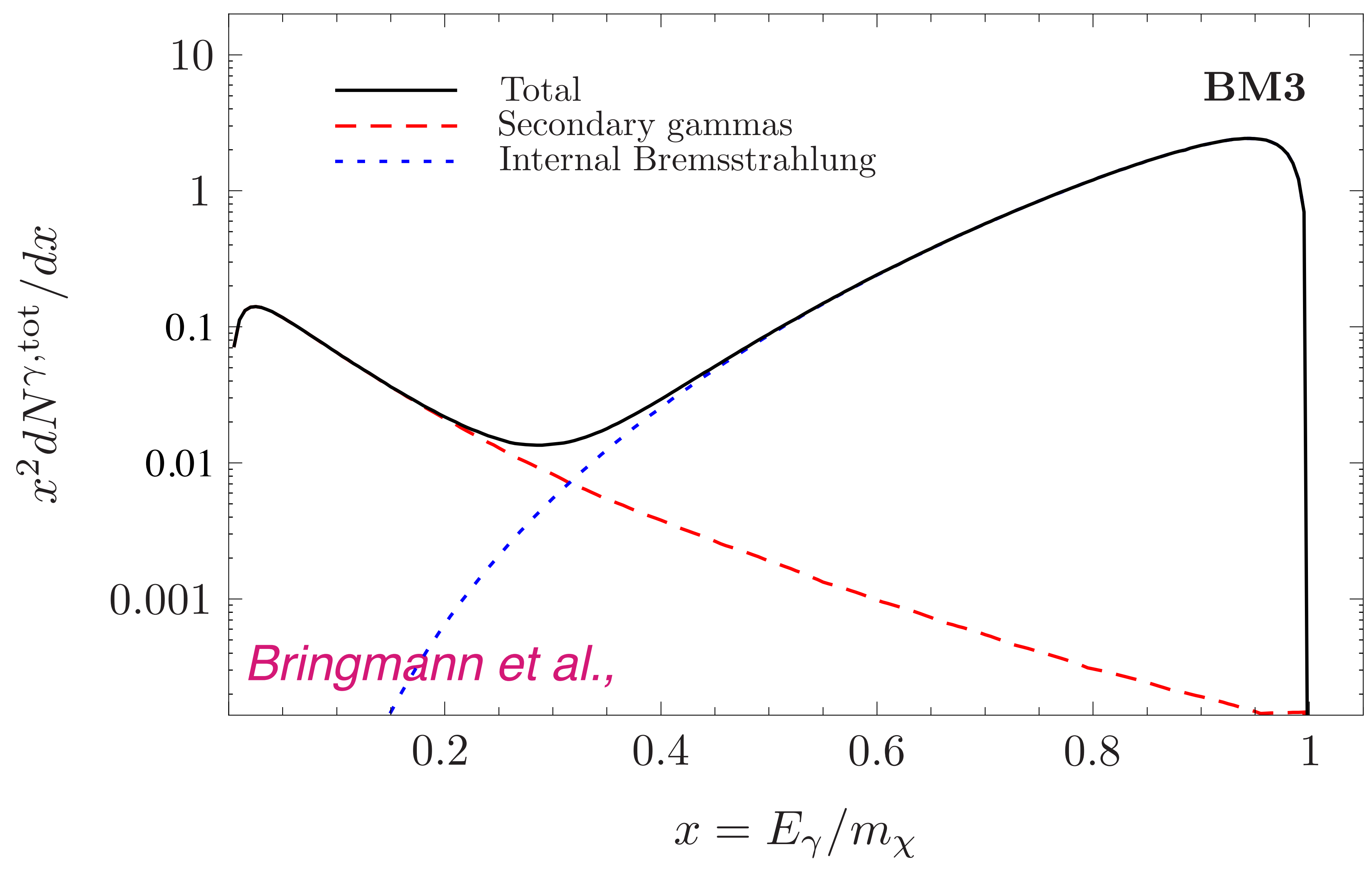
- **VIB**: lifiting of helicity suppression in t-channel diagrams => **model-dependent** spectrum

  Bergström et al., PRL'05; Bringmann et al., JHEP'08

Lightest Kaluza-Klein



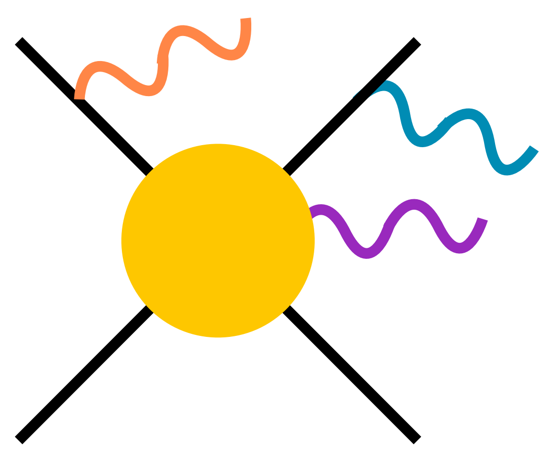
Neutralino in stau-coannihilation



Sharp spectral features at the high-end of the photon energy distribution

[Emission of W, Z, higgses => multi-messenger signal, opens up new channels *Ciafaloni et al., JCAP'11; Cirelli et al., JCAP'11; PPPC4DMID; Bringmann&Calore PRL'13; Kumar+ PLB'13; Bringmann,FC+ arXiv:1705.03466; etc*]

Radiative corrections to photon spectrum



$$\chi\chi \to f\bar{F}B$$
$$B = Z, W^{\pm}, h$$
$$[A, H, H^{\pm}]$$

- Emission of W, Z, higgses => multi-messenger signal, opens up new channels

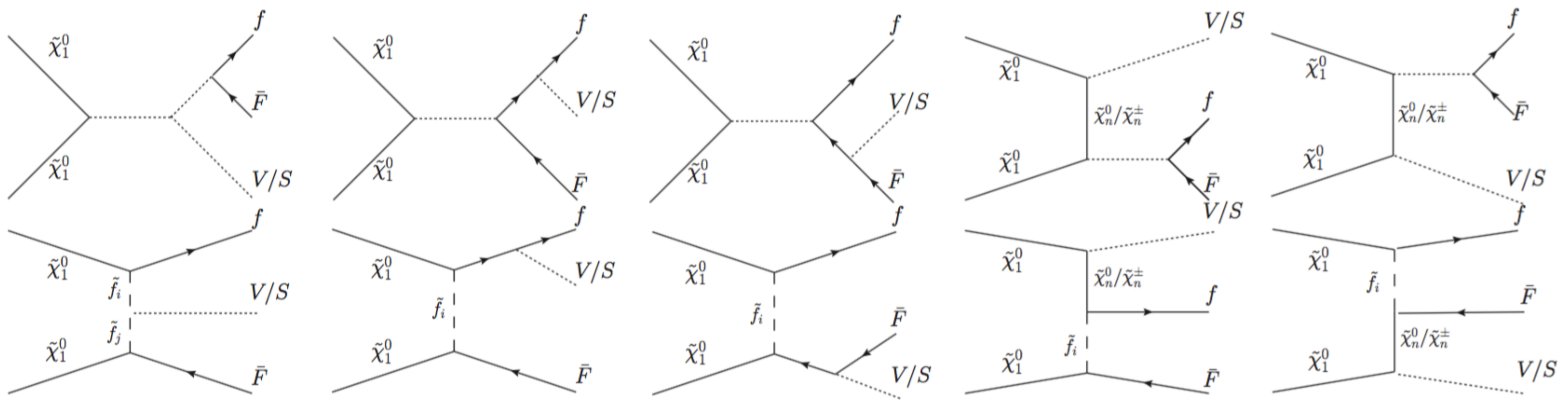
Kalchelriess et al., PRD'09

- **FSR**: soft collinear emission modelled by splitting functions => **model-independent** spectrum, sizeable changes at low enegies.

Ciafaloni et al., JCAP'11; Cirelli et al., JCAP'11; PPPC4DMID

- **VIB/ISR**: lifiting of helicity suppression => **model-dependent** spectrum

Ciafaloni+ JCAP'11/12; Bell+ PLB'11/PRD'11; Garny+ JCAP'11/12; Shudo&Nikei PRD'13; Bringmann&Calore PRL'13; Kumar+ PLB'13



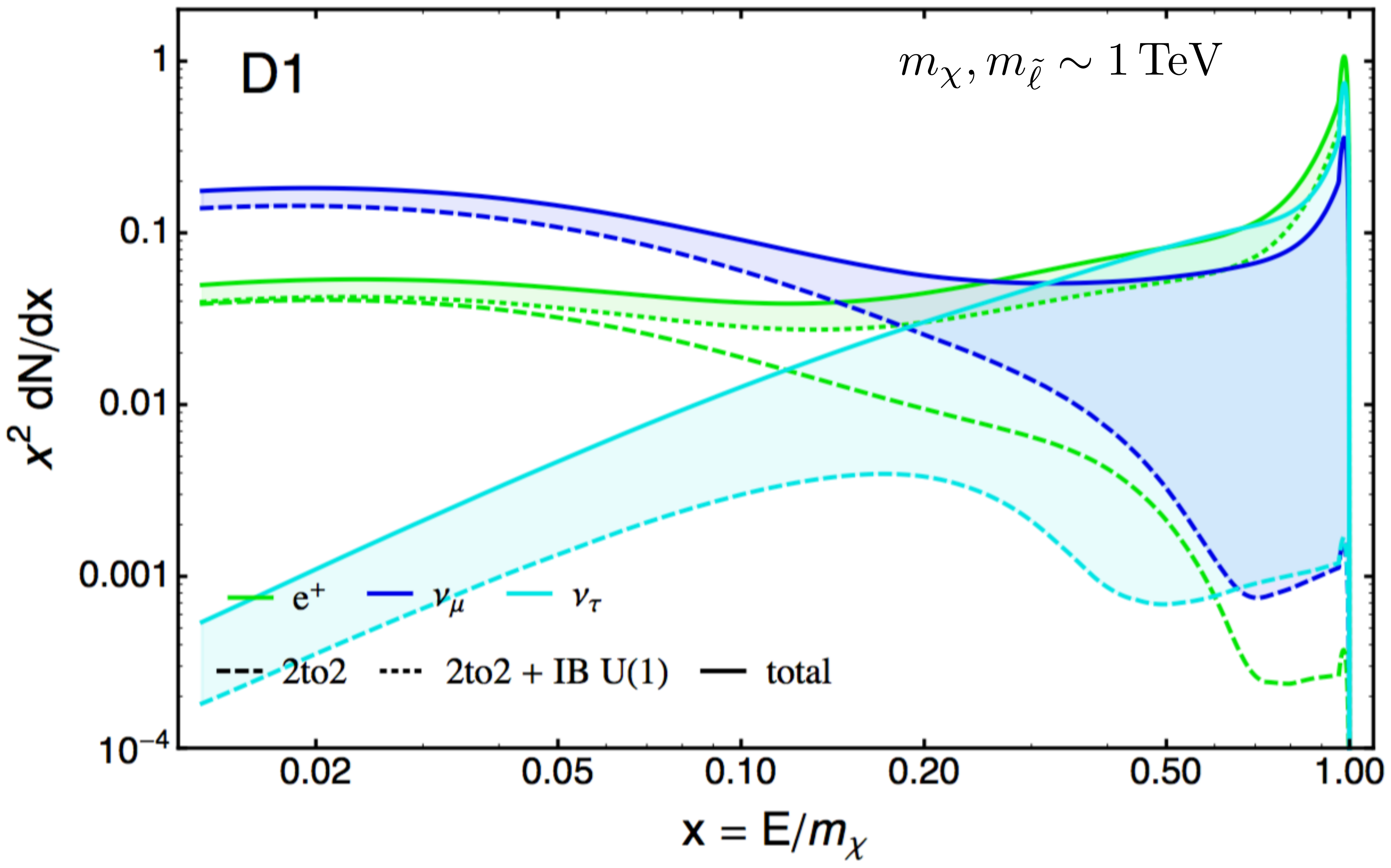
Bringmann&FC PRL'13
Bringmann,FC+ arXiv:1705.03466

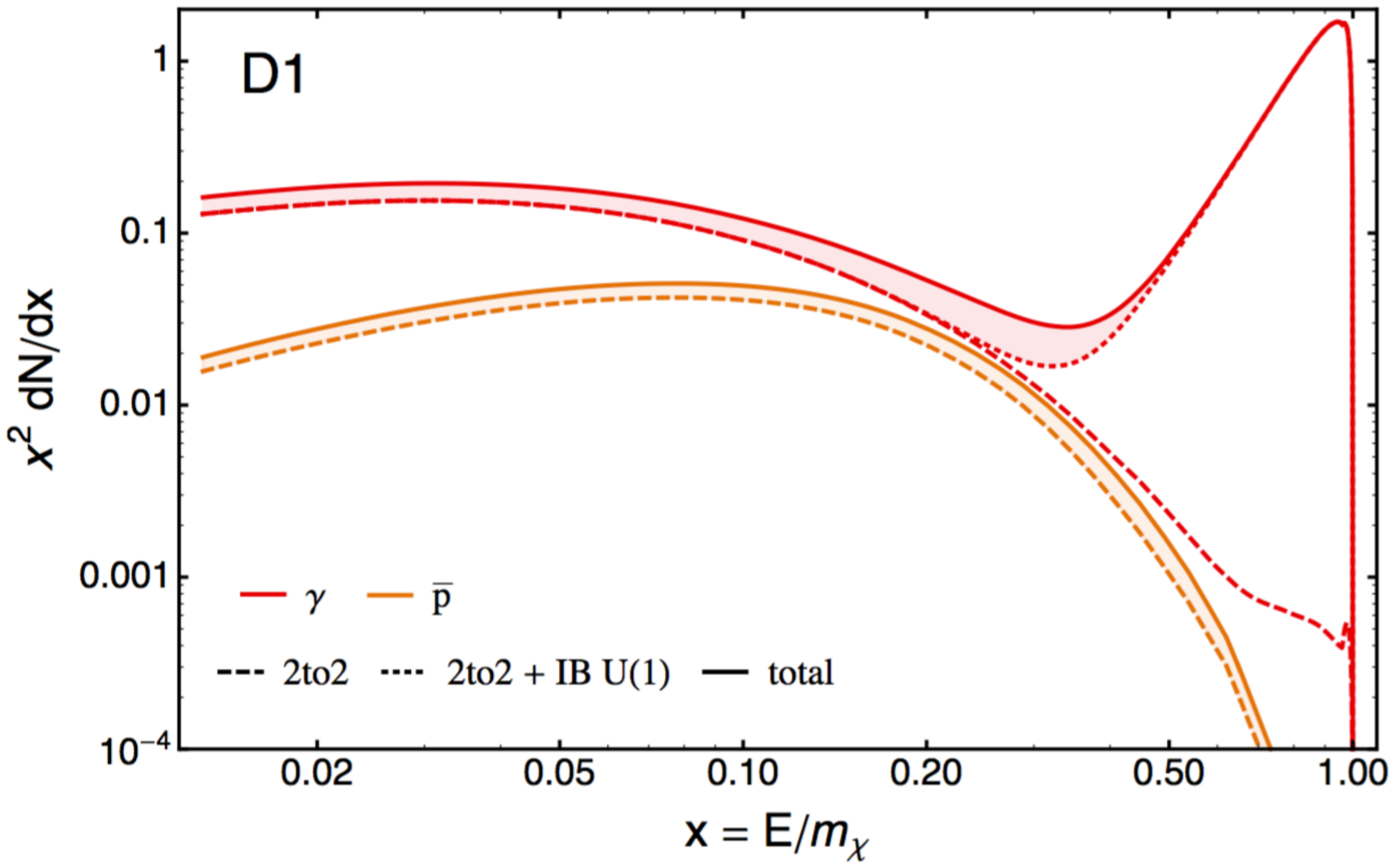
Full computation of Z, W and Higgses corrections for general Majorana dark matter and application to MSSM neutralinos

$$\chi\chi \to W^{+}\bar{F}f, Z\bar{f}f, H^{+}\bar{F}f, A\bar{f}f, H\bar{f}f, h\bar{f}f$$

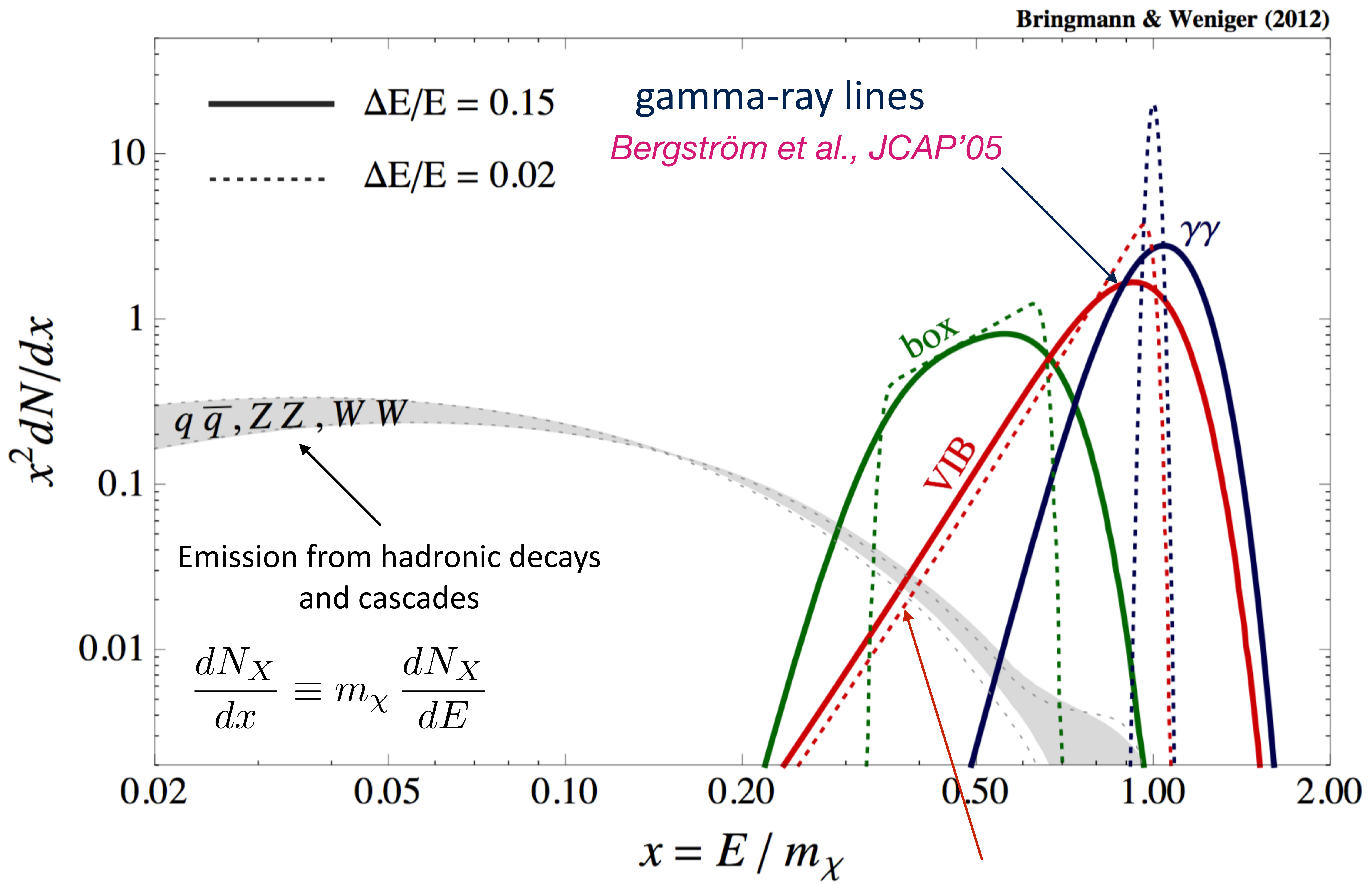
Spectral modifications

Bringmann,FC+ arXiv:1705.03466





Dark matter spectrum: prompt photons



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

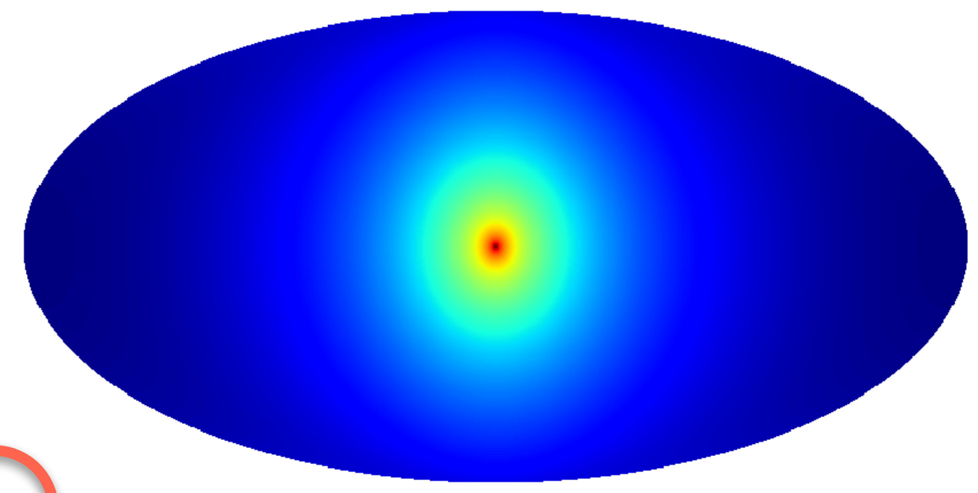
PPC 4 DM ID http://www.marcocirelli.net/PPPC4DMID.html
Cirelli+ JCAP 2012

Analytical fitting functions:

Fornengo, Pieri, Scopel, PRD 2004
Cembranos et al., PRD 2011

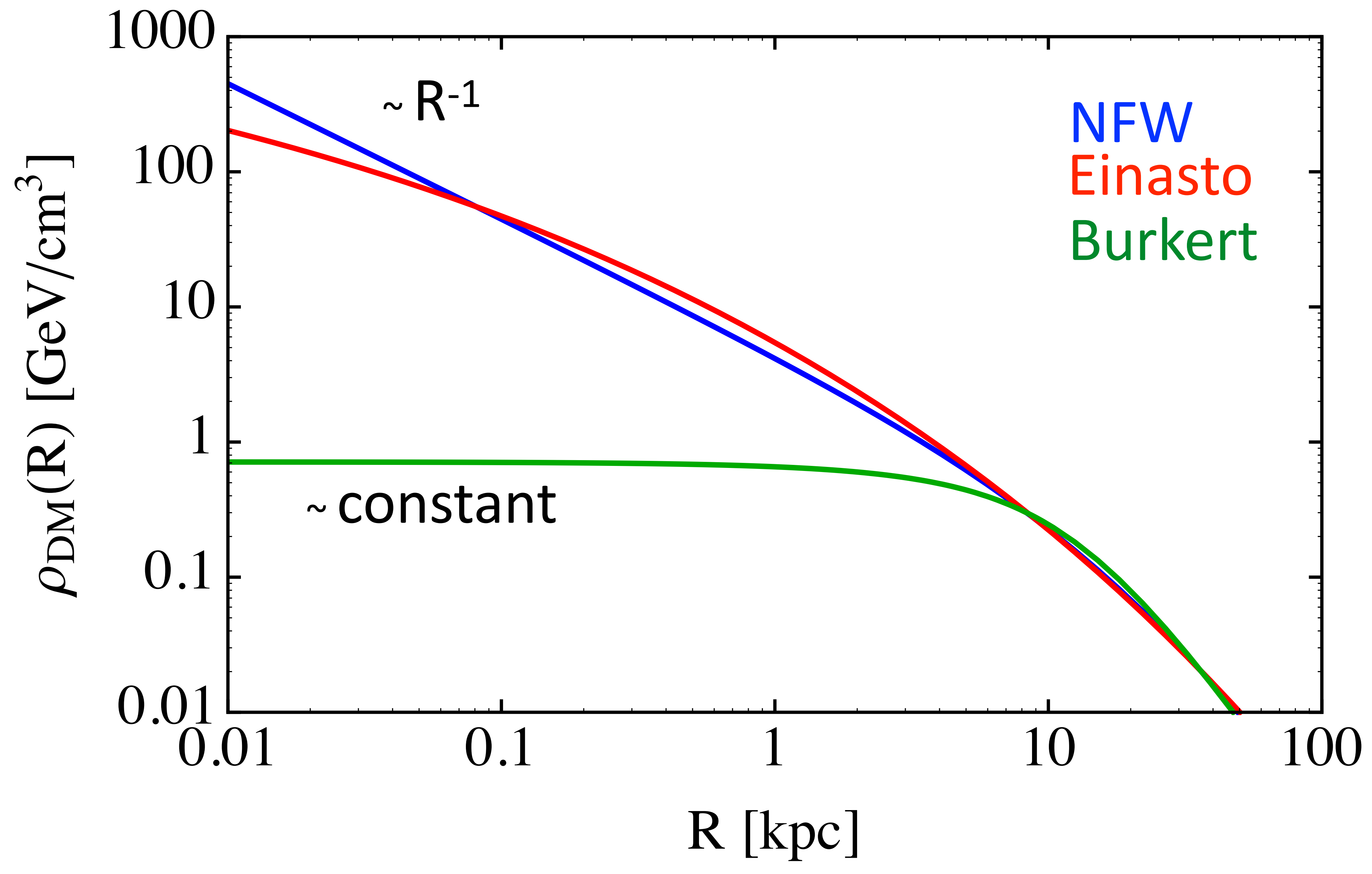
For dependence on event Monte Carlo generators see, e.g.,
Cembranos+ JHEP'13

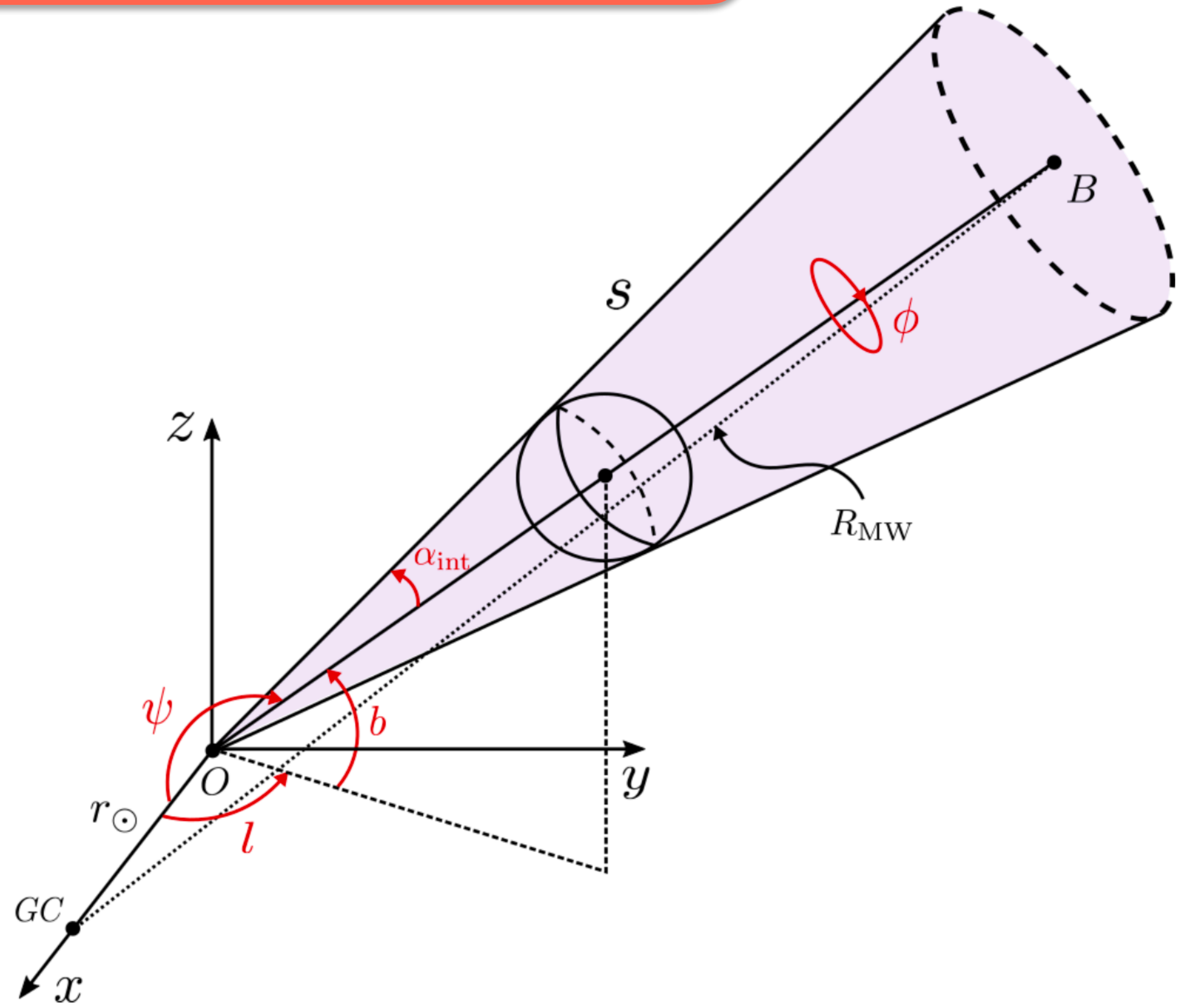
Dark matter annihilation flux



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

Dark matter density profiles

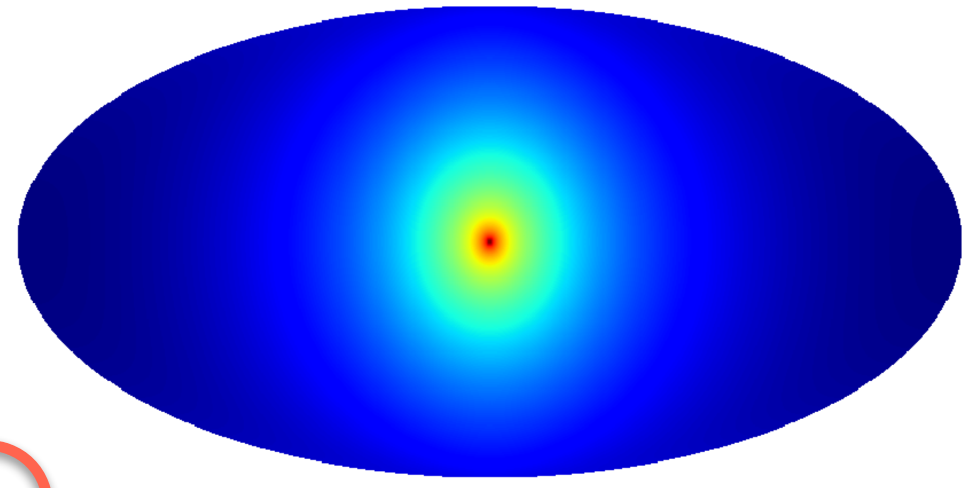




$$r(s) = (r_\odot^2 + s^2 - 2r_\odot s\cos b\cos l)^{1/2}$$

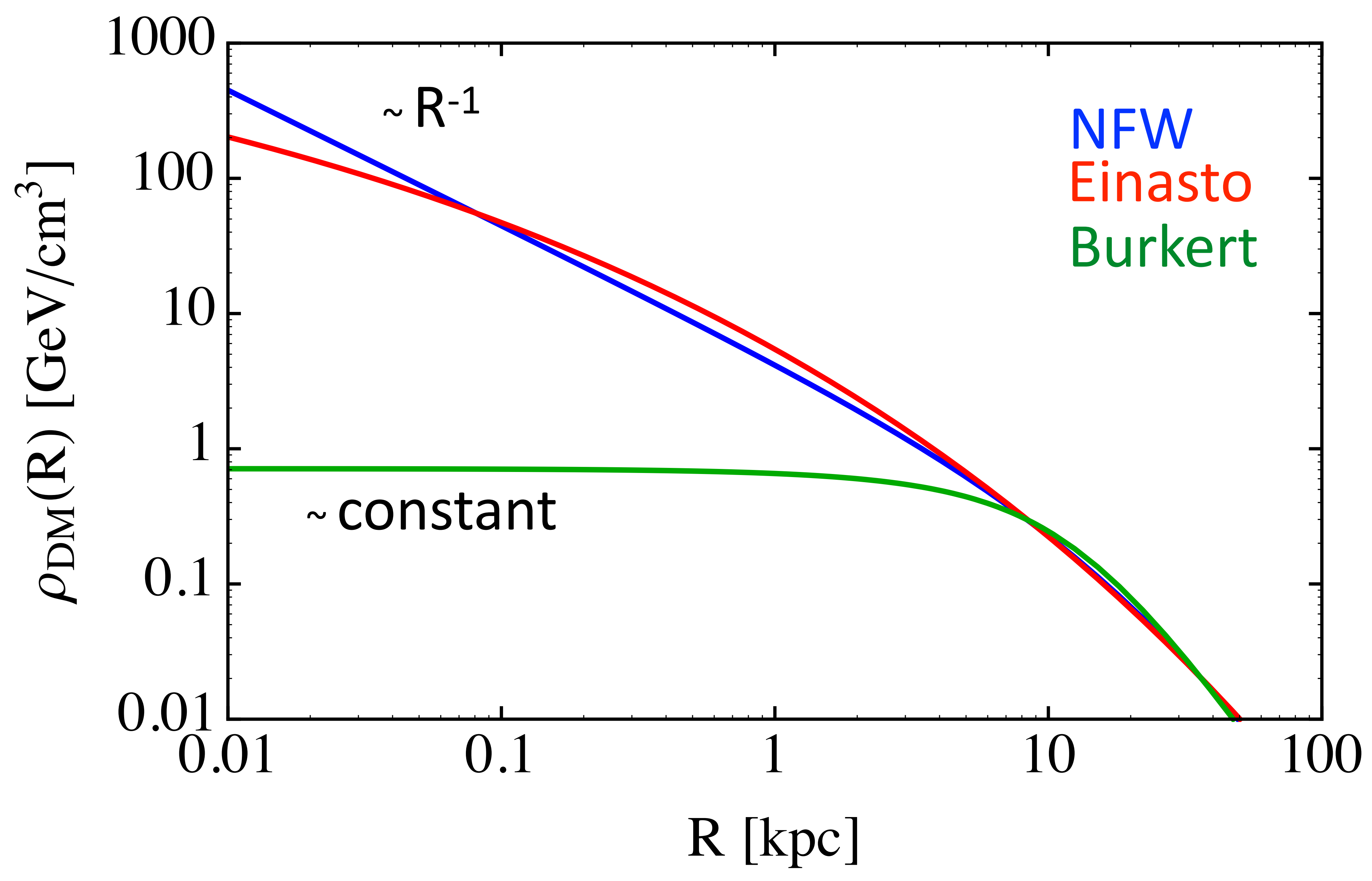
$$\cos\psi = \cos b\cos l$$

Dark matter annihilation flux

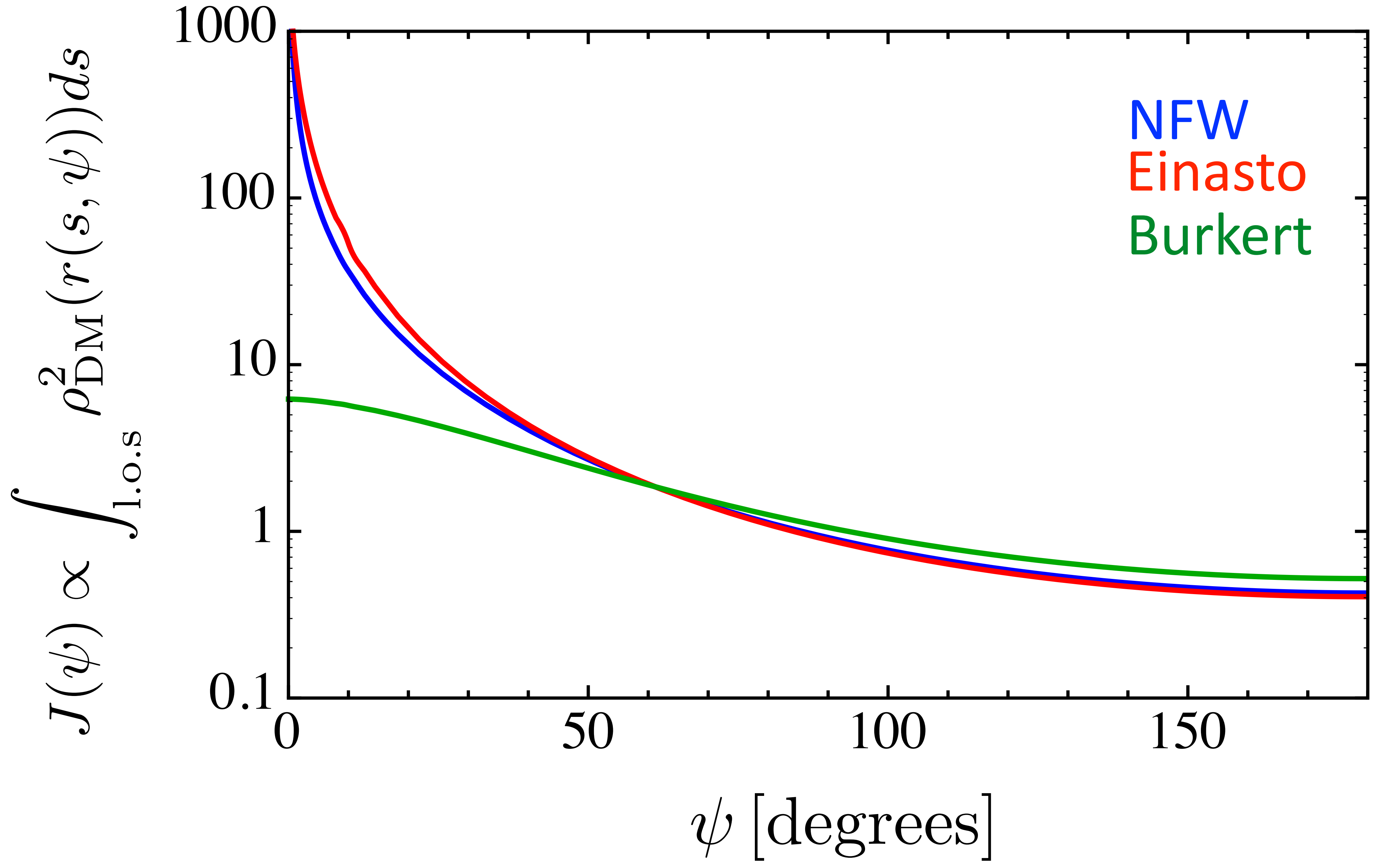


$$\frac{d\Phi_\gamma}{dE} = s\,\frac{\langle \sigma v \rangle}{4\pi m_{\rm DM}^2} \sum_f B_f \frac{dN_\gamma^f}{dE} \times \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho_{\rm DM}^2(\ell)\, d\ell$$

Dark matter density profiles

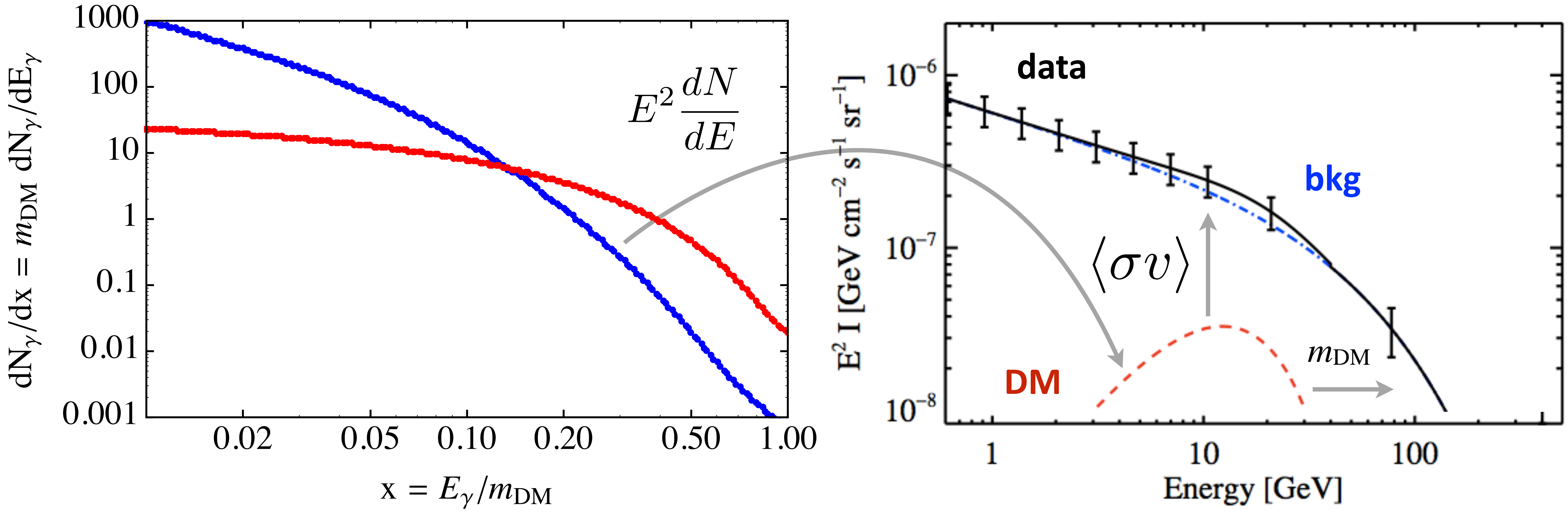


Spatial distribution of the signal



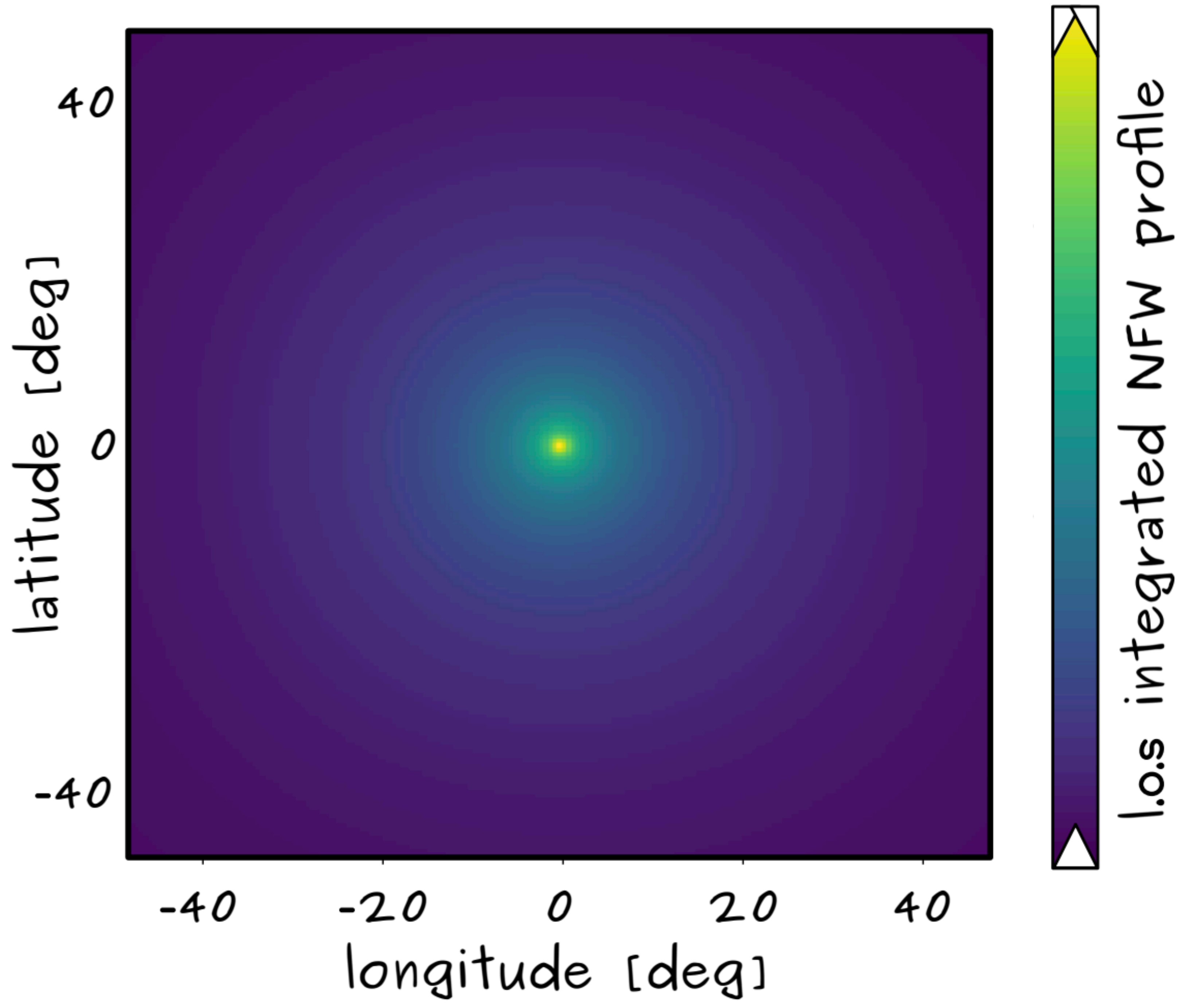
Dark matter annihilation flux

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



DM decay flux equation

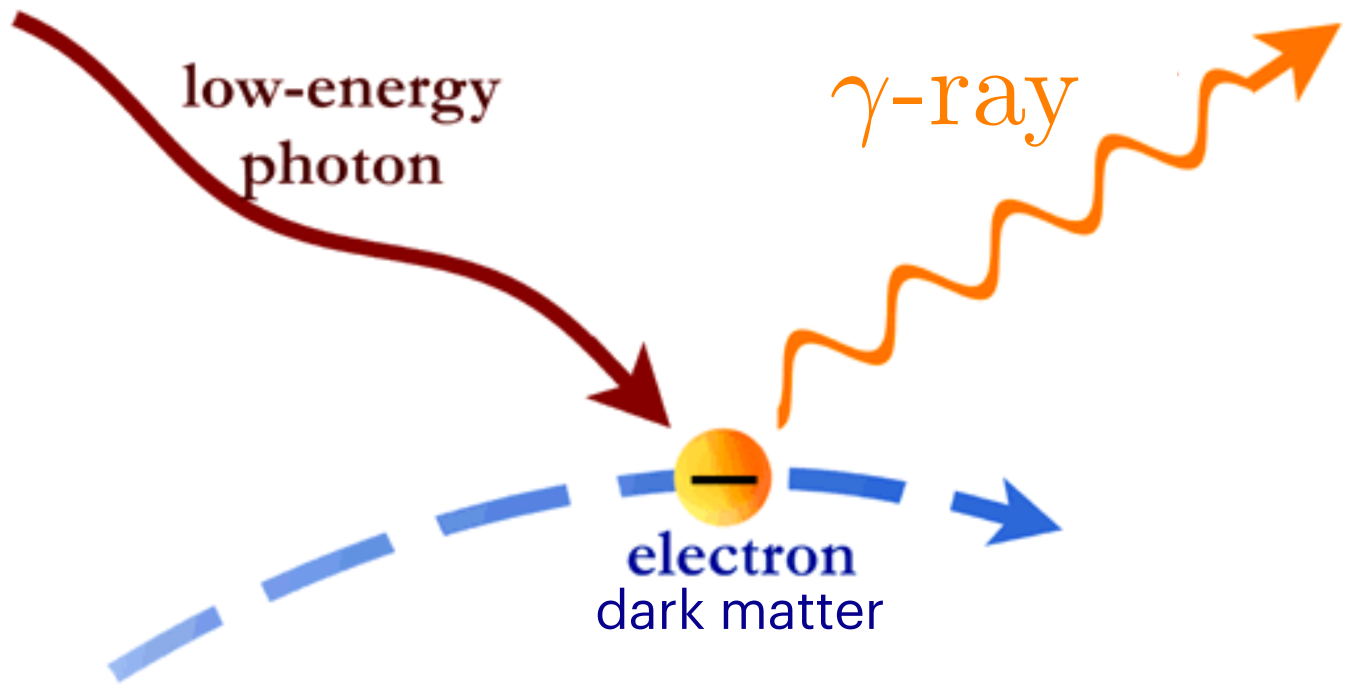
$$\frac{d\Phi_\gamma}{dE} = \frac{\Gamma(\mathrm{DM} \to \gamma\gamma)}{4\pi m_{\mathrm{DM}}} \frac{dN_\gamma}{dE} \times \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\ell) d\ell$$

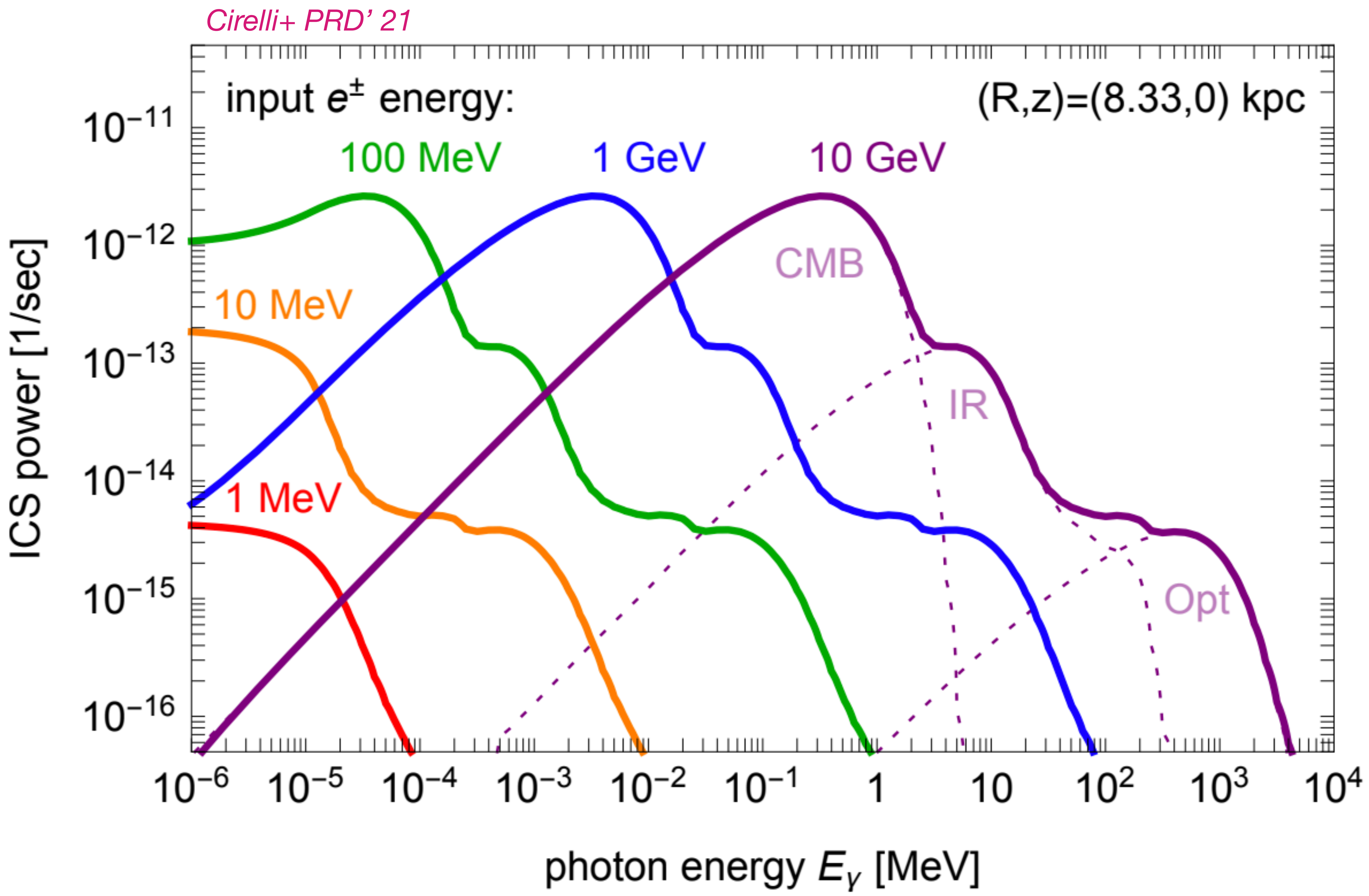


Flux from all galaxies: you need to integrate over redshift and galaxies' redshift distribution

Radiative emission from leptons

Inverse Compton scattering

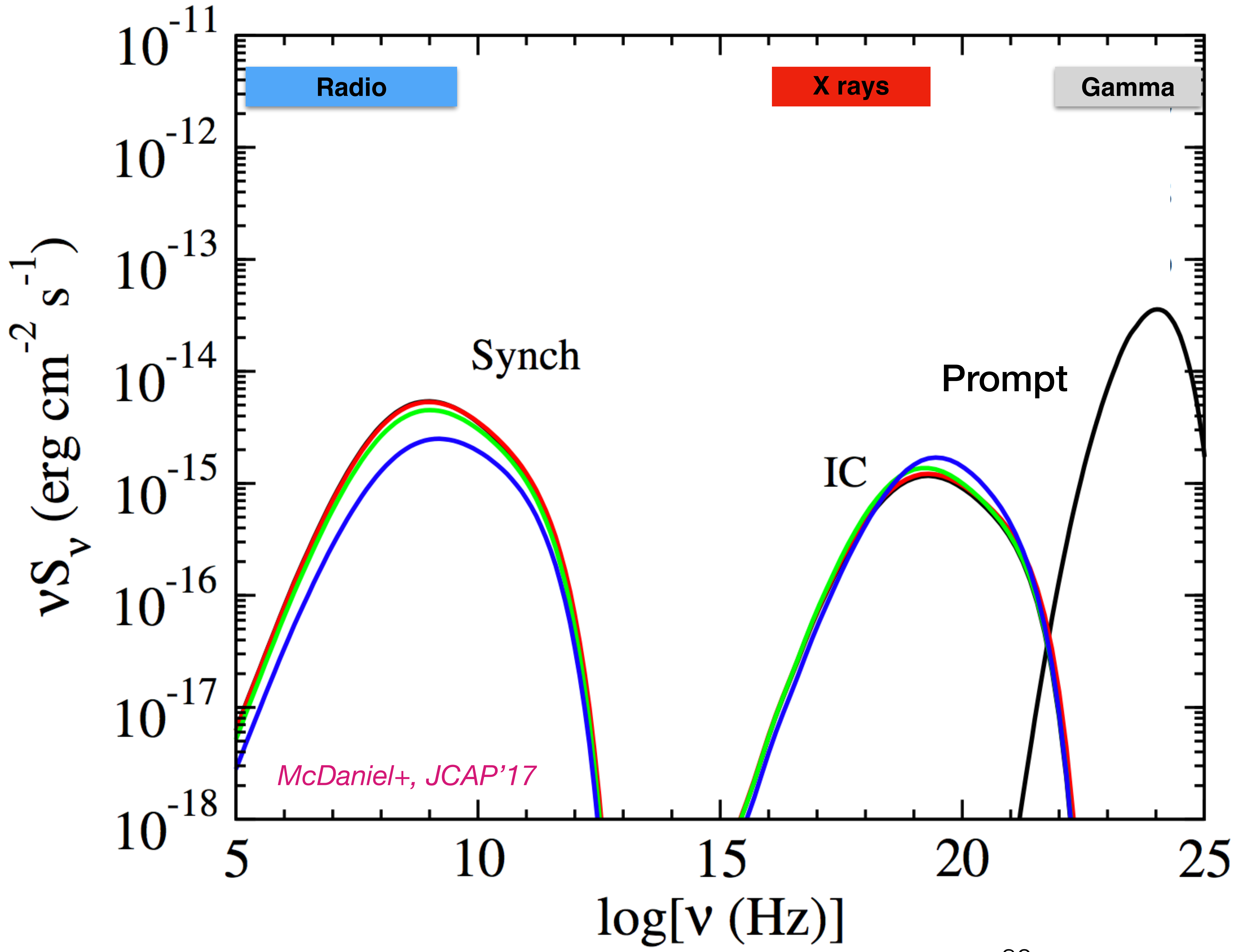




Secondary emission processes allow us to probe DM at much higher masses than prompt energy scales

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

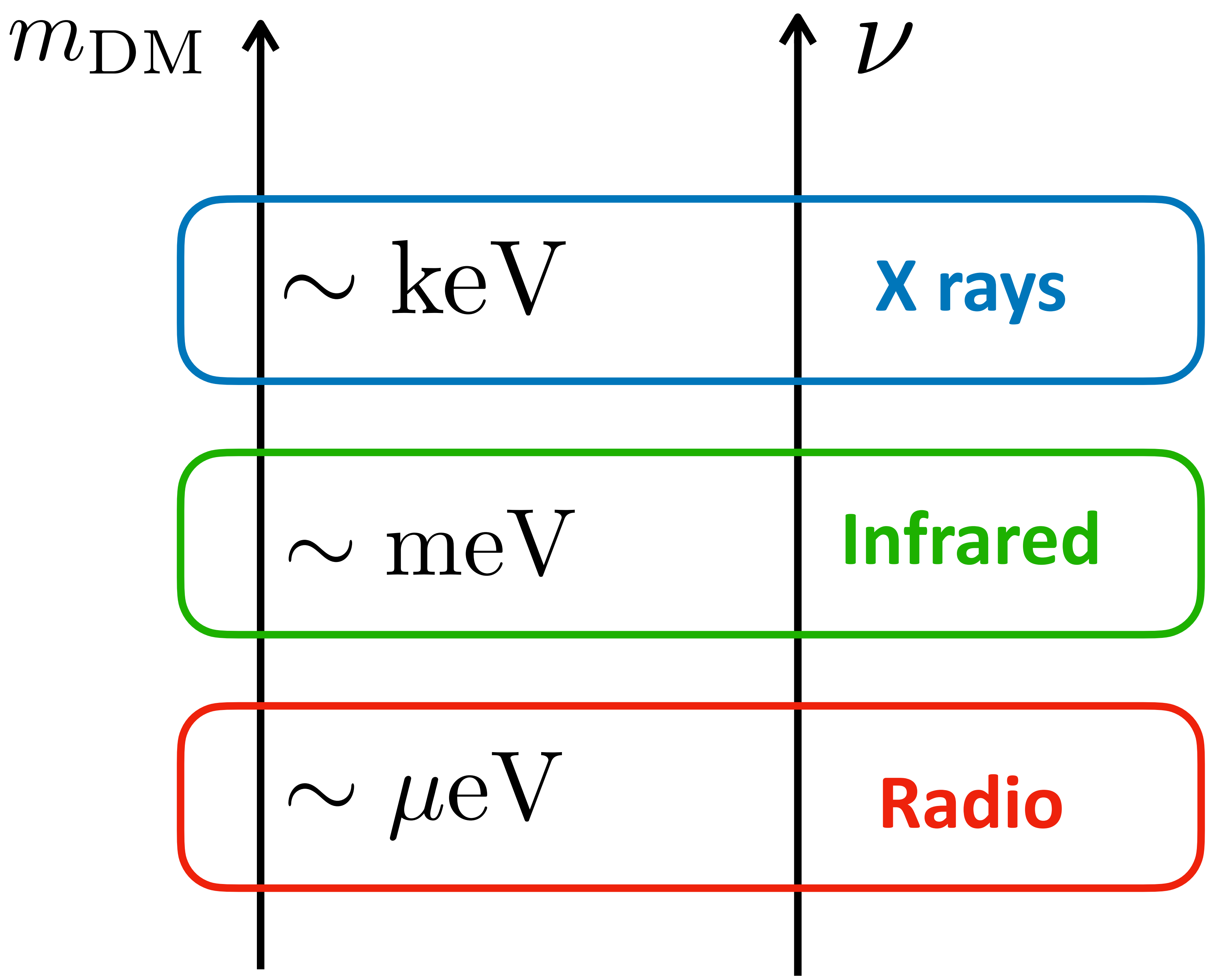
Light dark matter decay: lines

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

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

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

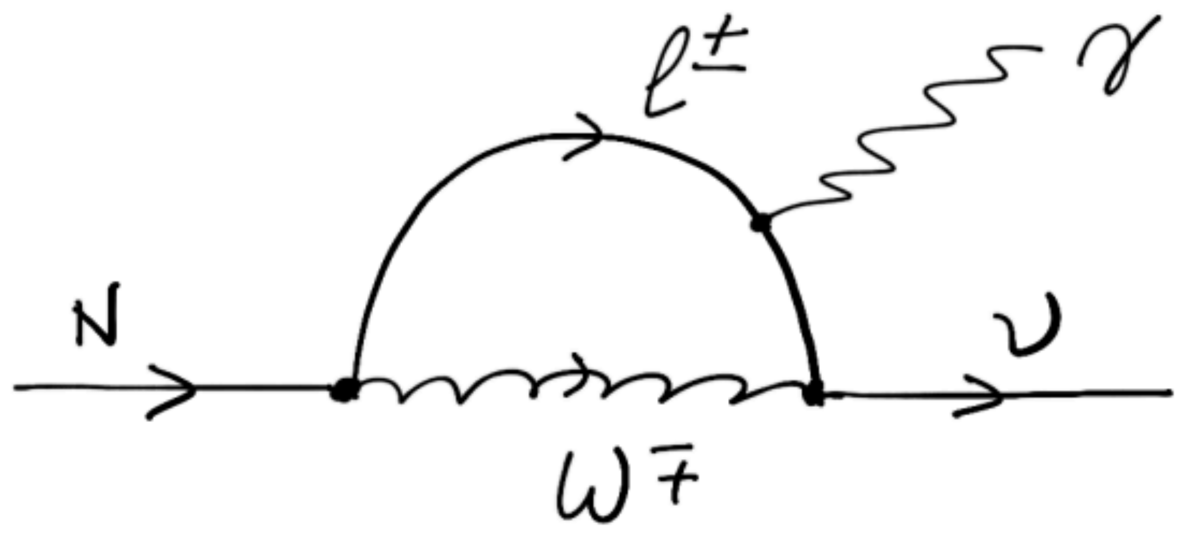
Narrow line signal @ energy scale of the DM mass



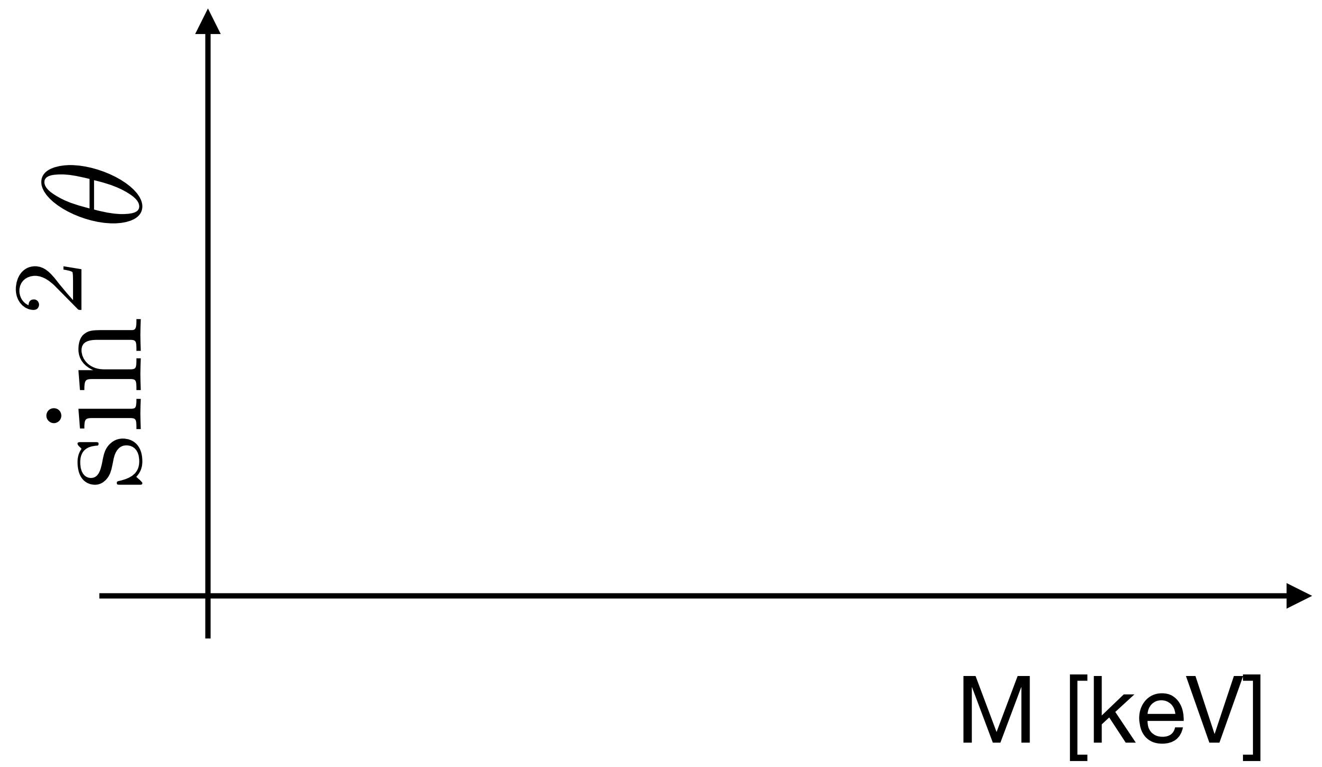
Sterile neutrinos X-ray lines

Model prediction

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



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



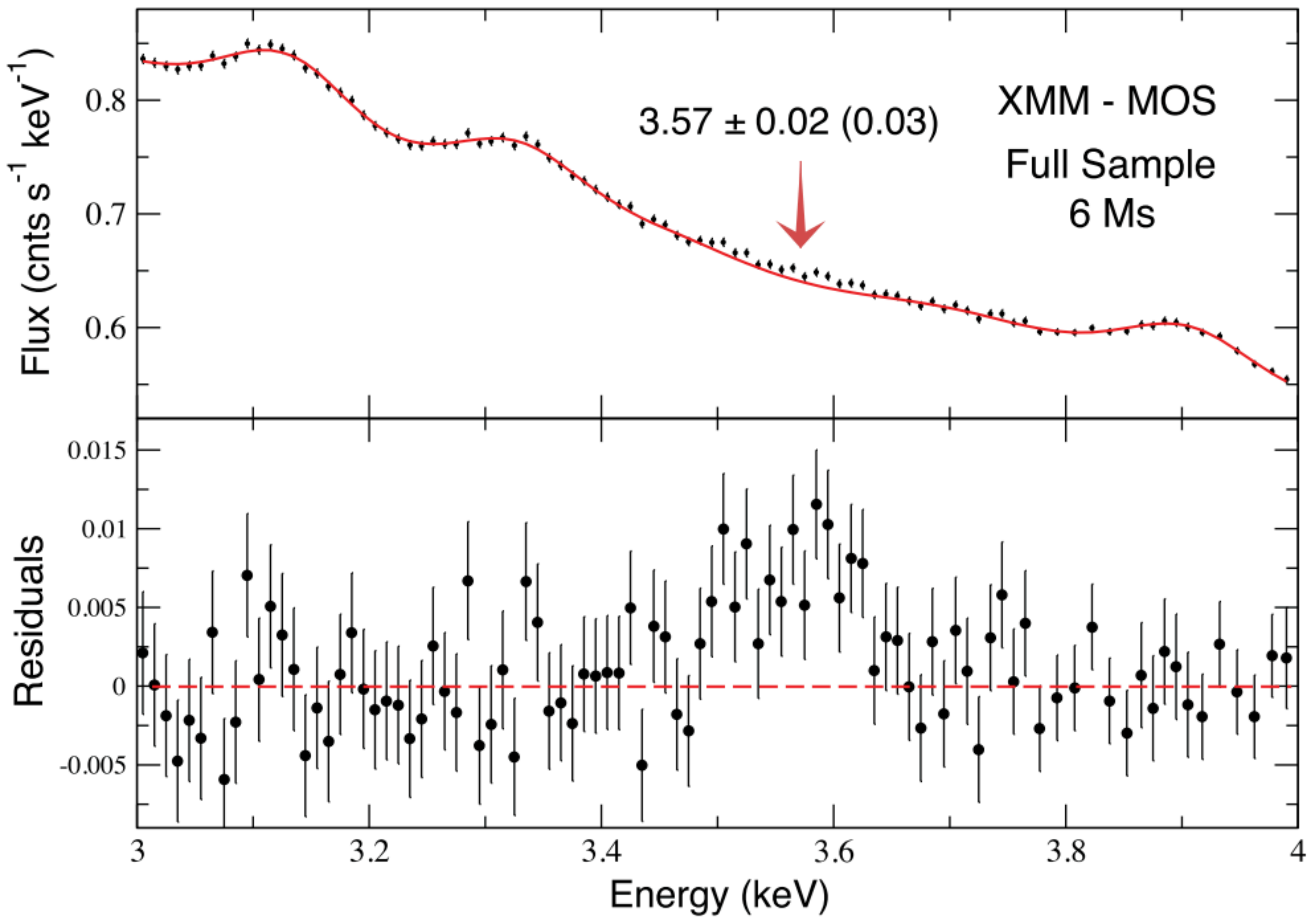
Review: K. N. Abazajian, Phys. Rept. 711-712, 1 (2017)

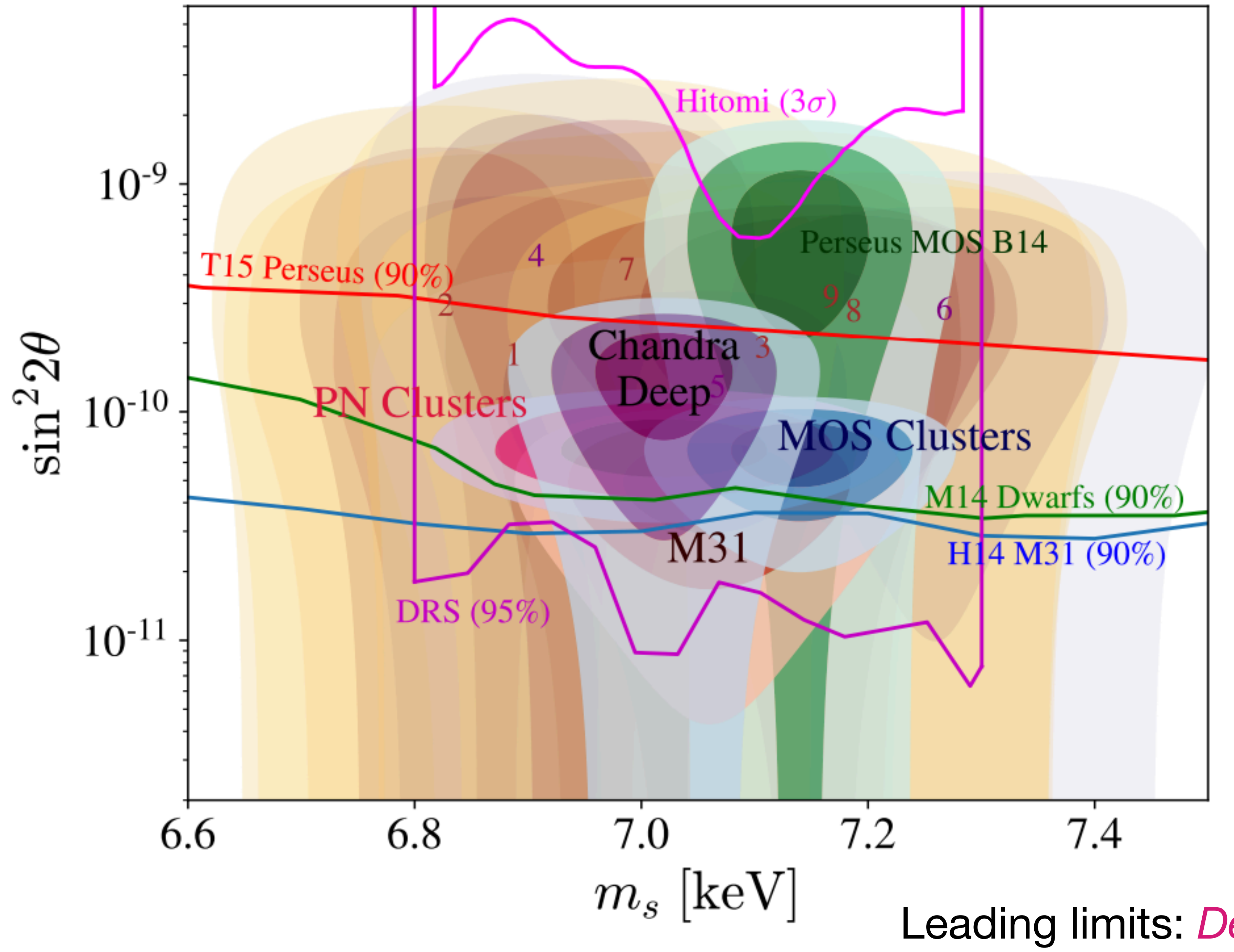
Sterile neutrinos X-ray lines

X-ray telescopes and spectral analysis

Starting from early 2014:

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

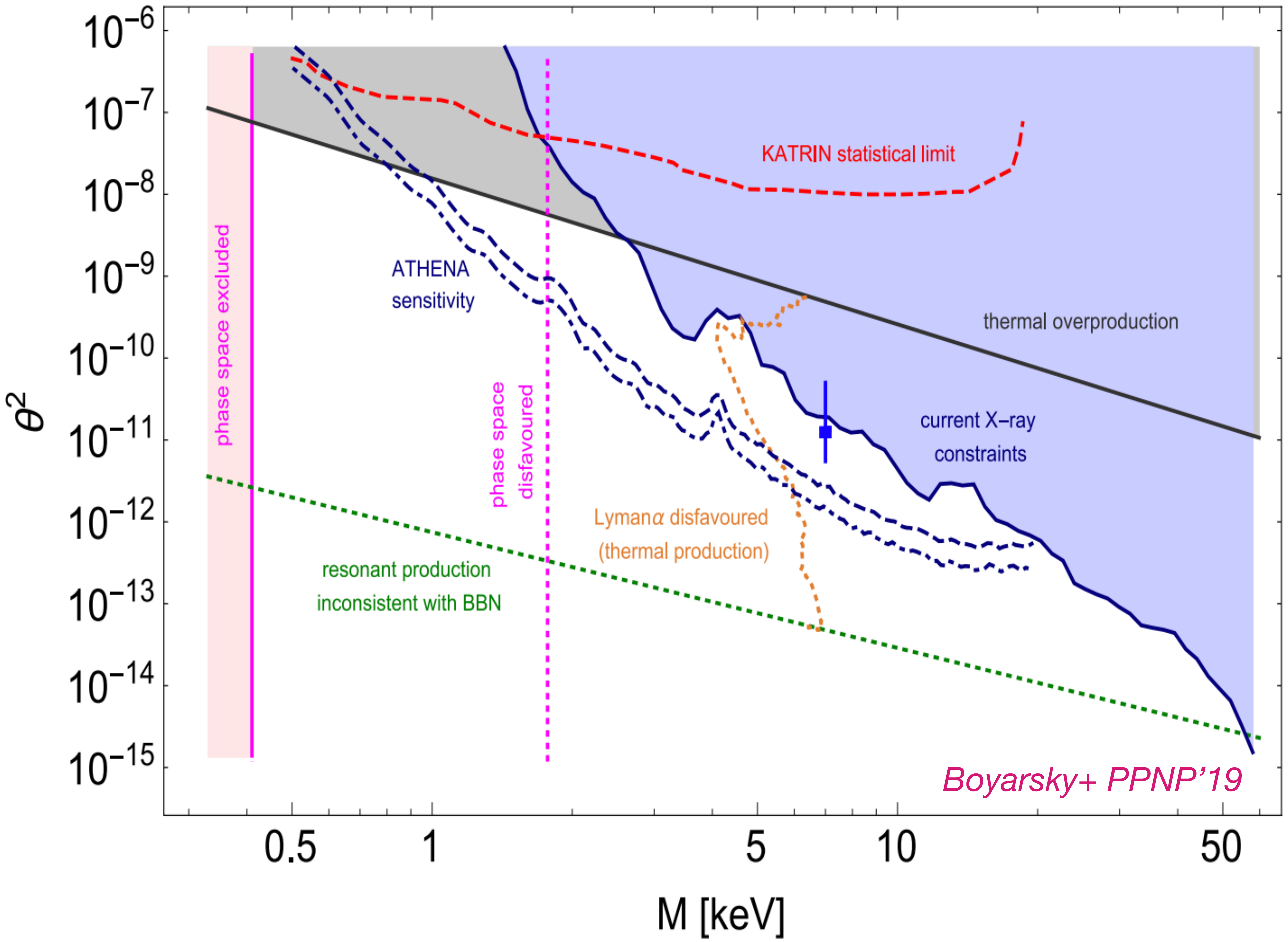




Leading limits: *Dessert+ Science' 20*

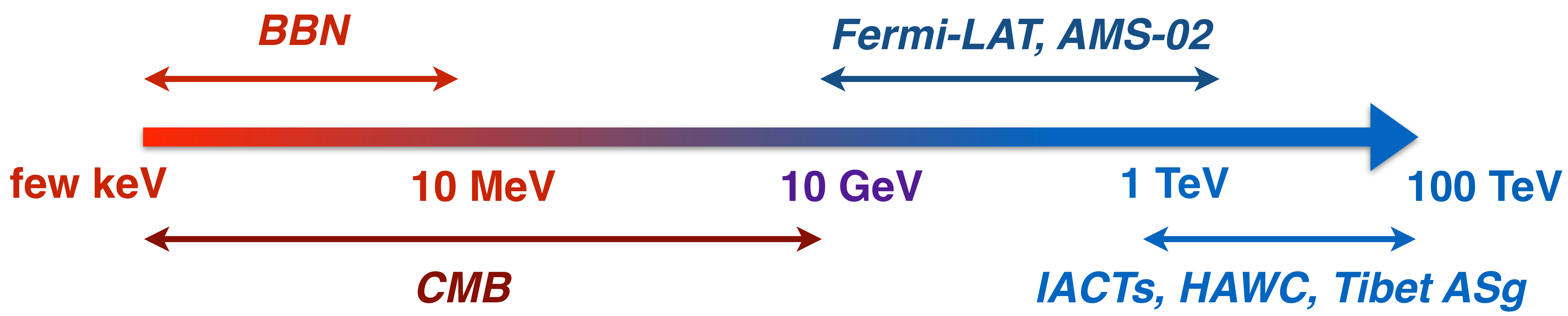
Sterile neutrinos X-ray lines

Constraints on parameter space

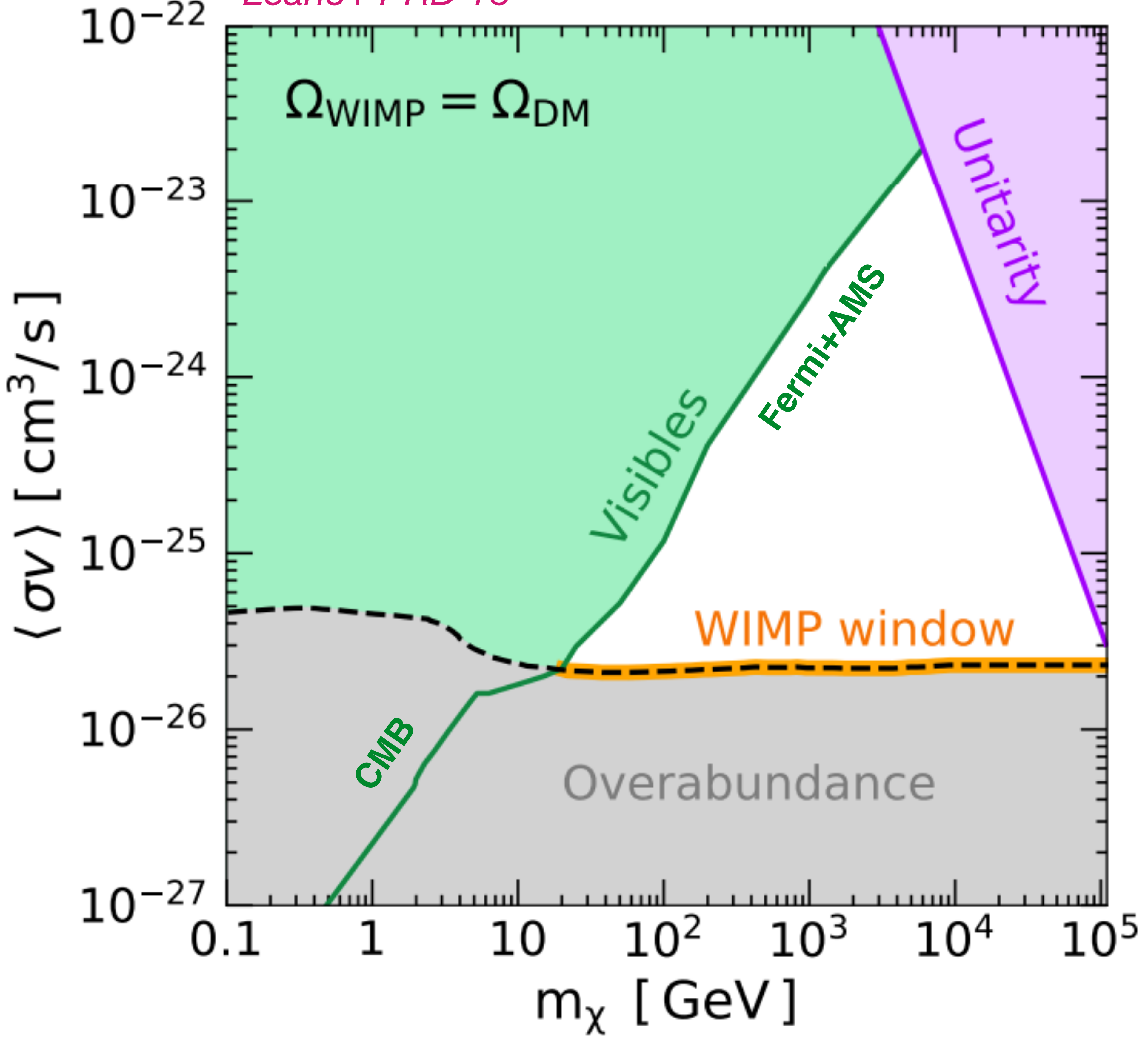


Future progresses with eROSITA, XARM (ex-Hitomi), Linx, and Athena+

WIMP annihilation window



Leane+ PRD'18

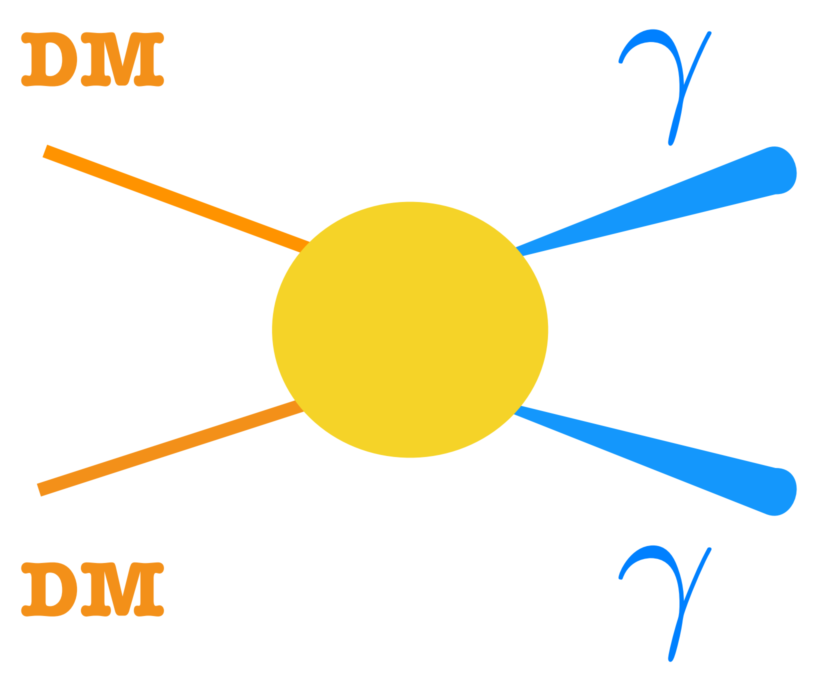


- **Total cross-section** sets **relic abundance**
- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

→ 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*]

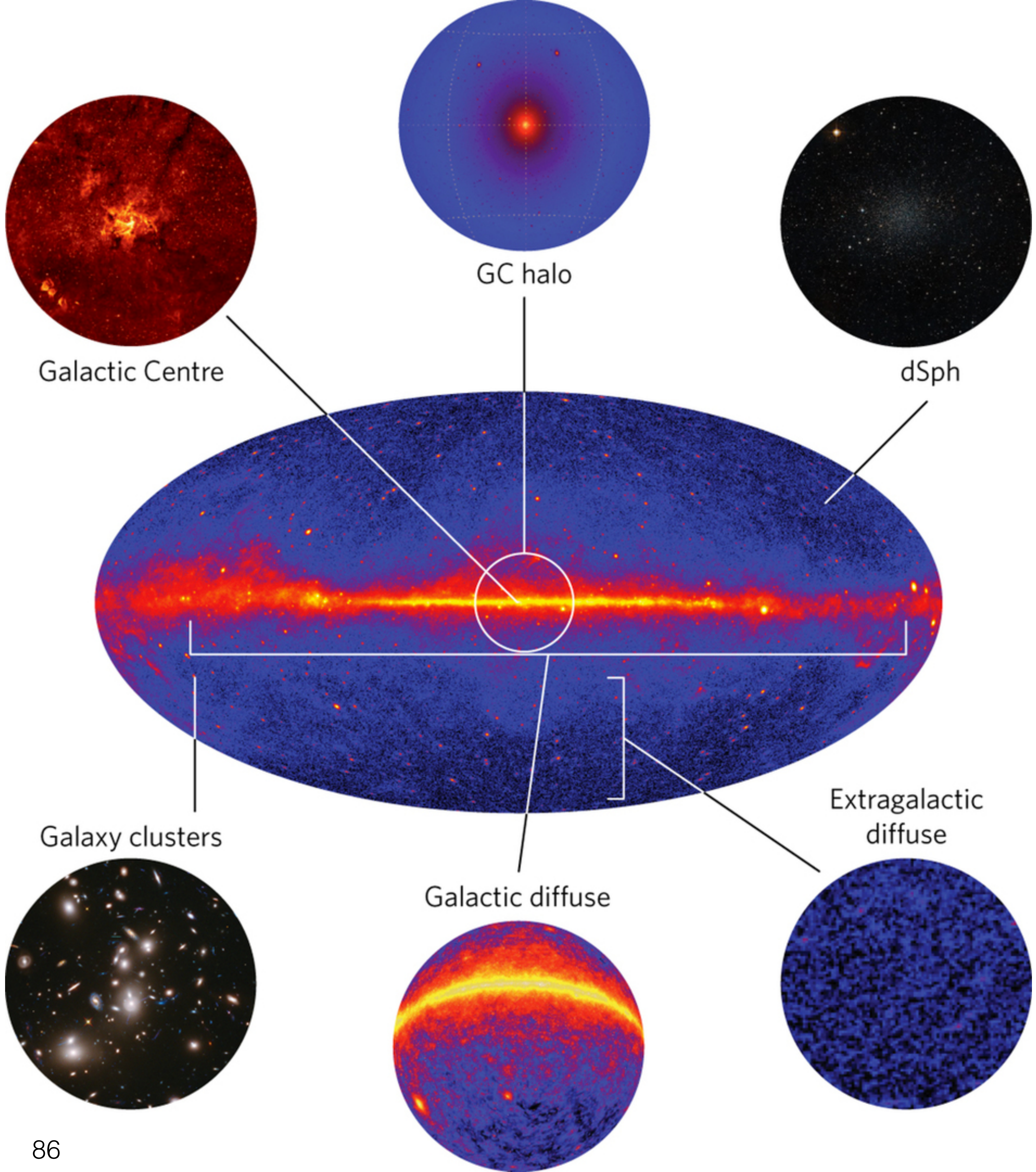
Targets for WIMP gamma-ray searches



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

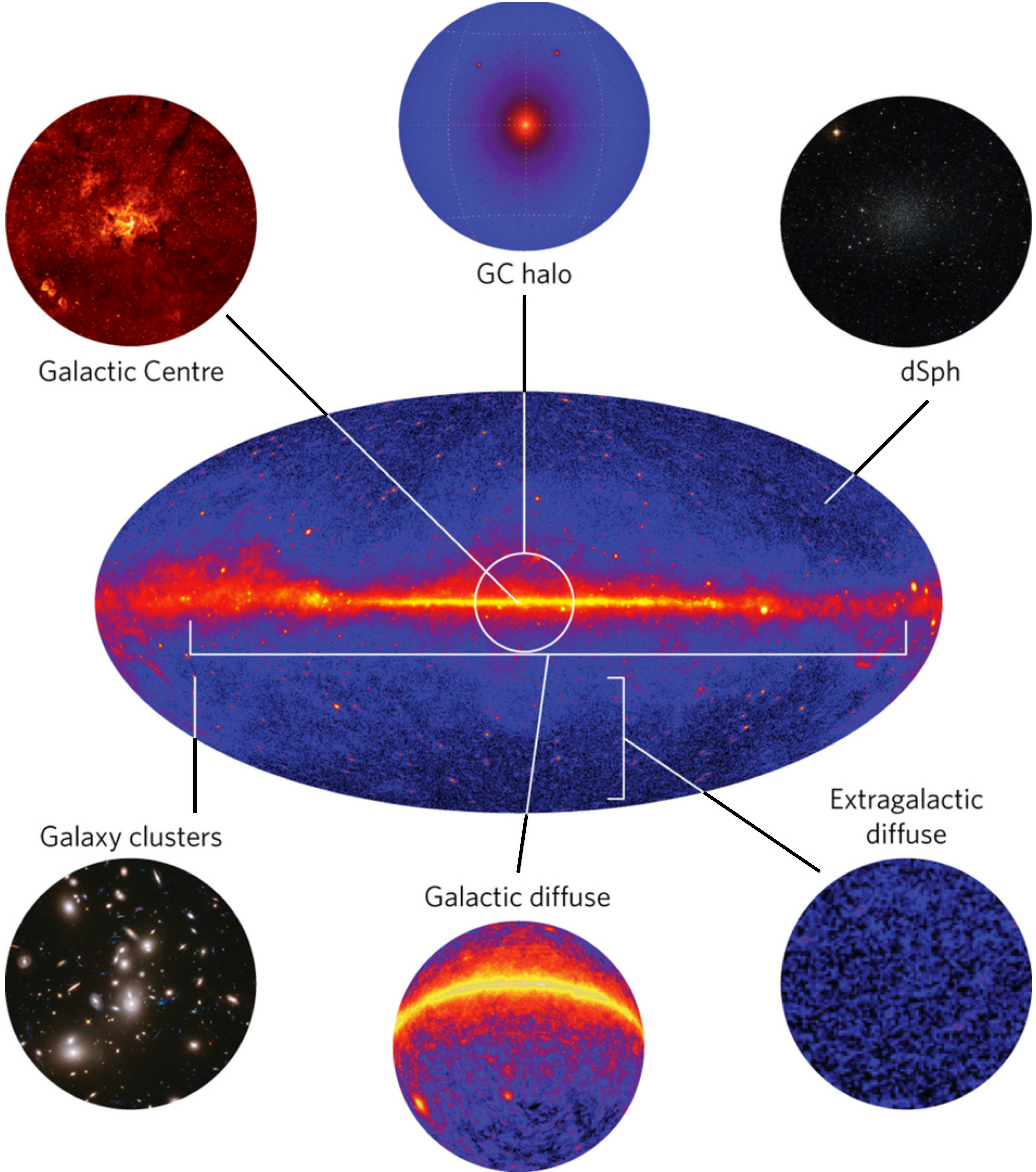
+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)

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

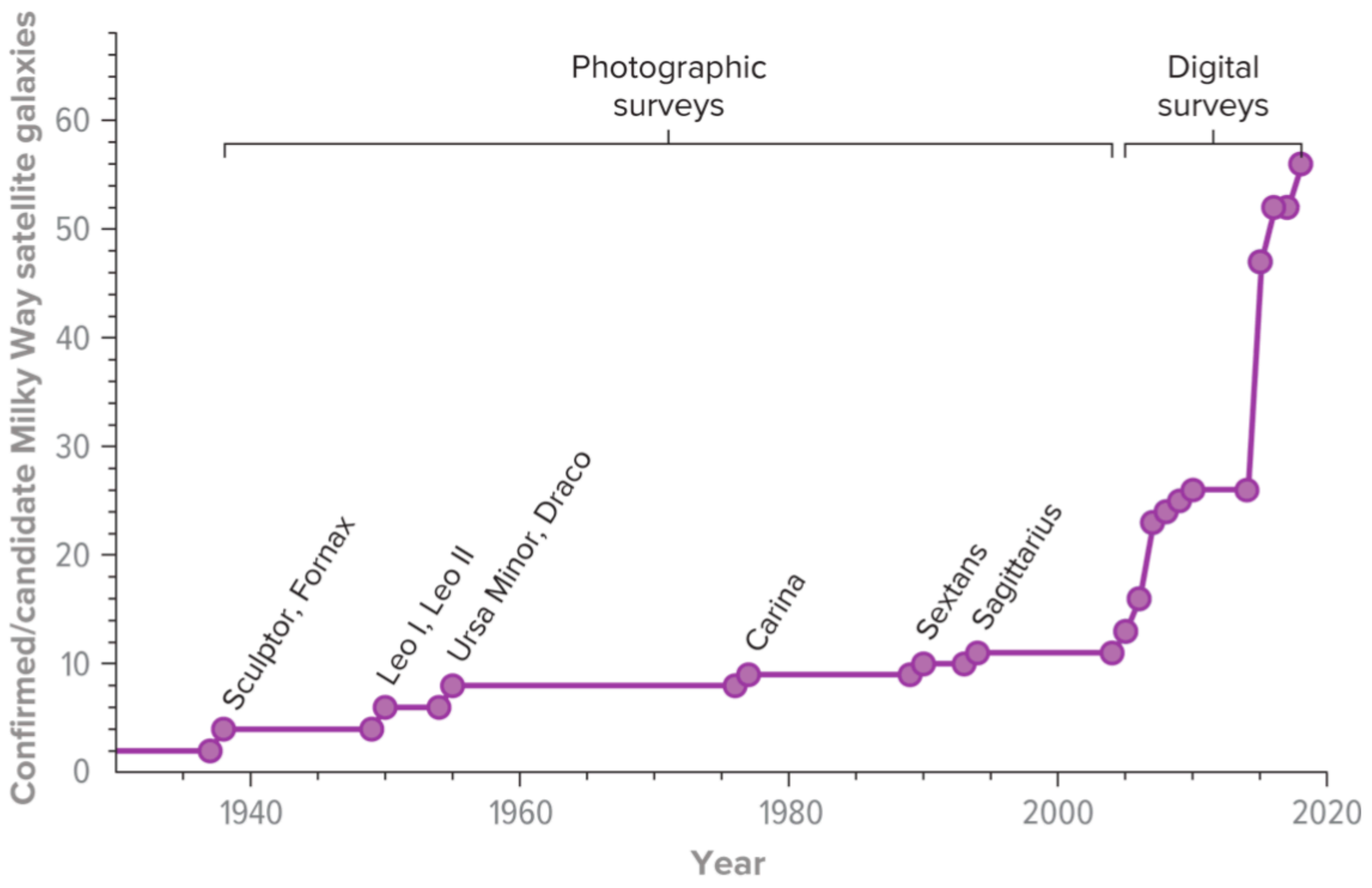
[NB: Models are predictive => can link different observables (direct/indirect/collider) and break degeneracies]

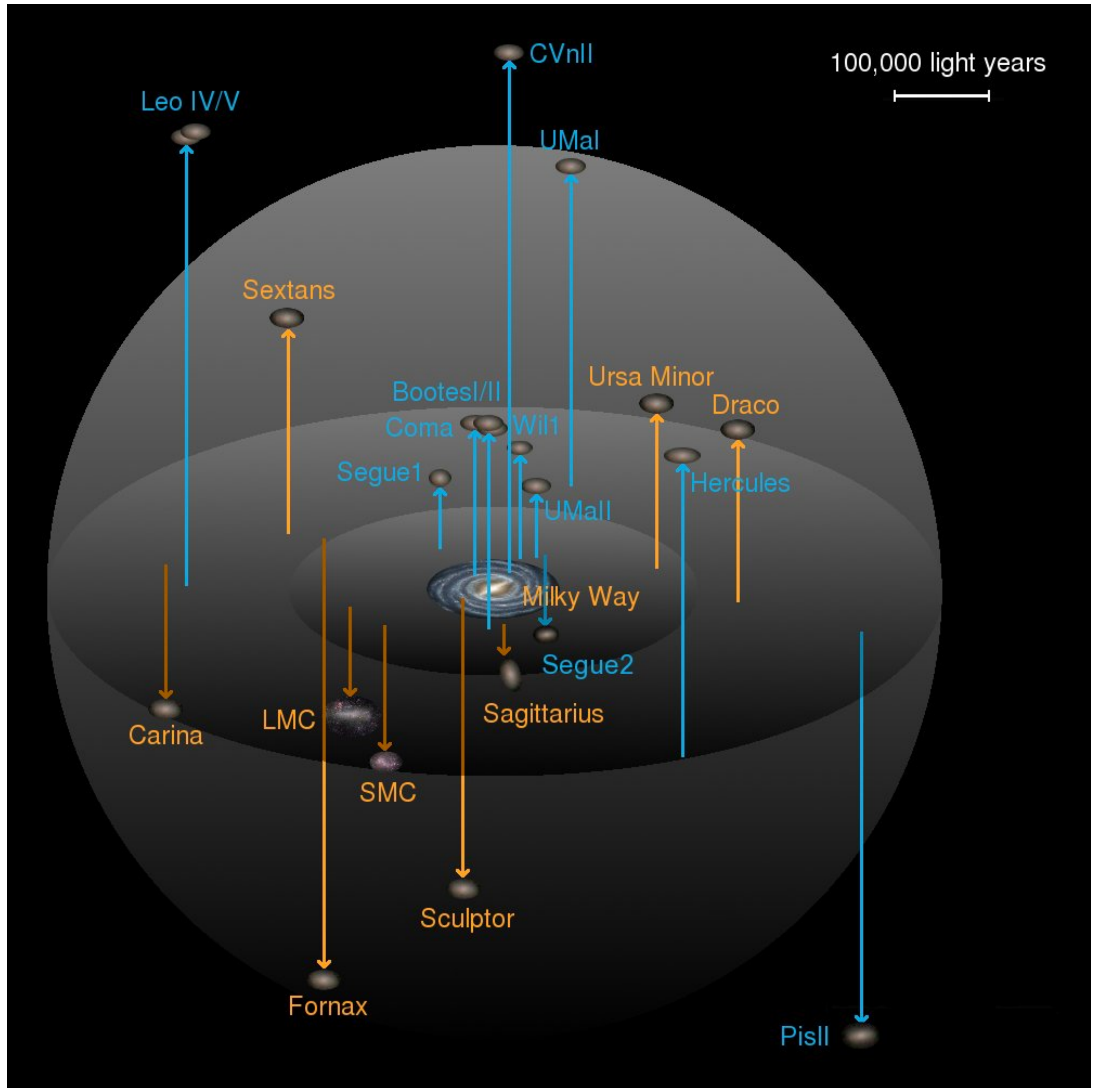
Dwarf spheroidal galaxies

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

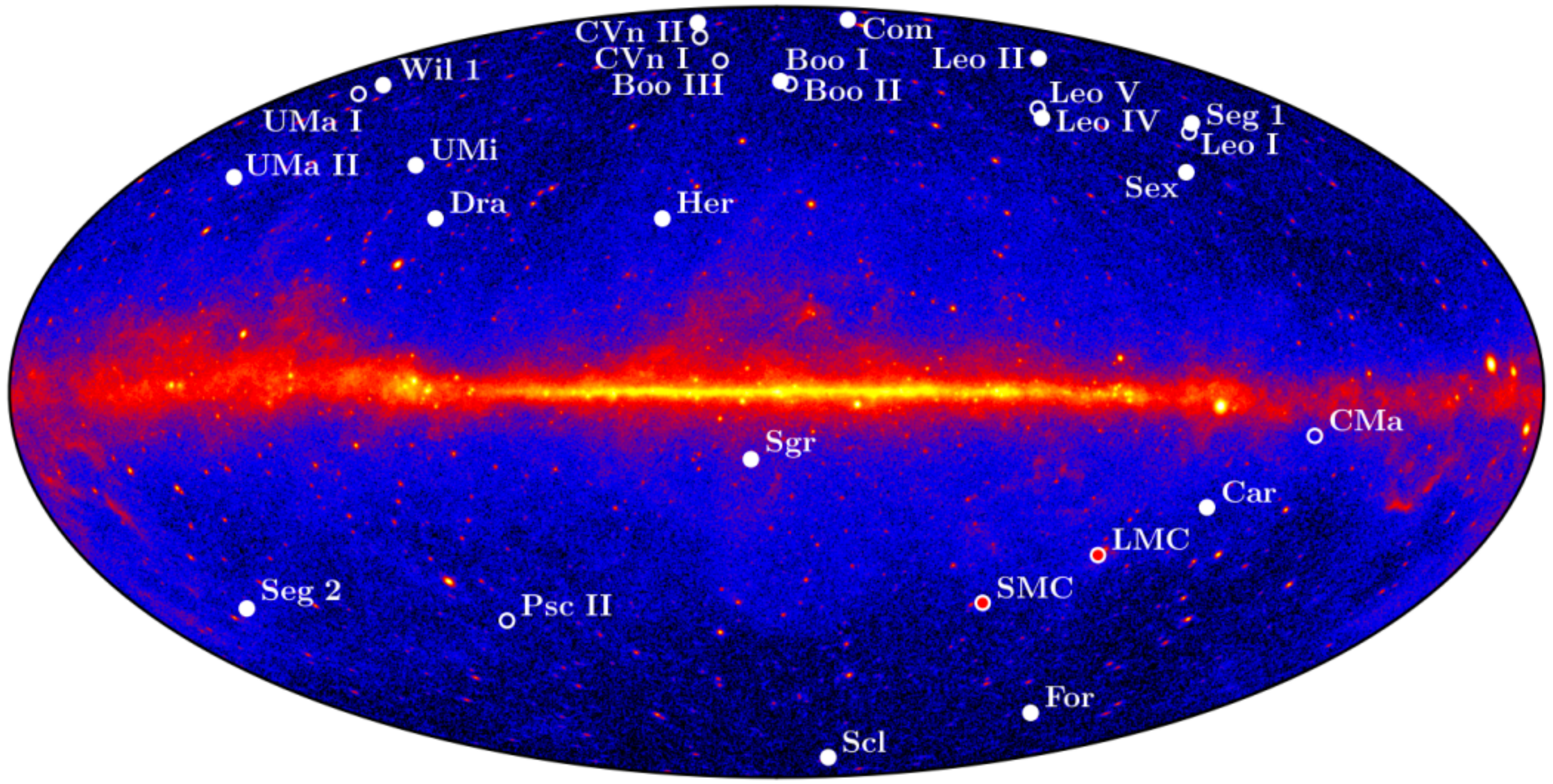




A growing Galactic crowd
> 50 satellites
(SDSS, PanSTARRS, DES)

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

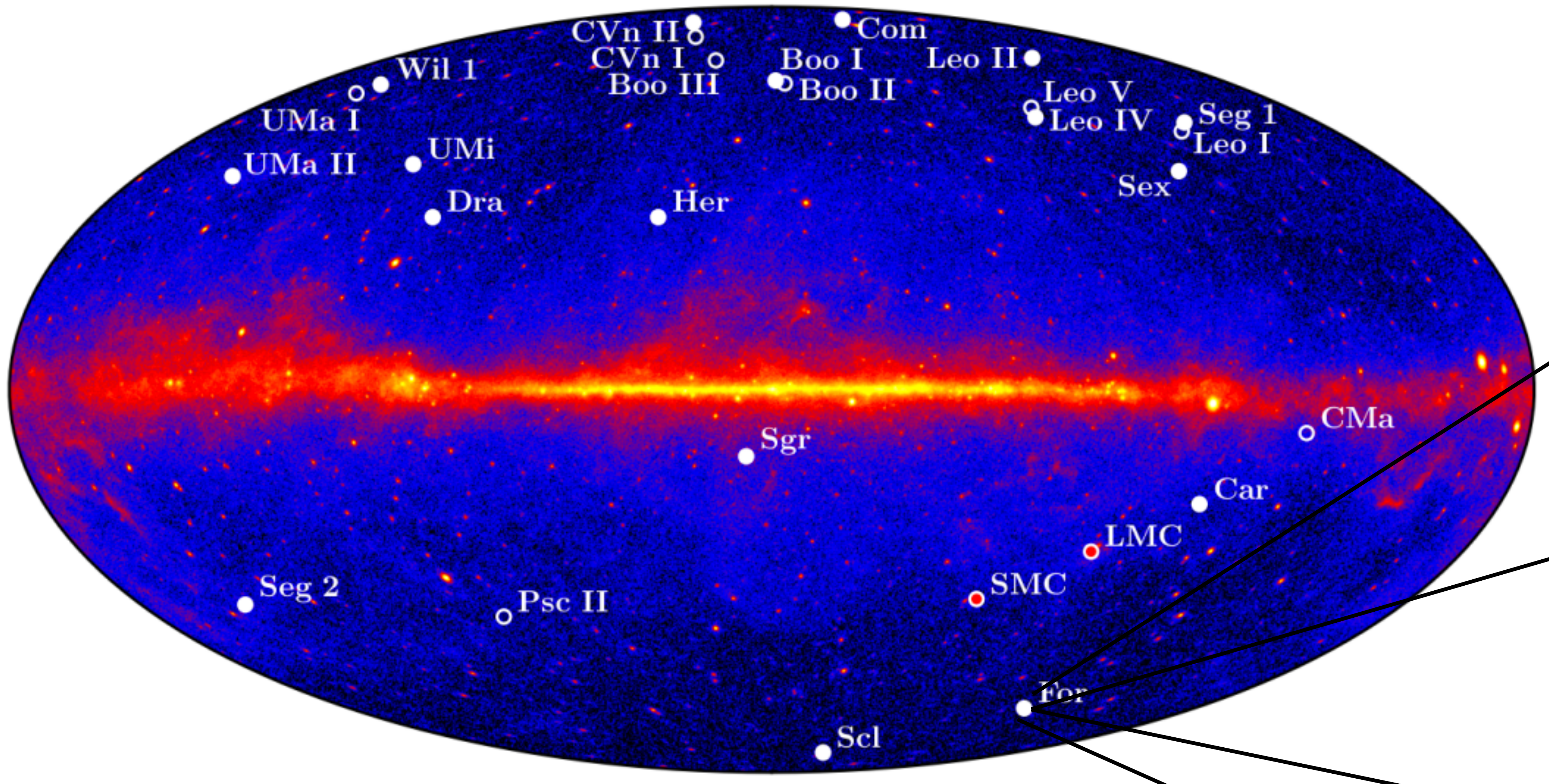
Limits from dwarf spheroidal galaxies



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

Fermi-LAT Collaboration, PRL'11

Limits from dwarf spheroidal galaxies

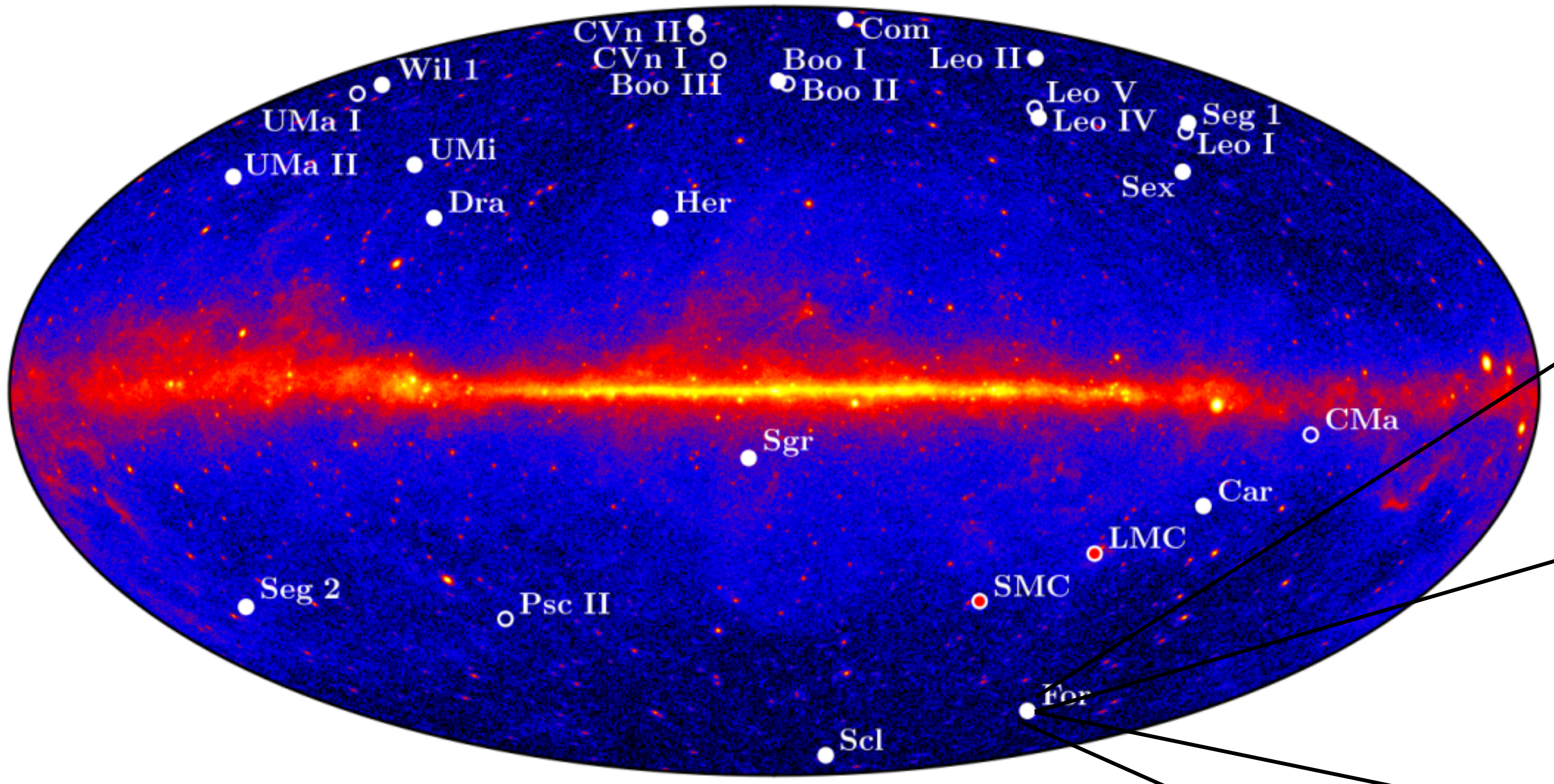


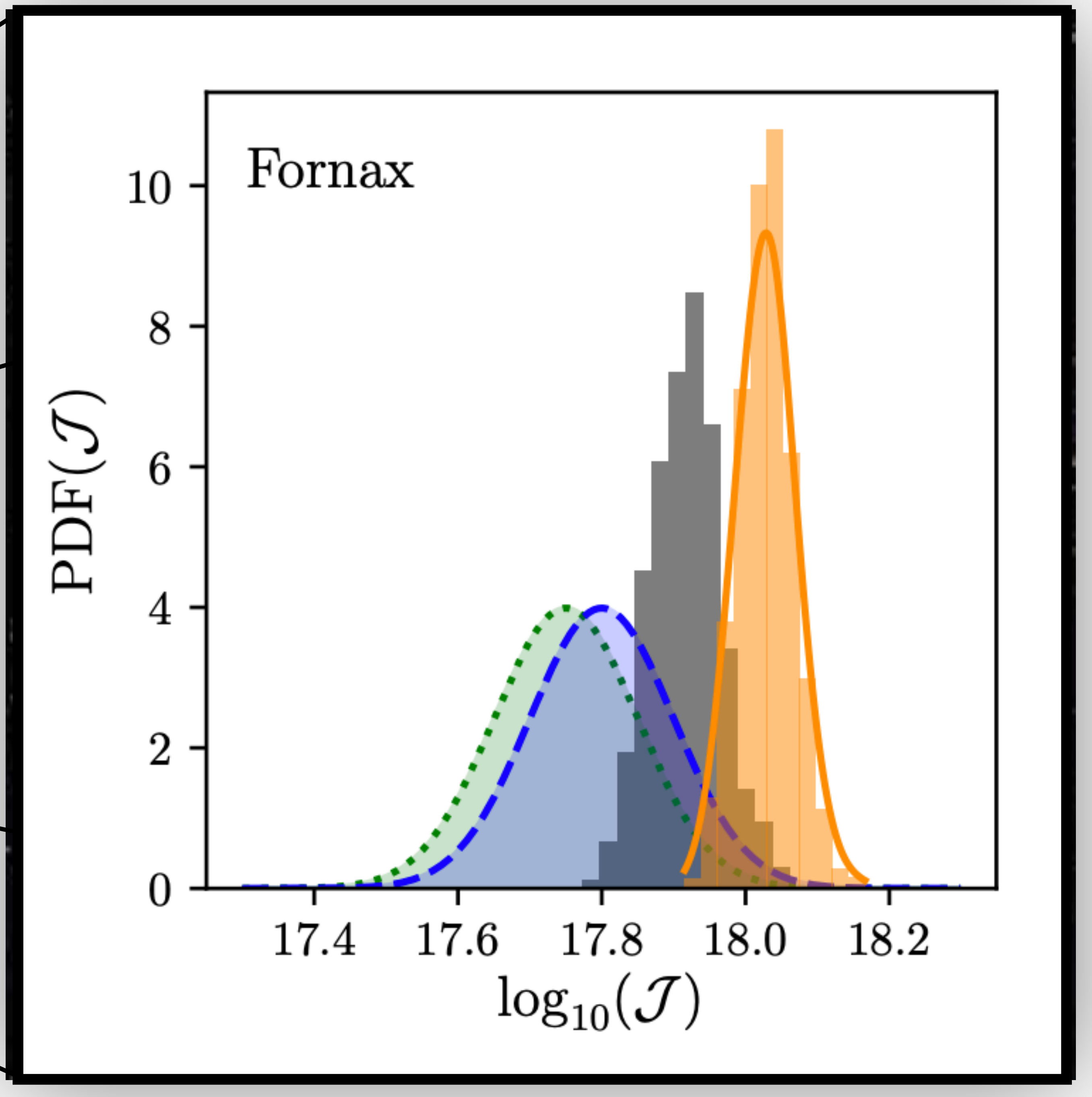
$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell,\psi)\right]^2$$

Fermi-LAT Collaboration, PRL'11

Credit: ESO/Fornax galaxy

Limits from dwarf spheroidal galaxies



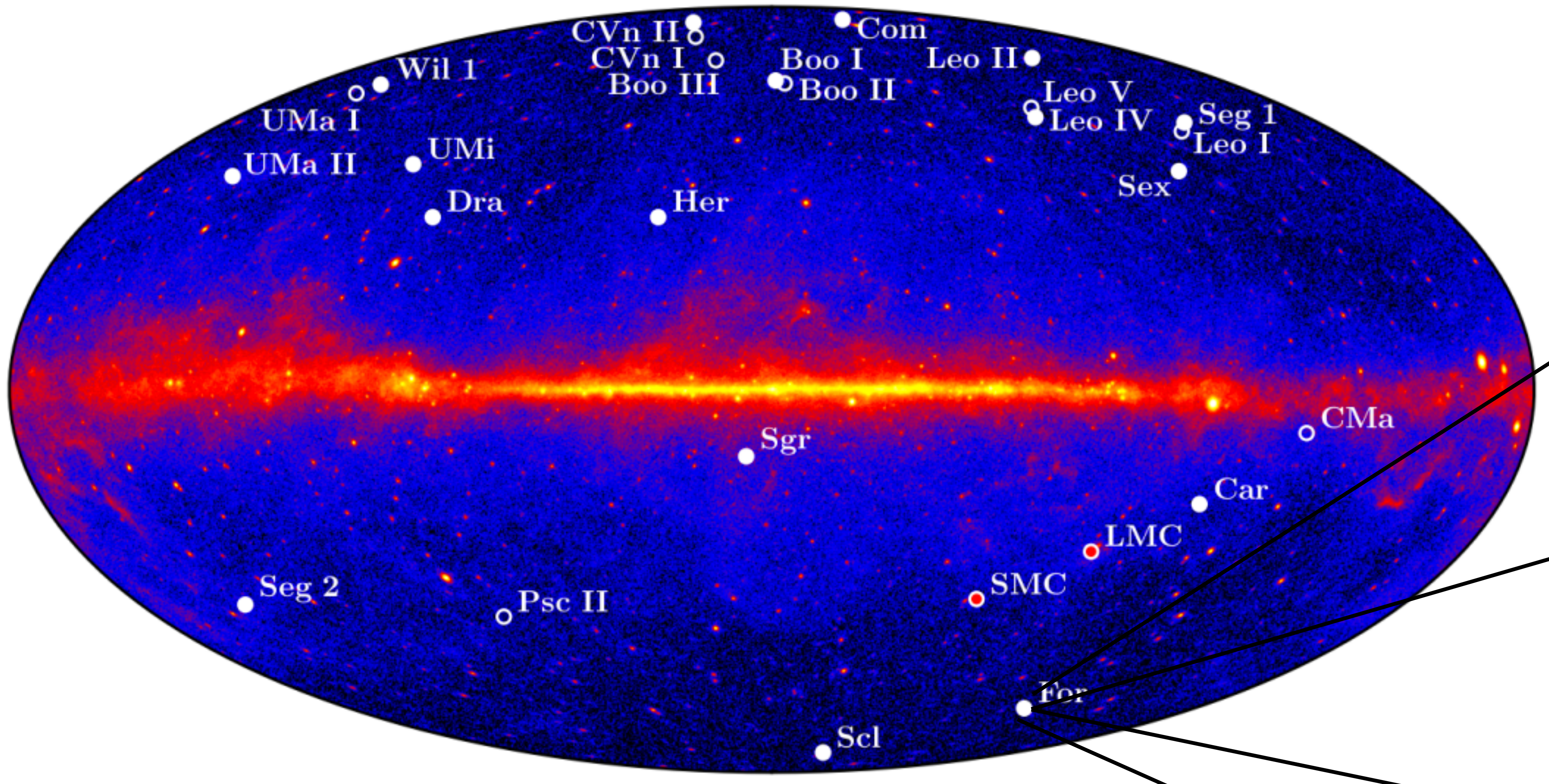


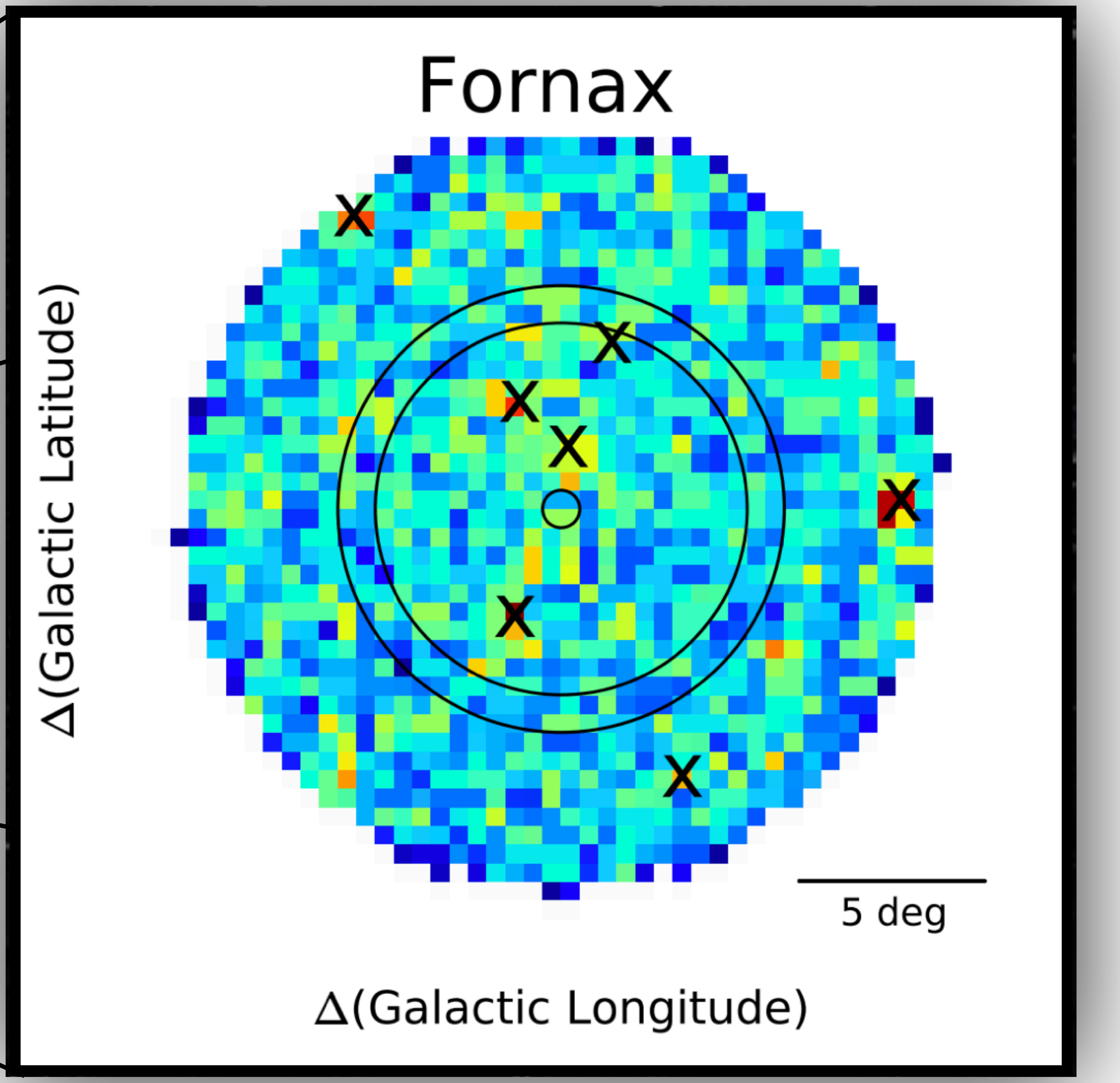
$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

Fermi-LAT Collaboration, PRL'11

GRAVSPHERE
Alvarez, FC+ JCAP'20

Limits from dwarf spheroidal galaxies



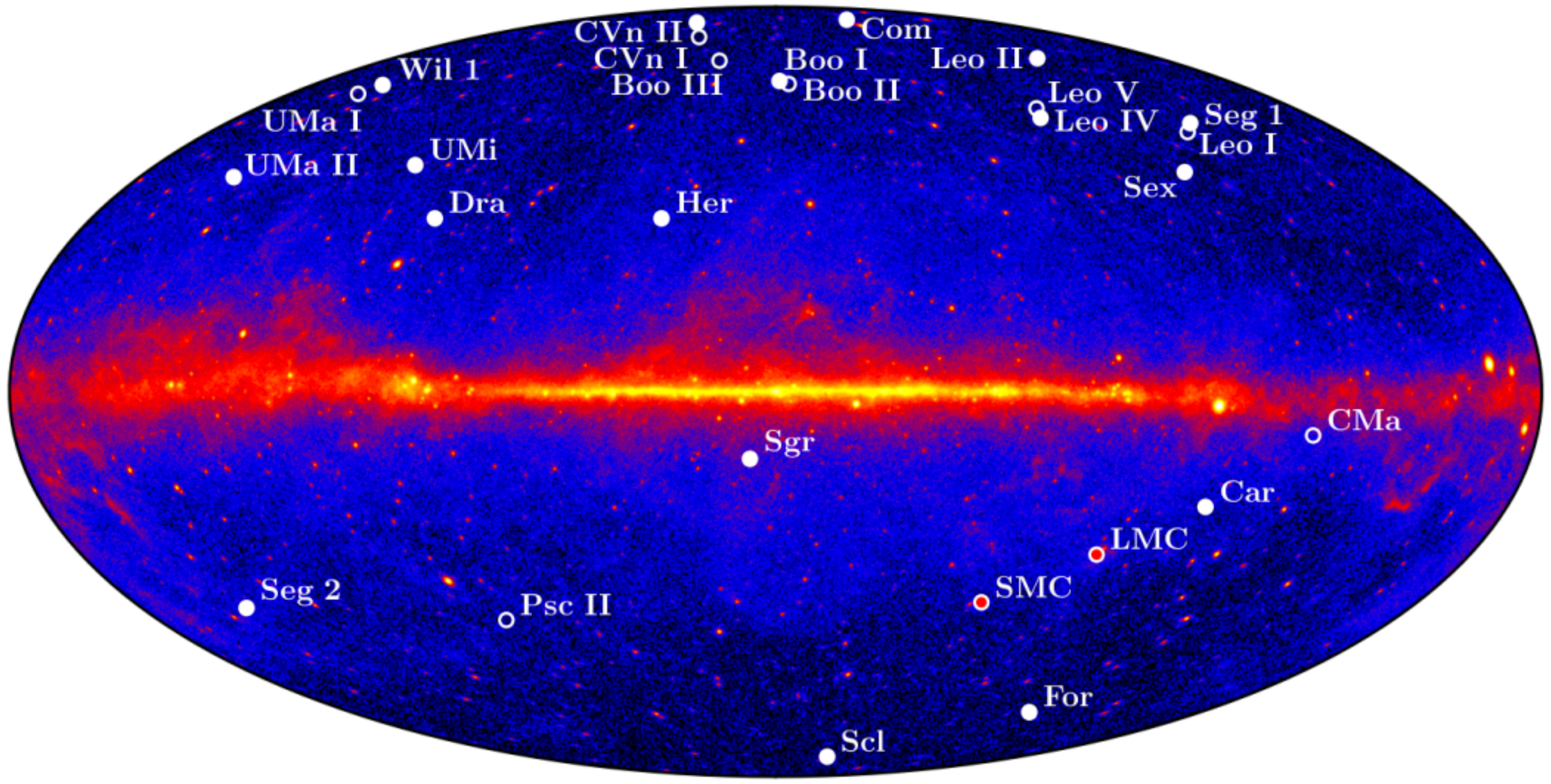


$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

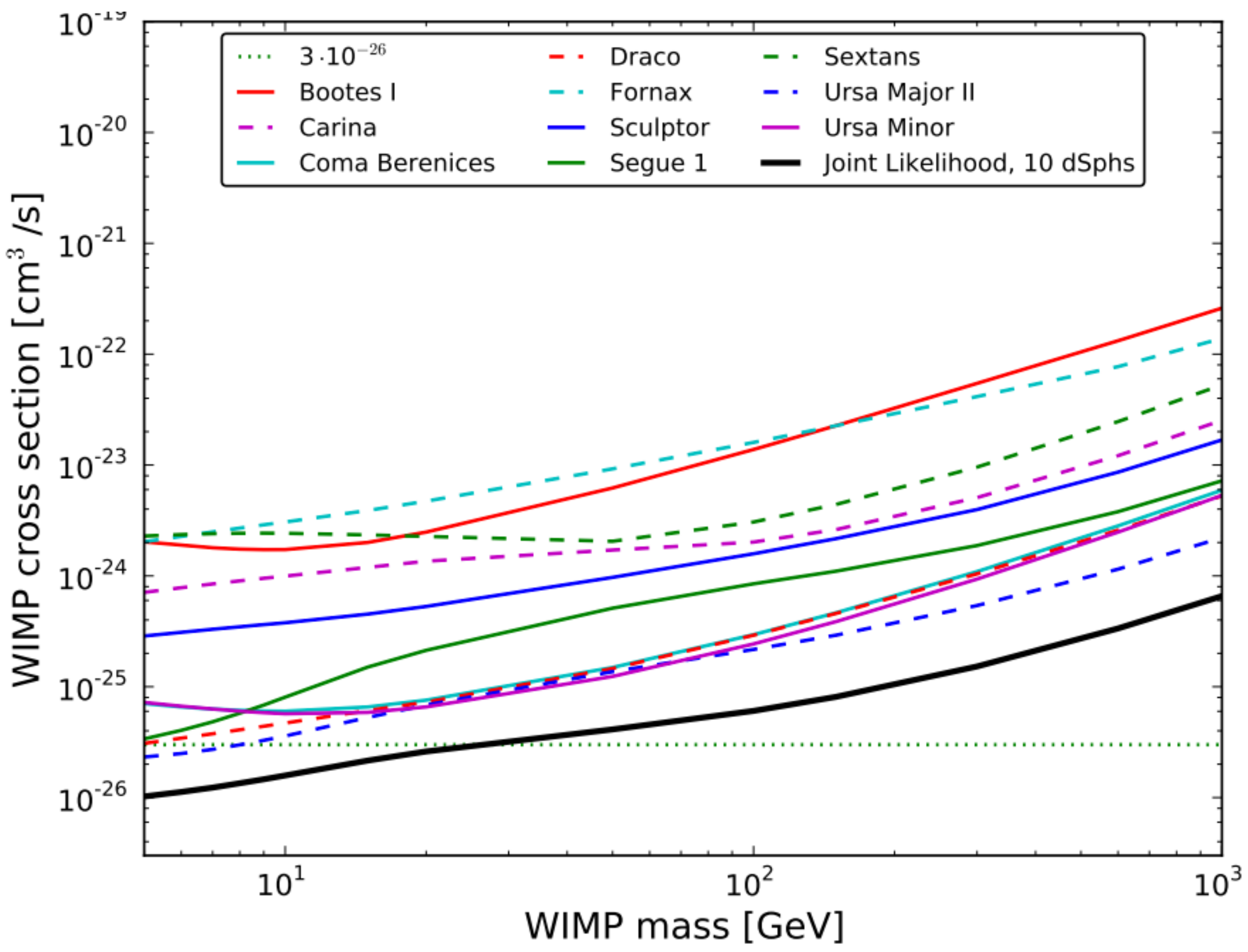
Fermi-LAT Collaboration, PRL'11

Mazziotta+Astrop. Phys.'12

Limits from dwarf spheroidal galaxies



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



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

Fermi-LAT Collaboration, PRL'11

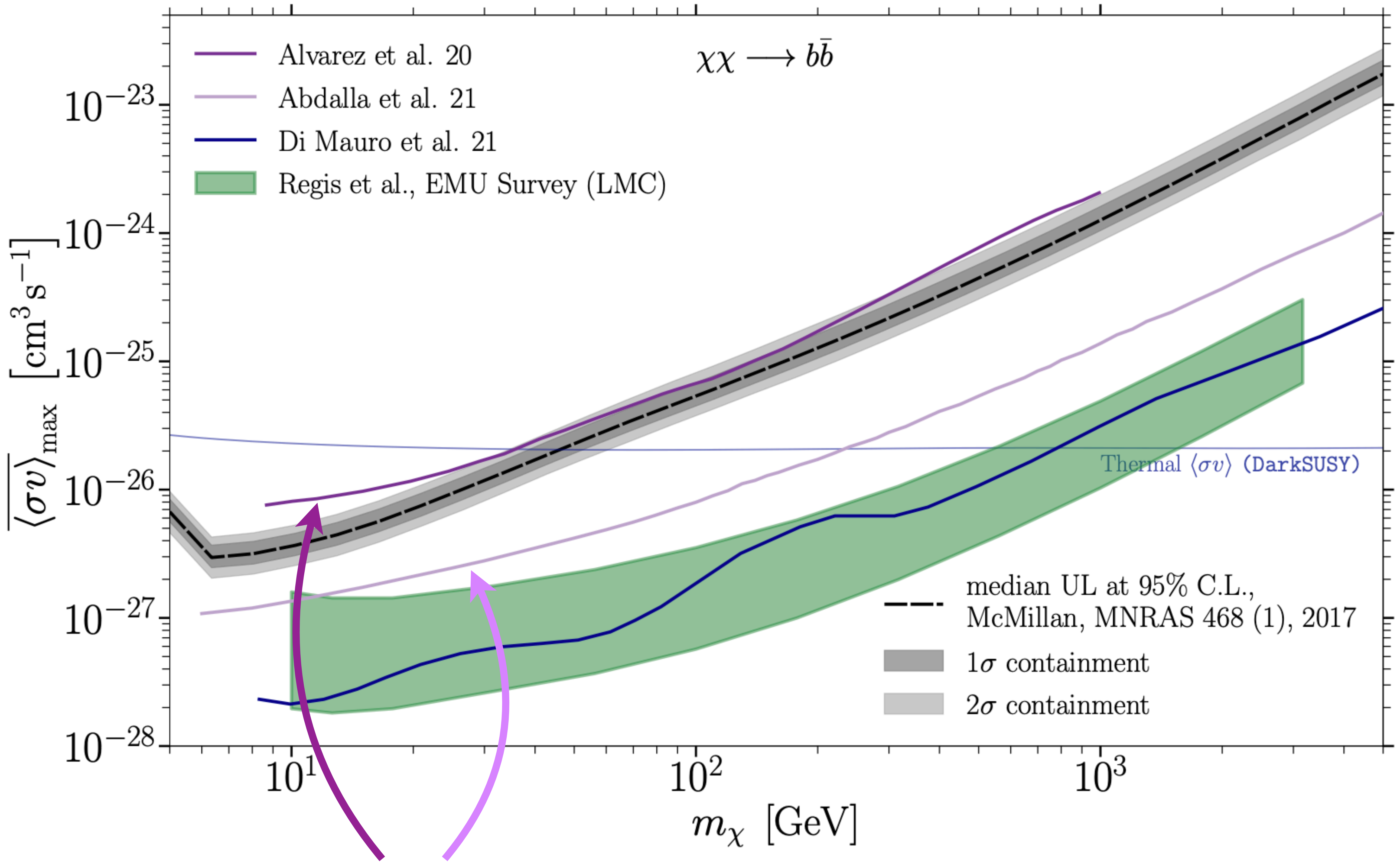
$$\mathcal{J} \propto \int d\ell\, \rho\left[r(\ell,\psi)\right]^2$$

Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

~ a few GeV — few TeV

Eckner, FC+ 2208.03312



Fermi-LAT dwarf galaxies

Alvarez, FC+ JCAP'20; Addalla+ PoS'21

Limits on annihilating WIMPs

Summary of multi-targets and MW constraints

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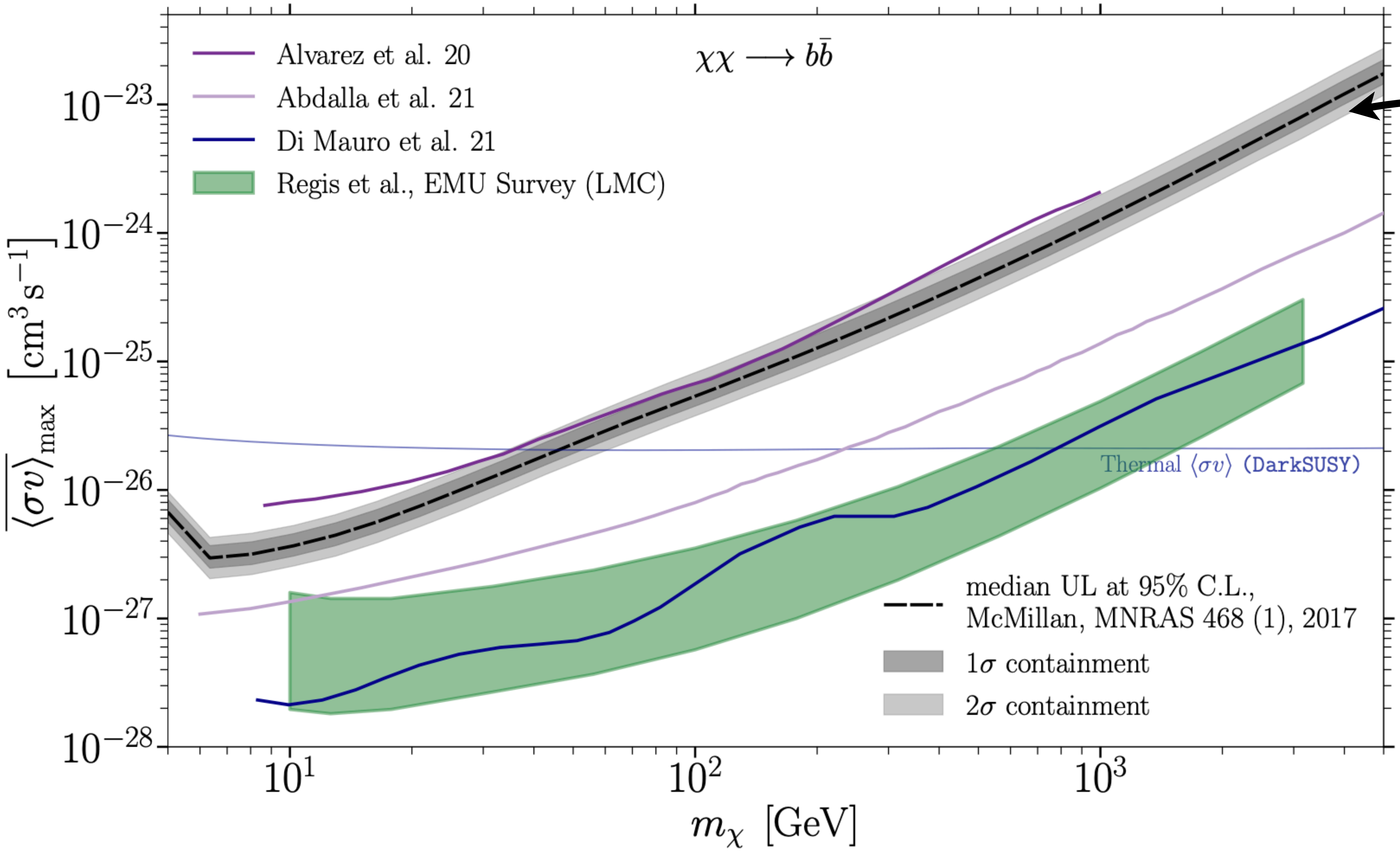
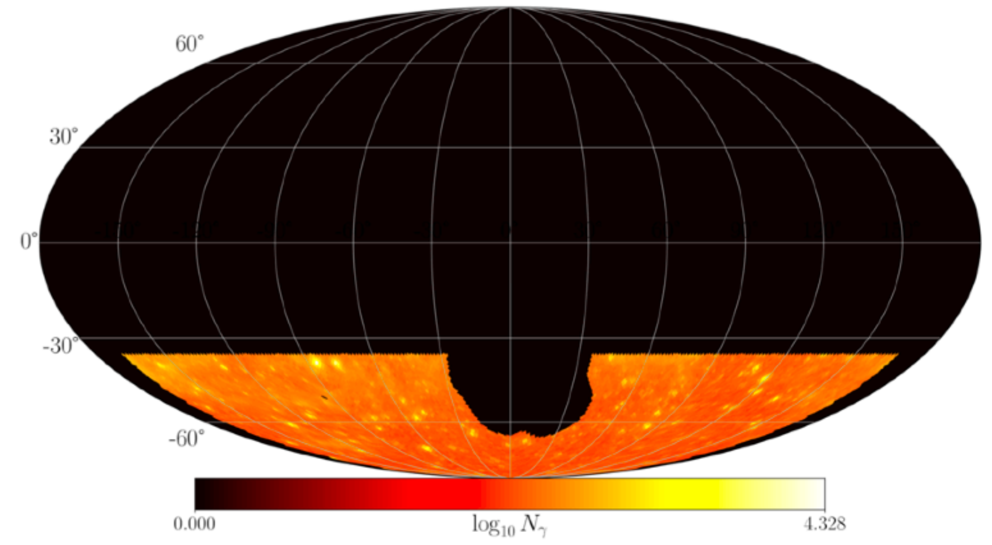
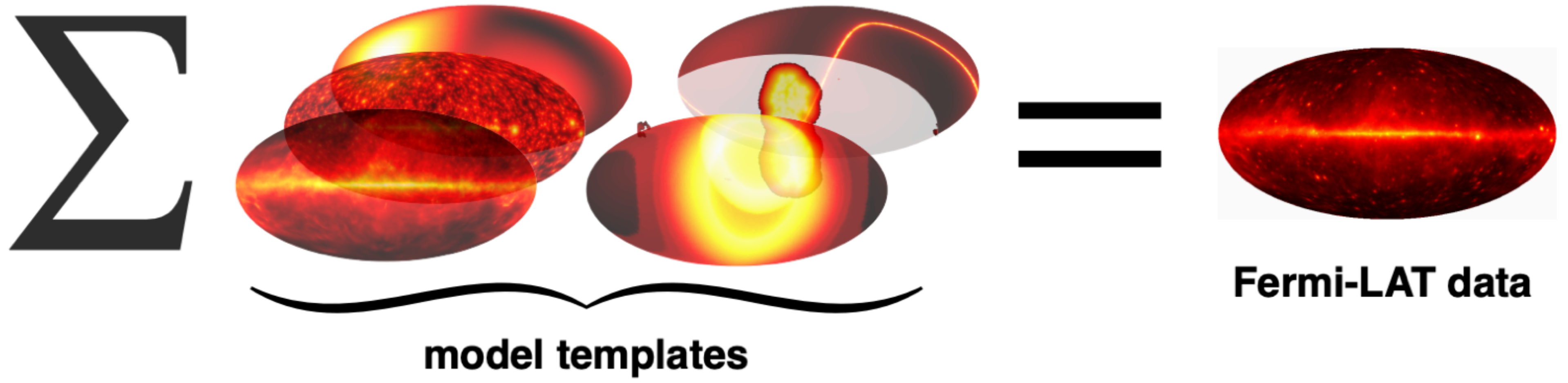
Eckner, FC+ 2208.03312



High-latitude Fermi-LAT sky

Eckner, FC+ 2208.03312





Limits on annihilating WIMPs

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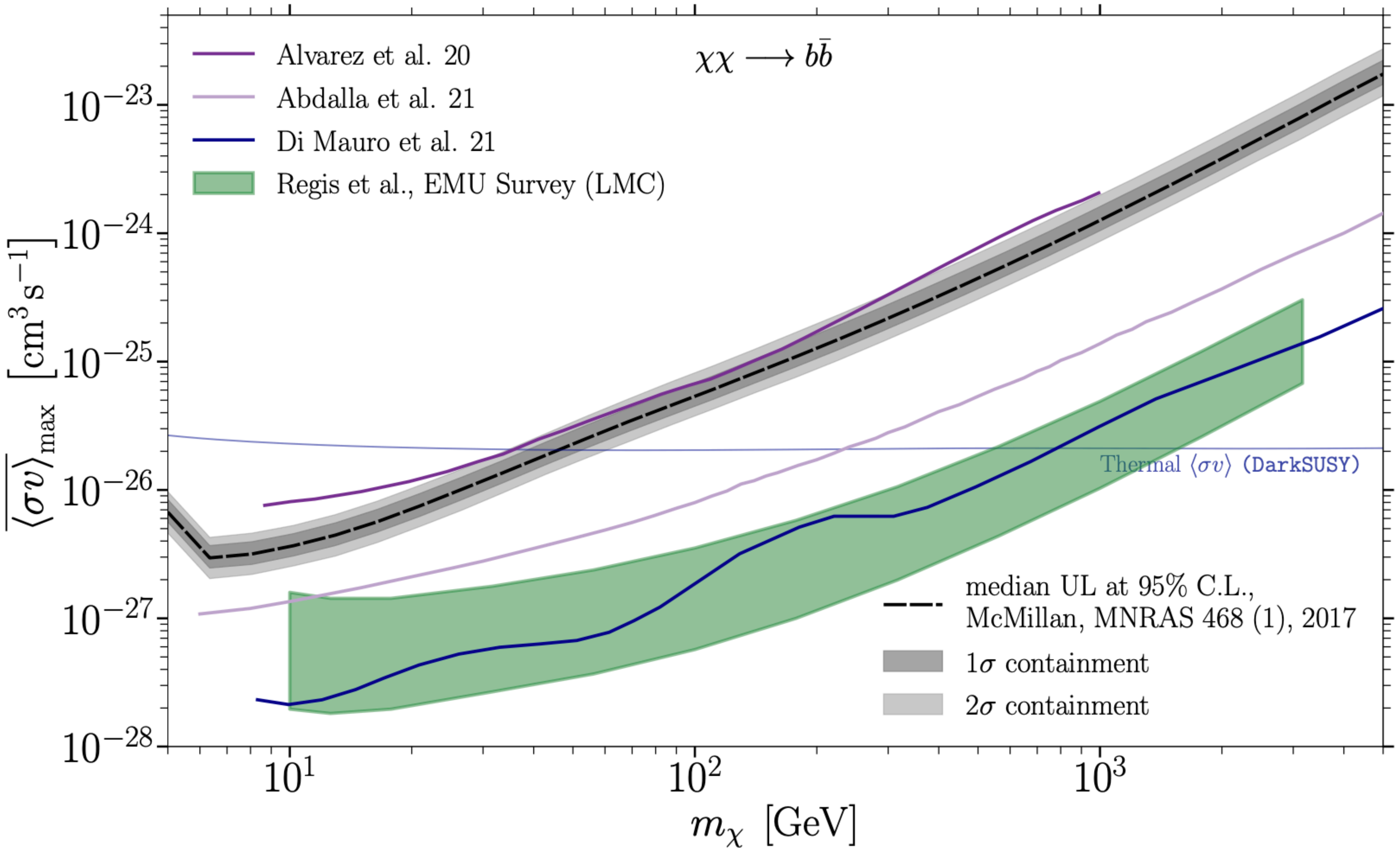
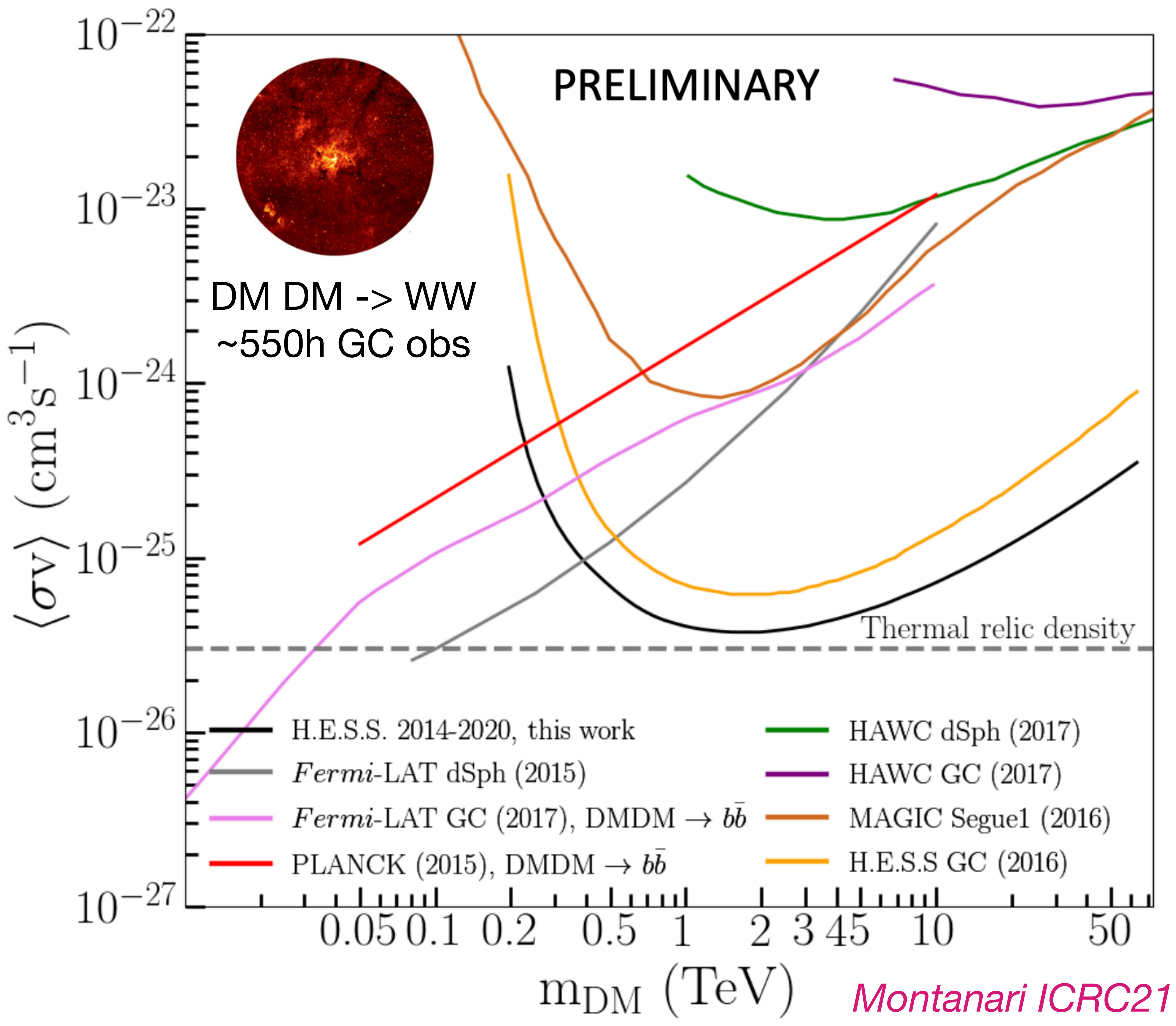


0.2 TeV — 50 TeV



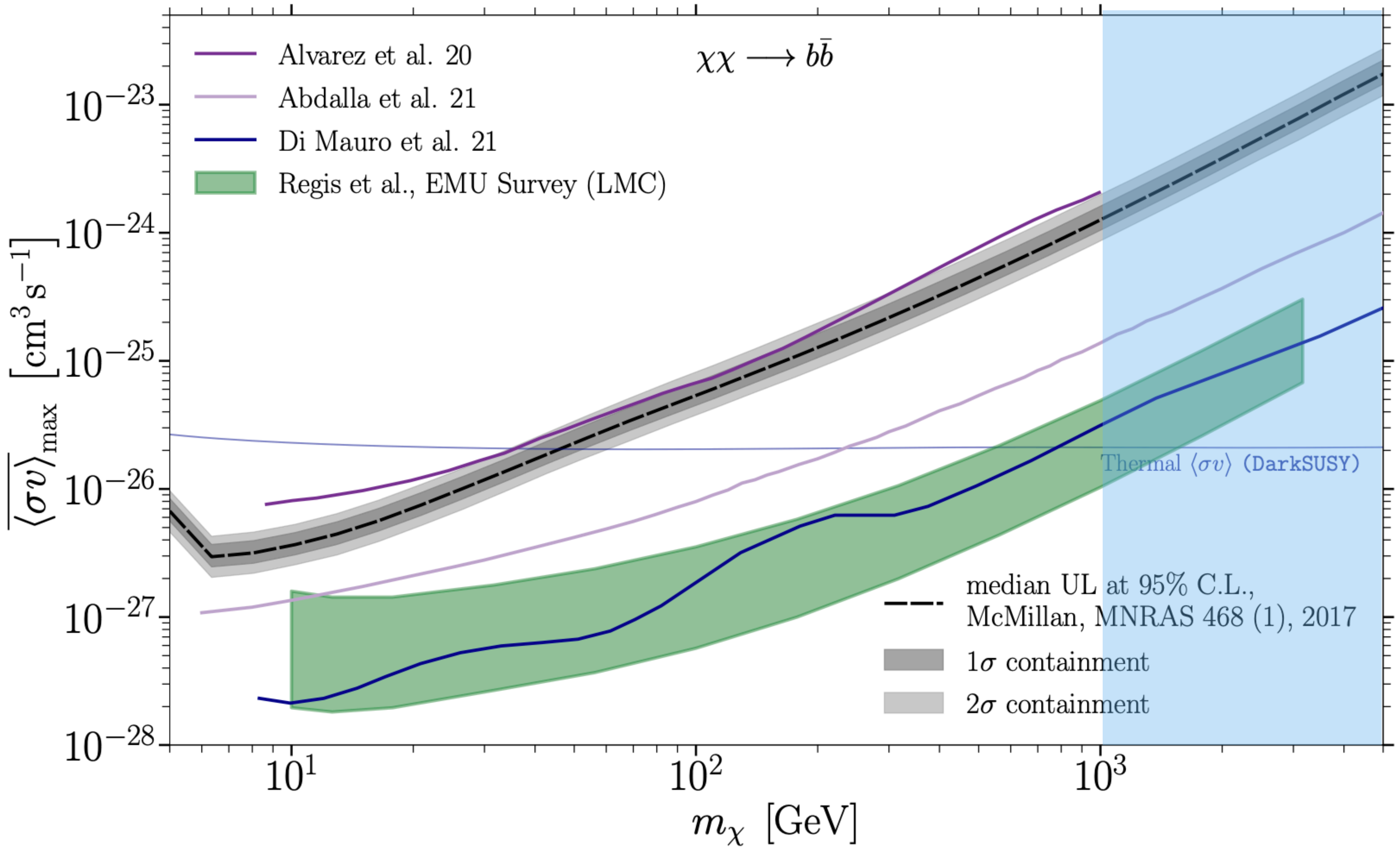
Montanari ICRC21

Prospects and opportunities

Extending the energy/mass scale

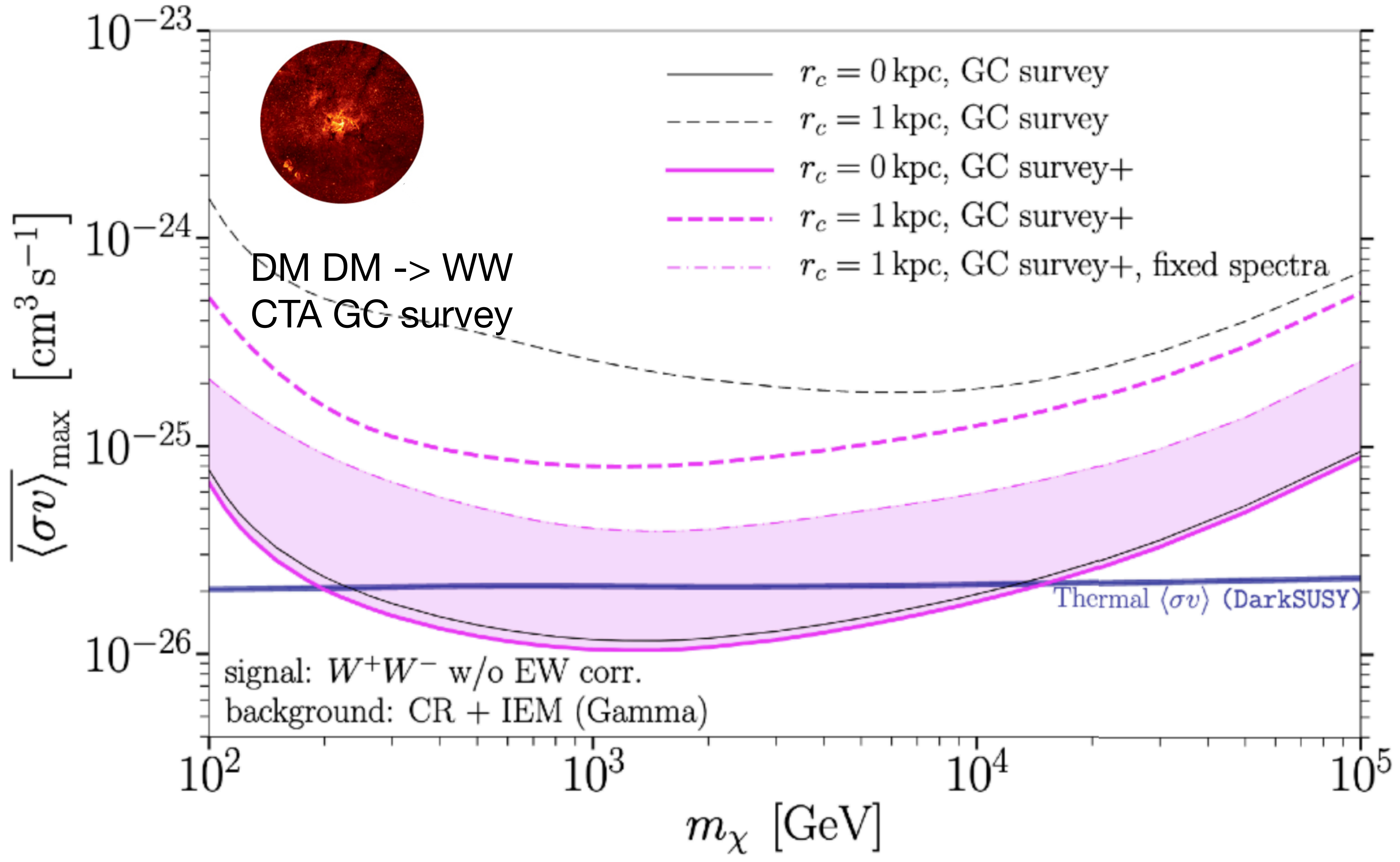
~ a few GeV — few TeV

Eckner, FC+ 2208.03312



TeV frontier

HAWC, CTA, SWGO

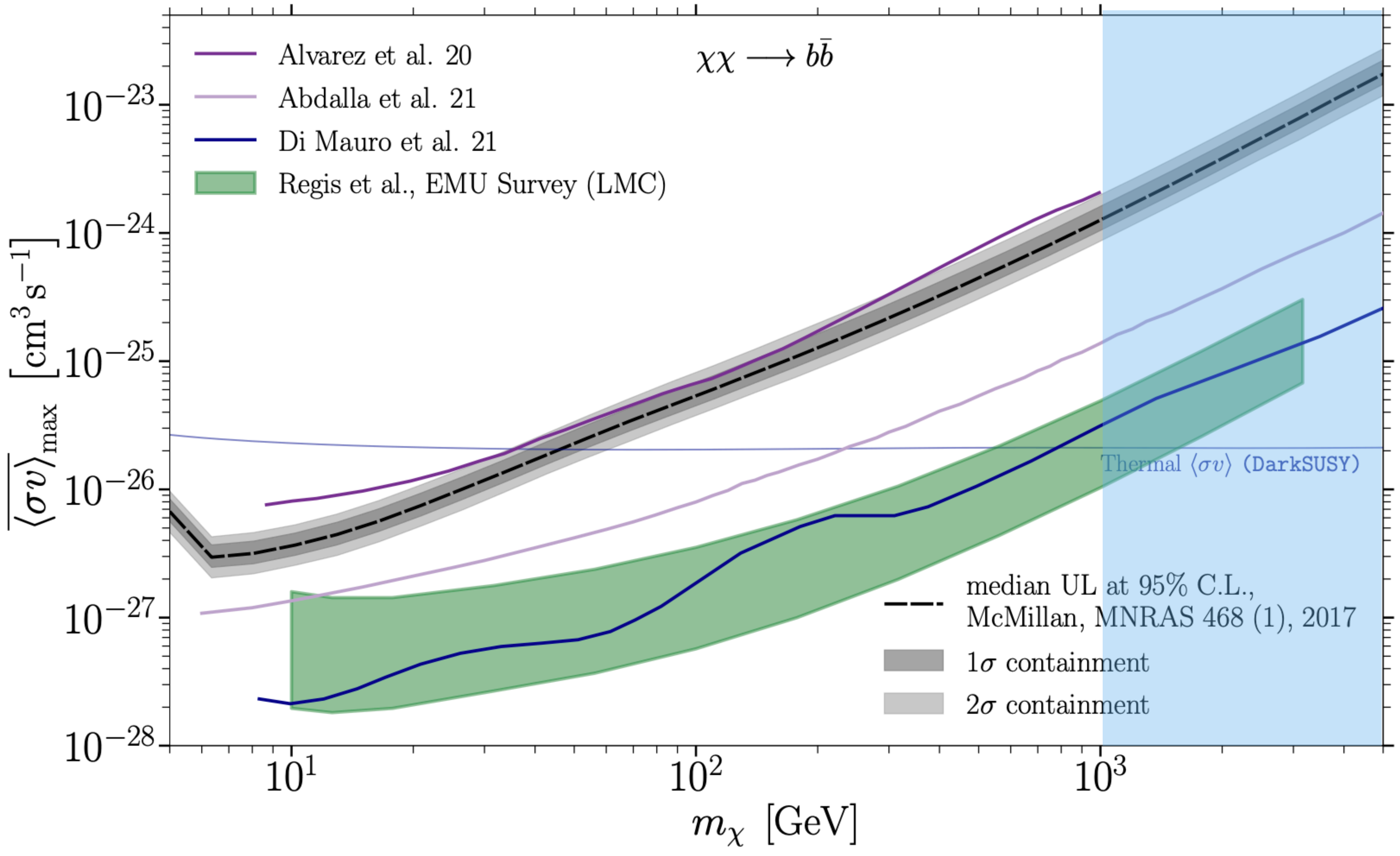


Prospects and opportunities

Extending the energy/mass scale

~ a few GeV — few TeV

Eckner, FC+ 2208.03312



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

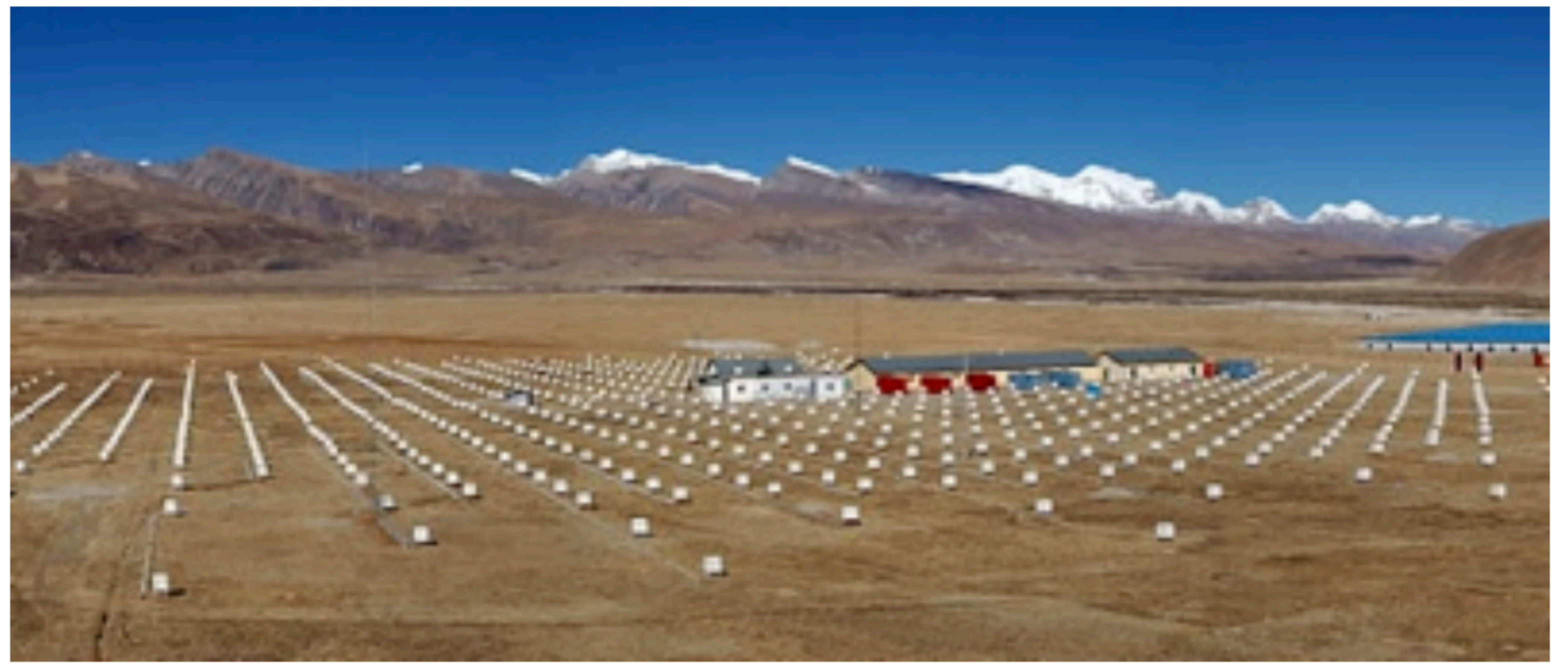
Esmaili & Serpico, PRD'21; *Chianese+ arXiv:2108.01678*

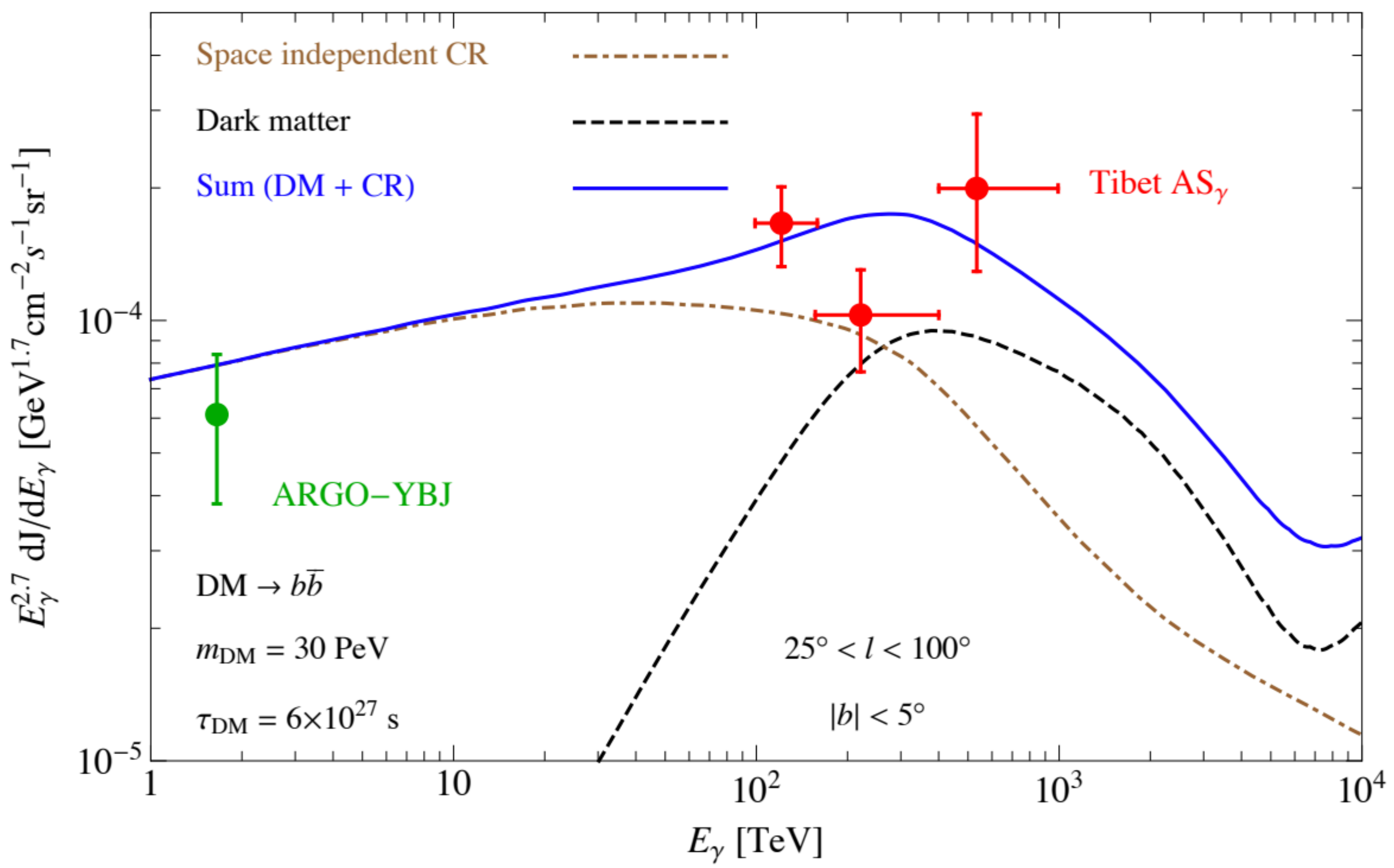
VHE gamma rays: PeV dark matter

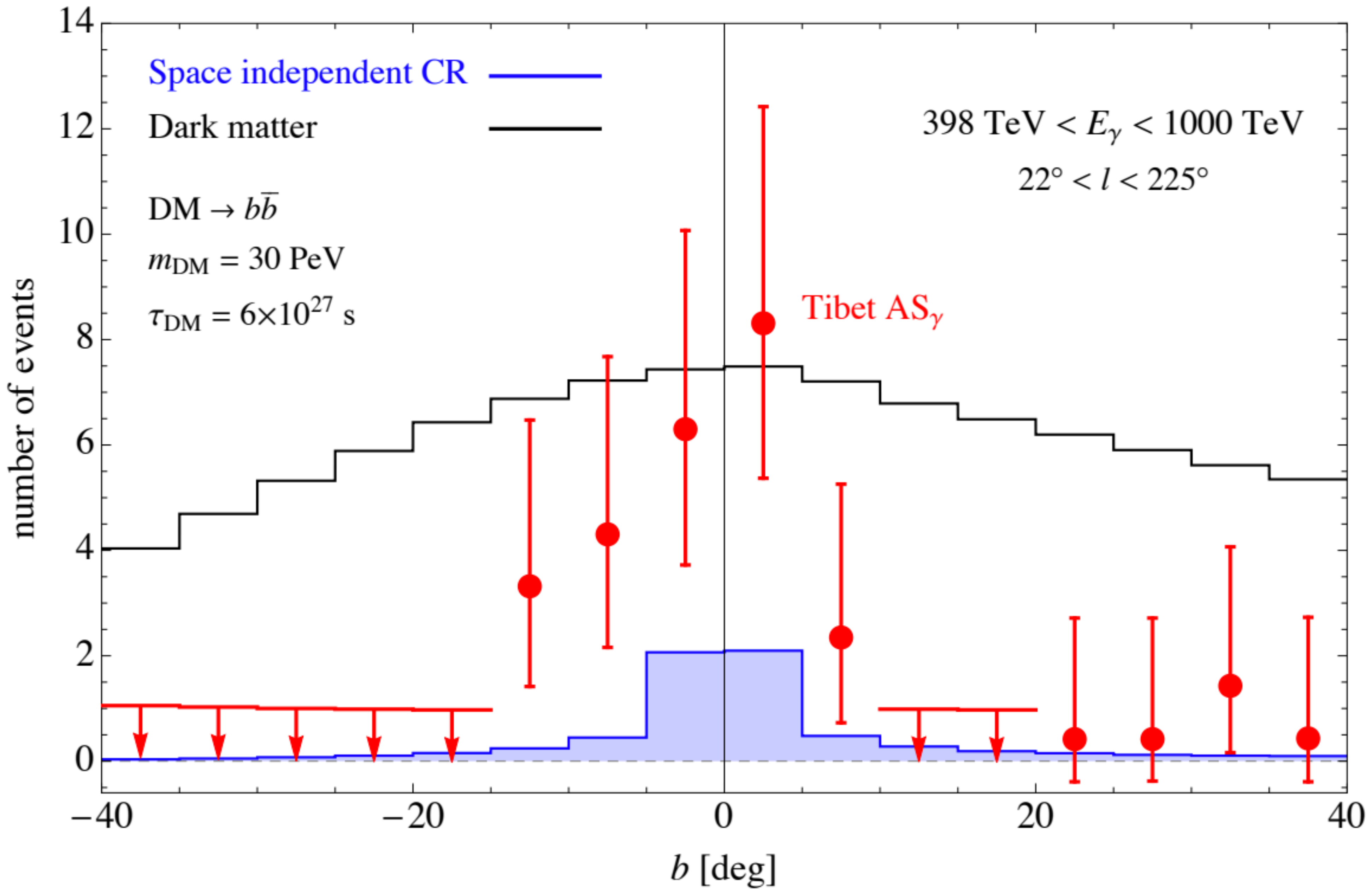
First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

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

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







DM spectrum ok, but unacceptable angular distribution of photons

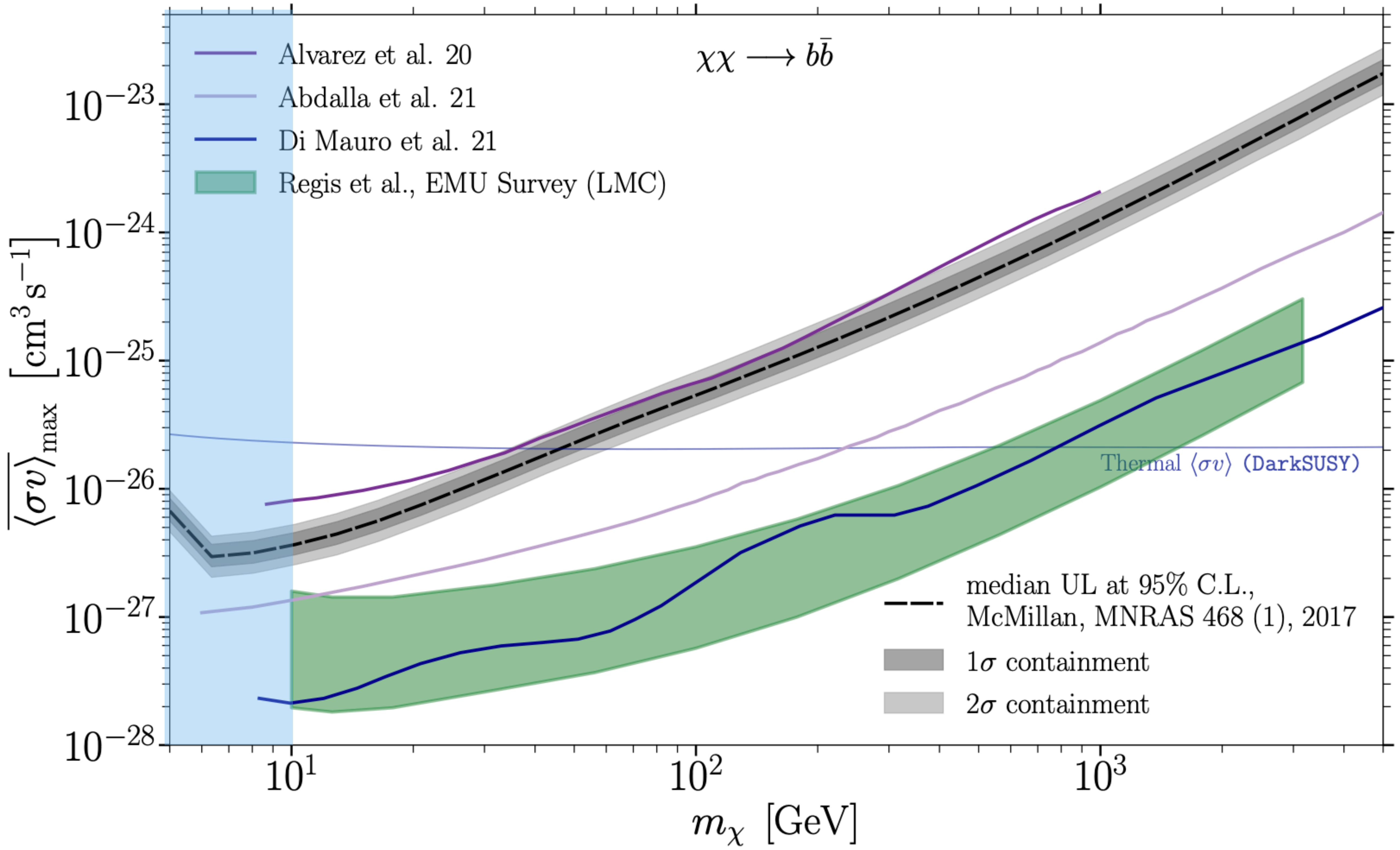
Esmaili & Serpico, PRD Letters'21

Prospects and opportunities

Extending the energy/mass scale

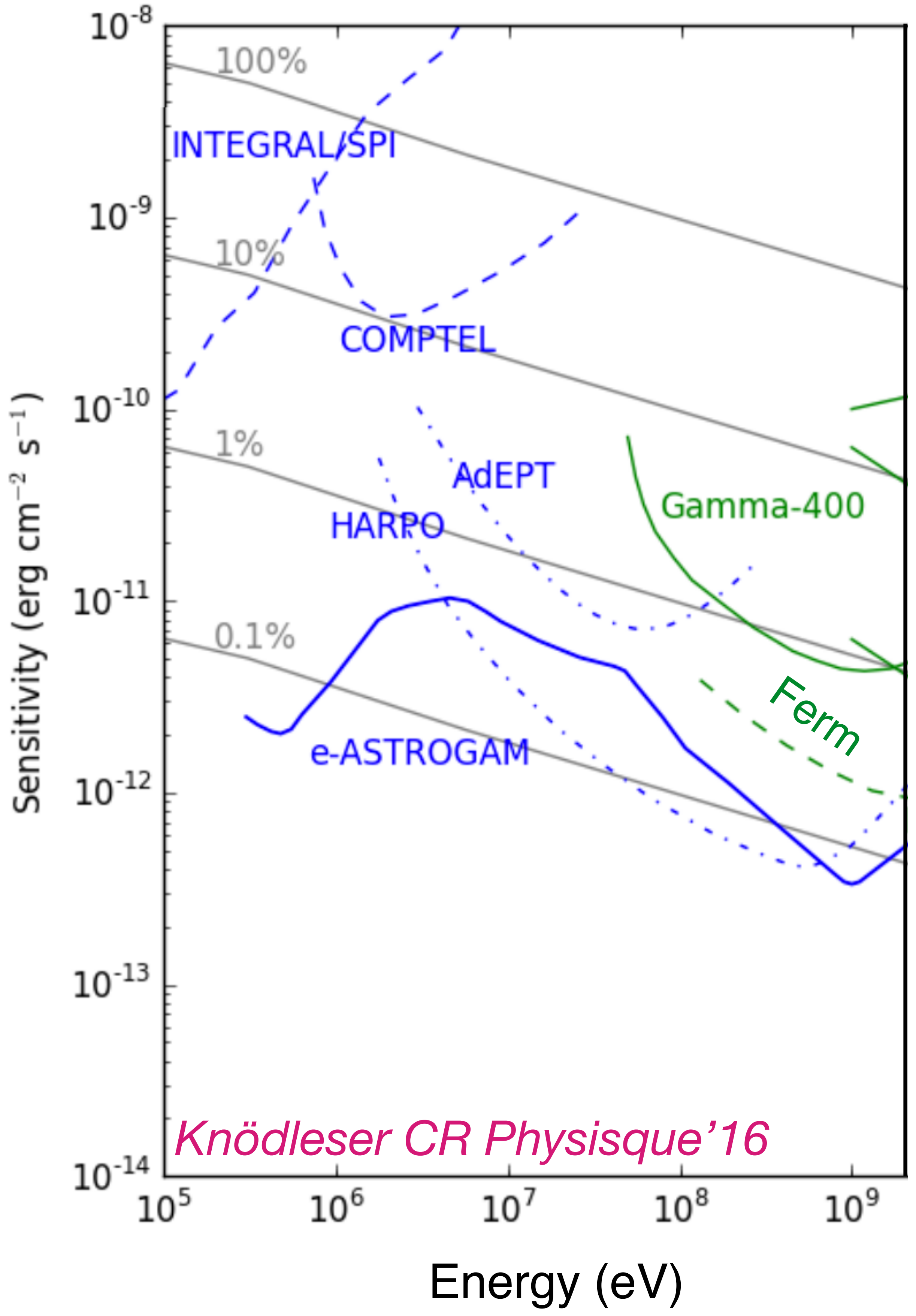
~ a few GeV — few TeV

Eckner, FC+ In preparation



MeV sensitivity gap

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

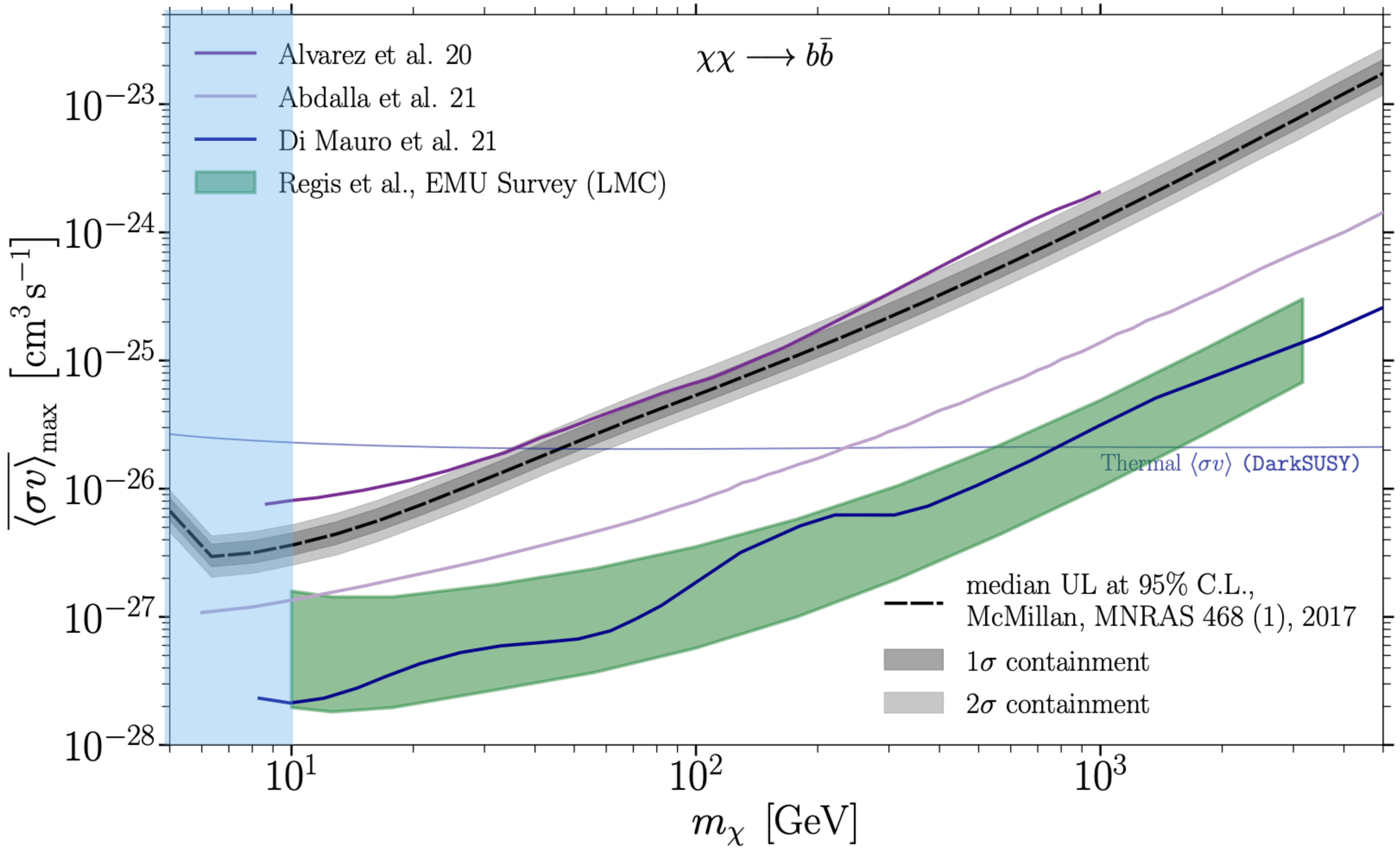


Prospects and opportunities

Extending the energy/mass scale

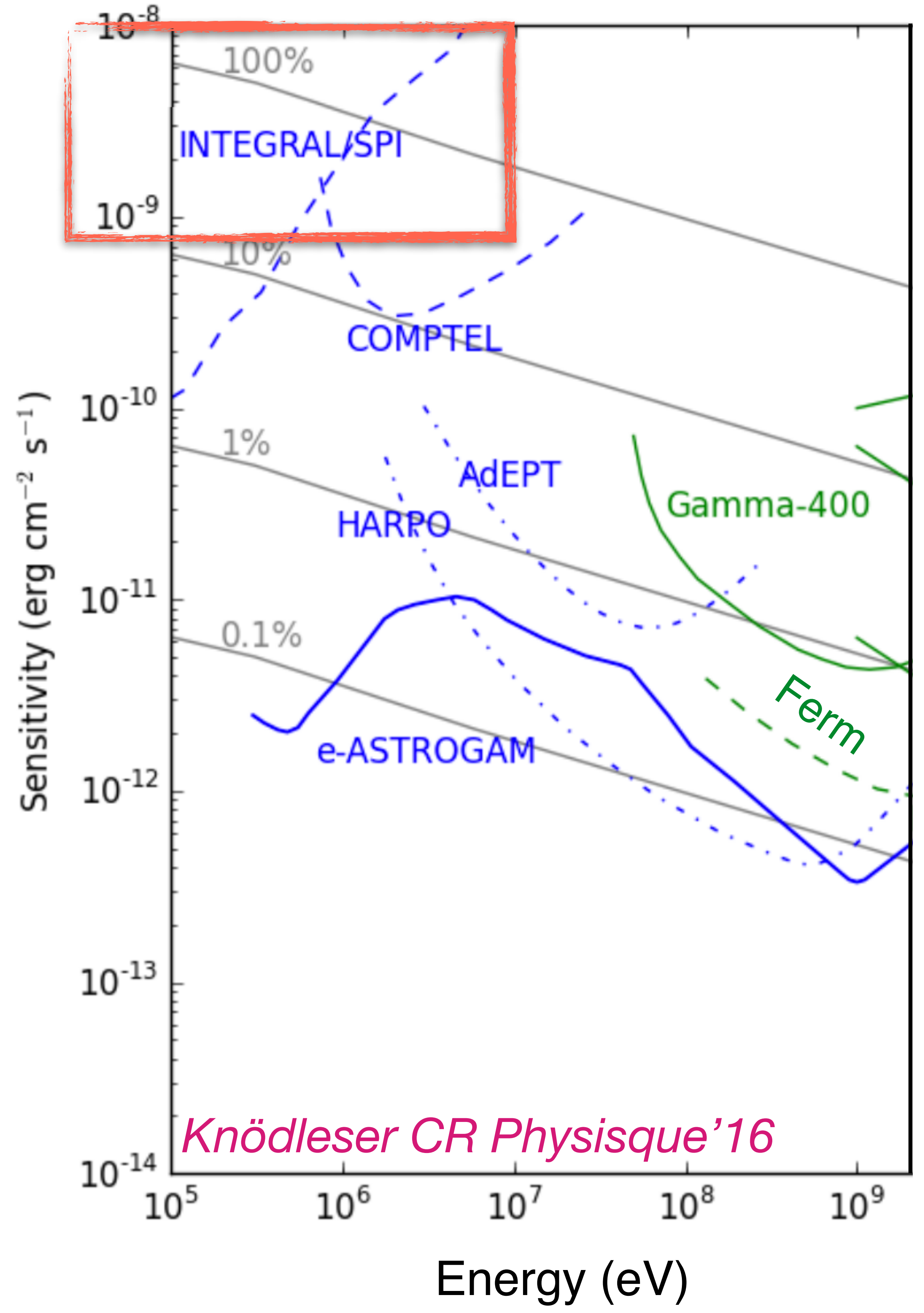
~ a few GeV — few TeV

Eckner, FC+ In preparation



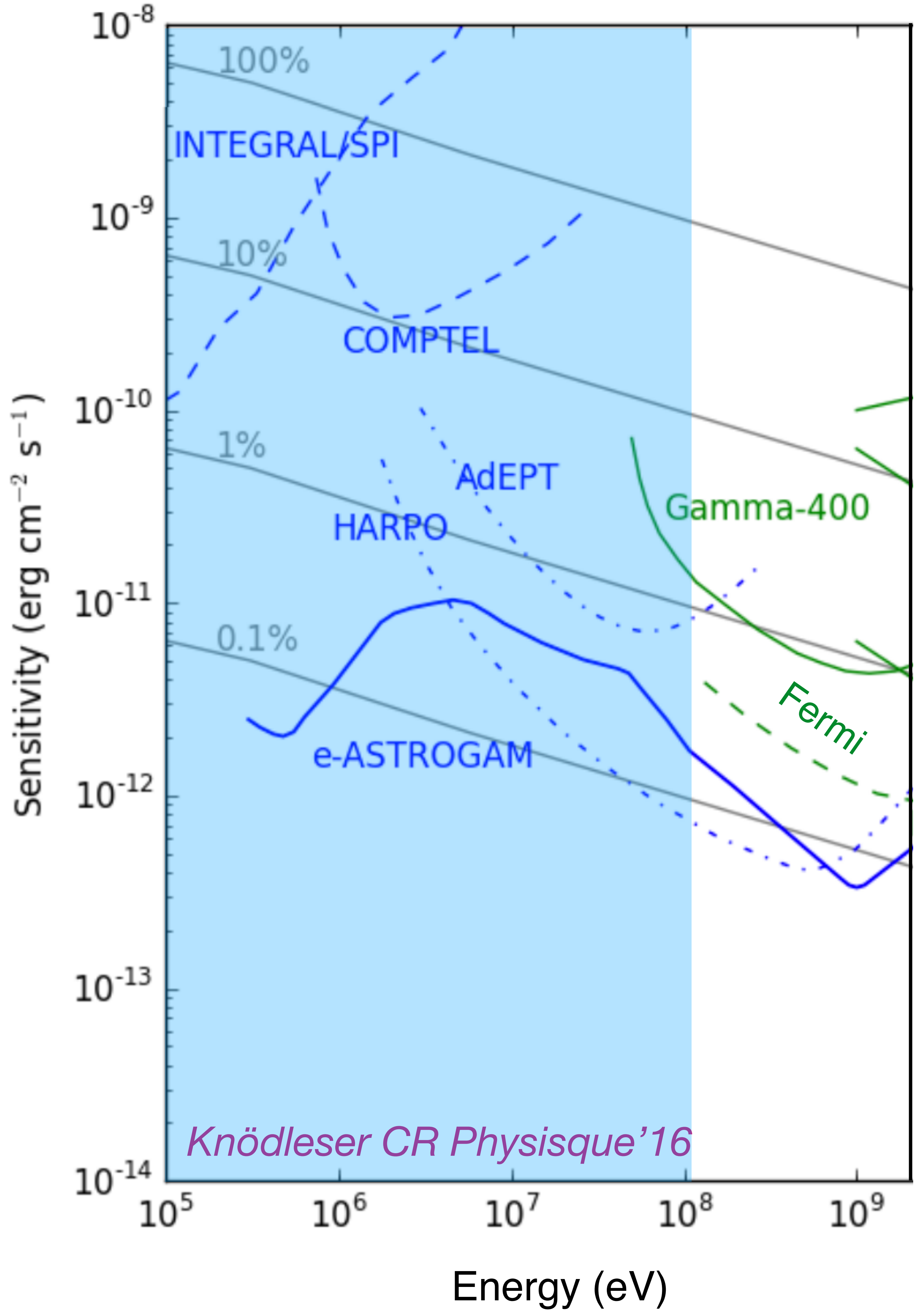
MeV sensitivity gap

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



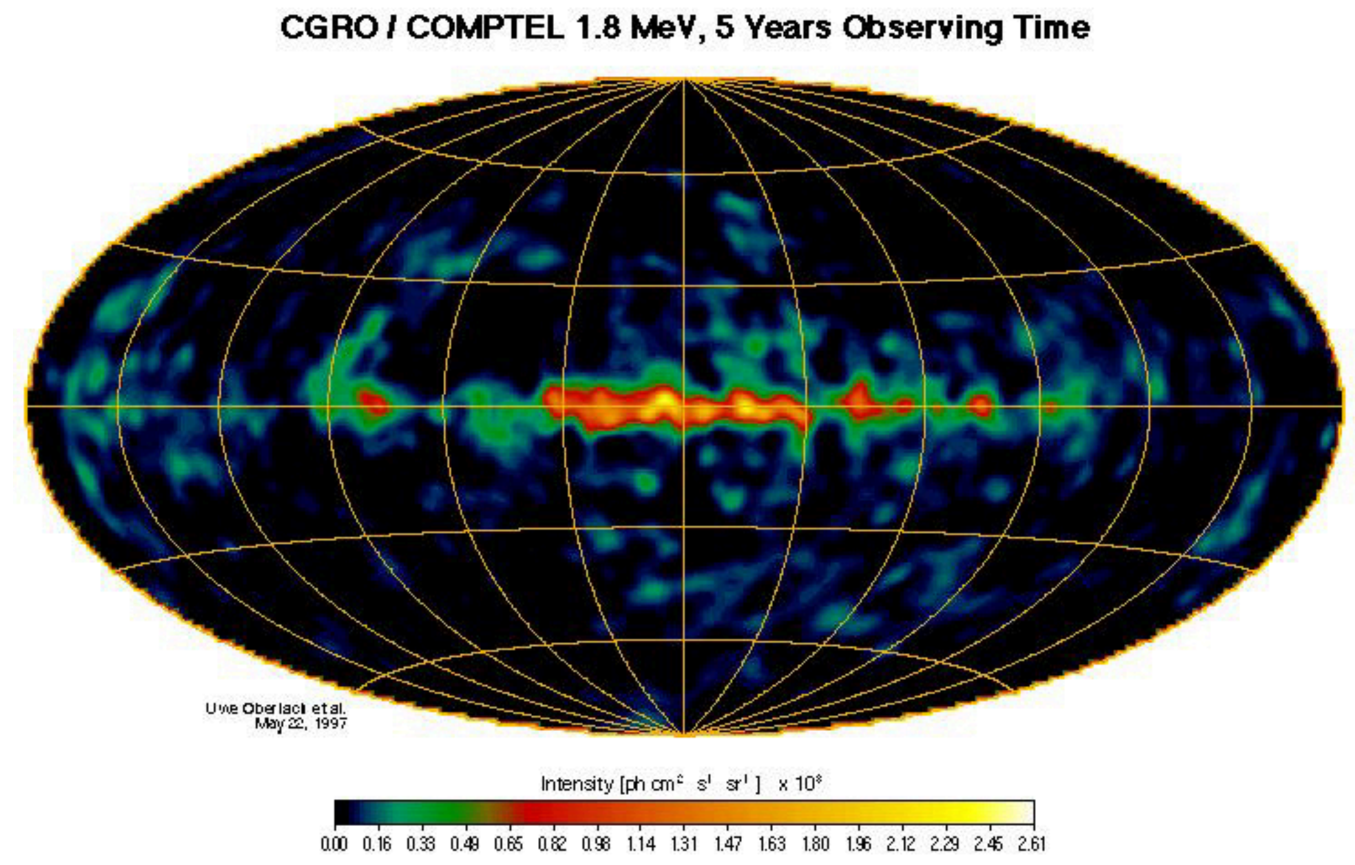
The data landscape

Hard X rays and gamma-ray sky



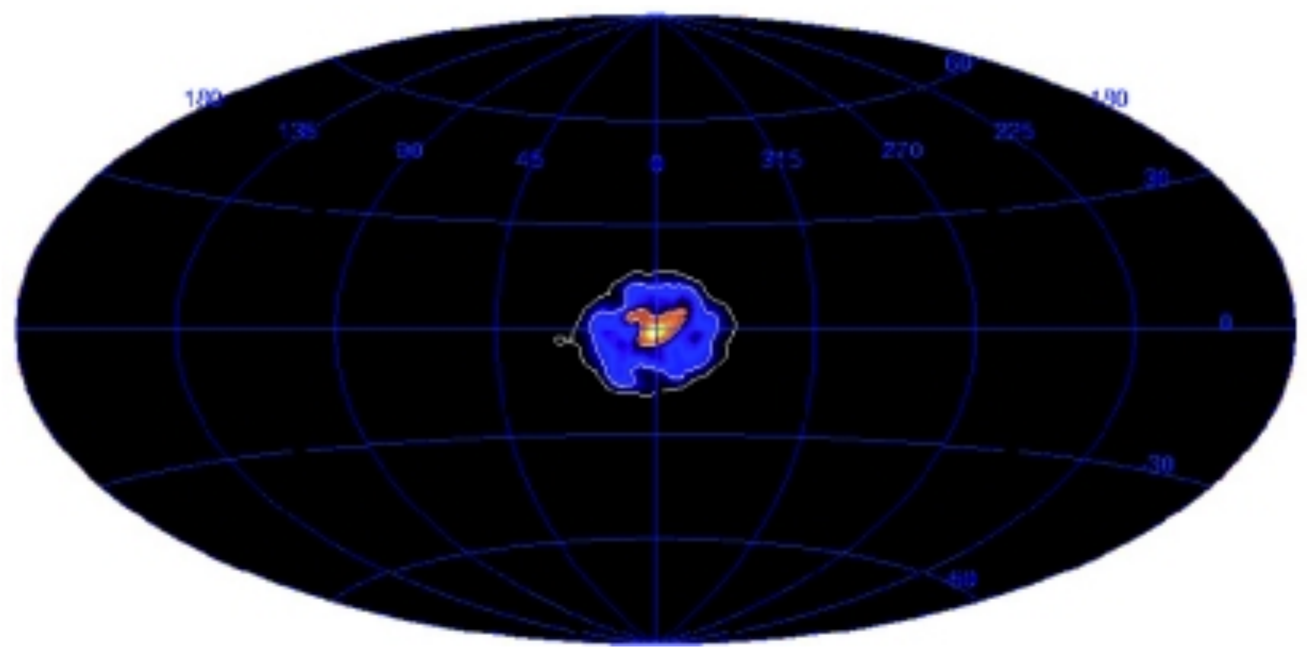
CGRO Compton Telescope (COMPTEL)

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

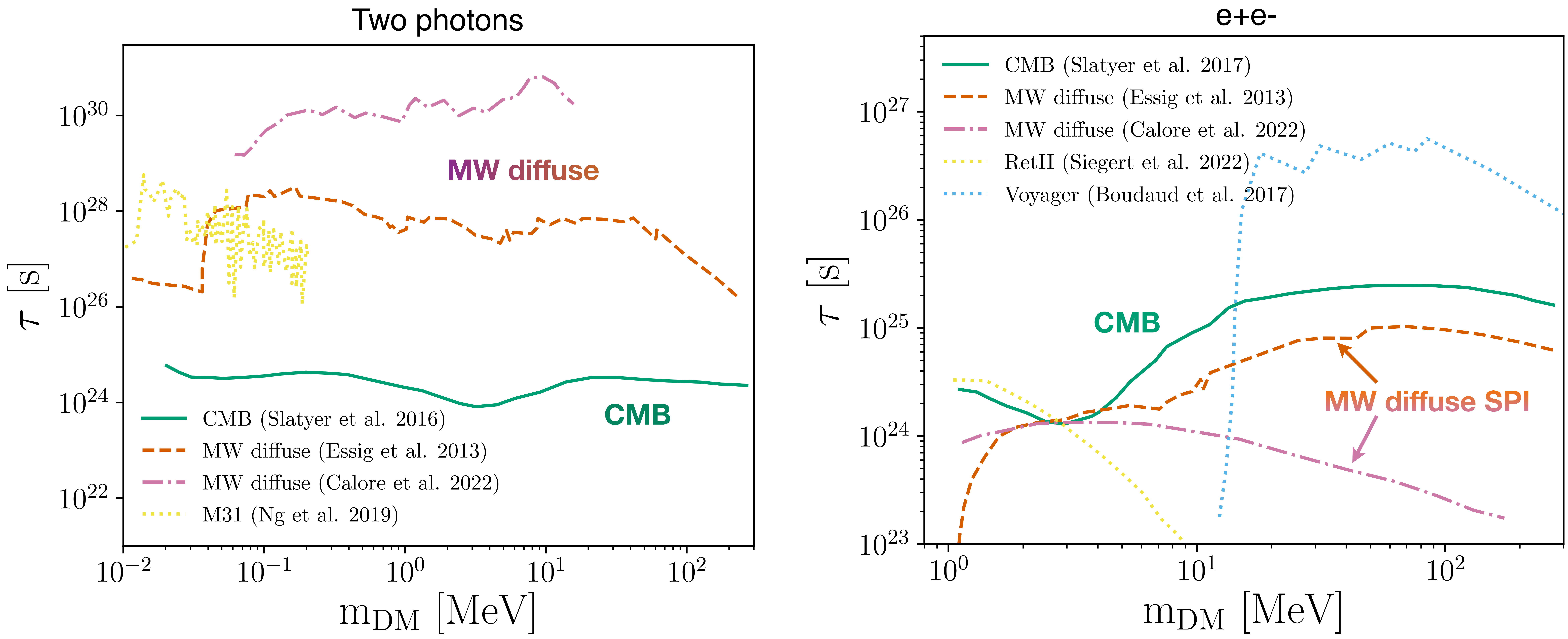


511 keV electron-positron line

Constraints on sub-GeV dark matter

Summary: decay

FC FIPs2022 Proceedings

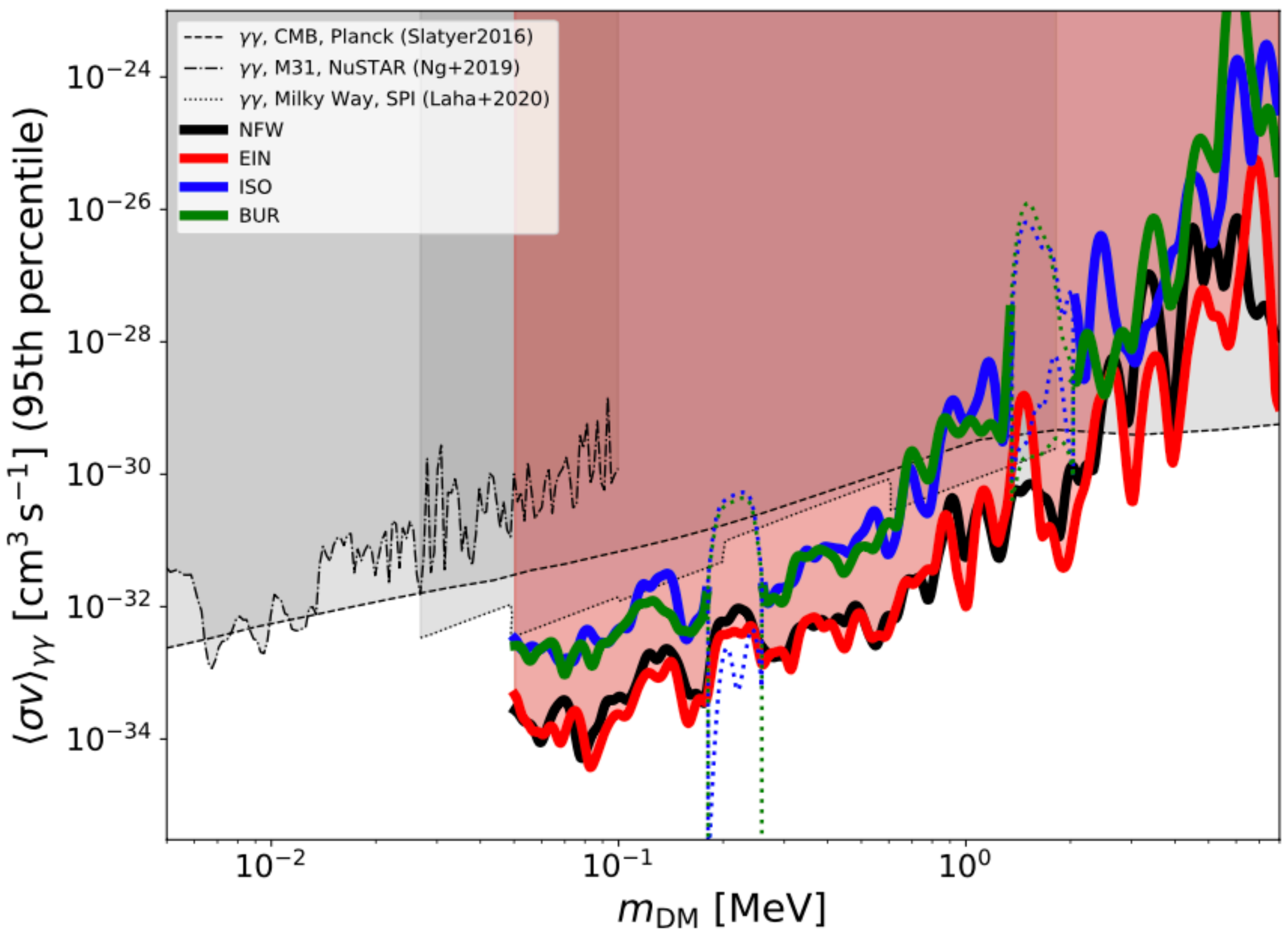


For e+e- channel, very relevant limits from Voyager 1 data *Boudaud+ PRL'17*

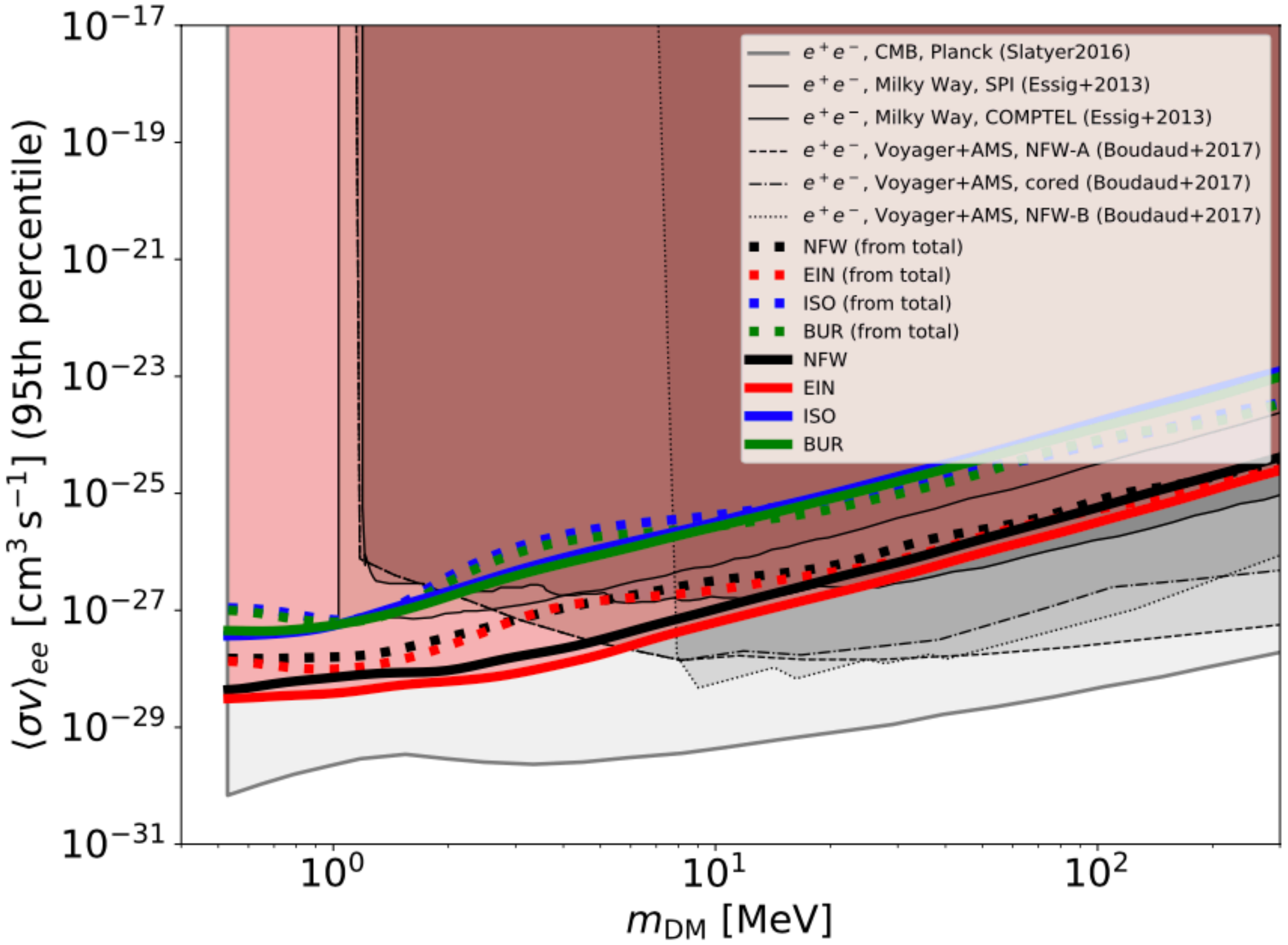
Constraints on annihilating dark matter

Summary from prompt emission

Two photons



e+e-

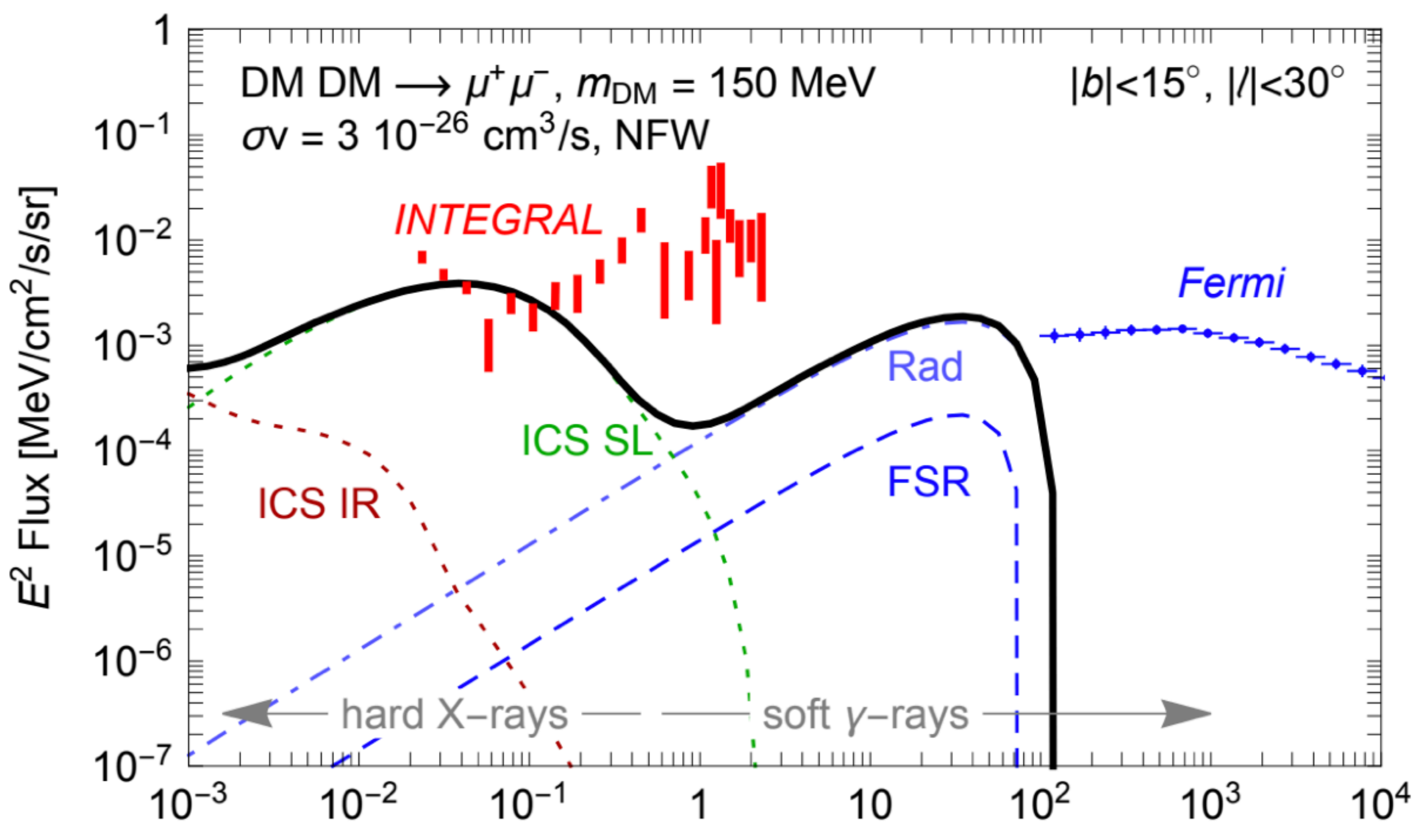


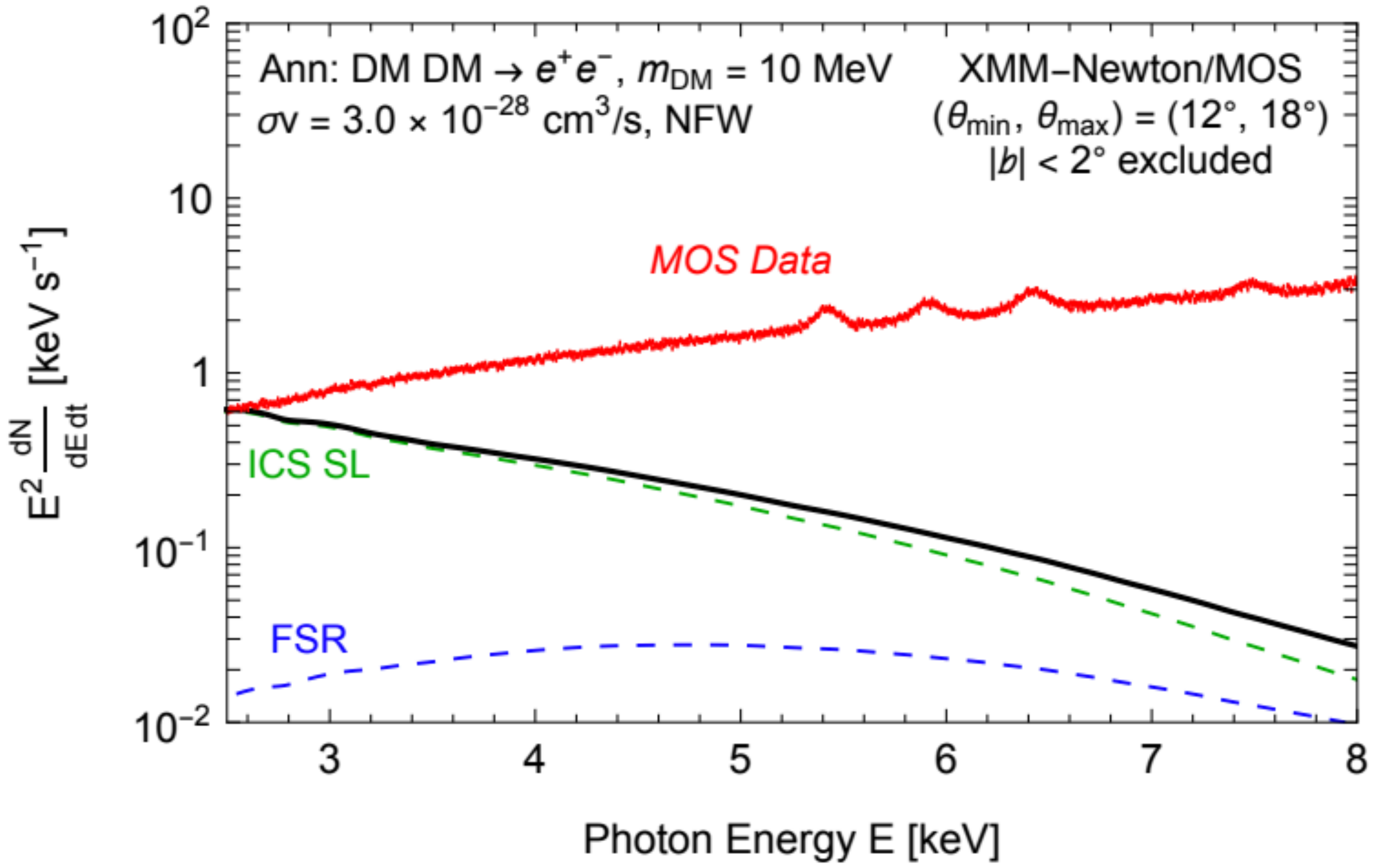
For e+e- channel, very relevant limits from Voyager 1 data *Boudaud+ PRL'17*

Constraints on annihilating dark matter

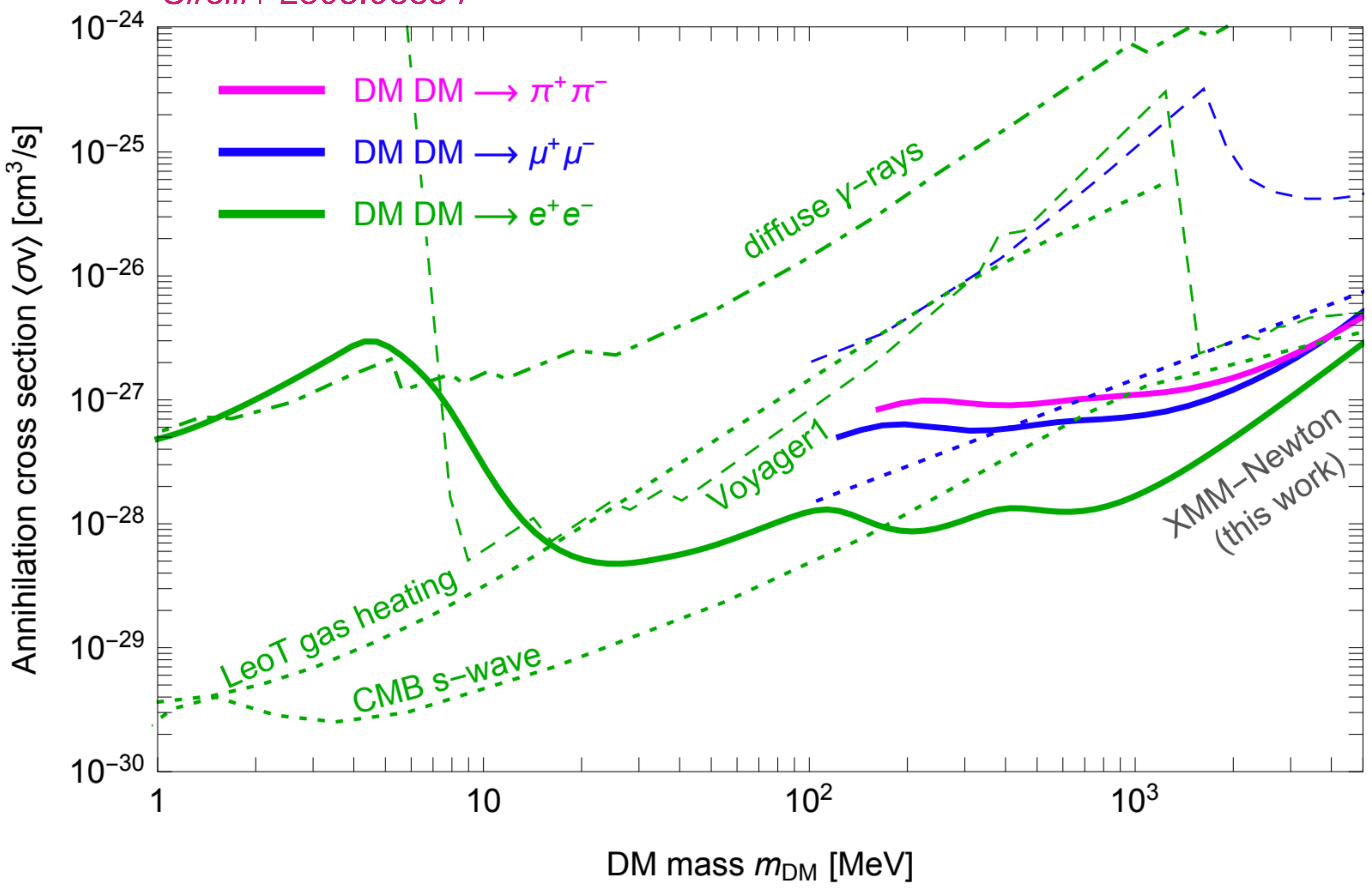
Constraining higher dark matter masses with inverse Compton

Cirelli+ PRD' 21





Cirelli+ 2303.08854



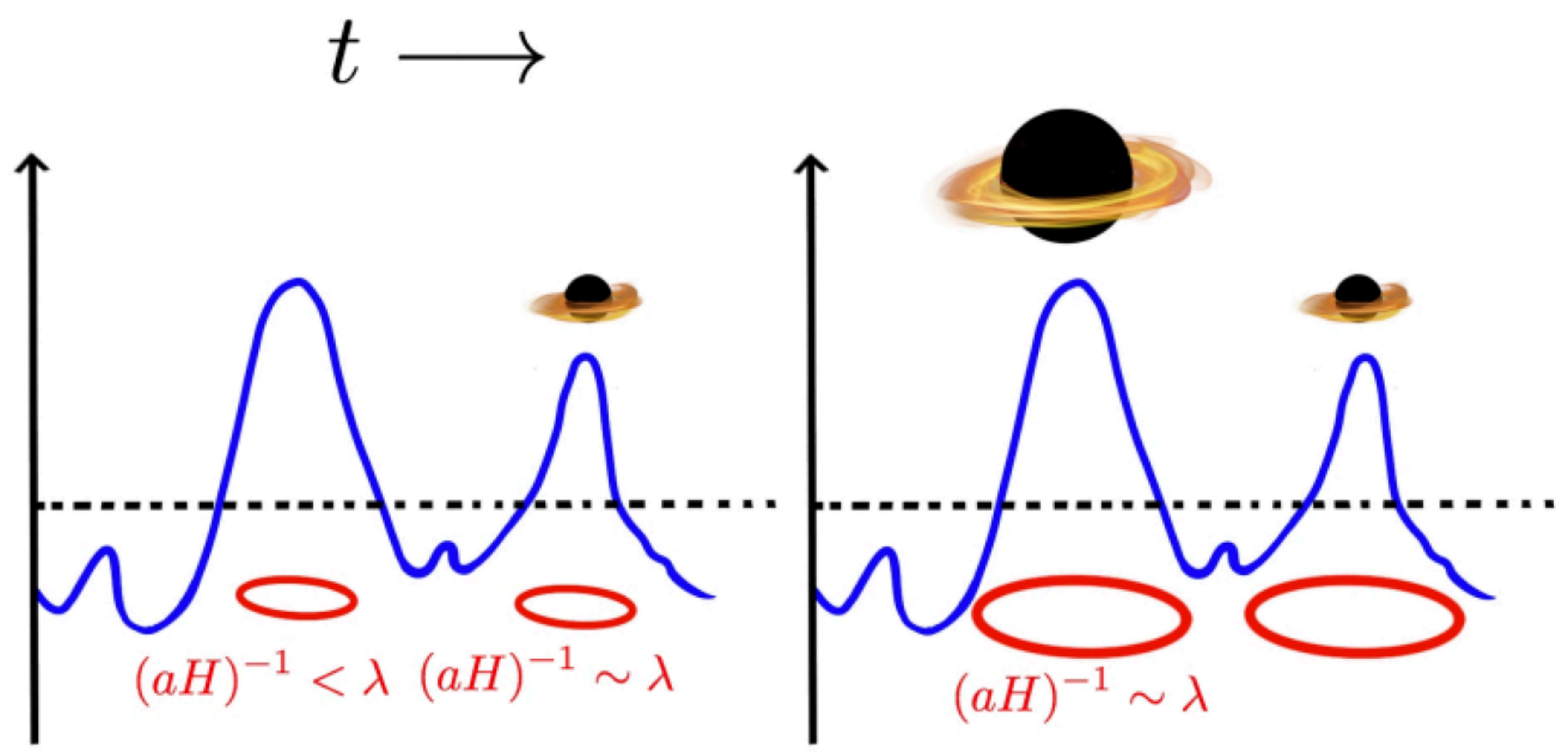
Limits on IC induced gamma-ray emission from **XMM-Newton blank-sky observations**

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

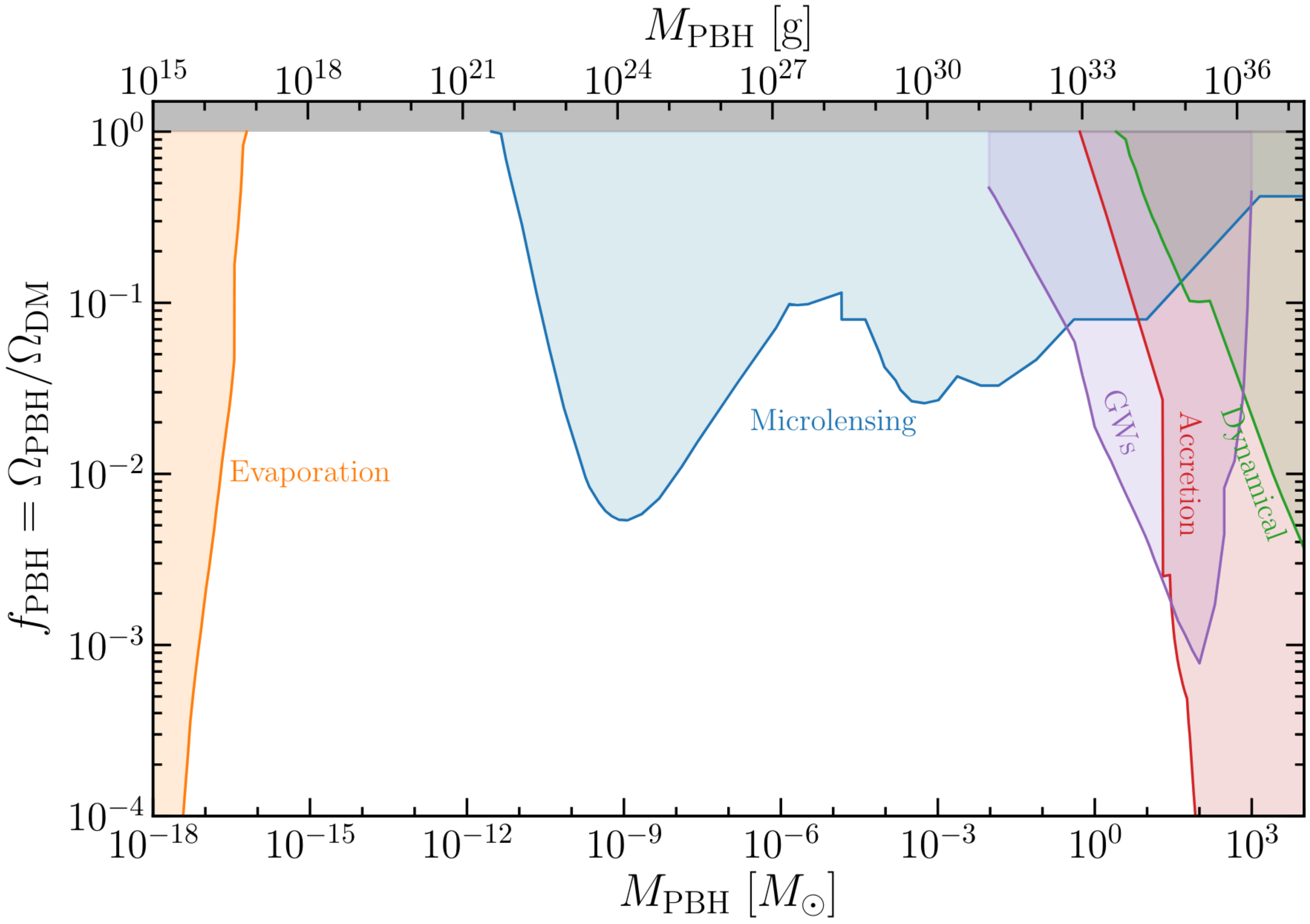
Page & Hawking ApJ'76

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

- 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

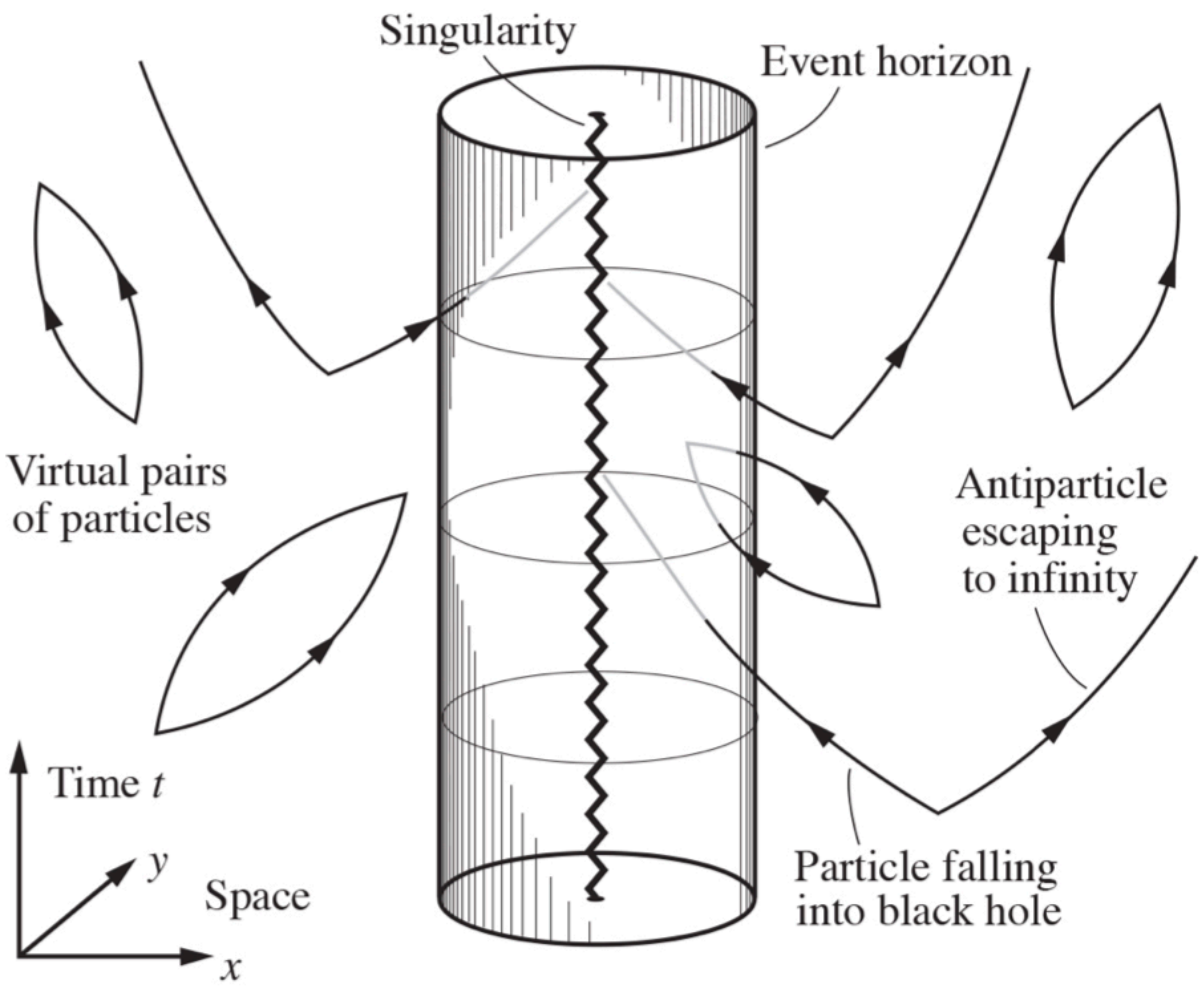
[Intermediate between unitarity bound and Planck scale: ultra-heavy dark matter]

Limits on primordial black holes



Green & Kavanagh J. Phys. G'19

Particle emission from primordial BHs



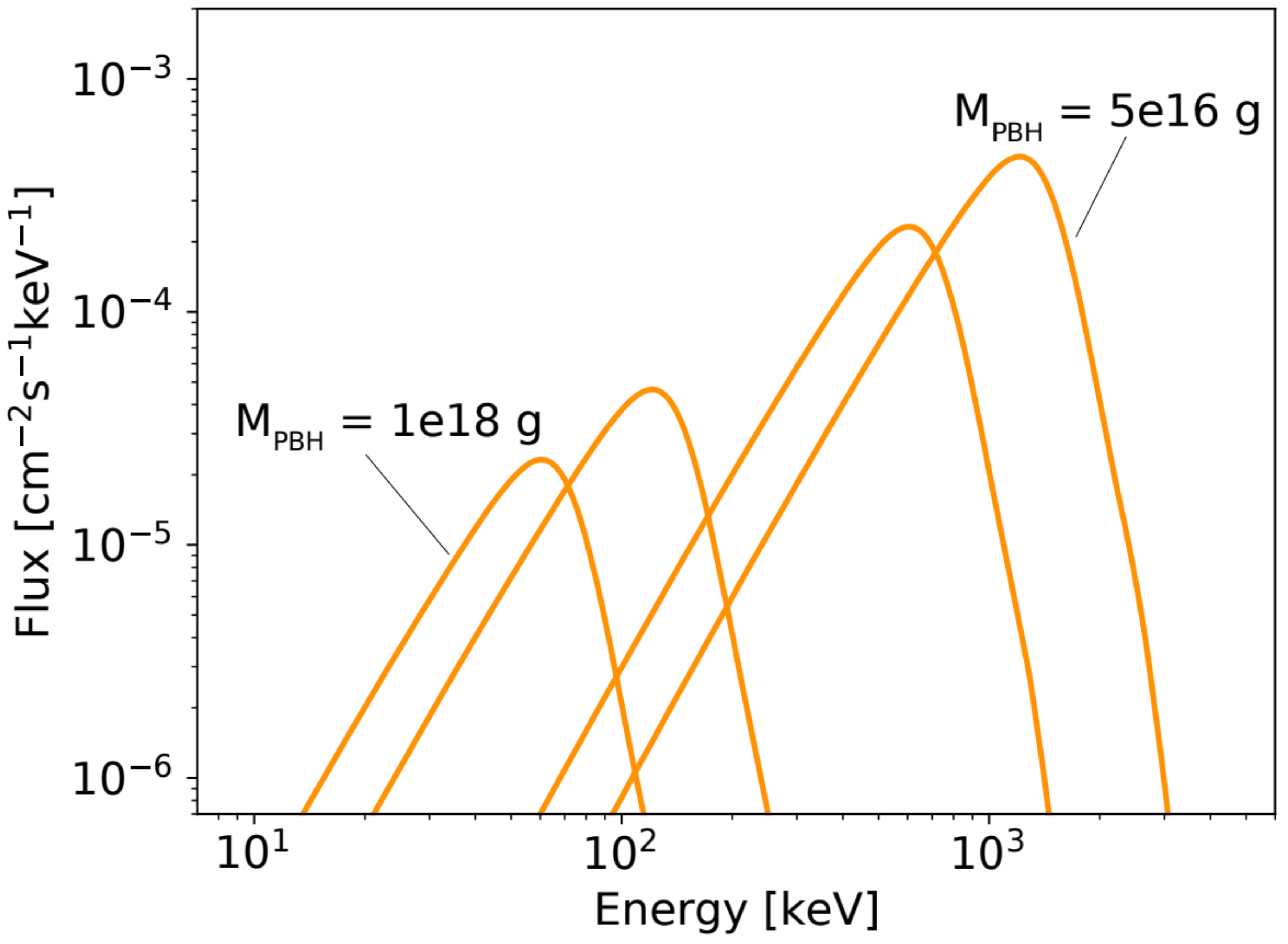
Hawking radiation

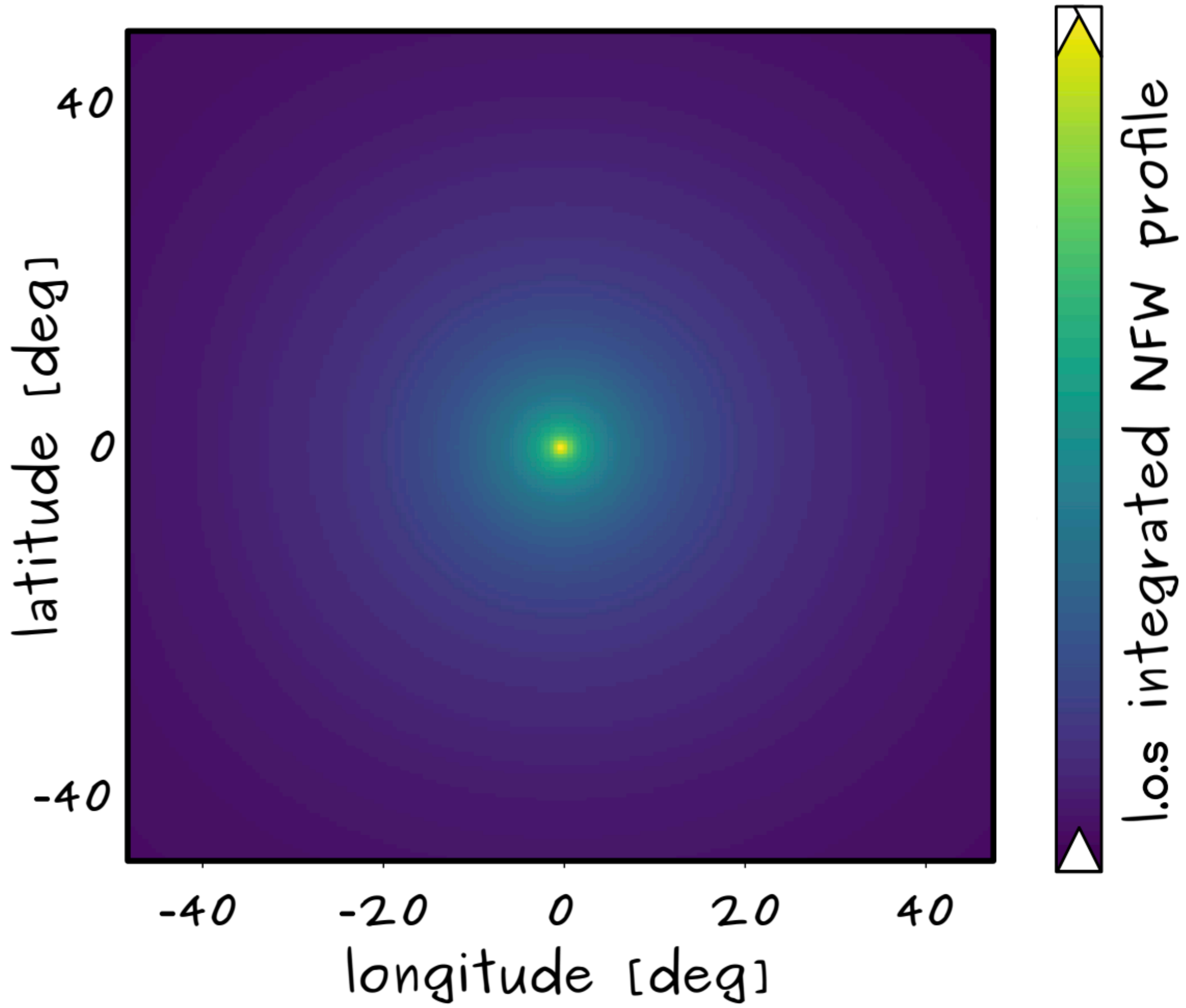
$$\frac{d^2N}{dEdt} = \frac{1}{2\pi}\frac{\Gamma(E, M_{BH})}{\exp(E/T_{BH}) - (-1)^{2S}}$$

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

Photons from PBHs

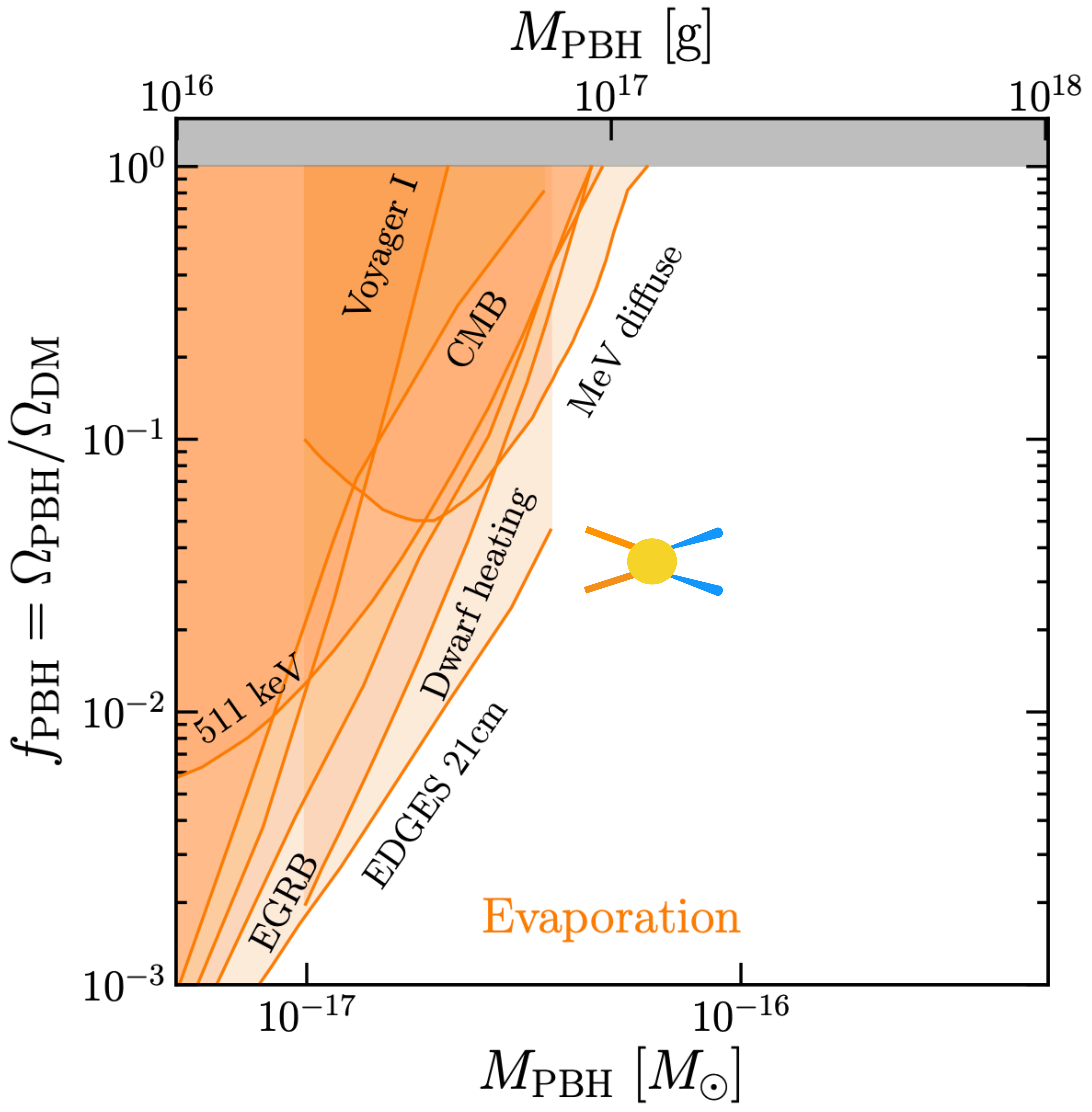
$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}(l,b) = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t} \int_{\mathrm{l.o.s.}} \mathrm{d}s\, \rho(r(s,l,b))$$





Berteaud, FC+ PRD'22

Limits on evaporating PBH



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

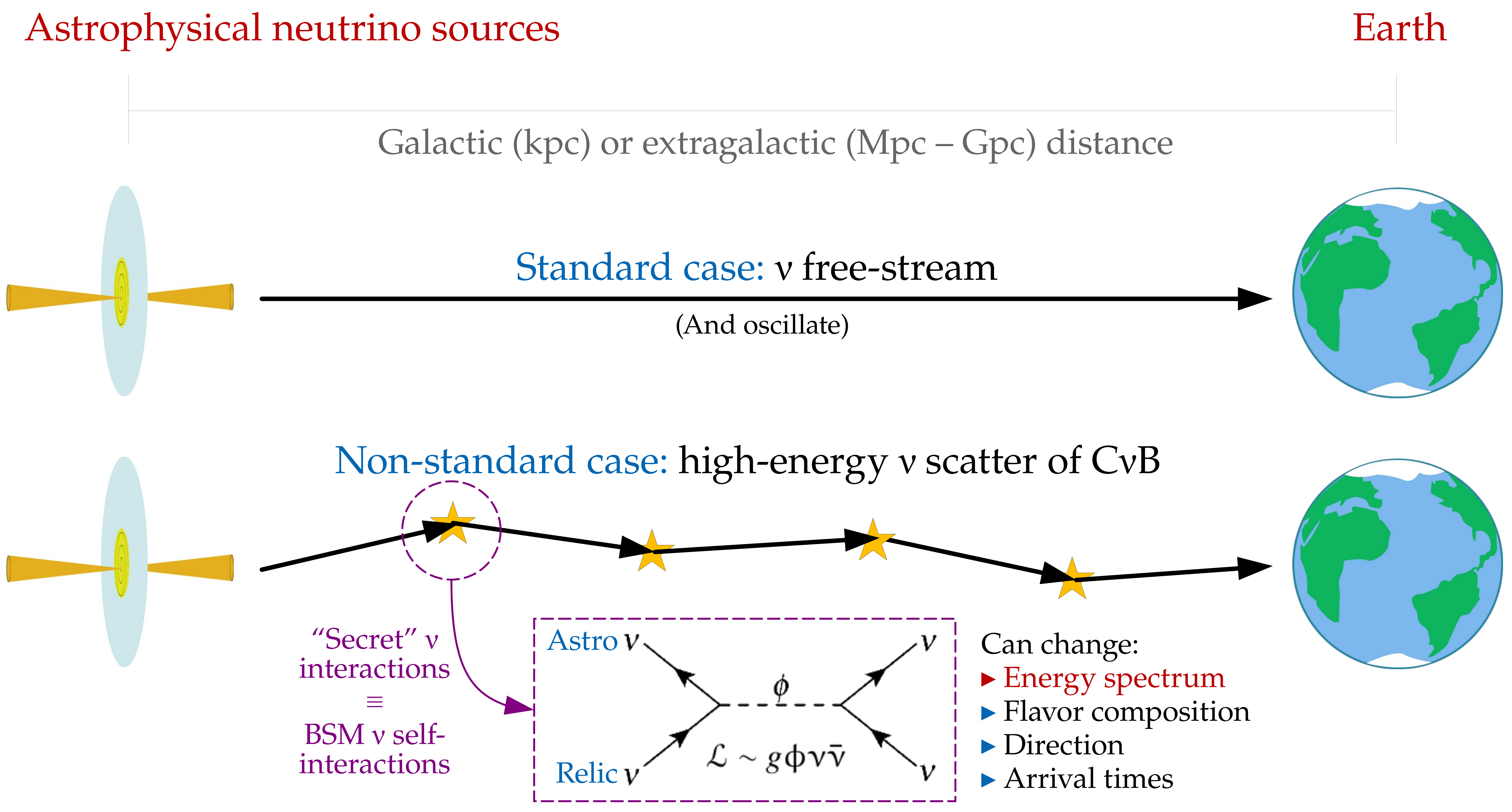
  Berteaud, FC+ PRD'22

- 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

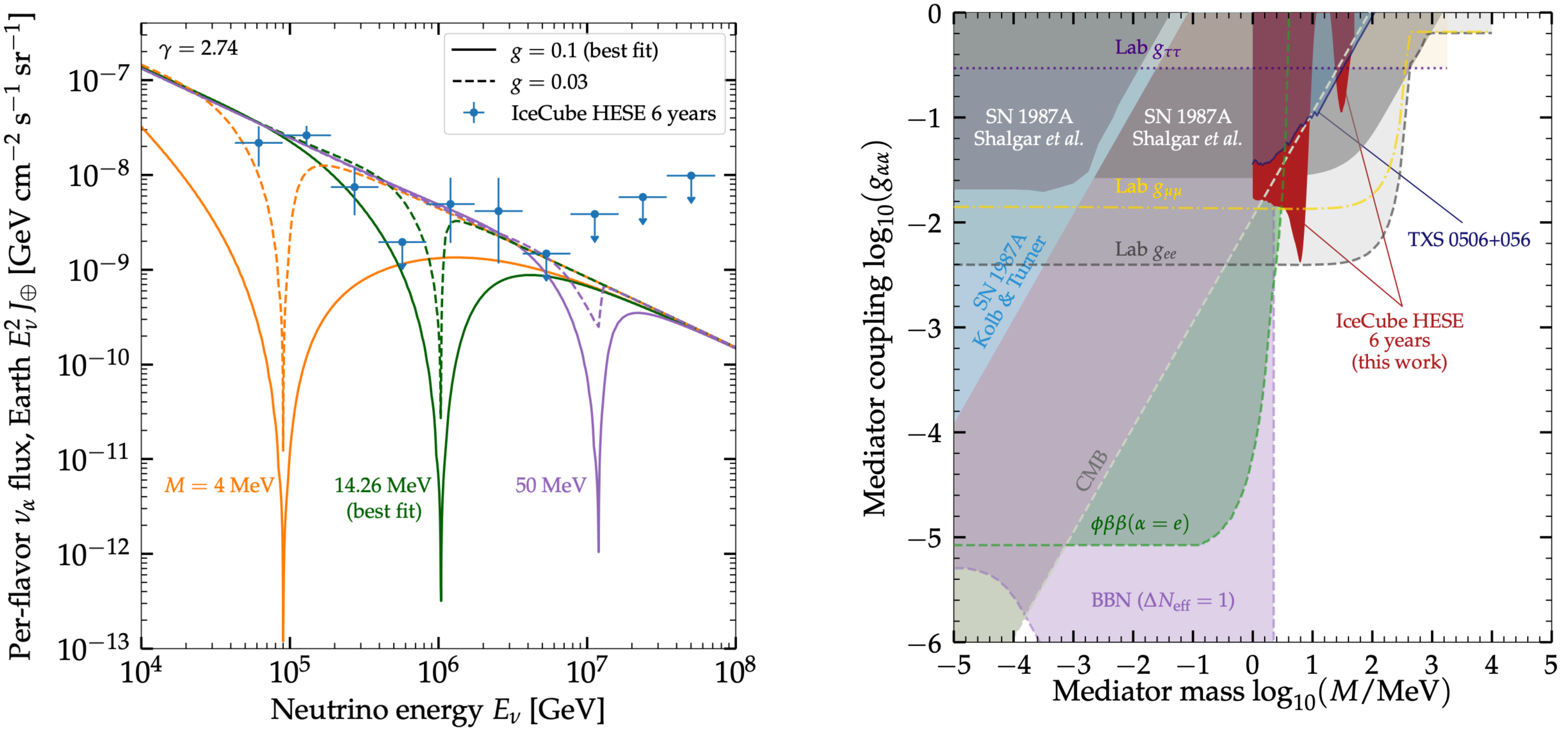
Anomalous propagation effects



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

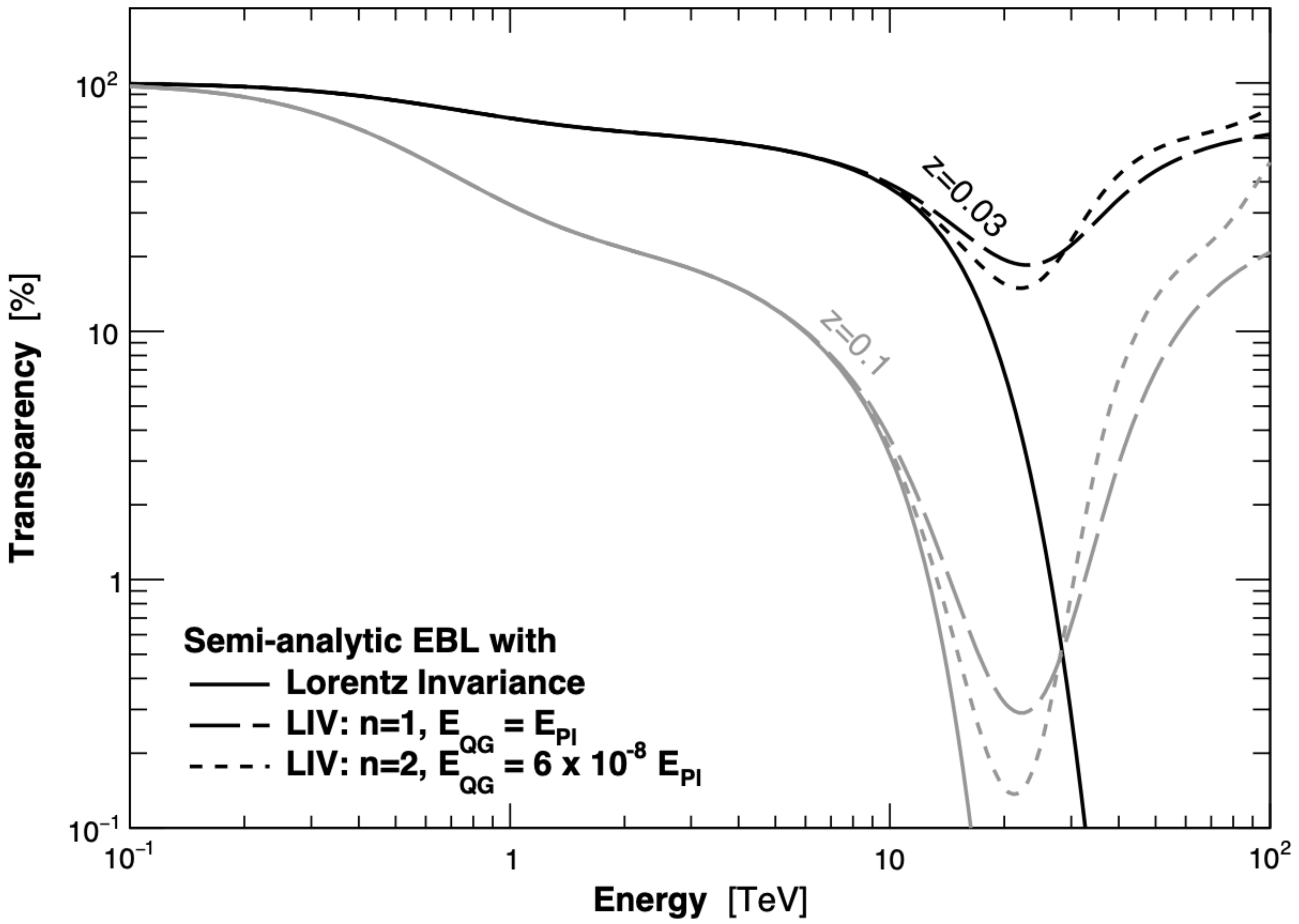


Figure 7.8: Attenuation factor, in percent, as a function of gamma-ray energy on Earth, for sources located at $z = 0.03$ and $z = 0.1$, following the semi-analytical EBL model of Gilmore et al. (2012) and the LIV formalism of Jacob and Piran (2008). Both linear ($n = 1$) and quadratic ($n = 2$) modifications 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

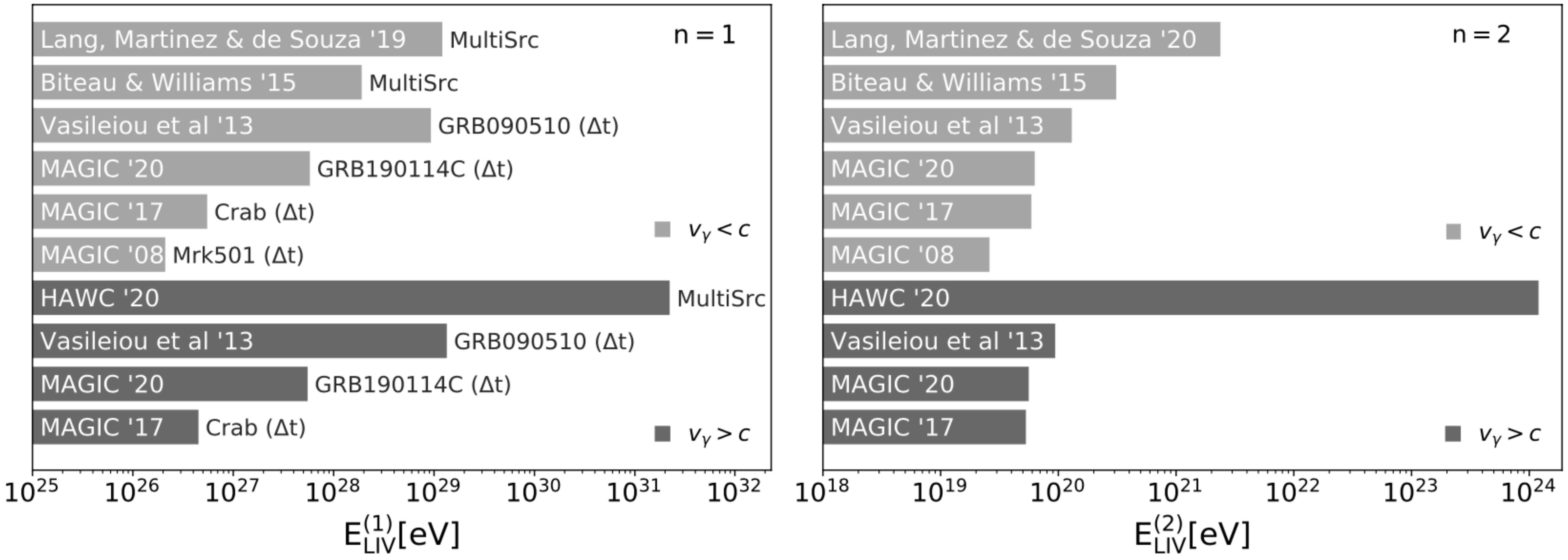


Figure 7.10: Summary of the lower limits on the energy scale of LIV, E_{LIV}. The left panel shows the limits on the linear term, the right panel on the quadratic term. Light grey bars assume a subluminal modification, while dark grey bars assume a superluminal modification. Credit: Humberto Martínez-Huerta,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