SuGAR MADISON 2024

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

The Fermi view of the Milky Way

Michela Negro

Louisiana State University

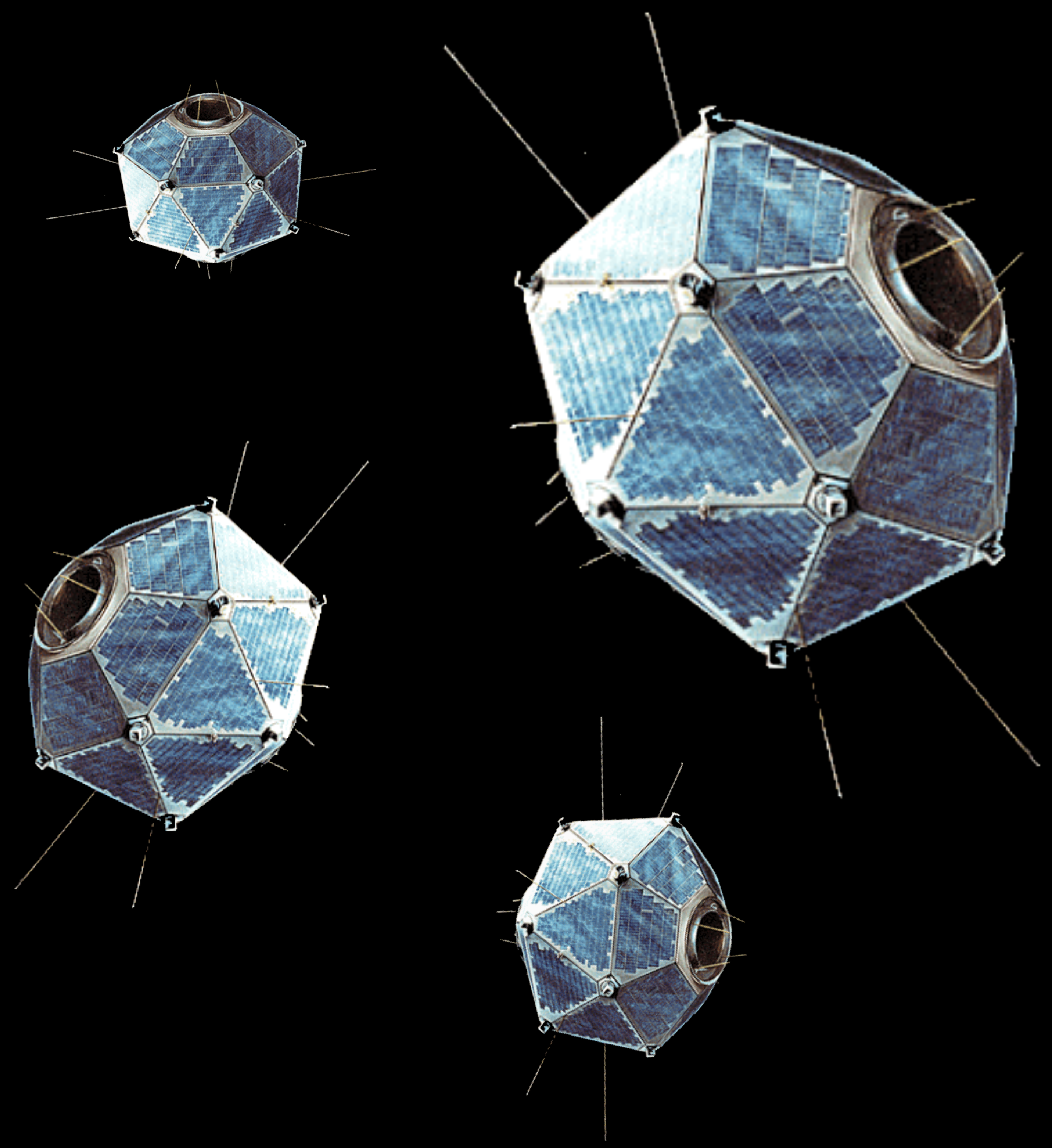
LSU

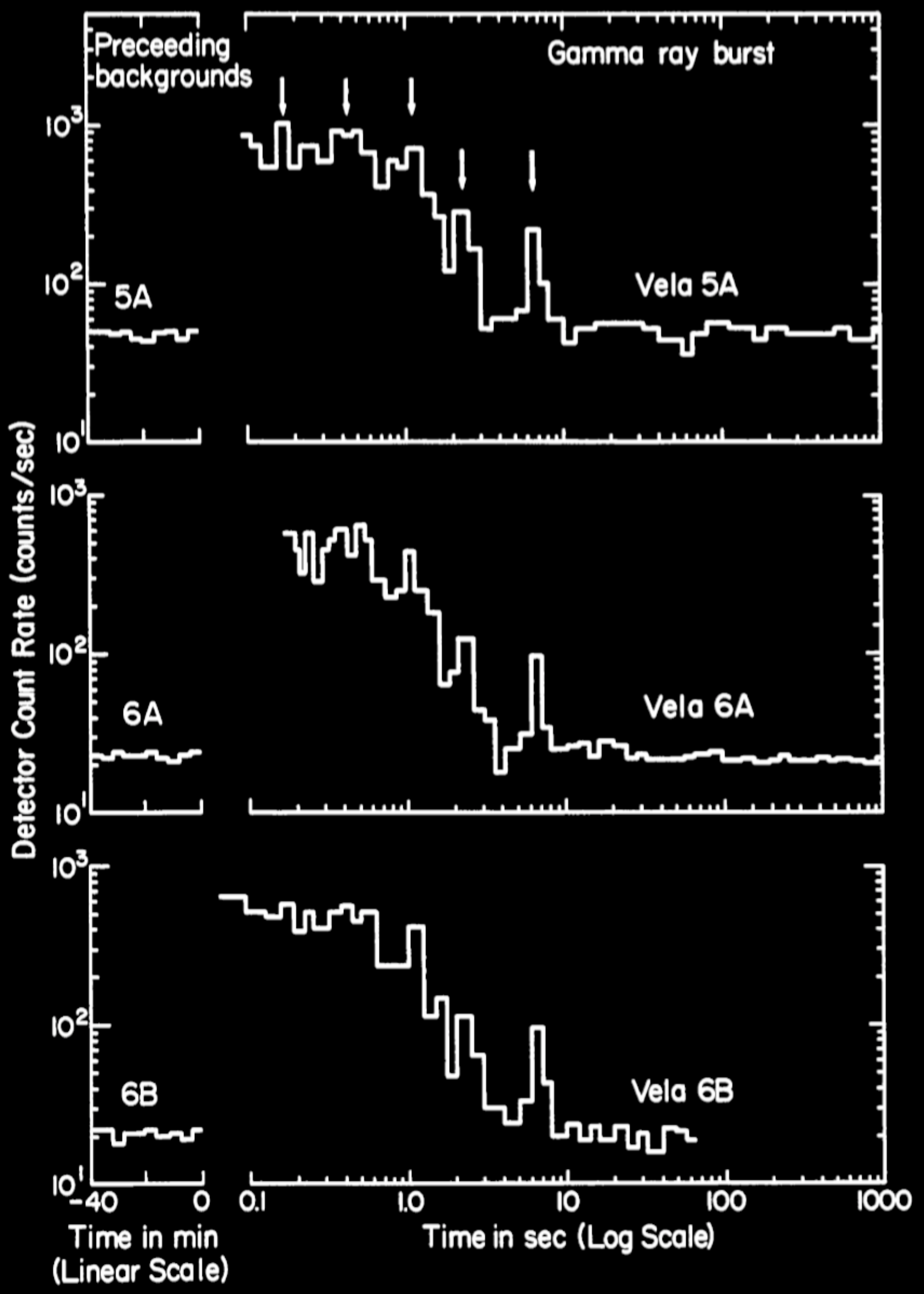
Department of Physics & Astronomy

The Fermi-LAT "Diffuse" people

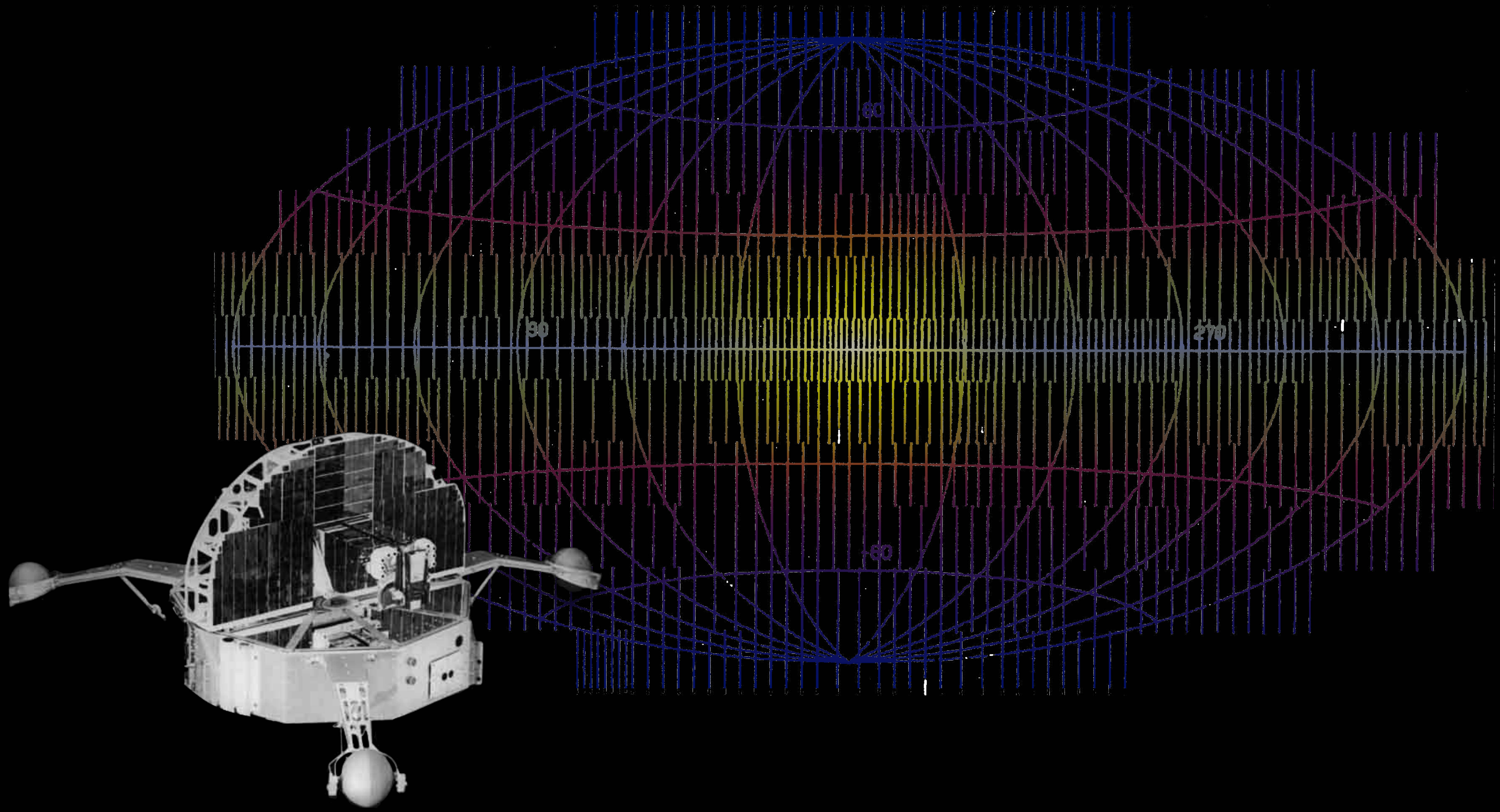
… J. M. **Casandjian**, S. W. **Digel**, A. **Franckowiak**, I. A. **Grenier**, G. **Jóhannesson**, M. **Kerr**, D. **Malyshev**, T. **Mitzuno**, I. V. **Moskalenko**, E. **Orlando**, T. A. **Porter**, A. W. **Strong**, L. **Tibaldo**, …, M. **Negro**

Vela Project

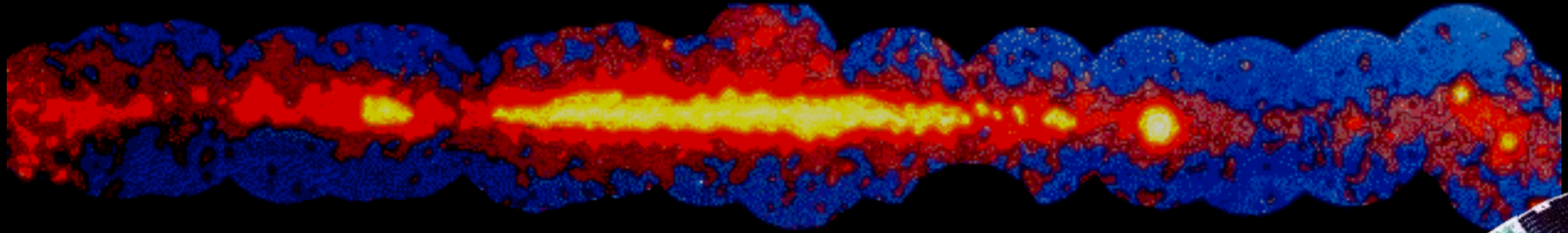


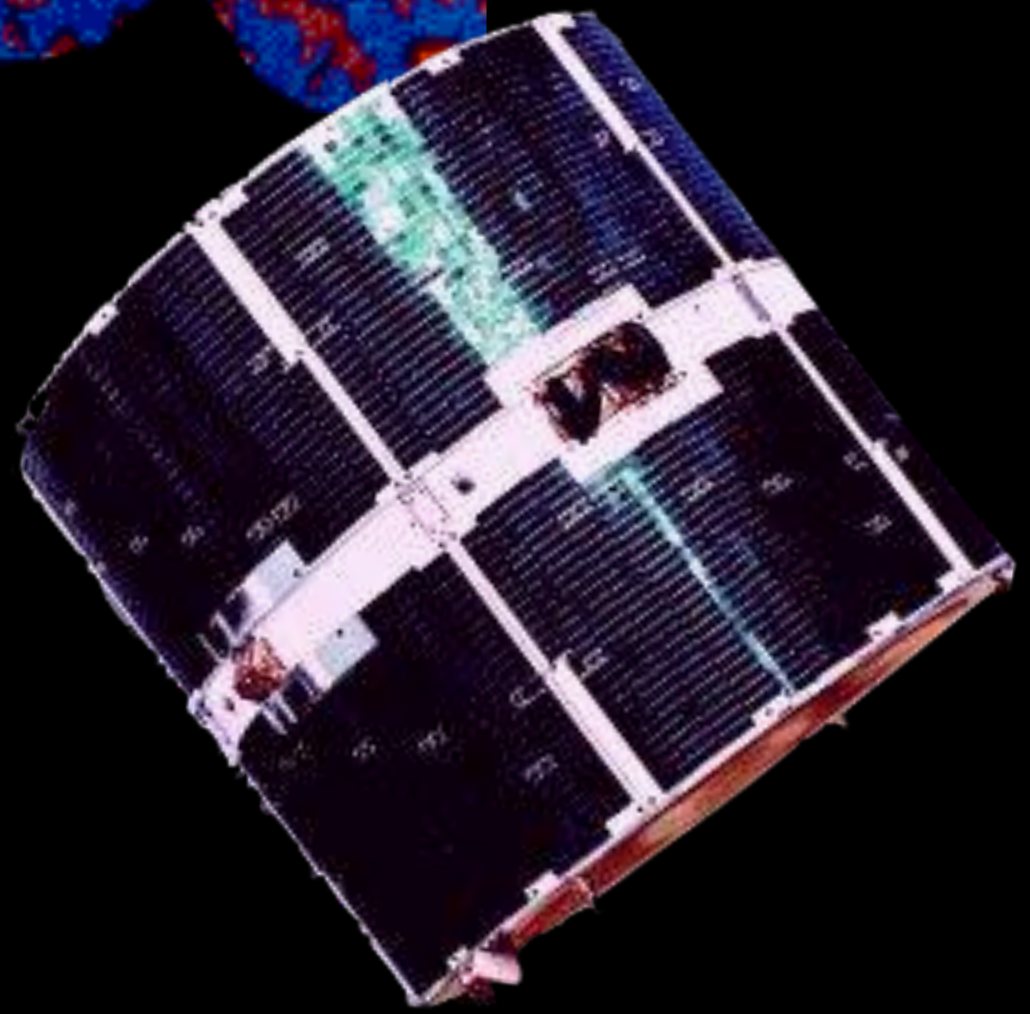


OSO-3

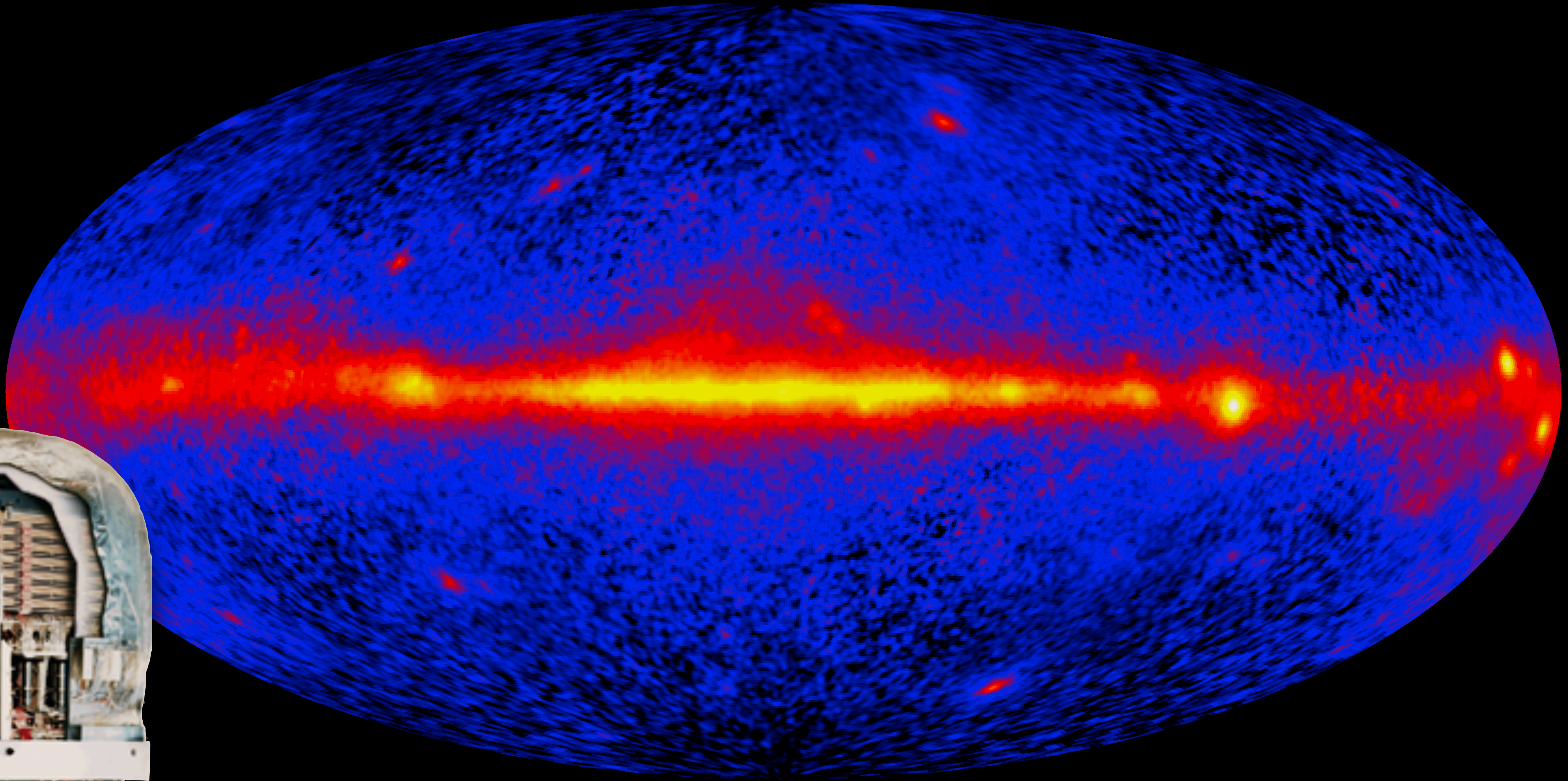


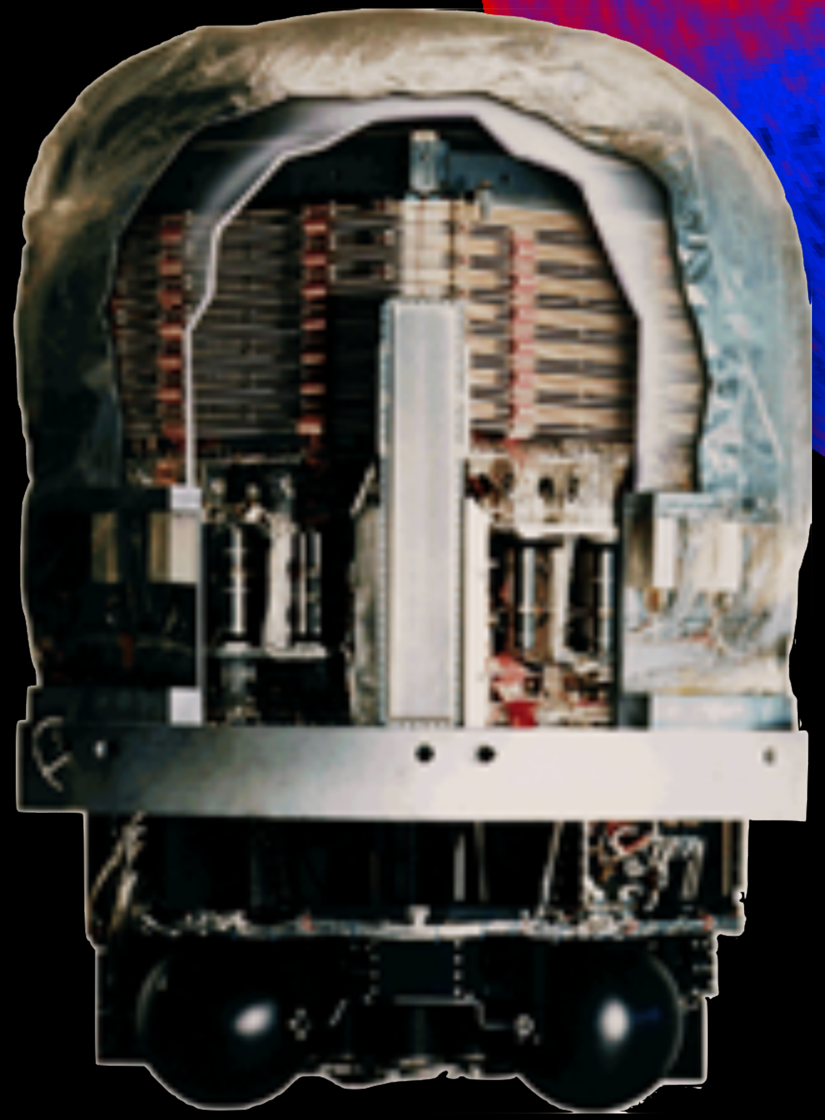
COS-B



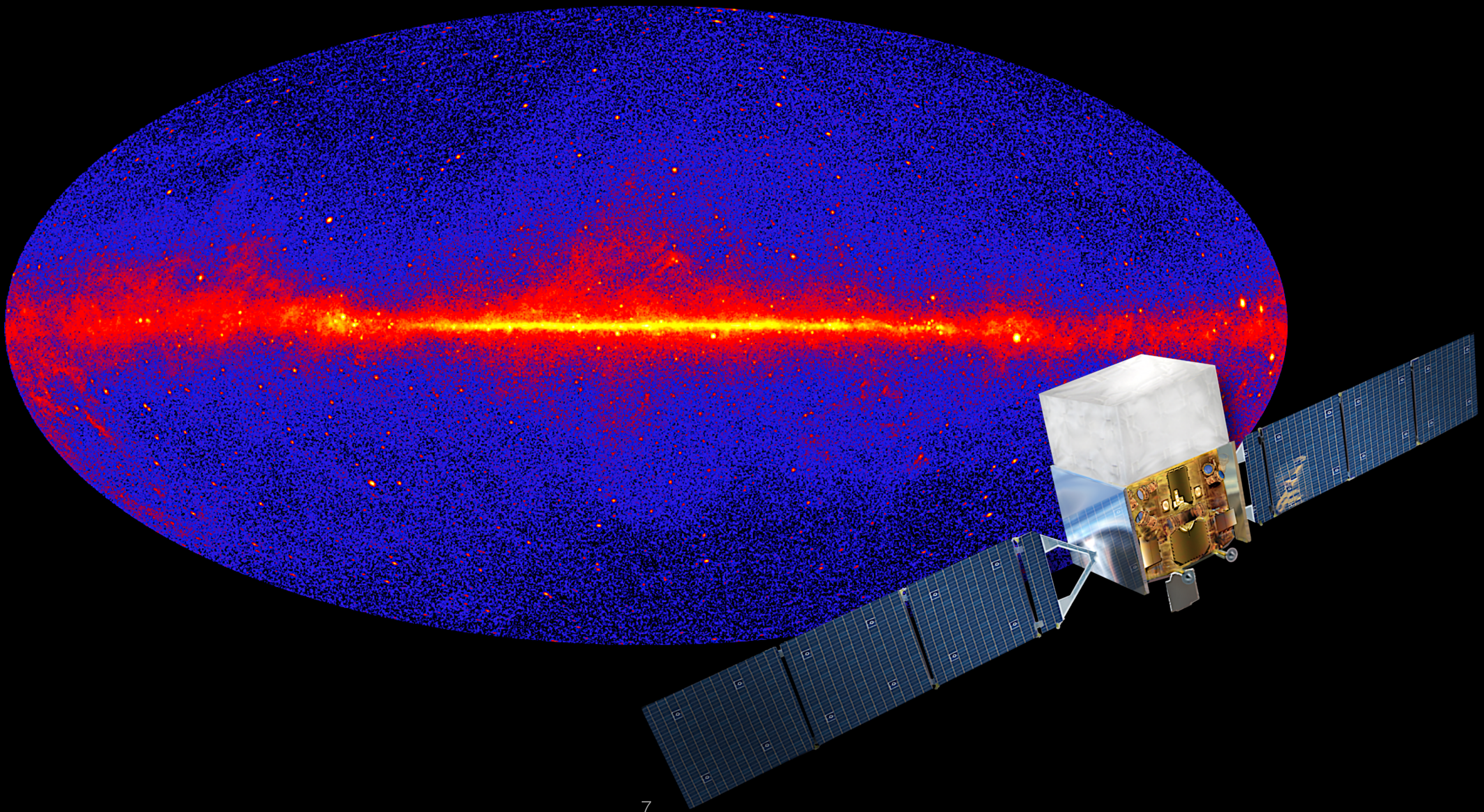


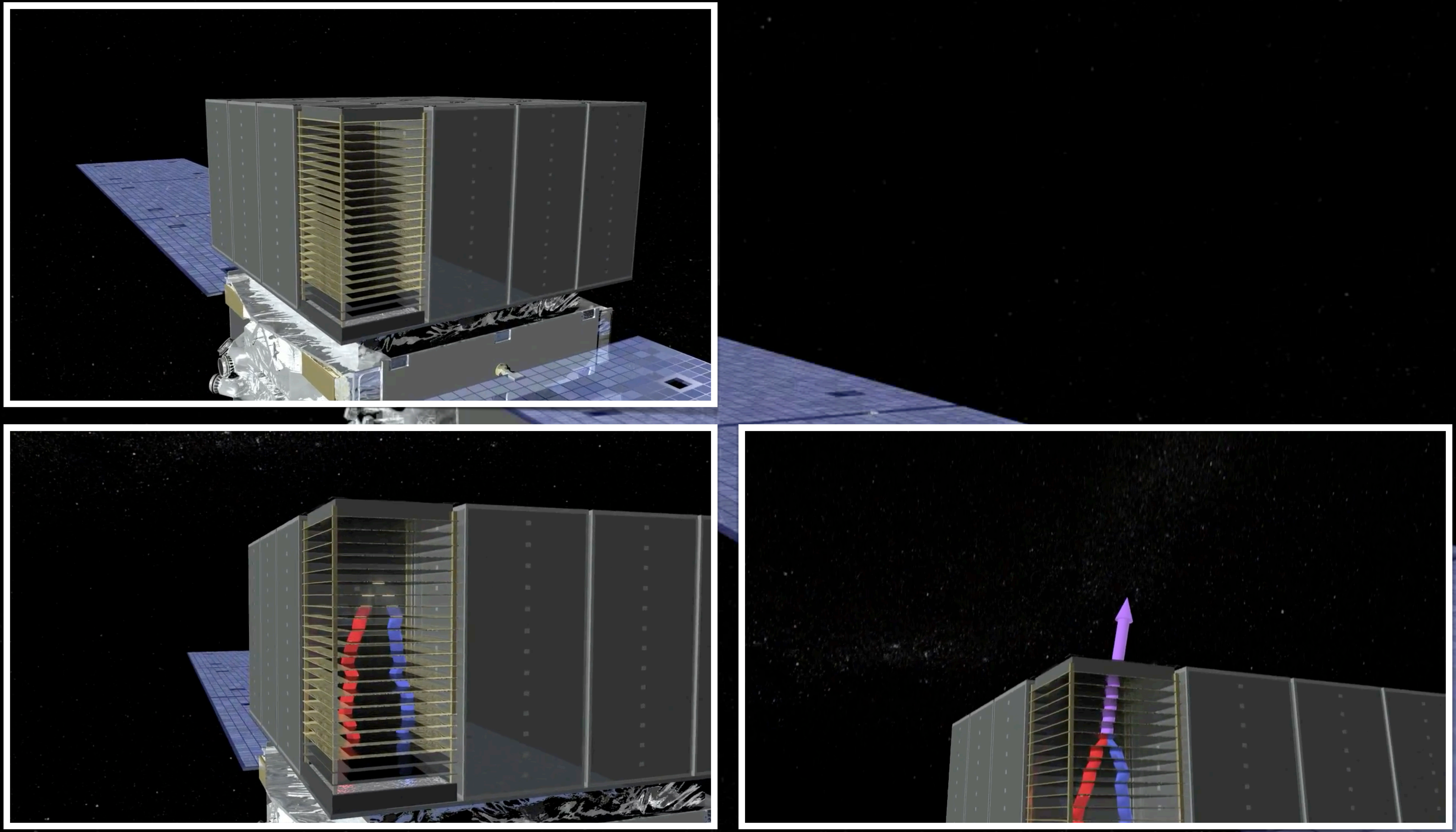
EGRET

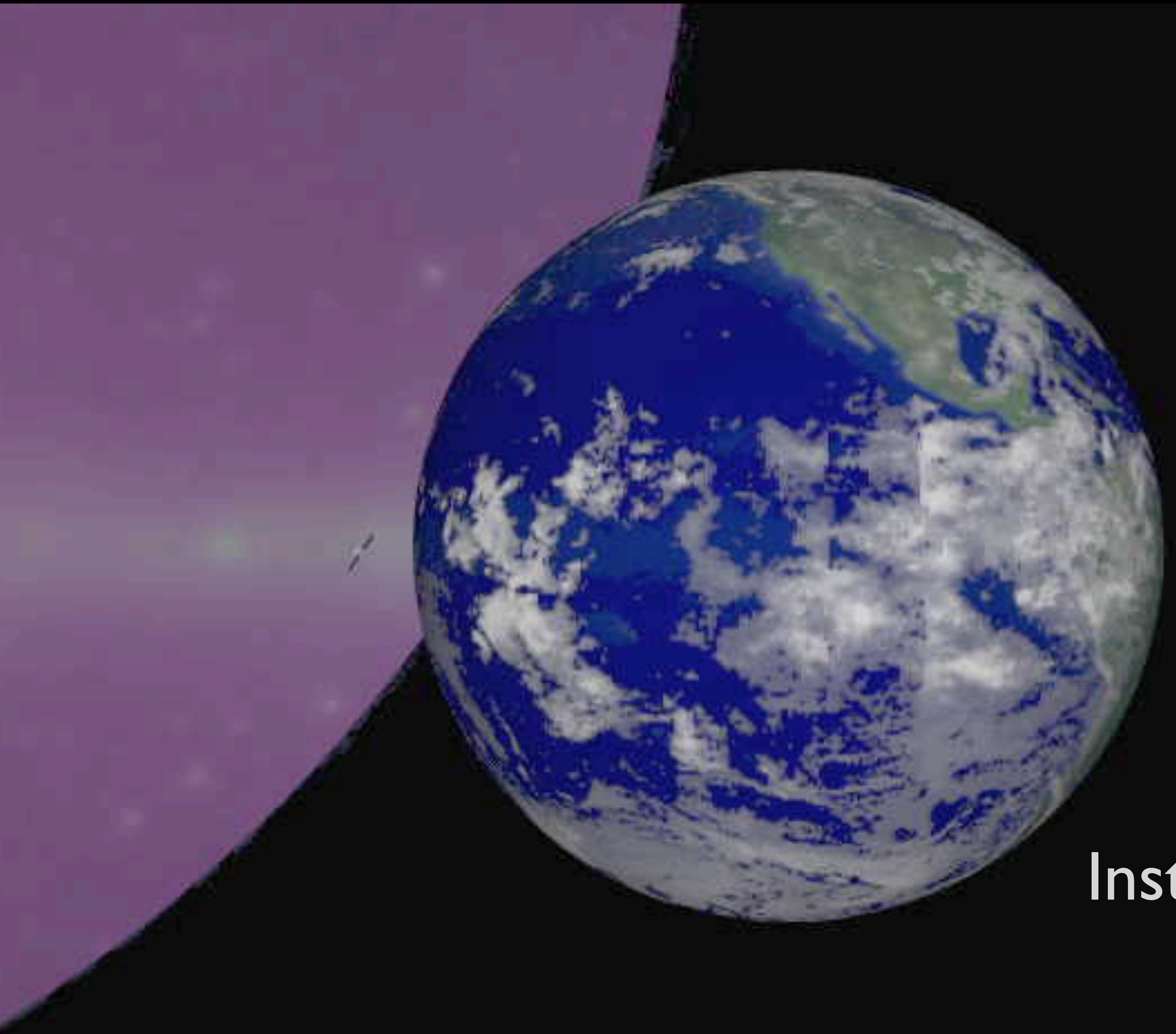




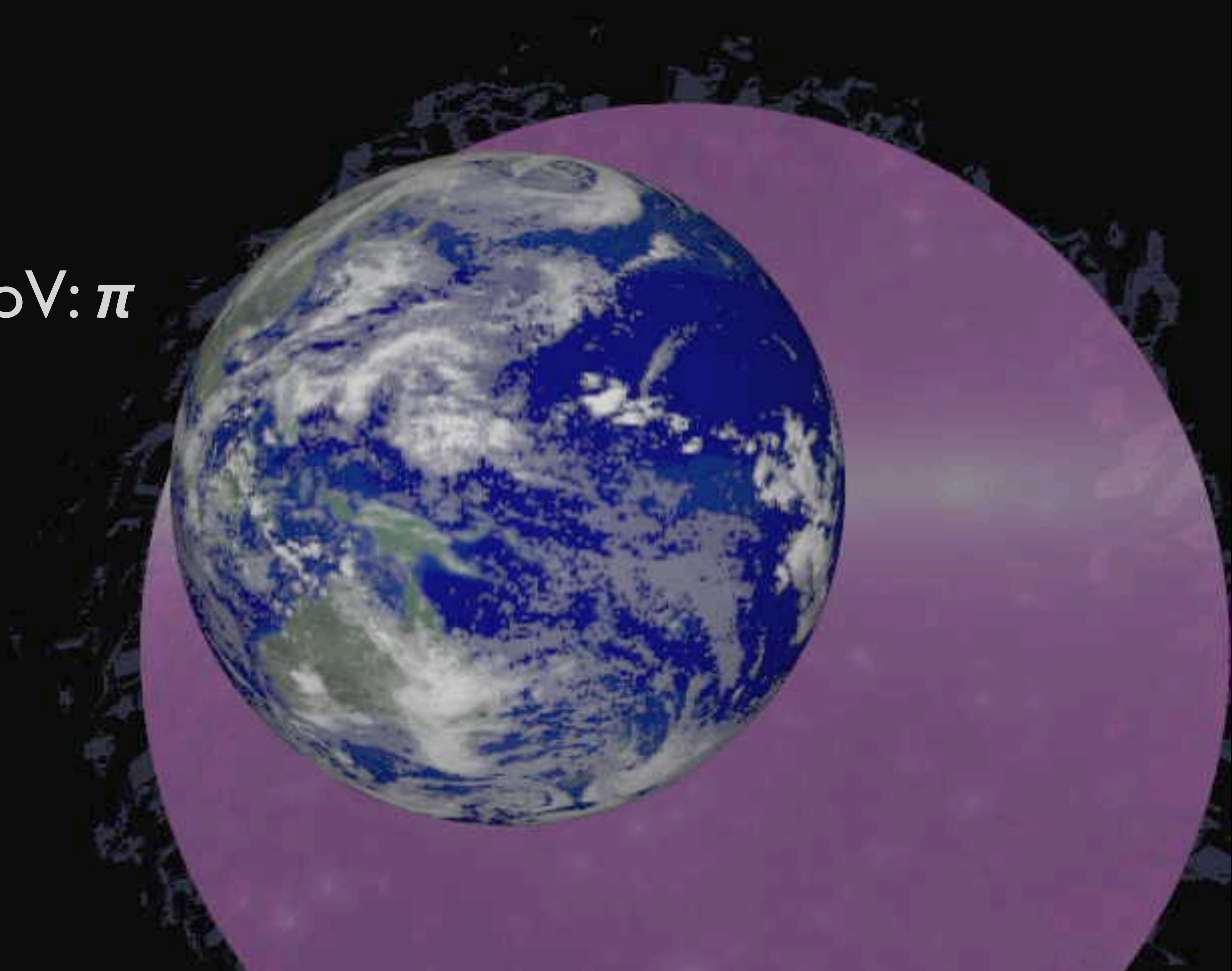
FERMI

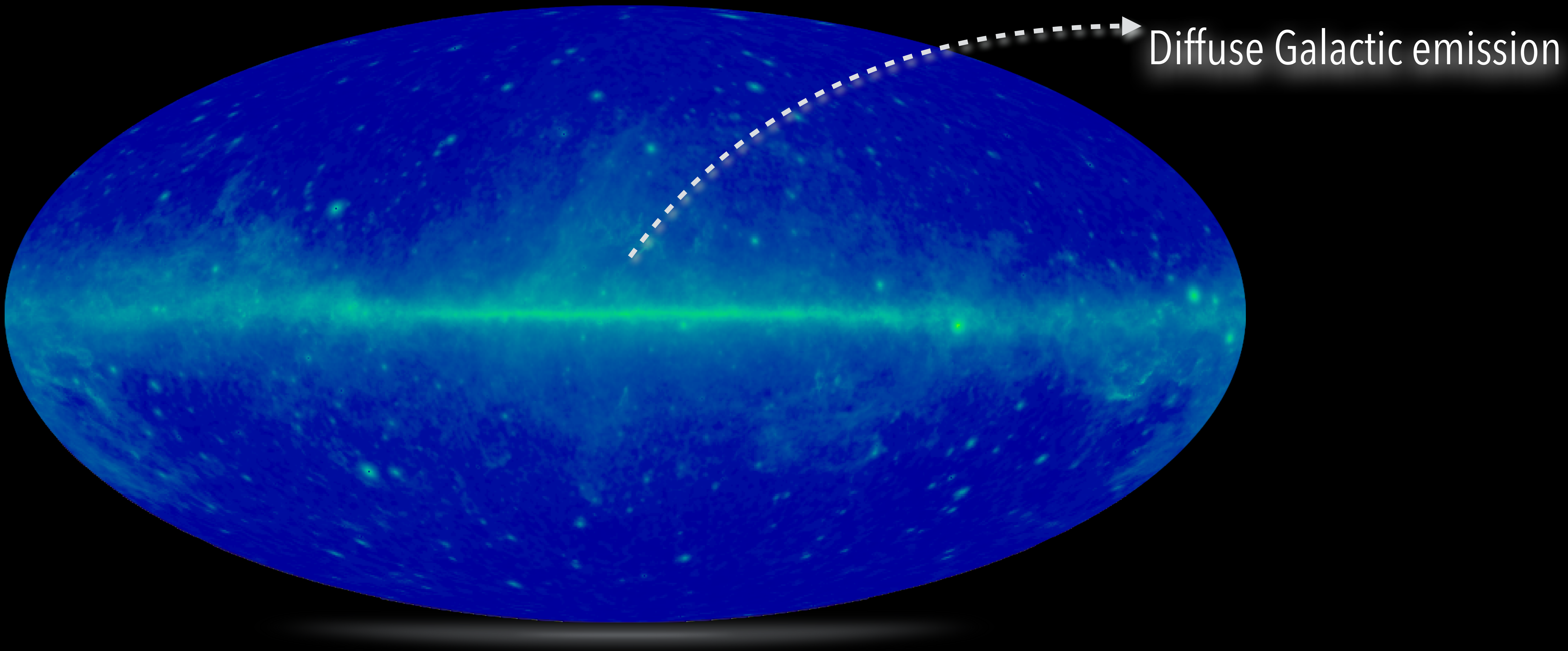


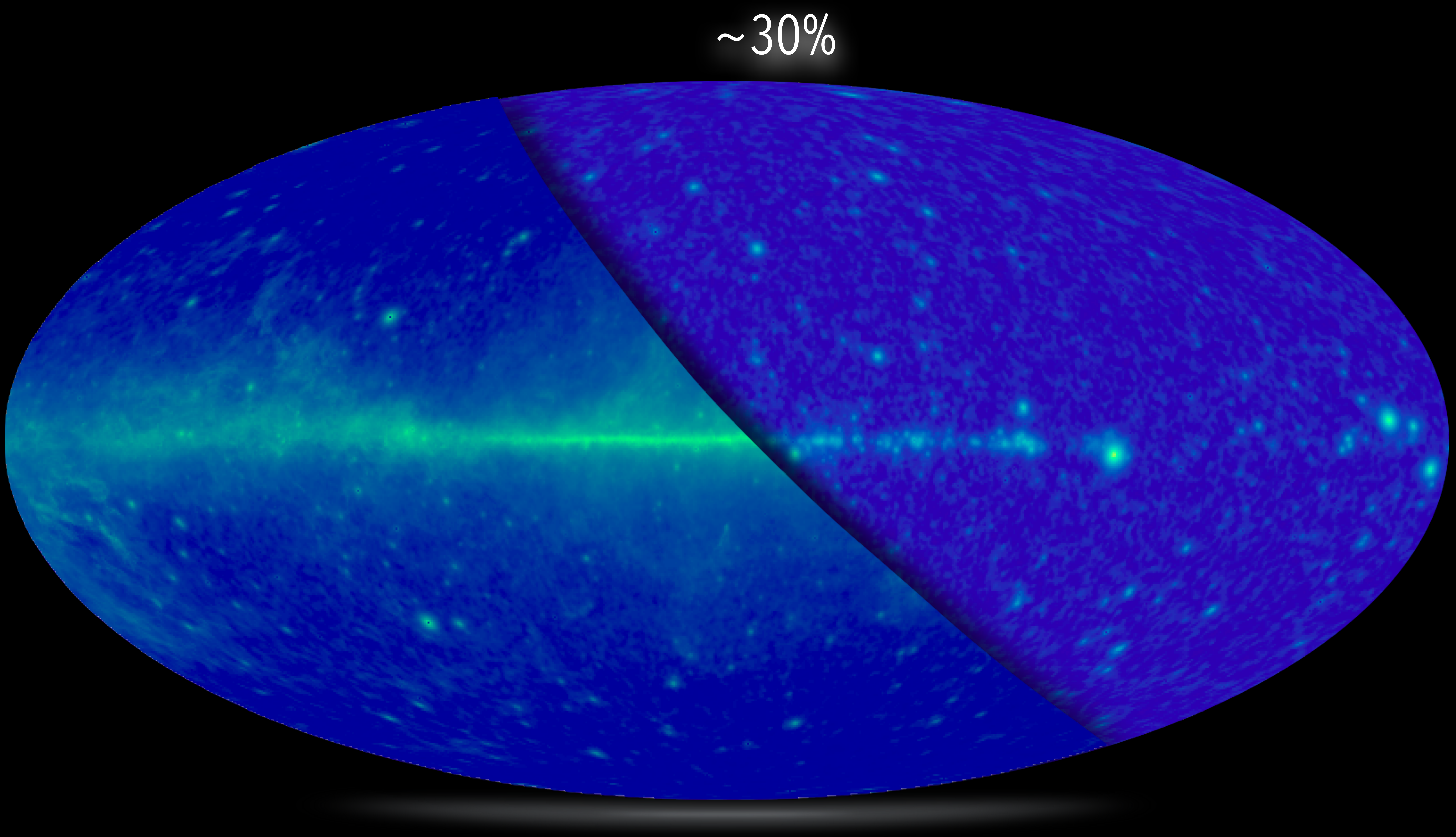




Instantaneous FoV: π

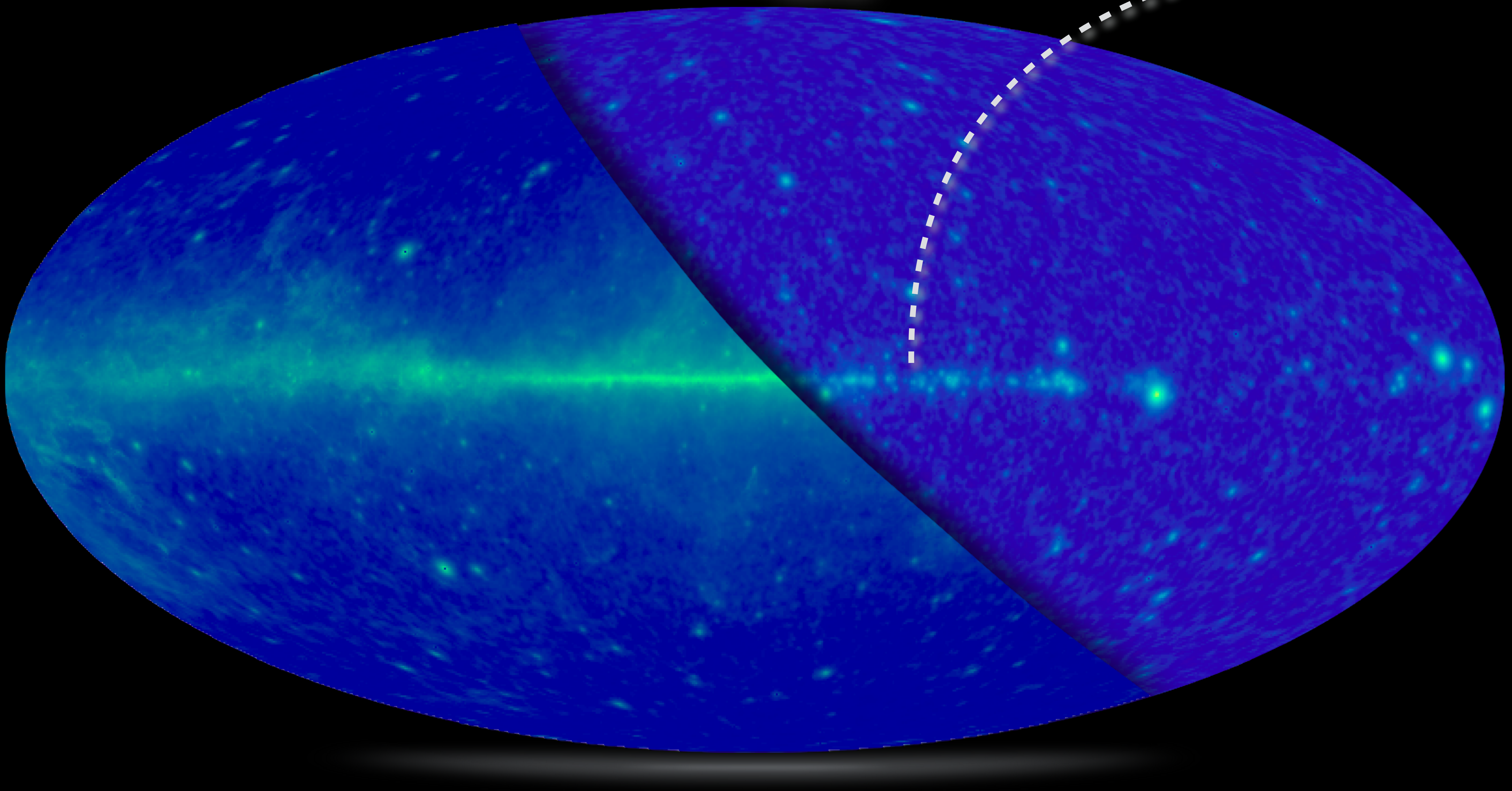



Diffuse Galactic emission


~30%

~30%

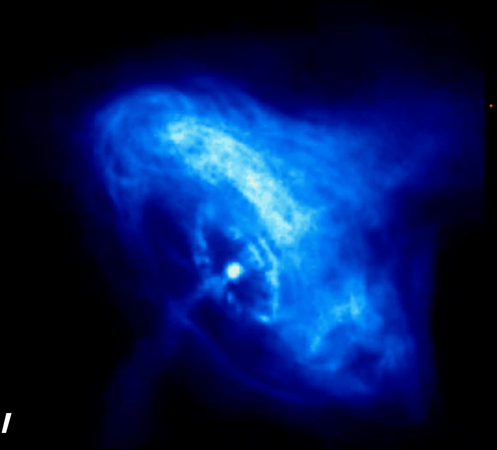
Galactic Sources



Globular clusters

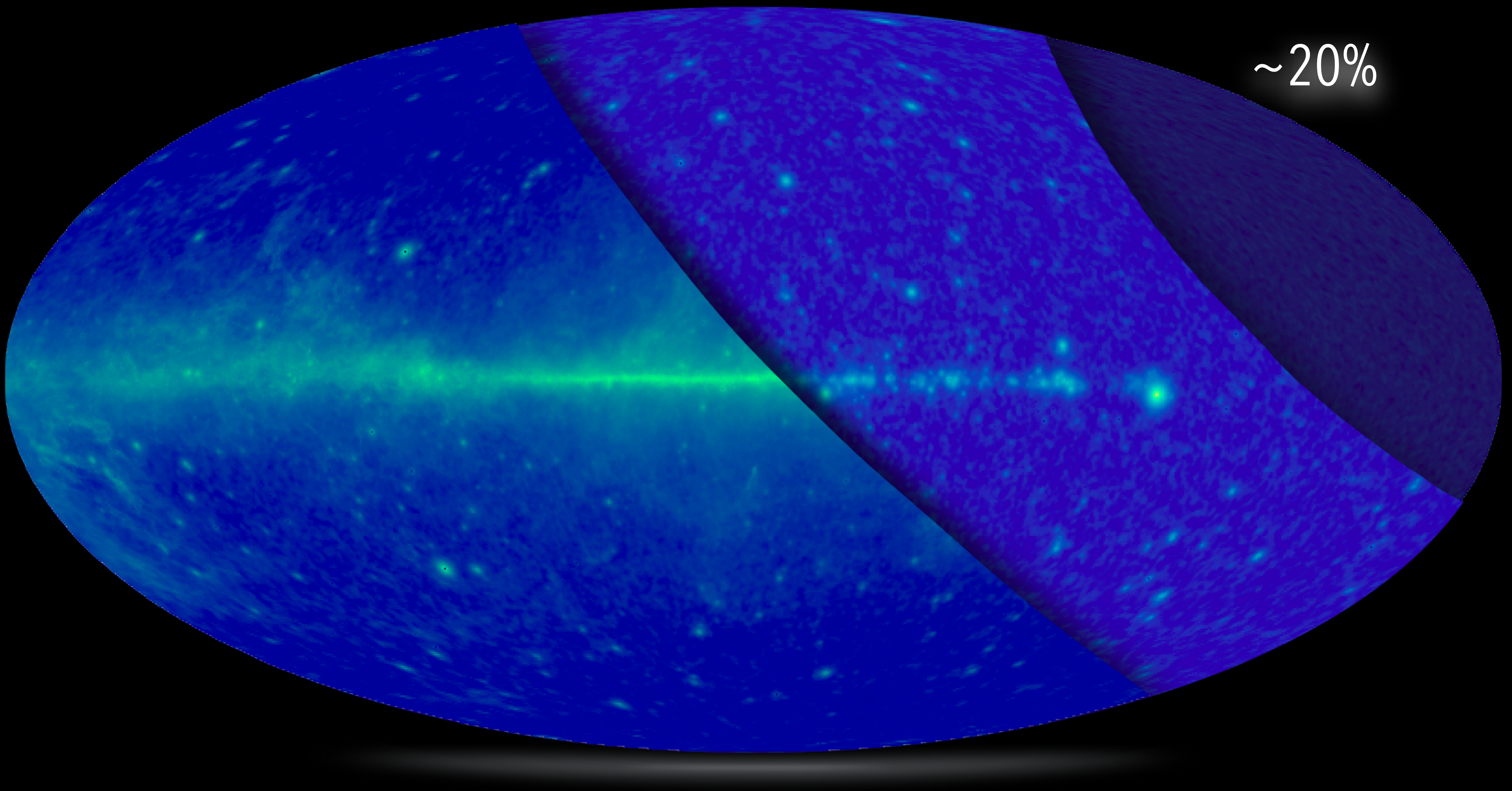
Star-forming regions

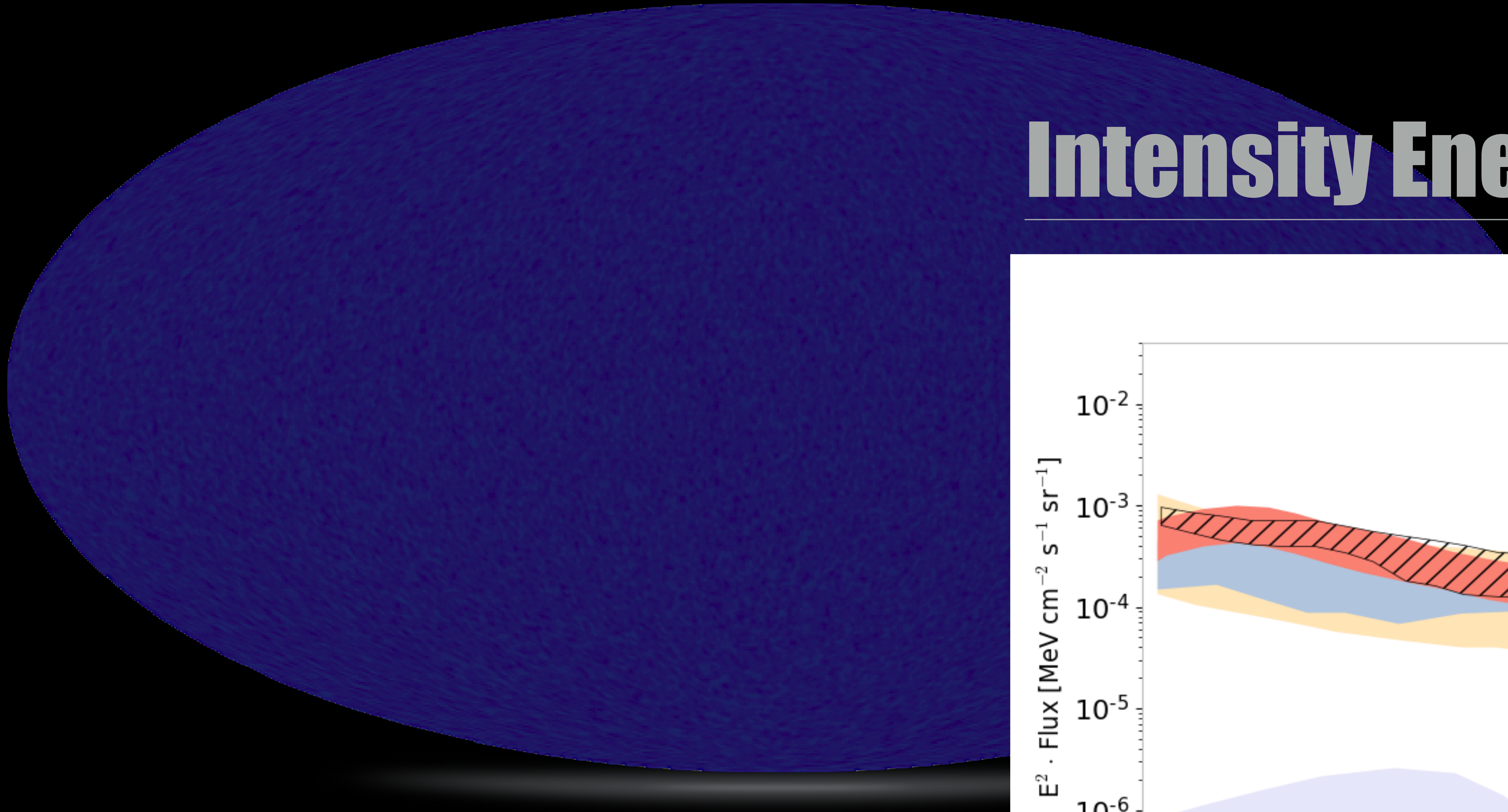
Binary systems



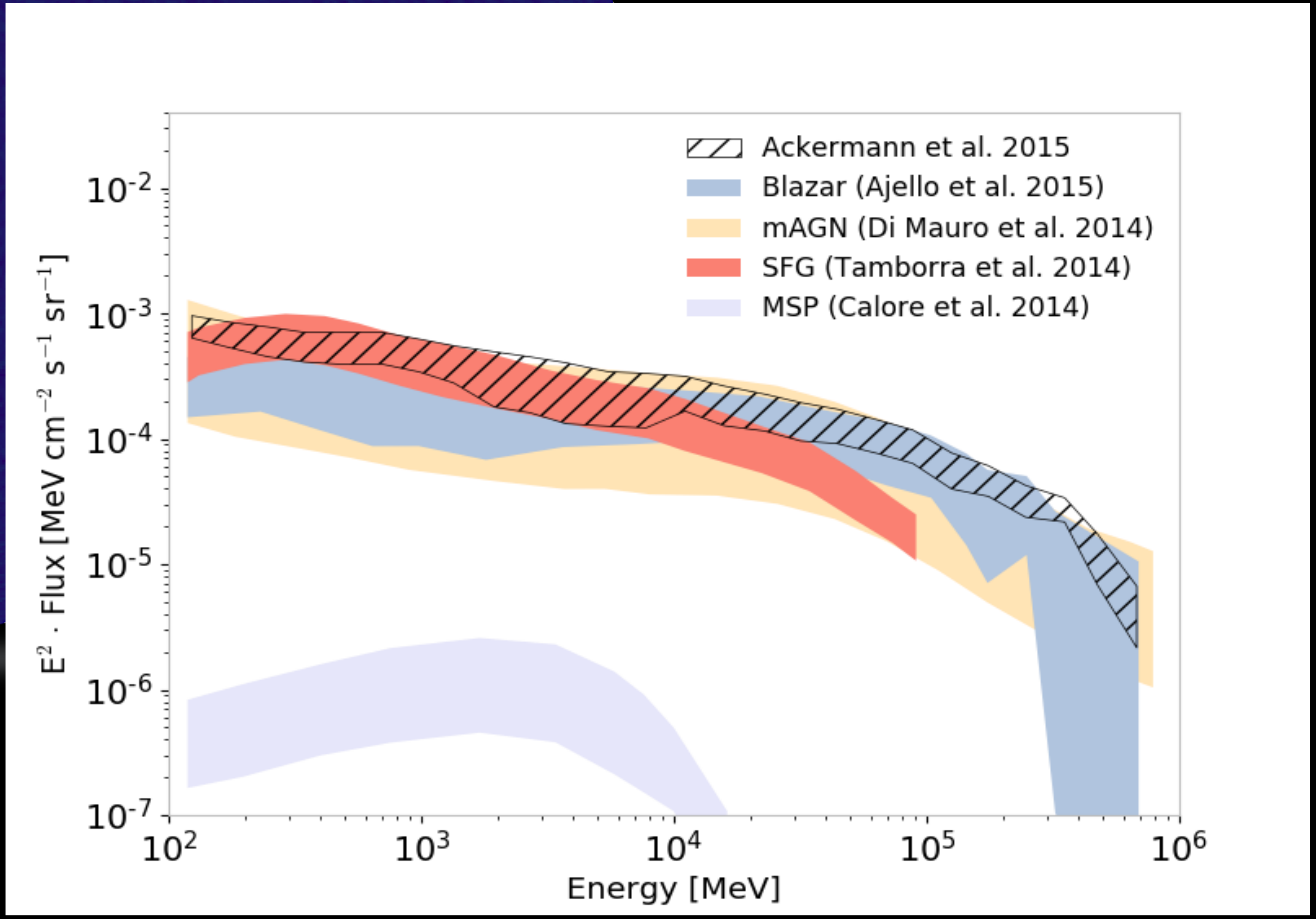
Pulsars,
pulsar wind nebulae
GeV halos

Novae,
Supernova Remnants

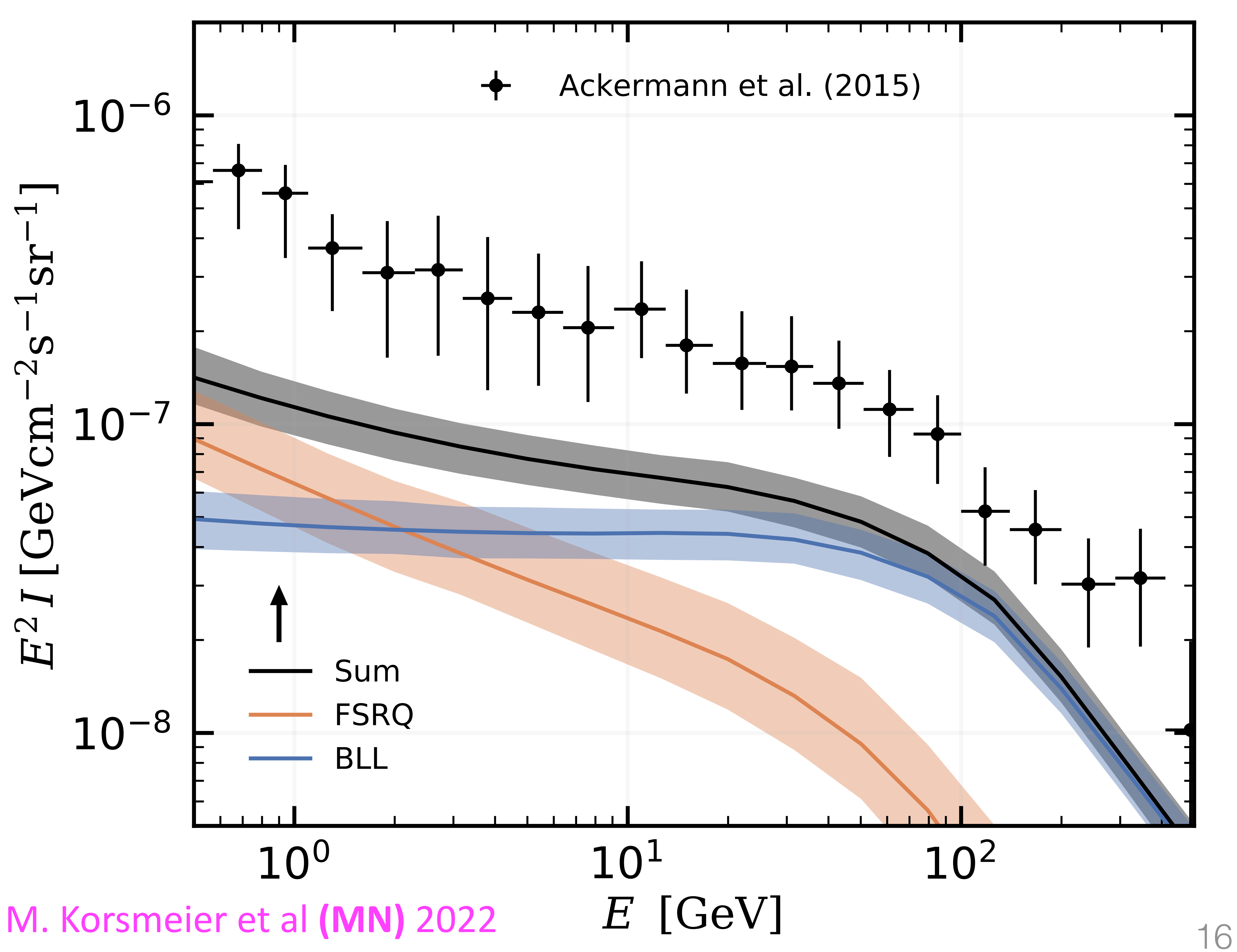

~20%



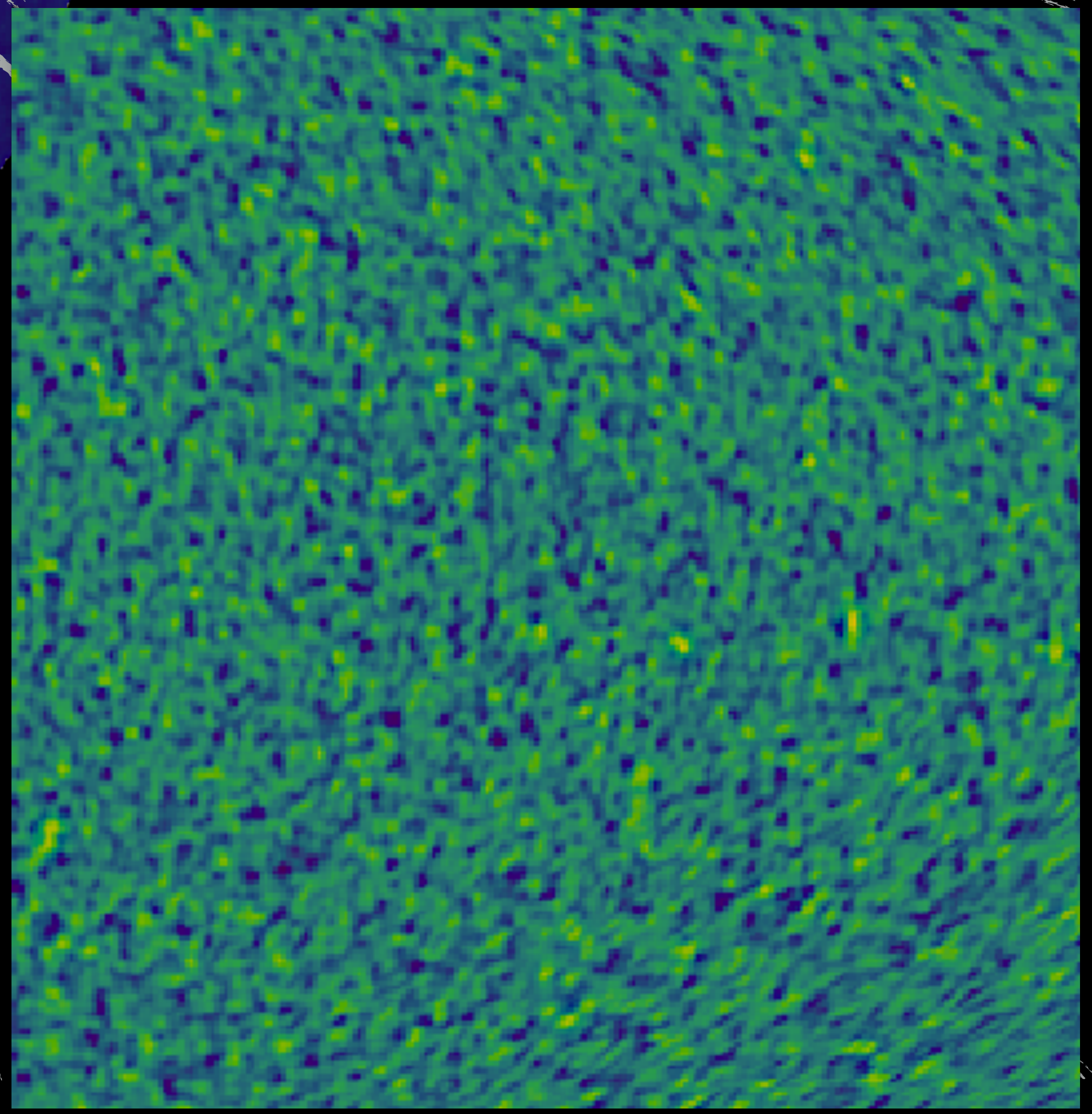
Intensity Energy Spectrum



100% Blazars anisotropy



M. Korsmeier et al **(MN)** 2022



Fluctuation field

An erratic journey through the Galaxy

Larmor radii of Galactic CRs range from 10^5 km at the lowest energies to 10^{-1} pc near 10^{15} eV

By Charles Carter/Keck Institute for Space Studies

An erratic journey through the Galaxy

From the sources…

PWNs
Pulsars Halos
Star Clusters
BH X-ray binaries

LHAASO Collaboration 11 Oct 2024

By Charles Carter/Keck Institute for Space Studies

An erratic journey through the Galaxy

Through the interstellar medium… for 10^8 years

By Charles Carter/Keck Institute for Space Studies

An erratic journey through the Galaxy

… some CR get to our instruments.

We observe CR composition locally directly… AMS, CALET, DAMPE, …

By Charles Carter/Keck Institute for Space Studies

An erratic journey through the Galaxy

… to our instruments.

… and indirectly via electromagnetic radiation

- γ rays trace CR interaction with gas, dust, ISRFs
- the ISM is transparent to gamma-ray

By Charles Carter/Keck Institute for Space Studies

How are γ-ray produced?

ISM is a multiphase medium

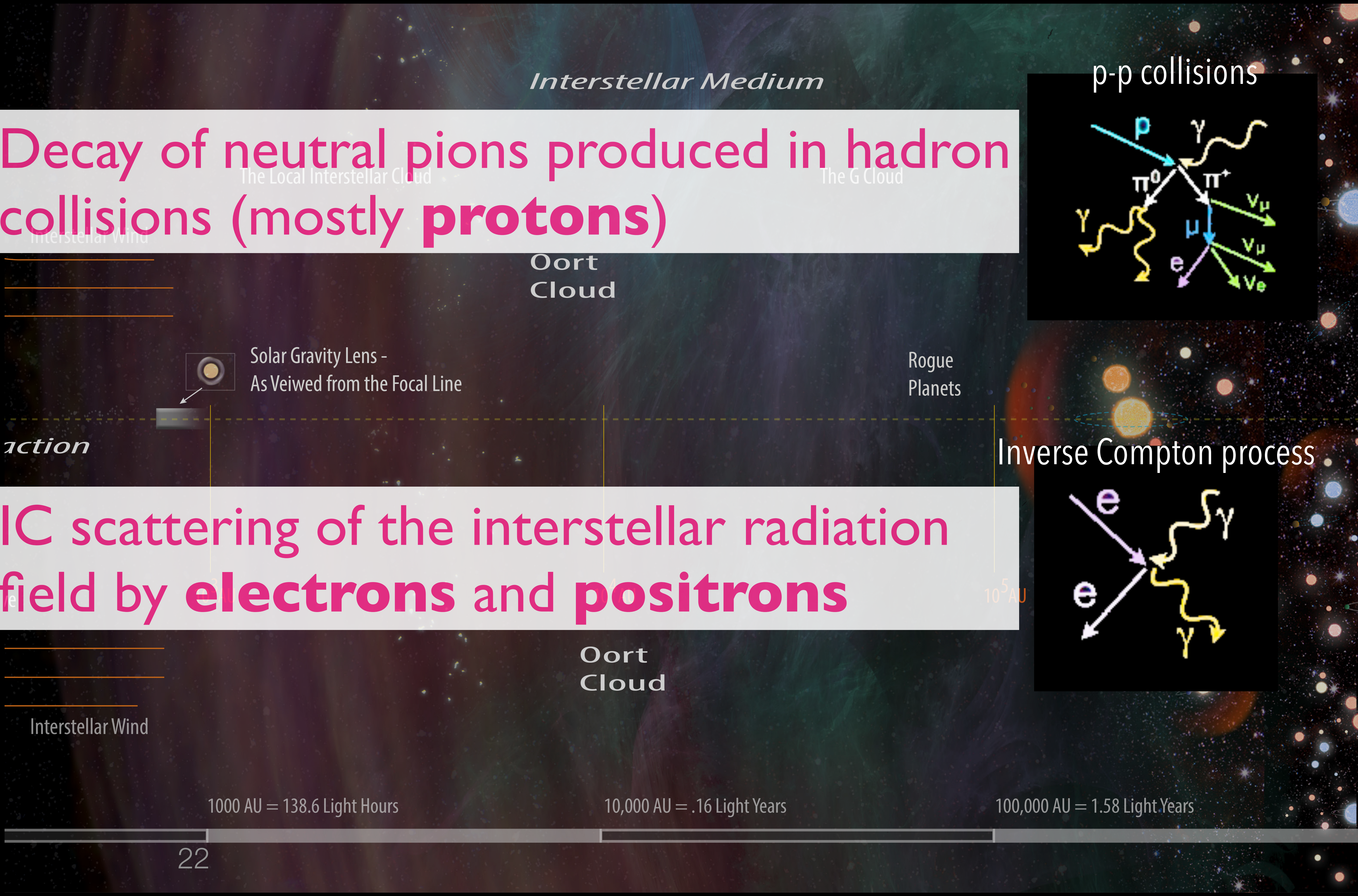
Gas

- neutral atomic hydrogen HI
- molecular hydrogen H_2
- Ionized hydrogen H^+
- Dark gas (DNM)*

Interstellar Dust

ISRF

- CMB
- NIR (stellar emission)
- FIR (re-processing of the starlight by dust)



Decay of neutral pions produced in hadron collisions (mostly **protons**)

IC scattering of the interstellar radiation field by **electrons** and **positrons**

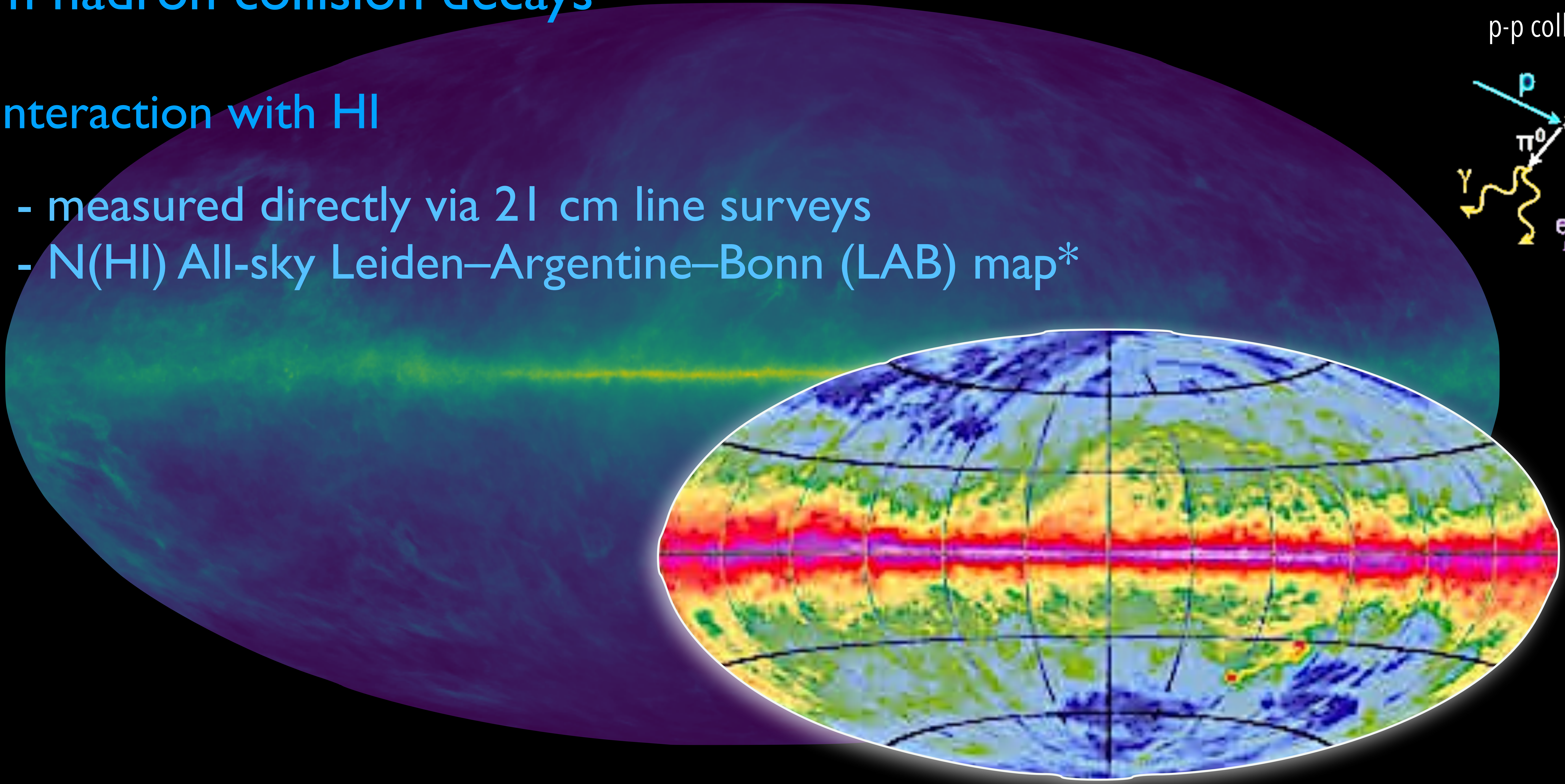
*Grenier et al. (2005)

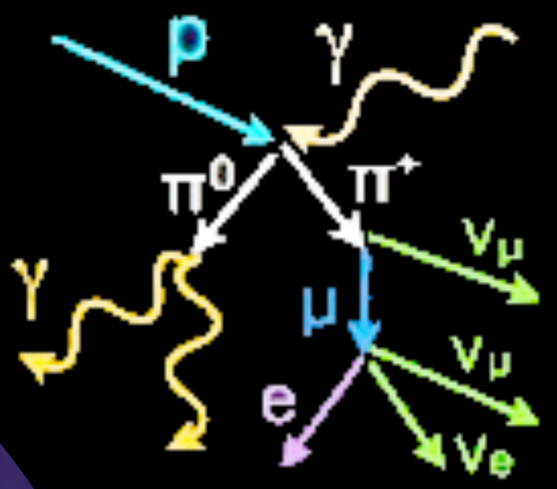
The Galactic diffuse emission

π_0 from hadron collision decays

CR interaction with HI

- measured directly via 21 cm line surveys
- N(HI) All-sky Leiden–Argentine–Bonn (LAB) map*



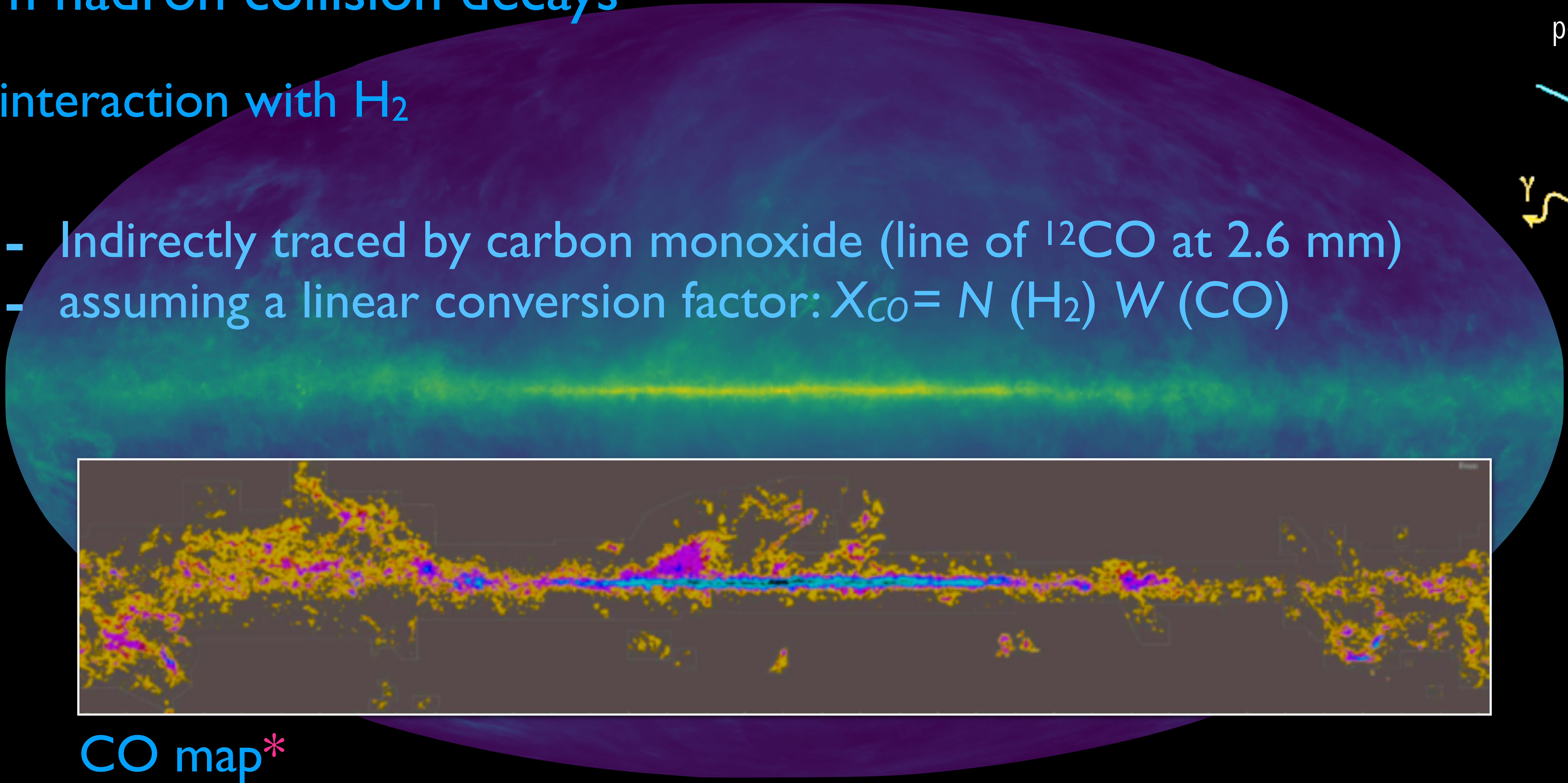


*Kalberla et al. 2005

The Galactic diffuse emission

π_0 from hadron collision decays

CR interaction with H_2



- Indirectly traced by carbon monoxide (line of ^{12}CO at 2.6 mm)
- assuming a linear conversion factor: $X_{CO} = N\ (H_2)\ W\ (CO)$

CO map*

p-p collisions

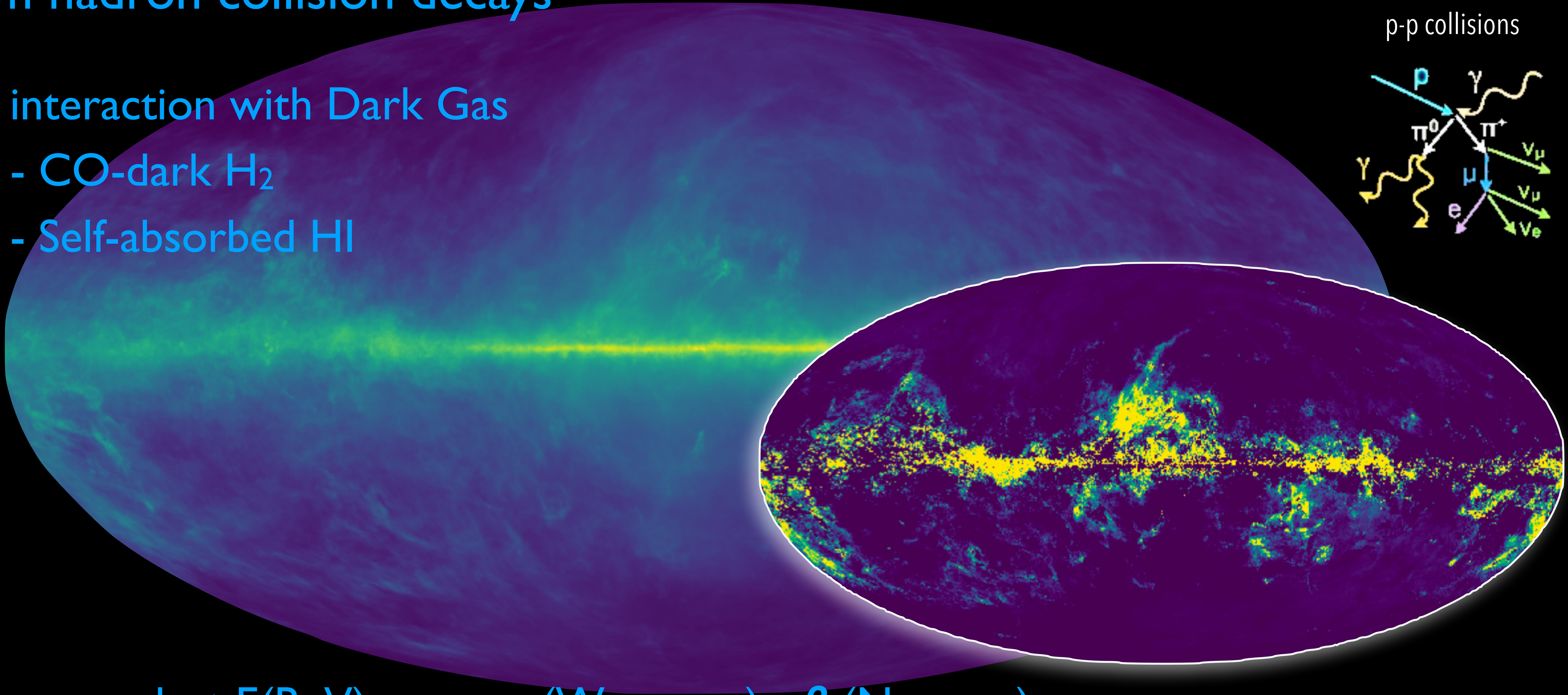
Dame, Hartman, Thaddeus 2001

The Galactic diffuse emission

π_0 from hadron collision decays

CR interaction with Dark Gas

- CO-dark H_2
- Self-absorbed HI

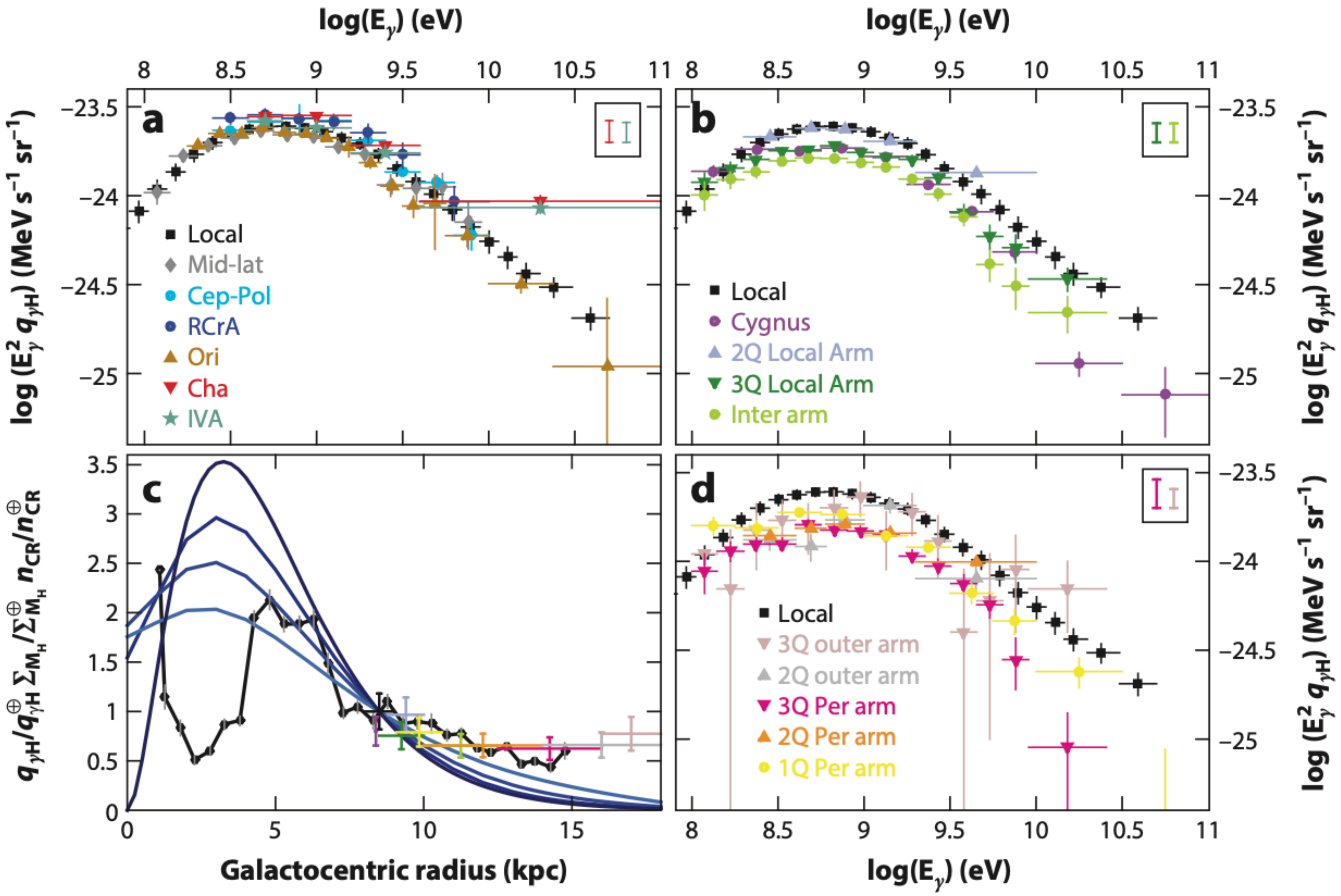


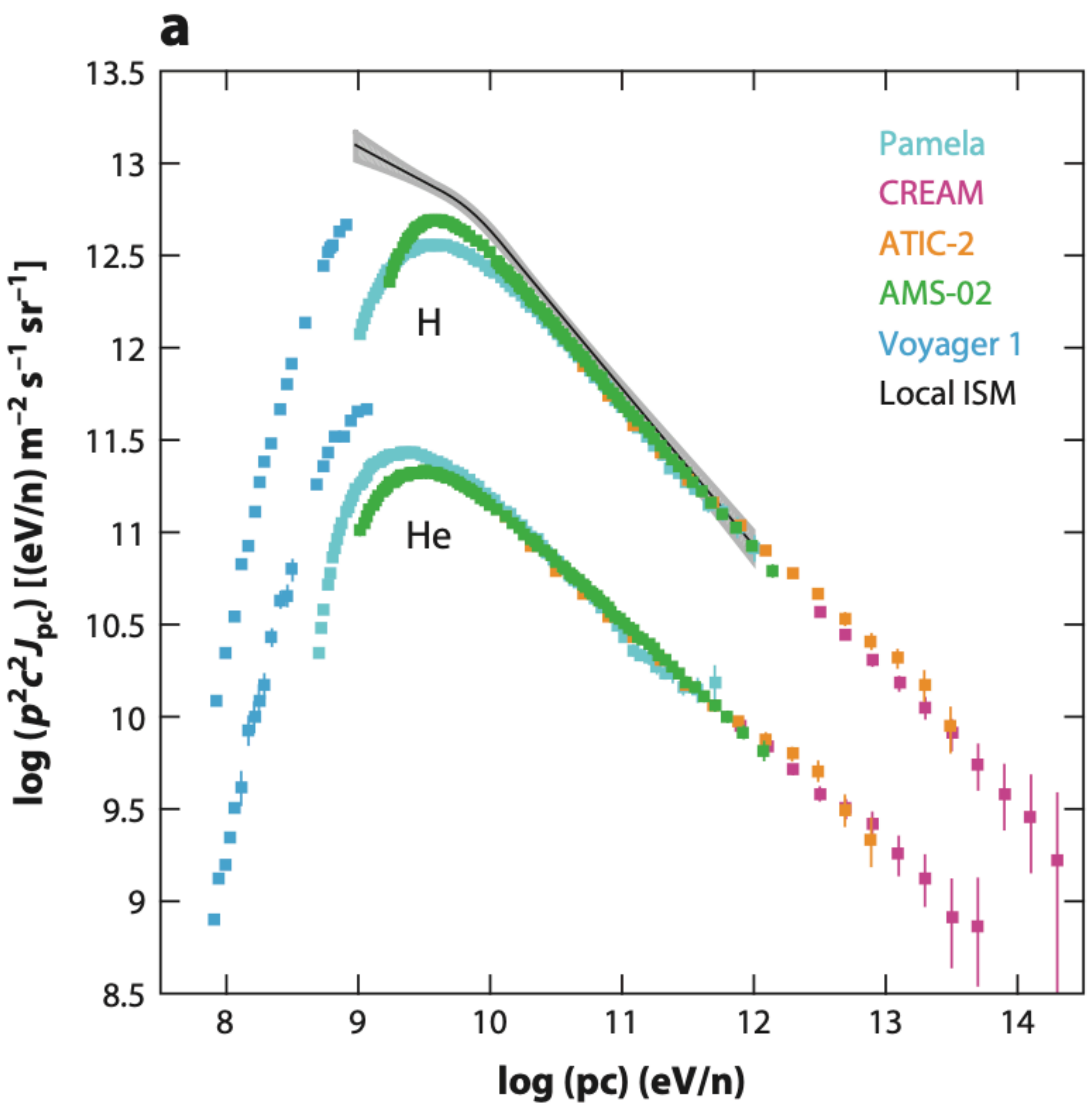
DNM* map = dust E(B–V) map - α (W_{CO} map) - β (N_{HI} map)

* Grenier et al. (2005)

γ-ray emissivity

The observation of a uniform emissivity in the Solar Neighborhood provides a reference for the local interstellar spectrum of CRs well outside the heliosphere



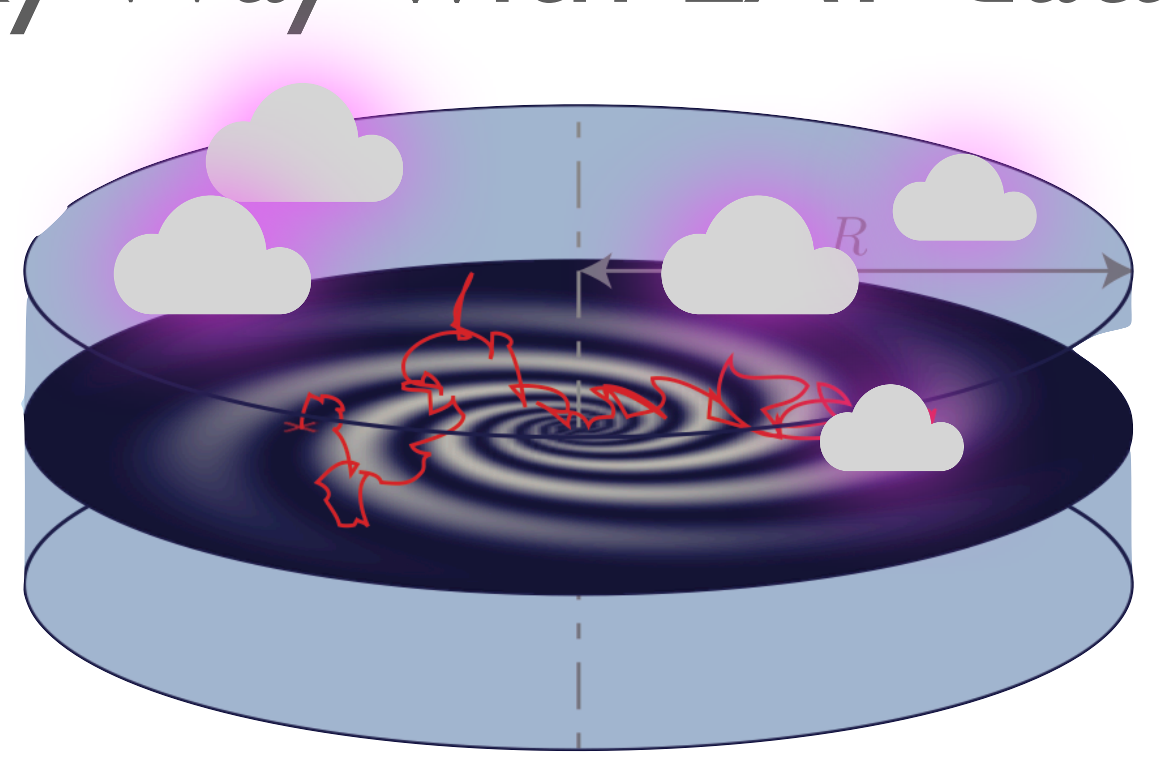


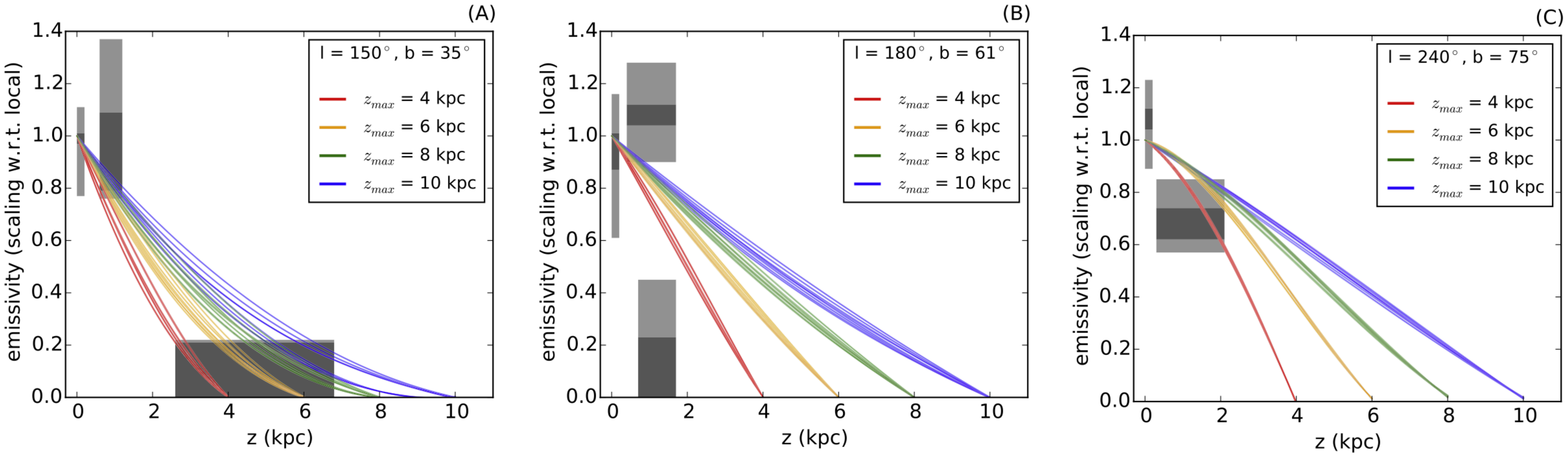
Abdo et al. 2009, 2010b; Ackermann et al. 2011b, 2012b,d,e; Casandjian 2012

Molecular clouds γ-ray emissivity

Constrain the propagation of CRs in the halo of the Milky Way with LAT data.

- Tracing the distribution of CR nuclei in the halo
- Uncertainty: distance of the clouds

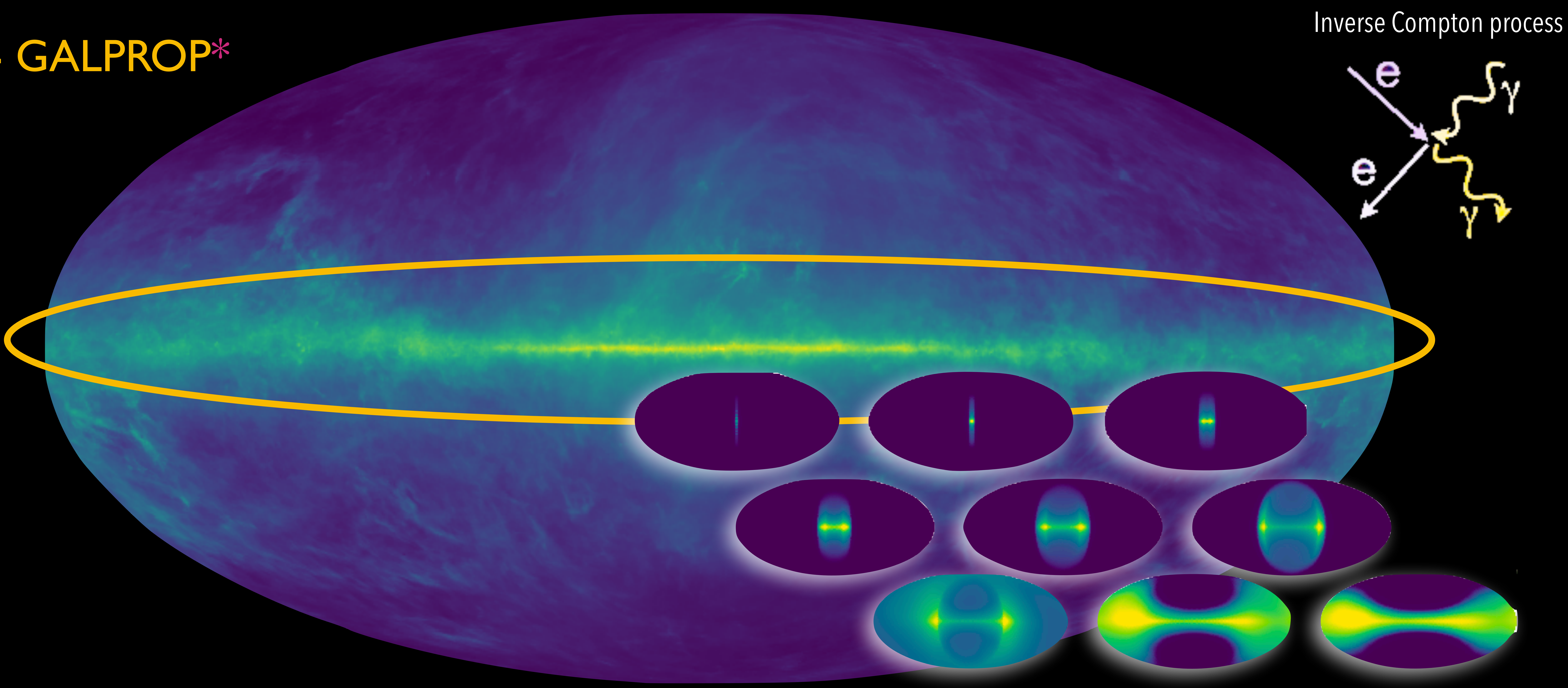




L. Tibaldo et al (MN) 2015 ApJ **807** 161

The Galactic diffuse emission

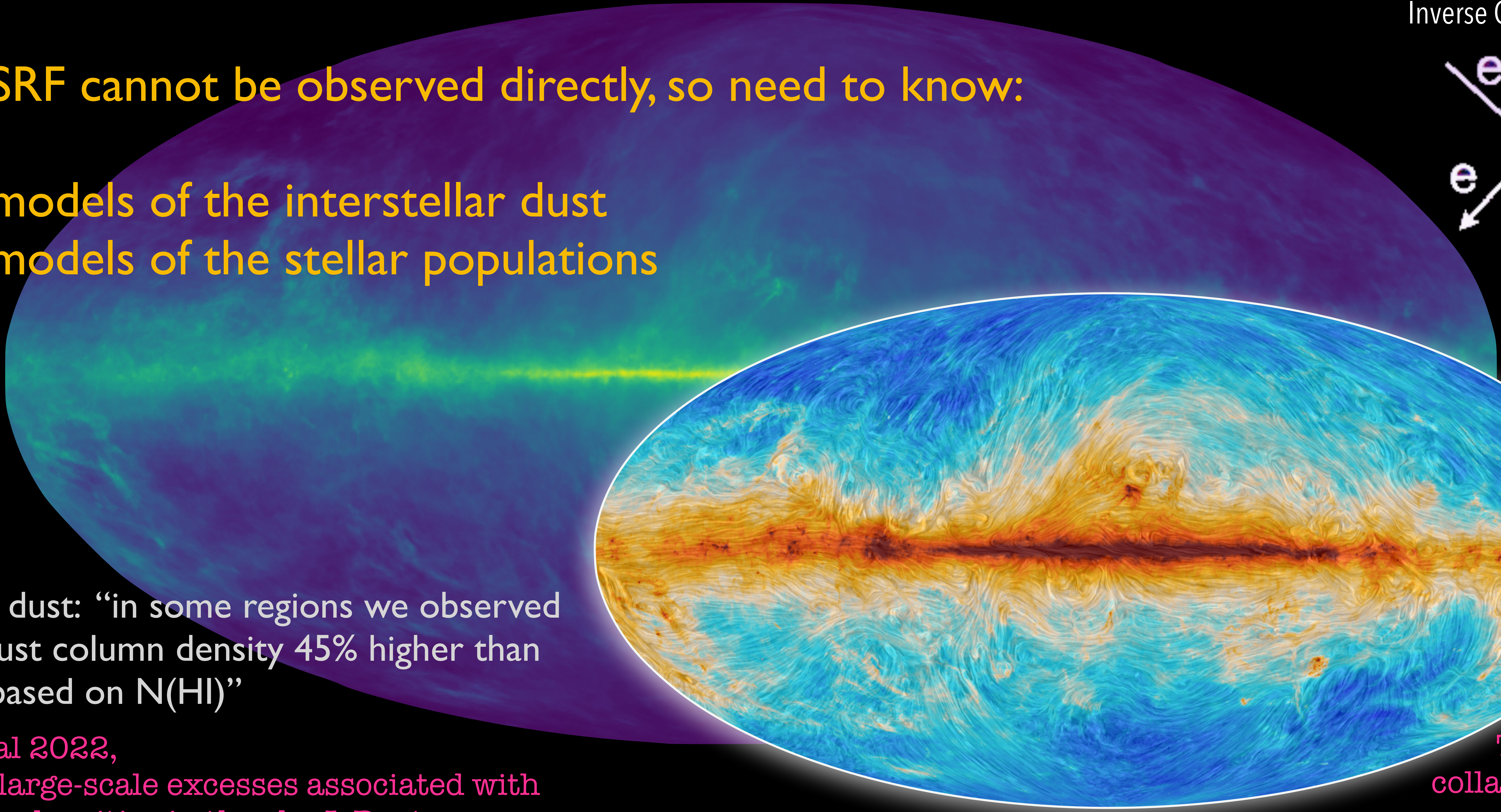
IC - GALPROP*



The Fermi-LAT collaboration 2019

*Porter et al. 2017

ISRFs



The ISRF cannot be observed directly, so need to know:

- models of the interstellar dust
- models of the stellar populations

Inverse Compton process

Note on the dust: “in some regions we observed an average dust column density 45% higher than predictions based on N(HI)”

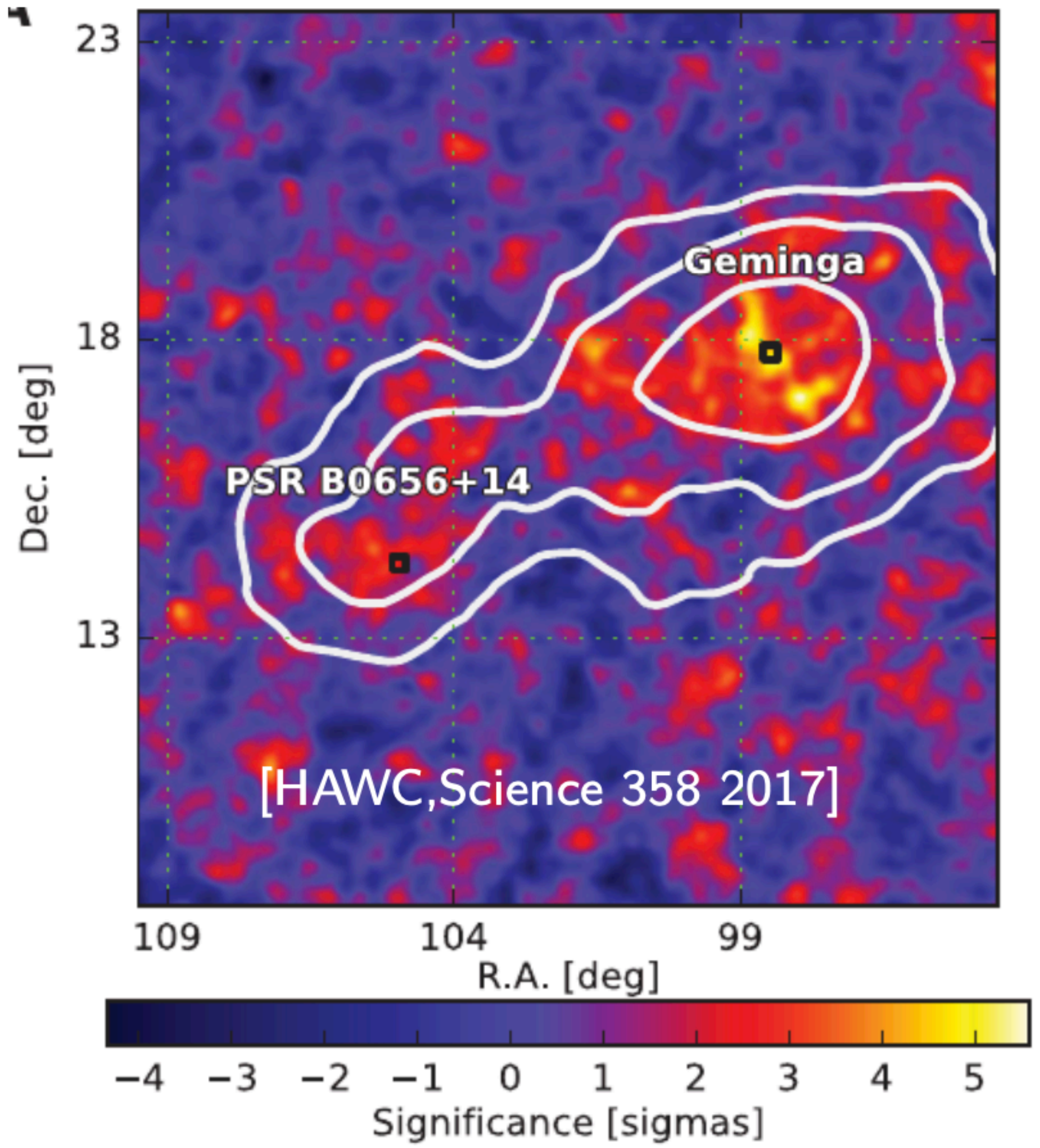
Casanjian et al 2022,
Evidence for large-scale excesses associated with low HI column densities in the sky I. Dust excess

The Plank collaboration 2019

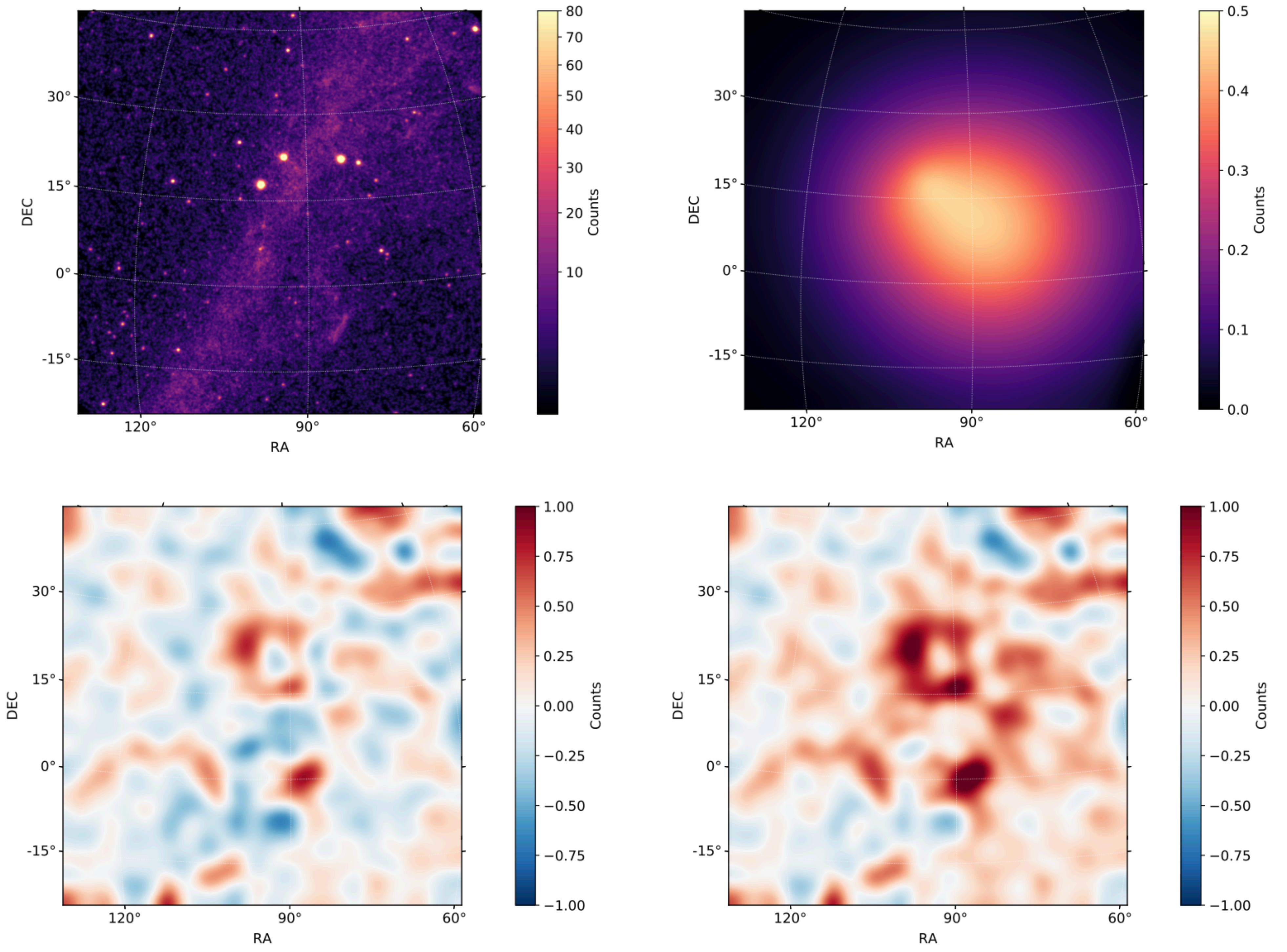
Know your sources of CRE

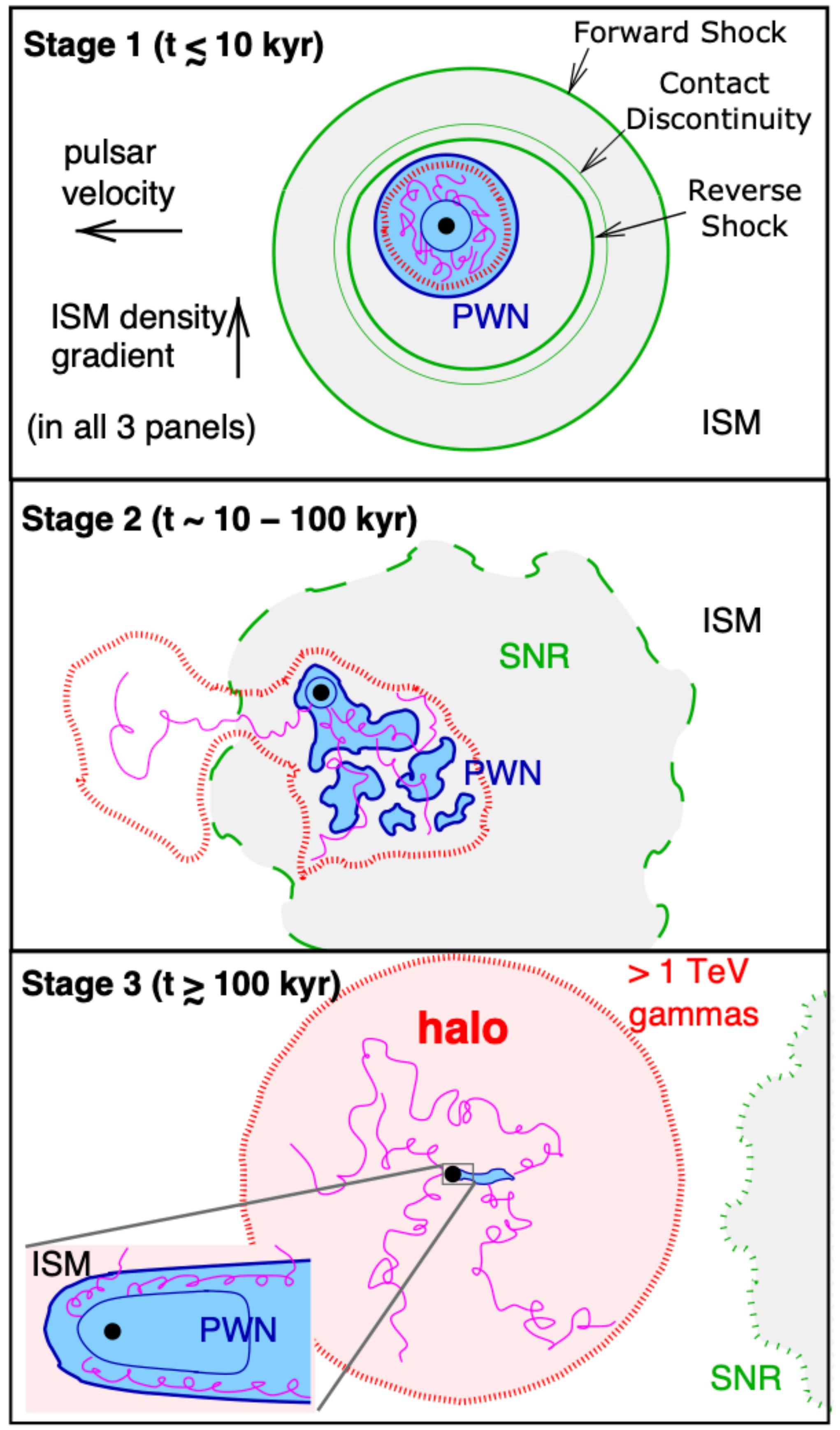
A few-degrees extended γ-ray halo in the direction of Geminga pulsar has been detected.

HAWC, Science (2017)



Di Mauro et al (2019)

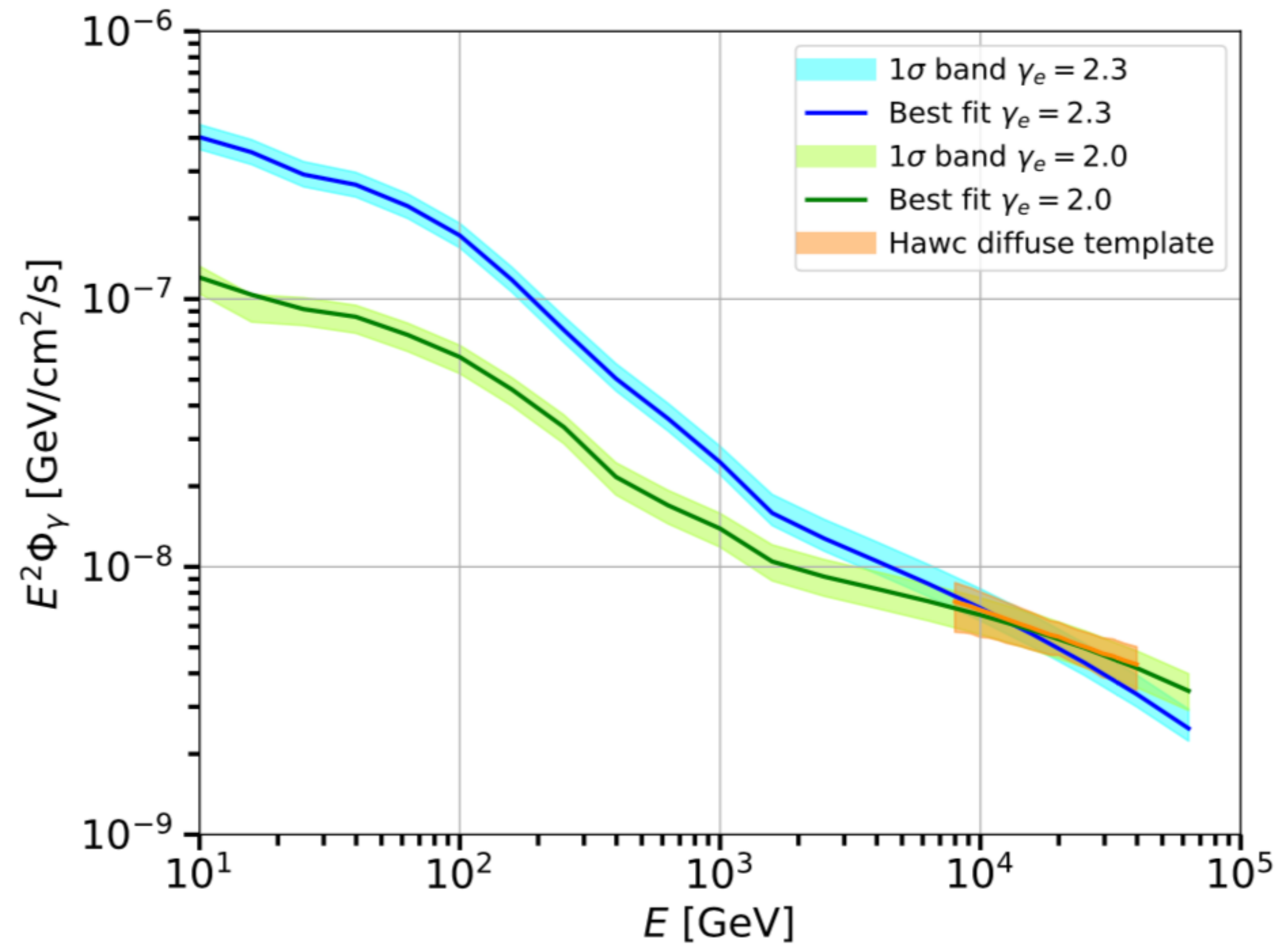


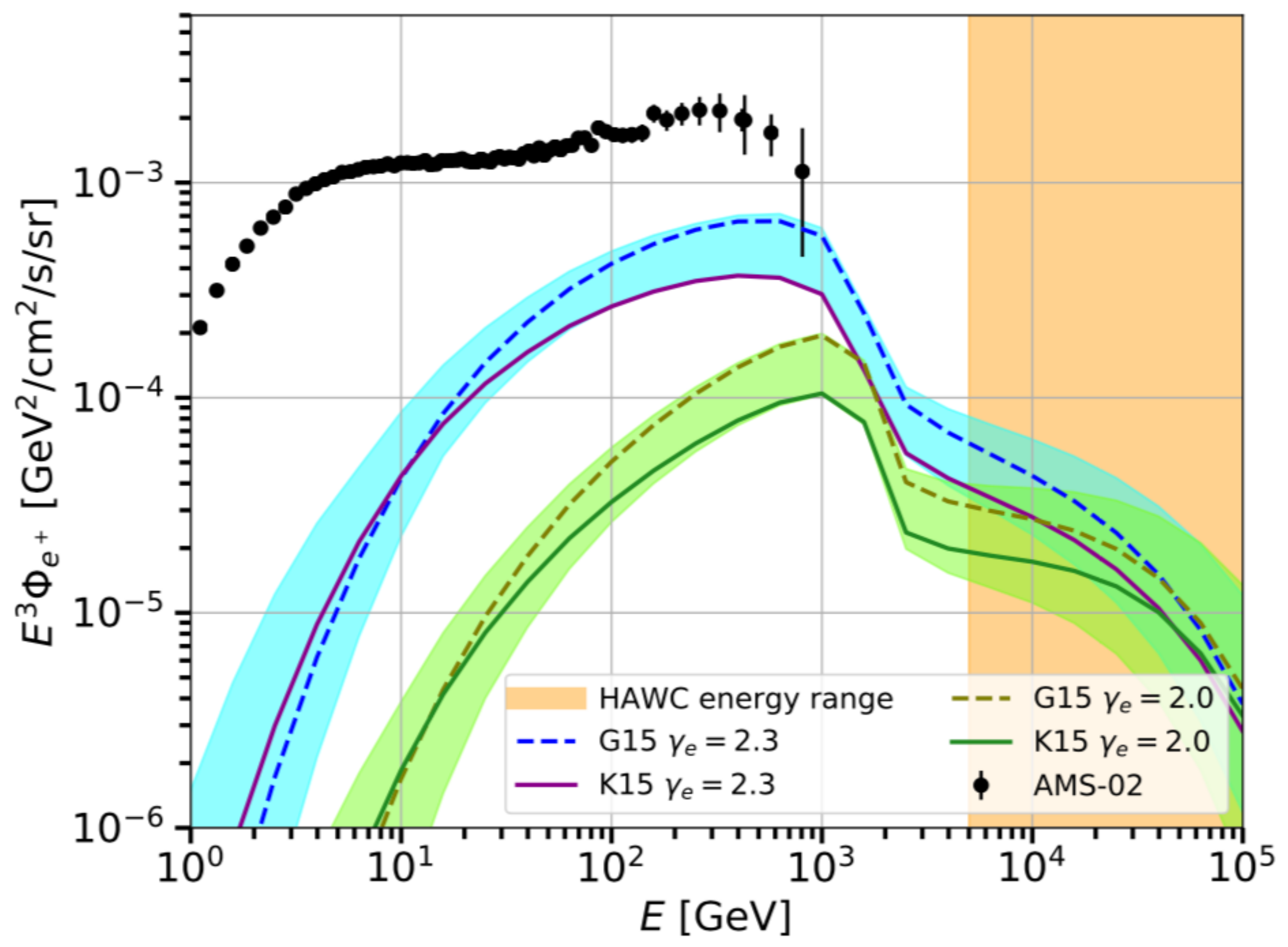


López-Coto, R., (2022)

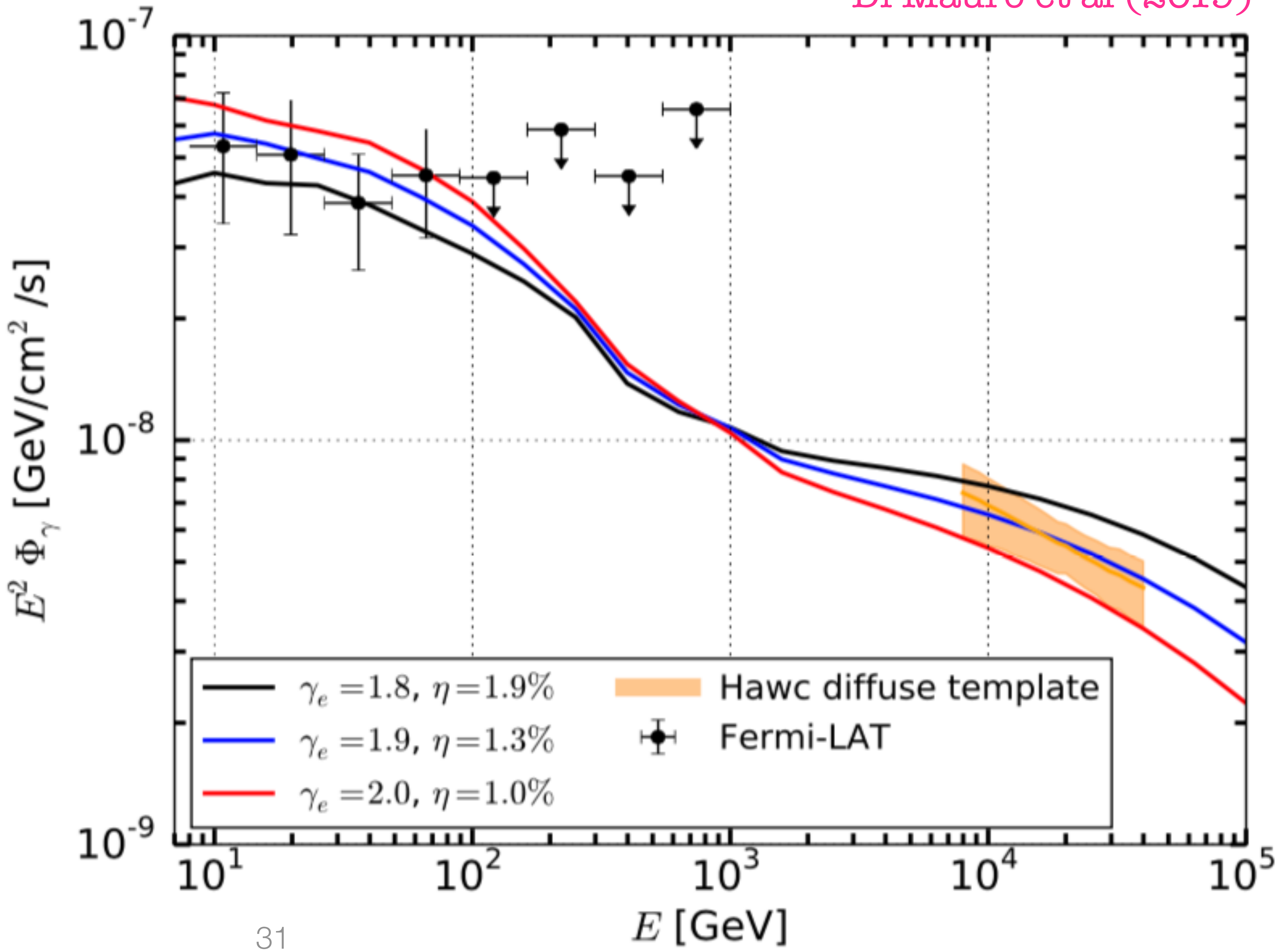
Why looking for a GeV Halo?

To better constrain the spectral index of the gamma-ray (and CRE) spectrum





Di Mauro et al (2019)



GeV haloes around pulsars

Many more halos found: all detected as extended with a GeV γ-ray (~15–80 pc)

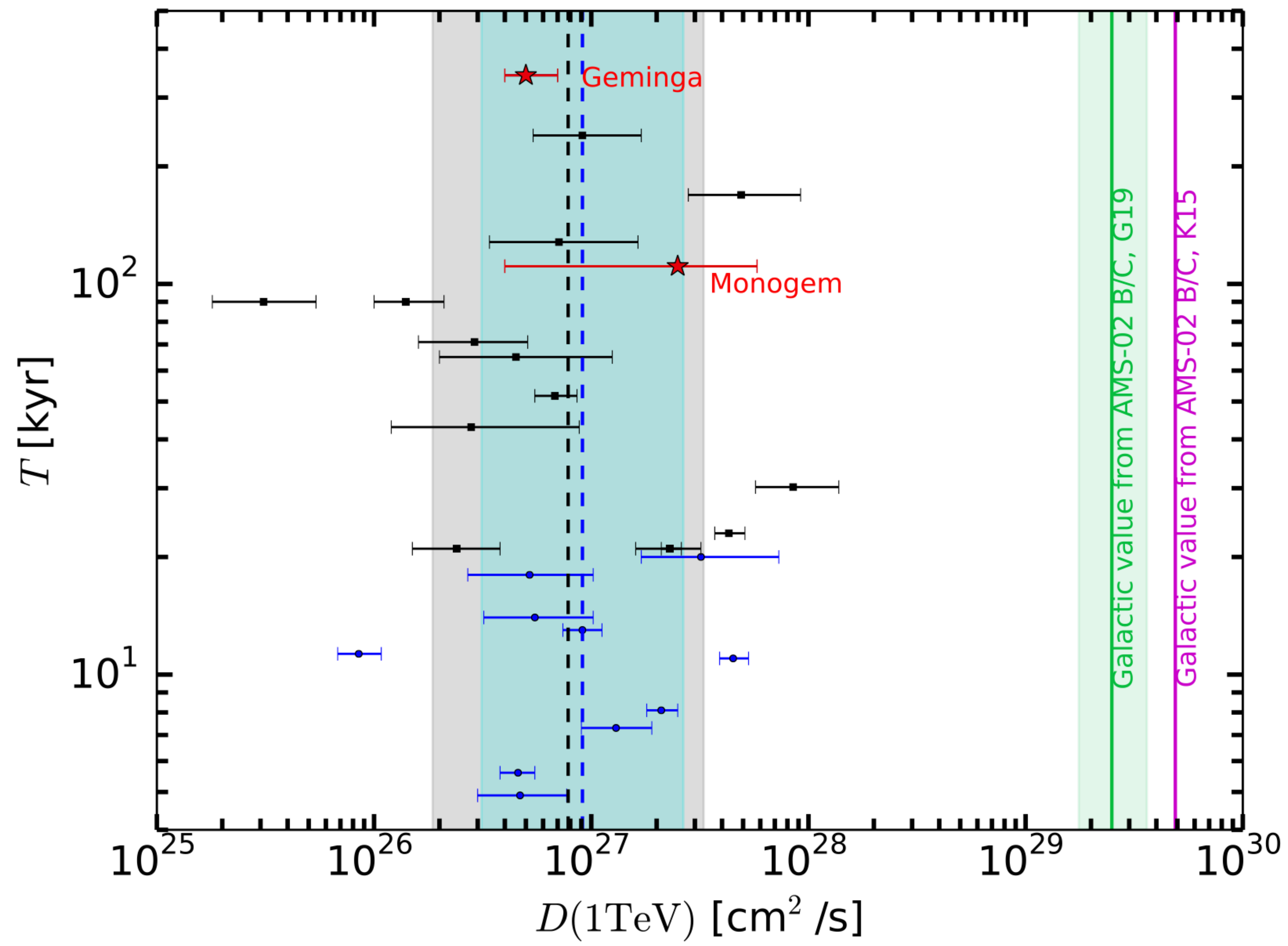
Evidences of **low-diffusion bubbles** around pulsars!

The diffusion coefficient is **(2–30)x10^{26} cm^2/s at 1 TeV** (x100 smaller than the average value in the Galaxy.

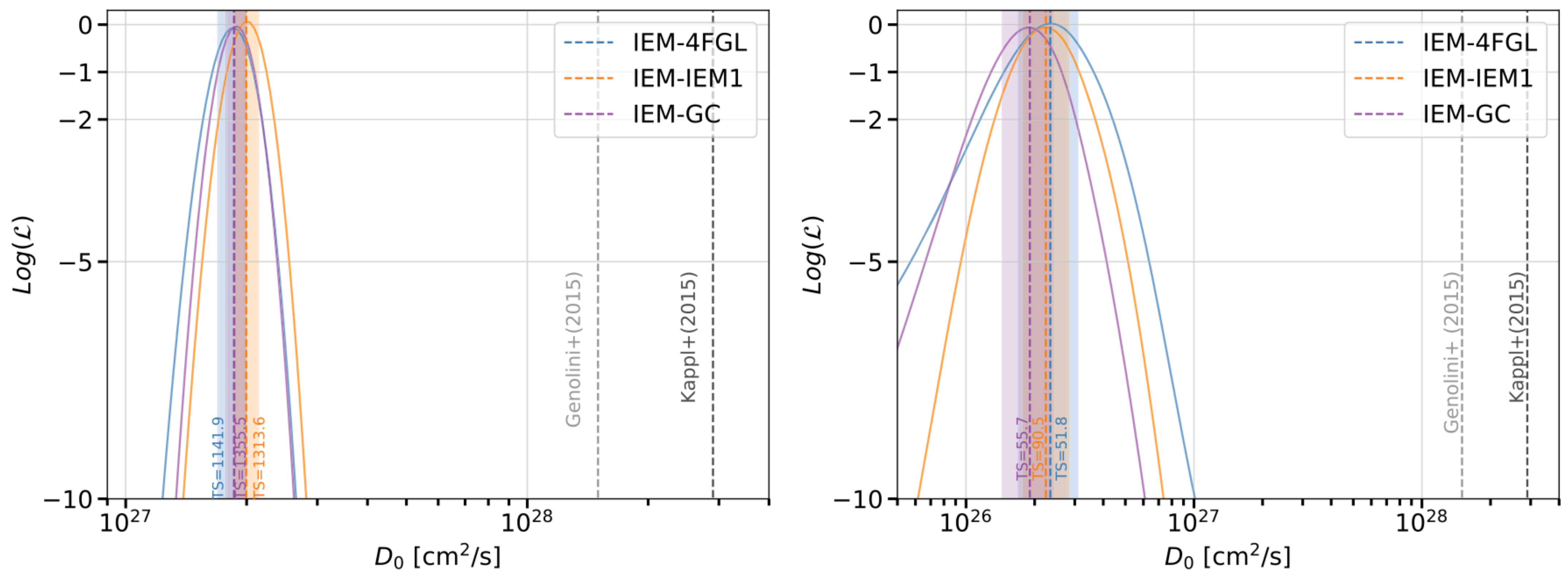
Implication on the interpretation of the local positron excess, and/or the GeV CG access (See TeV halos around MSP D. Hooper 2022)

Coming soon!– 2FGES: Catalog of GeV Extended Sources
(Fermi-LAT, Lead by S. Abdollahi & P. Martin)

Di Mauro, Manconi and Donato (2021)

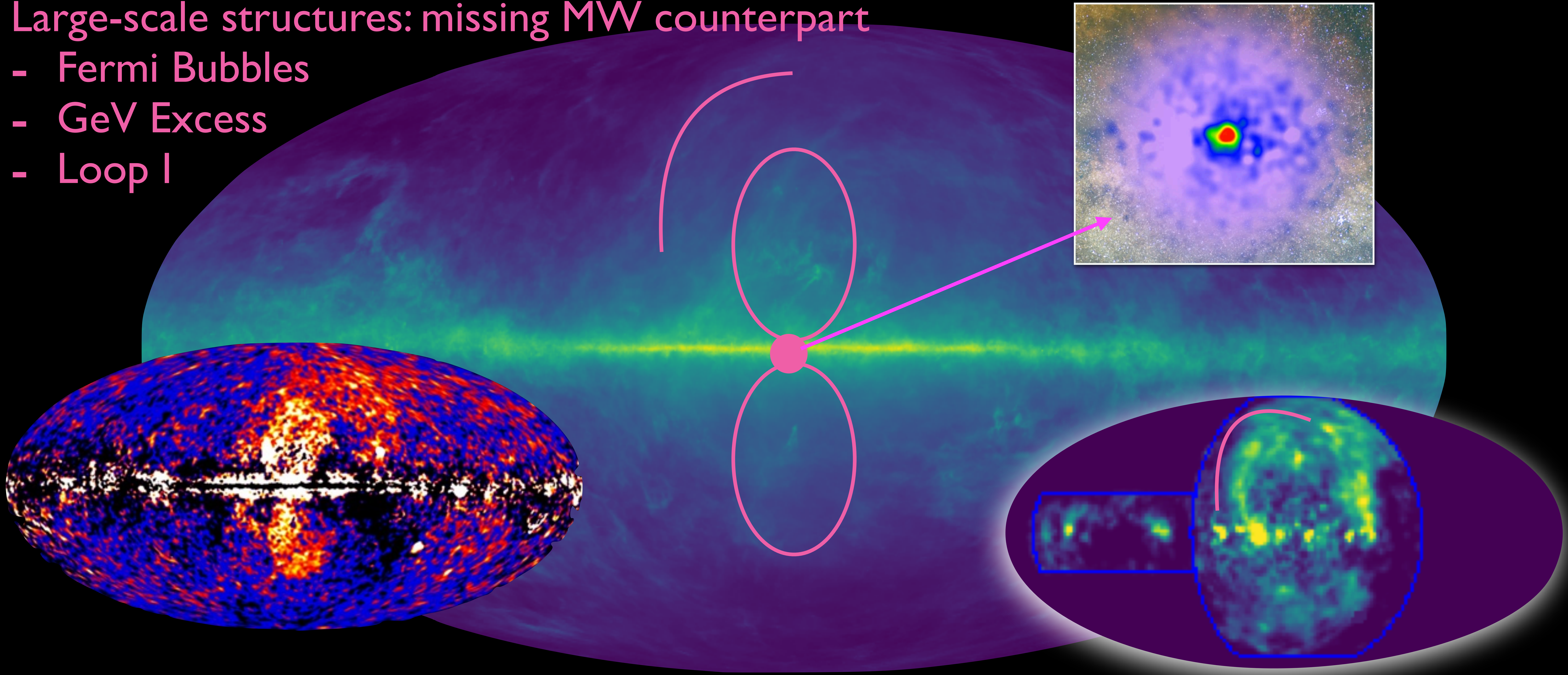


Di Mauro, Manconi, MN, Donato (2022)



The Galactic diffuse emission

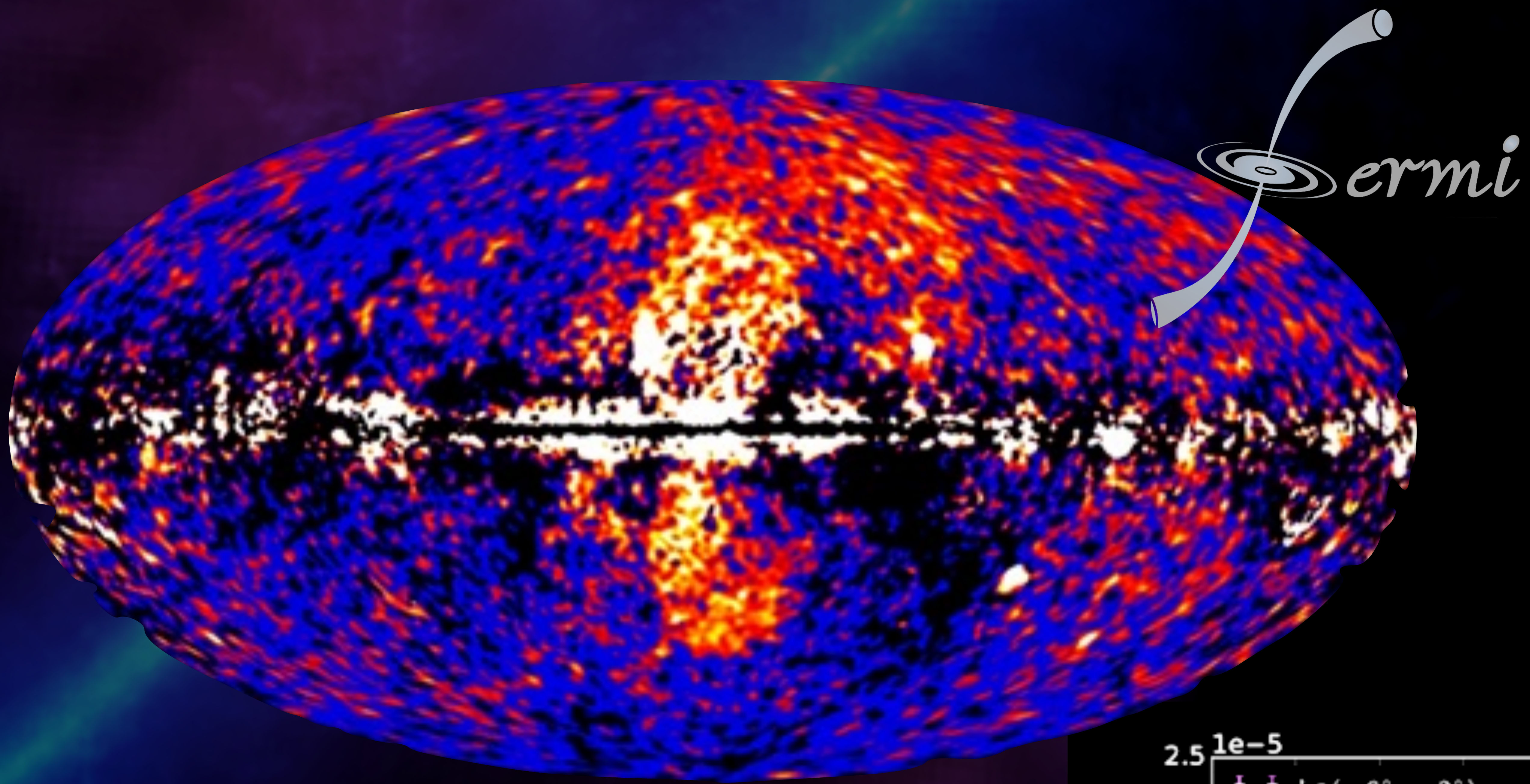
Large-scale structures: missing MW counterpart
- Fermi Bubbles
- GeV Excess
- Loop I



The Fermi-LAT collaboration 2019

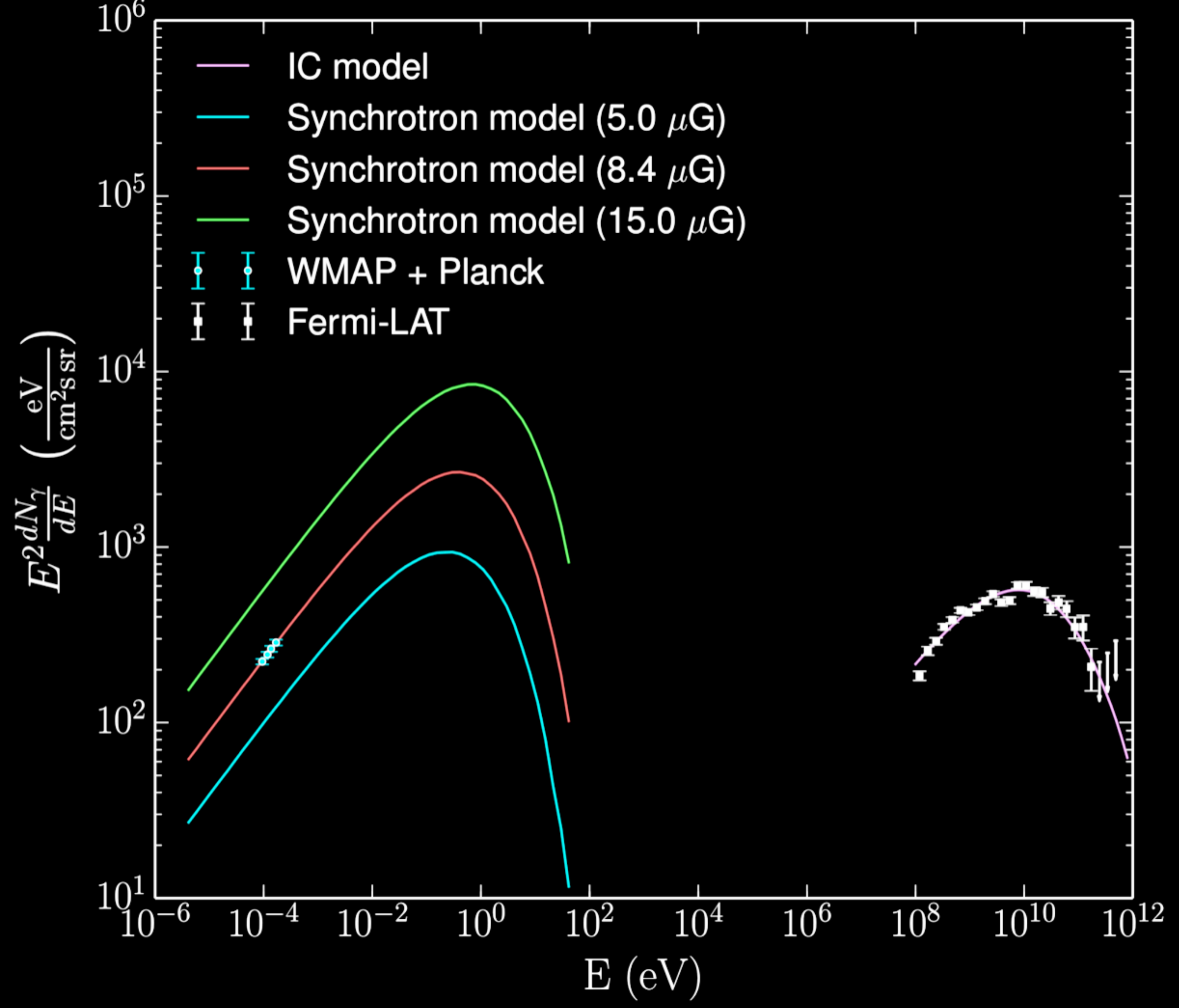
The Fermi Bubbles

Su, Slatyer, Finkbeiner 2010

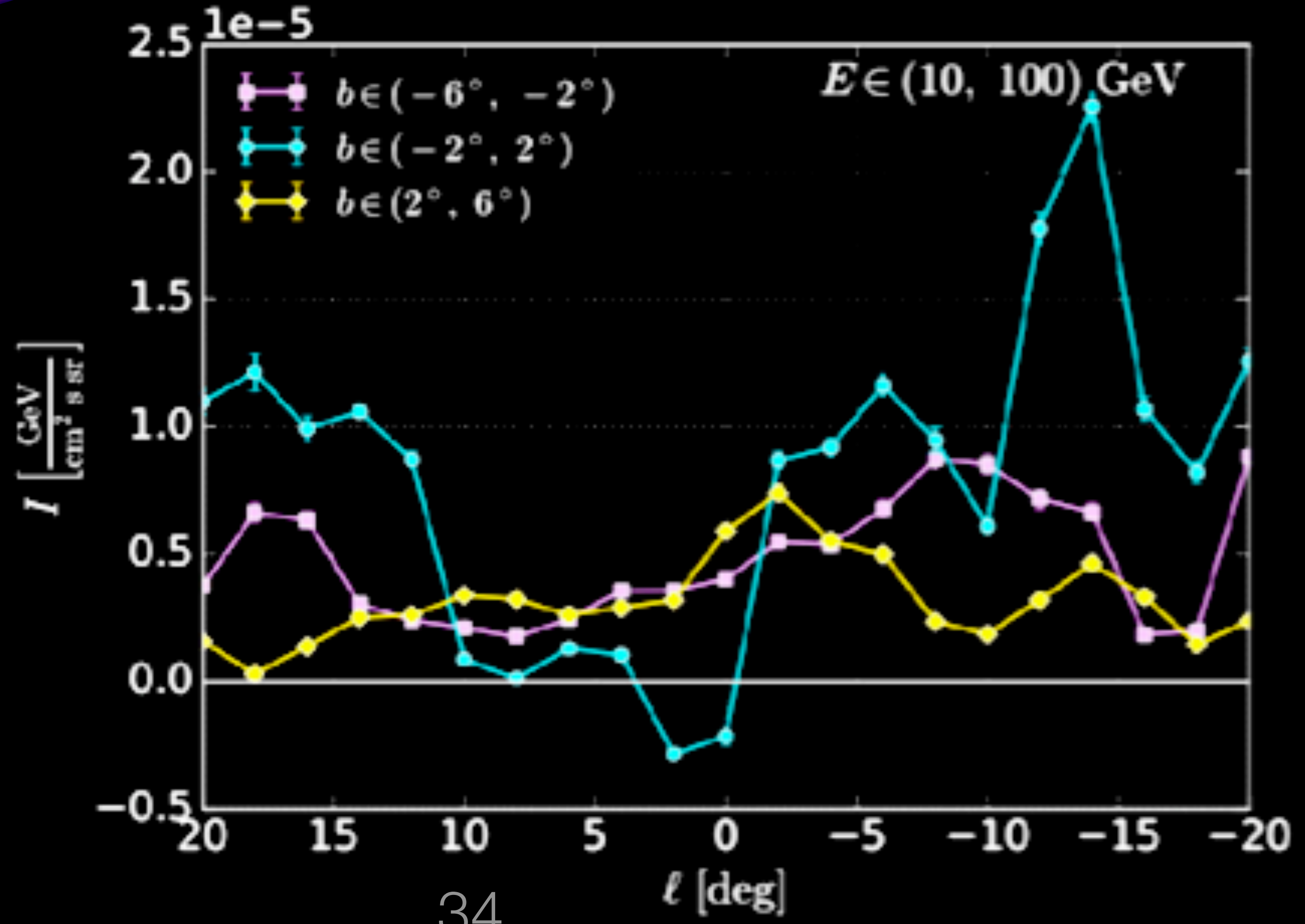


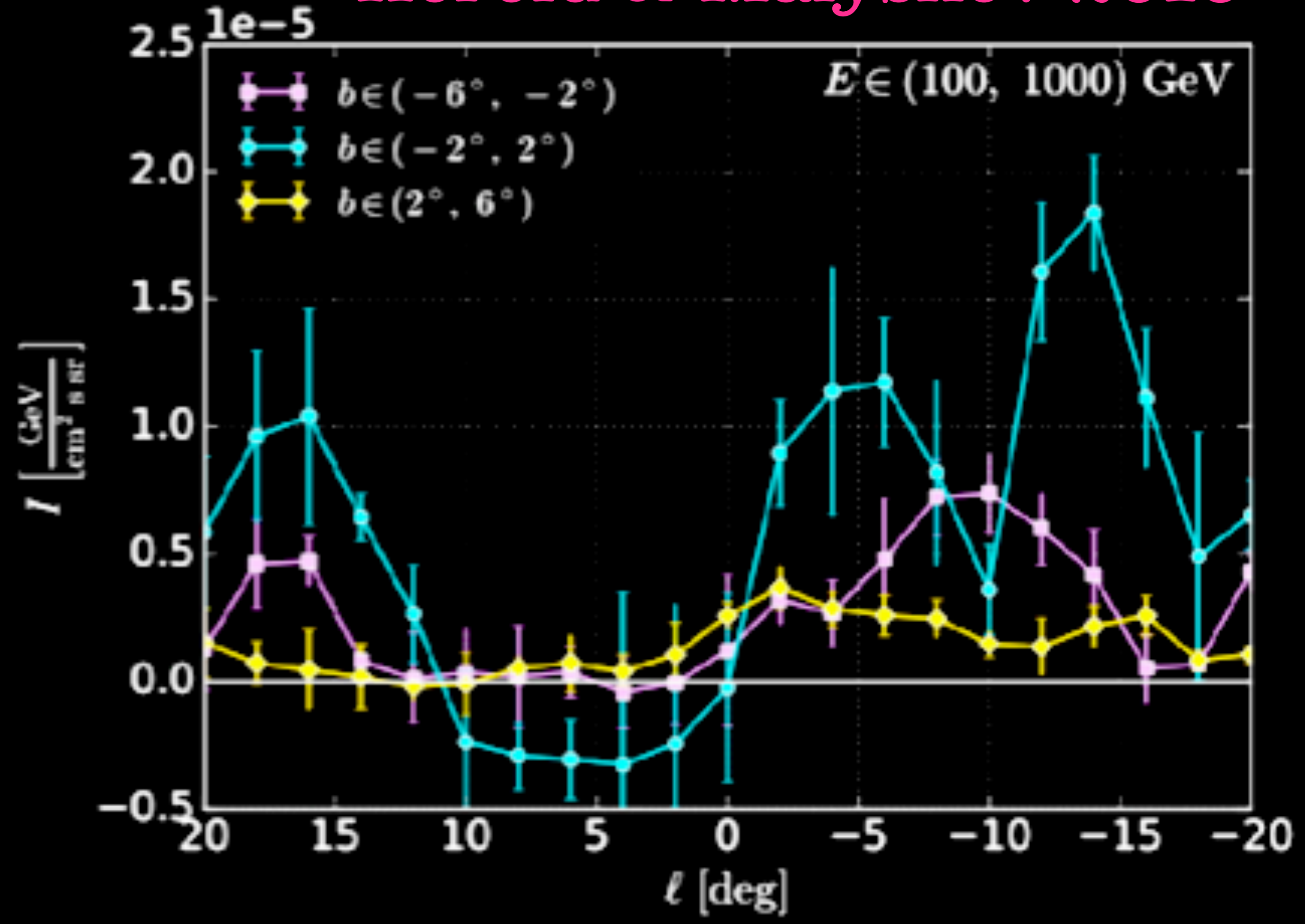
Finkbeiner 2003

Fermi-LAT Collaboration 2014



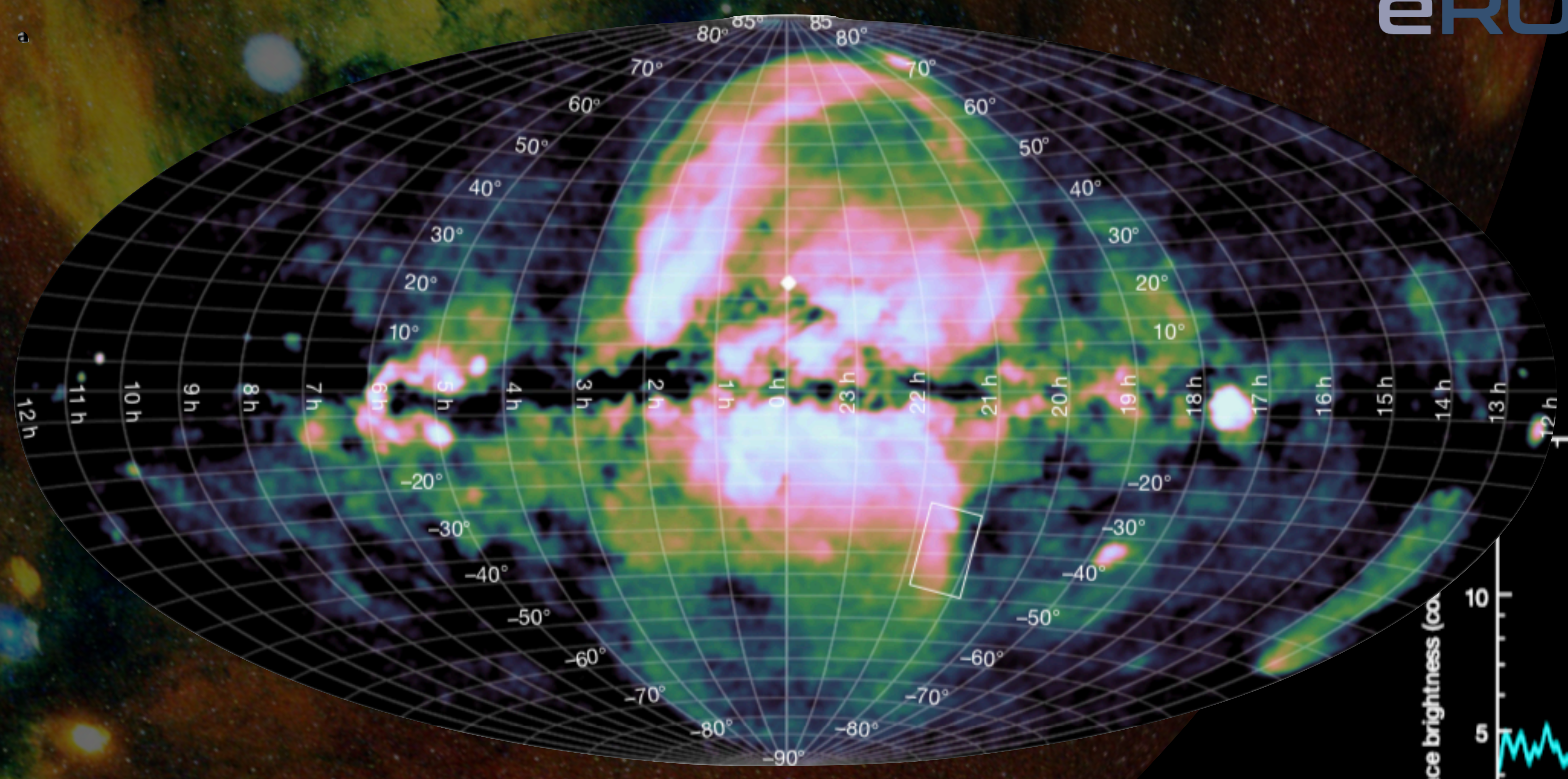
Herold & Malyshev 2019

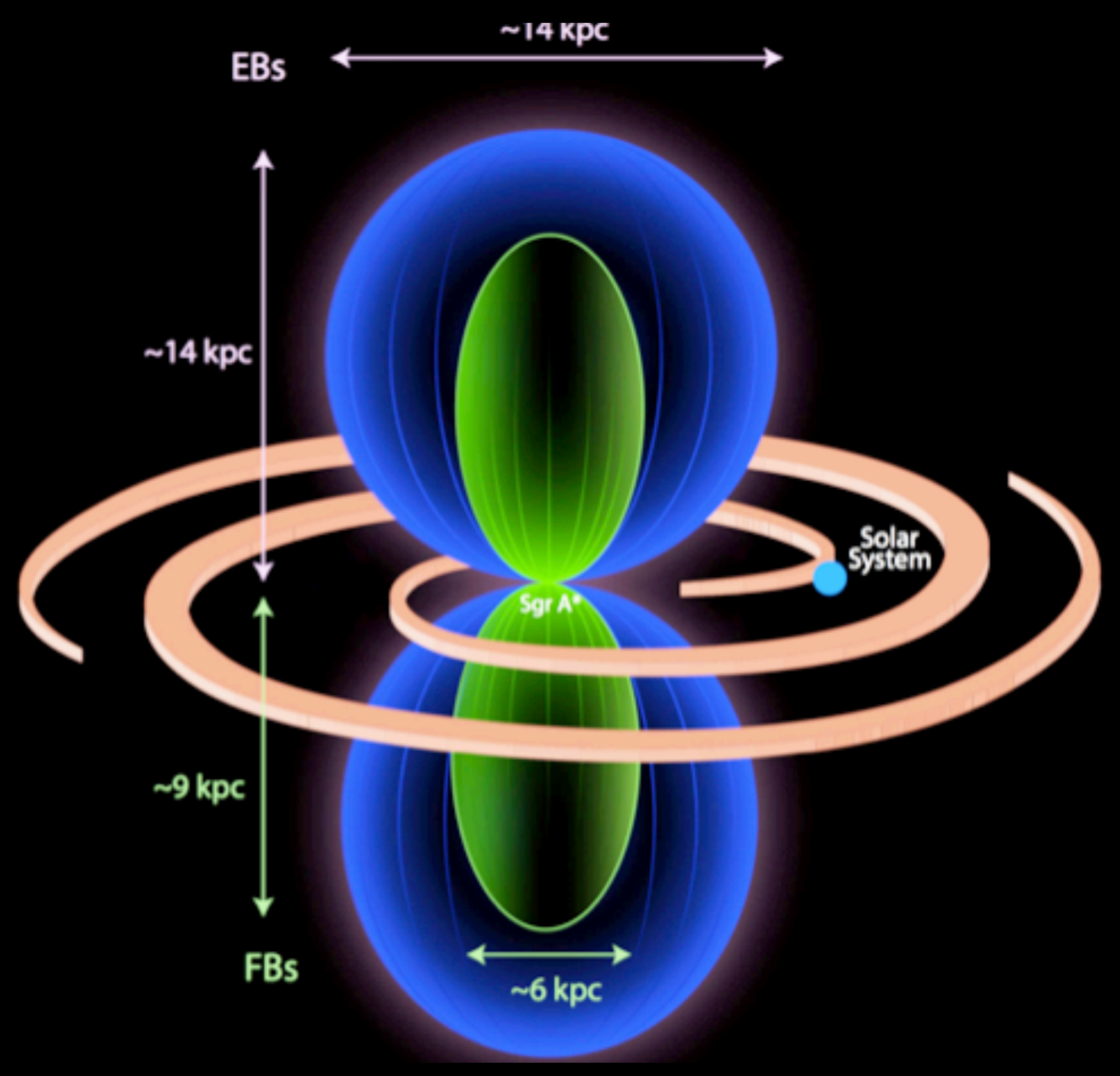


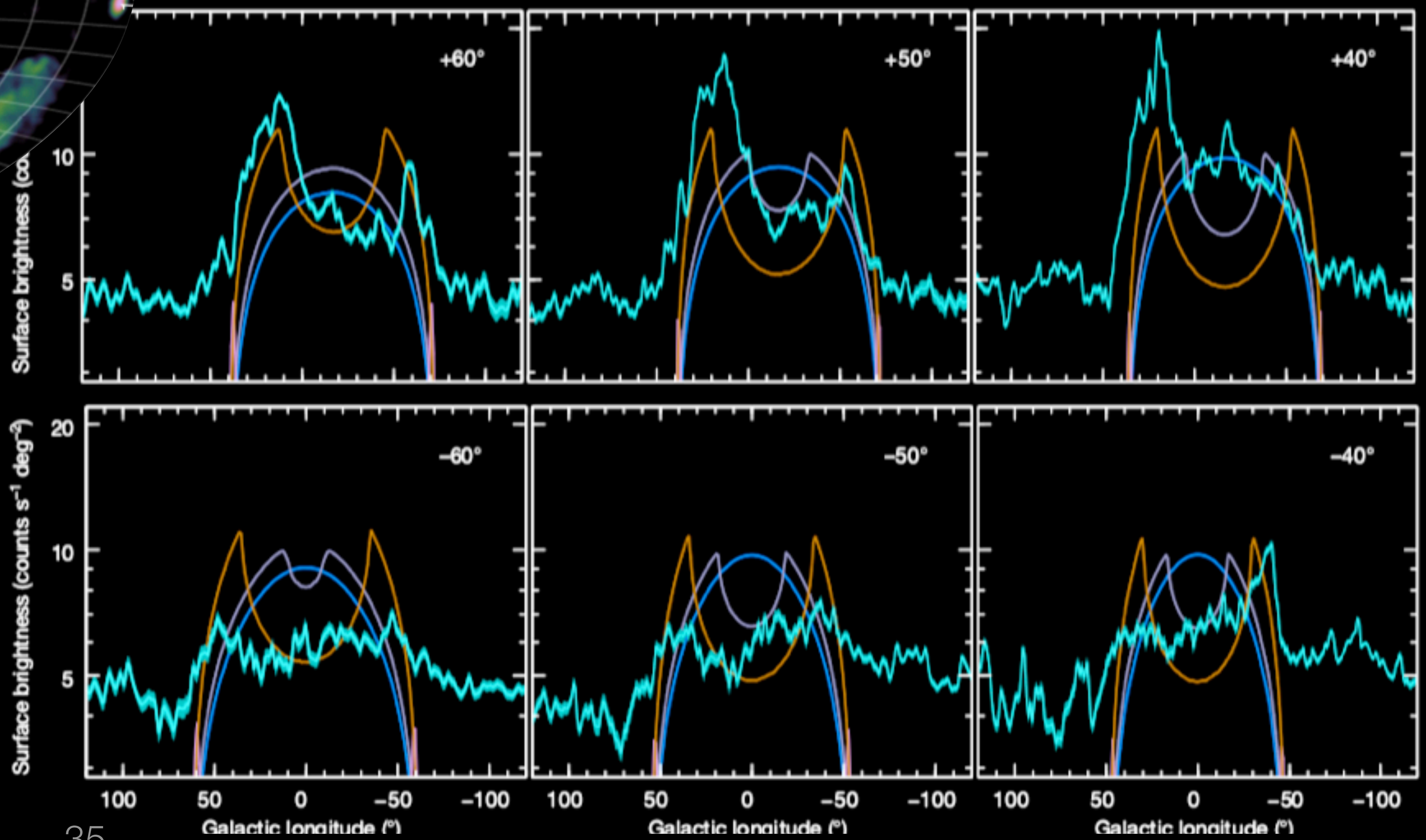


The eROSITA Bubbles

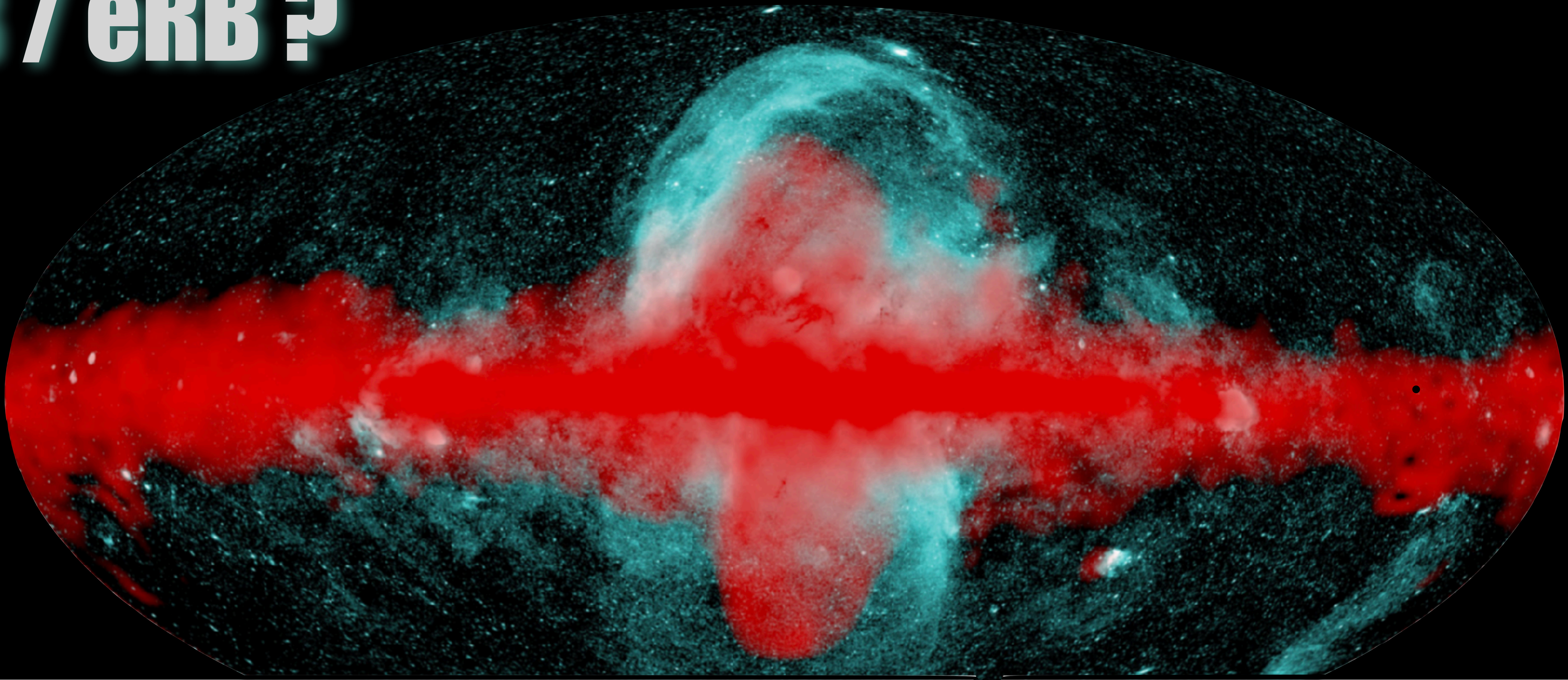
Predel et al. 2020







FB / eRB ?



FB

- elliptical
- ~ 55° × 45° (north–south, east–west) in diameter
- symmetric about the Galactic center (but not really, see next slide)
- vertical axis perpendicular to the Galactic plane
- roughly uniform in γ-ray intensity

eRB

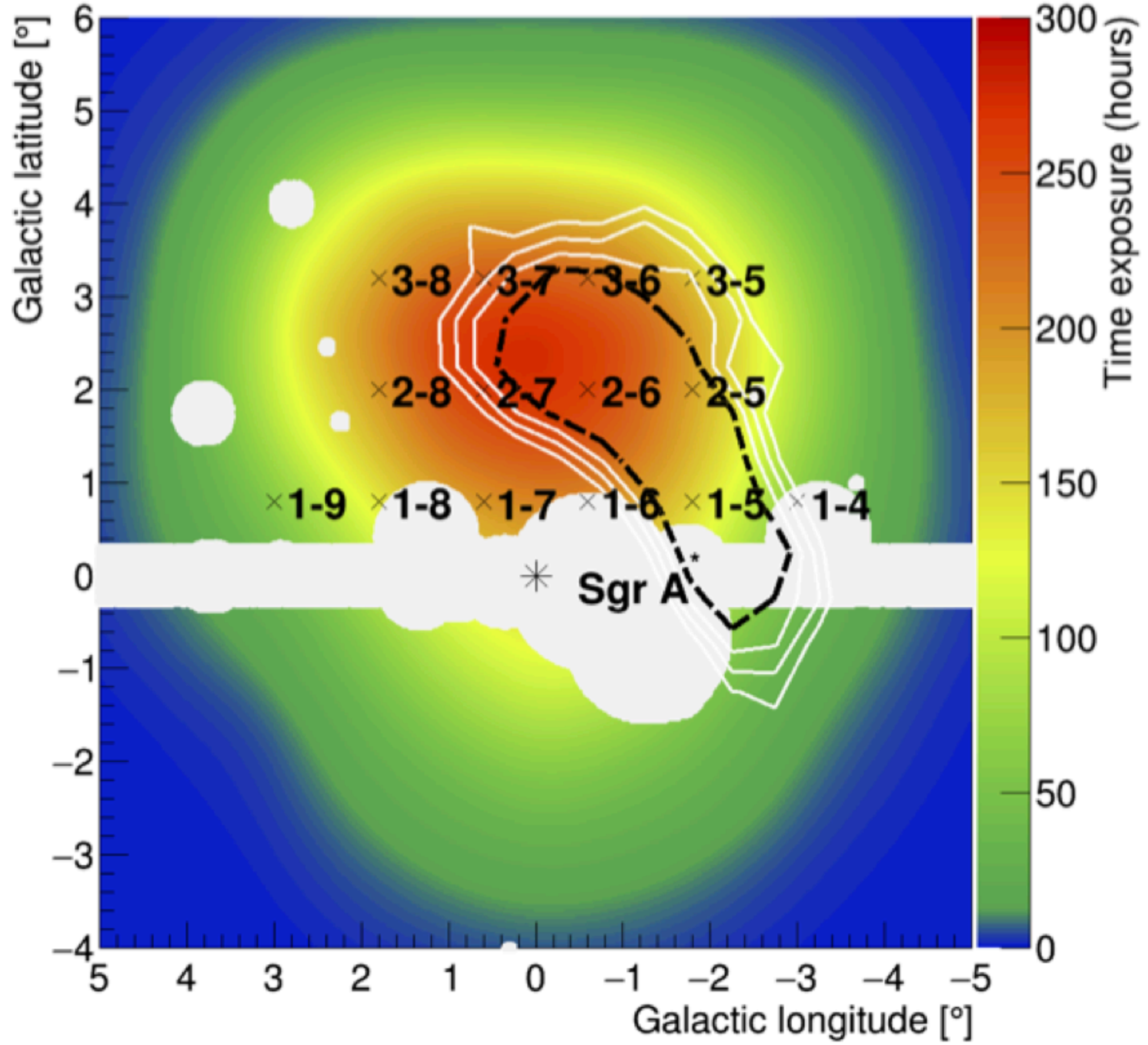
- ~spherical
- 80° x 80-85° (longitude, latitude)
- symmetric (????)
- vertical axis (????)
- Not uniform in x-ray intensity

VHE emission from Fermi Bubbles?

Detection of TeV gamma rays from the base of the Fermi bubbles by H.E.S.S.

Injection of relativistic CR at or near the Galactic Center about 100,000 years or less in the past

- supernova explosions near the GC
- outburst from Sagittarius A*

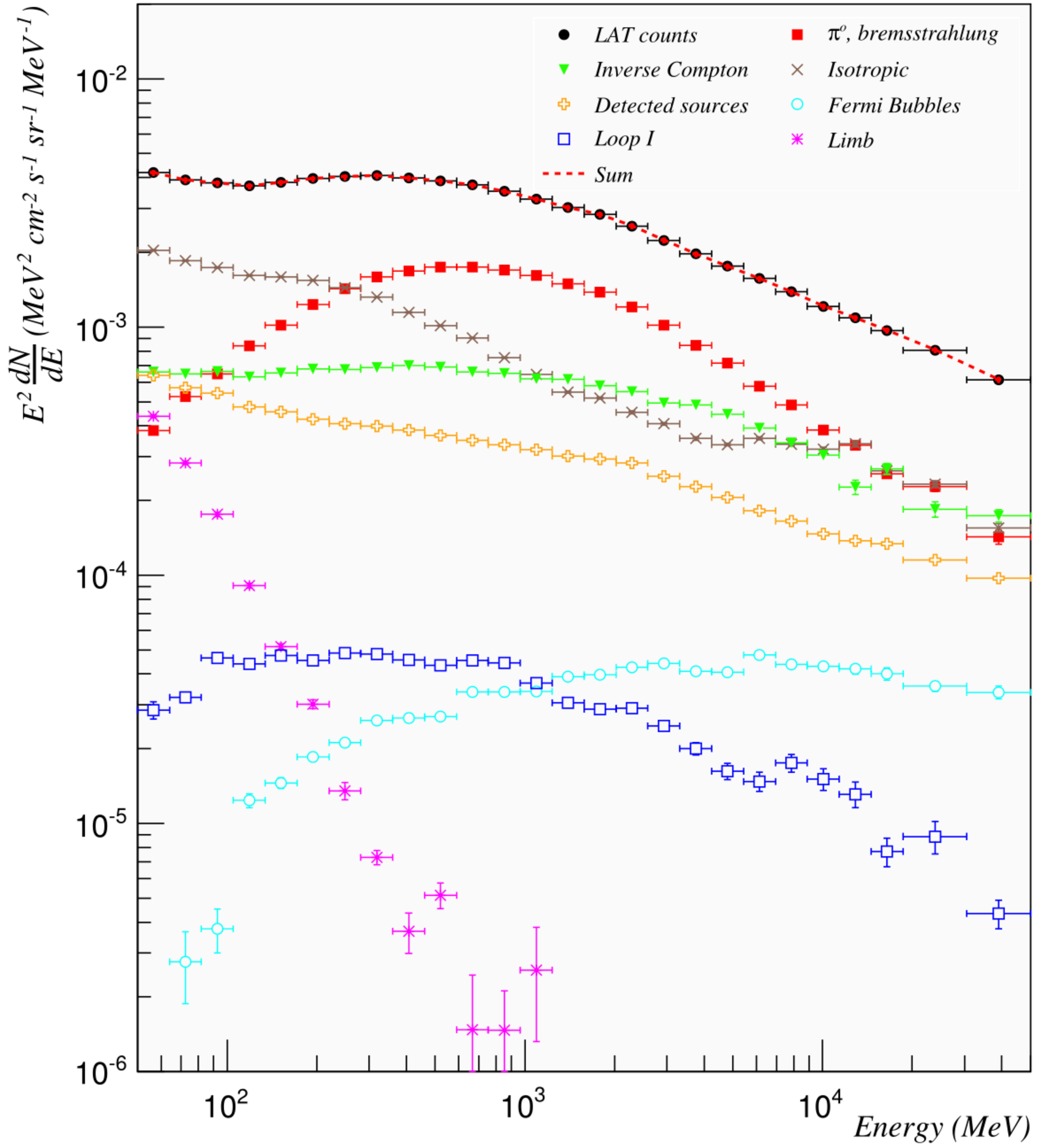


- PoS: E. Moulin,et al on behalf of the H.E.S.S. Collaboration
- The HESS and the Fermi-LAT Collaboration 2024 in prep

Template fitting

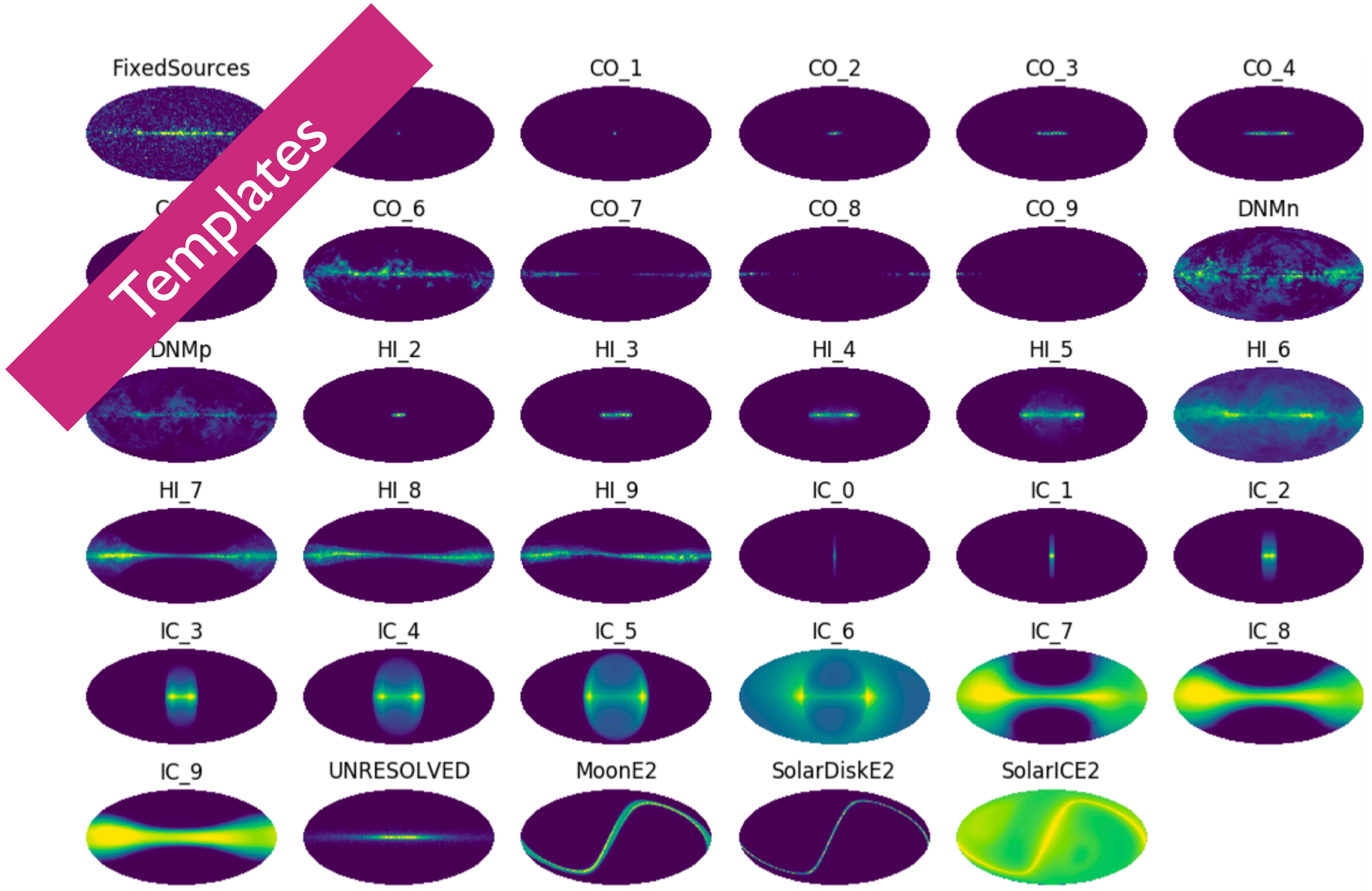
Method based on the fitting of the Fermi-LAT counts map by a linear combination of templates spatially correlated with predicted production sites of γ-rays.

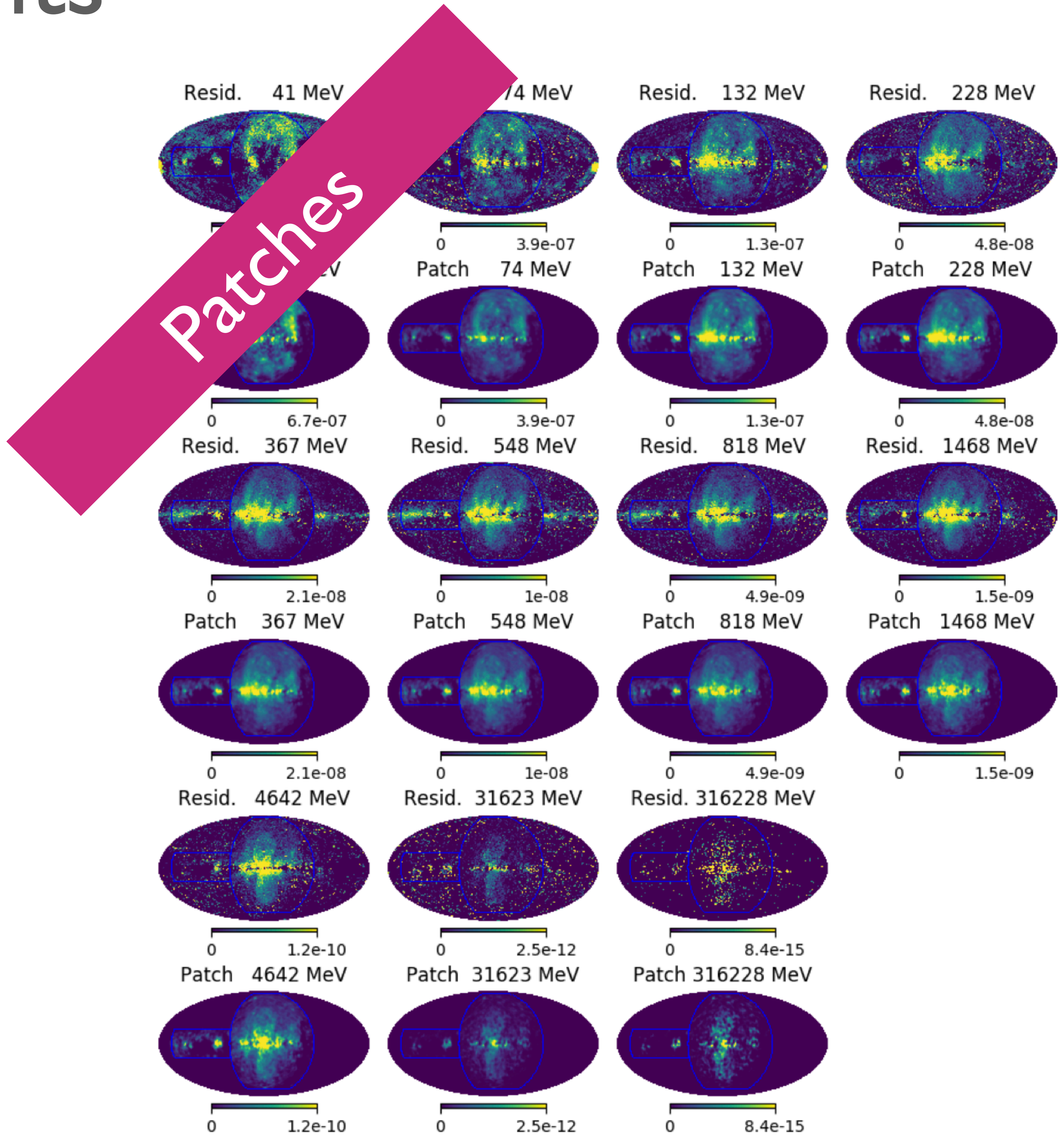
$$
\begin{aligned}
N_{\text{pred}}(E, l, b) = & \sum_{i=\text{gas}} q_i(E)\tilde{I}_i(l, b) + N_{\text{IC}}(E)\tilde{I}_{\text{IC}_p}(E, l, b) \\
& + N_{\text{iso}}(E)\tilde{I}_{\text{iso}} + N_{\text{LoopI}}(E)\tilde{I}_{\text{LoopI}}(l, b) \\
& + N_{\text{patch}}(E)\tilde{I}_{\text{patch}}(l, b) + N_{\text{Bubbles}}(E)\tilde{I}_{\text{Bubbles}}(l, b) \\
& + \sum_{i=\text{point src}} N_{\text{pt}_i}(E)\tilde{\delta}(l, b, i) \\
& + \sum_{i=\text{extend src}} N_{\text{ext}_i}(E)\tilde{I}_i(l, b) + \tilde{I}_{\text{Sun\_Moon}}(E, l, b) \\
& + N_{\text{limb}}(E)\tilde{I}_{\text{limb}}(l, b),
\end{aligned}
$$



The current model

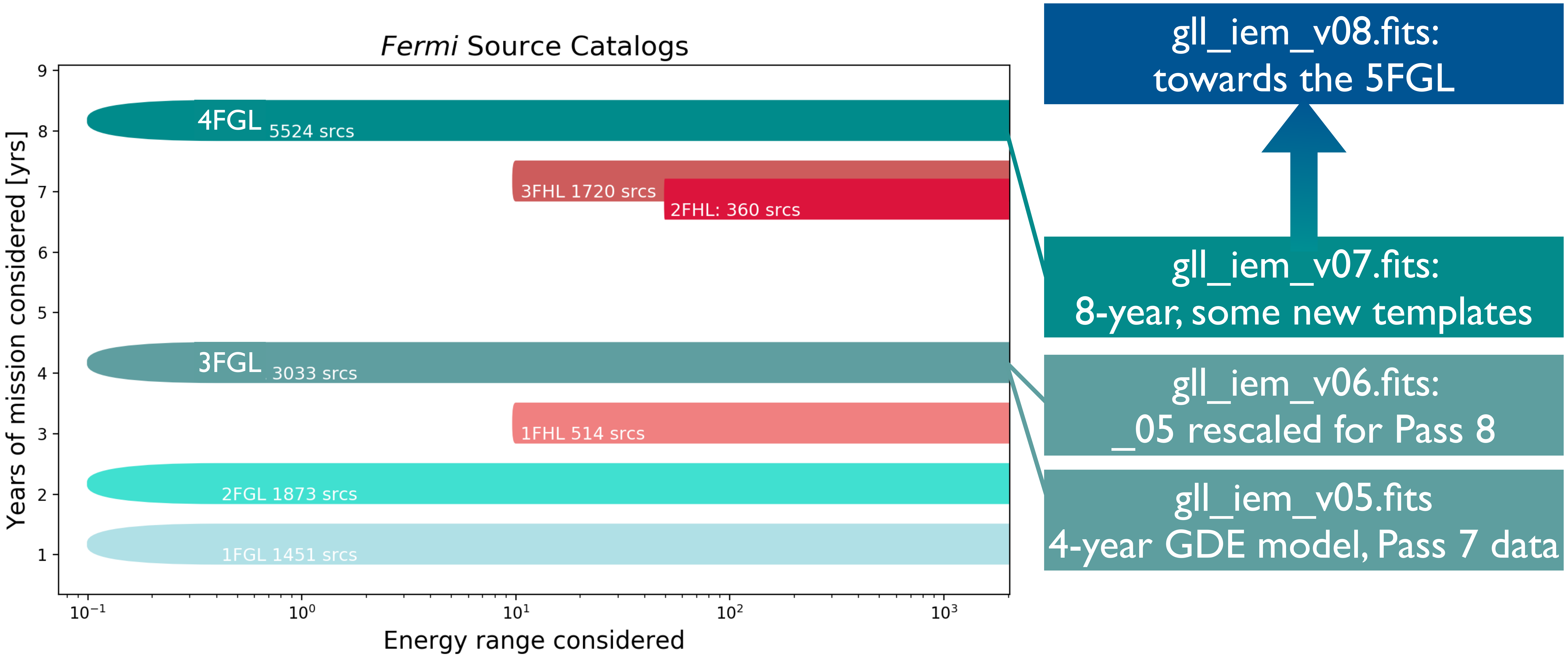
gll_iem_v07.fits





Uncertainties are inevitably large: bare this in mind when doing Fermi-LAT data analyses (especially of large region in the sky, e.g., the Galactic center)

The Fermi-LAT GDE model

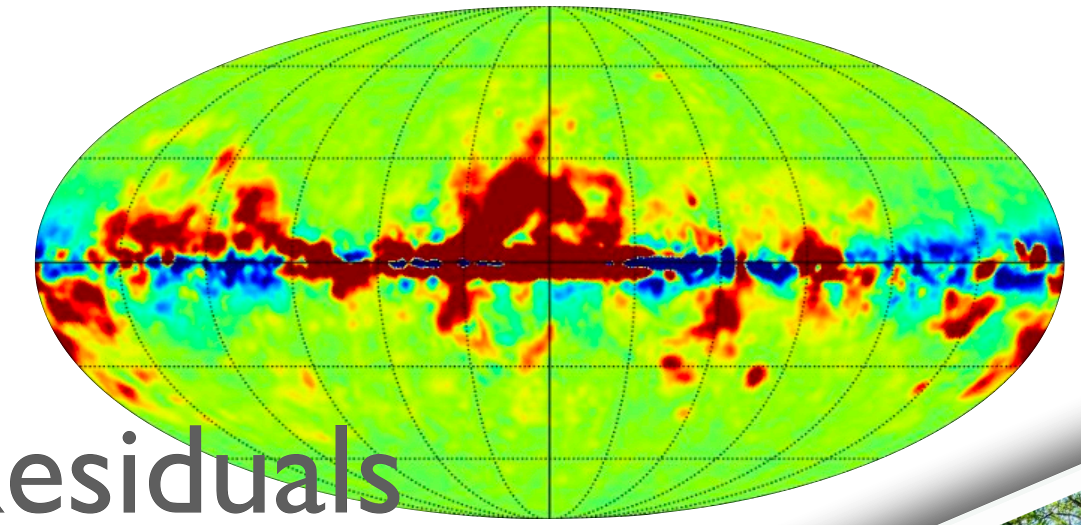


Time for new approaches?

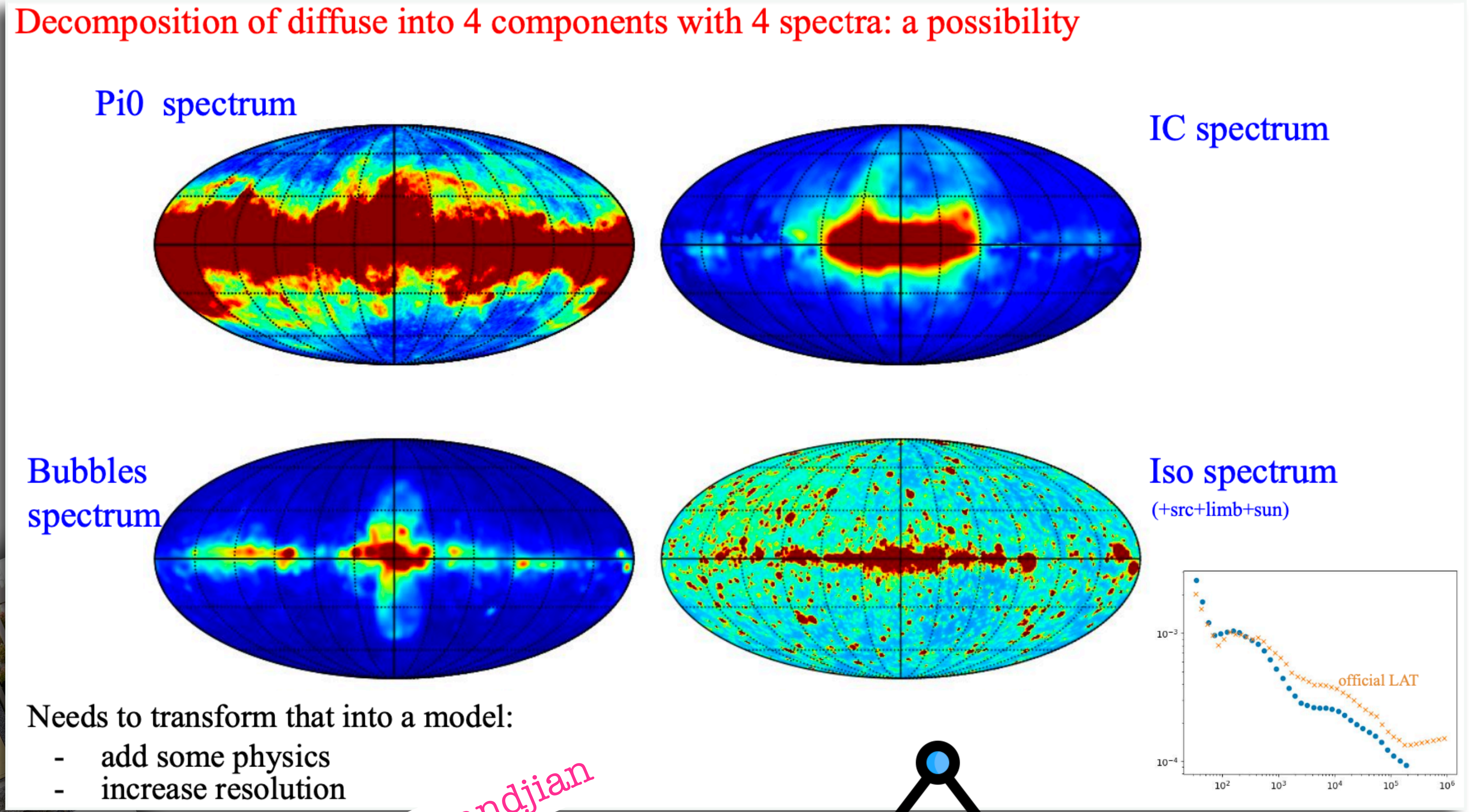
towards the 5FGL

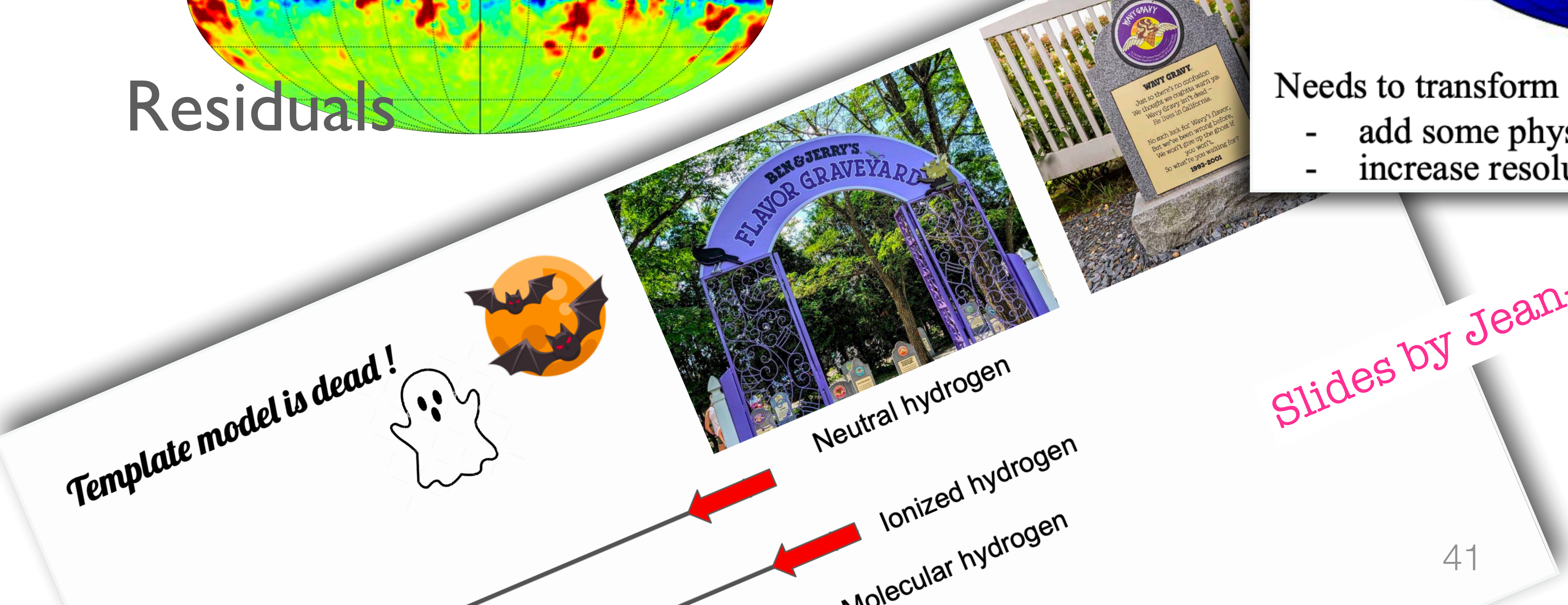
using spectral signatures to determine spatial distributions

There seem to be disagreements between dust and γ-ray emissivity



Residuals





Slides by Jean-Marc Casandjian

Uncertainties

- As much as ~50% uncertainties in the ISM gas column density and the CR intensity. Major sources of systematic errors:
  - ✴ 10–40% uncert. due to HI spin temperature (optical depth)
  - ✴ ??% the modeling of the IC scattering
  - ✴ 10% the absolute determination of the LAT effective area

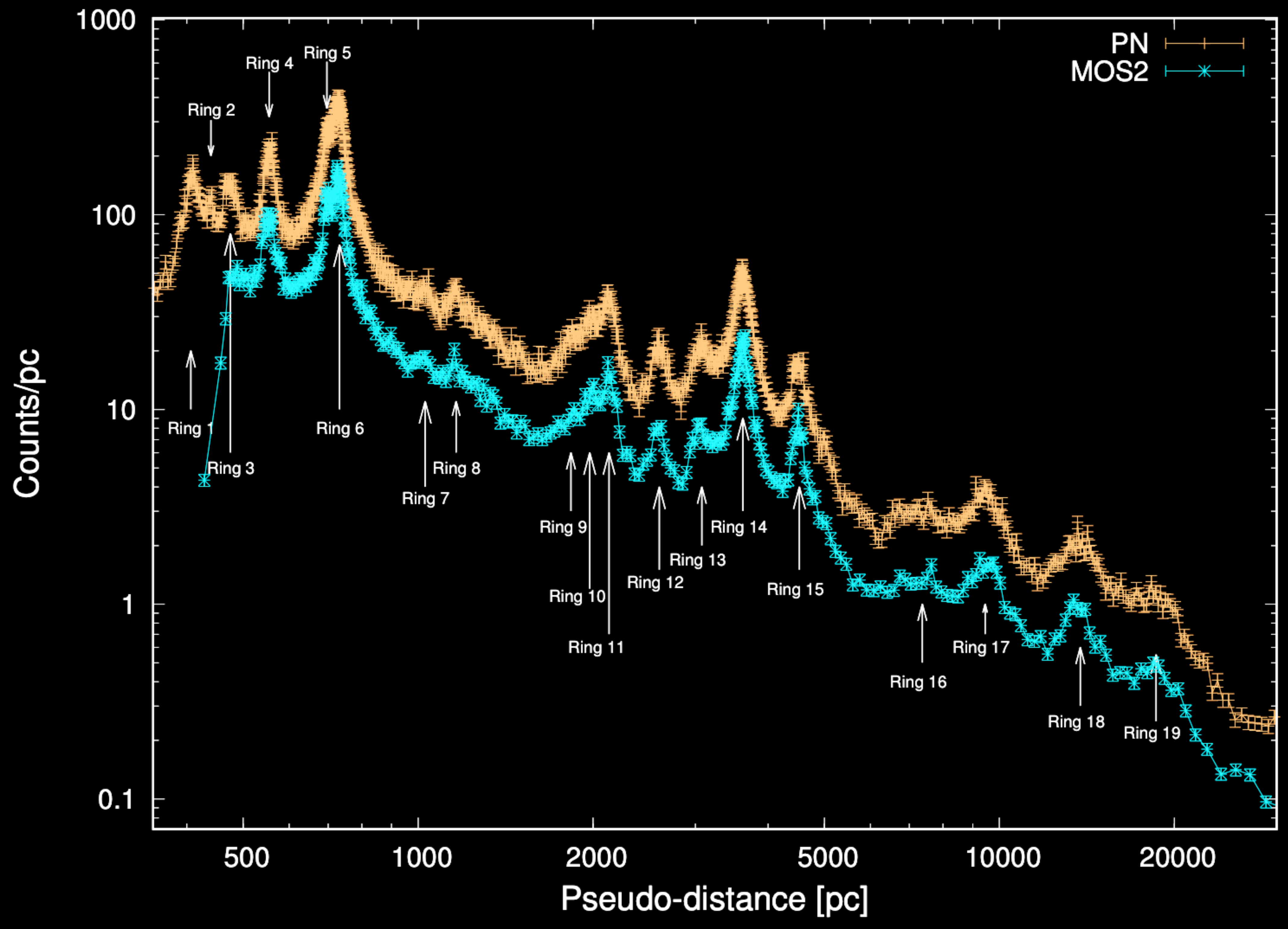
- Source confusion: inevitable contribution from unresolved point sources, it can result in significant systematic uncertainties

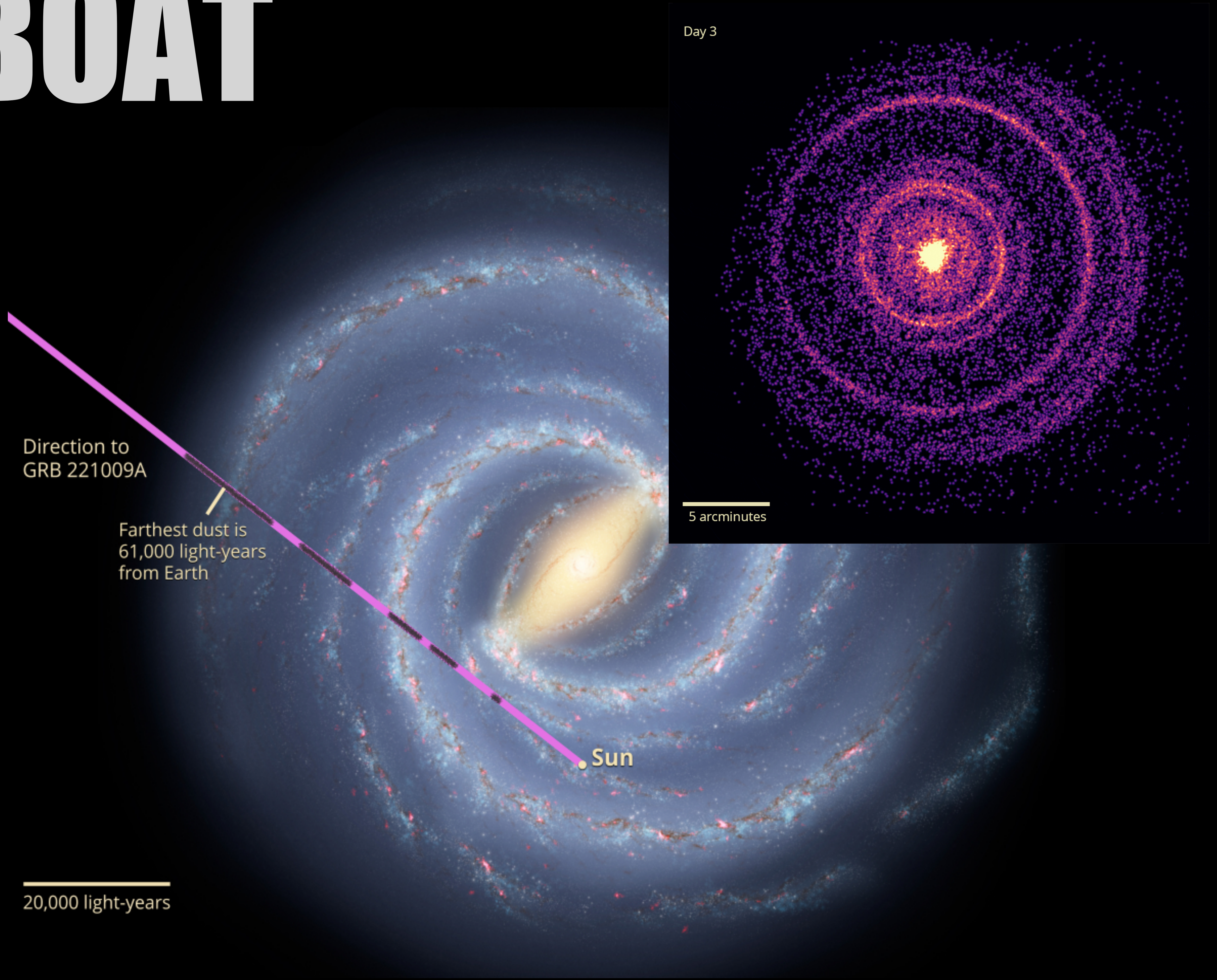
- Unknown unknowns about our Galaxy

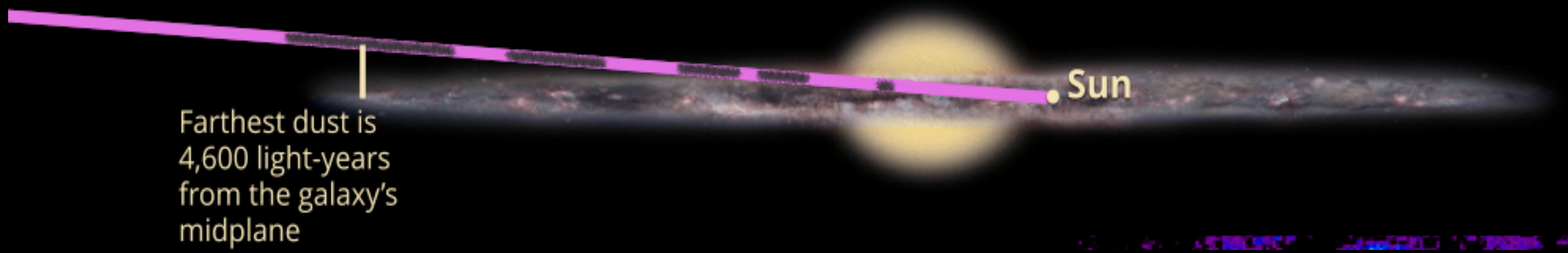
	Spatial distribution	Spectrum
HI	good (only local)	moderate (rest)
H+	very poor	poor
H2	moderate	moderate
IC	moderate	moderate
LSS	very poor	very poor
Isotropic	good	poor

Assessment by Jean-Marc Casandjian

The BOAT


1000
100
10
1
0.1
Counts/pc
500
1000
2000
5000
10000
20000
Pseudo-distance [pc]
PN
MOS2
Ring 1
Ring 2
Ring 3
Ring 4
Ring 5
Ring 6
Ring 7
Ring 8
Ring 9
Ring 10
Ring 11
Ring 12
Ring 13
Ring 14
Ring 15
Ring 16
Ring 17
Ring 18
Ring 19


Direction to
GRB 221009A
Farthest dust is
61,000 light-years
from Earth
Sun
20,000 light-years
Day 3
5 arcminutes


Farthest dust is
4,600 light-years
from the galaxy's
midplane
Sun

The Compton Spectrometer and Imager

COSI is the future NASA SMEX

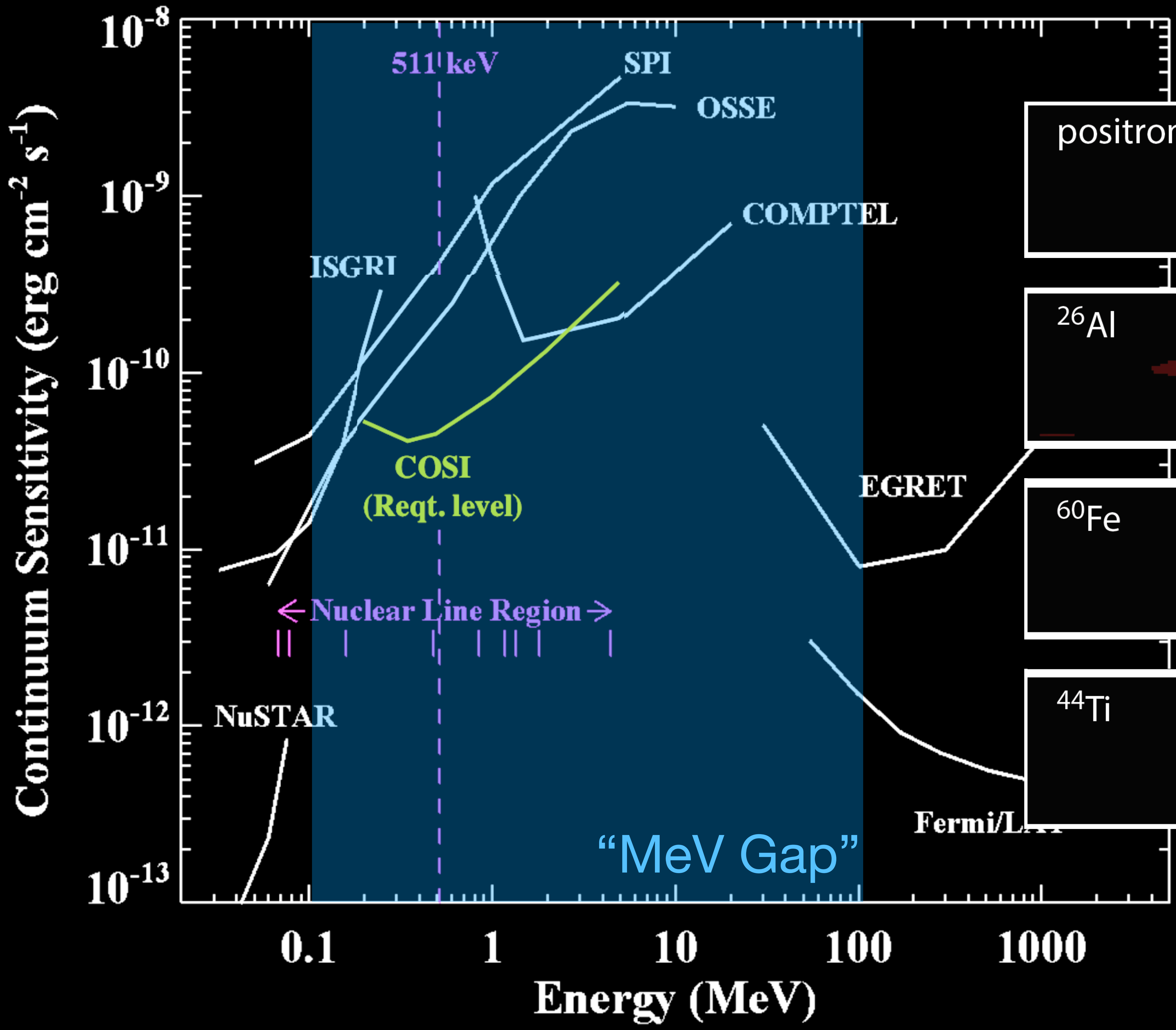
It is a soft gamma-ray survey telescope

- 0.2-5 MeV
- Spectrometer
- Imager
- Polarimeter

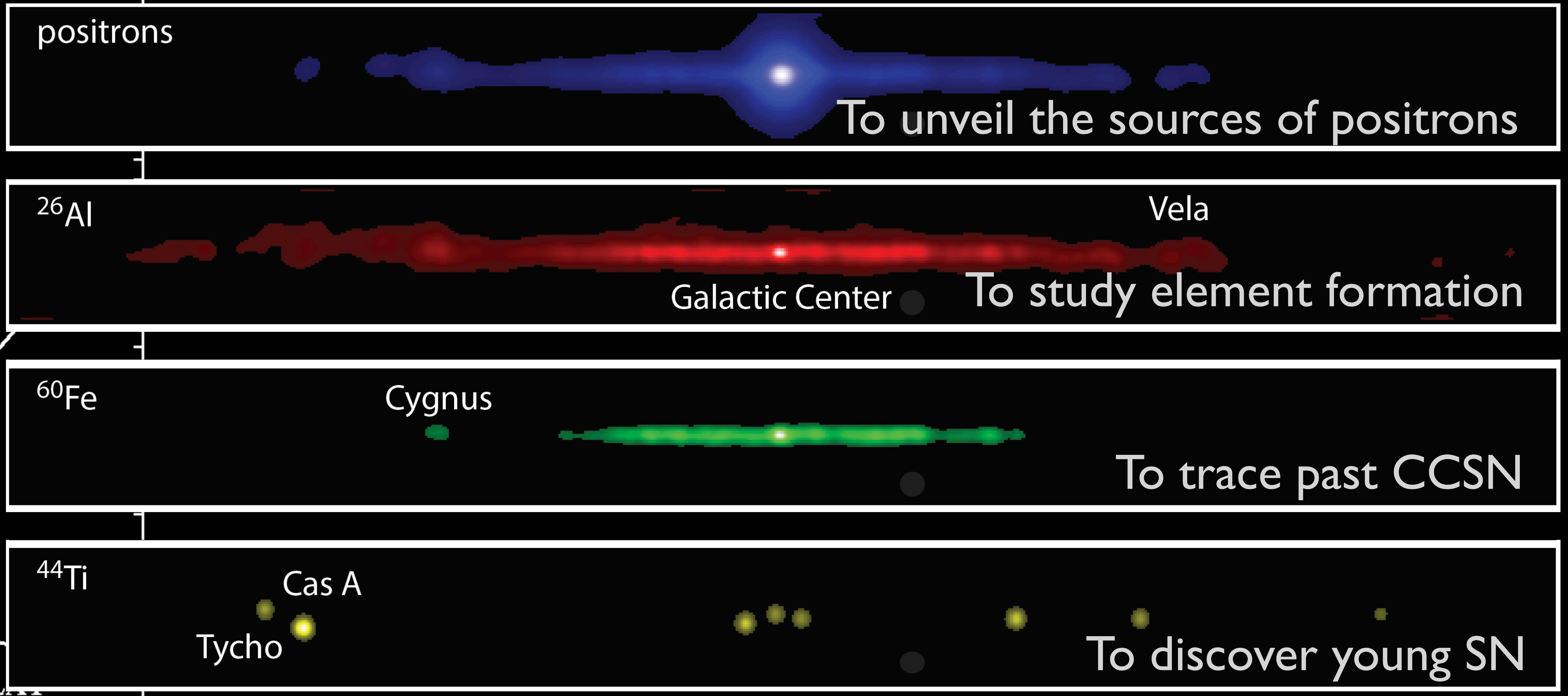
To be launched in **2027**!

Parameter	Requirements
Energy range	0.2-5 MeV
Sky coverage	100%-sky each day
Energy resolution	0.2-1% FWHM
Angular resolution	2.1^{o} FWHM @ 1.8 MeV (^{26}Al)
Localizations	<1.0^{o} for GRBs
Polarization sensitivity	For GRBs, AGN, Galactic BHs

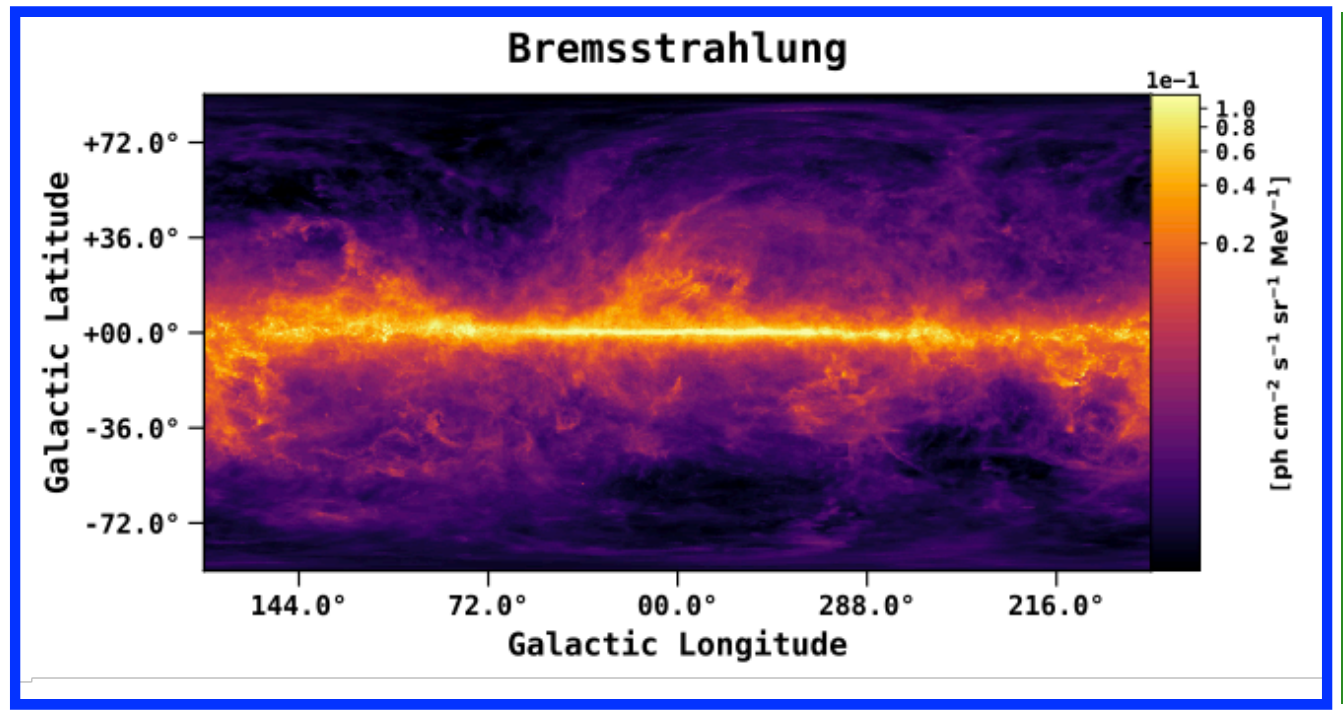
The Compton Spectrometer and Imager: COSI

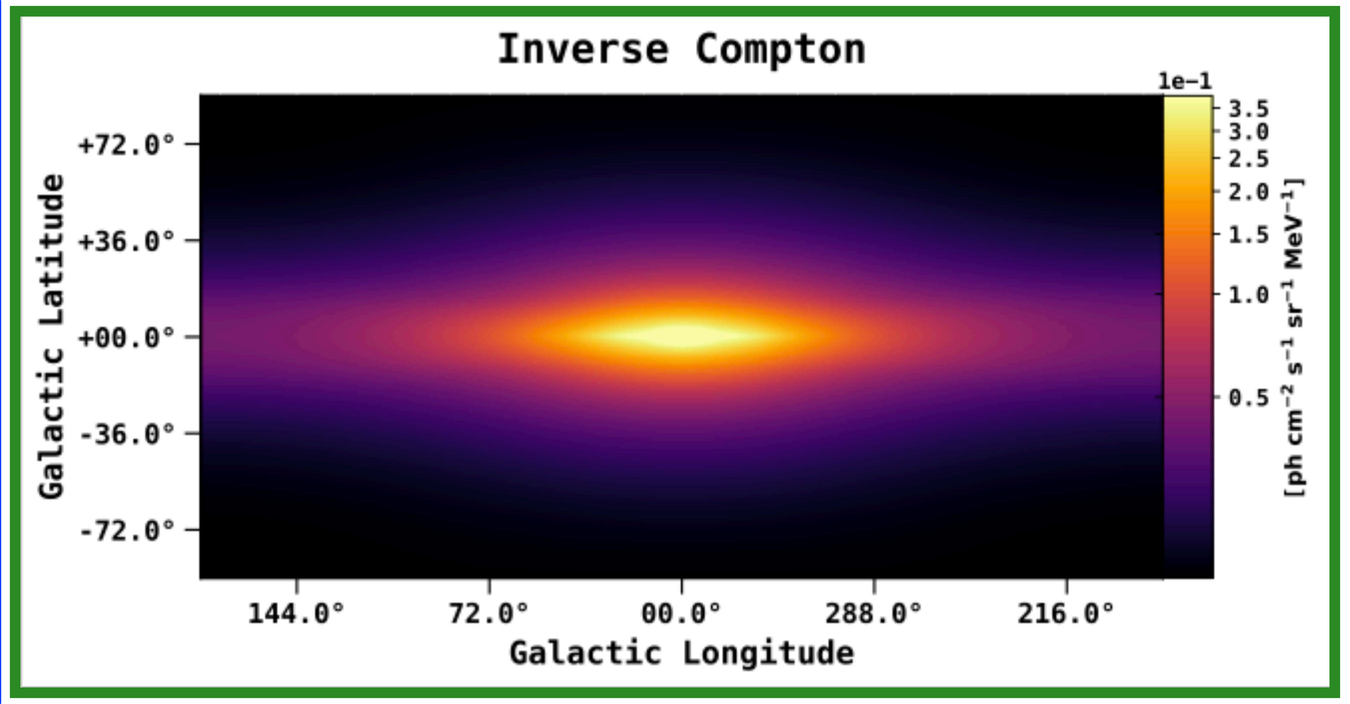


Simulated COSI maps

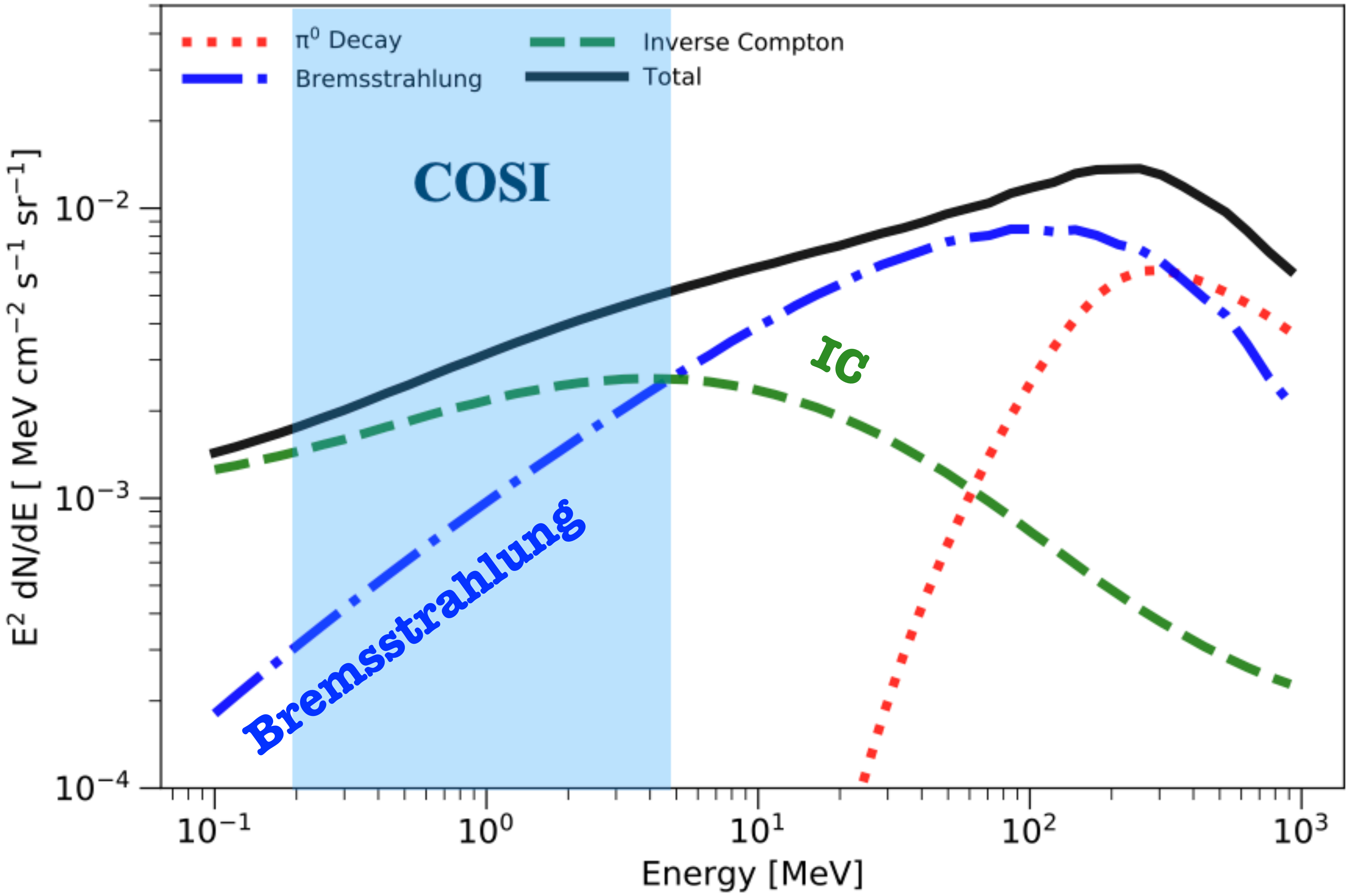


MeV view of the Galactic diffuse emission





- insights for CRE population that produce MeV gamma-rays through IC
- MeV Galactic diffuse emission with unprecedented sensitivity: better modeling



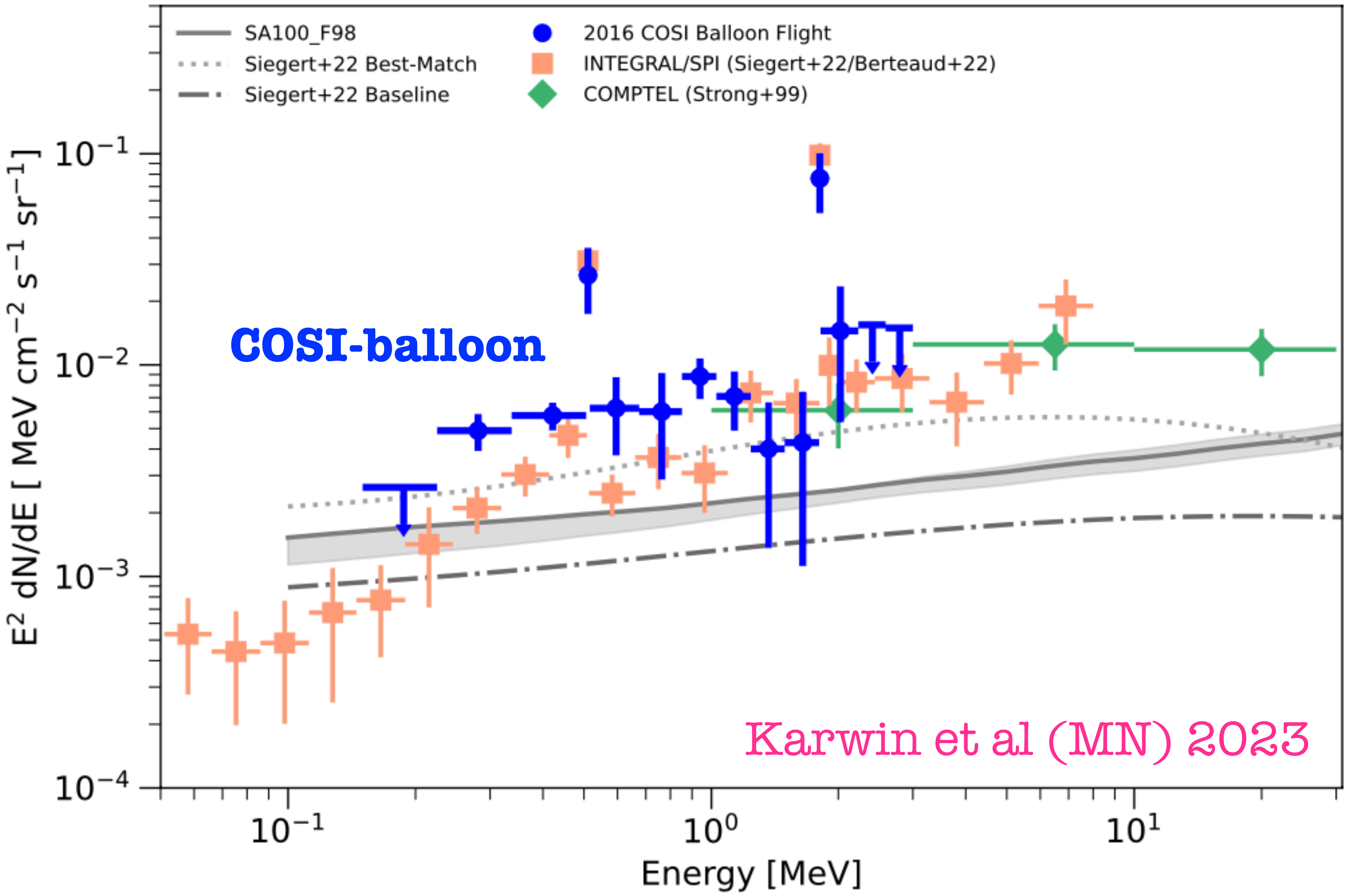


FIG SAG

Future Innovations in Gamma Rays

We will explore gamma-ray science priorities, necessary capabilities, new technologies, and theory needs to inspire work toward 2040.

Get involved and stay informed:

https://forms.gle/VBijBgapMRwJm9dU6

Chairs:
Chris Fryer & Michelle Hui, Paolo Coppi, Milena Crnogorčević, Tiffany Lewis, Marcos Santander, and Zorawar Wadiasingh

SuGAR MADISON 2024

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

Thank you for your attention!

Michela Negro
Louisiana State University

LSU
Department of Physics & Astronomy

SuGAR MADISON 2024

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

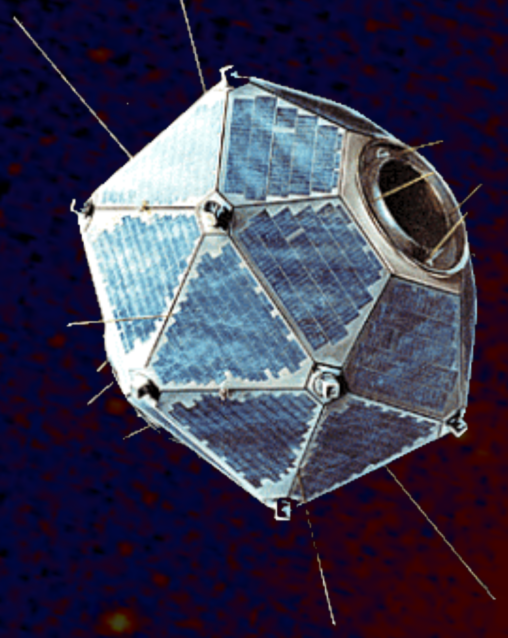
Back-up

Michela Negro

Louisiana State University

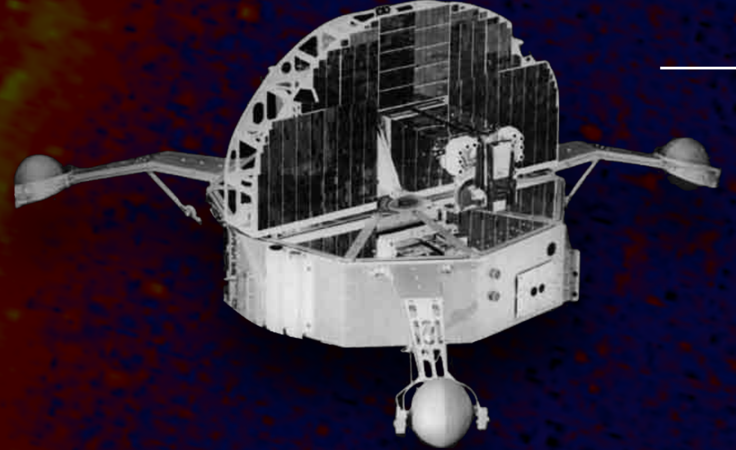
LSU

Department of Physics & Astronomy



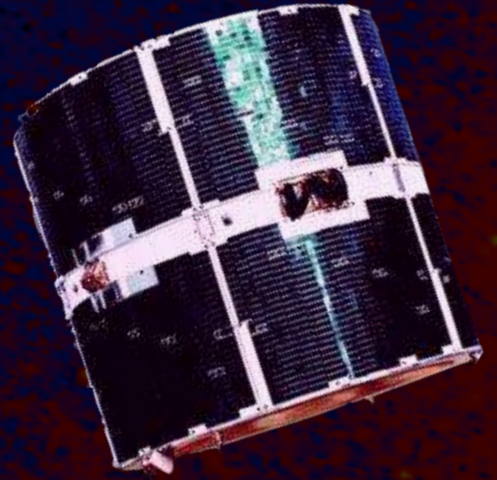
Vela satellites

1956 - 1982 —
NASA project to detect nuclear detonation in the atmosphere.



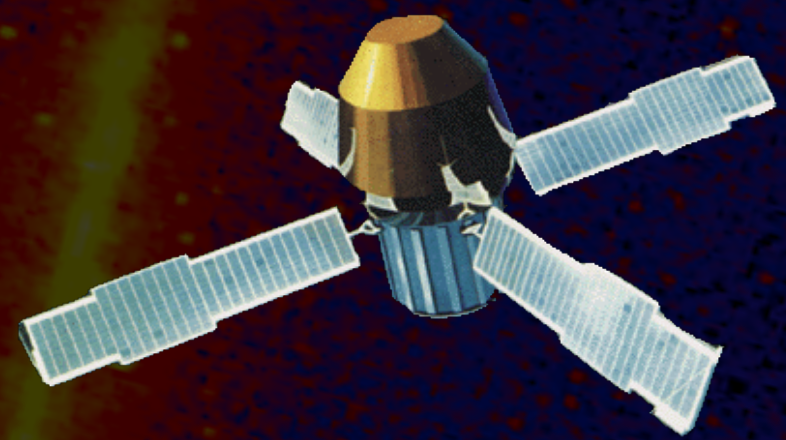
OSO-3

Late '60s —
NASA satellite which detected 621 γ-rays above 50 MeV.



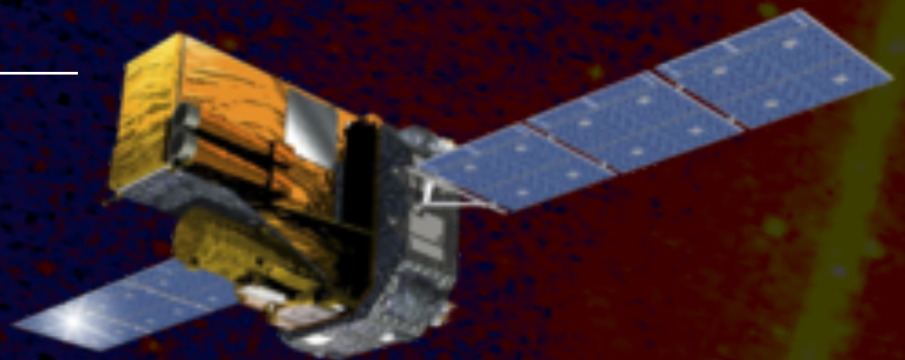
COS-B

Early '70s —
ESA mission which dedicated to the γ-ray sky exploration in the (0.05 - 10) GeV energy range.



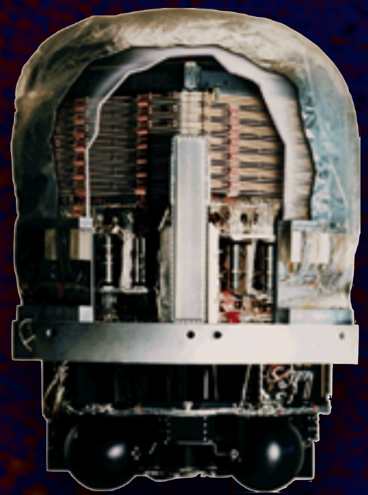
SAS-2

Early '70s —
NASA mission



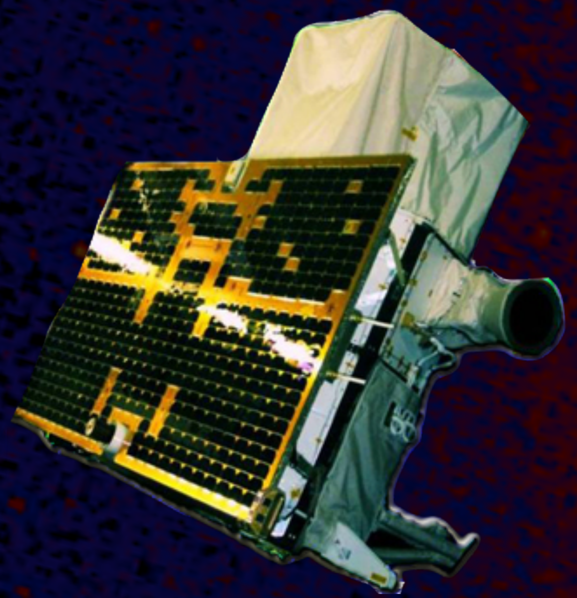
INTEGRAL

2002 - Now —
ESA mission devoted to the study of sources and transients events in the low-energy γ-ray regime (below 10 MeV)



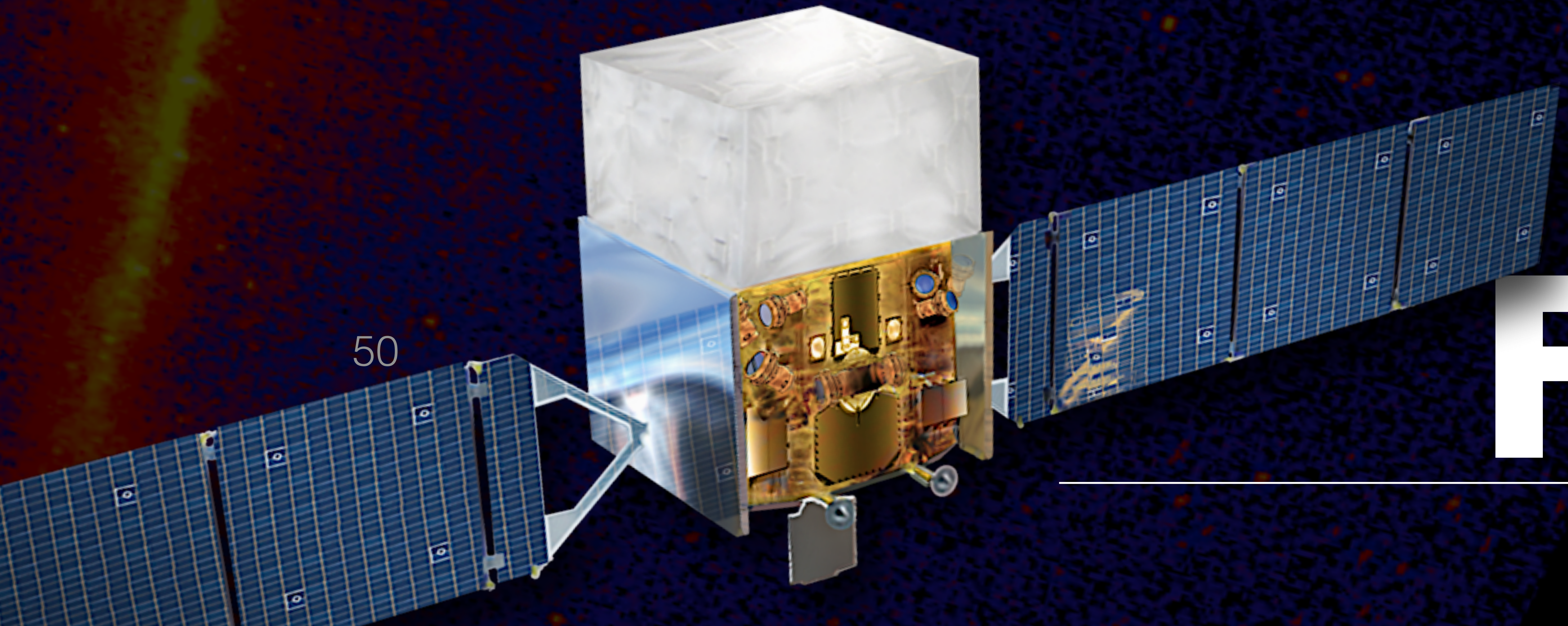
EGRET

1991 - 2000 —
NASA mission which detected γ-rays in the (0.02 - 30) GeV energy range.



AGILE

2007 - Now —
Small Italian Mission.

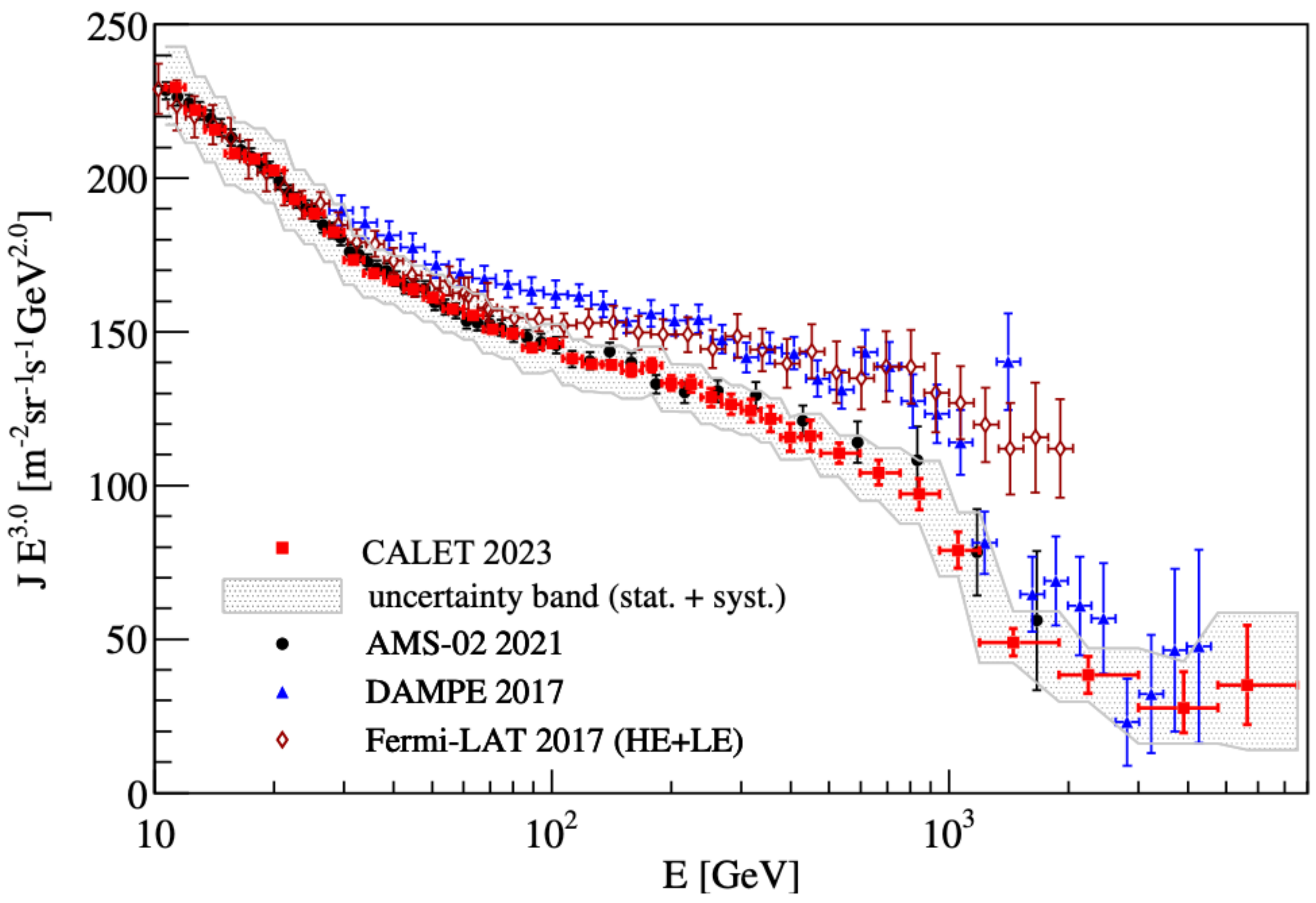


FERMI

2008 - Now —
NASA mission

Fermi-LAT CRE spectrum

- **GOAL:** identify ***electrons and positrons*** out of *cosmic rays background* in Fermi-LAT data (and compute their energy spectrum)



- **Supervised Learning:**
  - Boosted Decision Trees: published in 2017
  - Neural Networks → similar results
  - ☑ Supervised approach implies training on Monte Carlo simulations:
    → strong dependence on models and simulations quality
    → **sensitive to important systematic uncertainties or biases**

- **Unsupervised Learning:**
  - ✓ No labels and minimum human supervision:
    → independence of models / MC → **systematic uncertainties reduced**
  - ☑ ***Difficulty***: very different cluster sizes (i.e. background dominant wrt signal)
  - ☑ ***Potential drawback***: irreducible bkg (hadronic shower fluctuating into e.m. shower)

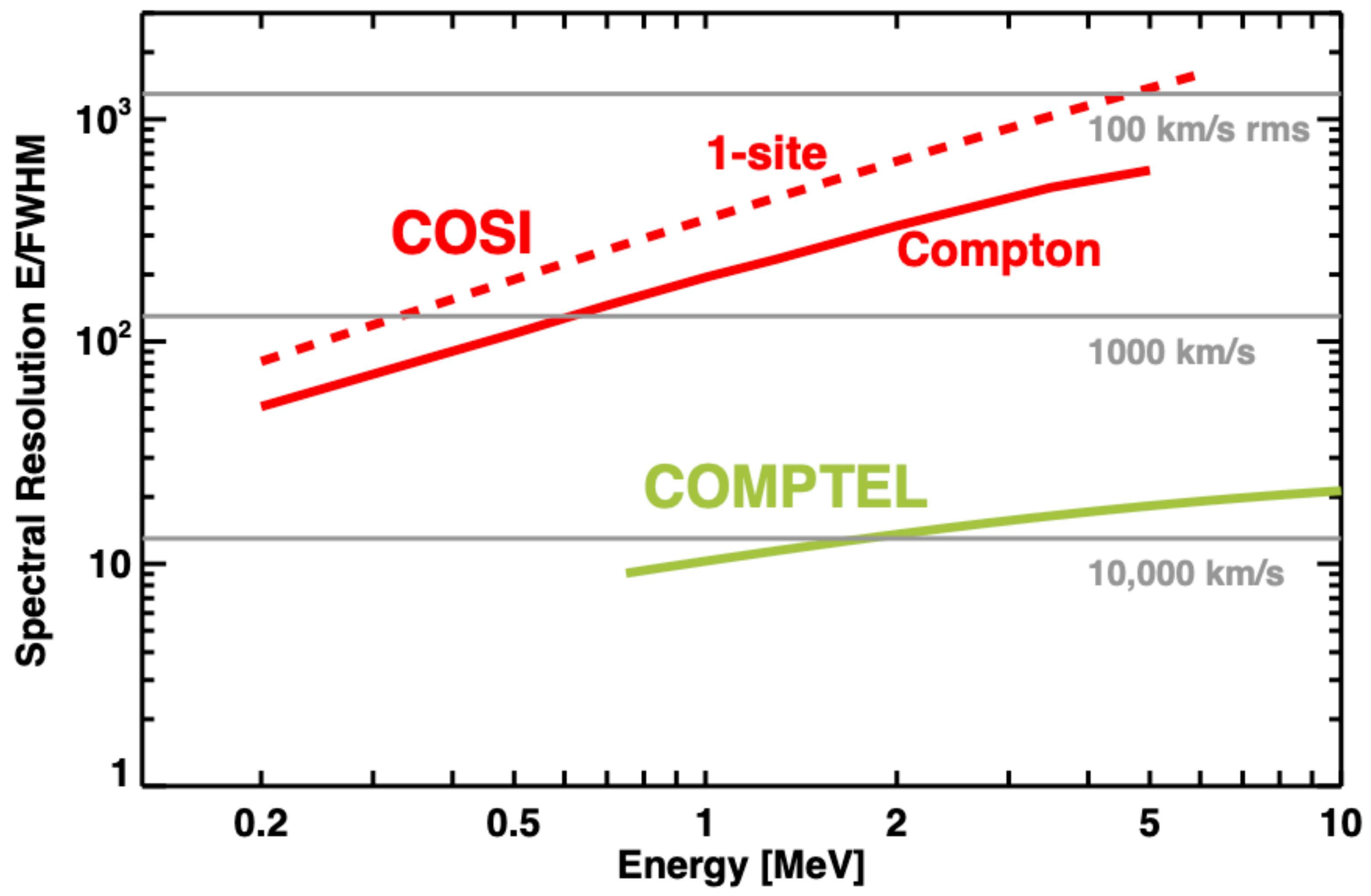
10

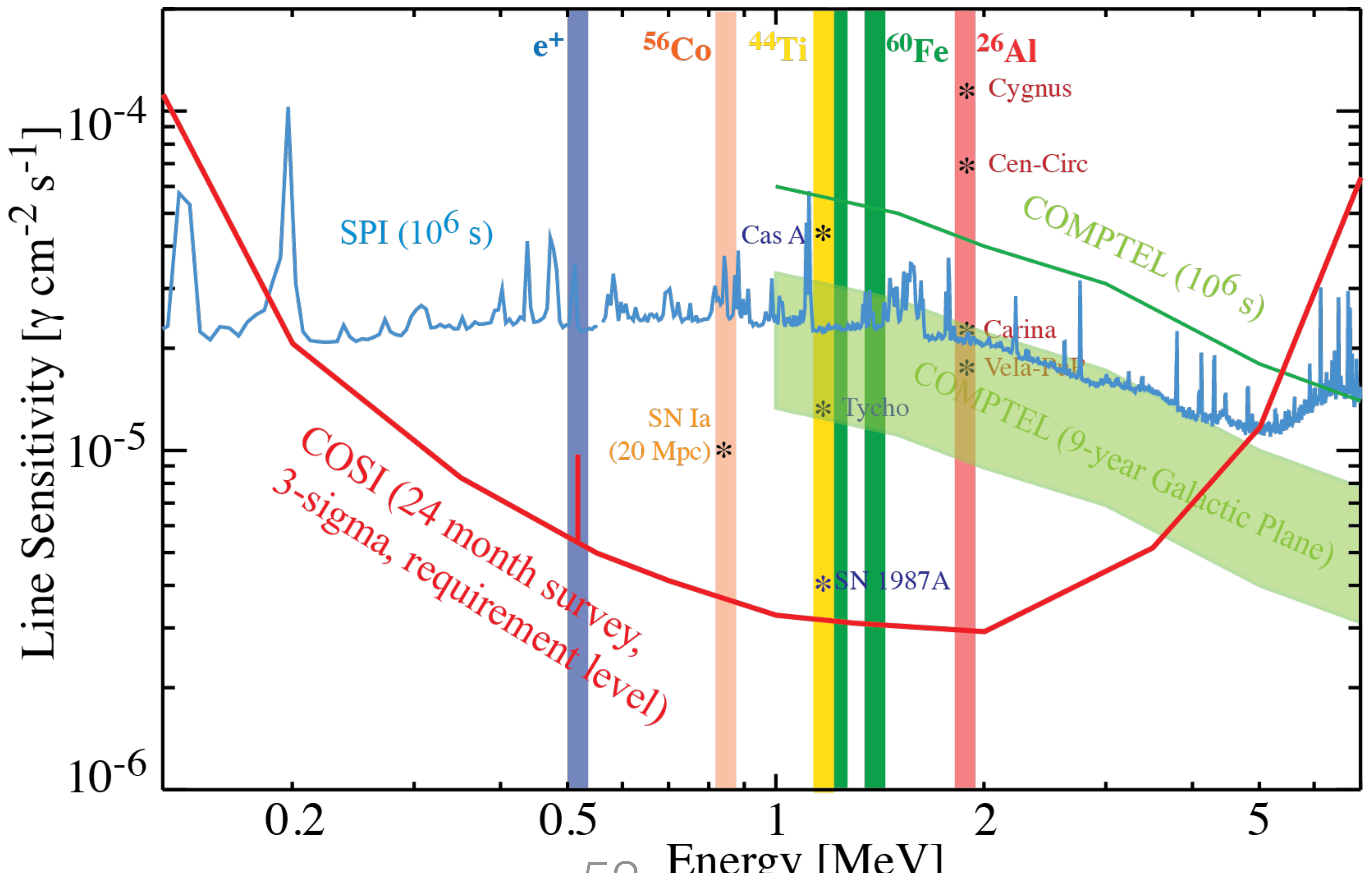
Work lead by R. Bonino, N. Cibrario, MN

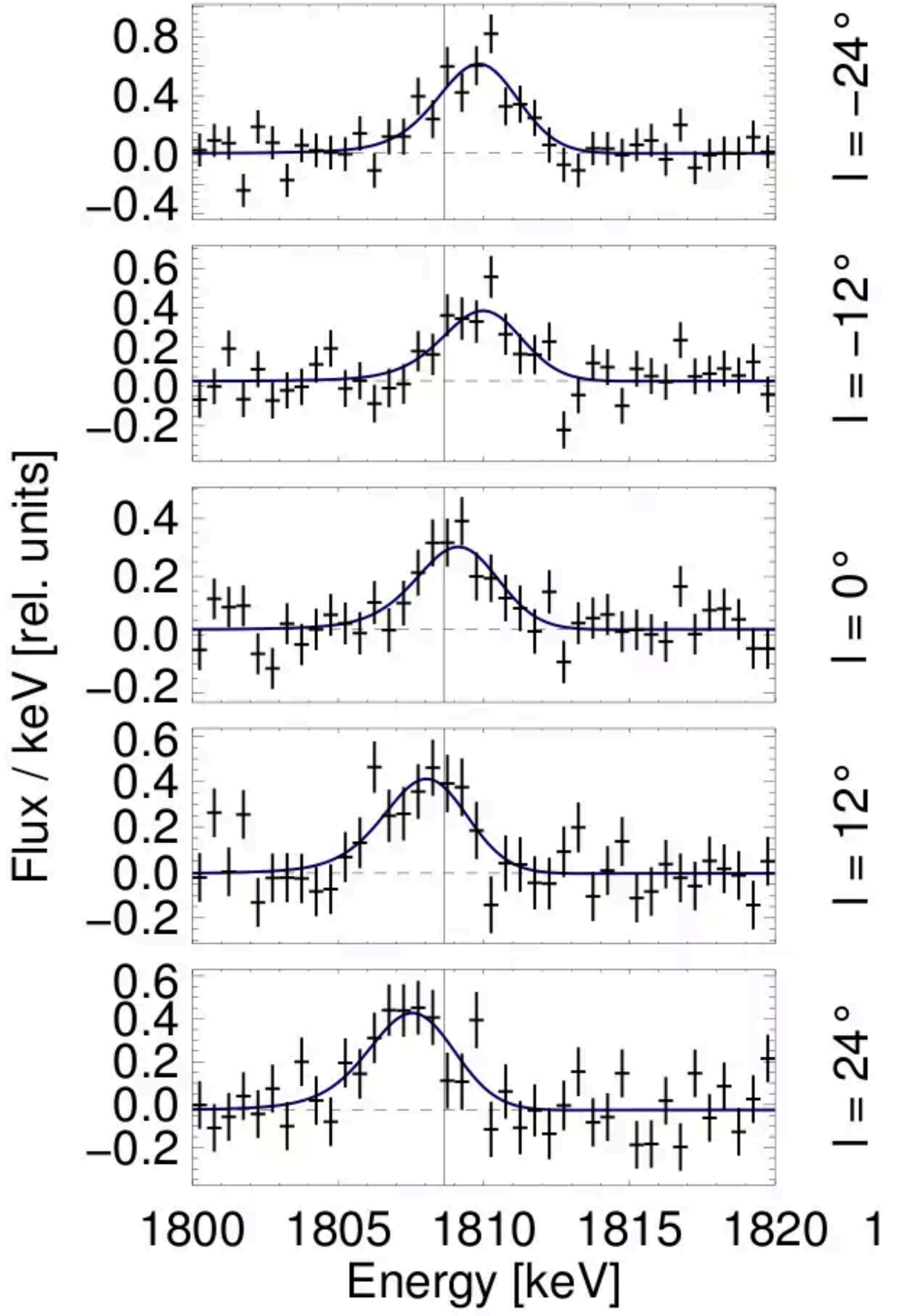
Stay tuned!

Nucleosynthesis to trace ISM

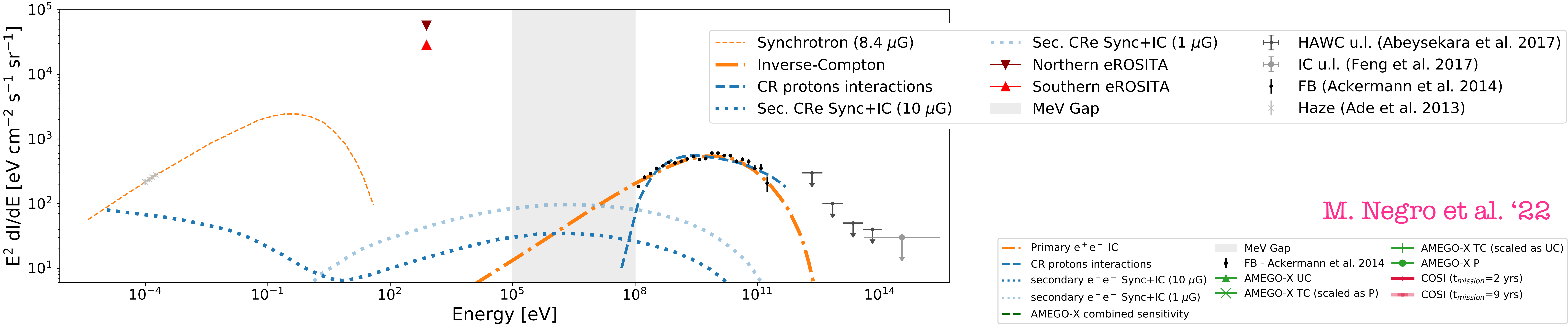
- Nucleosynthesis processes and their implications on the interstellar medium (Location of CR sources + feedback onto the ISM)
- line shape diagnostic: separate the rotational effect from the total line; improve the knowledge of galactic rotation



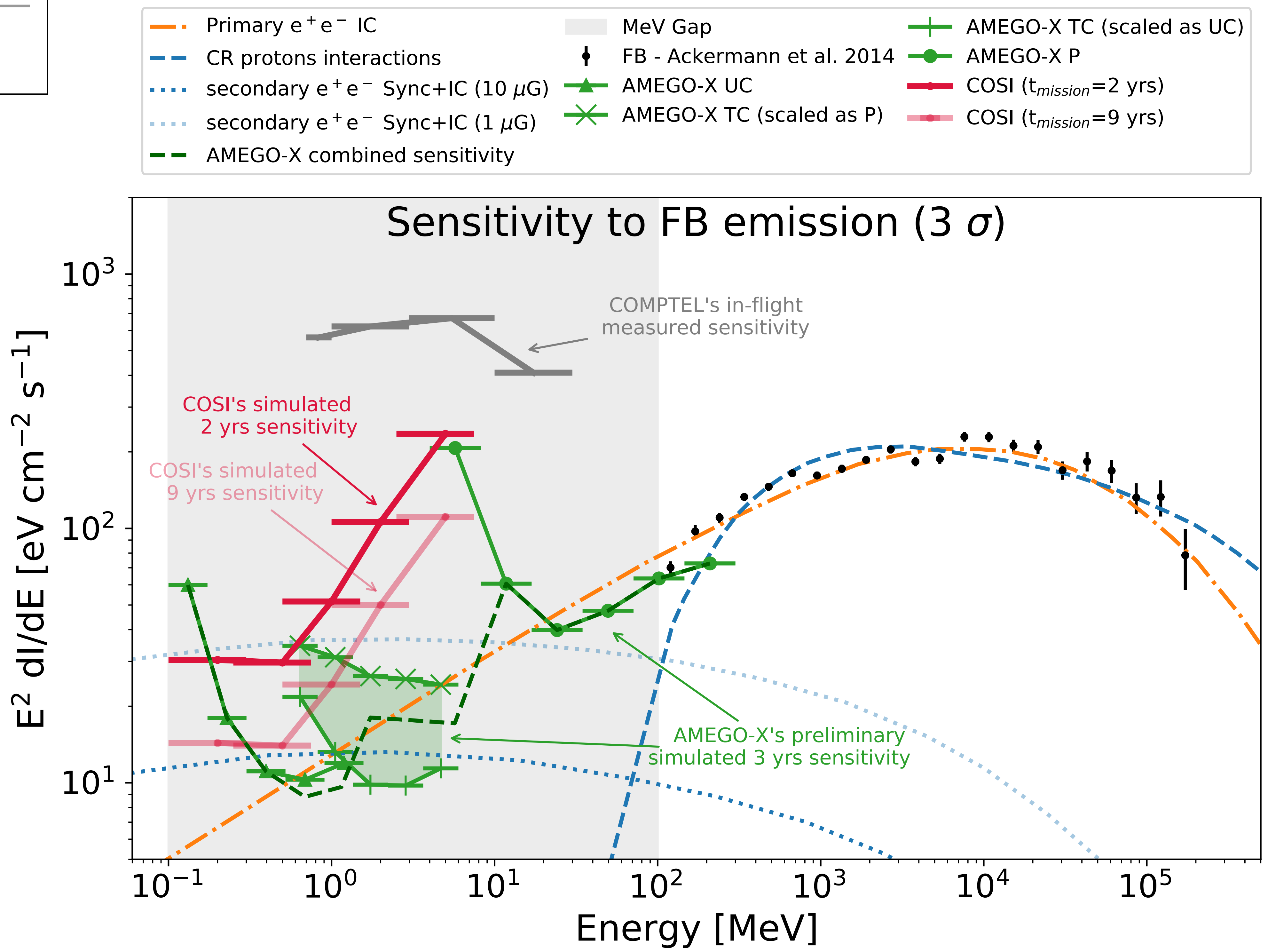




MeV view of the Fermi Bubbles



M. Negro et al. '22



- COSI could detect a secondary leptons component within the prime mission, constraining the magnetic field inside the FB.
- But a more sensitive sub GeV gamma-ray instrument would be better for this: AMEGO-X

Dust Exess

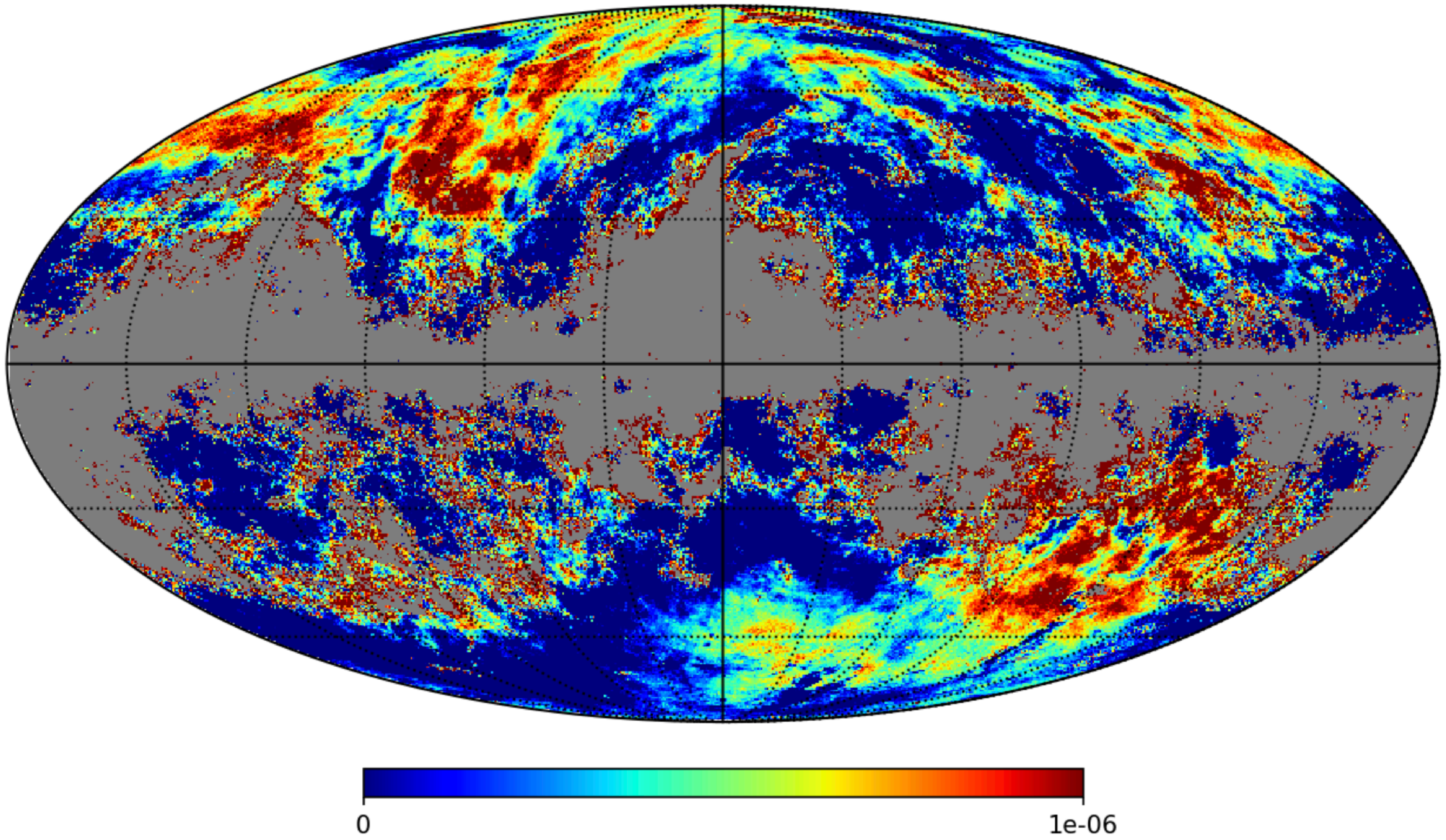


Figure 12. All-sky Mollweide display of the excess of optical depth at 353 GHz compared to $N_{\mathrm{H\,I}}$ predictions: $\tau_{353} - N_{\mathrm{H\,I}} \times \sigma_{e353}$. We used the opacity σ_{e353}=8.9×10^{-27} cm^2 measured in the Pegasus-Aquarius mask. The color is scaled linearly with the map intensity, and a 30° spaced grid is superimposed. We masked pixels with $\tau_{353}/\sigma_{e353} - N_{\mathrm{H\,I}} > 2\times10^{20}$ cm^{-2} where τ_{353} is not a good tracer for $N_{\mathrm{H\,I}}$.

UGRB Intensity Spectrum

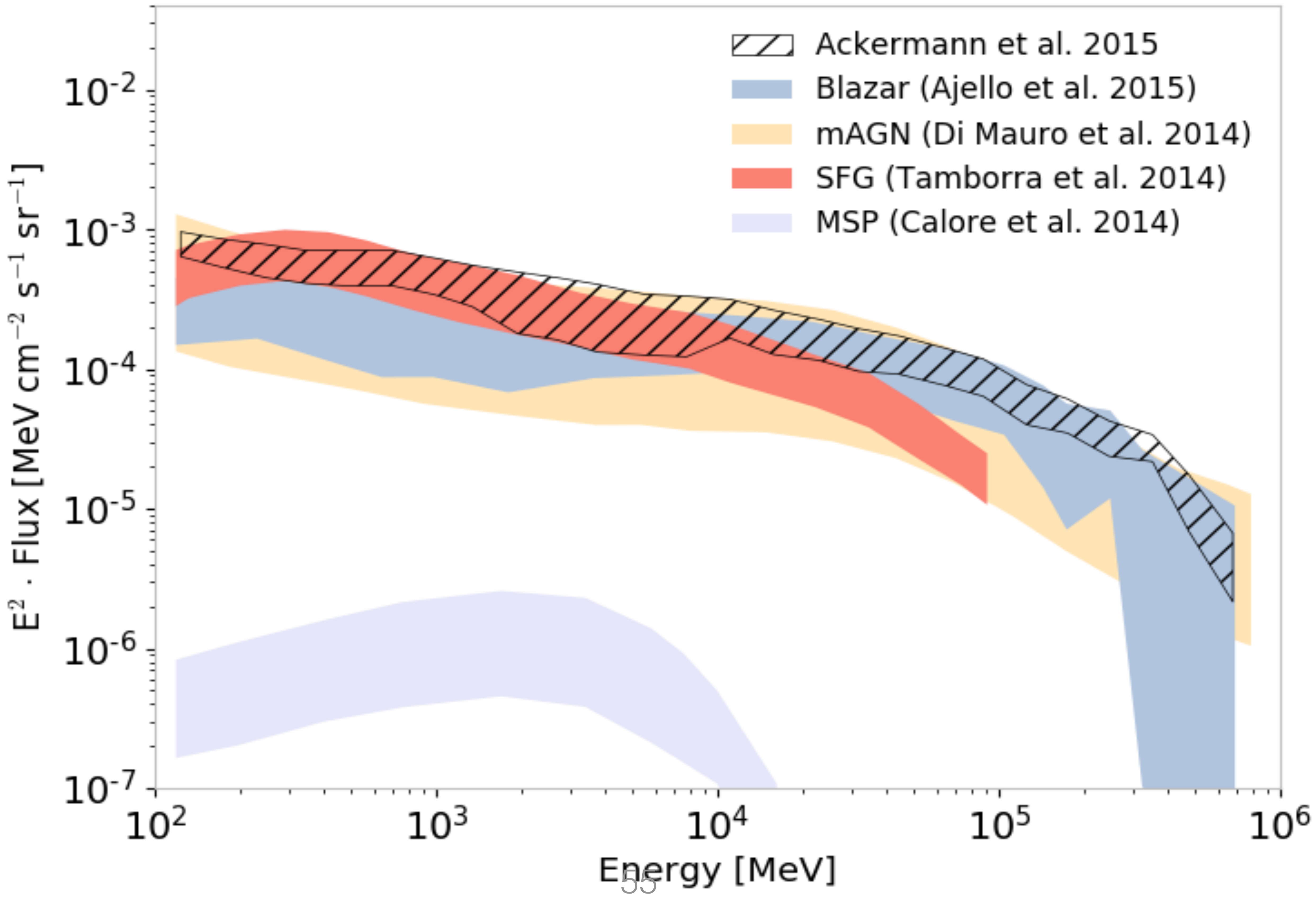

Blazars


Misaligned AGNs


Millisecond Pulsars

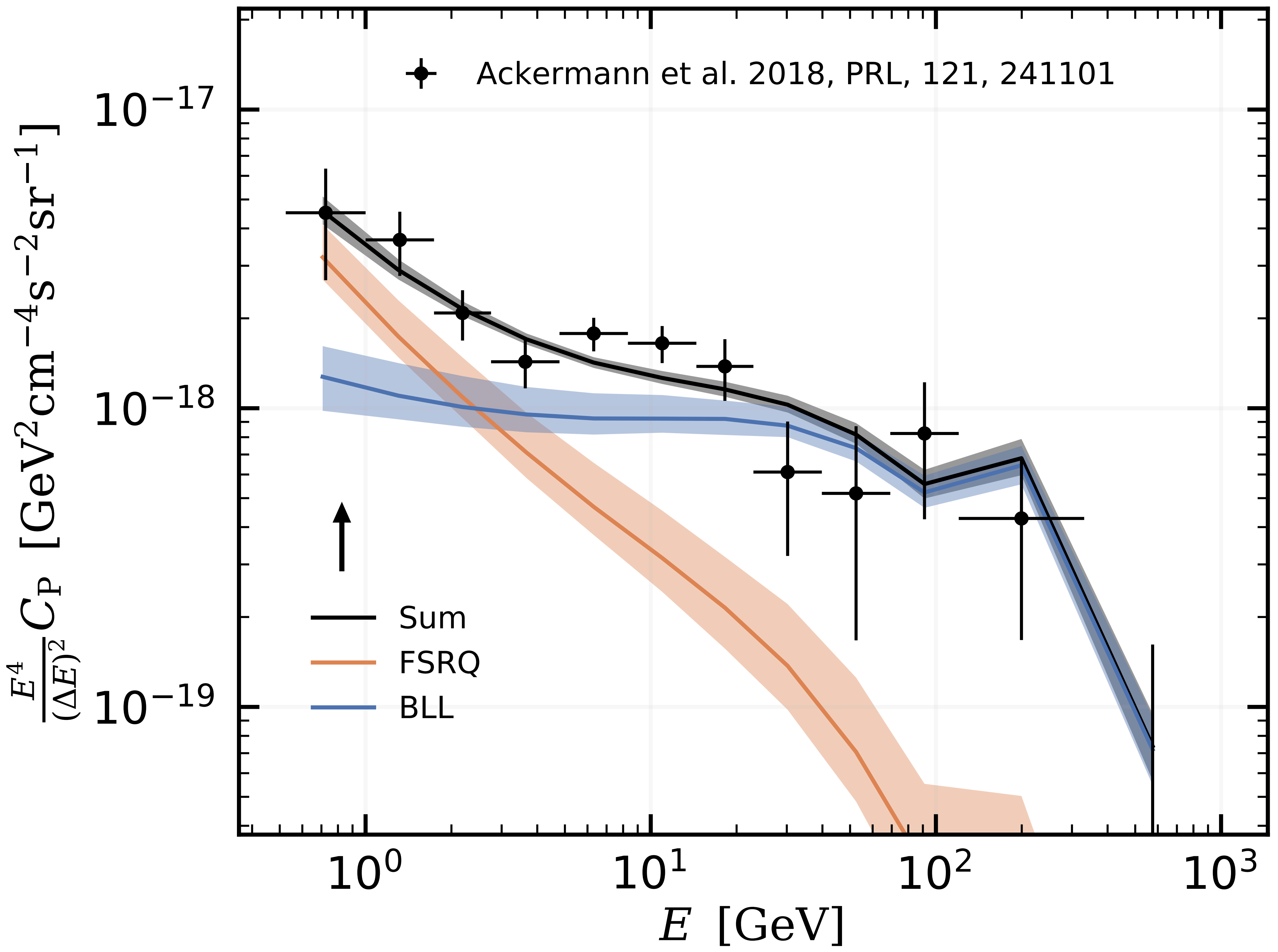

Star forming Galaxy

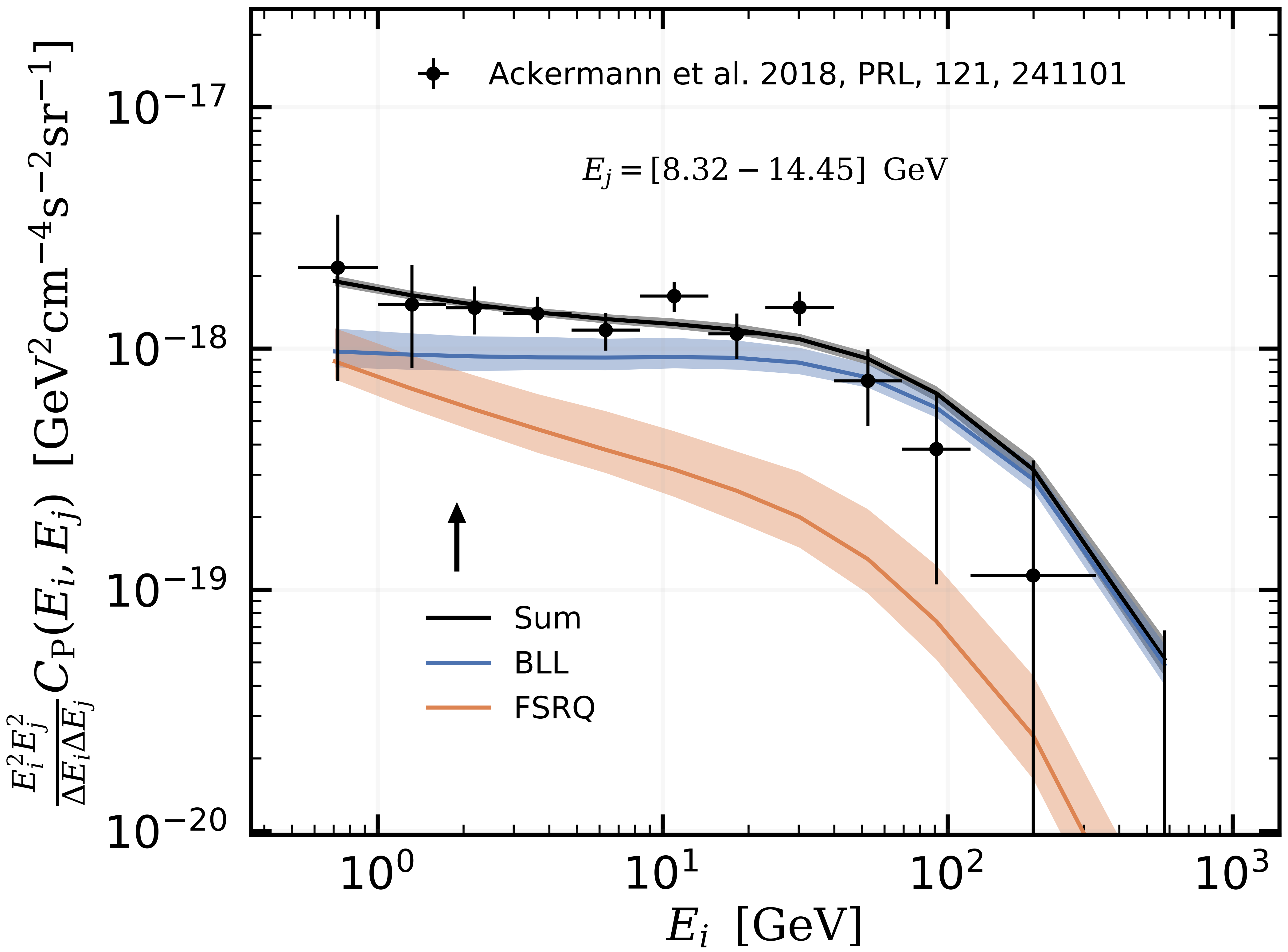

Dark Matter



Results

FSRQ + BLL = 100% UGRB anisotropy

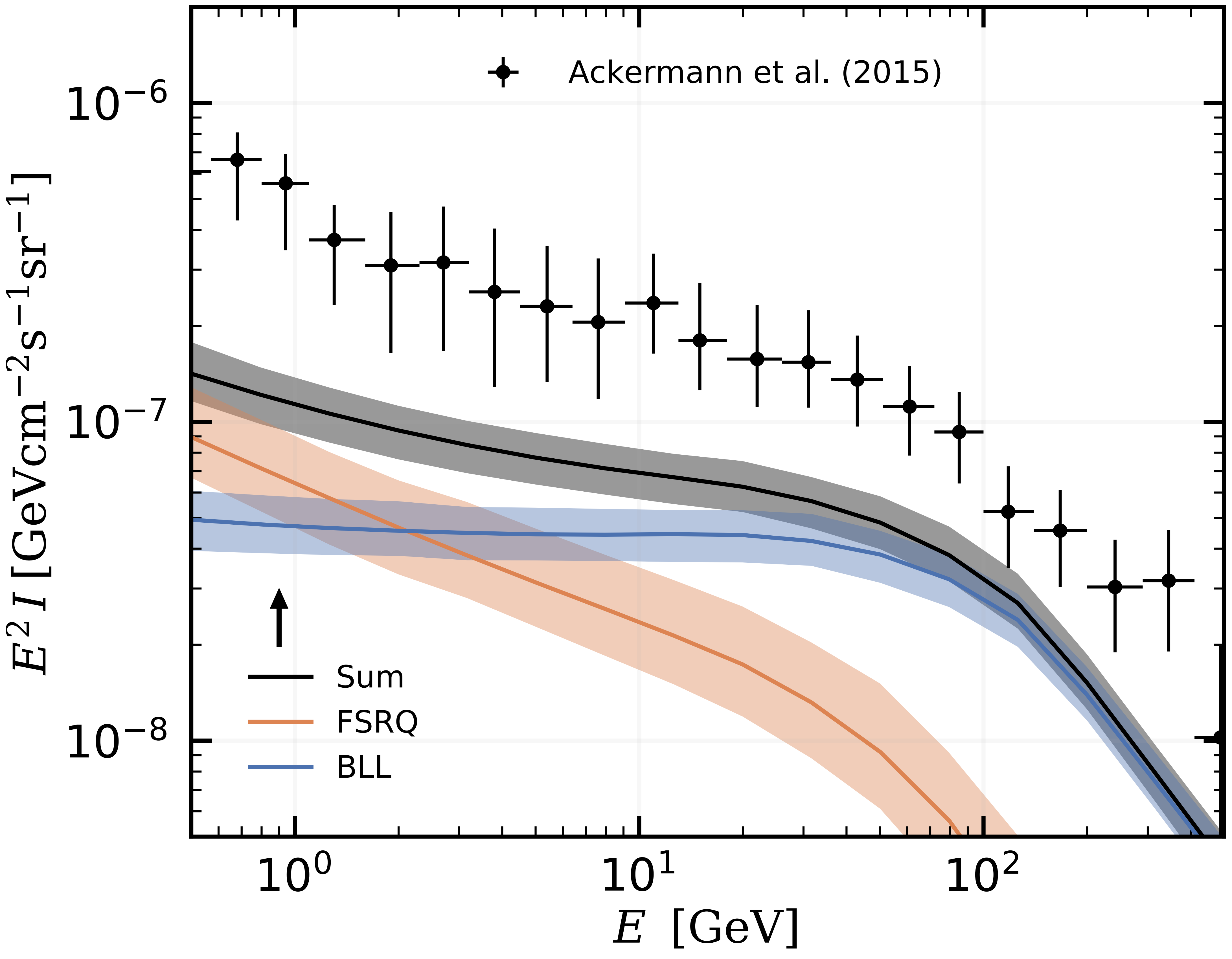




M. Korsmeier, E. Pinetti, **M.N** , M. Regis, N. Fornengo, ApJ 2022

Implications for the UGRB intensity spectrum

M. Korsmeier, E. Pinetti, **M.N.** , M. Regis, N. Fornengo, ApJ 2022

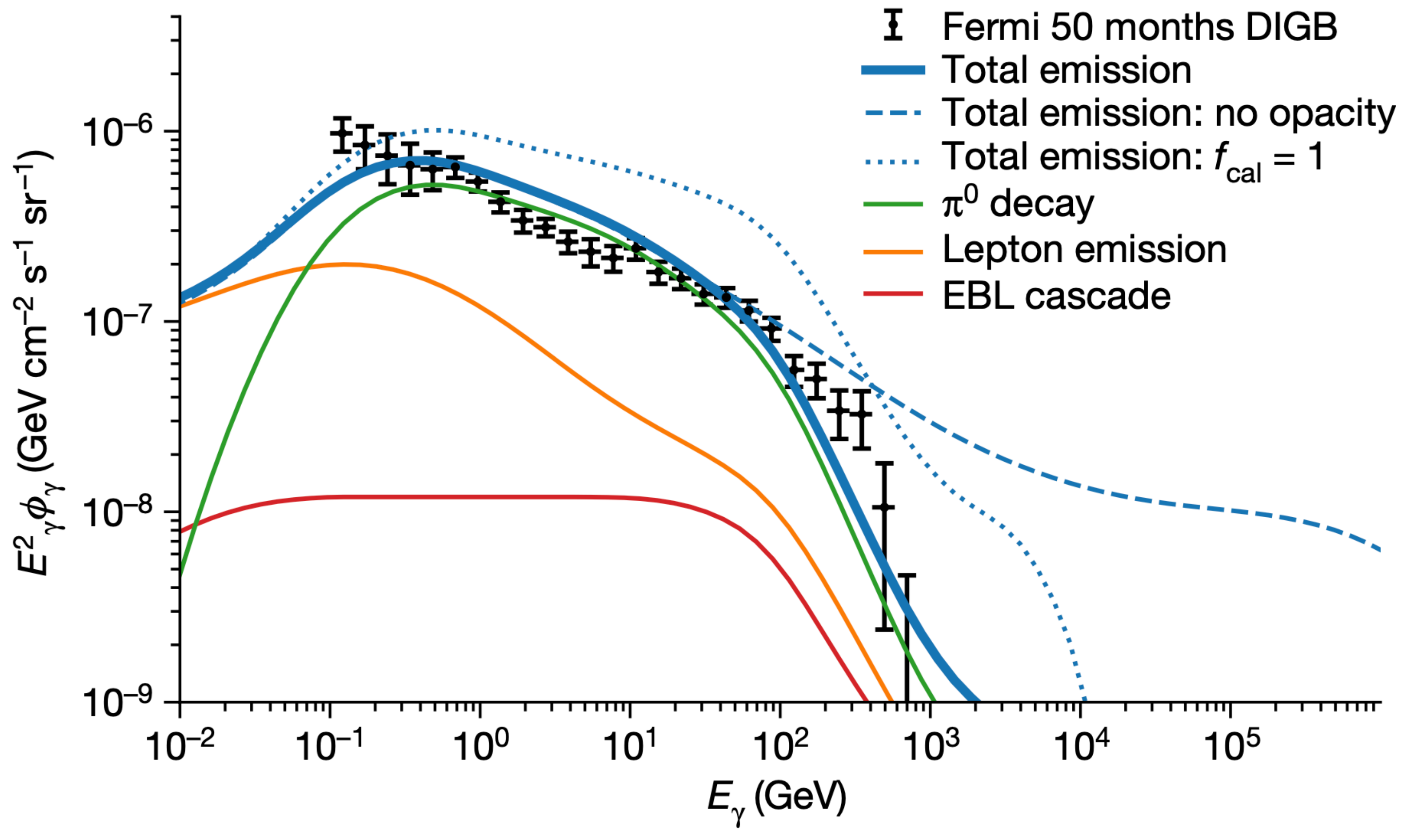


FSRQ + BLL = 100% UGRB anisotropy

Those blazars provide a significant contribution to the UGRB

- about 30% between 10 and 100 GeV
- about 20% below 1 GeV

M. A. Roth et al. Nature 597, 341–344 (2021)



HI line width

Mitzuno et al 2022

Use the line width to separate components in the gamma-ray emissivity fit

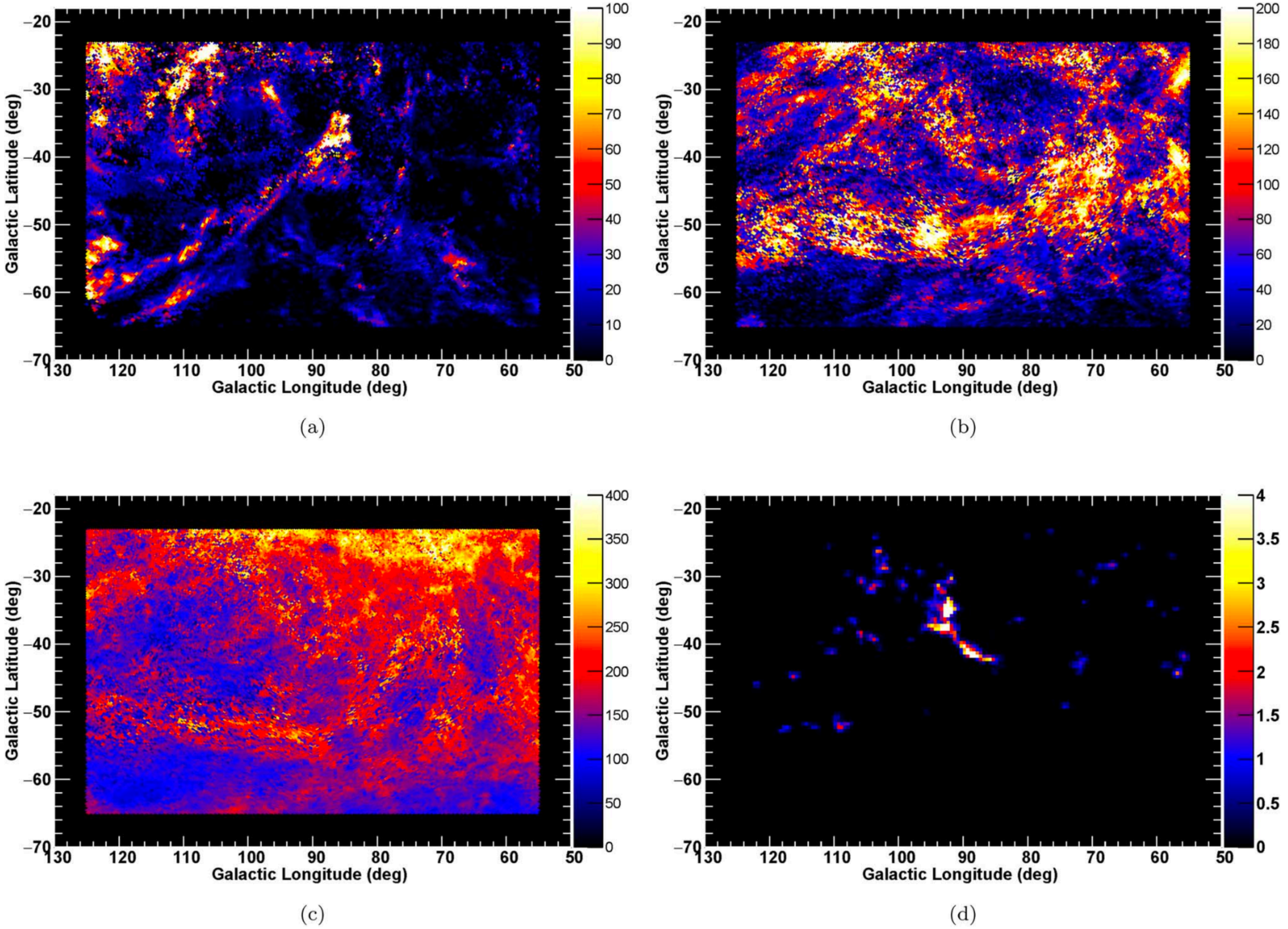


Figure 1. (a) W_{HI} map of the IVCs, (b) W_{HI} map of narrow H I, (c) W_{HI} map of broad H I, and (d) W_{CO} map. All these maps are shown in units of K km s^{-1}.