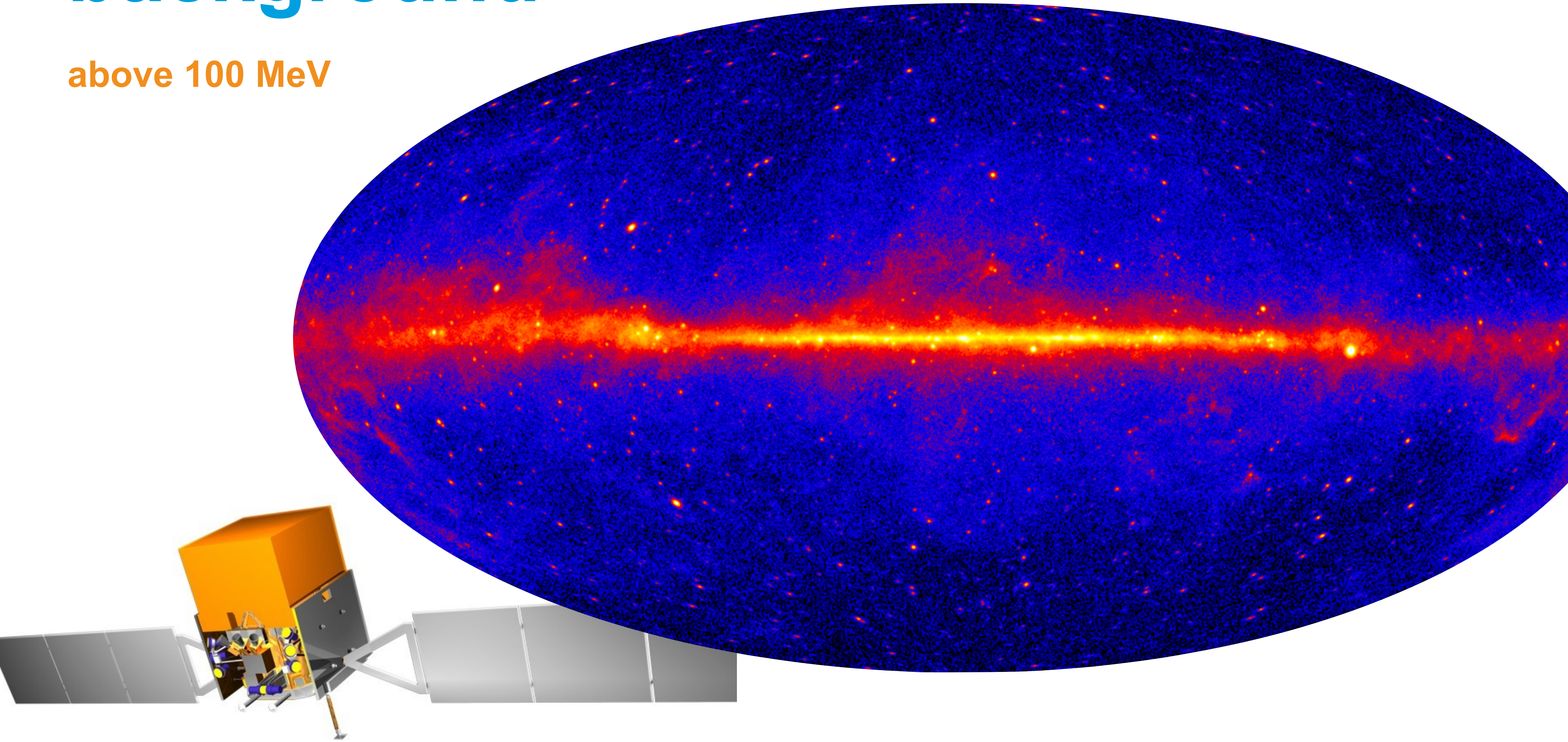
The extragalactic gamma-ray background

above 100 MeV

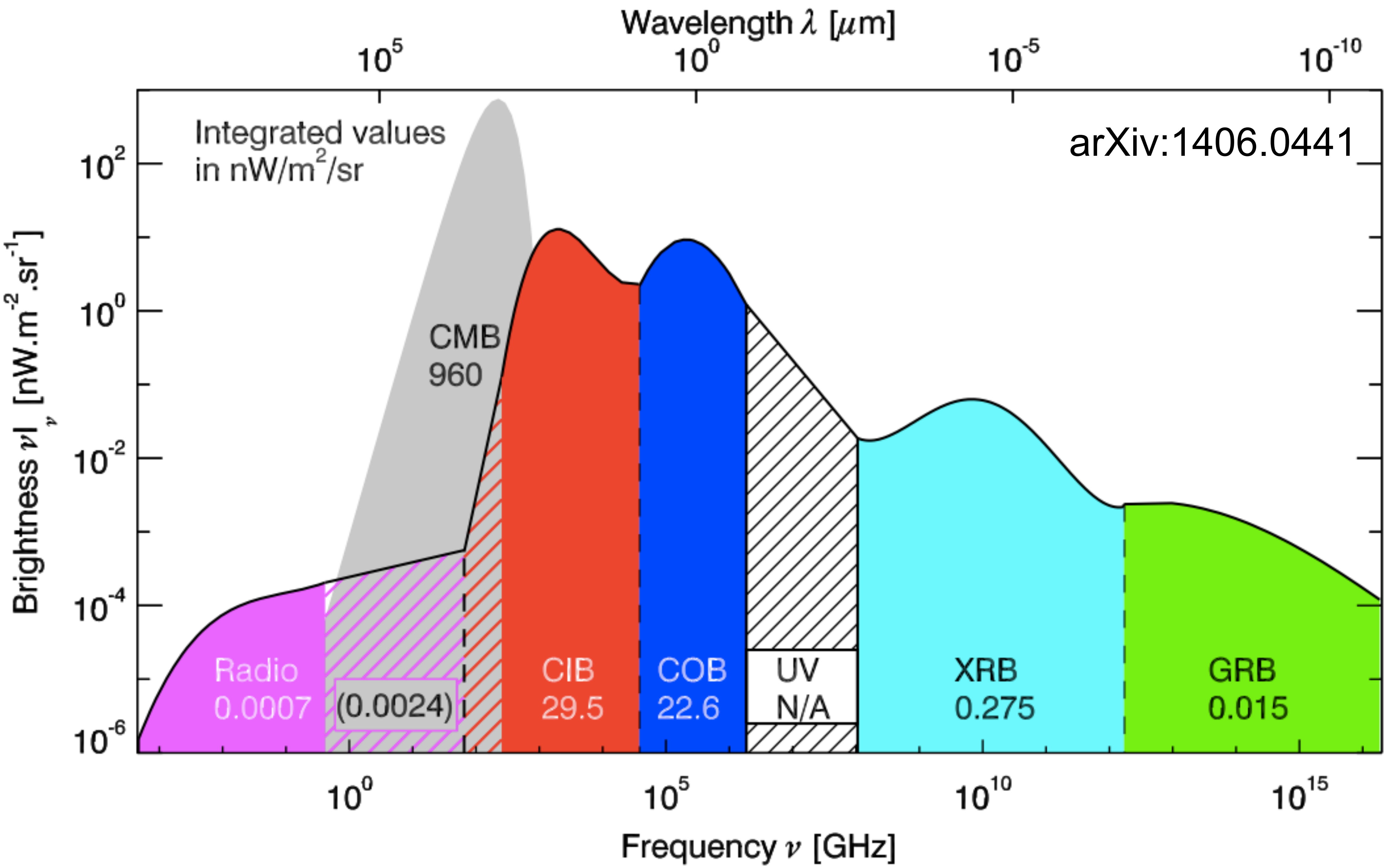


Markus Ackermann
UHECR 2018, Paris

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

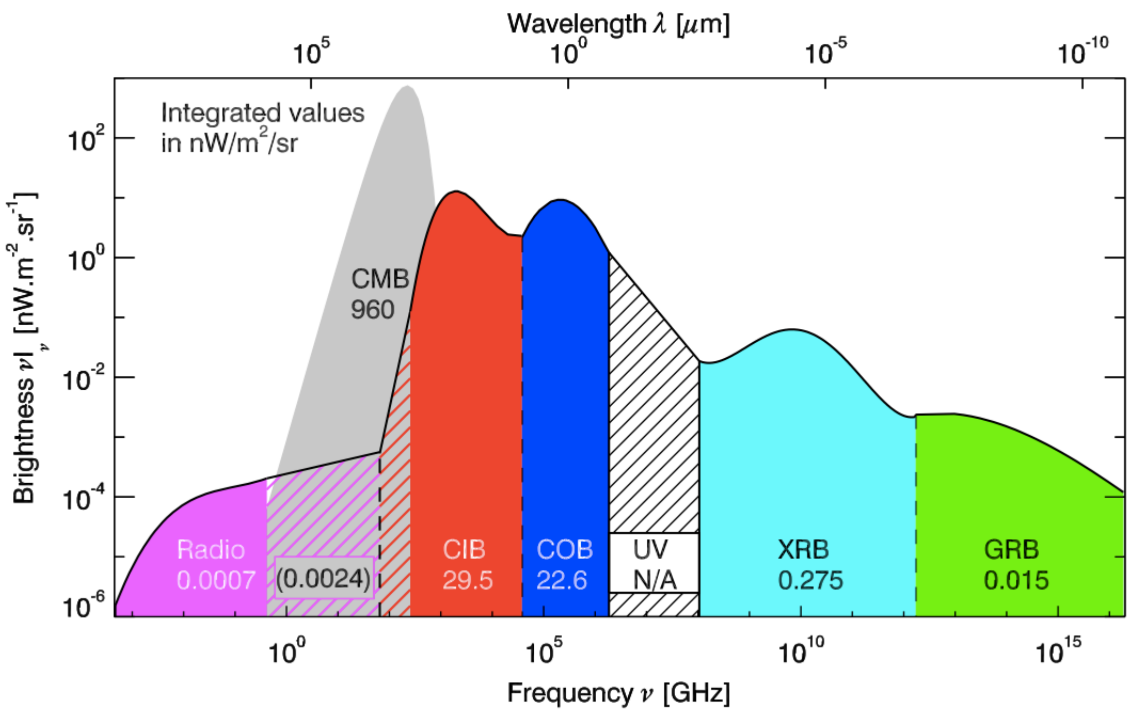
DESY.

Extragalactic radiation backgrounds

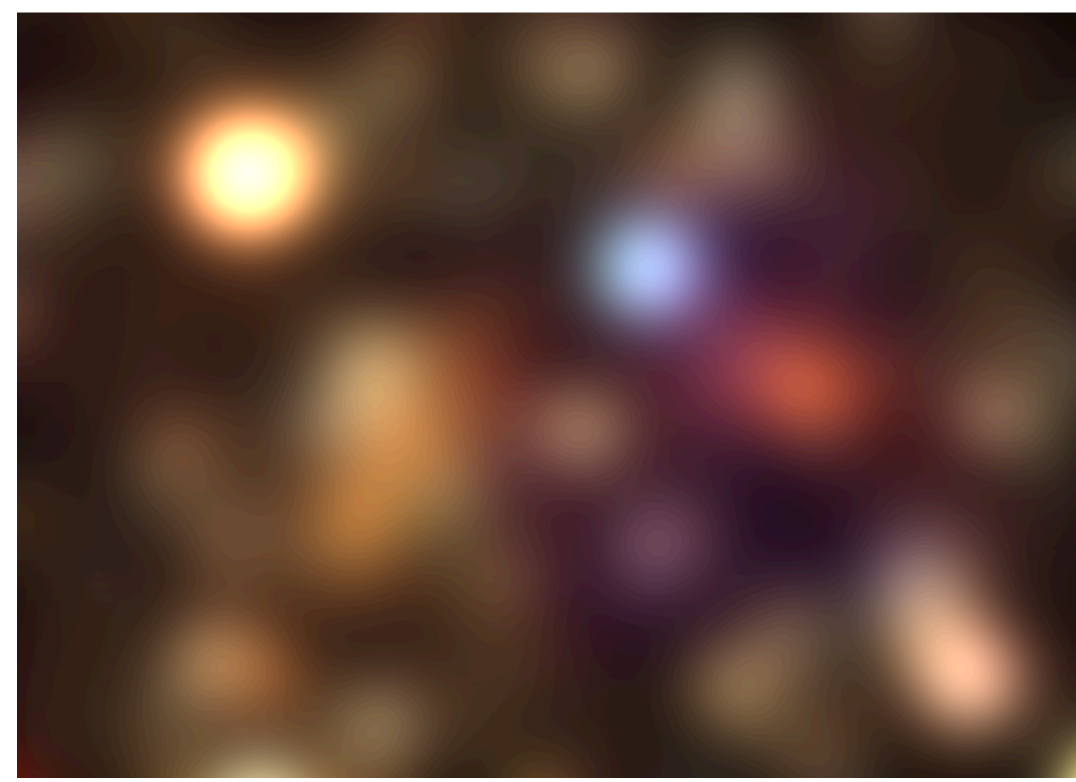


- **Radiation backgrounds** fill the universe from the lowest to the highest energies.

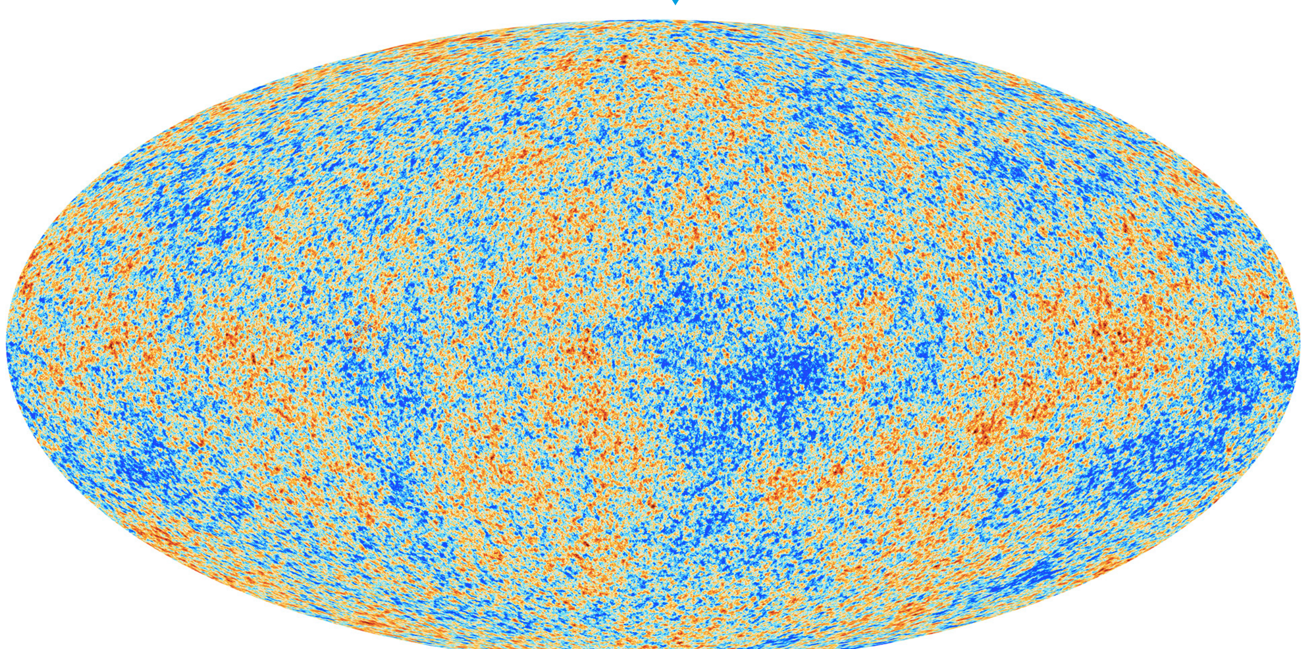
Origin of radiation backgrounds



Known source populations

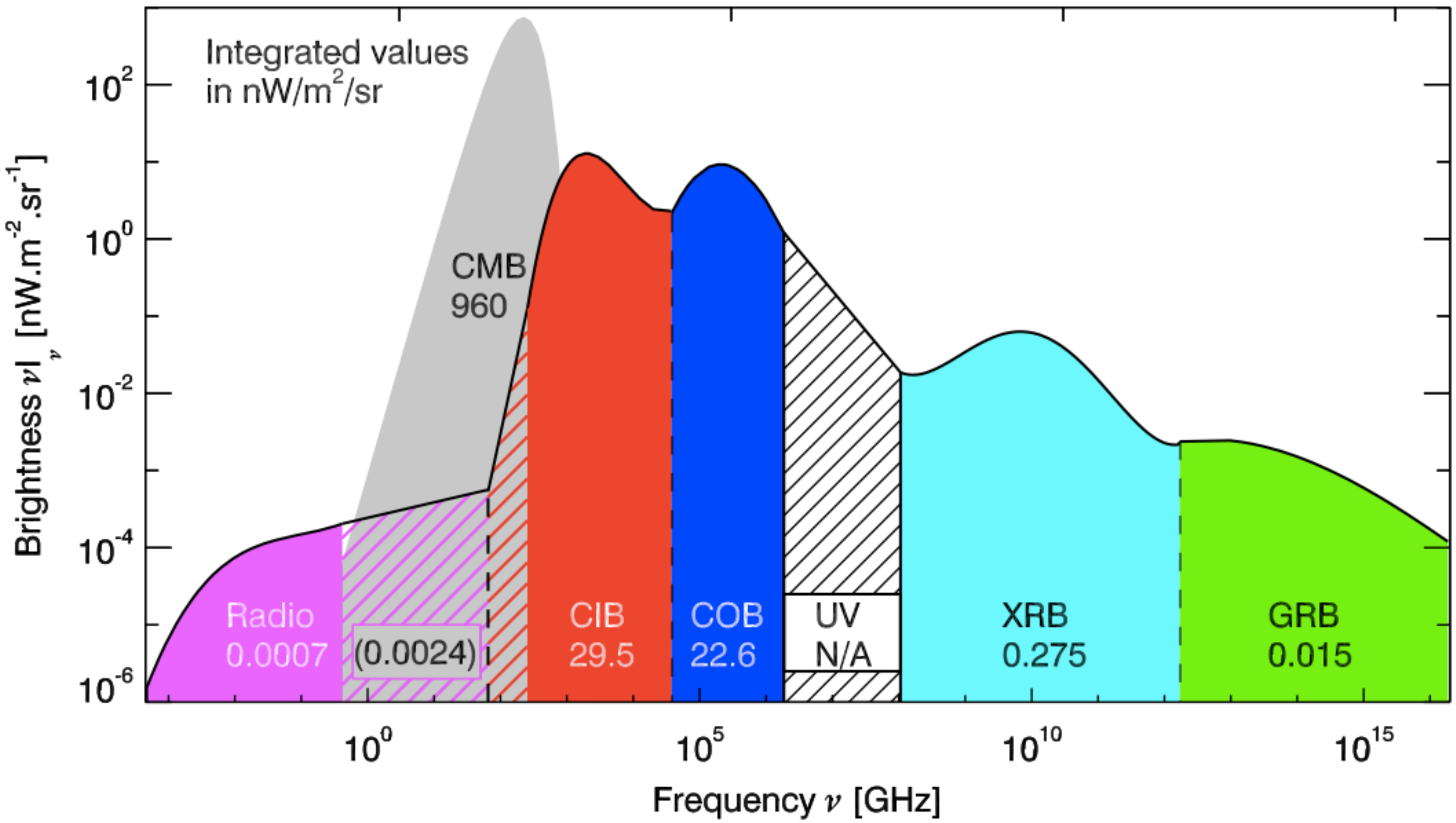


Sources too faint to be resolved.

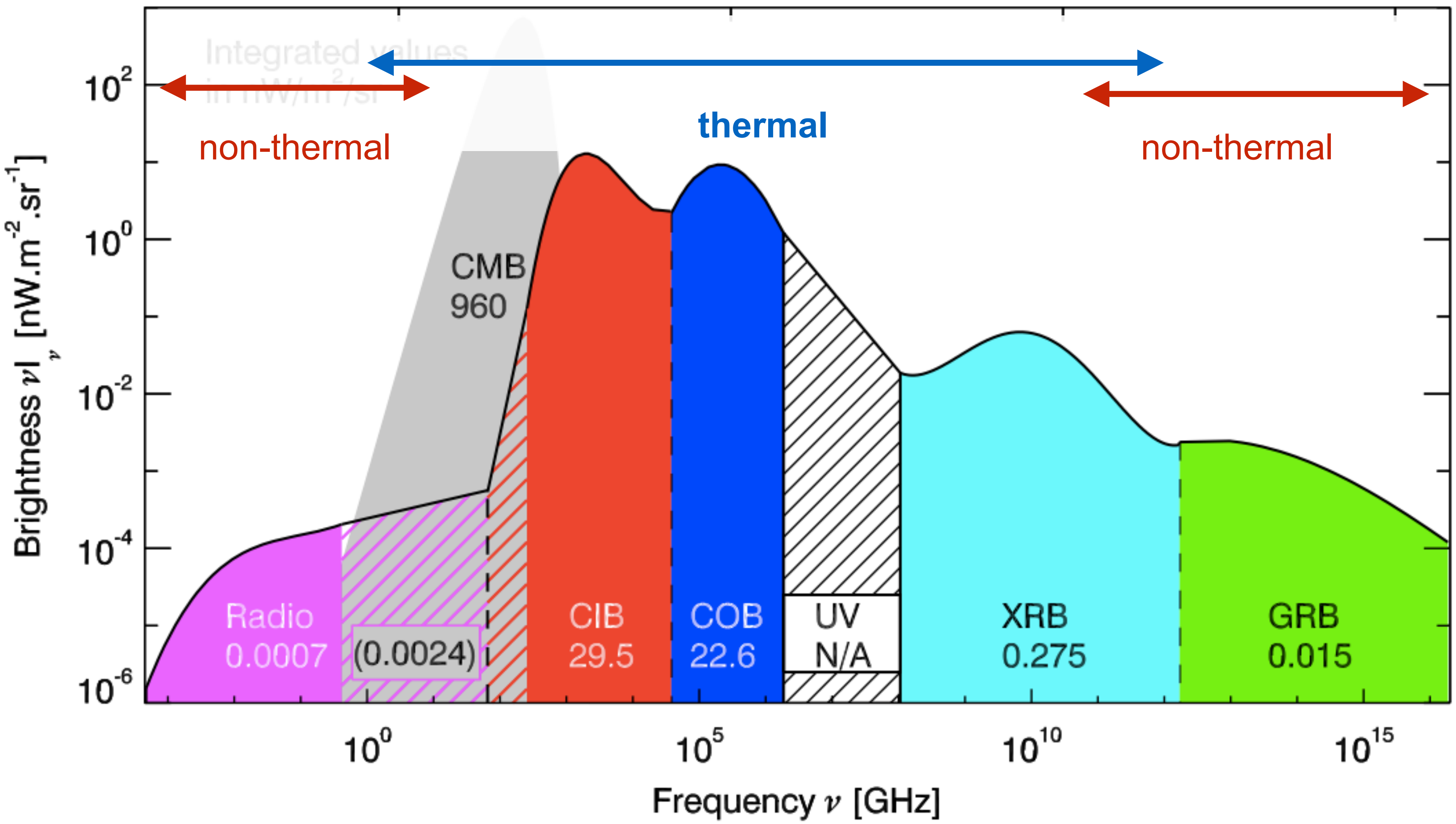


Diffuse radiation

Origin of radiation backgrounds



Origin of radiation backgrounds



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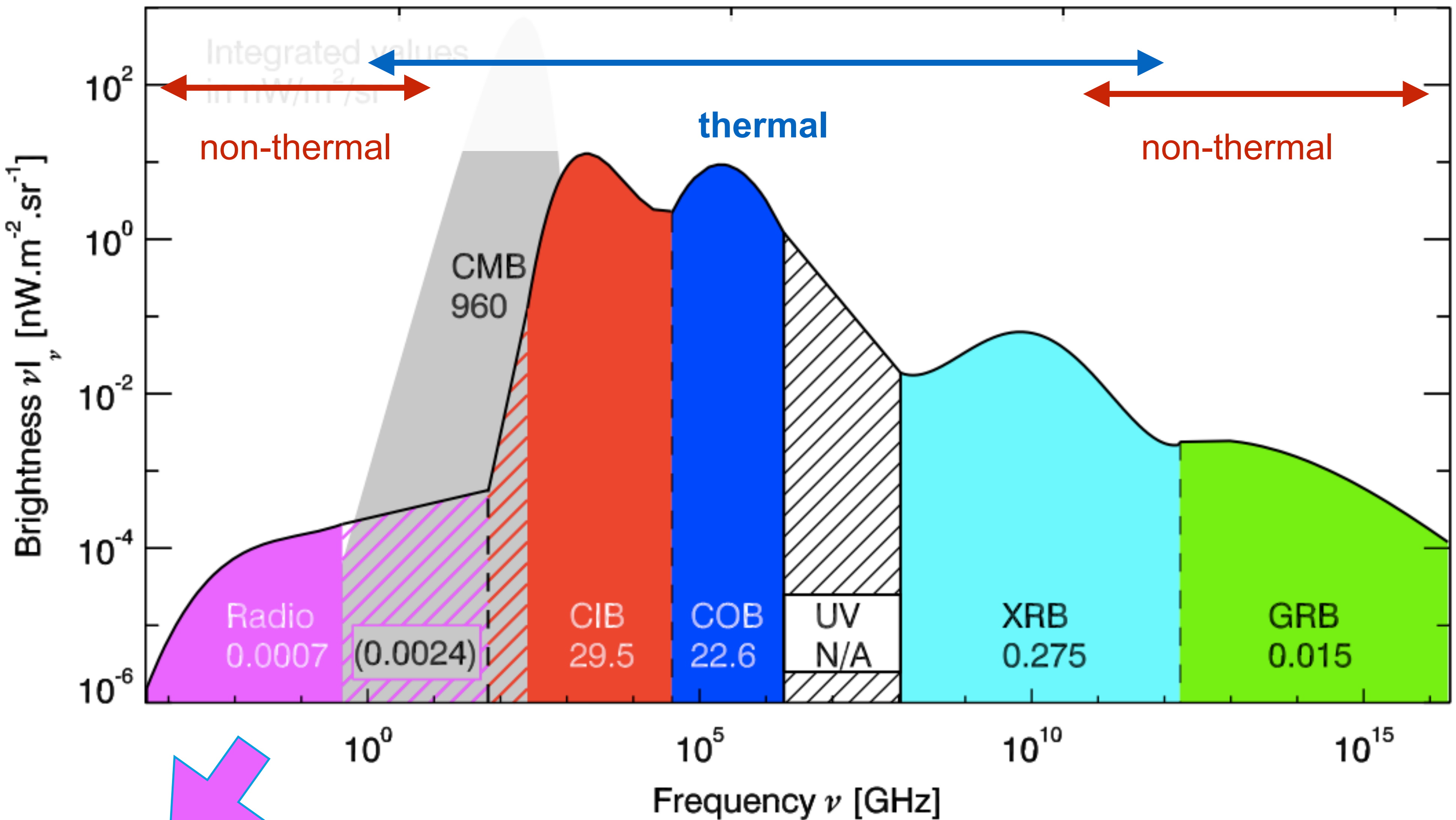
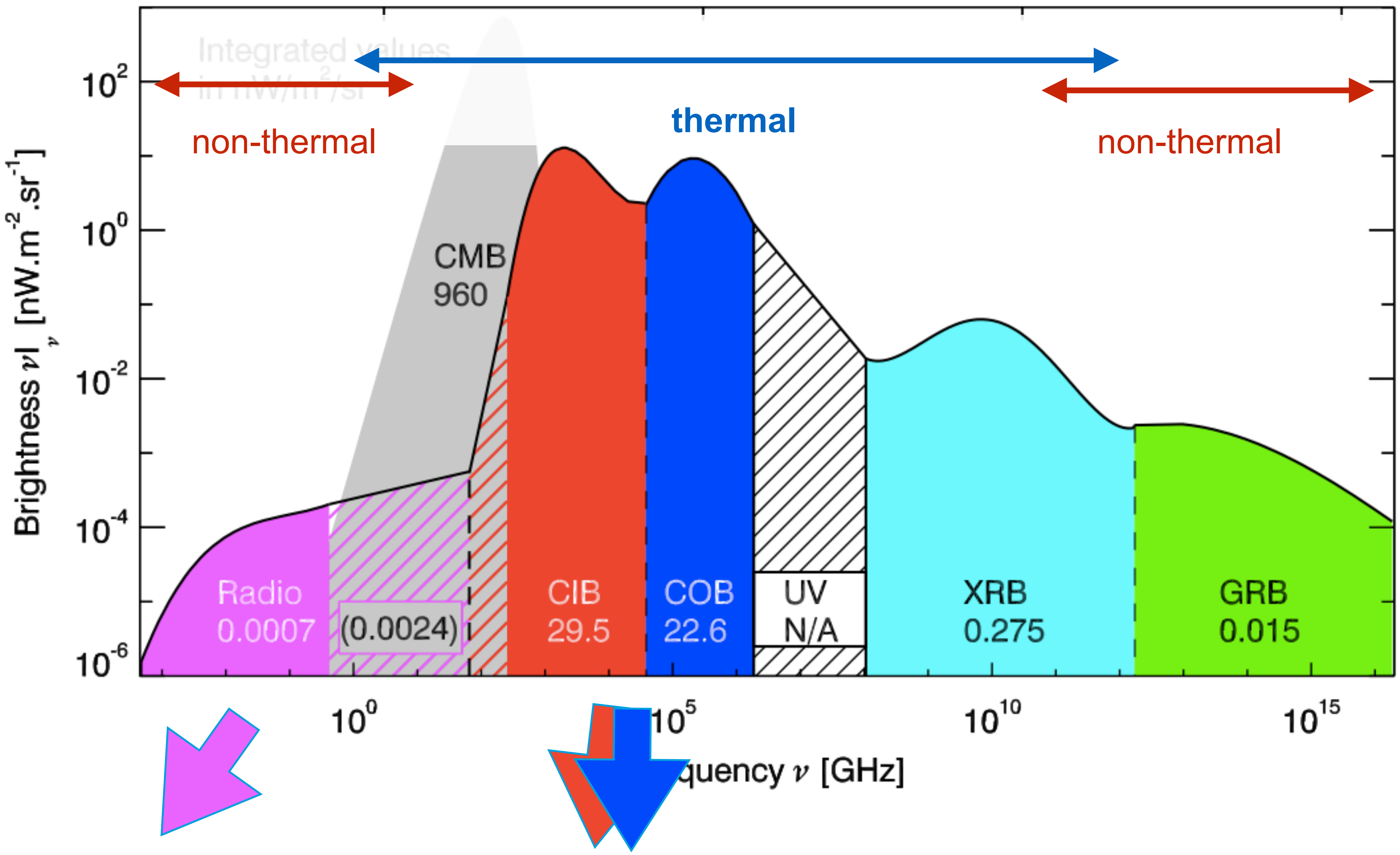


- **synchrotron emission** from galaxies & galactic cores.
- ???

Origin of radiation backgrounds



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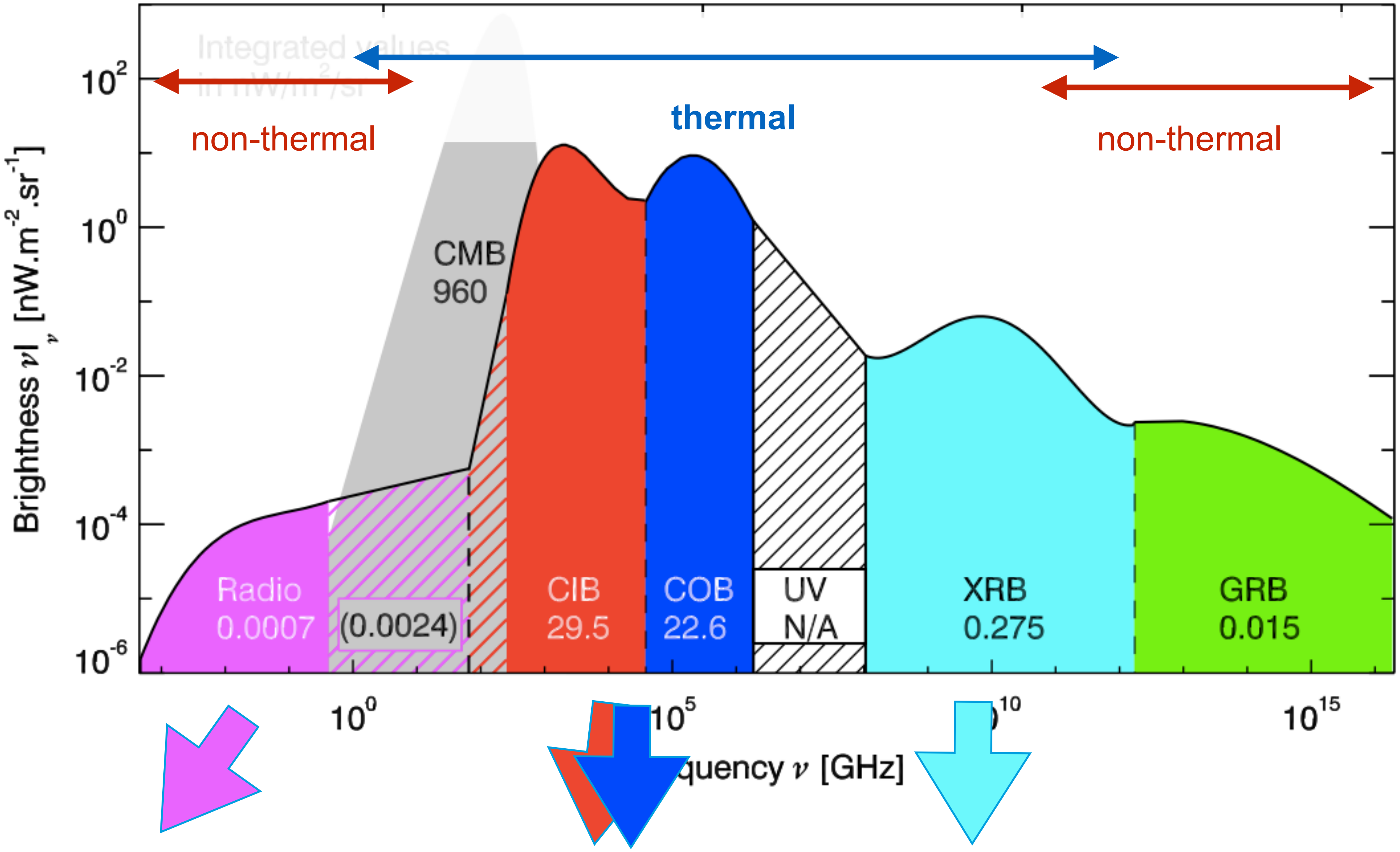
- **thermal emission** from stars and dust
- possible small contri-bution from **unknown stellar populations** (e.g., Pop III stars)

Origin of radiation backgrounds



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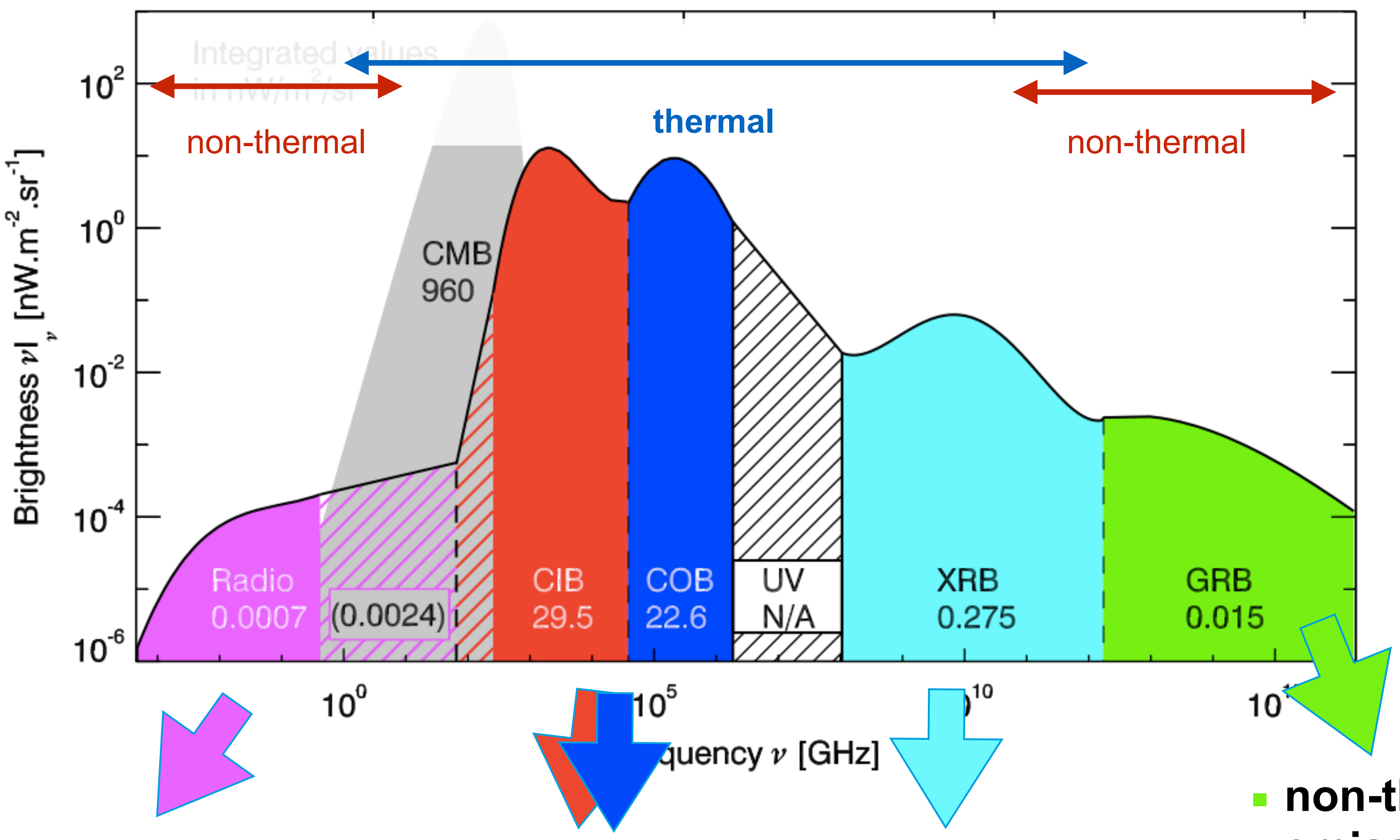
- **accretion disks** of active galactic nuclei (AGN)

DESY.

Origin of radiation backgrounds



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- ???

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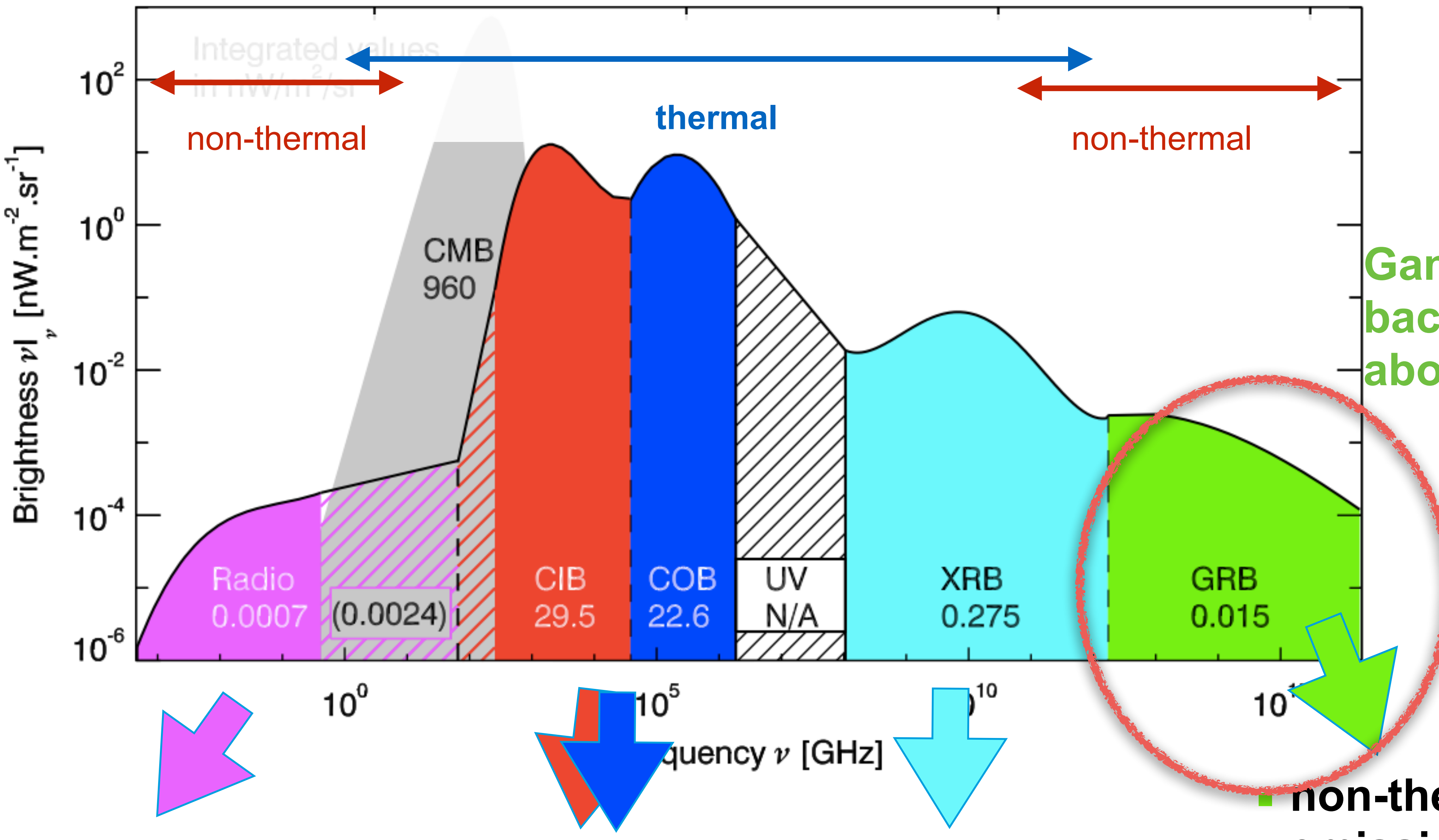
- **non-thermal emission** from normal and active galaxies
- **diffuse contributions** from CR, dark matter ??

Origin of radiation backgrounds



Gamma-ray background above 100 MeV

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- ???

- **thermal emission** from stars and dust
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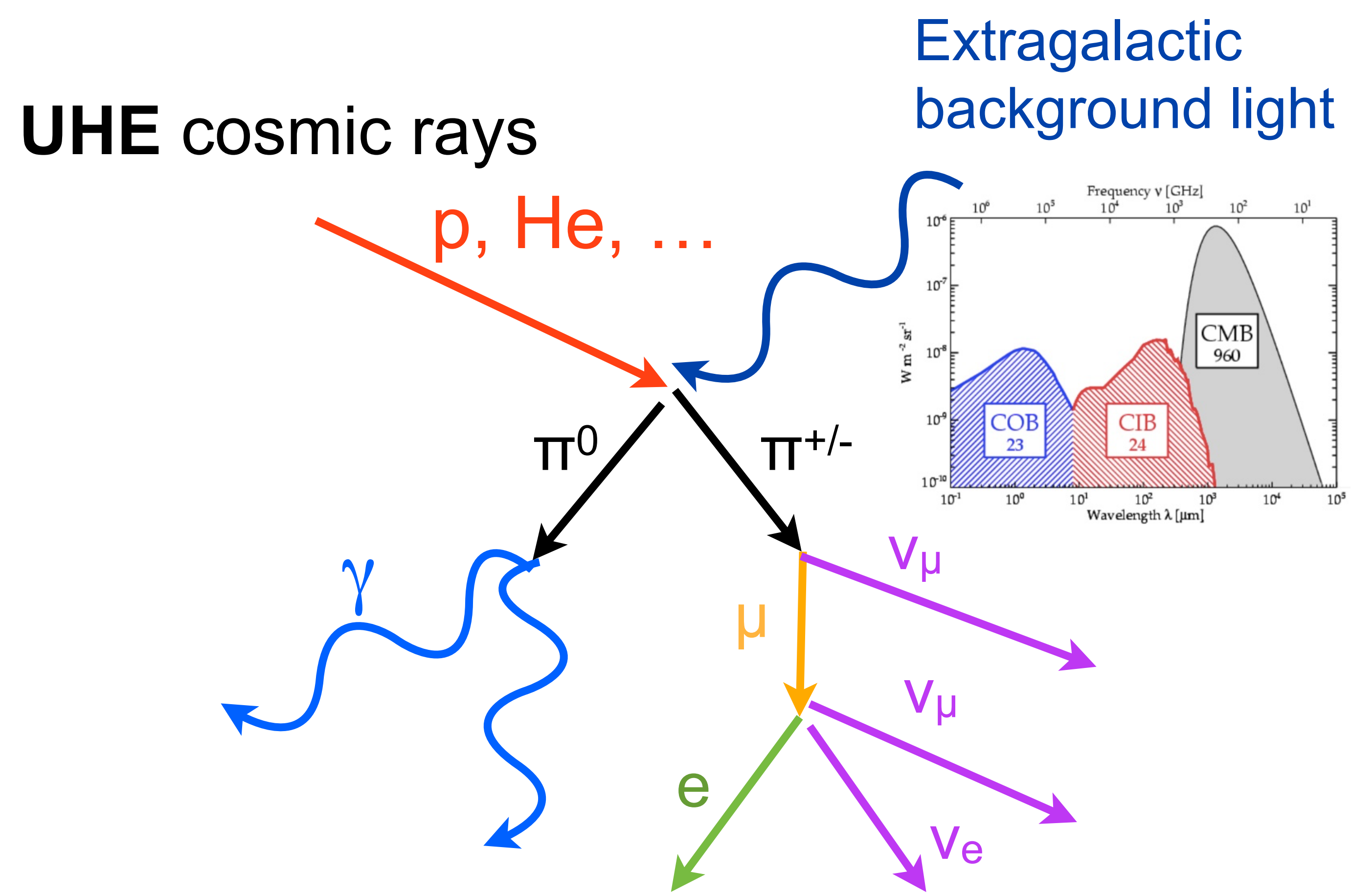
- **accretion disks** of active galactic nuclei (AGN)

- **non-thermal emission** from normal and active galaxies
- **diffuse contributions** from CR, dark matter ??

Extragalactic gamma rays and cosmic rays

- UHECR interact with radiation backrounds during propagation



Extragalactic gamma rays and cosmic rays

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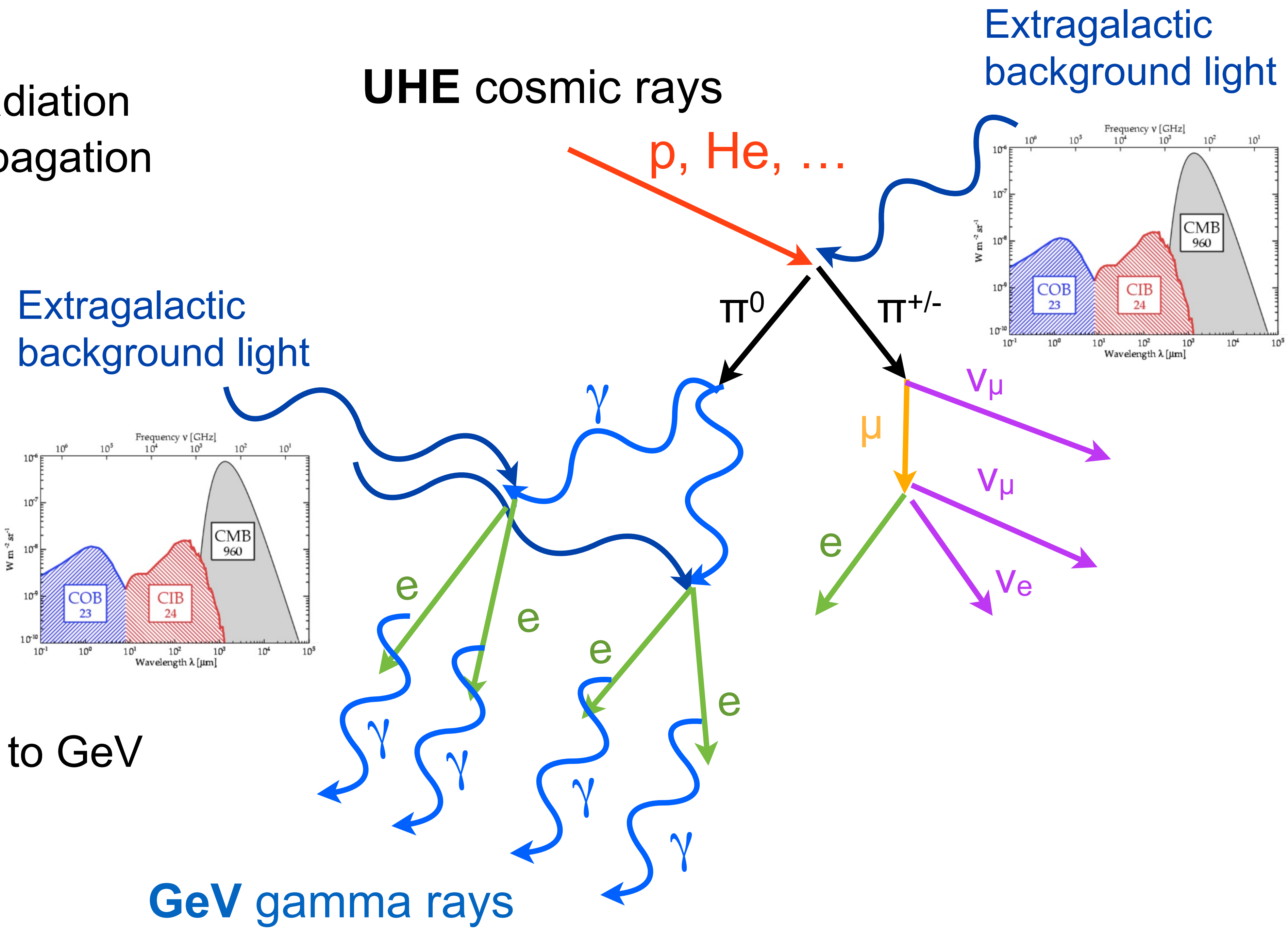

- Reprocessing of γ rays to GeV energies.

Extragalactic gamma rays and cosmic rays

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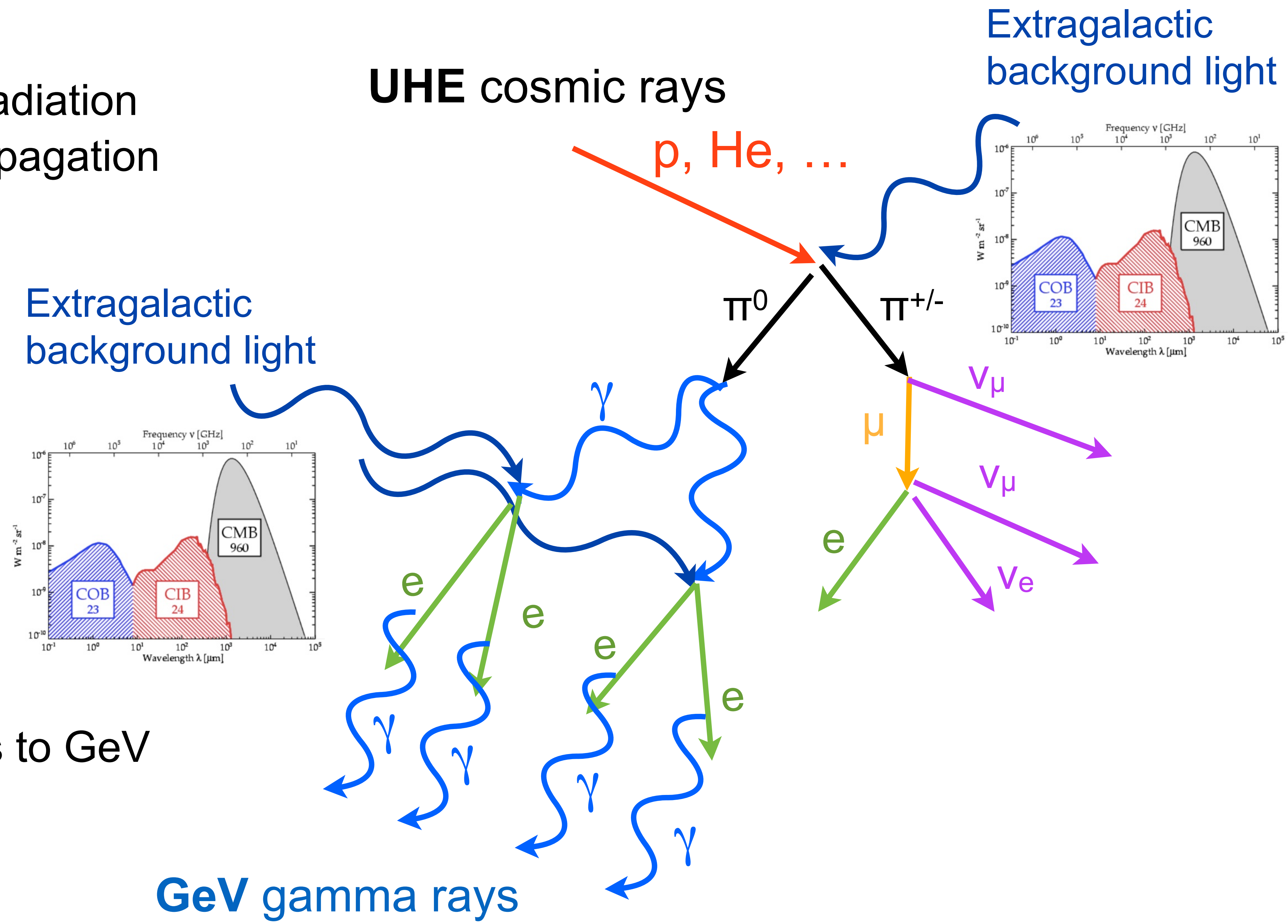
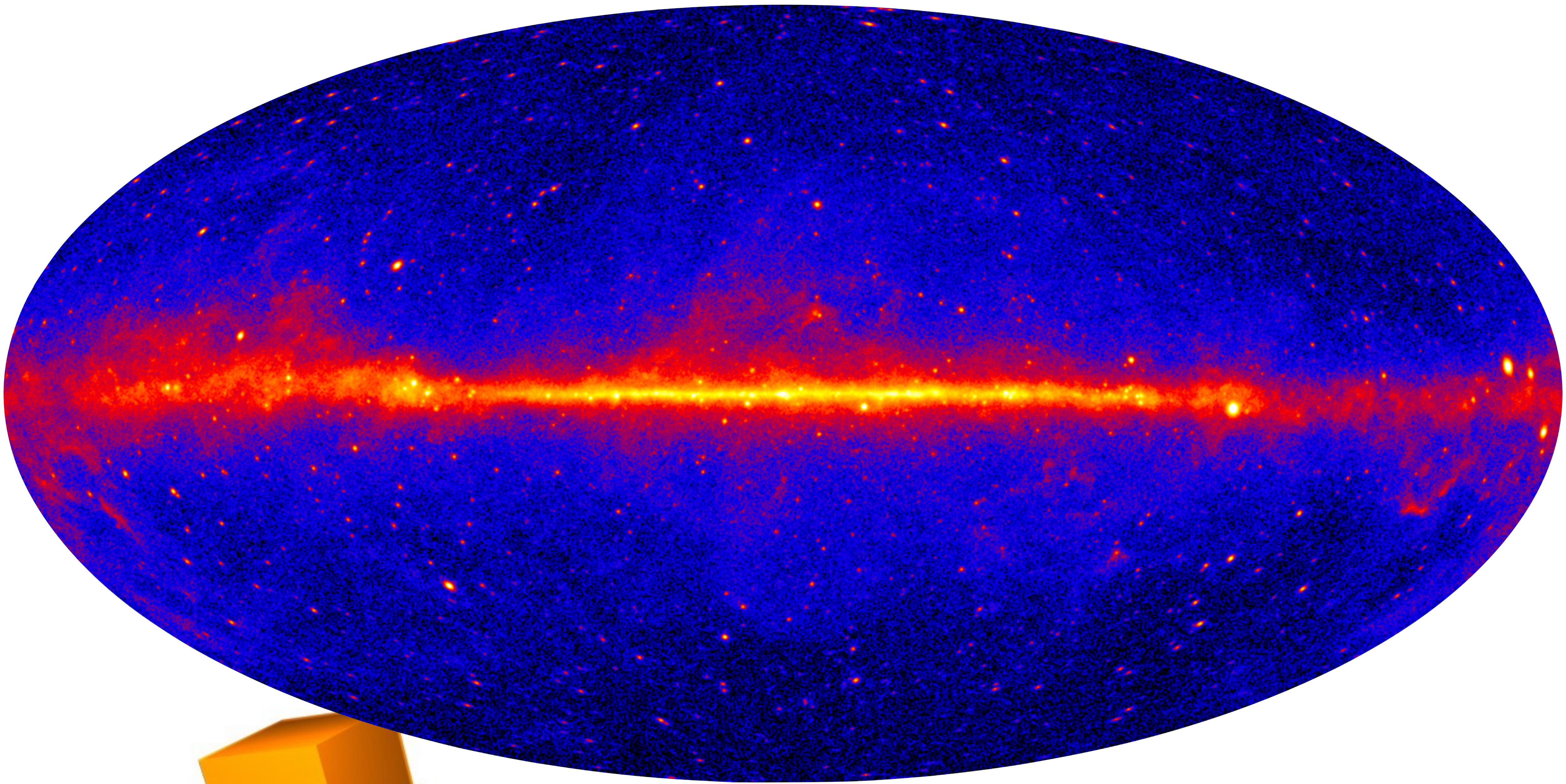


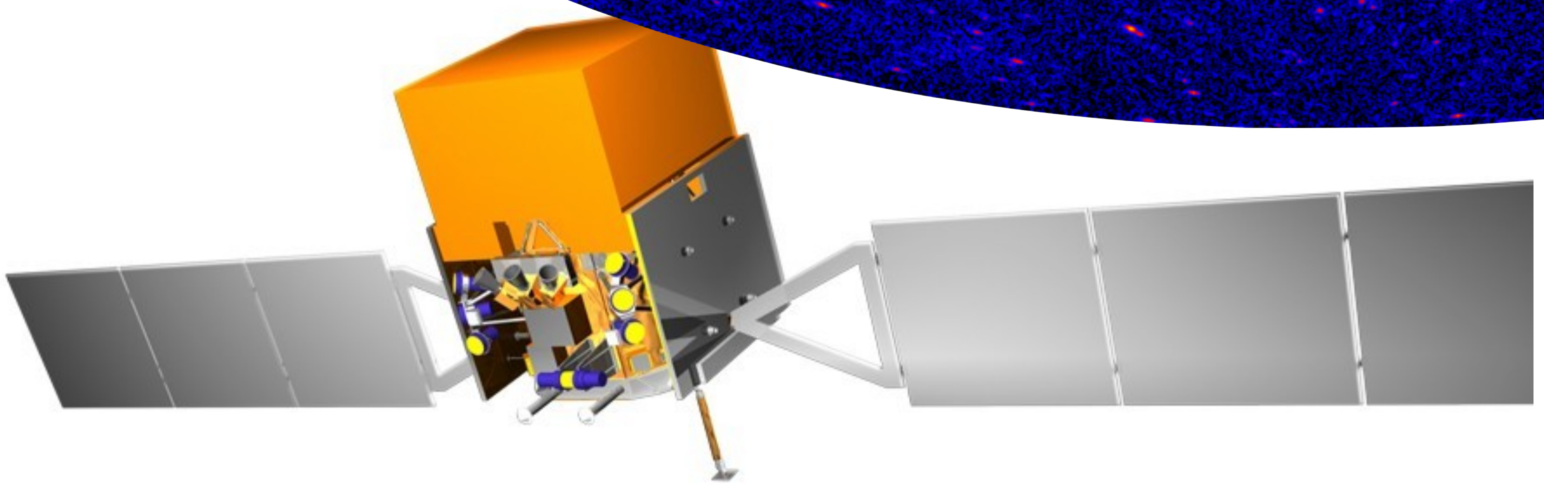
- Reprocessing of γ rays to GeV energies.

Extragalactic Gamma-ray Background (EGB) constrains UHECR propagation and interaction!

The gamma-ray sky observed by Fermi LAT

Fermi LAT, 4-year sky map, E > 1 GeV





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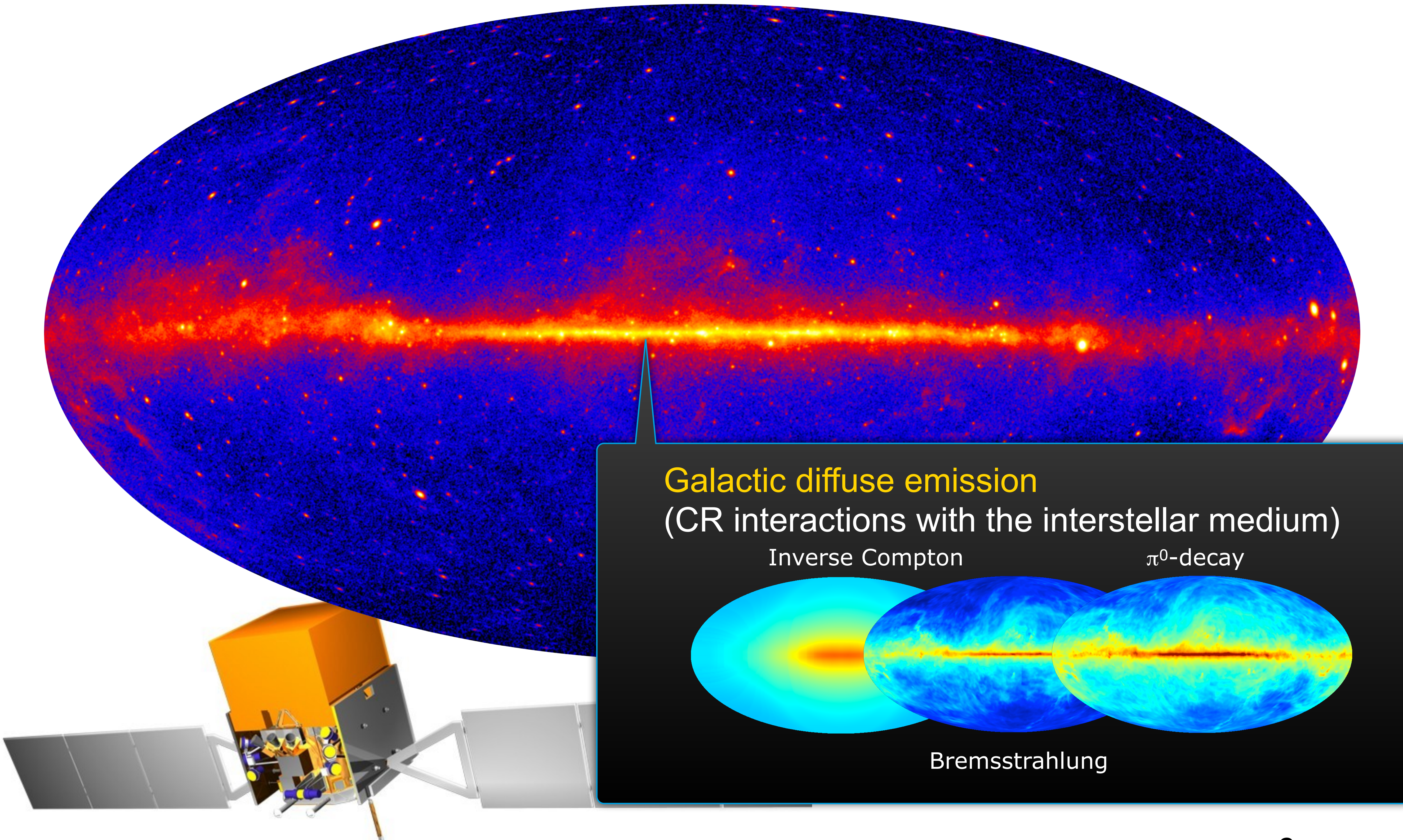

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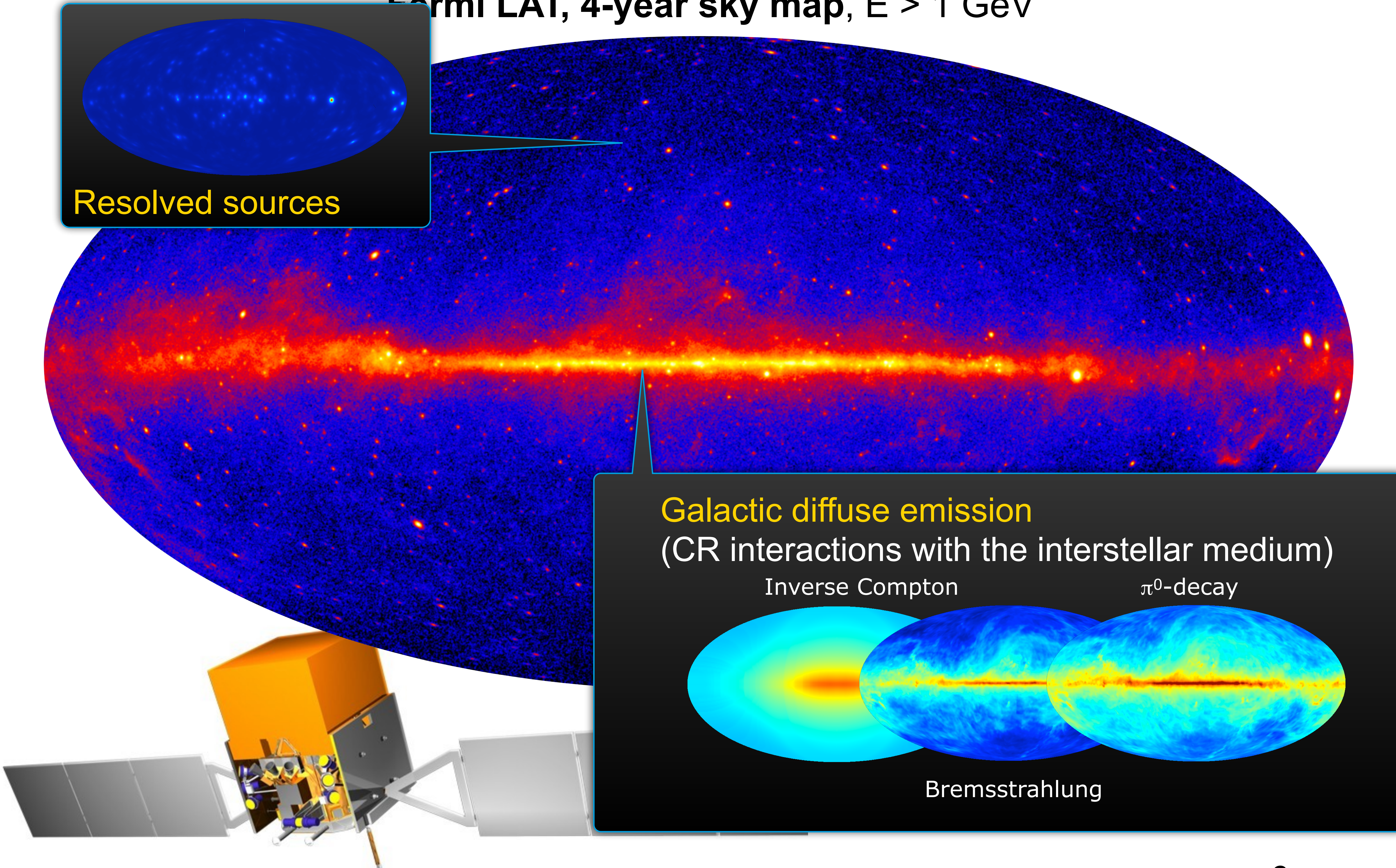

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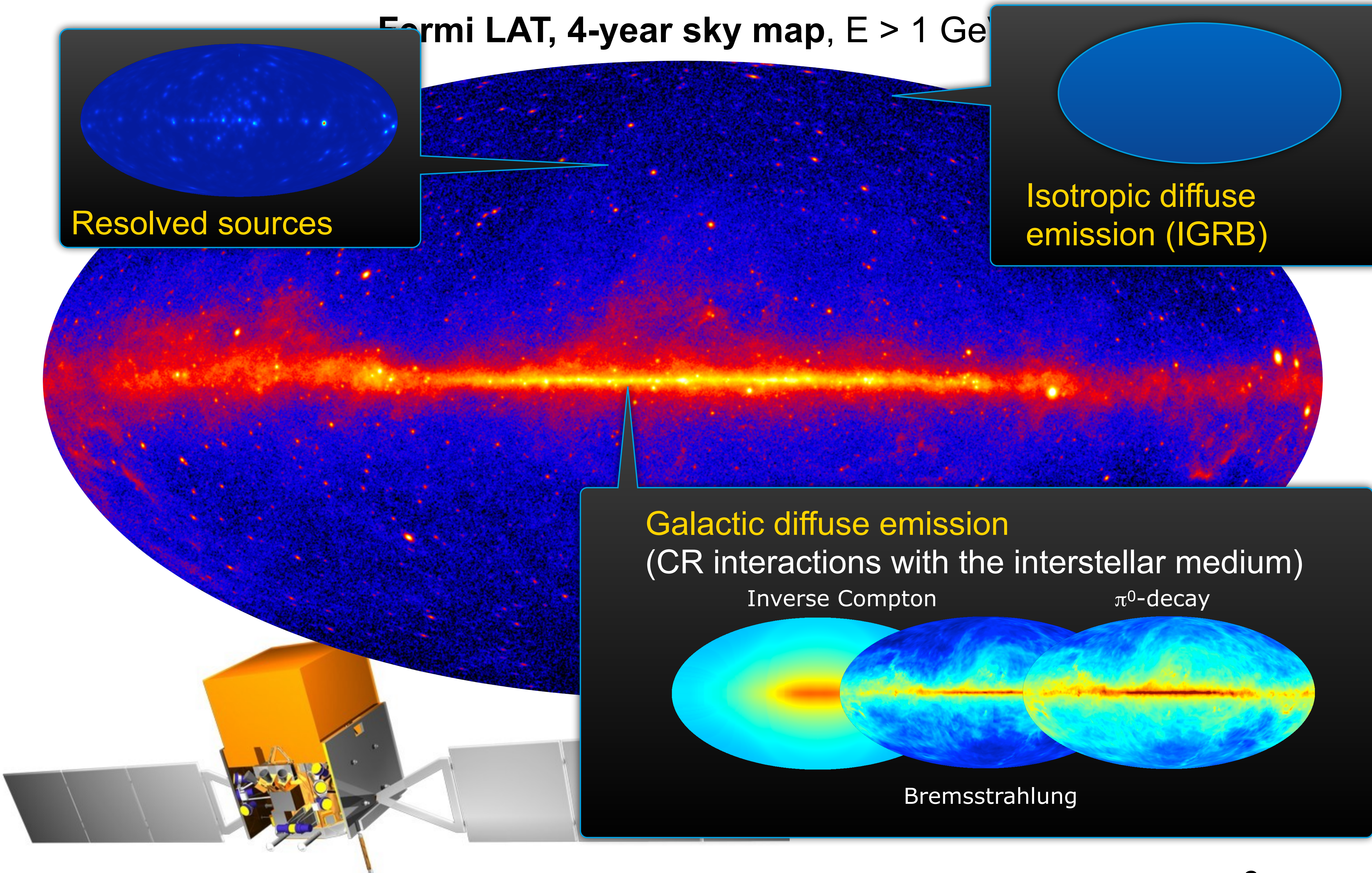
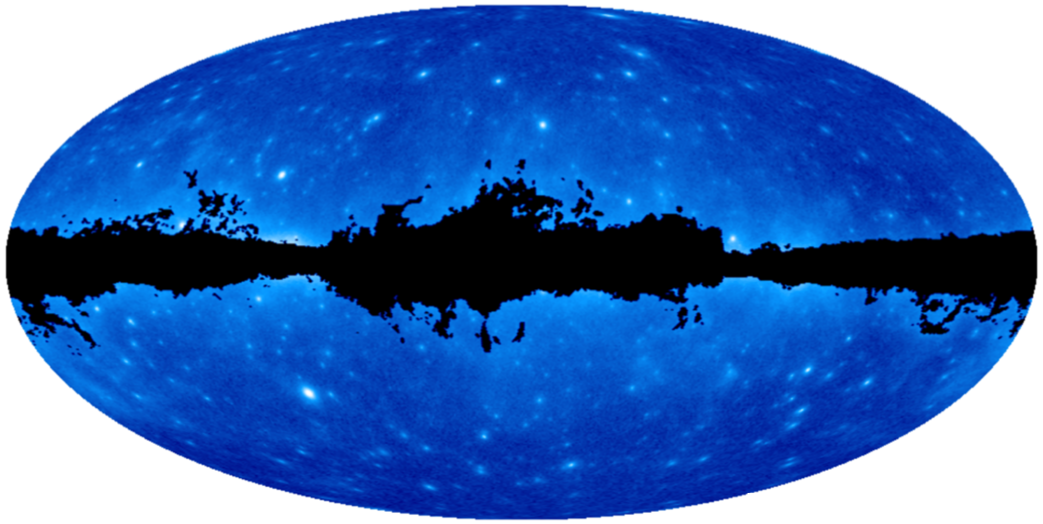


Derivation of the extragalactic background



Masked regions:
- Galactic plane
- Regions with dense molecular clouds
- Regions with non-local atomic hydrogen clouds

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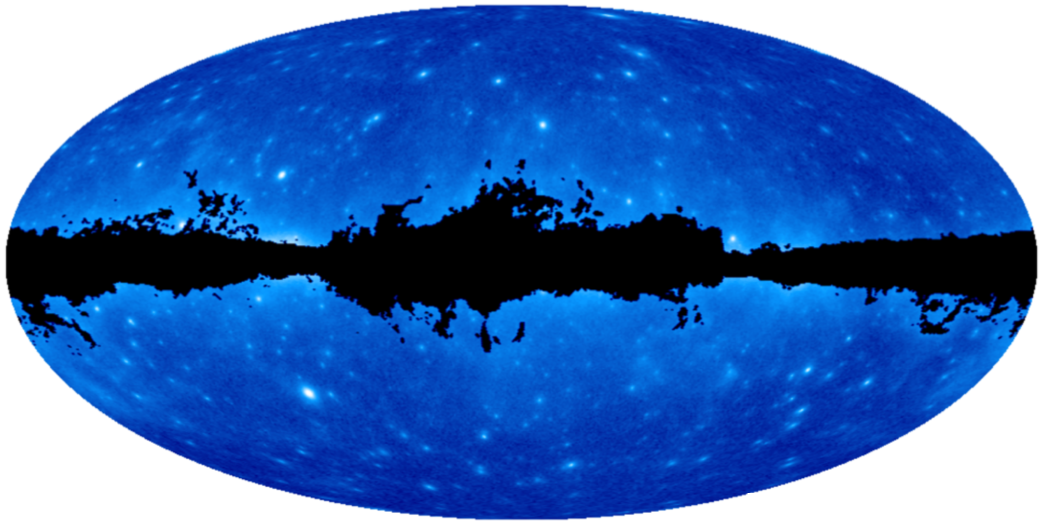

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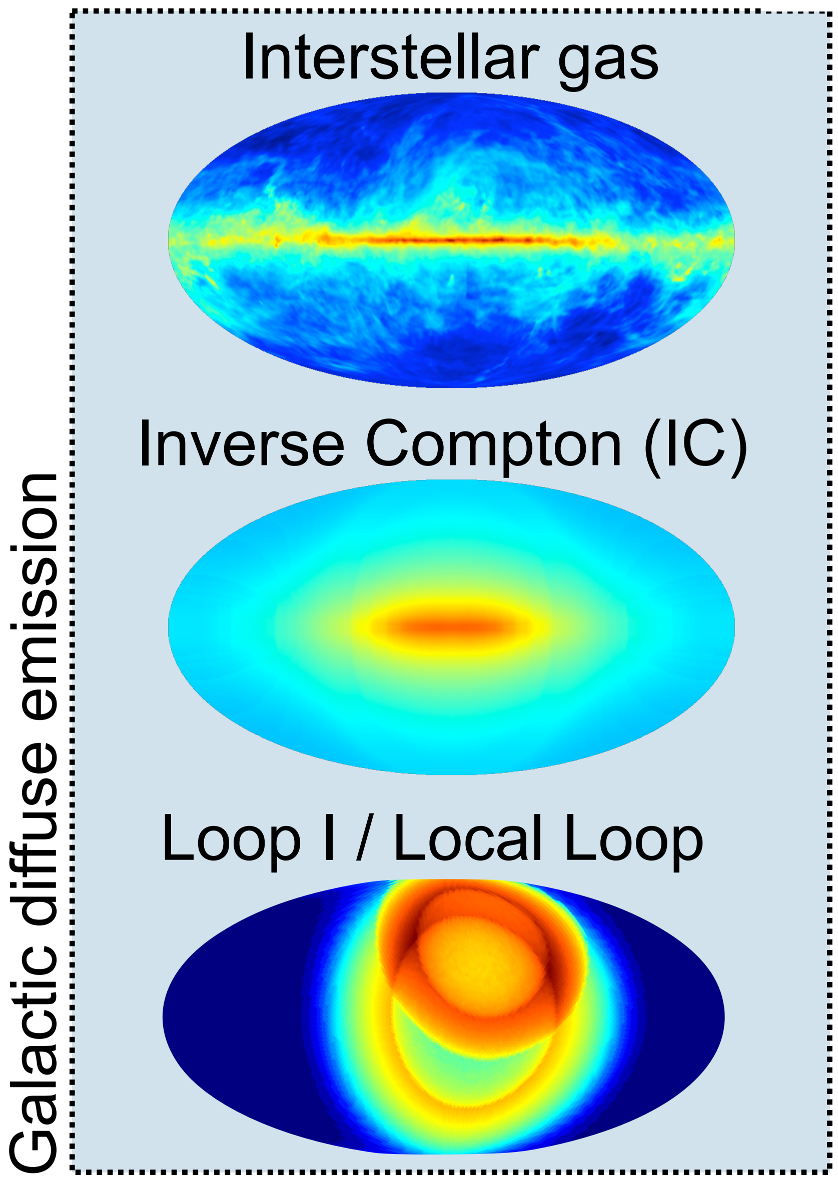

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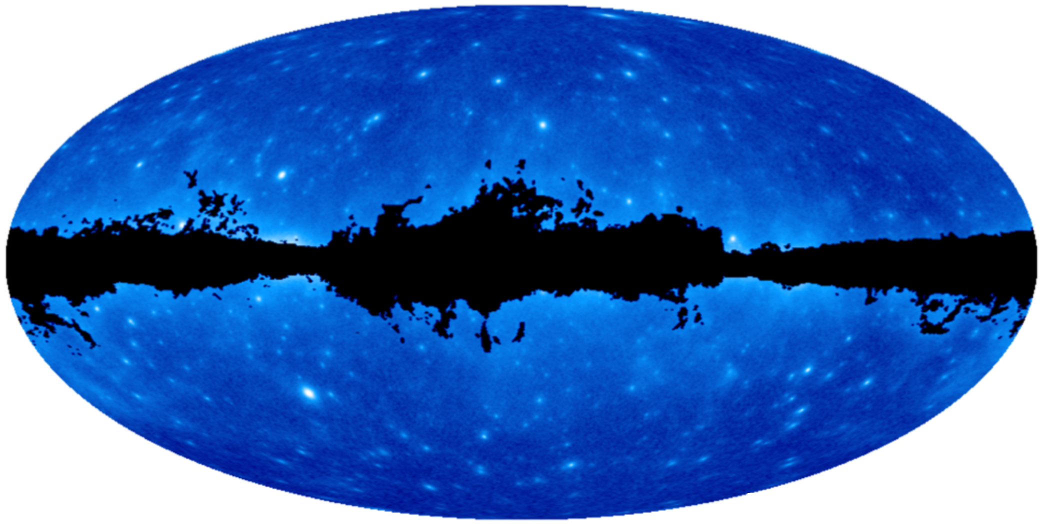

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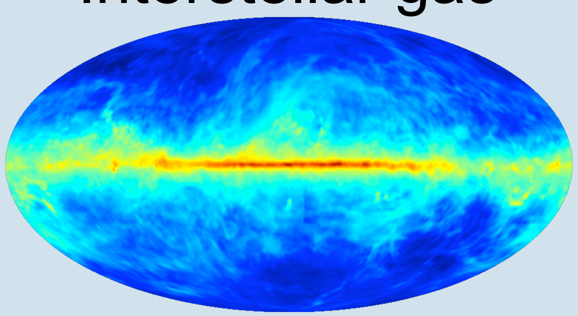
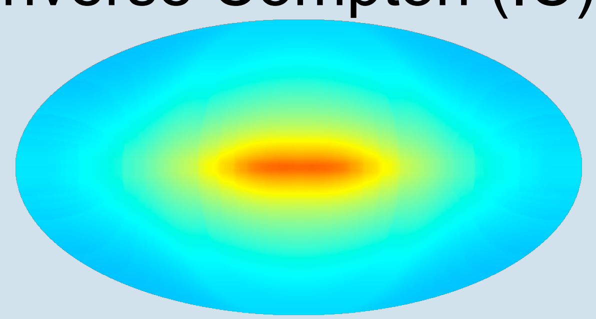
Galactic diffuse emission

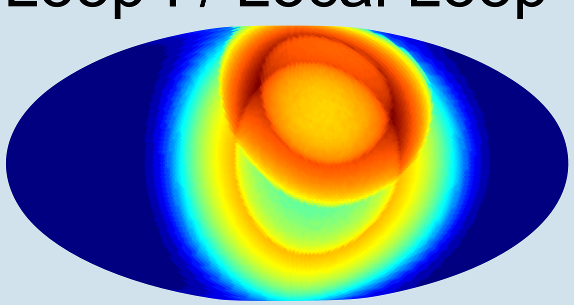
Interstellar gas



Inverse Compton (IC)

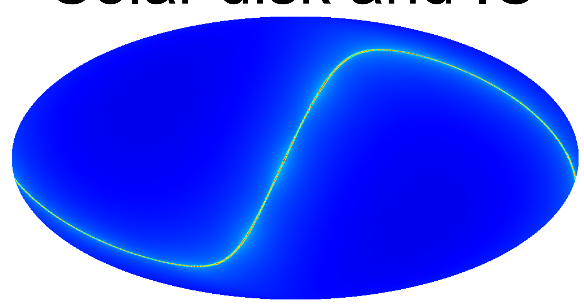


Loop I / Local Loop



+

Solar disk and IC



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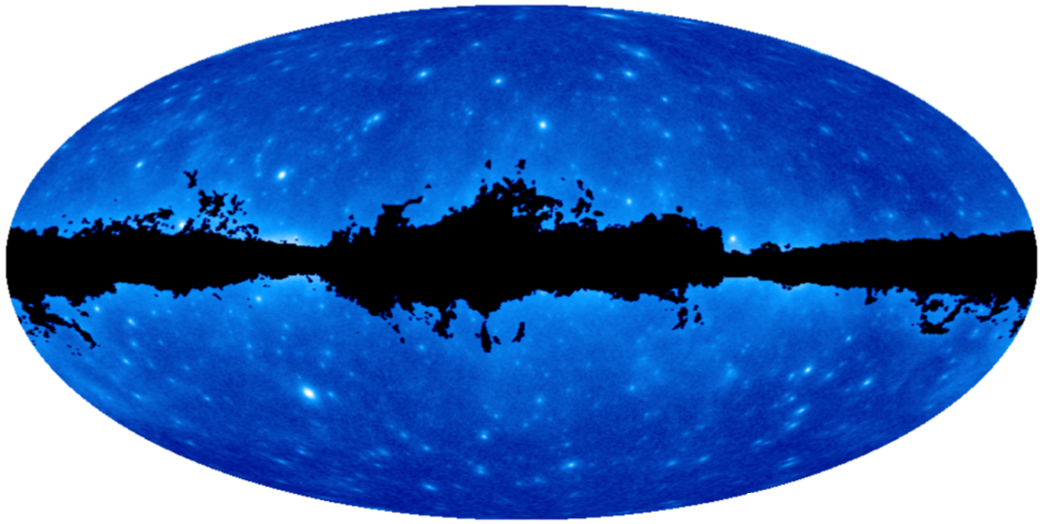

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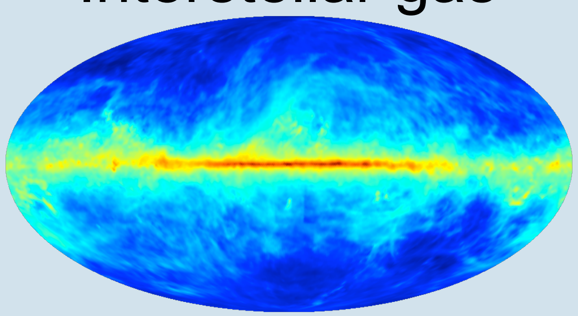

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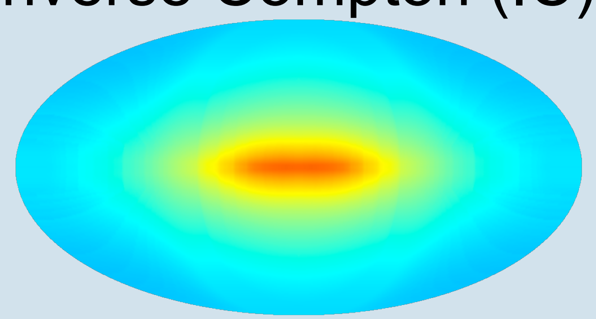

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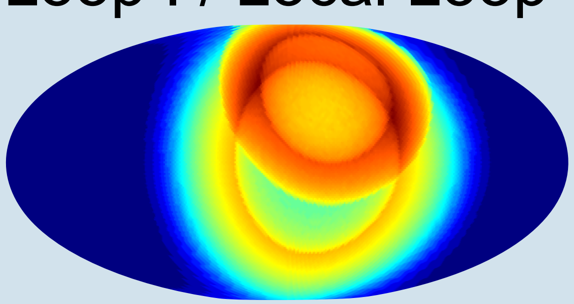

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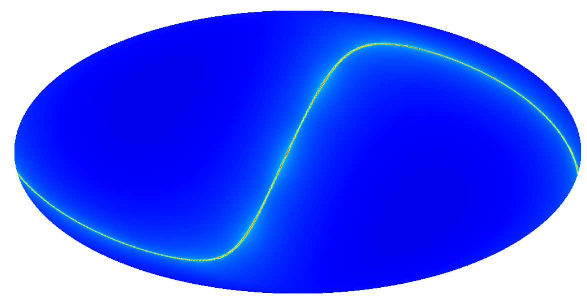

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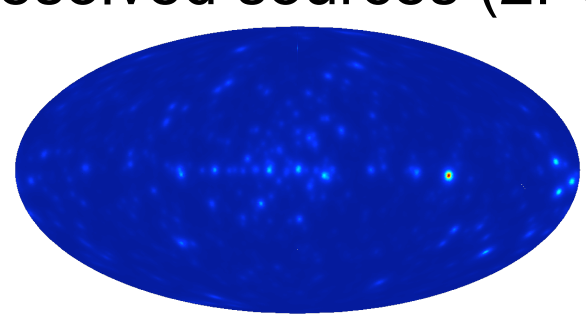
Resolved sources (2FGL)



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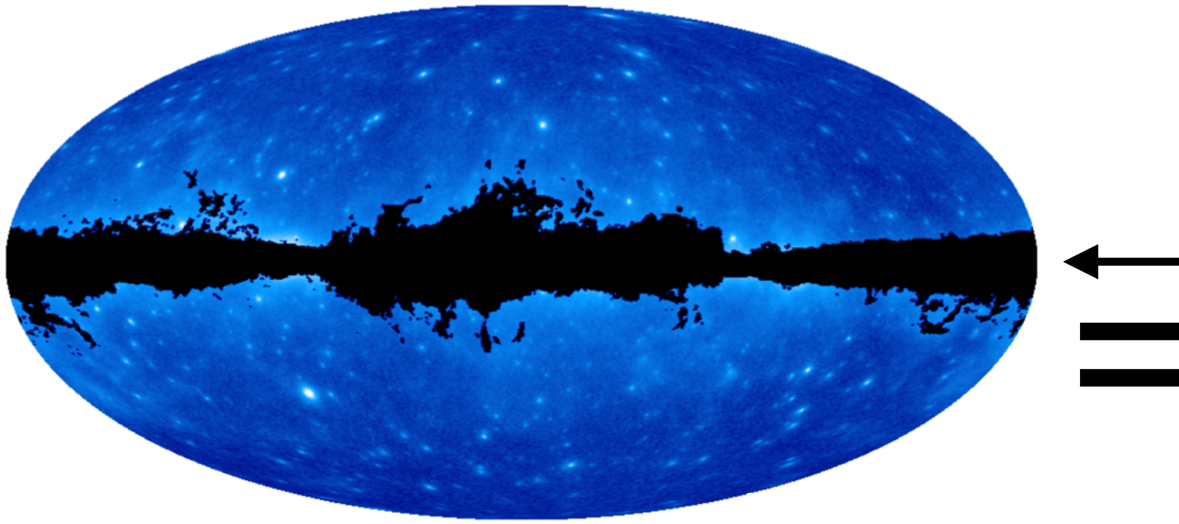

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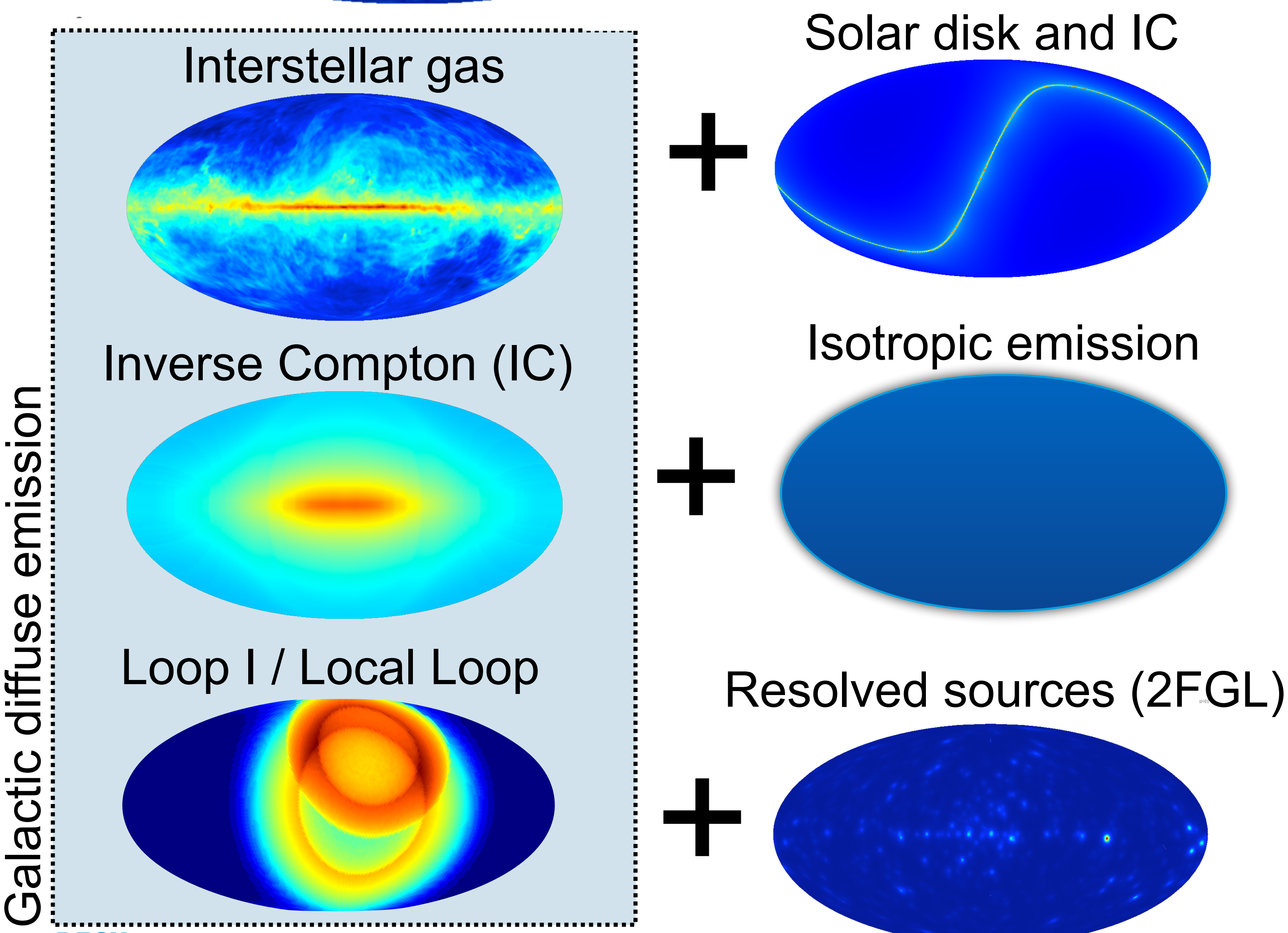

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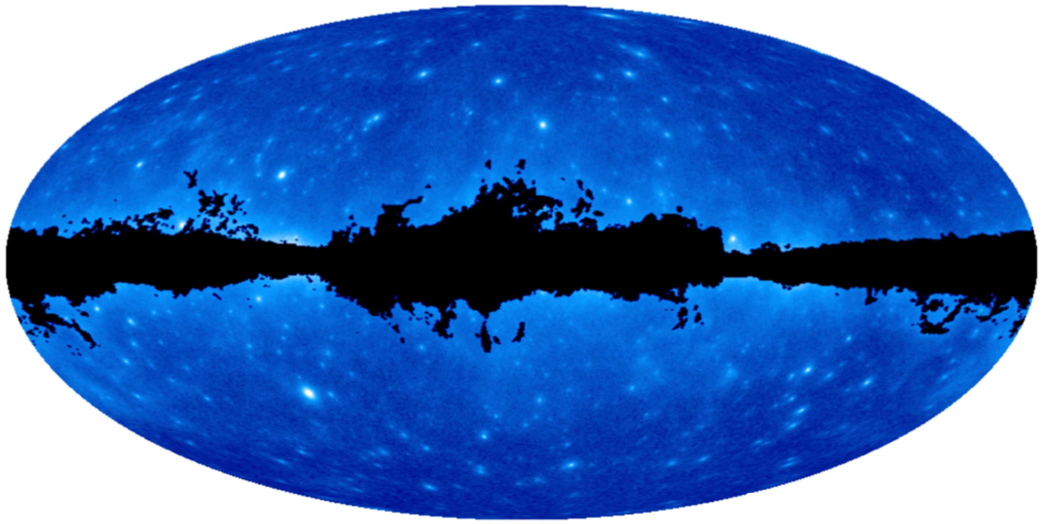

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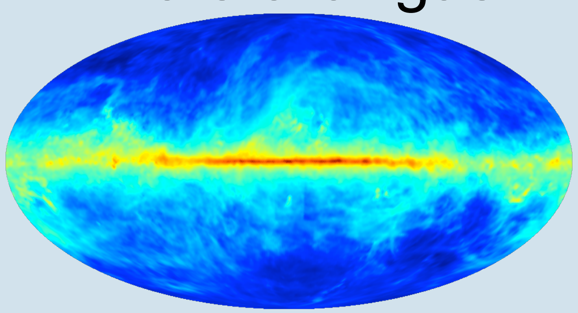
Galactic diffuse emission

Interstellar gas



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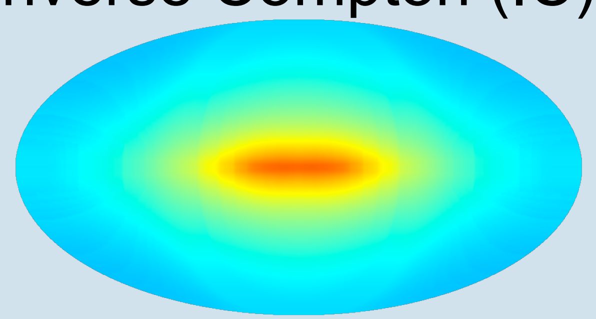

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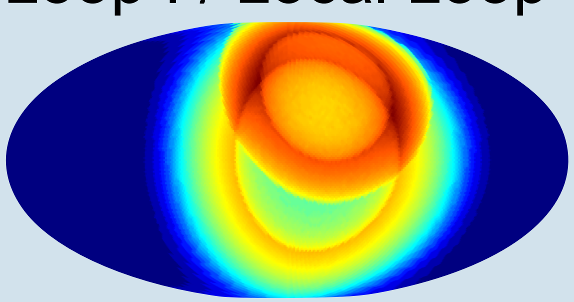

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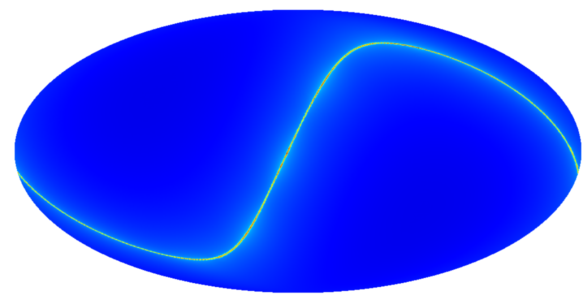
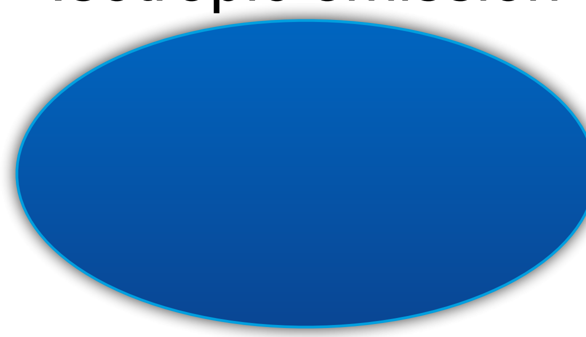
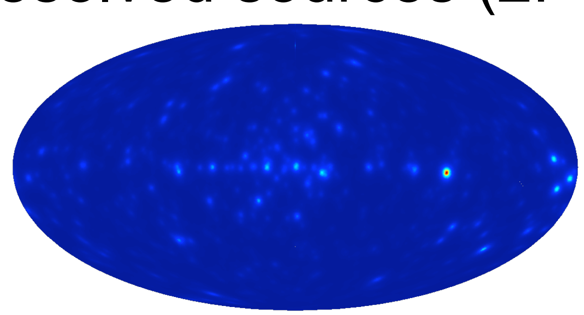


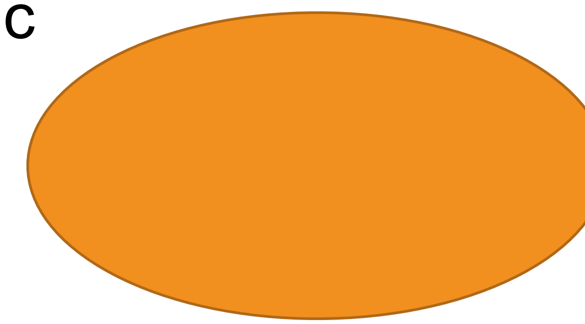
\+ Isotropic emission

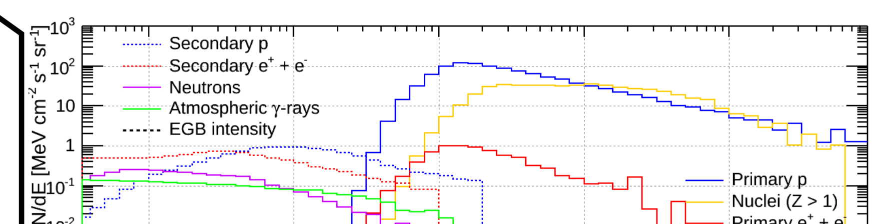


\+ Resolved sources (2FGL)



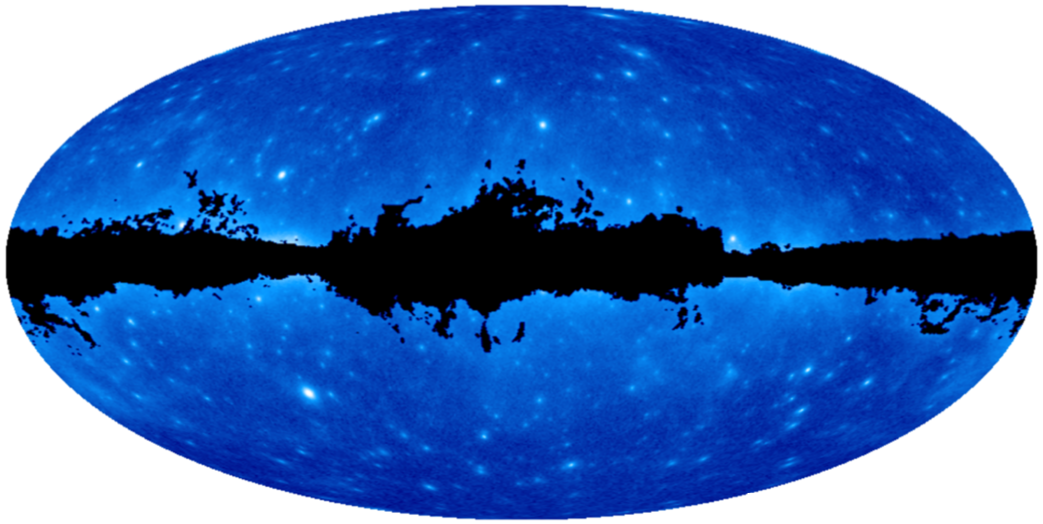
Isotropic γ-ray back-ground (IGRB)





Contamination from CR induced background

Derivation of the extragalactic background



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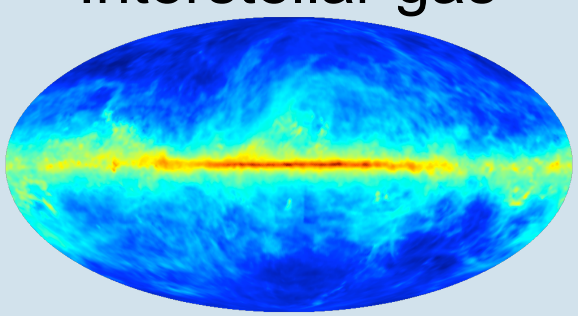

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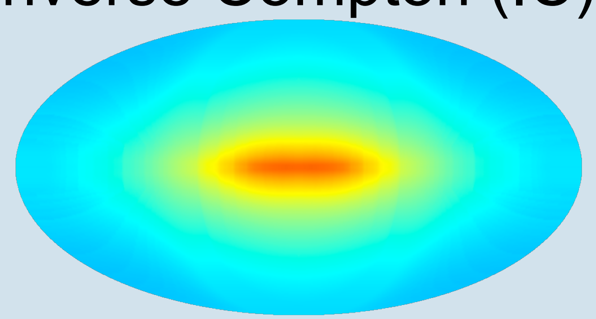

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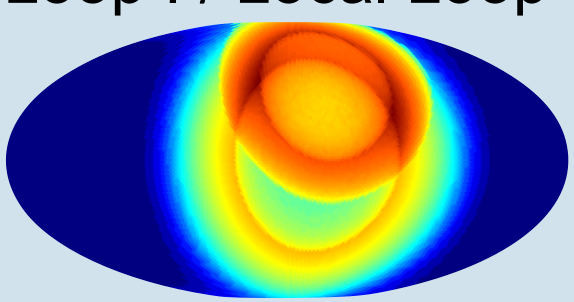

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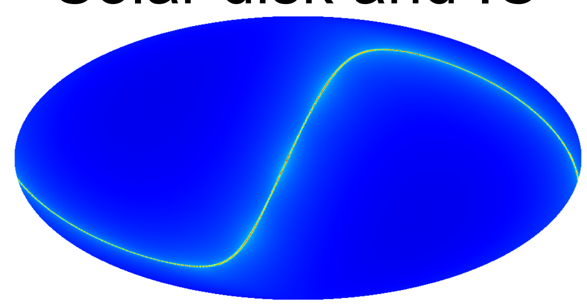
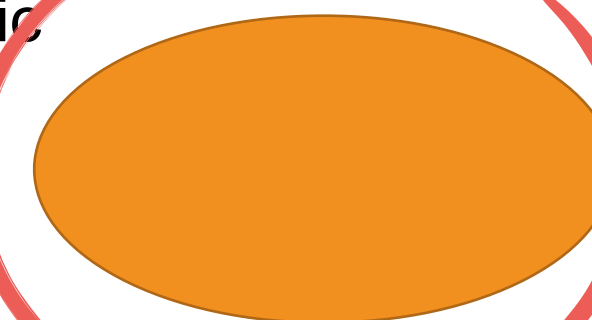
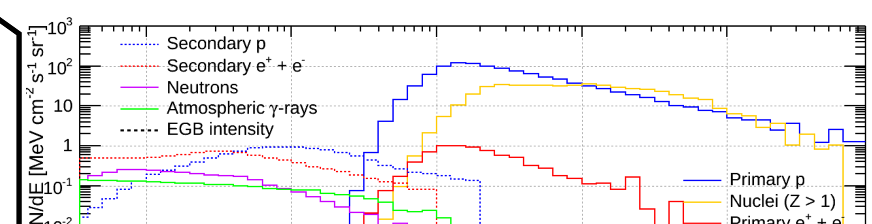


\+ Isotropic emission

Isotropic γ-ray background (IGRB)





Contamination from CR induced background

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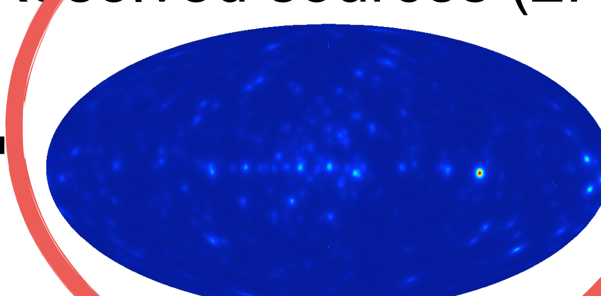
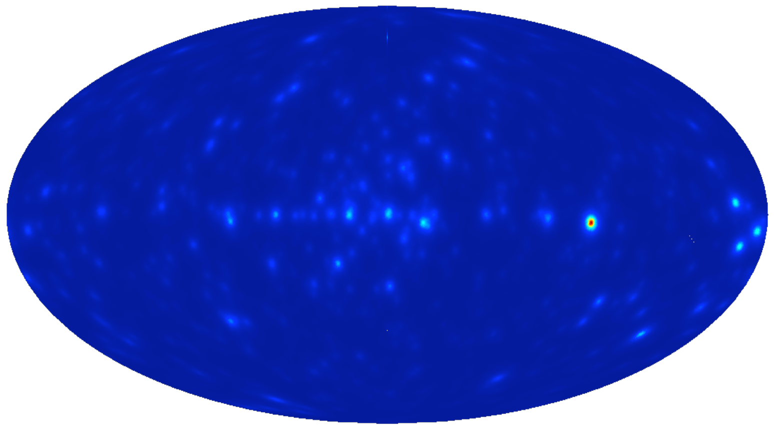


Isotropic and total extragalactic background



Resolved sources

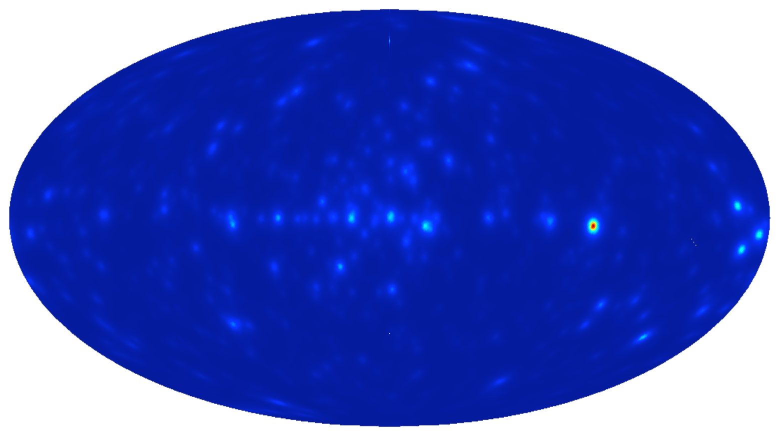
Intensity that can be **resolved into sources** depends on:

- the sensitivity of the instrument.
- the exposure of the observation.

Isotropic γ-ray background (IGRB)

- The **IGRB** depends on the sensitivity to identify sources.
- Important as an **upper limit on diffuse processes.**

Isotropic and total extragalactic background



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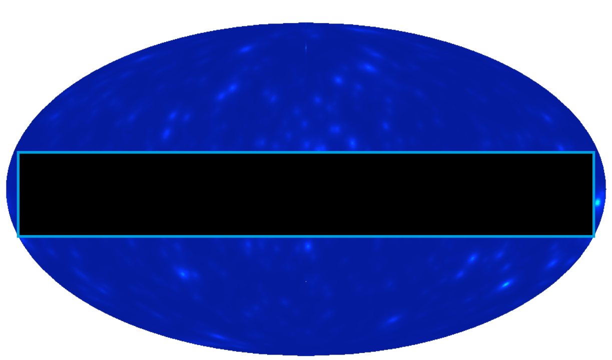

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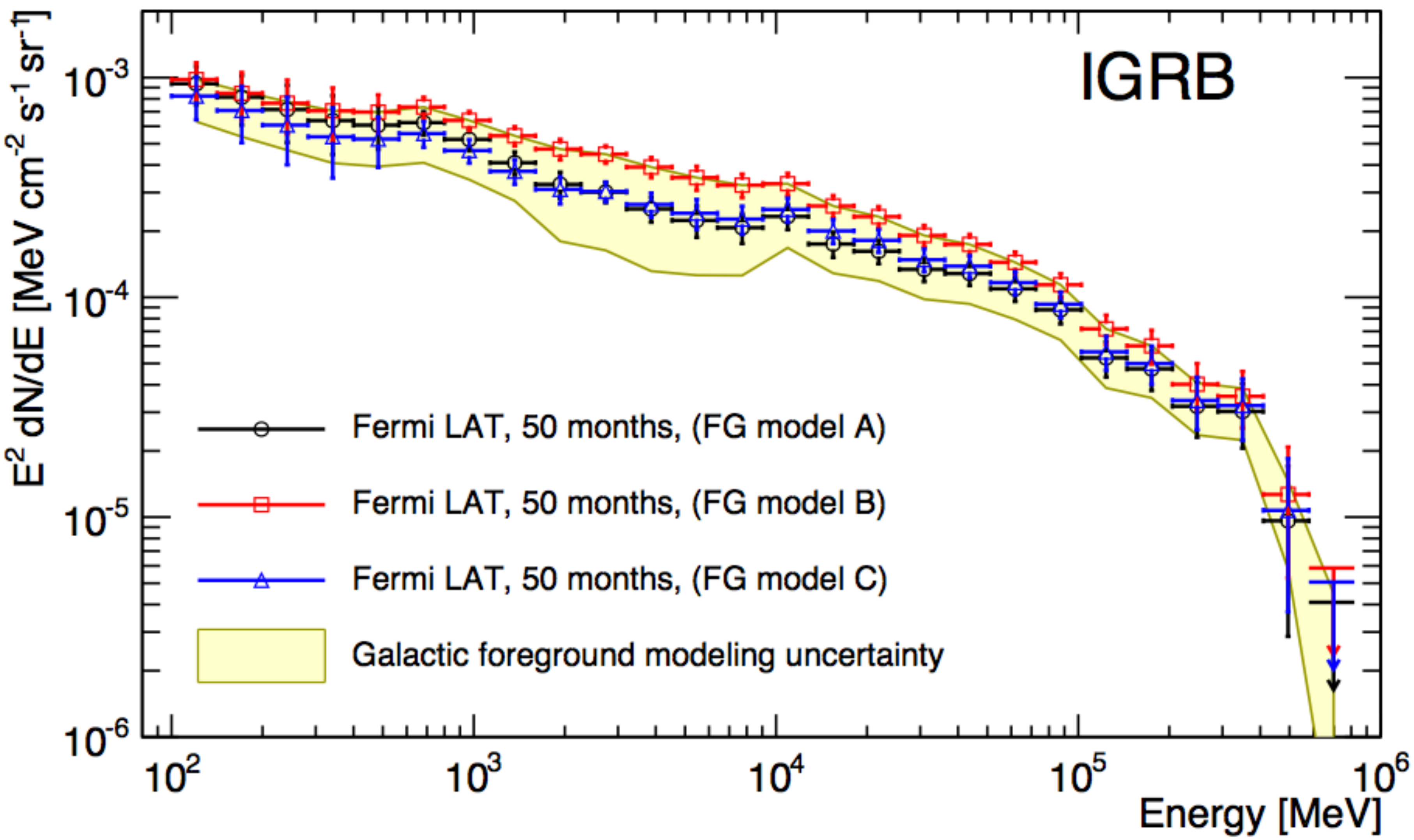
Total extragalactic γ-ray background (EGB)

- **The total EGB** is instrument and observation independent.
- Useful for **comparisons with source population models**.

The IGRB spectrum



- **Error bars**:

  statistical error

  + syst. error from effective area parametrization

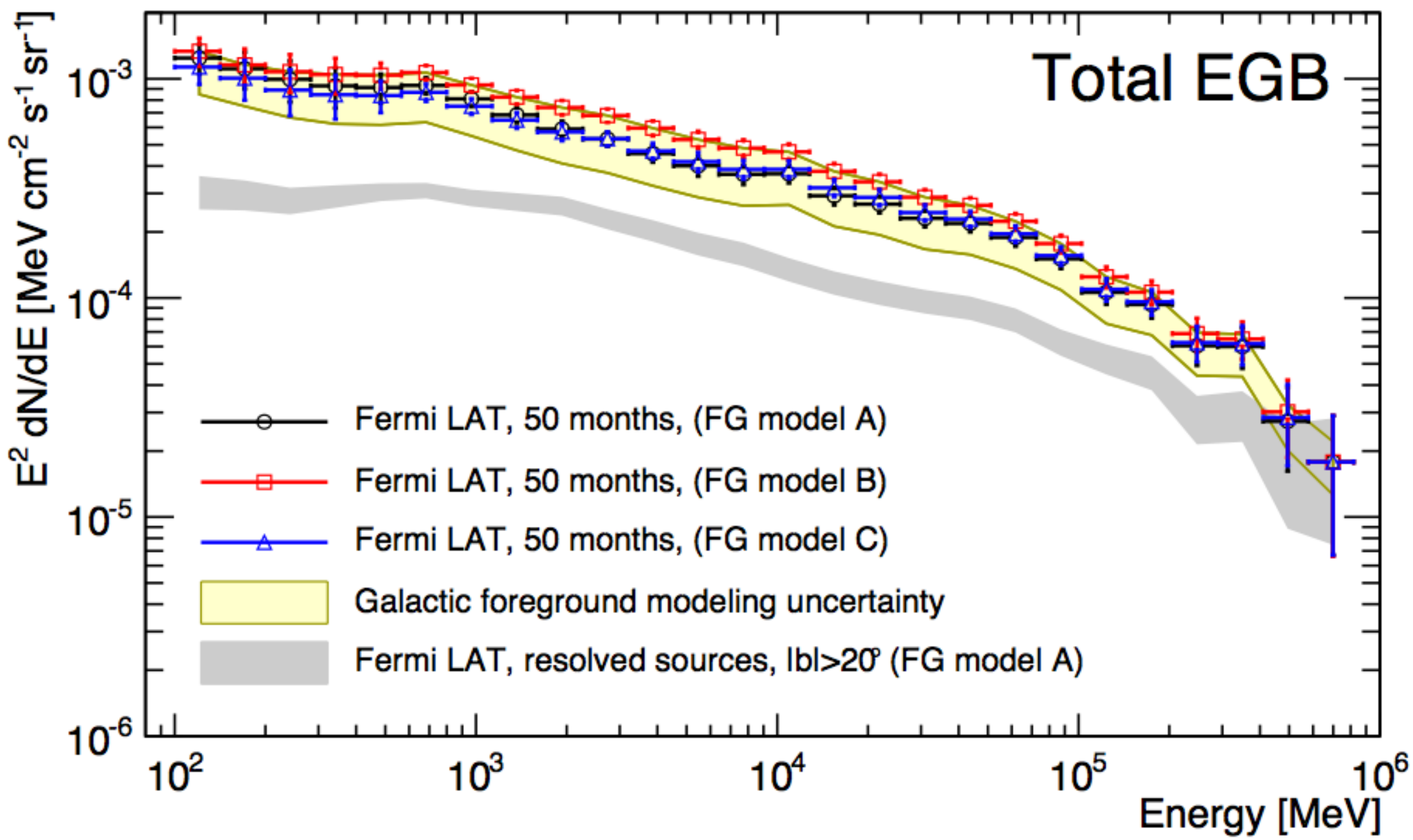
  + syst. error from CR background subtraction

- **Yellow band:** systematic uncertainties from foreground model variations.

- **IGRB spectrum** can be parametrized by single power-law + exponential cutoff.
- Spectral index **~ 2.3** , cutoff energy **~ 250 GeV.**
- It is **not compatible with a simple power-law** (χ^2 > 85).

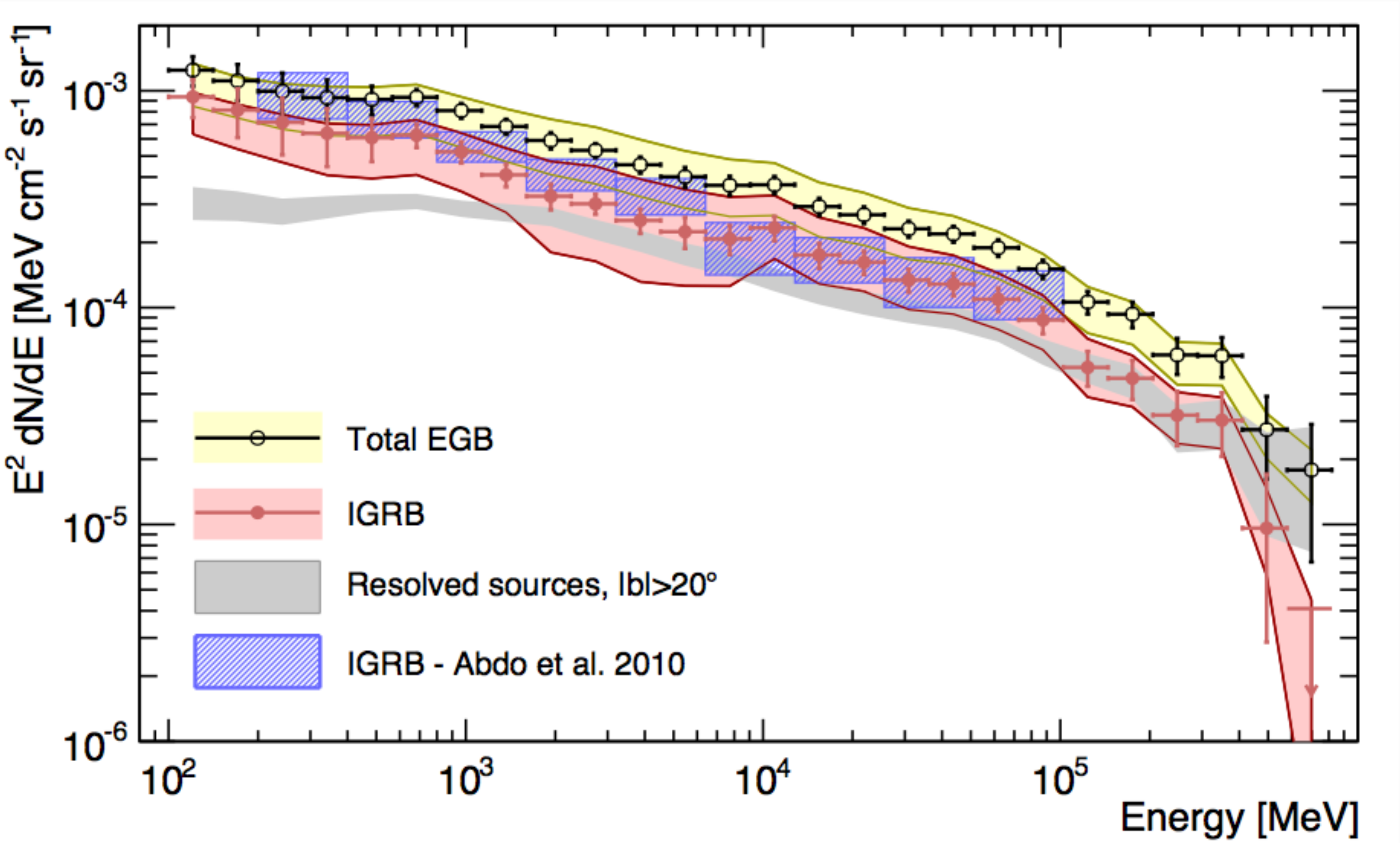
The total EGB spectrum

- **Sum of the intensities** of IGRB and the resolved high-latitude sources.
- Contribution of high-latitude Galactic sources **<< 5%.**
- Spectrum can be parametrized by **power-law with exponential cutoff**.
- Spectral index **~ 2.3**, cutoff energy **~ 350 GeV.**



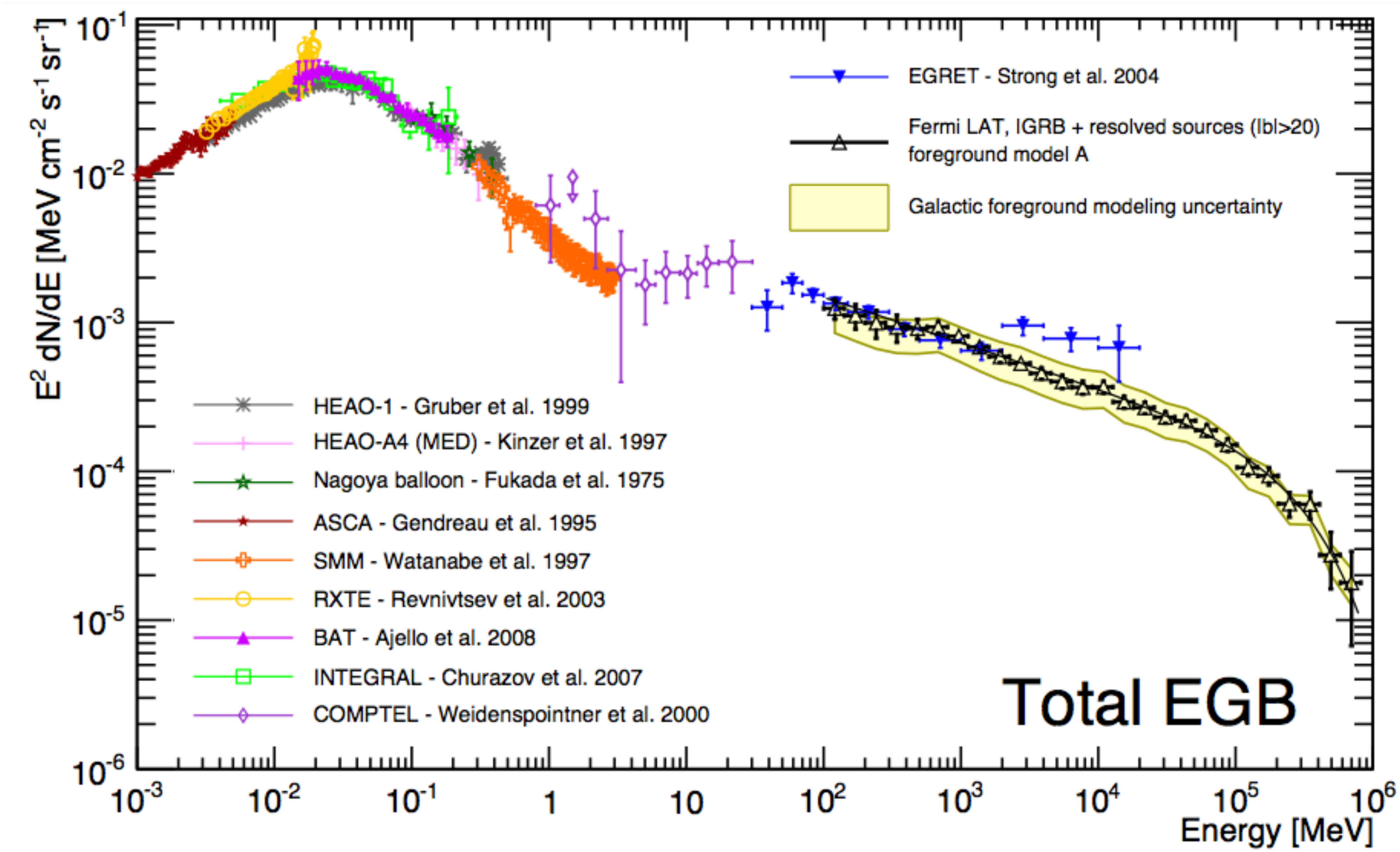
IGRB and total EGB in comparison

- Comparison for **baseline diffuse model**.
- **2FGL resolved sources and IGRB** have similar intensities above 100 GeV
- **Main differences to Abdo et al. 2010:** Improved diffuse foreground and CR background models.



The X-ray and gamma-ray background

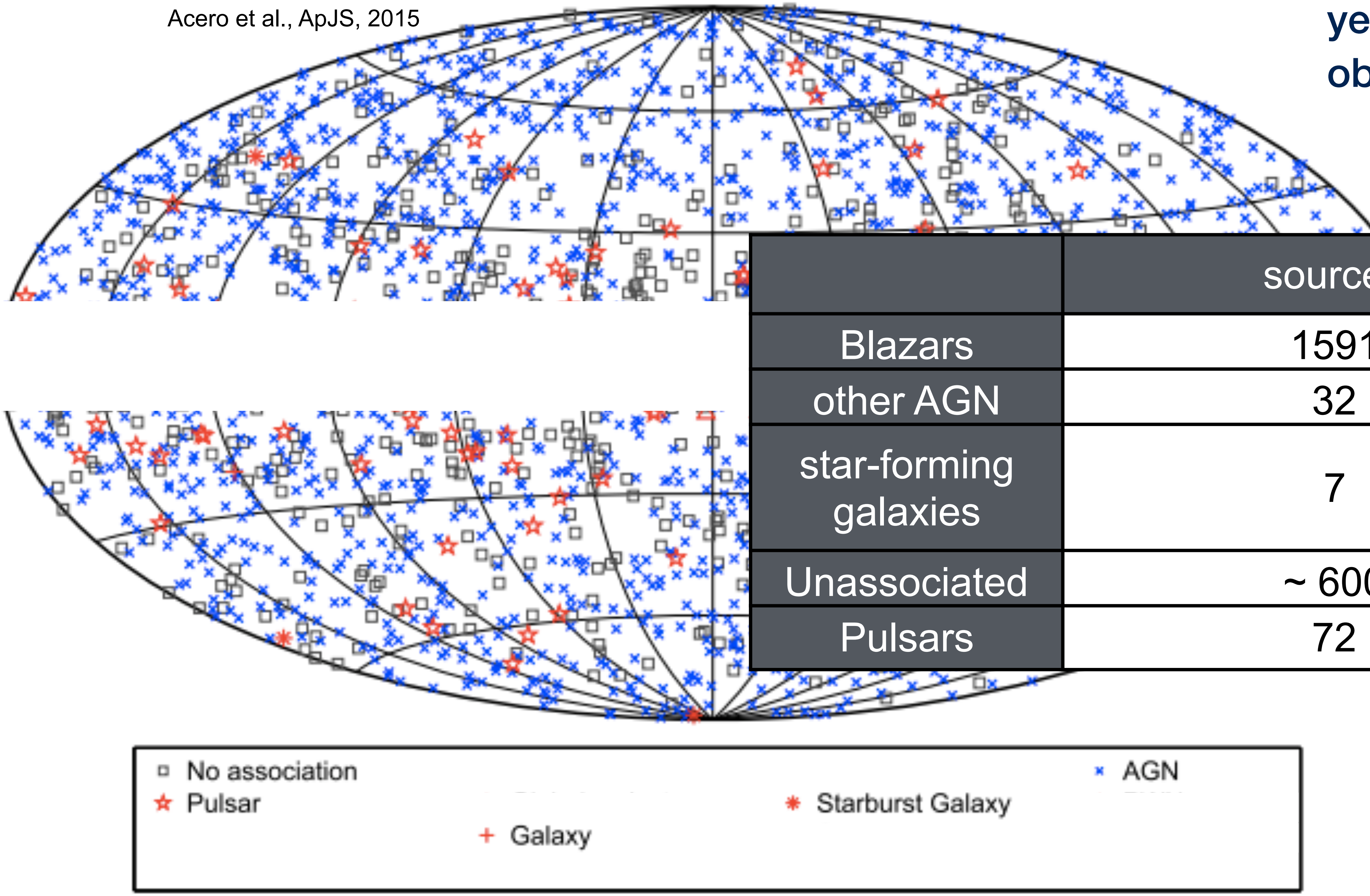
- Cosmic X-ray and gamma-ray background **measured over 9 orders of magnitude in energy**.
- Challenging to improve EGB measurement: Limited by foreground systematics



The origin of the γ-ray background above 100 MeV

The high-latitude gamma-ray sky

Acero et al., ApJS, 2015



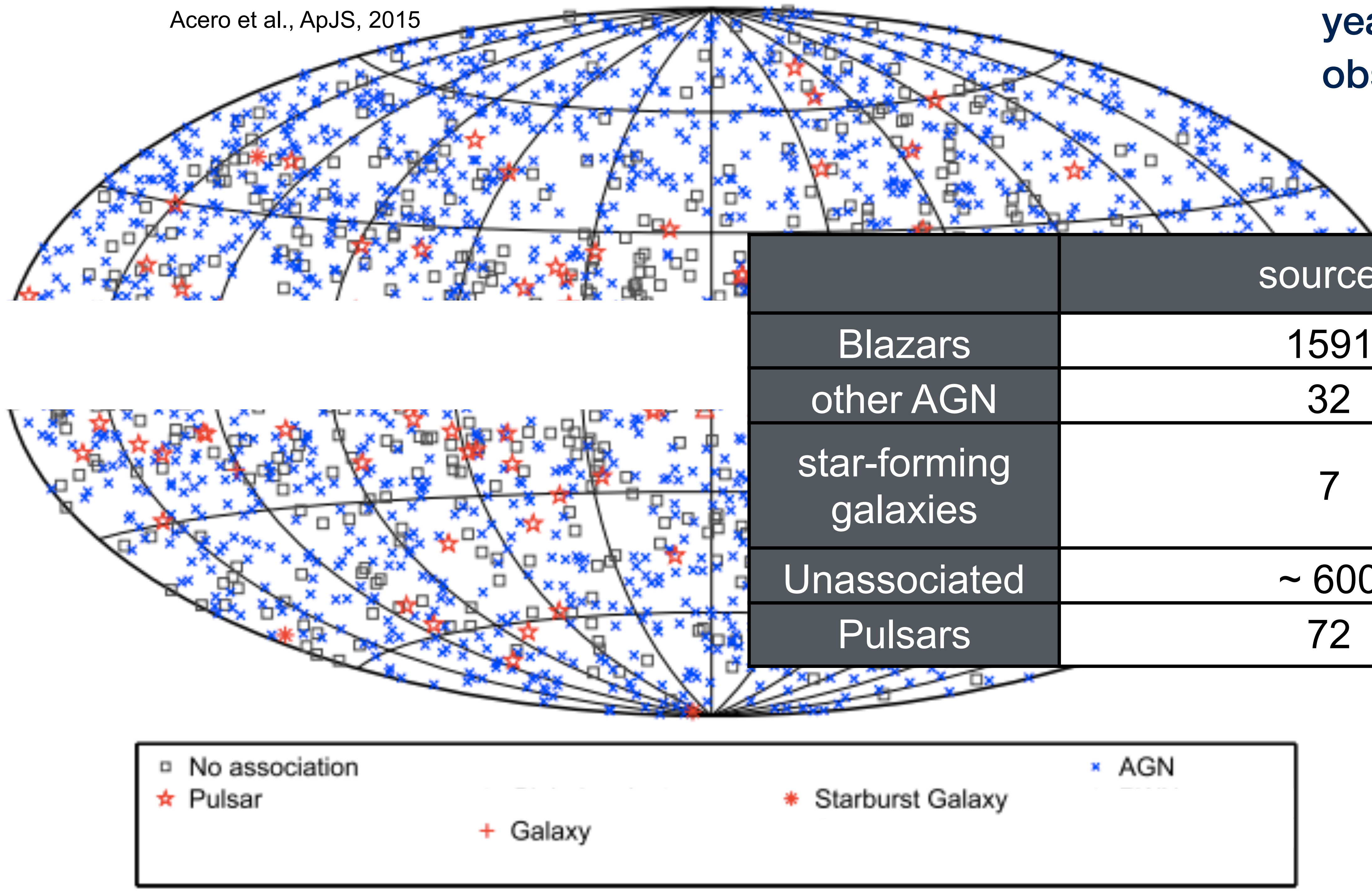
	sources
Blazars	1591
other AGN	32
star-forming galaxies	7
Unassociated	~ 600
Pulsars	72

- 3FGL catalog based on 4 years of LAT observations

The high-latitude gamma-ray sky

- 3FGL catalog based on 4 years of LAT observations

Acero et al., ApJS, 2015

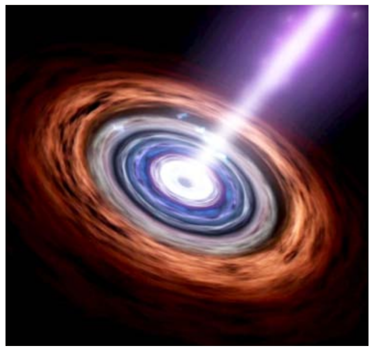


	sources
Blazars	1591
other AGN	32
star-forming galaxies	7
Unassociated	~ 600
Pulsars	72

Few source classes dominate the extragalactic gamma-ray sky

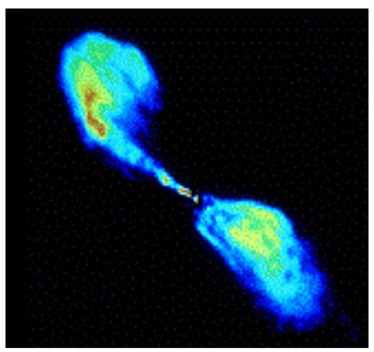
The origin of the EGB

Sources



Blazars

- Dominant class of extra-galactic GeV / TeV sources.

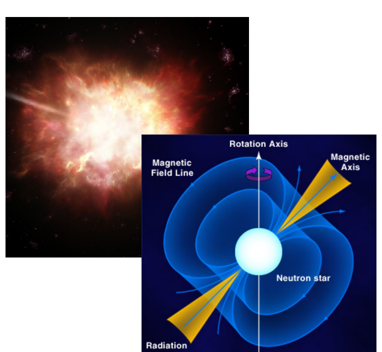


Radio galaxies

- ~ 30 sources resolved by LAT
- Less luminous but more abundant than Blazars

Star-forming galaxies

- Only few galaxies resolved in GeV band.
- Large number of sources → significant EGB contribution.

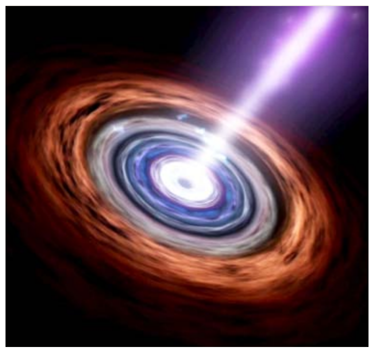


GRBs + High-latitude pulsars

- Small contributions expected.

The origin of the EGB

Sources



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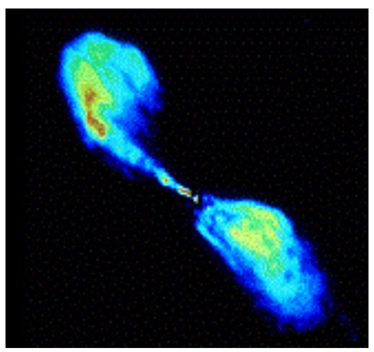

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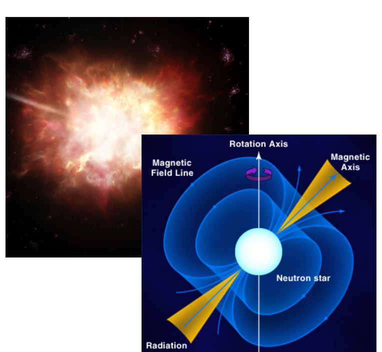


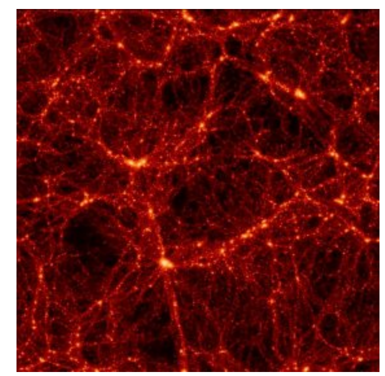
GRBs + High-latitude pulsars

- Small contributions expected.

Diffuse processes

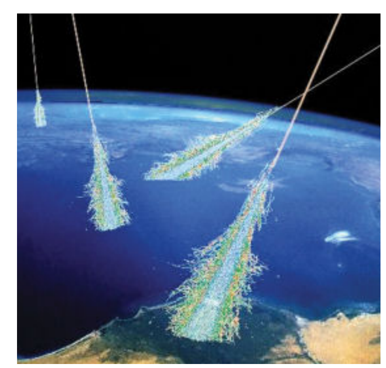
Intergalactic shocks

- Widely varying predictions of EGB contribution ranging from 1% to 100%.



Dark matter annihilation

- Potential signal dependent on nature of DM, cross-section and structure of DM distribution.



Interactions of UHE cosmic rays with the EBL

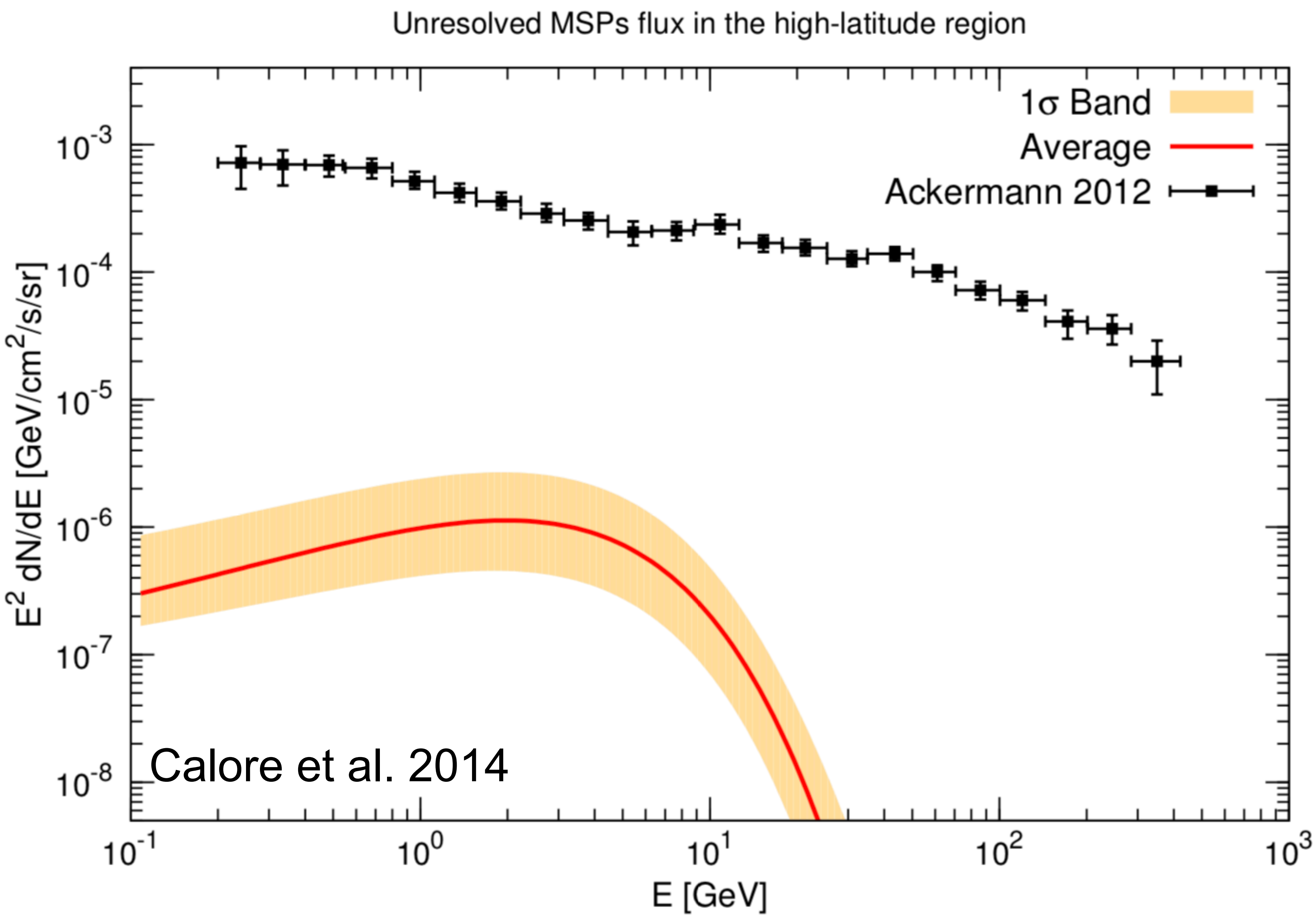
- Strongly dependent on evolution of UHECR sources.
- 1% - 100% of EGB emission.

Isotropic Galactic contributions

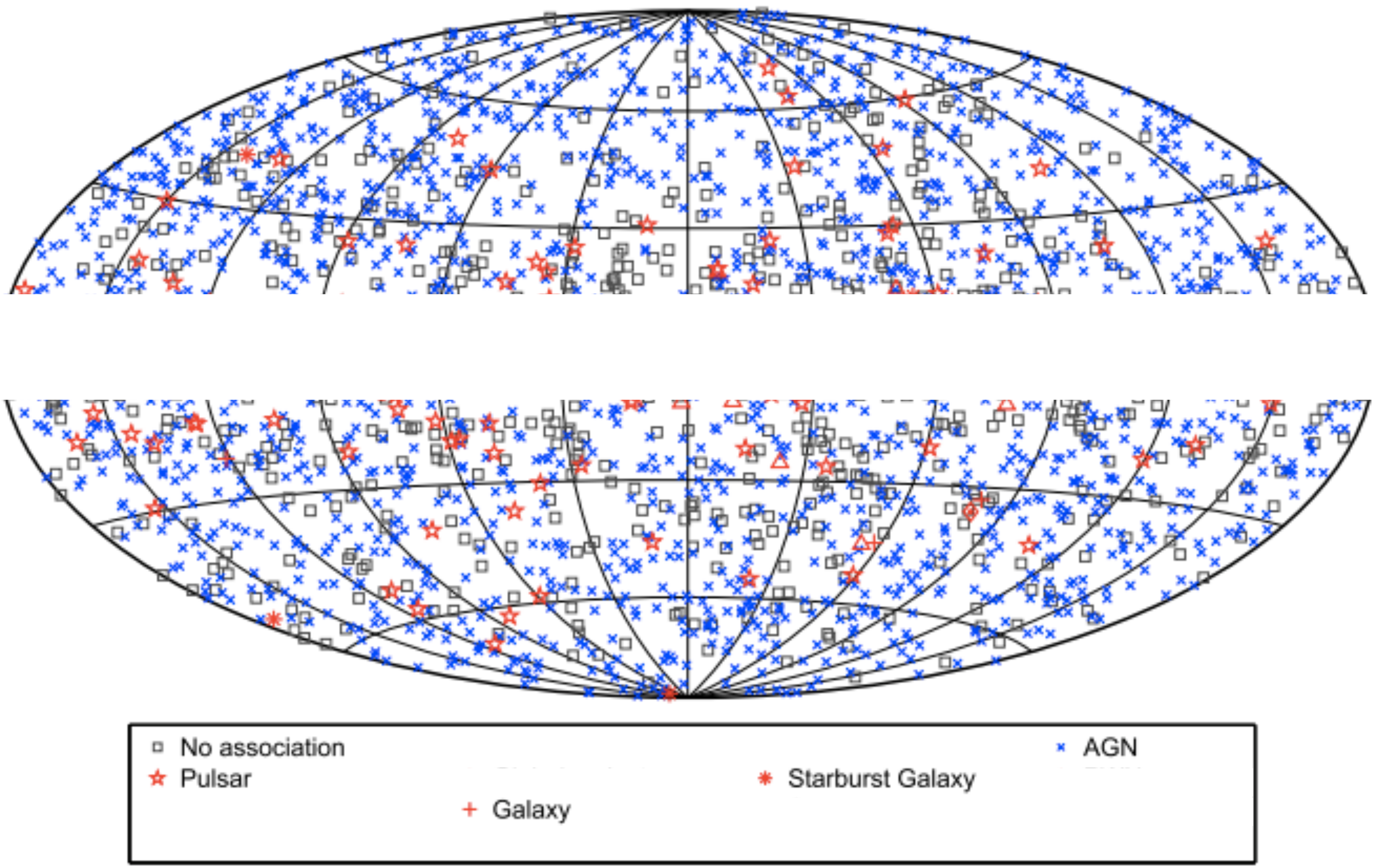
- Contributions from an extremely large Galactic electron halo.
- CR interaction in small solar system bodies.

Is the EGB galactic ?

- Unresolved Pulsars account for only a tiny fraction of the EGB



Counting the LAT blazars



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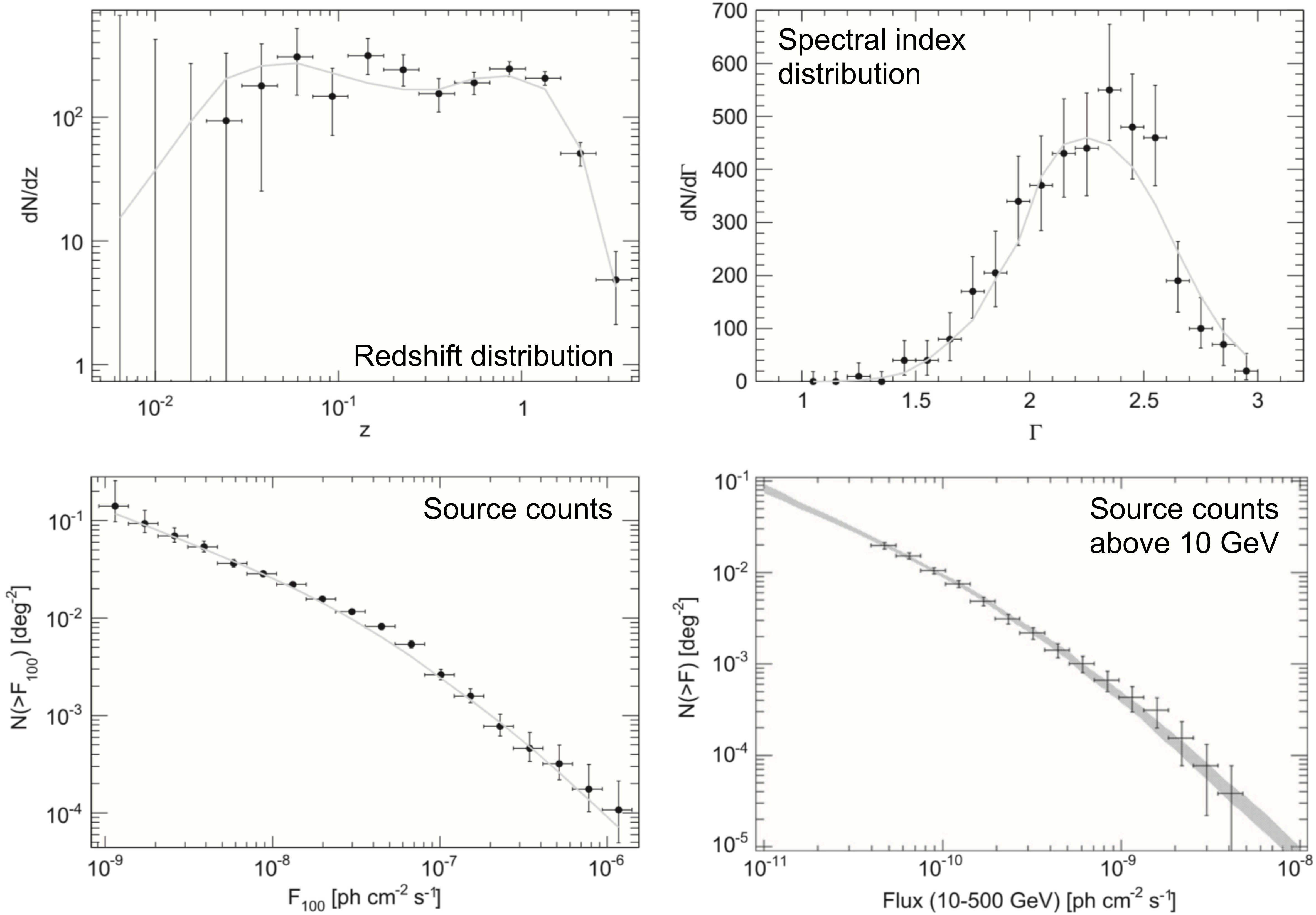
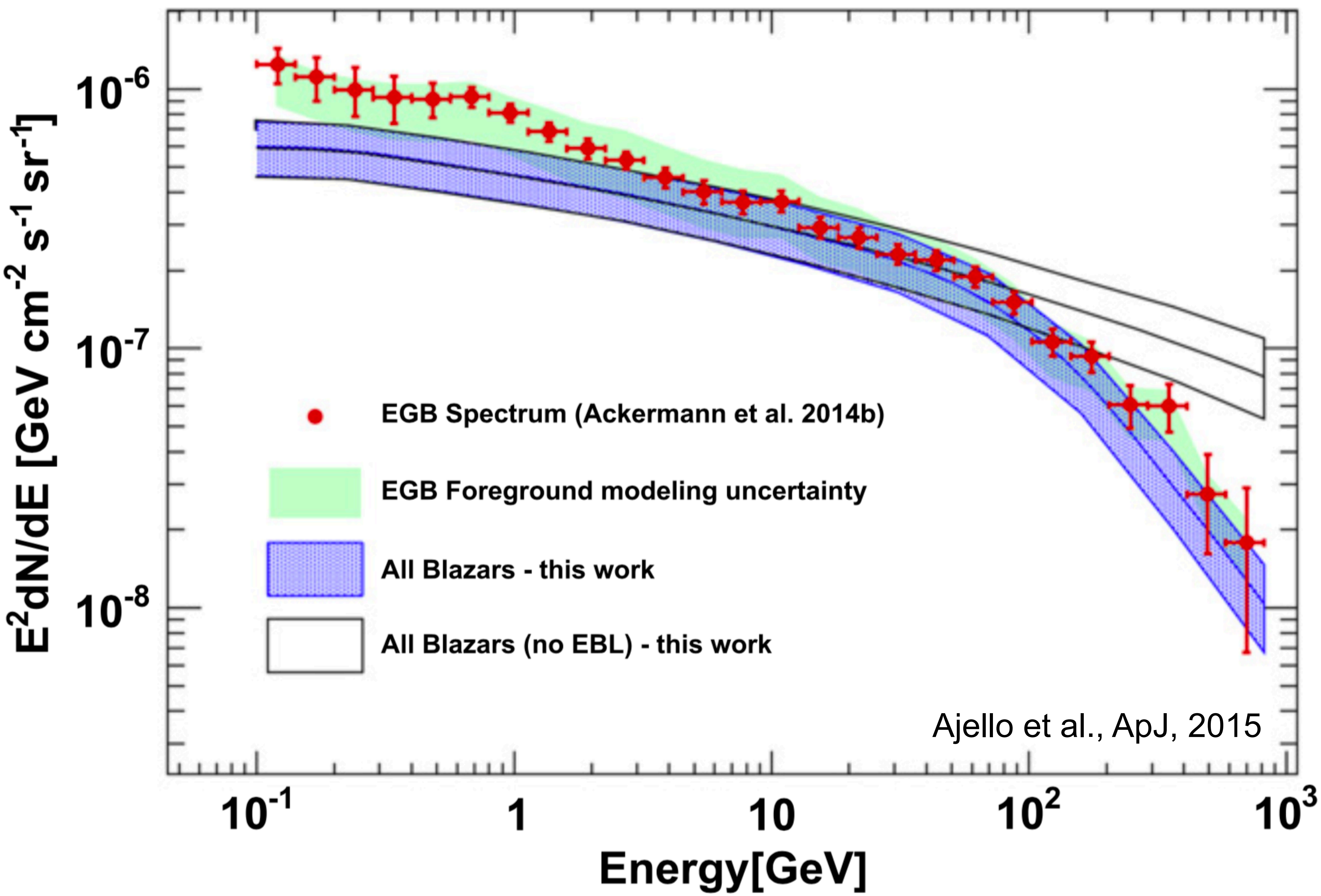


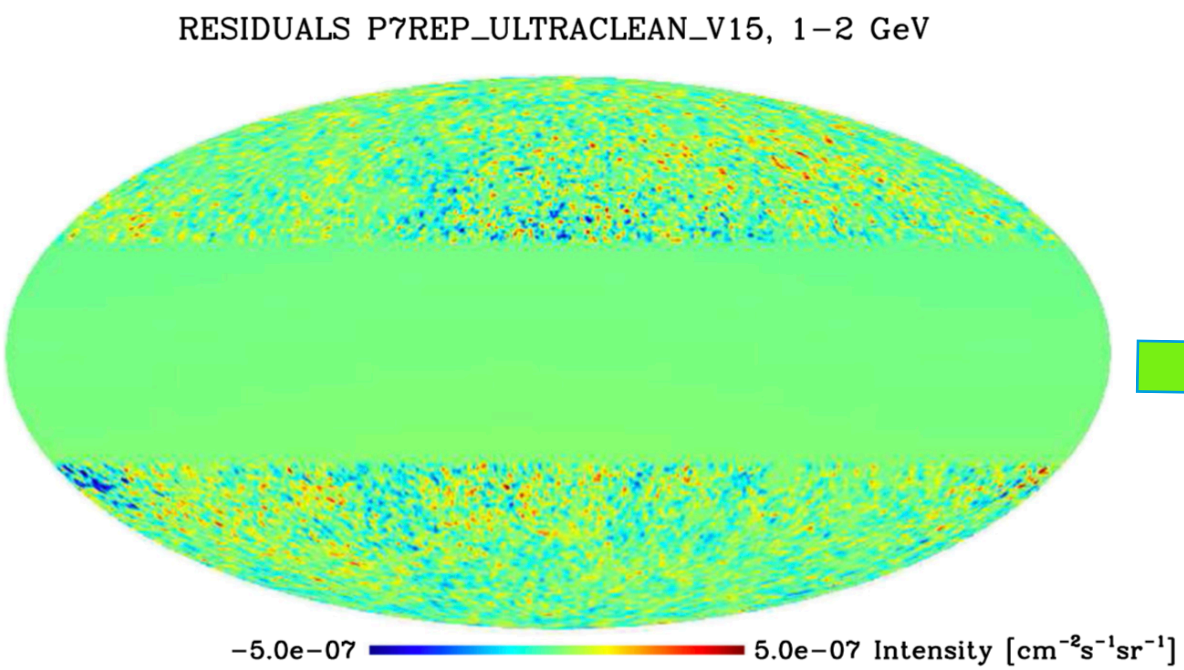
Ajello et al., ApJ, 2015

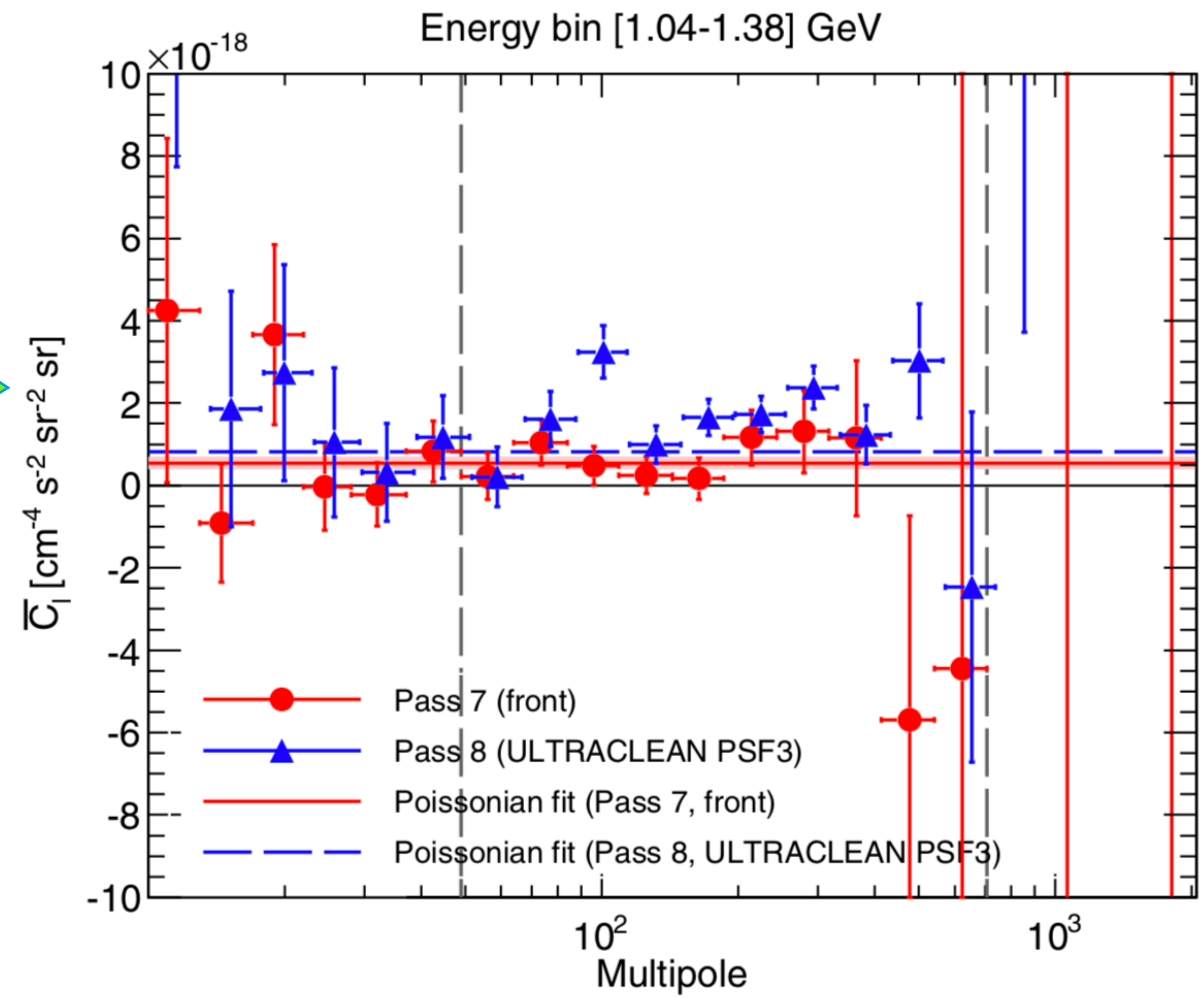
The contribution of Blazars to the EGB

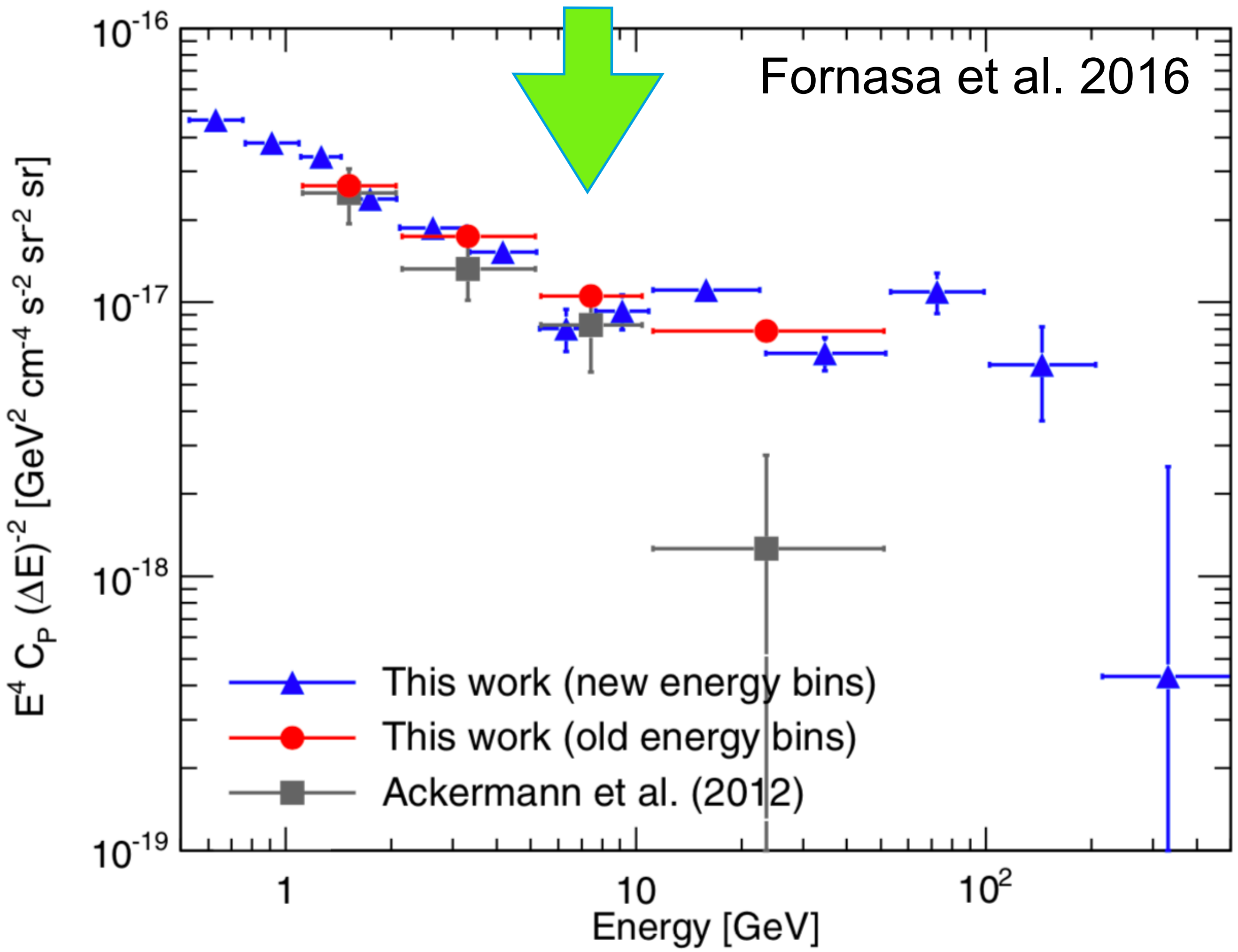
- Blazars dominate the EGB above 10 GeV
- Observed cutoff shape consistent with EBL absorption of Blazar emission



Anisotropies in the IGRB



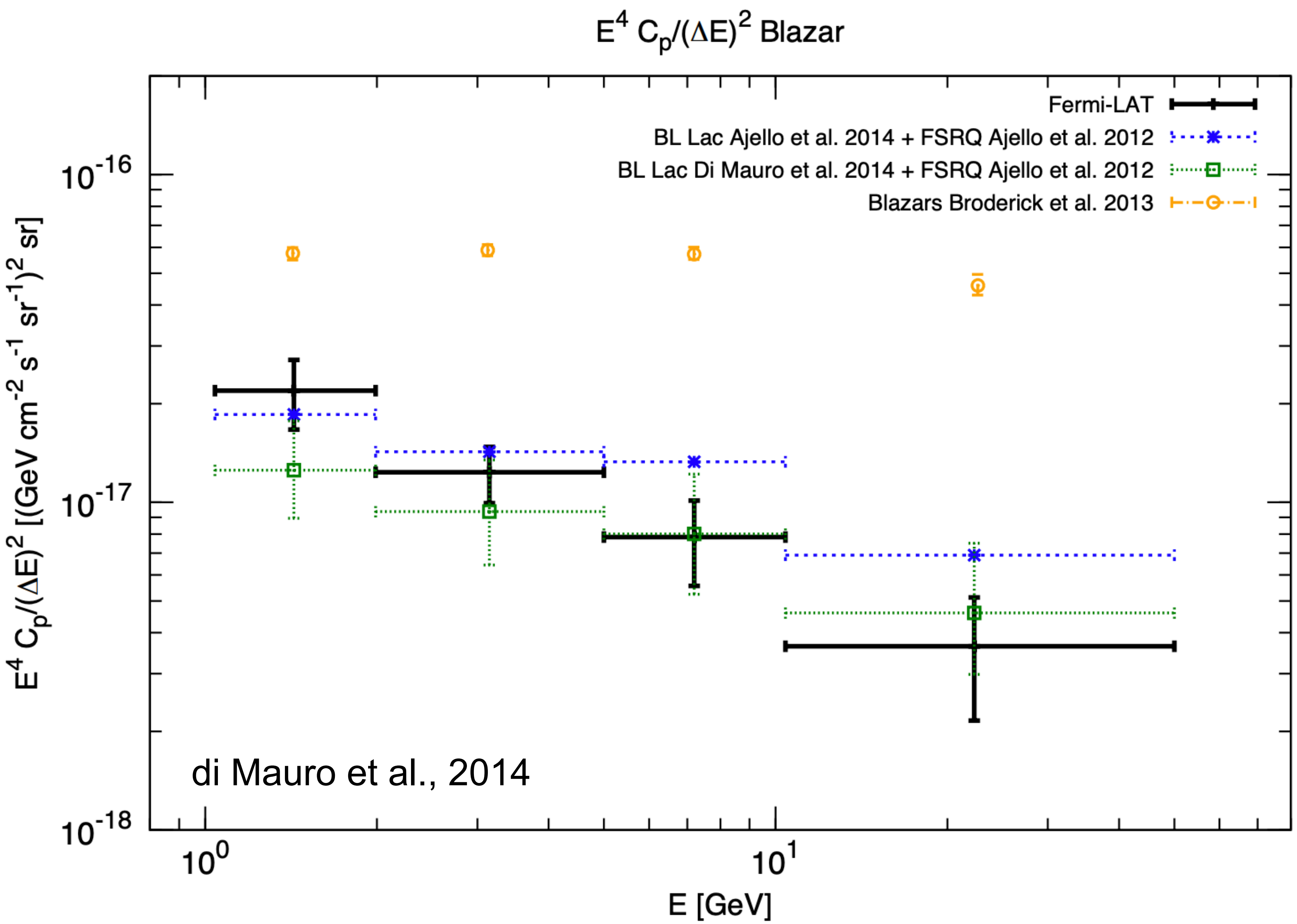




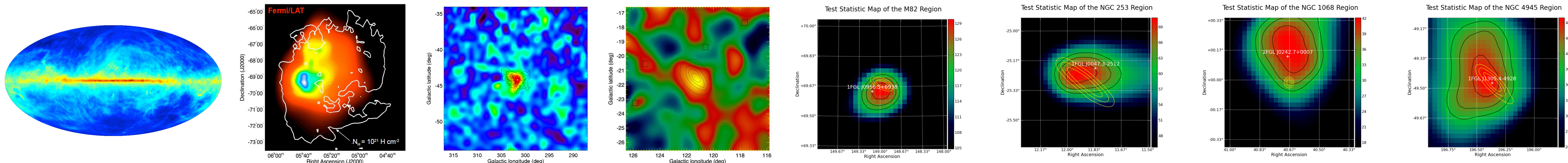
- **Angular power spectrum** consistent with being Poissonian
- **Energy dependence** of anisotropy suggests spectral break around 2 GeV

Anisotropies expected in the IGRB

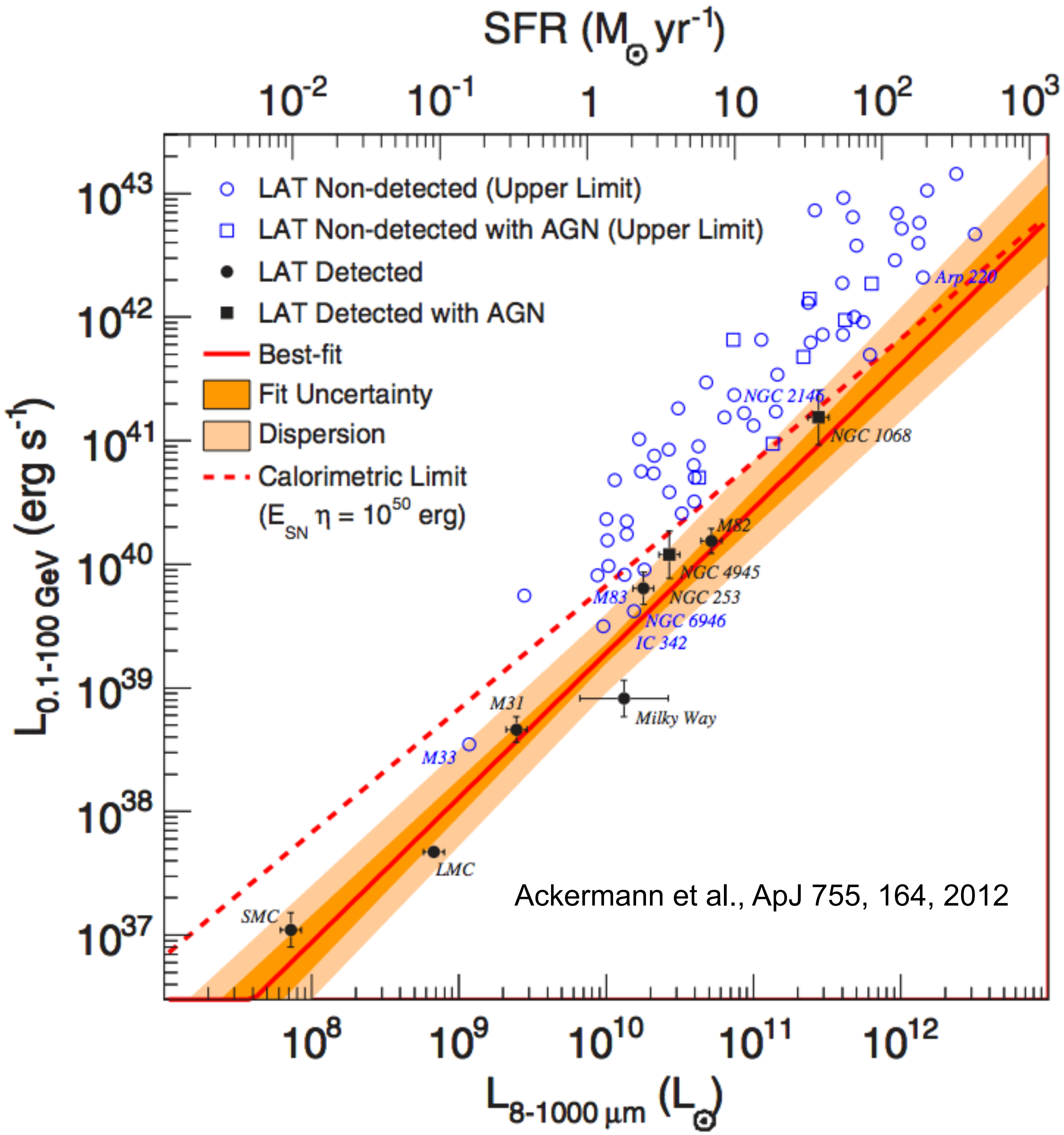
- Observed anisotropy **consistent with expectations from Blazars**



Contributions from star-forming galaxies

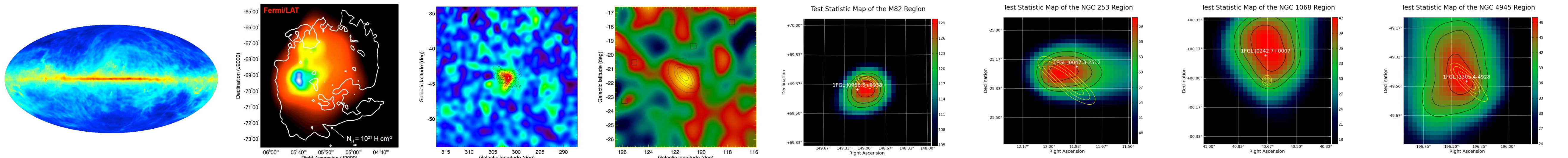


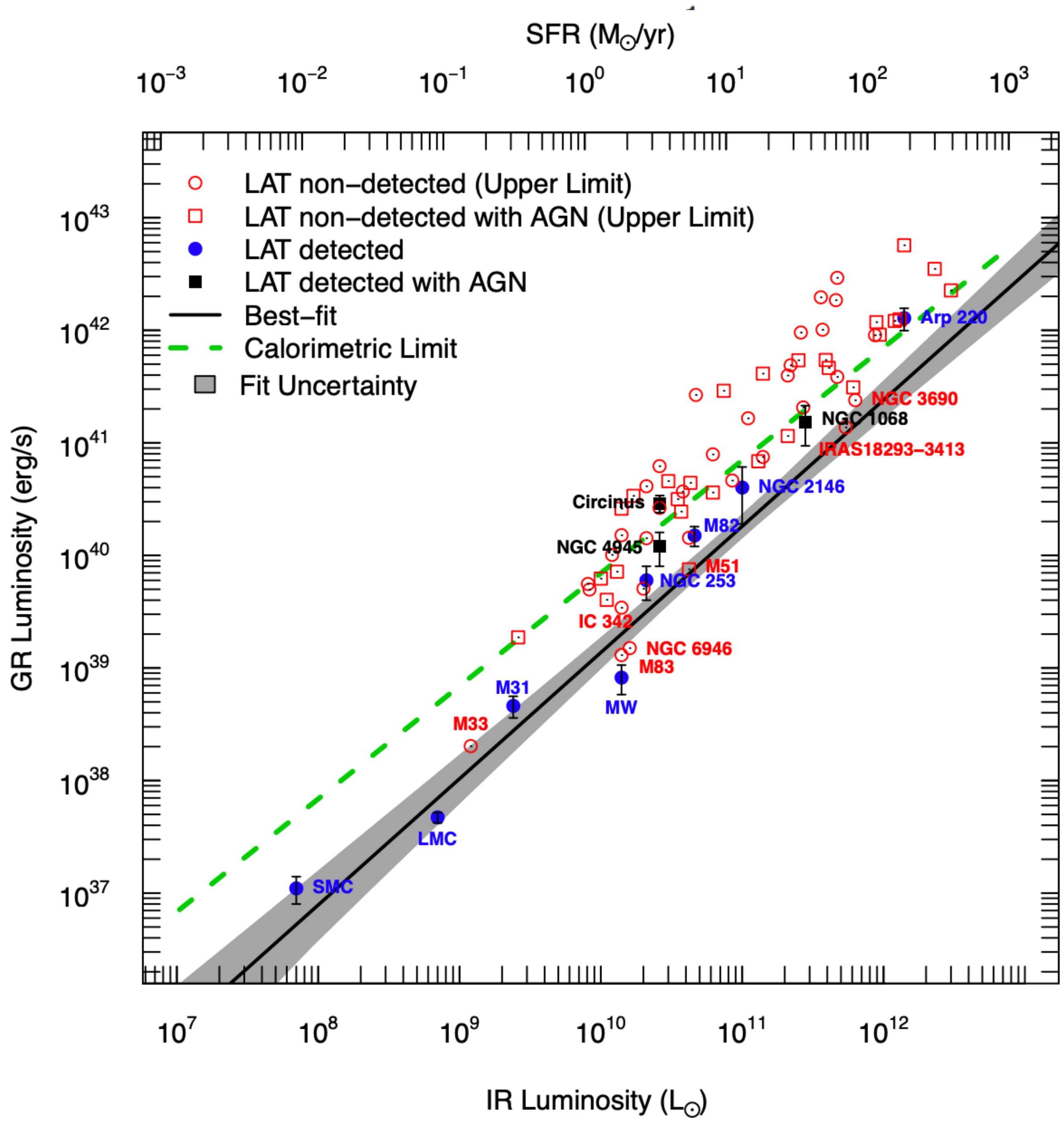
Milky Way LMC SMC M 31 M 82 NGC 253 NGC 1068 NGC 4945



- Now **10 galaxies** detected by the LAT
- **Almost linear correlation** between gamma-ray luminosity and tracers of star formation
- **Detections + upper limits** can be used to constrain correlation
- **Use gamma-ray / IR luminosity** correlation to calculate EGB contribution based on IR luminosity function of galaxies.

Contributions from star-forming galaxies





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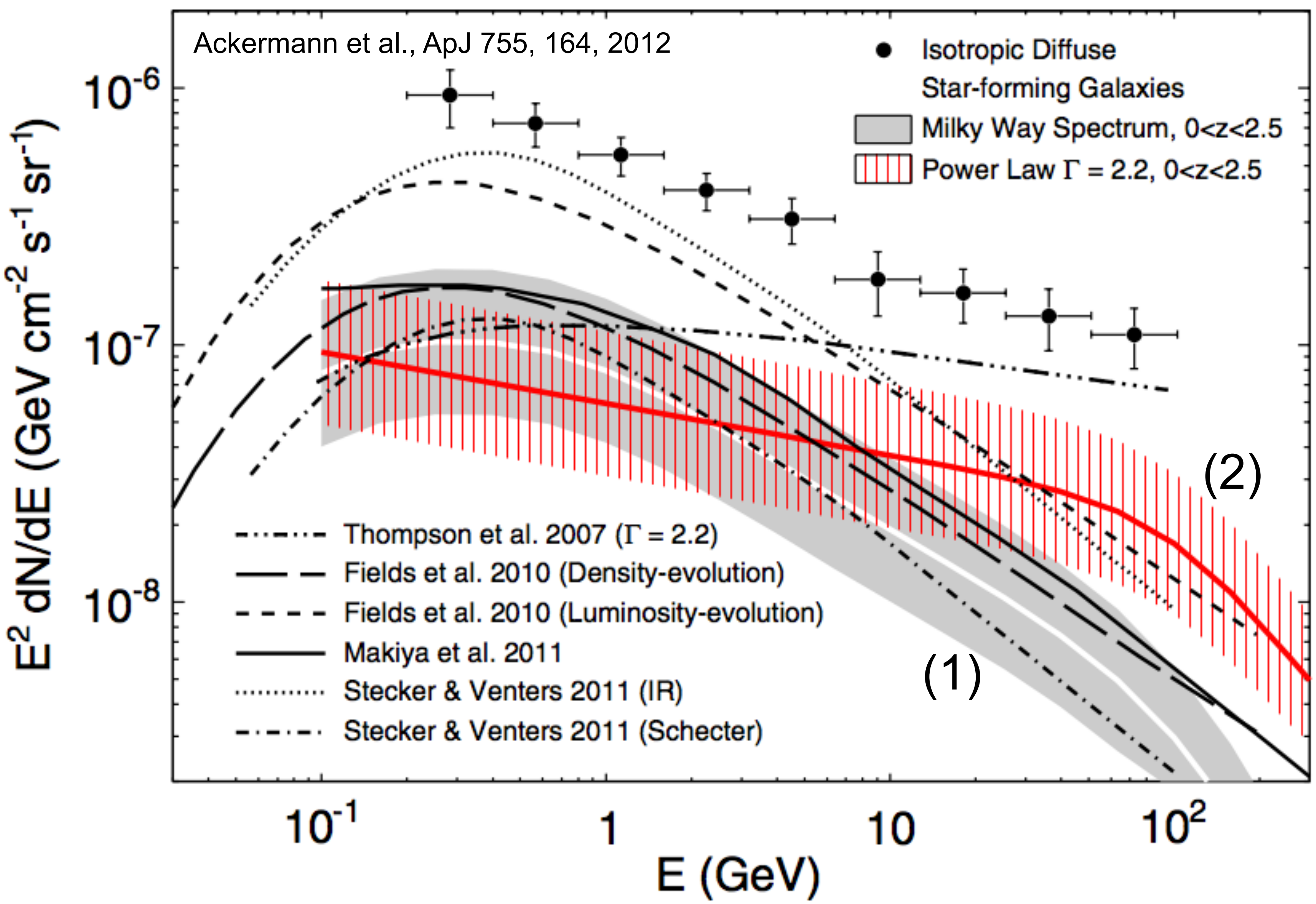
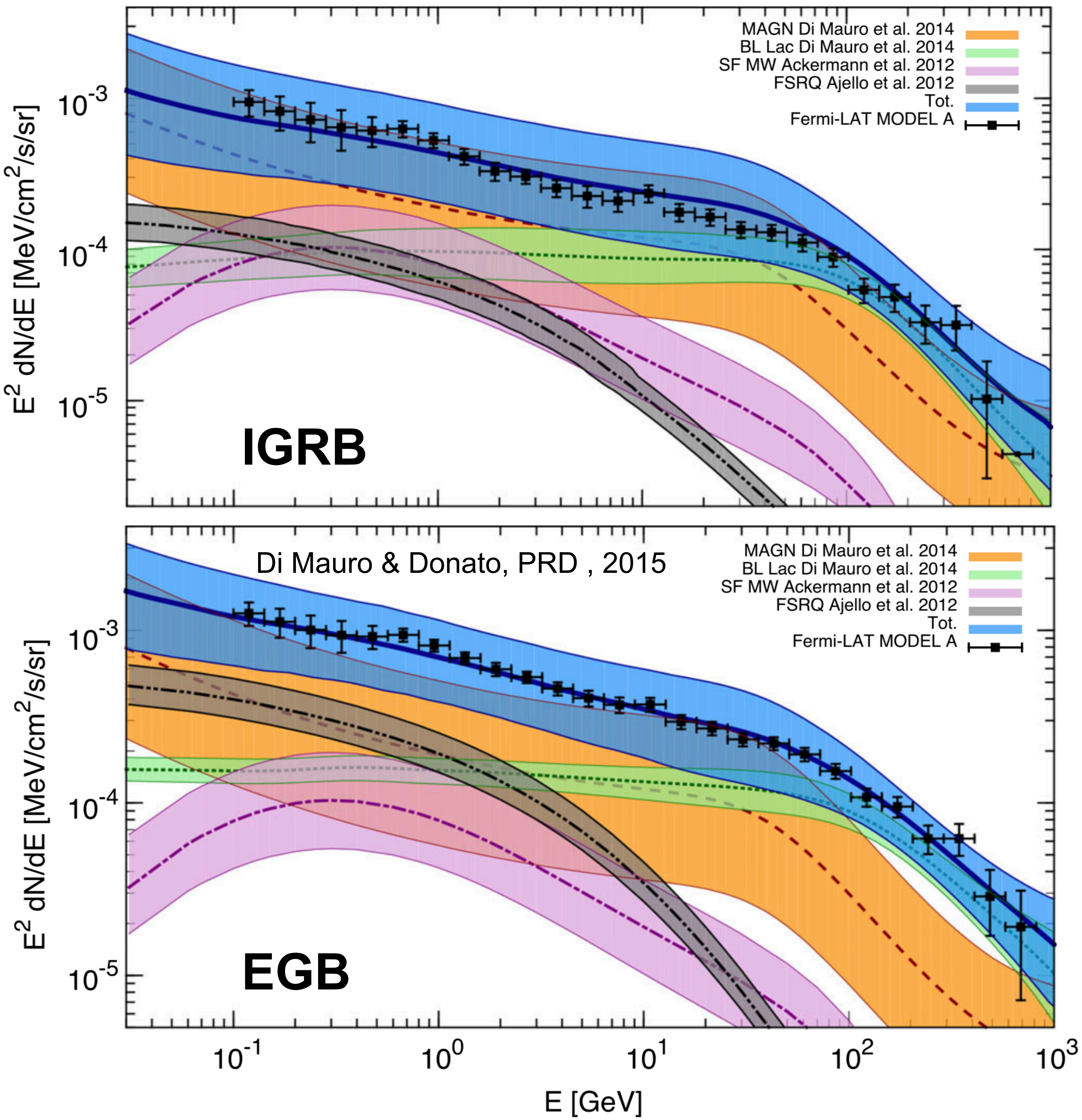
Contributions from star-forming galaxies

- **4% - 23% contribution to EGB** from star-forming galaxies ($0 < z < 2.5$)
- **Two scenarios** for gamma-ray spectrum: (1) rescaled Milky Way or (2) power-law spectrum observed for Starburst Galaxies
- **Similar technique** can be applied to estimate contributions from **misaligned AGN** (Radio-gamma correlation, e.g., Inoue 2011)



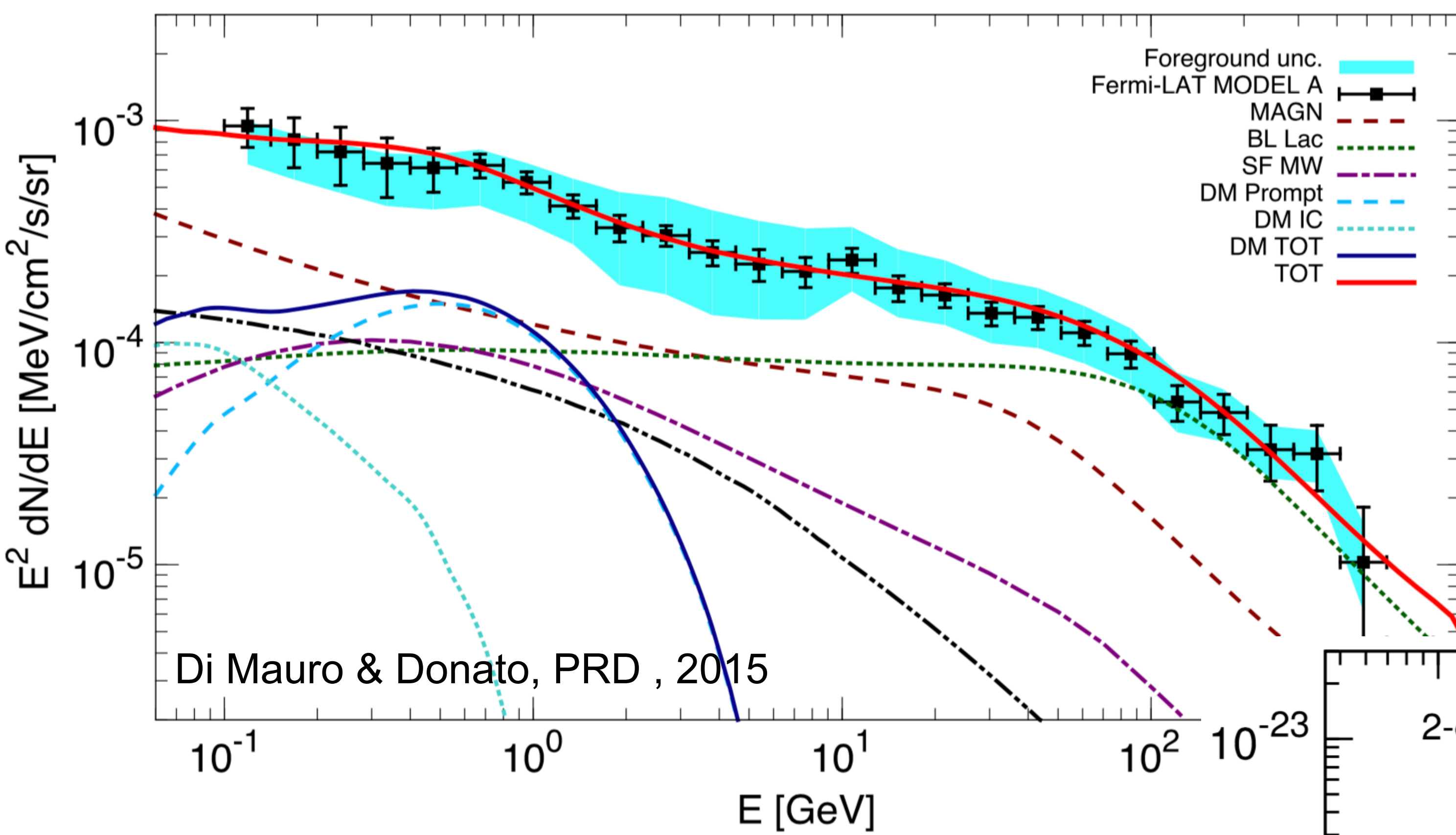
A census of the different contributions



- **Known extragalactic gamma-ray source populations** can fully explain the observed IGRB/EGB.
- But **uncertainties are generally large.**
- Energy range **around 100 GeV is constrained best** due to strong contribution from Fermi Blazars
- **There is potential** for (some) diffuse contributions from cosmic rays, DM, etc…

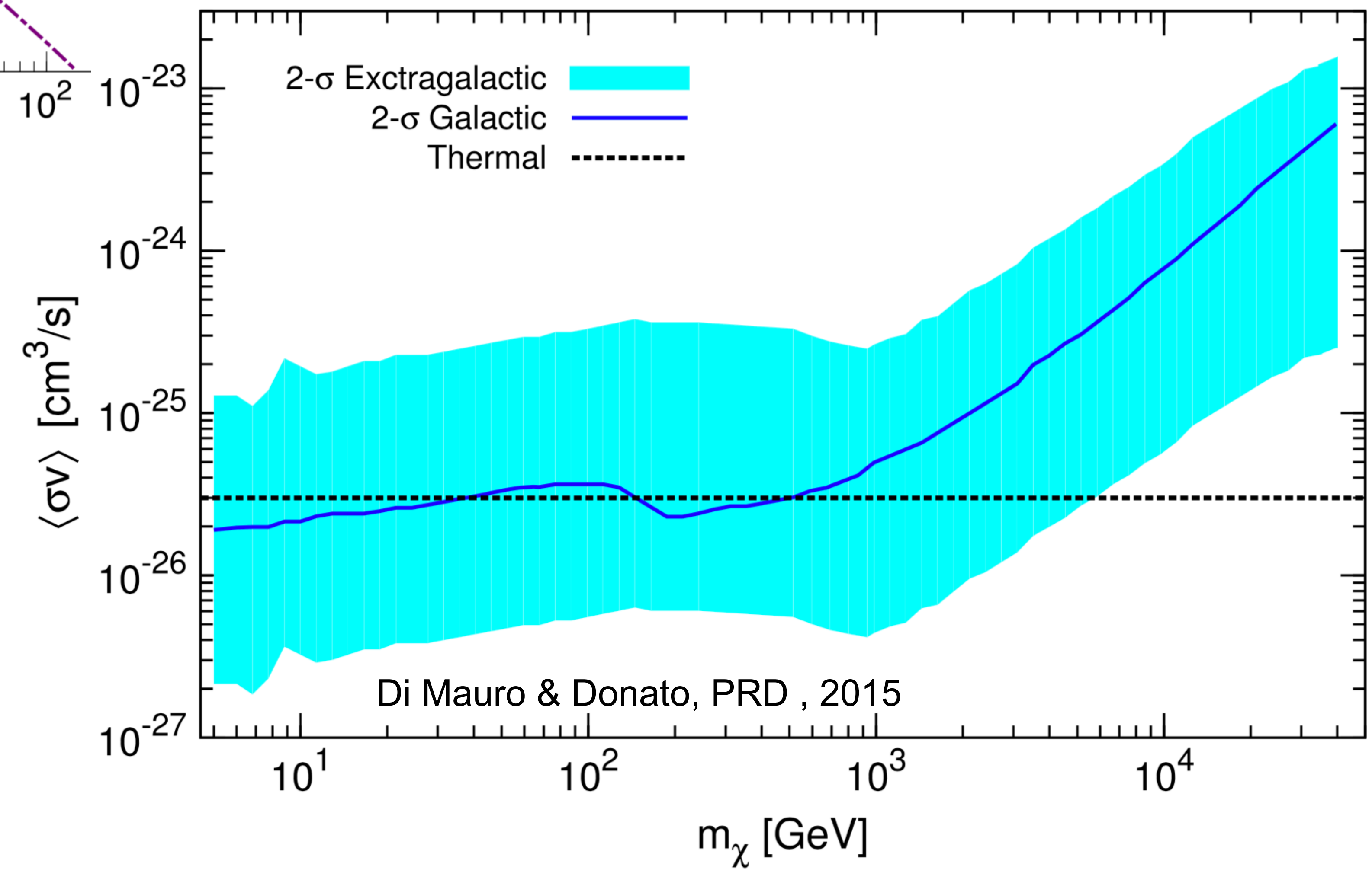
Constraints on contributions from Dark Matter

IGRB best fit with DM, bb channel



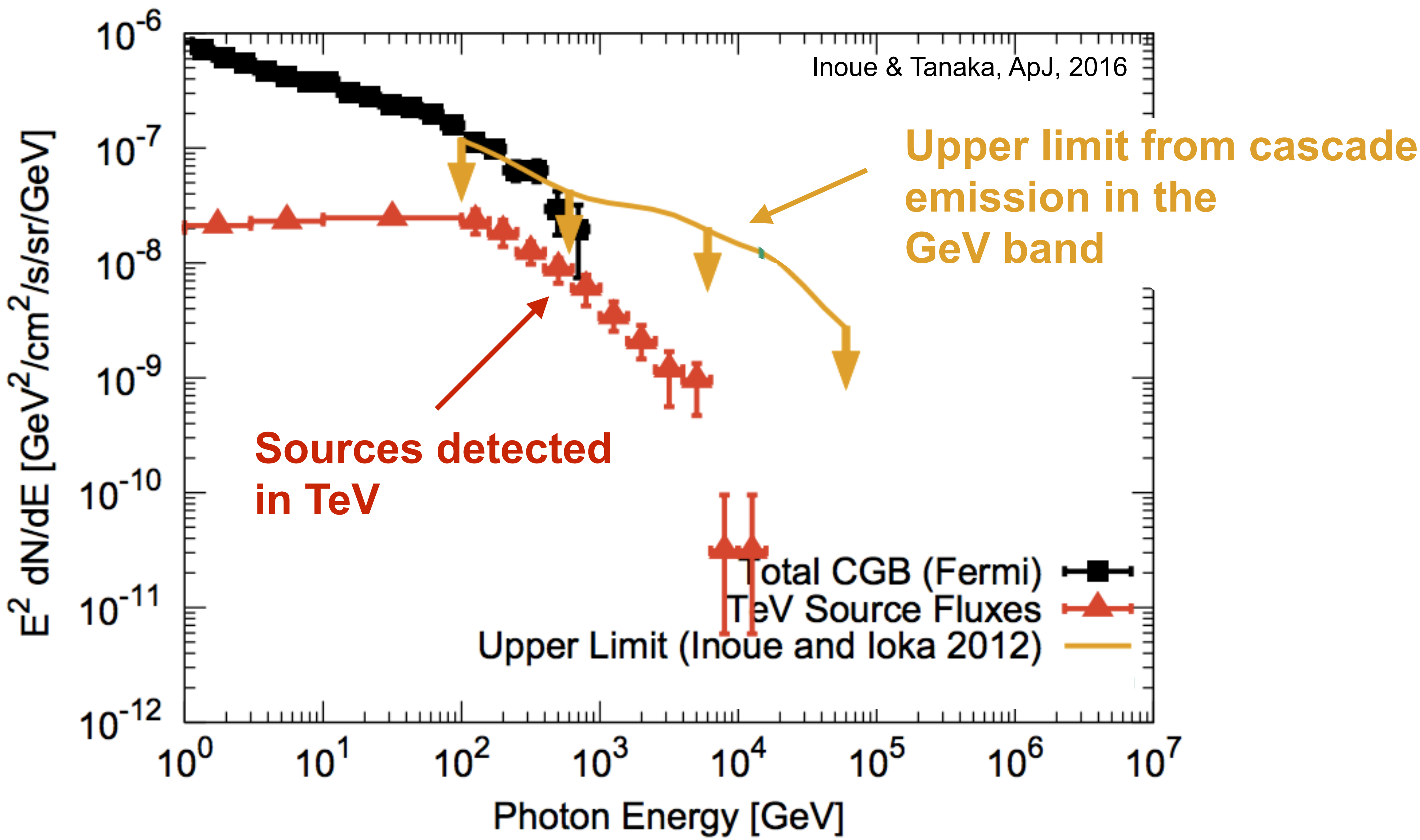
- **IGRB constrains DM contribution** from Galactic halo and from extragalactic DM annihilation

bb galactic and extragalactic



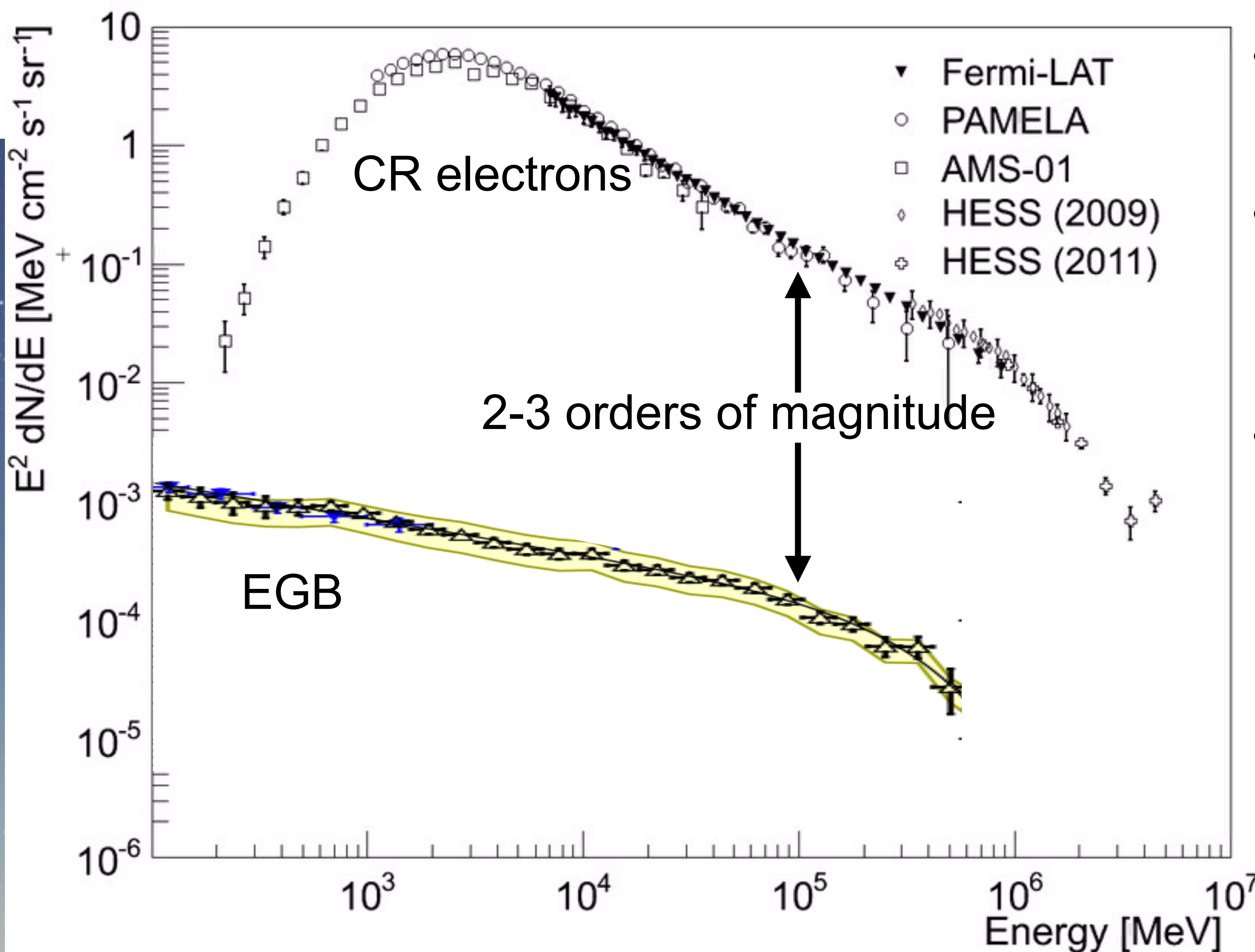
- **Large uncertainties on extragalactic contribution** due to unknown sub-halo mass function

Extending the IGRB measurement to TeV ?



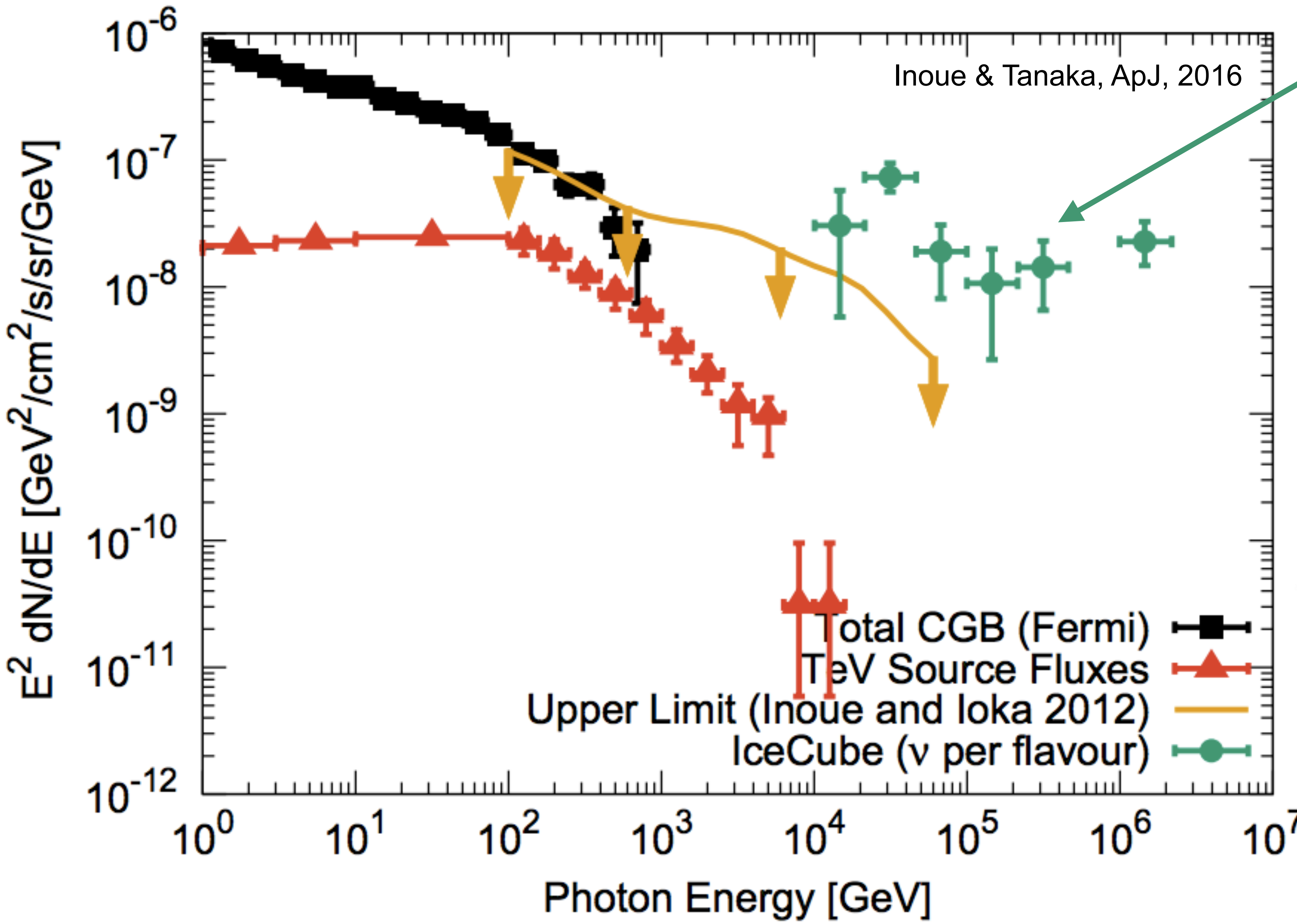
- **Lower limit** from counting TeV detected sources.
- **Upper limit** from requirement that the cascade emission is not higher than observed GeV background.

CTA and the IGRB

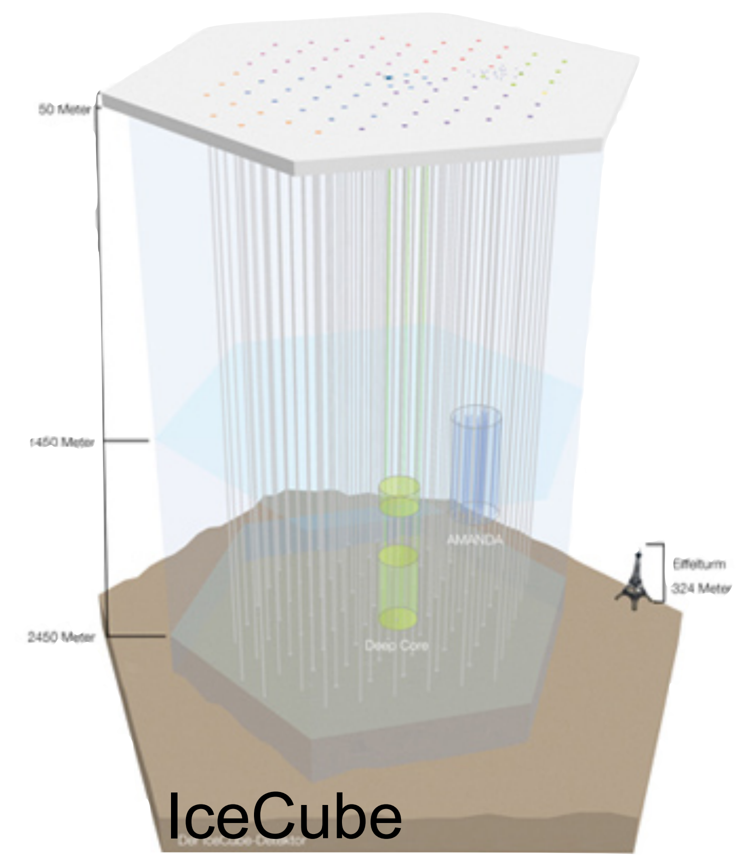


- **Cherekov telescopes** have very limited e / gamma separation.
- **CR electron background** dominates by at least two orders of magnitude.
- CTA can only observe **close-by TeV sources** and potentially **small-scale anisotropies.**

From the IGRB to the INB



astrophysical neutrino flux



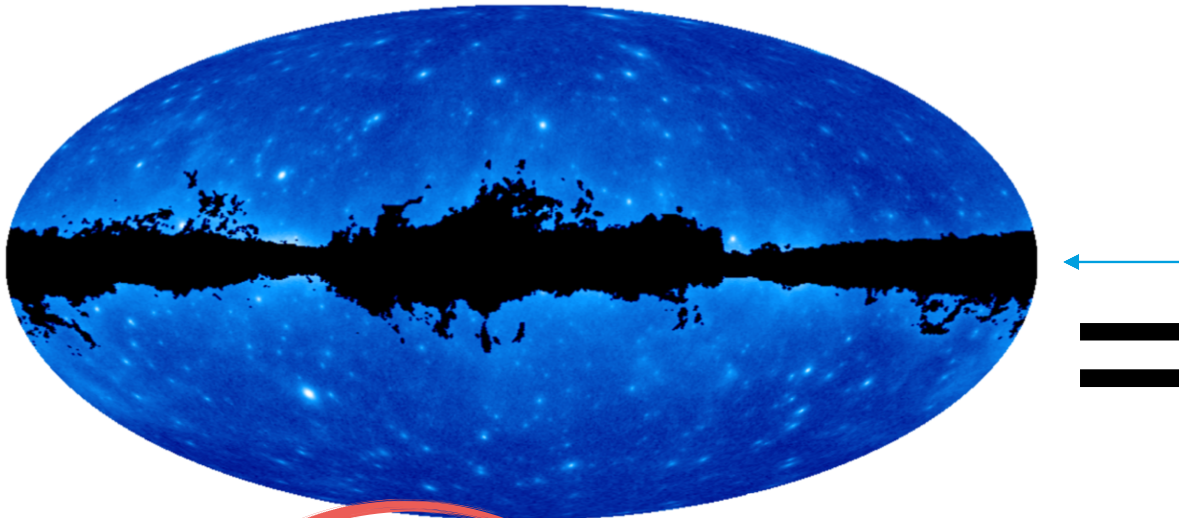
- **Neutrinos** give us an **unobscured view** of the **TeV-PeV universe**

Summary

- **The IGRB spectrum** between 100 MeV and 820 GeV can be described by a simple power-law of **index ~2.3** with an **exponential cutoff at ~250 GeV.**
- **The shape of the cutoff** is compatible with expectations due to **absorption** of the gamma-rays in the **extragalactic background light** and a **single dominating population.**
- **Uncertainty in diffuse foreground modeling** is the **largest systematic uncertainty** for the IGRB measurement.
- The observed EGB can be explained by the **emission of unresolved sources**.
- Diffuse radiation (UHECR, DM) can only contribute a small fraction.
- **Neutrinos** are the messenger of choice to measure non-thermal emission beyond few TeV

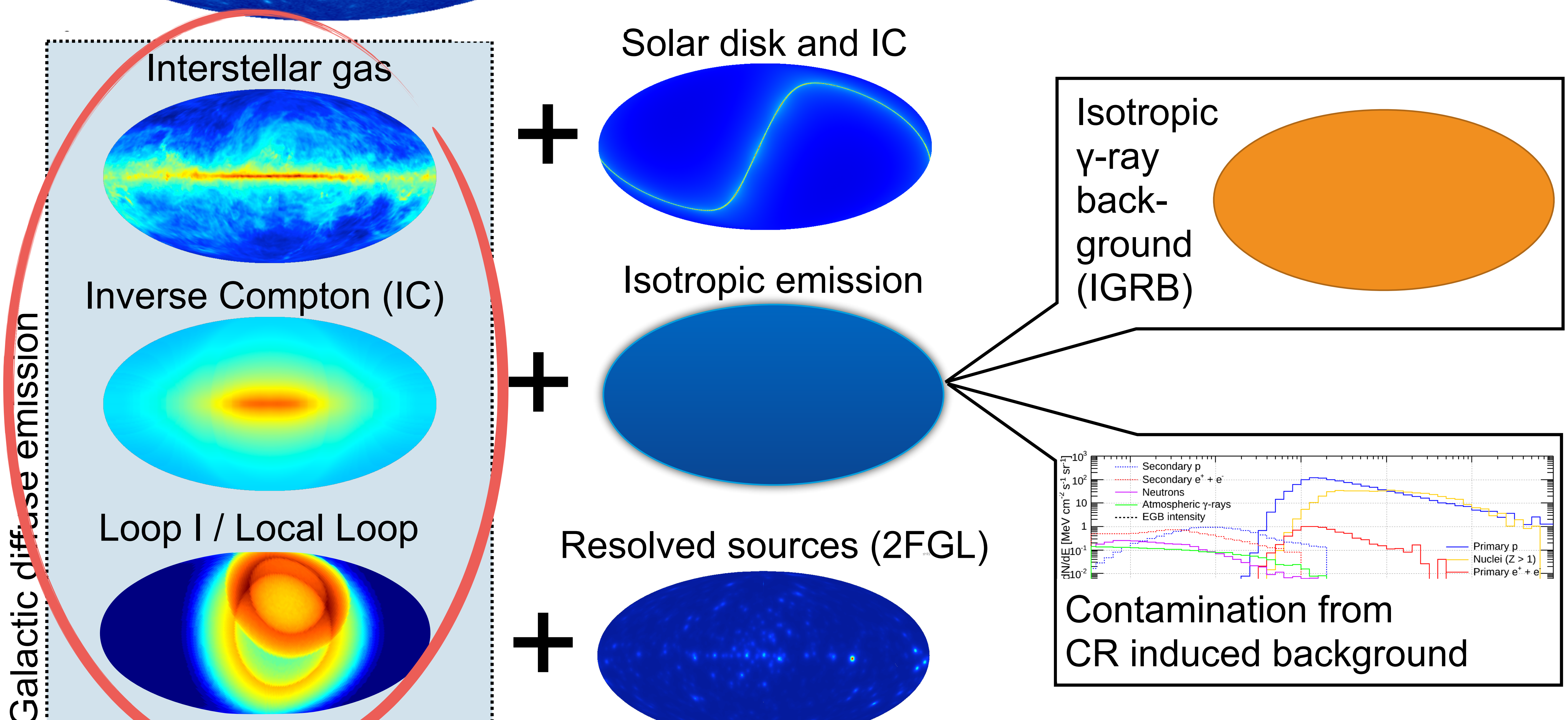
Backup

Derivation of the extragalactic background



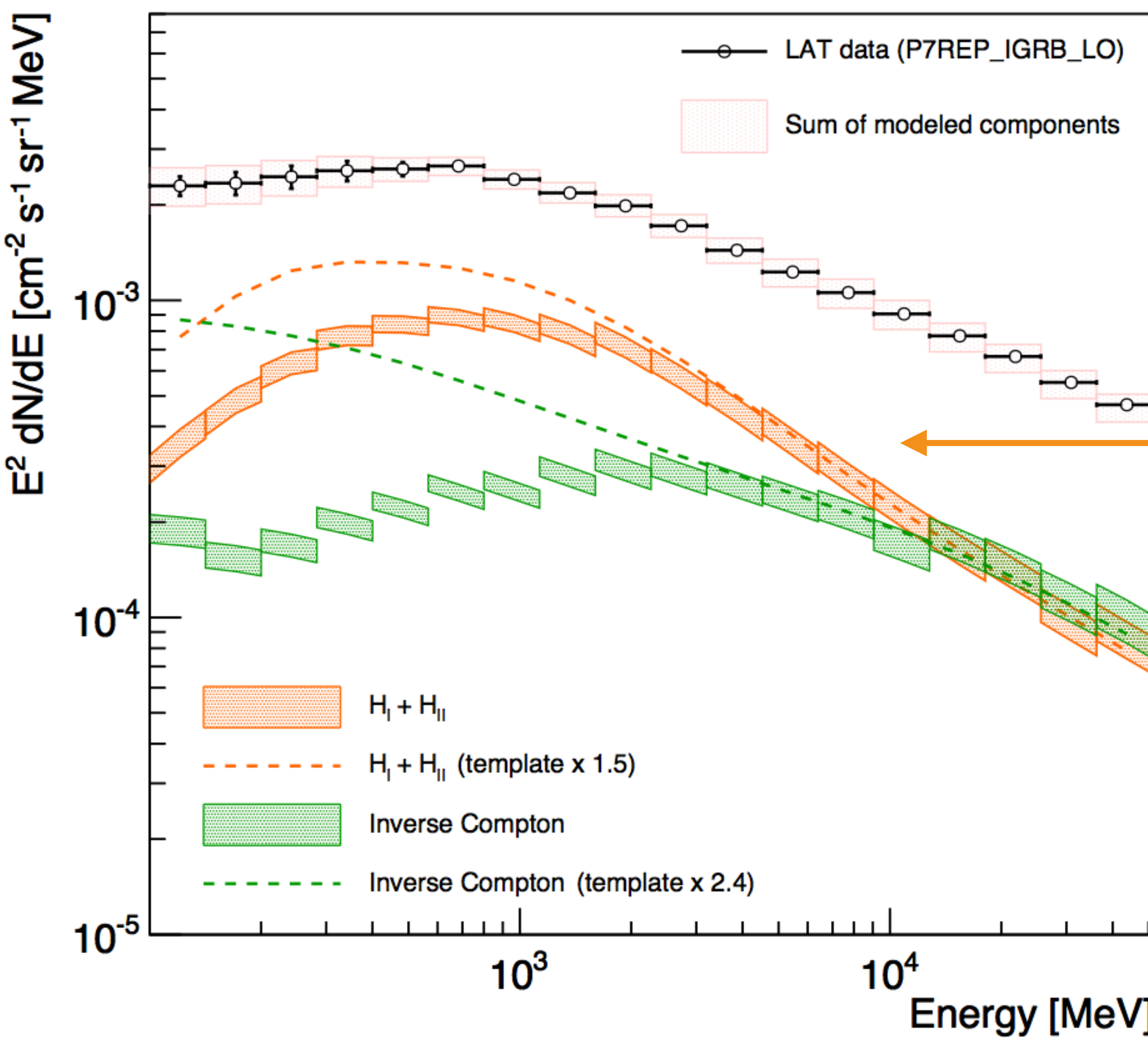
Masked regions:

- Galactic plane
- Regions with dense molecular clouds
- Regions with non-local atomic hydrogen clouds

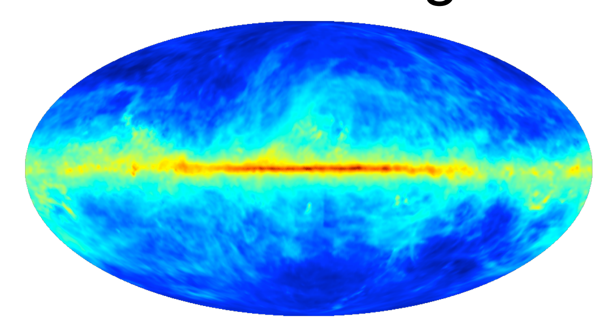


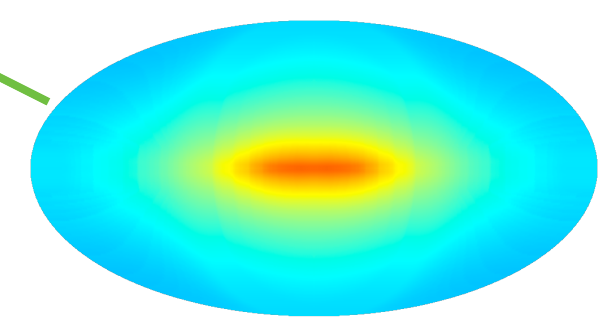
Galactic diffuse foreground model

- **GALPROP** code used to produce **template maps** for diffuse Galactic emission.
  - Baseline model: CR injection/propagation scenario as in Ackermann et al. 2012
- **Intensity** is derived from **fit to LAT data** in each energy band.



Interstellar gas





Inverse Compton (IC)

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