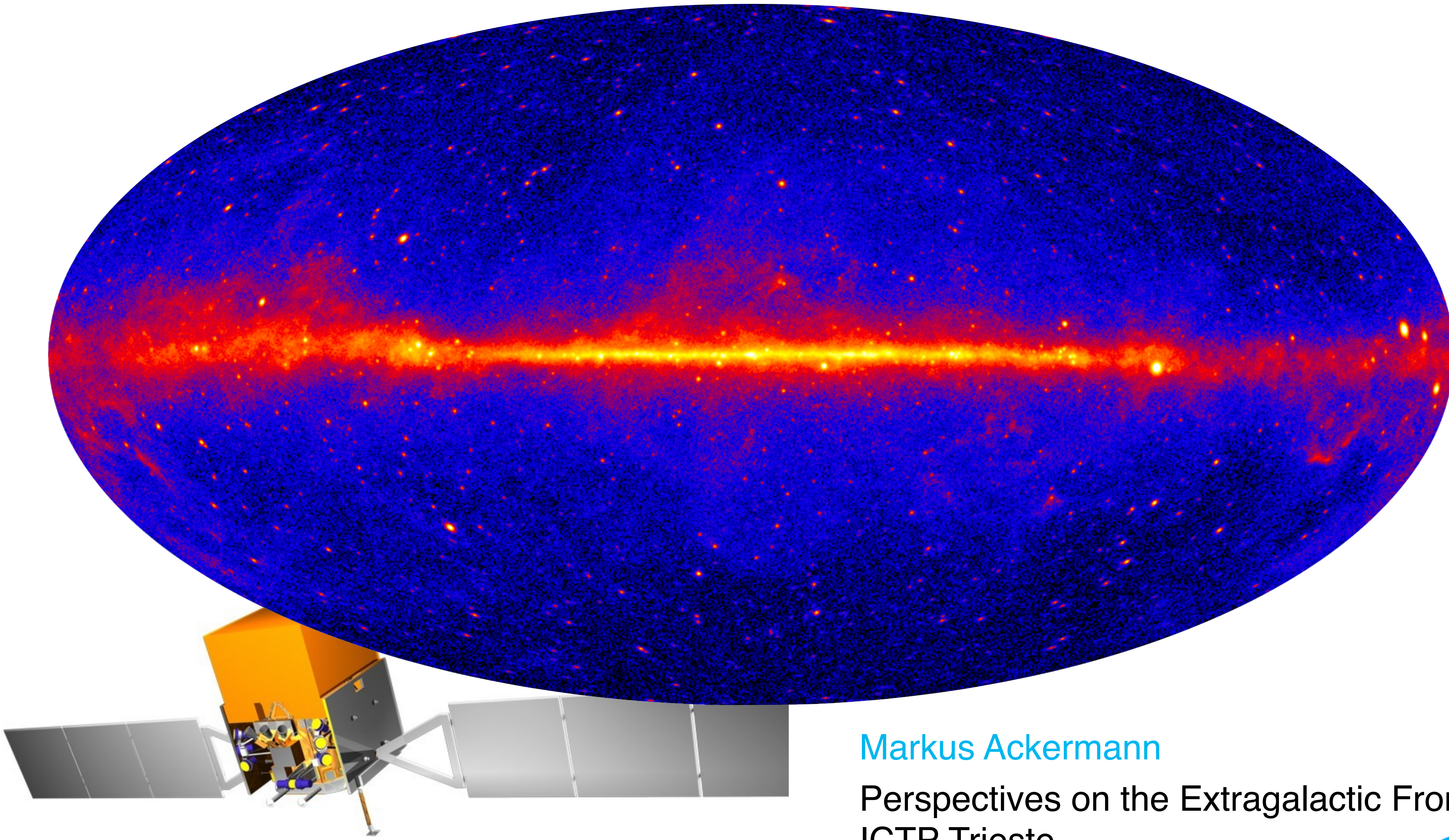
The extragalactic gamma-ray background.



Markus Ackermann

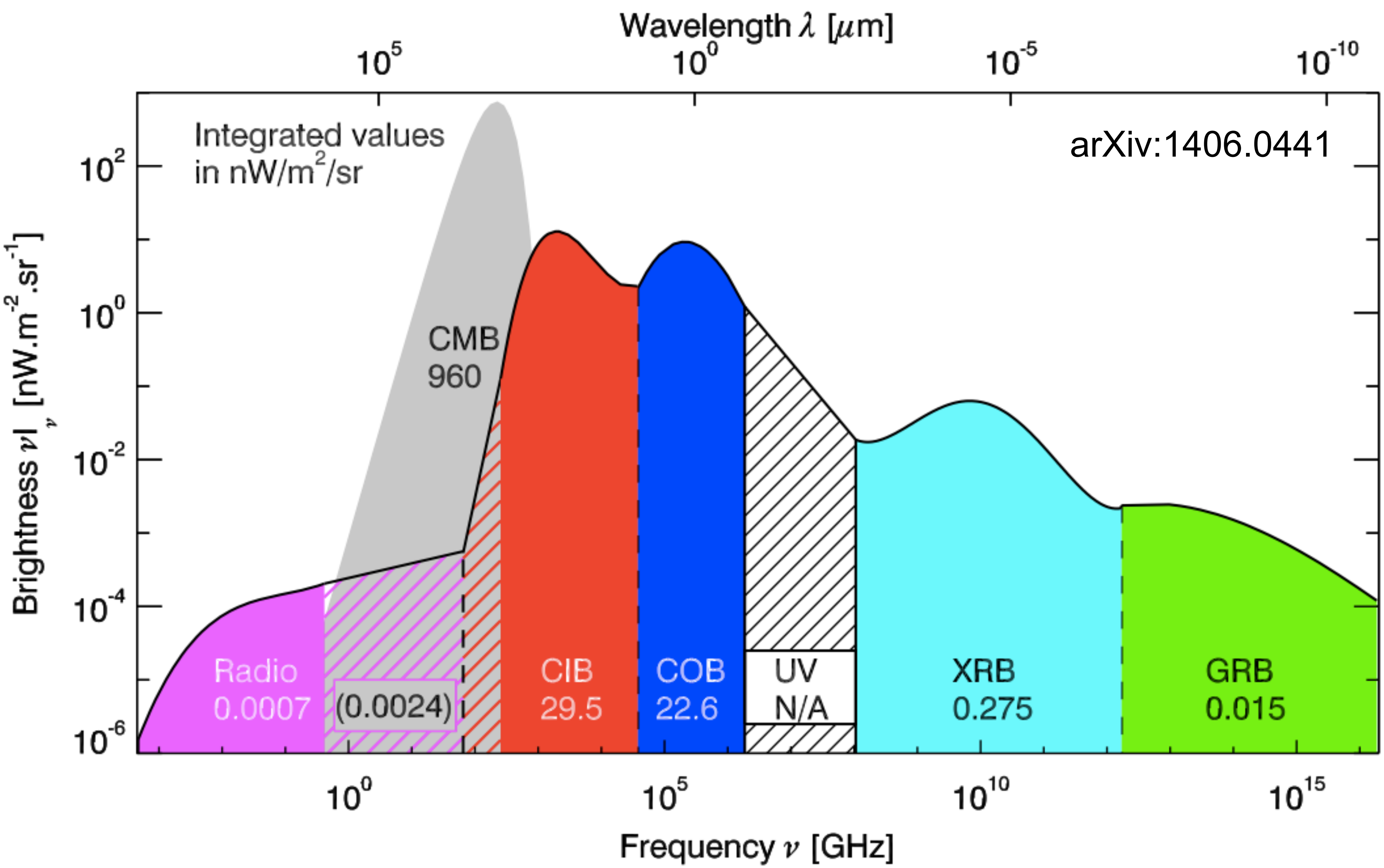
Perspectives on the Extragalactic Frontier
ICTP Trieste
May 2 - May 6, 2016

WIPAC
Wisconsin IceCube Particle Astrophysics Center

Alexander von Humboldt
Stiftung / Foundation

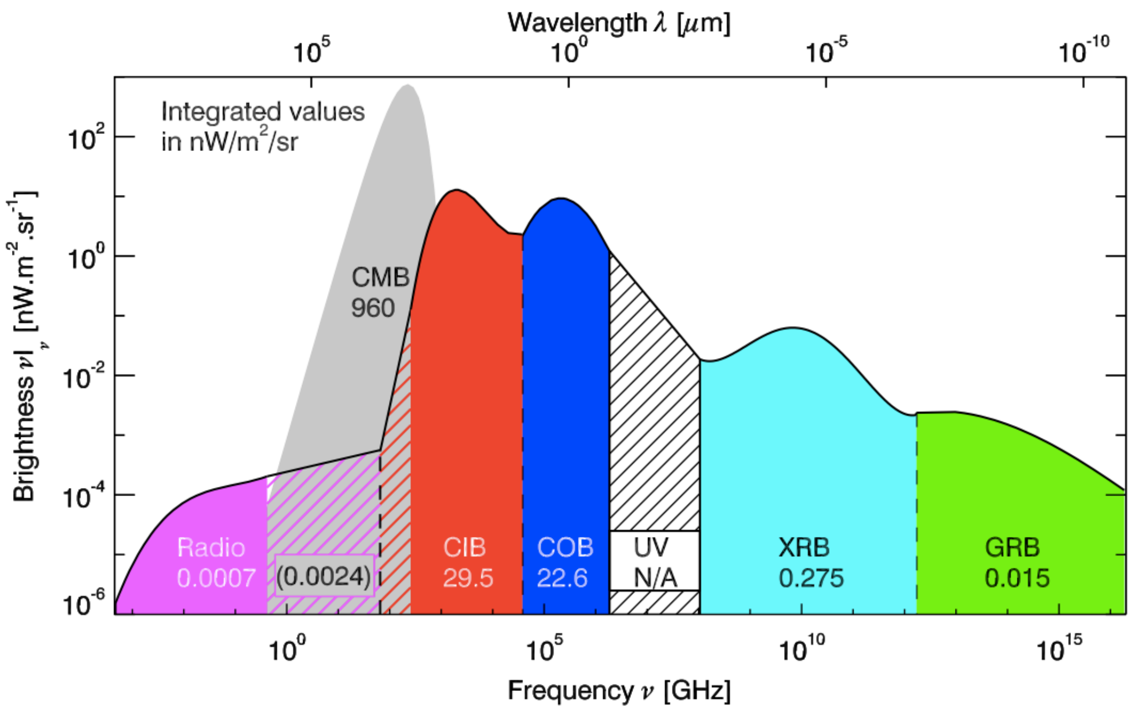
DESY

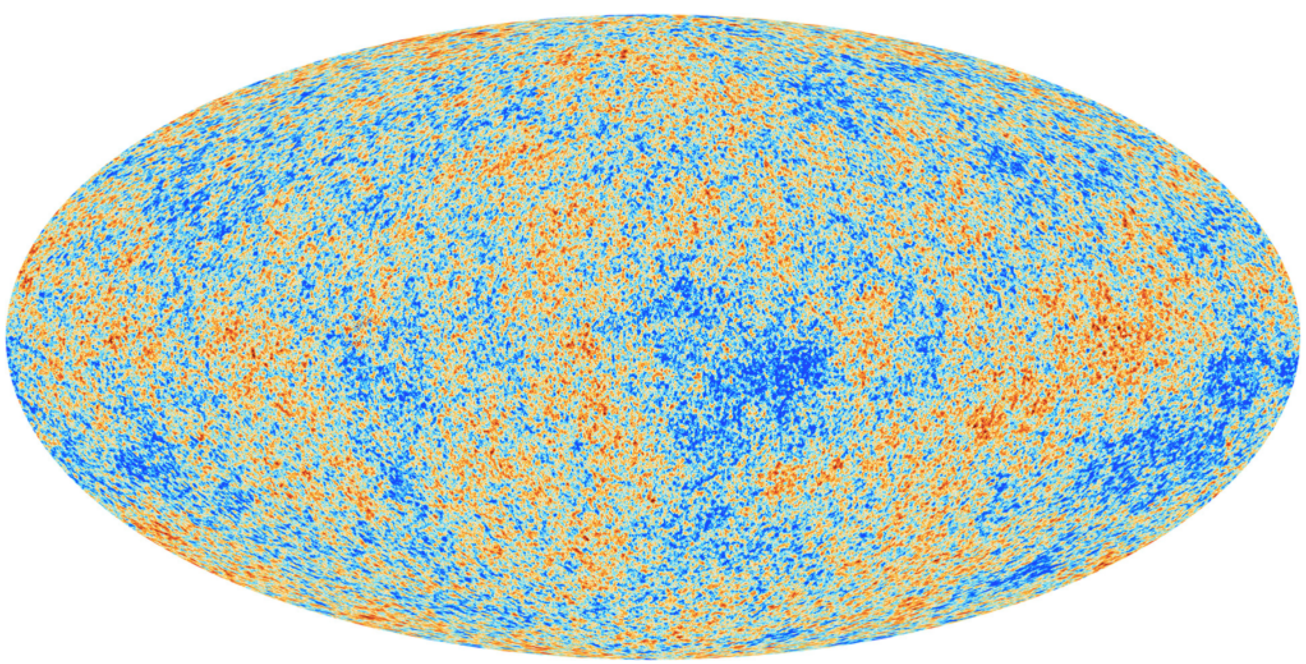
Extragalactic radiation backgrounds.



> The universe is **full of radiation backgrounds** from the lowest to the highest energies.

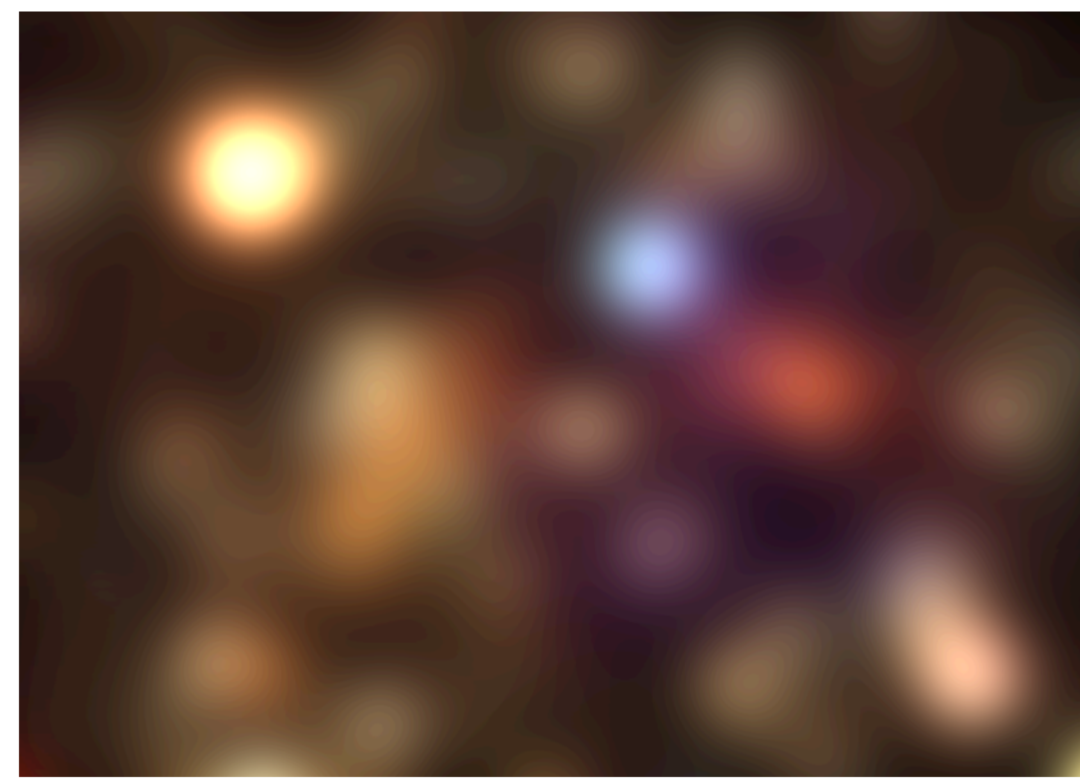
Origin of the radiation backgrounds.





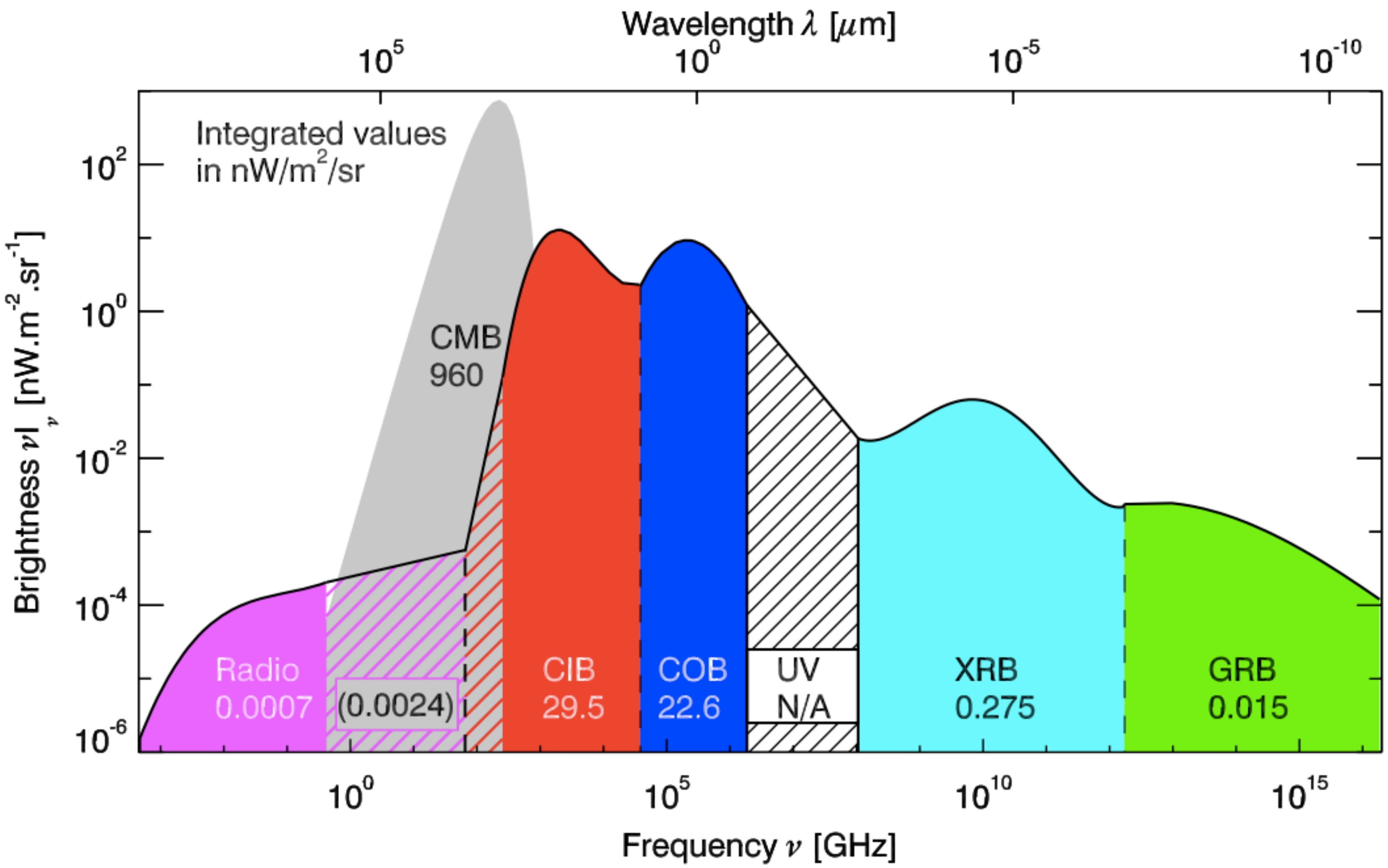
Diffuse radiation

Known source populations

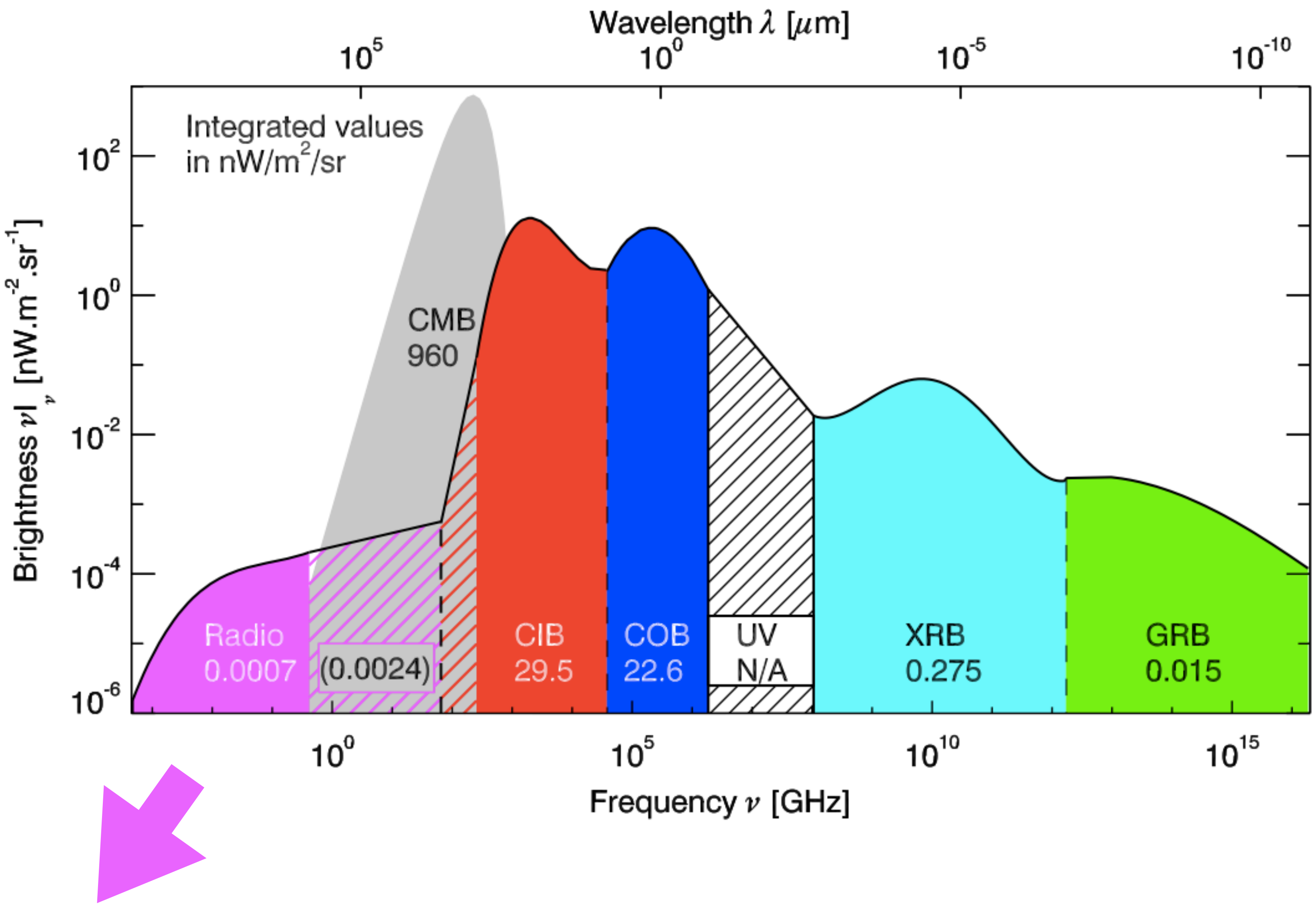


Sources too faint to be resolved.

Origin of the radiation backgrounds.



Origin of the radiation backgrounds.



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

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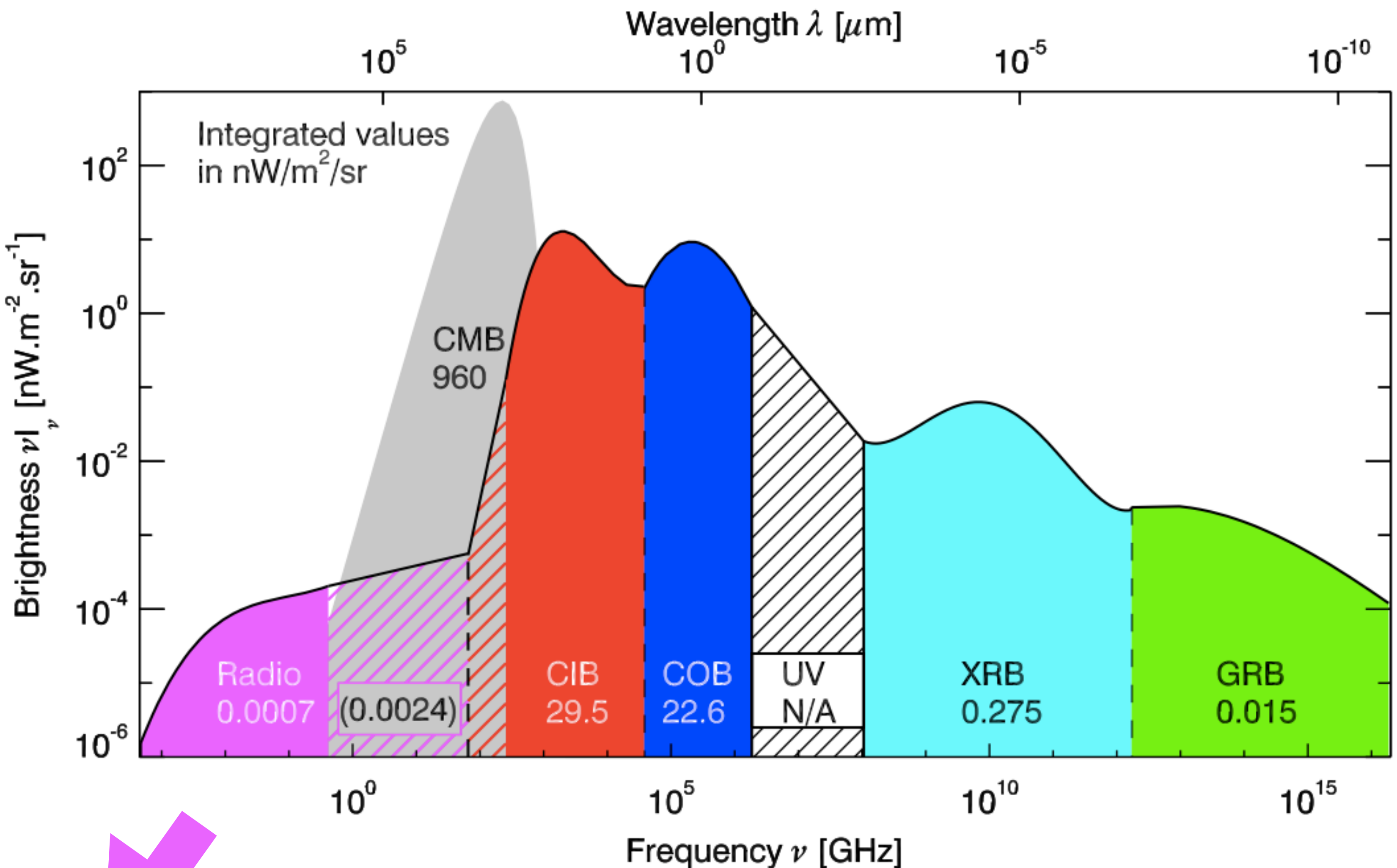

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- thermal emission from stars and dust
- possible small contri-bution from unknown stellar populations (e.g. Pop III stars)

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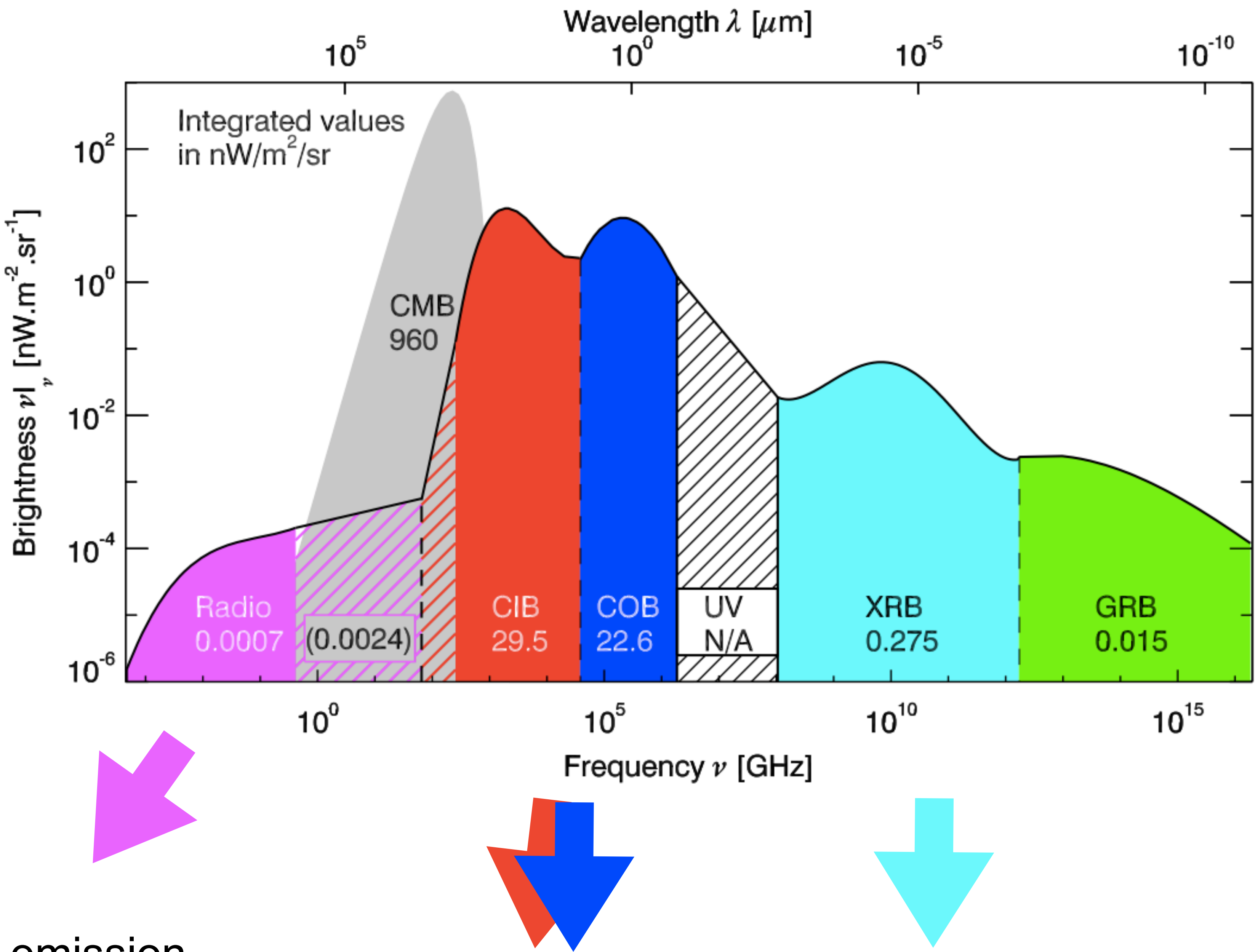

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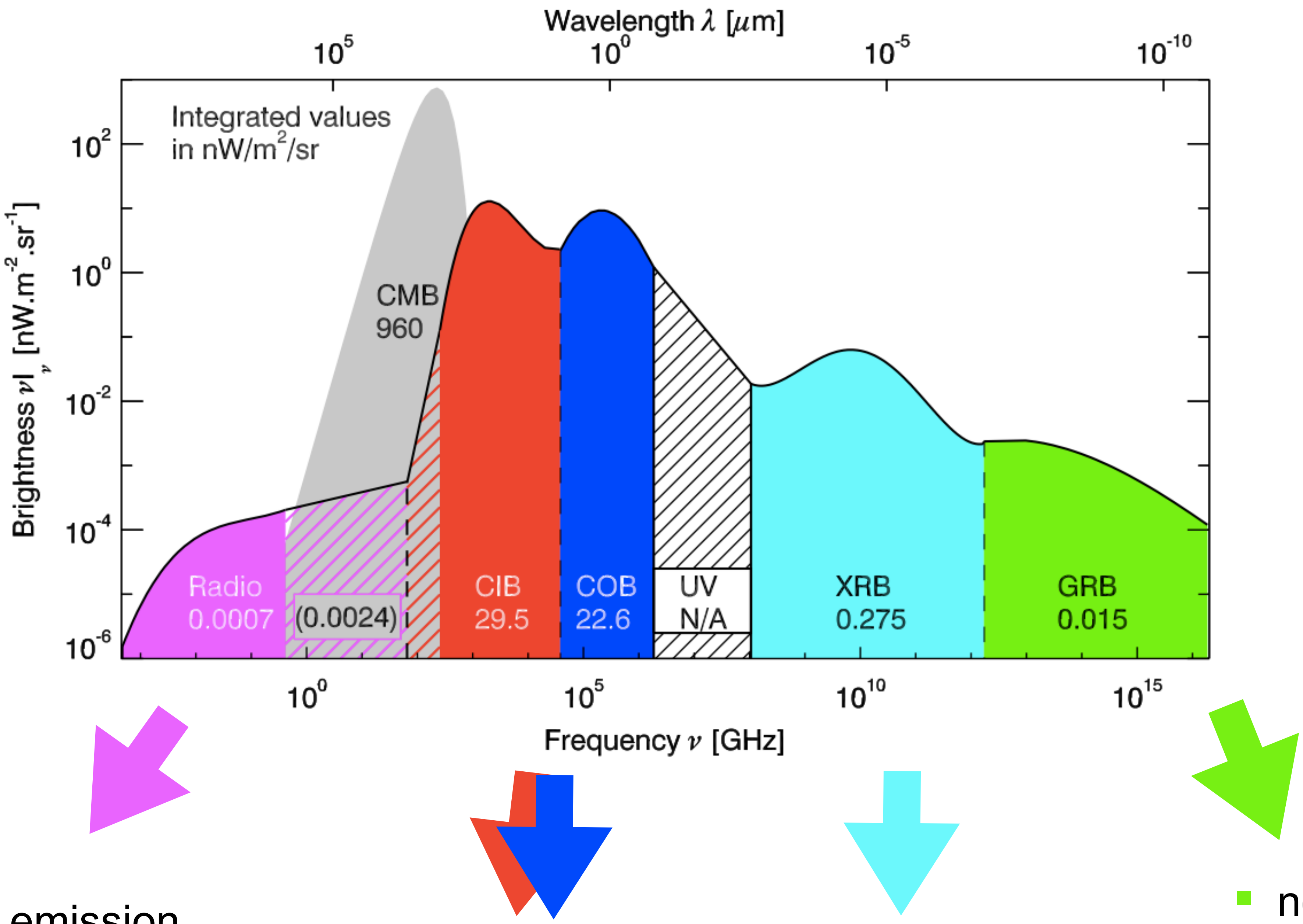

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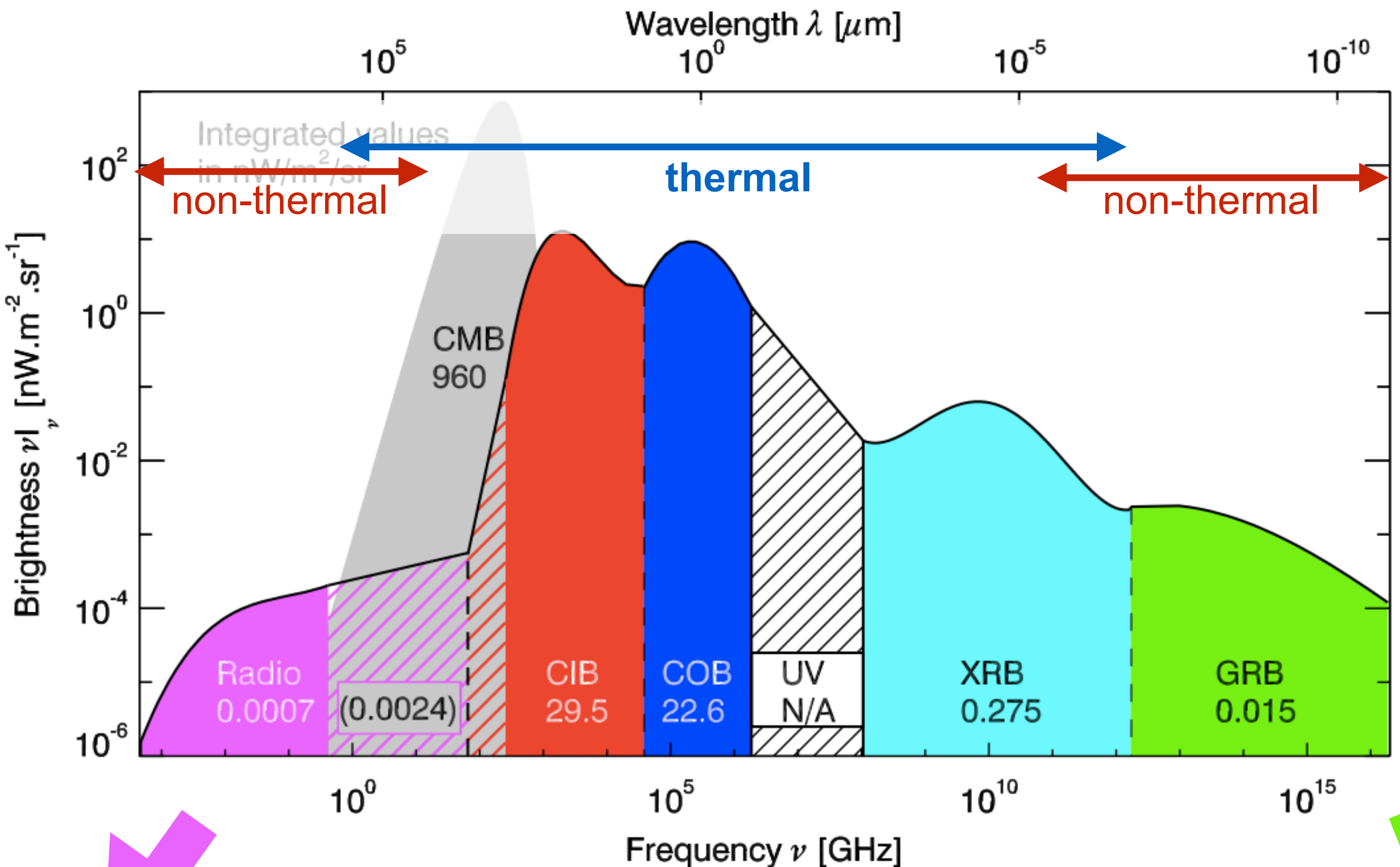

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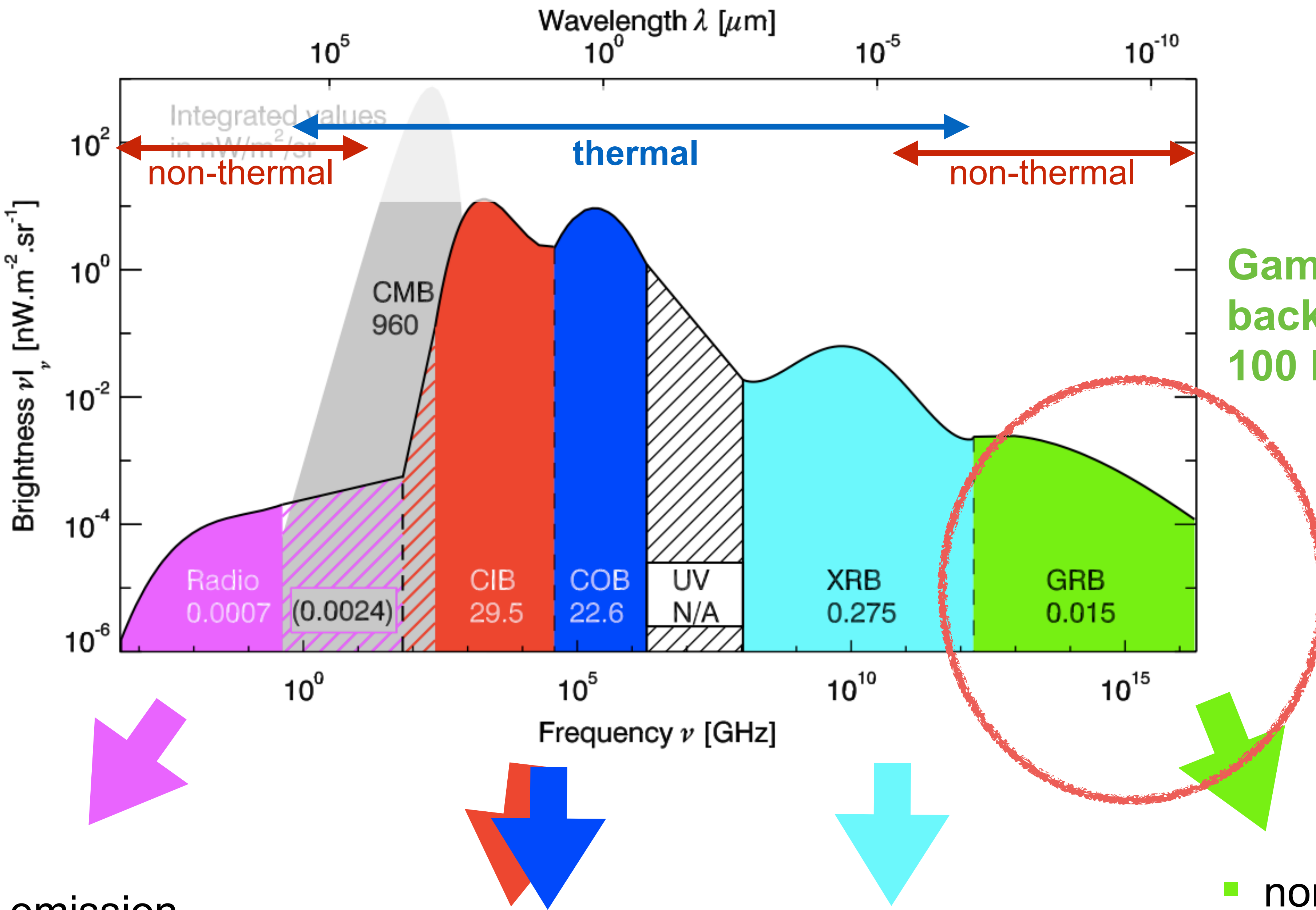


Gamma-ray background above 100 MeV

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

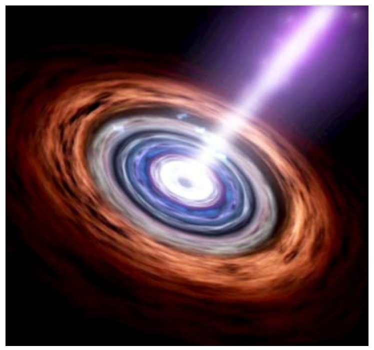
- thermal emission from stars and dust
- possible small contri-bution from unknown stellar populations (e.g. Pop III stars)

- accretion disks of active galactic nuclei (AGN)

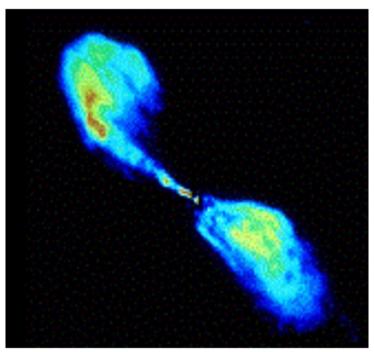
- non-thermal emission from AGN and normal galaxies
- diffuse contribu-tions from CR, dark matter ??

The origin of the GRB / EGB above 100 MeV.

Sources

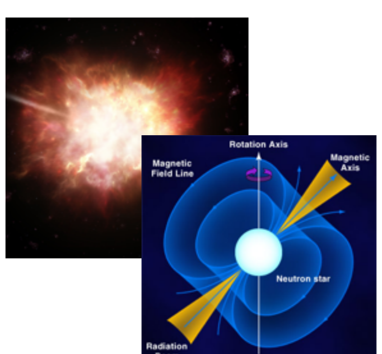


Blazars
- Dominant class of extra-galactic GeV / TeV sources.



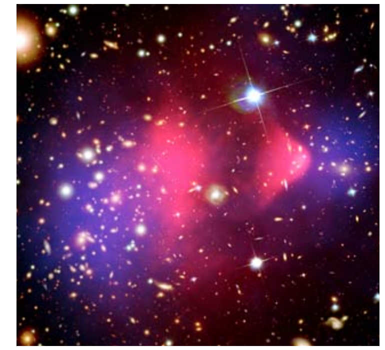
Radio galaxies
- ~ 30 sources resolved in GeV band.
- Less luminous but more abundant than Blazars

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

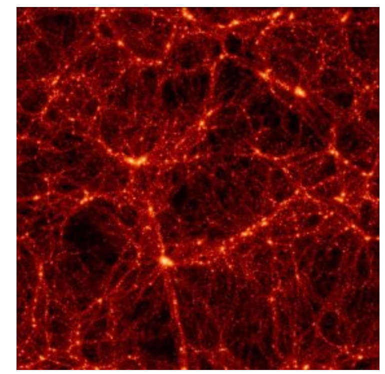


GRBs + High-latitude pulsars
- Small contributions expected.

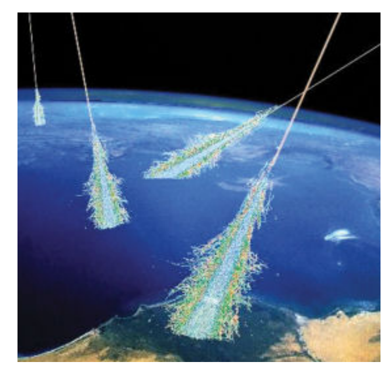
Diffuse processes



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.

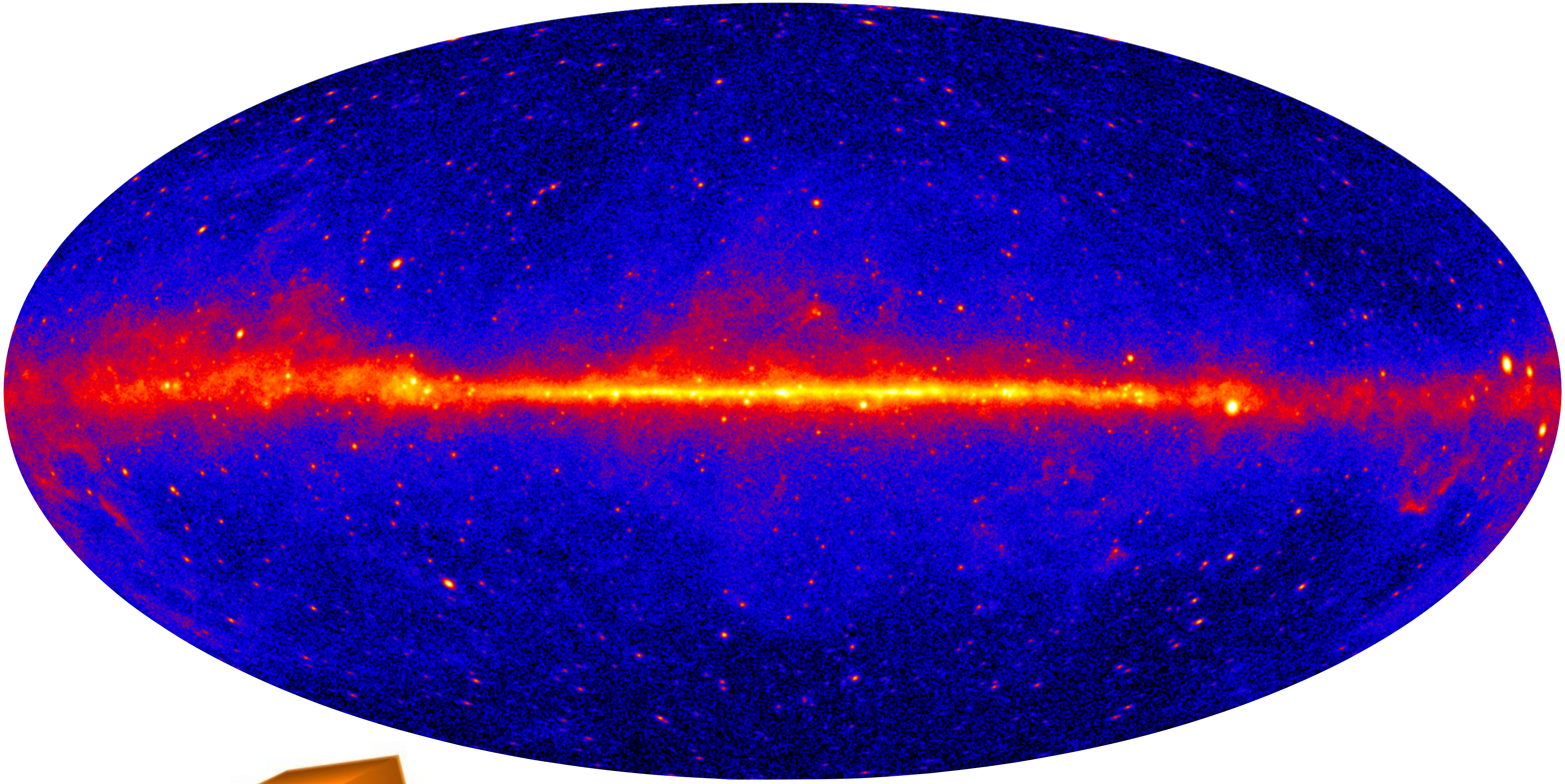


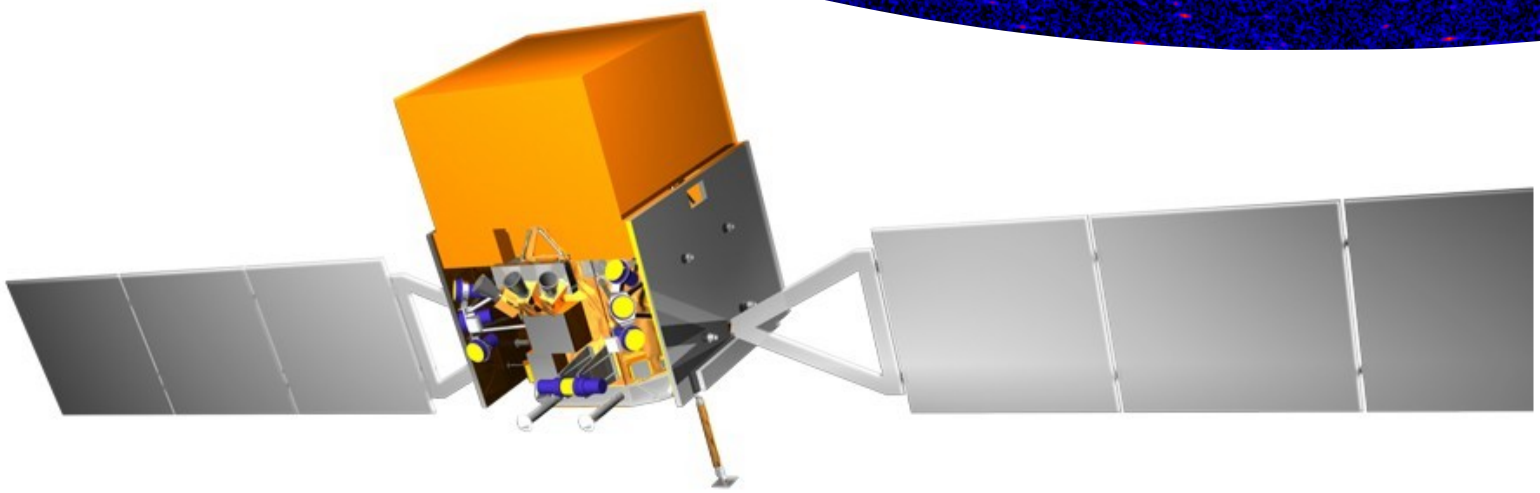
Interactions of UHE cosmic rays with the EBL
- Strongly dependent on evolution of UHECR sources.
- 1% - 100% of EGB emission.

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

The Fermi LAT gamma-ray sky.

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





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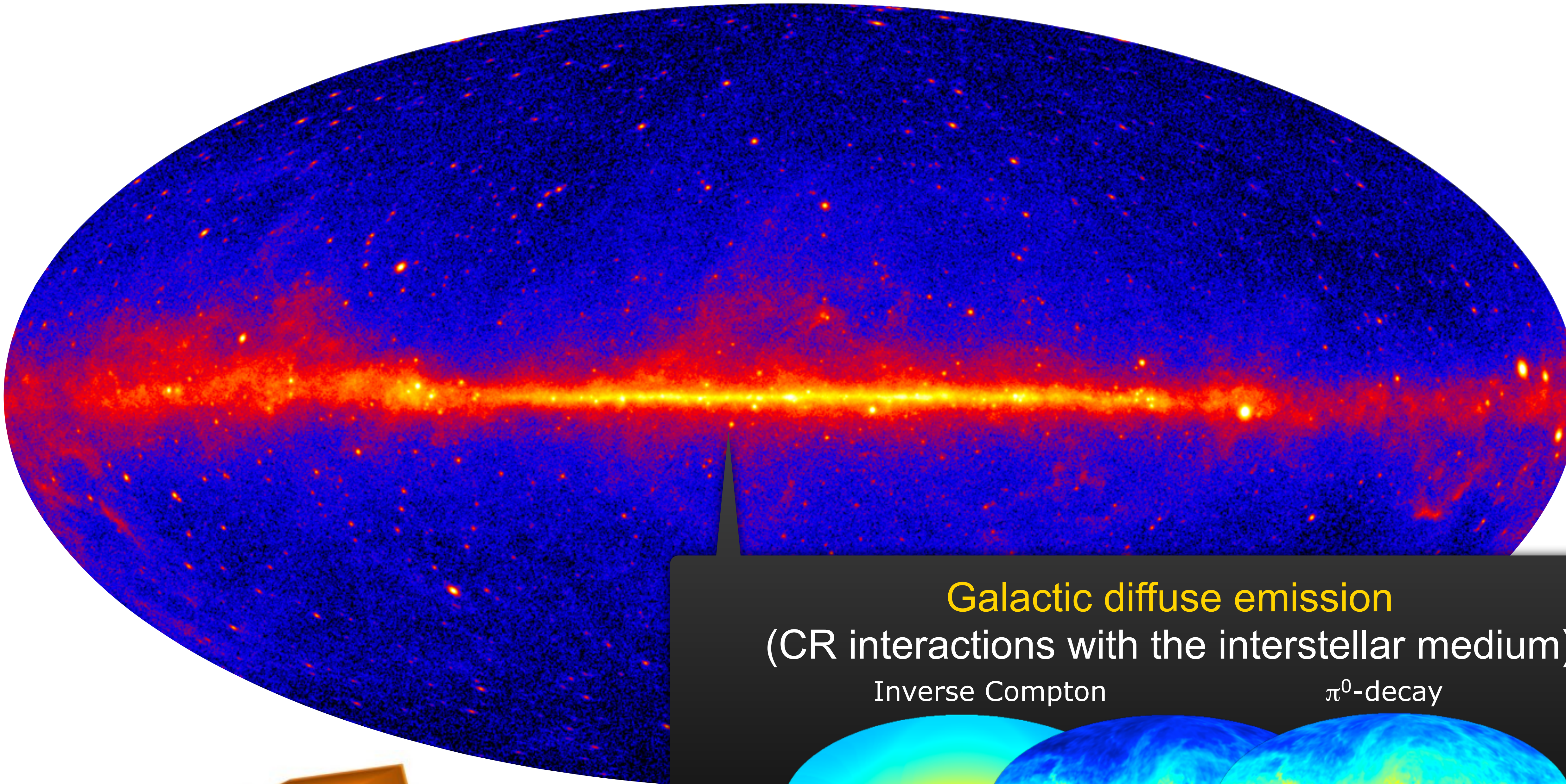
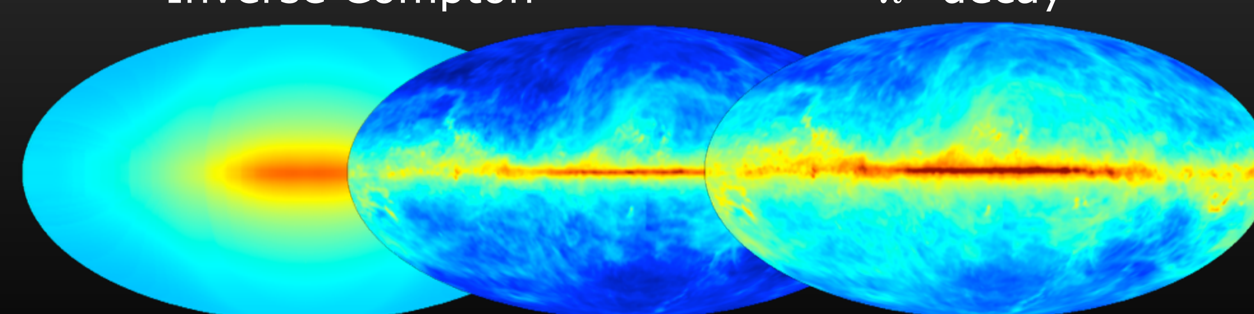
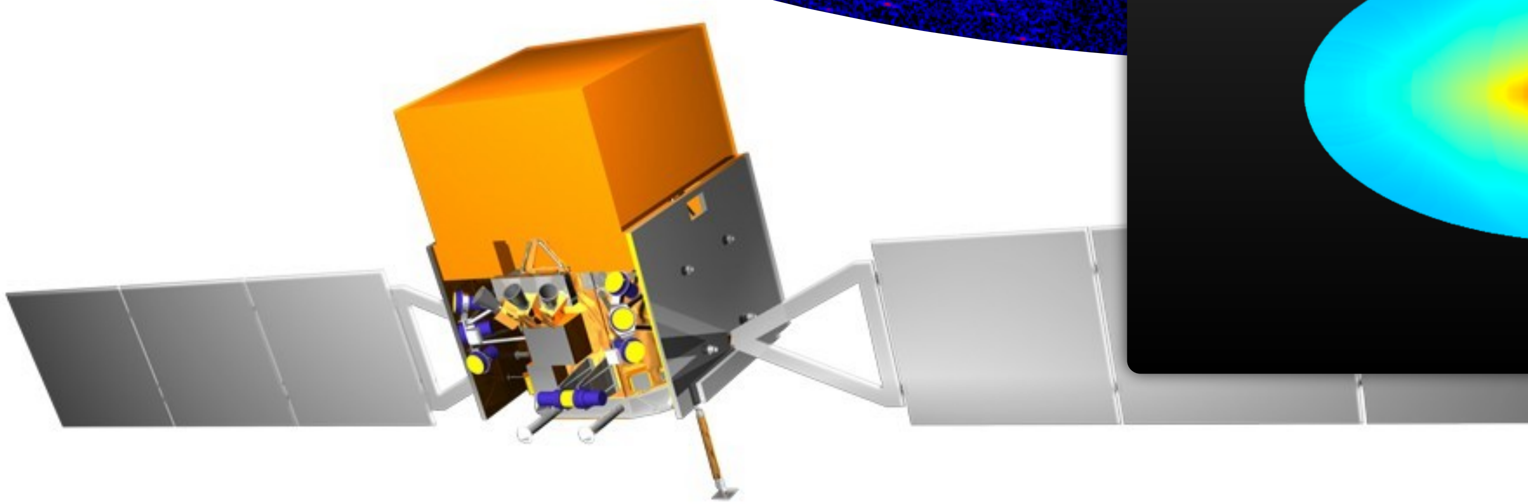


Galactic diffuse emission
(CR interactions with the interstellar medium)





The Fermi LAT gamma-ray sky.

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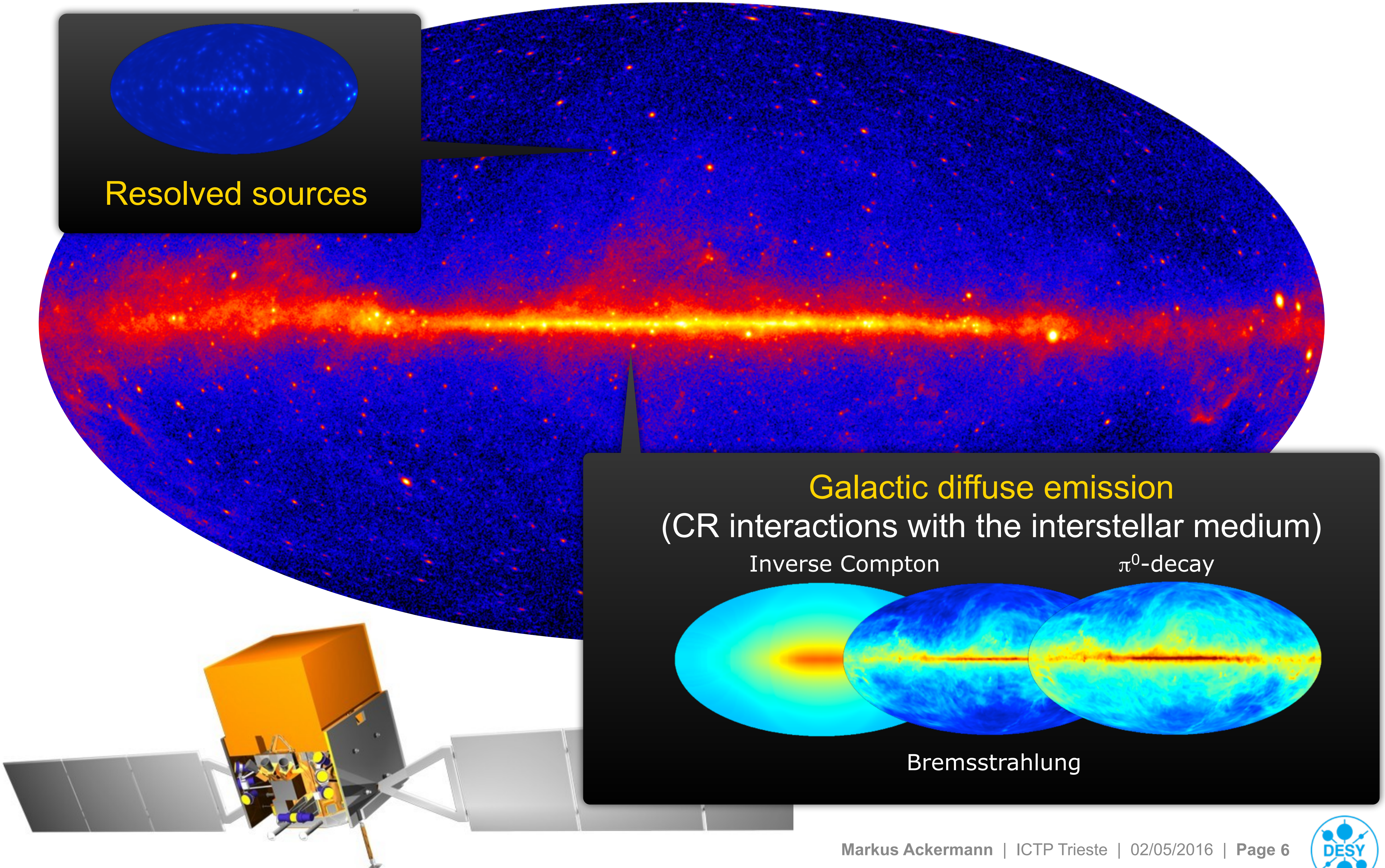
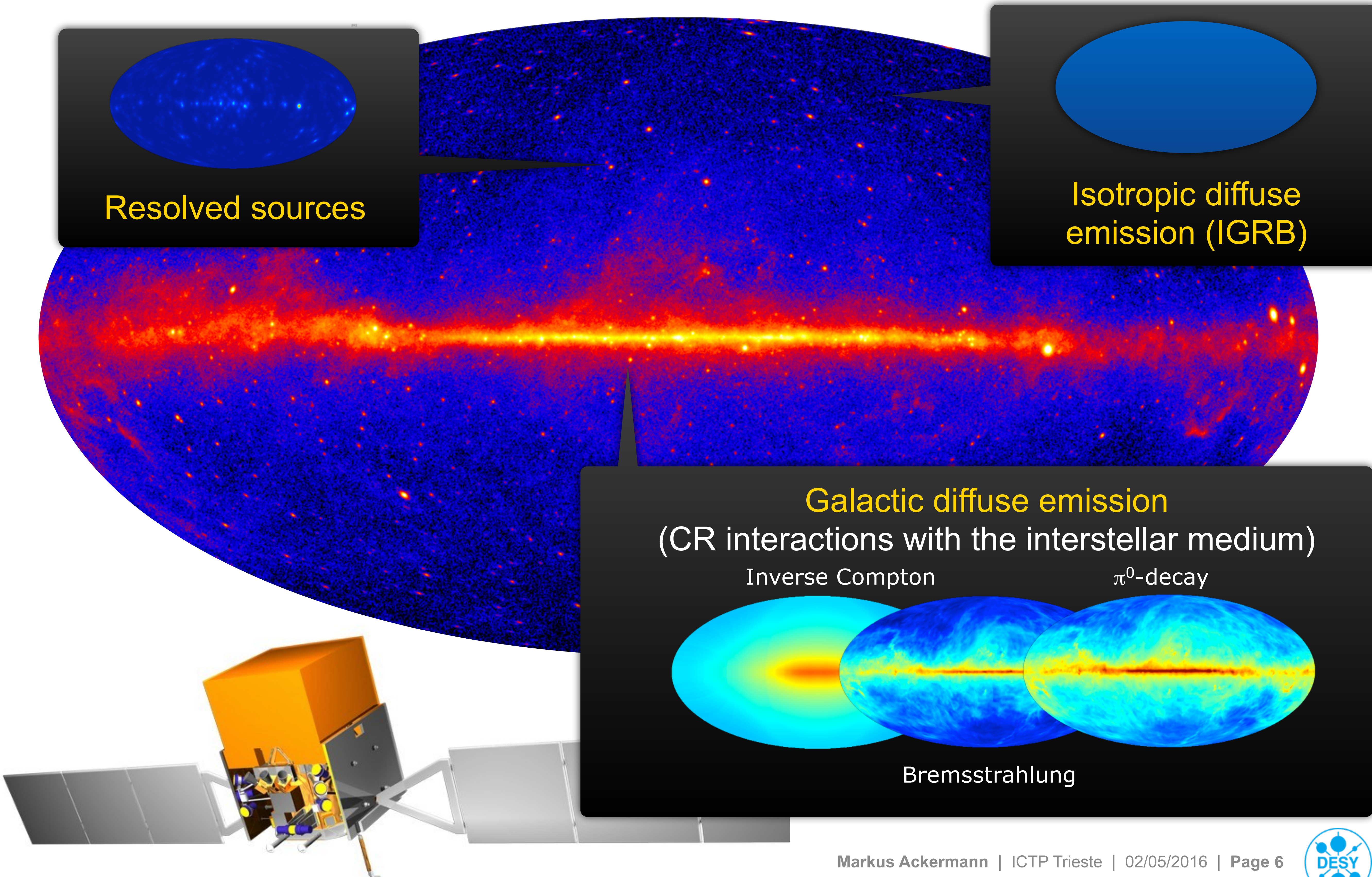
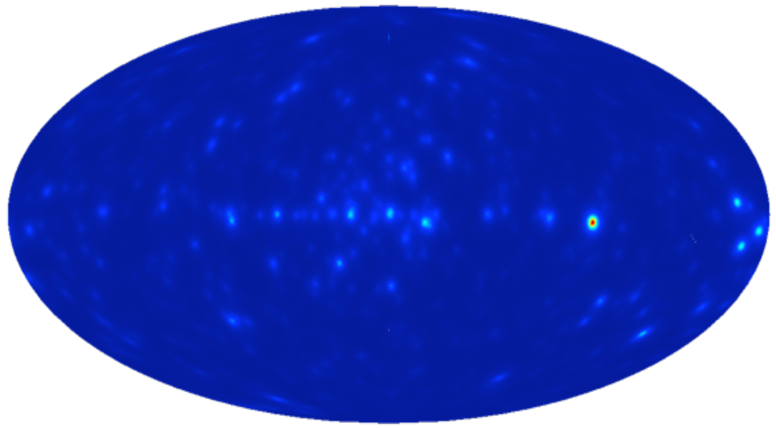


The Fermi LAT gamma-ray sky.

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



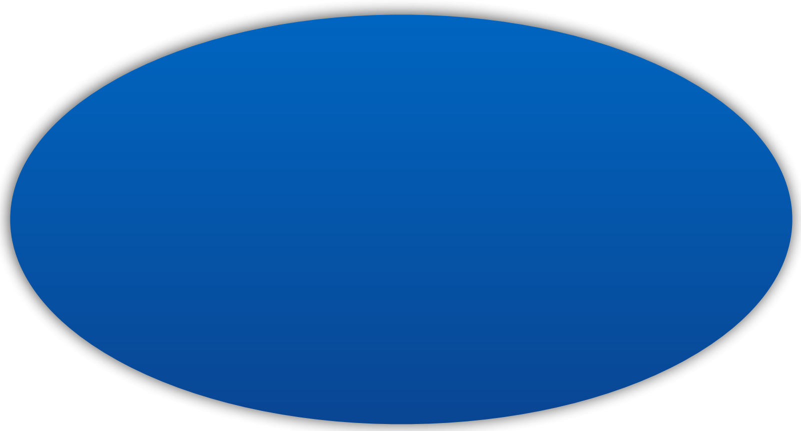
The isotropic and the total extragalactic background.



Resolved sources

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

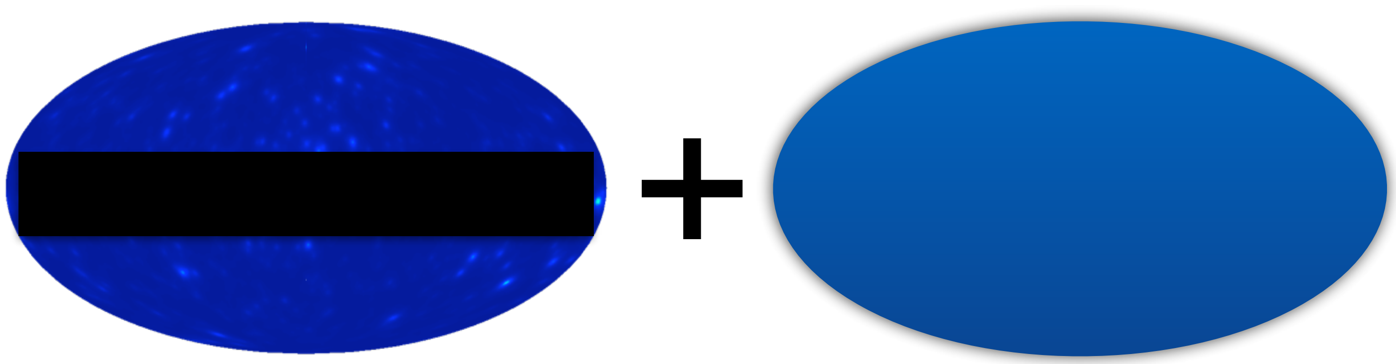
- the sensitivity of the instrument.
- the exposure of the observation.



Isotropic γ-ray background (IGRB)

→ The **isotropic γ-ray background** depends on the sensitivity to identify sources.

→ Important as an **upper limit on diffuse processes.**

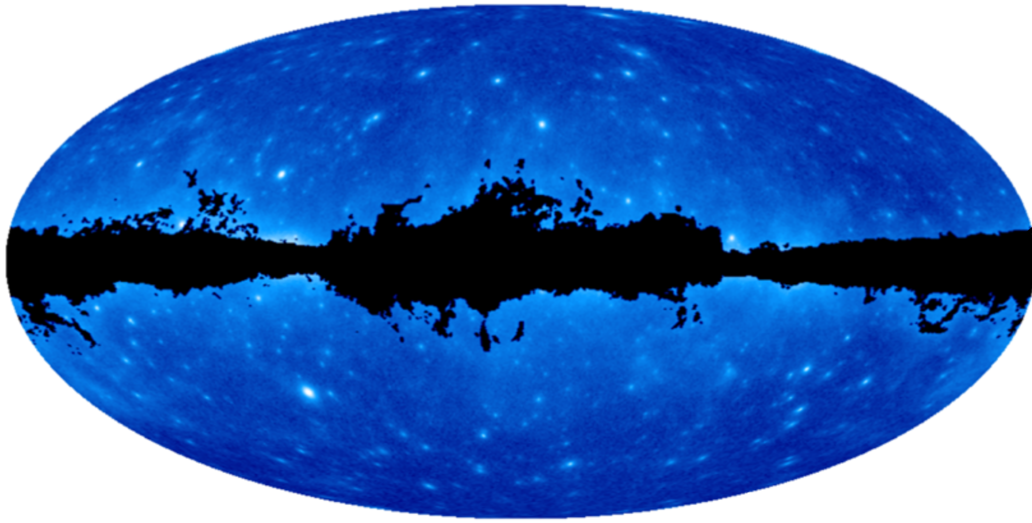


Total extragalactic γ-ray background (EGB)

→ **The total extragalactic γ-ray background** is instrument and observation independent.

→ Useful for **comparisons with source population models**.

Derivation of the isotropic gamma-ray background.

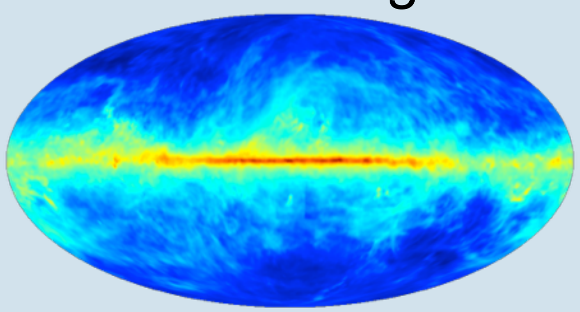


Not used in this analysis:

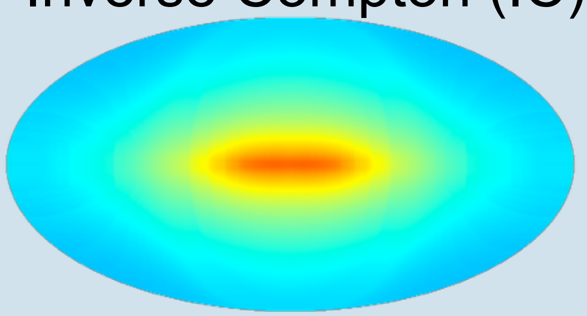
- Galactic plane
- Regions with dense molecular clouds
- Regions with non-local atomic hydrogen clouds

=

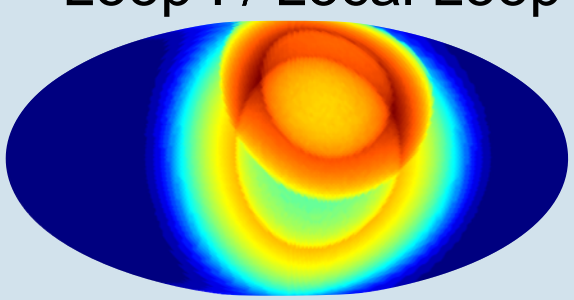
Interstellar gas



Inverse Compton (IC)



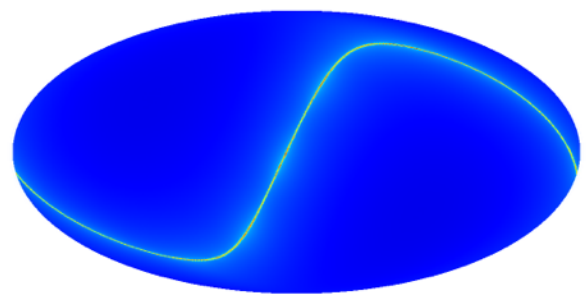
Loop I / Local Loop



Galactic diffuse emission

+

Solar disk and IC



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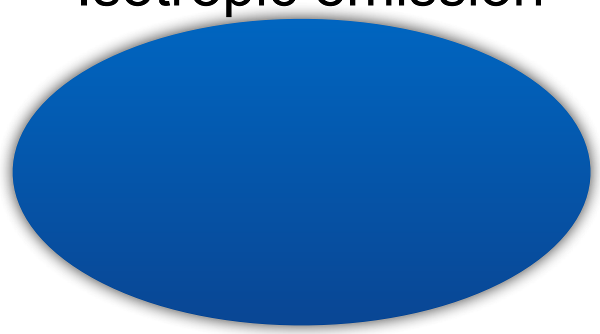
Isotropic emission



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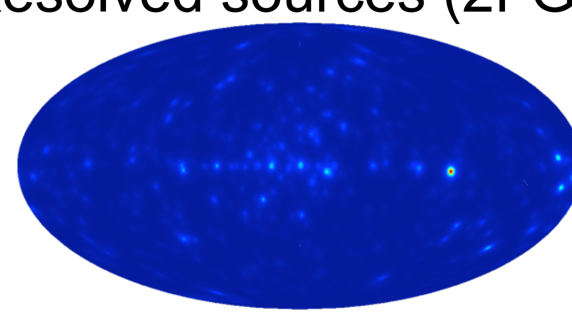
Resolved sources (2FGL)



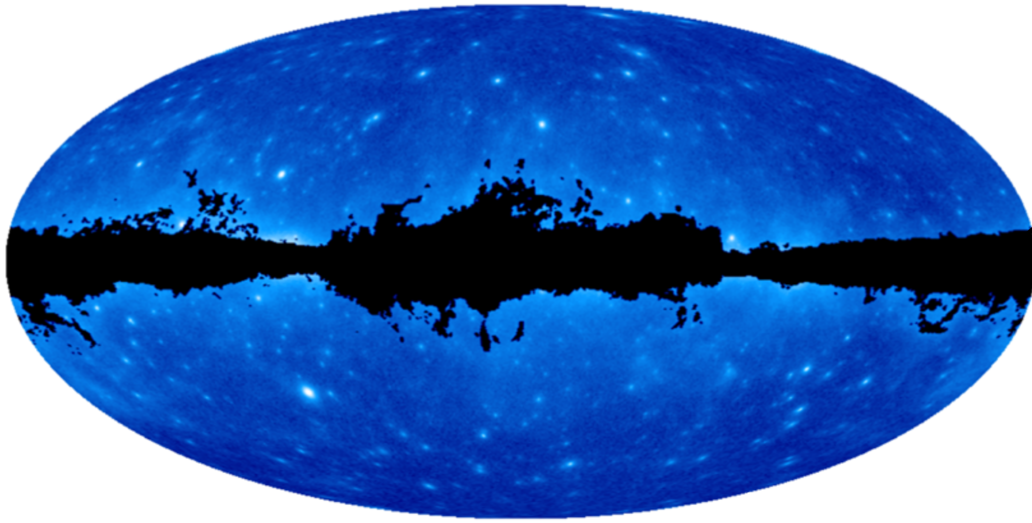
Low-energy analysis (100 MeV - 13 GeV)

- **High-statistics** regime.
- Intensity of **all components** is fitted in each energy band.

High-energy analysis (13 GeV - 820 GeV)

- **Low-statistics** regime
- **Only resolved sources** and **isotropic emission** are fitted in each energy band.

Derivation of the isotropic gamma-ray background.



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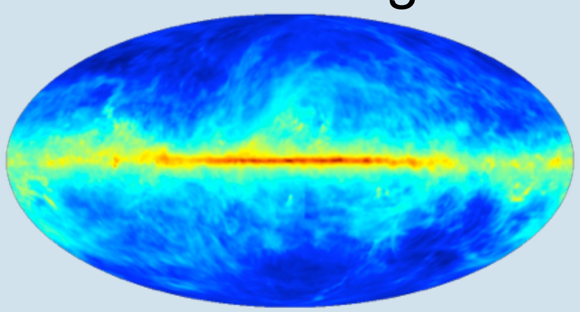
Interstellar gas



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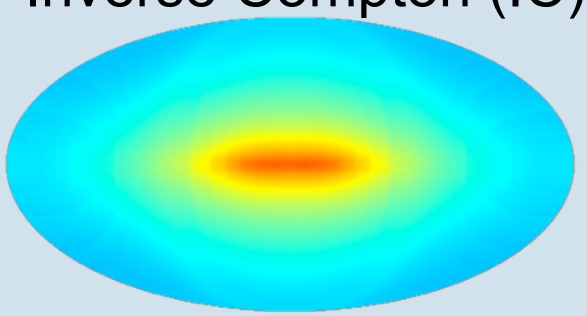
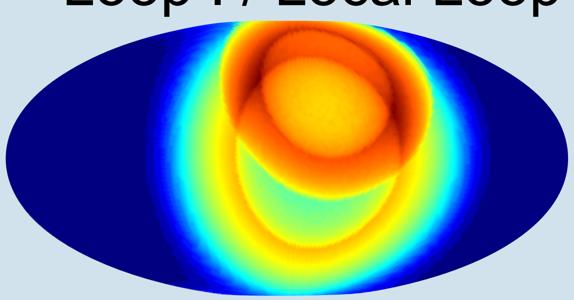
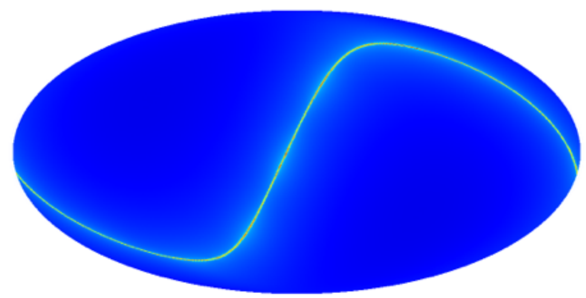


Loop I / Local Loop

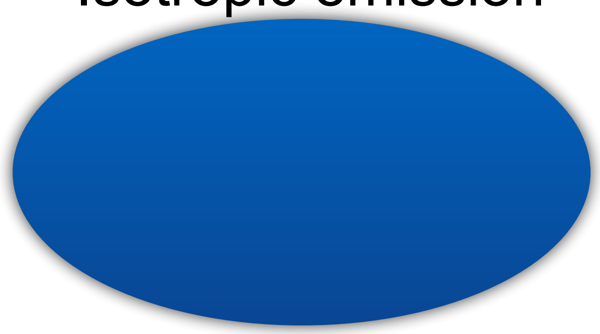


Galactic diffuse emission

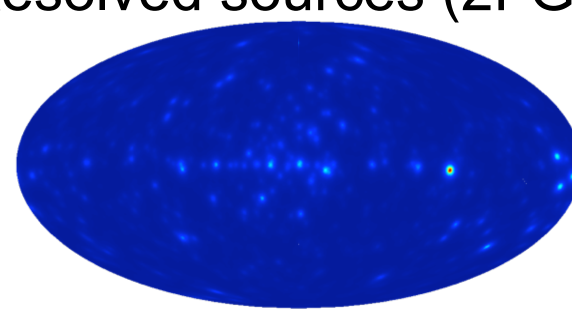
\+ Solar disk and IC



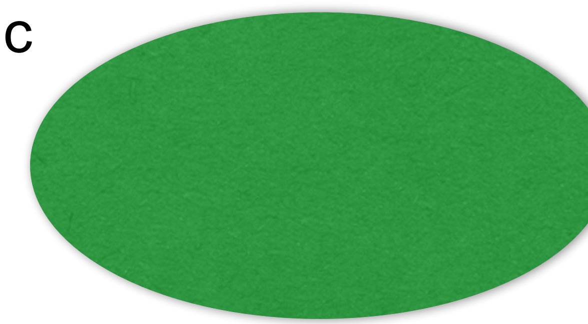
\+ Isotropic emission



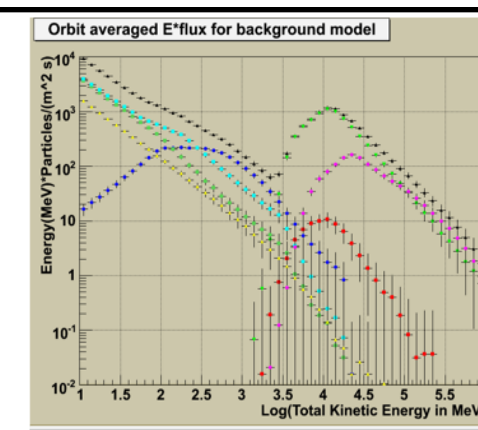
\+ Resolved sources (2FGL)



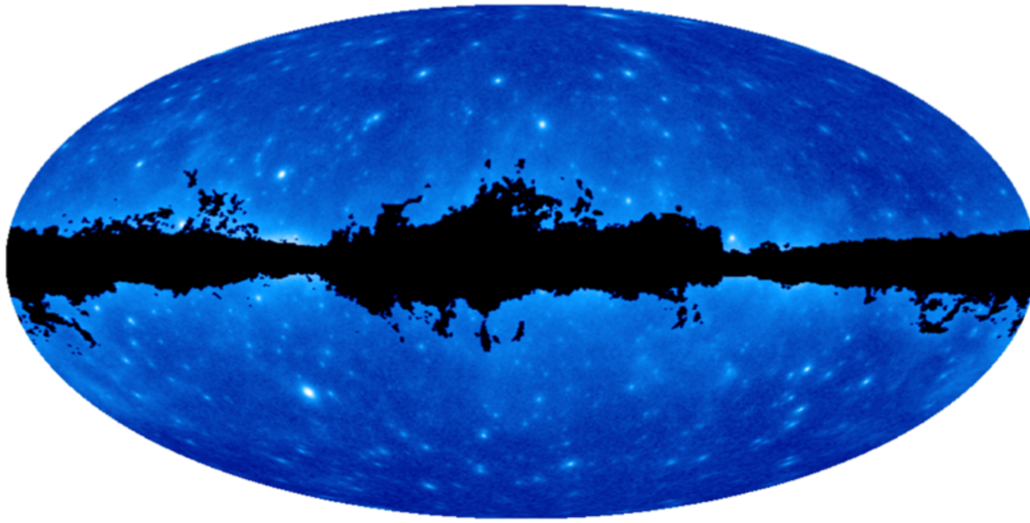
Isotropic γ-ray back-ground (IGRB)



Contami-nation from CR induced background



Derivation of the isotropic gamma-ray background.



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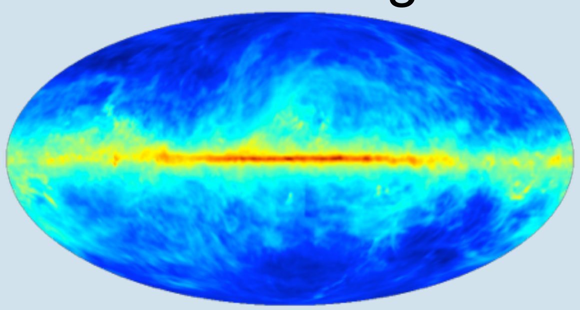
Interstellar gas



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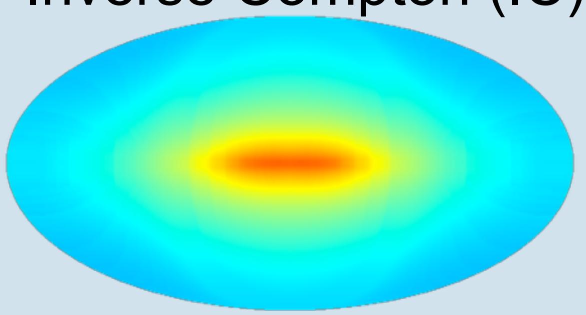
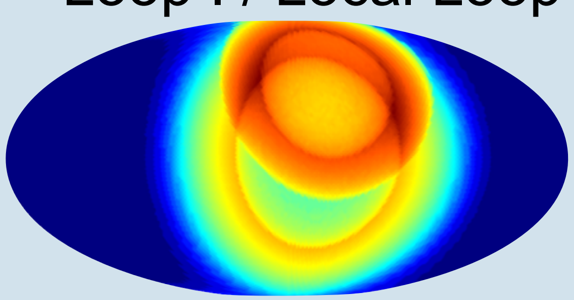


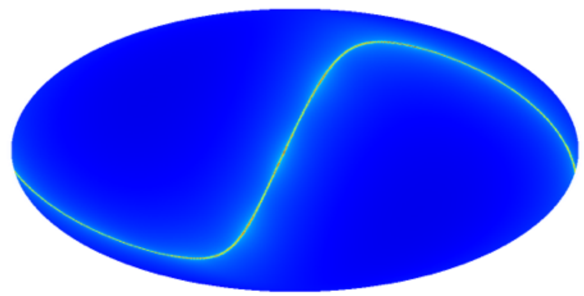
Loop I / Local Loop



Galactic diffuse emission

\+

Solar disk and IC



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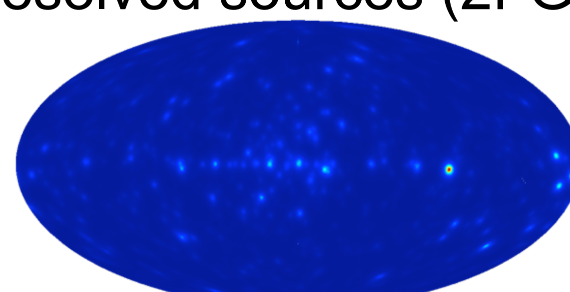
Isotropic emission

\+

Resolved sources (2FGL)



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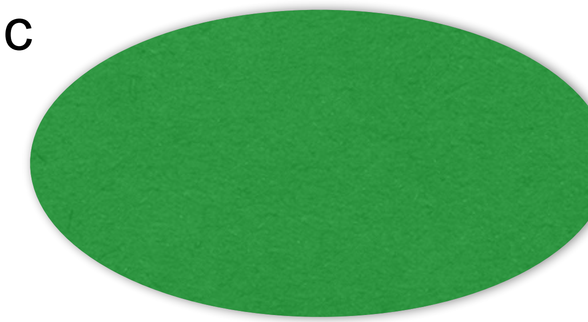
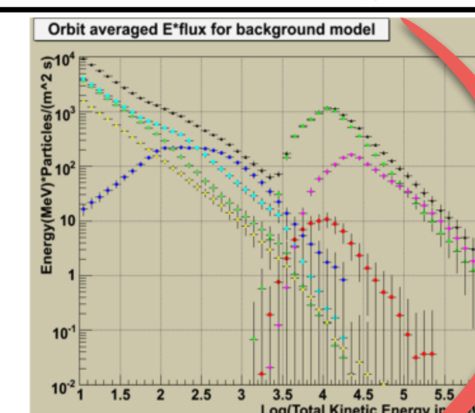
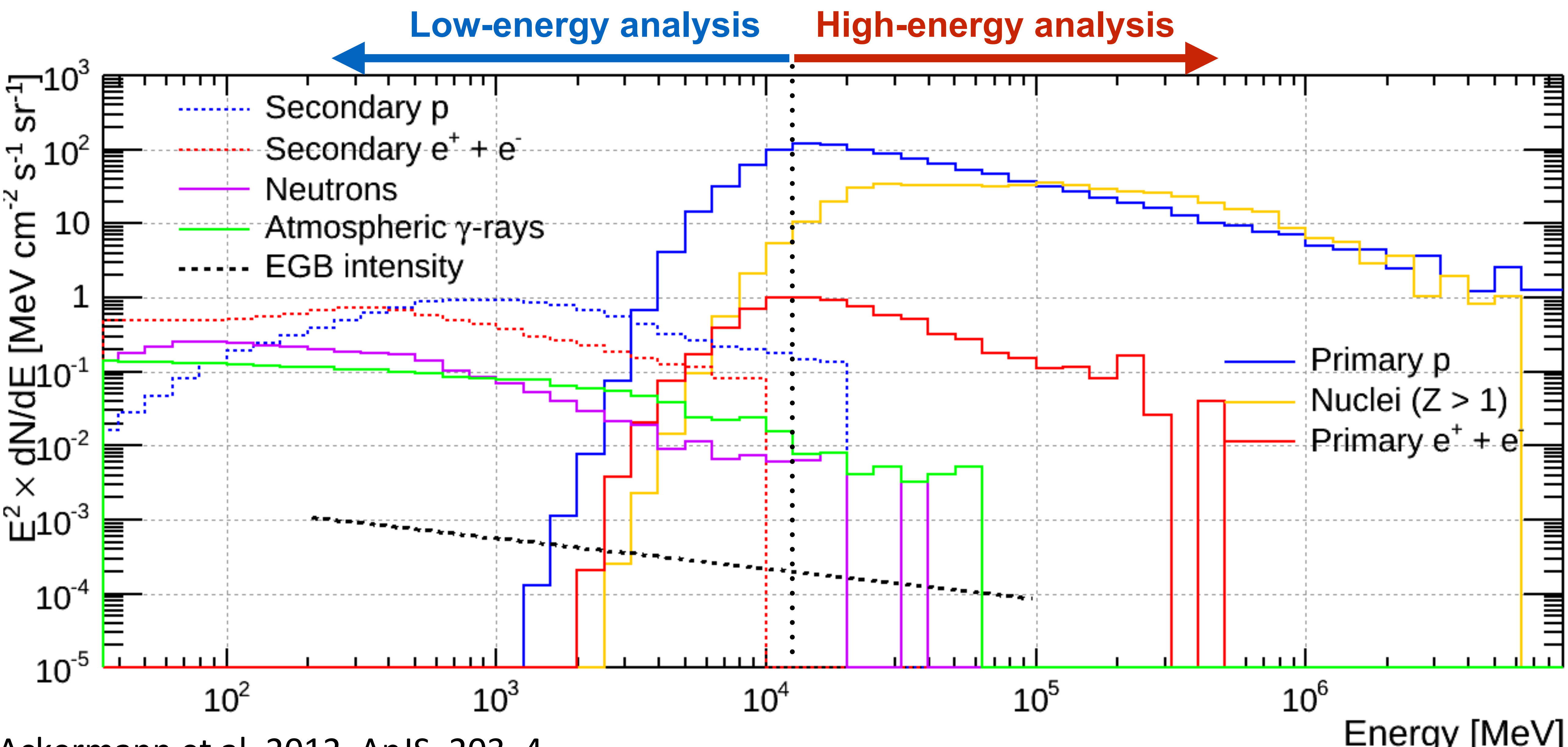


Contami-nation from CR induced background



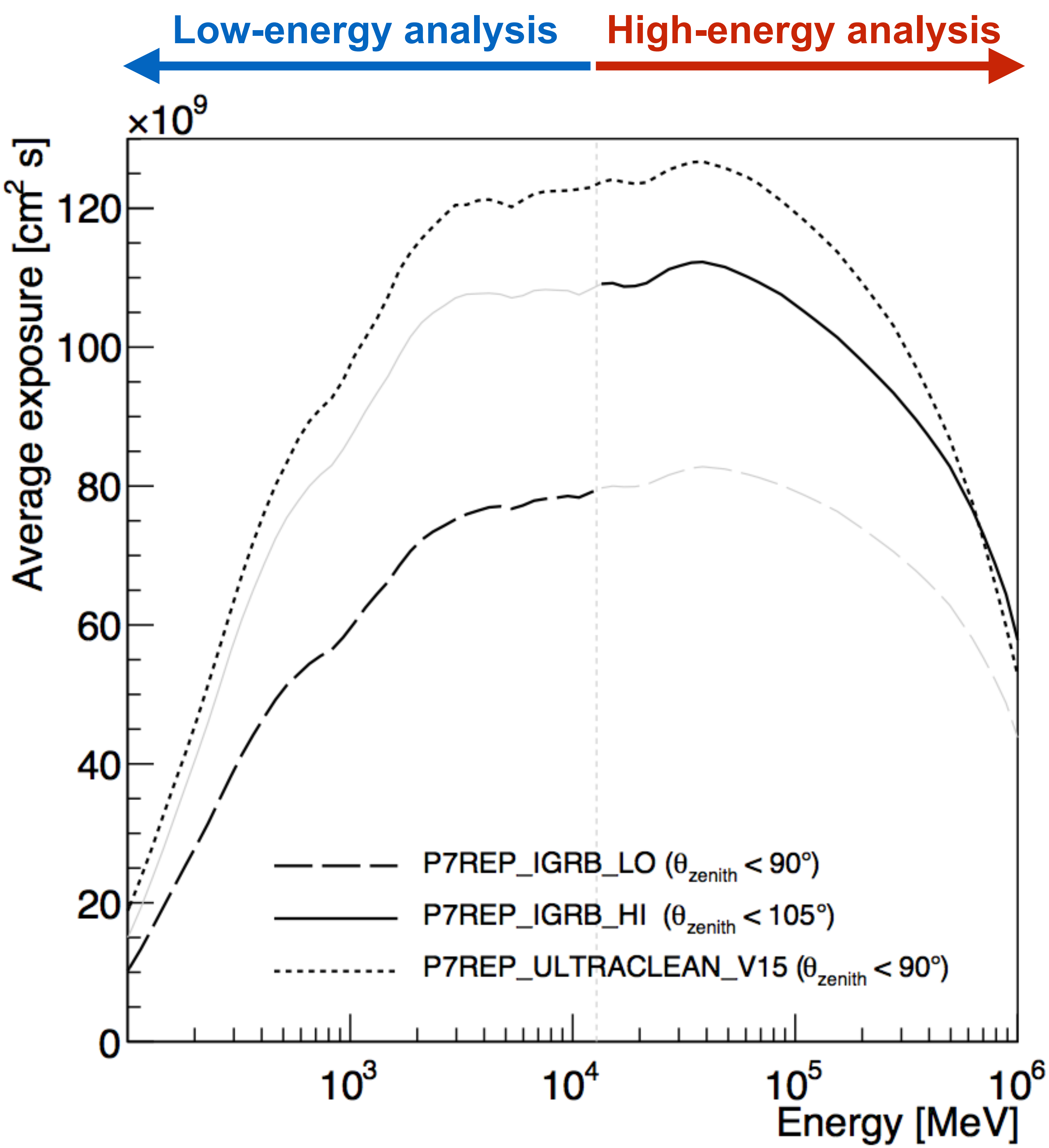
Cosmic-ray induced background in the LAT orbit.

- **CR intensity** up to **10^6 times higher** than EGB in the LAT orbit.
- Two energy regimes:
  - **Primary CR** dominate at **high energies**.
  - **Secondaries from CR** interactions in the atmosphere **dominate at low energies**.



Ackermann et al. 2012, ApJS, 203, 4

Dedicated event classes for the IGRB analysis.



> Publicly available LAT event classes (P7ULTRACLEAN) have **insufficient background rejection** at very low and very high energies.

> **New high-purity event classes** developed for this analysis.

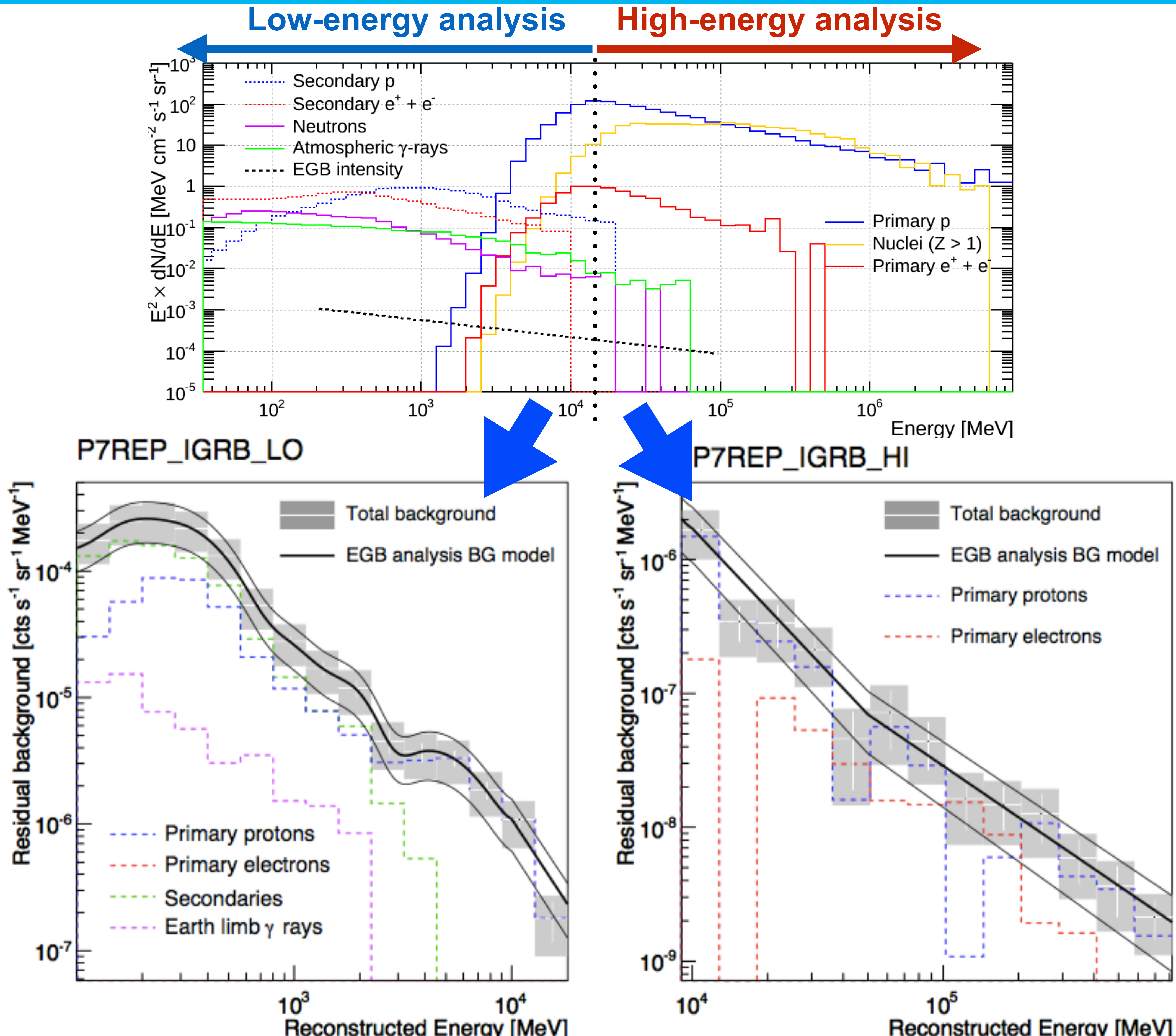
> **P7REP_IGRB_LO**

- Optimized to reject secondary CR background at low energies

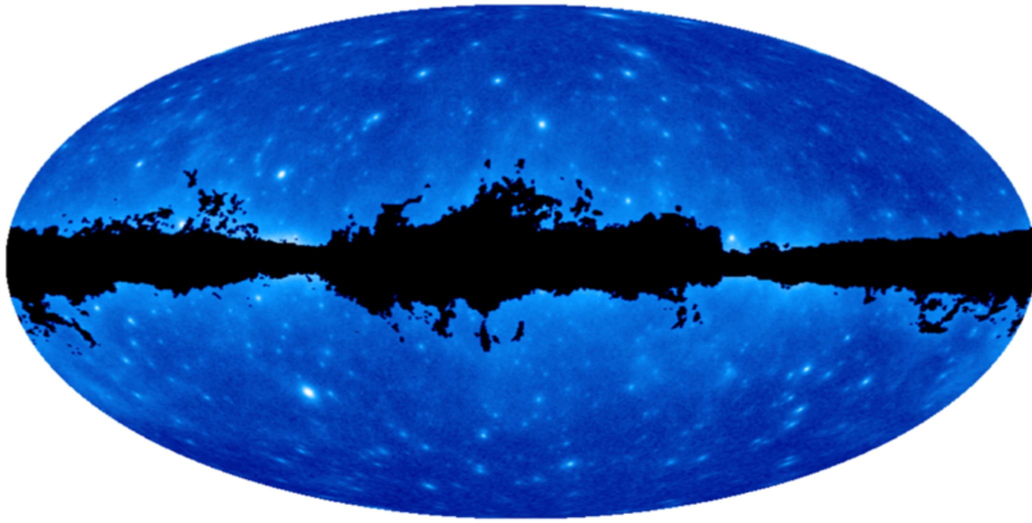
> **P7REP_IGRB_HI**

- Optimized to reject primary CR background while retaining high statistics

Residual cosmic-ray background.



Derivation of the isotropic gamma-ray background.



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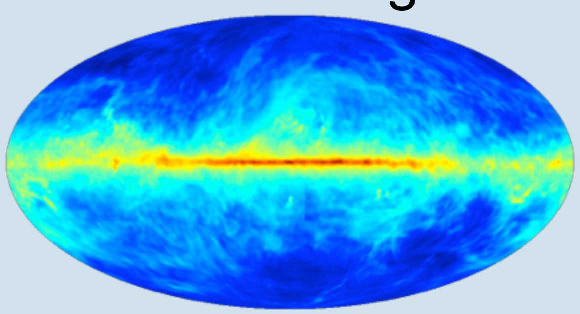
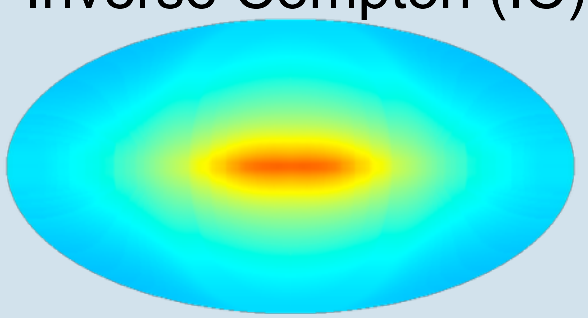
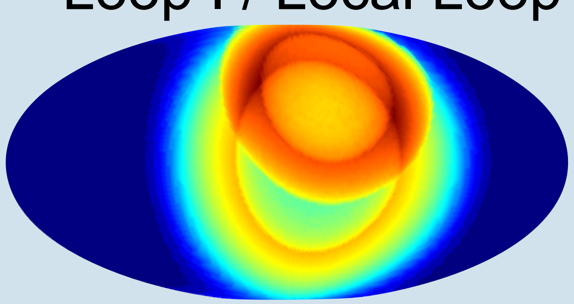
Interstellar gas



Inverse Compton (IC)



Loop I / Local Loop



Galactic diffuse emission

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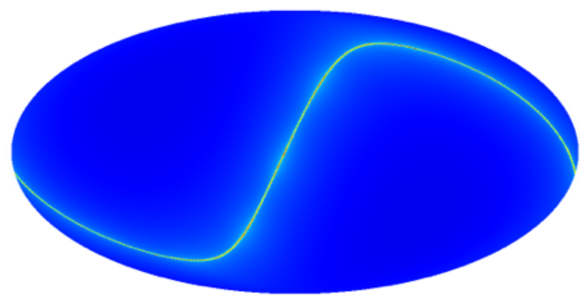
Solar disk and IC

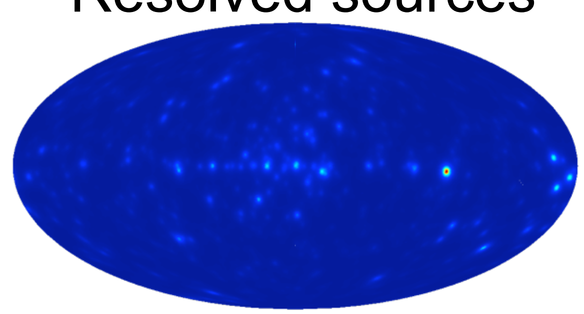


+

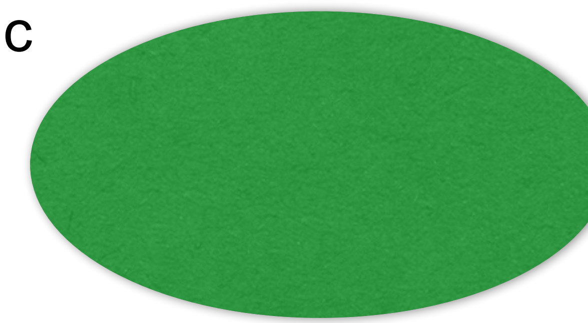
Isotropic emission

+

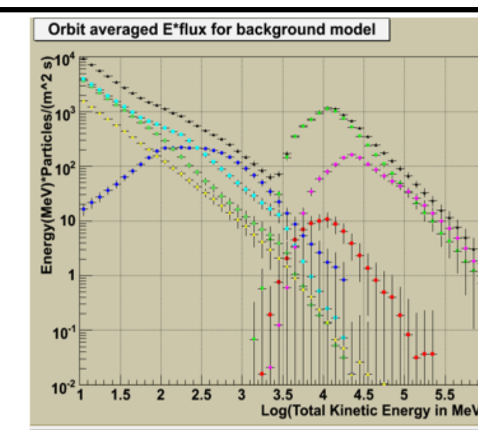
Resolved sources



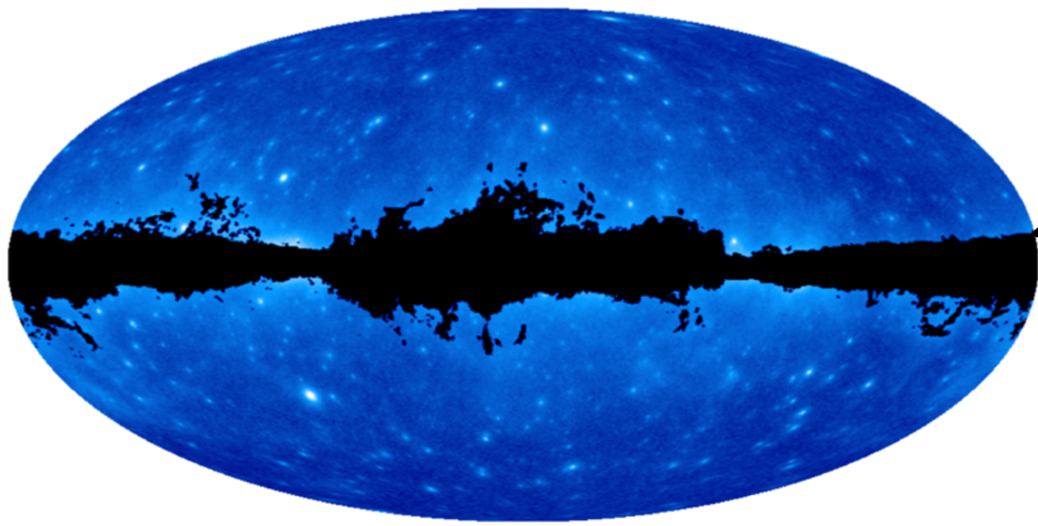
Isotropic γ-ray back-ground (IGRB)



Contami-nation from CR induced background



Derivation of the isotropic gamma-ray background.



Not used in analysis:
- Galactic plane
- Regions with dense molecular clouds
- Regions with non-local atomic hydrogen clouds

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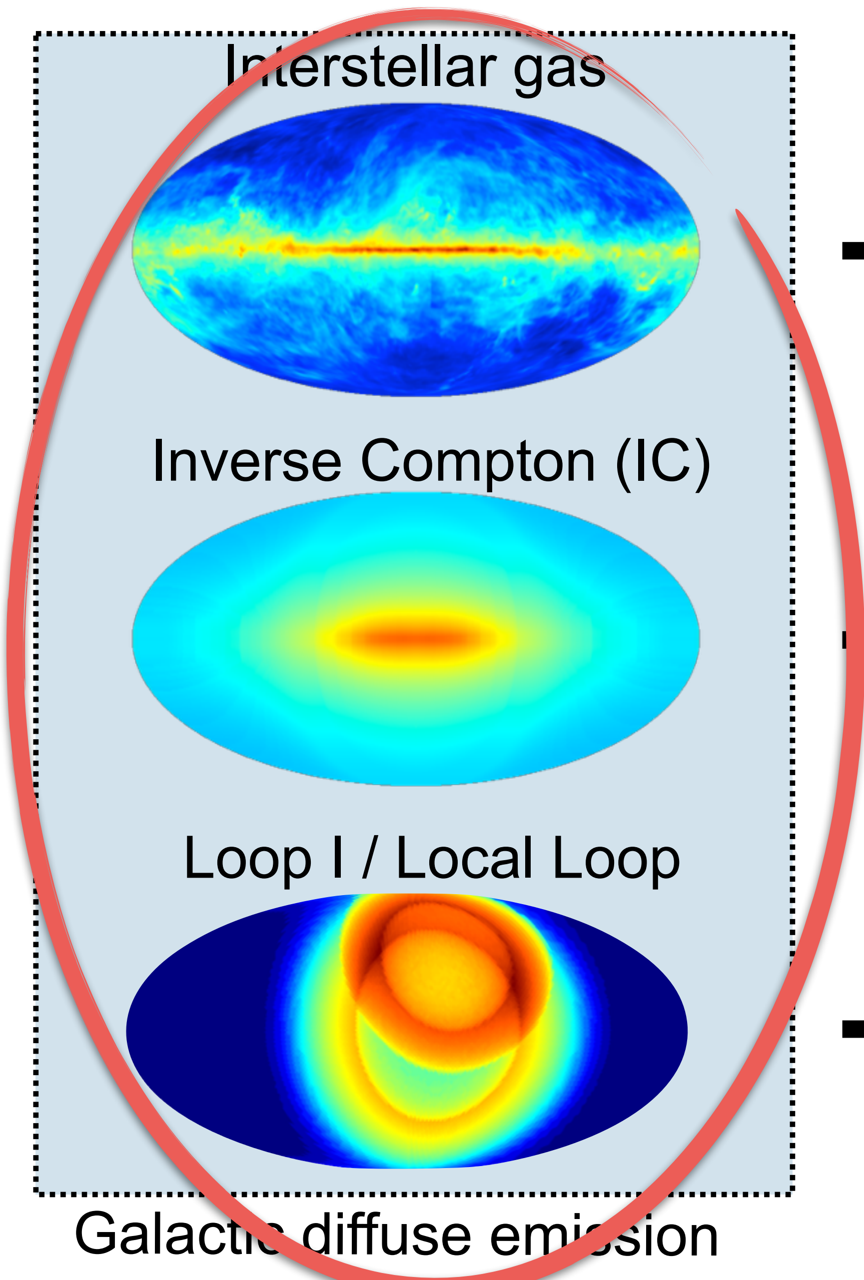

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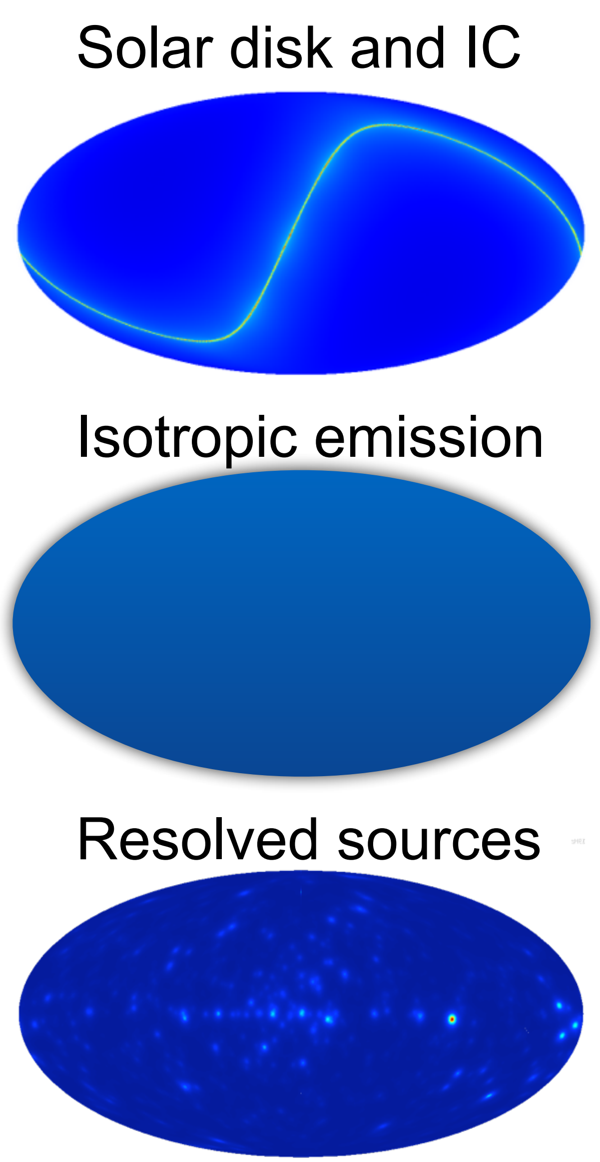
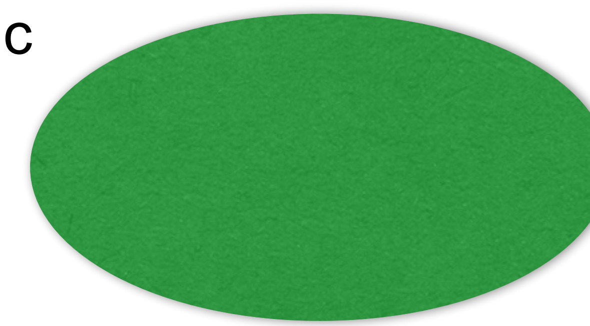
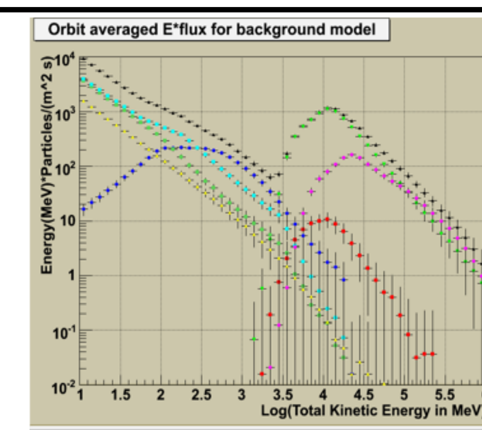


Isotropic γ-ray back-ground (IGRB)



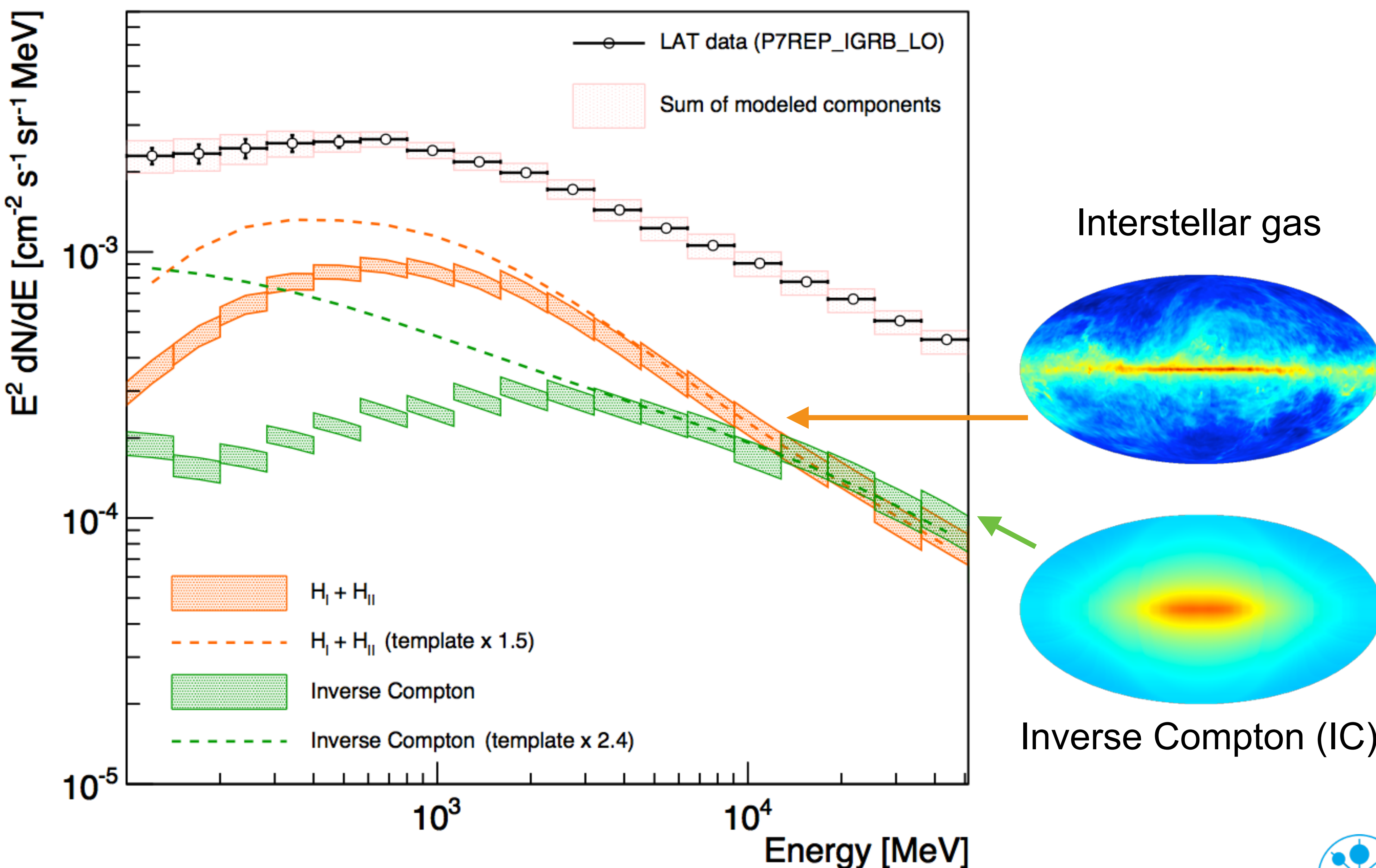
Contami-nation from CR induced background



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.



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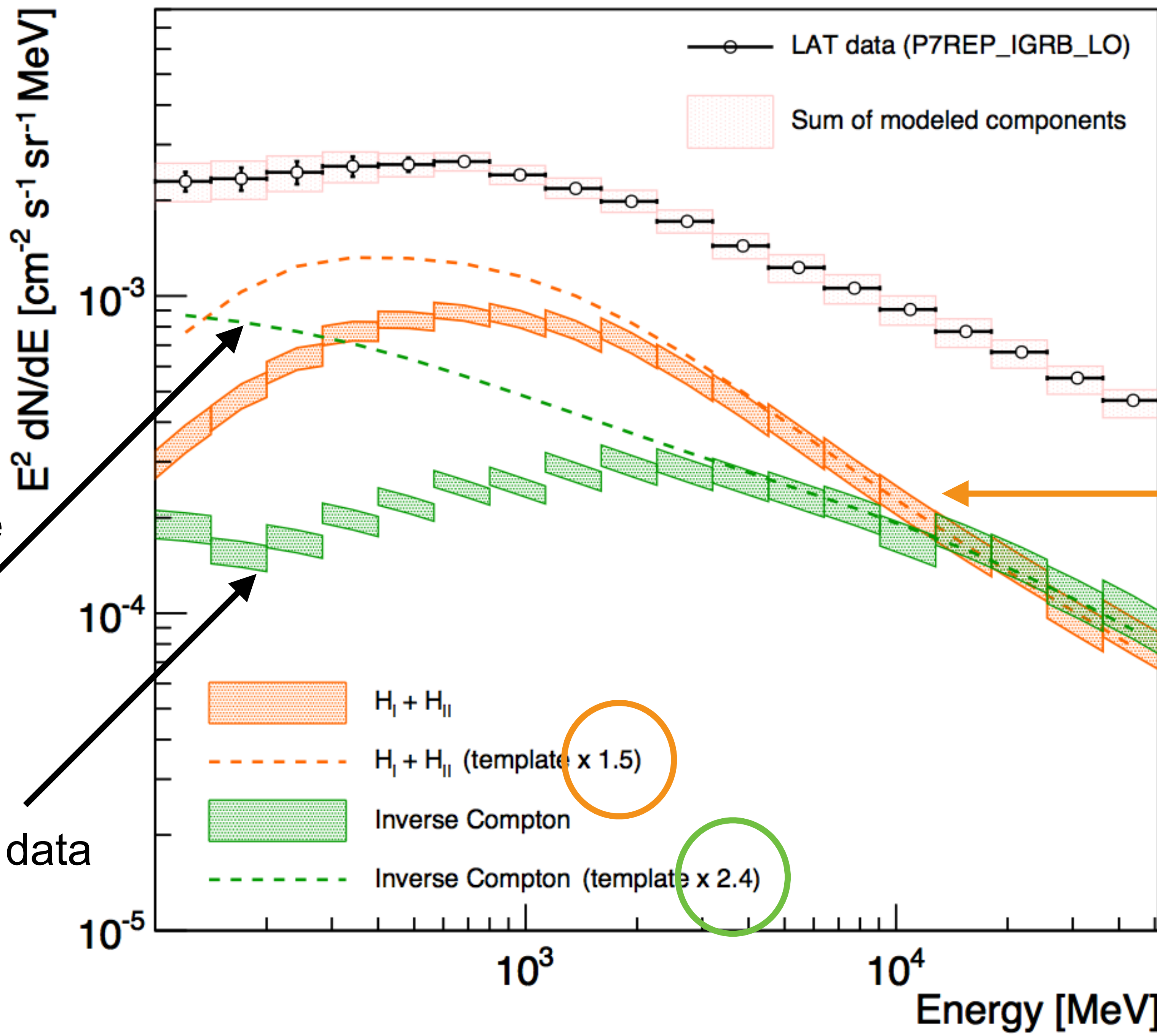
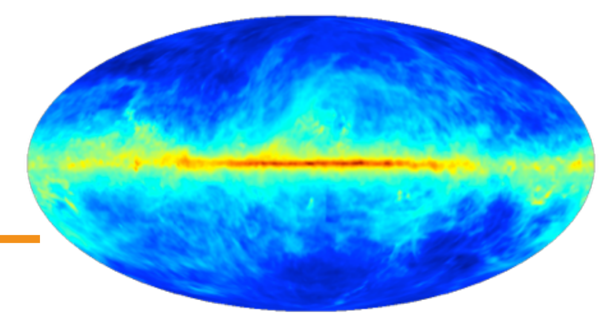
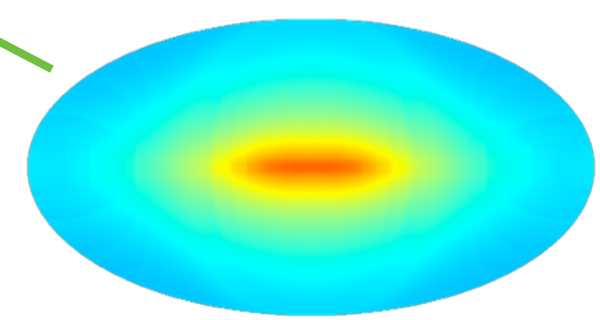
Spectral shape **predicted** by GALPROP model

Spectral shape **from fit** to LAT data



Interstellar gas

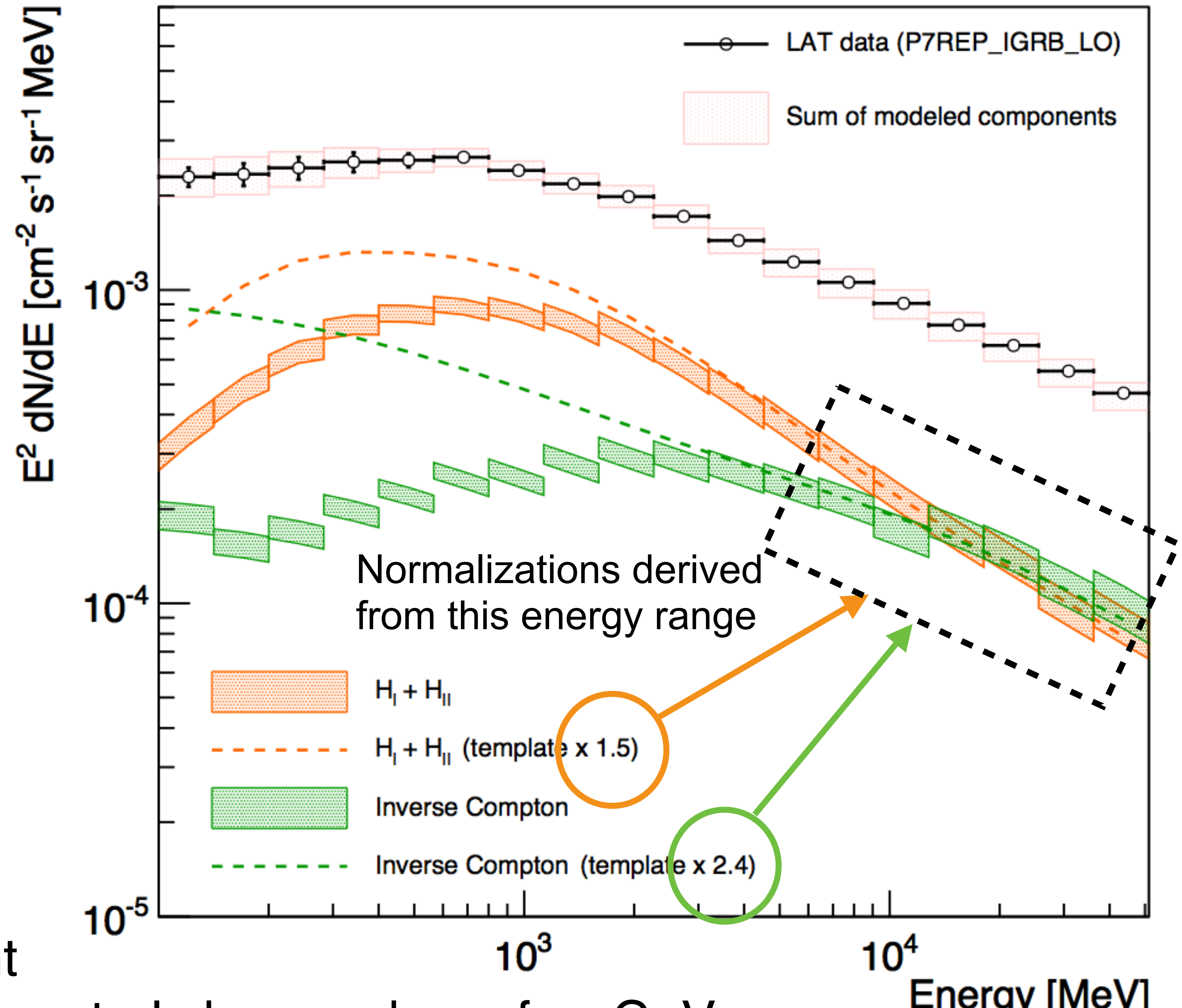


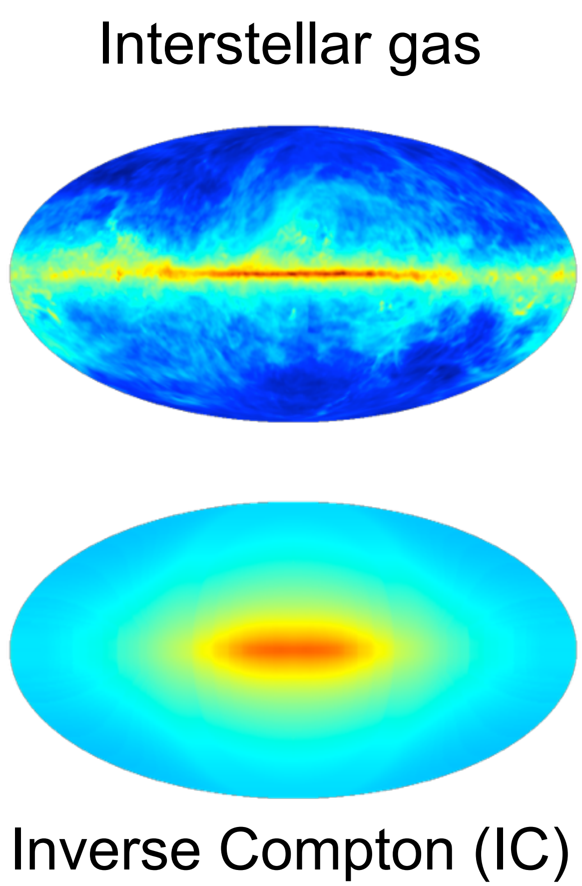


Inverse Compton (IC)

Galactic diffuse foreground model.

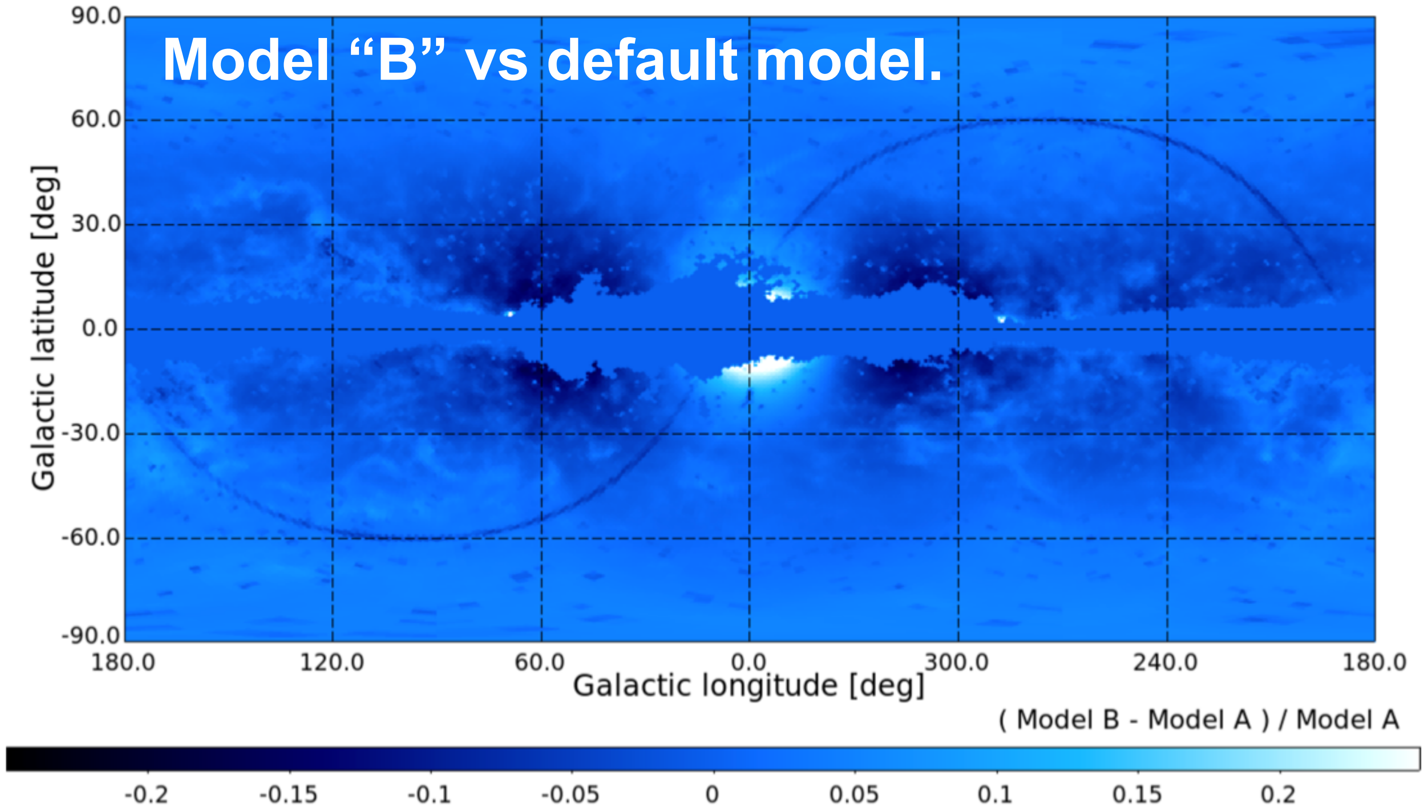
- **Fit in individual energy bands** is restricted to energies below ~ 50 GeV.
- Derive **universal normalization factor** for model templates in 5 - 50 GeV band.
- Use this normalization factor in **high-energy analysis** (13 GeV - 820 GeV).

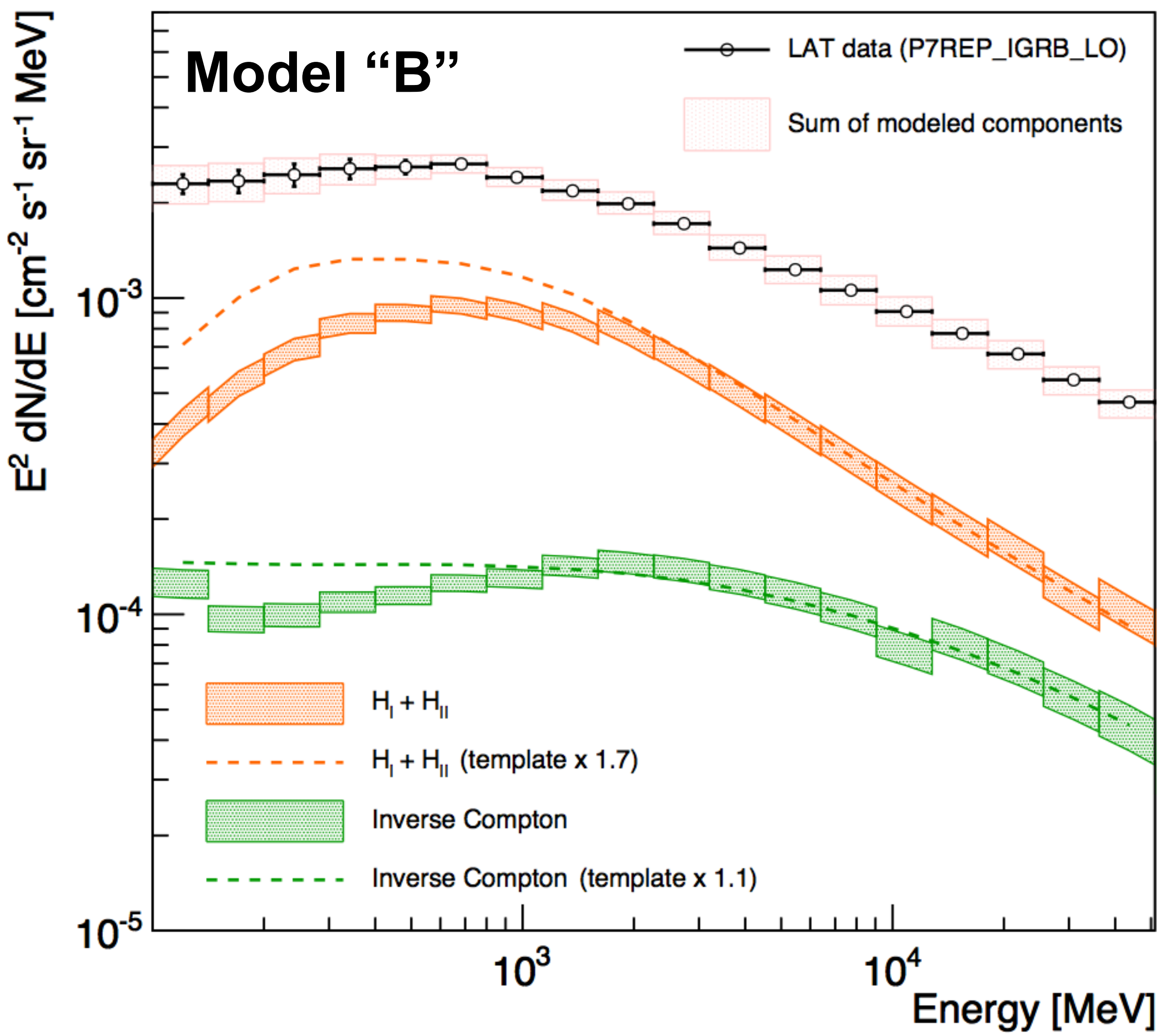


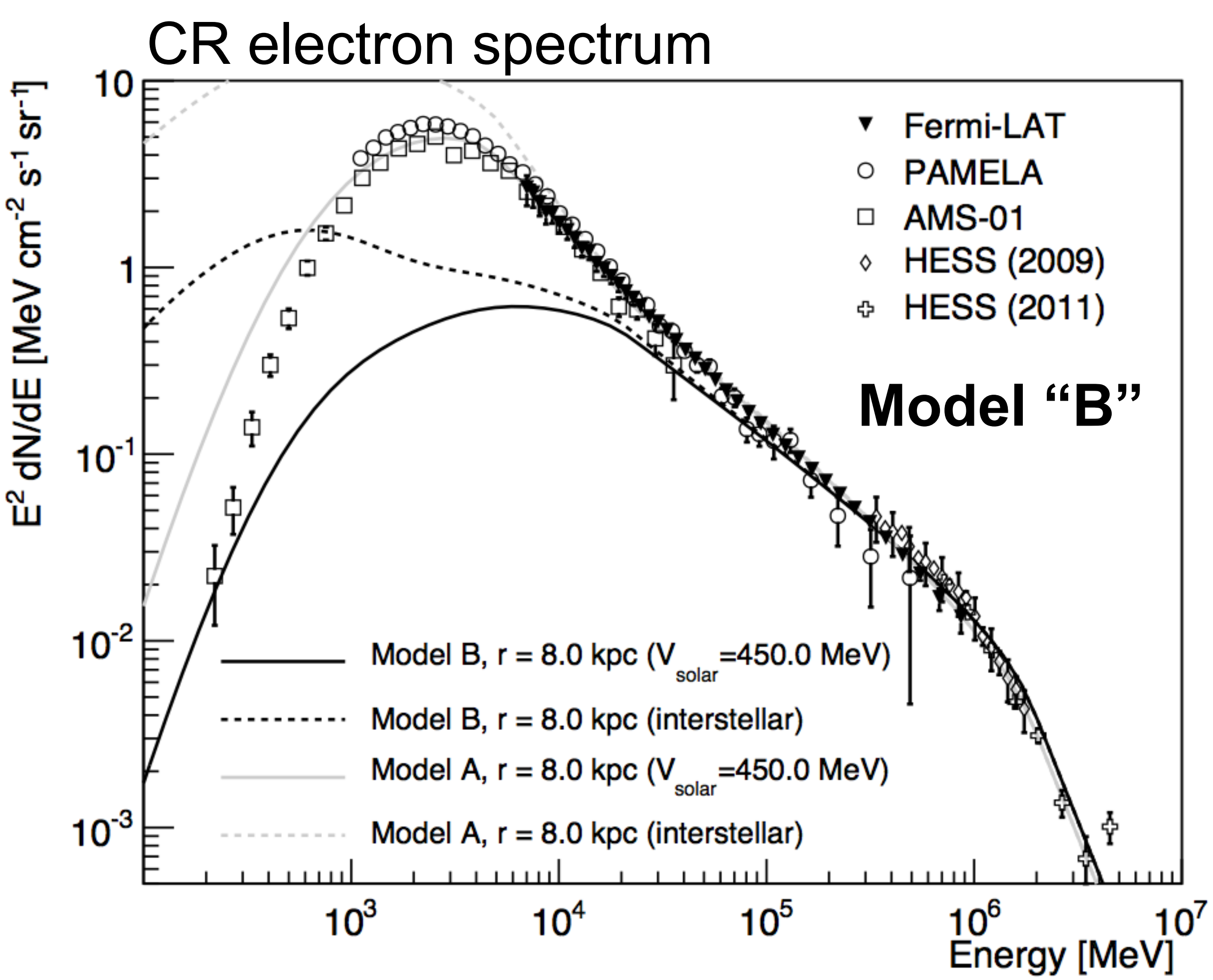


- Good agreement between spectral shapes above few GeV

Alternative foreground models.

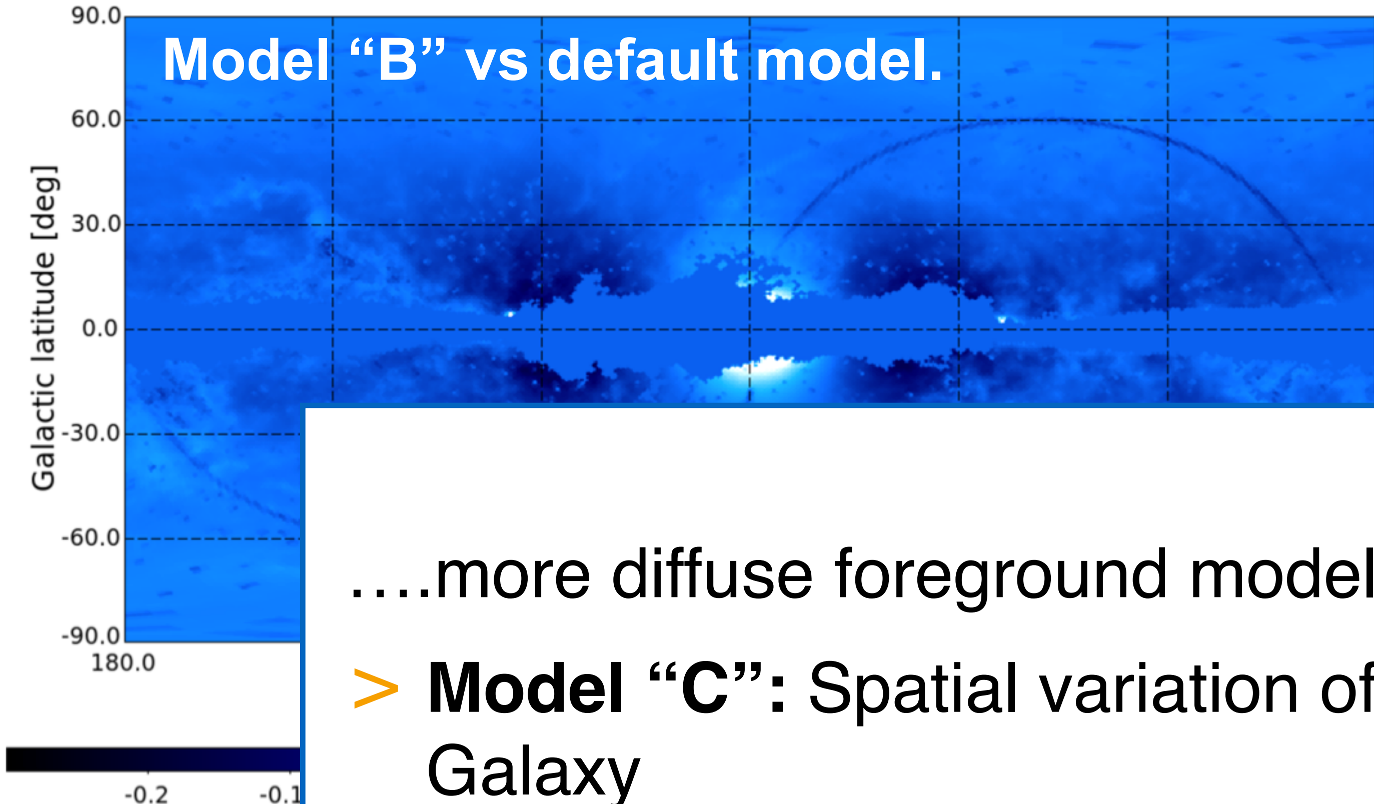


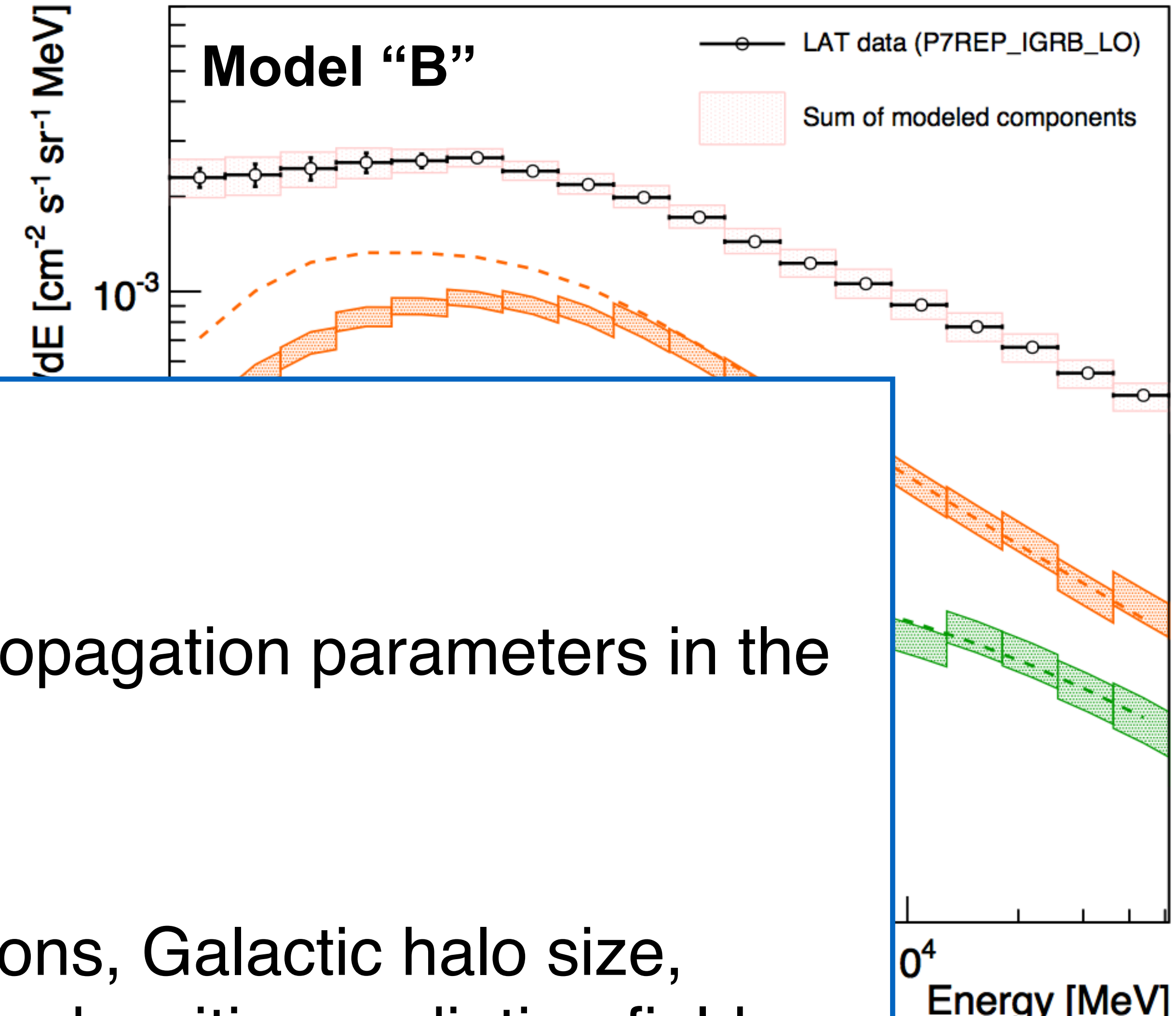


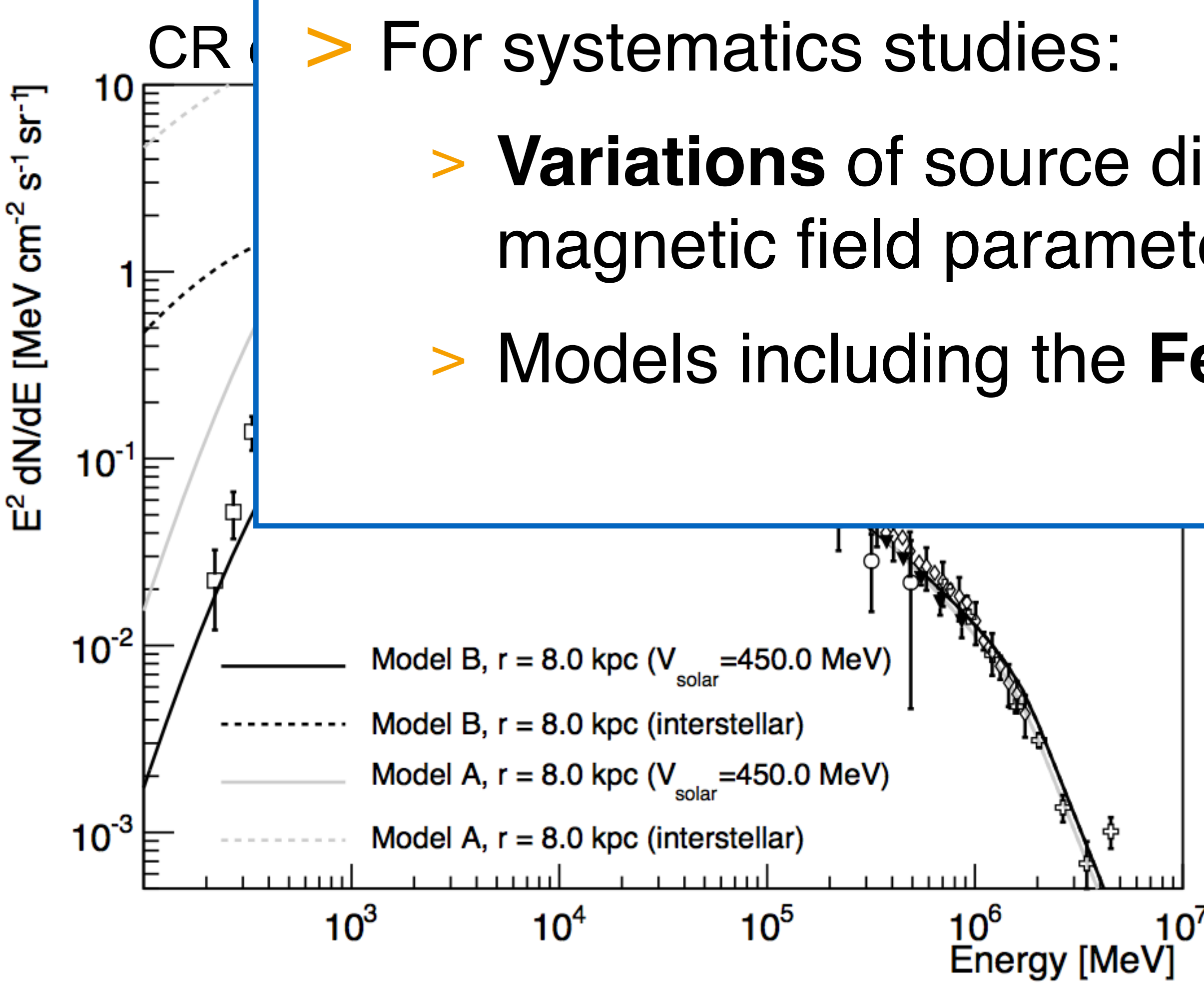


- Large discrepancies in IC spectrum between model and fit not well understood.
- Evaluated **alternative diffuse models**.
- **Example model "B"**: Injection of e^+/e^- by population close to Galactic center.
- Any effect on derived IGRB?

Alternative foreground models.







….more diffuse foreground models:

> **Model "C":** Spatial variation of propagation parameters in the Galaxy

> For systematics studies:

> > **Variations** of source distributions, Galactic halo size, magnetic field parameters, gas densities, radiation field…

> > Models including the **Fermi "Bubbles"**

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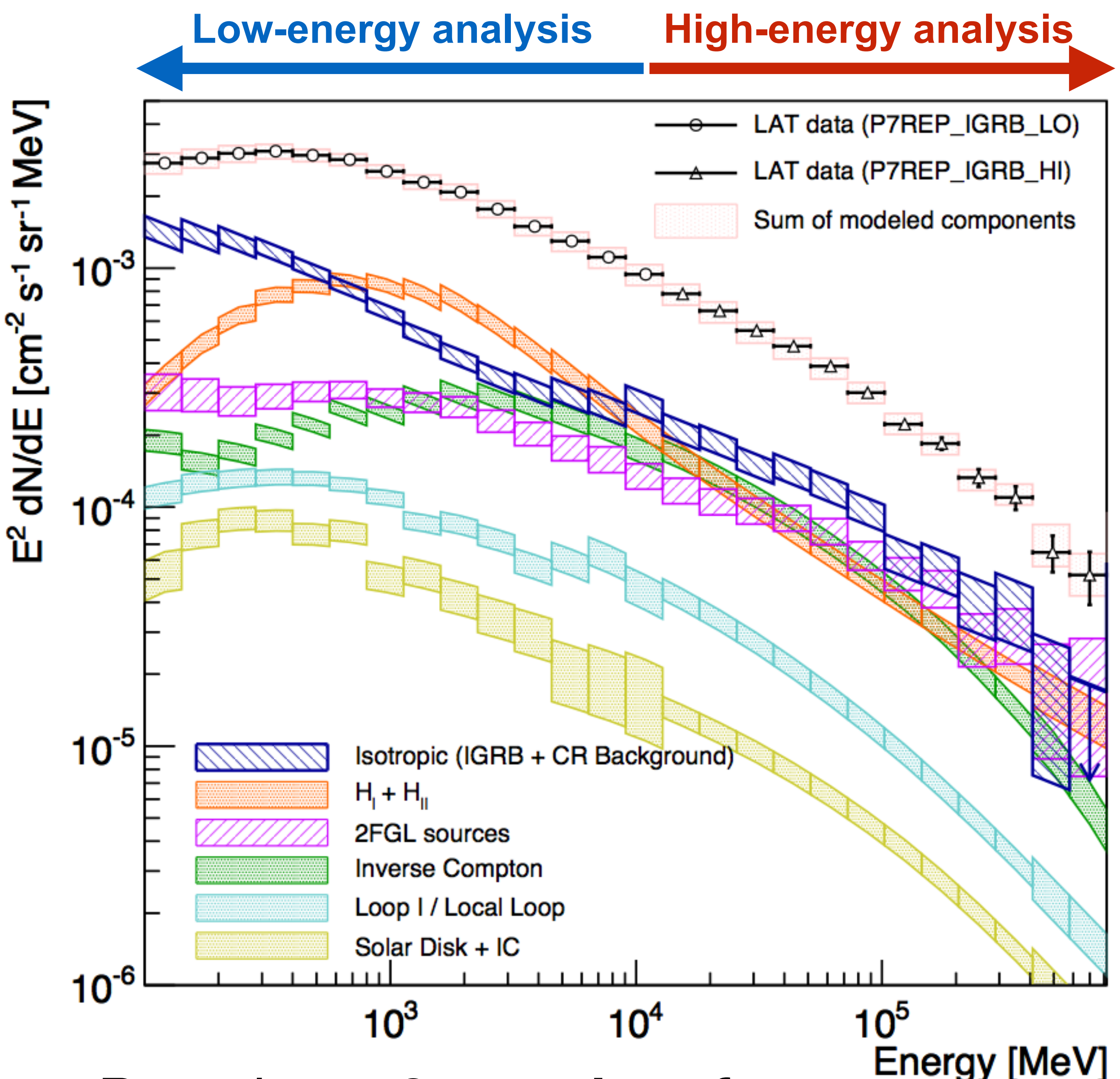
derstood.

dels.

> **Example model "B"**: Injection of e^+/e^- by population close to Galactic center.

> Any effect on derived IGRB?

Results from the IGRB fit.



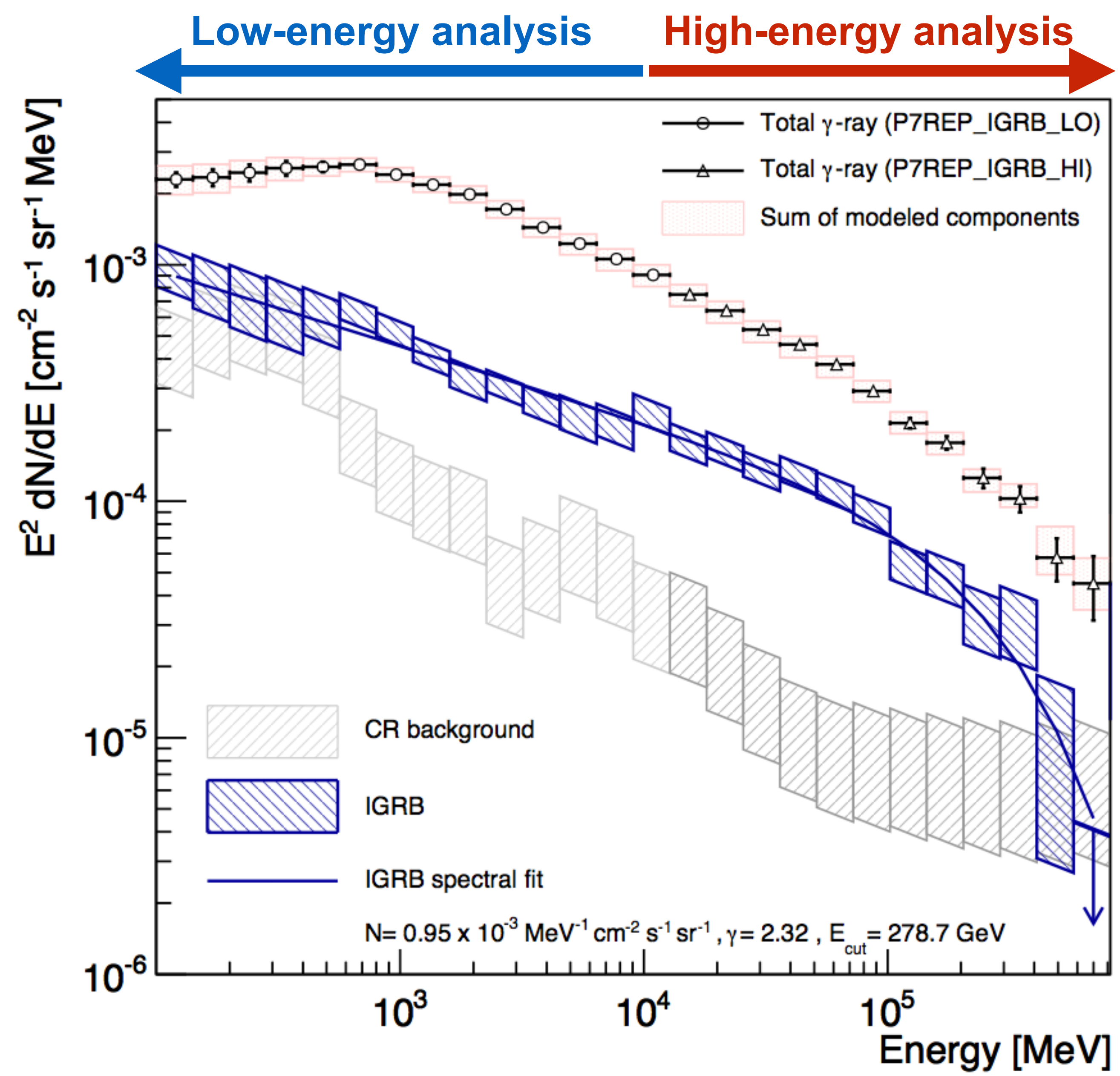
> Based on **50 months of reprocessed pass7 LAT data**.

> **Average intensities** (|b| > 20°) attributed to model templates.

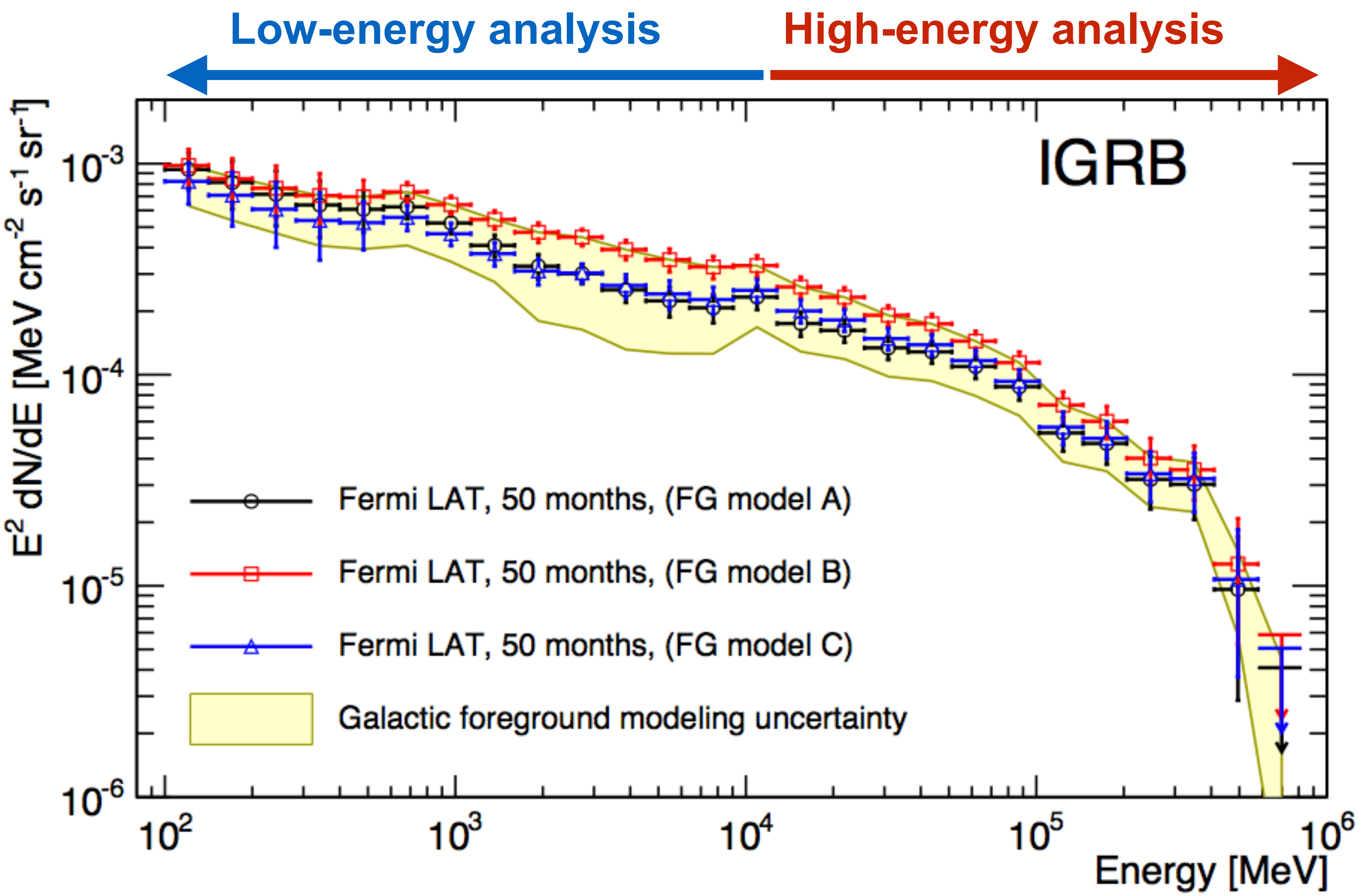
> **Baseline foreground model** used.

> **IGRB and CR contributions** to isotropic emission

> **Spectral fit of IGRB** by power-law with exponential cutoff.



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.

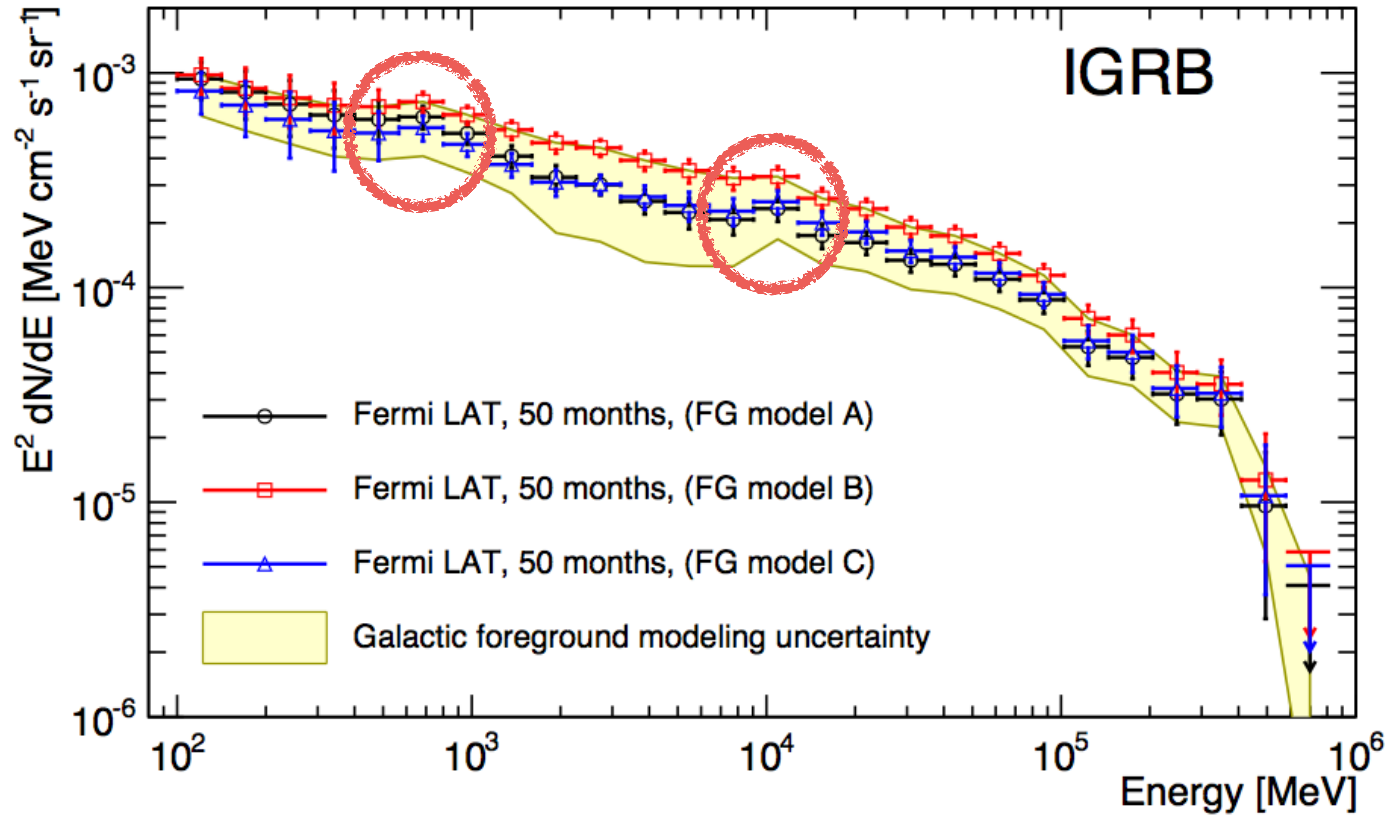
> **IGRB spectrum** can be parametrized by single power-law + exponential cutoff.

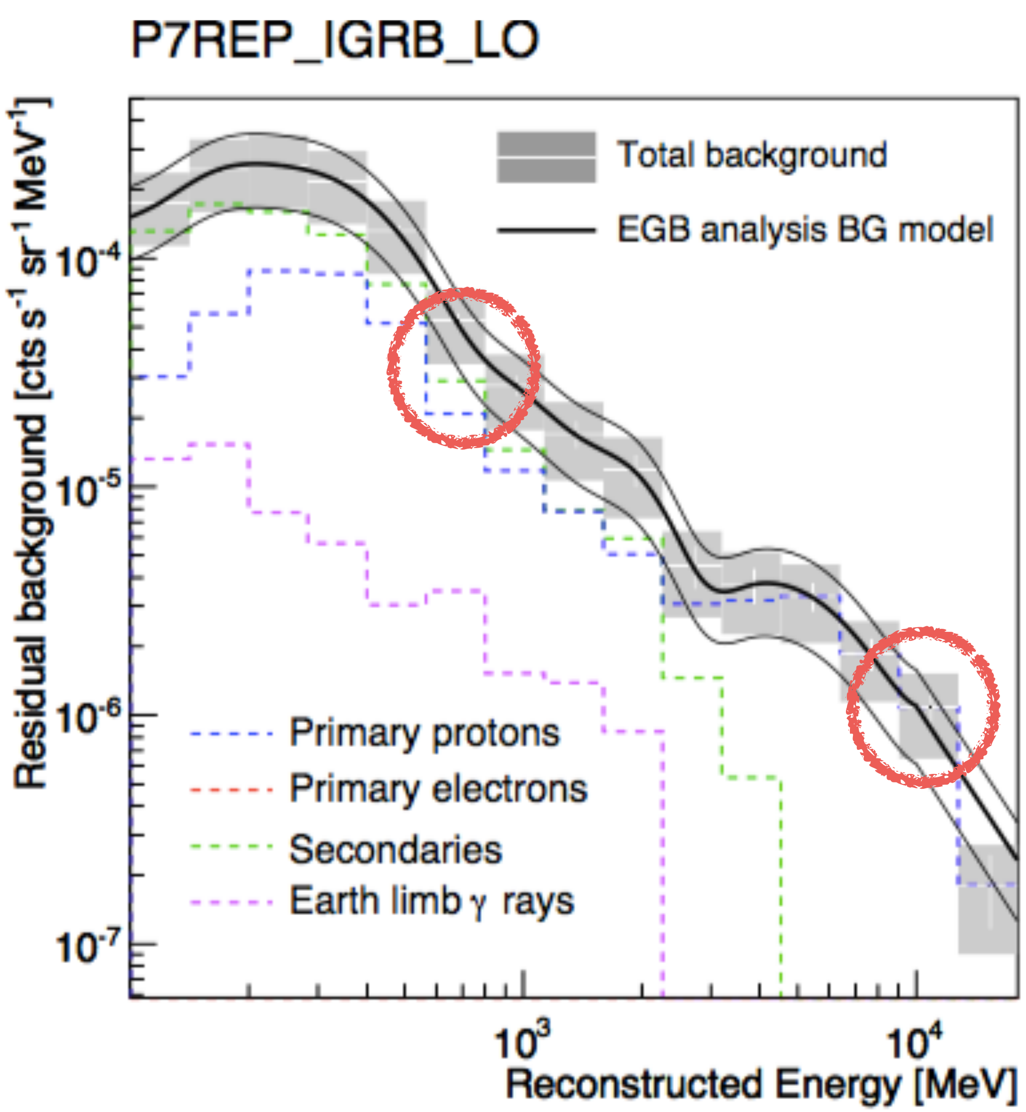
> Spectral index **~ 2.3** , cutoff energy **~ 250 GeV.**

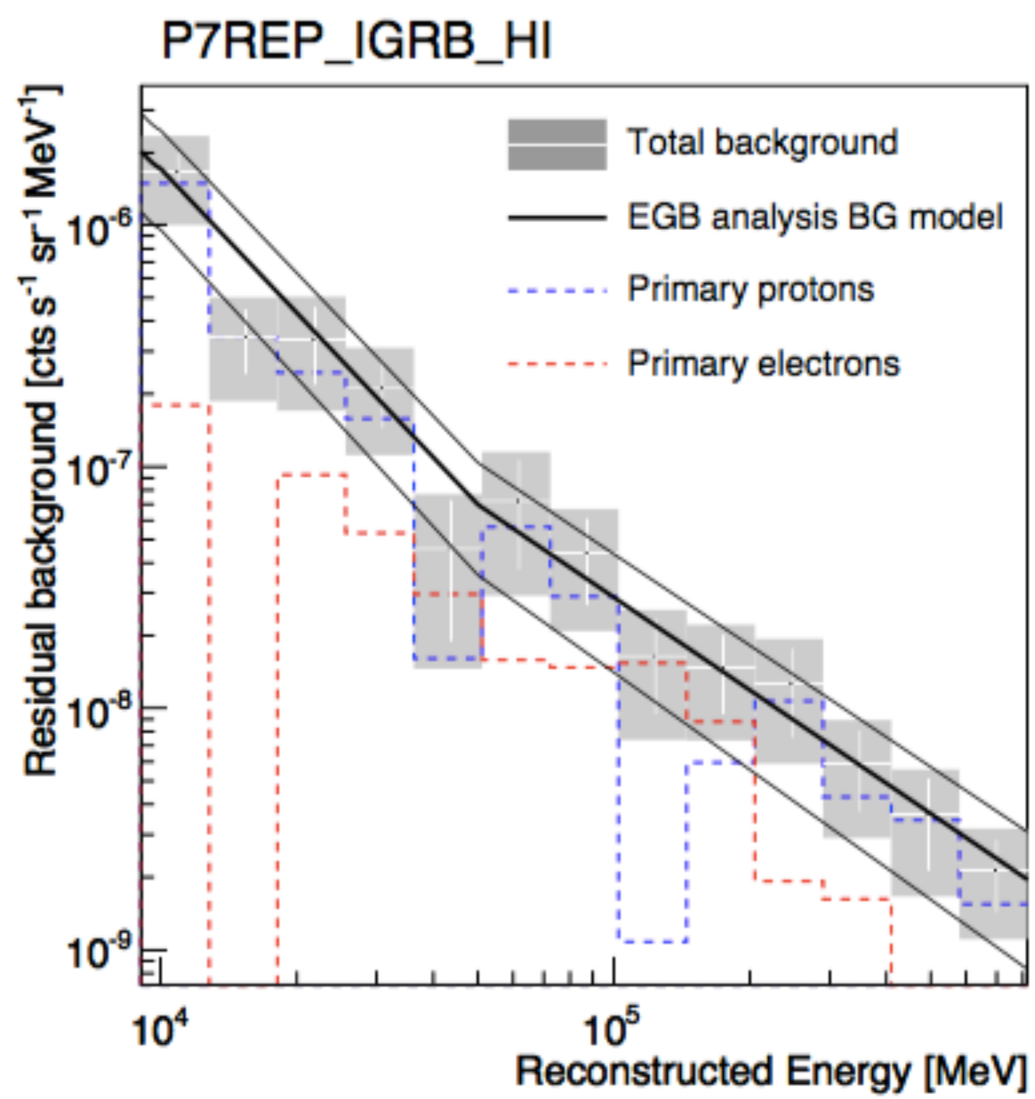
> It is **not compatible with a simple power-law** ($\chi^2 > 85$).

Are there spectral features ?

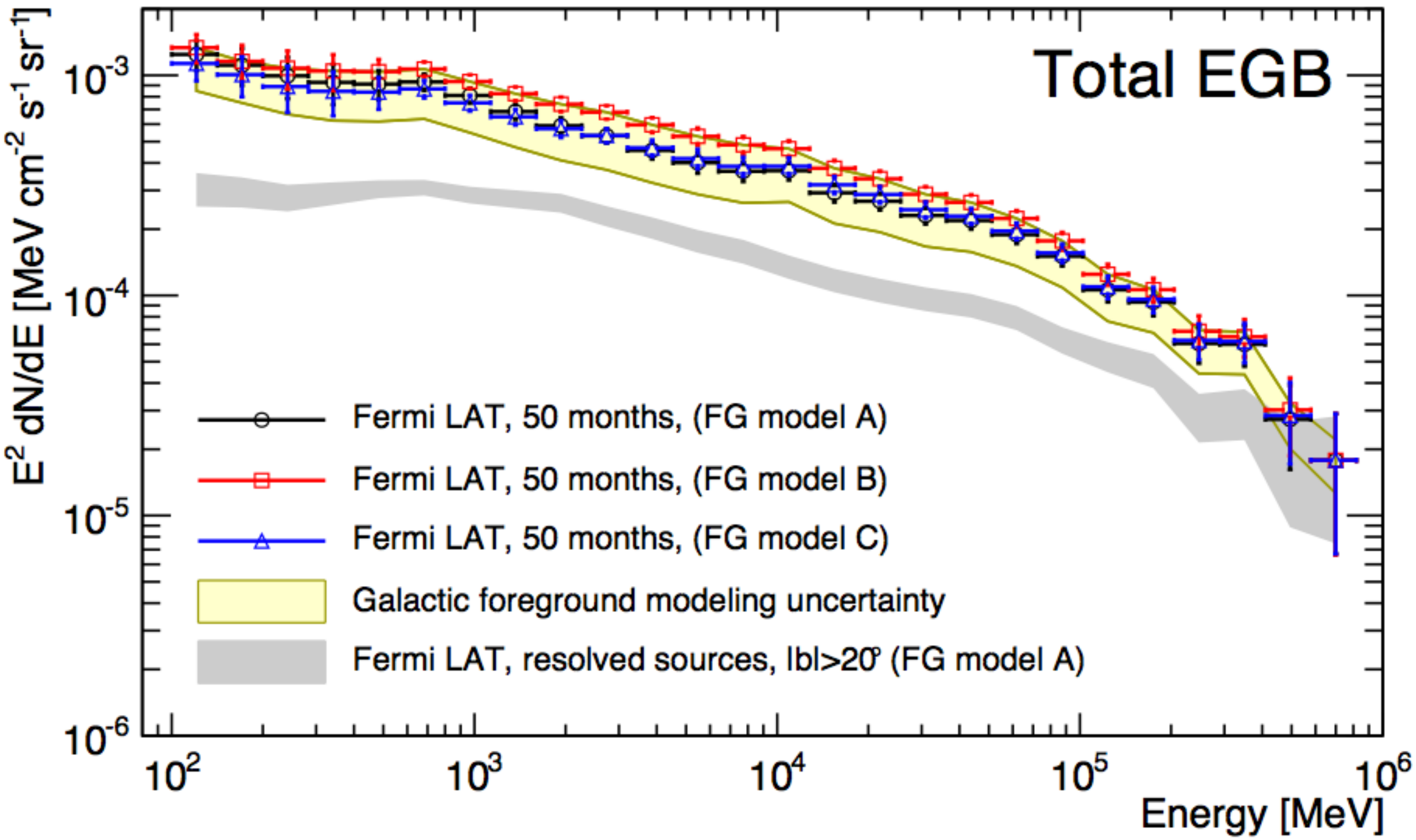
- No evidence within systematics
- residual CR background spectrum is not a simple & smooth function
- This might introduce apparent spectral structures into IGRB





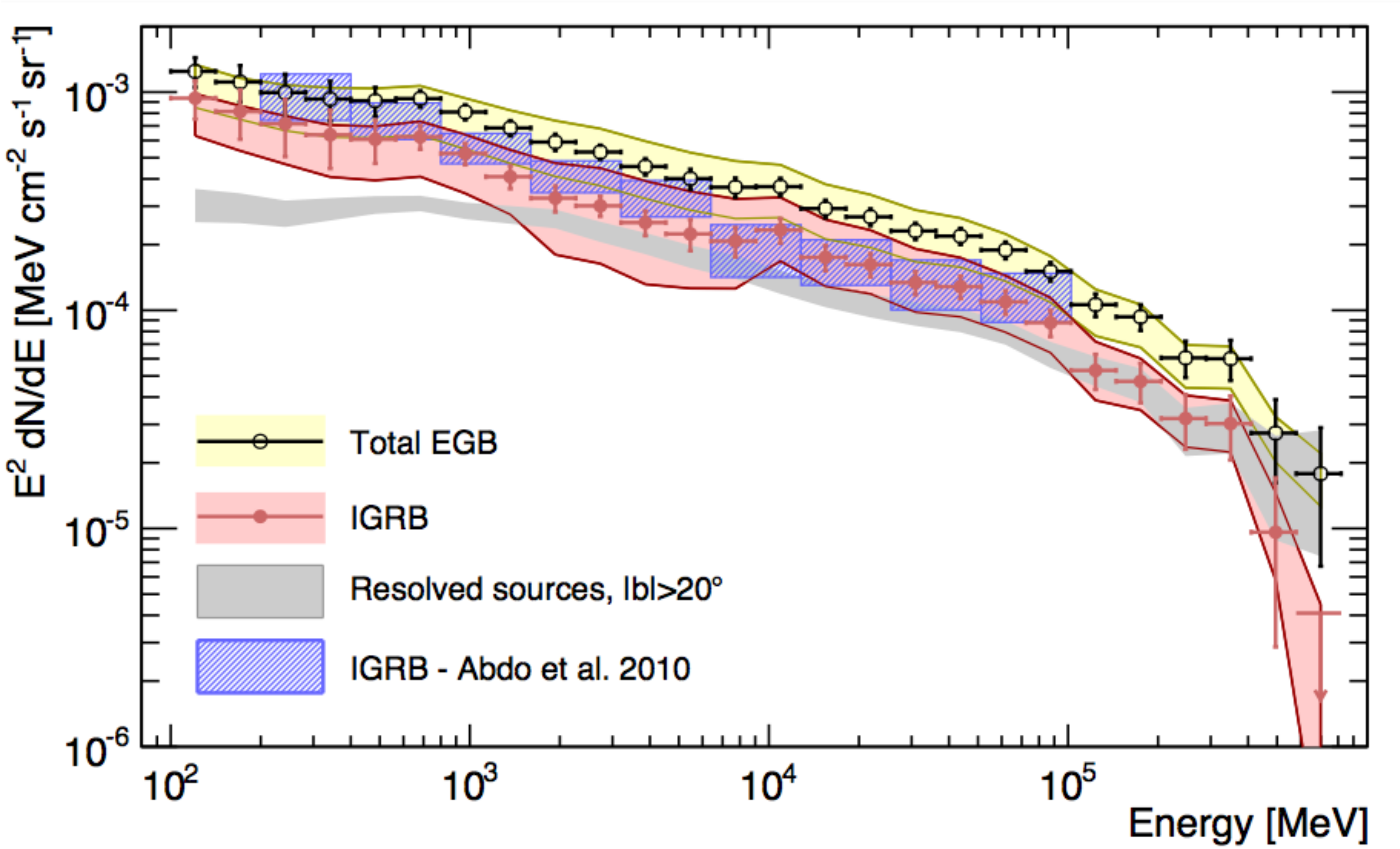


The total extragalactic background.



- **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.**

Comparison of LAT IGRB and EGB measurements.



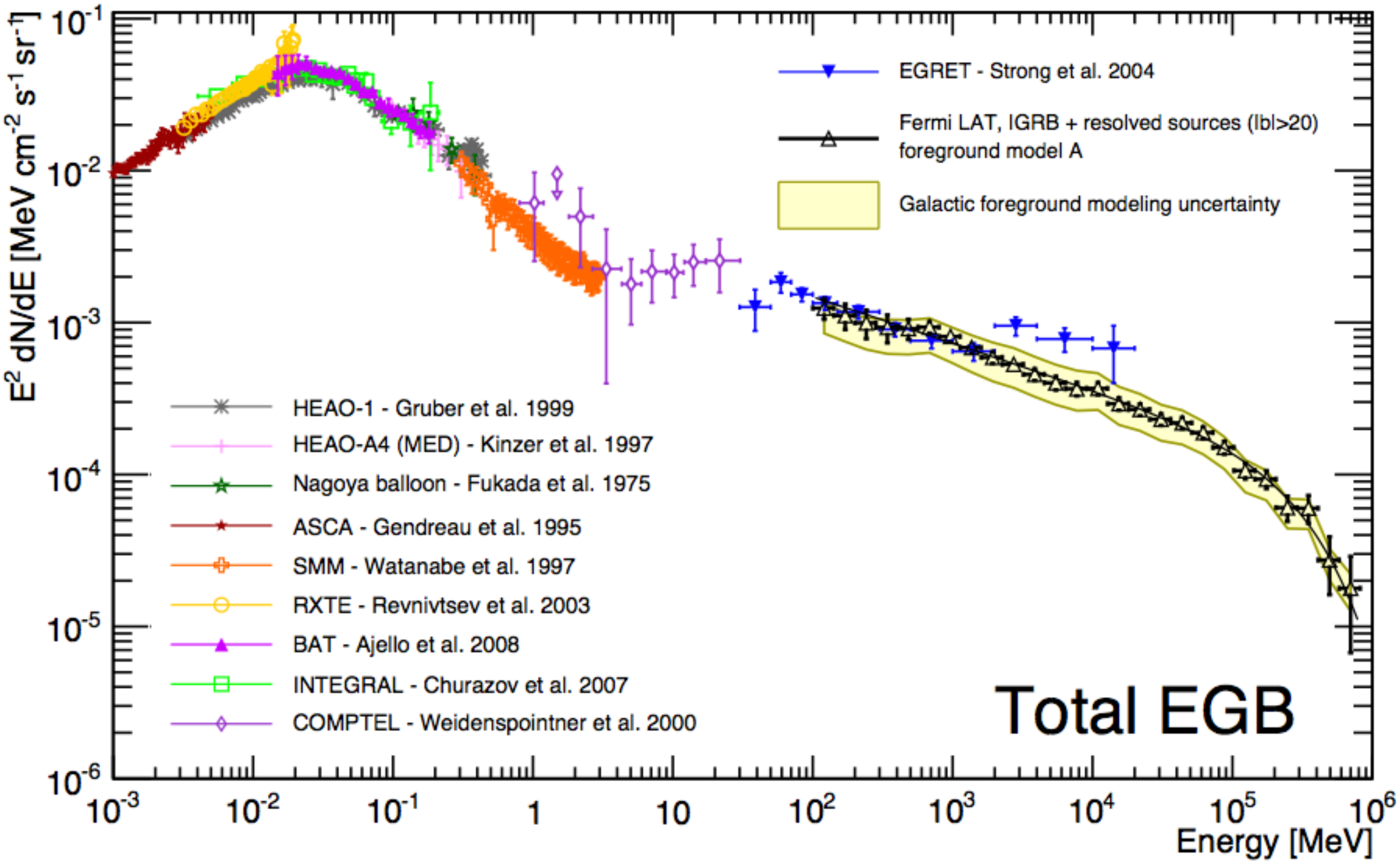
> Comparison for **baseline diffuse model**.

> **Integrated intensity** of IGRB about **30% below** measurement in Abdo et al. 2010.

> **Compatible** within systematic uncertainties.

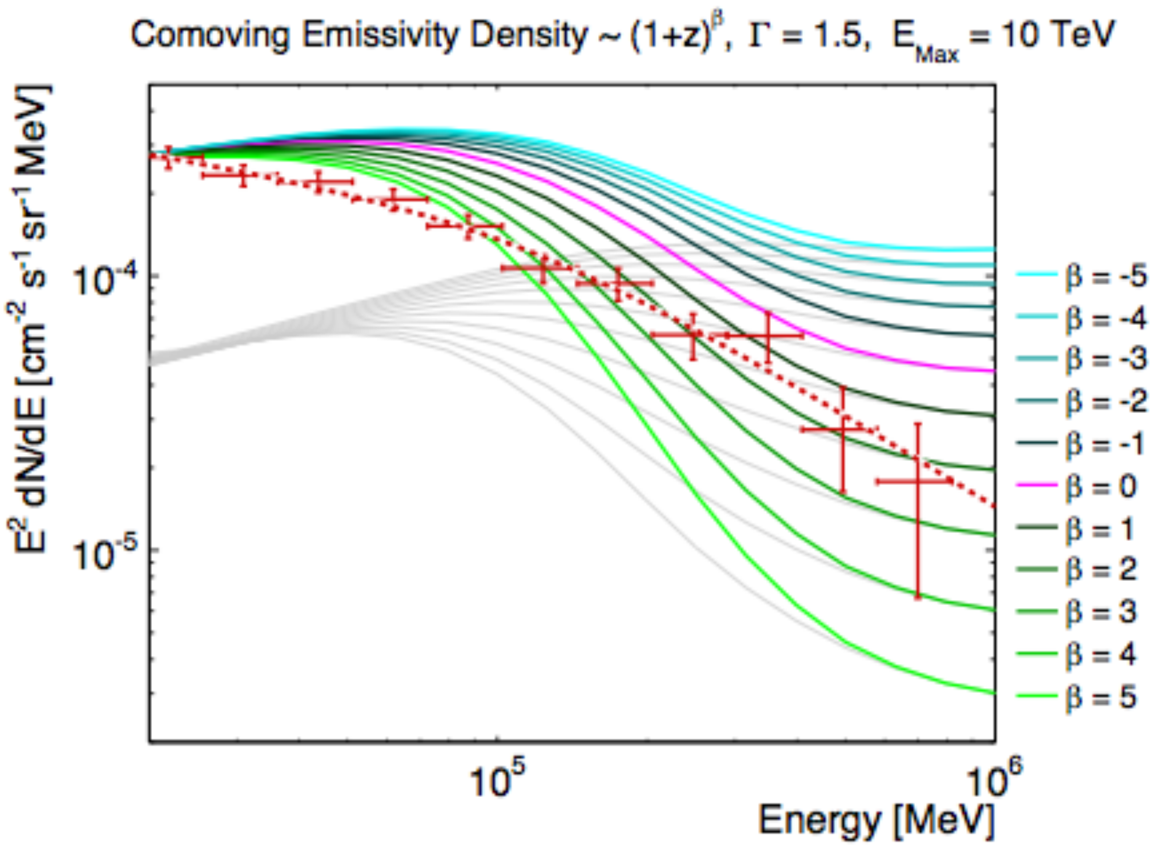
> **Main differences:** Improved diffuse foreground and CR background models.

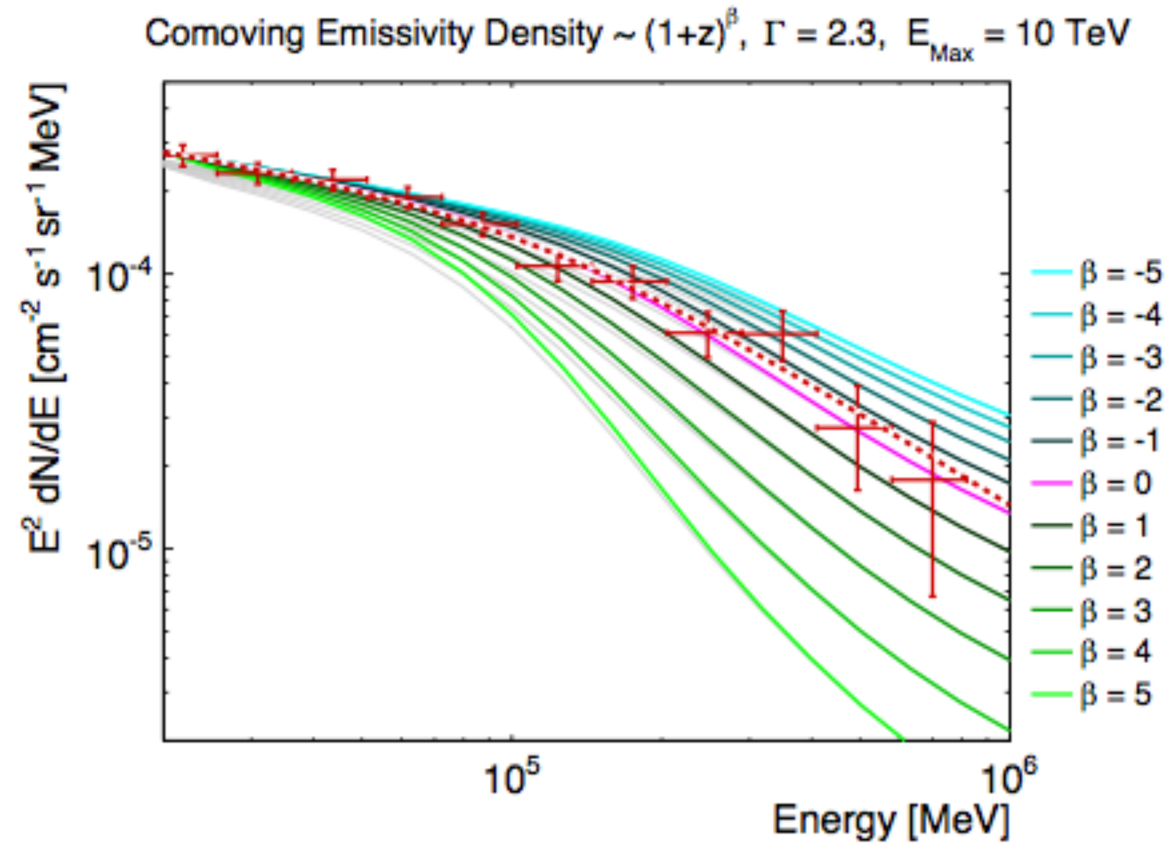
Comparison to other experiments.

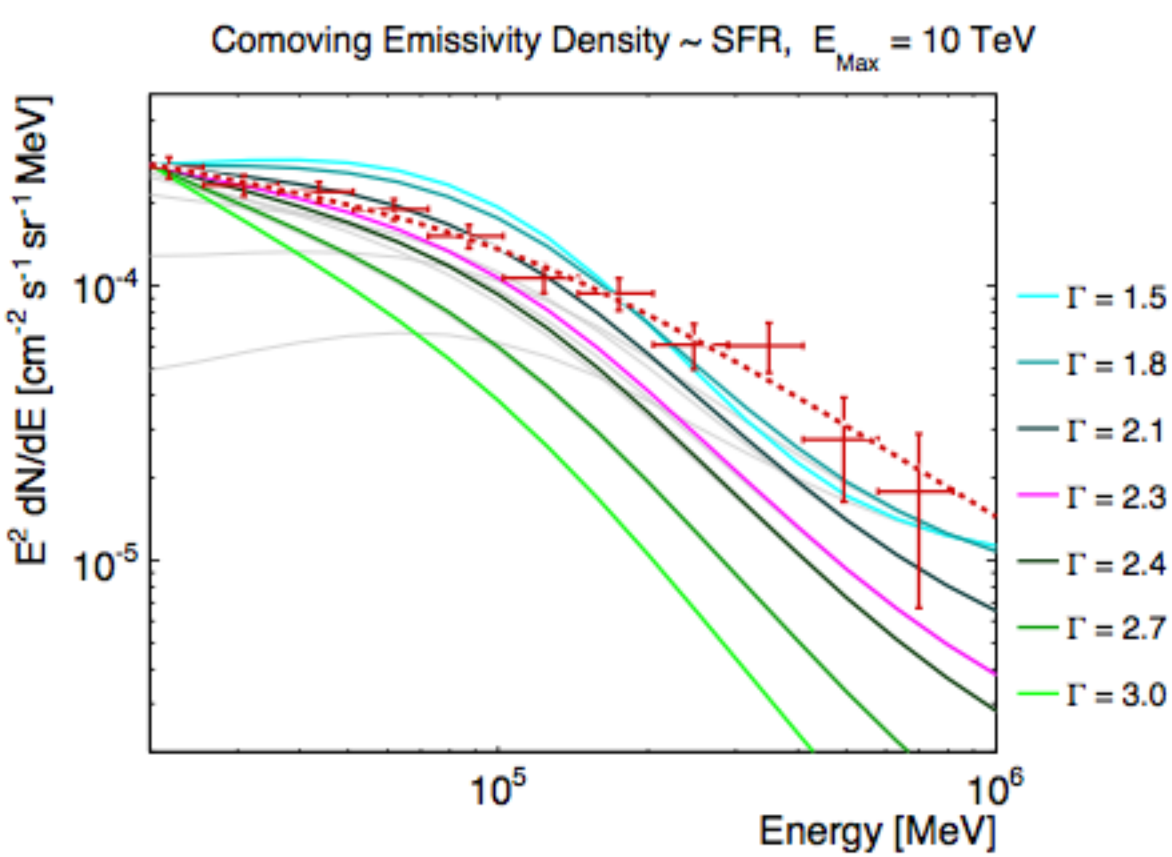


> Cosmic x-ray and gamma-ray background now **measured over 9 orders of magnitude in energy**.

The shape of the high-energy IGRB spectrum.

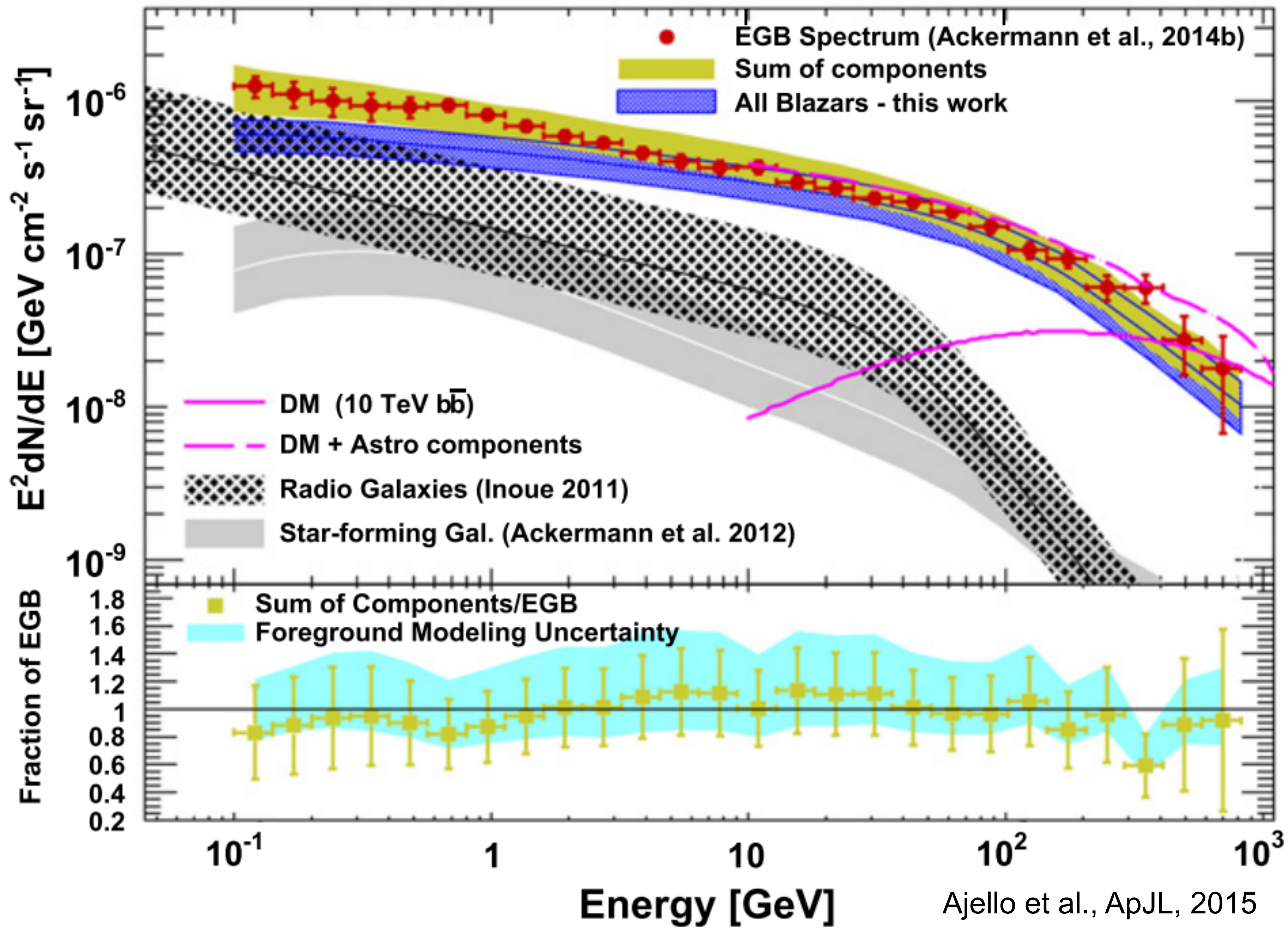






- **Simple population** of sources with **power-law spectrum** with index Γ
- Luminosity or density evolution ~ $(1+z)^{\beta}$ or following star-formation rate
- Observed EGB spectrum is **compatible with single population of sources** with power-law spectrum (Γ=2.3) and no evolution (β=0).

Source populations contributing to the EGB.



Ajello et al., ApJL, 2015

> **Reality** might be **more complex**.

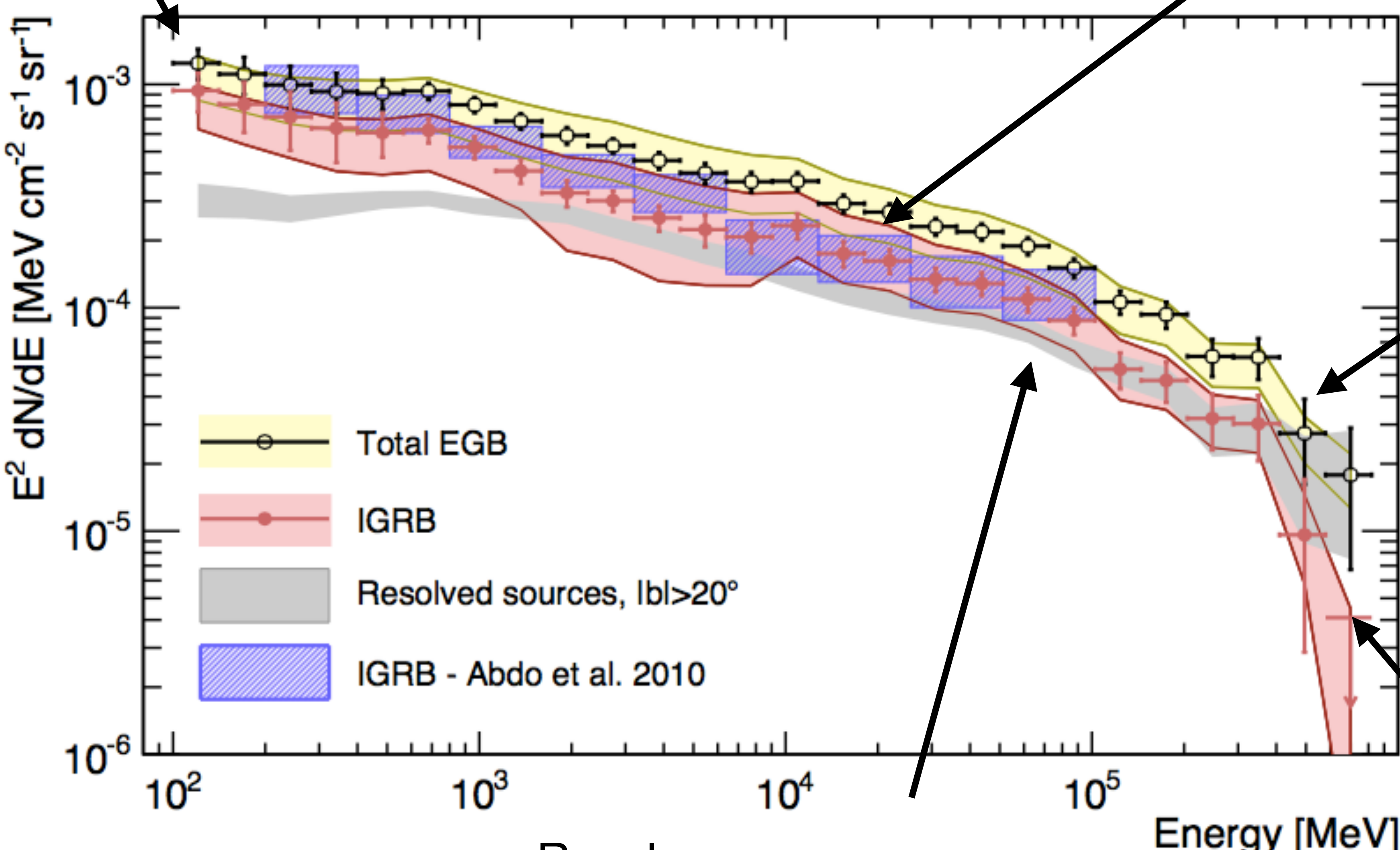
> Above few GeV **Blazars** seem to **dominate** the EGB

- luminosity dependent evolution, negative for low-luminosity HSP-BLLacs

Where to go from here: Pass8 analysis

Extend energy range to <~30 MeV

Reduce foreground modeling systematic uncertainty



Reduce high-energy statistical uncertainty

Resolve more sources.

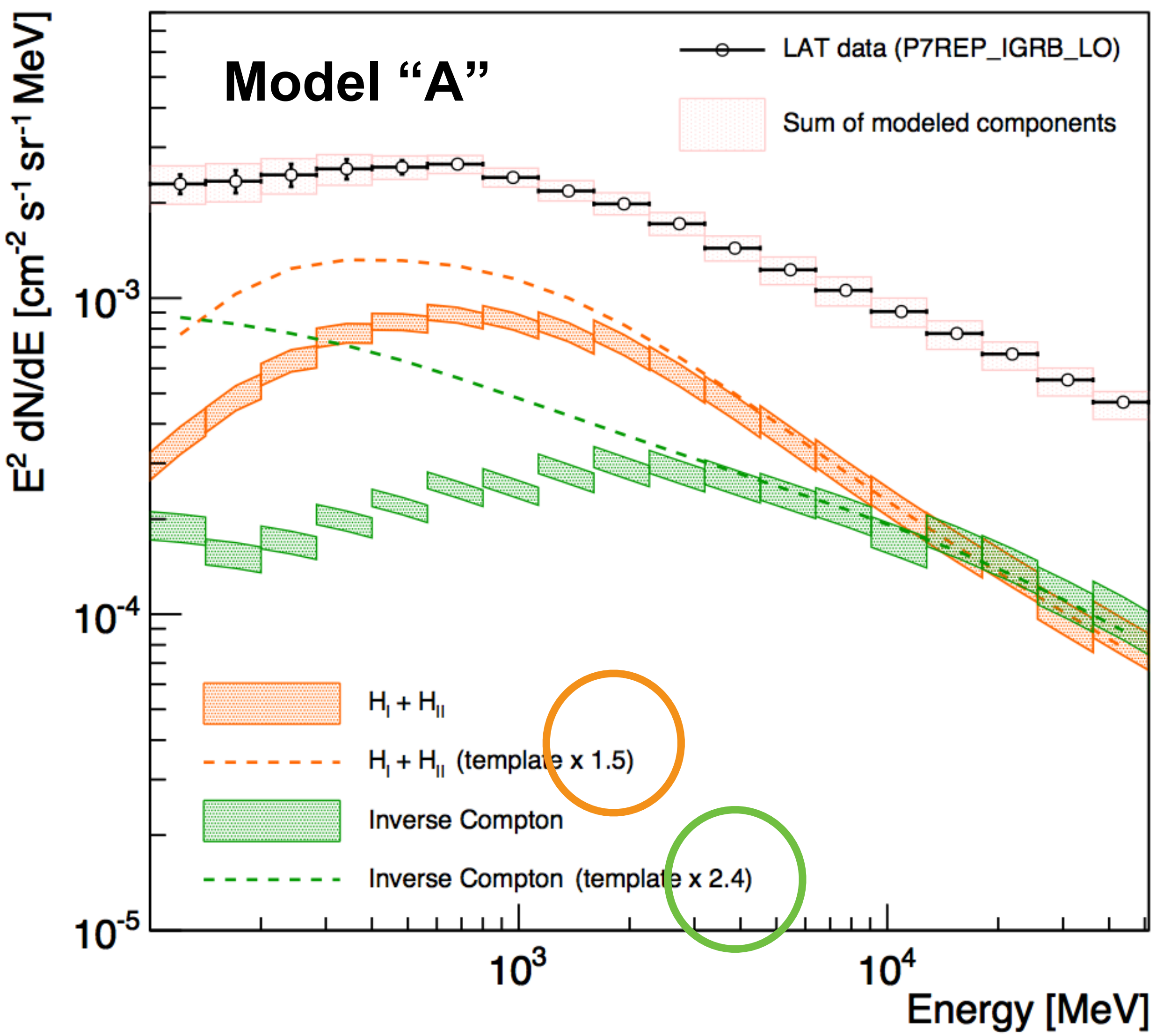
Extend the measurement to >~ 2 TeV (probably IGRB limits only)

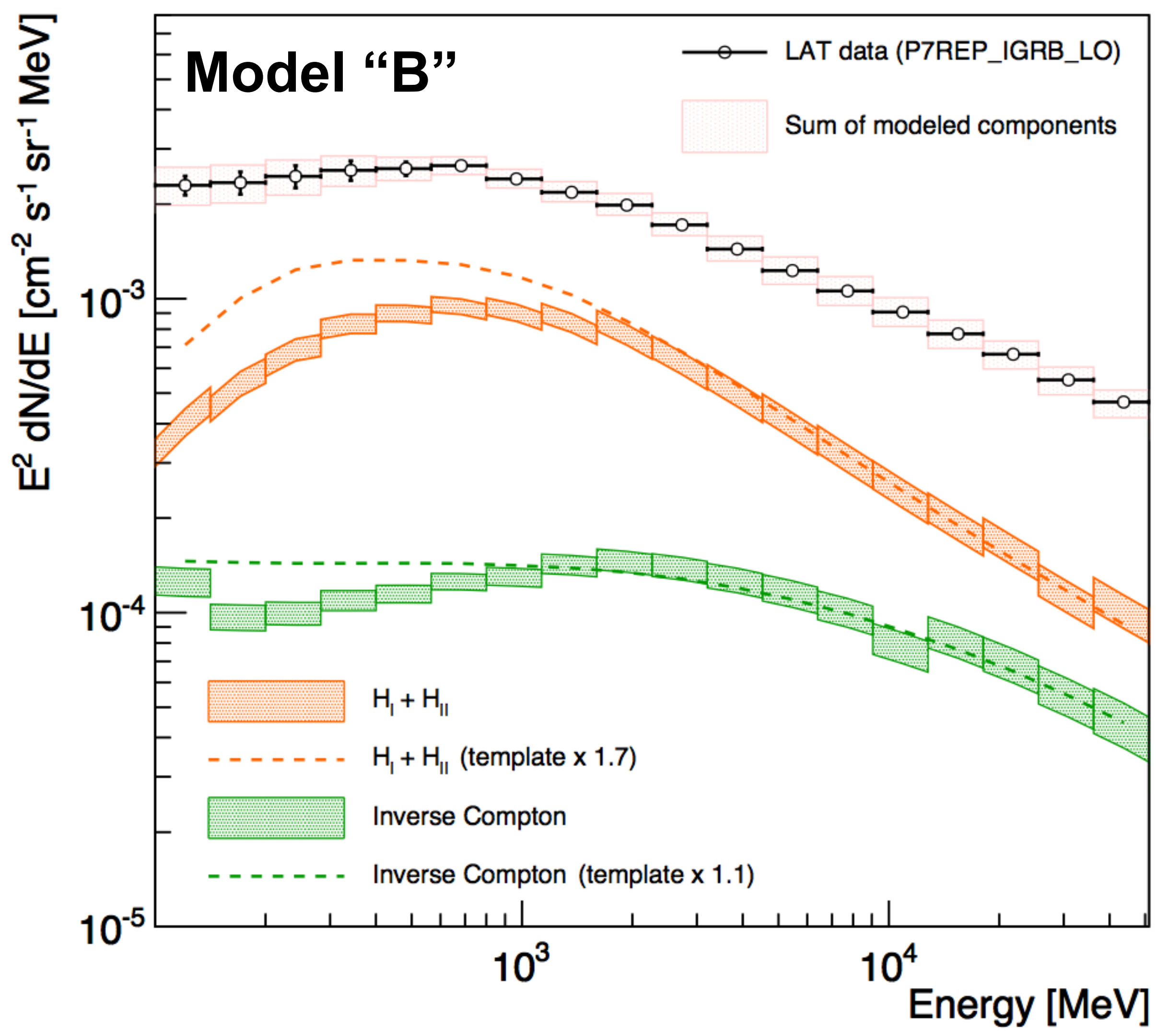
> 2 steps:

- High-energy analysis: above ~ 1 GeV
- Low-energy analysis: 30 MeV - 1 GeV (later)

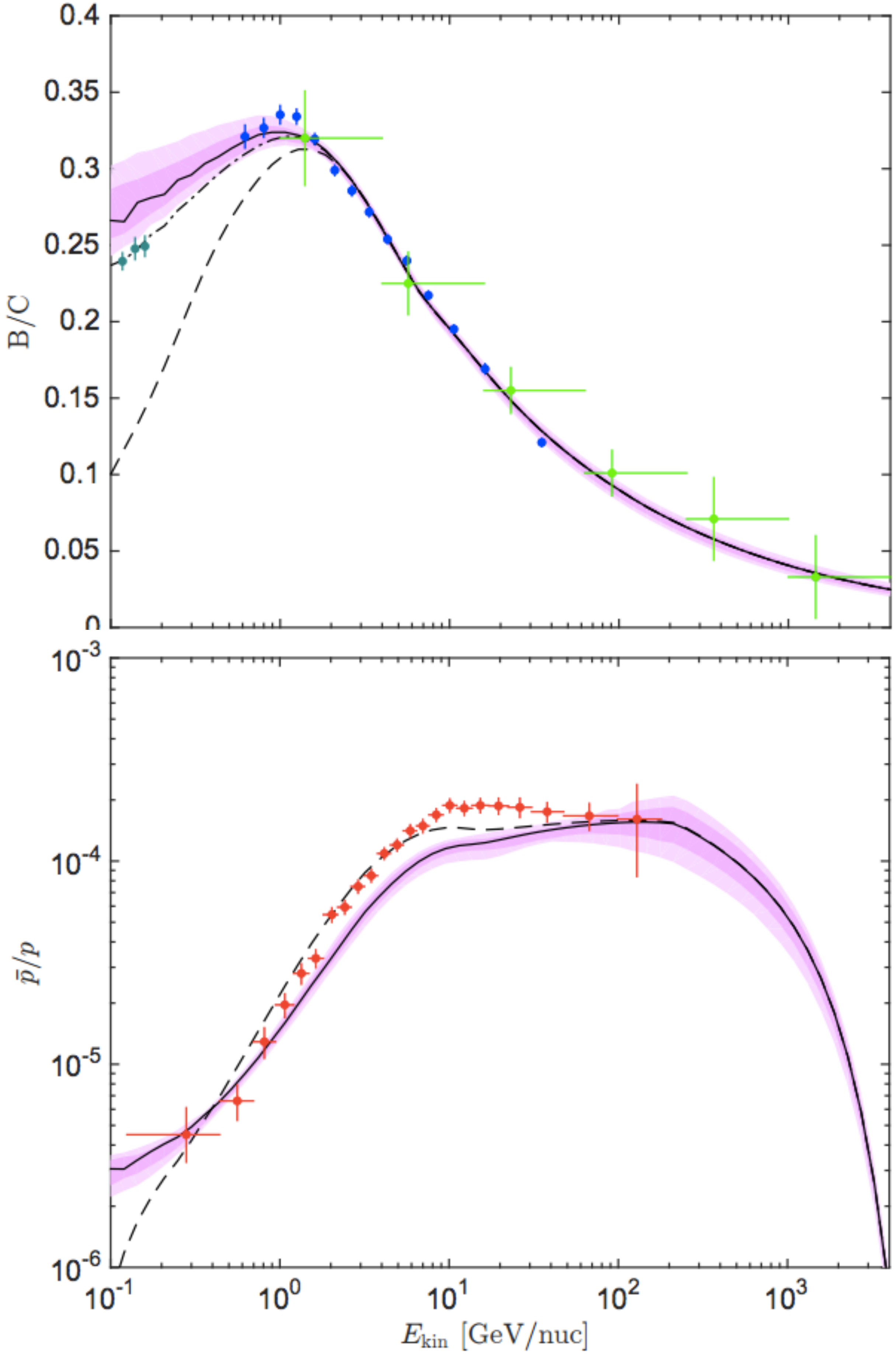
Potential foreground model improvements

> Foreground modeling improvements anticipated for pass8 EGB analysis
  - Investigate a systematics optimized mask.
  - Improve Loop I template
  - Model B derivate as default model (sources in galactic center region)
  - Evaluate North/South asymmetry of Galactic foreground
  - Evaluate effects of arm structure

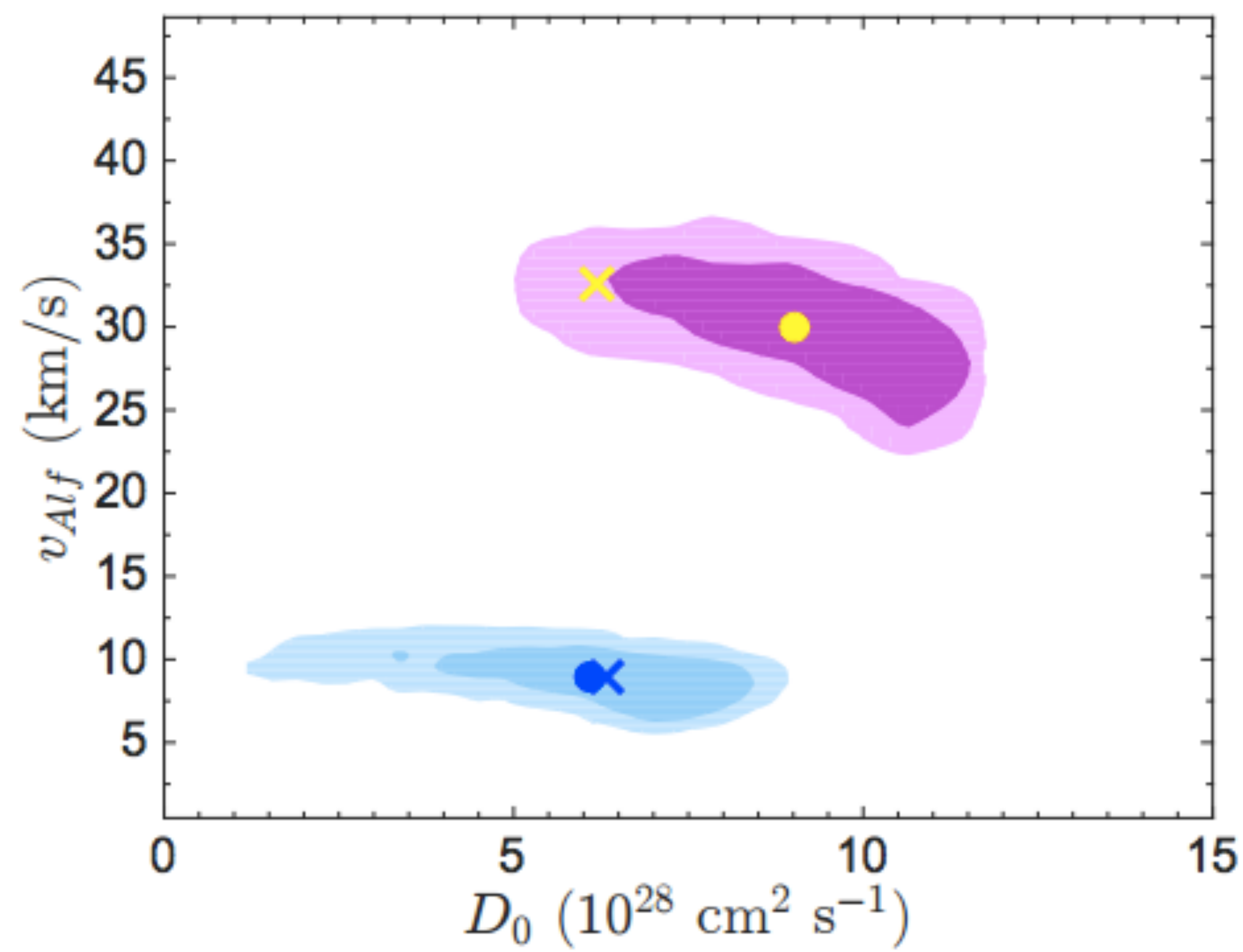




Evidence from CR for more complex propagation scenarios

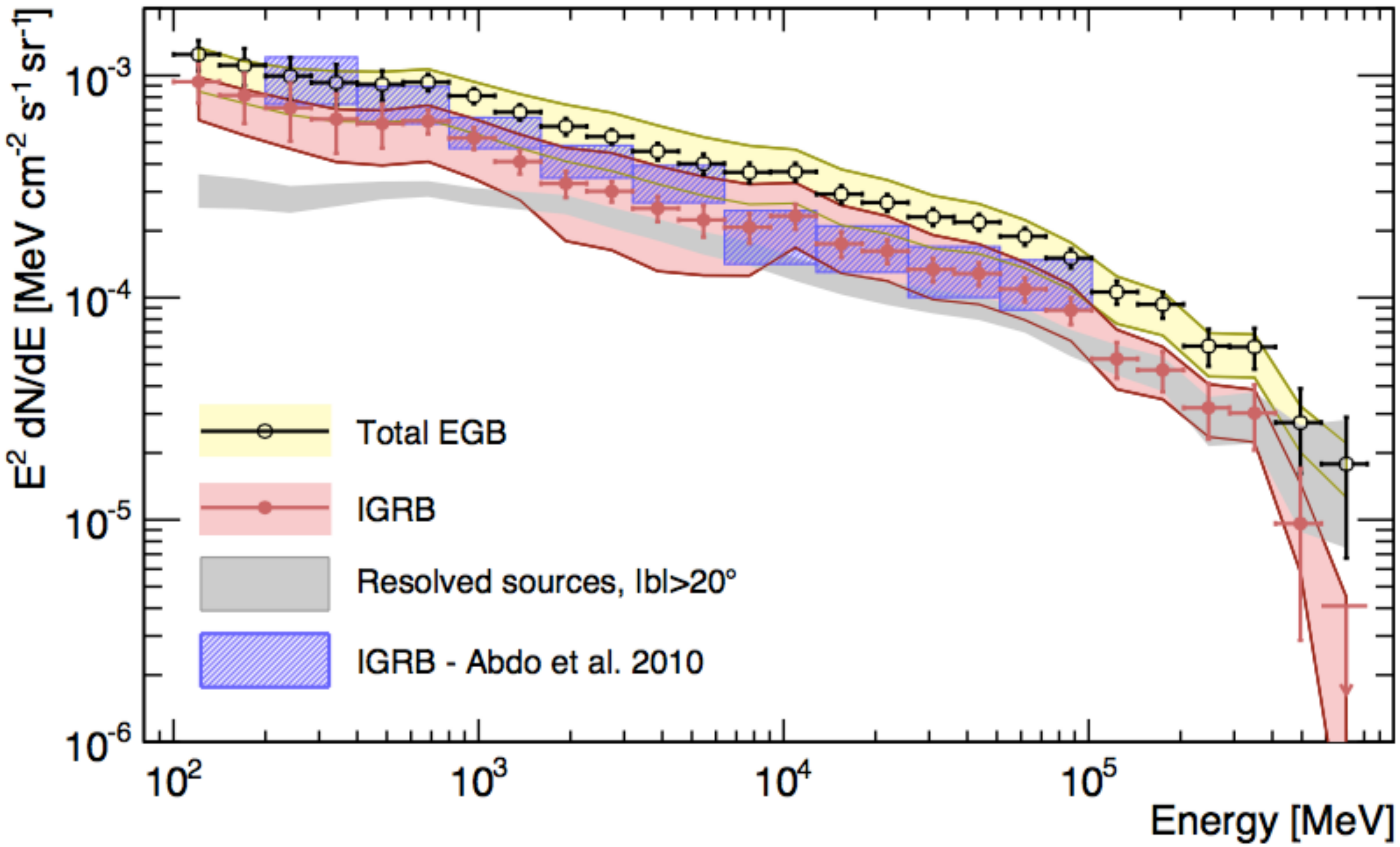


Johannesson et al., arXiv:1602.02243

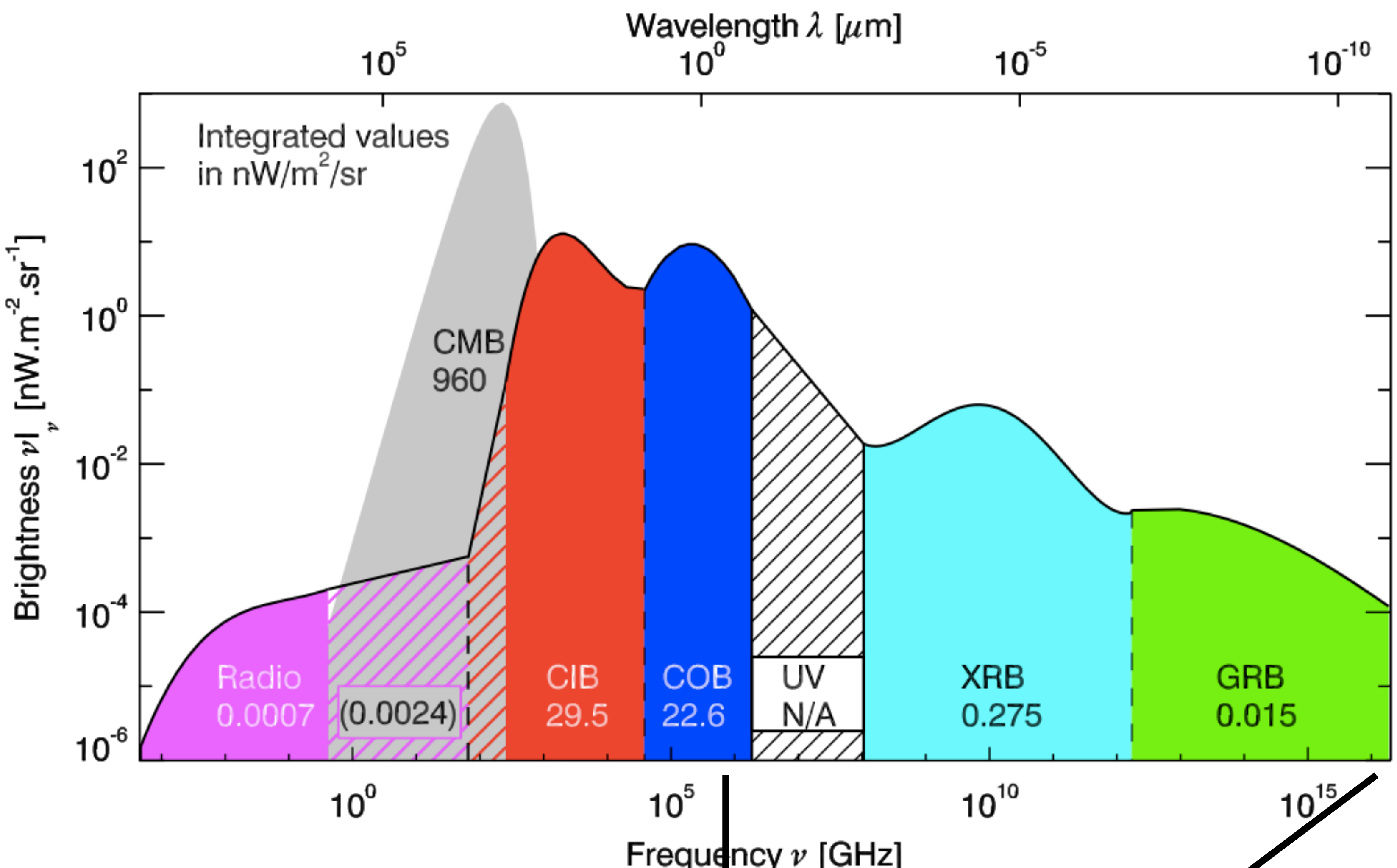


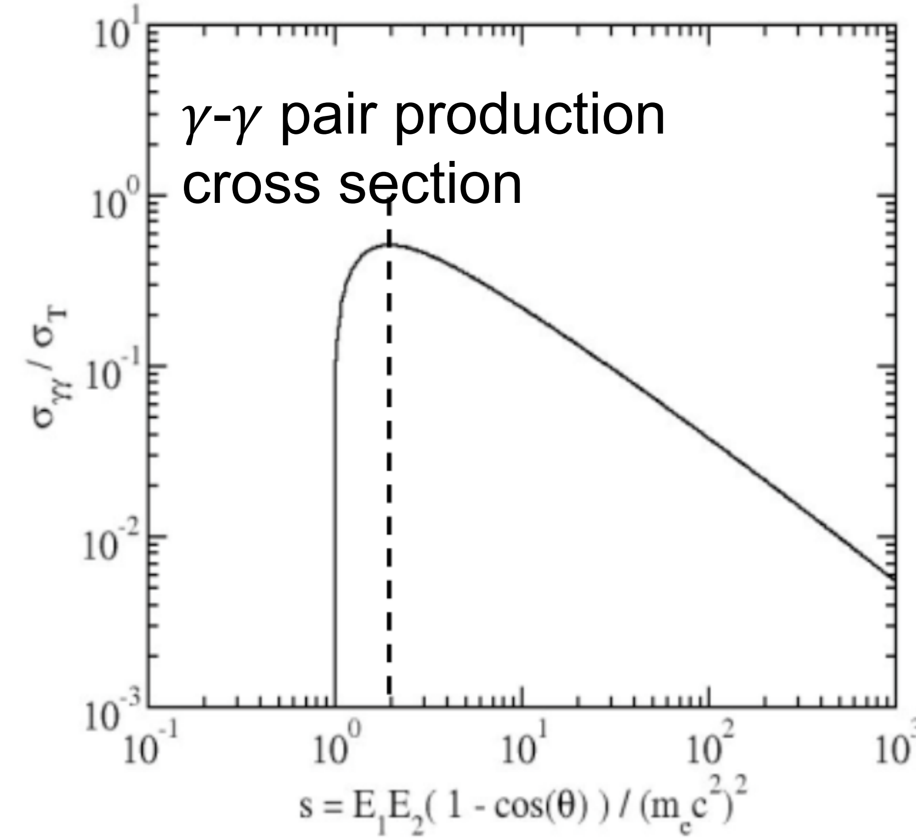
> A single set of (constant) propagation parameters cannot describe the light elements and B/C data simultaneously.

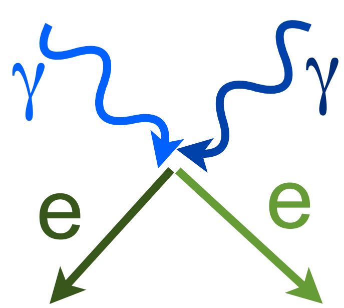
Can we measure the TeV extragalactic background ?



Gamma-ray backgrounds beyond 1 TeV





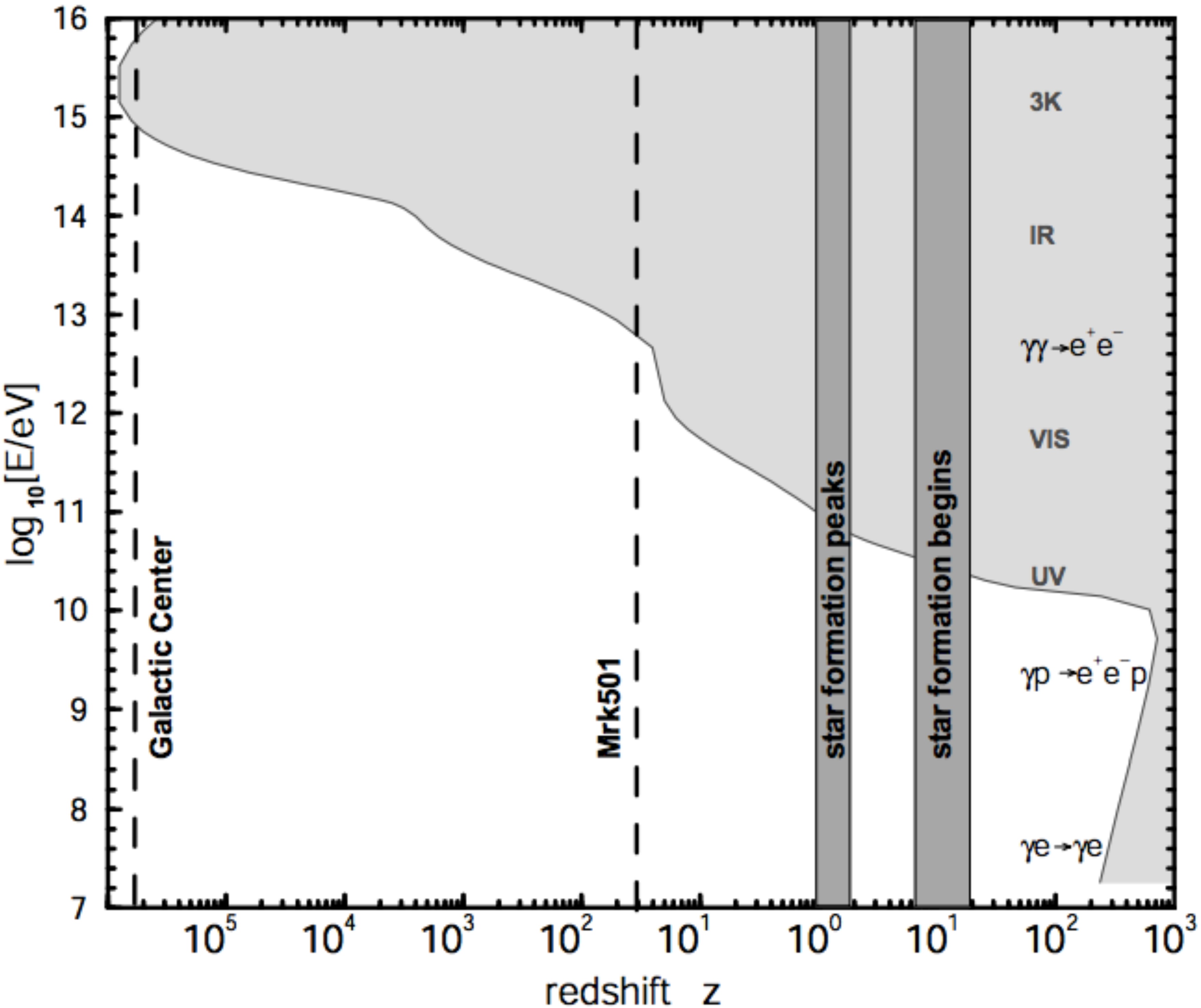


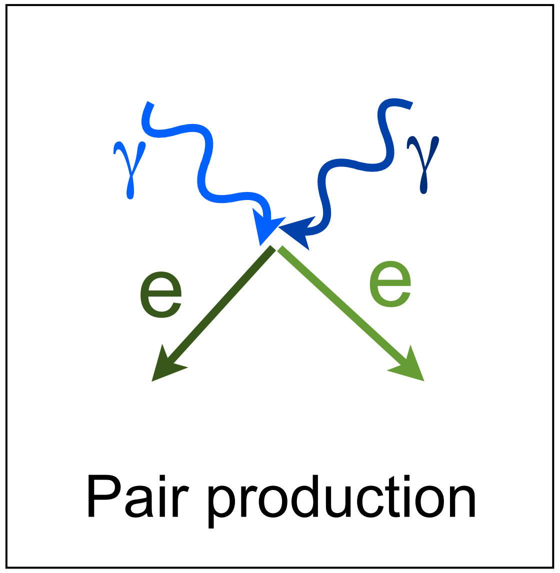
Pair production

> Absorption of gamma-rays in low-energy radiation fields introduces horizon at TeV energies

> Spectral cutoff expected (and observed) in the GRB

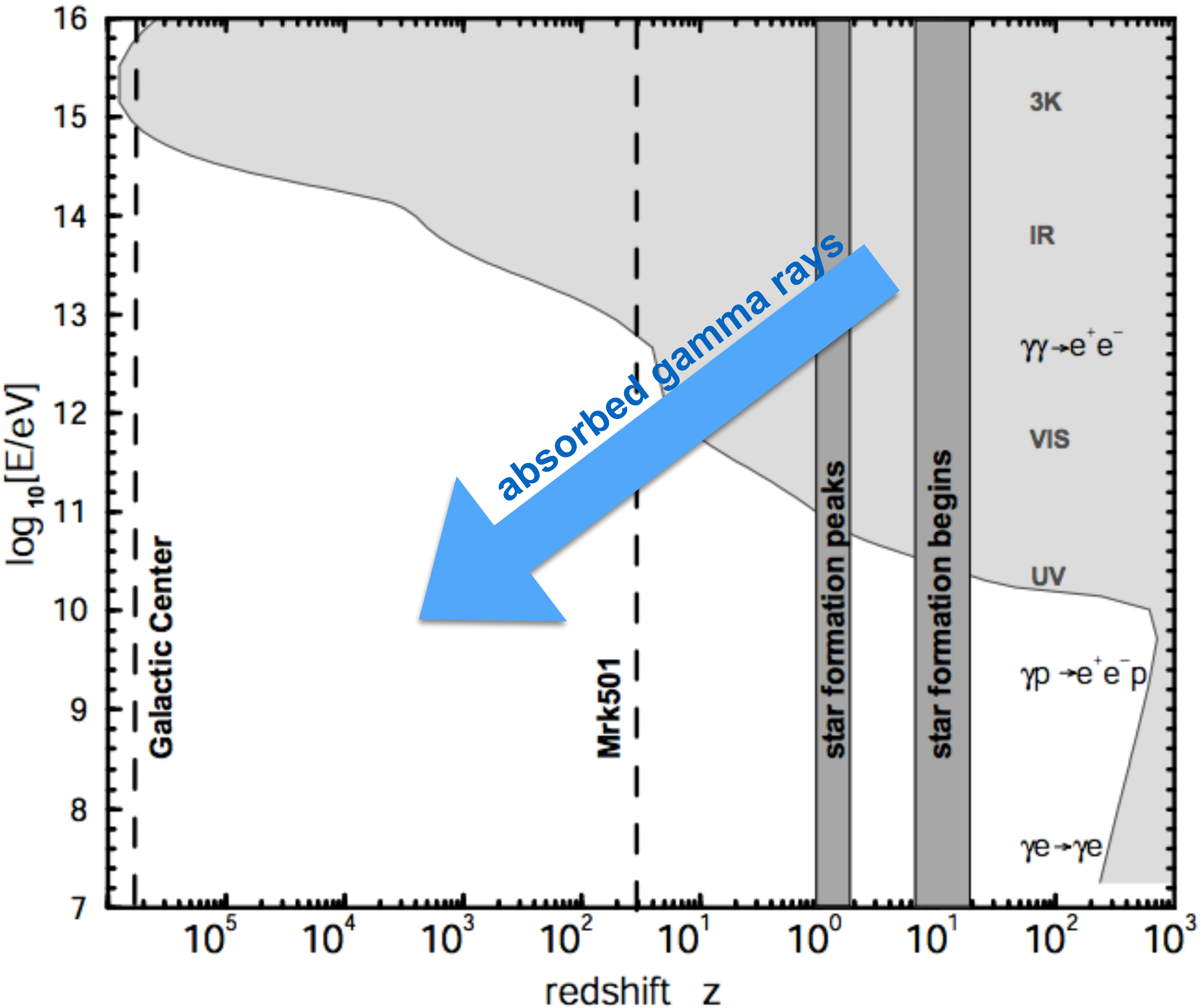
Absorption of γ-rays in the extragalactic background light (EBL).

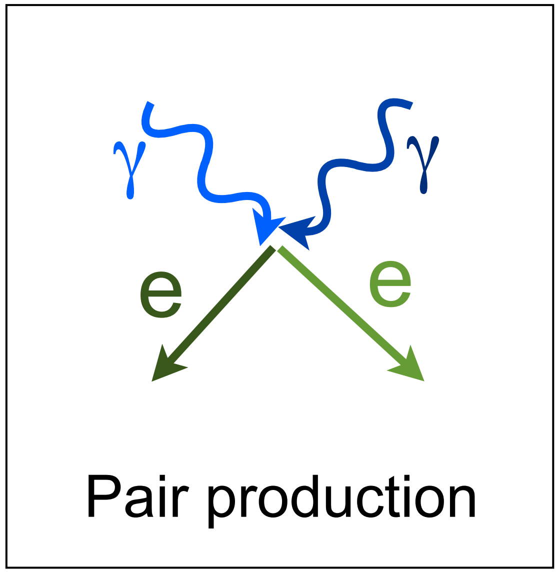




- TeV gamma rays can reach us only from the local universe
- Re-emission of absorbed TeV photons by inverse Compton processes in the GeV band: “cascade emission”

Absorption of γ-rays in the extragalactic background light (EBL).





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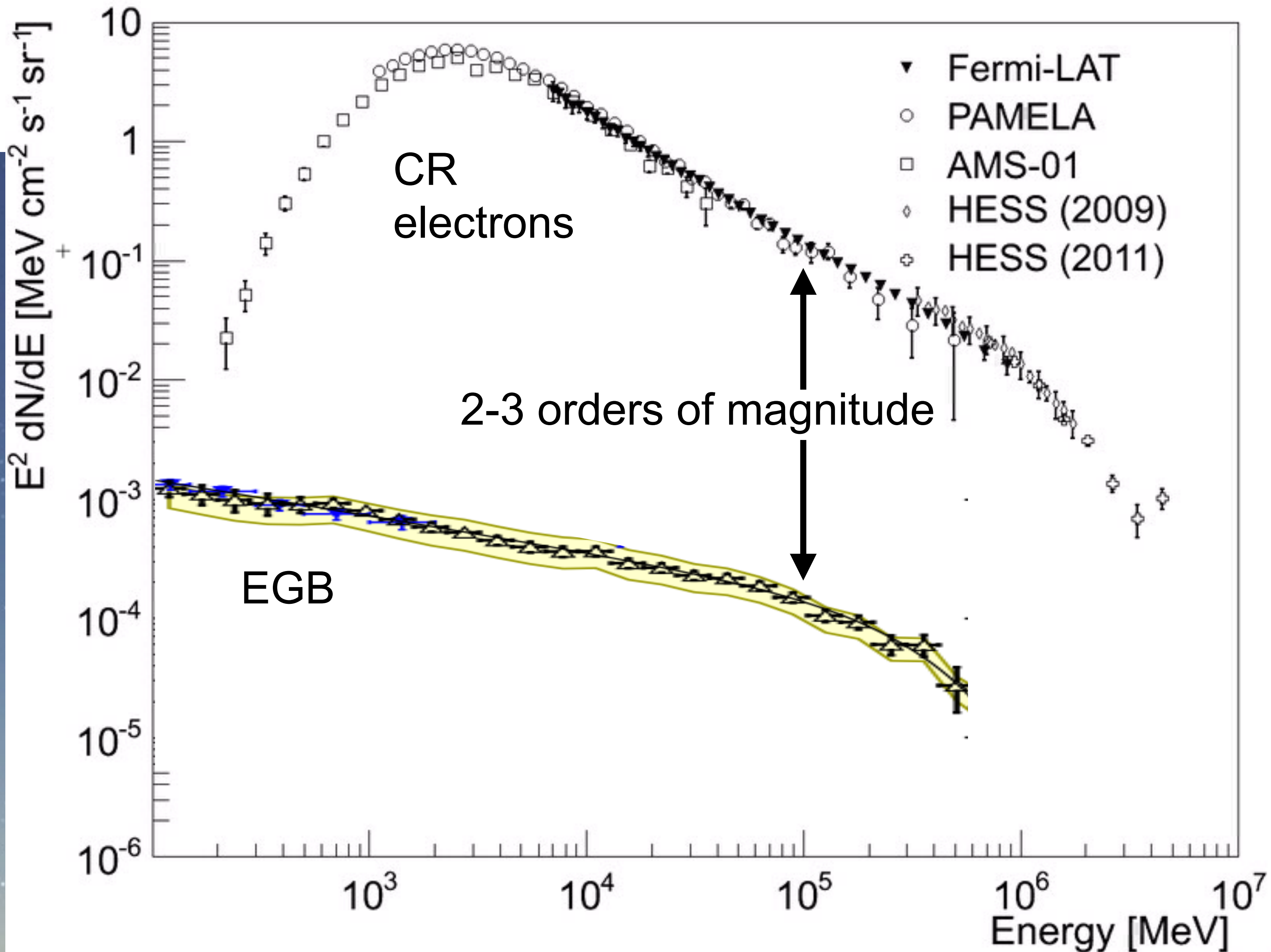
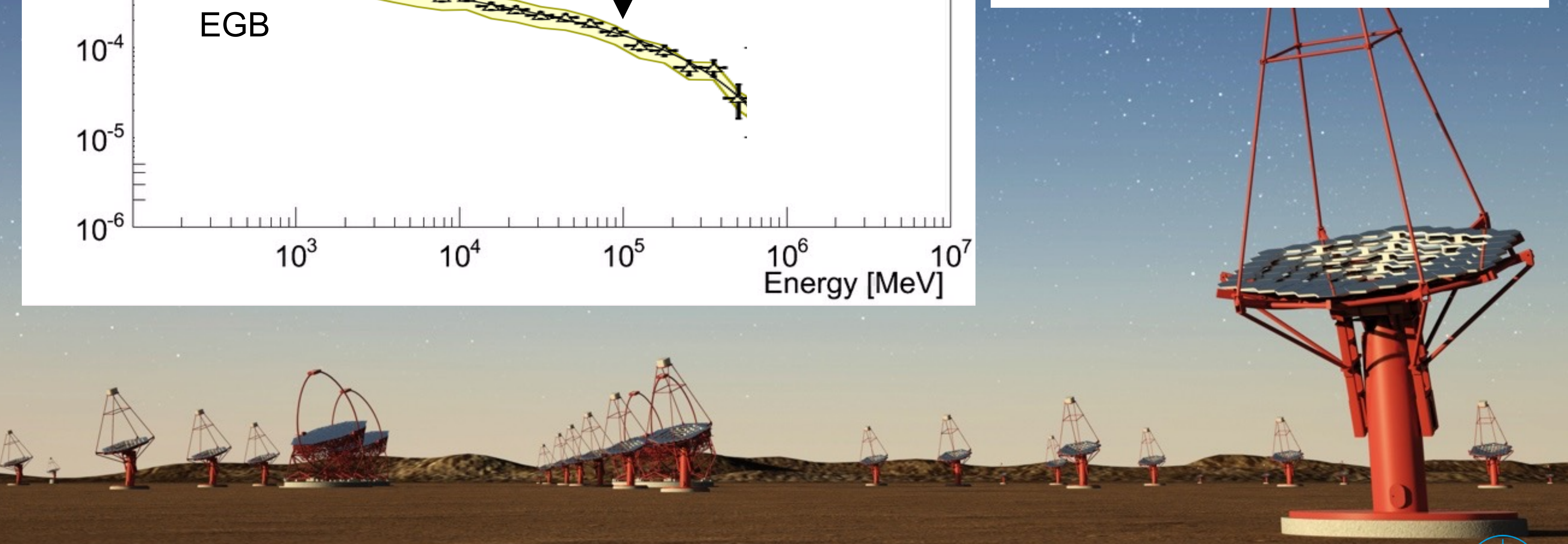
Instrumental constraints.

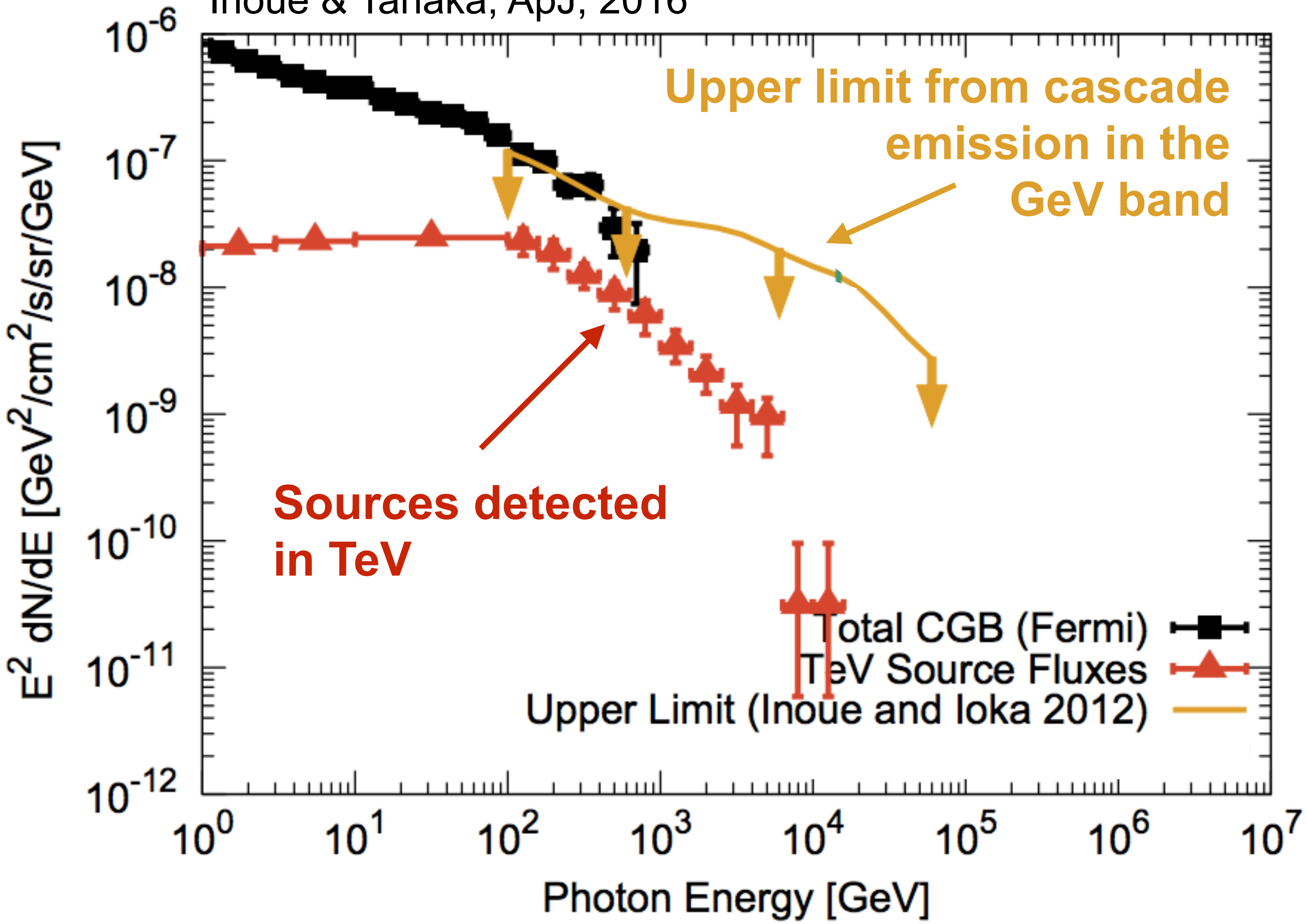


- **Ground-based telescopes** cannot distinguish electrons from gamma rays (very well)
- **CR electron background** dominates by more than an order of magnitude.
- But they can observe **close-by TeV sources.**



Constraints from observations.

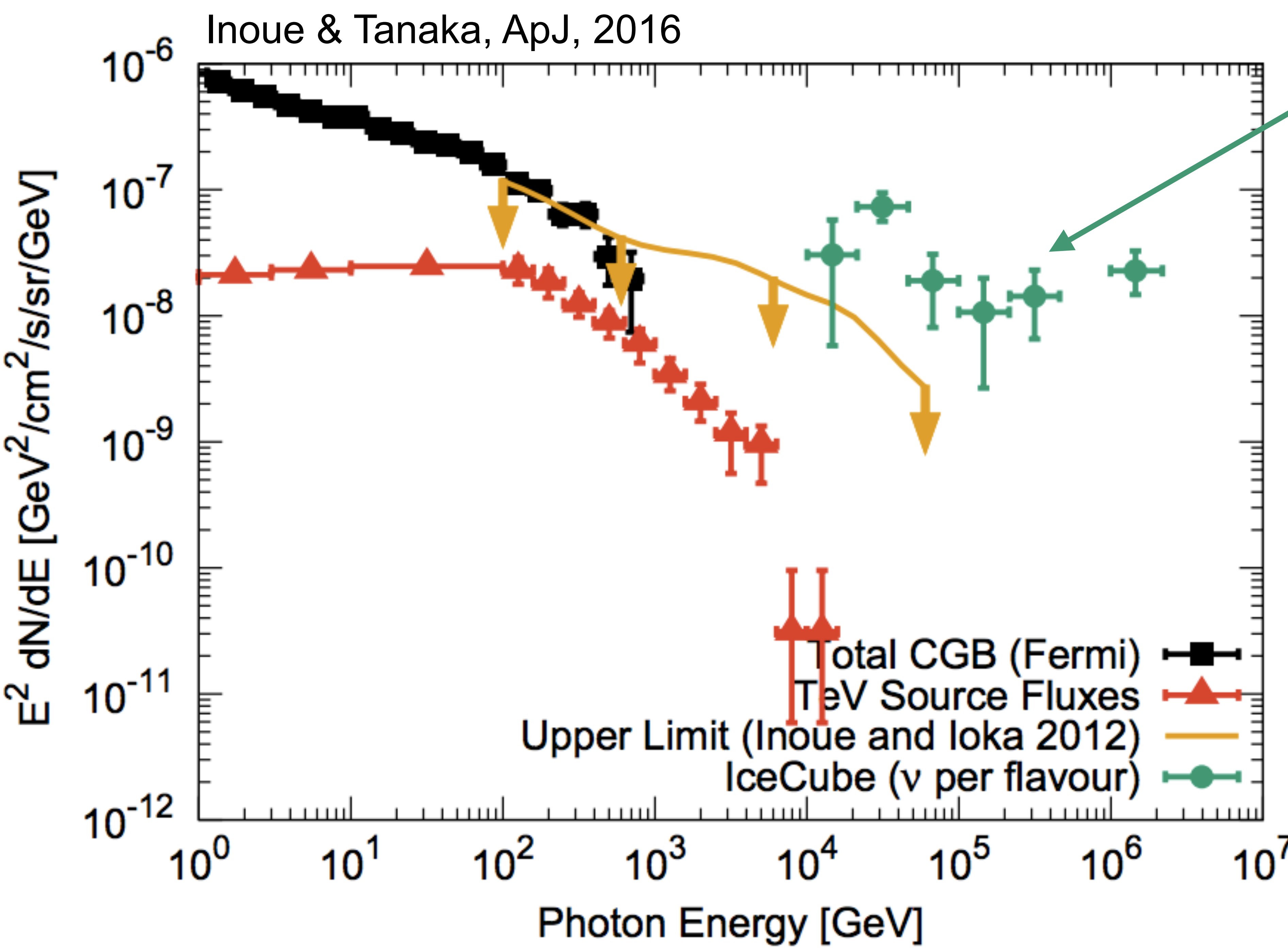
Inoue & Tanaka, ApJ, 2016



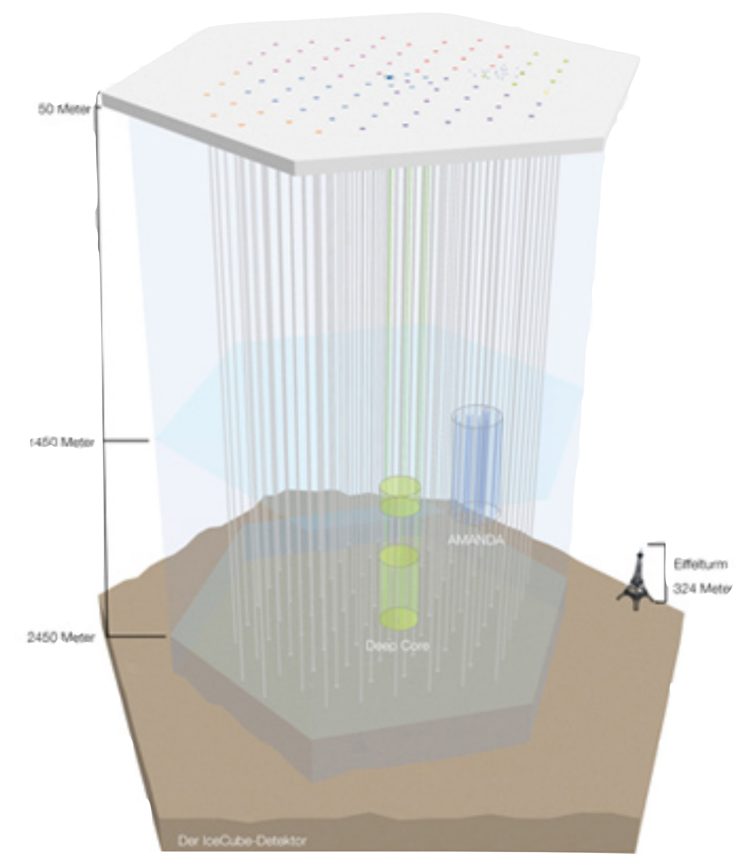
> **Lower limit** from counting TeV detected sources.

> **Upper limit** from requirement that the cascade emission is not higher than observed GeV background.

A different messenger of high-energy processes.



astrophysical neutrino flux



IceCube

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

> Produced only in **hadronic processes**.

Summary.

> **The IGRB spectrum** can be described over the full energy range 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.**
  - Confirmed by dedicated studies.

> **Uncertainty in diffuse foreground modeling** is the **largest systematic uncertainty** for the IGRB measurement.

> Pass 8 analysis is underway to address this, and yield other substantial improvements of this measurement.

> **Neutrinos** are a **powerful new messenger** to measure high-energy emission beyond few TeV