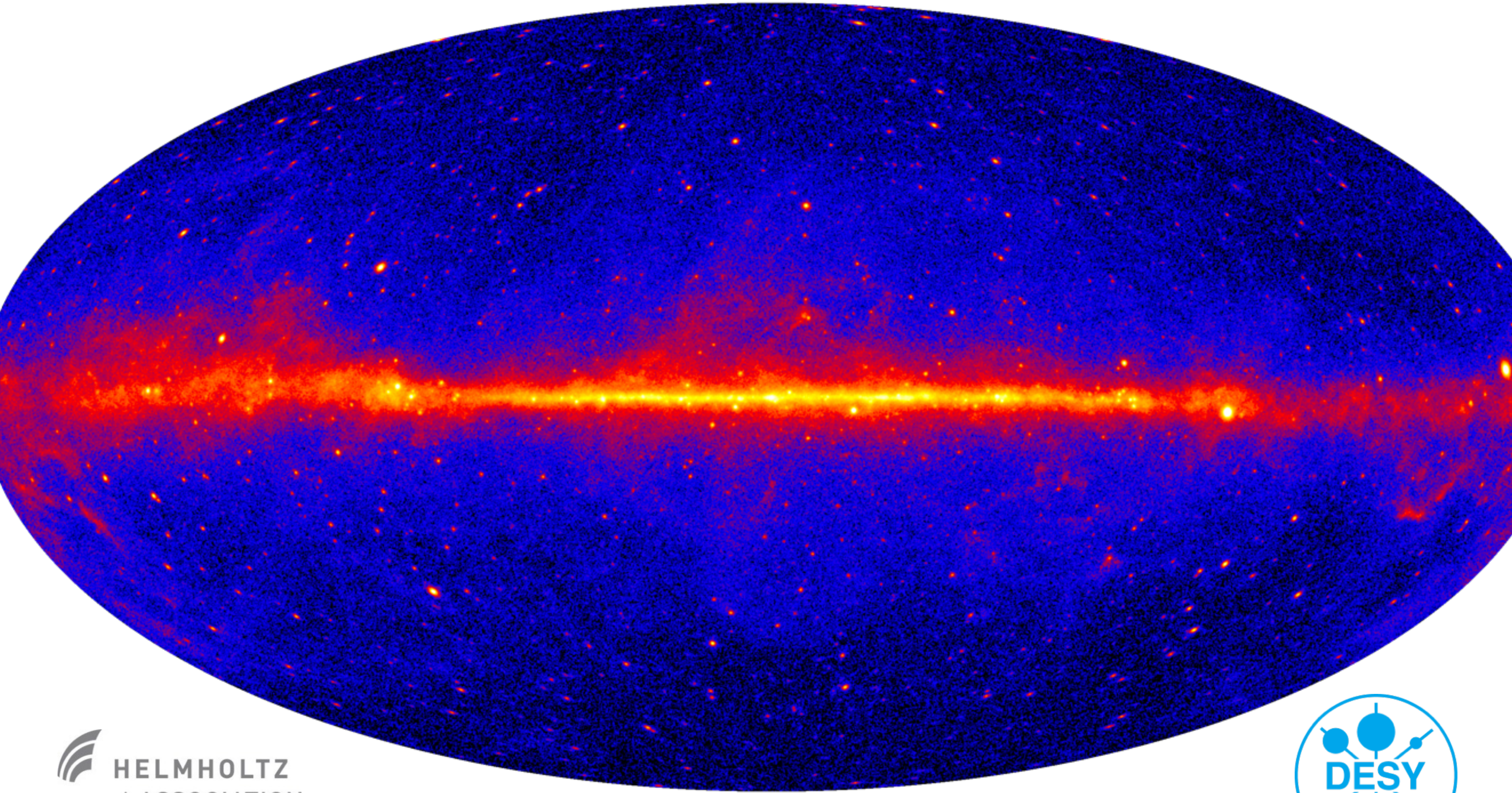
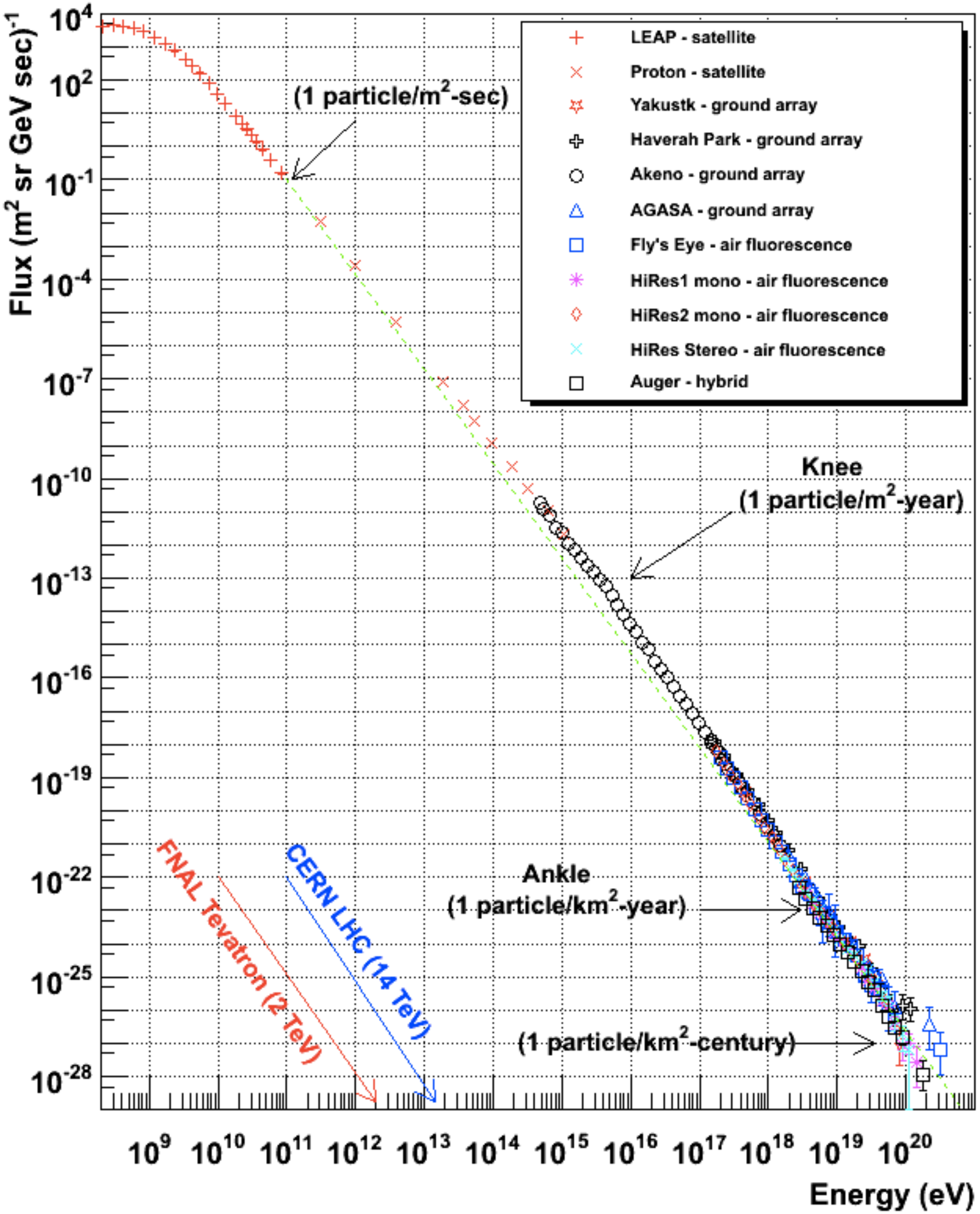
# Gamma-ray astronomy

## Lecture II: Sources, diffuse emission & the extragalactic background



# Cosmic rays




- We know that efficient particle accelerators must exist in the cosmos !
- Cosmic rays with energies > $10^{20}$ eV hit our atmosphere every day.
- What is the **connection** of the observed **non-thermal emission** to the **cosmic rays** at Earth ?
- What are **the sites** that can accelerate particles to > $10^{20}$ eV?
- Which **cosmic accelerators** dominate the CR flux in which energy range ?

# Cosmic rays are important!

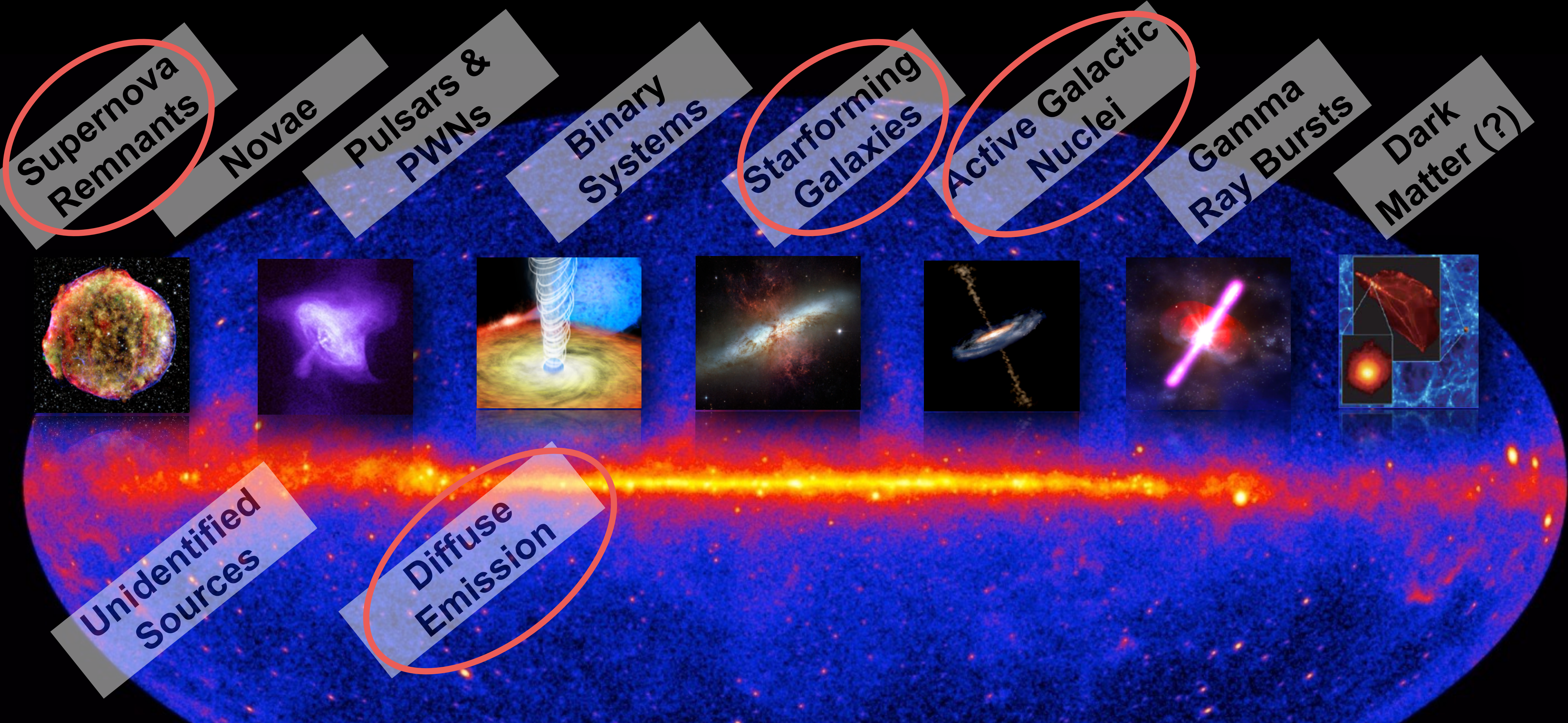
## Energy densities in the Milky Way

| | Energy density |
|---|---|
| **Cosmic rays** | **0.8 eV / cm$^3$** |
| CMB | 0.3 eV / cm$^3$ |
| Starlight | 0.5 eV / cm$^3$ |
| Magnetic fields | ~ 0.3 eV / cm$^3$ |
| Gas pressure | ~ 0.5 eV / cm$^3$ |


- Cosmic rays
  - **heat** the interstellar gas
  - **interact** with the magnetic fields
  - **influence** star formation

→ **They are important for Galaxy dynamics**

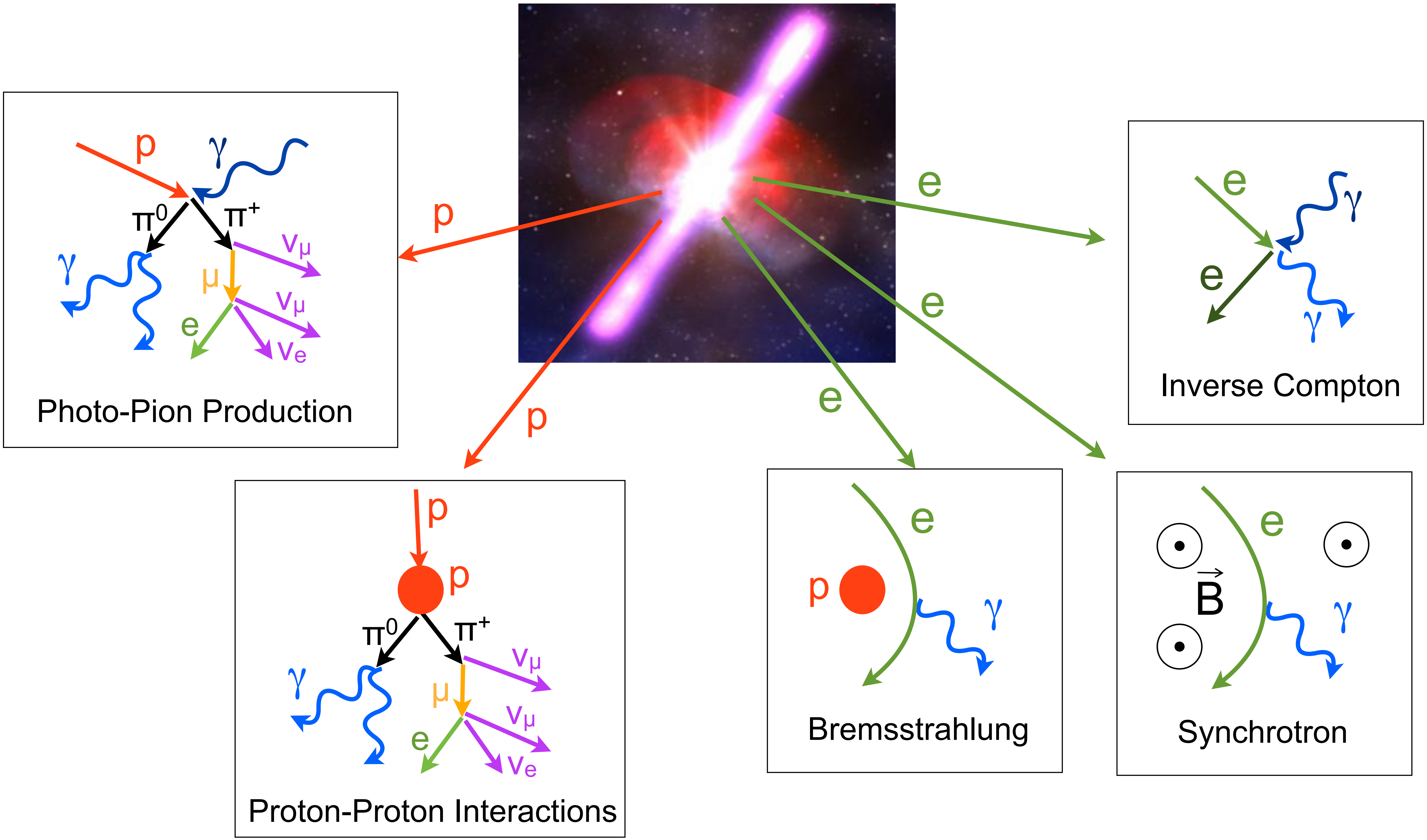
# The gamma-ray universe.



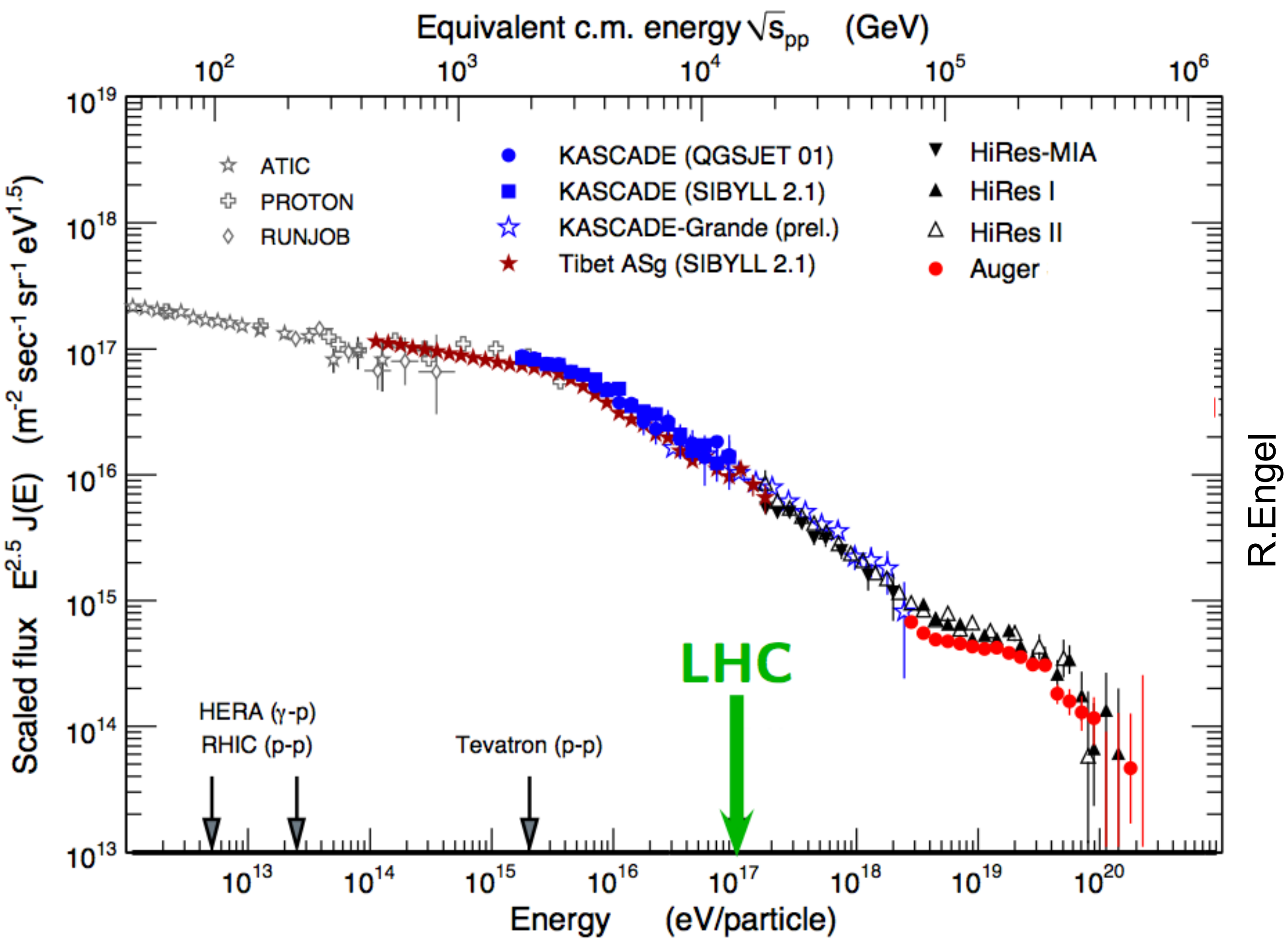

~3000 sources in the MeV-GeV range
~120 sources in the >100 GeV range

GeV/TeV radiation is ubiquitous to a wide range of astrophysical environments
non-thermal processes / cosmic particle accelerators

# Production mechanisms for gamma rays

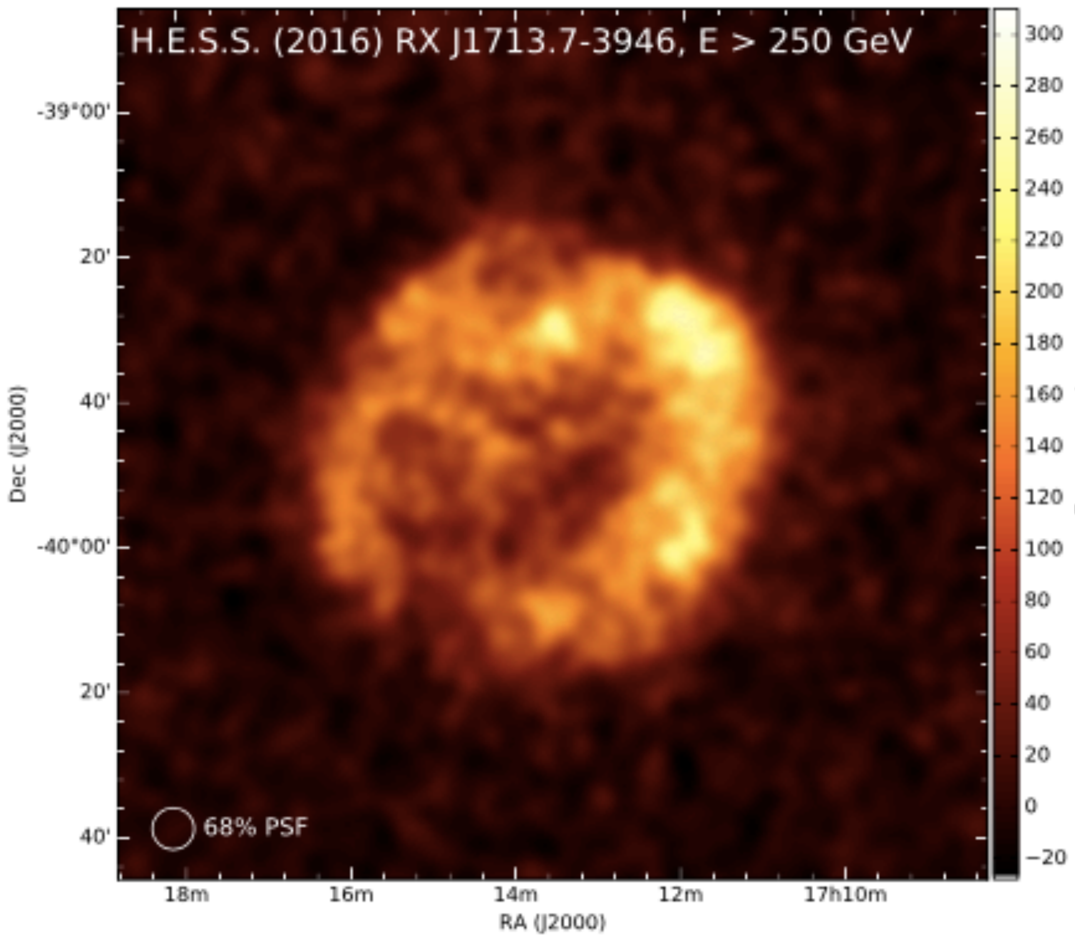


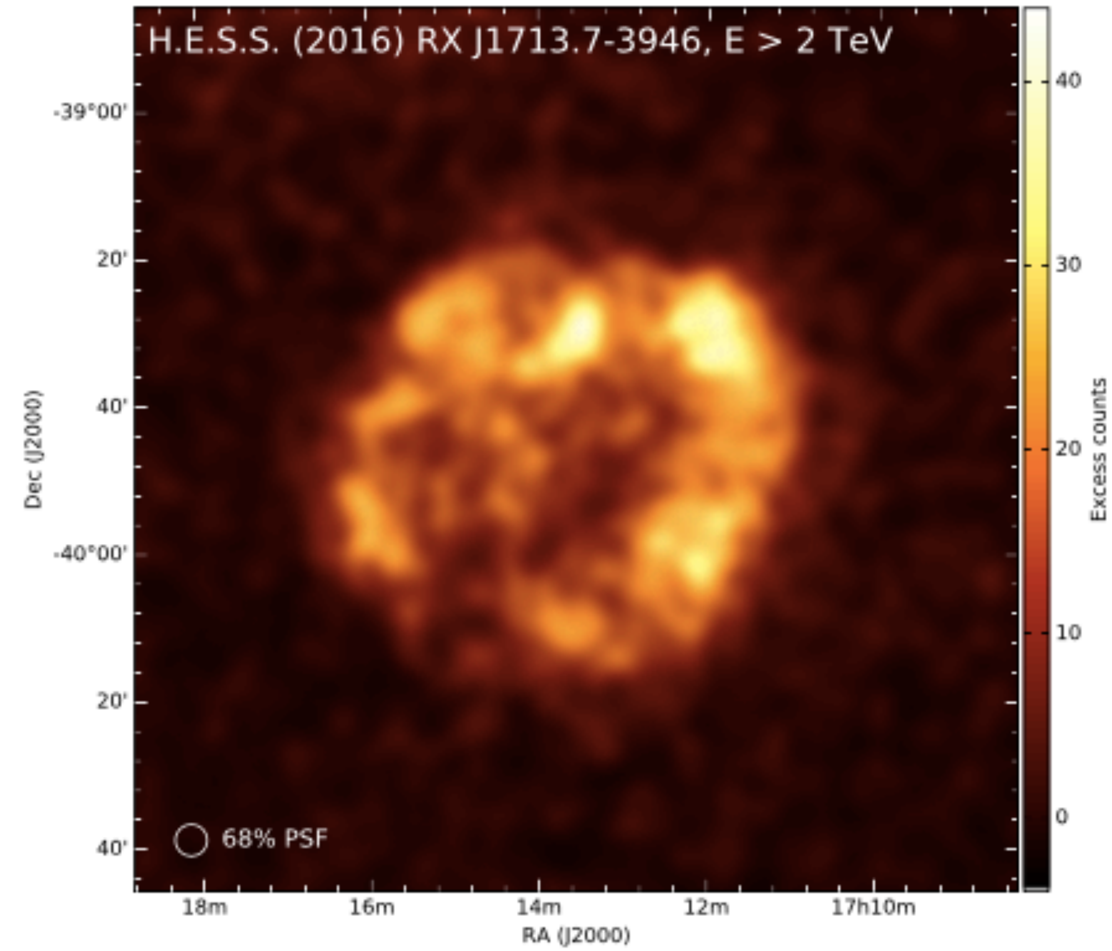
# Do Galactic CR originate from supernovae?

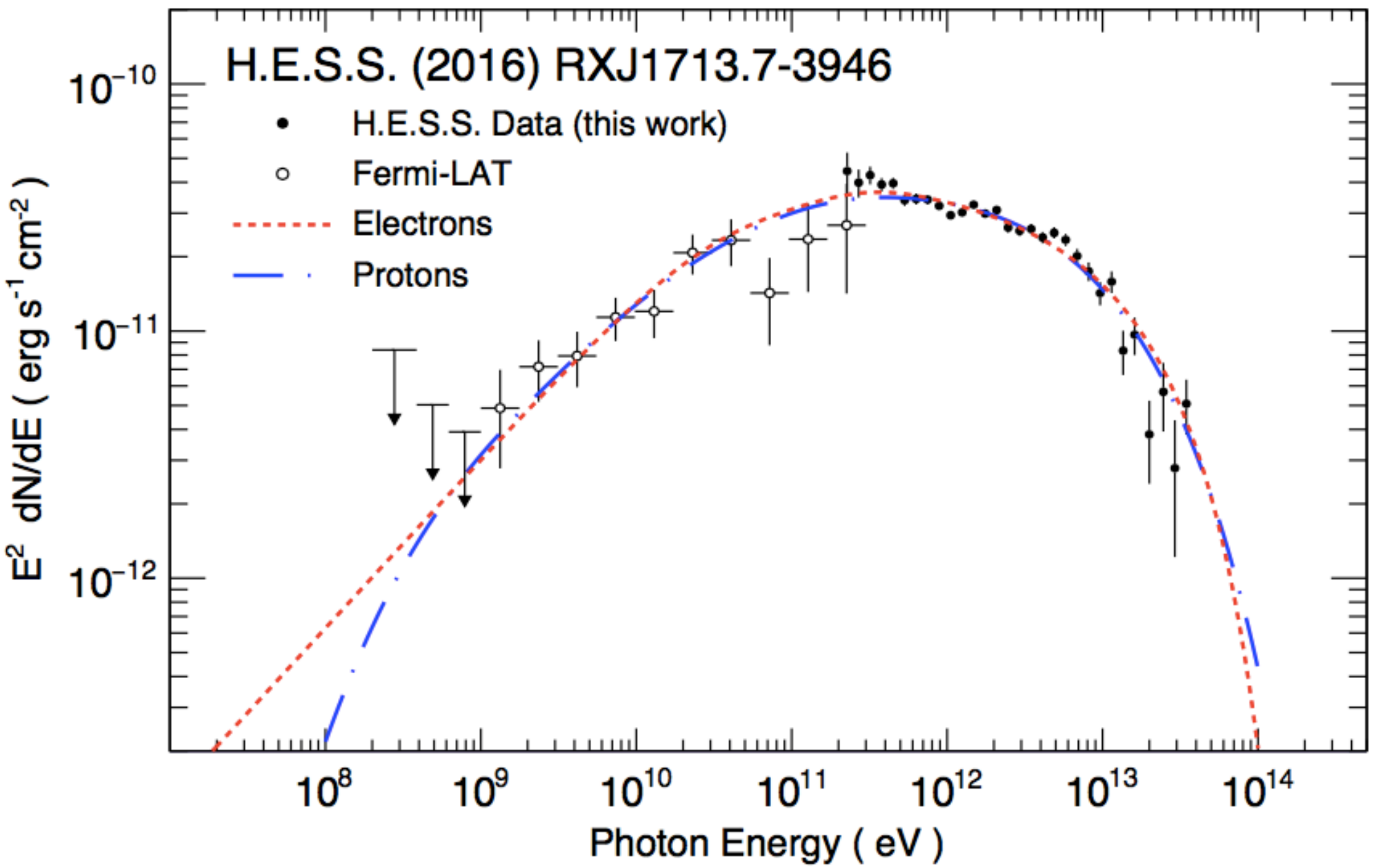



- CRs up to PeV energies are confined in the Galaxy.
- A small fraction of the explosion energy of SNe is enough to produce the observed CRs
- Nuclei can reach PeV energies by the Fermi shock acceleration mechanism
  - if magnetic field is substantially higher in SNR than in the interstellar medium
- Evidence is needed that nuclei are accelerated in the supernova remnants.

# The young SNR RXJ 1713.7-3946.

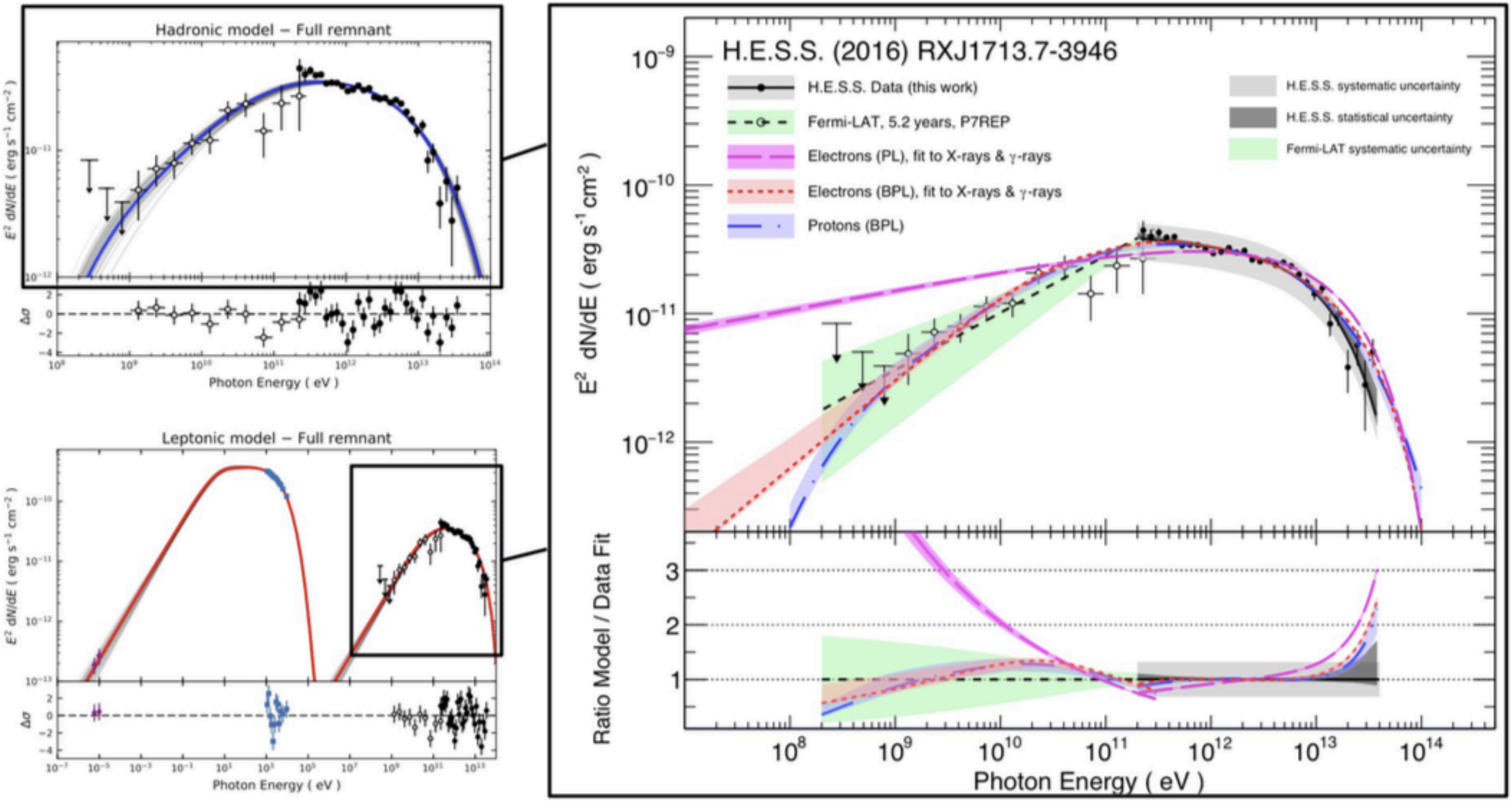


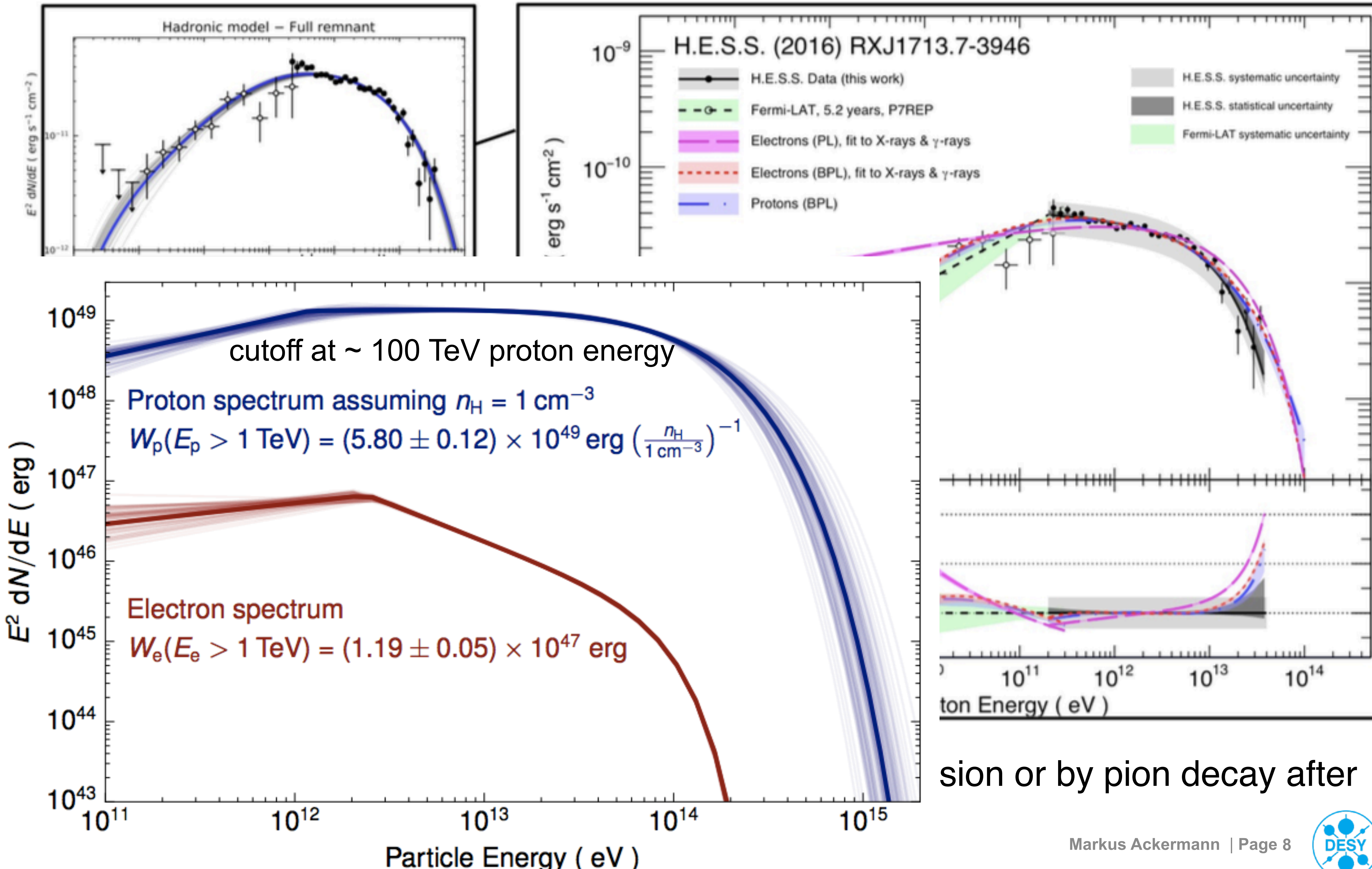

- Age: 1600 years
- Distance: 1-2 kpc
- Brightest SNR in TeV gamma rays
- Core collapse SN
- Spectral distribution points to leptonic ori-gin of gamma rays.

# Leptonic vs. hadronic gamma-ray emission



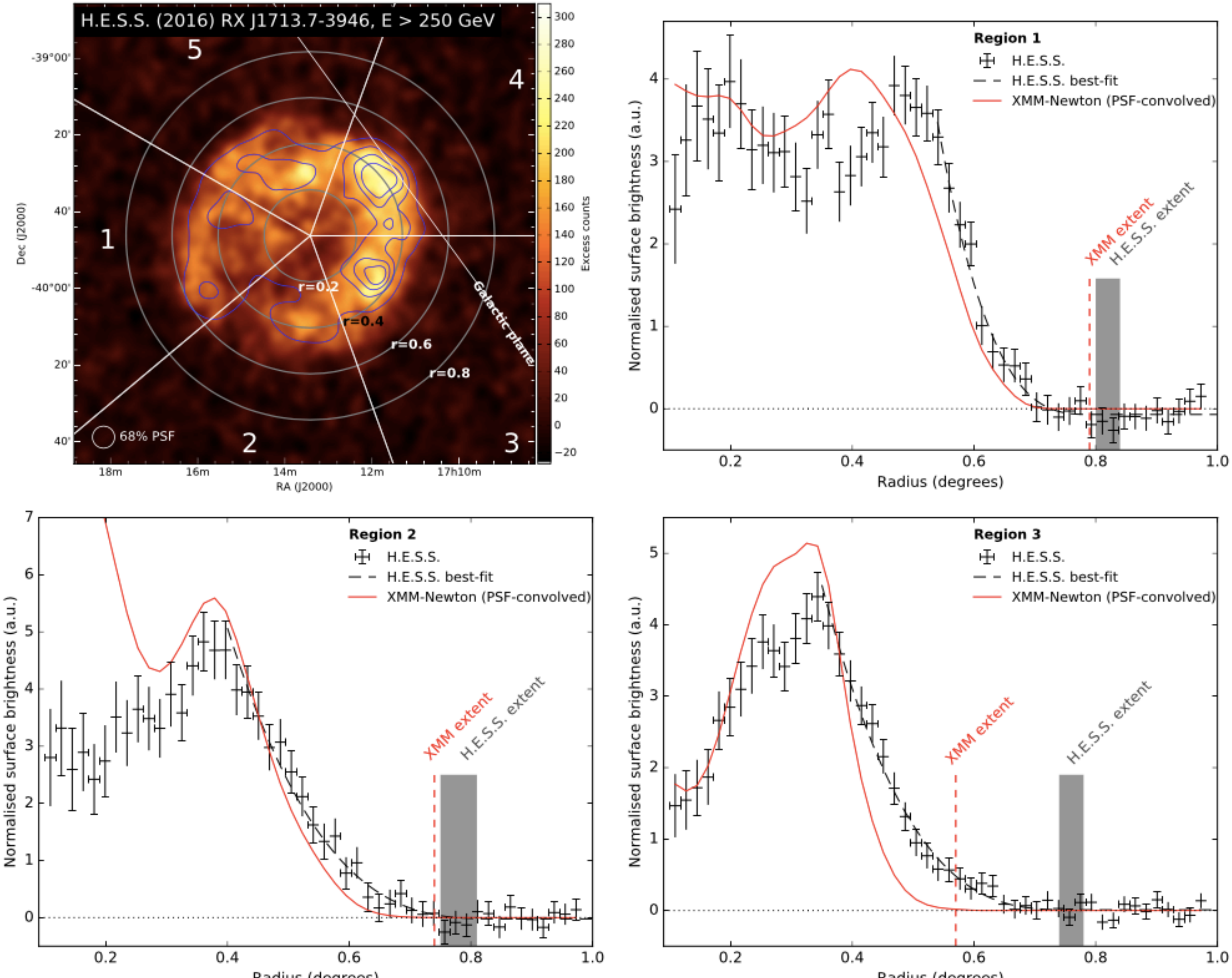

> Are the gamma-rays produced by inverse Compton emission or by pion decay after proton-proton collisions?

# Leptonic vs. hadronic gamma-ray emission




sion or by pion decay after

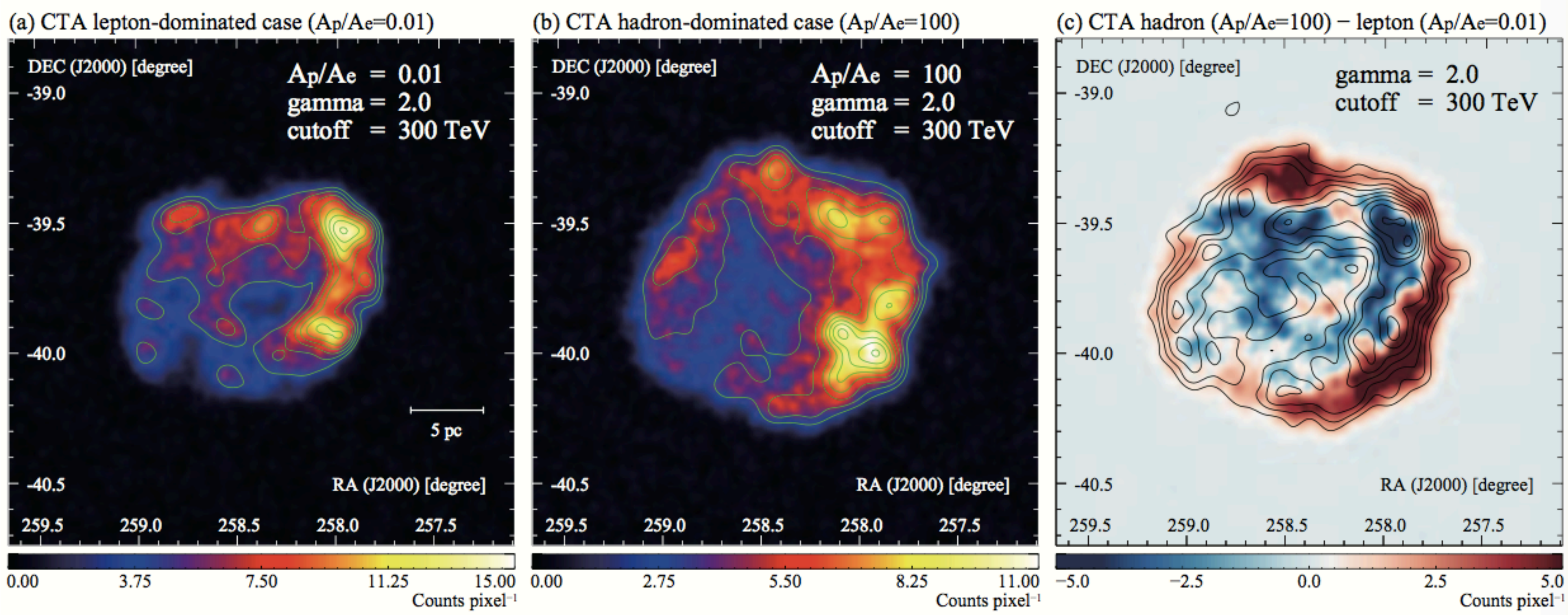
# Detailed morphologies




> Gamma-ray emission does not exactly match the x-ray intensities.

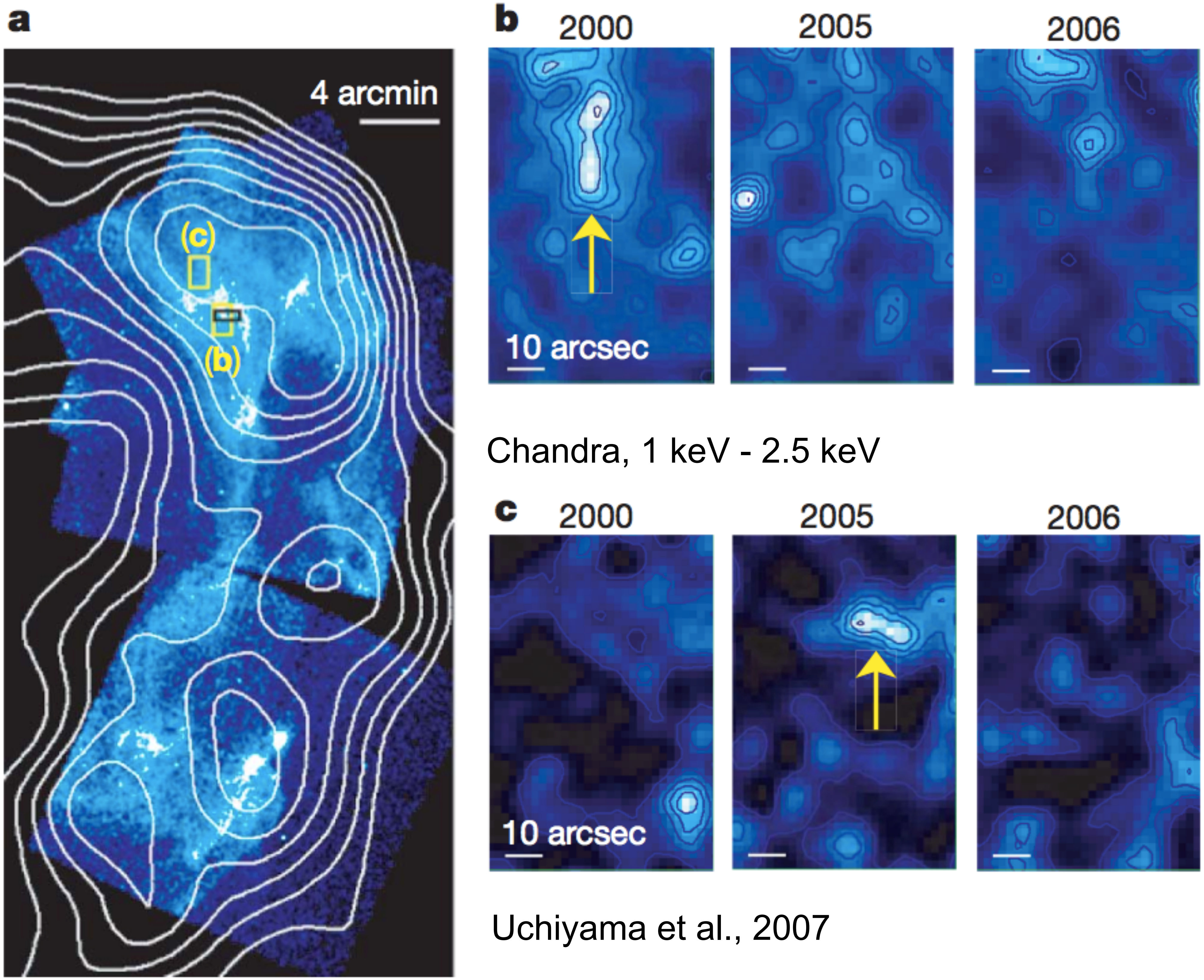
# Future deep morphological studies by CTA

CTA collaboration, arXiv:1704.04136




> Morphology observed by CTA could allow to distinguish hadronic vs. leptonic scenarios

# Variability of x-ray filaments in RXJ 1713.7-3946.

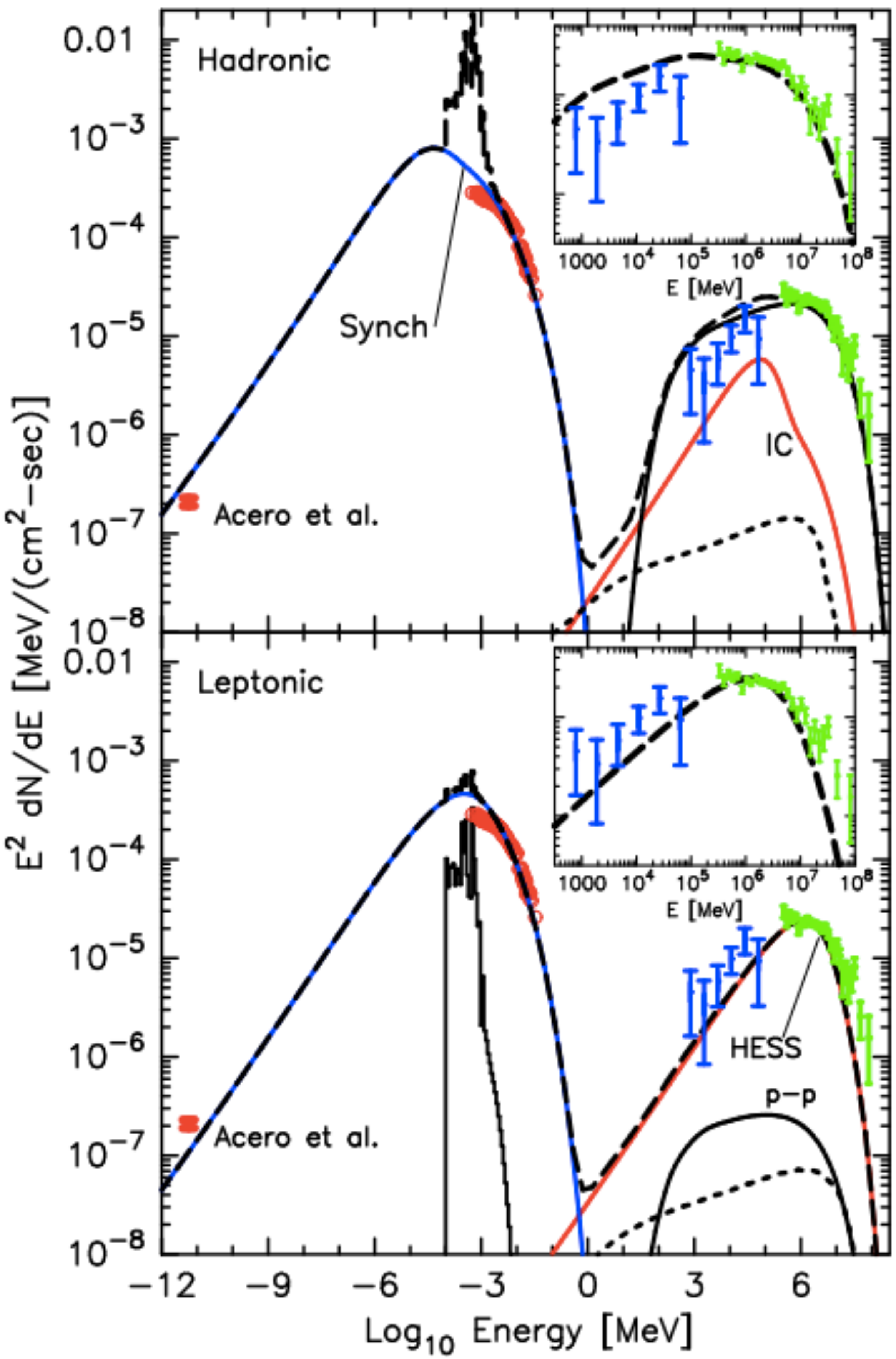



Chandra, 1 keV - 2.5 keV

Uchiyama et al., 2007

- Fast variability of x-ray filaments on few year time scales
- Evidence for mG magnetic fields
- » ~ 6μG magnetic fields in interstellar medium
- High magnetic fields could accelerate protons to PeV energies

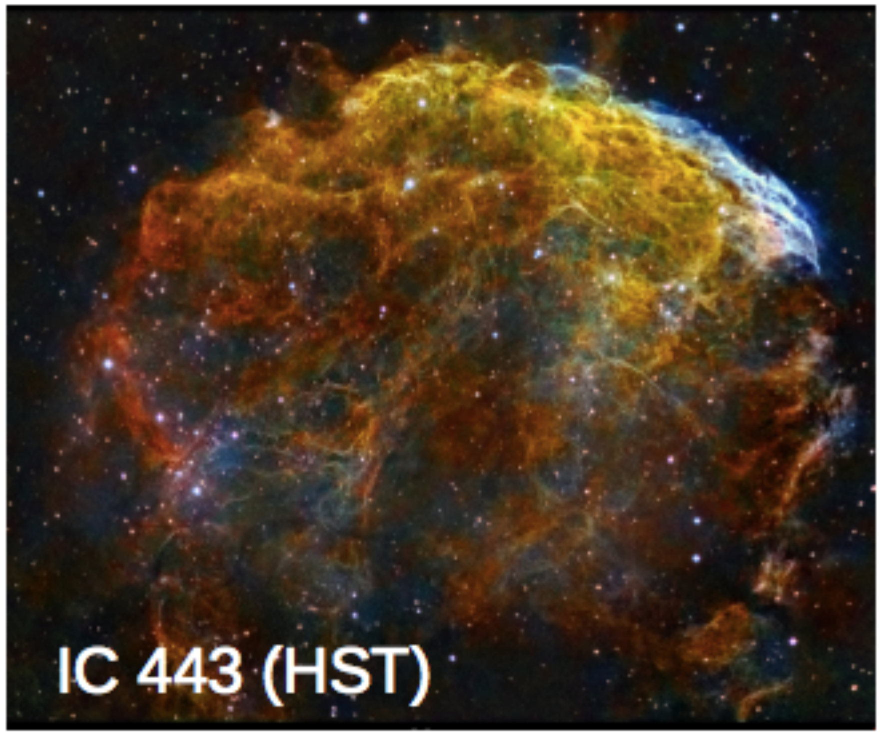
# (Missing) thermal x-ray line emission.

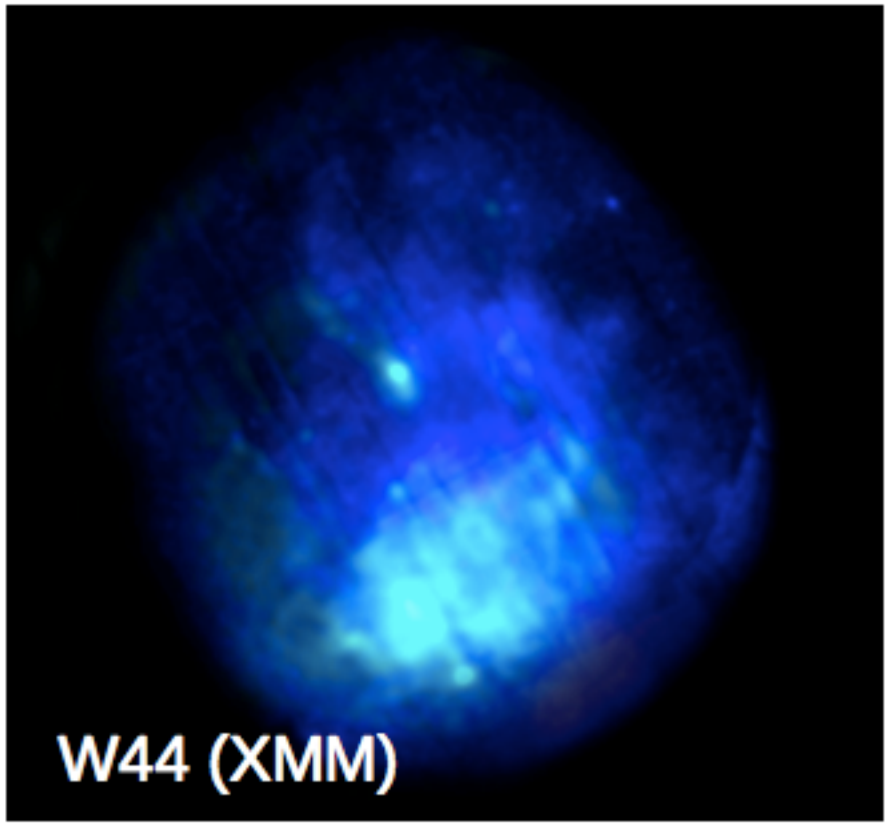



- > Electrons are heated by collisions with shock heated protons/nucleons
- > Production of intense x-ray line emission
  - for ambient proton/nucleon densities that are needed to explain gamma-ray emission.
- > Not observed by Suzaku satellite.
- > Models with IC dominated gamma-ray emission compatible with x-ray observations.

Ellison et al. 2010

# Observations of mid-age supernova remnants.



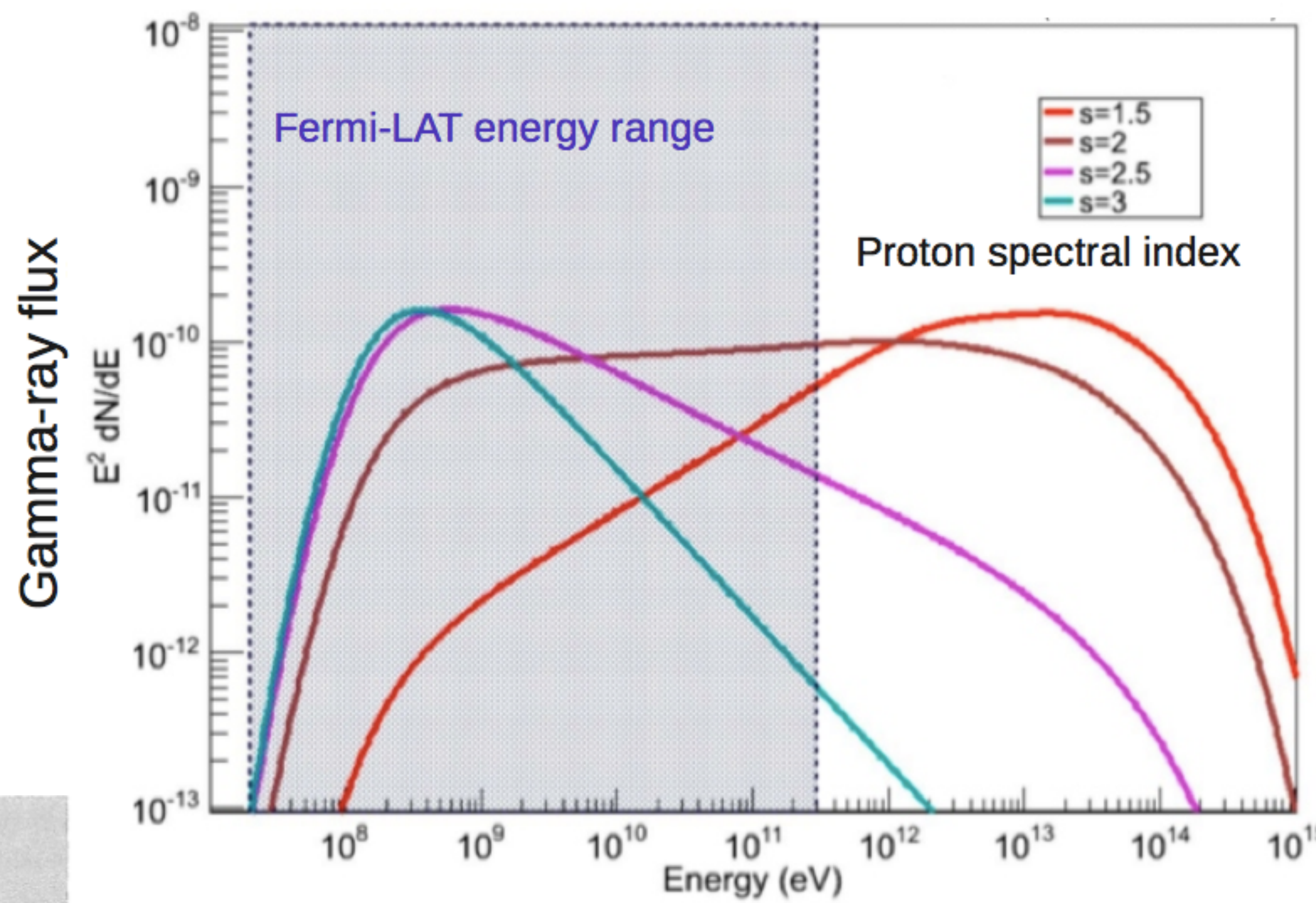

- Age: ~ 10000 - 20000 years
- SNRs interacting with molecular clouds in their environment.
- Brightest SNRs at GeV energies.
- Weak sources / not observed in TeV energies

# The pion decay cutoff.

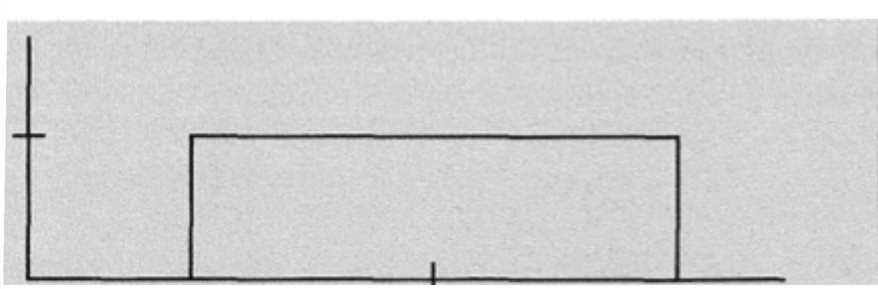
- Gamma rays from protons are dominantly produced via $\pi^0 \longrightarrow \gamma\,\gamma$.
- Steep spectral cutoff around ~ 70 MeV (1/2 of pion rest mass).
- No astrophysics involved, just particle decay kinematics.
- Independent of modeling

$\longrightarrow$ Smoking gun for hadronic acceleration.

$$\gamma \longleftarrow \pi_0 \longrightarrow \gamma$$




Stecker, 1970

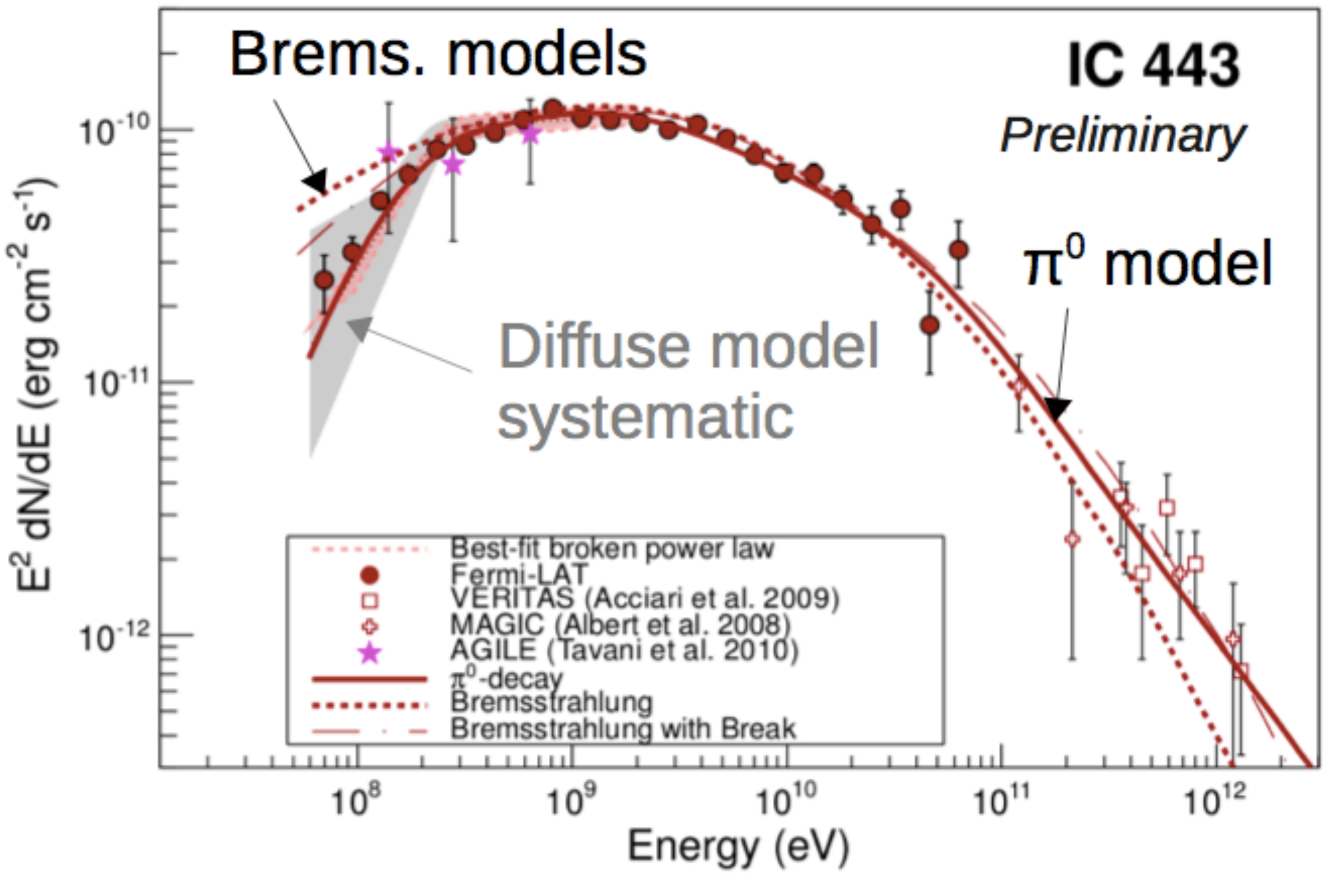


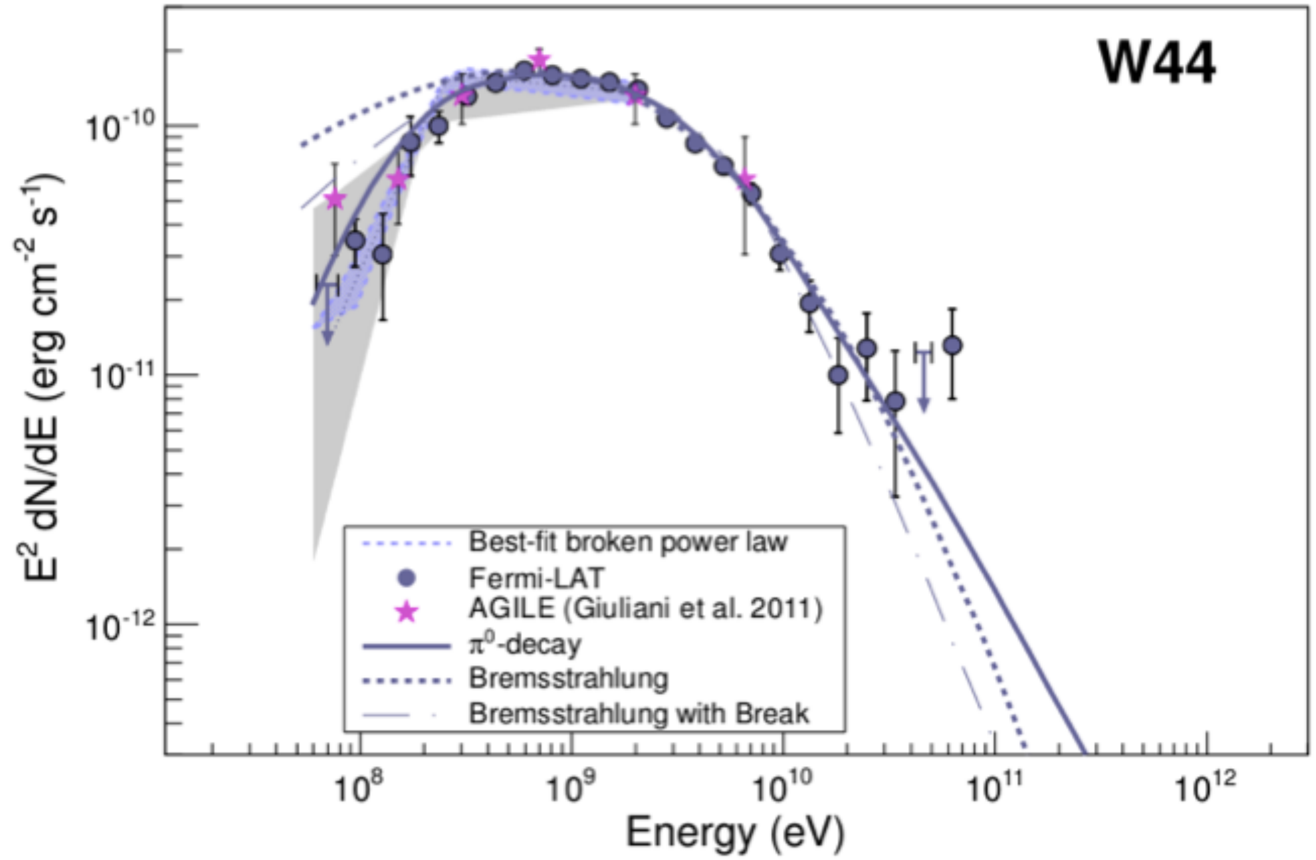
$$f(E_\gamma; E_\gamma^{(c)}) = 1/2\gamma_c\beta_c E_\gamma^{(c)},$$

$$\gamma_c E_\gamma^{(c)}(1-\beta_c) \leqslant E_\gamma \leqslant \gamma_c E_\gamma^{(c)}(1+\beta_c).$$

form of the energy distribution function for a particle formed isotropically from two-body decay.

# Spectrum of IC 443 and W44.




> Fermi LAT analysis extended to 60 MeV using > 4 years of data and new improved event classification.

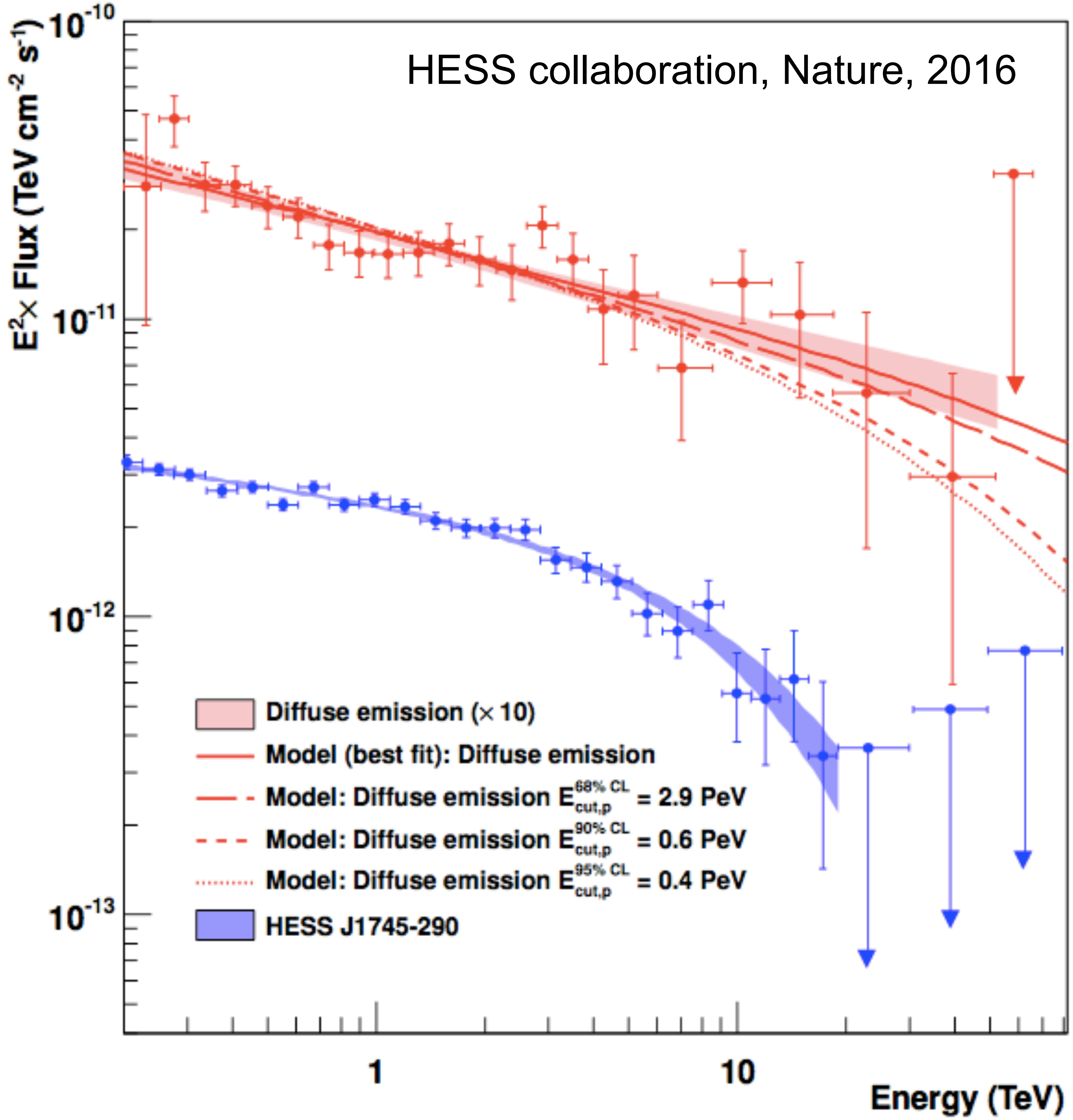
> Steep spectral cutoff observed for both IC 443 and W44

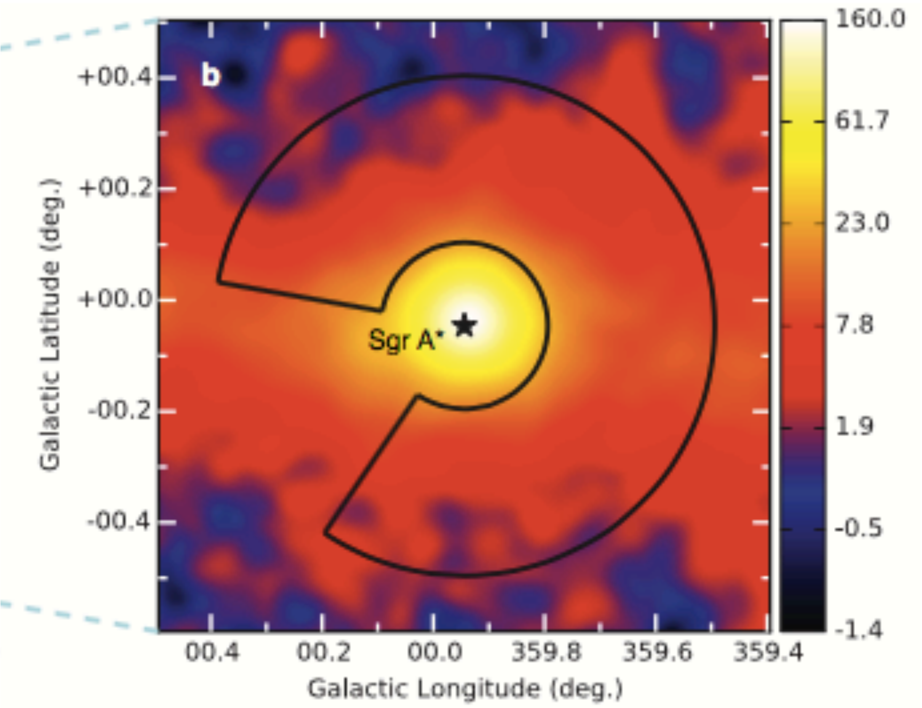
> Not compatible with Bremsstrahlung dominated models.

- Outside systematics band, even with artificial break introduced in underlying electron spectrum

> Gamma-ray emission from IC 443 and W44 is very likely from $\pi^0 \longrightarrow \gamma\gamma$

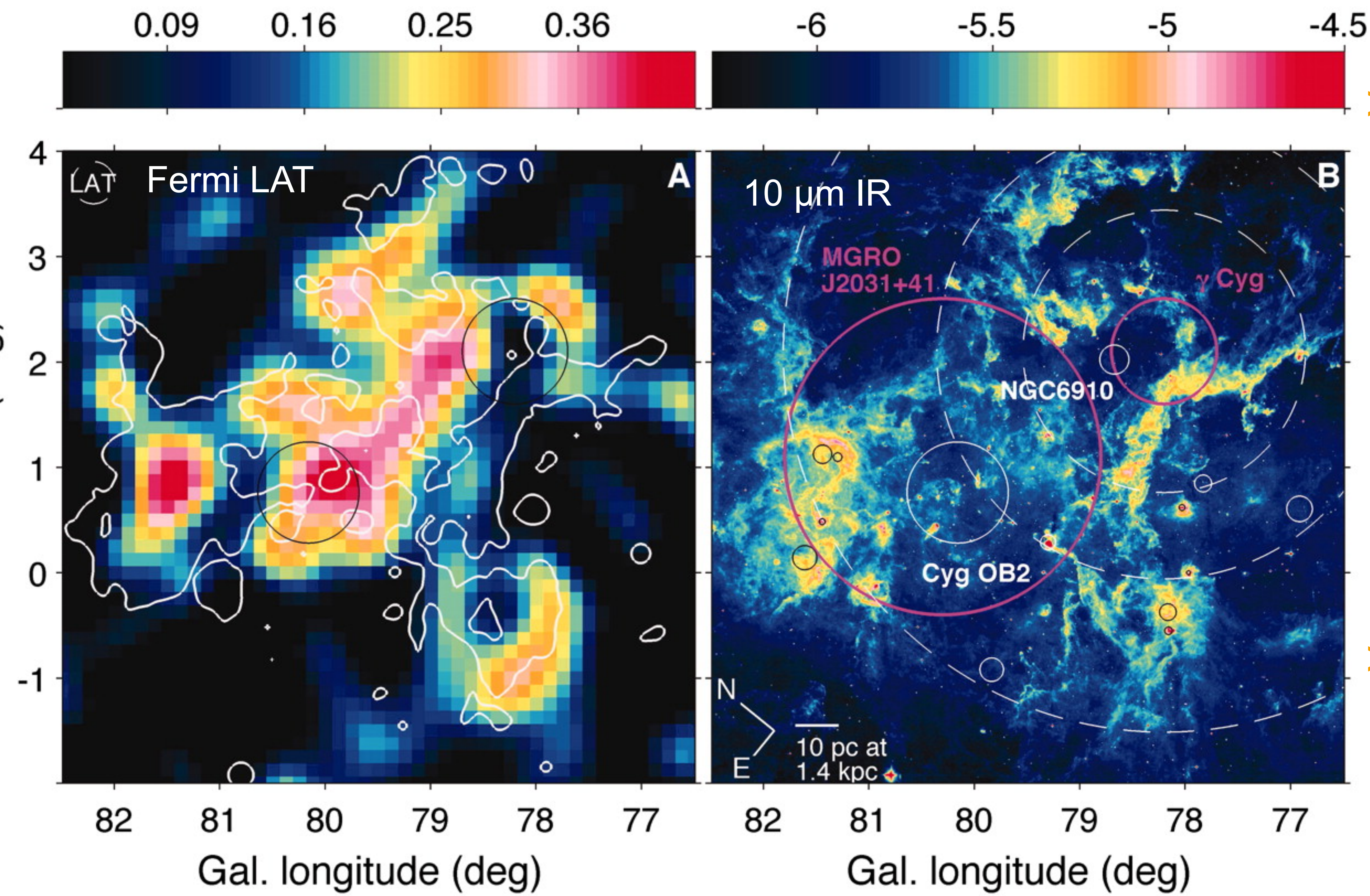
# A Pevatron in the Galactic Center




- Diffuse emission around Galactic center source does not show a high-energy cutoff
- Cutoff > 0.4 PeV in proton population at 95% CL

# Cygnus Cocoon



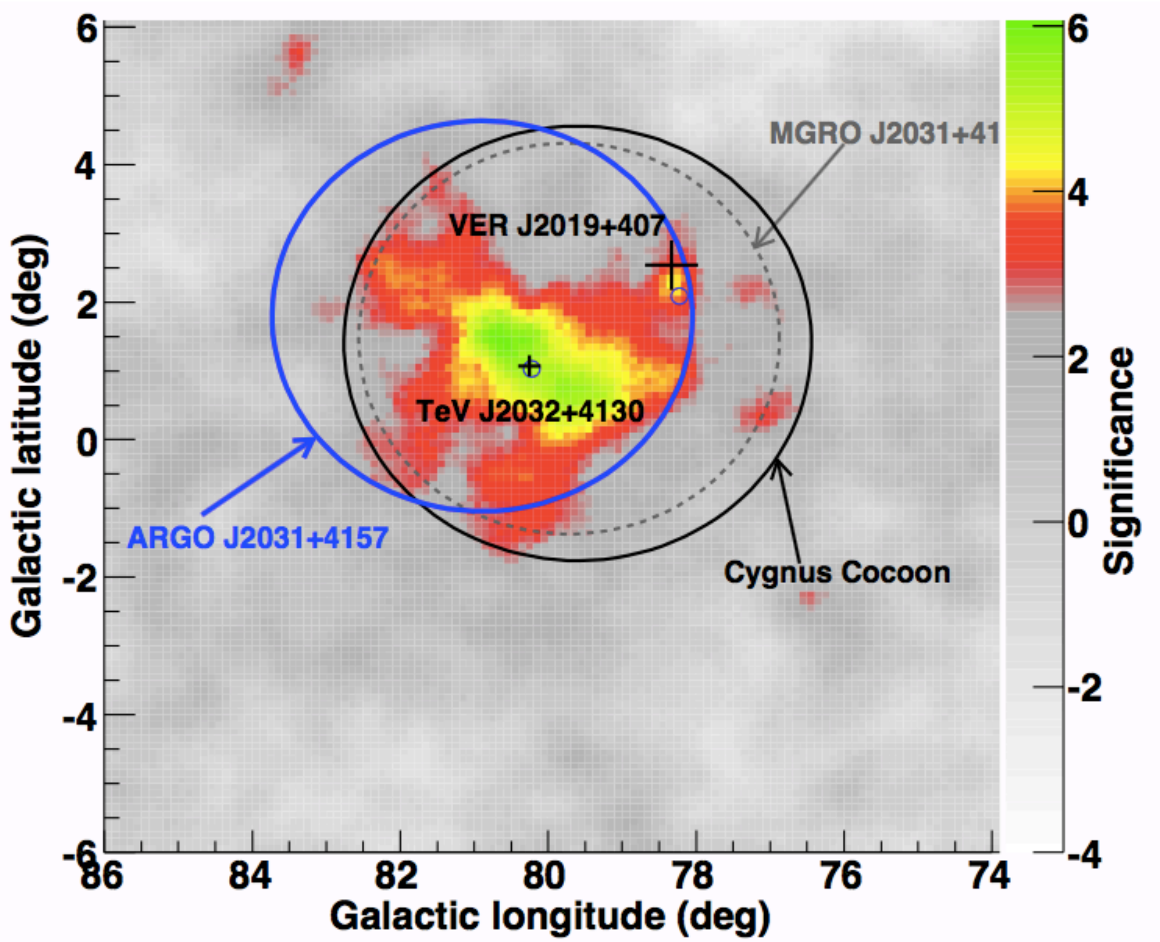

- > Spatially extended gamma-ray emission filling the voids between the ionized gas clouds
- > Evidence for a "cocoon" of freshly accelerated cosmic rays

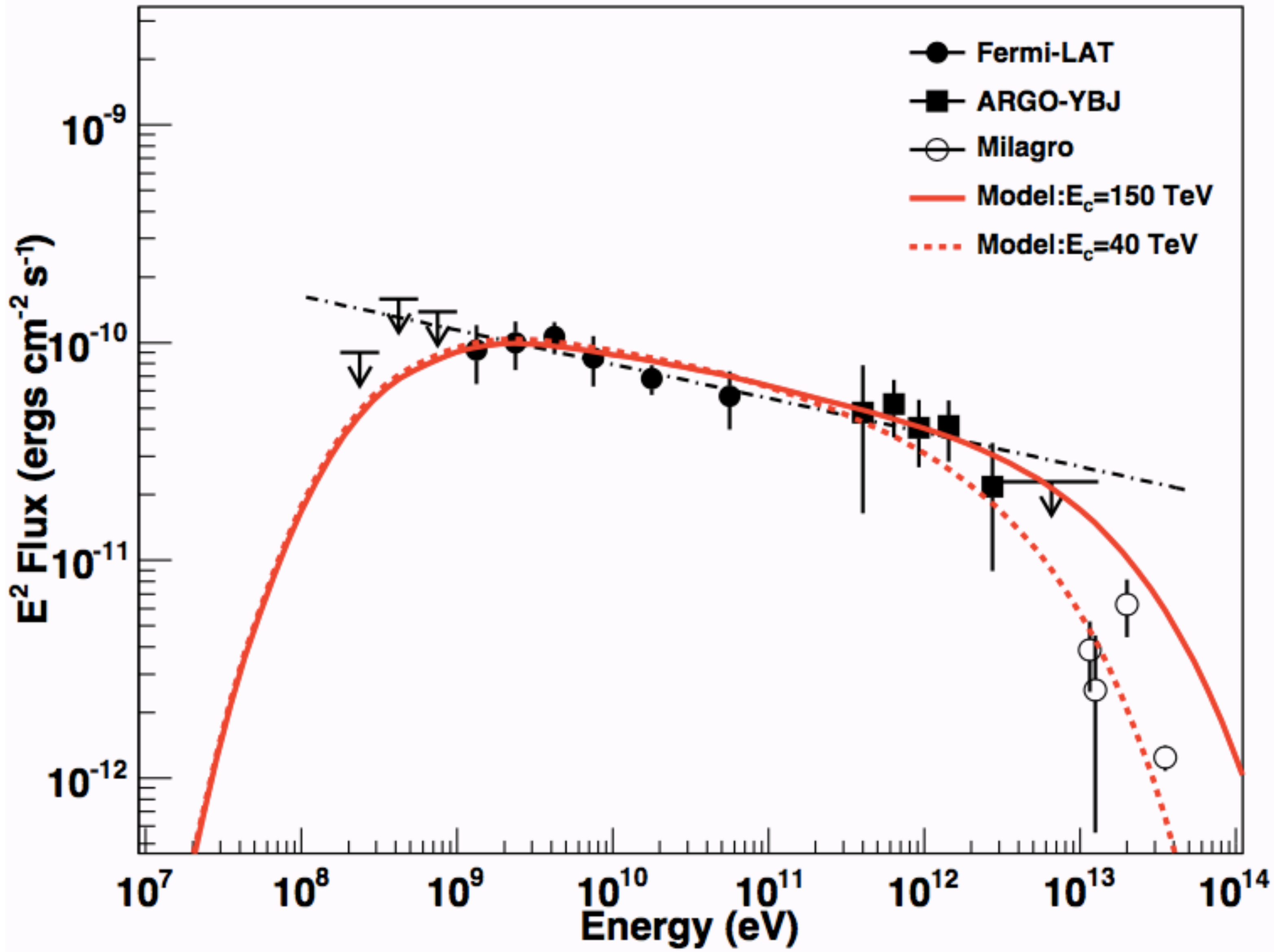
Cygnus X: intense star-formation region at about 1.4 kpc distance
~ $10^7$ solar masses in hydrogen gas

$\gamma$ Cygni: SNR observed in gamma rays

Cygnus OB2: cluster of massive stars

# Cygnus Cocoon




ARGO-YBJ

- Hard spectrum up to ~ 10 TeV
- If Milagro data points refer to the same source, high-energy cutoff present

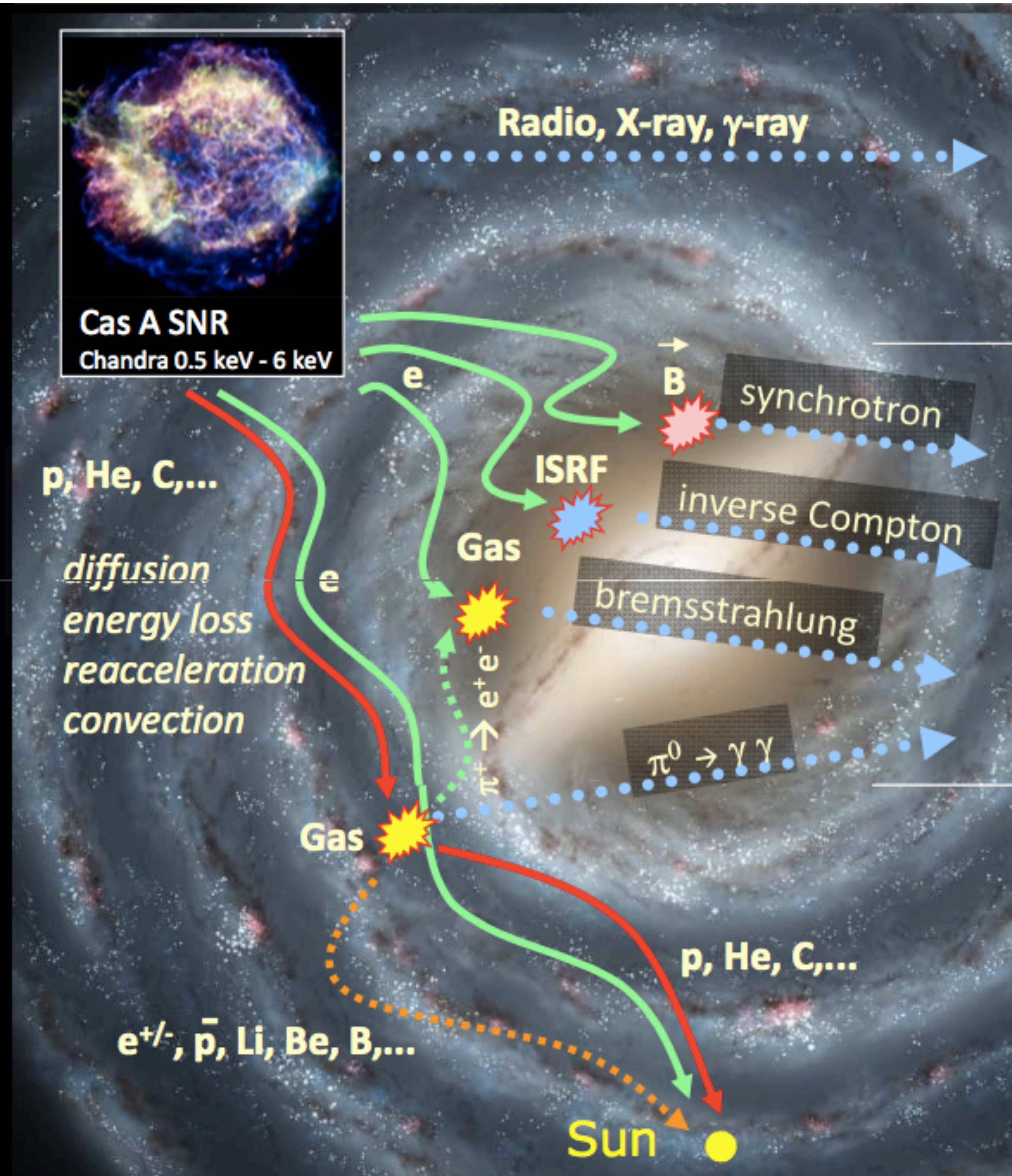
# Summary: The origin of the cosmic rays in the Galaxy

> Mid-aged supernova remnant seem to clearly accelerate cosmic rays
  - But they have spectral breaks / cutoffs in the GeV range

> It is not clear if we see leptonic or hadronic emission from young supernova remnants
  - Spectra show clear cutoff around 10 TeV
  - If emission is hadronic, that implies a maximum energy of ~ 100 TeV for protons

> The galactic center is so far the most promising place for a “PeVatron”

# Studying the propagation of cosmic rays with photons

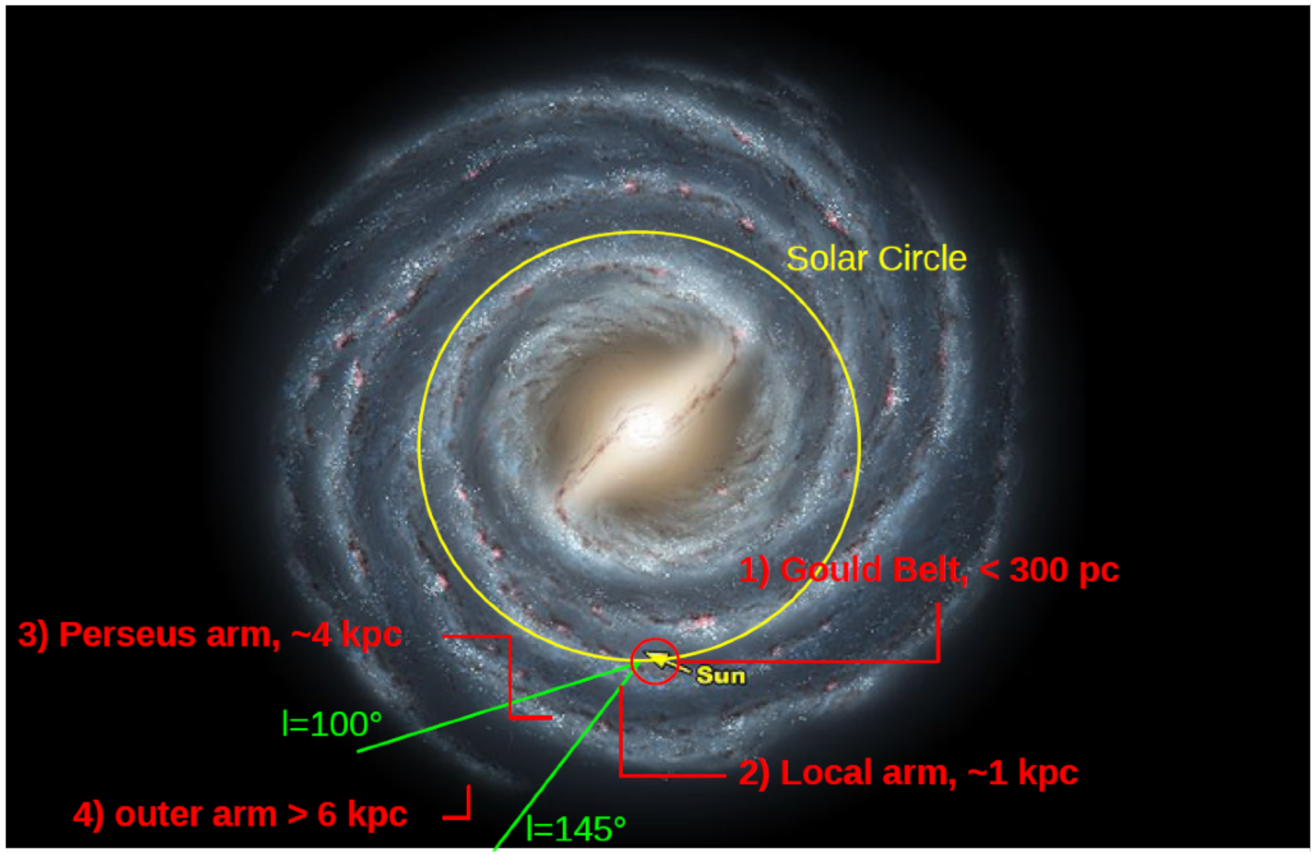


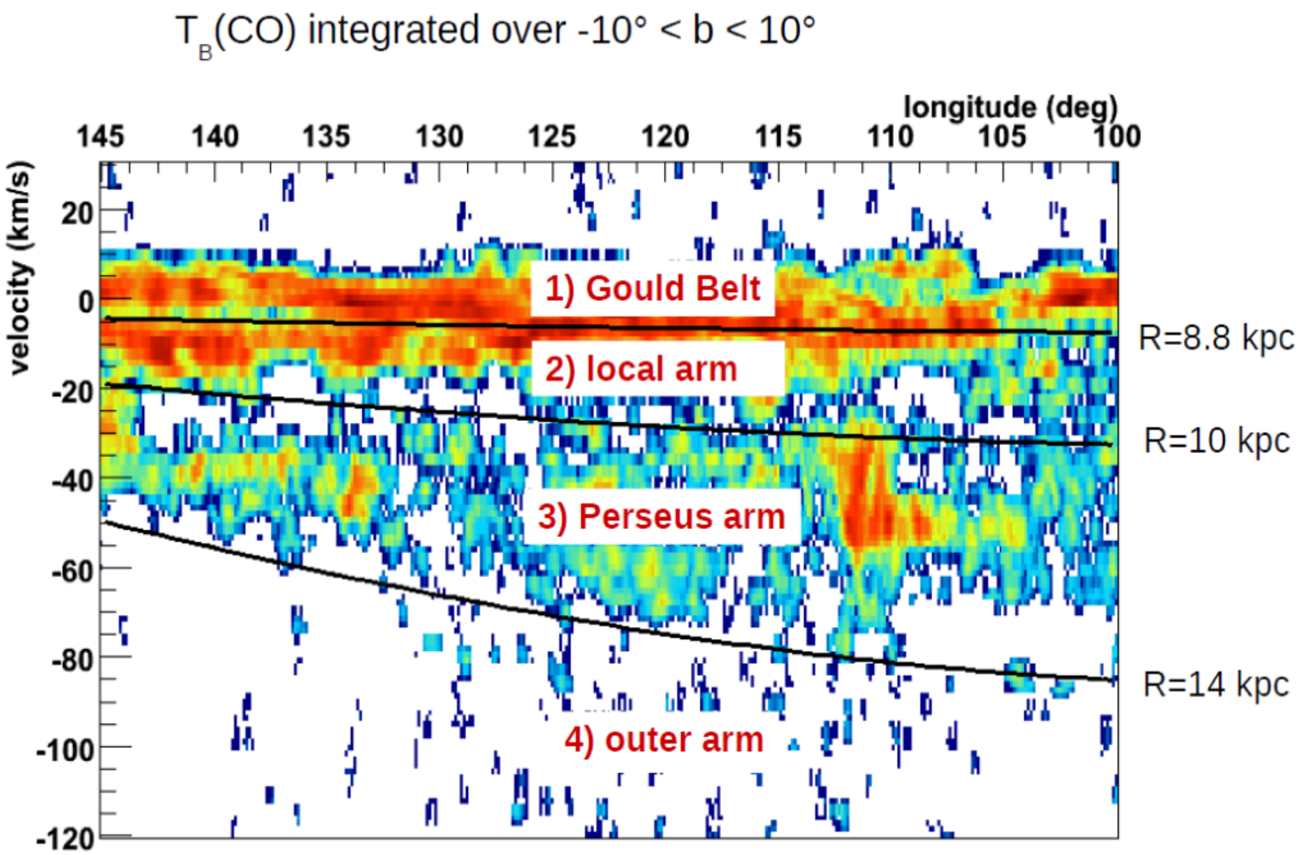

**direct photons:**
Sources of non-thermal emission in radio, X-ray and γ rays

**diffuse photons:**
Probe CR Interactions with
magnetic field → radio
radiation field → γ-rays (MeV-TeV)
interstellar gas → γ-rays (MeV-TeV)

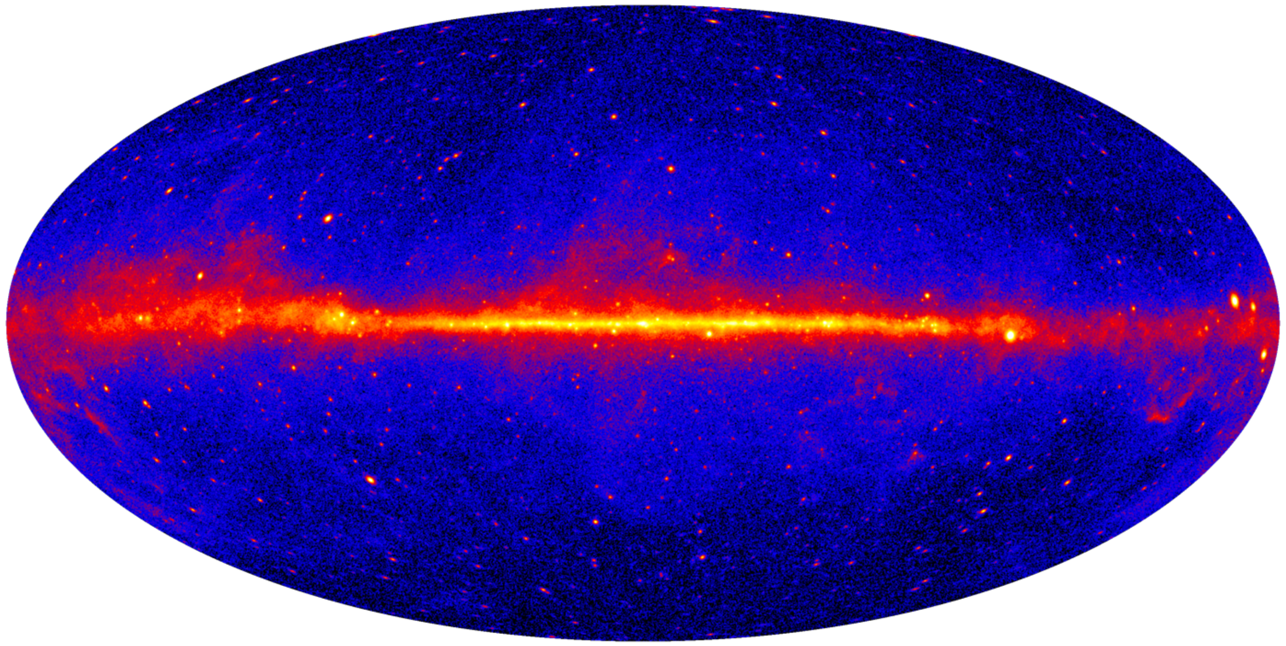
**local CR observations:**
PAMELA, ACE, BESS, ATIC, etc.
- CR composition
- CR primary & secondary intensities
- modulated by solar potential

# The propagation of CRs in the Galaxy.

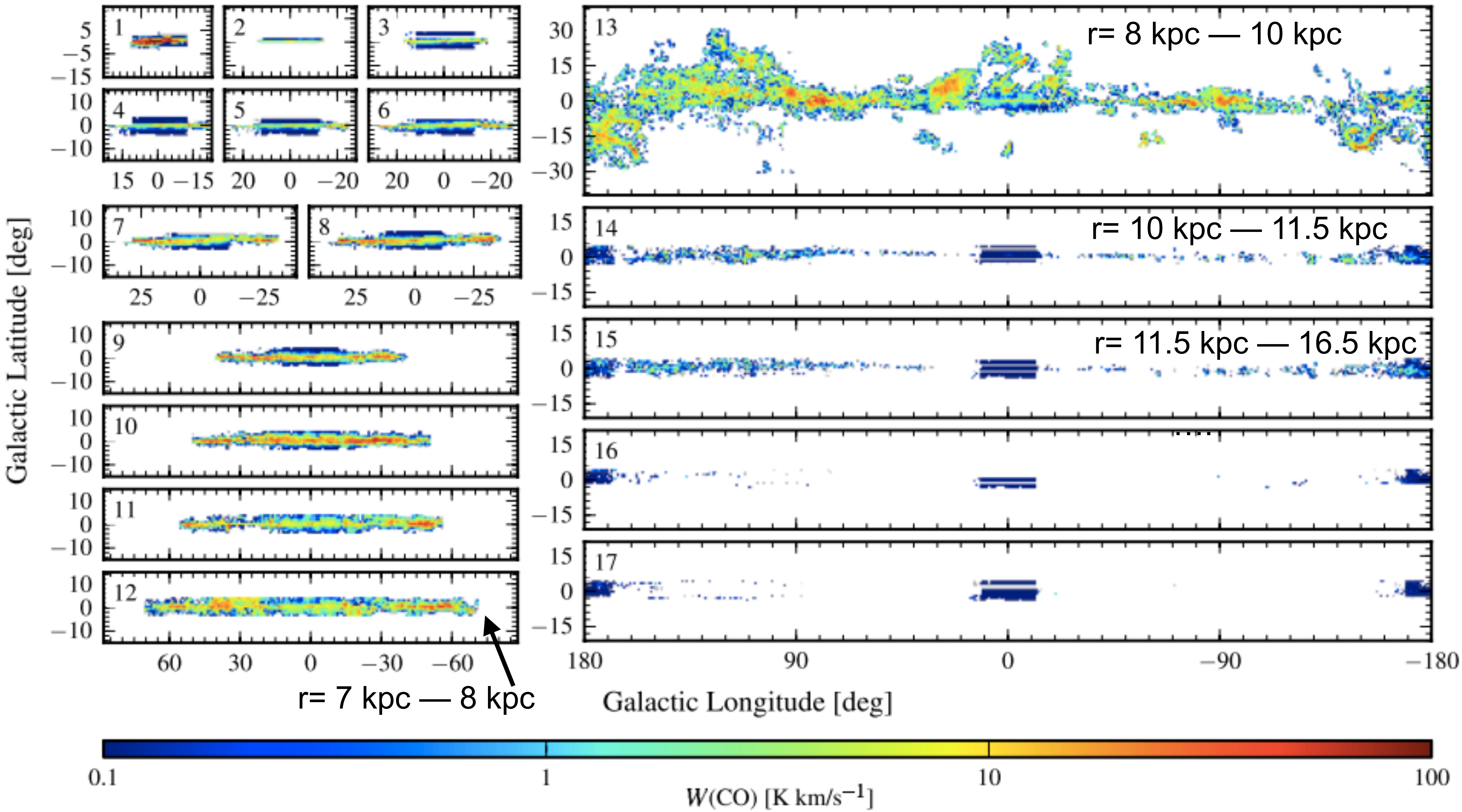



- Cosmic rays interact with interstellar gas while propagating in the Galaxy.
- Gas clouds shine in gamma rays.
- Doppler shift in radio emission from gas clouds allows to make a 3D map of the interstellar gas in the Galaxy.

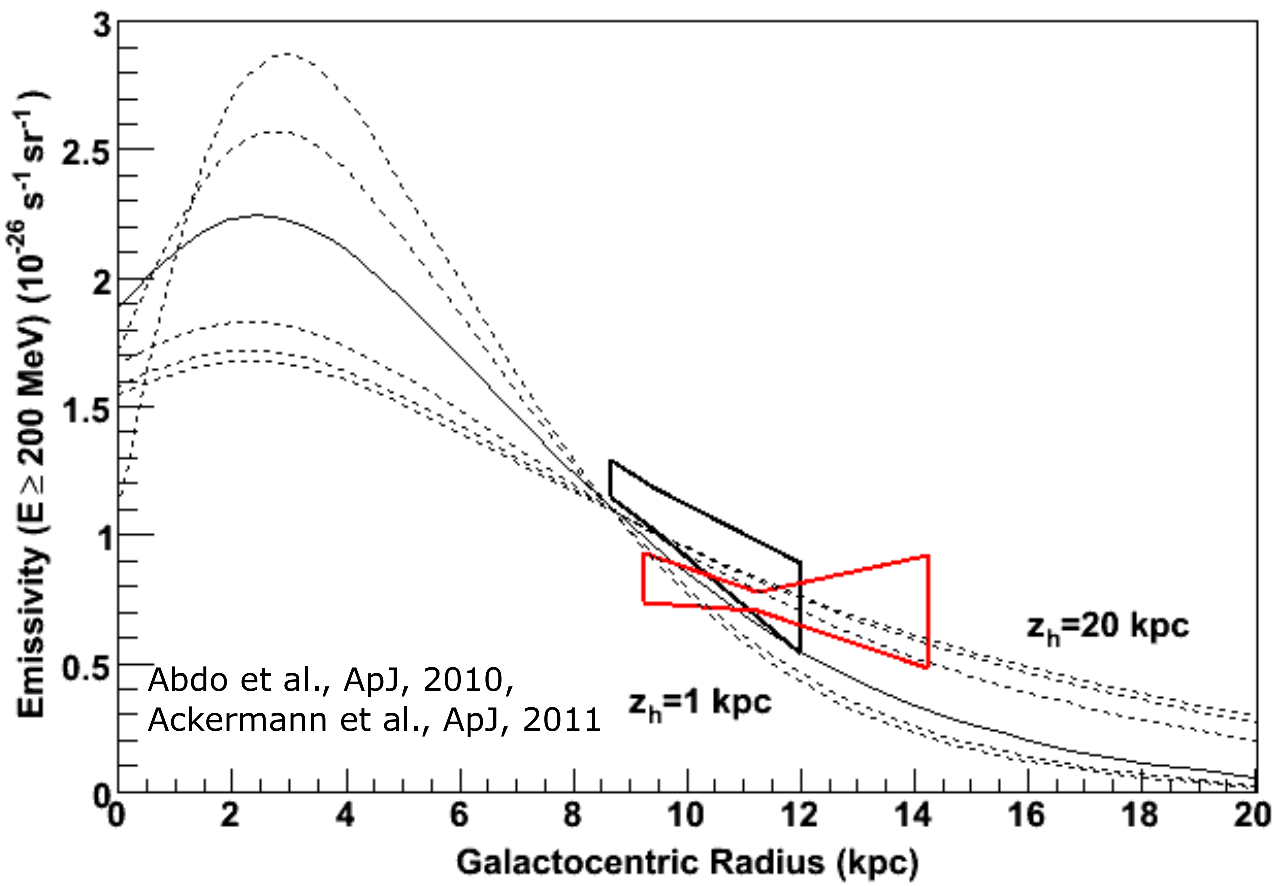


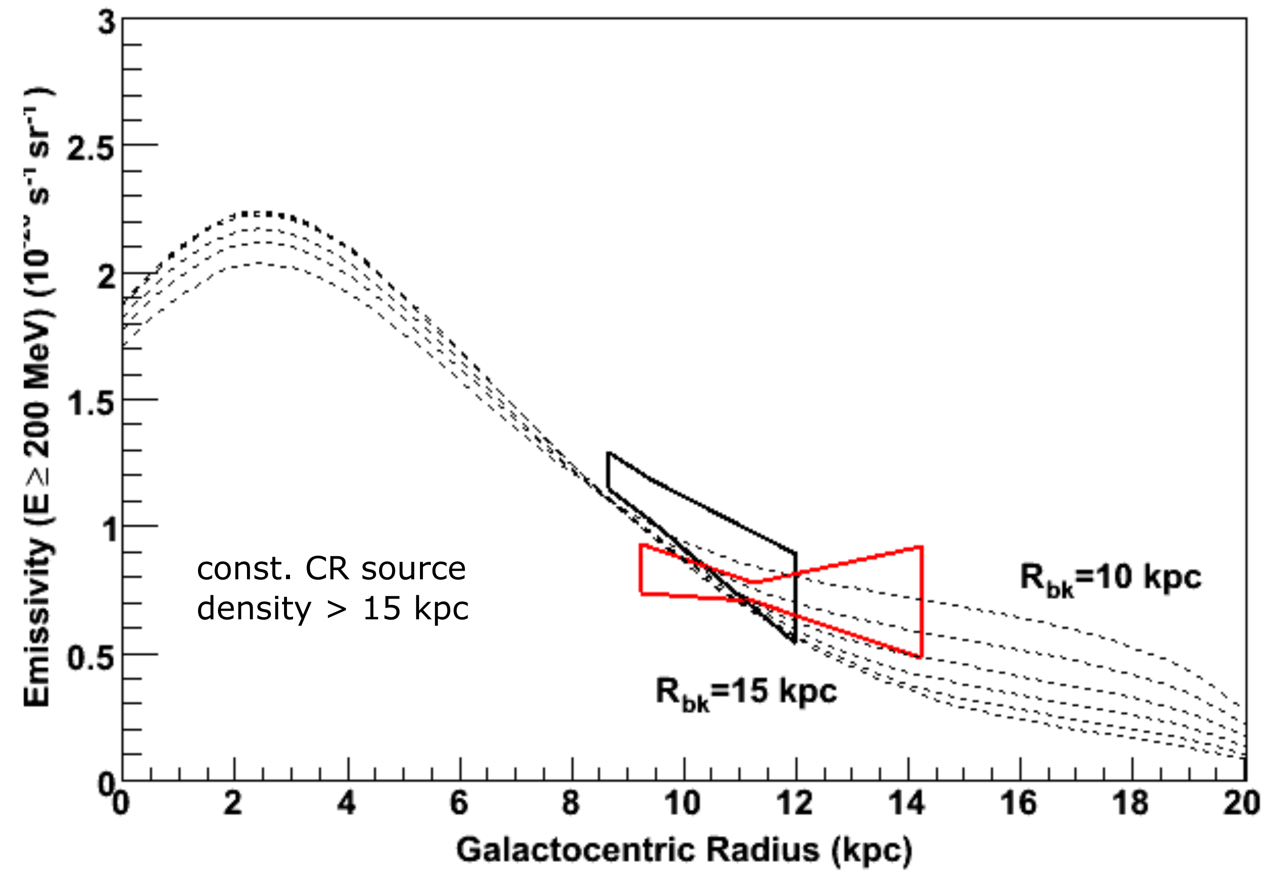
# The propagation of CRs in the Galaxy.




> Fitting the contribution from different distances allows to make a radial profile of the CR density.

# The cosmic ray density in the Galaxy.




> Gradient in CR density towards outer Galaxy is softer than expected from numerical calculations of CR propagation.

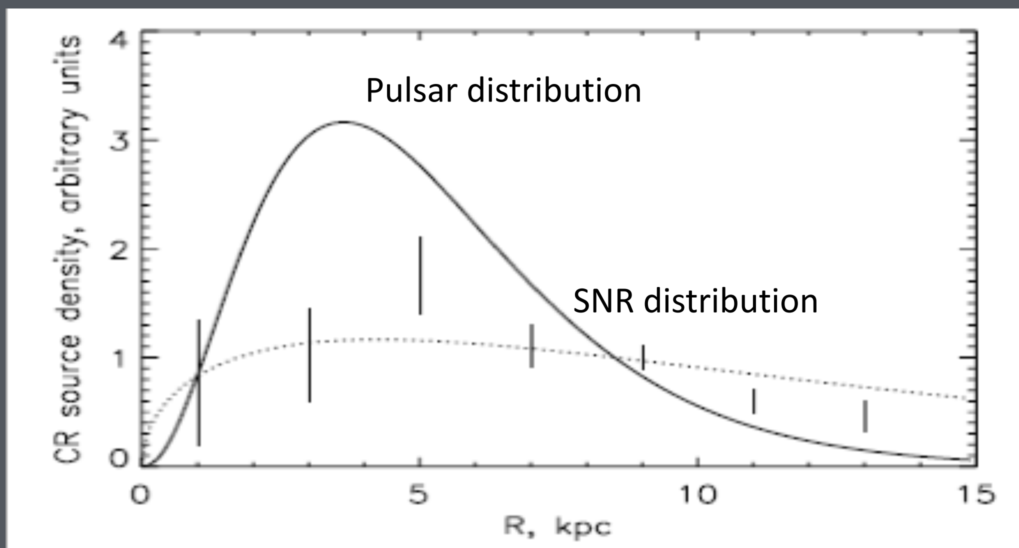
> Needs large CR confinement region or high CR source density outside the solar radius to be compatible with standard propagation models.

> Both hypotheses not supported by observations.

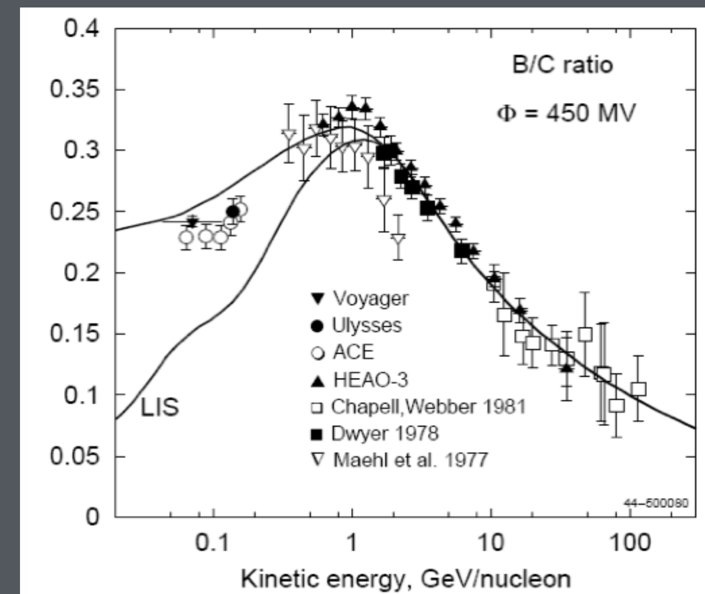
> More complex propagation models needed.

# Global modeling of diffuse gamma-ray emission

- Cosmic-ray source distribution

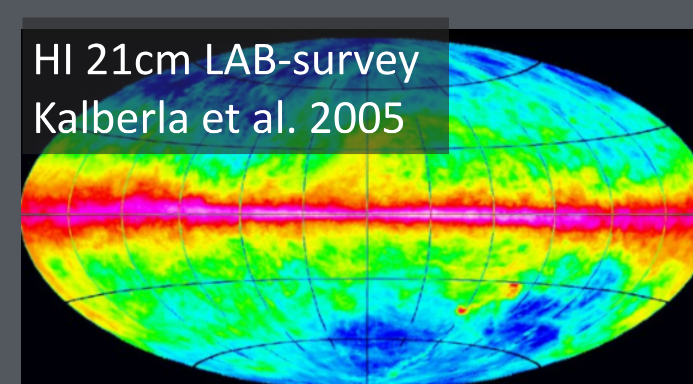


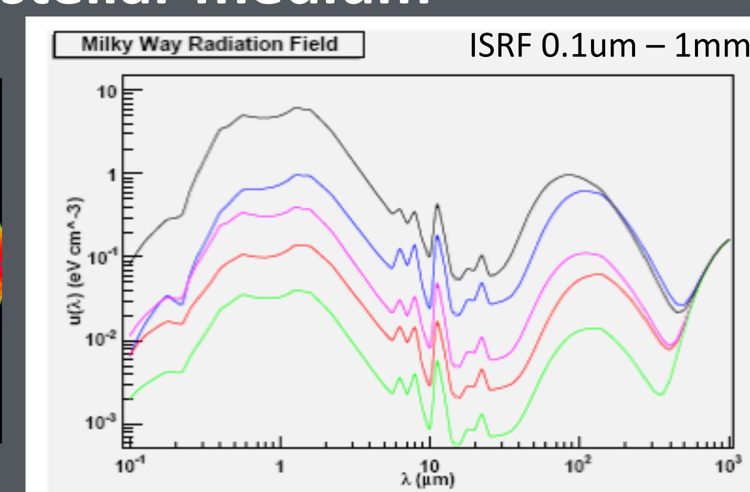

- **Cosmic-ray propagation**
  - constrained by local CR data

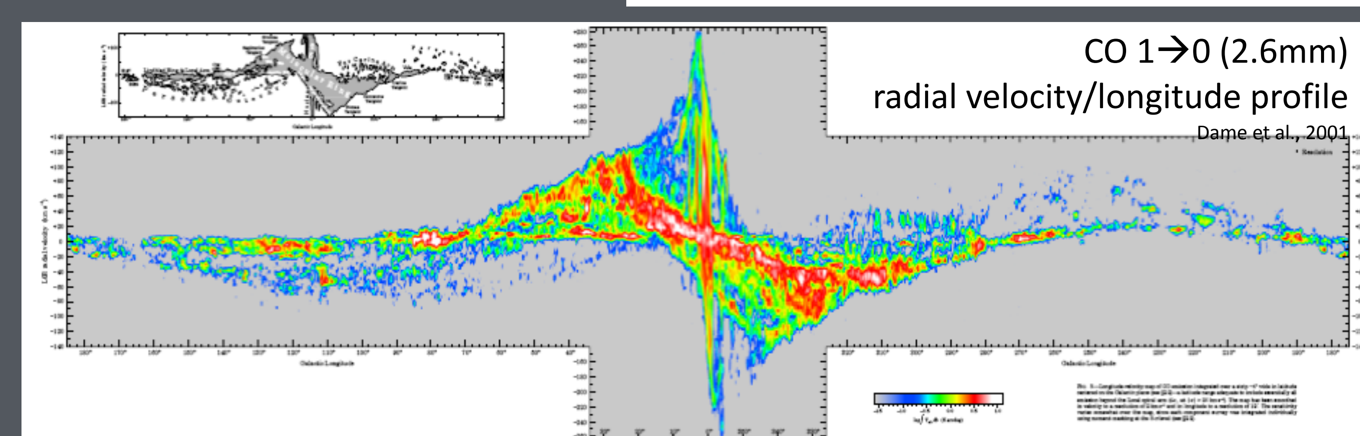


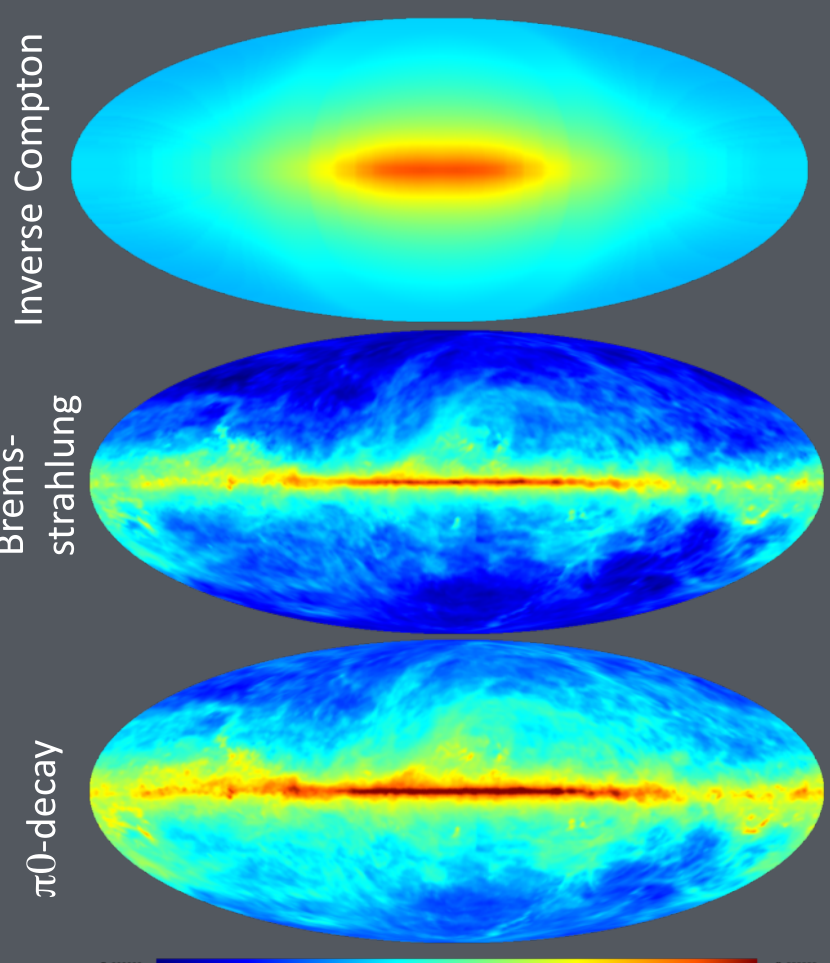

$$\frac{\partial \psi}{\partial t} = q(r, p) + \nabla \cdot (D_{xx} \nabla \psi - V \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} (\nabla \cdot V) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi ,$$

- **Interaction with interstellar medium**



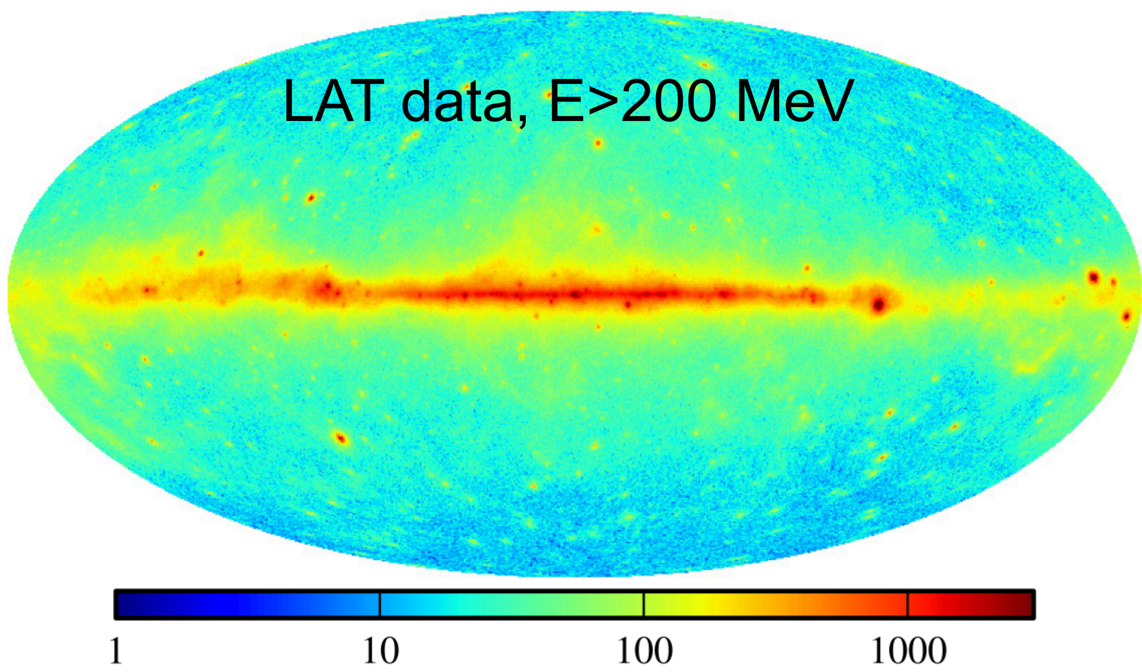




- Line-of-sight integration of produced gamma-ray intensities

# Residuals in the diffuse emission.

> Fulll-sky comparison of LAT data to model of Galactic CR injection, propagation and interaction (GALPROP code).

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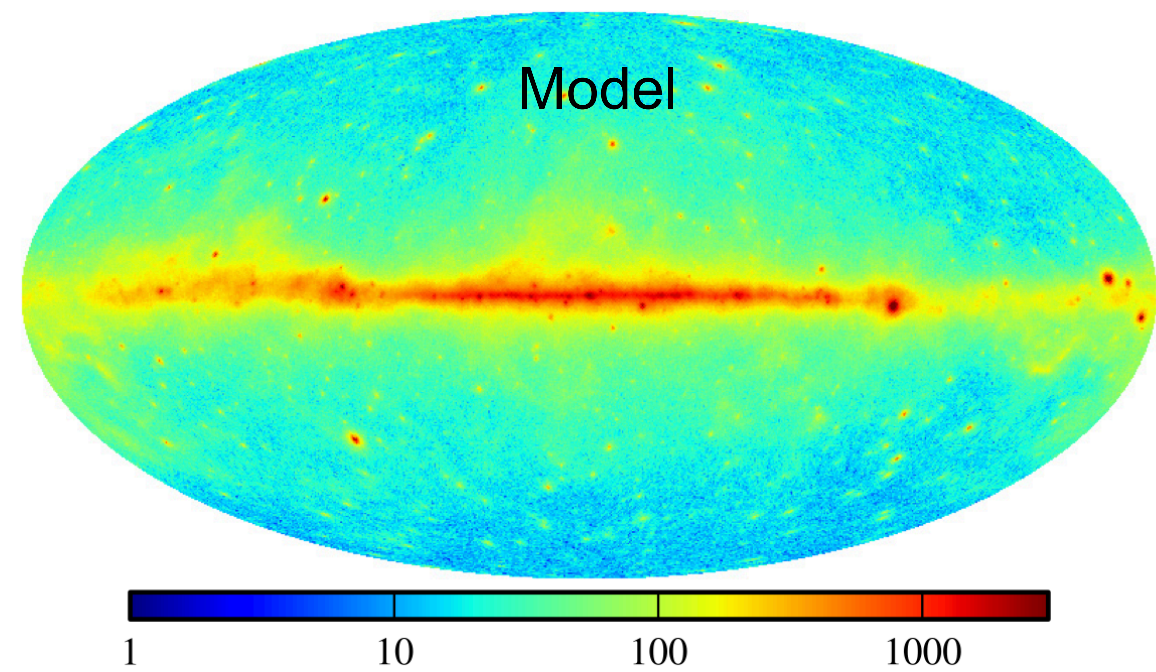


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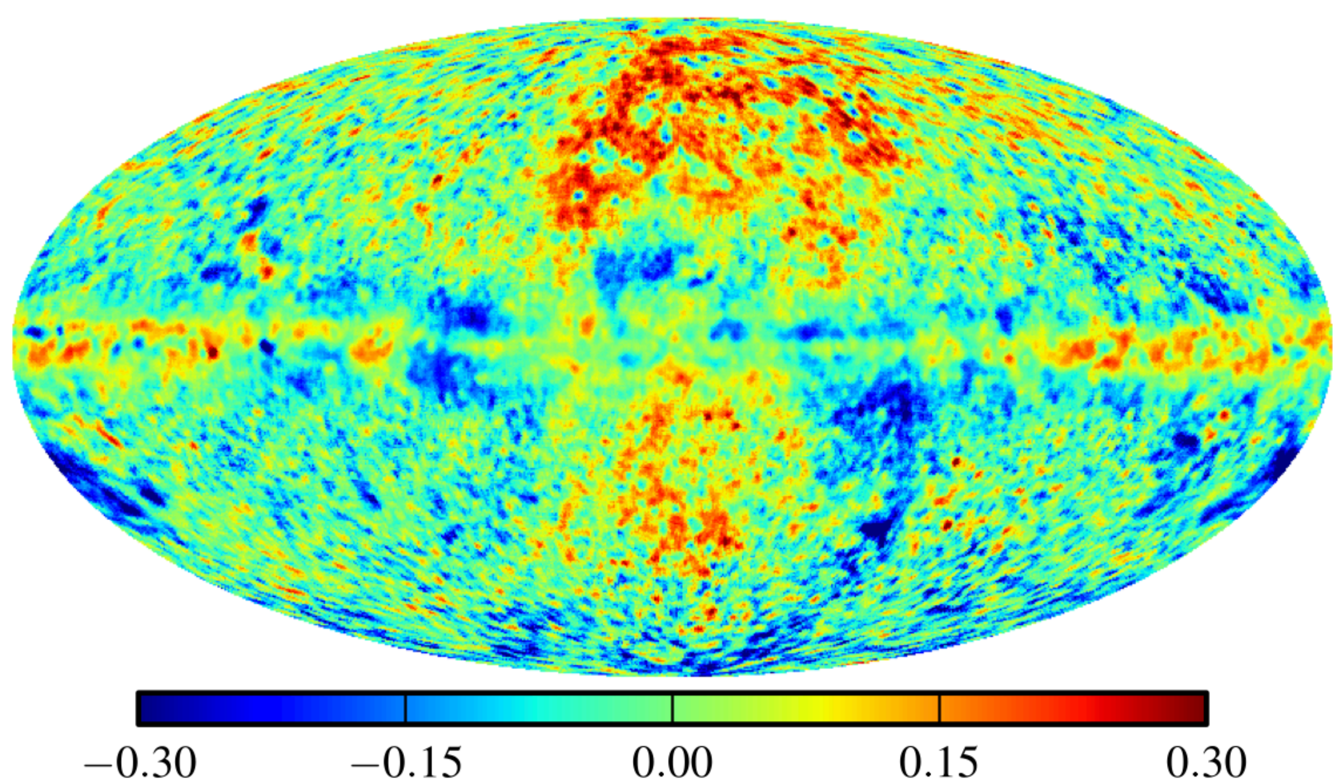


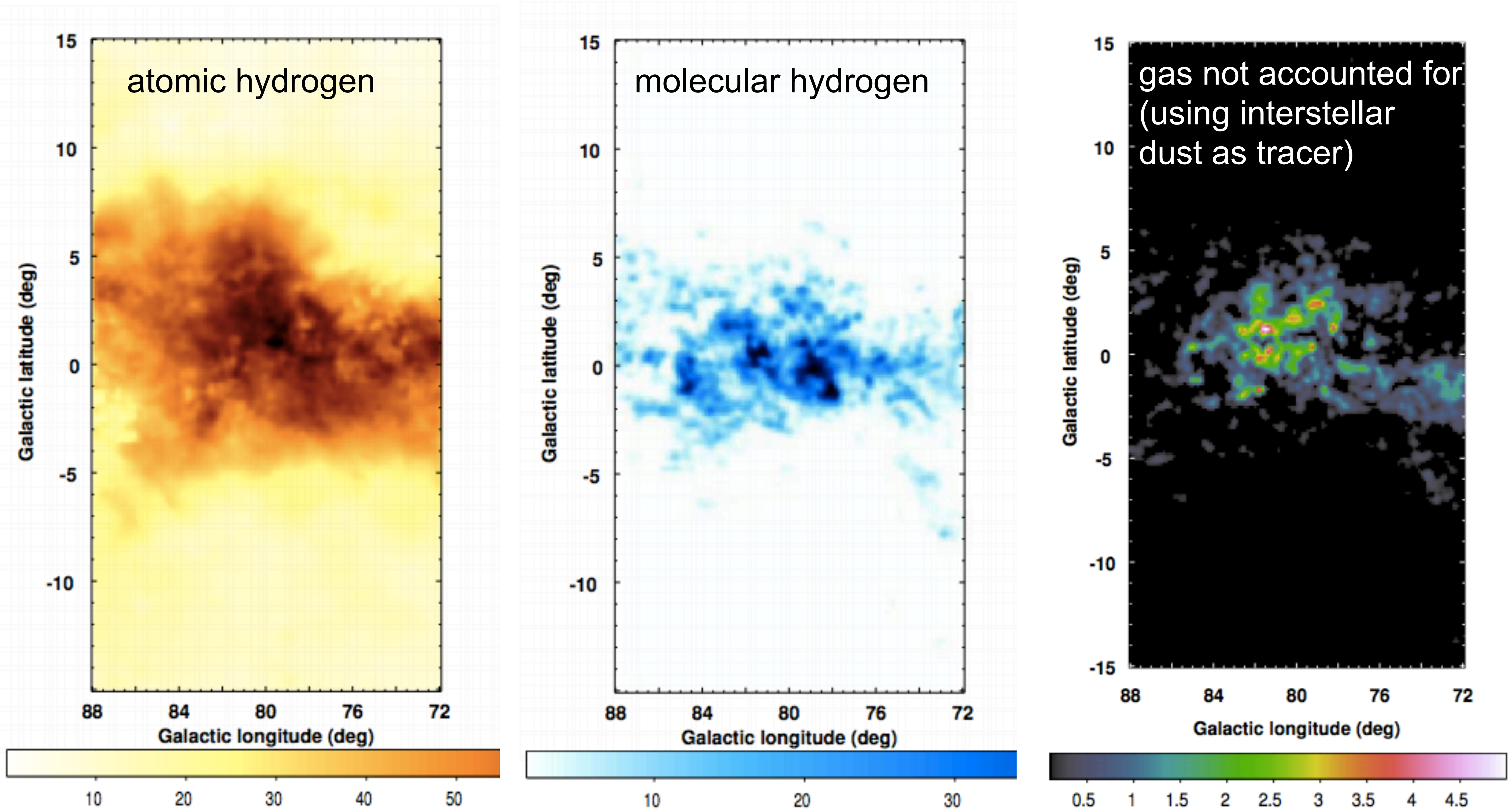

> Several notable structured residuals in diffuse γ-ray model.

> Loop I, molecular clouds, etc.

> Residuals on large scales

Ackermann et al., 2012

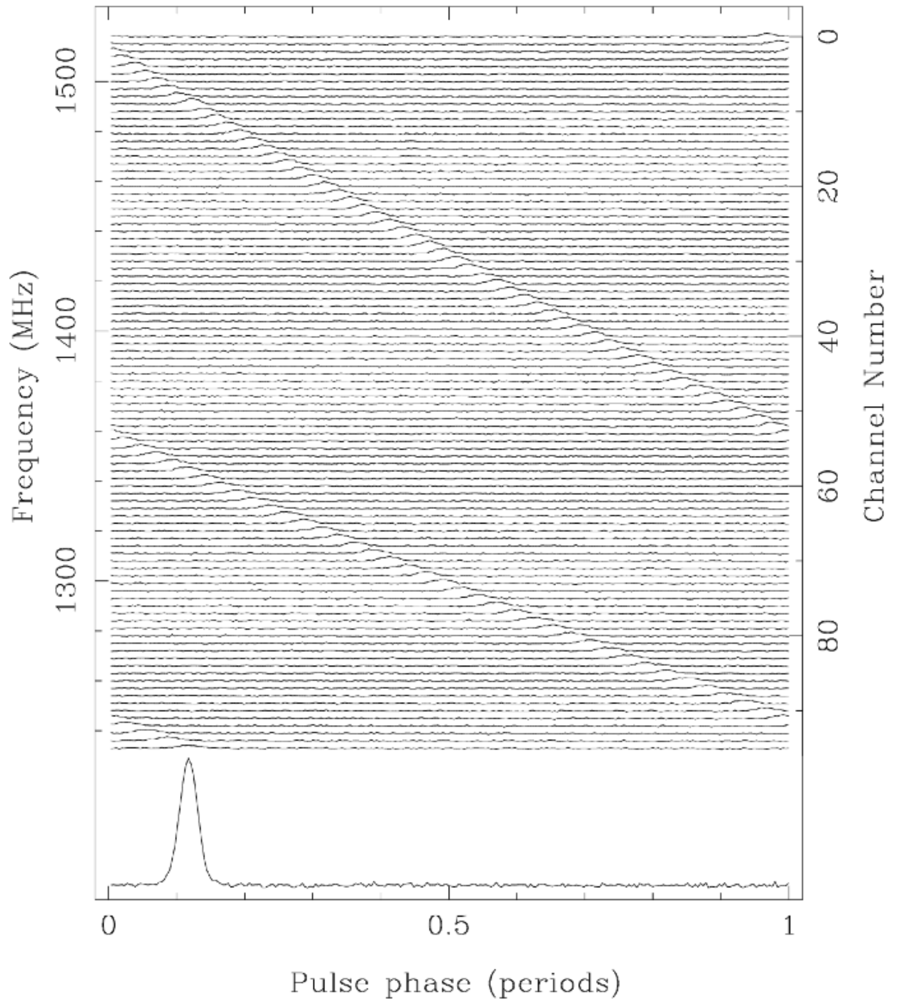
# Dark hydrogen gas

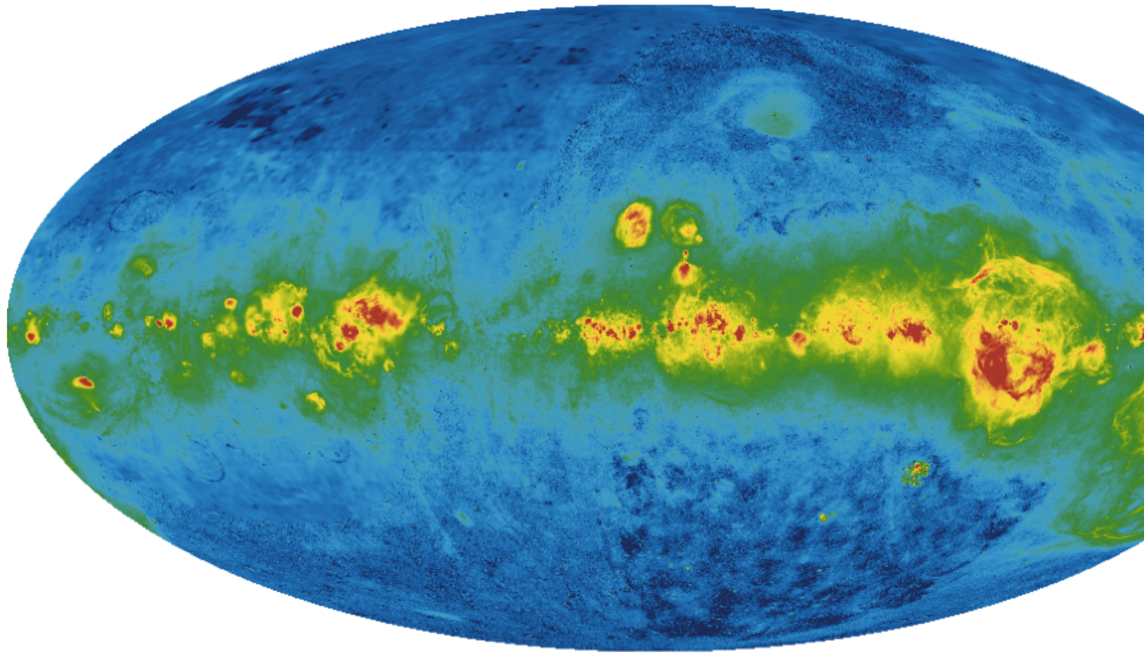



> Discrepancies between hydrogen gas traced by radio observations and by interstellar dust emission

> Attributed to “dark” neutral gas

# Ionized gas



$$t \approx \frac{d}{c} + \frac{e^2 \int_0^d n_e ds}{2\pi c m_e \nu^2}$$

$\Delta t_p$ = time delay relative to light speed

$$I_\nu(H\alpha) = \frac{h\nu_{32}}{4\pi} \int n_e n_p \alpha_{32} dl$$

recombinations per sec per volume that produce n=3-2

**Pulsar dispersion measure**

- Pulse time delay as a function of frequency
- Sensitive to electron density along line of sight

**Emission measure**

- Ha emission as a tracer of ionized gas
- Sensitive to electron density squared

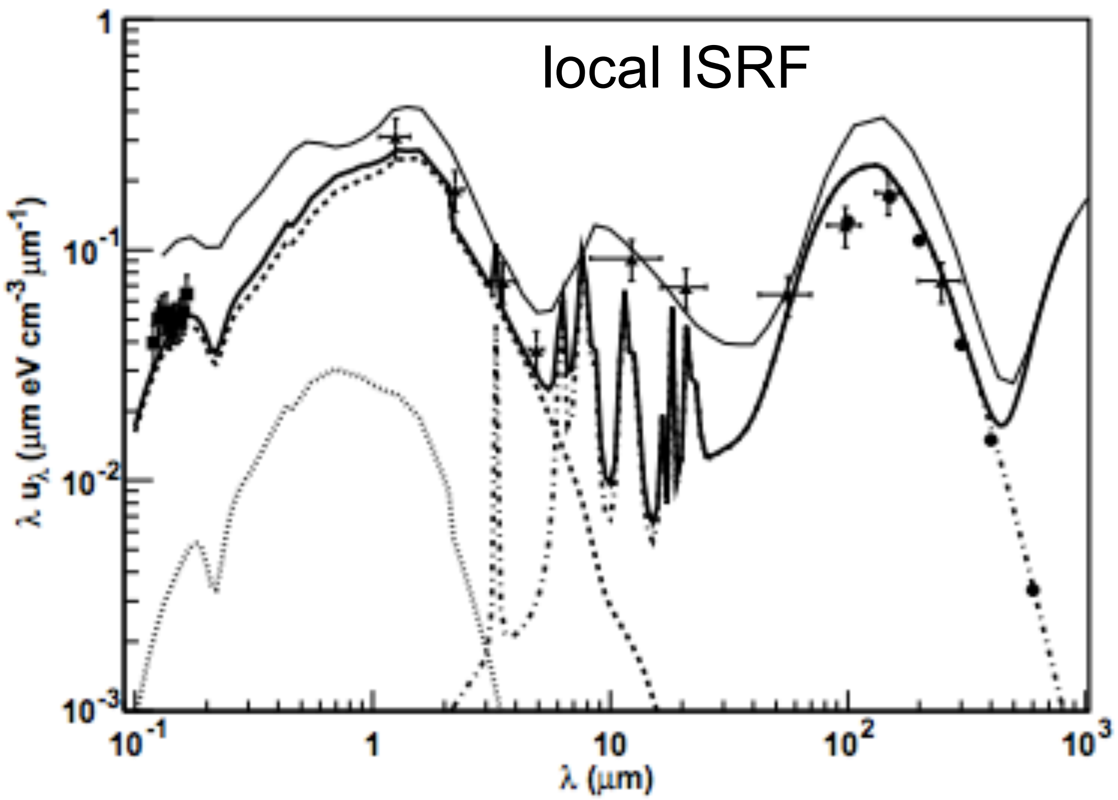
> Important at intermediate Galactic latitudes

> Scale height ~ 1kpc, much higher than atomic gas

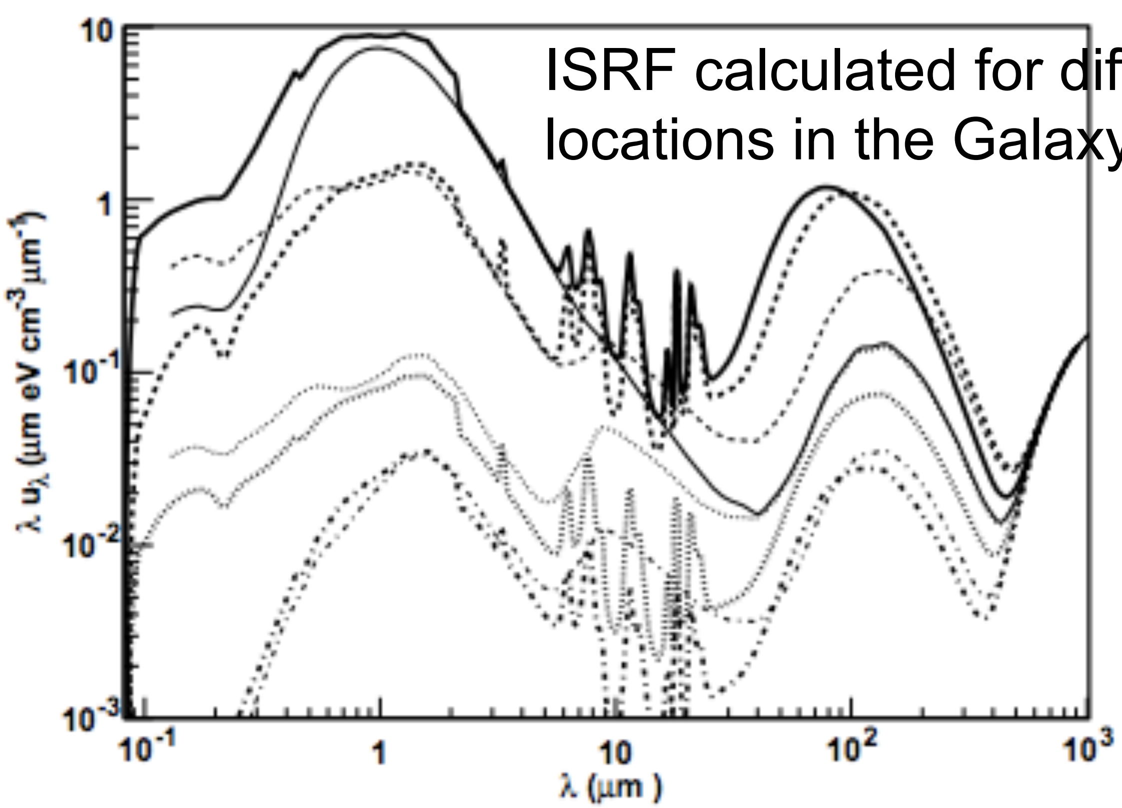
> Not smoothly distributed, large voids between “clouds” of ionized gas

> Almost impossible to make a good template for gamma-ray emission

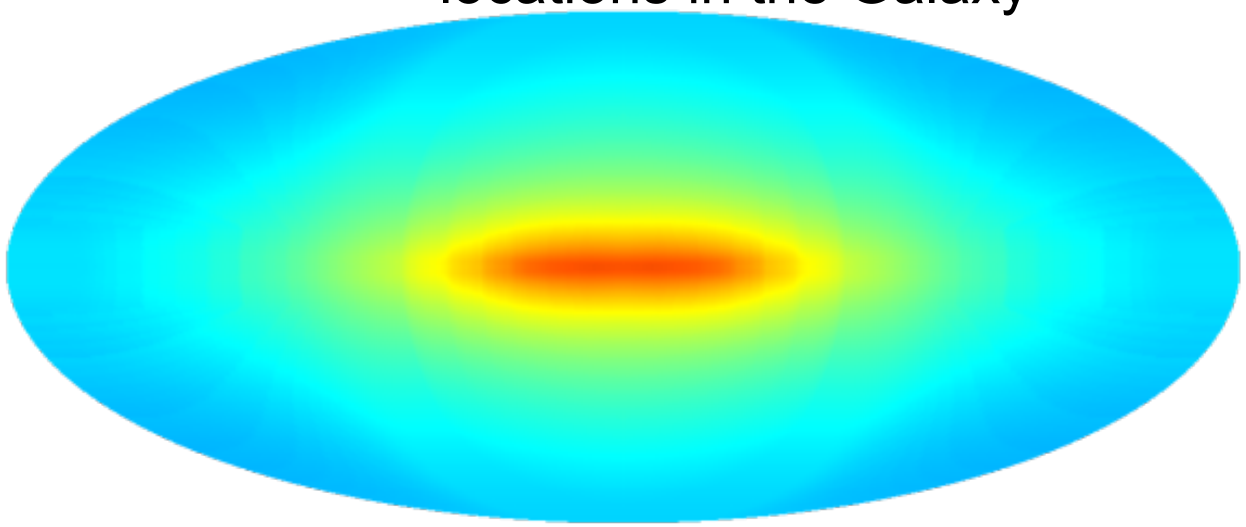
# The interstellar radiation field




- Impossible to measure radiation field at other locations in the Galaxy
- Models based on stellar population synthesis and radiation transport
- Considerable uncertainty on shape of inverse Compton component

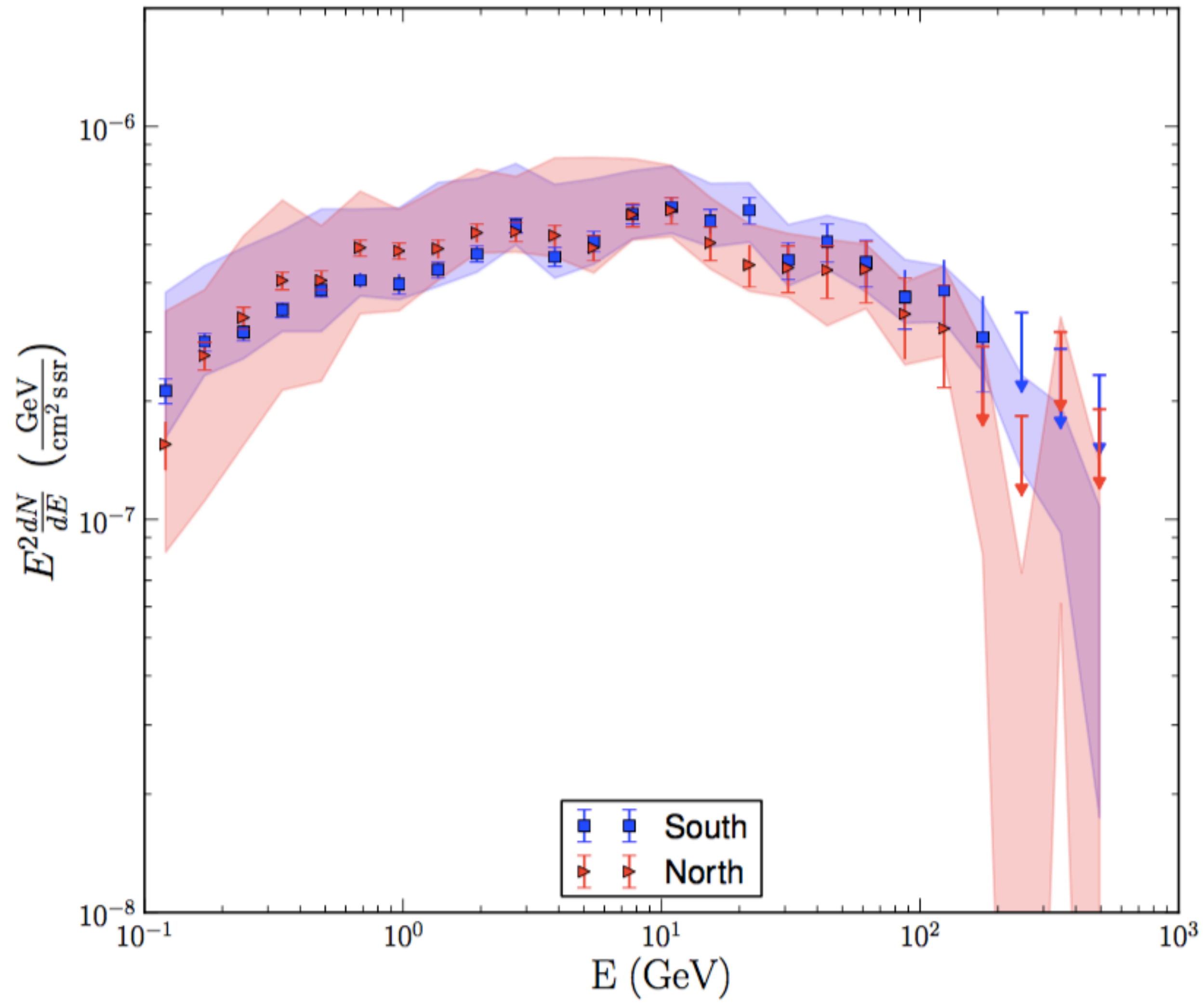


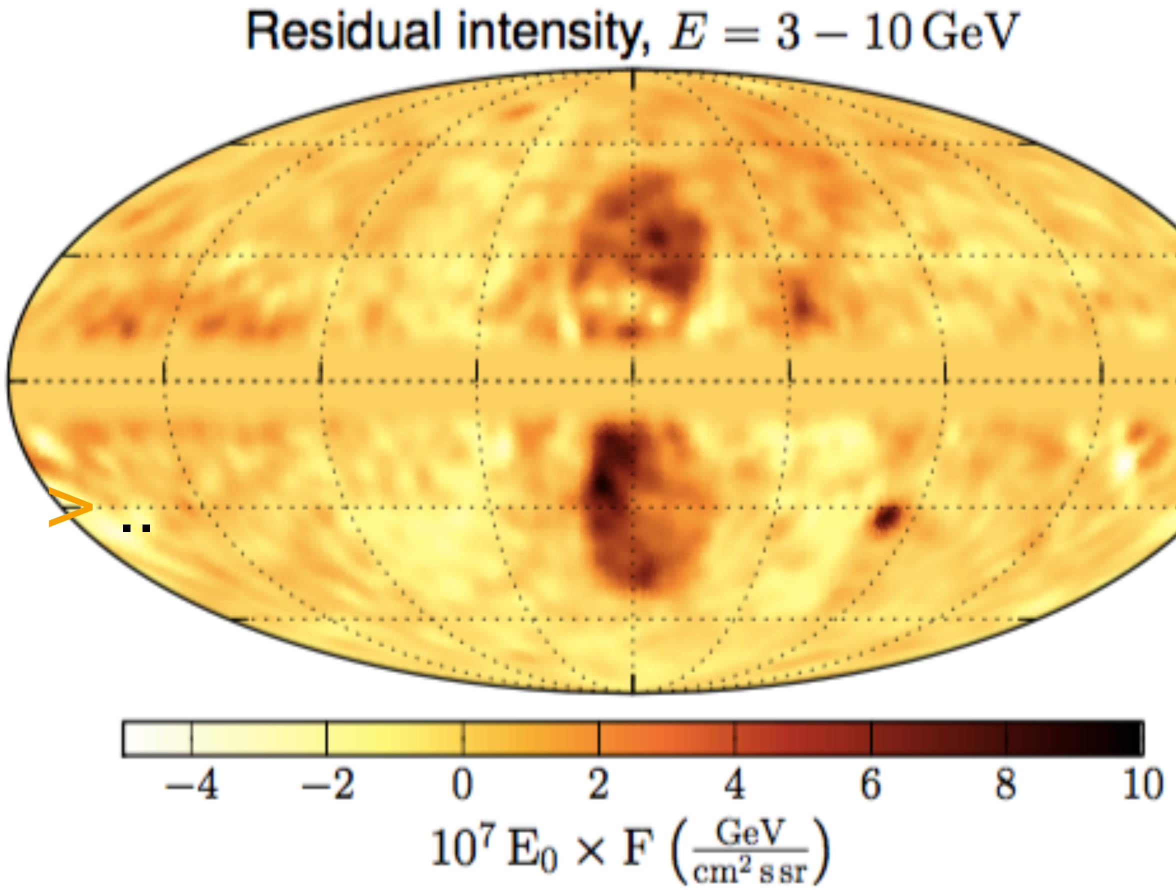

ISRF calculated for different locations in the Galaxy

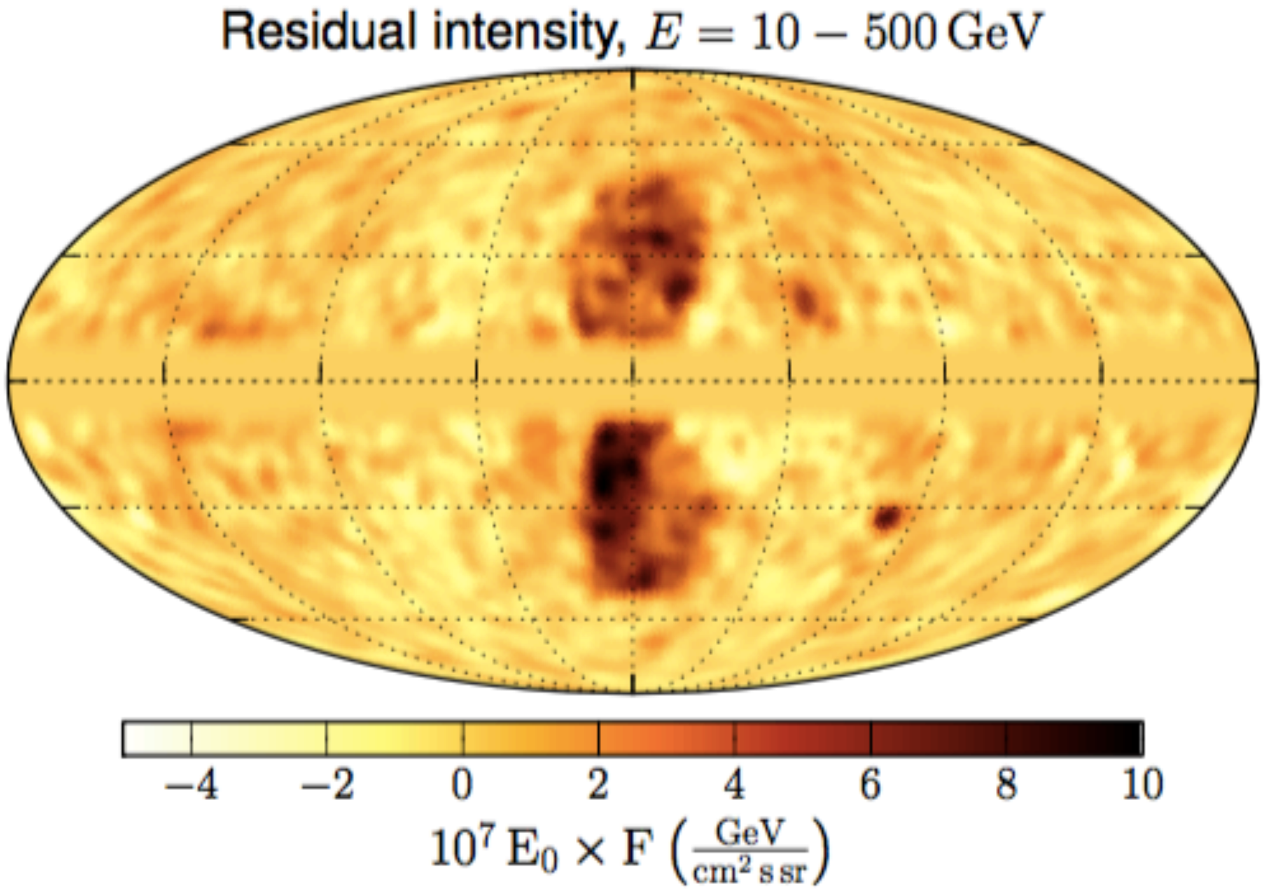


# The Fermi Bubbles.

- Fermi “bubbles” are largest unexplained residual above few GeV.
- Hard spectrum.
- “Bubbles” are symmetric around GC and reach high latitudes above the plane.
- Many explanation attempts in literature: Galactic wind, former Milky way jet, produced by proton / electron interaction etc…
- ..

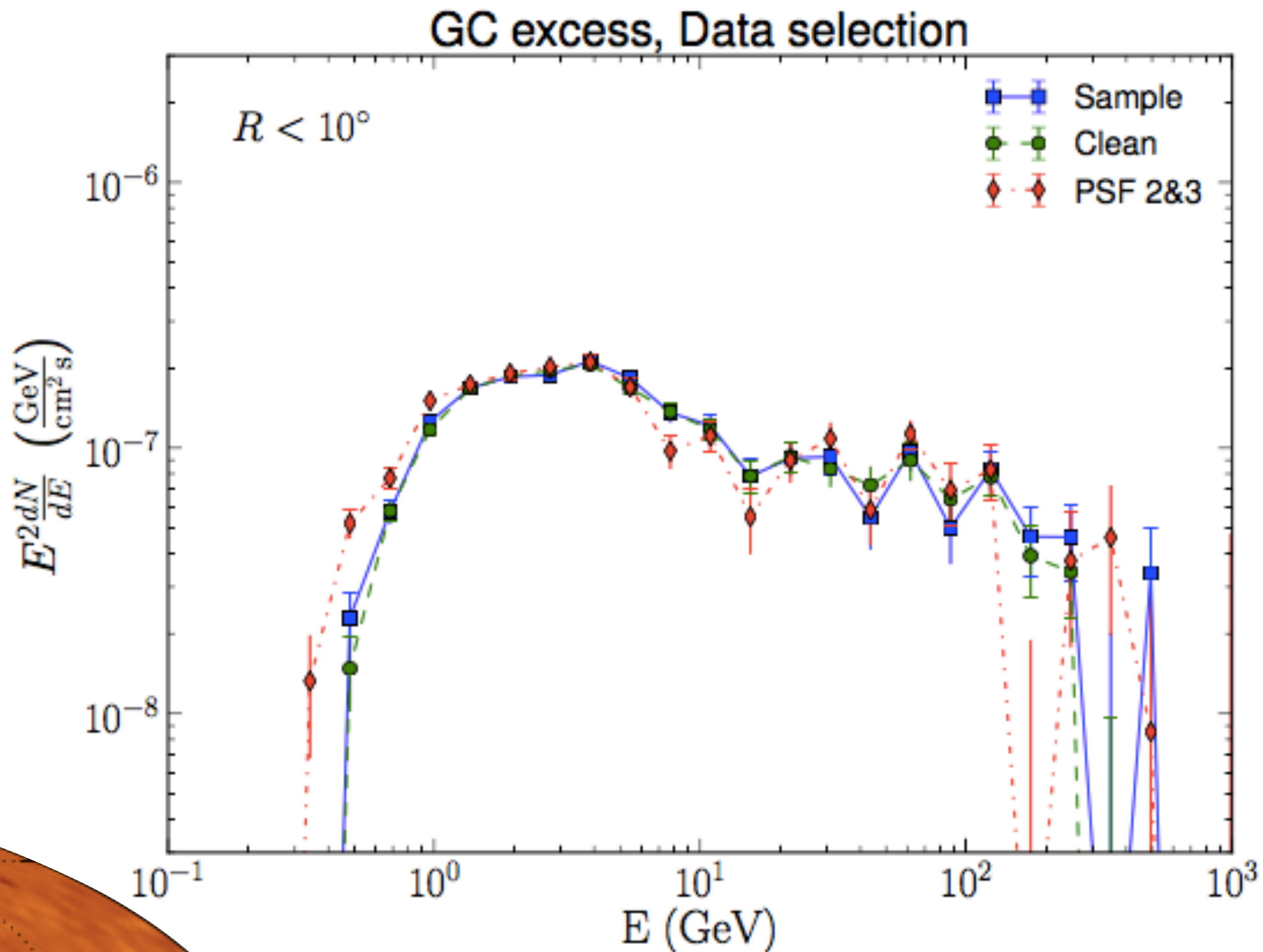


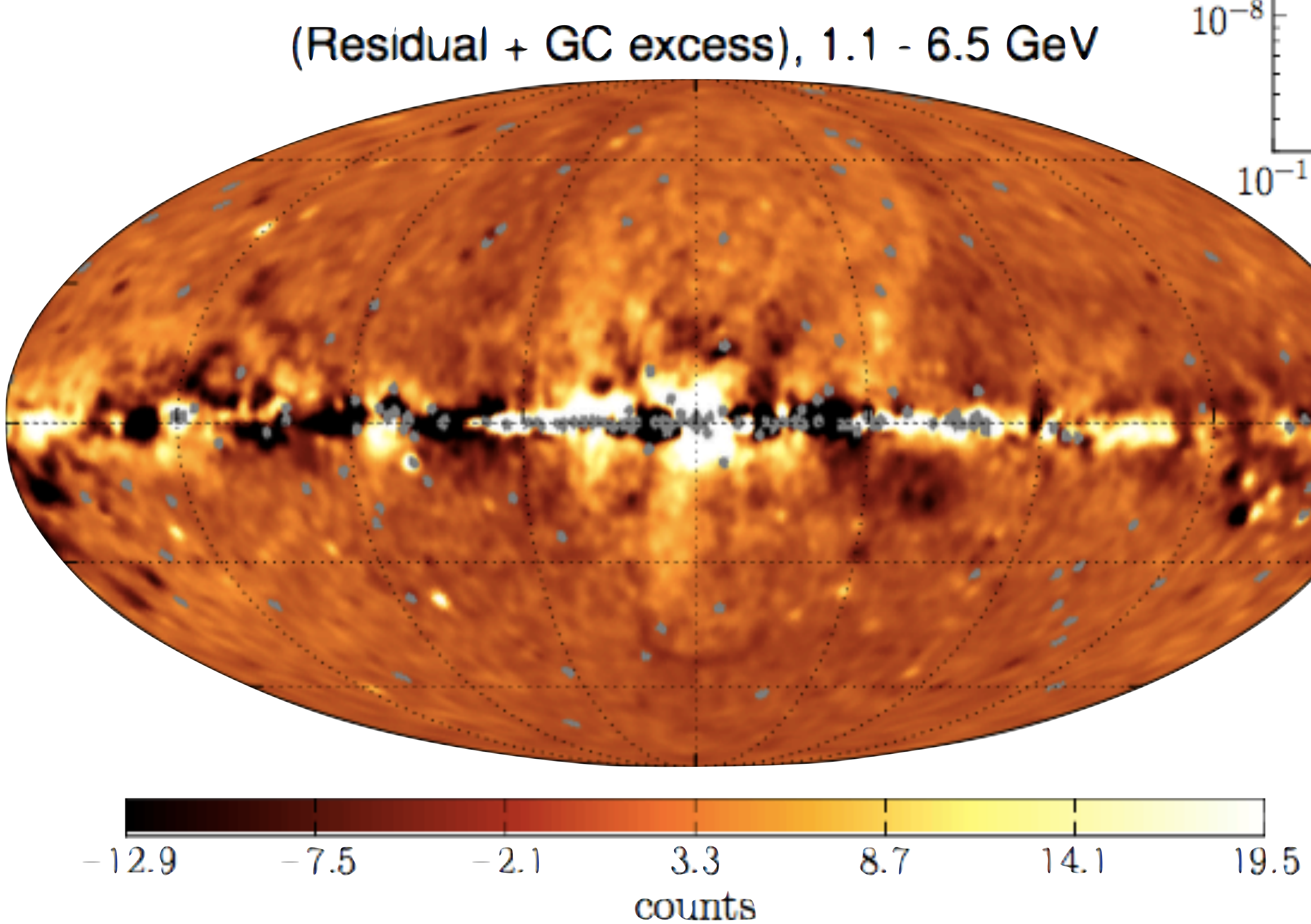



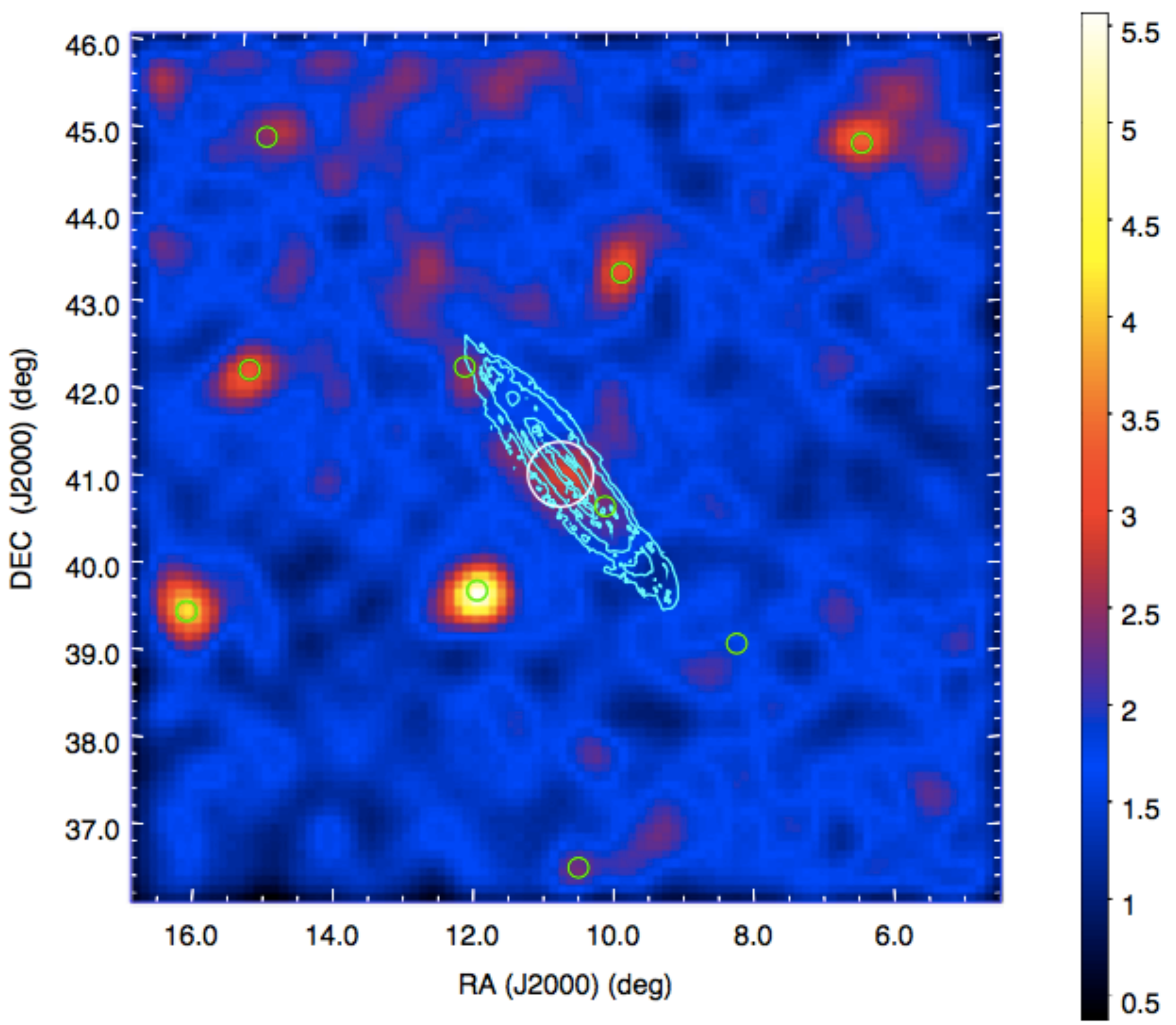
# The galactic center excess

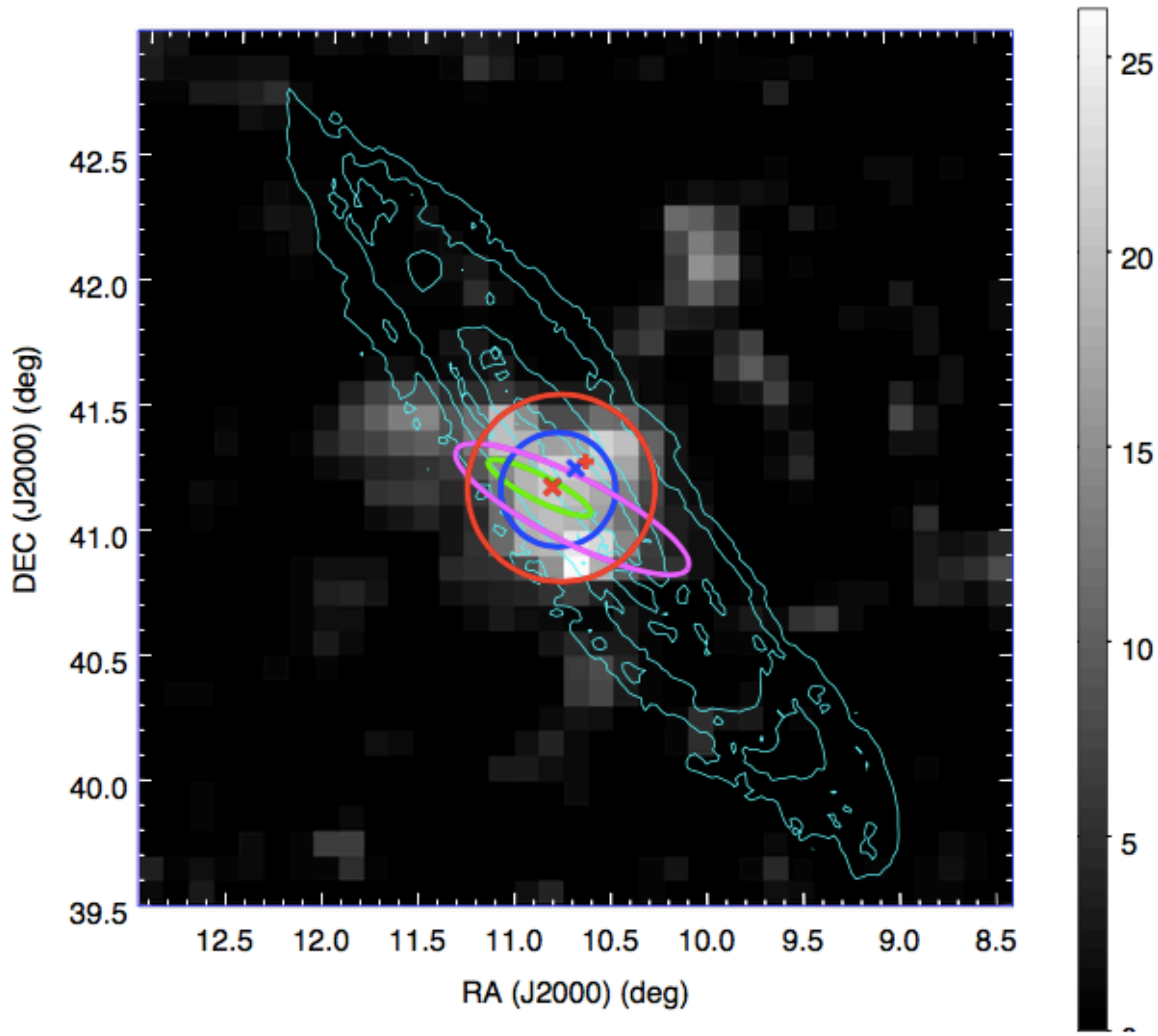
- (Hopefully) covered in detail by Francesca
- Currently favored explanations: Millisecond Pulsar population or DM
- Extremely difficult region to analyze.



# A galactic center excess also in Andromeda ?




- Andromeda (M31) is a weak gamma-ray source.
- Gamma-ray luminosity centrally peaked.
- Doesn't follow the gas distribution.

Significance of source extension only ~ 4 sigma

# Propagation summary

> There is still a lot to learn about cosmic ray propagation

> Simple propagation models fail to describe the data

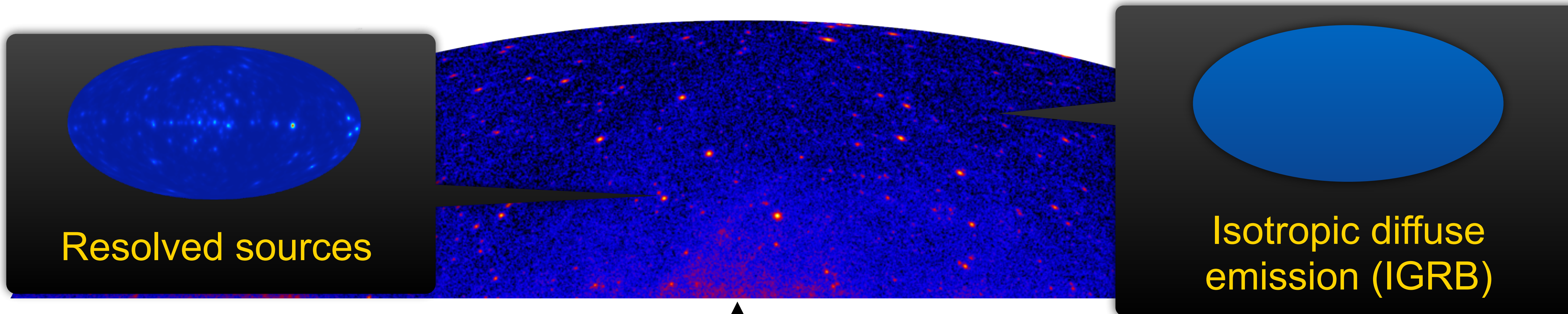
> Limited understanding of gas and radiation targets limit our capabilities for global modeling

> Some of the moste interesting features that Fermi LAT discovered are diffuse:

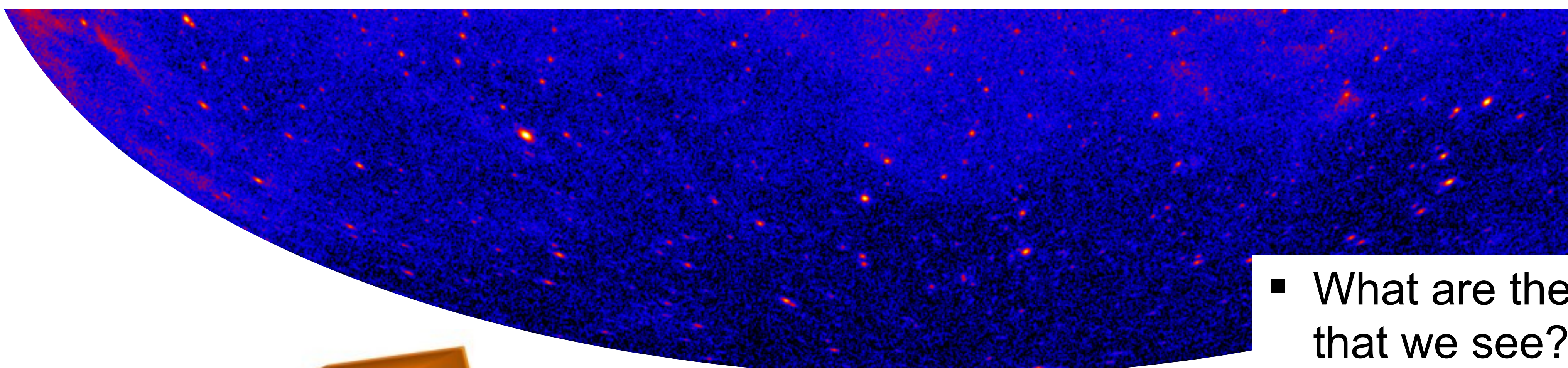
- Fermi Lobes
- Galactic Center excess

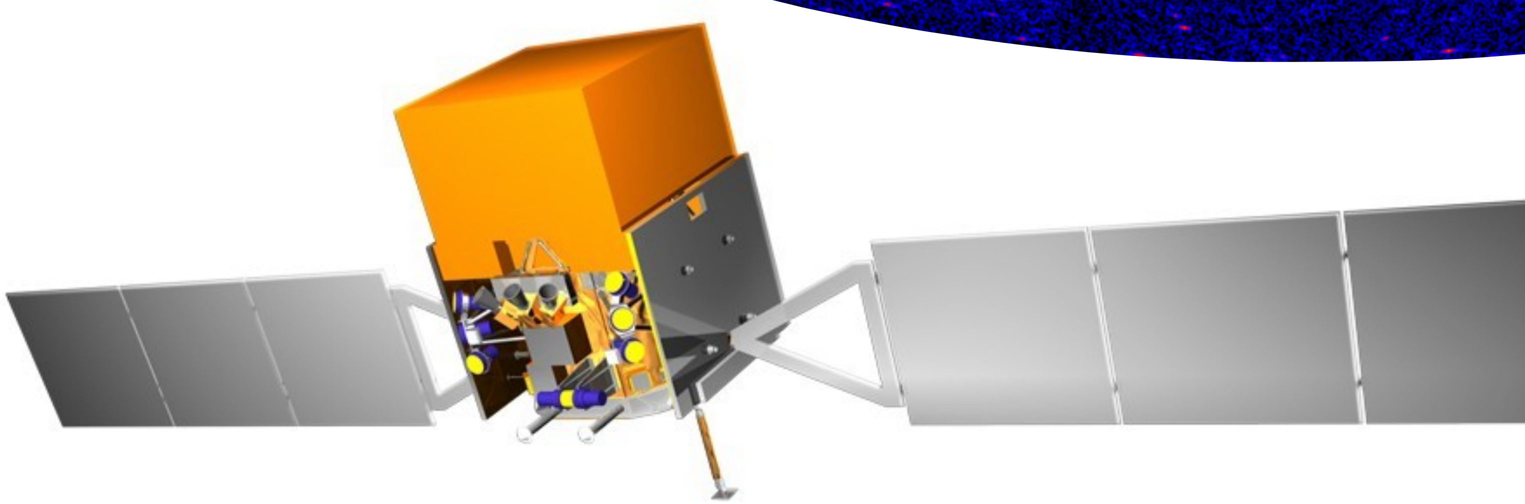
# The extragalactic GeV gamma-ray sky.

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




The extragalactic sky

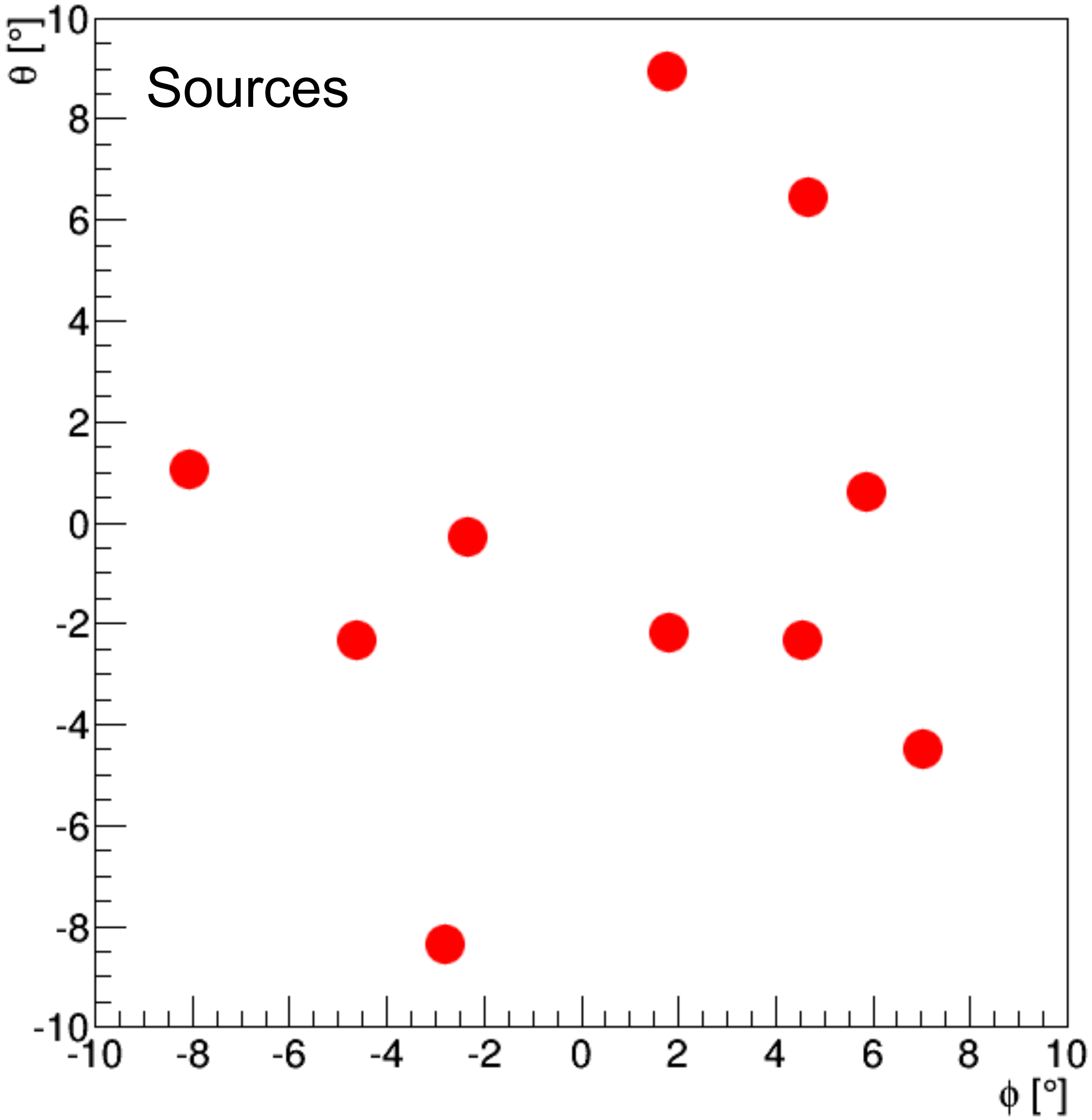


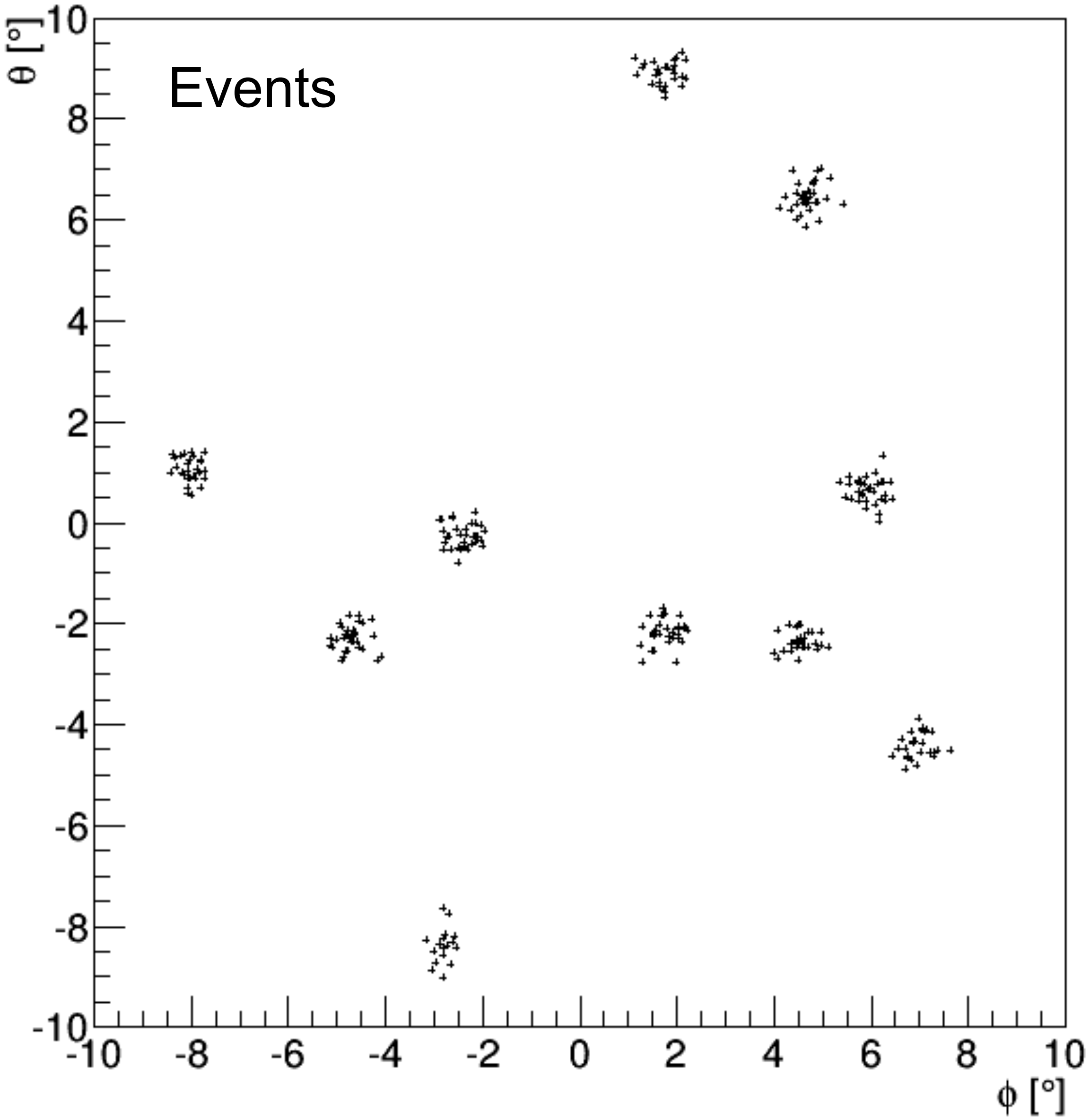


- What are the source populations that we see?
- How do they contribute to the total gamma-ray emission?
- Is there any sign of something new and unexpected ?

# Source detection: Strong sources

> **Strong sources:** All sources can be detected individually.



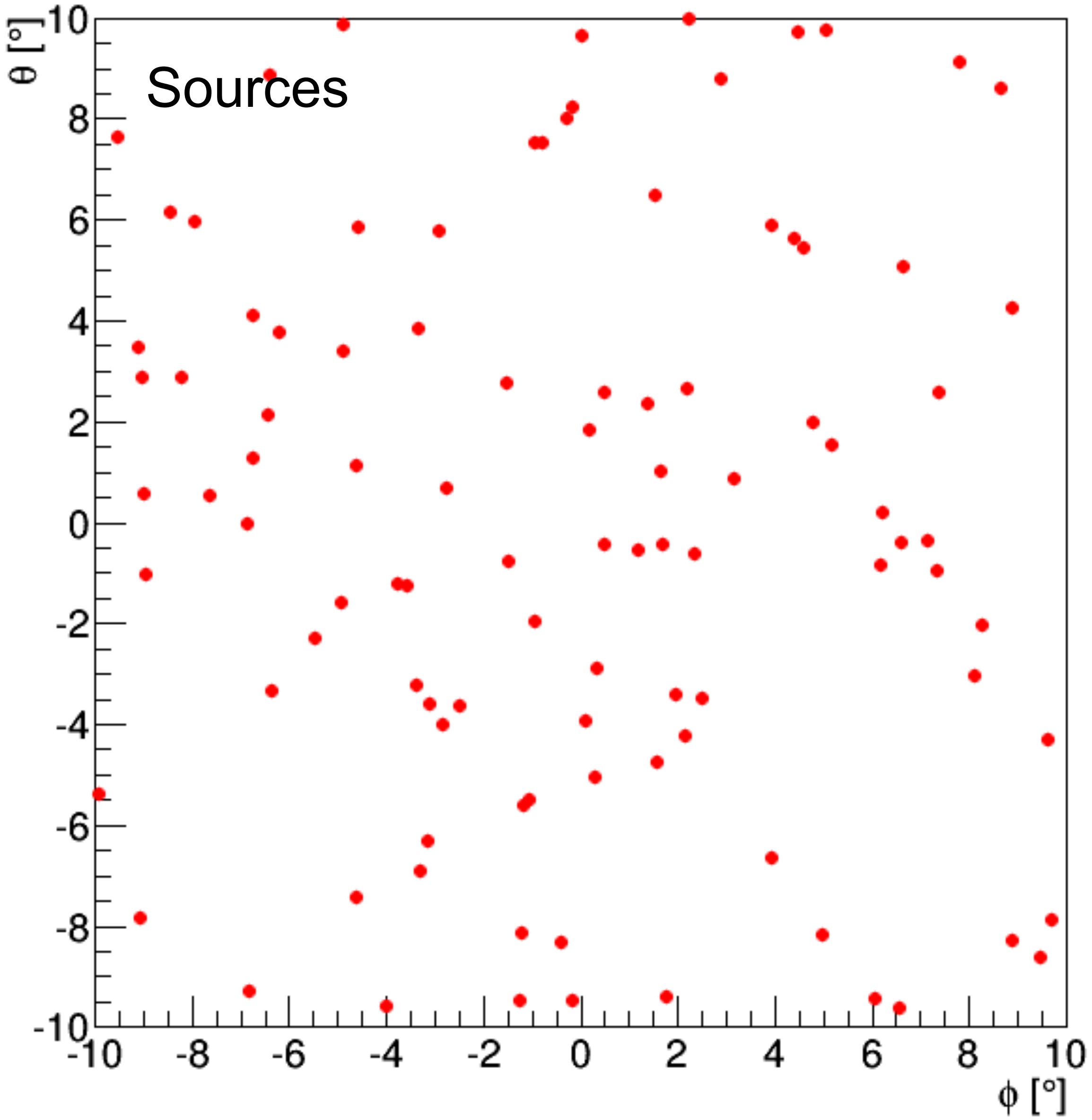



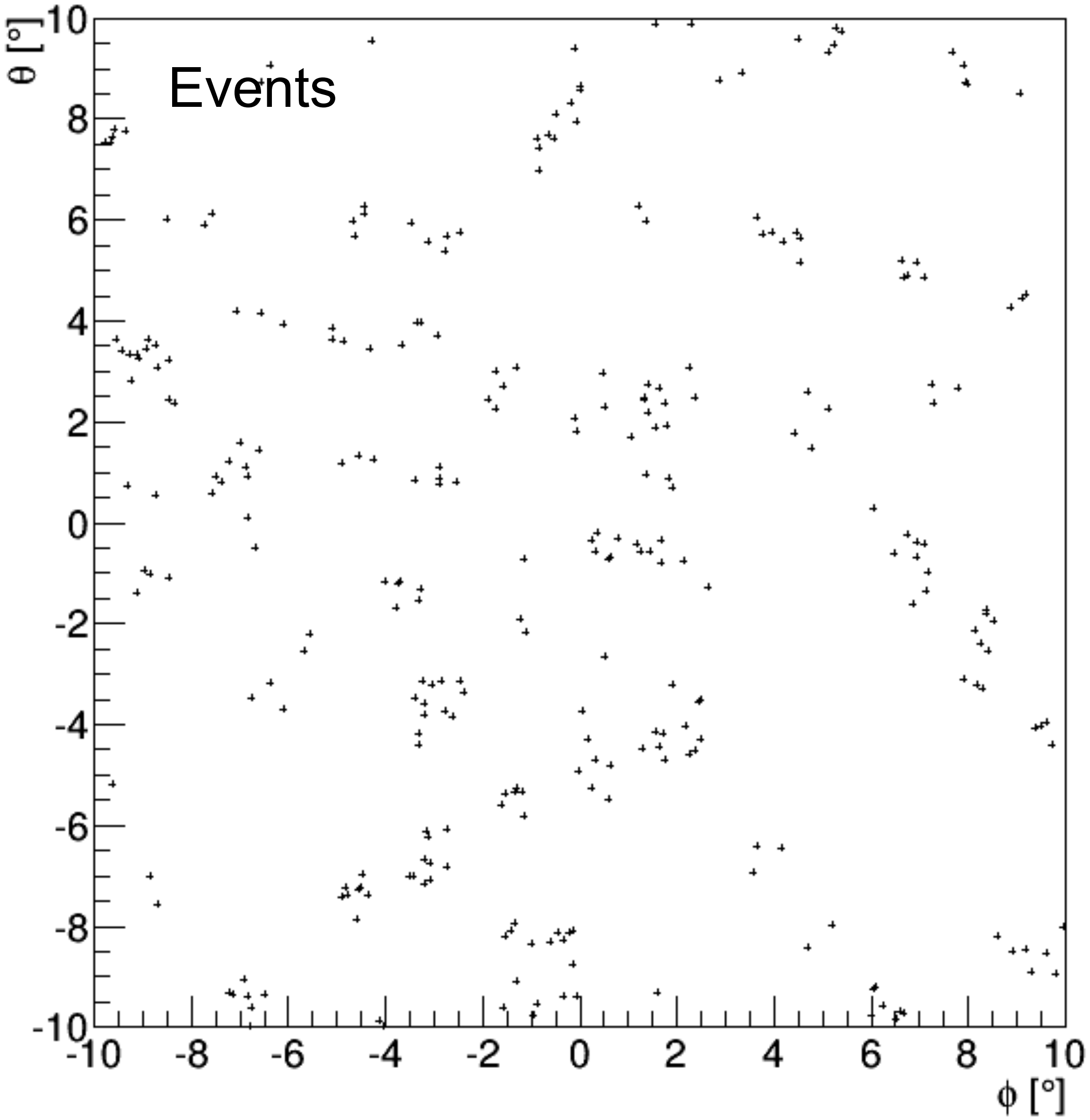

30 events / source

# Source detection: Intermediate sources

> **Intermediate sources:** Some sources can be detected individually.

> Source detection efficiency is < 100%

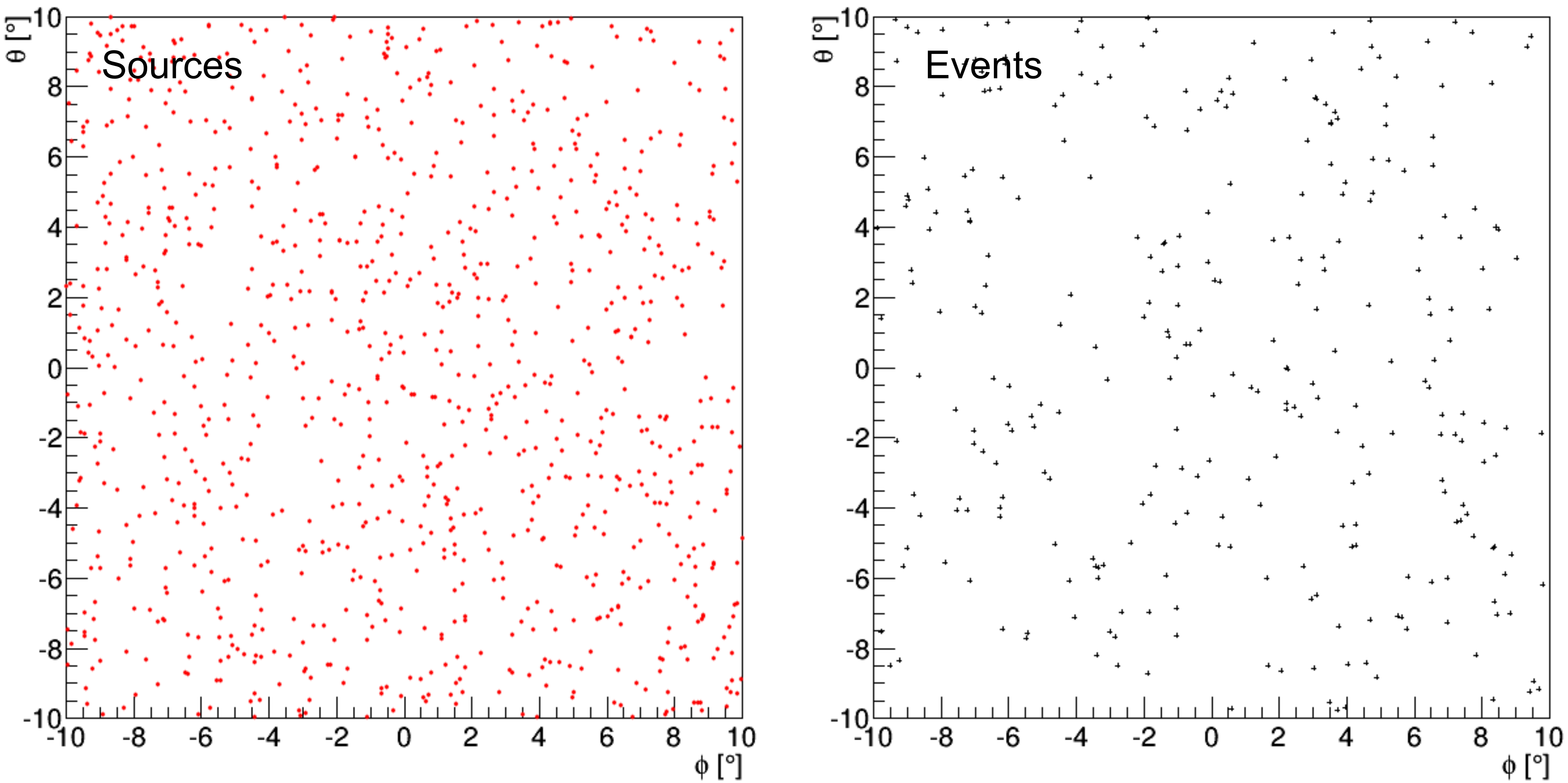



3 events / source

# Source detection: Weak sources

- **Weak sources:** Cannot be detected individually
- Isotropic distribution of events (if source distribution is isotropic)



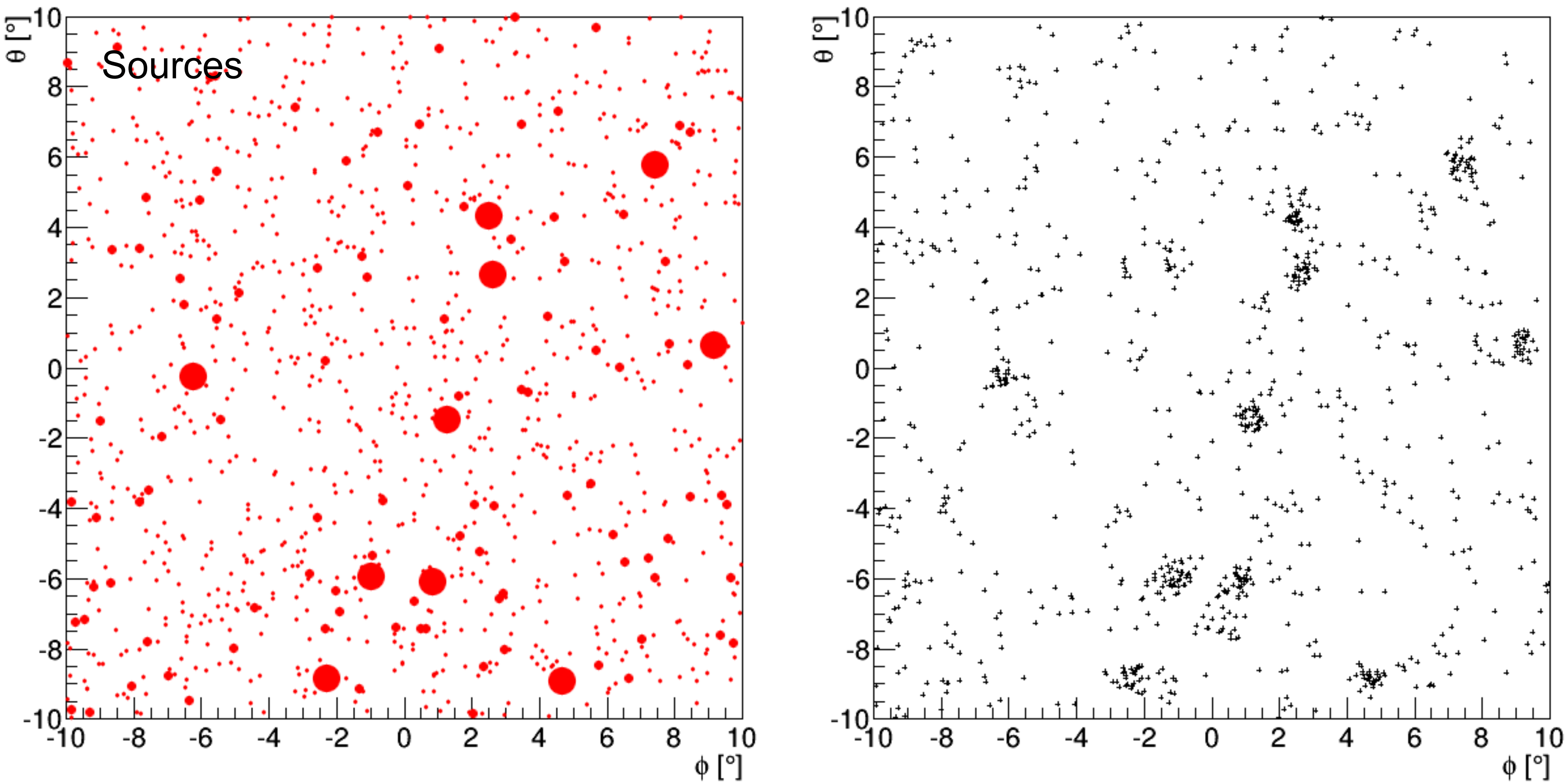

0.3 events / source

# The real case: A mixture of weak & strong sources

> Part of the intensity of a source population can be resolved into individual sources

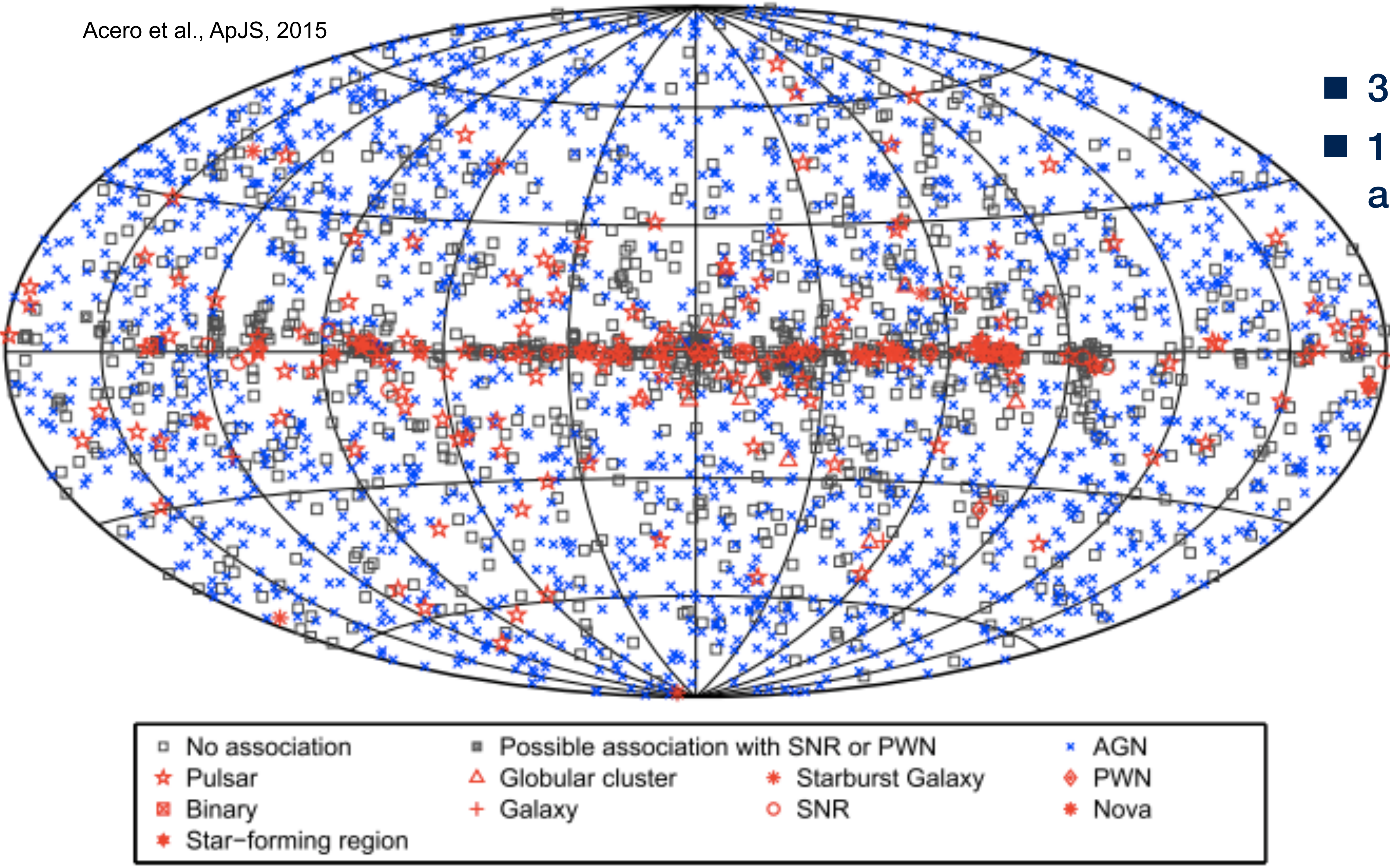
> The remaining part **contributes to a diffuse background.**

> Dependent on instrument sensitivity, PSF and population properties.



# There 3rd Fermi LAT Catalog

Acero et al., ApJS, 2015

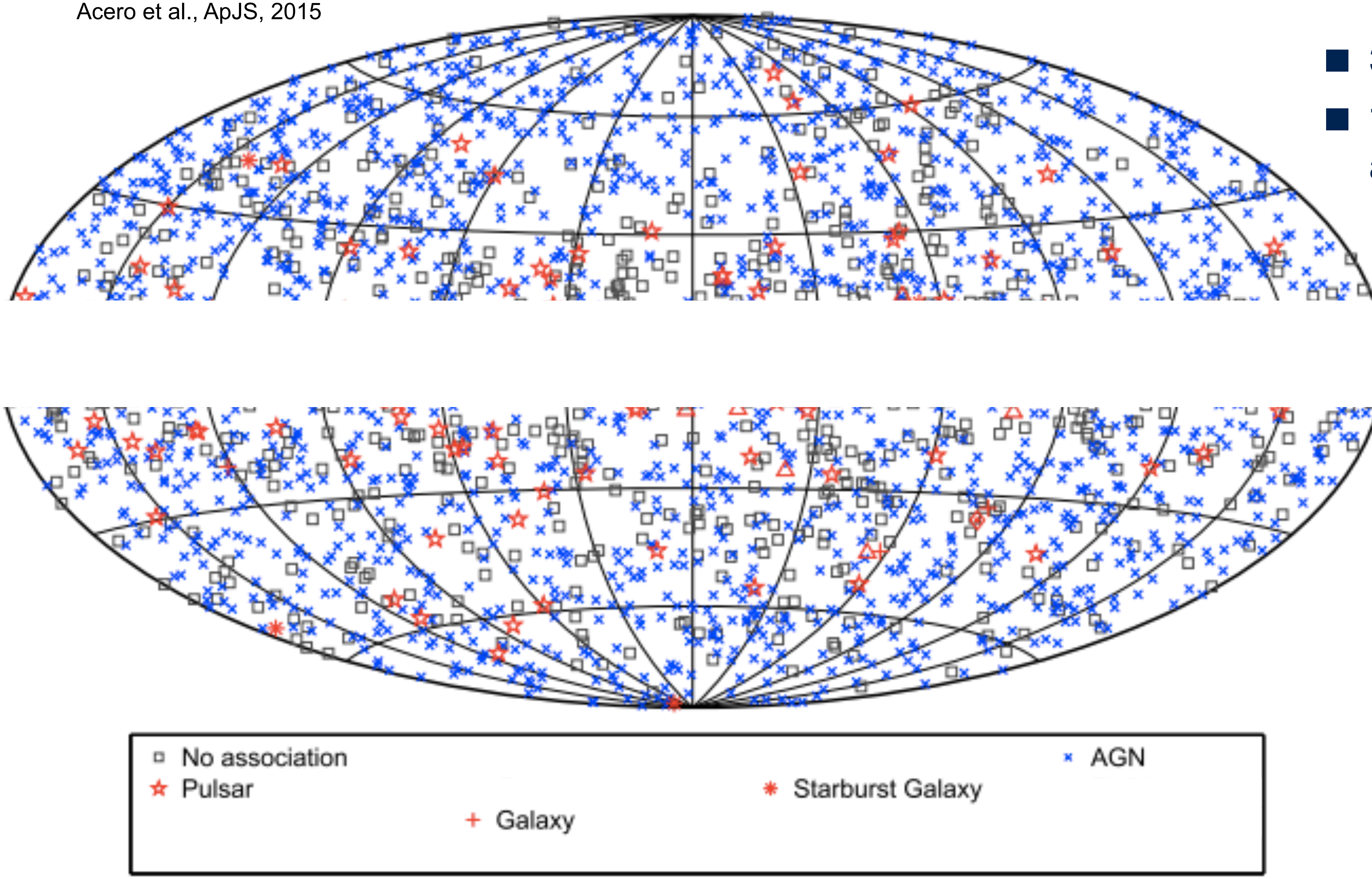



- 3033 sources
- 1010 without association

- 3rd catalog of LAT gamma-ray sources (3FGL) published in 2015
- 4 years of LAT data (pass7 event analysis)

# The extragalactic sky

Acero et al., ApJS, 2015

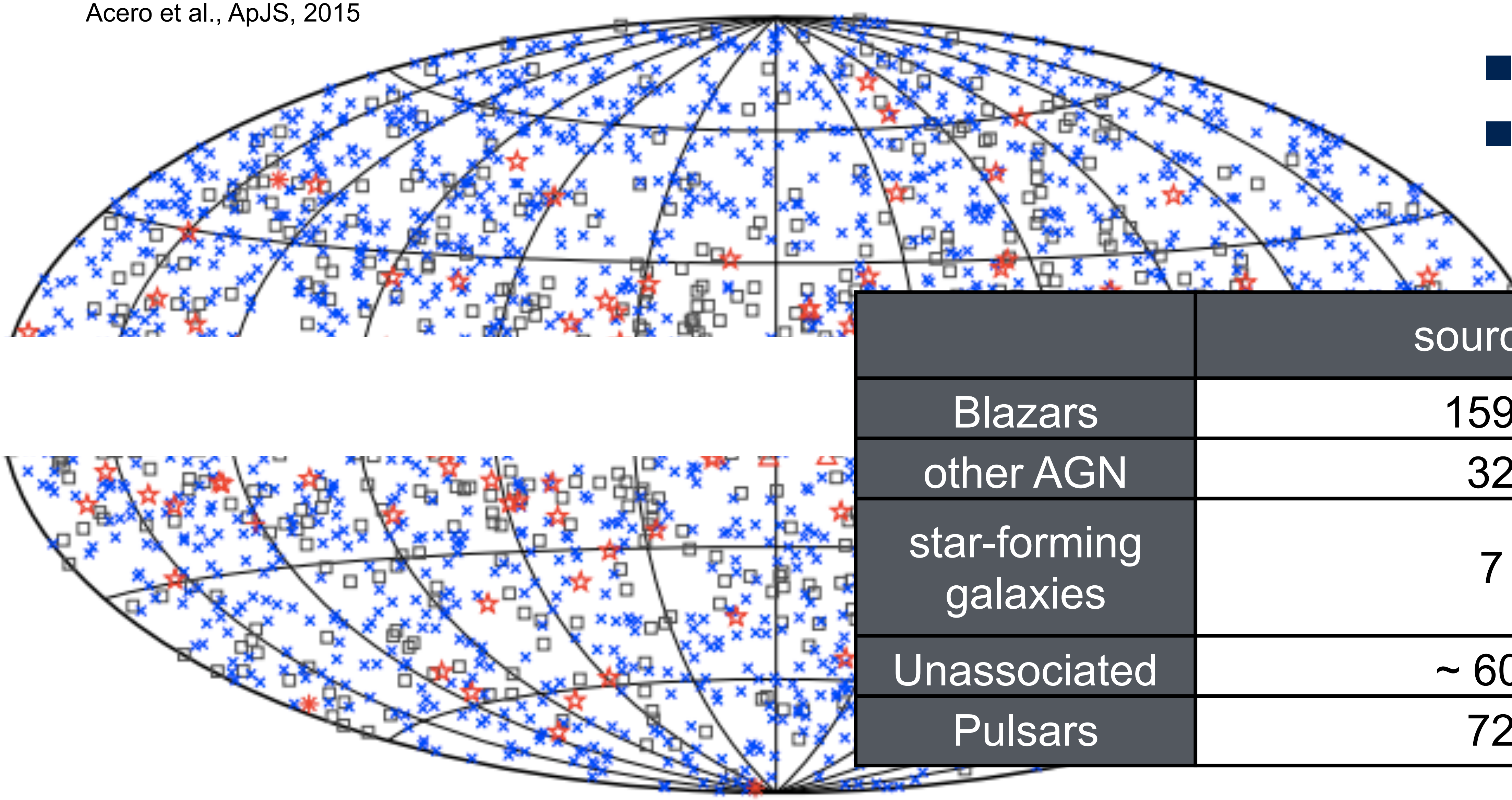



- 3033 sources
- 1010 without association

- Only few populations in the extragalactic sky
- Most high-latitude sources are Blazars
- Transients are not in this catalog (GRBs)

# The extragalactic sky

Acero et al., ApJS, 2015



- 3033 sources
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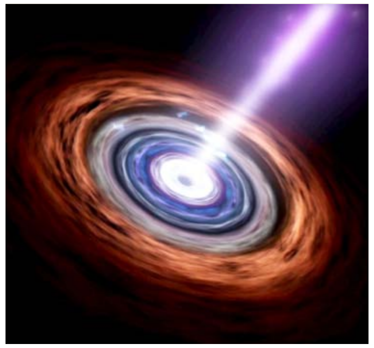
| | sources |
|---|---|
| Blazars | 1591 |
| other AGN | 32 |
| star-forming galaxies | 7 |
| Unassociated | ~ 600 |
| Pulsars | 72 |

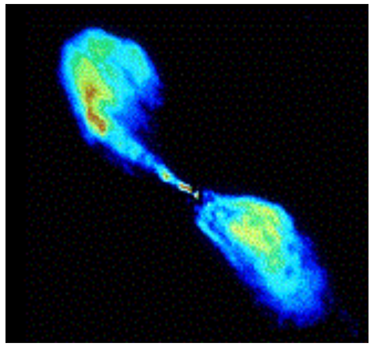

- Only few populations in the extragalactic sky
- Most high-latitude sources are Blazars
- Transients are not in this catalog (GRBs)

# The origin of the IGRB in the LAT energy range.

## Undetected sources

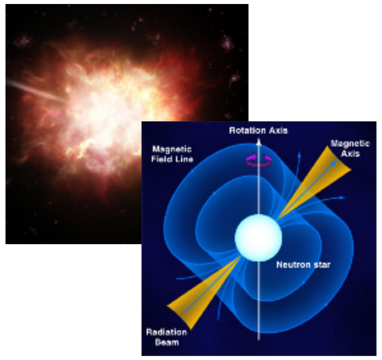


### Blazars
- Dominant class of LAT extra-galactic sources.



### Misaligned active Galaxies
- 27 sources resolved in 2FGL.

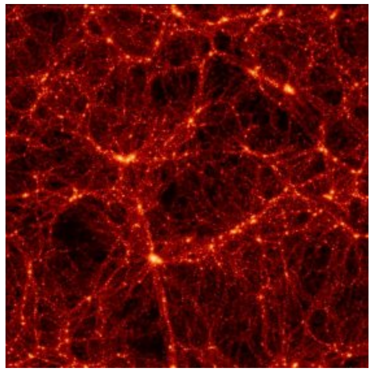
### Star-forming galaxies
- Some galaxies outside the local group resolved by LAT.



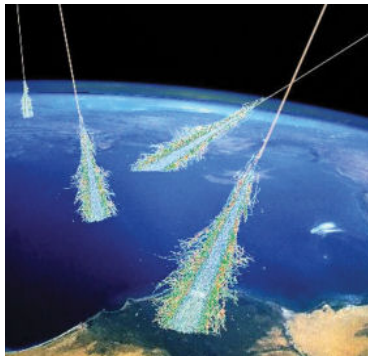

### GRBs + High-latitude pulsars
- Only small contributions expected.

## Diffuse processes

### Intergalactic shocks
- produced in galaxy cluster mergers

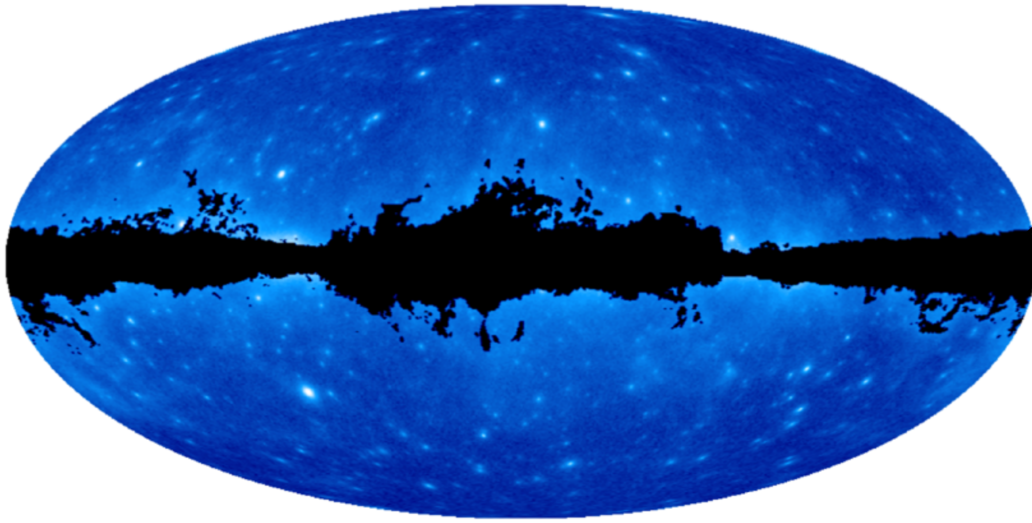


### Dark matter annihilation
- Potential signal dependent on nature of DM.



### Interactions of UHE cosmic rays with the EBL
- Strongly dependent on evolution of UHECR sources..

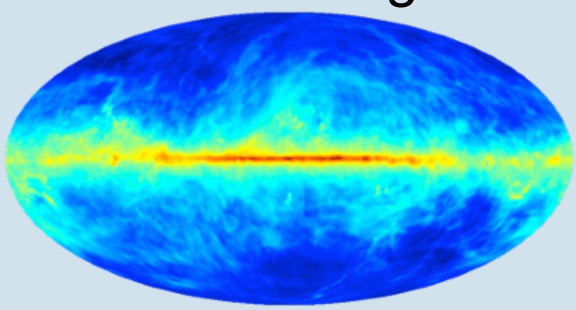
# Derivation of the isotropic gamma-ray background.



=

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

Interstellar gas



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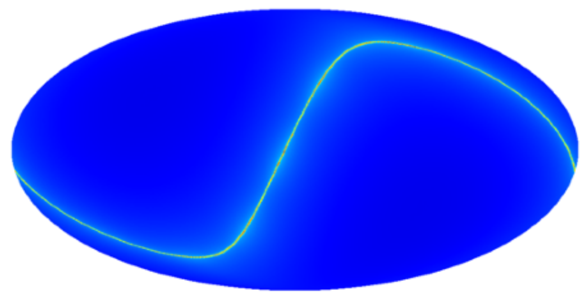
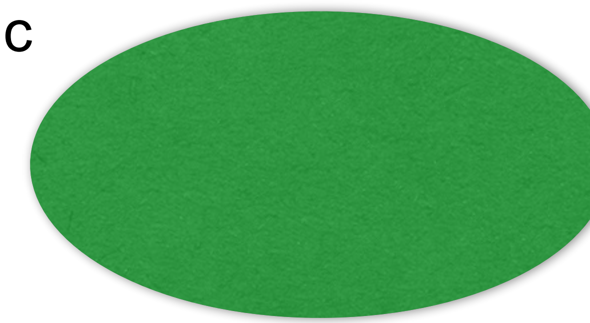
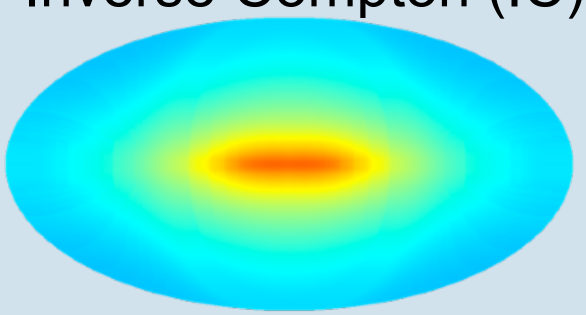
Solar disk and IC



Isotropic γ-ray back-ground (IGRB)



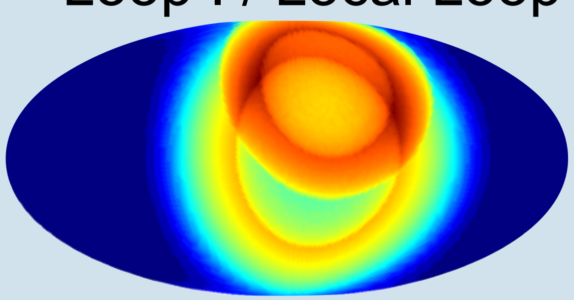
Inverse Compton (IC)



+

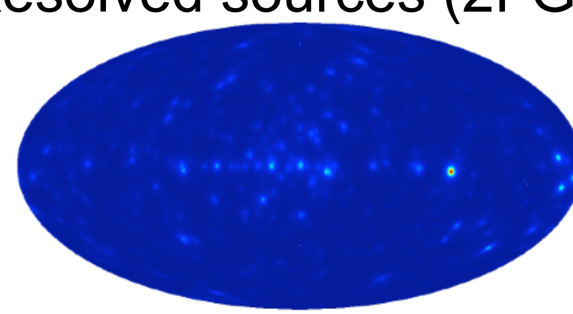
Isotropic emission

Loop I / Local Loop

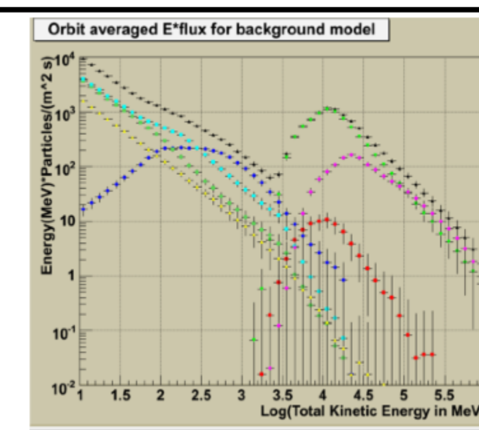


+

Resolved sources (2FGL)

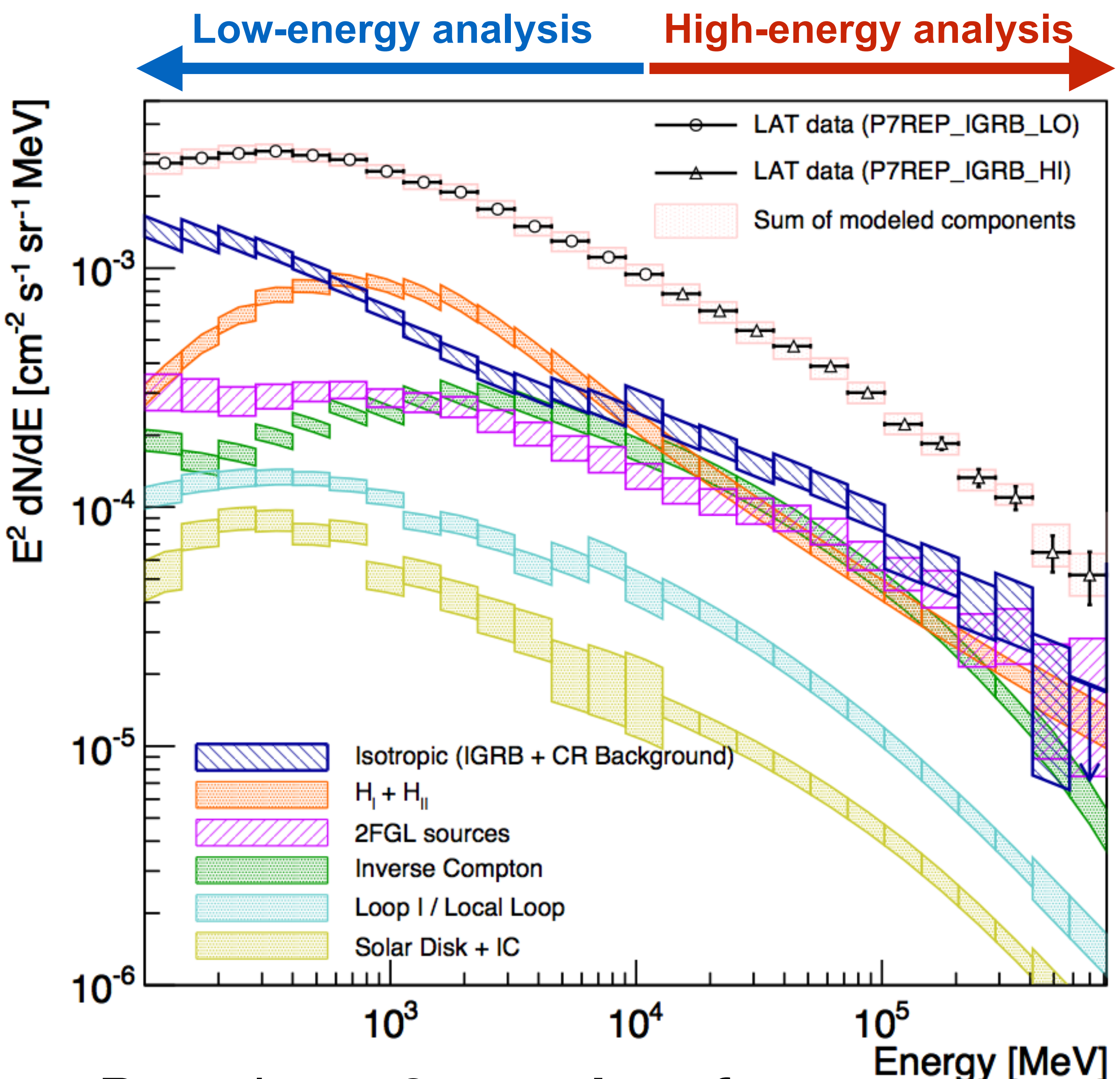


Contami-nation from CR induced background



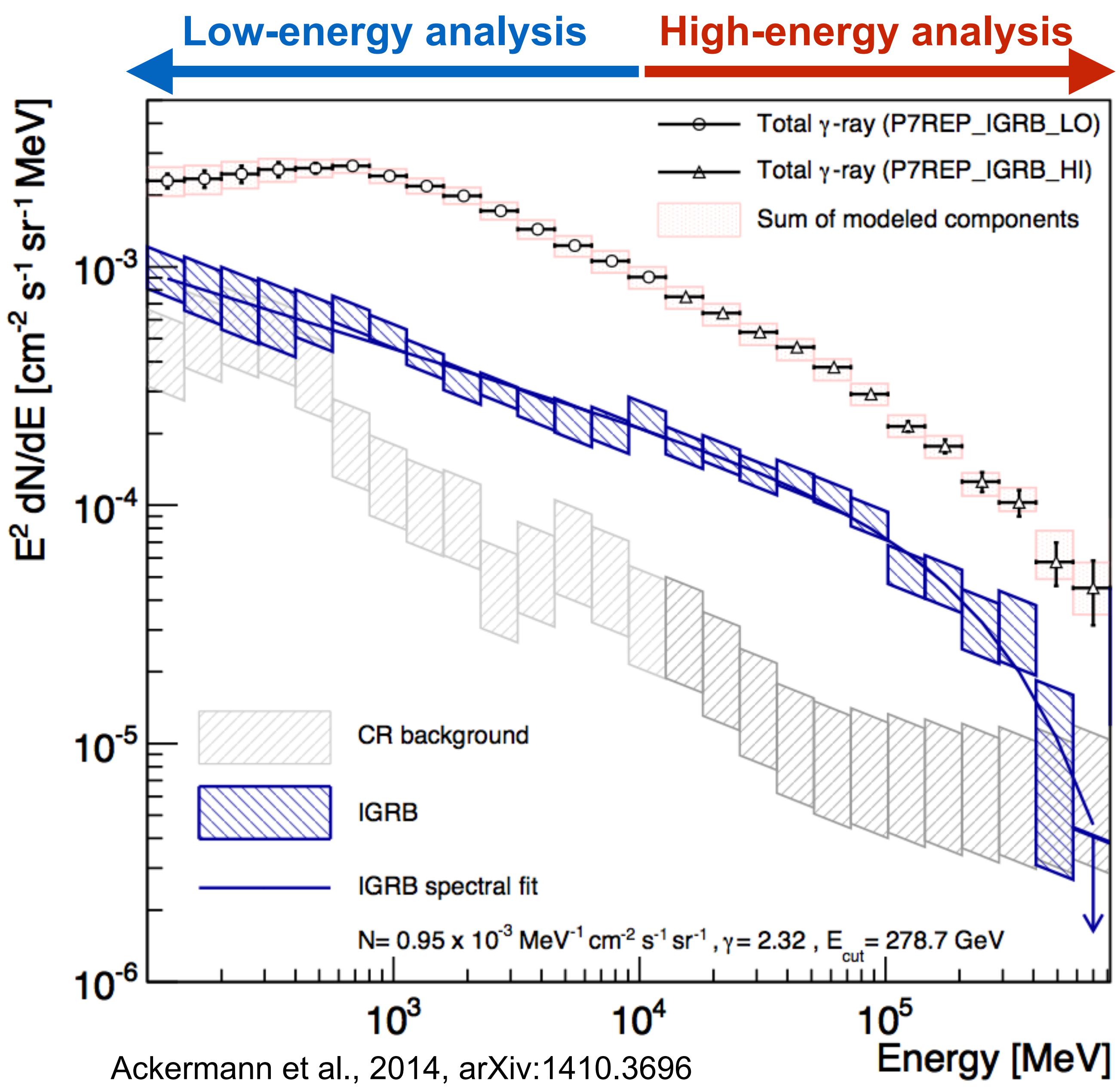

Galactic diffuse emission

# Results from the IGRB fit.




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

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



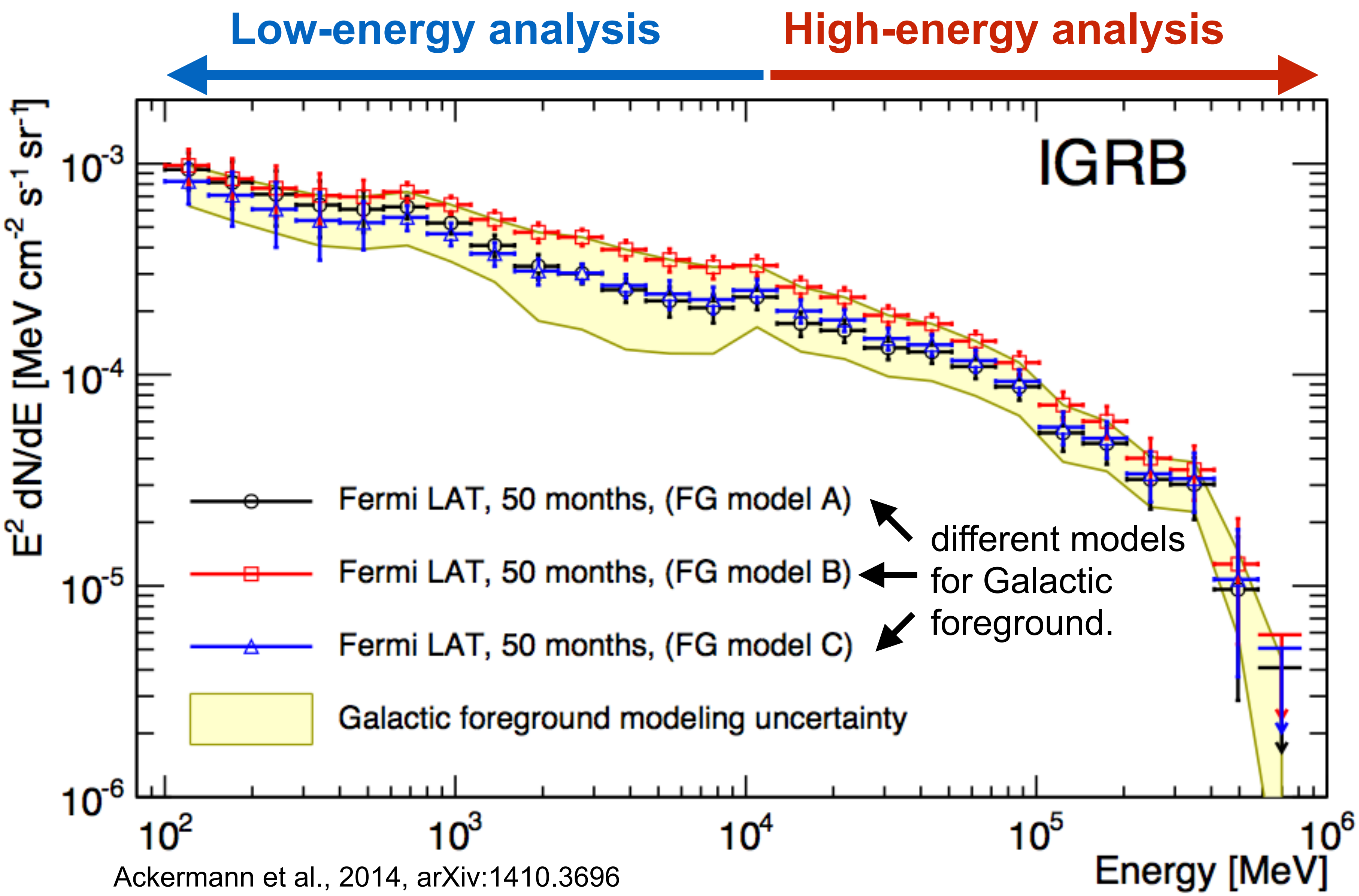

Ackermann et al., 2014, arXiv:1410.3696

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

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

> **Baseline foreground model** used.

# The IGRB spectrum




Ackermann et al., 2014, arXiv:1410.3696

> **Error bars**:
>
> statistical error
>
> + syst. error from effective area parametrization
>
> + syst. error from CR background subtraction

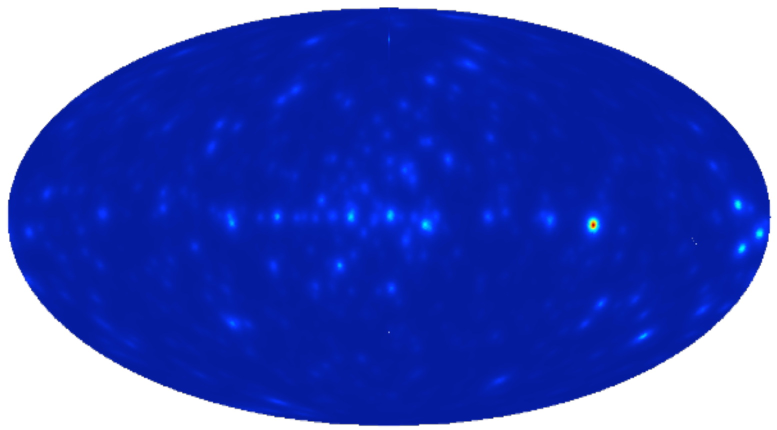
> **Yellow band:** systematic uncertainties from foreground model variations.

> **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** ($\chi^2 > 85$).

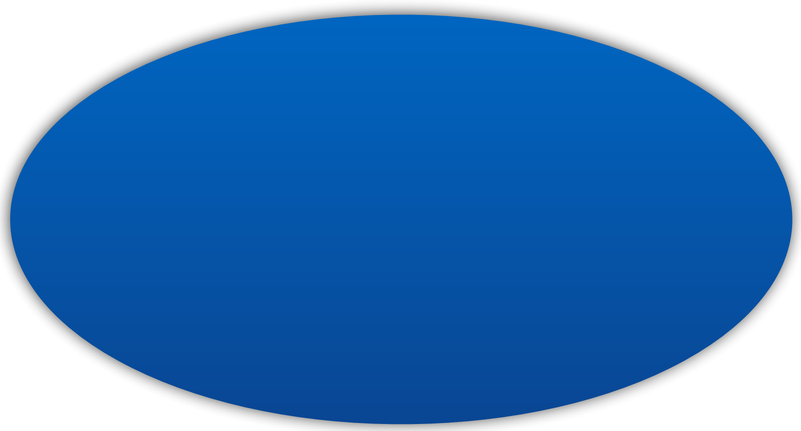
# The isotropic and the total extragalactic background.



Resolved sources

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

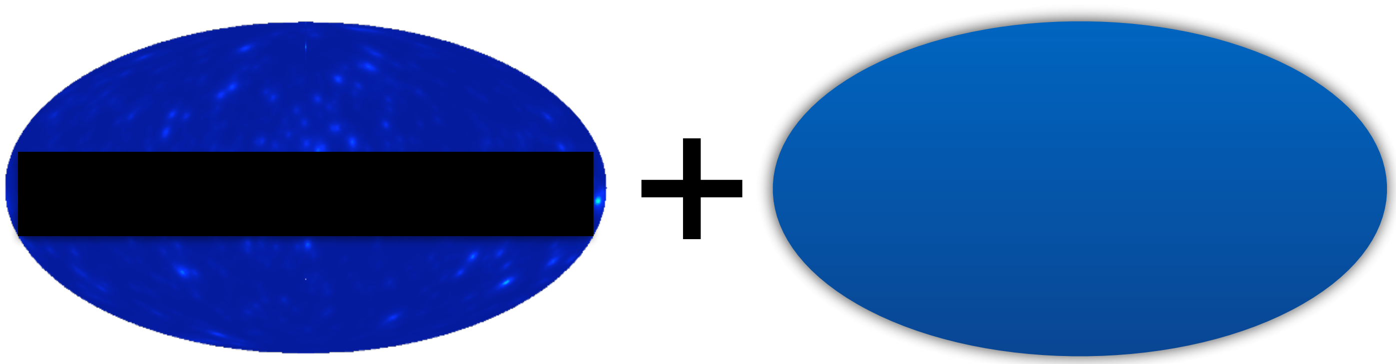
- the sensitivity of the instrument.
- the exposure of the observation.



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.**

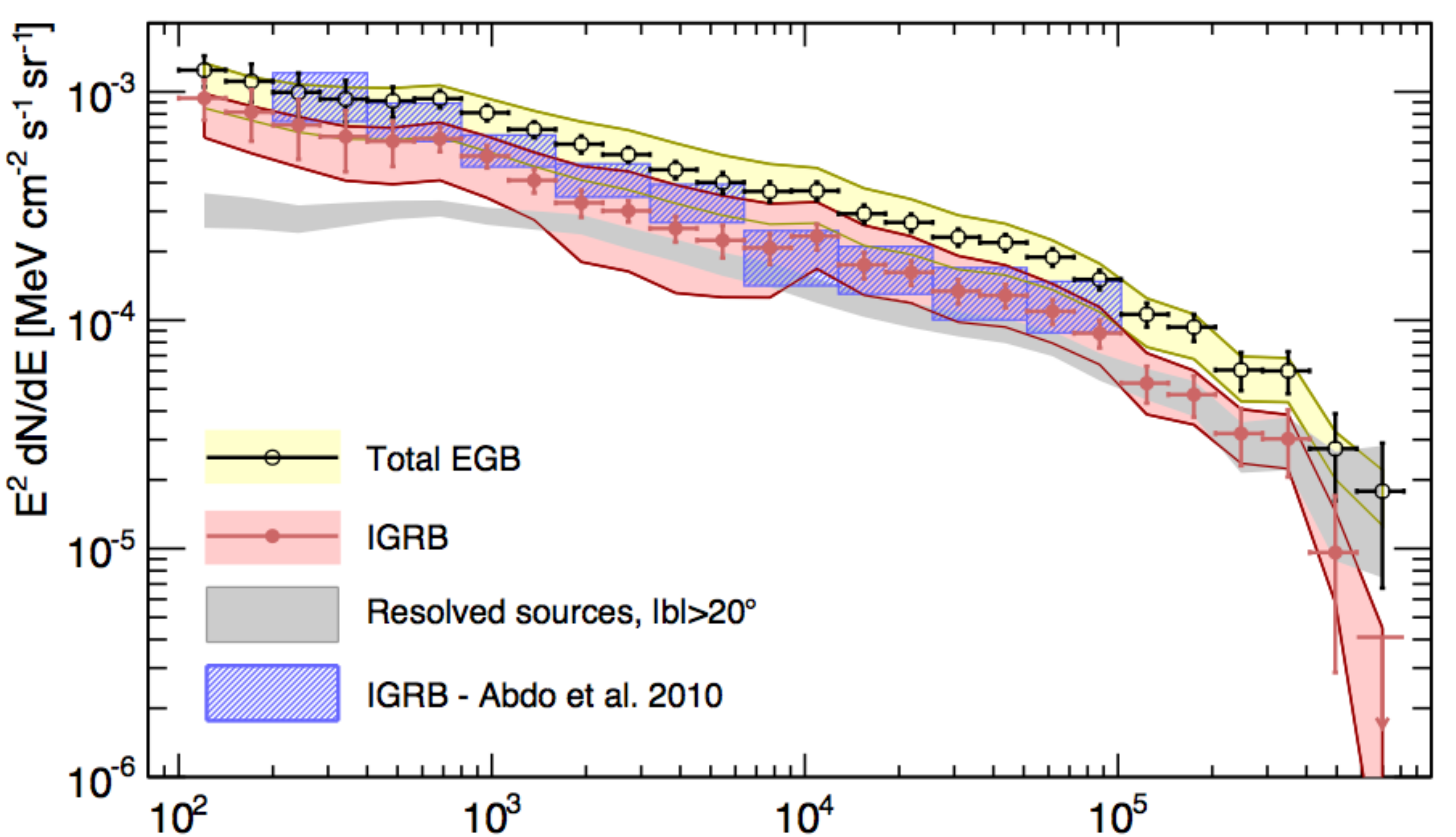


**Total extragalactic γ-ray background (EGB)**

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

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

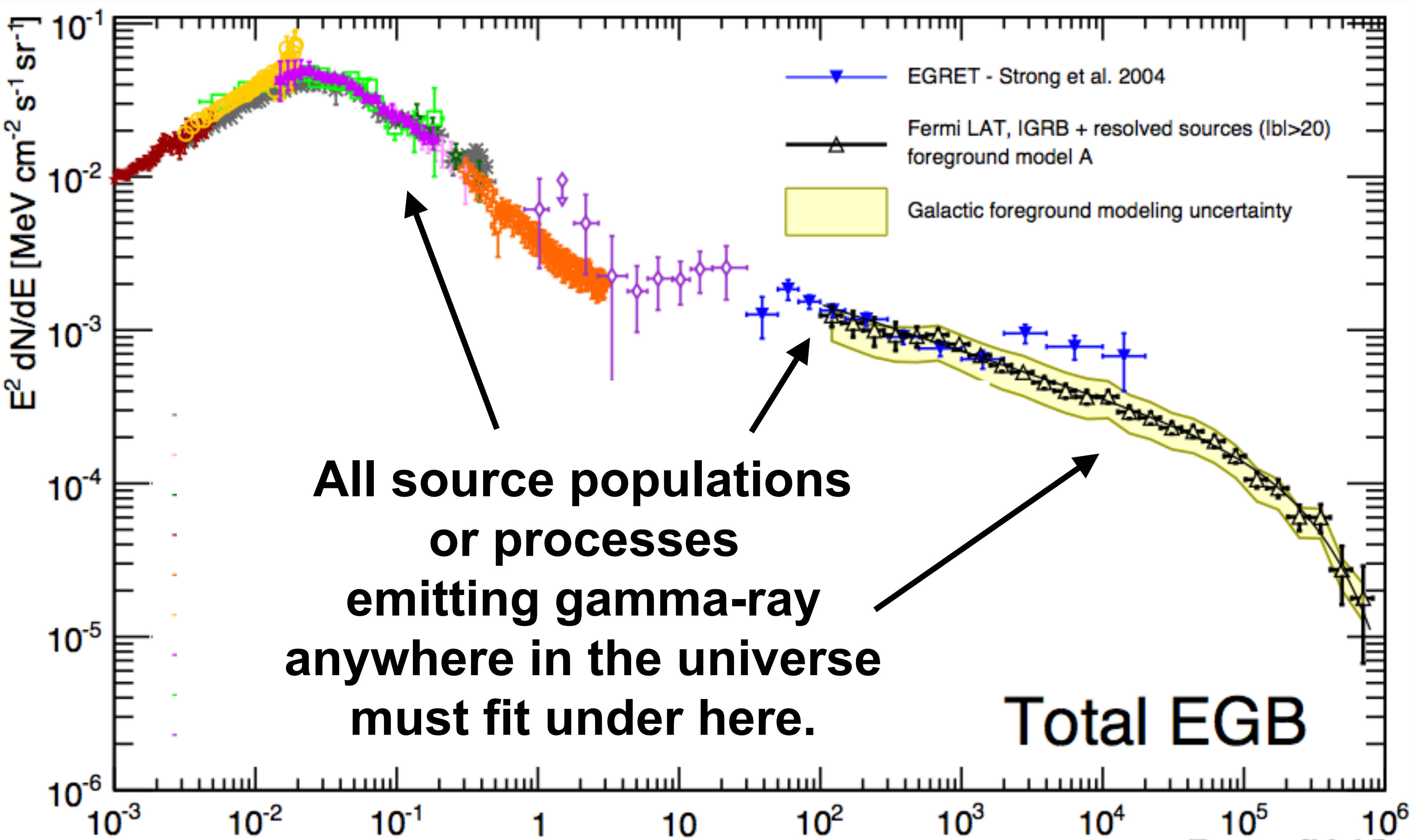
# Comparison of LAT IGRB and EGB measurements




Ackermann et al., 2014, arXiv:1410.3696

> Total extragalactic gamma-ray background (EGB) = IGRB + resolved sources.
> **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.

# Why is it so important?

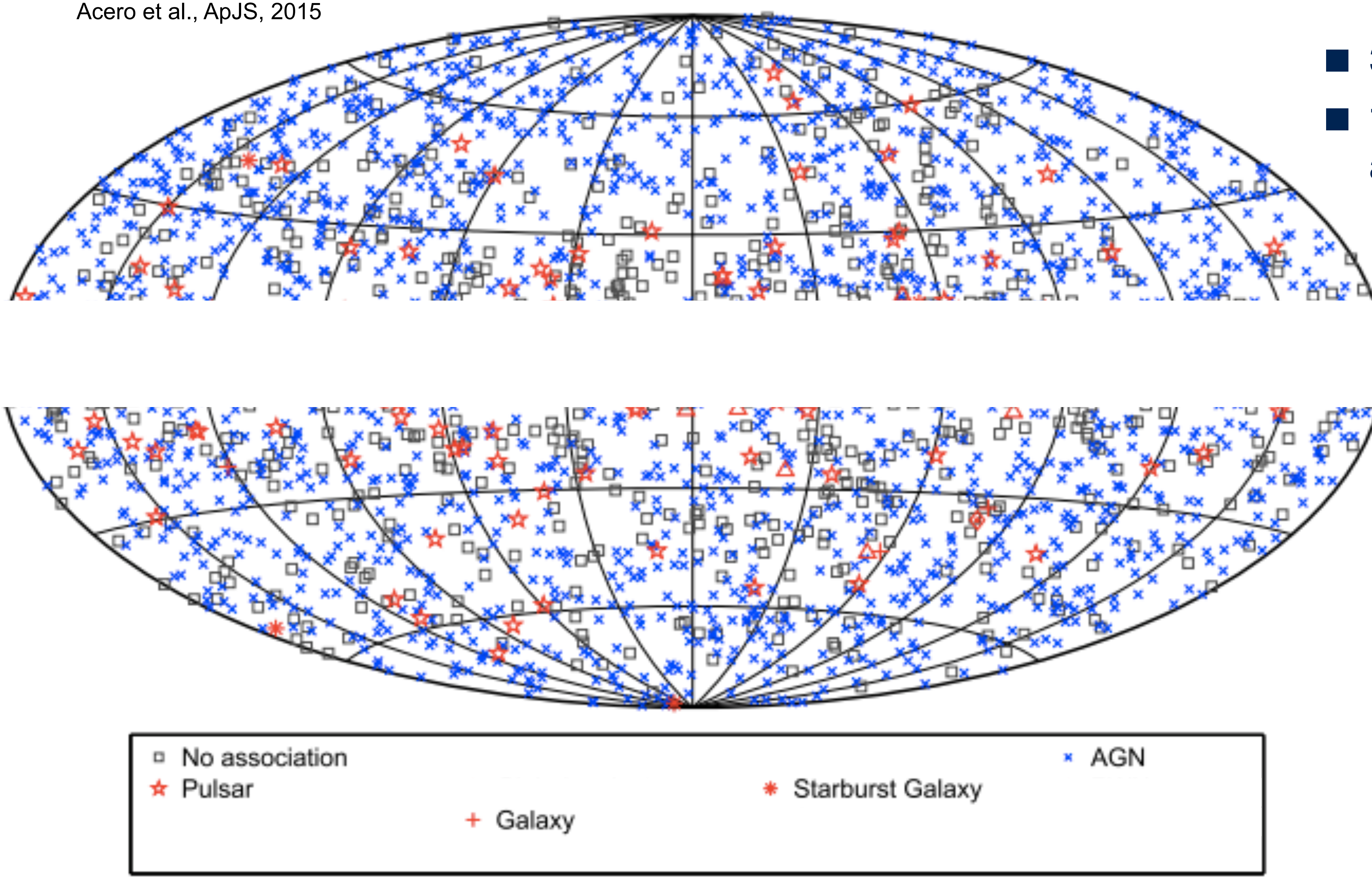



Ackermann et al., 2014, arXiv:1410.3696

- Cosmic x-ray and gamma-ray background now **measured over 9 orders of magnitude in energy**.
- The universe is transparent to gamma-rays (E<~10 GeV) to z > 10.

# The extragalactic sky

Acero et al., ApJS, 2015

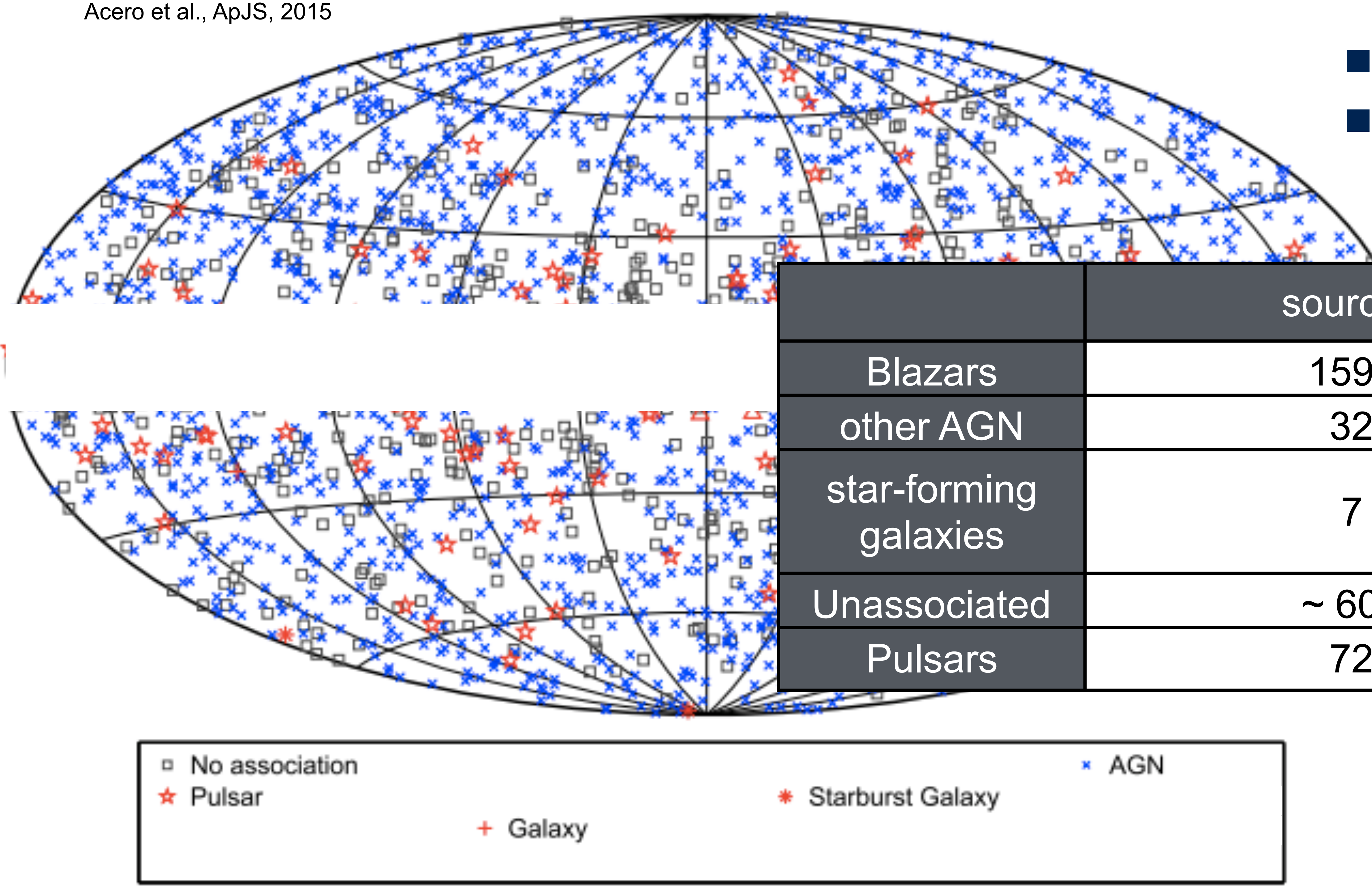



- 3033 sources
- 1010 without association

**What is the contribution of the different source classes ?**

# The extragalactic sky

Acero et al., ApJS, 2015

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

**What is the contribution of the different source classes ?**

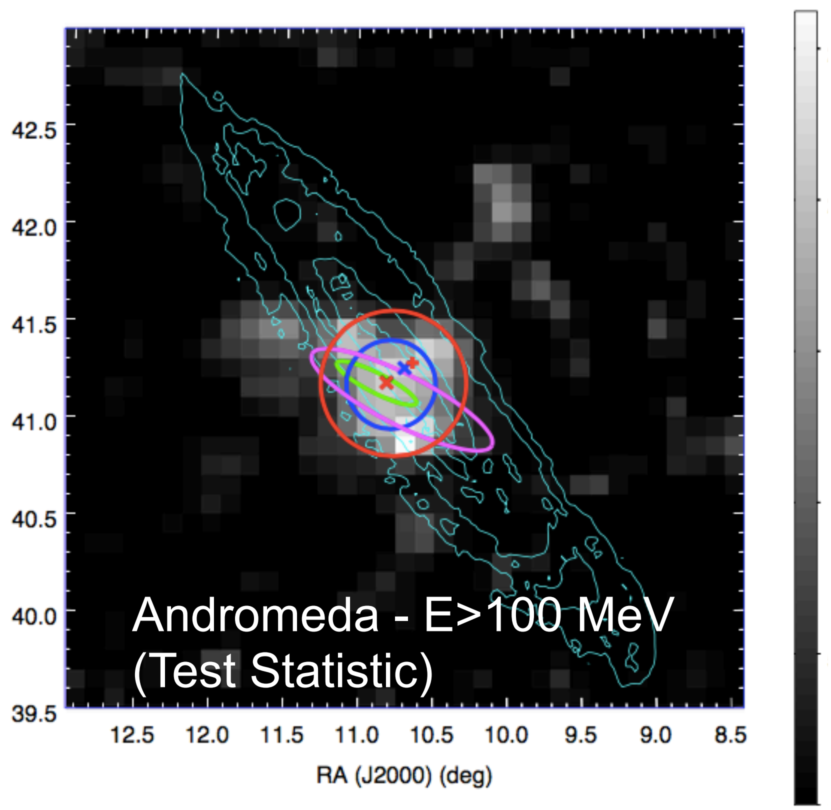
# Star-forming / Starburst Galaxies.

"normal" star-formation rate

extreme star-formation rate "starburst"

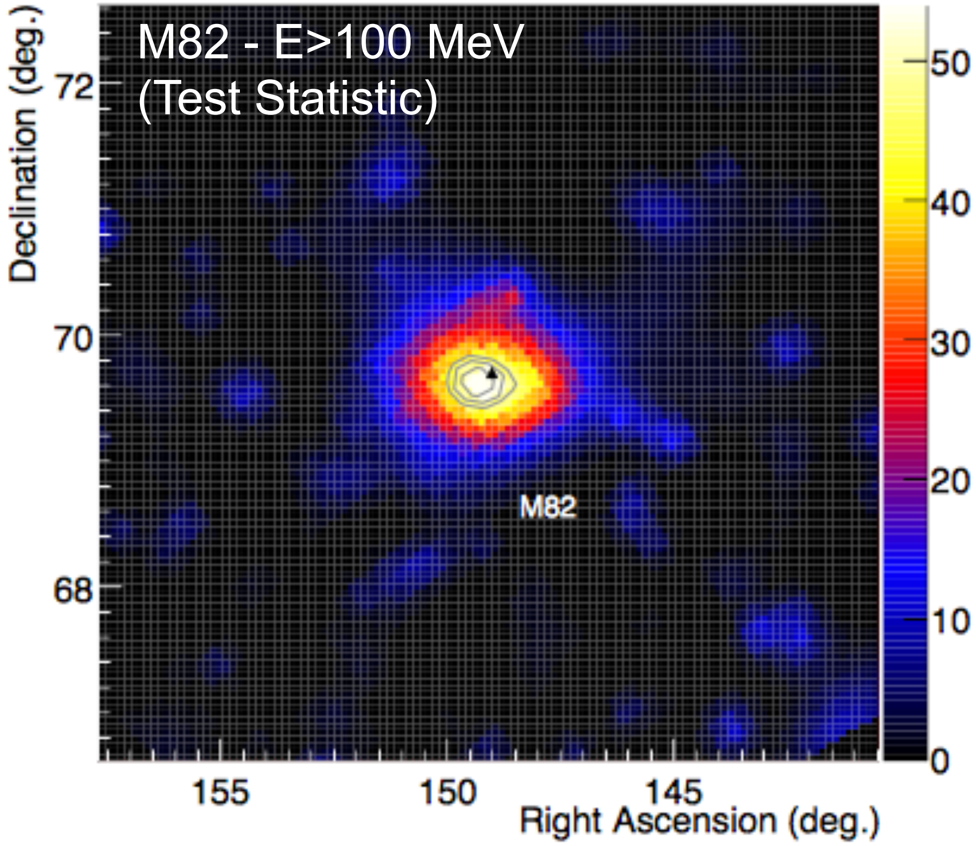


LAT collaboration, 2017




d=600 kpc

Abdo et al., 2010



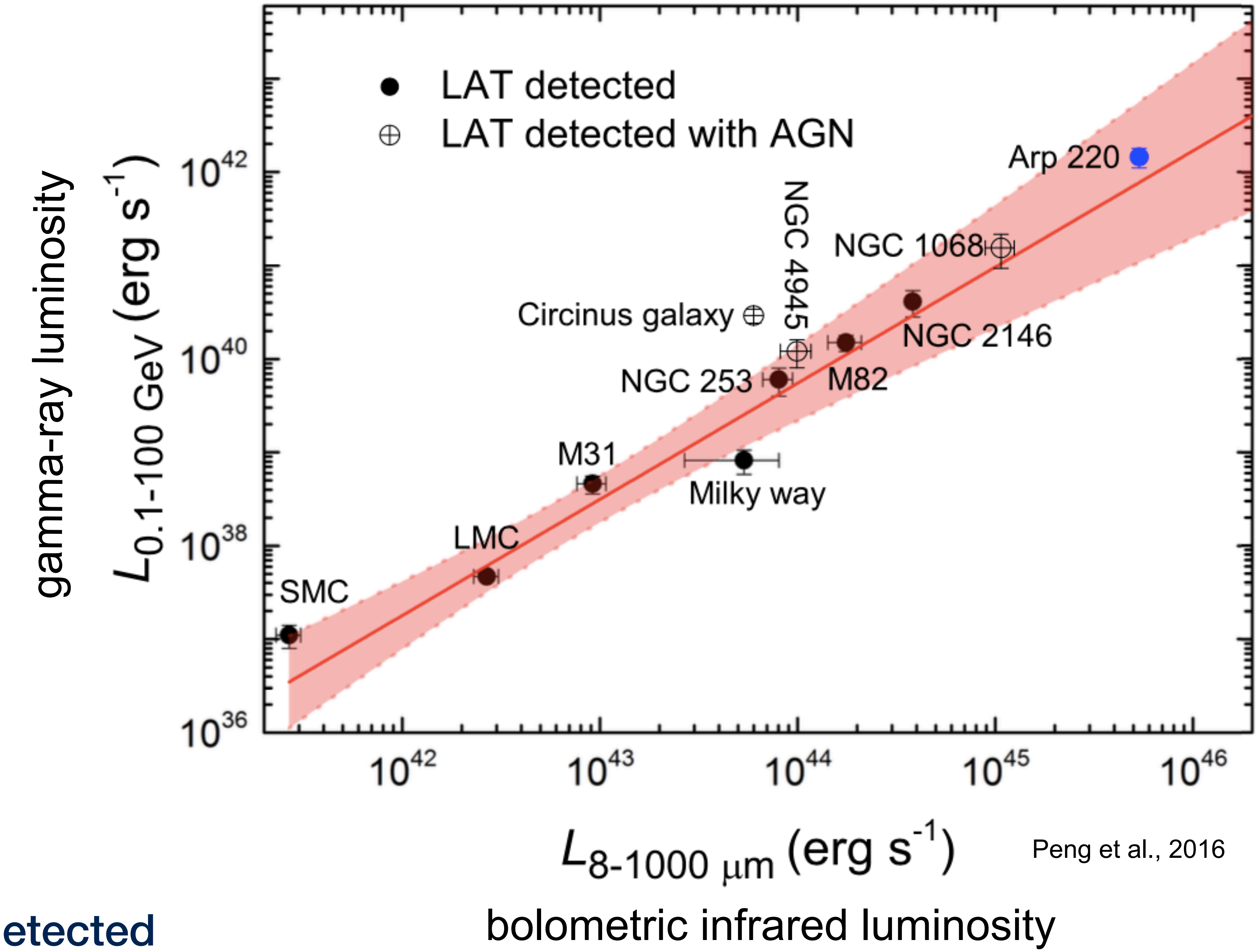

d=4 Mpc

- 7 **starburst galaxies** detected with the LAT
- 4 local **"normal" galaxies** detected.
  - Andromeda, LMC, SMC & Milky Way
- Weak gamma-ray sources, but very abundant in the universe

# Star-forming galaxies

M82

Milky Way

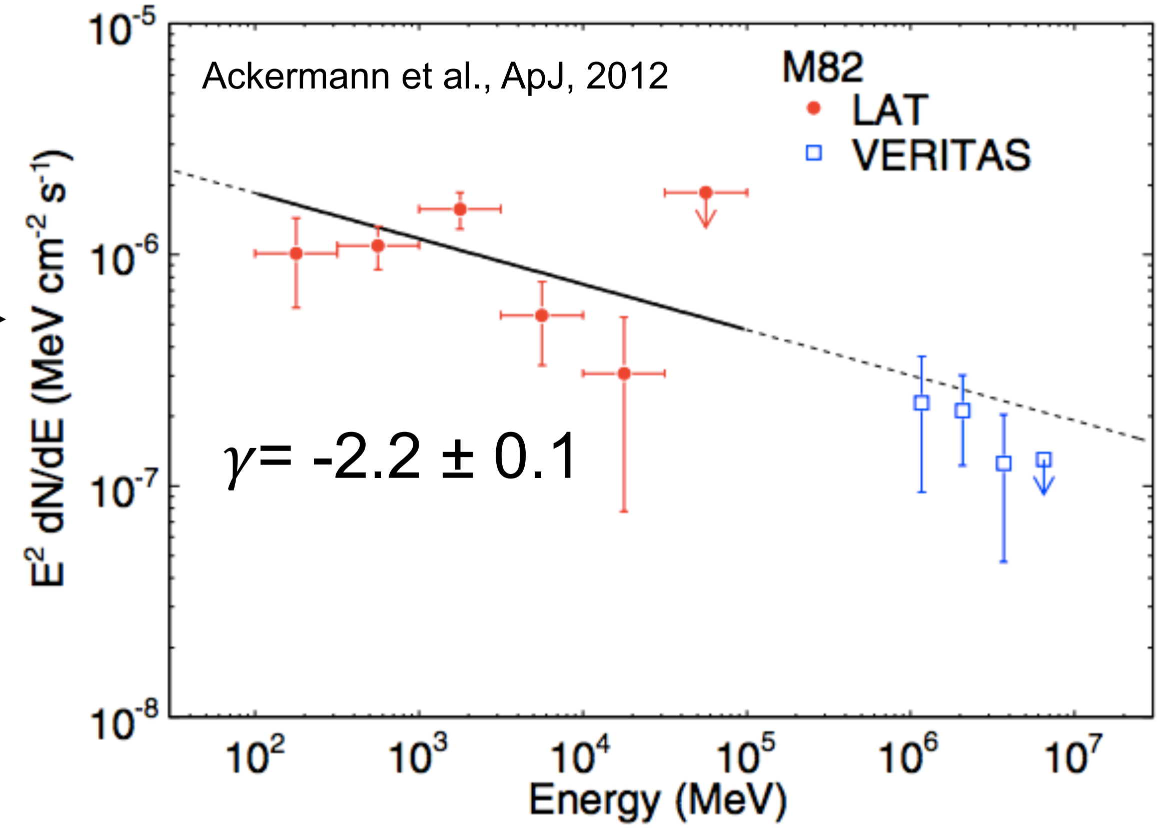



Peng et al., 2016

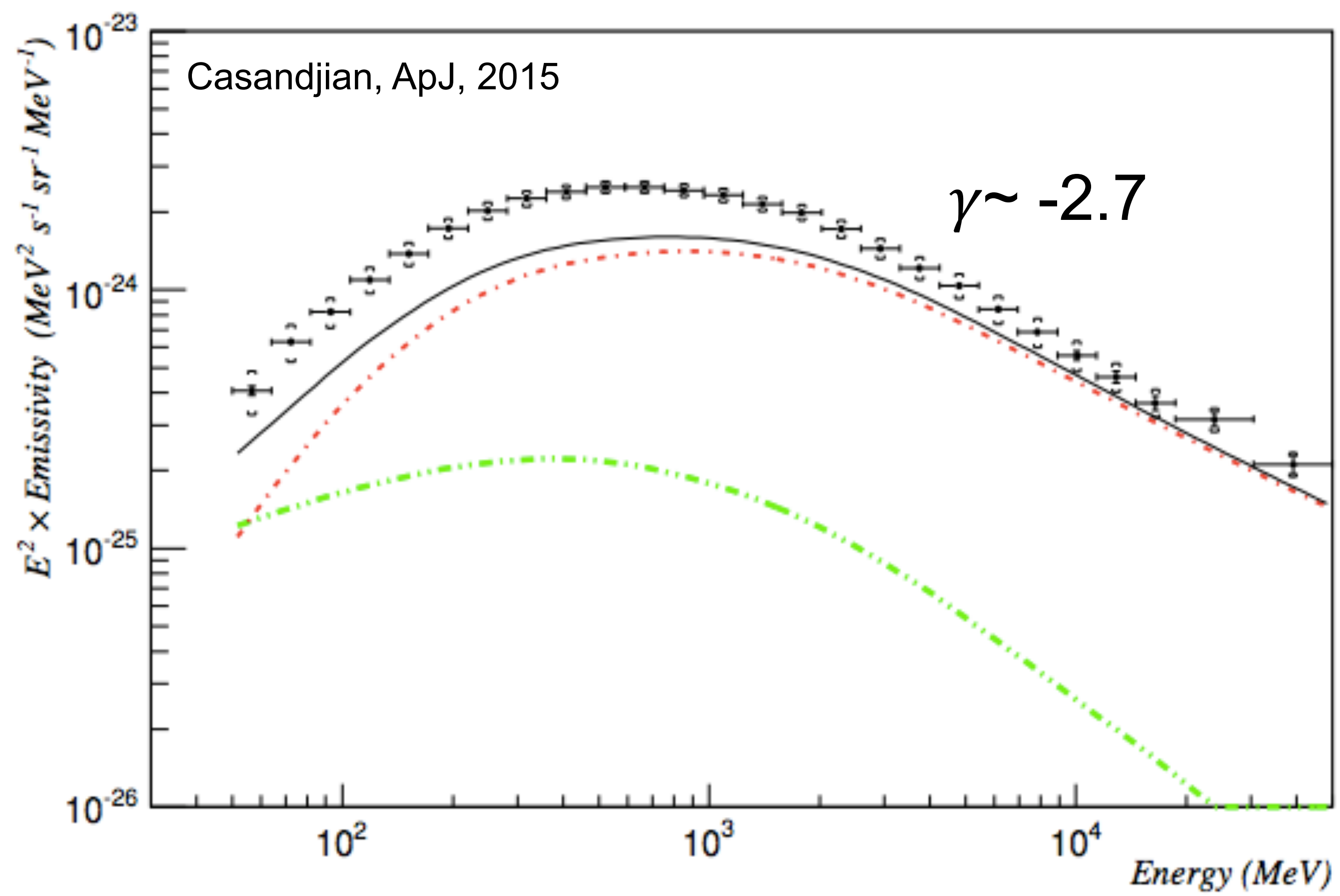
- Only 8 local galaxies detected (4 regular / 4 starburst)
- Use correlation of gamma-ray emission to star-formation rate to estimate their total contribution to the gamma ray sky

# Gamma-ray spectrum of local star-forming galaxies

M82

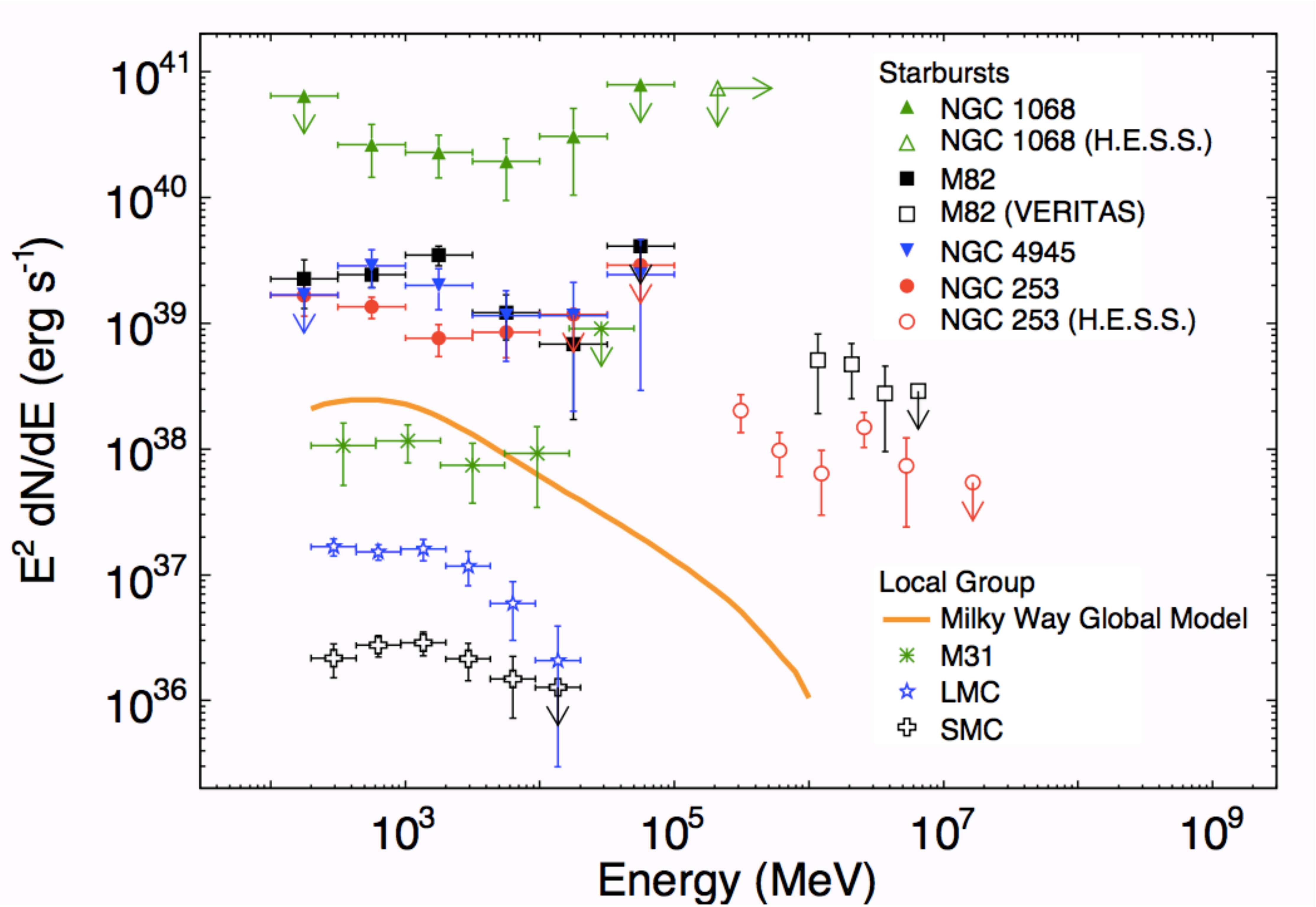



Milky Way



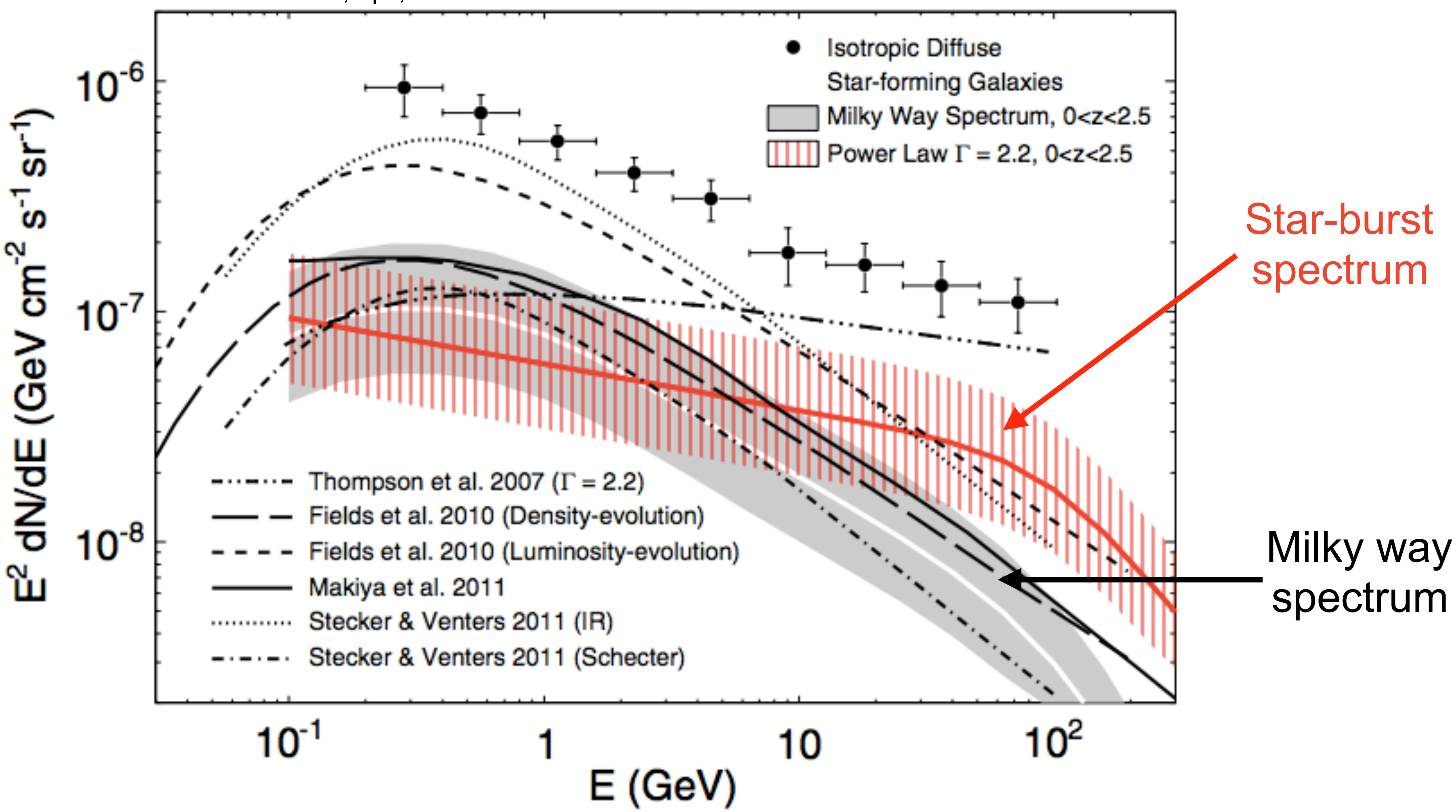

- Large spectral variations between “normal” galaxies and starburst galaxies

# Gamma-ray spectra of star forming galaxies



# Star-forming galaxies

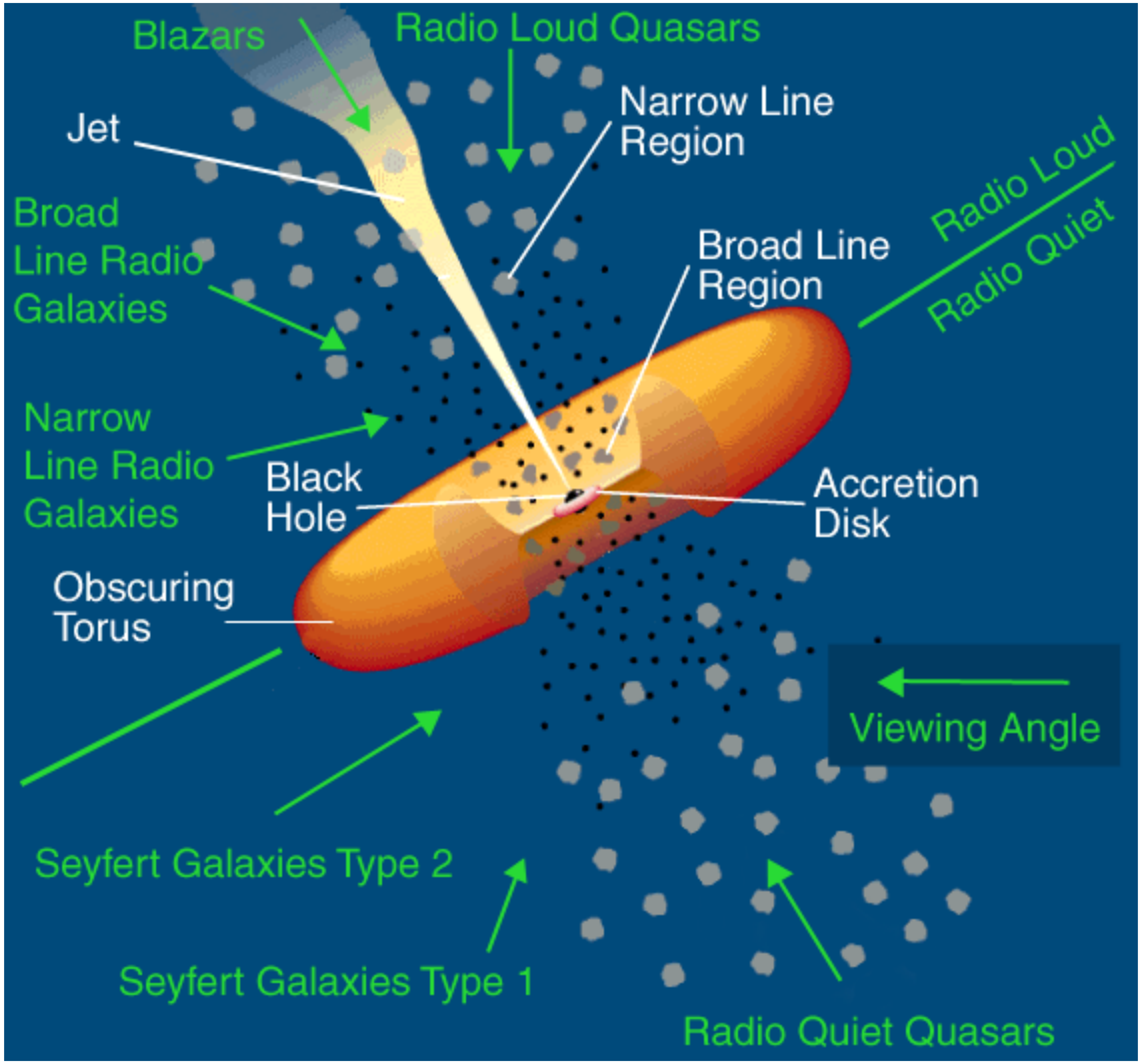
Ackermann et al., ApJ, 2012




- Small contributions on the level of 20% of the EGB
- Spectral variations lead to very different predictions if you try to extrapolate the contribution to higher energies.

# Active Galactic Nuclei

> The overwhelming majority of extragalactic LAT sources are Active Galactic Nuclei (AGN)

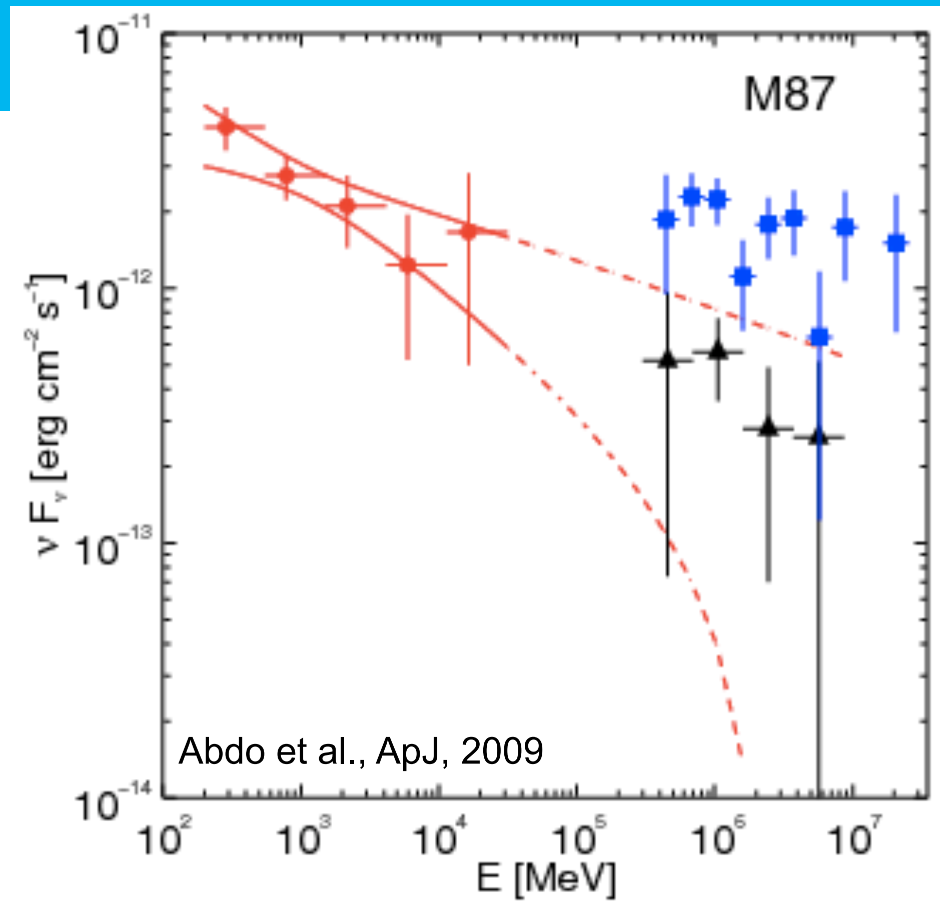



> **Blazars:**
- Observer line-of-sight into the relativistic jet
- Relativistic doppler boost of intensities

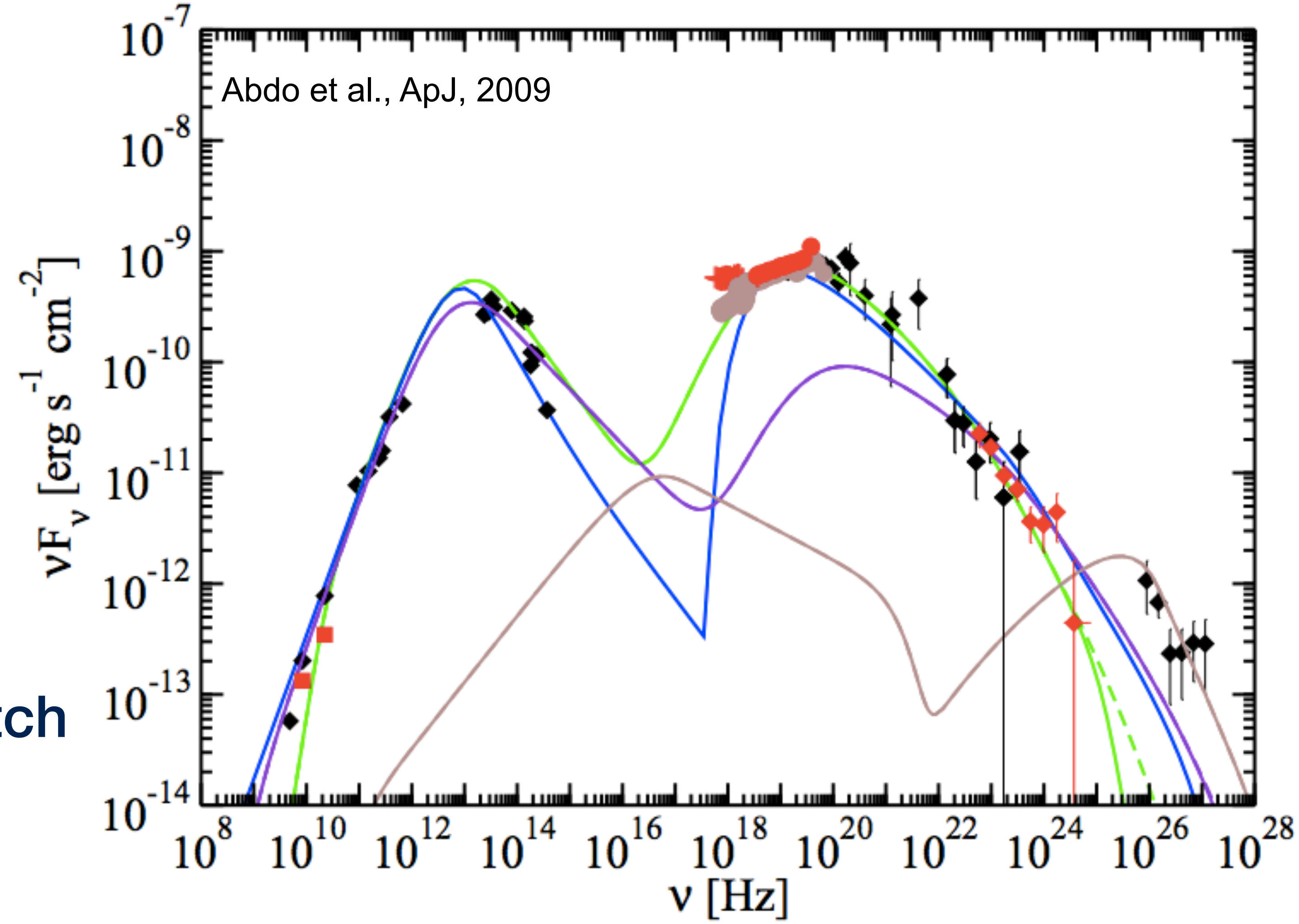
> **Misaligned AGN:**
- Large viewing angle to jet
- Characterization by radio emission properties

# Spectra of nearby AGN

M87



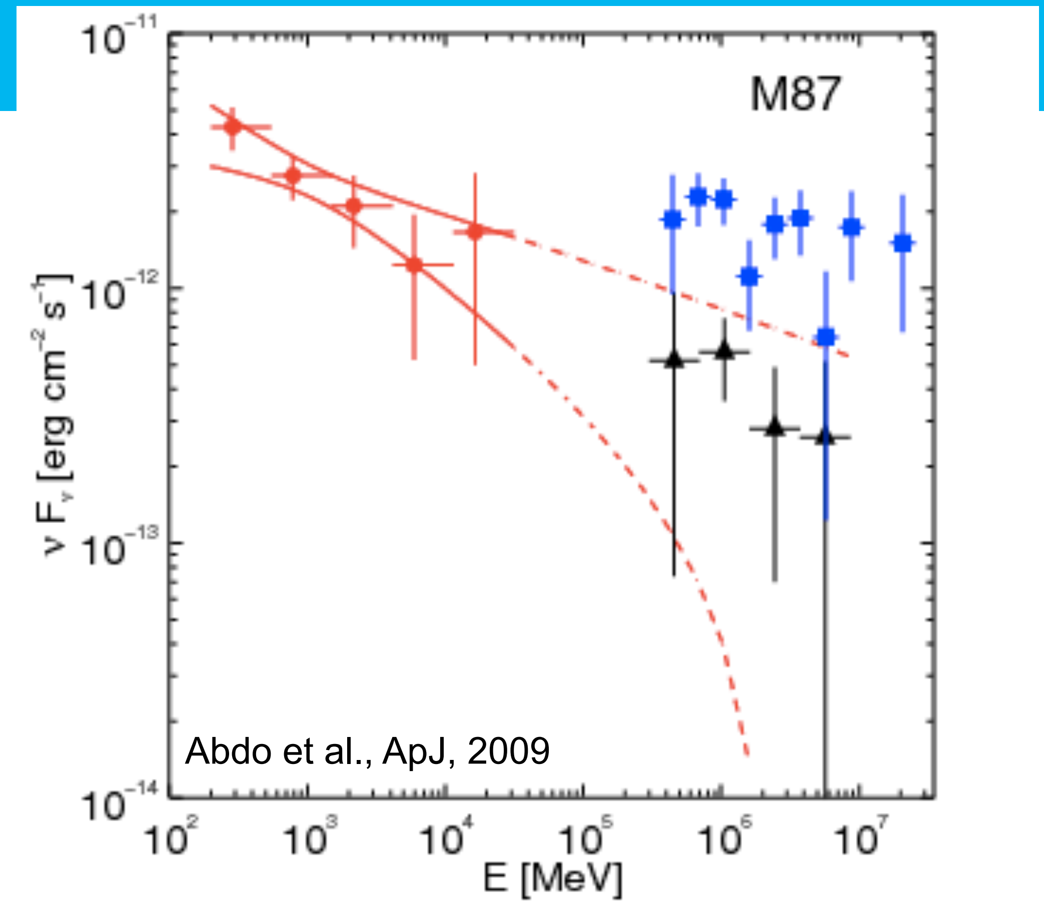

Centaurus A



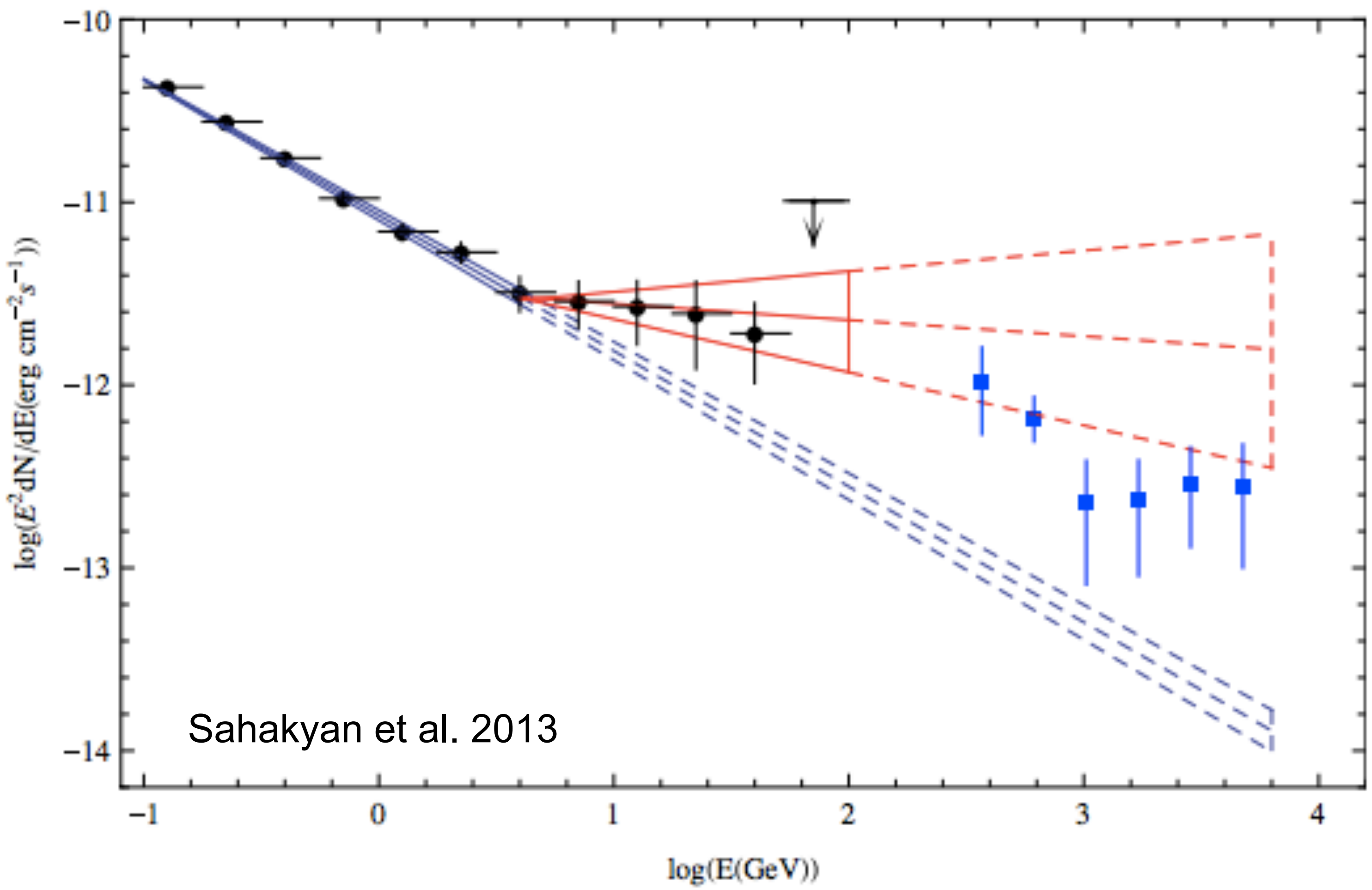

- Complicated:
  - GeV-TeV spectra do not match
  - Variability

# Spectra of nearby AGN

M87

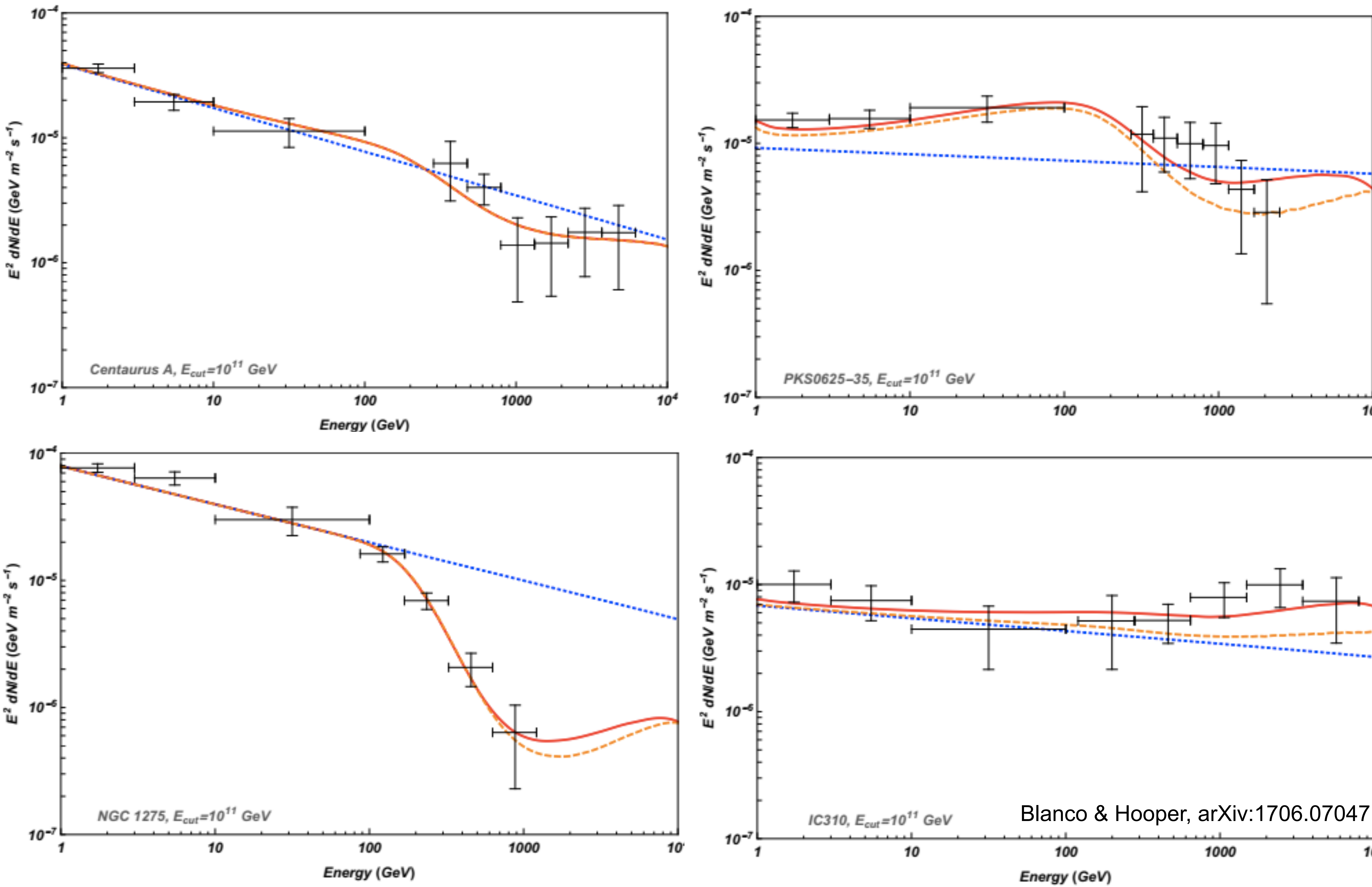



Centaurus A




- Complicated:
  - GeV-TeV spectra do not match
  - Variability

# Spectra of nearby Radio galaxies

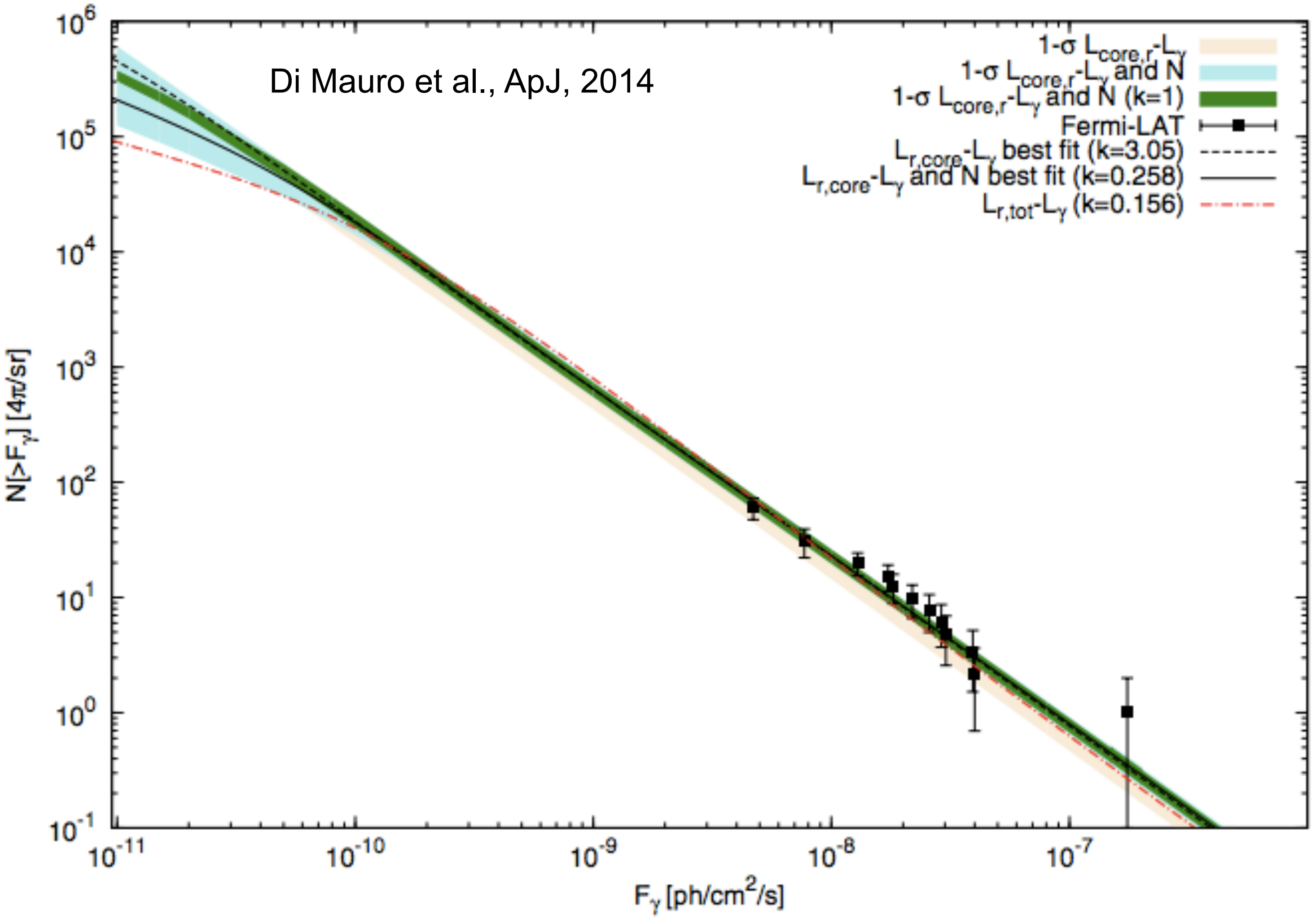



> Simple power-law + absorption models

# Total contribution of radio galaxies

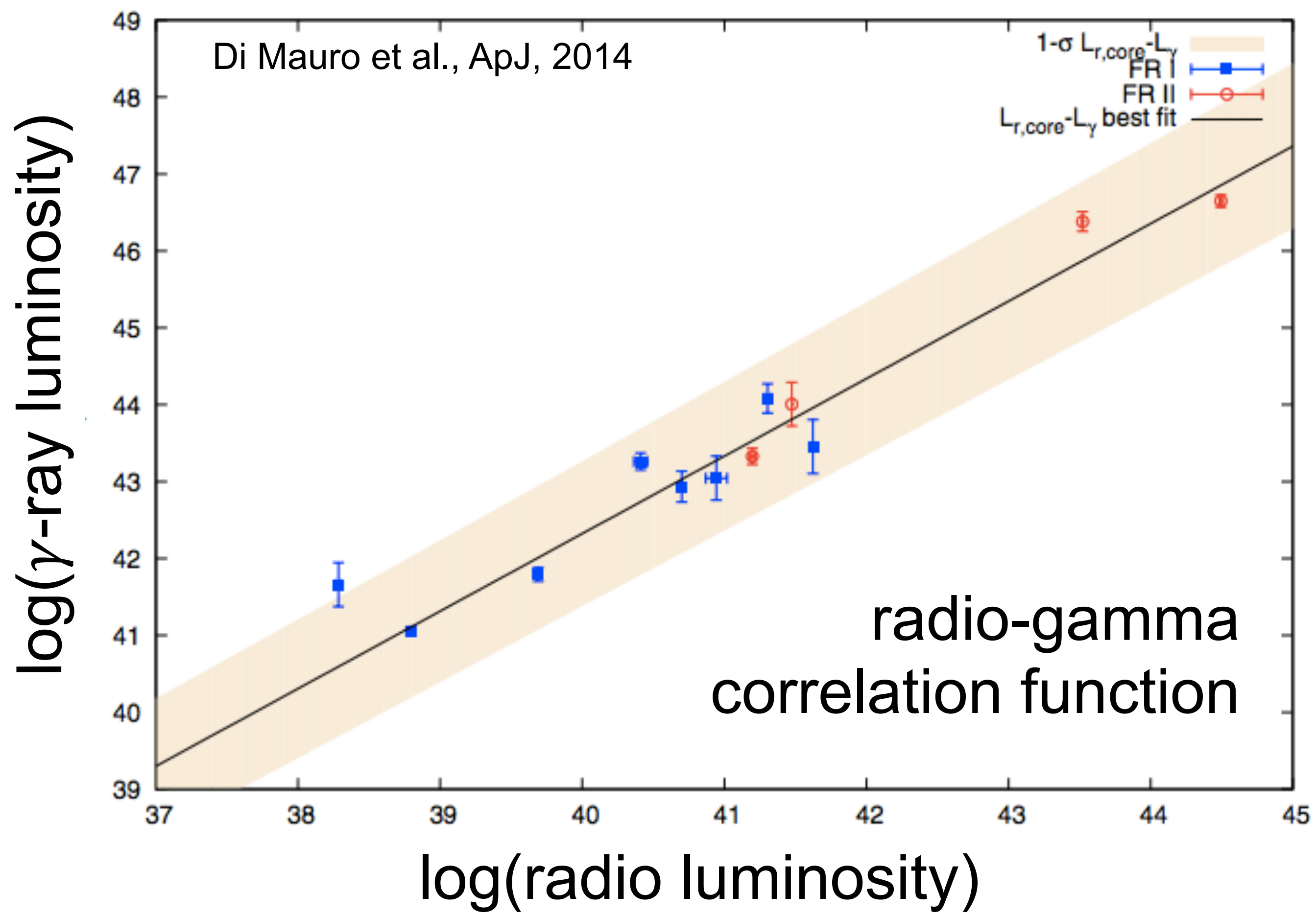
M87

Centaurus A



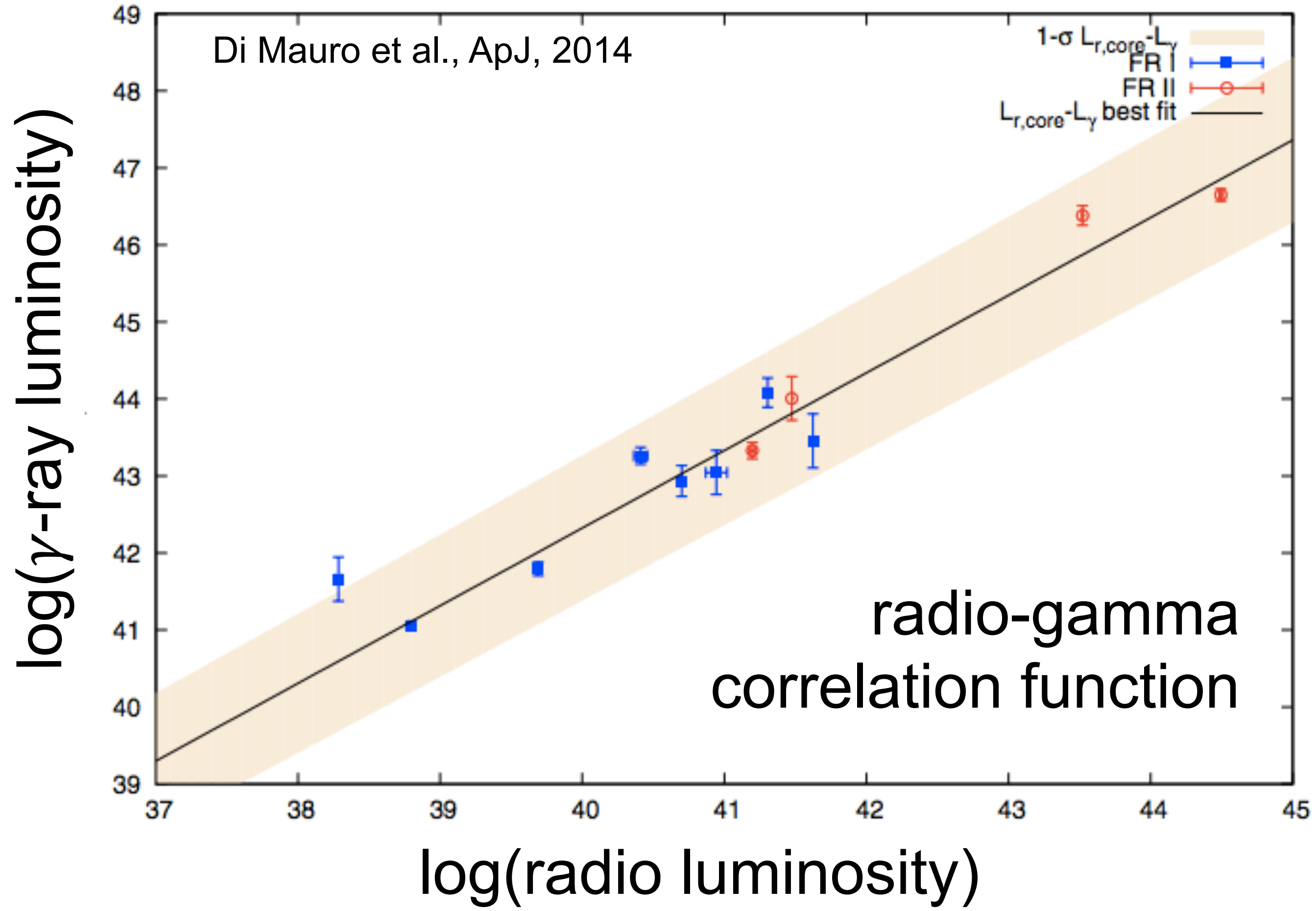

- Misaligned AGN: More abundant than Blazars, but lower luminosities
- Only 34 Radio Galaxies detected in 3rd LAT catalog
- Not enough to derive gamma-ray emission from source count distribution

# Total contribution of radio galaxies

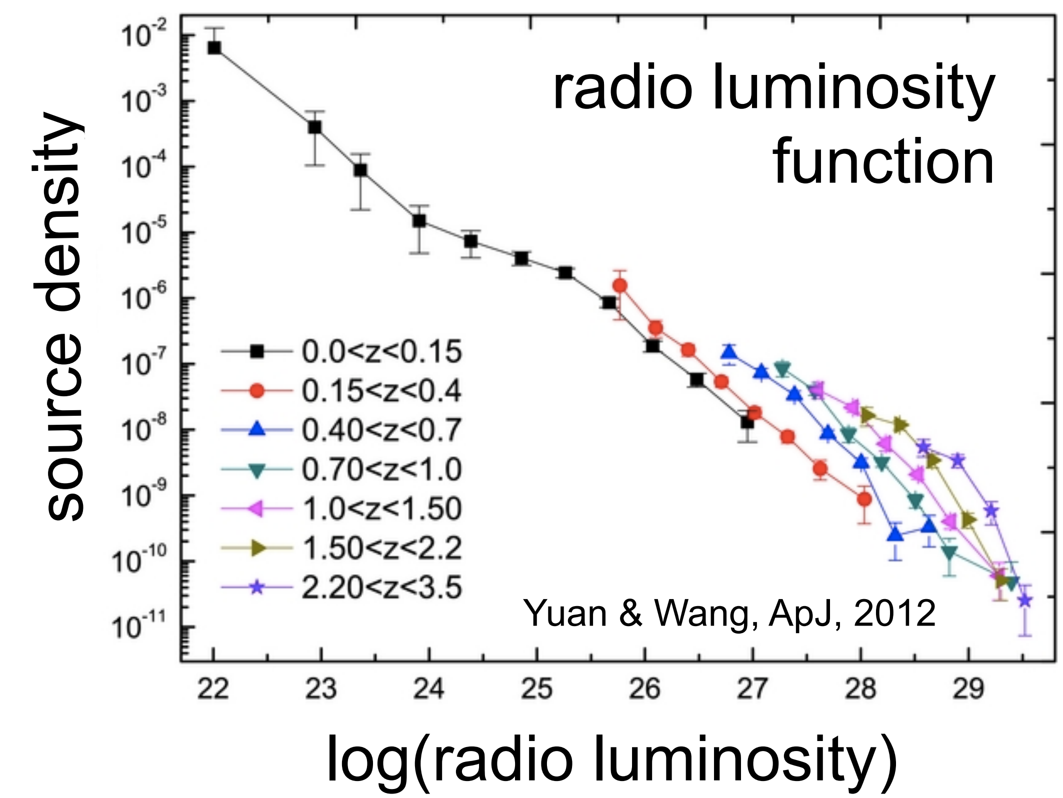



- Radio galaxy contribution to the extragalactic emission can be modeled from
  - radio-gamma correlation
  - radio luminosity function
  - spectral model

# Total contribution of radio galaxies




⊗

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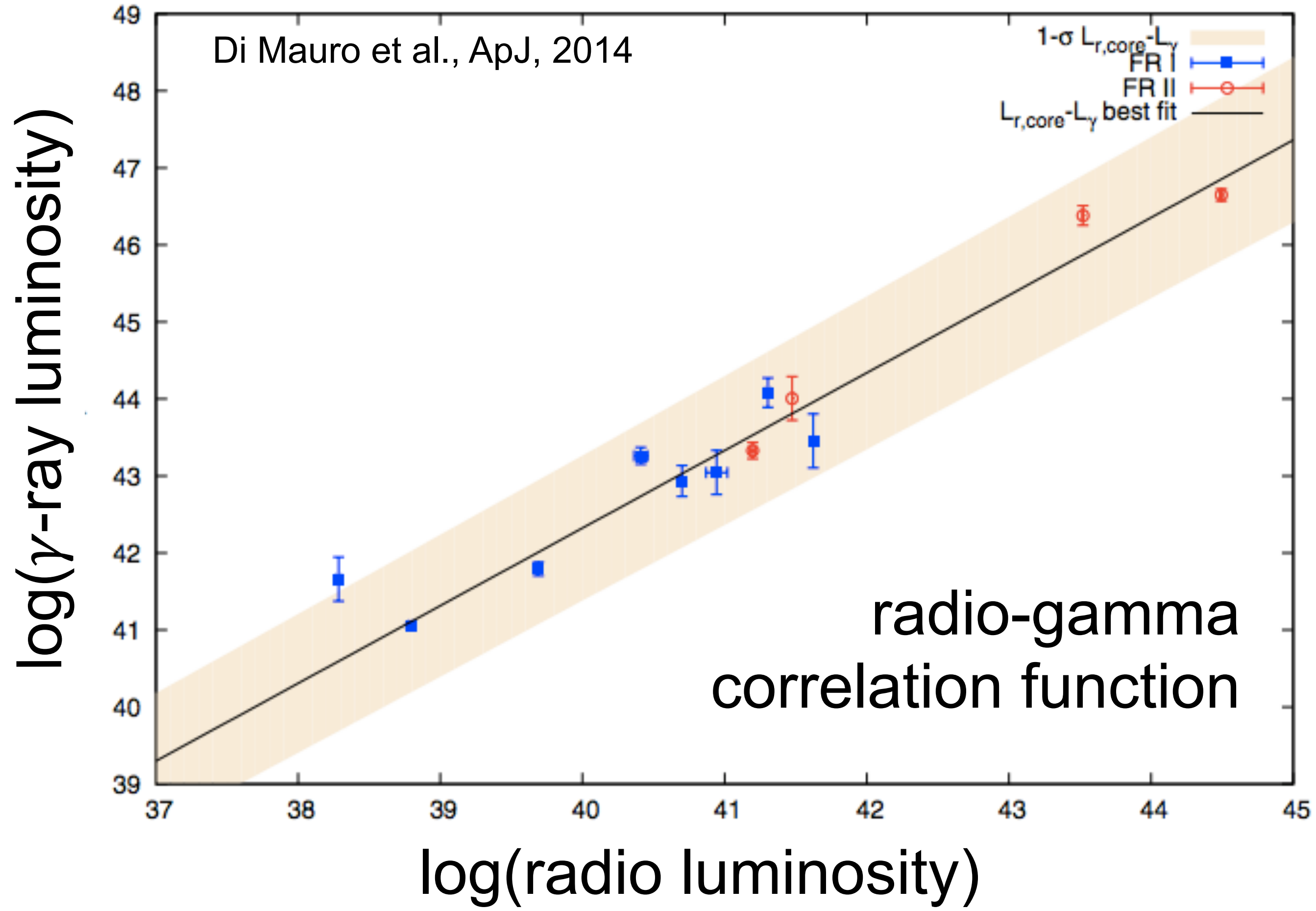
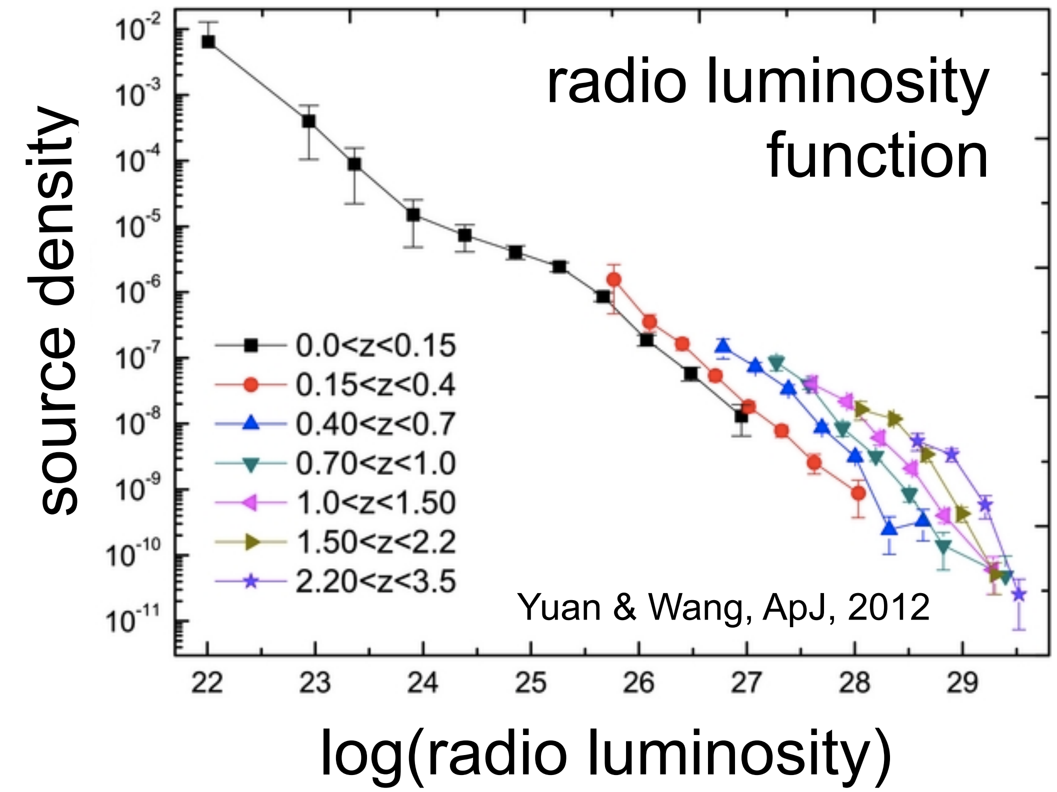
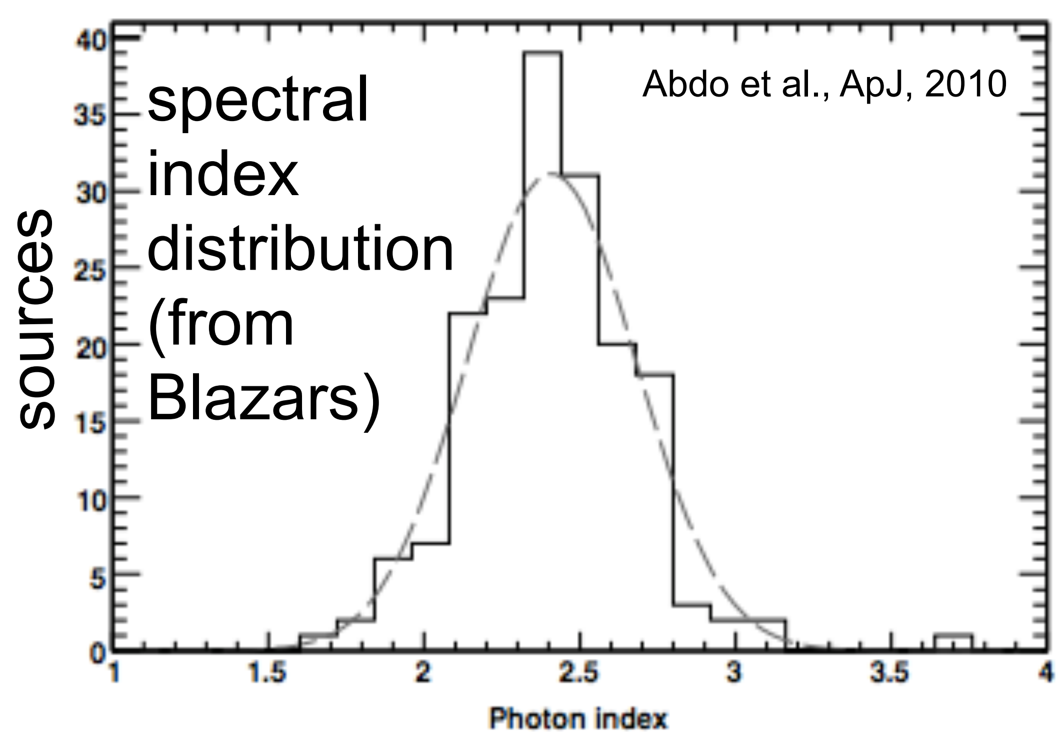
# Total contribution of radio galaxies




⊗

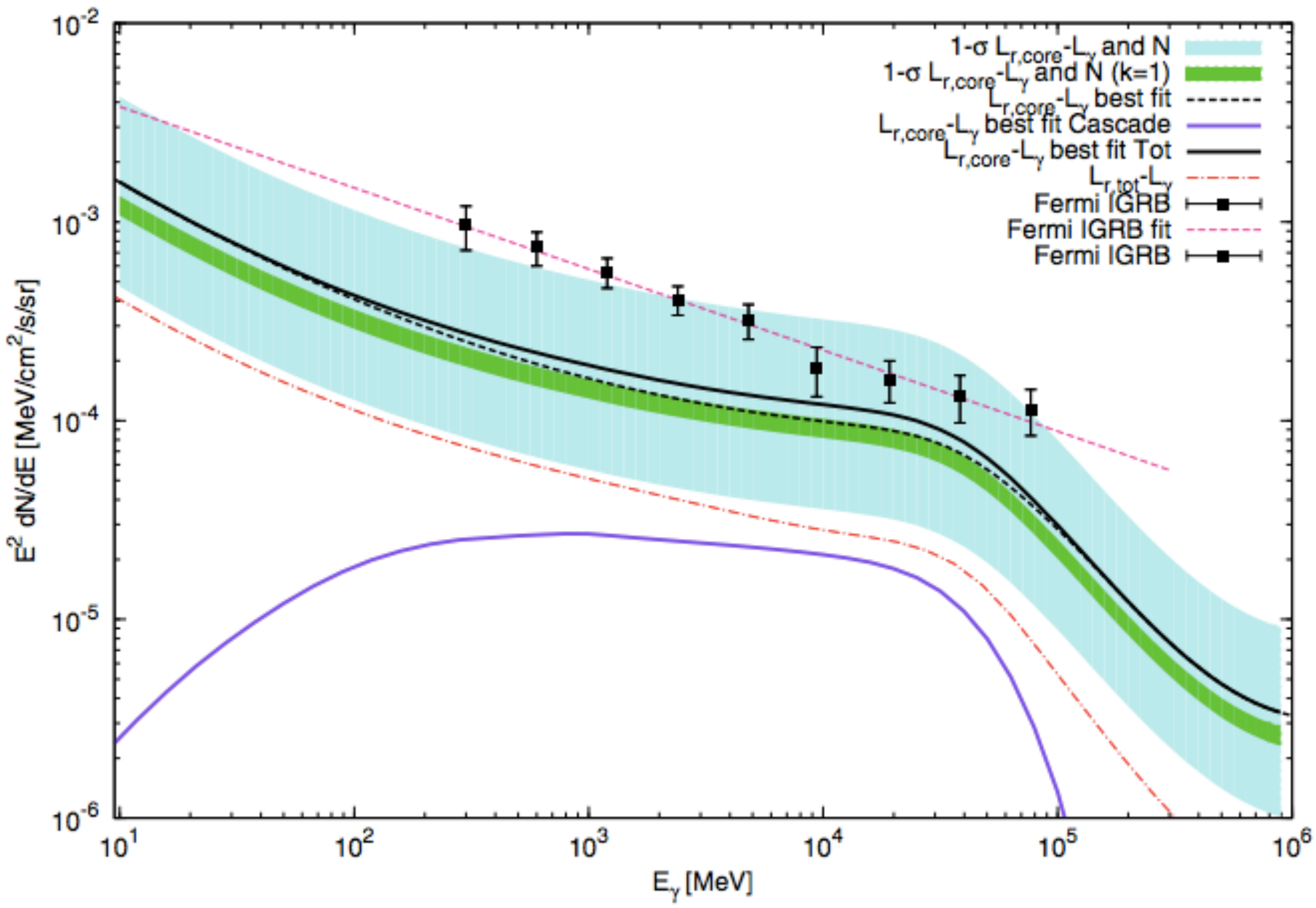



⊗

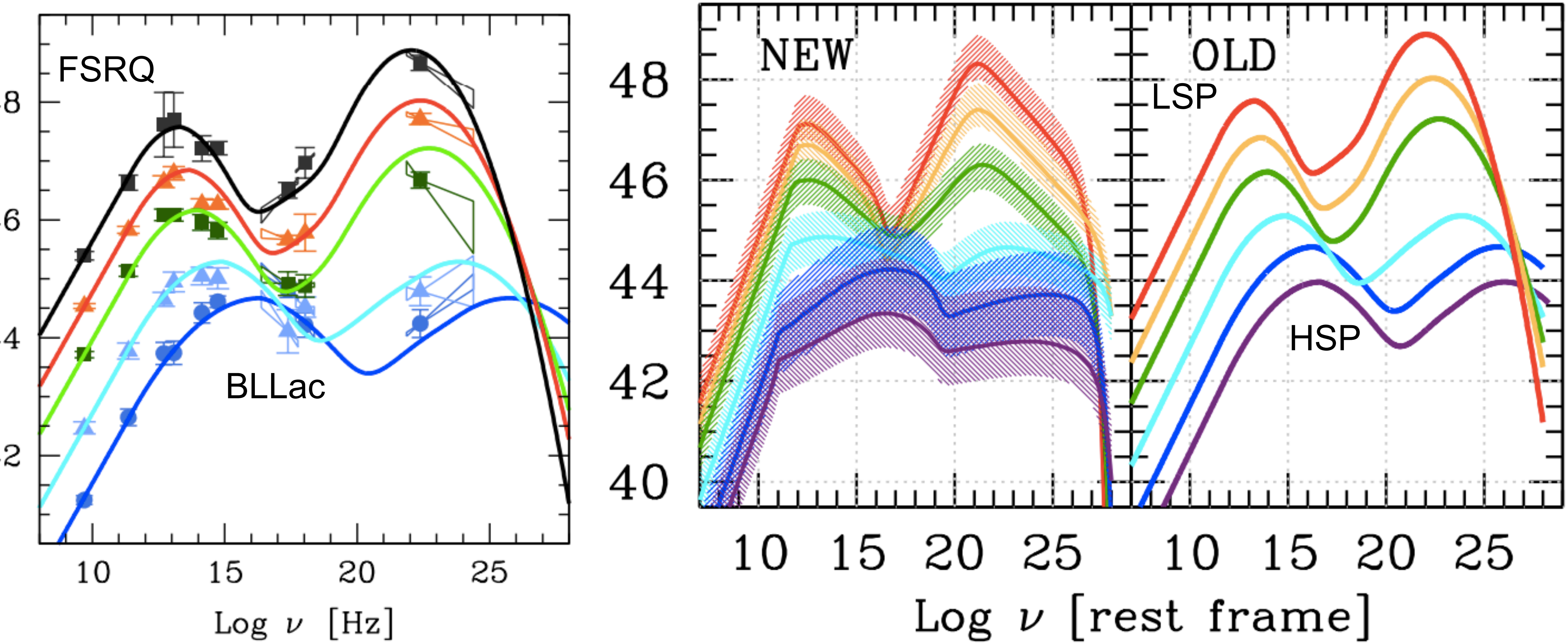



- Radio galaxy contribution to the extragalactic emission can be modeled from
  - radio-gamma correlation
  - radio luminosity function
  - spectral model

# Total contributions of radio galaxies

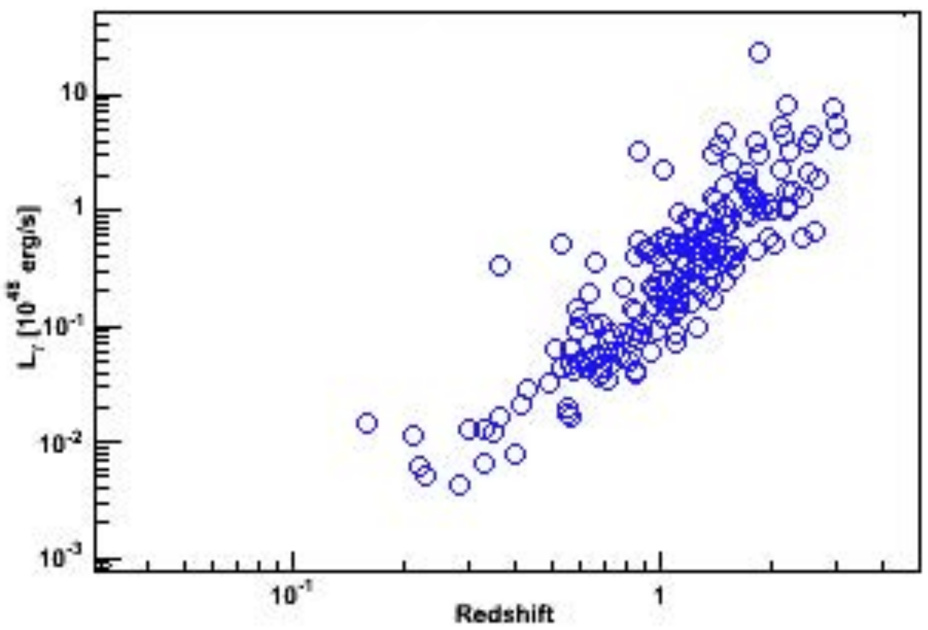


# Blazar classification - The Blazar sequence




- > Position of the spectral peak and spectral index is correlated with the luminosity.
- > **Flat Spectrum Radio Quasars (FSRQ):** Hard(flat) radio spectrum, broad optical emission lines
- > **BL Lac:** BL Lacertae type spectra, strong continuum emission, no emission lines

# Blazars: FSRQ gamma-ray luminosity function.



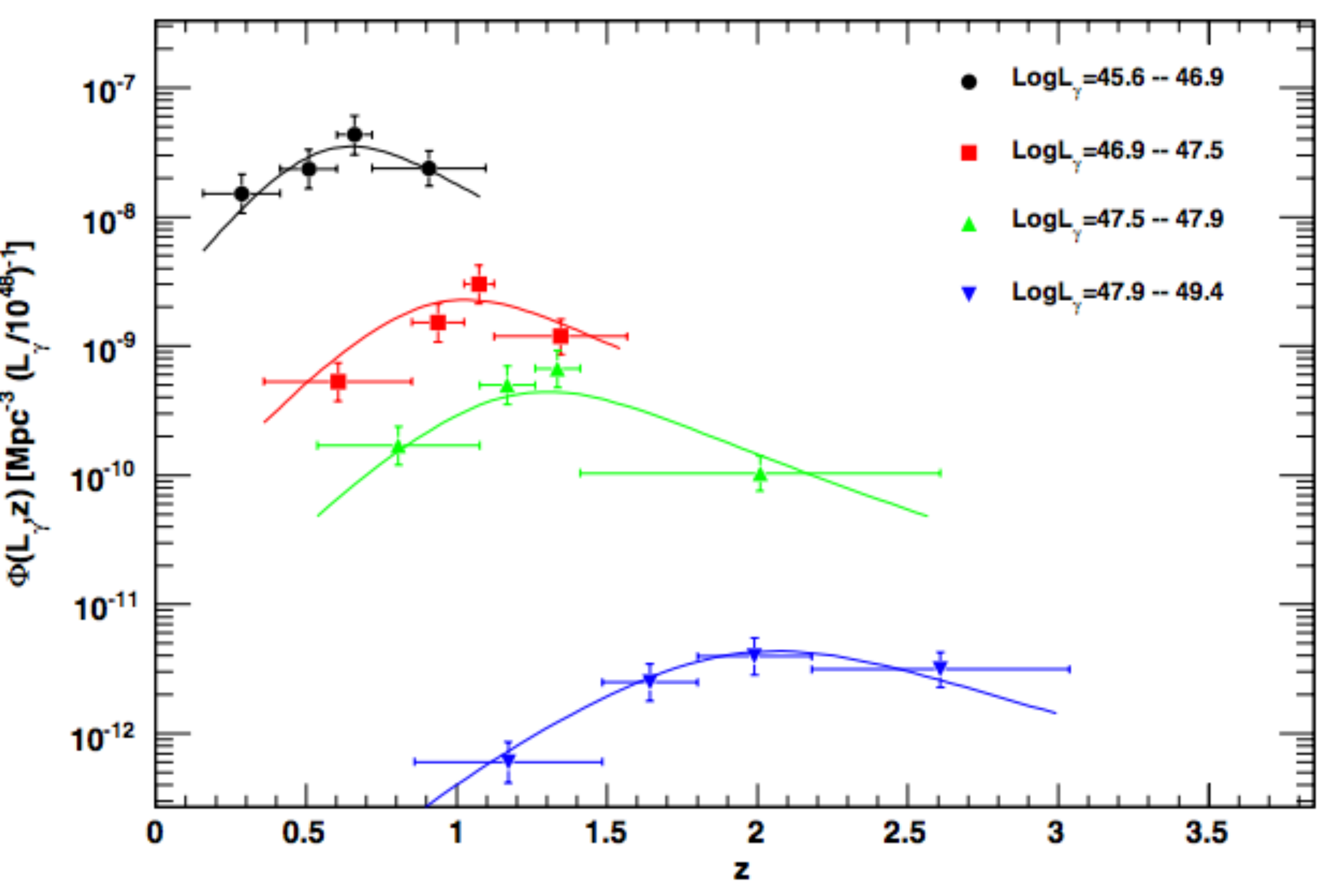

Ajello et al., ApJ 751, 108, 2012

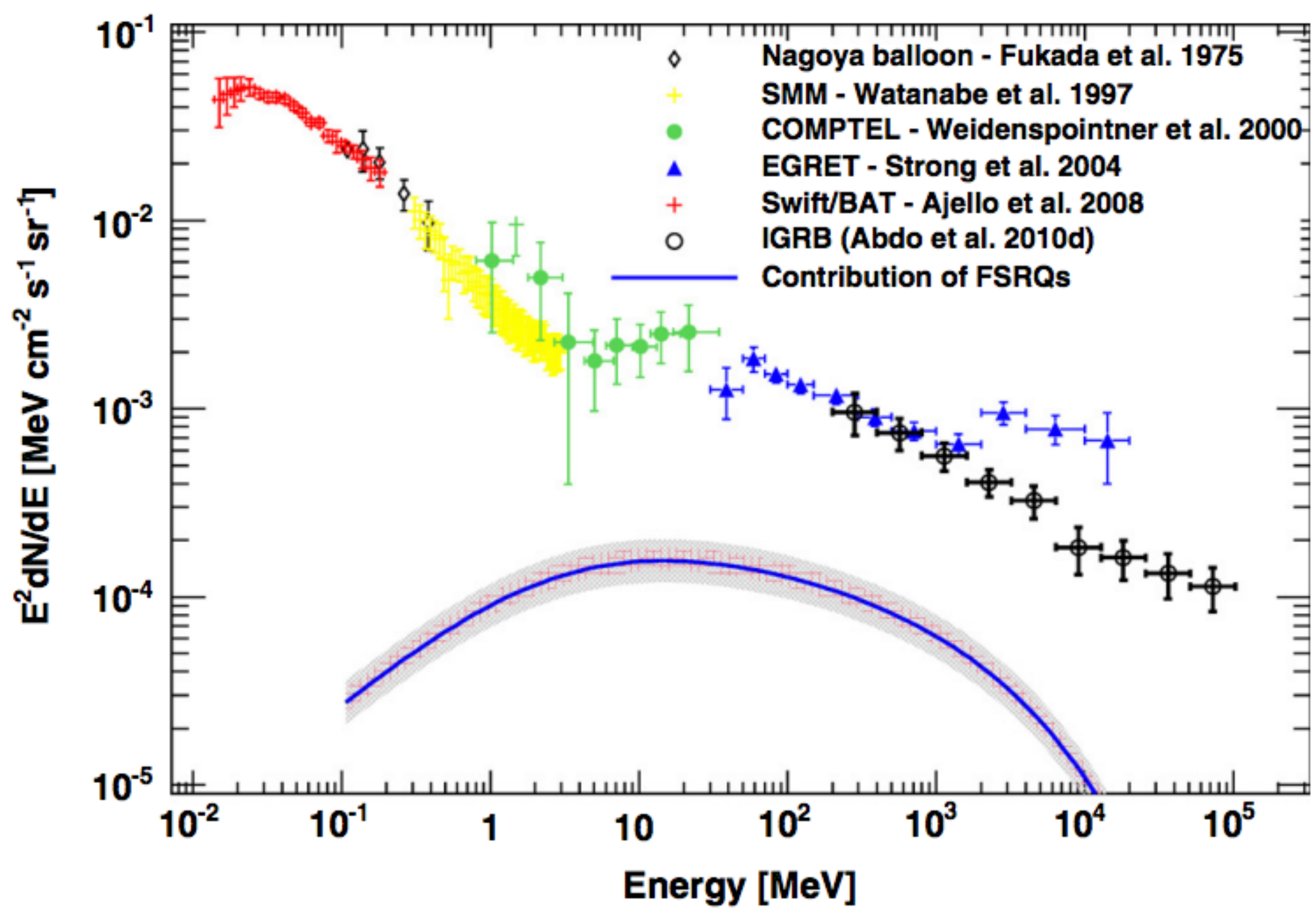
> LAT resolved FSRQ population spans wide range in redshift and luminosity

> Allows to build gamma-ray luminosity function (GLF) based on LAT data alone

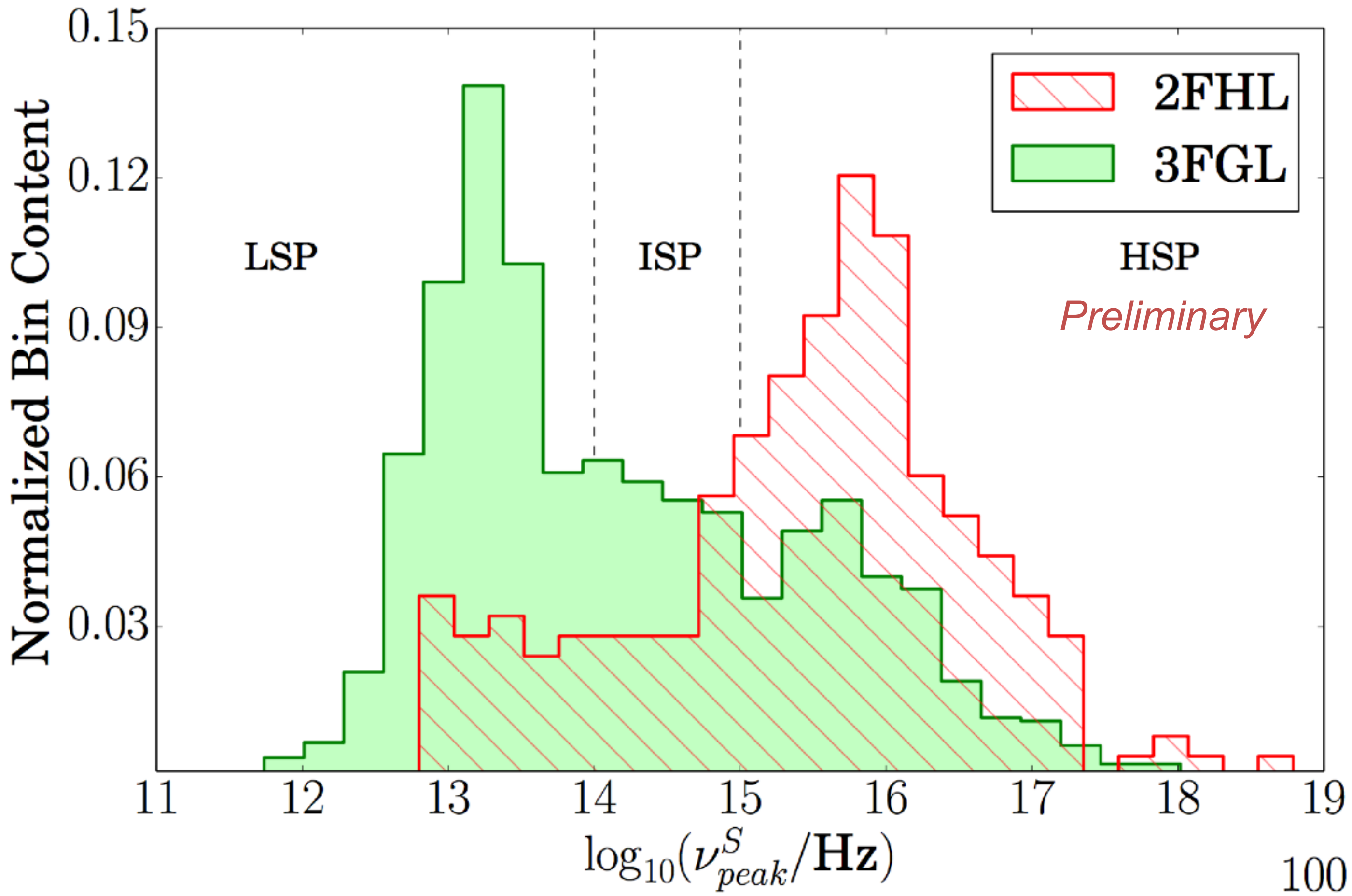
> Luminosity-dependent density evolution (LDDE) fits LAT population best

> Prediction of EGB contribution based on GLF + spectral modeling



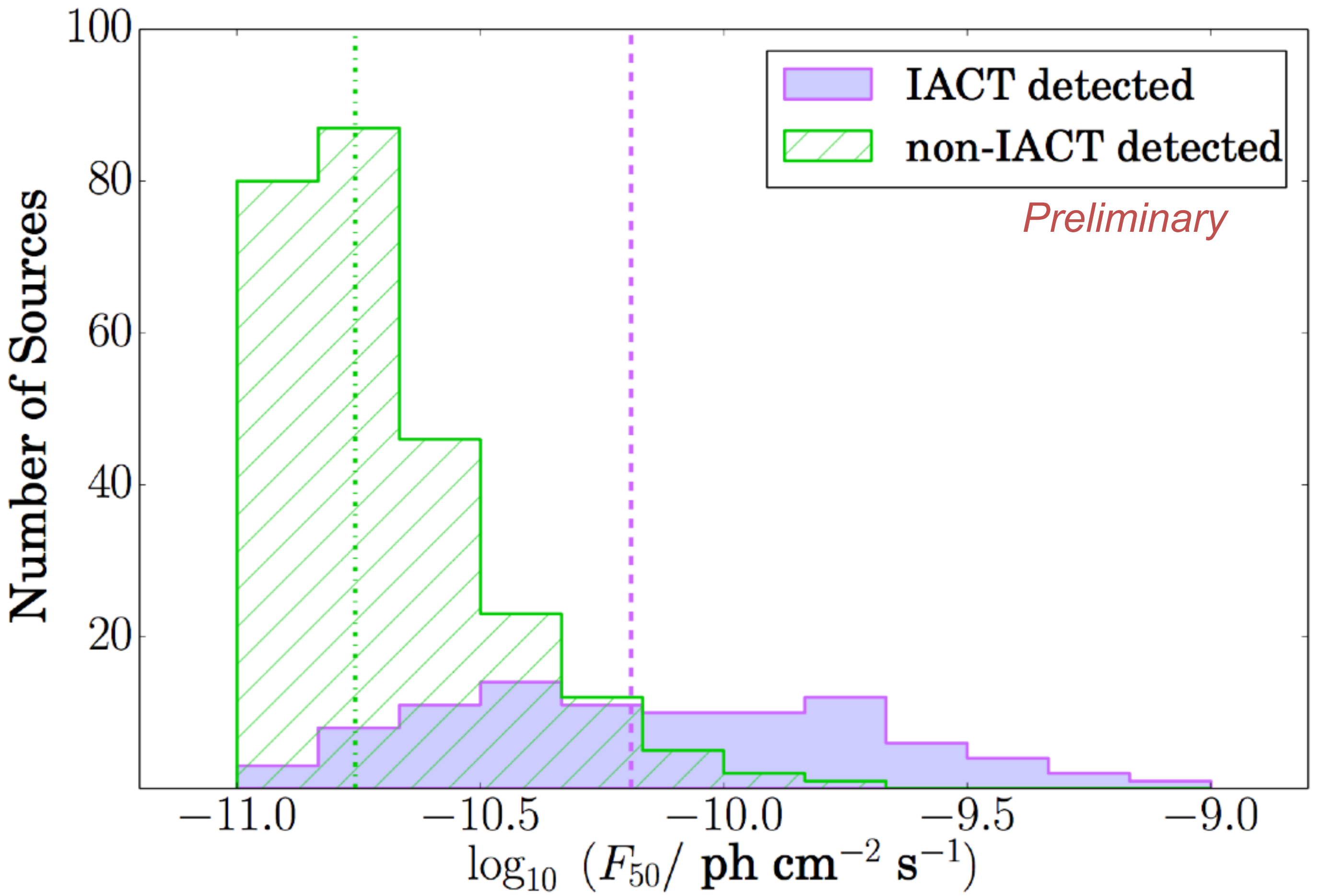



# The Fermi sky above 50 GeV

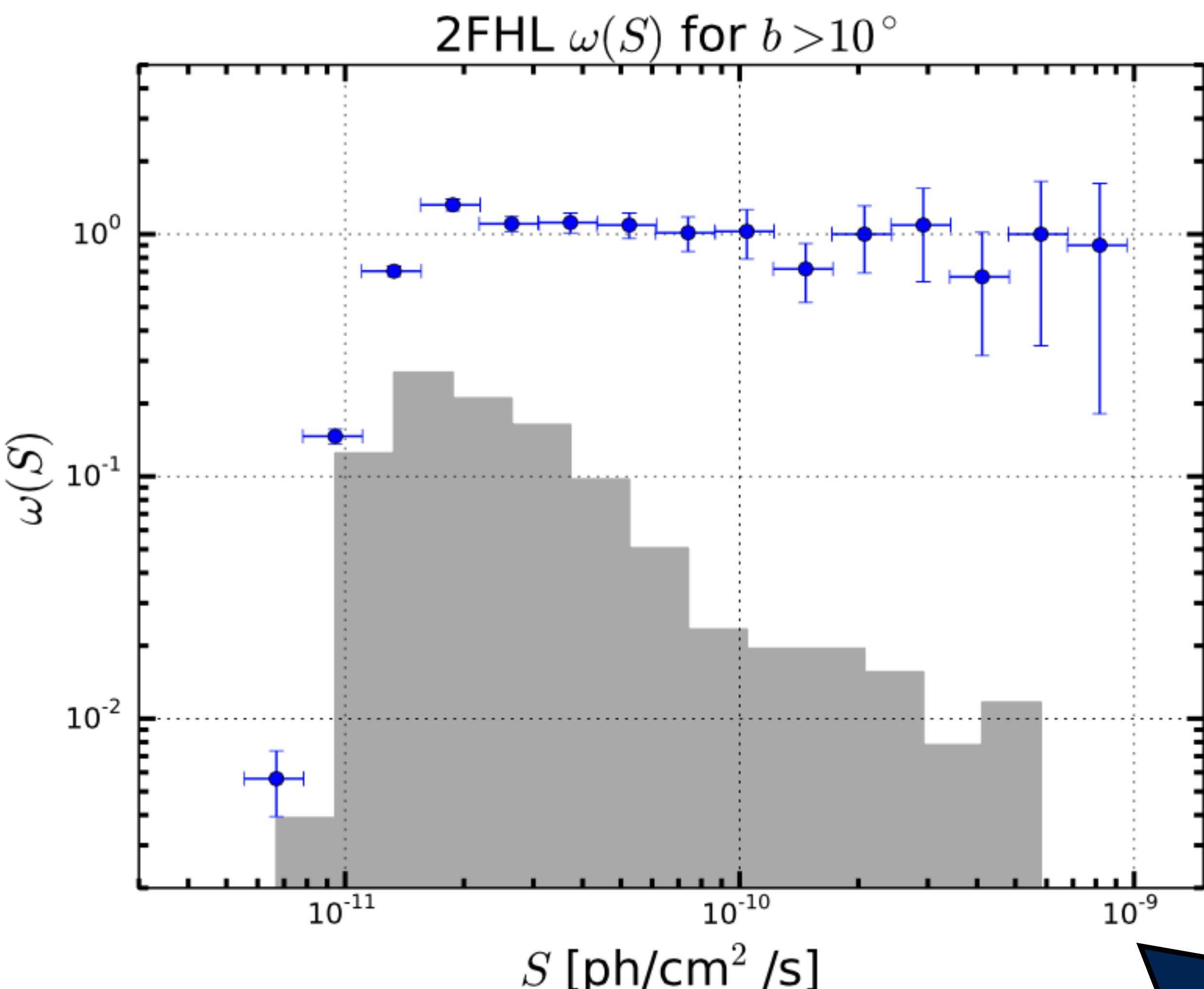



- 2FHL catalog bridges the regime between Fermi LAT and Cherenkov telescopes
- Dominant population (HSP BLLacs) different from 3FGL

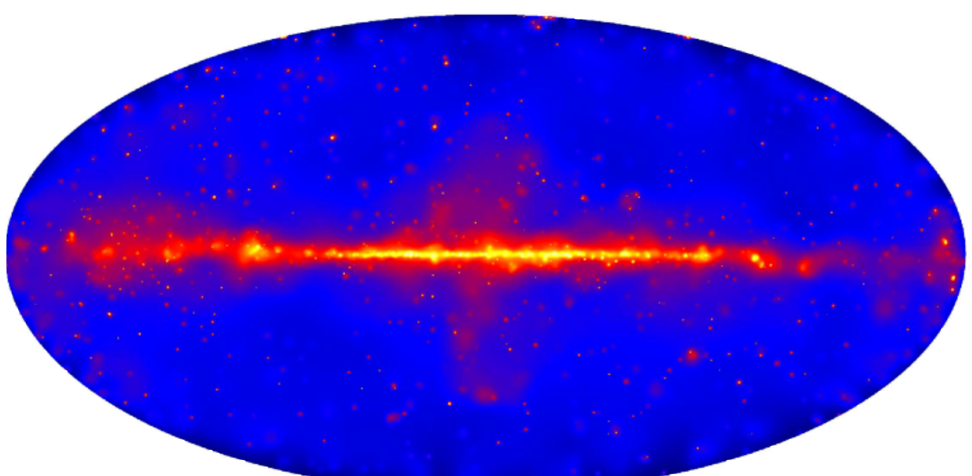
- Many of the brighter sources have already been detected with Cherenkov telescopes
- The others are interesting new candidates for TeV observations. (and IceCube ?)



# The Blazar contribution to the extragalactic gamma-ray sky

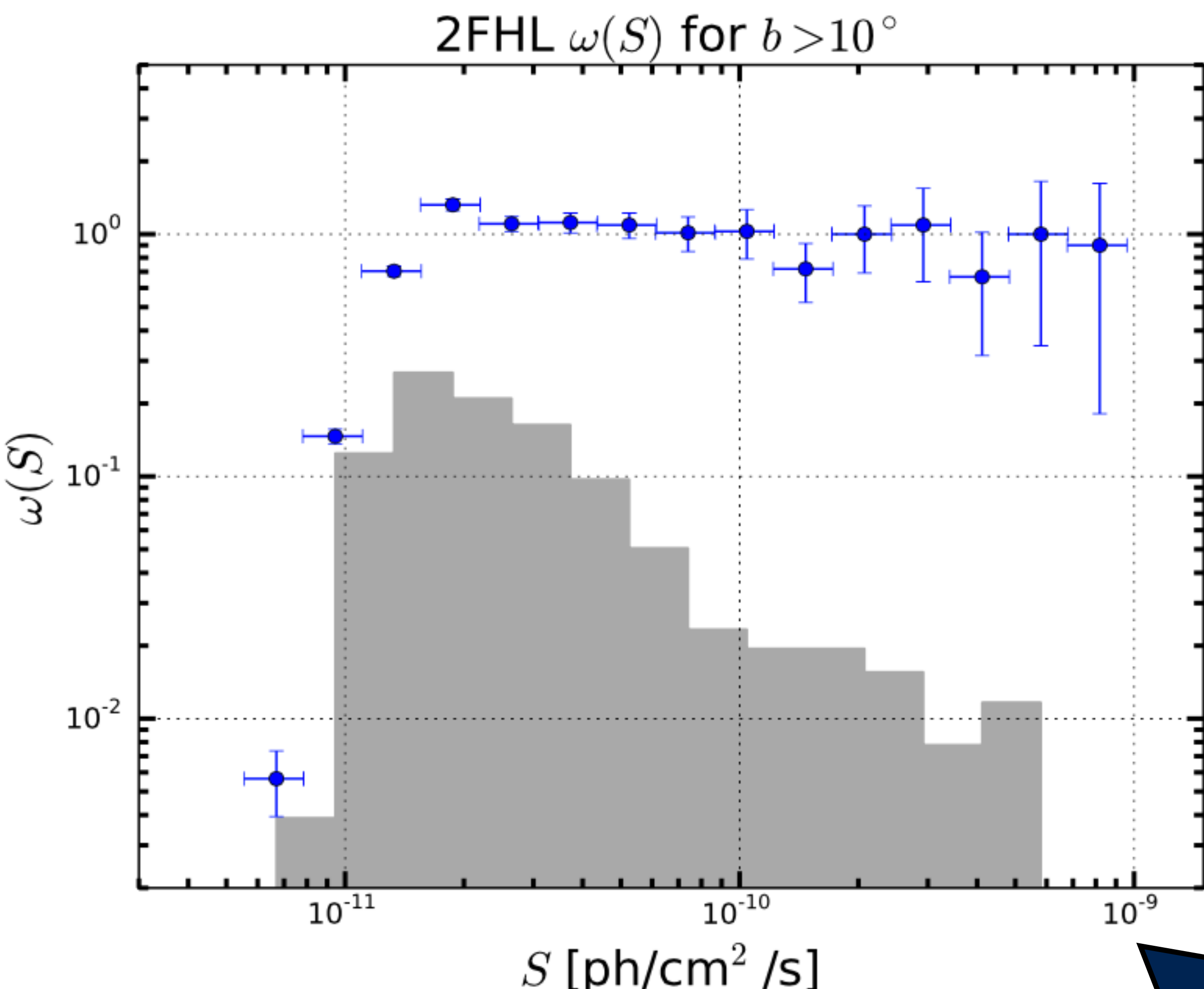



Detection efficiency
+
Sources



- Almost all high-latitude 2FHL sources are likely BLLac-type Blazars.
- If you know the detection efficiency, contribution of the unresolved sources.
- "Diffuse" contribution does not converge for $N(>S) \sim S^{-1.5}$

# The Blazar contribution to the extragalactic gamma-ray sky




Detection efficiency
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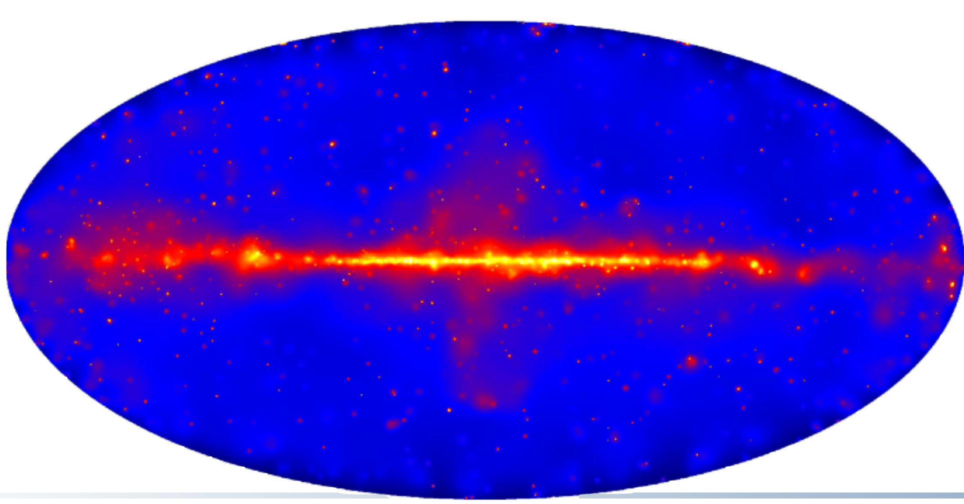

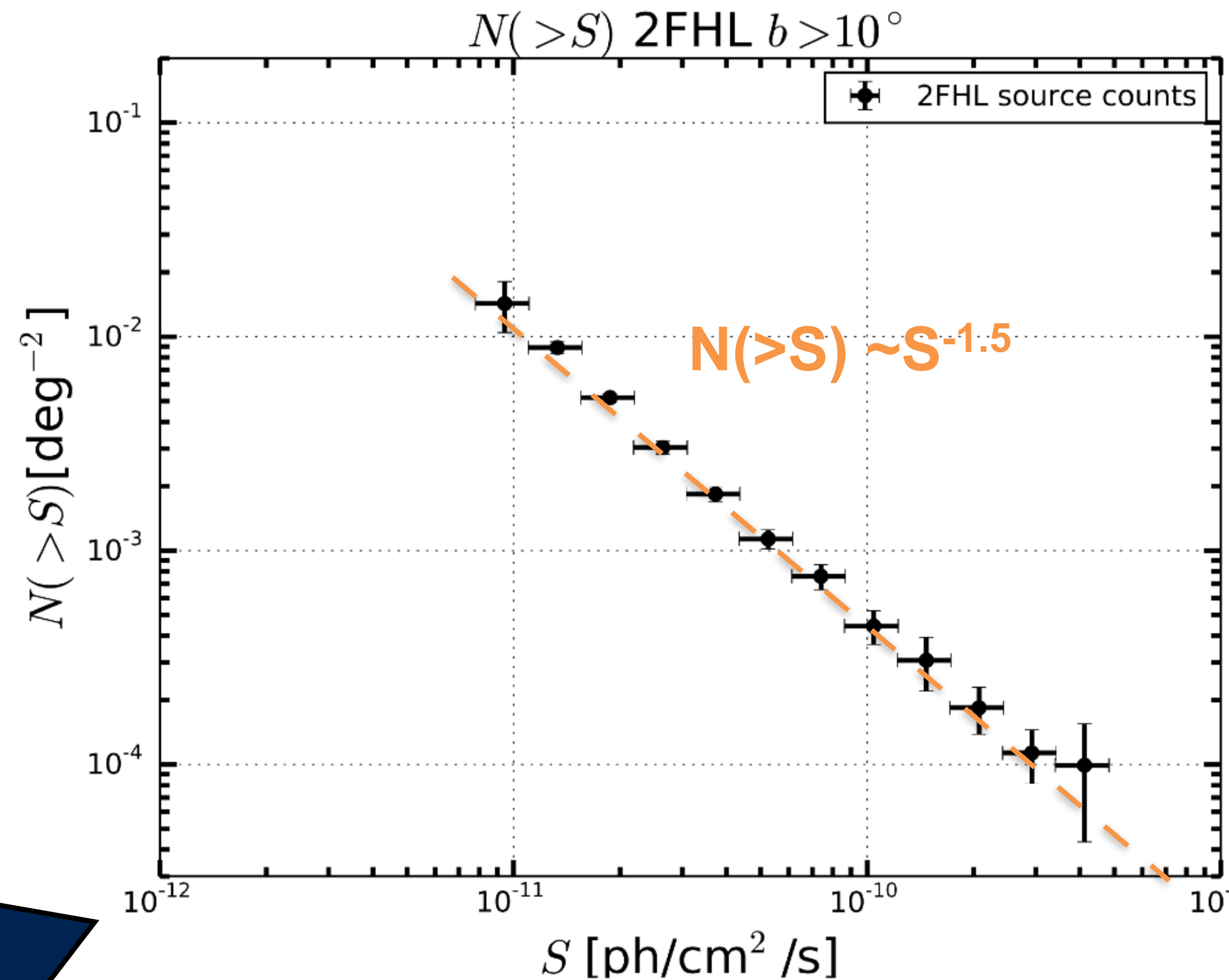


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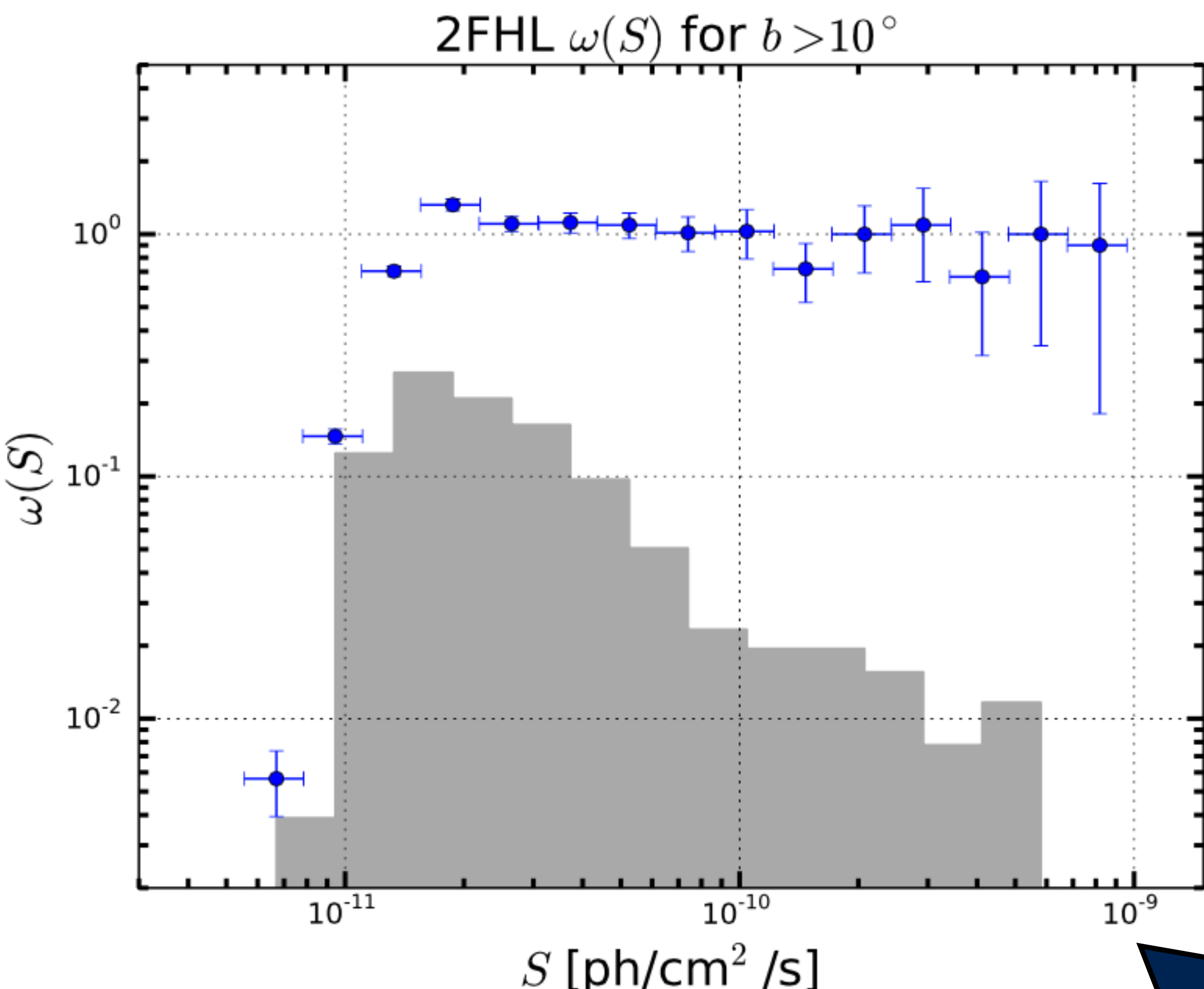
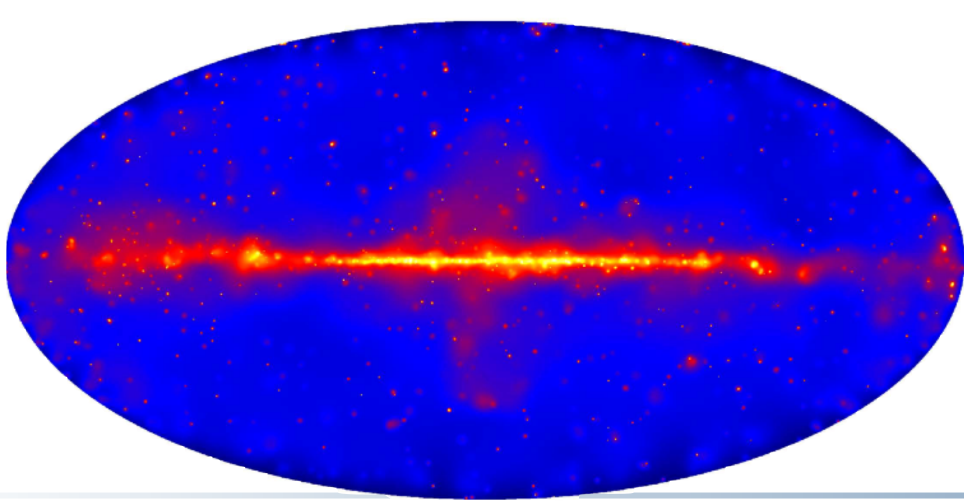
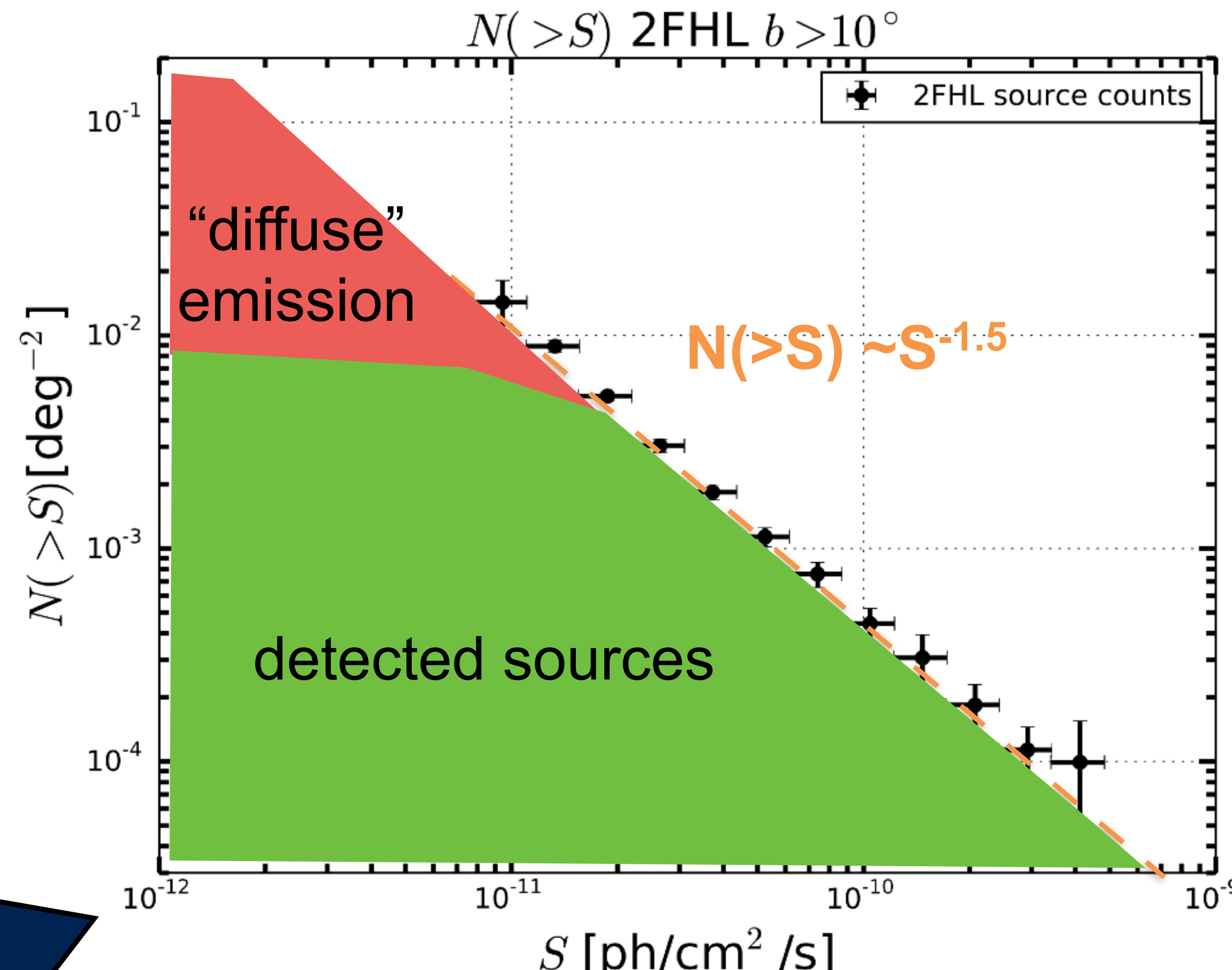



Detection efficiency

+

Sources



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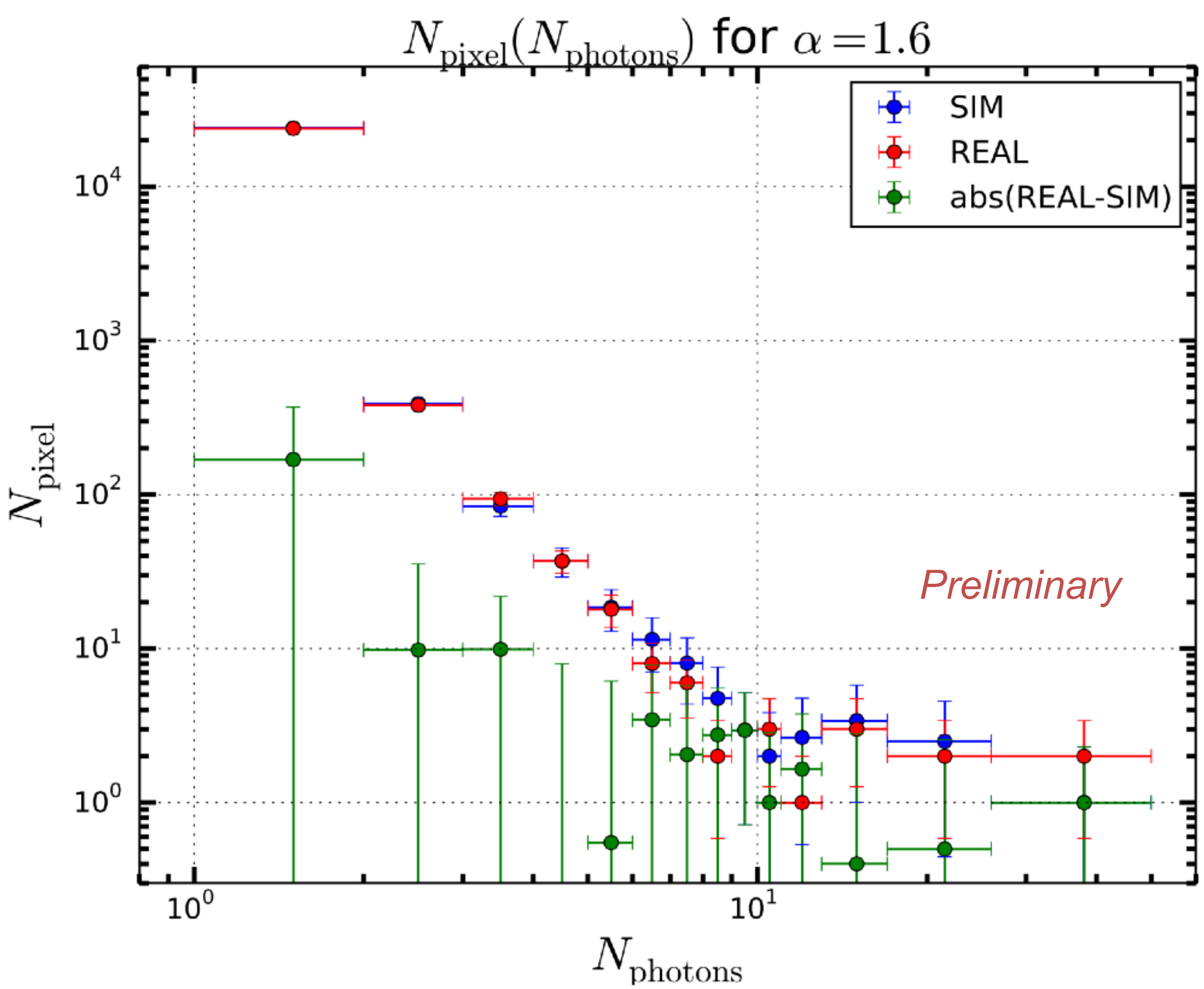
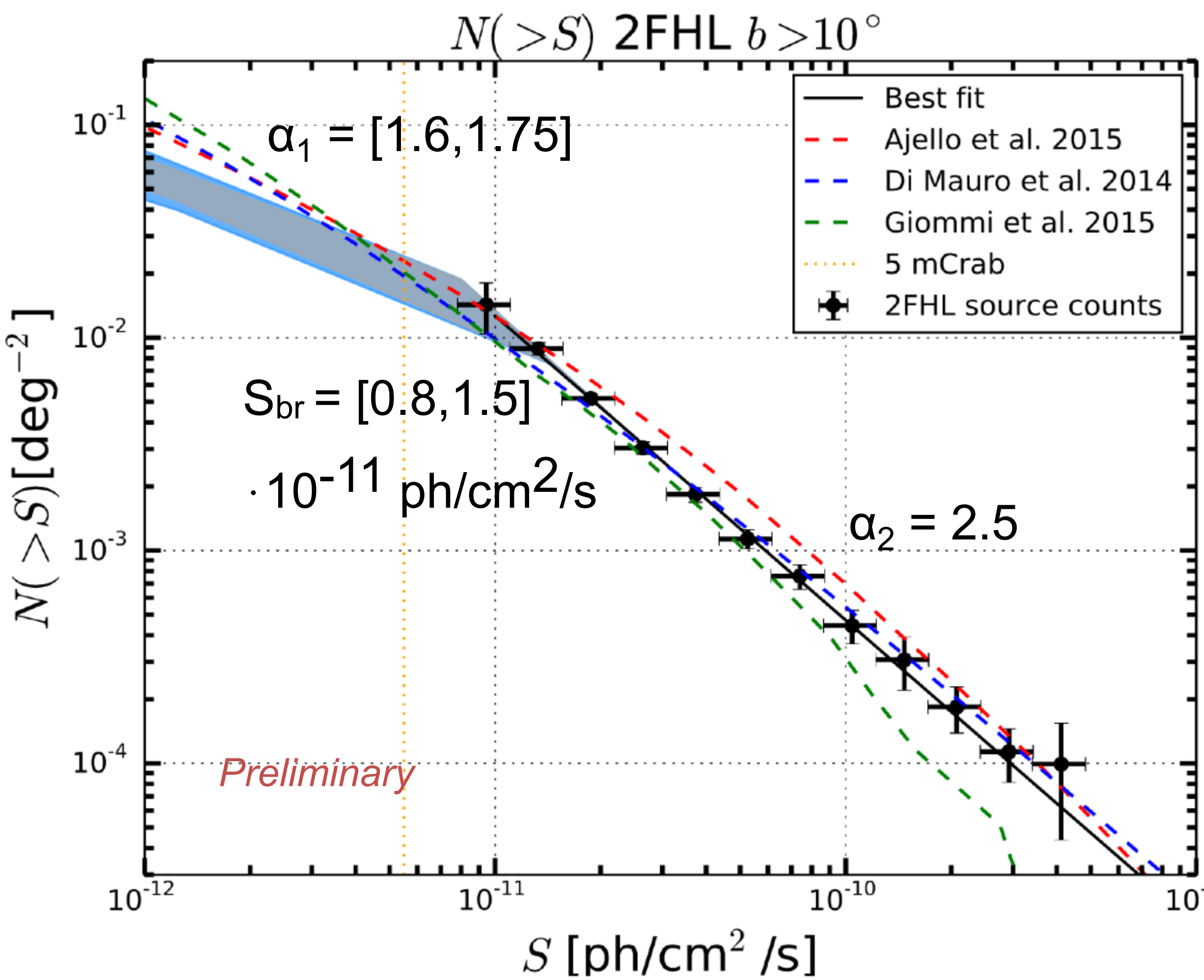
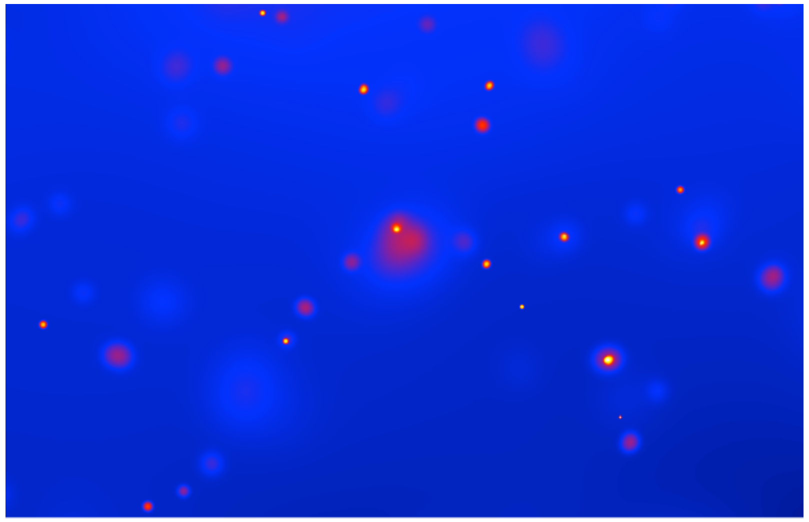
# The Blazar contribution to the extragalactic gamma-ray sky

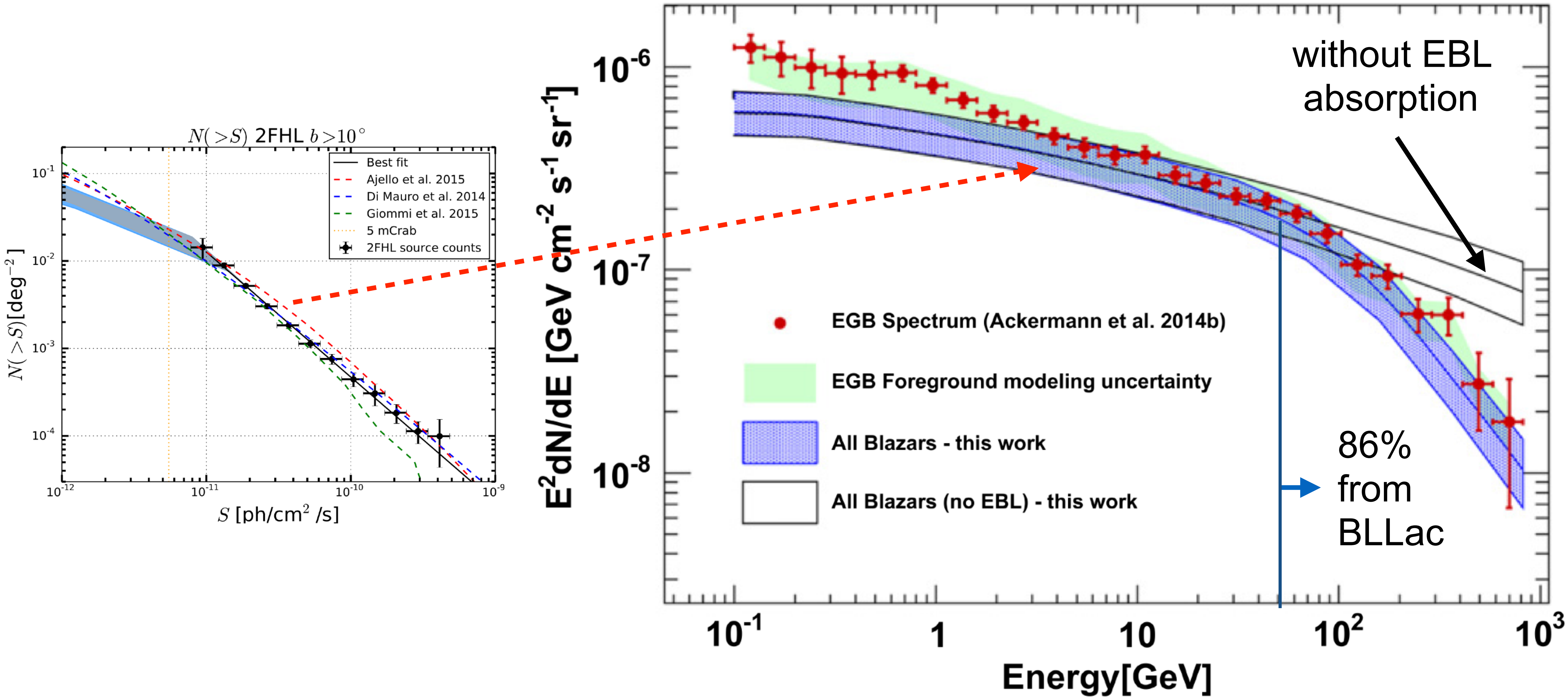


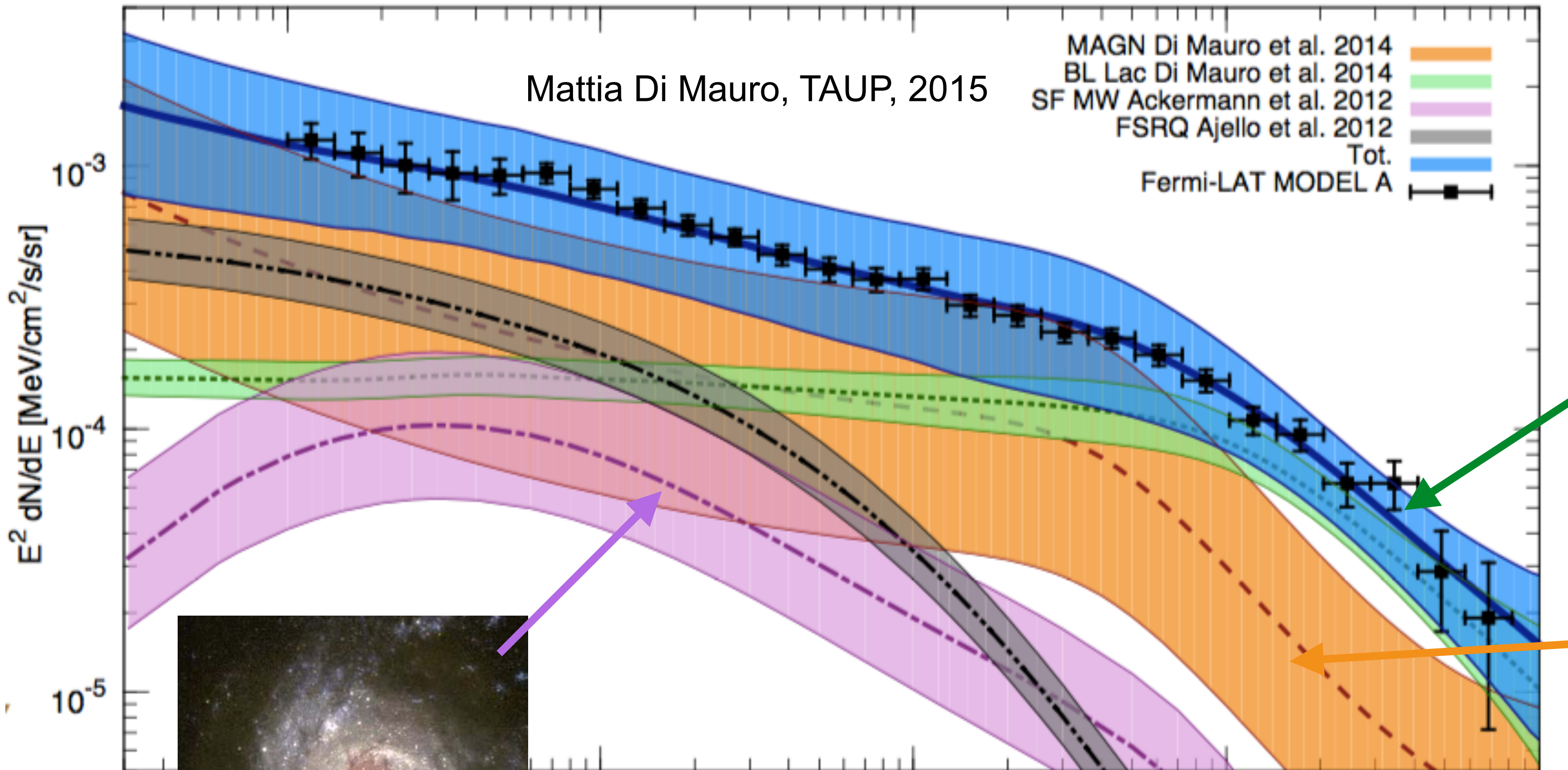
- Based on data used for 2FHL catalog
- Fit number of sources needed to obtain the observed photon count statistics

# The Blazar contribution to the extragalactic gamma-ray sky

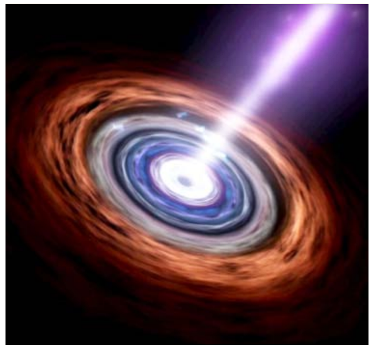



- 86% (+16% /-14%) of extragalactic gamma-ray emission at E>50 GeV originates from Blazars
- Source count distribution + spectral model = EGB contribution

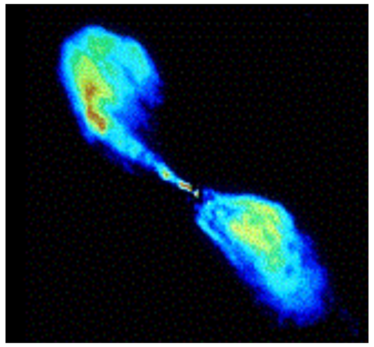
# Extragalactic gamma-ray emission in the GeV band.



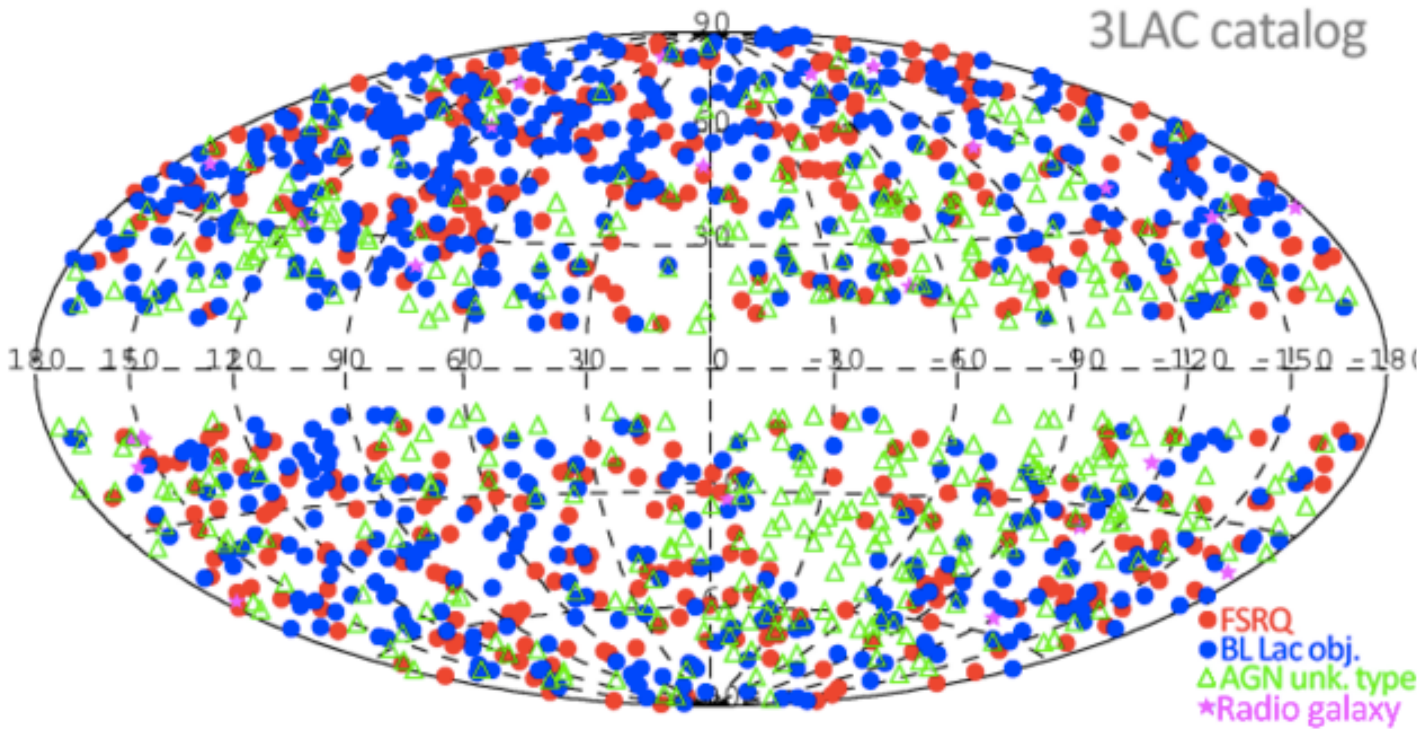

Blazars



Radio Galaxies



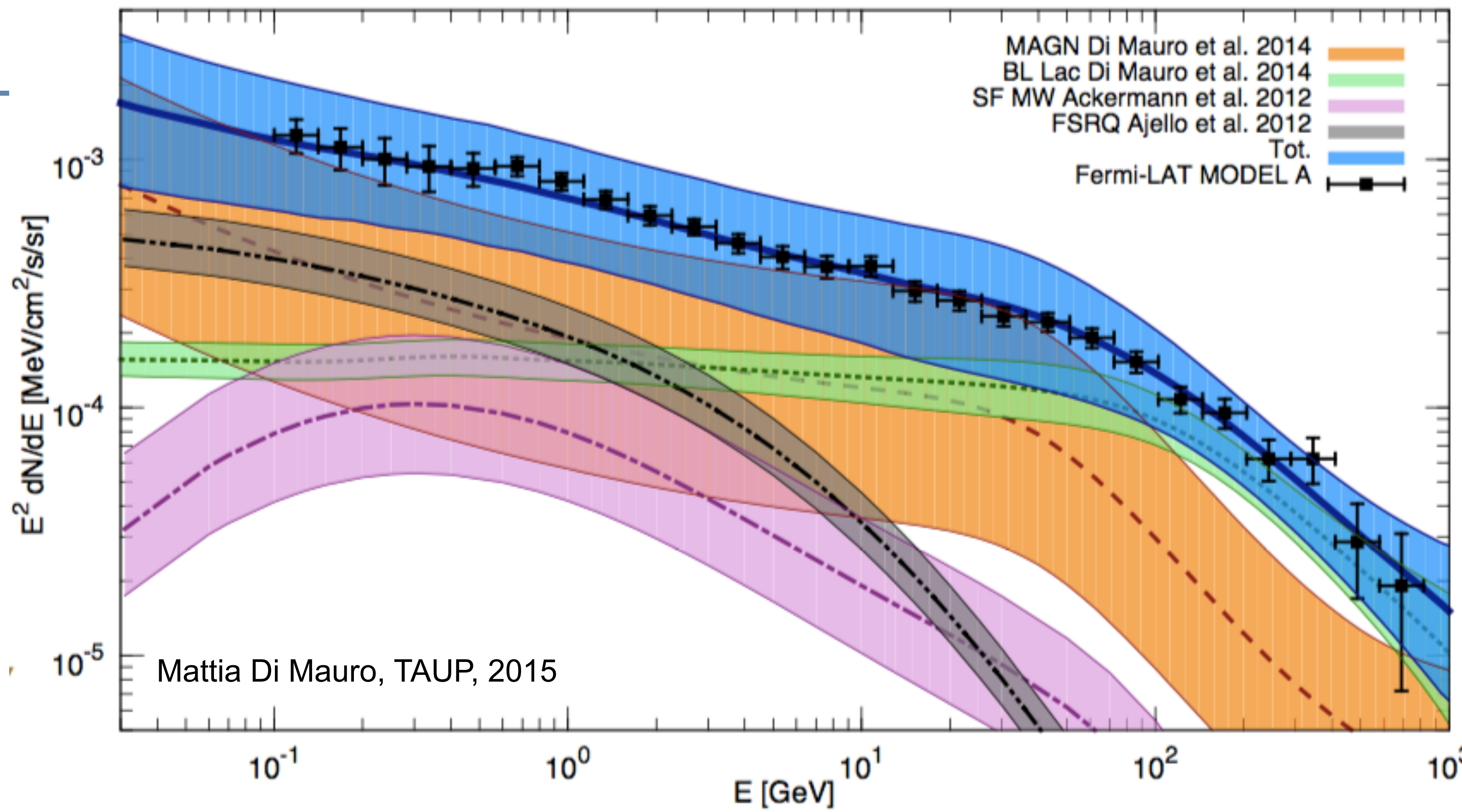
Star-forming galaxies

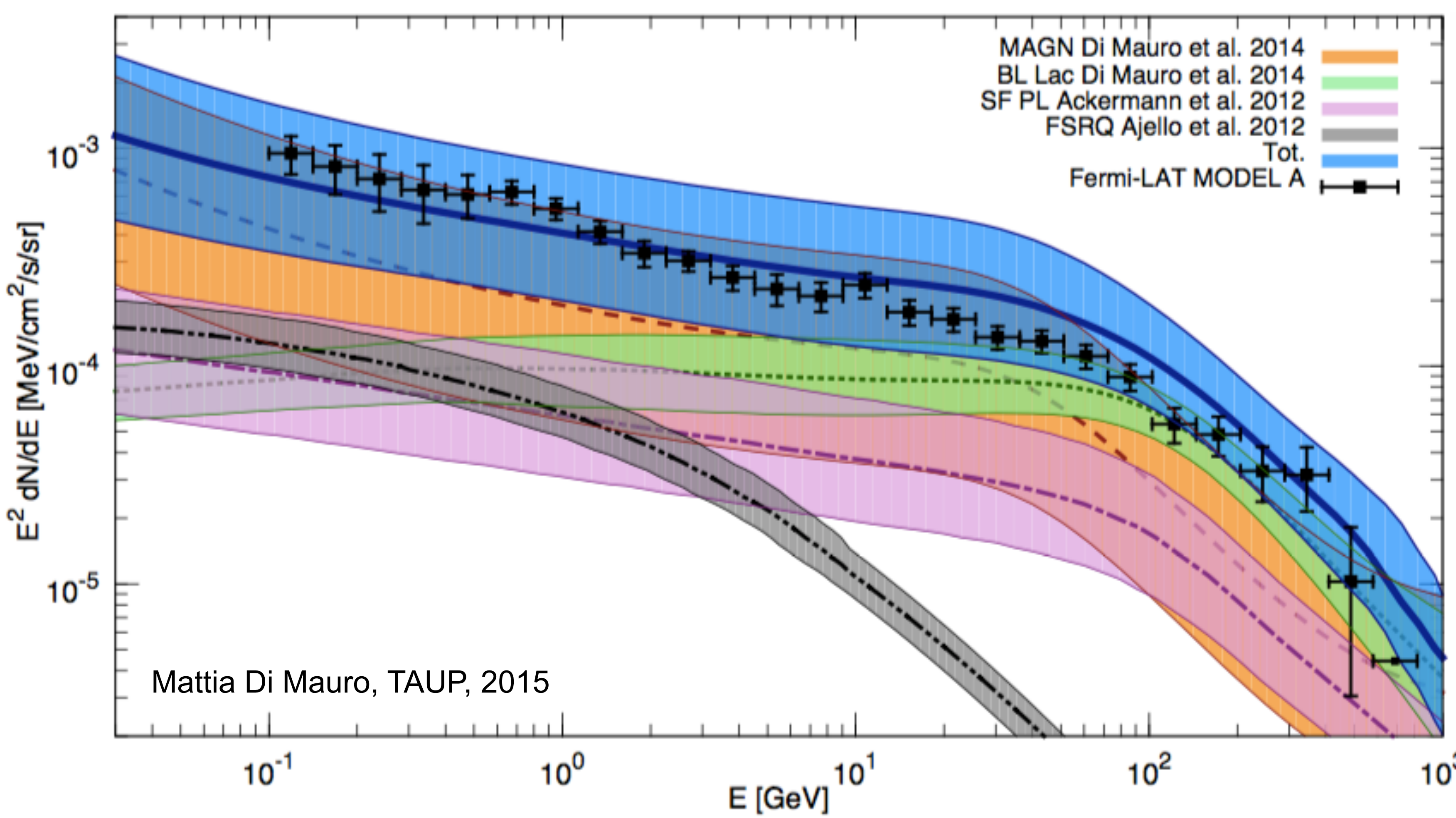



- Contribution from unresolved sources can be estimated.
- Most of the extragalactic gamma-ray emission above 10 GeV originates from Blazars.

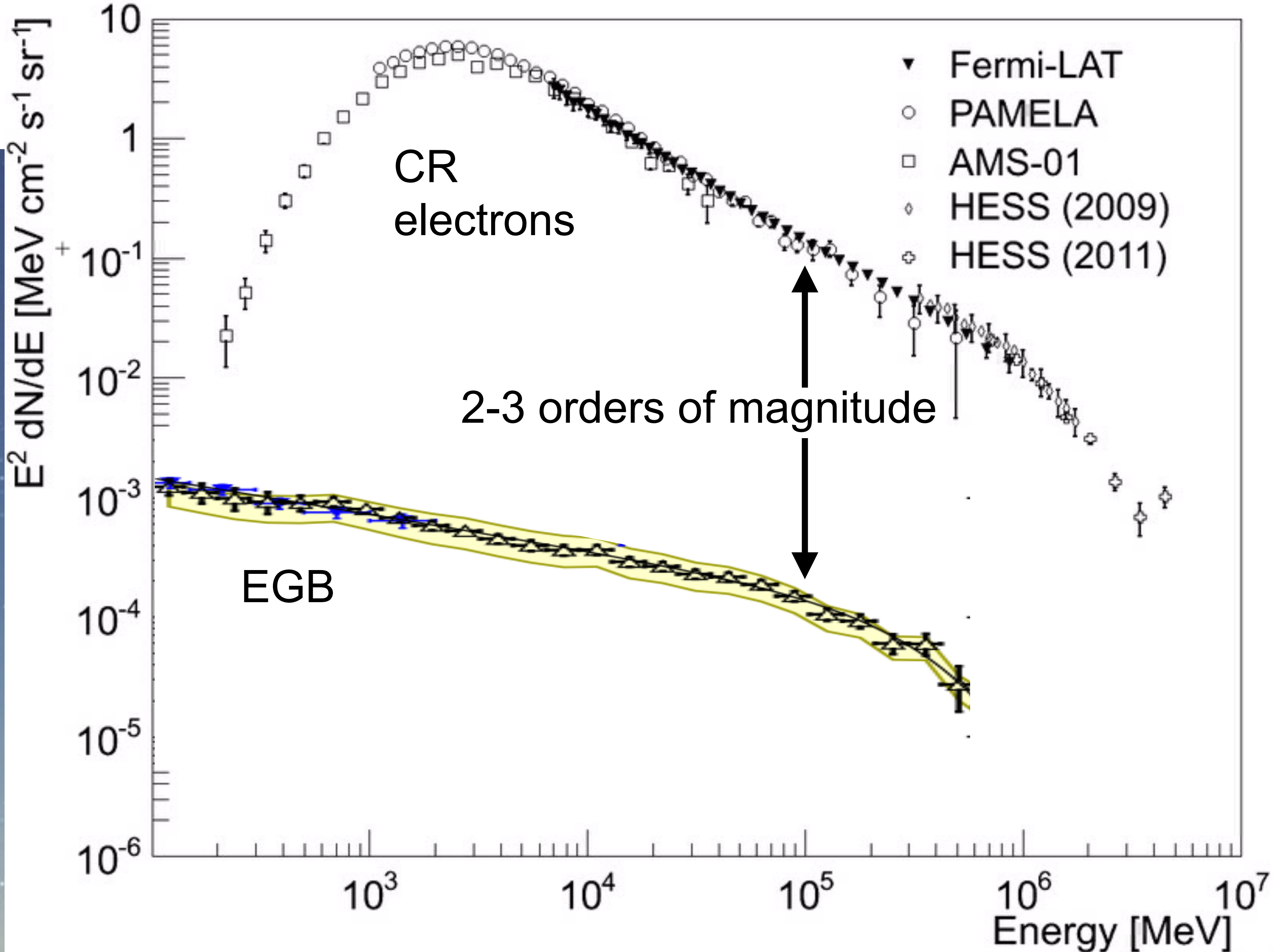
# A census

- BL Lac class of Blazars dominates the high-energy gamma-ray emission
  - 86% (+16%/-14%) above 50 GeV
- Large uncertainties in radio-galaxy and star-forming galaxy contributions
- Real diffuse contributions must be small
  - UHECR interactions
  - WIMP annihilation
  - etc.

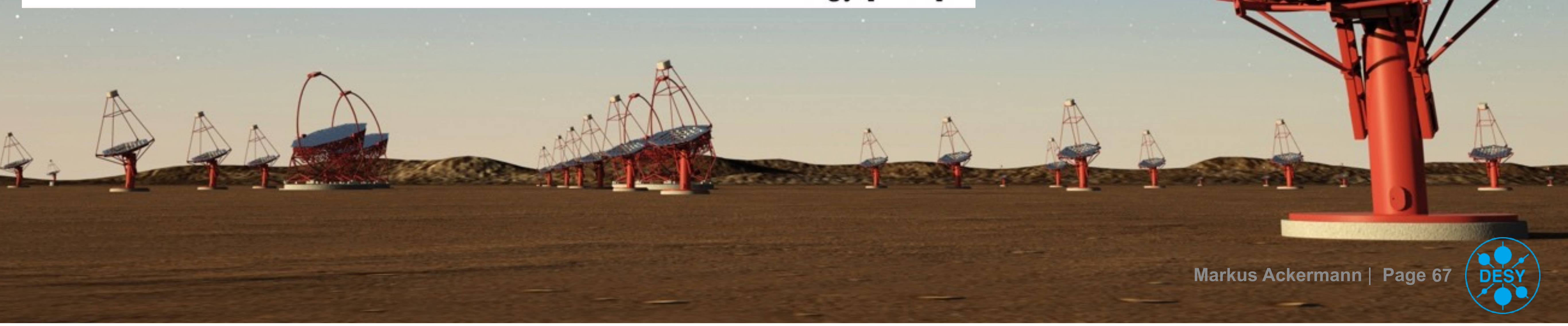


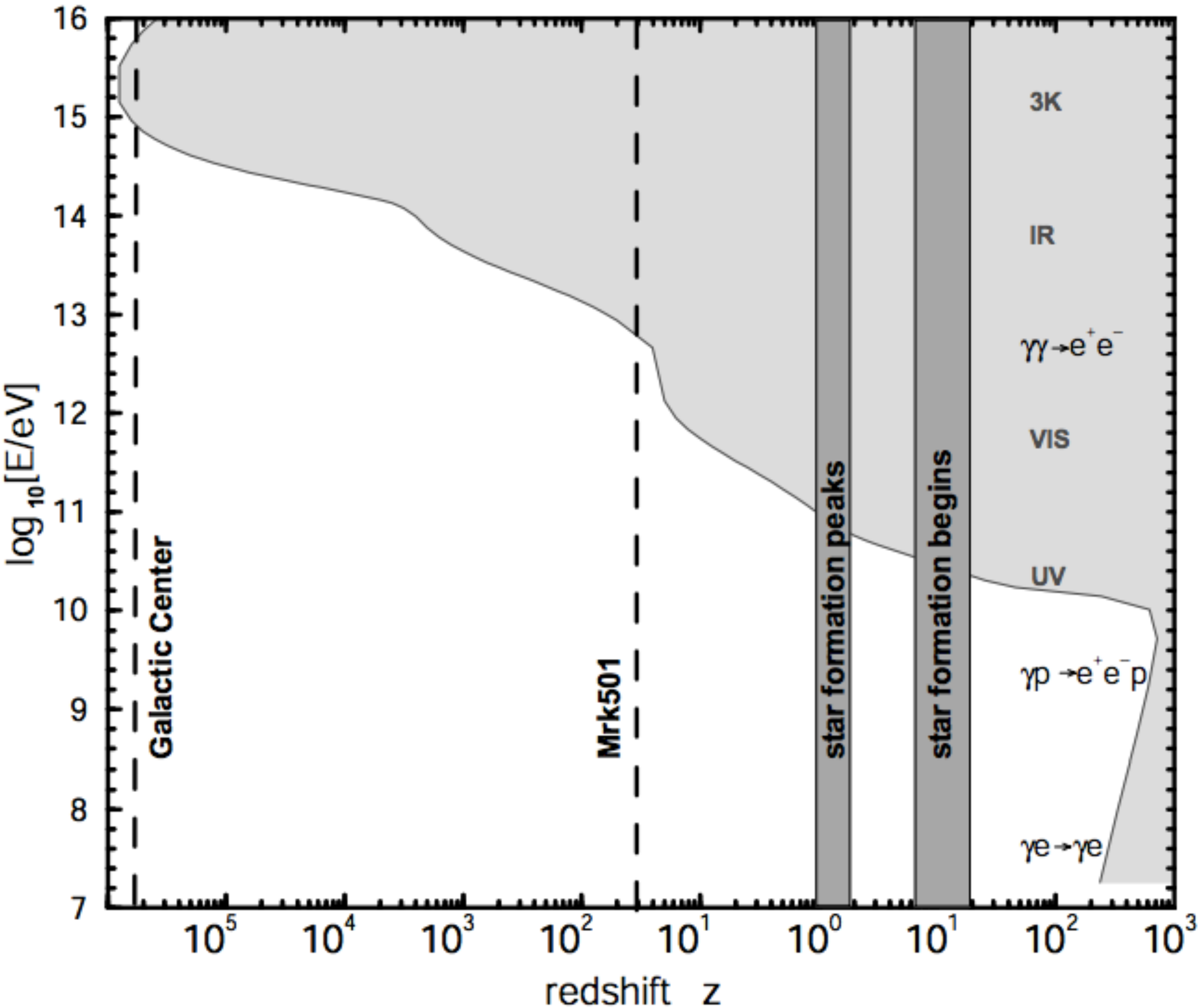
# Is there an isotropic TeV background ? - Instrumental constraints

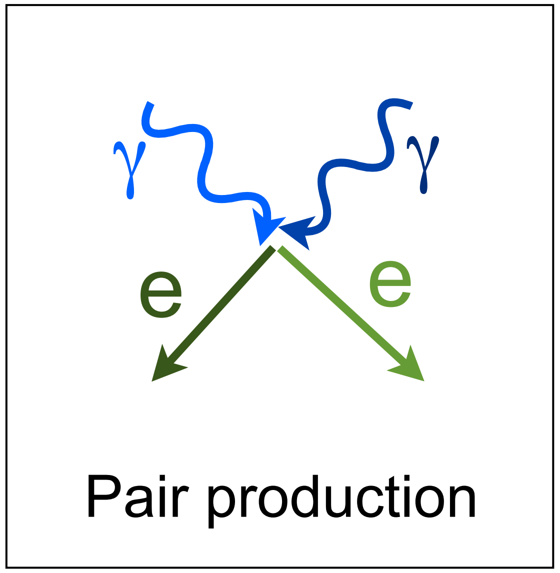



- **Ground-based telescopes** cannot distinguish electrons from gamma rays (very well)
- **CR electron background** dominates by more than an order of magnitude.
- But they can observe **close-by TeV sources.**



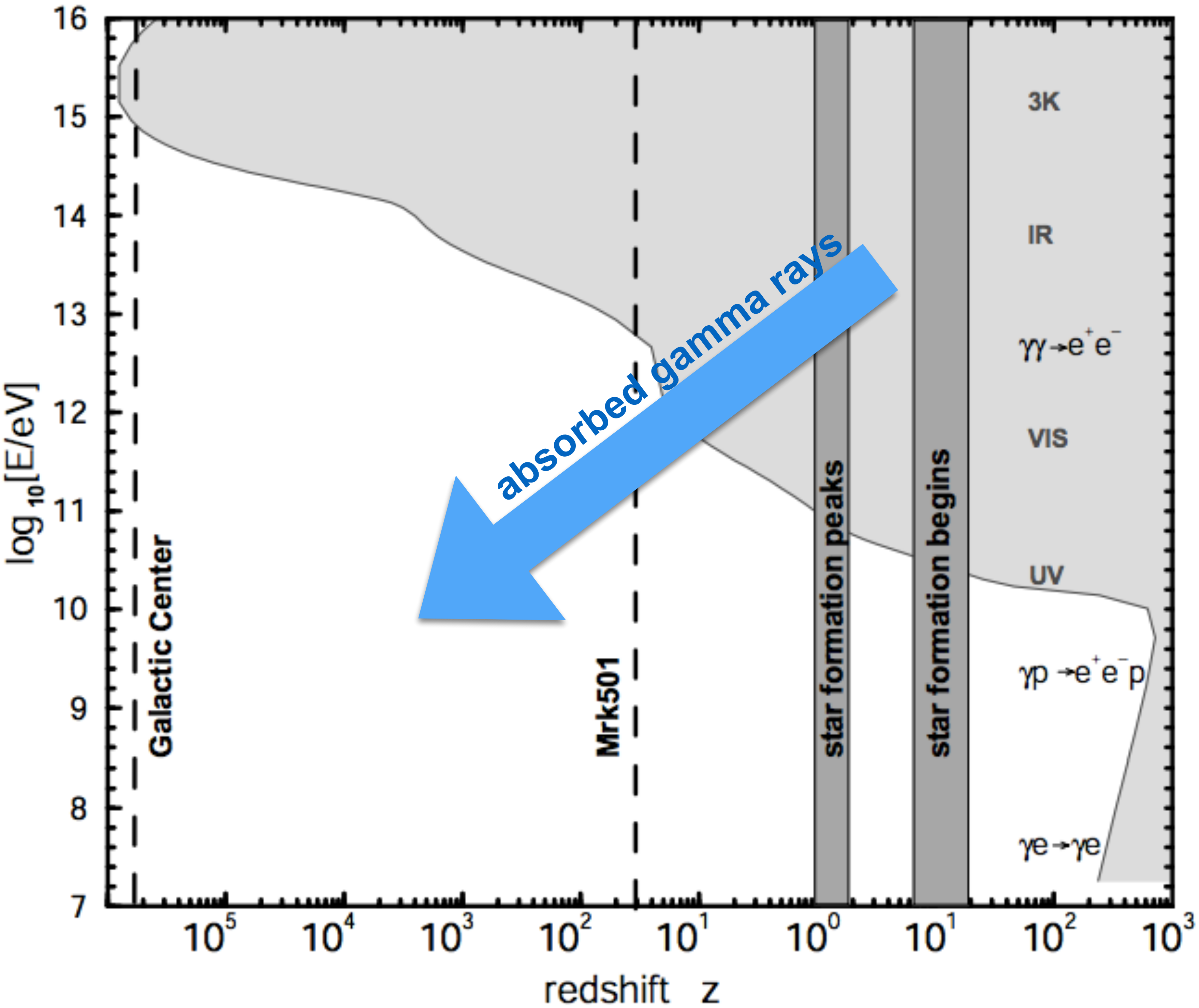
# Absorption of γ-rays in the extragalactic background light (EBL).

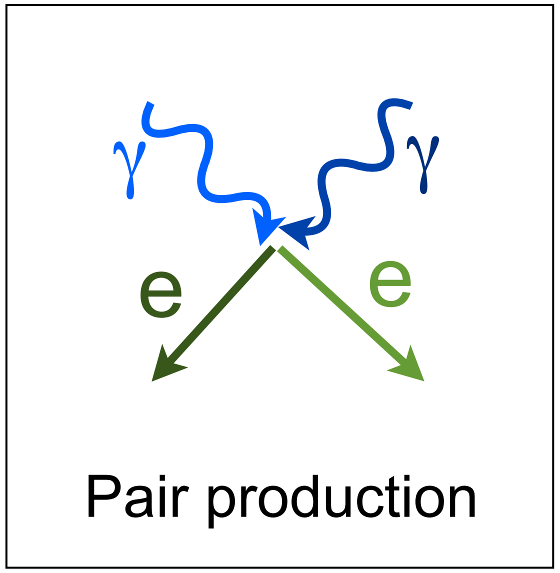



- TeV gamma rays can reach us only from the local universe
- Re-emission of absorbed TeV photons by inverse Compton processes in the GeV band: "cascade emission"

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

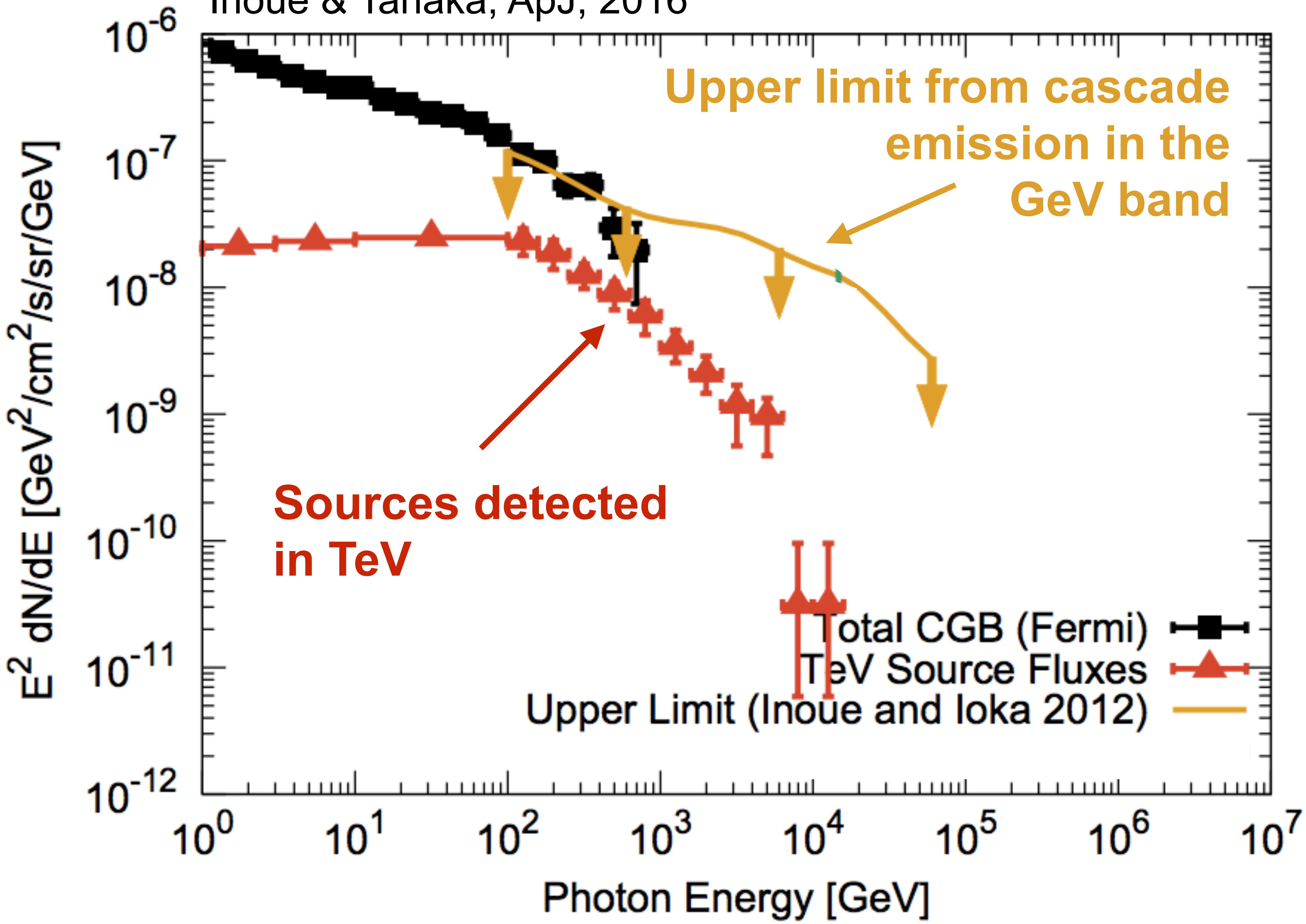



- TeV gamma rays can reach us only from the local universe
- Re-emission of absorbed TeV photons by inverse Compton processes in the GeV band: "cascade emission"

# And you can still count sources ….

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.

# Extragalactic Summary

> Blazars dominate the extragalactic gamma-ray sky above ~ 10 GeV

> Small contributions from Radio Galaxies and Starforming Galaxies
  - But large modeling uncertainties

> Emission from star-forming galaxies correlates well with star-formation rate

> Radio galaxies exhibit complex gamma-ray spectra.