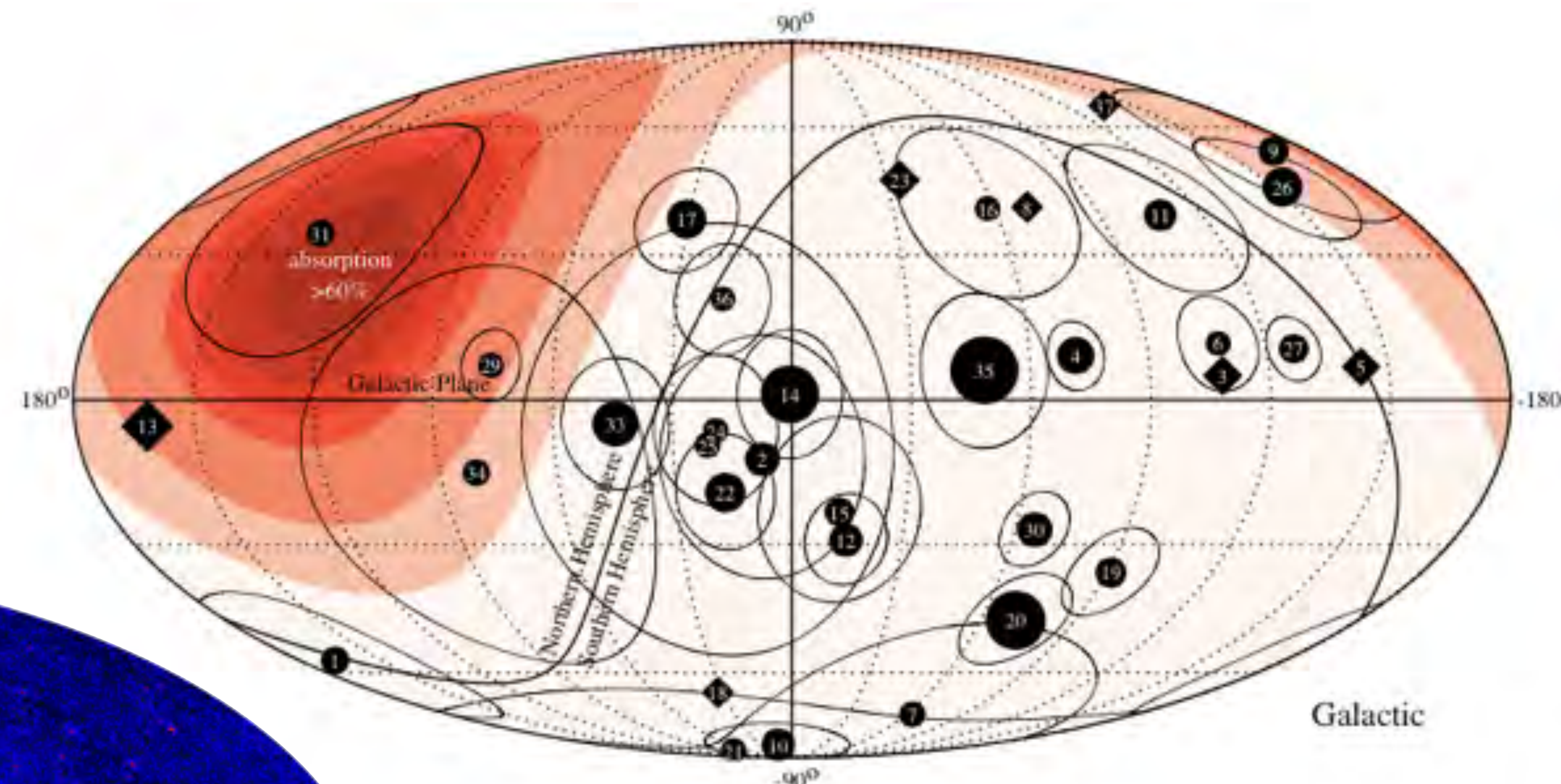
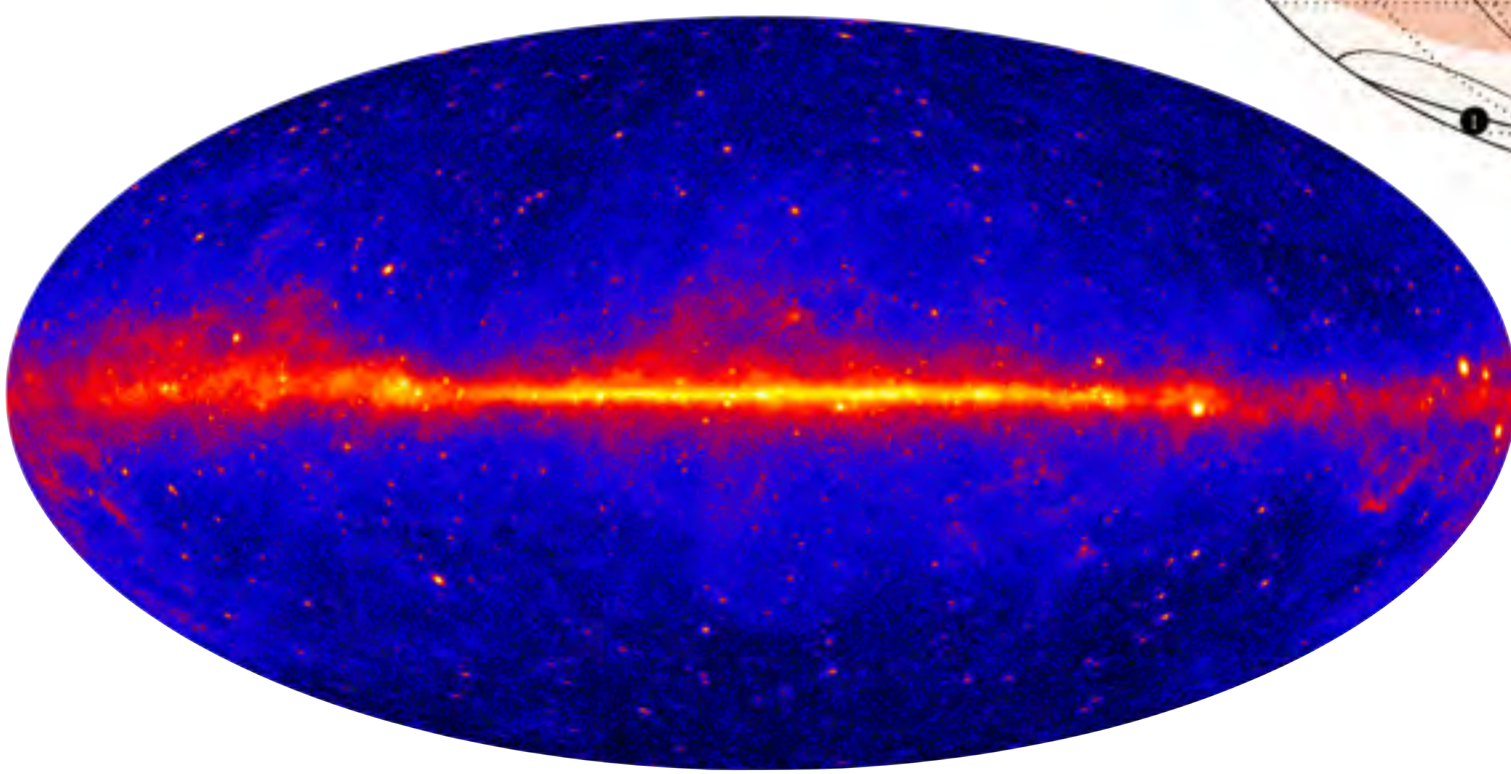
Neutrinos & gamma rays

Complementary views on the high-energy universe.





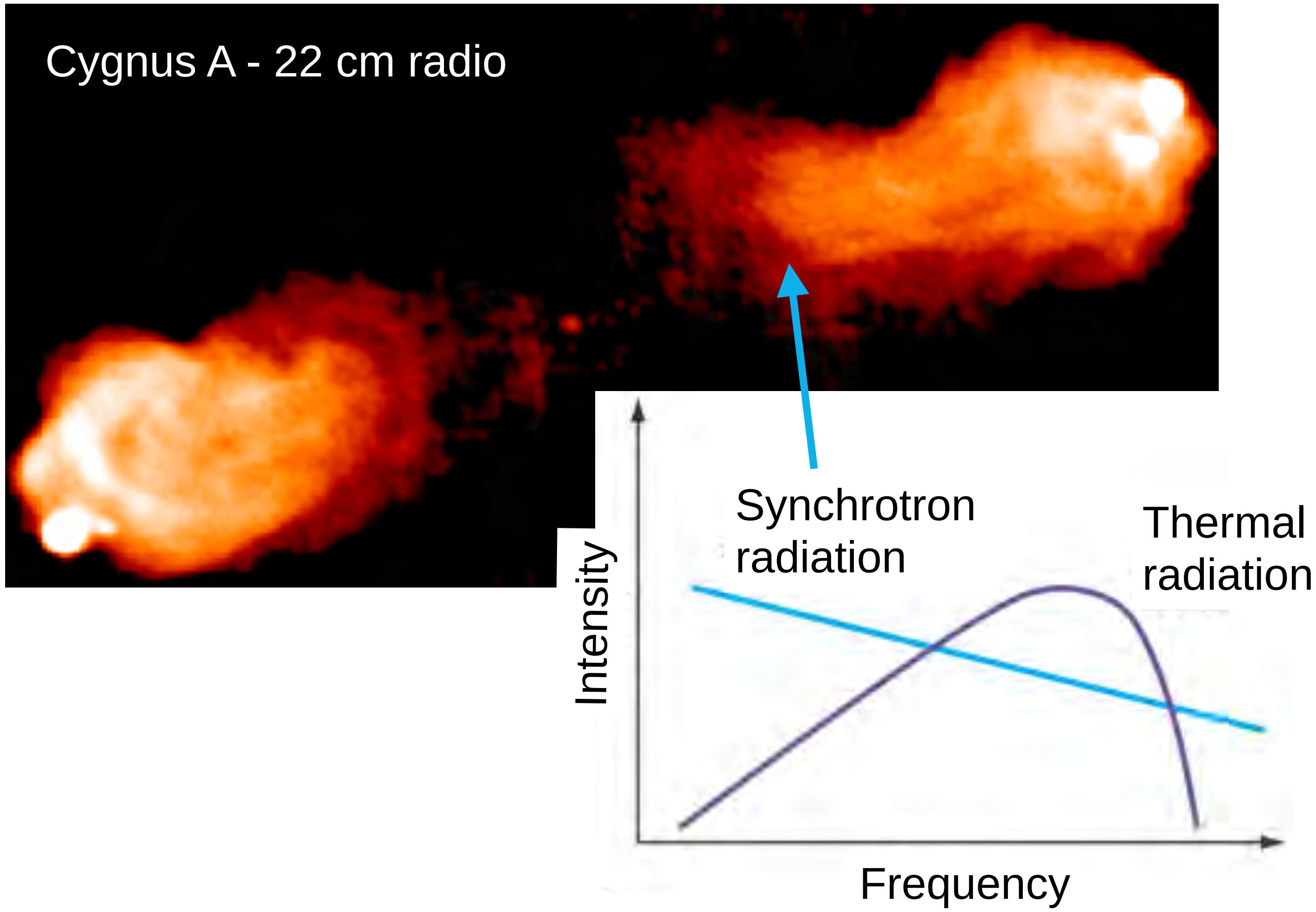
Markus Ackermann

Physikseminar
Hamburg, 13.01.2015

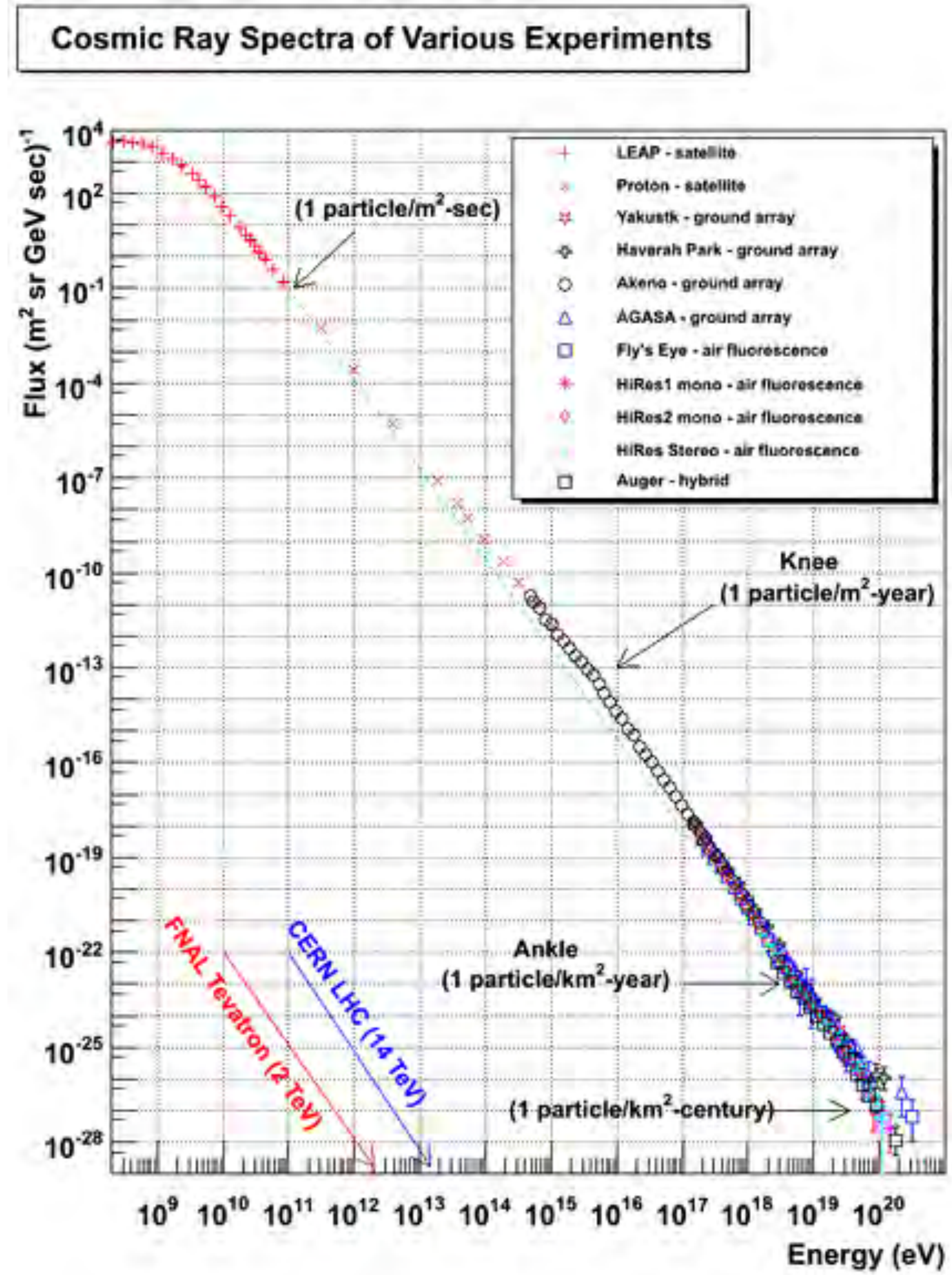
HELMHOLTZ | ASSOCIATION

DESY

The origin and the propagation of cosmic rays.



- 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 ?



Are cosmic rays 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

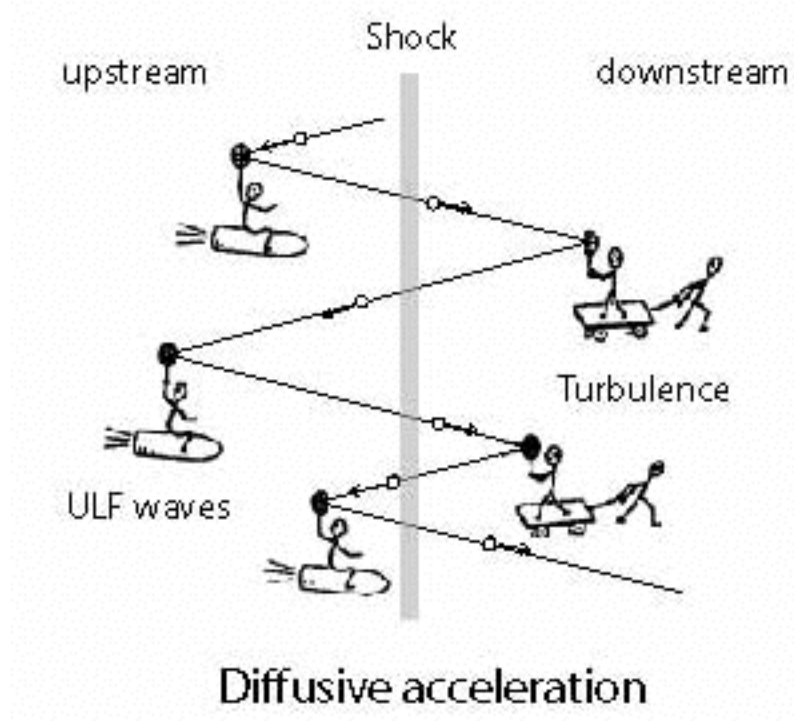
> Cosmic rays
- **heat** the interstellar gas
- **interact** with the magnetic fields
- **influence** star formation

→ **They are important for Galaxy dynamics**

Astrophysical mechanisms / environments for particle acceleration

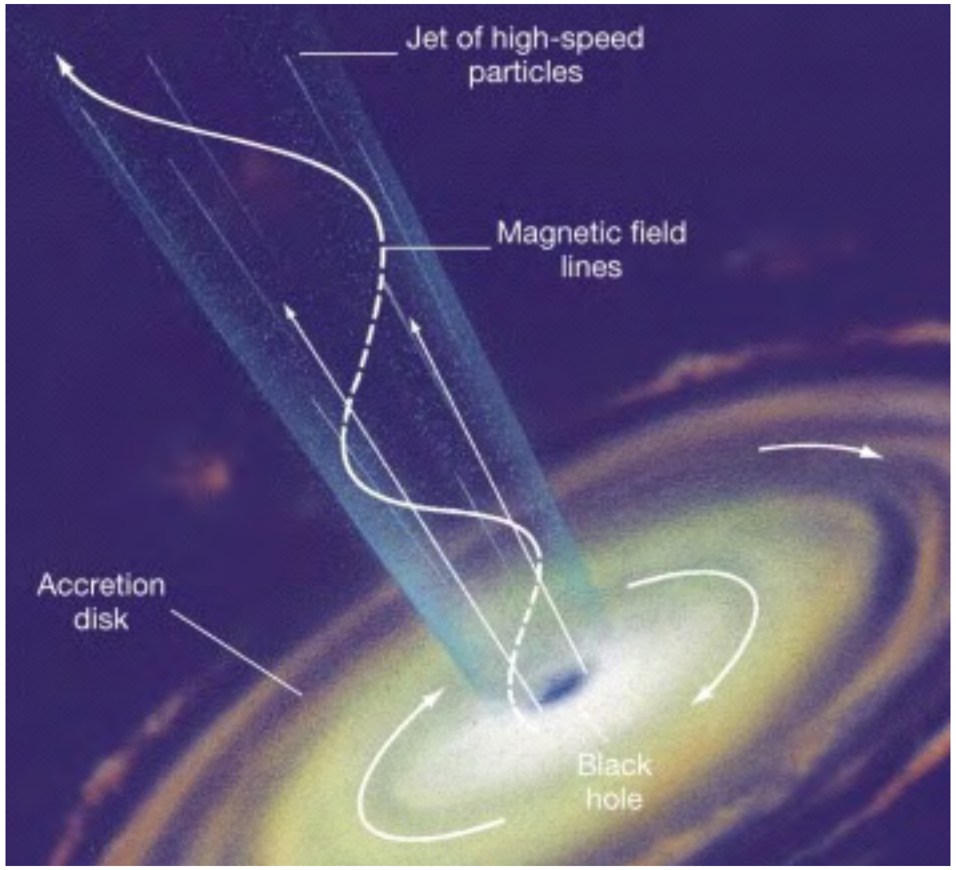
> What are **the mechanisms** driving such extreme particle acceleration ?

- Diffusive shock acceleration
- Acceleration in plasma turbulence
- Magnetic reconnection
- Electrostatic gaps



> What can we learn about the **astrophysical environments** ?

- gas & photon densities
- magnetic fields
- bulk motion

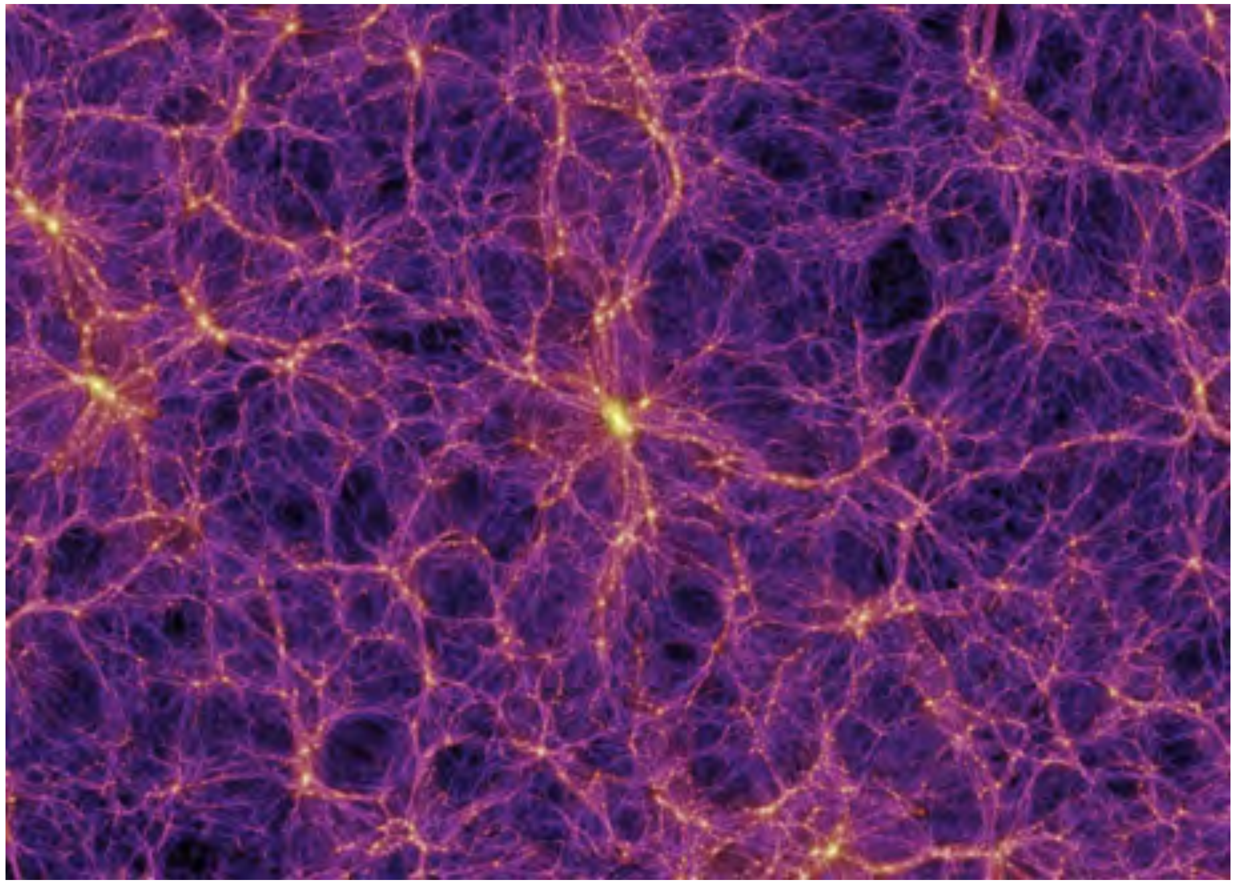


Signatures of new physics in the universe.

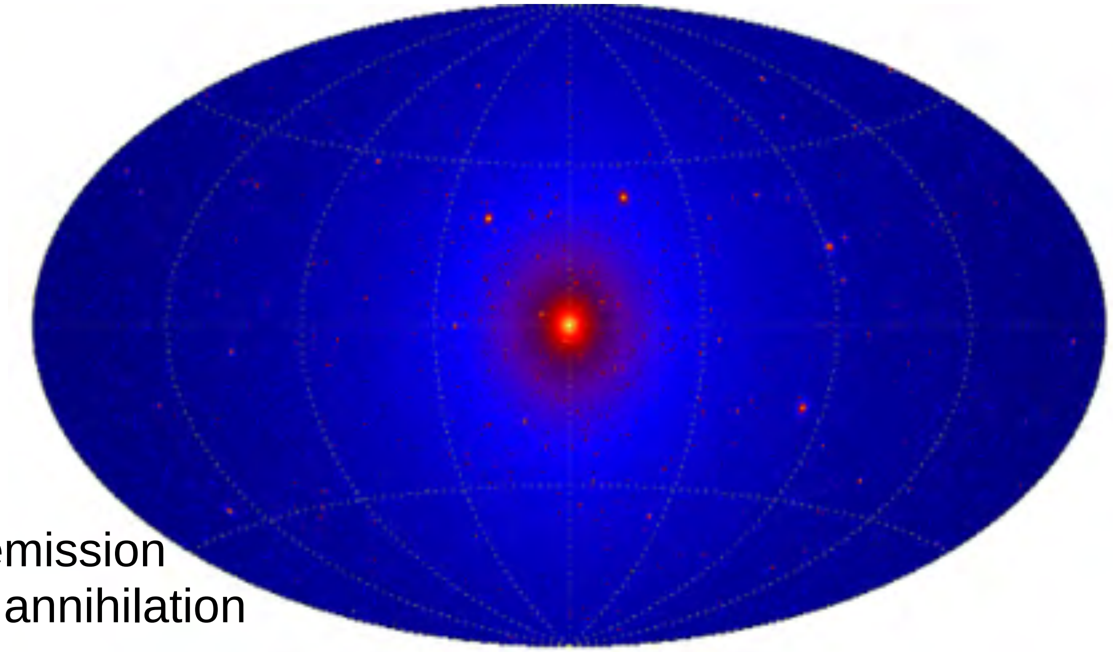
> Some **high-energy particles** might not have been accelerated…

> …but have been produced in the **annihilation** or decay of **massive particles**.

> Many particle physics motivated models for dark matter **predict observable signatures** in the **non-thermal sky**.



large scale dark matter distribution

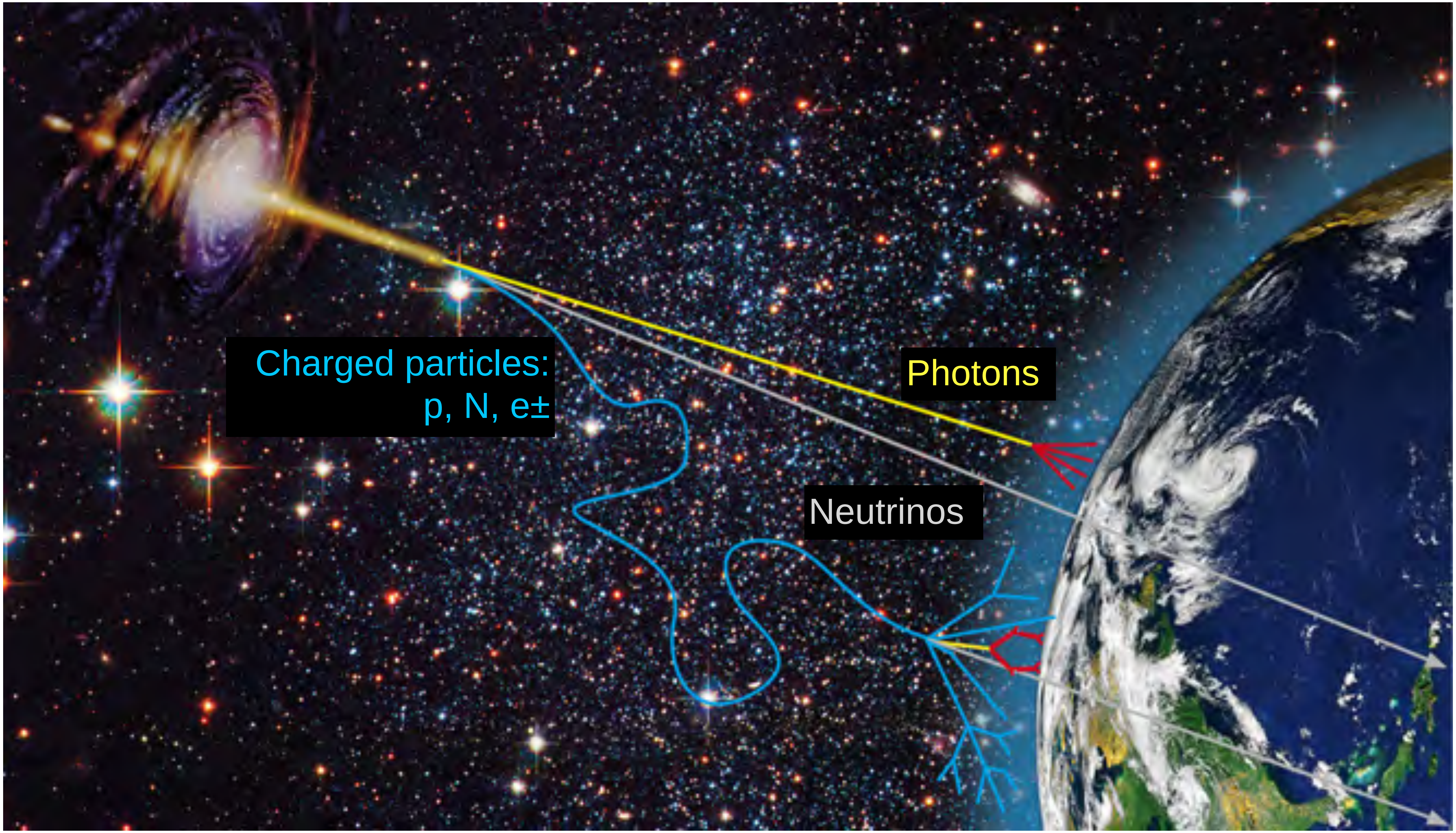


simulated γ-ray emission
from dark matter annihilation

www.particlezoo.net

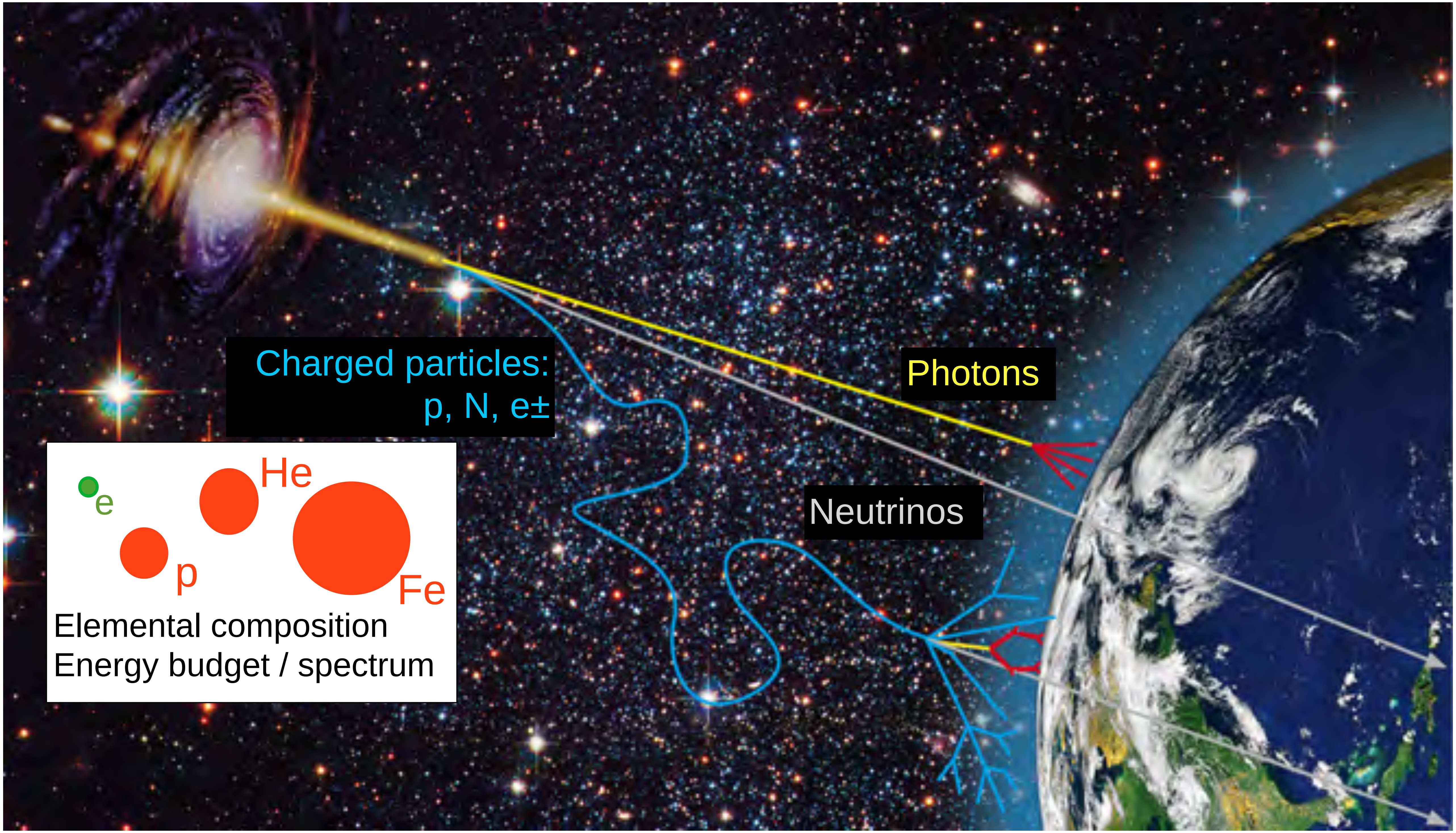
The multi-messenger approach.

> Every messenger is unique.



The multi-messenger approach.

> Every messenger is unique.



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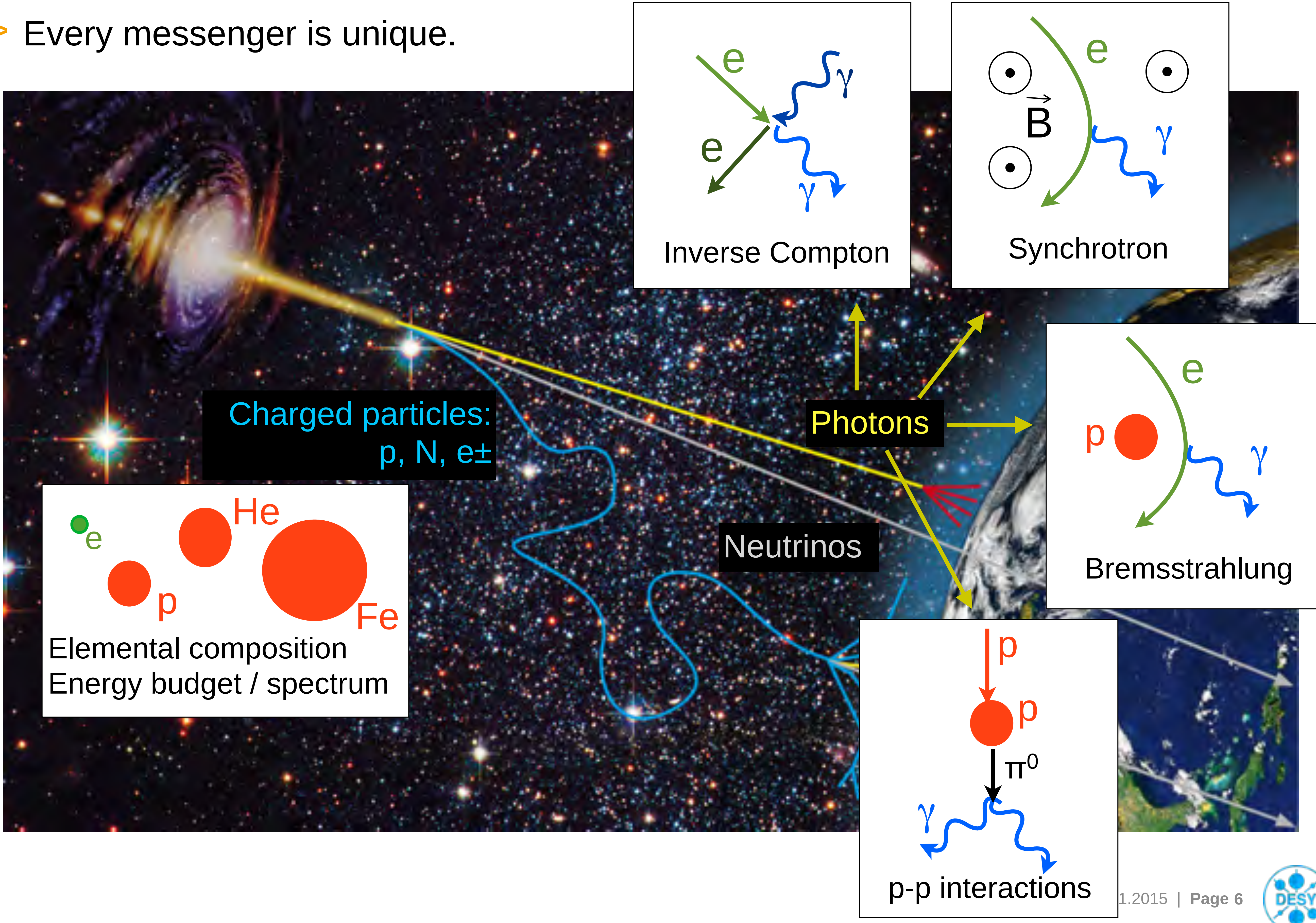

The multi-messenger approach.

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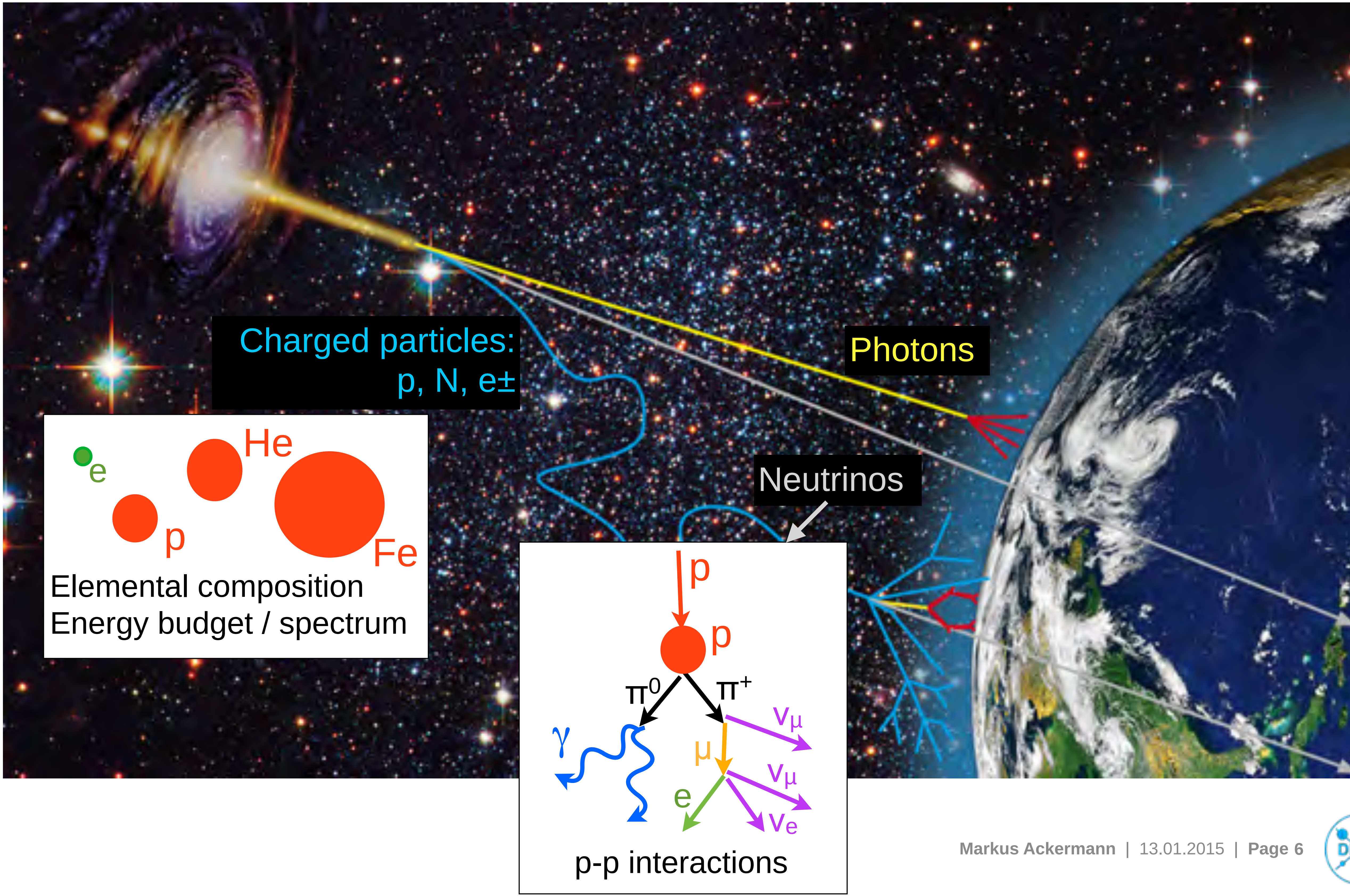
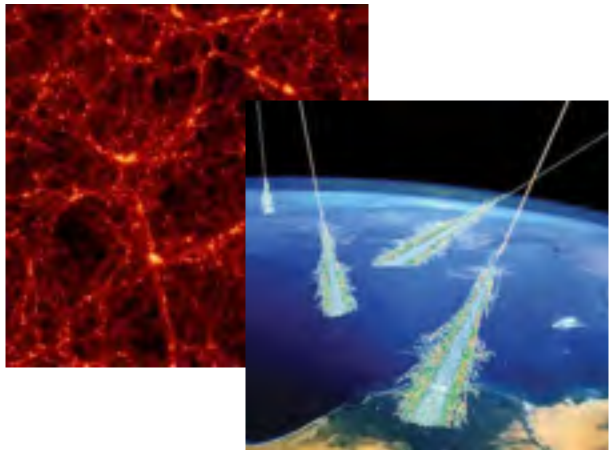


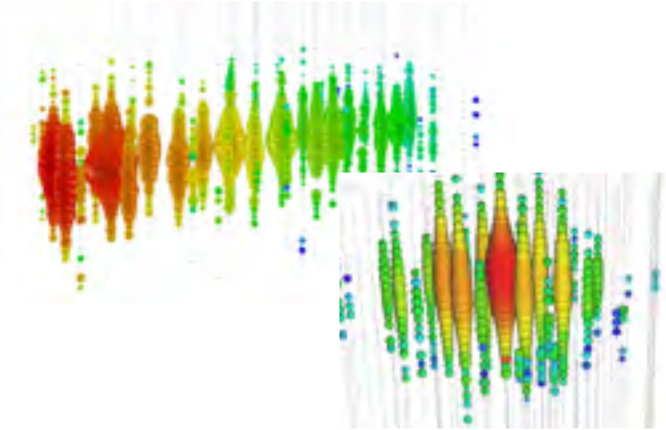
Topics addressed in this talk

> A measurement of the total extragalactic **high-energy** gamma-ray emission in the universe

- …and what we know about the sources that produce it.



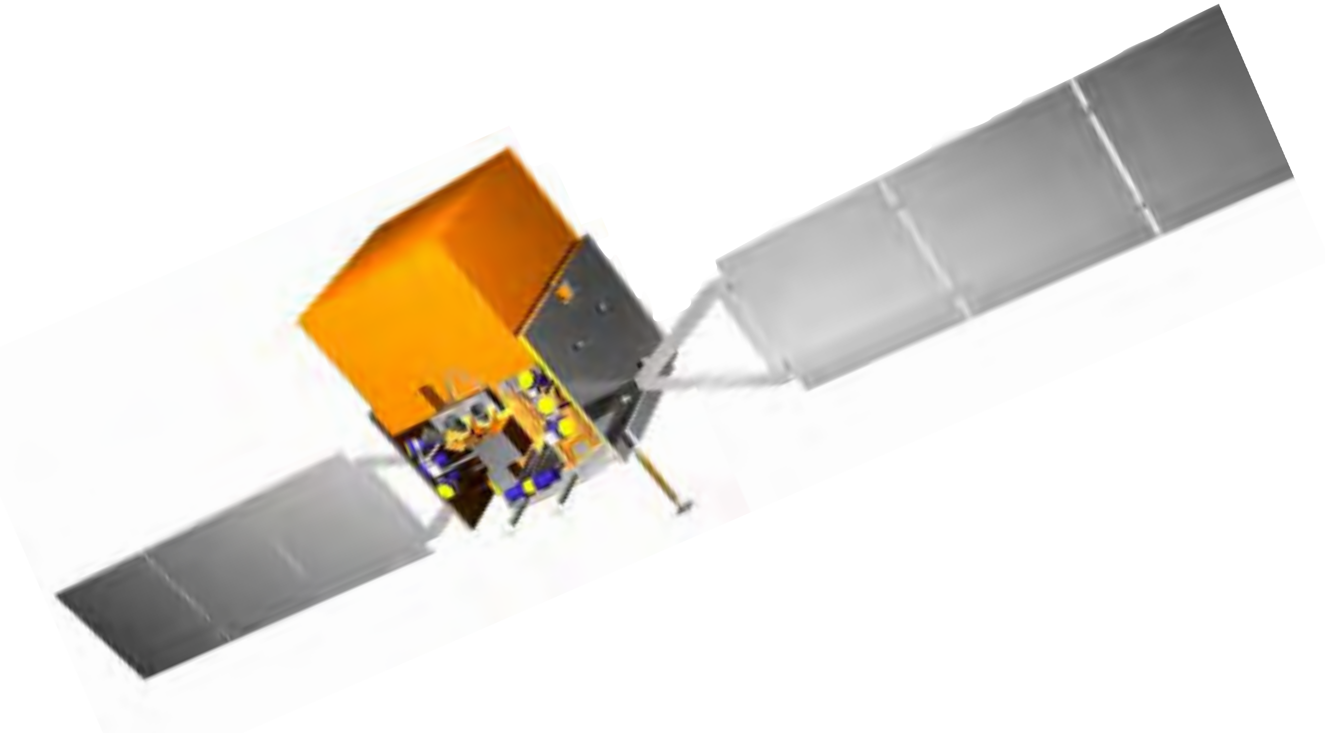
> The **connection** to CR production/propagation, dark matter annihilation & new physics.

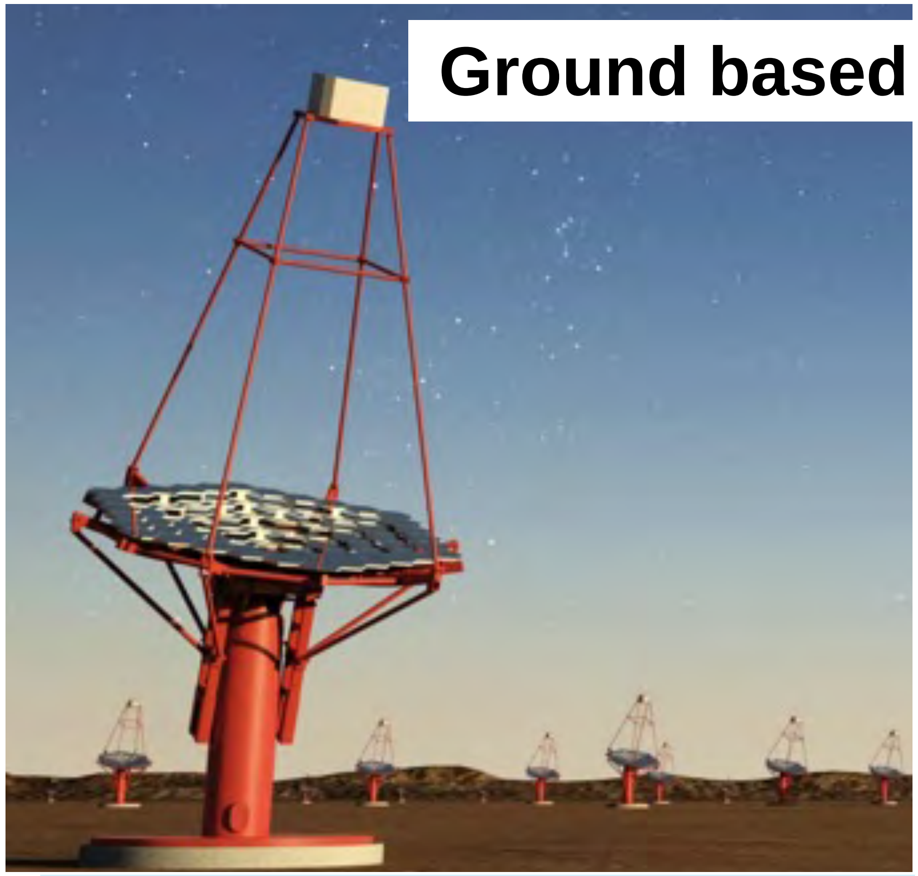


> The **very special value** of astrophysical neutrinos.

Gamma-ray astronomy.

Space based

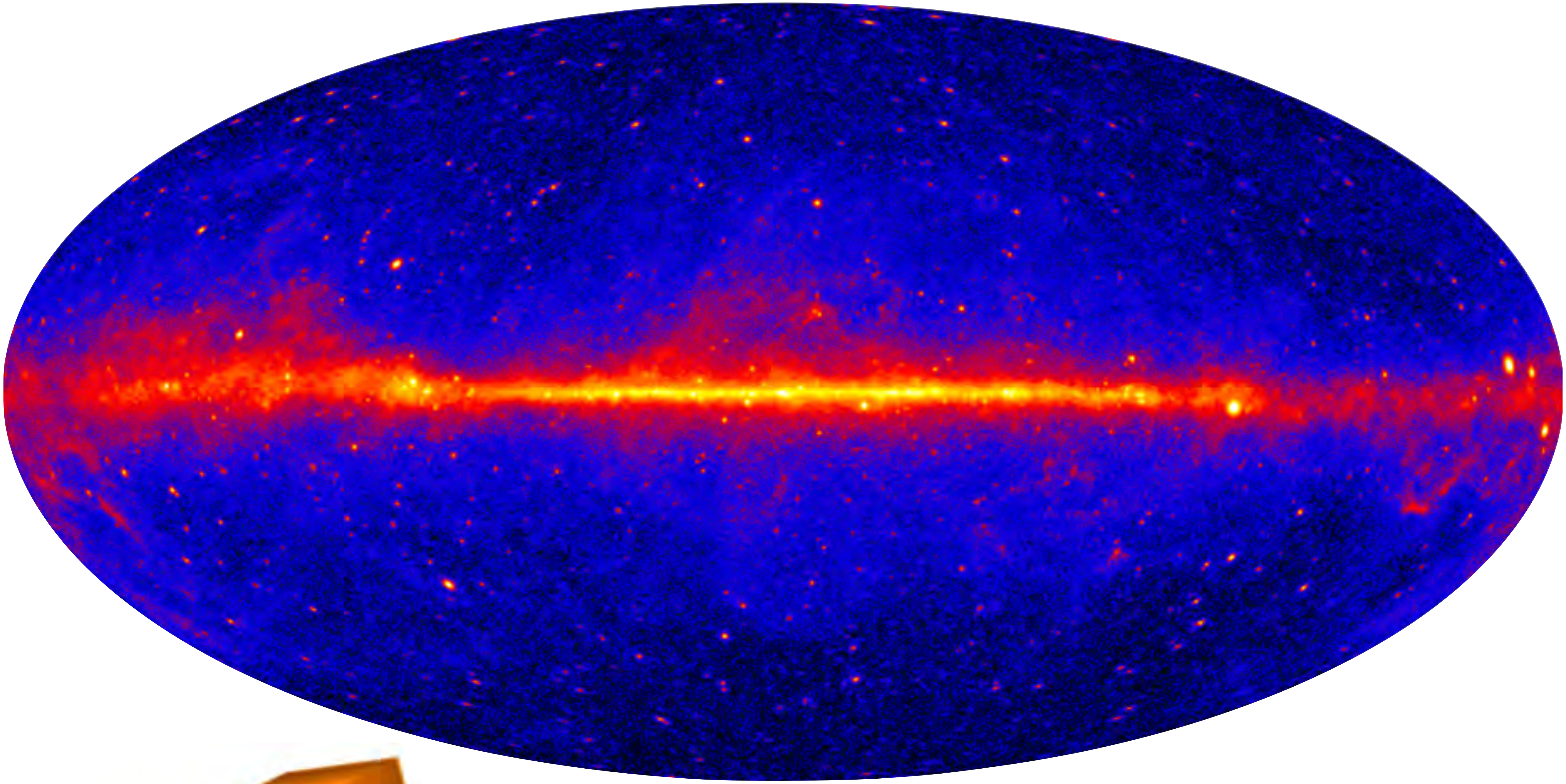




Fermi LAT	Instruments	HESS, MAGIC, Veritas
30 MeV - 1 TeV	**Energy range**	50 GeV - 100 TeV
20% of the sky	**Field-of-view**	~ 0.02% of the sky
~1 m^2	**Effective area**	~10000 m^2
85% of the year	**Duty cycle**	10% of the year

The GeV gamma-ray sky.

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



> Fermi LAT images the full non-thermal sky above 100 MeV

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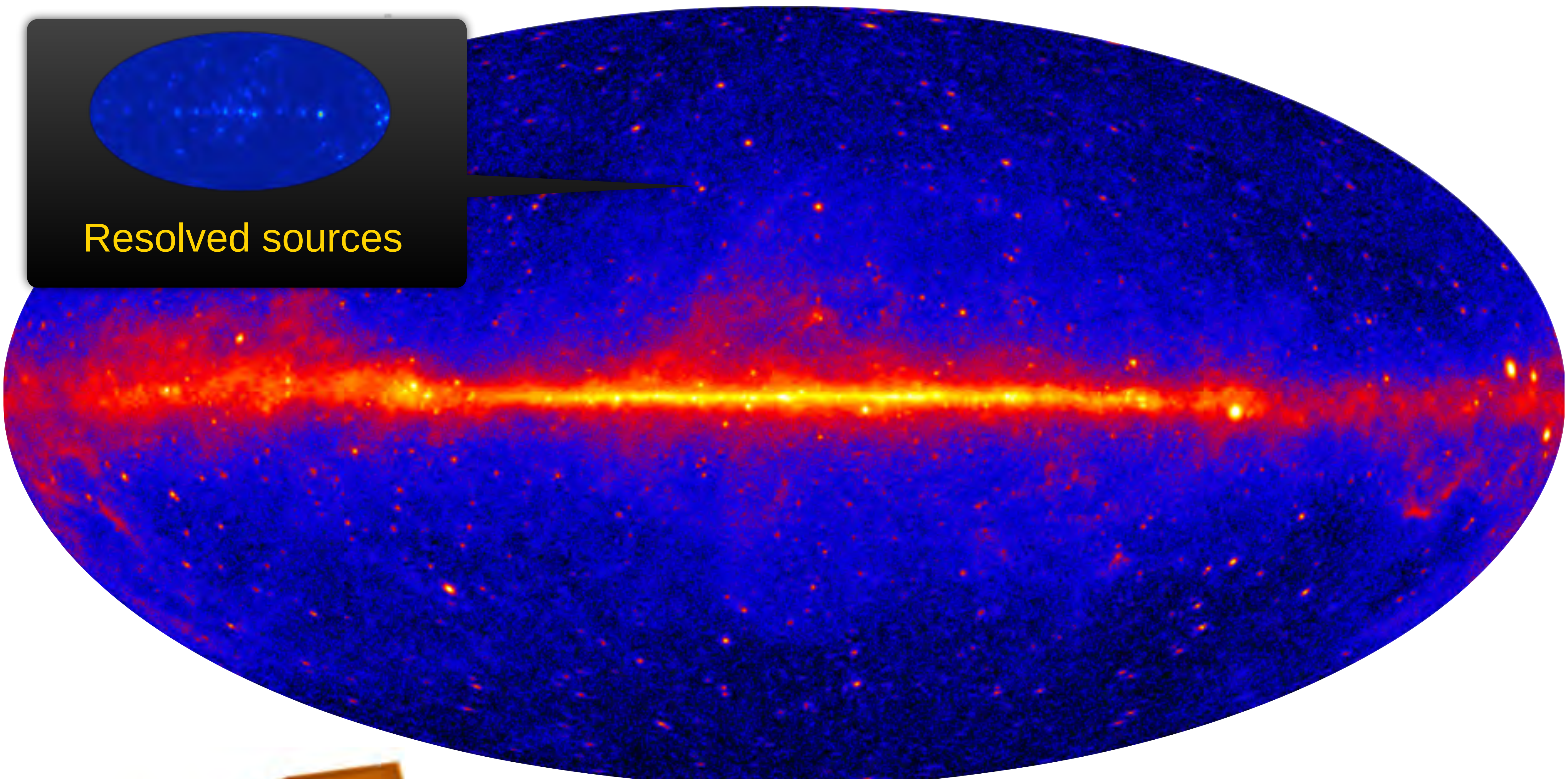

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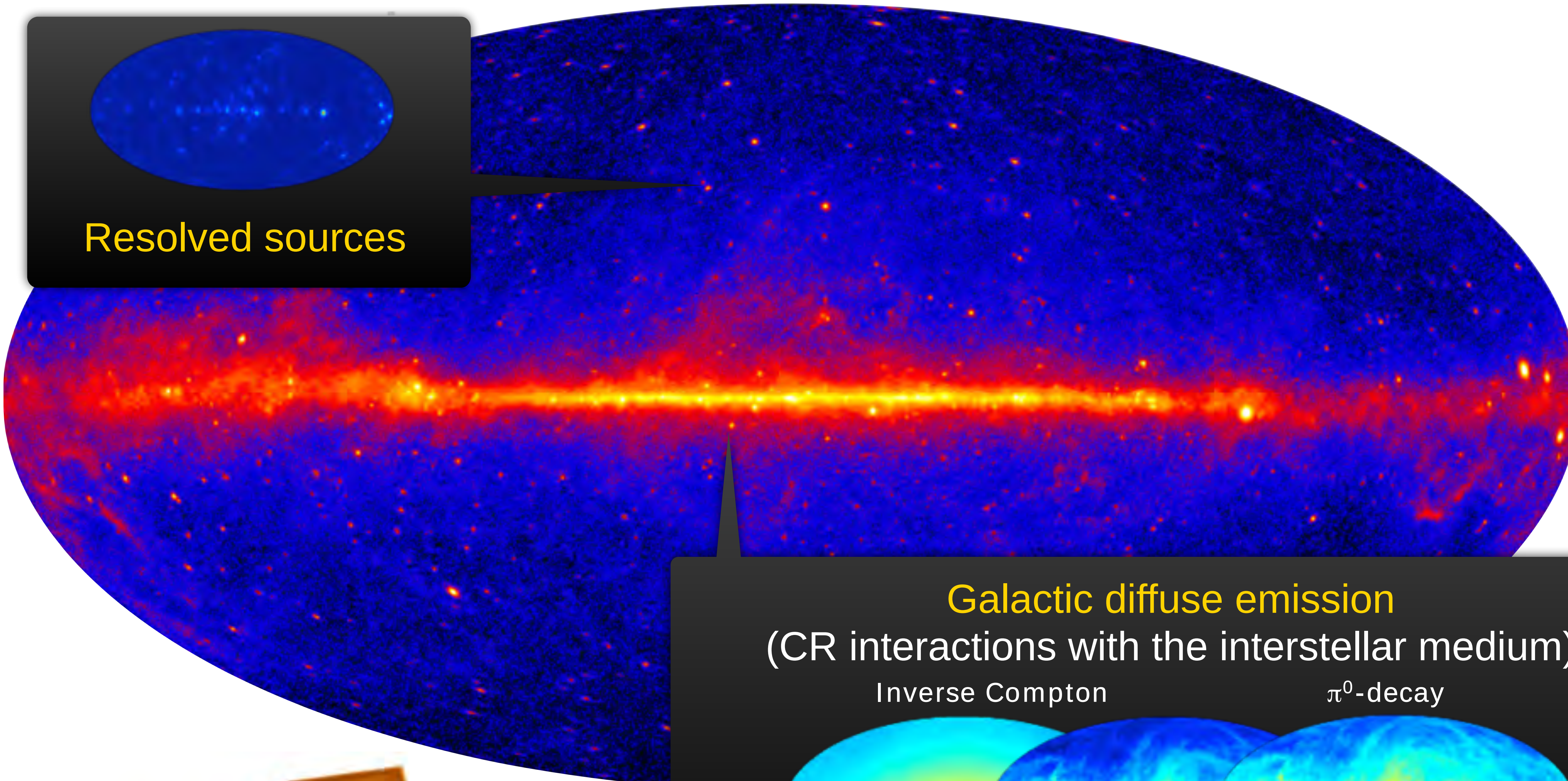
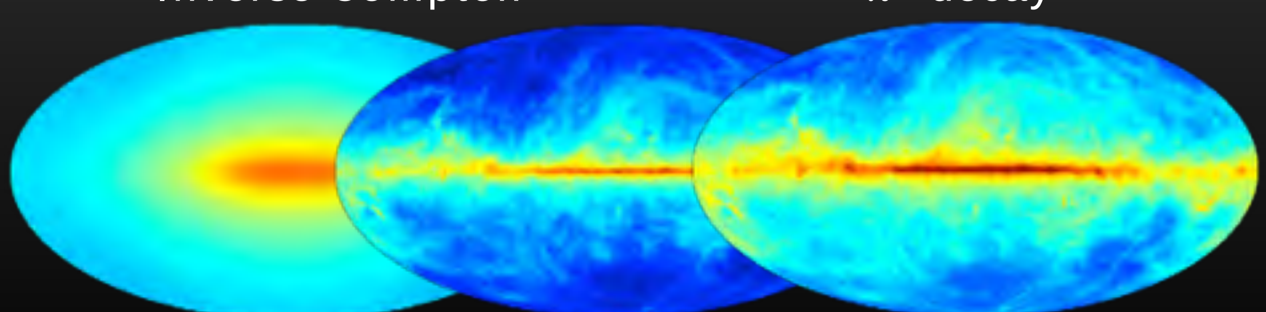


Resolved sources

Galactic diffuse emission

(CR interactions with the interstellar medium)



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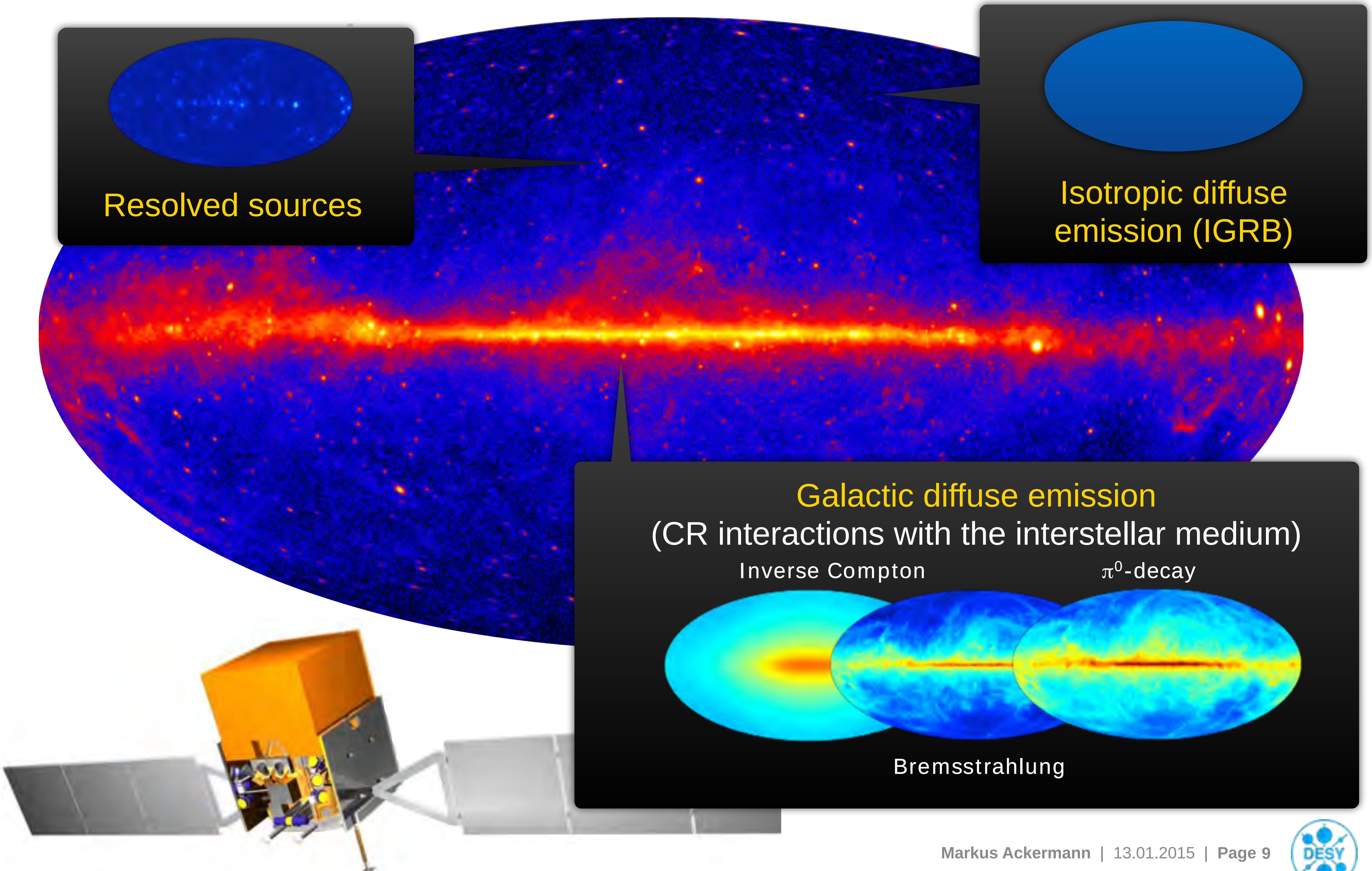
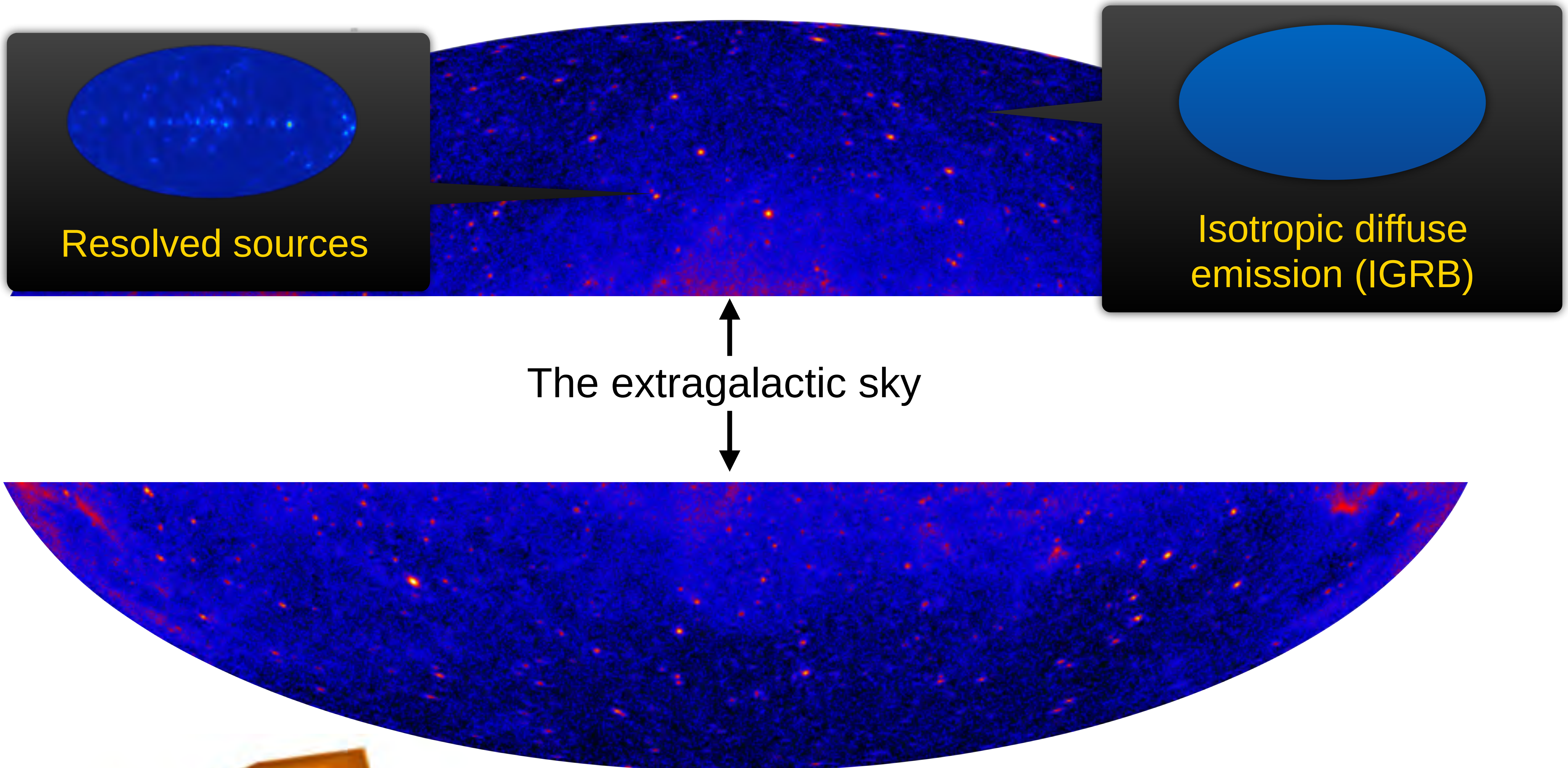
Fermi LAT, 4-year sky map, E > 1 GeV



The extragalactic GeV gamma-ray sky.

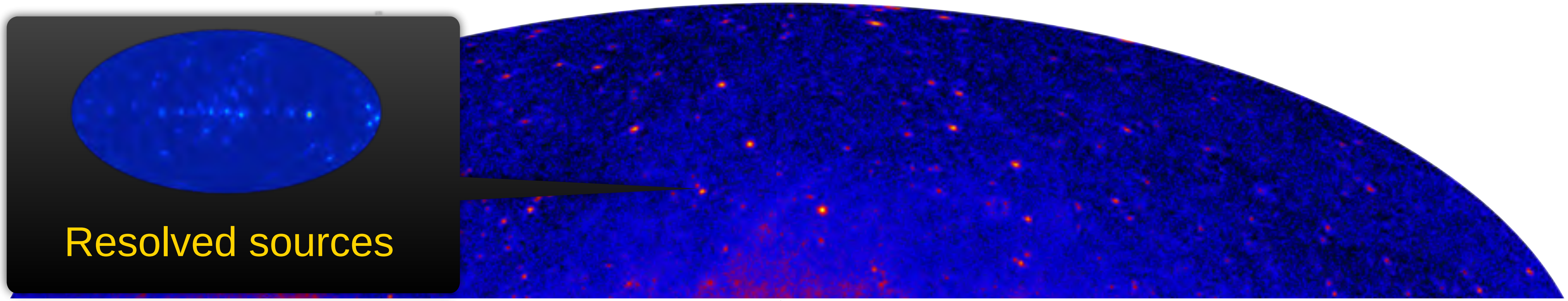
Fermi LAT, 4-year sky map, E > 1 GeV



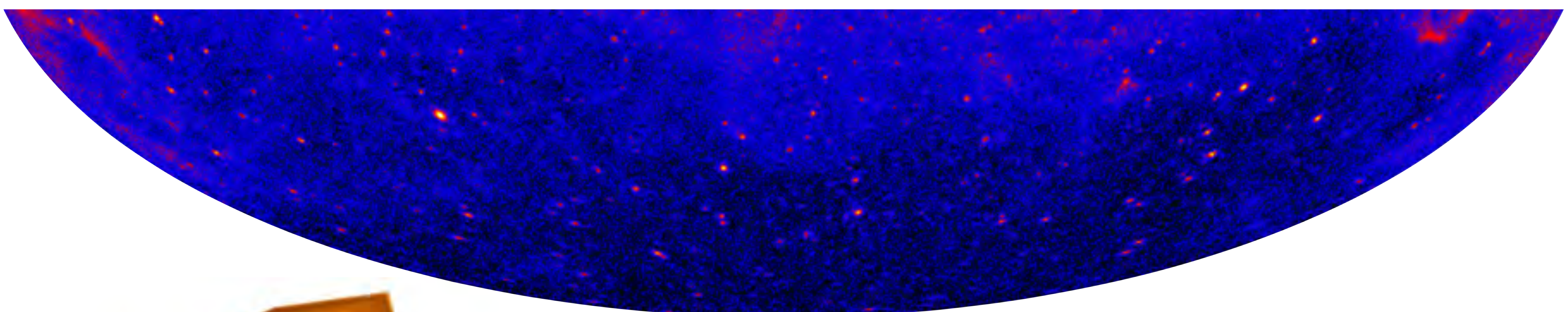
- Fermi LAT images the full non-thermal sky above 100 MeV

The extragalactic GeV gamma-ray sky.

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



The extragalactic sky



> Fermi LAT images the full non-thermal sky above 100 MeV

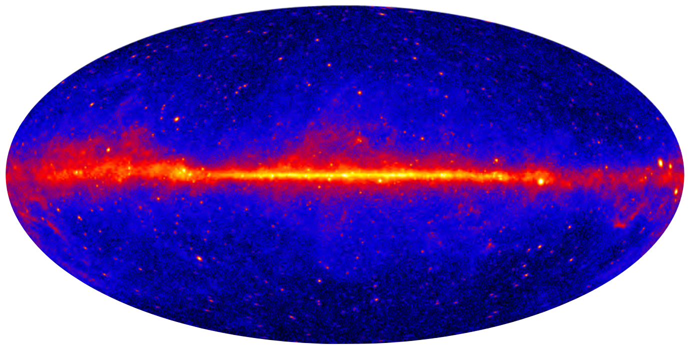
A census of the sky: 3FGL

> 3FGL: **3rd Fermi LAT gamma-ray source catalog** based on 4 years of data

- Systematic scan of the sky for sources, source identification or association
- Replaces 2FGL based on 2 years of data

	2FGL	3FGL
Total	1873	3033
Unassociated	649 (35%)	992 (33%)
AGNs	991 + 28 (ID) (57%)	1691 + 66 (ID) (58%)
PSRs	25 + 83 (ID)	29 + 137 (ID)
PWN	3 (ID)	2+9 (ID)
SNR	4 +6 (ID)	11+12 (ID)
GLC	11	15
SBG	4	4
HMB	4 (ID)	3 (ID)
spp	58	51
Others	7 (gal+Nova+...)	11 (gal+Nova+BIN...)
Extended	12	25
High/Low |b|	1319/554	2193/841

preliminary



Elisabetta Cavazzuti
5th Fermi Symp.
Nagoya, 2014

A census of the sky: 3FGL

> 3FGL: **3rd Fermi LAT gamma-ray source catalog** based on 4 years of data

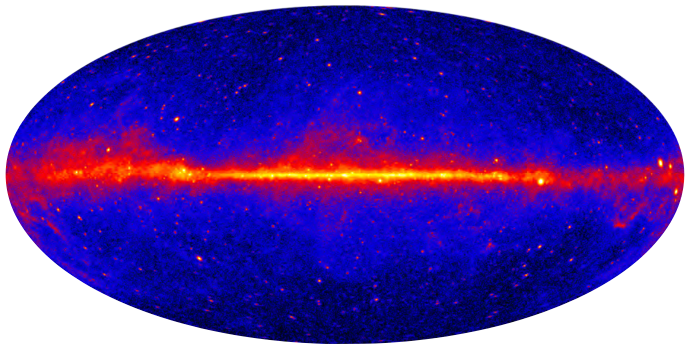
- Systematic scan of the sky for sources, source identification or association
- Replaces 2FGL based on 2 years of data

No compelling association to a known source

Active Galactic Nuclei:
- Blazars
- Radio Galaxies
- Seyfert Galaxies

Starburst Galaxies

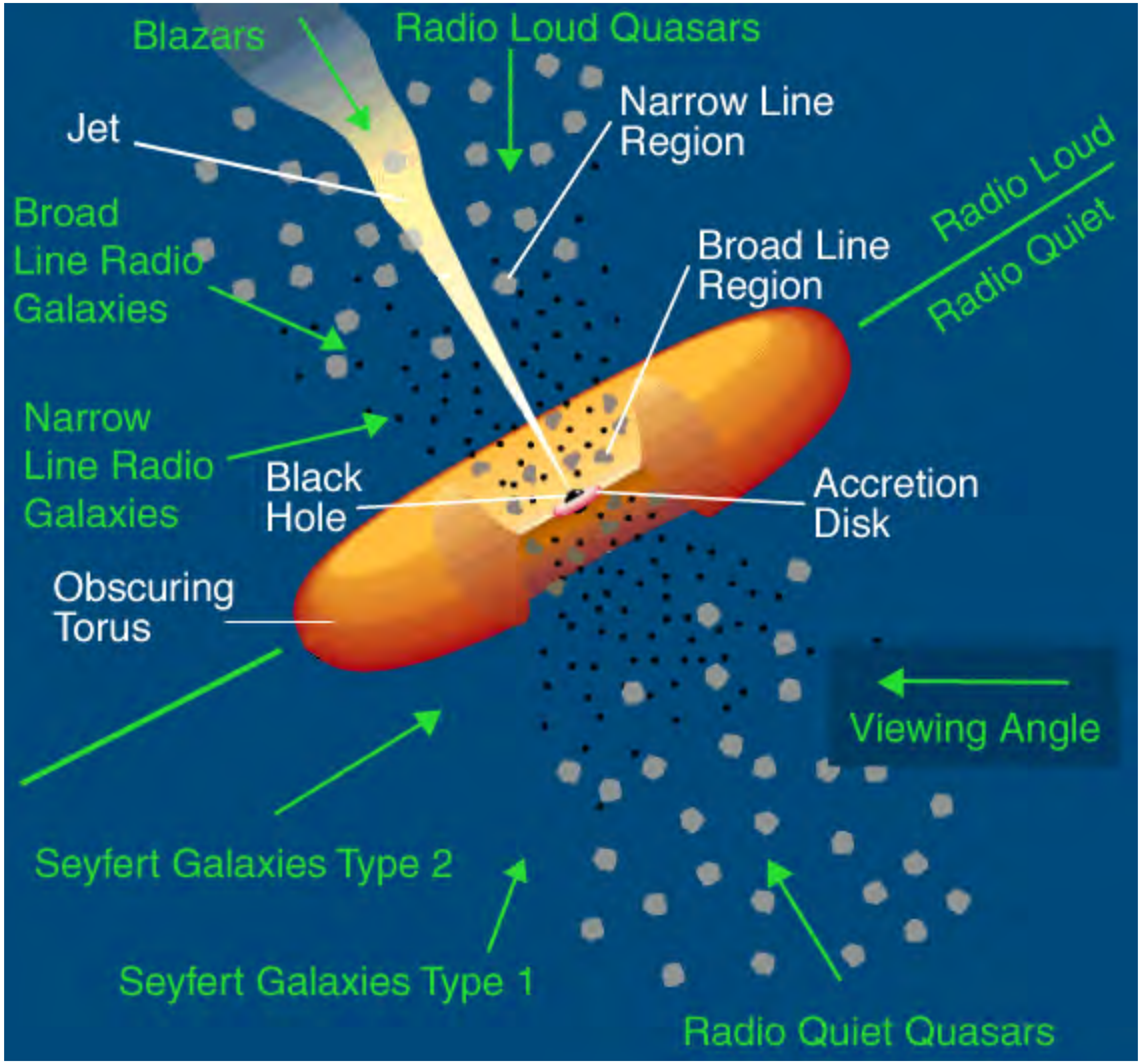
	2FGL	3FGL
Total	**1873**	**3033**
Unassociated	649 (35%)	992 (33%)
AGNs	991 + 28 (ID) (57%)	1691 + 66 (ID) (58%)
GALACTIC		
SBG	4	4
GALACTIC		
High/Low |b|	1319/554	2193/841

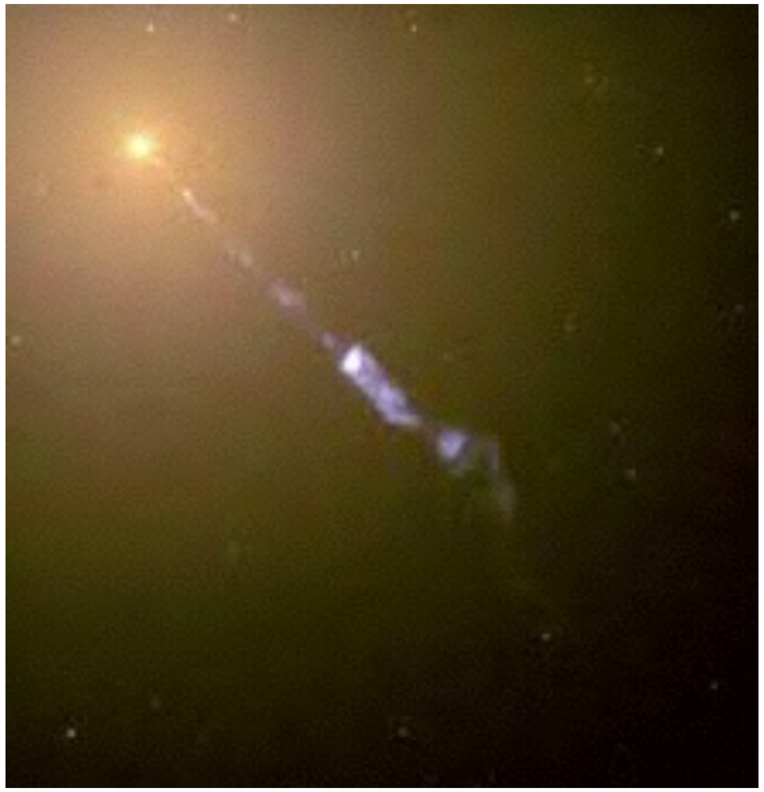


Elisabetta Cavazzuti
5th Fermi Symp.
Nagoya, 2014

Active Galactic Nuclei

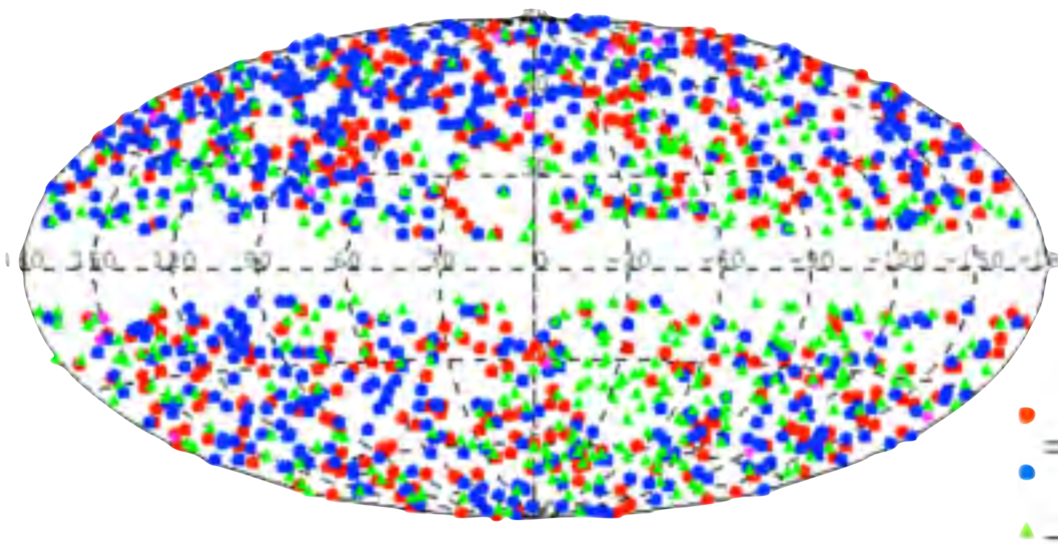
- The overwhelming majority of extragalactic LAT sources are Active Galactic Nuclei (AGN)





- **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

The 3rd LAT AGN catalog



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3LAC

Preliminary

AGN type	Entire 3LAC	3LAC Clean Sample[a]	Low-latitude sample
All	1591	1444 +64%	182
FSRQ	467	414 +34%	24
...LSP	412	366	16
...ISP	47	42	3
...HSP	3	2	4
...no classification	5	4	1
BL Lac	632	604 +52%	30
...LSP	162	150	15
...ISP	178	173	4
...HSP	272	265	10
...no classification	20	16	1
Blazar of Unknown type	460	402 +164%	125
...LSP	198	164	54
...ISP	89	79	26
...HSP	120	118	39
...no classification	53	41	6
Other AGN	32	24	3

Benoit Lott
5th Fermi Symp.
Nagoya, 2014

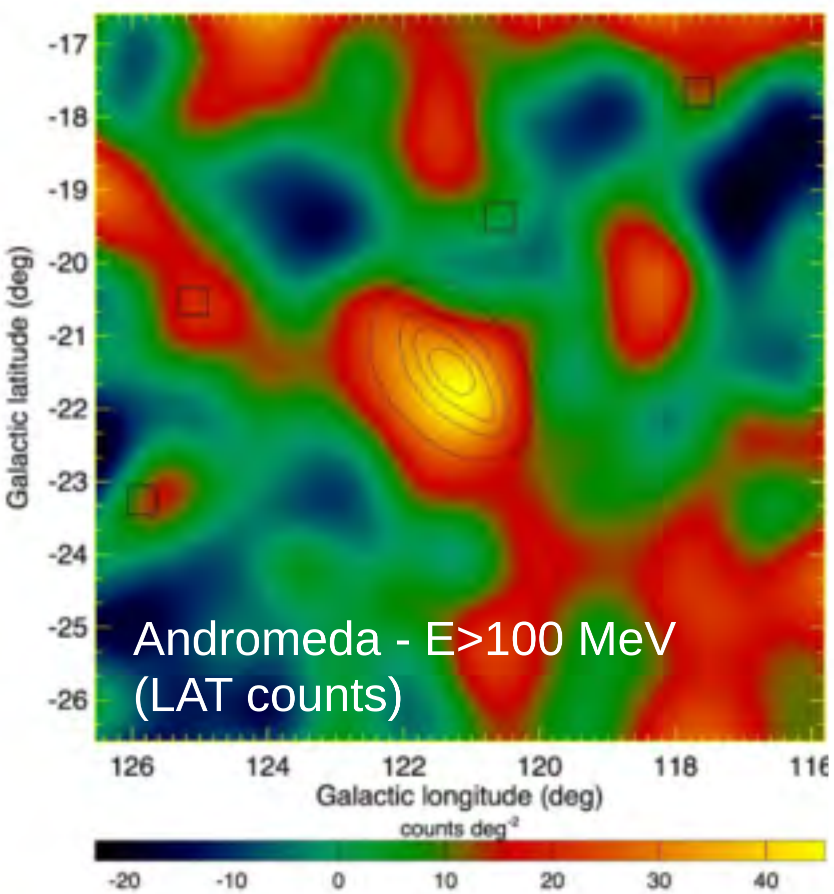
- 1591 high-latitude LAT sources associated with AGN
  - 1559 associated with Blazars
  - 32 associated with misaligned radio Galaxies
- Blazars are the dominant extragalactic gamma-ray sources
- Large fraction of unidentified sources are likely Blazars.

Star-forming / Starburst Galaxies.

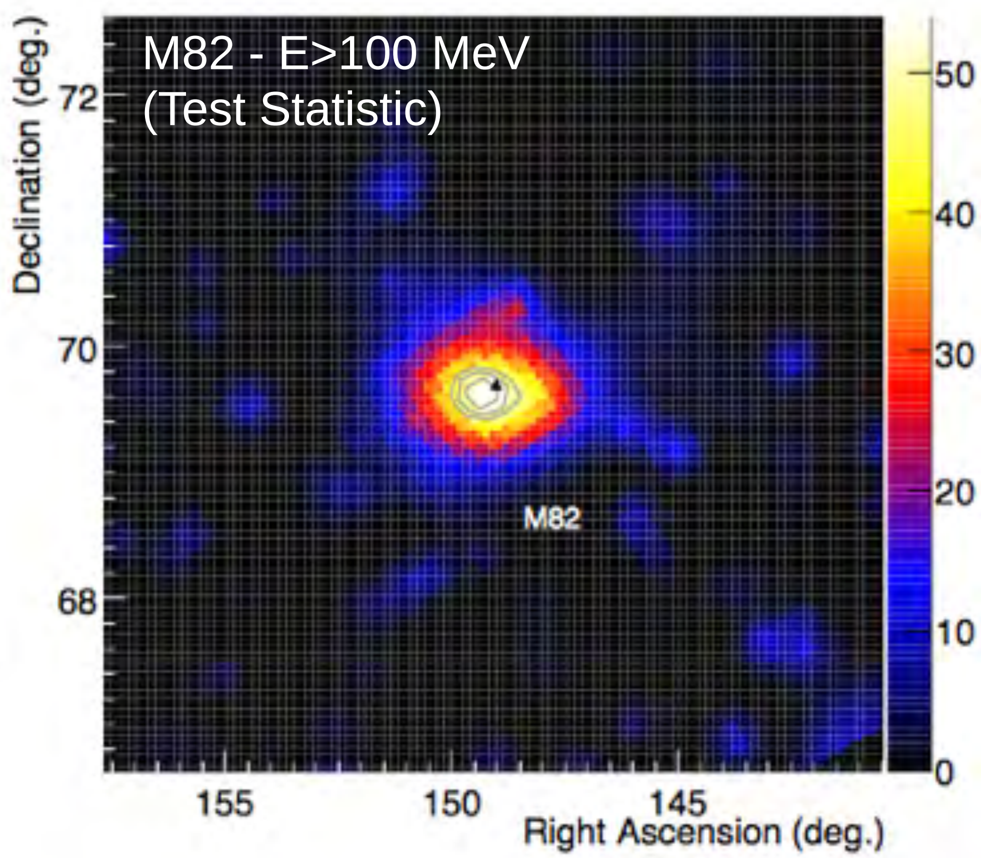
“normal” star-formation rate

extreme star-formation rate
“starburst”

Abdo et al., 2010



Abdo et al., 2010



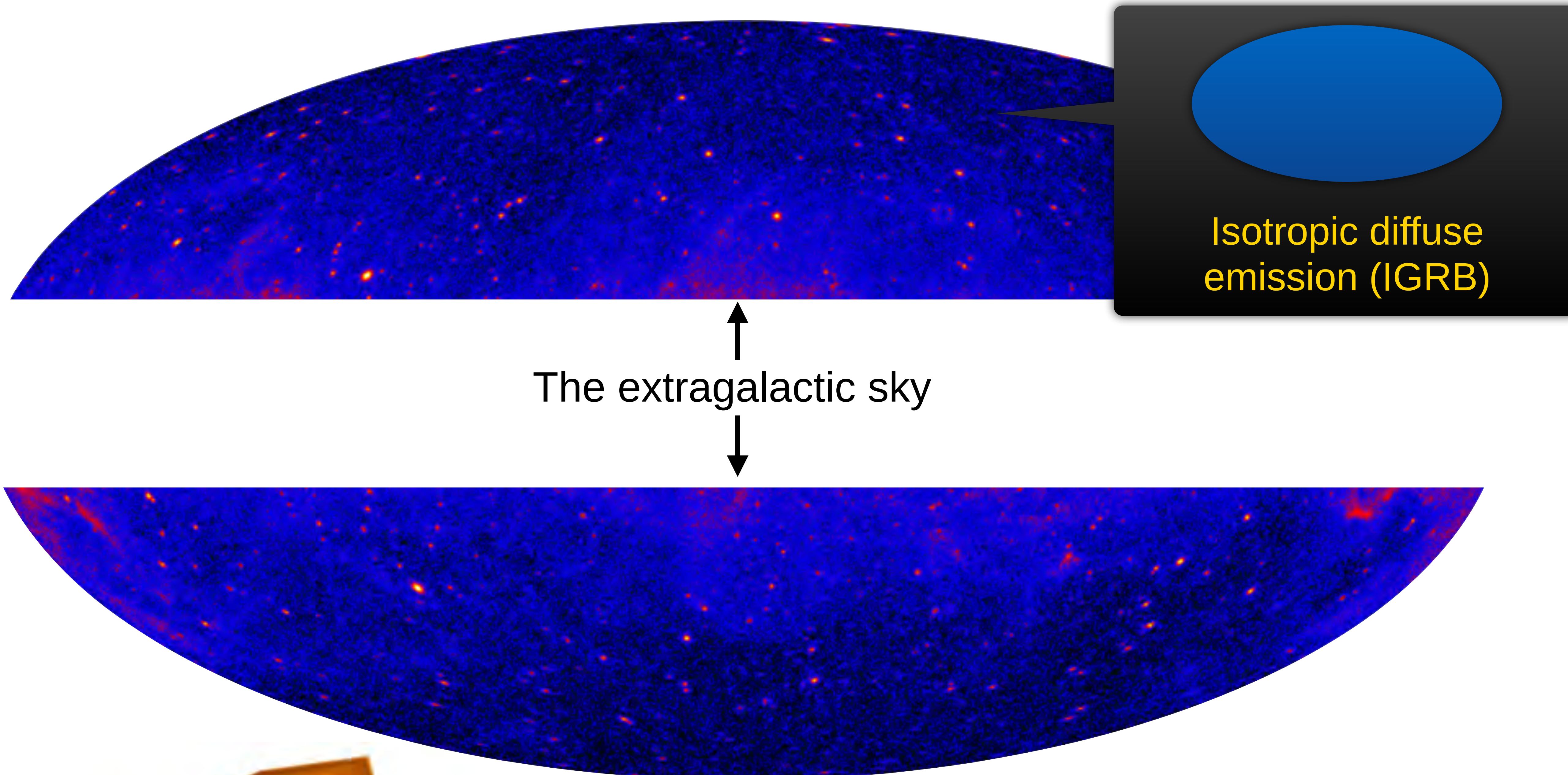
- 4 **starburst galaxies** detected with the LAT
- 4 local **“normal” galaxies** detected.
  - Andromeda, LMC, SMC & Milky Way
- Weak gamma-ray sources, but very abundant in the universe

Sources on the extragalactic gamma-ray sky

	Number of sources visible	Luminosity	Density in the universe
Blazars	~ 1500	bright	low
Misaligned active Galaxies	32	medium	medium
Starforming Galaxies	8	dim	high
Unknown	~ 1000	?	?

The extragalactic GeV gamma-ray sky

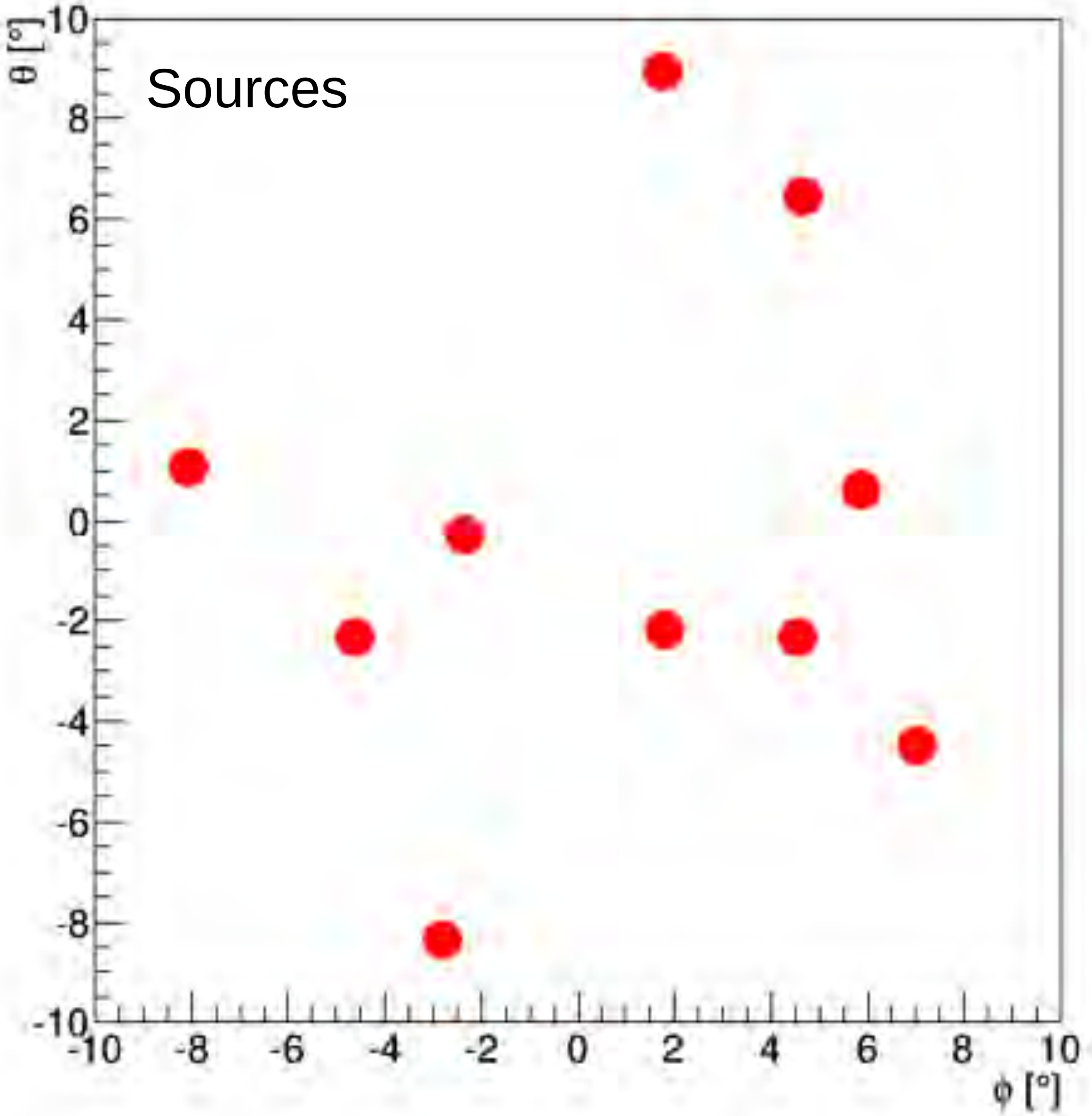
Fermi LAT, 4-year sky map, E > 1 GeV

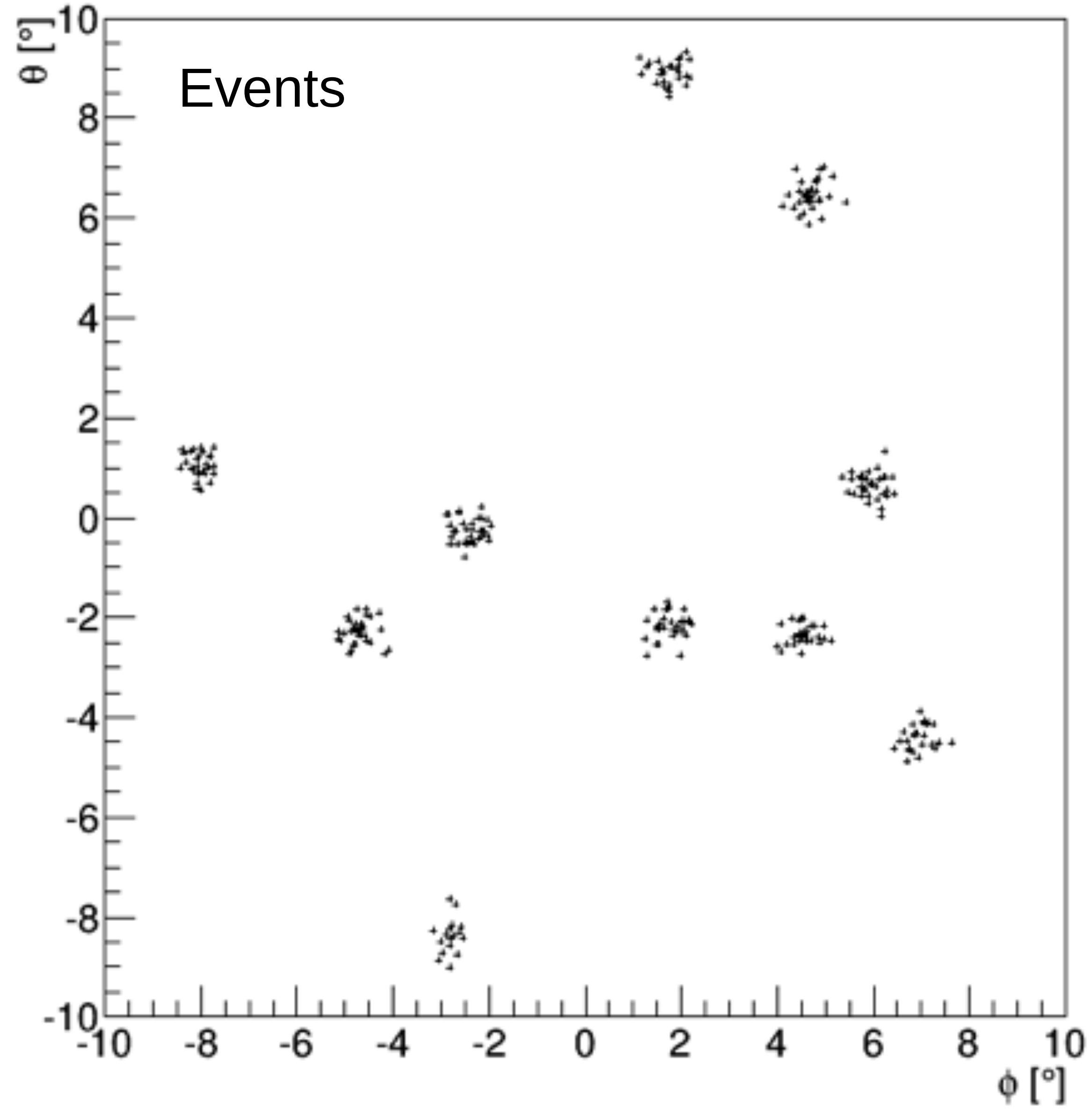


> Fermi LAT images the full non-thermal sky above 100 MeV

Source detection: Strong sources

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

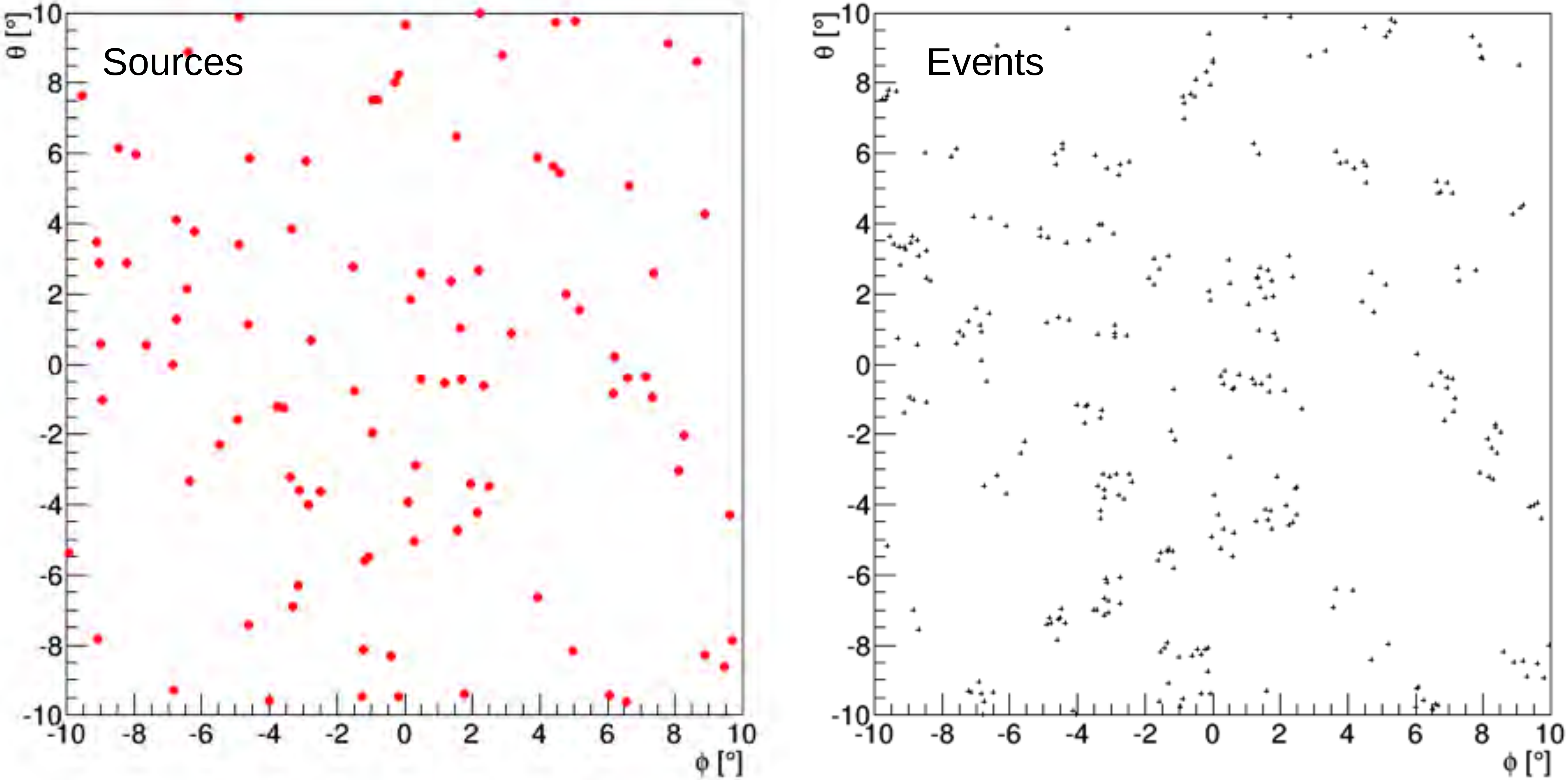




30 events / source

Source detection: Intermediate sources

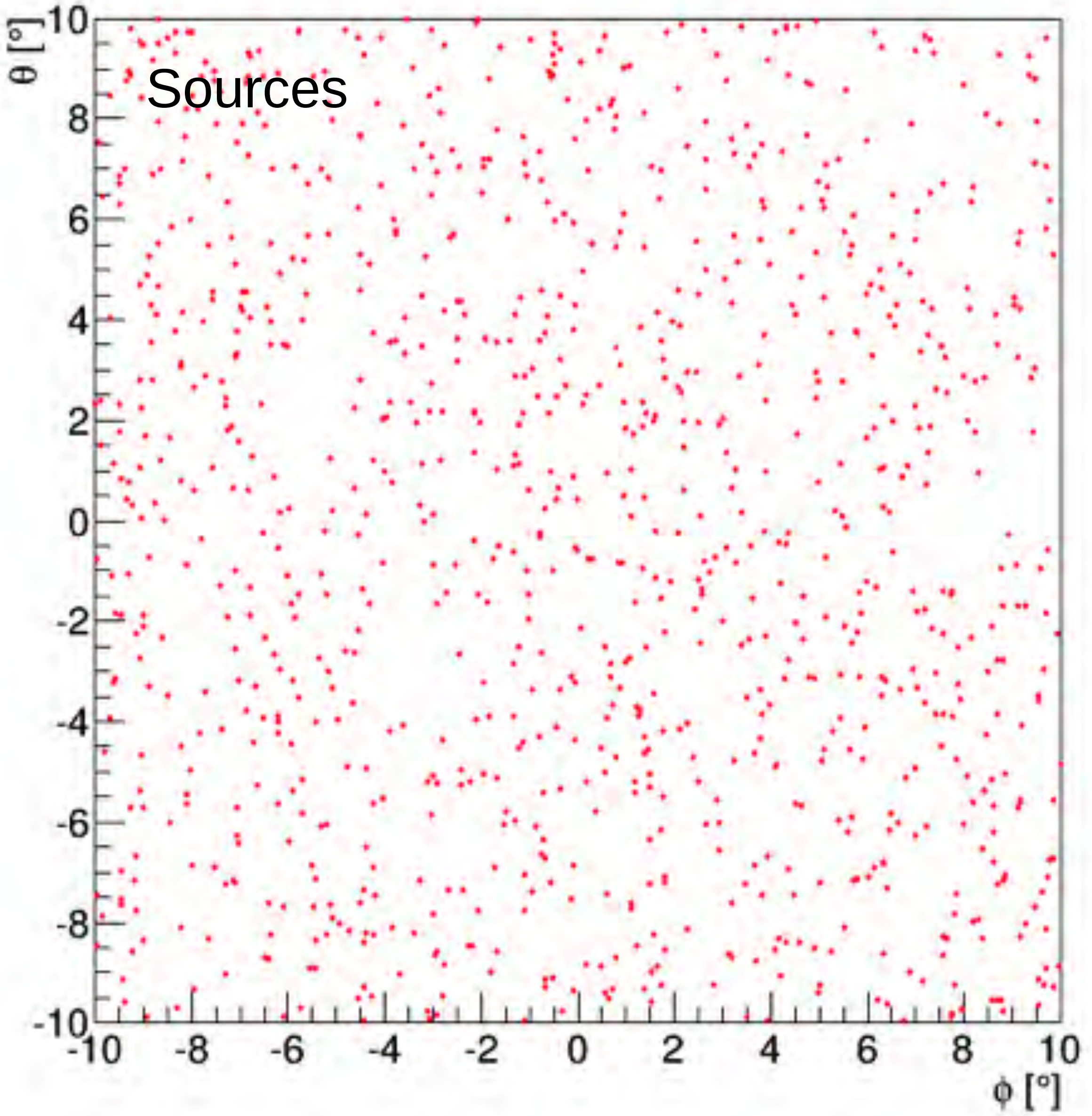
- **Intermediate sources:** Some sources can be detected individually.
- Source detection efficiency is < 100%

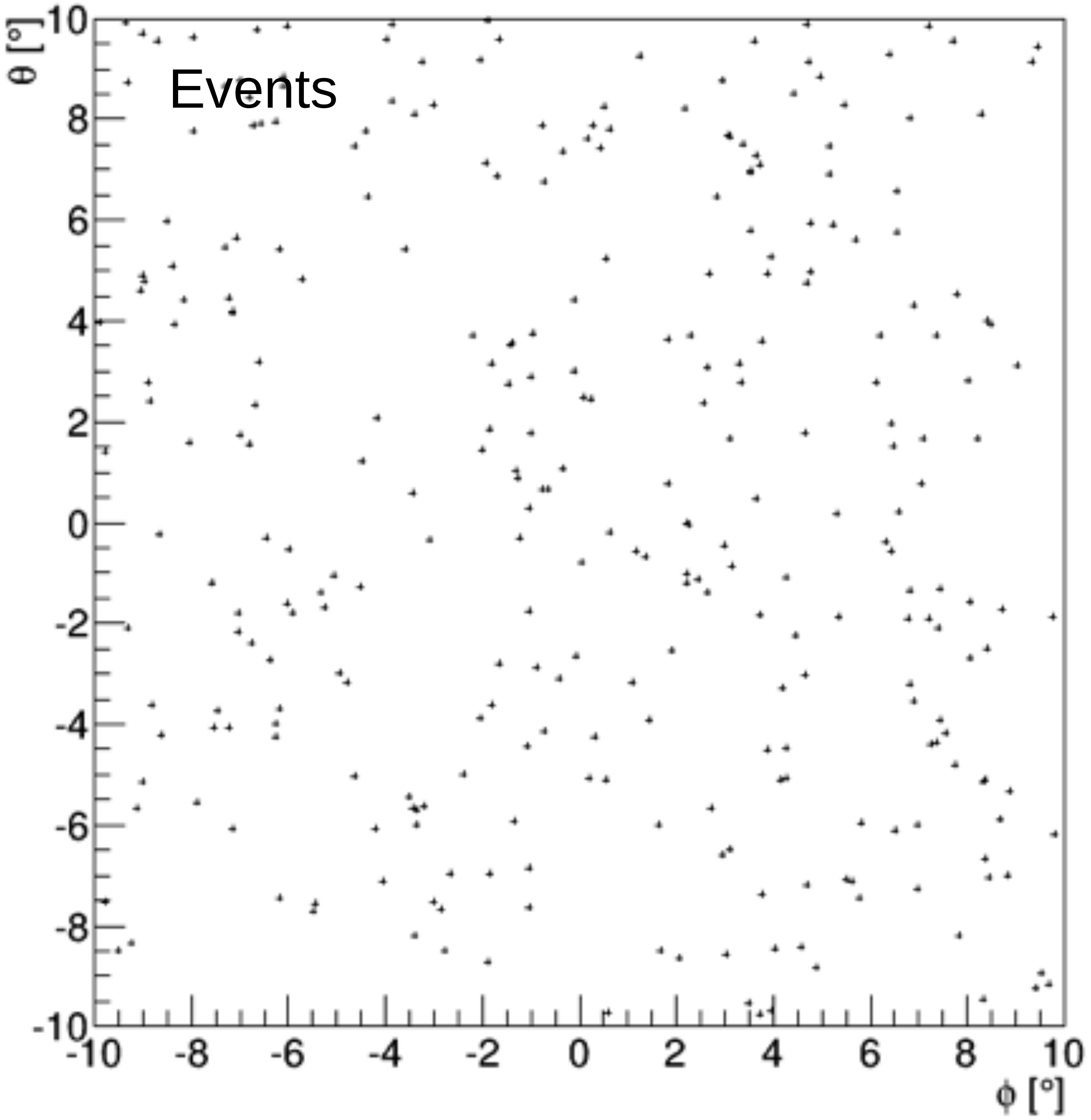


3 events / source

Source detection: Weak sources

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

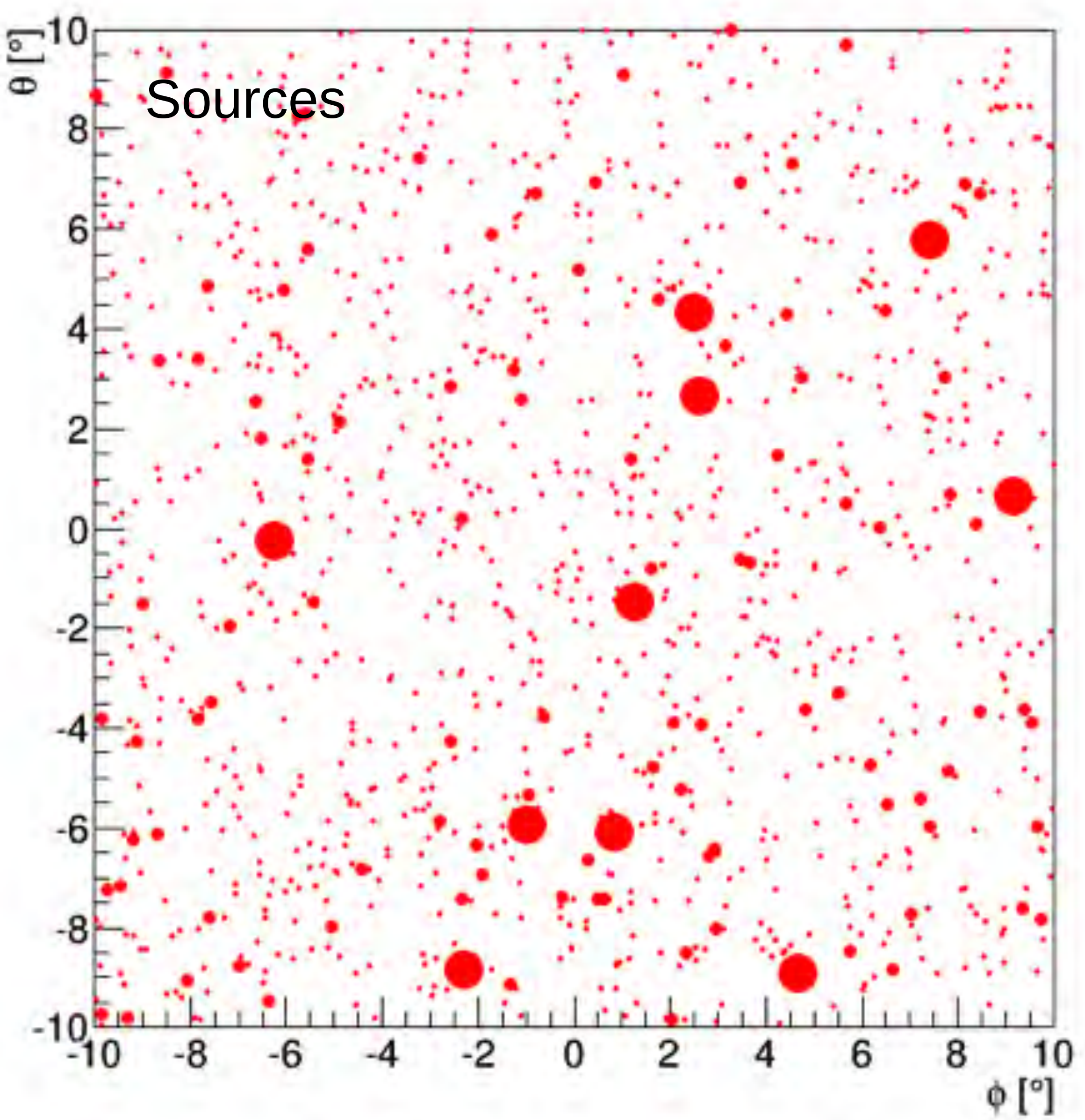


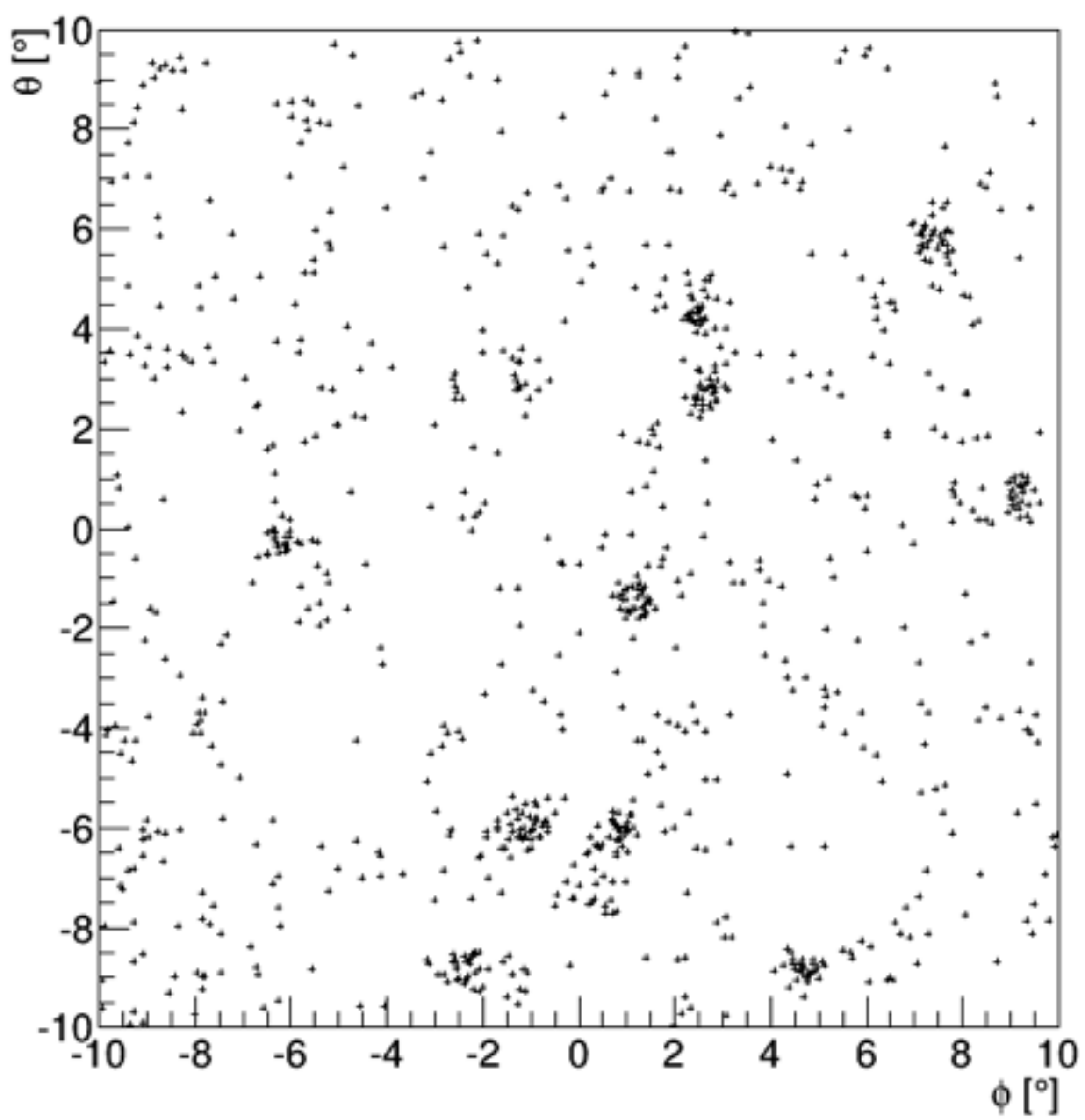


0.3 events / source

The real case: A mixture of weak & strong sources

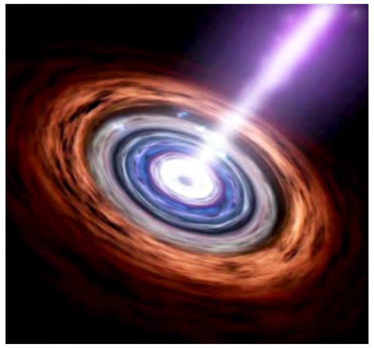
- Part of the intensity of a source population can be resolved into individual sources
- The remaining part **contributes to a diffuse background.**
- Dependent on instrument sensitivity, PSF and population properties.





The origin of the IGRB in the LAT energy range.

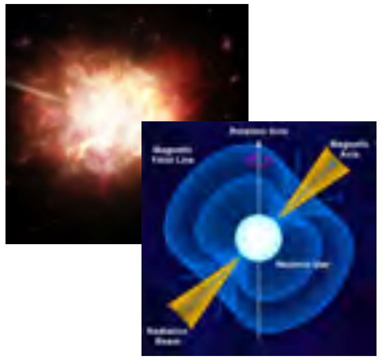
Undetected sources



Blazars
- Dominant class of LAT extra-galactic sources.

Misaligned active Galaxies
- 27 sources resolved in 2FGL.

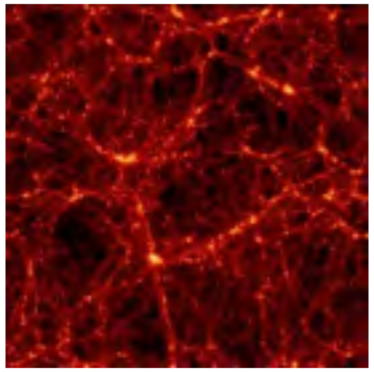
Star-forming galaxies
- Some galaxies outside the local group resolved by LAT.



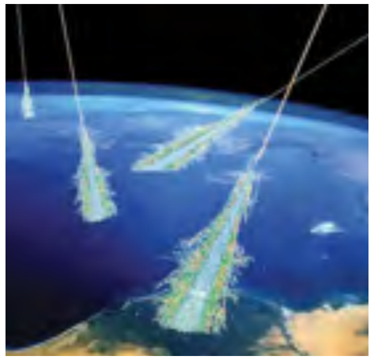
GRBs + High-latitude pulsars
- Only small contributions expected.

Diffuse processes

Intergalactic shocks
- produced in galaxy cluster mergers

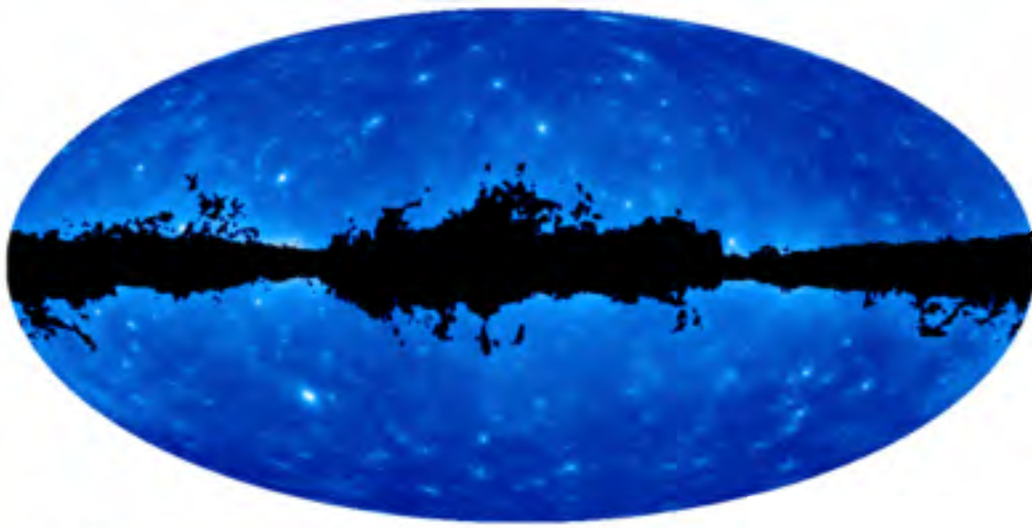


Dark matter annihilation
- Potential signal dependent on nature of DM.



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

Derivation of the isotropic gamma-ray background.

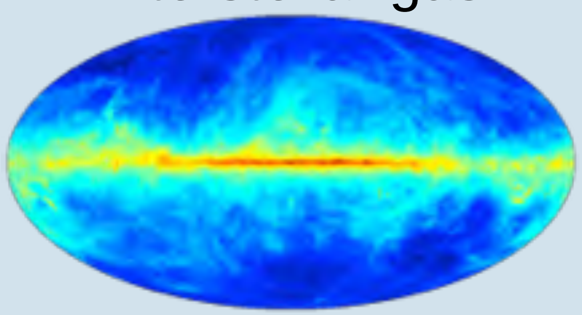


Not used in analysis:

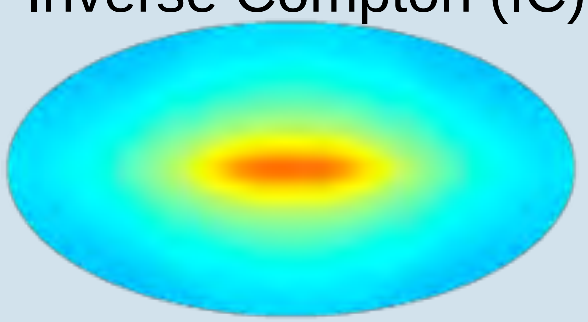
> Galactic plane
> Regions with dense molecular clouds
> Regions with non-local atomic hydrogen clouds

=

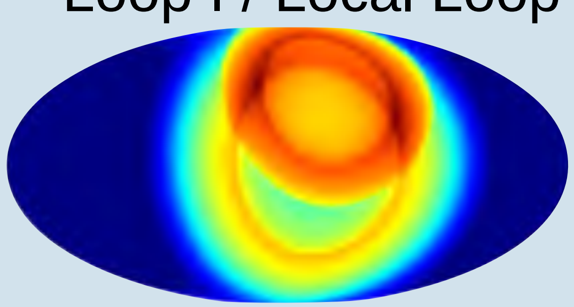
Interstellar gas



Inverse Compton (IC)

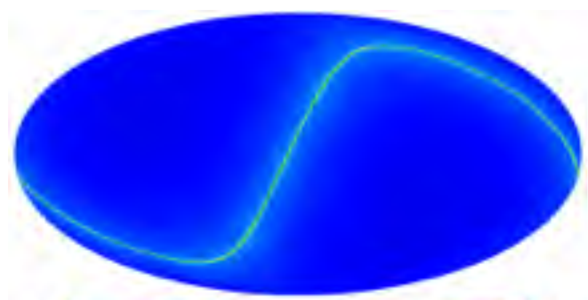


Loop I / Local Loop

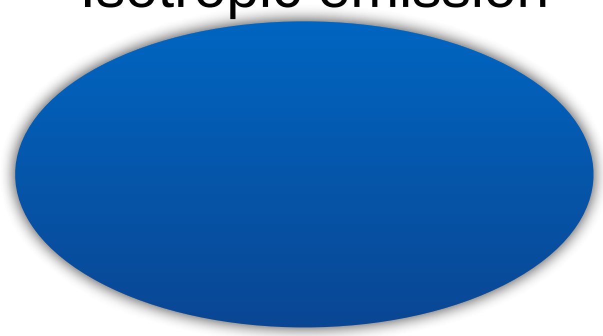


Galactic diffuse emission

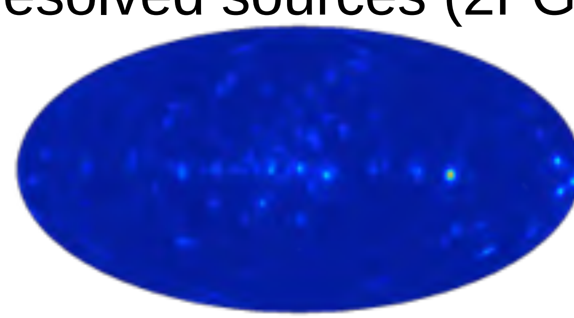
+ Solar disk and IC



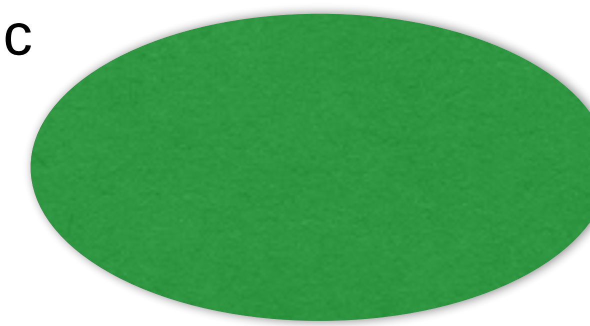
+ Isotropic emission



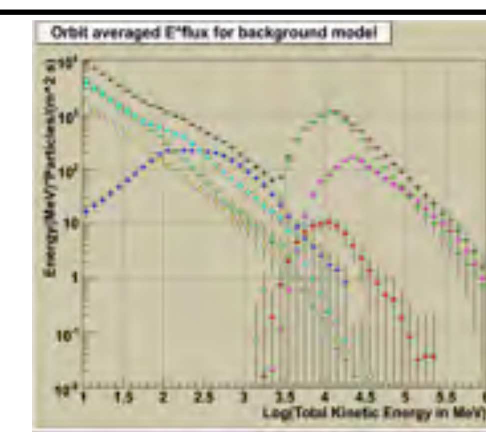
+ Resolved sources (2FGL)



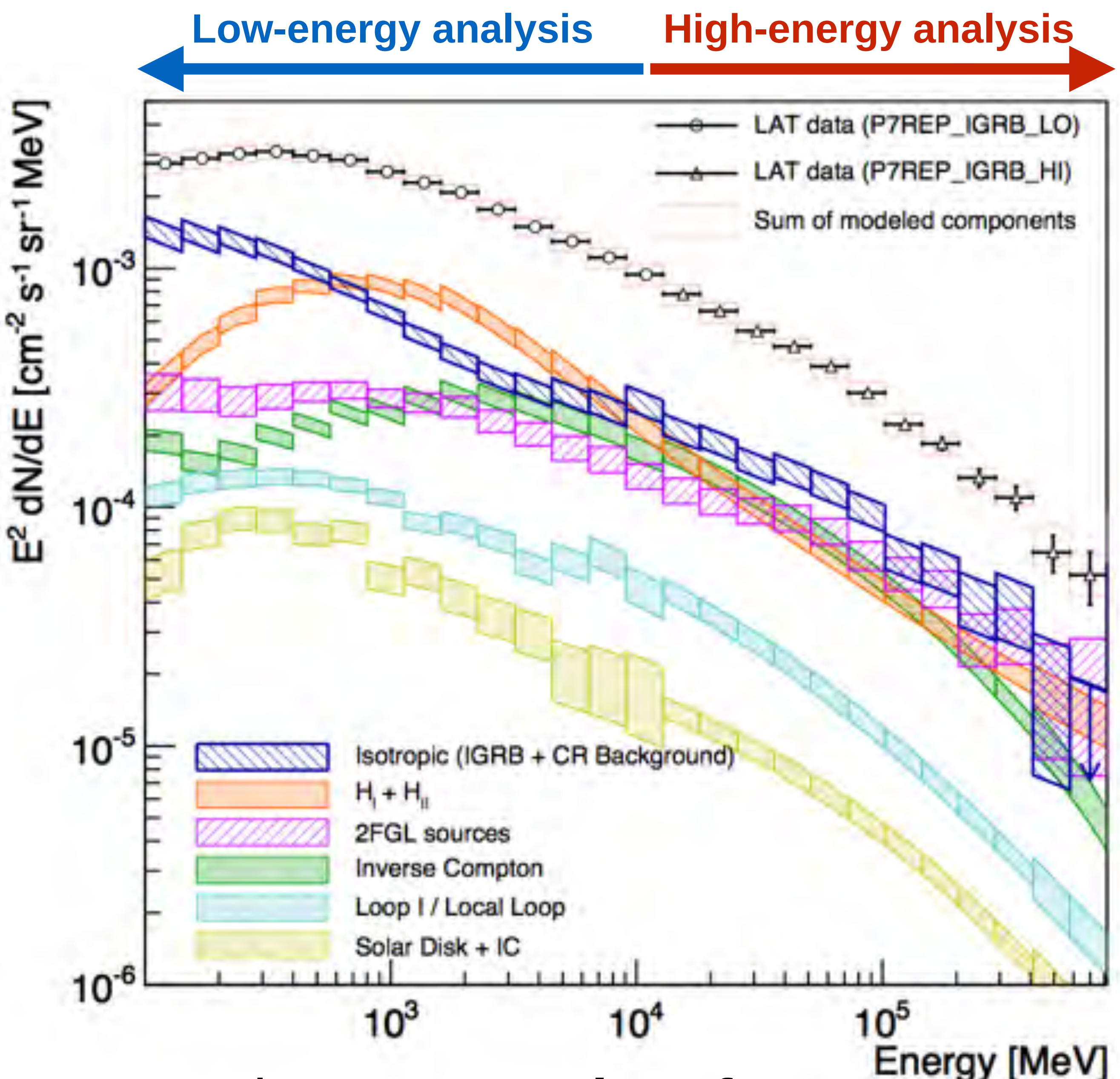
Isotropic γ-ray back-ground (IGRB)



Contami-nation from CR induced background

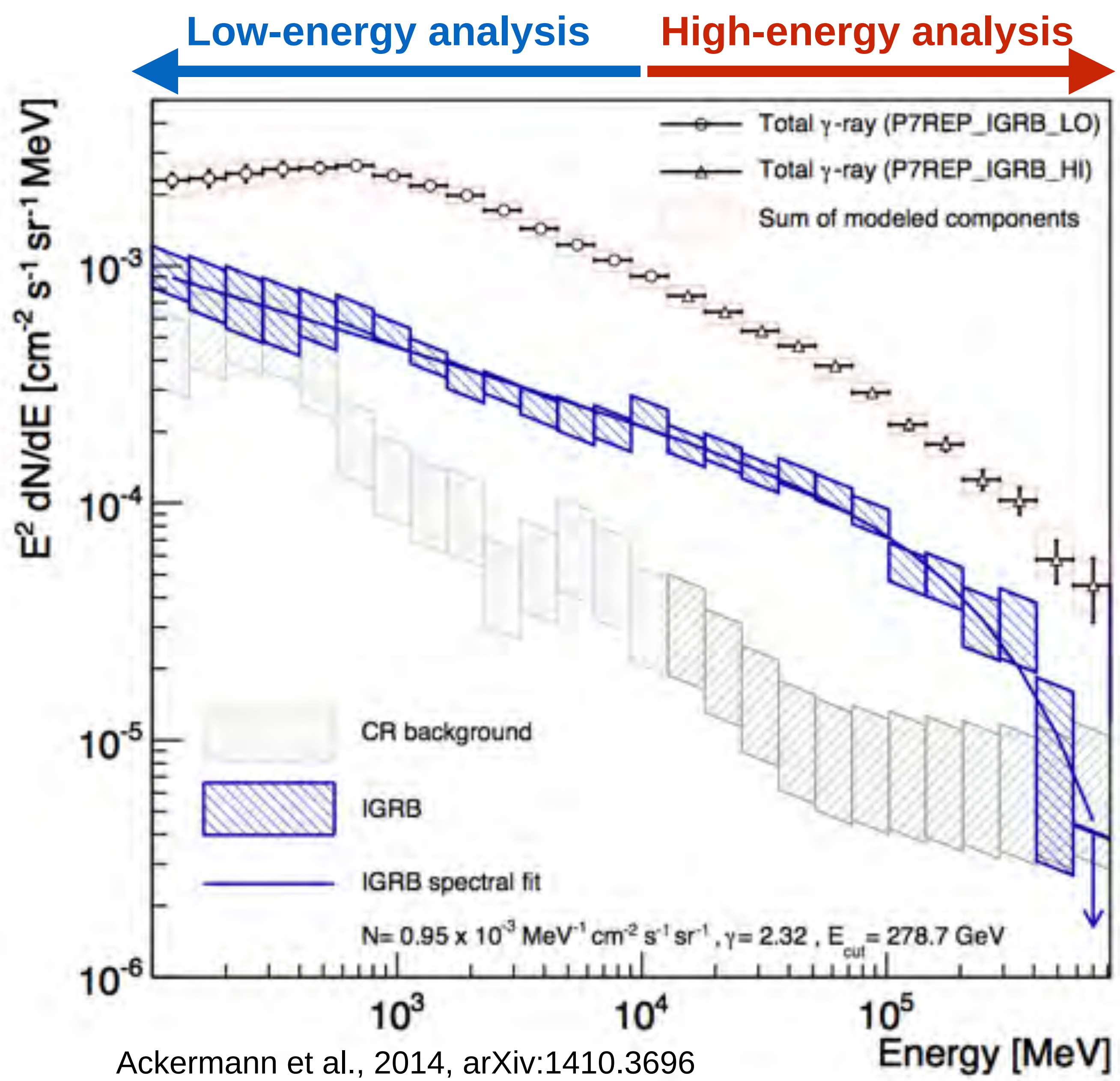


Results from the IGRB fit.



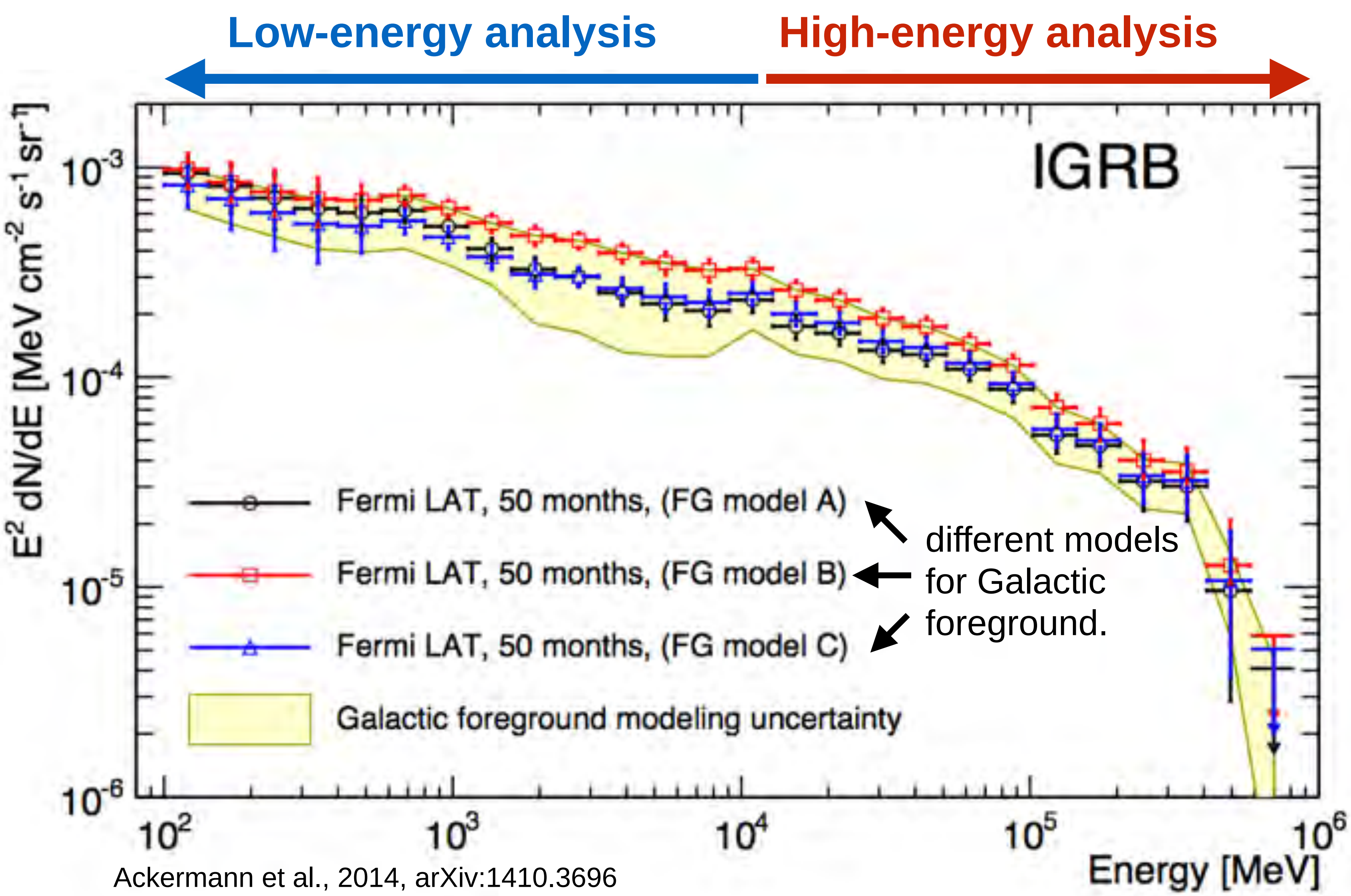
- Based on **50 months of reprocessed LAT data**.
- **Average intensities** (|b| > 20°) attributed to model templates.
- **Baseline foreground model** used.

- **IGRB and CR contributions** to isotropic emission
- **Spectral fit of IGRB** by power-law with exponential cutoff.



Ackermann et al., 2014, arXiv:1410.3696

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

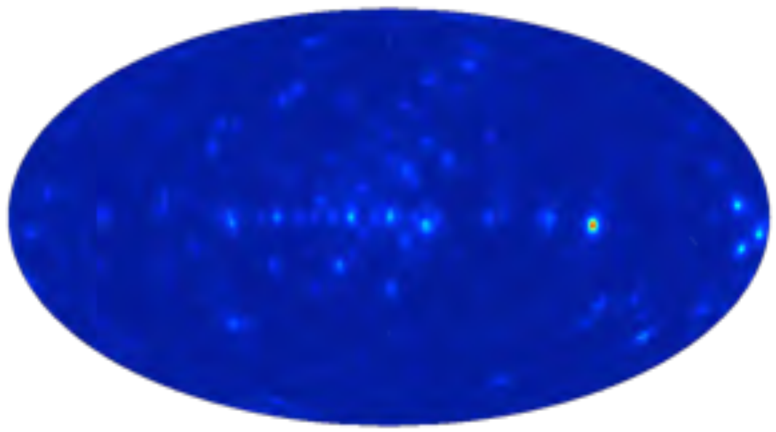
> **Yellow band:** systematic uncertainties from foreground model variations.

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

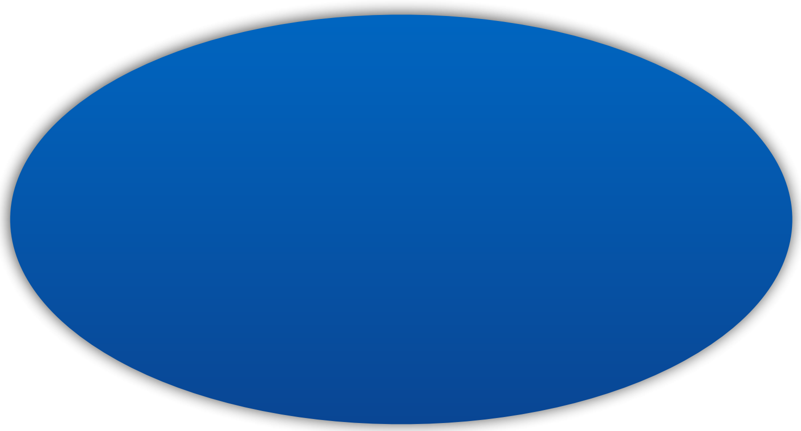
The isotropic and the total extragalactic background.



Resolved sources

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

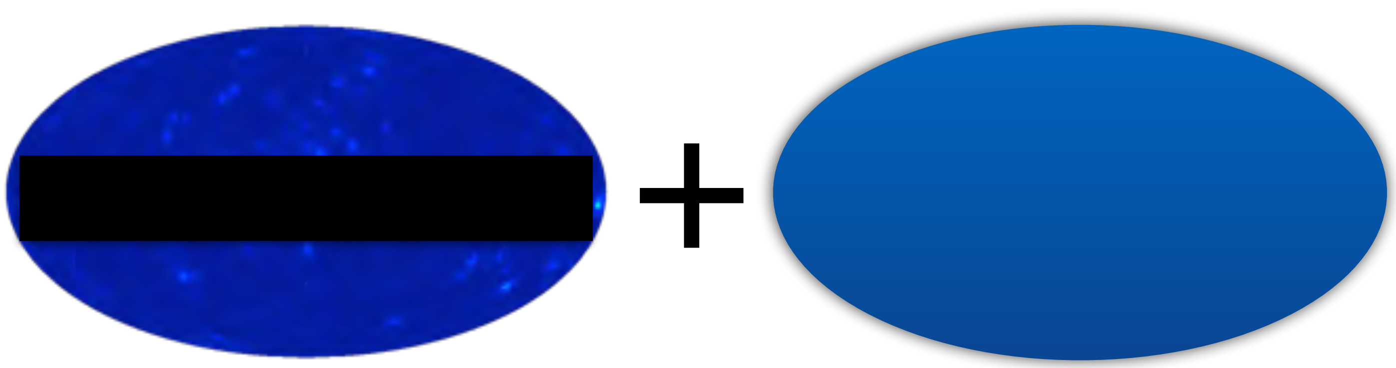
- the sensitivity of the instrument.
- the exposure of the observation.



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.**

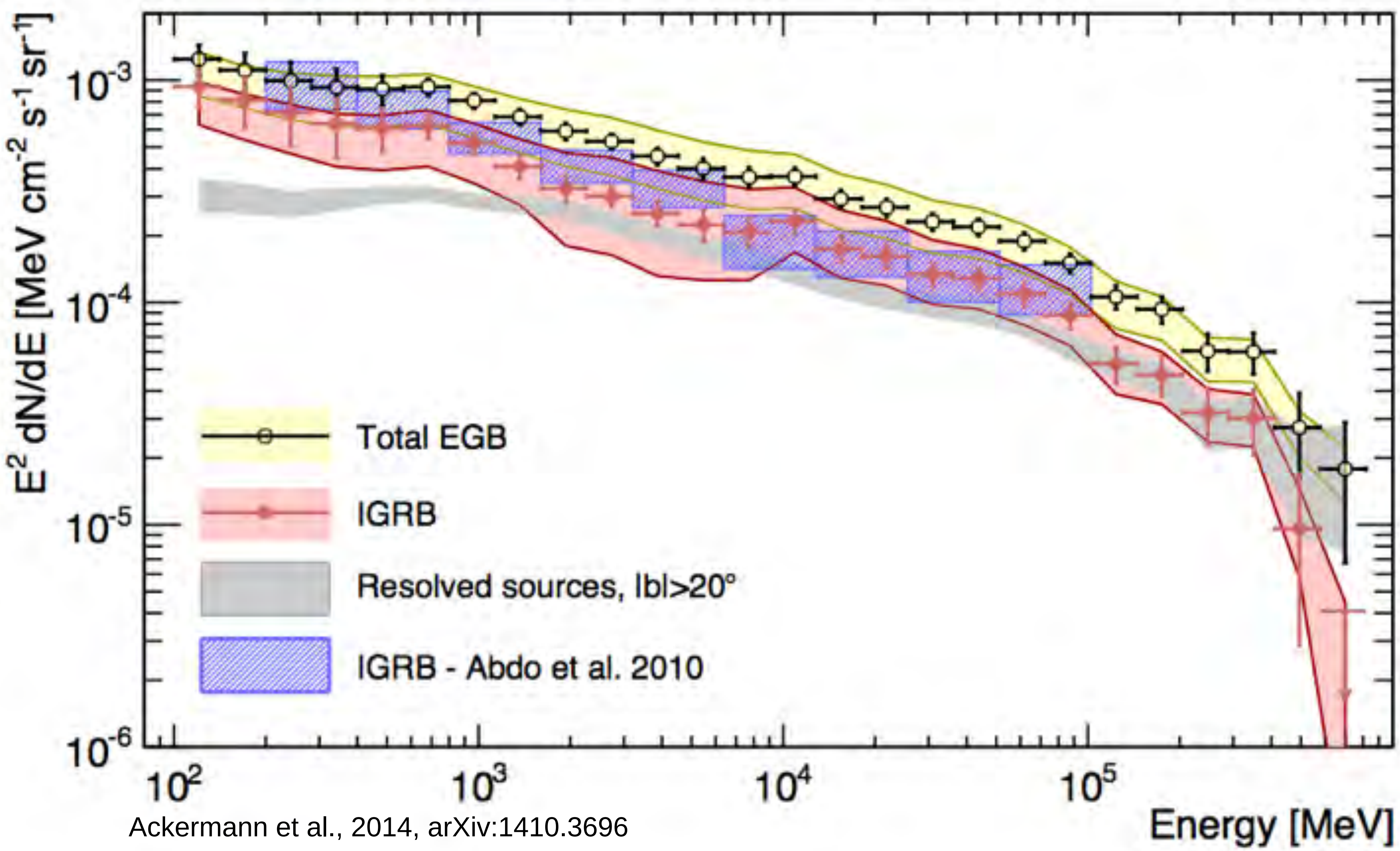


Total extragalactic γ-ray background (EGB)

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

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

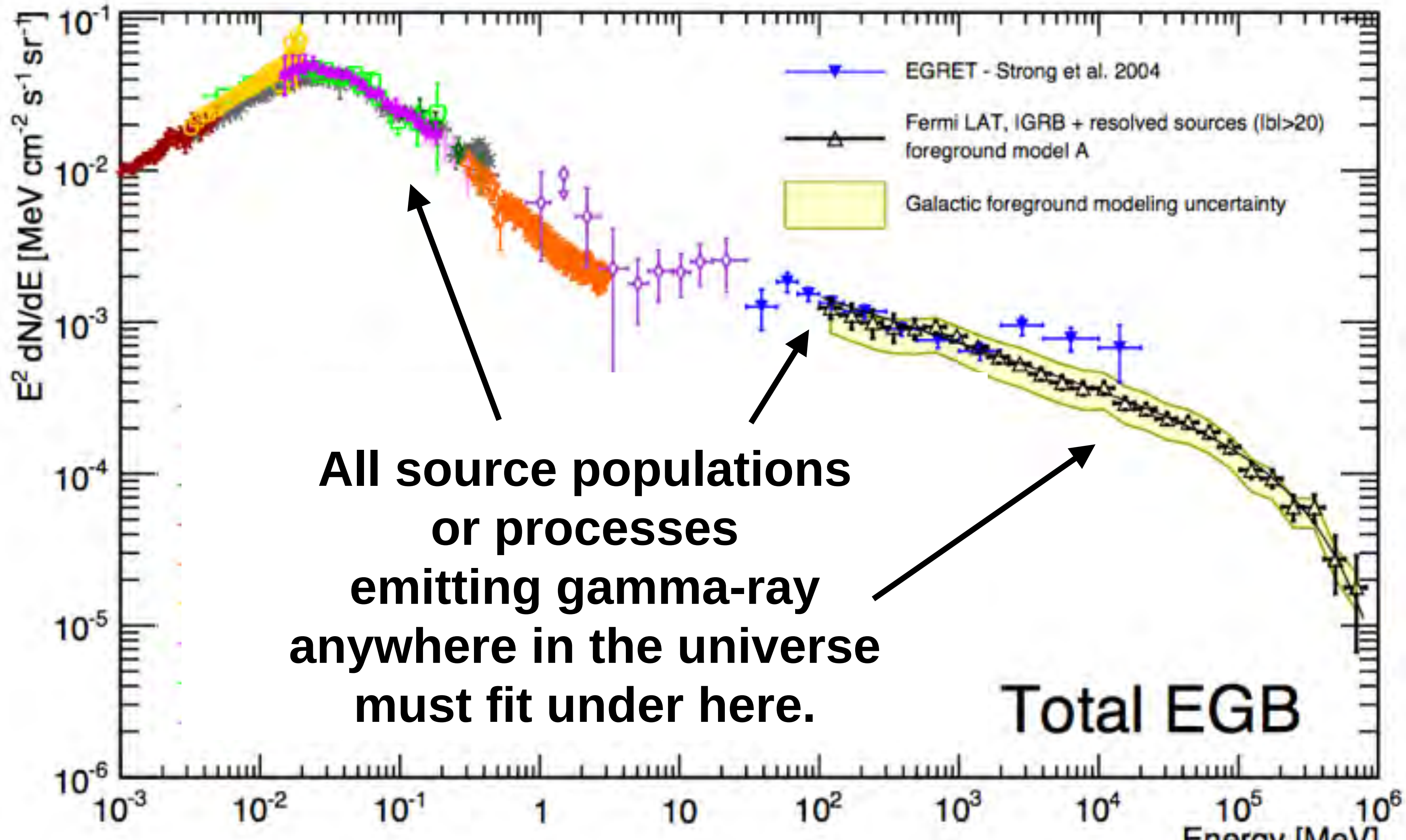
Comparison of LAT IGRB and EGB measurements



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?

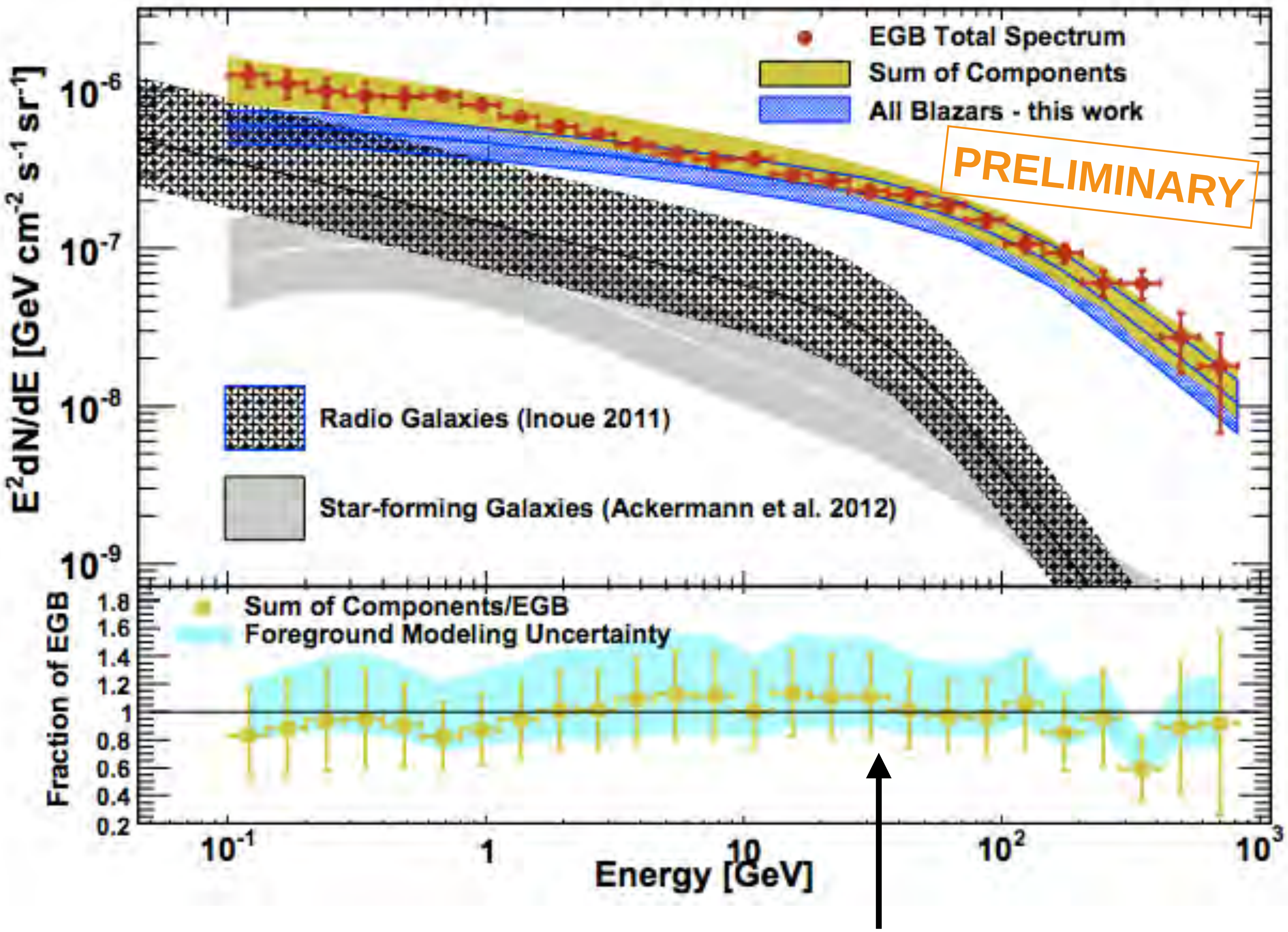


Ackermann et al., 2014, arXiv:1410.3696

- 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.

Contributions of known extragalactic sources.

Ajello et al., 2014, submitted to ApJL



<~ 30% left for diffuse processes

And we already know where most of the emission comes from!

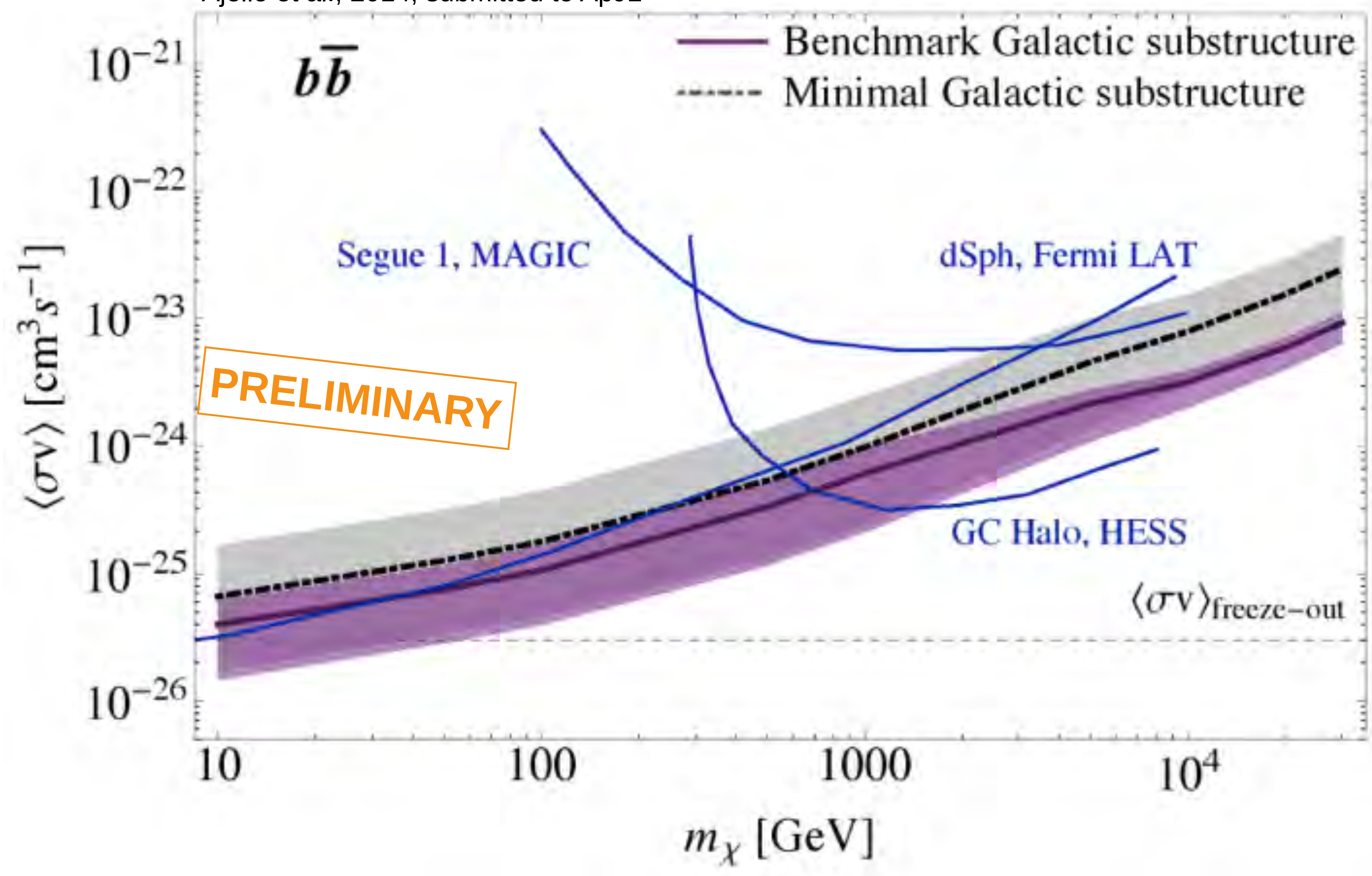
> At low energies:

- 10% - 20% contribution from star-forming galaxies
- 10% - 50% from misaligned AGN

> Blazars seem to dominate at GeV energies.

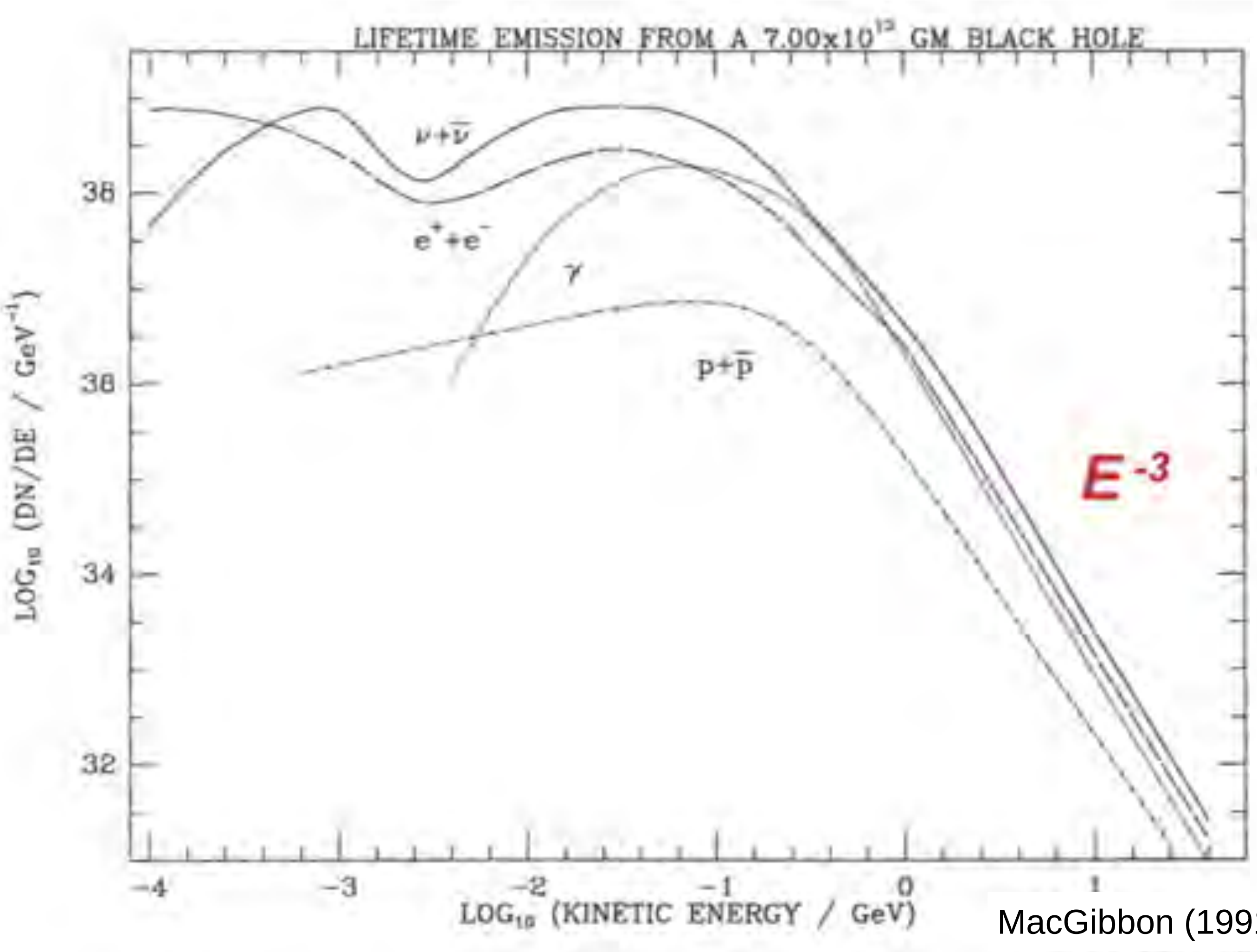
Constraints on gamma-ray emission from DM annihilation.

Ajello et al., 2014, submitted to ApJL

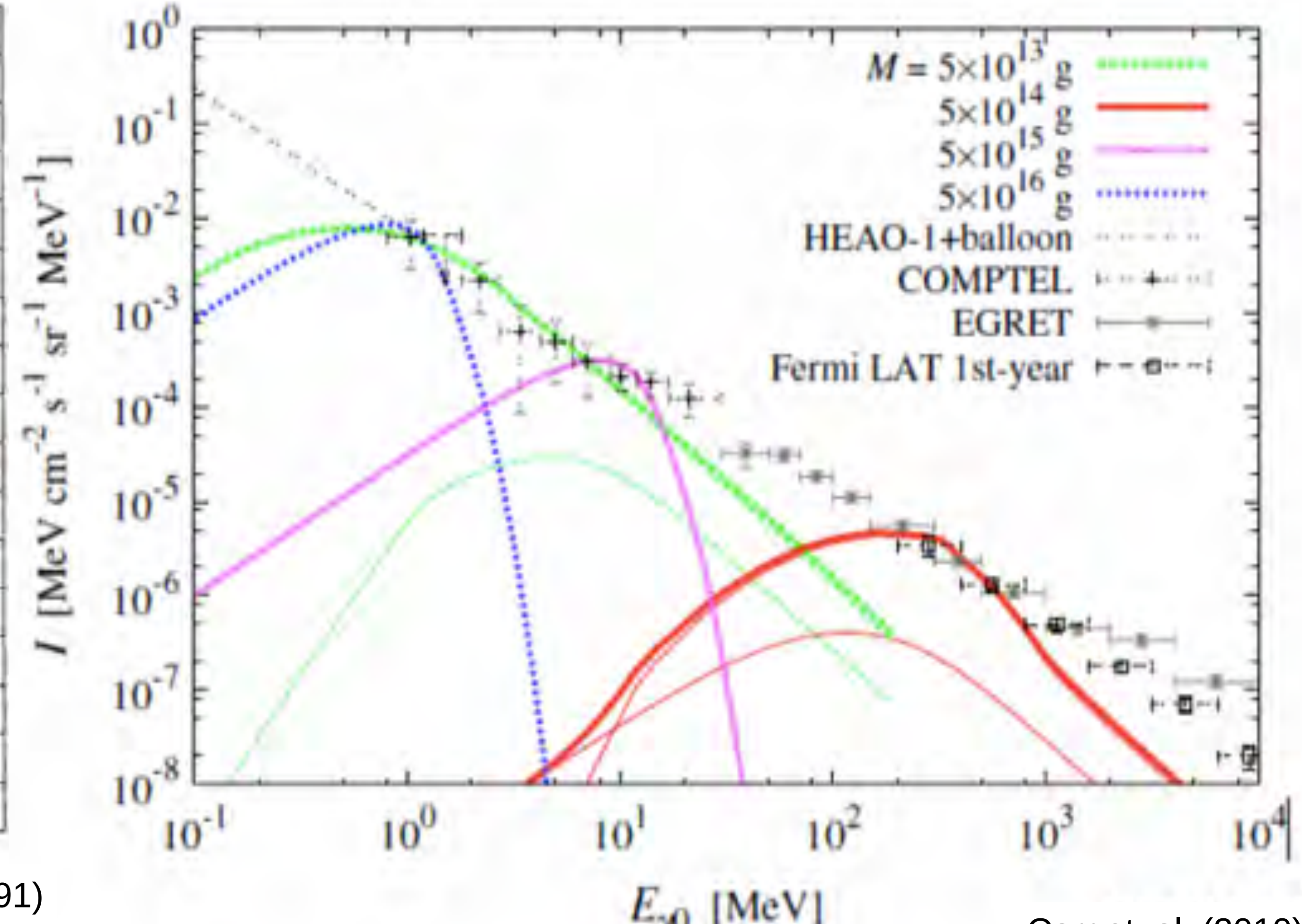


> Tight limits on contributions from diffuse processes, e.g. dark matter annihilation.

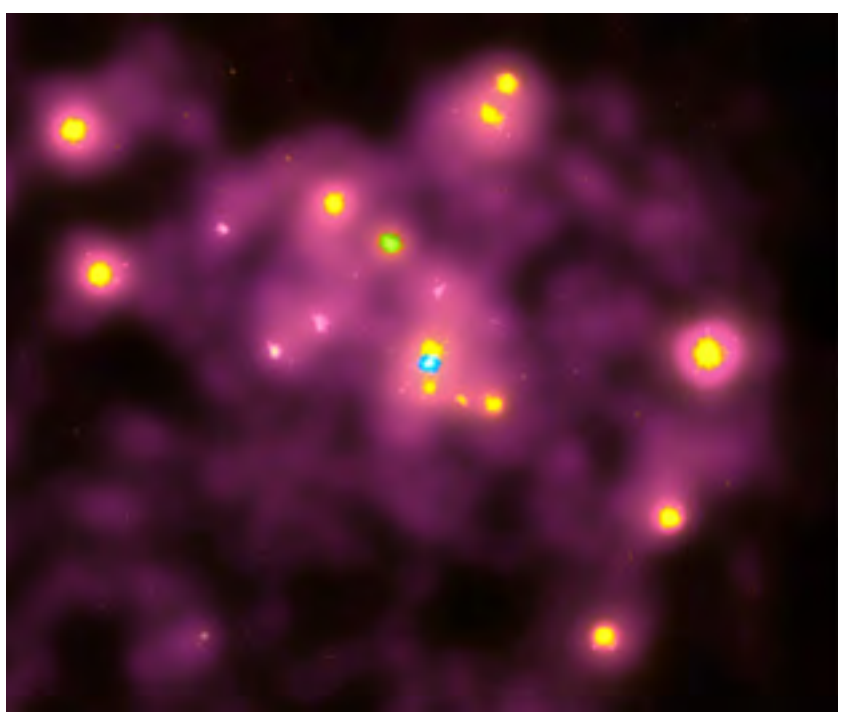
Constraints on the density of primordial black holes



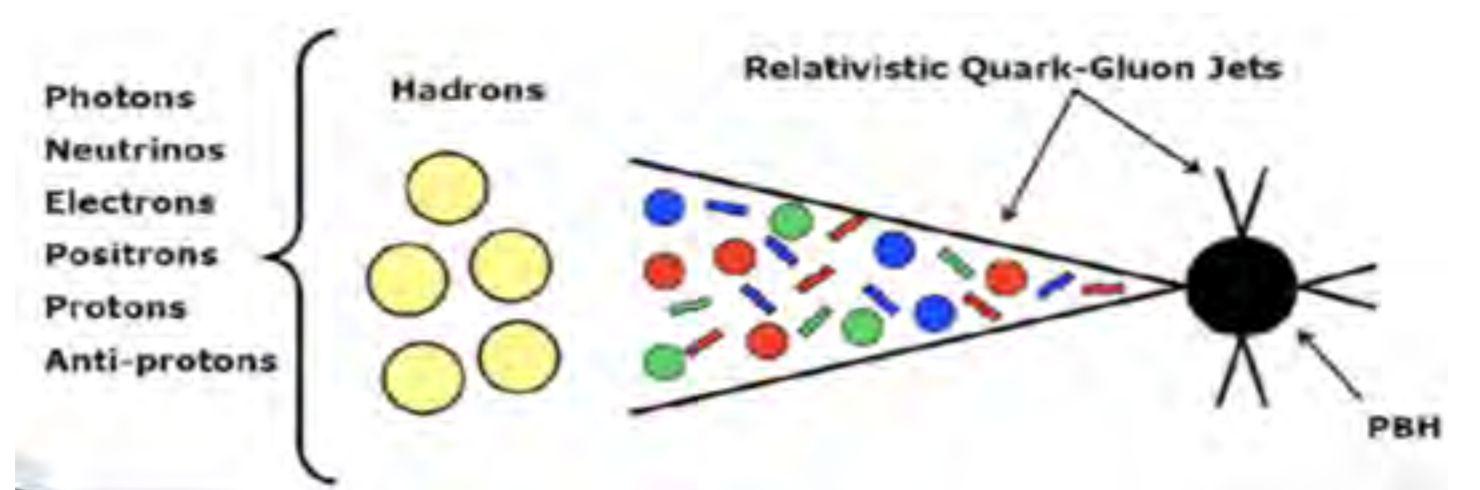
MacGibbon (1991)



Carr et. al. (2010)



- Primordial black holes evaporate into gamma rays (and other particles).
- $T_{BH} \sim 1/M_{BH}$



And the next step is….

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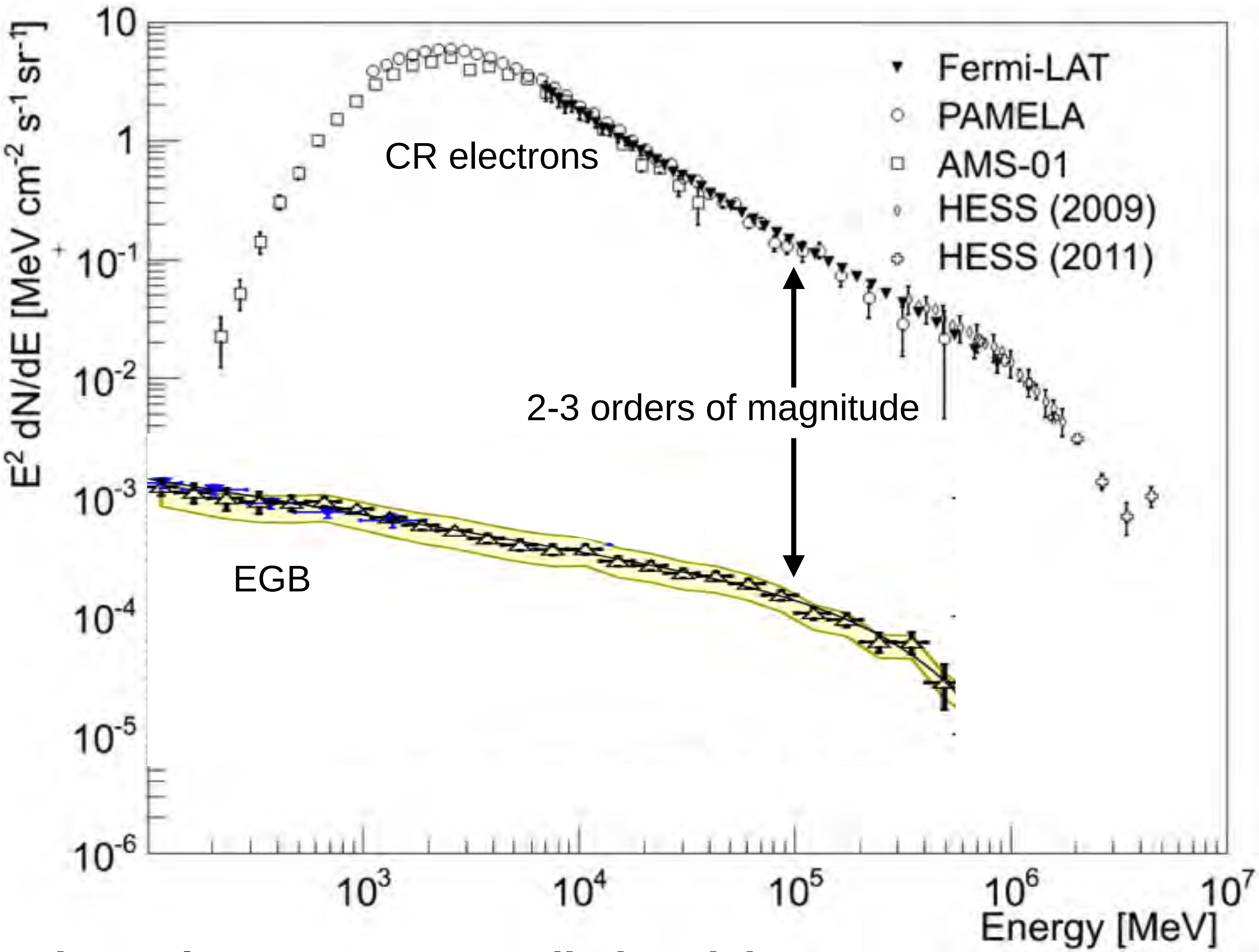
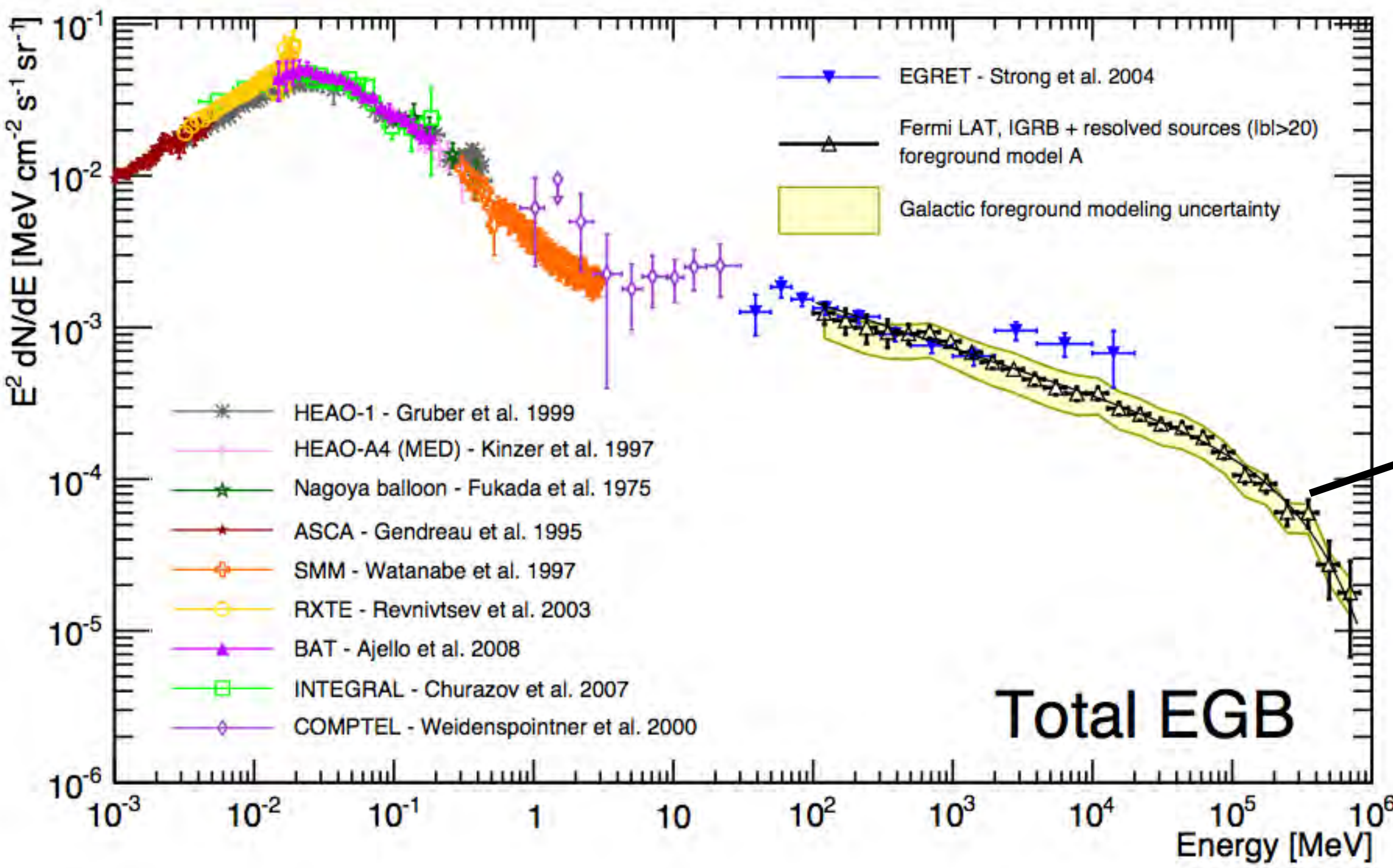
Cherenkov telescopes, the EGB, and cosmic-ray electrons.

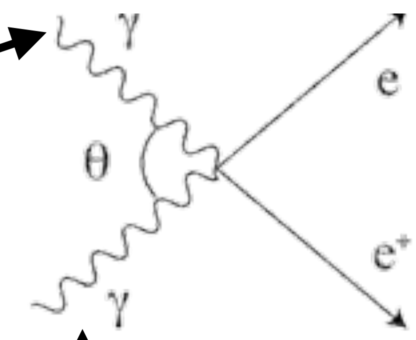


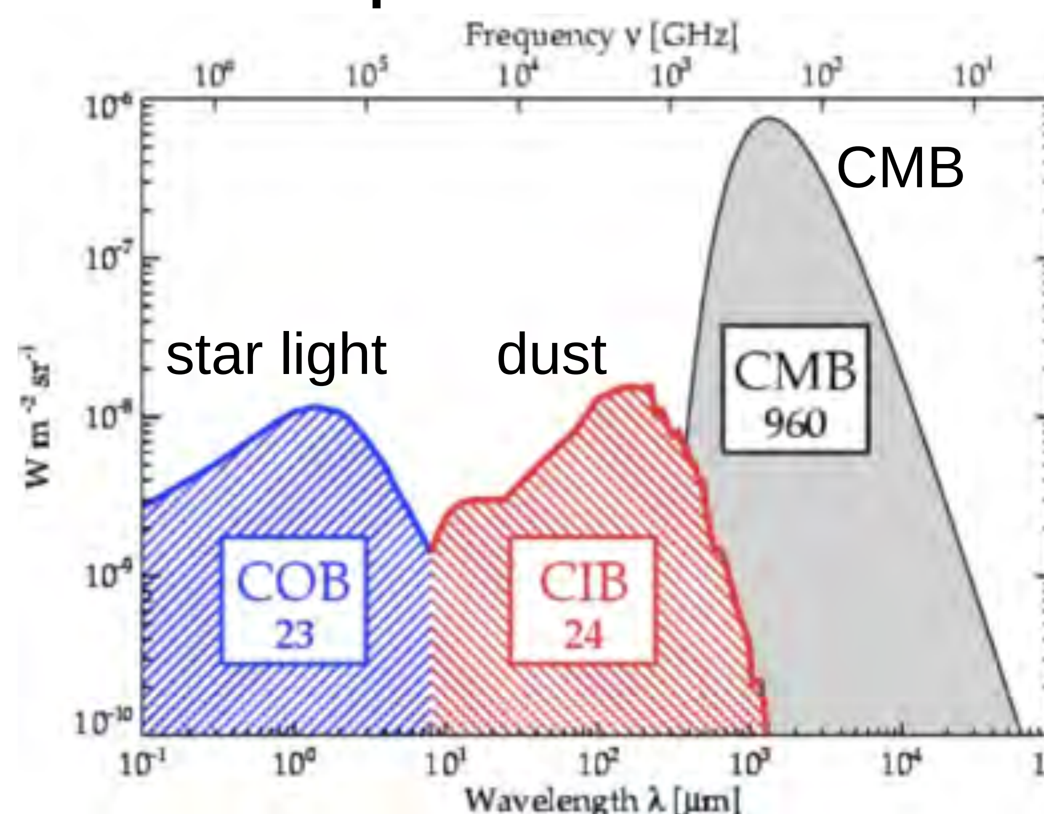
Cherenkov telescopes cannot distinguish photons and electrons at high confidence!

The high-energy EGB cut-off.



Pair production in the Extragalactic Background Light introduces an energy dependent γ-ray horizon.

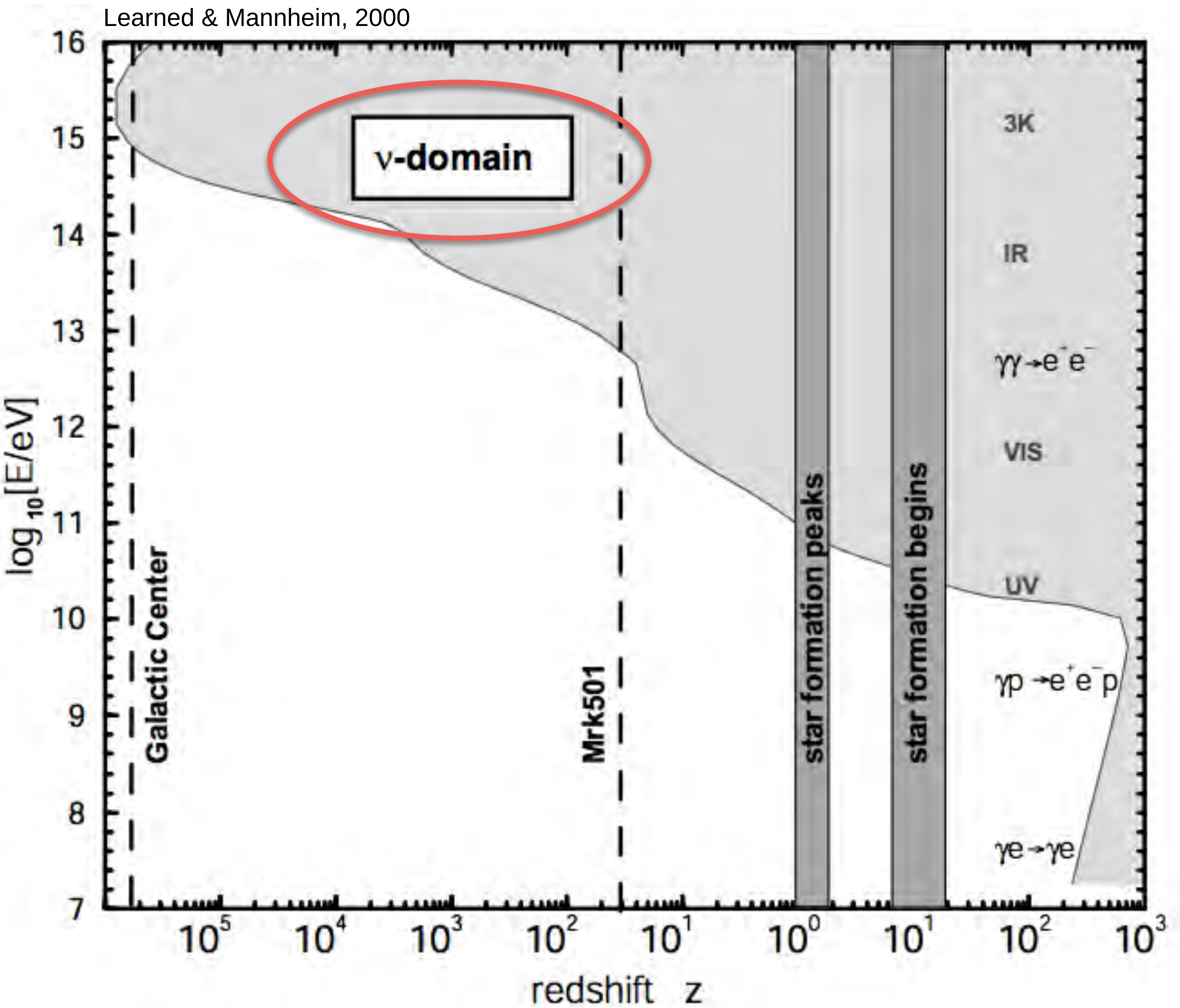




→ **Cut-off feature** in the EGB spectrum above ~ 100 GeV.

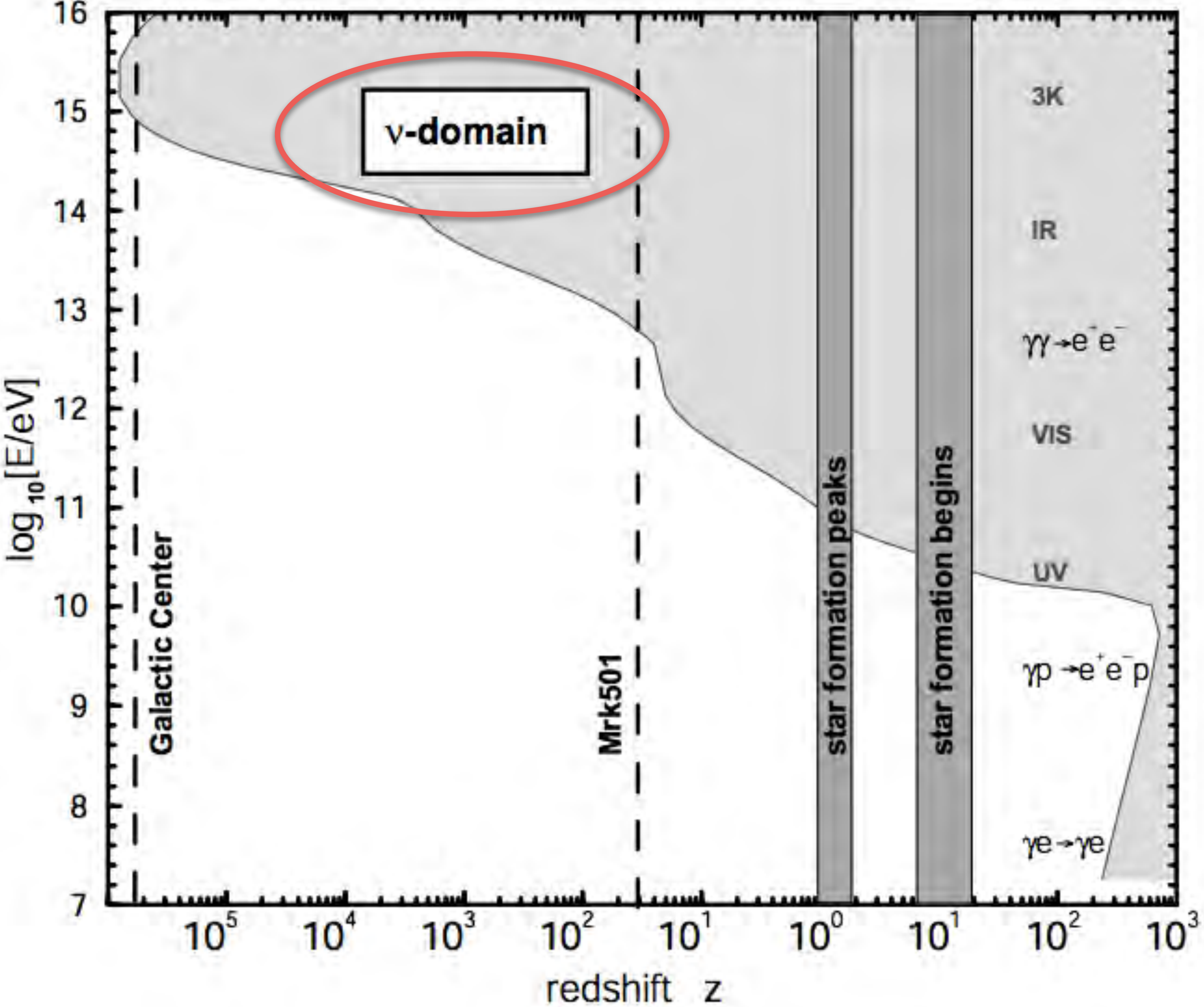
- If the bulk of the intensity comes from z > 0.1 sources.

The gamma-ray horizon and the neutrino domain.



The gamma-ray horizon and the neutrino domain.

Learned & Mannheim, 2000



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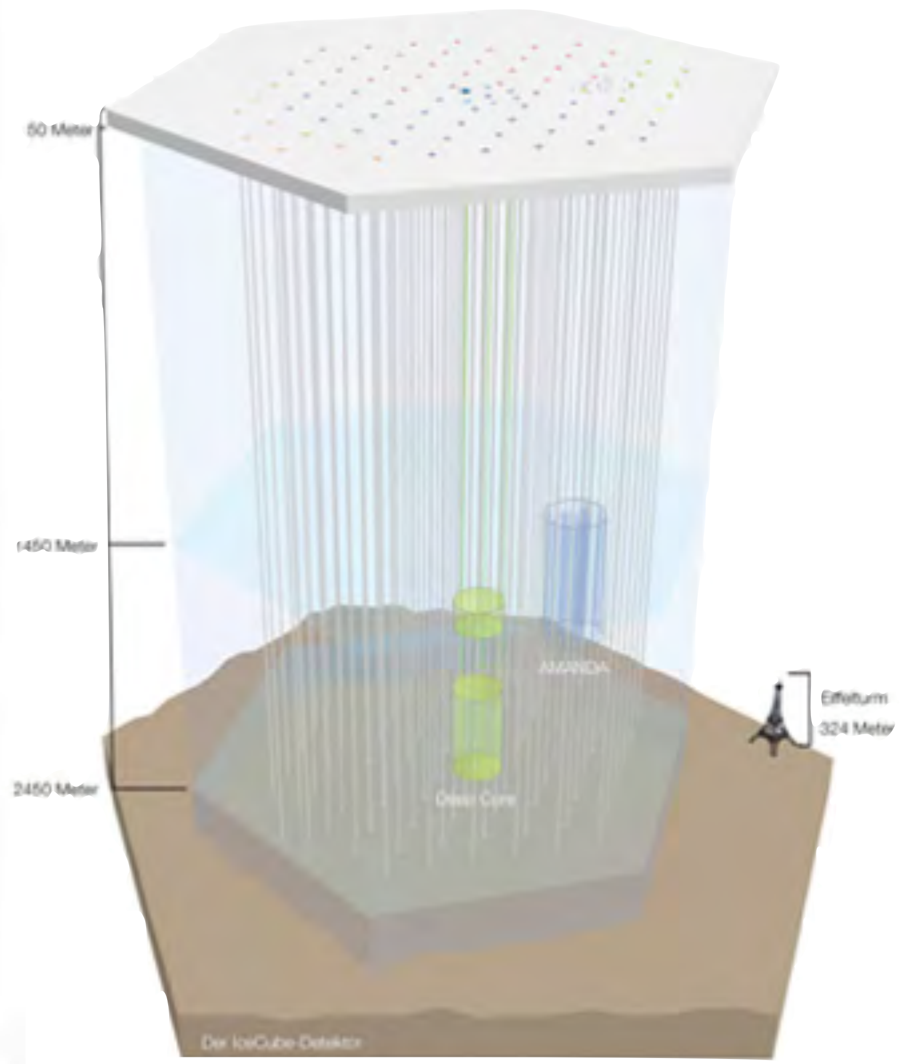
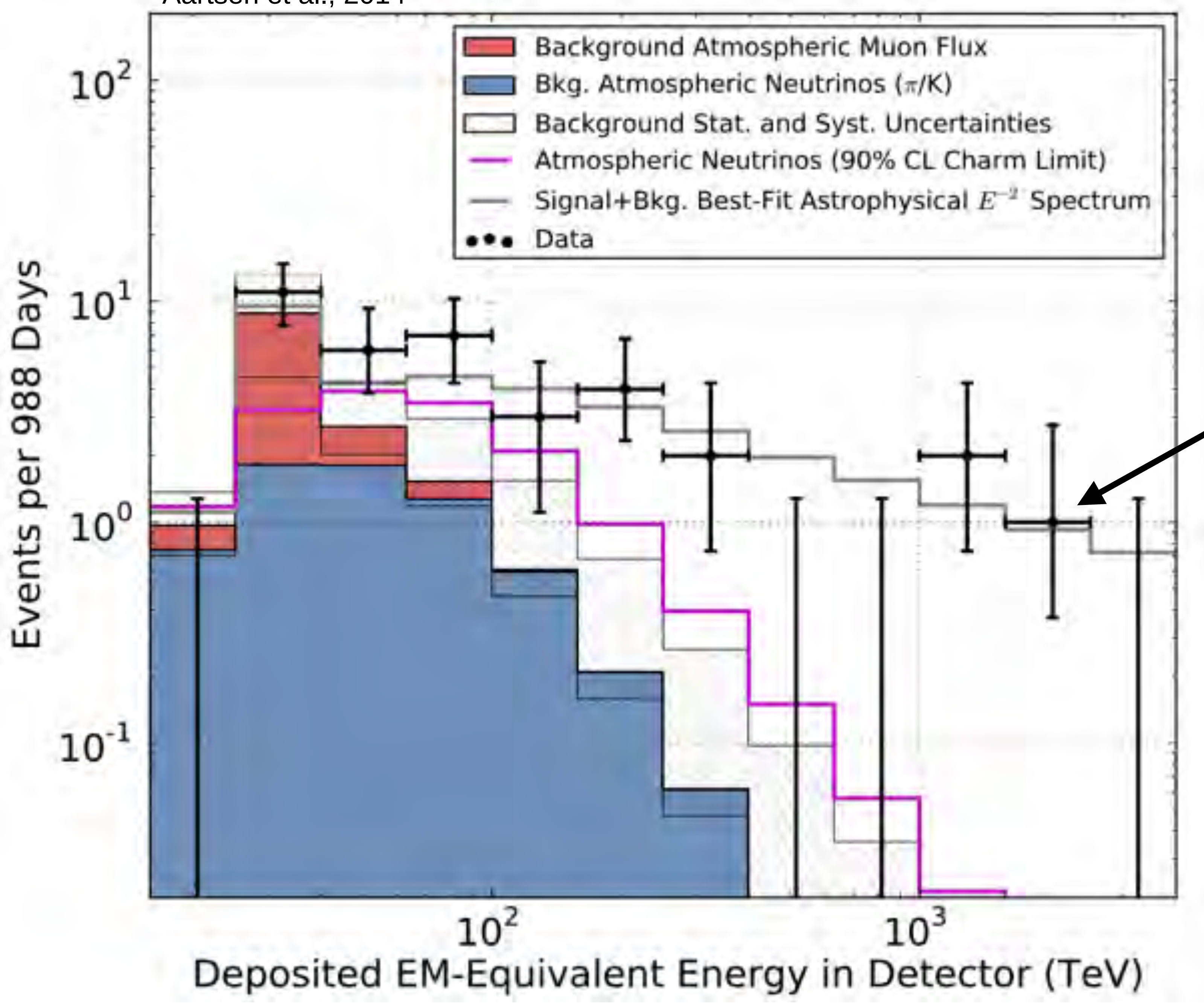
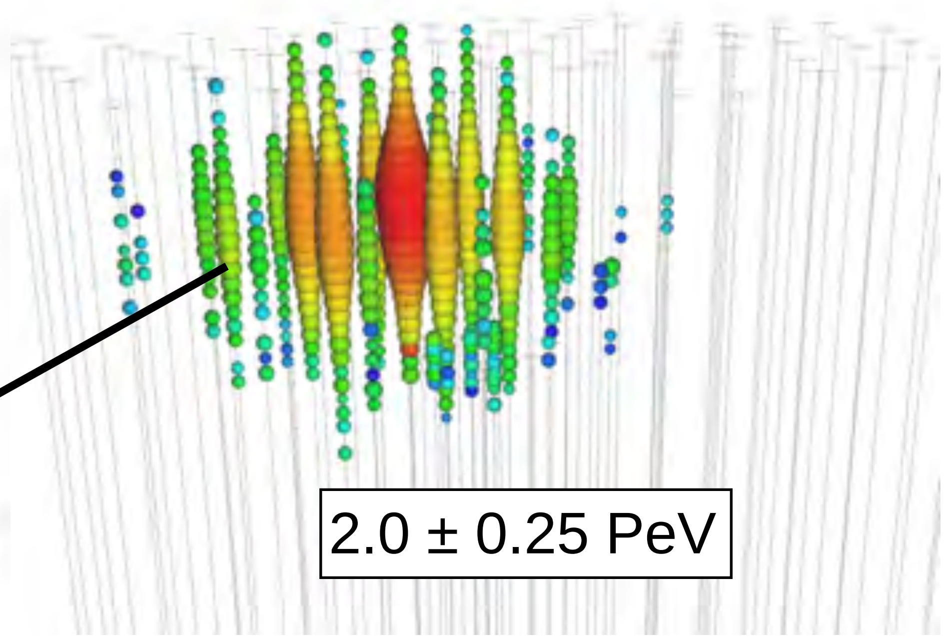


Discovery of astrophysical neutrinos.

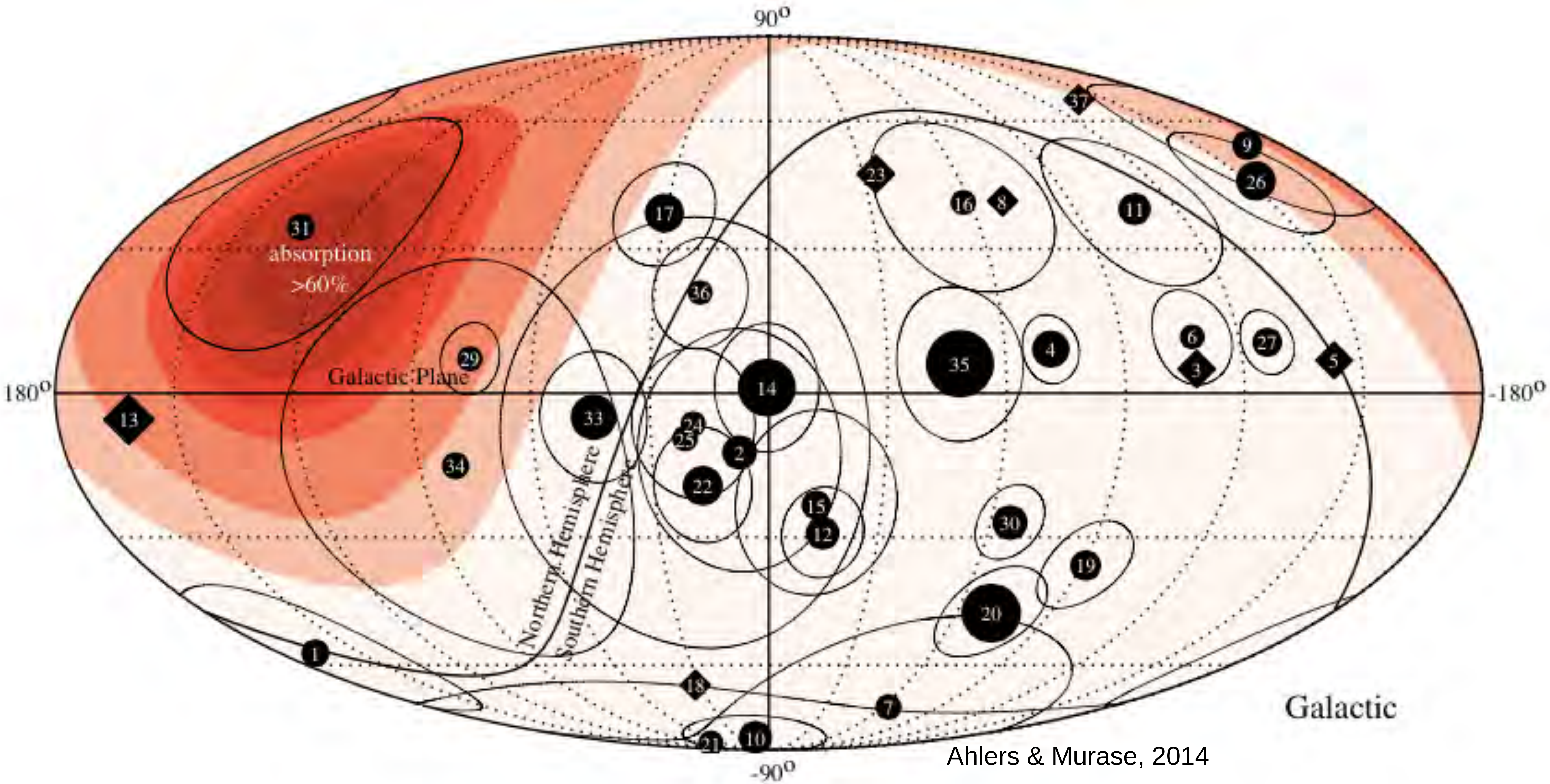
- Astrophysical neutrinos are the only way to probe the non-thermal processes in the distant universe above tens of TeV.
- Good that IceCube has proven sensitive enough to see them.

Aartsen et al., 2014





The astrophysical neutrino flux.



Ahlers & Murase, 2014

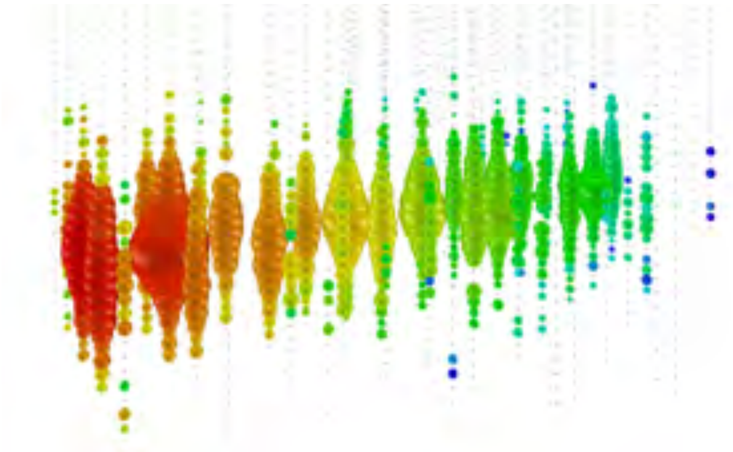
> The astrophysical neutrino flux must arise from **multiple sources**.
  - No sources seen in (more sensitive) Point Source analysis

> Part of it is from **high Galactic latitudes.**
  - Points to an extragalactic origin.

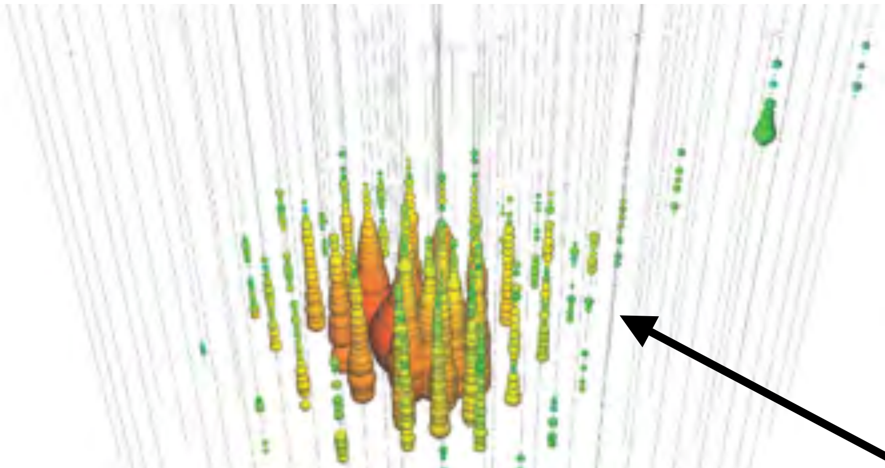
> Event distribution is **compatible with an isotropic** neutrino flux.

Signatures of neutrinos in IceCube

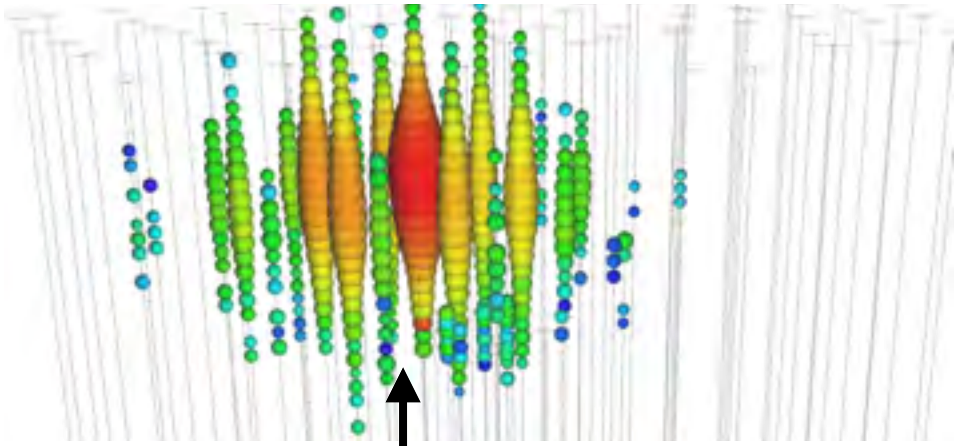
Tracks
μ from CC-ν_μ interactions **outside** the instrumented volume



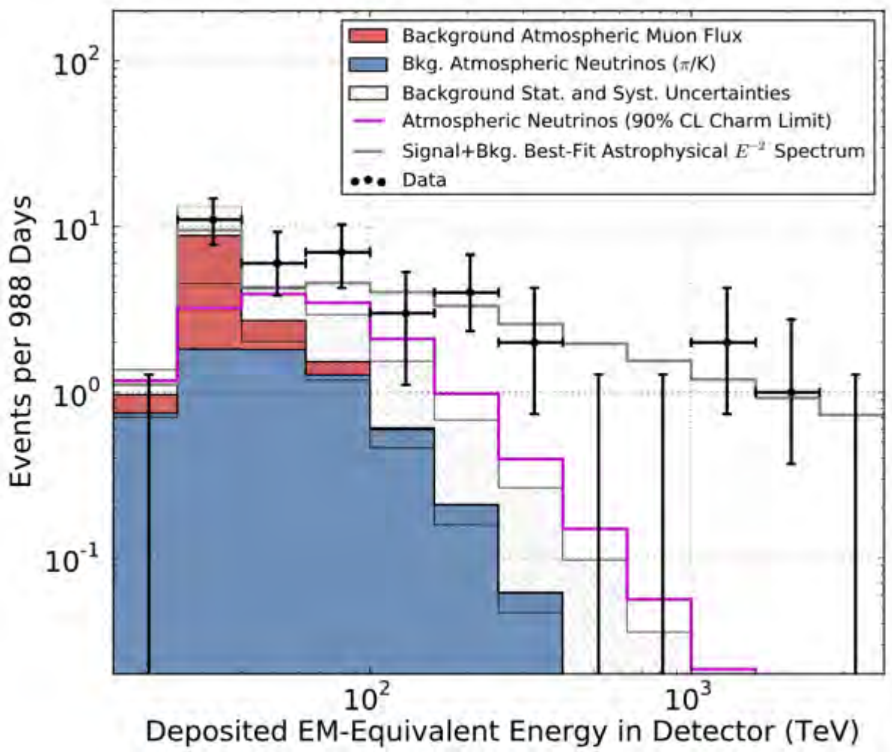
Starting tracks
μ from CC-ν_μ interactions **inside** the instrumented volume



Showers
ν_e, ν_τ and ν_μ-NC interactions



Aartsen et al., 2014



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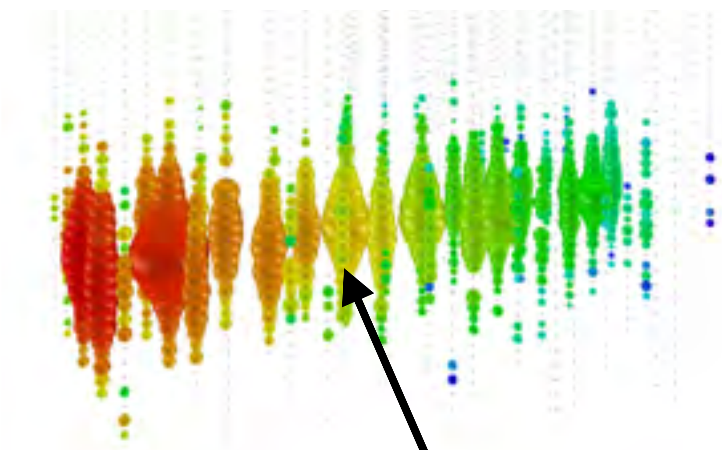
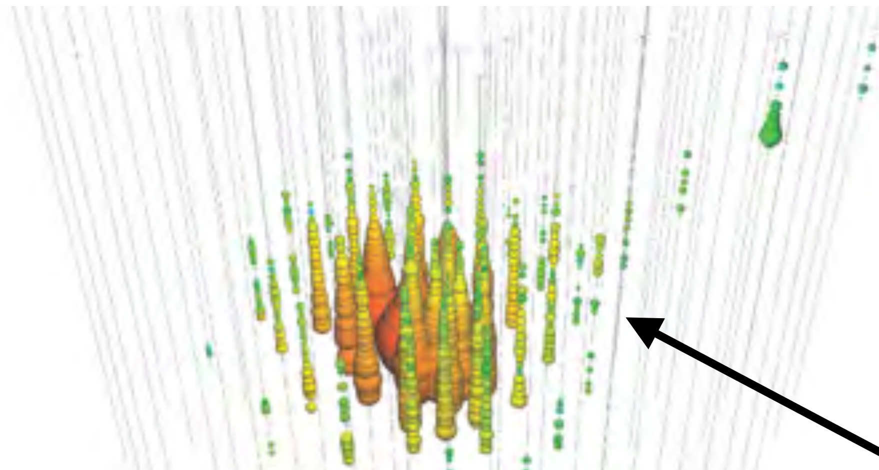
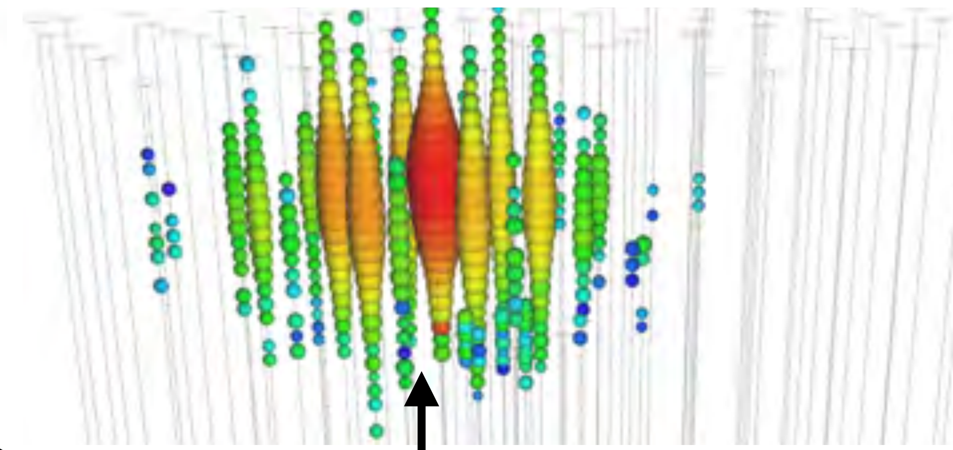
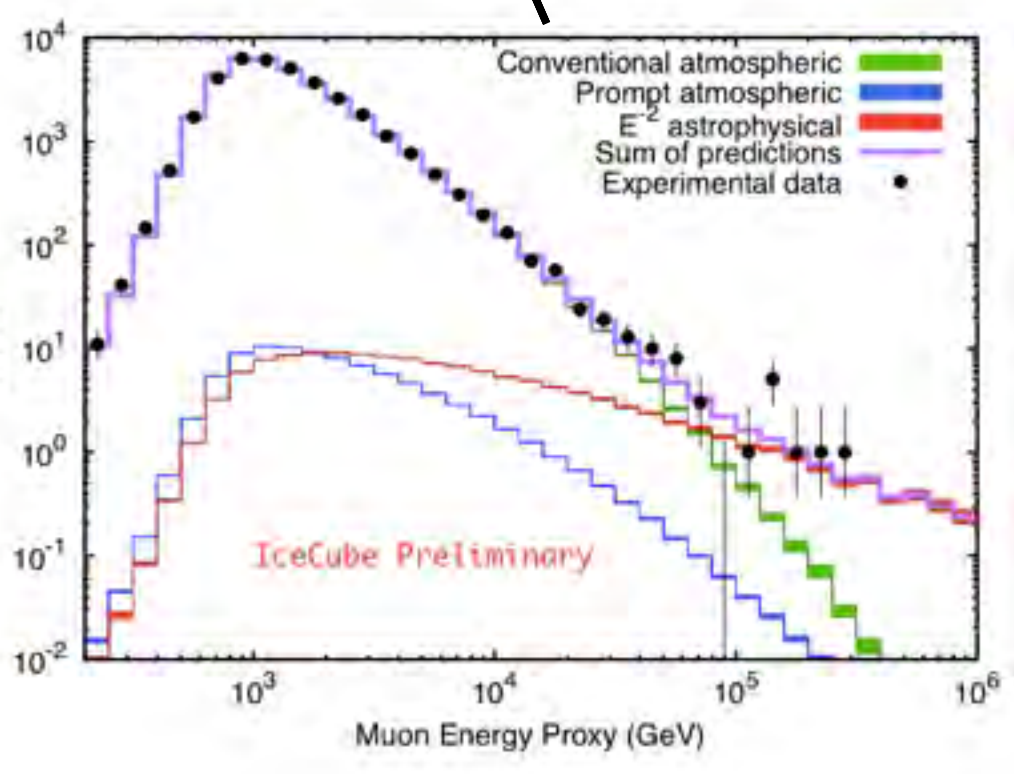
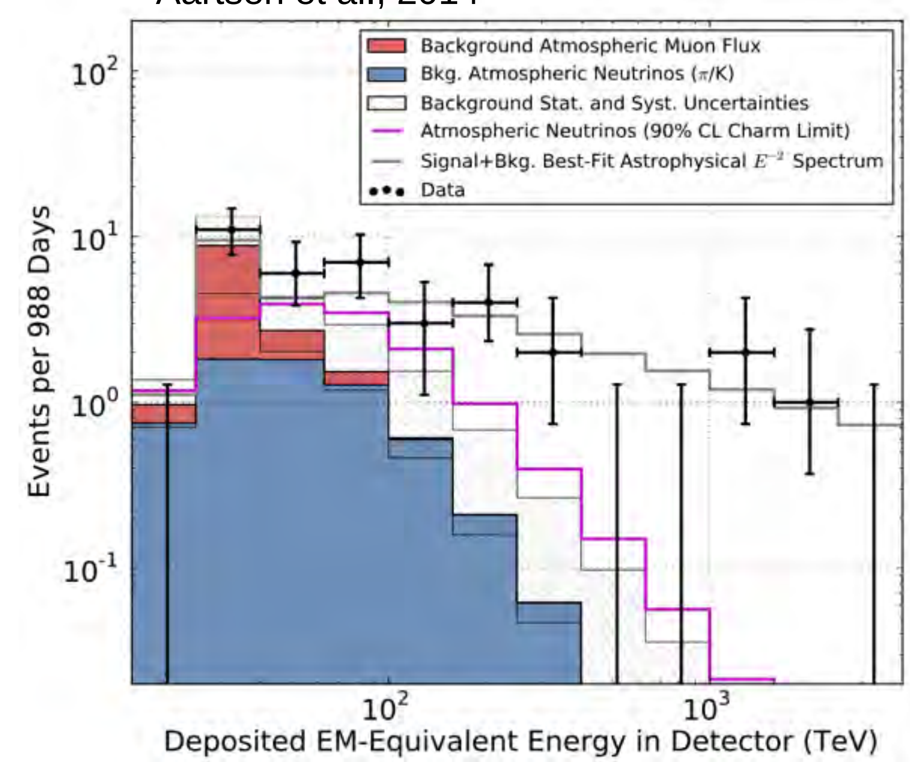








Aartsen et al., 2014



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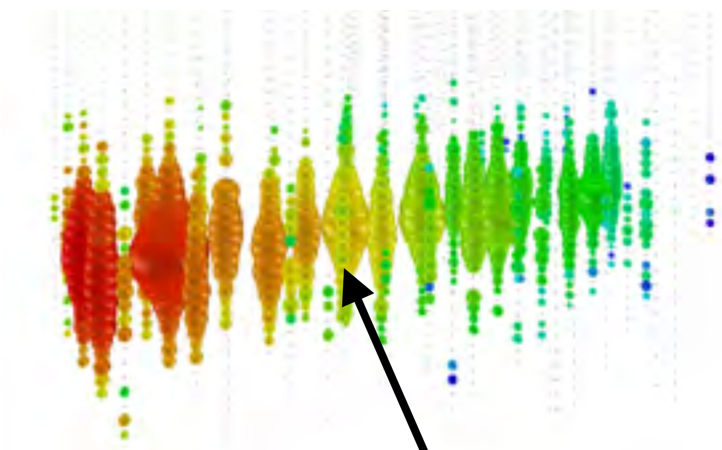

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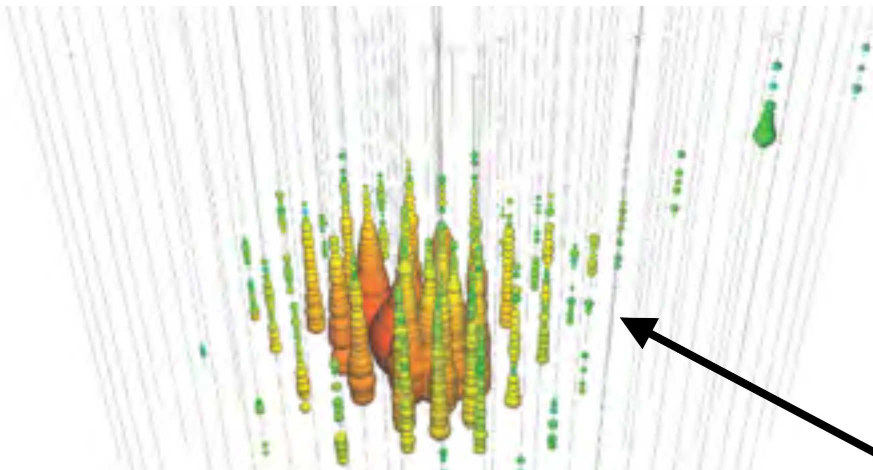

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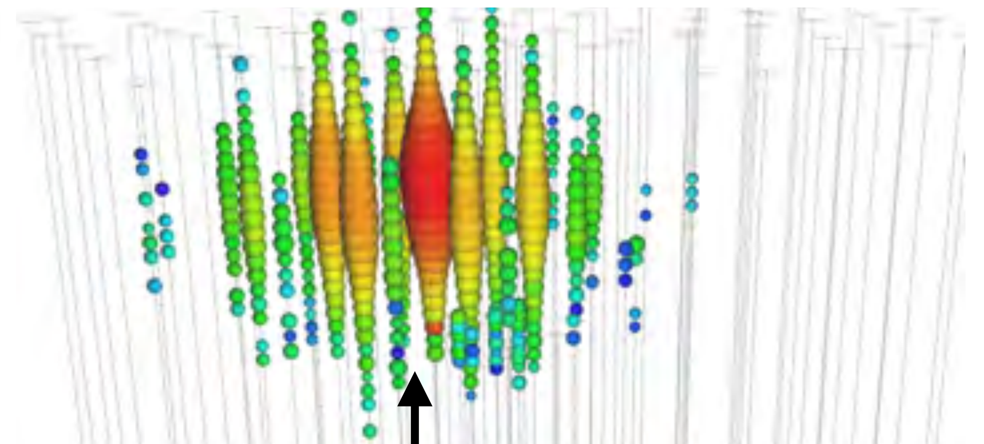

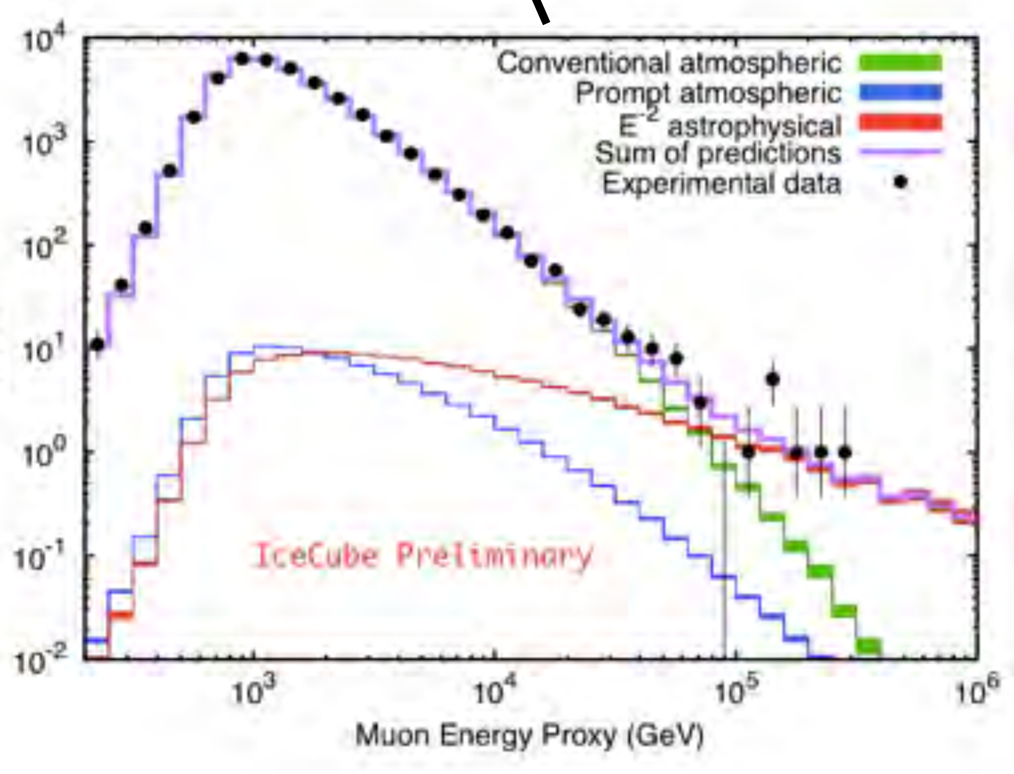

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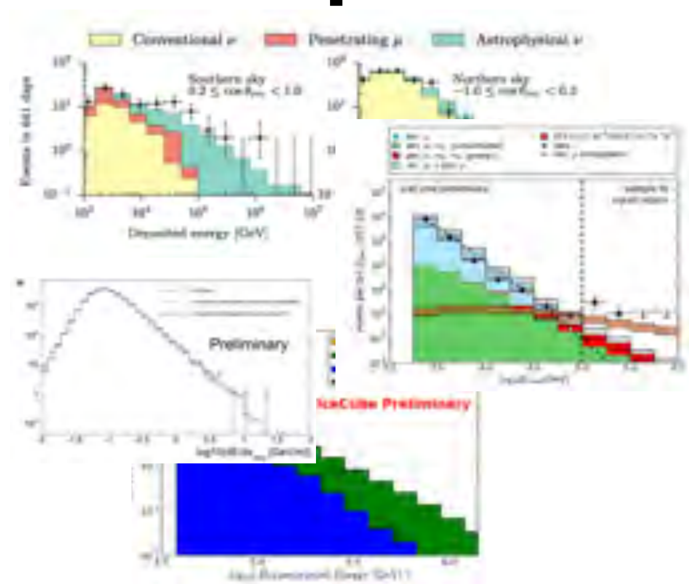
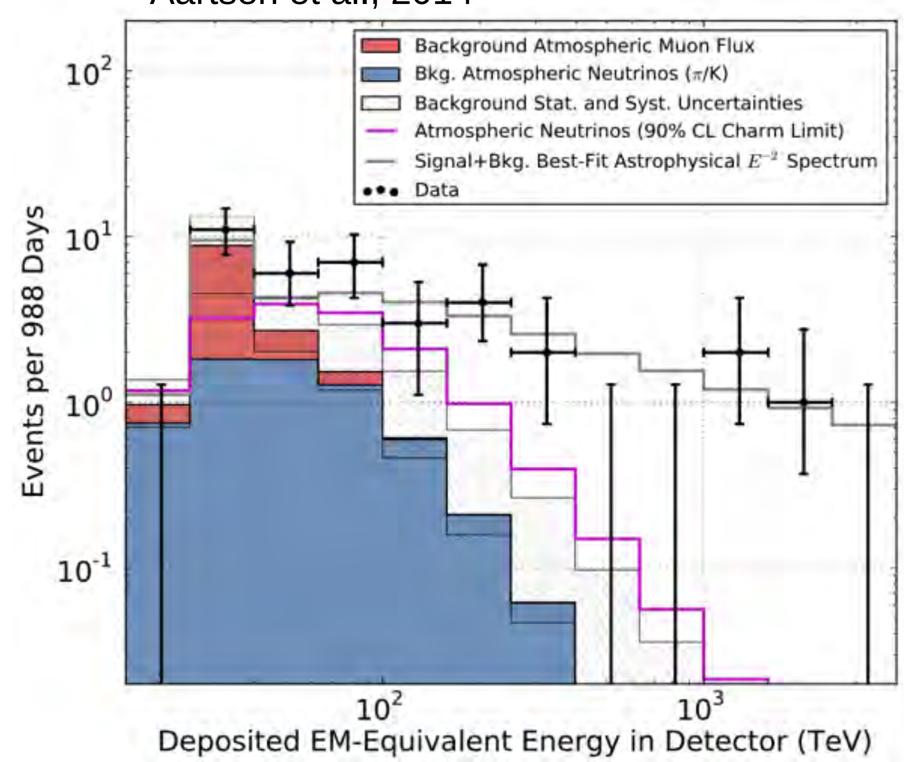
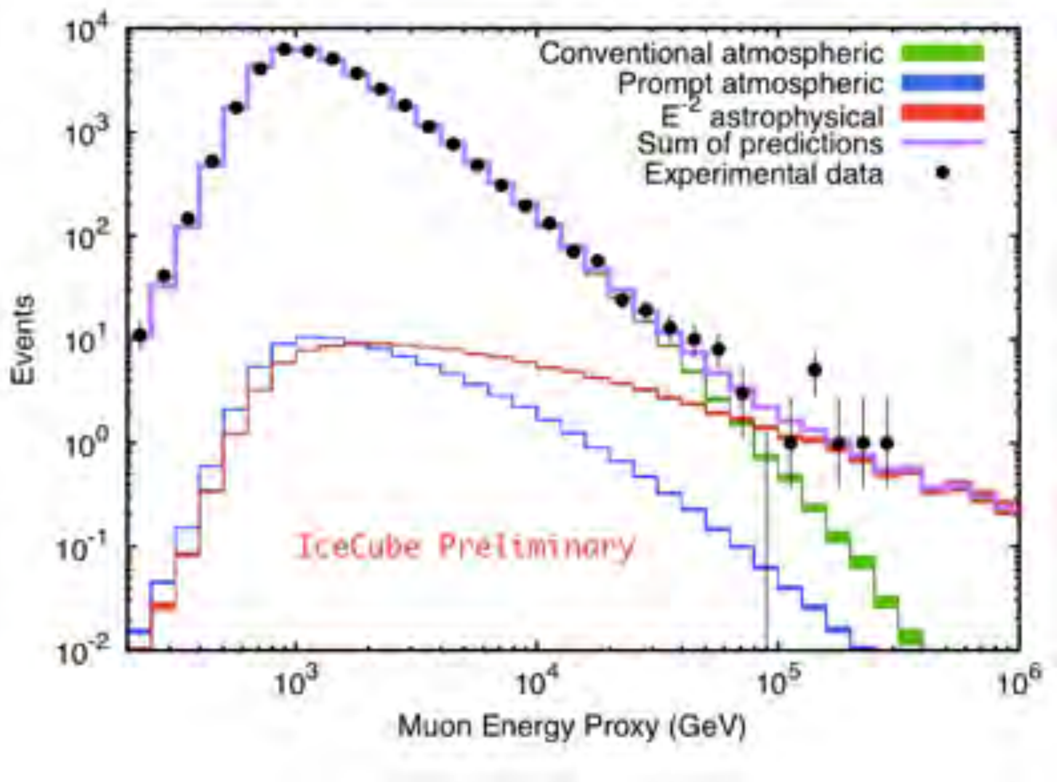


several more searches, partly using construction phase data

Aartsen et al., 2014





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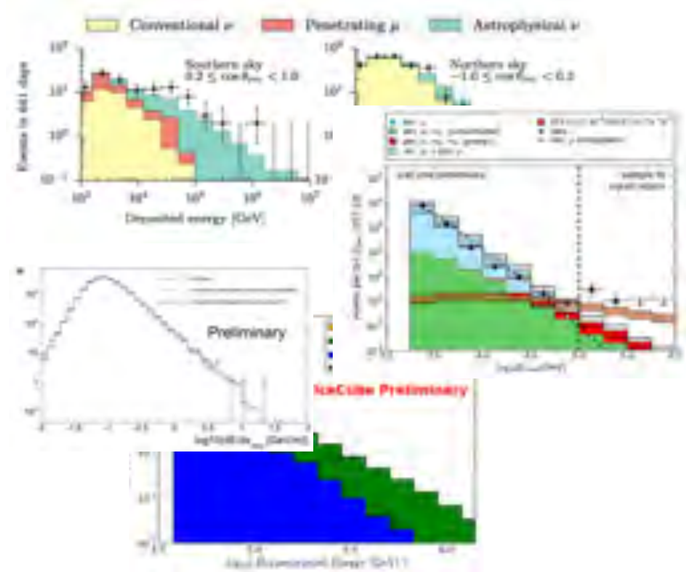

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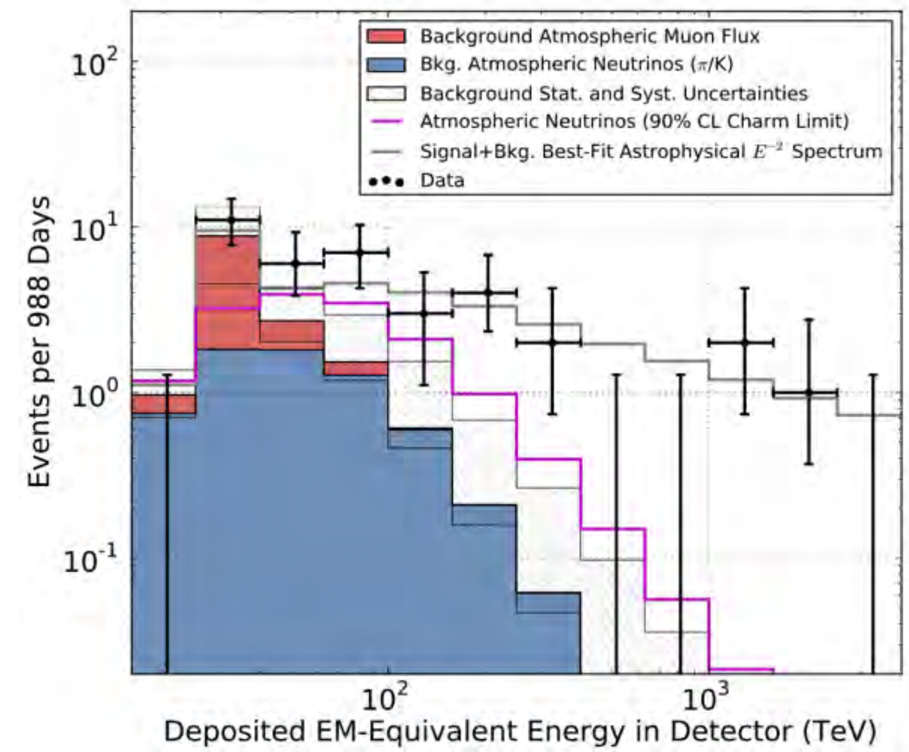
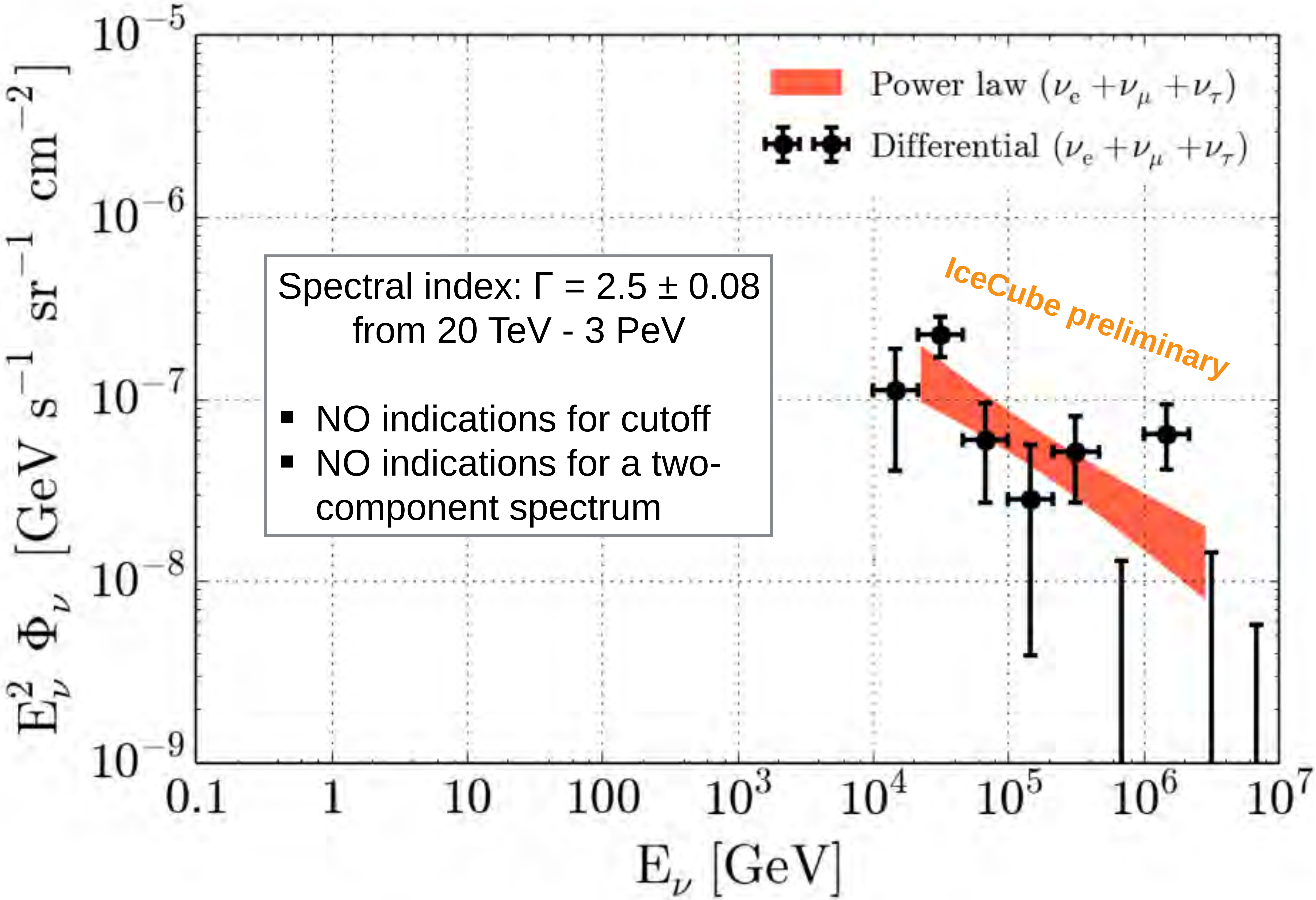


Global Fit of Astrophysical ν Spectruum

Lars Mohrmann, DESY

Extragalactic gamma rays and neutrinos.

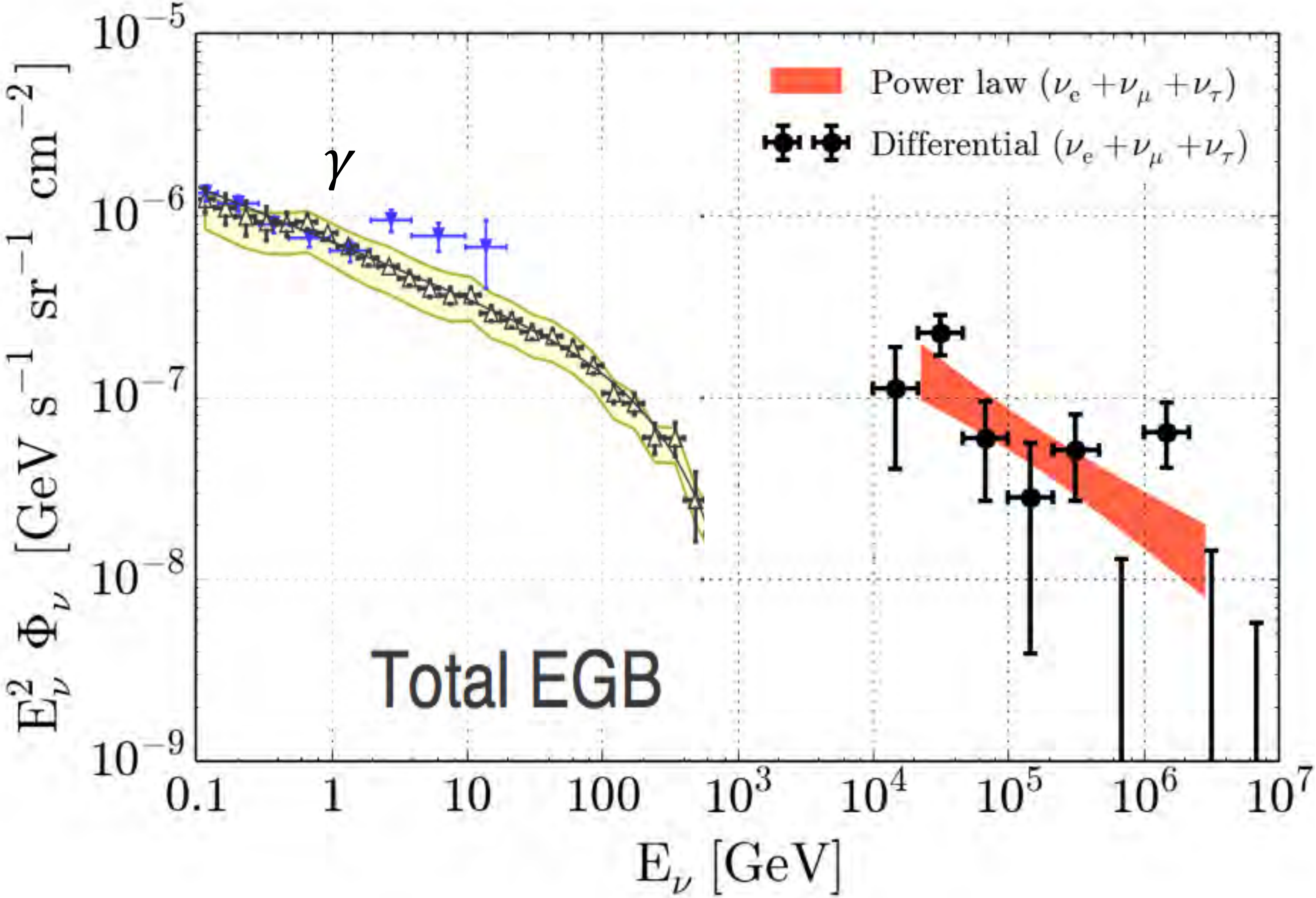


Spectral index: Γ = 2.5 ± 0.08
from 20 TeV - 3 PeV

- NO indications for cutoff
- NO indications for a two-component spectrum

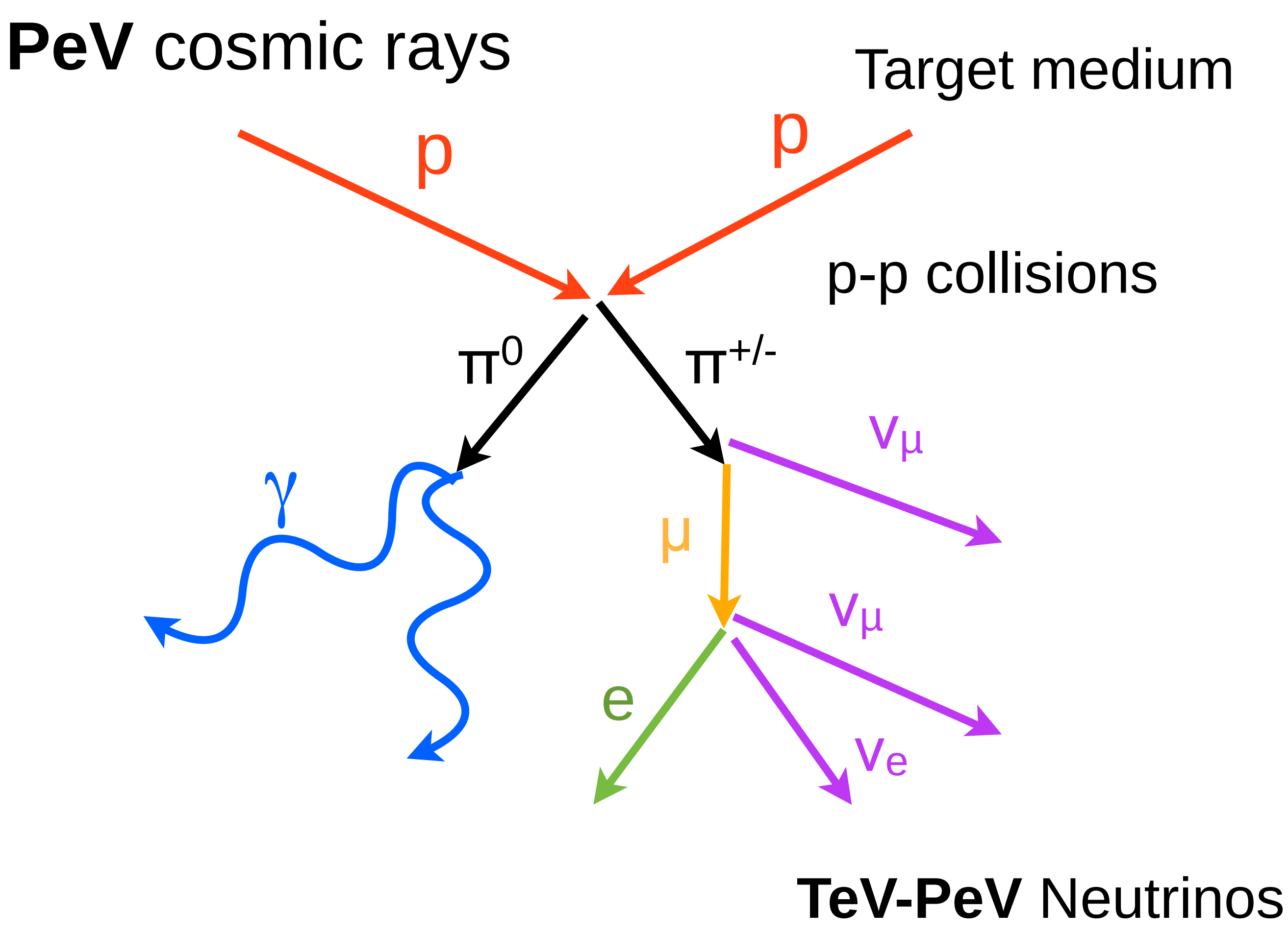
Lars Mohrmann, DESY

Extragalactic gamma rays and neutrinos.



The cosmic-ray / gamma / neutrino connection

- Cosmic rays interact with a target medium close to the source.
- Neutrino/Gamma production via p-p collisions
- Reprocessing of gamma rays to GeV energies



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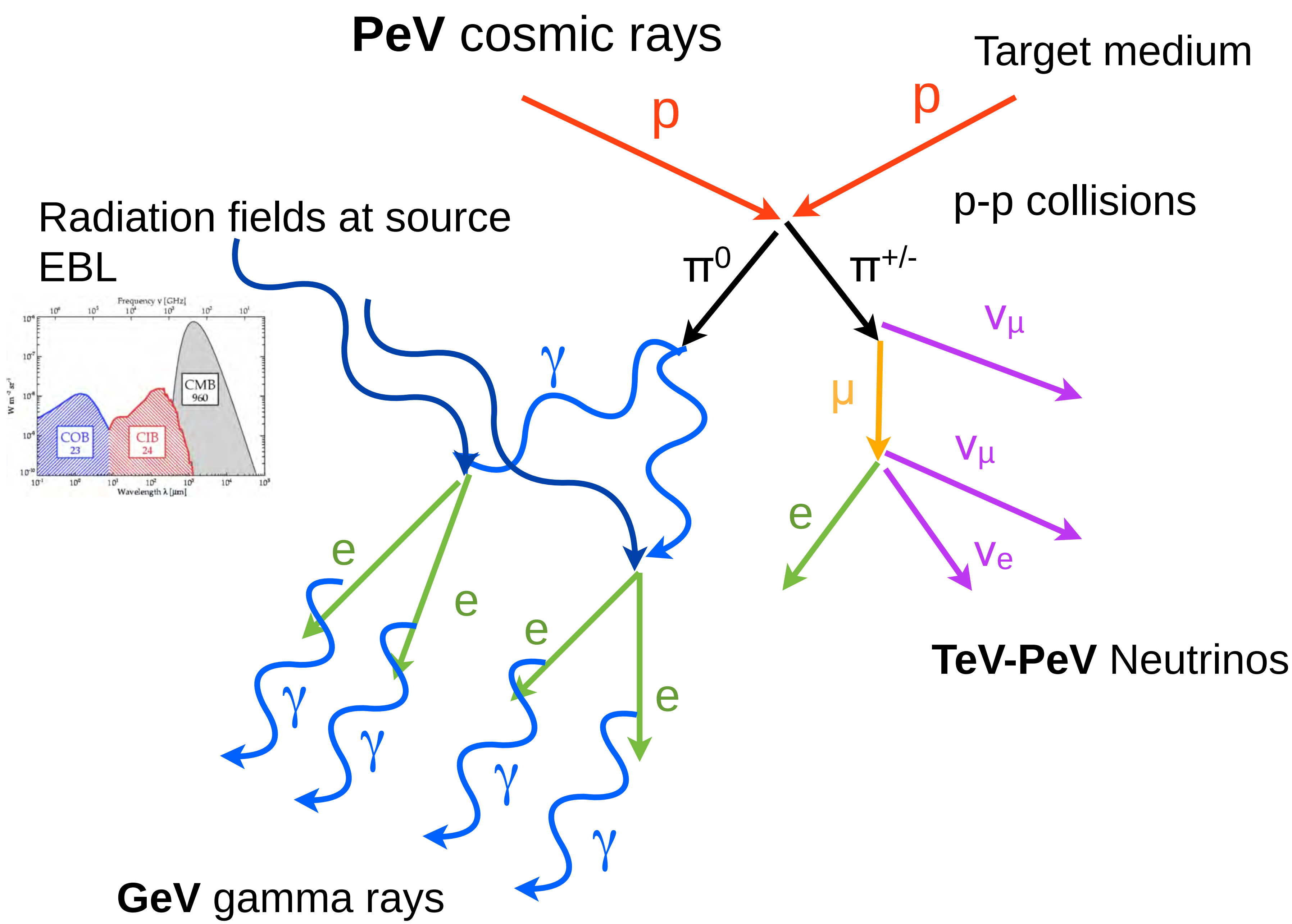


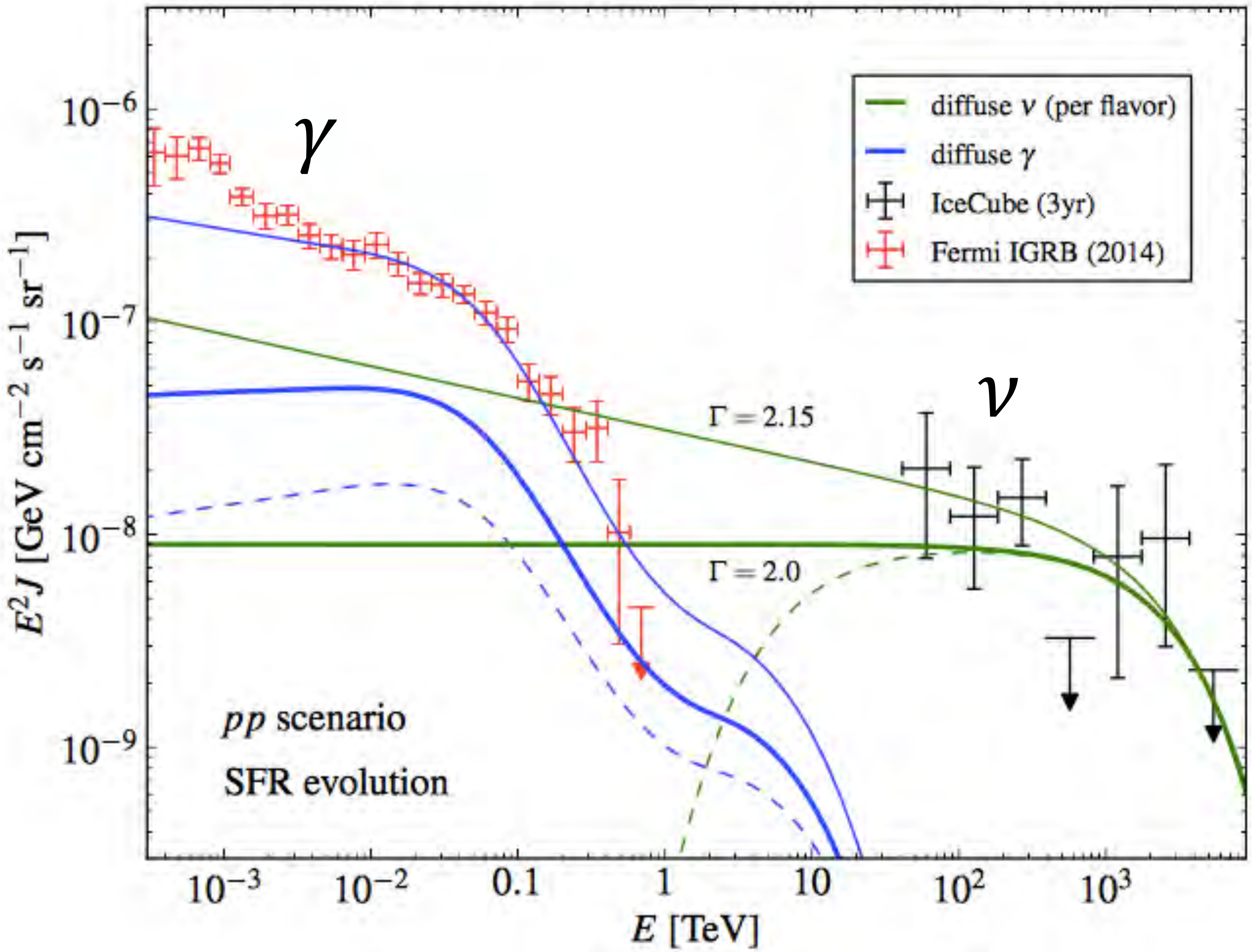
A proper calculation.

- If extragalactic p-p collisions produce the observed ν
  ➔ hard ν-spectrum below 10 TeV needed.

- …but difficult to explain spectra considerably harder than Γ~2 in p-p scenario.

- First hint at p-γ interactions being the dominant neutrino production mechanism?

- Or maybe that part of the signal is Galactic ?



[Murase, MA & Lacki'13; updated with Fermi 1410.3696]

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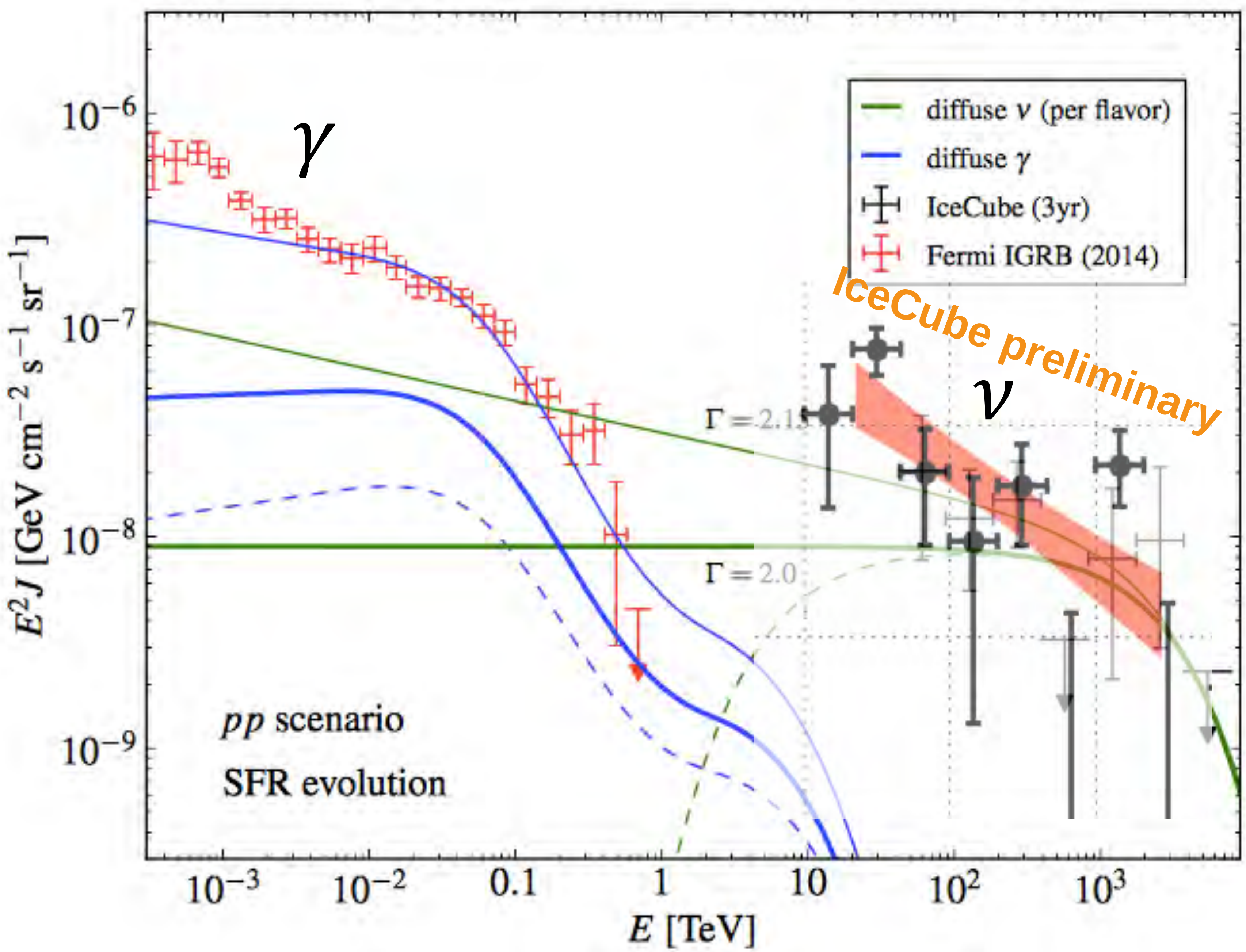
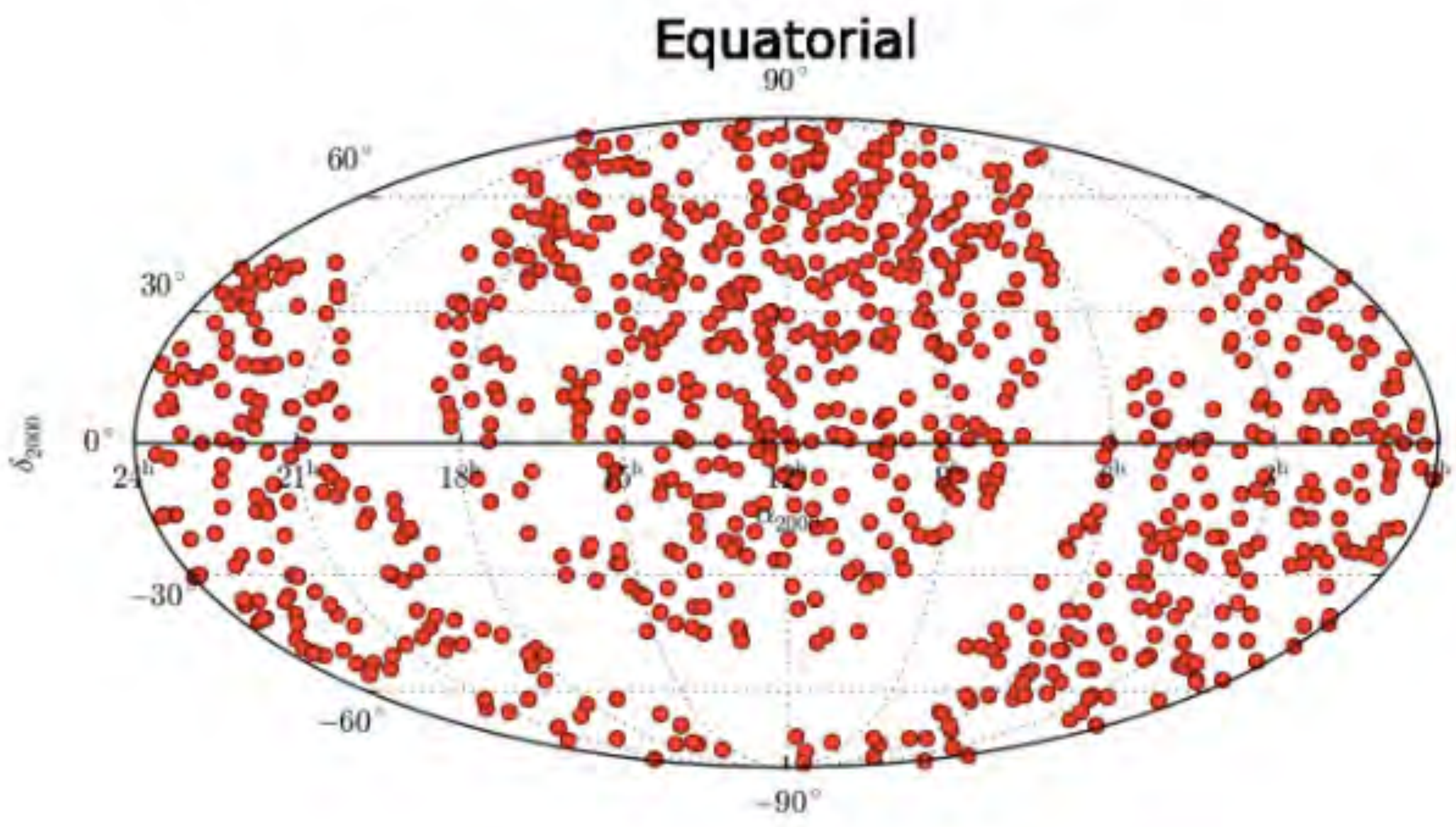


[Murase, MA & Lacki'13; updated with Fermi 1410.3696]

Search for correlation of ν to the sample of Fermi Blazars.

- Most of the extragalactic GeV gamma-ray emission is from Blazars
- Most of the emission is resolved in individual Fermi LAT sources.
- Search for neutrino emission spatially coincident with 2LAC Blazar sample.
- Neutrino dataset for point source analysis used (several 10^5 events).

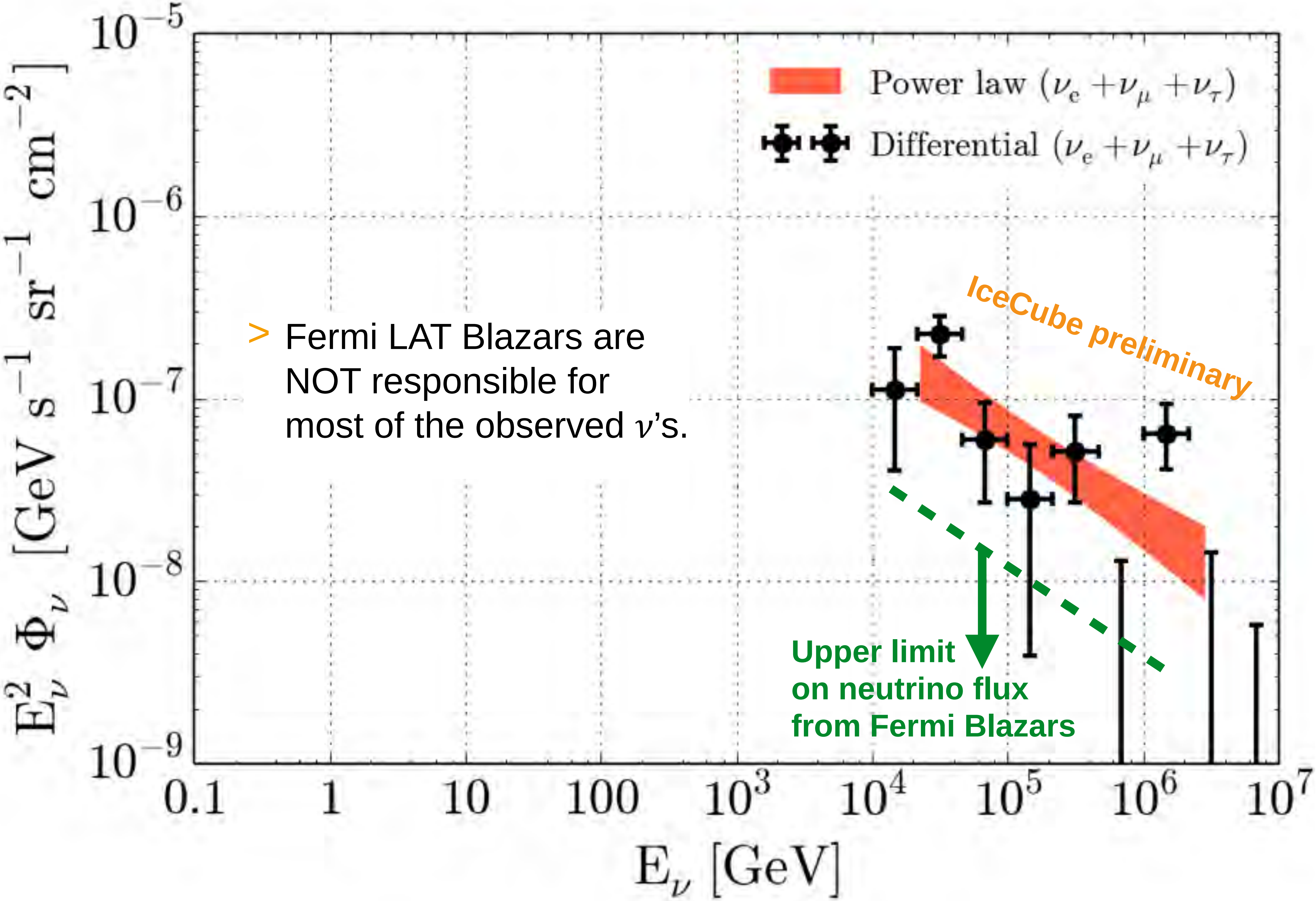
All blazars from 2-*LAC* – 862 objects



Thorsten Glüsenkamp, DESY

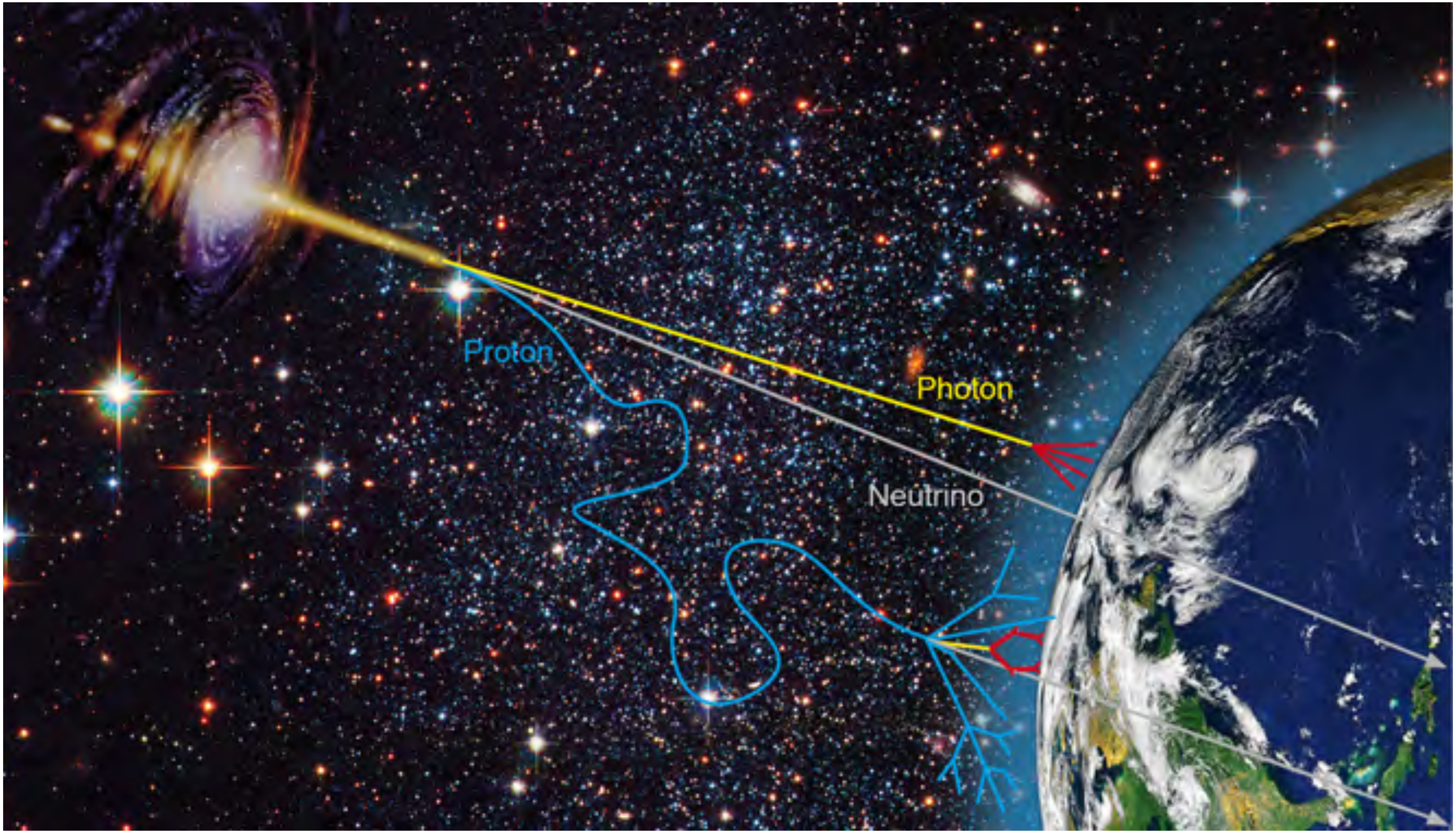
Extragalactic gamma rays and neutrinos.

- Fermi LAT Blazars are NOT responsible for most of the observed ν's.



The cosmic-ray / gamma / neutrino connection (II)

> Ultra-high energy protons produce gamma-rays and neutrinos during propagation.



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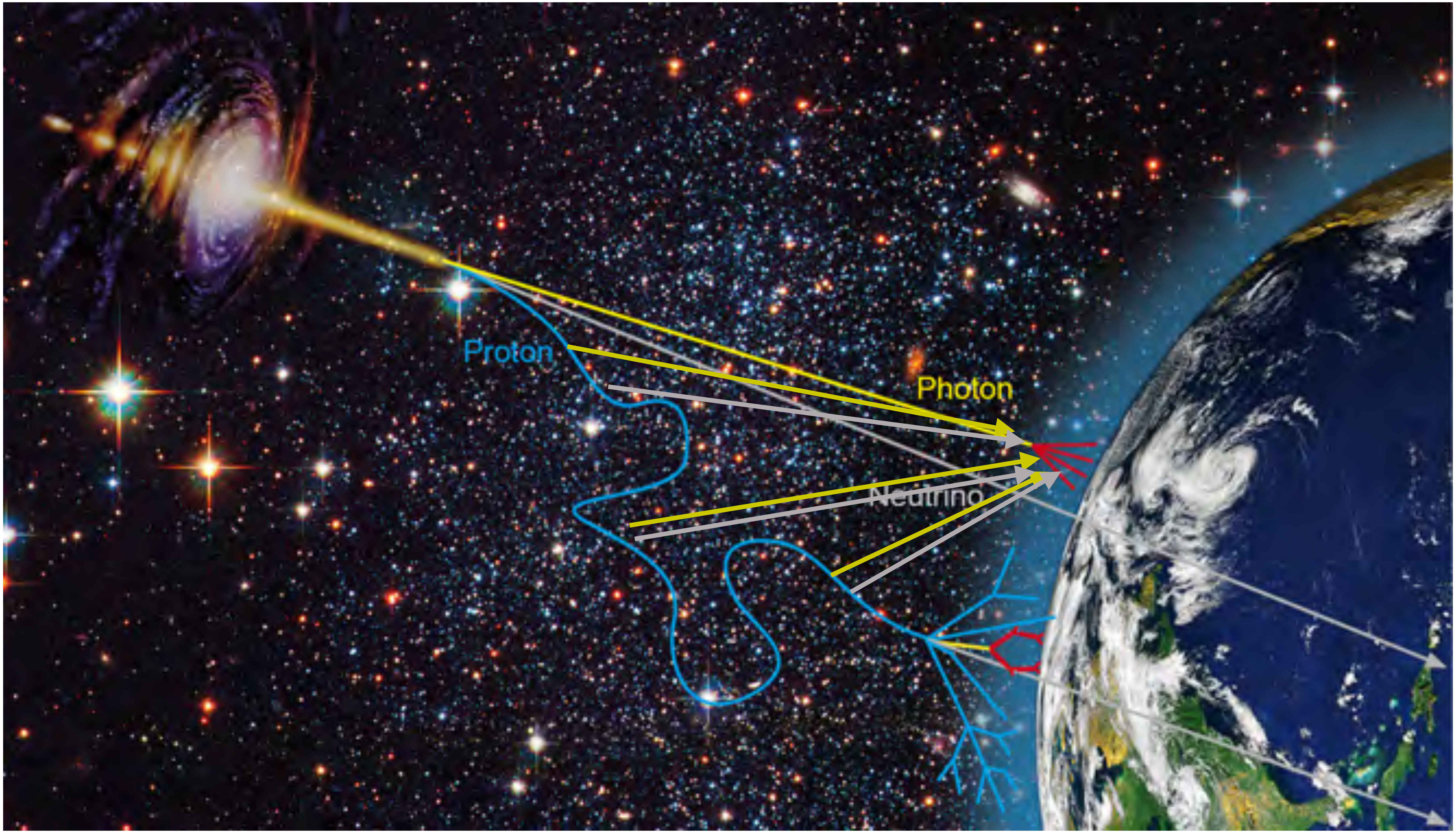

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- High-energy cosmic rays interact with the EBL during propagation.
- Neutrino/Gamma production via pγ-interactions
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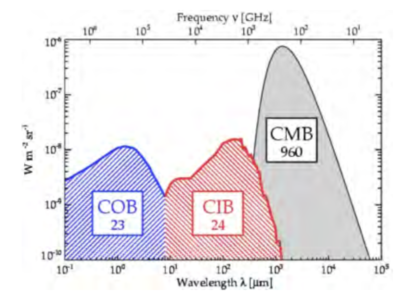

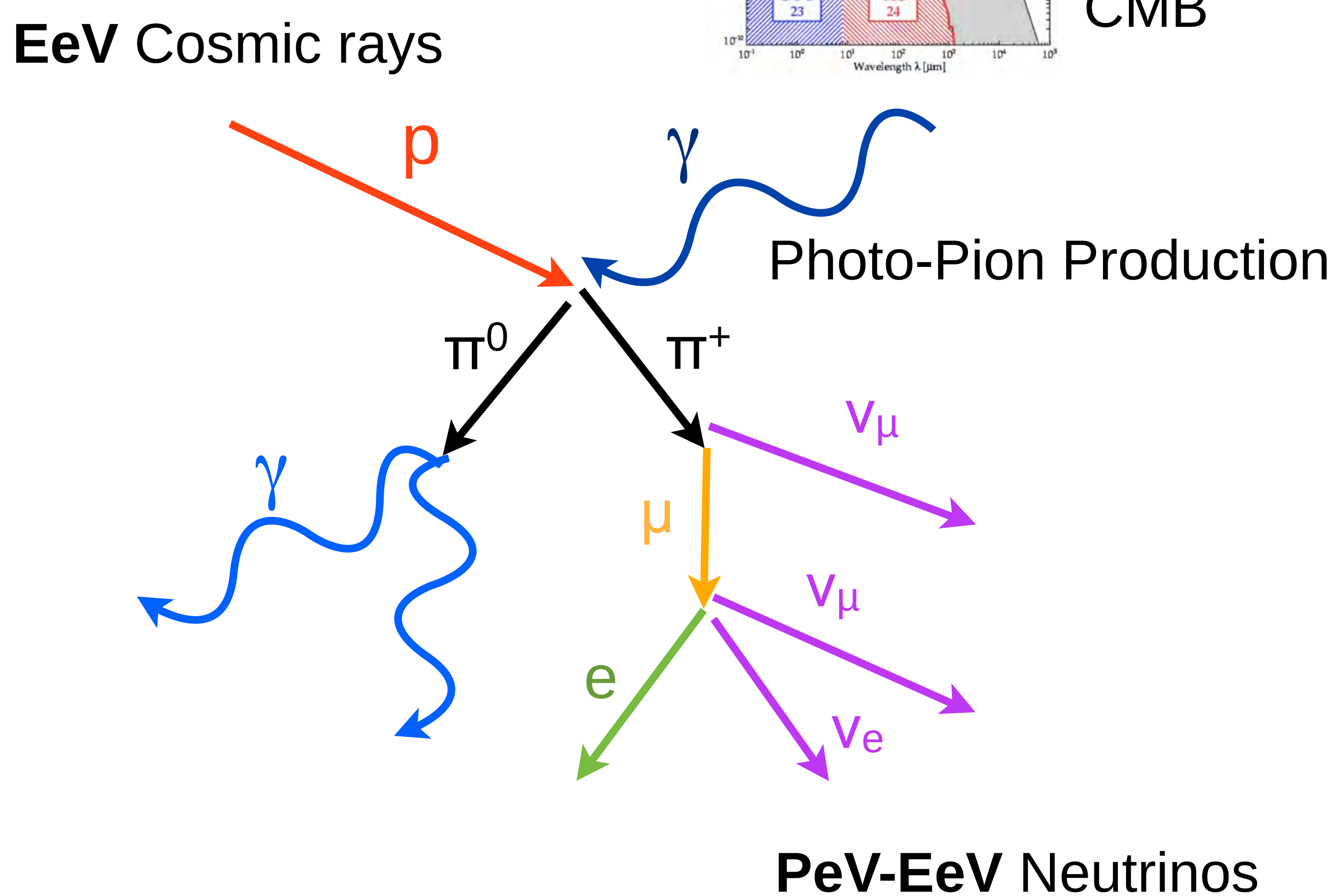

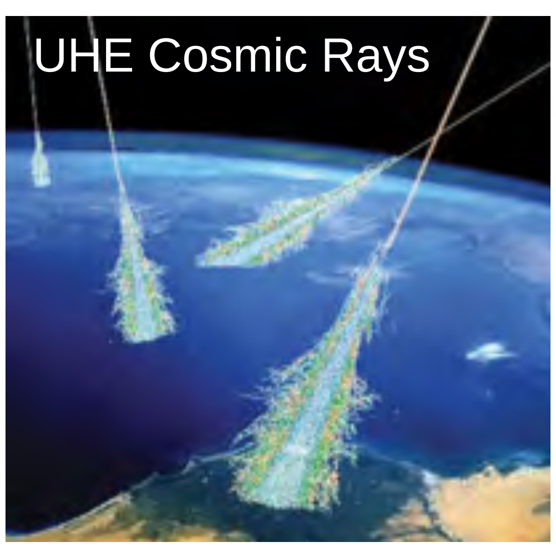

EBL=extragalactic background light

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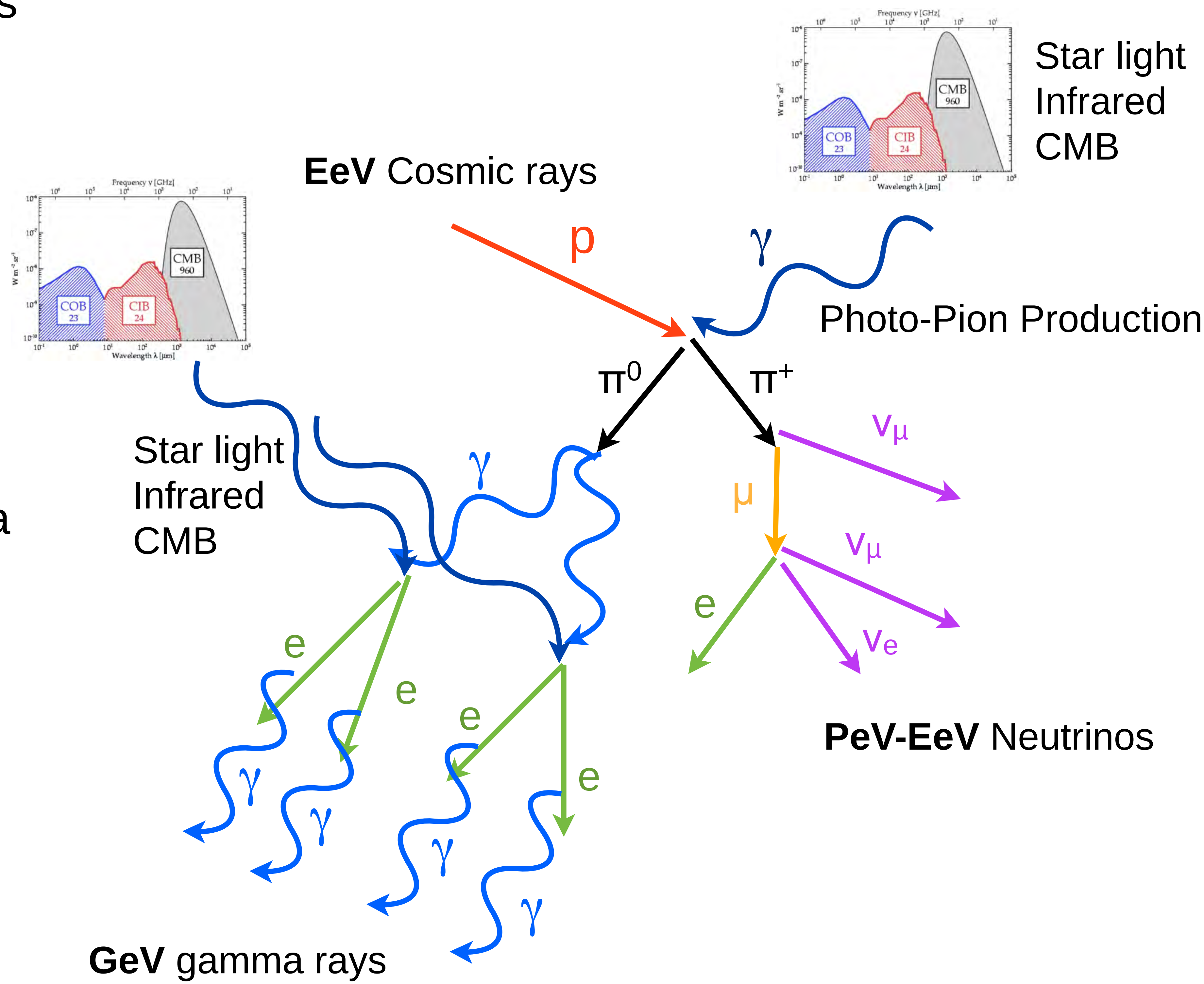
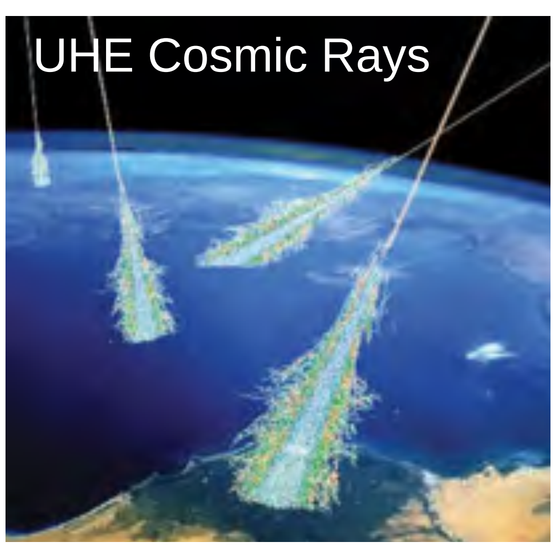
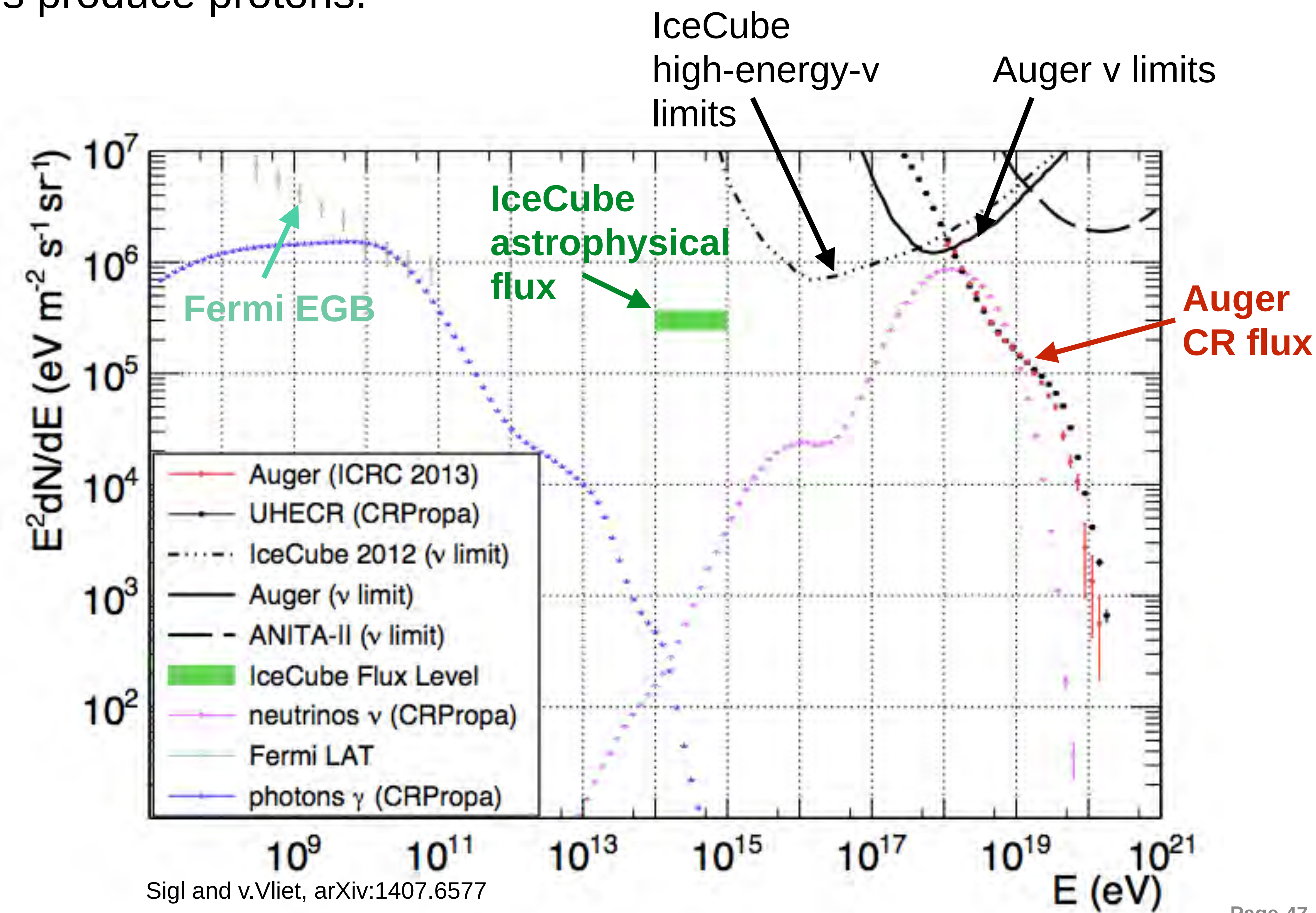




EBL=extragalactic background light

Multi-messenger constraints on UHECR properties.

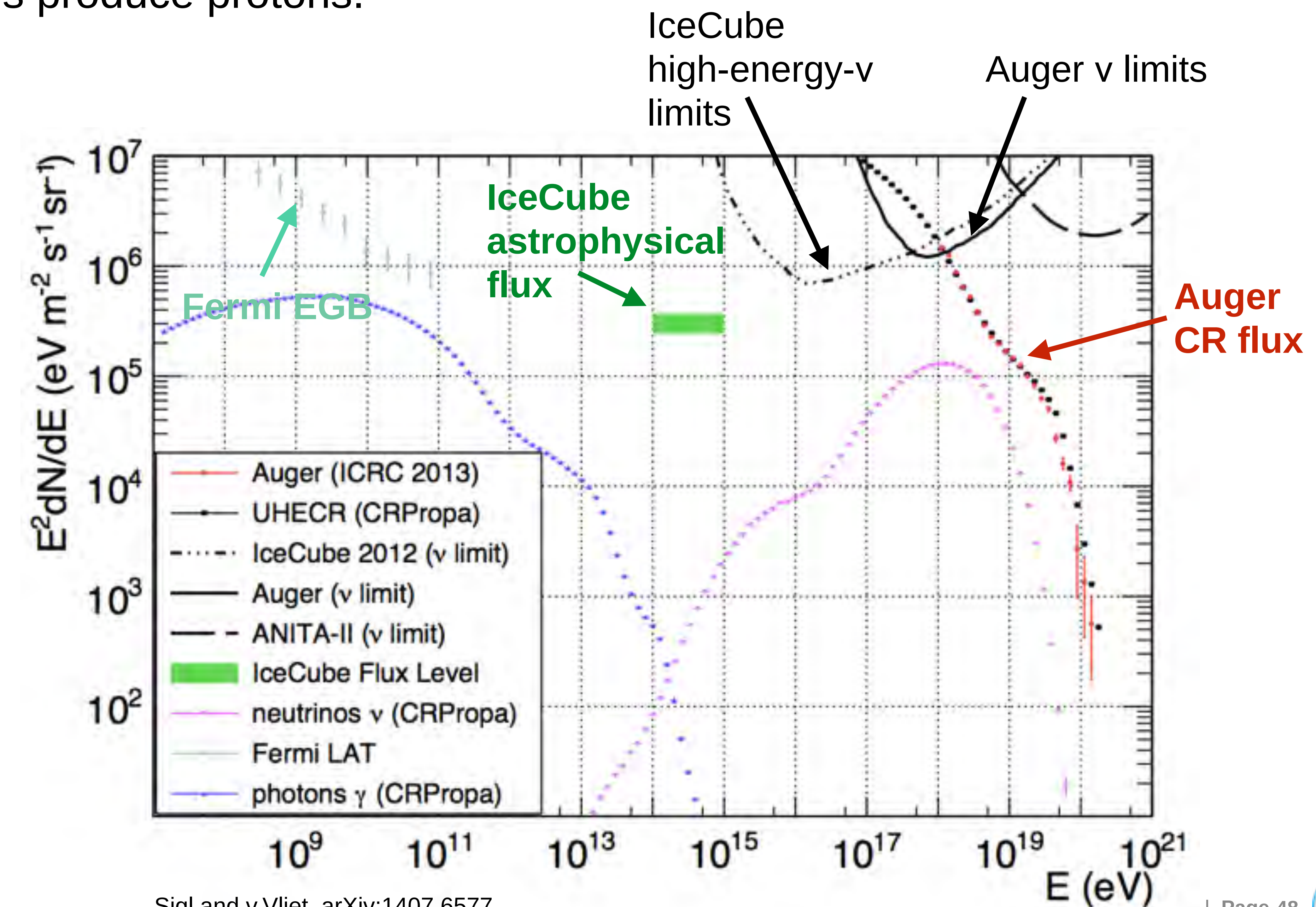
- CR, neutrino and gamma-ray spectrum from propagation code.
- Cosmological evolution of sources corresponds to **FR-II galaxy evolution.**
- CR sources produce protons.



Sigl and v.Vliet, arXiv:1407.6577

Multi-messenger constraints on UHECR properties.

- CR, neutrino and gamma-ray spectrum from propagation code.
- Cosmological evolution of sources corresponds to **GRB evolution.**
- CR sources produce protons.



Sigl and v.Vliet, arXiv:1407.6577

What we learned so far.

- **The origin of more than half of the EGB** can be attributed to known source populations.
  - Allows strong constrains on exotic processes in the universe.

- We see the **signatures of CR** acceleration / interaction up to **tens of PeV** in energy.
  - The origin seems to be at least partly extragalactic.

- The astrophysical neutrino spectrum between **20 TeV and 3 PeV** can be described by a single power-law with **index α = 2.5**.

- The EGB constrains the **low-energy neutrino spectrum**.
  - required hard spectrum might create tensions to an origin from p-p collisions.

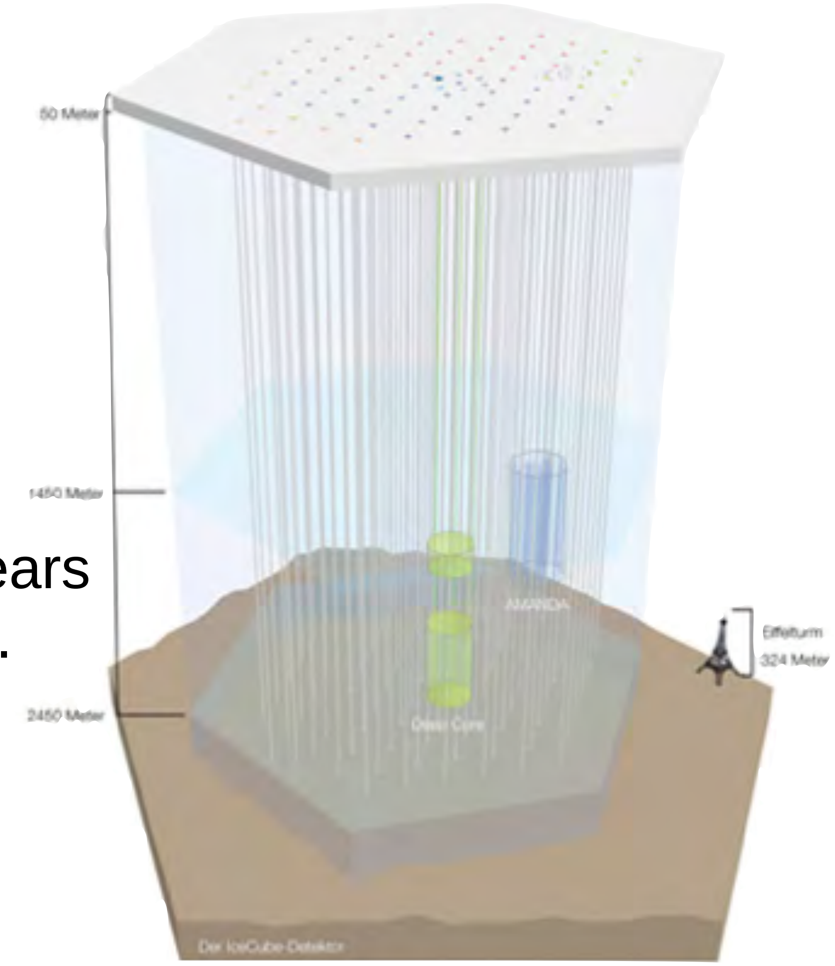
- **LAT Blazars are not responsible** for the bulk of astrophysical neutrinos.

- There is likely **no connection** between the observed **neutrinos** and the **ultra-high-energy cosmic rays**
  - Need to observe a signal at higher energies.

What we will learn soon …..

5 years more of Fermi LAT
data expected.

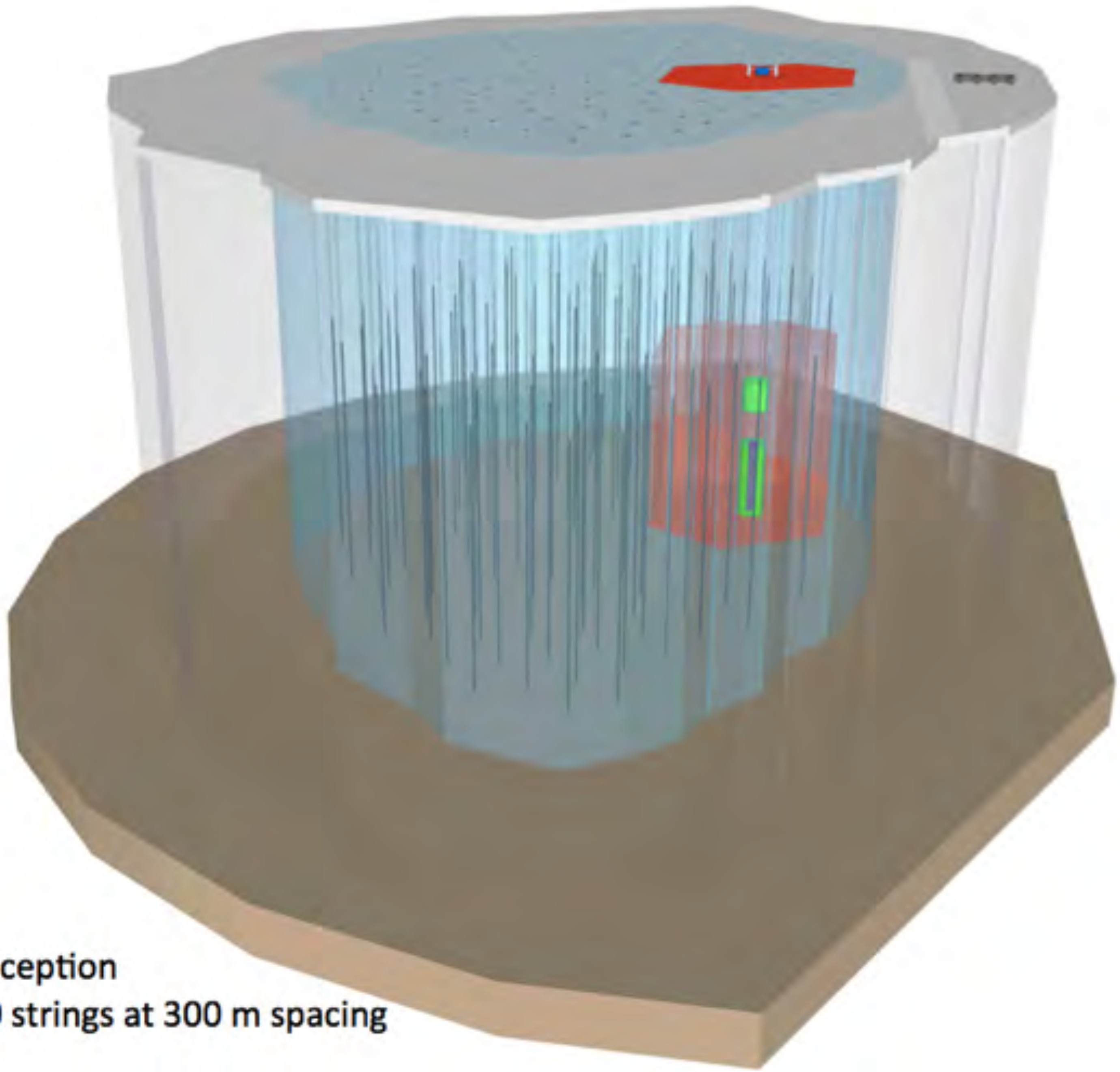
At least 10 more years
of IceCube data.



➔ **Narrow down the source population(s) that produce high-energy cosmic rays.**

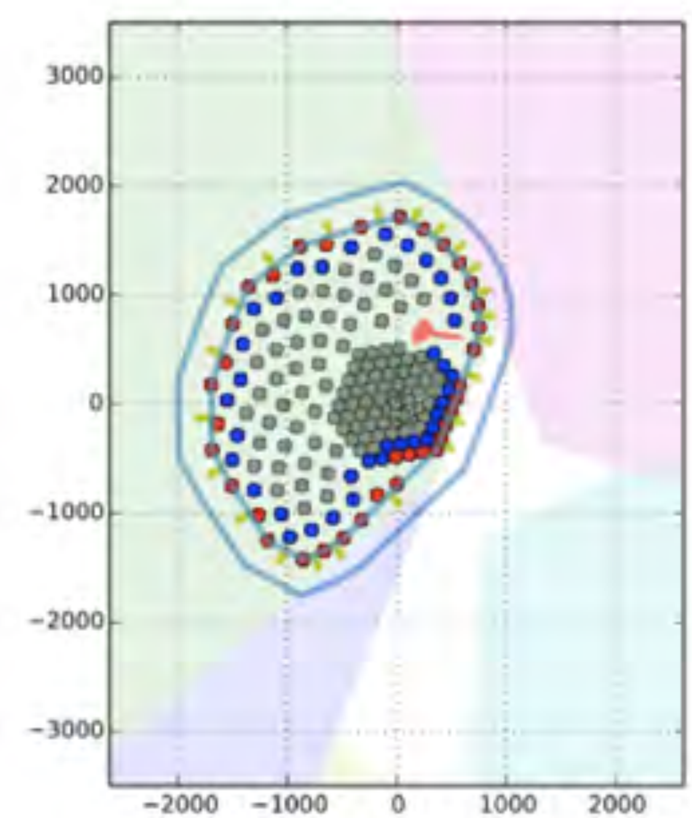
- **Improved accuracy** of **EGB** measurement above 100 GeV.
- **Better constraints on spectral parameters** of ν-flux, extended energy range.
- Find out if there is a **Galactic contribution or anisotropy** to the ν-flux.
- More **stringent constraints** on **extragalactic multi-PeV CR accelerators** from the combination of EGB and astrophysical ν's.
- Discovery of **sub-dominant ν-flux contributions** from Blazars, Radio Galaxies, or UHECR ?

From discovery to high-statistics neutrino astronomy.



Artist conception
Here: 120 strings at 300 m spacing

NOT an official Logo



- ~100 more strings, 6 - 10 km³ instrumented volume.
- Optimized for 10 TeV - 10 PeV astrophysical neutrinos.
- ~100 M€ Investment.

Backup.