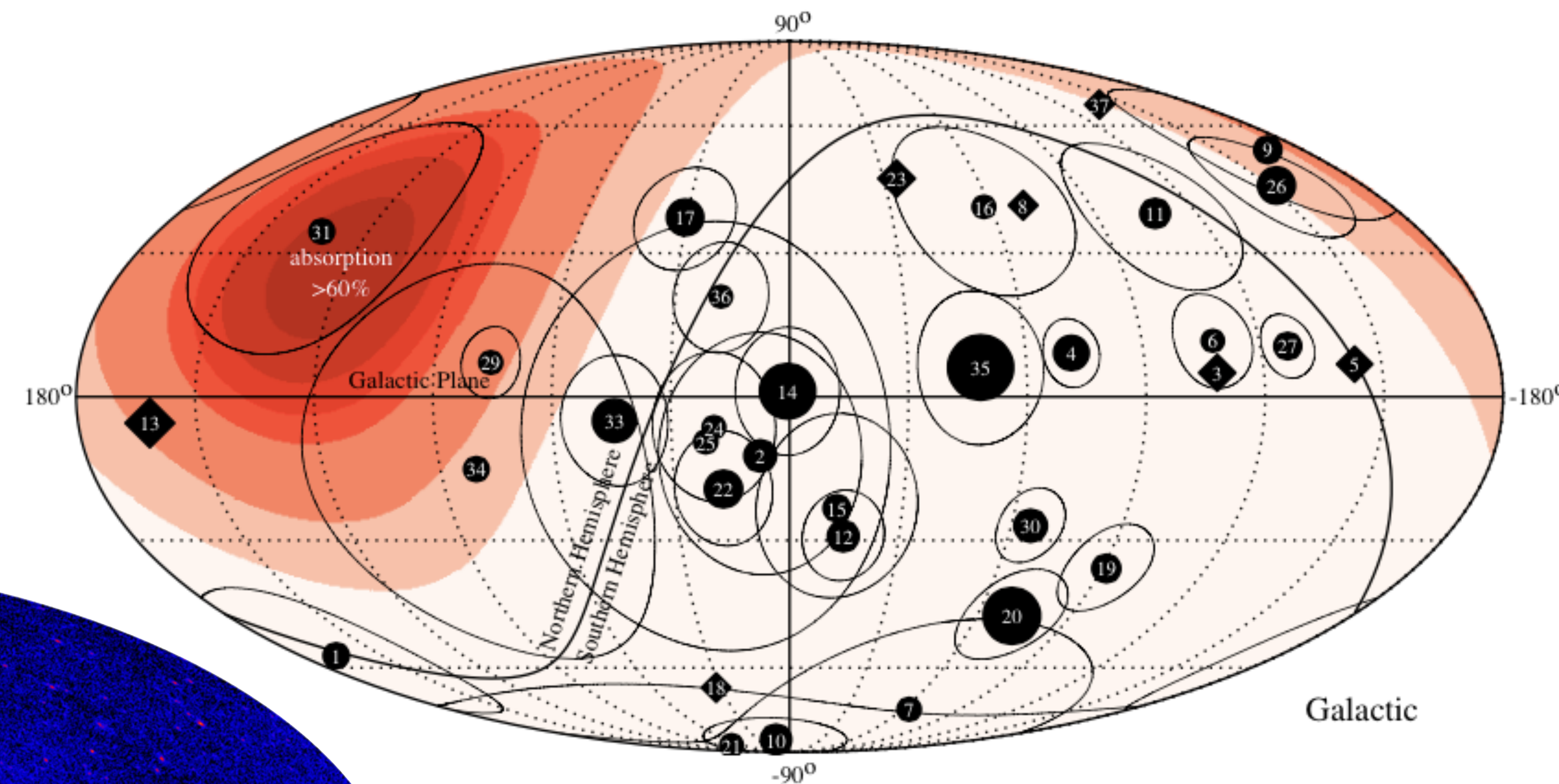
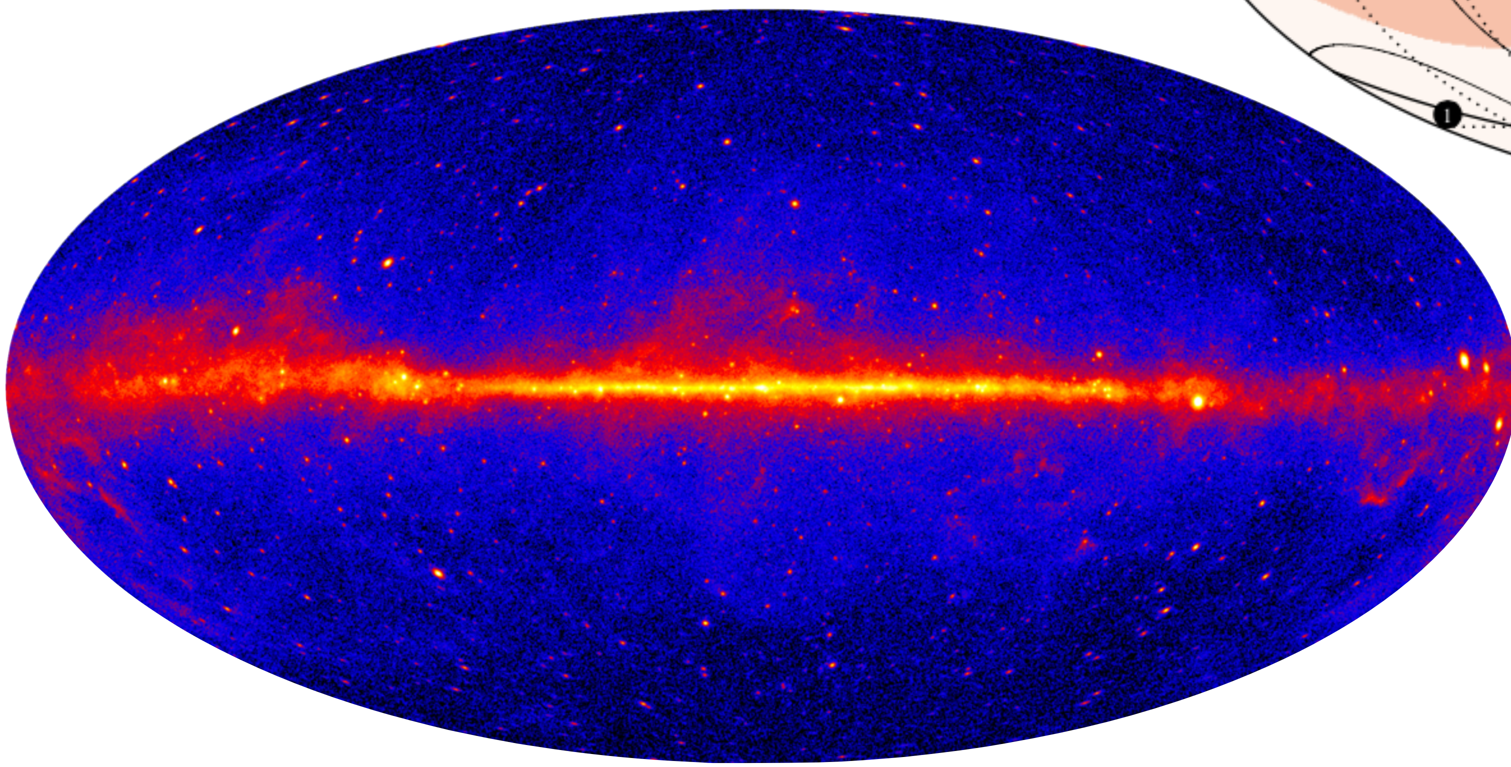
Neutrinos & gamma rays

Complementary views on the high-energy universe.





Markus Ackermann

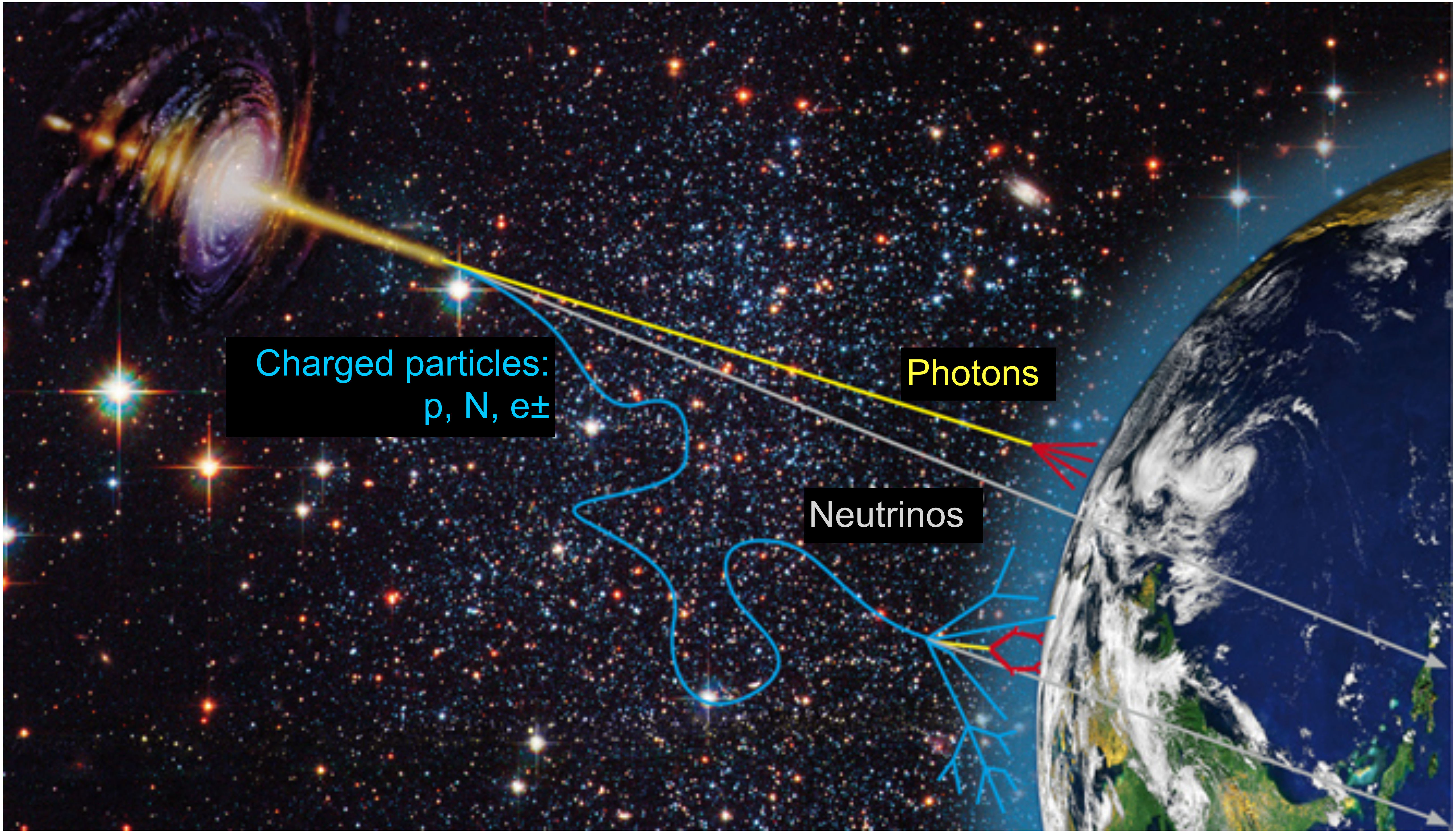
IPA 2015
Madison, WI, May 4 2015

HELMHOLTZ
ASSOCIATION

DESY

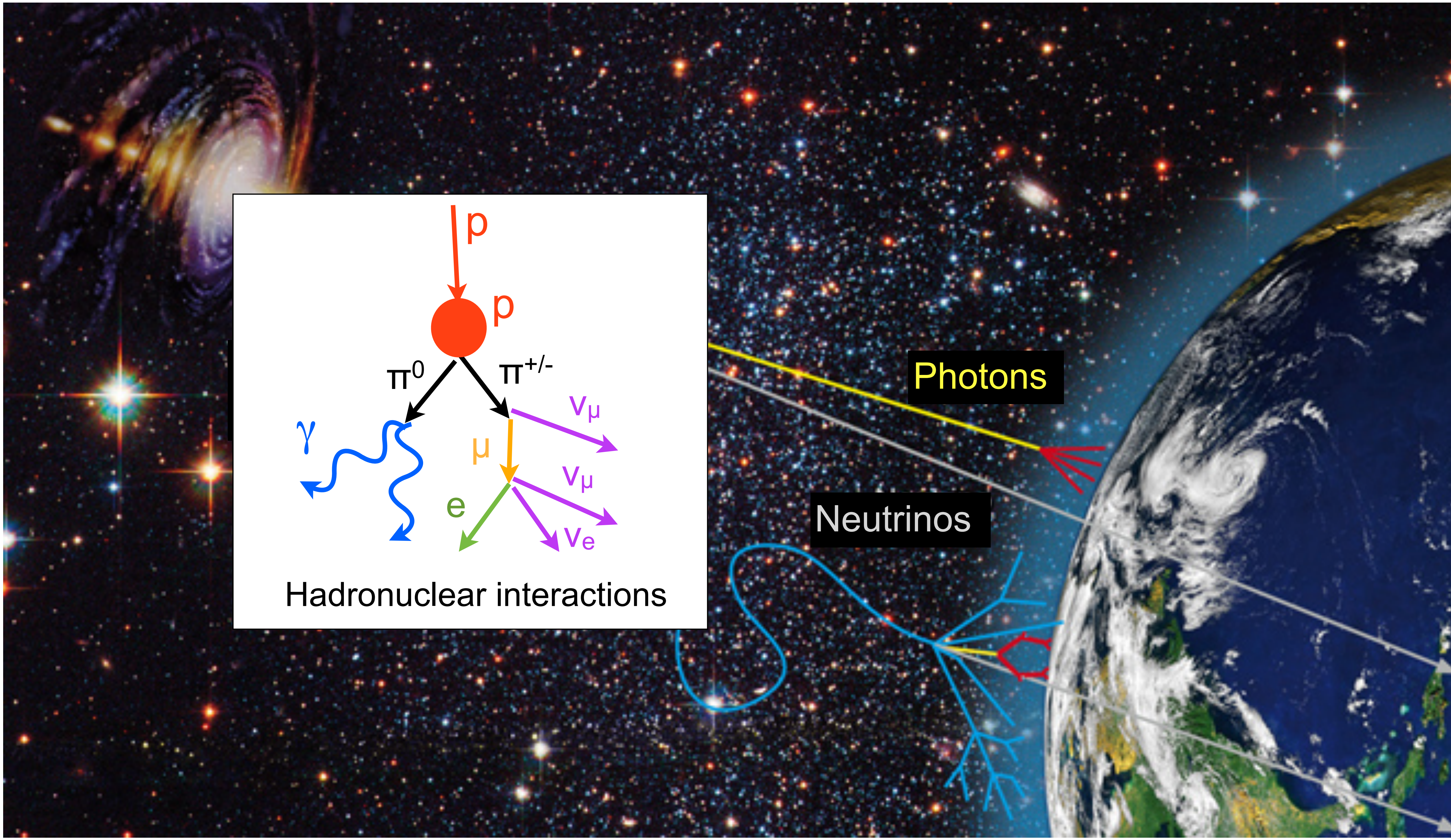
The multi-messenger approach.

> 3 messengers to study the non-thermal universe.

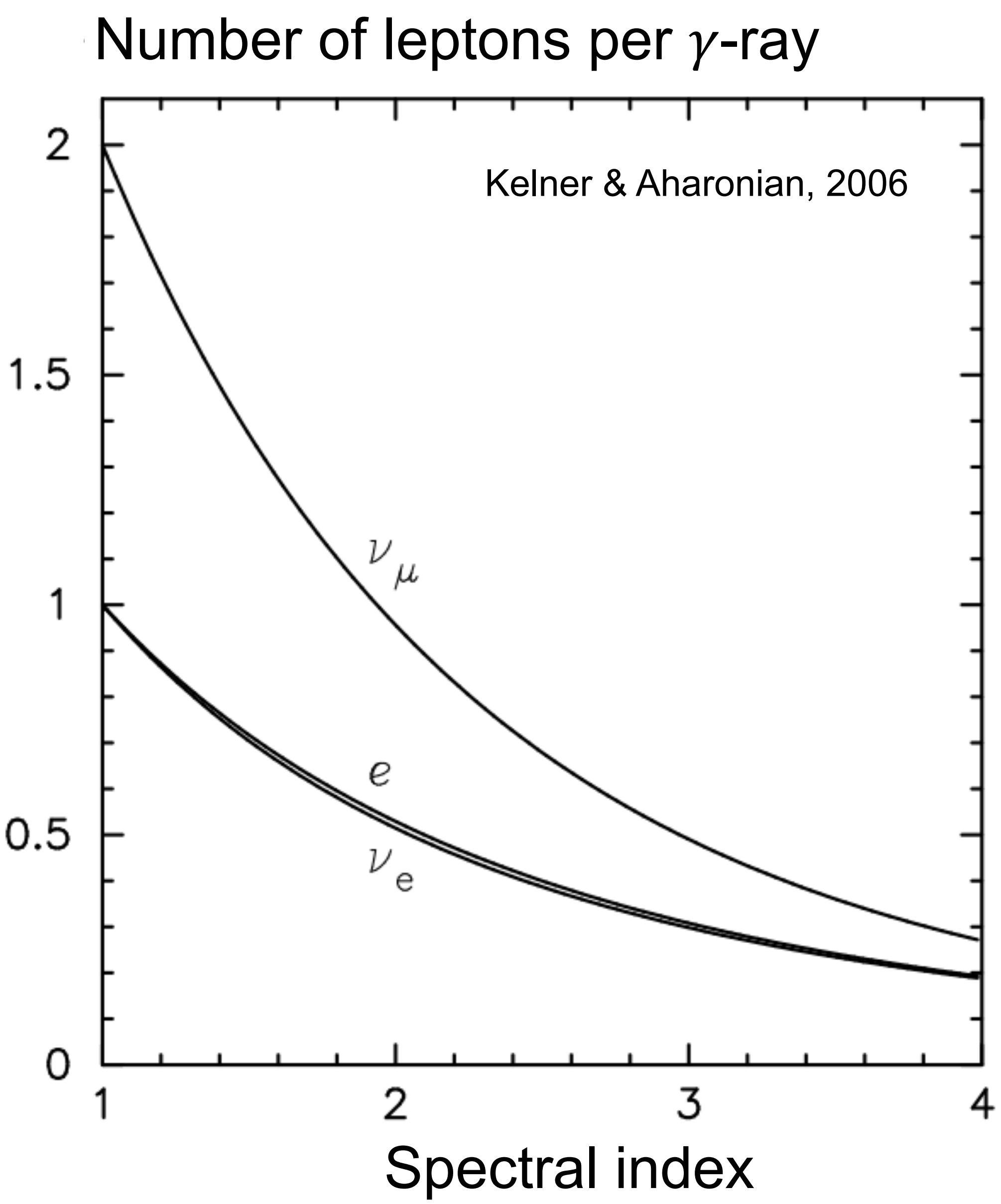


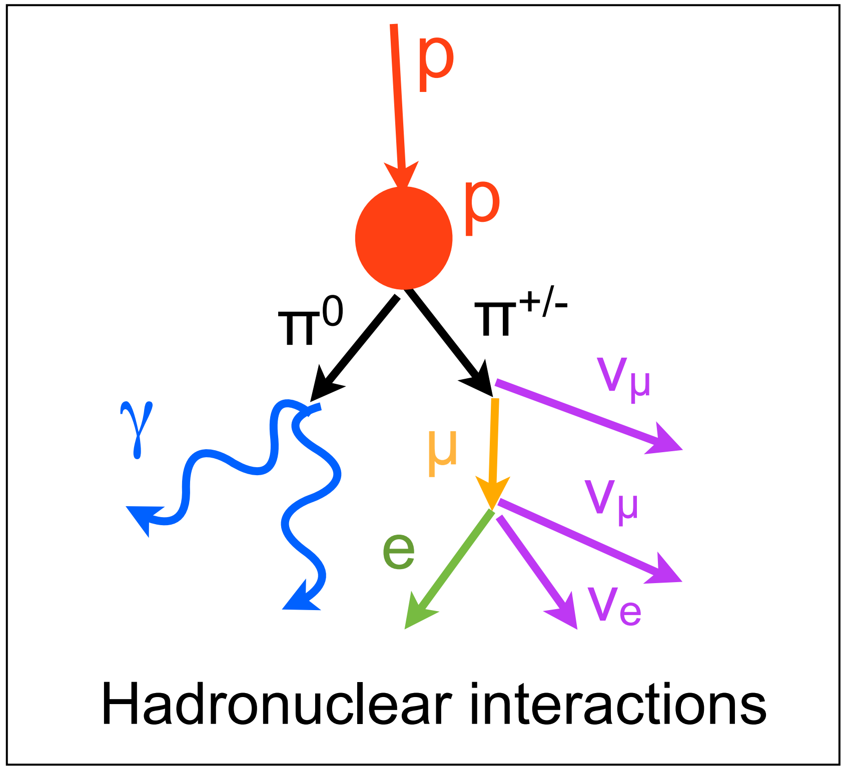
The multi-messenger approach.

> Gamma-ray and neutrino production in hadronuclear interactions.

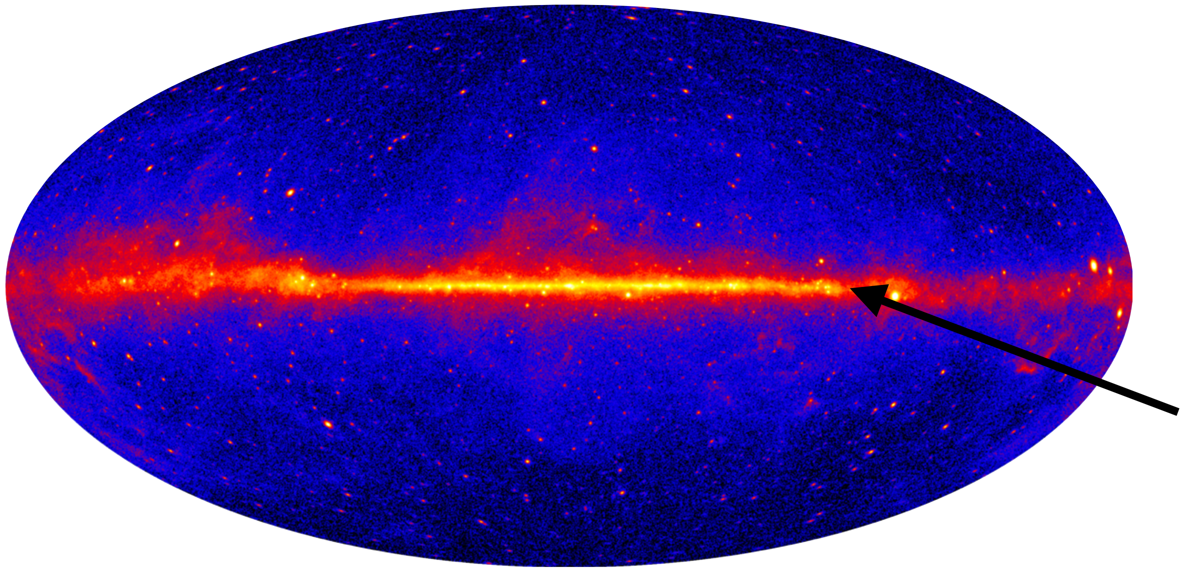


Hadronuclear interactions.





- Interactions of **high-energy nuclei** with **target gas.**
- ν / γ spectrum follows **spectrum of nuclei.**
- Simple **relative γ / ν yields**.
- **Well-known example:** GeV Galactic diffuse emission



GeV diffuse emission dominantly produced in hadronuclear interactions.

The multi-messenger approach.

> Photo-hadronic interactions in radiation field targets.

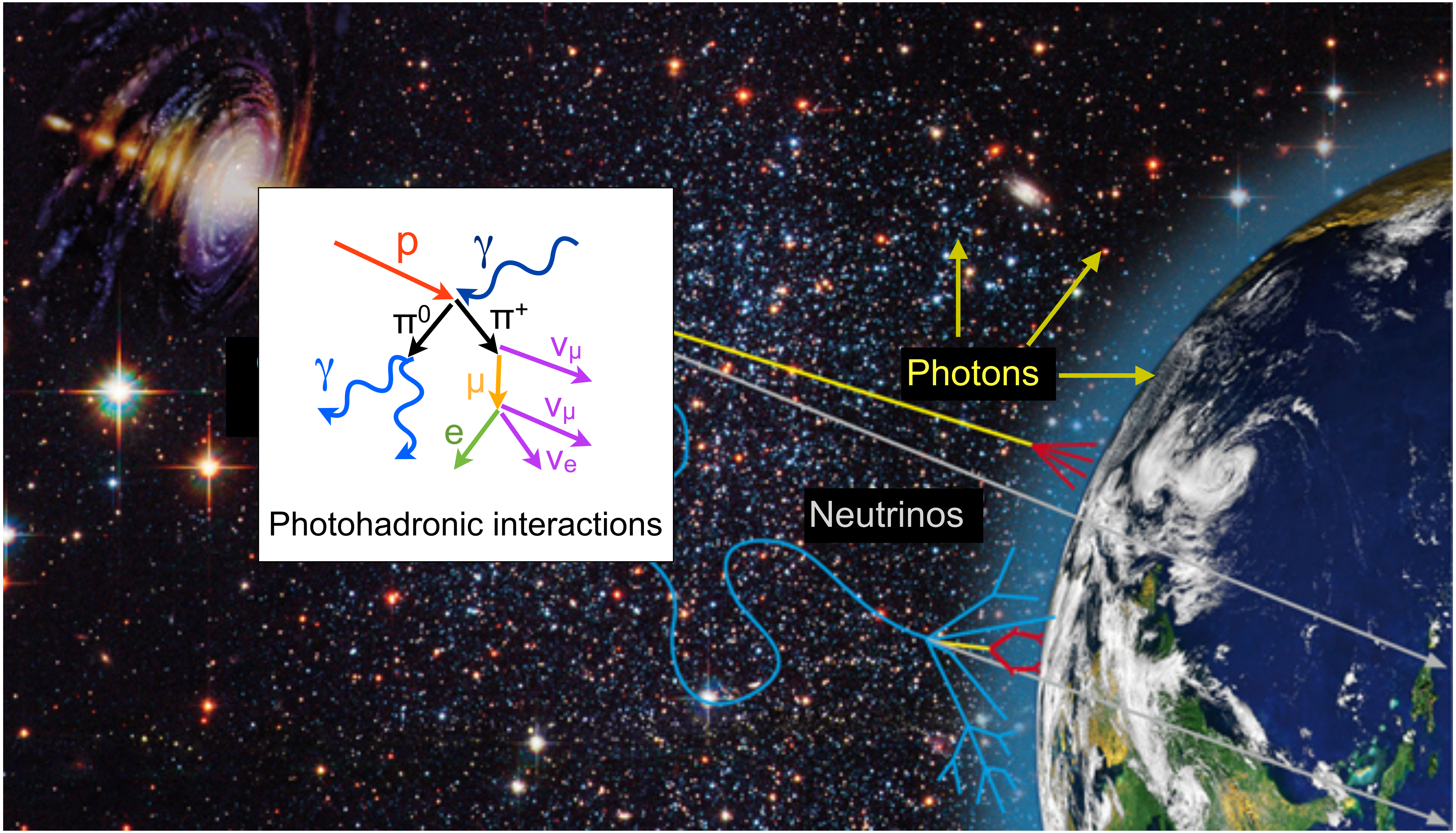
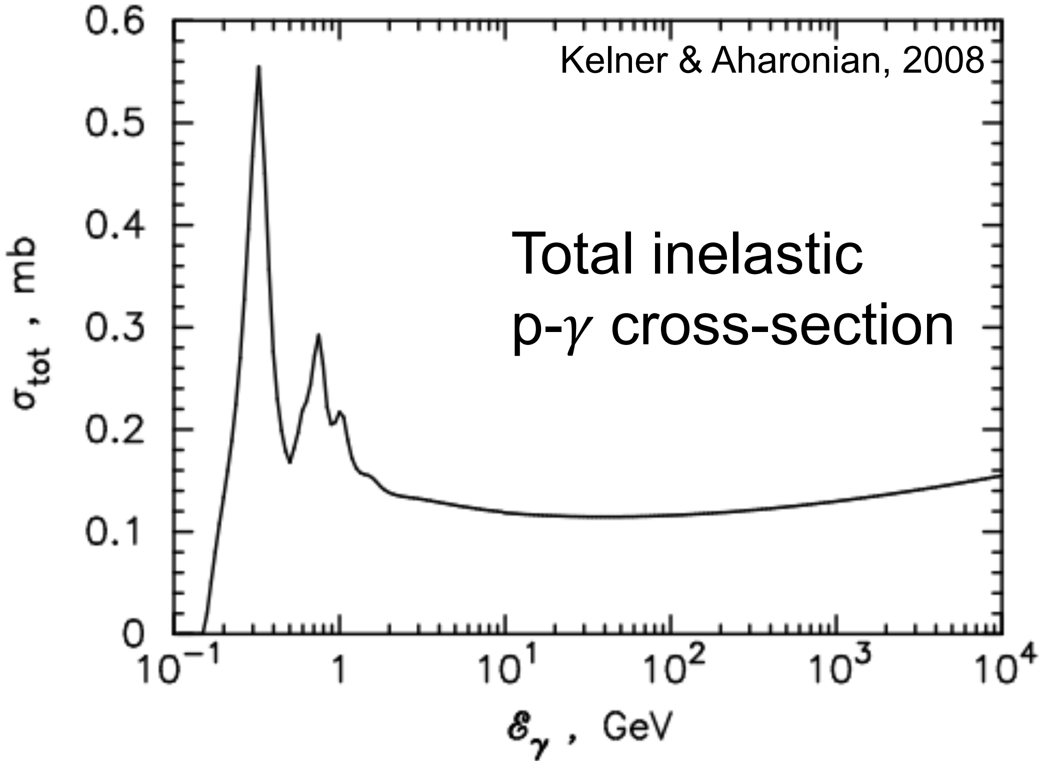
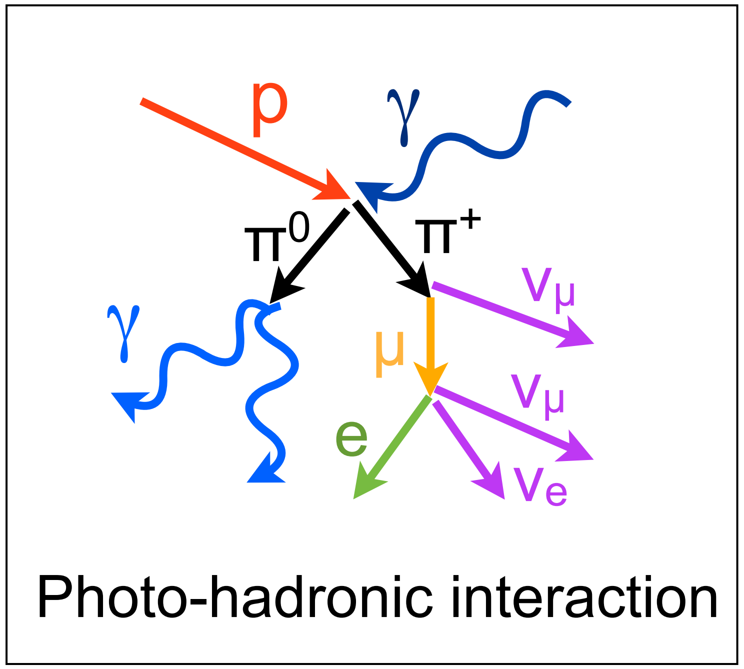
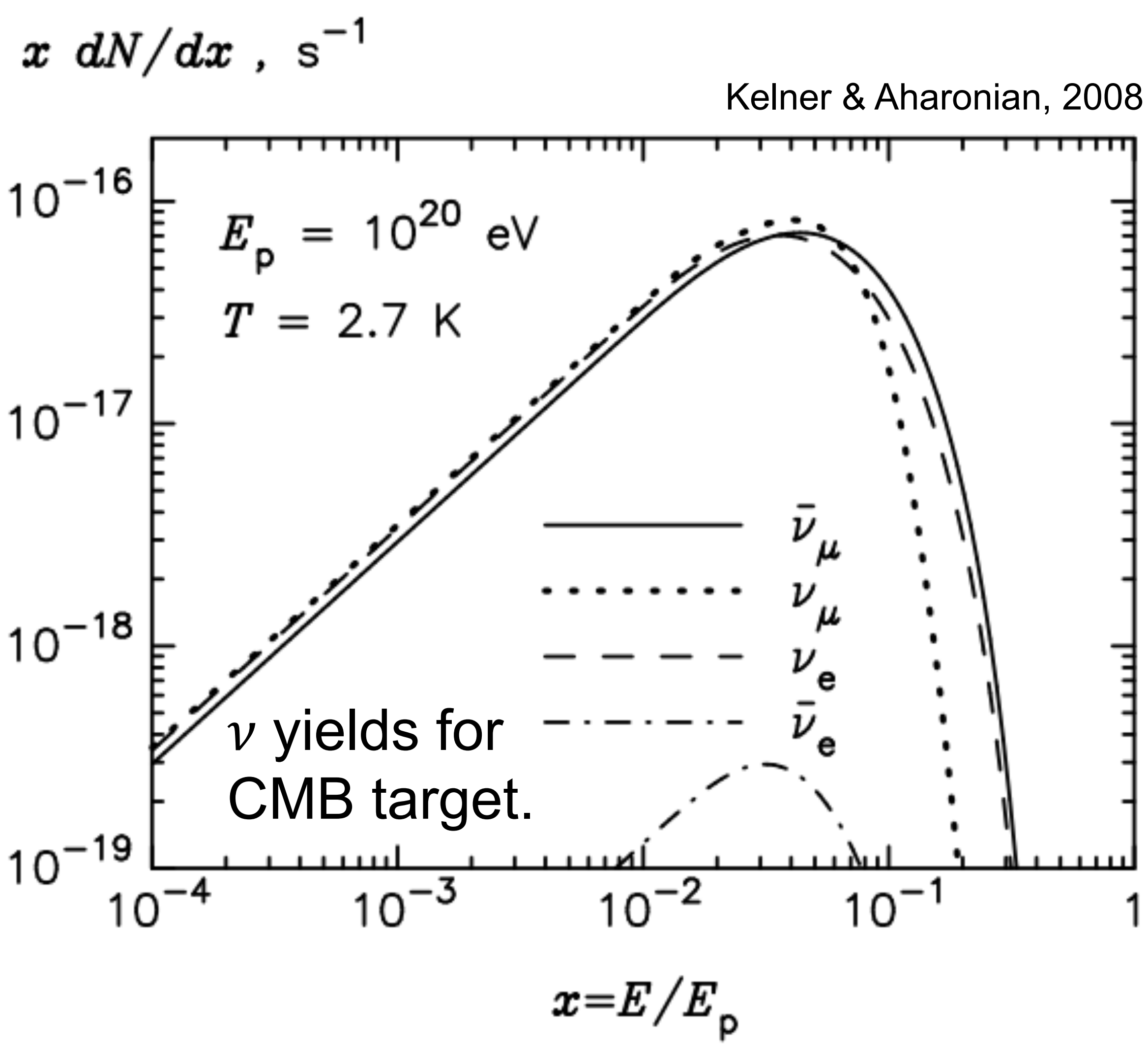


Photo-hadronic interactions.







> Dominated by **resonances** in the **cross section**.

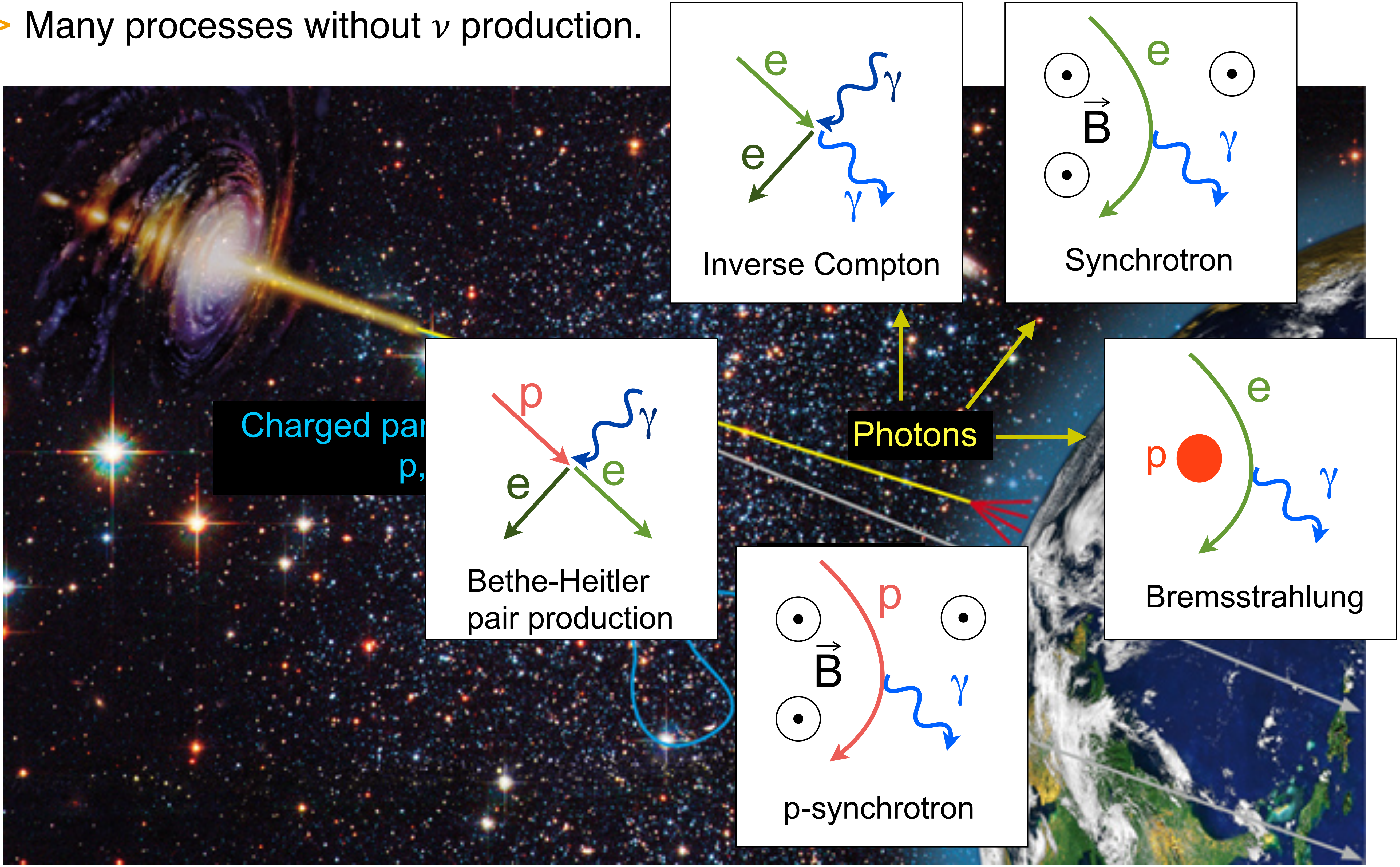
> ν and γ spectra **depend on target photon** fields.

> **High energy threshold** for process: $E_p \gtrsim 7 \times 10^{16}\ eV^2 / E_\gamma$

> **Different yields** of ν and anti-ν.

The multi-messenger approach.

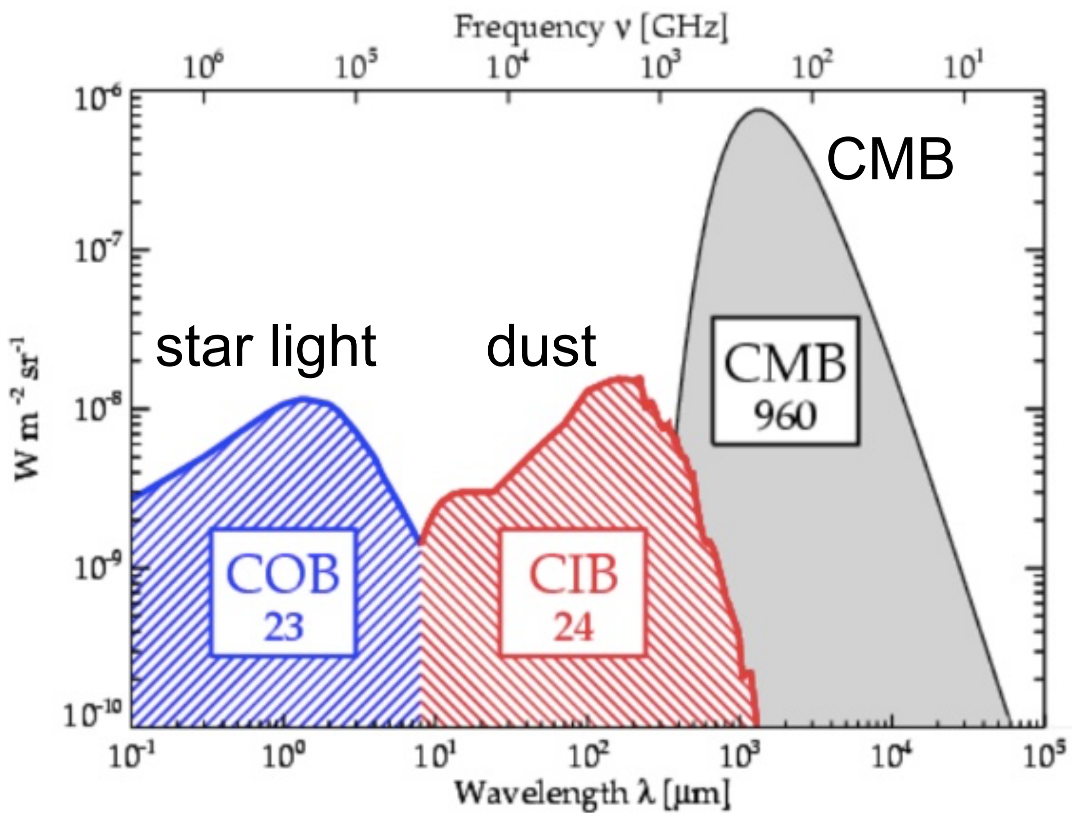
> Many processes without ν production.



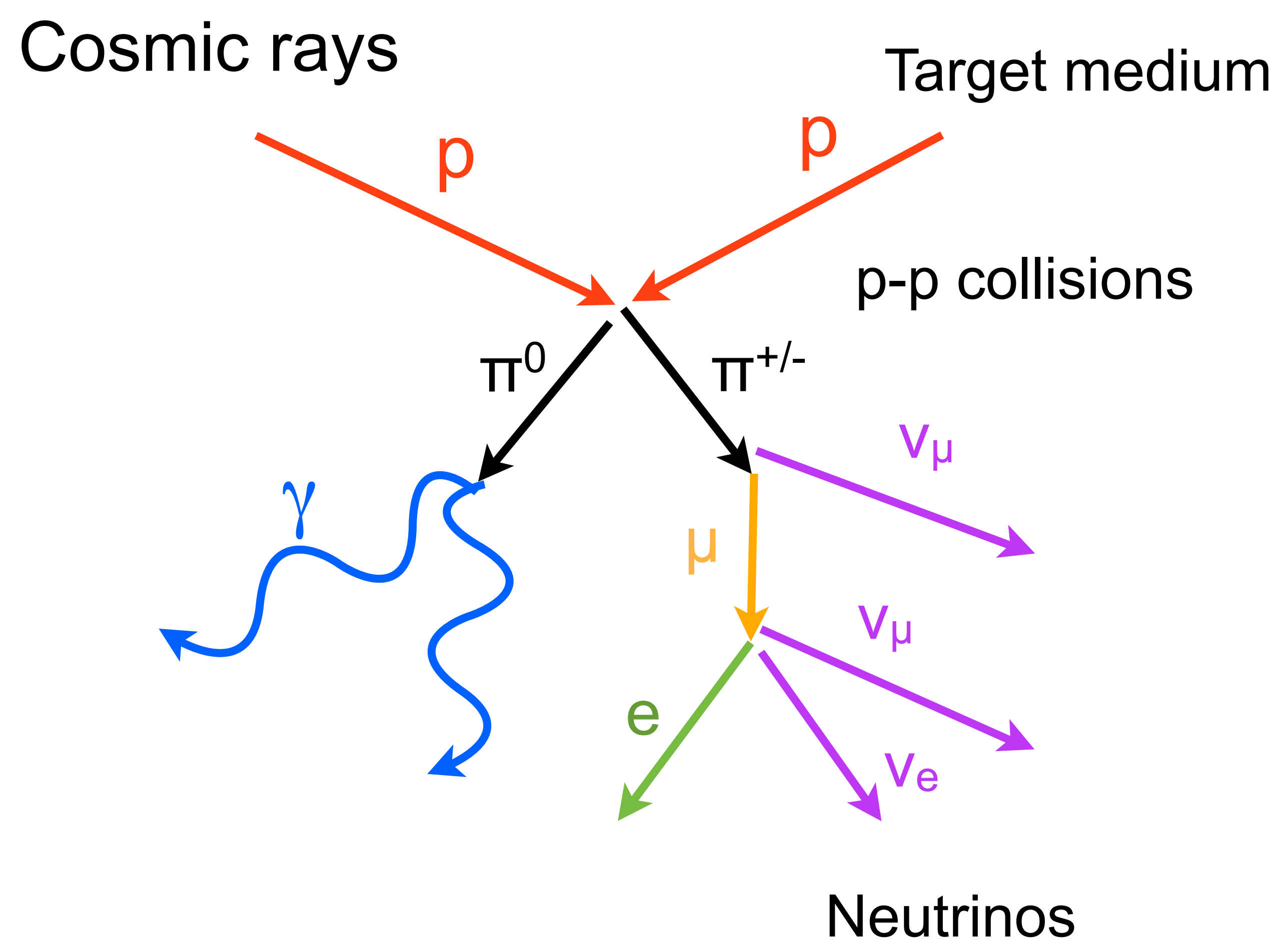
> ν are a diagnostic for CR interaction processes.

Propagation of high-energy γ-rays.

Extragalactic background light (EBL)



+ radiation fields at source



Propagation of high-energy γ-rays.

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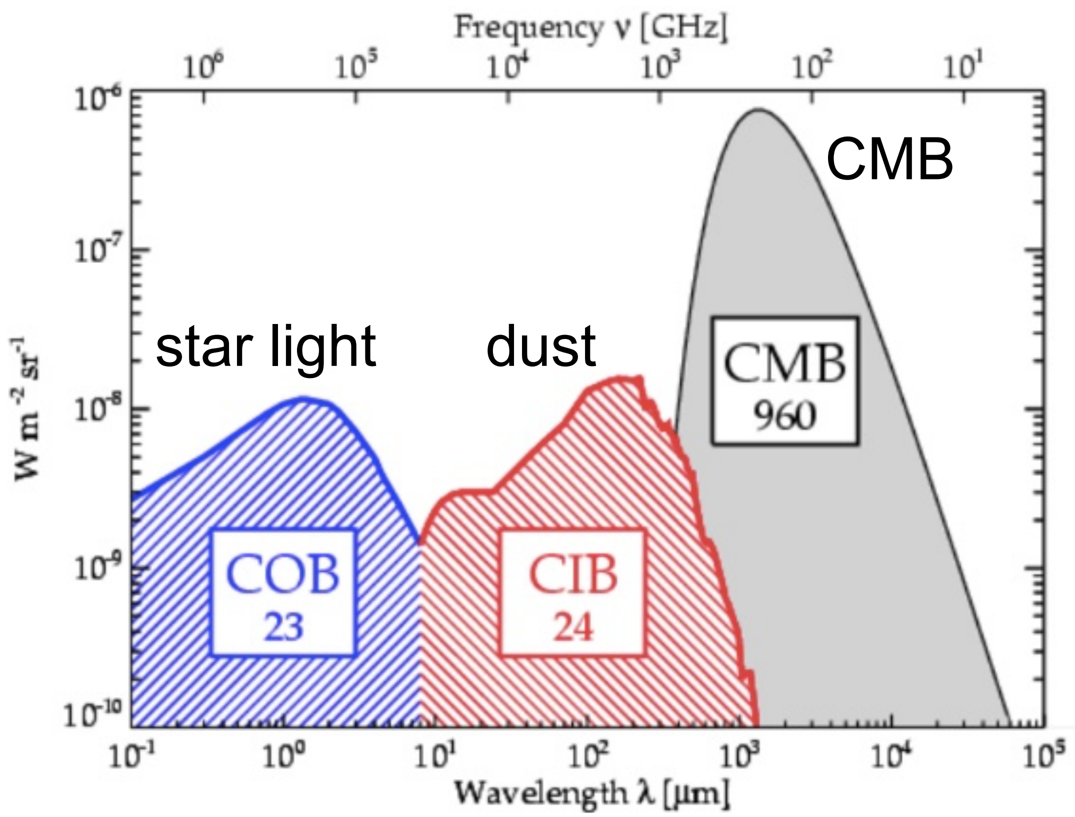
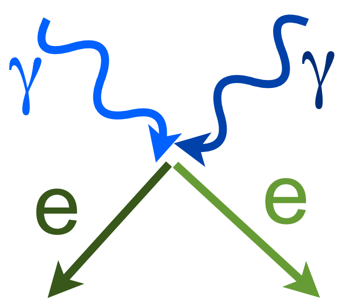


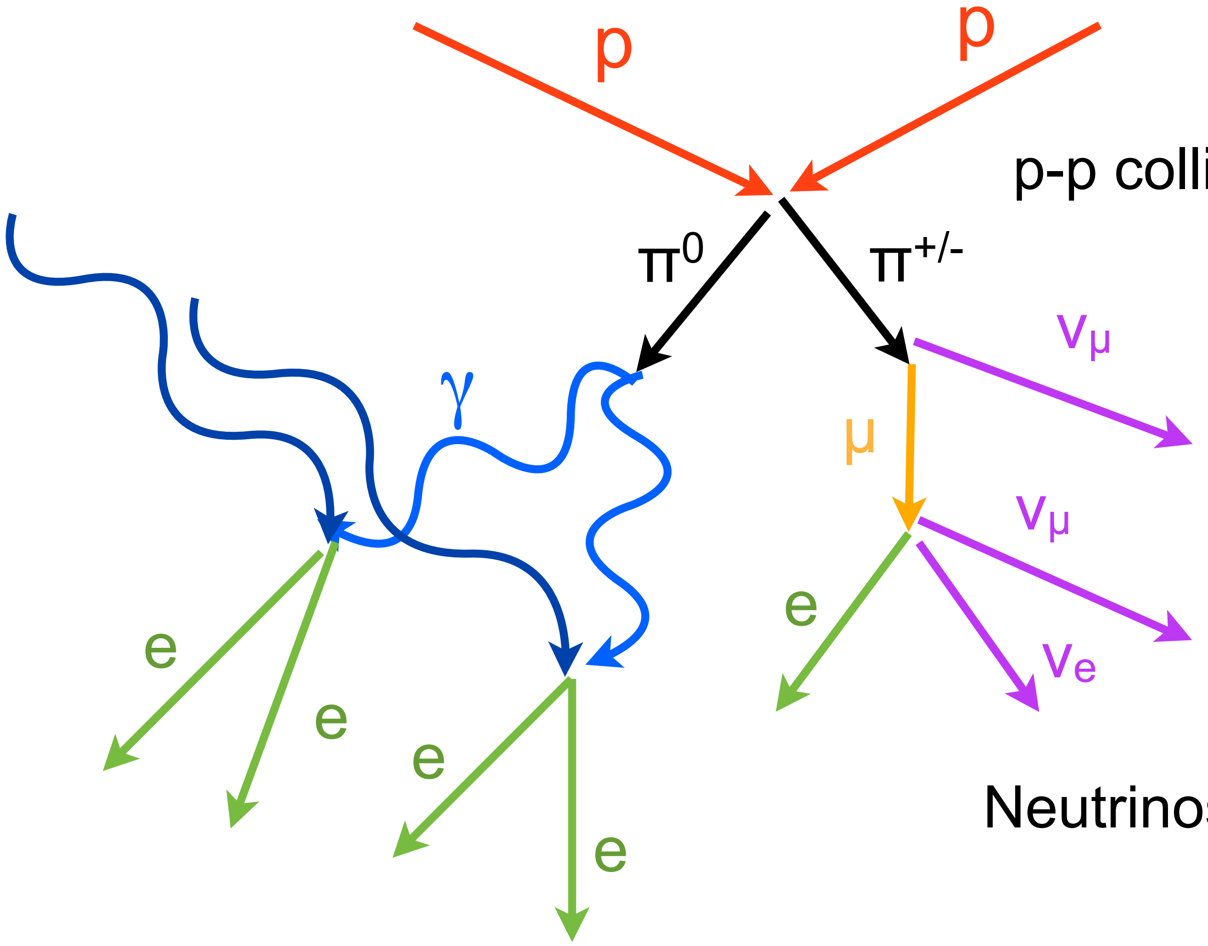
+ radiation fields at source



Pair production

Cosmic rays

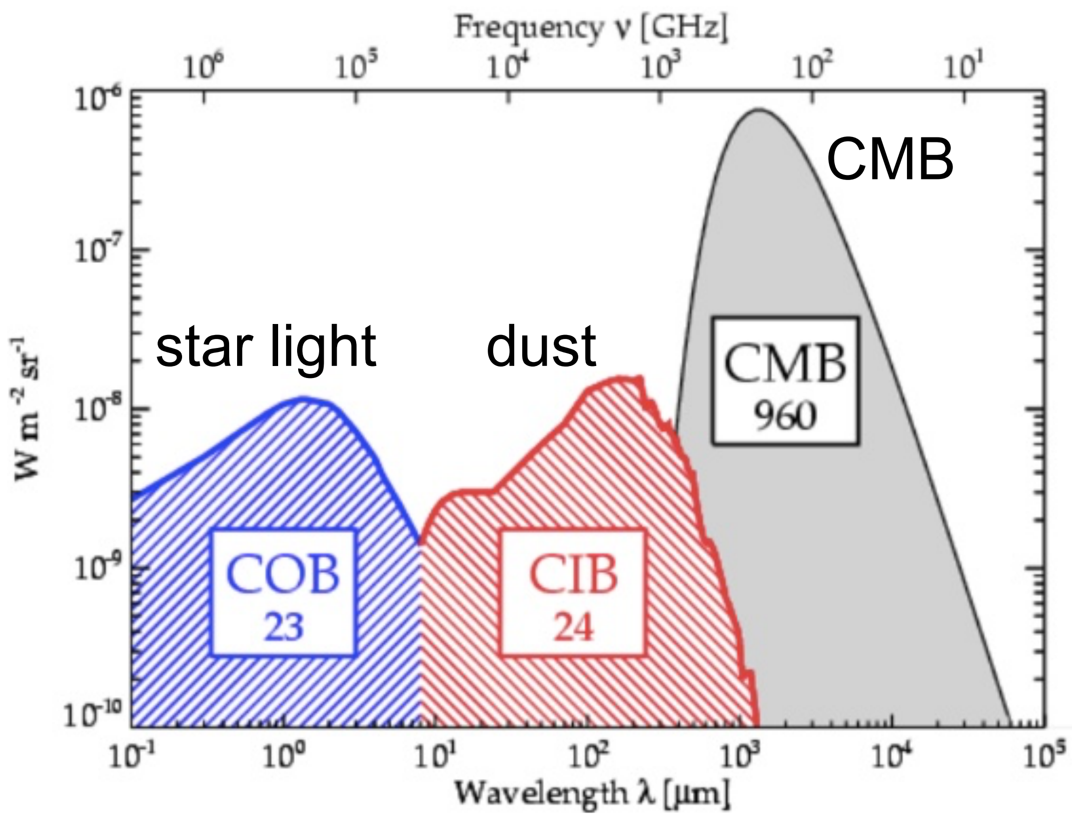
Target medium



Neutrinos

Propagation of high-energy γ-rays.

Extragalactic background light (EBL)



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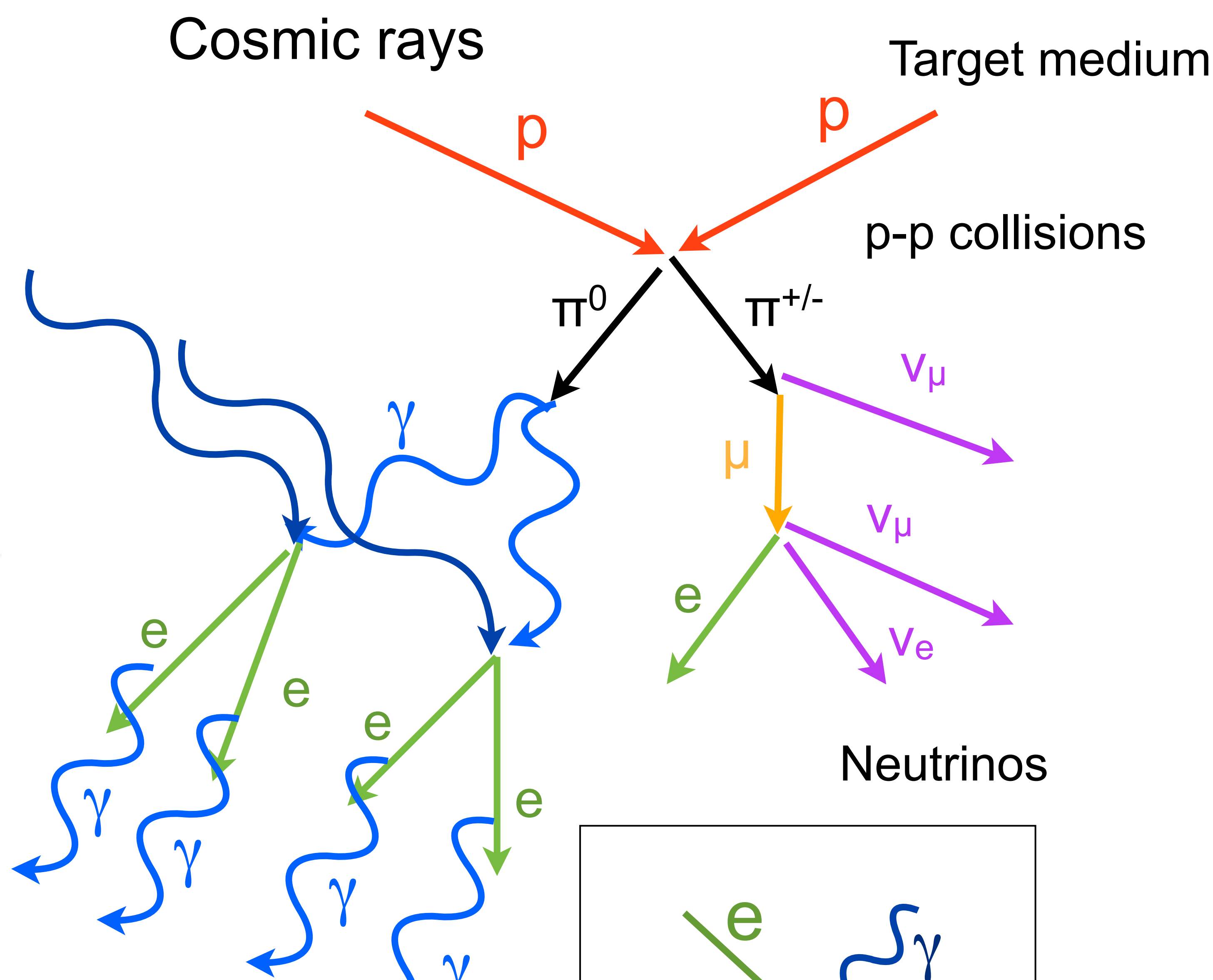
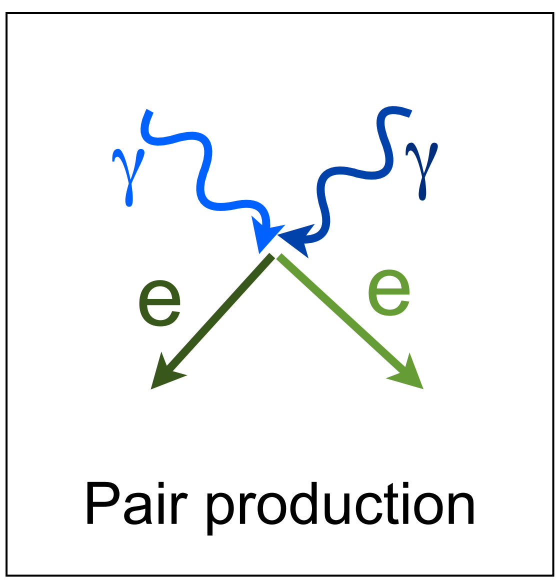
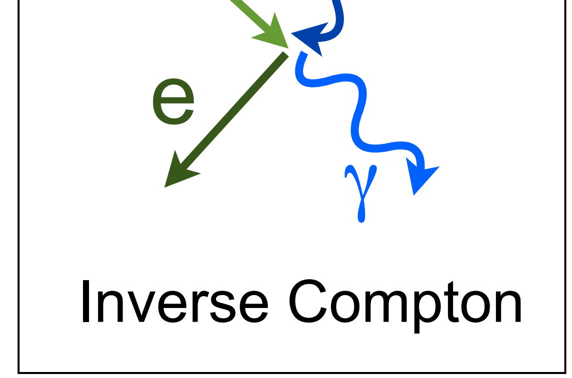
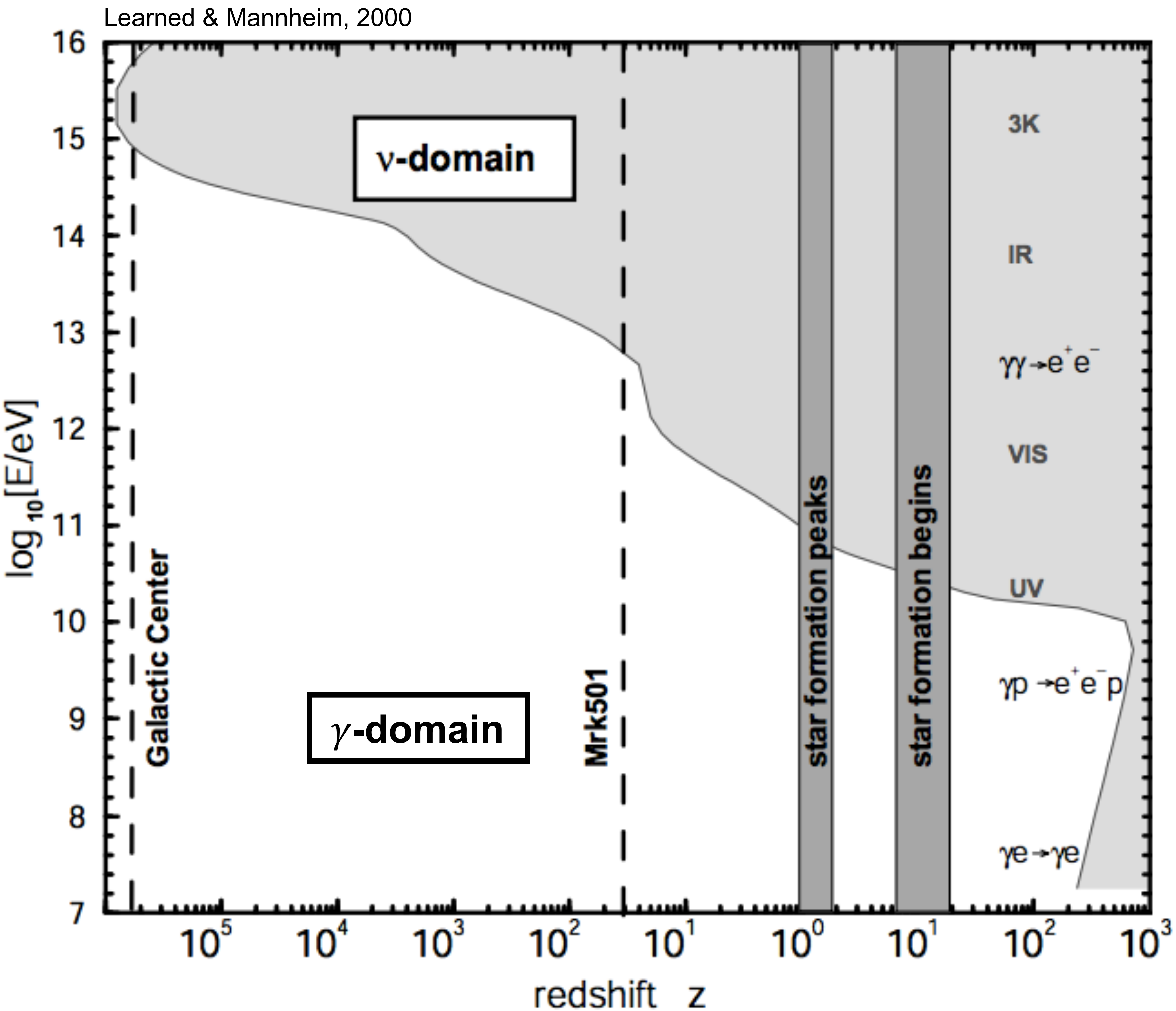


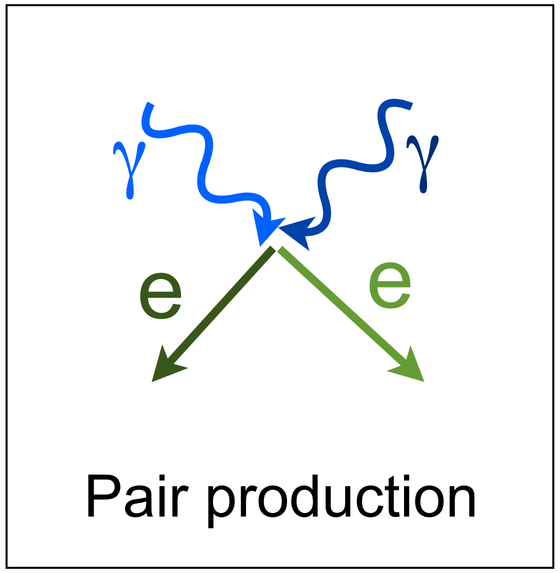
lower energy
“cascade radiation”

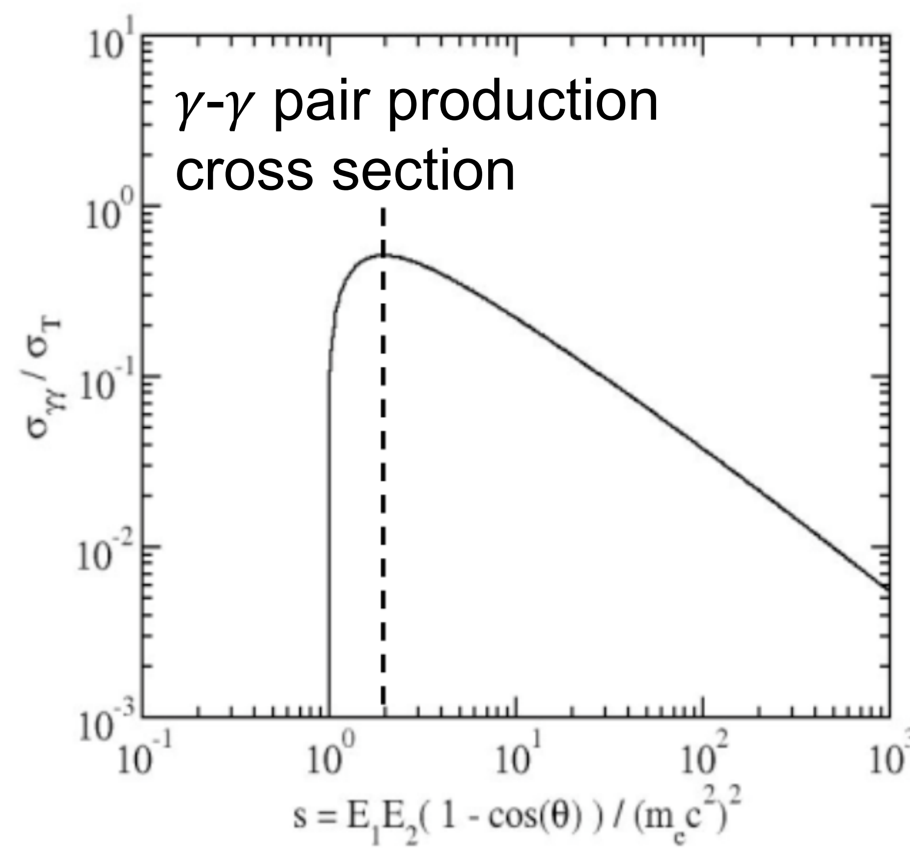




The γ-ray horizon.

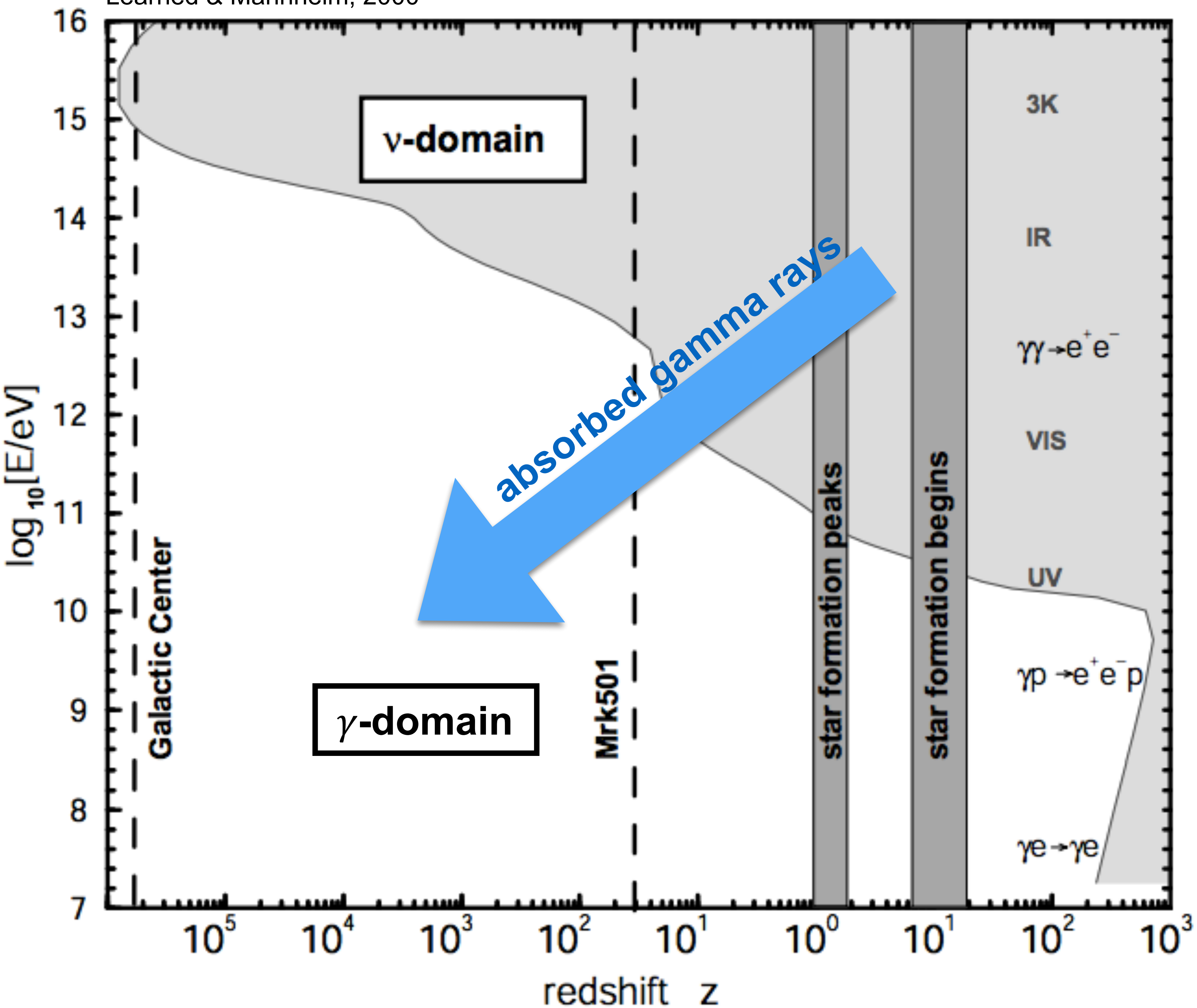


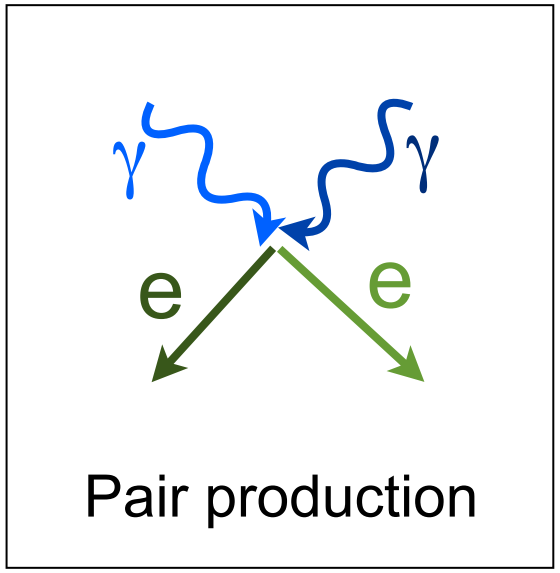


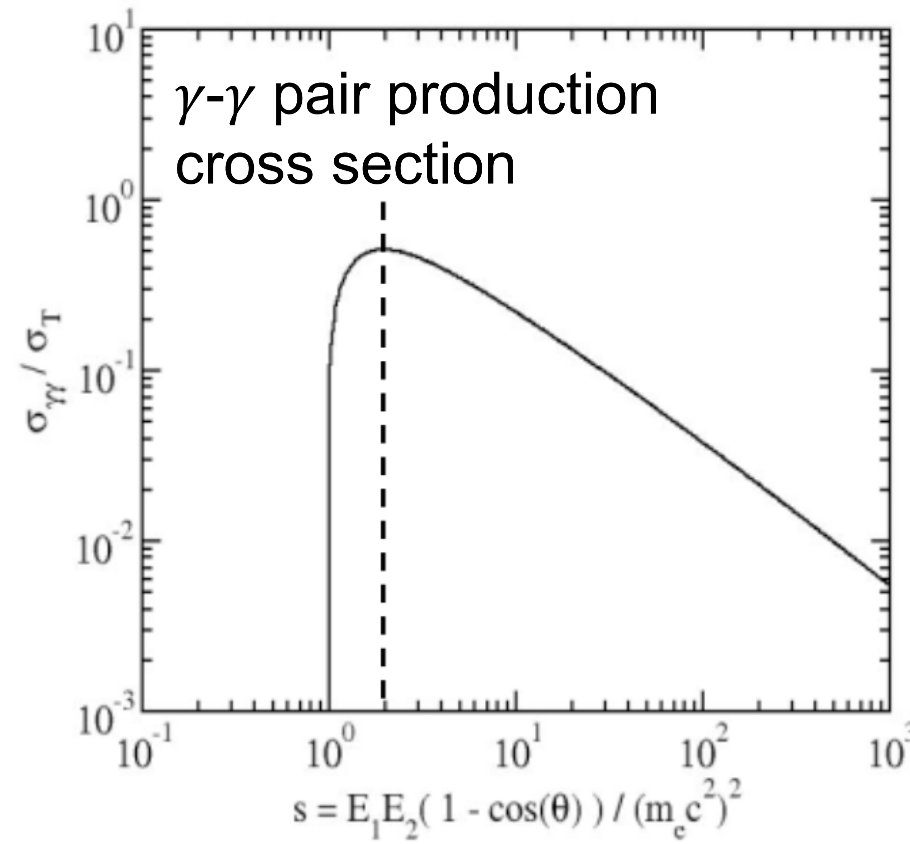


The γ-ray horizon.

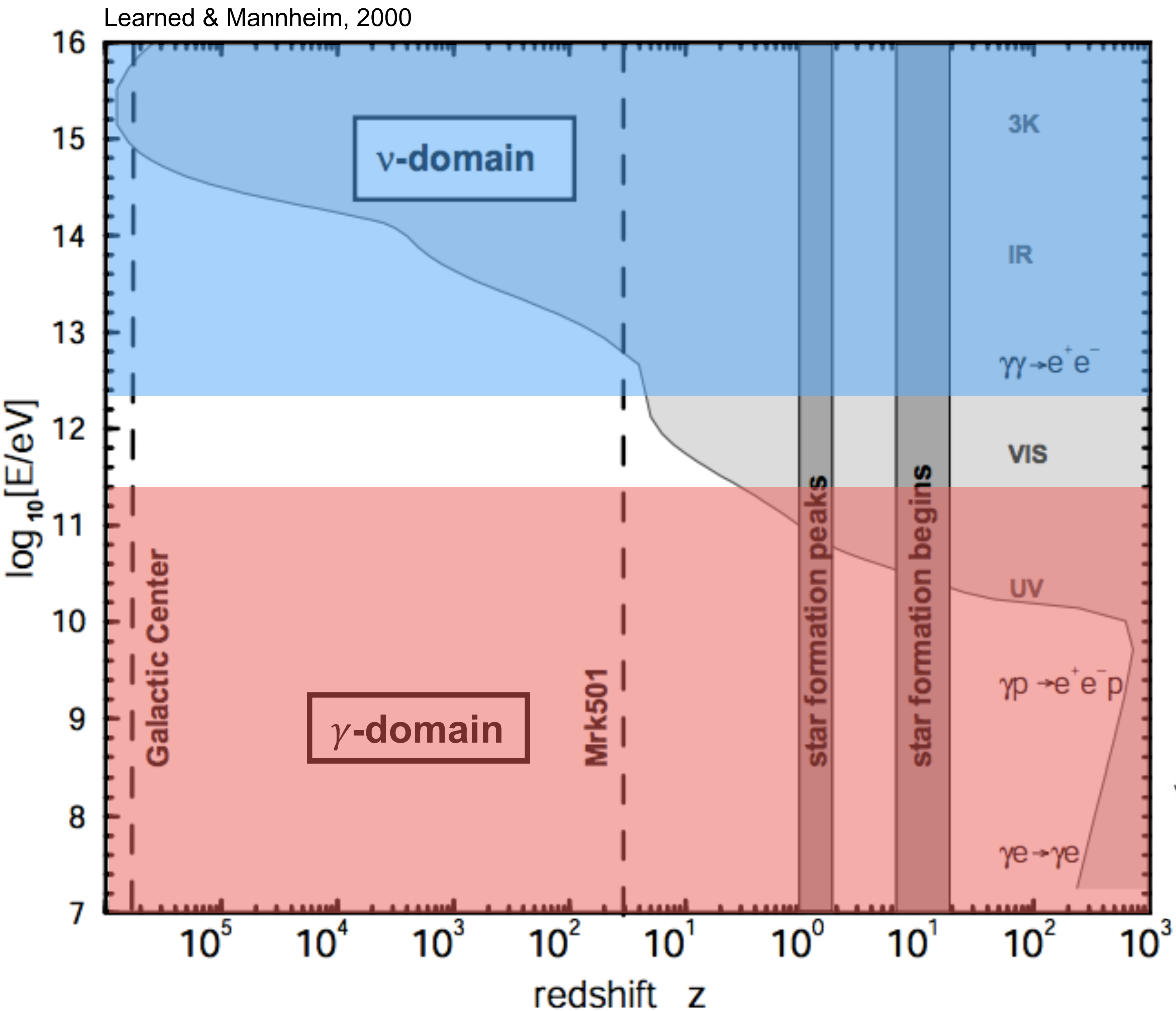
Learned & Mannheim, 2000

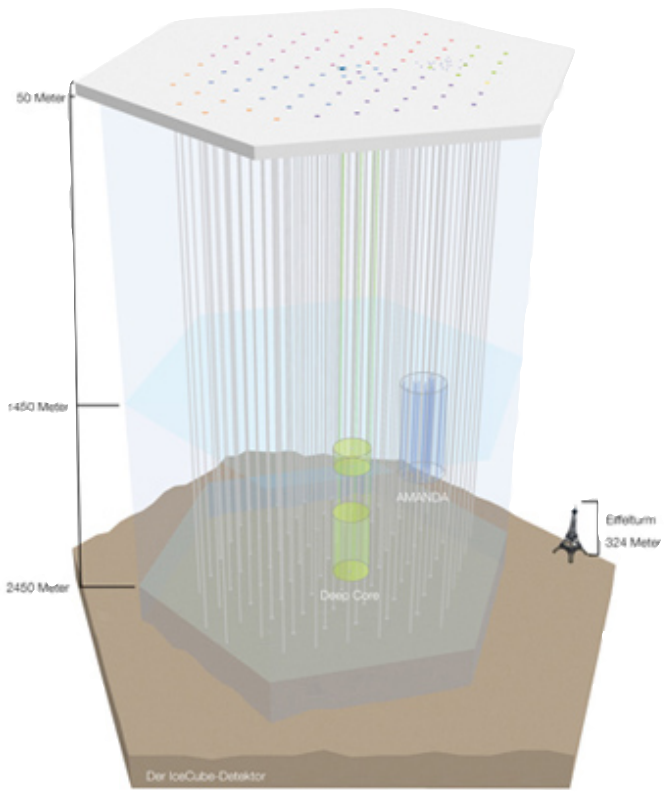




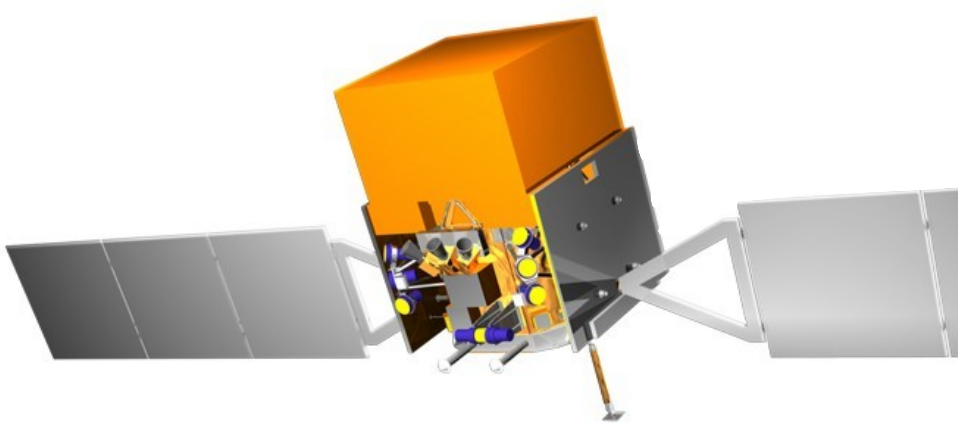


The gamma-ray and the neutrino domain.



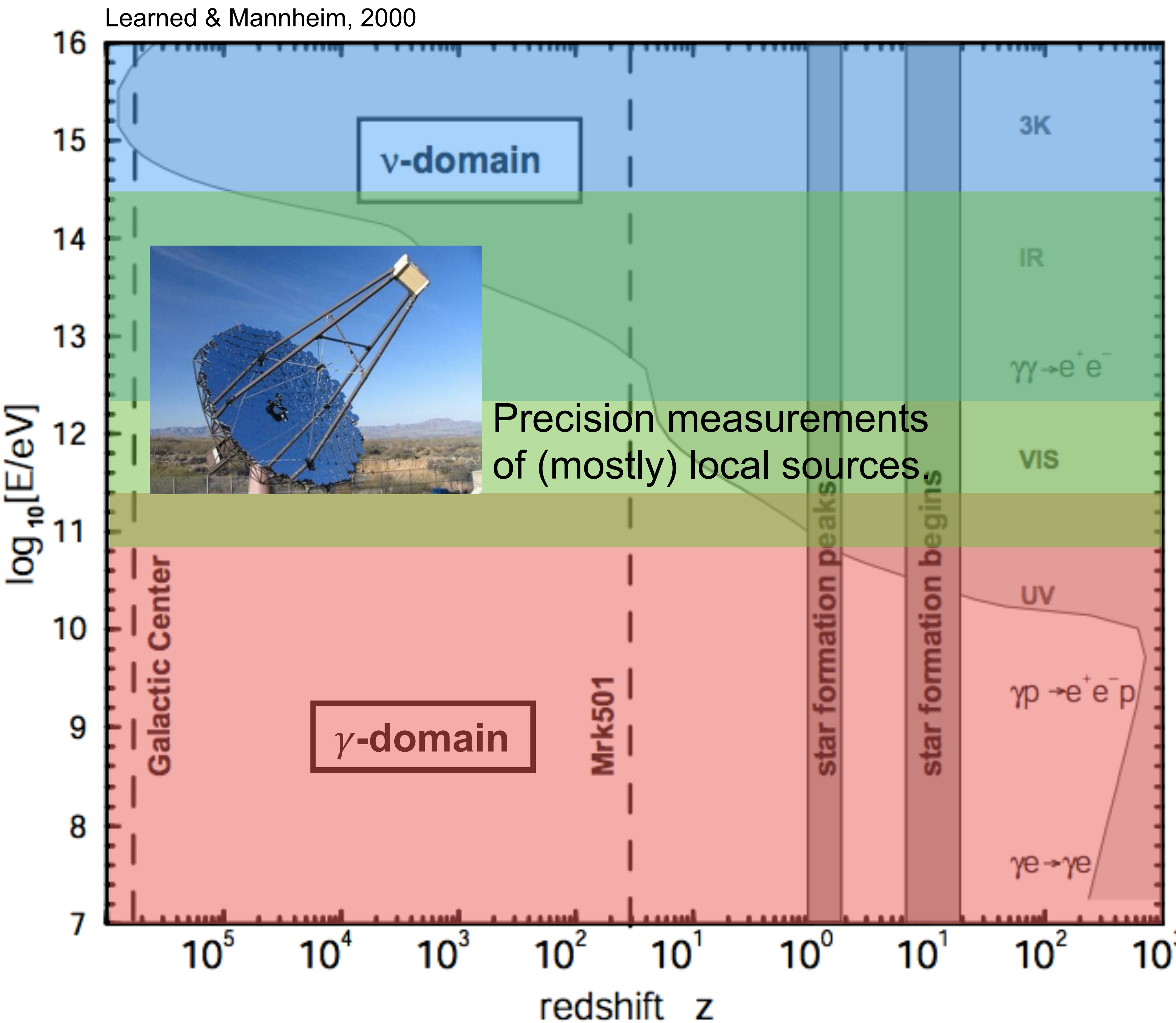


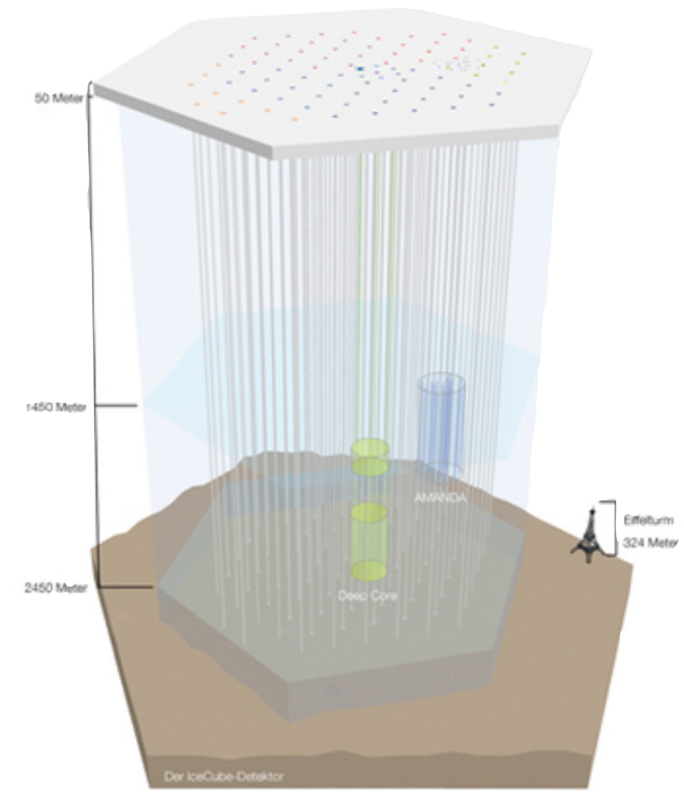
IceCube: ν-sky survey



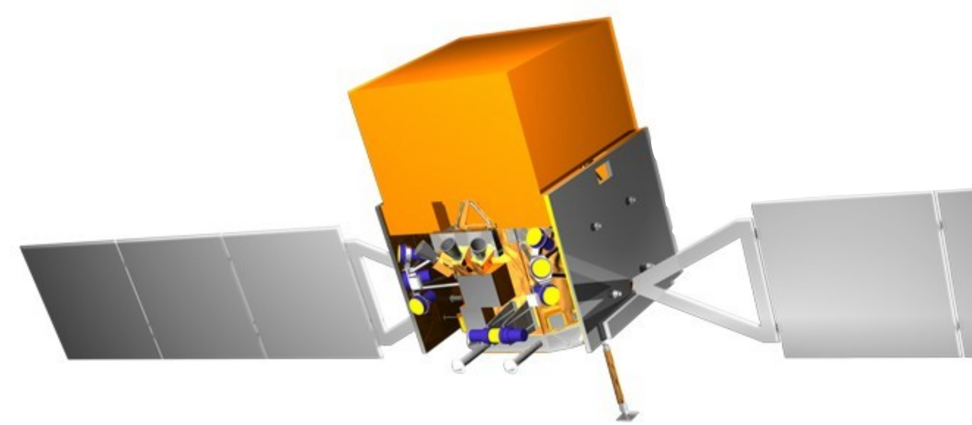
Fermi LAT: γ-sky survey

The gamma-ray and the neutrino domain.





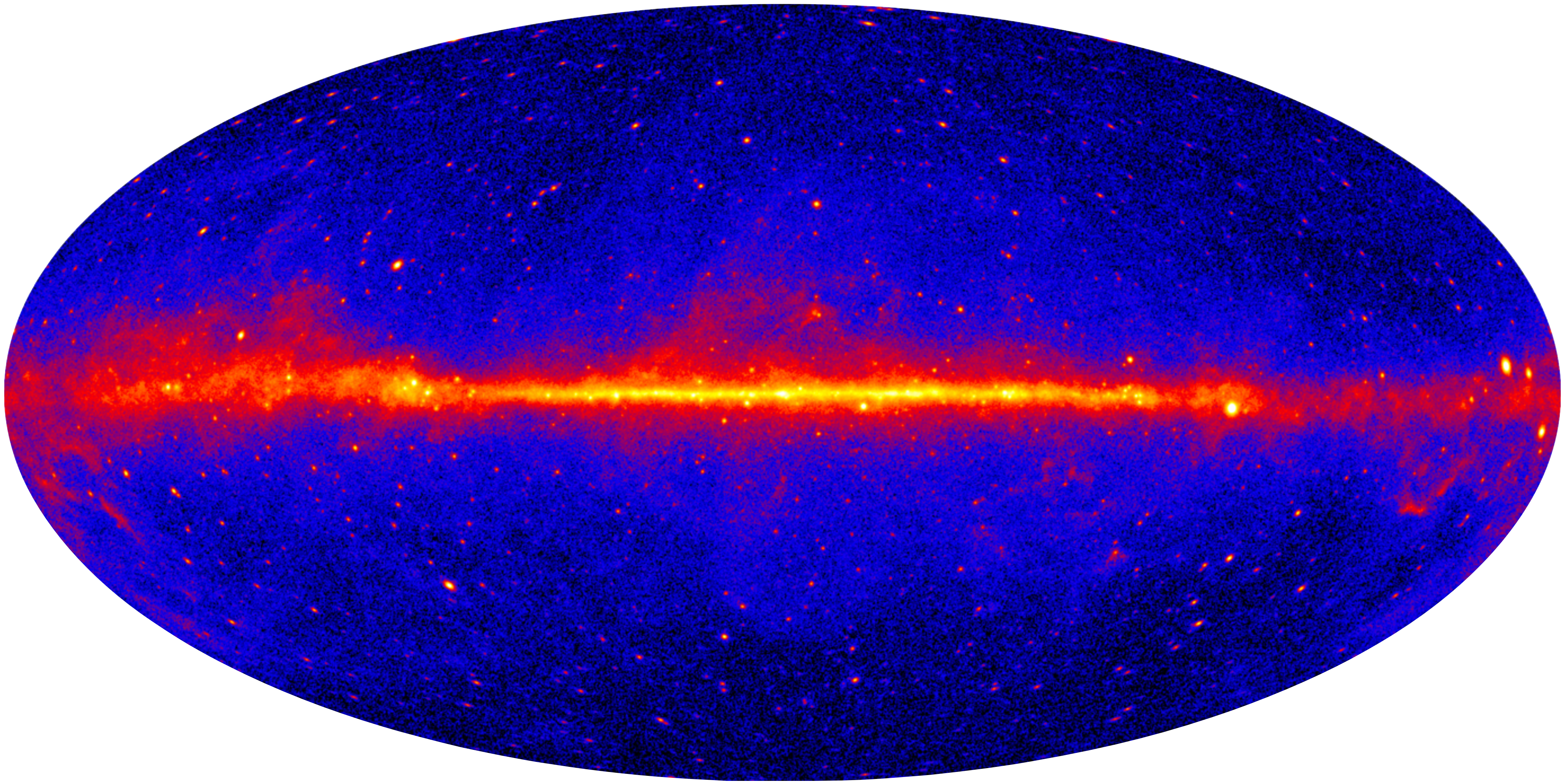
IceCube: ν-sky survey

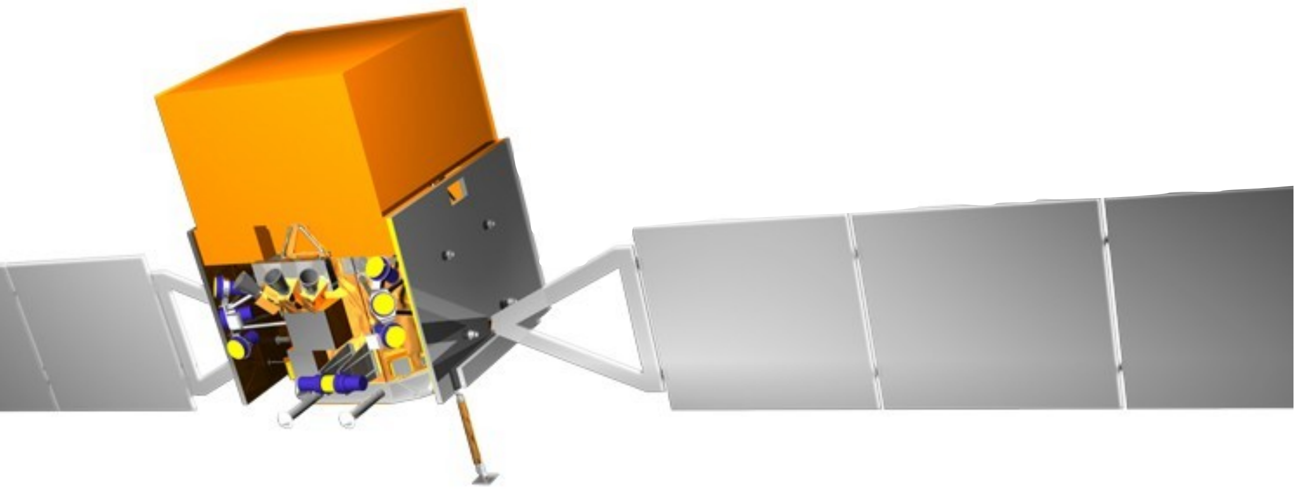


Fermi LAT: γ-sky survey

The GeV gamma-ray sky.

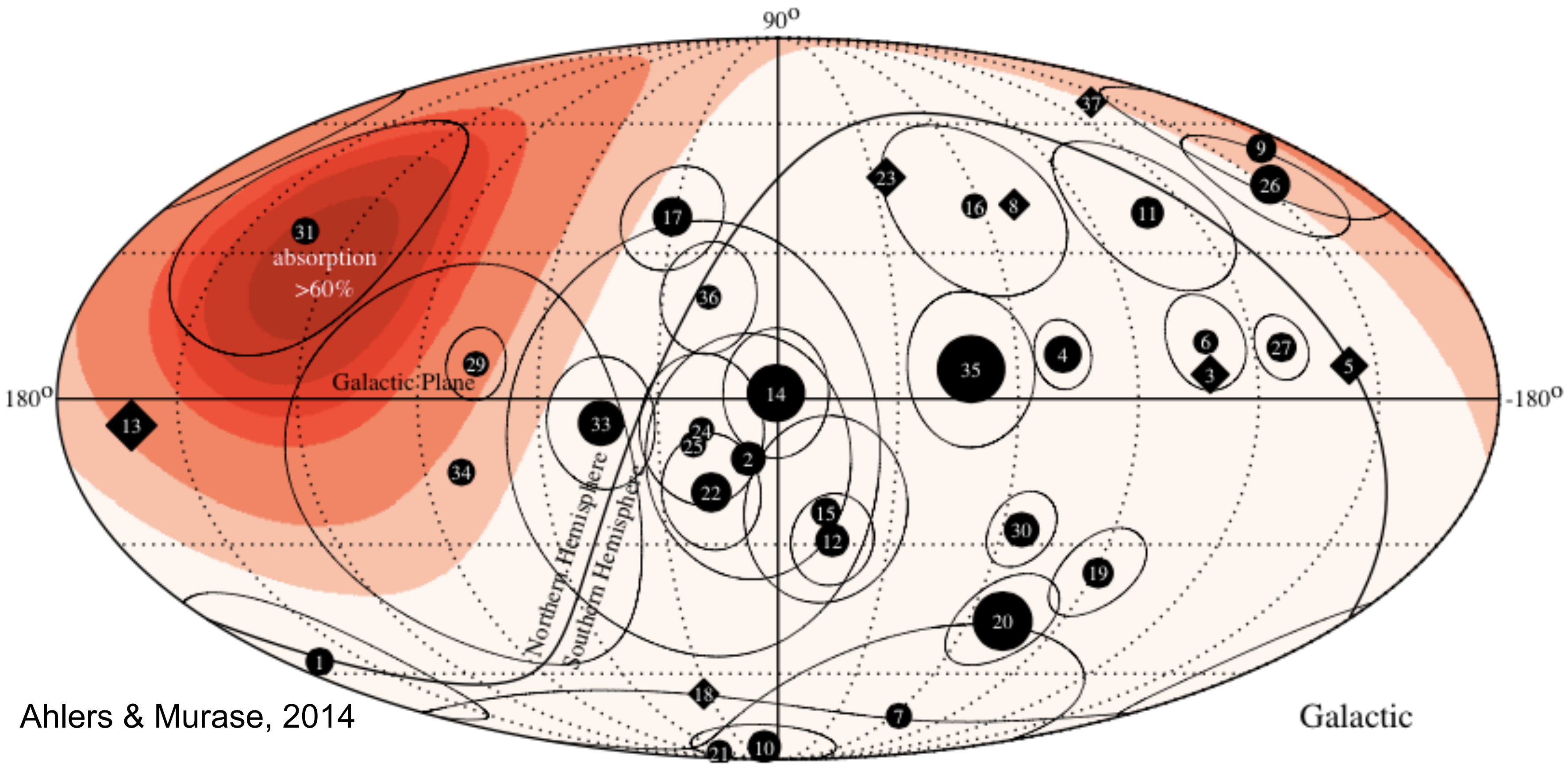
Fermi LAT, 4-year sky map, E > 1 GeV





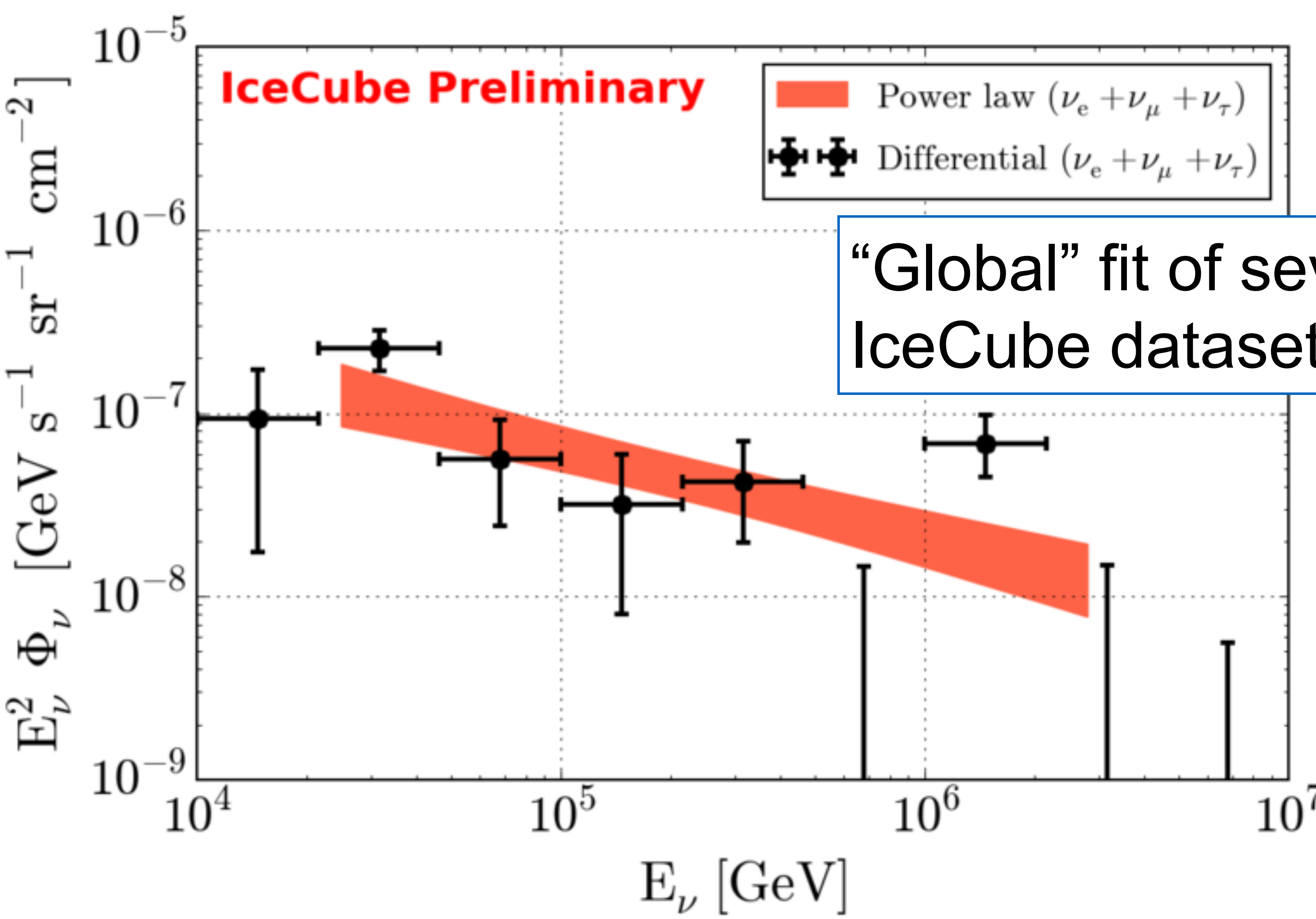
- More than **3000 sources.**
- **Many** Galactic and extragalactic **source populations.**
- Galactic & extragalactic **diffuse emission.**

The neutrino sky.

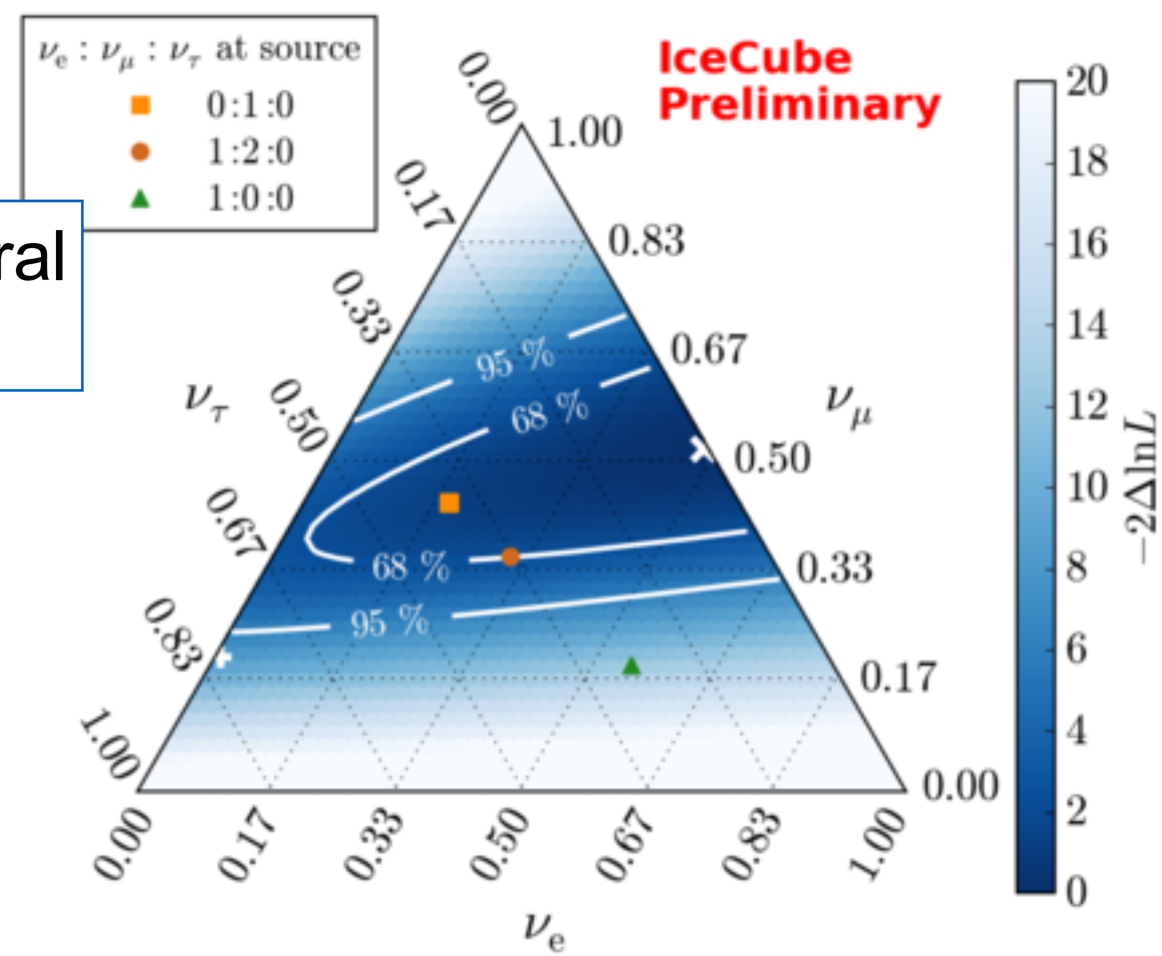


Ahlers & Murase, 2014

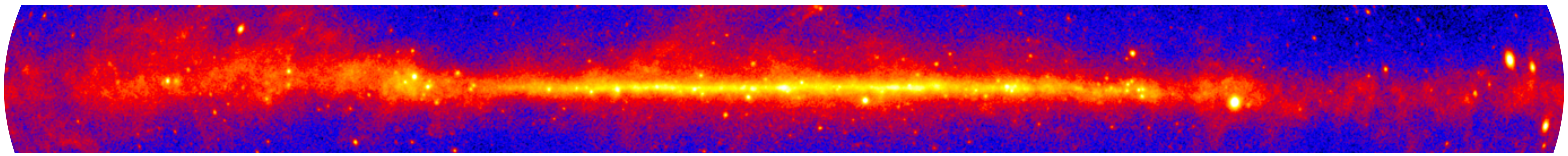
- Locations of E > 30 TeV events compatible with **isotropic distribution**.
- Spectrum can be described by a **single power law**.
- Measured **flavor ratio as expected** from astro-physical production.



"Global" fit of several IceCube datasets



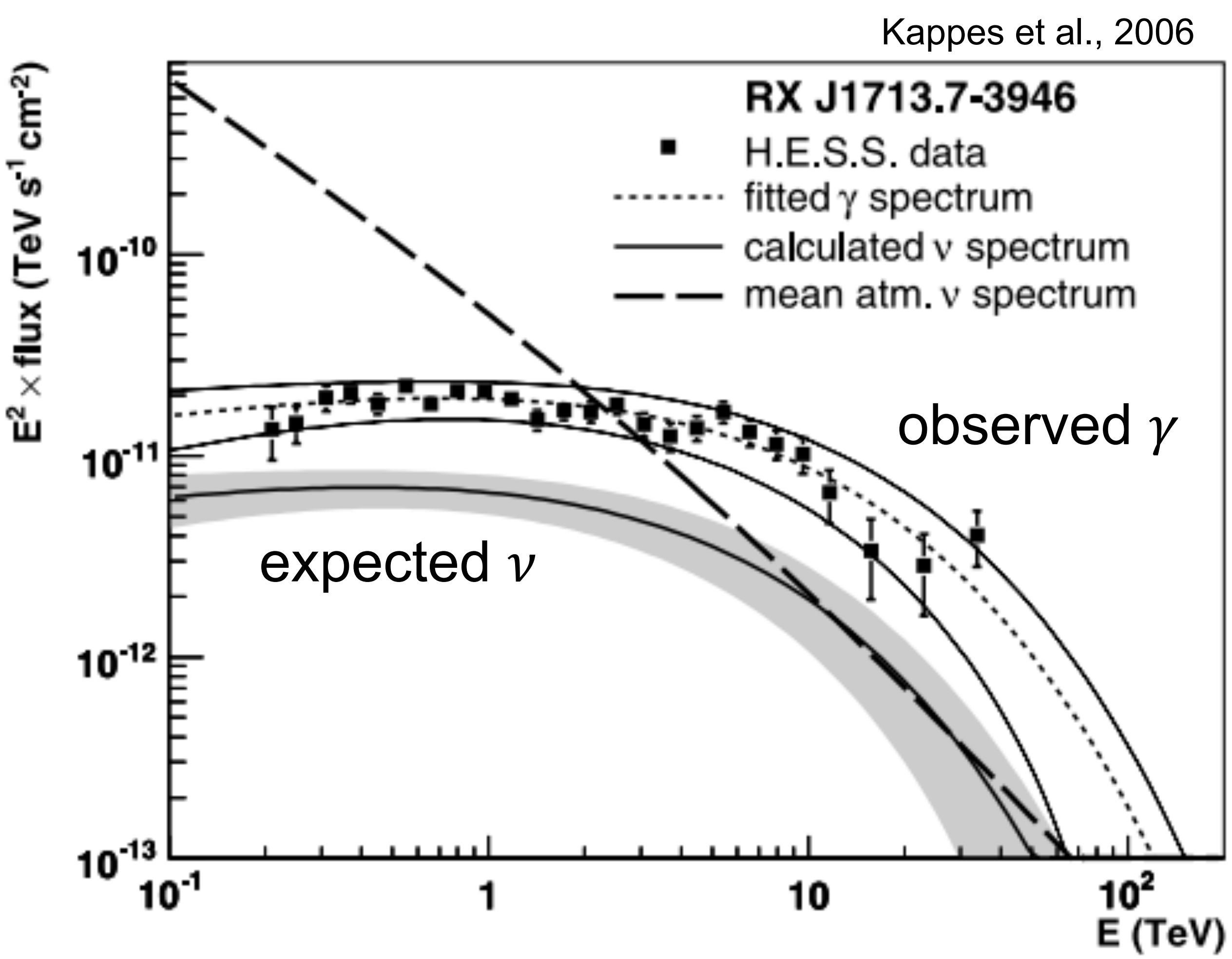
Neutrinos and gamma rays from the Galaxy.

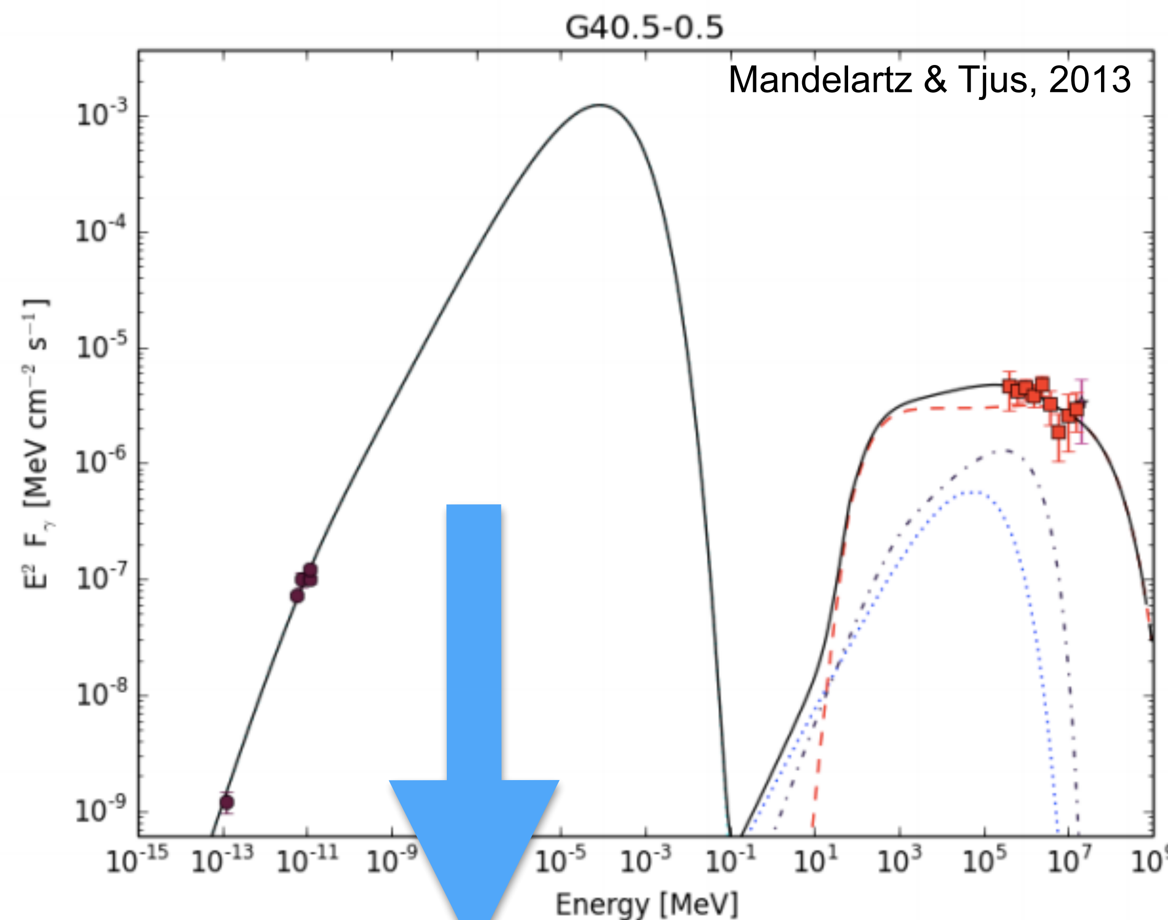


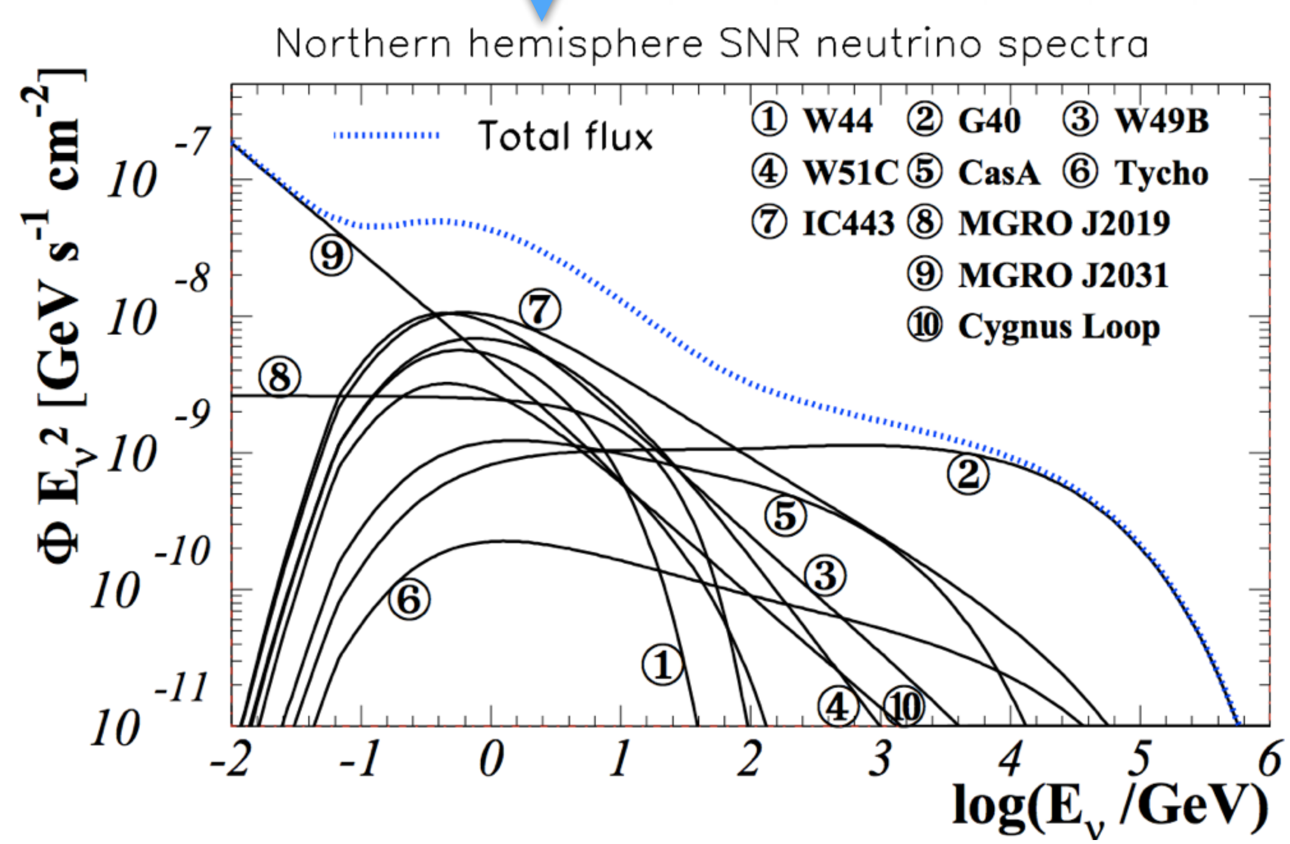
Is there a **Galactic component** in the astrophysical neutrino flux ?

Do we see the signs of **Galactic cosmic-ray acceleration** ?

Galactic γ-ray and neutrino emission.





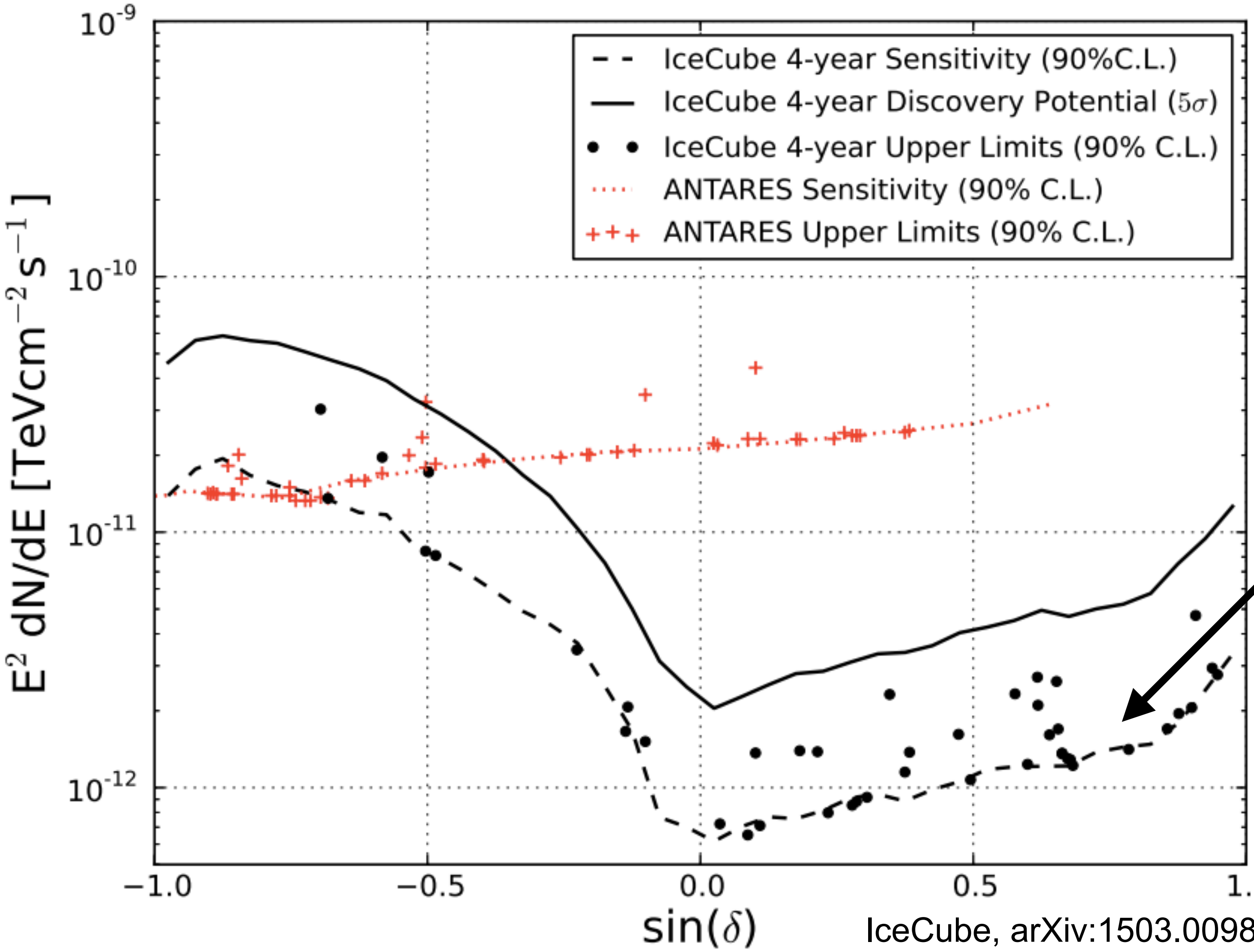


> Most **Galactic sources** are expected to be **transparent to γ-rays**.

> Assuming all emission to be **hadro-nuclear** gives **upper limit** on the ν - flux.

> **ν - flux predictions** from emission model based on **broadband SED**.

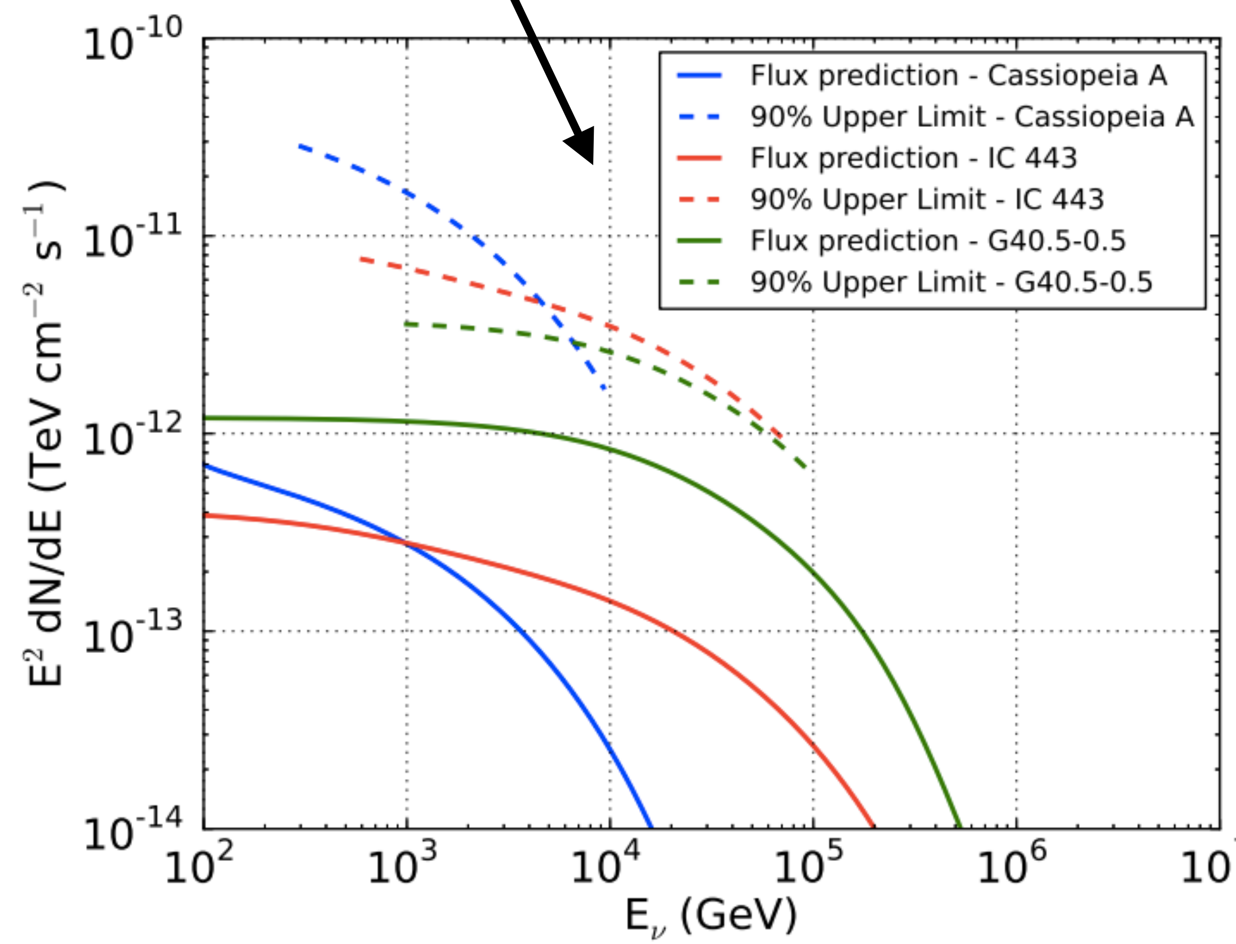
Neutrino flux upper limits from IceCube data.



IceCube, arXiv:1503.0098

IceCube **flux upper limits** for generic sources with **power-law spectrum of index -2**.

Upper flux limits for **specific** source models.

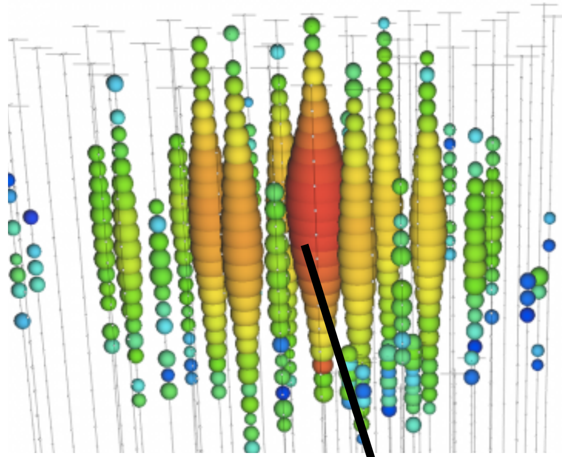


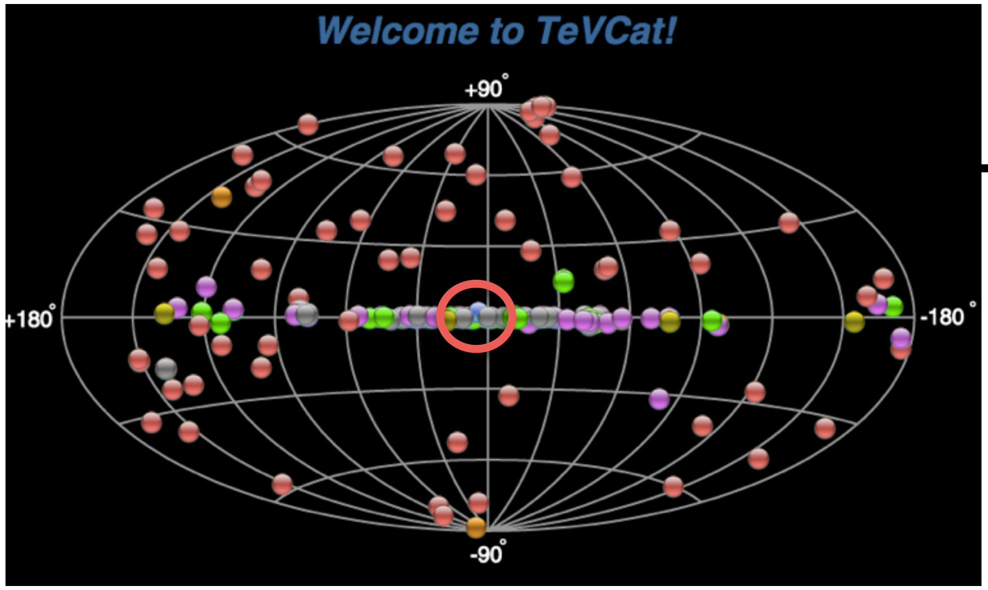
> IceCube is **not sensitive enough yet** to observe individual Galactic sources.

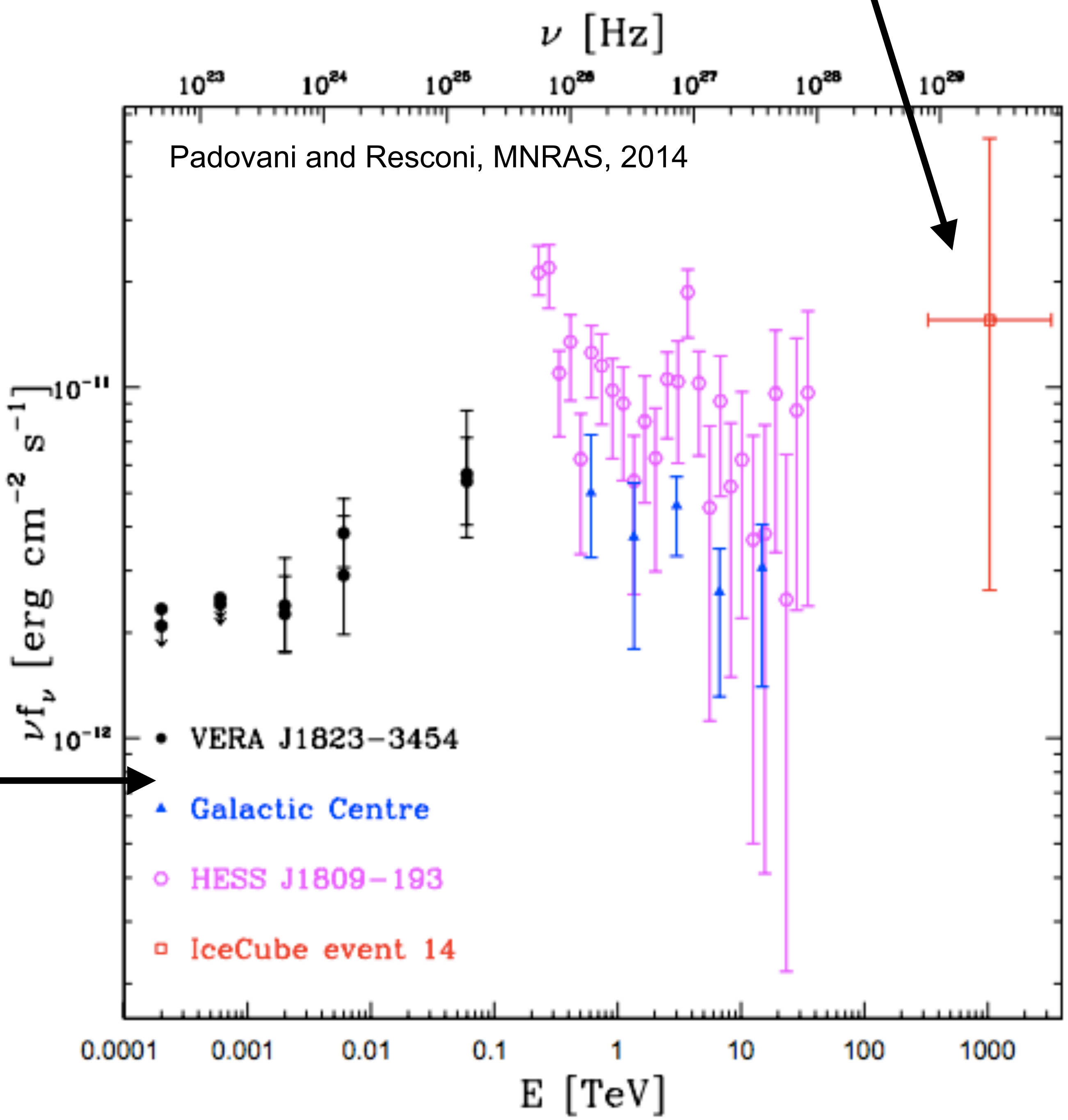
> Expected **spectral cutoffs** at TeV energies for Galactic sources **limit sensitivity.**

The origin of the astrophysical neutrino flux.

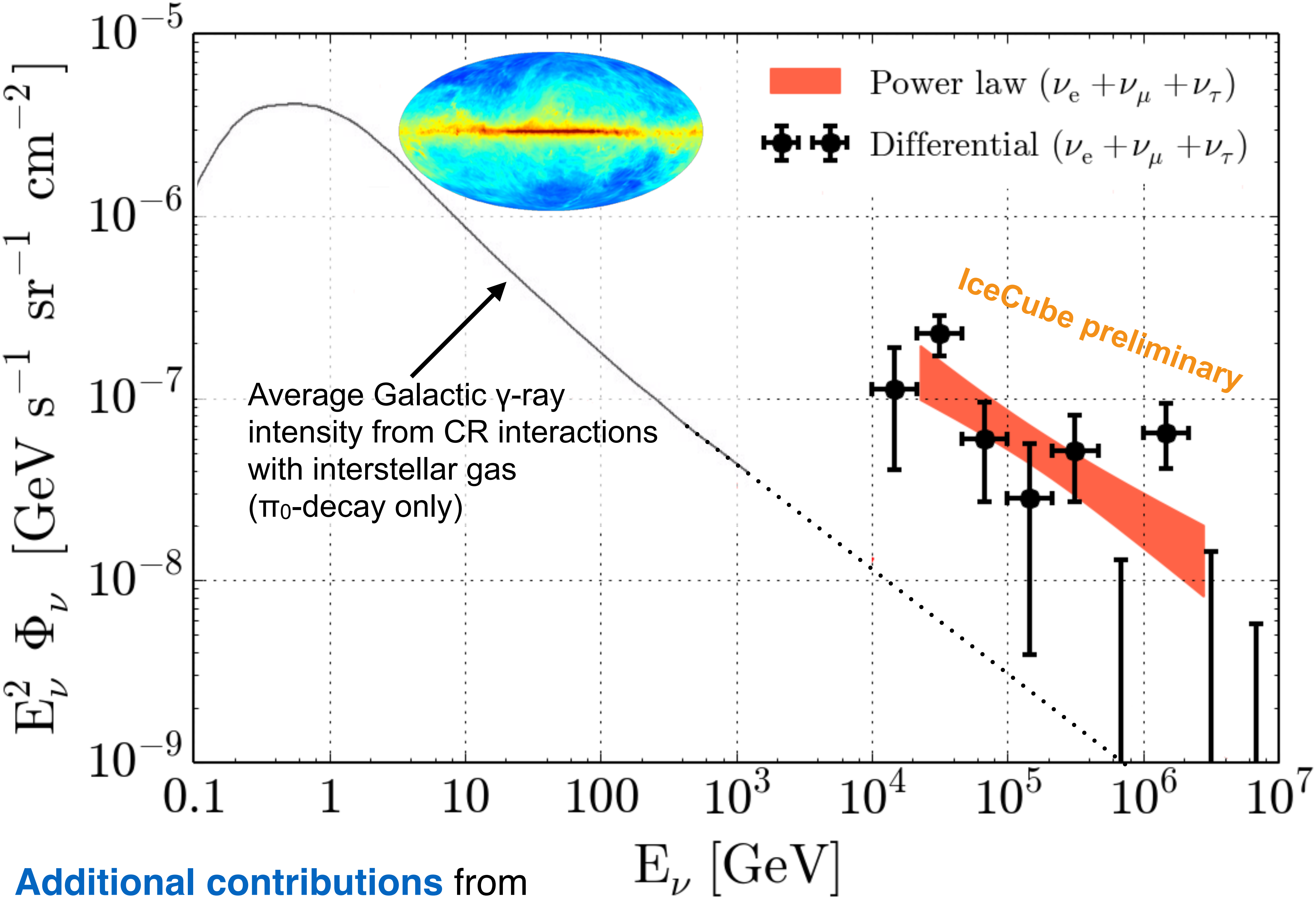
- Search for **possible counterparts** in TeV gamma-ray source catalog.
- IceCube shower events have **10° — 15° angular resolution**.
- **Compare power** emitted in γ-rays to power in neutrinos.
- Several **Blazars and Galactic sources** found as potential TeV counterparts to neutrino sources.







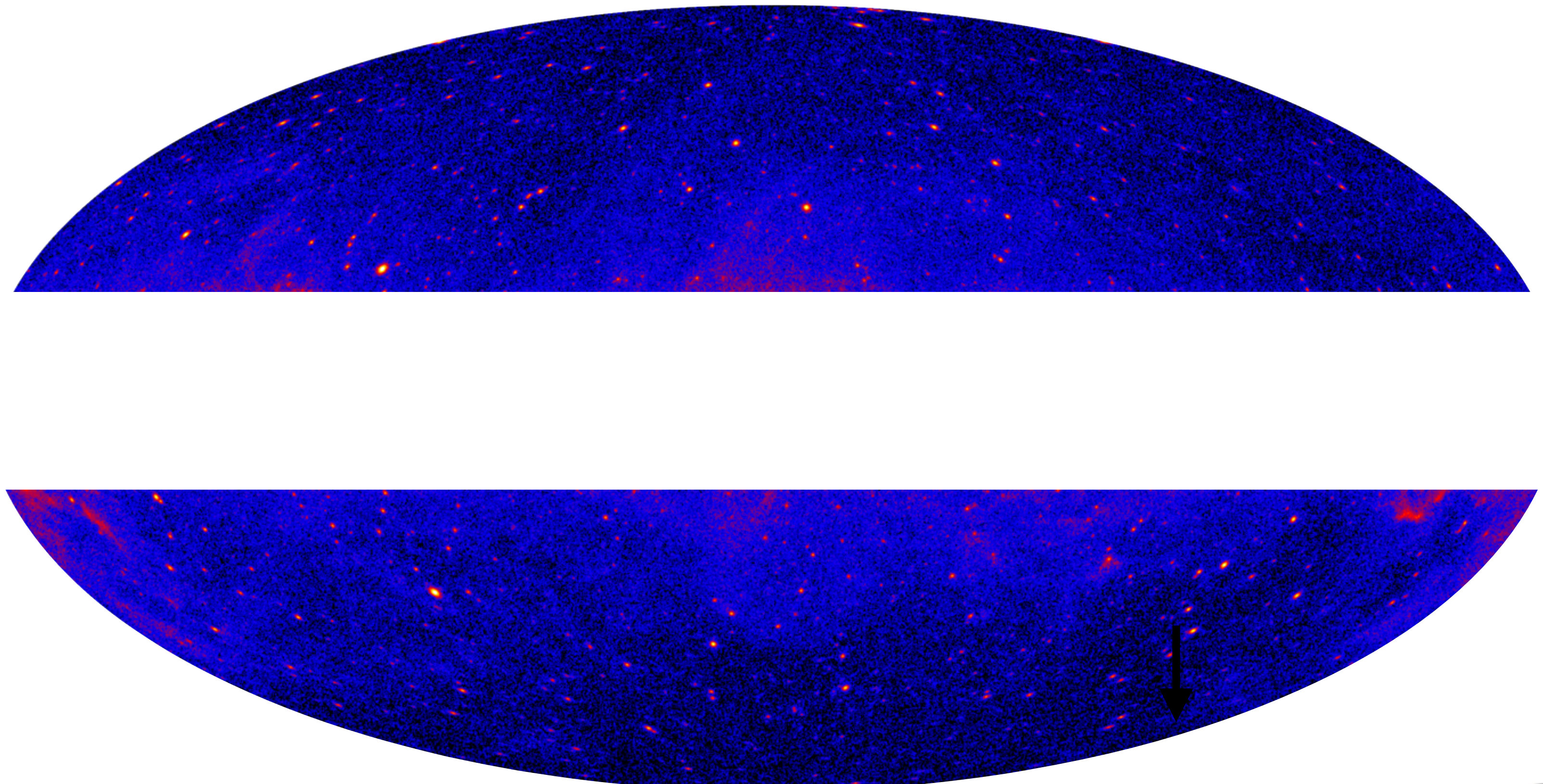
Neutrinos from CR interactions in the Galaxy ?



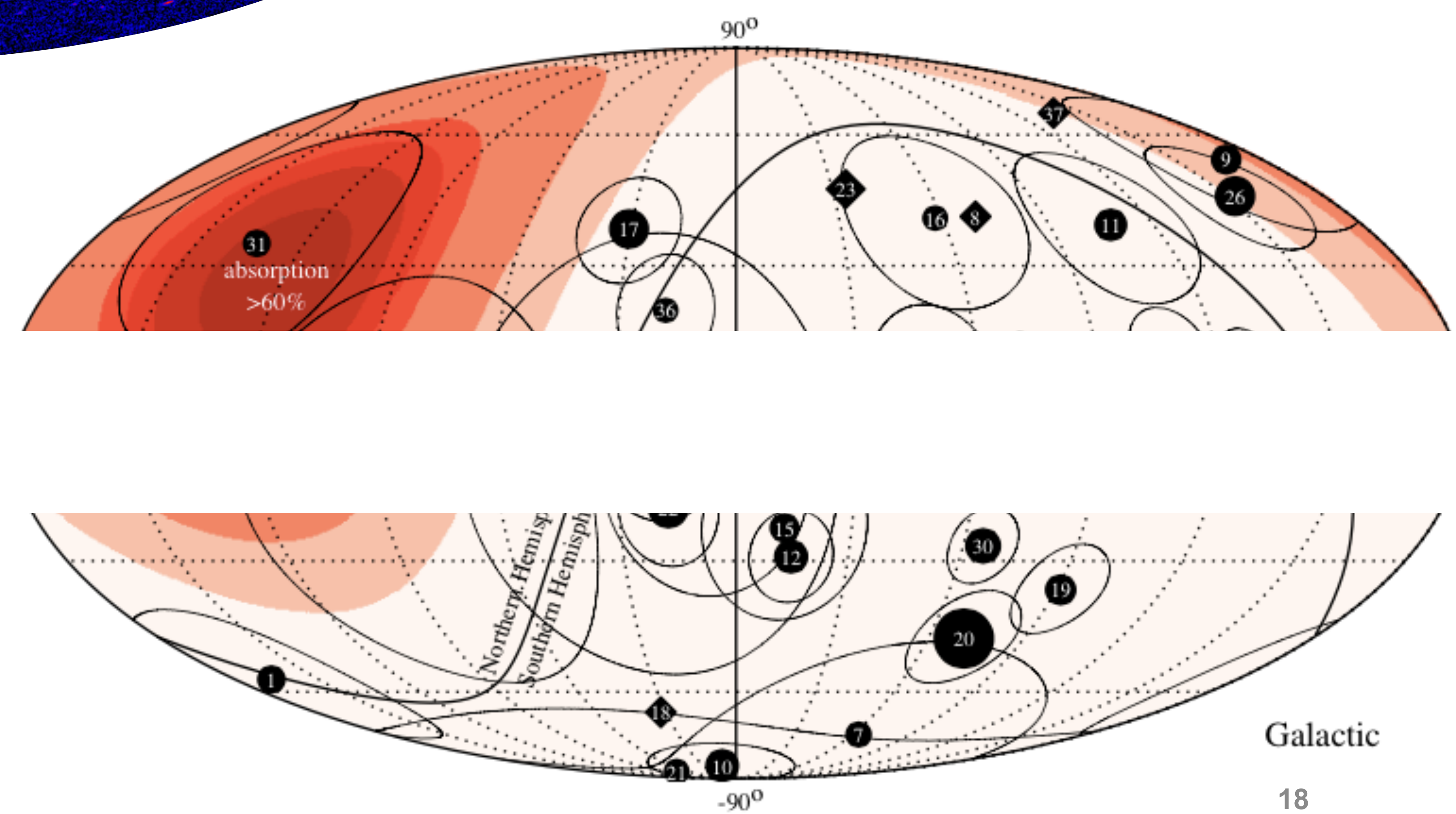
> **Additional contributions** from hard Galactic sources expected!

The extragalactic gamma-ray and neutrino sky.

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

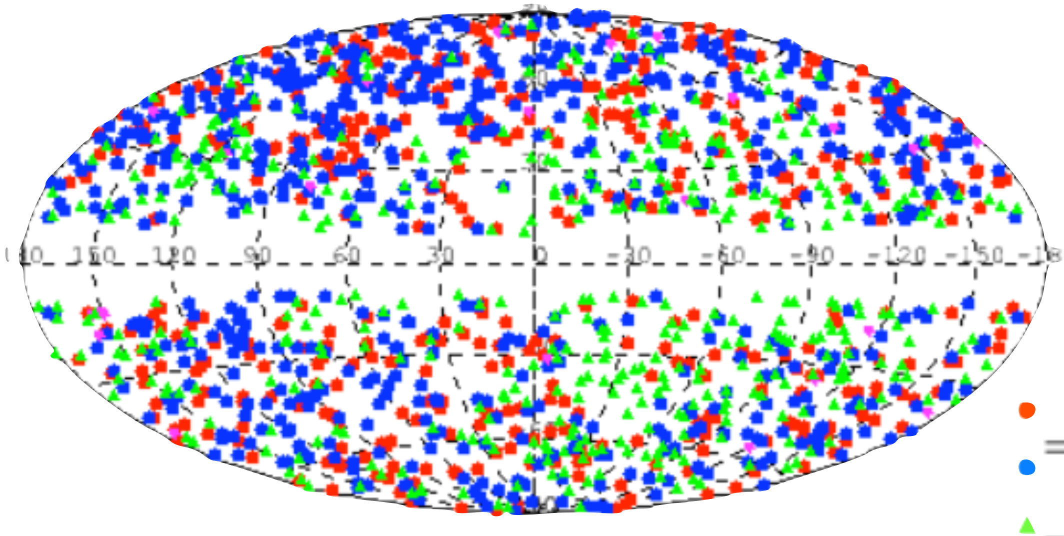


Can we **identify the populations** producing the neutrinos far from the Galactic plane ?



What ist the **connection** to ultra-high-energy **cosmic rays** ?

The 3rd LAT catalog of Active Galactic Nuclei (AGN)



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3LAC

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

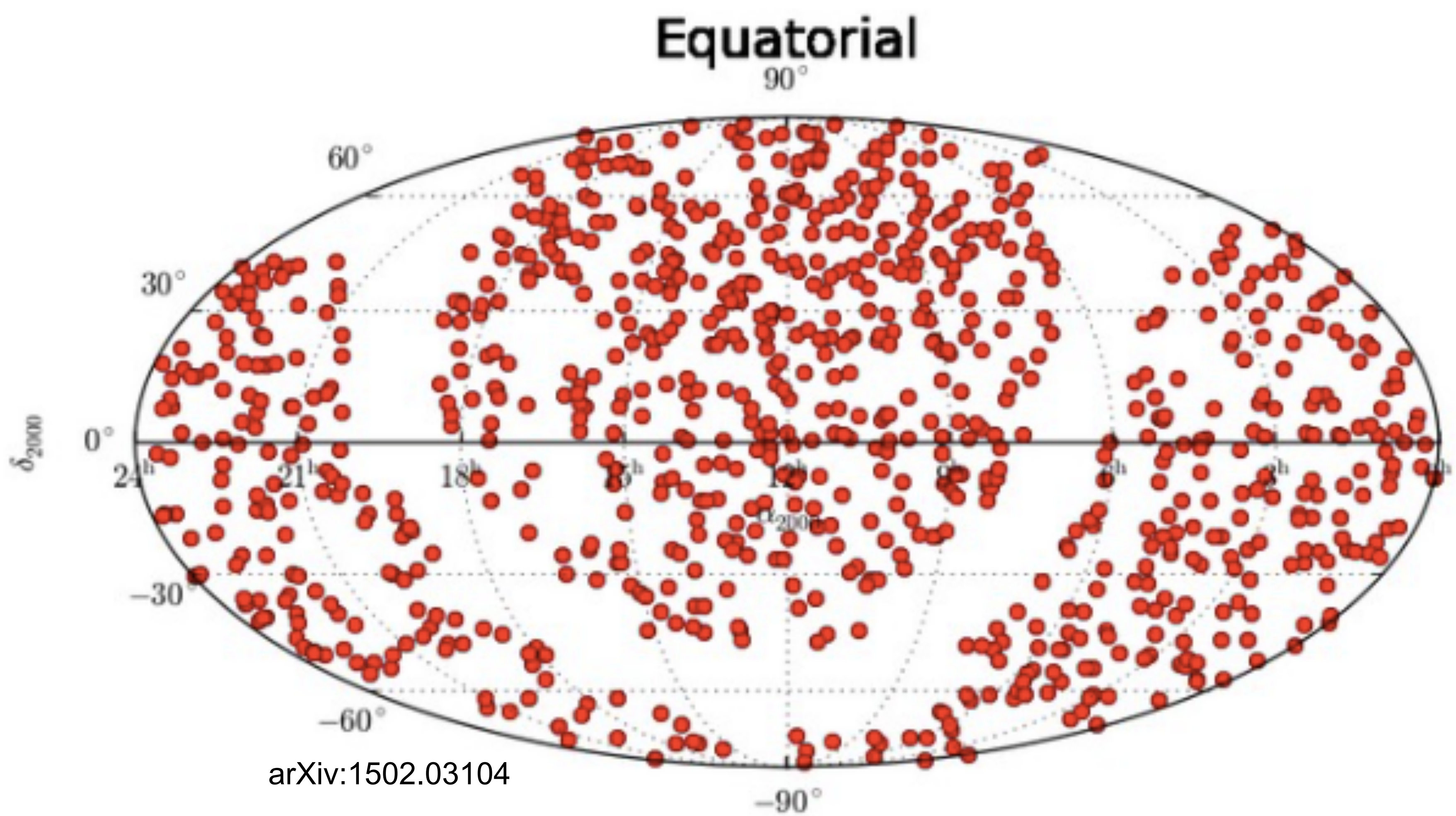
Benoit Lott, 5th Fermi Symp., Nagoya, 2014
arXiv:1501.06054

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

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

- Most of the γ-ray emission from **Blazars** is from the **individually detected Fermi LAT sources**.
- Search for neutrino emission **spatially coincident with 2LAC Blazar** sample.
- **3 years of IceCube data** used (2009-2012).

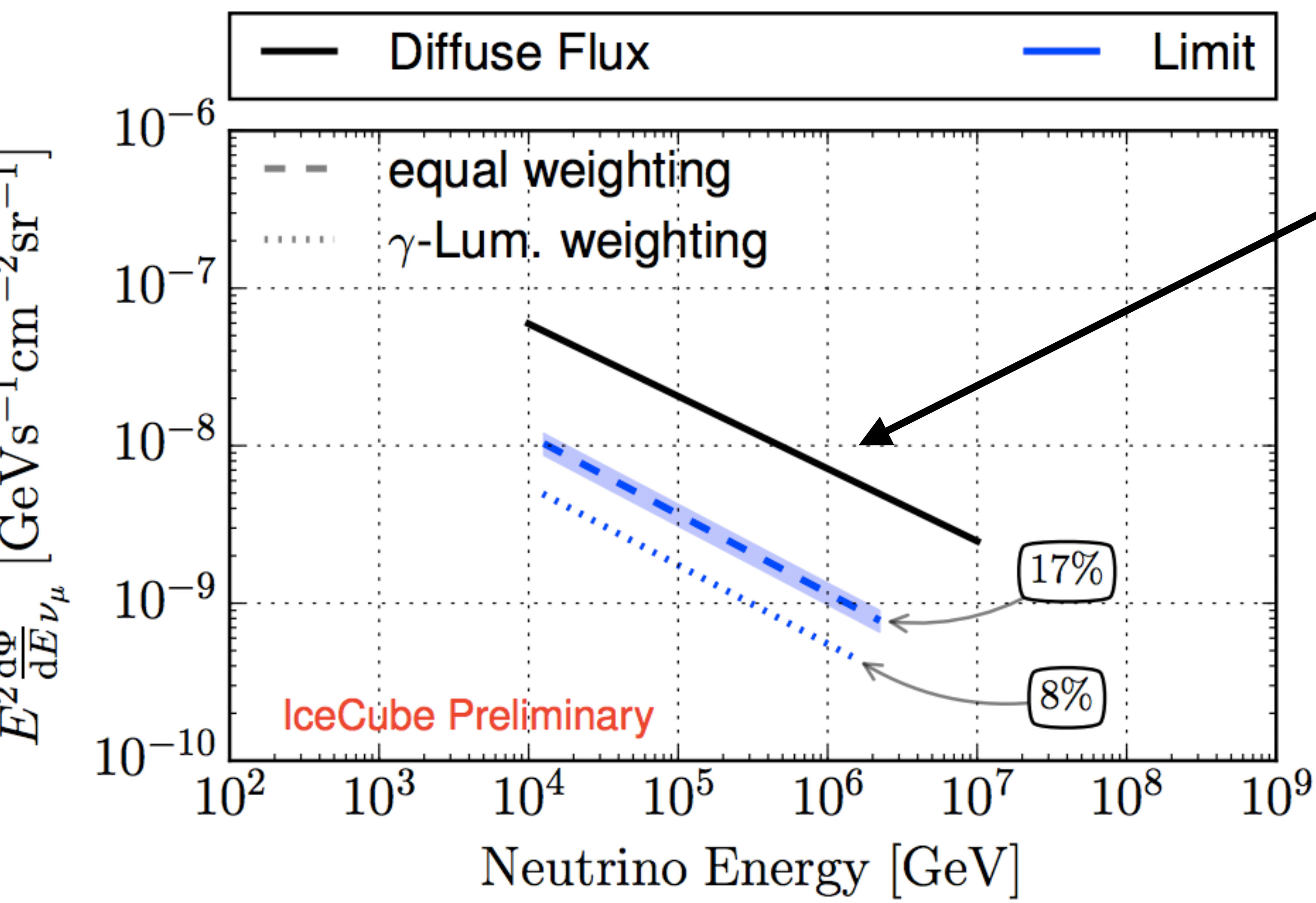
All blazars from *2-LAC* – 862 objects

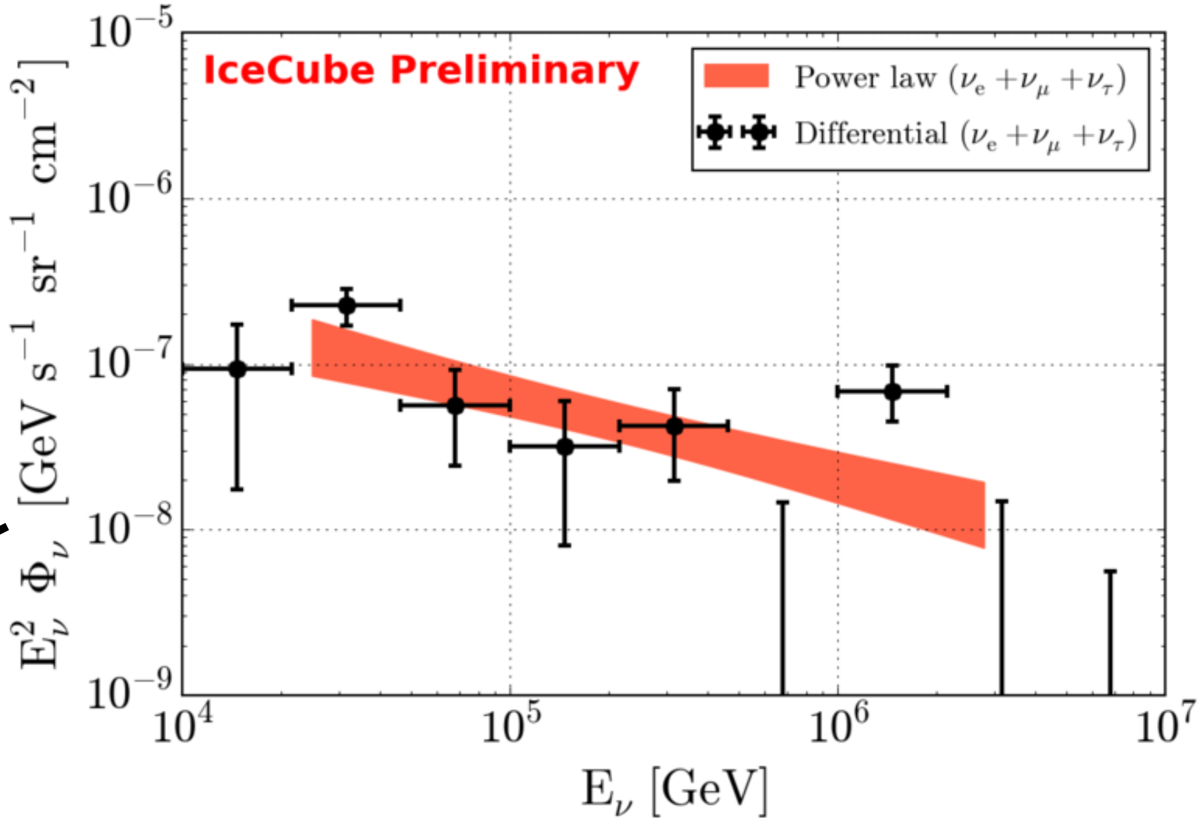


arXiv:1502.03104

Limit on neutrino emission from Fermi Blazars.

arXiv:1502.03104





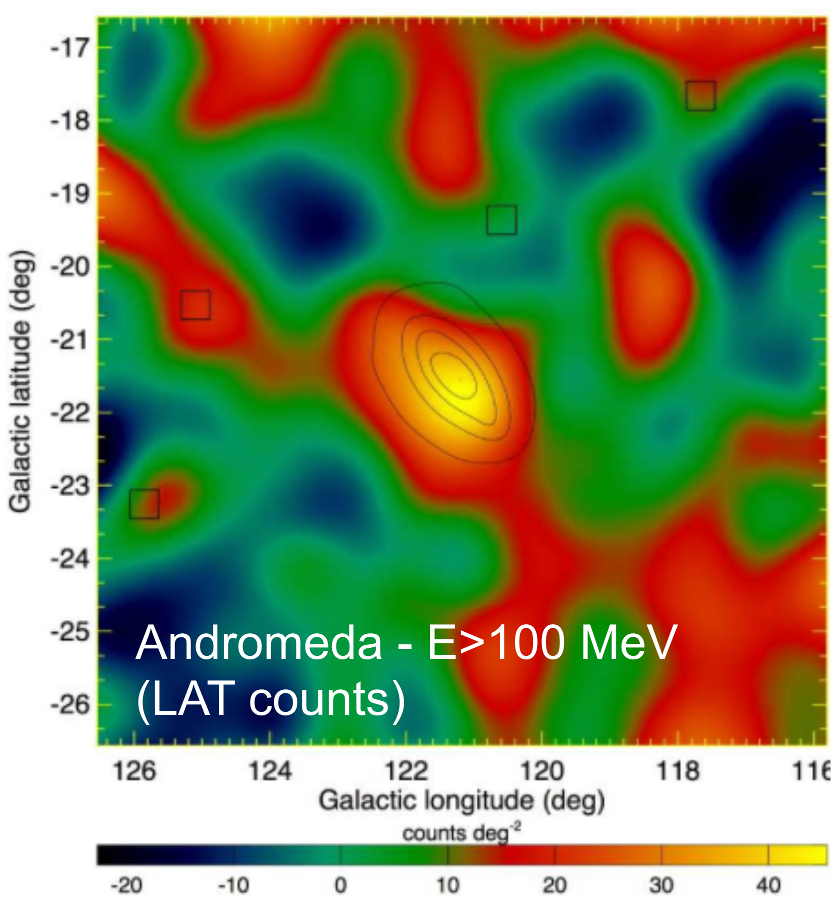
> **Less than 20% of the observed diffuse flux** is produced by the Fermi LAT detected Blazars (based on 2LAC catalog).

Star-forming / starburst galaxies.

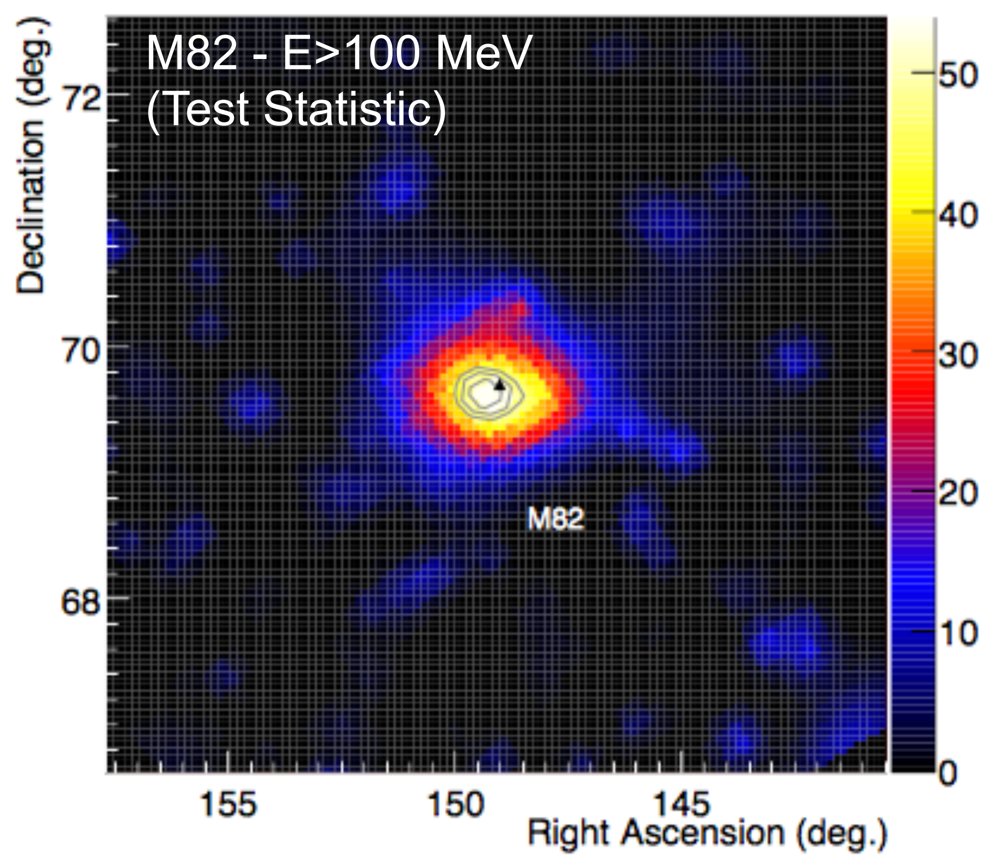
“normal” star-formation rate

extreme star-formation rate
“starburst”

Abdo et al., 2010

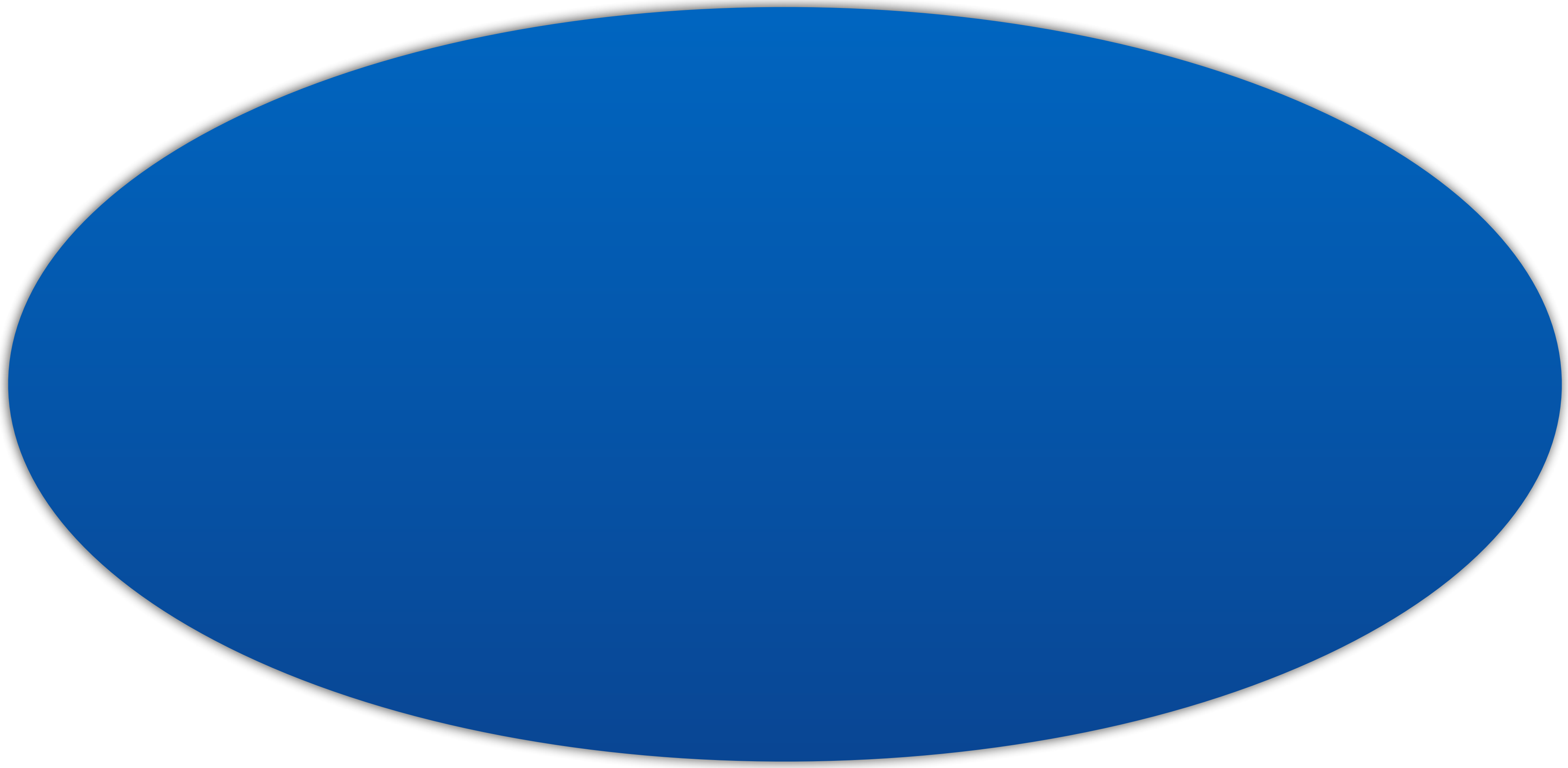


Abdo et al., 2010



- 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.

The isotropic diffuse gamma-ray background (IGRB).



> Extragalactic sources **too weak to be detected** form an **isotropic background**.

> Emission from undetected sources can be **many times stronger** than from detected ones if:

- Source density is high, but their luminosity low.
- Instrument sensitivity is low.

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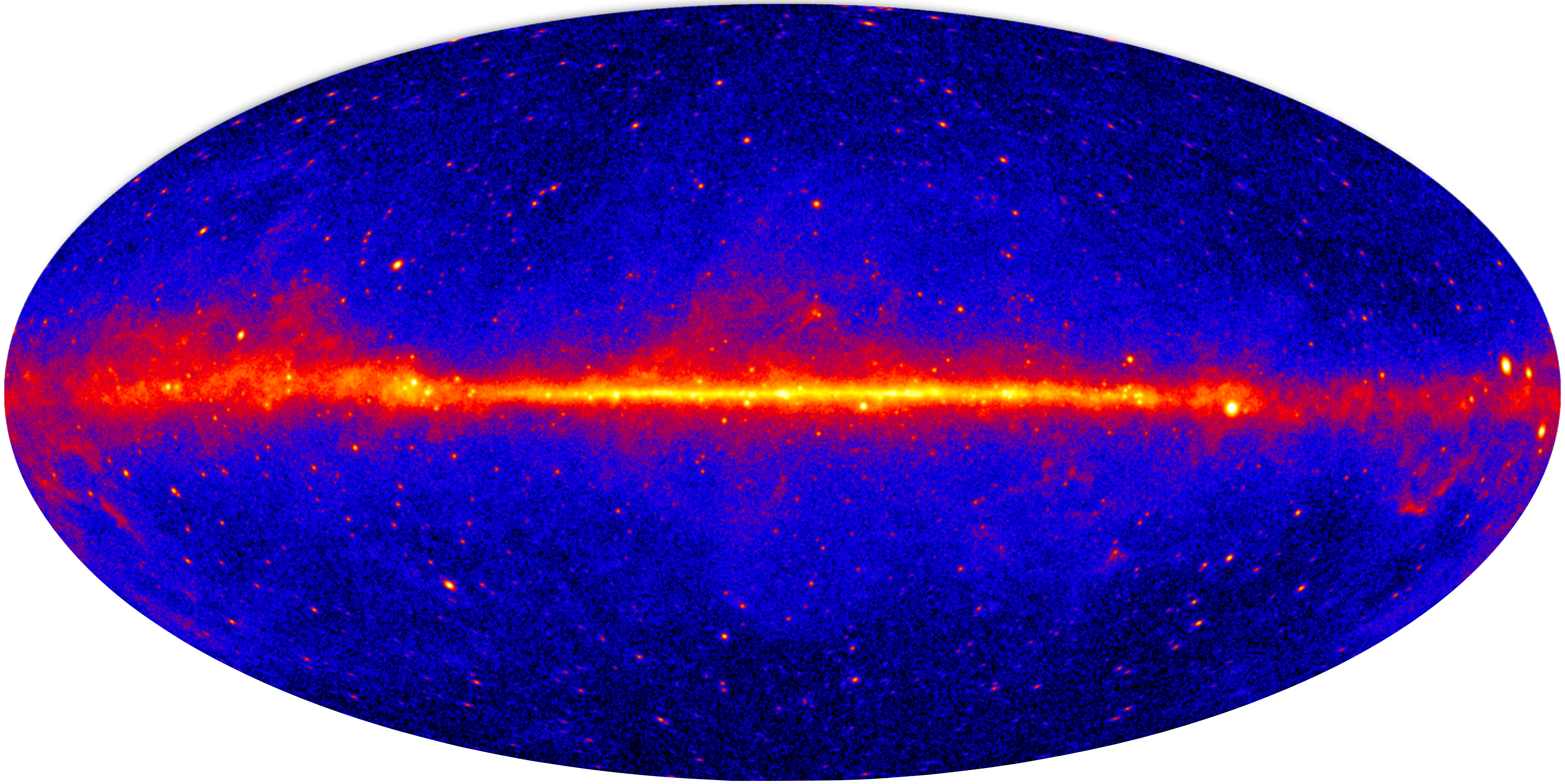

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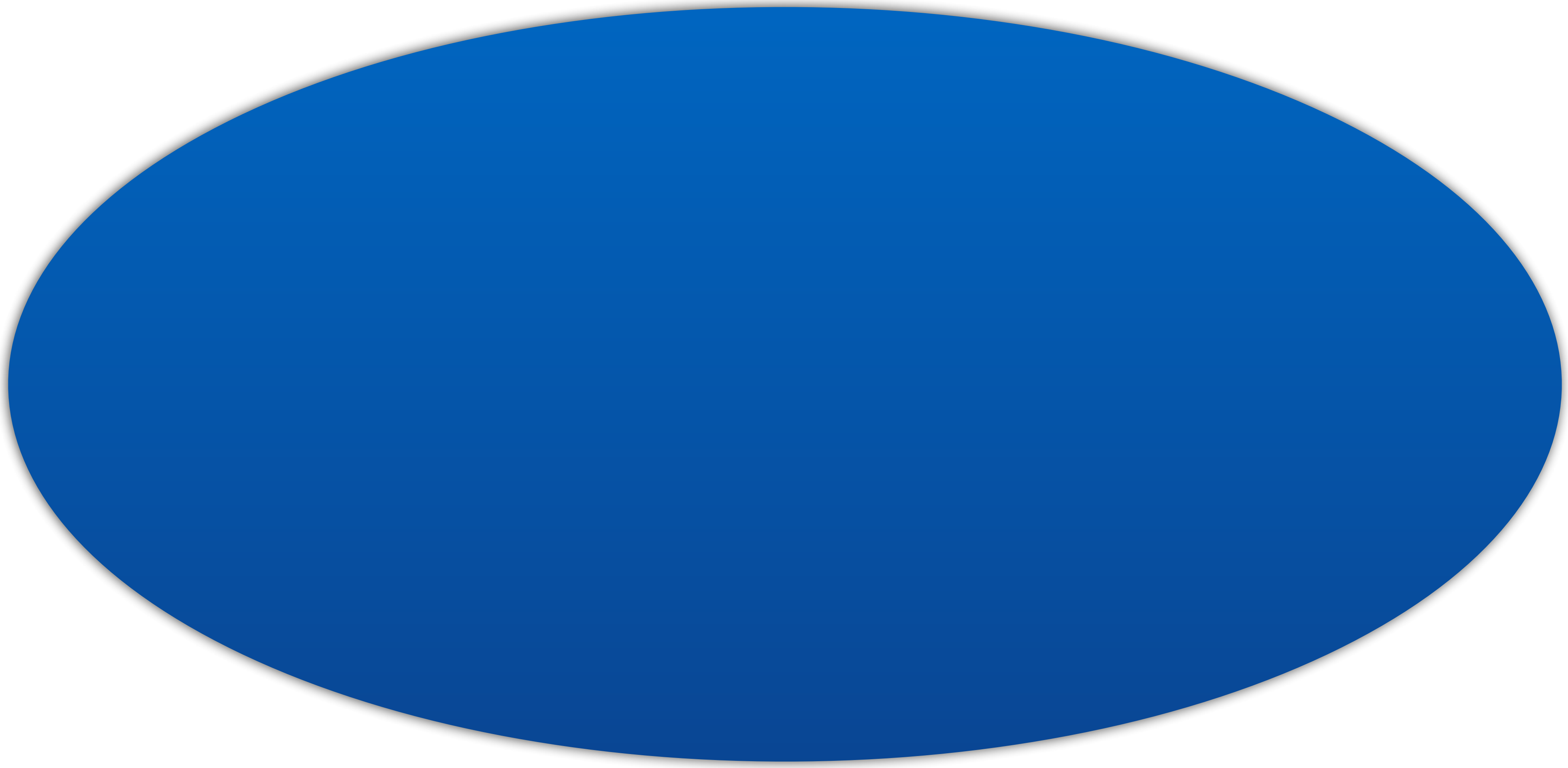

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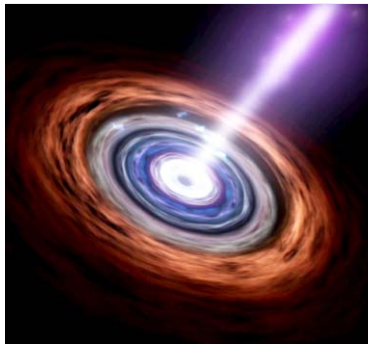
The origin of the IGRB in the LAT energy range.

Undetected sources



Blazars

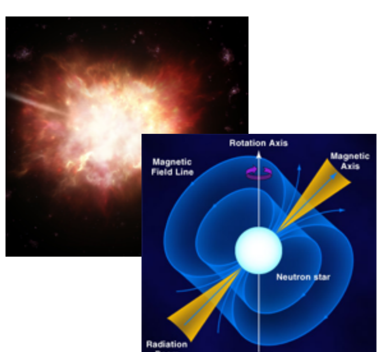
- Dominant class of LAT extra-galactic sources.

Radio galaxies

- 32 sources resolved in 3LAC.

Star-forming galaxies

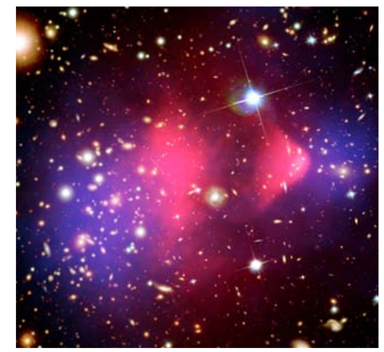
- Some galaxies outside the local group resolved by LAT.



GRBs + High-latitude pulsars

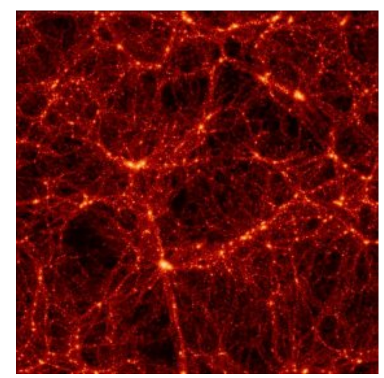
- Only small contributions expected.

Diffuse processes



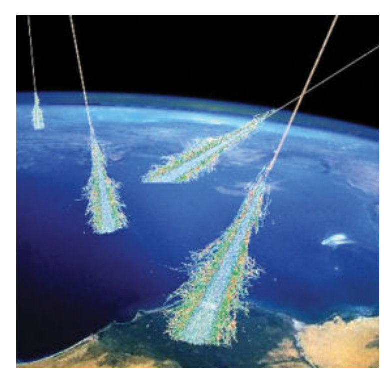
Intergalactic shocks

- produced in galaxy cluster mergers



Dark matter annihilation

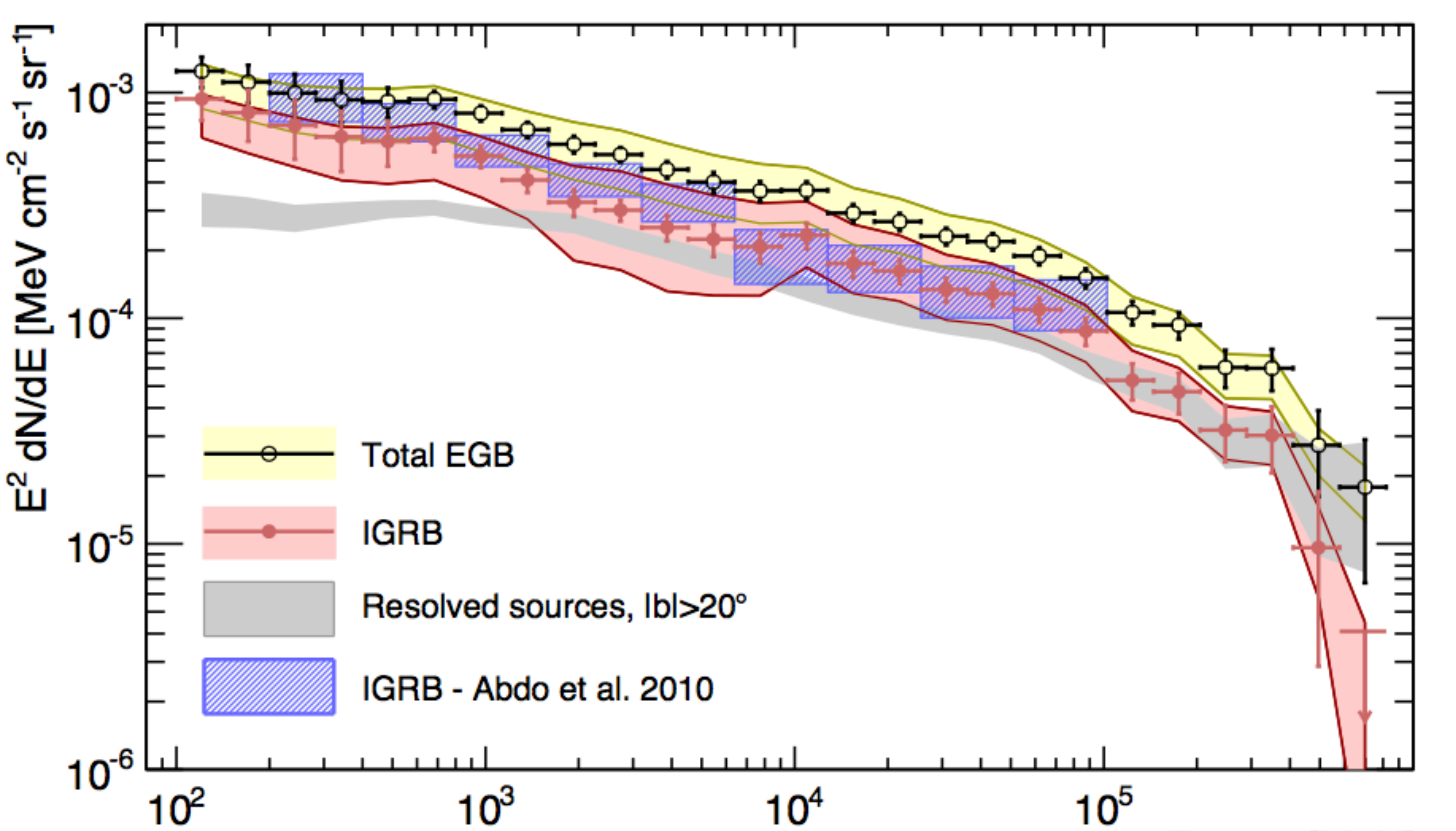
- Potential signal dependent on nature of DM.



Interactions of UHE cosmic rays with the EBL

- Strongly dependent on evolution of UHECR sources..

LAT IGRB and EGB measurements



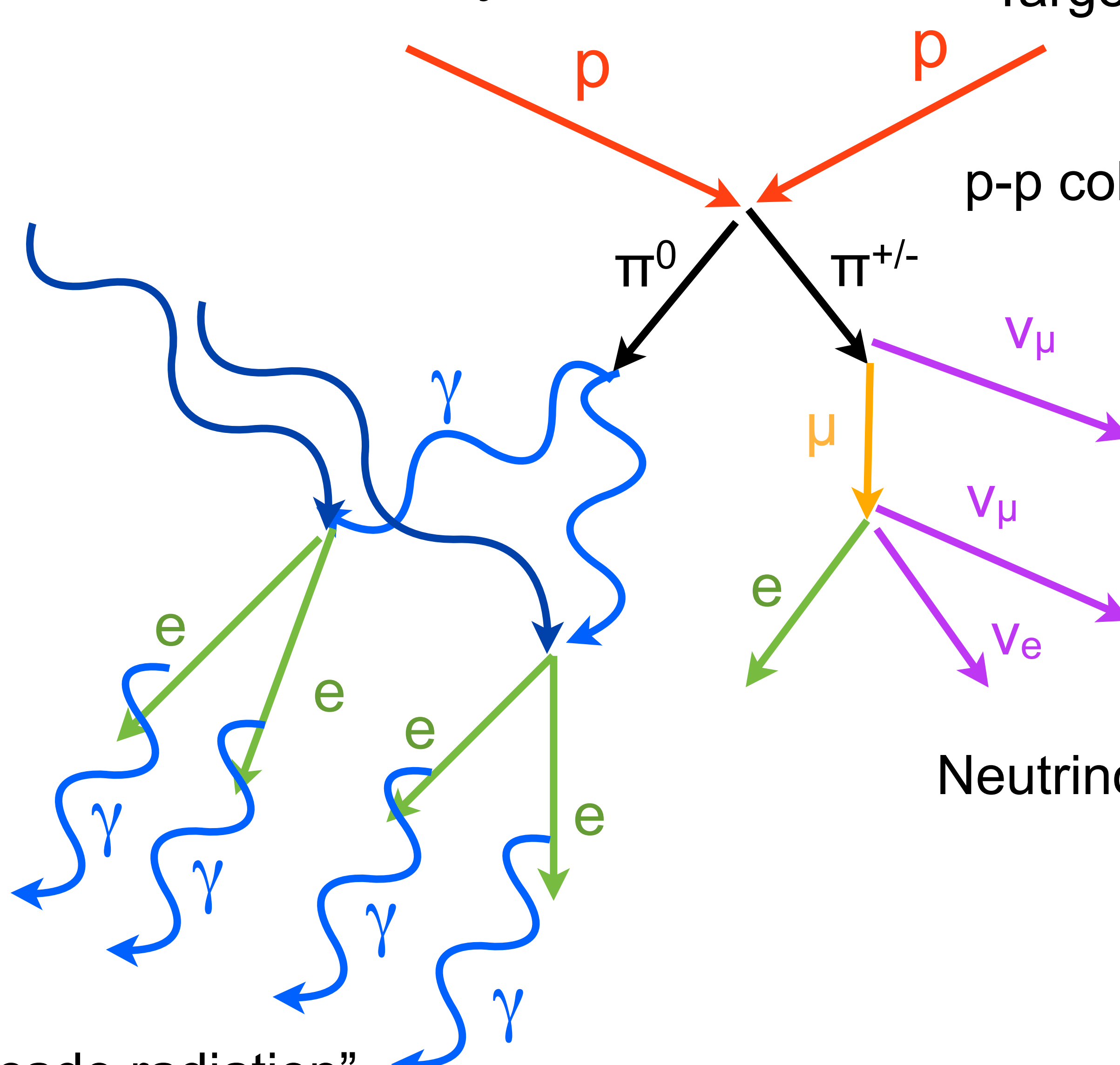
Ackermann et al., 2014, arXiv:1410.3696

- Measured by Fermi LAT between **100 MeV and 820 GeV**.
- Large **systematic uncertainties** from foreground subtraction.
- **Total** extragalactic gamma-ray background (EGB) = IGRB + resolved sources.
- EGB is **independent** of the sensitivity of the **instrument.**

Neutrinos and γ-rays from star-forming galaxies.

Cosmic rays

Target medium

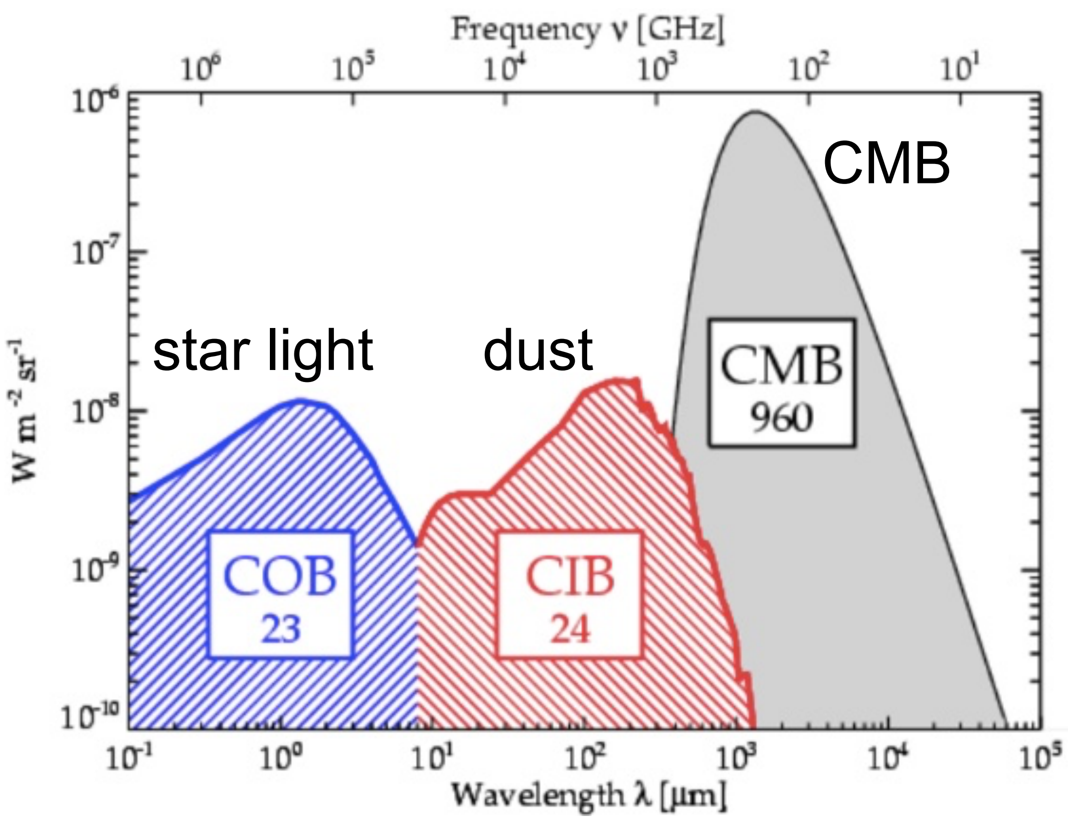


p-p collisions

Neutrinos

“cascade radiation”
at GeV energies

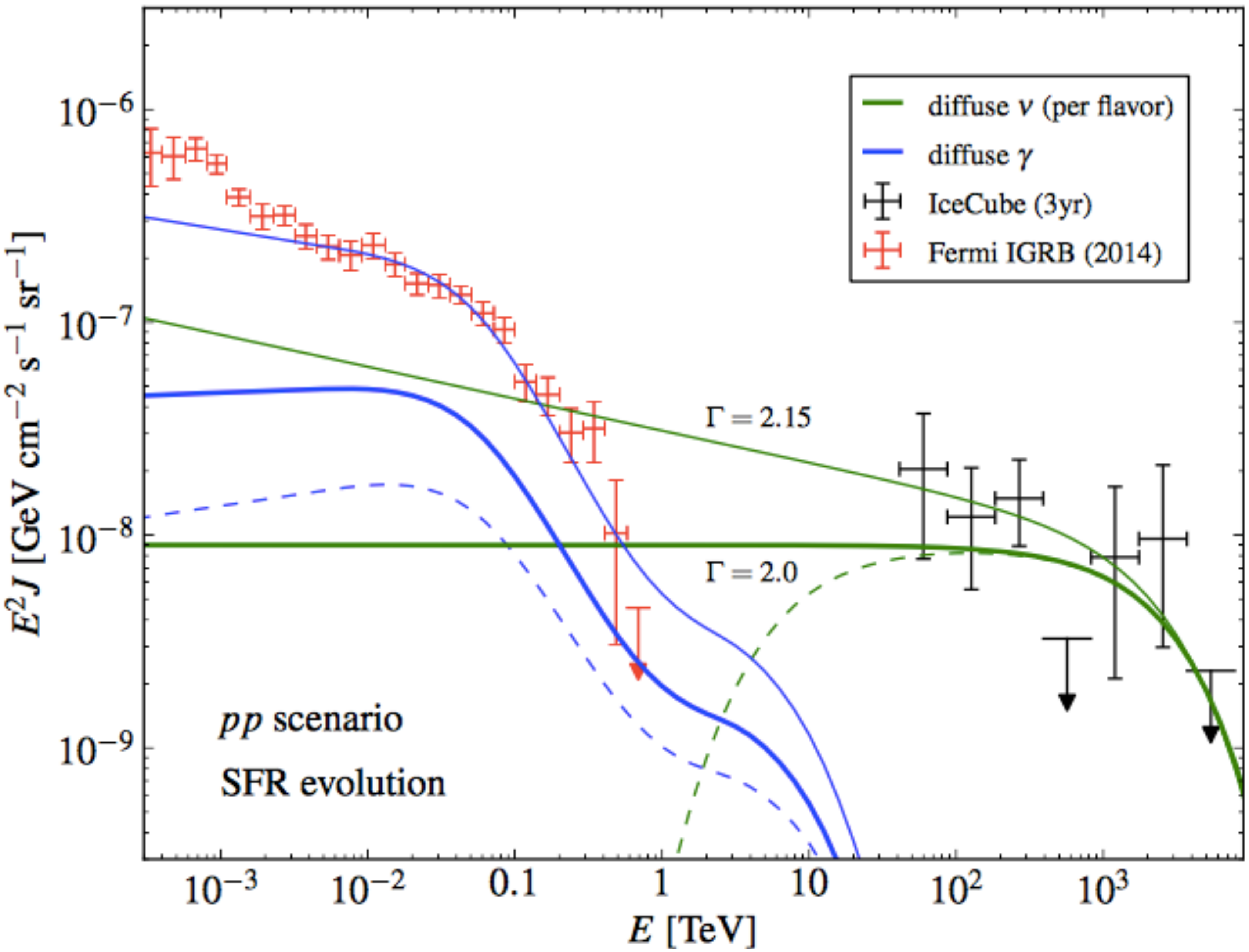
Extragalactic background light (EBL)



+ radiation fields at source

Neutrinos and γ-rays from star forming Galaxies.

- If **extragalactic p-p collisions** produce the observed ν:
  ➔ **hard ν-spectrum below 10 TeV** needed.
- **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, Ahlers & Lacki, 2013
updated to new IGRB measurement (Ackermann et al. 2015)

Similar constraints would apply to ν emission from galaxy clusters

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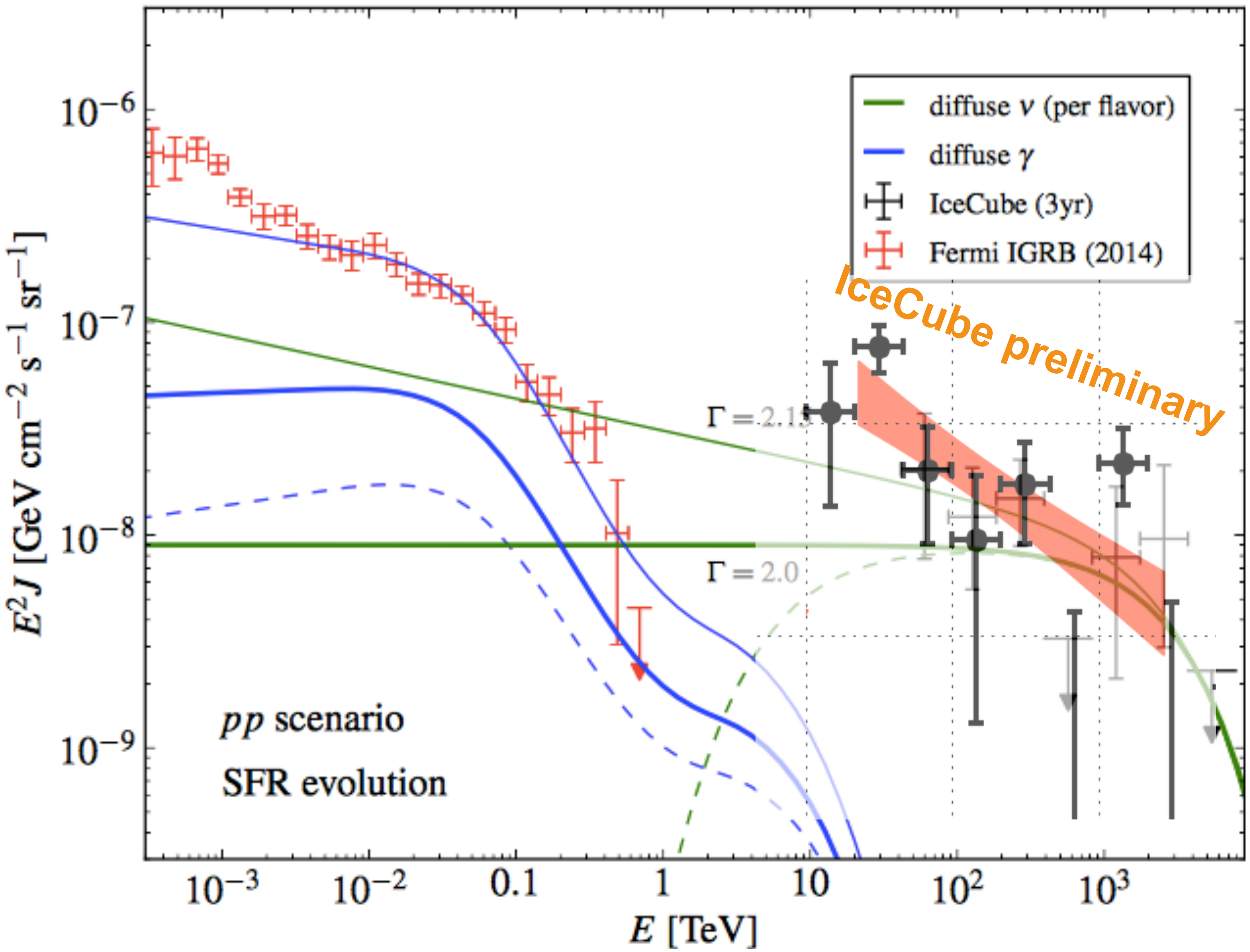

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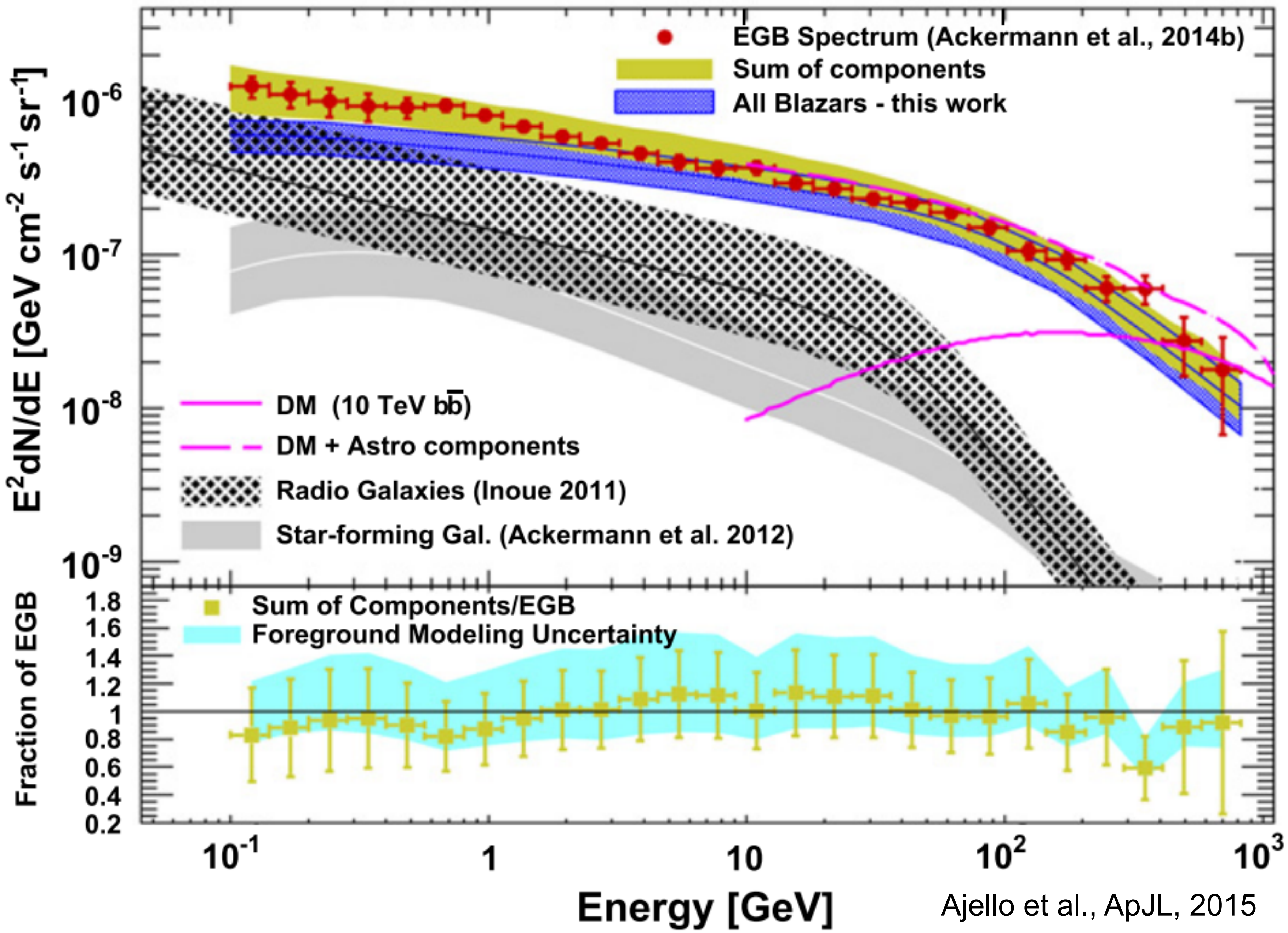
Similar constraints would apply to ν emission from galaxy clusters

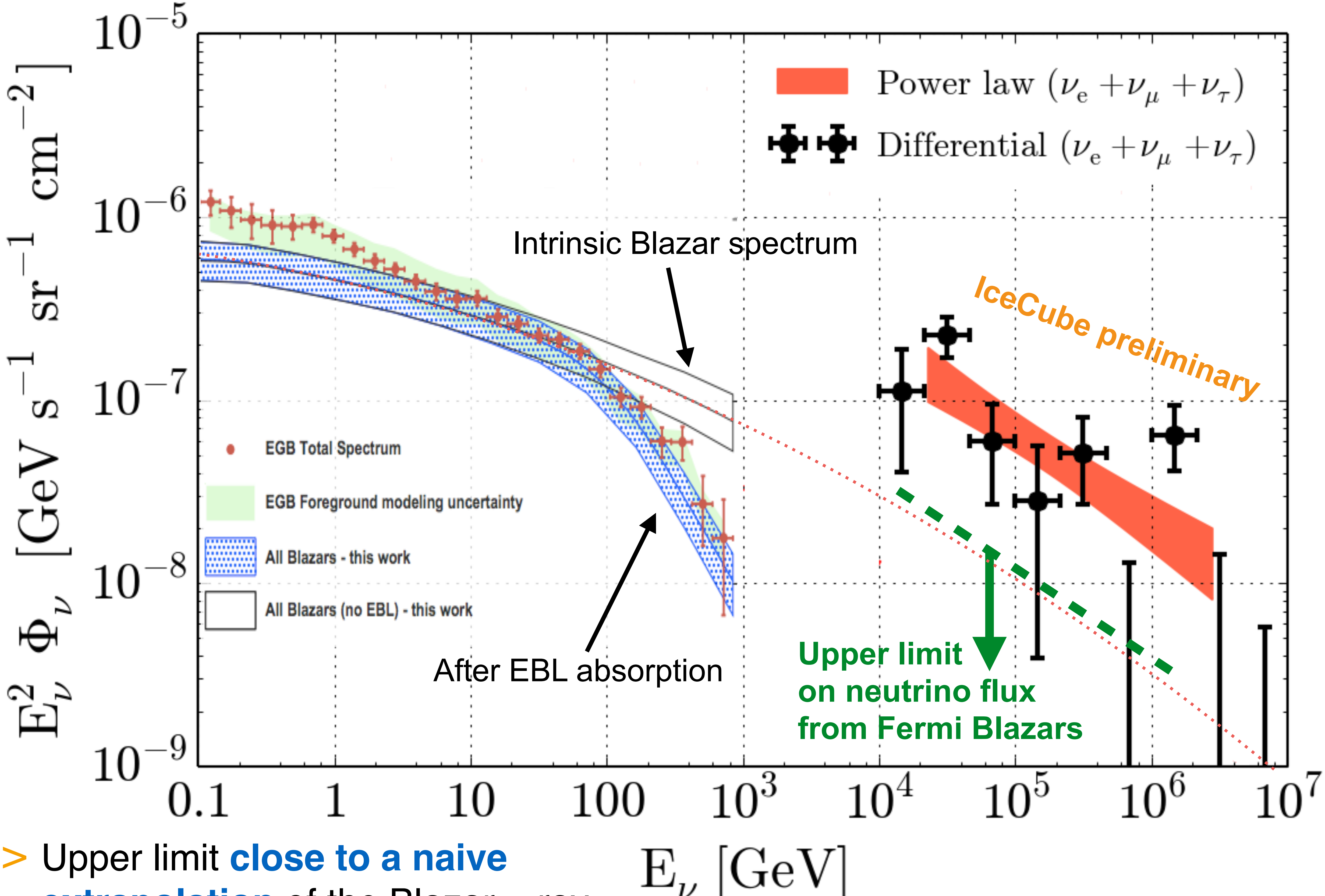
Source population contributions to the EGB.



Ajello et al., ApJL, 2015

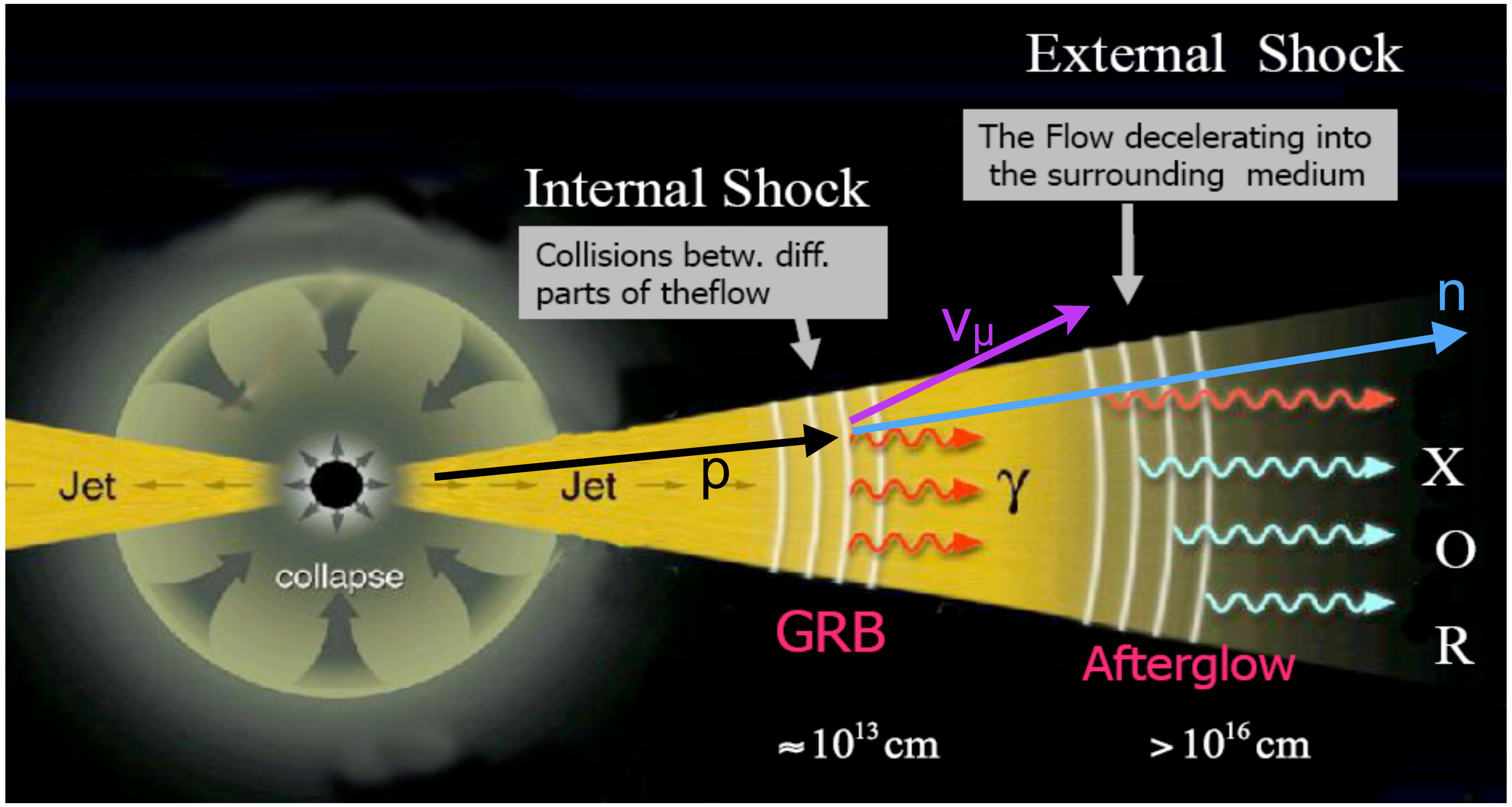
> **Observed** extragalactic LAT **source populations** can account for the EGB intensity.

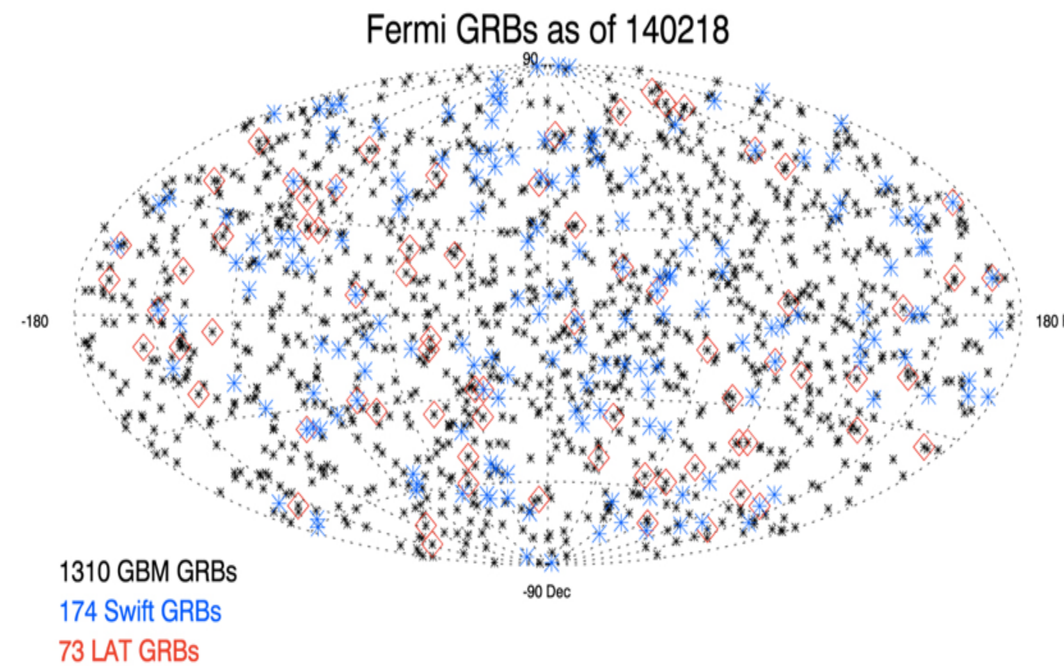
> **Blazars dominate** the EGB, but significant uncertainties in modeling contributions.

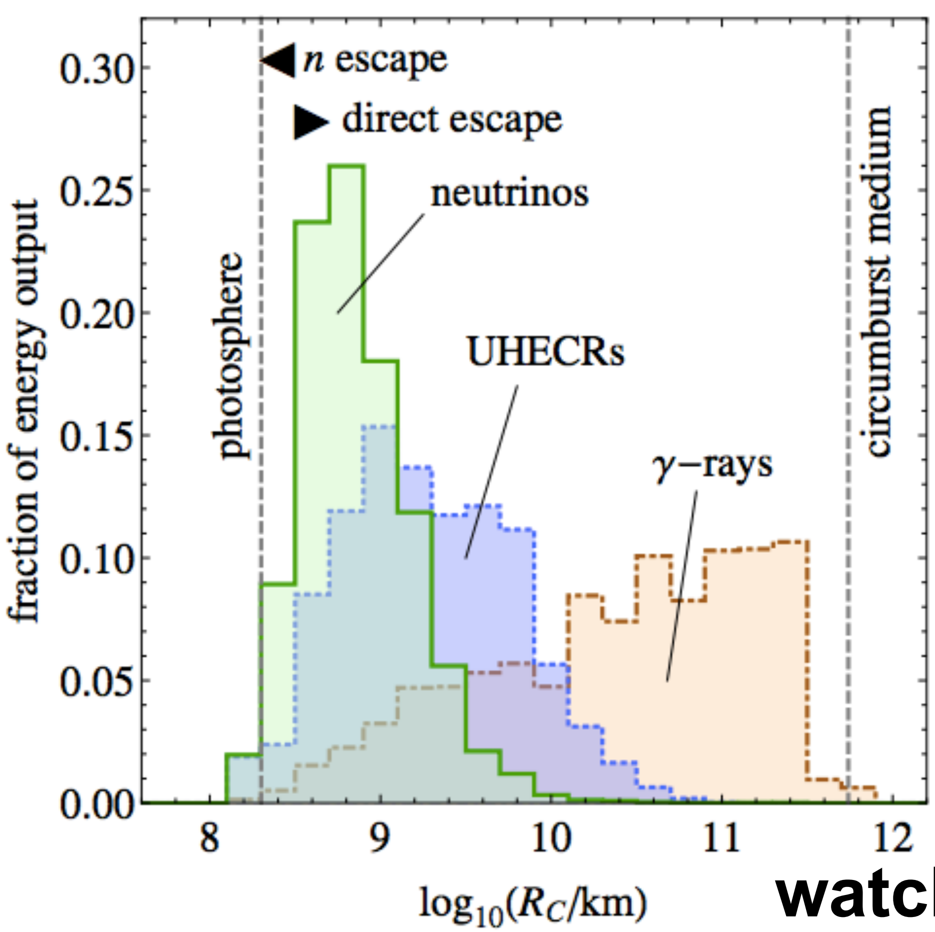


> Upper limit **close to a naive extrapolation** of the Blazar γ-ray spectrum.

Gamma-ray bursts.







- GRBs have been prime candidates for ultra-high-energy CR production.
- Search for coincidence between GRB and neutrino emission.
- So far no coincidence detected.
- Sophisticated modeling attempts to predict the connection between neutrino and gamma-ray emission.

watch the talk by W. Winter!

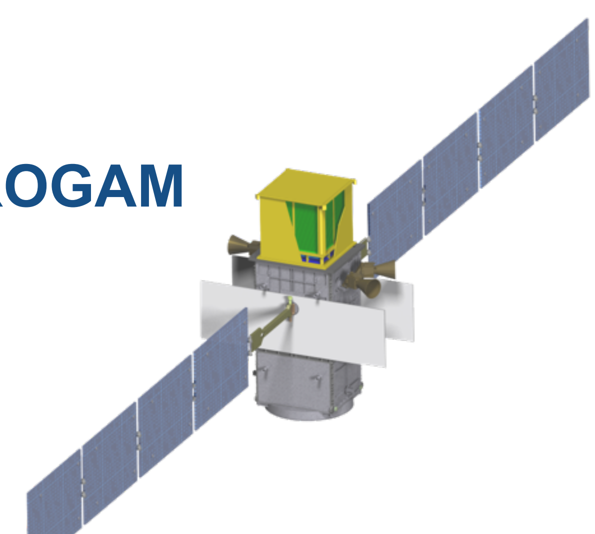
Summary

> Neutrinos and gamma rays are indeed complementary messengers. They probe
  - different high-energy interactions.
  - different energy regimes.
  - different distance regimes.

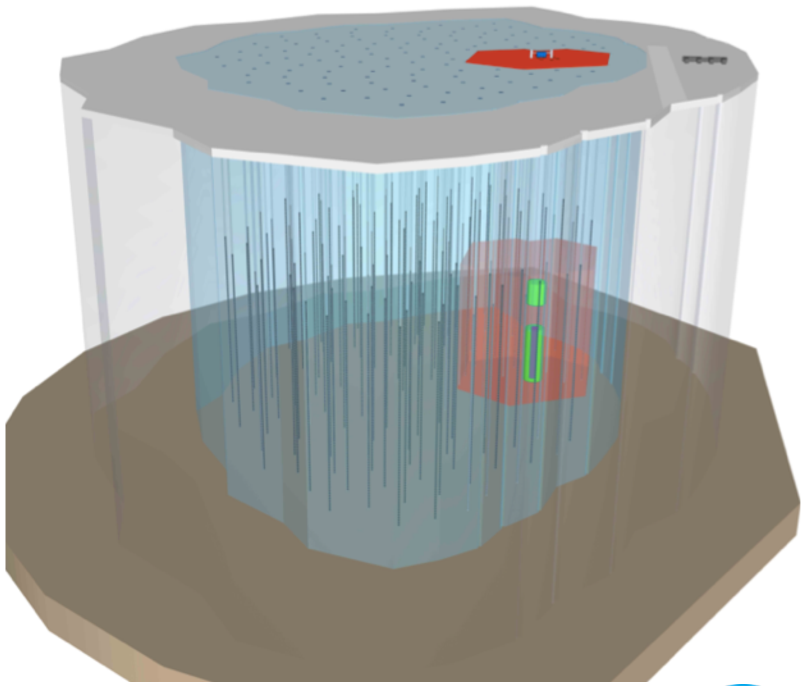
> The correlations between the two messengers can be used to understand the high-energy emission of various source populations better.
  - Galactic high-energy ν sources compatible with γ-ray data, but no identification yet.
  - LAT Blazars contribute less than 20% to the diffuse ν-flux.
  - Extragalactic p-p scenarios (like star-forming galaxies) problematic.
  - No coincidence with GRBs detected yet.

> New instruments proposed promise a bright future.

ASTROGAM



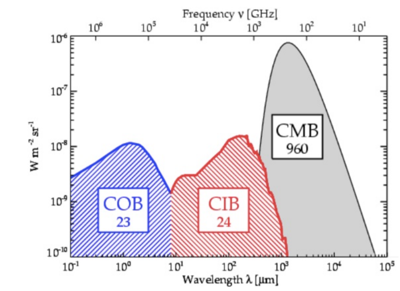
IceCube-Gen2



Backup

Cosmogenic neutrinos

- Ultra-high-energy cosmic rays interact with the EBL during propagation.
- Neutrino/Gamma production via pγ-interactions
- Reprocessing of gamma rays to GeV energies



Star light
Infrared
CMB

EeV Cosmic rays

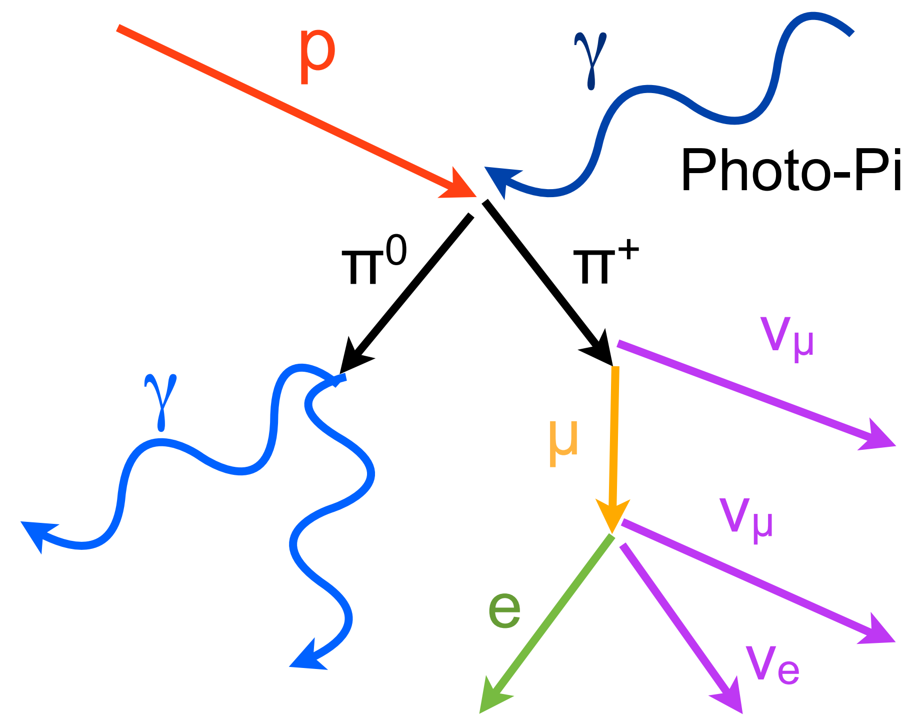
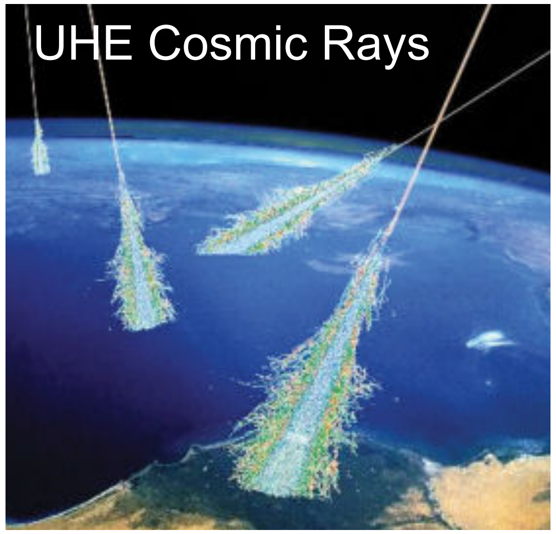


Photo-Pion Production

PeV-EeV Neutrinos



EBL=extragalactic background light

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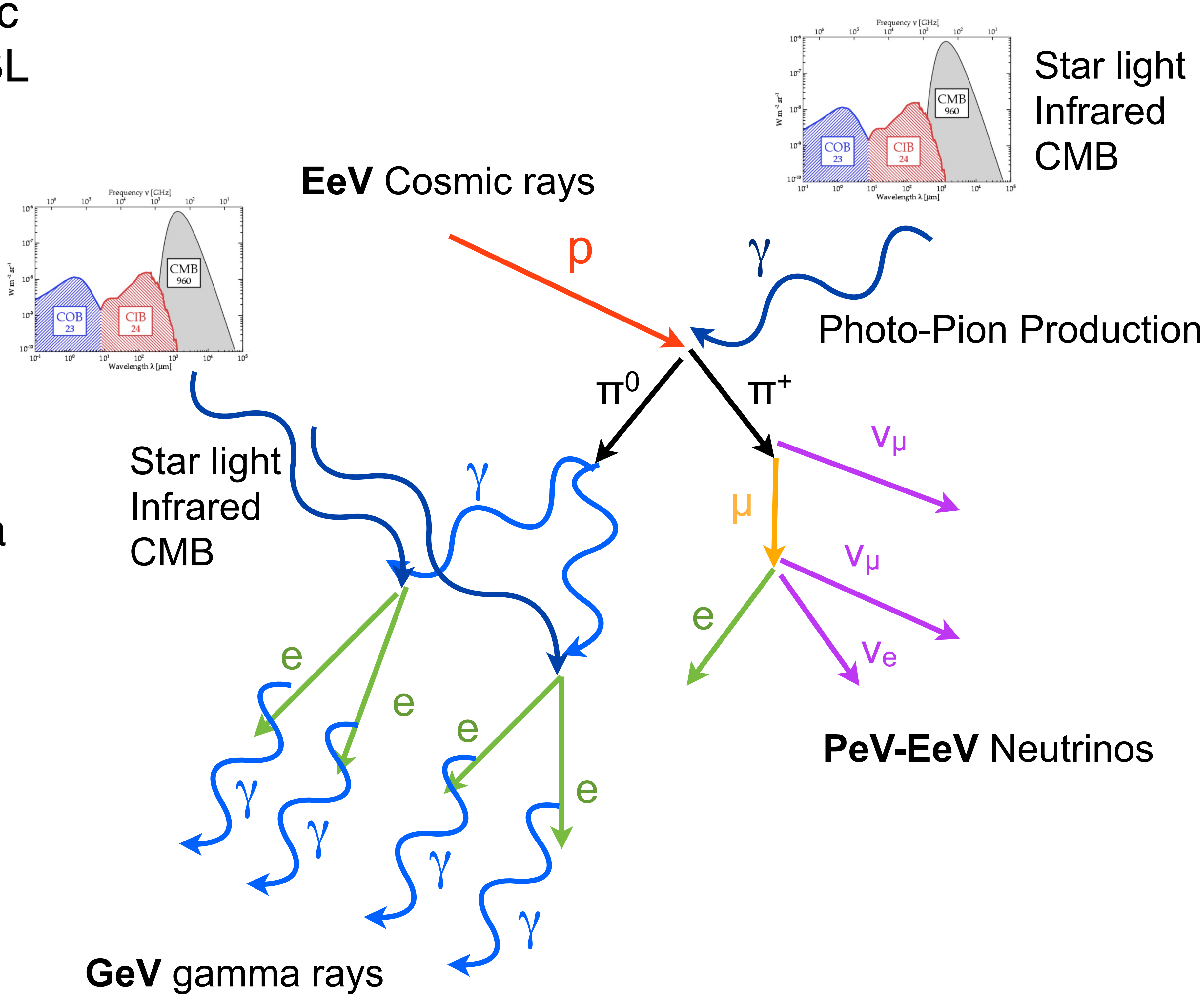
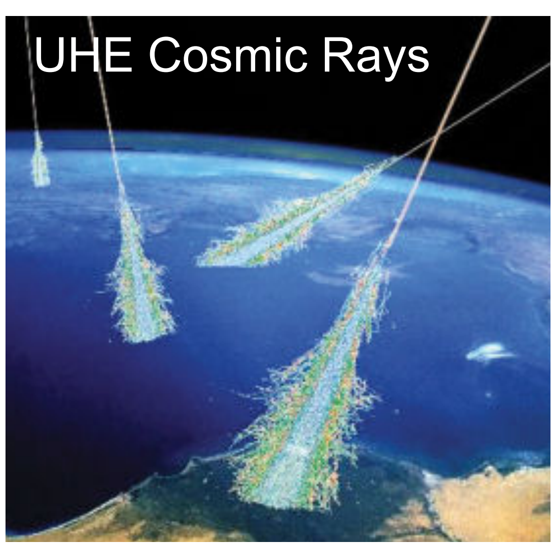
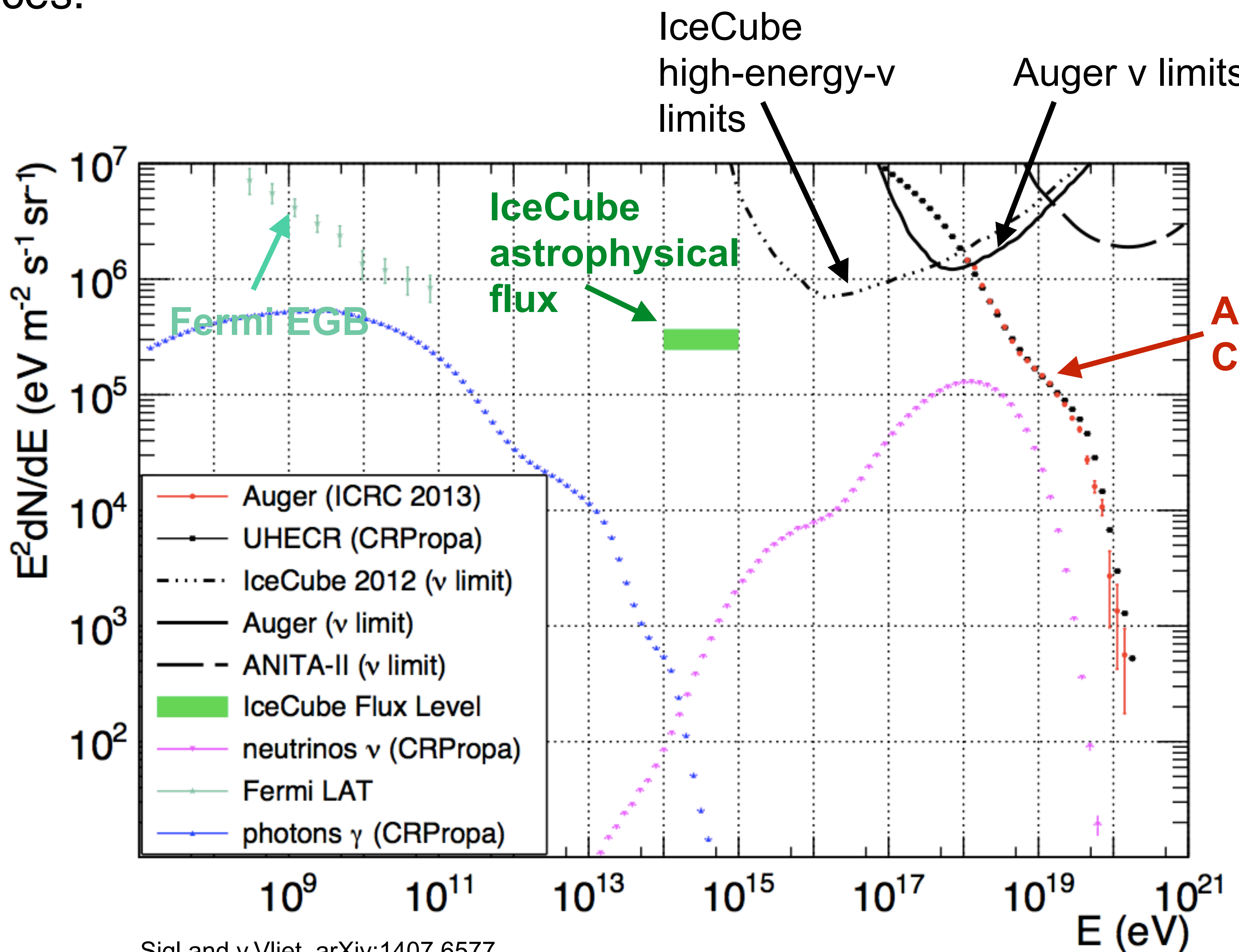




EBL=extragalactic background light

Multi-messenger constraints on UHECR properties.

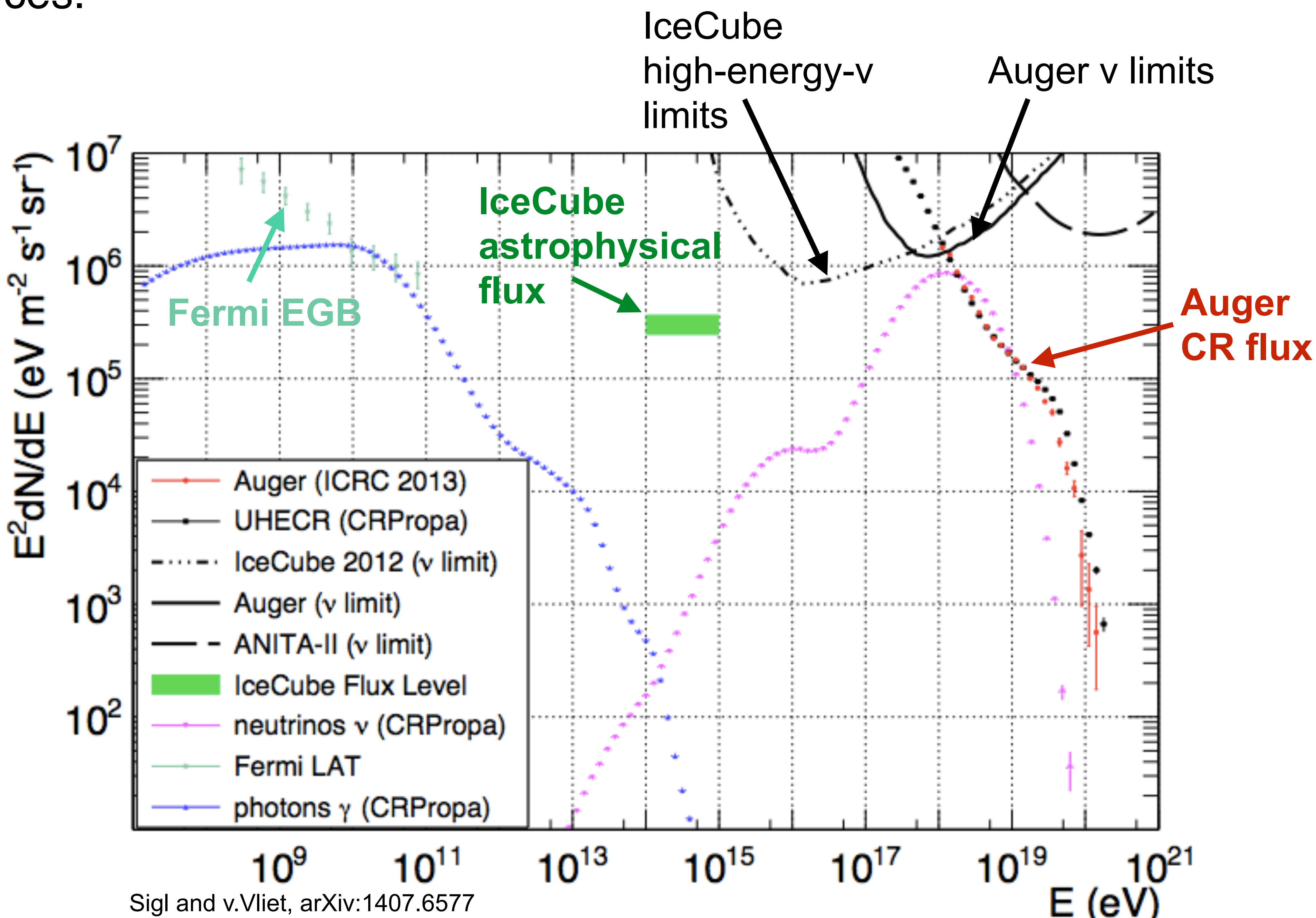
> CR, neutrino and gamma-ray spectrum from propagation code.
> Cosmological evolution of sources corresponds to **GRB evolution.**
> Proton sources.



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 **FR-II galaxy evolution.**
- Proton sources.



Sigl and v.Vliet, arXiv:1407.6577