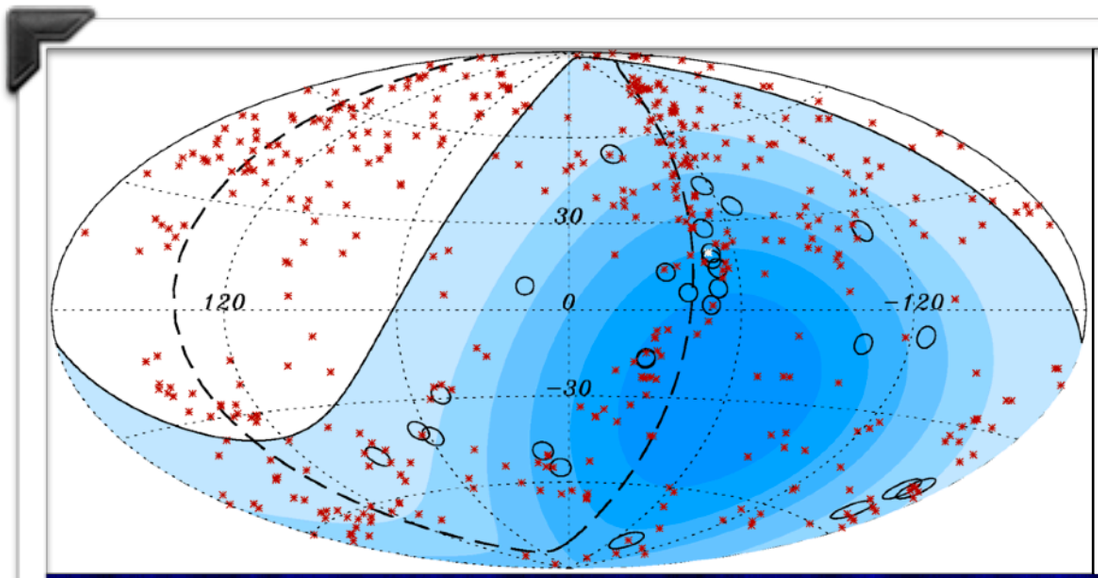
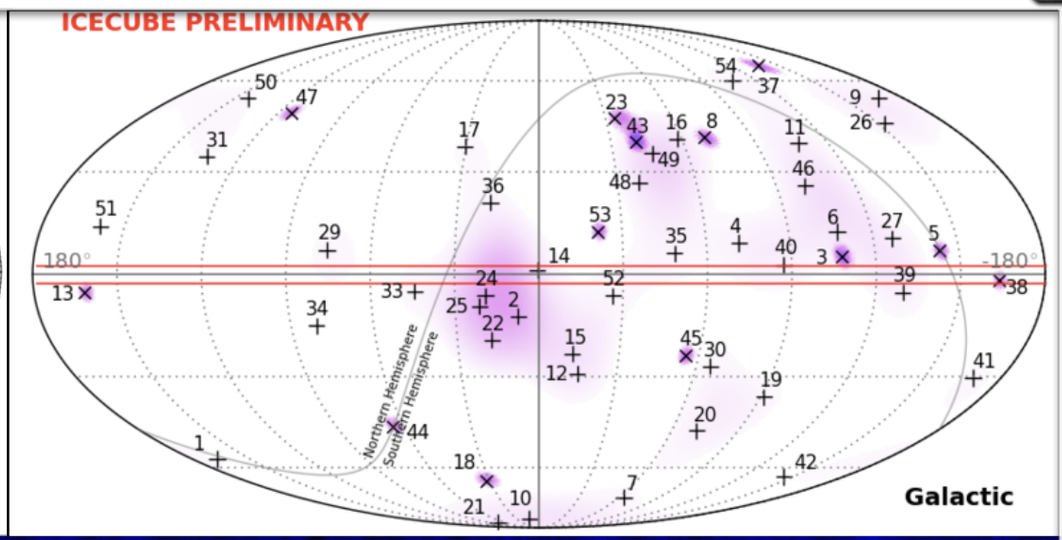
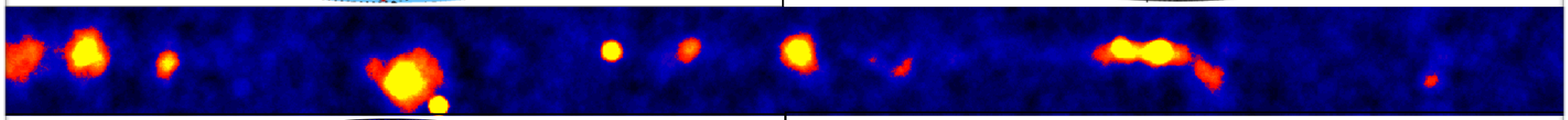
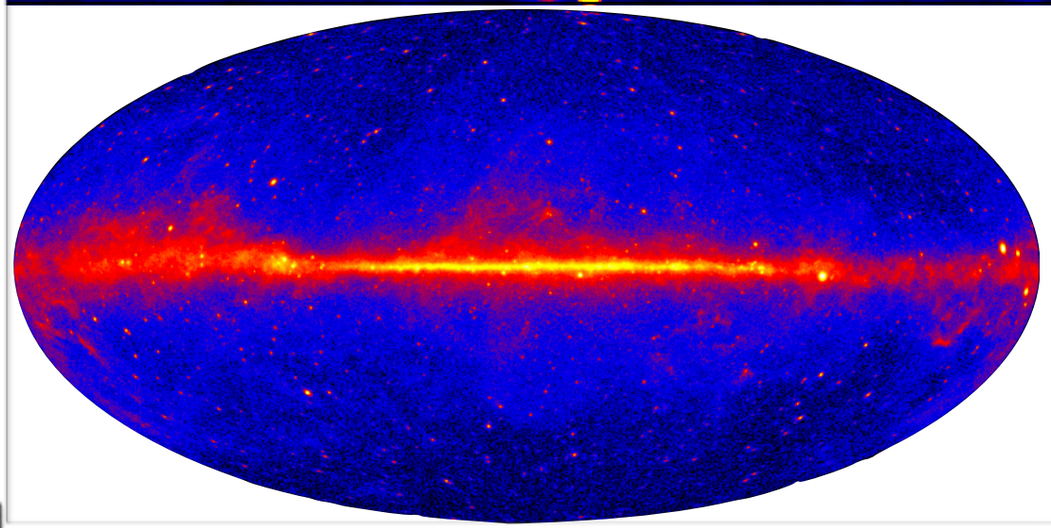
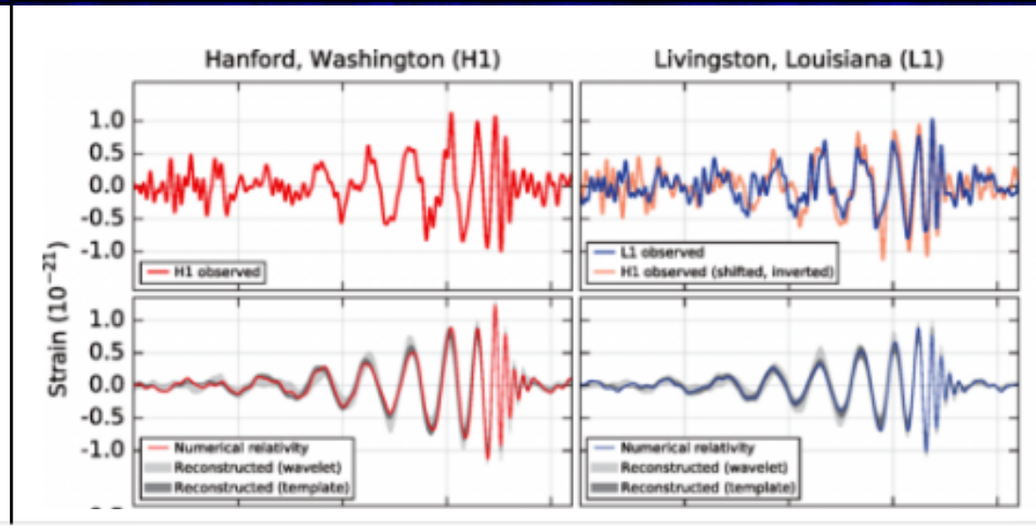
The multi-messenger picture











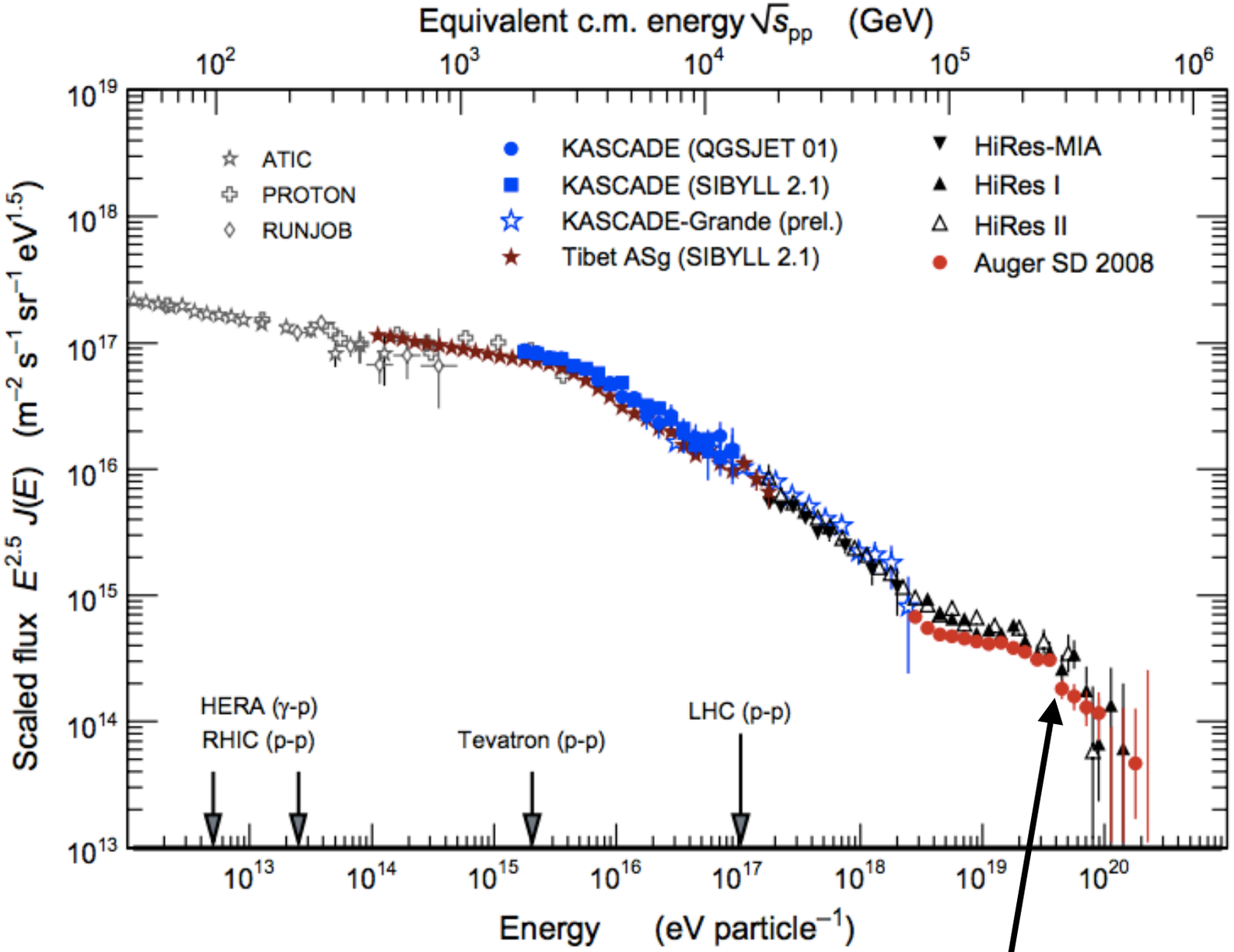
Markus Ackermann

HAP Workshop
The non-thermal universe
Erlangen, 21.09.16 - 23.09.16

HELMHOLTZ ASSOCIATION

DESY

The cosmic-ray puzzle.



What are the processes that drive the universe so far out of thermal equilibrium and in which cosmic environments do they happen ?

Cosmic rays are important!

Energy densities in the Milky Way

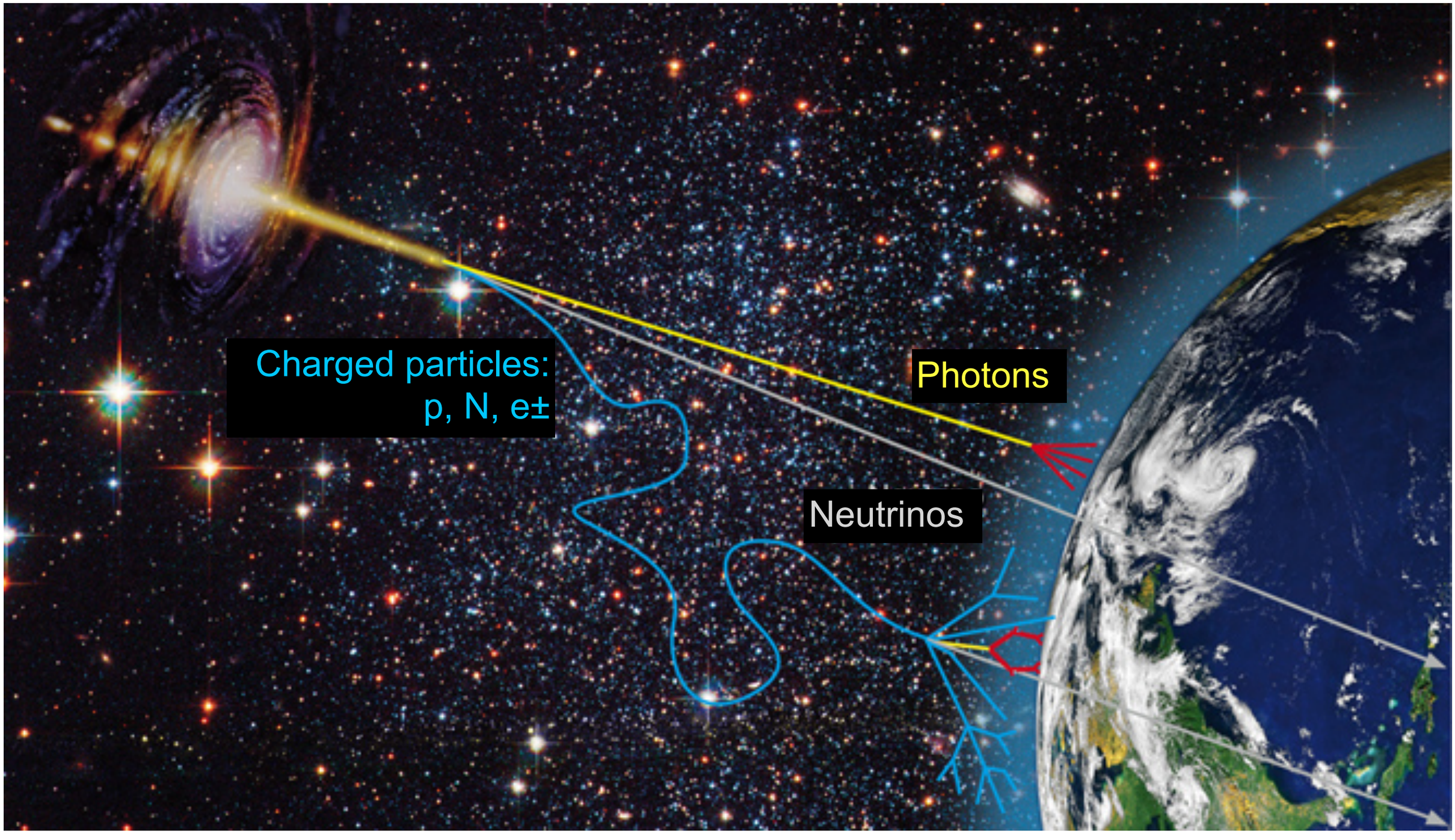
	Energy density
Cosmic rays	**0.8 eV / cm^3**
CMB	0.3 eV / cm^3
Starlight	0.5 eV / cm^3
Magnetic fields	~ 0.3 eV / cm^3
Gas pressure	~ 0.5 eV / cm^3

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

→ **They are important for Galaxy dynamics**

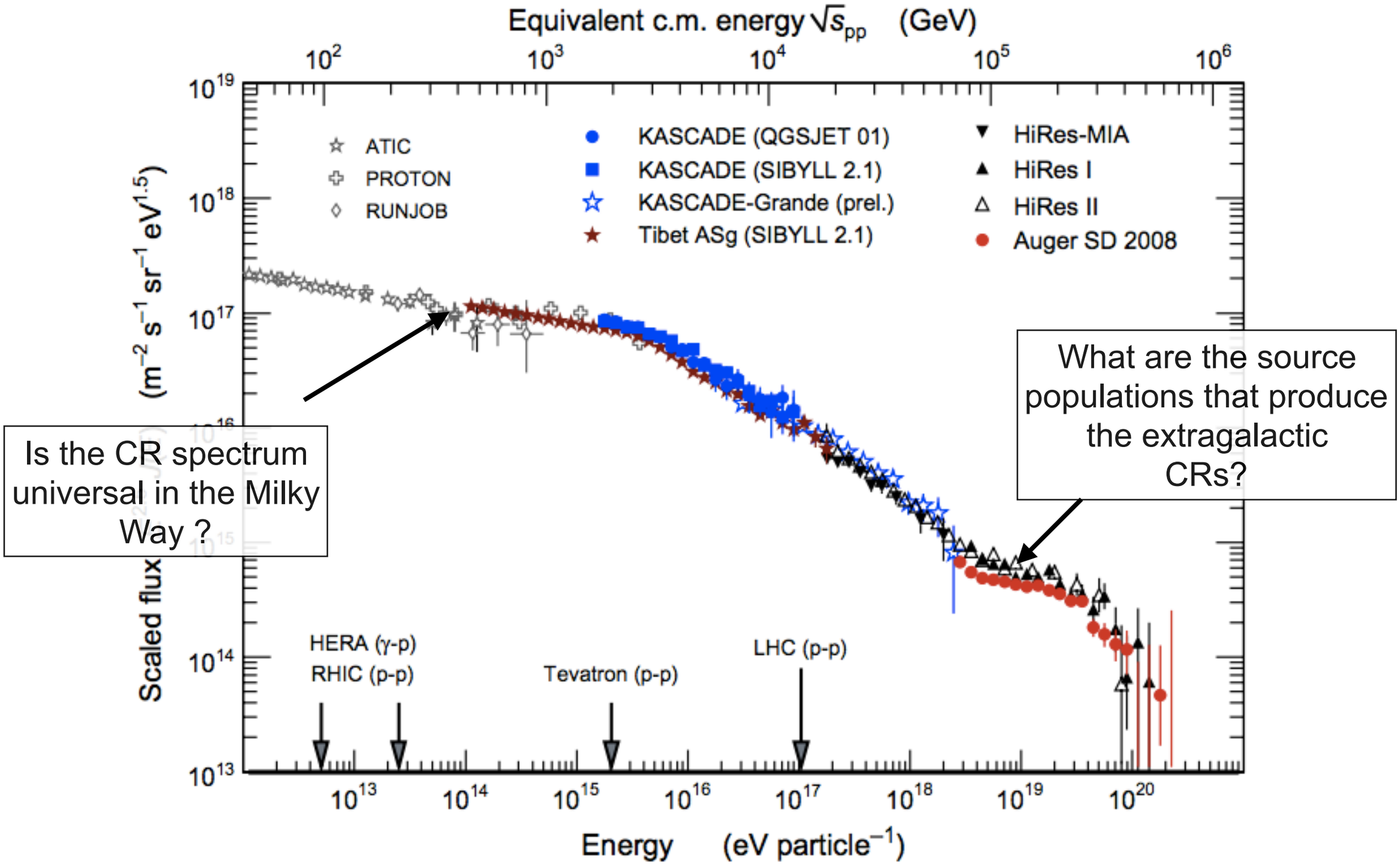
Multimessenger astronomy

> Three messengers can be used to study cosmic rays



> … you all know the advantages / limitations of each messenger.

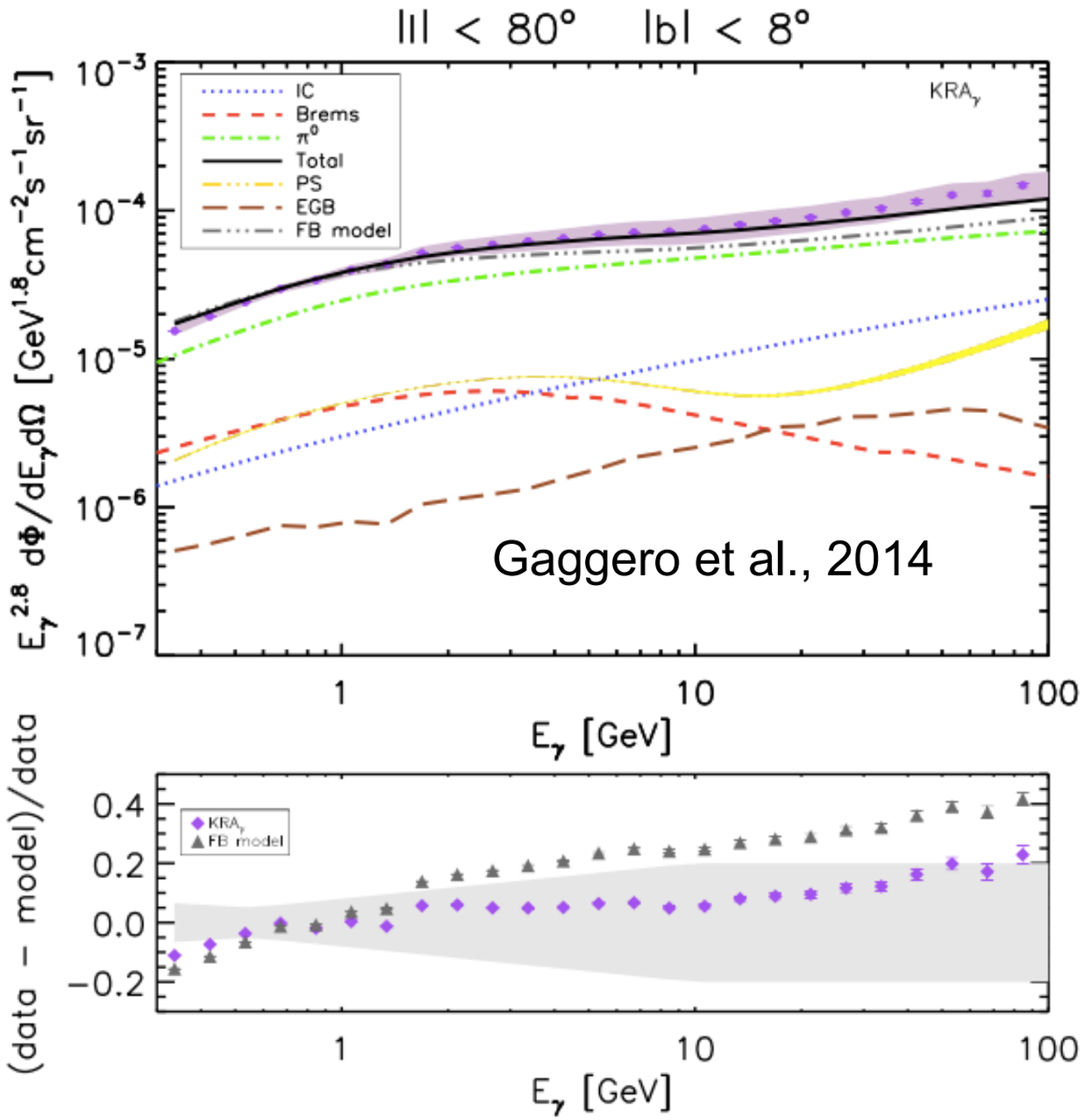
Specific questions addressed by multi-messenger astronomy

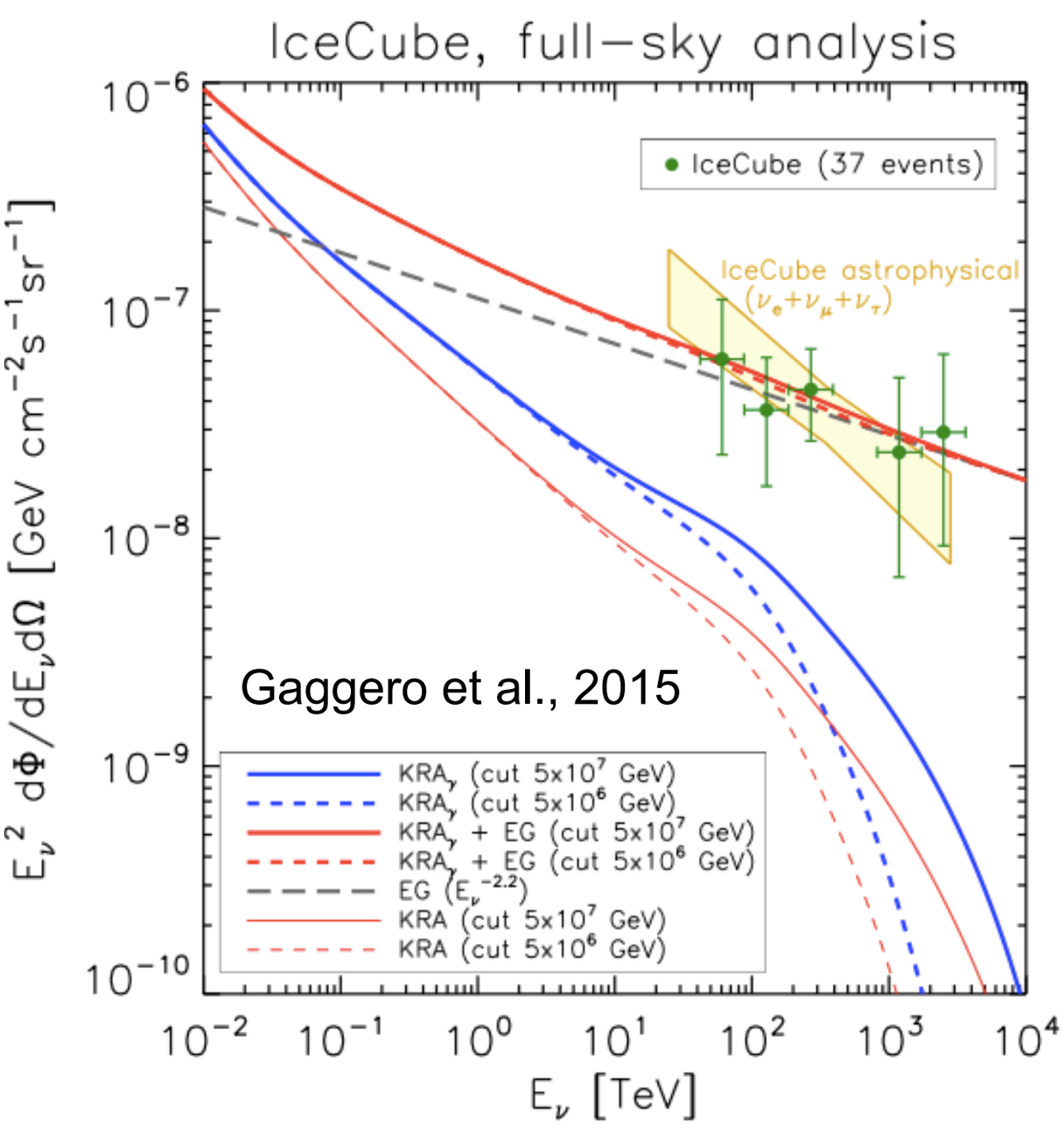


Is the CR spectrum universal in the Milky Way ?

What are the source populations that produce the extragalactic CRs?

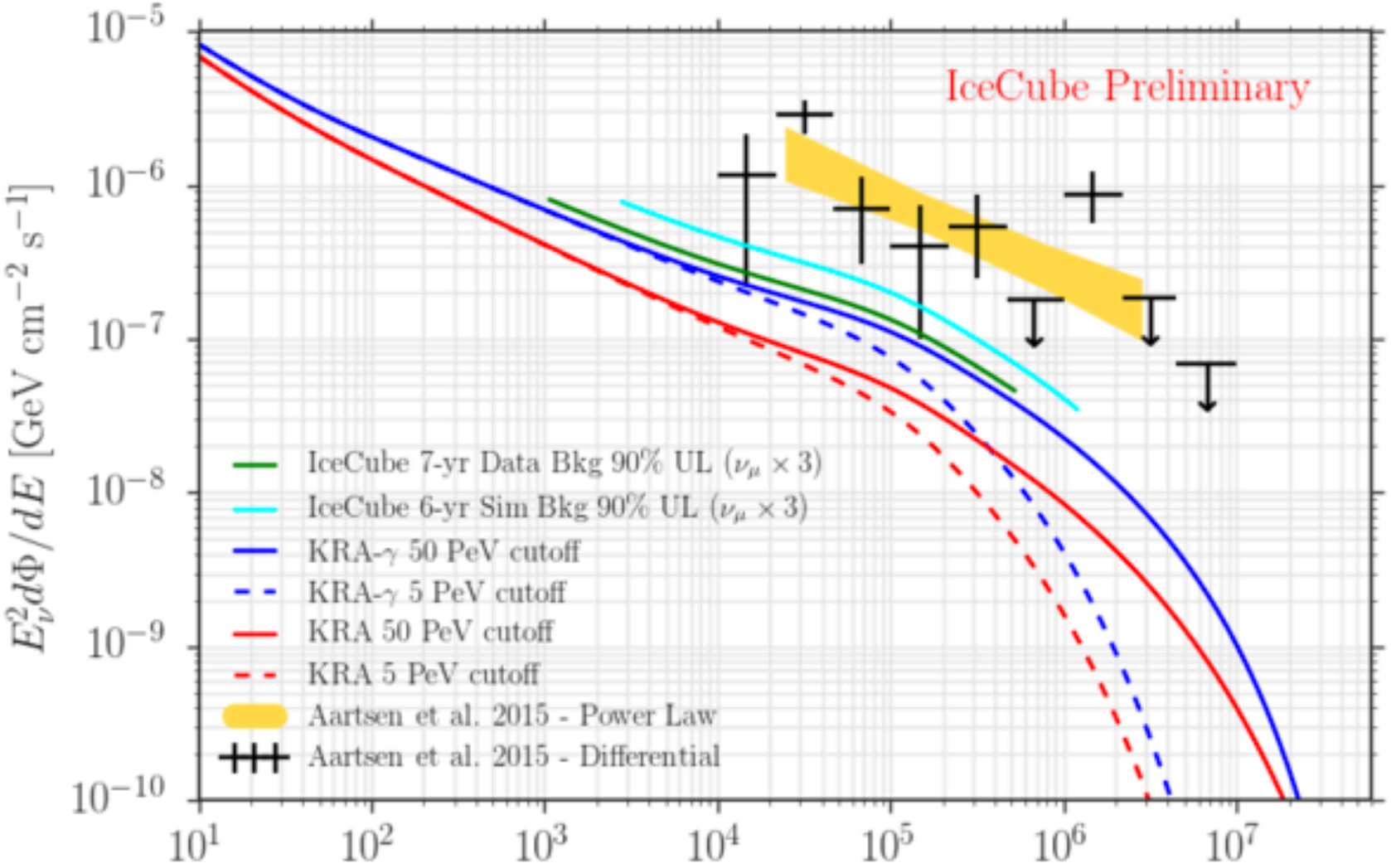
Is the CR spectrum universal in the Milky Way ?

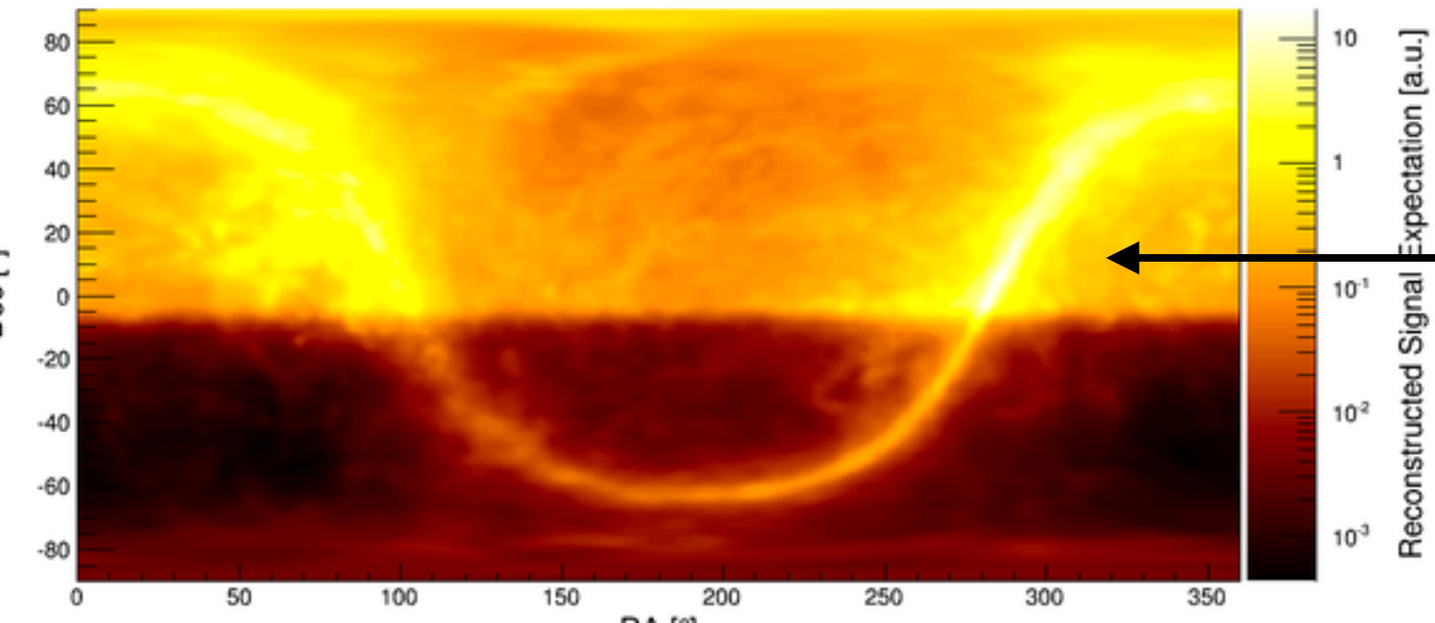




- Harder spectrum in the inner galaxy due to spatial variations of diffusion properties.
- Better description of Fermi LAT / Milagro data.
- Neutrino telescopes can provide constraints/measurements at tens to hundreds of TeV

Is the CR spectrum universal in the Milky Way ?

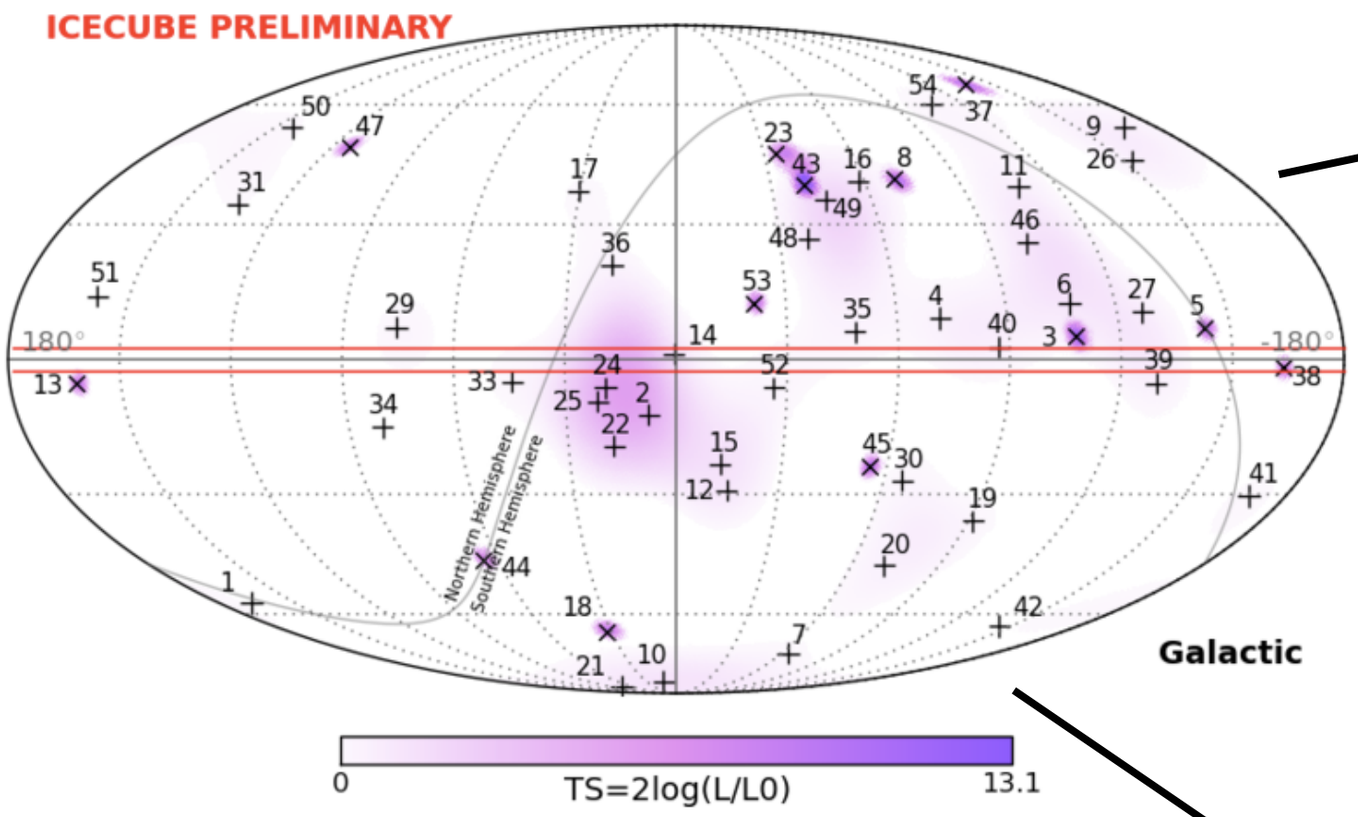


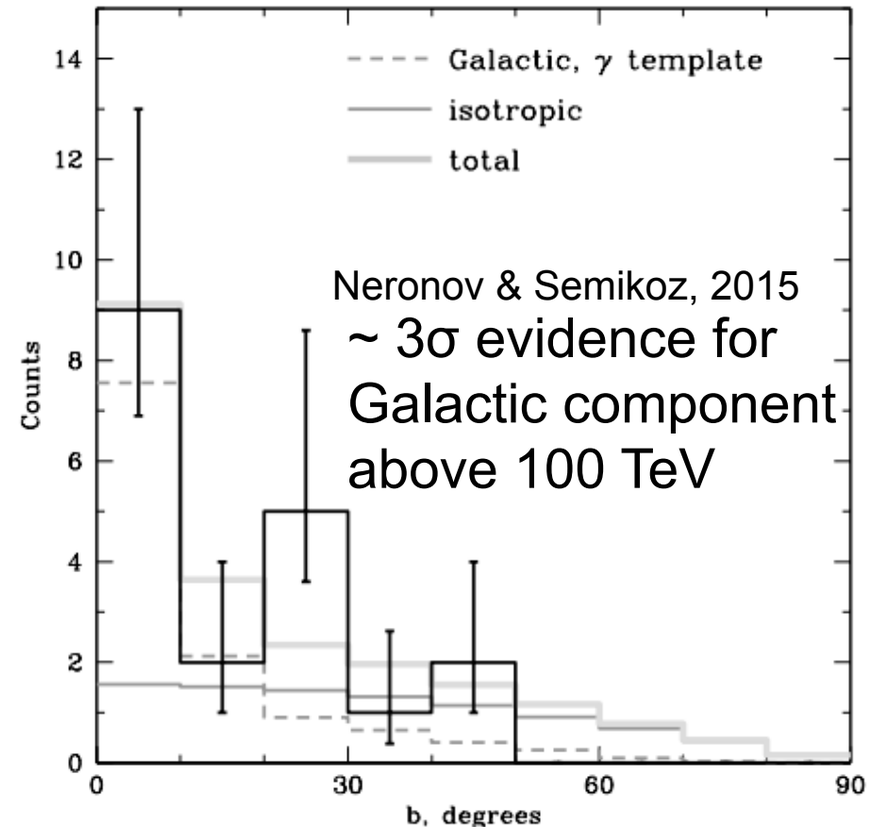


Expected signal

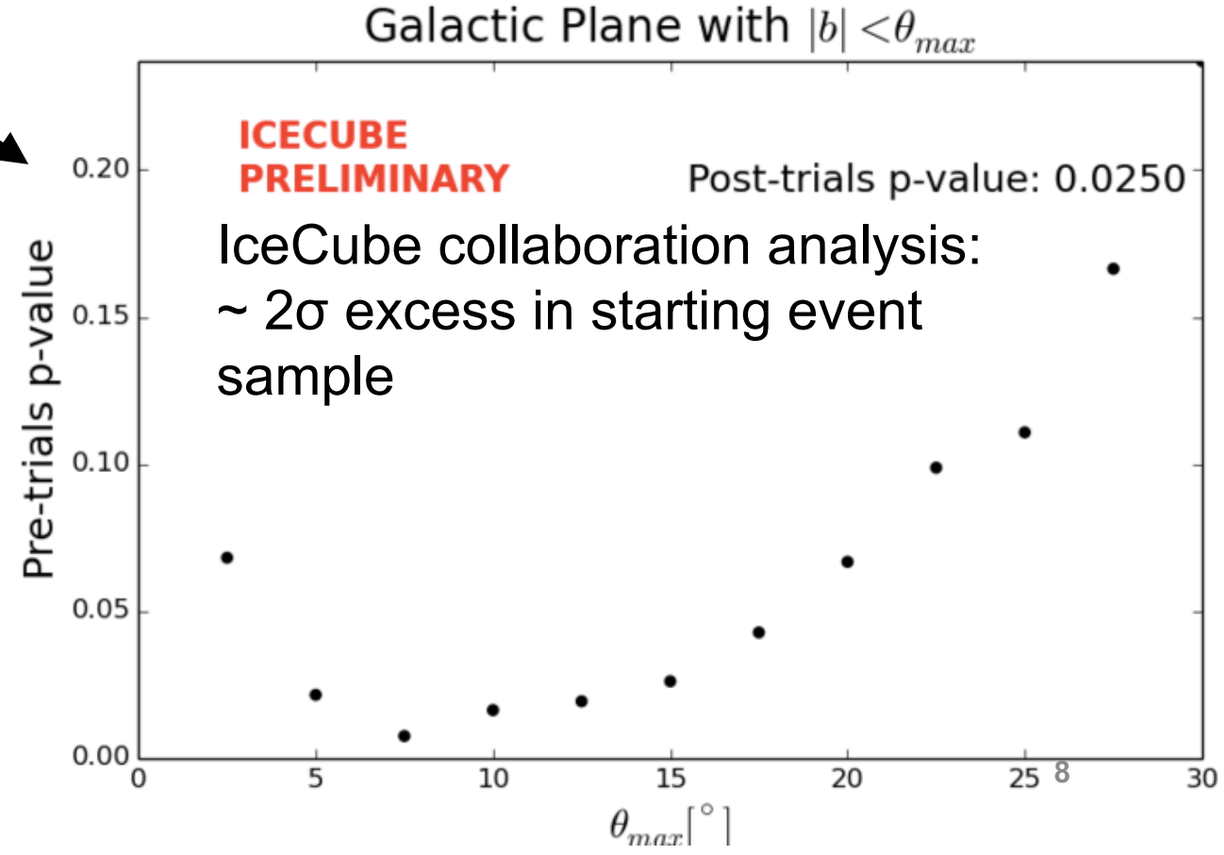
- No evidence of enhanced emission from the Galactic plane
- Based on 700.000 muon tracks and 7 years of IceCube data.
- But limits yet to weak to really constrain models.
- less than 16% of the observed cosmic neutrino flux correlated with galactic plane.

Low significance Galactic plane excess.





- But some evidence for correlation found by Neronov & Semikoz above 100 TeV.
- 200 TeV neutrinos are produced by ~ 4 PeV nucleons.
- Isotropic/extragalactic component exists in any case



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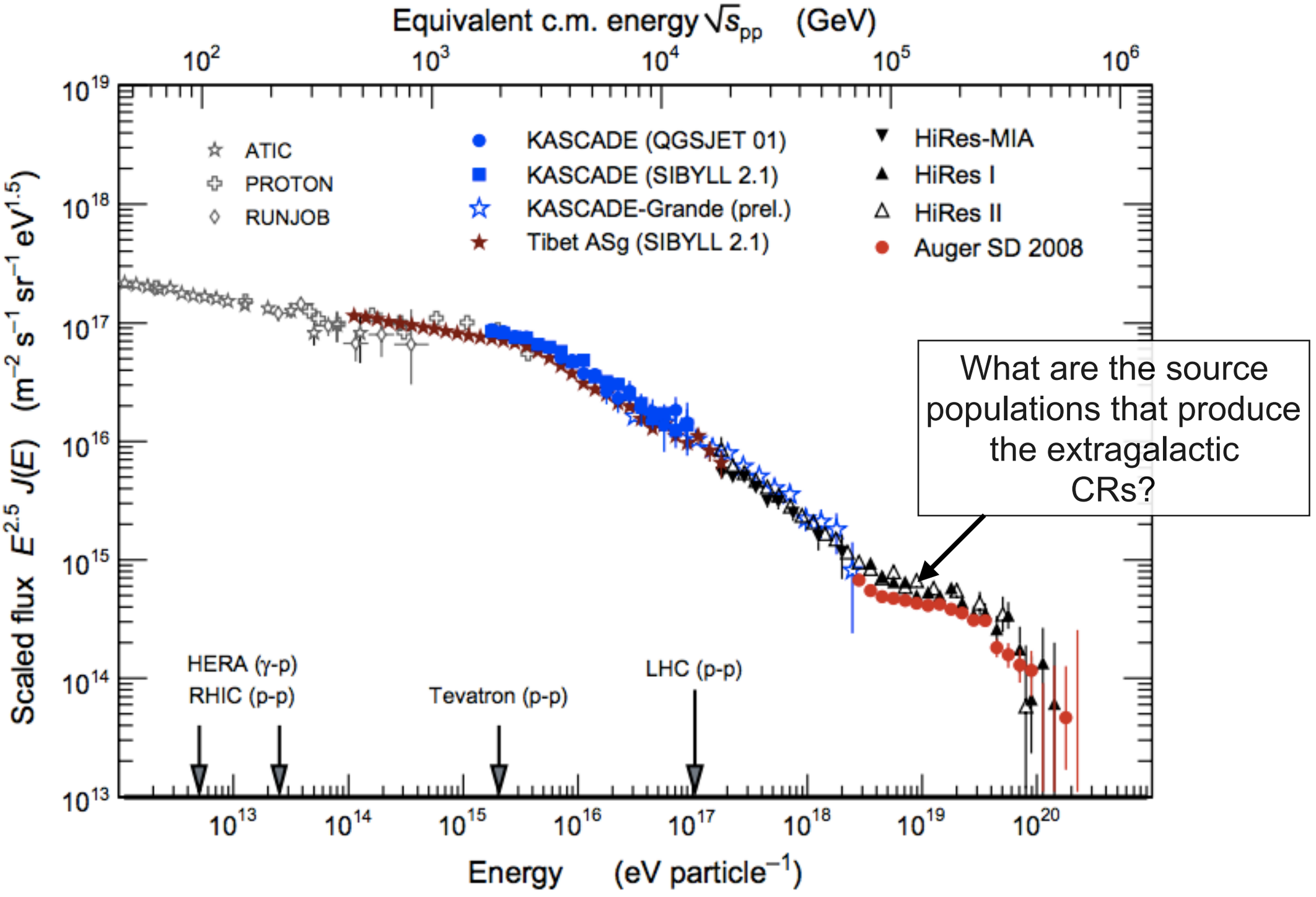
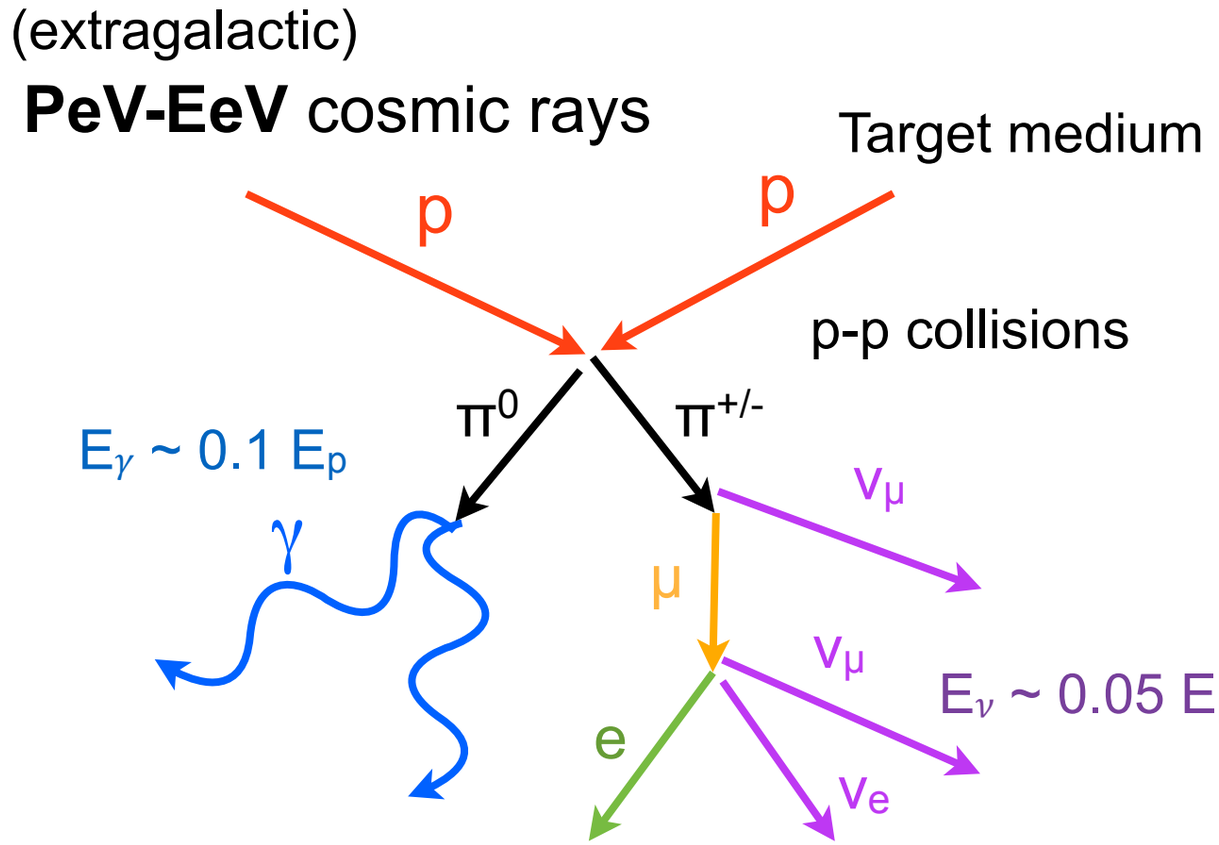


The cosmic-ray / gamma / neutrino connection

> Cosmic rays interact with a target medium close to the source.

> ν / γ - production via p-p or p-γ collisions

> Reprocessing of γ rays to GeV energies.



TeV-PeV Neutrinos

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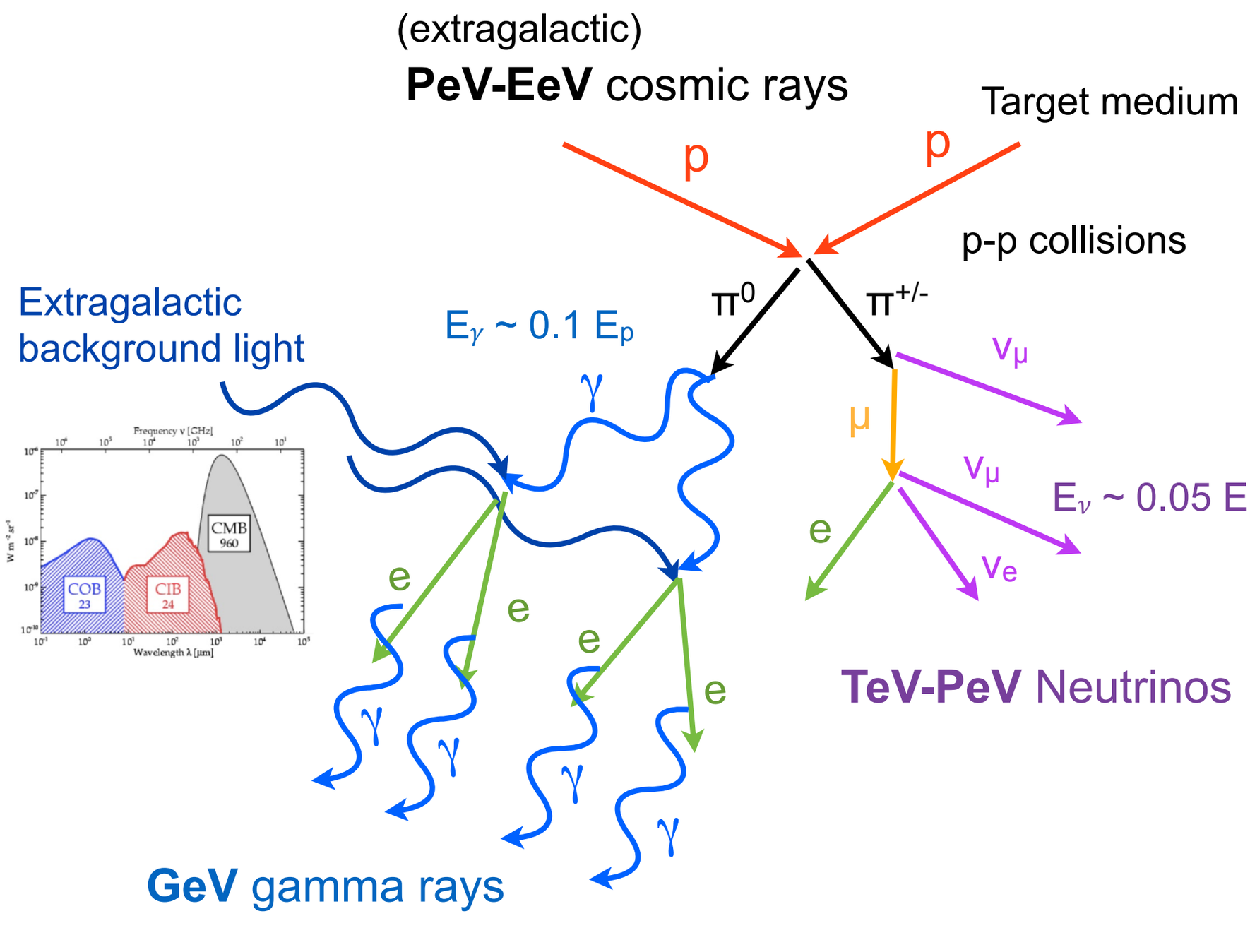
- Reprocessing of γ rays to GeV energies.



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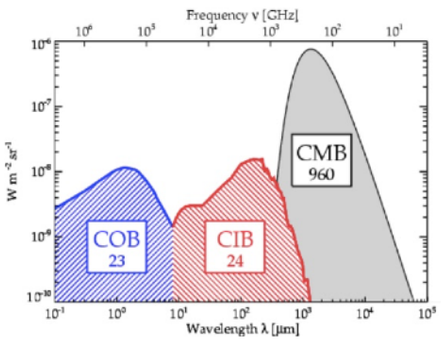
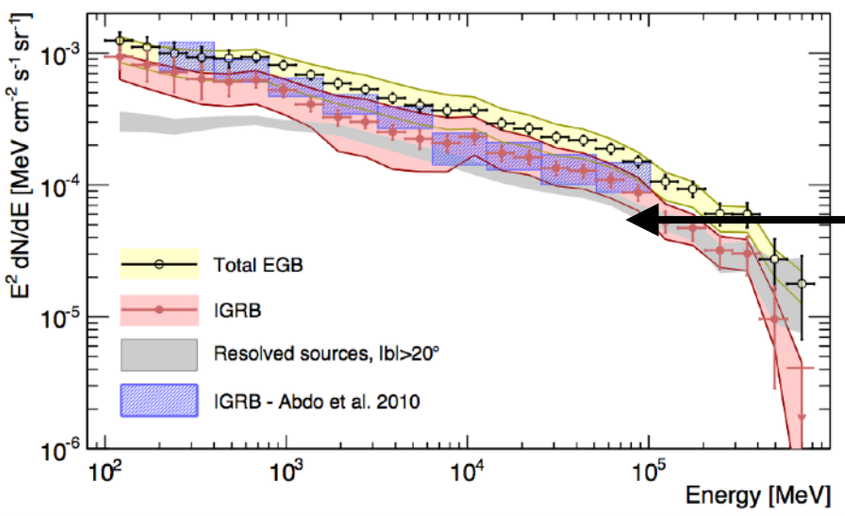
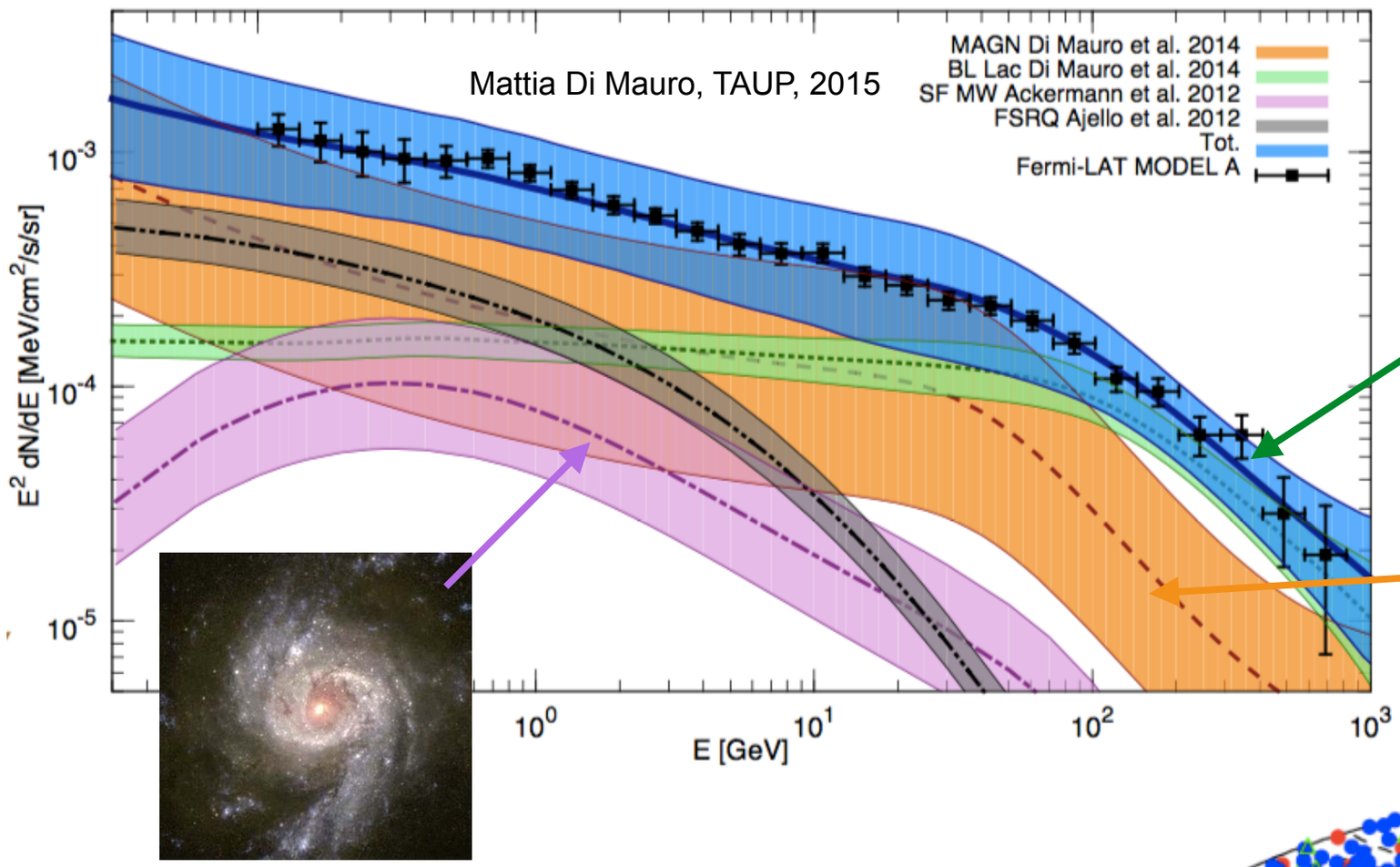




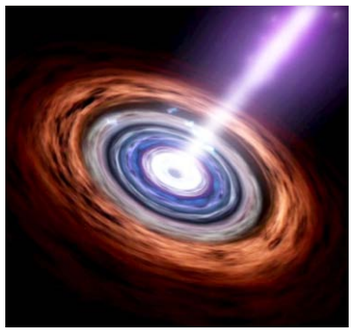
EGB is an upper bound on CR interaction and the production mechanisms for extragalactic TeV-PeV neutrinos!

Extragalactic gamma-ray emission in the GeV band.

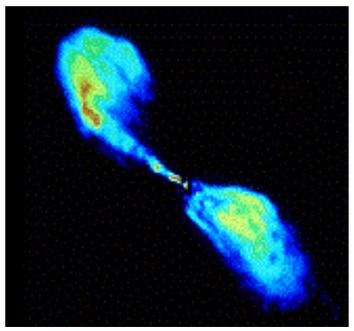


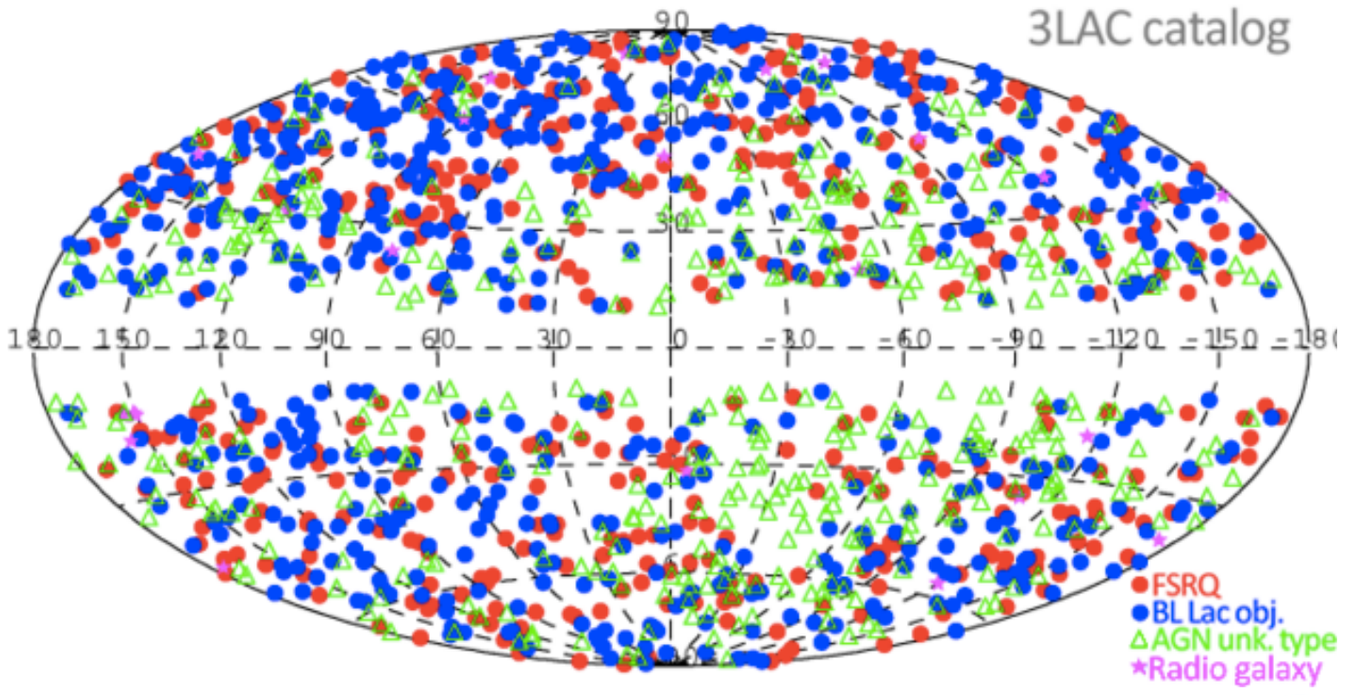
Star-forming galaxies

Blazars



Radio Galaxies



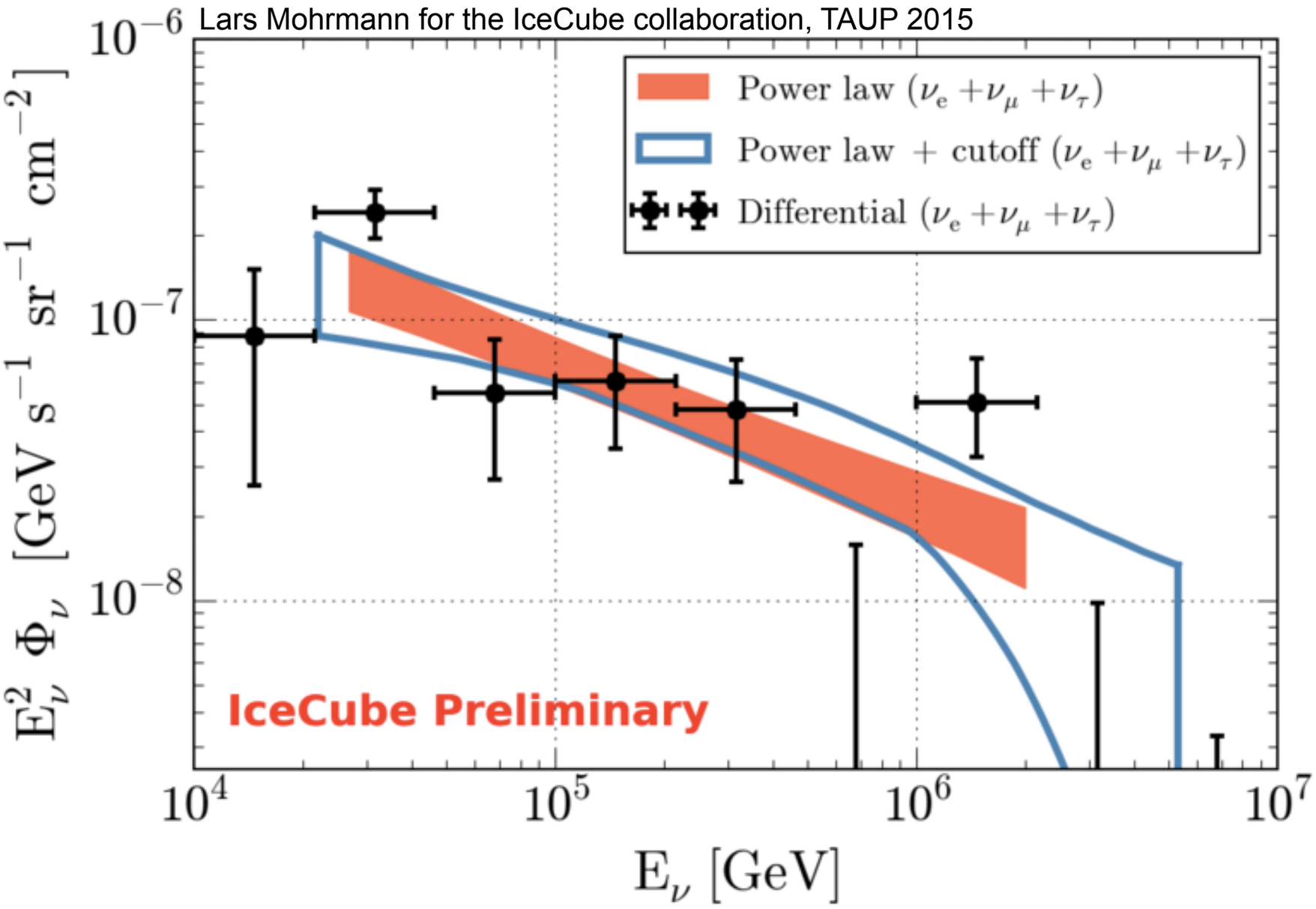


- Contribution from unresolved sources can be estimated.
- Most of the extragalactic gamma-ray emission above 10 GeV originates from Blazars.

The extragalactic neutrino background

> New measurements indicate features in the spectrum.

Lars Mohrmann for the IceCube collaboration, TAUP 2015



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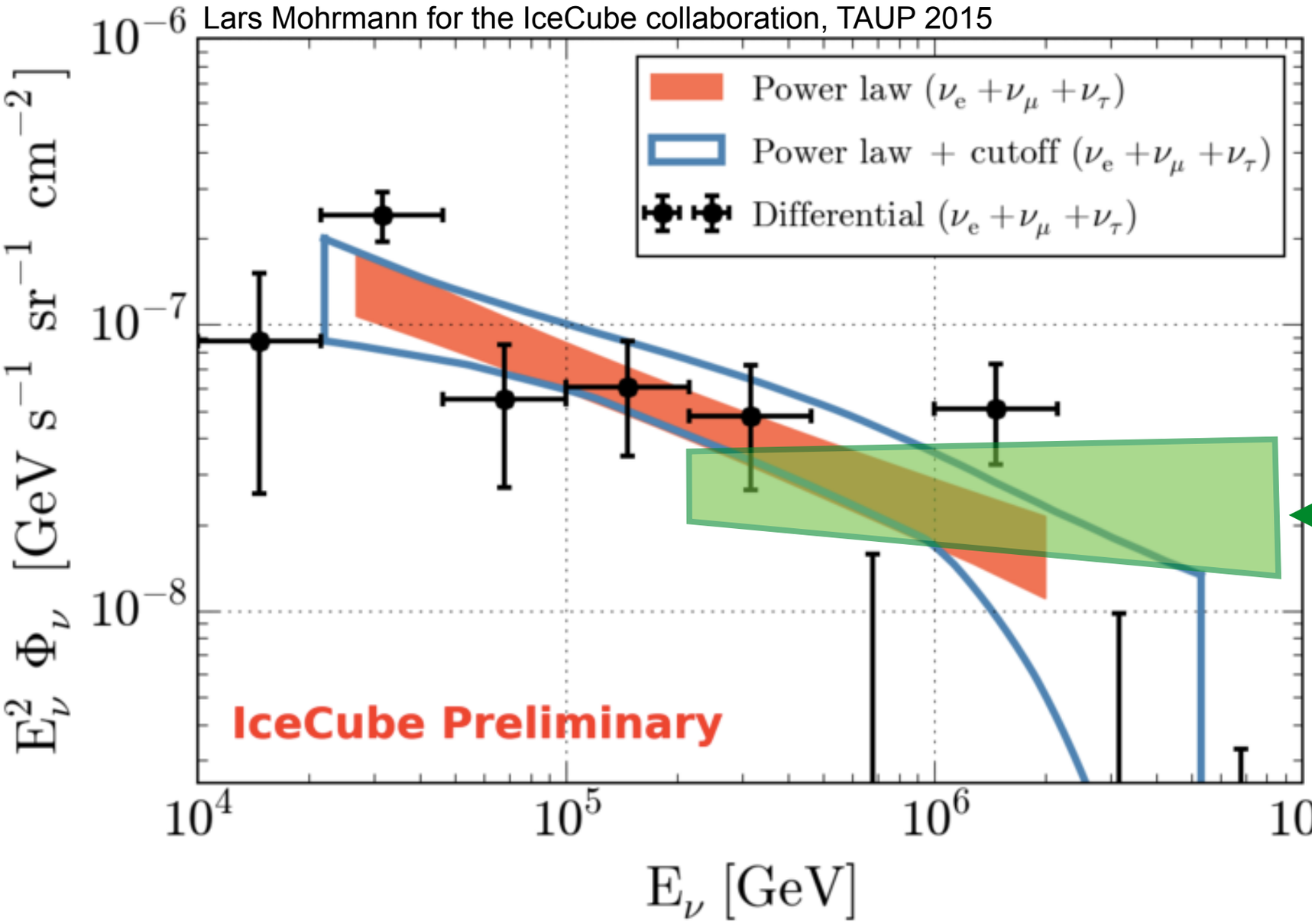

arXiv:1607.0800

This energy range assumes an unbroken power-law

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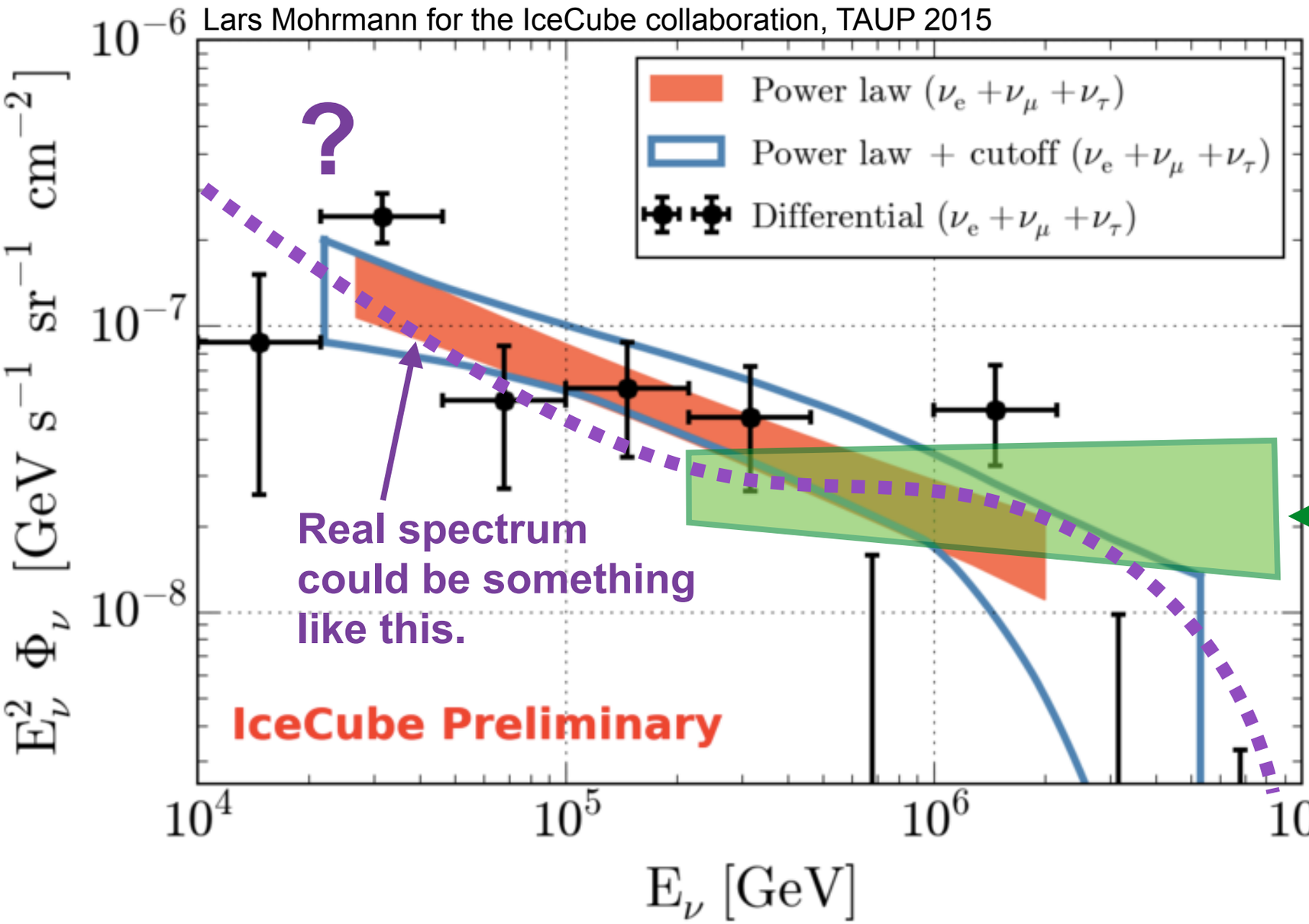
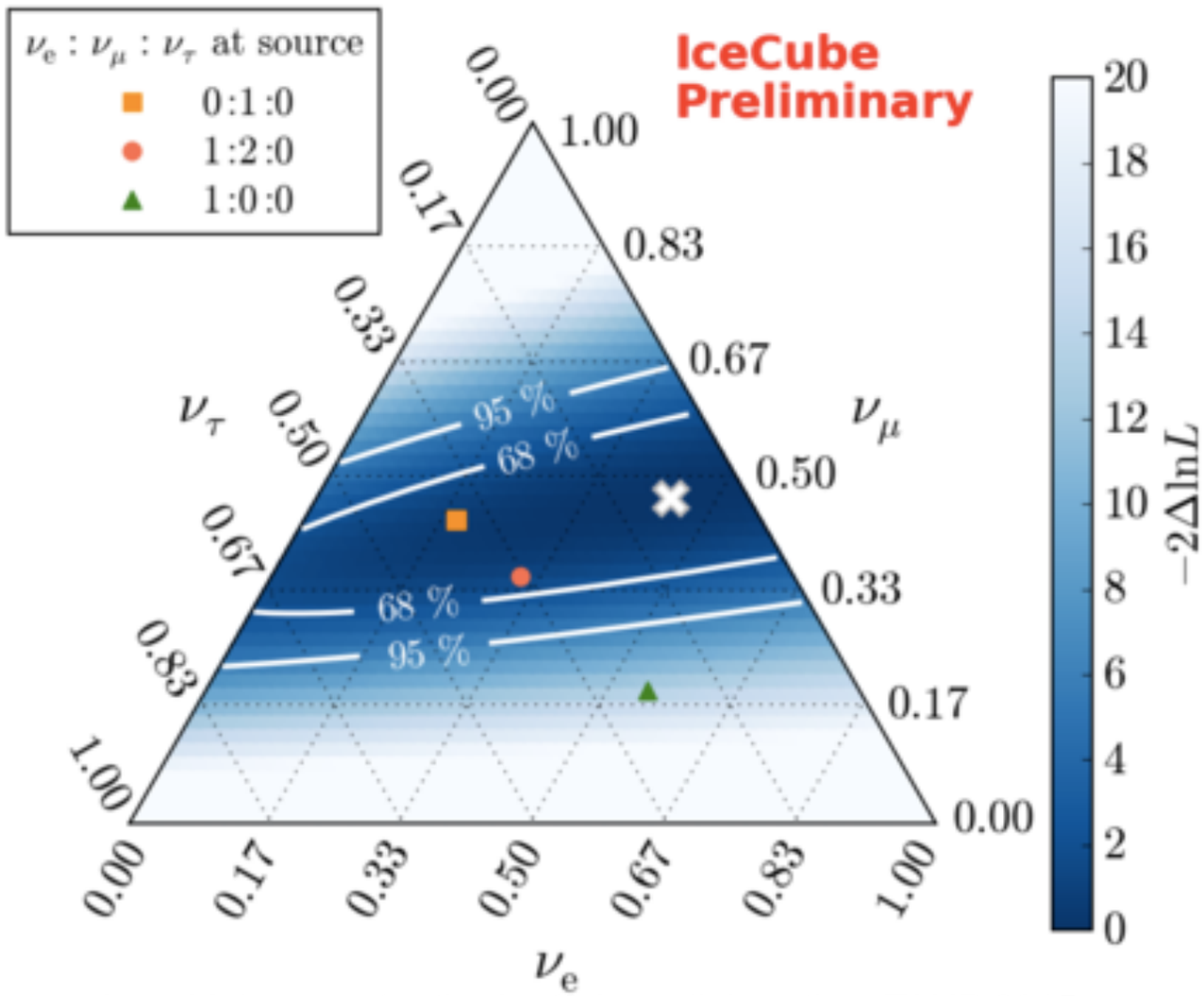


arXiv:1607.0800

This energy range assumes an unbroken power-law

Neutrino flavor ratio constraints.



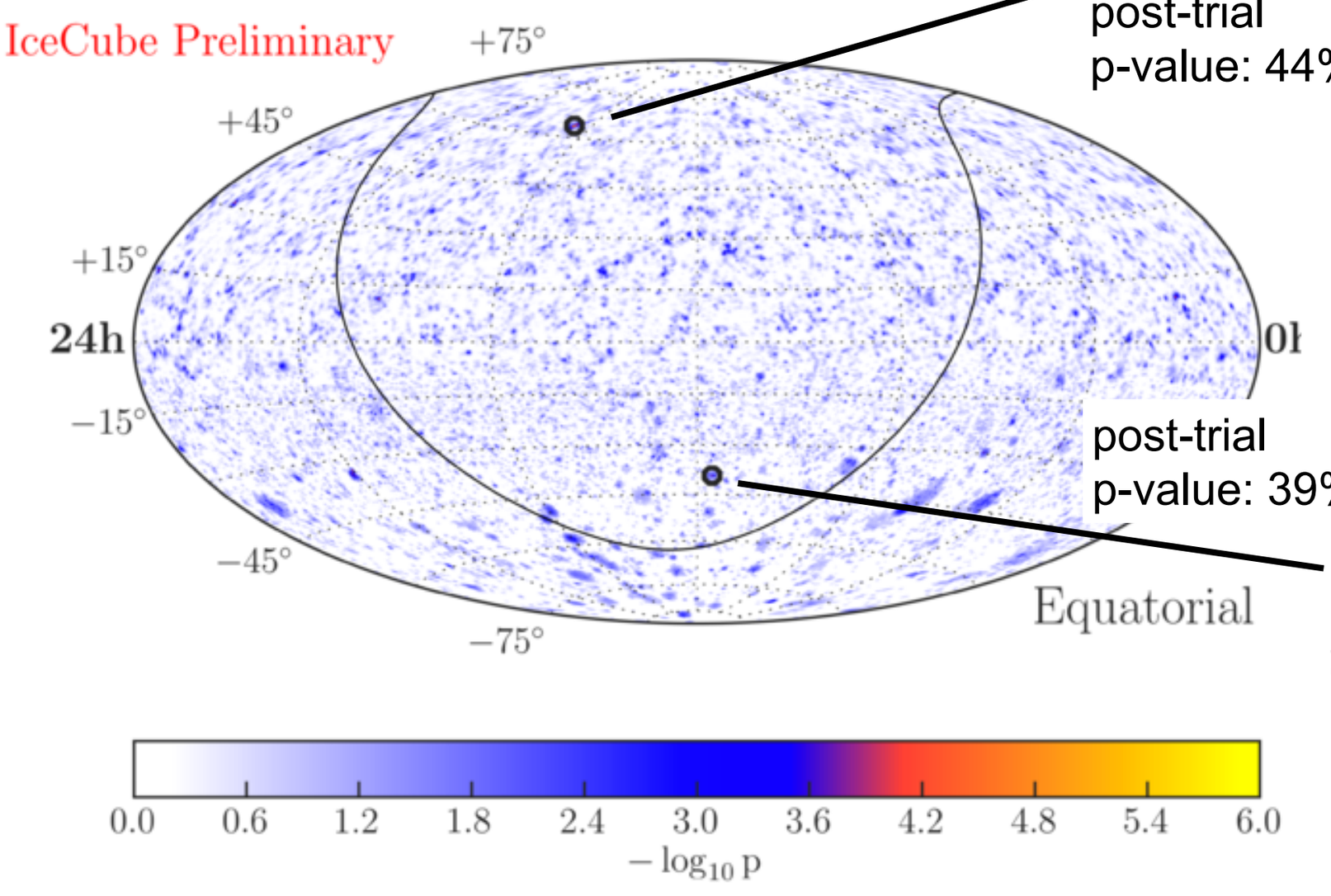
Lars Mohrmann for the IceCube collaboration, TAUP 2015

> Flavor ratios **compatible with standard pion decay production** (1:2:0) and **muon damped scenarios** (0:1:0)

> **Beta decay origin** (1:0:0) can be excluded at 3σ level.

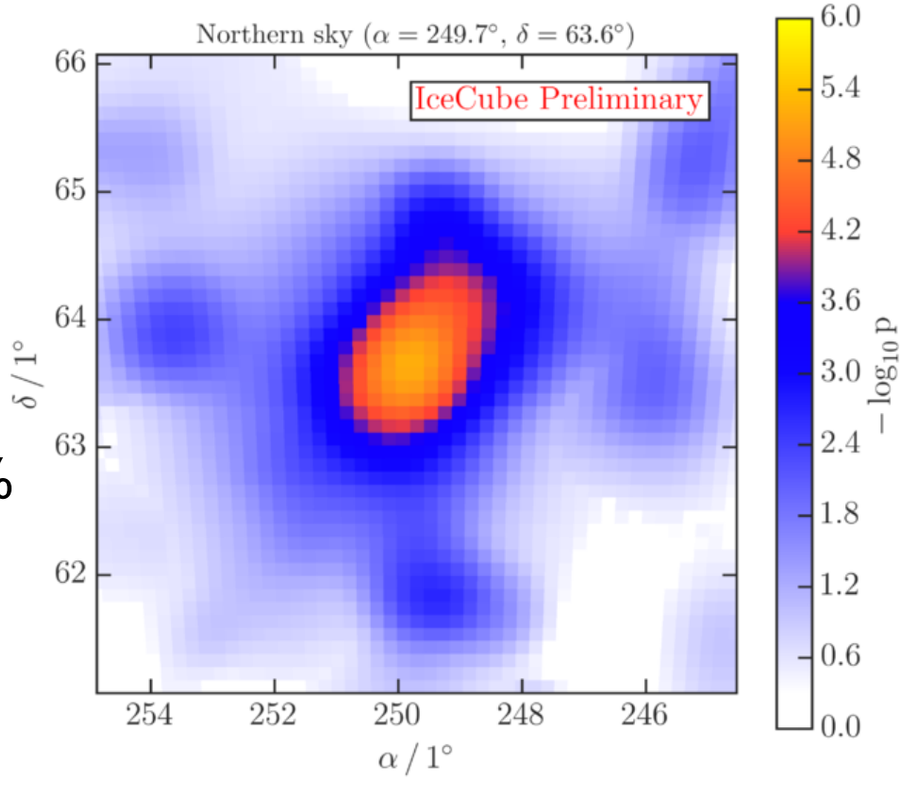
But there are no sources !

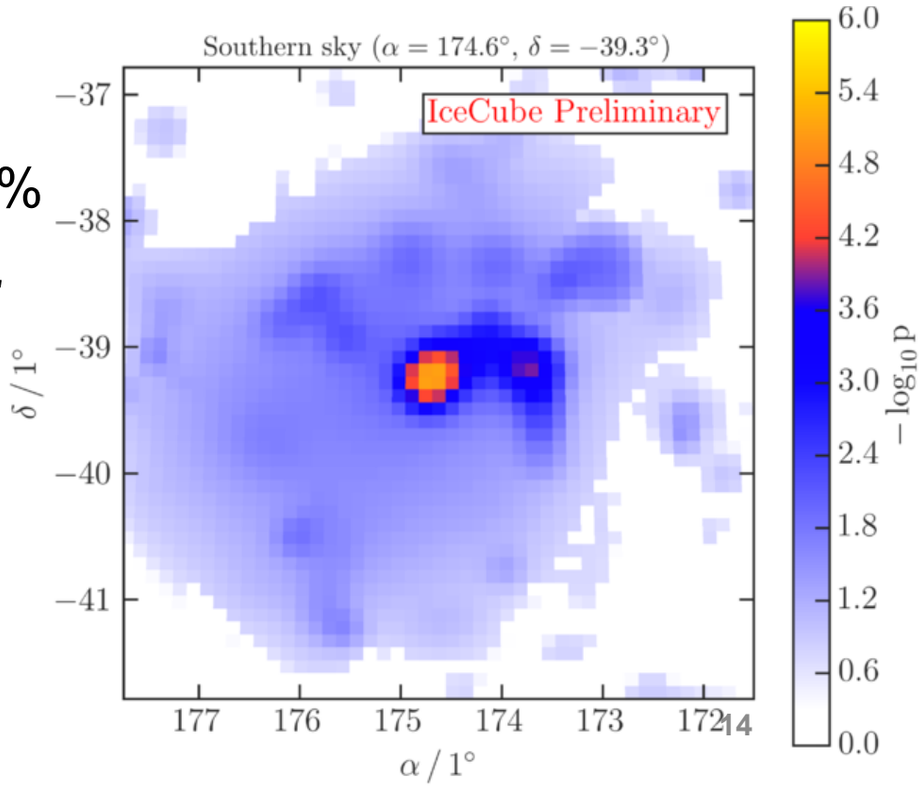
- 7 **years** of IceCube data (construction phase + full array)
- **700.000 muon track events**
- Median **angular resolution:** ~0.5 deg @ 10 TeV
- No statistically significant excess found.
- No transient found.



post-trial
p-value: 44%

post-trial
p-value: 39%

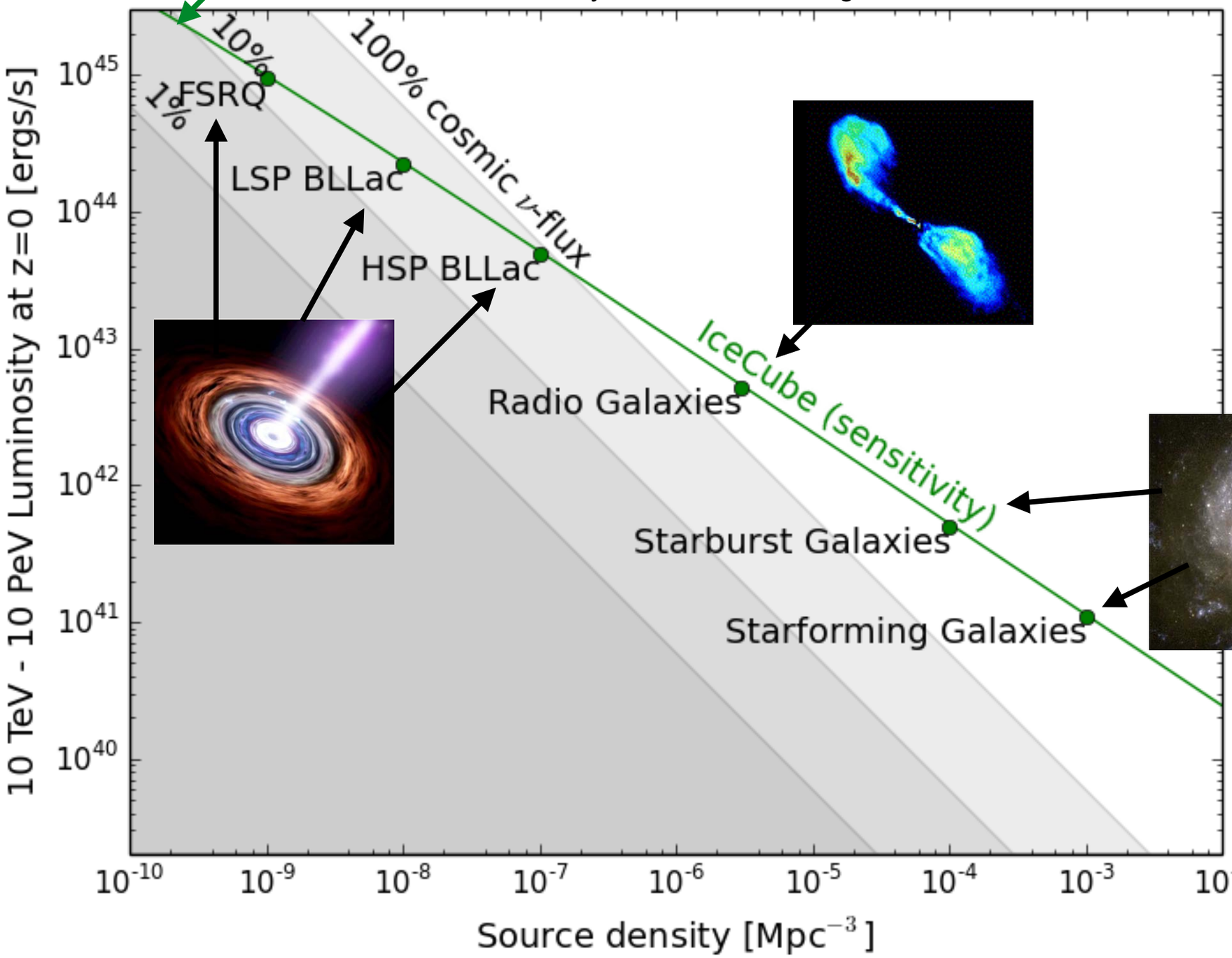


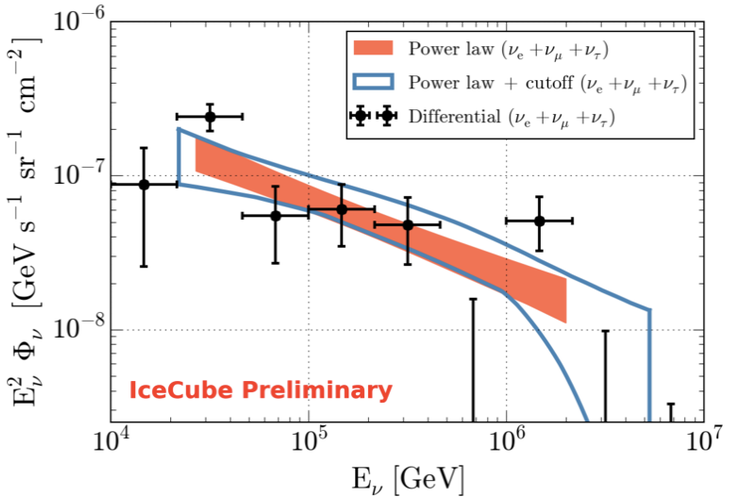


What does that imply?

Sensitivity of point source and correlation searches

a luminosity evolution according to SFR evolution is assumed

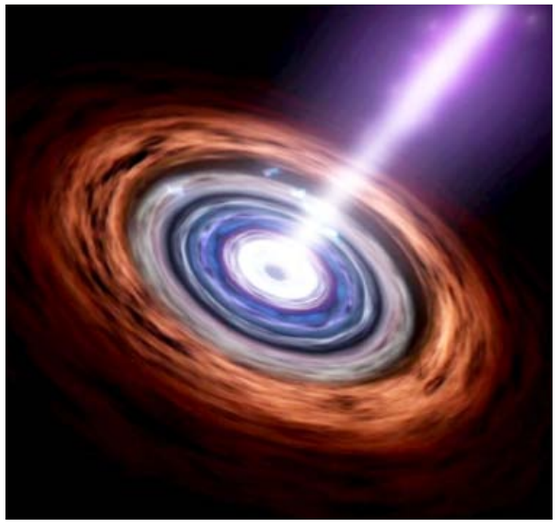


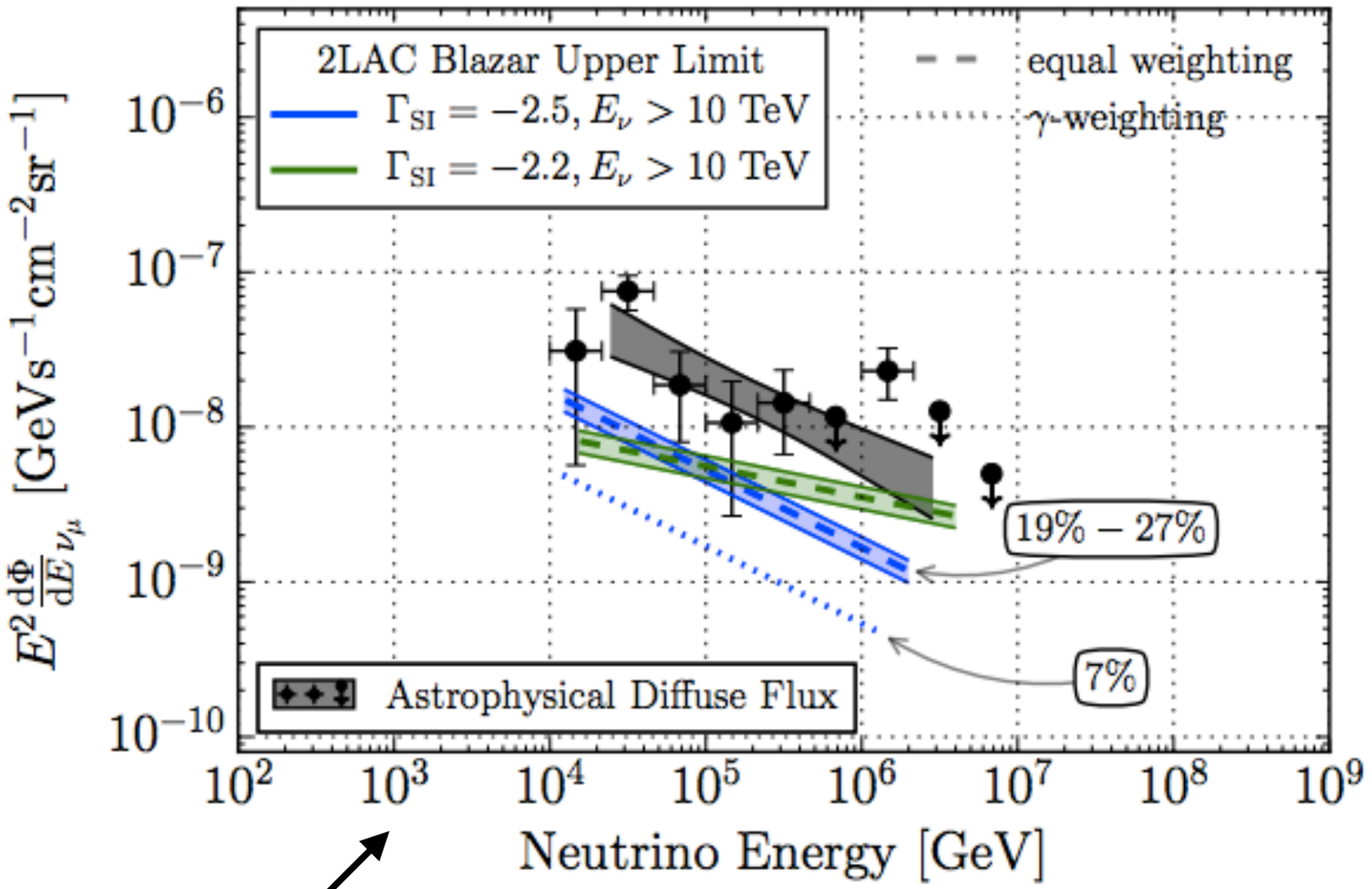


The sources of the astrophysical neutrinos must be **high-density** and **low-luminosity**

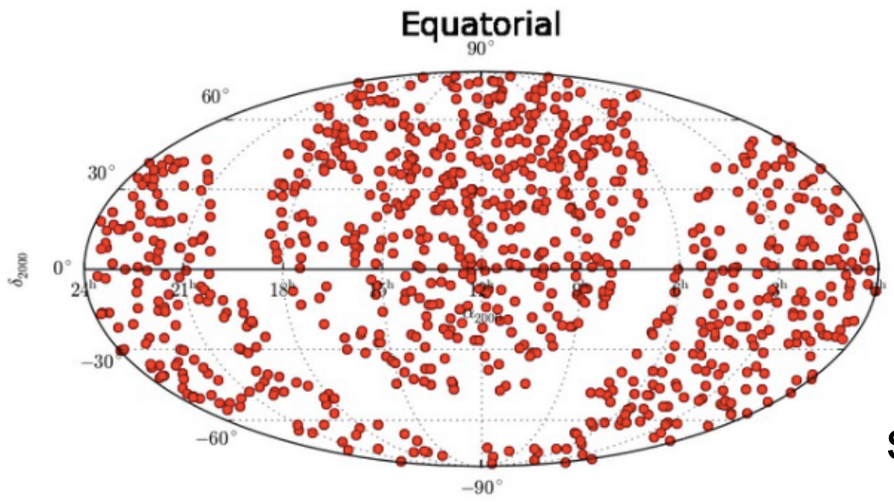
Similar arguments can be made for transient sources!

Extragalactic gamma rays and neutrinos.





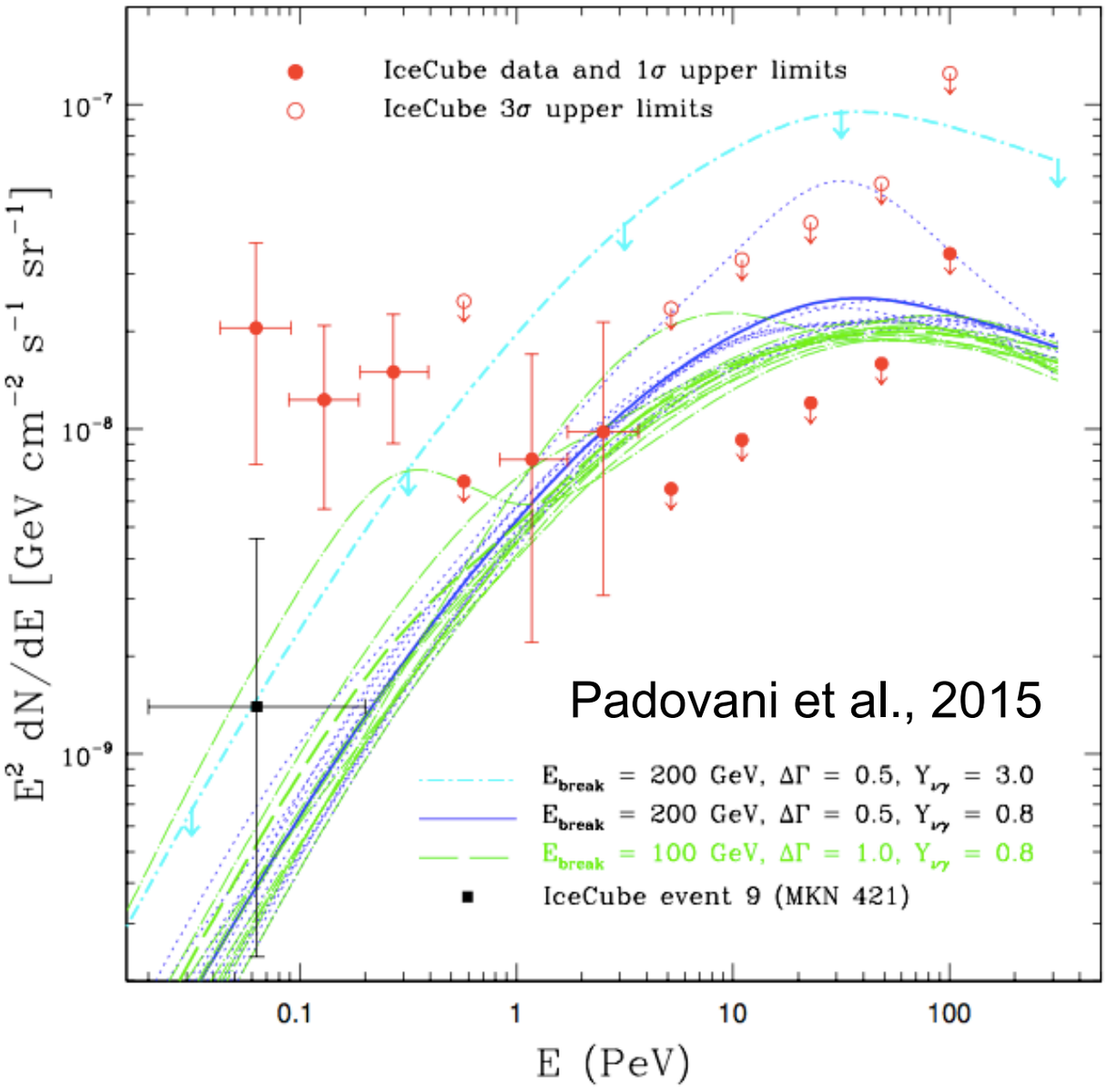
All blazars from *2-LAC* – 862 objects

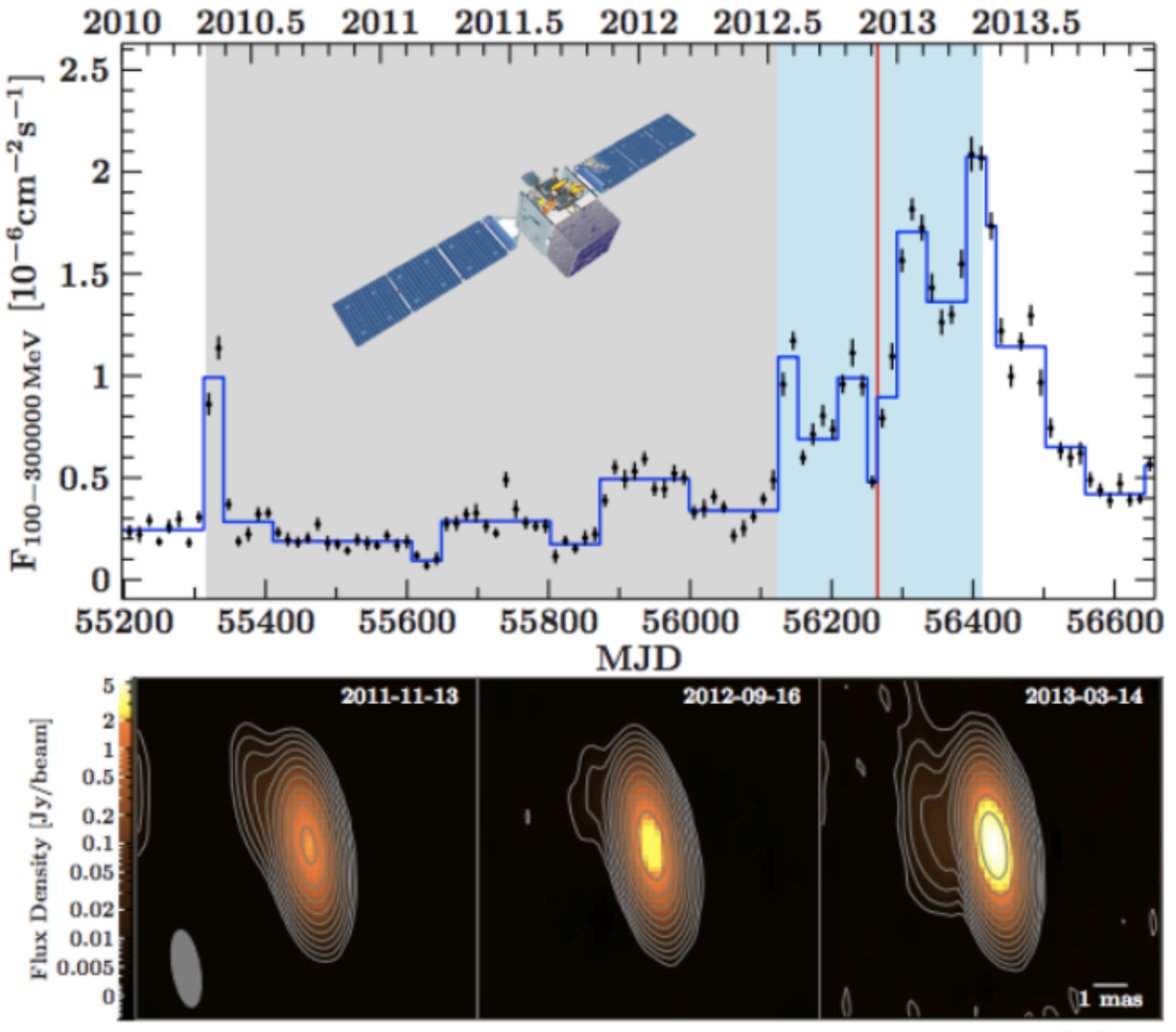


> Fermi Blazars are **NOT** responsible for most of the observed ν's.

see also talk by Anna Franckowiak

Blazars can still be subdominant populations





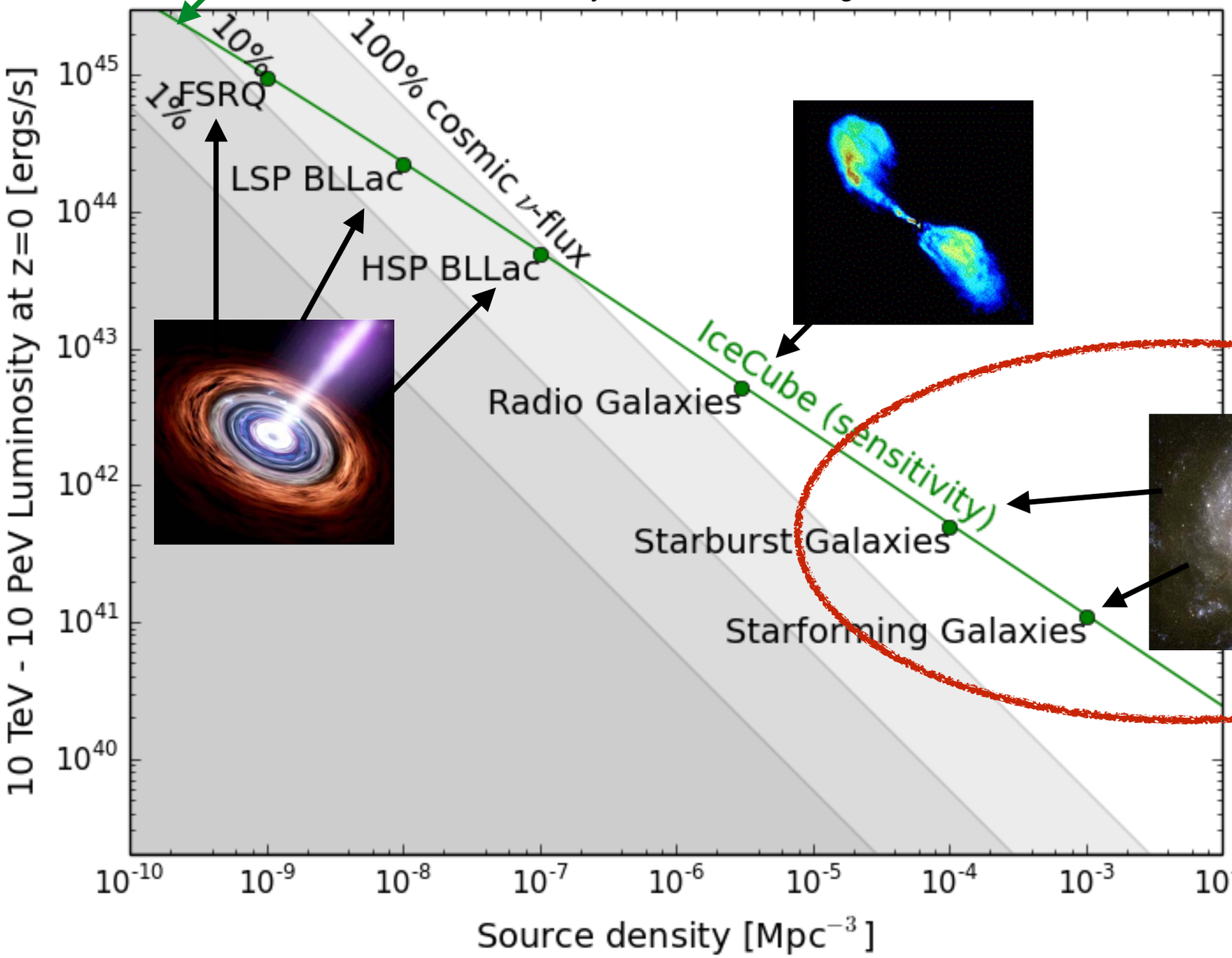
Kadler et al., 2016

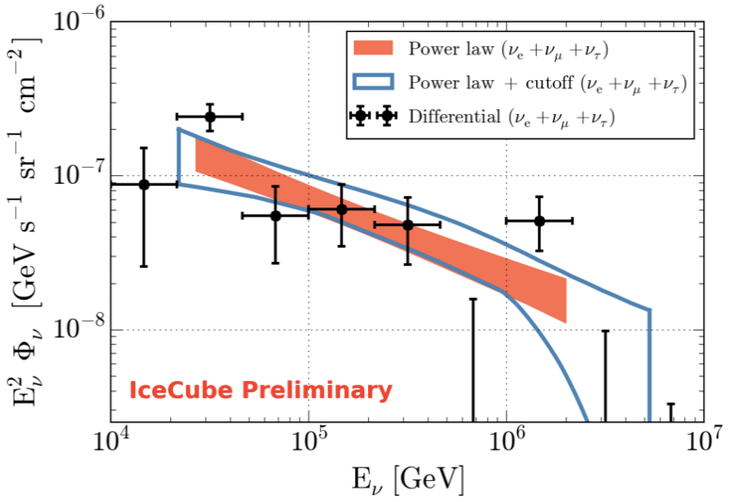
> Limits do not exclude Blazars as a subdominant population that contribute e.g. the PeV events.

What does that imply?

Sensitivity of point source and correlation searches

a luminosity evolution according to SFR evolution is assumed



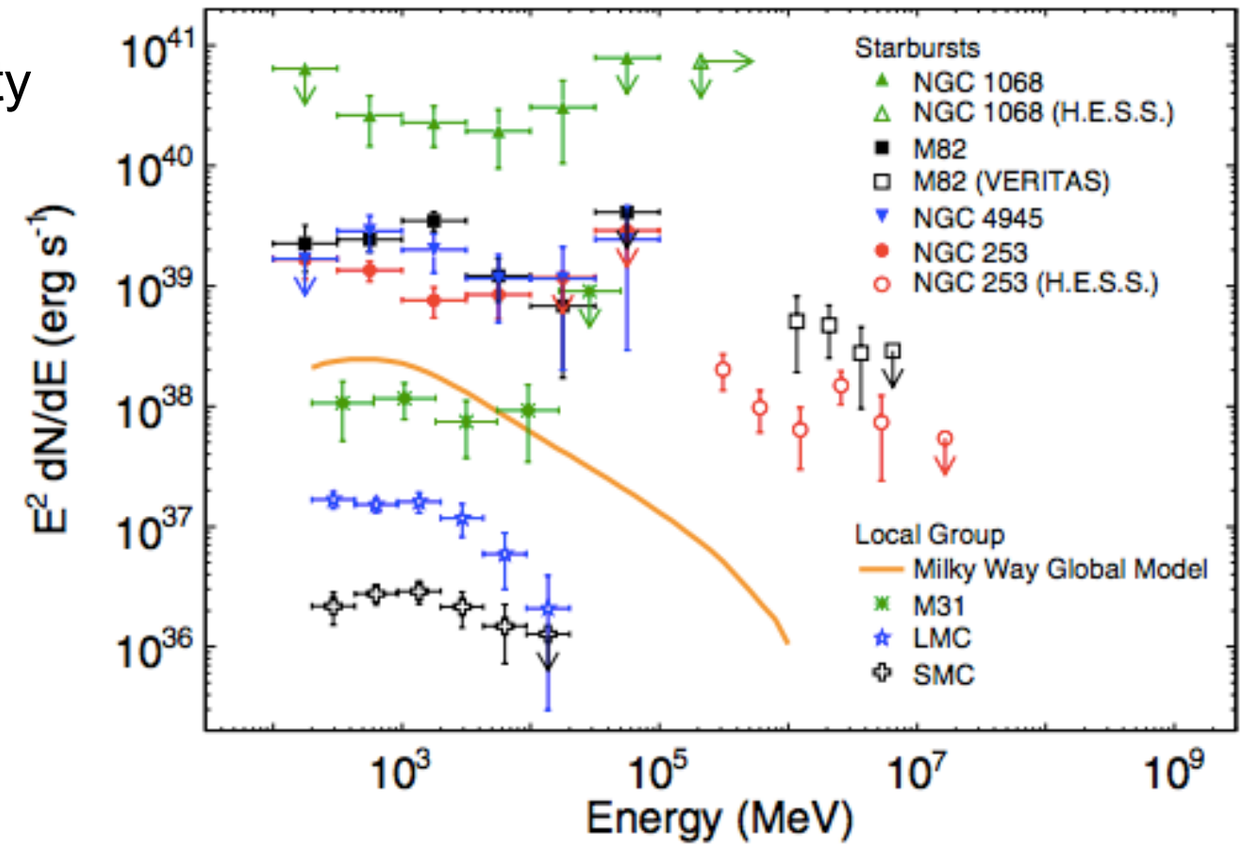


The sources of the astrophysical neutrinos must be **high-density** and **low-luminosity**

Similar arguments can be made for transient sources!

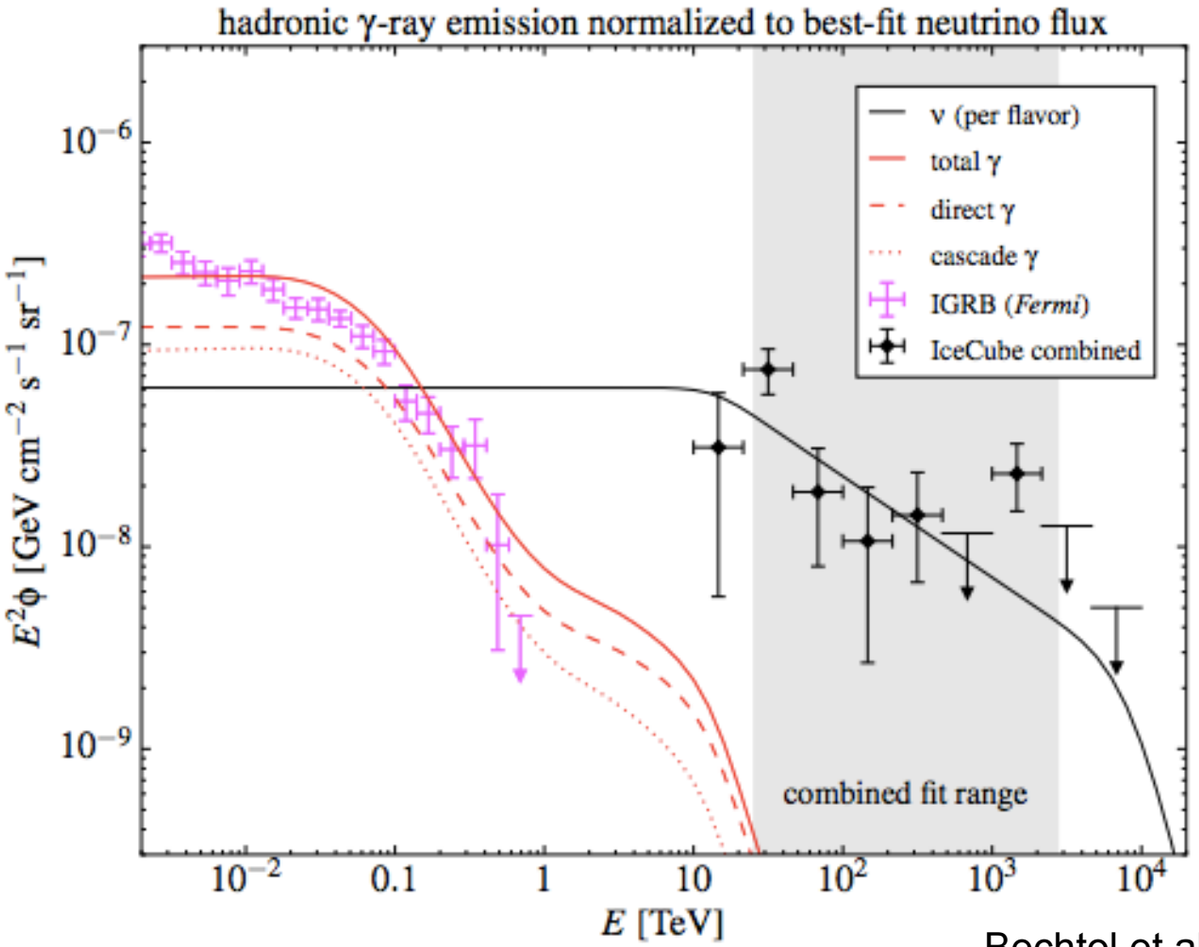
Indirect constraints on star-forming galaxies

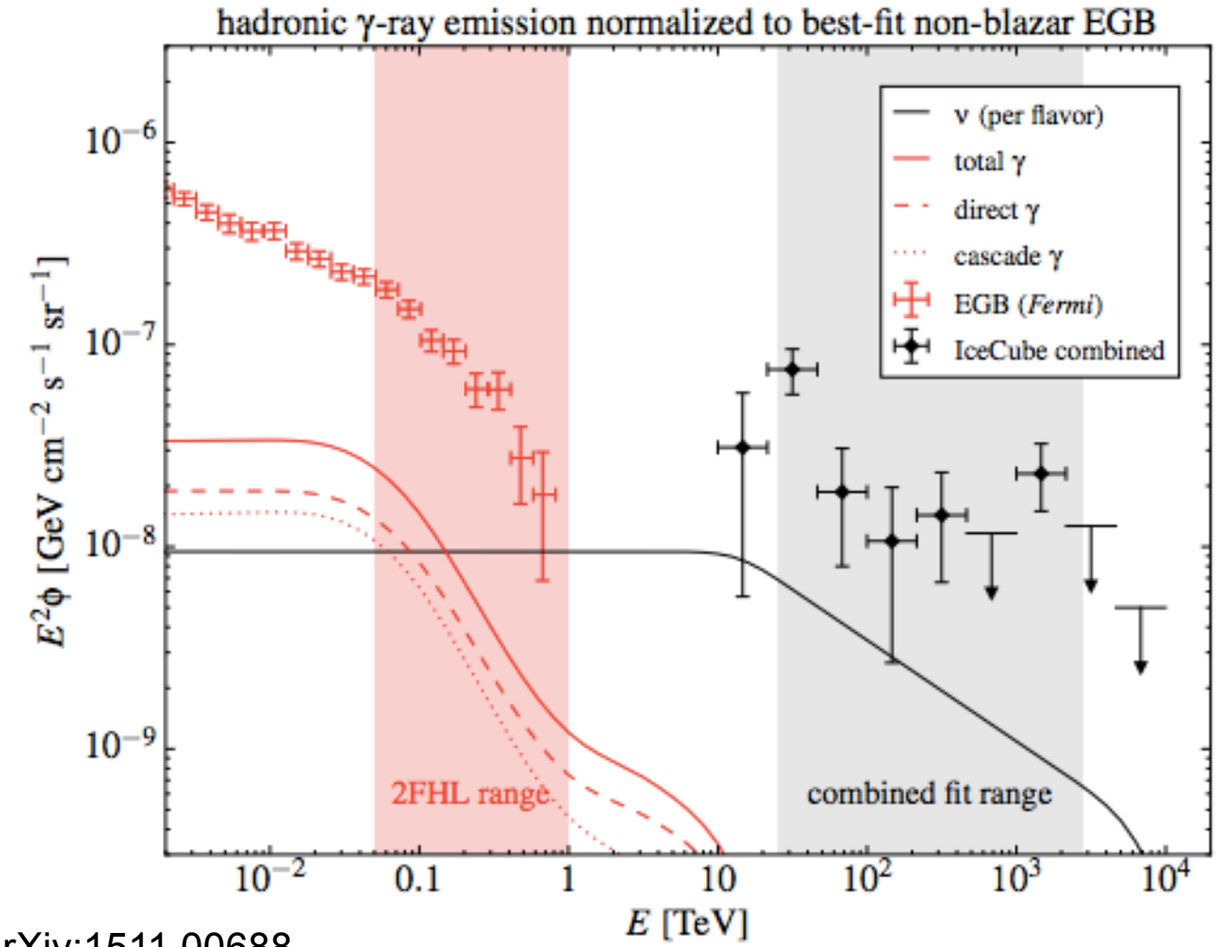
Good correlation between
SFR and gamma-ray luminosity



- Transparent sources
- Gamma-ray spectrum likely dominated by p-p interactions
- Neutrino spectrum follows gamma-ray spectrum
- Neutrino luminosity ~ gamma-ray luminosity

Neutrinos from star-forming galaxies.



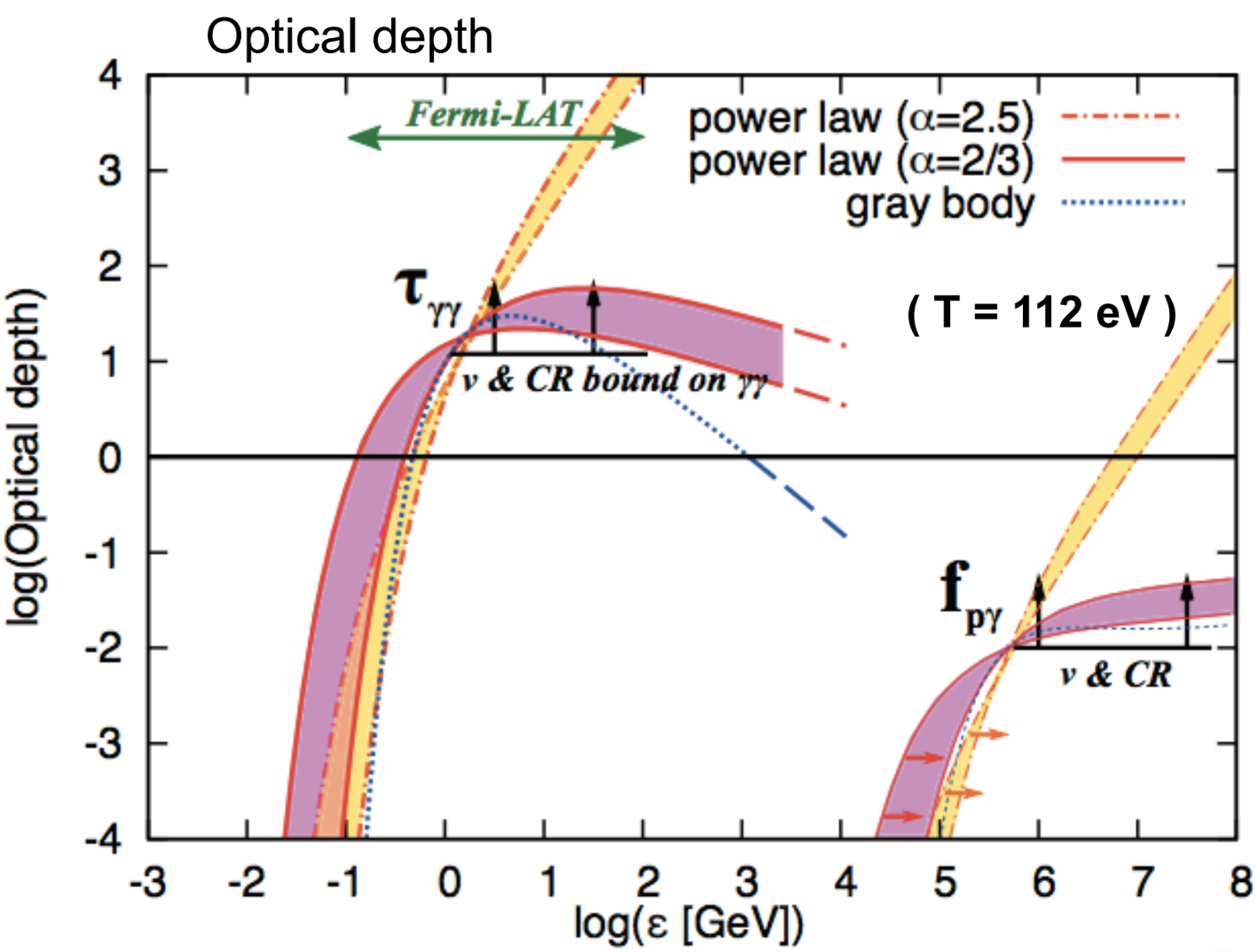


Bechtol et al., arXiv:1511.00688

> Gamma-ray emission associated with star-forming galaxies would fill up entire EGB

> Contradicts findings that most of the EGB originates from Blazars.

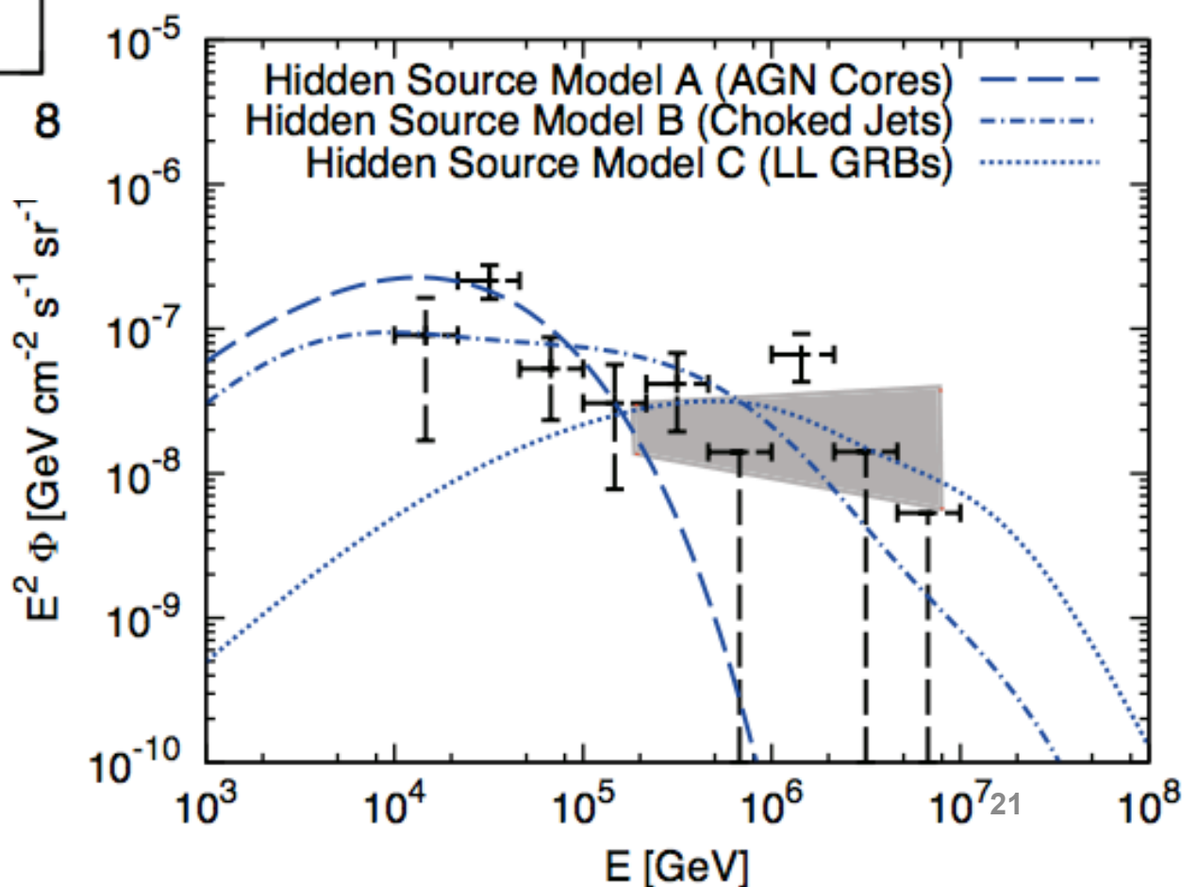
A possible solution: gamma-ray opaque sources



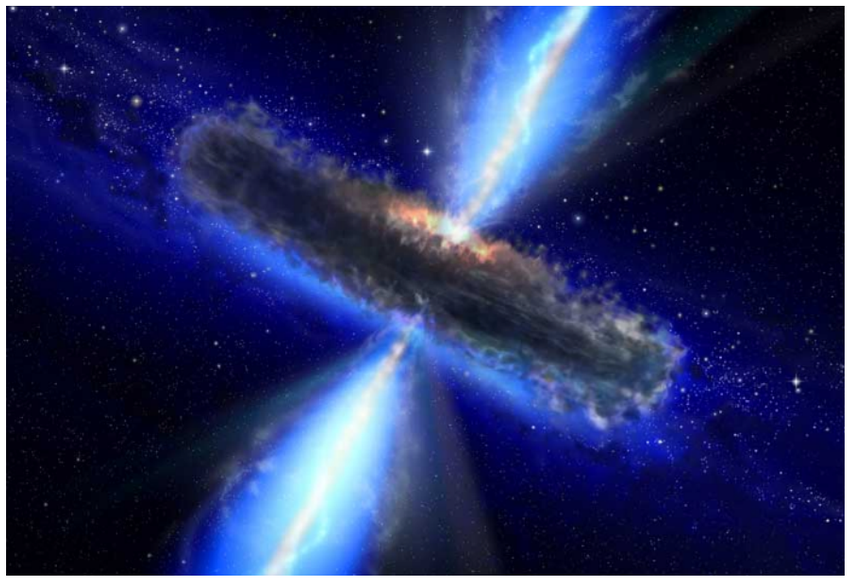
- Sources that efficiently absorb gamma rays in the GeV band

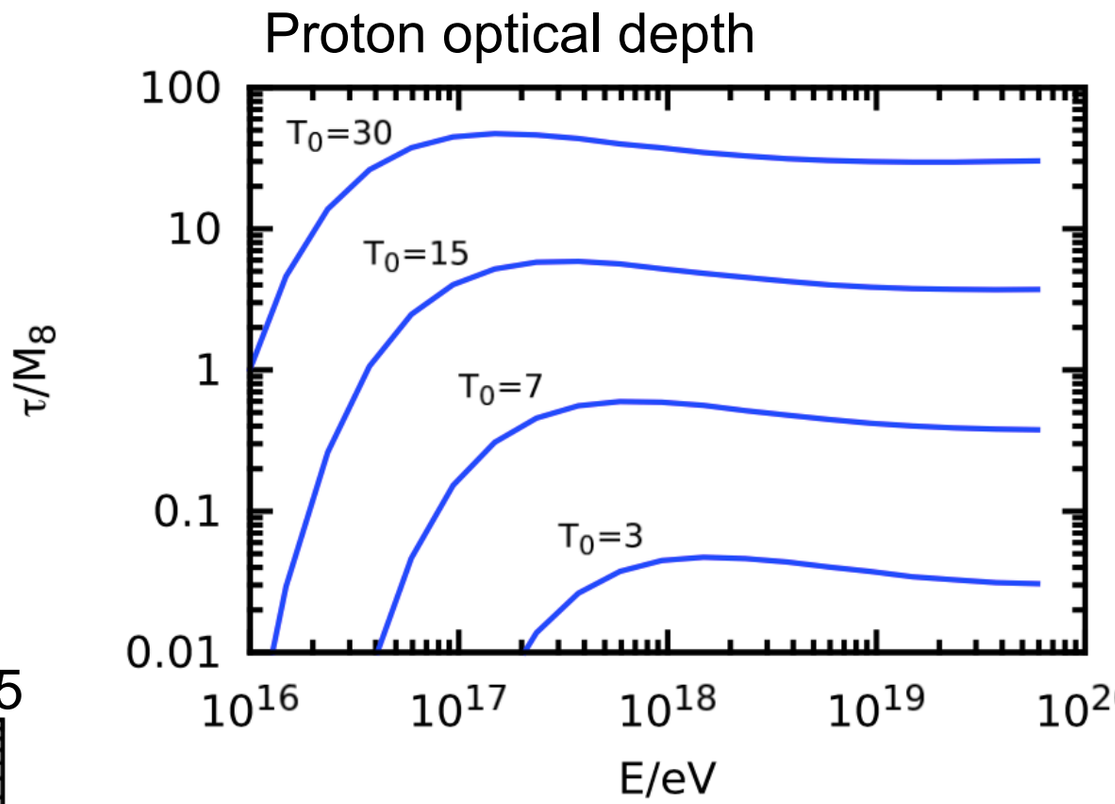
- **The neutrino sky is very different to the gamma-ray sky!**

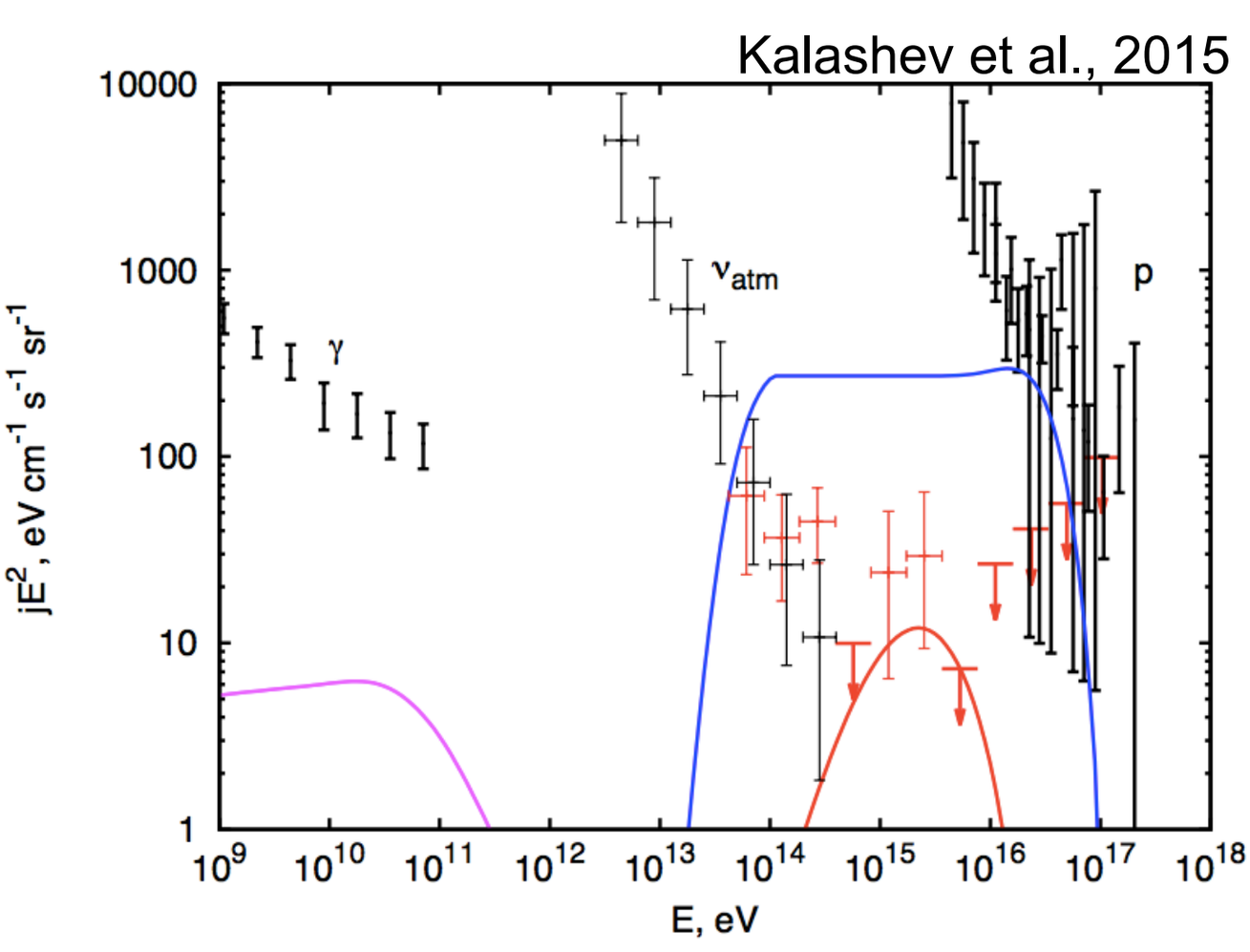
Murase, Guetta & Ahlers, 2015



Gamma-ray opaque sources: AGN cores

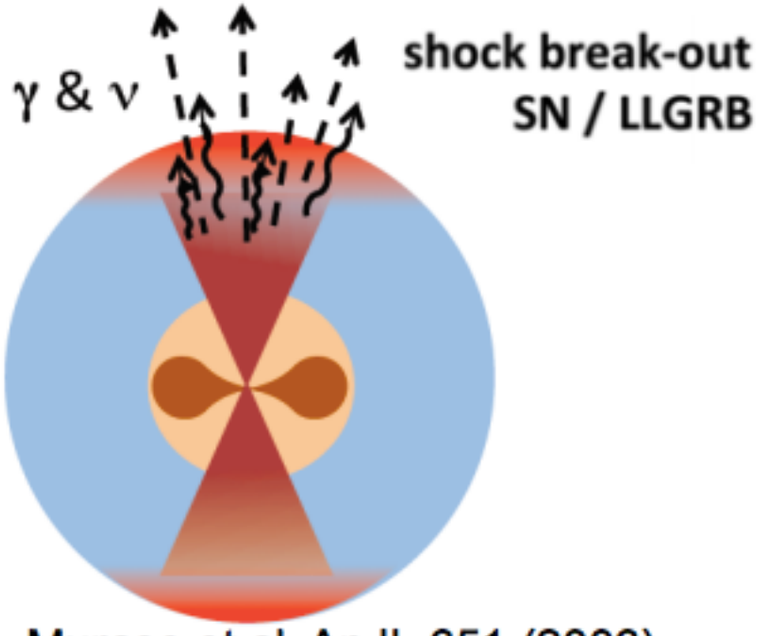




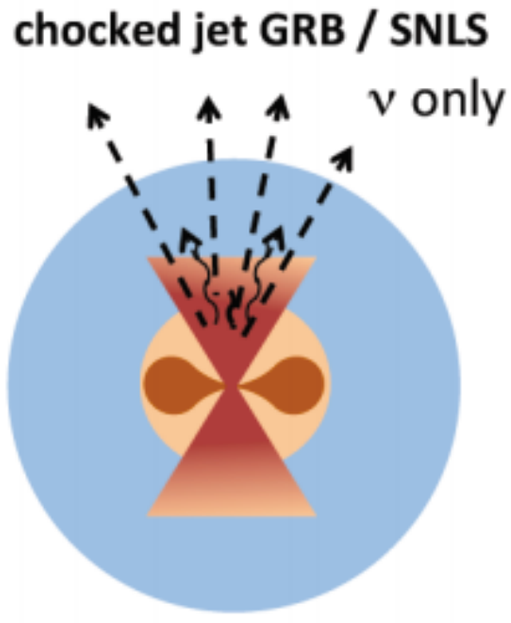


- Accretion disks provide intense UV photon fields
- Opaque for CR above ~ 100 PeV
- Opaque for gamma rays above few GeV

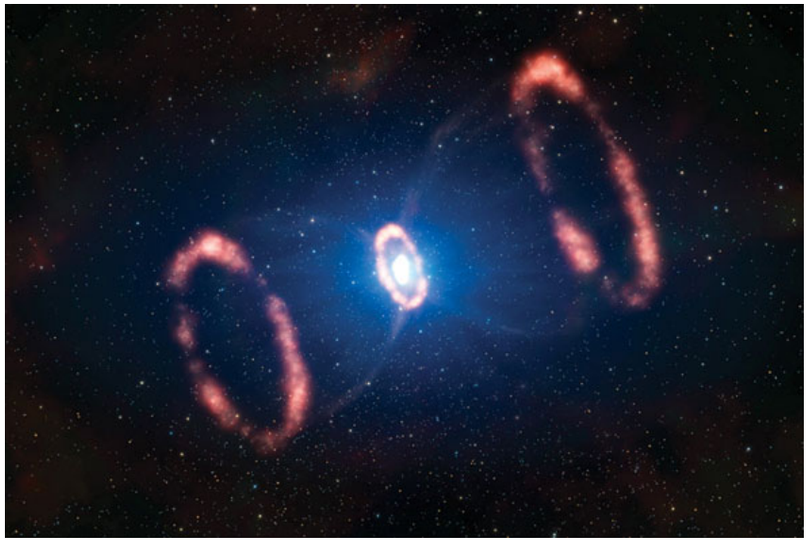
Gamma-ray opaque sources: SNe, low-luminosity GRBs

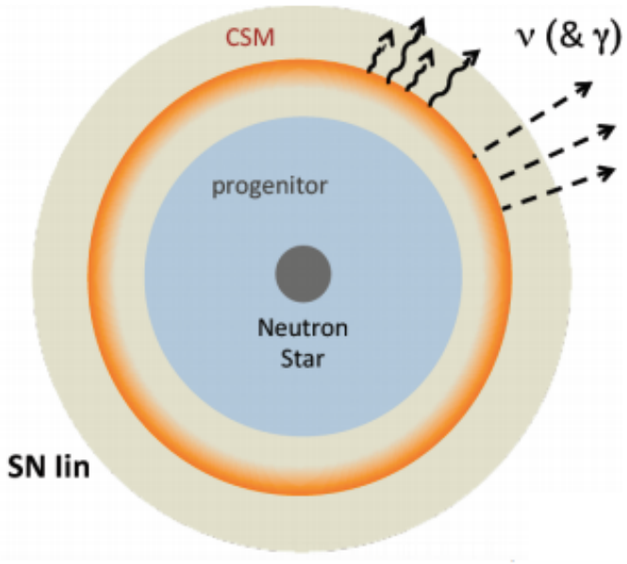


Murase et al, ApJL,651 (2006)



Ando & Beacom, PRL 95 (2005)



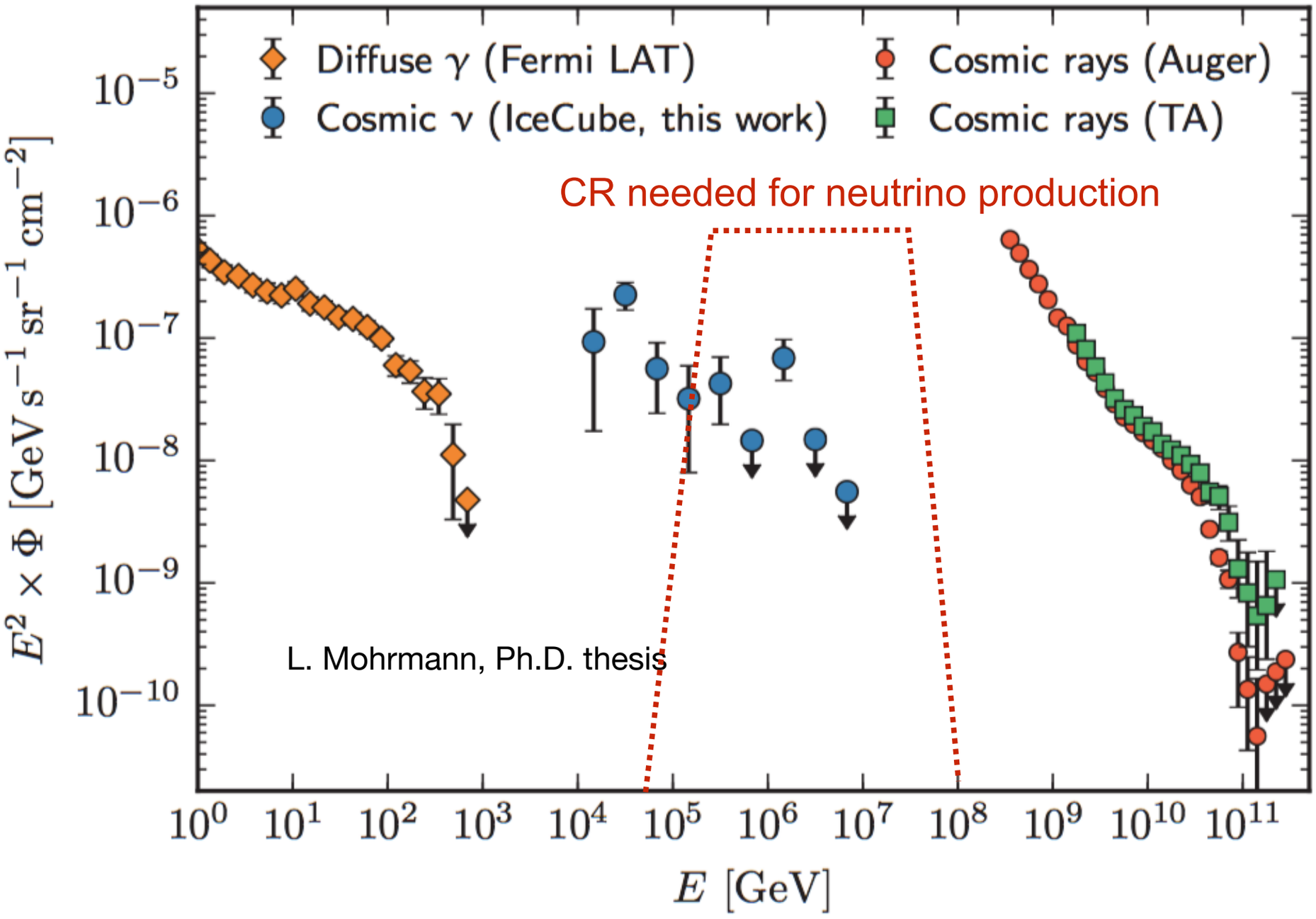


Murase et al., PRD 84 (2011)

> High-energy neutrinos from core-collapse SNe.

> See Anna Franckowiak's talk for more details

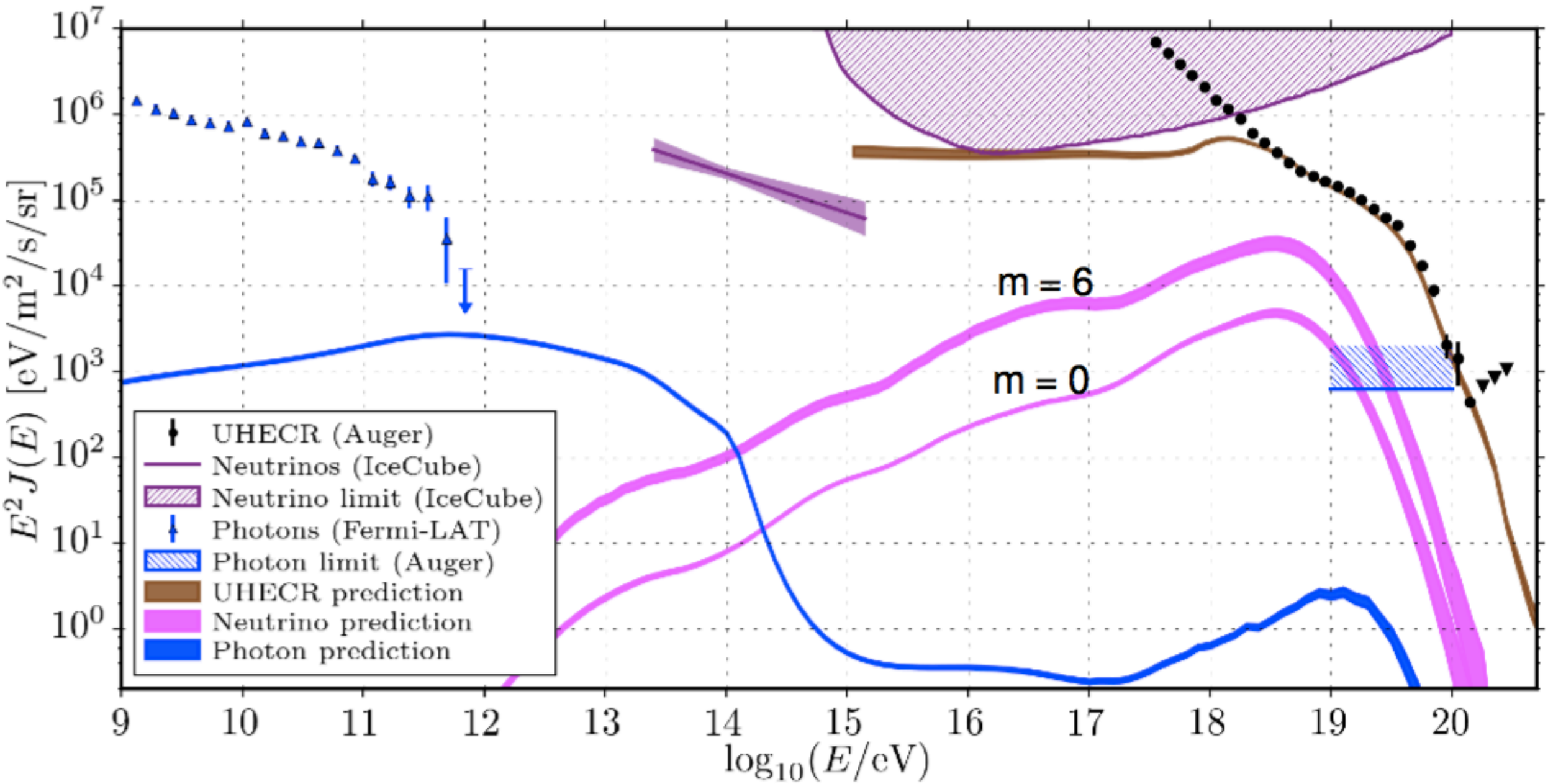
Observed cosmic neutrino source unrelated to UHECR ?



> Blazars or GRBs might produce UHECR, but the associated neutrino production is low.

> Observed neutrino flux is unrelated to the UHECR ?

Other options: Neutrinos from the propagation of CR?



Multimessenger with CRPropa 3
David Walz

> Talk by David Walz

> Observed neutrino spectrum does not fit to spectrum expected from UHECR propagation

Summary

> In recent years we have seen the transition from 2-messenger astronomy to 3+1 messenger astronomy

> We get interesting new insights into the high-energy universe.

> Extragalactic neutrino and gamma-ray skies seem to be very different.

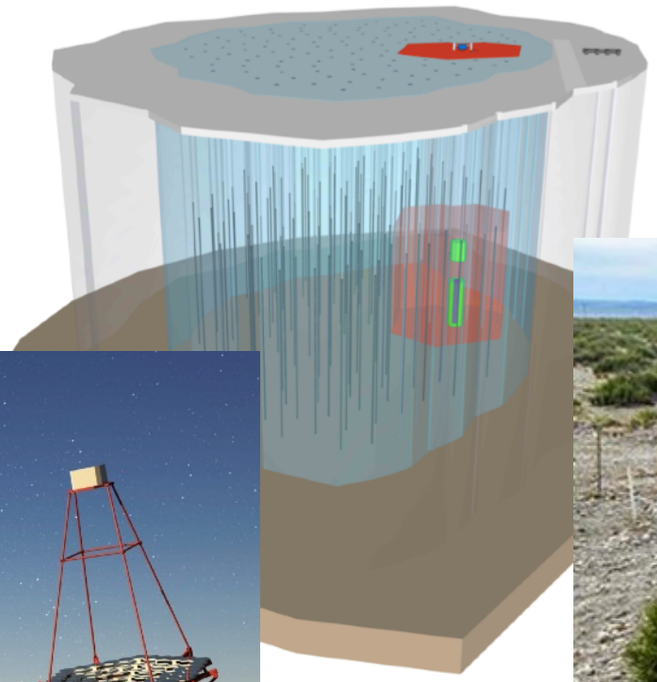
> Cosmic neutrinos are produced by high-density / low-luminosity source.

> Neutrino sources and UHECR sources might be different populations.

> Hint of a Galactic component (that might well be a statistical fluctuation)

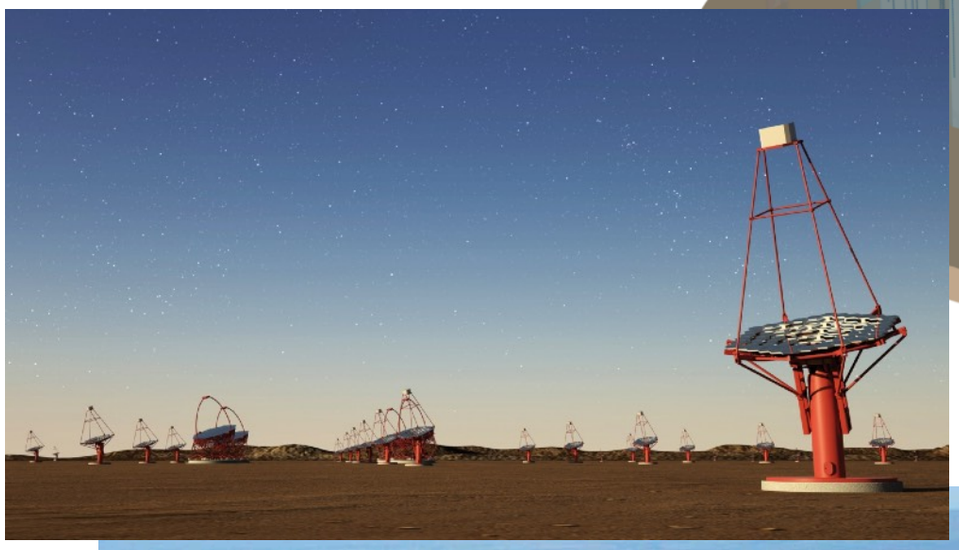
> Expect more exciting insights from current and next generation instruments

Multi-messenger astronomy in 10 years



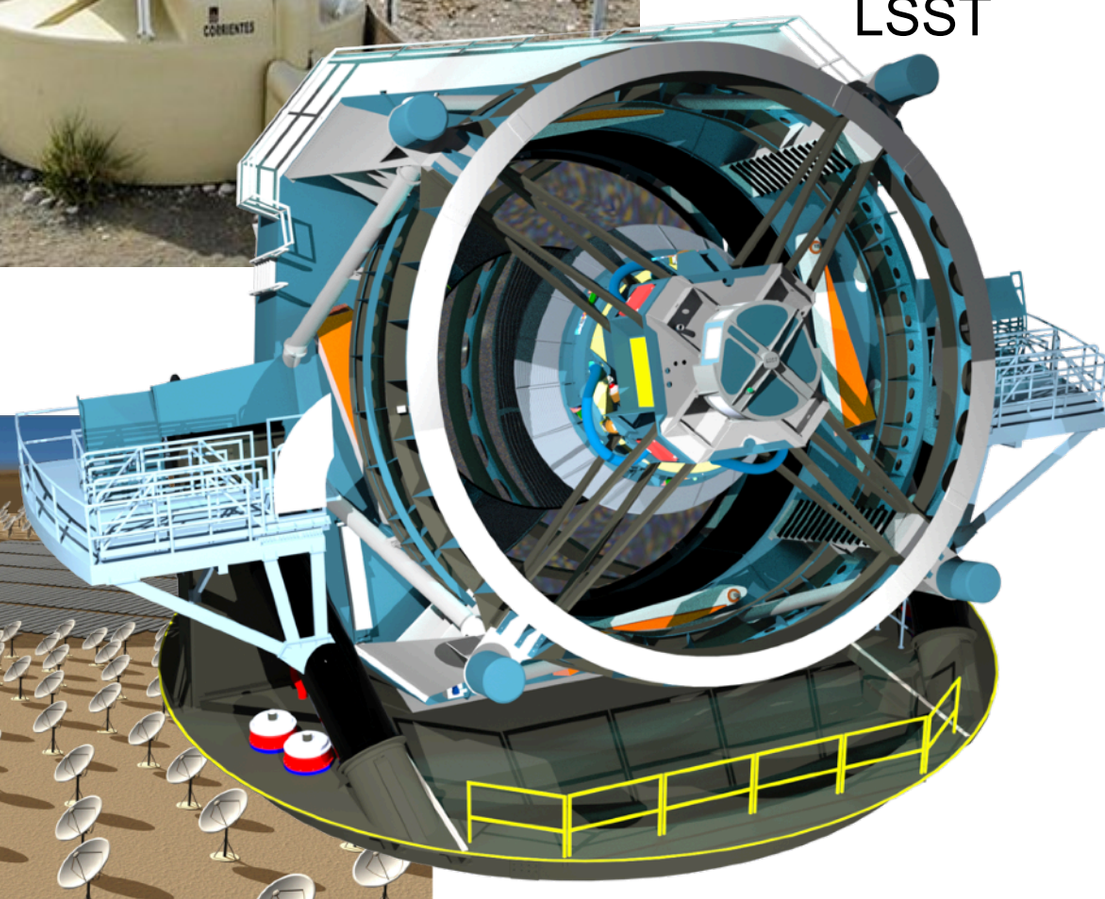
IceCube-Gen2

CTA

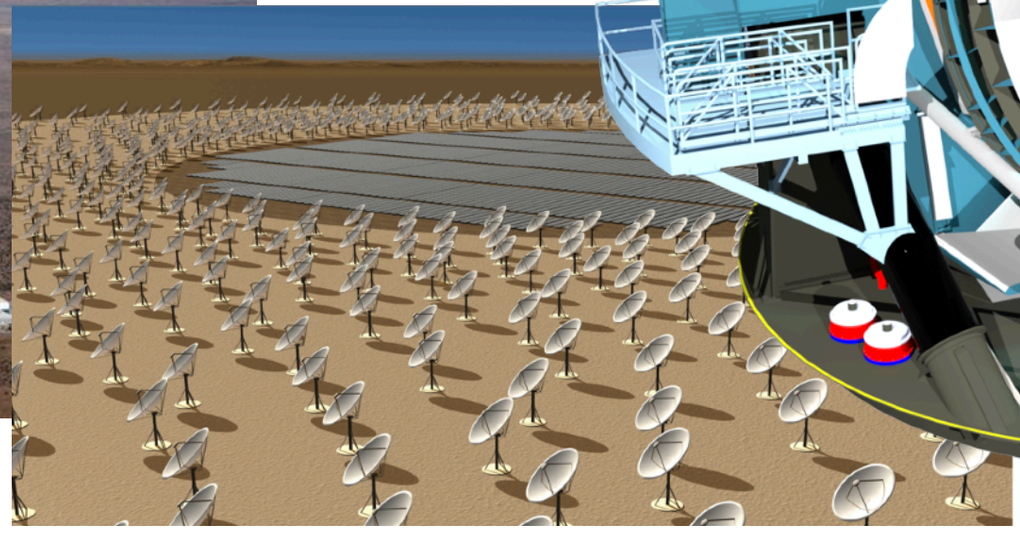


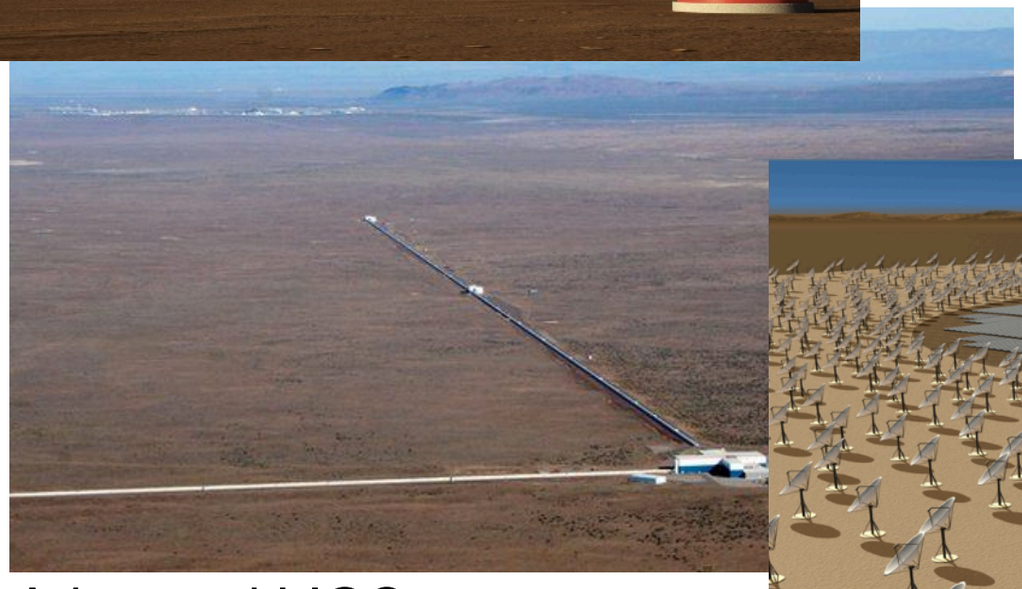
Auger upgrade

LSST



SKA



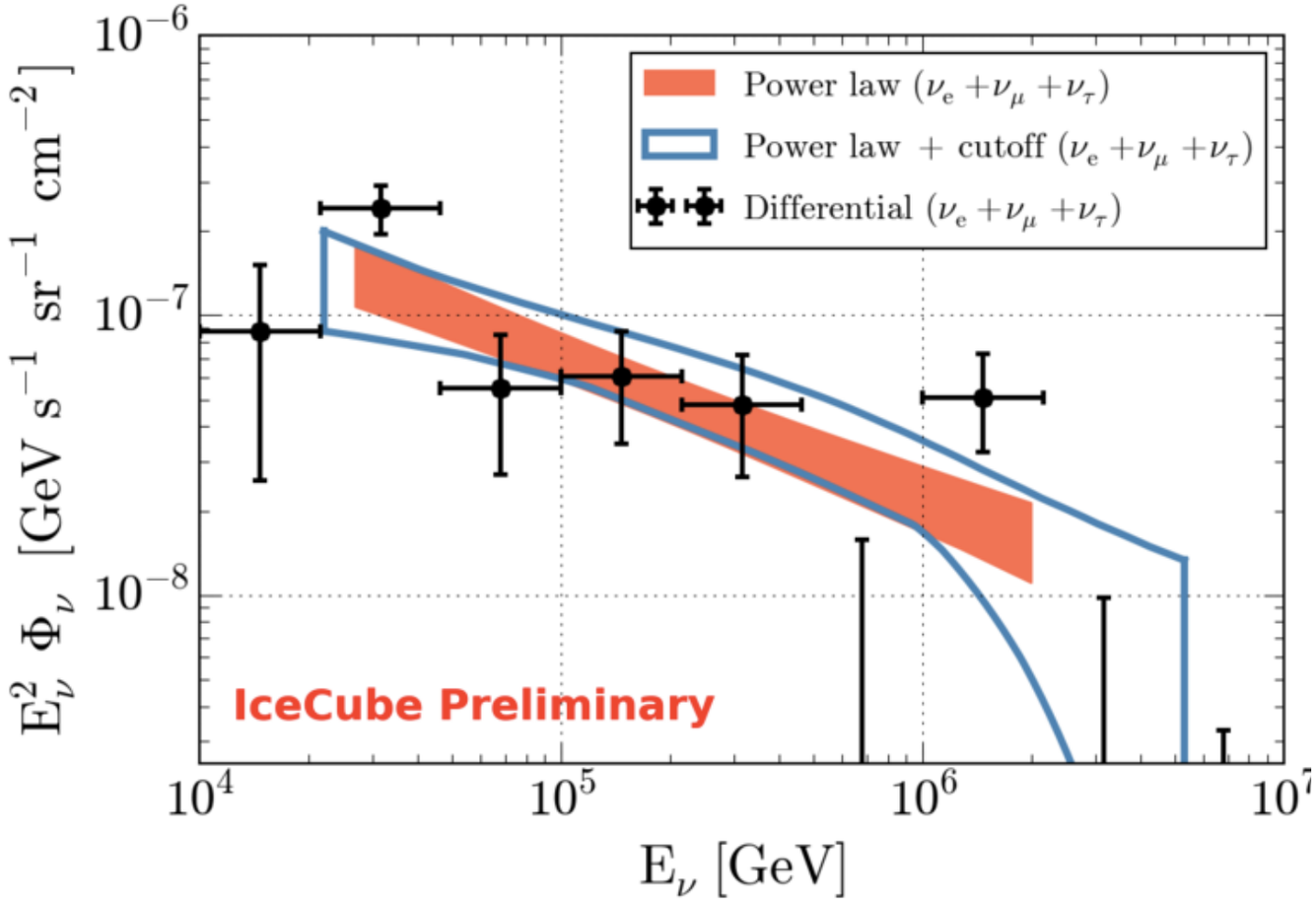


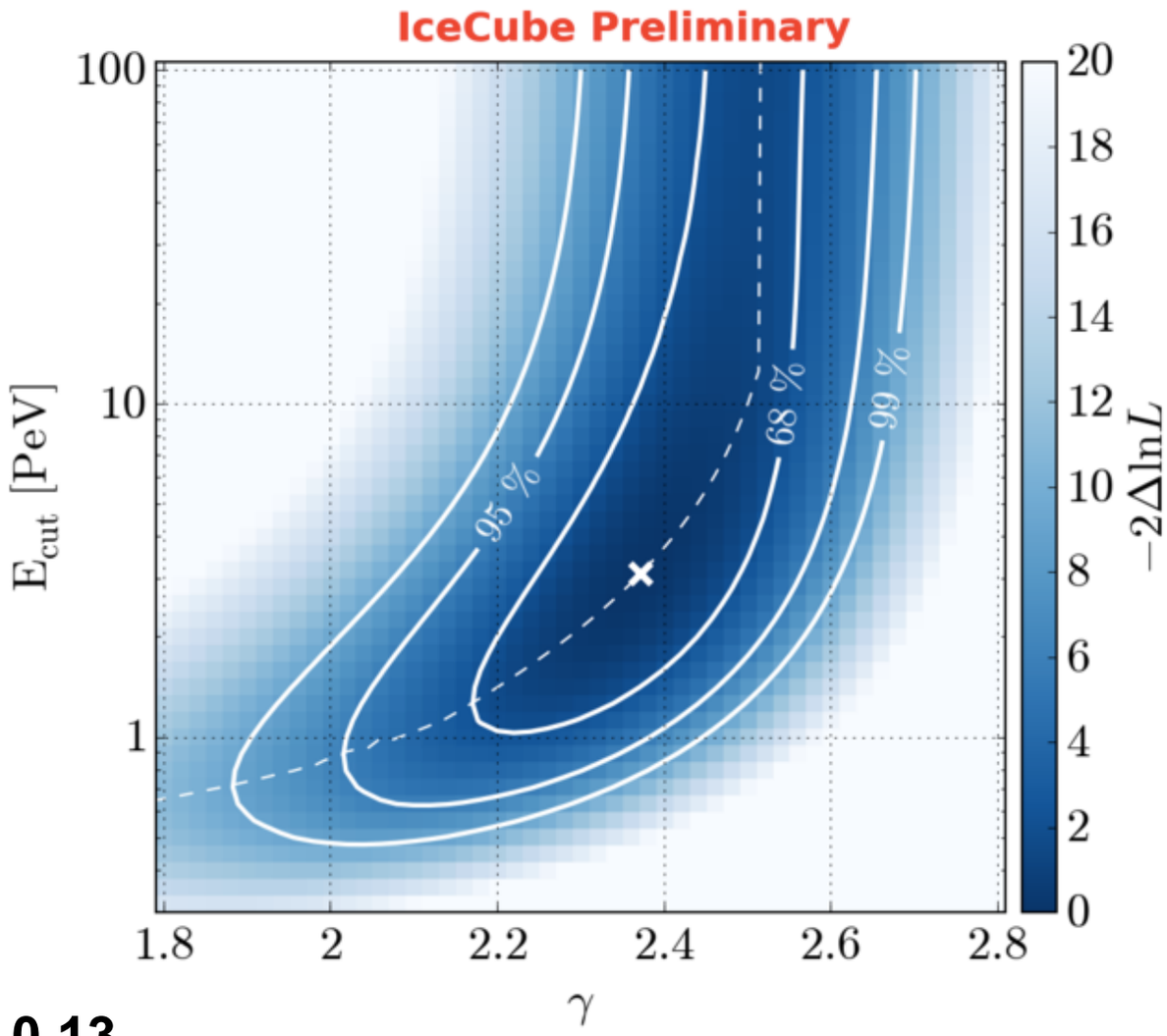
Advanced LIGO

> New instrumentation might allow a new level of multi-messenger astronomy

Backup

Best fit astrophysical neutrino spectrum using all channels

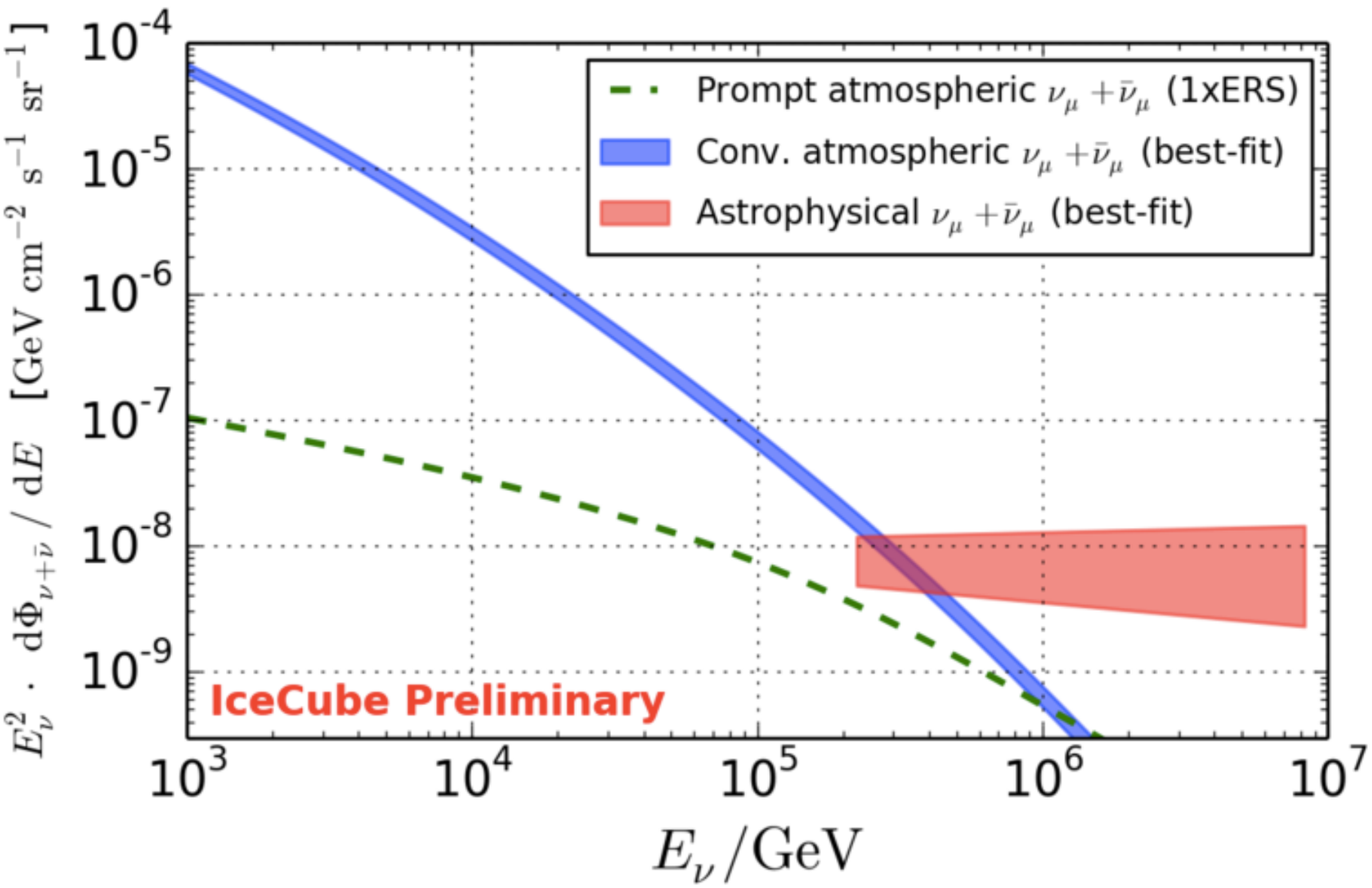




spectral index: **2.52 ± 0.07** or spectral index: **2.37 ± 0.13**
cutoff energy: **3.1 PeV**

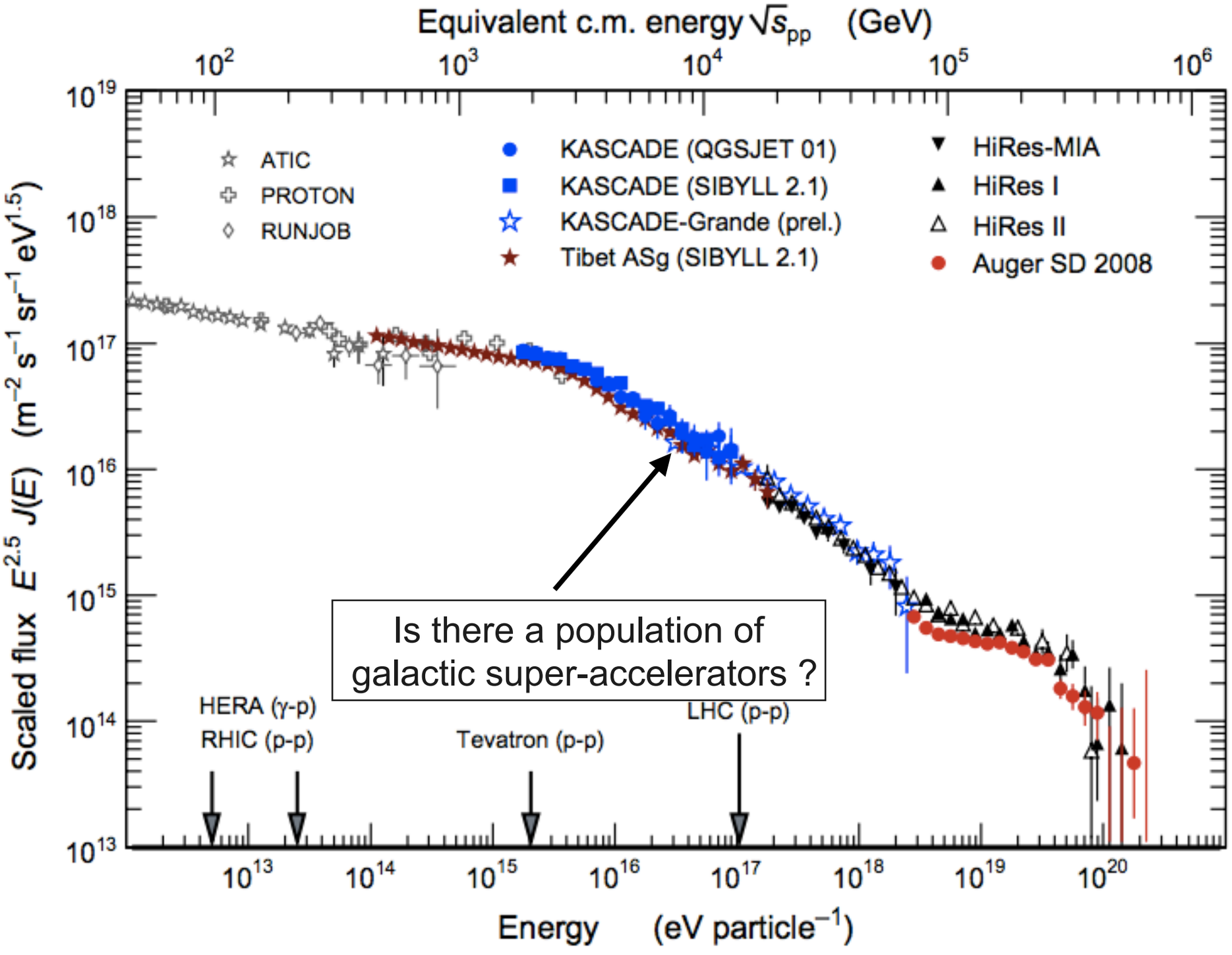
- **Combines** starting event, shower, track and tau **channels**.
- Does only contain **3 years of through-going track** data !
- Simple power law spectrum and power law + cutoff both compatible with IceCube data.

A new measurement…

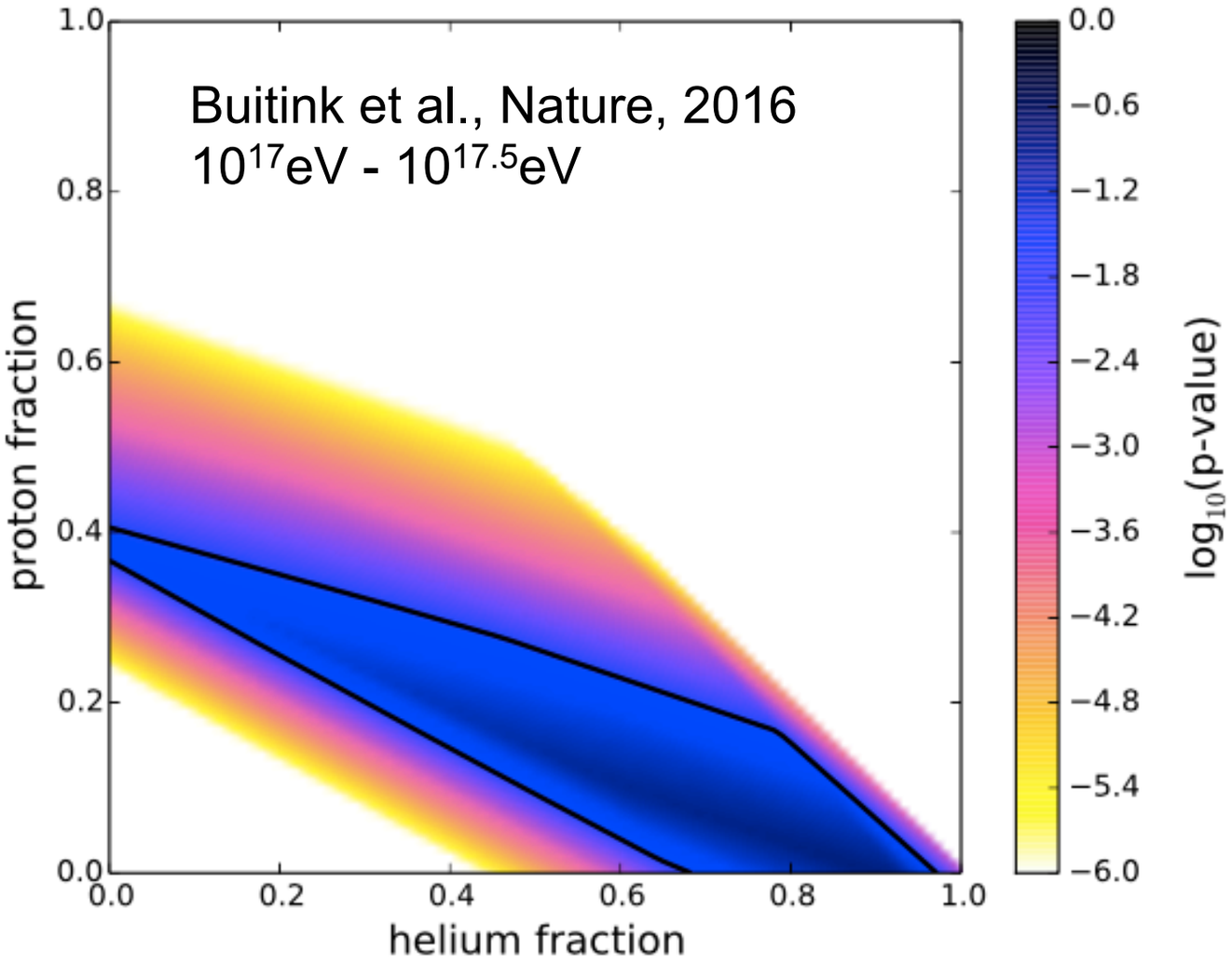


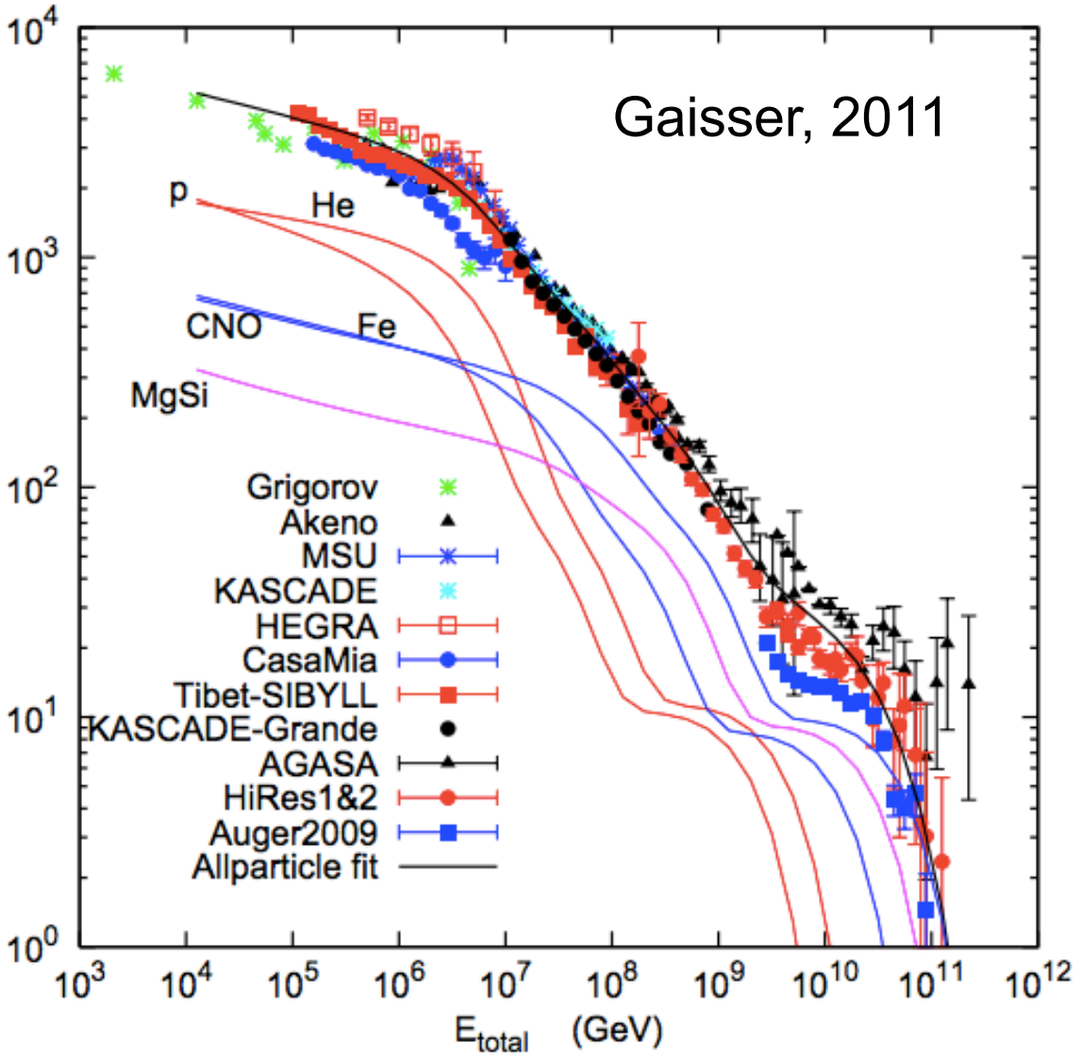
- New analysis of 6 years of Northern hemisphere through-going muons
- Harder spectrum with index ~ 2.1 above ~200 TeV
- see talk by A. Franckowiak

Specific questions addressed by multi-messenger astronomy.



Cosmic ray composition above the knee.

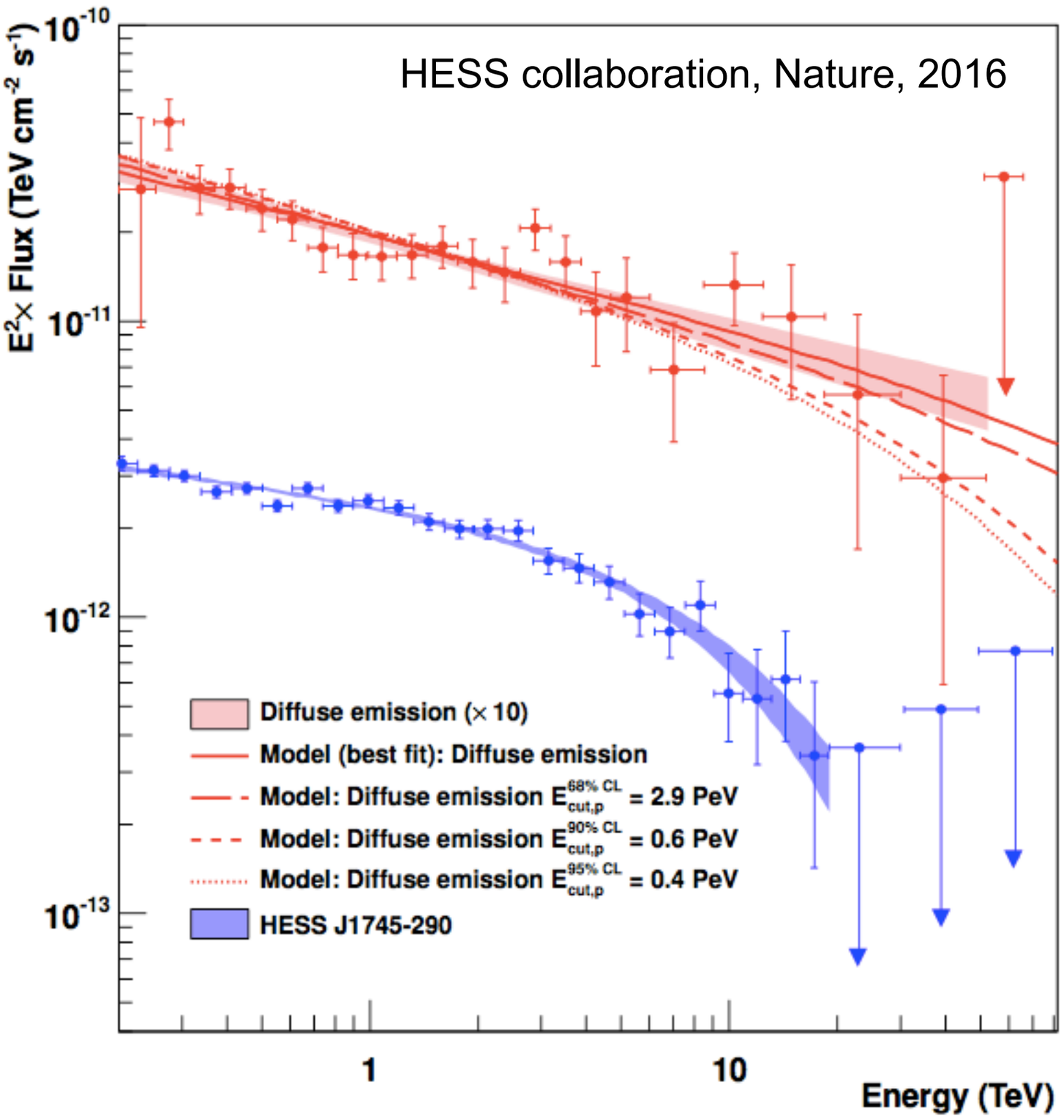


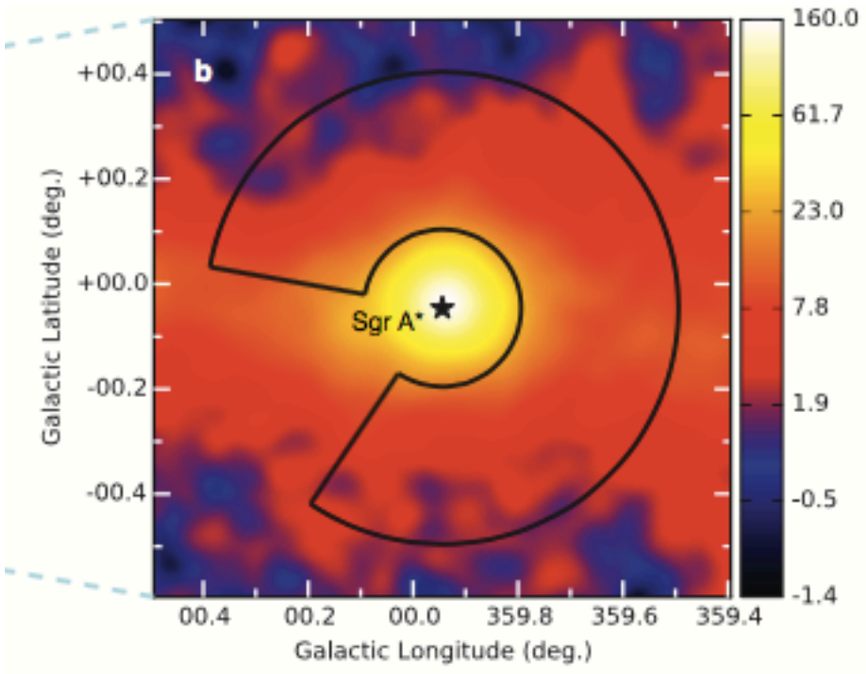


- Evidence for light component in radio measurements of shower maximum
- Extra component with cutoff at tens of PeV used in several fits of CR spectrum.
- Could produce PeV Neutrinos.

R_c
γ for Pop. 1
Population 1: 4 PV
Pop. 2: 30 PV
Pop. 3 (mixed): 2 EV

A Pevatron in the Galactic Center

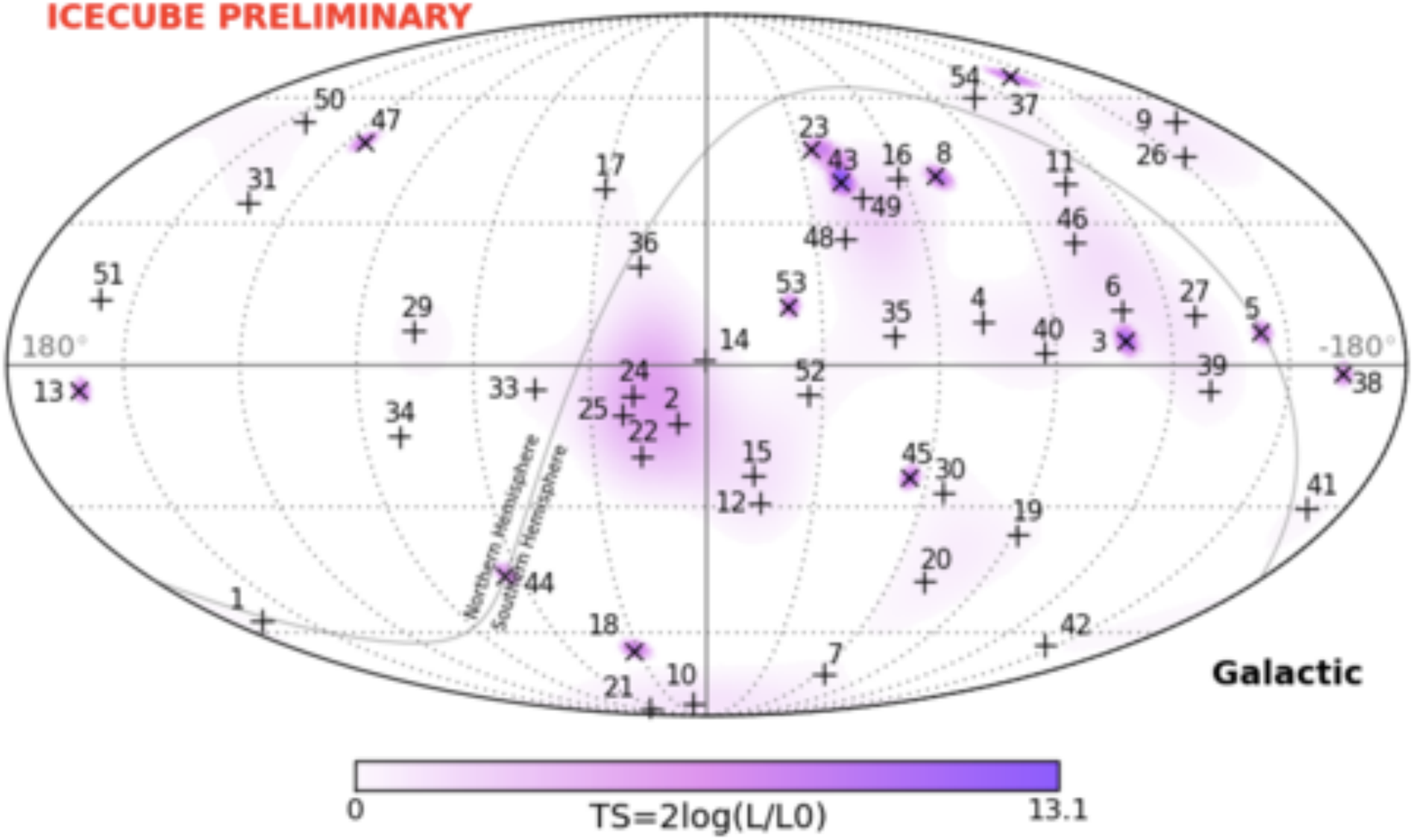


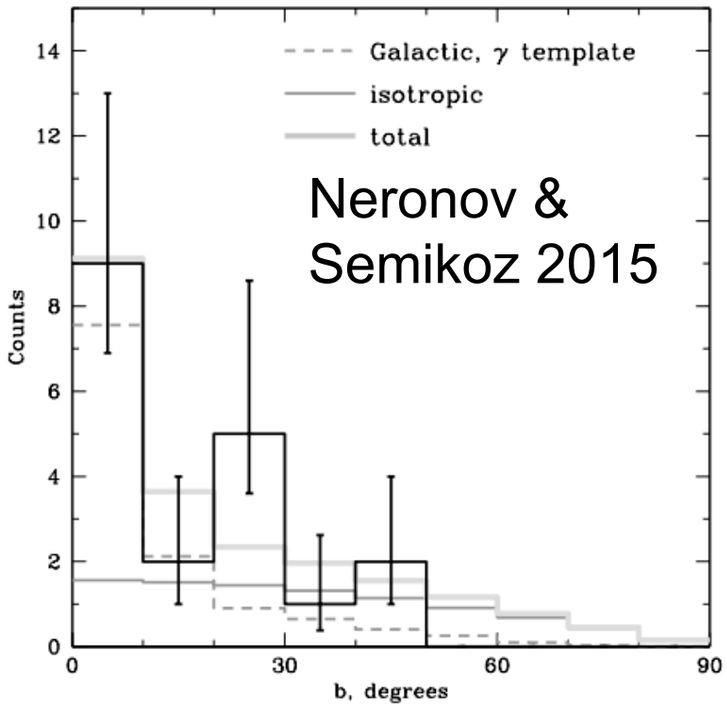


> Diffuse emission around Galactic center source does not show a high-energy cutoff

> Cutoff > 0.4 PeV in proton population at 95% CL

Analysis of the high-energy starting tracks





- One of the PeV neutrinos apparently comes from the Galactic center
  - … but angular resolution is ~ 15°, so don't get over-excited
- As shown: mild excess of events in a band around the galactic plane
  - Still compatible with a statistical fluctuation.
  - Distribution of events consistent with an isotropic origin
- No conclusive answer at the moment.