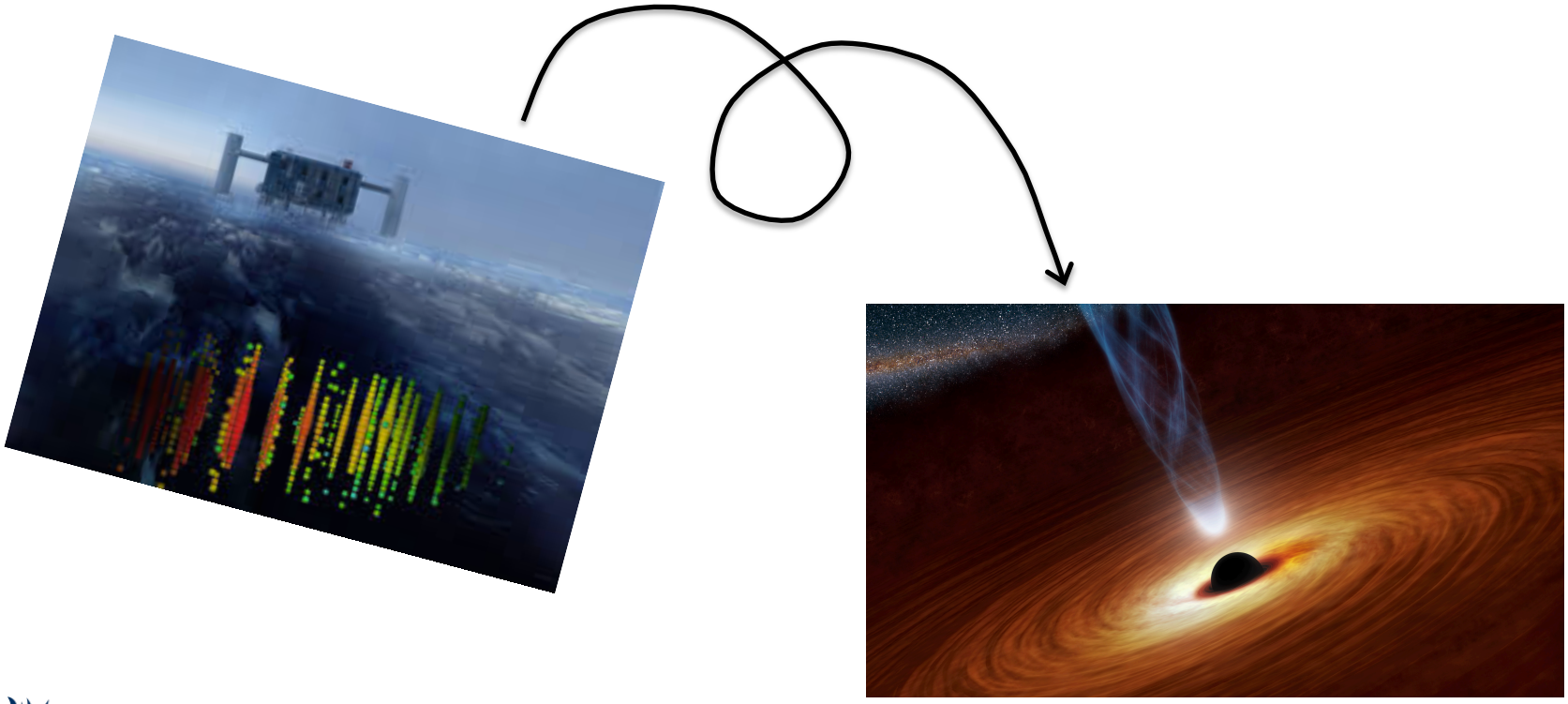
Neutrinos: Origins and Connections



Jon Dumm

OKC-days, Skåvsjöholm

2015 Nov 12

Stockholm University

Oskar Klein centre

Active Interplay

- Exciting time for Neutrino Astronomy
  - Many ‘old/persistent’ ideas changing
  - Many new ideas picking up steam

- Today: summarize the latest exchanges between theorists and multi-messenger astronomers as they relate to IceCube

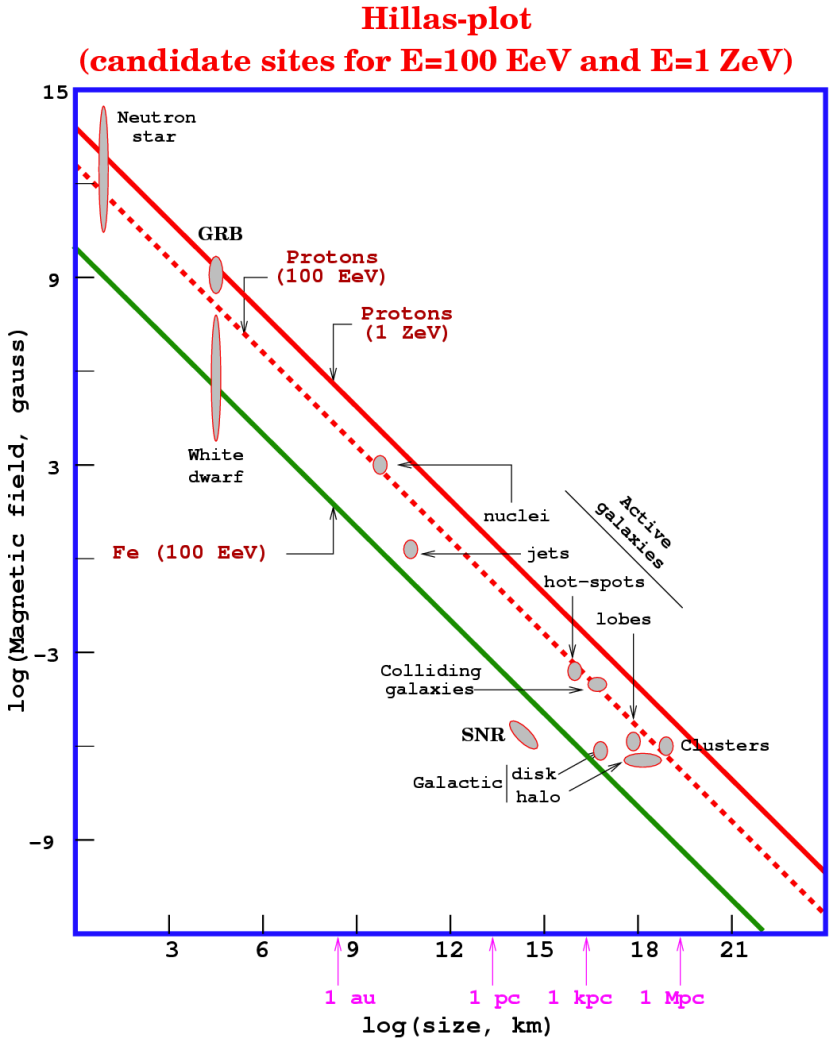
Proposed Galactic Sources

- **Diffuse galactic gamma-ray emission**
- Unidentified galactic gamma-ray sources
- Supernova remnants
- Pulsars
- Microquasars
- Sagittarius A*
- Fermi Bubbles
- Galactic Halo – advected CRs
- **Heavy dark matter decay**

Proposed Extragal. Sources

- **Active galactic nuclei (AGN)**
- Gamma-ray Bursts (GRBs)
- **Star-formation (-burst) galaxies**
- Galaxy clusters
- Cosmogenic (GZK) neutrinos
- Association with sources of UHE CRs
- **Association with diffuse gamma-ray background**

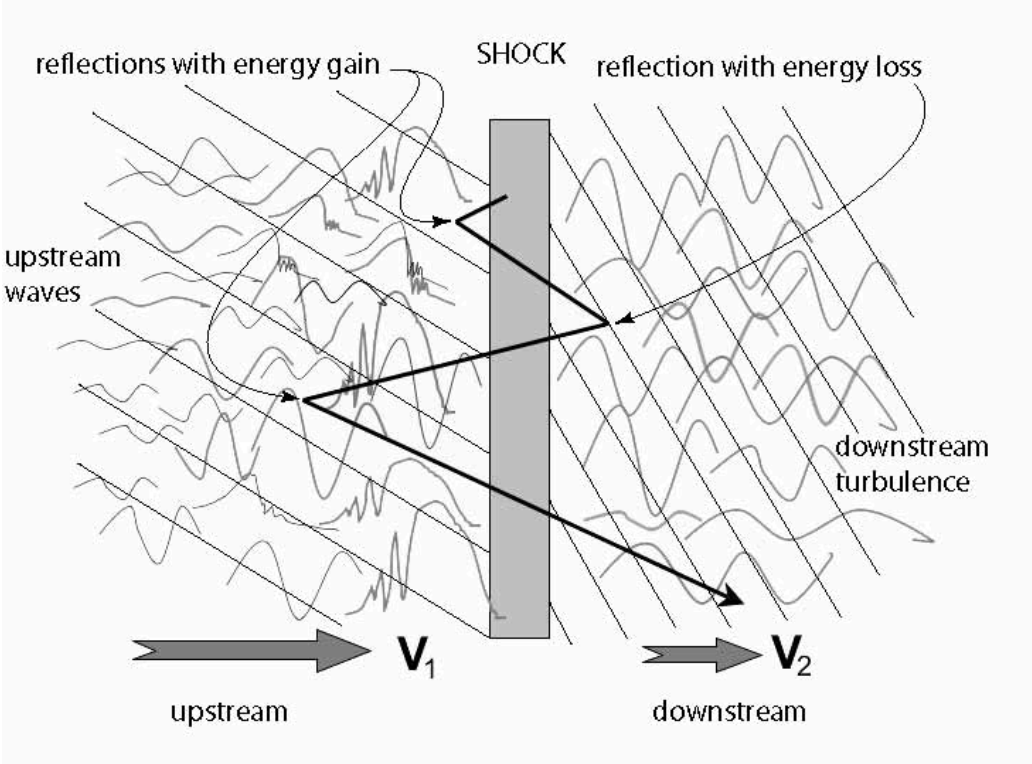
Commonality – B confinement



- Maximum energy (ideal):
  - E_{max} ~ ZBL
  - "Hillas criterion"
- Can either be large size or large magnetic field
- Realistic case not so clear:
  - Magnetics probably not aligned as well as LHC
  - Energy losses important
  - Accel. time important

image credit: https://www-zeuthen.desy.de/~kappes/lehre/ws11/vat/v08/Hillas-plot.png

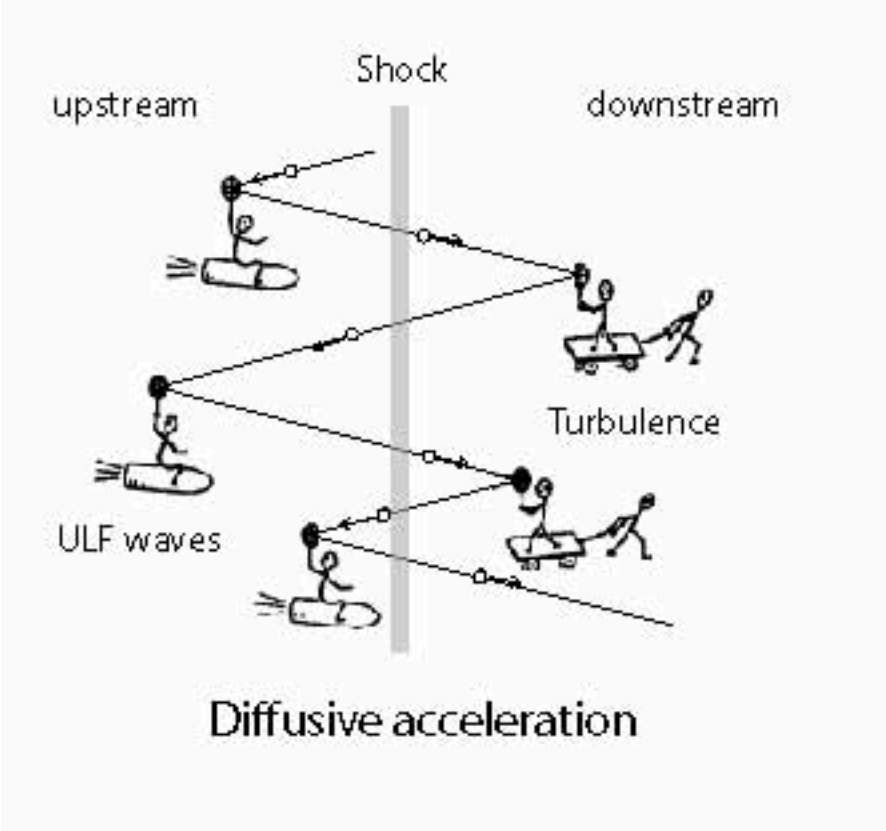
Commonality – Shock Accel.



- Turbulent magnetic fields scatter charged particles – act as magnetic mirrors
- Any compressive flow between magnetic mirrors provide conditions for first-order Fermi acceleration
- Balance between the probability of cosmic ray to escape versus stay in acceleration region yields power in energy spectrum
  - $dN/dE \sim E^{-2}$ is naïve prediction from linear Diffusive Shock Acceleration theory
  - Non-linear (CR feedback) DSA models predict small deviations, concave

image credit: arXiv:0806.4046

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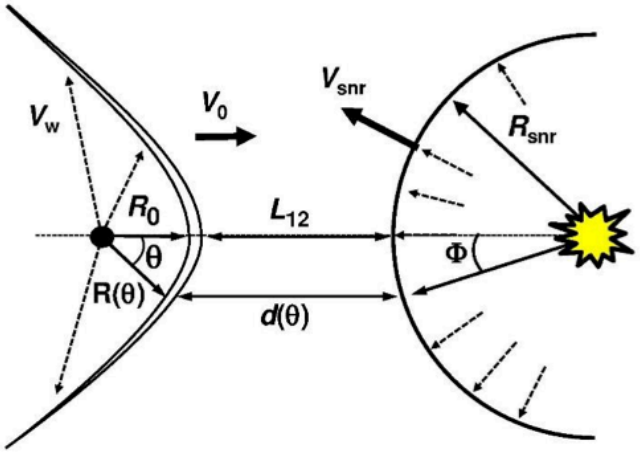


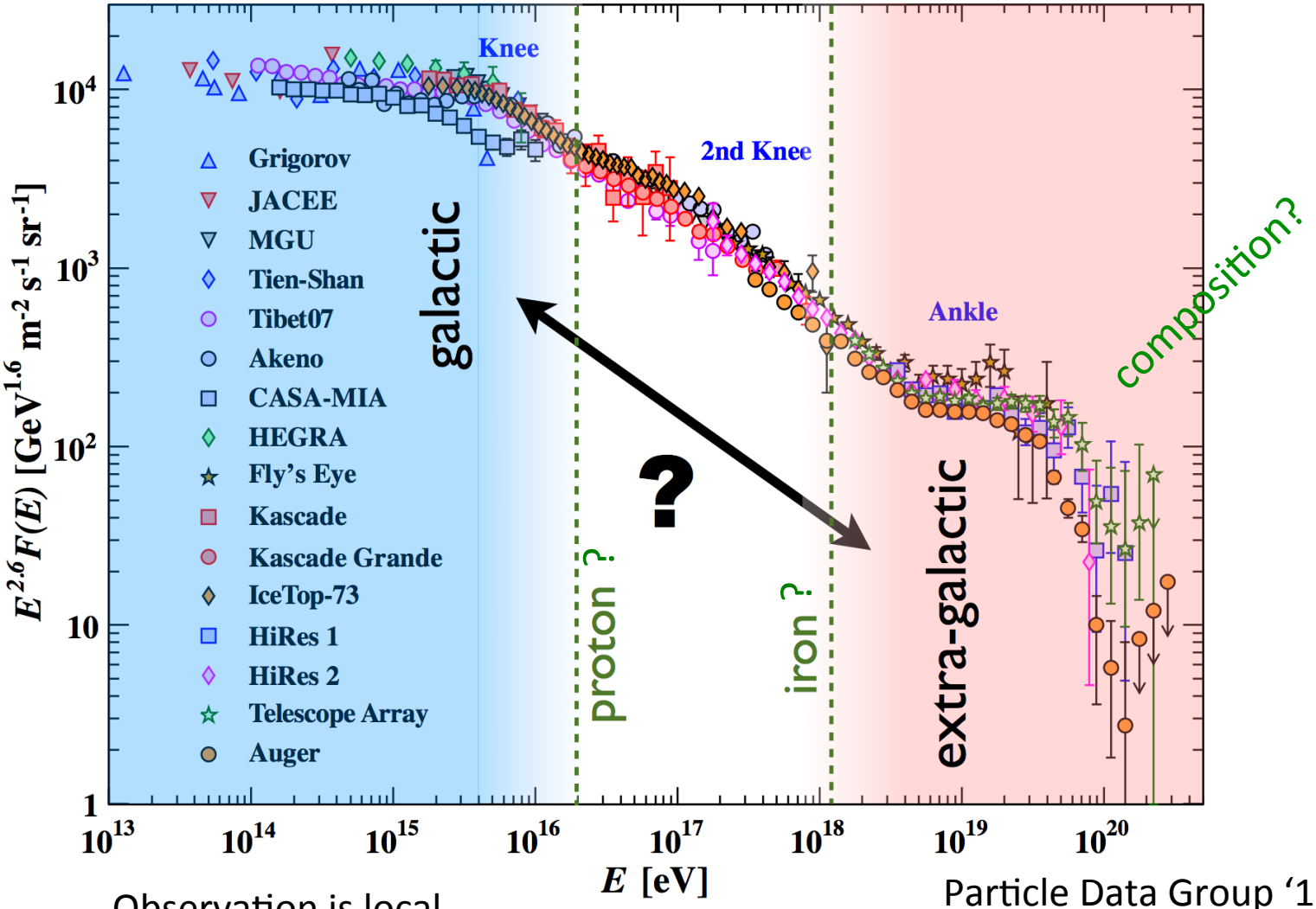
Figure 1. Colliding flow geometry where the stellar wind (left) was approximated from the analytic model of (Wilkin 1996), while the SNR shock was assumed to be spherical. The star, or cluster center, approaches the SN explosion center with speed V_0. The spectrum of the Fermi accelerated CRs was derived taking into account effects of the flow velocity projection on the curved shock surfaces.

- Turbulent magnetic fields scatter charged particles – act as magnetic mirrors
- Any compressive flow between magnetic mirrors provide conditions for first-order Fermi acceleration
- Balance between the probability of cosmic ray to escape versus stay in acceleration region yields power in energy spectrum
  - $dN/dE \sim E^{-2}$ is naïve prediction from linear Diffusive Shock Acceleration theory
  - Non-linear (CR feedback) DSA models predict small deviations, concave

Textbook physics doesn't always apply to messy astrophysics!

Westerlund 1 star cluster
[arXiv:1507.04018v1]

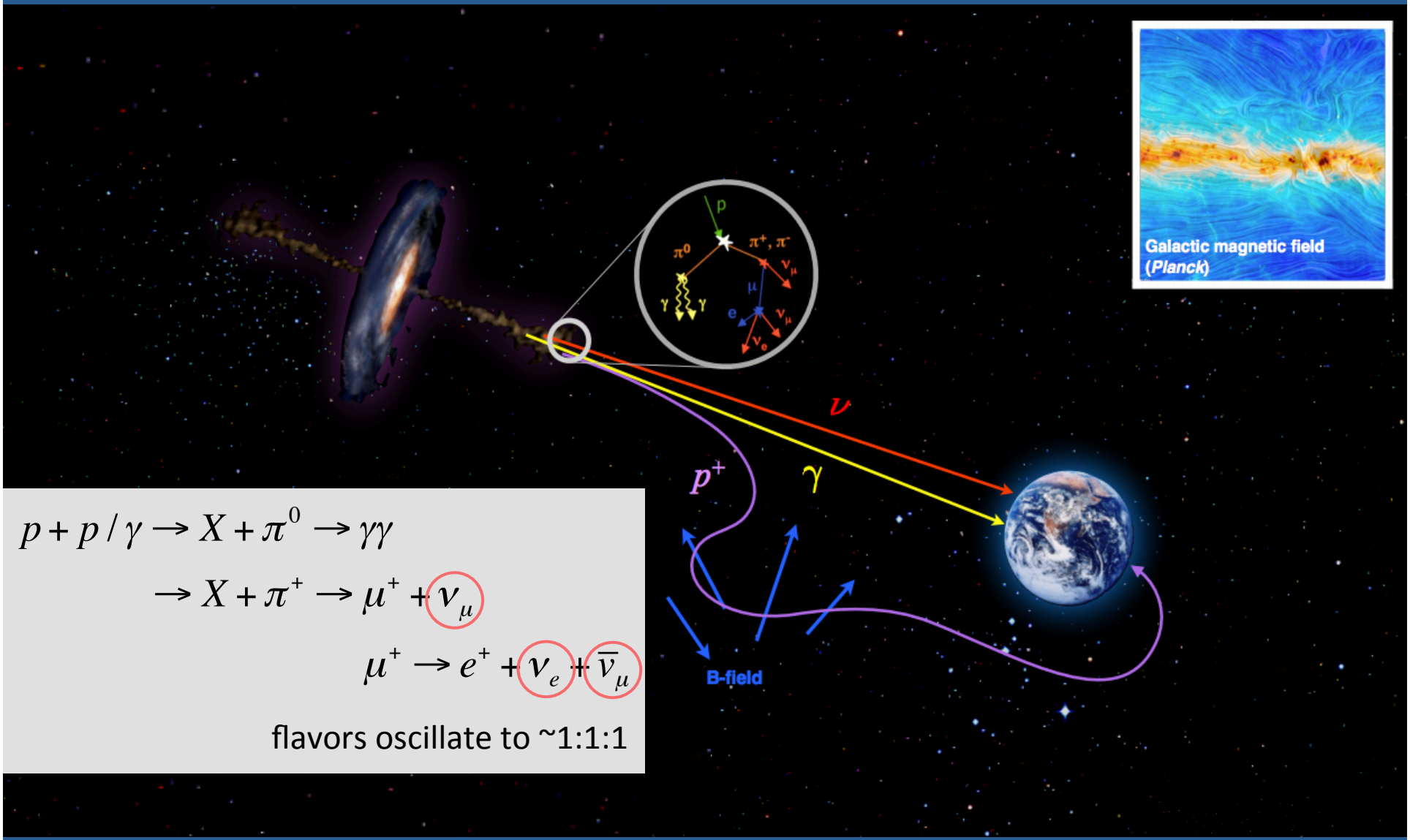
Cosmic "Beam"



Observation is local

Particle Data Group '13

Multi-messenger Astronomy



$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$

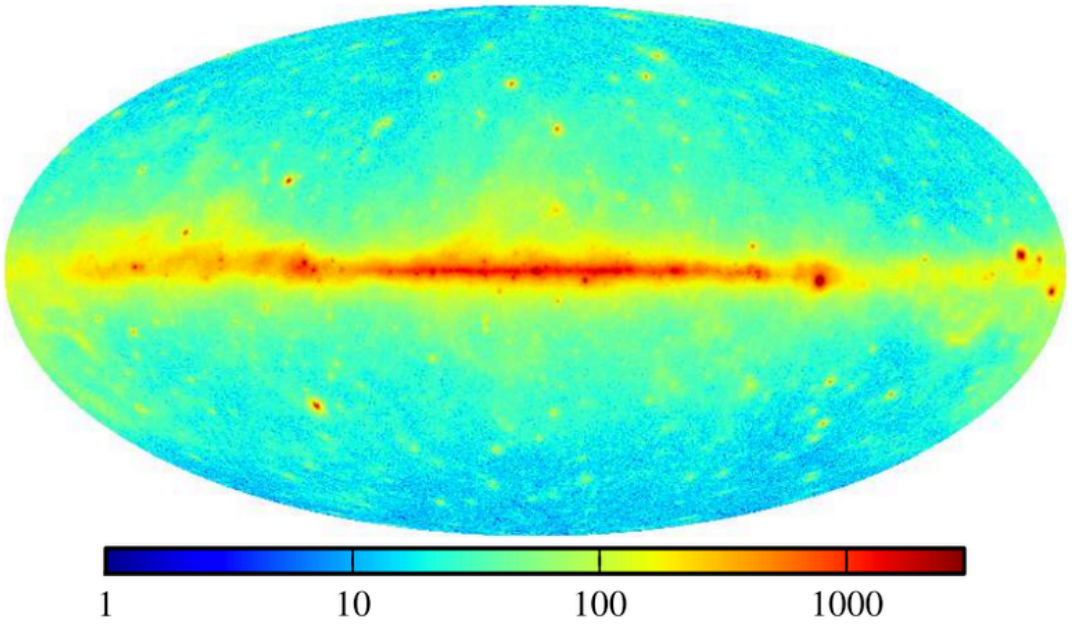
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

flavors oscillate to ~1:1:1

- Galactic

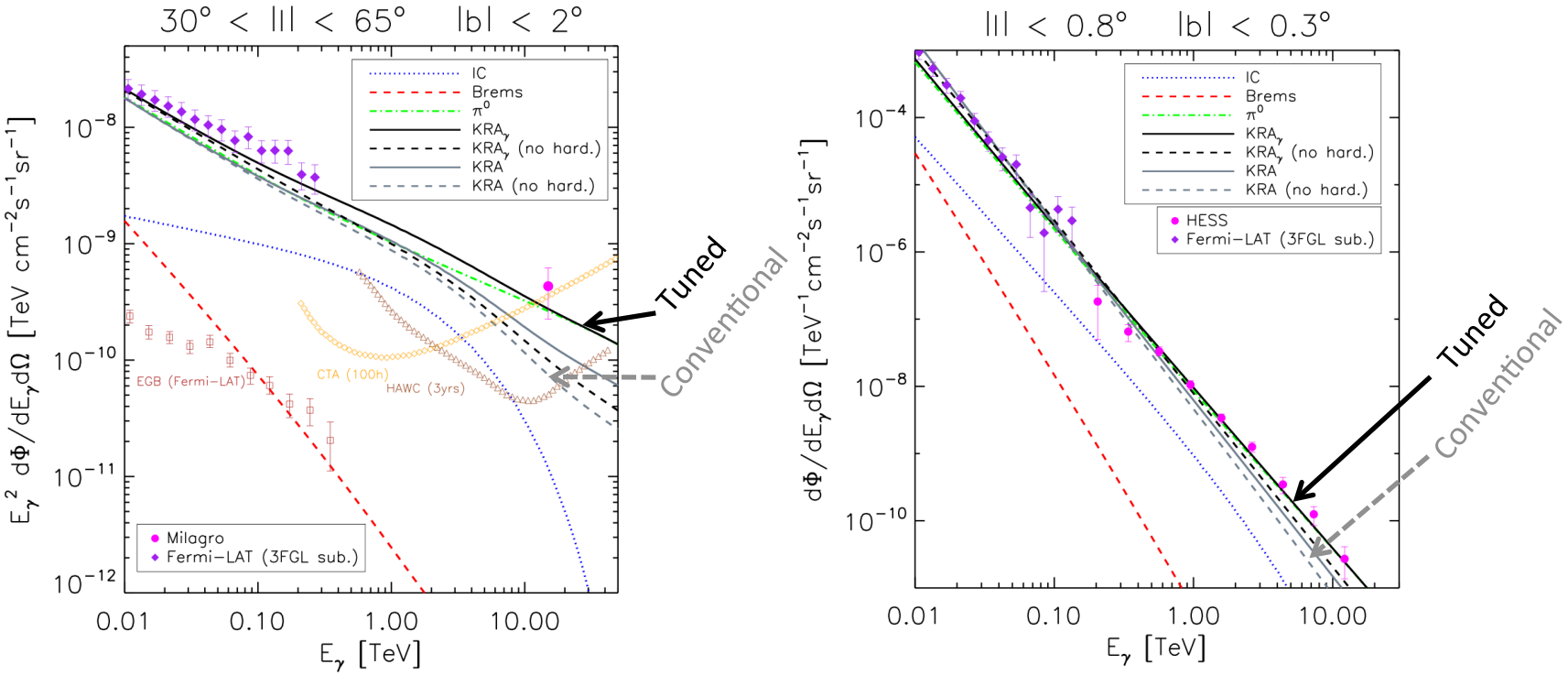
- Galactic (Diffuse)



Gal CR Interactions

- Until now, CR spectral index observed at Earth assumed same everywhere
  - Fermi+Milagro+HESS ϒ-rays now allow us to test this assumption

ϒ-ray Models



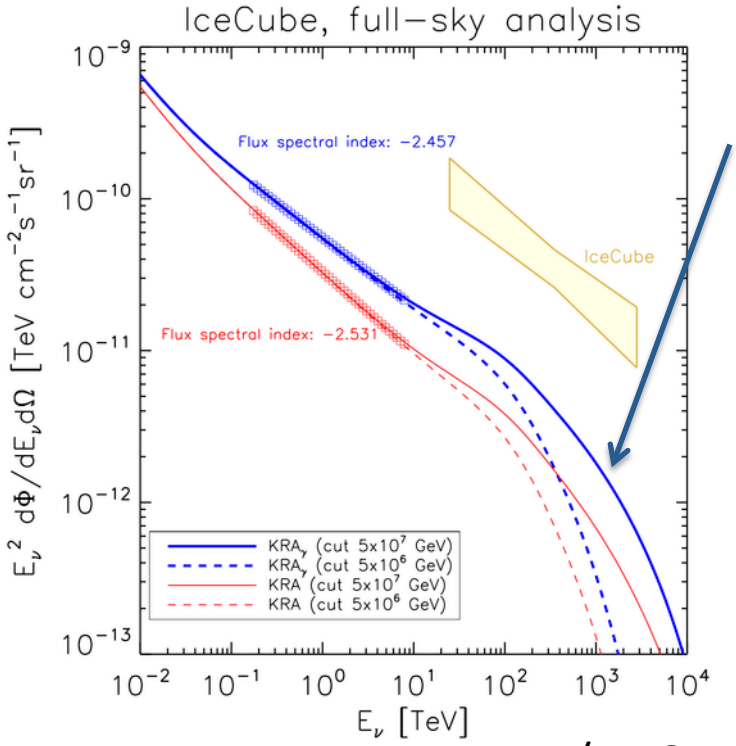
- New: Incorporate PAMELA/AMS measured p & He hardening and allow CR diffusion to change with gal. radius

Gaggero et al 2015
arXiv:1504.00227v2

Gal CR Interactions

- Until now, CR spectral index observed at Earth assumed same everywhere
  - Fermi+Milagro+HESS ϒ-rays now allow us to test this assumption

ϒ-ray Models → ν predictions



After tuning CR propagation to the gamma-ray data: up to ~20% of our diffuse neutrino flux comes "for free"

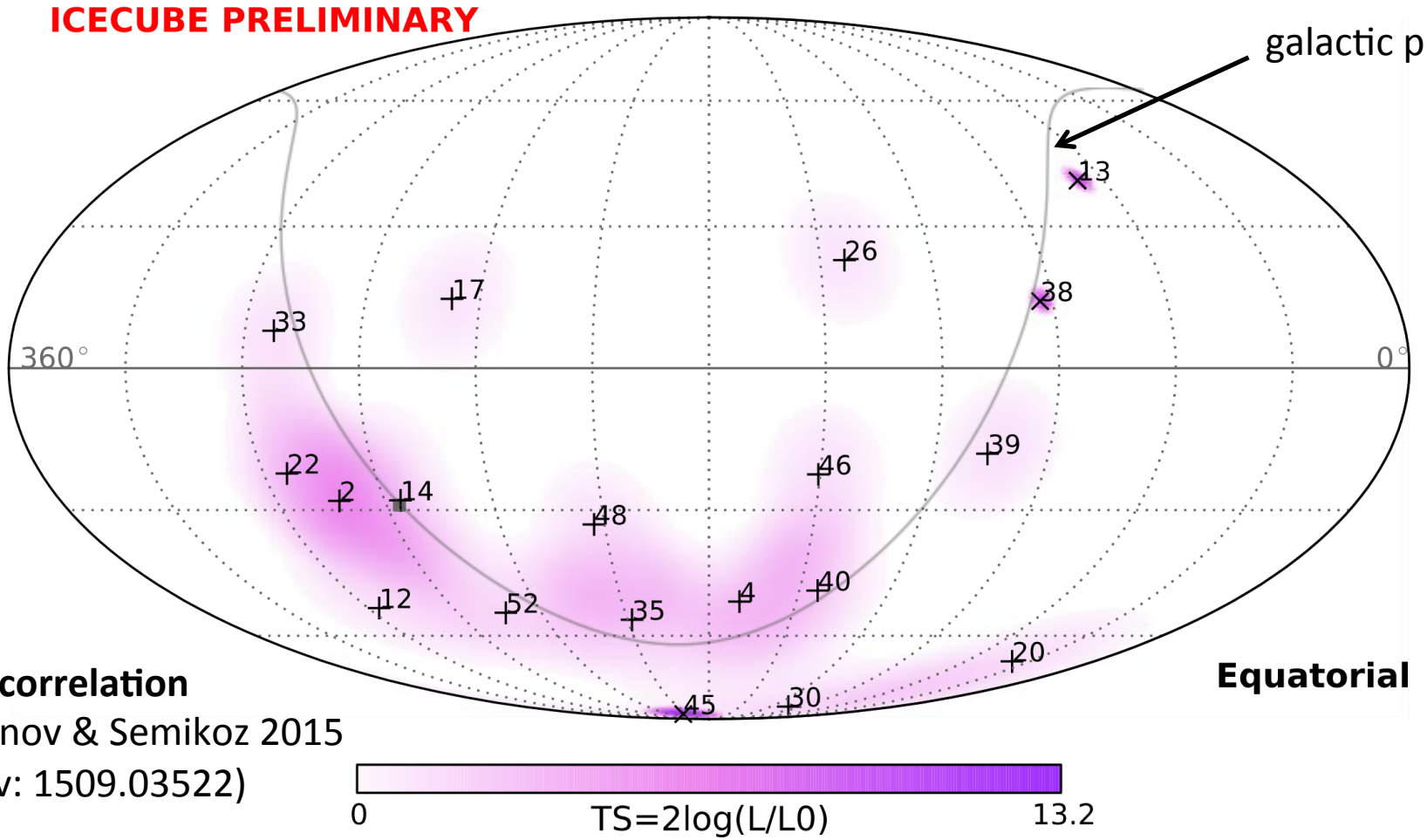
Specifics:

- Assumes PAMELA/AMS p & He hardening is global
- Gal CR cutoffs: 5 (dotted), 50 (solid) PeV
- red = Conventional + global hardening
- blue = Tuned to ϒ-ray observations (Fermi-LAT, HESS, & Milagro)

- New: Incorporate PAMELA/AMS measured p & He hardening and allow CR diffusion to change with gal. radius

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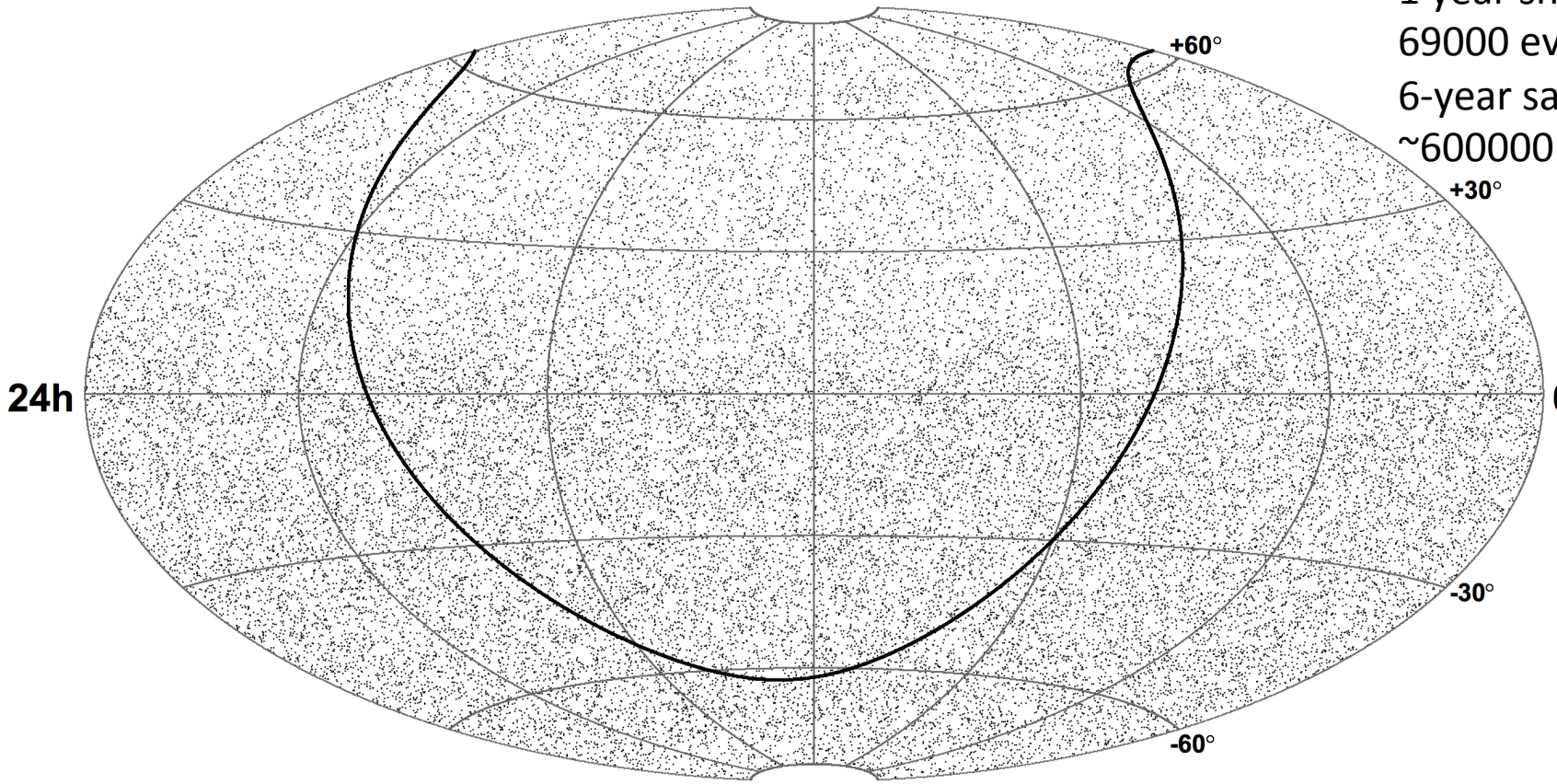
>100 TeV *A Posteriori*



~3 σ correlation
Neronov & Semikoz 2015
(arXiv: 1509.03522)

- Difficult to interpret the very highest energy neutrinos as galactic...

Lower Energy Sample



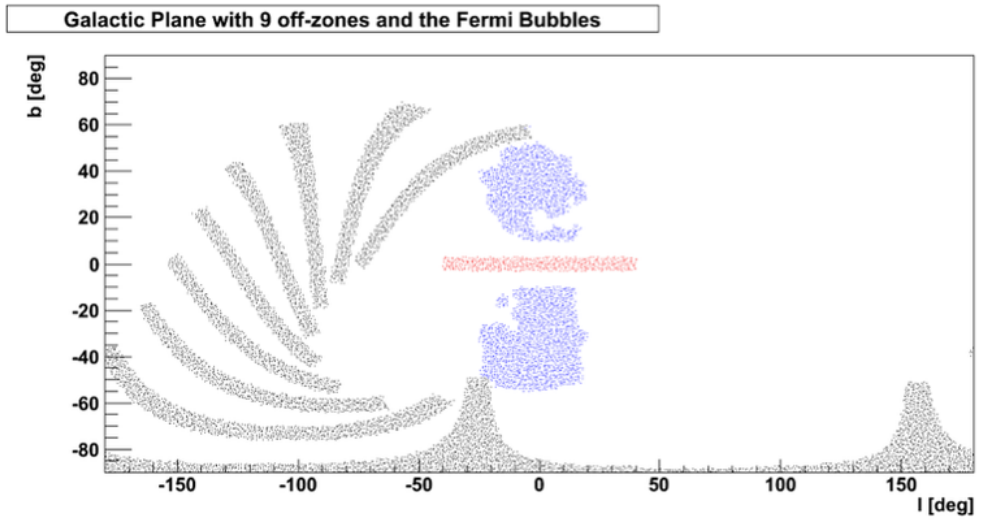
1 year shown:
69000 events
6-year sample:
~600000 events

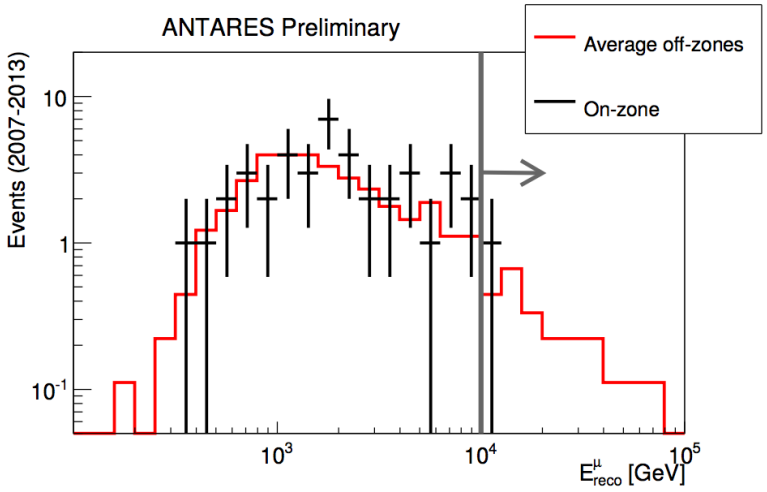
- Can we lower energy threshold to look for O(~1000) events in higher-background through-going muon sample?

New IceCube Gal Plane Results

- [Sorry, results not available in your region]

ANTARES Results

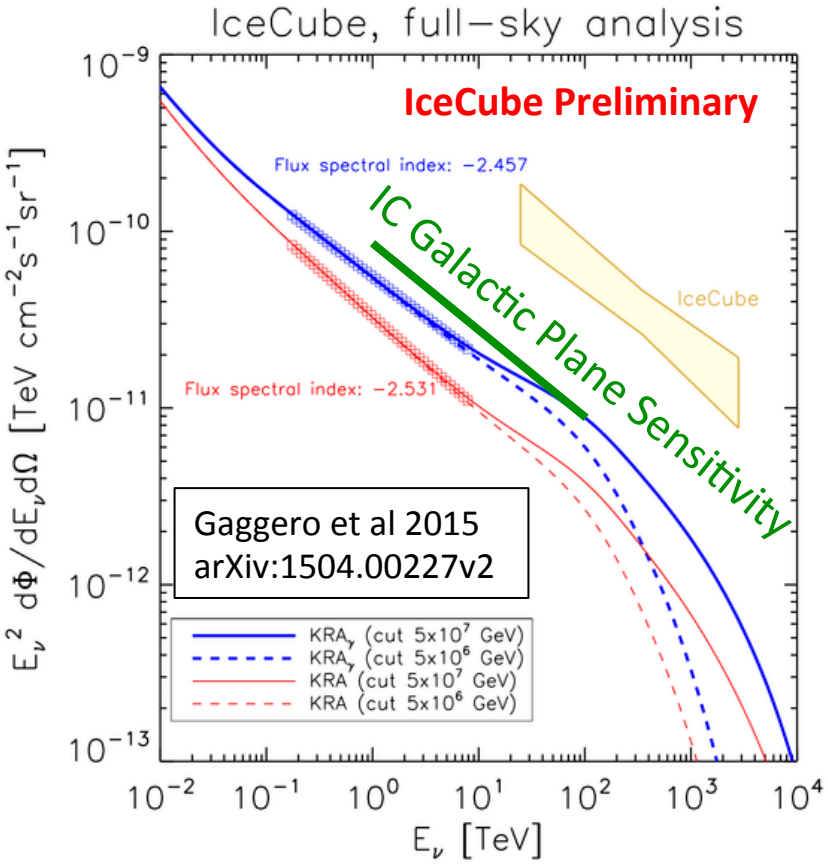


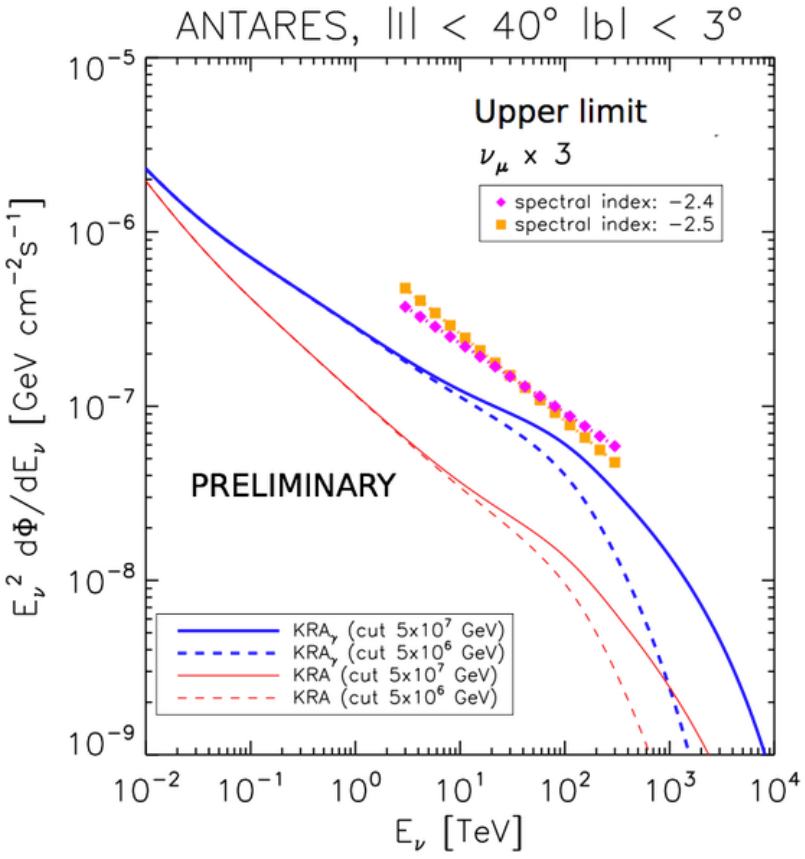


- ANTARES ~1/10th the effective area as IceCube
  - Even so, comparable sensitivity to galactic plane because of distribution
- 1 event observed on a background expectation of 2.5 events

ANTARES results from Luigi Antonio Fusco, shown at VLVNT 2015

IceCube/ANTARES limits





Sensitivities to new GP model comparable between ANTARES/IceCube

The VHDM Models

- Authors simulate a couple of valid models, tuned to explain the neutrinos and stay within constraints from gamma-rays:

"**ES13**" parameters:

$$m_{\rm dm} = 3.2 \text{ PeV}$$

$\text{DM} \to q\bar{q}$ BR: 88%

$\text{DM} \to \nu_e \bar{\nu}_e$ BR: 12%

$$\tau_{\rm dm} = 3.0 \times 10^{27} \text{ s}$$

"**RKP14**" parameters:

$$m_{\rm dm} = 2.4 \text{ PeV}$$

$\text{DM} \to l^{\pm} W^{\mp}$ BR: 50%

$\text{DM} \to \nu Z$ BR: 25%

$\text{DM} \to \nu h$ BR: 25%

$$\tau_{\rm dm} = 3.5 \times 10^{27} \text{ s}$$

$$E_\nu^2 \Phi_\nu = E_\nu^2 \Phi_\nu^{\rm EG} + E_\nu^2 \Phi_\nu^{\rm G}$$ (~equal gal. and extragal. contributions)

$$\approx \frac{c t_H \xi_z}{4\pi} \frac{\rho_{\rm dm} c^2}{\tau_{\rm dm} \mathcal{R}_\nu} + \frac{R_{\rm sc} \mathcal{J}_\Omega}{4\pi} \frac{\rho_{\rm sc} c^2}{\tau_{\rm dm} \mathcal{R}_\nu}$$

$$\sim 4 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Murase et al. 2015
arXiv:1503.04663v1

ES13 Model

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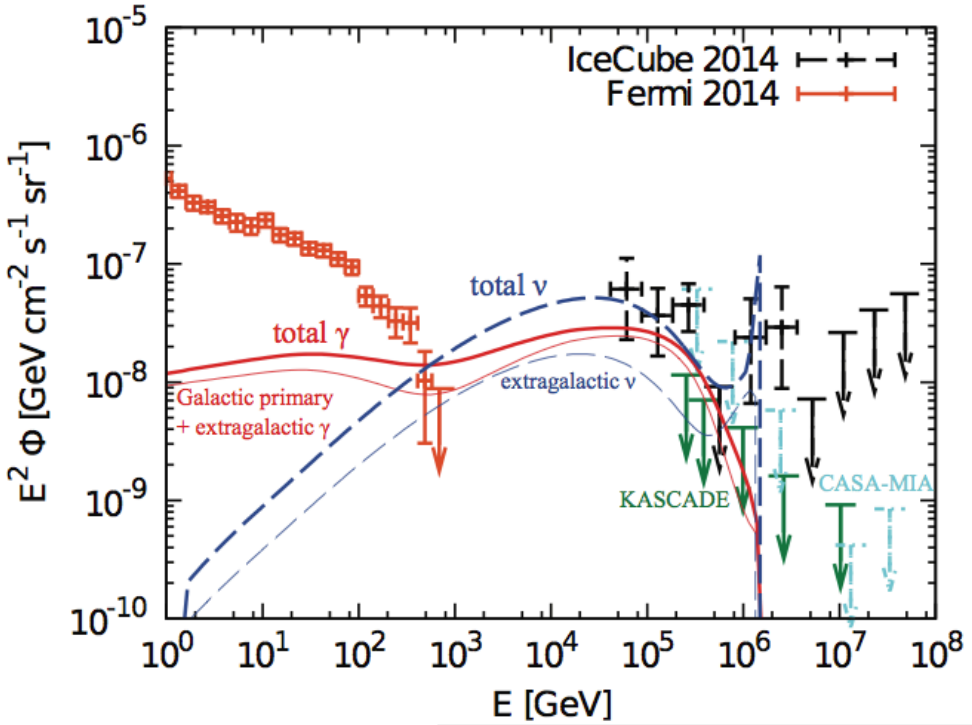
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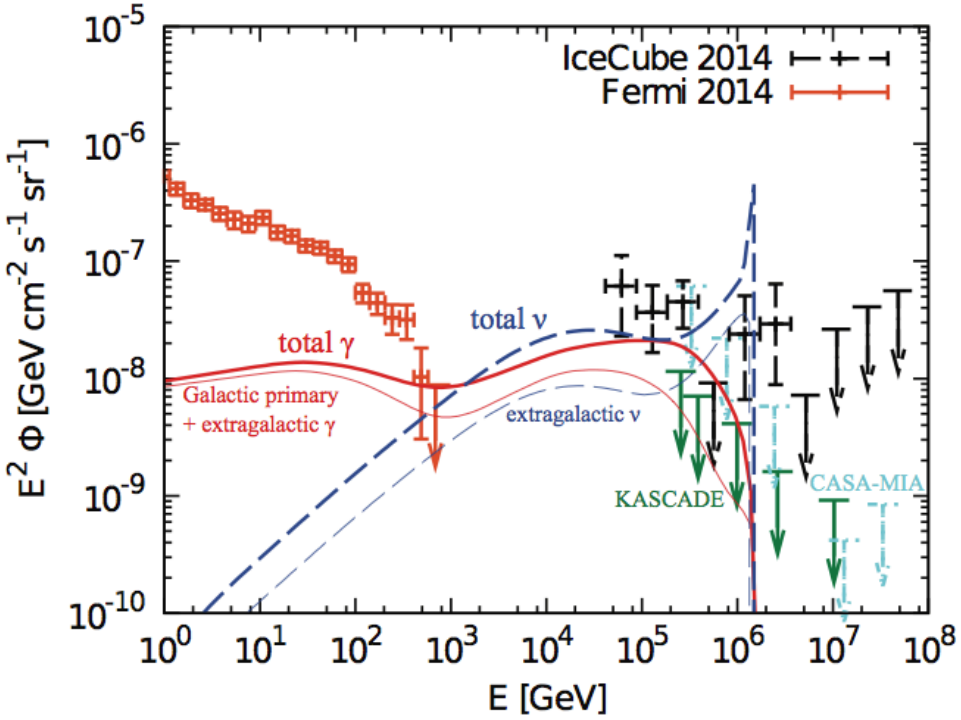
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- Extragalactic

Starburst Scenario



Starburst Scenario

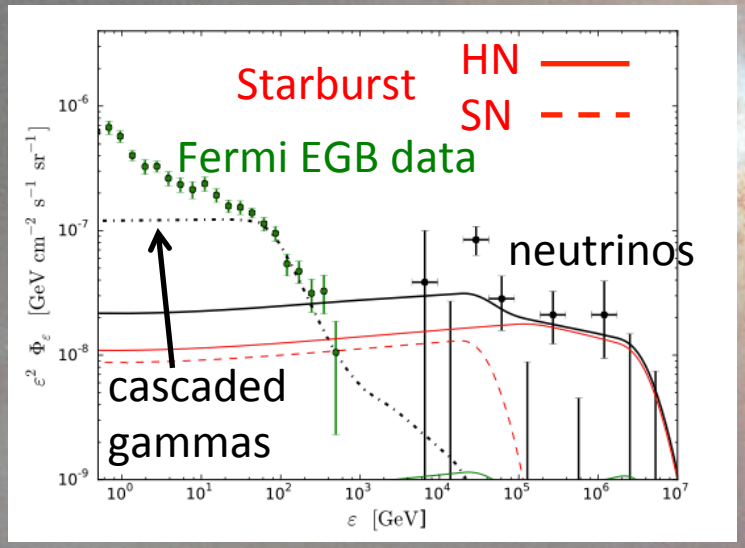
- Candidate: Starburst galaxies
  - High star formation rates -> Lots of supernovae -> Lots of cosmic ray acceleration
  - Lots of target material (high interstellar gas density)
  - Both factors lead to efficient neutrino production through pp interactions and subsequent pion decay

M82 - HST

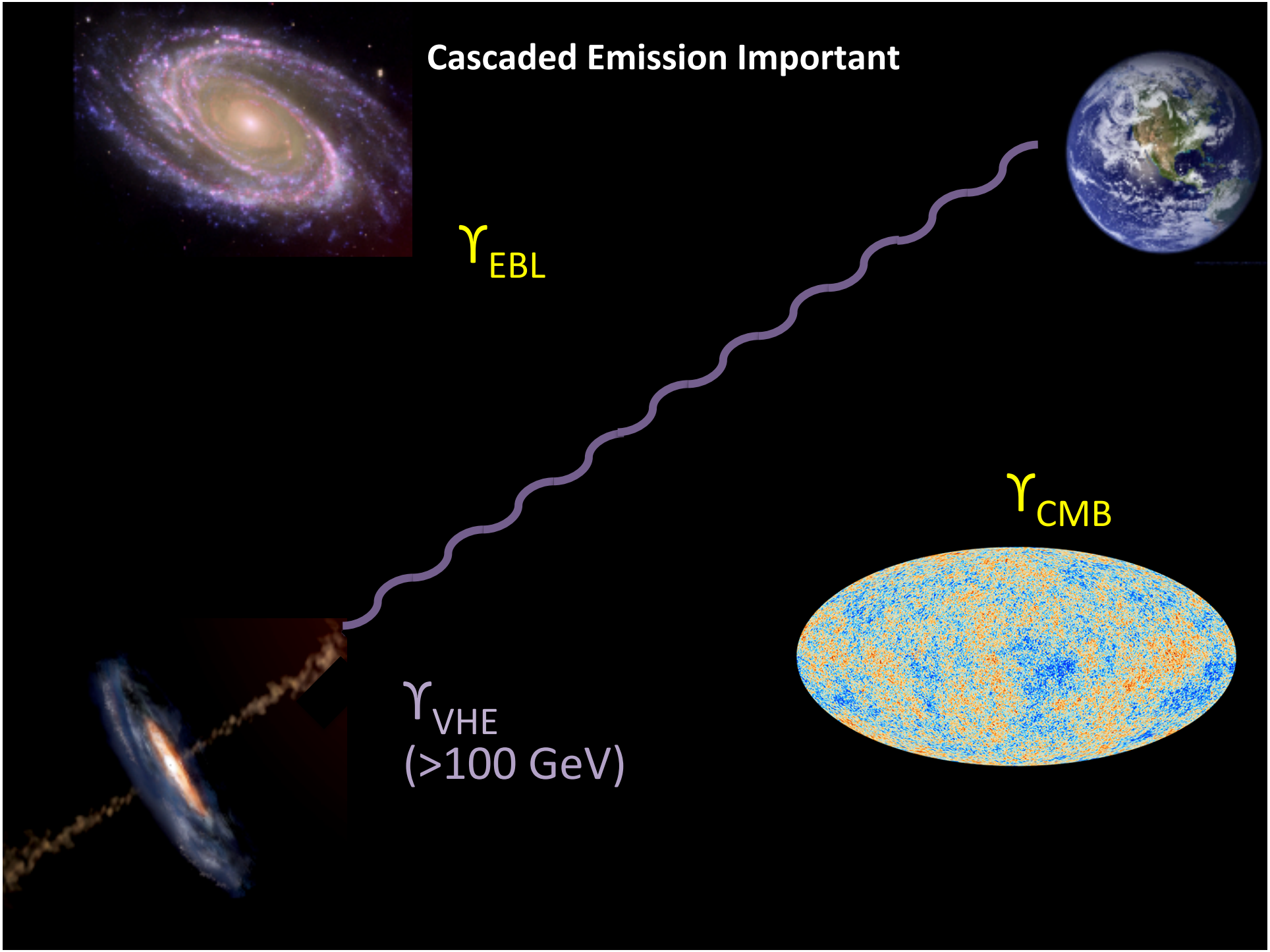
Starburst Scenario

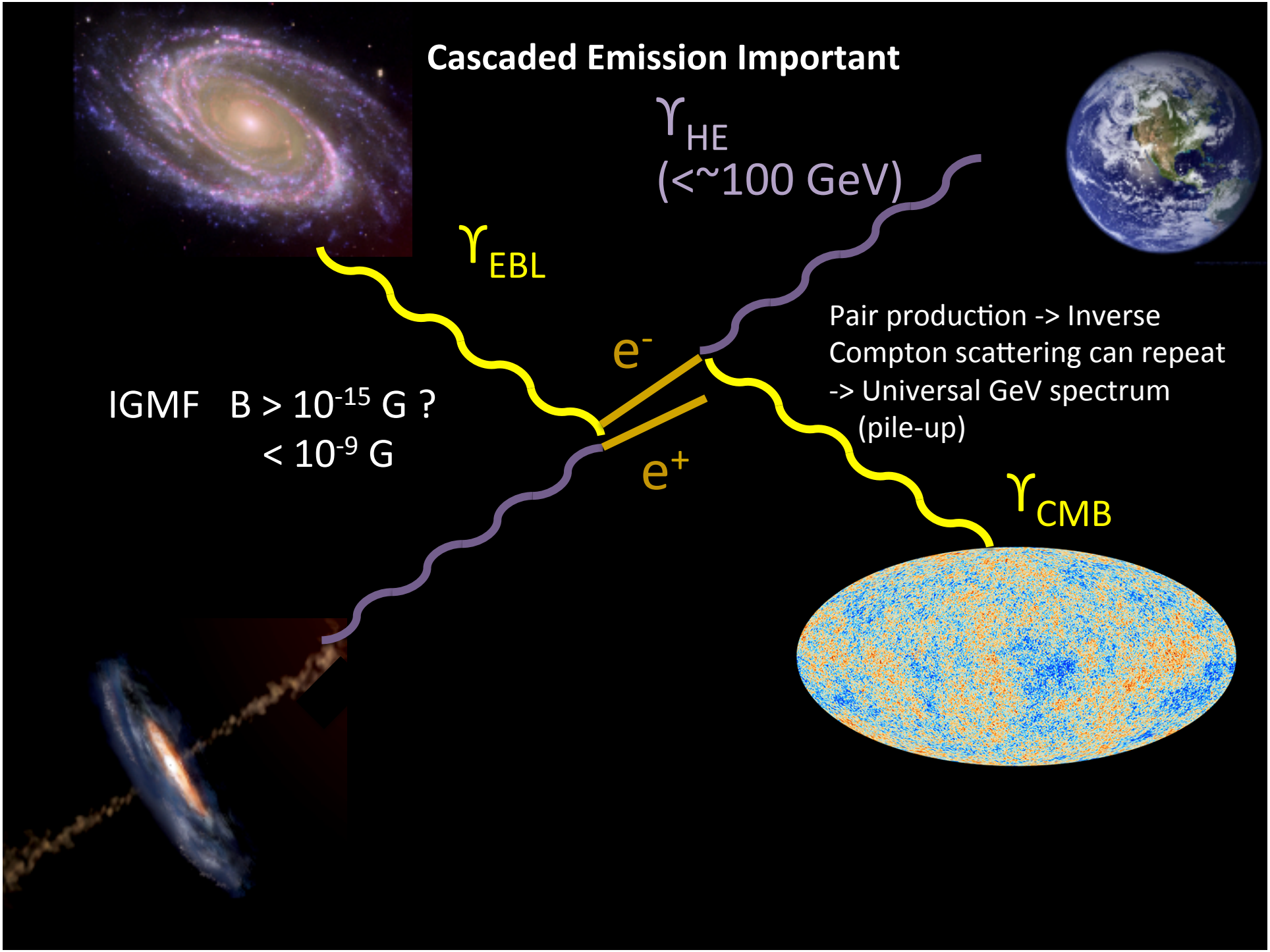
Senno et al 2015
arXiv:1501.04934v1

- Recent paper explores the link between supernovae and hypernovae in starburst/starforming galaxies
  - Case shown where starbursts dominate neutrino production
- PeV neutrino production implies PeV photon production, which cascade down to lower energies (GeV)!

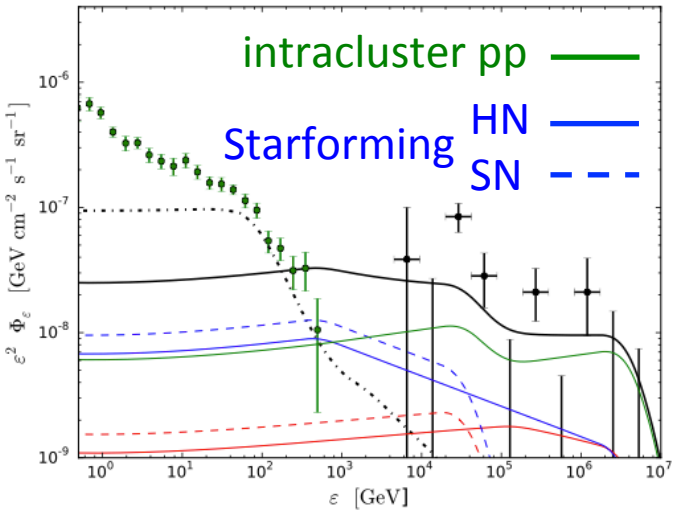


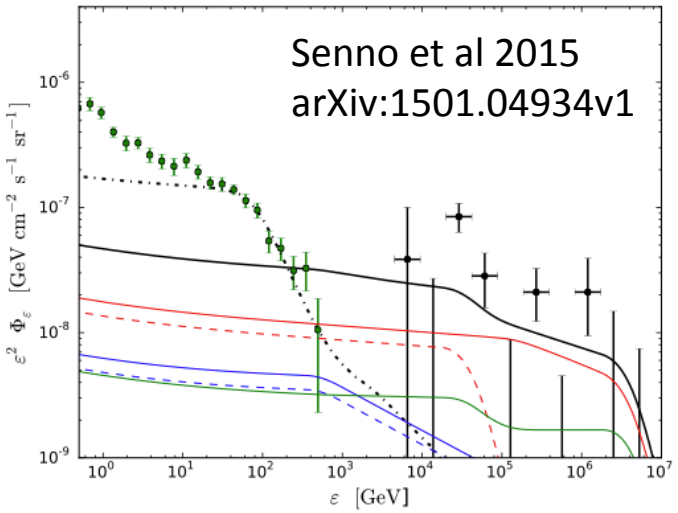
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

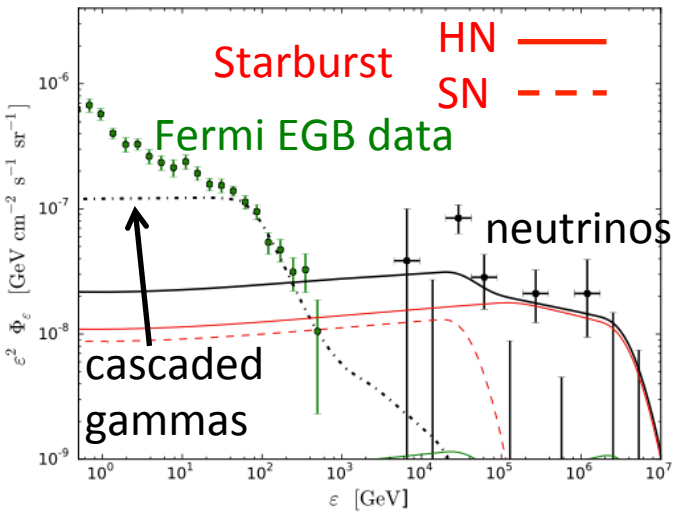

Cascaded Emission Important
γ_{EBL}
γ_{CMB}
γ_{VHE}
(>100 GeV)


Cascaded Emission Important
γ_{HE}
(<~100 GeV)
γ_{EBL}
e^-
e^+
γ_{CMB}
IGMF B > 10^{-15} G ?
< 10^{-9} G
Pair production -> Inverse Compton scattering can repeat
-> Universal GeV spectrum (pile-up)

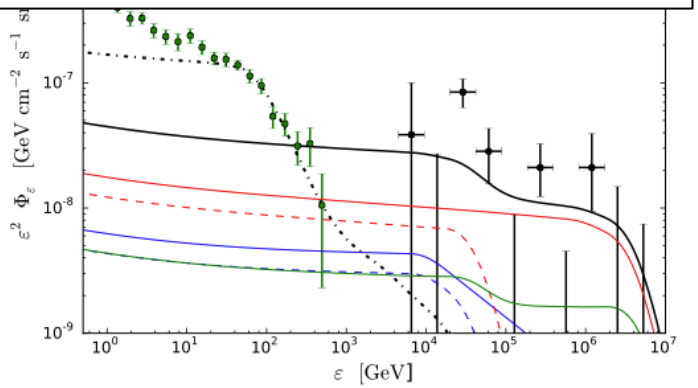
(Large Parameter Space)







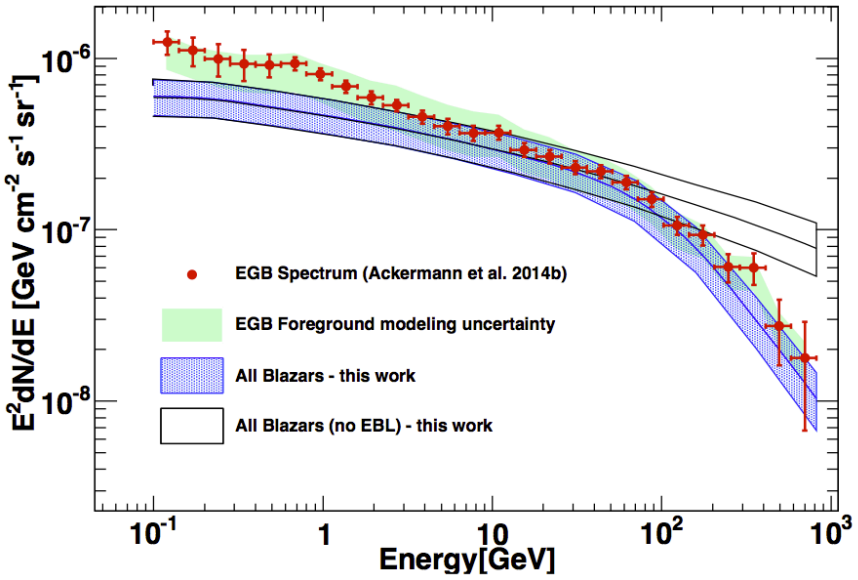
Testing:
- -CR diffusion coefficients
- -CR spectral indices
- -Source population contributions



Cascaded Emission Important

- Starburst scenario implies most (or all) of Fermi's >~100 GeV extragalactic gamma-ray background are from reprocessed PeV gamma rays

- Recent publication already makes the claim that all the >100 GeV EGB is from blazars
  - Detailed prediction of gamma rays, integrating over all blazars

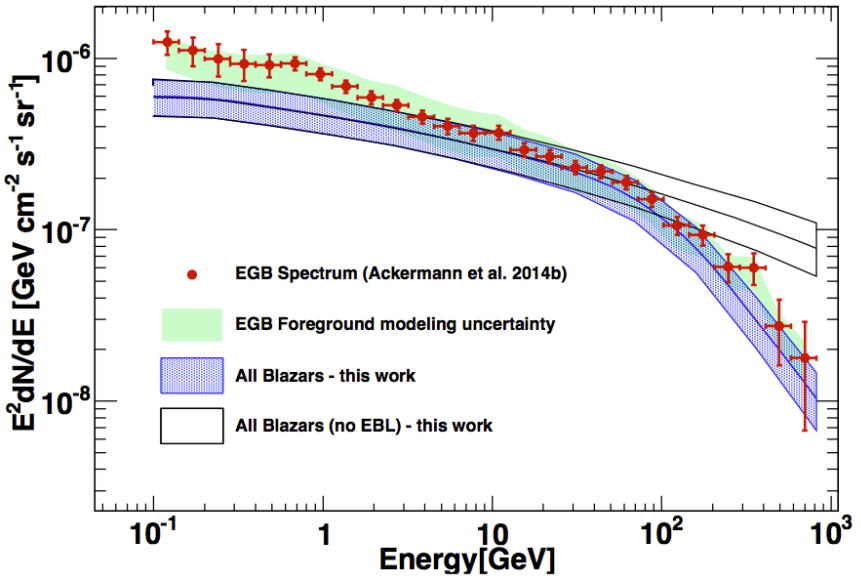


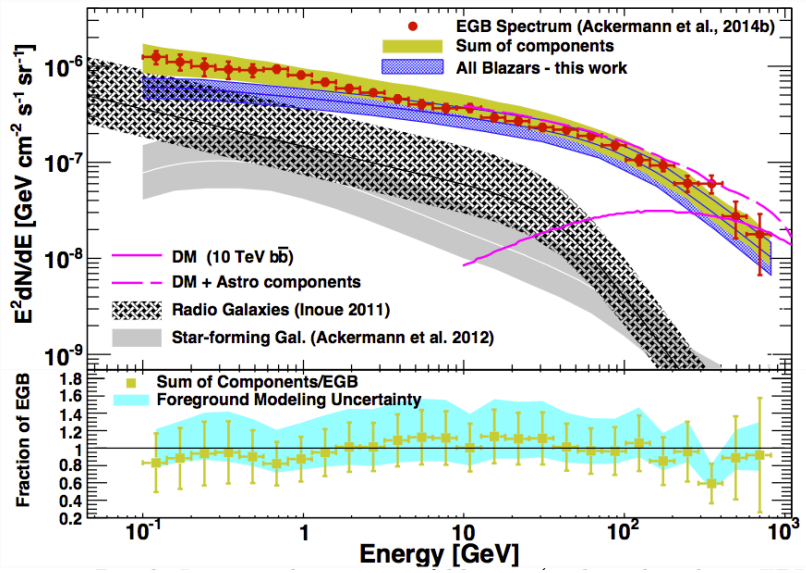
Ajello et al. arXiv:1501.05301v1

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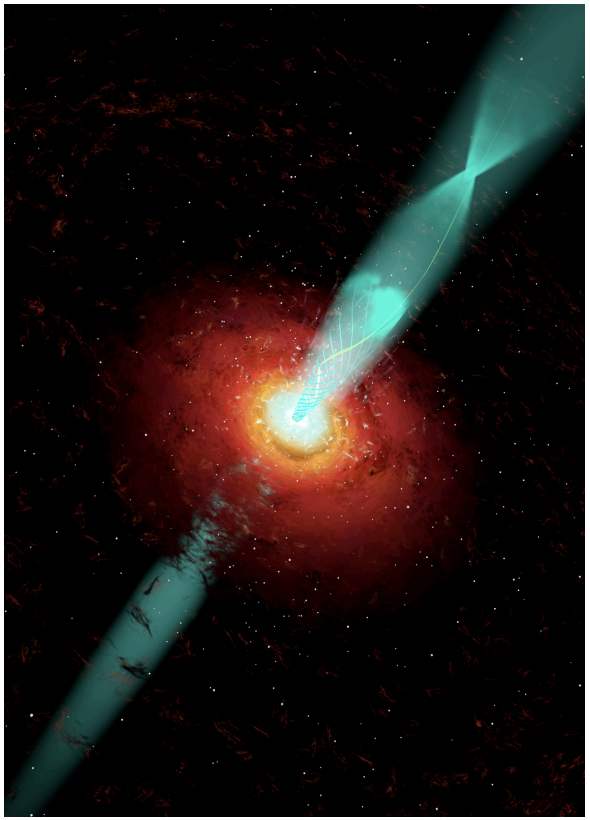
- Recent publication already makes the claim that all the >100 GeV EGB is from blazars
  - Detailed prediction of gamma rays, integrating over all blazars
  - Enough confidence to set competitive limits on the Dark Matter annihilation cross section
  - Problem: Any (transparent) extragalactic source has the same problem!
  - Solution: 'Hide' gamma rays or IceCube's neutrinos from blazars





Blazars Scenario

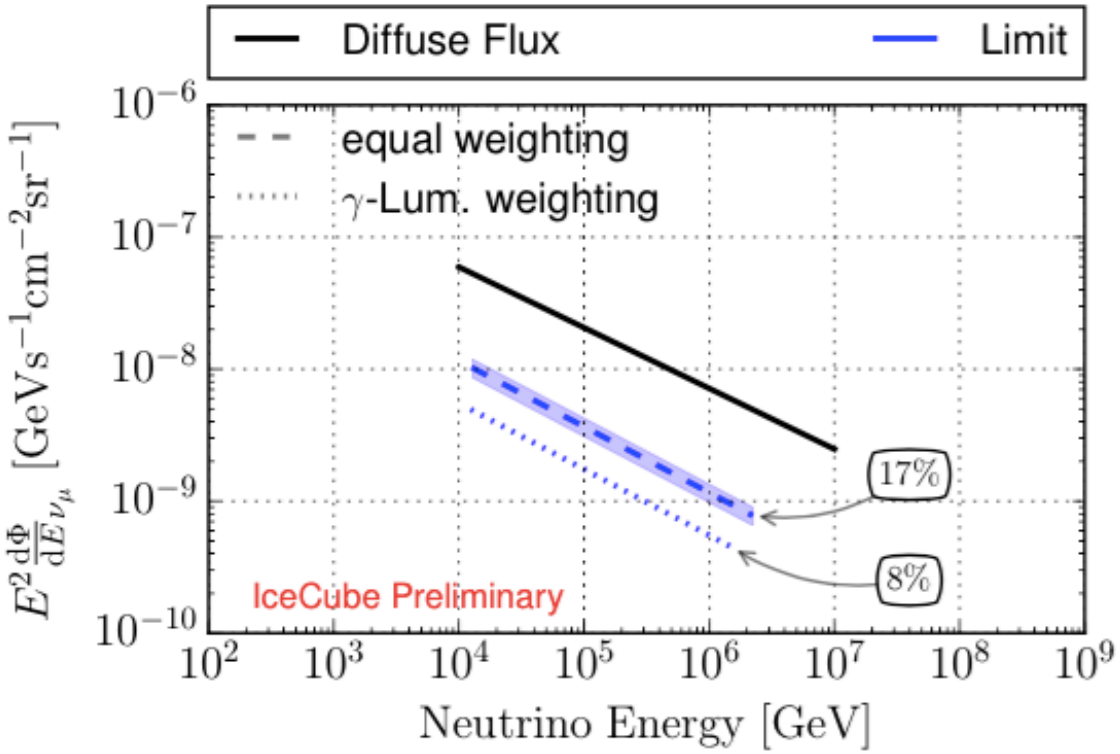
- Blazars are active galactic nuclei (AGN) with jets directed along our line of sight
  - Powered by accretion onto supermassive black holes
  - Particle acceleration occurs somewhere in the jet
- Great candidates for ultra-high energy cosmic ray production
  - Great neutrino source candidate
- Detected readily in gamma rays
  - Can be modeled with purely leptonic processes
  - Can also be explained with mixed leptohadronic processes



Blazar Stacking

- We performed stacked searches for neutrinos from known blazars
  - Fermi-LAT 2FGL catalog of 862 blazars
- No significant excess observed in IceCube stacked search
- Total flux upper limit is well below measured diffuse neutrino flux
- Sub-categories of blazars all produce strong limits
  - FSRQs
  - BL Lacs
    - classified based on emission peak frequency
    - Low-, Intermediate-, and High-synchrotron-peaked

Glüsenkamp, RICAP 2014 Proceedings



Highlights

- Hints for >100 TeV correlation with the gal plane
  - IceCube results may challenge models of CR transport in the galaxy
  - Galactic source populations are next focus

Direct link to Fermi-LAT gal plane diffuse model

- Standard populations of blazars, GRBs, and starbursts excluded as sole source of neutrino flux
  - Must not violate Fermi extragal. background gammas
  - 'Dark' versions of many source classes possible
  - Must be a large number of sources
  - Neutrinos might be unique signature

Direct link to Fermi EGB

We may have no other way to learn about the sources than modeling

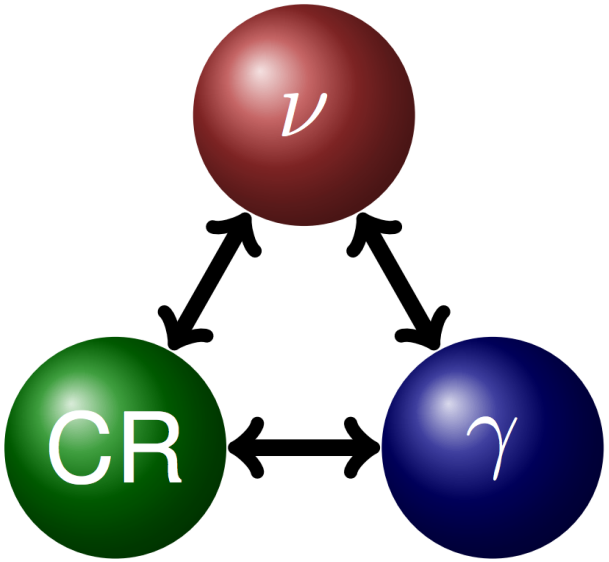
- As more 'standard' sources excluded, dark matter (decay) becomes more attractive
  - Even the next few years of data may prove interesting

exotic dark matter

Backup

Multi-messenger Paradigm

- Neutrino production closely linked to cosmic ray and γ-ray production
- Pion production in CR interactions with gas ("pp") or radiation ("pγ")
  - ν carries ~5% of CR nucleon energy
  - 1 PeV ν: 20 PeV CR nucleons, 2 PeV γ-rays
- This is highly interesting energy range
  - Galactic to Extragal. transition in CRs
  - Glashow resonance
  - Not well-constrained by γ-ray observations

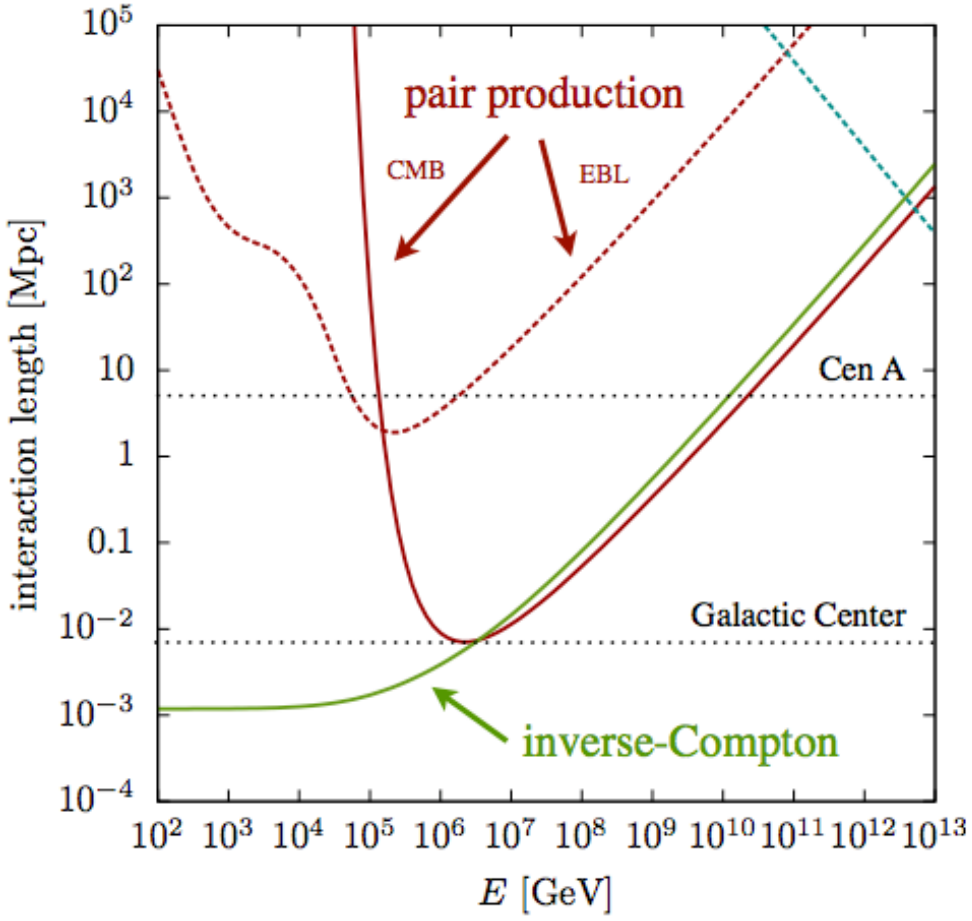


Cascading Process

- CMB interactions **(solid lines)** dominate in casade:
  - inverse Compton scattering (ICS)
    $e^{\pm} + \gamma_{\rm CMB} \rightarrow e^{\pm} + \gamma$
  - pair production (PP)
    $\gamma + \gamma_{\rm CMB} \rightarrow e^{+} + e^{-}$
- extragalactic background light **(red dashed line)** determines the "edge" of the spectrum.

  [EBL: Franceschini *et al.* '08]
- rapid cascade interactions produce universal GeV-TeV emission

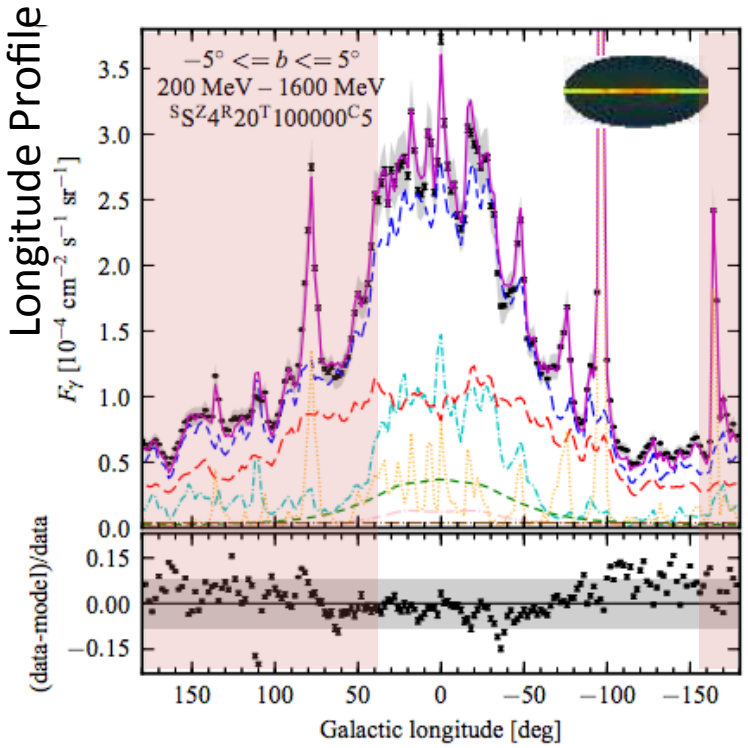
  [Berezinsky&Smirnov'75]



[MA'11]

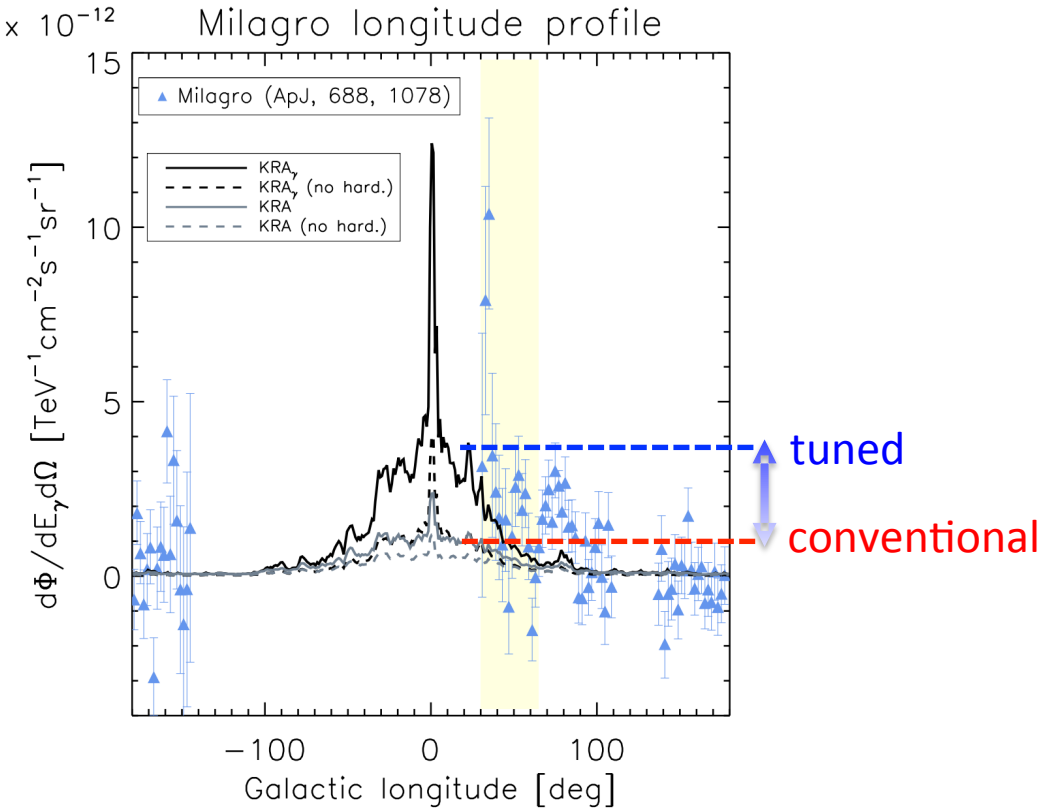
Longitude Profiles

Fermi Pion-decay profile in **red**



Northern Sky: IC Sensitive

M. Ackermann et al 2011
arXiv:1202.4039v2

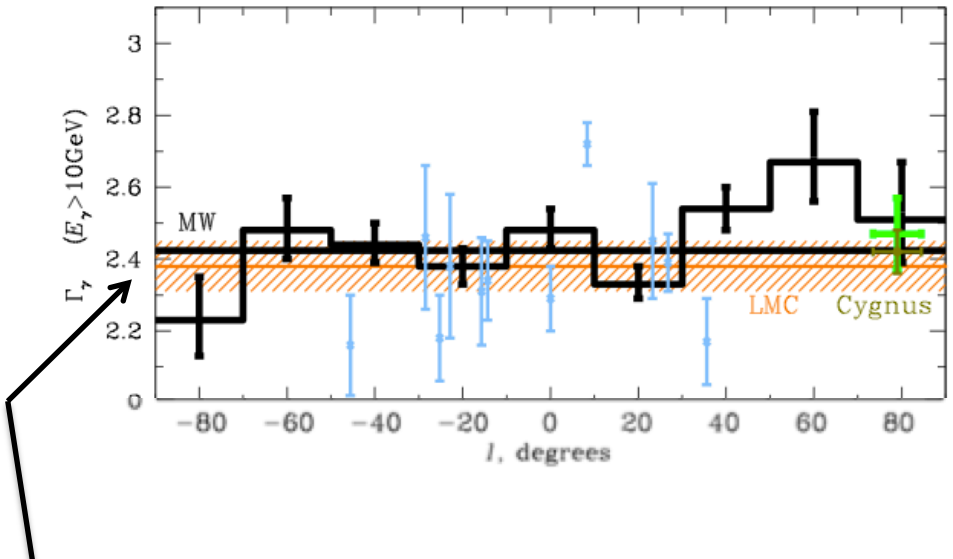


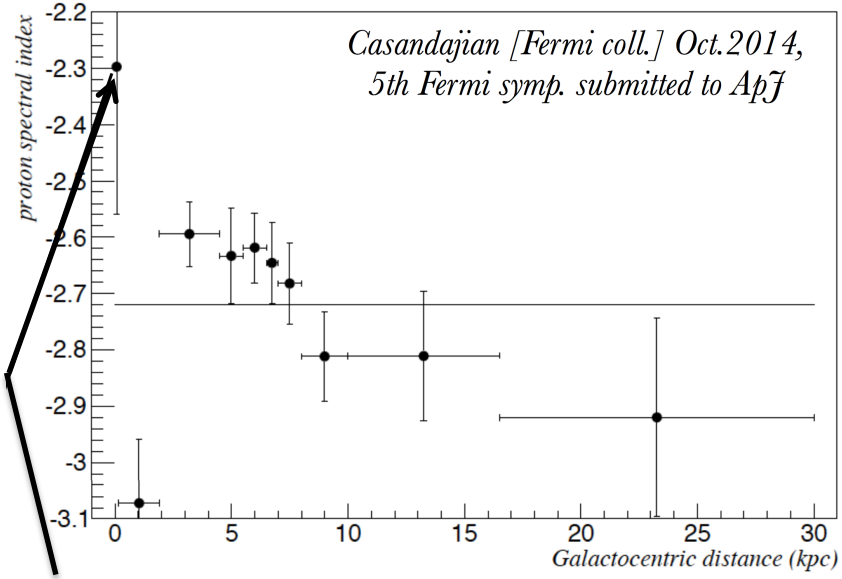
Large uncertainty in flux from inner galaxy!

Gaggero et al 2015
1507.07796v1.pdf

Remote CR Spectrum

Υ-ray spectral index vs gal lon.

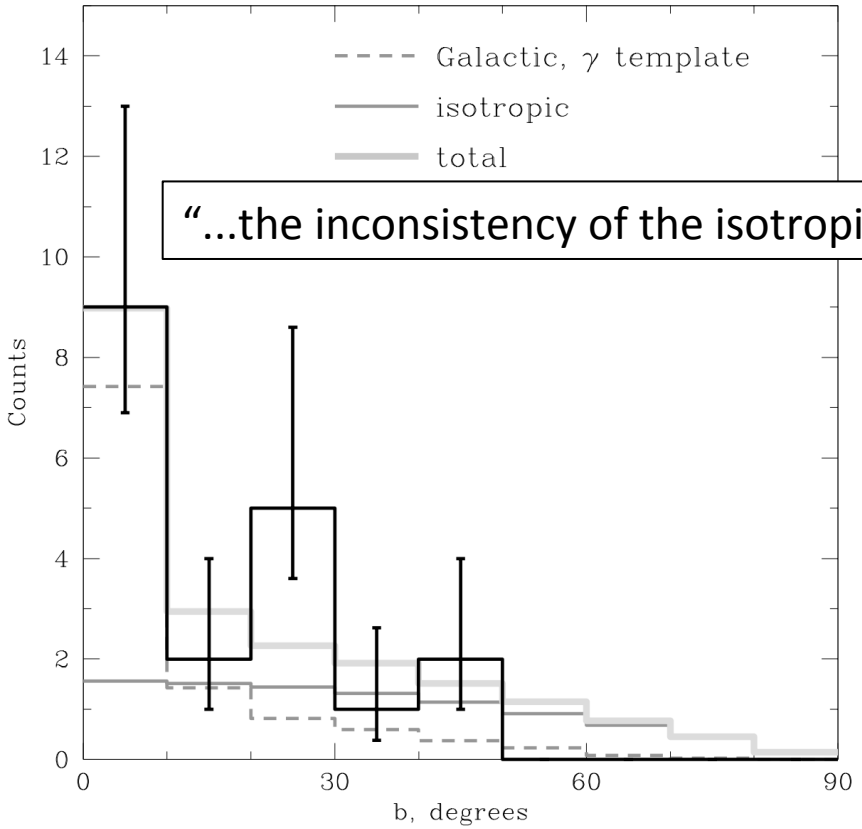


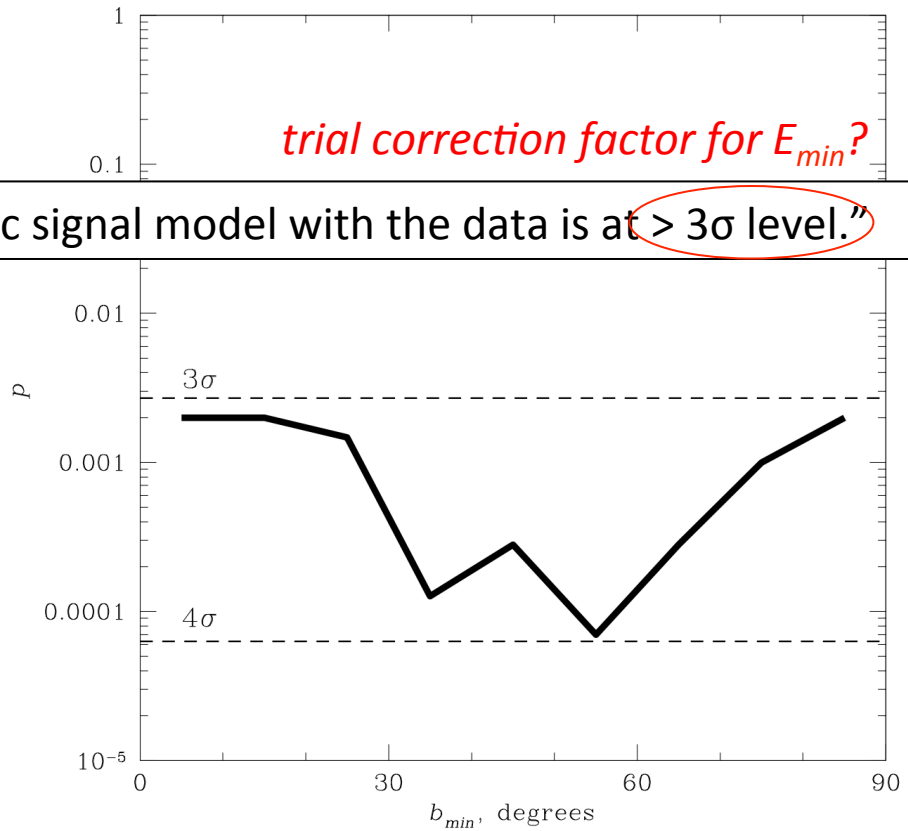


- Neronov & Malyshev 2015 (arXiv:1505.07601v1)
- **Claim: Average CR spectral index: $E^{-2.5}$**
  - Universal? Seen in both MW & LMC
- Earth in softer-than-typical fluctuation due to discrete sources

- Fermi-LAT work in progress
- **Claim: CR spectral index varies with galactic radius**
- Earth in softer region of the galaxy

>100 TeV *A Posteriori*



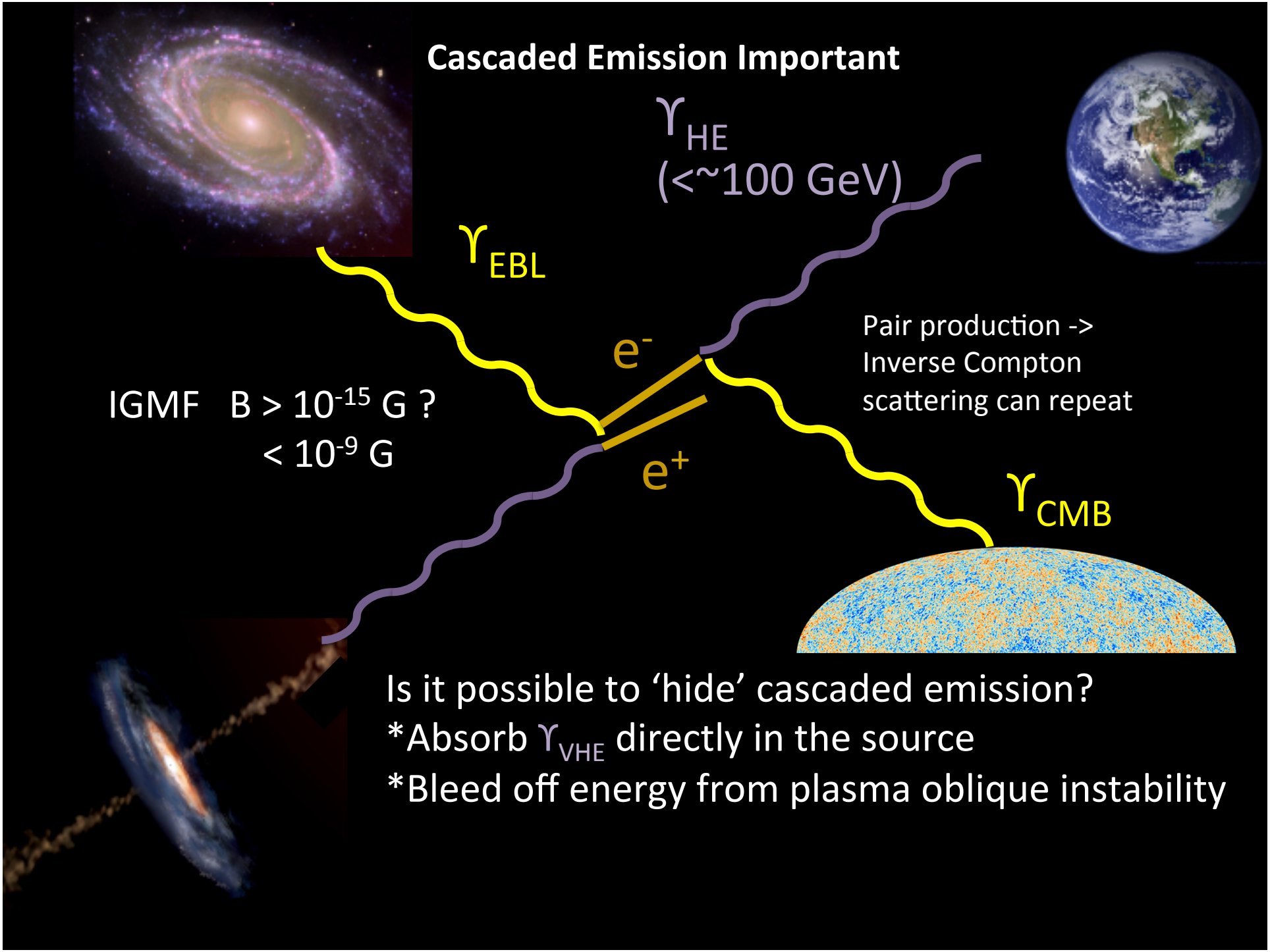


trial correction factor for E_{min}?

"...the inconsistency of the isotropic signal model with the data is at > 3σ level."

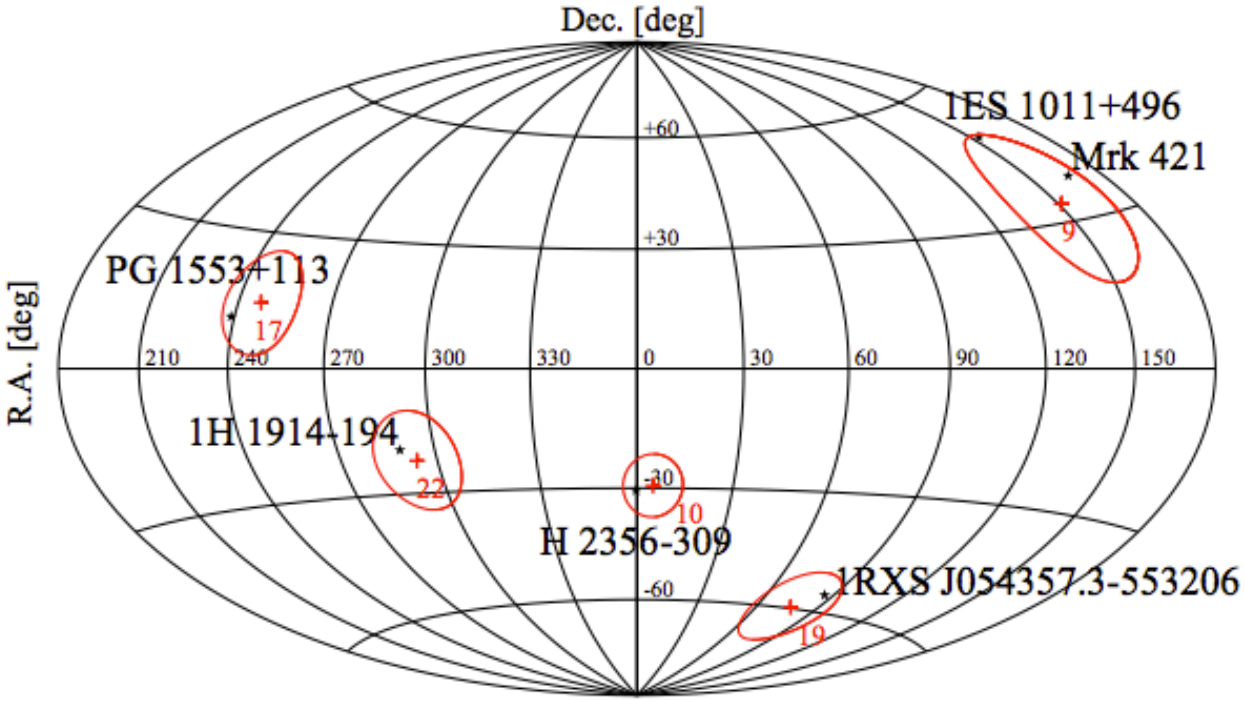
"A model which contains 50% contributions from the galactic and extragalactic components provides a satisfactory fit to the data [left]."

Neronov & Semikoz 2015 (arXiv: 1509.03522)


Cascaded Emission Important
γ_{HE}
(<~100 GeV)
γ_{EBL}
e^-
e^+
Pair production ->
Inverse Compton
scattering can repeat
γ_{CMB}
IGMF B > 10^{-15} G ?
< 10^{-9} G
Is it possible to 'hide' cascaded emission?
*Absorb γ_{VHE} directly in the source
*Bleed off energy from plasma oblique instability

HSP Associations?

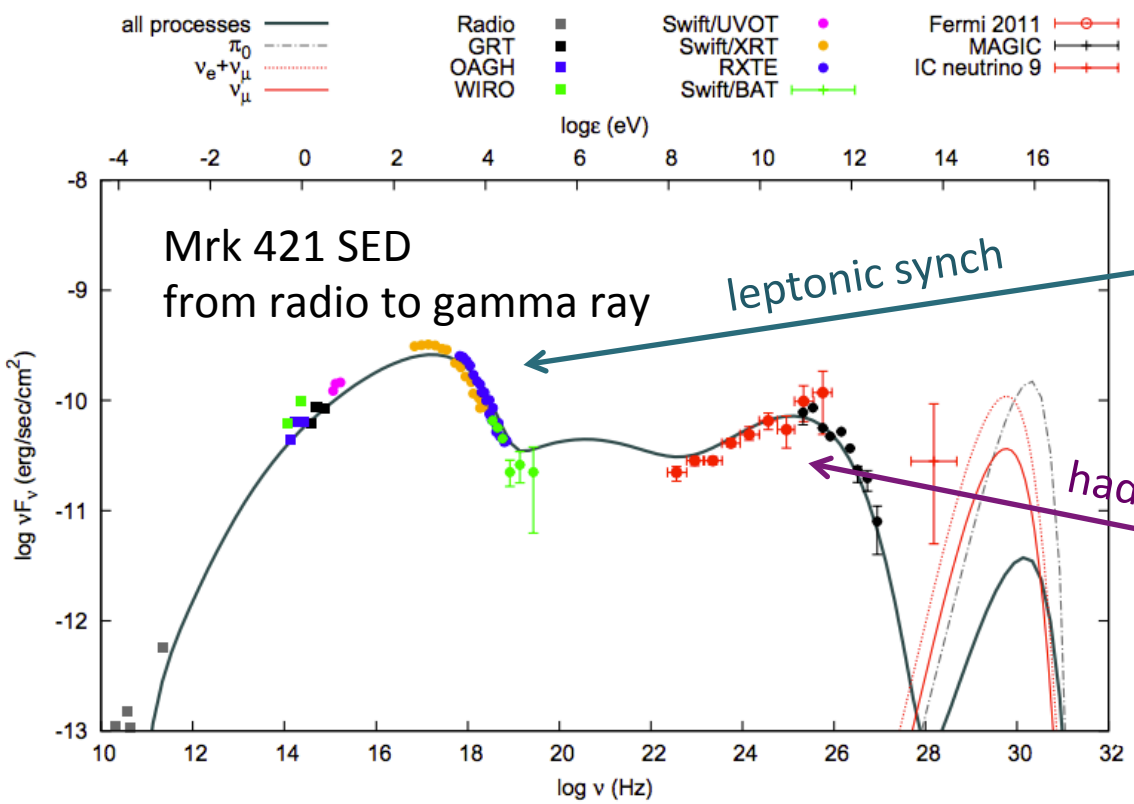
- Despite strict limits on blazar contribution to the diffuse flux, there is renewed interest in hadronic modeling of HSP blazars
  - Due to both **stretching** of leptonic model parameters and observed **association** with high energy starting events
  - If spectrum does not extend down as a power law, may circumvent limit calculation assumptions
  - Recall: ~15° ang. res. for cascades
  - HSPs peak at the highest observed gamma-ray energies, so a natural candidate for the PeV events

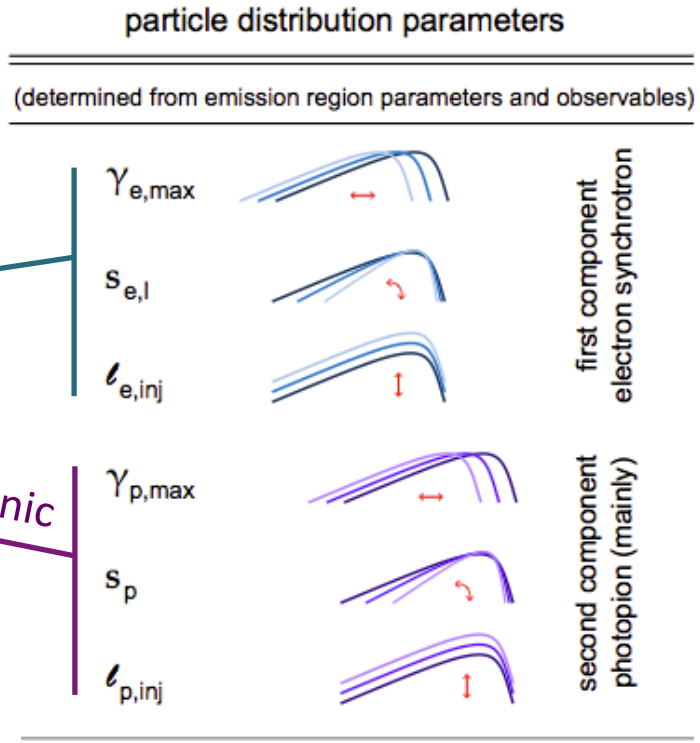


Associations of five HE starting neutrinos with HSP BL Lacs are suggestive but not significant

Blazar Modeling

- Simplified model, agnostic about mechanism of acceleration
  - Assumes power law injections of electrons and protons into region with turbulent magnetic and possibly photon fields
  - Many free parameters

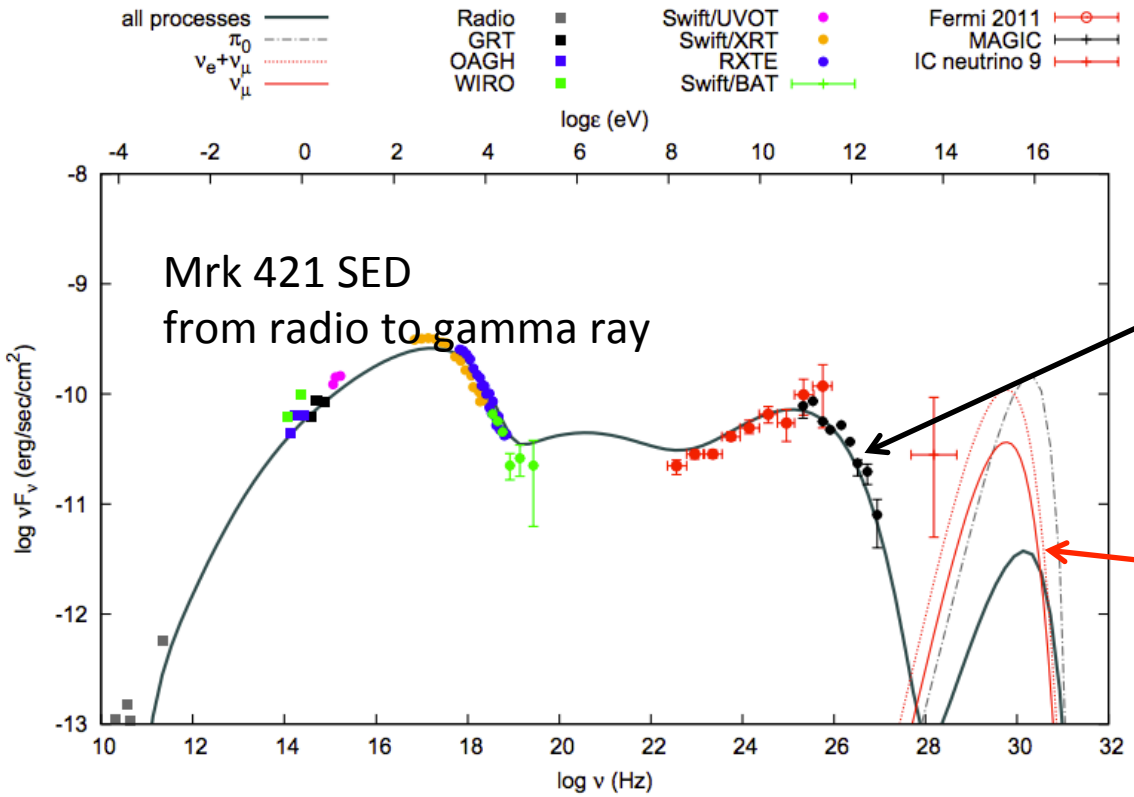




arXiv:1501.07115v1
Petropoulou et al., 2015

Blazar Modeling

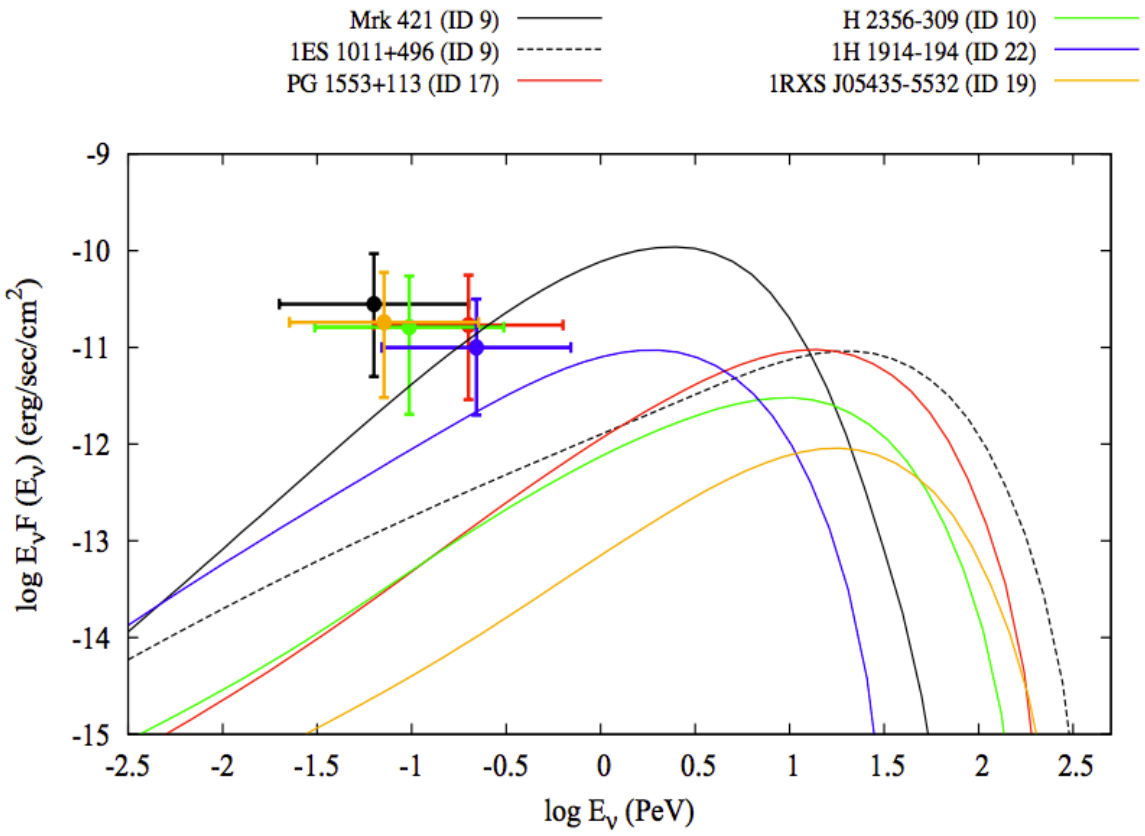
- Simplified model, agnostic about mechanism of acceleration
  - Assumes power law injections of electrons and protons into region with turbulent magnetic and possibly photon fields
  - Many free parameters



- High energy peak from hadrons, but choice in dominant emission mechanism
  - π^0 decay
  - p synchrotron
  - **π-decay product (μ,e) synchrotron**
- Choosing the latter gives a sharp neutrino peak
  - No extension as power law down to lower energy

arXiv:1501.07115v1
Petropoulou et al., 2015

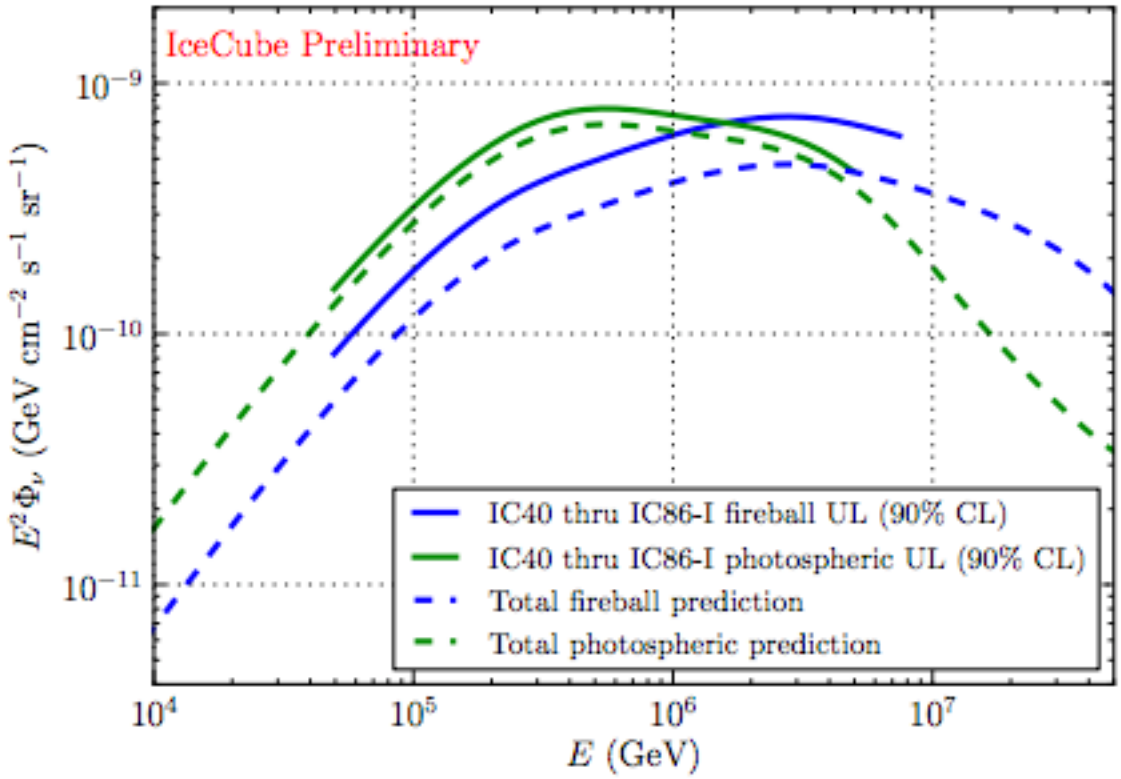
Predictions for All Assoc. Blazars



- Five out of six associated HSP Blazars allow neutrino flux predictions with ~3 σ of IceCube flux
- While association is not significant, certainly an interesting source class candidate

arXiv:1501.07115v1
Petropoulou et al., 2015

GRBs



- We have not seen any HE events from stacking 492 GRBs (2008-2012)
- Excludes GCN-triggered GRBs as origin of our measured flux
- Latest upper limits close to fireball/photospheric emission models

arXiv:1412.6510