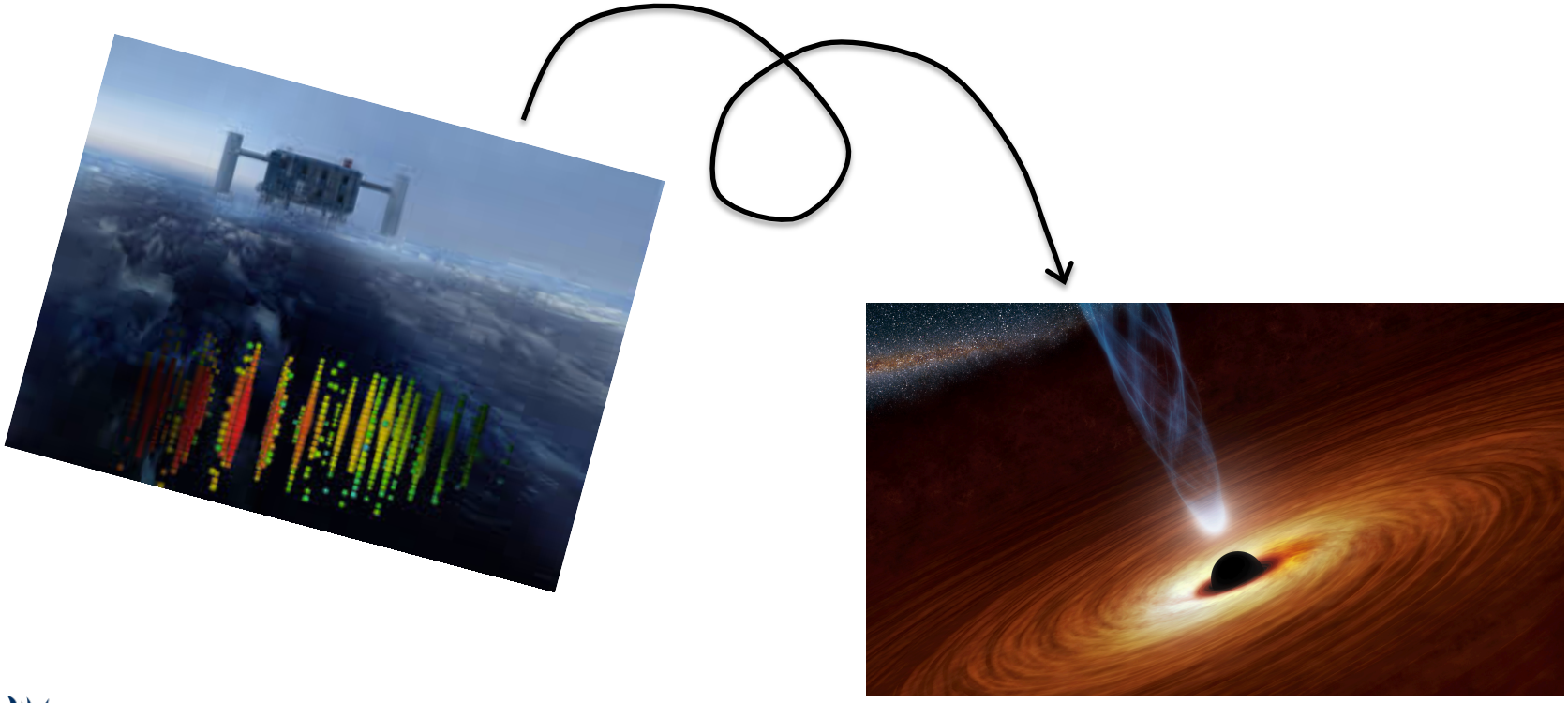
Neutrinos: Origins and Connections



Jon Dumm

EO meeting

2016 Jan 28

Stockholm University

Oskar Klein centre

The Future of Neutrino Astronomy

The Future of Neutrino Astronomy

- Sudden clarity

The Future of Neutrino Astronomy

- Sudden clarity
- Mounting evidence
  until acceptance

The Future of Neutrino Astronomy

- Sudden clarity
- Mounting evidence
  until acceptance
- No resolution

IceCube Neutrino Observatory

86 strings

60 Optical Modules per string

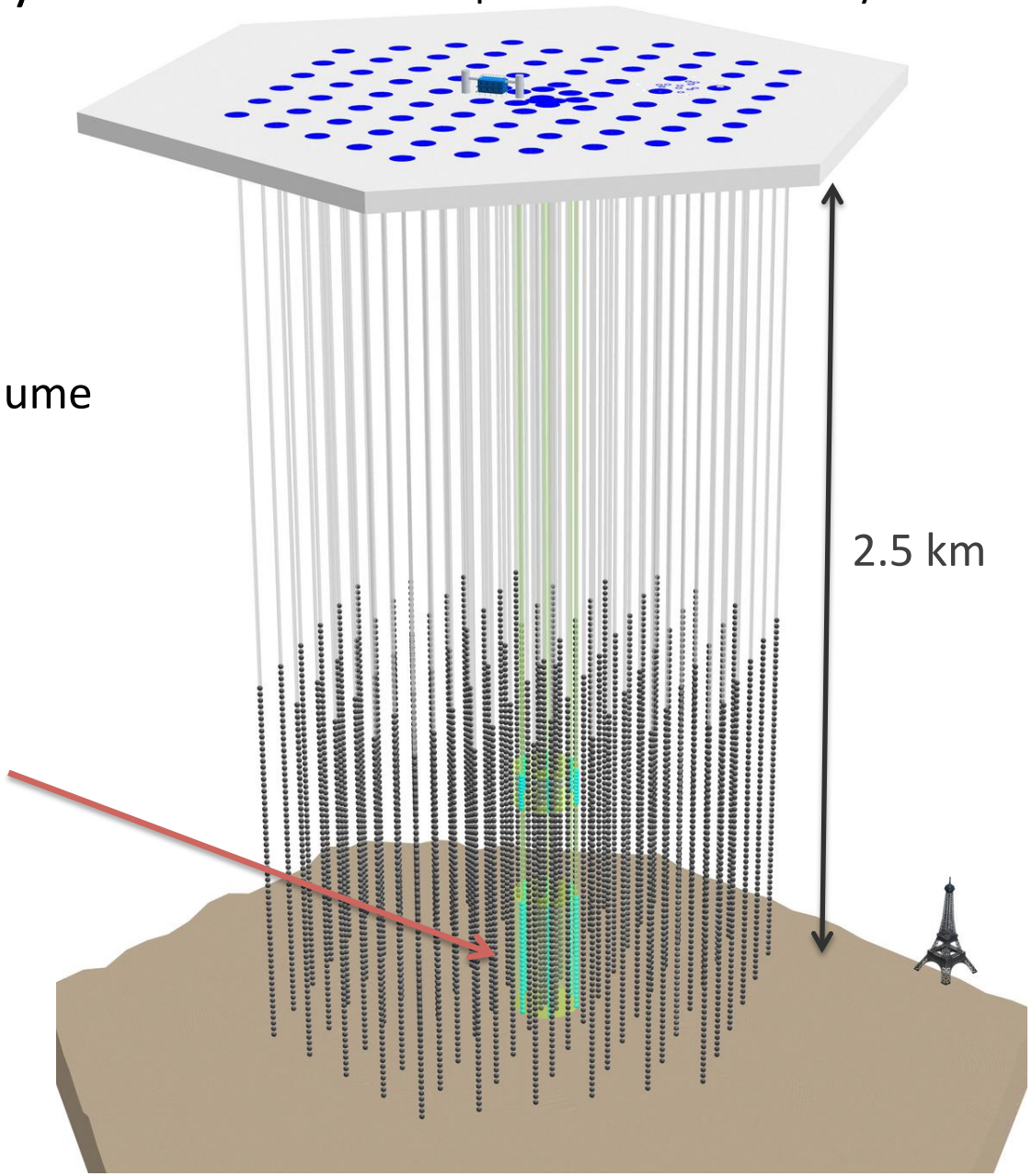
5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

Began full operations May 2011

DeepCore
Low-energy Extension

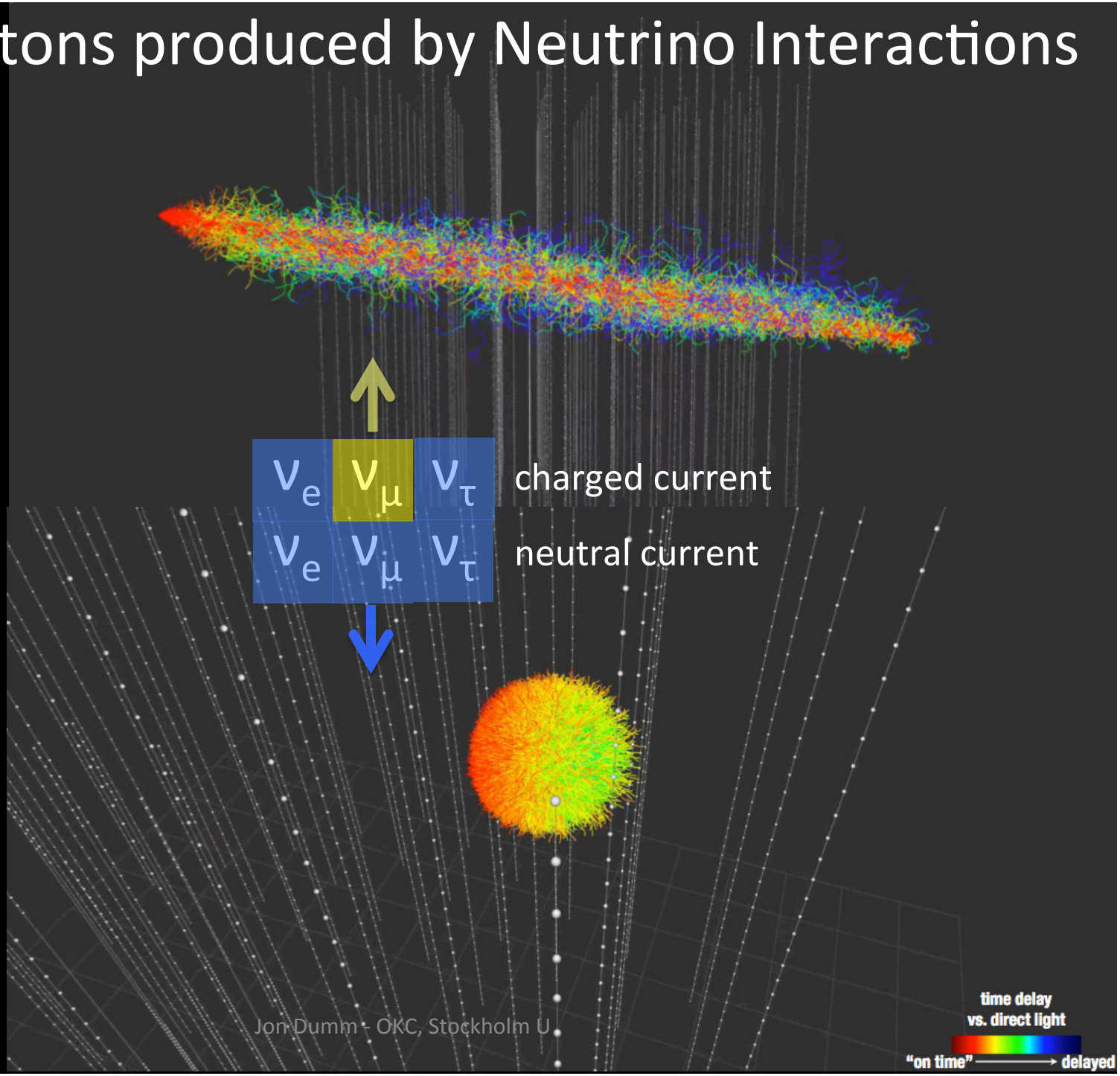
Dark Matter,
Neutrino Oscillations



Photons produced by Neutrino Interactions

Track topology
(e.g. induced by muon neutrino)

Good pointing, 0.1° - 1°
Lower bound on energy

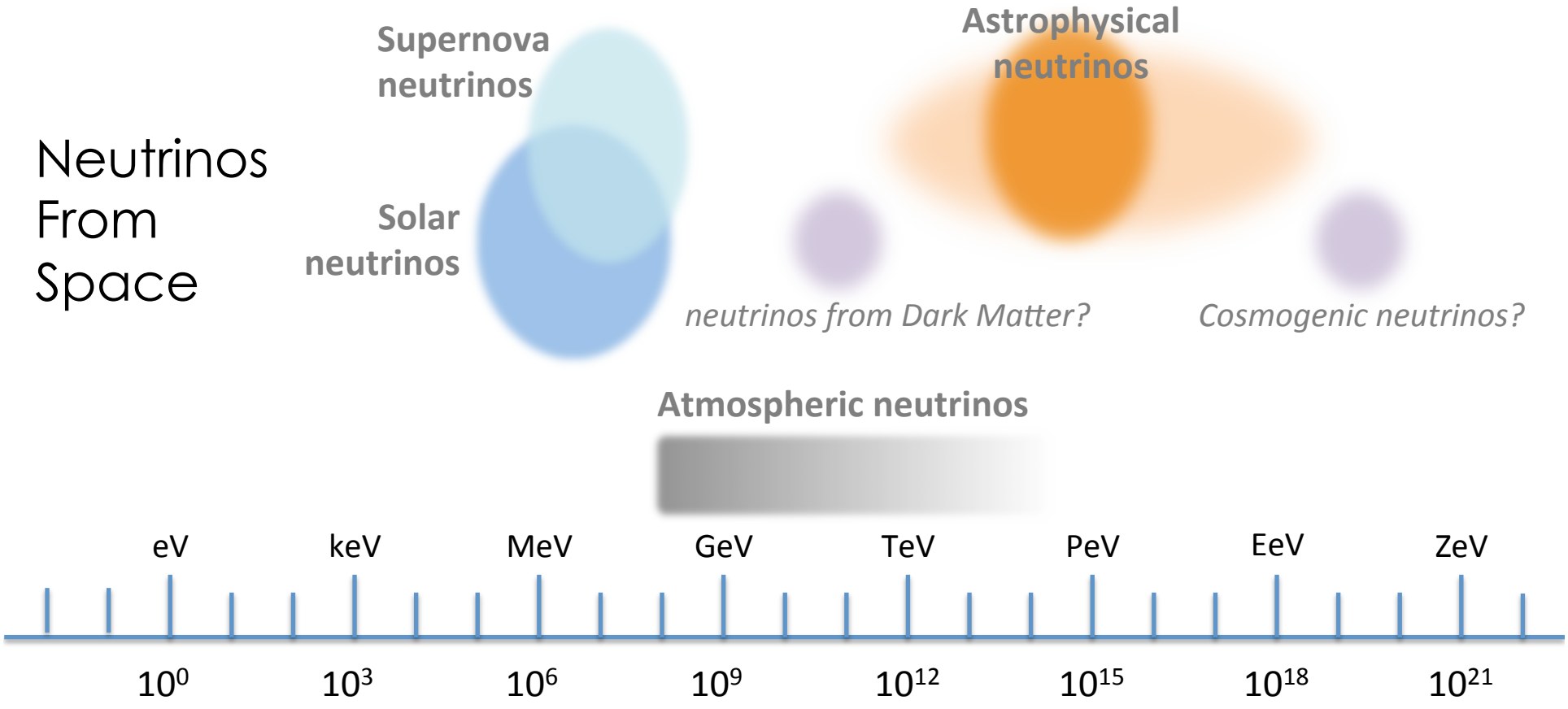


Cascade topology
(e.g. induced by electron neutrino)

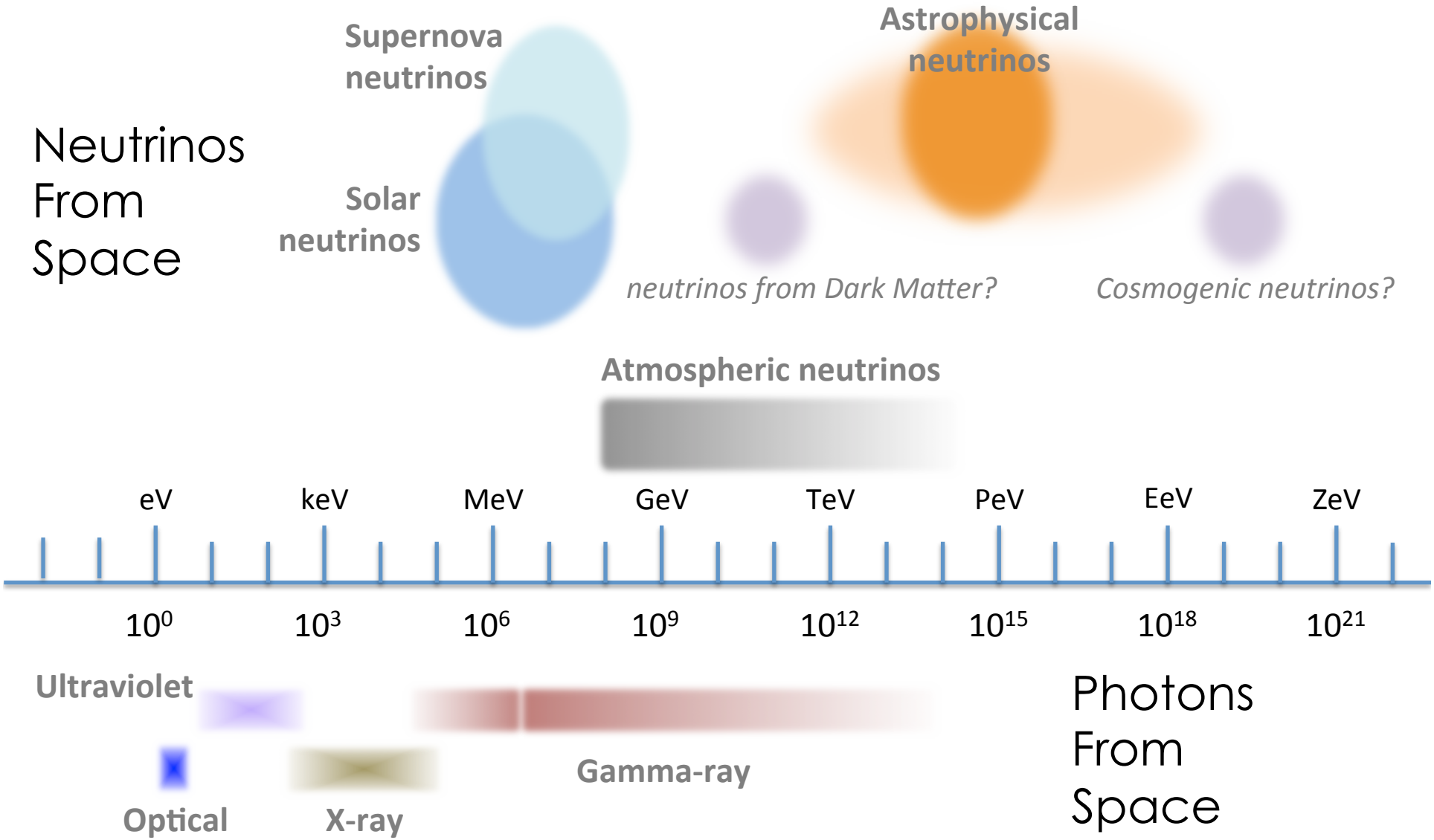
Good energy resolution, 15%
Some pointing, 10° - 15°

HE Neutrino Astro - Context

Neutrinos From Space



HE Neutrino Astro - Context



HE Neutrino Astro - Context

Supernova neutrinos

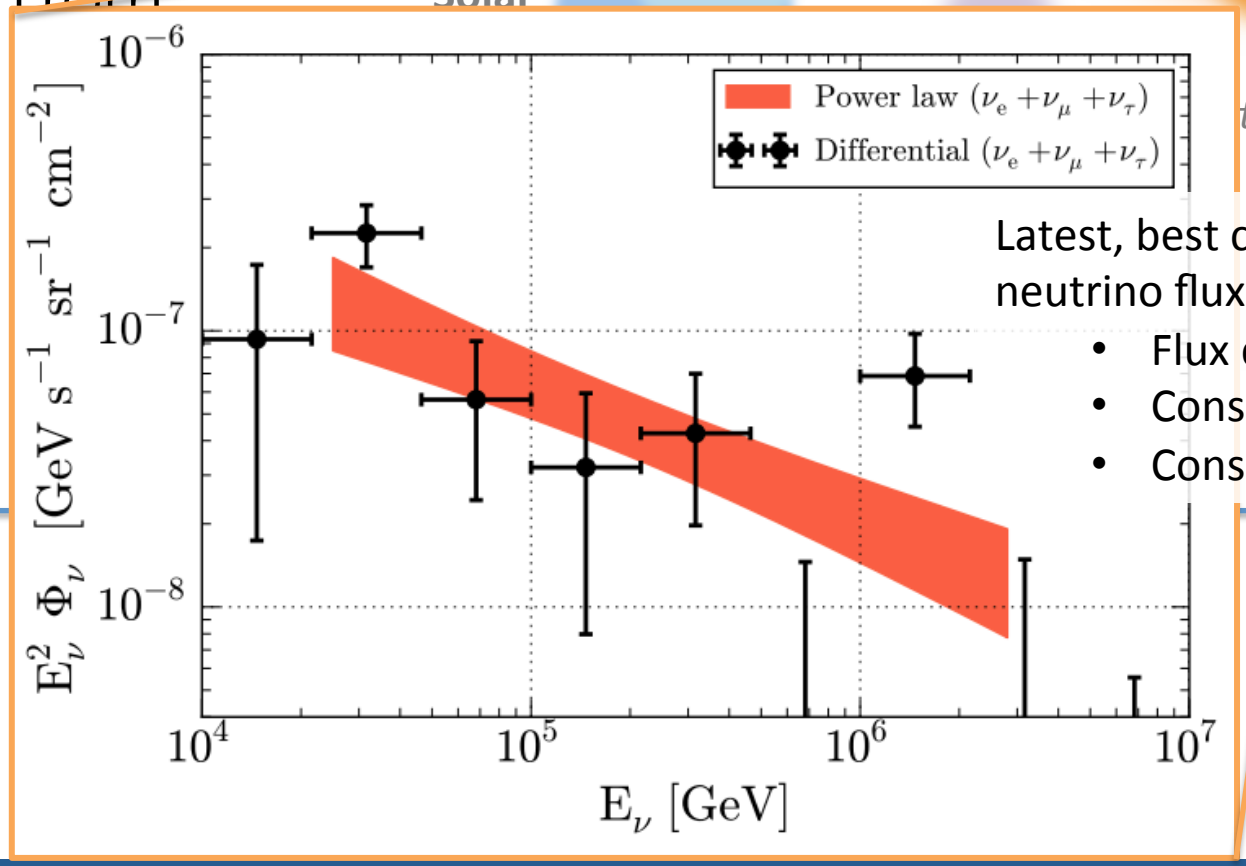
Astrophysical neutrinos

Neutrinos From

Solar

ter?

Cosmogenic neutrinos?



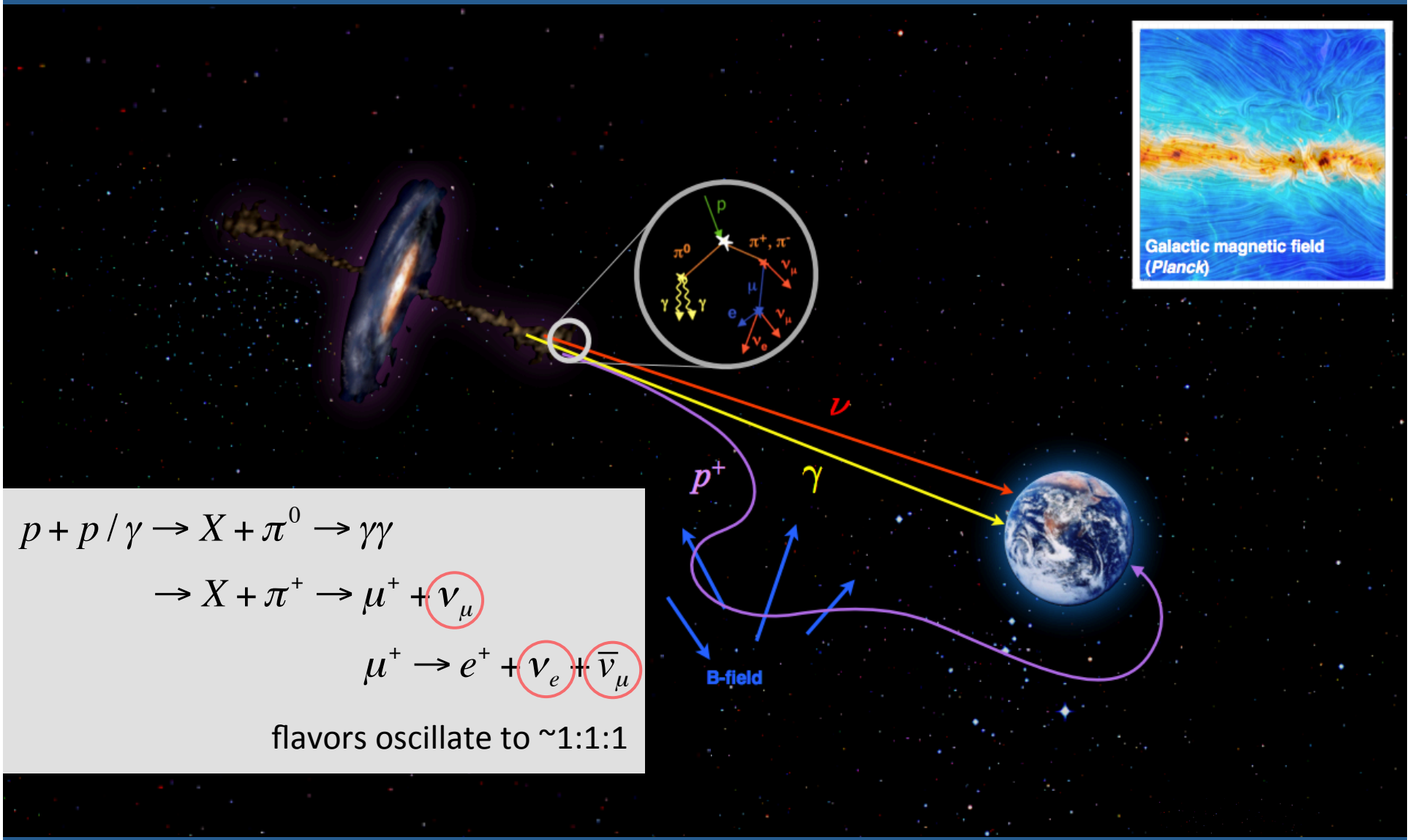
Latest, best characterization of the diffuse neutrino flux (arXiv:1507.03991v2)

- Flux α $E^{(-2.5 \pm 0.09)}$
- Consistent with isotropy
- Consistent with 1:1:1 flavor ratios

PeV EeV ZeV

10^{15} 10^{18} 10^{21}

Multi-messenger Astronomy



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

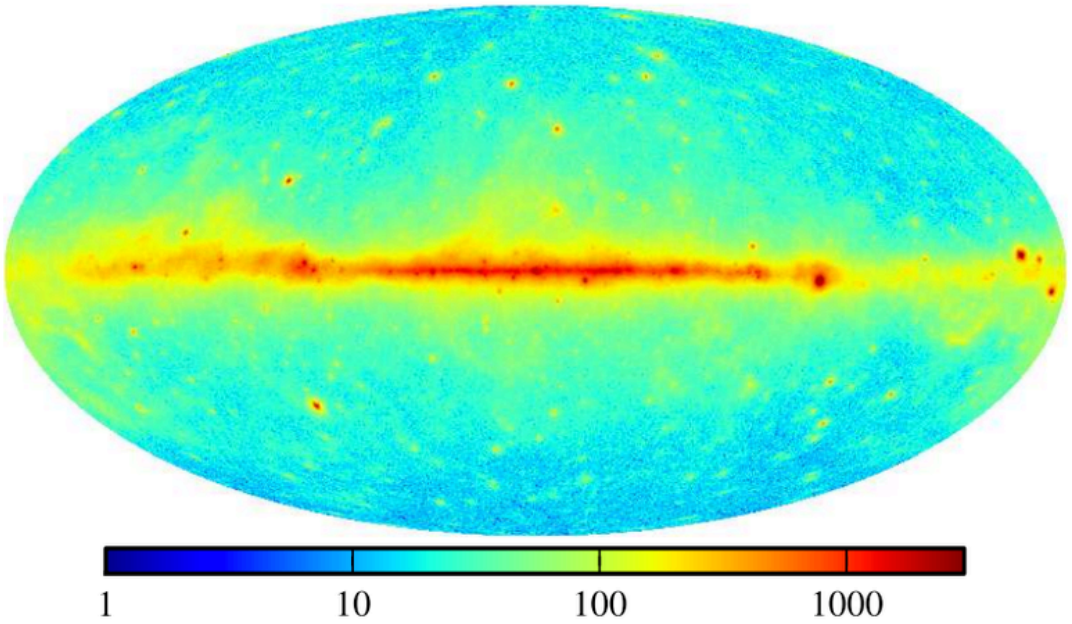
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

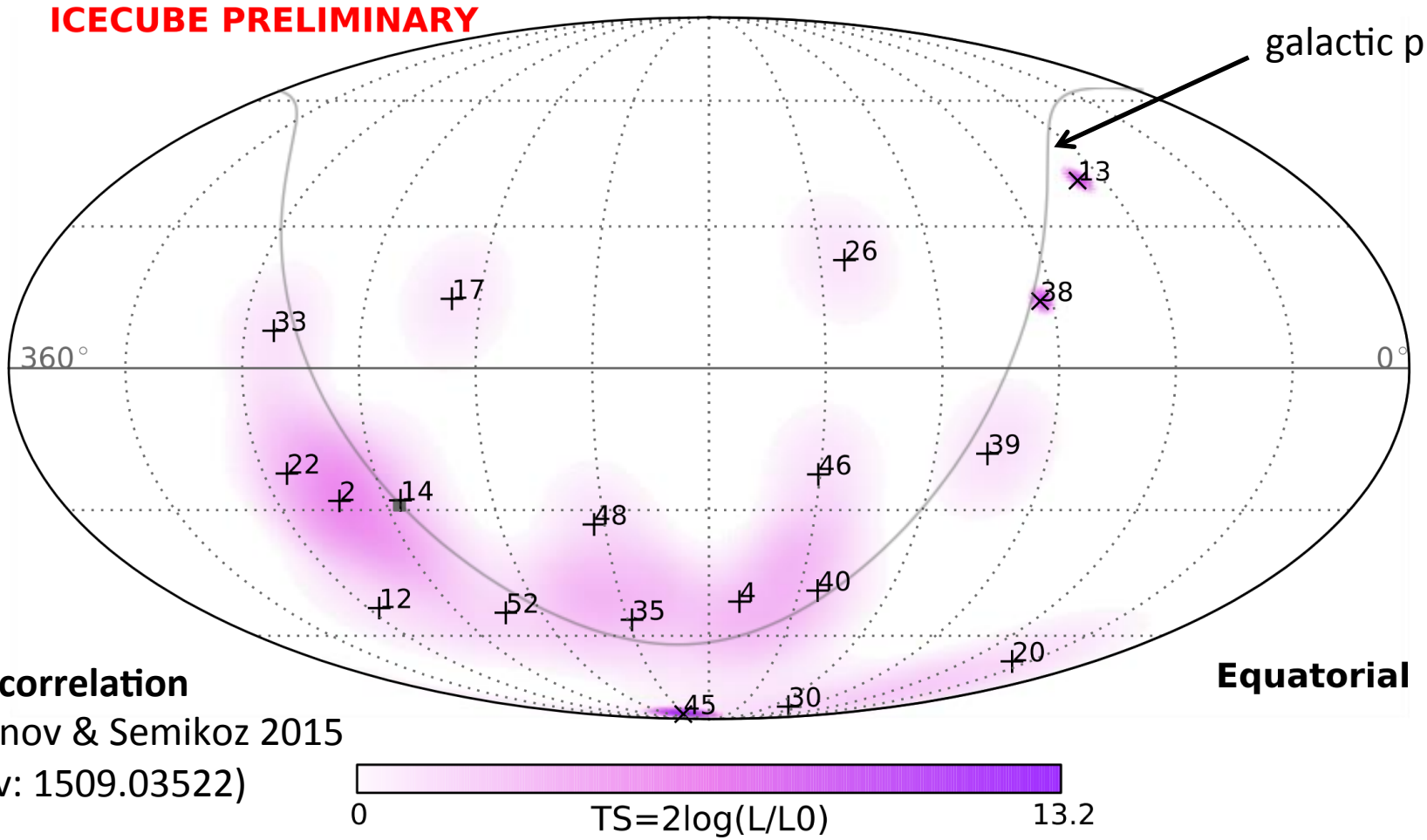
flavors oscillate to ~1:1:1

- Galactic

- Galactic (Diffuse)



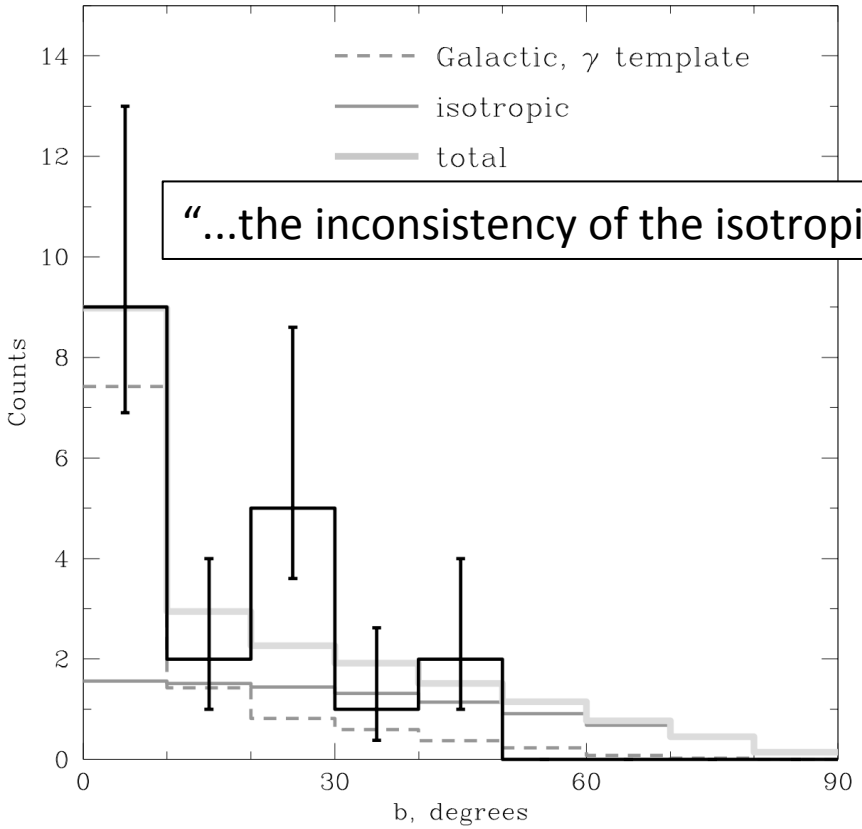
>100 TeV *A Posteriori*

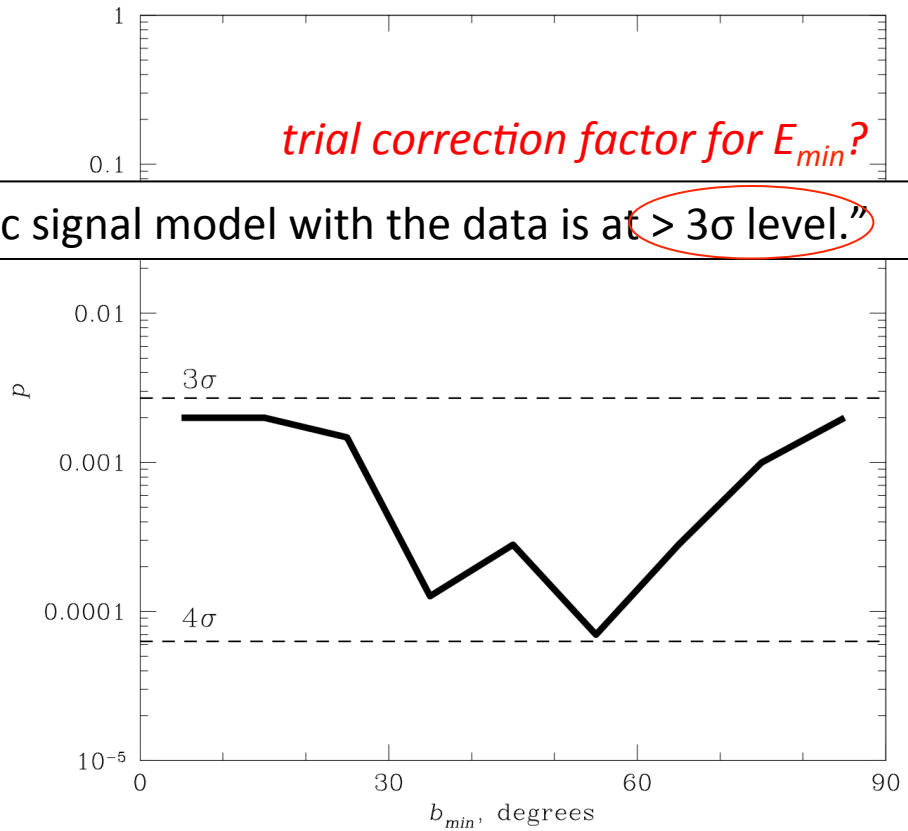


~3 σ correlation
Neronov & Semikoz 2015
(arXiv: 1509.03522)

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

>100 TeV *A Posteriori*





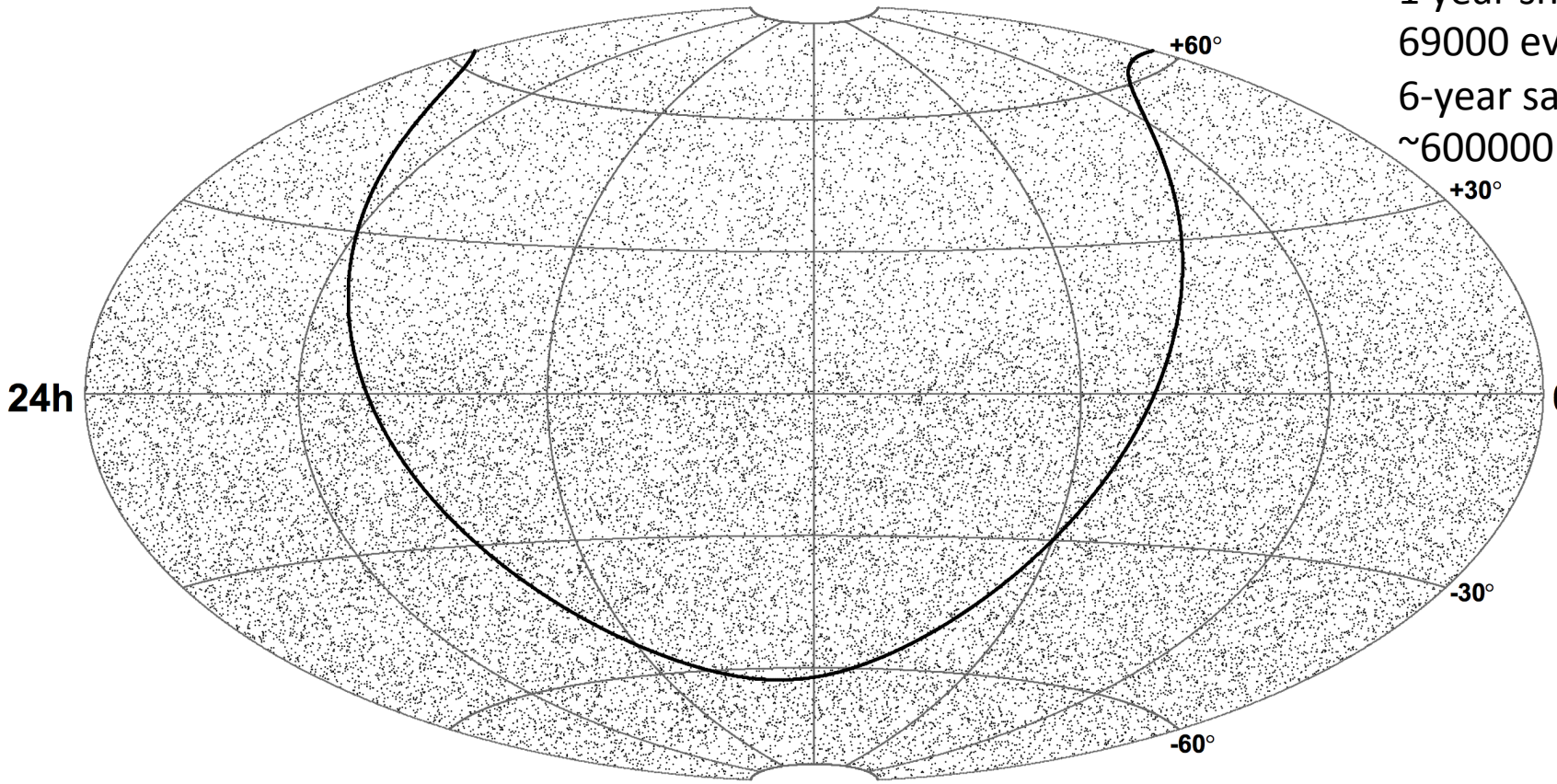
trial correction factor for E_{min}?

"...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)

Lower Energy Sample



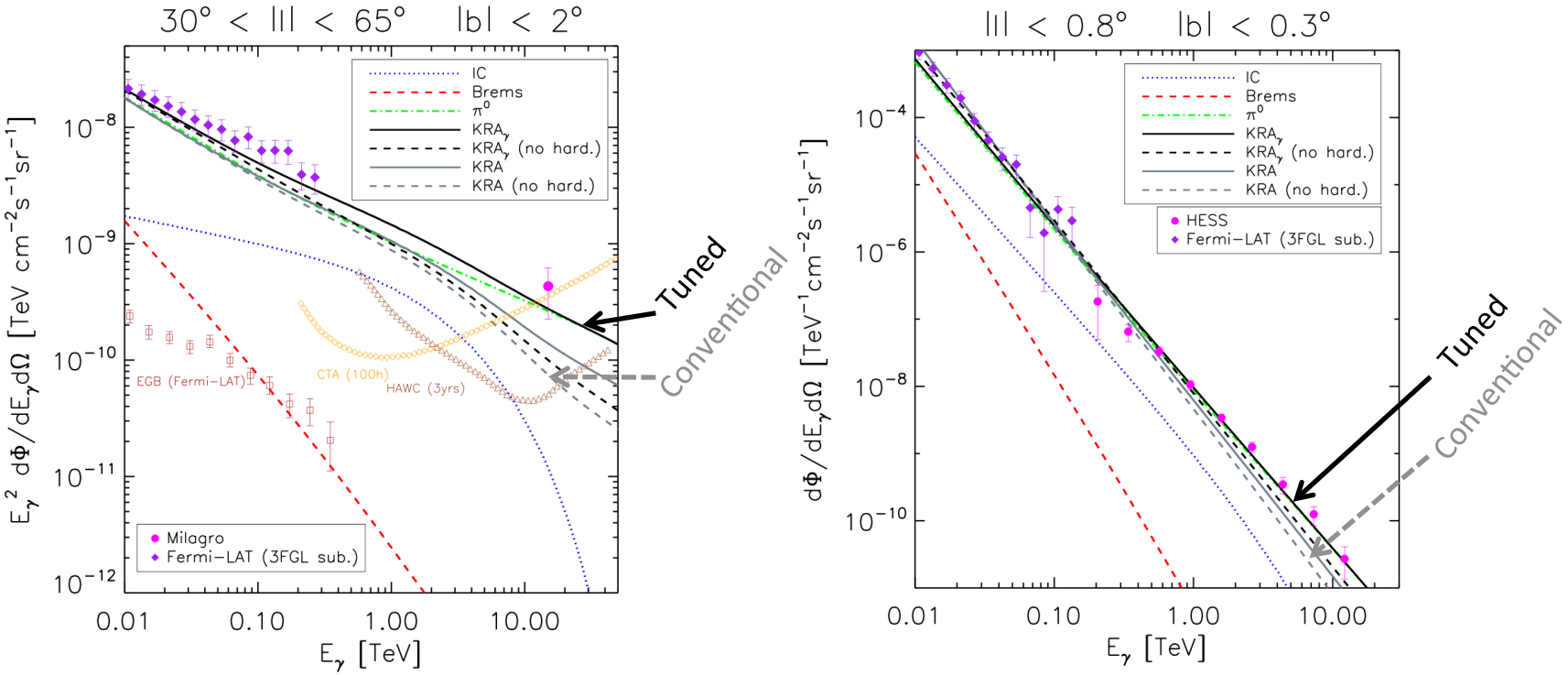
1 year shown:
69000 events
6-year sample:
~600000 events

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

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



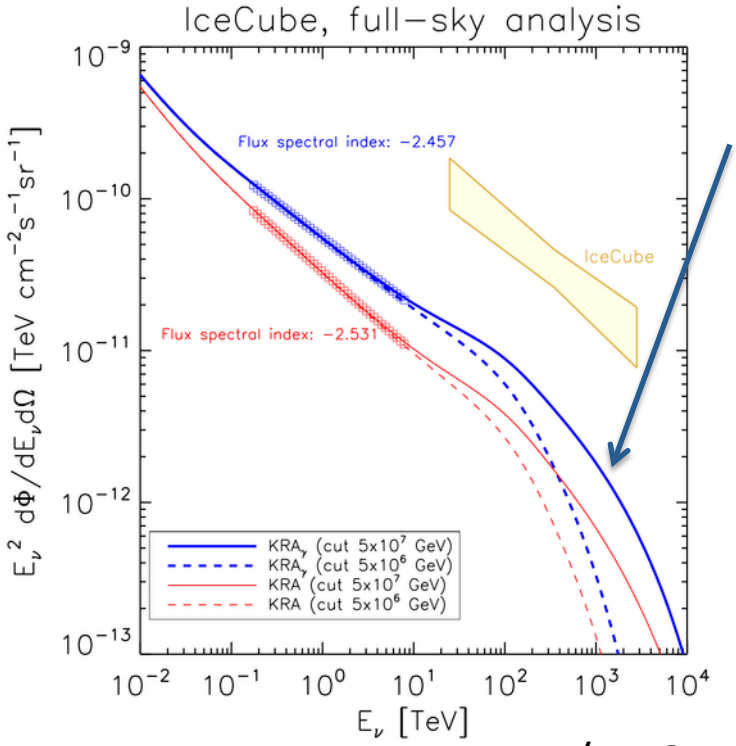
- New: Incorporate PAMELA/AMS measured p & He hardening and allow CR diffusion to change with gal. radius

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



Tuning CR propagation to the gamma-ray data: explains up to ~20% of our diffuse neutrino flux

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

Gaggero et al 2015
arXiv:1504.00227v2

Galactic Plane Search

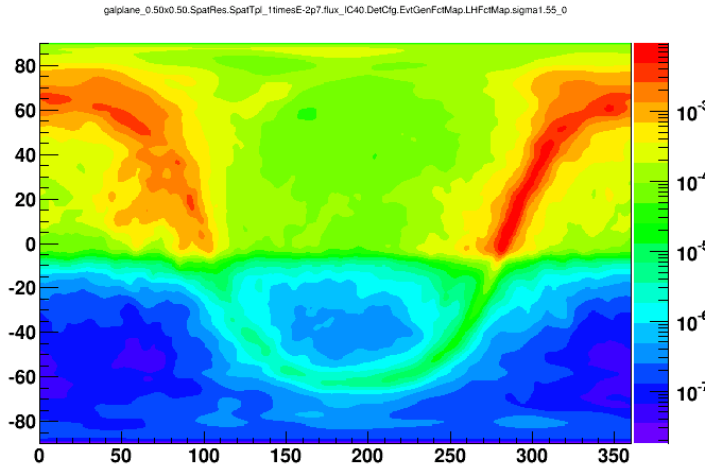
- Max Likelihood **Spatial Template** Analysis

$$L(n_s) = \prod_i \left[\frac{n_s}{n_{\rm tot}} S_i(\mathbf{x}_i, E_i, \sigma_{i,\rm parab}) + \left(1 - \frac{n_s}{n_{\rm tot}}\right) B_i(\mathbf{x}_i, E_i) \right],$$

$$B(\mathbf{x}_i, E_i) = \left(1 + \frac{n_s}{n_{\rm tot}}\right) D_i(\delta_i, E_i) - \left(\frac{n_s}{n_{\rm tot}}\right) S_{sc,i}(\delta_i, E_i)$$

Data

Signal
Scrambled in RA

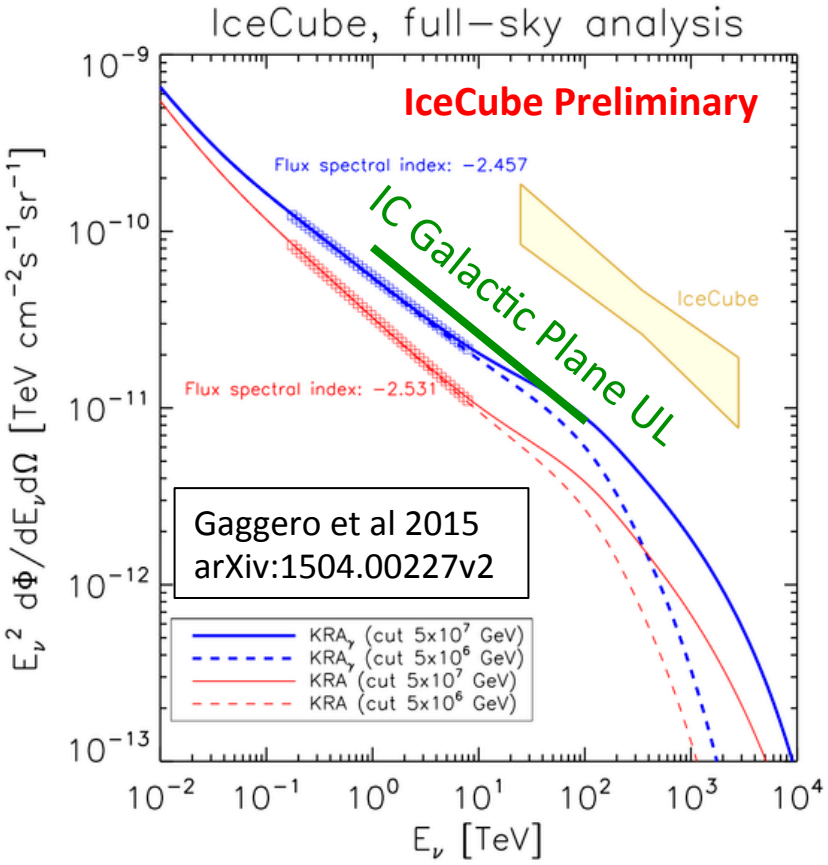


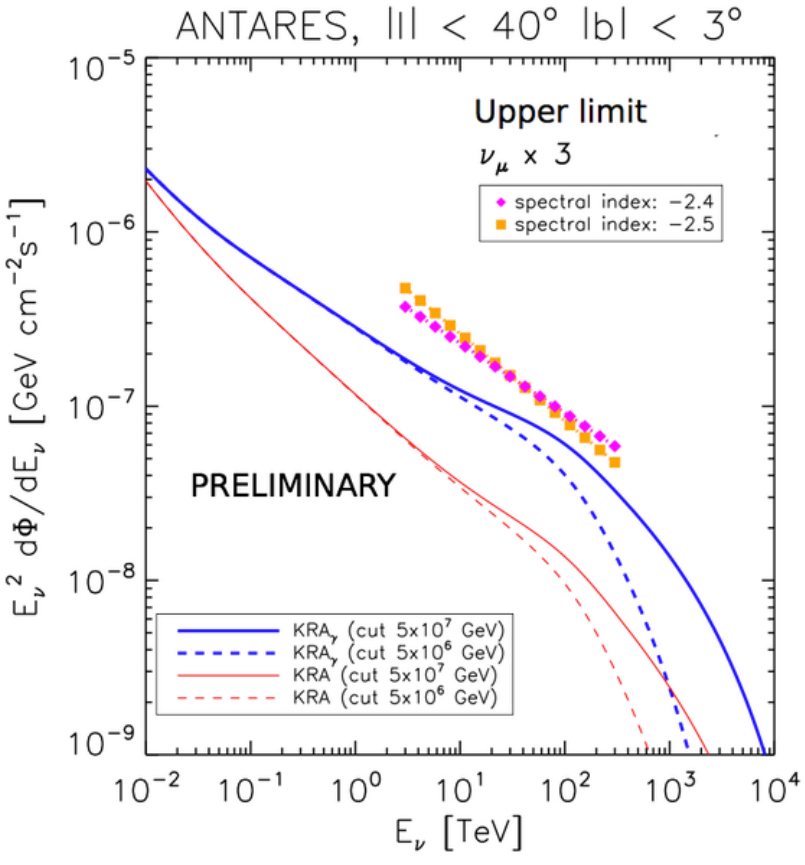
Fermi-LAT pion-decay map, smoothed

- Looked at **6 years** of data
  - Searched for spectral indices between $\mathbf{E^{-1.0}}$ and $\mathbf{E^{-4.0}}$
- Found **no excess** events over background expectations
  - 90% CL **Upper Limit = 13%** of observed diffuse flux*

* Assuming power-law extrapolation to lower energy

IceCube/ANTARES limits



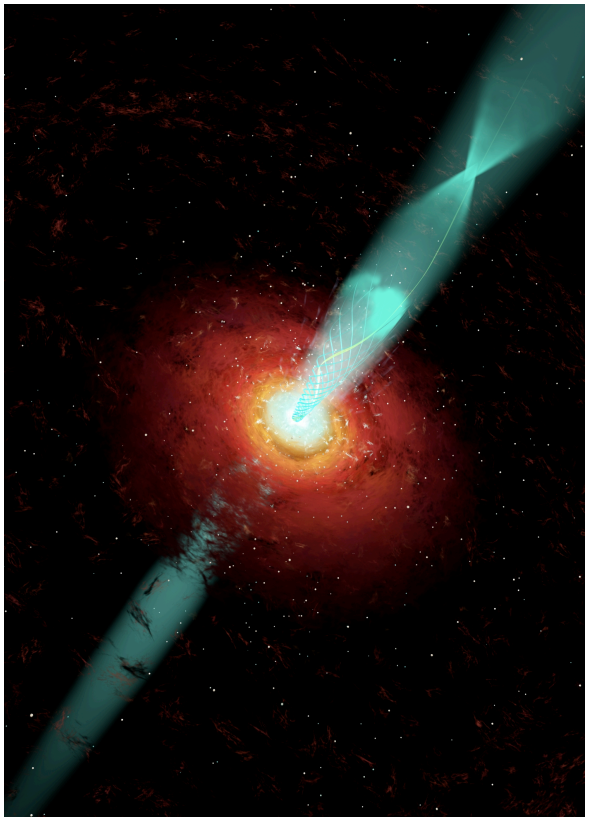


Galactic diffuse emission (and any source population distributed similarly to the gas in the galaxy) can only be a subdominant of the observed astrophysical neutrino flux.

- Extragalactic

Blazars Scenario

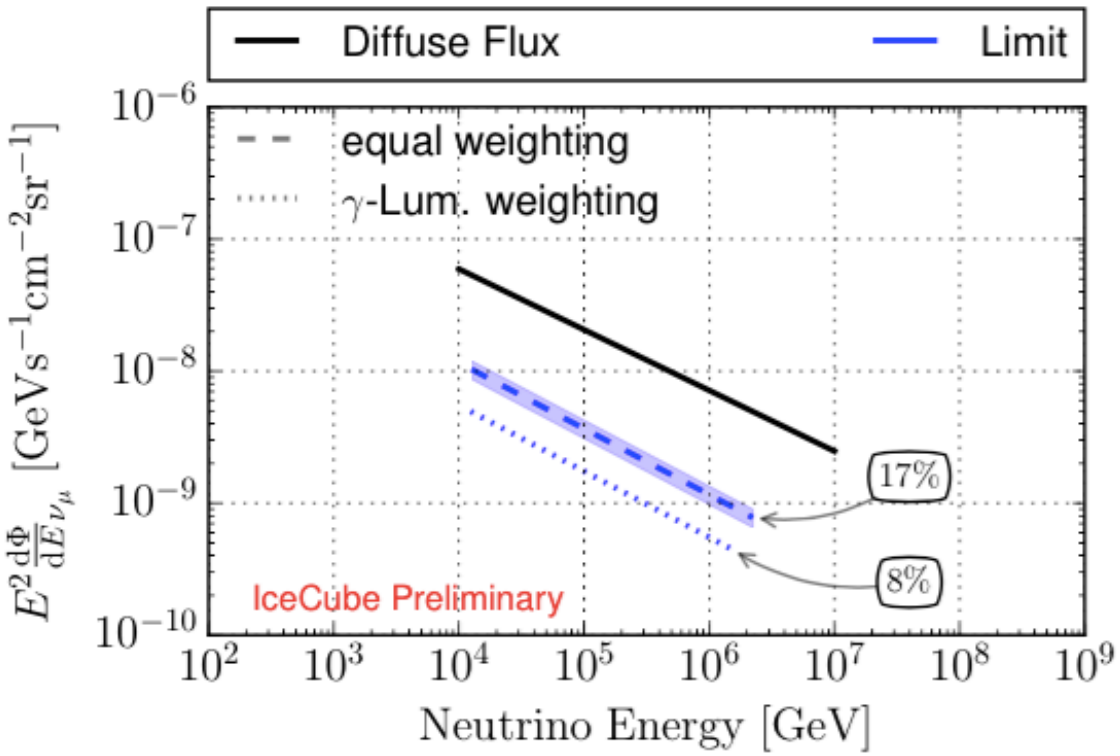
- Blazars are active galactic nuclei (AGN) with jets directed along our line of sight
  - Powered by accretion onto supermassive black holes
  - Particle acceleration occurs somewhere in the jet
- Great candidates for ultra-high energy cosmic ray production
  - Great neutrino source candidate
- Detected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



Blazar Stacking

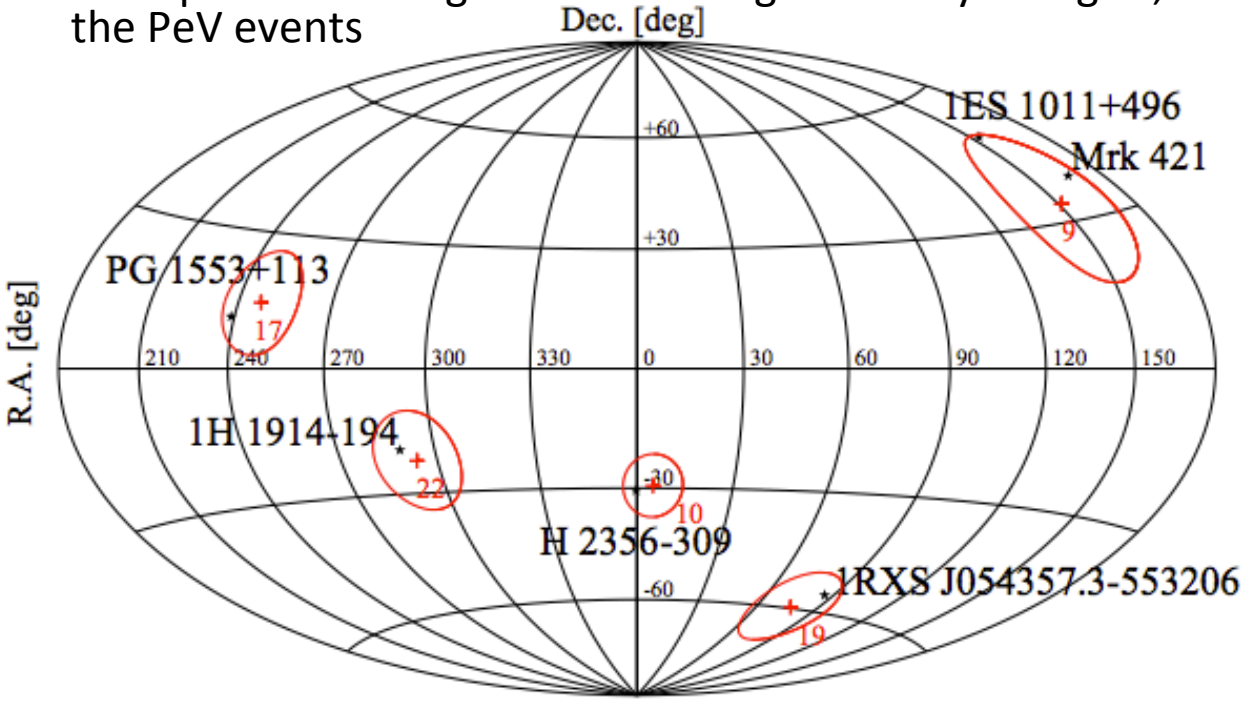
- We performed stacked searches for neutrinos from known blazars
  - Fermi-LAT 2FGL catalog of 862 blazars
- No significant excess observed in IceCube stacked search
- Total flux upper limit is well below measured diffuse neutrino flux
- Sub-categories of blazars all produce strong limits
  - FSRQs
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

Glüsenkamp, RICAP 2014 Proceedings



HSP Associations?

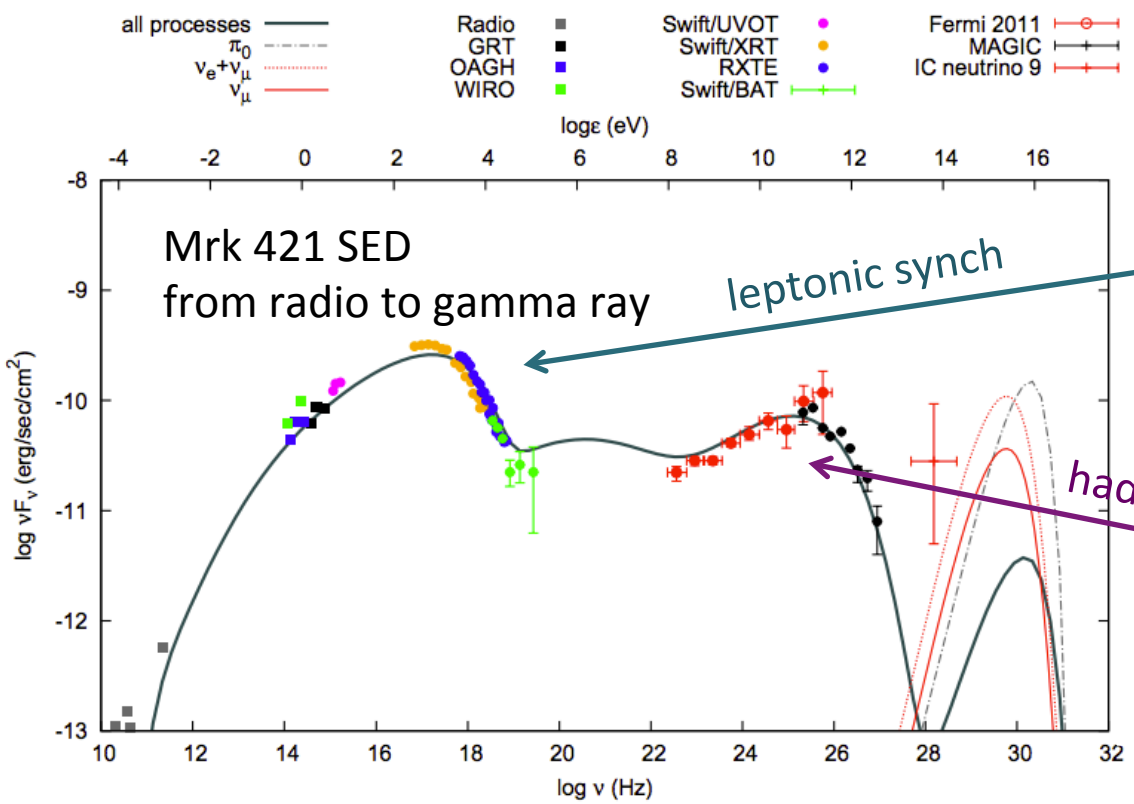
- There is renewed interest in hadronic modeling of HSP blazars
  - Due to both **stretching** of leptonic model parameters and observed **association** with high energy neutrinos
  - Extreme spectra: can't explain all of our diffuse flux but could be dominant at HE
  - Recall: ~15° ang. res. for cascades
  - HSPs peak at the highest observed gamma-ray energies, so a natural candidate for the PeV events

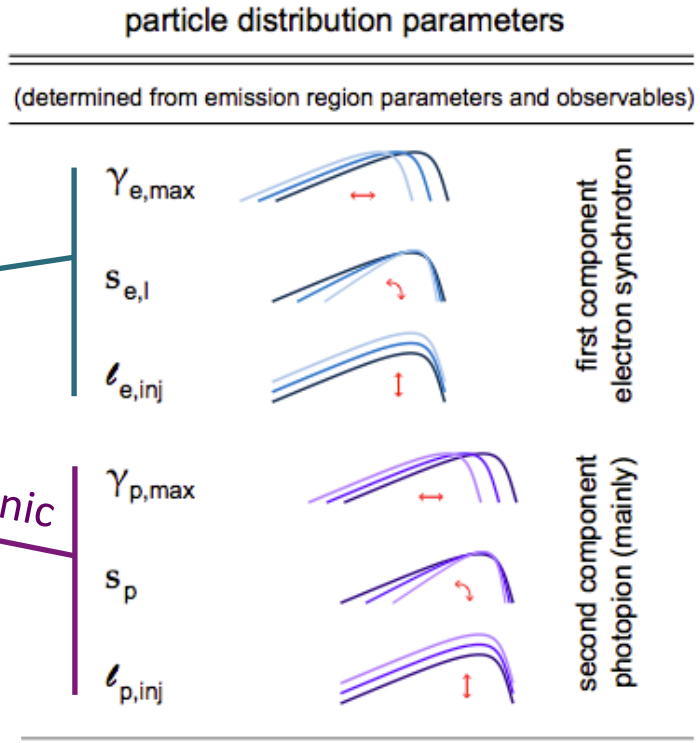


Associations of five HE starting neutrinos with HSP BL Lacs are suggestive but not significant

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

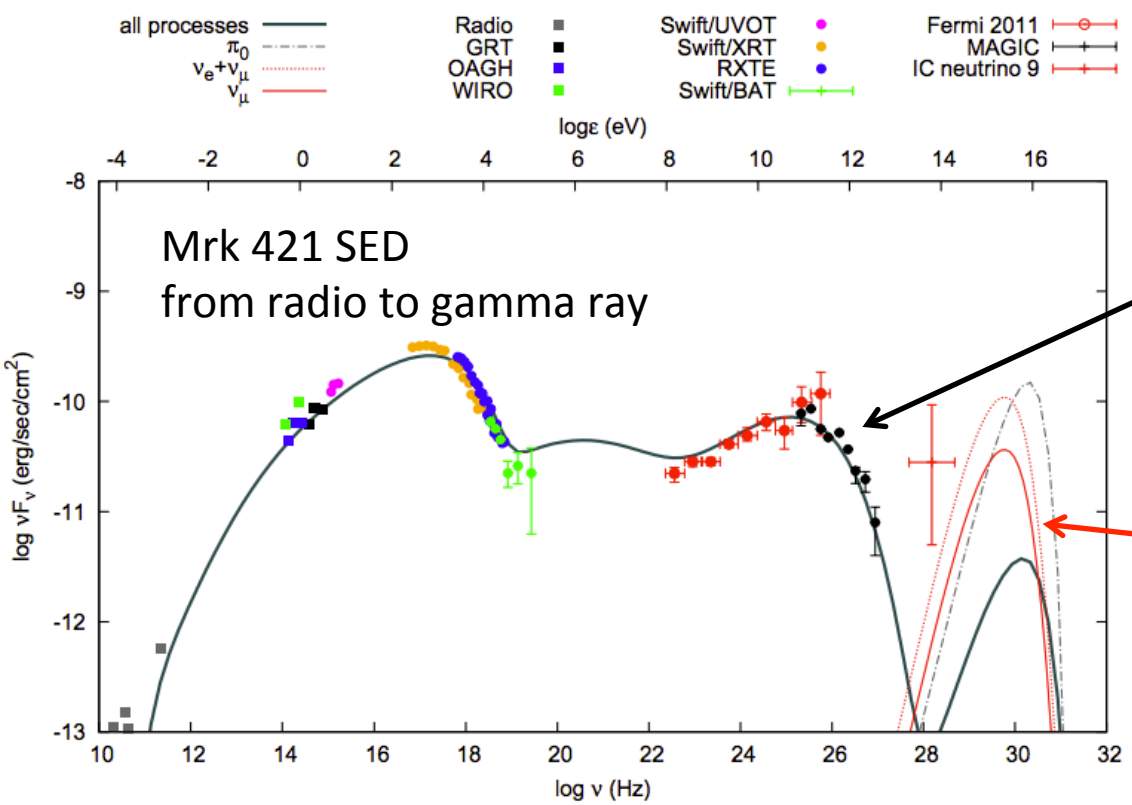




arXiv:1501.07115v1
Petropoulou et al., 2015

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

Starburst Scenario



Starburst Scenario

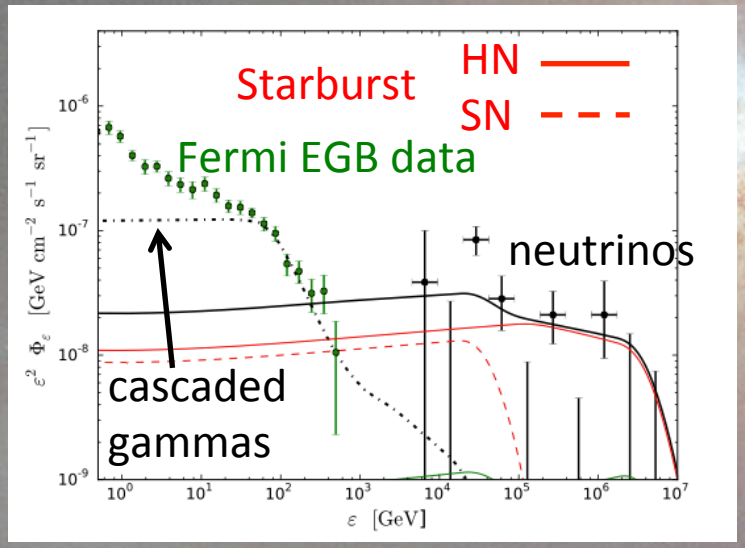
- Candidate: Starburst galaxies
  - High star formation rates -> Lots of supernovae -> Lots of cosmic ray acceleration
  - Lots of target material (high interstellar gas density)
  - Both factors lead to efficient neutrino production through pp interactions and subsequent pion decay

M82 - HST

Starburst Scenario

Senno et al 2015
arXiv:1501.04934v1

- Paper from last year 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)!



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

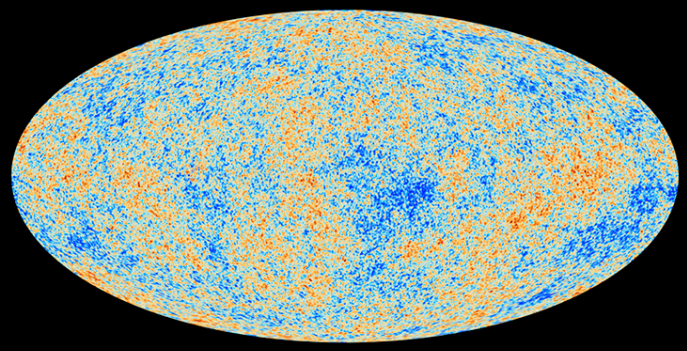
Cascaded Emission Important





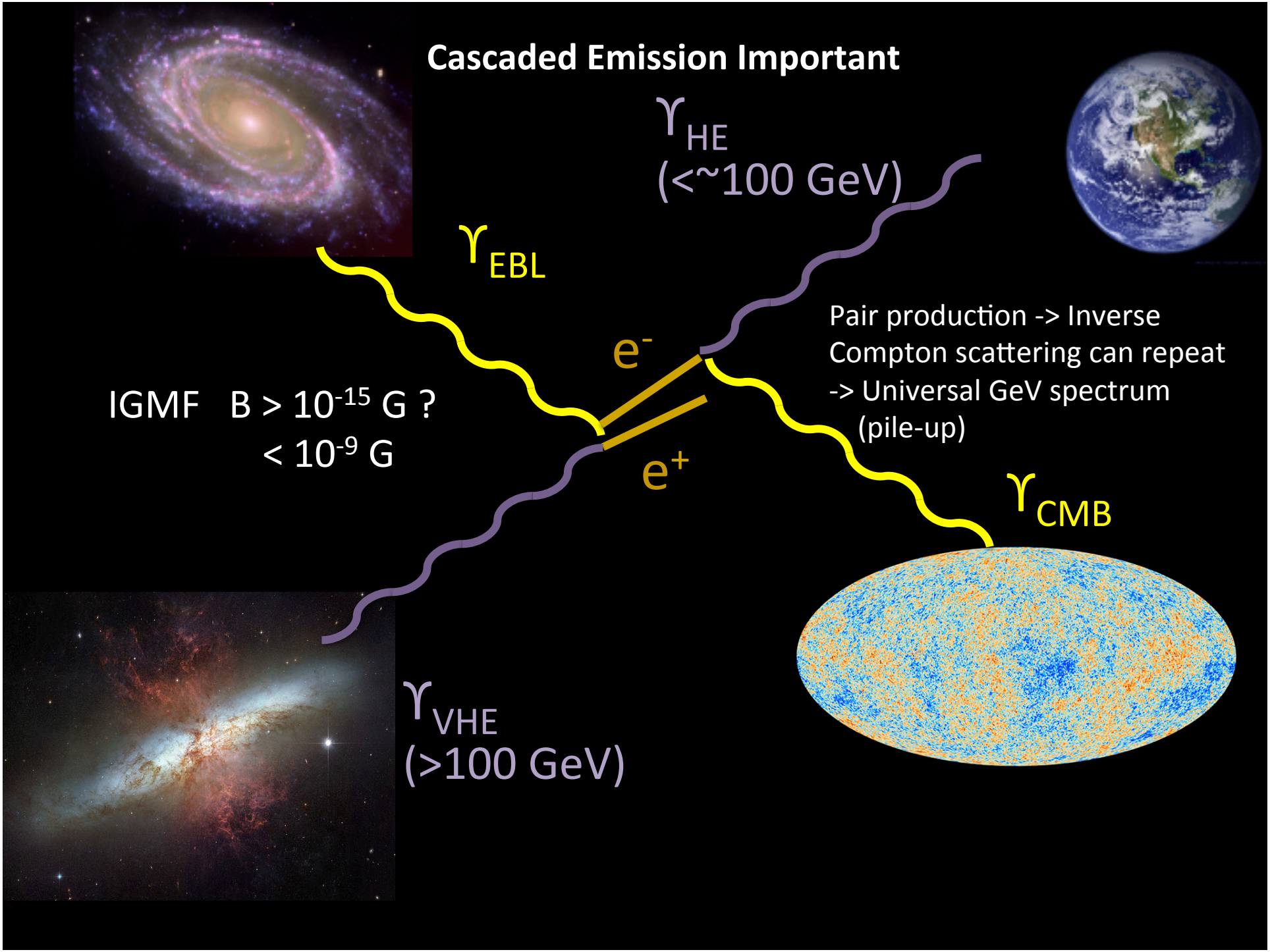
γ_{EBL}

γ_{CMB}

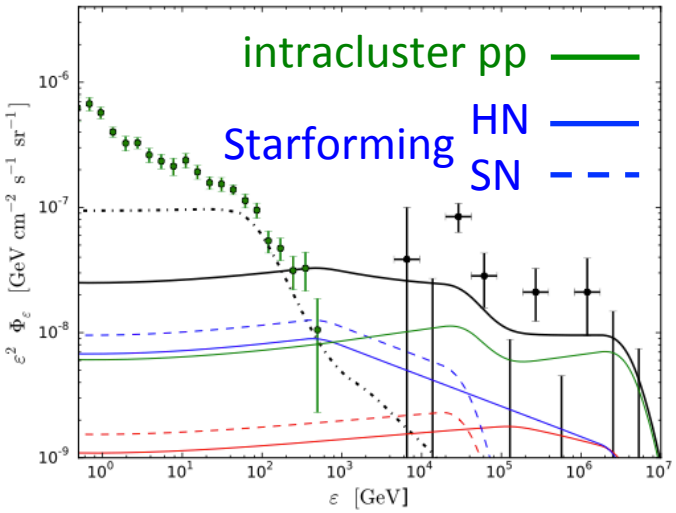


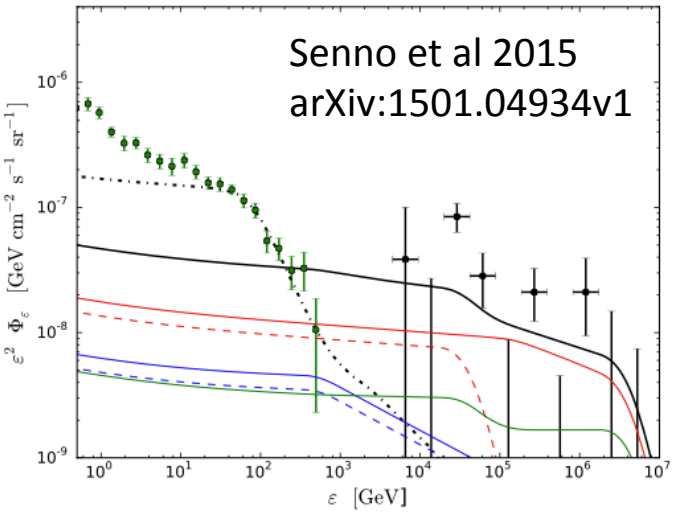


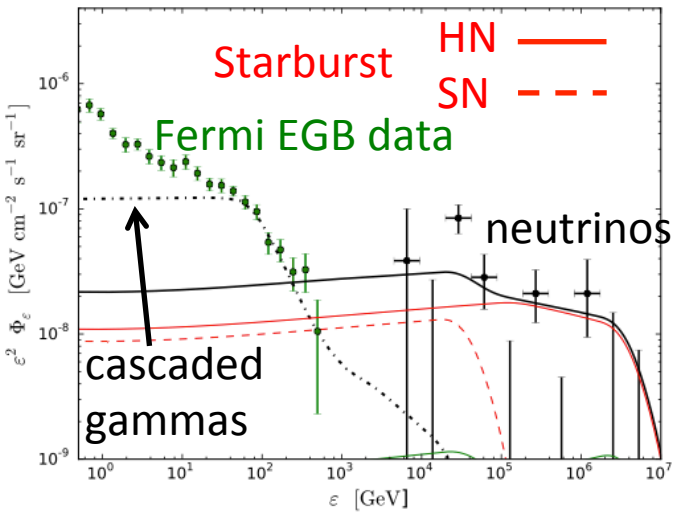
γ_{VHE}
(>100 GeV)


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

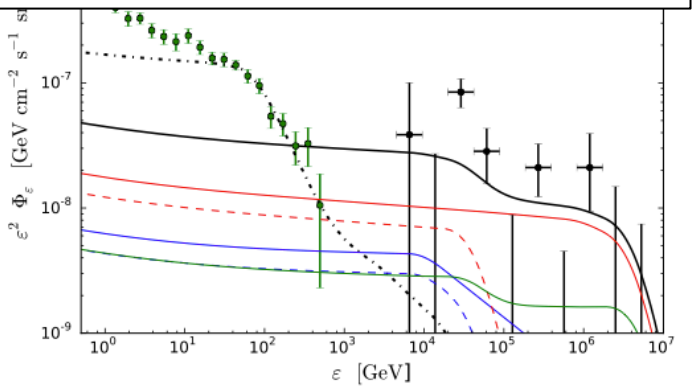
(Large Parameter Space)







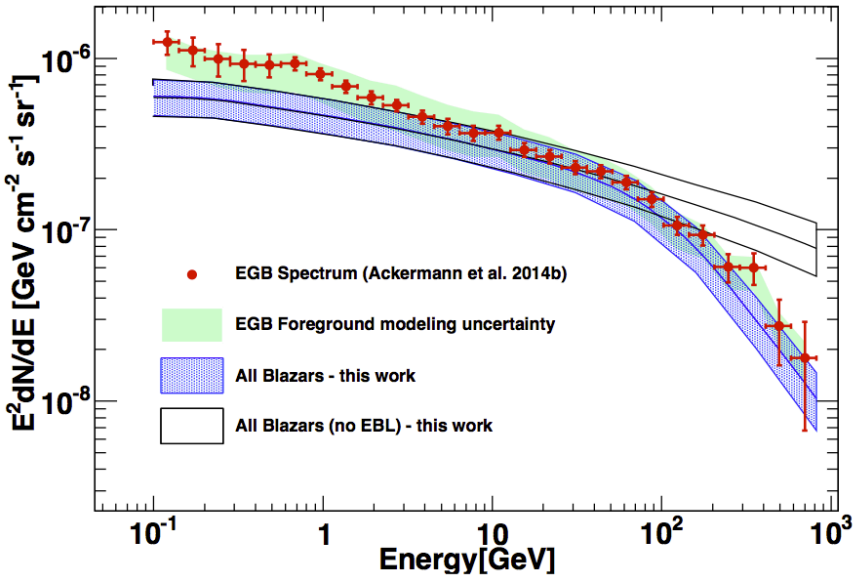
Testing:
- -CR diffusion coefficients
- -CR spectral indices
- -Source population contributions



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

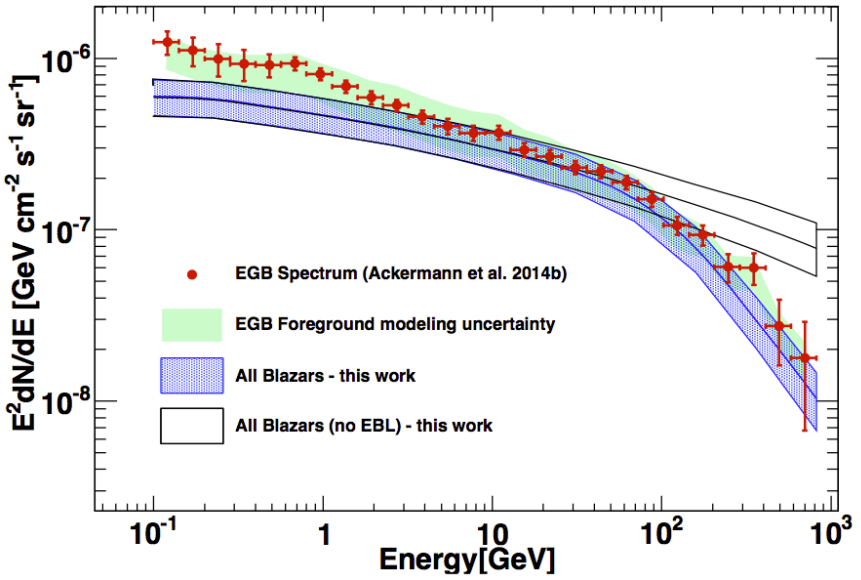


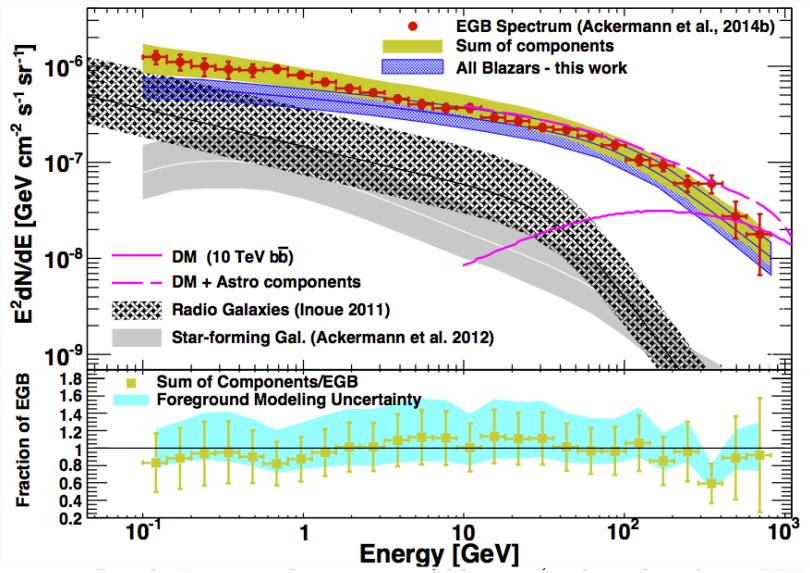
Ajello et al. arXiv:1501.05301v1

Cascaded Emission Important

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

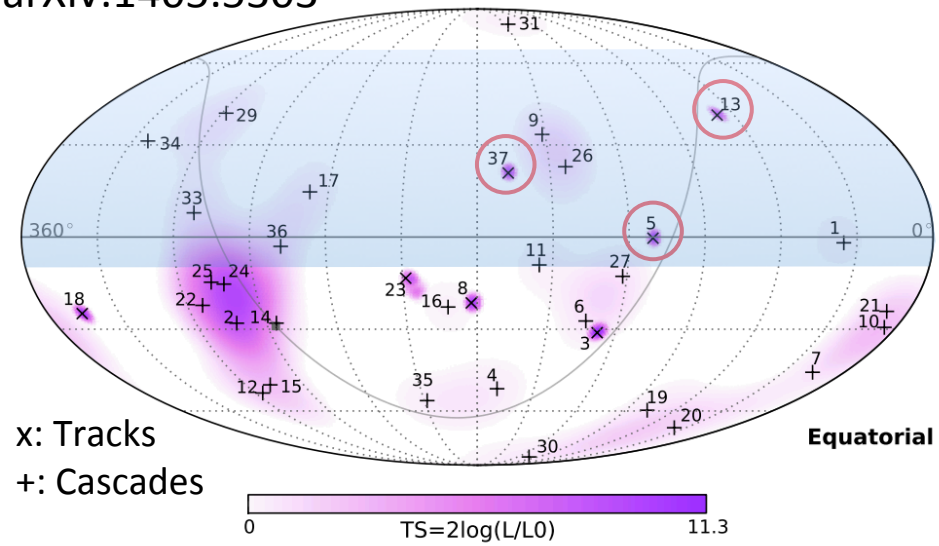
- Recent publication already makes the claim that all the >100 GeV EGB is from blazars
  - Detailed prediction of gamma rays, integrating over all blazars
  - Enough confidence to set competitive limits on the Dark Matter annihilation cross section
  - Problem: Any (transparent and not-too-distant) extragalactic source has the same problem!
  - One solution: '**Hide**' the gamma ray emission from the neutrino sources





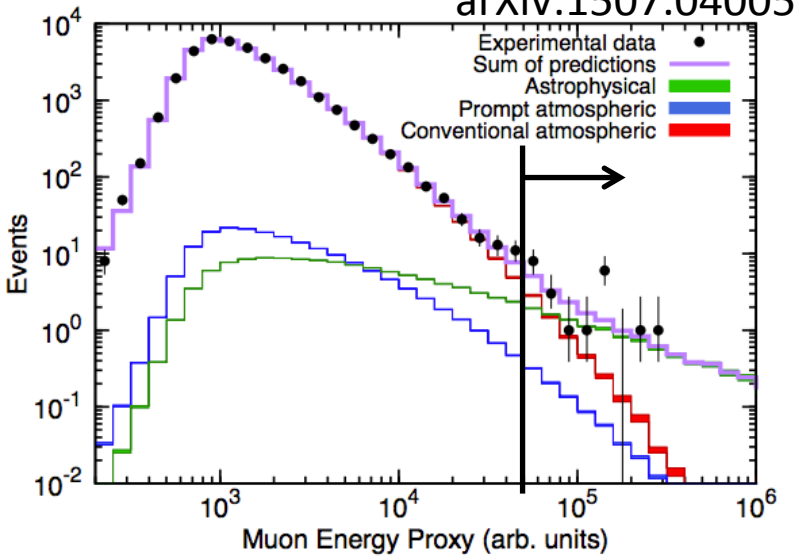
Gamma Ray Searches

arXiv:1405.5303



- **Three** HE **contained**-vertex tracks in the northern sky observable by VERITAS
- Positions are publicly available
- Angular uncertainty < 1.2° for the tracks

arXiv:1507.04005



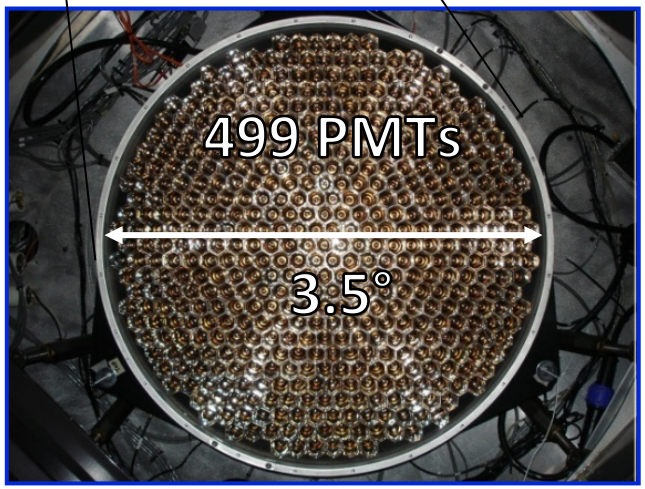
- **20** highest energy **uncontained** tracks
- Events from a 2-year HE northern-sky diffuse muon neutrino search
  - Directions not public, shared through MoU
- Relatively high astrophysical purity
- Angular uncertainty < 1.0°

ϒ-ray Search w/ VERITAS

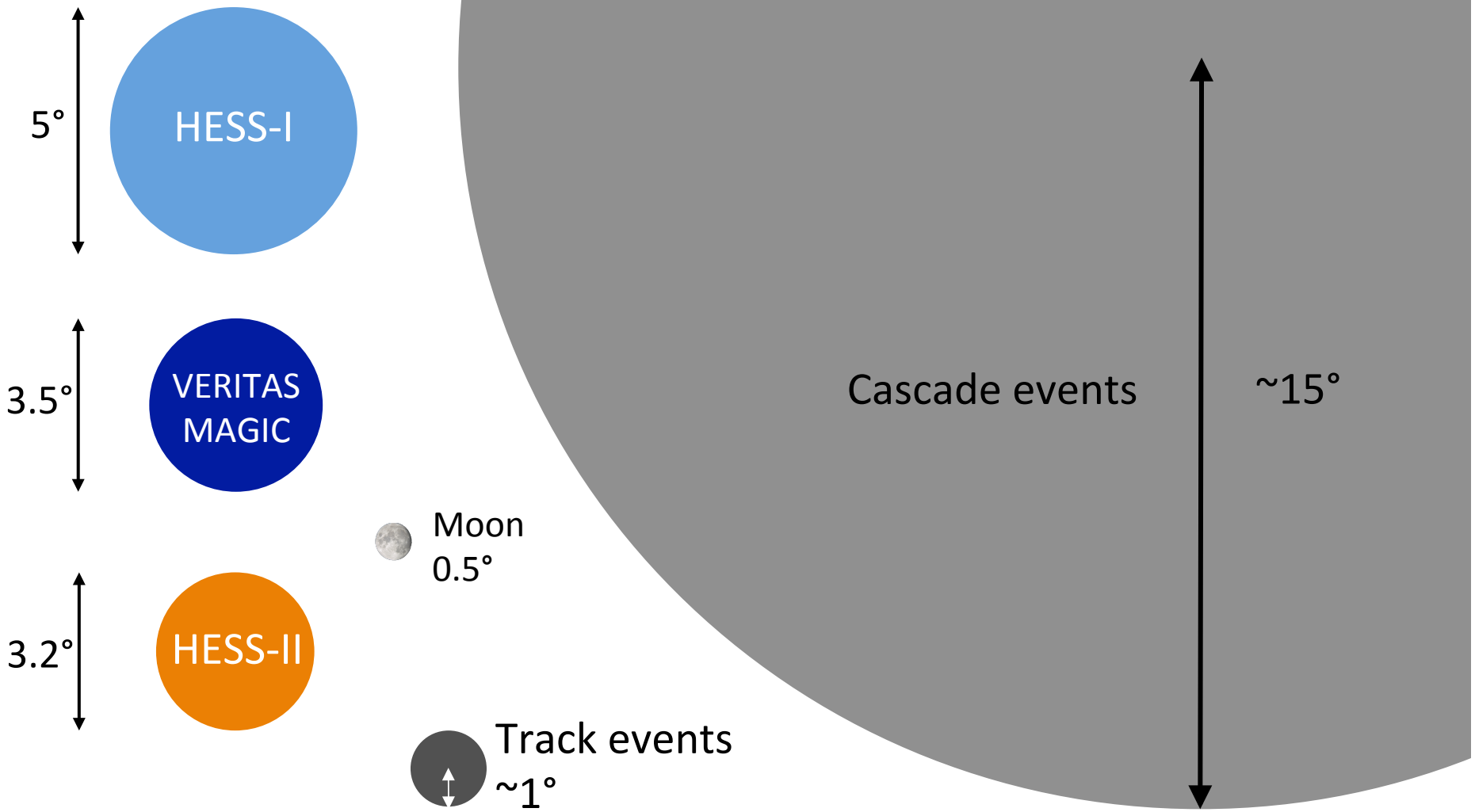


- Array of four 12-m IACTs
- 85 GeV – 30 TeV
- 15 – 25% energy resolution
- 0.1° angular resolution
- 1% Crab detection in < 30 hrs
- ~1000 hrs of observations/yr

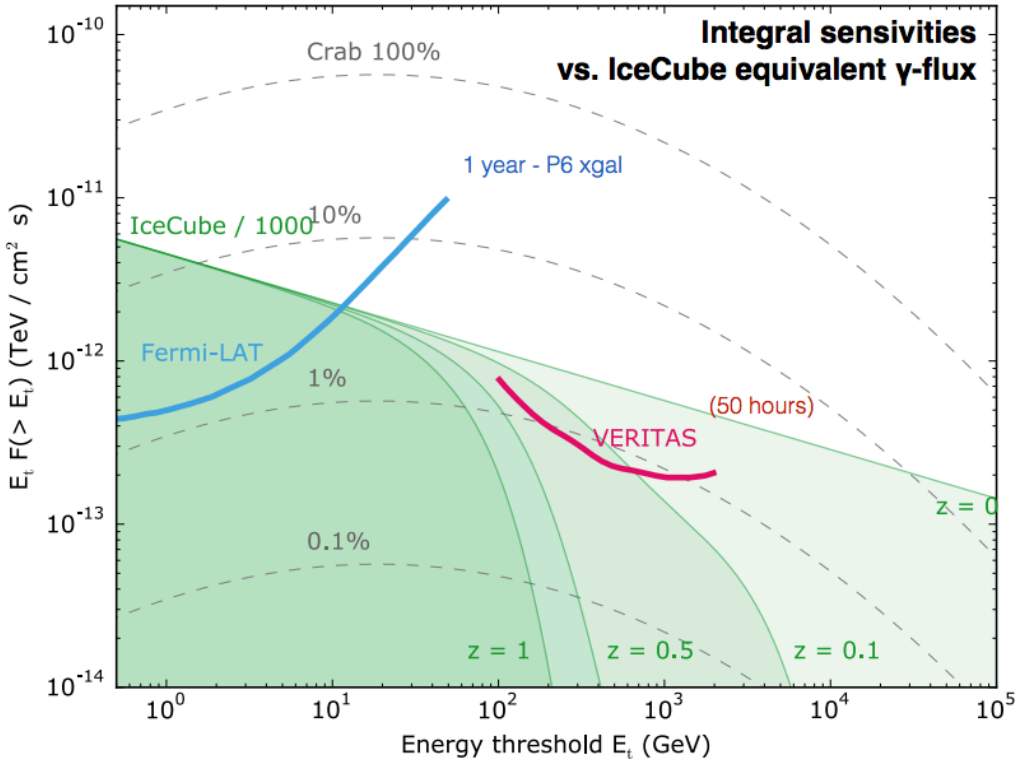




IACT FOVs & IceCube Events



ϒ-ray Searches



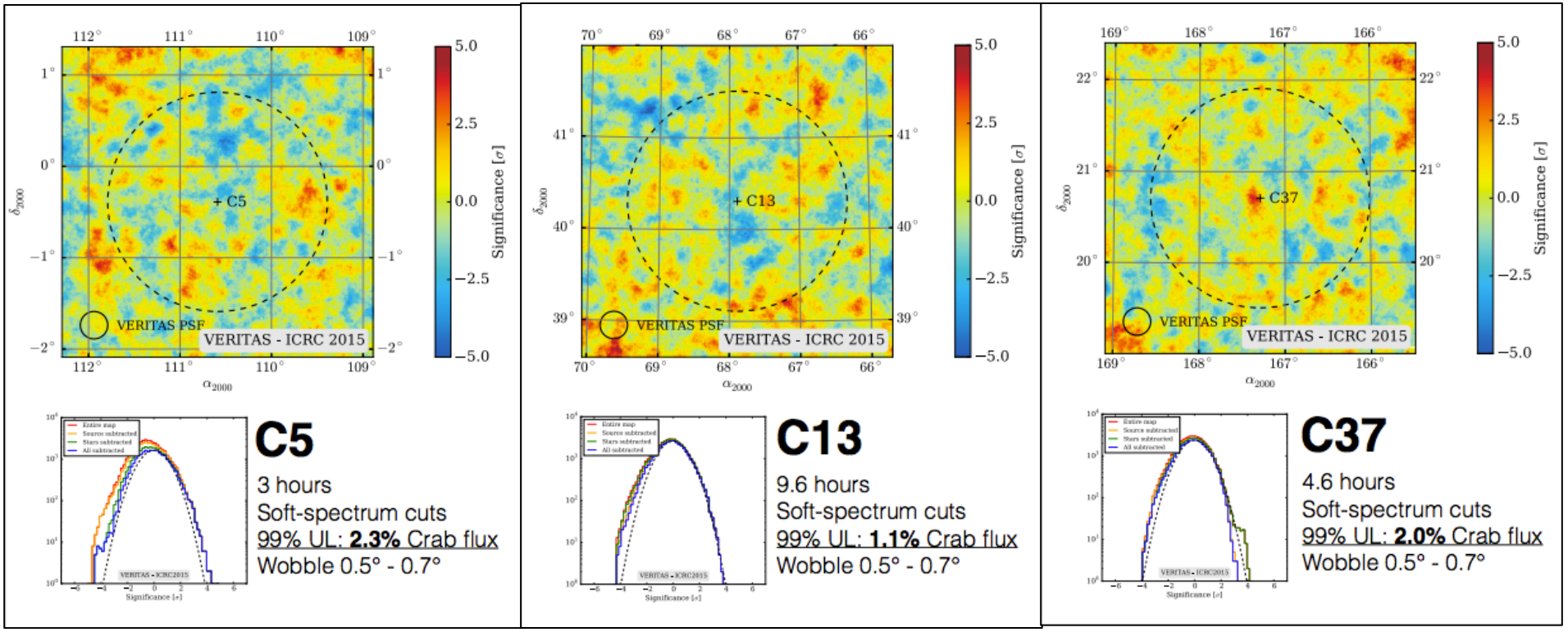
IceCube flux from arXiv:1405.5303 converted 1:1 to gamma rays and spread over 1000 uniform sources

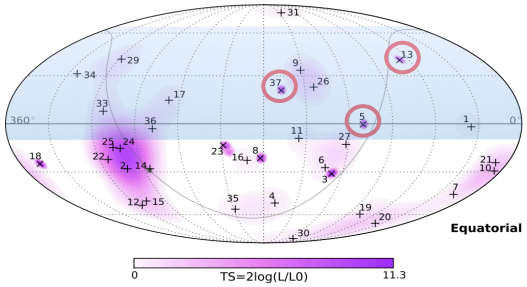
Franceschini et al. EBL absorption model arxiv:0805.1841

- Fermi (GeV) and IACTs like VERITAS (>100 GeV) can set point-source limits on the flux that are **1000 to 10000 times** lower than the all-sky IceCube flux

- Sensitivity is a function of redshift > 100 GeV due to EBL absorption

Observations by VERITAS





- No significant >100 GeV gamma-ray emission
- Most significant hotspot is in **C37** field: 4.3σ pre-trials, 2.0σ post-trials
- Upper limits ~1—5% of the Crab Nebula flux for ~20 candidates
- These observations taken months or years after the neutrino detection!

Correlated Variability in FSRQs

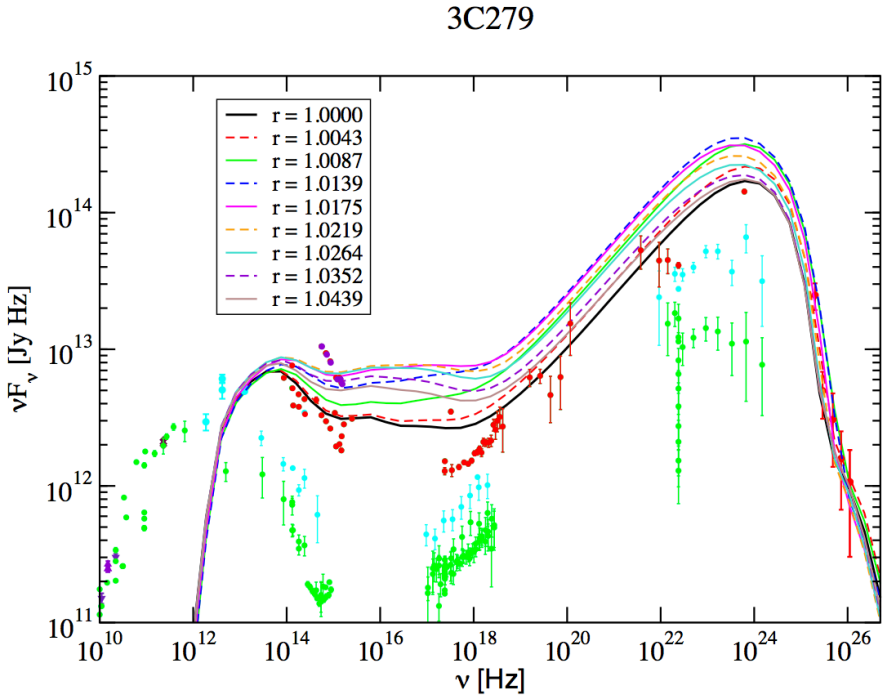
Time Dependent Hadronic Modeling of Flat Spectrum Radio Quasars.

C. Diltz[1], & M. Böttcher[2,1], G. Fossati[3]

arXiv:1502.03950v1

We know the extragalactic sky is **dynamic.**

1) Generate time-dependent lepto-hadronic models for real flaring FSRQs
2) Ask which model parameters could explain state changes



Correlated Variability in FSRQs

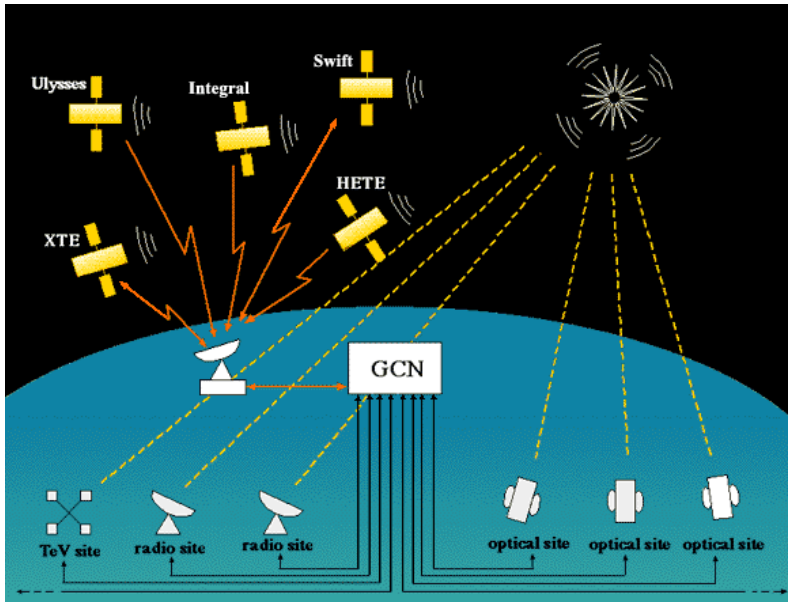
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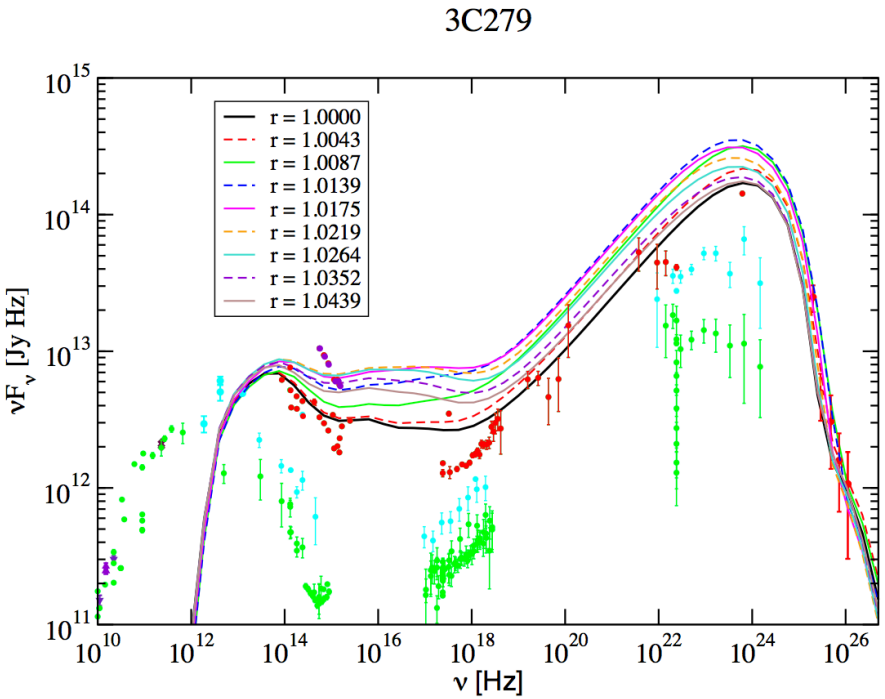
arXiv:1502.03950v1

We know the extragalactic sky is **dynamic.**

Proposal: Use GCN alert system to send neutrino alerts to catch transients!



1) Generate time-dependent lepto-hadronic models for real flaring FSRQs
2) Ask which model parameters could explain state changes

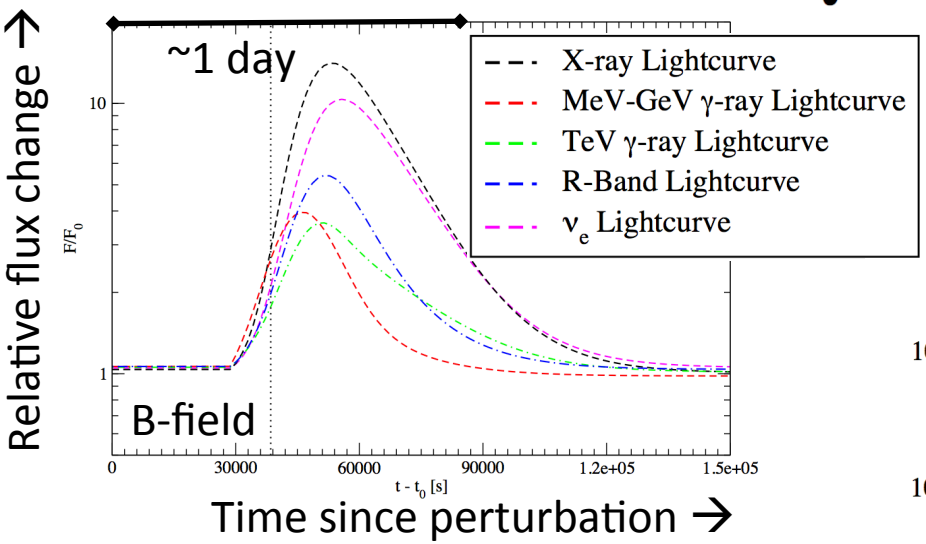


Correlated Variability in FSRQs

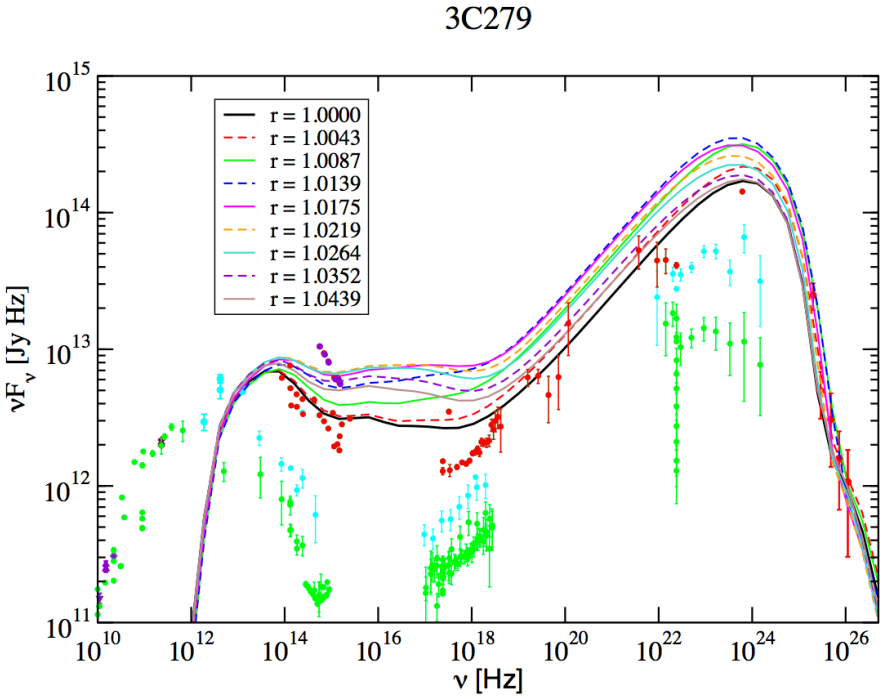
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1) Generate time-dependent lepto-hadronic models for real flaring FSRQs
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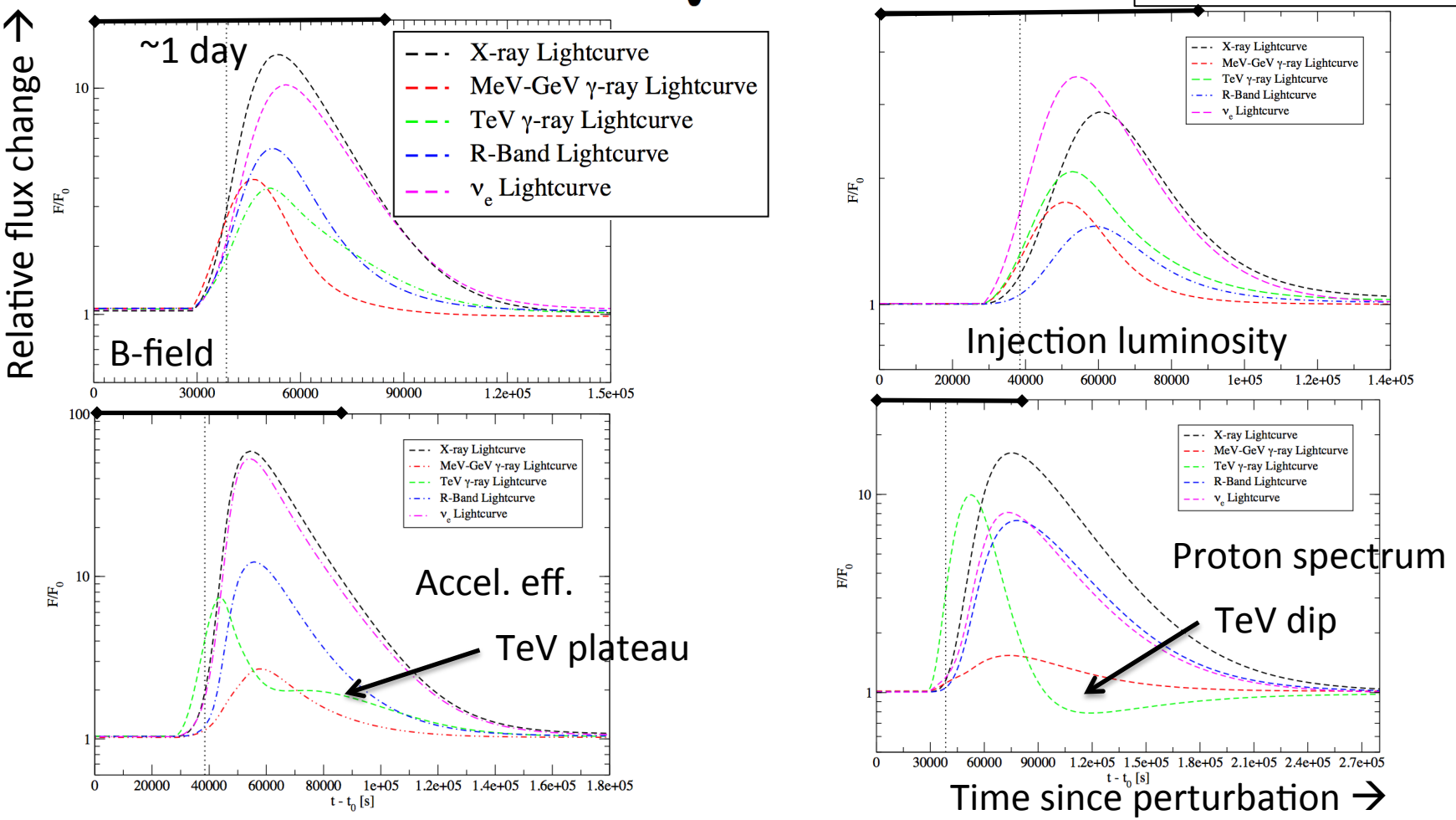


Correlated Variability in FSRQs

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Conclusions

- **Flux of HE astrophysical neutrinos** still consistent with isotropy and equal flavor ratios
- **Galactic Plane:** New limits exclude diffuse CR interactions with ISM as dominant component to astrophysical neutrino flux
  - Hints for >100 TeV correlation with the gal plane (±10°)
  - Galactic source populations are next focus
- **Blazars, GRBs, and starbursts** also must be subdominant
  - Must not violate extragalactic background gamma rays from Fermi-LAT
  - 'EM-dark' versions blazars and GRBs possible
- **As standard sources excluded** from being the sole contribution to the diffuse flux, a unique and multifaceted field of neutrino astronomy may emerge on the road ahead
  - Continue to accumulate HE events in the coming years
  - New real time alerts undergoing final collaboration approval – opens up transient phenomena
  - Dark accelerators and even dark matter (decay) become more enticing
  - Build a larger detector! – IceCube-Gen2

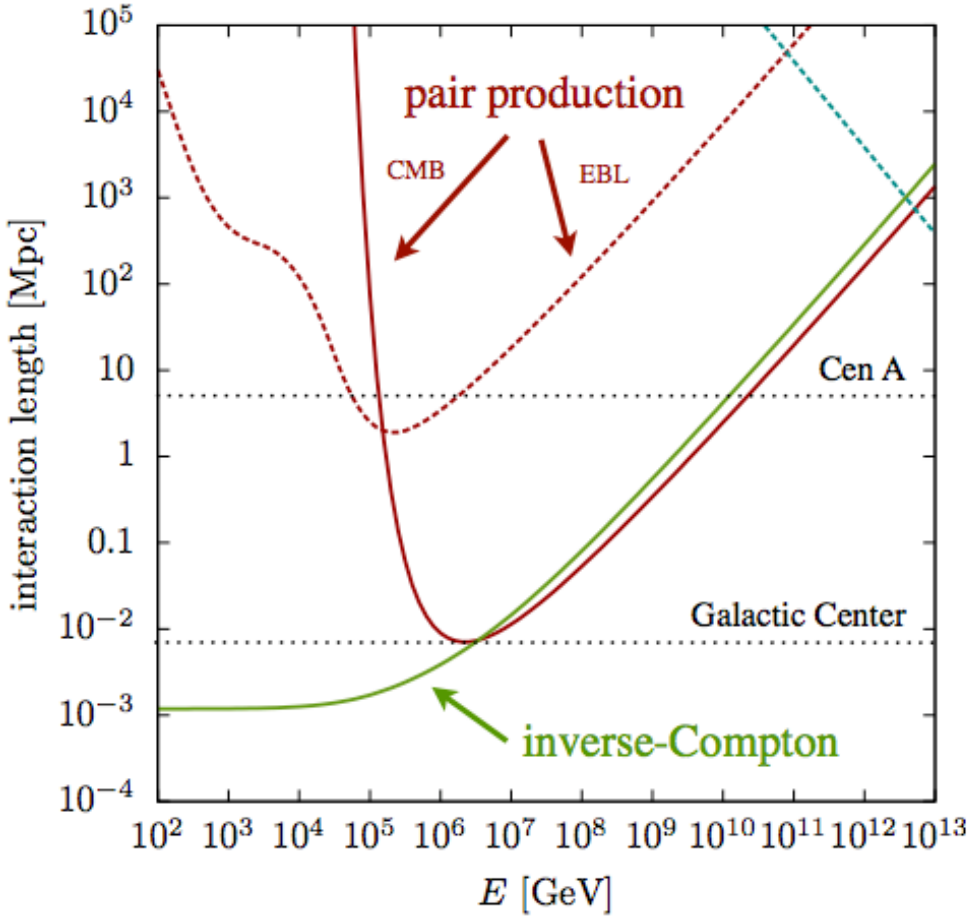
Backup

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

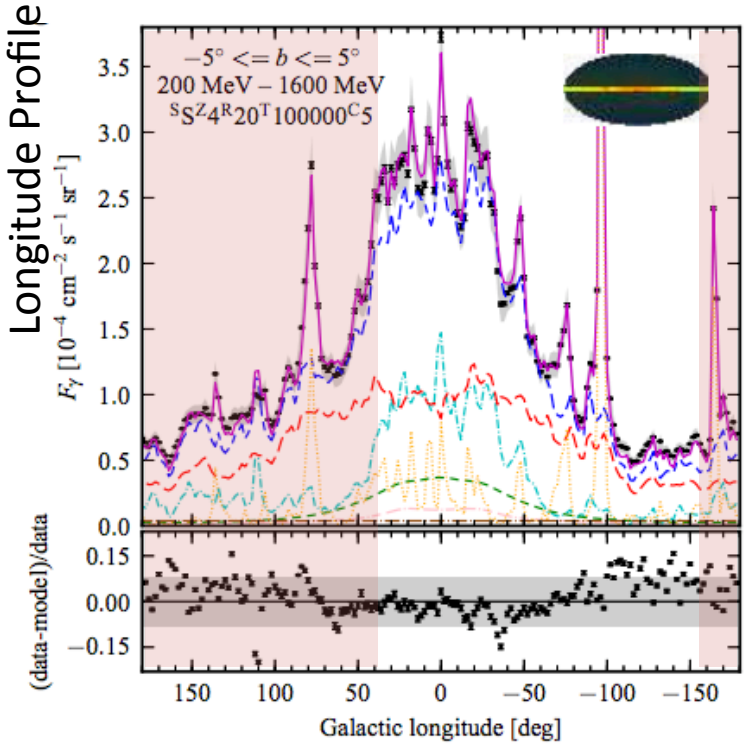
  [Berezinsky&Smirnov'75]



[MA'11]

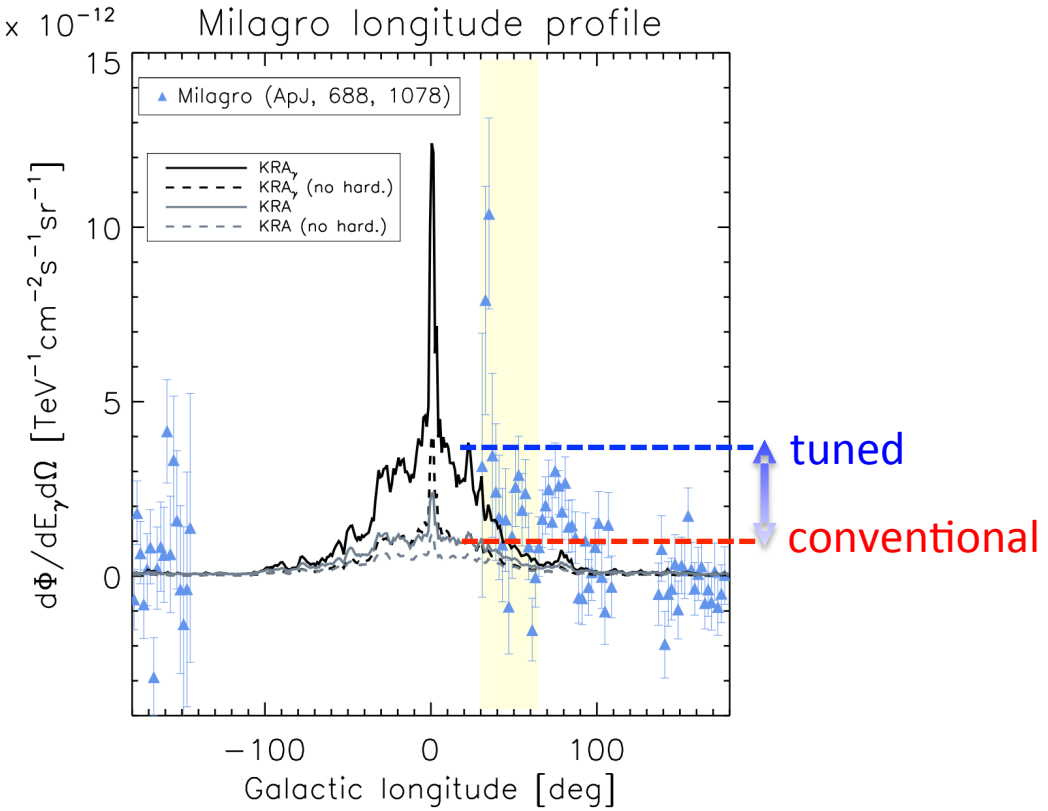
Longitude Profiles

Fermi Pion-decay profile in **red**



Northern Sky: IC Sensitive

M. Ackermann et al 2011
arXiv:1202.4039v2

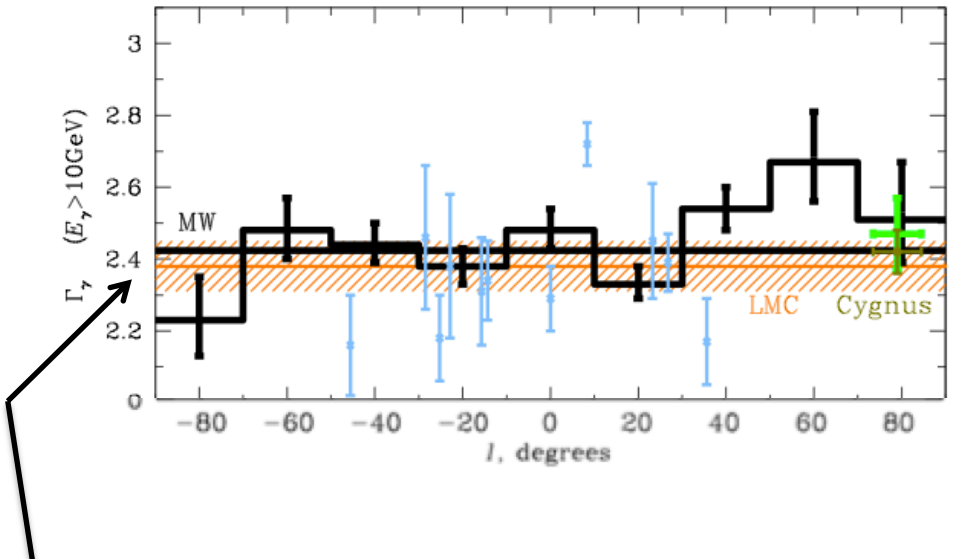


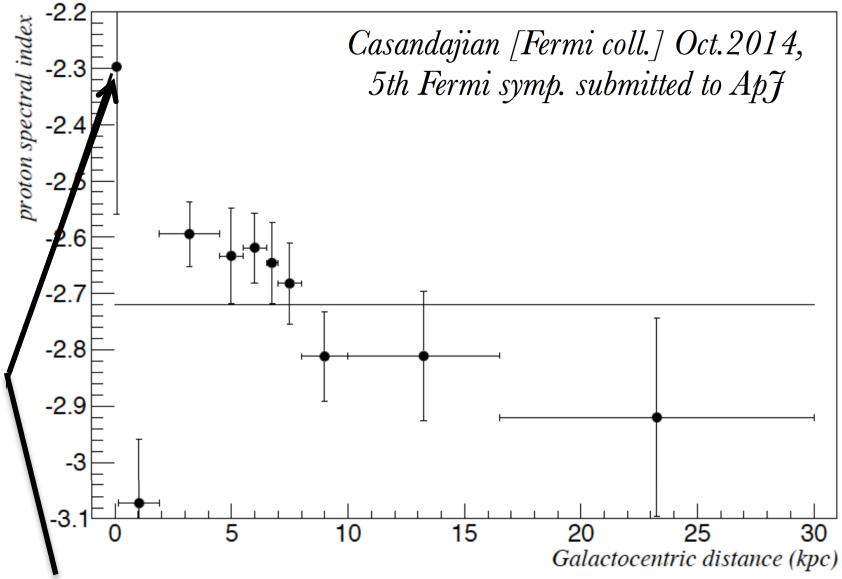
Large uncertainty in flux from inner galaxy!

Gaggero et al 2015
1507.07796v1.pdf

Remote CR Spectrum

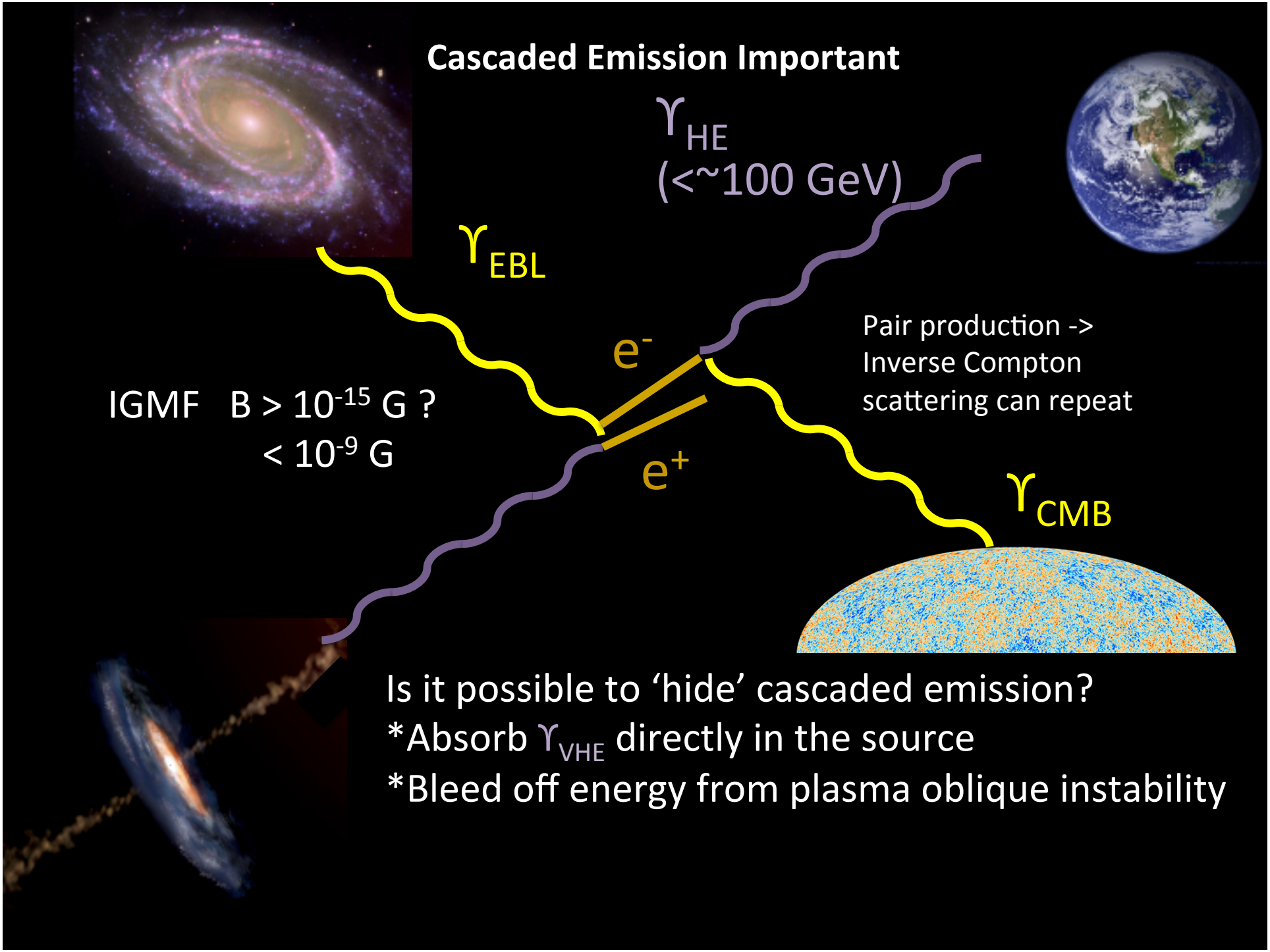
Υ-ray spectral index vs gal lon.



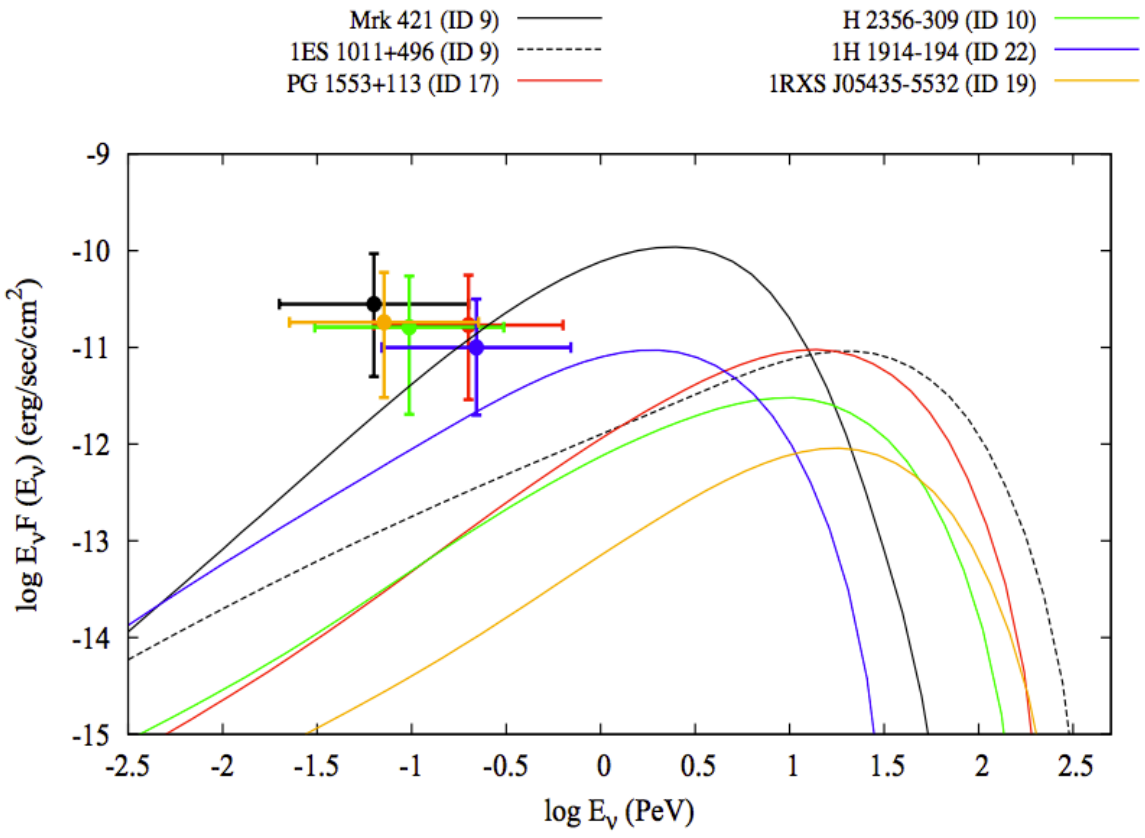


- Neronov & Malyshev 2015 (arXiv:1505.07601v1)
- **Claim: Average CR spectral index: $E^{-2.5}$**
  - Universal? Seen in both MW & LMC
- Earth in softer-than-typical fluctuation due to discrete sources

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


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

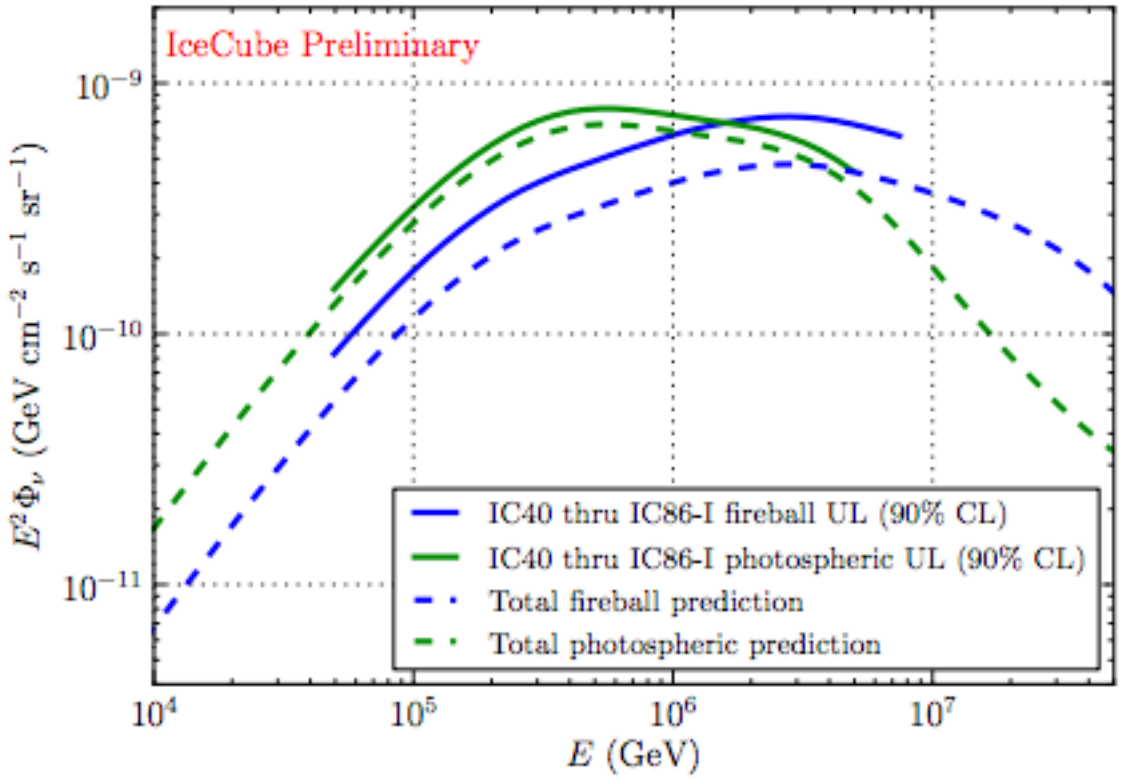
Predictions for All Assoc. Blazars



- 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

The VHDM Models

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

"**ES13**" parameters:

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

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

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

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

"**RKP14**" parameters:

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

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

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

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

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

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

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

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

Murase et al. 2015
arXiv:1503.04663v1

ES13 Model

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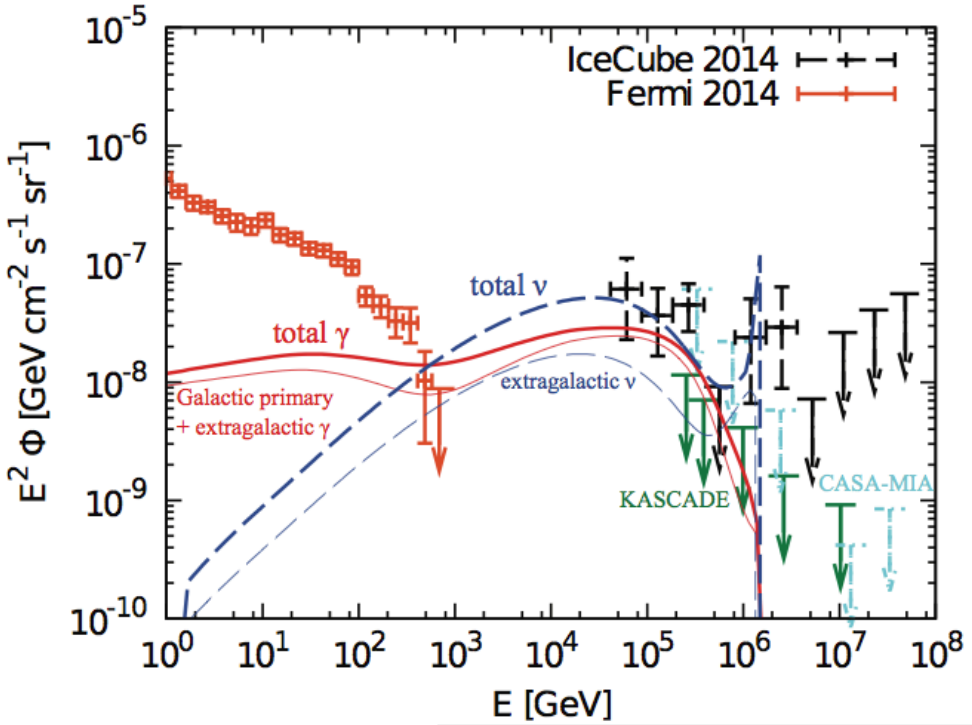
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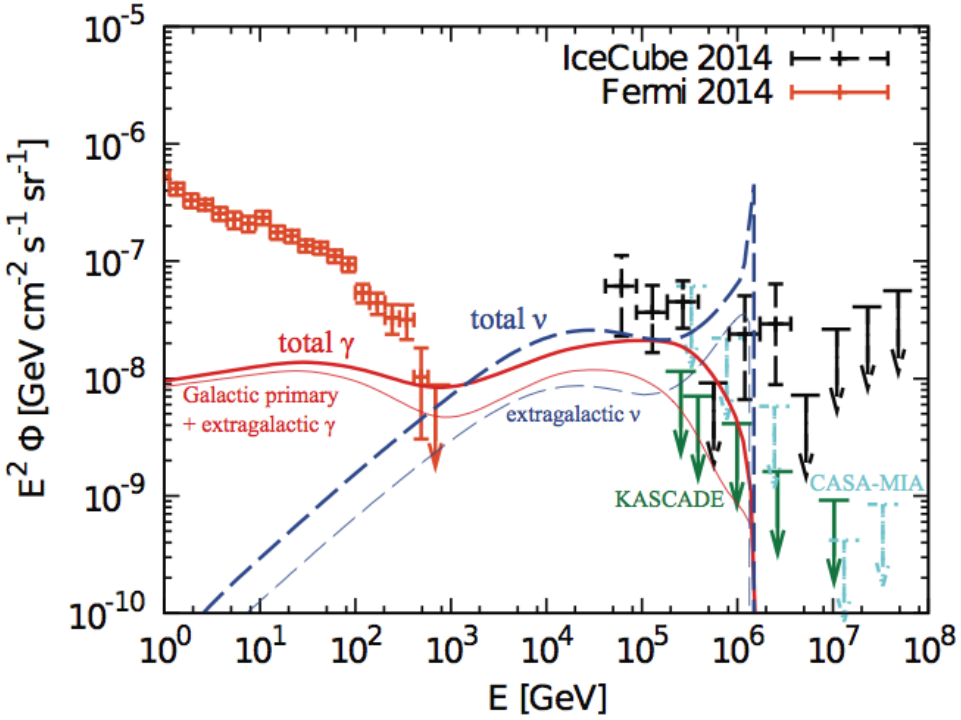
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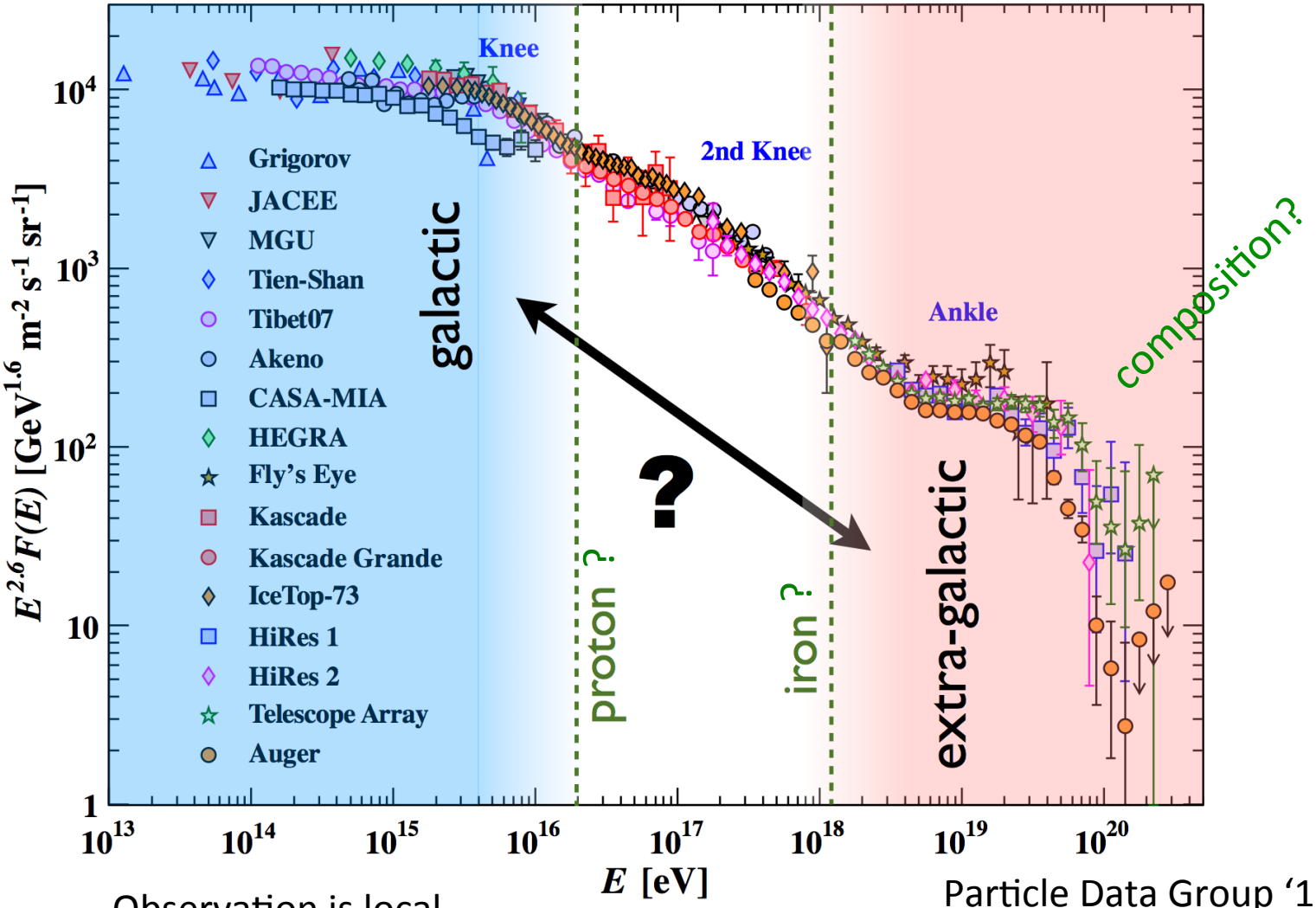
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Murase et al. 2015
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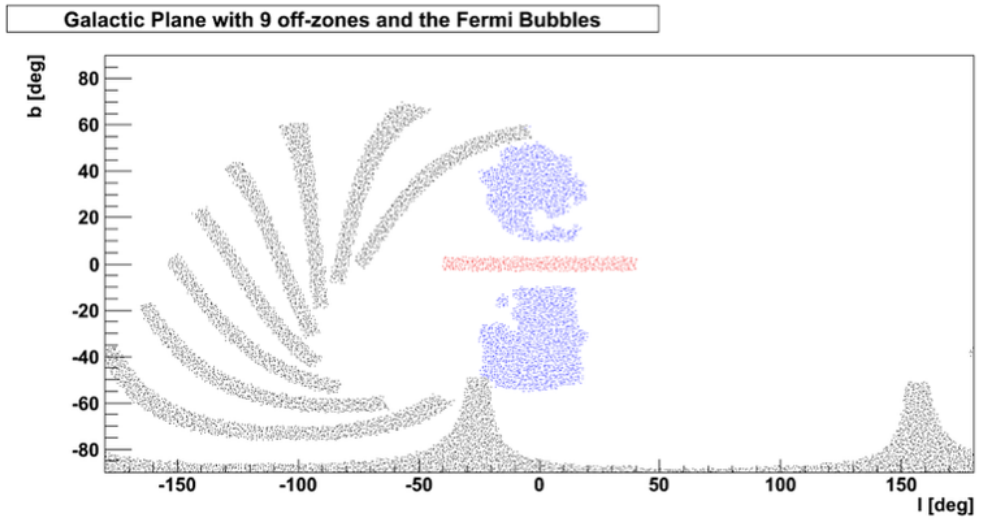
Cosmic "Beam"

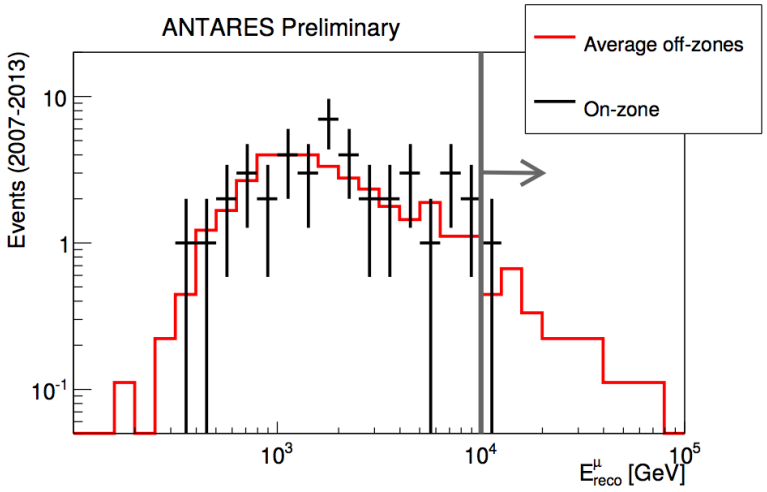


Observation is local

Particle Data Group '13

ANTARES Results

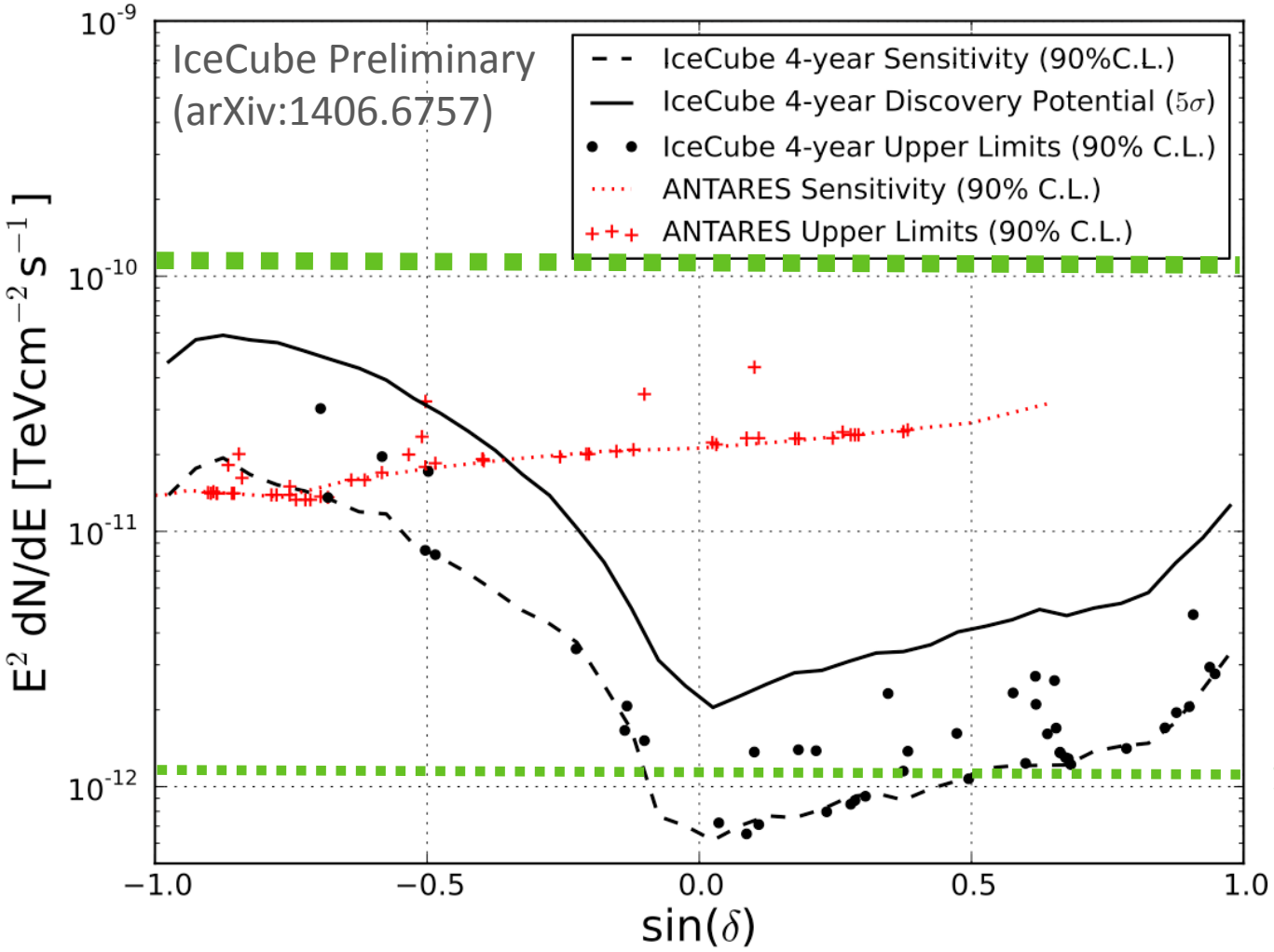




- ANTARES ~1/10th the effective area as IceCube
  - Even so, comparable sensitivity to galactic plane because of distribution
- 1 event observed on a background expectation of 2.5 events

ANTARES results from Luigi Antonio Fusco, shown at VLVNT 2015

Point Source Analysis



Point-source equivalent flux if the diffuse flux came from:

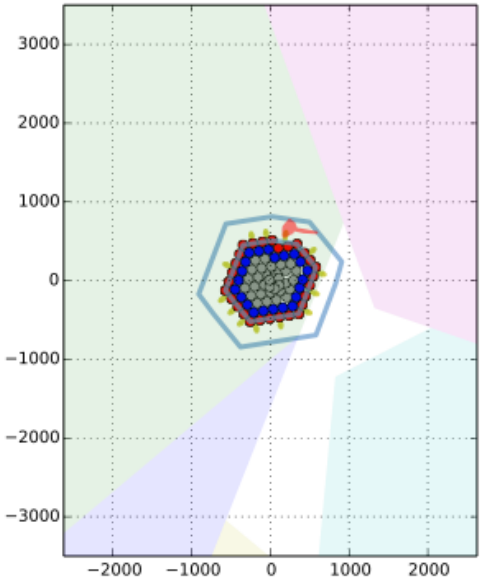
one point in the sky

100 points in the sky

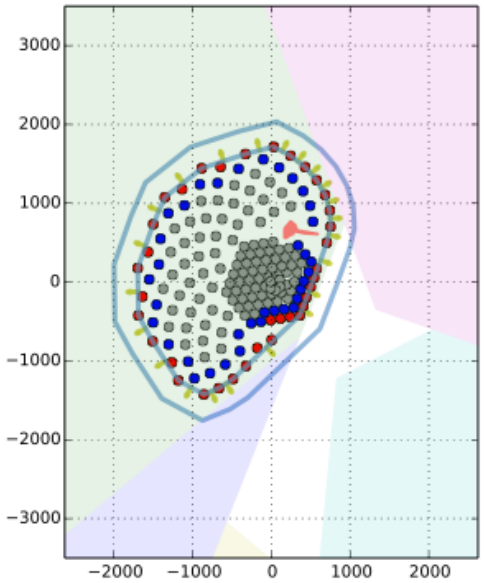
Population studies with Stacking Searches:

1000 points in the sky

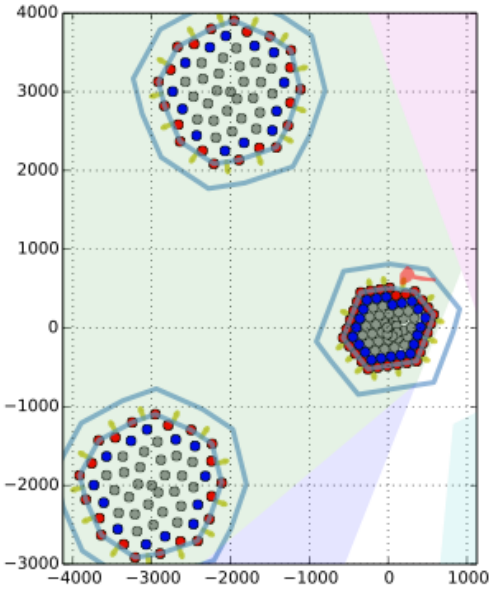
strings: IC86 spacing: ~125m



strings: IC86+96 spacing: ~240m



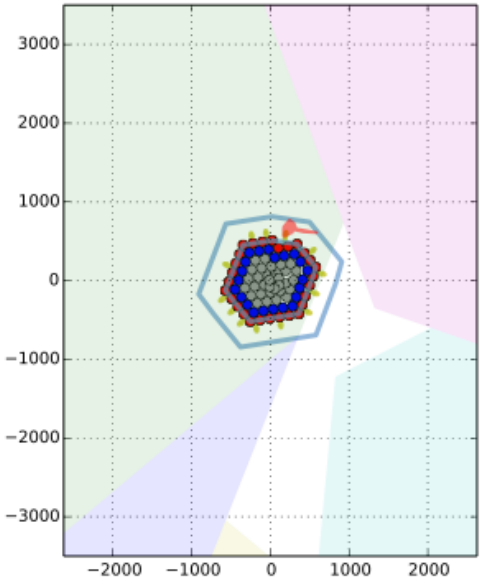
strings: IC86+2x60 spacing: ~240m



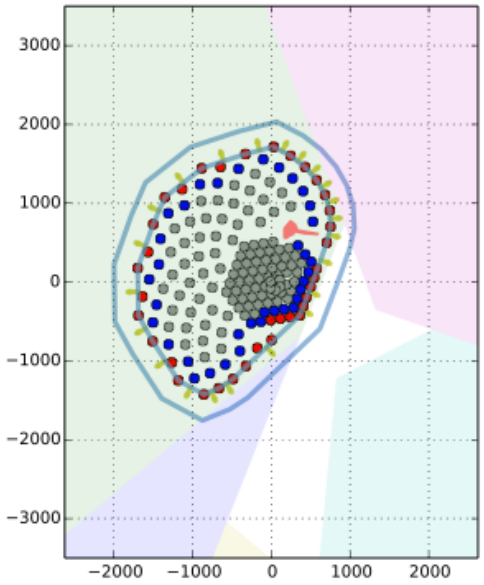
Future High Energy Extension

InIce Strings

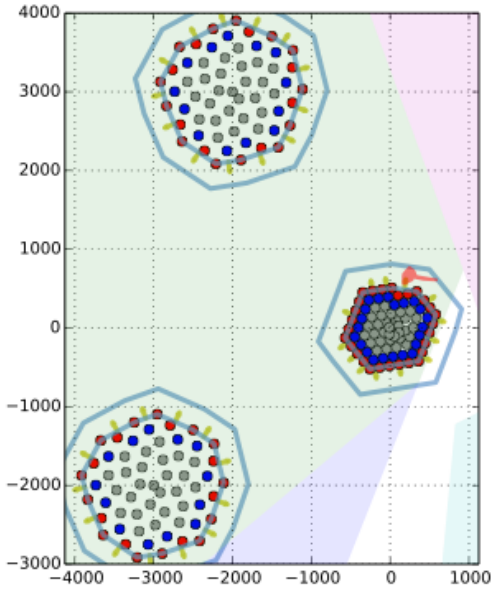
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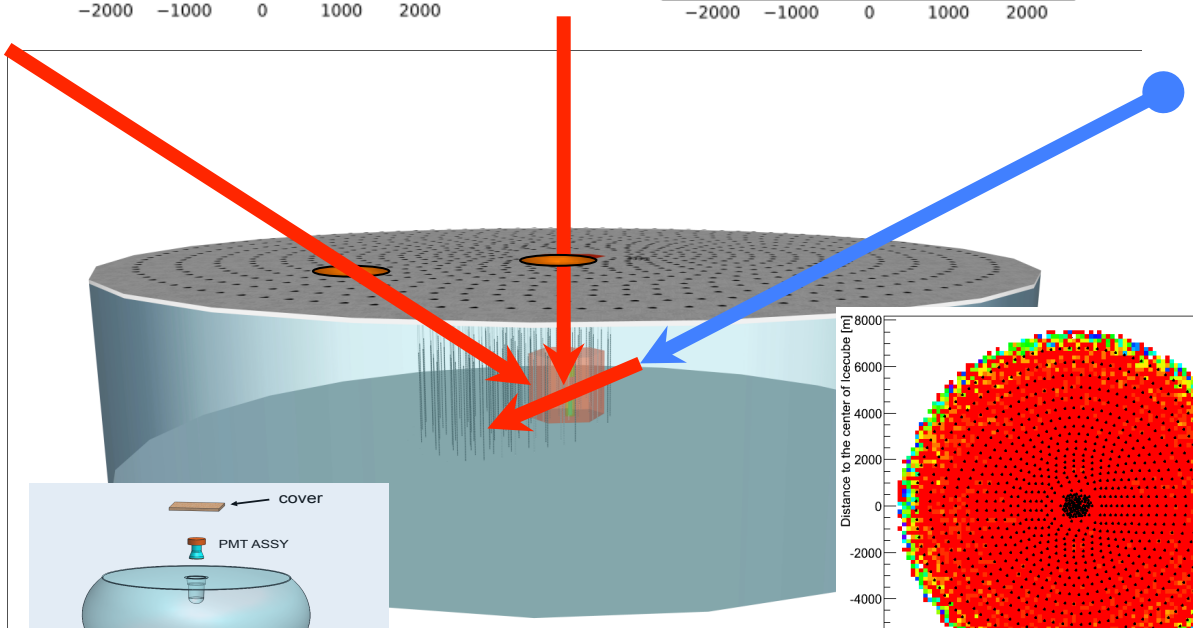


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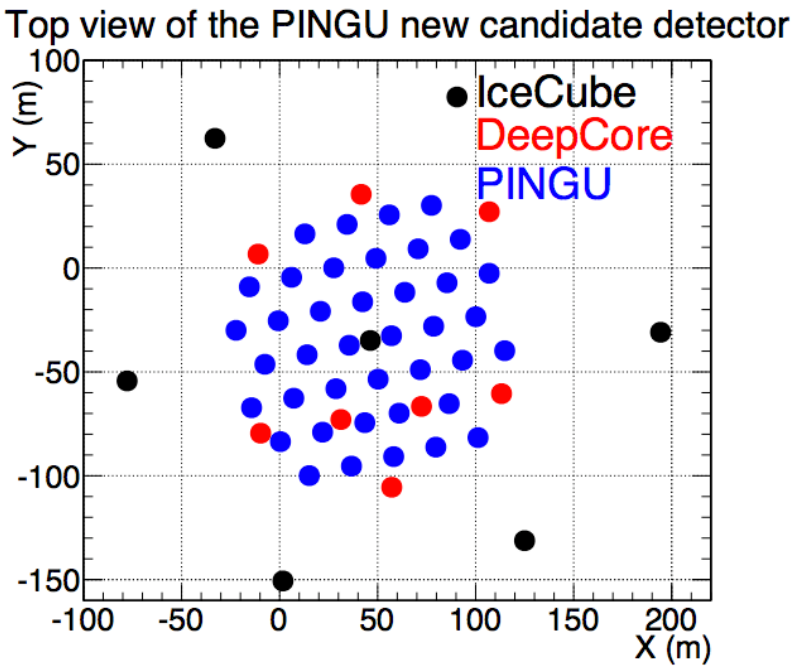




Future High Energy Extension

InIce Strings
+
Surface Veto

PINGU





- PINGU infill would push the energy threshold down to a few GeV
- Opens possibility for measure **neutrino mass hierarchy** and atm **tau neutrino appearance**
- PINGU itself could be a pathfinder for an even larger infill array for neutrino physics