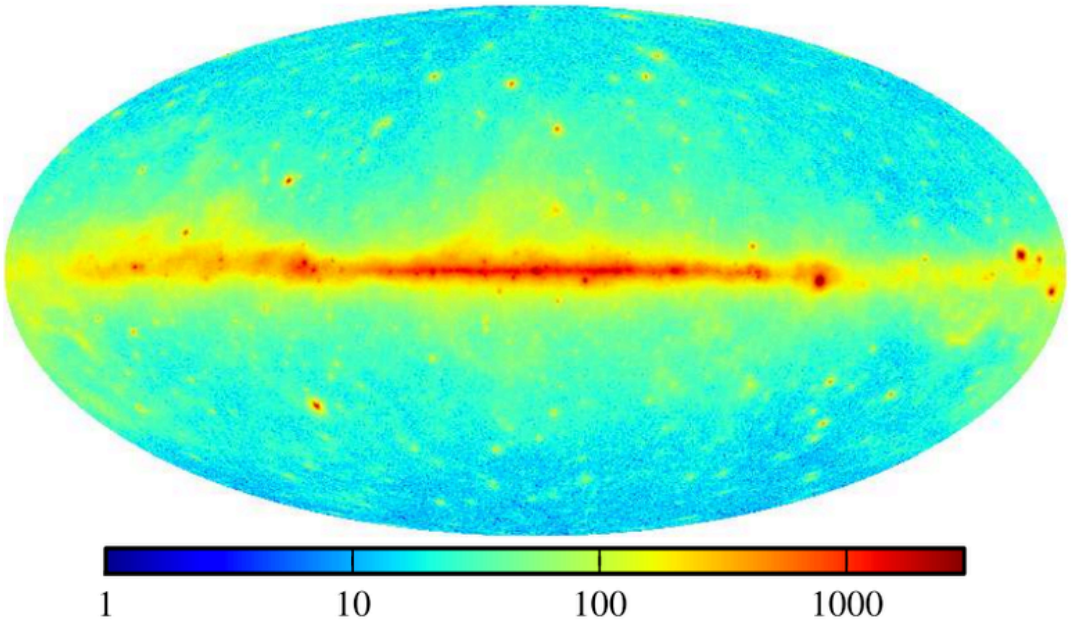
Neutrinos and γ-rays: The Milky Way and More



Jon Dumm

Drexel University

June 21, 2016

Stockholm University

Oskar Klein centre

Overview

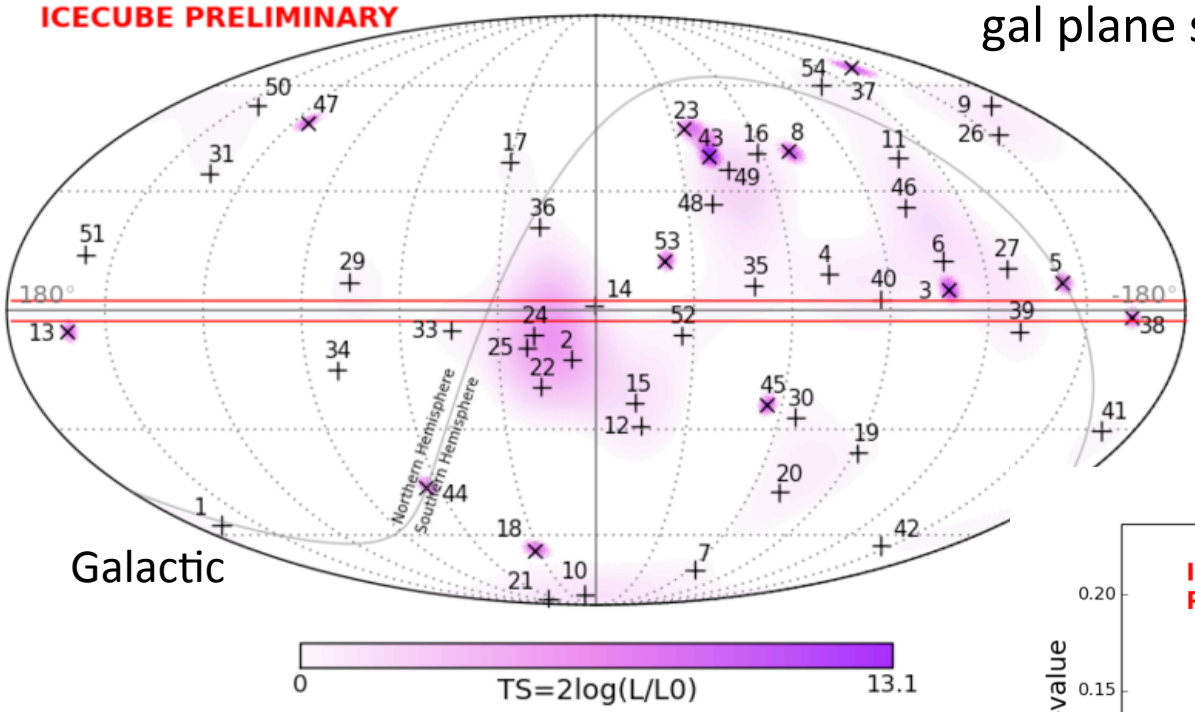
- Searching for a galactic contribution to the astrophysical neutrino flux

- Further prospects for extragalactic gamma-ray and neutrino connections

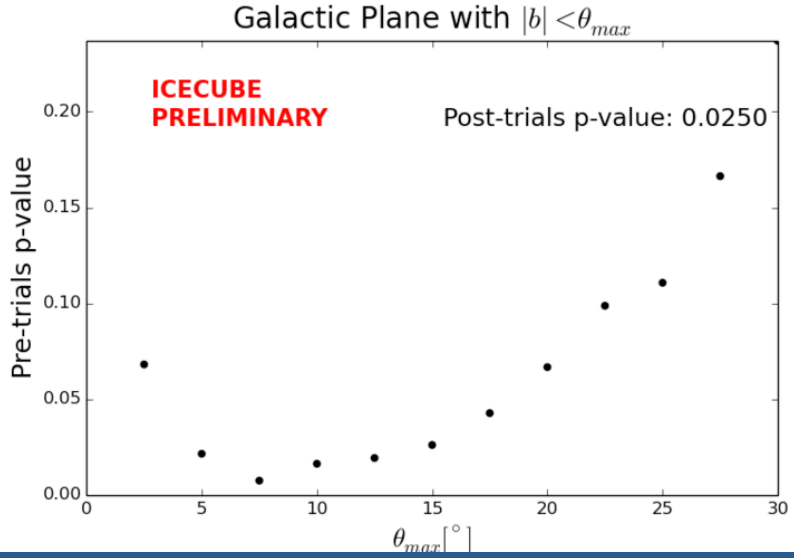
High-Energy Starting Events

- Post-trial p-value in 4-year HESE: 2.5%

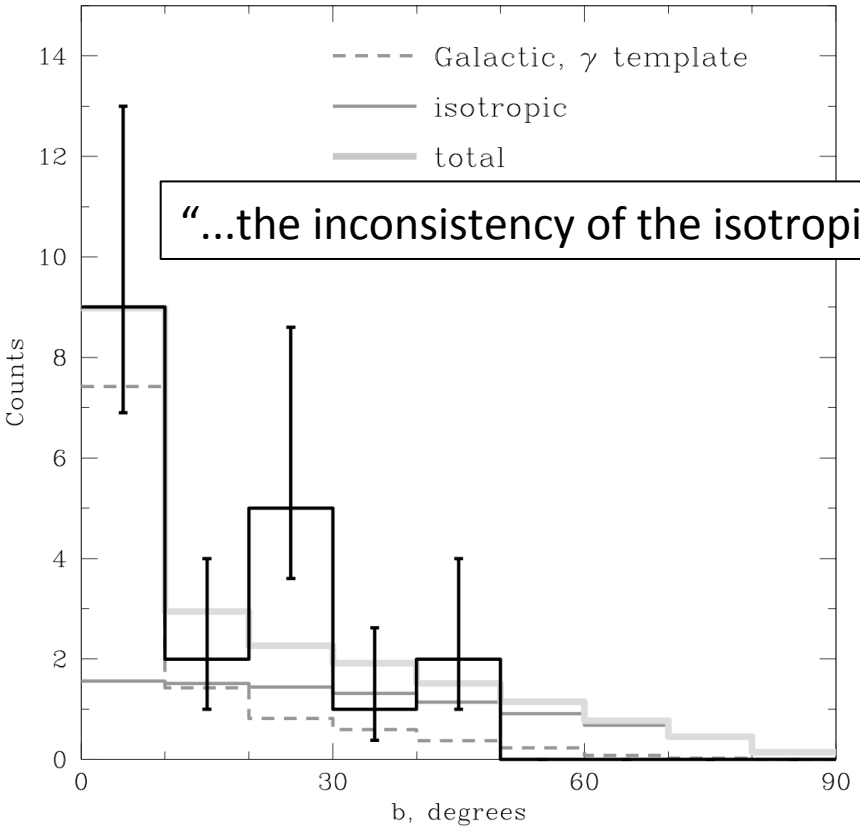
gal plane scan within ± 7.5° gal latitude

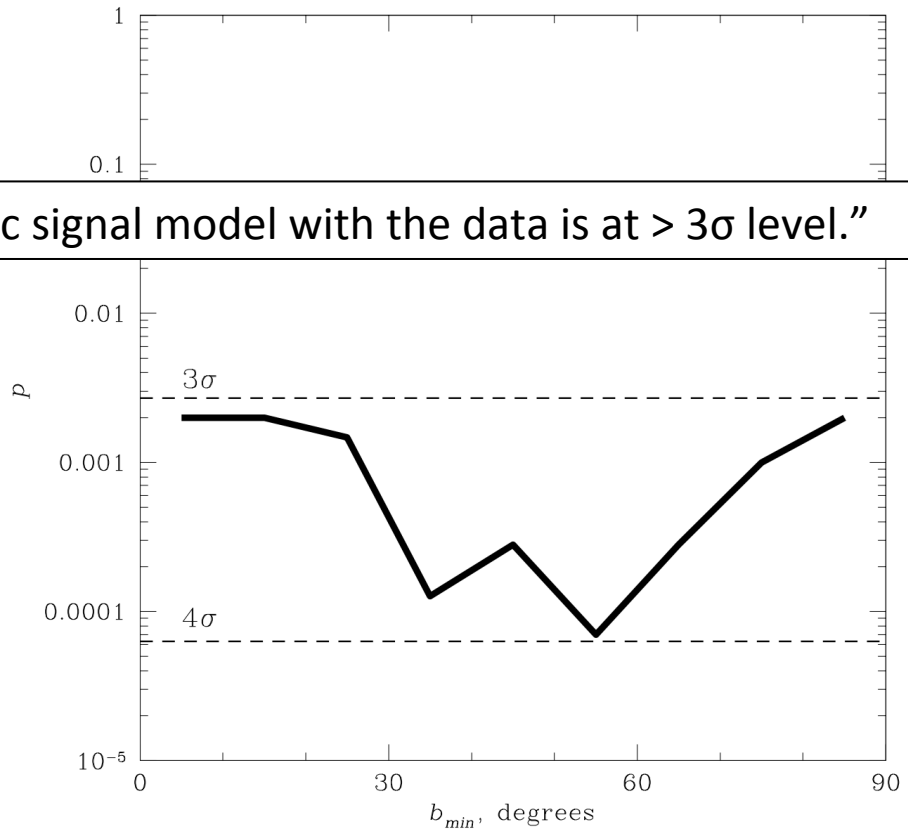


Galactic



>100 TeV *A Posteriori*



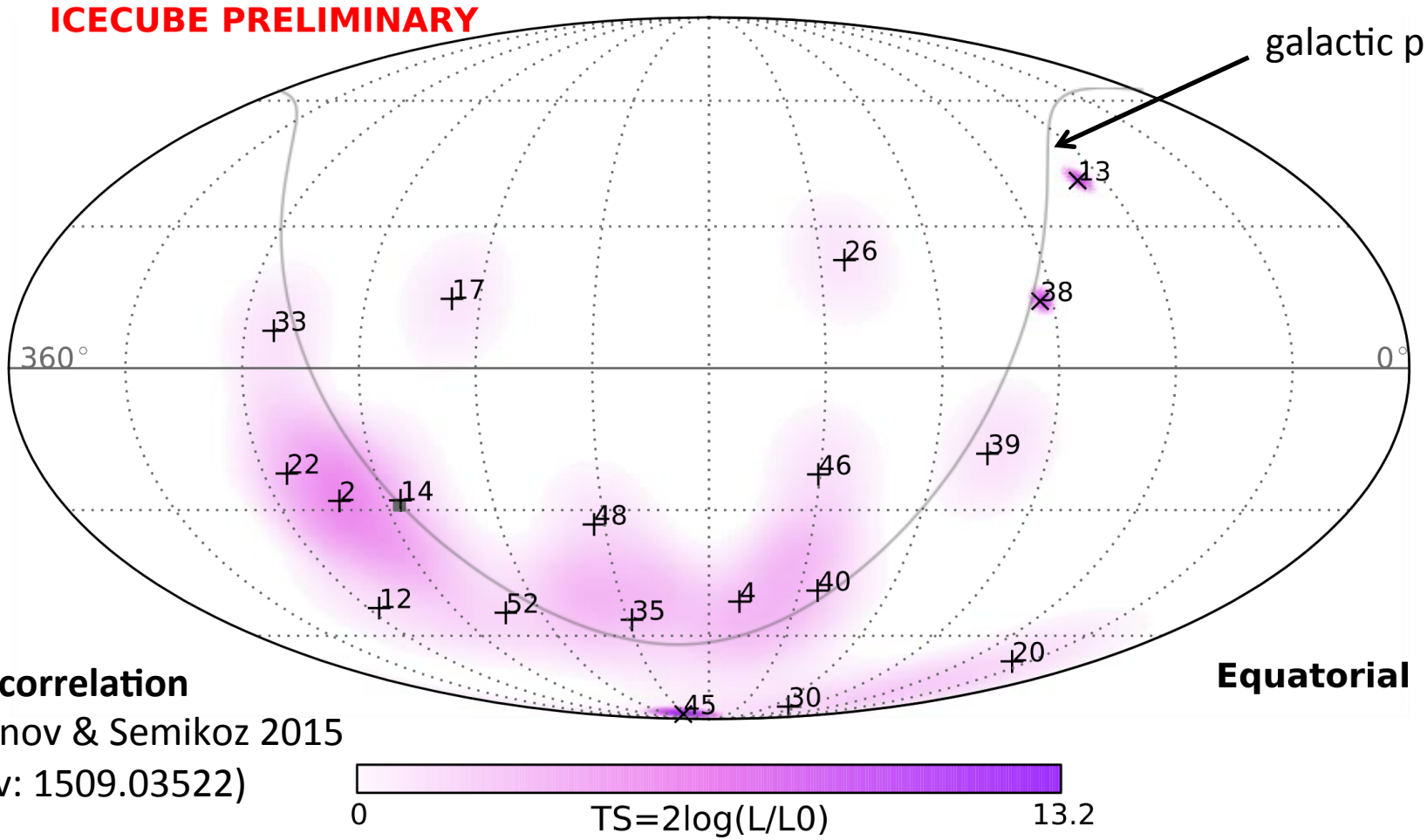


"...the inconsistency of the isotropic signal model with the data is at > 3σ level."

"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)

>100 TeV *A Posteriori*



~3 σ correlation

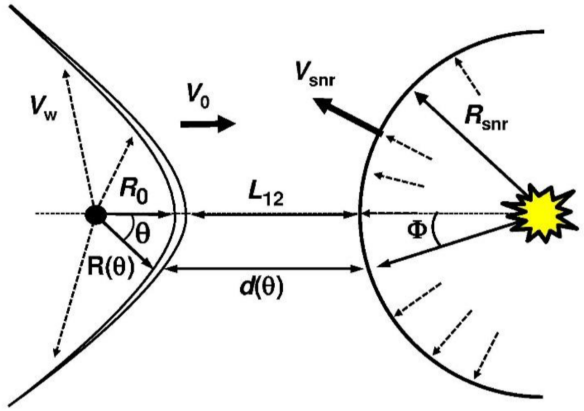
Neronov & Semikoz 2015

(arXiv: 1509.03522)

- Yes, high energy events are more likely signal, but could the very highest energy neutrinos be galactic?

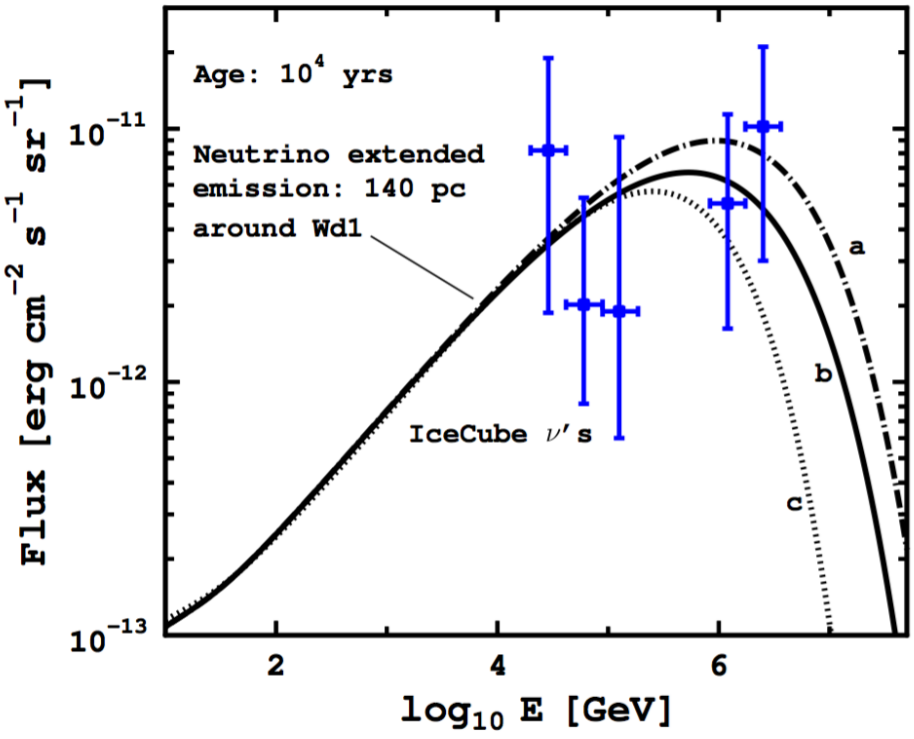
>100 TeV in the Galaxy?

- There are several models that interpret the very highest energy neutrinos as galactic
  - Gamma-ray sources often observed to cut off above ~10 TeV



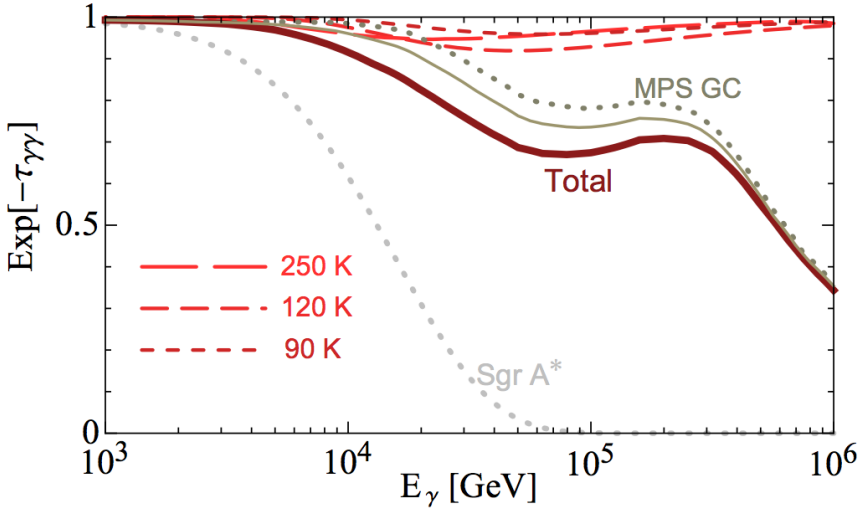
- Westerlund 1 star cluster
  - Interacting stellar winds and SNR shocks
  - Very hard emission

A.M.Bykov et al 2015
arXiv:1507.04018



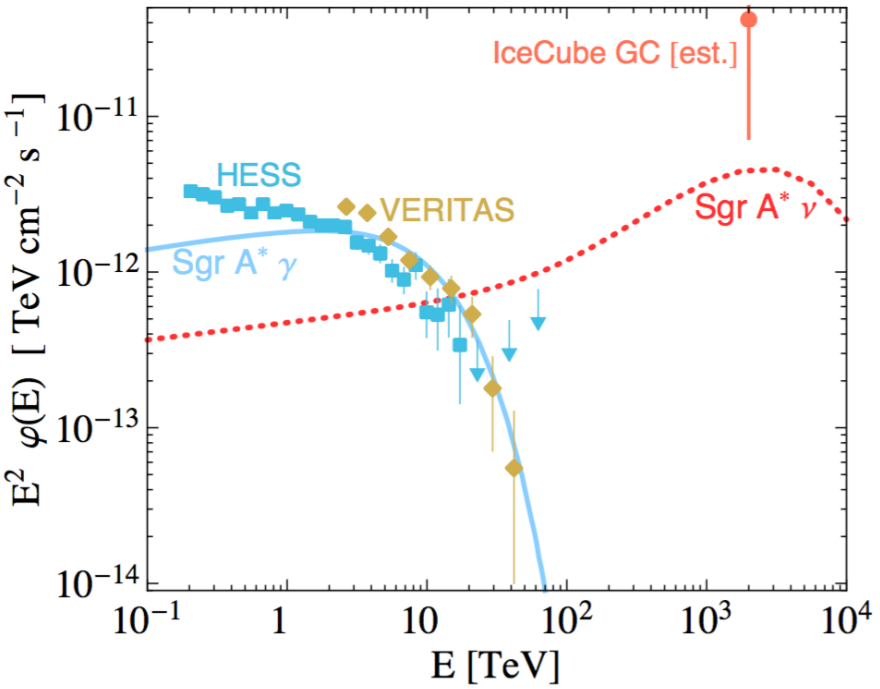
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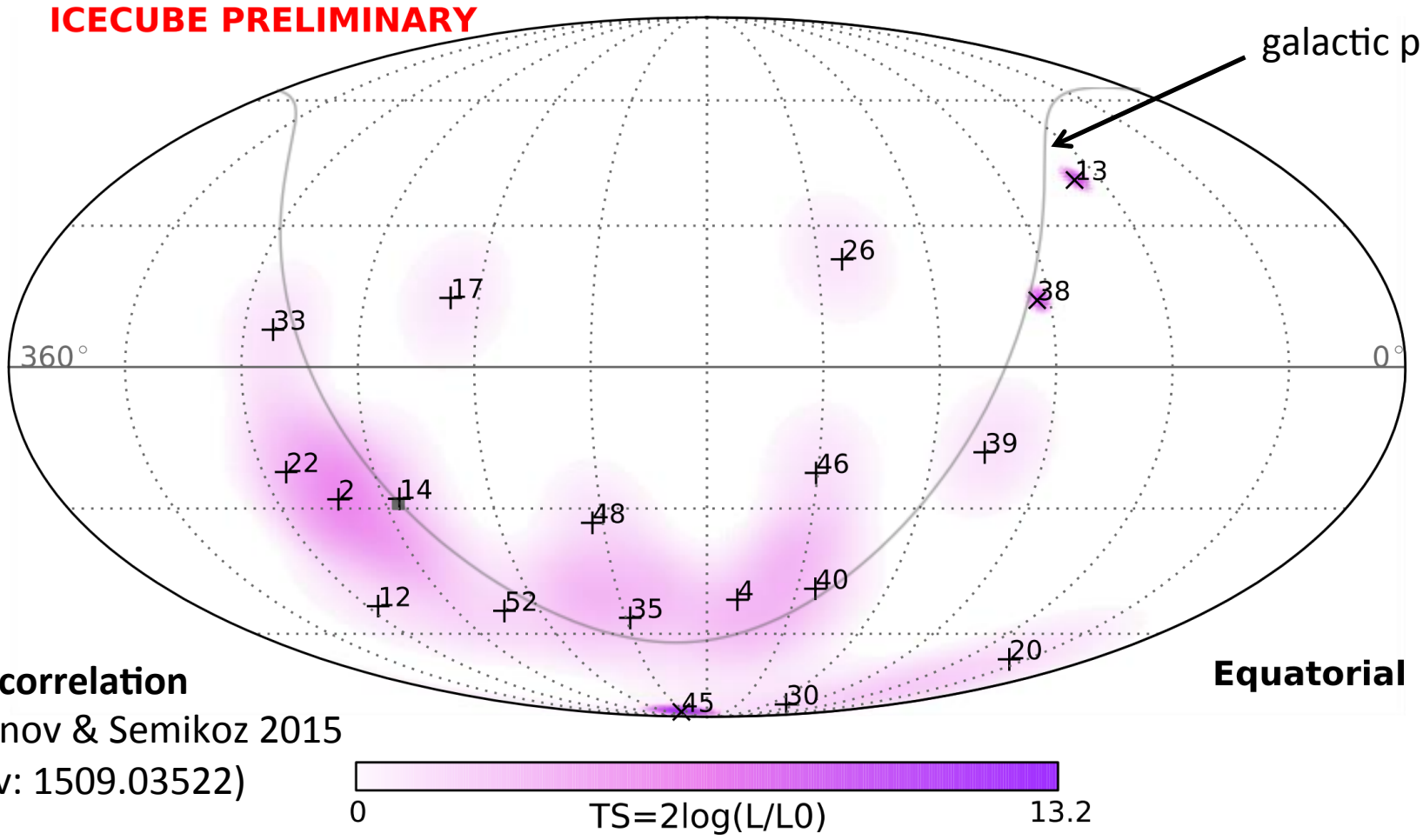
- Sgr A* model
- Gamma-ray attenuation varies drastically
  - Very strong near accretion disk

Kistler 2015
arXiv:1511.00723



Kistler 2015
arXiv:1511.05199

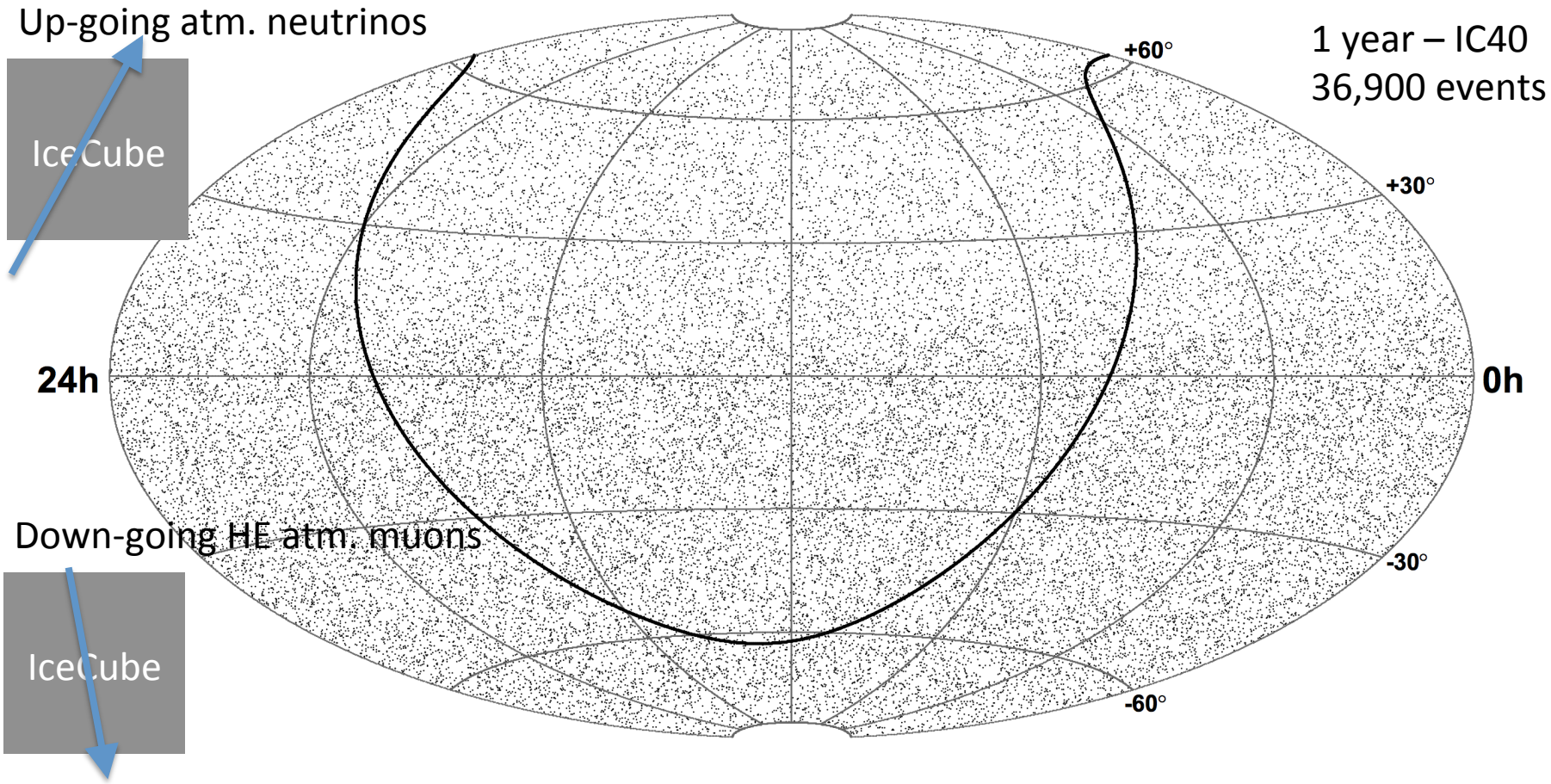
>100 TeV *A Posteriori*



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

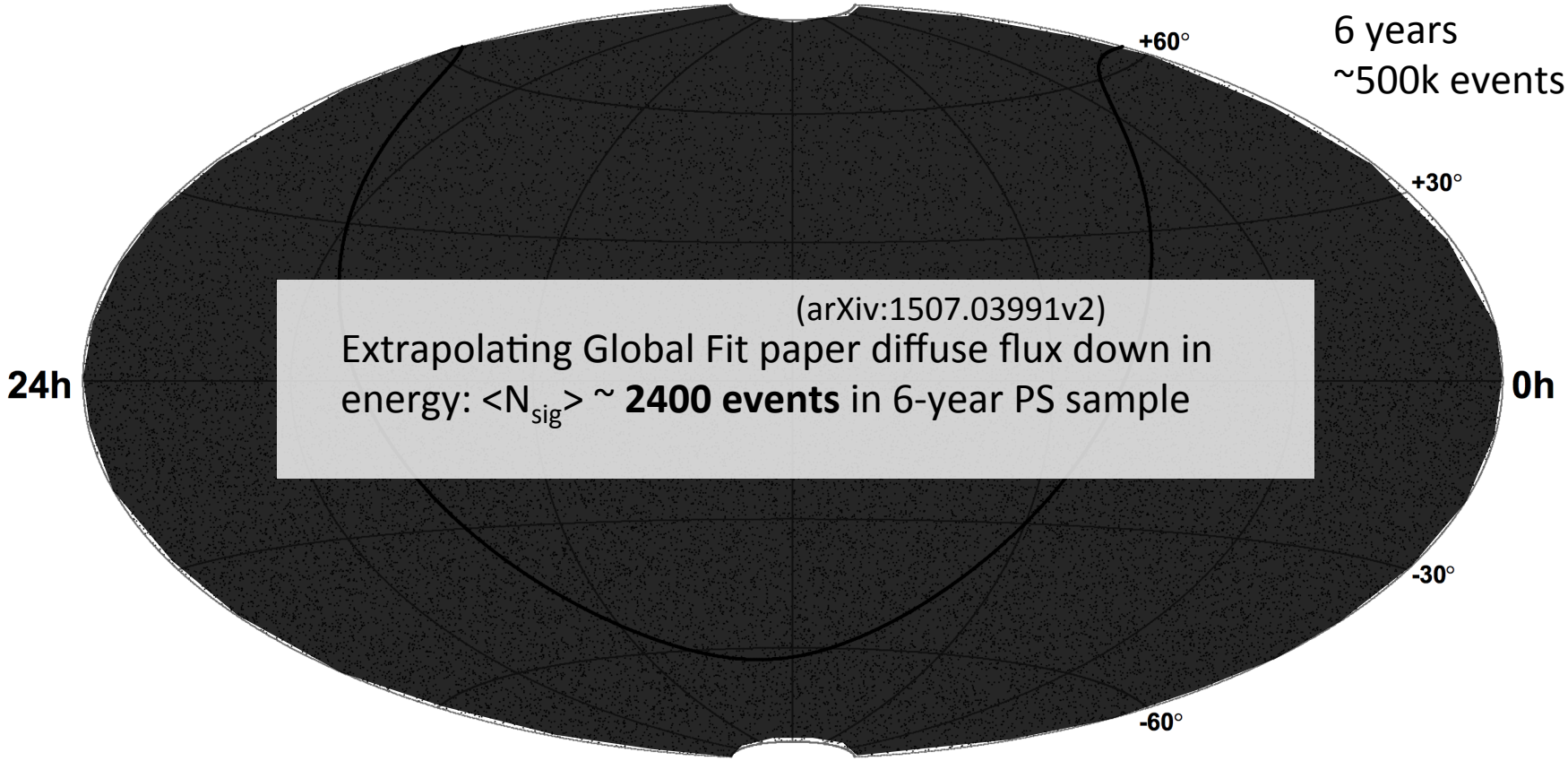
- **Limited by small statistics of sample**

Point Source Sample



- Too many events to show full sample – 40-string sample for illustration
- Can we find some ~hundreds of events distributed along the plane?

6 Years of PS Data



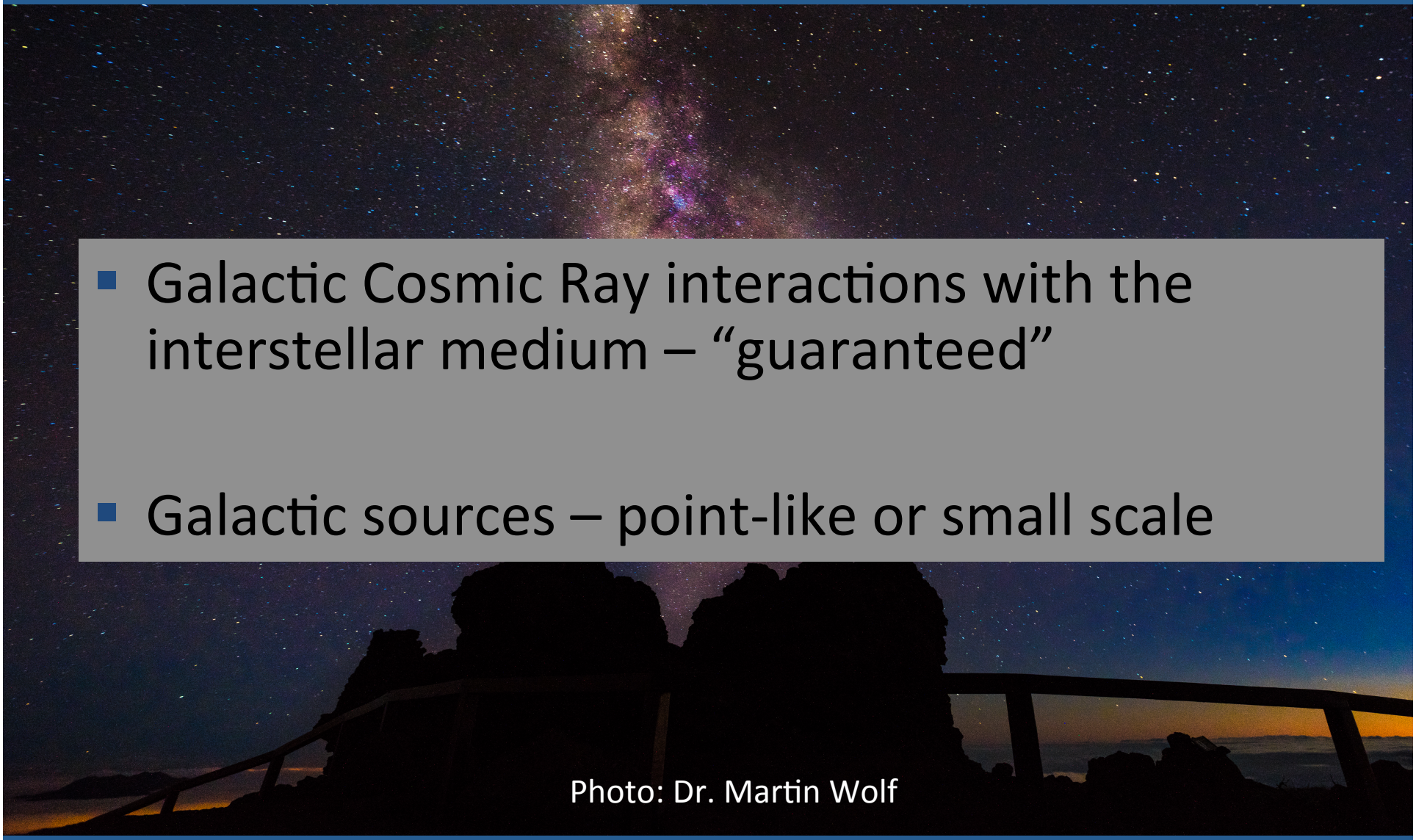
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The Milky Way



Photo: Dr. Martin Wolf

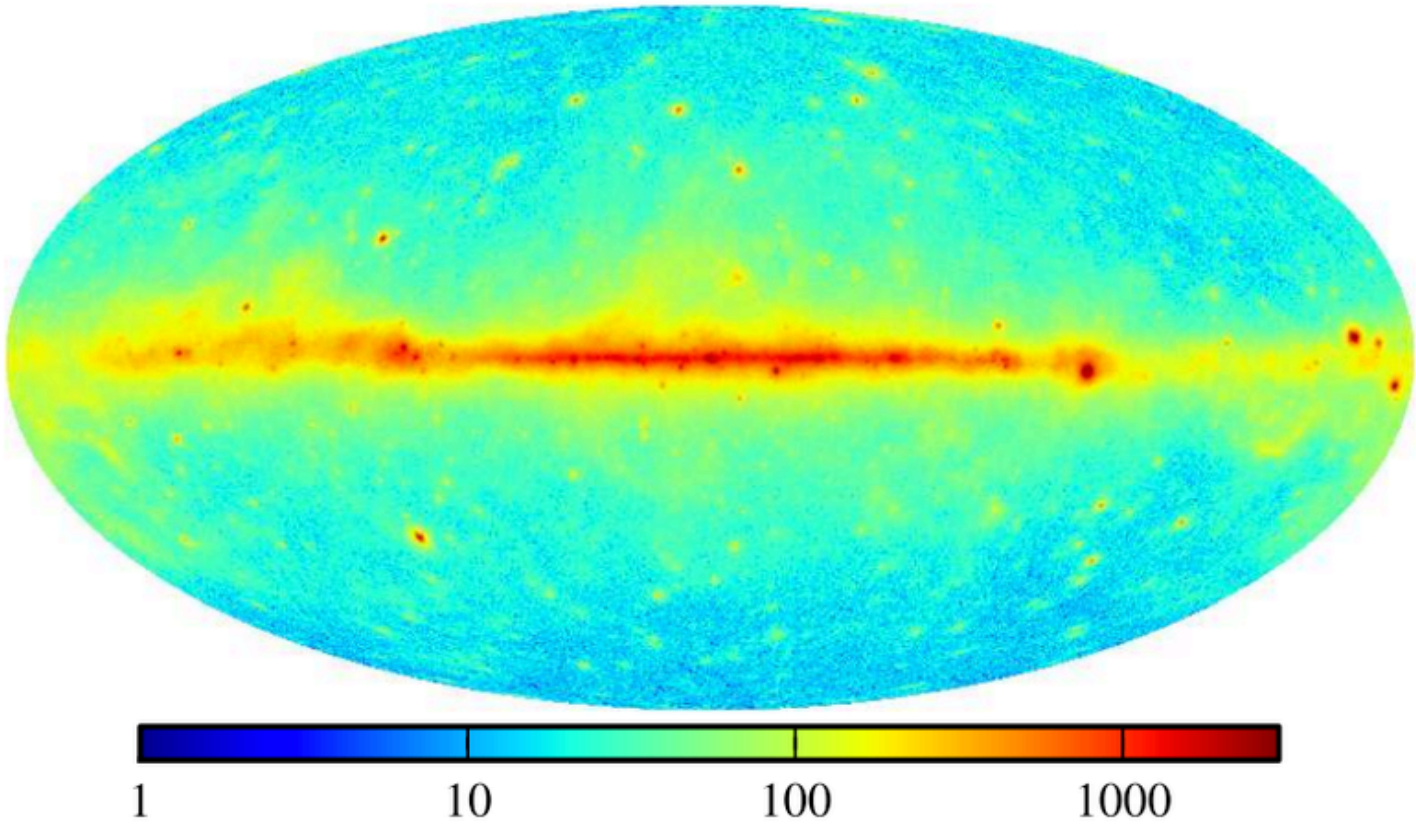
The Milky Way



- Galactic Cosmic Ray interactions with the interstellar medium – “guaranteed”
- Galactic sources – point-like or small scale

Photo: Dr. Martin Wolf

Raw γ-ray Counts > 100 MeV



The Fermi GP Diffuse Map

- While the Fermi gal plane diffuse emission model has its own scientific merit, it is primarily used for foreground subtraction in source identification

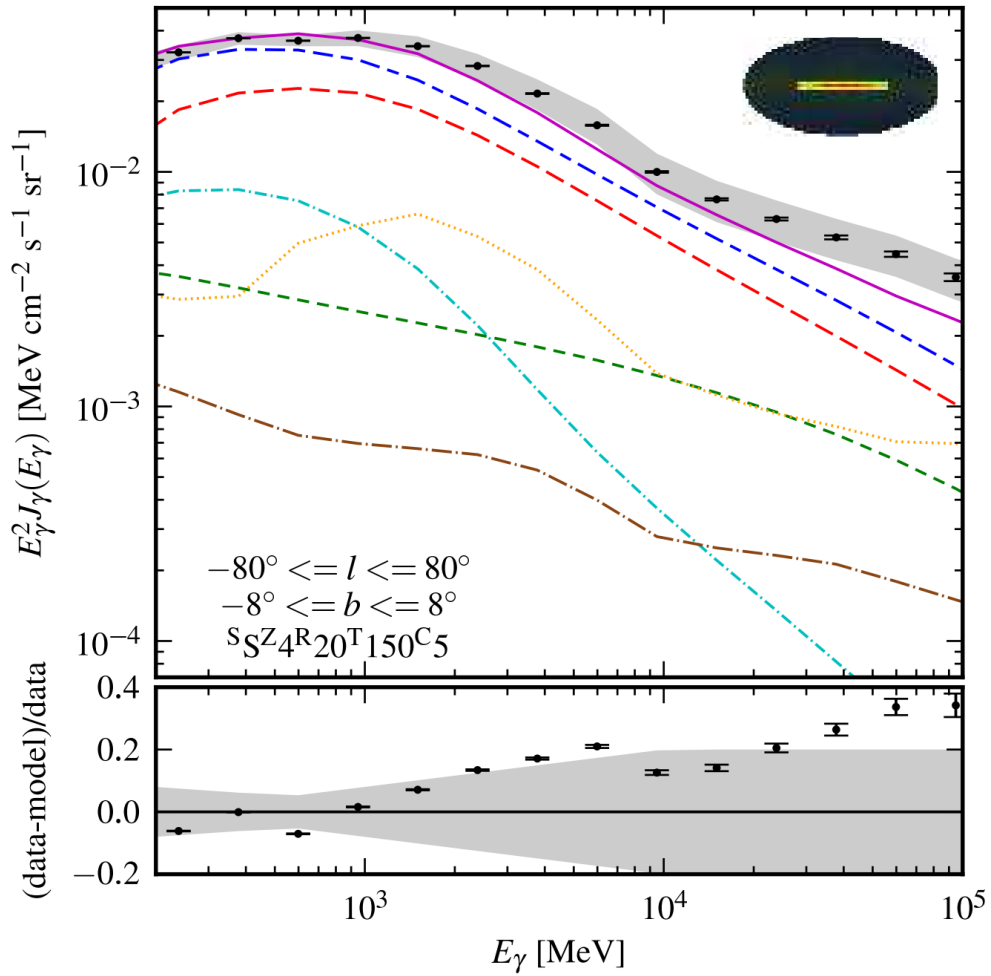
- The model is built using surveys of H_1 & H_2
  - H_1 and H_2 make up 70% of the matter in ISM, itself 99% gas
  - H_1 observed from 21-cm line → 3D map from Doppler shift
  - H_2 observed from 2.6-mm CO line since CO only formed in presence of H_2
  - Heavier elements assumed distributed as H_1 & H_2
  - Infrared tracers of dust used for corrections
  - CRs **assumed to be $E^{-2.7}$** and intensity varies with R_{gal}
    - CR intensity in R_{gal} bins are only free parameters in the fit to the gamma-ray data
  - Inverse Compton component purely from GALPROP modeling

- I use only the Pion-decay component in my analysis

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

Fermi Model Spectrum

Gamma-ray spectrum from **Inner Gal Plane**



- Diffuse emission from the plane dominated by **pion decay**

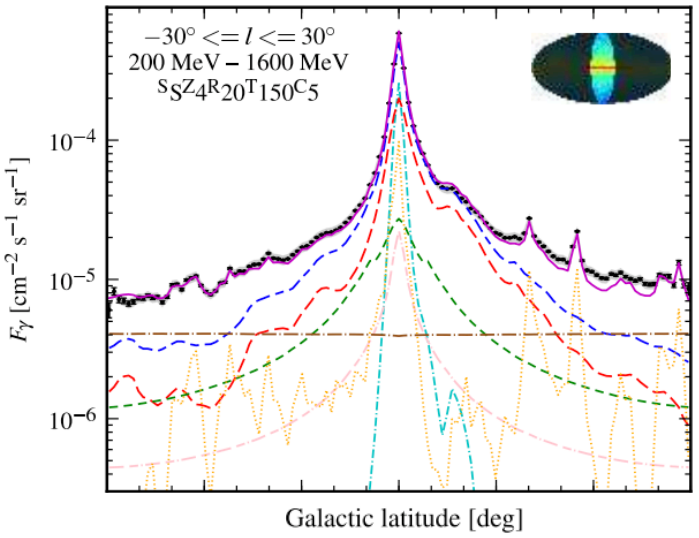
Total 'characterized' emission
Diffuse Galactic emission
Pion decay
Sources
Inverse Compton
Isotropic Extragal.
Bremsstrahlung

- Diffuse model assumes CR spectrum observed at Earth

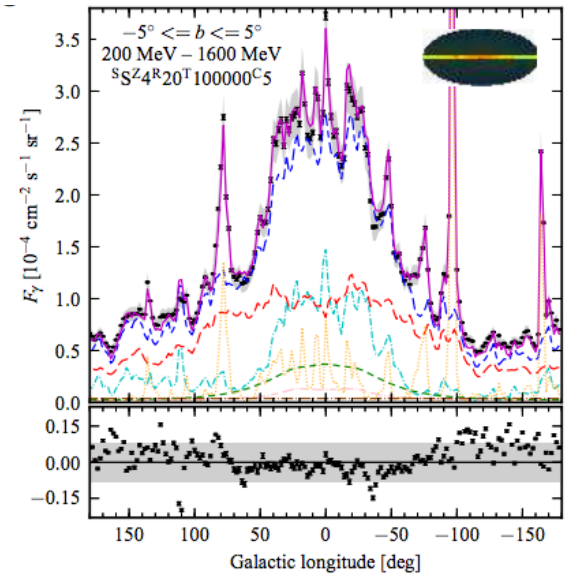
M. Ackermann et al 2011
arXiv:1202.4039v2

Model Profiles

Latitude Profile



Longitude Profile

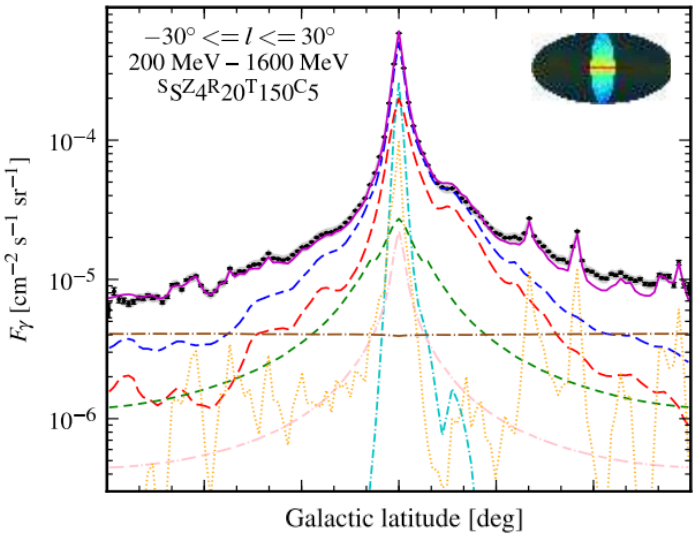


Total 'characterized' emission
Diffuse Galactic emission
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Sources
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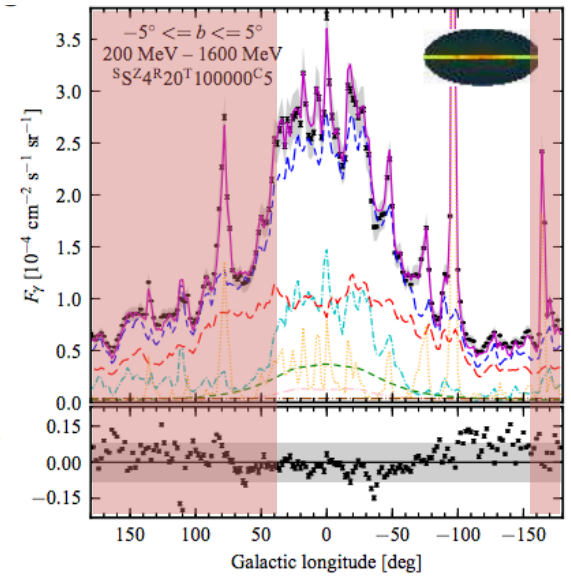
M. Ackermann et al 2011
arXiv:1202.4039v2

Model Profiles

Latitude Profile



Longitude Profile



- Northern sky integrates about **1/3** of the pion decay model

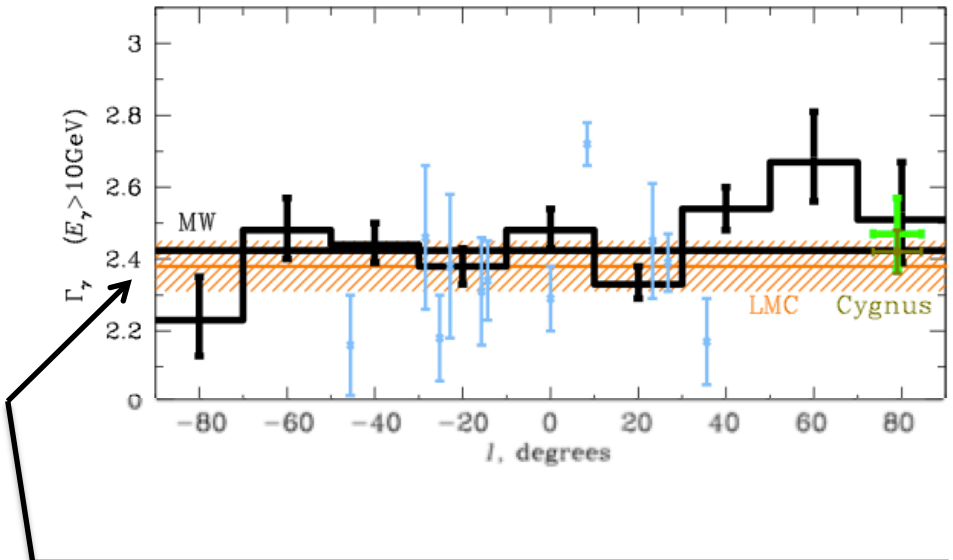
Total 'characterized' emission
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Sources
Inverse Compton
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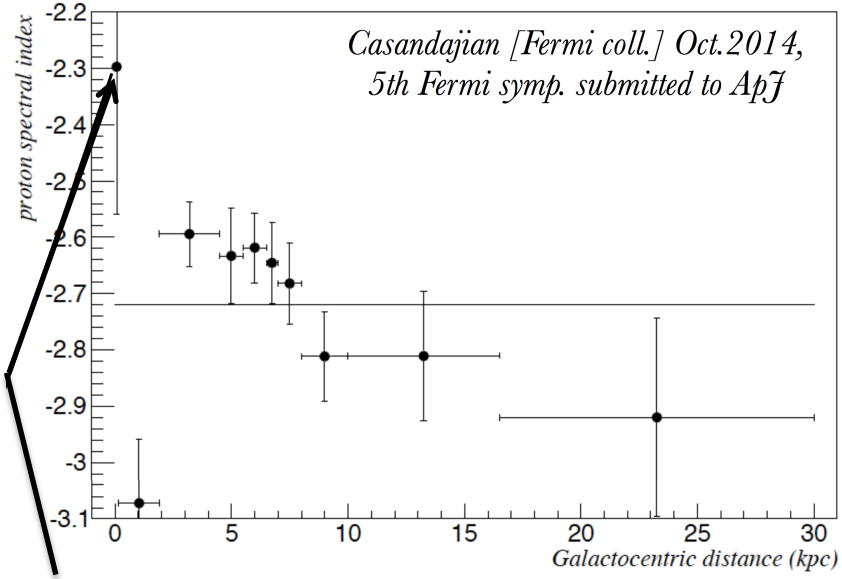
Northern Sky: IceCube Sensitive in muons

M. Ackermann et al 2011
arXiv:1202.4039v2

Remote CR Measurements

γ-ray spectral index vs gal lon.





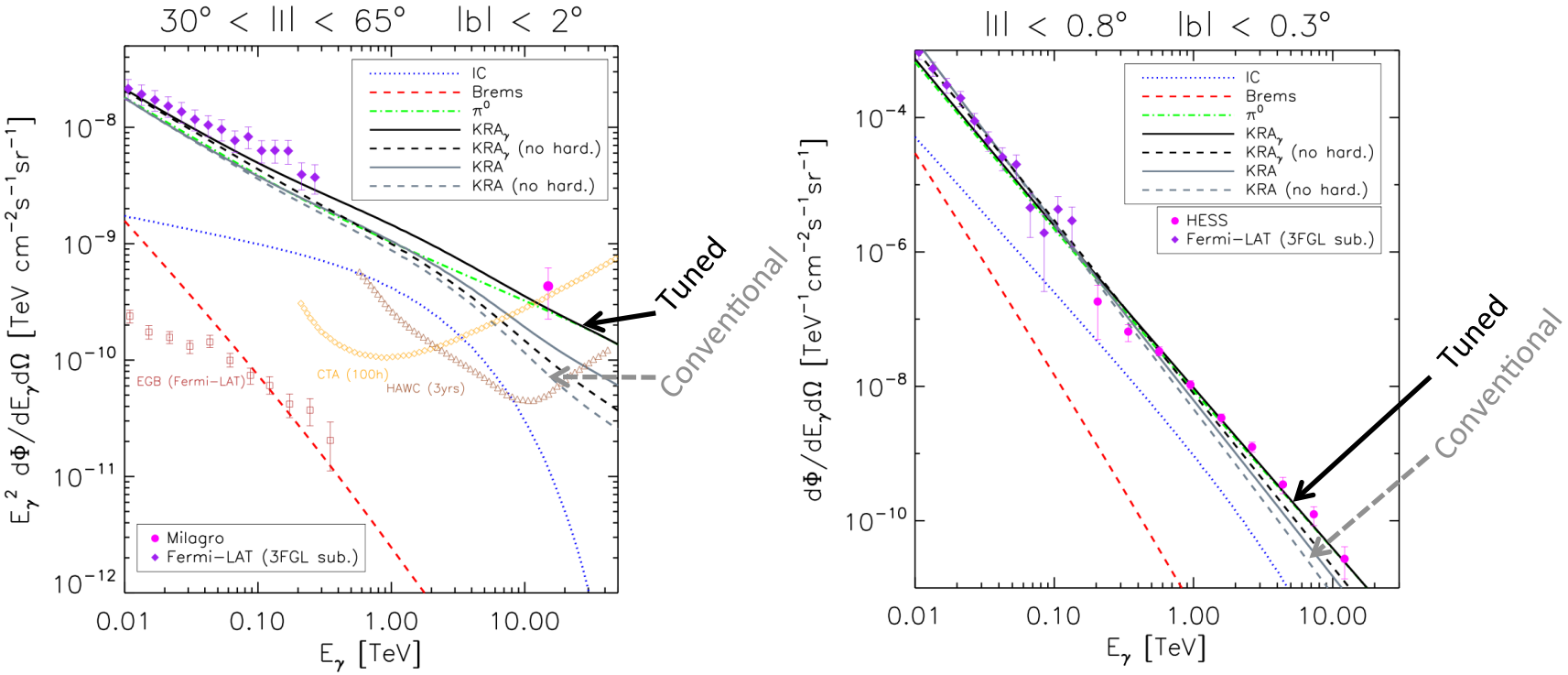
- Neronov & Malyshev 2015 (arXiv:1505.07601v1)
- **Claim: Average CR spectral index: $E^{-2.5}$**
  - Universal? Seen in both MW & LMC
- Earth in softer-than-typical fluctuation due to discrete sources

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

Gal CR Interactions

- Previous modeling assumed ~$E^{-2.7}$ CR spectrum uniform in galaxy
- Fermi+Milagro+HESS γ-ray data combined now allow us to build new models, allowing CR diffusion to change with galactic radius

γ-ray Models

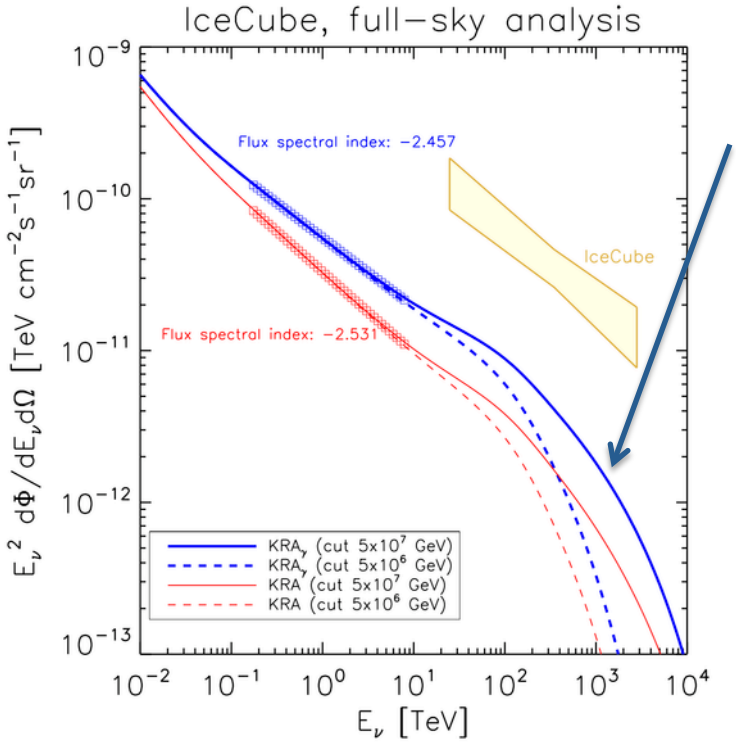


Gaggero et al 2015
arXiv:1504.00227

Gal CR Interactions

- Previous modeling assumed ~$E^{-2.7}$ CR spectrum uniform in galaxy
- Fermi+Milagro+HESS γ-ray data combined now allow us to build new models, allowing CR diffusion to change with galactic radius

γ-ray Models → ν predictions



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

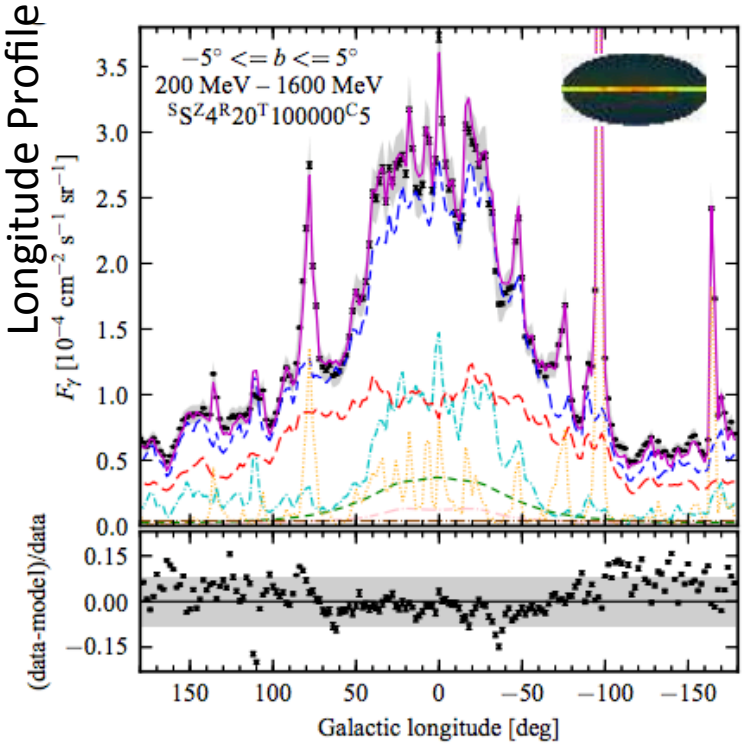
Specifics:

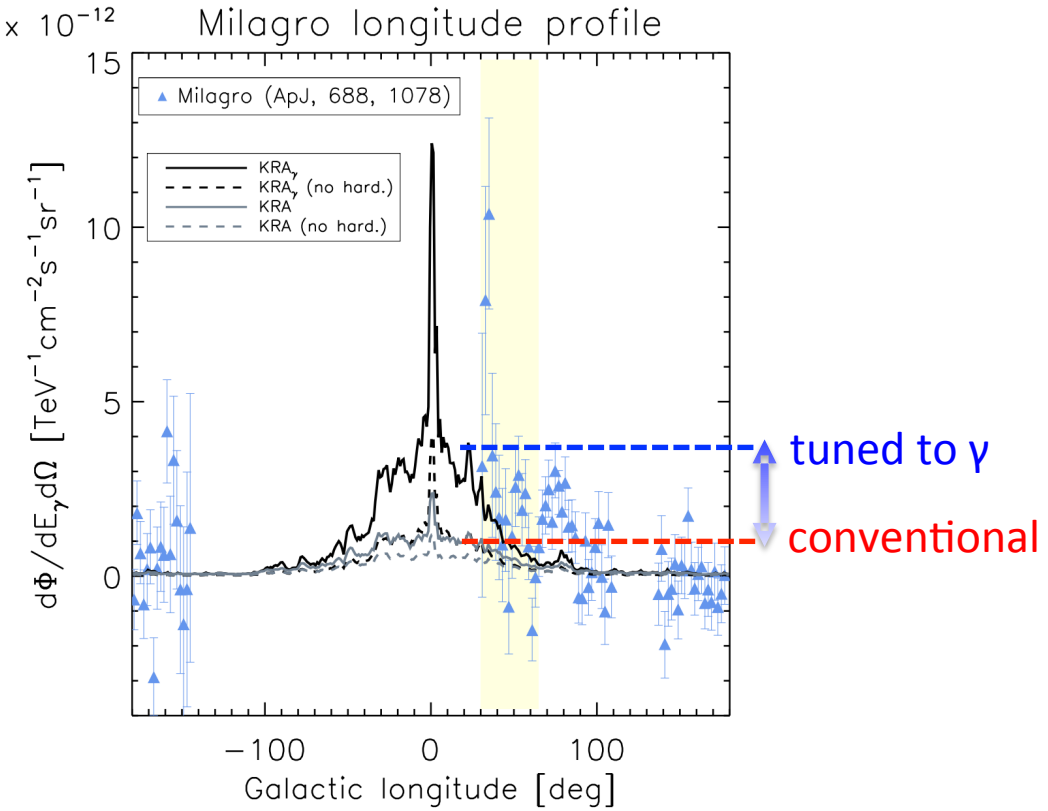
- Assumes PAMELA/AMS p & He hardening is global
- Gal CR cutoffs: 5 (dotted), 50 (solid) PeV
- red = Conventional + global hardening
- blue = Tuned to γ-ray observations (Fermi-LAT, HESS, & Milagro)

Gaggero et al 2015
arXiv:1504.00227

Large Uncertainty in Inner Galaxy

Fermi Pion-decay profile in **red**





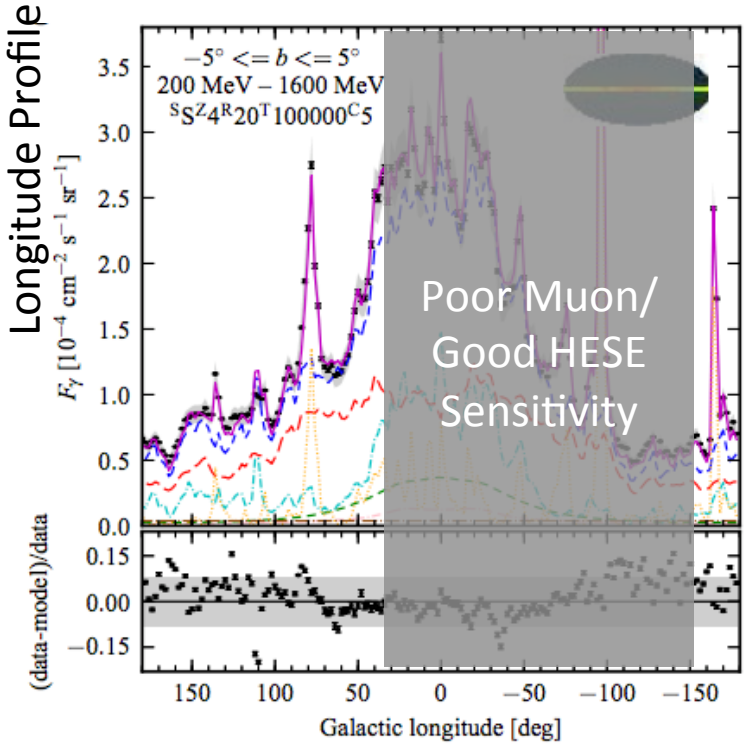
Large uncertainty in flux from inner galaxy!

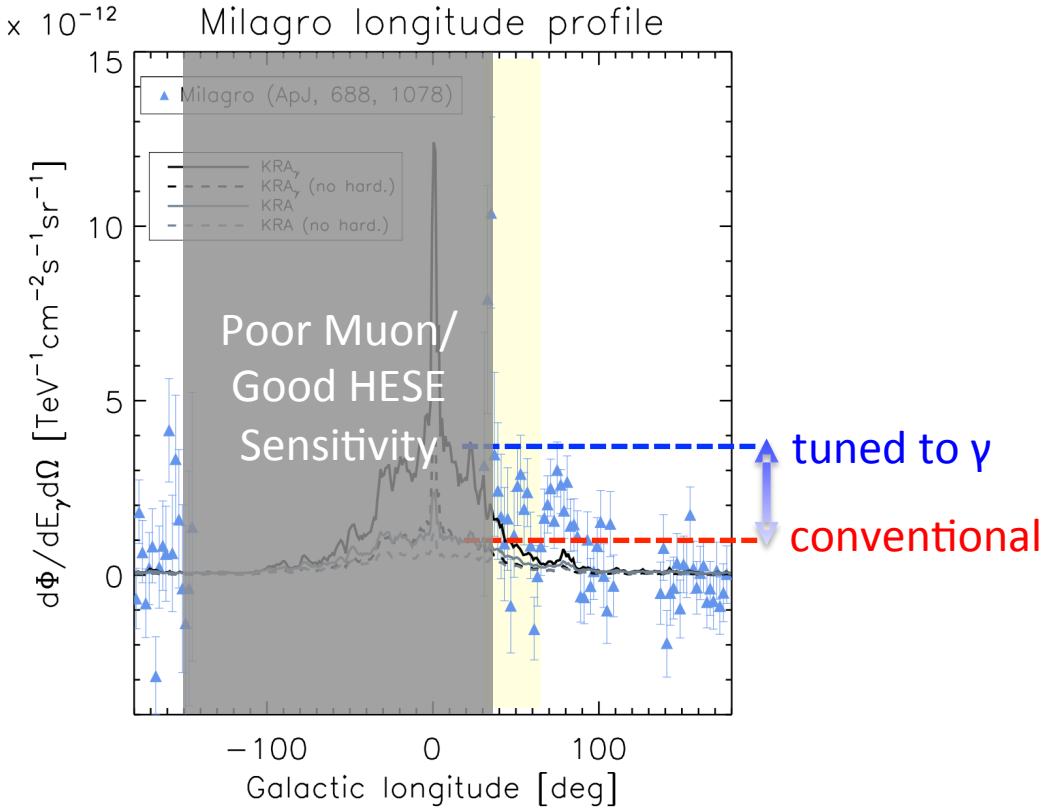
M. Ackermann et al 2011
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Gaggero et al 2015
1507.07796v1.pdf

Large Uncertainty in Inner Galaxy

Fermi Pion-decay profile in **red**



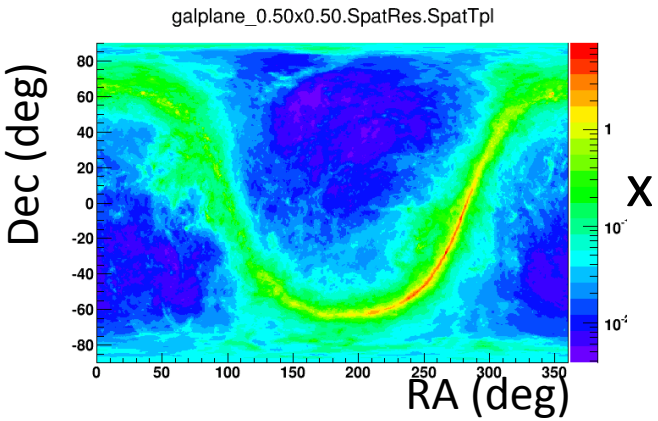


Large uncertainty in flux from inner galaxy!

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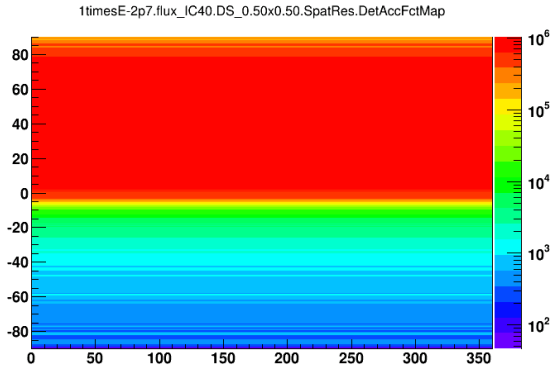
Gaggero et al 2015
1507.07796v1.pdf

Max LH Spatial Template



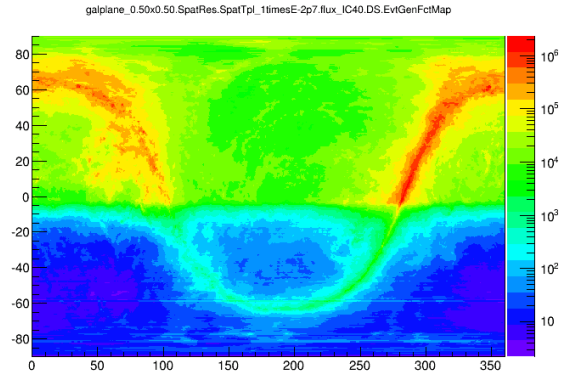
Gamma-ray Gal Plane π^0 Decay Map from *Fermi*-LAT

x



IceCube Acceptance (IC40 PS sample, $E^{-2.7}$)

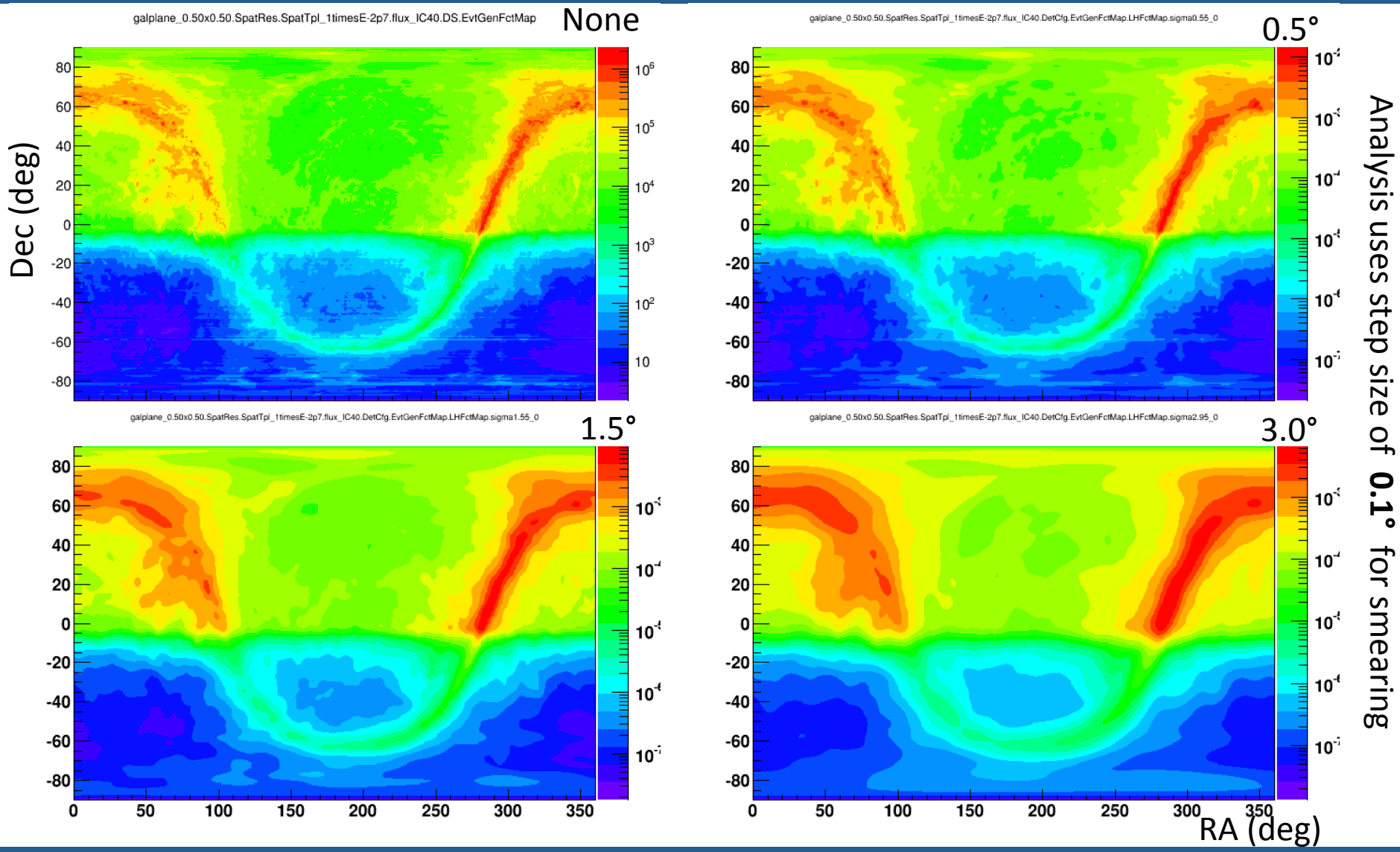
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Where we should see neutrinos originate before PSF smearing

- One more step (see next slide): convolve with event-wise PSF

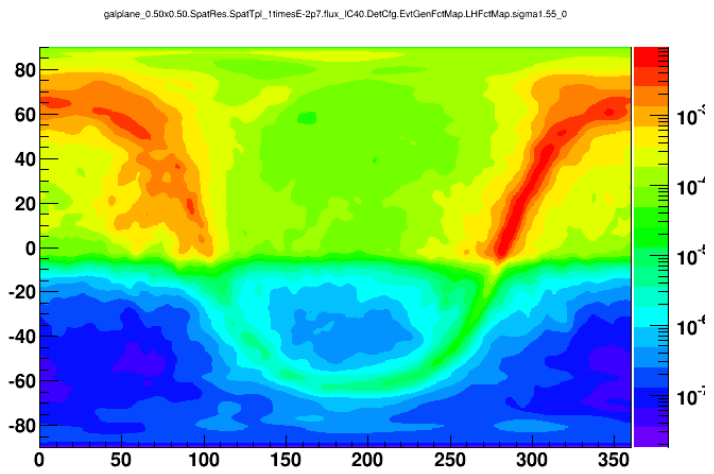
Convolutions – PSF Smearing



Galactic Plane Search

- Max Likelihood **Spatial Template** Analysis

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



pion-decay map + detector acceptance

Galactic Plane Search

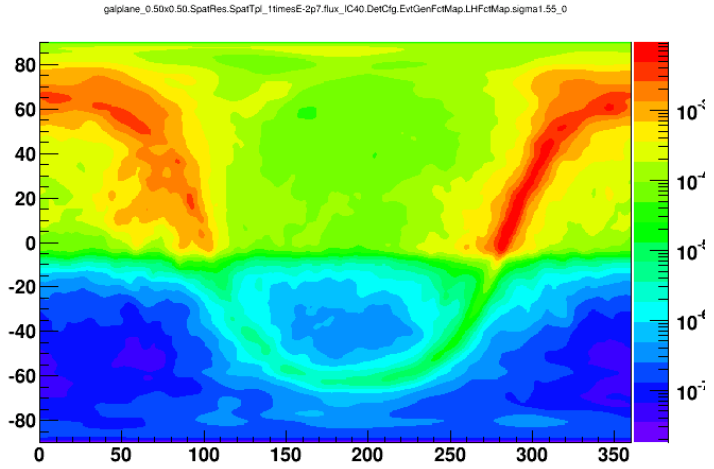
- Max Likelihood **Spatial Template** Analysis

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

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

Data

Signal
Scrambled in RA



pion-decay map + detector acceptance

Galactic Plane Search

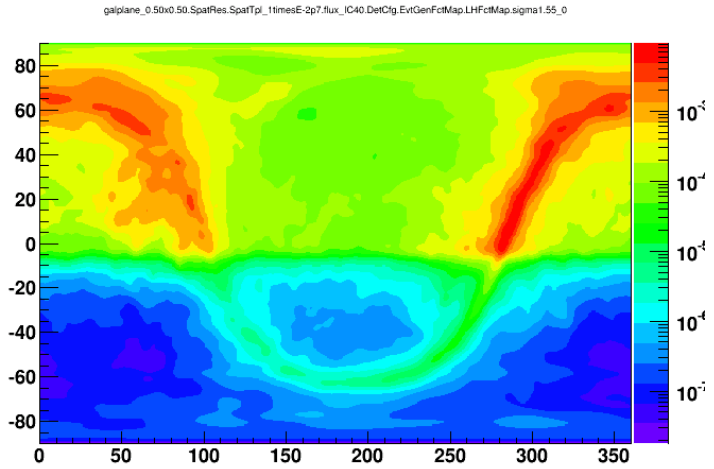
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Signal
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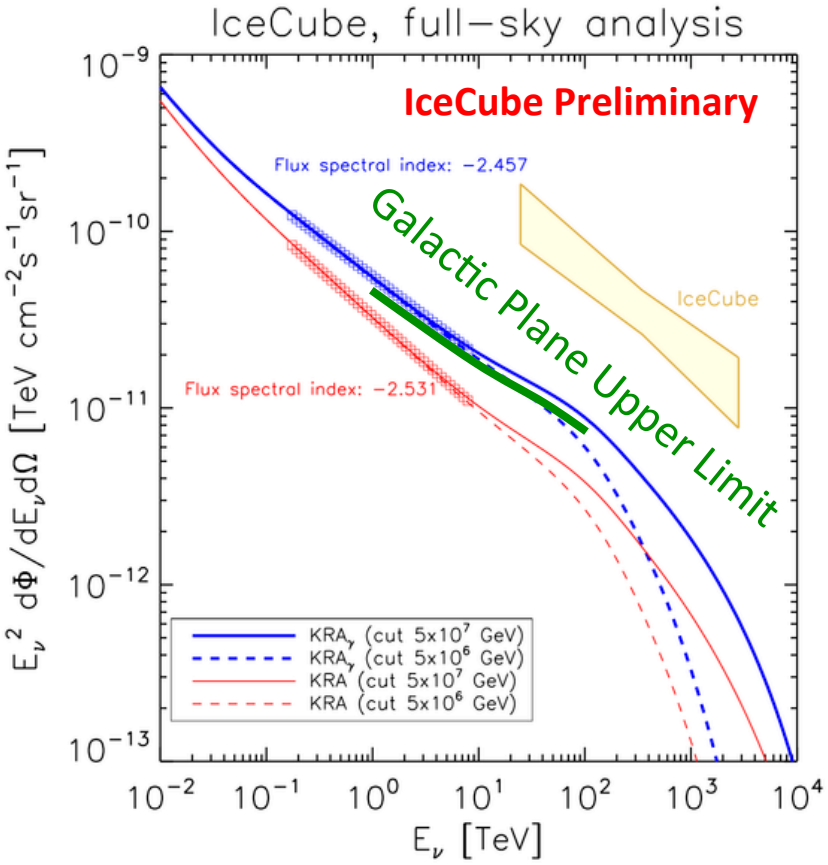


pion-decay map + detector acceptance

- 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 (preliminary)
  - 90% CL **Upper Limit = 11%** of observed diffuse flux*

* Assuming power-law extrapolation to lower energy

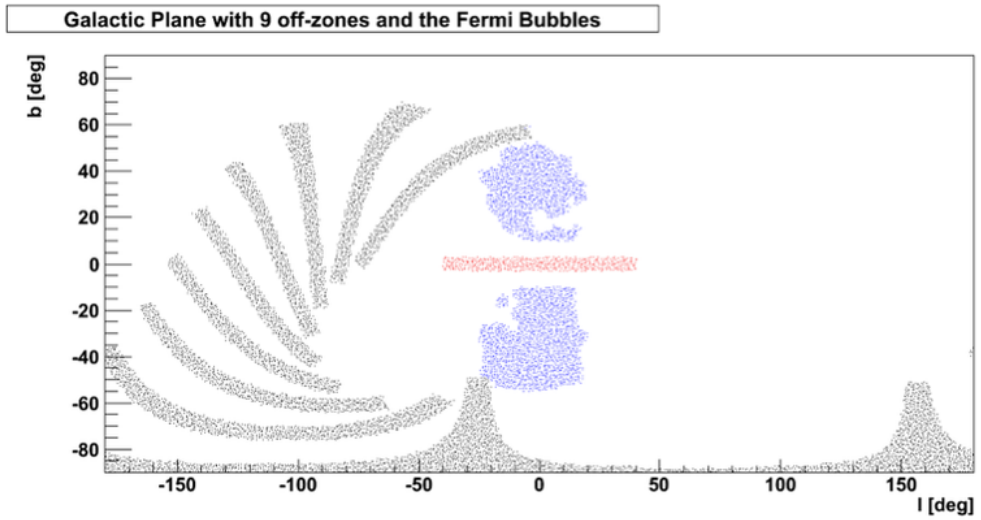
IceCube/ANTARES limits

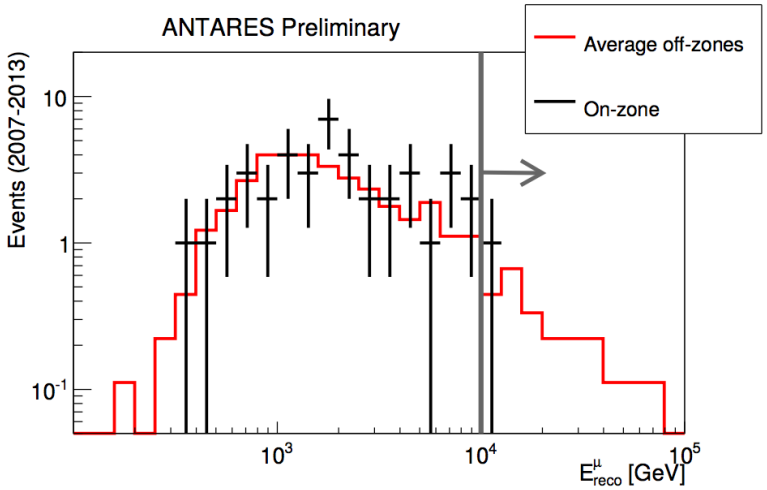


Gaggero et al 2015
arXiv:1504.00227

- Upper limit bites into the KRA-γ model space: **85%** of the most optimistic prediction (Preliminary)
- IceCube results constraining cosmic ray propagation models in the galaxy!

ANTARES Results

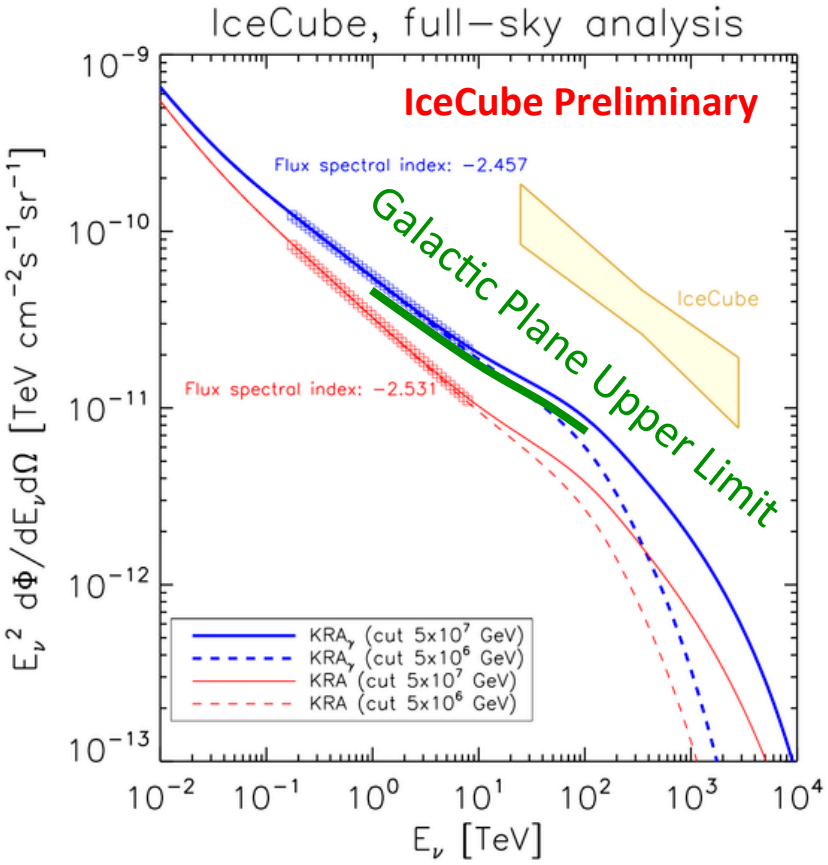


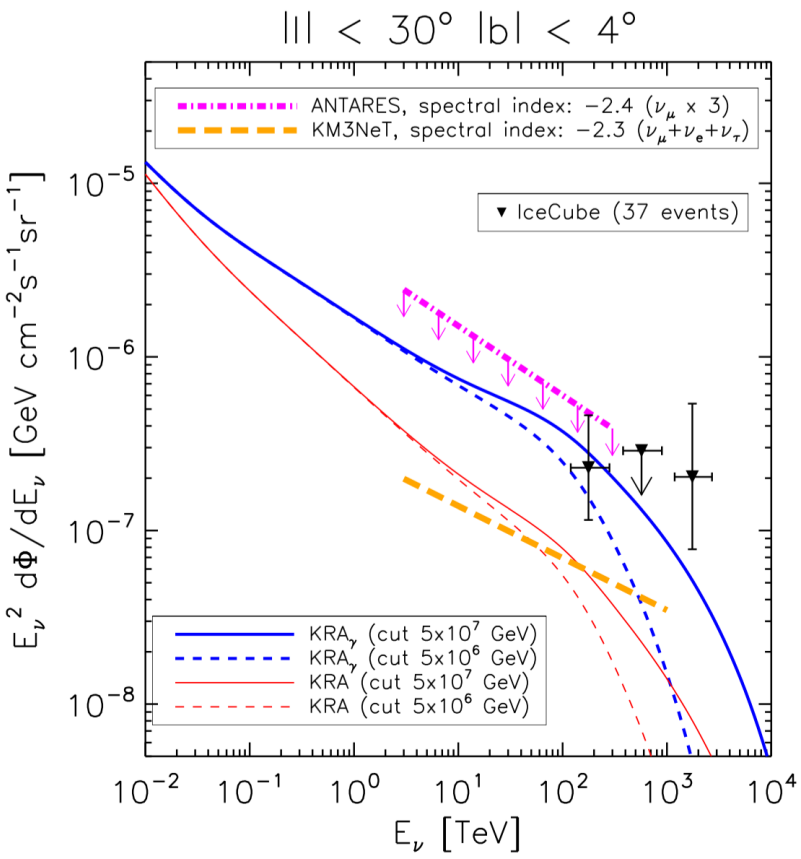


- 1 event observed on a background expectation of 2.5 events

ANTARES upper limits to same model
Fusco et al 2015, VLVNT proceedings

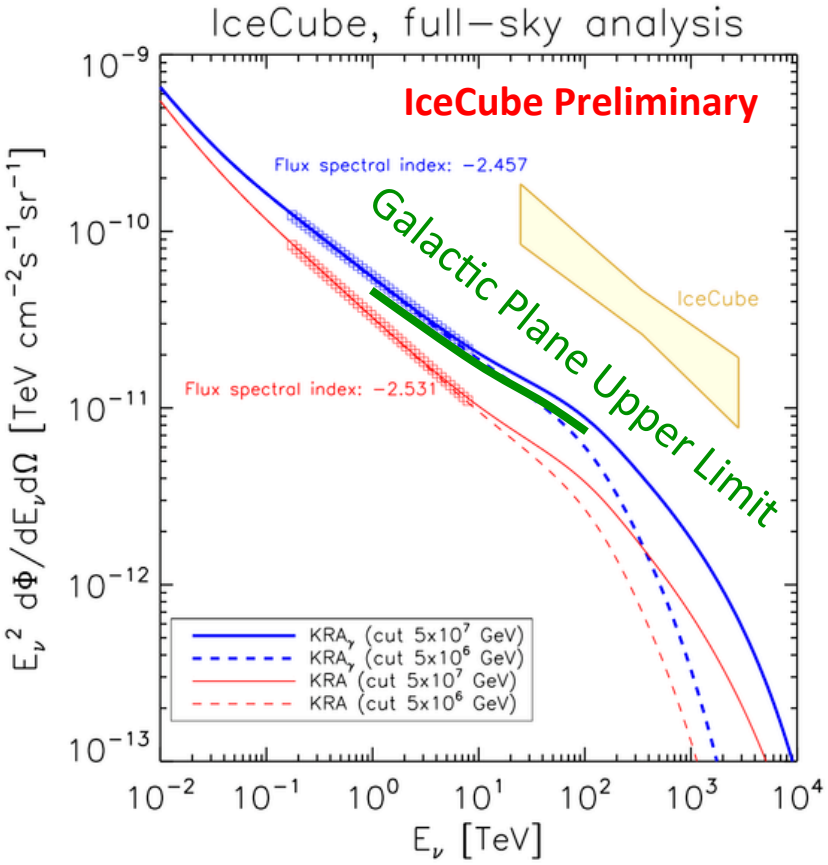
IceCube/ANTARES limits

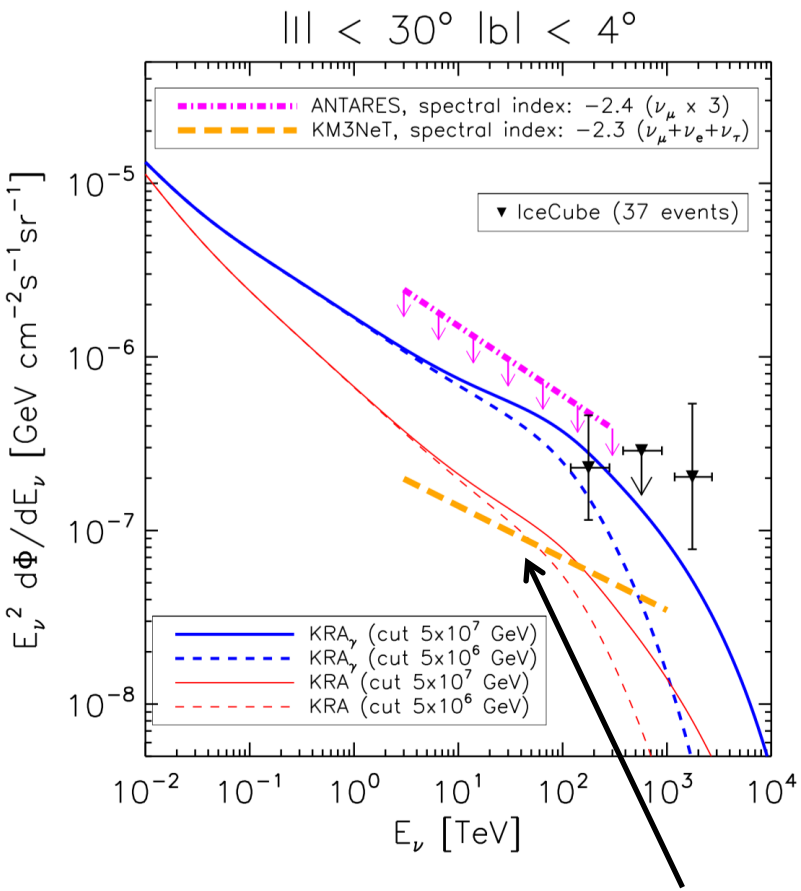




Gaggero et al 2015
arXiv:1504.00227

IceCube/ANTARES limits



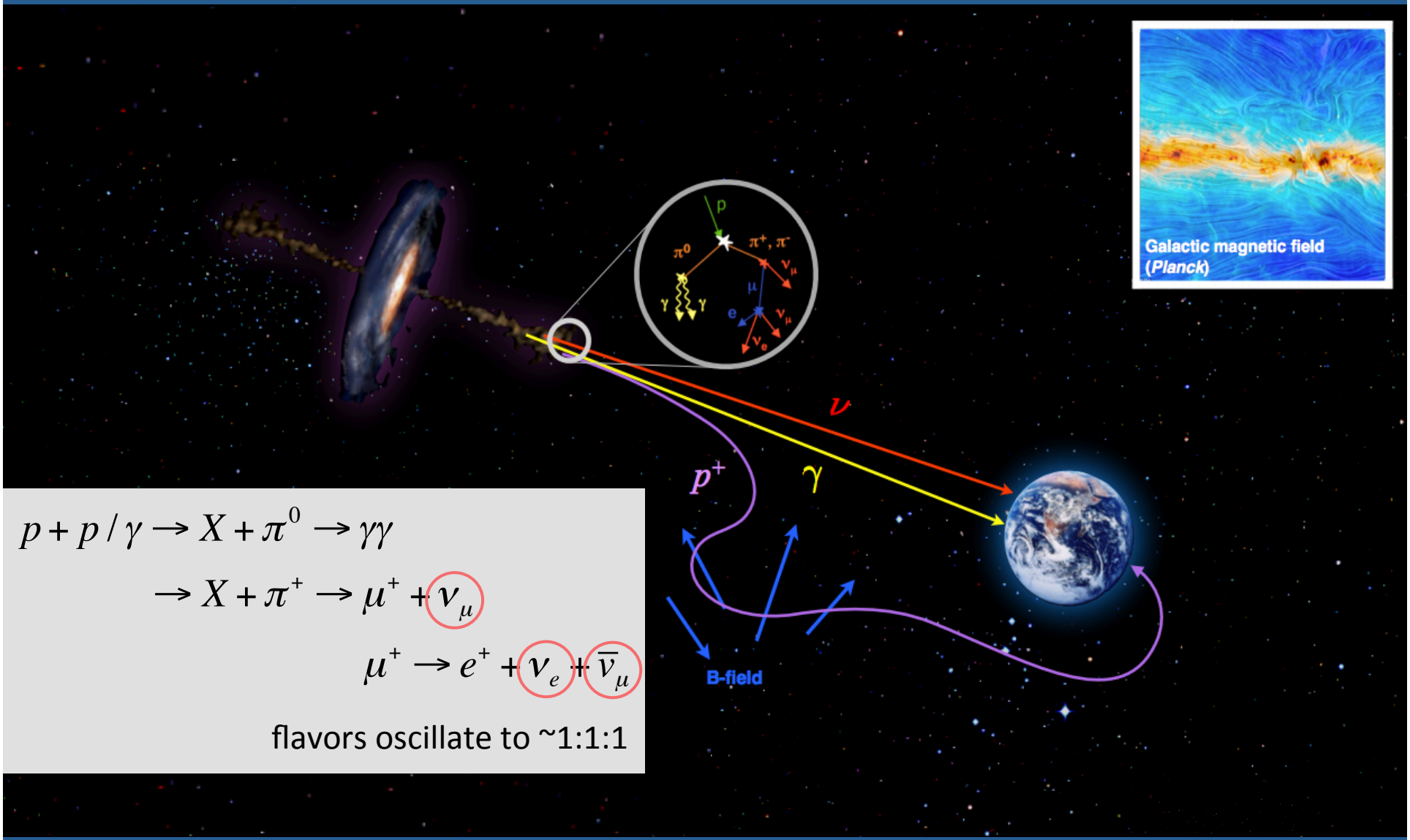


Gaggero et al 2015
arXiv:1504.00227

Nearly guaranteed detection with KM3NeT after 4 years!

Joint analysis with cascades and KM3NeT very promising

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

Starburst Scenario



Starburst Scenario

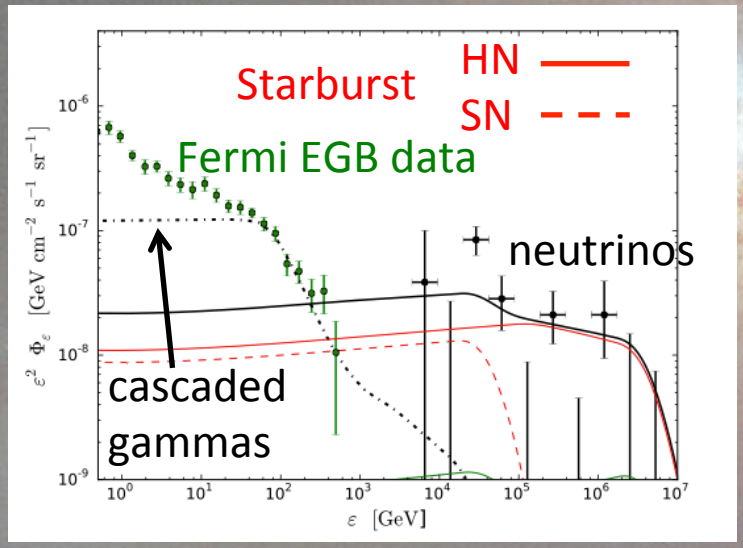
- Candidate: Starburst galaxies
  - High star formation rates -> Lots of supernovae -> Lots of cosmic ray acceleration
  - Lots of target material (high interstellar gas density)
  - Both factors lead to efficient neutrino production through pp interactions and subsequent pion decay

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)!



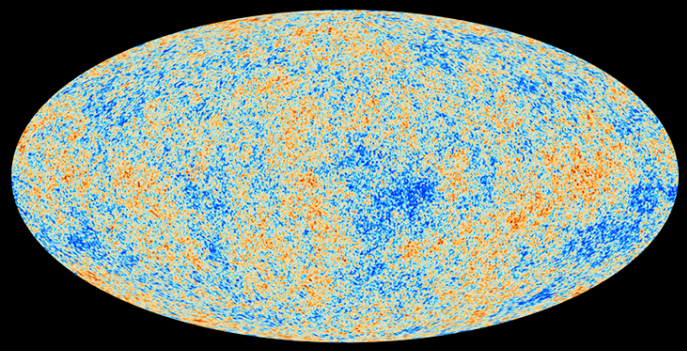


Cascaded Emission Important



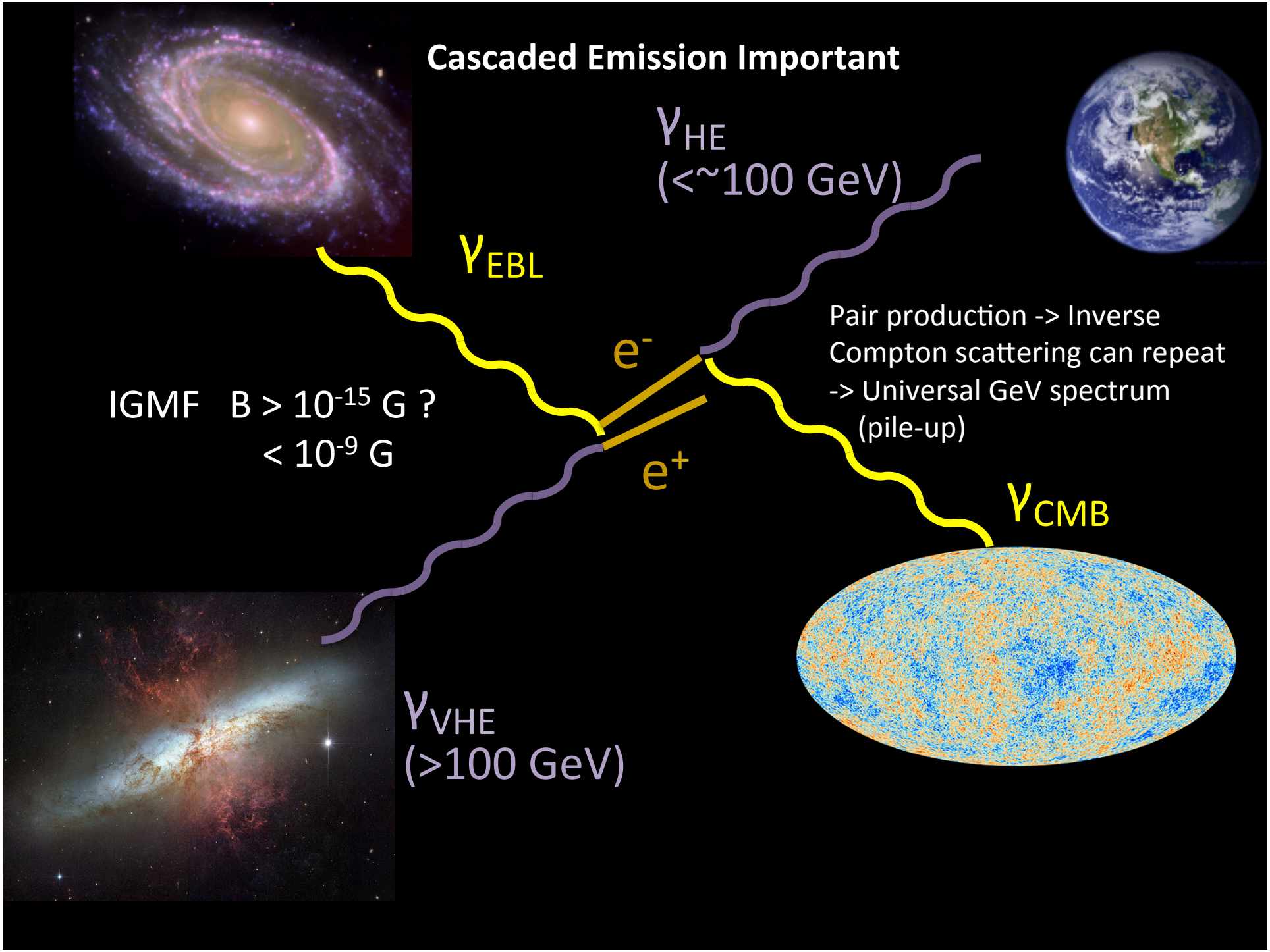
γ_{EBL}

γ_{CMB}





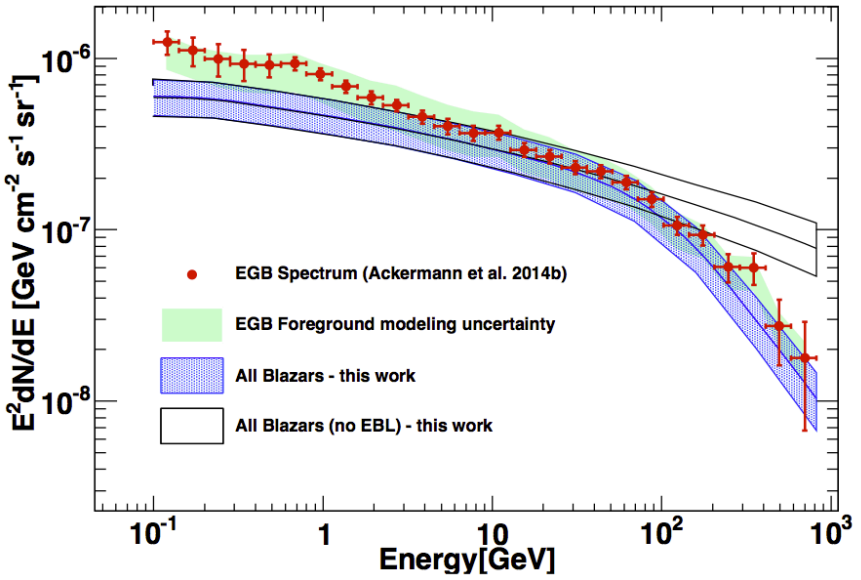
γ_{VHE}
(>100 GeV)


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)

Cascaded Emission Important

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

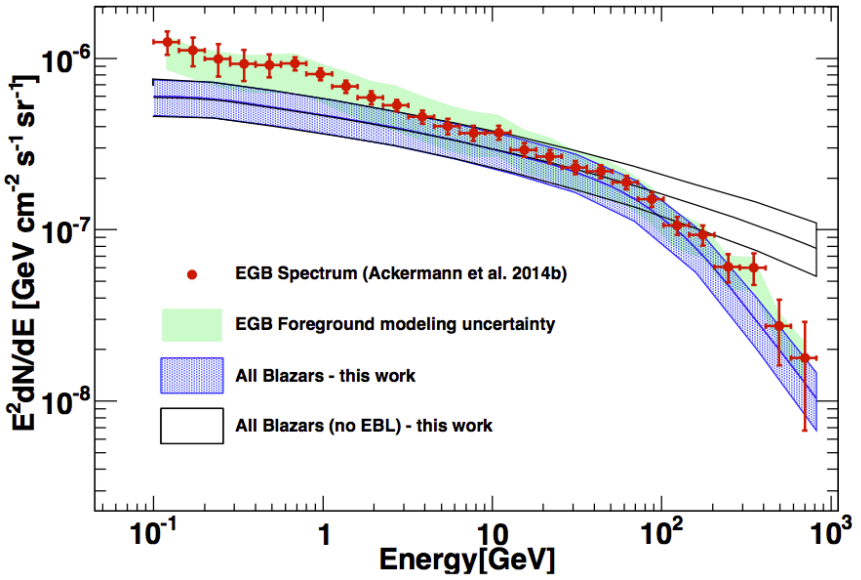
- Another publication already makes the claim that nearly all the >100 GeV EGB is from blazars
  - Detailed prediction of gamma rays, integrating over all blazars

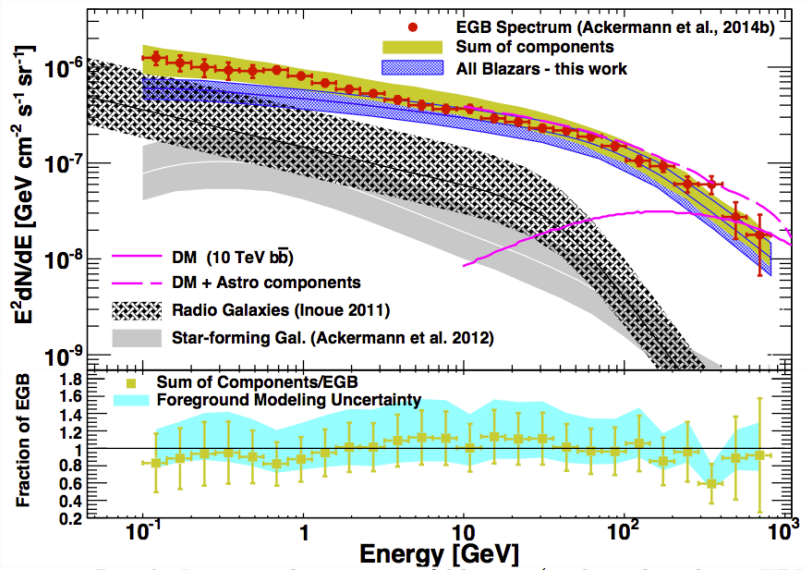


Cascaded Emission Important

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

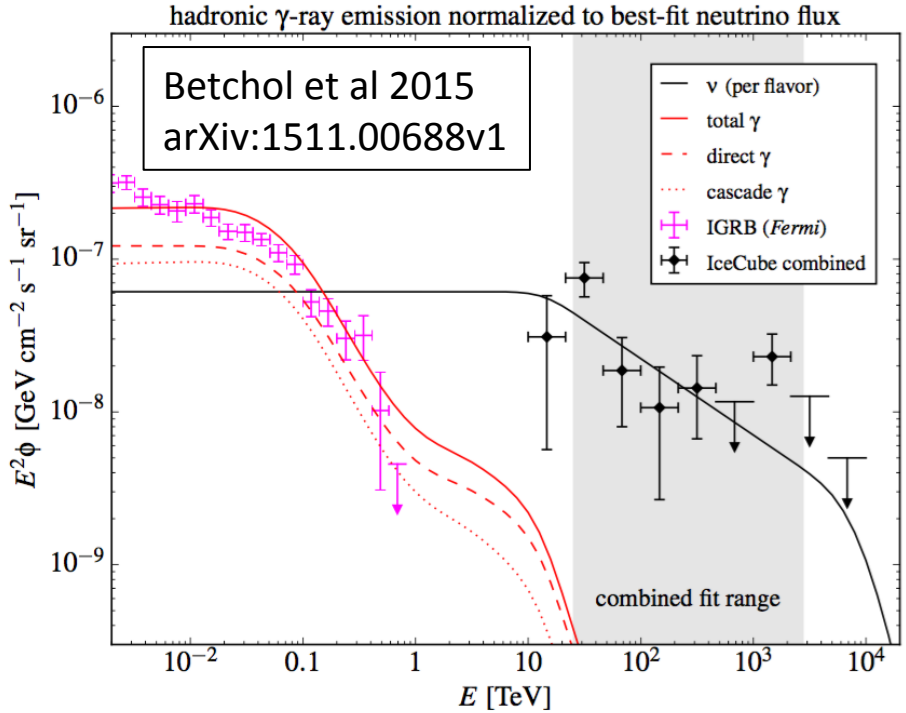
- Another publication already makes the claim that nearly all the >100 GeV EGB is from blazars
  - Detailed prediction of gamma rays, integrating over all blazars
  - Enough confidence to set competitive limits on the Dark Matter annihilation cross section





Cascaded Emission Important

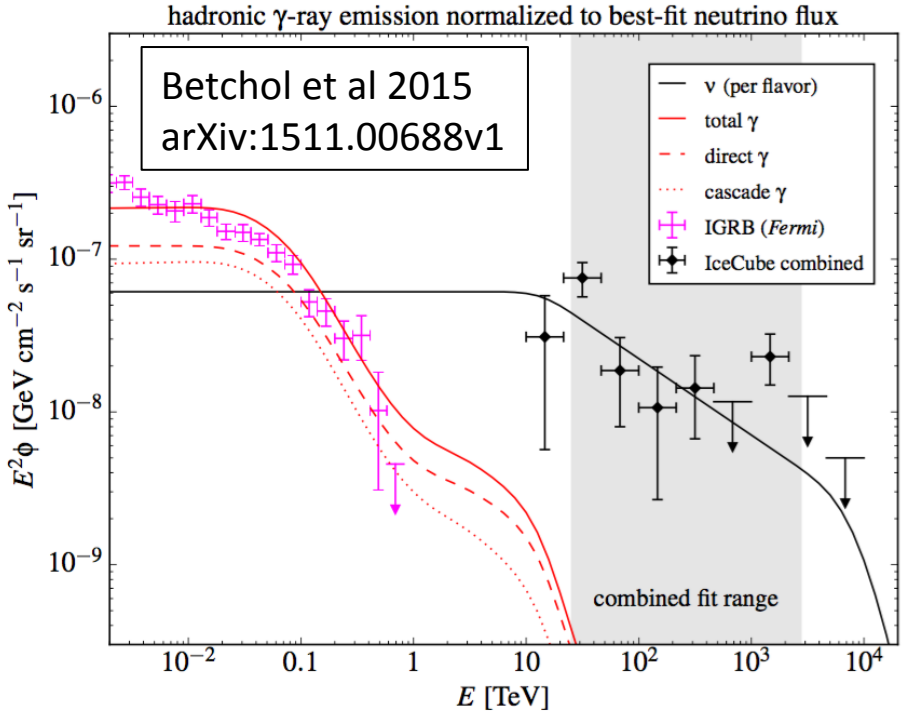
- How much flux can come from starburst galaxies without overproducing GeV gammas?



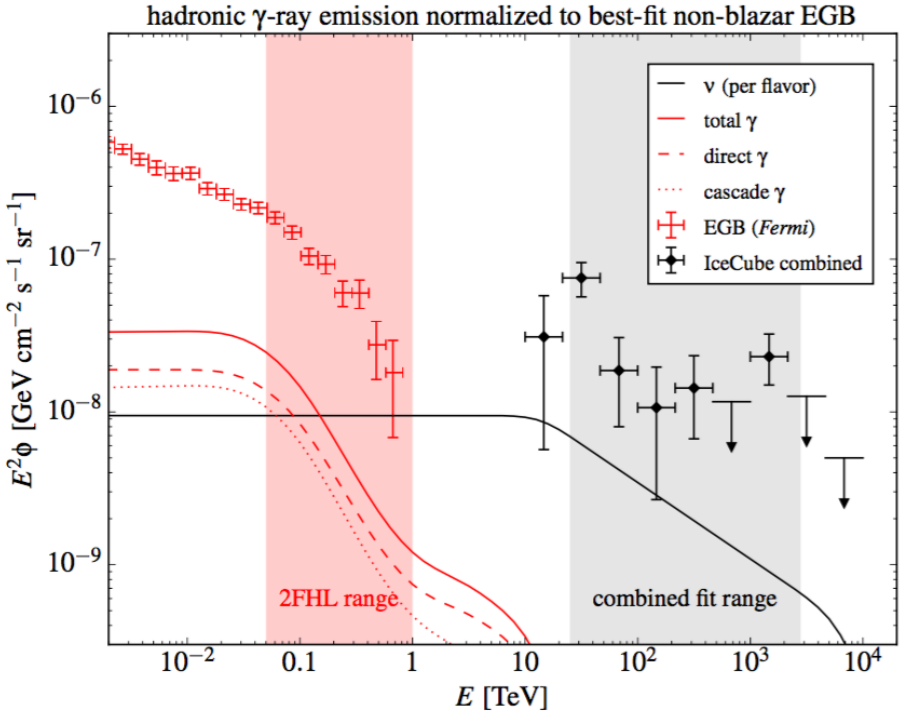
Without blazar contributions taken into account

Cascaded Emission Important

- How much flux can come from starburst galaxies without overproducing GeV gammas?



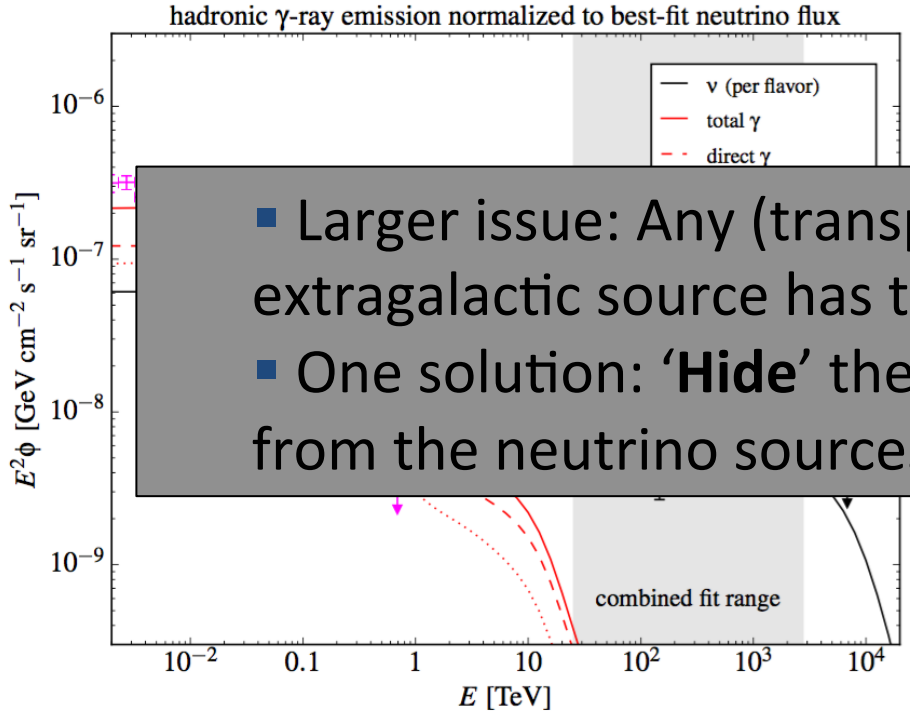
Without blazar contributions taken into account



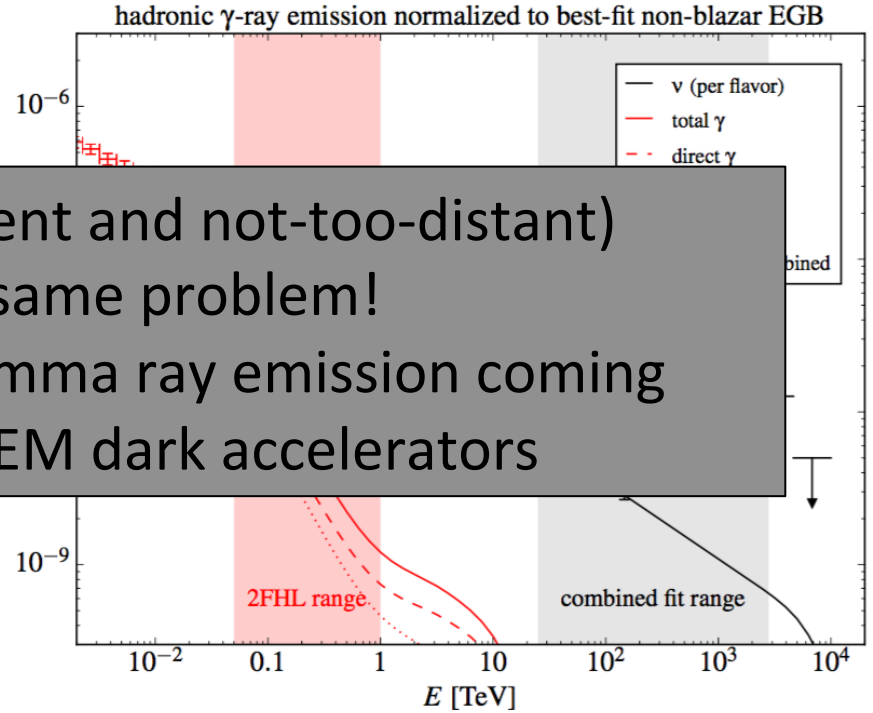
With blazar contributions yielding all but 14% of the EGB

Cascaded Emission Important

- How much flux can come from starburst galaxies without overproducing GeV gammas?



Without blazar contributions taken into account

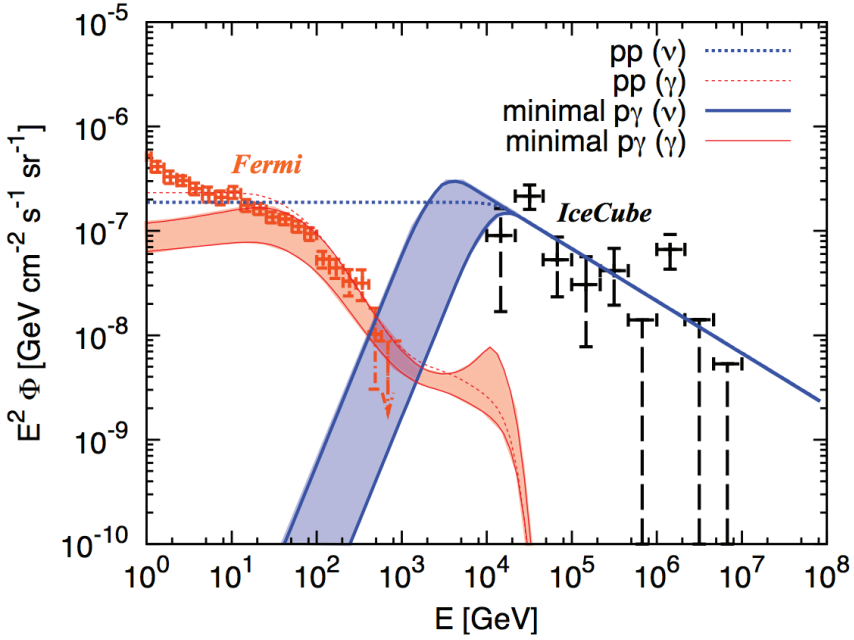


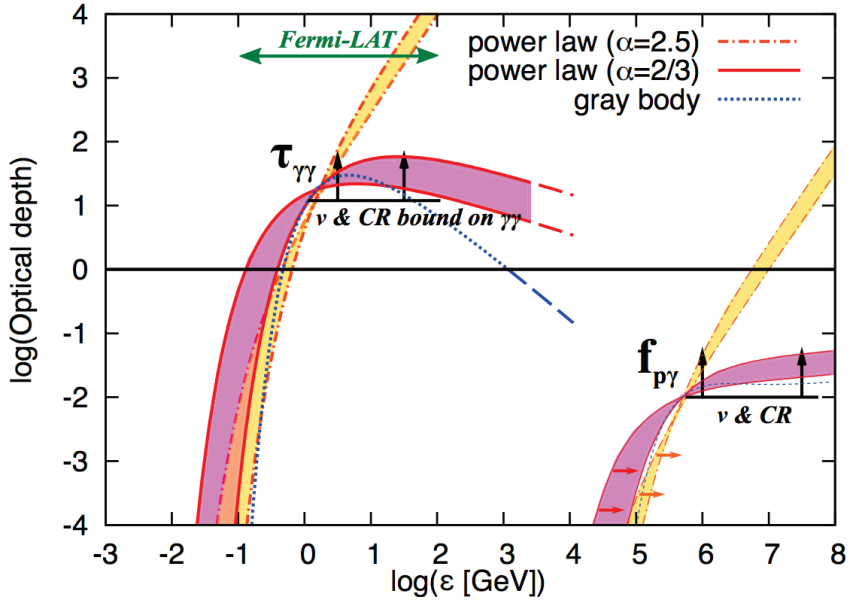
With blazar contributions yielding all but 14% of the EGB

- Larger issue: Any (transparent and not-too-distant) extragalactic source has the same problem!
- One solution: '**Hide**' the gamma ray emission coming from the neutrino sources – EM dark accelerators

Cascaded Emission Important

- Choked GRBs, Low luminosity GRBs, Cores of AGNS, ...
  - pγ scenarios can turn on the flux above E_{thresh}
  - high π production implies strong γγ absorption within source



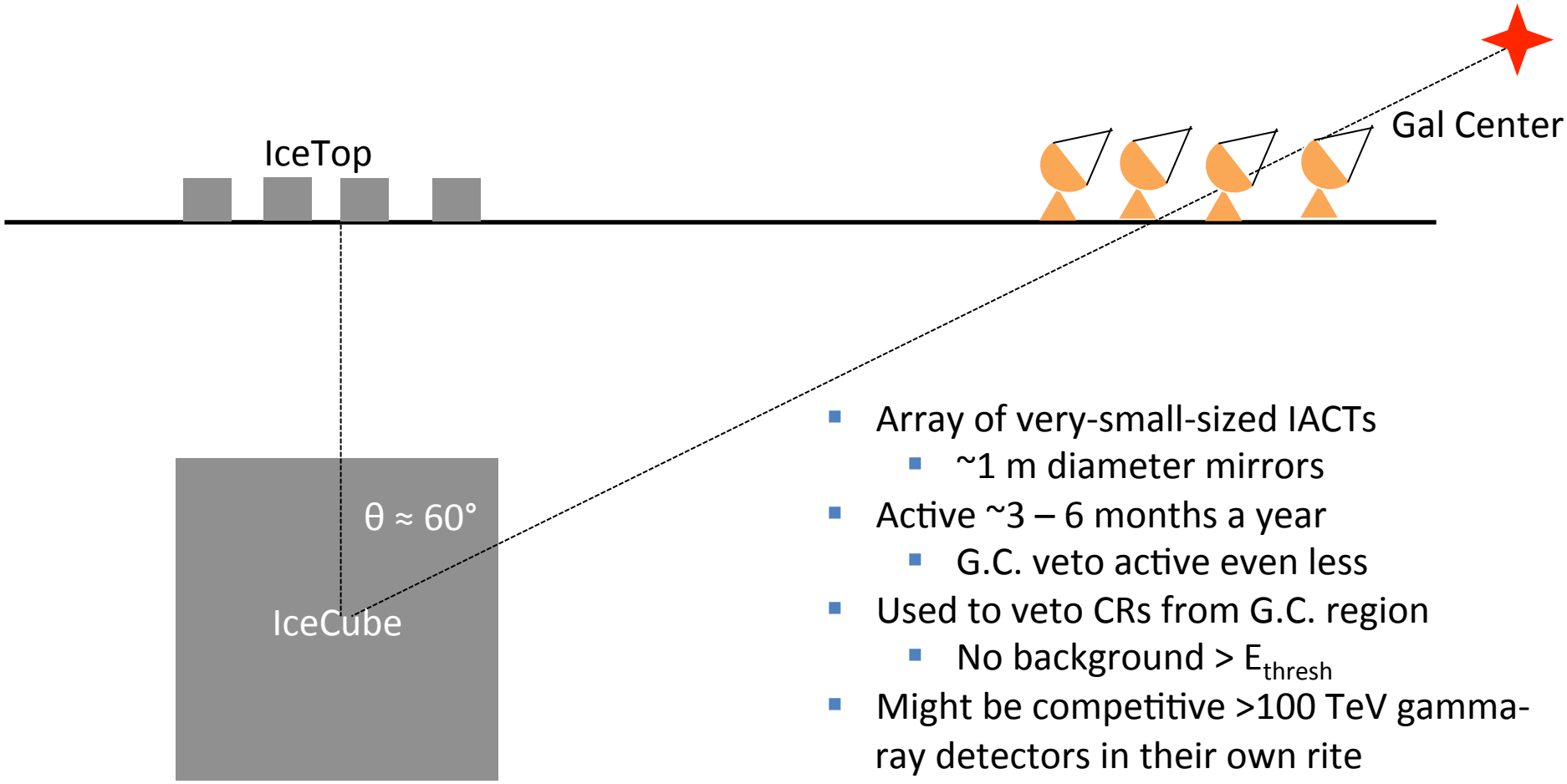


- Absorption features might be detectable
- Also motivates looking in MeV, X-ray, optical, radio...

My Bet

- With additional years of HESE data:
  - New >100 TeV cascades associated with the galactic center
    - Between 3 and 4 sigma evidence of source
  - **Triggers race** to build KM3NeT and IceCube surface veto targeting the galactic center

My Bet

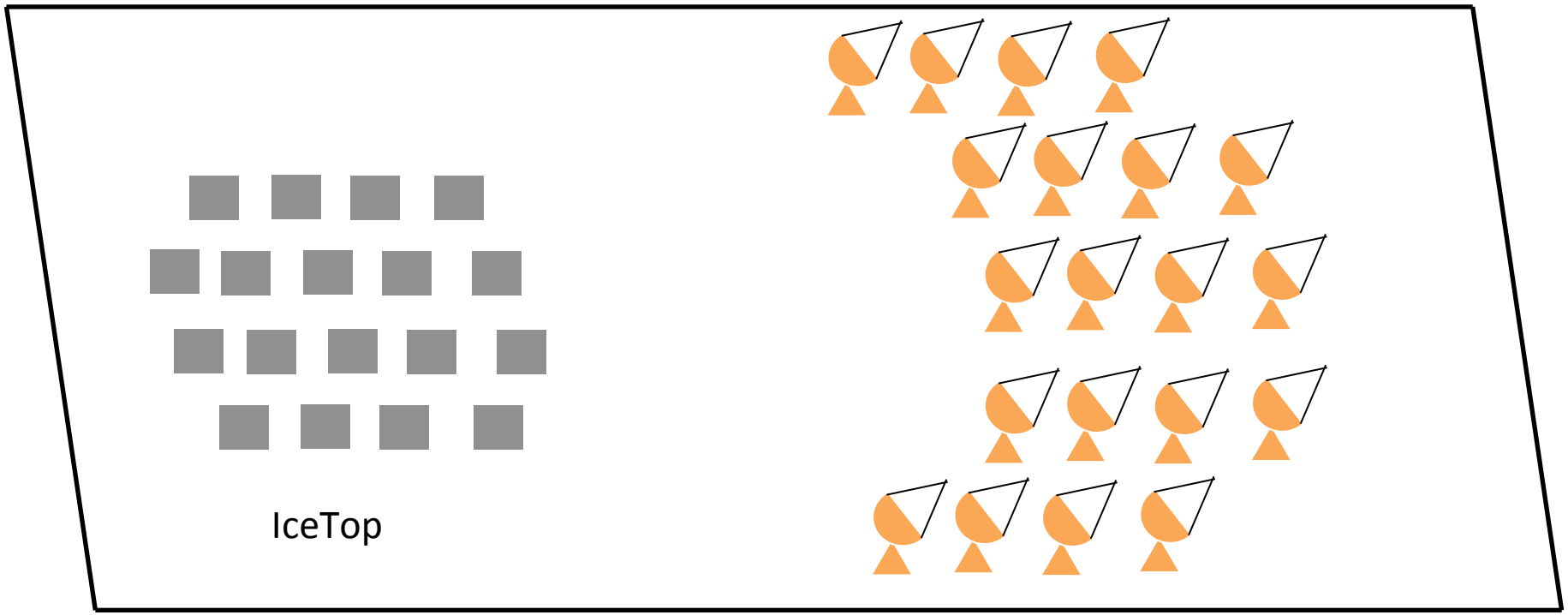


- Array of very-small-sized IACTs
  - ~1 m diameter mirrors
- Active ~3 – 6 months a year
  - G.C. veto active even less
- Used to veto CRs from G.C. region
  - No background > E_{thresh}
- Might be competitive >100 TeV gamma-ray detectors in their own rite

My Bet



Gal Center



My Bet

- With additional years of HESE data:
  - New >100 TeV cascades associated with the galactic center
    - Between 3 and 4 sigma evidence of source
  - **Triggers race** to build KM3NeT and IceCube surface veto targeting the galactic center
  - G.C. discovered as first point-like source
    - Unclear if PS or extended halo
    - Gives estimate of local photon attenuation near accretion disk and circumvents problems with GeV overproduction
    - Slowly, we associate extragalactic flux with supermassive black holes
- (Oh, and eventually we see the diffuse galactic emission tracking ISM in joint KM3NeT/IceCube analysis)

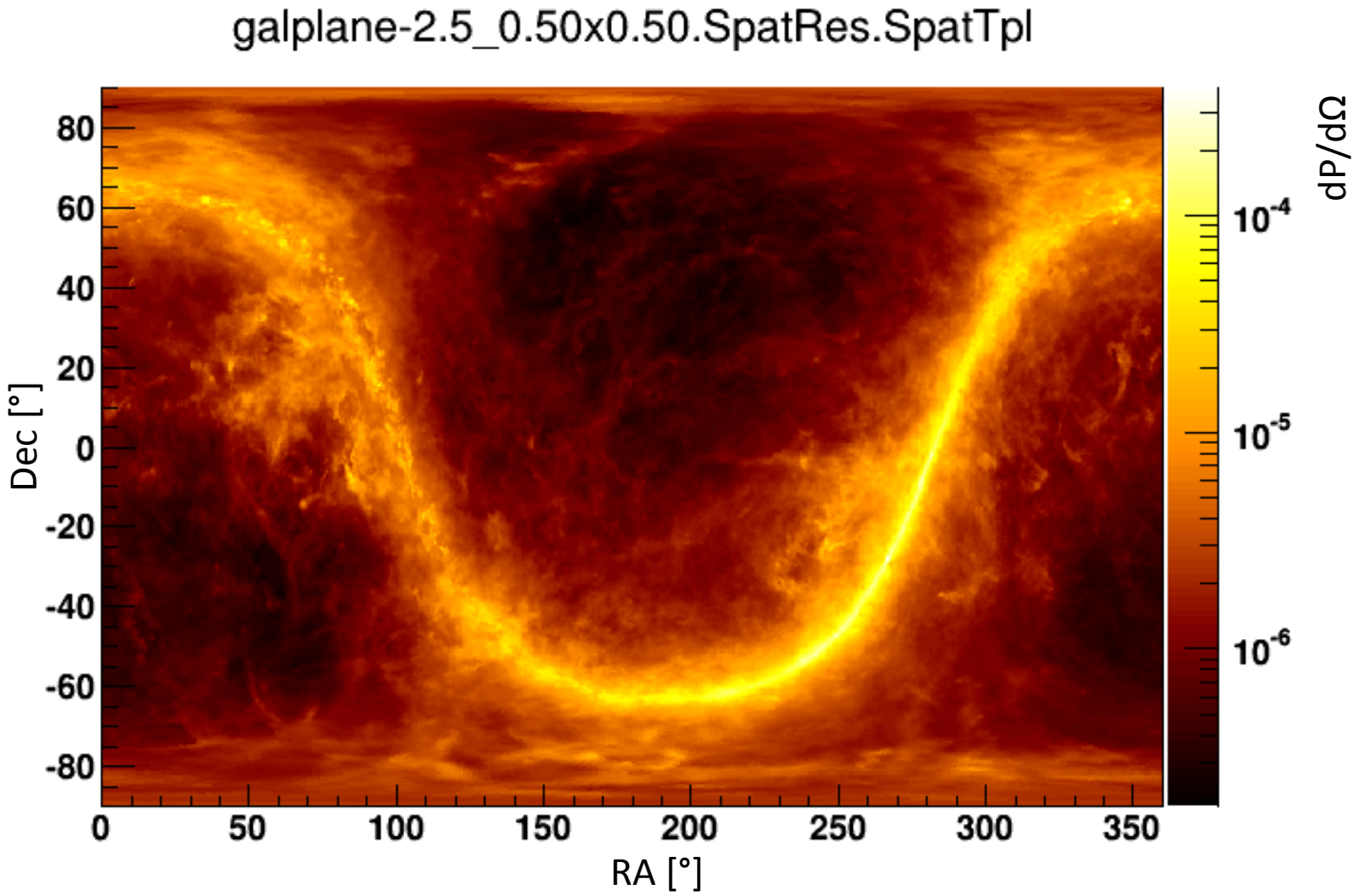
Conclusions

- Galactic Plane tested as neutrino origin
  - No excess observed, no more than 11% of diffuse flux tracking the expected diffuse gal plane emission
  - Room for 'hidden' flux in inner galaxy
  - Results constrain cosmic ray propagation beyond γ-ray observations alone

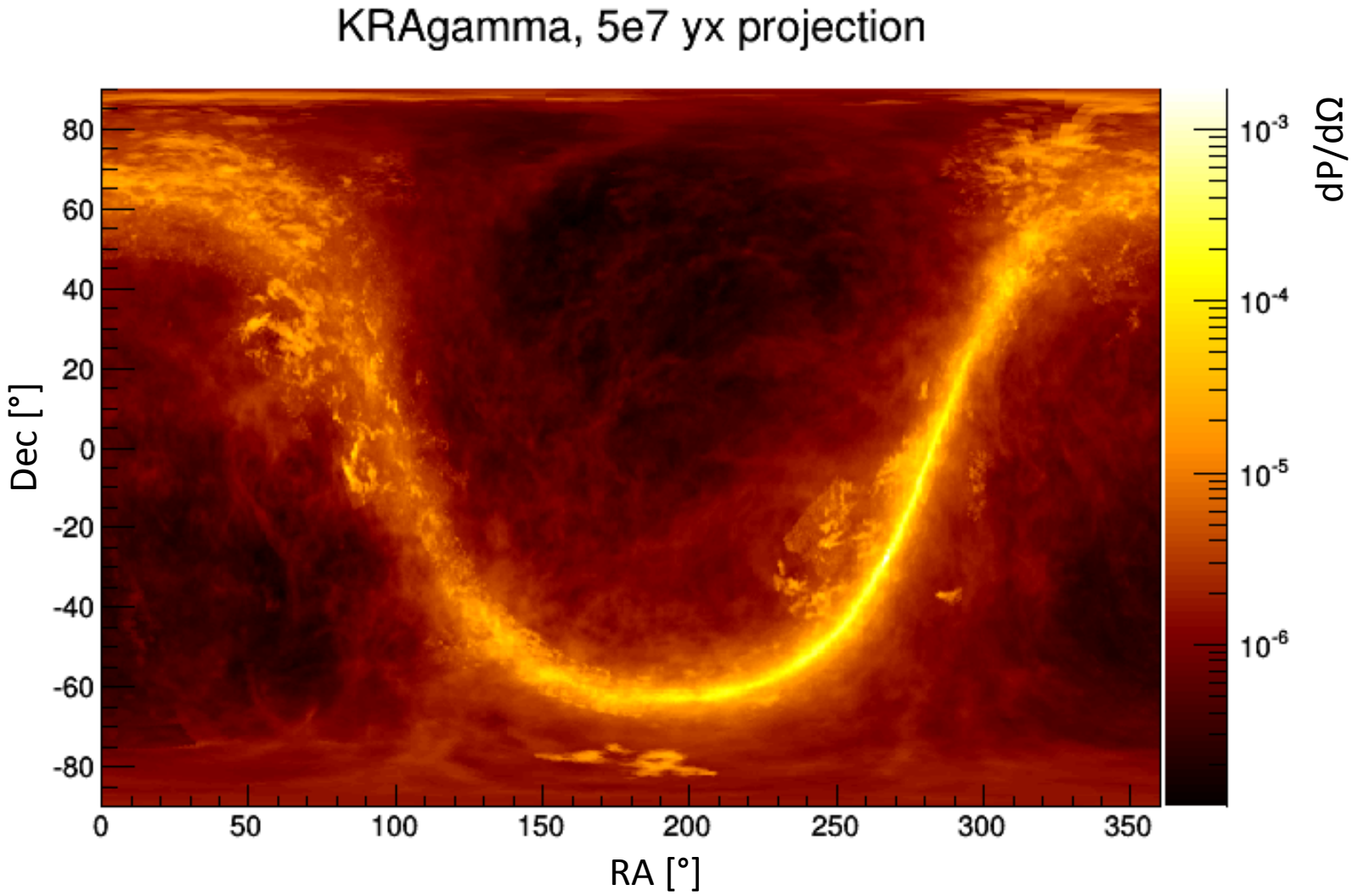
- The astrophysical neutrino puzzle is a tough nut to crack
  - Excluding certain source classes from dominating total flux
    - Likely a **mixed, rich field** of neutrino astronomy for IceCube-Gen2 and KM3NeT
  - The prospect of EM dark accelerators could make this a lonely journey but also implies neutrinos offer unique insight!

Backup

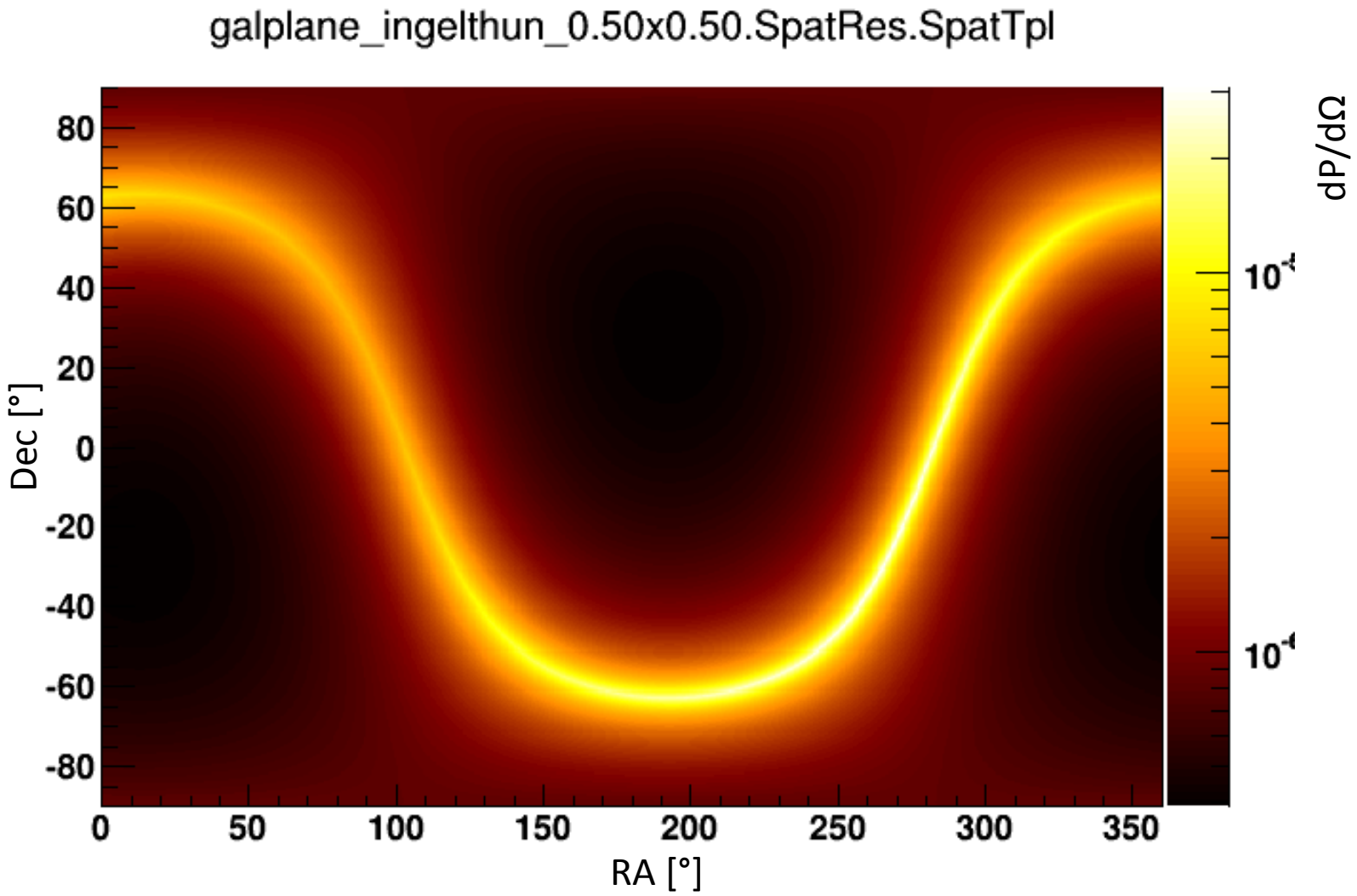
Fermi π^0 Decay Map



KRAγ

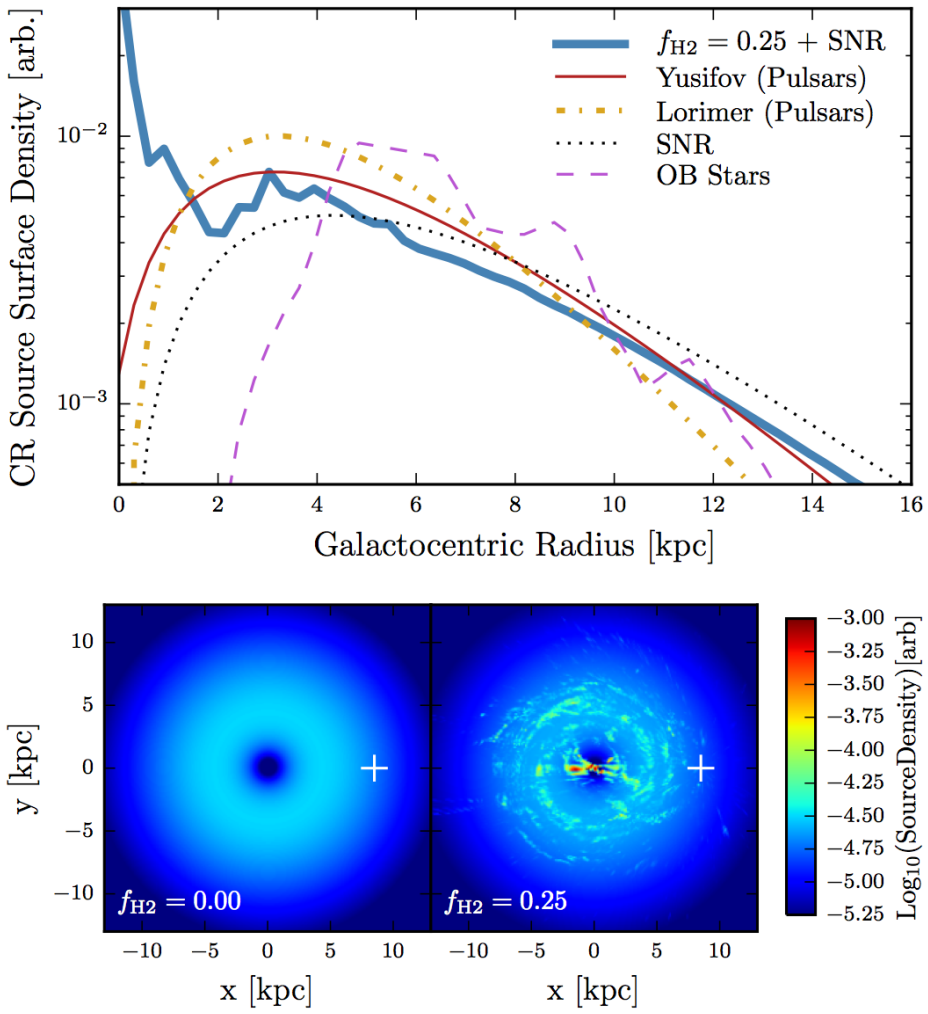

KRAgamma, 5e7 yx projection
Dec [°]
RA [°]
80
60
40
20
0
-20
-40
-60
-80
0
50
100
150
200
250
300
350
dP/dΩ
10^-3
10^-4
10^-5
10^-6

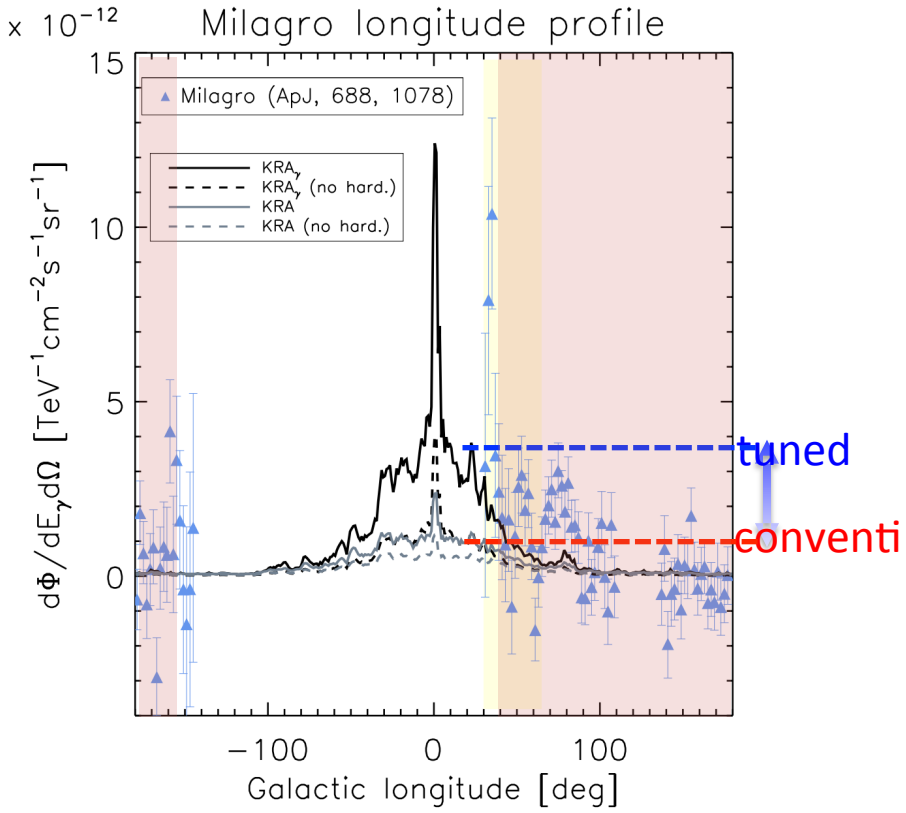
Ingelman & Thunman



GC CR Enhancement

Carlson, Profumo, Linden, 2015, arXiv:1510.04698v1



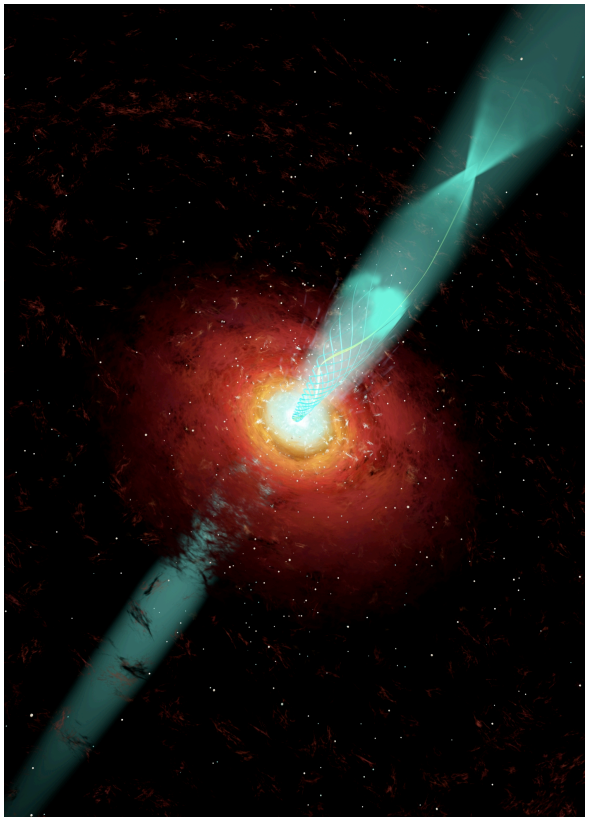


Large uncertainty in flux from inner galaxy!

Gaggero et al 2015
arXiv:1507.07796v1

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

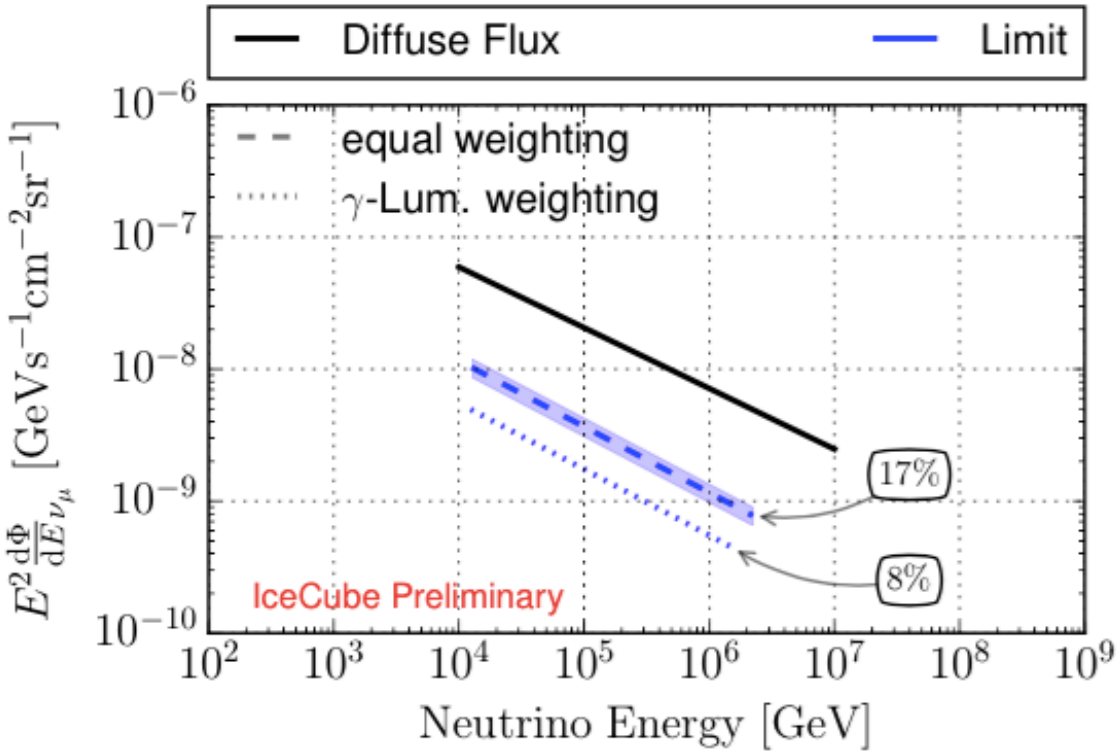


Ajello et al.
arXiv:1501.05301v1

Blazar Stacking

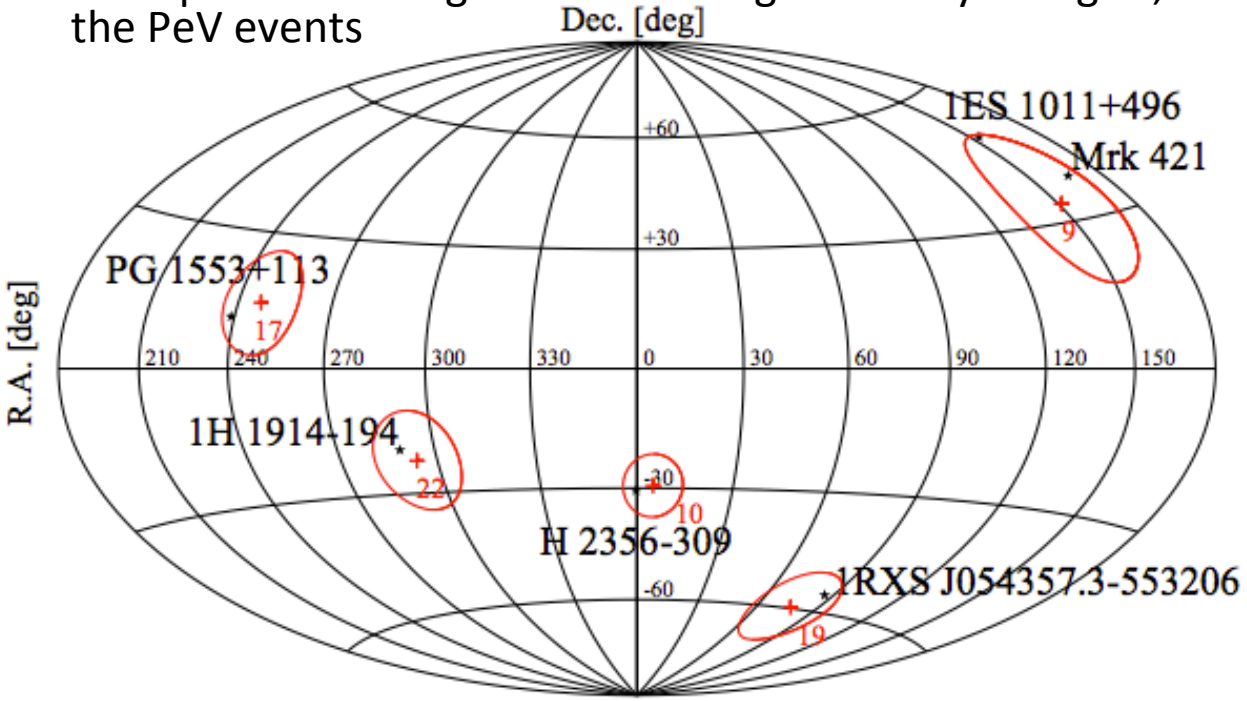
- We performed stacked searches for neutrinos from known blazars
  - Fermi-LAT 2FGL catalog of 862 blazars
- No significant excess observed in IceCube stacked search
- Total flux upper limit is well below measured diffuse neutrino flux
- Sub-categories of blazars all produce strong limits
  - FSRQs
  - 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



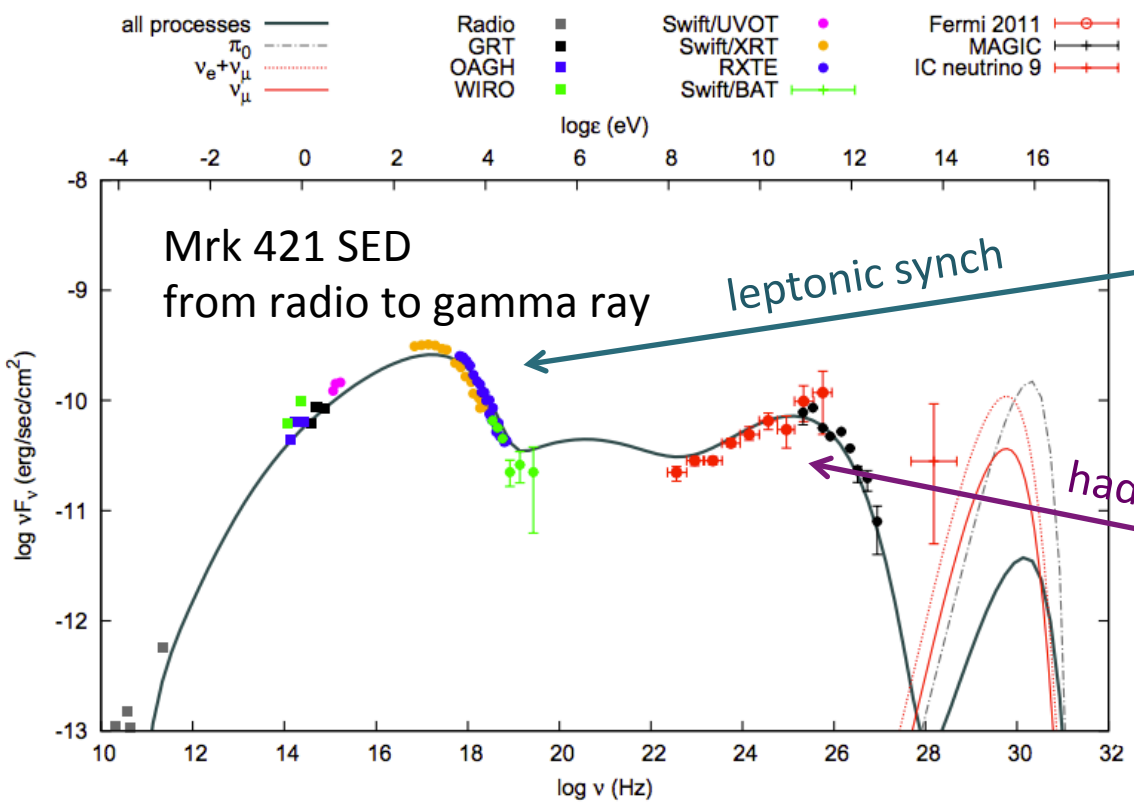
Associations of five HE starting neutrinos with HSP BL Lacs are suggestive but not significant

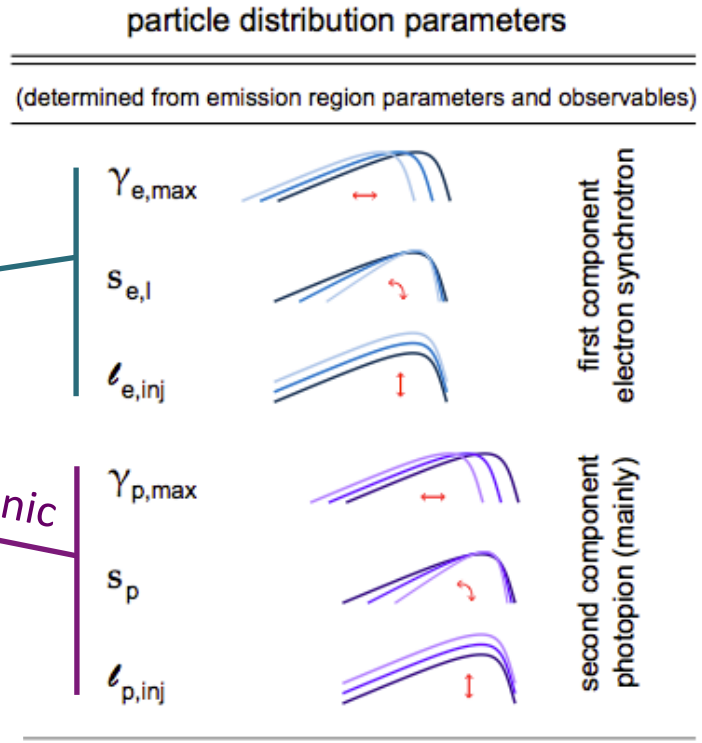
see also: Cerruti et al, 2015 arXiv:1411.5968v1

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

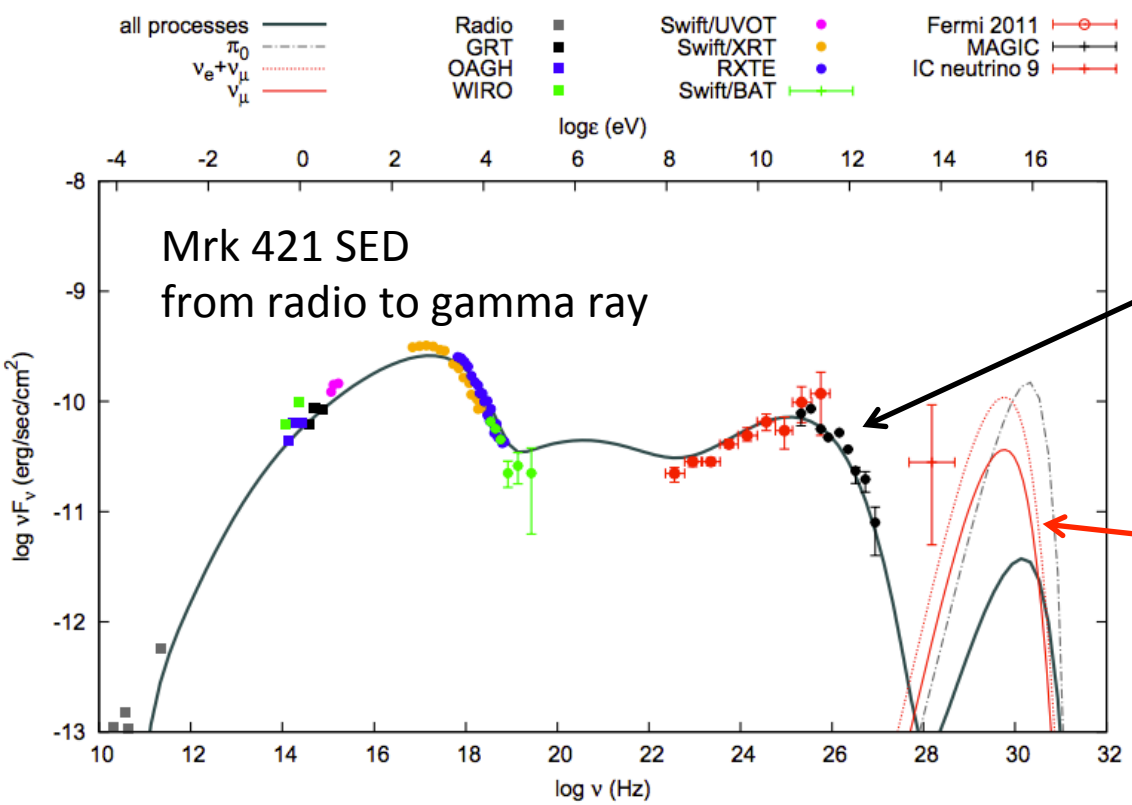




arXiv:1501.07115v1
Petropoulou et al., 2015

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

Correlated Variability in FSRQs

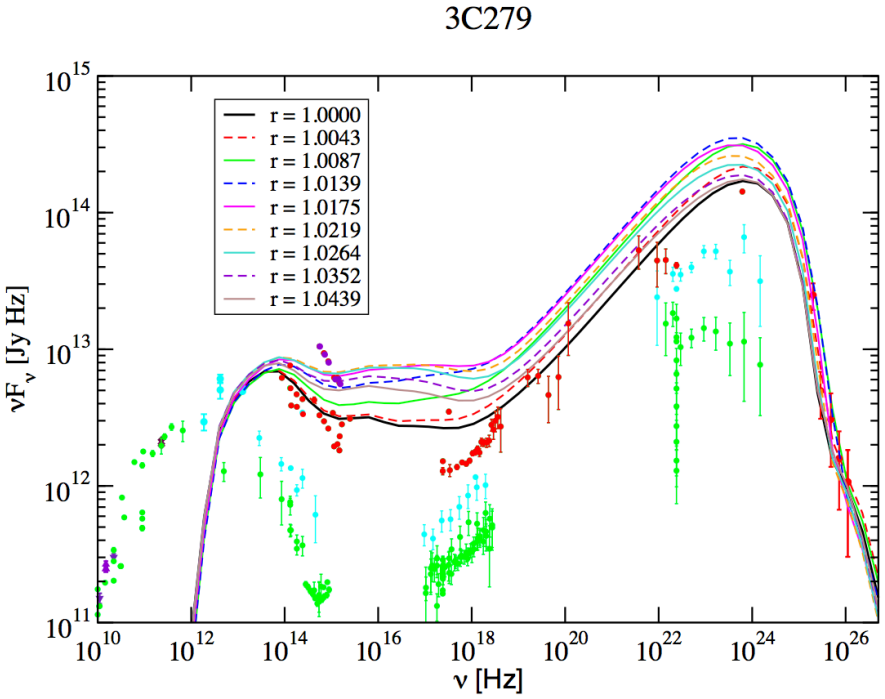
Time Dependent Hadronic Modeling of Flat Spectrum Radio Quasars.

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

arXiv:1502.03950v1

We know the extragalactic sky is **dynamic** as we enter new age of transient astronomy!

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



Correlated Variability in FSRQs

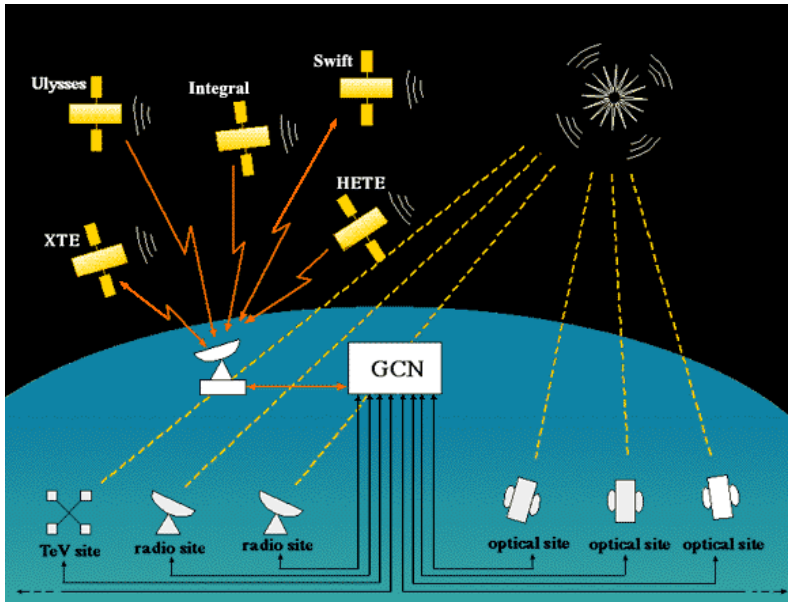
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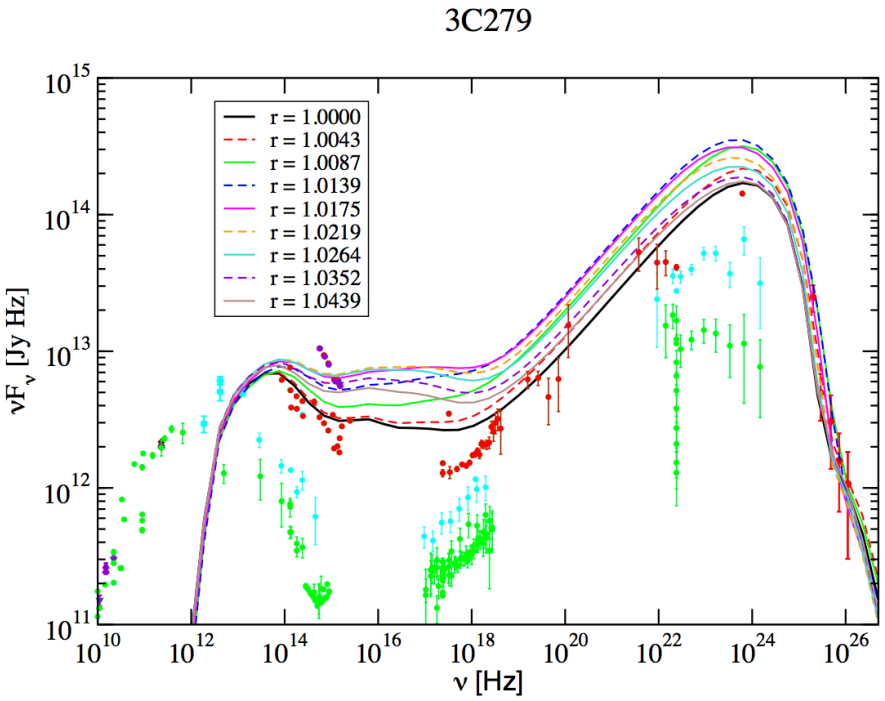
arXiv:1502.03950v1

We know the extragalactic sky is **dynamic** as we enter new age of transient astronomy!

New: 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

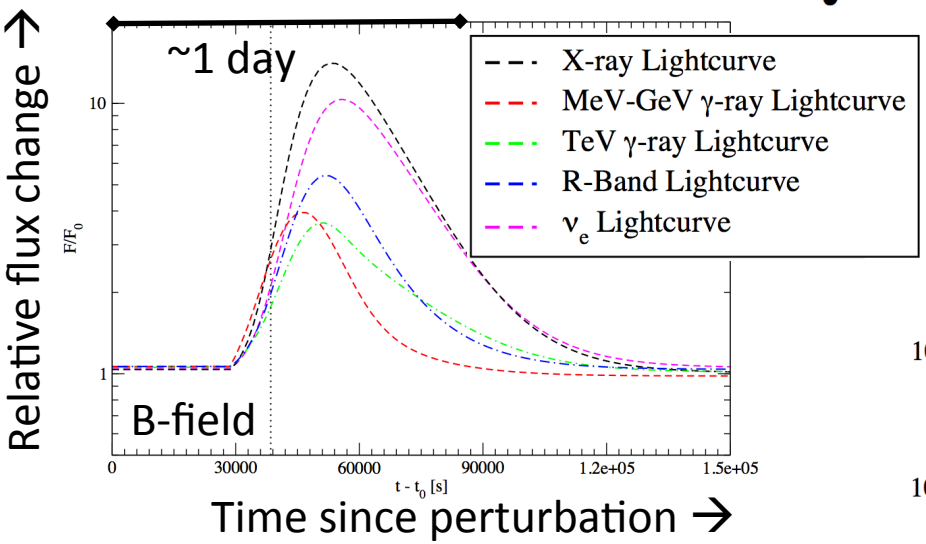


Correlated Variability in FSRQs

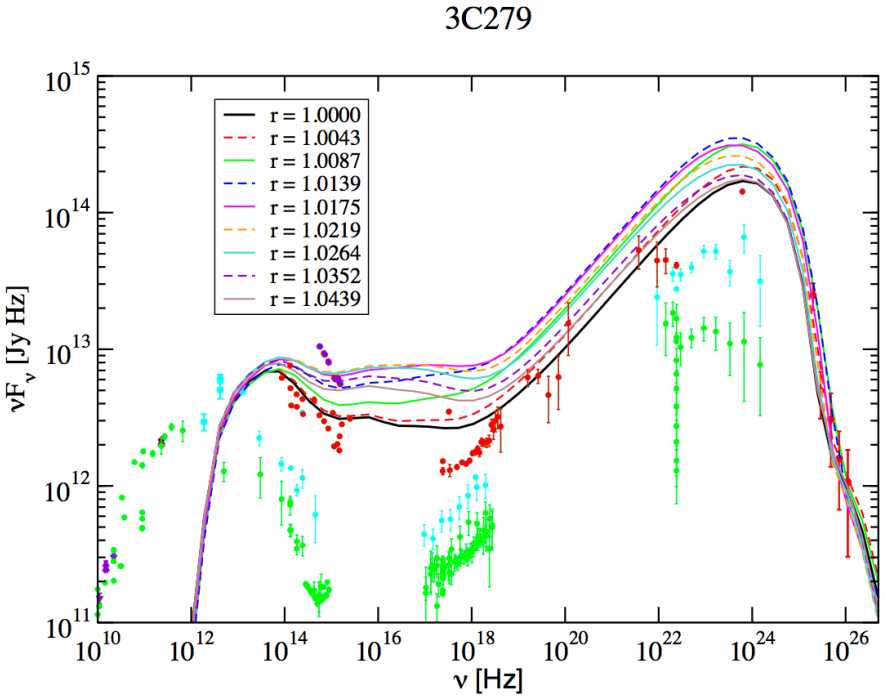
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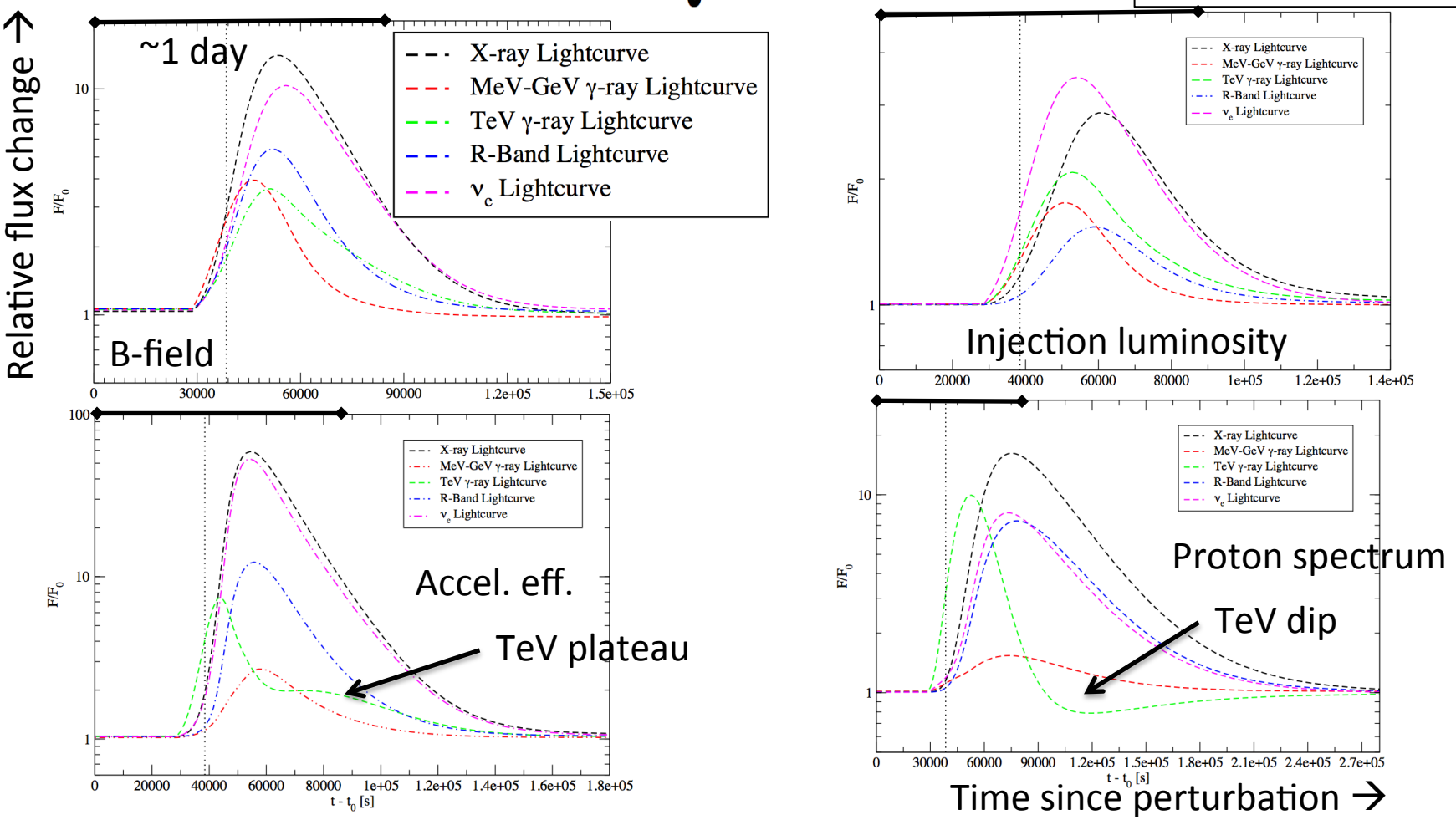


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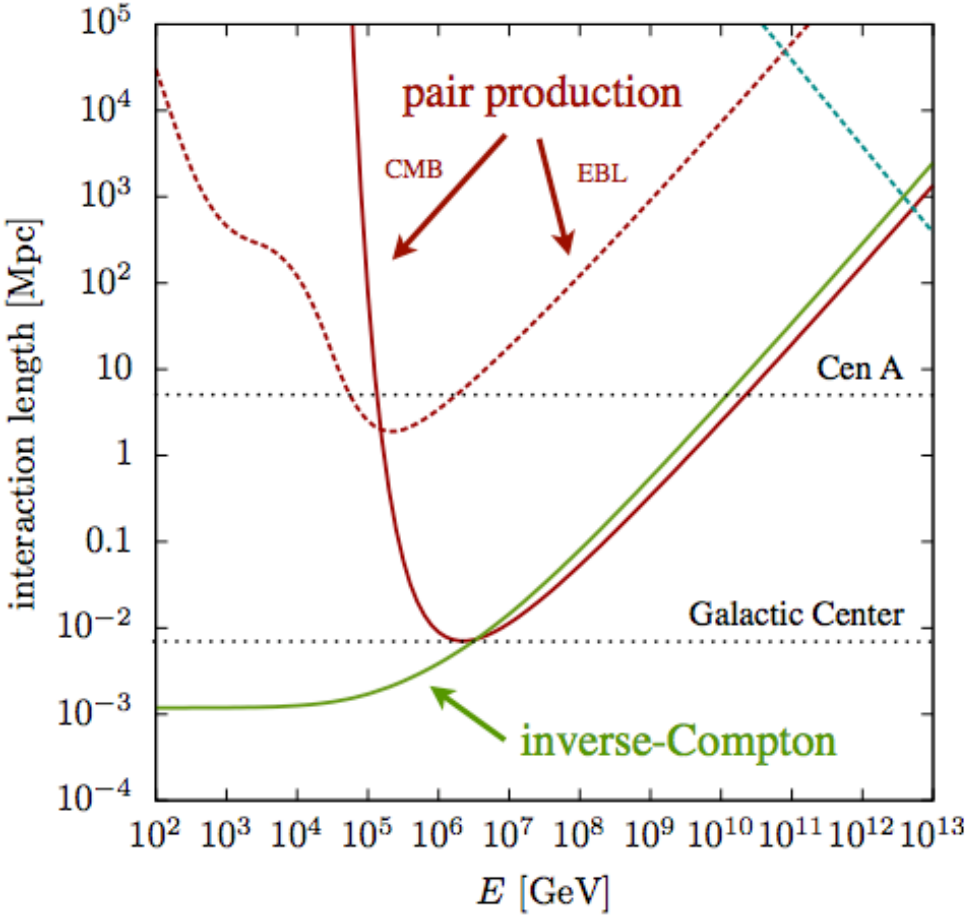


Cascading Process

- 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.

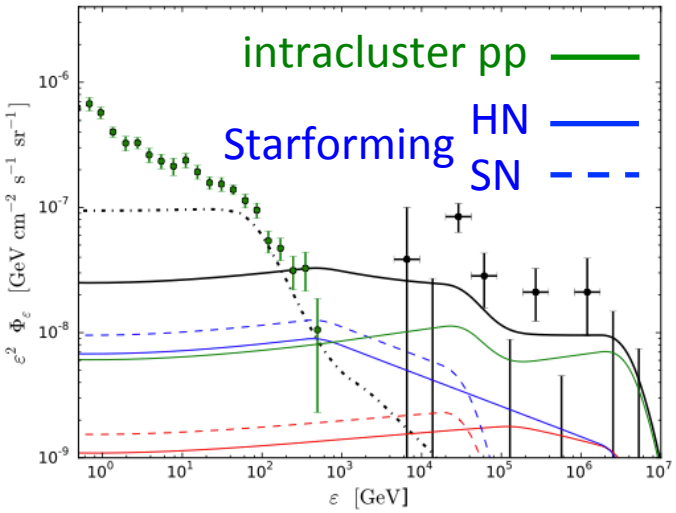
  [EBL: Franceschini *et al.* '08]
- rapid cascade interactions produce universal GeV-TeV emission

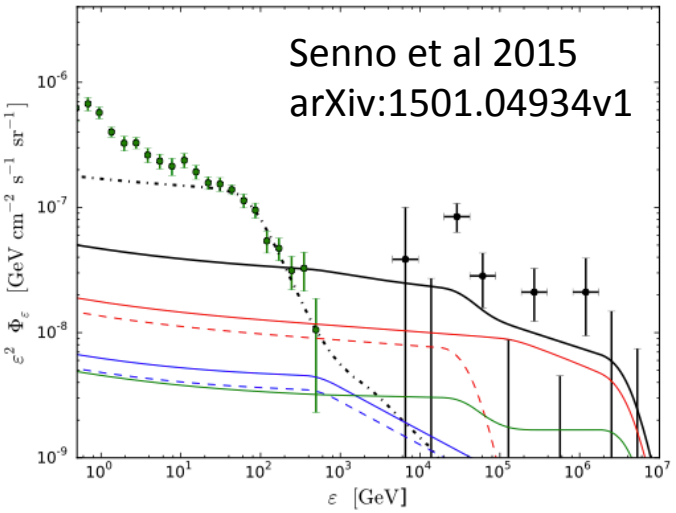
  [Berezinsky&Smirnov'75]

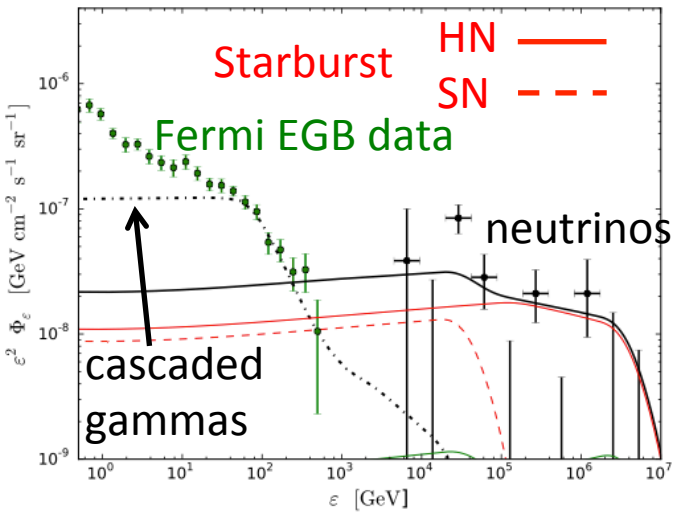


[MA'11]

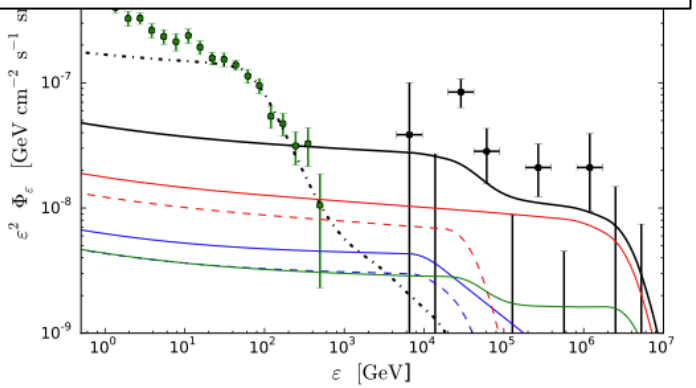
(Large Parameter Space)







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



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

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

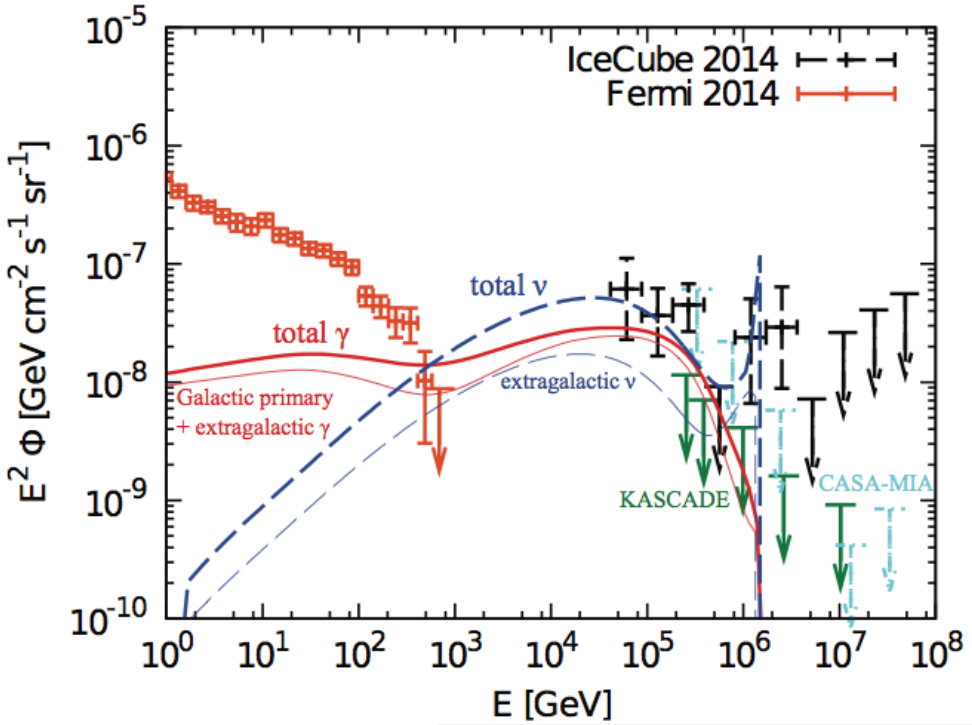
"**ES13**" parameters:

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

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

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

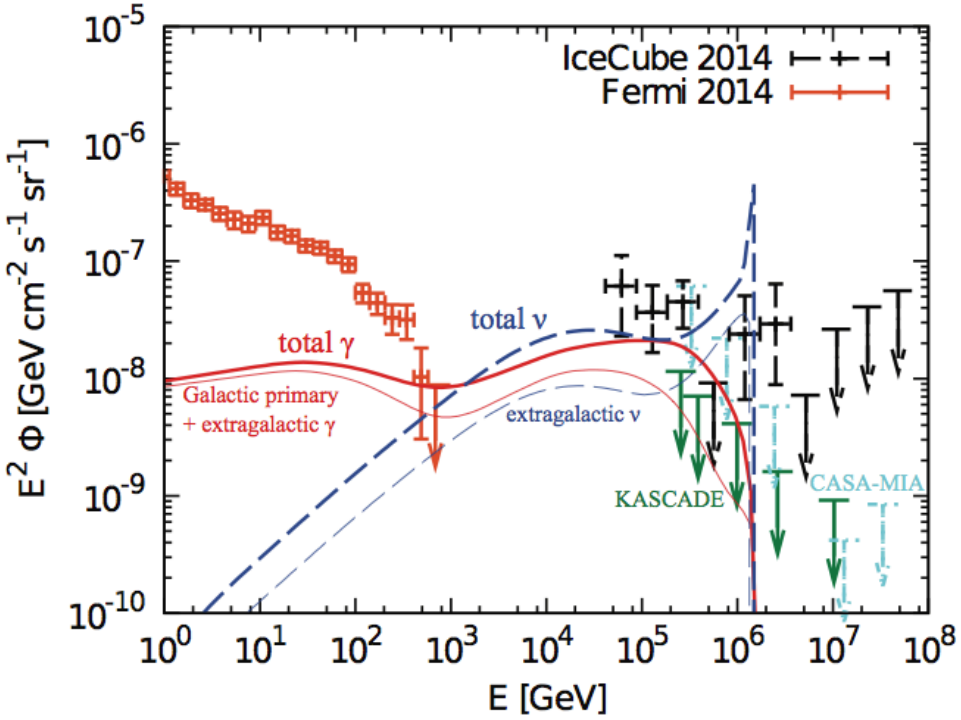
$$\tau_{\rm dm} = 3.0 \times 10^{27} \text{ s}$$



Murase et al. 2015
arXiv:1503.04663v1

The VHDM Models

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



"**RKP14**" parameters:

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

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

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

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

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

Murase et al. 2015
arXiv:1503.04663v1