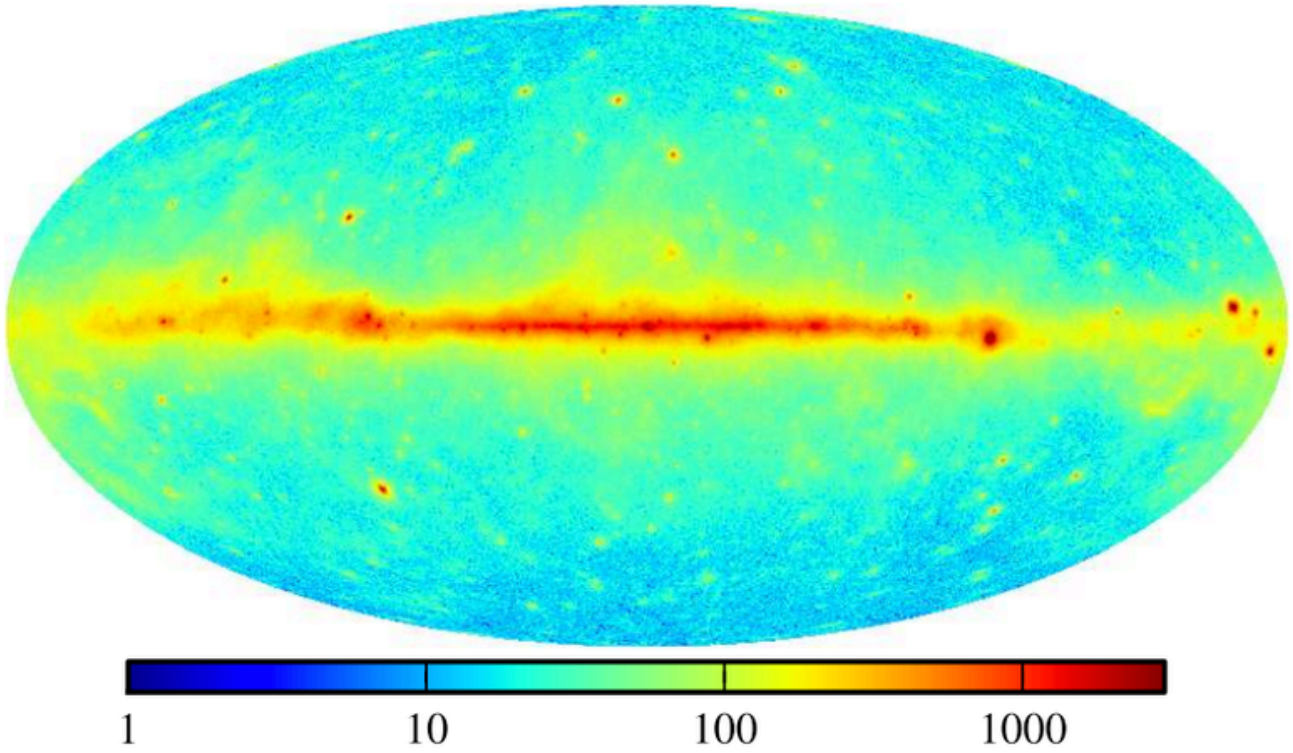
A Search for Neutrinos from the Galactic Plane



Jon Dumm w/ Chad Finley & Martin Wolf

MANTS Meeting - Amsterdam

Oct 17, 2015

Overview

- Summarize latest evidence for a galactic component in our measured neutrino flux
  - IceCube data
  - New models of CR transport, gamma rays & neutrino emission
- Analysis method
  - Maximum likelihood spatial template analysis on 6 years of IceCube point-source data
- Sensitivity and comparisons to ANTARES

IceCube Hints

- **High-Energy Starting Events** skymap
  - p=2.5% in gal plane scan within ±7.5° gal latitude

- **Global fit** spectrum and N/S hemisphere check
  - Soft extragalactic ν spectrum overproduces GeV gamma rays

  Murase, Ahlers, Lacki 2013 (arXiv:1306.3417)

  - Spectral index North vs South

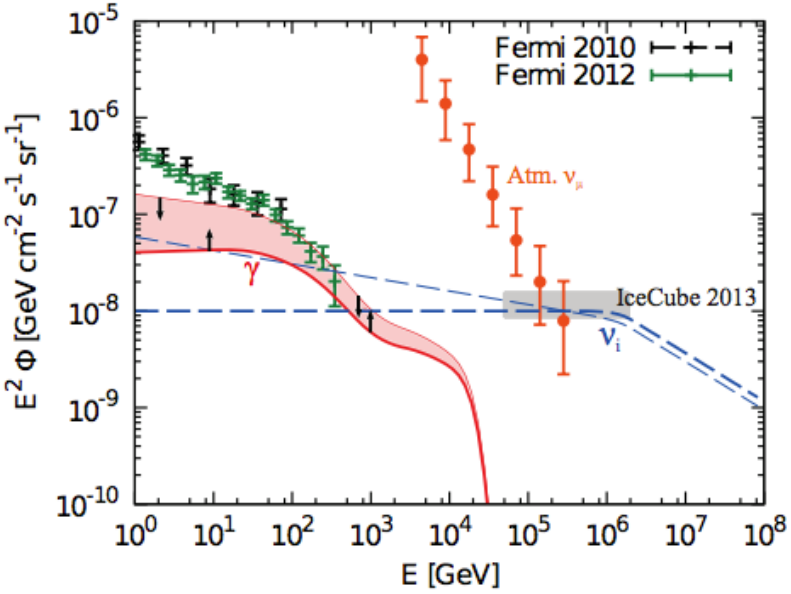


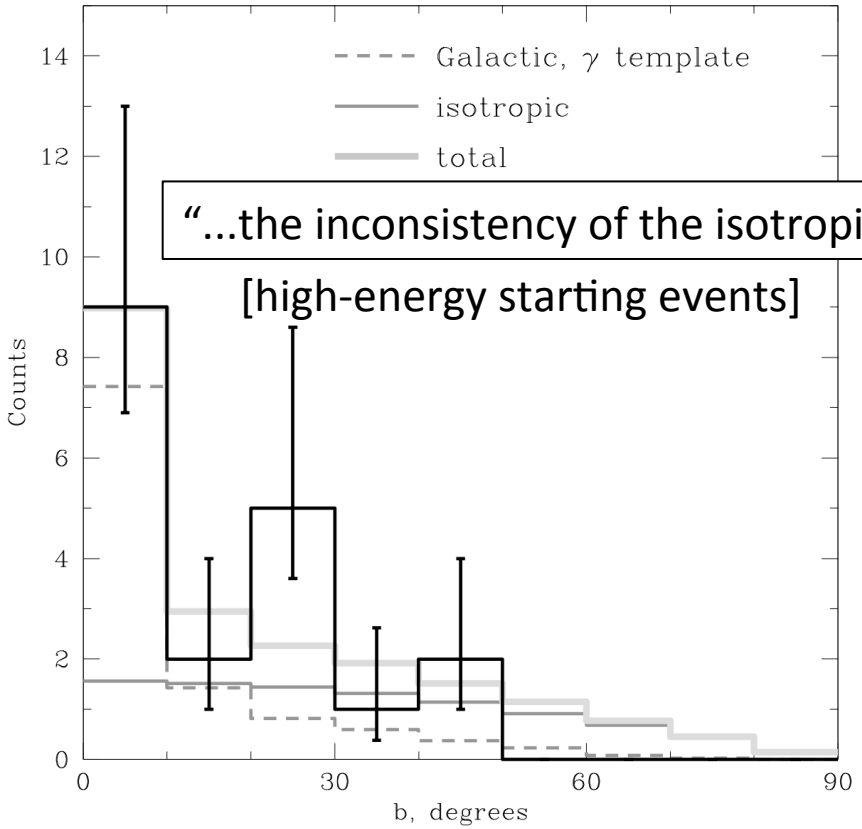
Table 7
Best-Fit Parameter Values for the North-South Model.

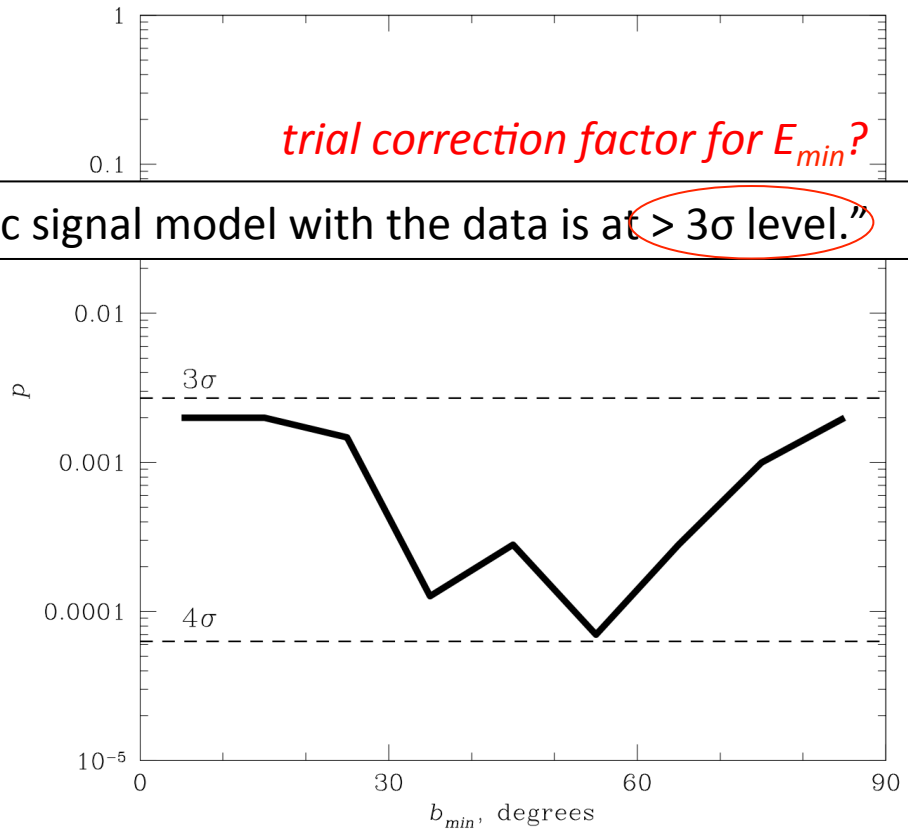
Parameter	Best fit	68% C.L.	90% C.L.
ϕ_N	2.1	$0.5 - 5.0$	$0.1 - 7.3$
γ_N	2.0	$1.6 - 2.3$	$1.2 - 2.5$
ϕ_S	6.8	$5.3 - 8.4$	$4.4 - 9.5$
γ_S	2.56	$2.44 - 2.67$	$2.36 - 2.75$

Note. — ϕ_N and ϕ_S are the all-flavor neutrino fluxes at 100 TeV in the northern and southern sky, respectively; γ_N and γ_S are the corresponding spectral indices. The fluxes are given in units of 10^{-18} GeV^{-1}s^{-1}sr^{-1}cm^{-2}.

arXiv:1507.03991v2

>100 TeV *A Posteriori*





trial correction factor for E_{min}?

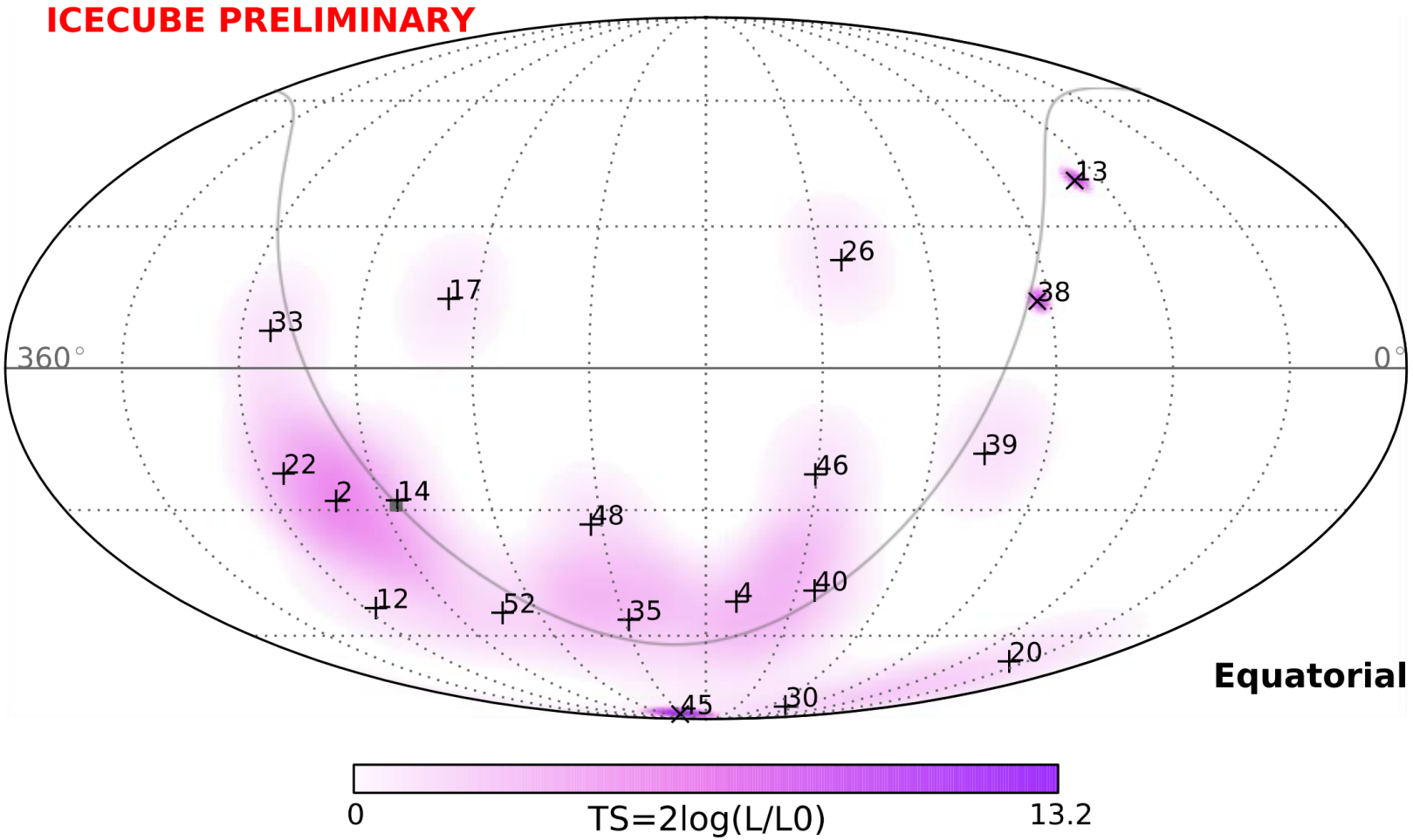
"...the inconsistency of the isotropic signal model with the data is at > 3σ level."

[high-energy starting events]

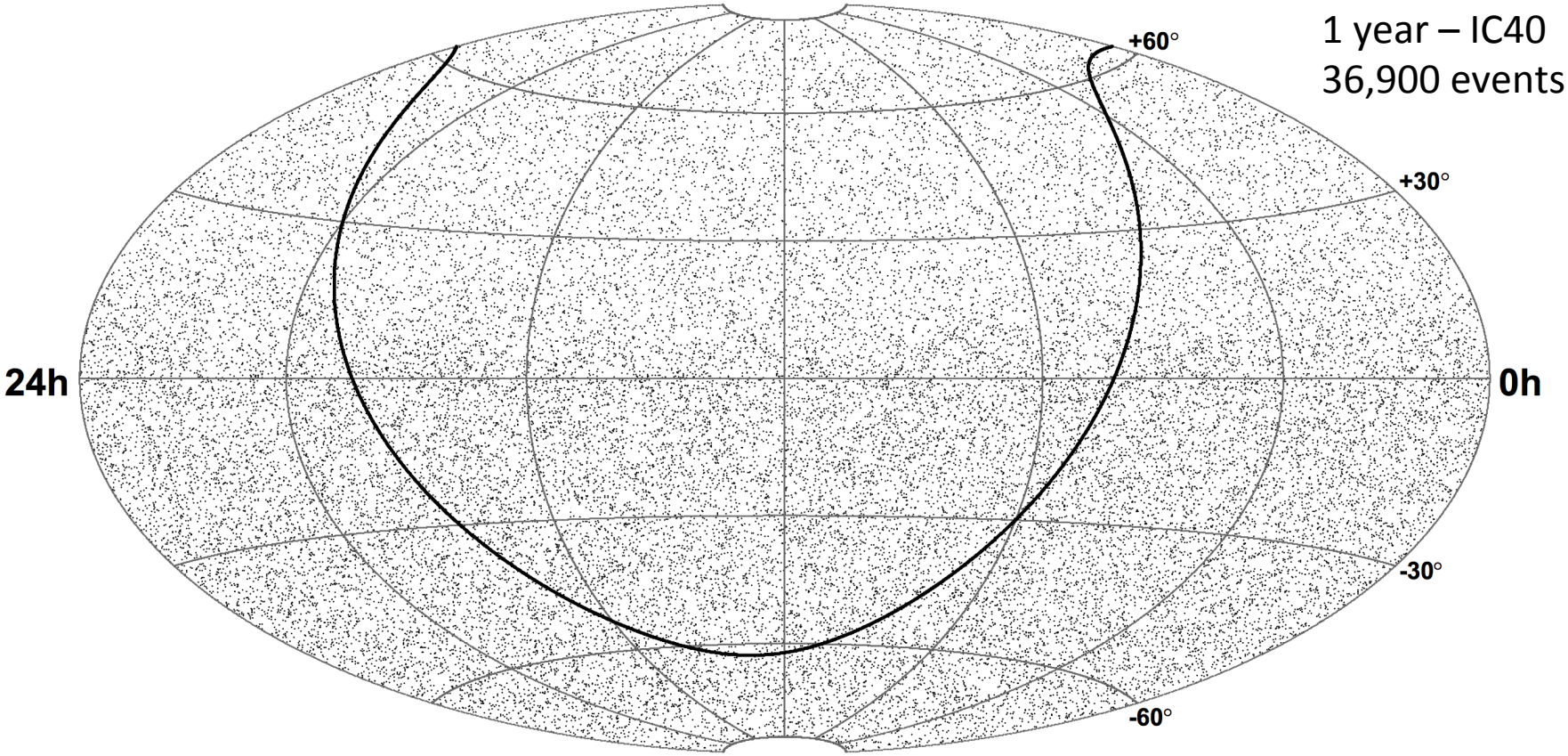
"A model which contains 50% contributions from the galactic and extragalactic components provides a satisfactory fit to the data [left]."

Neronov & Semikoz 2015 (arXiv: 1509.03522)

>100 TeV *A Posteriori*

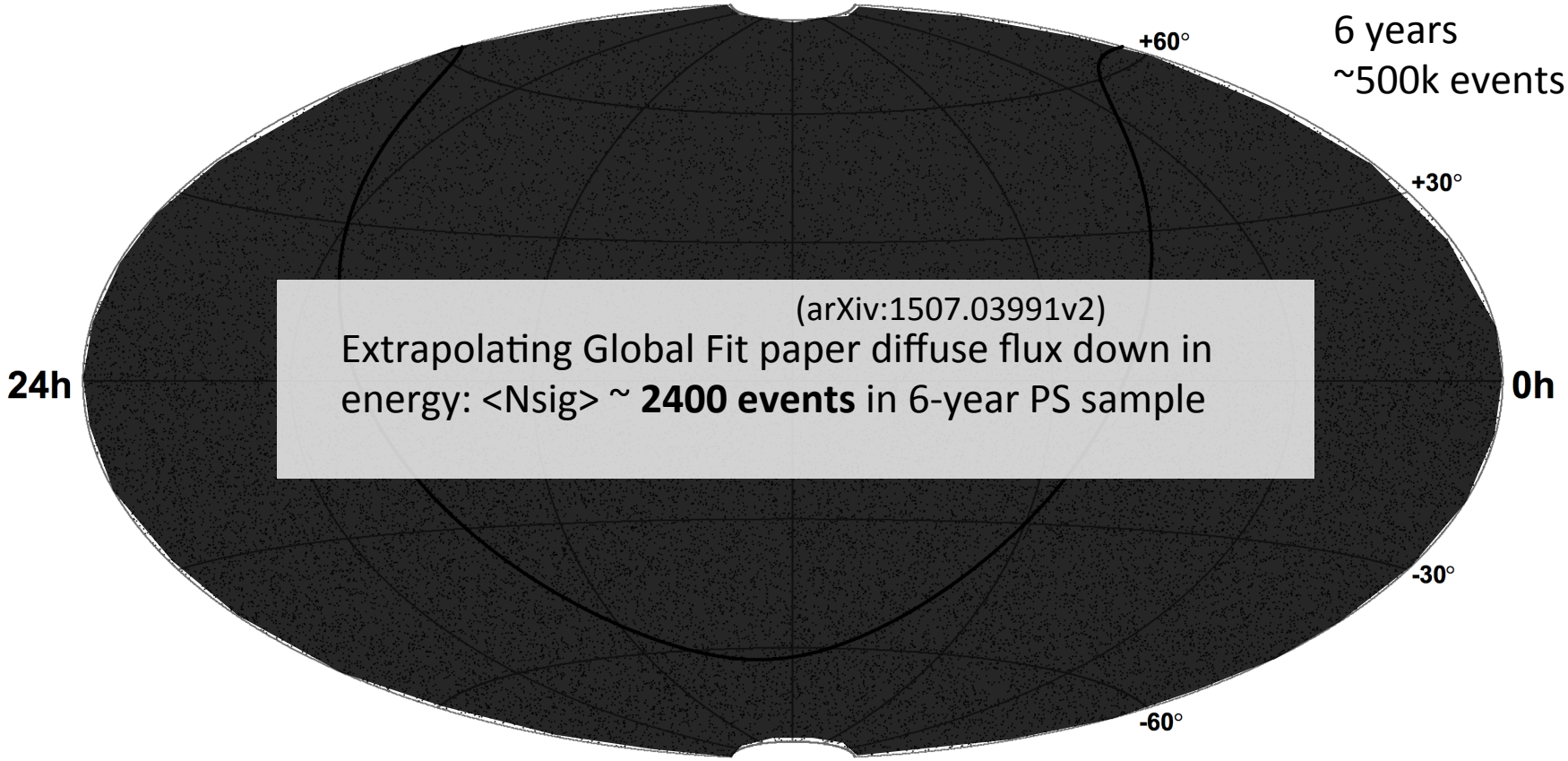


Point Source Sample



- Too many events to show full sample – 40-string sample for illustration
- Extrapolate diffuse flux down: $<N_{sig}>=208$ events in skymap above
- Can we determine if these few events are distributed along the plane?

6 Years of PS Data



- Too many events to show full sample – 40-string sample for illustration
- Extrapolate diffuse flux down: $<N_{sig}>=208$ events in skymap above
- Can we determine if these few events are distributed along the plane?

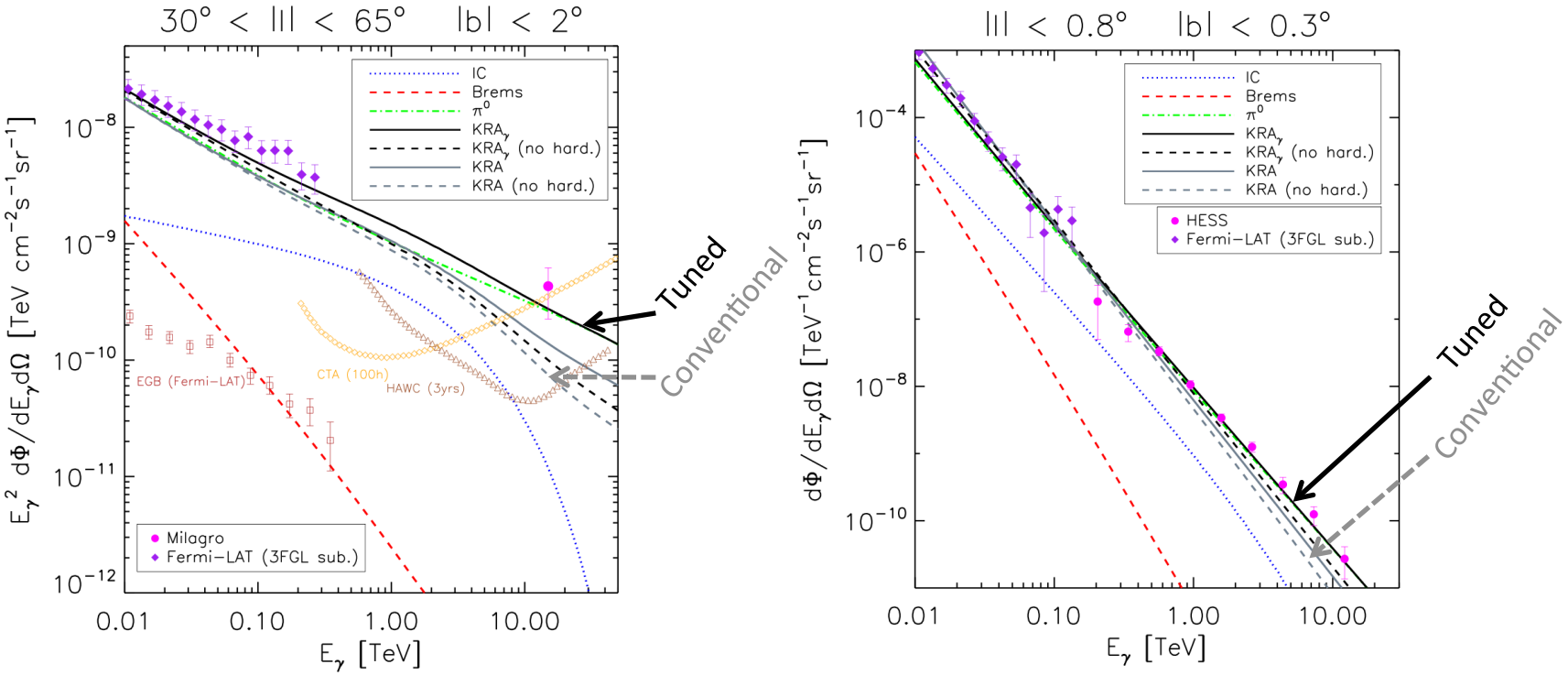
GP Emission Mechanisms

- Two likely origins for ν flux from plane:
  - Gal CR interactions with interstellar gas (p-p)
    - Conventional models: If flux ~ $E^{-2.7}$ as observed at Earth is uniform throughout galaxy → relatively small neutrino flux
    - Large scale, **gamma-rays** act as CR-interaction tracers
  - Unresolved gal CR sources and interactions with local material
    - Perhaps very many point sources → nearly diffuse in plane
    - Perhaps a handful of sources along the plane

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



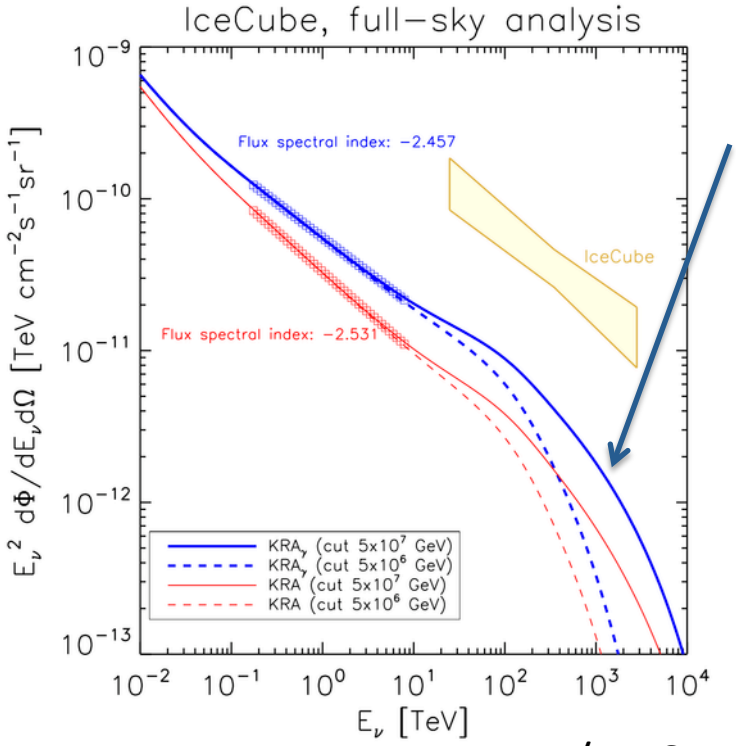
- New: Incorporate PAMELA/AMS measured p & He hardening and allow CR diffusion to change with gal. radius

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:

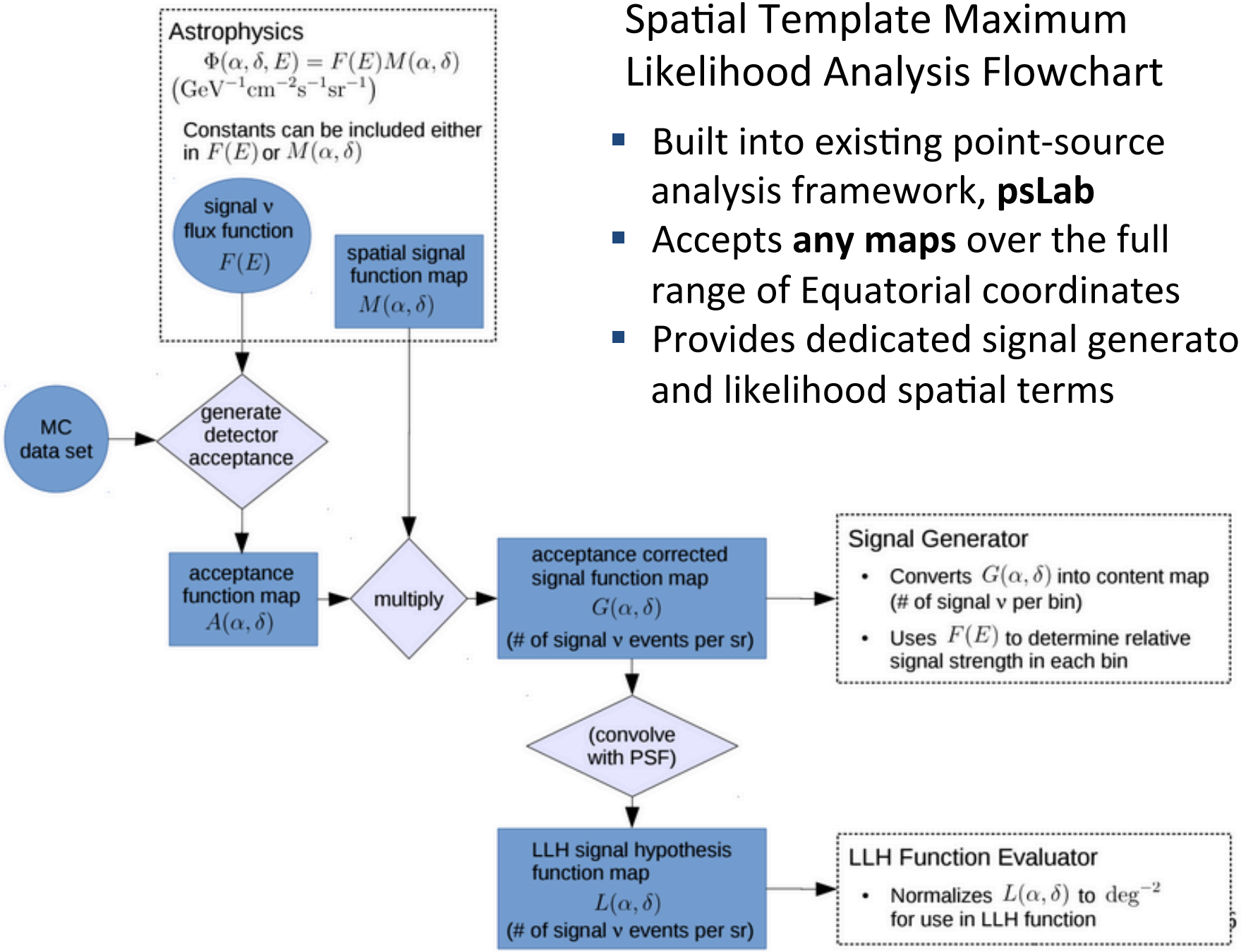
- Assumes PAMELA/AMS p & He hardening is global
- Gal CR cutoffs: 5 (dotted), 50 (solid) PeV
- red = Conventional + global hardening
- blue = Tuned to ϒ-ray observations (Fermi-LAT, HESS, & Milagro)

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

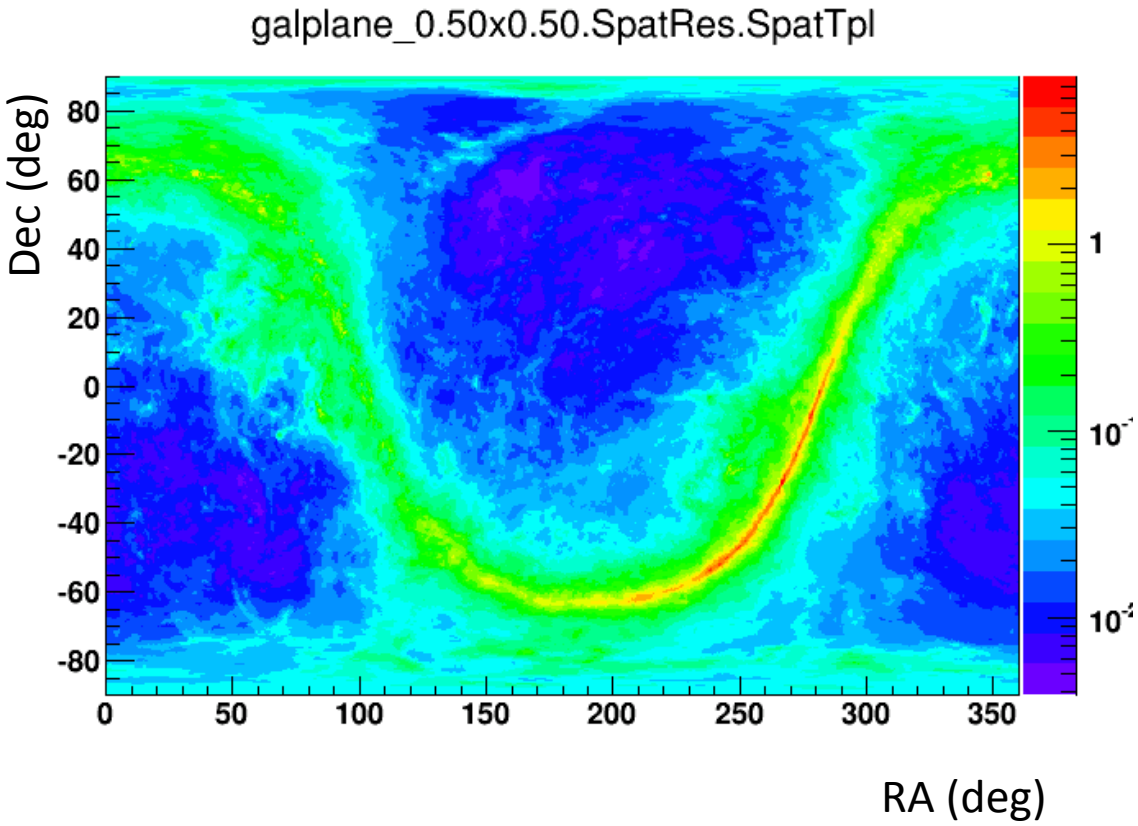
Gaggero et al 2015
arXiv:1504.00227v2

Spatial Template Maximum Likelihood Analysis Flowchart

- Built into existing point-source analysis framework, **psLab**
- Accepts **any maps** over the full range of Equatorial coordinates
- Provides dedicated signal generator and likelihood spatial terms



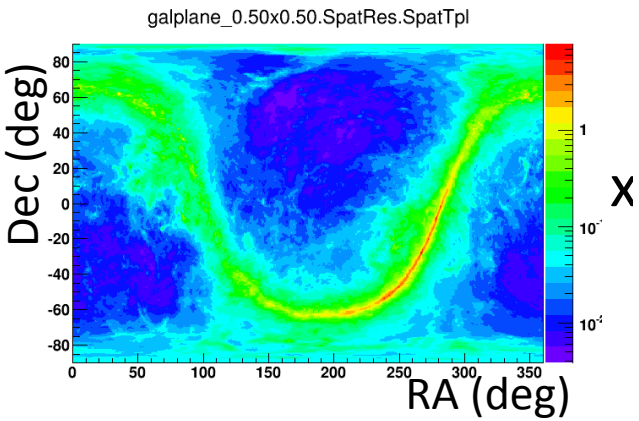
Max LH Spatial Template



Pion-decay Gal Plane Map from Fermi-LAT

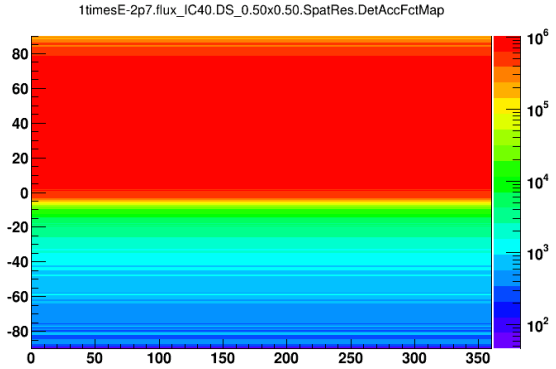
- Map built from H surveys of the galaxy
- CR intensity fit to gamma-ray data in galactic radius bins
- Pion-decay component used as template for neutrinos

Max LH Spatial Template



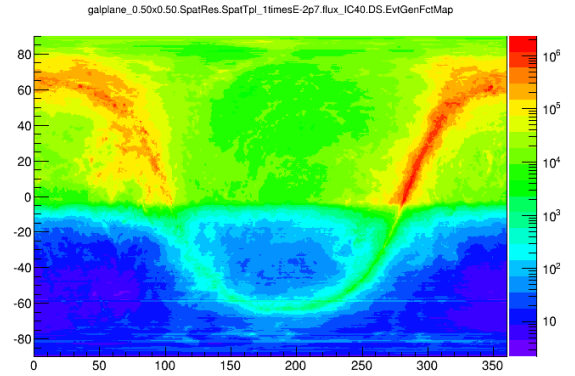
Pion-decay Gal Plane Map from Fermi-LAT

x



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

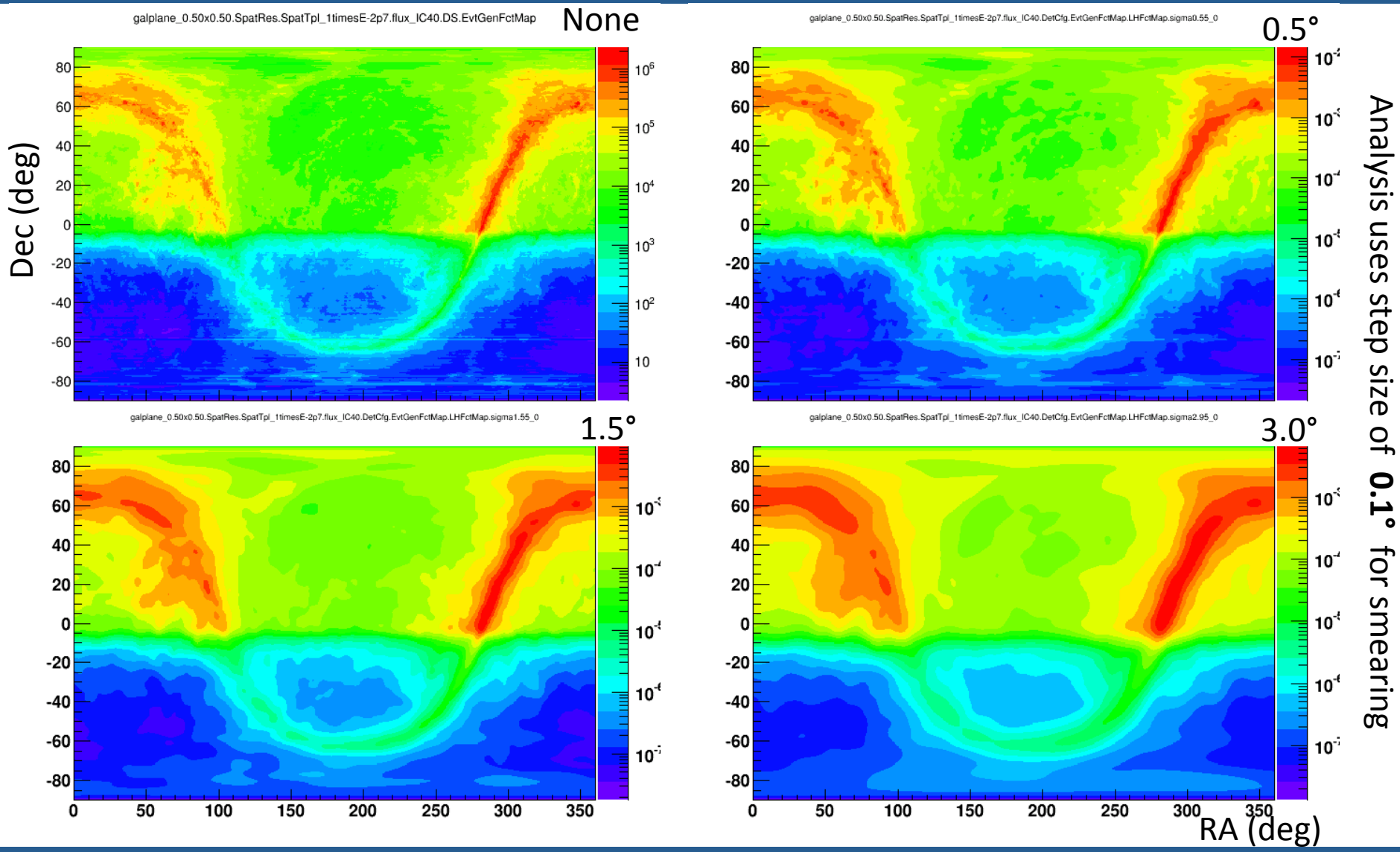
=



Where we should see neutrinos originate before PSF smearing

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

Convolutions – PSF Smearing

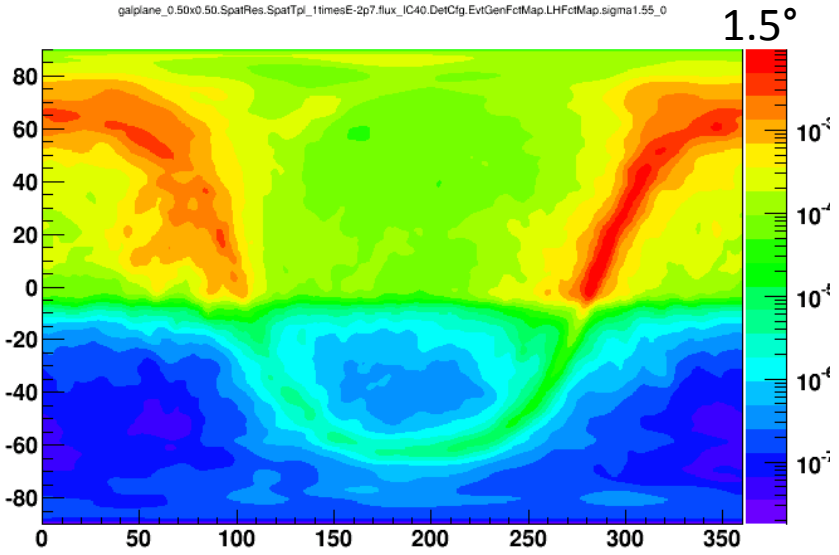


Likelihood Function

- Signal extends to all regions of the sky – no clear "off" regions
- Likelihood function derives background pdf by subtracting off scrambled version of signal pdf from the data

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

(spatial component)



Likelihood Function

- Signal extends to all regions of the sky – no clear "off" regions
- Likelihood function derives background pdf by subtracting off scrambled version of signal pdf from the data

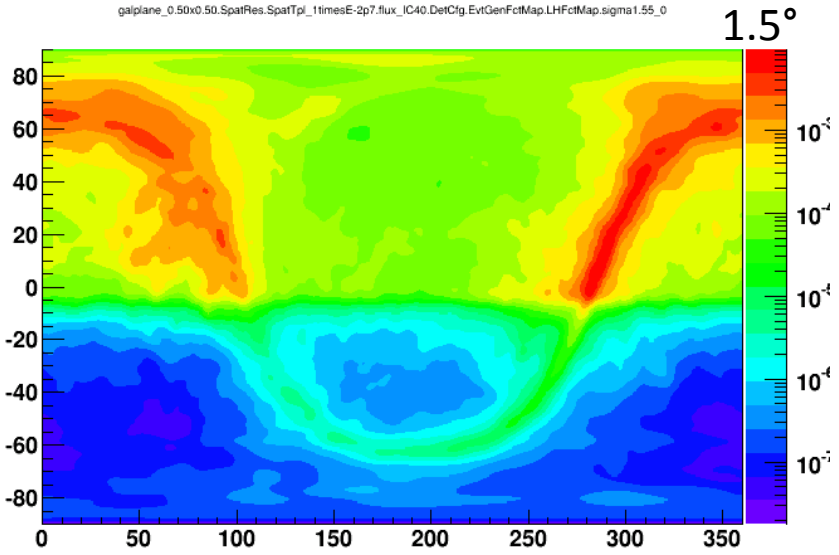
$$L(n_s) = \prod_i \left[\frac{n_s}{n_{\rm tot}} S_i(\mathbf{x}_i, E_i, \sigma_{i,\rm parab}) + \left(1 - \frac{n_s}{n_{\rm tot}}\right) B_i(\mathbf{x}_i, E_i) \right],$$

(spatial component)

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

Data

Signal Scrambled in RA



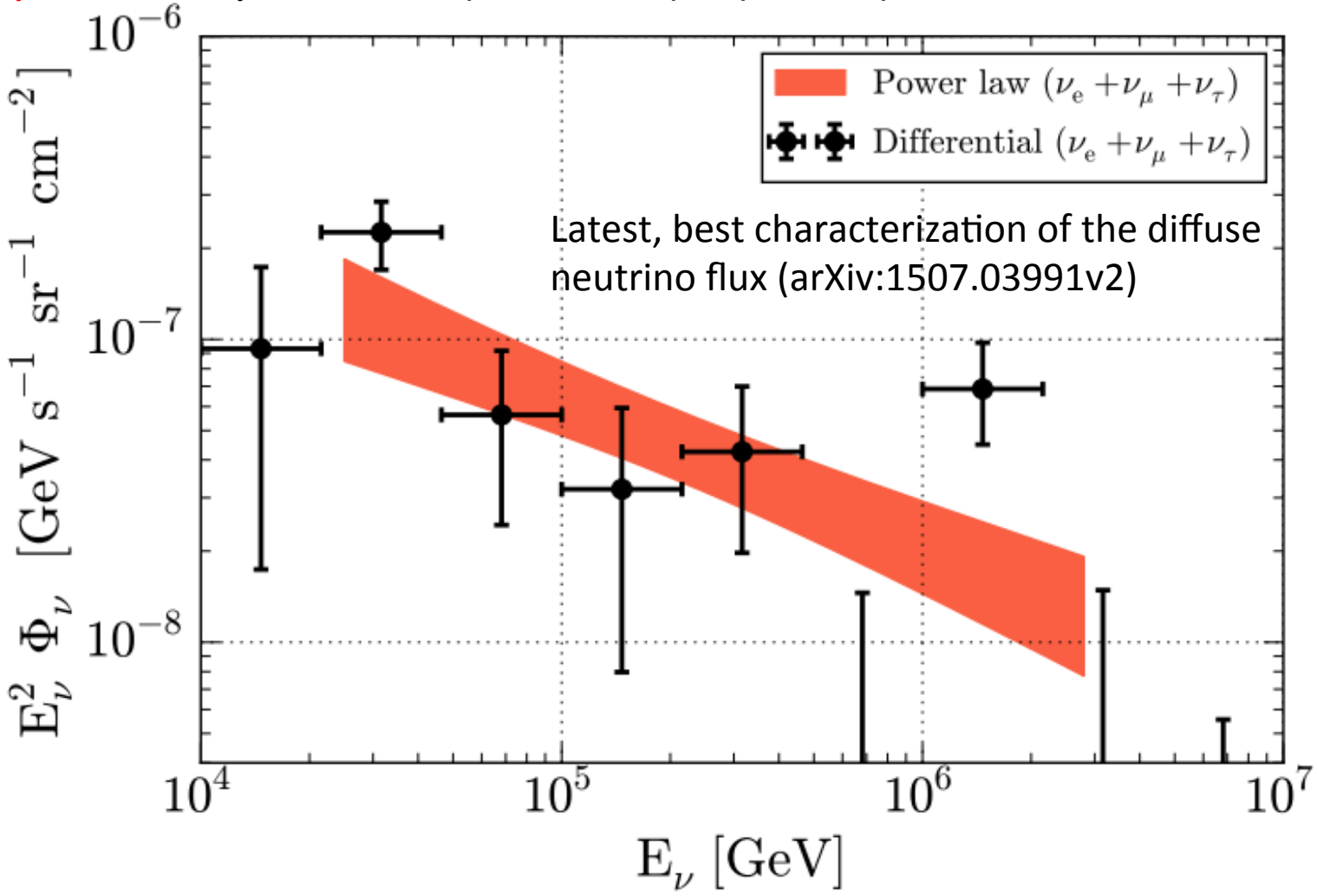
- Tried using standard PS likelihood
  - Assumption: all data are background
- This 'signal-subtracted' likelihood important for unbiased results

GP Sensitivity

Preliminary Sensitivity: $dN/dE = (1.21\times10^{-5}) \times (E/GeV)^{-2.5}\ GeV^{-1}\ cm^{-2}\ s^{-1}$

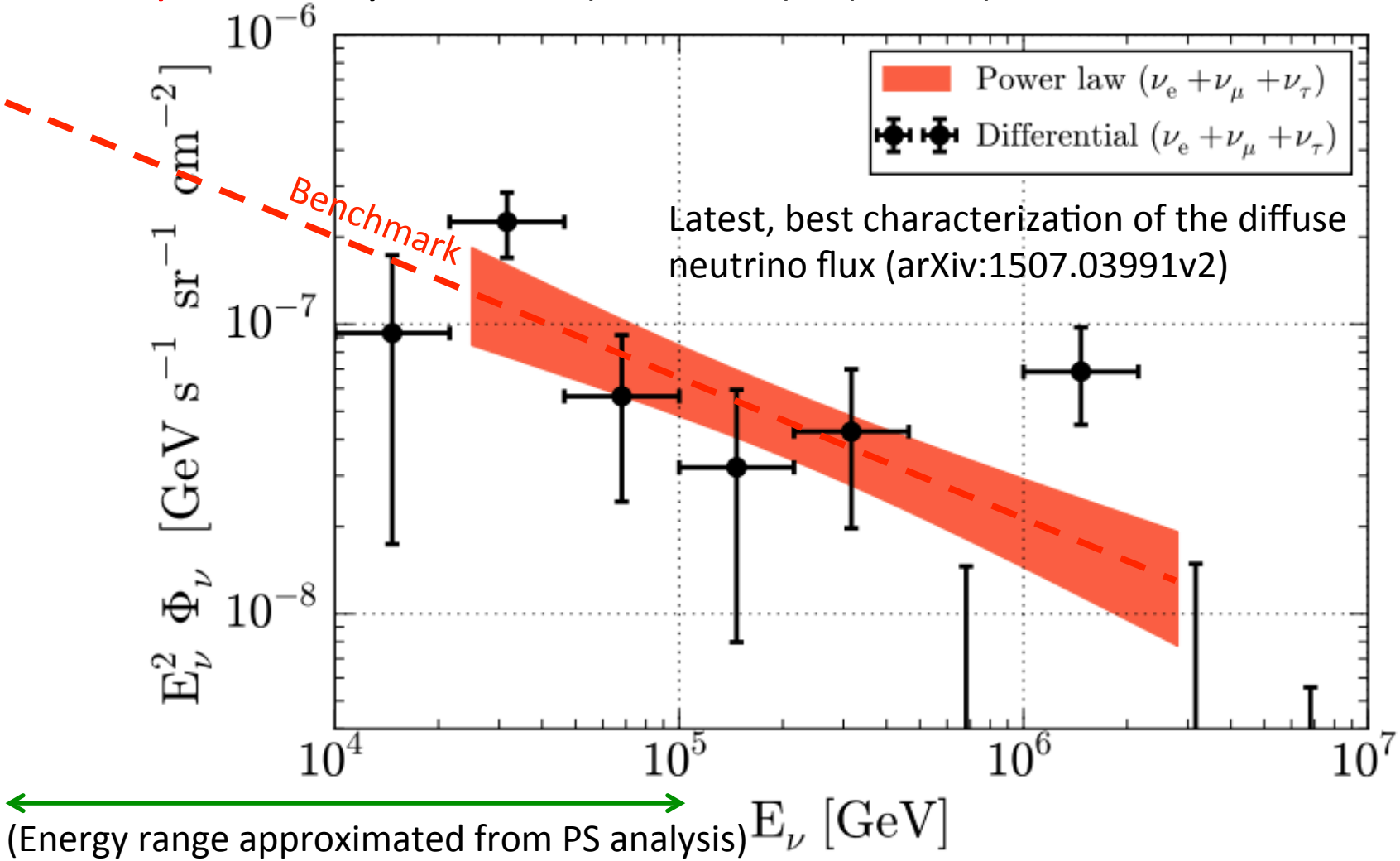
GP Sensitivity

Preliminary Sensitivity: $dN/dE = (1.21\times10^{-5}) \times (E/GeV)^{-2.5}\ GeV^{-1}\ cm^{-2}\ s^{-1}$



GP Sensitivity

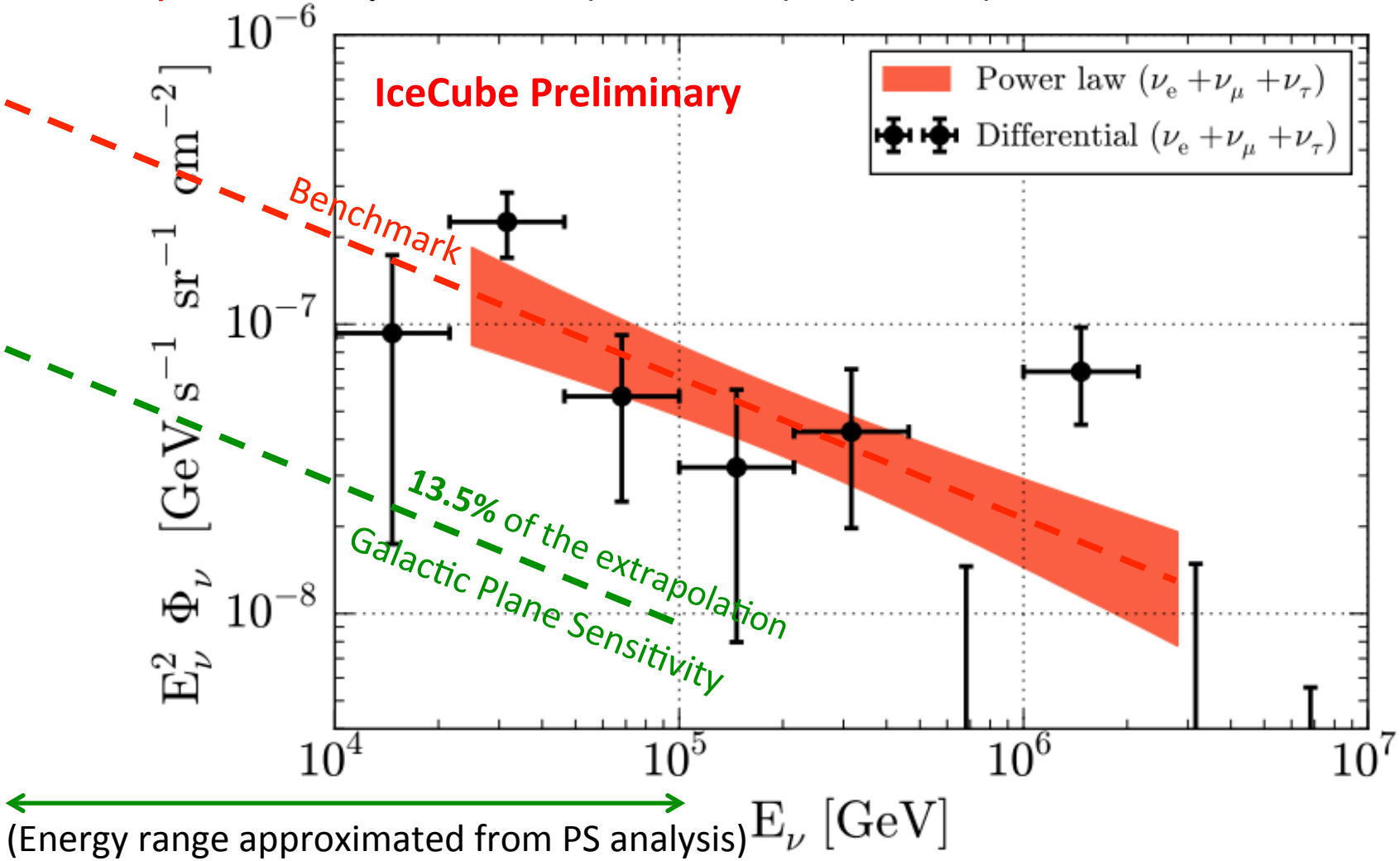
Preliminary Sensitivity: $dN/dE = (1.21\times10^{-5}) \times (E/GeV)^{-2.5}$ GeV^{-1} cm^{-2} s^{-1}



(Energy range approximated from PS analysis)

GP Sensitivity

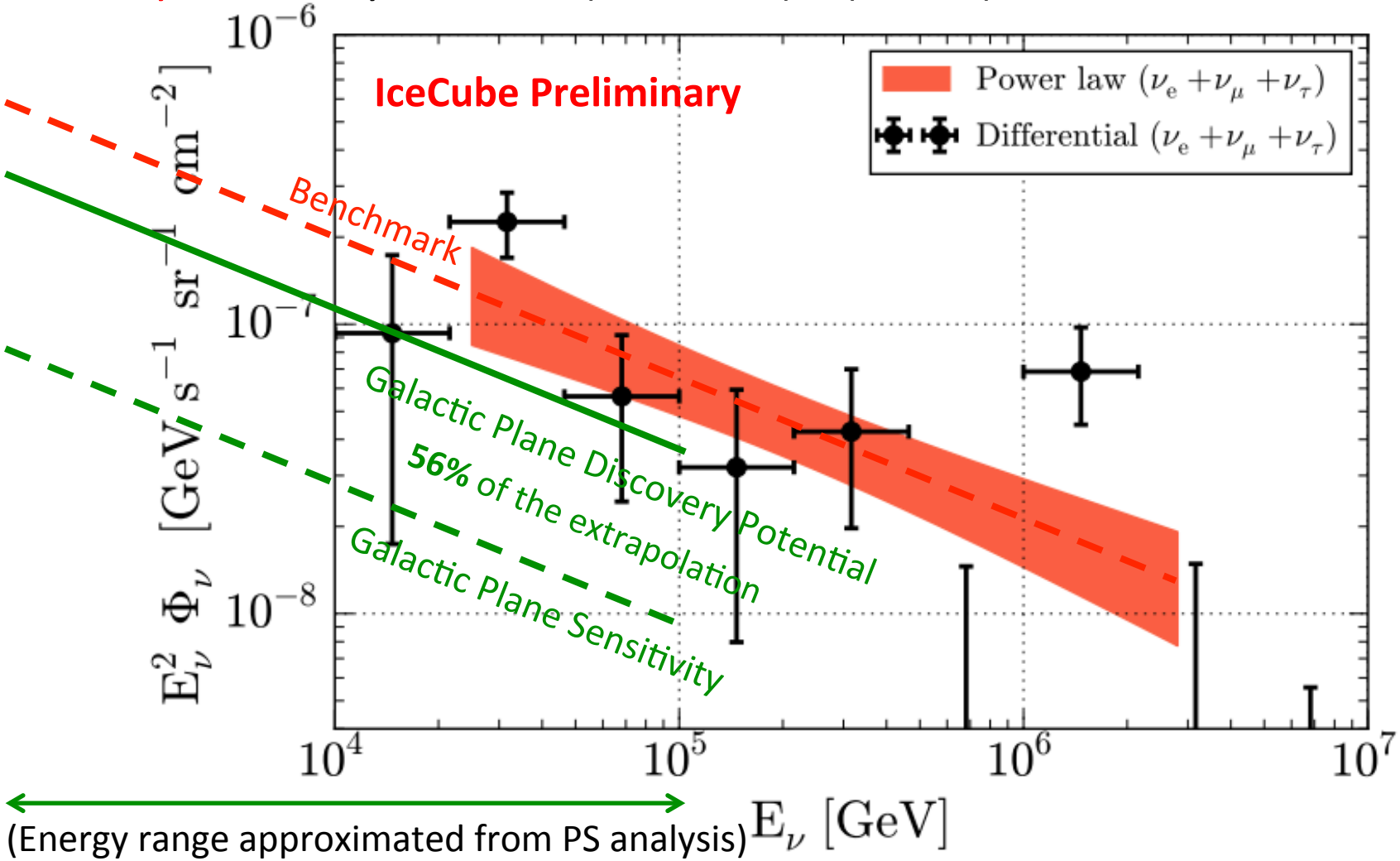
Preliminary Sensitivity: $dN/dE = (1.21\times10^{-5}) \times (E/GeV)^{-2.5}\ GeV^{-1}\ cm^{-2}\ s^{-1}$



(Energy range approximated from PS analysis)

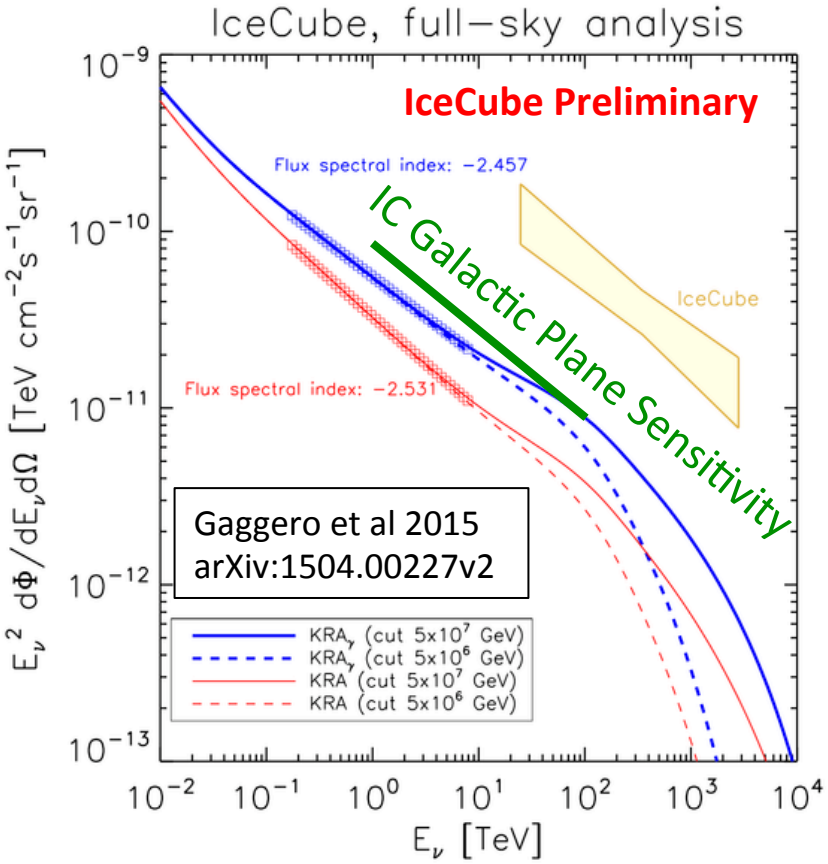
GP Discovery Potential

Preliminary Sensitivity: $dN/dE = (1.21\times10^{-5}) \times (E/GeV)^{-2.5}\ GeV^{-1}\ cm^{-2}\ s^{-1}$



(Energy range approximated from PS analysis)

Comparison to Model

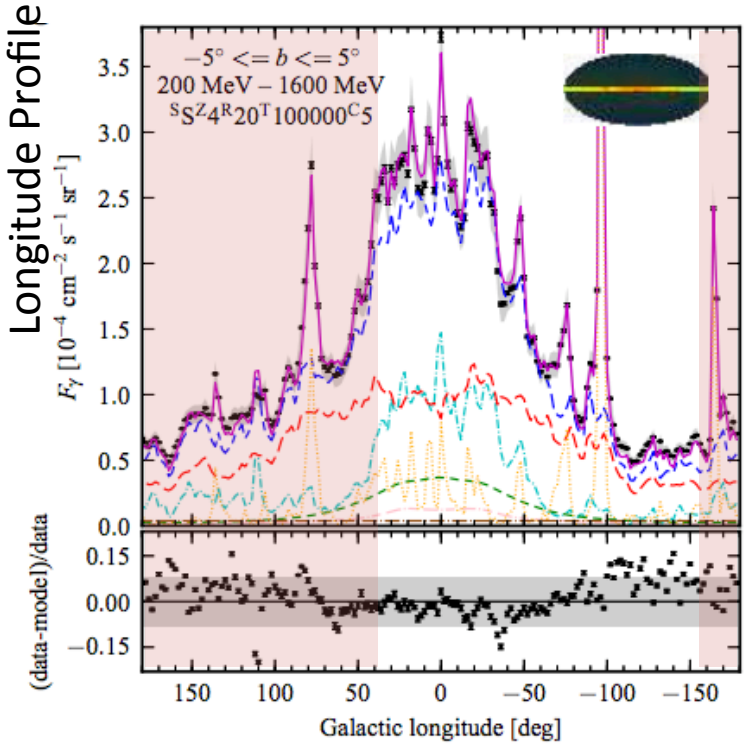


- IceCube sensitivity allows us to set limit near the latest models (in the absence of an excess)

Caveat on left: model represents an average flux over the whole sky but flux is higher towards gal center where IC analysis insensitive

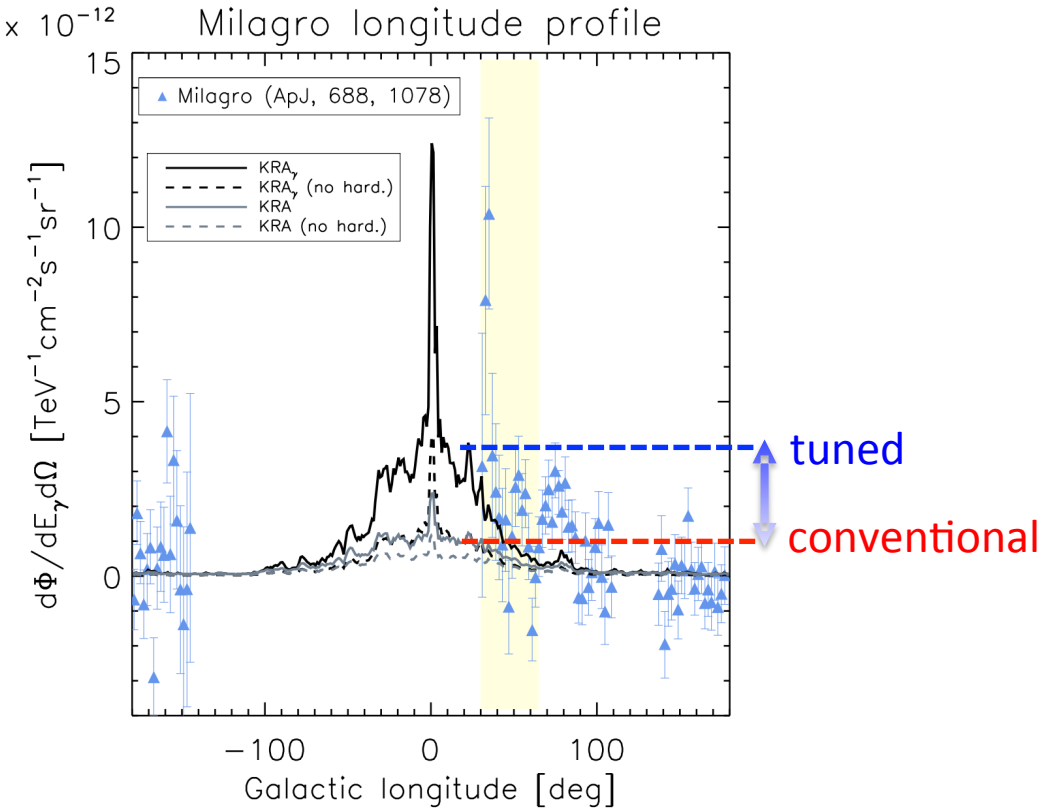
Longitude Profiles

Fermi Pion-decay profile in **red**



Northern Sky: IC Sensitive

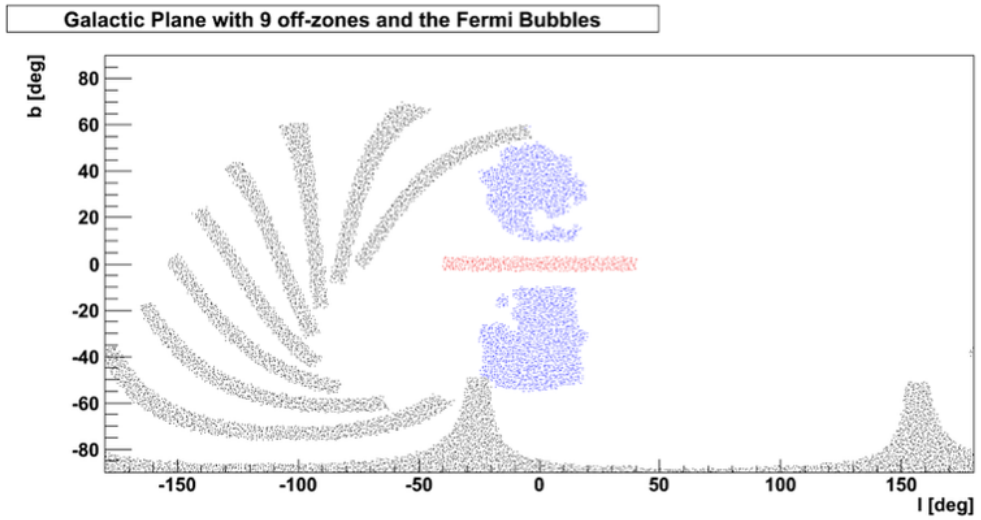
M. Ackermann et al 2011
arXiv:1202.4039v2

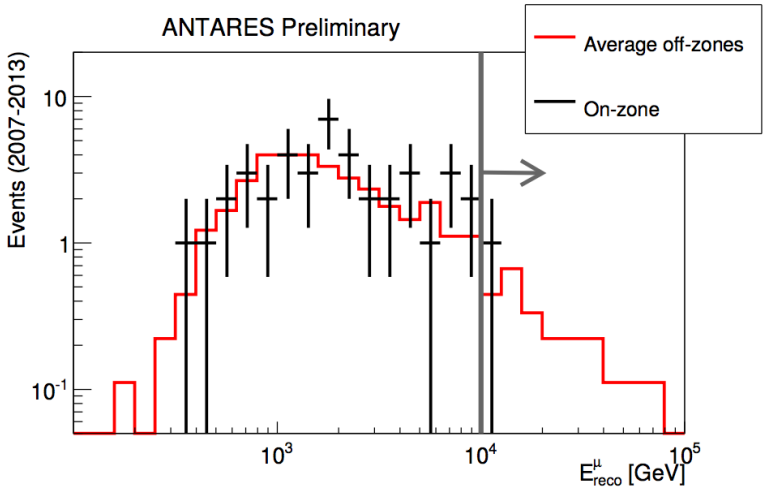


Large uncertainty in flux from inner galaxy!

Gaggero et al 2015
1507.07796v1.pdf

ANTARES Results

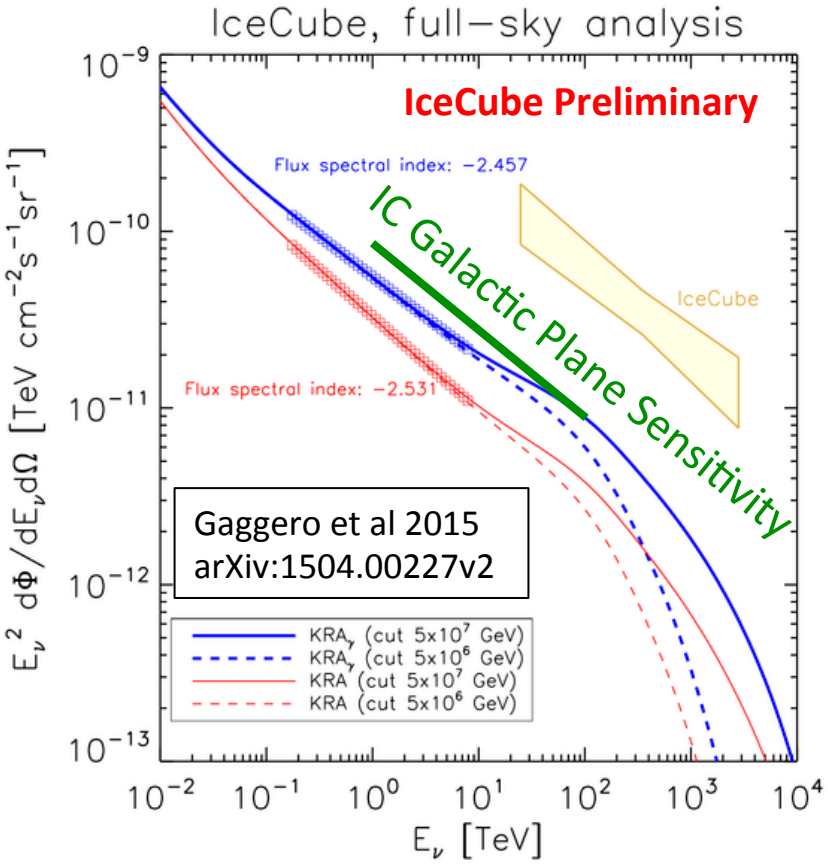


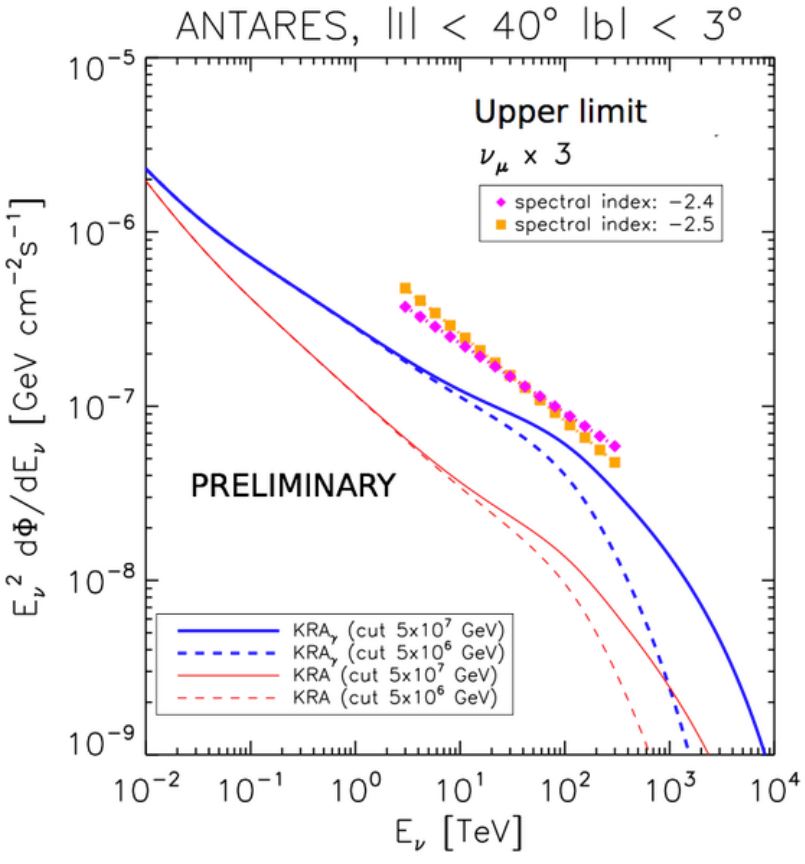


- 1 event observed on a background expectation of 2.5 events

ANTARES results from Luigi Antonio Fusco, shown at VLVNT

IceCube/ANTARES limits





Caveat on left: model represents an average flux over the whole sky but flux is higher towards gal center where IC analysis insensitive

Sensitivities to new GP model comparable between ANTARES/IceCube

Roadmap

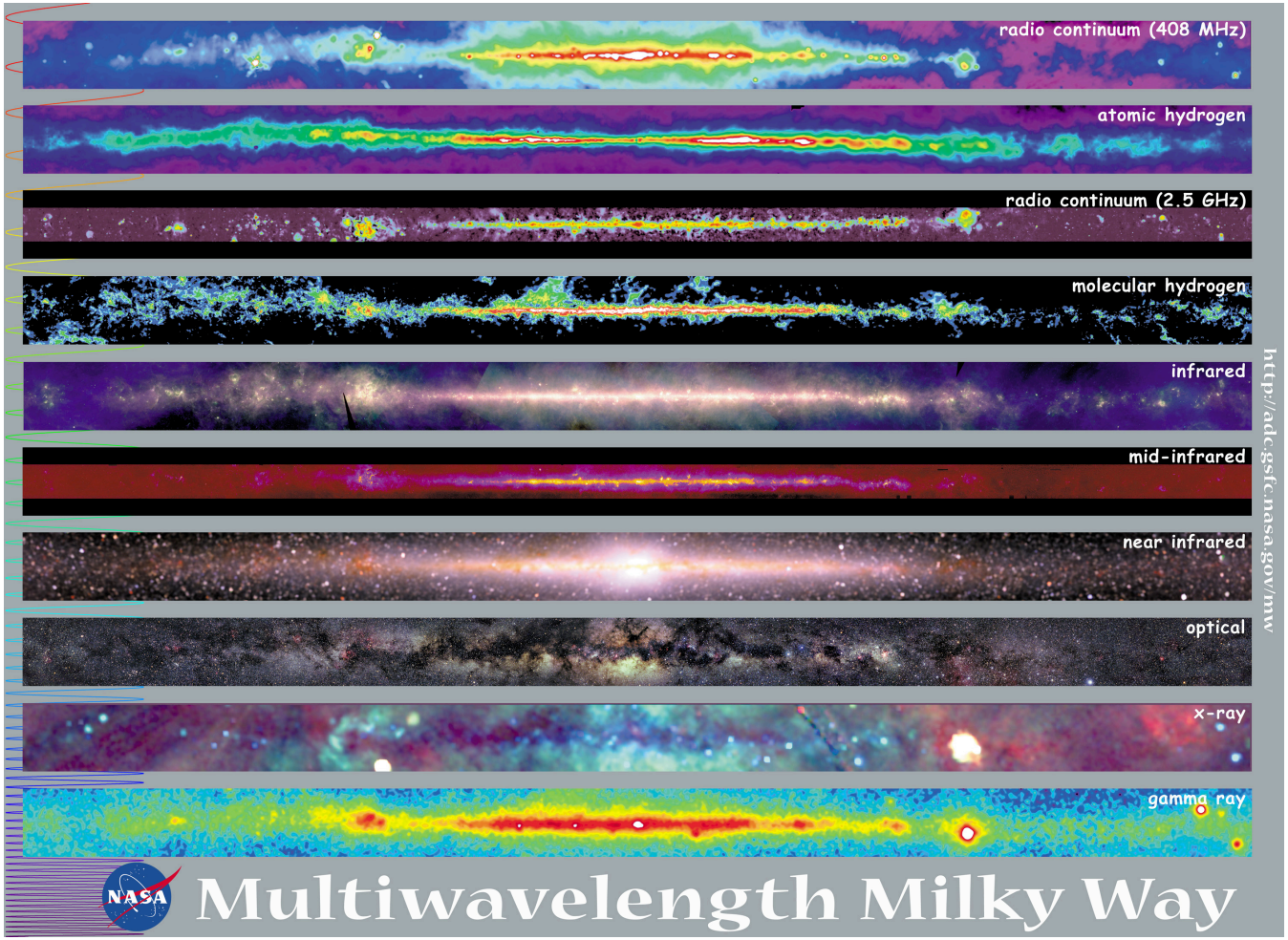
- **IceCube unblinding** of 6 years of PS muon tracks currently undergoing collaboration review
  - Possible to add cascades
  - Possible to add lower energy threshold tracks in southern sky

- Galactic plane is ideal target for a **joint analysis**
  - Rely on experience gained in joint PS analysis
  - IceCube+ANTARES together could probe deeper into the model space or help characterize any excess

Summary

- Lots of recent work suggests there may be a sizable galactic component to IceCube's measured diffuse neutrino flux
  - High-energy neutrino data correlations with small gal latitude
  - New consistent CR-transport models tuned to gamma-ray measurements
- Best upper limits of neutrino flux from galactic plane < ~50% of diffuse flux
  - External analysis of HESE events: Ahlers et al, 2015 (arXiv:1505.03156v1)
  - If 50% of the diffuse flux is coming from the plane, could yield a 5-σ discovery in this IceCube analysis
- If no excess, new CR transport models in the galaxy begin to be tested
- A joint analysis between IceCube & ANTARES is on the horizon

Thanks!



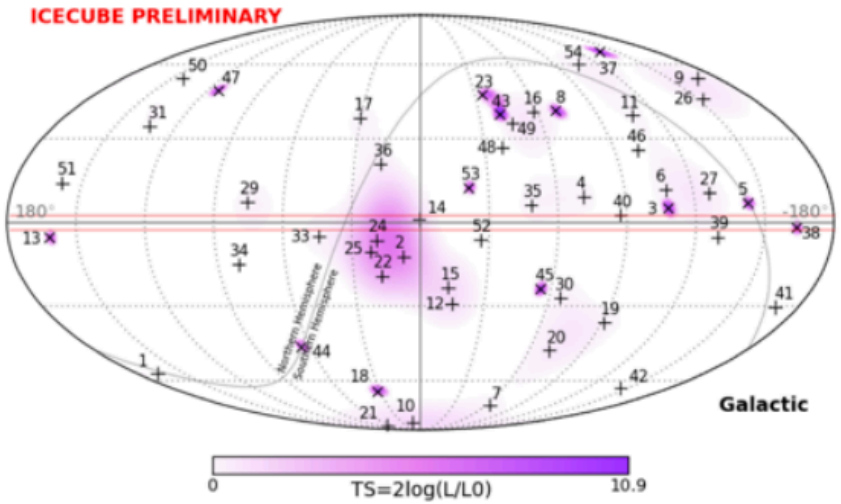
IceCube Gen2 + KM3NeT? ν

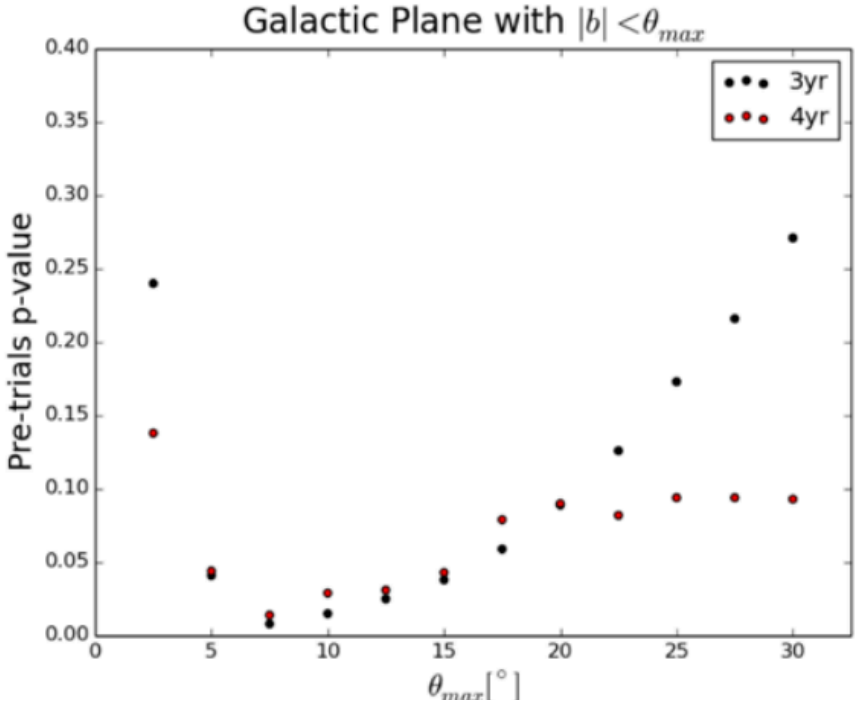
Backup

High-Energy Starting Events

Post trial

- 3 year: 2.8%
- 4 year: 2.5%

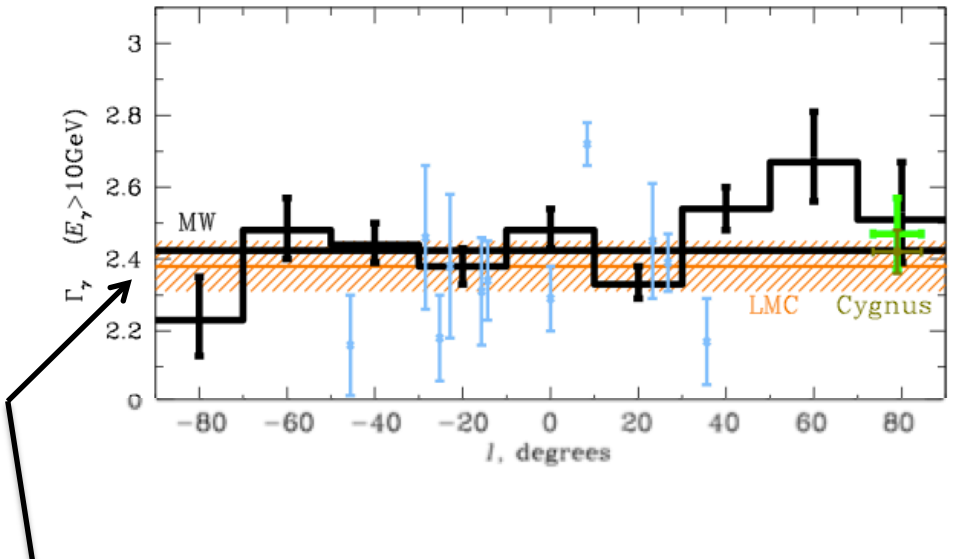


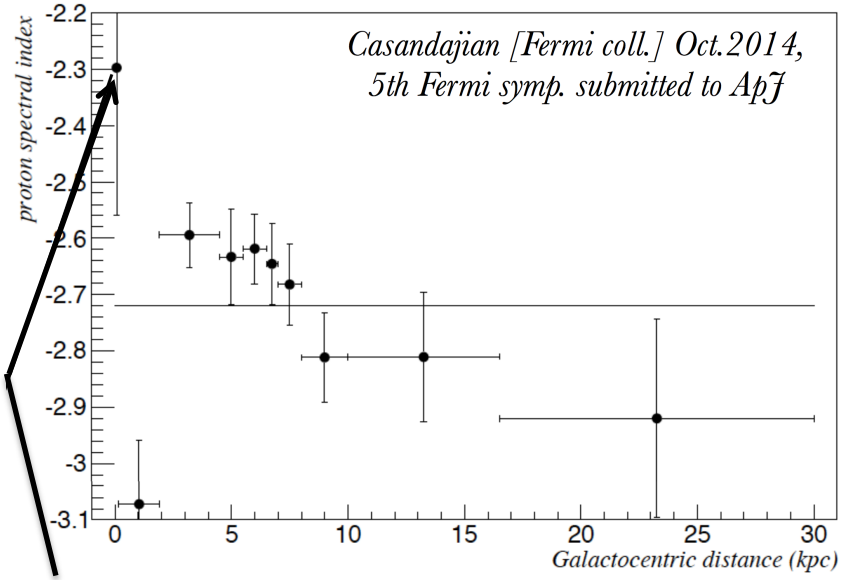


- p=2.5% in gal plane scan within ± 7.5° gal latitude

Remote CR Spectrum

Υ-ray spectral index vs gal lon.



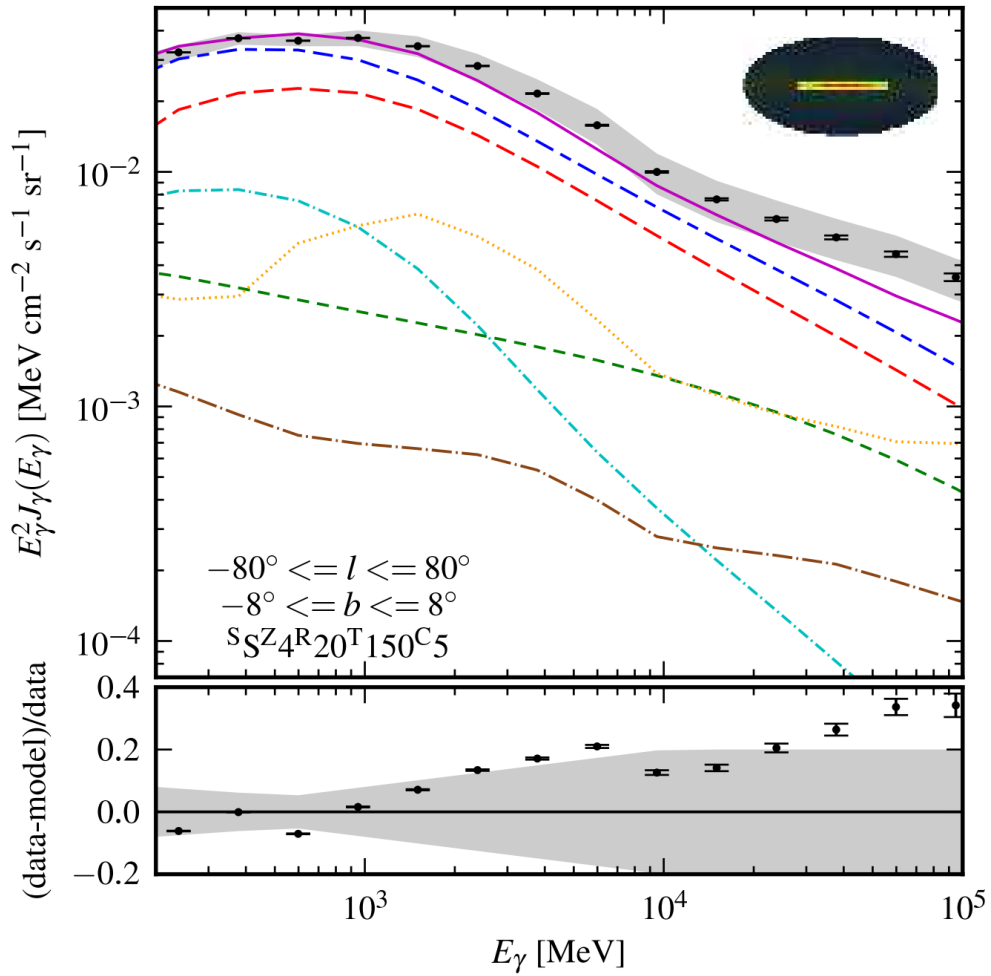


- Neronov & Malyshev 2015 (arXiv:1505.07601v1)
- **Claim: Average CR spectral index: $E^{-2.5}$**
  - Universal? Seen in both MW & LMC
- Earth in softer-than-typical fluctuation due to discrete sources

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

Fermi Model Spectrum

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



- Diffuse emission from the plane dominated by

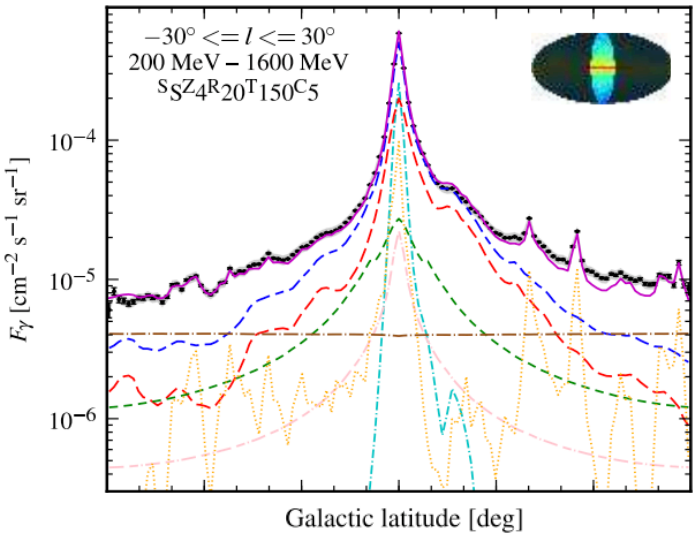
  pion decay

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

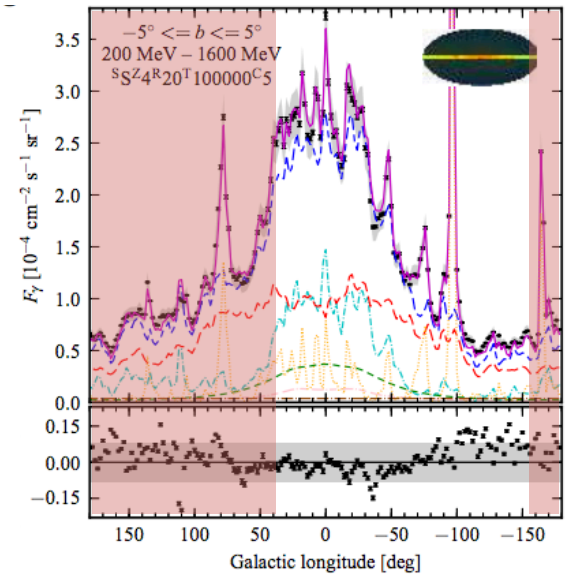
M. Ackermann et al 2011
arXiv:1202.4039v2

Model Profiles

Latitude Profile



Longitude Profile



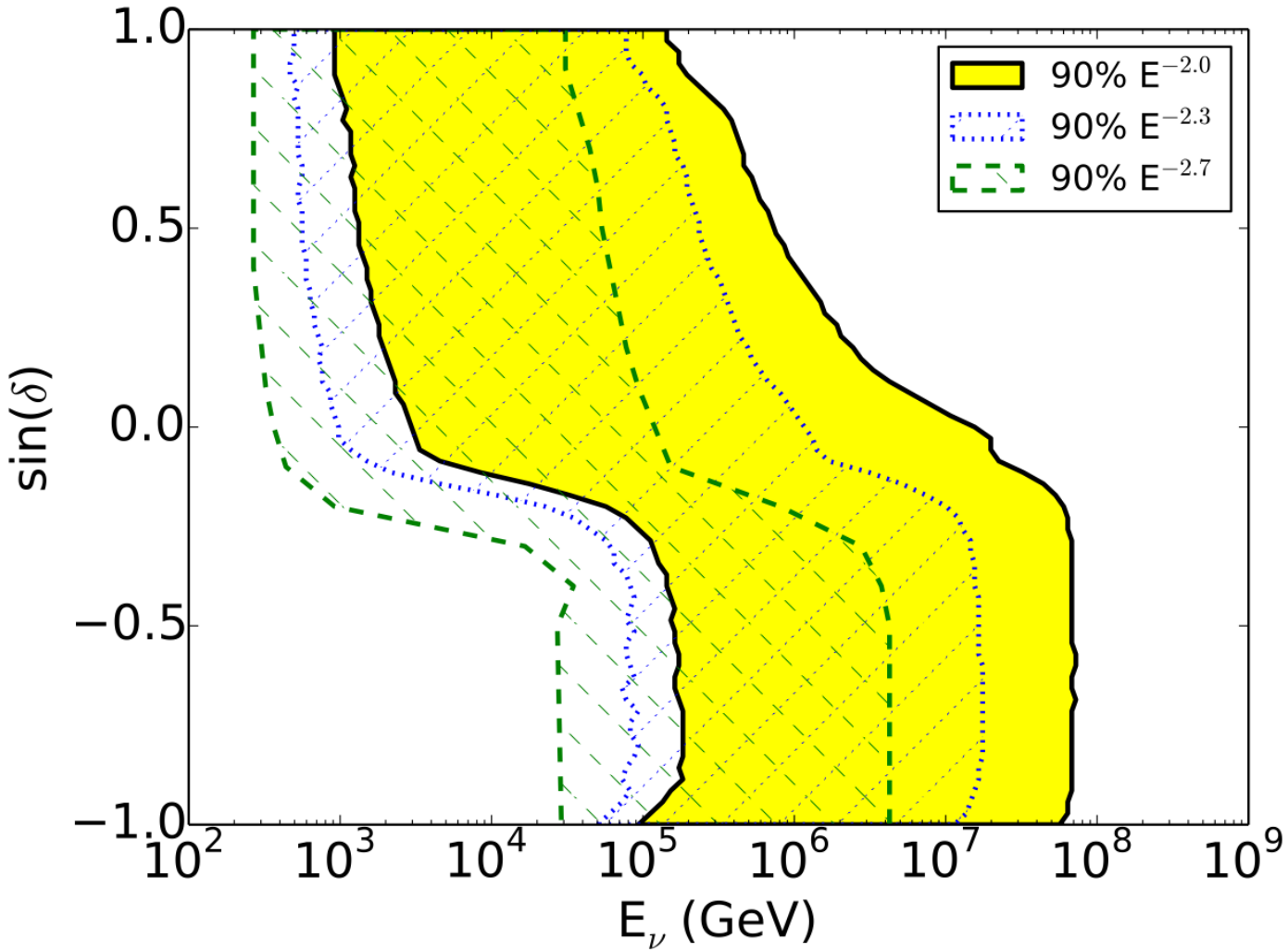
- Northern sky integrates about 1/3 of the pion decay model

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

Northern Sky: IC Sensitive

M. Ackermann et al 2011
arXiv:1202.4039v2

Energy Range of 4-year PS



Unresolved Source Pops

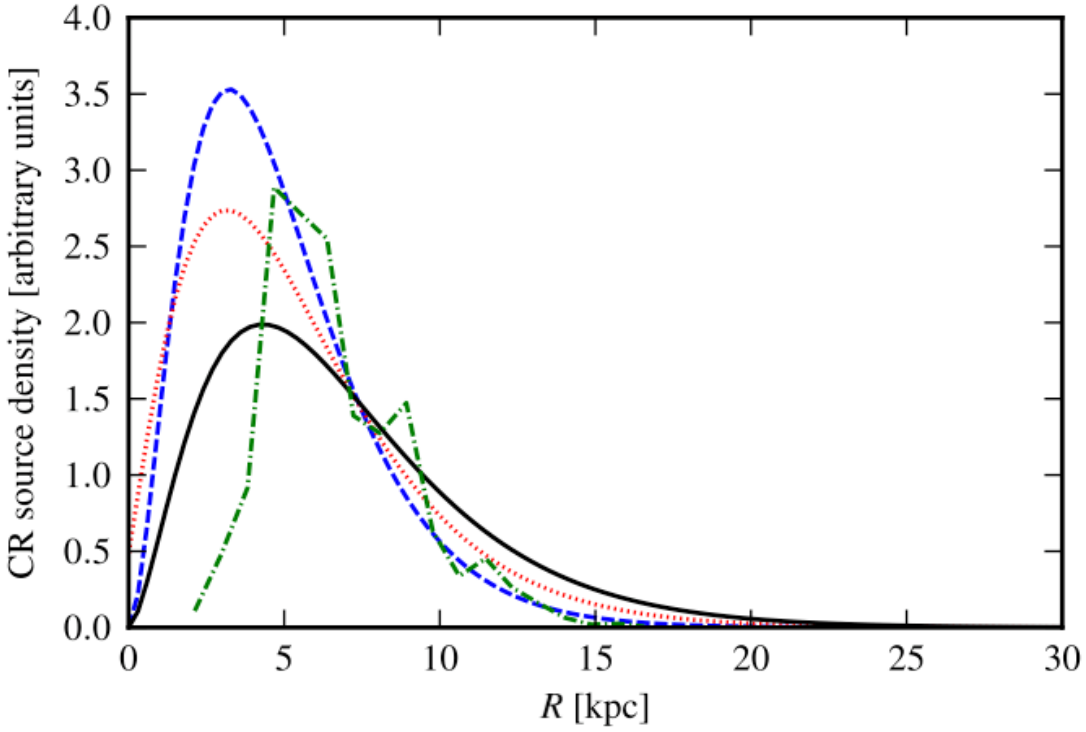


Fig. 1.— CR source density at $z = 0$ in arbitrary units as a function of Galactocentric radius. Solid black curve: SNRs (Case & Bhattacharya 1998). Dashed blue curve: Pulsars (Lorimer et al. 2006). Dotted red curve: Pulsars (Yusifov & Küçük 2004). Dash-dotted green curve: OB stars (Bronfman et al. 2000). While the units are arbitrary, the relative normalisations of the curves in the figure match those found in the *GALPROP* models used in this analysis. The CR flux of the models is normalised to the observed CR flux at the solar circle after propagation. The normalisation is done at 100 GeV and is therefore unaffected by modulation.

Next step: set up a MC to generate source populations and see what kinds of limits we can set to these scenarios