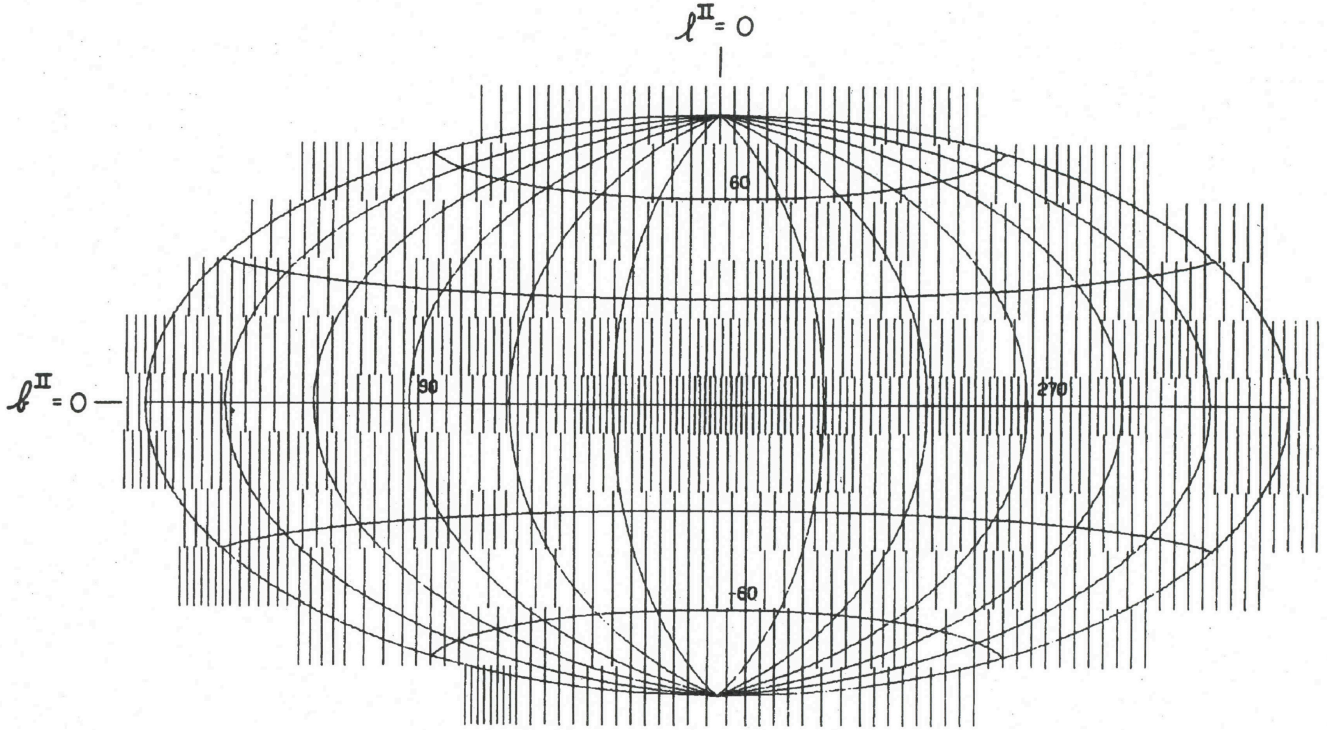
Neutrinos and γ-rays in the Milky Way



Jon Dumm

MANTS

02 Oct 2016

Stockholm University

Oskar Klein centre

> 50 MeV, OSO 3 (1967)

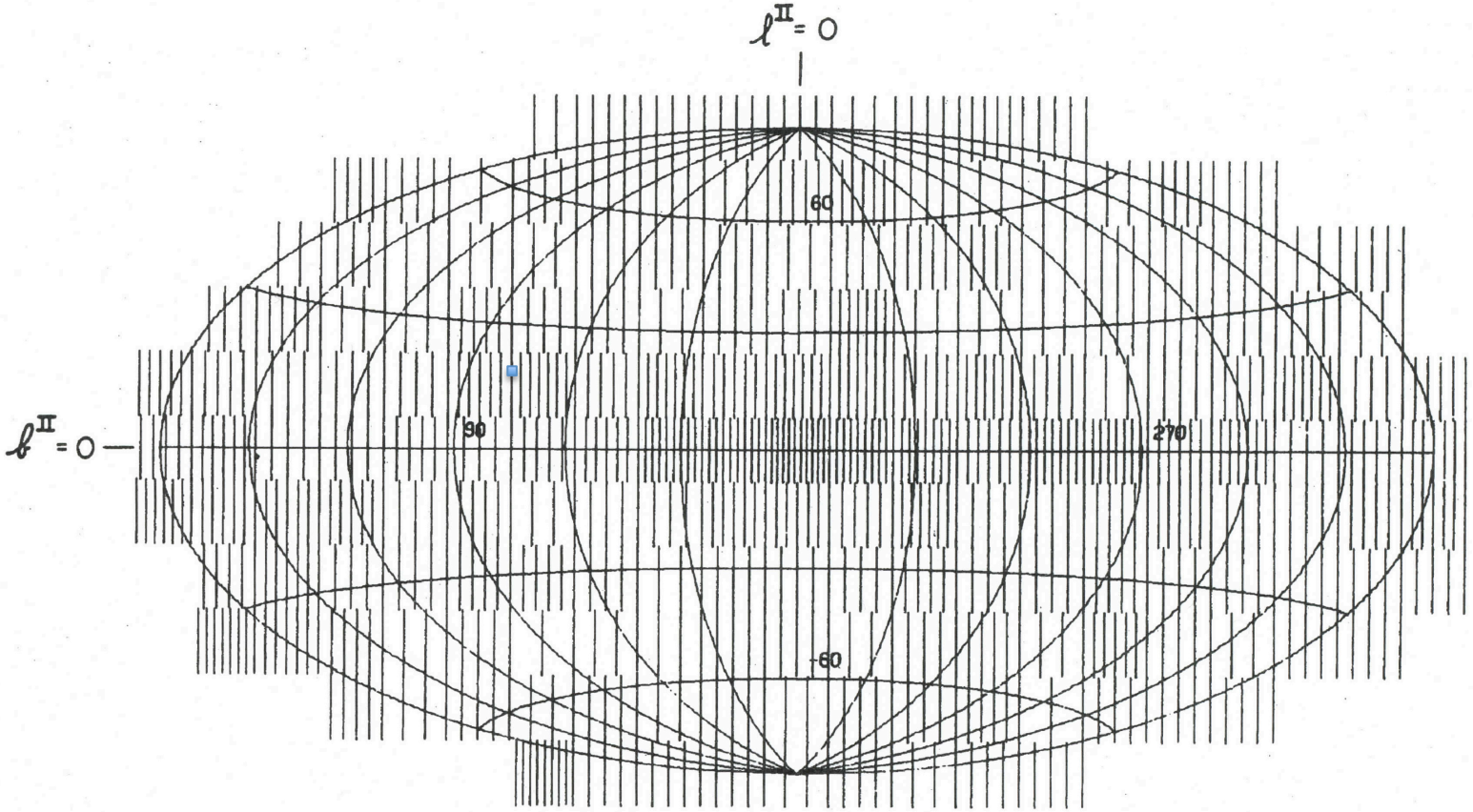
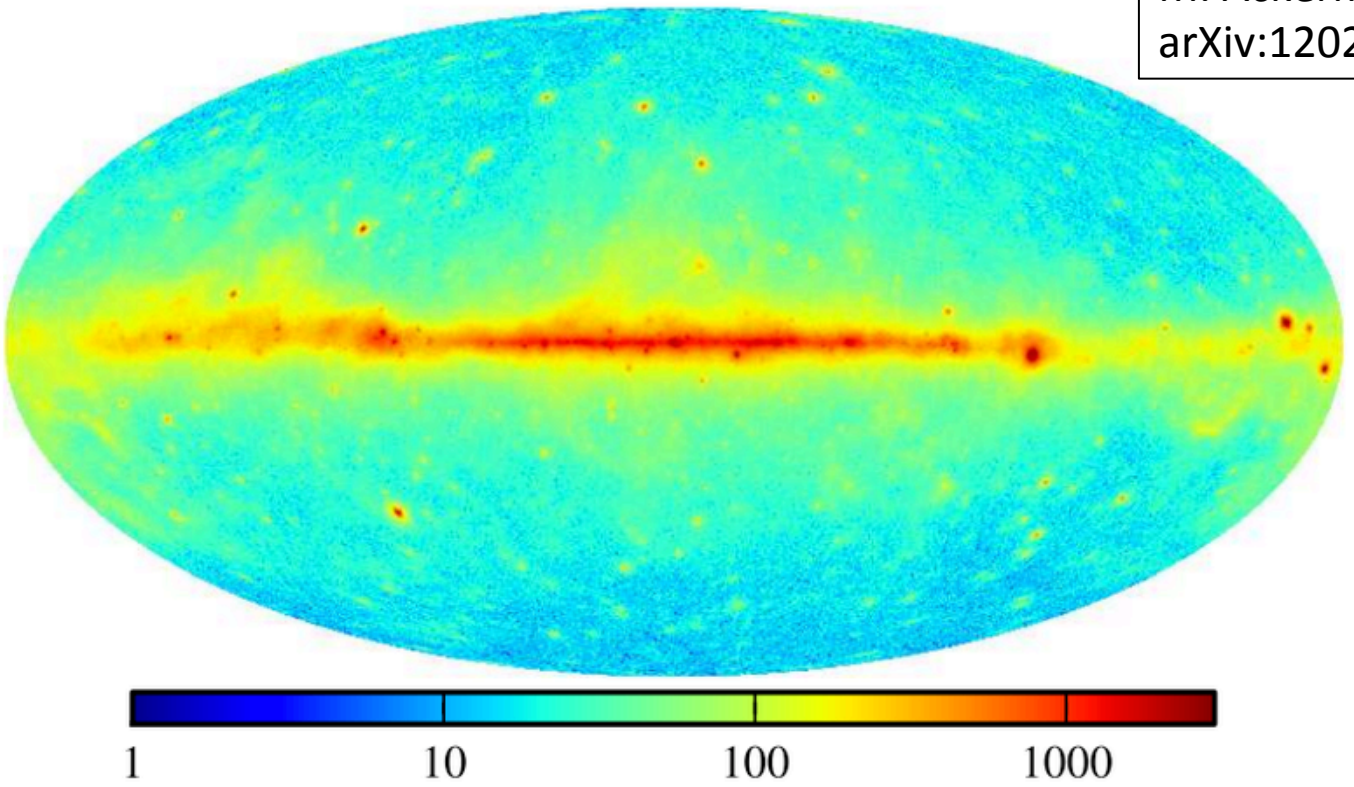


figure: http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/x-ray/science/index.html

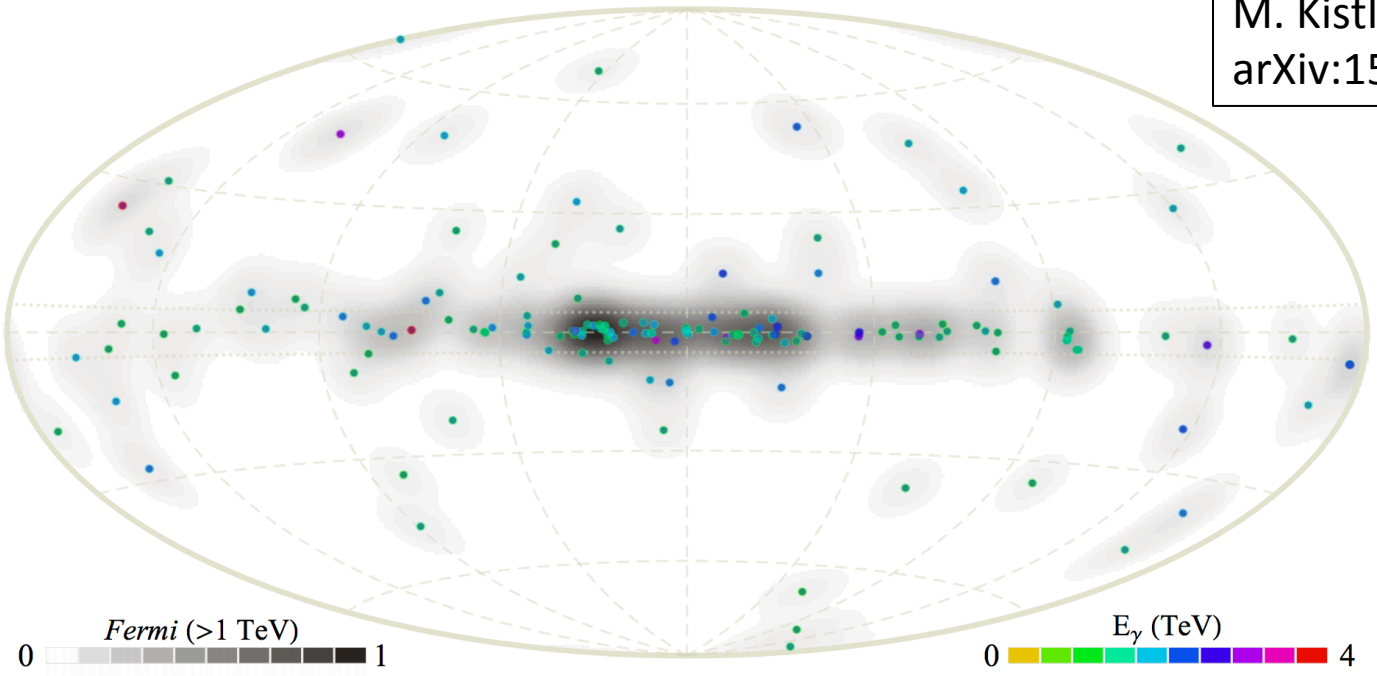
> 100 MeV, *Fermi*-LAT (2012)

M. Ackermann et al.
arXiv:1202.4039



> 1 TeV, *Fermi*-LAT (2015)

M. Kistler
arXiv:1511.05199



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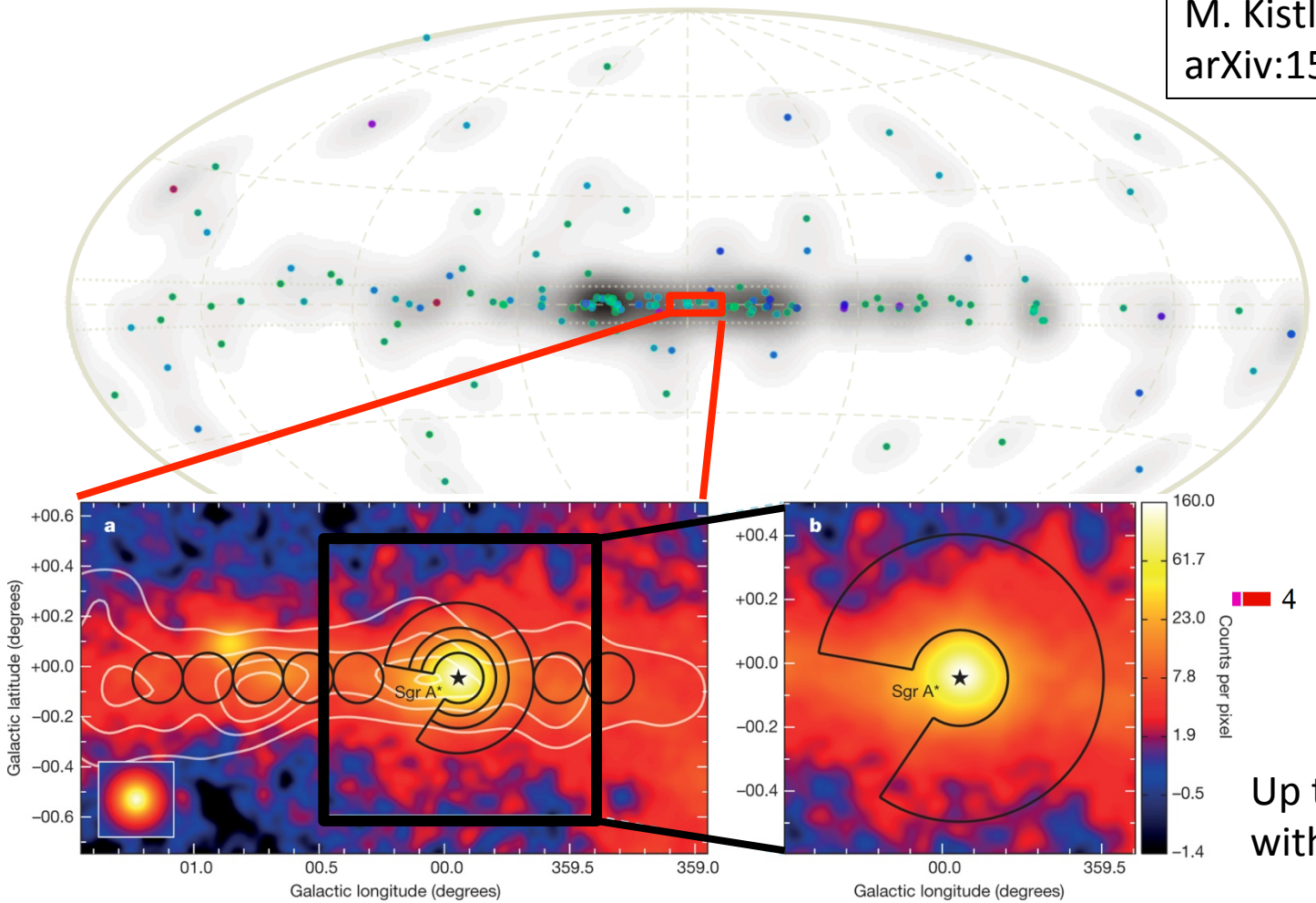
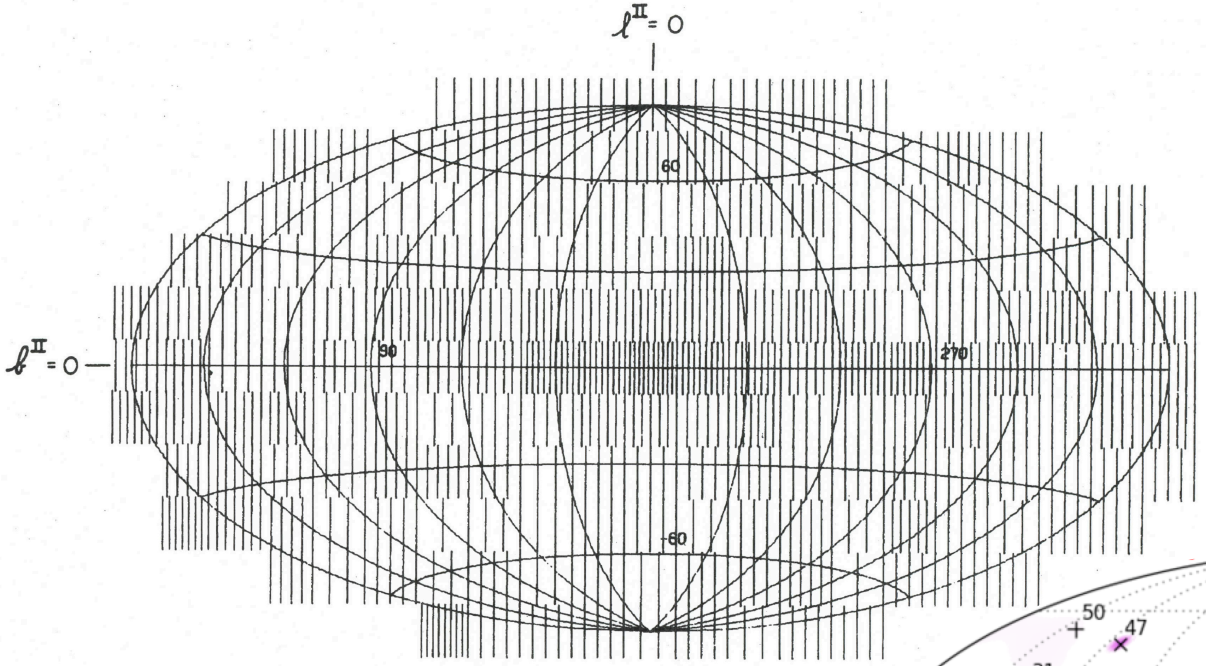
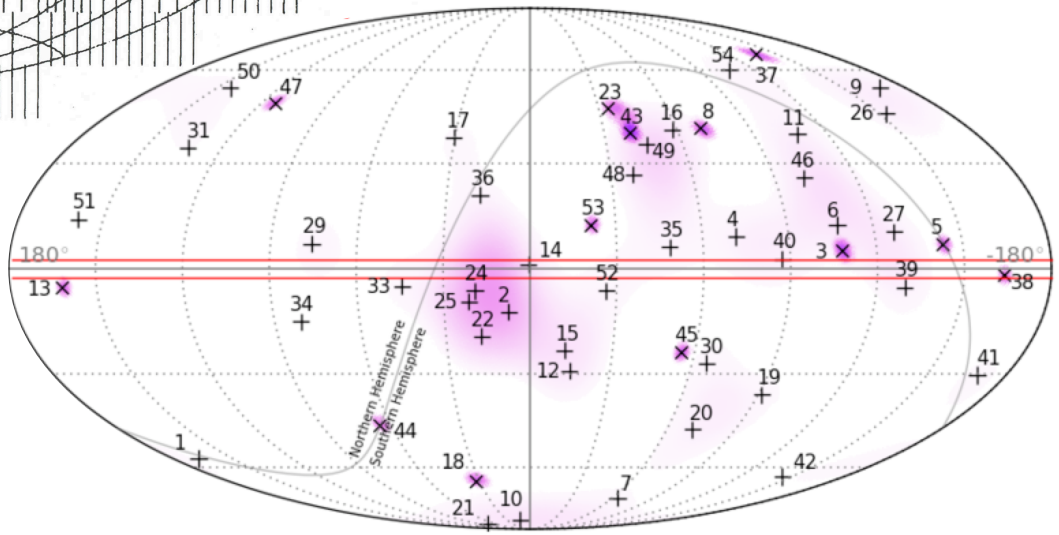


Up to 10 TeV
with no cut-off!

HESS Collaboration. *Nature* 1–4 (2016) doi:10.1038/nature17147

Origins – 47 years apart!



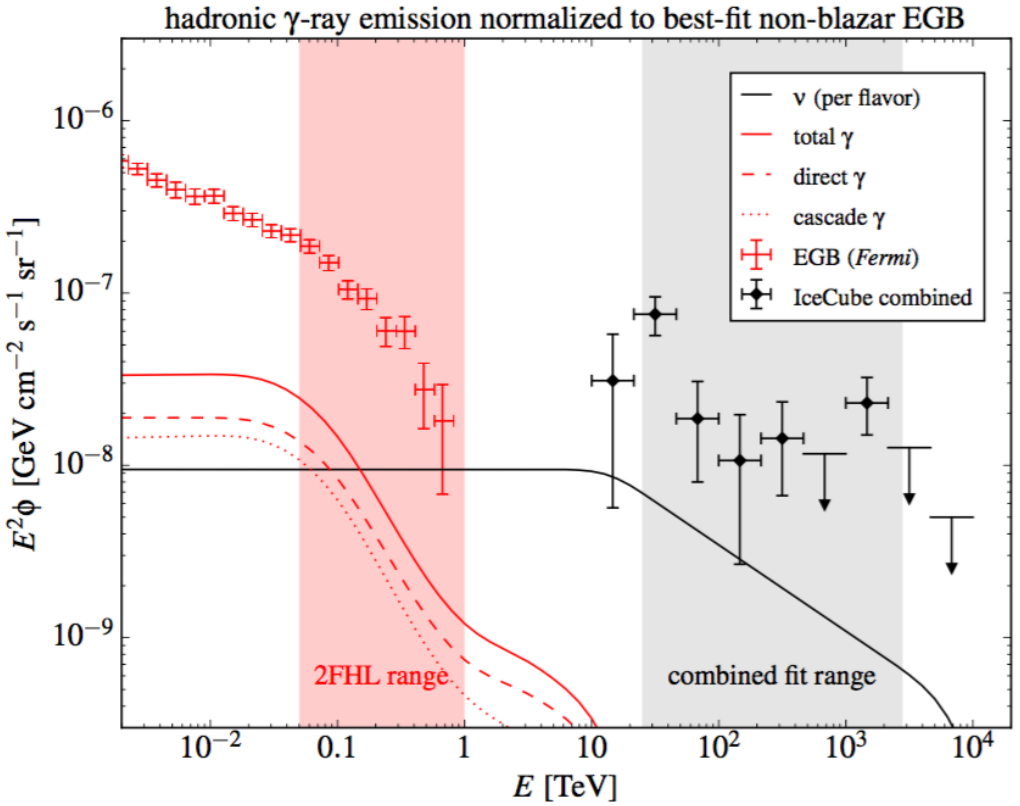


Impact of Gal Discovery
(hypothetical)

- Establish Neutrino Astronomy as a ***rich*** field
- Cosmic ray distribution and transport in the galaxy
  - Guaranteed flux at some level
  - Large multimessenger impact
- Gal plane is poster child for GNN
  - Unresolved sources vs diffusive emission

Convenience of Gal Signal

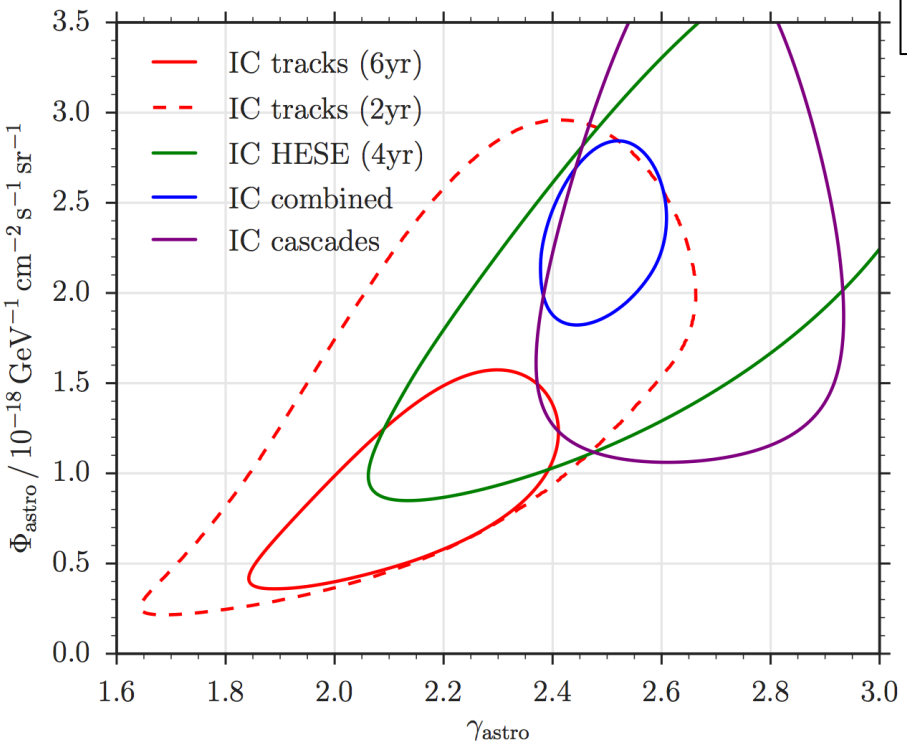
- Starbursts, blazars, GRBs all strongly constrained



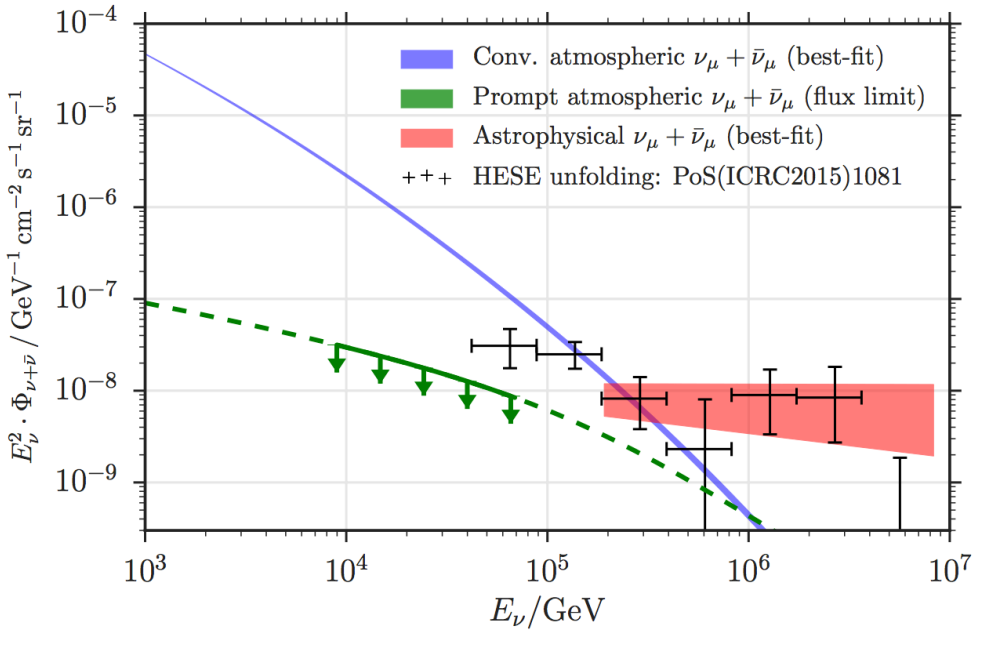
Betchol et al 2015
arXiv:1511.00688v1

- The extra-gal gamma-ray background (EGB) is mostly (86%) filled up by blazars
- Direct+cascaded gamma-ray emission show SFG at most 15% of the IceCube flux

Convenience of Gal Signal



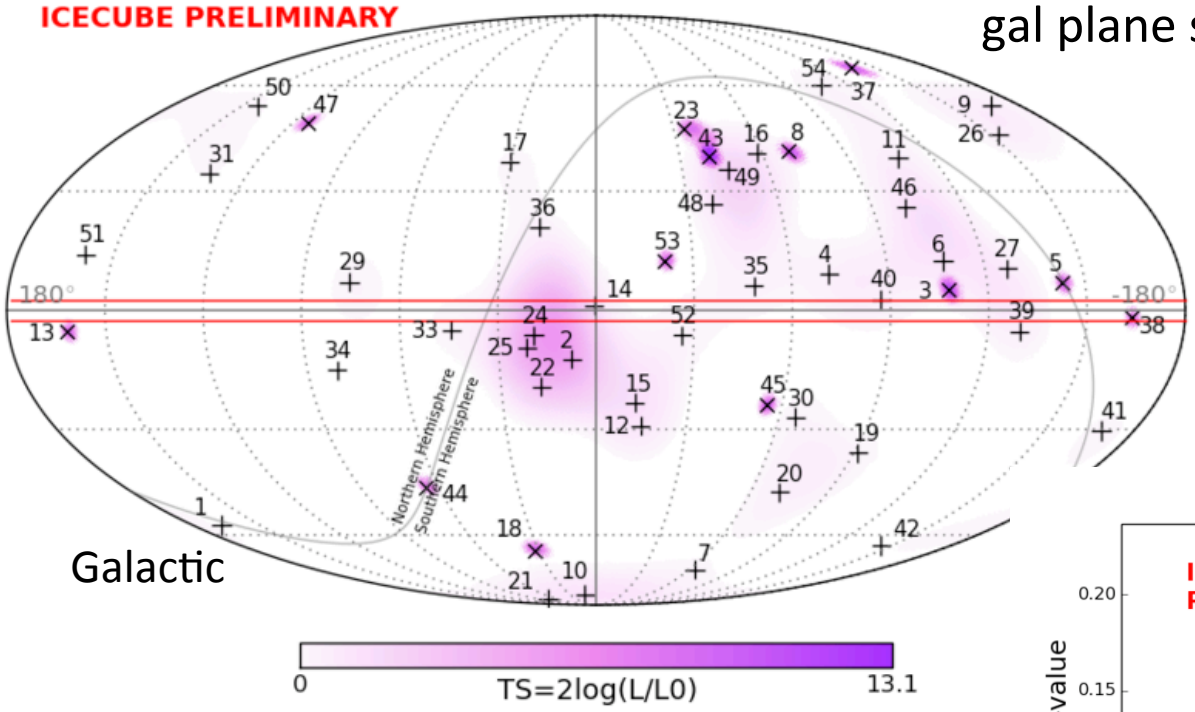
arXiv:1607.08006



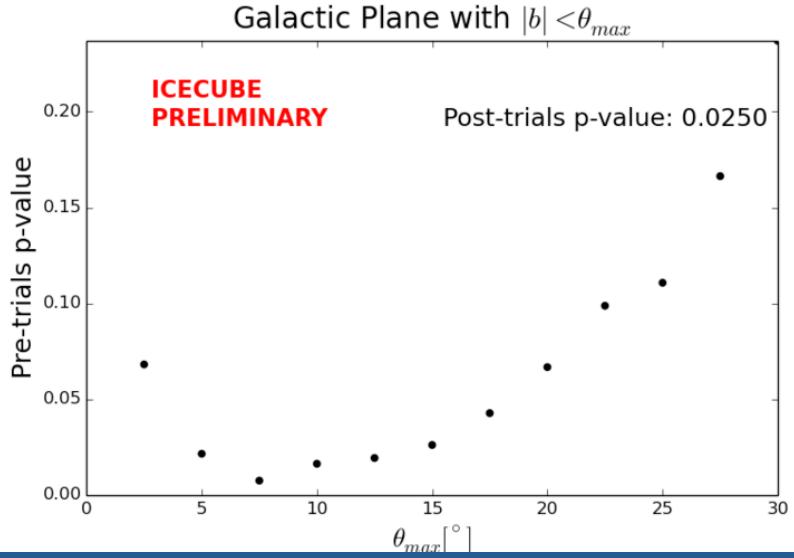
- Tension between IceCube analyses assuming power law
  - Energy threshold or not isotropic?

High-Energy Starting Events

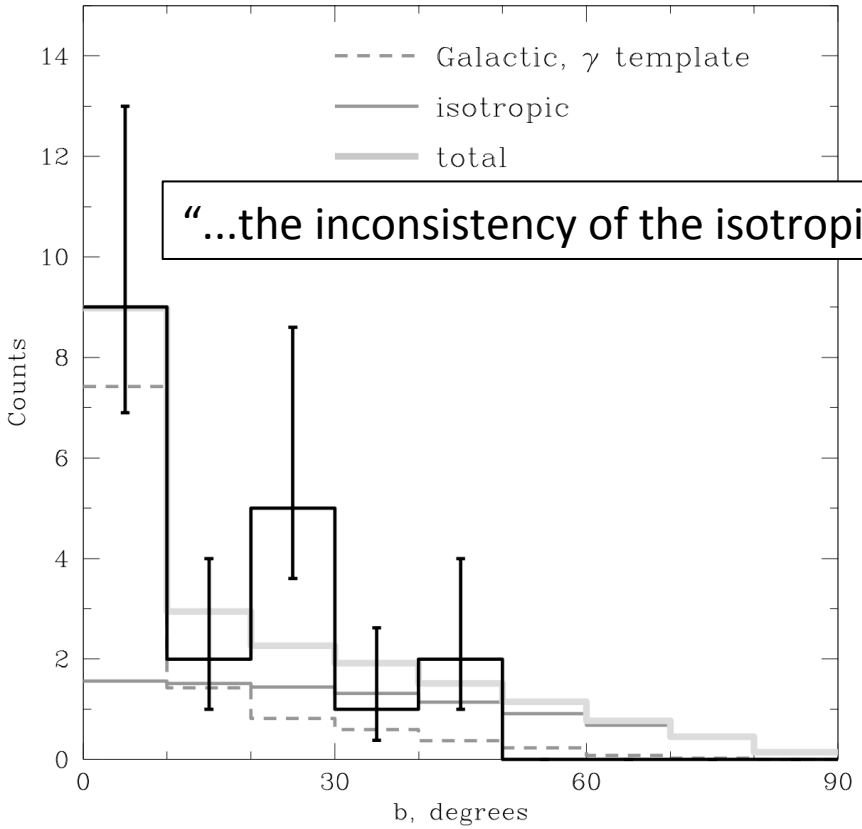
- Post-trial p-value in 4-year HESE: 2.5% gal plane scan within ± 7.5° gal latitude

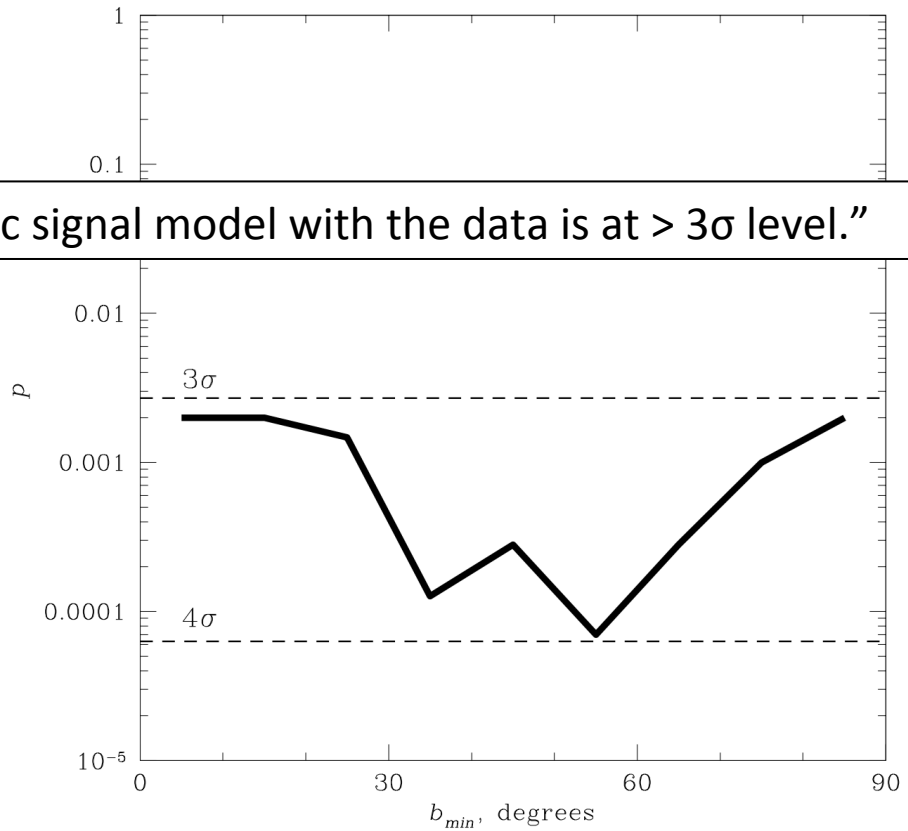


Galactic



>100 TeV *A Posteriori*



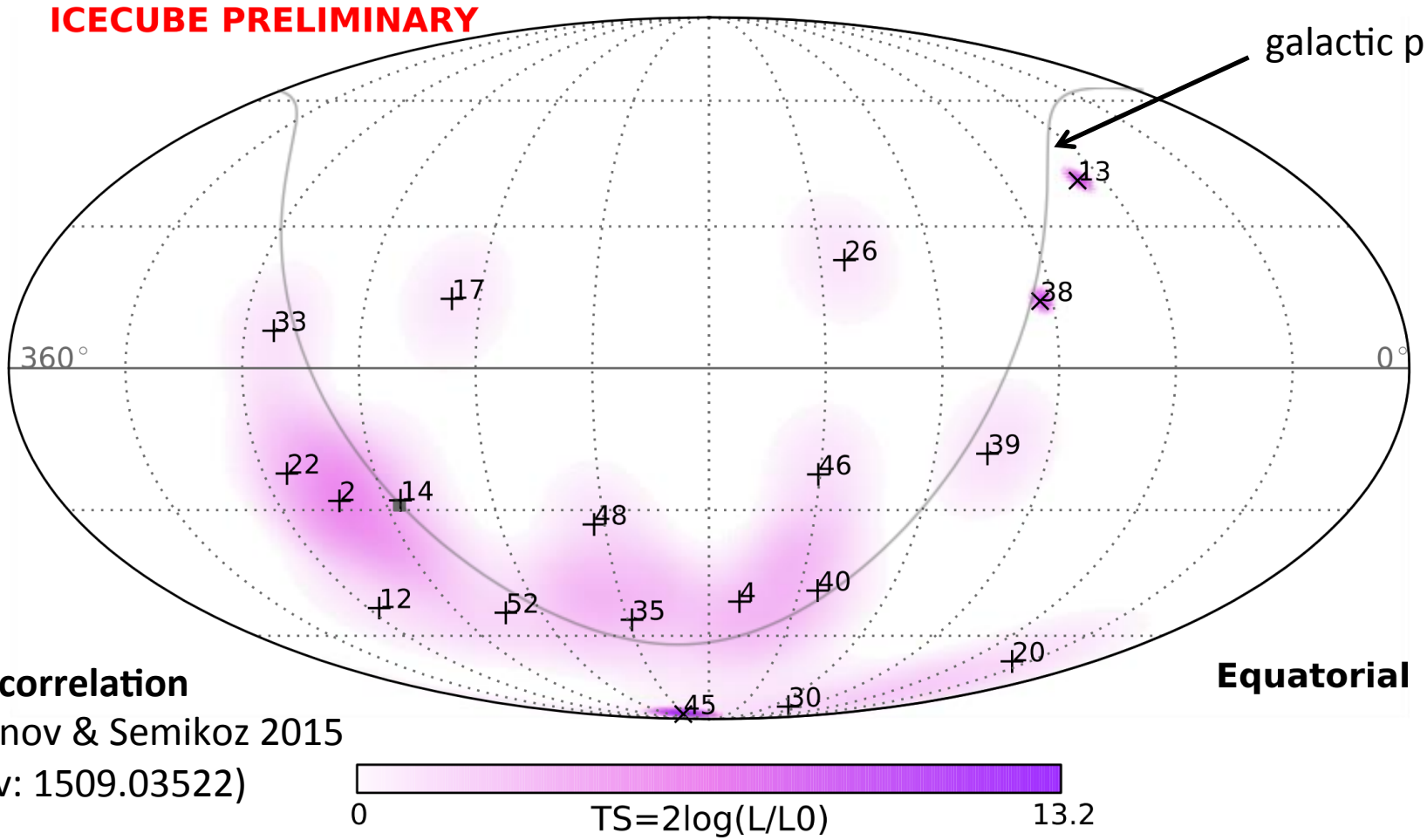


"...the inconsistency of the isotropic signal model with the data is at > 3σ level."

"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)

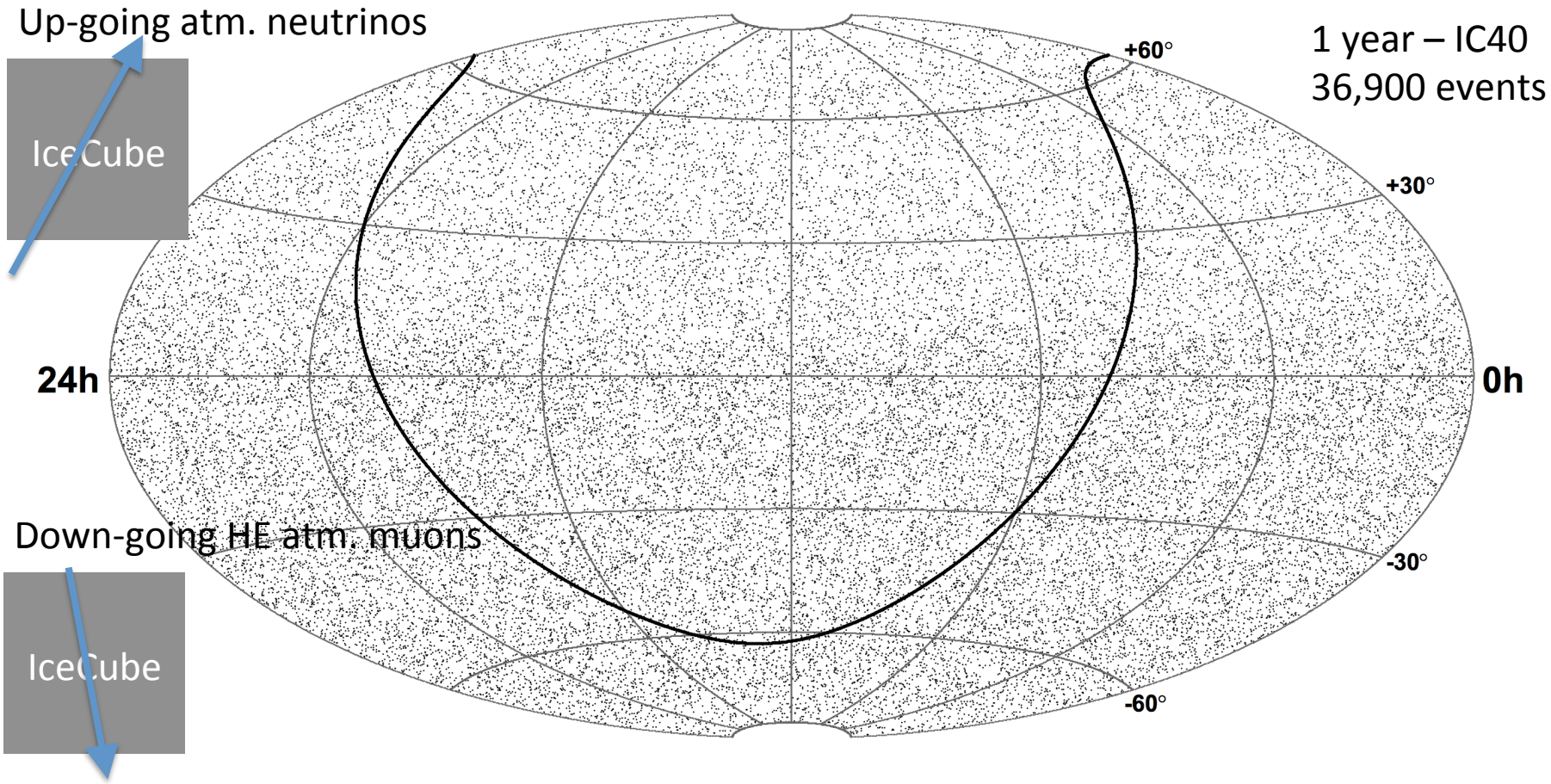
>100 TeV *A Posteriori*



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

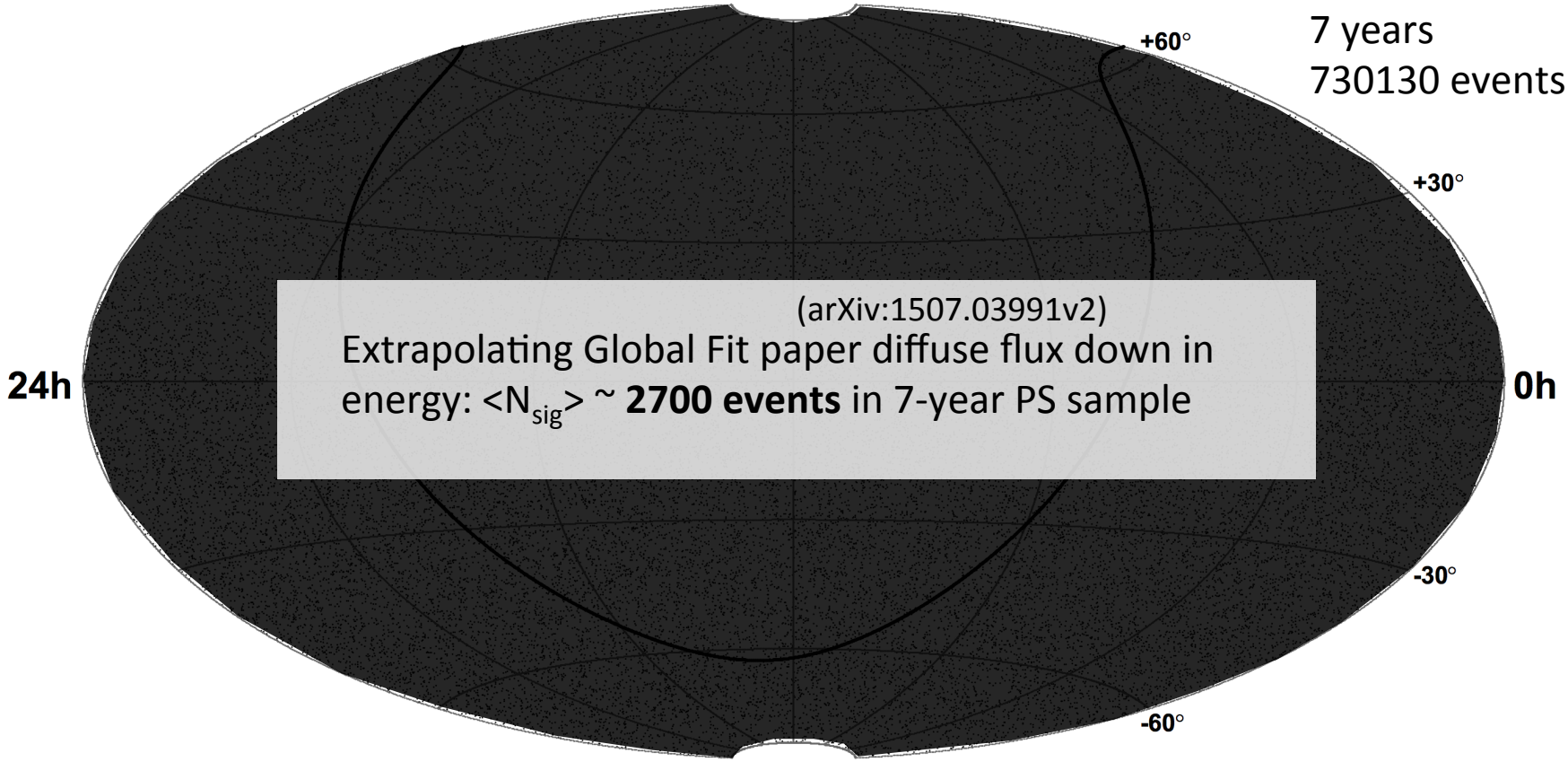
- **Limited by small statistics of sample**

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?

7 Years of PS Data

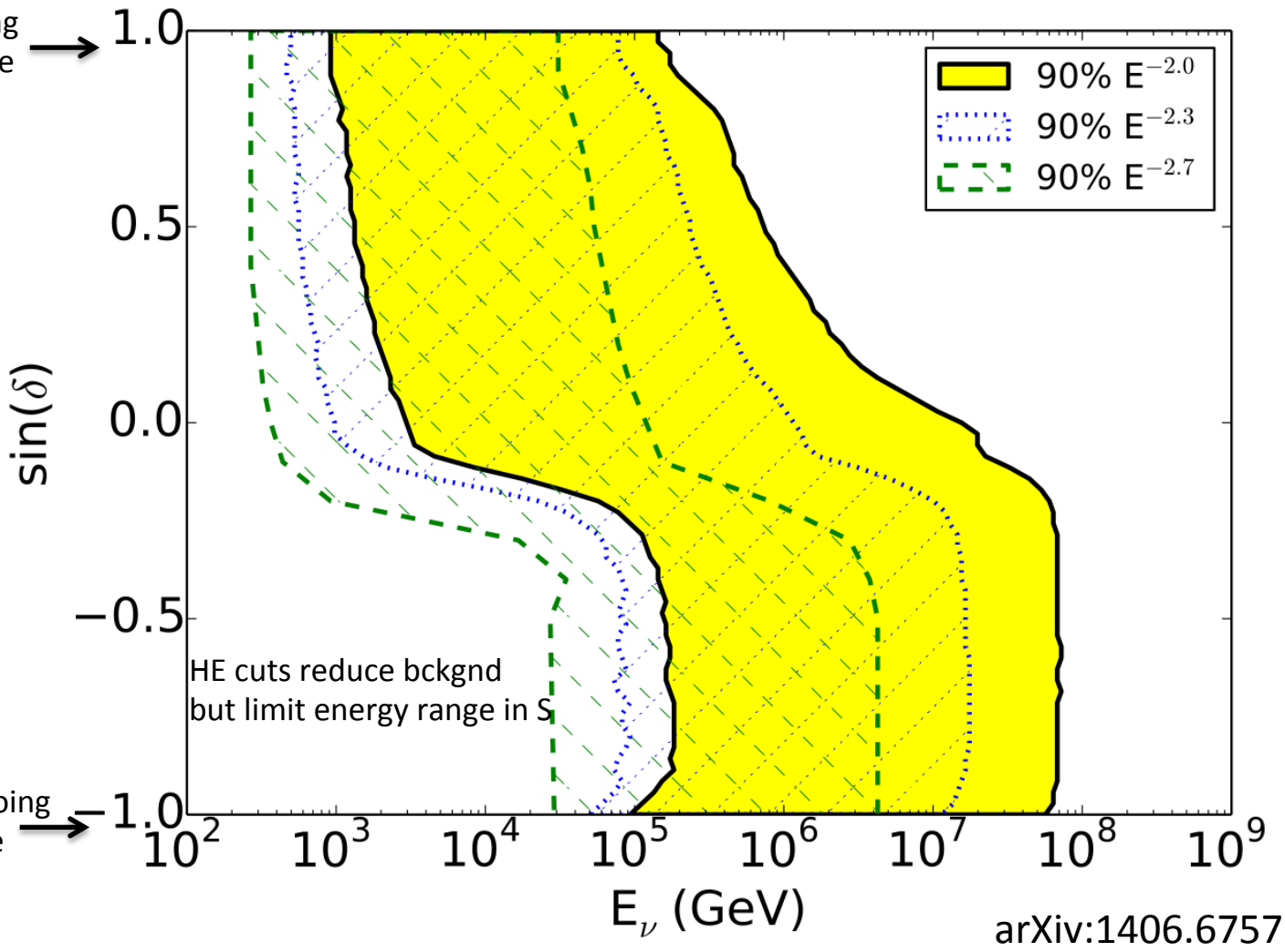


- Too many events to show full sample – 40-string sample for illustration
- Can we find some ~hundreds of events distributed along the plane?

Energy Range for N/S

Vertically upgoing events in IceCube →

Vertically downgoing events in IceCube →

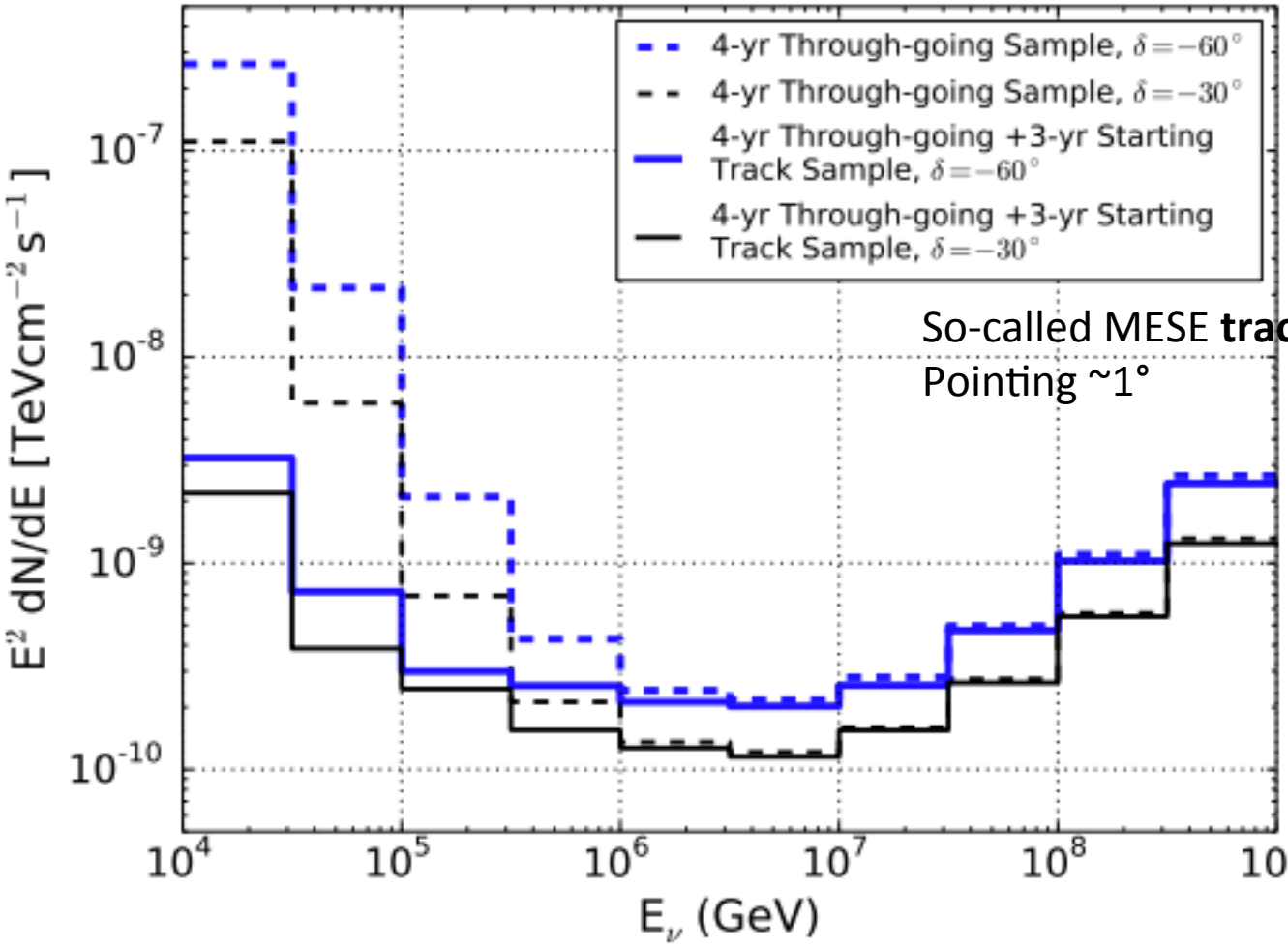


arXiv:1406.6757

Includes Starting Tracks

Lowering IceCube's Energy Threshold for Point Source Searches in the Southern Sky

arXiv:1605.00163



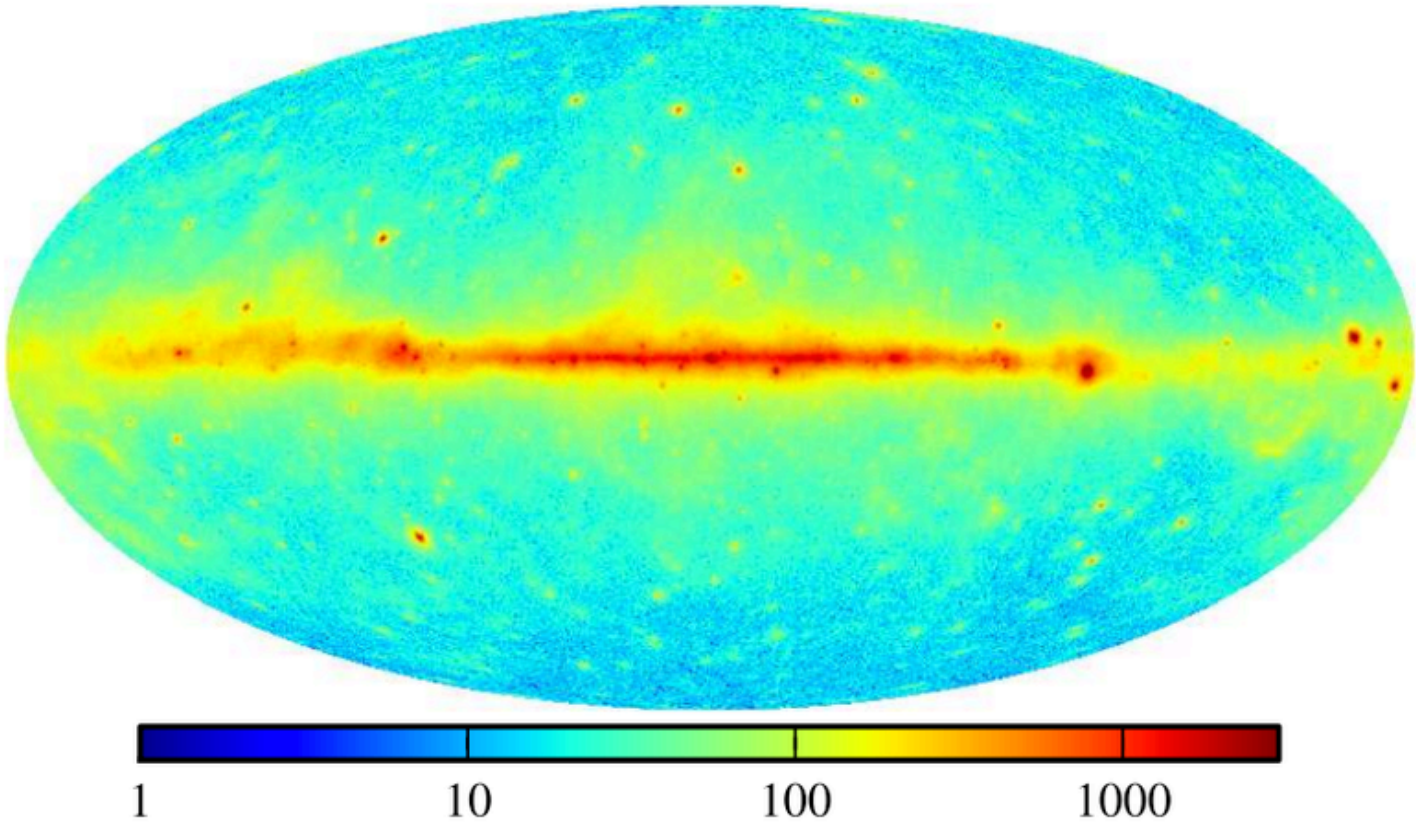
So-called MESE **tracks** included

Pointing ~1°

The Milky Way

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

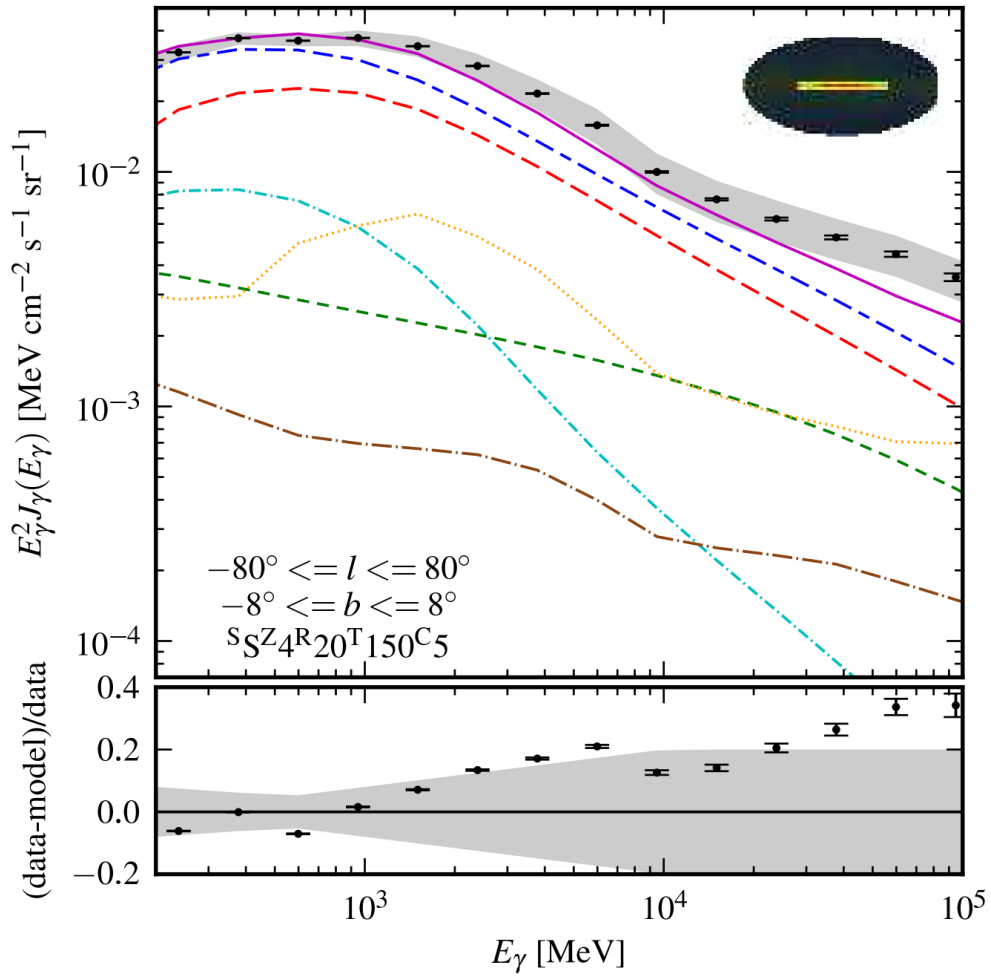
- The model is built using surveys of H_1 & H_2
  - H_1 and H_2 make up 70% of the matter in ISM, itself 99% gas
  - H_1 observed from 21-cm line → 3D map from Doppler shift
  - H_2 observed from 2.6-mm CO line since CO only formed in presence of H_2
  - Heavier elements assumed distributed as H_1 & 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

- Only the Pion-decay component used for neutrino template

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**

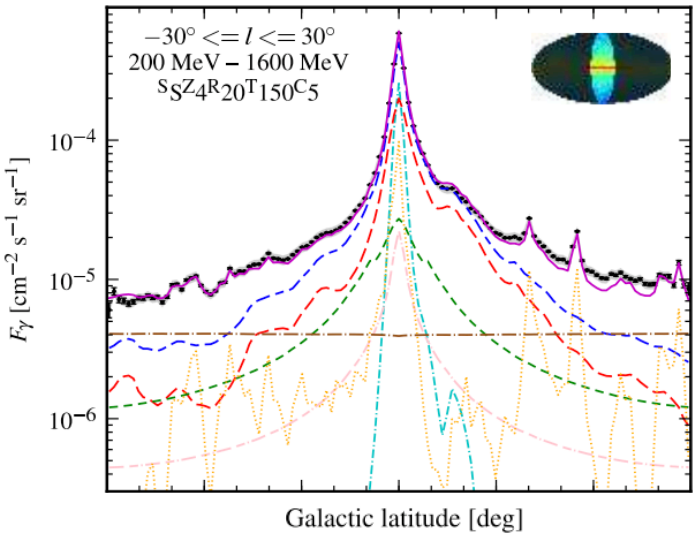
Total 'characterized' emission
Diffuse Galactic emission
Pion decay
Sources
Inverse Compton
Isotropic Extragal.
Bremsstrahlung

- Diffuse model assumes CR spectrum observed at Earth

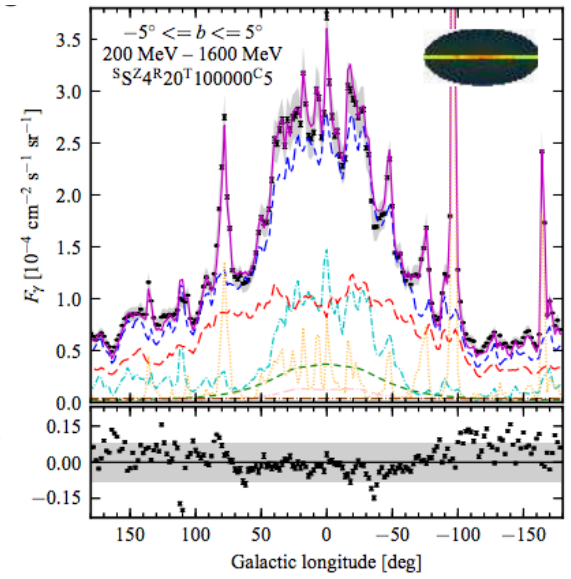
M. Ackermann et al 2011
arXiv:1202.4039v2

Model Profiles

Latitude Profile



Longitude Profile



Total 'characterized' emission
Diffuse Galactic emission
Pion decay
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Model Profiles

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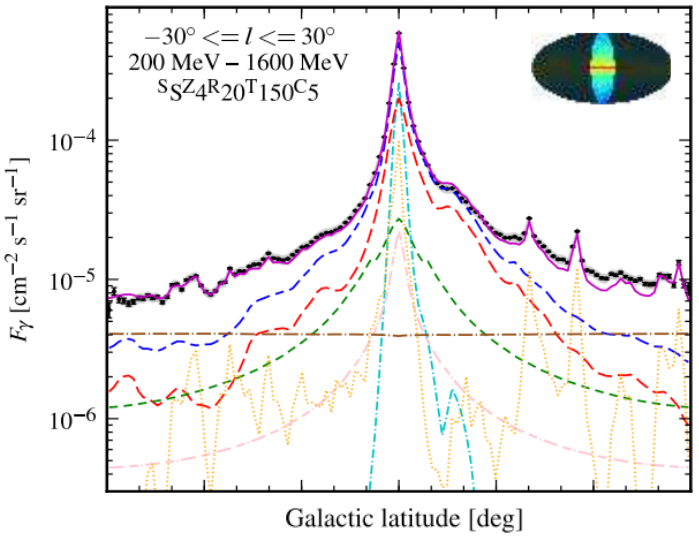
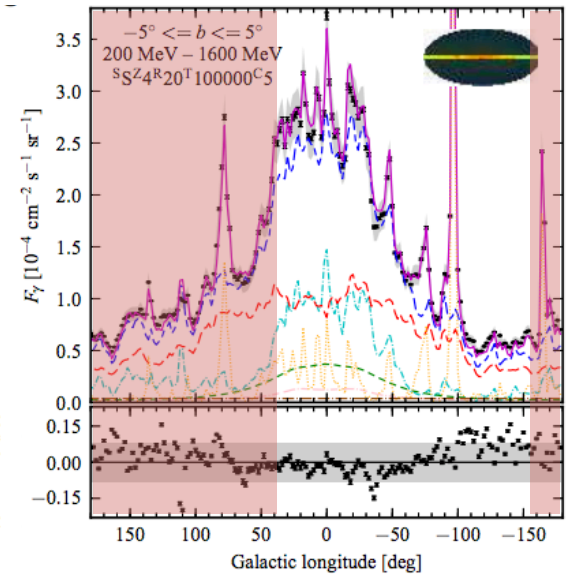


Longitude Profile



- 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

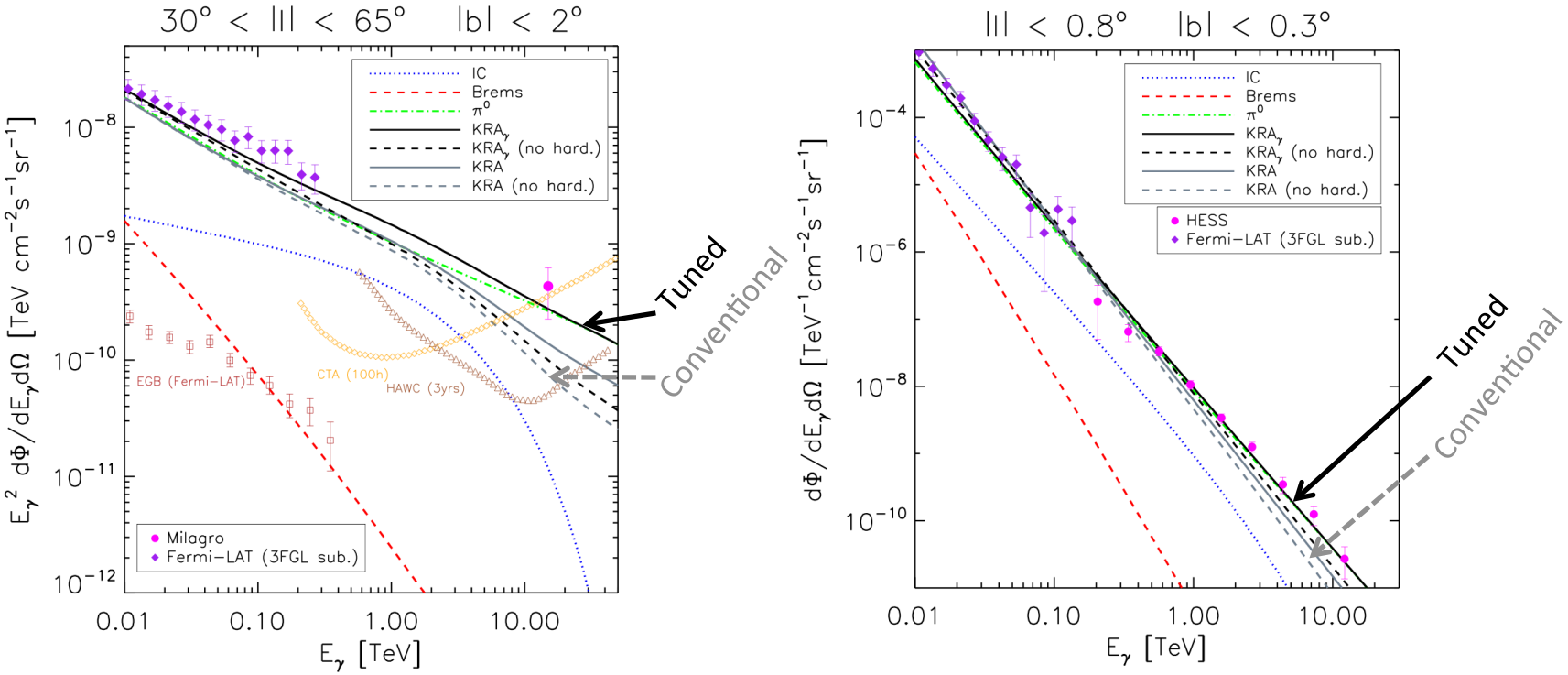
Northern Sky: IceCube Sensitive in muons

M. Ackermann et al 2011
arXiv:1202.4039v2

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
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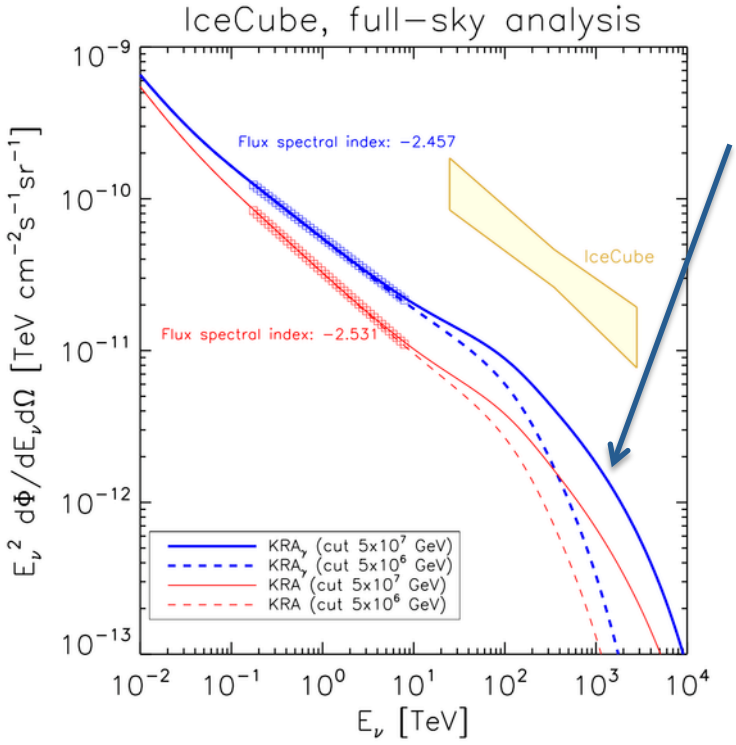
γ-ray Models → ν predictions



After tuning CR propagation to the gamma-ray data: up to ~15% of our diffuse neutrino flux

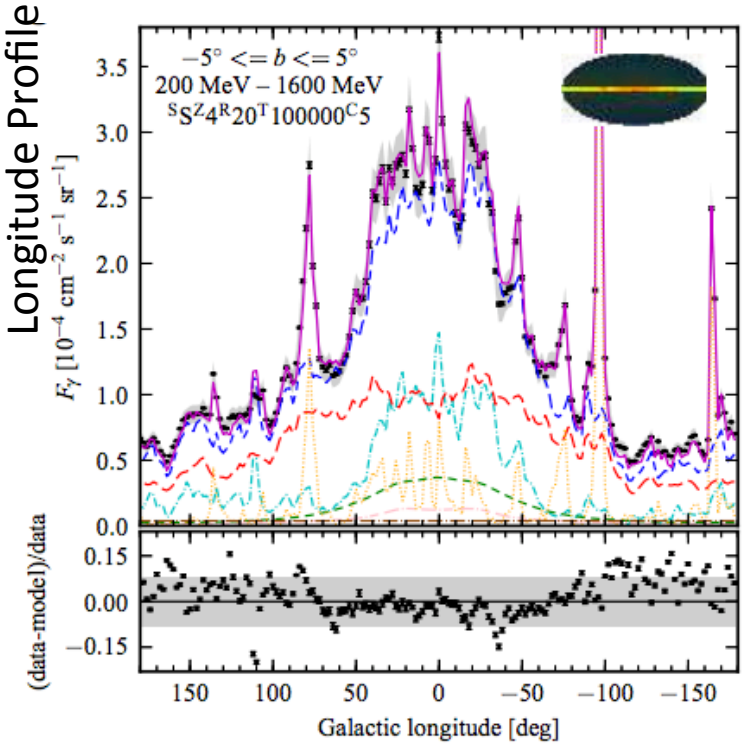
Specifics:

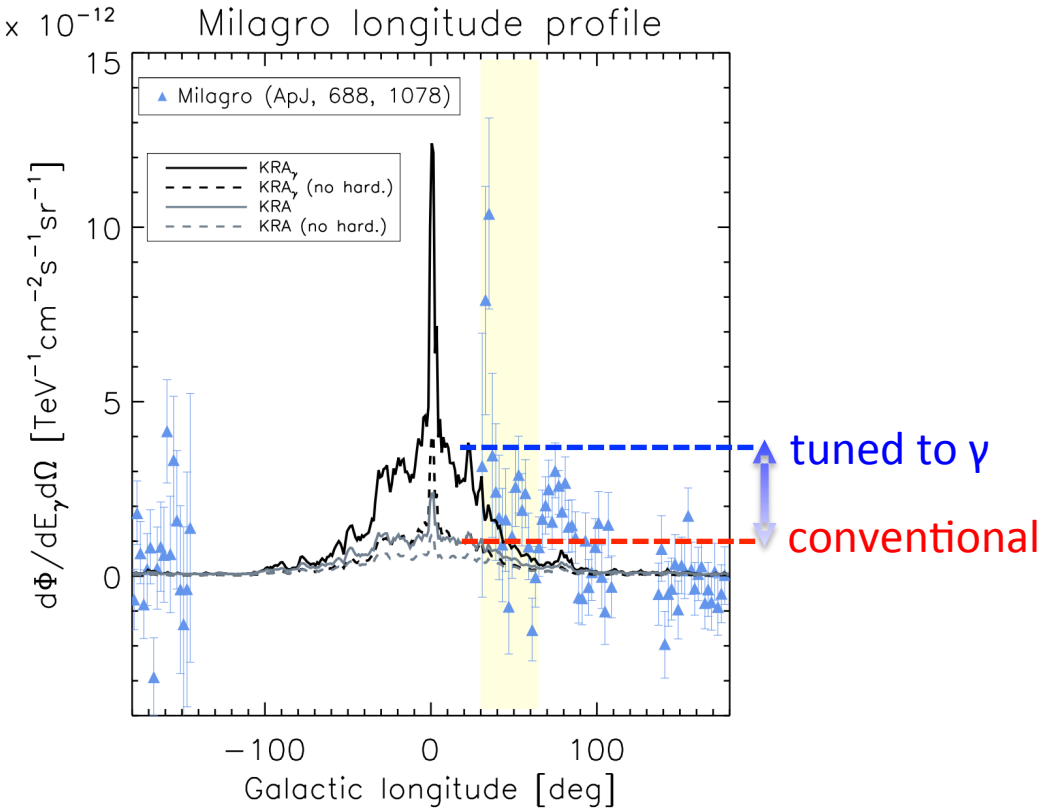
- Assumes PAMELA/AMS p & He hardening is global
- Gal CR cutoffs: 5 (dotted), 50 (solid) PeV
- red = Conventional + global hardening
- blue = Tuned to γ-ray observations (Fermi-LAT, HESS, & Milagro)

Gaggero et al 2015
arXiv:1504.00227

Large Uncertainty in Inner Galaxy

Fermi Pion-decay profile in **red**





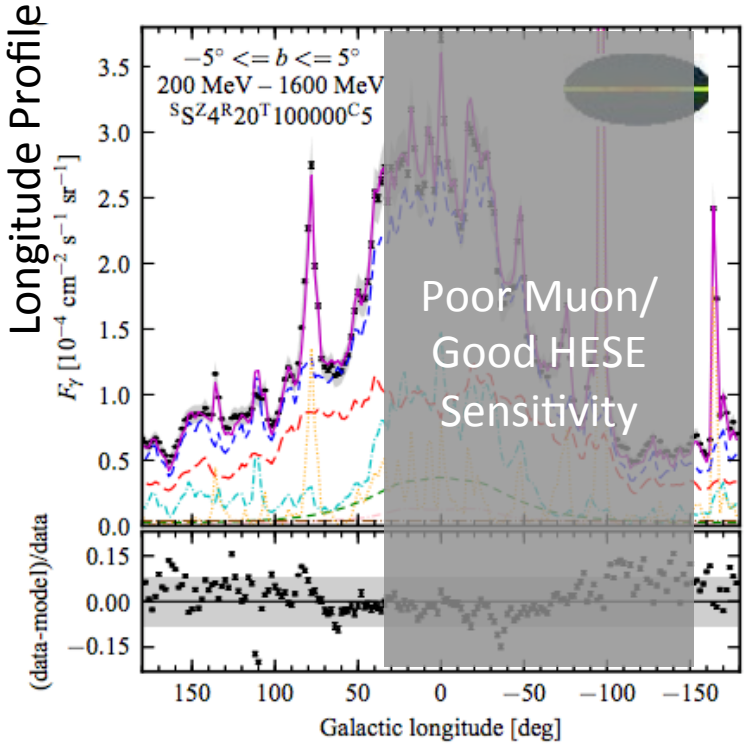
Large uncertainty in flux from inner galaxy!

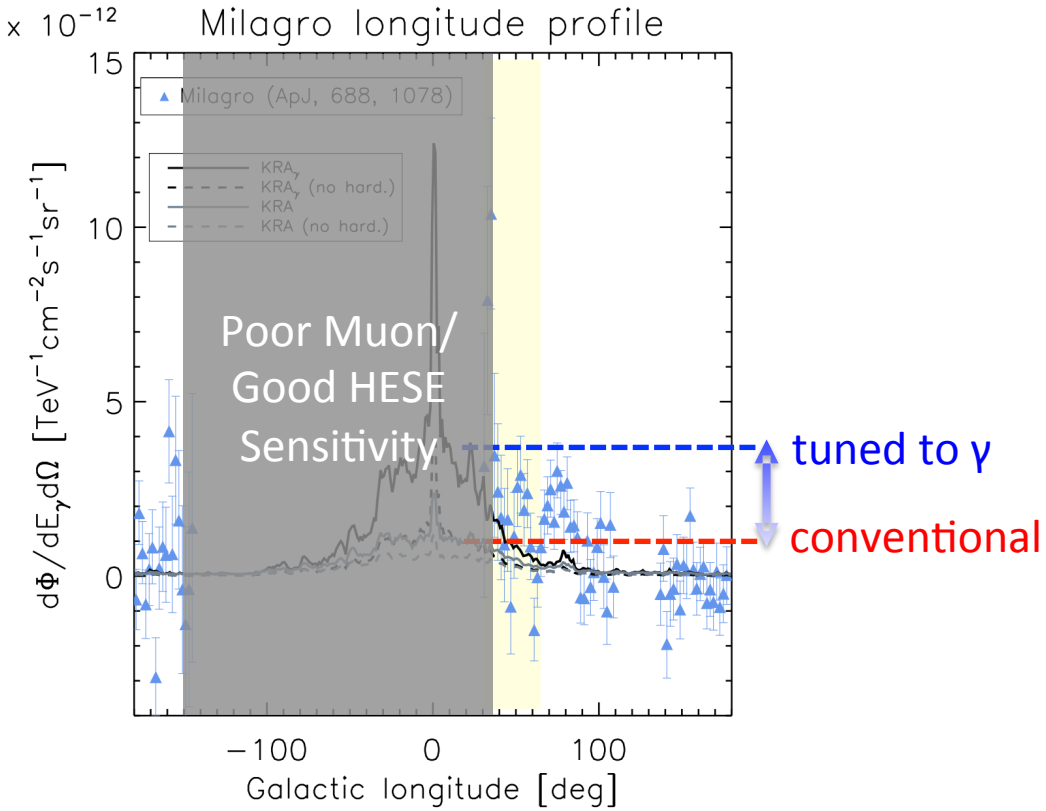
M. Ackermann et al 2011
arXiv:1202.4039v2

Gaggero et al 2015
1507.07796v1.pdf

Large Uncertainty in Inner Galaxy

Fermi Pion-decay profile in **red**





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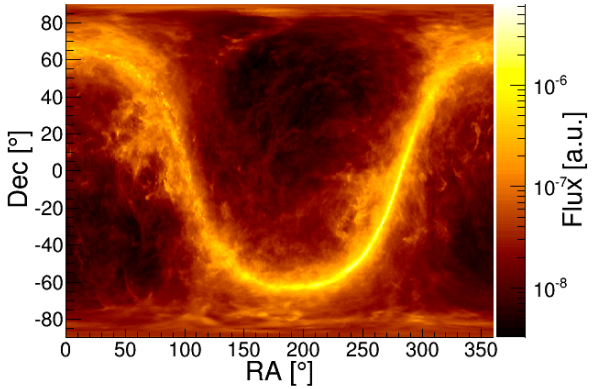
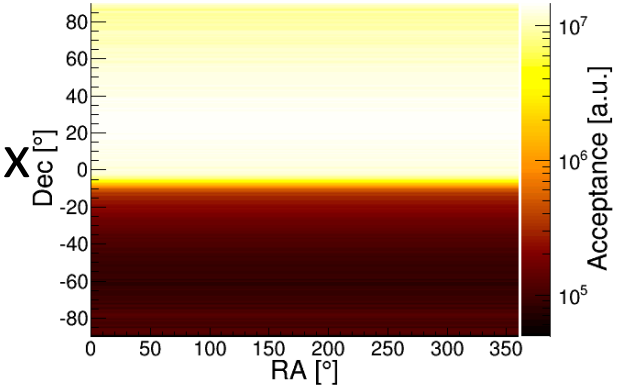
Max LH Spatial Template



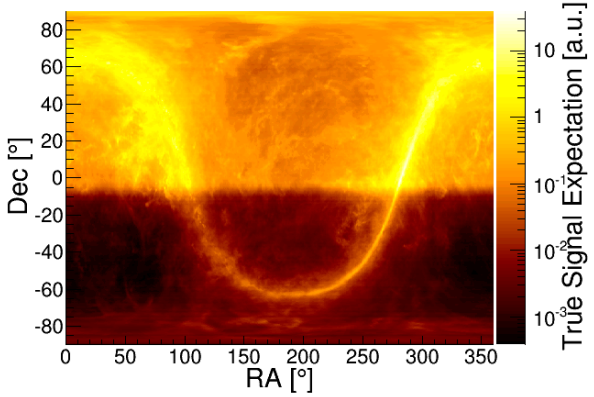
Gamma-ray Gal Plane π^0 Decay Map from *Fermi*-LAT

x



IceCube Acceptance (IC86 PS sample, $E^{-2.5}$)

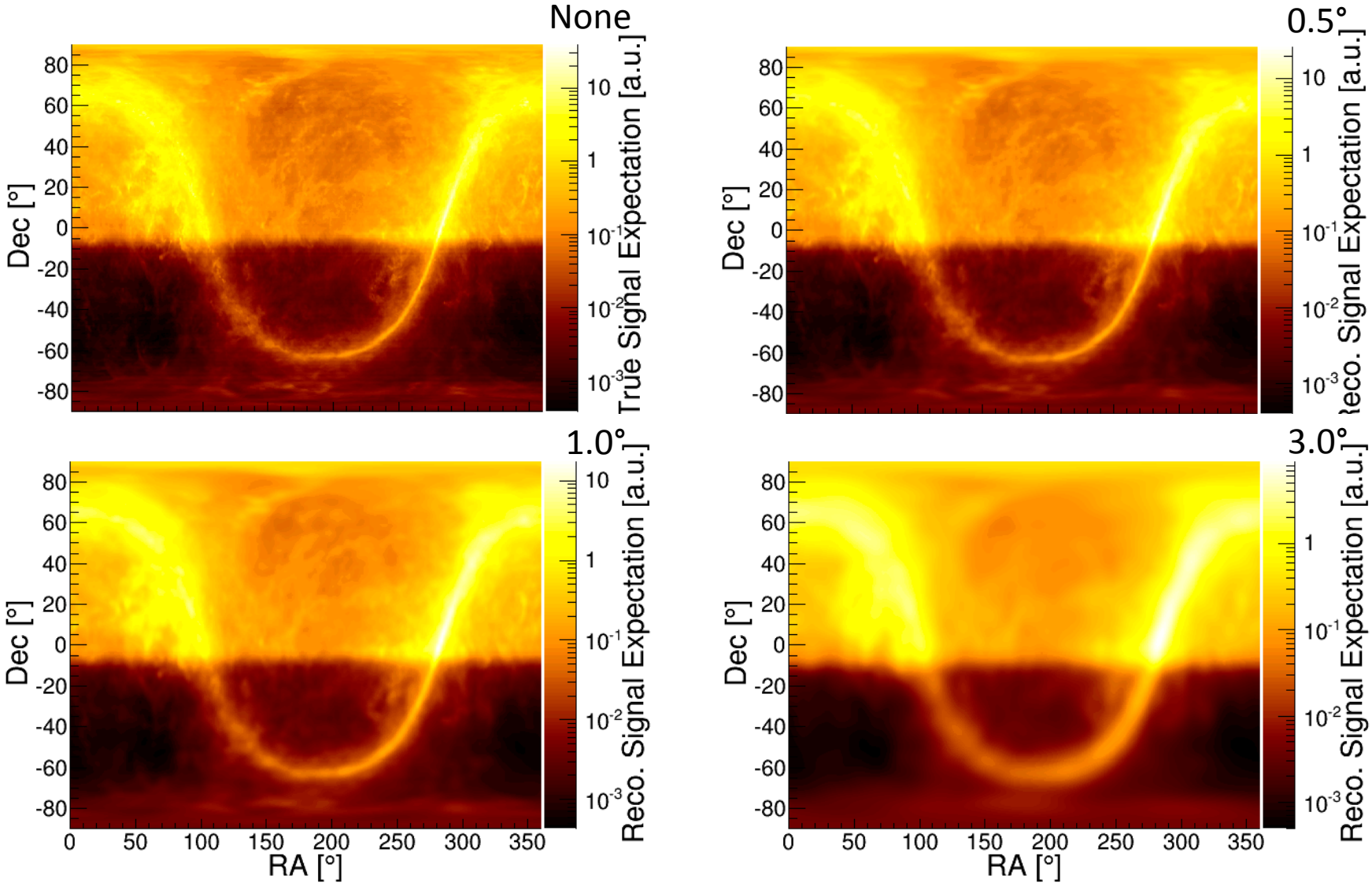
=



Where we should see neutrinos originate before PSF smearing

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

Convolutions – PSF Smearing

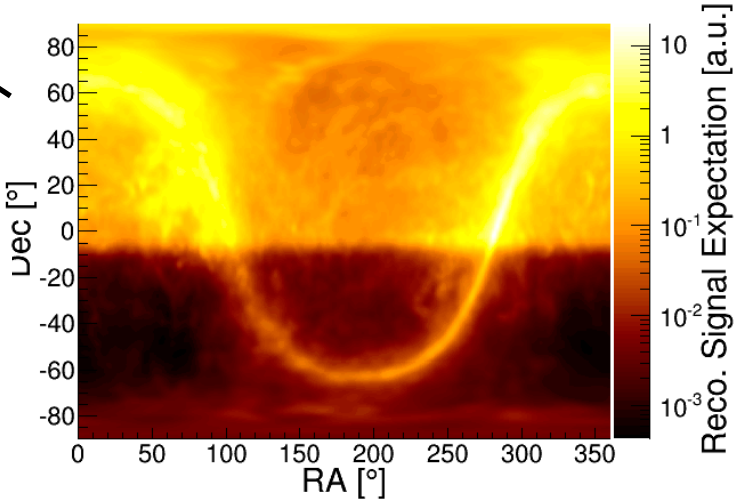


Analysis uses step size of **0.1°** for smearing

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

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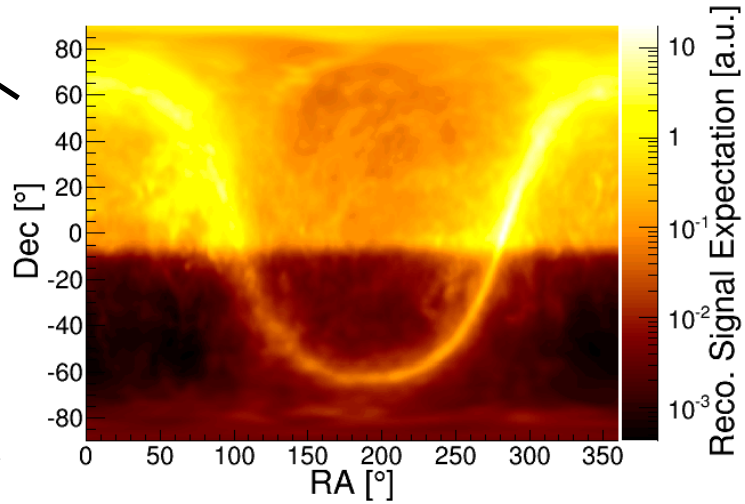
$$B(\mathbf{x}_i, E_i) = D_i(\delta_i, E_i) - \left(\frac{n_s}{n_{\rm tot}}\right) S_{sc,i}(\delta_i, E_i)$$

Data

Signal Scrambled in RA



pion-decay map + detector acceptance

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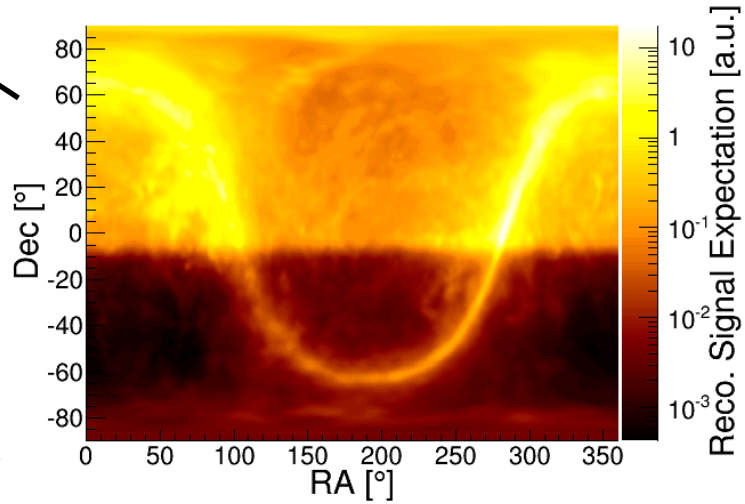
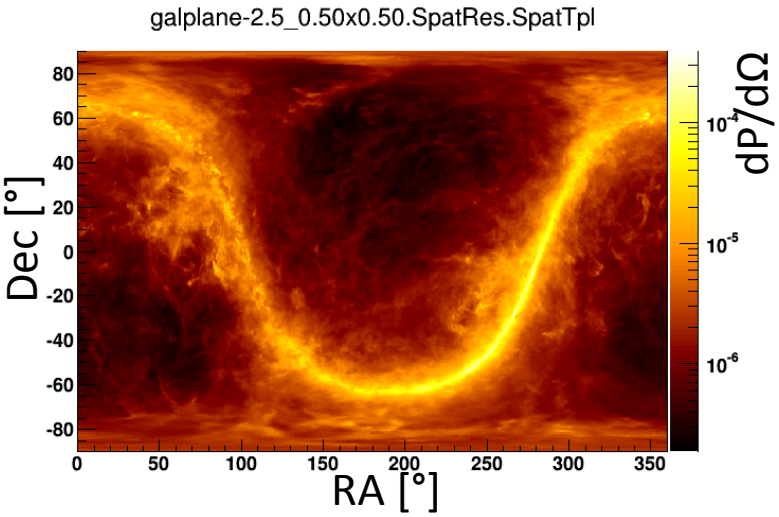


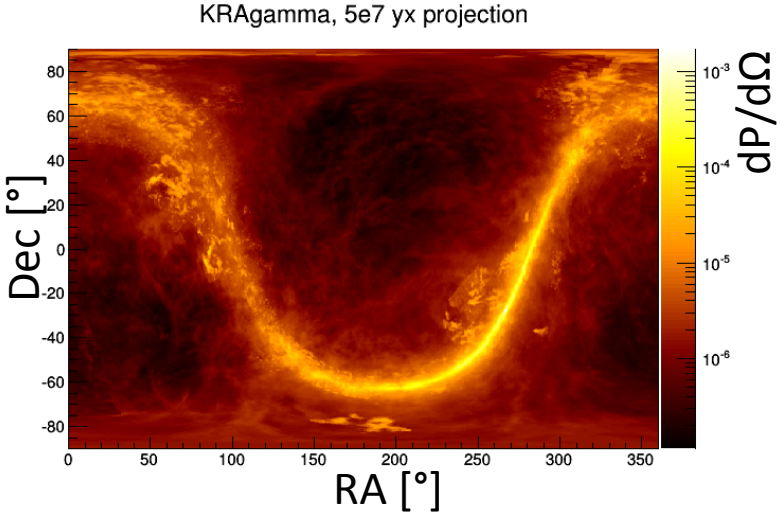
pion-decay map + detector acceptance

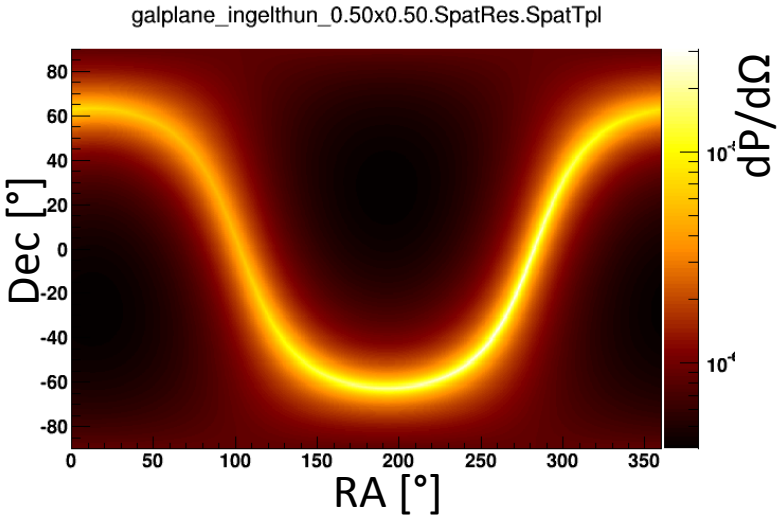
- Unblinded **7 years** of data
  - Searched for spectral indices between $\mathbf{E^{-1.0}}$ and $\mathbf{E^{-4.0}}$
- Found **~150** events over background expectations with p=37% (preliminary)
  - 90% CL **Upper Limit = 16%** of observed diffuse flux*

* Assuming power-law extrapolation to lower energy

Three Models

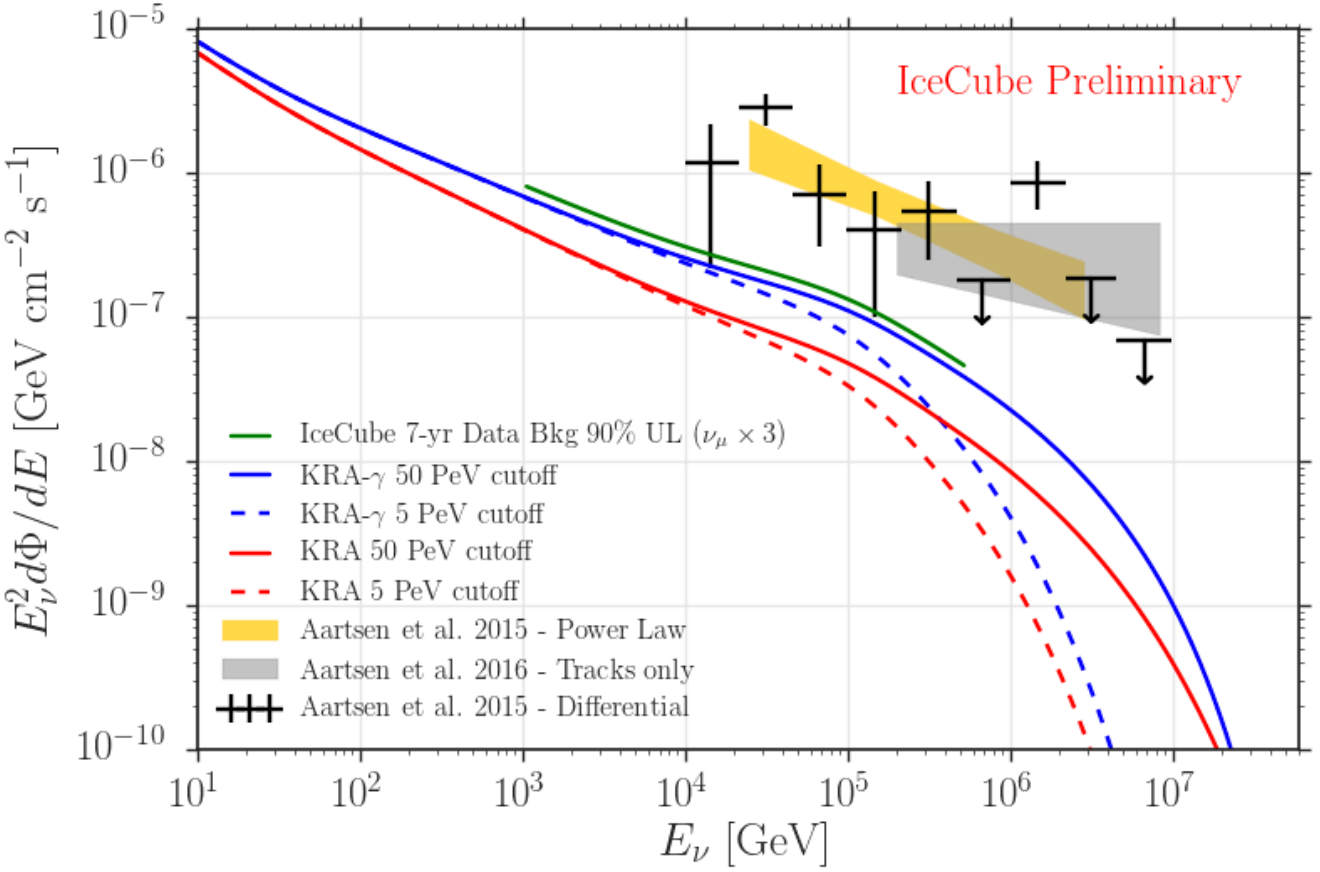






- Fermi π^0 decay map
- KRA-γ (tuned to γ-rays)
- Ingelman & Thunman toy model

IceCube/ANTARES limits



- Upper limit is 120% of the most optimistic model prediction
  - Sensitivity is 78% of model
- IceCube results nearly constrain cosmic ray propagation models in the galaxy!

Track Method 2 – Sim Bckgnd

ONLY NORTHERN HEMISPHERE

Forward-Folding Poissonian LH Fit

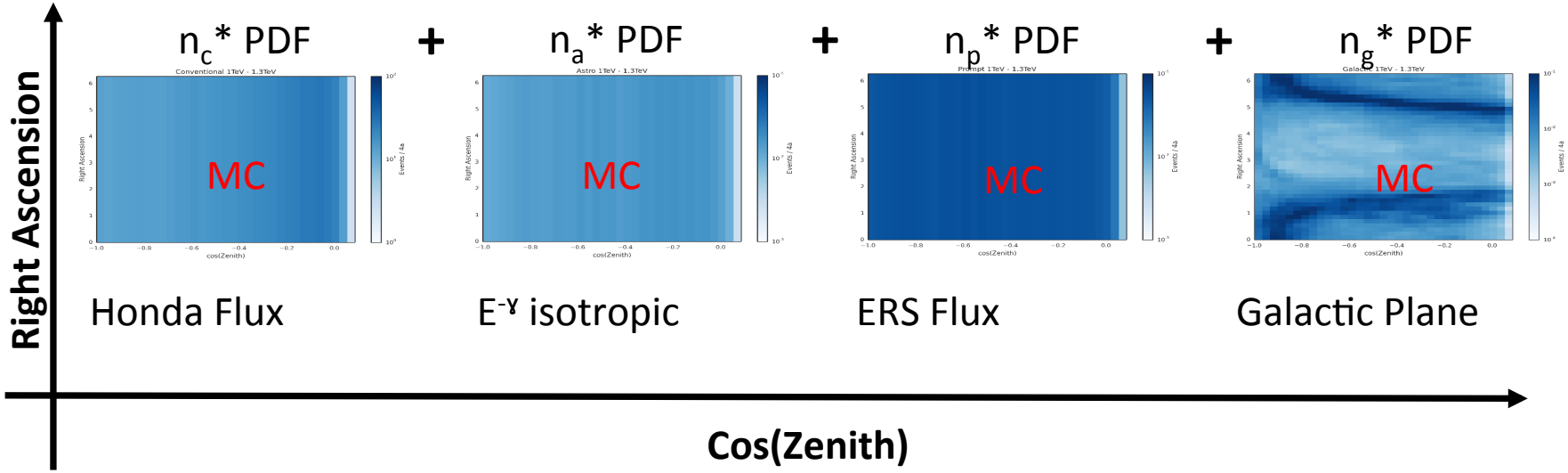
Ab-initio neutrino simulation to calculate detector response to neutrino fluxes.

Background: Conventional Atmospheric (Honda et. Al.)
Prompt Atmospheric (ERS)

Signal: Isotropic Astrophysical
Galactic Plane

Four 3D Histograms
Fit normalization to
Data with poiss. LH.

n_c* PDF + n_a* PDF + n_p* PDF + n_g* PDF



Honda Flux | $E^{-\gamma}$ isotropic | ERS Flux | Galactic Plane

- Analysis also unblinded with 1 yr less data: p=7%

Analysis Style Crossref

‘Point-Source style’ vs. ‘Diffuse style’

(i.e. Data background estimate)

- Background is just ‘everything but signal’
- Looser cuts allowed
- Unbinned – full spatial resolution
- Background independent in declination bands
- Background is background

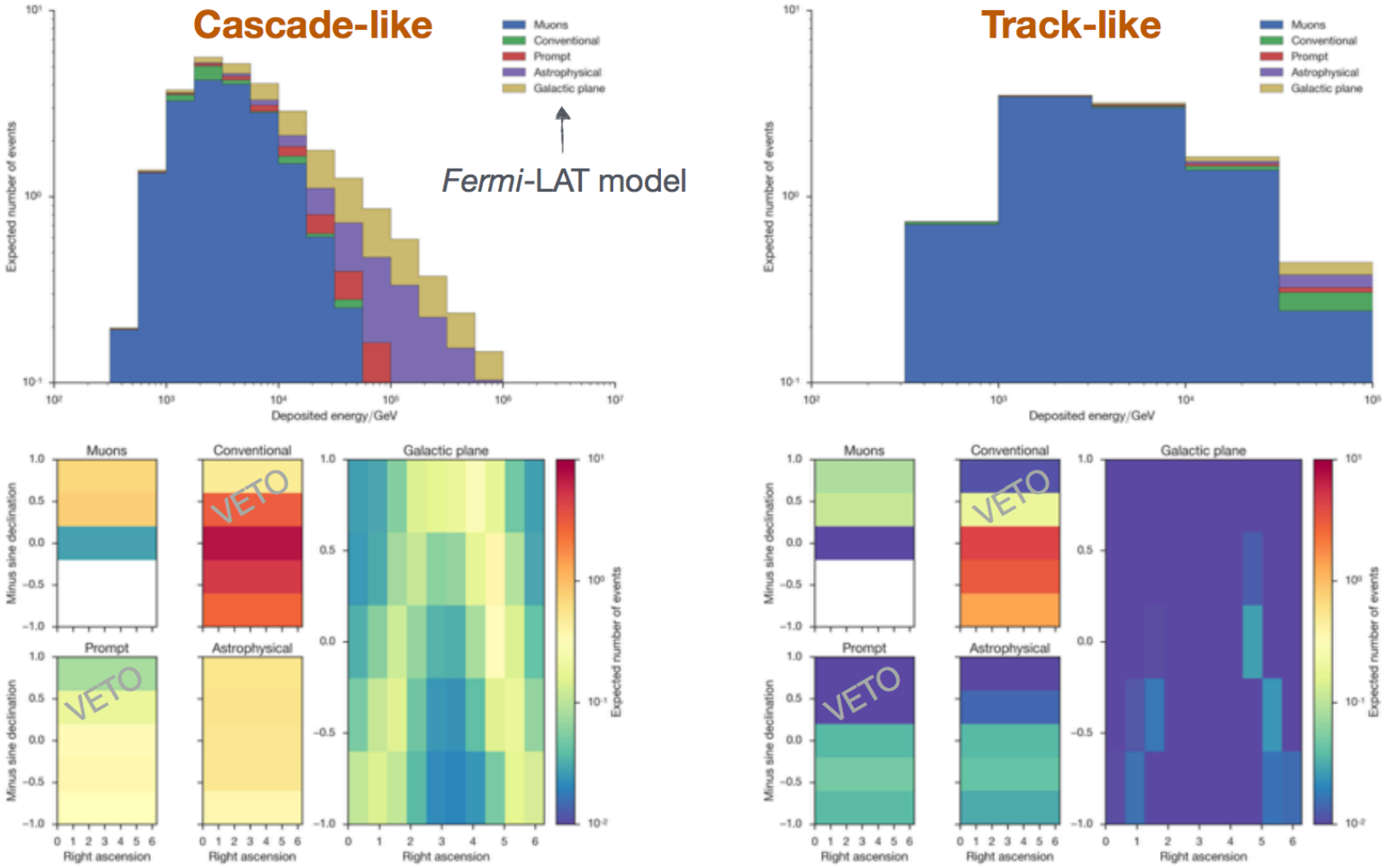
(i.e. Sim. background estimate)

- All backgrounds must be modeled
- Requires high purity
- Simulation statistics often determine (coarse) bin sizes
- Background coupled over the whole sky
- Physics nuisance parameters (e.g. charm, astro flux) must be coupled in joint analysis

Joint analysis easier in the PS style

MC flux templates

2-yr starting event analysis – dominated by cascades



MC flux templates

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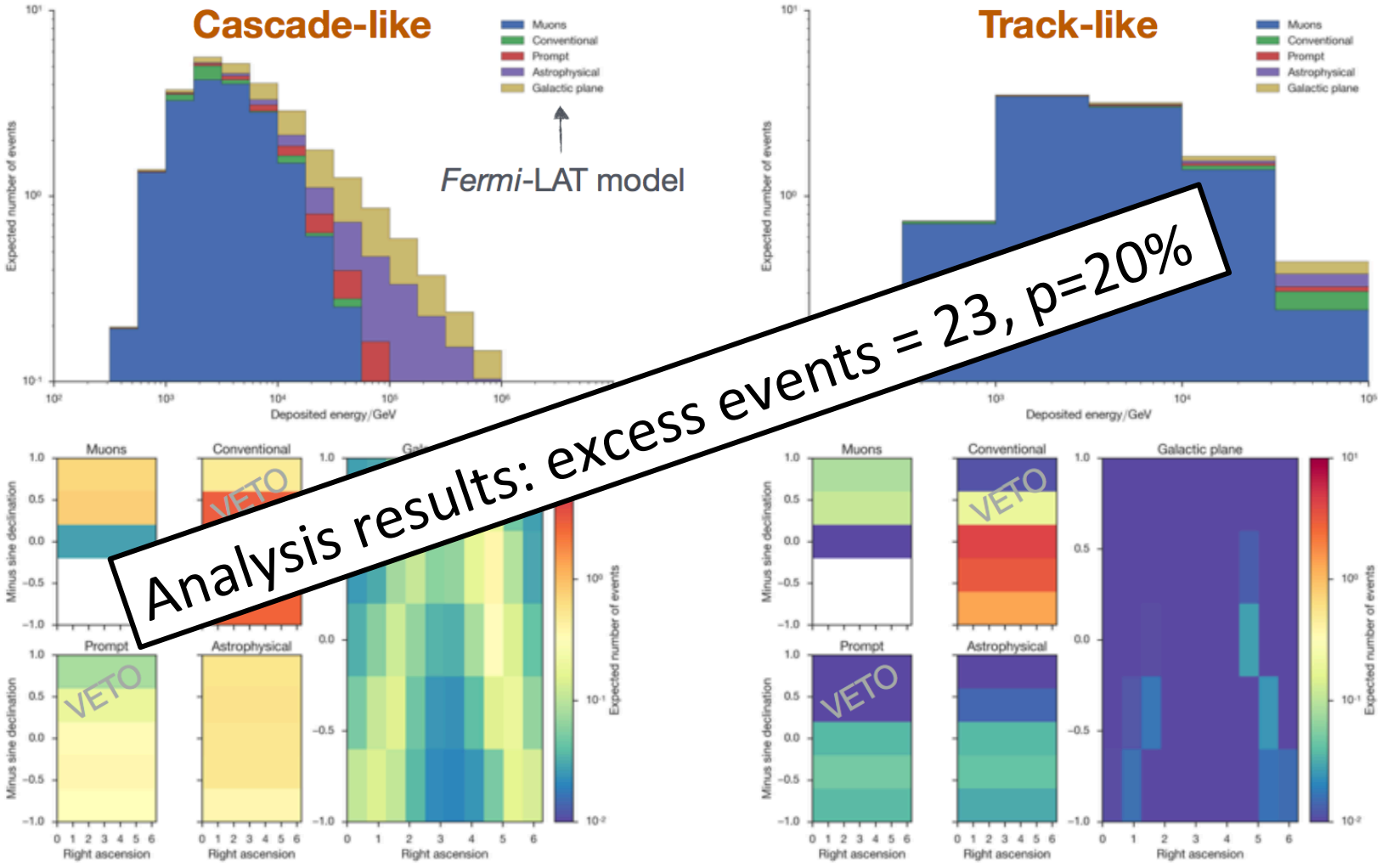
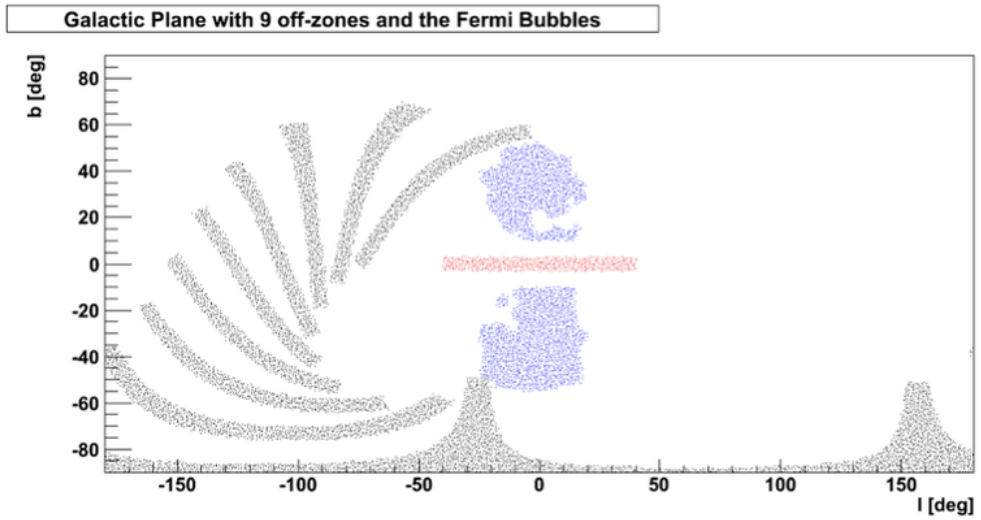
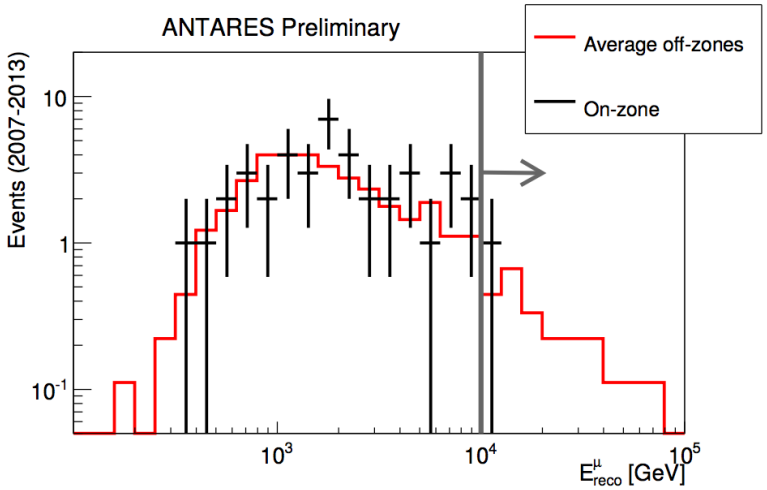


ANTARES Results

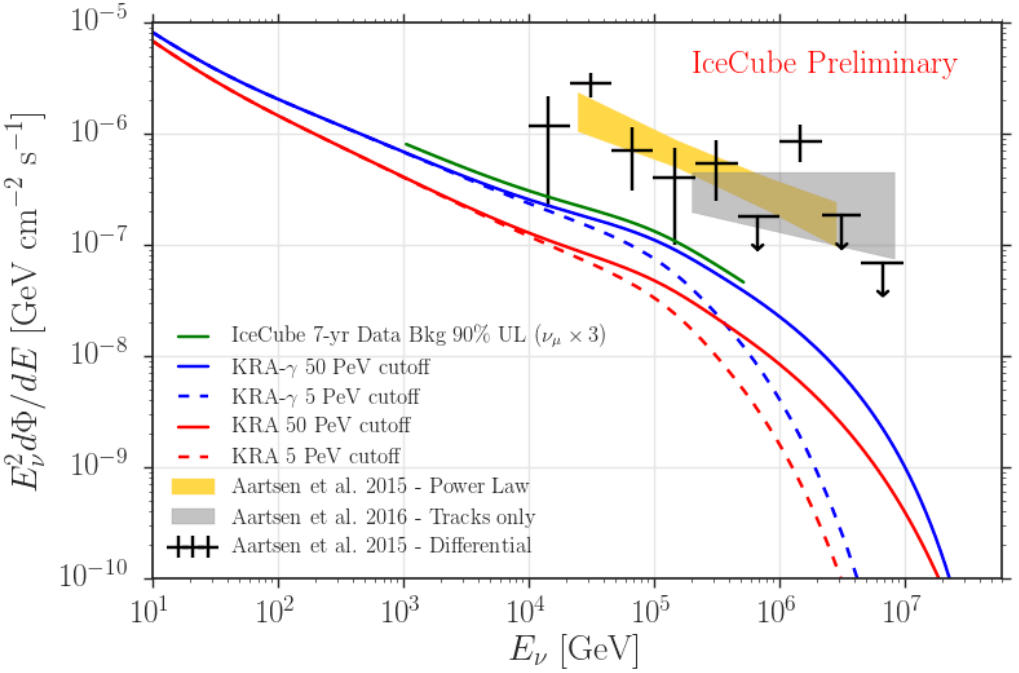


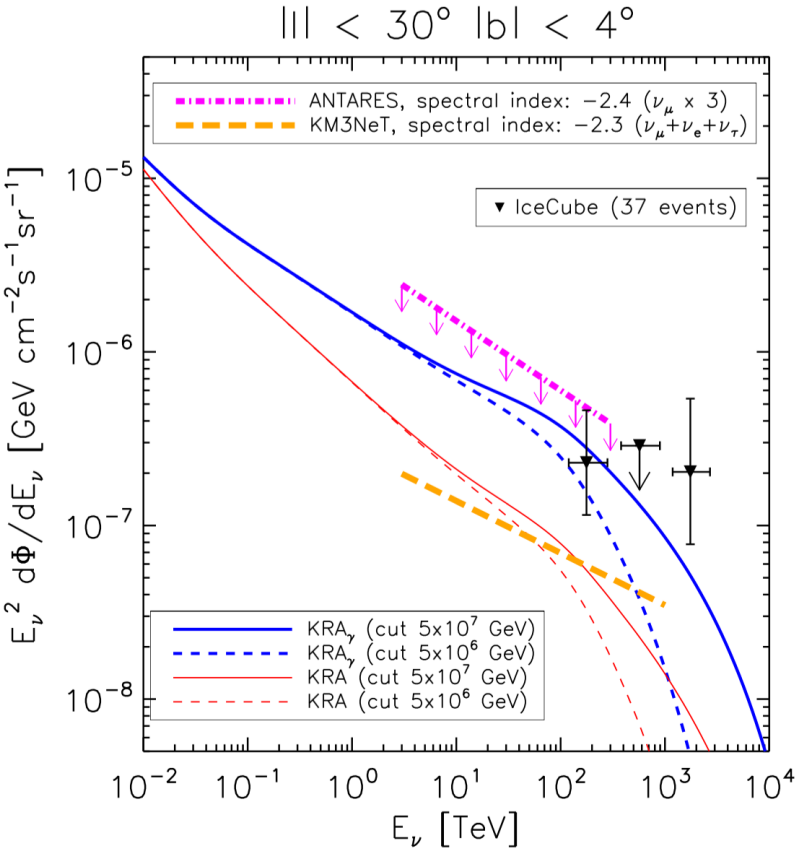


- 1 event observed on a background expectation of 2.5 events
- (These results are perhaps out of date...)

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

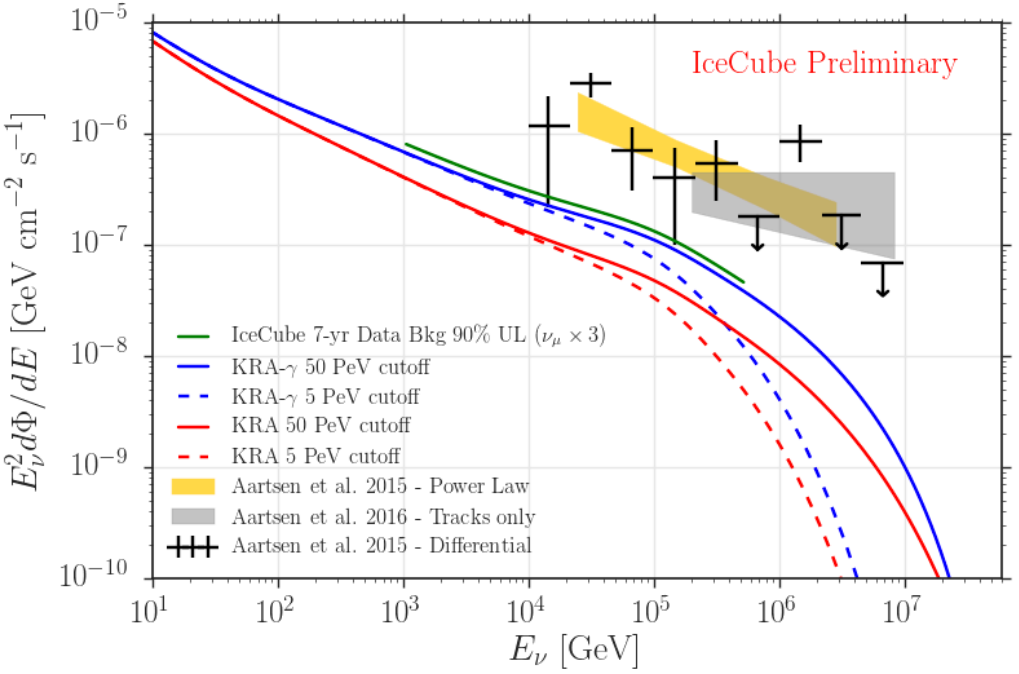
IceCube/ANTARES limits

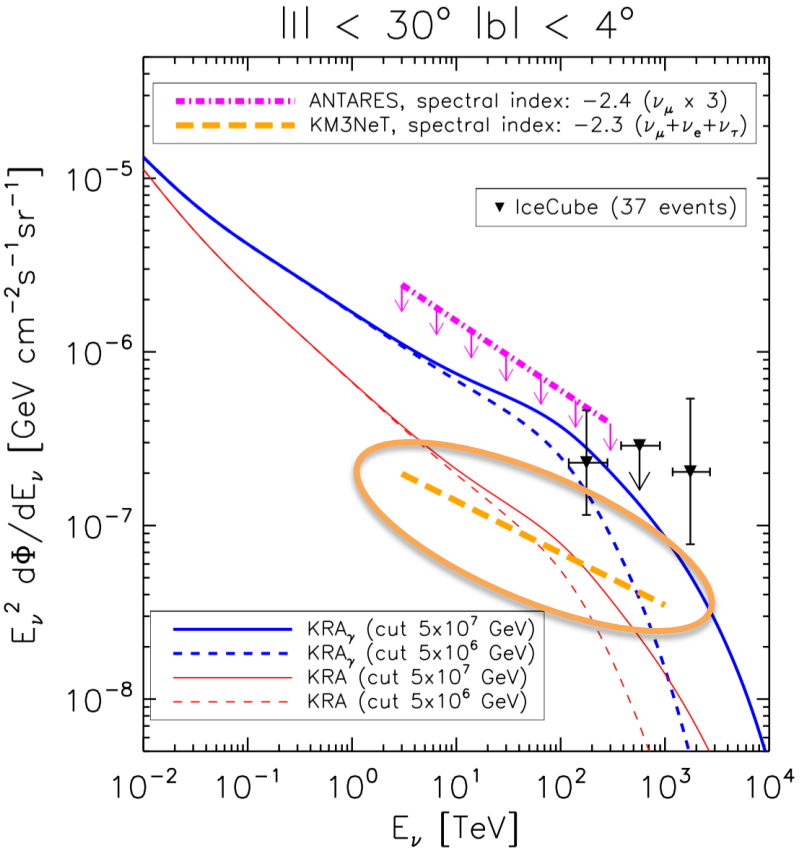




- Upper limit to KRA model quite similar
  - IceCube: Sensitivity is 78% of model
  - ANTARES sensitivity = upper limit BUT ~50% (?) improvement possible from method?

IceCube/ANTARES limits

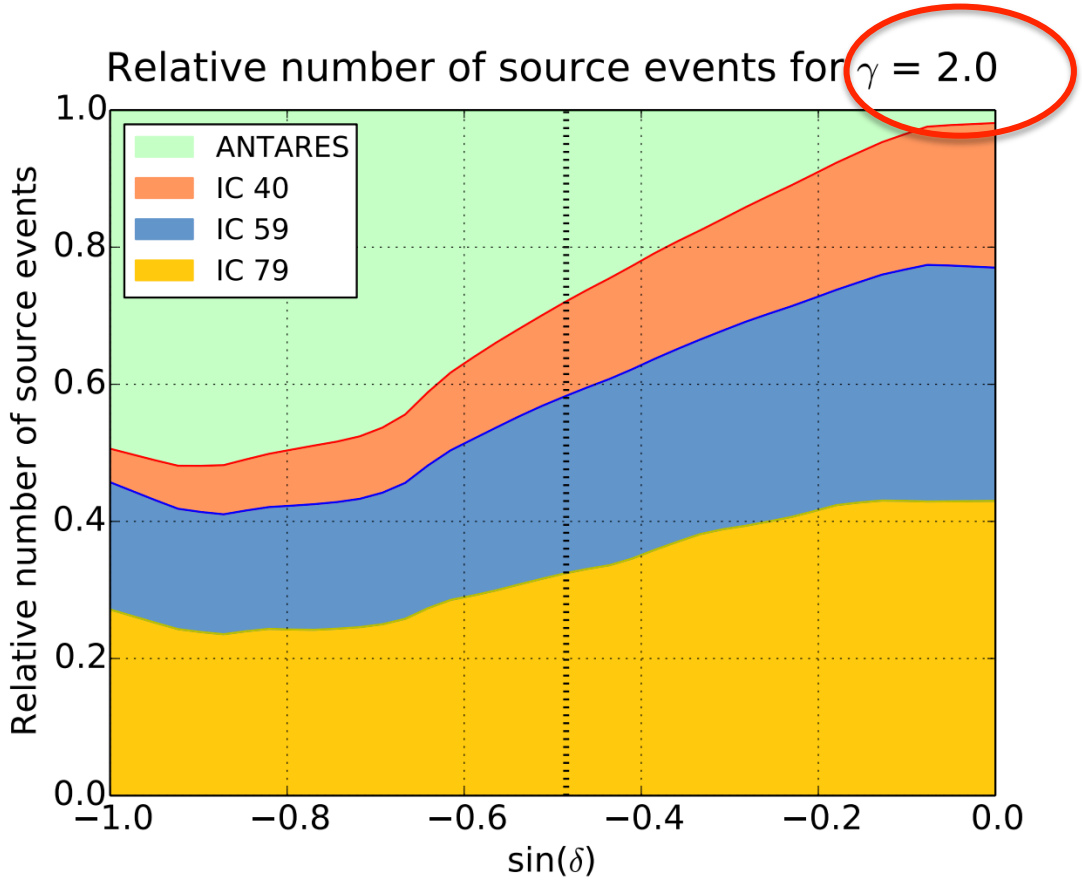




- Upper limit to KRA model quite similar
  - IceCube: Sensitivity is 78% of model
  - ANTARES sensitivity = upper limit BUT ~50% (?) improvement possible from method?
- **Nearly** guaranteed detection from KM3NeT after 4 years!

Issues in Joint Analysis

First combined search for neutrino point-sources in the Southern Hemisphere with the ANTARES and IceCube neutrino telescopes



ANTARES 5yr shown
(update = 1.5x)

IceCube 3yr shown
(update = 3x)

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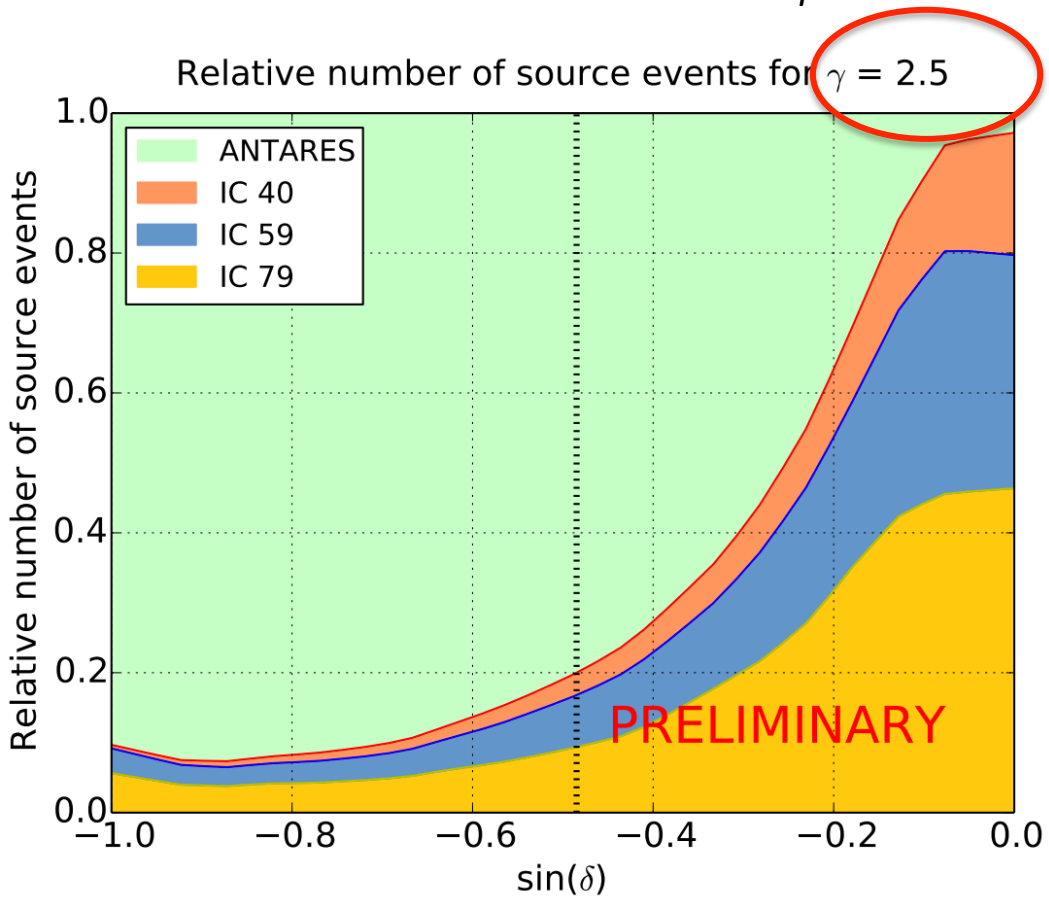

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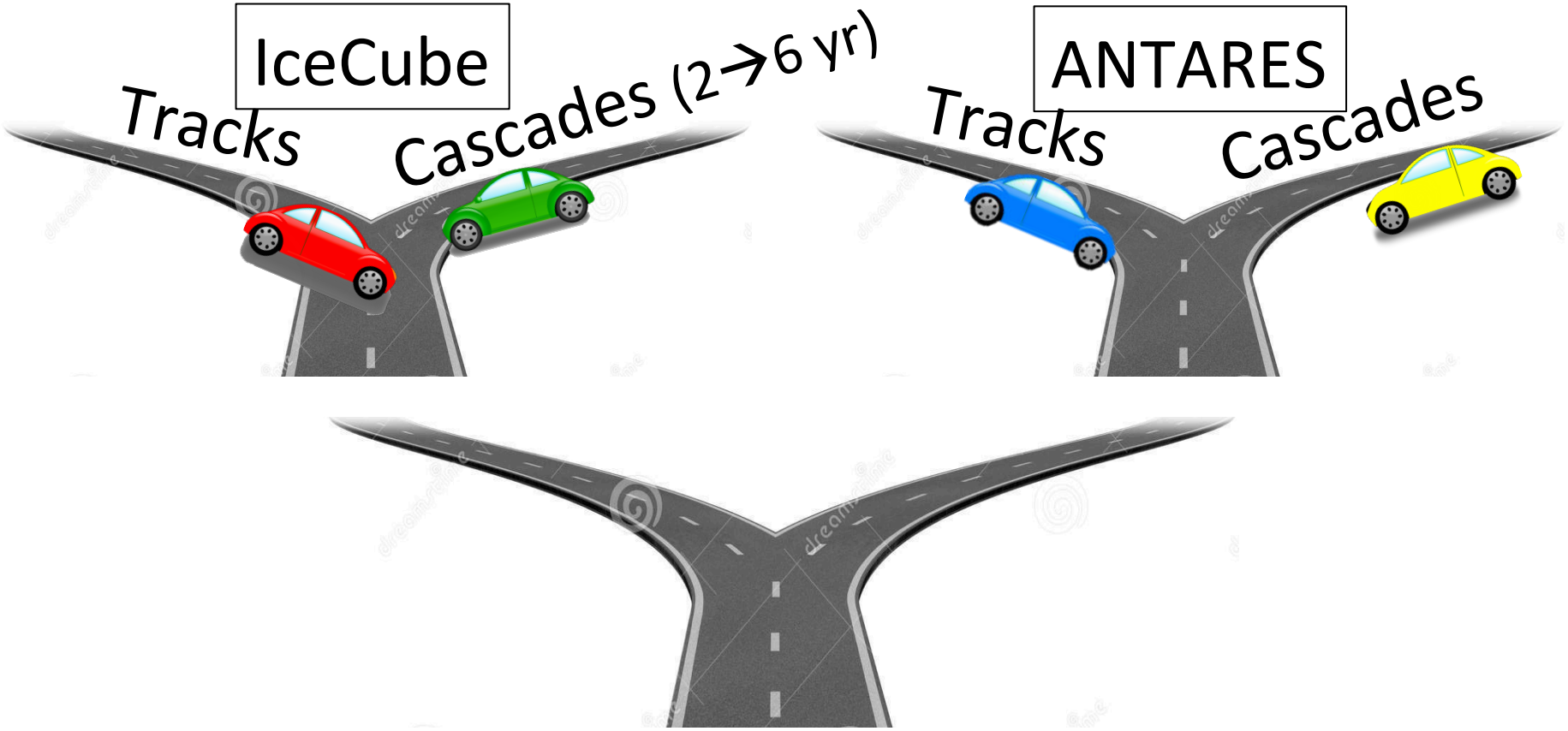
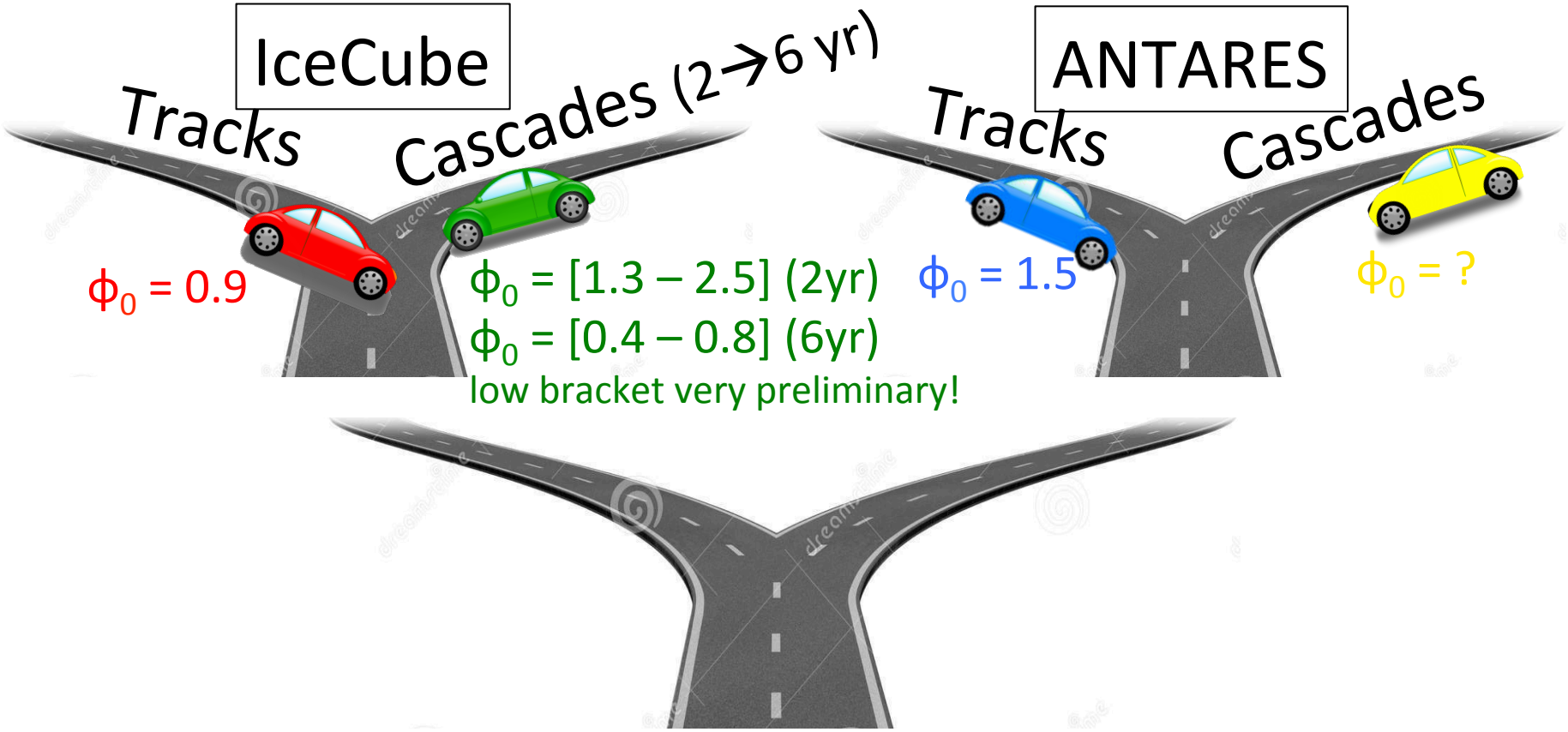
Analysis Road Map

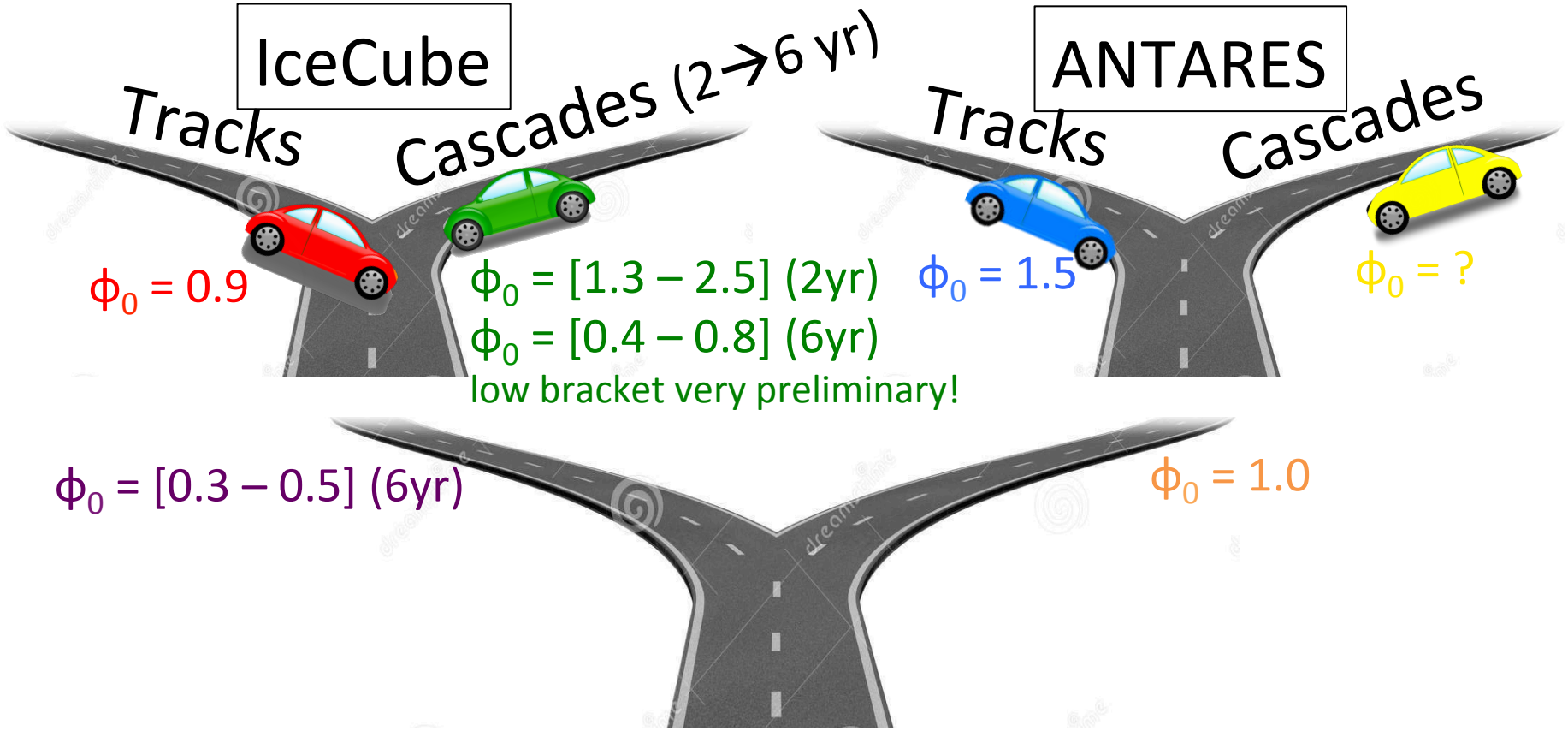


Sensitivity Road Map



- Sensitivities in form: $\phi = \phi_0 \times 10^{-5}\ (E/GeV)^2\ GeV/cm/s$
- Some approximations and near-future optimizations!
- 6yr IceCube cascade sample coming in next months

Sensitivity Road Map



ϕ_0 = [0.25 – 0.4] (6yr)

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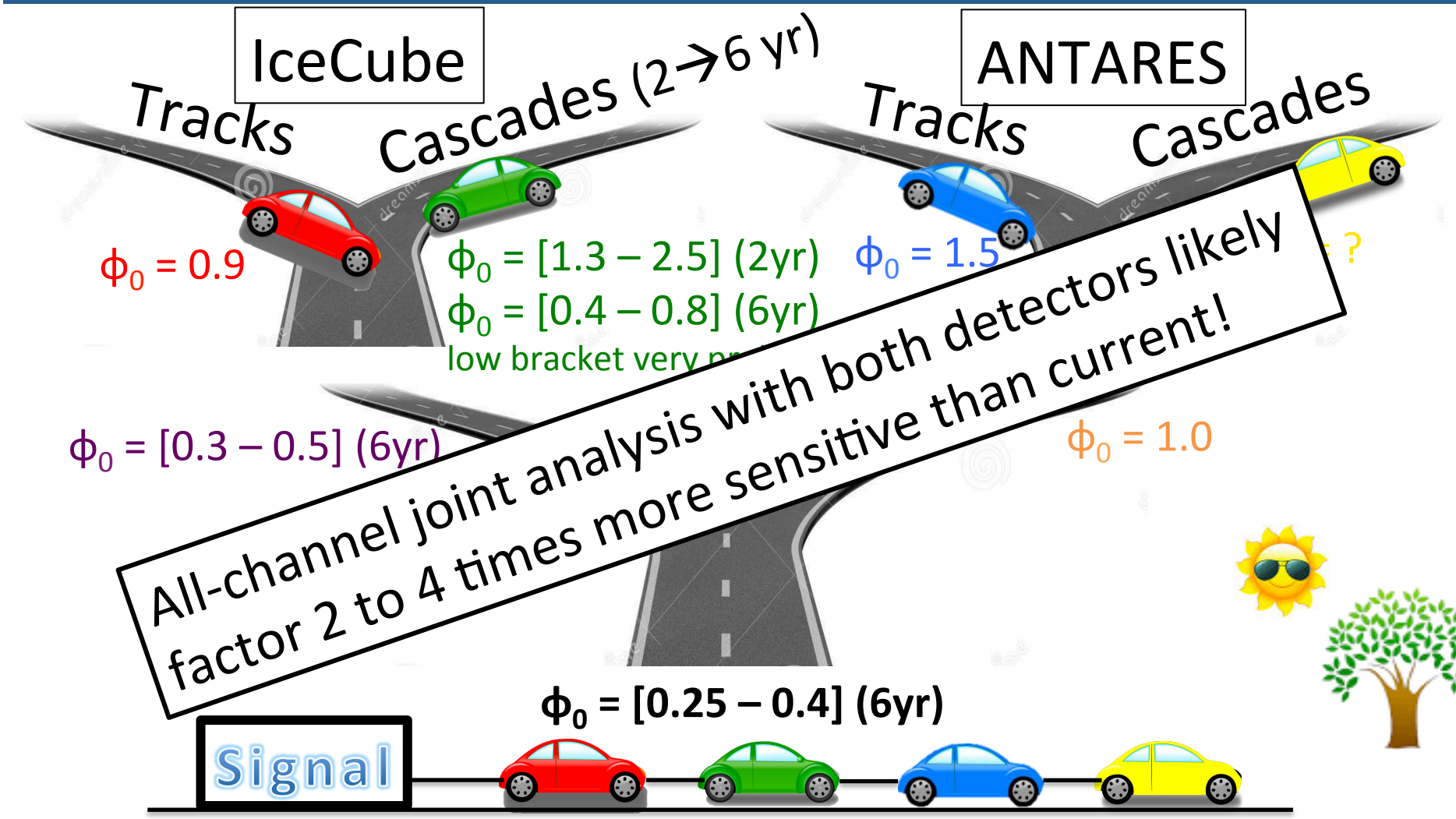


Issues in Joint Analysis

Combined Test Statistic	vs.	Common Framework
(i.e. Simply add indep. TS values)		(i.e. Develop one common tool)
▪ Uniform treatment of data		▪ Data/sim might require different treatment
▪ Can move very fast		▪ Unclear where to start
▪ Black-boxy		▪ Transparent to all

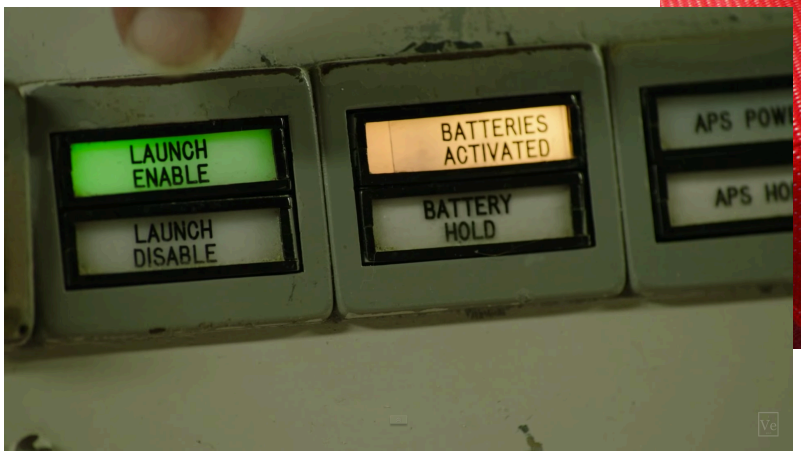
We should certainly do fast sensitivity study with combined TS

Issues in Joint Analysis

Combined Test Sta

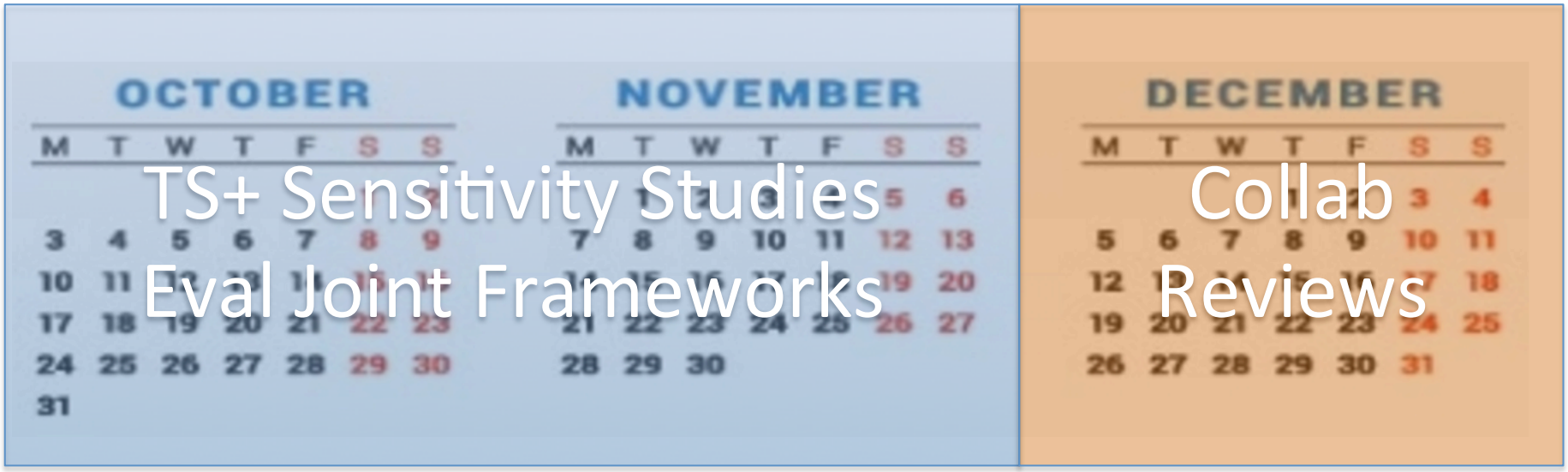
(i.e. Simply add indep

- Uniform treatmen



We should certainly do fast sensitivity study with combined TS

Possible Timeline



- Timeline probably driven more by will power than technical issues
- Do we want to relax timescale to allow individual results to stand alone or go straight for the best result possible?
- I only encourage us to work on the joint analysis in parallel instead of waiting

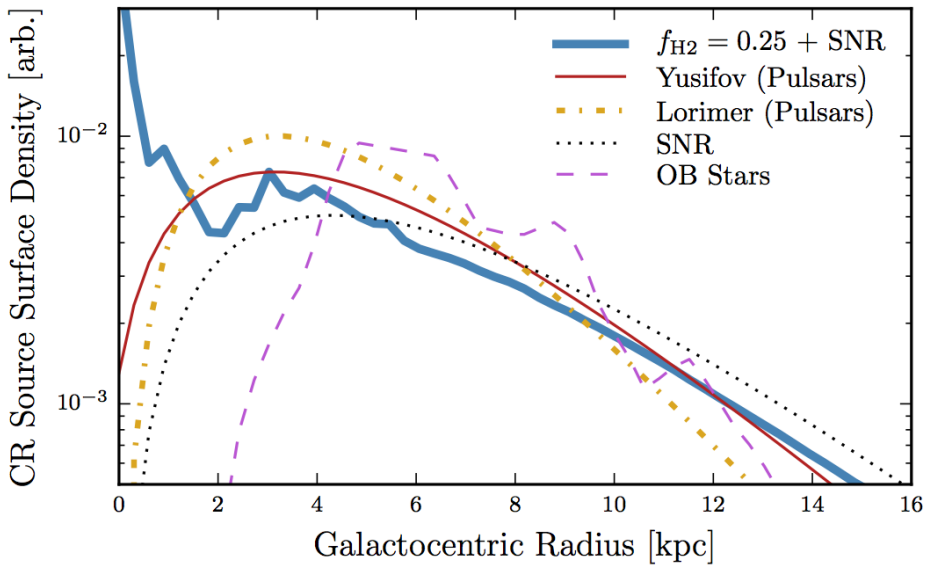
Conclusions

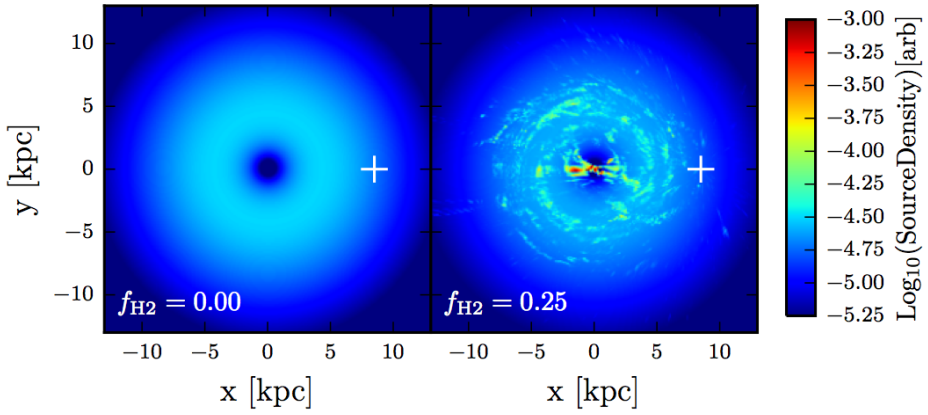
- New constraints on galactic neutrino emission based on 7 years of muon tracks in IceCube
  - Small excess observed (~150 excess events, p=37%)
  - Cross-check using '*Diffuse-style*' a bit more significant (p=7%, 1 yr less data)
  - No more than 16% of diffuse flux tracking the expected diffuse gal plane emission
  - Room for 'hidden' flux in inner galaxy
- Cascade channel (2yr starting events) also unblinded recently
  - Small excess observed (23 excess events, p=20%)
  - Sensitivity worse than muon channel but will soon >triple the data!
- Joint analyses are the way forward
  - We know the signal is there, how deep do we have to dig?
  - Both collaborations working on all-channel searches
  - Need to explore joint analysis frameworks vs after-the-fact TS combinations
- Our best constraints on the gal plane flux could impact our next-gen designs

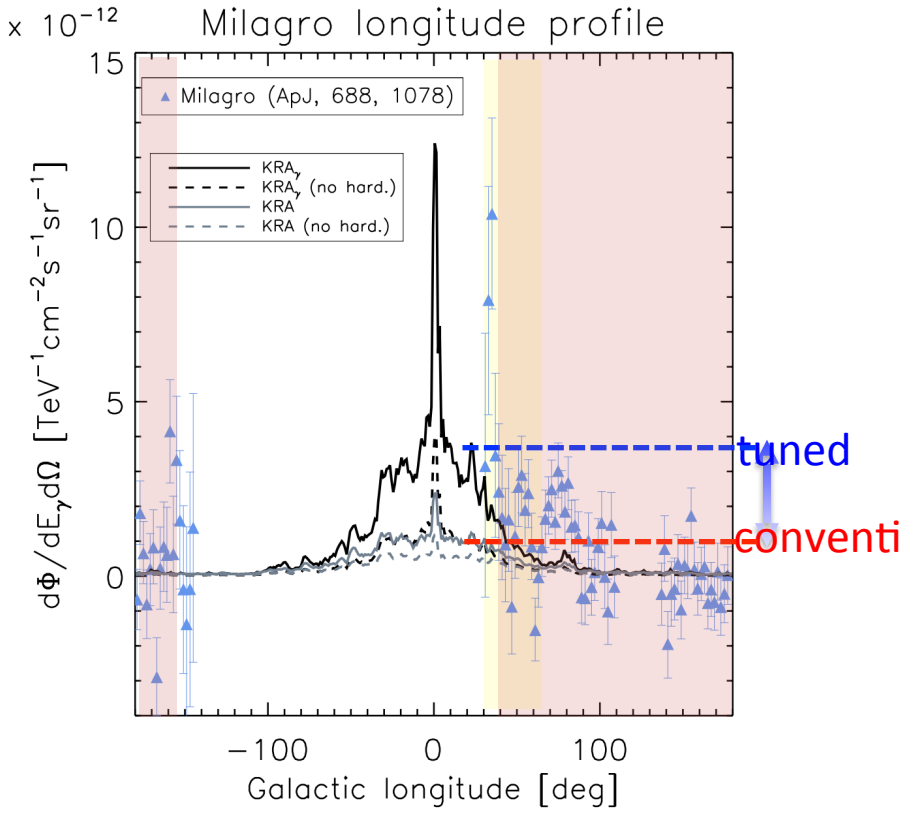
Backup

GC CR Enhancement

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



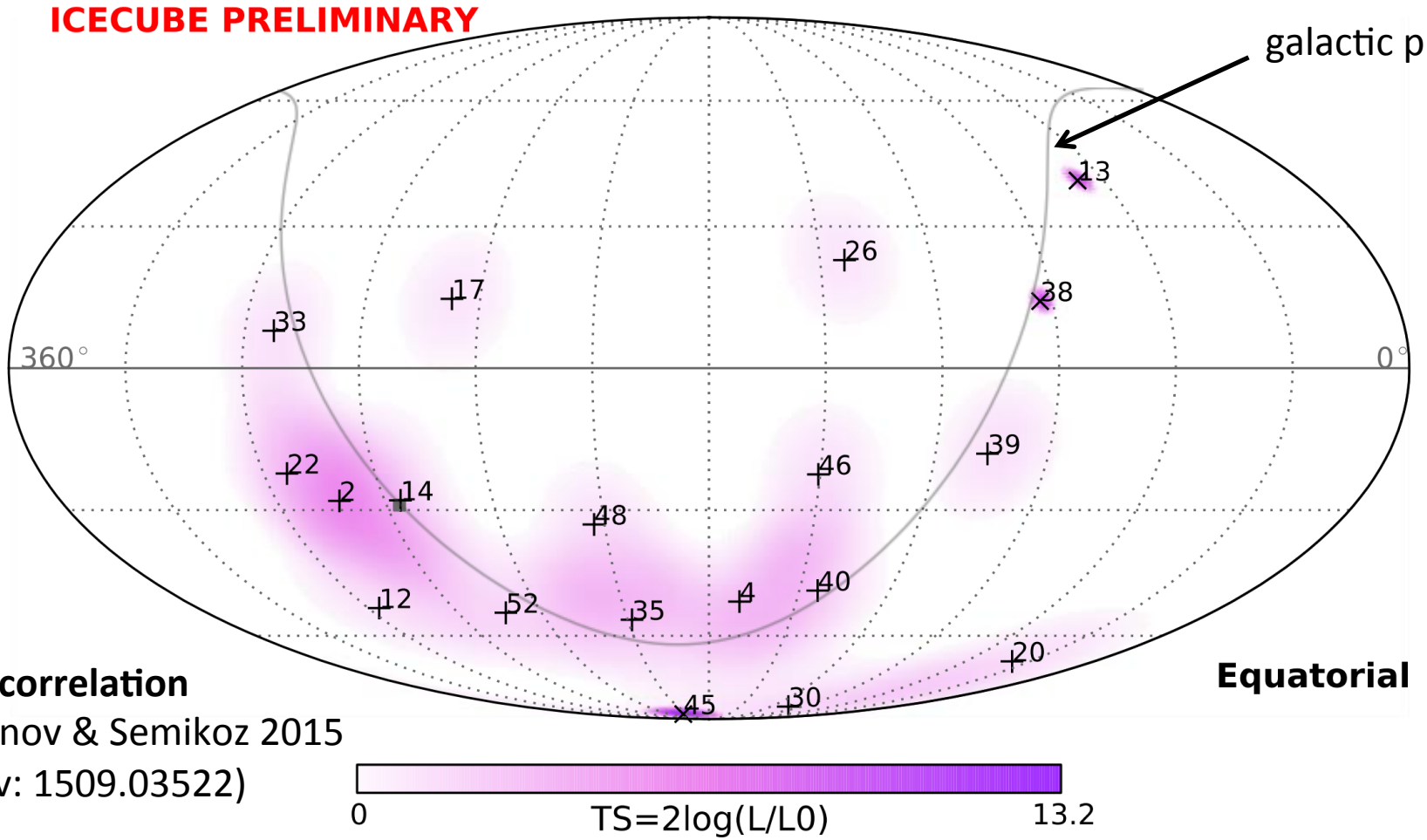




Large uncertainty in flux from inner galaxy!

Gaggero et al 2015
arXiv:1507.07796v1

>100 TeV *A Posteriori*



~3 σ correlation

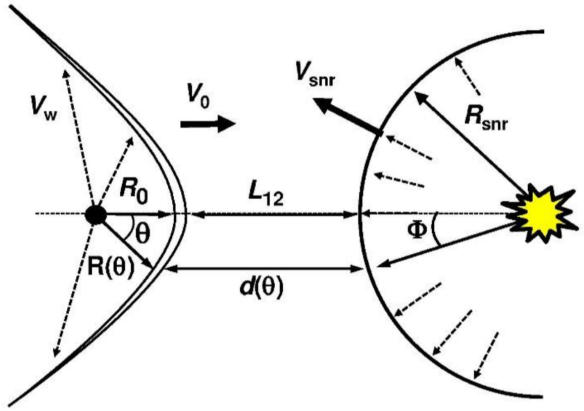
Neronov & Semikoz 2015

(arXiv: 1509.03522)

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

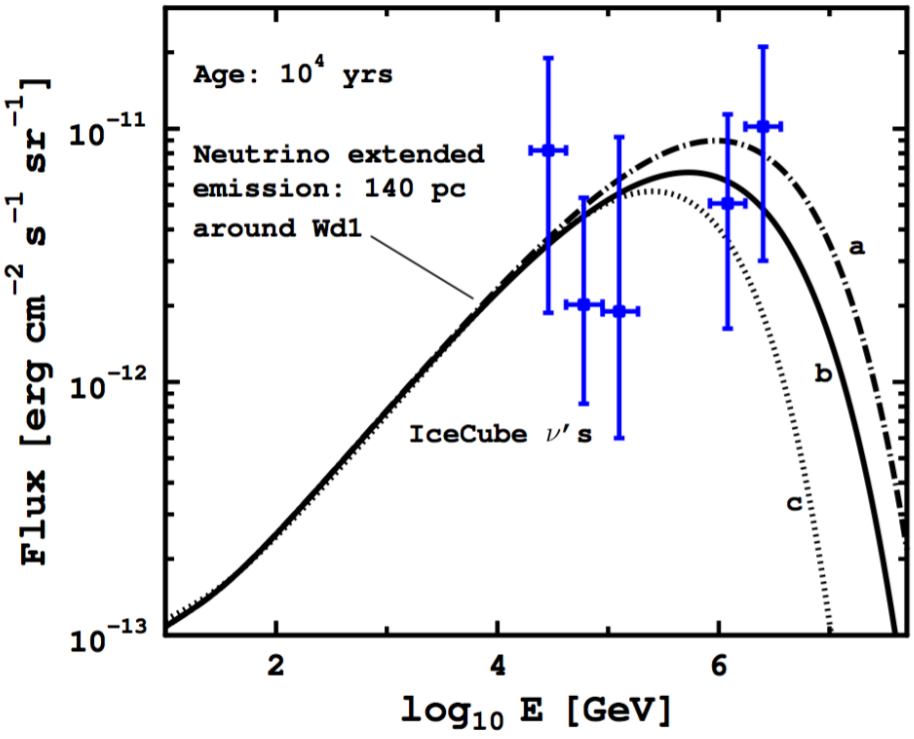
>100 TeV in the Galaxy?

- 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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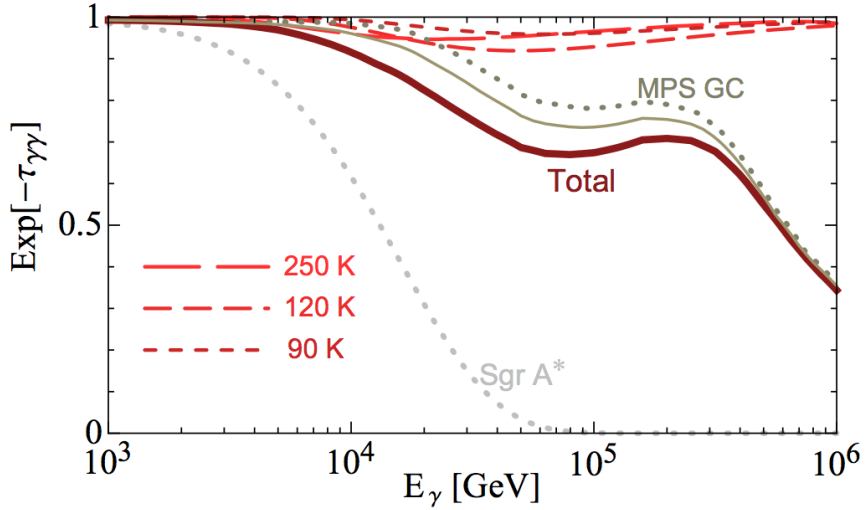
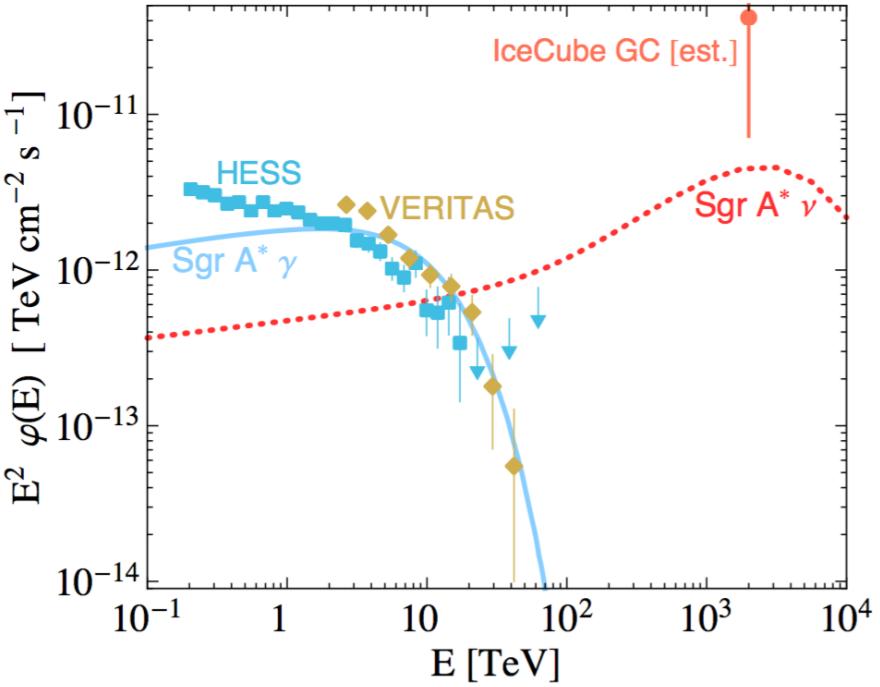


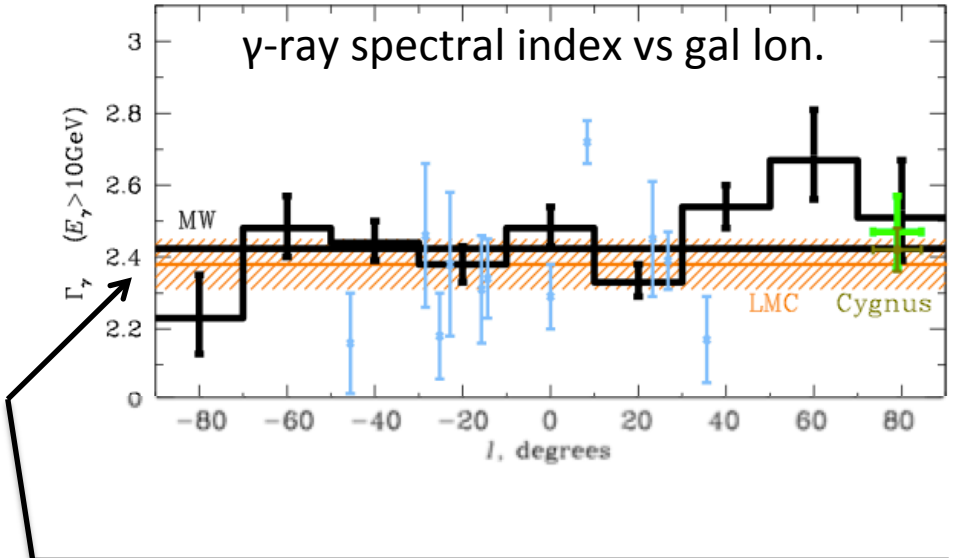
- Sgr A* model
- Gamma-ray attenuation varies drastically
  - Very strong near accretion disk

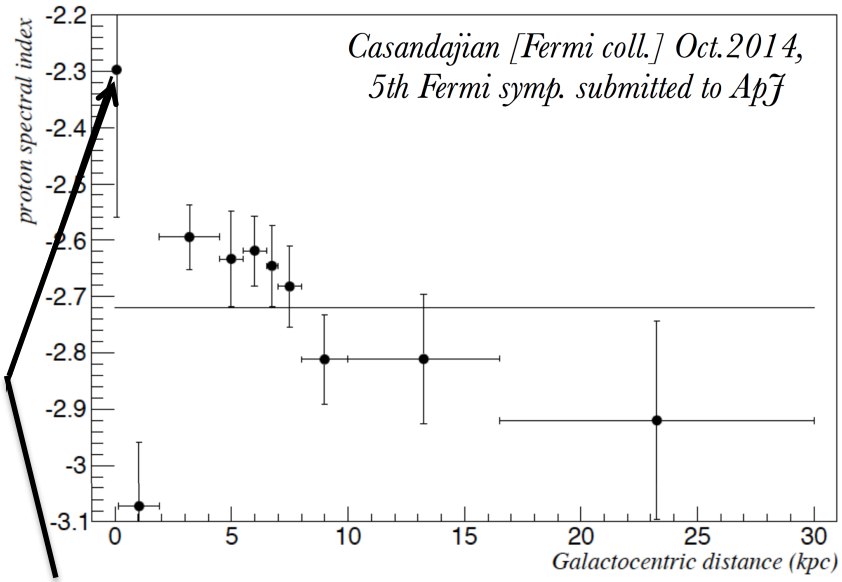
Kistler 2015
arXiv:1511.00723



Kistler 2015
arXiv:1511.05199

Remote CR Measurements





- 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