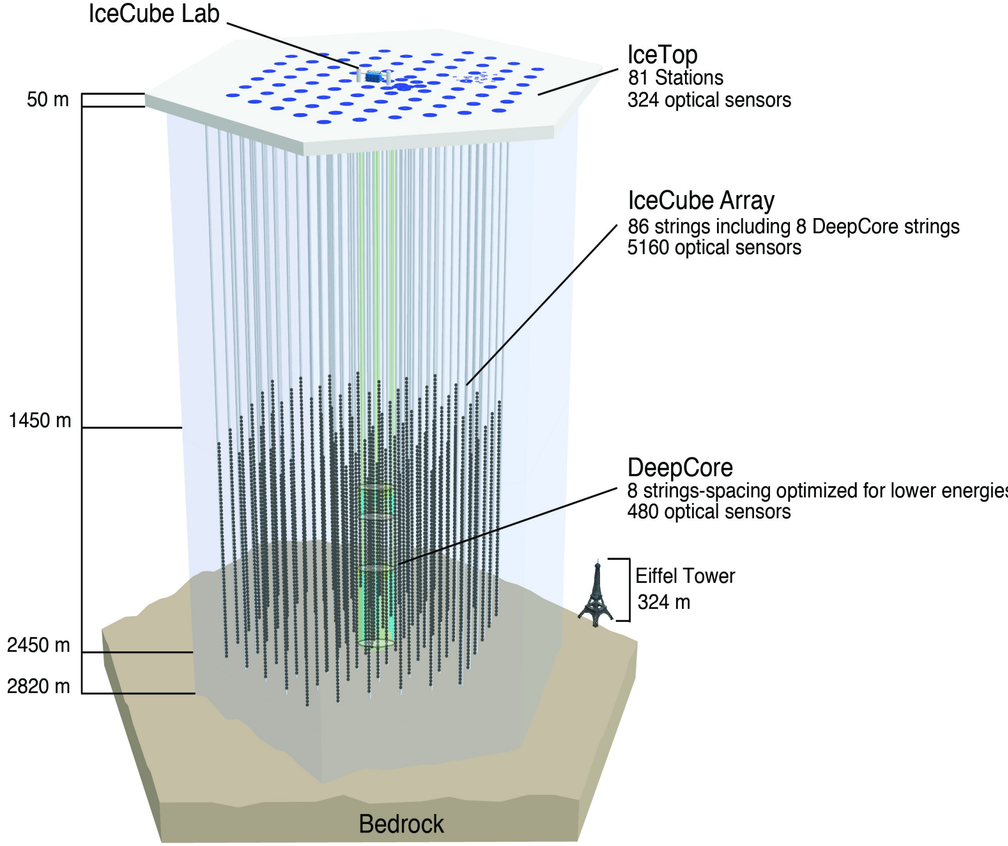
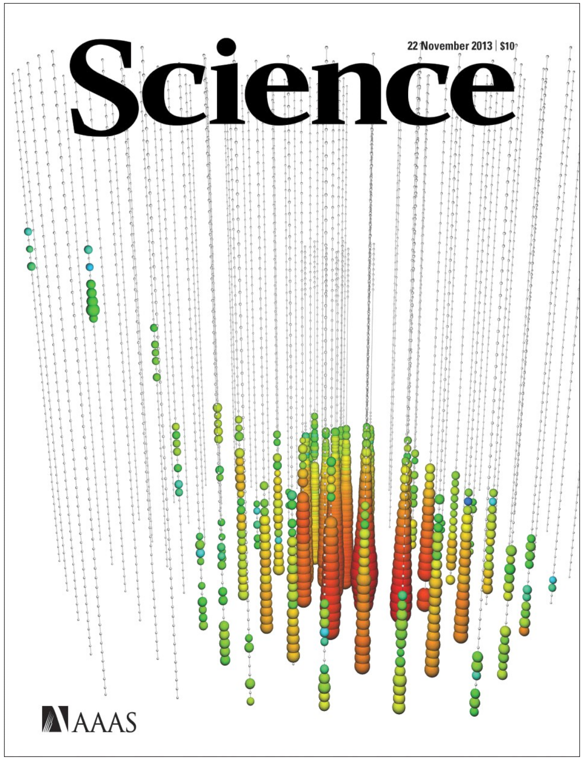
Cosmic Neutrinos in IceCube





Naoko Kurahashi Neilson
University of Wisconsin, Madison
IceCube Collaboration

HEM KICP UChicago – 6/9/2014

Outline

- IceCube capabilities
- The discovery analysis – *with updated data*
- Other IceCube analyses and what they tell us

  – *is there a coherent picture?*
- Future outlook – *input from you*

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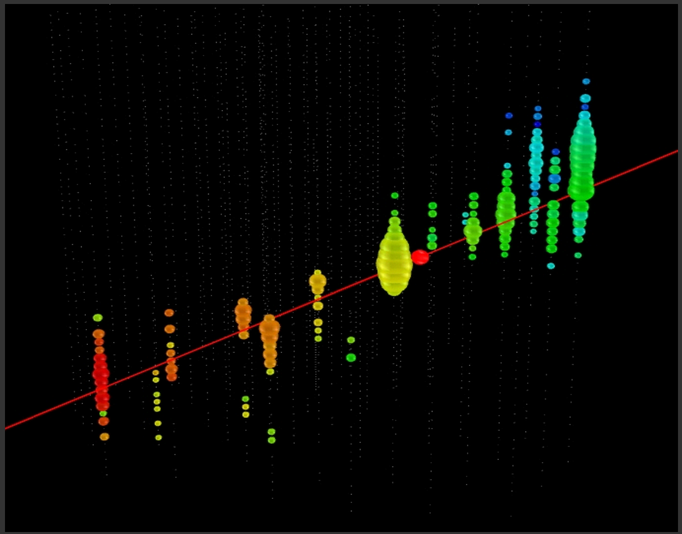
Topologies of different event types

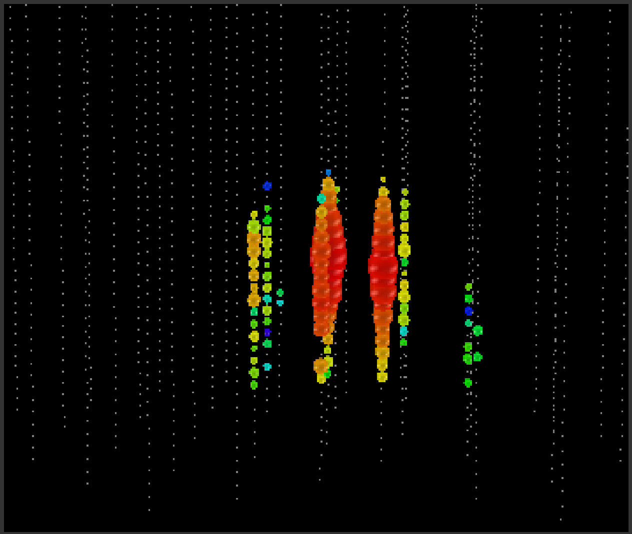
Charge Current (muon)



$$\nu_\mu + N \rightarrow \mu + X$$

Track

Charge Current (others)
Neutral Current

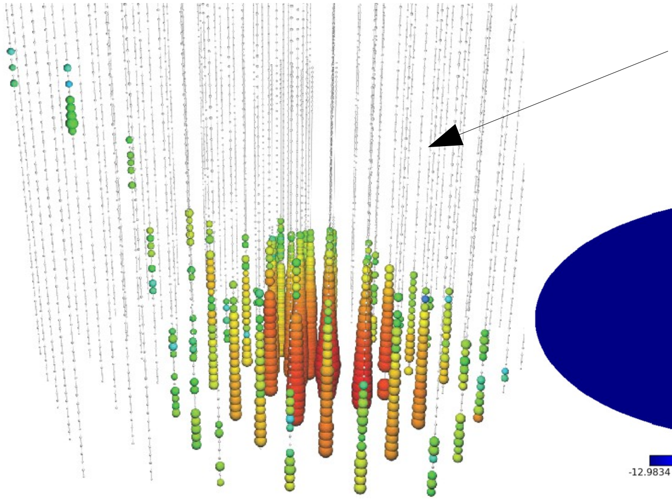


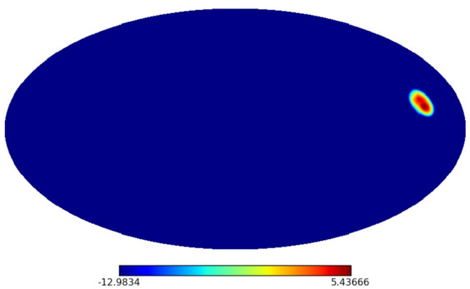
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

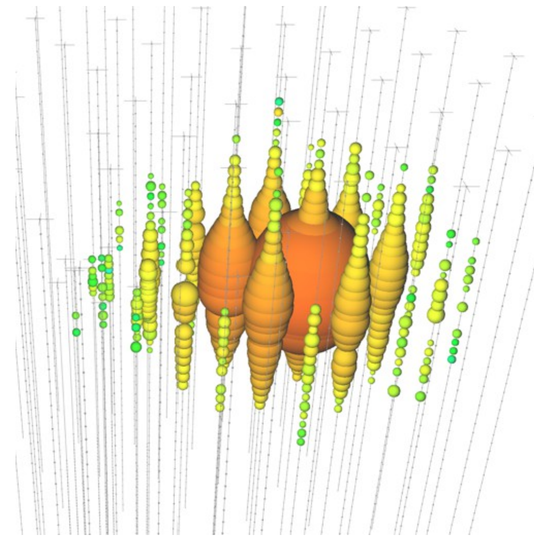
$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

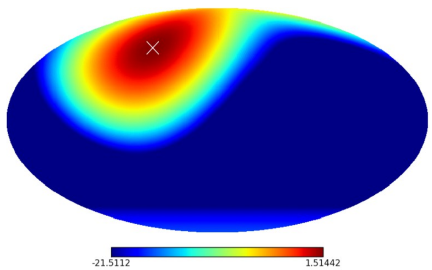
Shower

Reconstruction Capabilities









Reconstruction maps in local coordinates

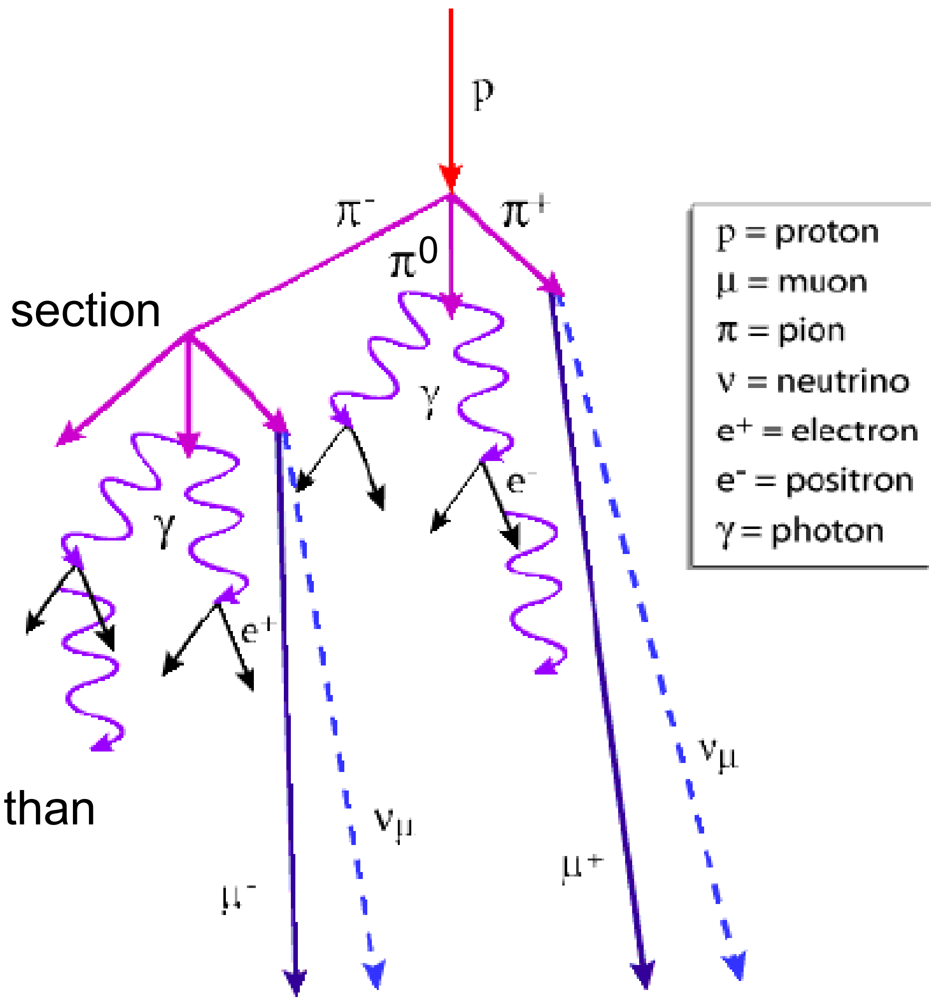
@ 100 TeV energies

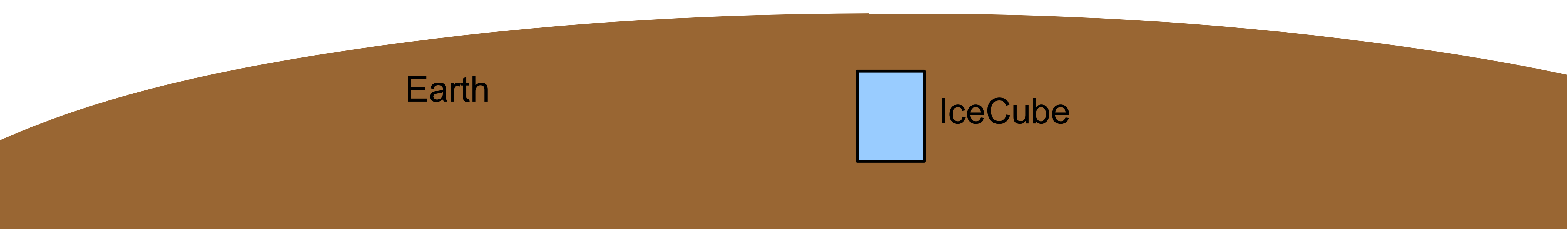
	Energy Reconstruction*	Directional Reconstruction*
Tracks	**~factor 2**	**~0.5 degrees**
Showers	**10%**	**~15 degrees**

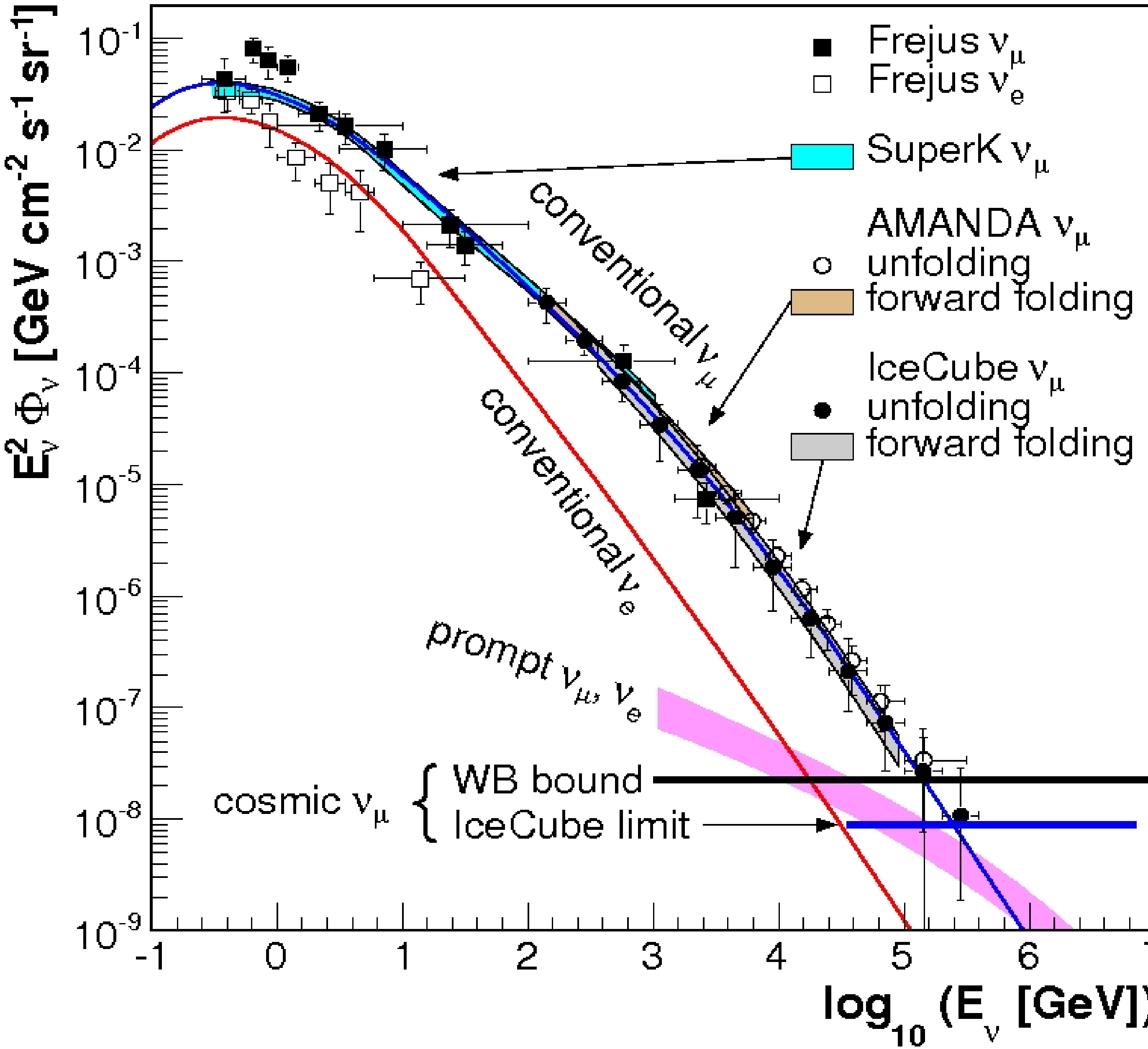
* against primary neutrino energy and direction

IceCube backgrounds are atmospheric shower components

- Most charged π/K decay to μ rather than e
- ν produced in the same interaction, but lower cross section
  - Most common bkg: $\mu > \nu_\mu > \nu_e$
- At higher energy, meson lifetime longer → more interact rather than decay
  - Spectra softer than primary CR
- At higher energies, charmed mesons produced
- Shorter lifetime, decay products are harder spectra than π/K decay → “prompt” flux





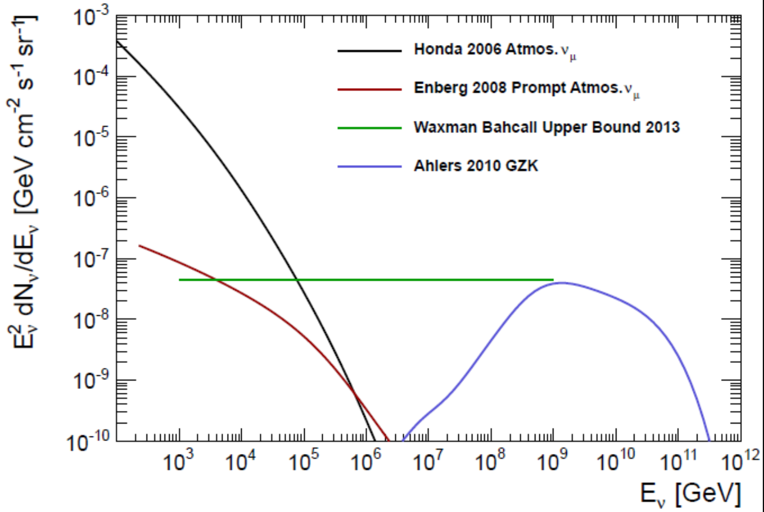


Frejus ν_μ
Frejus ν_e
SuperK ν_μ
AMANDA ν_μ
unfolding
forward folding
IceCube ν_μ
unfolding
forward folding
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
cosmic ν_μ
WB bound
IceCube limit
$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
$\log_{10}$ (E_ν [GeV])

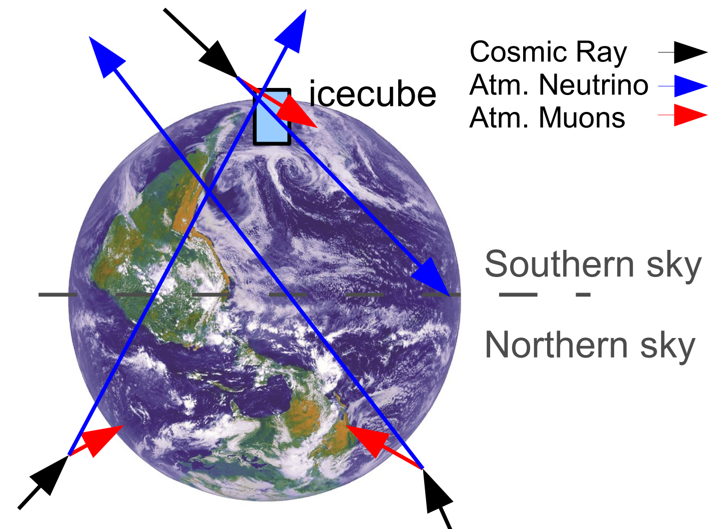
4 ways of dealing w/ backgrounds

Look at **higher energies** (**all backgrounds**)

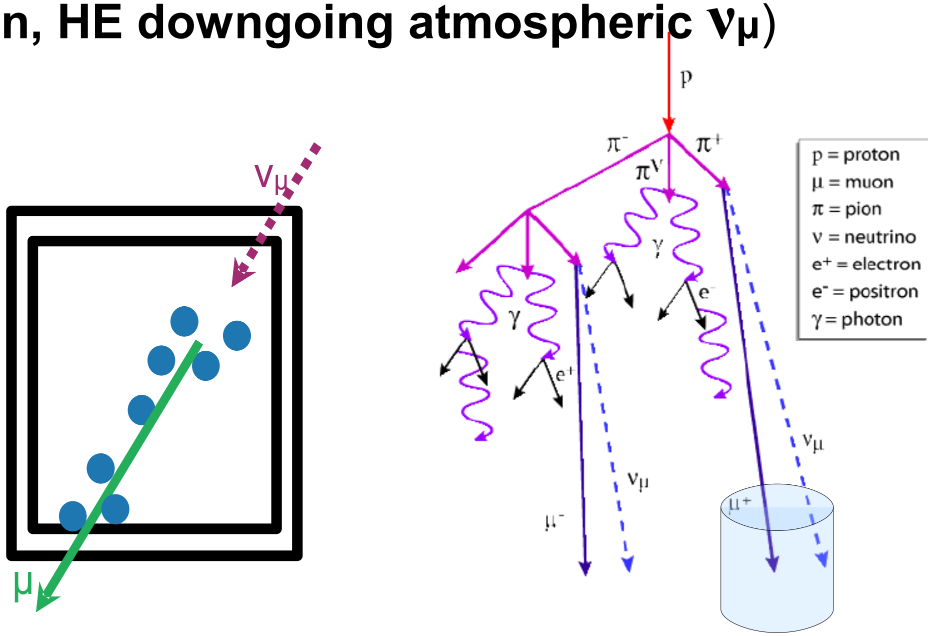
Shower component particle spectra are always softer than the primary spectra



Look for **upgoing** events (**muon**)

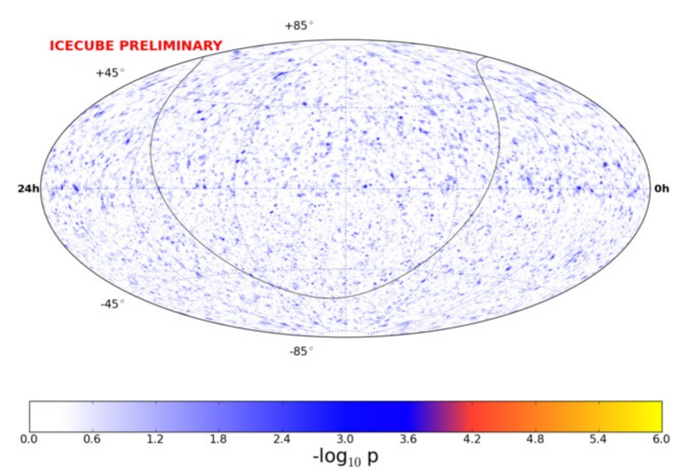


Look for **starting** events (**muon, HE downgoing atmospheric νμ**)



Look for anisotropy/**clustering** (**all backgrounds**)

Showers are thought to hit the atmosphere isotropically



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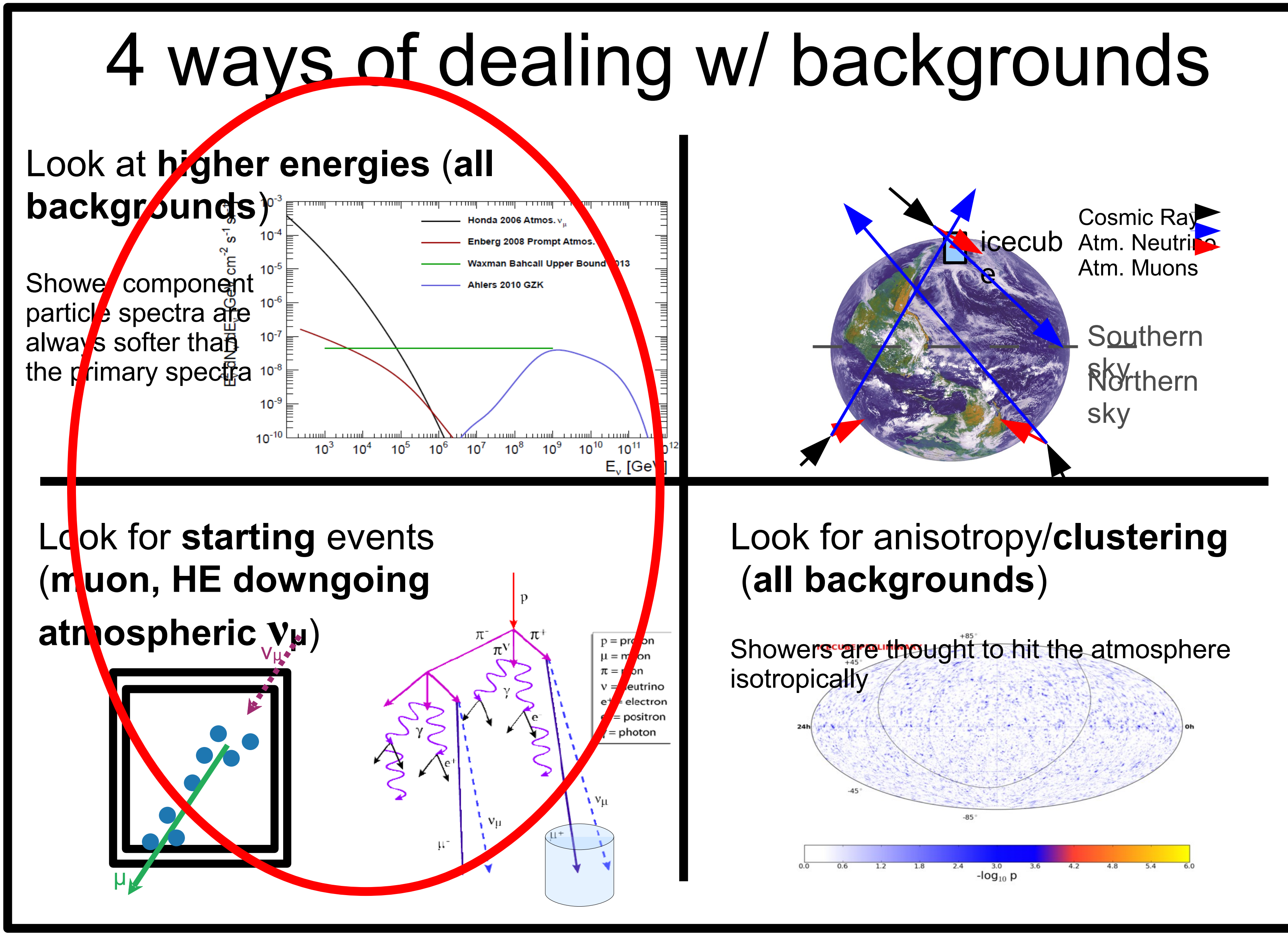
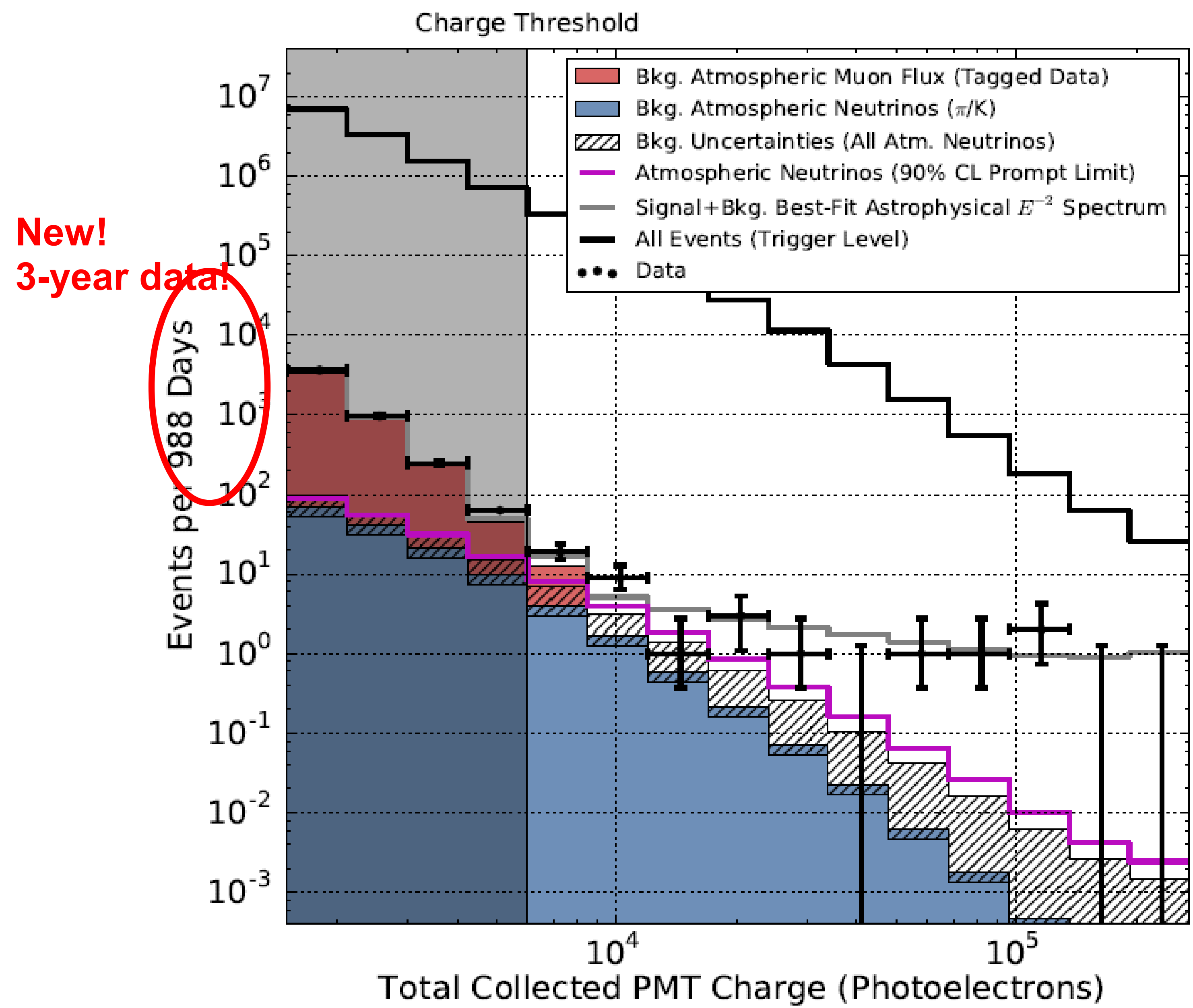
Analysis 1: High Energy Starting Events



IceCube Discovers Comic Neutrinos

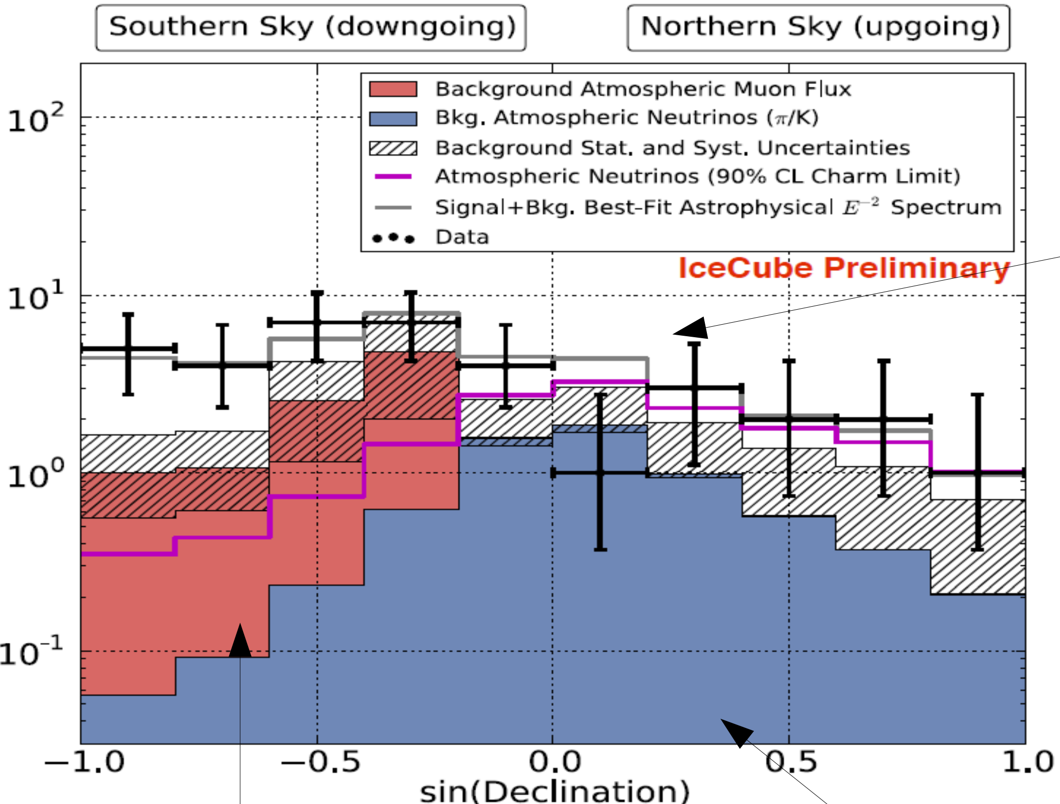


Full glory:
arXiv:1405.5303

Compared to the 1st paper:
- same conclusions stronger
- new highest energy event

Declination Distribution of Events

= zenith



Signal

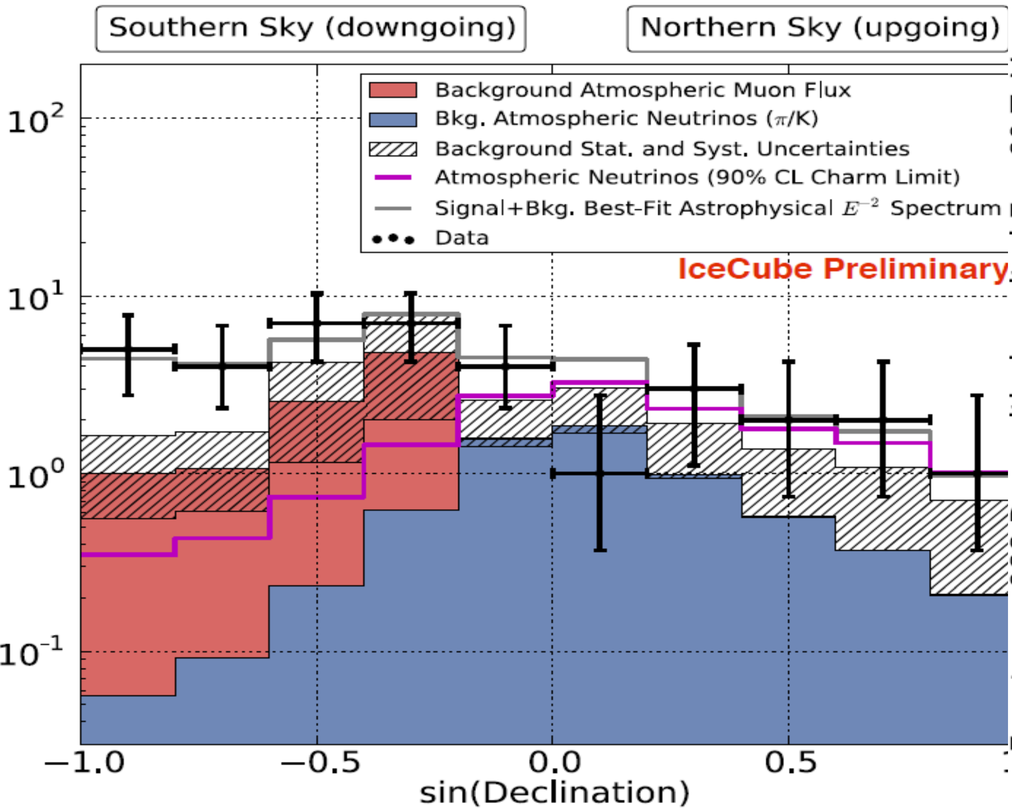
Muon background only in the southern sky

Atm. Neutrino background dominant
- in northern sky (no accompanying muons)
- but near the horizon (earth absorption)

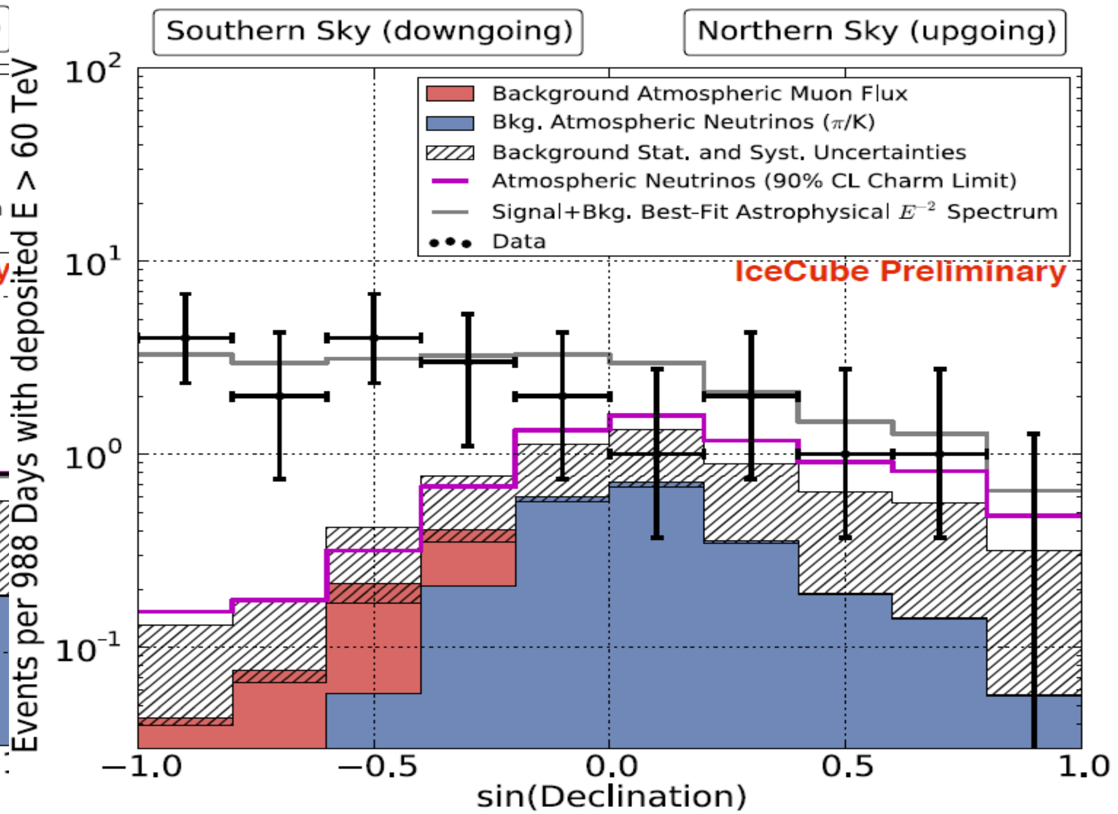
Declination Distribution of Events

= zenith

ALL EVENTS



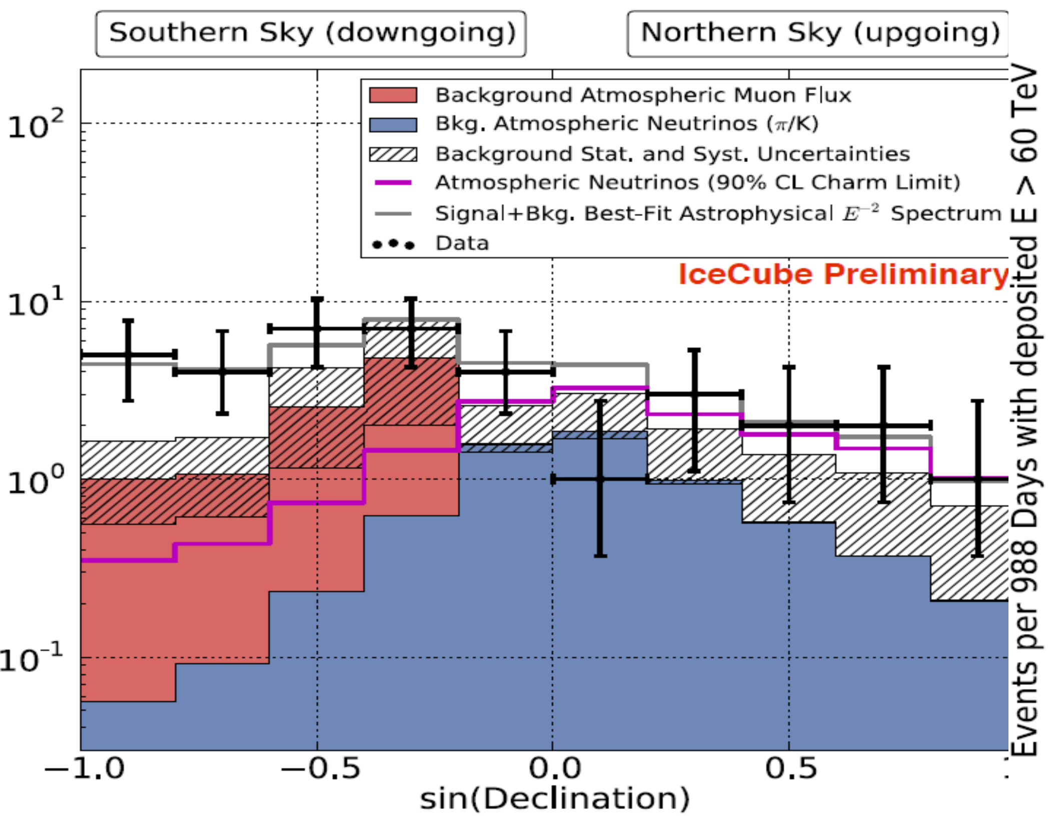
EVENTS > 60 TeV



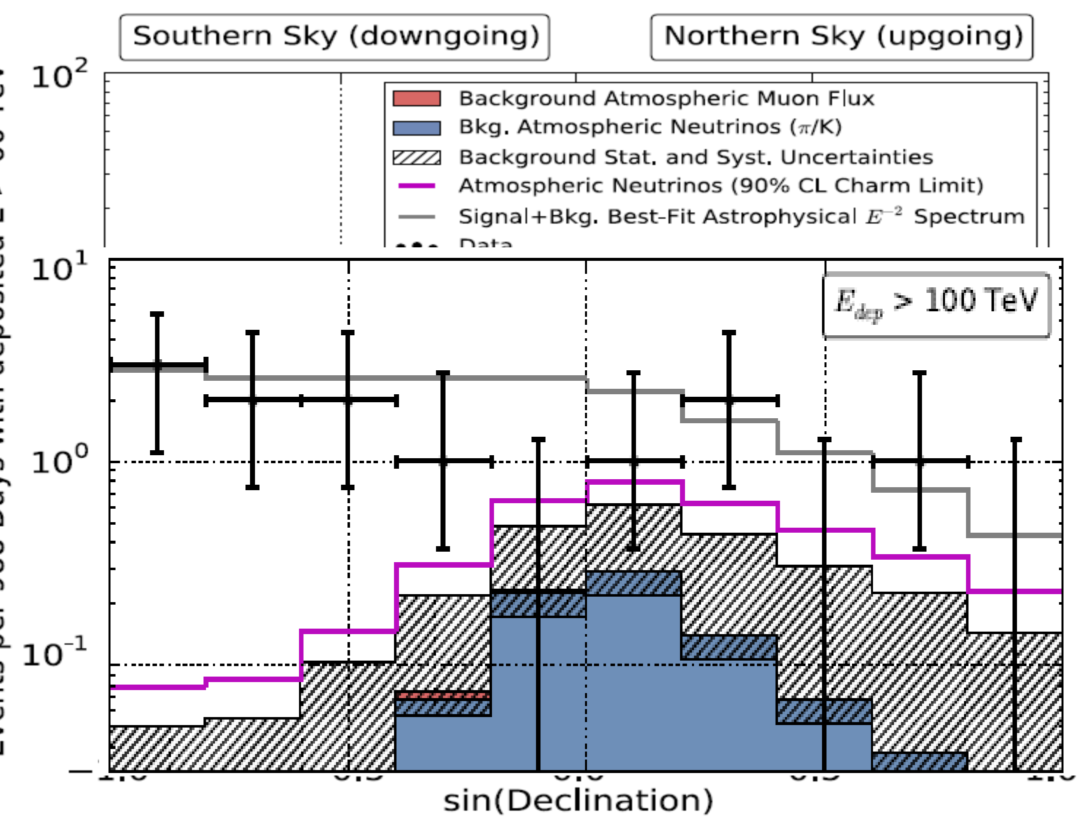
Declination Distribution of Events

= zenith

ALL EVENTS

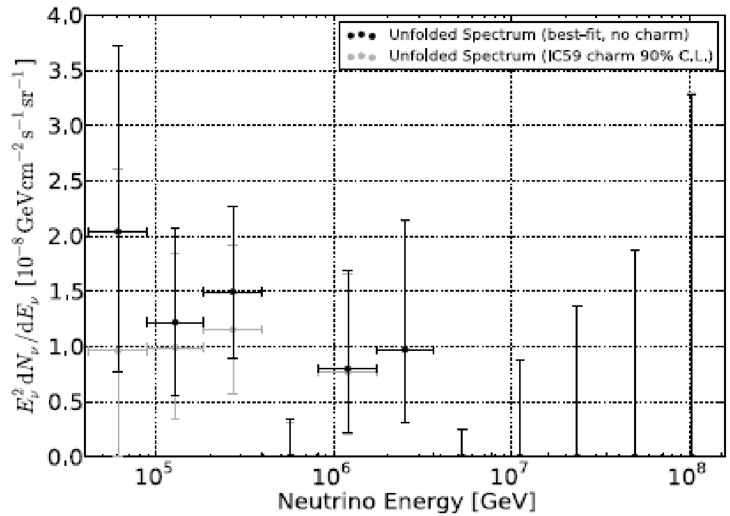


EVENTS > 100 TeV



Properties observed from Analysis 1

Flux Level: ~1 x 10^{-8} E^2 [/GeV/cm^2/s/sr] per flavor
Spectral index: -2.3

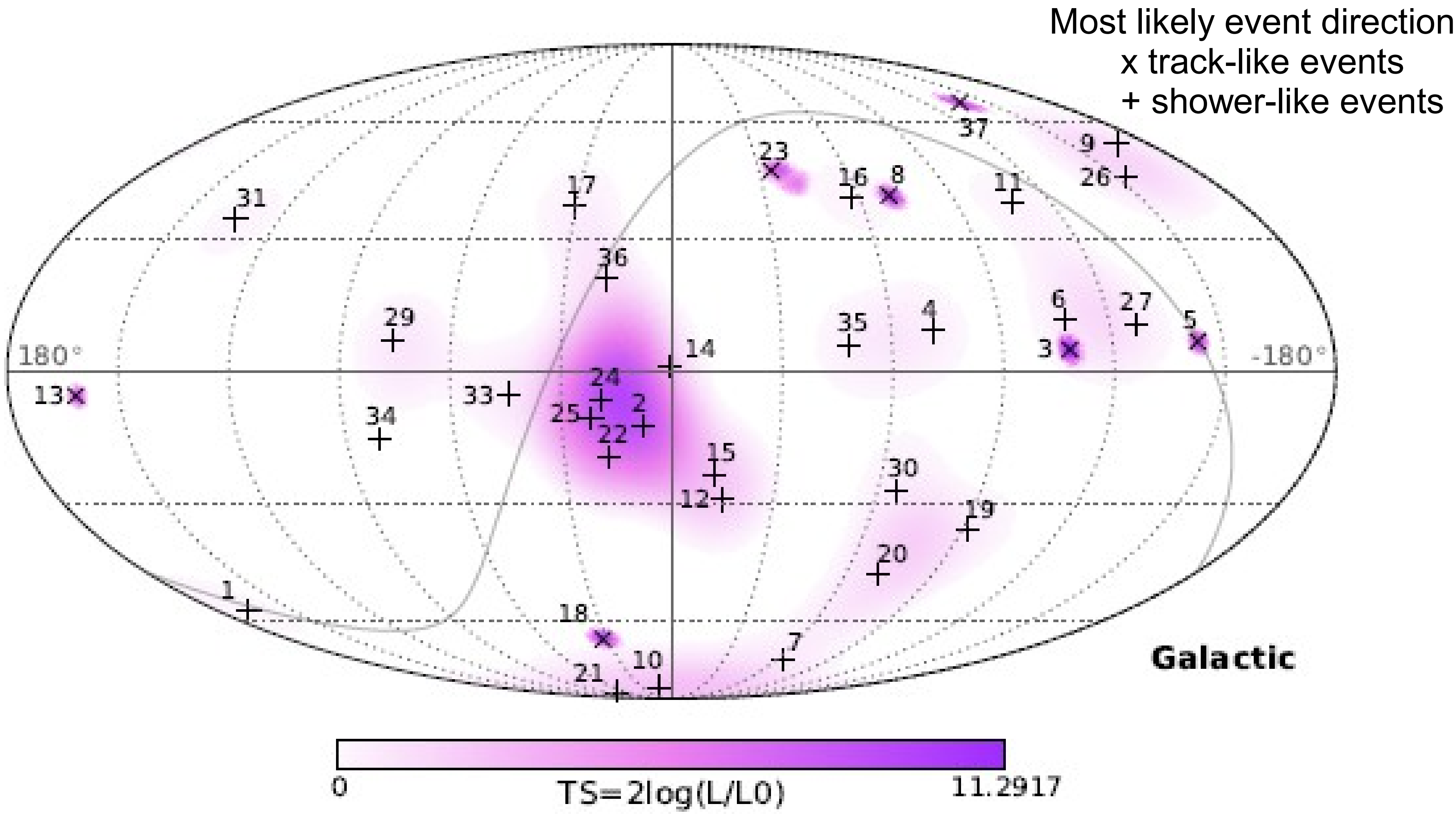


Isotropy: consistent with isotropic

27 from southern sky, 9 from northern sky
Background includes muons which is only from the southern sky
At high energy, earth absorption of neutrinos (both signal and bkg)

ν flavor ratio: consistent with 1:1:1

9 tracks, 27 showers
Background is track rich (mesons branch to more muons then electrons)
Signal is shower rich (only 1/6 interaction channels create tracks)



- No significant clustering
- No significant clustering around the galactic plane

- Extragalactic component very likely

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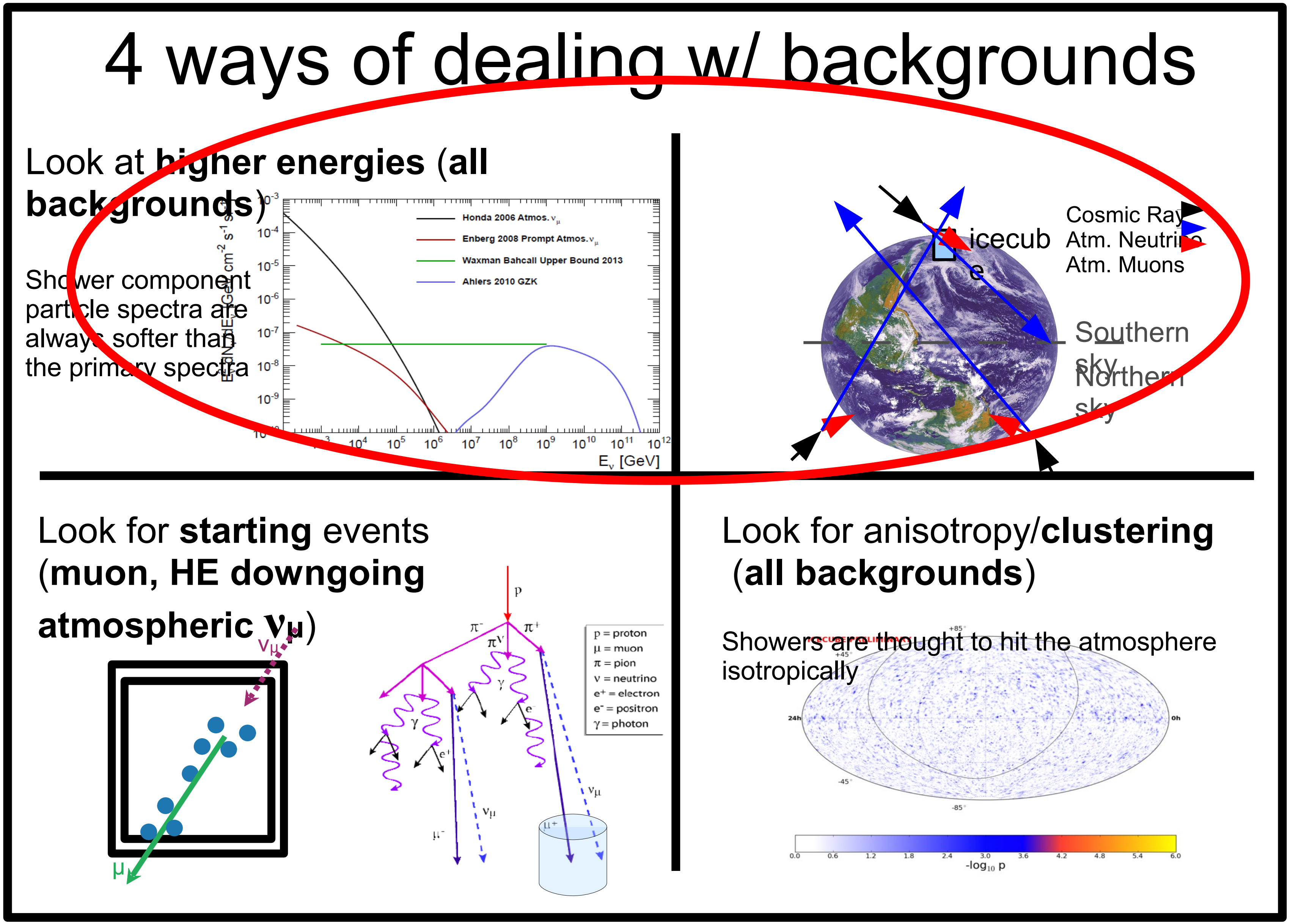
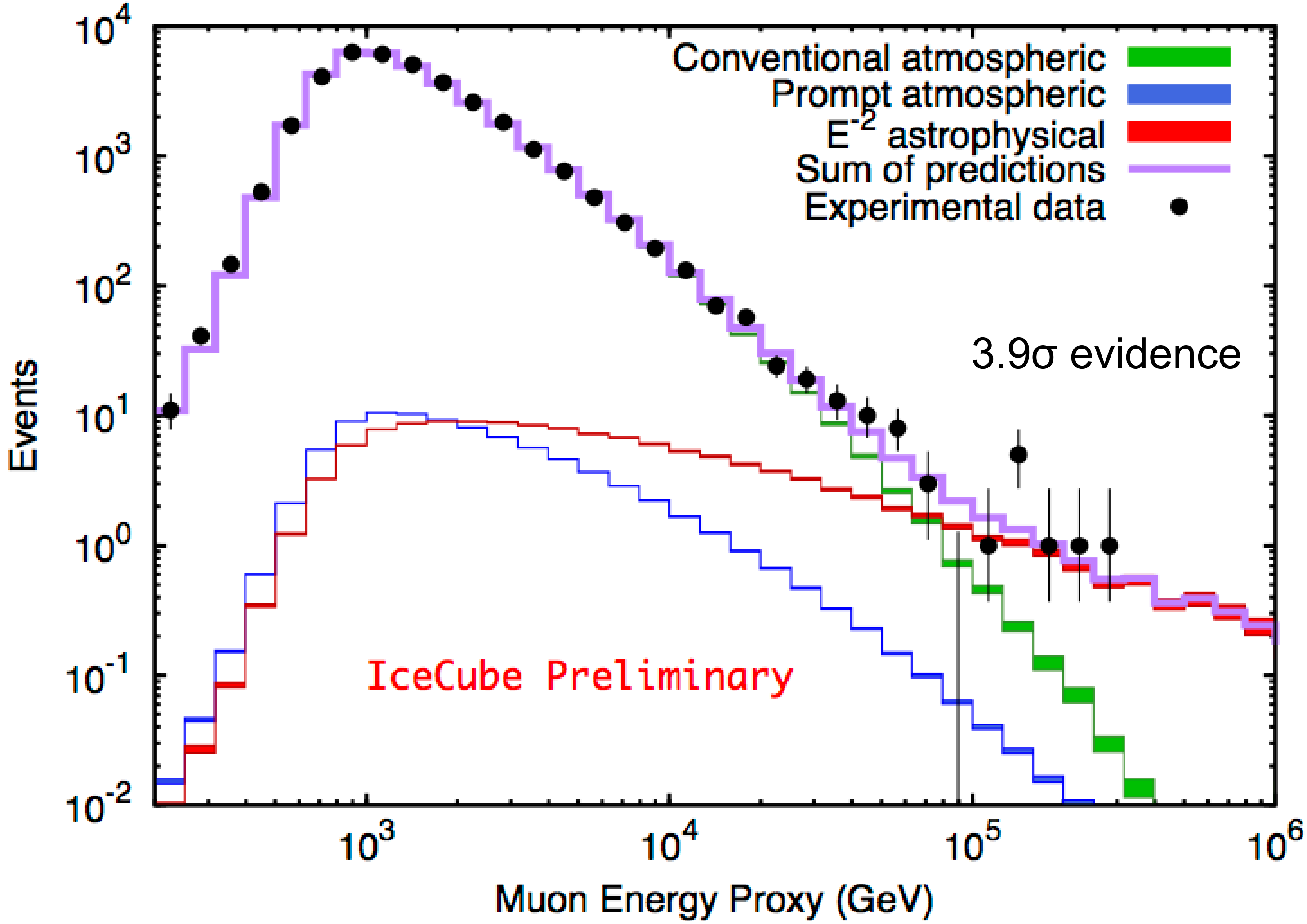
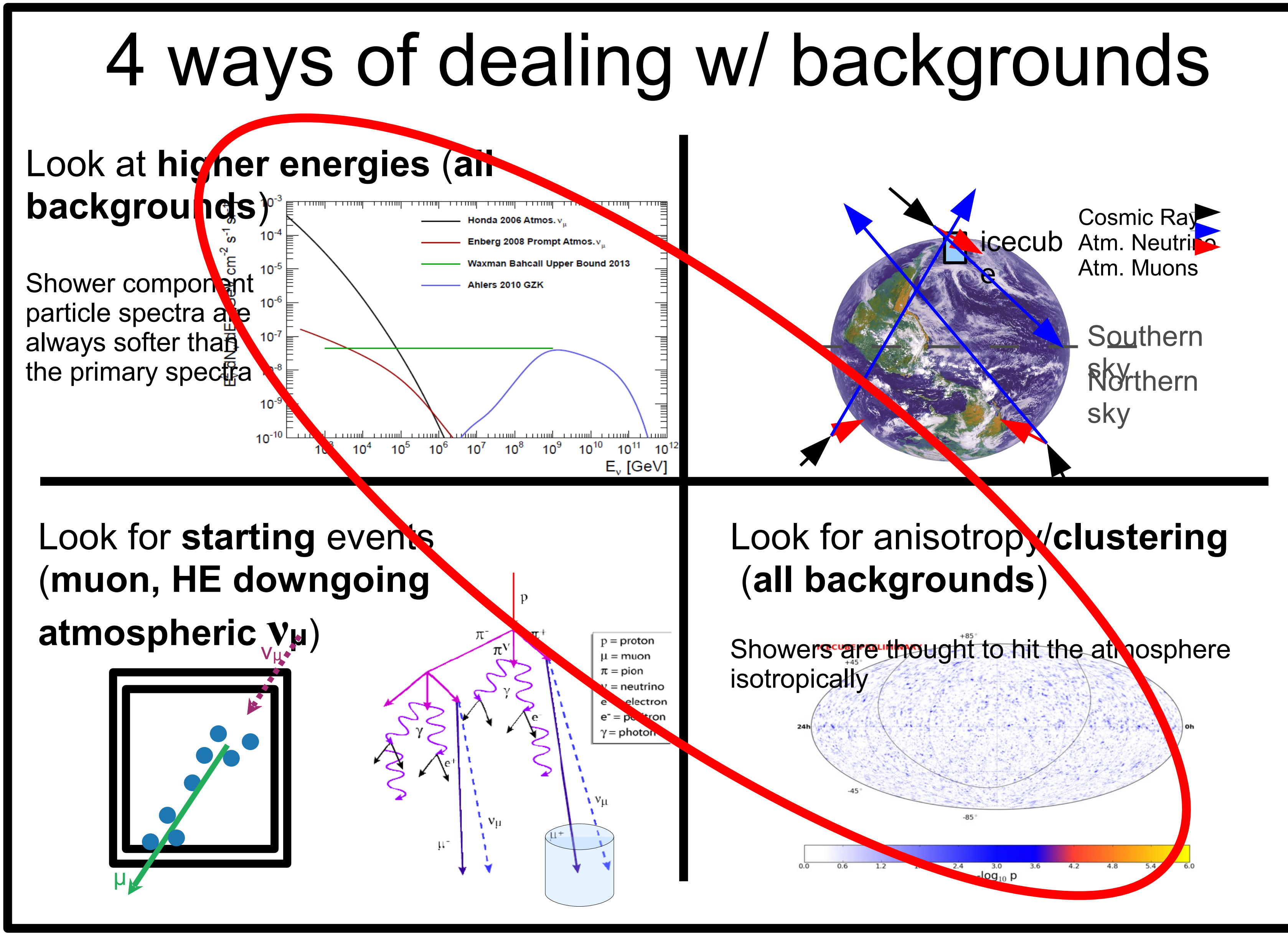
Analysis 2: High Energy Upgoing Tracks



Data is well-resolved upgoing tracks

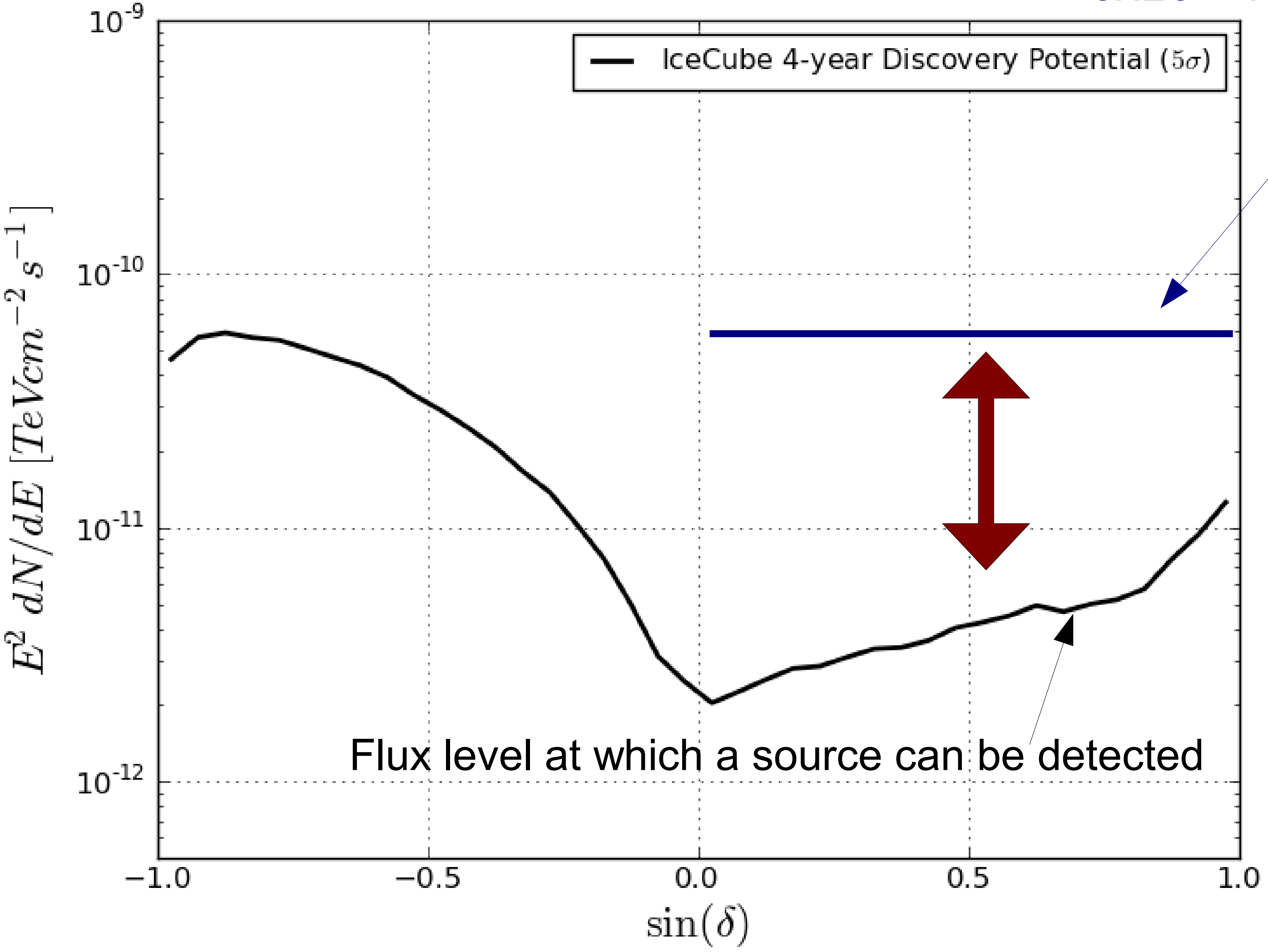


Analysis 3: Point Source Search of Track Events



No evidence of point source → Limit on point source flux

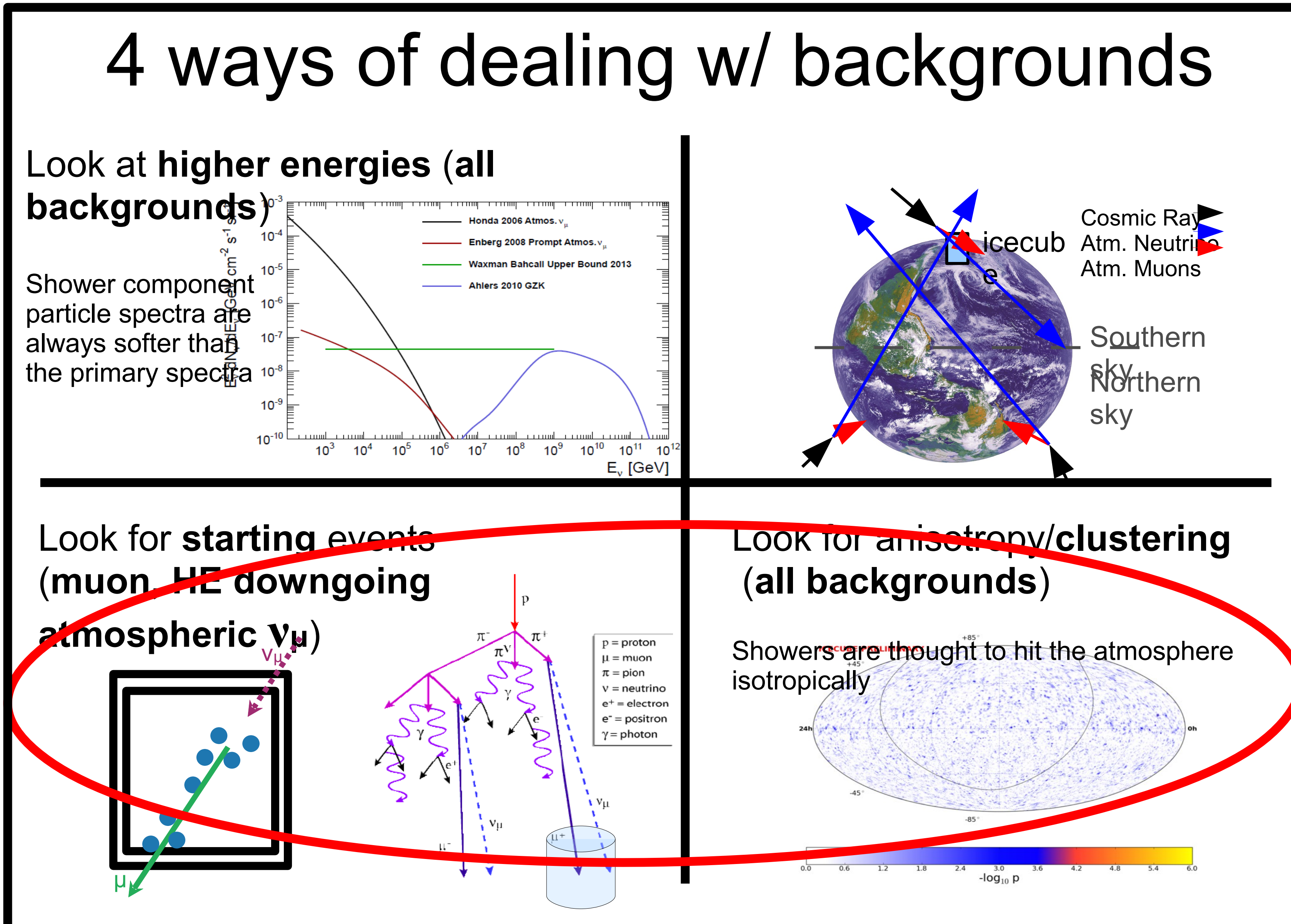
Measured Flux in northern hemisphere:
~ 10^{-8} GeV/cm^2/s/sr x 2π
~ 6×10^{-11} TeV/cm^2/s



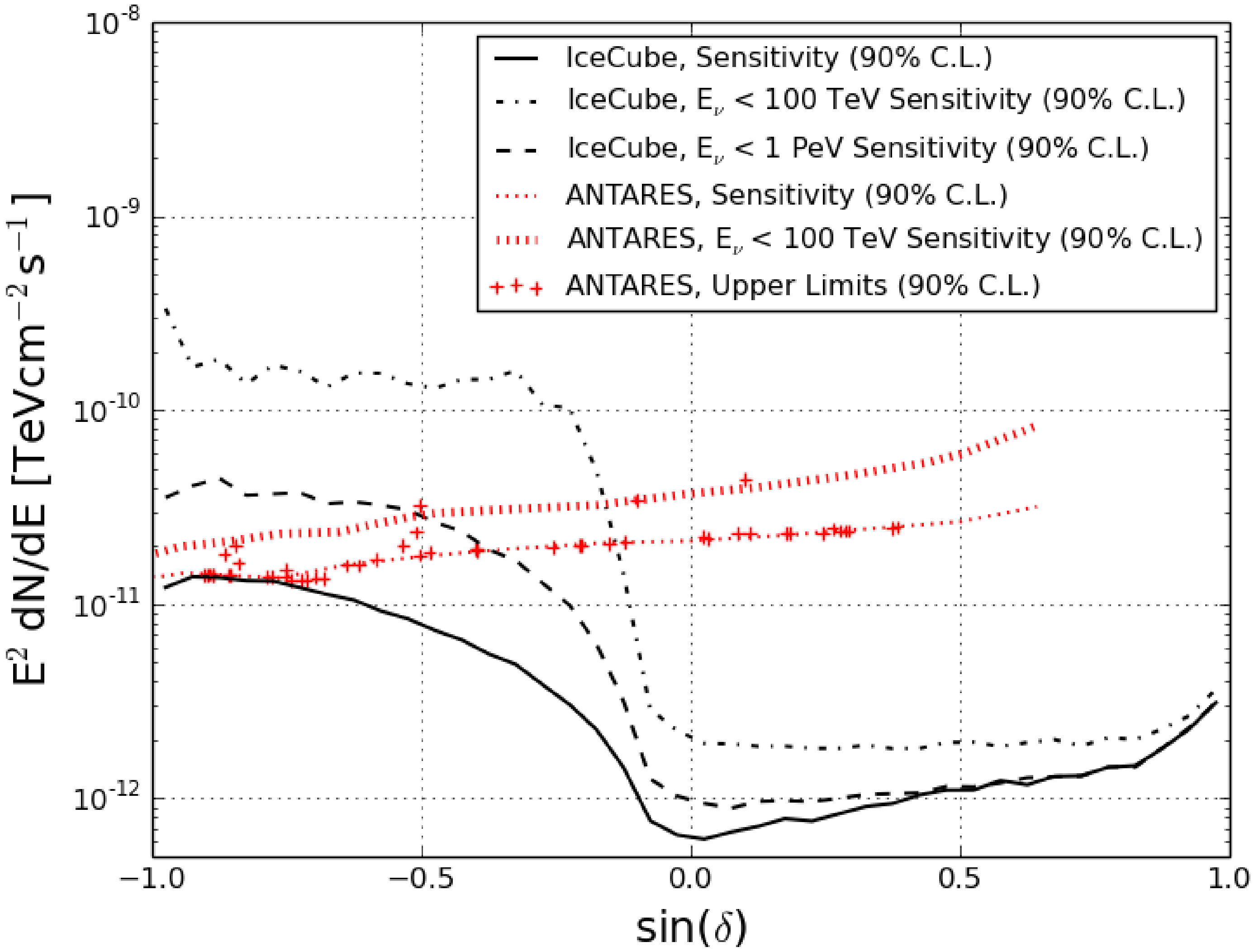
$N_{sources} \geq$ ~15

Many ways around it
- extended sources
- much softer spectrum

Future Analysis 4: Point source search with starting tracks

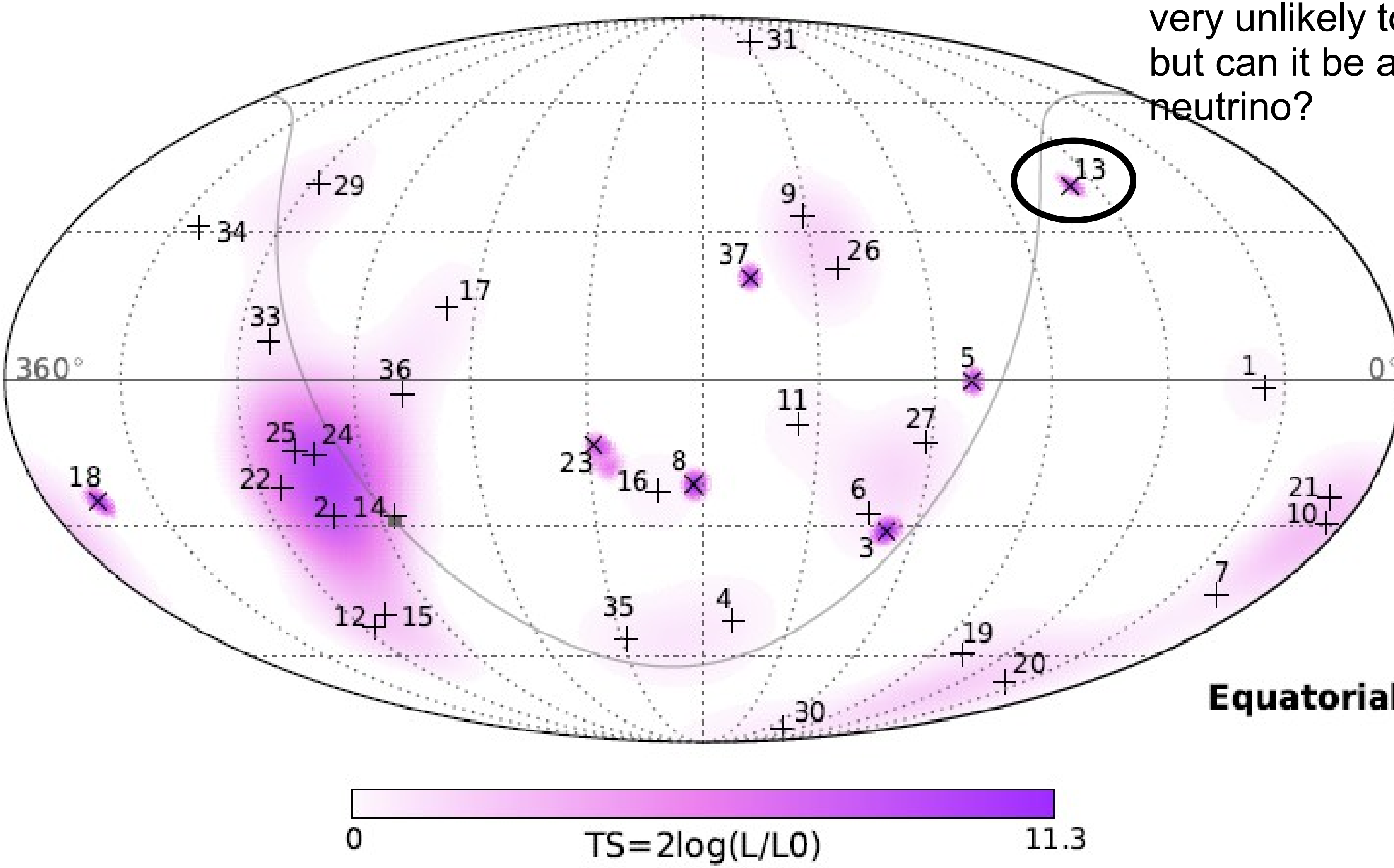


Great improvement in the southern sky!



Lets look at the sky map from Analysis1 again....

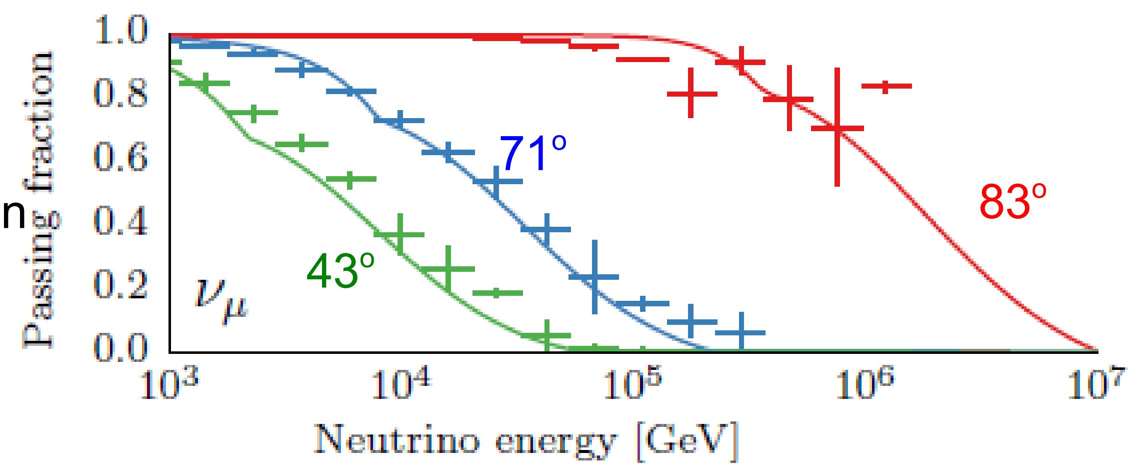
Is this track event special? It points, it's over 200TeV so very unlikely to be a muon... but can it be an atmospheric neutrino?



Atmospheric neutrinos can have accompanying muons from the same vertex

The event is ~200TeV at ~50 degrees

Chance that you don't see an accompanying muon

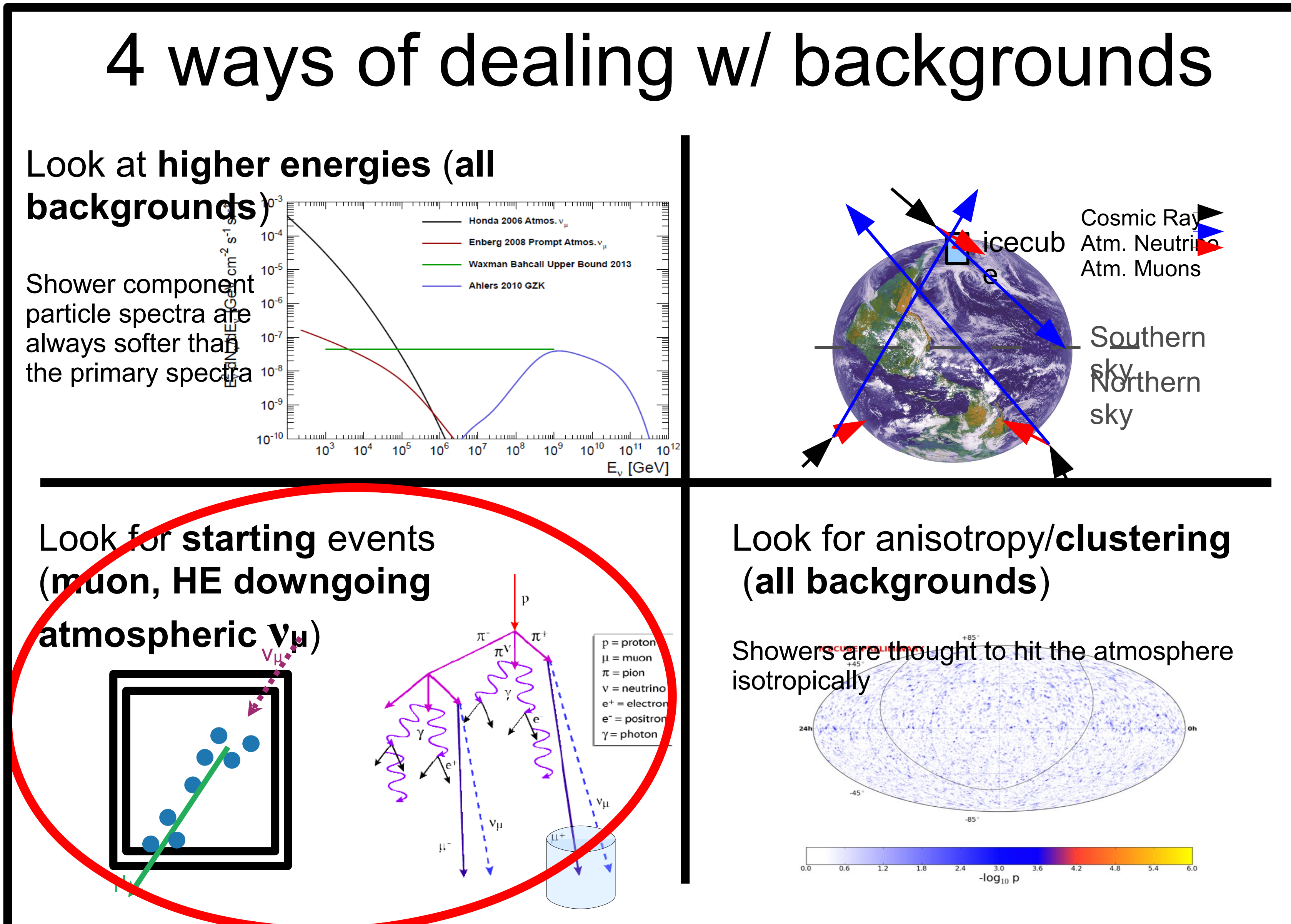


arXiv:1405.0525 J. vanSanten et al

Southern sky tracks (especially close to vertical) that start inside the detector are the ost interesting because

- **they point**
- **they can't be atm. muons at HE**
- **they can't be atm. neutrinos at HE because of the lack of an accompanying muon**

Future Analysis 5: Spectral fit on starting showers



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Source speculations

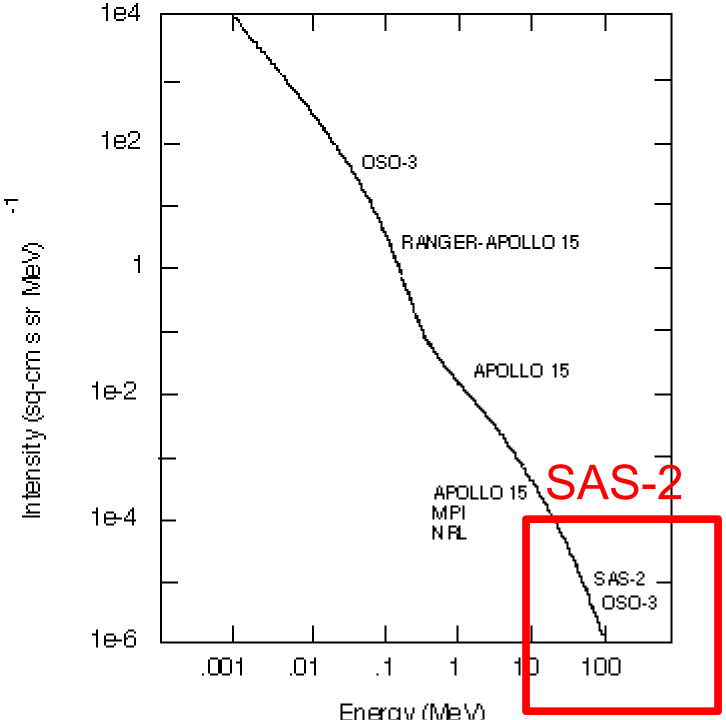
- GRBs seem unlikely (IceCube limit)
- AGN maybe (extragalactic compatible to isotropy, but spectrum?)
- Starburst Galaxies (can't be close-by & luminous due to IceCube limit)
- Dark Matter (what's the “smoking gun?”)
- Galactic component still possible! (neutrinos don't interact → background is not dark → hard for galactic component to “stick out”.... but maybe still our best bet!)

Optimism:
History is on our side!

Gamma-ray Astronomy

Diffuse signal → first source → catalog!

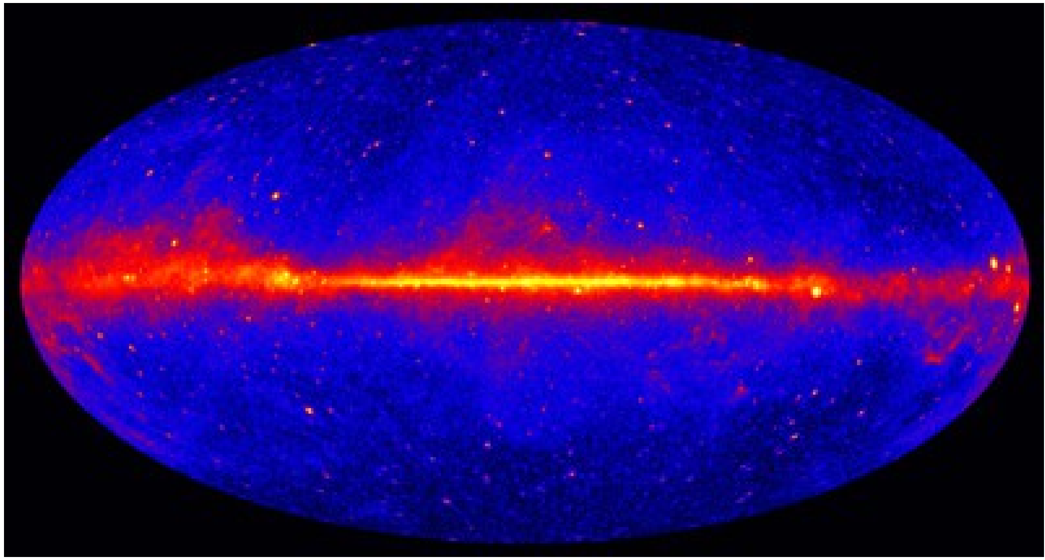
1970's



SAS-2

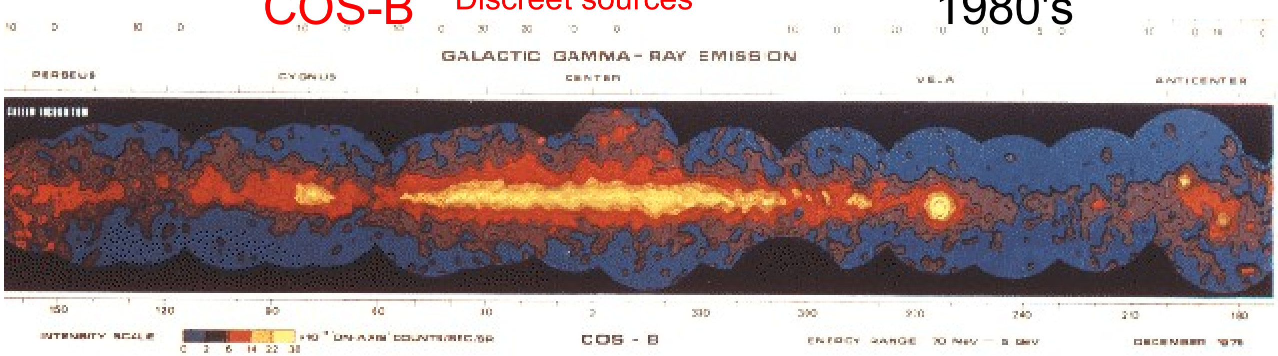
Diffuse celestial radiation

NOW Fermi 5-year data



GSFC nasa.gov

COS-B Discreet sources 1980's



GSFC nasa.gov

X-ray Astronomy

Diffuse signal → first source → catalog

(Sun detected in x-rays 1940's)

Diffuse emission and Scorpius X-1 1960's

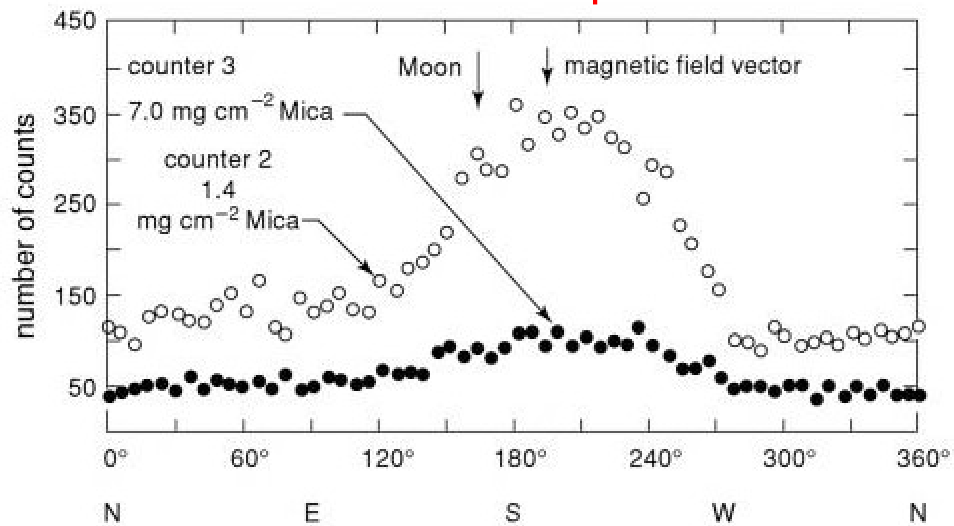
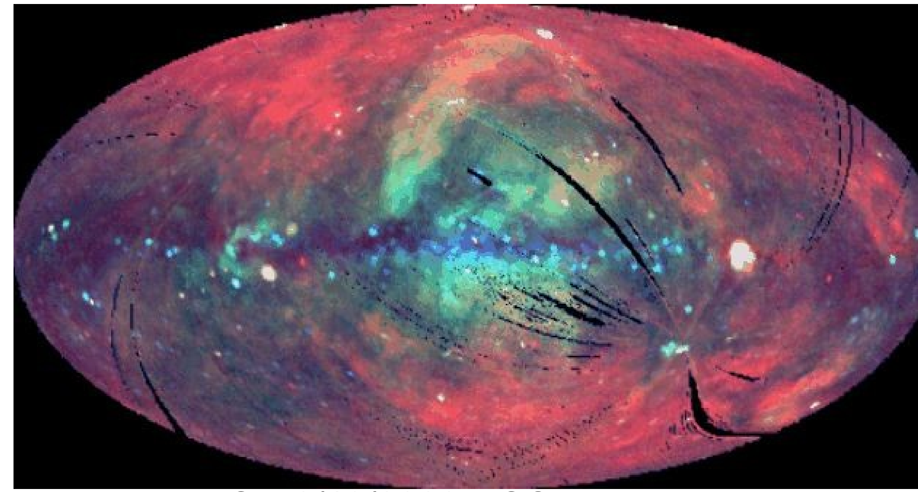
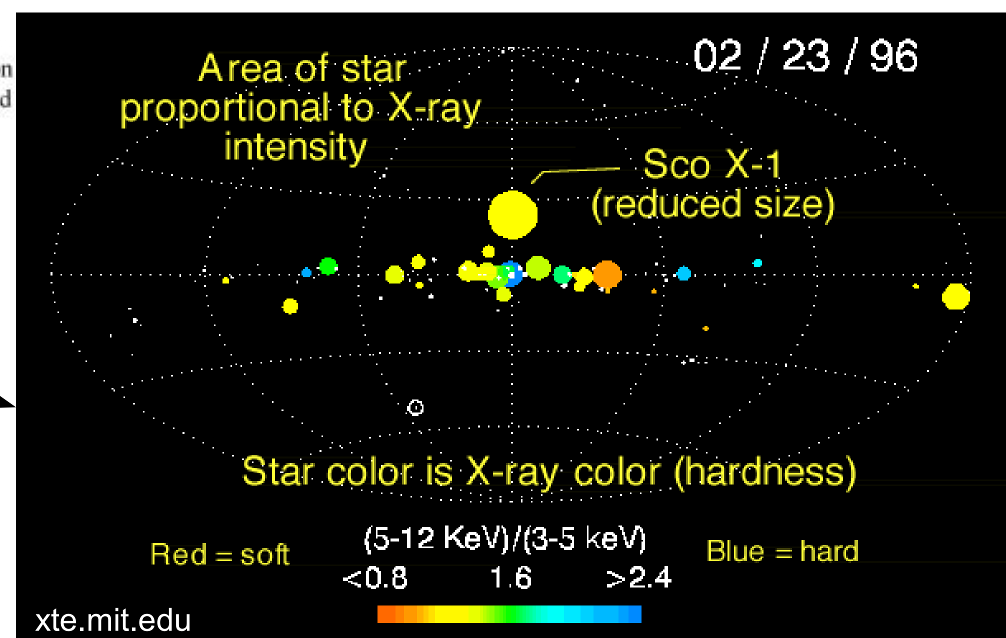


Figure 7.7: The discovery record of the X-ray source Sco X-1 and the X-ray background emission Giacconi and his colleagues in a rocket flight of June 1962. The prominent source was observed both detectors, as was the diffuse background emission (Giacconi *et al*., 1962).

"The Cosmic Century" M. S. Longair

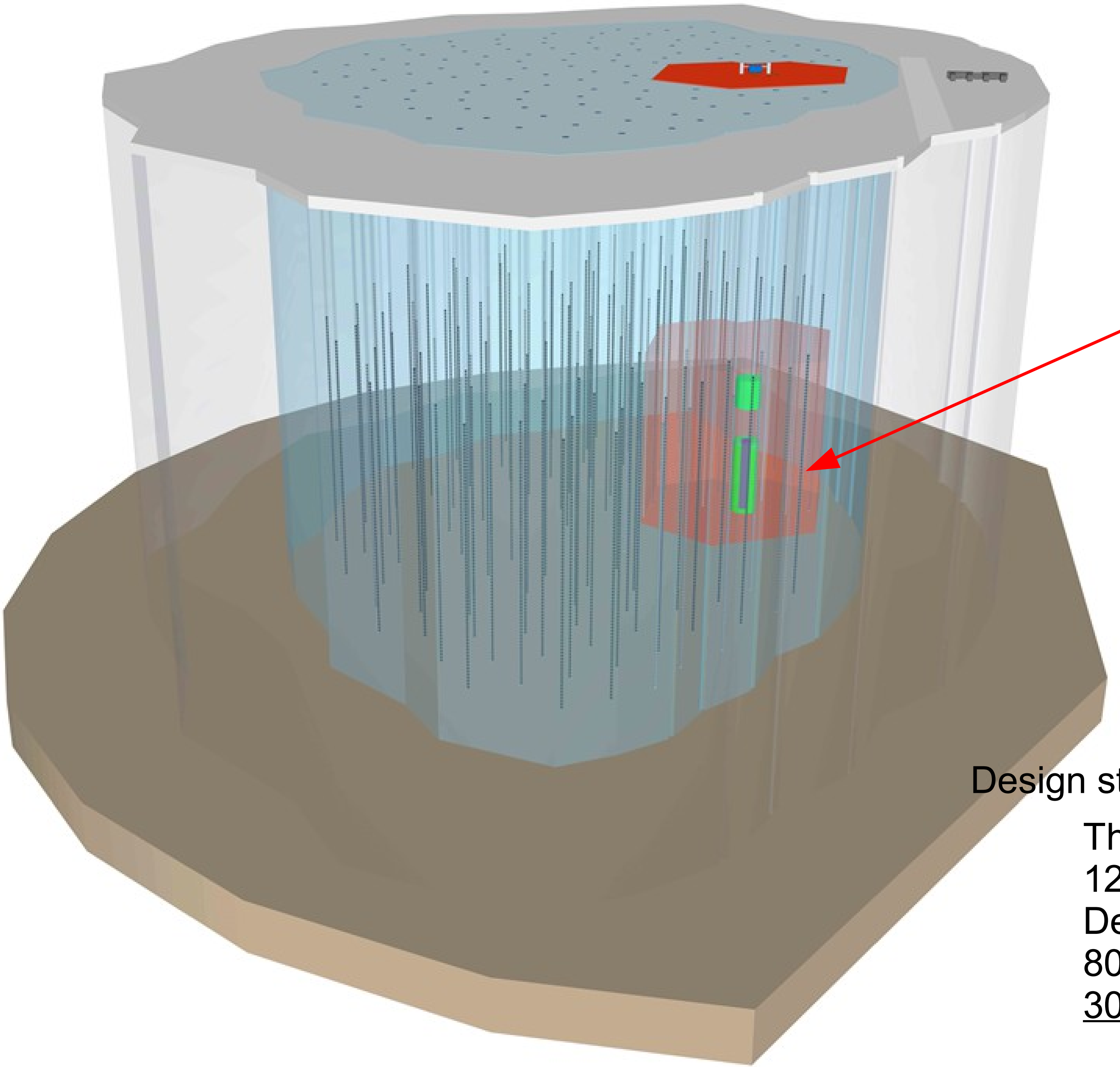


APOD 8/19/2000 ROSAT



Only question: How do we get there quickly and efficiently?

Next Generation IceCube



Design studies under way!

This figure:
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

Input from you!

- What's the priority? Diffuse flux? Anisotropy? Or point sources?
- Background rejection vs statistics (Is a single event that's not from known backgrounds at 5σ a point source? …. actually, stay tuned on this!)
- Focus on galactic (southern sky) or extragalactic?
- Energy threshold, PSF vs volume, etc

Backups

Likelihood Search for a Source
- Test Statistic (TS) Calculation -

Maximize the likelihood L assuming a source at point x with energy spectrum $E^{-\gamma}$

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Total # of events (n_{tot})

# of events from source Varied to maximize L (n_s)

$S_i(x)$: Probability density that event i comes from a source at position x × Probability density that event i comes form a source with spectrum γ

$B_i(x)$: Probability density that event i is from backgrounds expected at position x × Probability density that event i comes form a known background energy spectrum

TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left(L(x) / L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$

Could it be Starburst Galaxies?

IceCube does a stacking analysis on close-by starburst galaxies using the traditional muon data set and has a strong upper limit

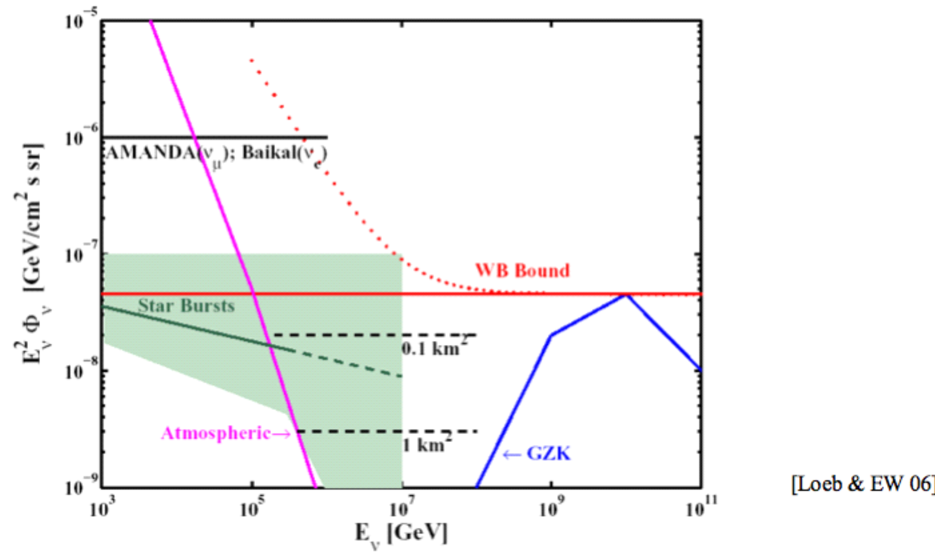
arxiv:1307.6669

Stacking of catalog of 127 starbursts

- Within $z < 0.03$
- F_{FIR}(60 micron) > 4 Jy
- F_{radio}(1.4 GHz) > 20 mJy

Starburst galaxies: predicted ν emission

Waxman, TeVPA '13



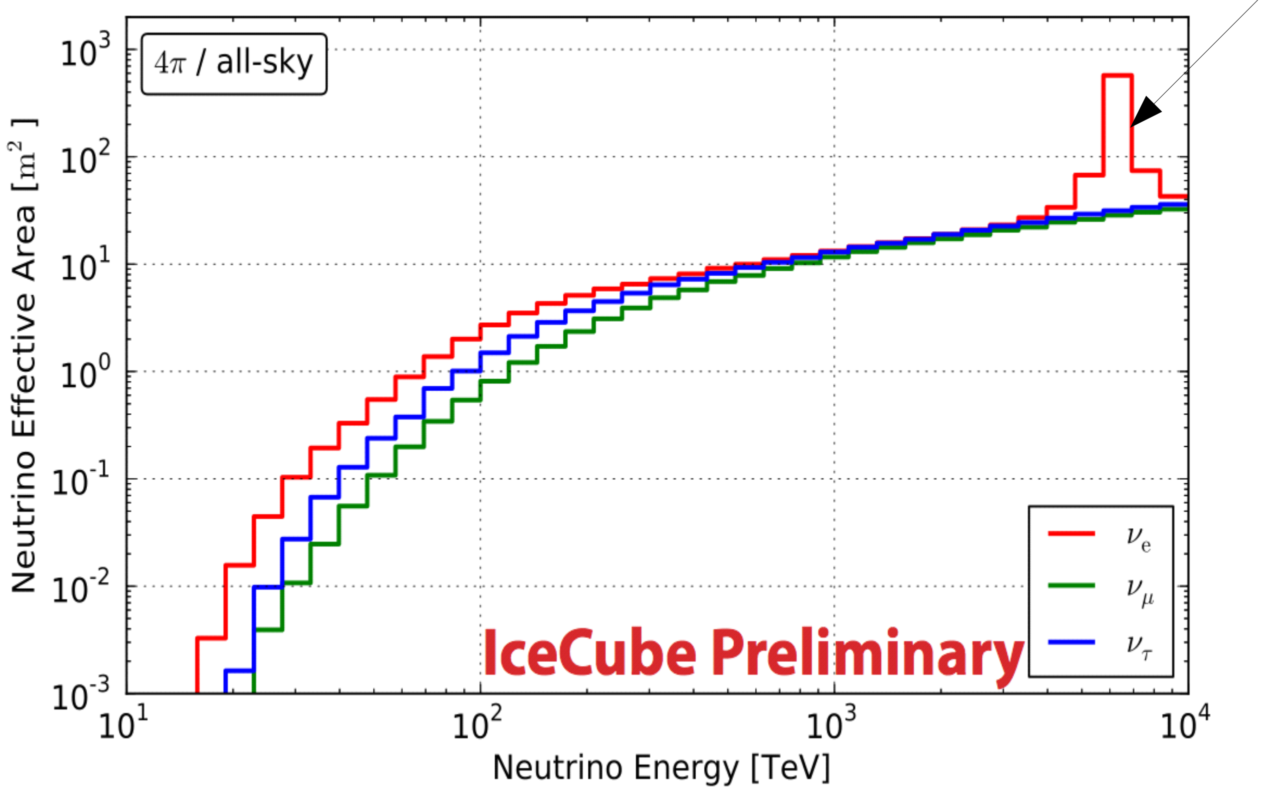
Unbroken E^{-2} flux limit: 7×10^{-10} E^{2} GeV $cm^{-2}s^{-1}sr^{-1}$

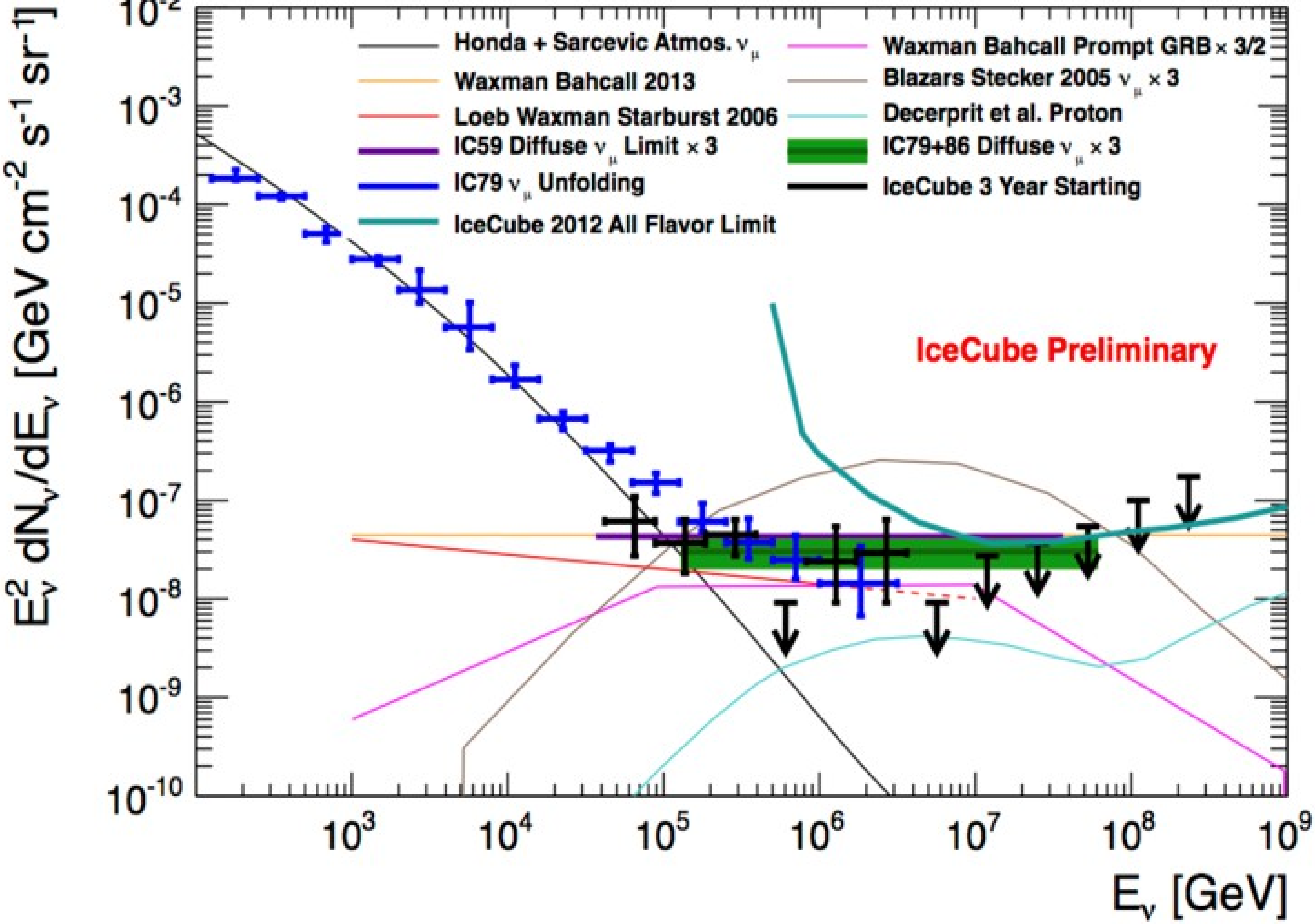
Bright, nearby starbursts can only be responsible for ~< 10% of HESE flux

Speculation of a cutoff

A flux level of ~$10^{-8}E^{-2}$[GeV/cm^2/s/str] predicts another 3-6 events in 2-10PeV range

Glashow resonance





Honda + Sarcevic Atmos. ν_μ
Waxman Bahcall 2013
Loeb Waxman Starburst 2006
IC59 Diffuse ν_μ Limit × 3
IC79 ν_μ Unfolding
IceCube 2012 All Flavor Limit
Waxman Bahcall Prompt GRB × 3/2
Blazars Stecker 2005 ν_μ × 3
Decerprit et al. Proton
IC79+86 Diffuse ν_μ × 3
IceCube 3 Year Starting
IceCube Preliminary
$E_\nu^2\, dN_\nu/dE_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{3}
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