Introduction to Physics Analyses in IceCube

IceCube BootCamp 2016
WIPAC, UW-Madison
June 16, 2016

Donglian Xu

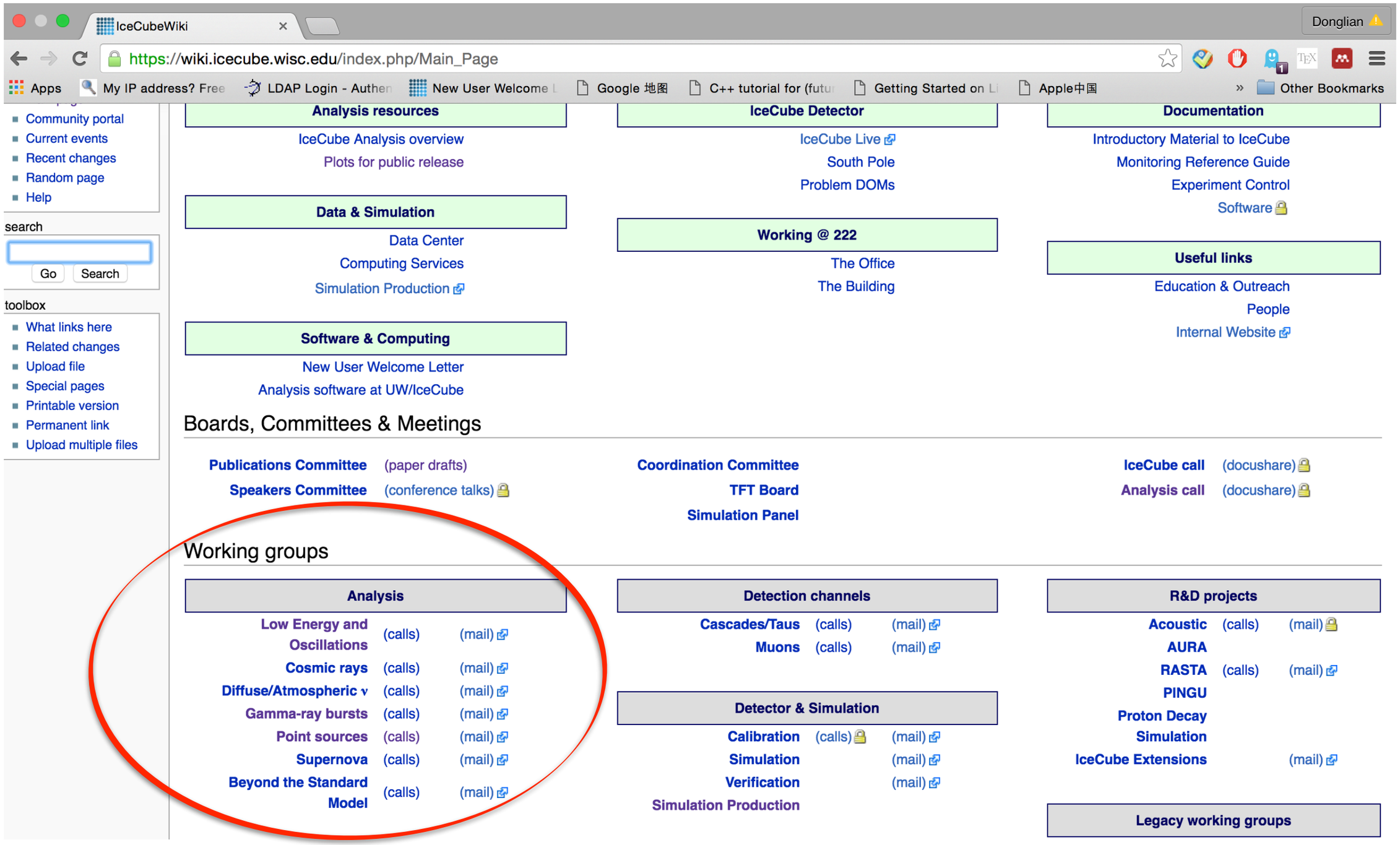
Outline

- Ongoing Physics Analyses
  - Diffuse/Atmospheric Neutrinos
    - Cosmogenic neutrinos (EHE)
    - All flavor (cascades and tracks)
    - Through-going NuMu (tracks)
    - NuTau (double cascades)
    - Flavor ratios
  - Point sources/Transient
  - Low-energy and Oscillations —> See Moriah's talk
  - Supernova
  - Cosmic Rays (IceTop: Energy spectrum, anisotropy)
  - Beyond the Standard Model (BSM)
  - …
- Event Selection/Cuts

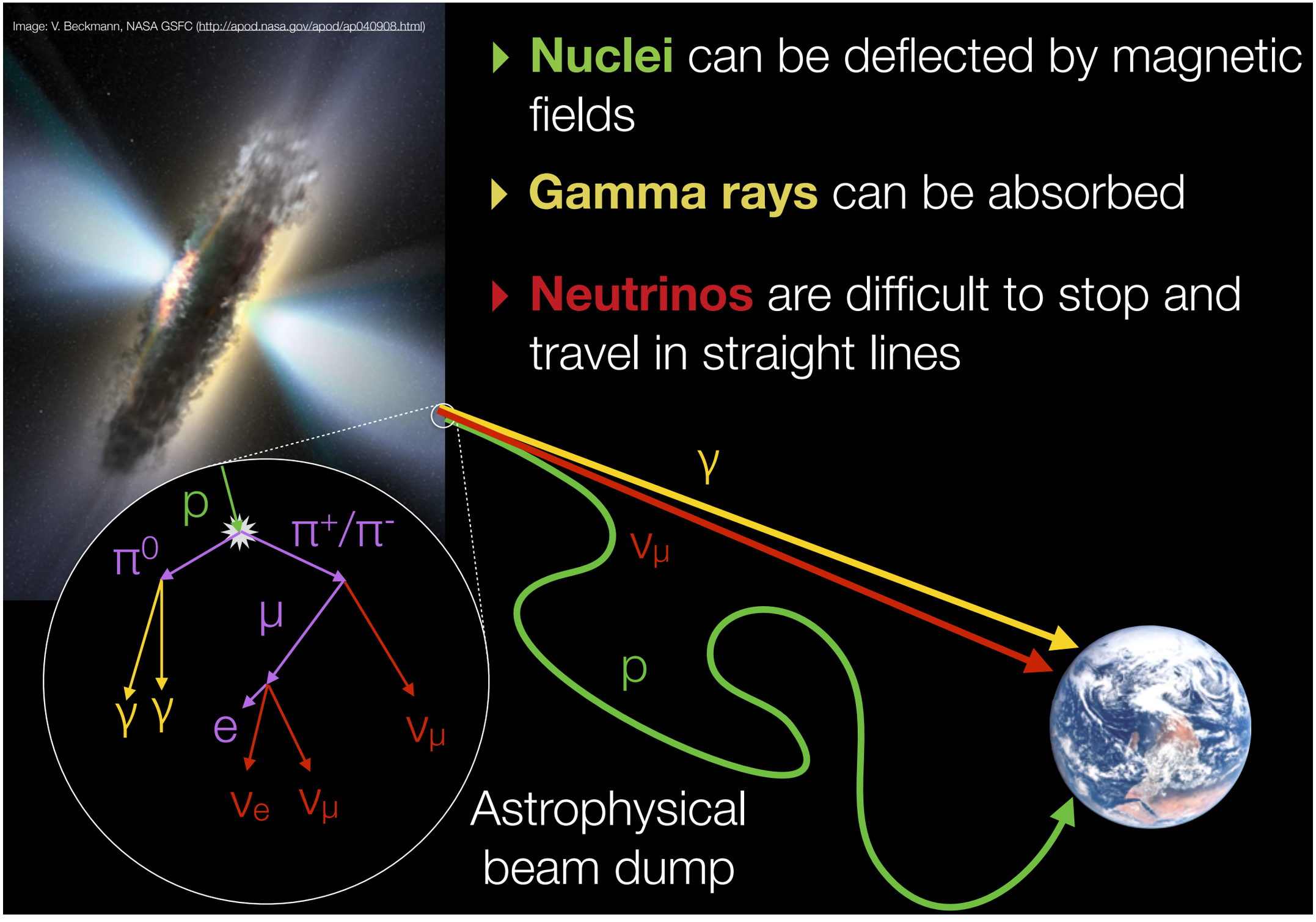
Ongoing Physics Analyses

(Not Exhaustive)

Where do you find them?



Astrophysical Beam Dump



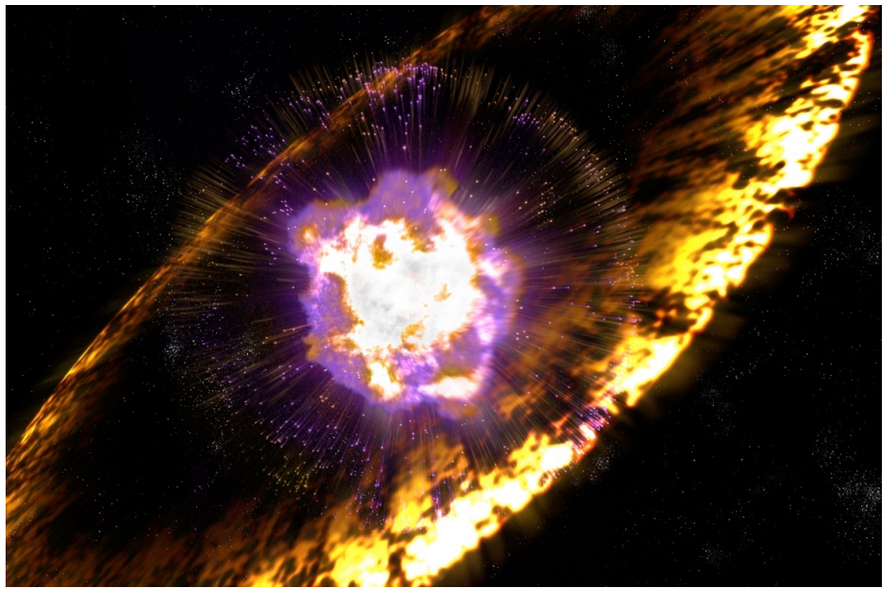
WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Astrophysical Neutrinos

Active Galactic Nuclei (AGNs)

Gamma Ray Burst (GRB)



Supernovae

- Fermi acceleration:

$$\frac{dN}{dE} \sim E_\nu^{-2}$$

If cosmic rays interact before decaying, spectrum is softer

- At Earth's surface:

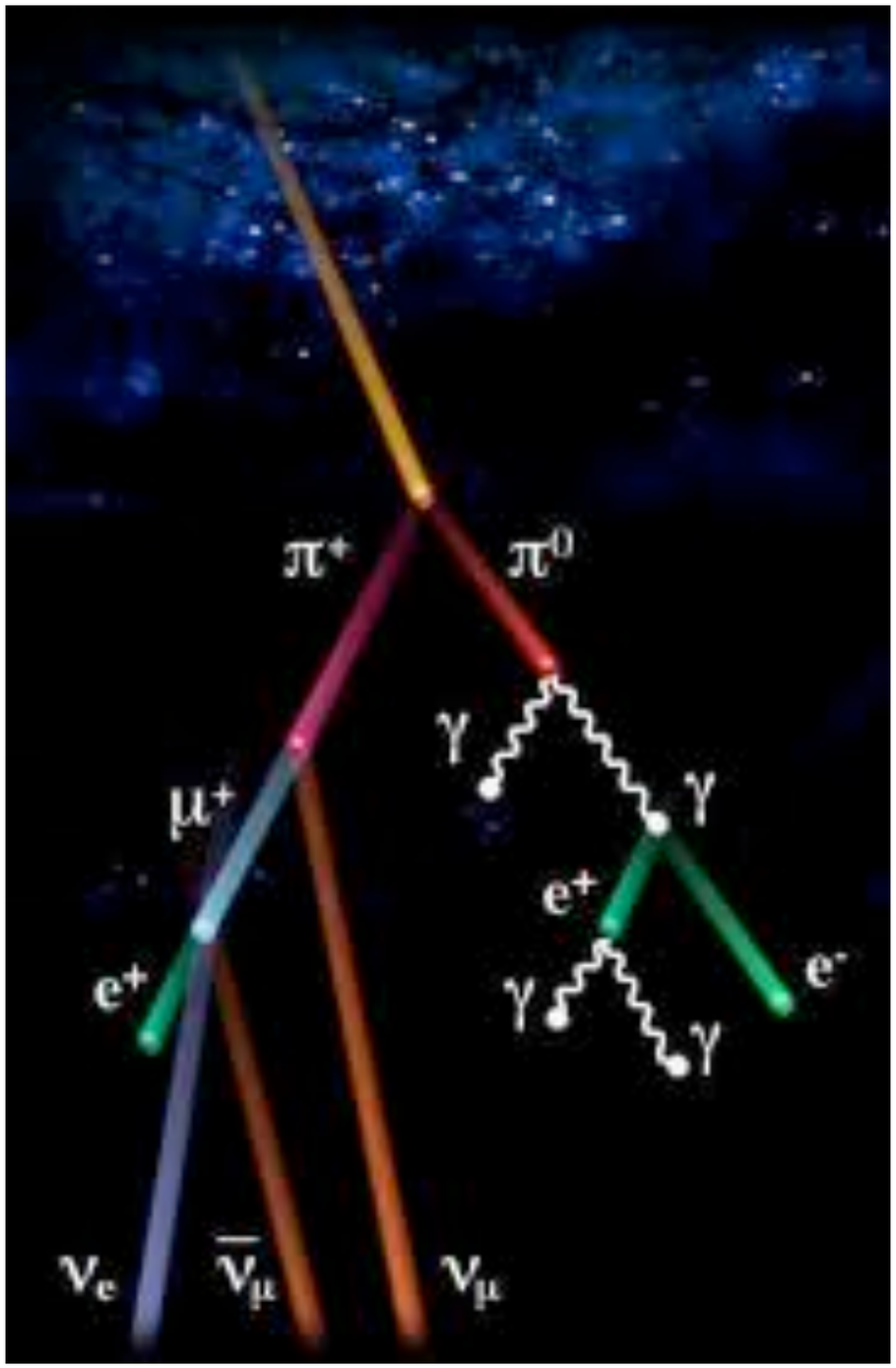
$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

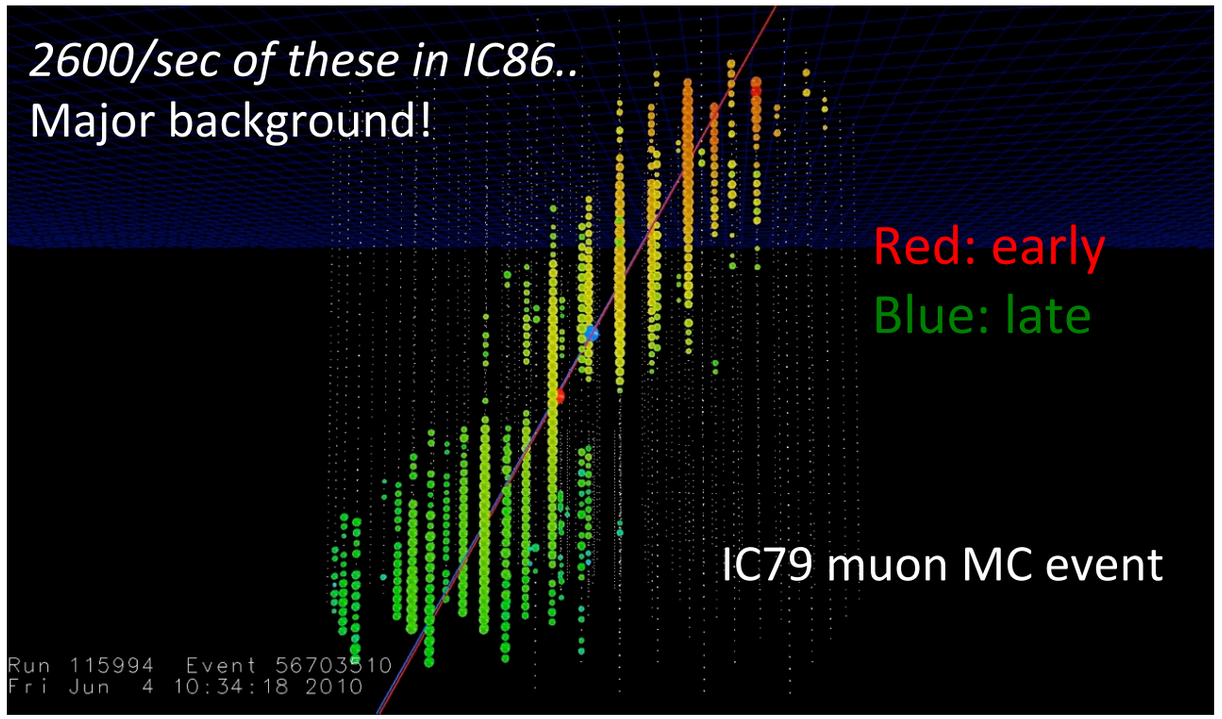
Expected astro. ν flux at Earth $E^2\phi_\nu \sim 10^{-8}$ *GeV cm*$^{-2}$ *s*$^{-1}$ *sr*$^{-1}$ *(TeV-PeV)*

WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Atmospheric Neutrinos





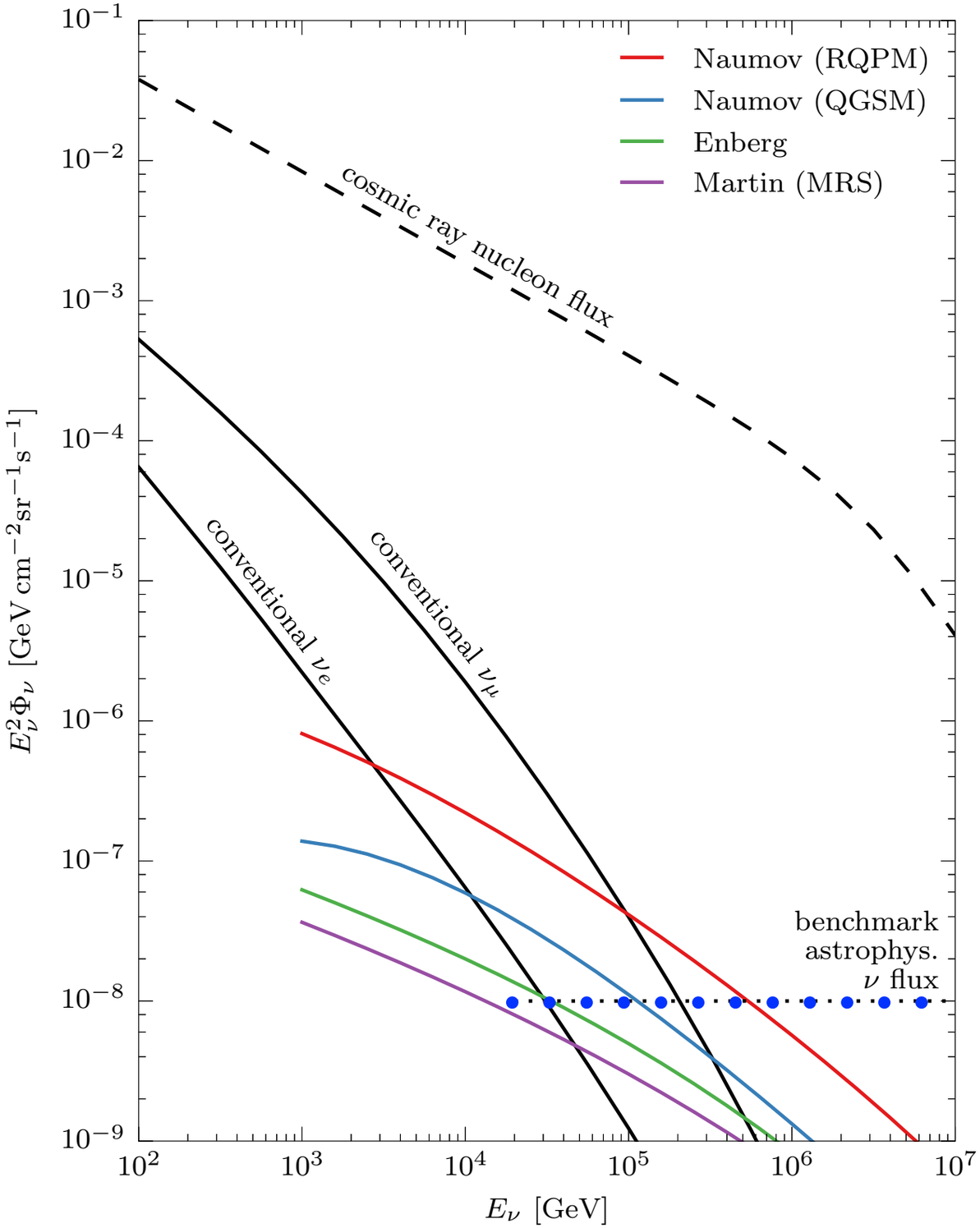
- Conventional: $\frac{dN}{dE_\nu} \sim E_\nu^{-3.7}$ $\nu_e : \nu_\mu \simeq 1 : 2$
- Prompt: $\frac{dN}{dE_\nu} \sim E_\nu^{-2.7}$ $\nu_e : \nu_\mu \simeq 1 : 1$

Atmospheric prompt ν_τ is ~10 times lower than ν_μ and ν_e

WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Diffuse/Atmospheric Neutrinos



https://inspirehep.net/record/1339582/files/thesis.pdf

Conventional: $\sim \mathrm{E}^{-3.7}$

Prompt: $\sim \mathrm{E}^{-2.7}$

Astrophysical: $\sim \mathrm{E}^{-2}$

Prompt neutrino models:

Naumov RQPM:
http://link.springer.com/article/10.1007%2FBF02509070

Naumov QGSM:
http://link.springer.com/article/10.1007%2FBF02509070

Enberg: Phys. Rev. D, 78(4):043005

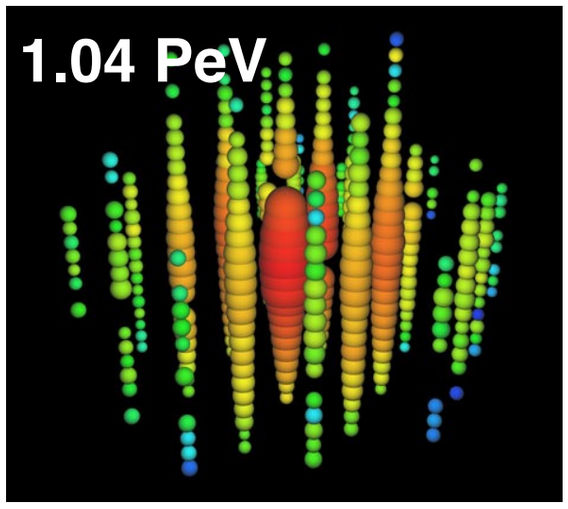
Martin: http://arxiv.org/abs/hep-ph/0302140v2

WIPAC Wisconsin IceCube Particle Astrophysics Center

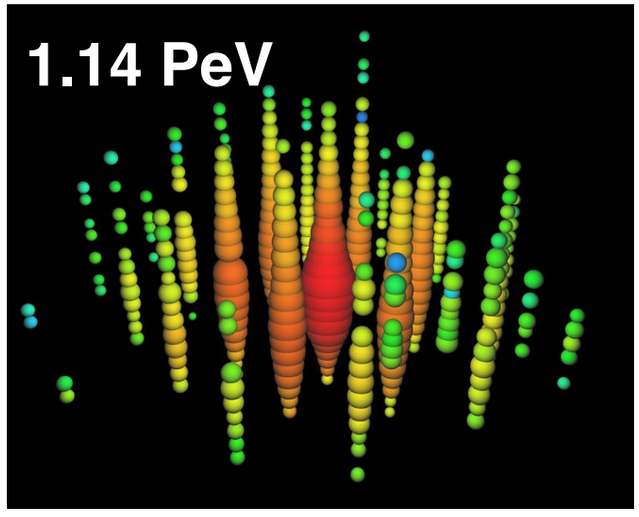
IceCube South Pole Neutrino Observatory

Diffuse: extremely-high energy cosmogenic neutrinos

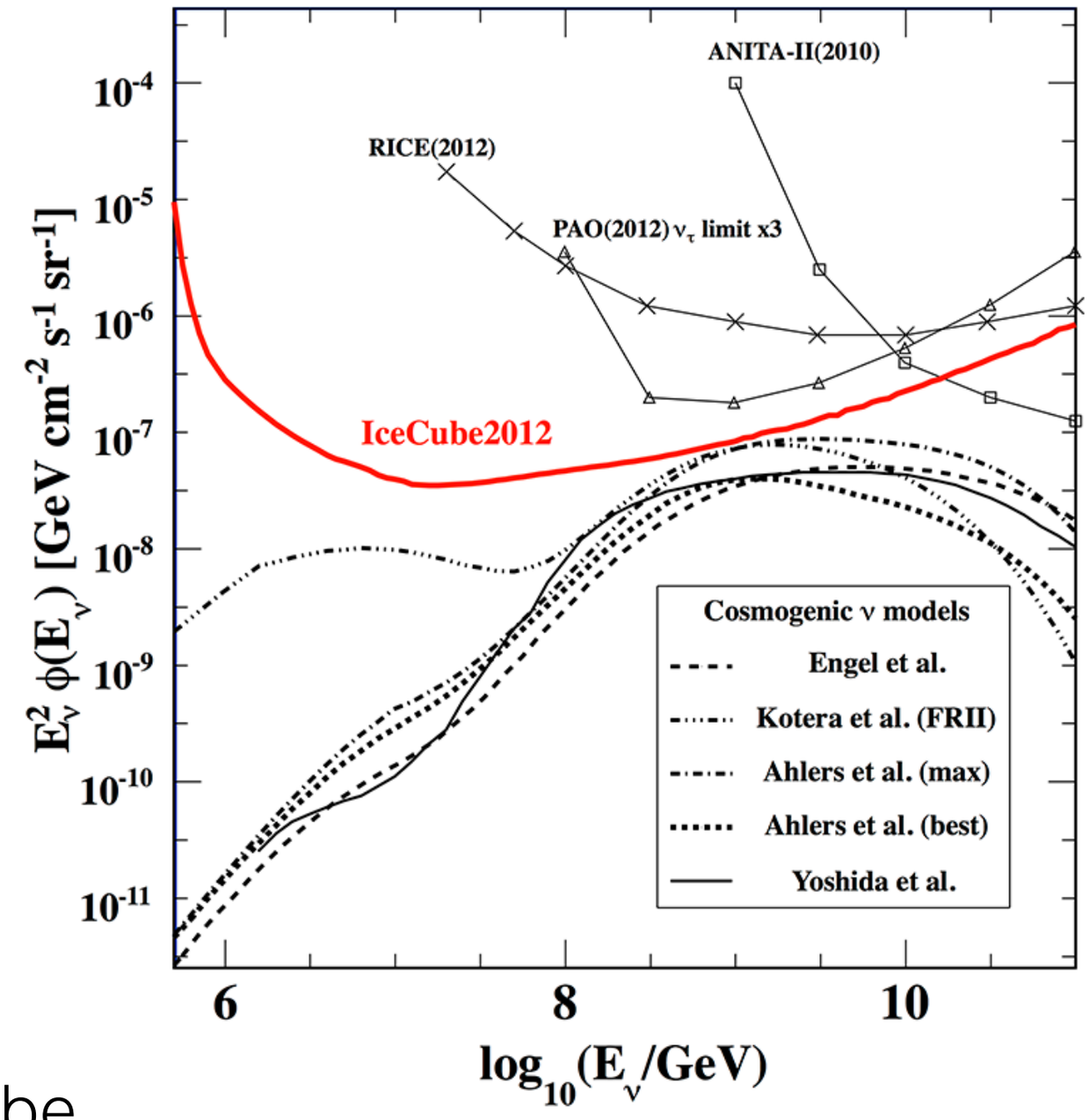
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow \begin{cases} \pi^{+} + n, \ 1/3 \\ \pi^{0} + p, \ 2/3 \end{cases}$$



“Bert”



“Ernie”



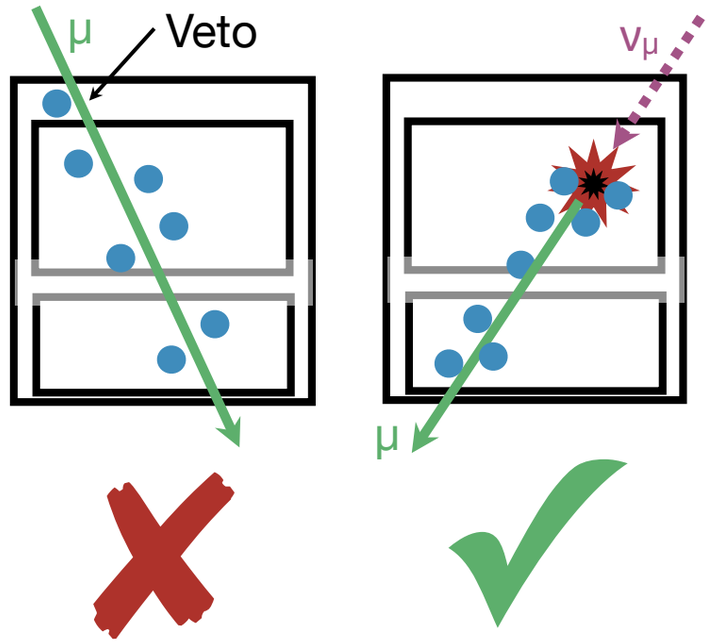
This analysis led to the discovery of first PeV neutrino events in IceCube

Phys. Rev. D88 (2013) 112008

WIPAC Wisconsin IceCube Particle Astrophysics Center

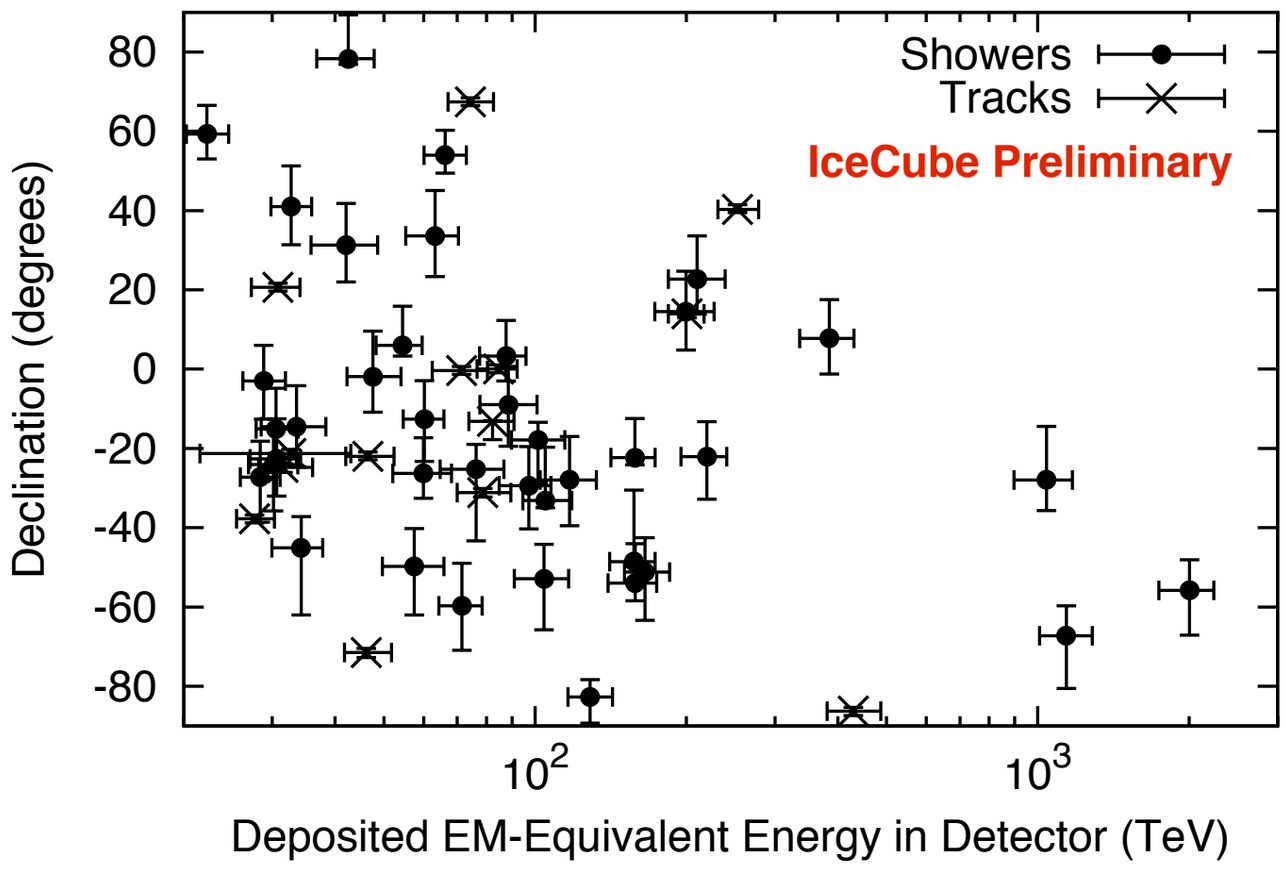
IceCube South Pole Neutrino Observatory

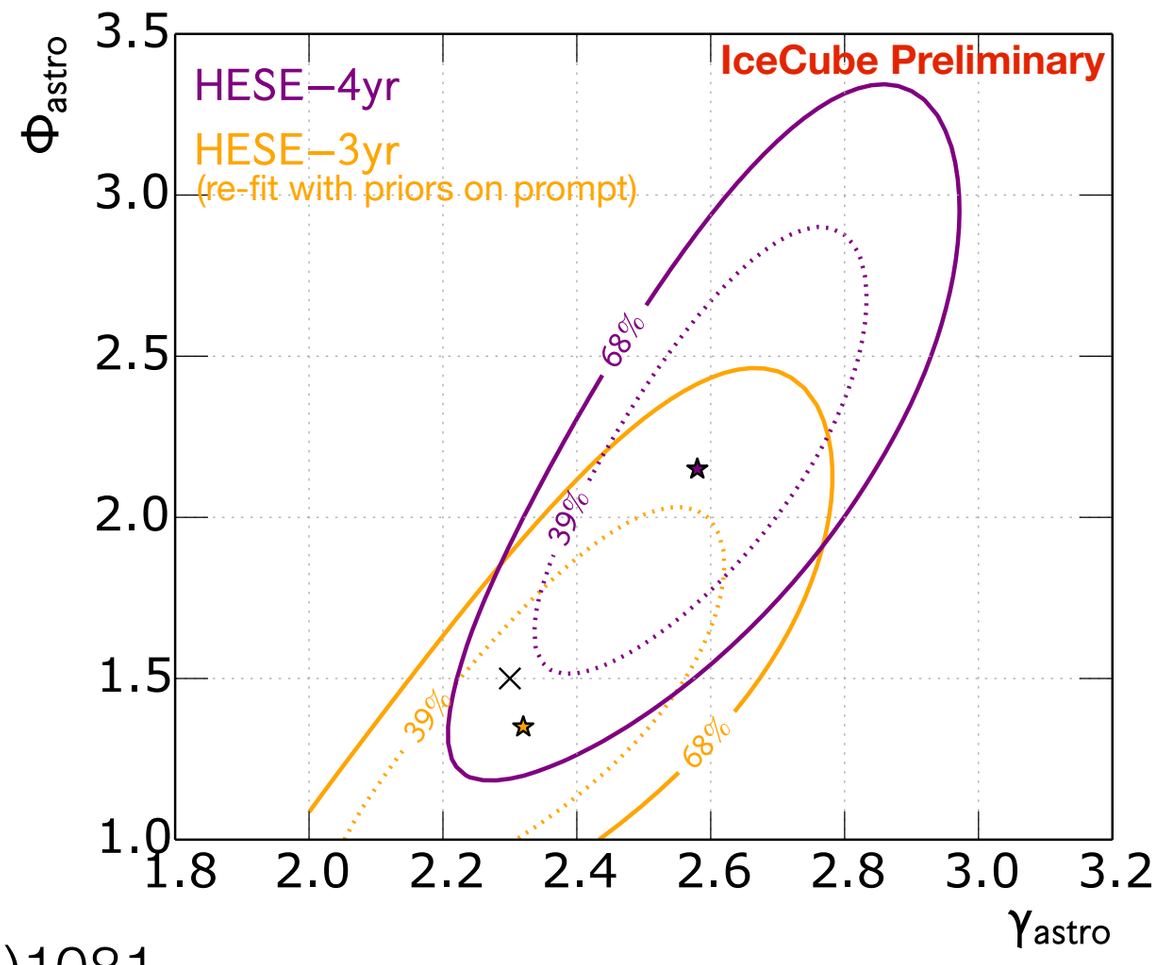
Diffuse: all-sky, all-flavor



High Energy Starting Events (HESE)

- 54 events found in 4 years, with expected atmo. background events of $21.6^{+9.5}_{-5.6}$
- Events are cascade dominated (40/54)
- The highest energy cascade event is ~ 2 PeV.





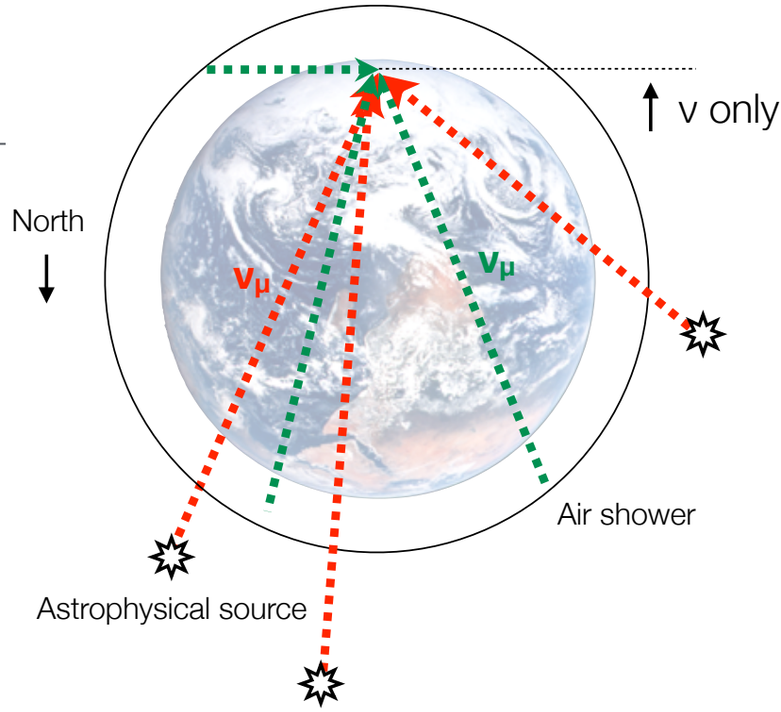
PoS(ICRC2015)1081

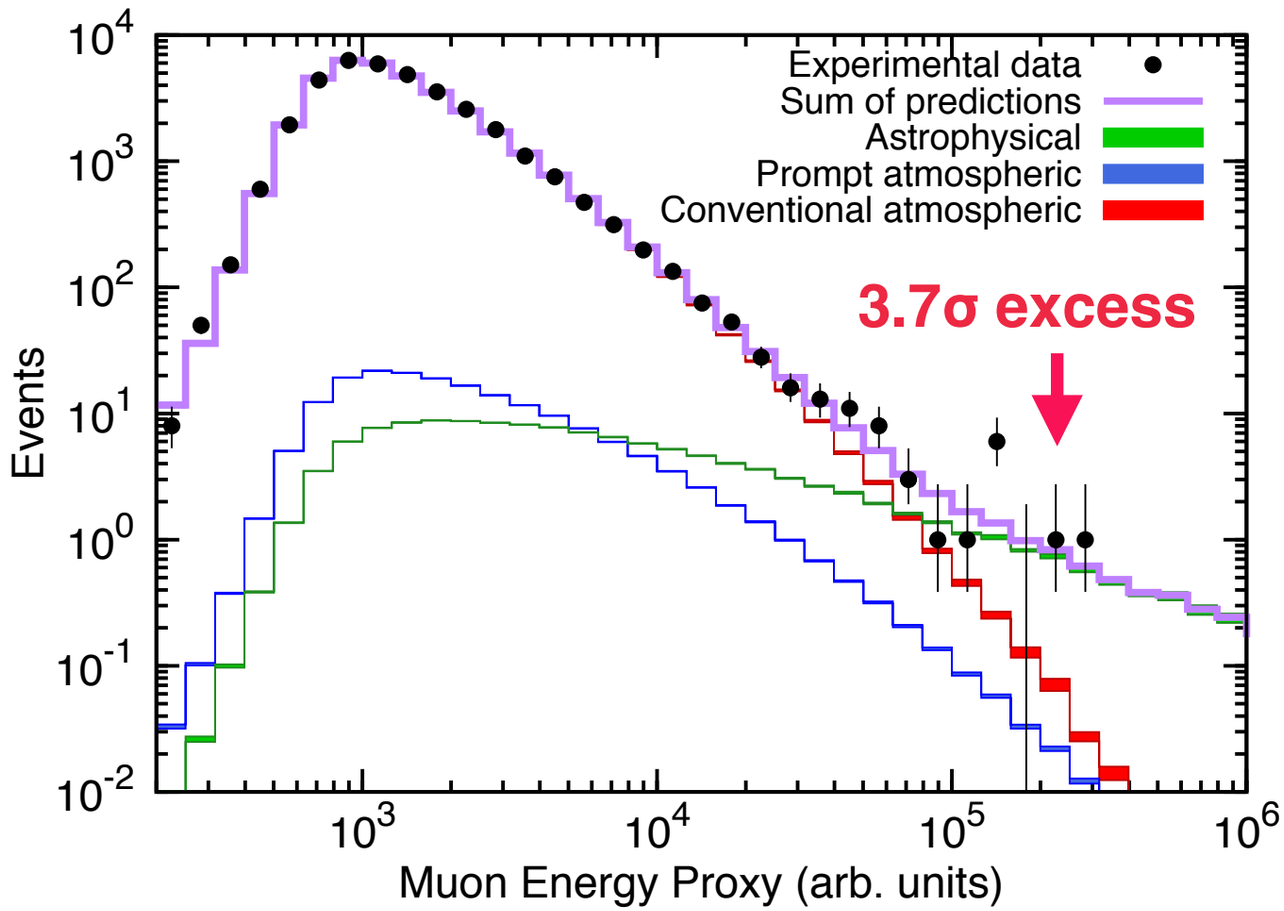
WIPAC Wisconsin IceCube Particle Astrophysics Center

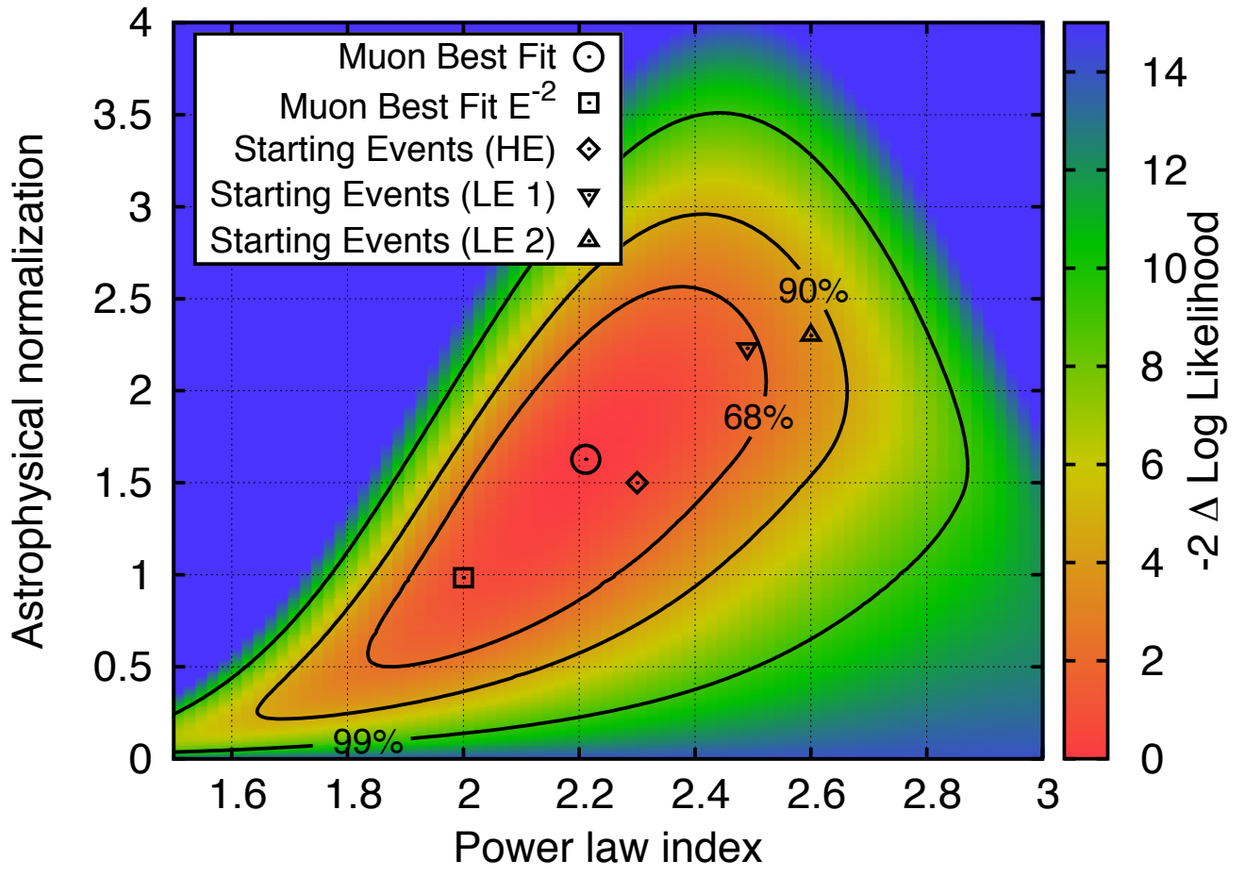
IceCube South Pole Neutrino Observatory

Diffuse: up-going Muon Neutrinos

- PRL 115 (2015) 081102 : 2 Yr data, only upgoing ν_μ CC events
- **Use the earth as an atmospheric muon filter**
- An independent selection of astrophysical neutrinos
- Results are consistent with the all-sky all-flavor selection





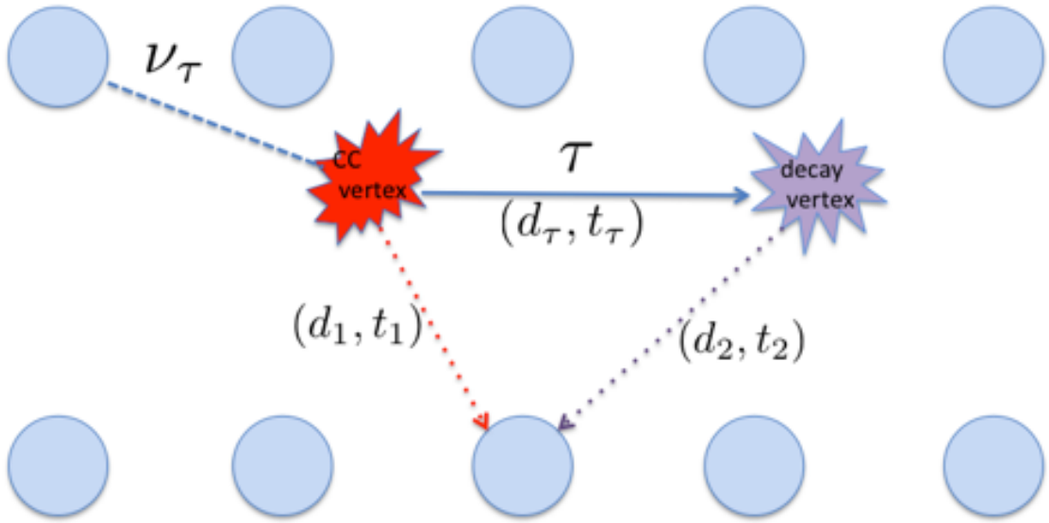


WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Diffuse: Astrophysical Tau Neutrinos (ν_τ)

Schematic ν_τ CC interaction in IceCube

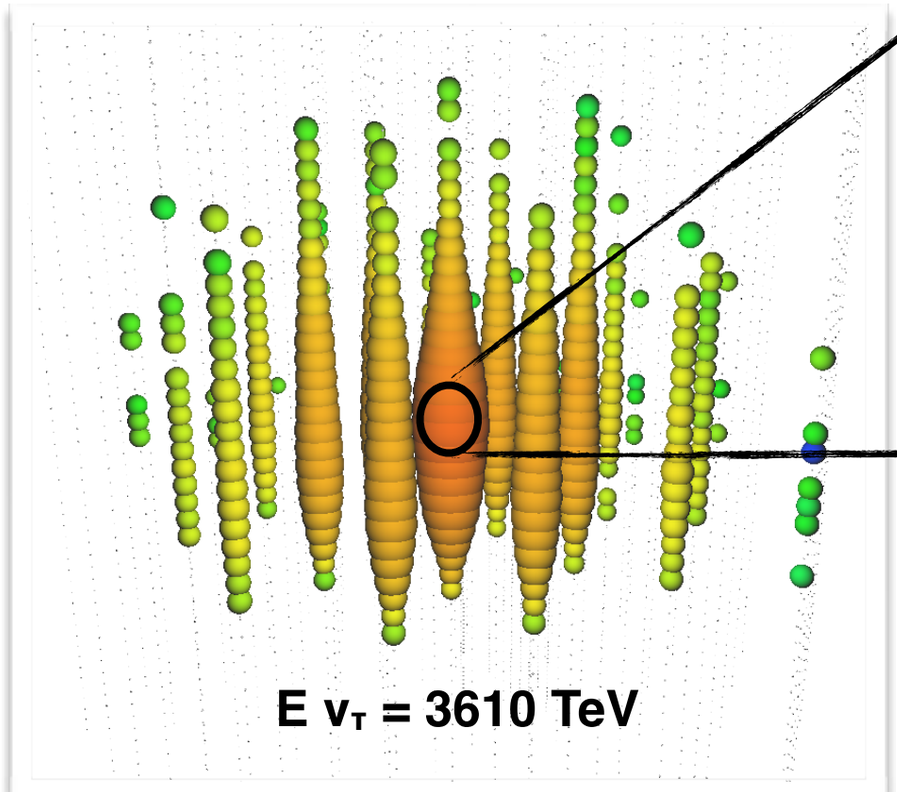


$$\nu_\tau + N \rightarrow \tau^- + X$$

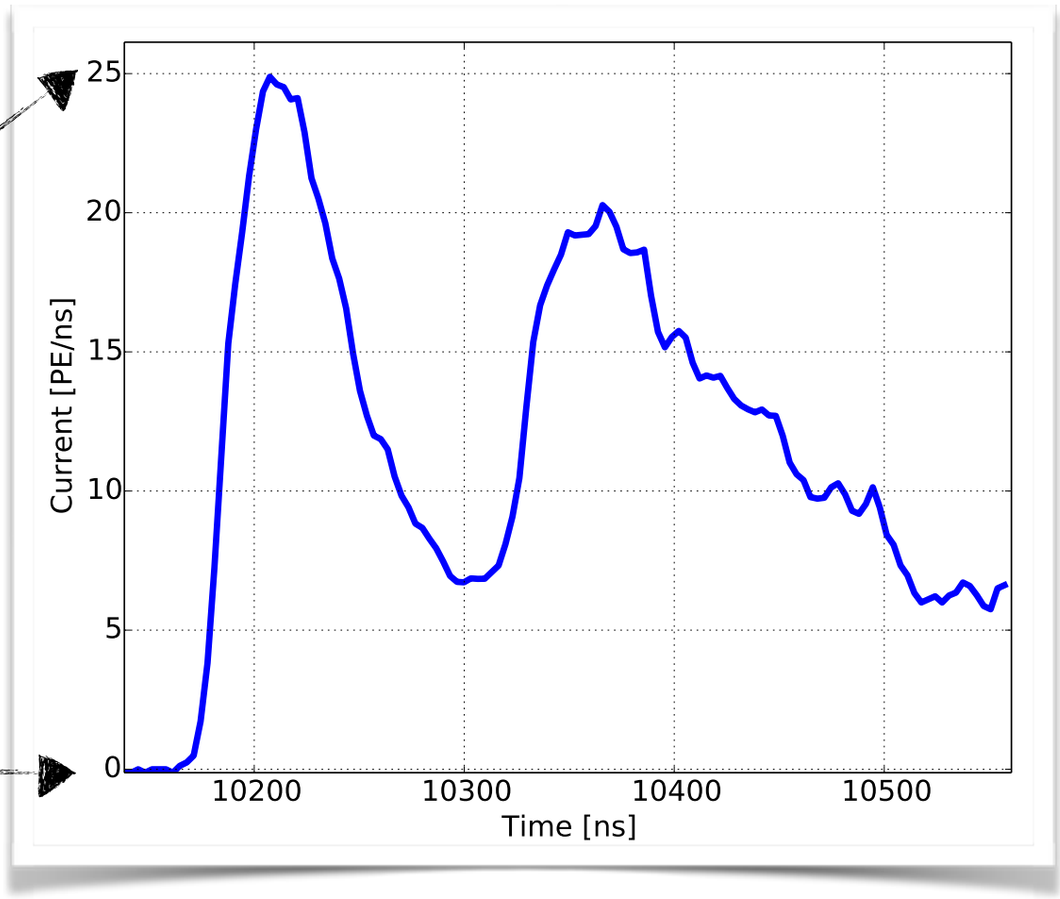
$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%) \checkmark$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%) \checkmark$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$



E ν_τ = 3610 TeV



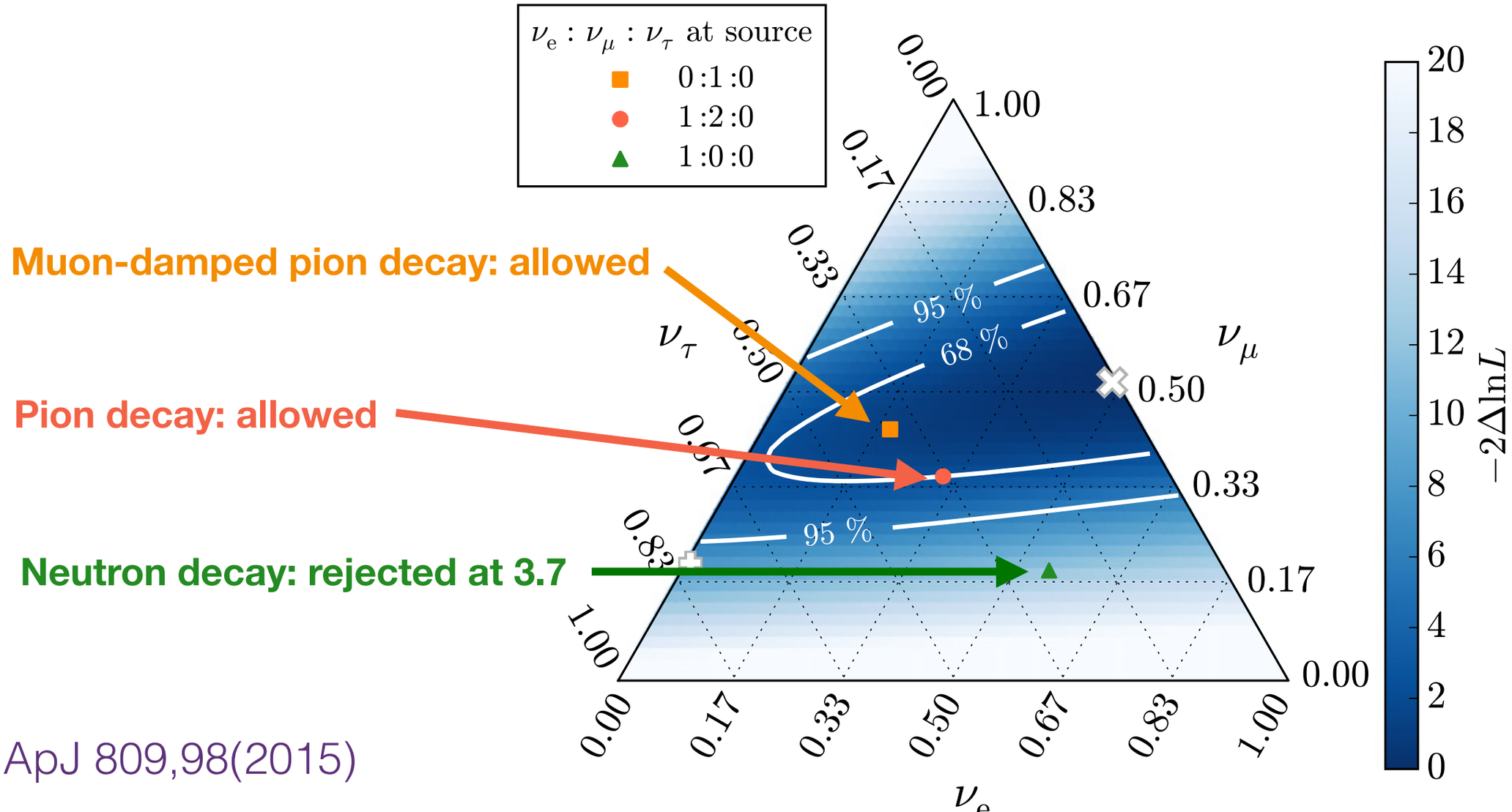
Phys. Rev. D 93, 022001

WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Diffuse: Astrophysical Neutrino Flavor Ratios

- **Precision measurement of neutrino flavor ratio at Earth**
  - Test standard oscillation over extremely long baselines
  - Probe dominant emission processes at source
  - Constrain new physics models.



ApJ 809,98(2015)

WIPAC Wisconsin IceCube Particle Astrophysics Center

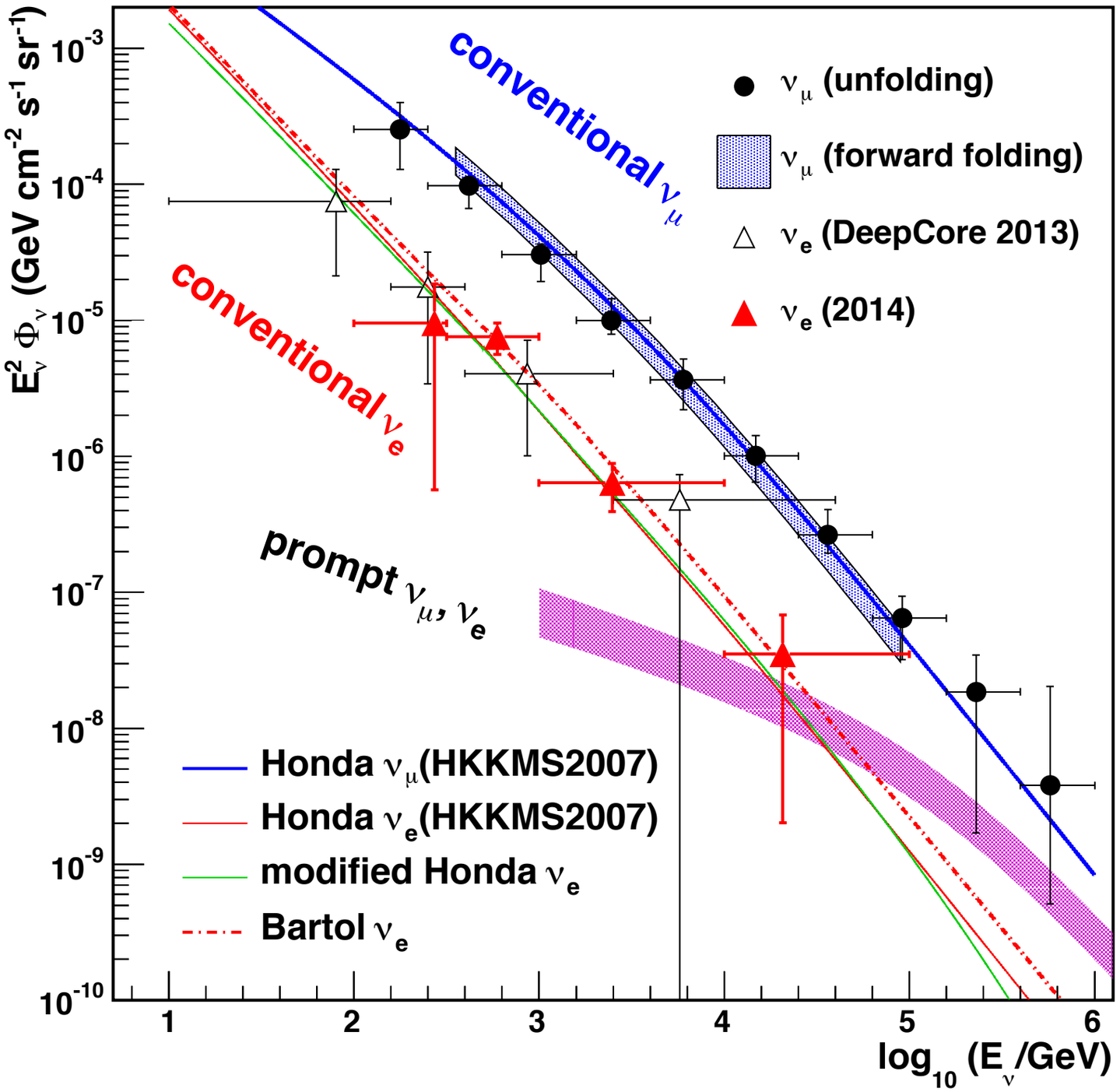
IceCube South Pole Neutrino Observatory

Atmospheric Neutrino Spectra

Phys.Rev. D91:122004,2015

Honda HKKMS2007:

Phys.Rev.D75:043006,2007



Likelihood: $$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_i^N (\frac{n_s}{N}\mathcal{S}_i + (1 - \frac{n_s}{N})\mathcal{B}_i)$$

The source probability density $\mathcal{S}_i$:

$$\mathcal{S}_i = \mathcal{N}(r_i) \times \mathcal{E}(\mathrm{E}_i) \times \mathcal{T}(\mathrm{T}_i)$$

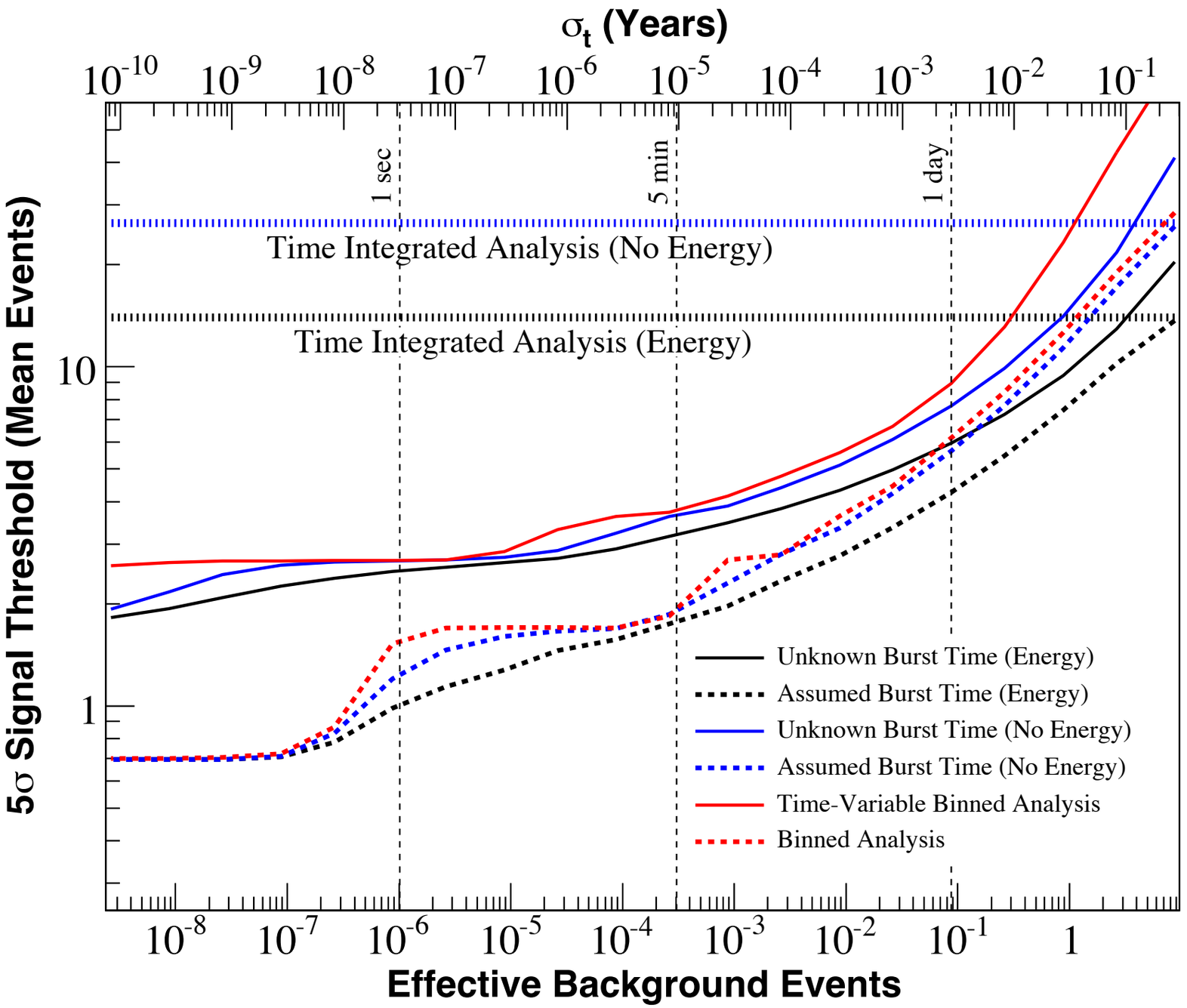
Space angle p.d.f. energy p.d.f. time p.d.f.

The background probability density $\mathcal{B}_i$ also contains a space, energy, time component .

Test Statistics: $$D = -2\log[\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s, \hat{\gamma})}] \times \mathrm{sign}(\hat{n}_s)$$

Braun, Jim, et al. Astroparticle physics 33.3 (2010): 175-181.

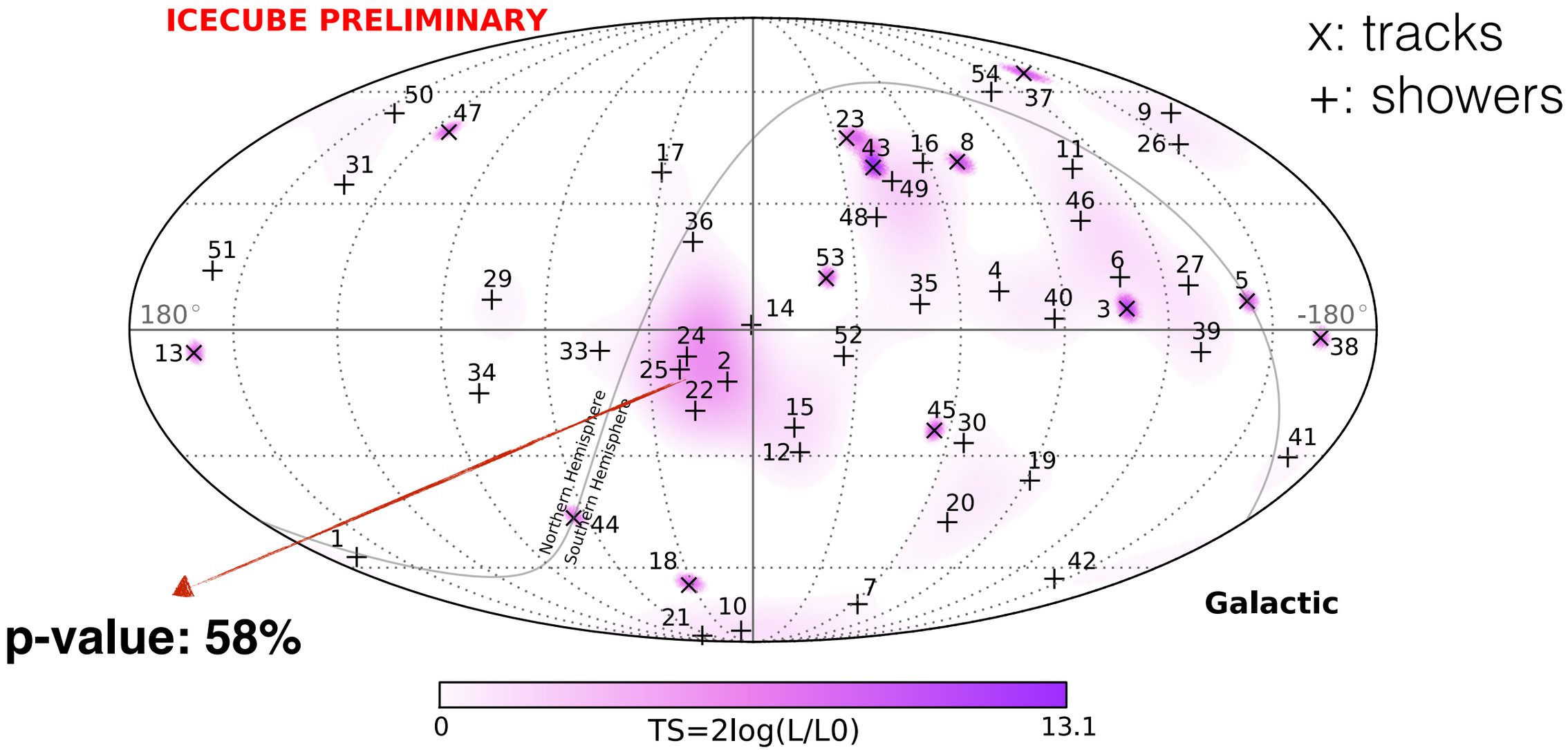
Neutrino Point Source Searches



- Unbinned likelihood is more powerful than binned one
- Sensitivity gained when more (correct) information is provided

Braun, Jim, et al. Astroparticle physics 33.3 (2010): 175-181.

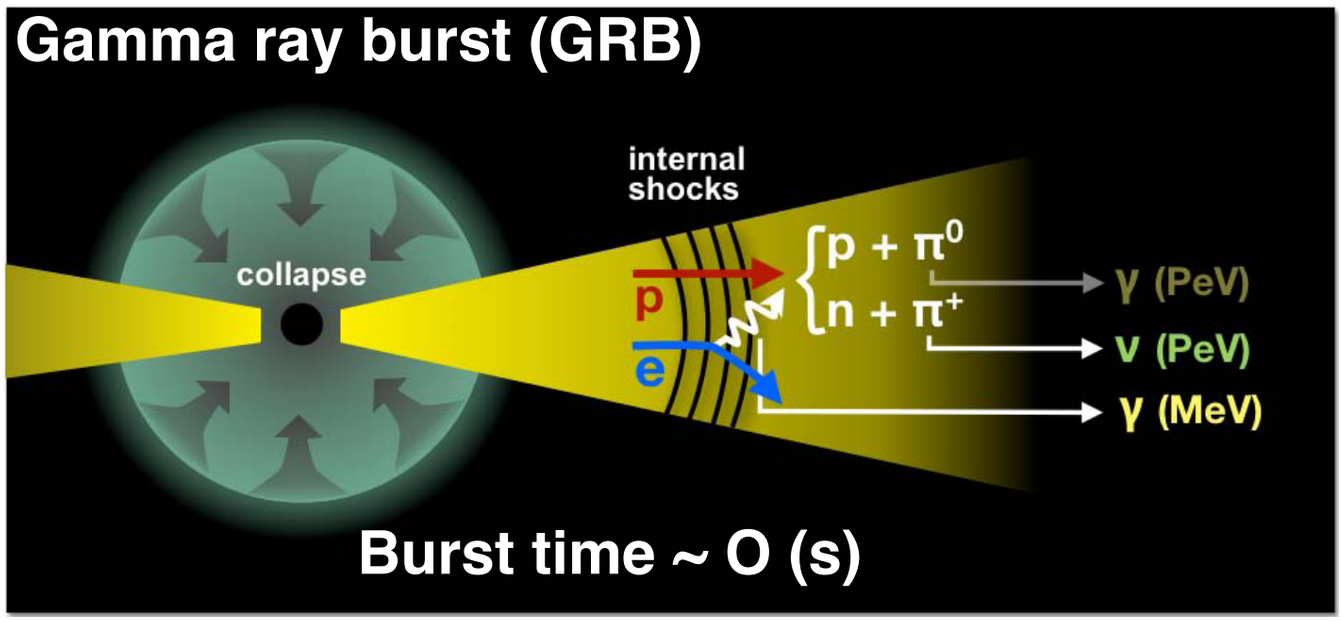
Spatial clustering



p-value: 58%

PoS(ICRC2015)1081

Spatial & Time clustering



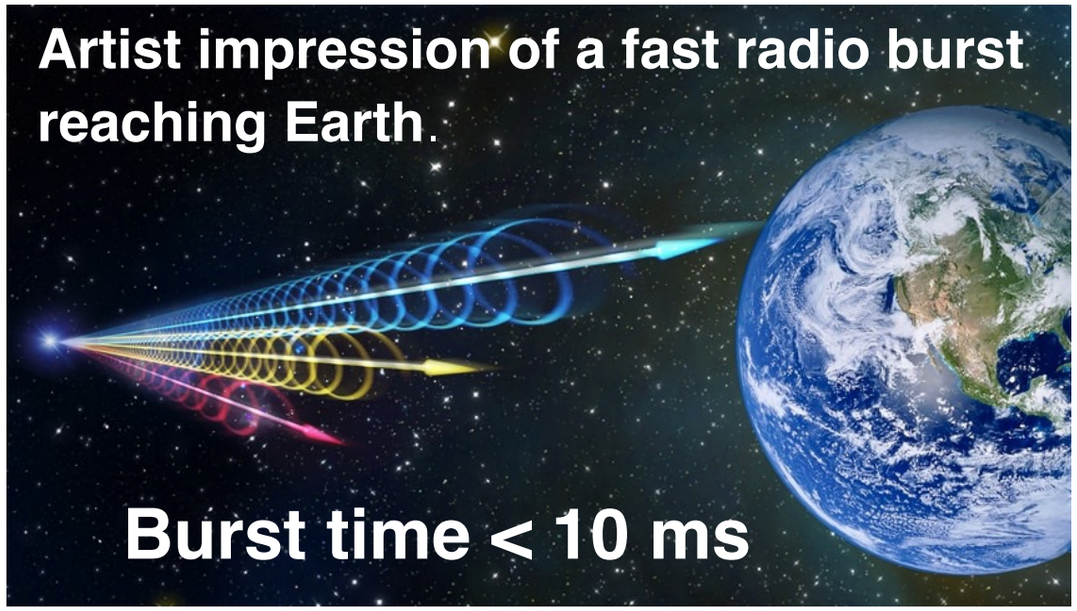
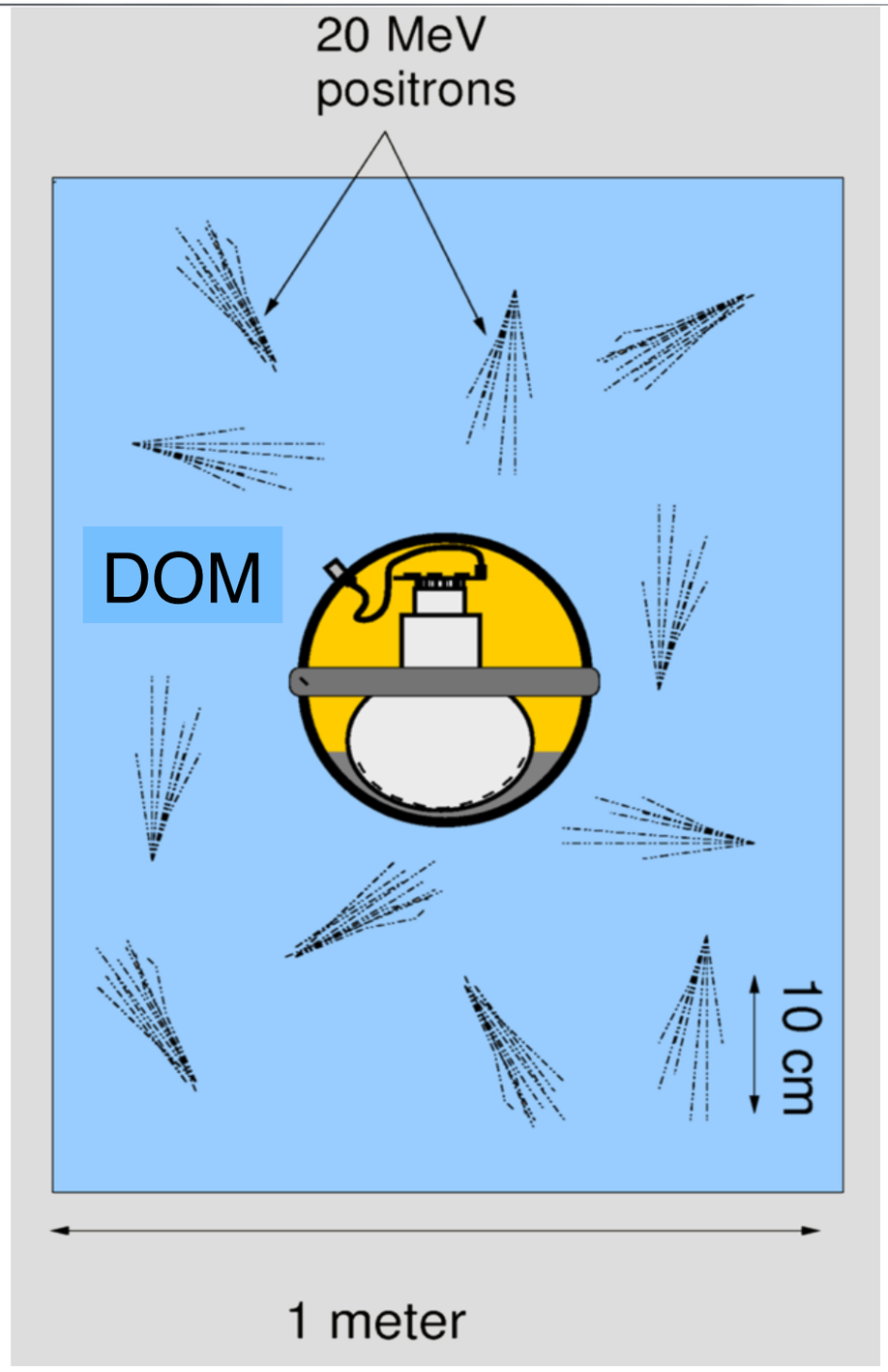


Photo credit: Jingchuan Yu, Beijing Planetarium

Background free within the prompt time window.
One coincident event could be statistically significant.

Supernova: SN DAQ

- Supernova
  - Uniform illumination in the ice
    - ~0.5 to 1×10^6 events in 10 seconds
  - DOM to DOM correlated increase in detector noise
- Advantage
  - Low DOM noise - ~280 Hz
  - High Statistics - 0.25% error
  - 2 ms time resolution
- Disadvantage
  - No pointing
  - No individual events
  - No energy information

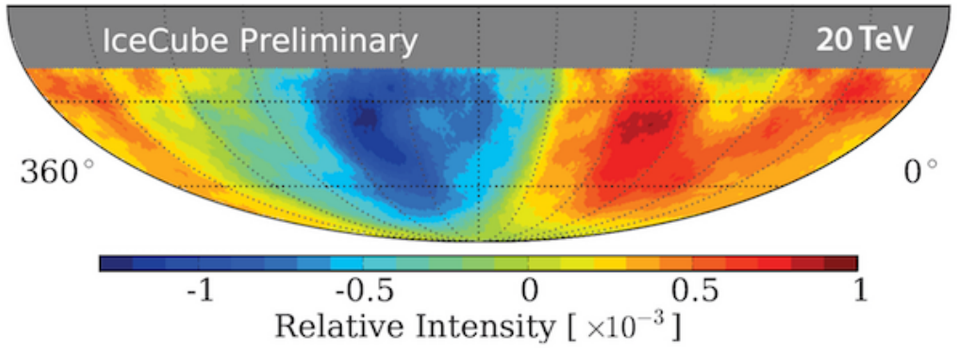


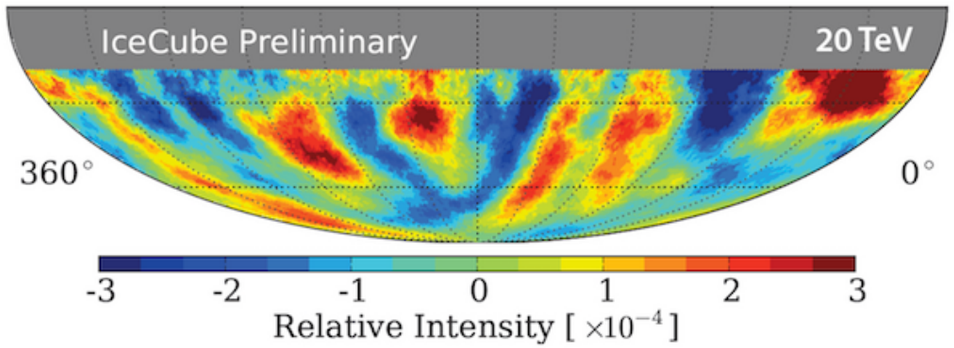
Supernova rate in the Galaxy: 3±2 per century B. Riedel

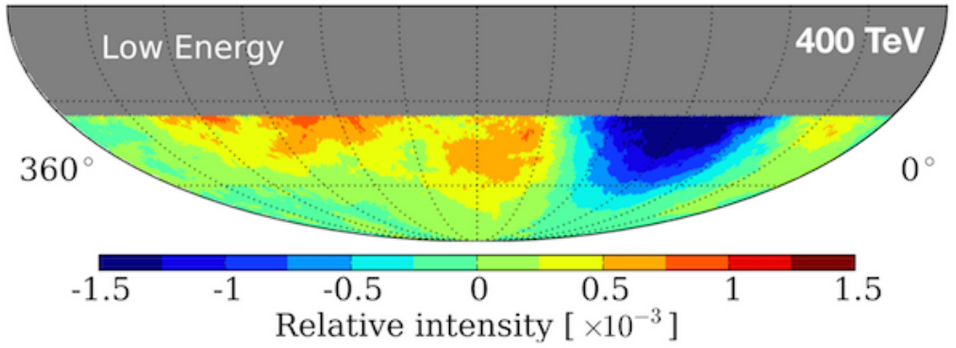
WIPAC Wisconsin IceCube Particle Astrophysics Center

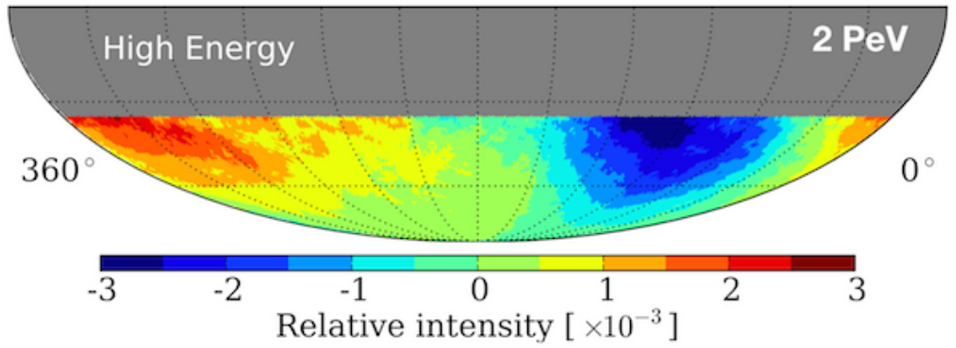
IceCube South Pole Neutrino Observatory

Cosmic Rays: IceTop + IceCube





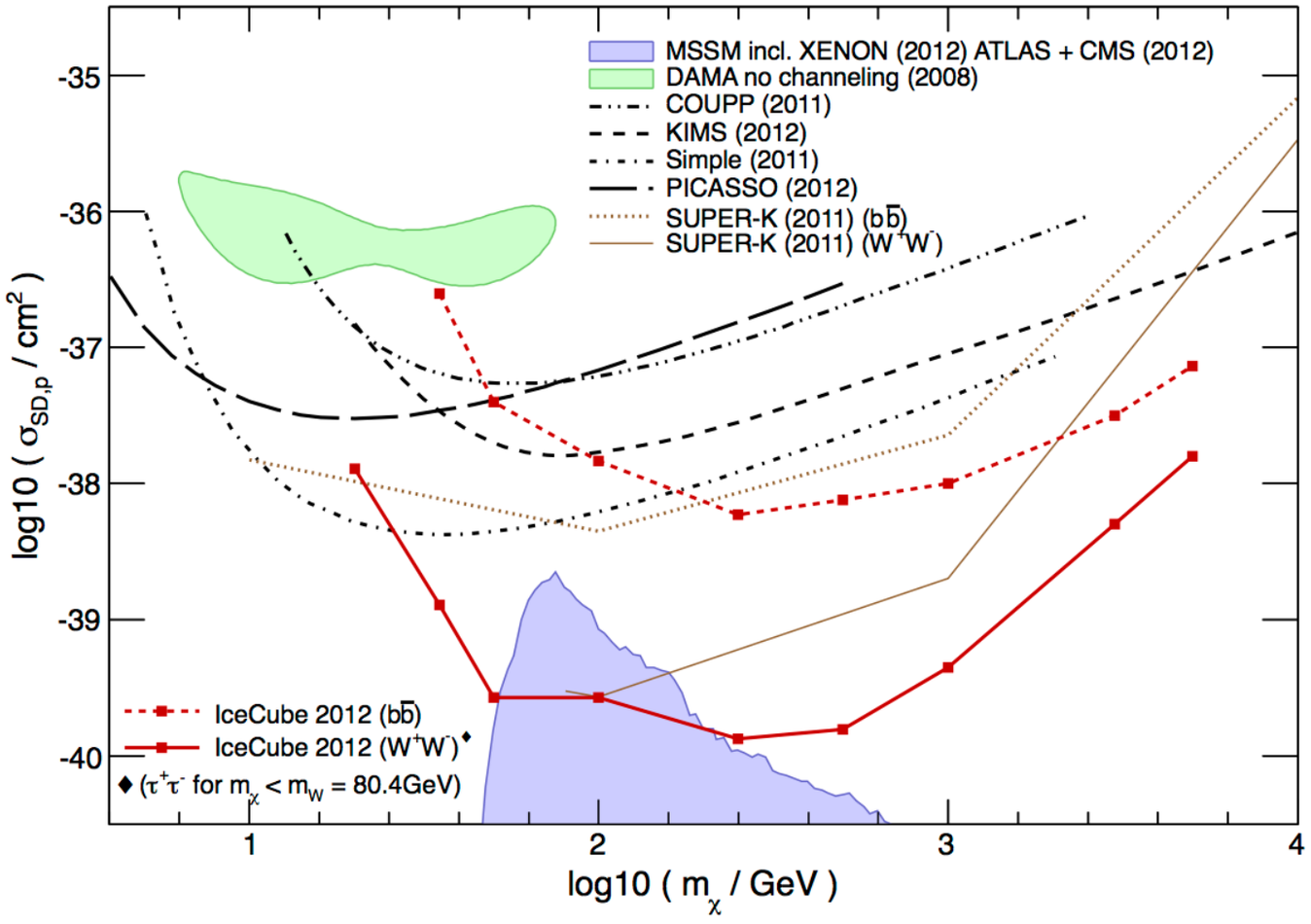




IceTop: Cosmic-ray anisotropy (10^{-3}) in the southern hemisphere

IceTop+IceCube: chemical composition
IceTop: all-particle cosmic ray energy spectrum in PeV - EeV

- Indirect dark matter search
  - The Sun
  - Galactic Center
- Slow Monopole
- …



World's best limits on WIMP's **spin-dependent** cross sections

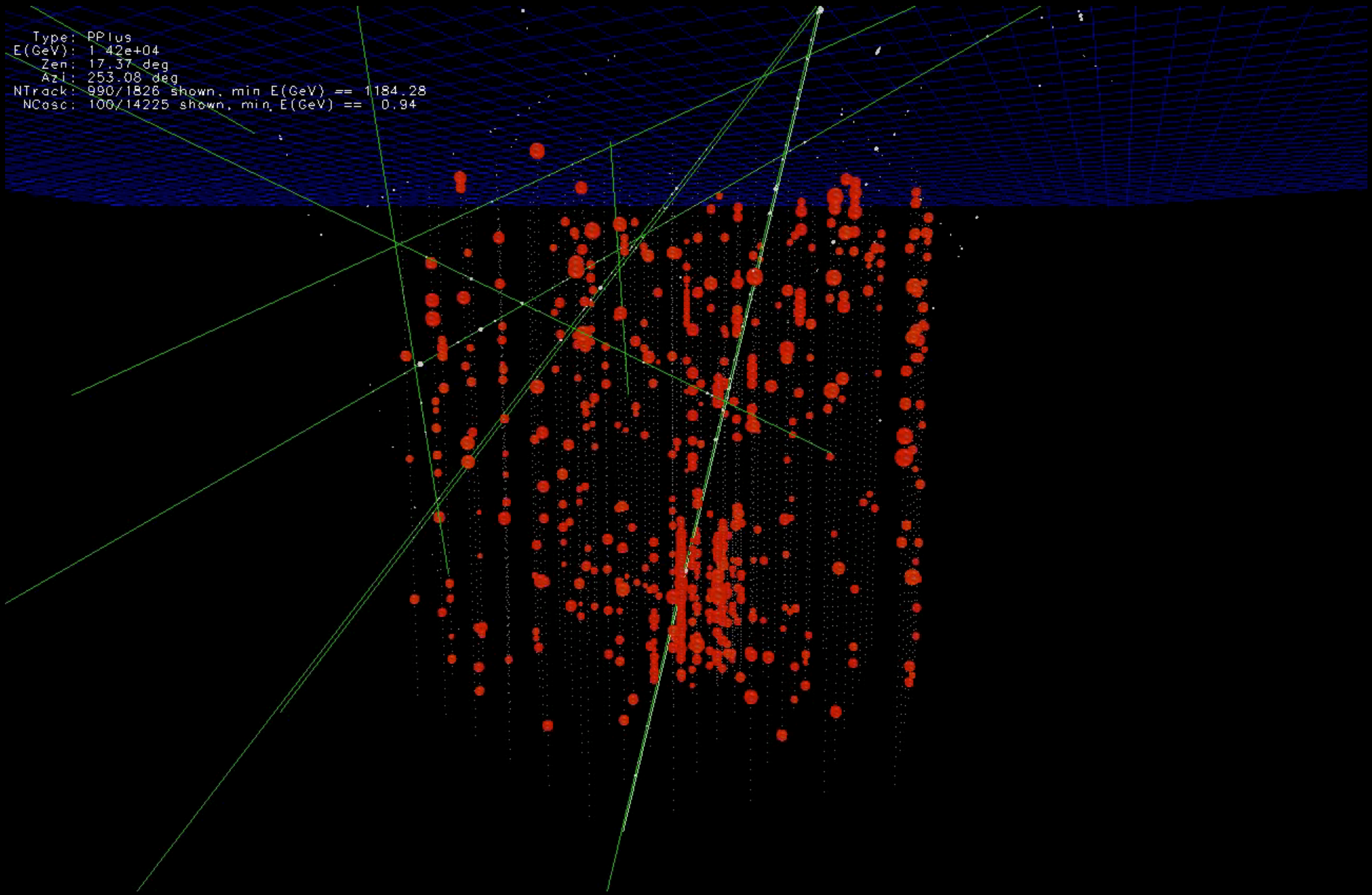
WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Event Selection

"Cuts"

—Proof of Concept—

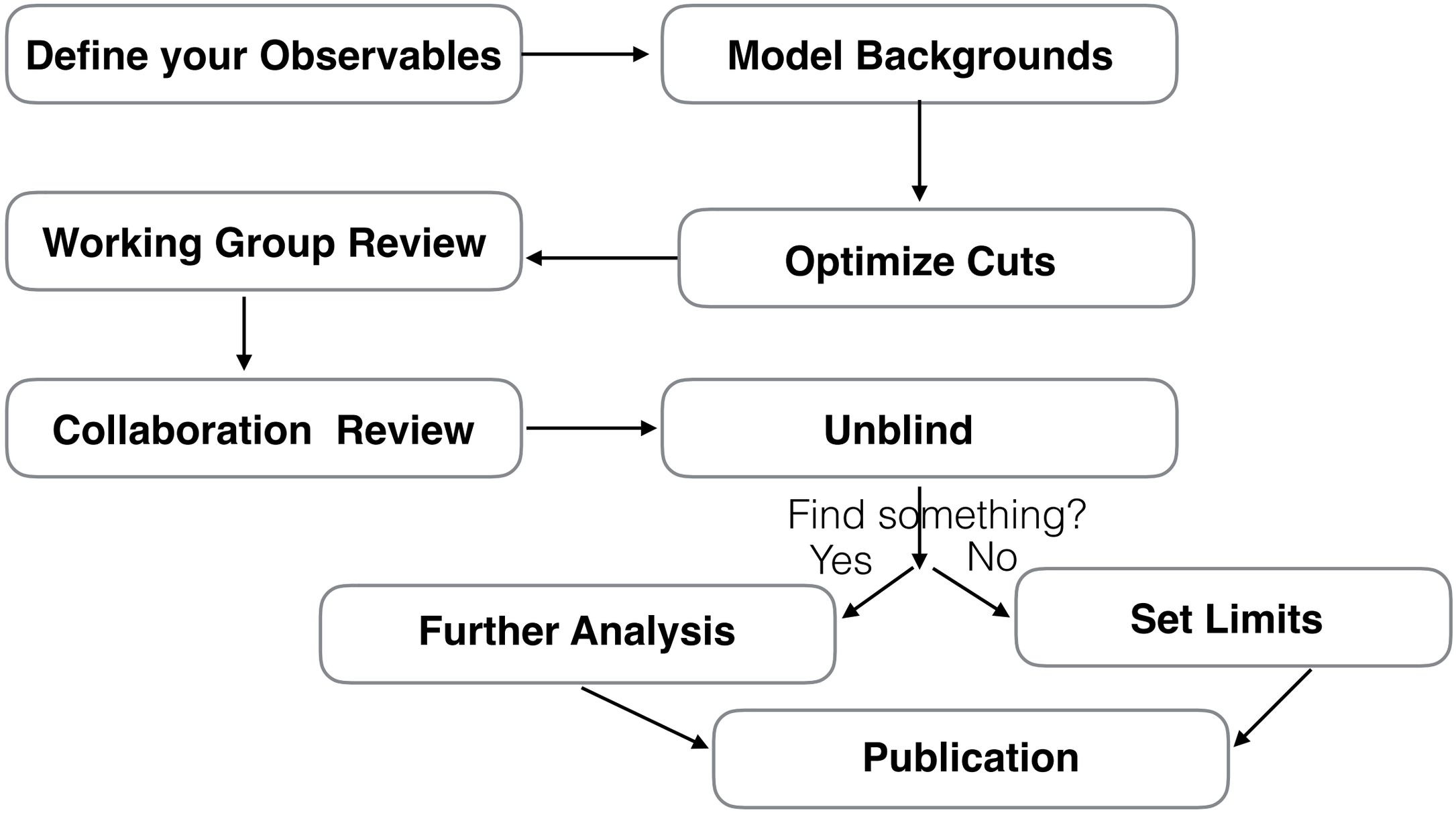

Type: PPlus
E(GeV): 1.42e+04
Zen: 17.37 deg
Azi: 253.08 deg
NTrack: 990/1826 shown, min E(GeV) == 1184.28
NCosc: 100/14225 shown, min E(GeV) == 0.94

… you just saw 10 ms of data …

- **Atmospheric μ $7x10^{10}$ (3000/s)**
- **Atmospheric ν μ $>8x10^{4}$ (1/6 minuts)**
- **Cosmic ν μ ~10**

Event Selection + Analysis Chain

Cuts: A cut is a selection criteria to reduce background and improve the purity of the event sample of interest.



—Rule of thumb—

"Neutrino level"
"Signal purity comparable to signal strength"
"Sensitivity optimization based on S/N ratio"

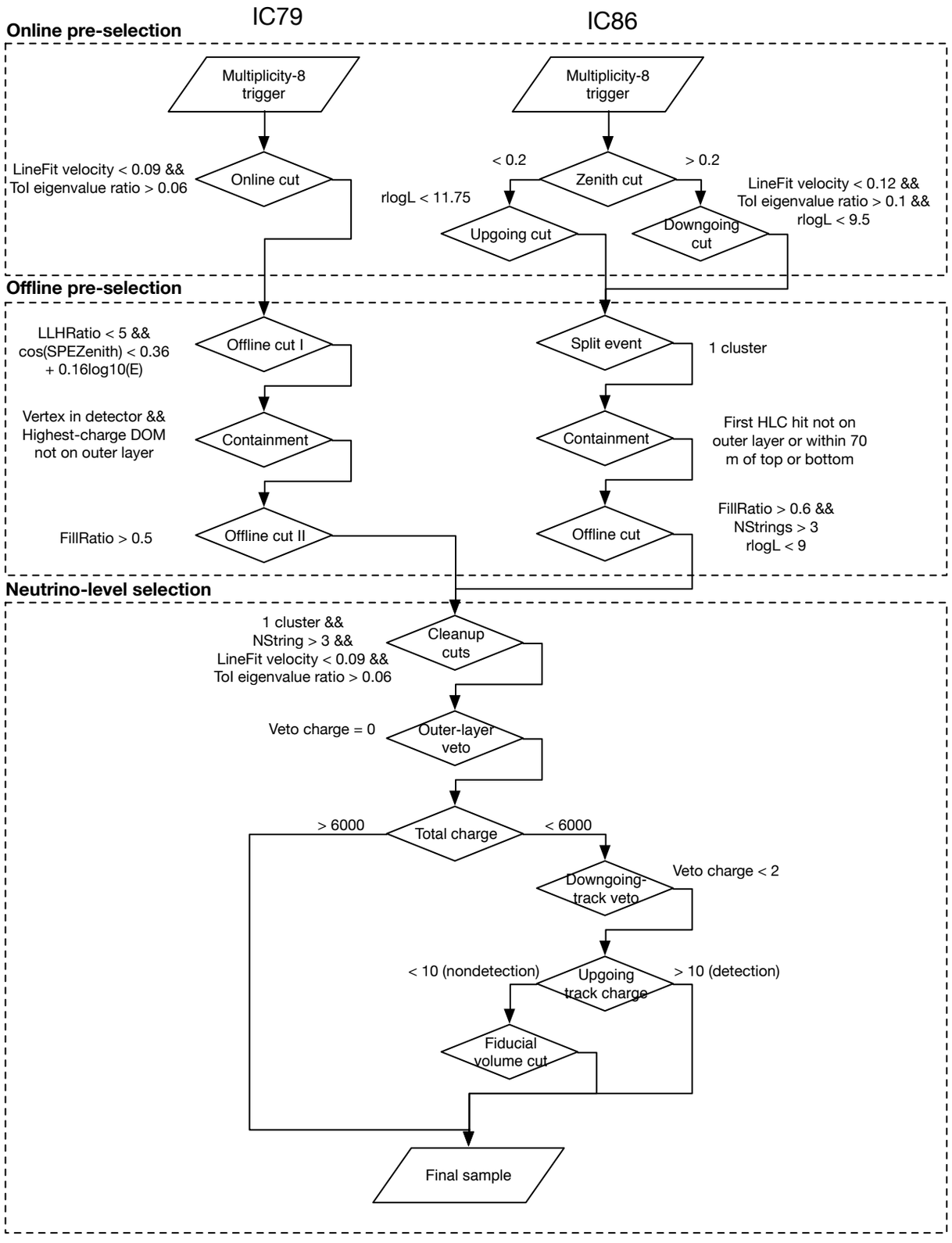
- Diffuse analyses usually require higher purity than point source analyses

- Transient analyses could be even more background tolerant than the steady point source analyses

WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

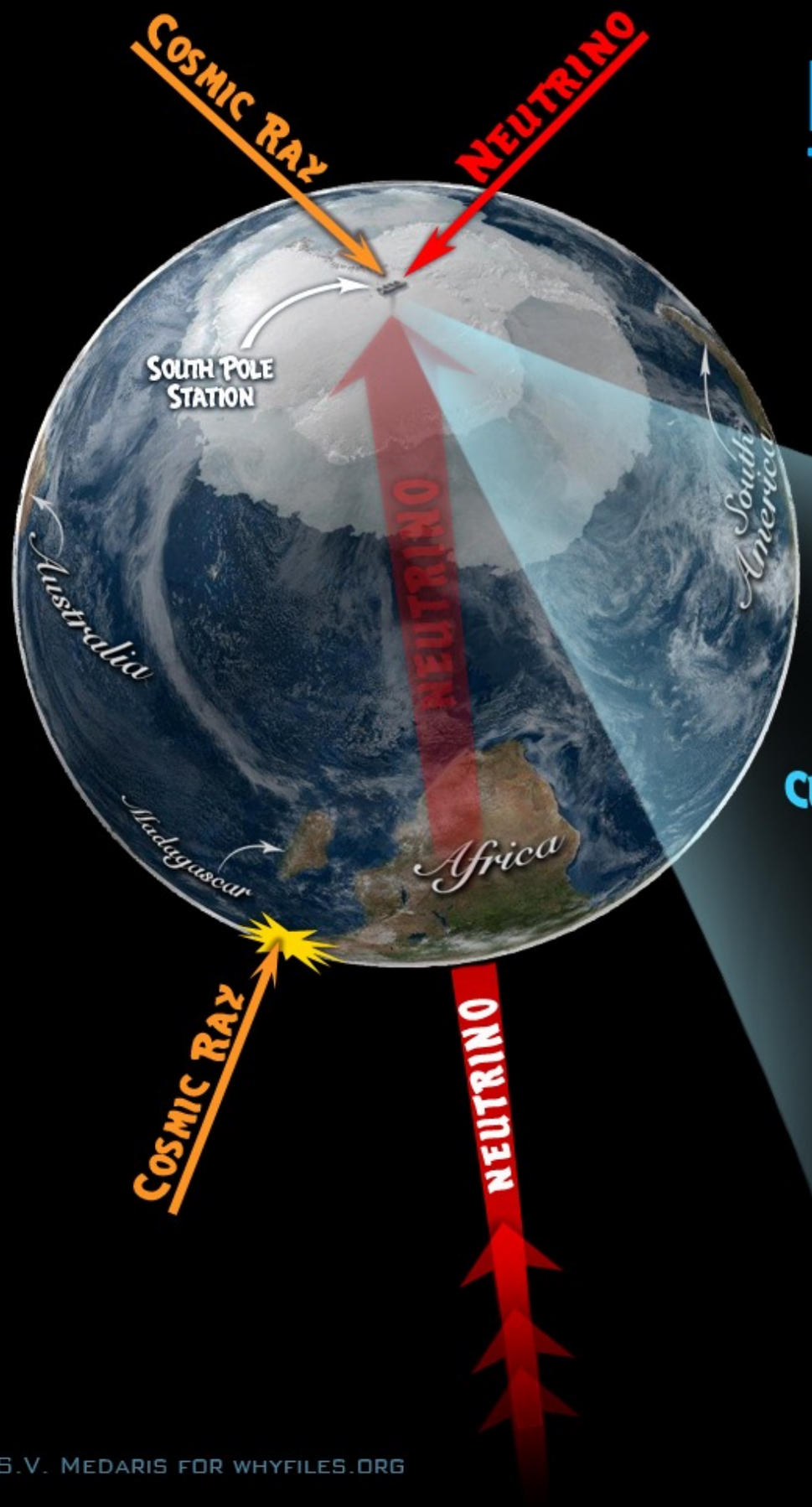
Event Selection Example

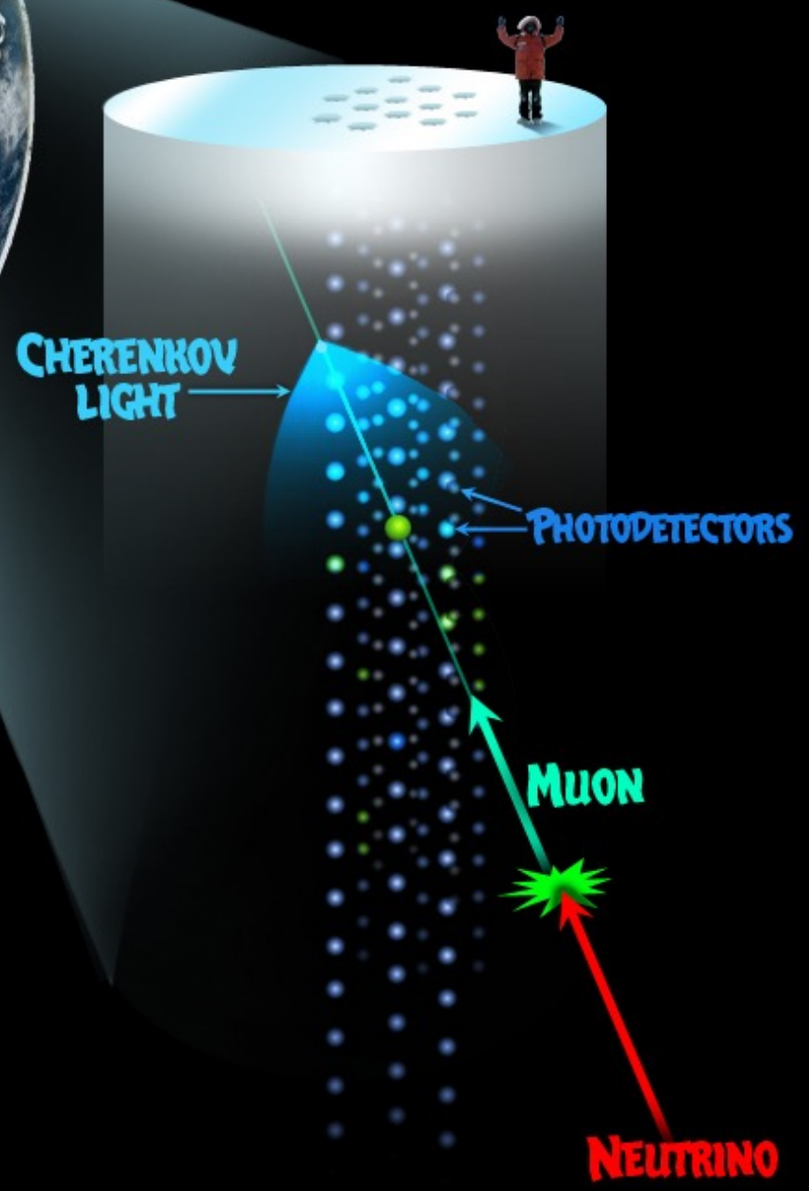


Jakob van Santen, dissertation 2015
https://inspirehep.net/record/1339582/files/thesis.pdf

Backup Slides

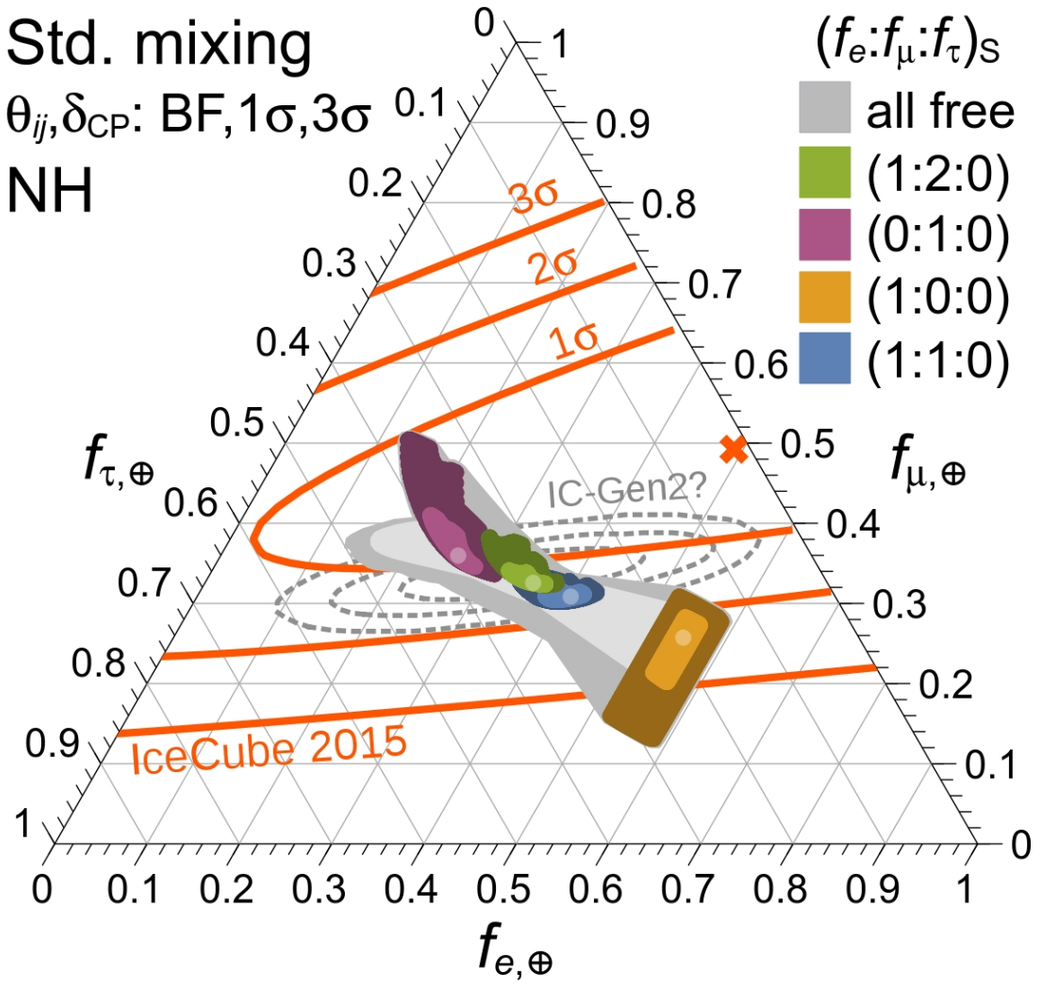
IceCube:
The Downward-Looking Telescope

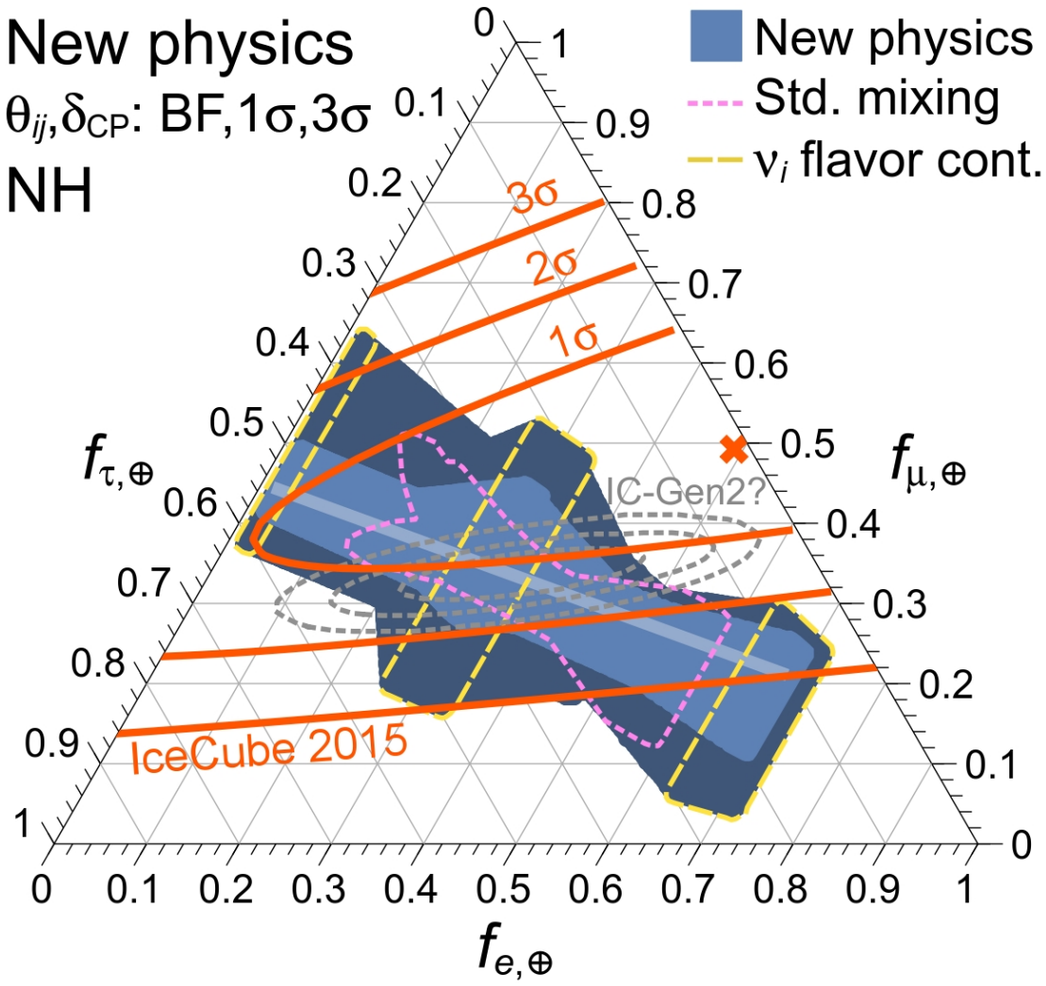




S.V. Medaris for whyfiles.org

Astrophysical Neutrino Flavor Ratios





M. Bustamante, J. F. Beacom, and W. Winter, Phys. Rev. Lett. 115, 161302 (2015).
C. A. Argüelles, T. Katori, and J. Salvado, Phys. Rev. Lett. 115, 161303 (2015).

WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory