# Introduction to Physics Analyses in IceCube

IceCube BootCamp 2017
WIPAC, UW-Madison
June 8, 2017

Donglian Xu

# Outline

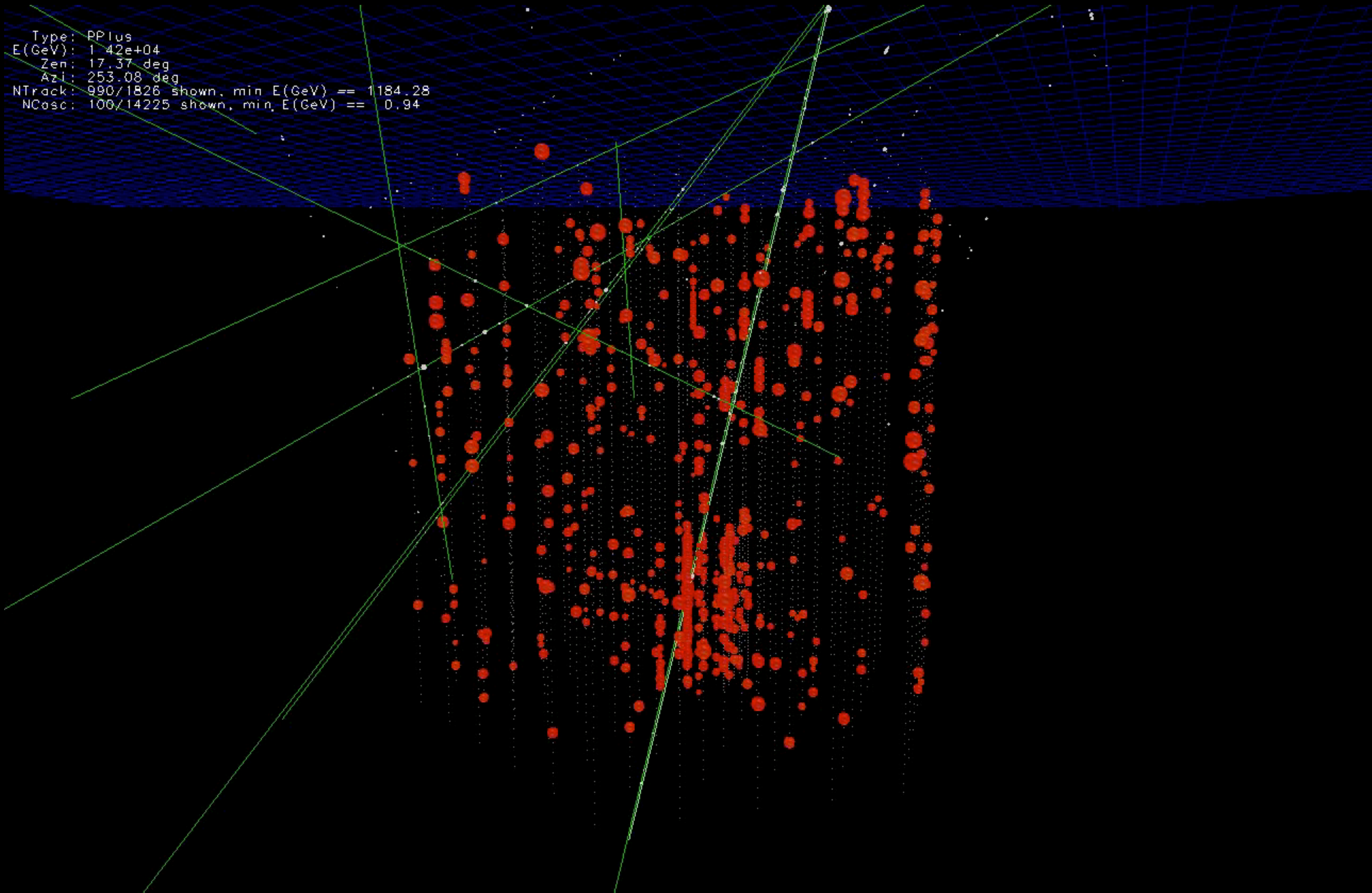


- Event Selection/Cuts
- Ongoing Physics Analyses
  - Diffuse/Atmospheric Neutrinos
    - Cosmogenic neutrinos (EHE)
    - All flavor (cascades and tracks)
    - Through-going NuMu (tracks)
    - NuTau (double cascades)
    - Flavor ratios
  - Point sources/Transient
  - Low-energy and Oscillations
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

# 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
NCasc: 100/14225 shown, min E(GeV) == 0.94

**… you just saw 10 ms of data …**

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



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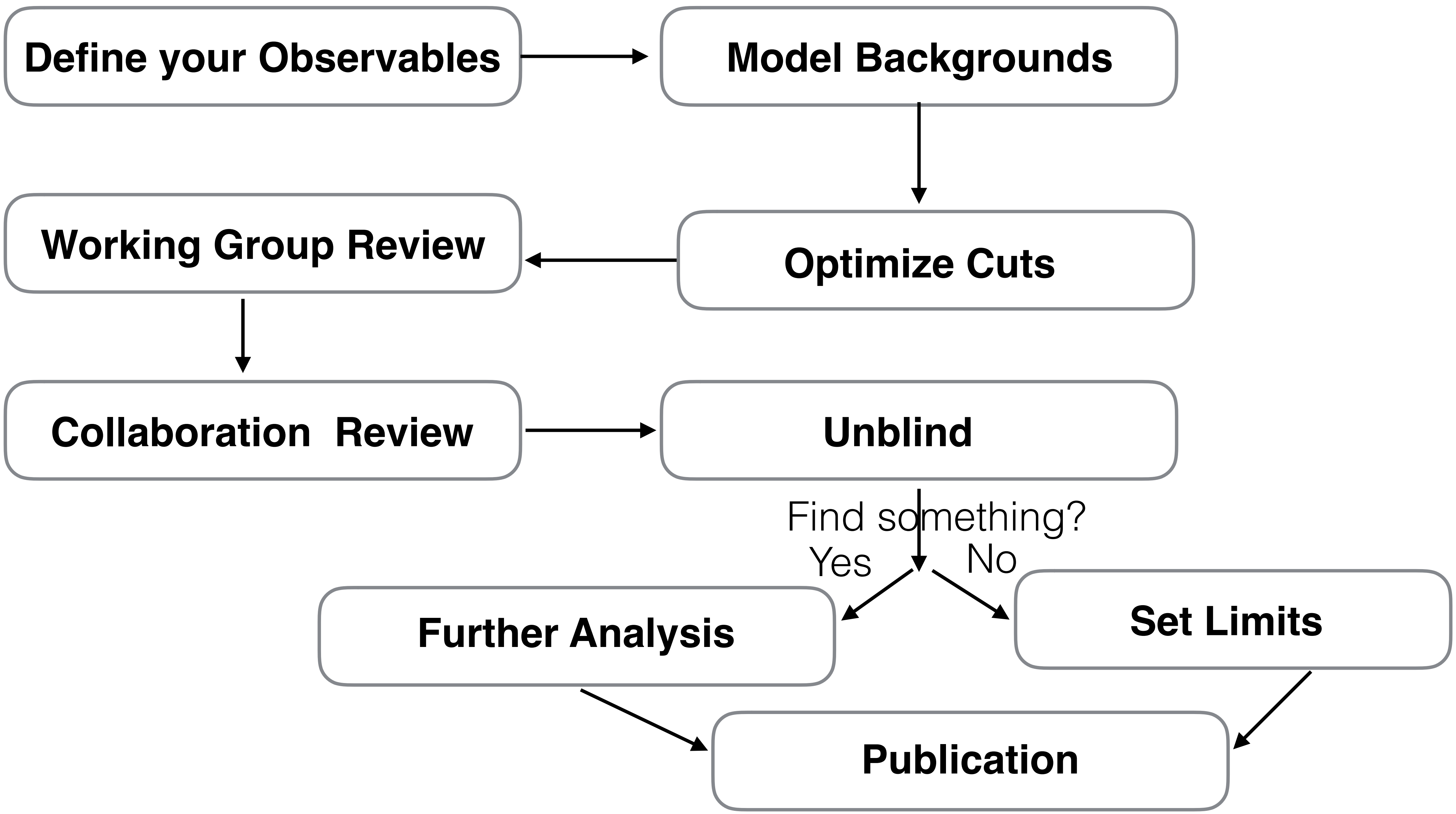
# Event Selection + Analysis Chain

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



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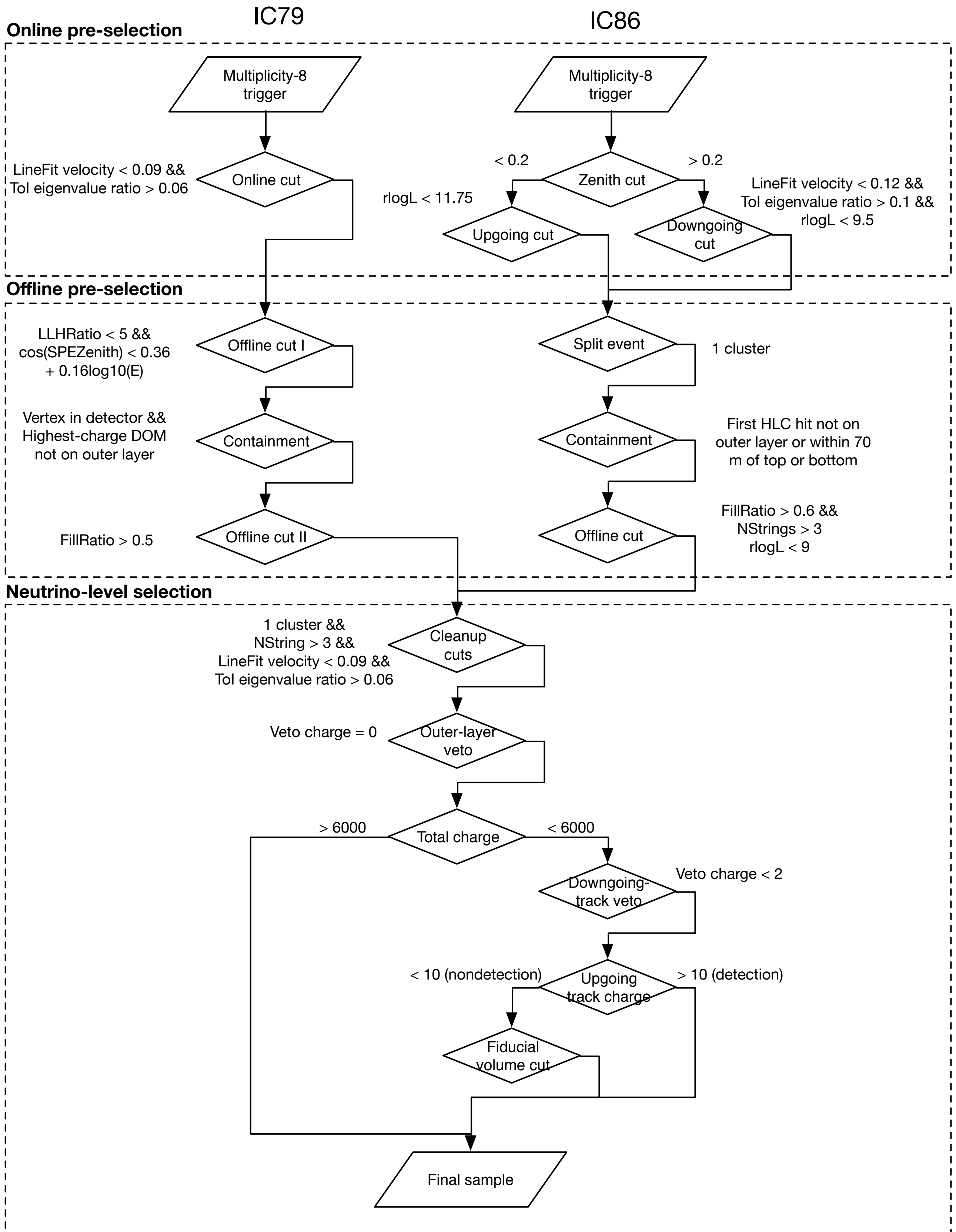
# Event Selection Example






Jakob van Santen, dissertation 2015

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



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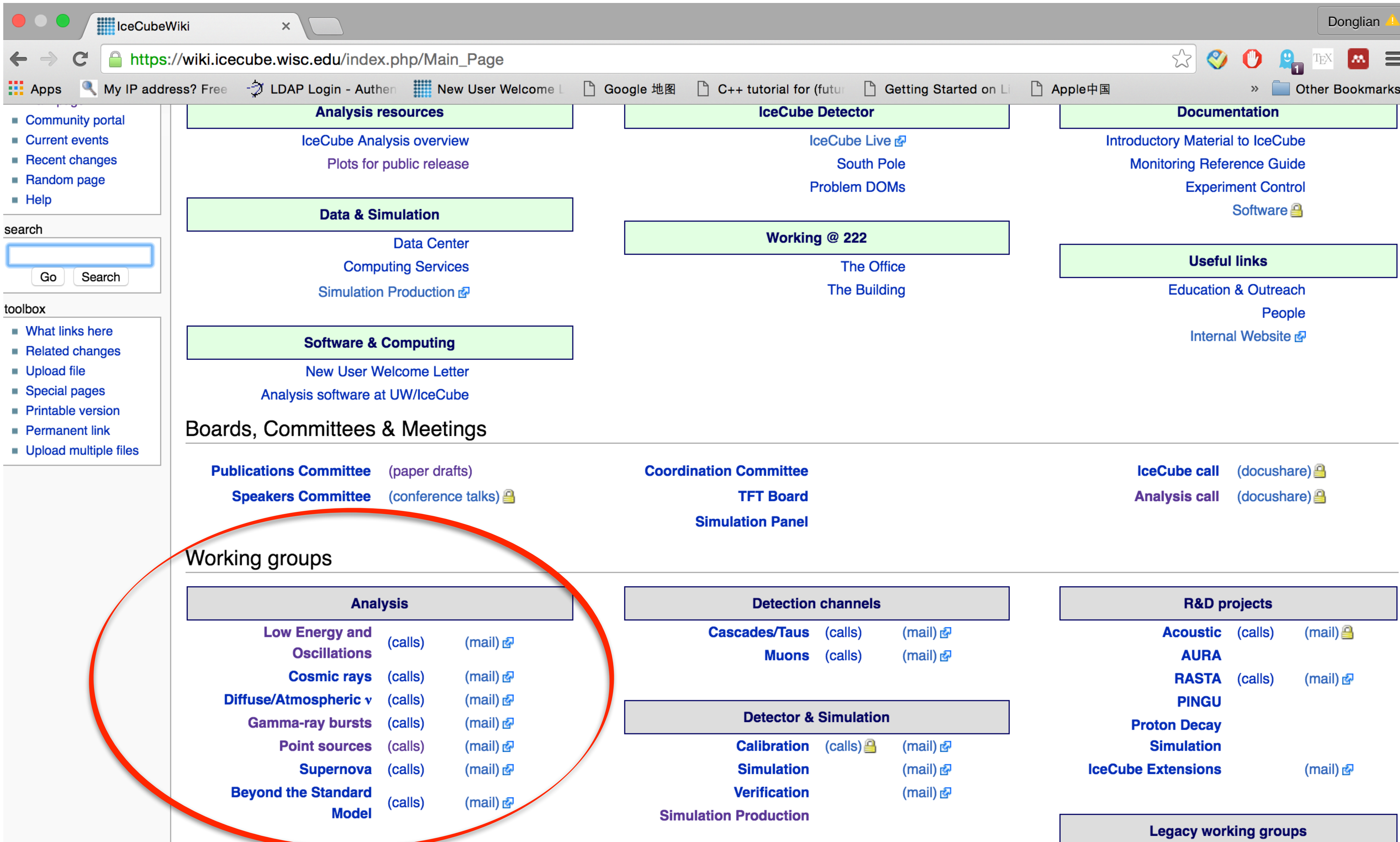
# Ongoing Physics Analyses (Not Exhaustive)

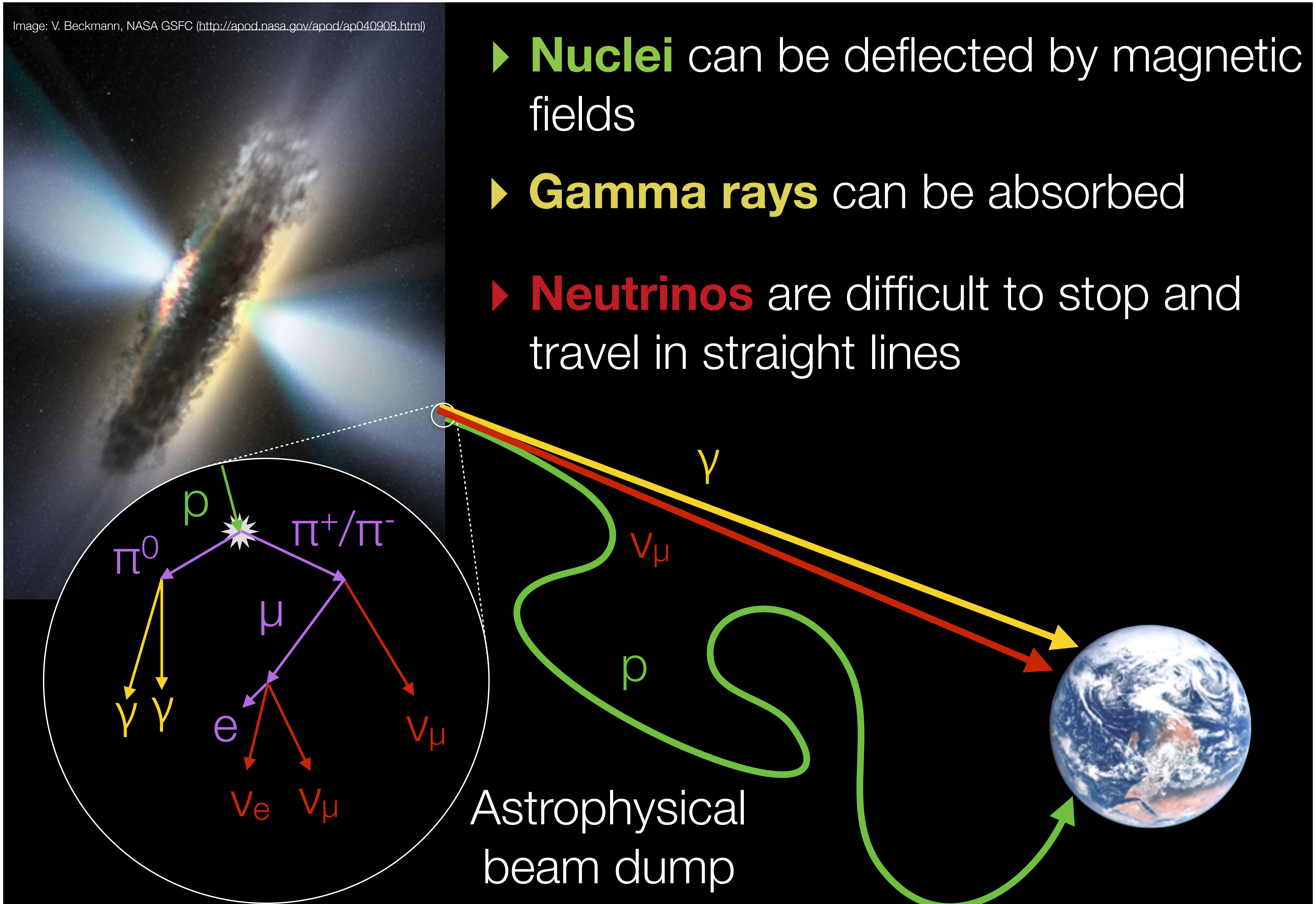
# Where do you find them?





# Astrophysical Beam Dump

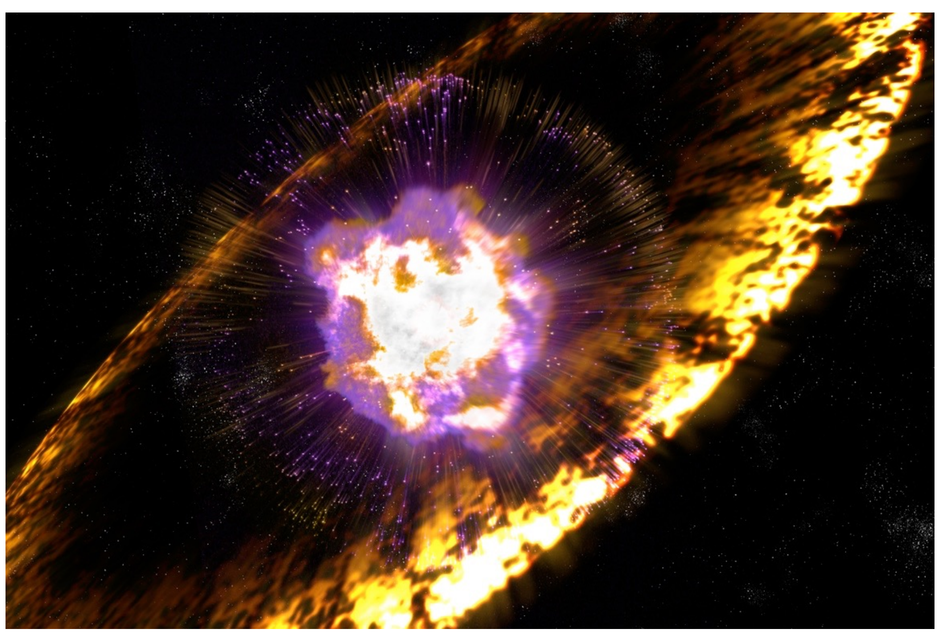
- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines



# Astrophysical Neutrinos

Active Galactic Nuclei (AGNs)

Gamma Ray Burst (GRB)



Supernovae

- **Fermi acceleration:**

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

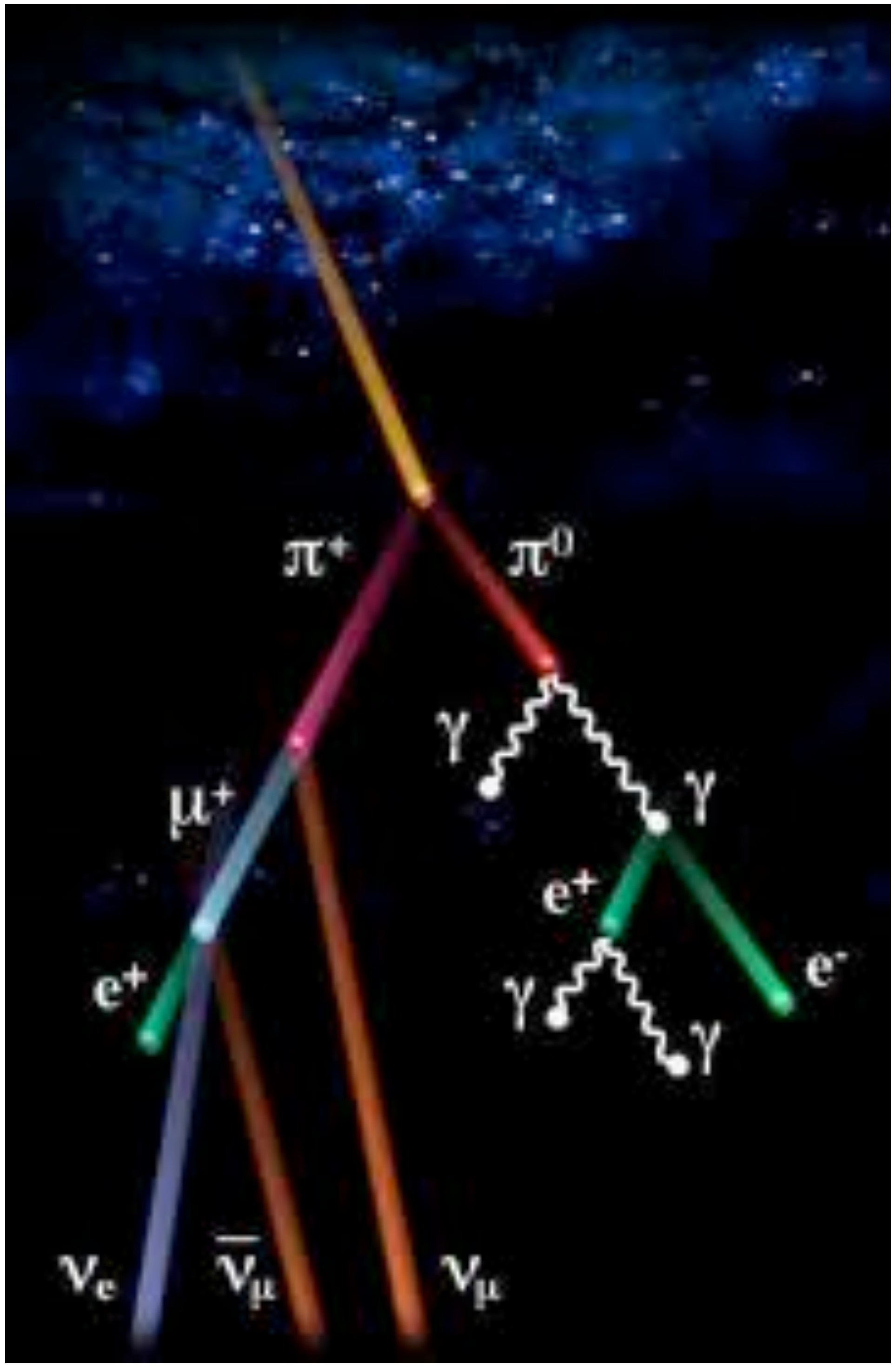
If cosmic rays interact before decaying, spectrum is softer

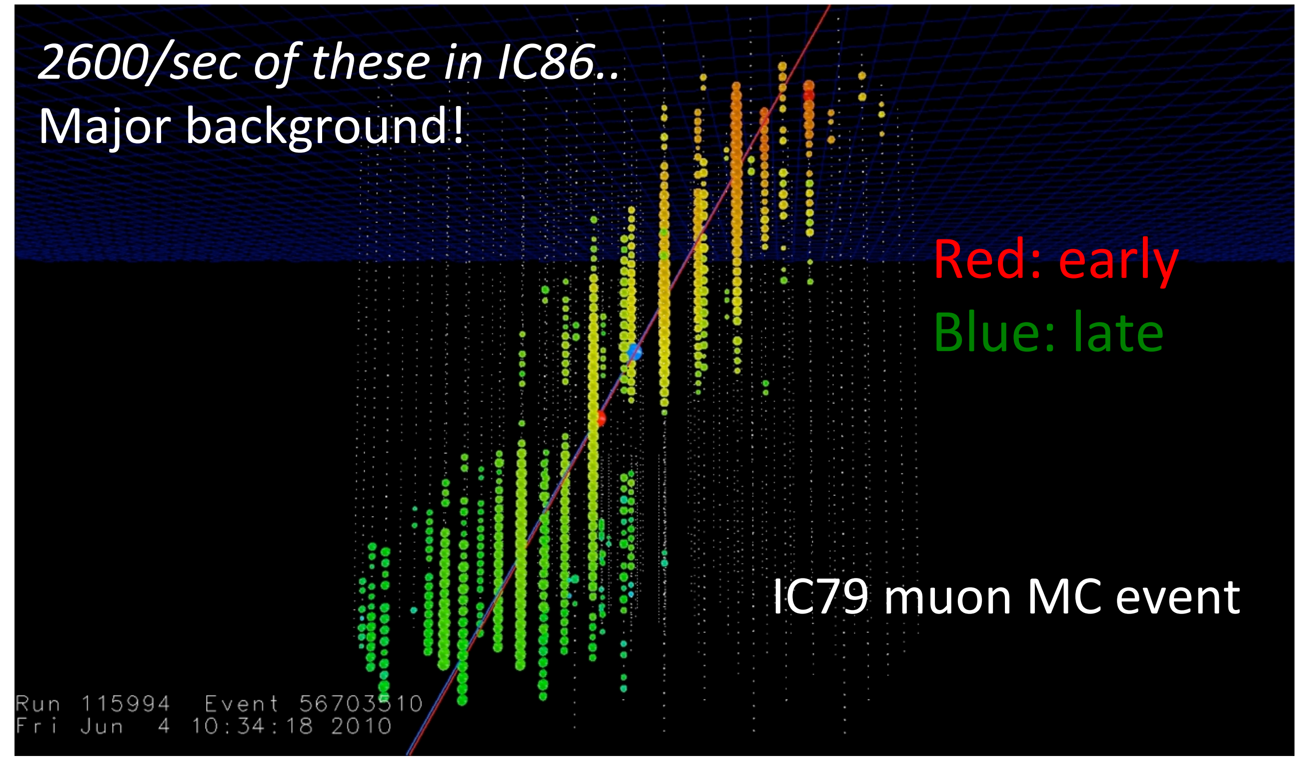
- **At Earth's surface:**

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

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

# Atmospheric Neutrinos




- **Conventional:** $\frac{dN}{dE_\nu} \sim E_\nu^{-3.7}$

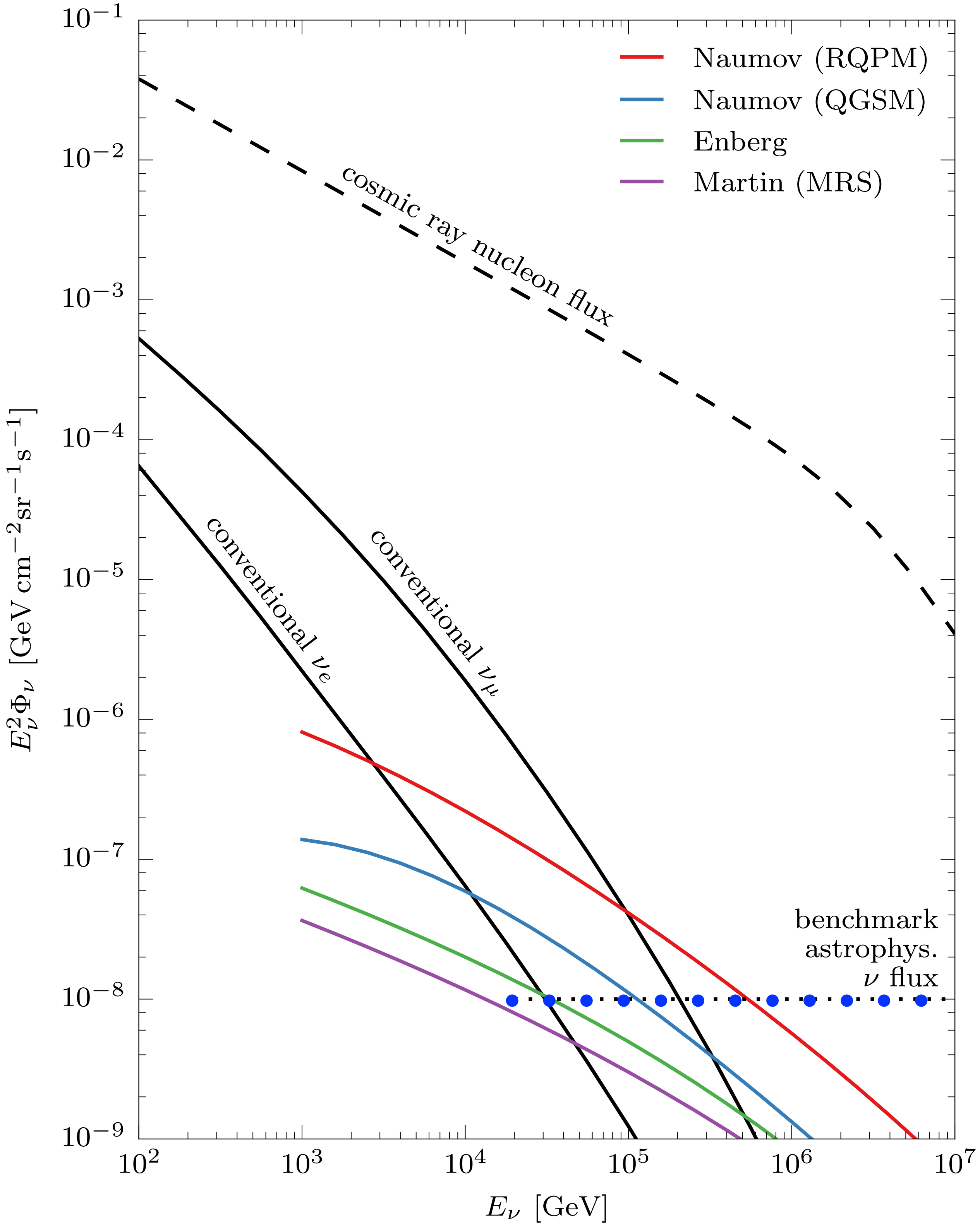
  $\nu_e : \nu_\mu \simeq 1 : 2$

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

**Atmospheric prompt $\nu_\tau$ is ~10 times lower than $\nu_\mu$ and $\nu_e$**

# 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:

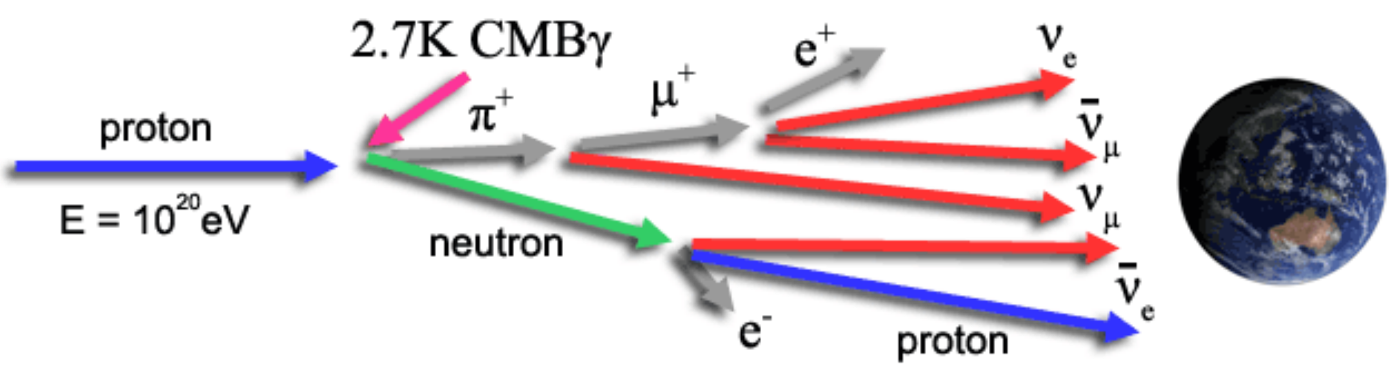
Naumov RQPM: http://link.springer.com/article/10.1007%2FBF02509070

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

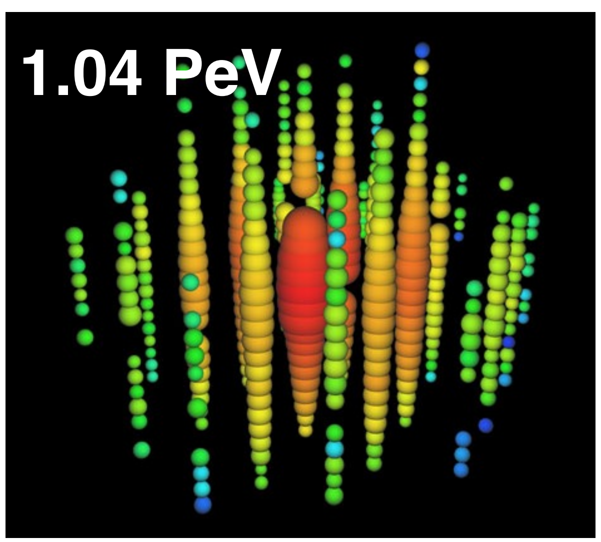
Enberg: Phys. Rev. D, 78(4):043005

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

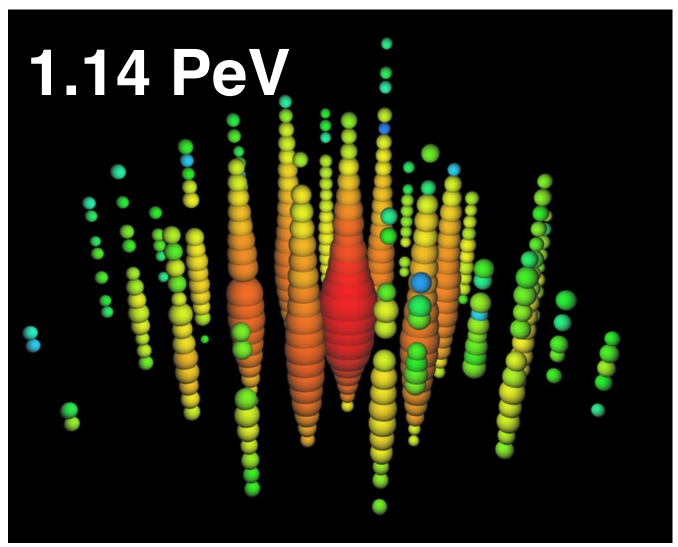
# Diffuse: extremely-high energy cosmogenic neutrinos



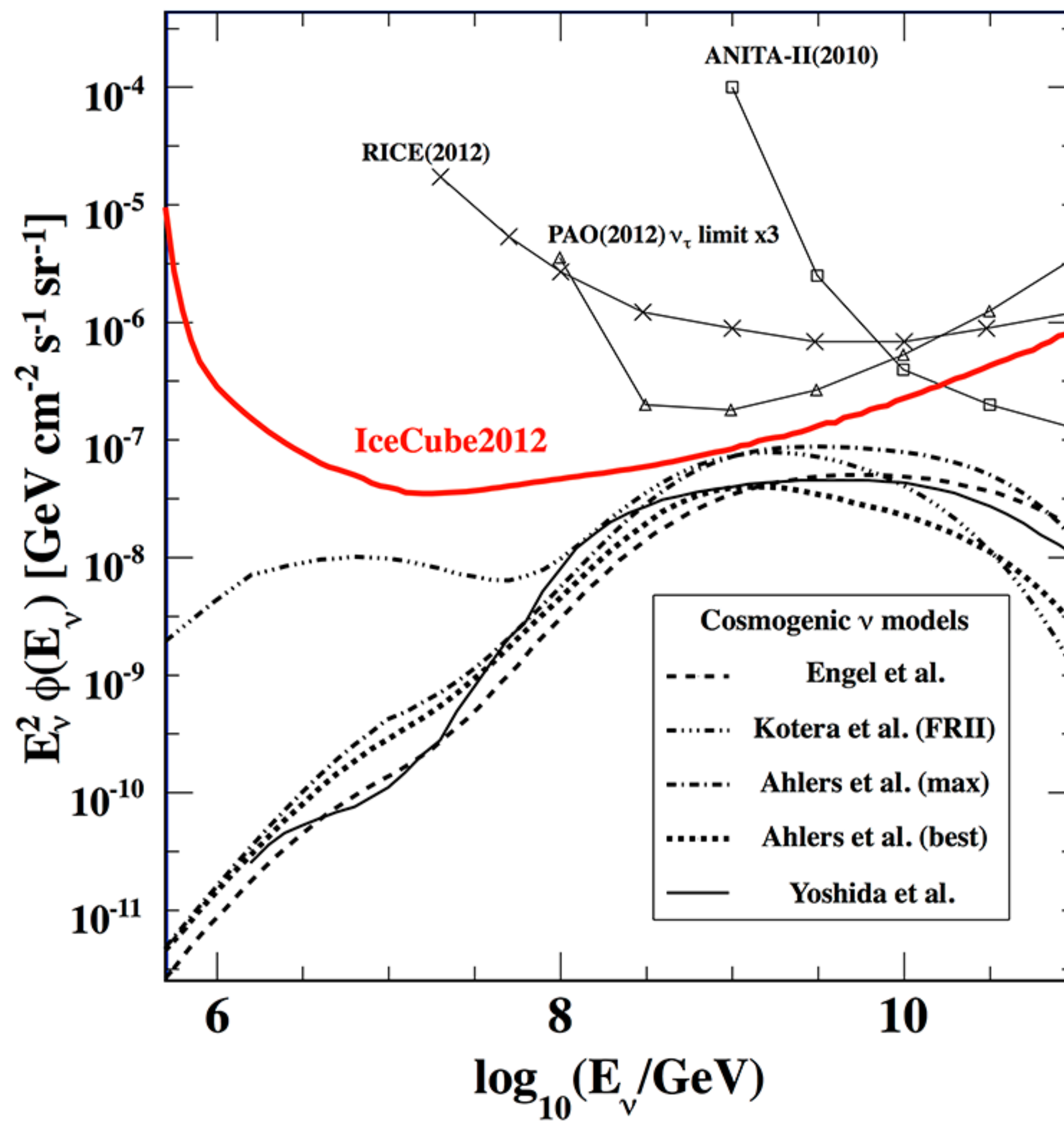

$$p + \gamma_{\rm CMB} \to \Delta^+ \to \begin{cases} \pi^+ + n, & 1/3 \\ \pi^0 + p, & 2/3 \end{cases}$$




"Bert"




"Ernie"

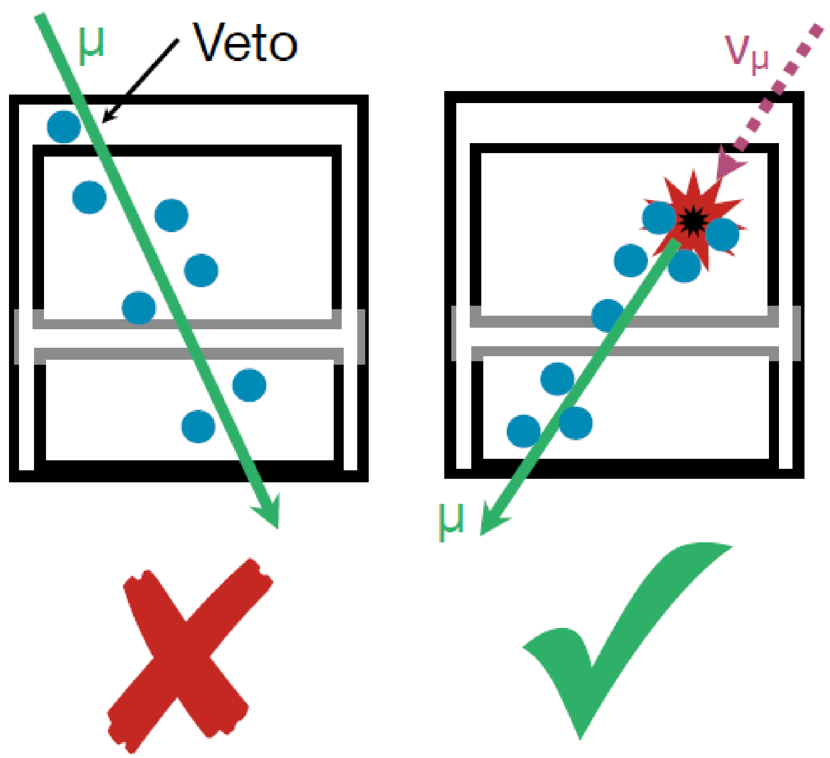



This analysis led to the discovery of first PeV neutrino events in IceCube

Phys. Rev. D88 (2013) 112008

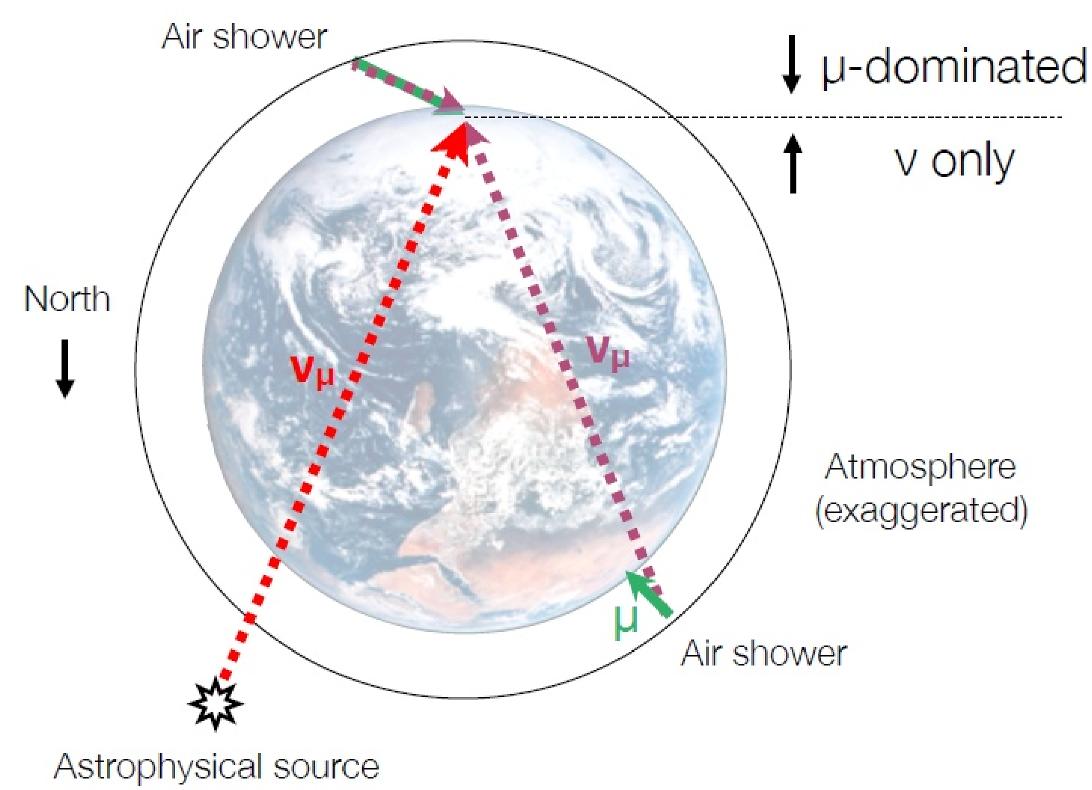
# Diffuse Astrophysical Neutrinos: Detection Strategy

## (1) Veto method: all sky, all flavor, starting events




- Containment required, effective volume smaller than detector

## (2) Through-going events: northern sky, $\nu_\mu$ CC and muonically decay $\nu_\tau$ CC events

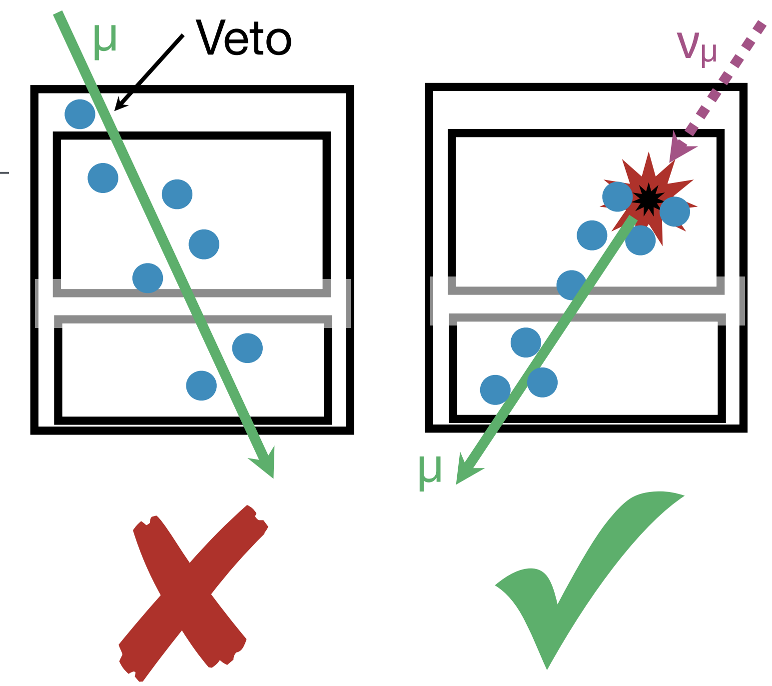


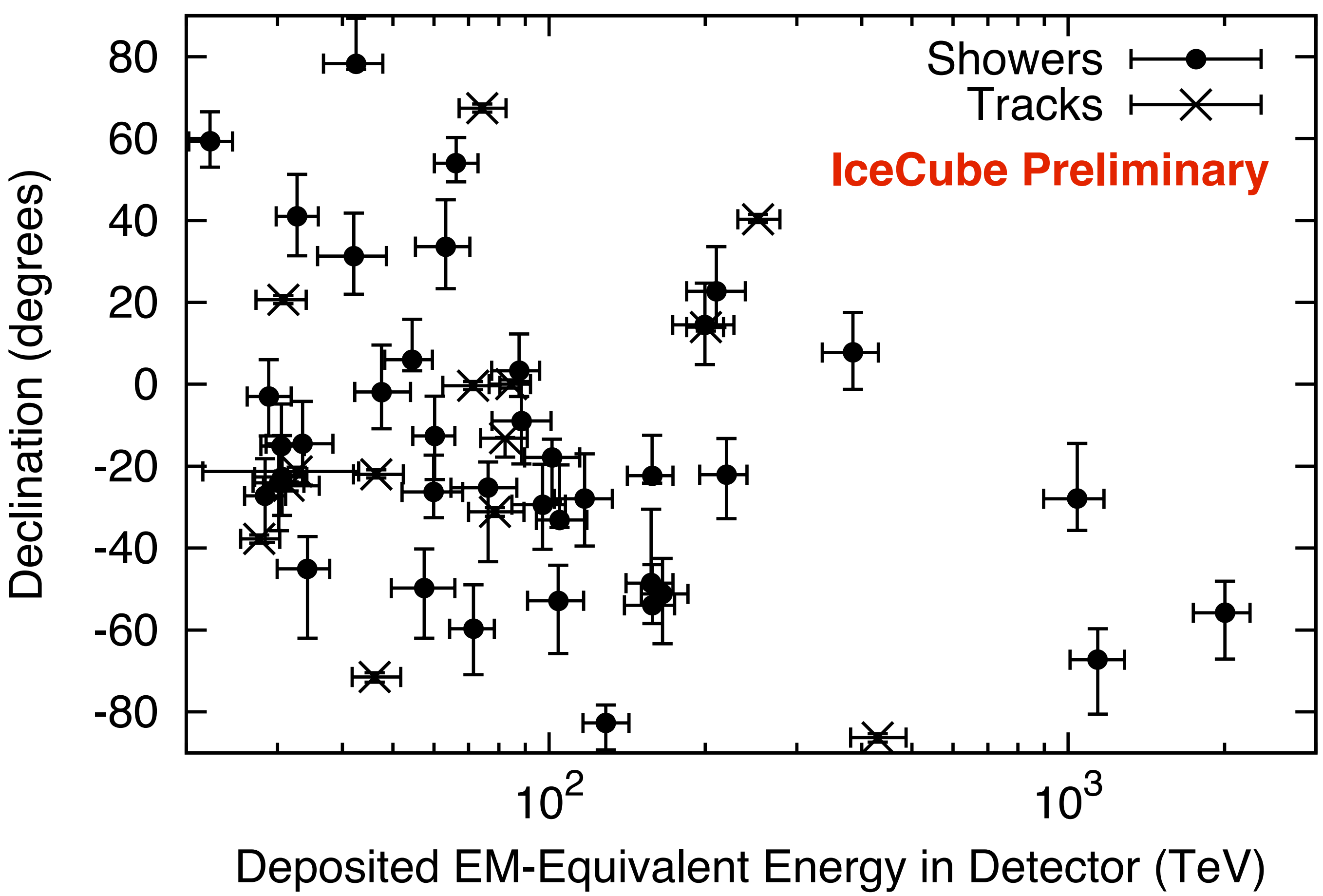

- No containment required, effective volume larger than detector

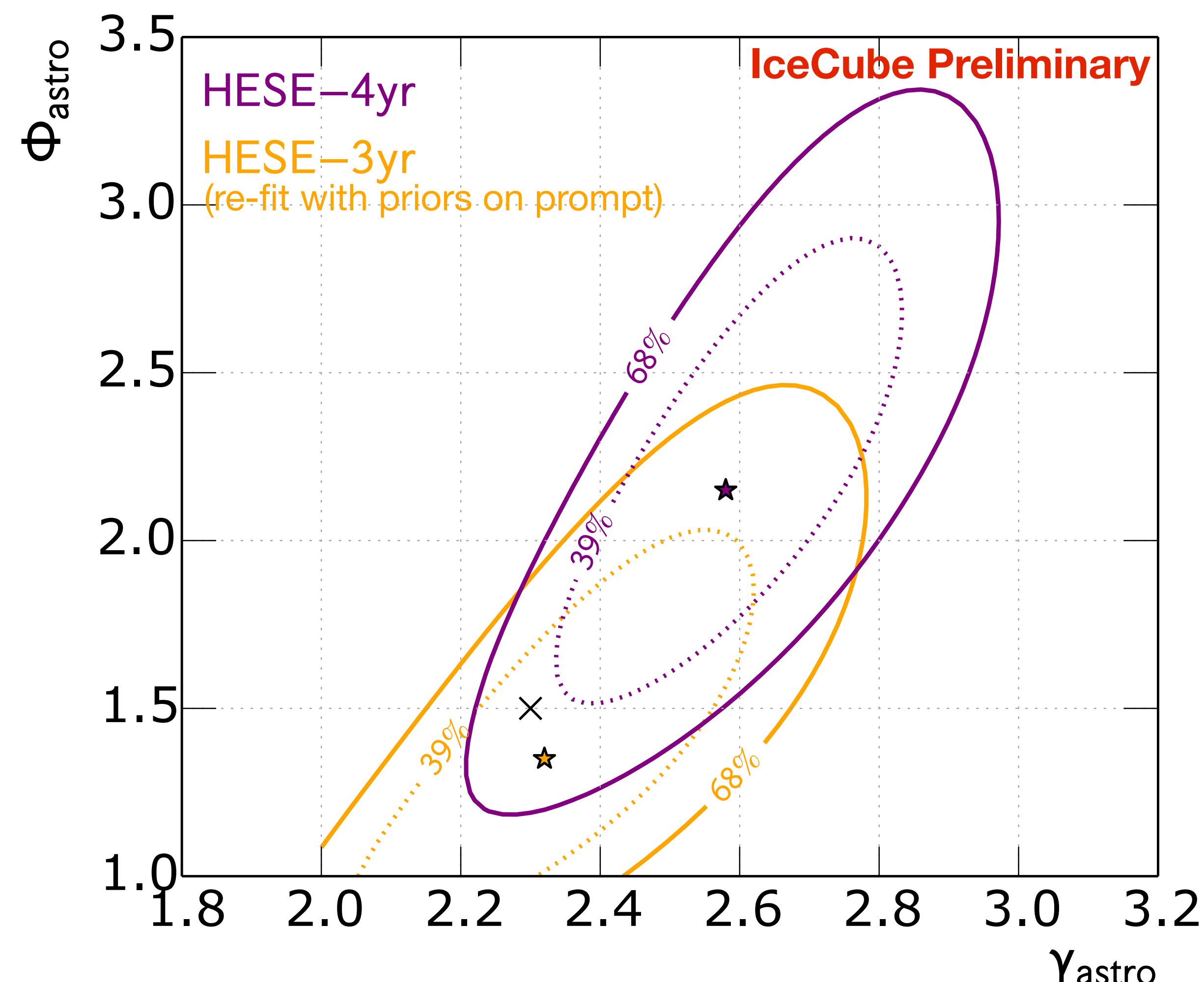
# Diffuse: all-sky, all-flavor

## 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.



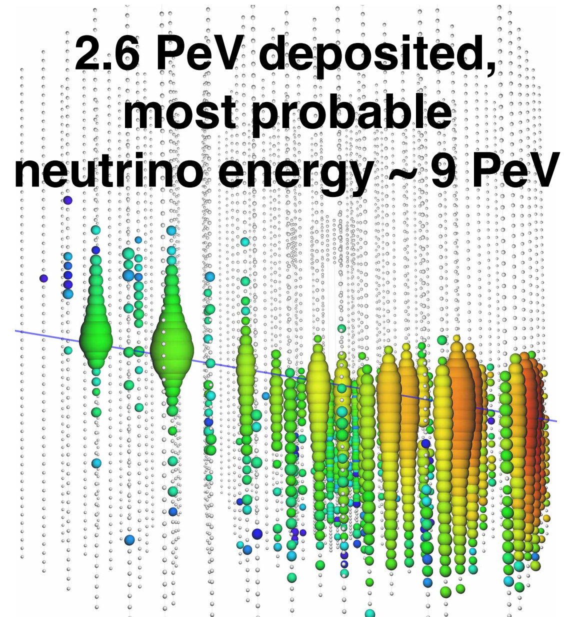



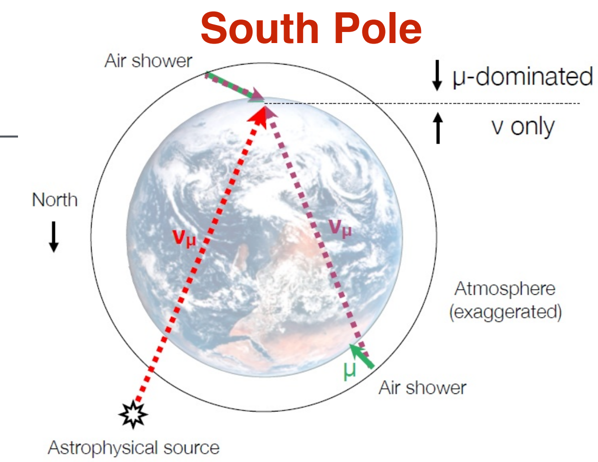

PoS(ICRC2015)1081

# Diffuse: up-going Muon Neutrinos



- **352, 294 events, highest 2.6 PeV**
- **Reject pure atmo. origin at 5.6σ**
- **No point sources, no clustering**
- **Astro. flux best fit:**

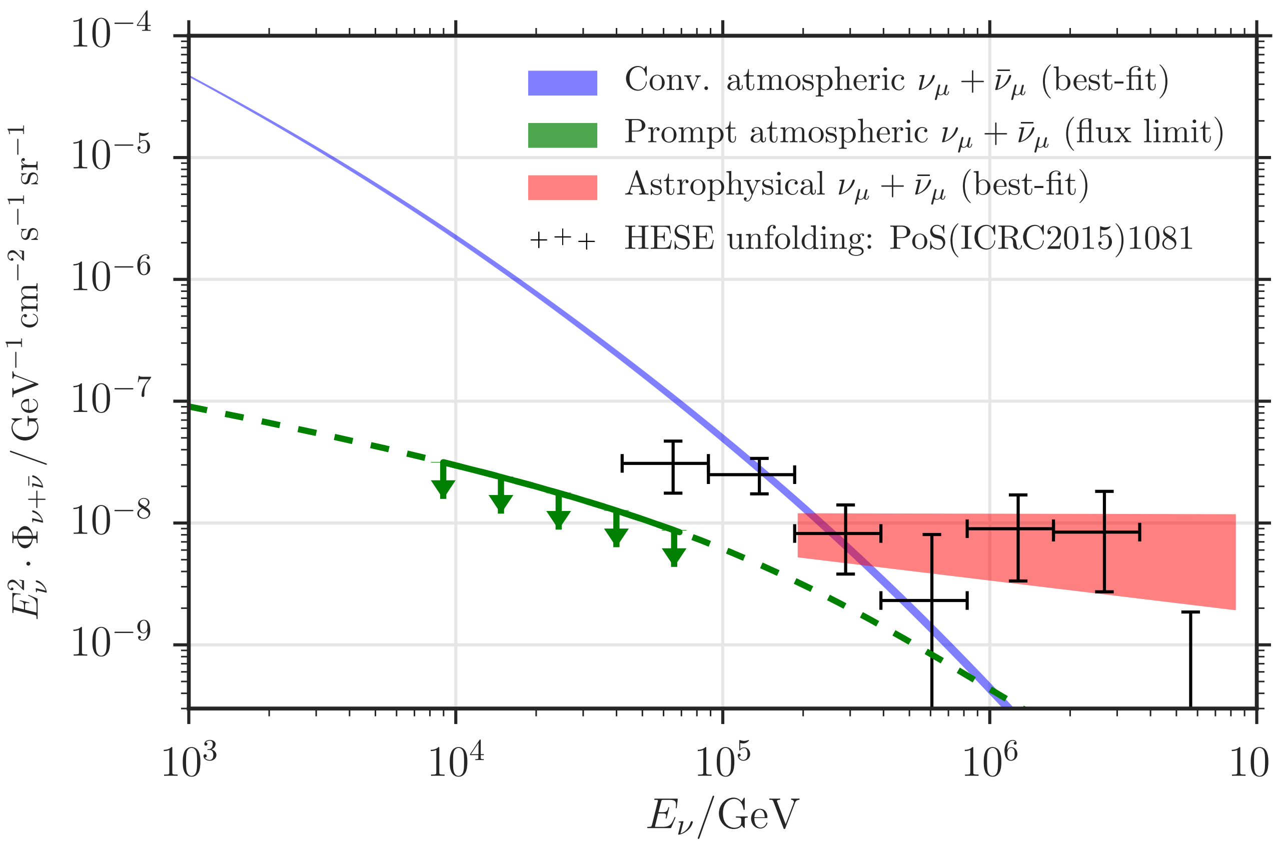


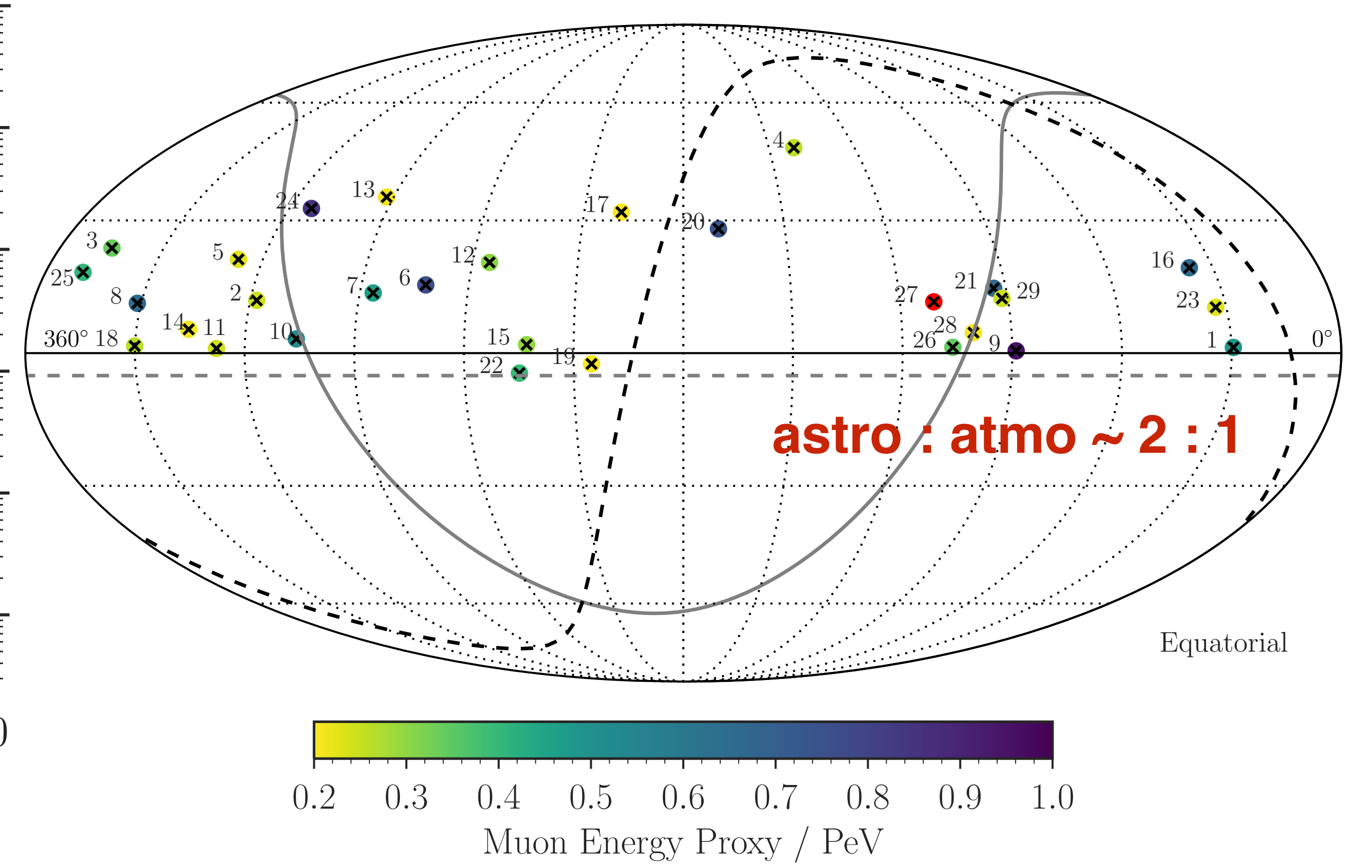




**Using the Earth as a shield for cosmic-ray induced muons**

$$\Phi_{\nu+\bar{\nu}} = (0.90^{+0.30}_{-0.27}) \cdot \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-(2.13\pm0.13)} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

**29 events > 200 TeV**




Phys. Rev. Lett. 115, 081102 (2 yr)
https://arxiv.org/abs/1607.08006 (6 yr)



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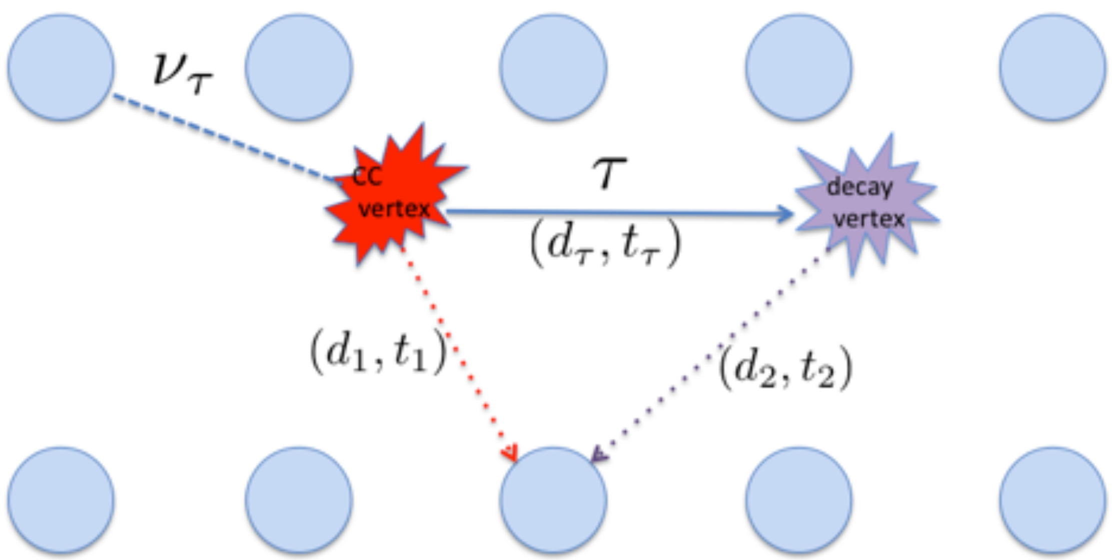
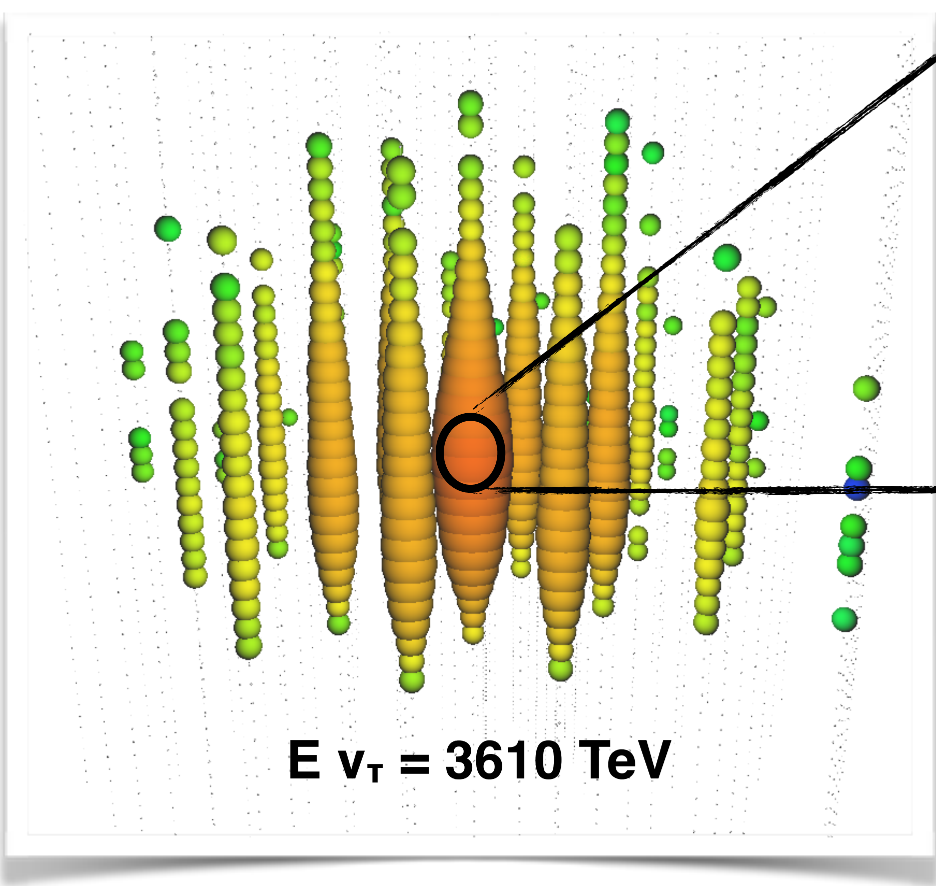
# Diffuse: Astrophysical Tau Neutrinos ($\nu_\tau$)

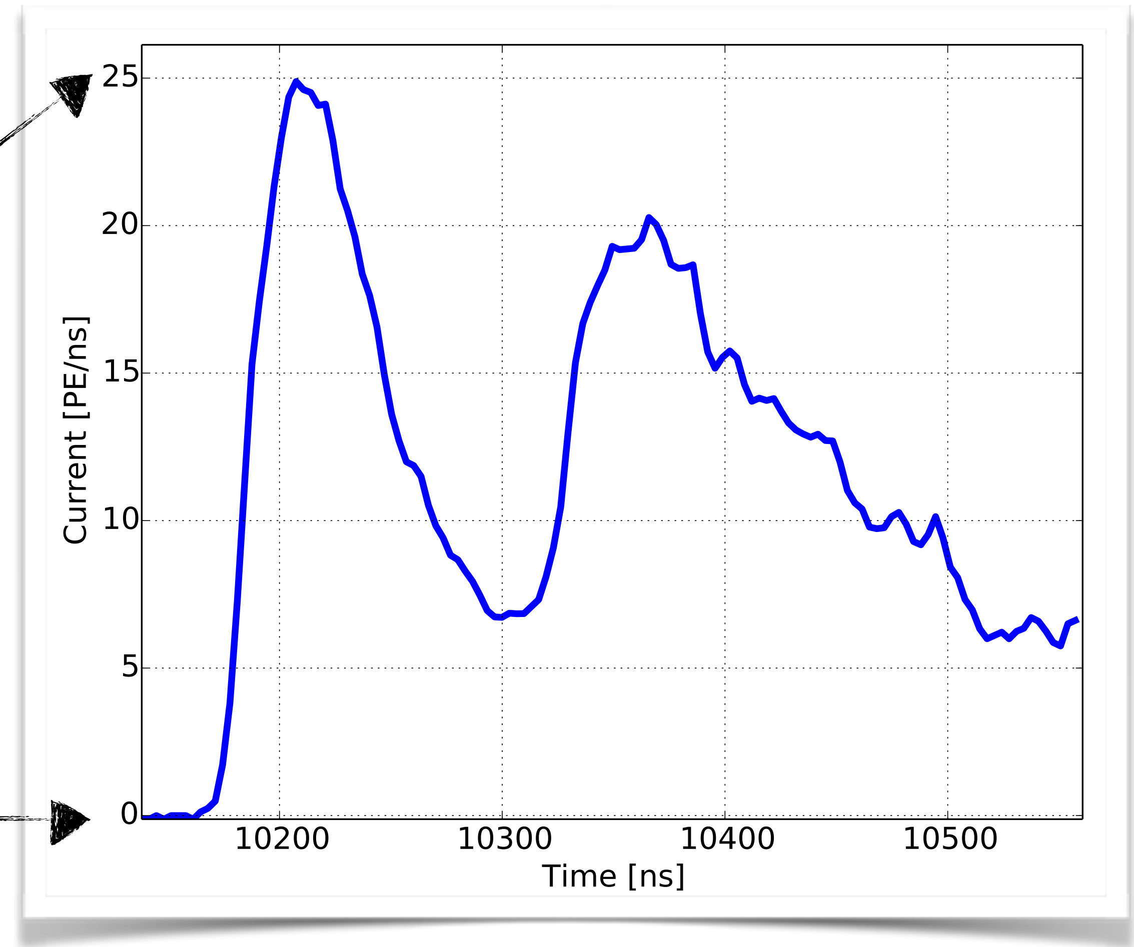
**Schematic $\nu_\tau$ CC interaction in IceCube**




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

$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%) ✓$$
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%) ✓$$
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$



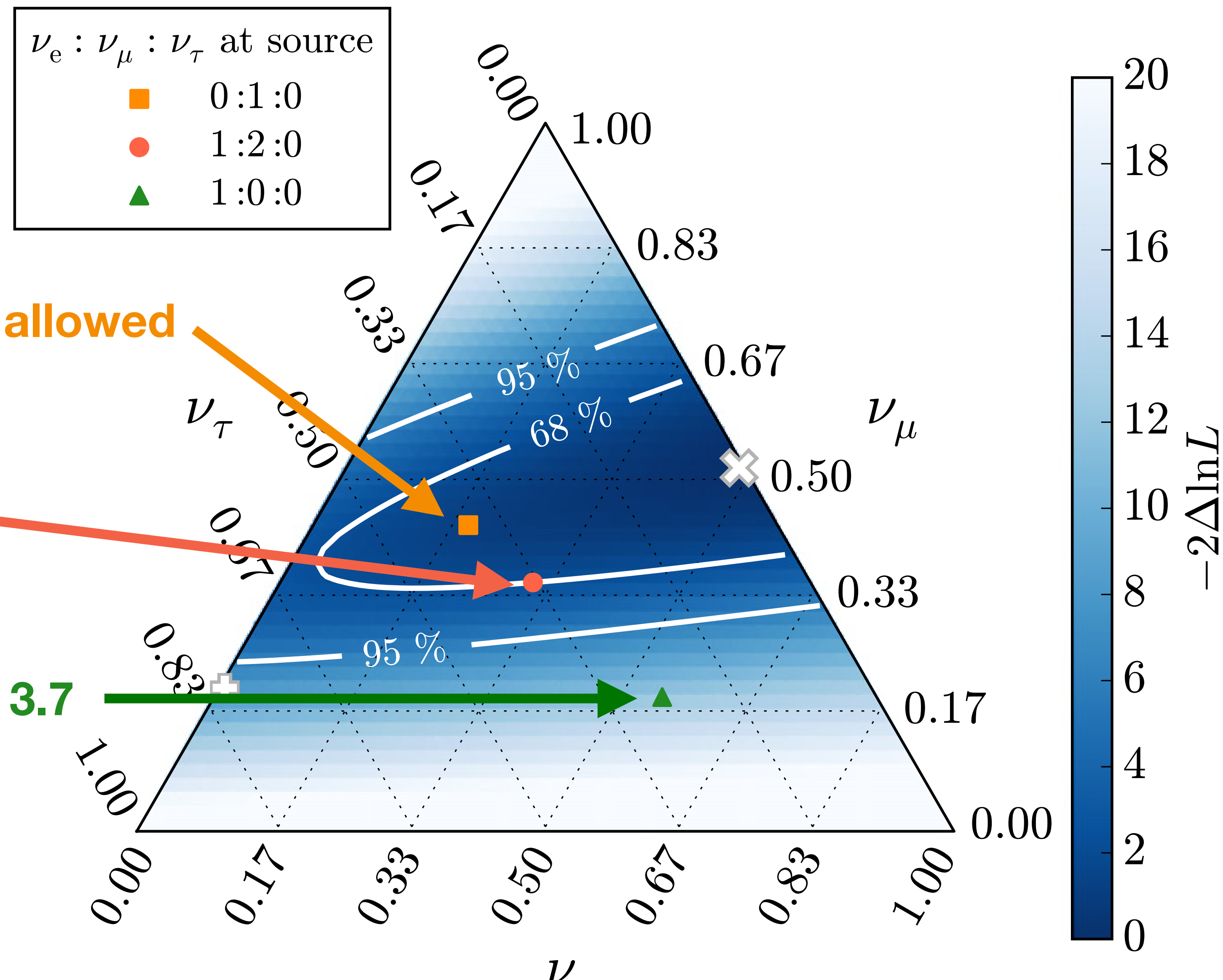

*Phys. Rev. D 93, 022001*

- **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.

Muon-damped pion decay: allowed

Pion decay: allowed

Neutron decay: rejected at 3.7

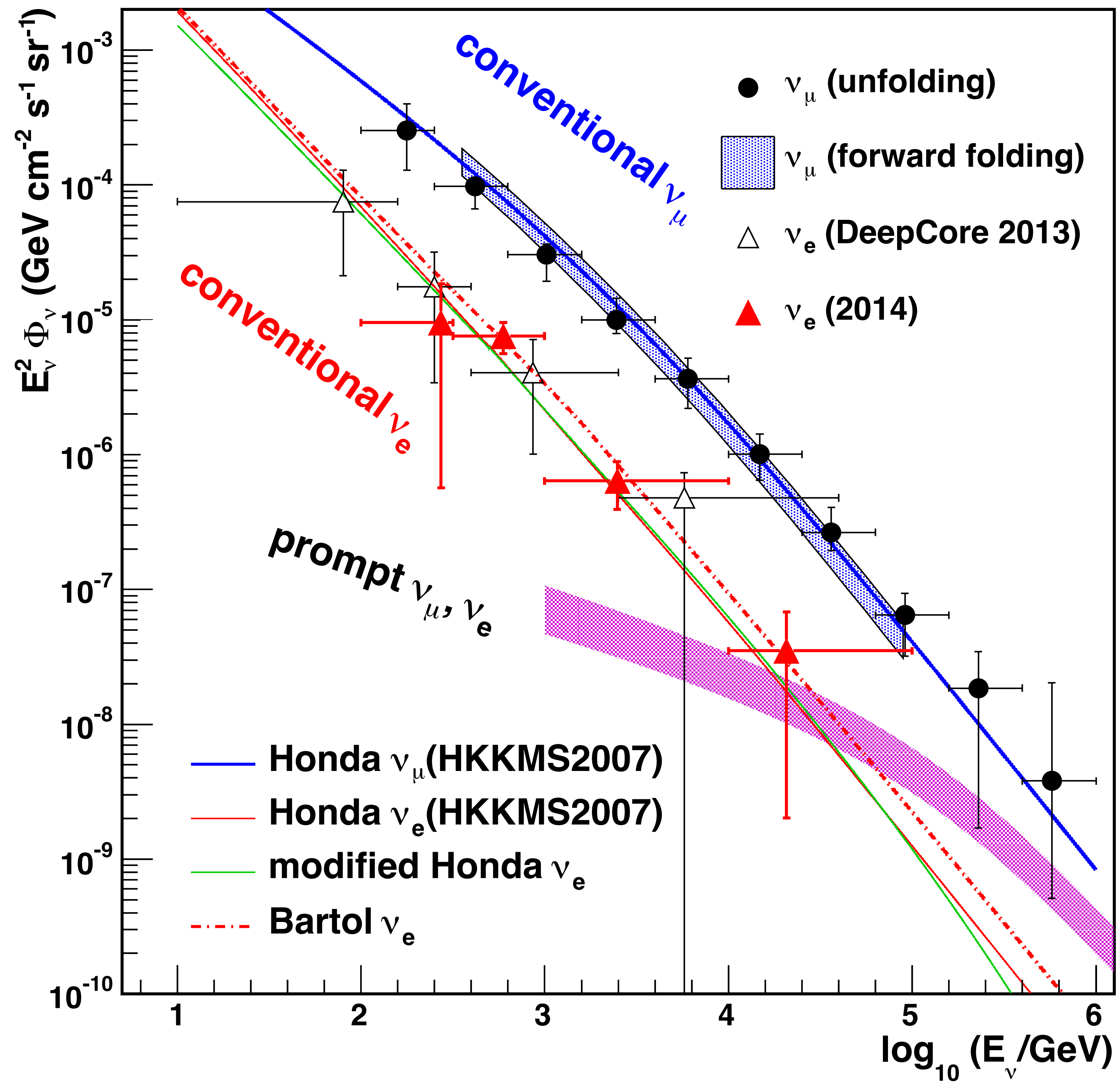



ApJ 809,98(2015)

# Atmospheric Neutrino Spectra

Phys.Rev. D91:122004,2015

Honda HKKMS2007:
Phys.Rev.D75:043006,2007



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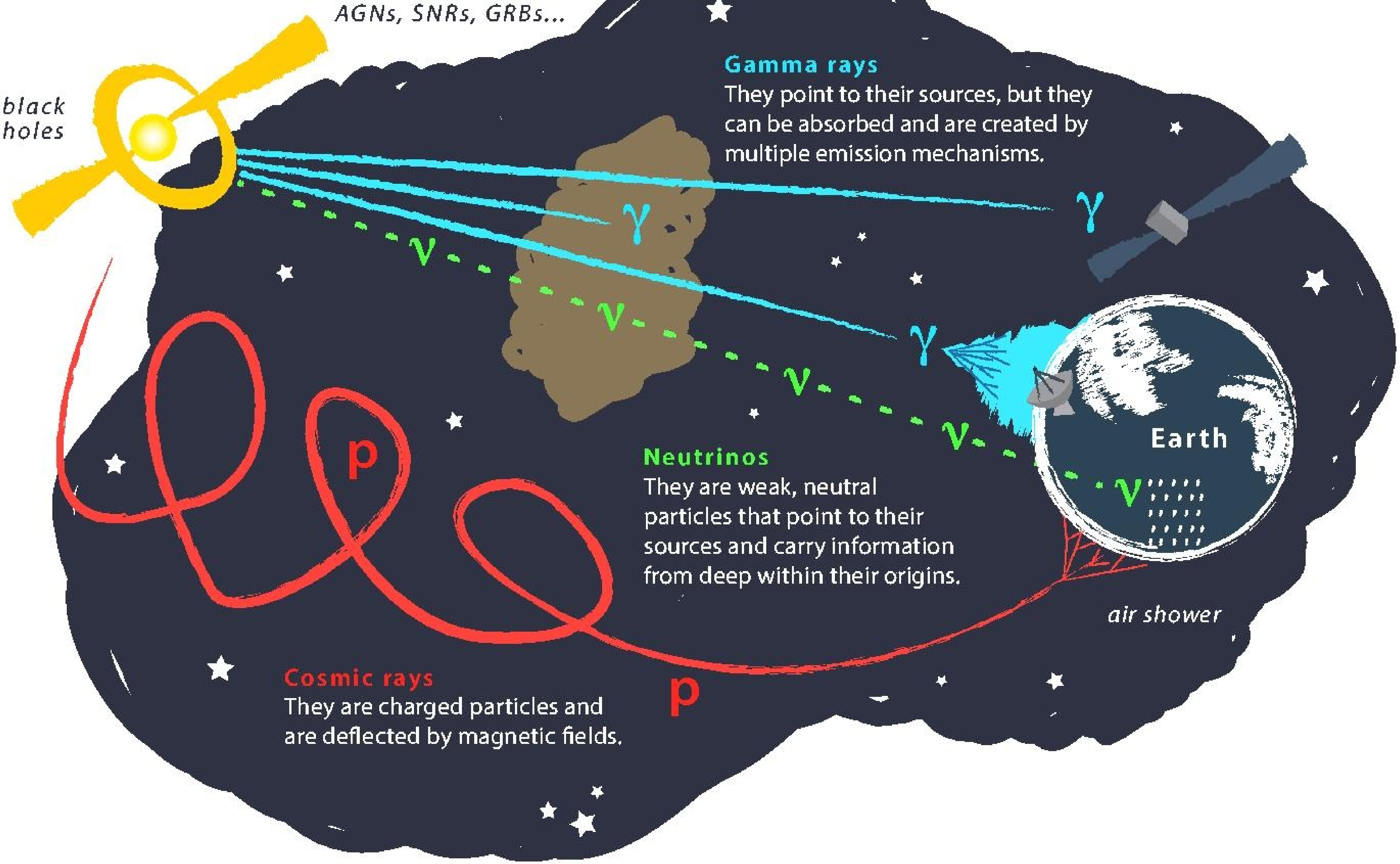
# Where are Astrophysical Neutrinos from?

**Source identification requires good angular resolution**

**Multi-messenger enables correlating to known sources**



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.



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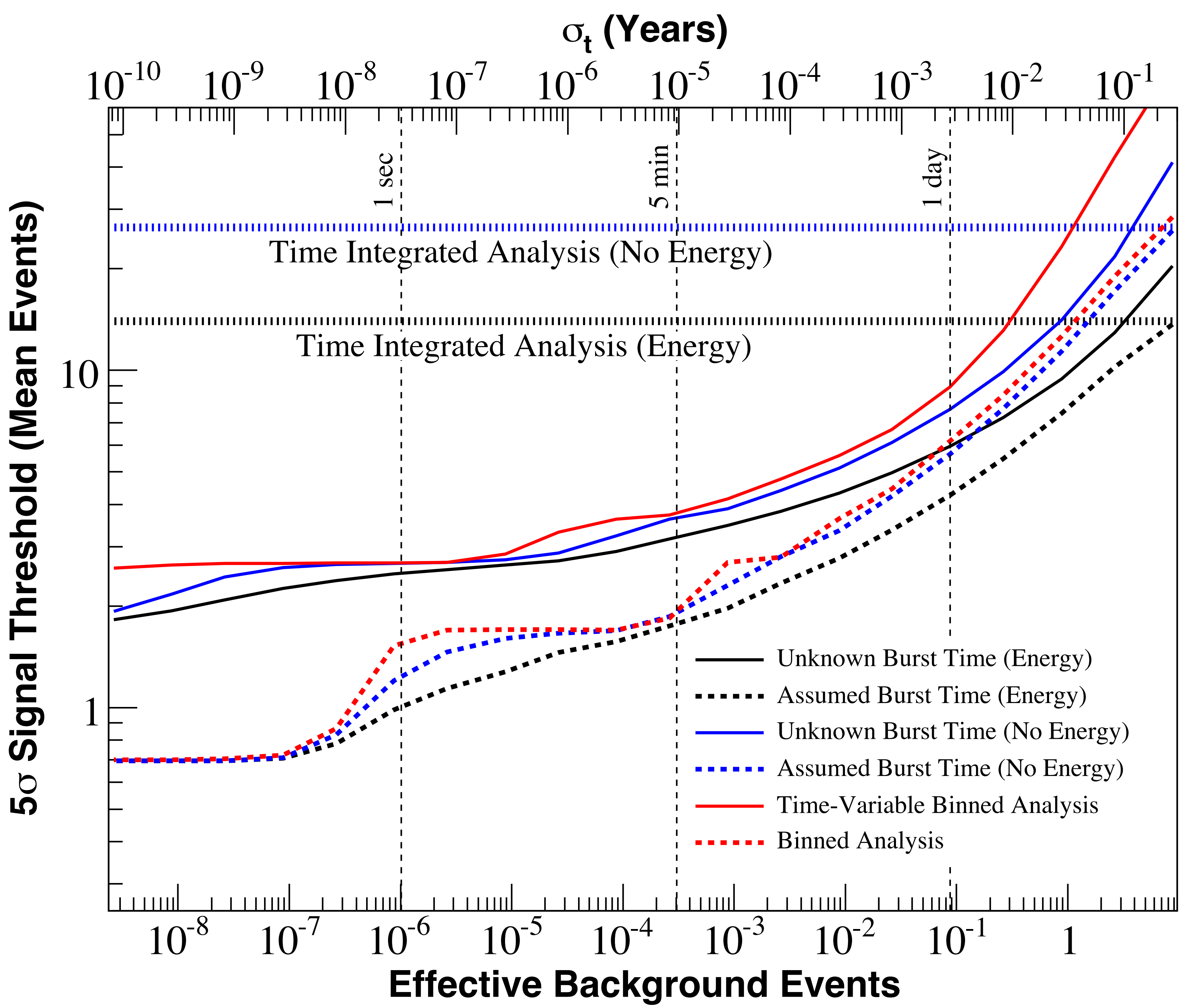
# Neutrino Point Source Searches



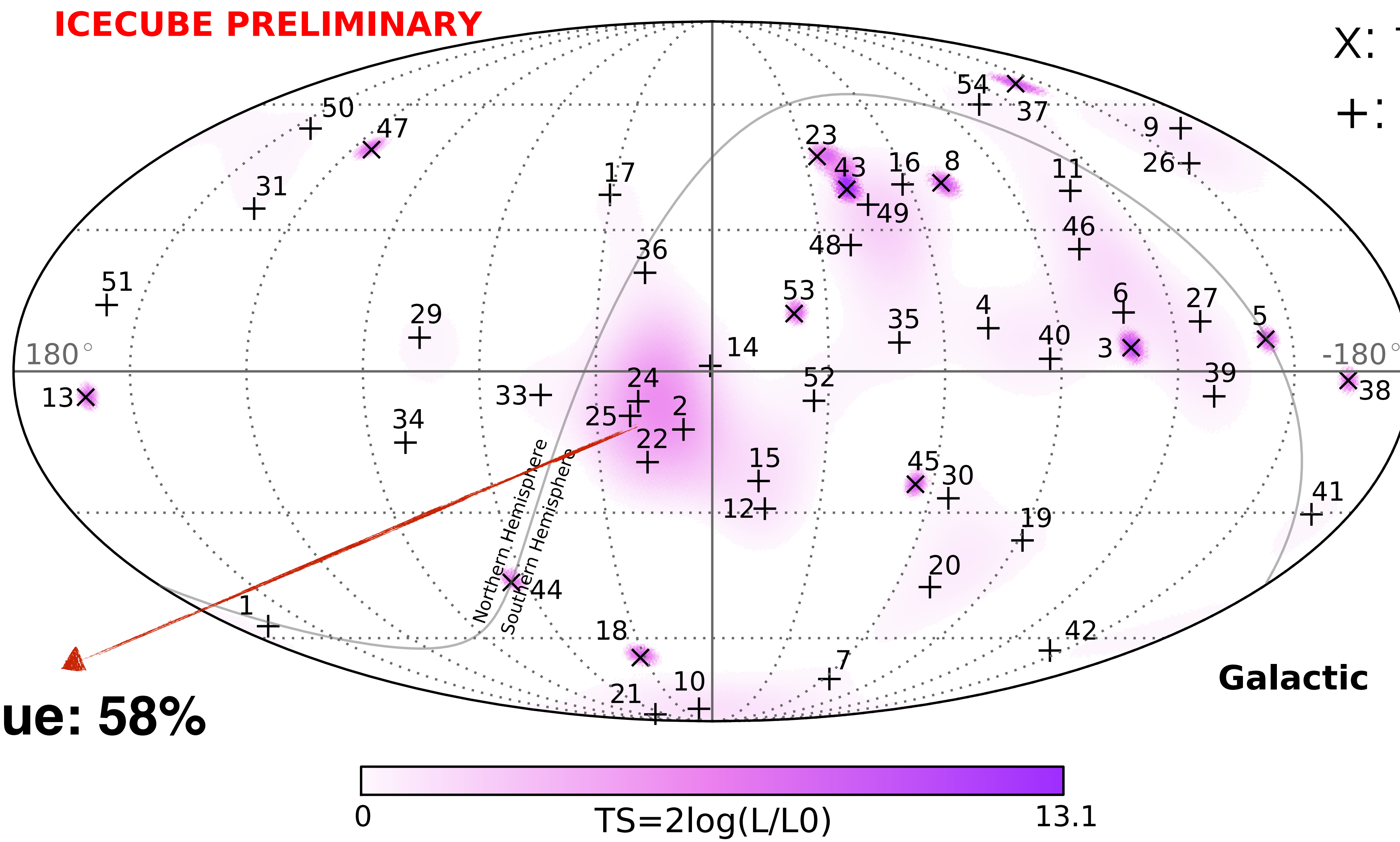



- Unbinned likelihood is more powerful than binned one
- Sensitivity gained when more (correct) information is provided

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

## Spatial clustering

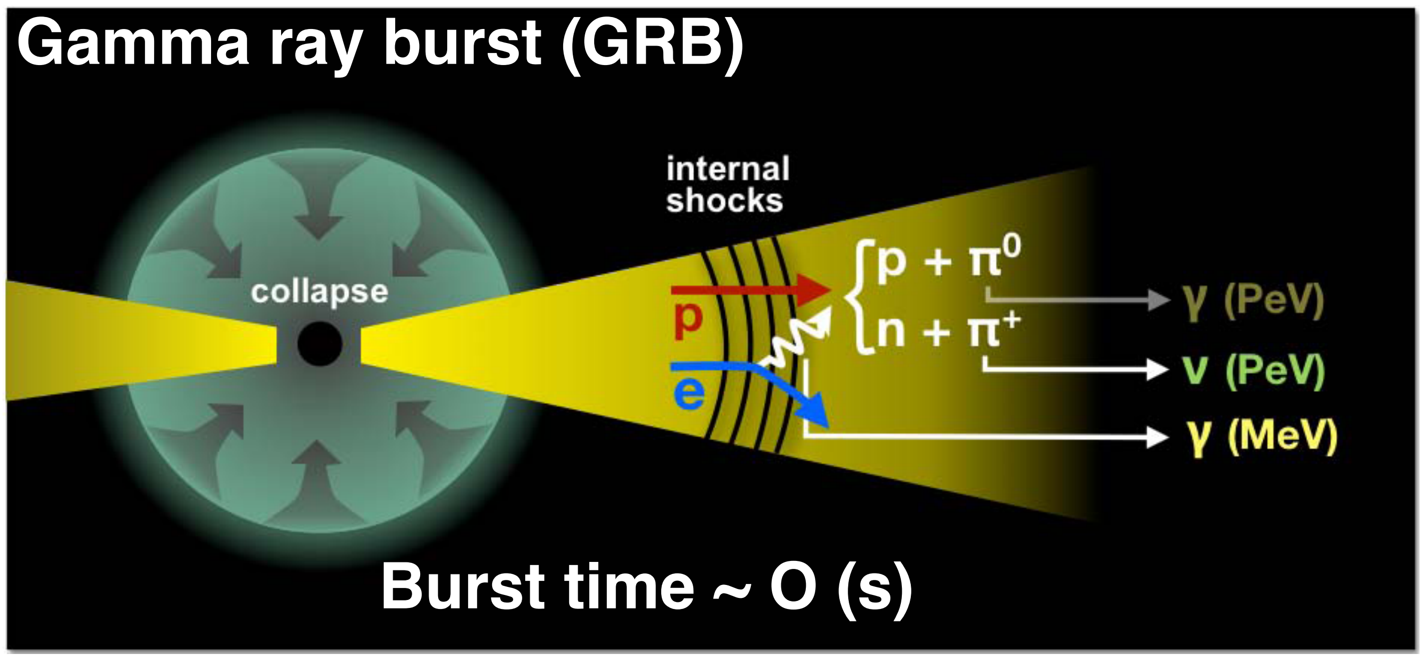
x: tracks
+: showers




**p-value: 58%**

PoS(ICRC2015)1081

## Spatial & Time clustering



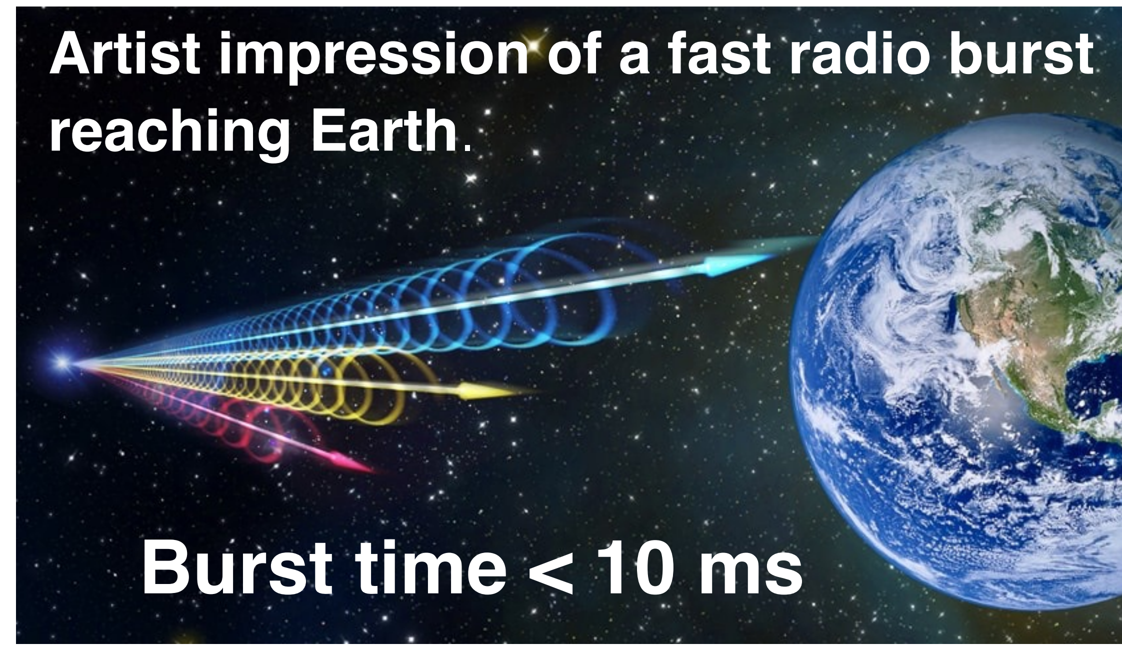
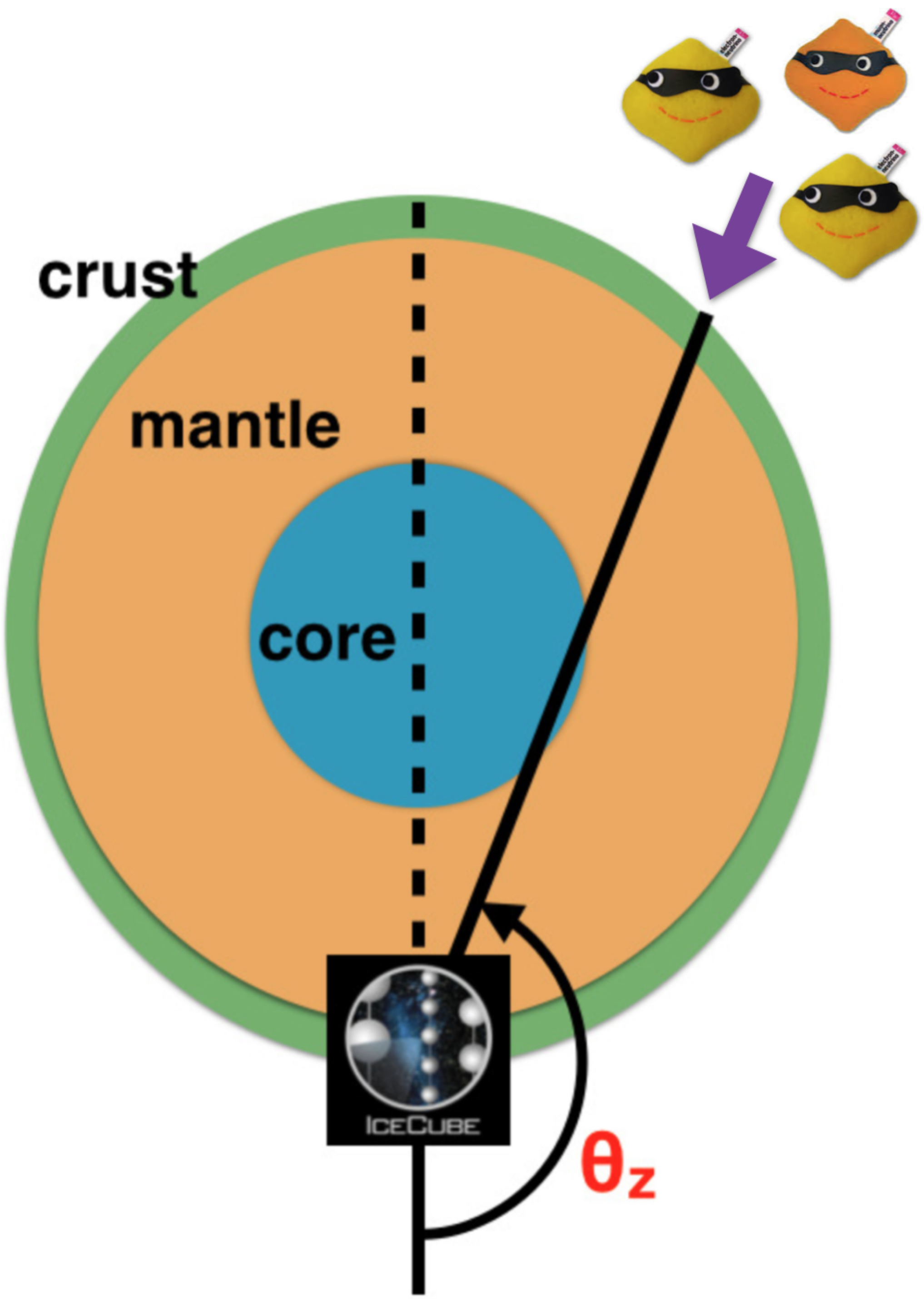




Photo credit: Jingchuan Yu, Beijing Planetarium

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

# Neutrino Oscillations through the Earth

The neutrinos come from different zenith angles ($\theta_z$) traversing different layers of the Earth




**core** :

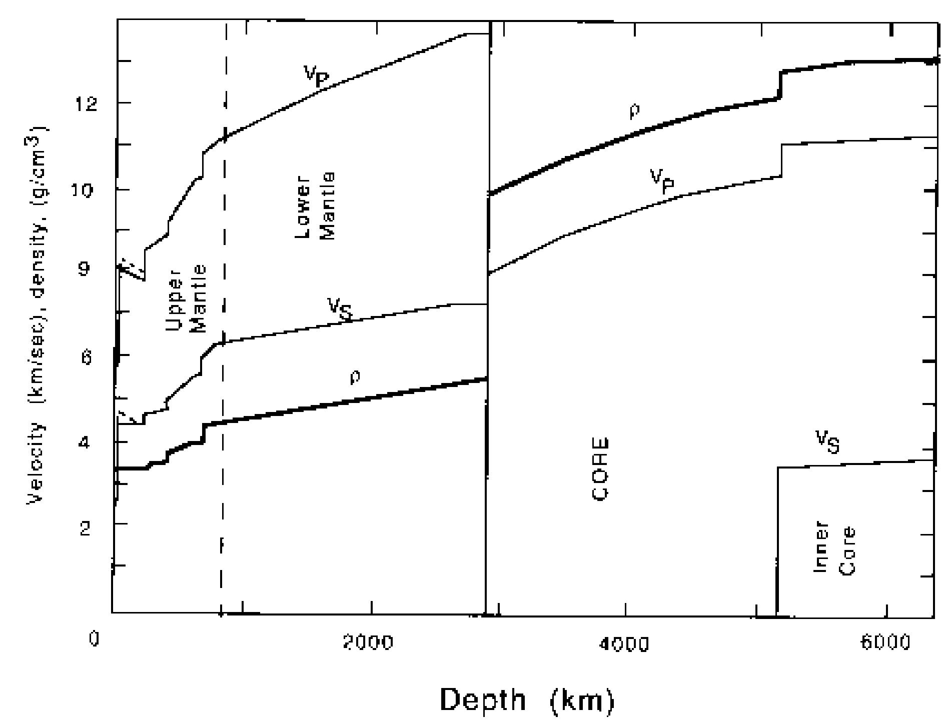
$\cos\theta_z \sim [-1, -0.8]$

**mantle** :

$\cos\theta_z \sim [-0.8, -0.1]$

**crust** :

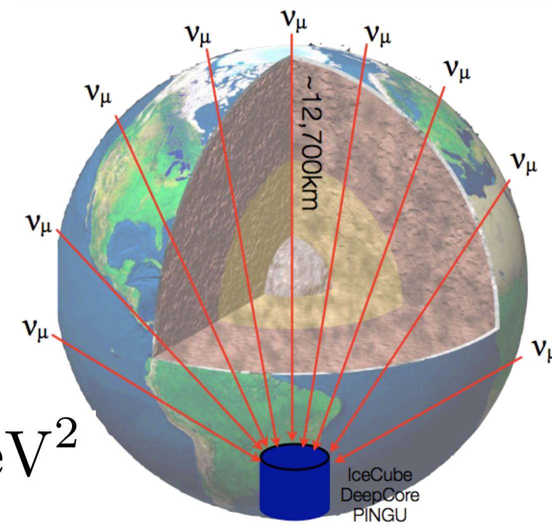
$\cos\theta_z > -0.1$

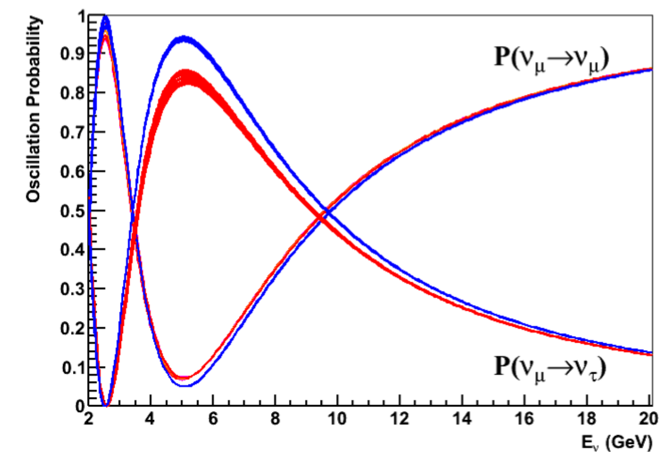


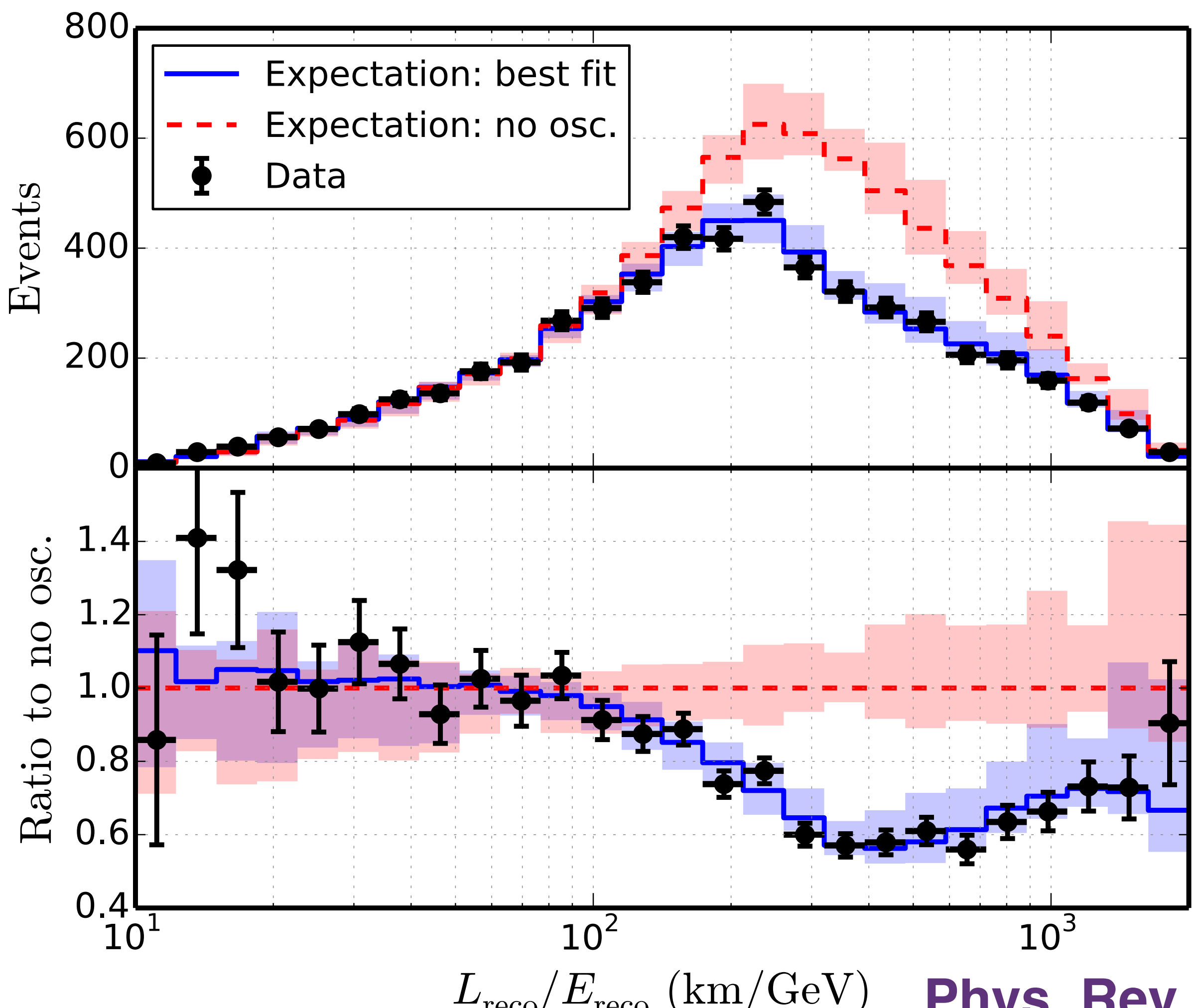
# Atmospheric Muon Neutrino Disappearance

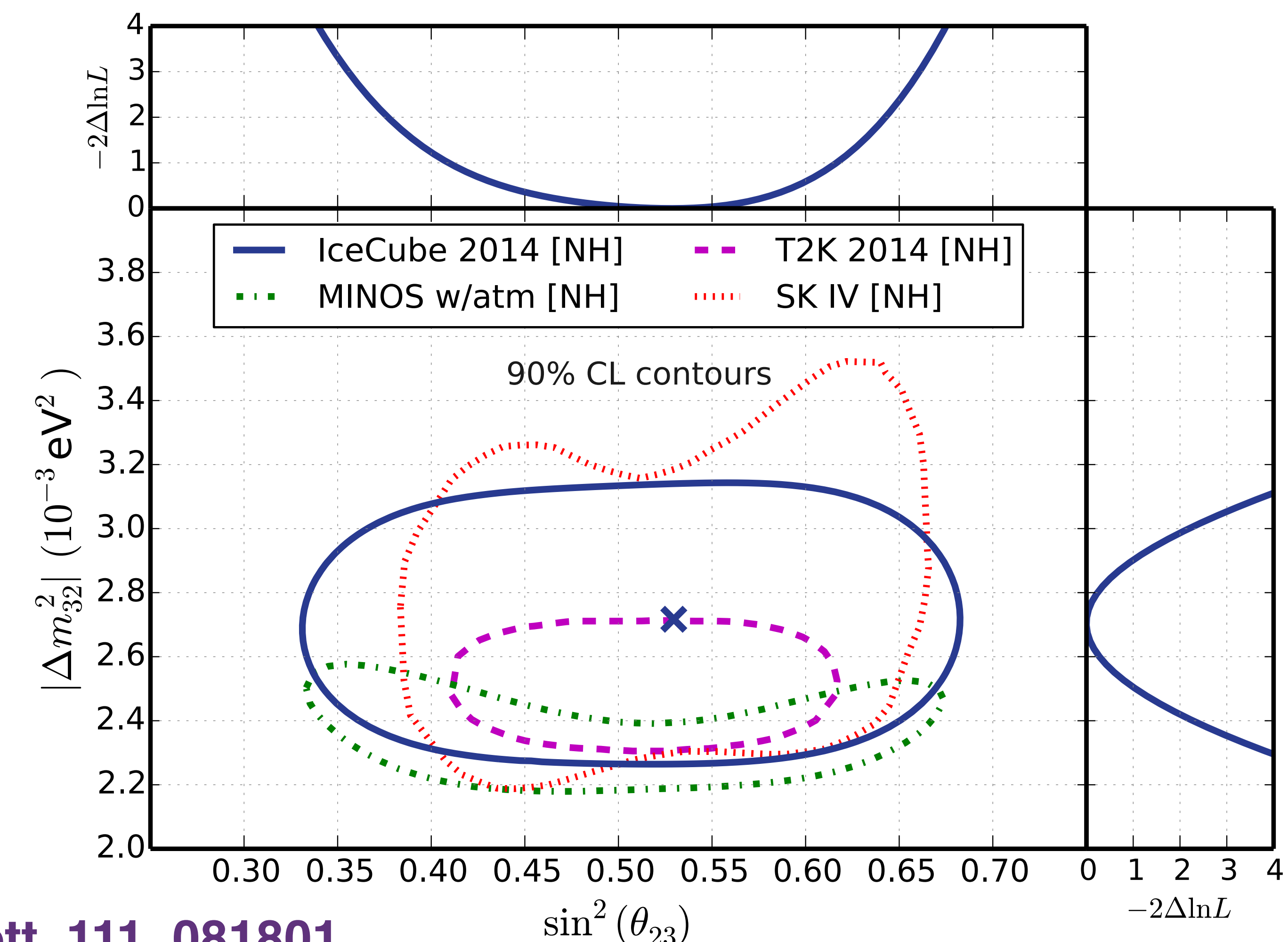
- **5293 high quality events in 953 days**
- **10 - 100 GeV (DeepCore)**
- **Best fit oscillation parameters:**

$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$ and $|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\mathrm{eV}^2$




**Phys. Rev. Lett. 111, 081801**
**Phys. Rev. D 91, 072004**



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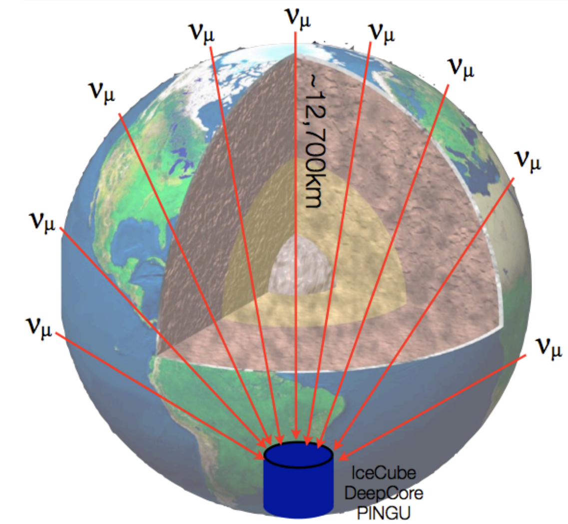
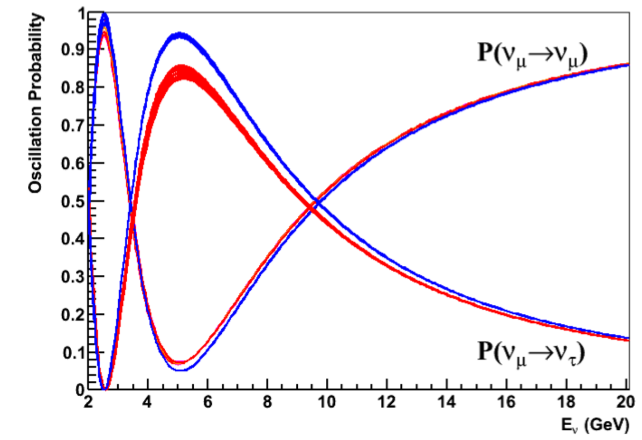
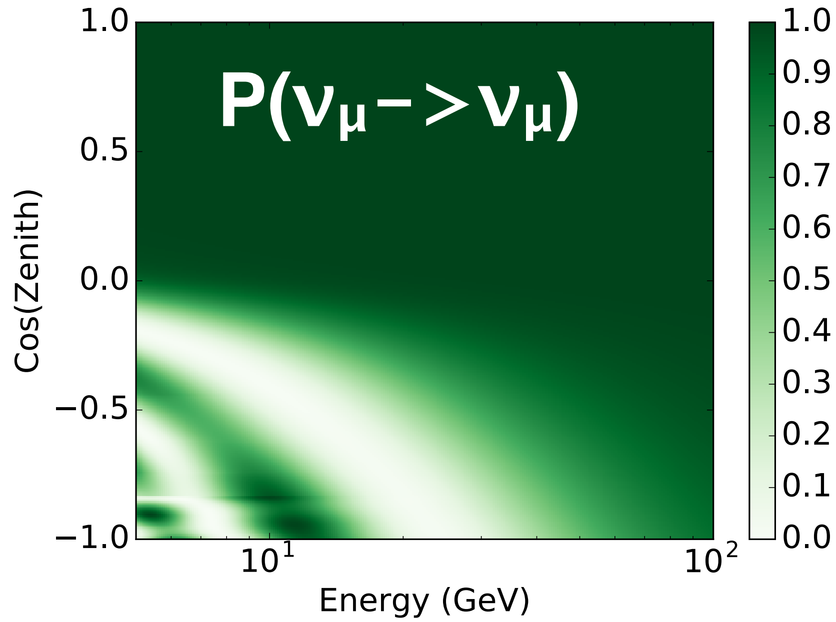
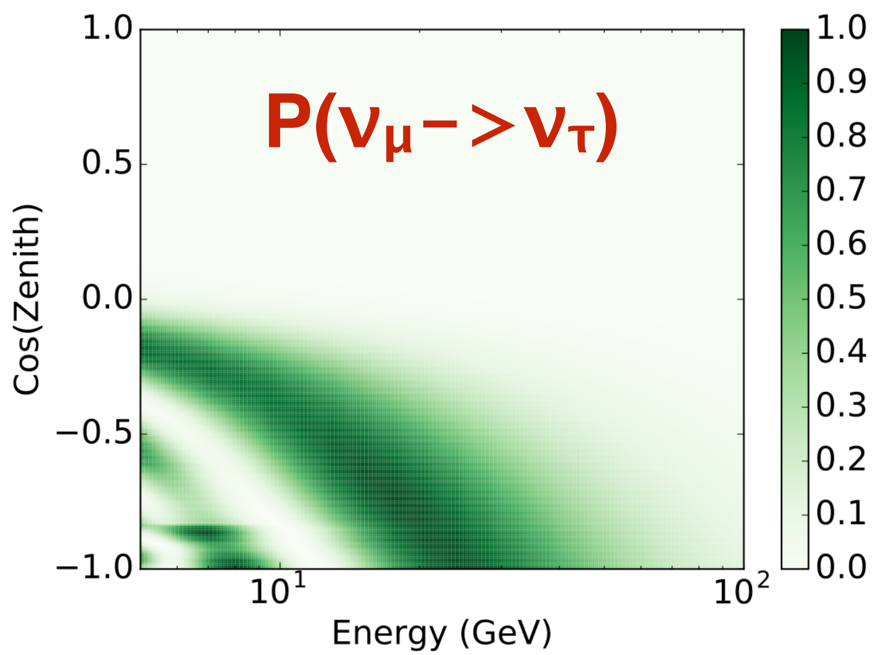
# Atmospheric Tau Neutrino Appearance

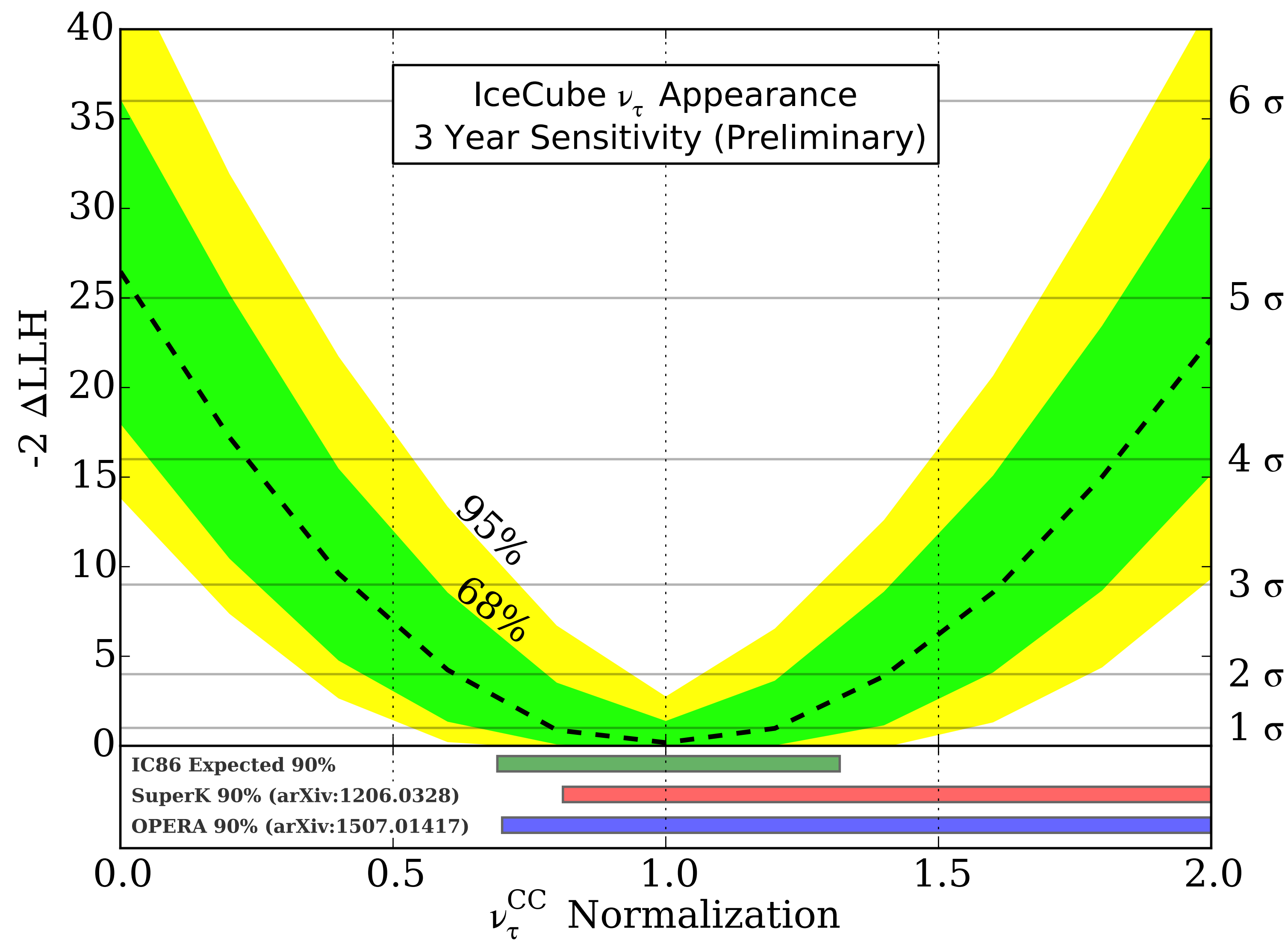
- **Measure tau appearance in terms of cascade excess**
- **High statistics sample**



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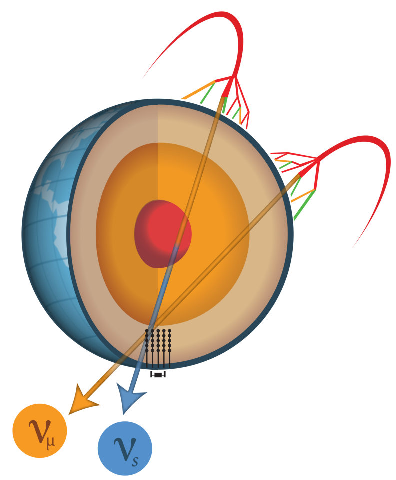
# Atmospheric Neutrinos Oscillating to Sterile Neutrinos

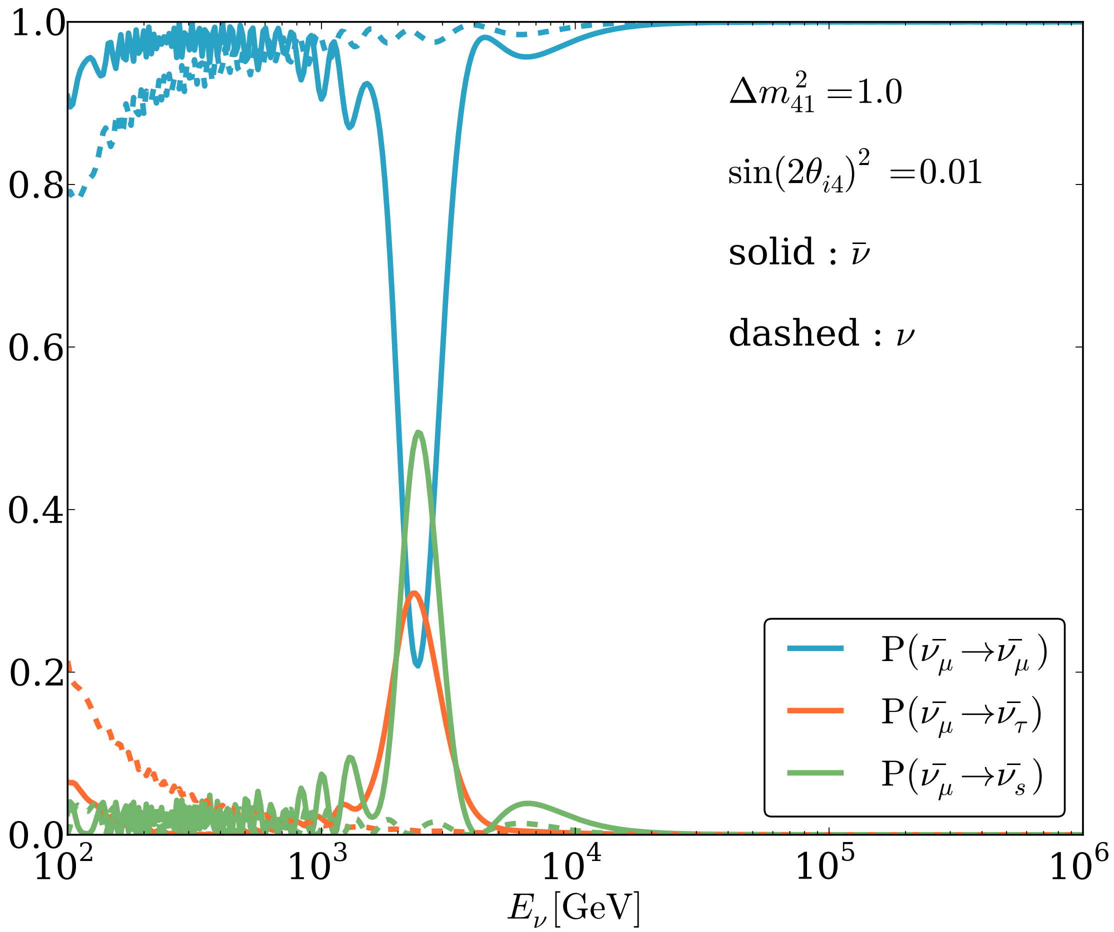
**For sterile neutrinos with**

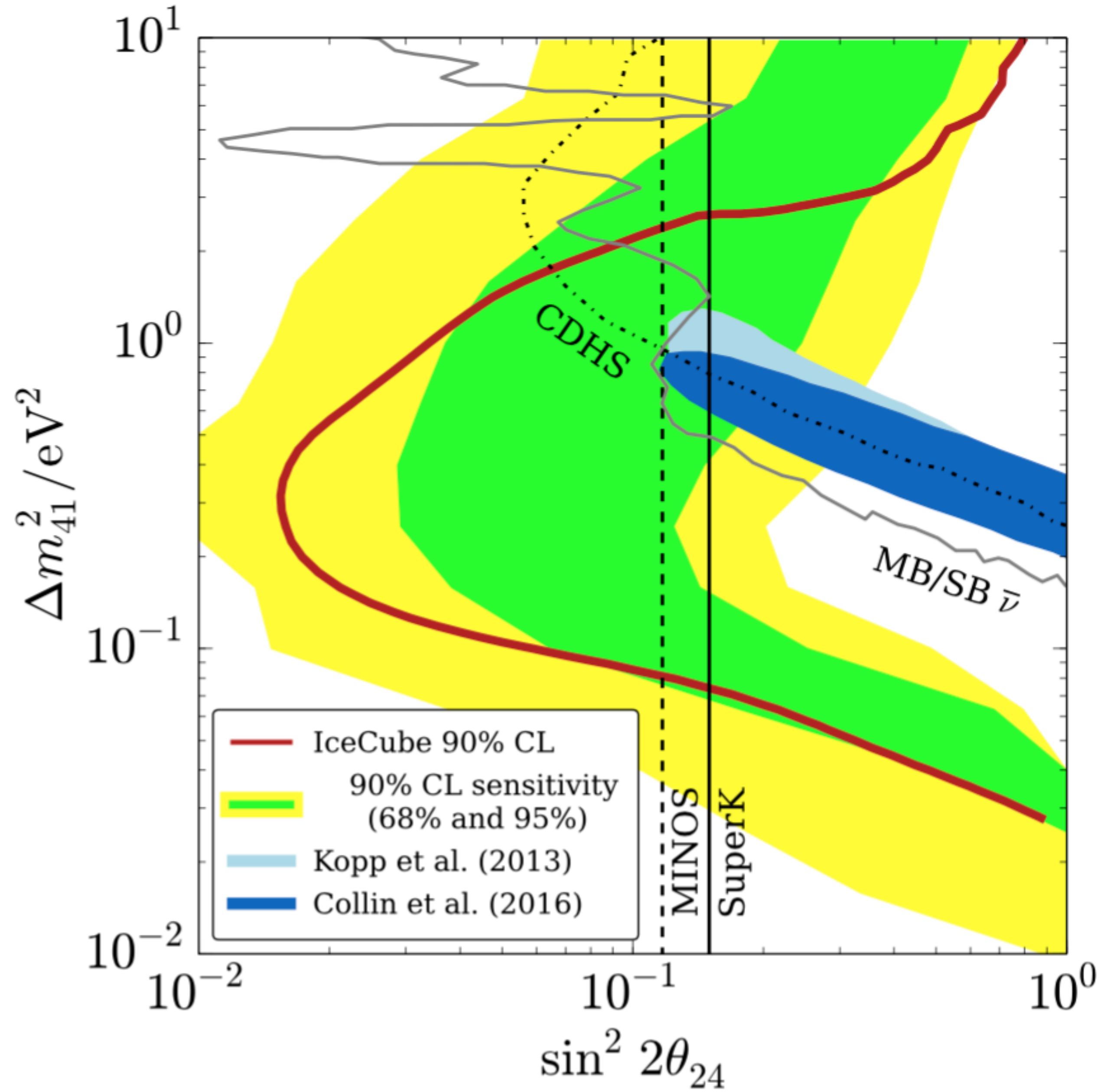
$$\Delta m^2 = O(1eV^2)$$

$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



- **~ 20,000 events in 344 days**
- **Minimal 3+1 model**
- **LSND/MB region excluded at ~ 99% CL**



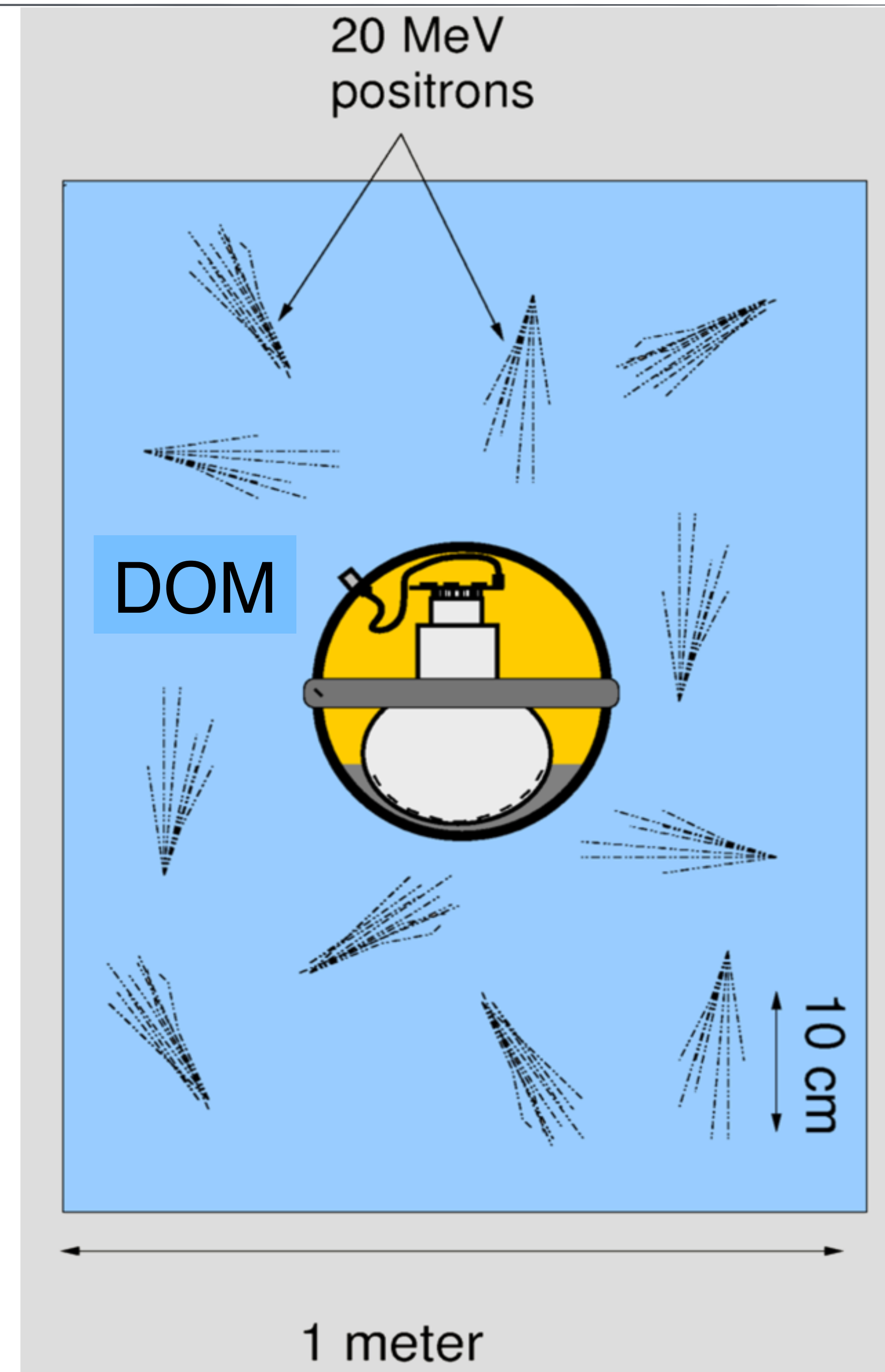




**Nunokawa et al. PLB, B562, 279 (2003). arXiv:hep-ph/0302039**

**Phys. Rev. Lett. 117, 071801**

# 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




B. Riedel

**Supernova rate in the Galaxy: 3±2 per century**



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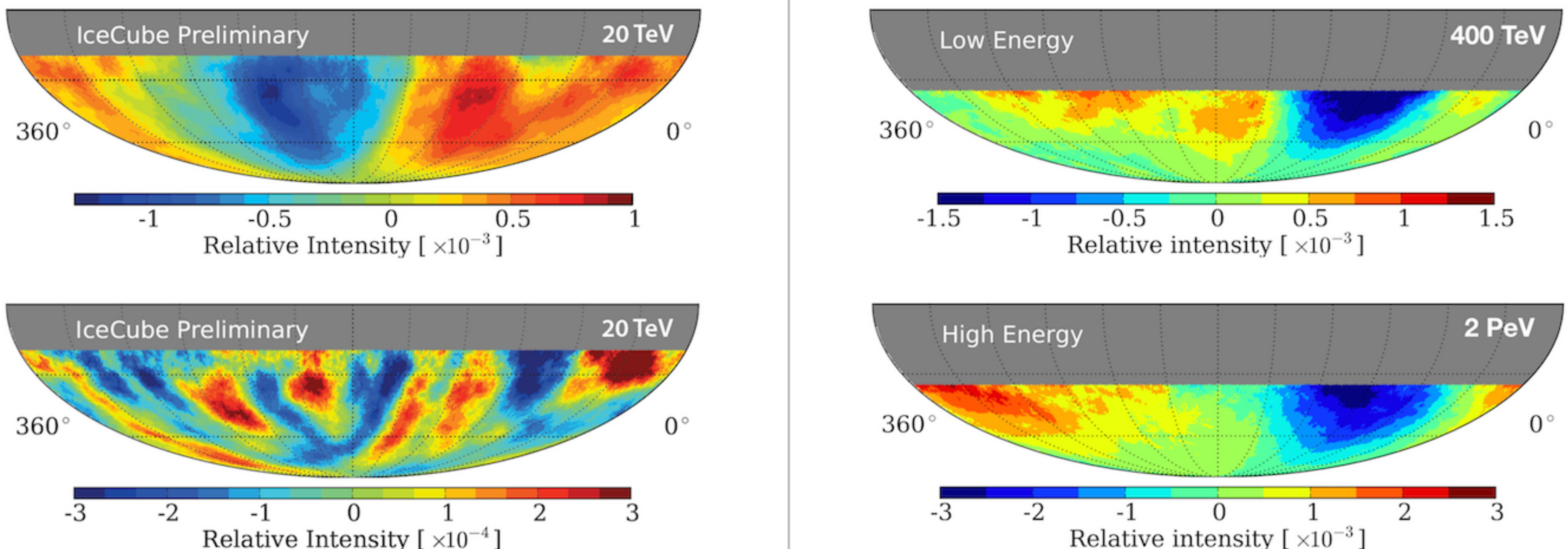
# Cosmic Rays: IceTop + IceCube

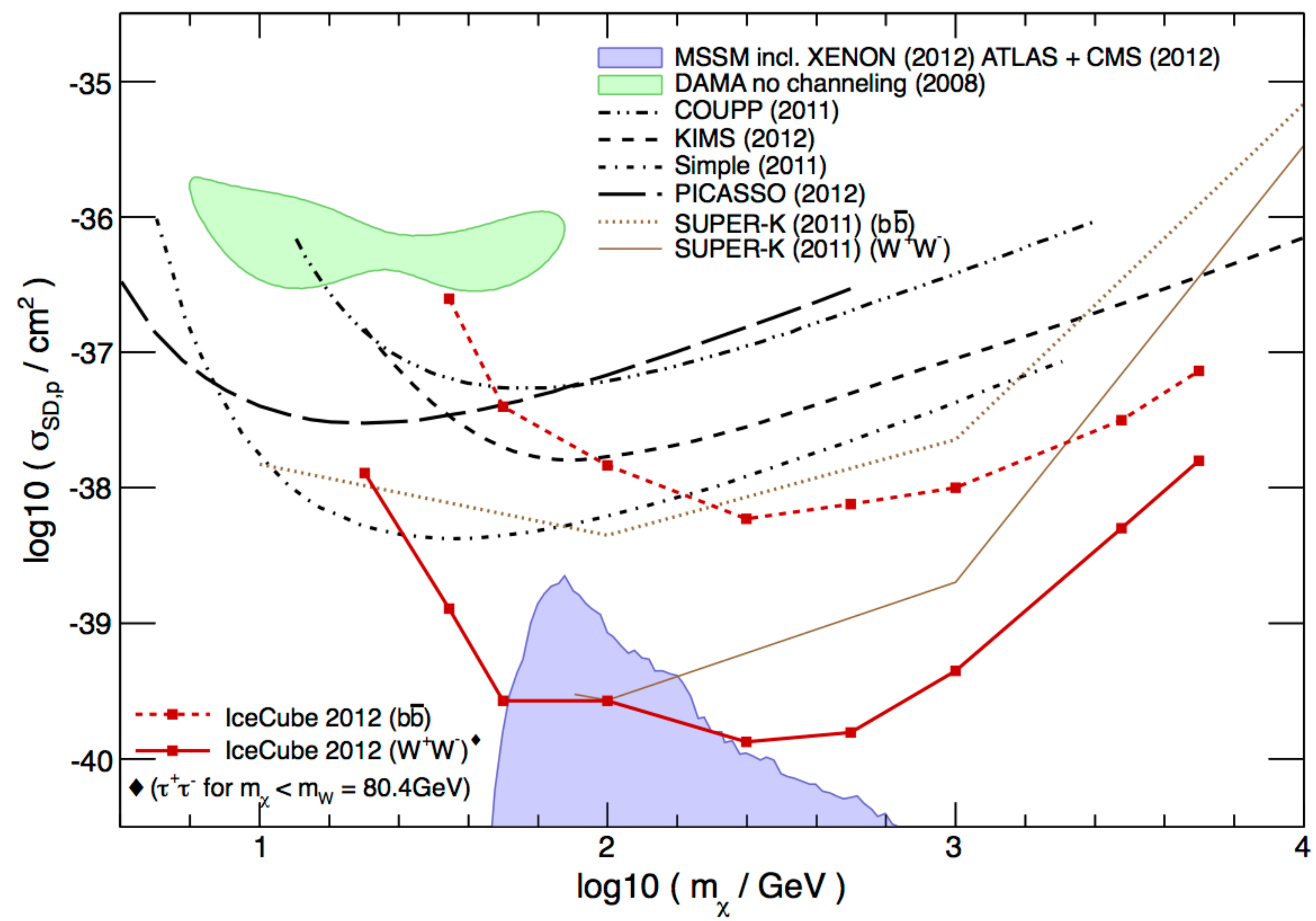





IceTop: Cosmic-ray anisotropy ($10^{-3}$) in the southern hemisphere

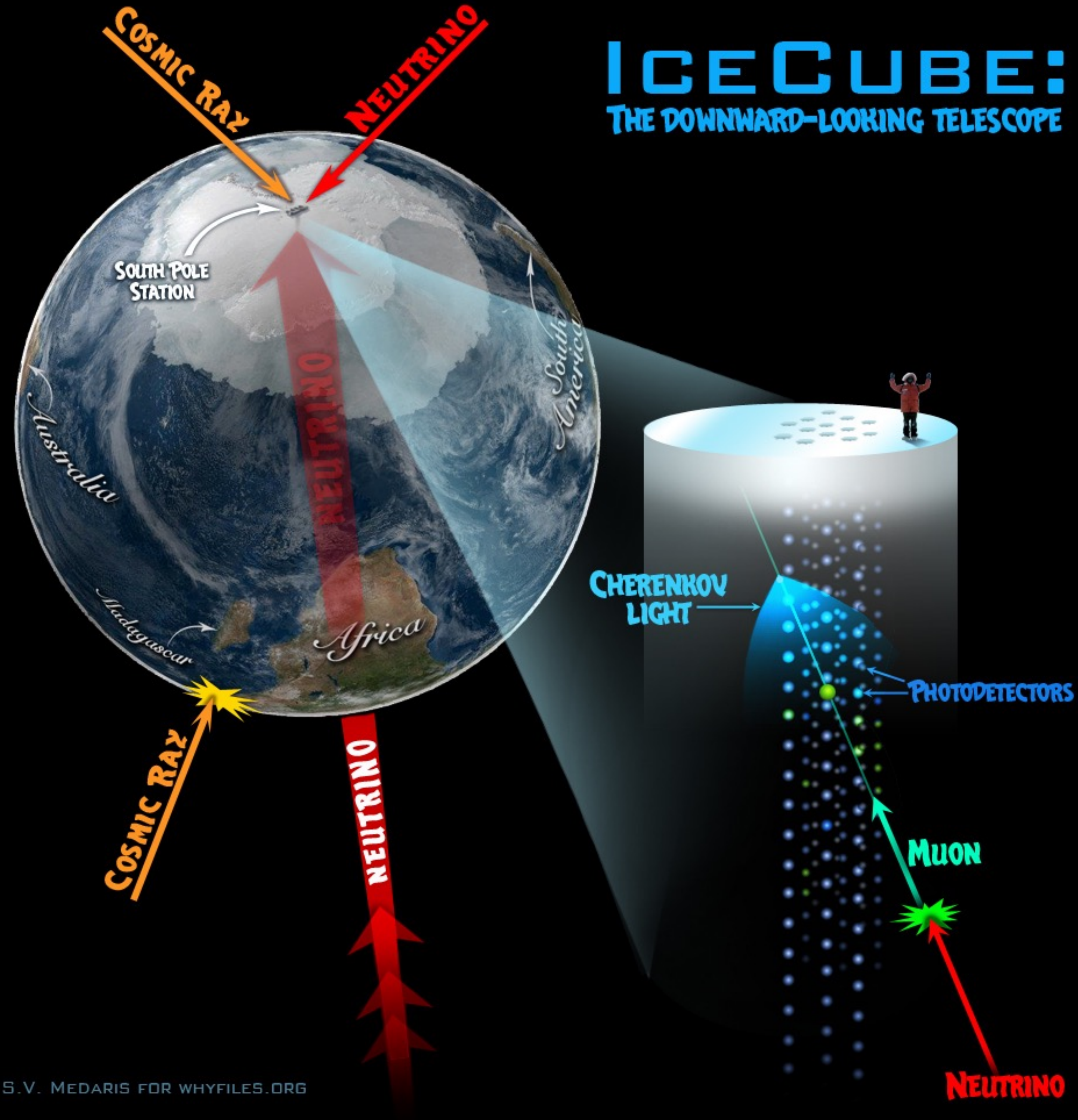
<u>IceTop+IceCube:</u> chemical composition
<u>IceTop:</u> all-particle cosmic ray energy spectrum in PeV - EeV

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



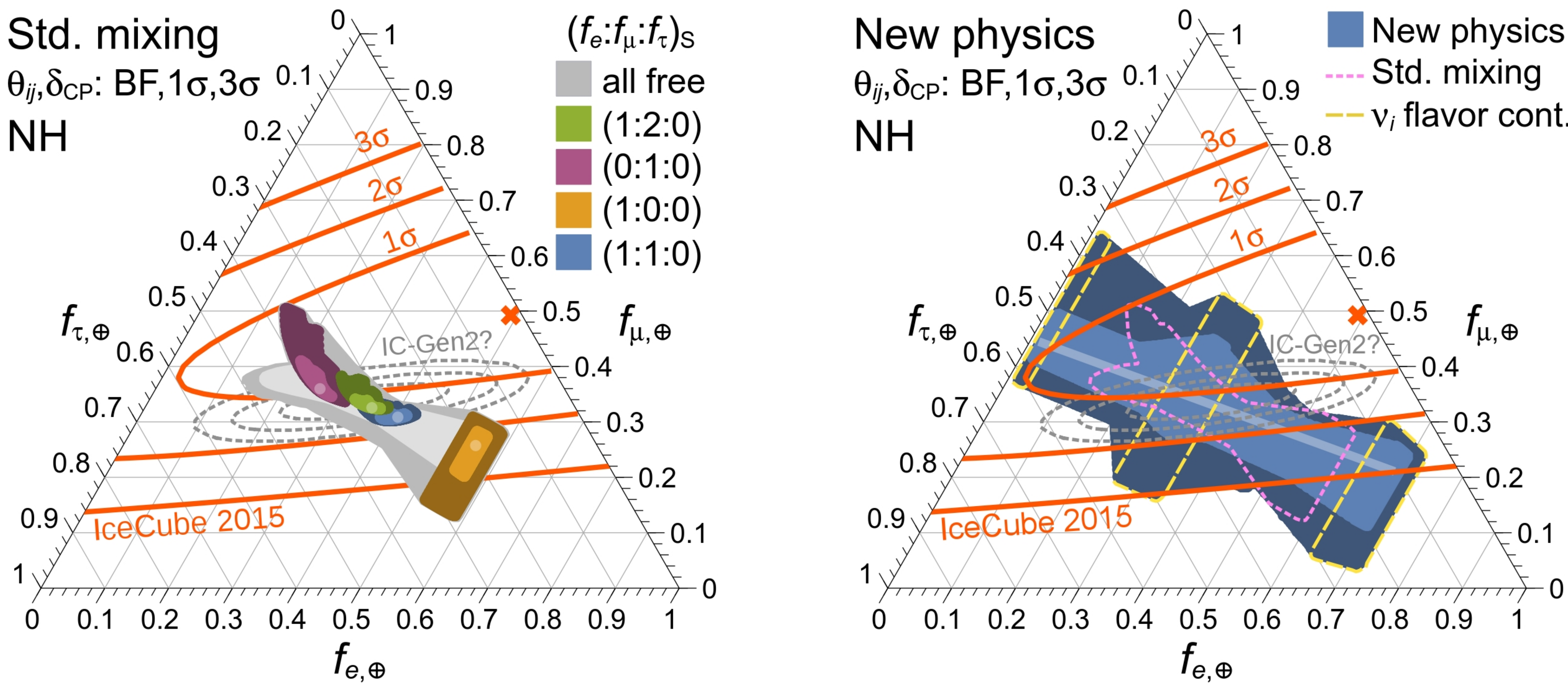

World's best limits on WIMP's **spin-dependent** cross sections

# Backup Slides


IceCube:
The downward-looking telescope
Cosmic Ray
Neutrino
South Pole Station
Neutrino
South America
Australia
Madagascar
Africa
Cosmic Ray
Neutrino
Cherenkov light
Photodetectors
Muon
Neutrino
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).