Pre Thesis Defense Seminar
December 14, 2015

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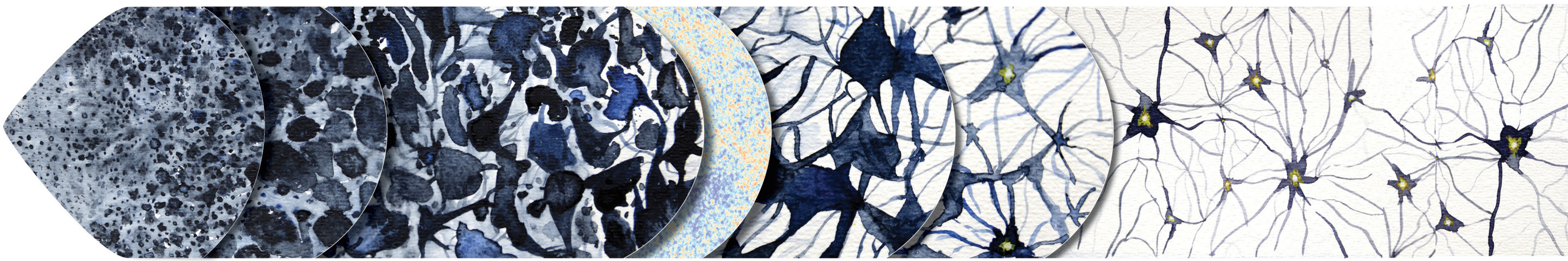
Public Defense December 18, Polhemsalen 13:15
Opponent: Prof. Lawrence R. Sulak, Boston University

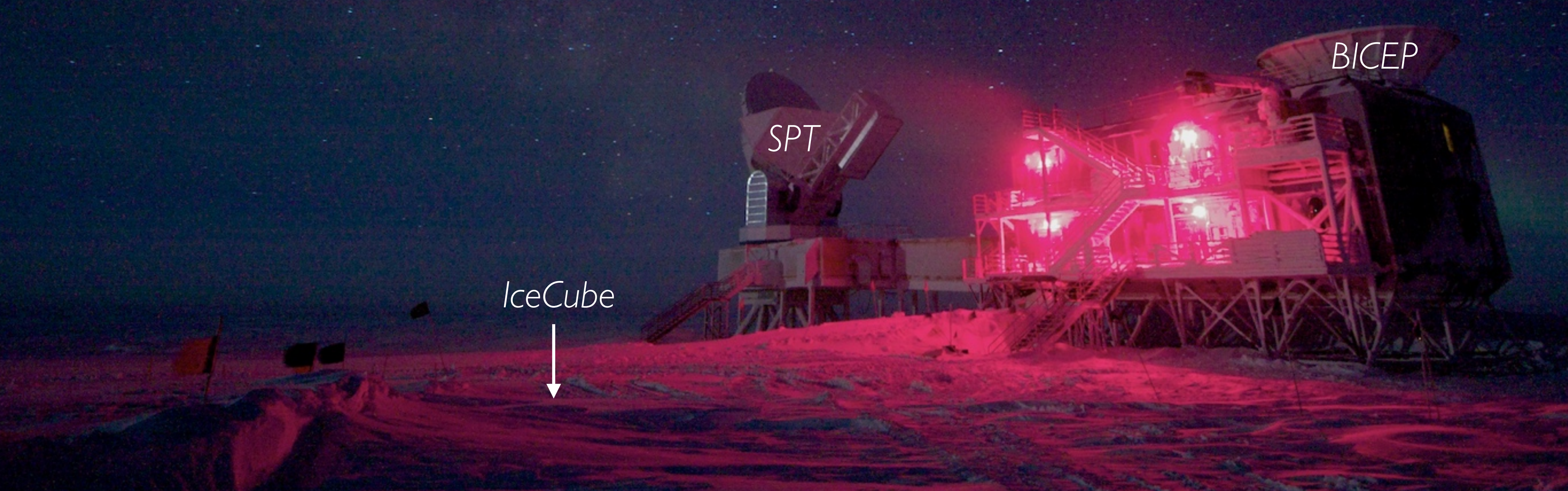


Exploring the Universe Using Neutrinos

A Search for Point Sources in the Southern Hemisphere Using the IceCube Neutrino Observatory

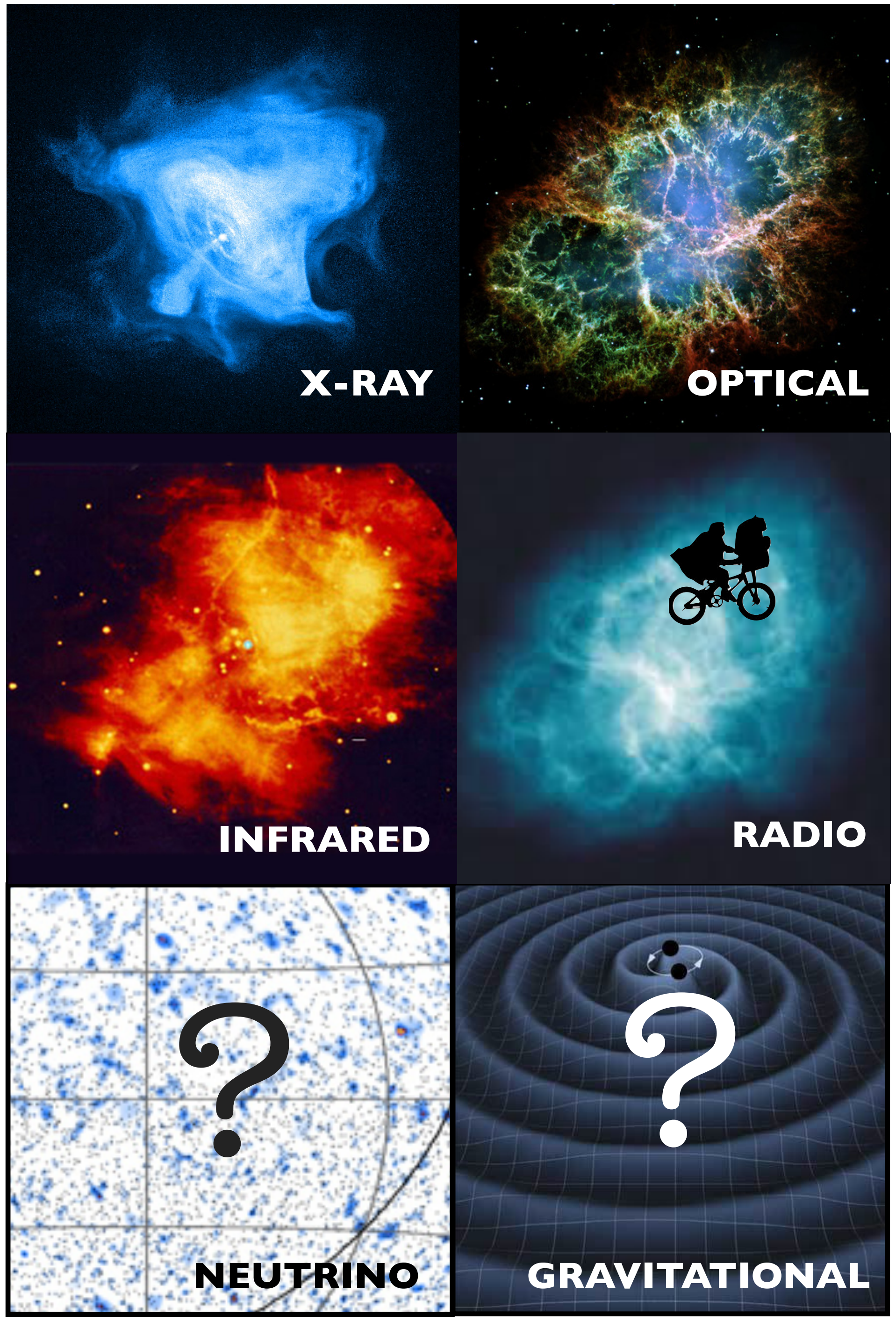
Outline

- Multi-Messenger Astronomy
- The IceCube Neutrino Observatory
- Point Source Searches in IceCube
- Low-Energy Searches
- Search for Clustering of Neutrino Candidate Events
- Conclusions & Summary



Multi-Messenger Astronomy

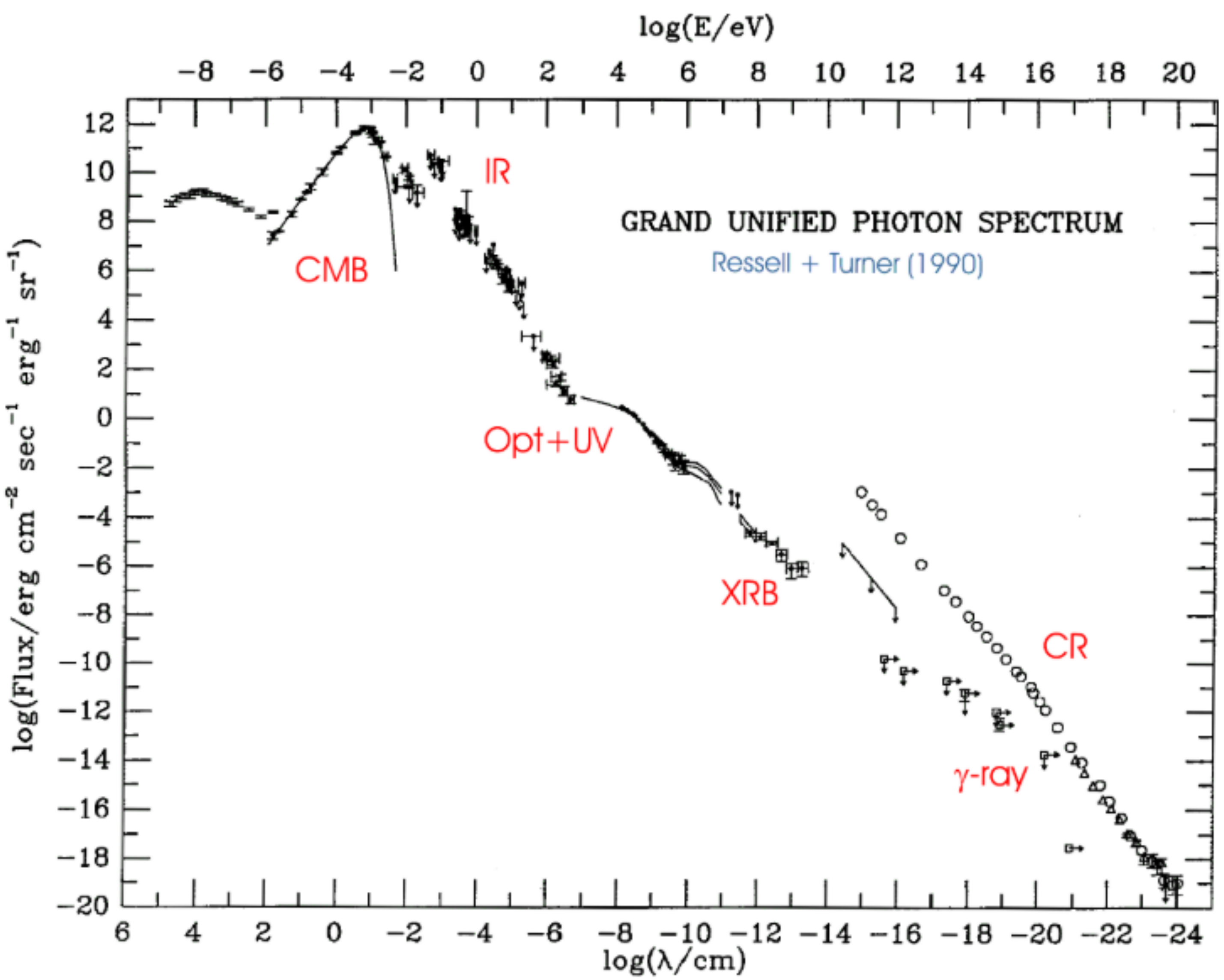
Crab Nebula (NH source), Supernova Remnant,
Bright supernova observed by Chinese astronomers in 1054.



- What's out there? Historically - Telescopes in the optical regime.
- Now - Photons (radio-to-gamma), Cosmic-Rays, Neutrinos.
- Future - gravitational waves.
- Combining these powerful tools enables us to further explore the Universe.

- Point Source: Object with localized radiation ➜ Neutrino "Stars"

Light in the Universe

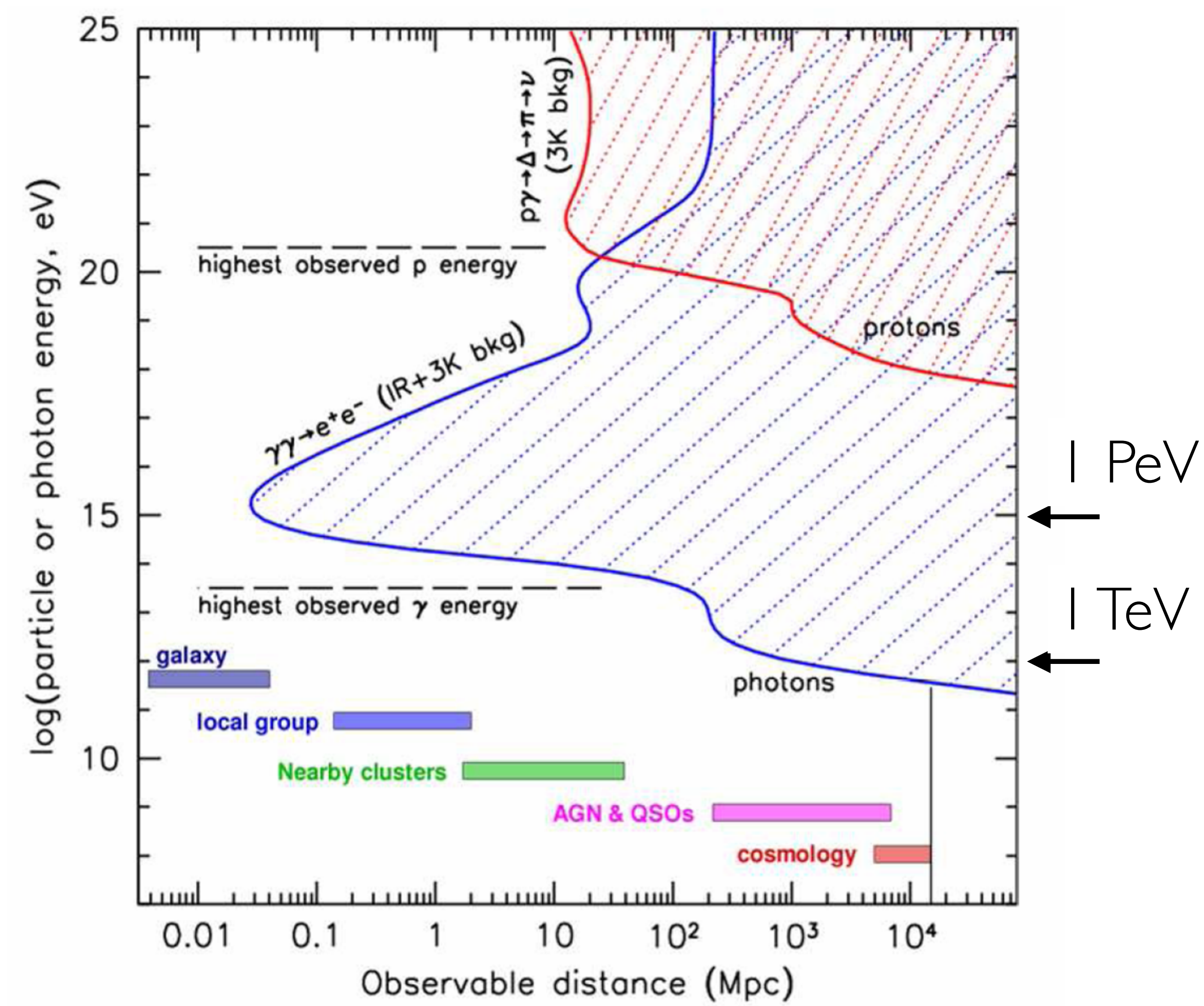


- Extraordinary particle accelerators needed.
- Different mechanisms likely at work for different energies.
- What is the connection?
- **Cosmic-rays** interact with matter and photons near source:
  ➜ γ**-rays**, **neutrinos**
- Production/Acceleration
- Uncharted territory,
- Extremely dense regions,
- Dark Matter, etc.

Why Neutrinos?

- Cosmic rays directions scrambled,
- Photons absorbed above PeV,

- Neutrinos are the ideal messenger,
  - electrically neutral,
  - essentially massless,
  - essentially unabsorbed,
  - but extremely challenging to detect
  - need very large detectors



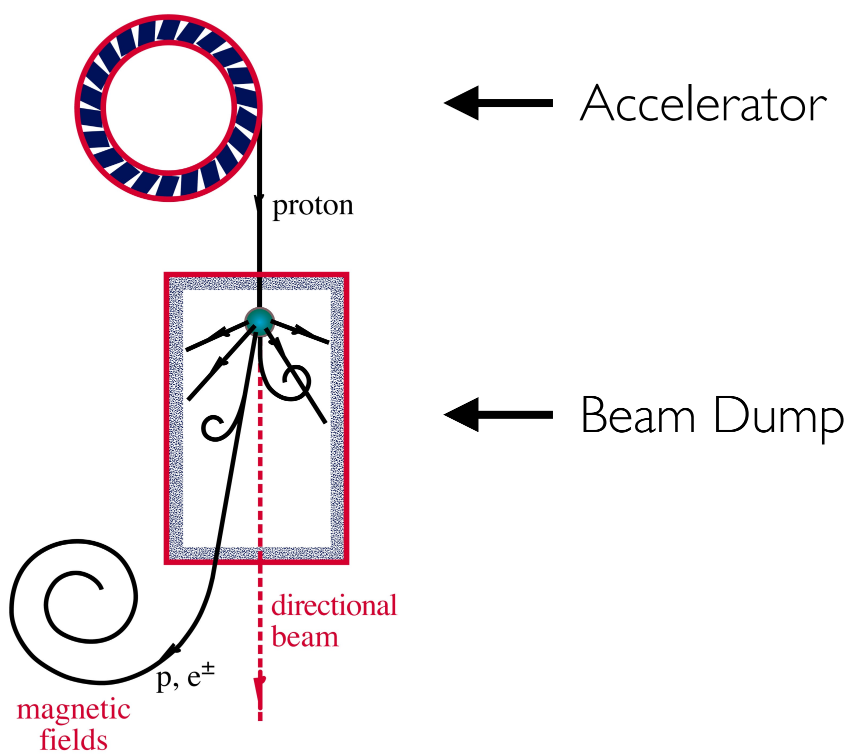
IMB detector (USA): "In 1987, it gained fame for detecting 8 of the roughly 10^{58} neutrinos emitted by Supernova 1987A"

Sources of High-Energy Cosmic Rays

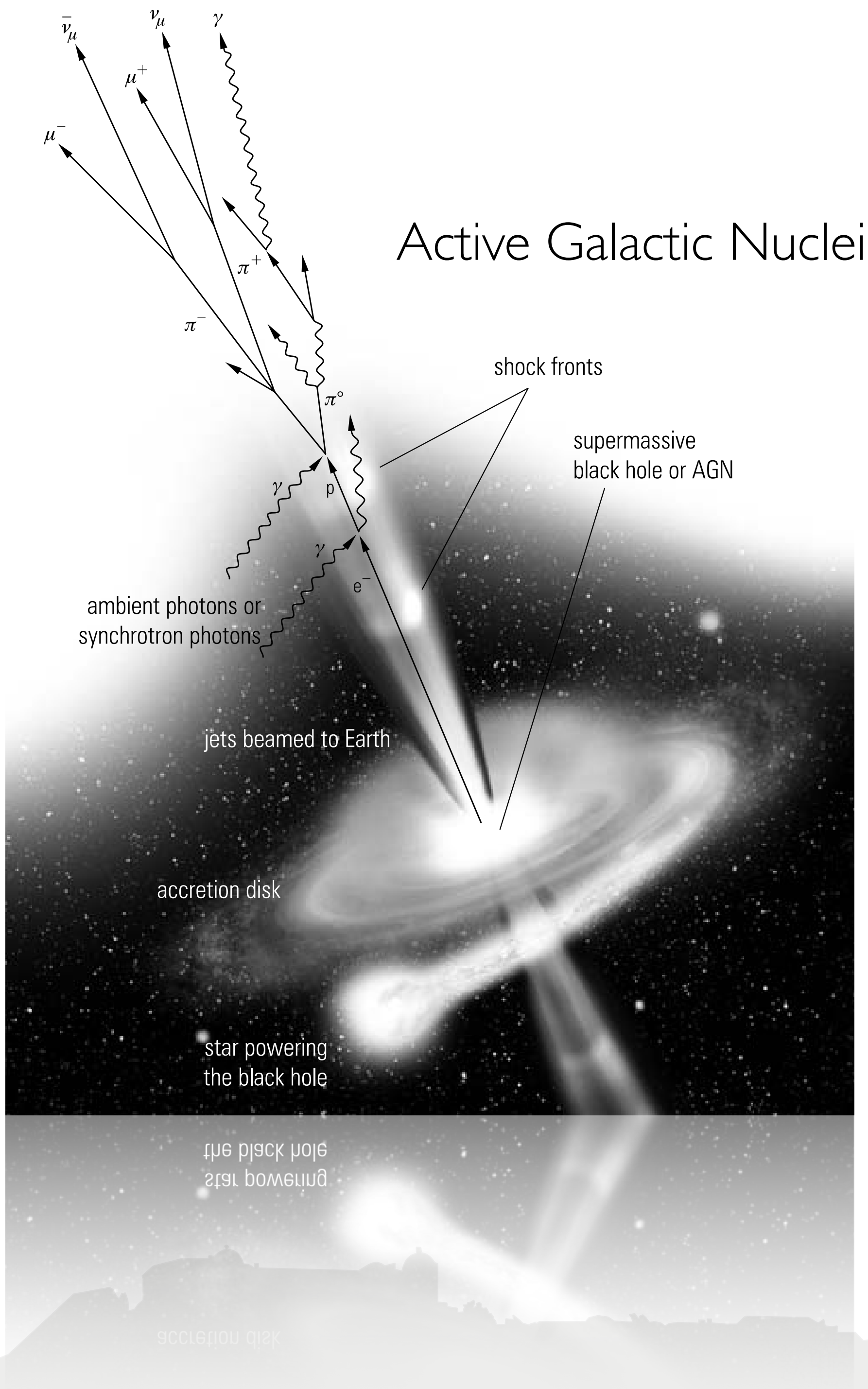
- Production in jets and accretion disk of Active Galactic Nuclei, etc,
- Production at ”beam dump” sites, where accelerated material interact with gas, radiation,
- Hadronic or Leptonic?

$$p + \gamma \to \Delta^+ \to n(p) + \pi^+(\pi^0) \qquad \pi^+ \to \mu^+ + \nu_\mu$$

$$p + p \to p + n(p) + \pi^+(\pi^0) \qquad \pi^0 \to 2\gamma$$

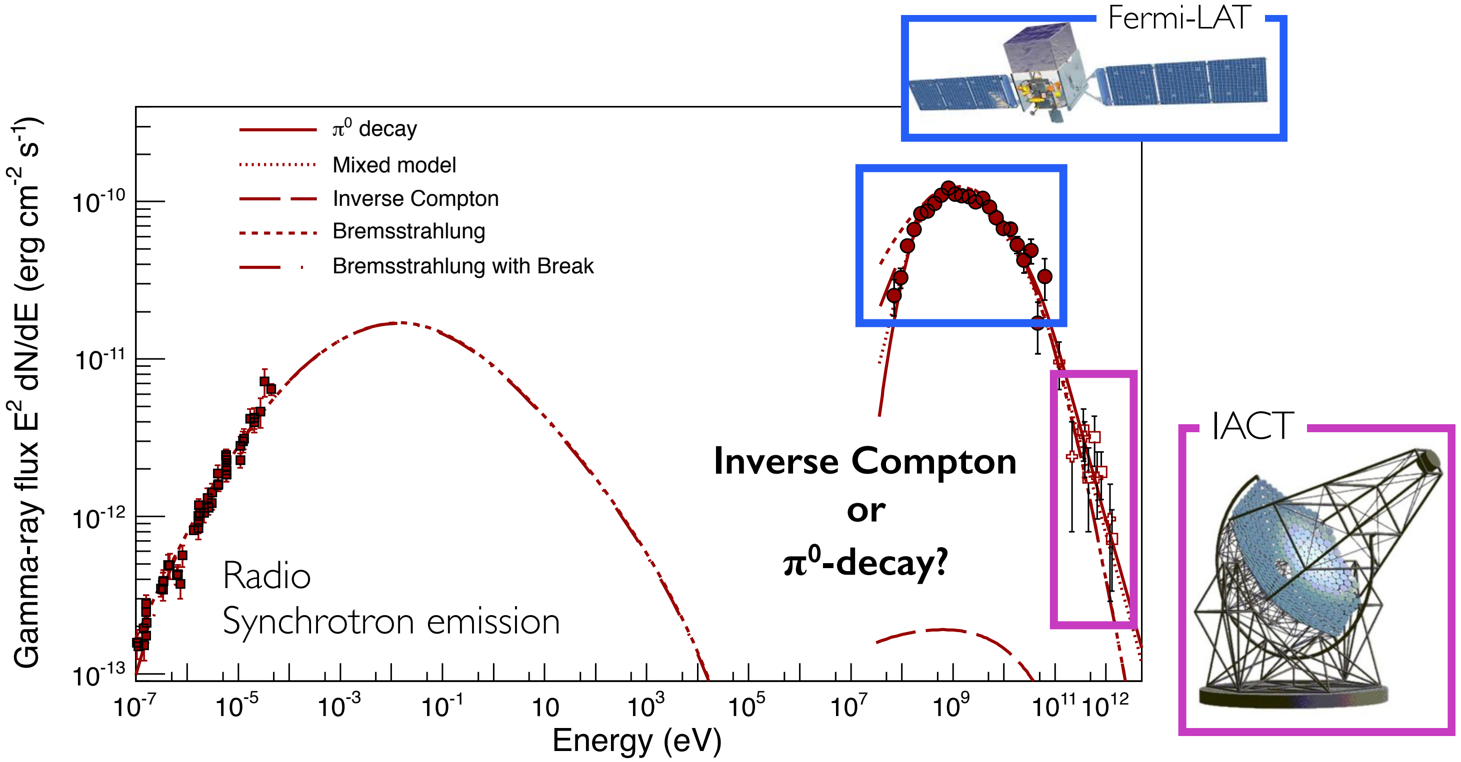


Hadronic or Leptonic?

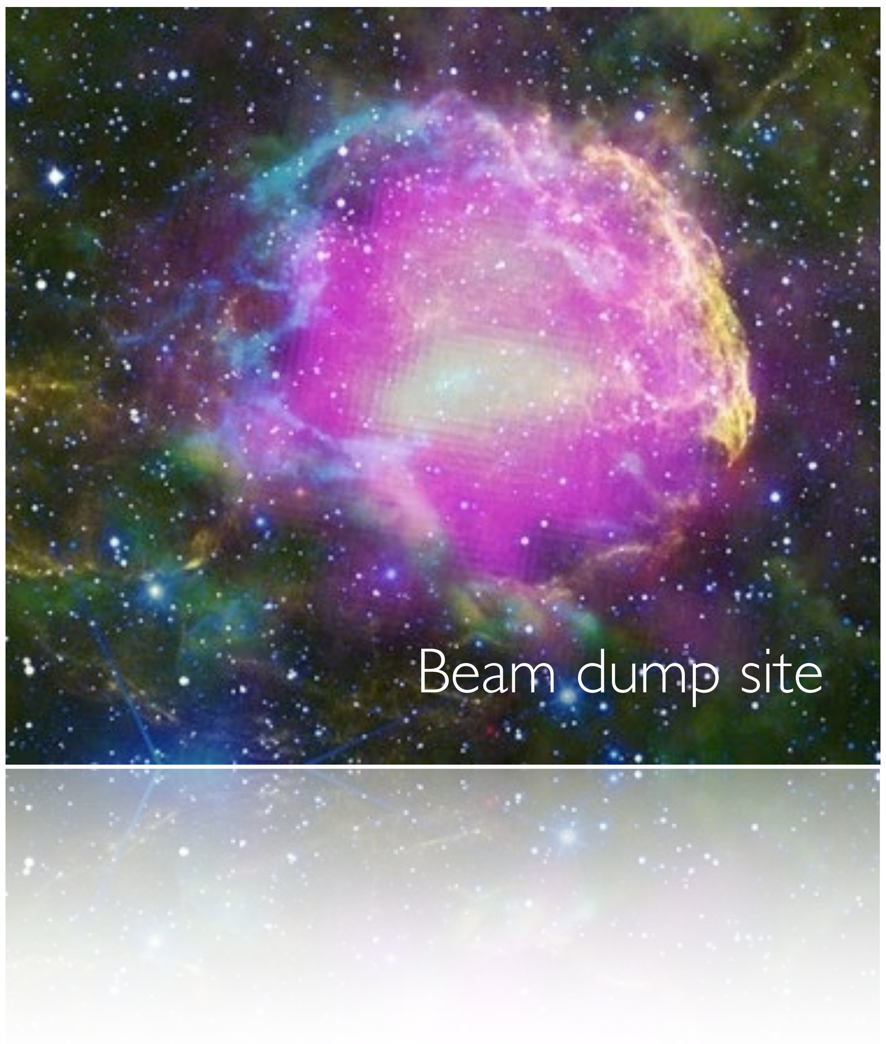


Hadronic Acceleration

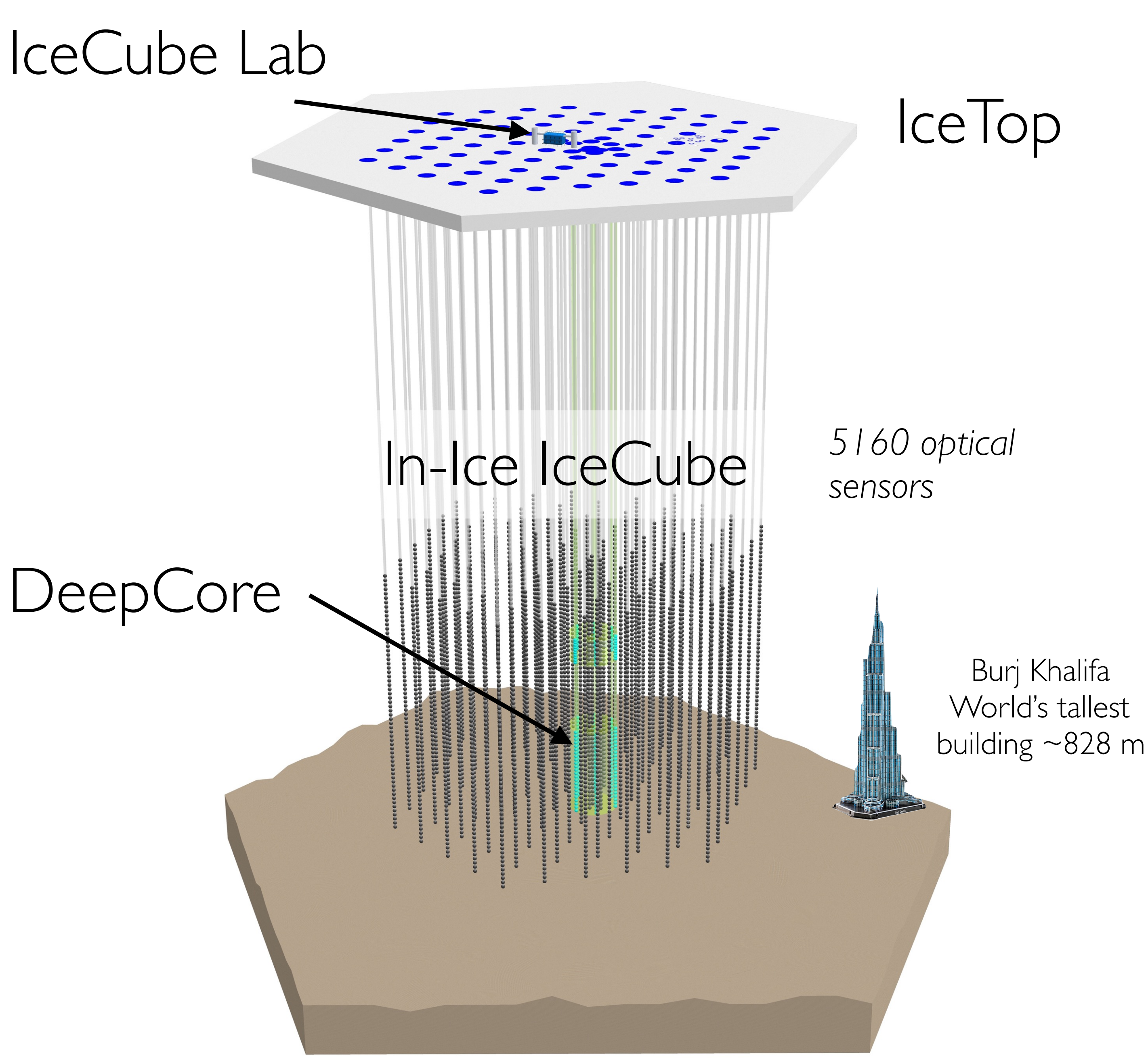
- Can we identify the source of the high-energy cosmic-rays?
- Hadronic vs. Leptonic
- Fermi-LAT - Proof for hadronic acceleration in IC 443, etc. (point source),
- Potential site for neutrino production.



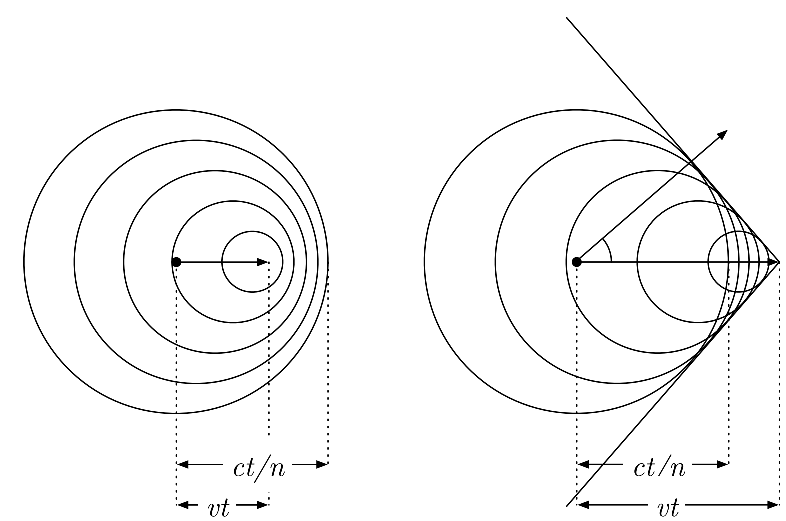
SNR IC 443 'Jellyfish Nebula' (NH)
Embedded in a molecular cloud



The IceCube Neutrino Observatory

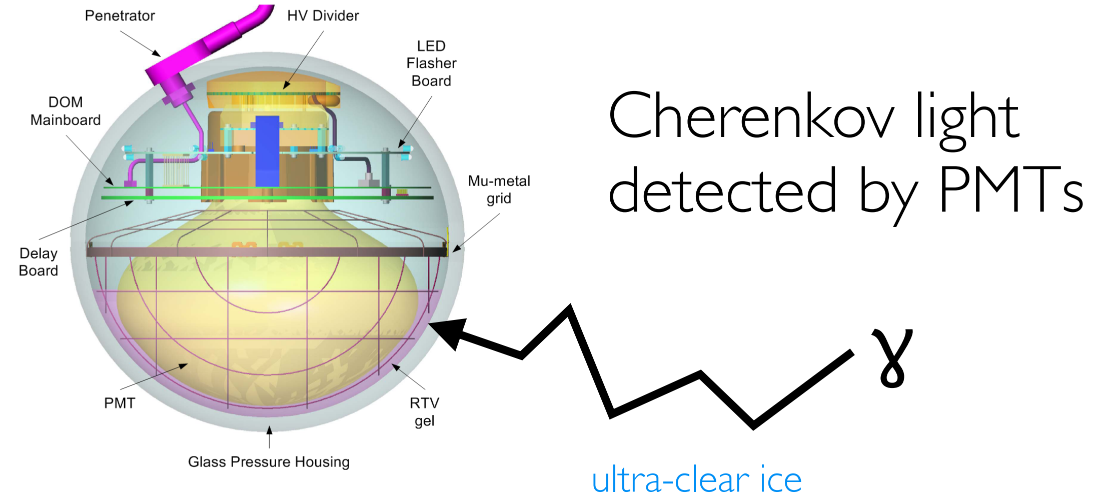


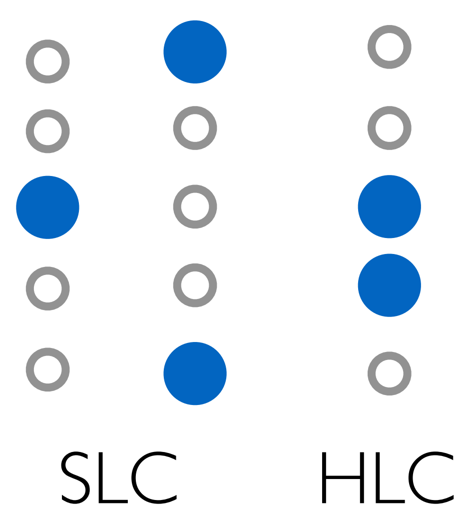
- IceCube is a cubic-kilometer sized detector,
- Located in the ice cap at the South Pole, Antarctica,
- Monitors over 1 billion tons of ultra-clear glacial ice,
- Operates in 4**π** mode,
- Detects Cherenkov radiation of neutrino induced charged particles traversing the ice.



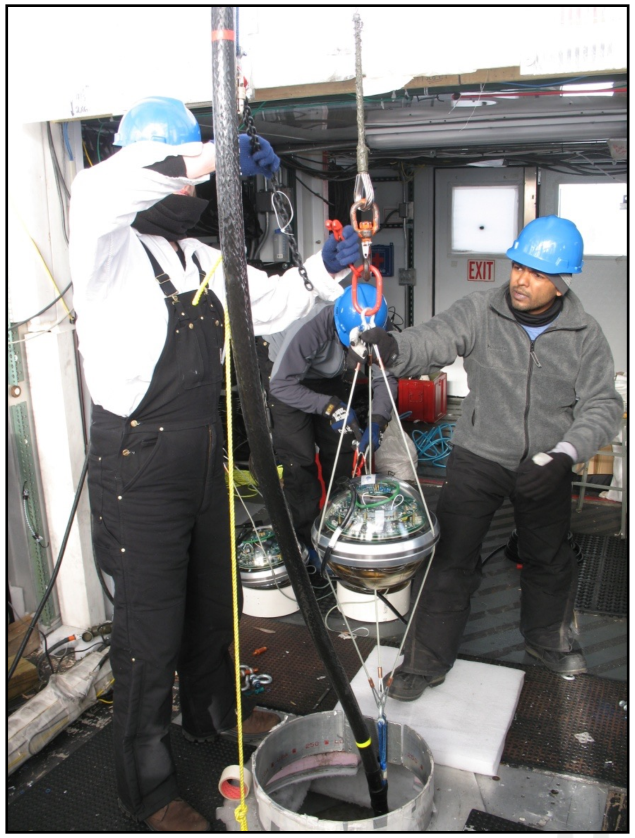
Optical Sensor - Digital Optical Module

- DOM - Digital Optical Module,
- PMT, digitizing electronics, calibration LEDs,
- 13 mm pressure-resistant glass sphere,
- 25 cm HAMAMATSU PMT,
- Amplification of 10^7,
- Noise rate ~650 Hz,
- Trigger based on local coincidence.





HLC (Hard Local Coincidence) hit: two (next-to-) neighboring optical sensors both over threshold within 1 μs.



Light Picture - Event Topology

Muon Neutrino
Charge Current (CC)

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

All Neutral Current/
CC Electron Neutrino

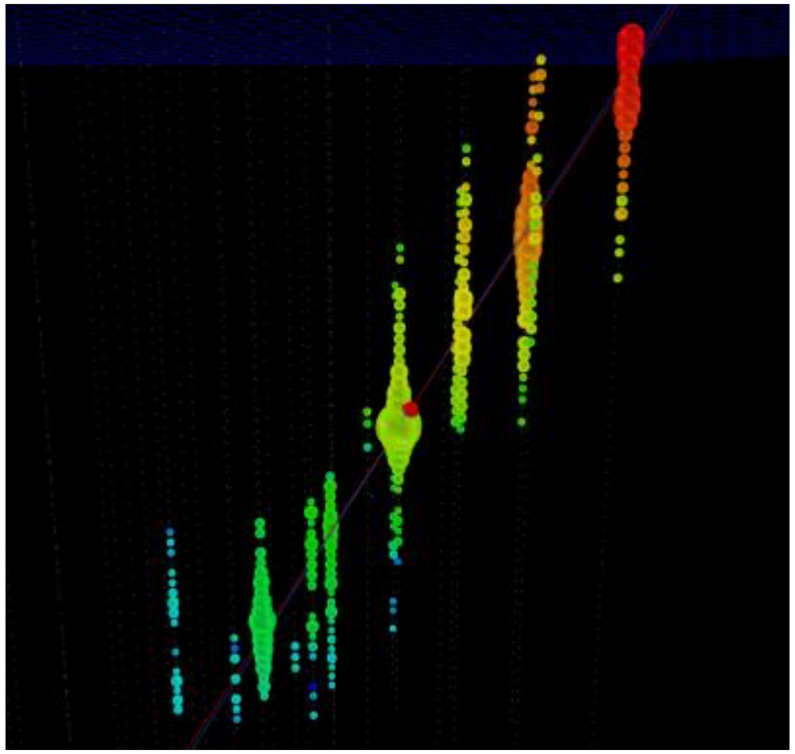
$$\nu_{\mathrm{e}} + N \rightarrow \mathrm{e} + X$$

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

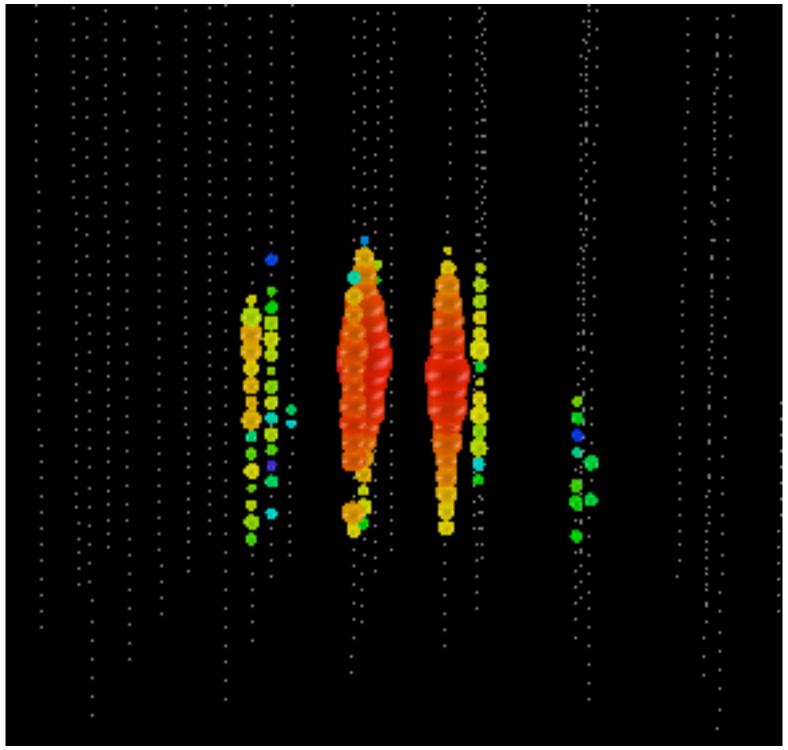
Charge Current
Tau Neutrino

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

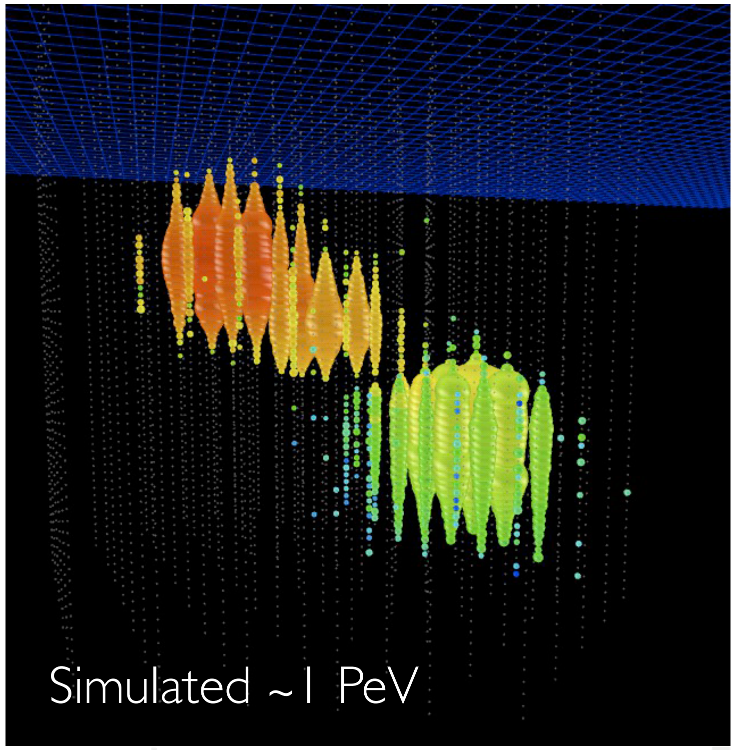
Track



Cascade

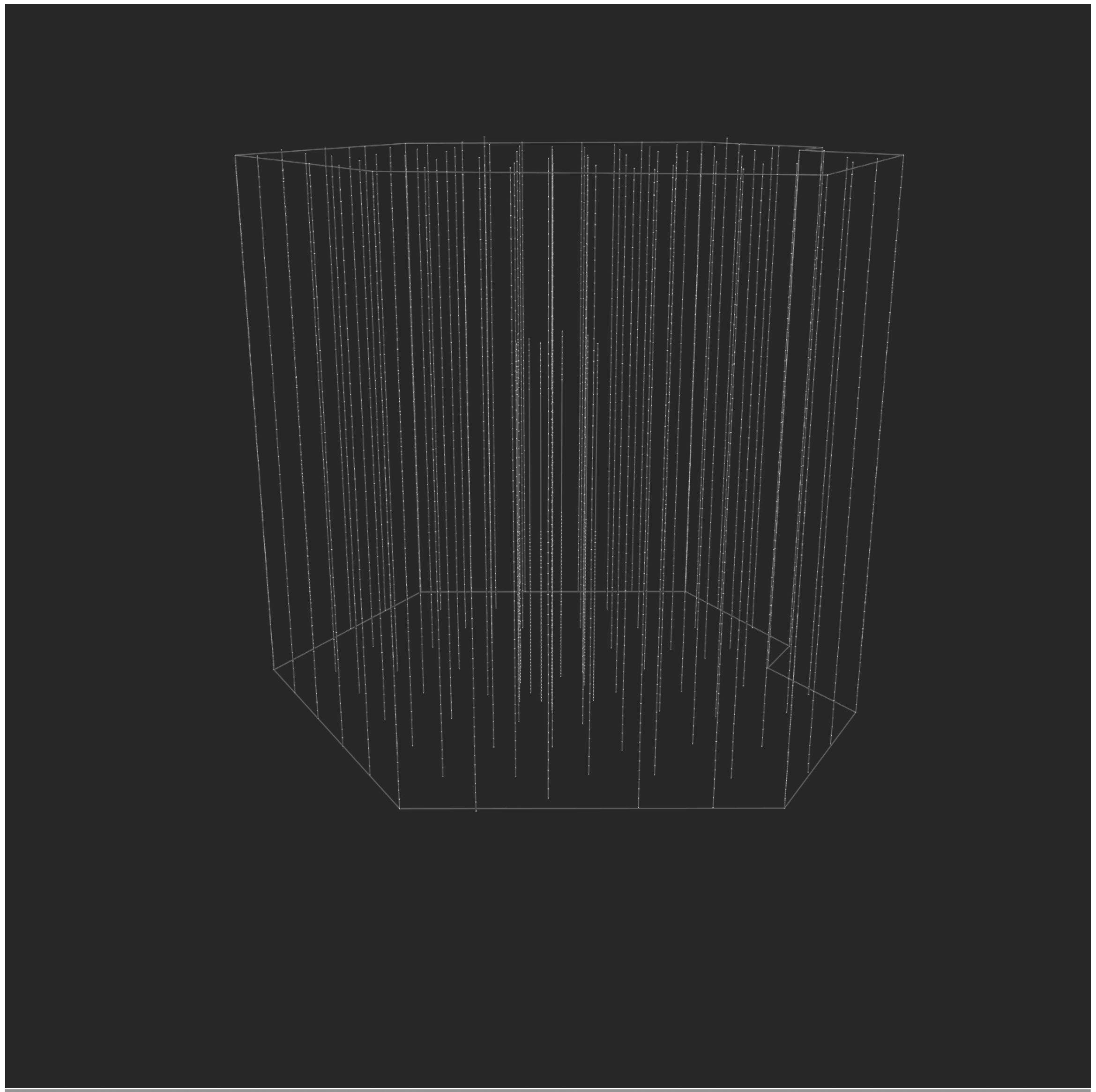


Double-Bang

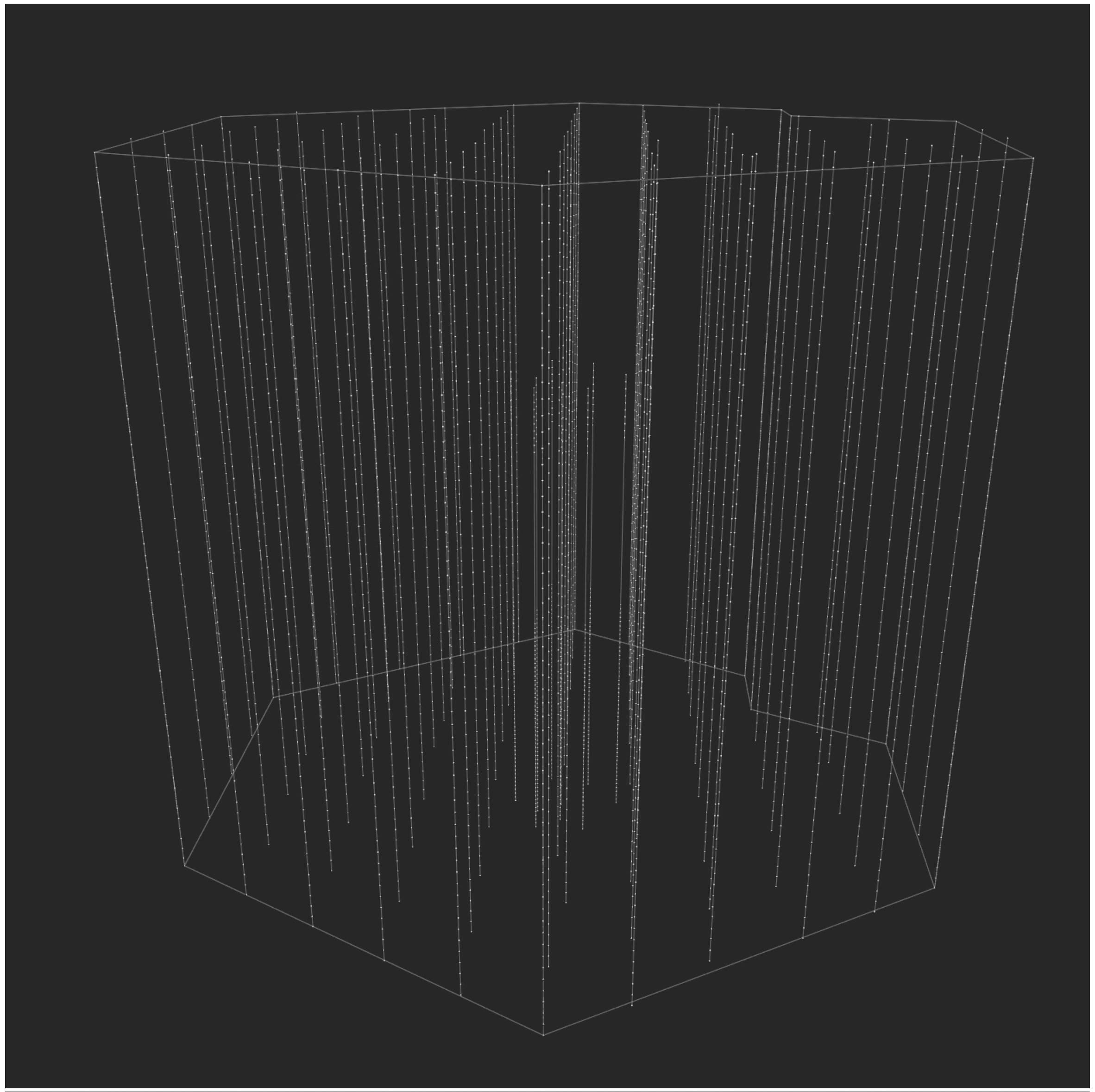


Light Picture - Event Topology

10 TeV ν_μ

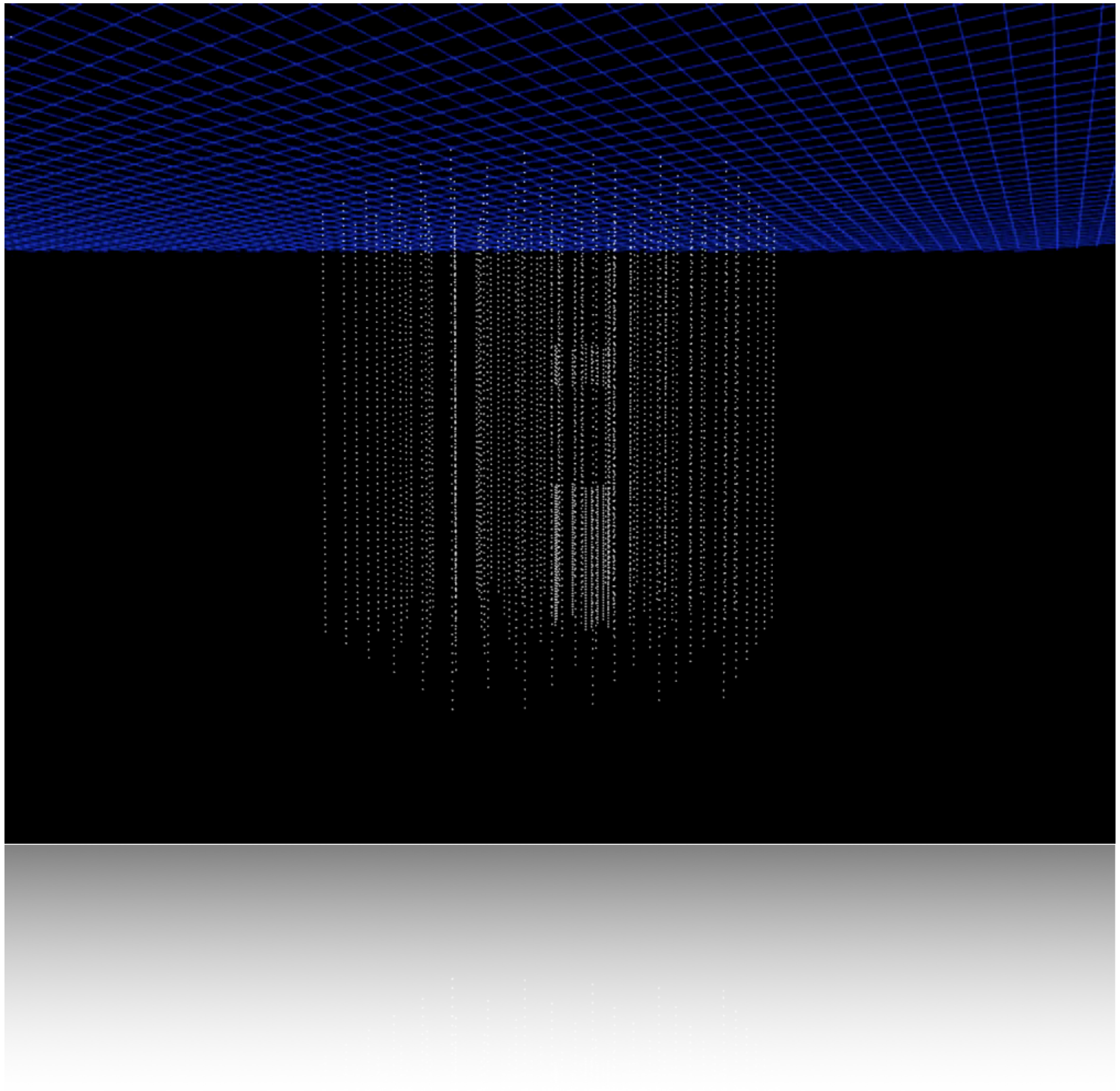


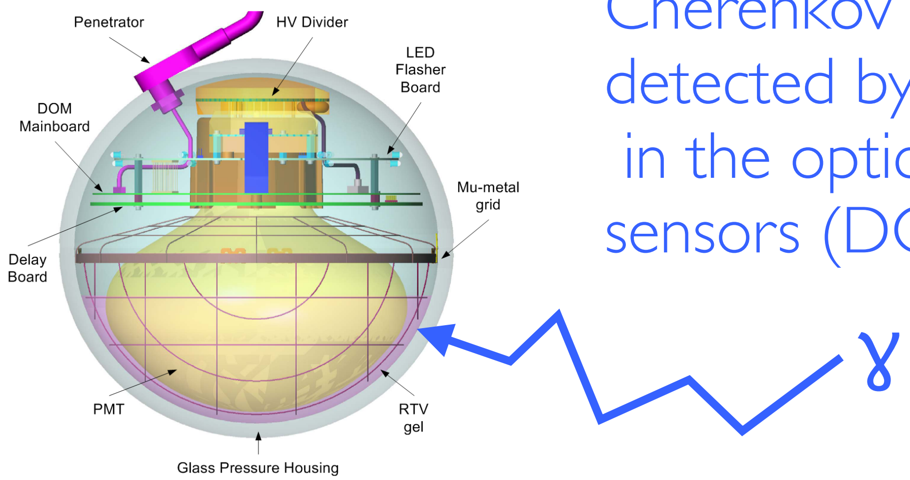
100 GeV ν_μ



Showing every 10 000th Cherenkov photon, Time ~ red ➟ purple

IceCube - Ready for Christmas?





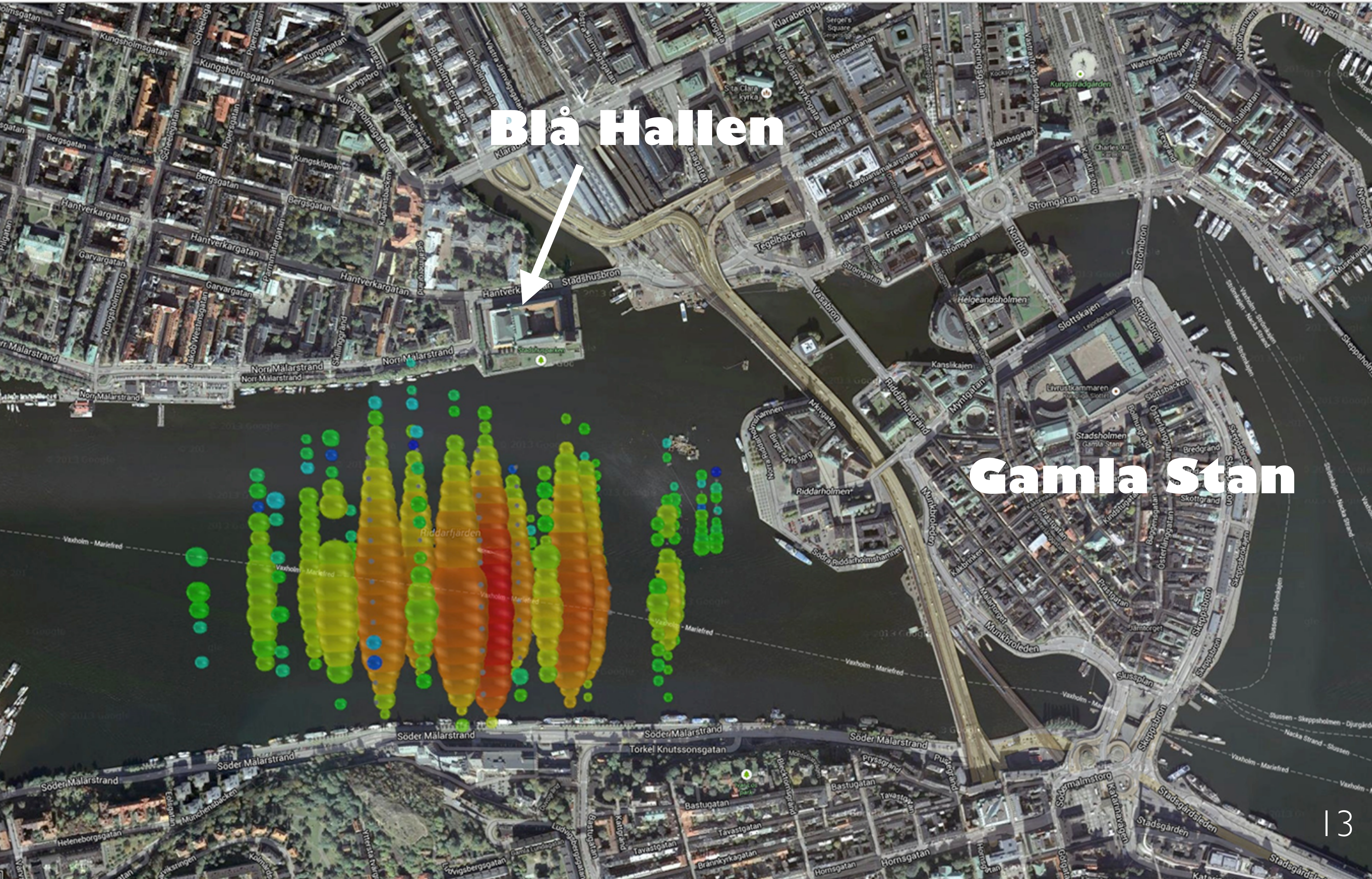
Cherenkov light detected by PMTs in the optical sensors (DOMs)

10 ms of simulated events!

Events per year:

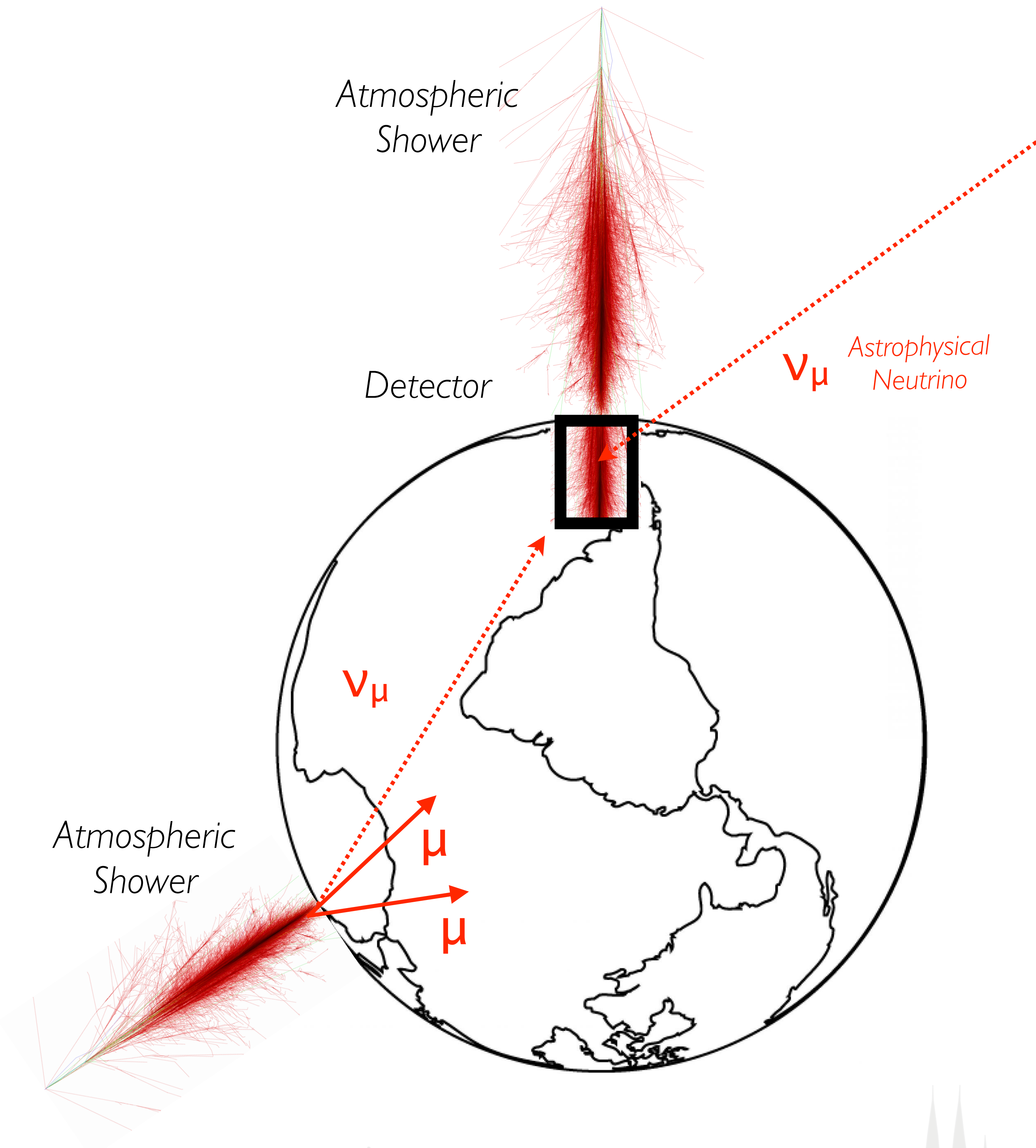
- Atmospheric muons ~10^{11}
- Atmospheric neutrinos ~ 10^5
- Astrophysical neutrinos ~ 10 *(diffuse)*

Light Picture - Event Topology

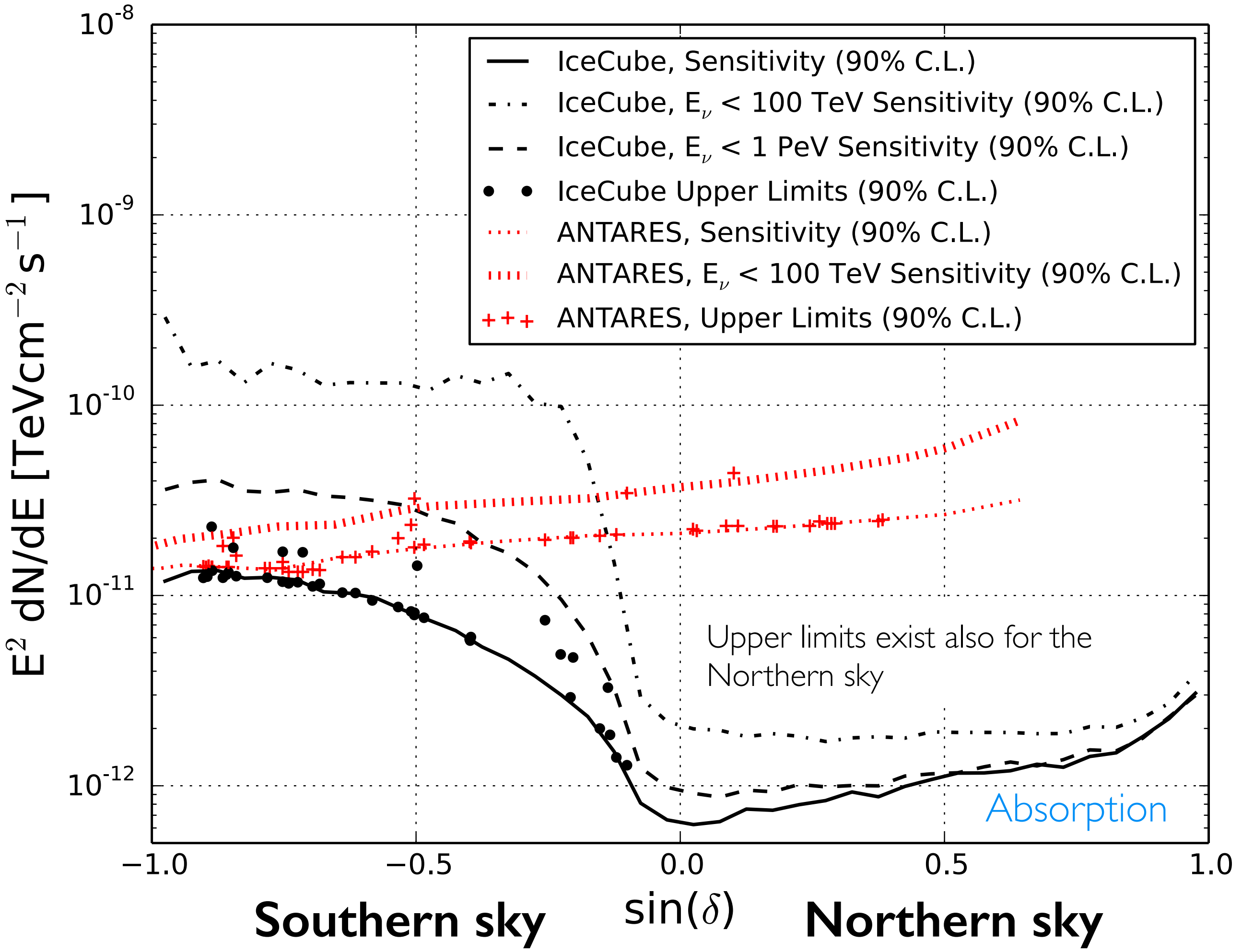


Point Source Searches in IceCube

- Standard point source searches mainly sensitive in the Northern Hemisphere,
- Studying clustering of through-going events.
- Previous Southern sky **starting** events analyses have focused on energies above 100 TeV,
- Many interesting sources in the Southern sky, potentially at low-energies below 100 TeV,
- Using advanced veto techniques, i.e. starting events: Point source sensitivity down to 100 GeV.



Point Source Searches in IceCube



- High sensitivity at the Northern sky,
- But absorption at high energy,

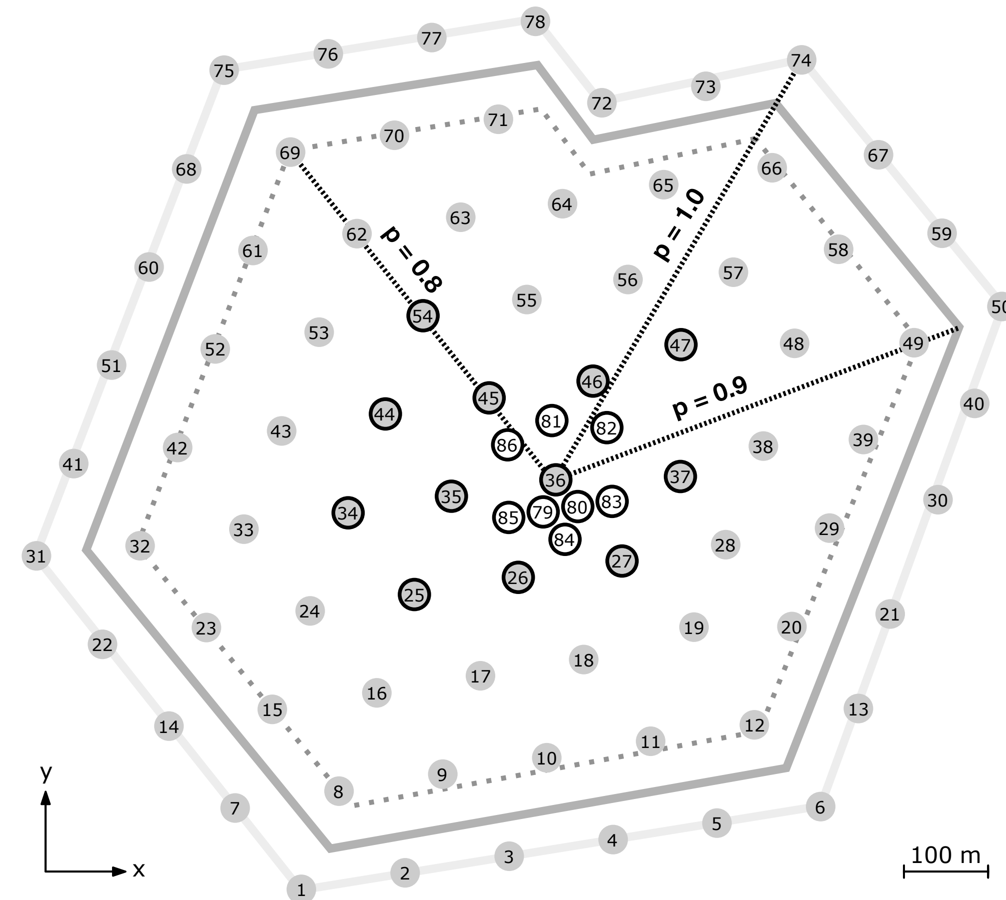
- Very high atmospheric background in the Southern sky,
- At high energy, background is low.
- What can we do for even lower energies in the Southern sky?

Low-Energy Searches

LESE Analysis

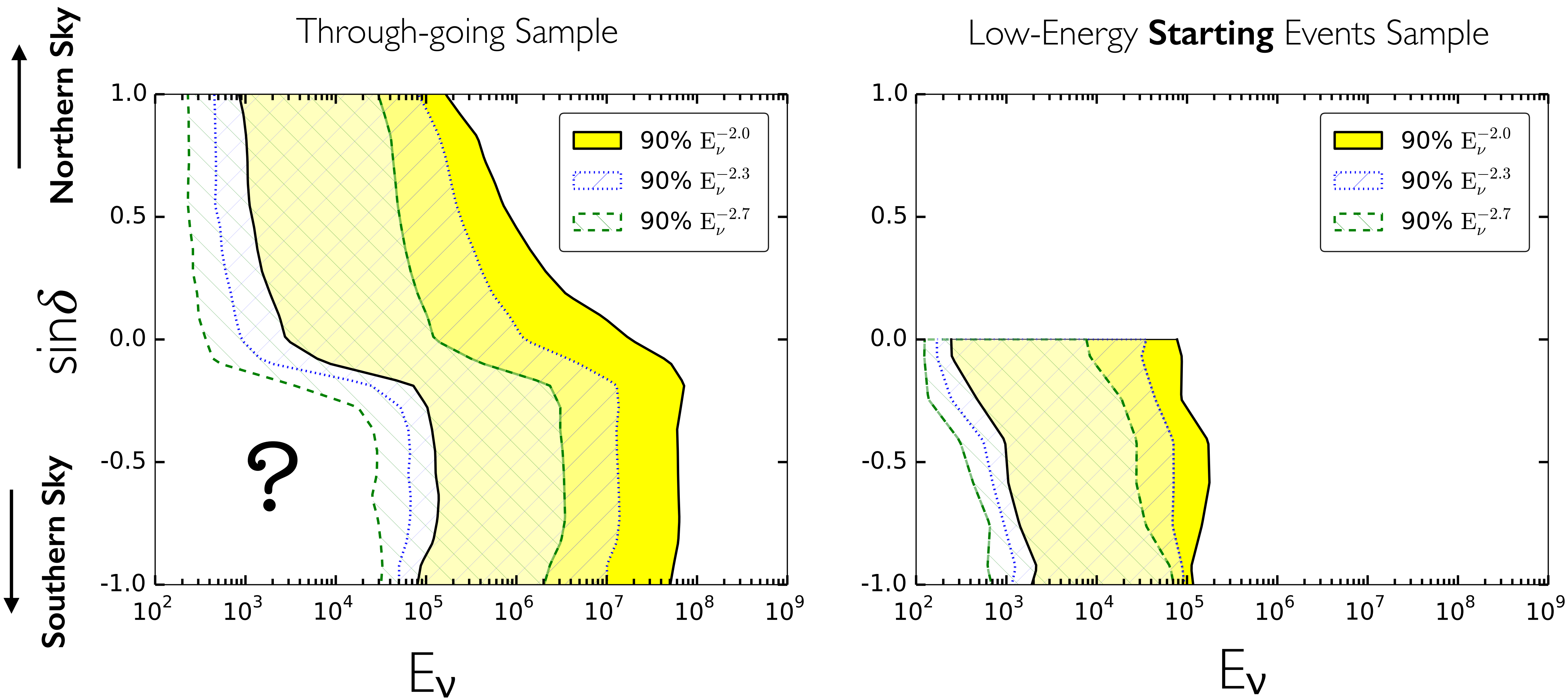
LESE = Low-Energy Starting Events

- Southern Hemisphere point source analysis,
- Focus on ”low-energies” 100 GeV - few TeV,
- Background of atmospheric muons ’leaking in’ mimicking starting events,
- Idea: using part of IceCube as a veto,
- I.e. identify starting events,
- Leads to a pure starting events sample,
- Search for clustering of events,
- Using 1 year of data from the completed 86-string configuration.



Low-Energy Searches

Simulated signal event distributions in final event samples:

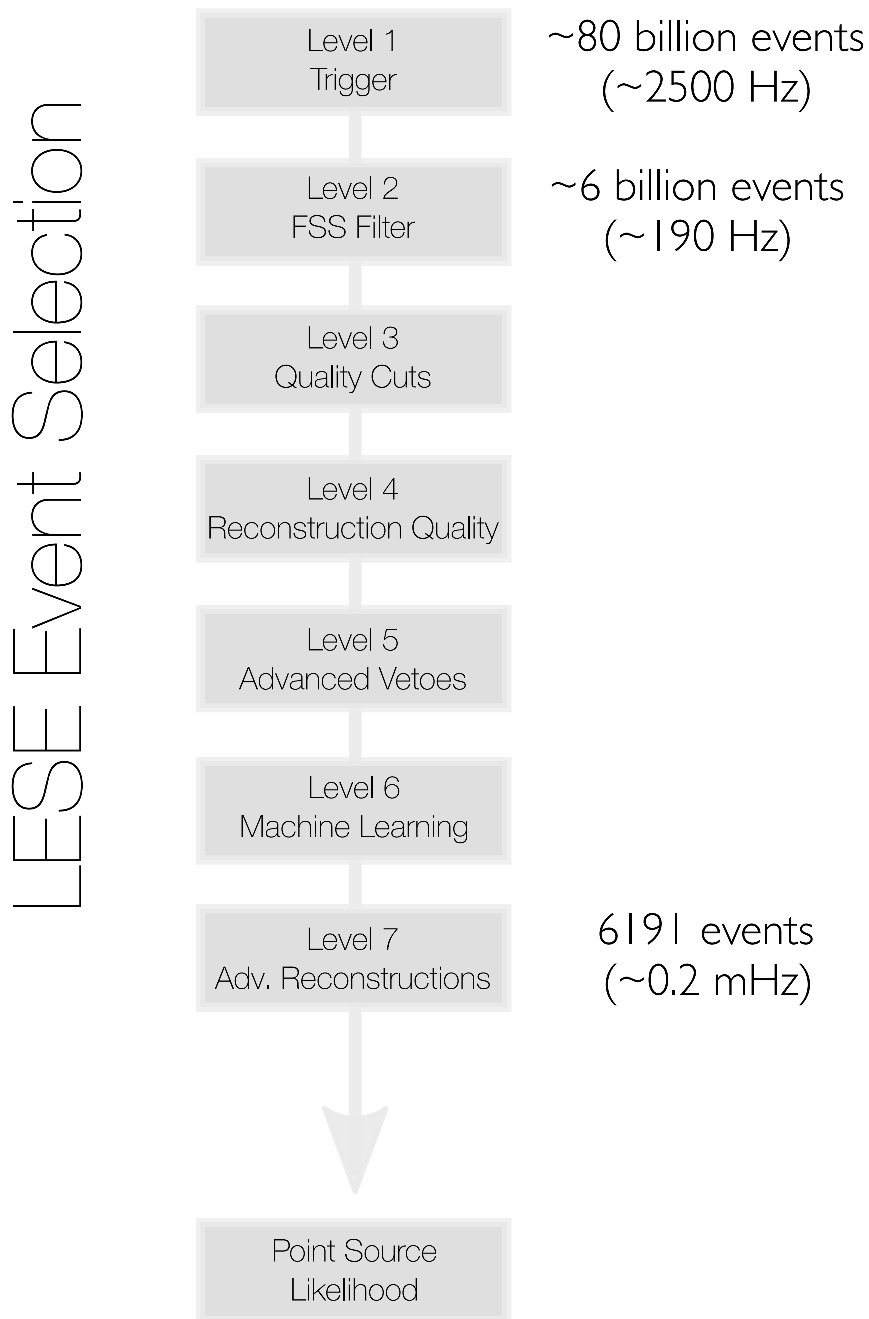


Veto-Based Event Selection

- Reject as much background as possible,
- Keep low-energy events
- "Good" pointing: ~ 1°-2°
- Event selection optimized for:

$$\frac{d\Phi_\nu}{d\mathrm{E}_\nu} = \Phi_0 \cdot \mathrm{E}_\nu^{-2}\ e^{-\mathrm{E}_\nu/10\ \mathrm{TeV}}\ \mathrm{TeV\ cm^{-2}\ s^{-1}}$$

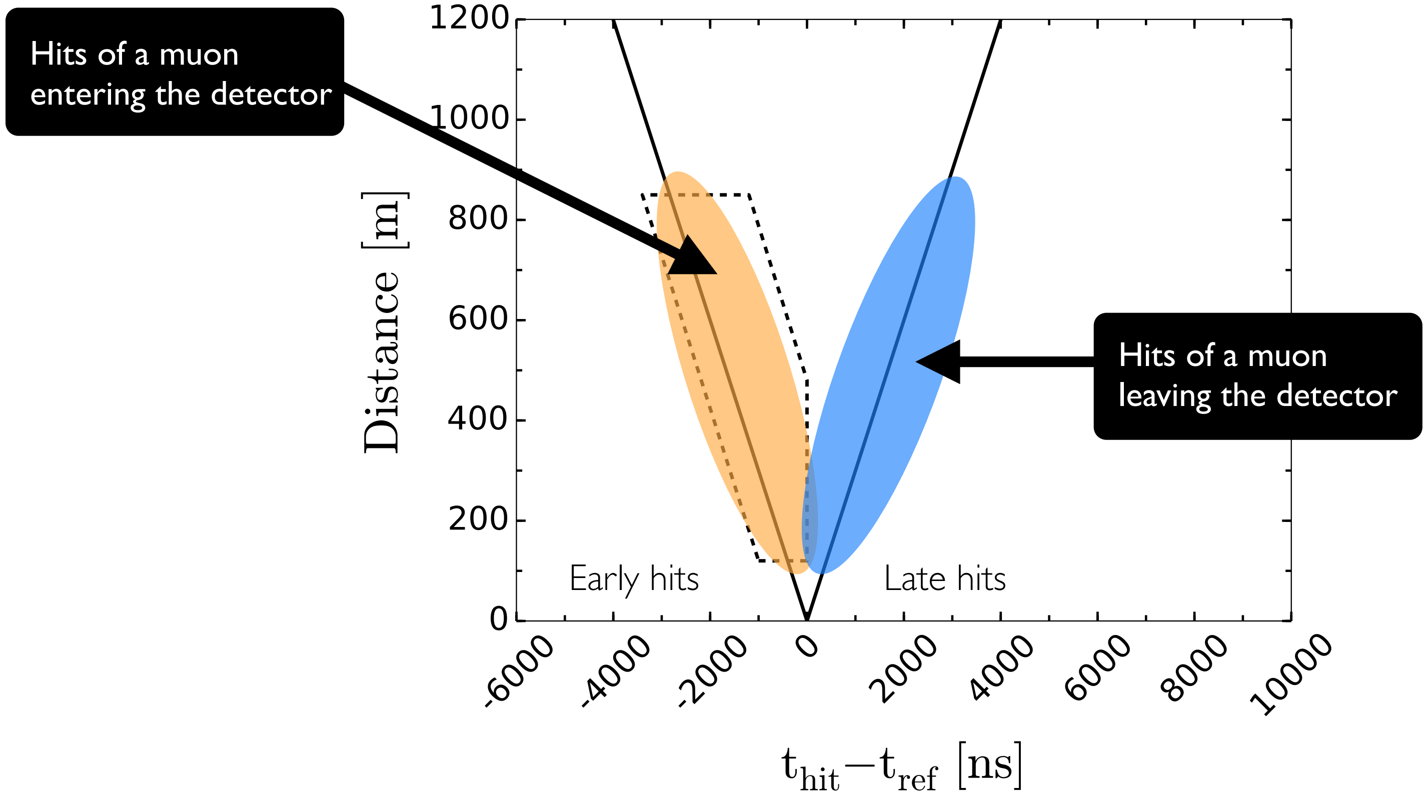
- Rate(final)/Rate(trigger) < 1e-7
- Starting signal retention ~ 2-8 % (compared to filter)
- Angular Uncertainty (@final): 1.4° - 1.7°

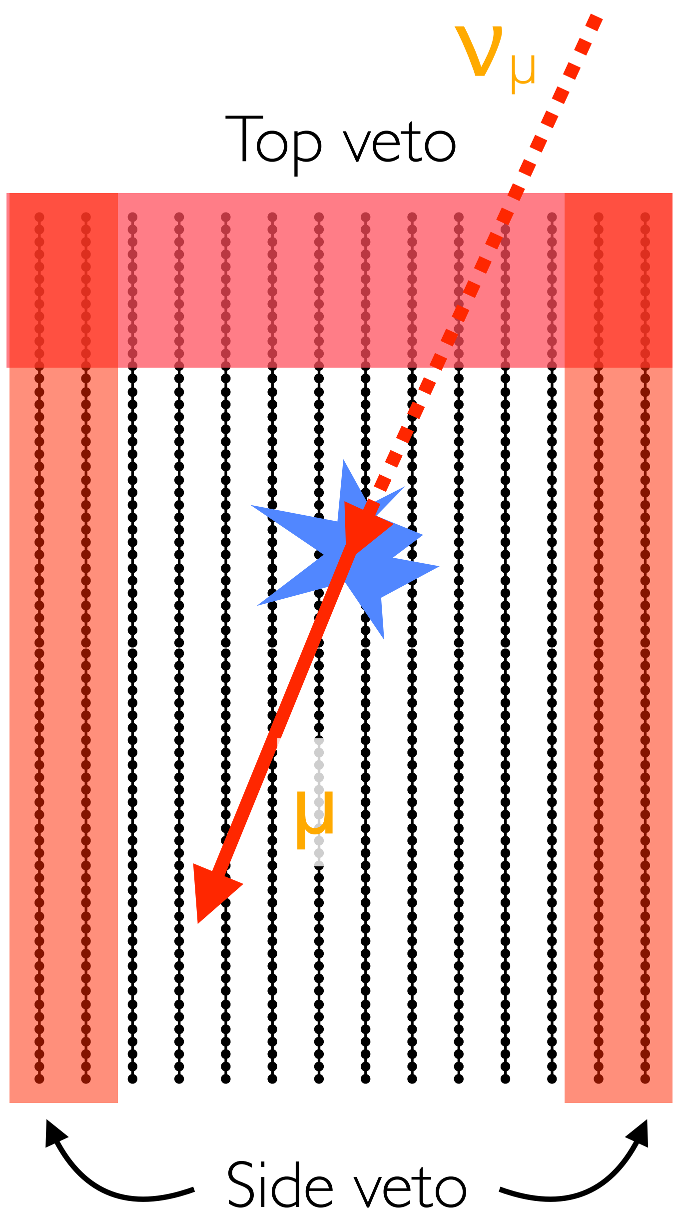


• Angular Uncertainty (@final): 1.4° - 1.7°

Causality Veto - Level 6

- Study causality of SLC hits in outer layers relative to first HLC (reference) in the fiducial volume.
- Are the hits consistent with particle traveling with speed of light through the detector?
- Causality is studied for all pulses in the veto regions: top and side.





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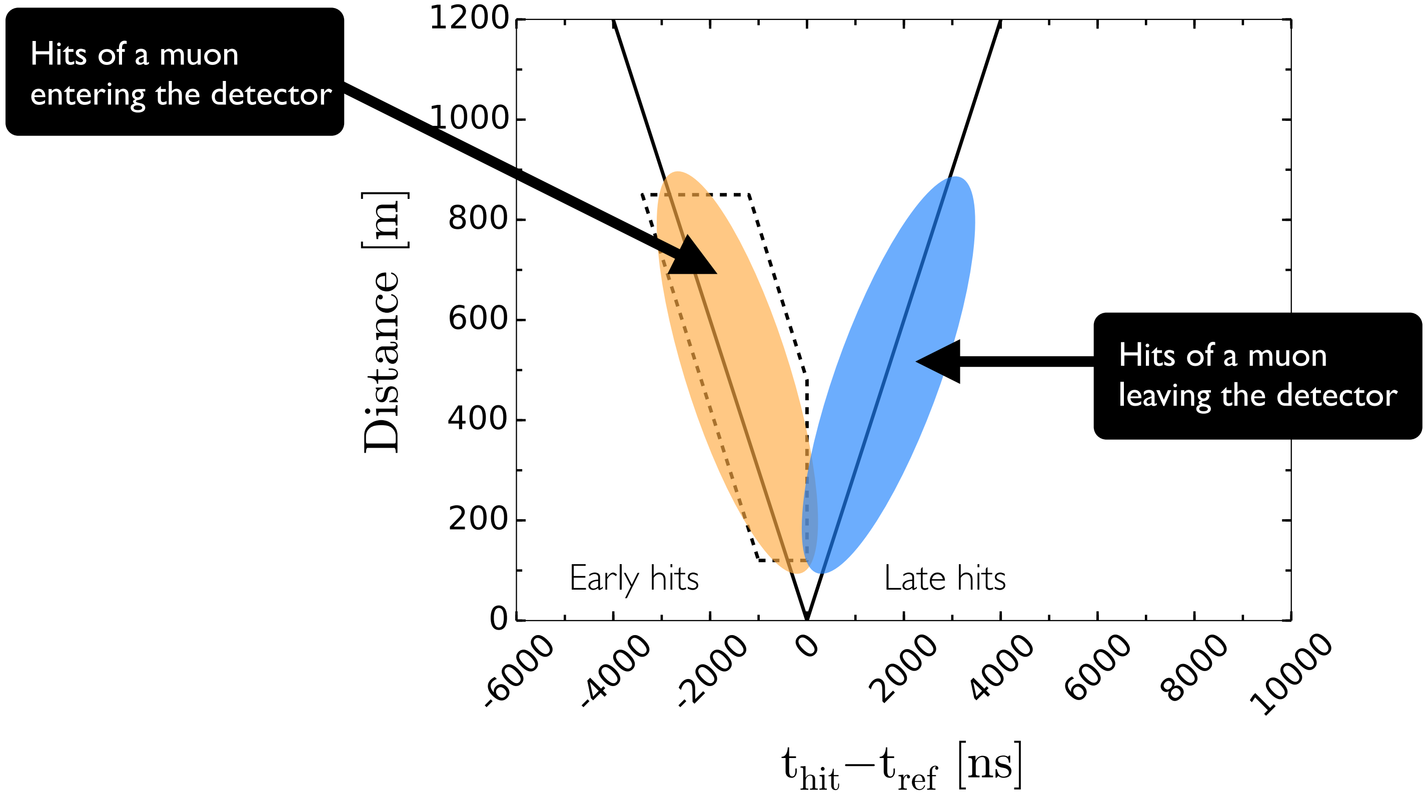
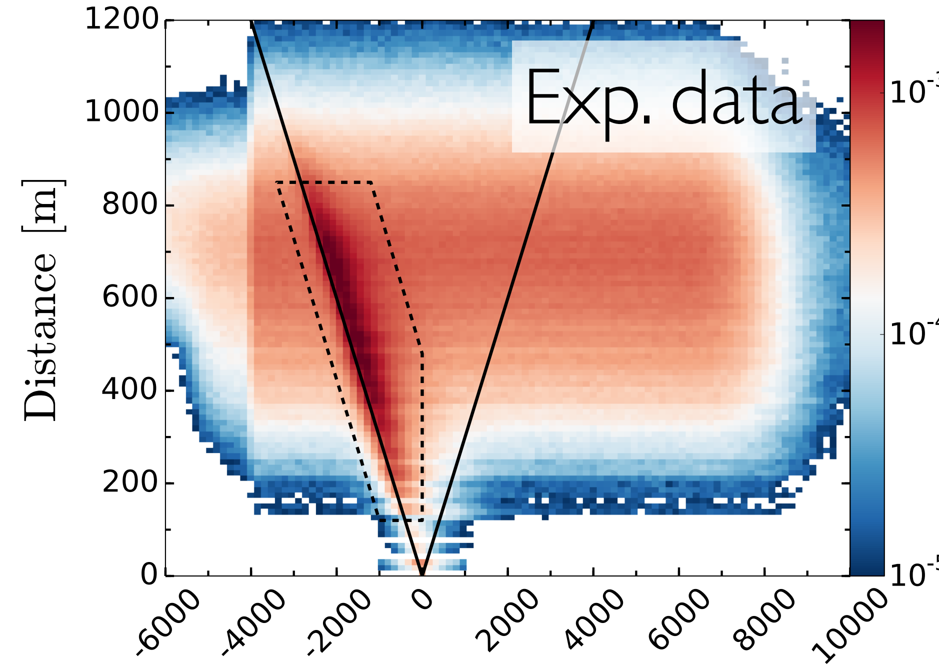
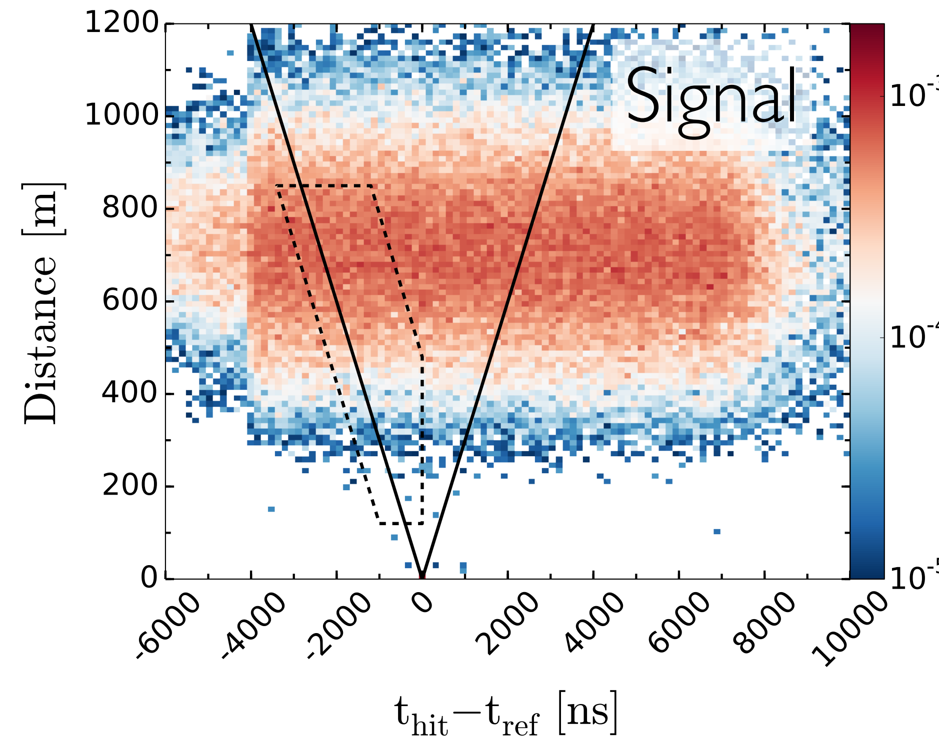


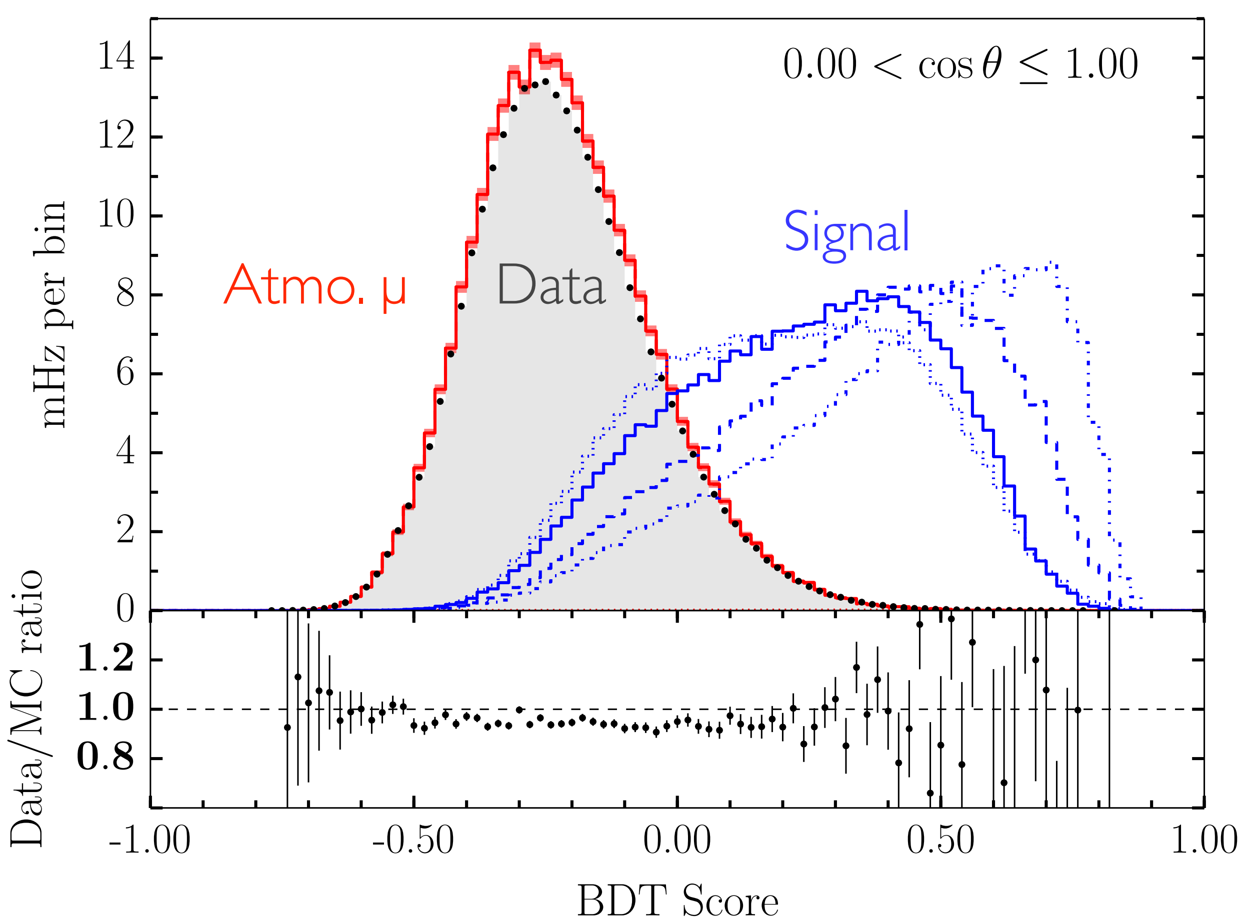




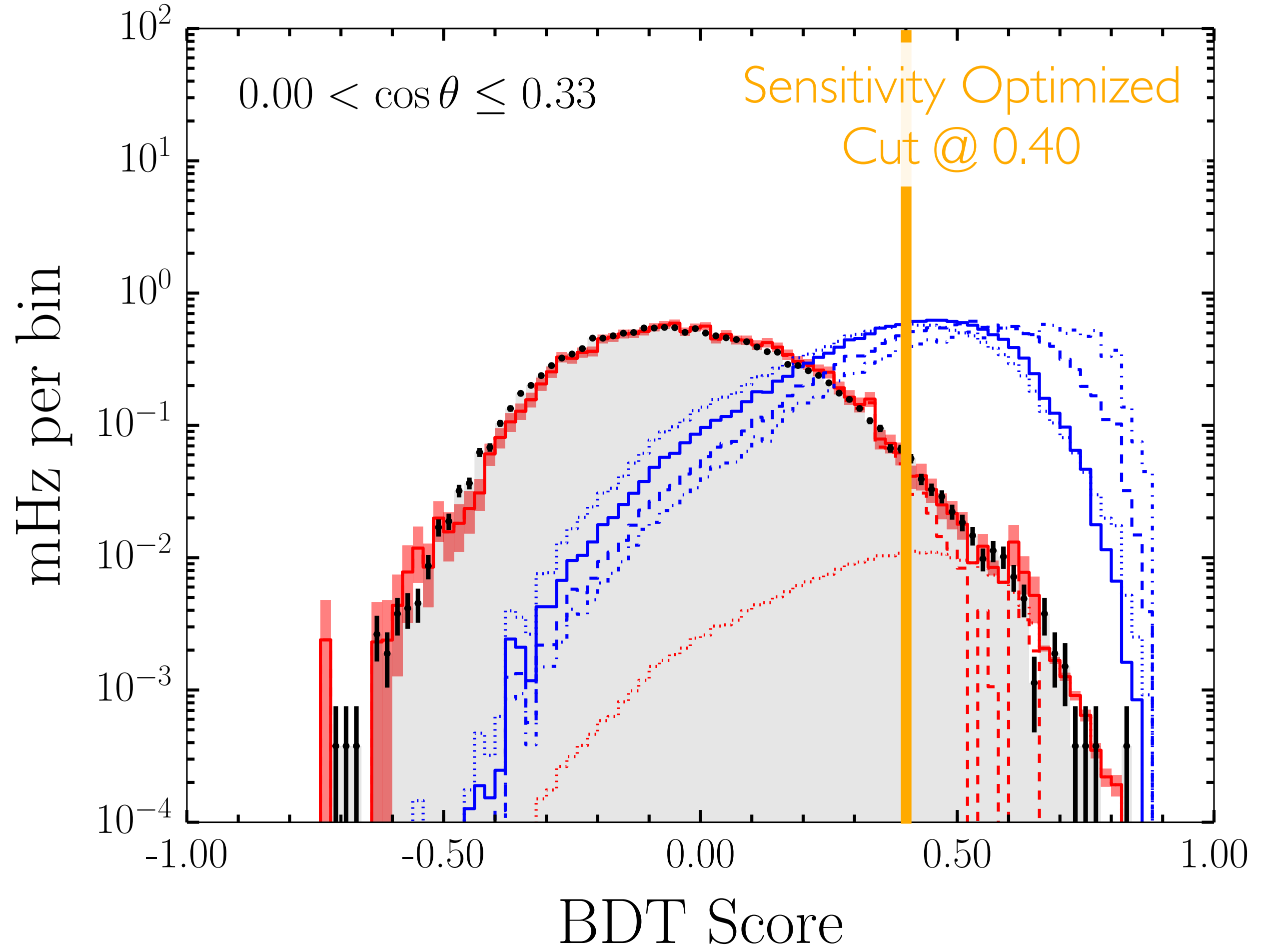
BDT Score

- Boosted Decision Trees + Random Forest,
- Input: 14 variables with good separation,
- Atmospheric **neutrinos** @ event scores > 0.5 (horizontal events)

Southern Hemisphere



Southern Hemisphere - Horizontal Events



Search for Clustering of Neutrino Candidate Events

- Unbinned maximum likelihood analysis using 3 observables:
  Angular reconstruction, Angular uncertainty estimate, Energy proxy
- Point Source Likelihood:

$$\mathcal{L}(n_s, \gamma) = \prod_{i}^{N} \left[\underbrace{\frac{n_\mathrm{S}}{N} \mathcal{S}(\vec{x}_i, \sigma_i, \mathrm{E}_i; \vec{x}_\mathrm{S}, \gamma)}_{\text{Signal}} + \underbrace{\left(1 - \frac{n_\mathrm{S}}{N}\right) \mathcal{B}(\delta_i; \mathrm{E}_i)}_{\text{Background}} \right]$$

$$\mathcal{S} = \underbrace{S(|\vec{x}_i - \vec{x}_\mathrm{S}|, \sigma_i)}_{\text{Spatial}} \times \underbrace{\mathcal{E}(\mathrm{E}_i, \delta_i, \sigma_i; \gamma)}_{\text{Calorimetric}}$$

$$\mathcal{B} = \underbrace{S_\mathrm{bkg}(\delta_i)}_{\text{Spatial}} \times \underbrace{\mathcal{E}_\mathrm{bkg}(\mathrm{E}_i, \delta_i, \sigma_i, \gamma)}_{\text{Calorimetric}}$$

Best fit: $\hat{\gamma}, \hat{n}_s$

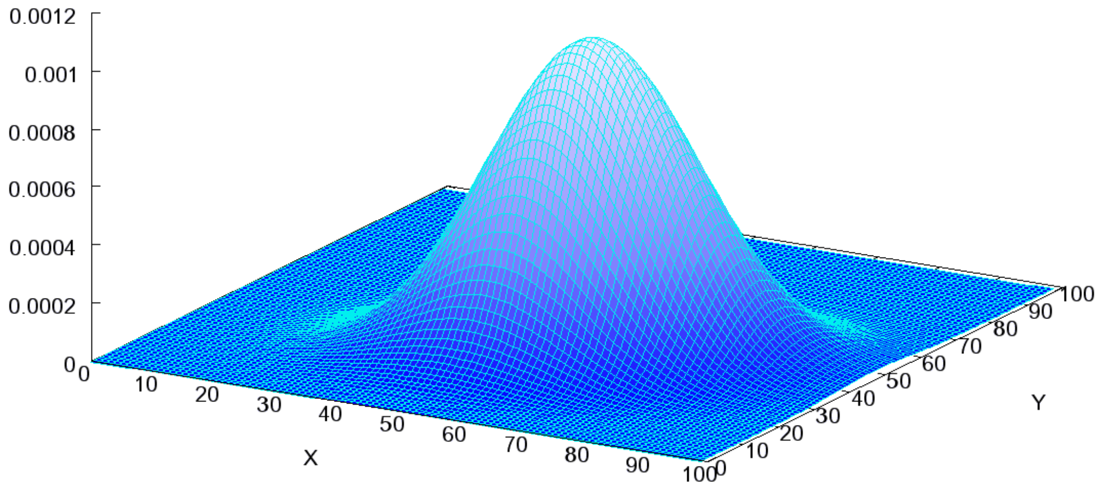
Test Statistics: $$\mathcal{TS} = 2 \ln \left[\frac{\mathcal{L}(\hat{n}_\mathrm{S}, \hat{\gamma})}{\mathcal{L}(n_\mathrm{S} = 0)} \right]$$

Wilks' theorem: χ^2 with 2 d.o.f. as sample approaches ∞

Likelihood Analysis - Spatial

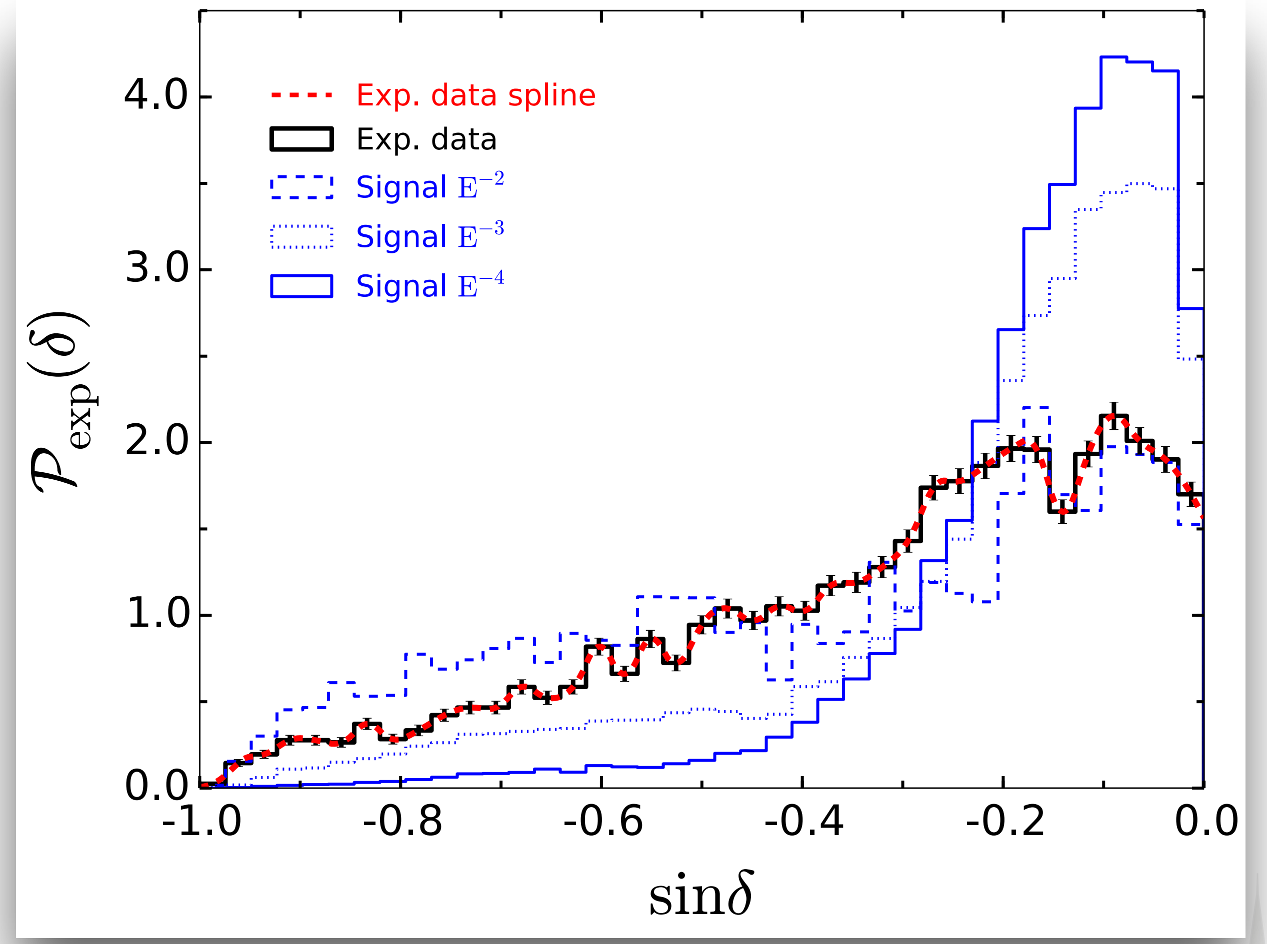
Spatial - Signal

$$S(|\vec{x}_i - \vec{x}_S|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_S|^2}{2\sigma_i^2}}$$



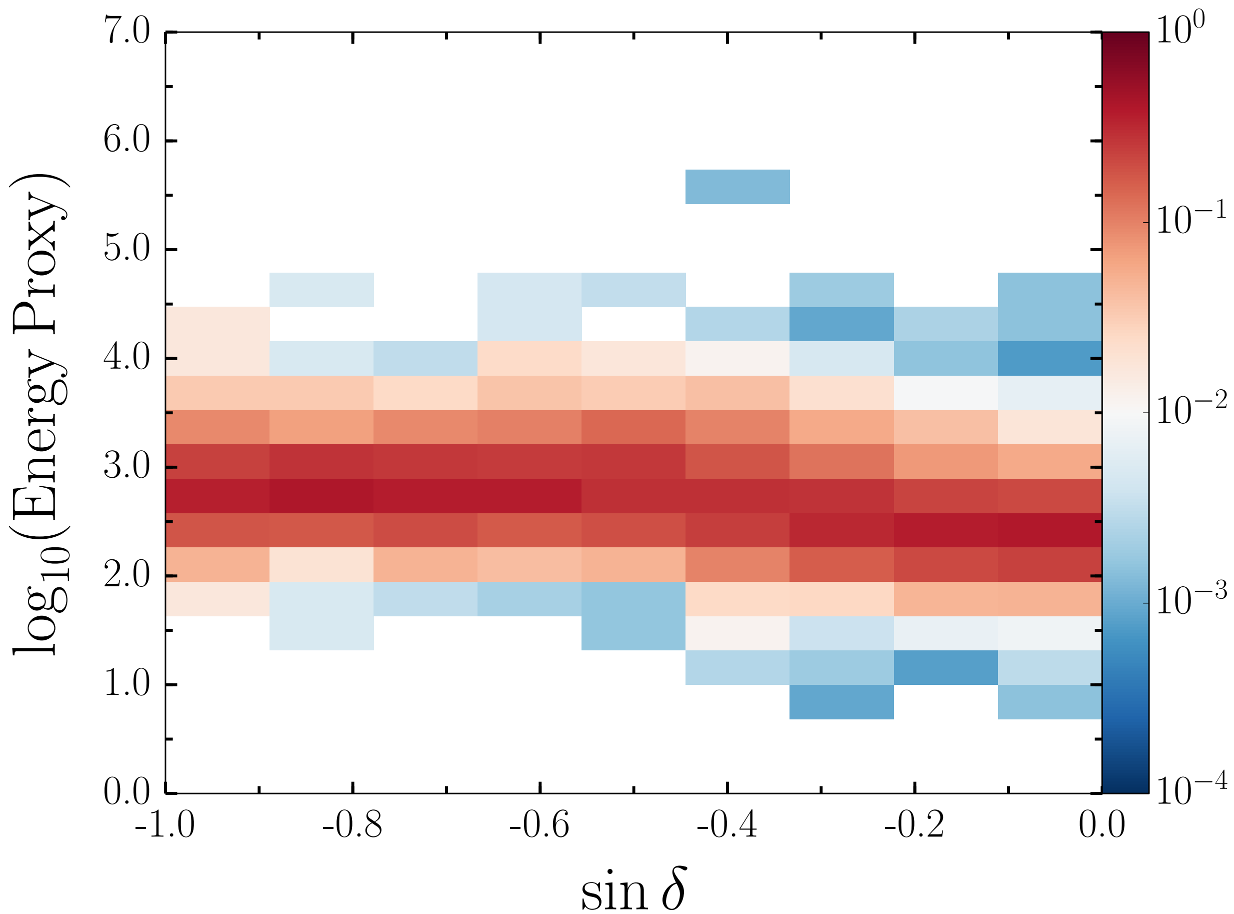
Spatial - Background

$$S_{\mathrm{bkg}} = \frac{1}{2\pi} \mathcal{P}_{\mathrm{exp}}(\delta)$$

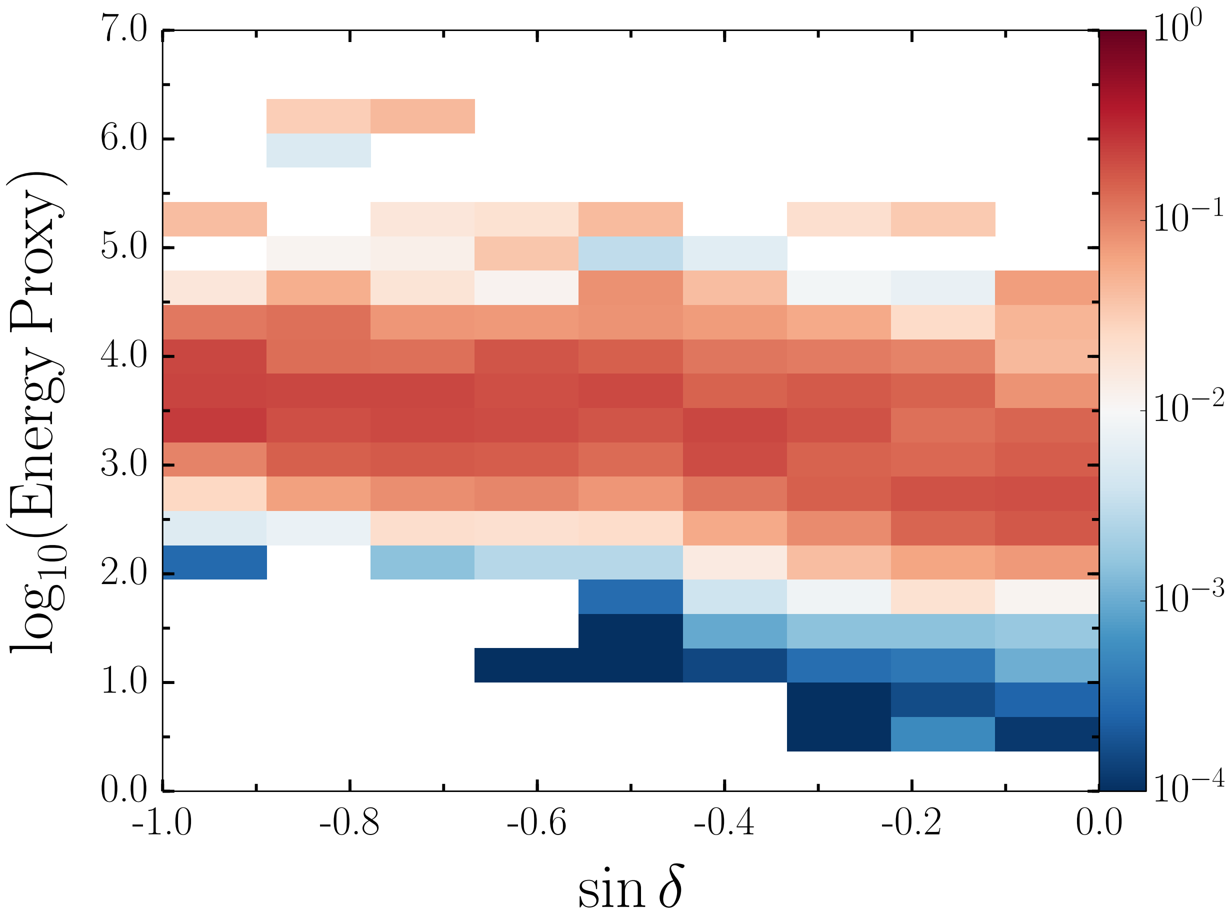


Likelihood Analysis - Calorimetric

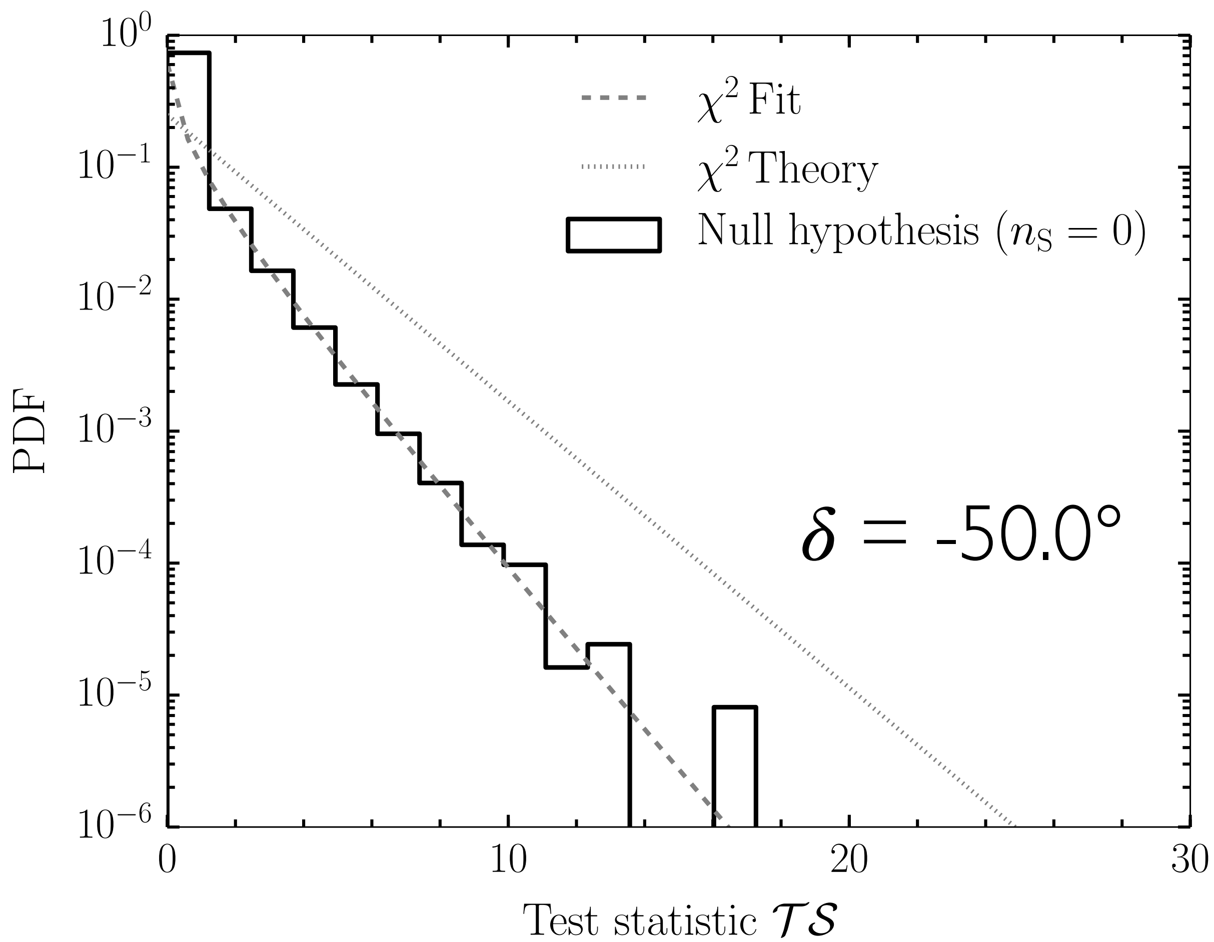
Exp. data



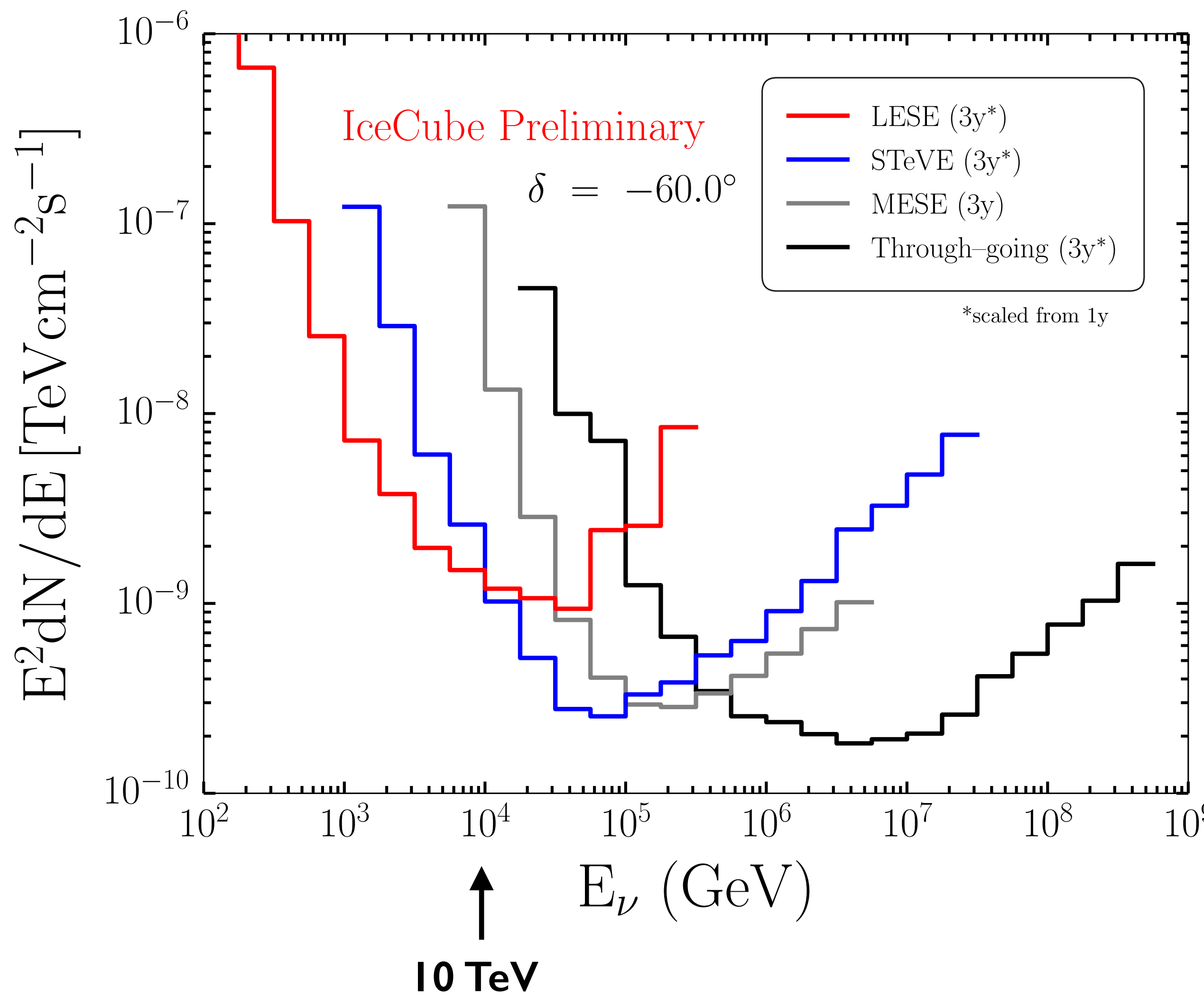
Signal E^{-2}



Point Source Sensitivity



$$\mathcal{TS} = 2\ln\left[\frac{\mathcal{L}(\hat{n}_S, \hat{\gamma})}{\mathcal{L}(n_S = 0)}\right]$$



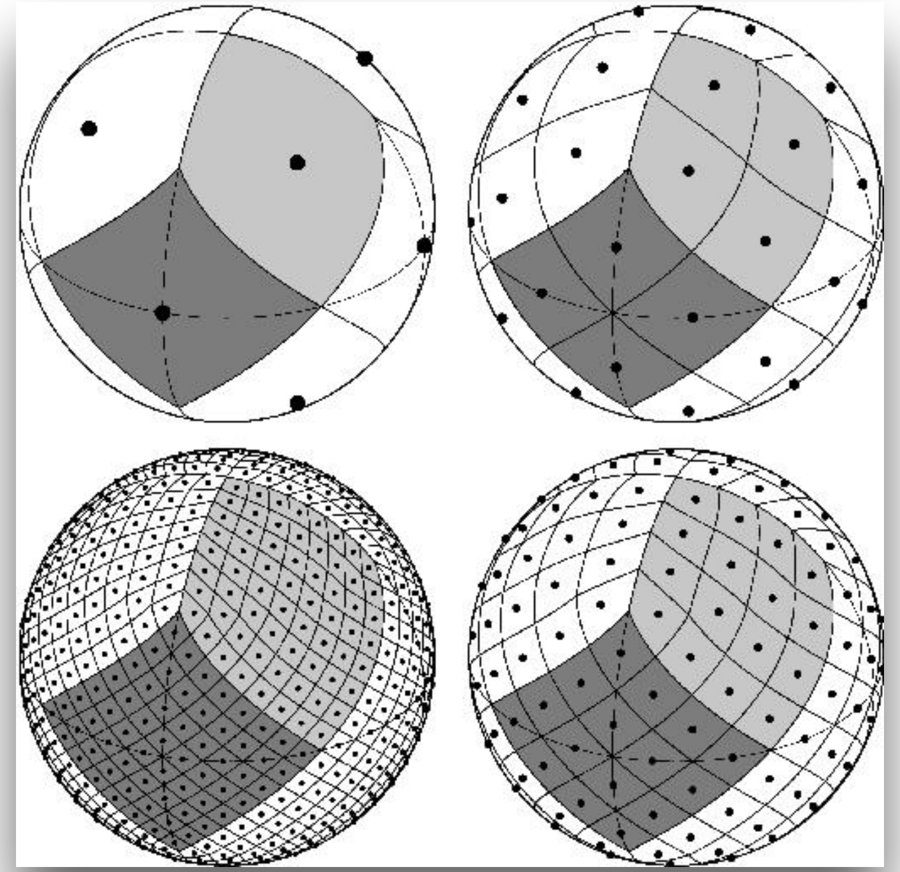
- P-values are calculated for each declination using a fit to the test statistic distribution of the null hypothesis trials.

Search for Clustering of Neutrino Candidate Events

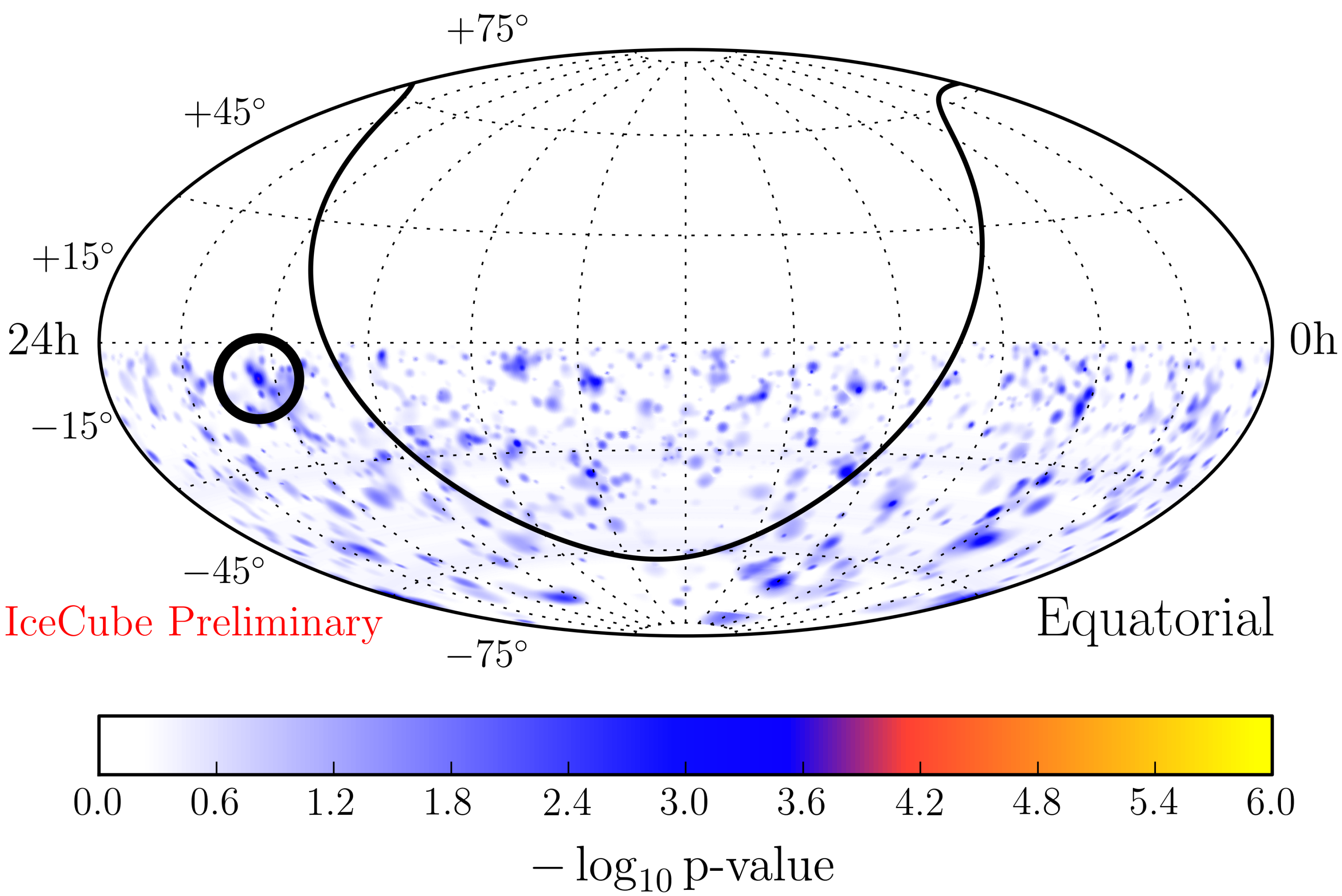
Searches:

- Southern sky scan
  - Scan on a HEALPIX grid
  - Report hottest spot (best p-value)
- Source scan
  - Scan known sources of gamma-rays
  - Report hottest source (best p-value)

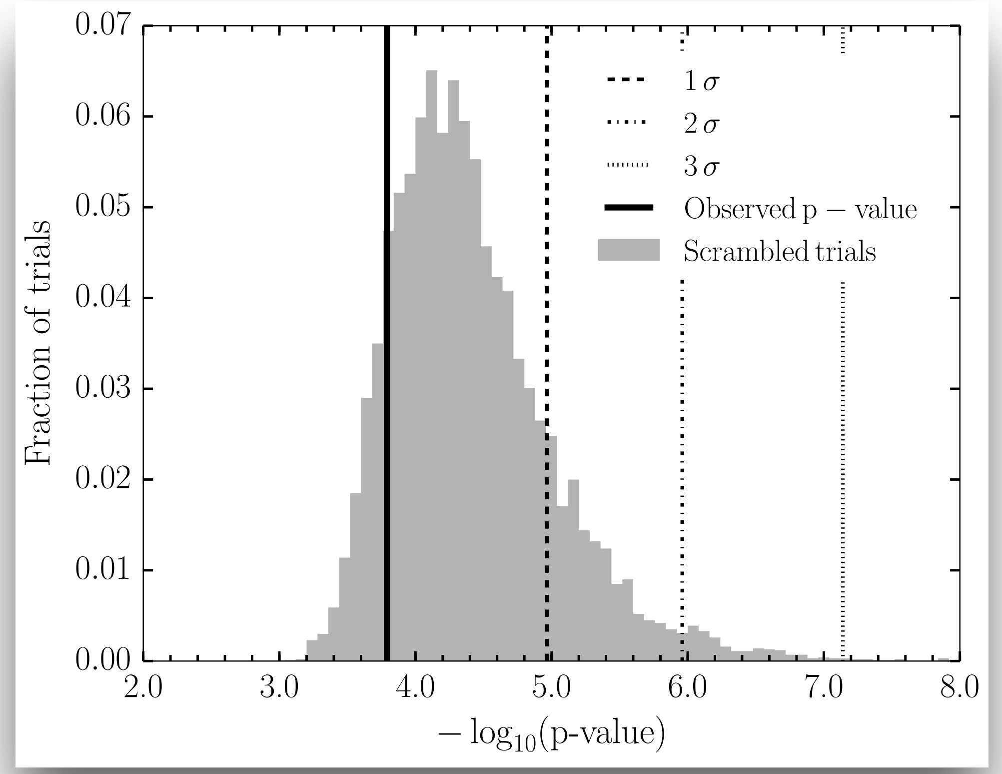
HEALPIX Grid



Results - Southern Sky Scan



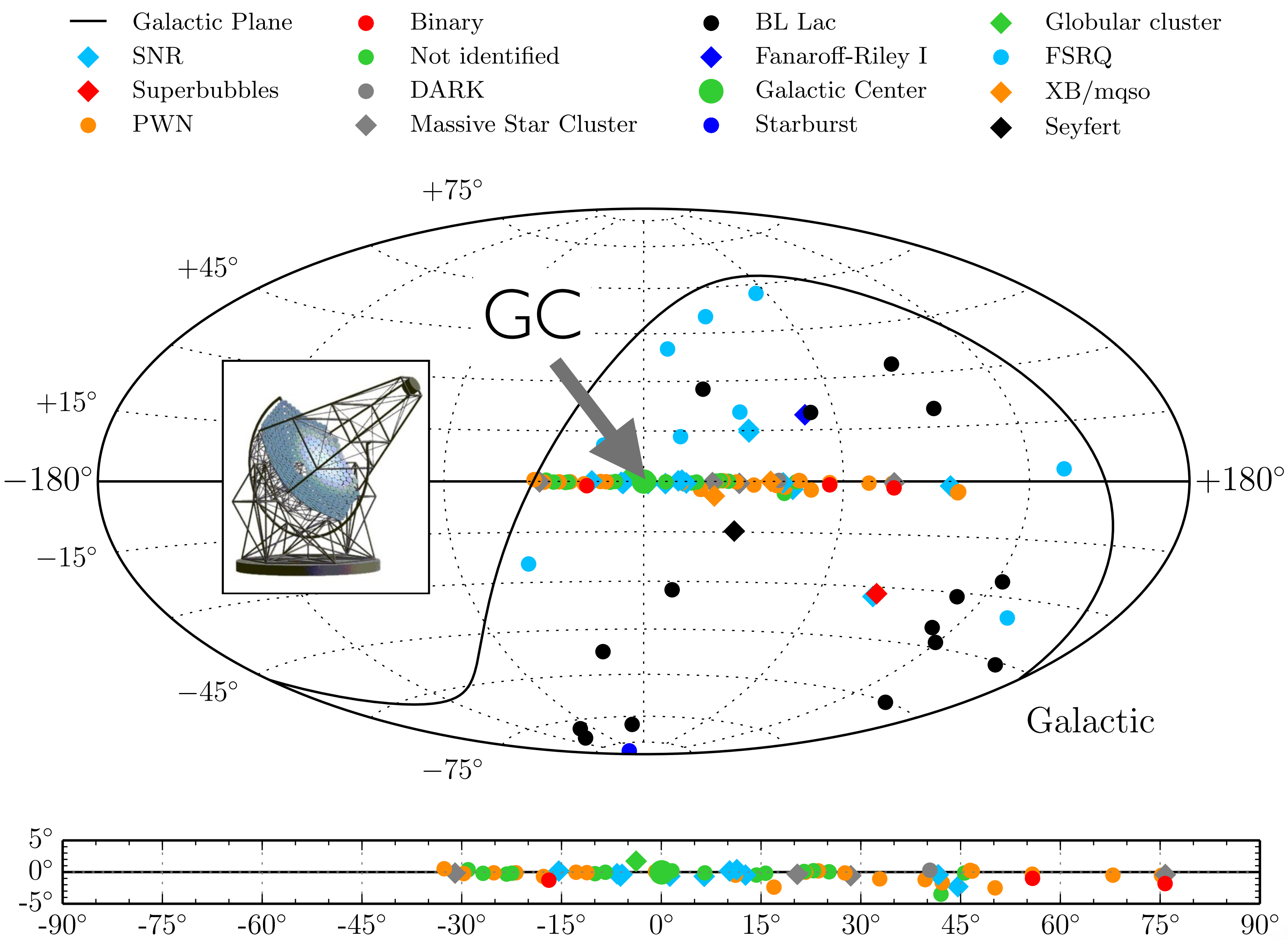
10 000 Scrambled Trials



Hottest spot:

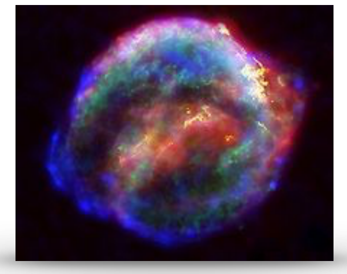
- R.A. 305.2°, Dec. -8.5° (best-fit n_S = 18.3, γ = 3.5),
- pre-trial p-value 1.6e-4 (-log10 → 3.79),
- post-trial p-value **88%**

Source List of Known Gamma-Ray Emitters



Source list definition (total of 96 sources):

- All 84 Southern sky TeVCat sources in the stable catalogs '*Default Catalog*' and '*Newly Announced*',
- 12 additional source traditionally investigated by IceCube,
- Known gamma-ray emitting sources as observed by ground-based experiments such as VERITAS, MAGIC, and HESS.



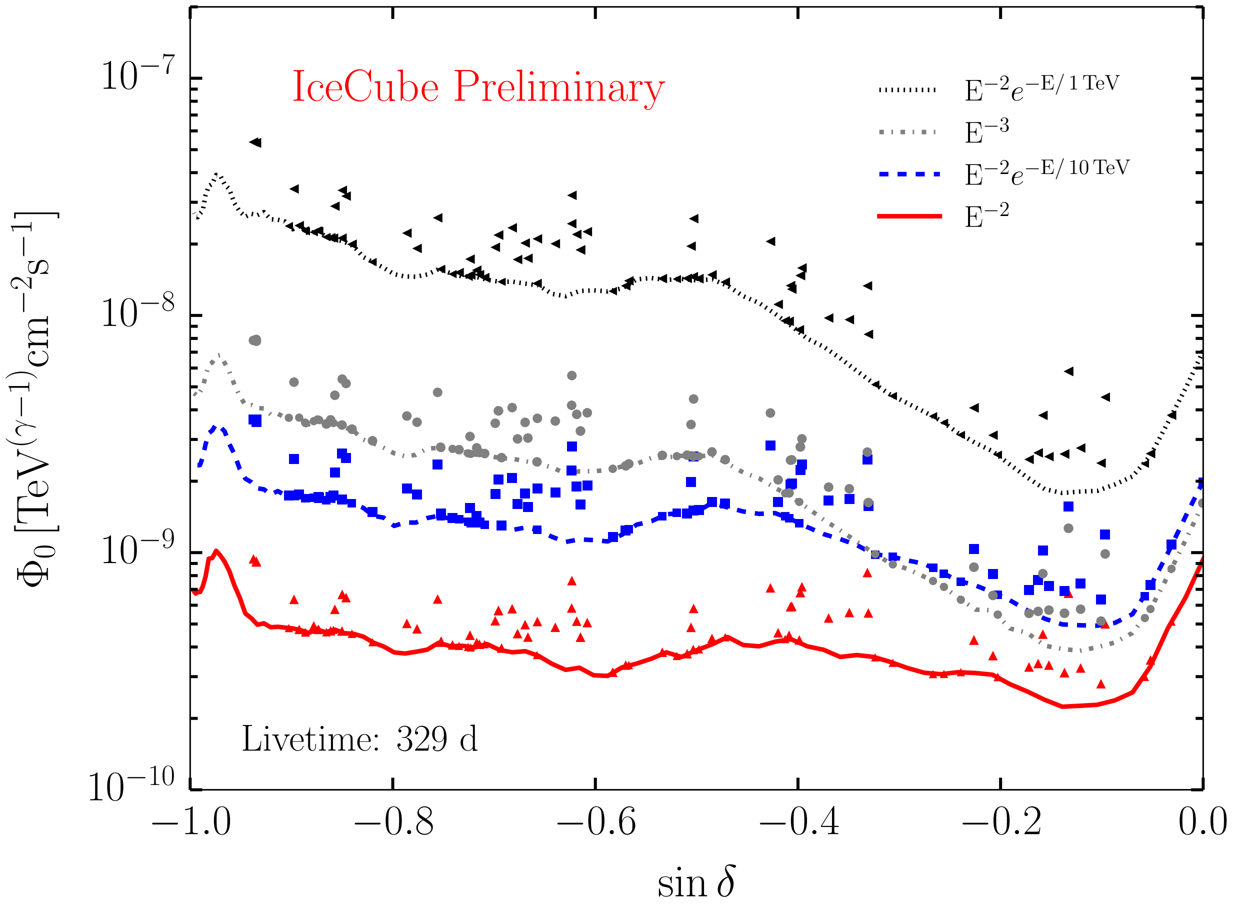
Supernova Remnants

Pulsars

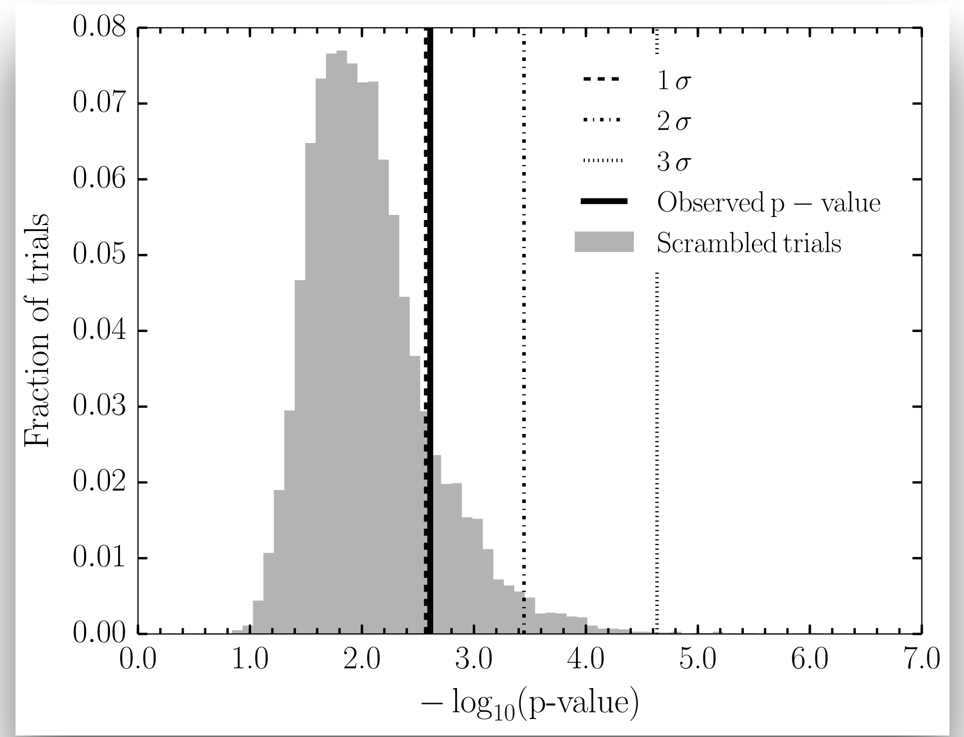
Results - Source List

- Hottest source:
  - LESE: QSO 2022-077 (FSRQ) (Dec: -7.6°, RA: 306.5°) (best-fit n_S = 17.3, γ = 3.5),
  - pre-trial p-value 2.5e-3 (-log10 → 2.61),
  - post-trial p-value **14.8%**

Upper Limits for Soft Spectra:

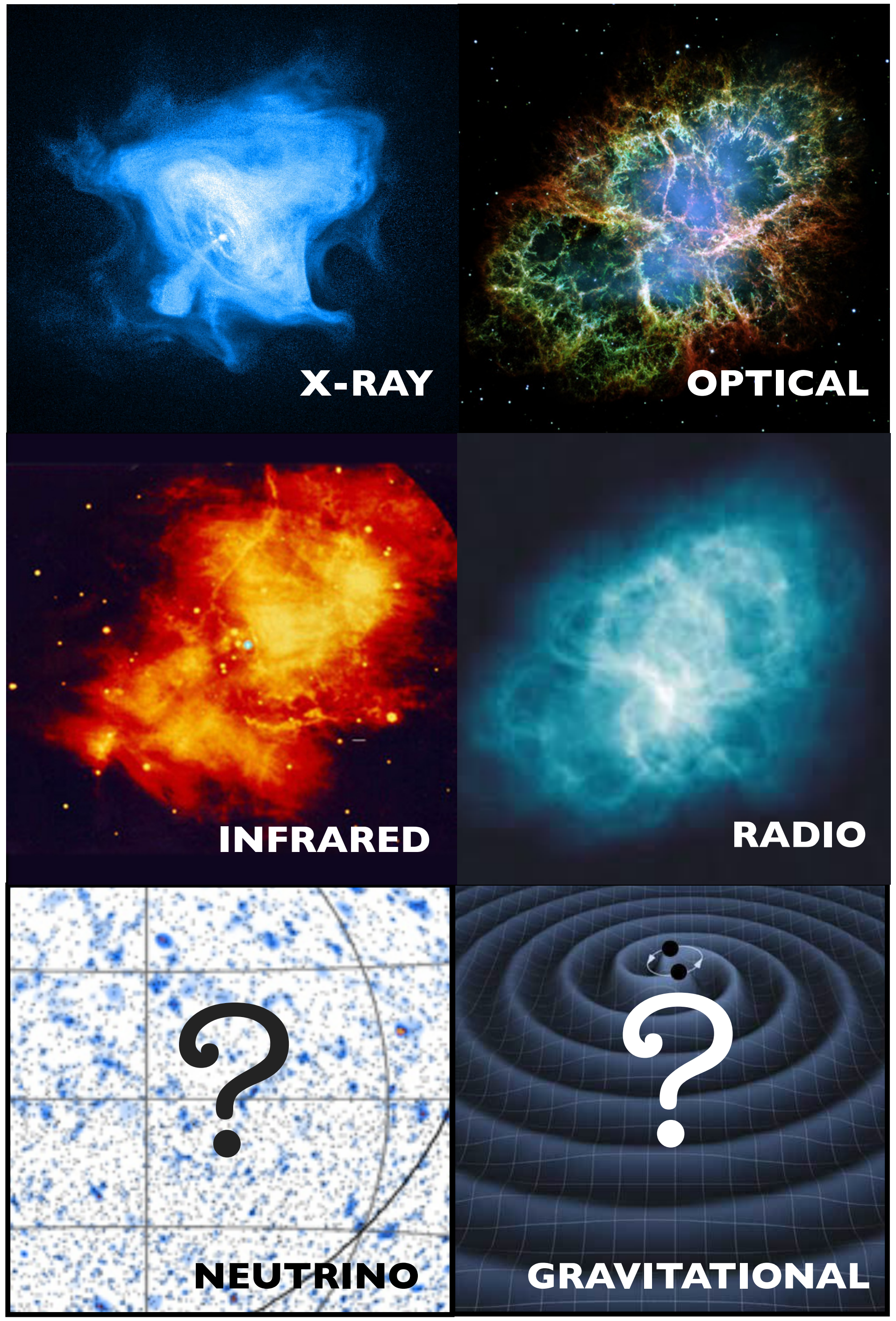


Post-trial correction:



Conclusions & Summary

- Neutrinos are an important piece in the multi-messenger puzzle, AND a unique probe to extremely dense astrophysical objects, AND only probe from far away at high energies.
- I developed an event selection that for the first time with IceCube enables searches in the Southern sky at energies as low as 100 GeV (standard IceCube search: above 100 TeV),
- Event selection relies on veto techniques,
- Searching for a clustering of starting events,
- No evidence for localized neutrino sources found yet (Southern sky search + *a prior* list),
  - Results compatible with background fluctuations,
  - Put limits on a number of sources.
- Improvement with a factor of 3-4 adding 4 more years.



Outlook:
- **Time-dependent searches,**
- **Galactic plane,**
- **Extended source searches.**

The End of This Presentation but

The Beginning

of Neutrino Astronomy

Pre Thesis Defense Seminar
December 14, 2015

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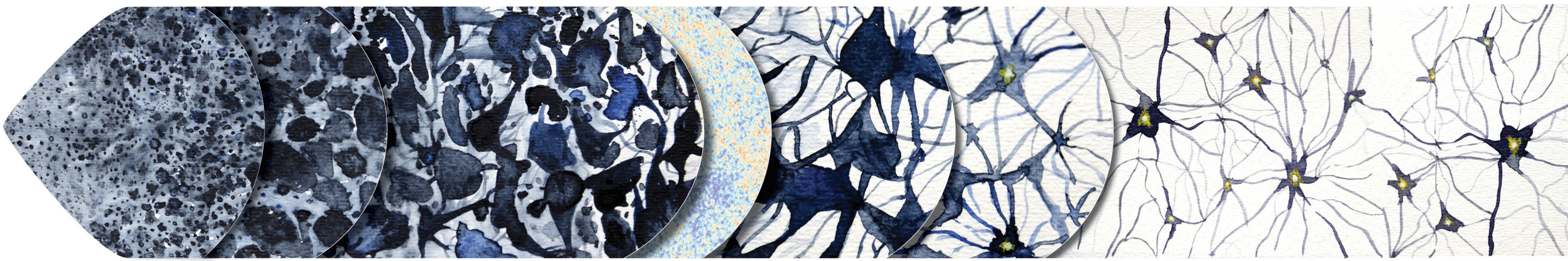
Public Defense December 18, Polhemsalen 13:15
Opponent: Prof. Lawrence R. Sulak, Boston University

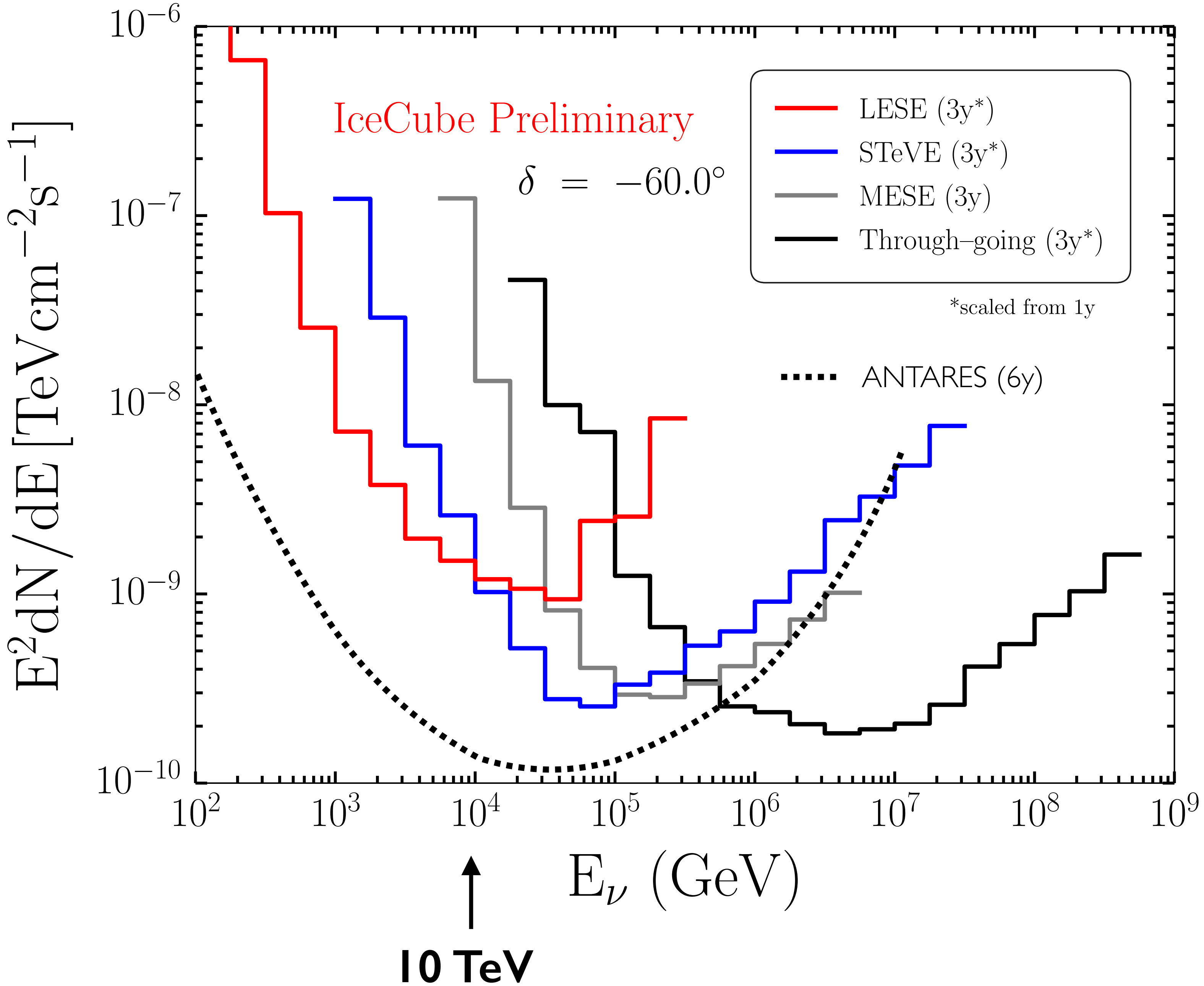


Exploring the Universe Using Neutrinos

A Search for Point Sources in the Southern Hemisphere Using the IceCube Neutrino Observatory

Backup Slides

Point Source Sensitivity



IceCube - Gen2