Point Source Searches with the IceCube Detector

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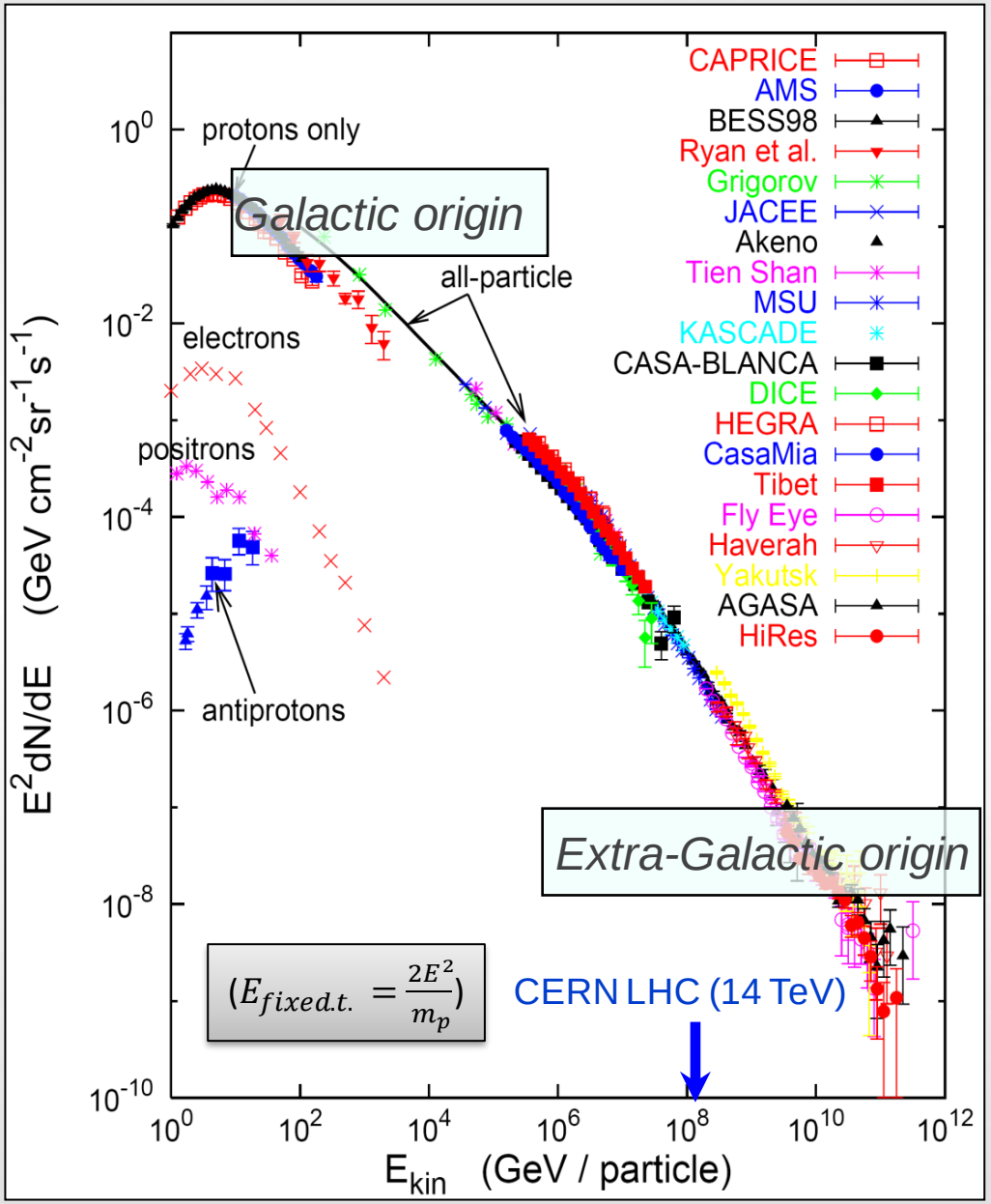
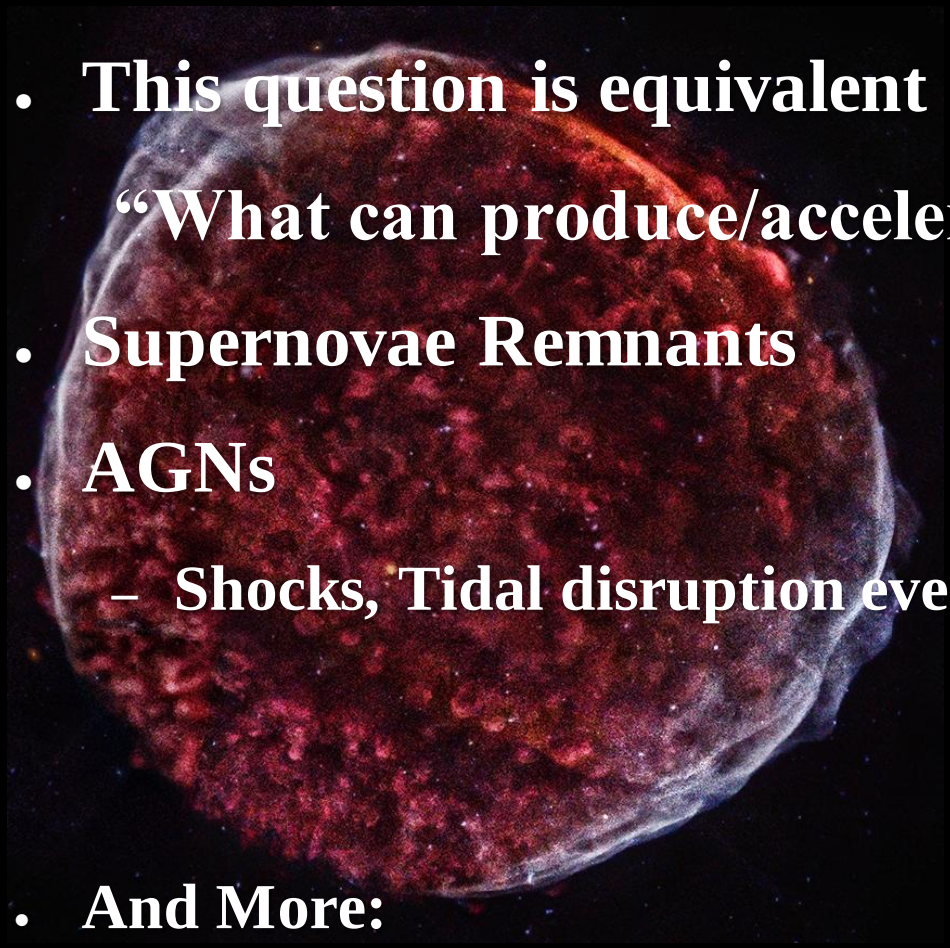
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

The motivations behind neutrino astronomy

- Cosmic Rays spectrum spans 10 decades of energy.
- Where is the origin of these particles? Or how do they get to have such high energies?
- Galactic CRs: Supernova remnants?
- Extra-Galactic CRs: AGNs, GRBs?
- CR are hadrons (protons at LE, composition changes at HE)
  - Neutrinos will be produced in their interactions.
  - Chance to pinpoint the origin!



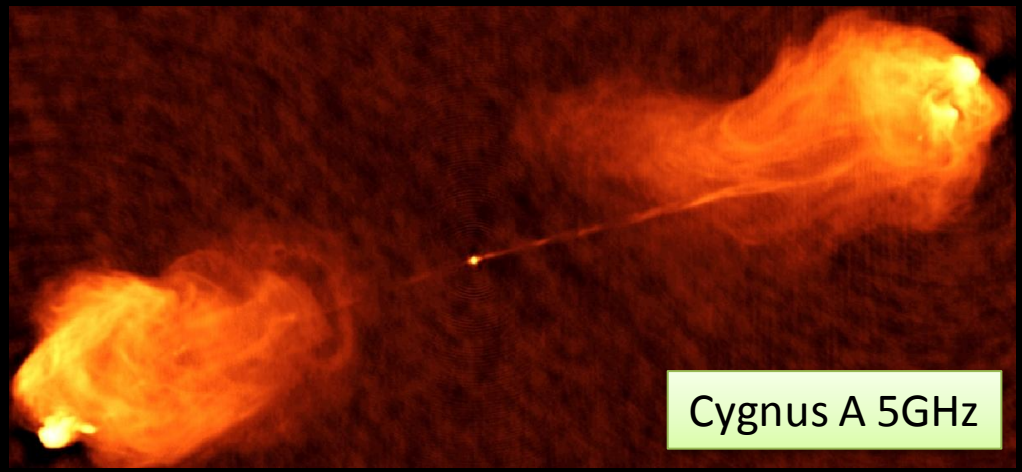
Candidates for CR sources?



- **This question is equivalent to:**

  "What can produce/accelerate particles to those energies?"

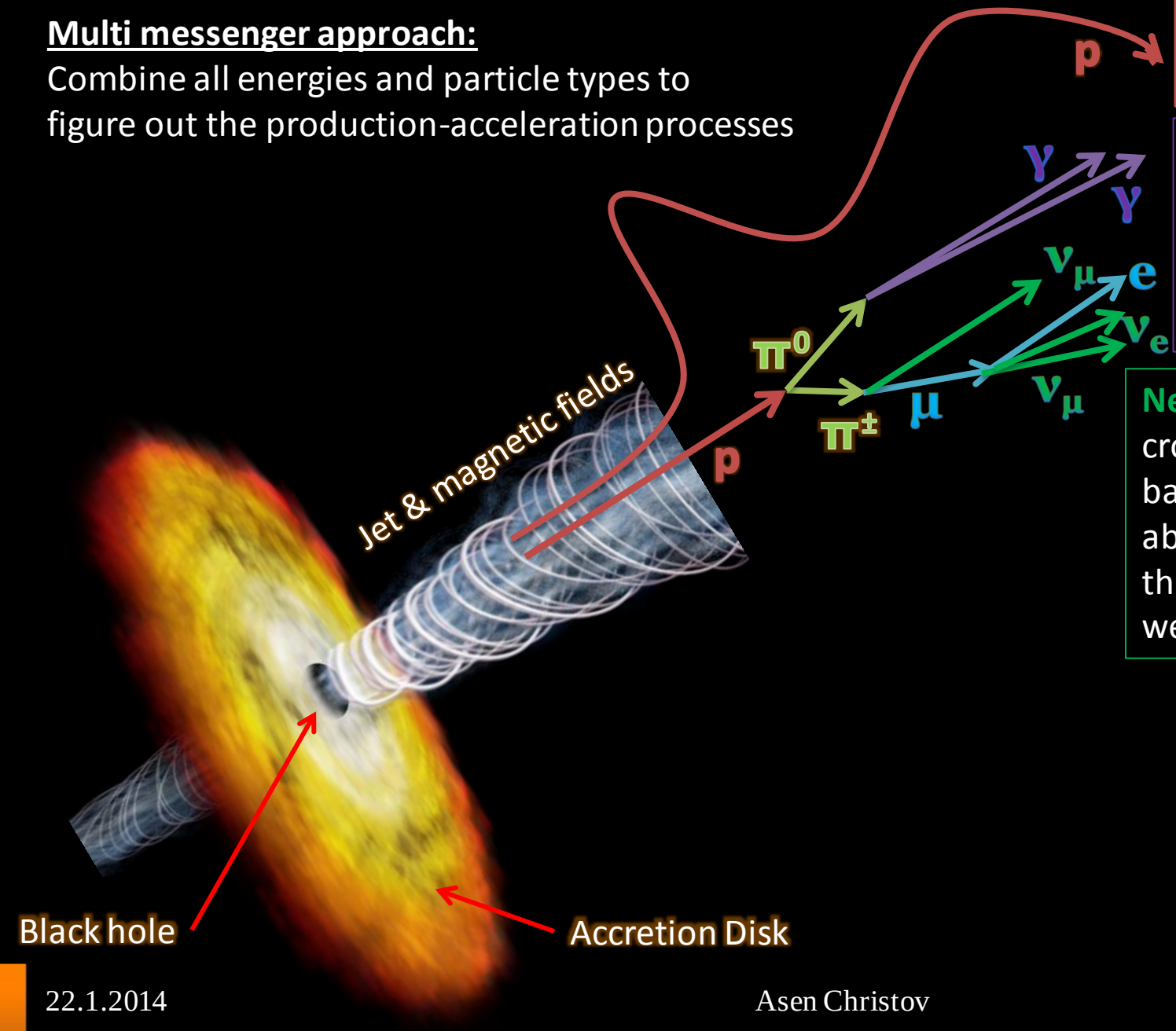
- **Supernovae Remnants**
- **AGNs**
  - **Shocks, Tidal disruption events**



- **And More:**
  - **GRBs**
  - **Colliding galaxies (strong shocks)**
  - **Decay or annihilation of some super-heavy particles or cosmological relics**

The virtues of neutrino astronomy

Multi messenger approach:
Combine all energies and particle types to figure out the production-acceleration processes

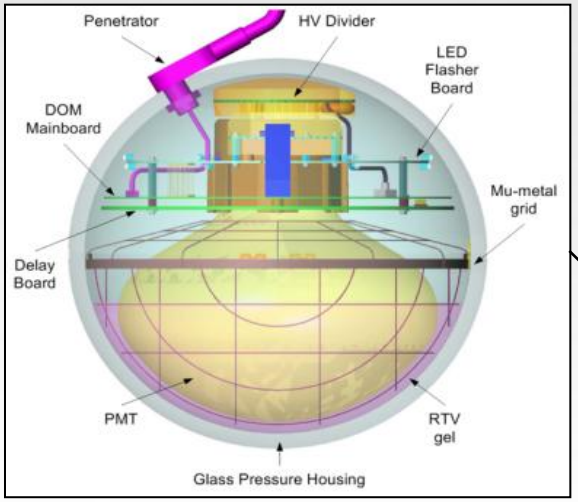


Protons: **Deflected by magnetic fields (above EeV energies negligible)**

Gamma-rays: Absorbed at highest energies, multiple emission mechanisms (π^0 decay, synchrotron rad., inverse Compton scattering, …)

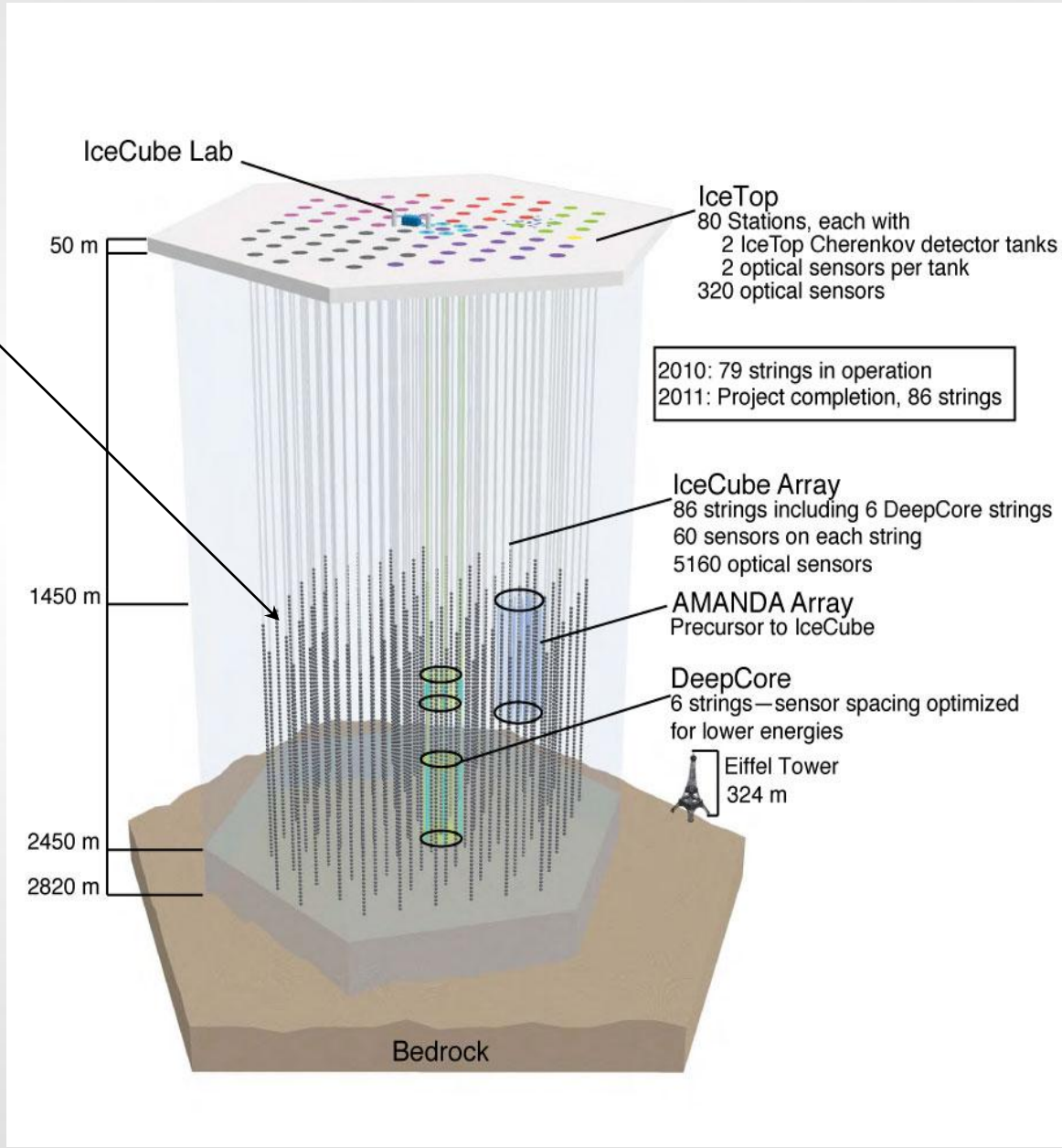
Neutrinos: No charge and low cross-section mean they point back to source and are not absorbed. Moreover they tell us the source accelerated particles were hadrons (protons or nuclei)

The IceCube Detector - Layout

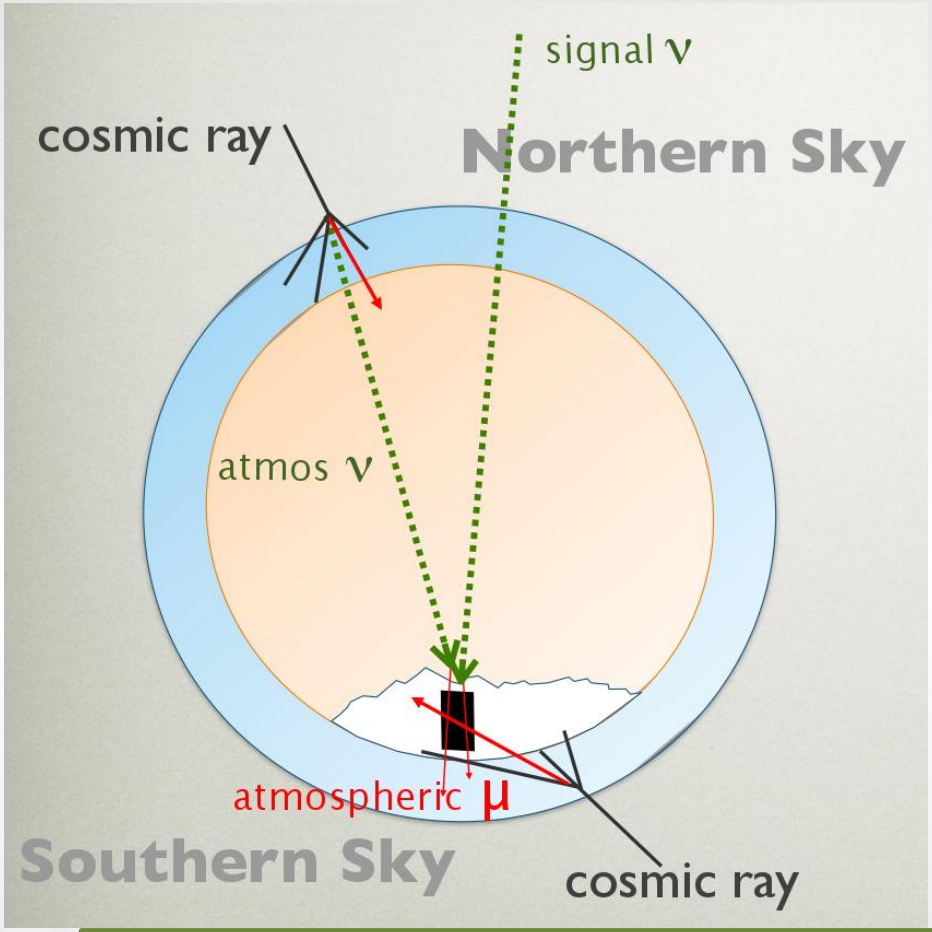


Digital **O**ptical **M**odule

- Volume: 1 km^3 of instrumented ice
- Detection principle: Amount of Cherenkov light produced by secondary charged particles



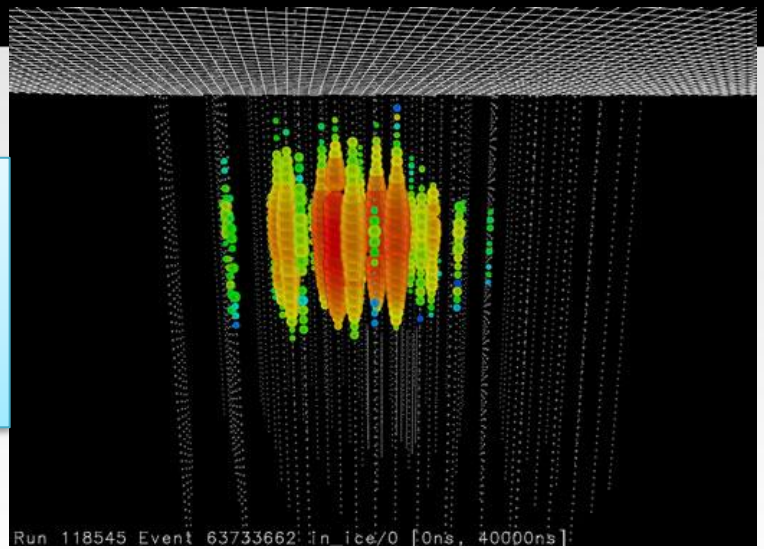
IceCube Events



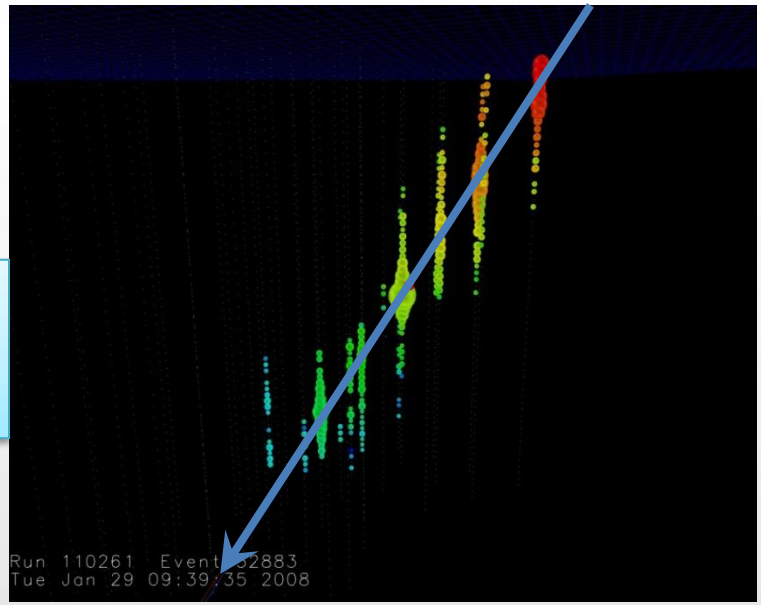
210 atmosferic neutrinos a day (Analysis

2.6 x 10^8 muon events a day (trigger rate)

Cascade



Track



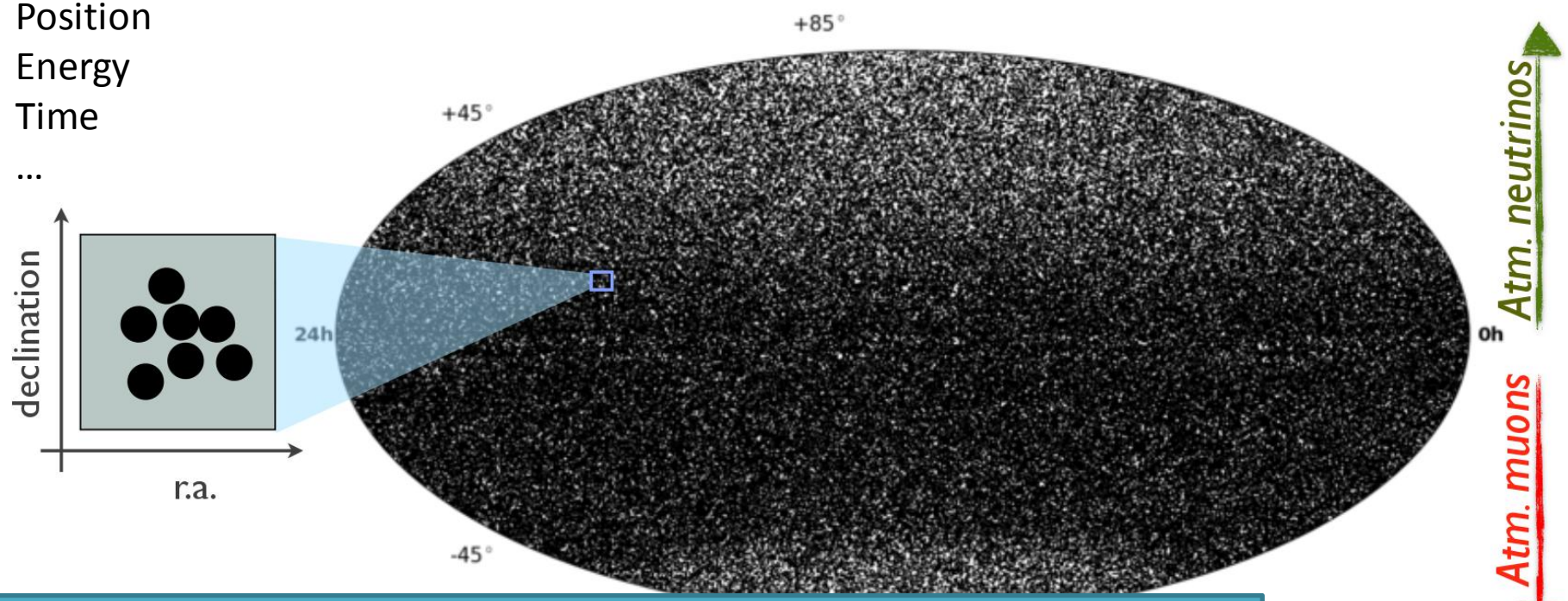
- The color indicates the time of the DOM registering photons: From early firing DOMs (red) to late ones (green), the size indicates the signal amplitude

The Event sample

The selection is based on track quality

After event selection we obtain a list of events with their properties:

- Position
- Energy
- Time
- …



Total Events (4 years): 394,000 (178k upgoing + 216k downgoing)
Livetime: 1371 days

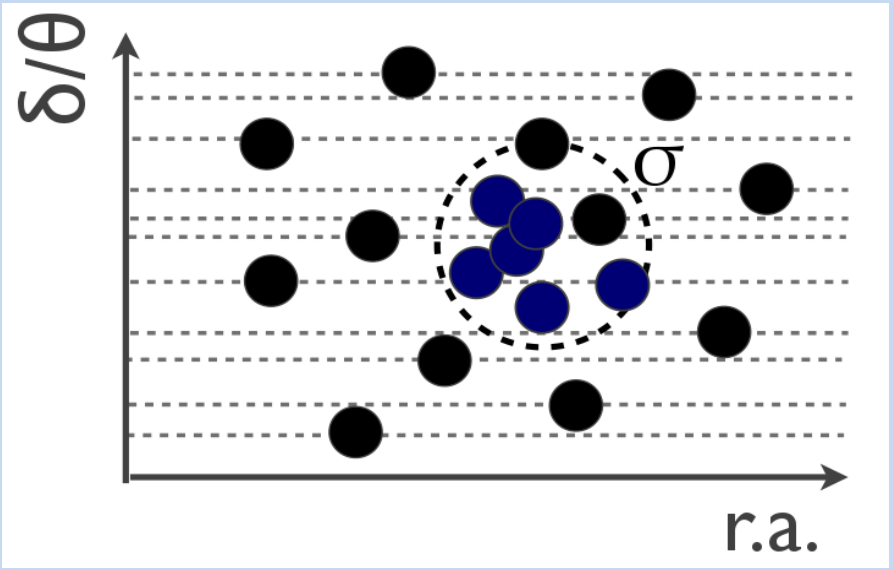
The un-binned Likelihood Method (1)

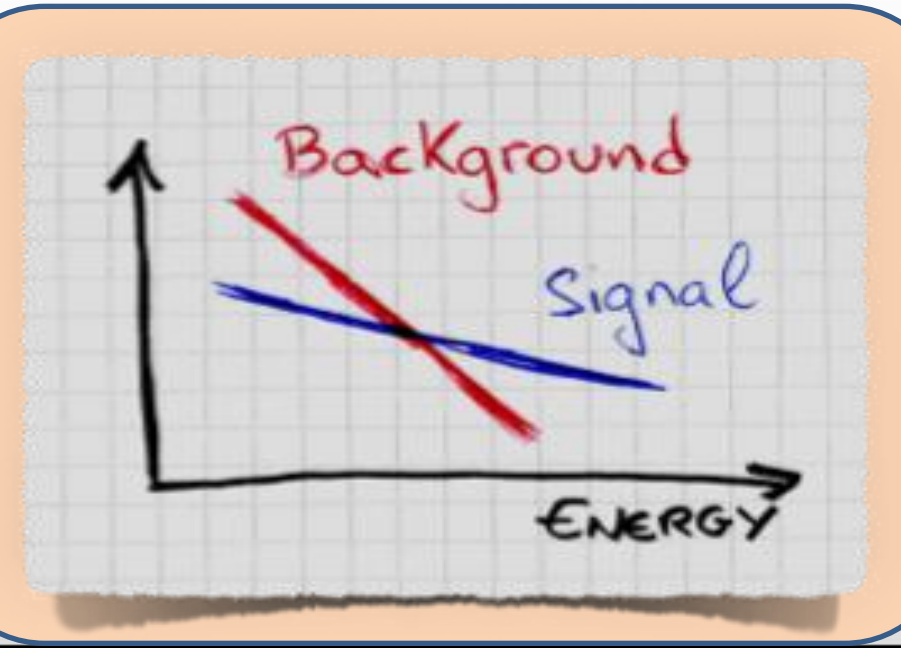
Signal PDF:

$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma)$$

Background PDF:

$$B_i = B(\theta_i) \cdot P_{atm}(E_i)$$





The un-binned Likelihood Method (2)

Signal PDF:

$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma)$$

Background PDF:

$$B_i = B(\theta_i) \cdot P_{atm}(E_i)$$

Likelihood

$$\mathcal{L}(n_s, \gamma) = \prod_{N}^{i=1} \left(\frac{n_s}{N} S_i(\gamma) + (1 - \frac{n_s}{N}) B_i \right)$$

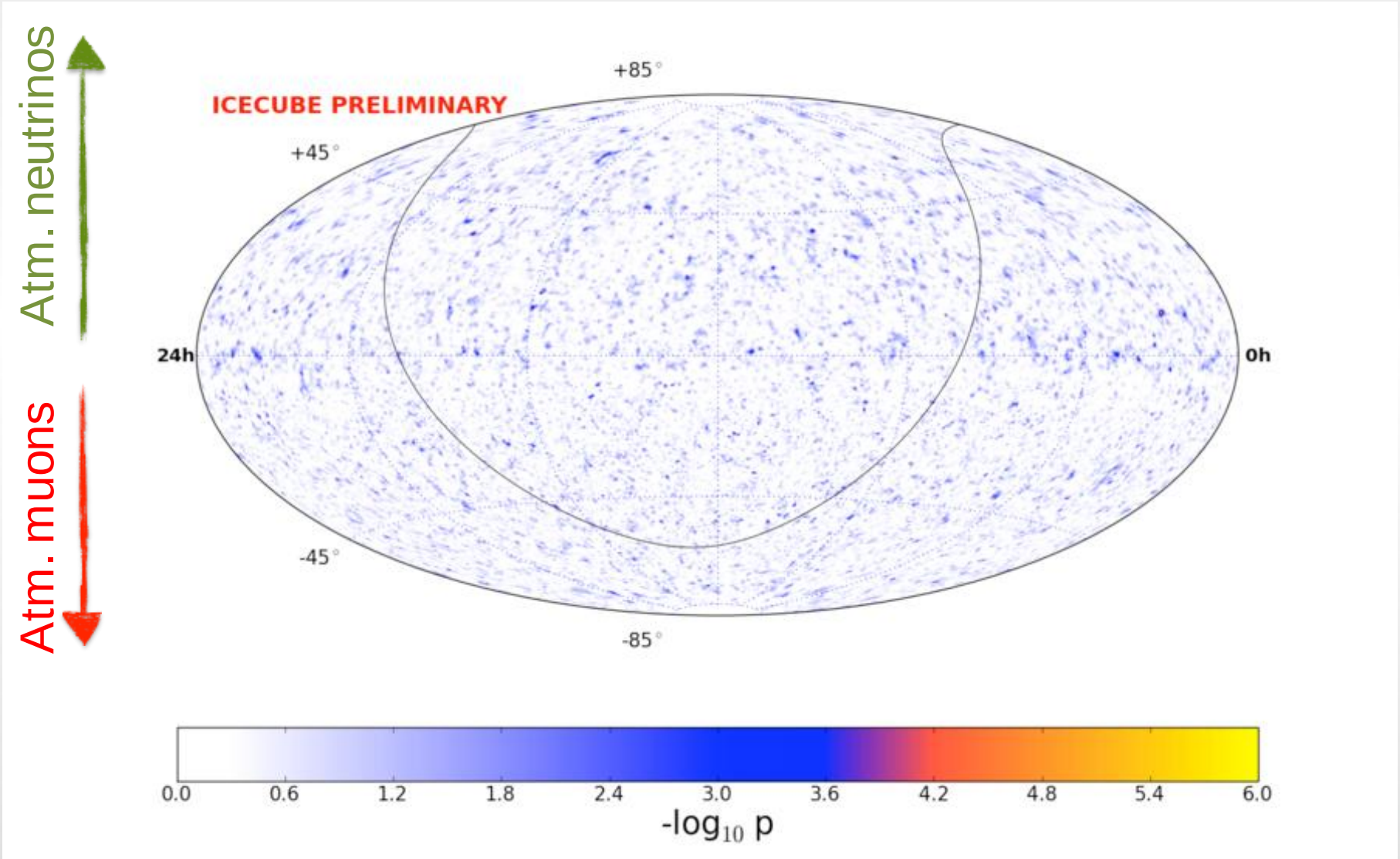
$$log\lambda = log\left(\frac{\mathcal{L}(\hat{\gamma}, \hat{n}_s)}{\mathcal{L}(n_s = 0)} \right)$$

Maximize the likelihood ratio with respect to γ, n_s to obtain the values (estimates) $\hat{\gamma}, \hat{n}_s$

The significance is obtained by repeating the analysis on "scrambled" data

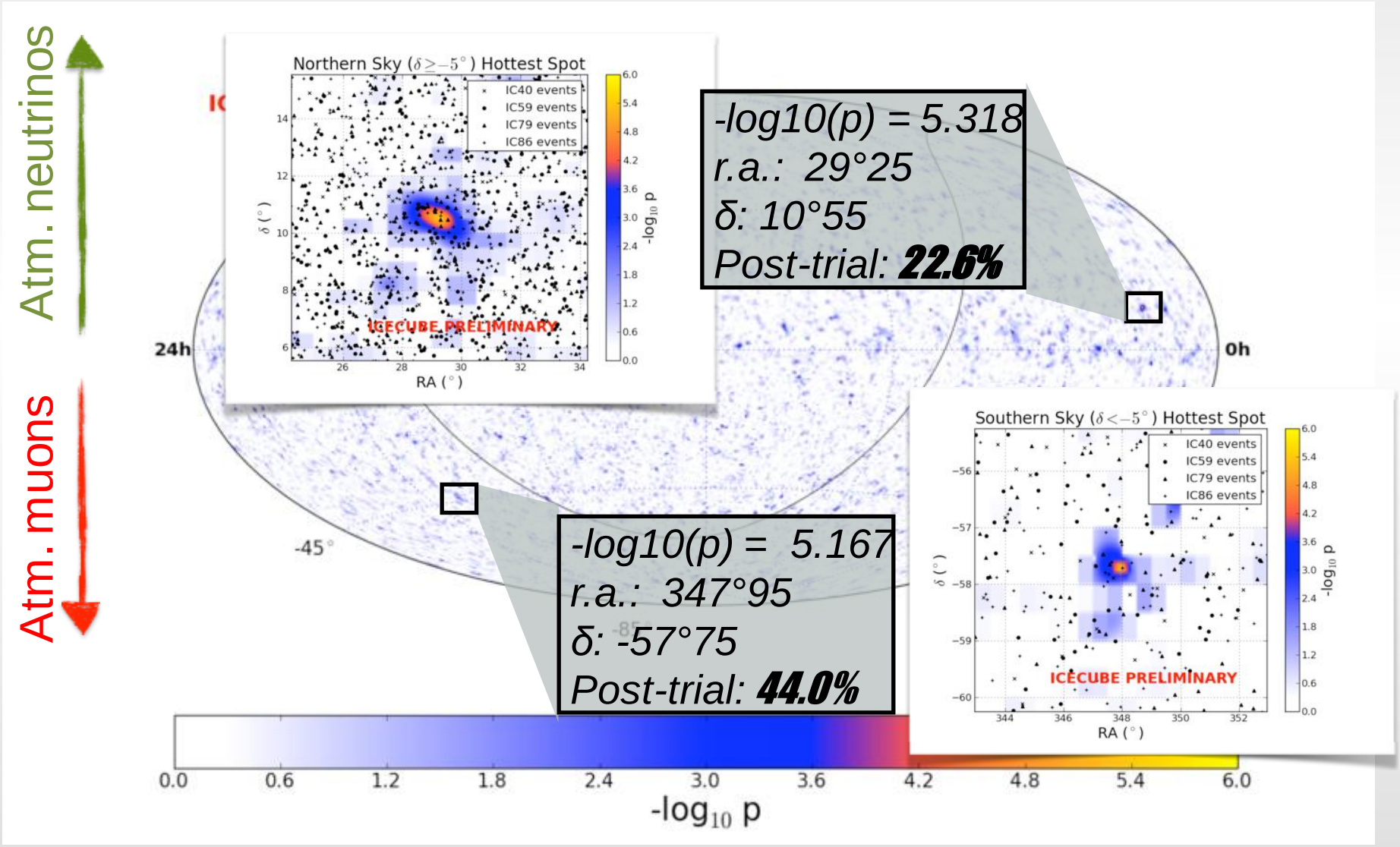
Point Source Search Skymap

4 years



Point Source Search Skymap

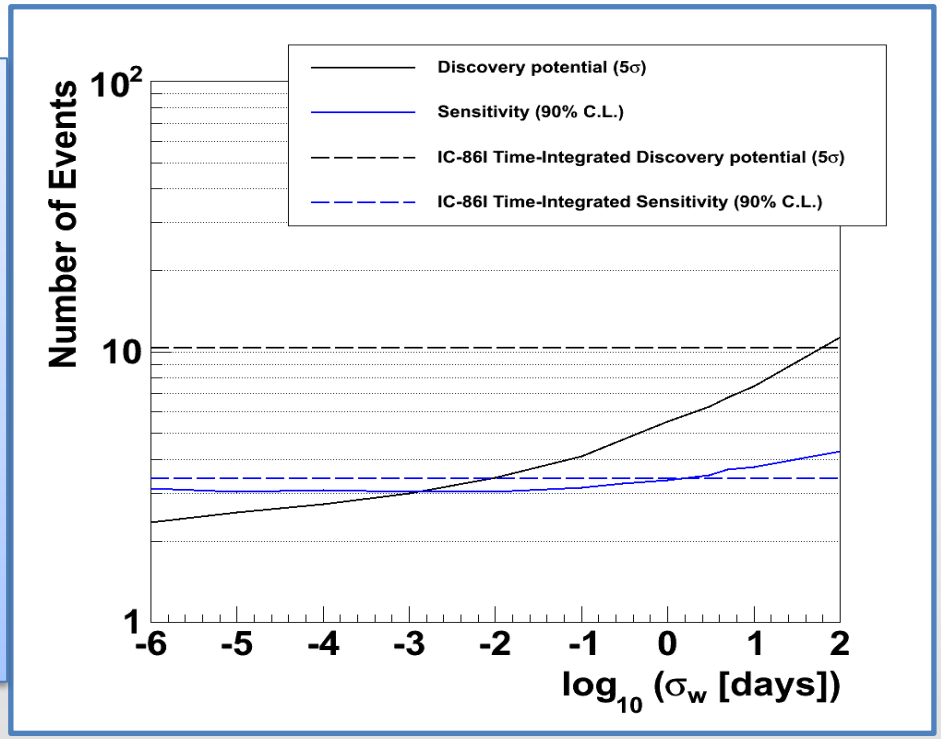
4 years

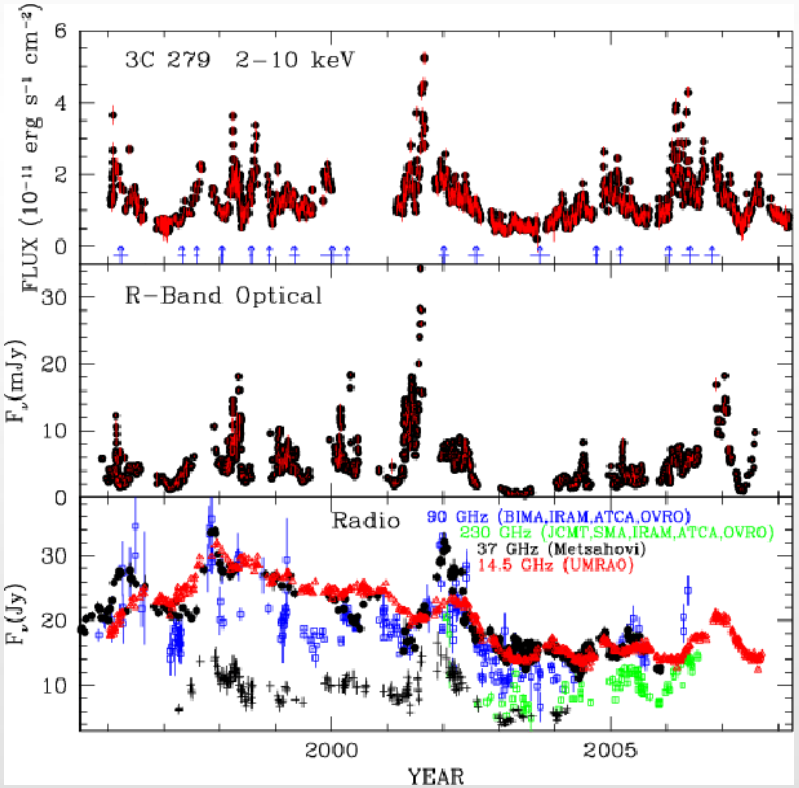


Time dependent point source searches

- The background is constant in time
- Potential sources (i.e. Blazars) show high variability in multiple wavelengths
- Might be variable in neutrinos
- Clustering/correlations of the neutrino arrival times can distinguish them from background

Discovery potential
All sky Time Dependent search





Time Dependent Searches – All sky scan

Lets start with generic search:

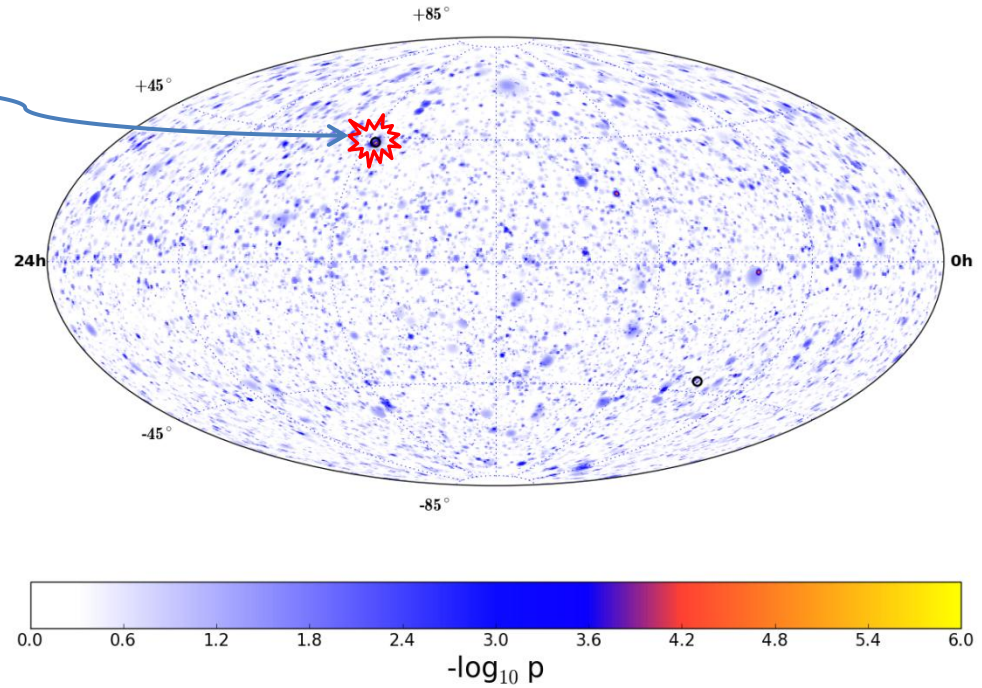
Gaussian in time

Signal PDF:

$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma) \qquad \frac{1}{\sqrt{(2\pi)}\sigma_T} exp\left(-\frac{(t_i - T_0)^2}{2\sigma_T^2}\right)$$

-log10(p) = 5
Ra: 236, Dec: 43
Width: 7.5 days

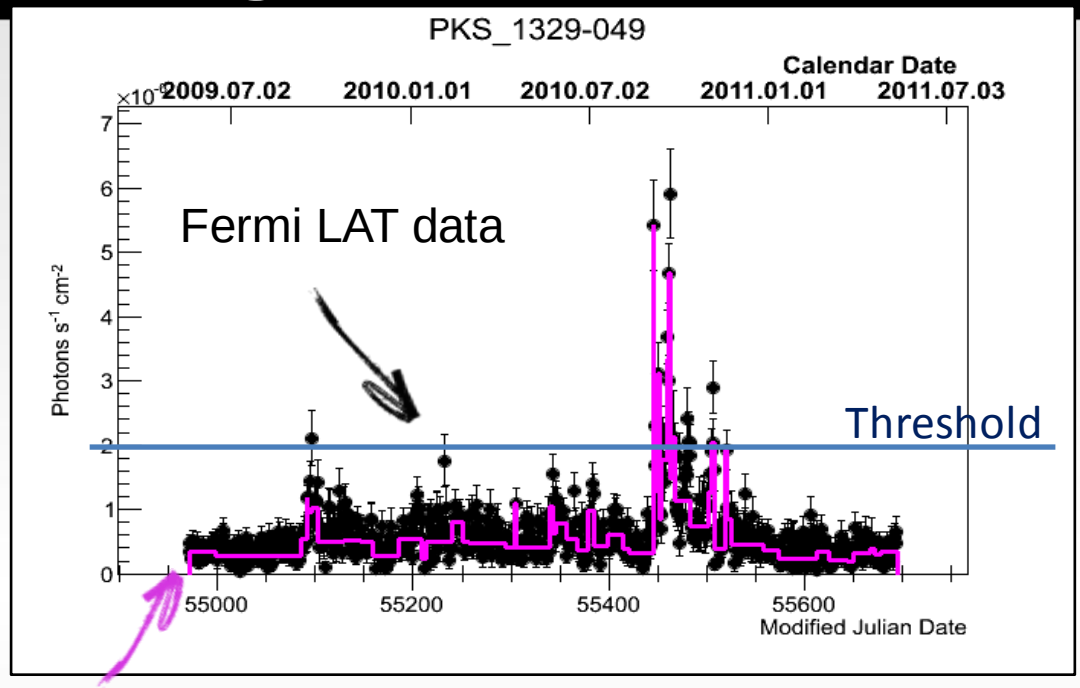
Sky map of significances



- Only IC86-I sample.
- The most significant spot post trial p-value = 0.63

Triggered Multi-Wavelength Flares

Hypothesis: neutrino & gammas produced at same time (with ±1/2 d tolerance)



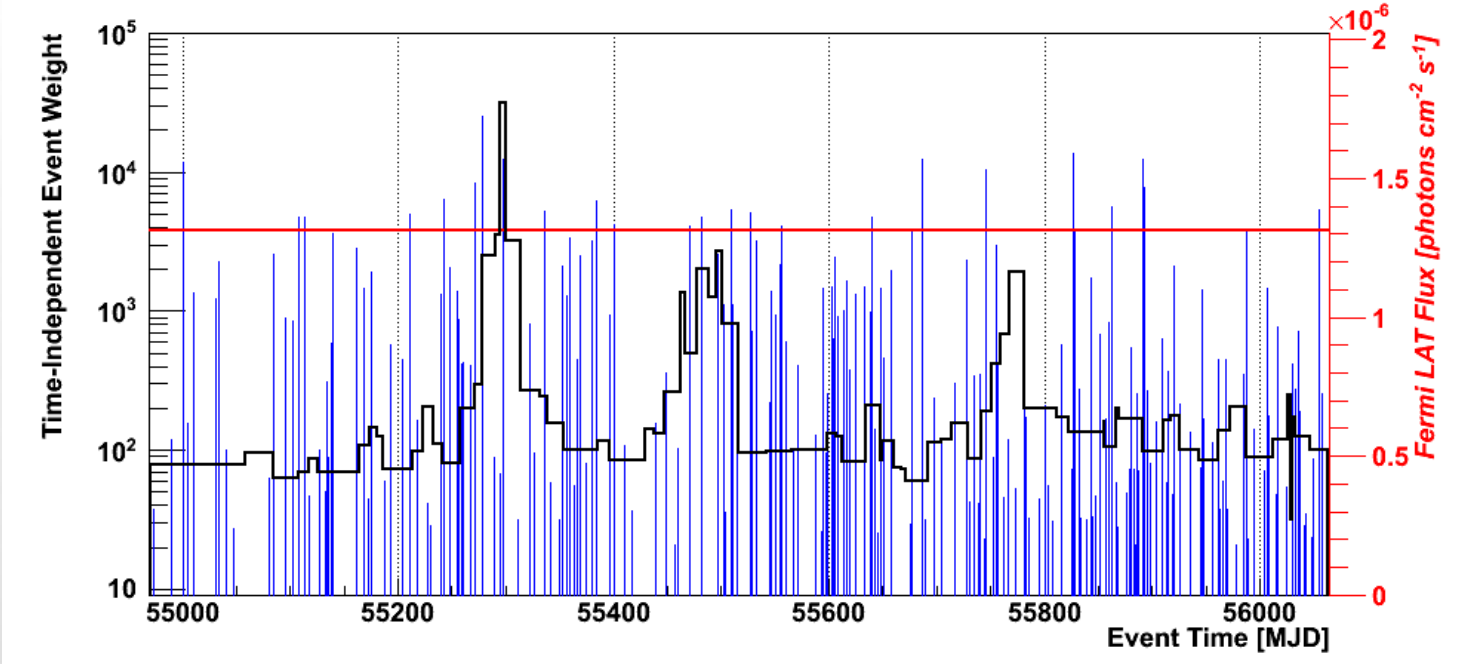
LLH fit parameters:

- Spectral index
- Number of signal events
- Threshold
- Lag (allowed ± half day)

$$log\lambda = log\left(\frac{\mathcal{L}(\hat{\gamma}, \hat{n_s}, \hat{th}, \hat{lag})}{\mathcal{L}(n_s = 0)}\right)$$

Results

- The most significant source PKS 2142-75
  - Pre-trial p-value: 2.3%
  - Post-trail p-value: 77% → fully compatible with the Bkg only hypothesis
  - Best fit: n_s: 1.9, gamma 3.95



Conclusions

- No evidence yet for point sources or time dependent point sources
- IceCube sensitivity approaching interesting regions
- Time Dependent searches and the event selection process are being modified to run on monthly basis.