Point Source Searches with the IceCube Detector

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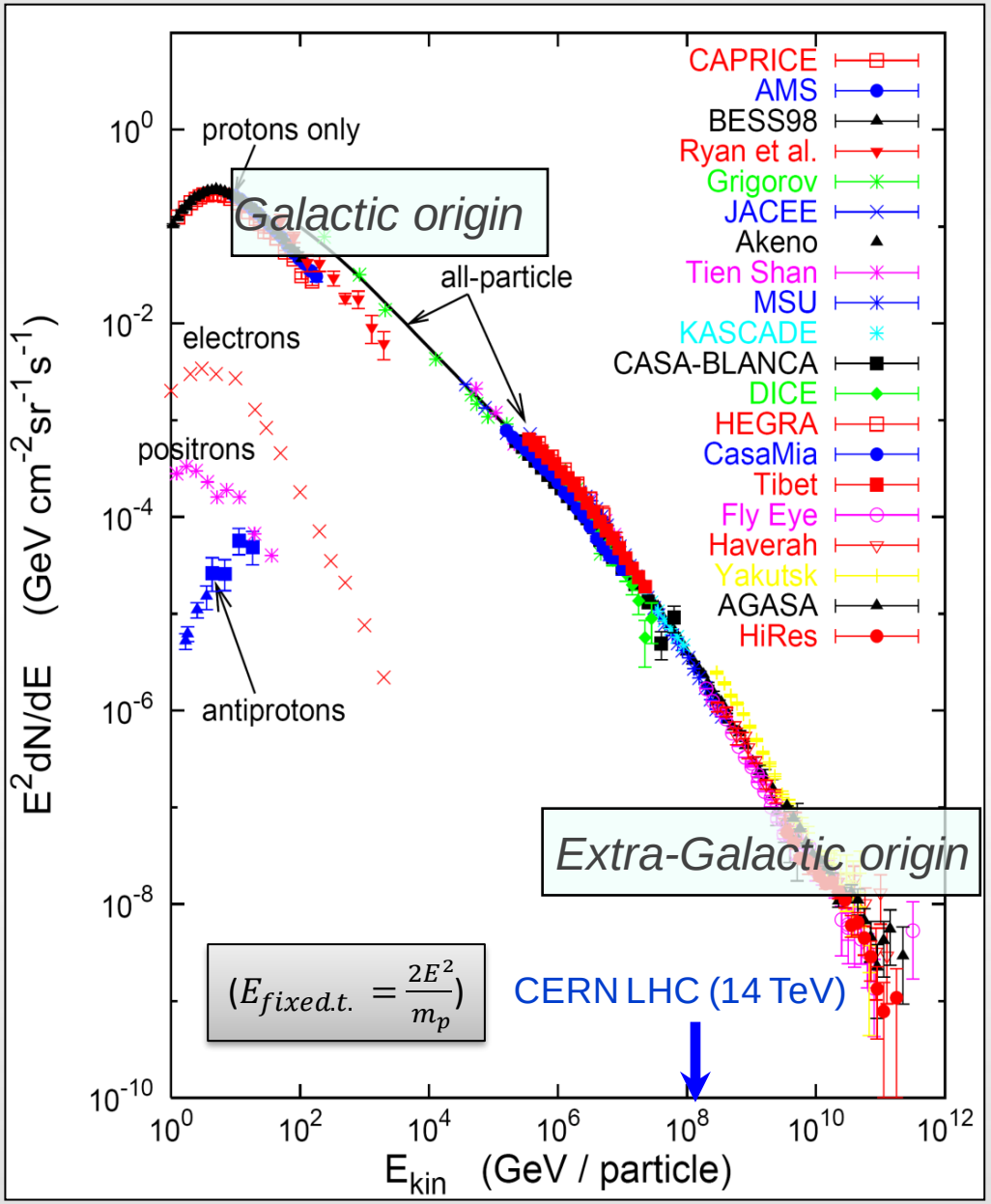
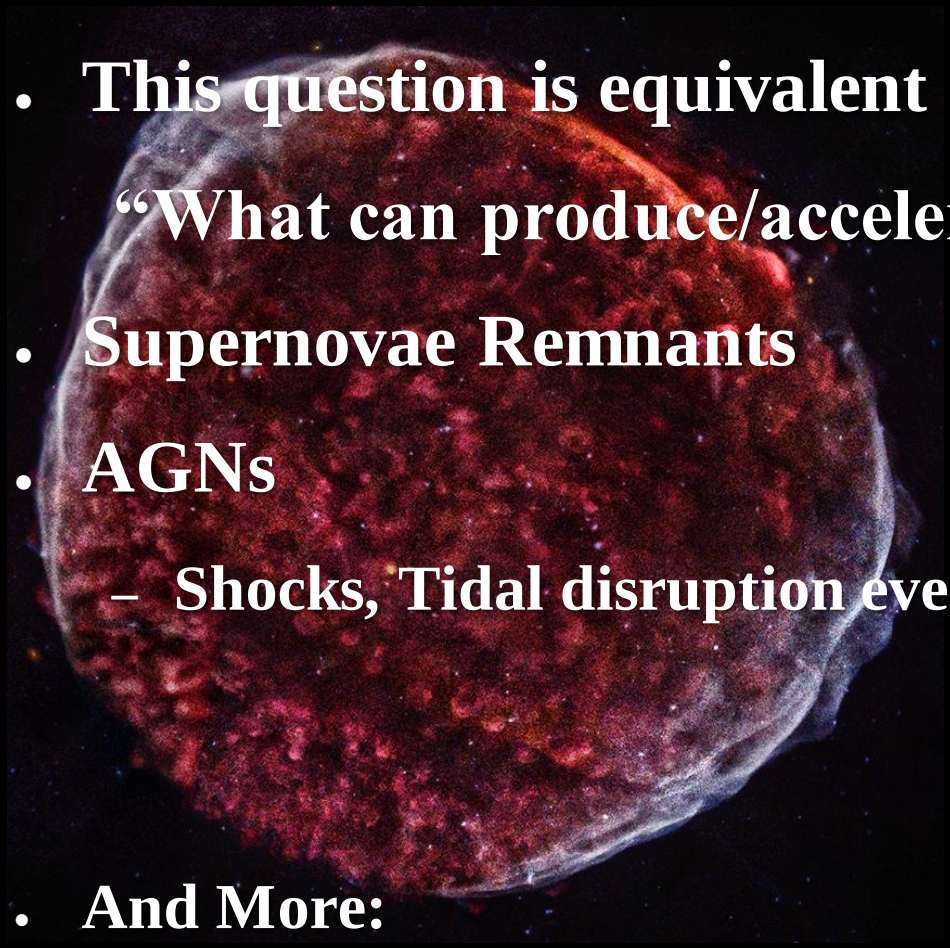
IceCube SOUTH POLE NEUTRINO OBSERVATORY

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!



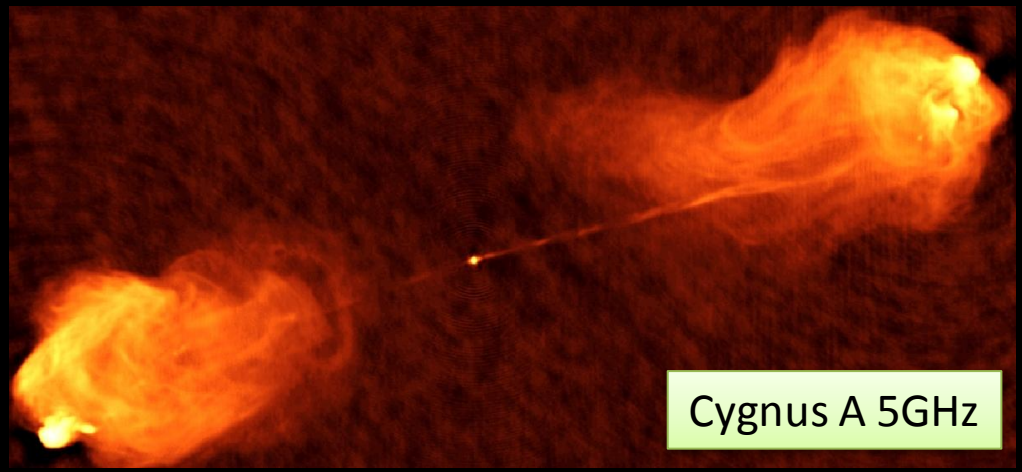
Candidates for CR sources?



- **This question is equivalent to:**

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

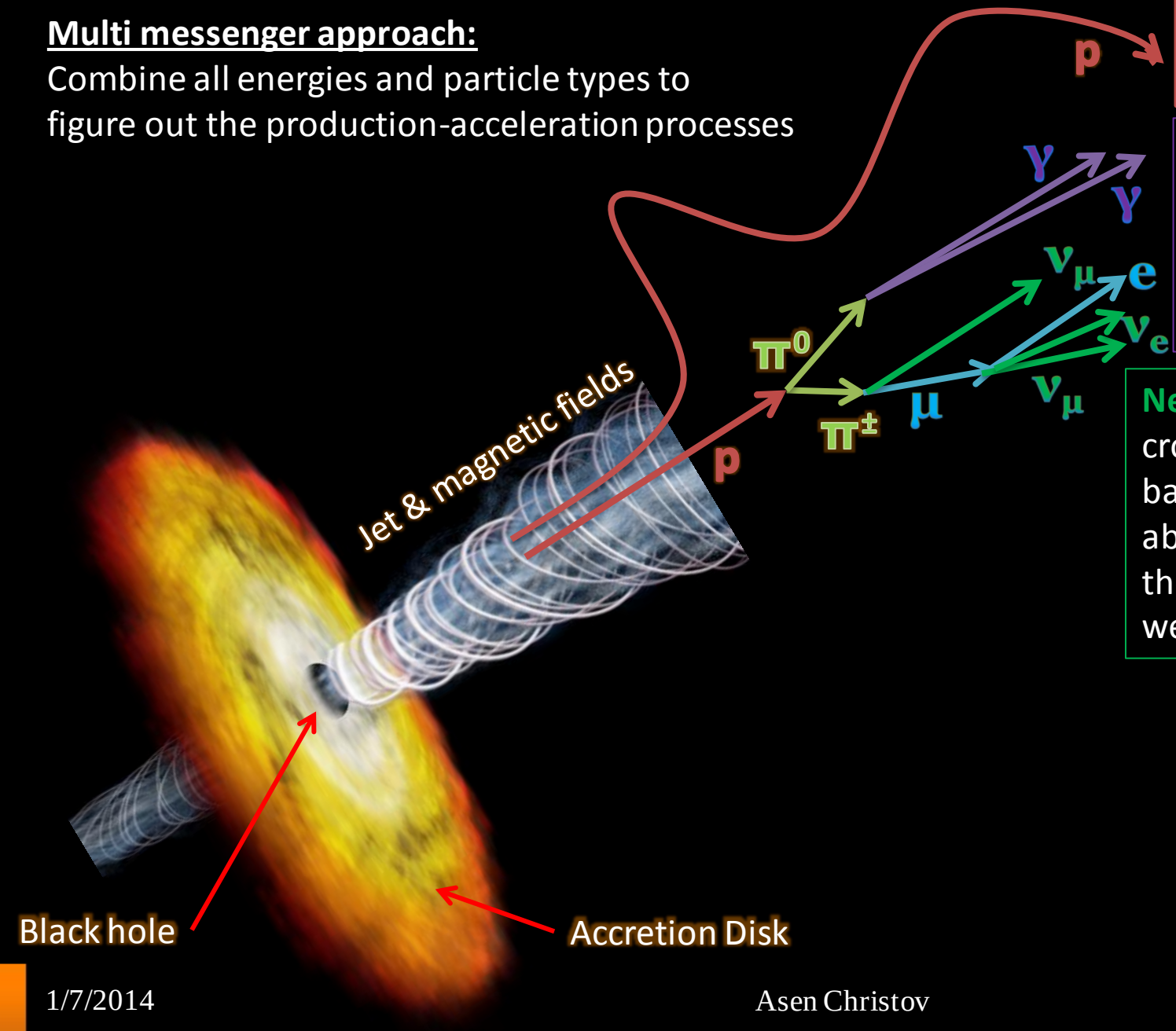
- **Supernovae Remnants**
- **AGNs**
  - **Shocks, Tidal disruption events**



- **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

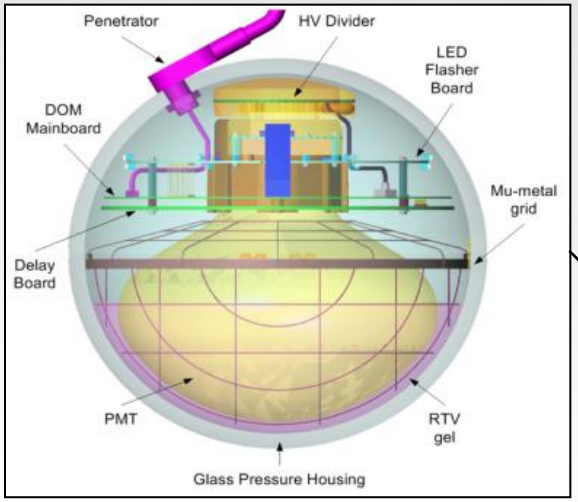


Protons: **Deflected by magnetic fields (above EeV energies negligible)**

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

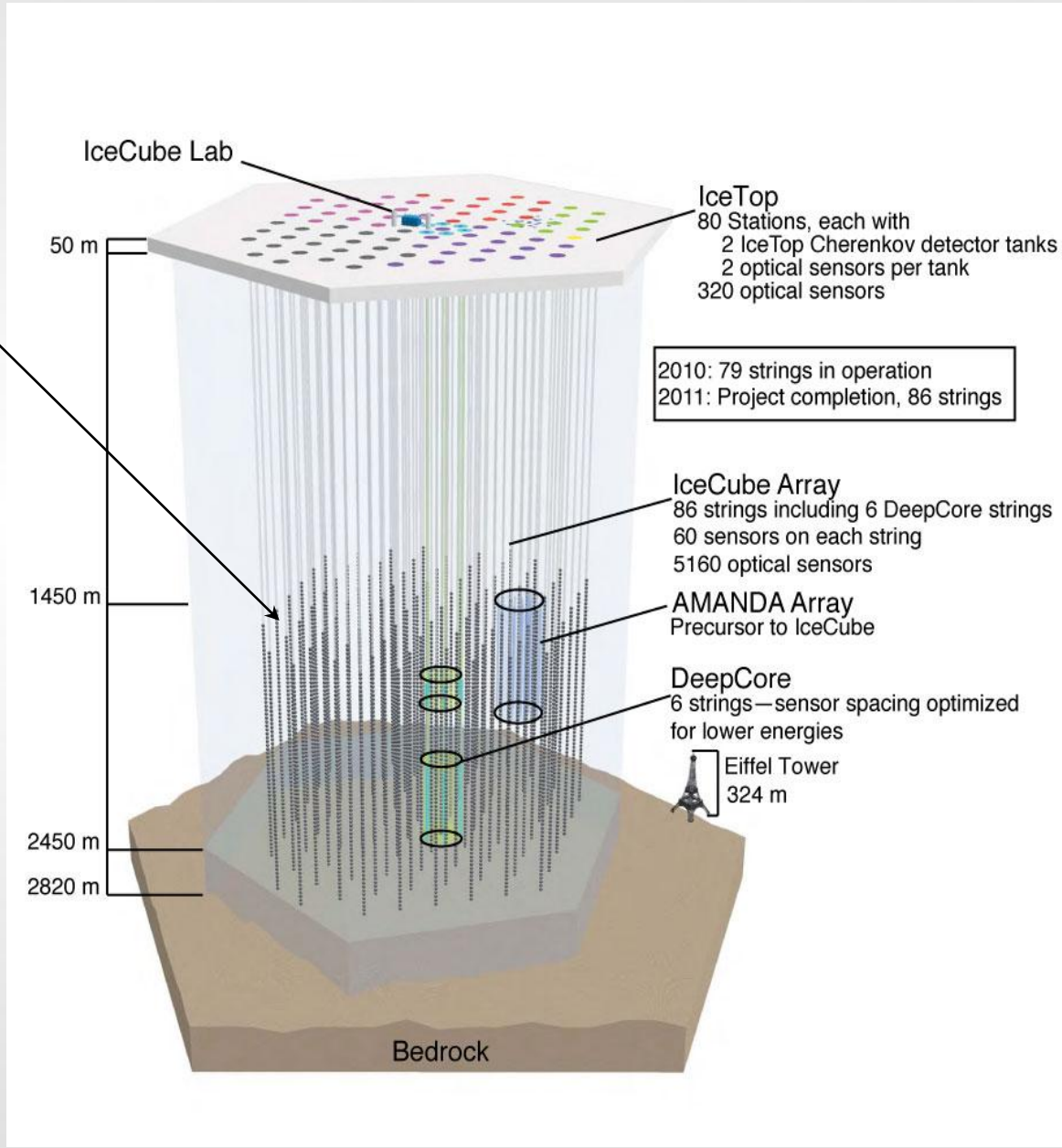
Neutrinos: No charge and low cross-section mean they point back to source and are not absorbed. Moreover they tell us the source accelerated particles were hadrons (protons or nuclei)

The IceCube Detector - Layout

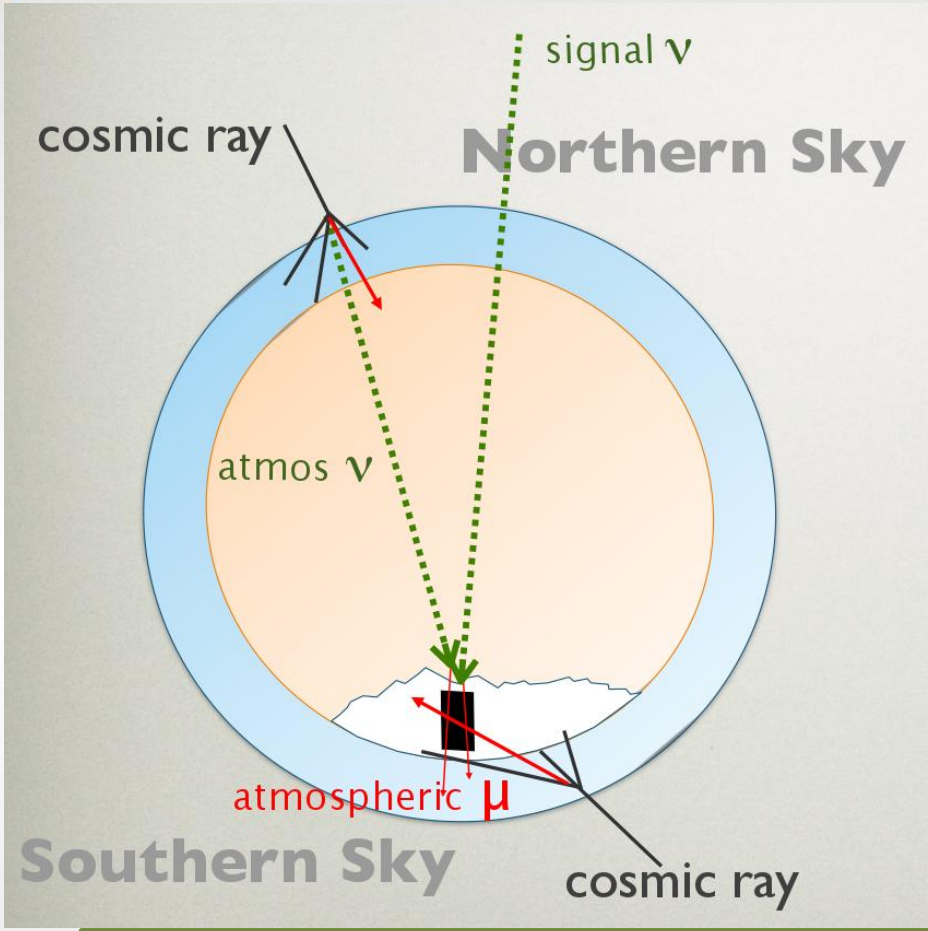


Digital **O**ptical **M**odule

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



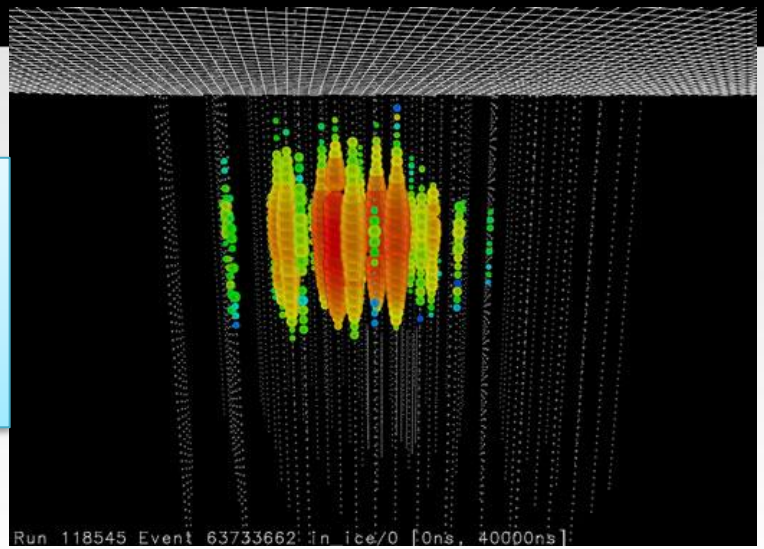
IceCube Events



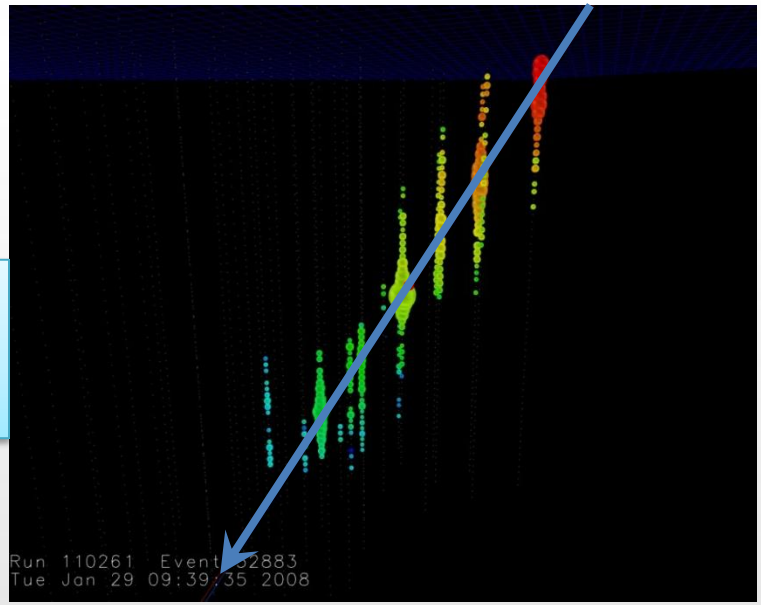
210 atmosferic neutrinos a day (Analysis

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

Cascade



Track



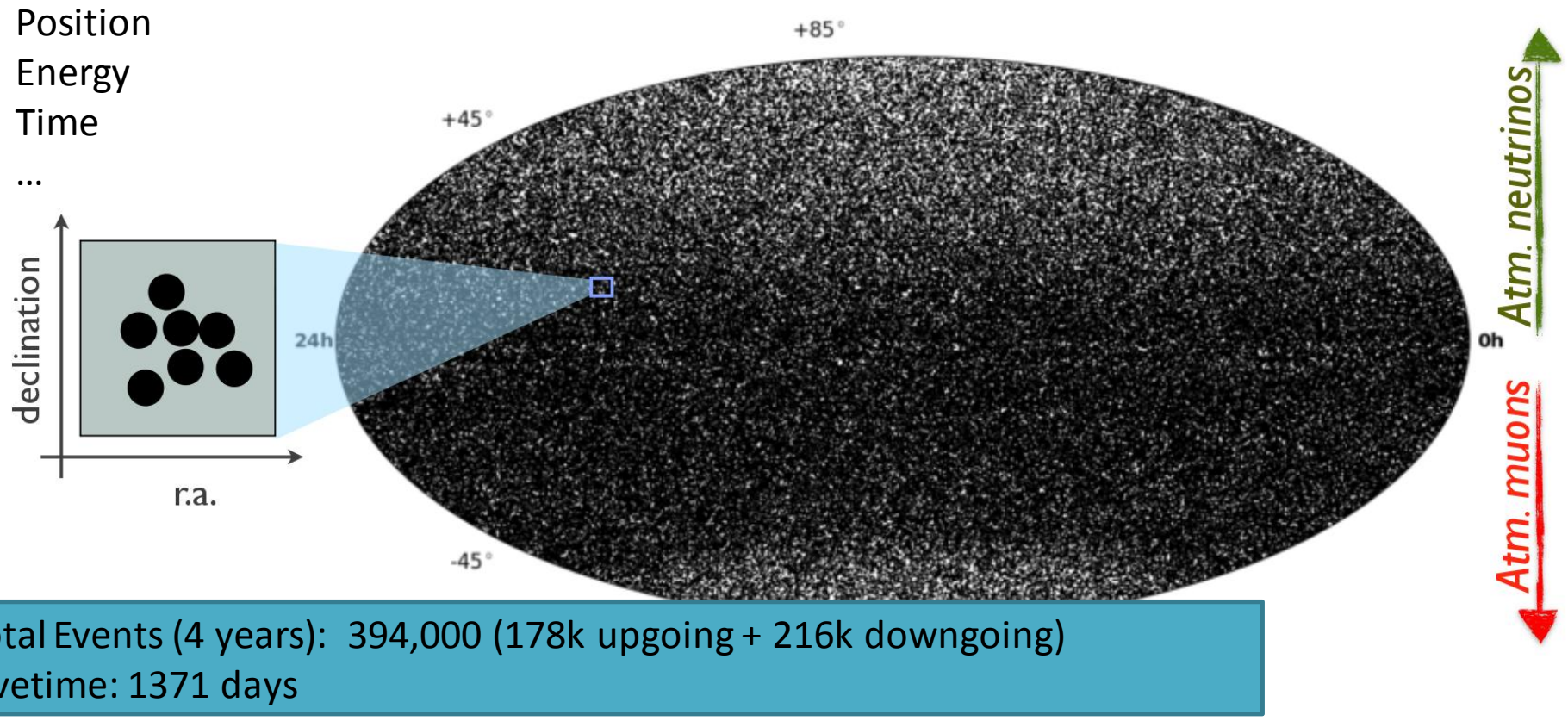
- The color indicates the time of the DOM registering photons: From early firing DOMs (red) to late ones (green), the size indicates the signal amplitude

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

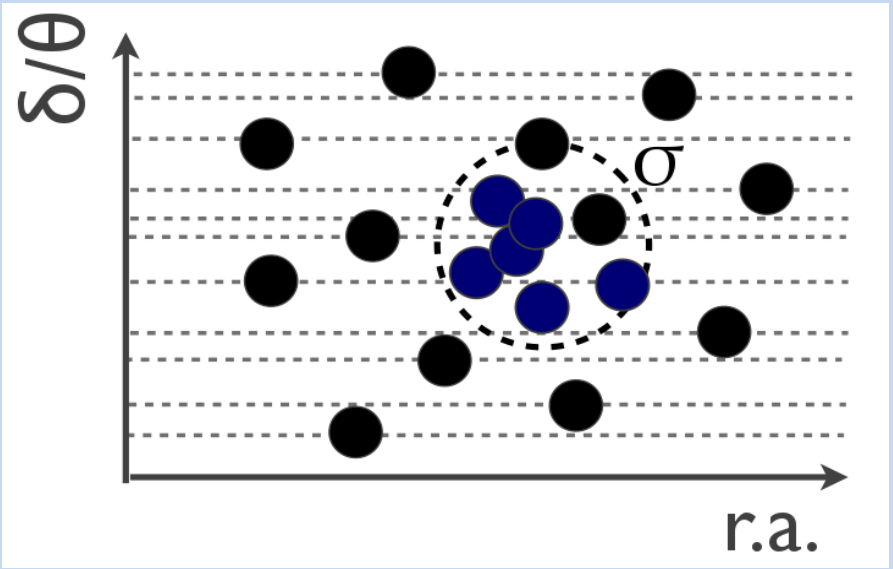
The un-binned Likelihood Method (1)

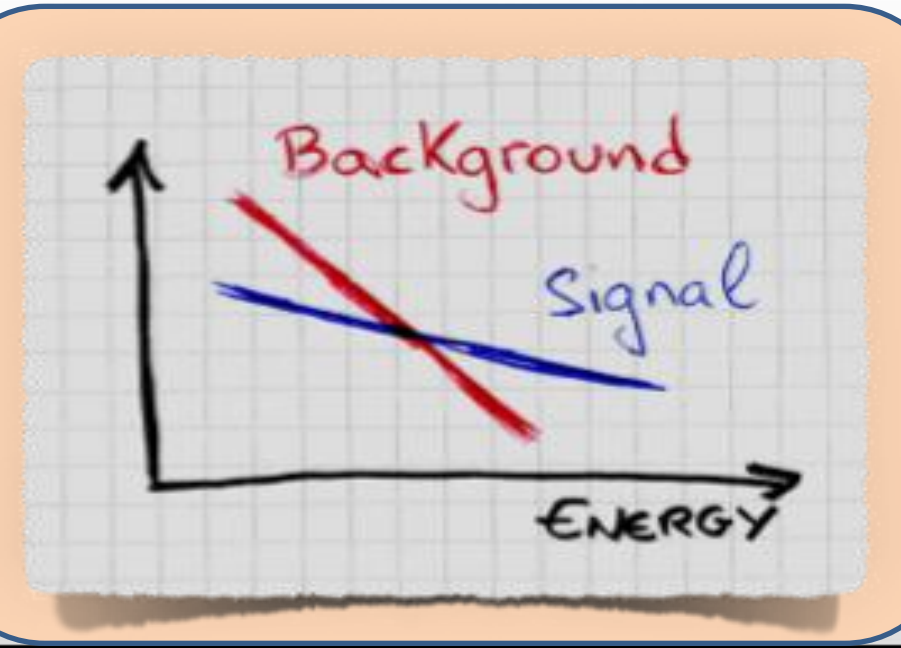
Signal PDF:

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

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

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

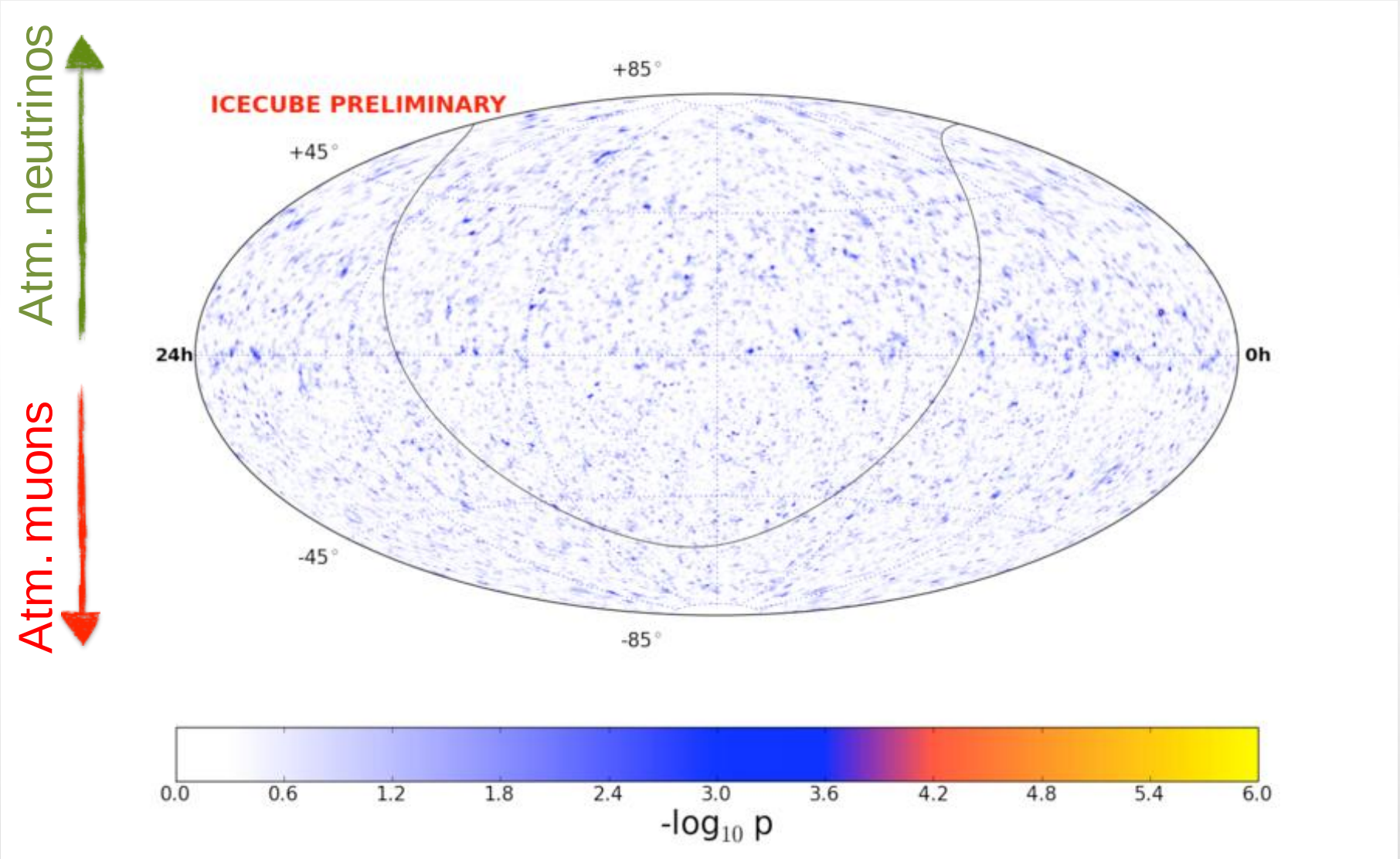
$$log\lambda = log\left(\frac{\mathcal{L}(\hat{\gamma}, \hat{n}_s)}{\mathcal{L}(n_s = 0)} \right)$$

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

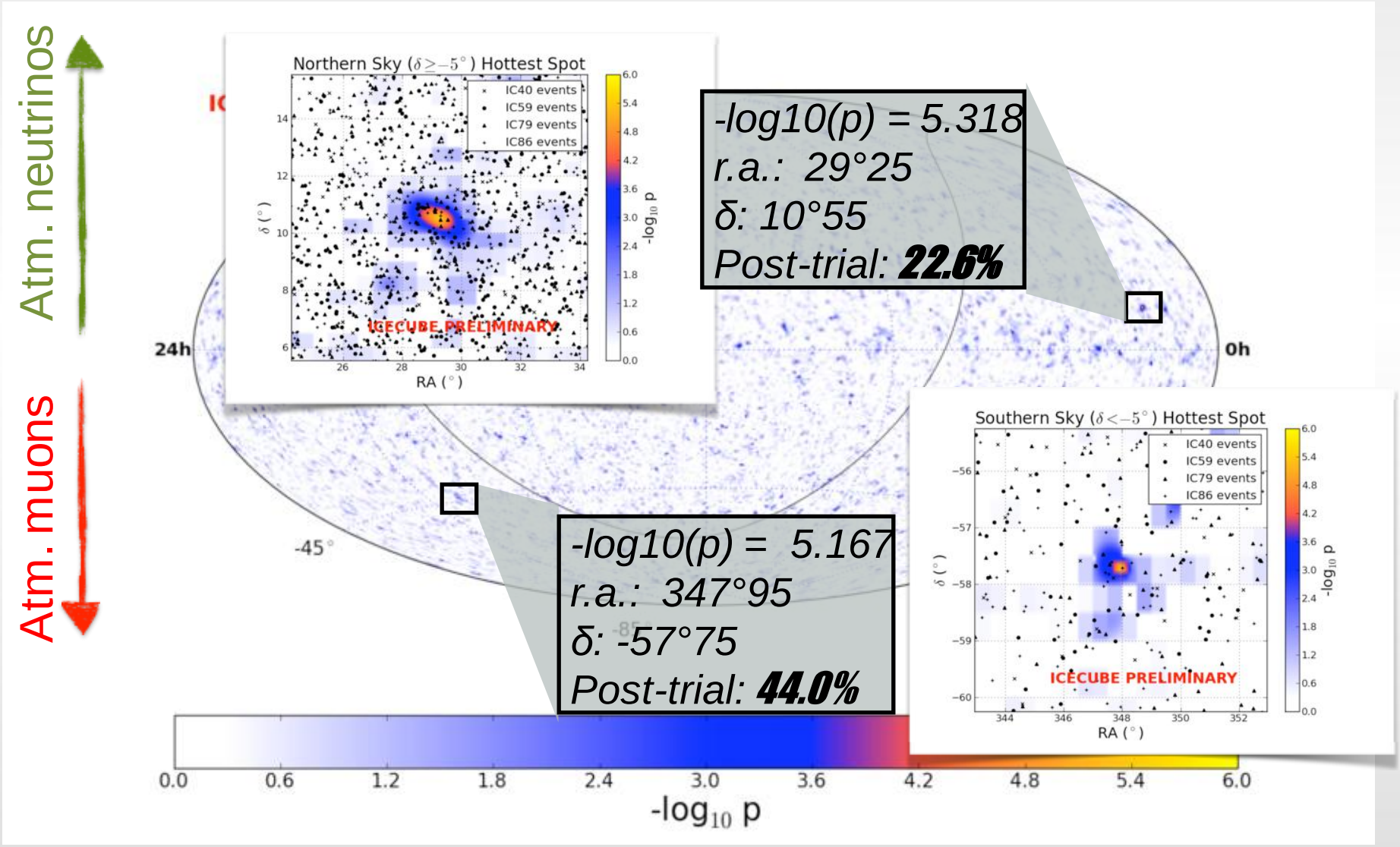
Point Source Search Skymap

4 years



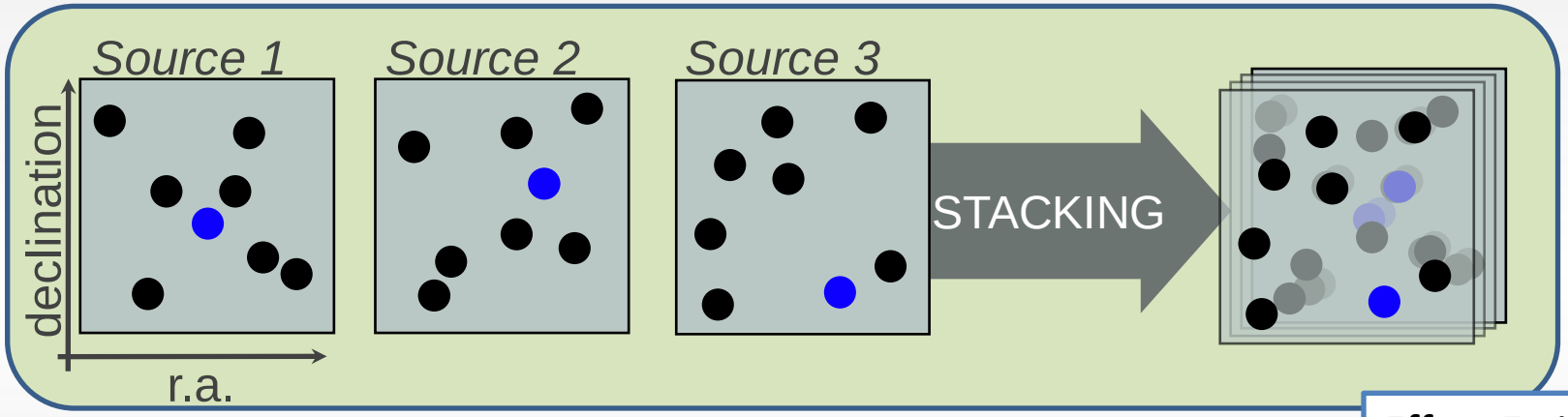
Point Source Search Skymap

4 years



Stacking Searches (1)

- Analysis using the PS sample
- Select a catalog of sources, based on potential neutrino production mechanism
- "Stack" them together to enhance the discovery potential



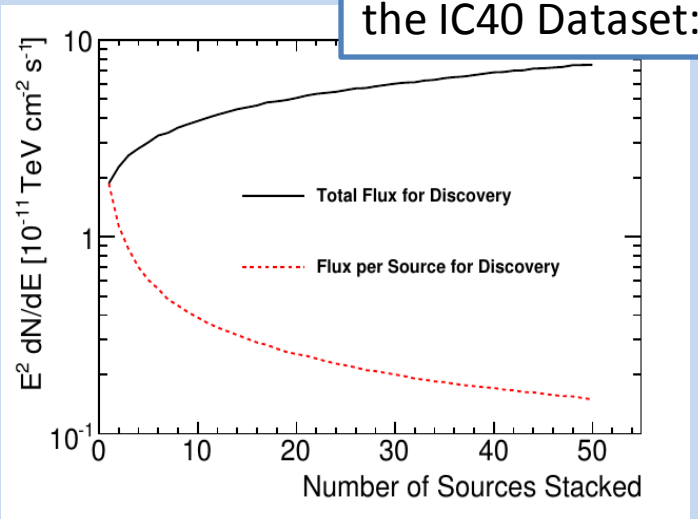
$$S_i = \sum_{j=1}^{N} W^j R^j(\gamma) S_i^j(r_i, E_i)$$

Signal PDF

Source Weight

Detector Acceptance

Effect Estimated on the IC40 Dataset:



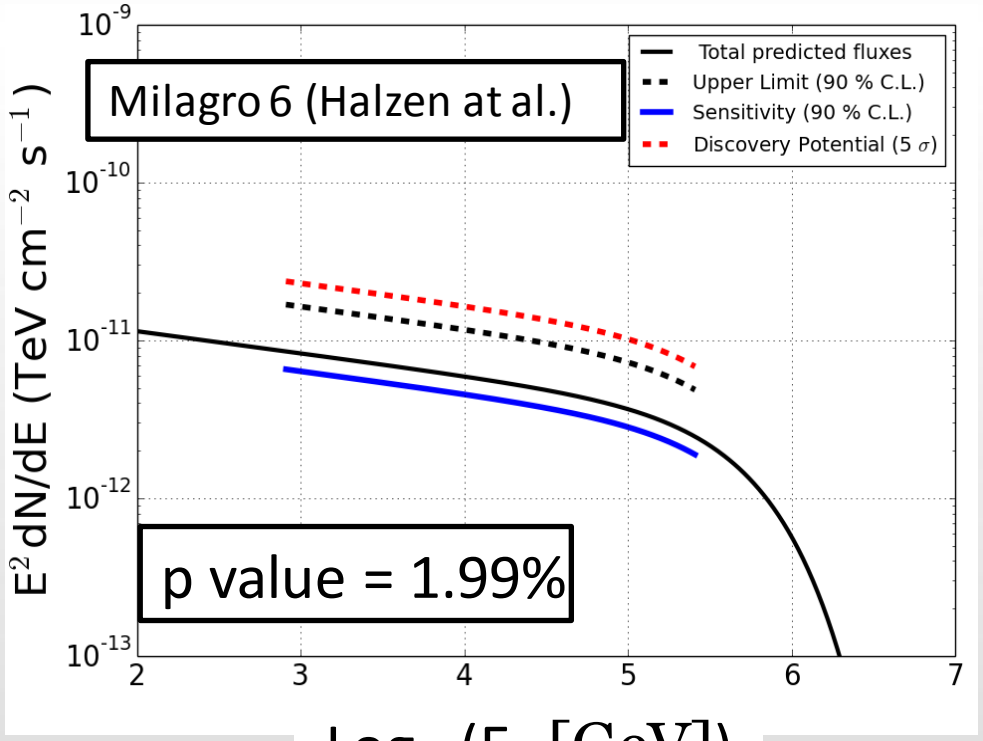
Stacking Searches (2)

- Performed on several catalogues:
  - "127 Starburst Galaxies", SNRs with Molecular Clouds Associations, …
- Most interesting result: "Milagro 6":
  - 6 sources of TeV photons with SNR Associations Reported by Milagro Collaboration. 5 detections, 1 excess. (arXiv:0705.0707)

p value	: 1.99%
n_s fitted	: 51
γ fitted	: 3.95

Significance Evolving over time

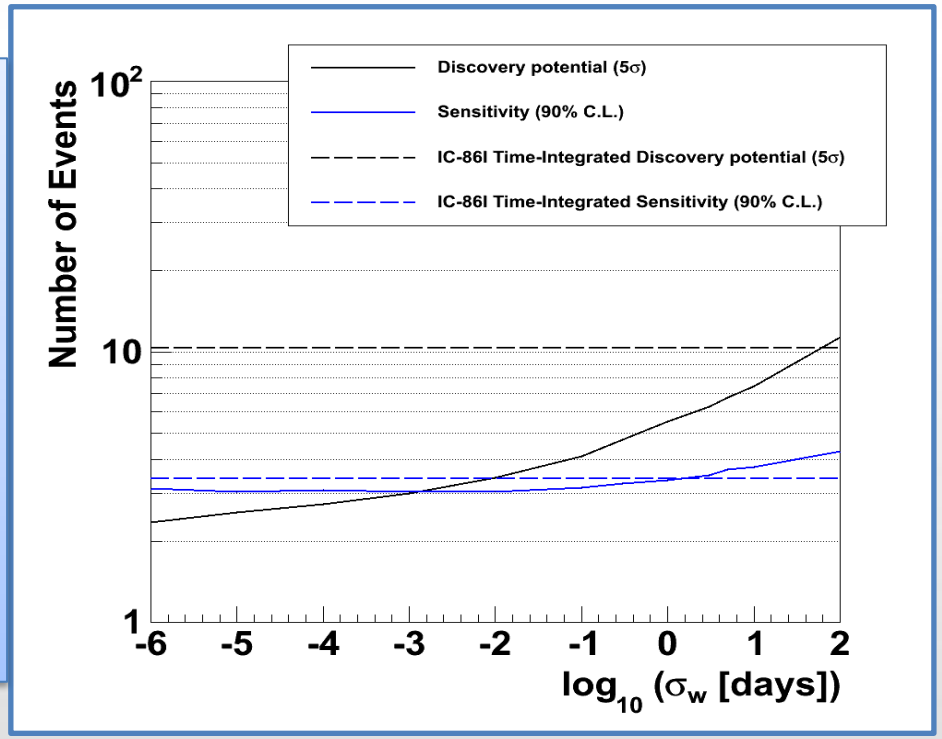
IC40	: 2% (a posteriori)
IC59	: >= 50%
IC79+59	: 20.4%
IC86-1 + 79 + 59	: 1.99%

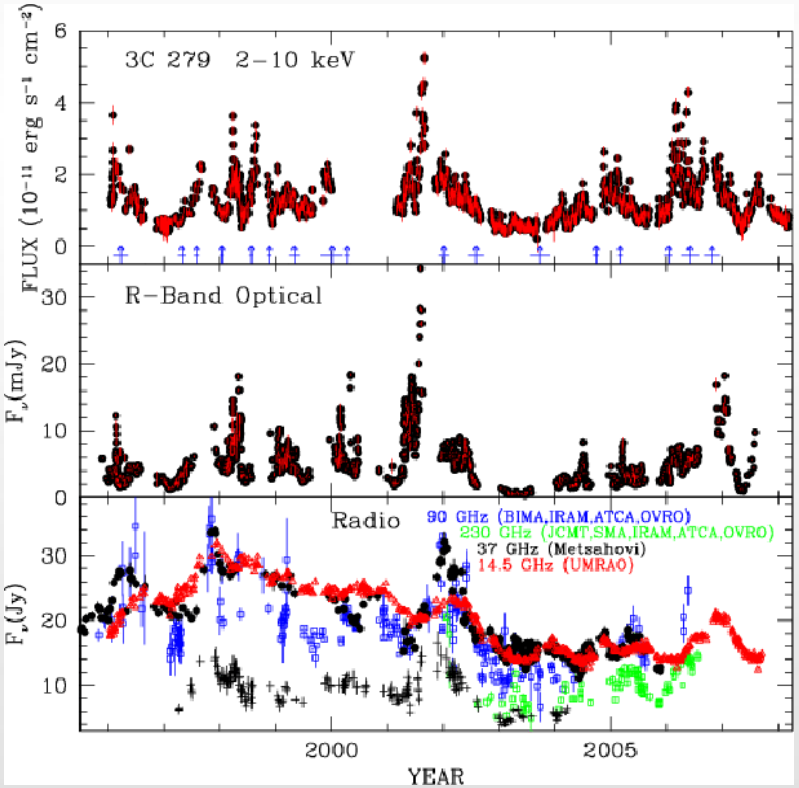


Time dependent point source searches

- 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:

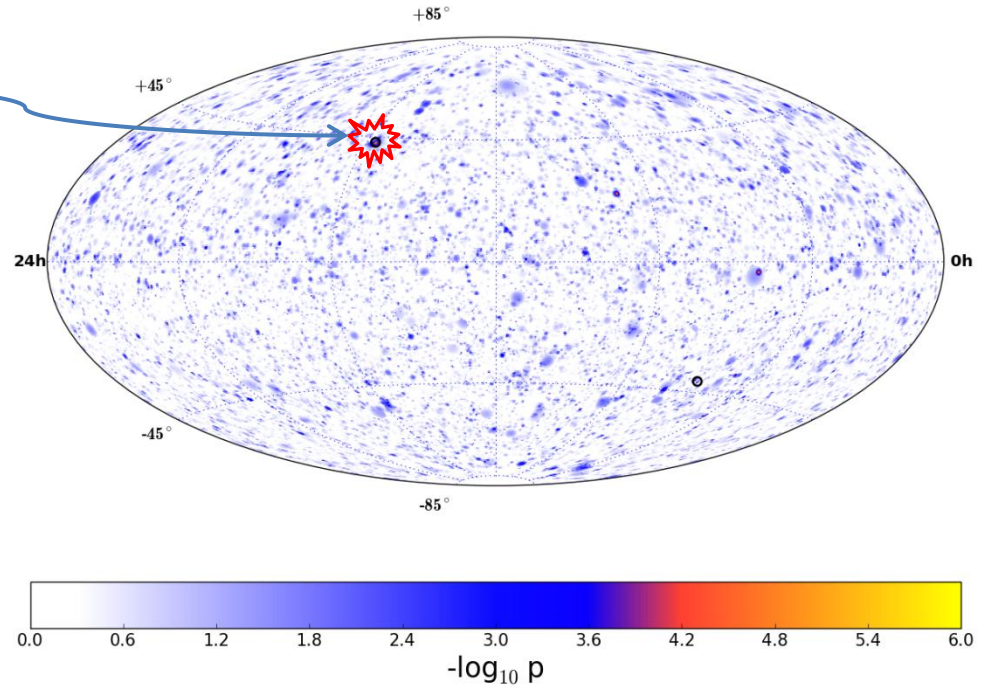
Gaussian in time

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

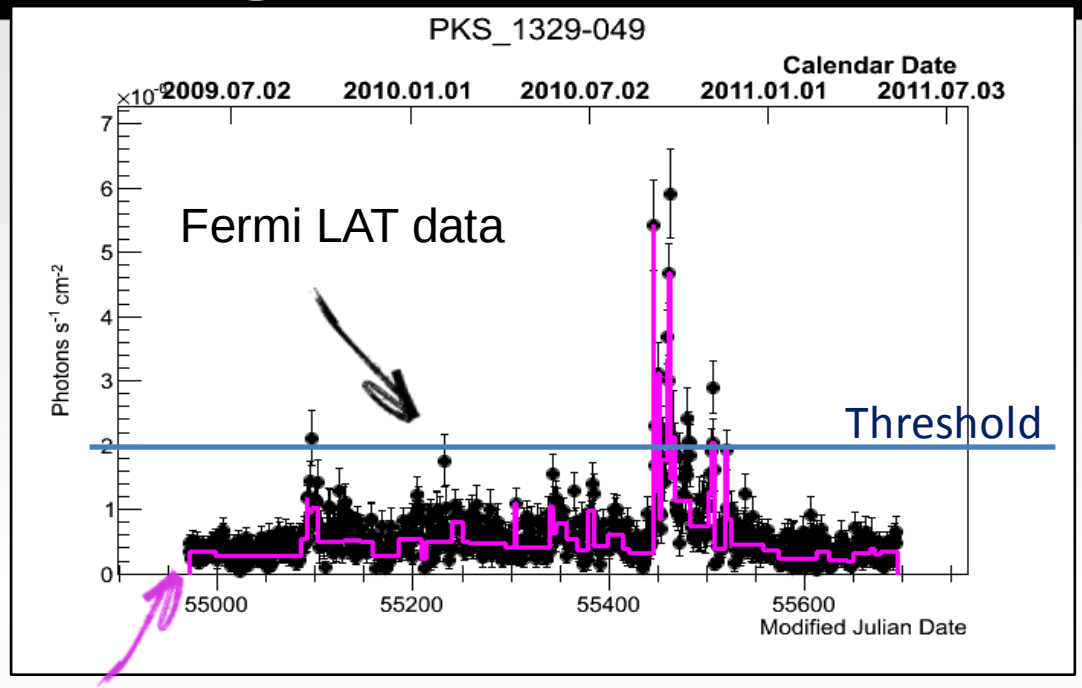
Sky map of significances



- 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:

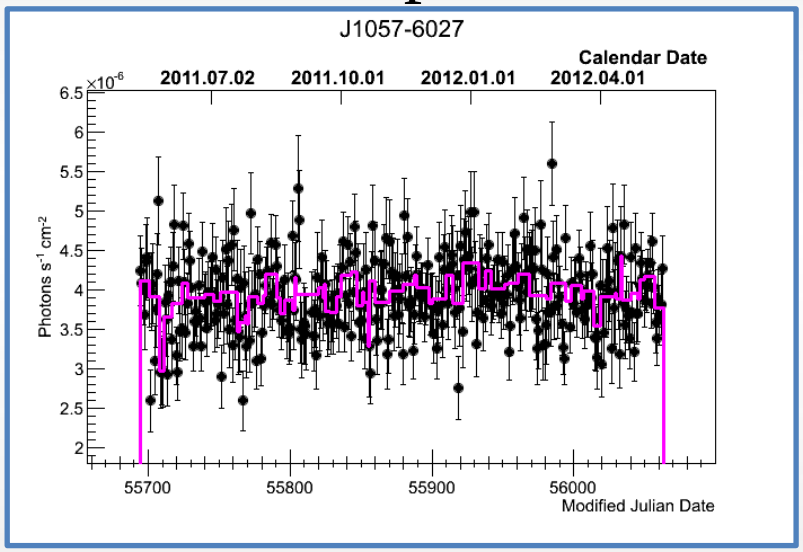
- Spectral index
- Number of signal events
- Threshold
- Lag (allowed ± half day)

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

Flare list selection procedure

- Starting point: Fermi LAT Monitored Source List
- Get the lightcurves, apply the Bayesian Blocks de-noising
- Selection cut: de-noised lightcurve must reach 10^{-6} ph cm^{-2} s^{-1}

- We reduced the Fermi LAT monitored list, but not all selected lightcurves are useful …
- Select only the once with significant time variations

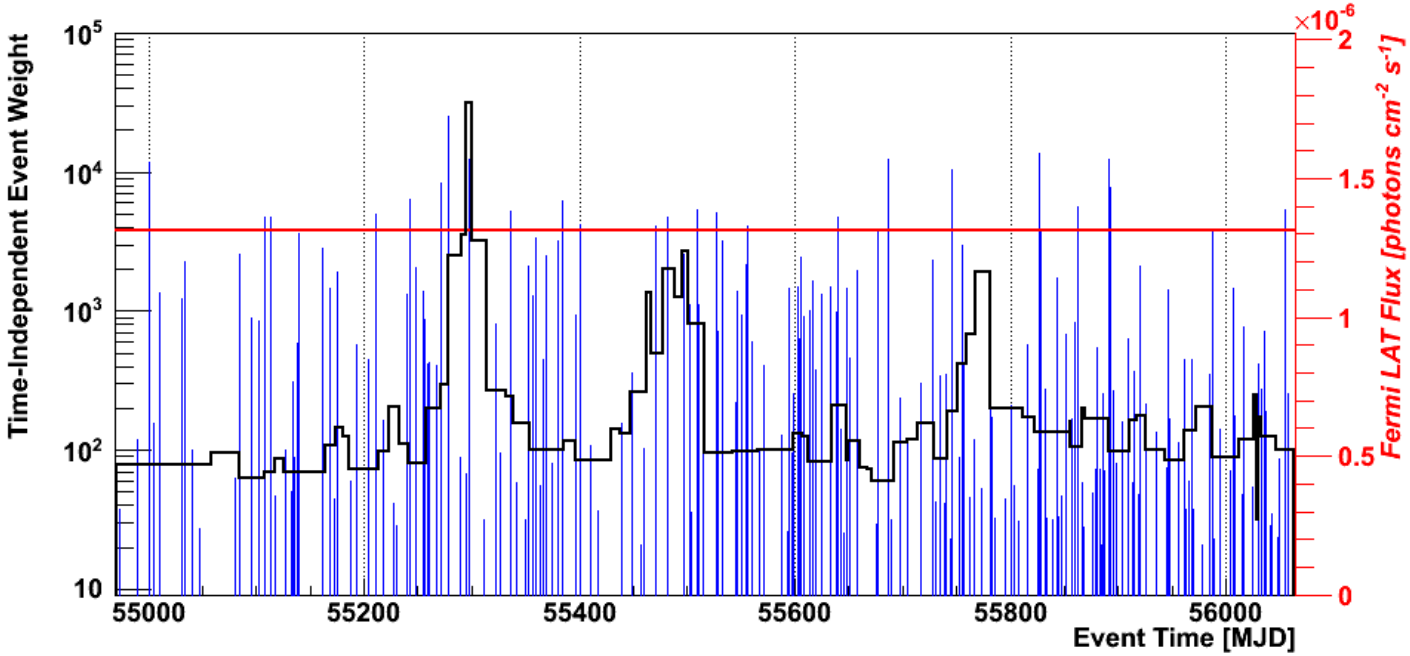


- Selection cut based on 11 days running mean: $\frac{(max_{11days} - min_{11days})}{overall\ mean} > 0.5$

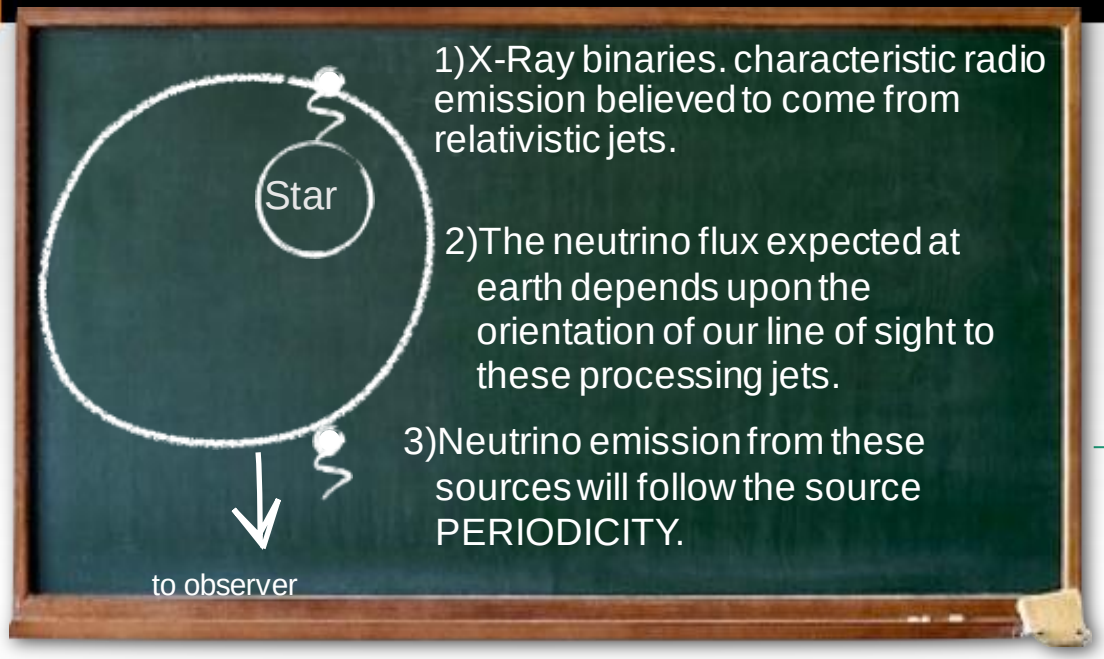
- The source selection is now automatic:
  - Can be applied on monthly basis without modification
  - 25 sources selected for the IC86-I period

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



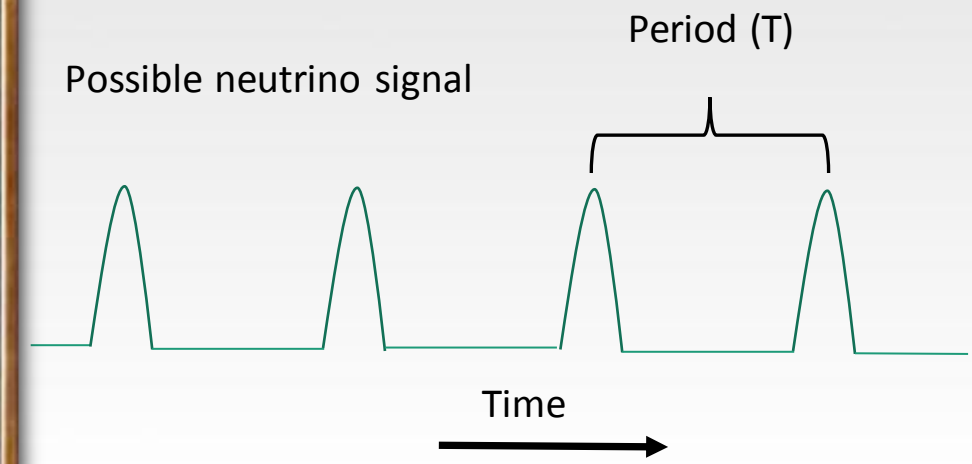
Time Dependent Searches - Periodic



1) X-Ray binaries. characteristic radio emission believed to come from relativistic jets.

2) The neutrino flux expected at earth depends upon the orientation of our line of sight to these processing jets.

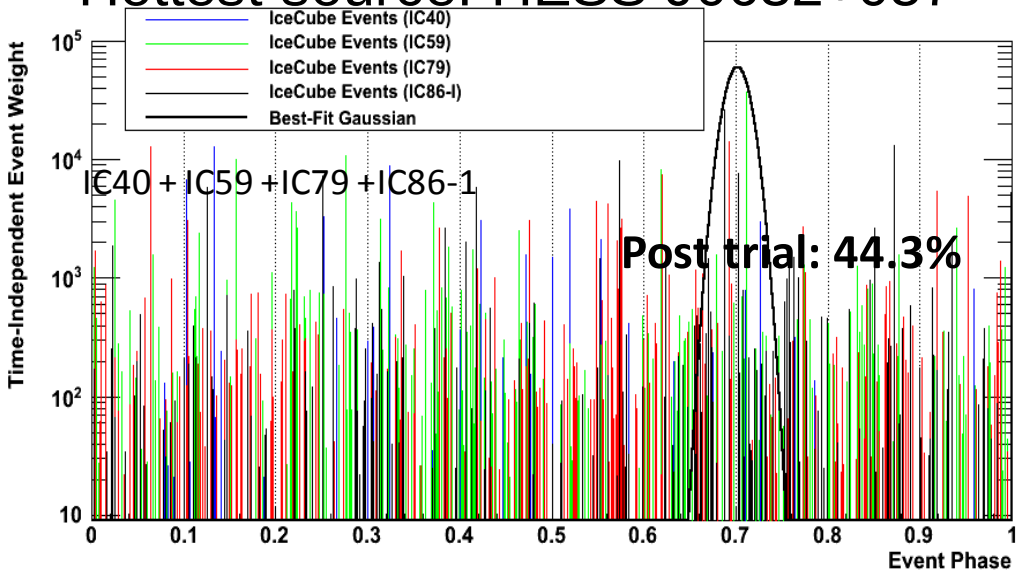
3) Neutrino emission from these sources will follow the source PERIODICITY.



Periodic Searches :

- Convert event times to phase : Period obtained from multi-wavelength observations.
- Look for clustering in phase space

Hottest source: HESS J0632+057



Conclusions

- No evidence yet for point sources or time dependent point sources
- IceCube sensitivity approaching interesting regions (i.e. Milagro 6 stacking search)
- Time Dependent searches and the event selection process are being modified to run on monthly basis.