Search for the origin of the diffuse extra-terrestrial neutrino-flux in IceCube

René Reimann

III. Physikalisches Institut B

Schule für Astroteilchenphysik

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DFG Deutsche Forschungsgemeinschaft

HELMHOLTZ GEMEINSCHAFT

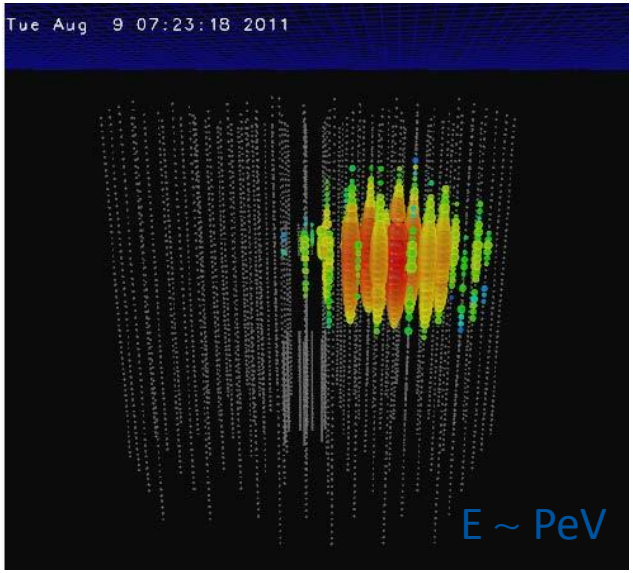
Allianz für Astroteilchenphysik

IceCube

No more general introduction to IceCube!

Neutrino Event Signature

“cascade”



Neutral-Current

$$\nu_x + N \rightarrow \nu_x + X$$

CC Electron Neutrino

$$\nu_e + N \rightarrow e + X$$

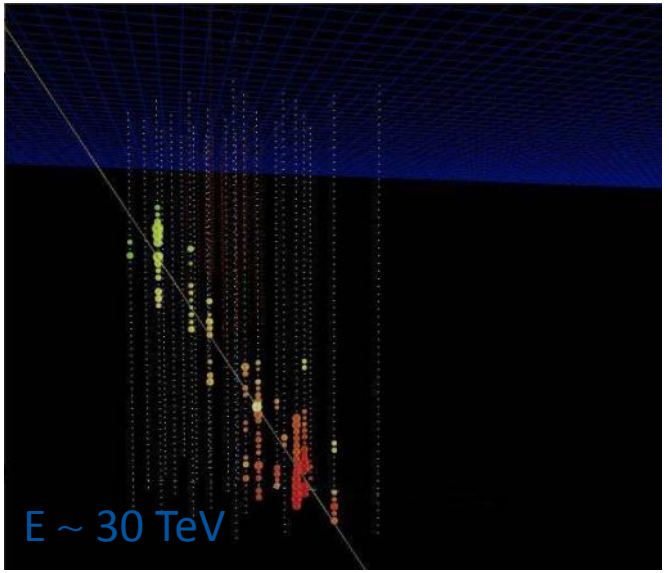
- all light in detector

→ ~ 10% energy resolution

- nearly spherical geometry

→ ~ 10° angular resolution

“track”



CC Muon Neutrino

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

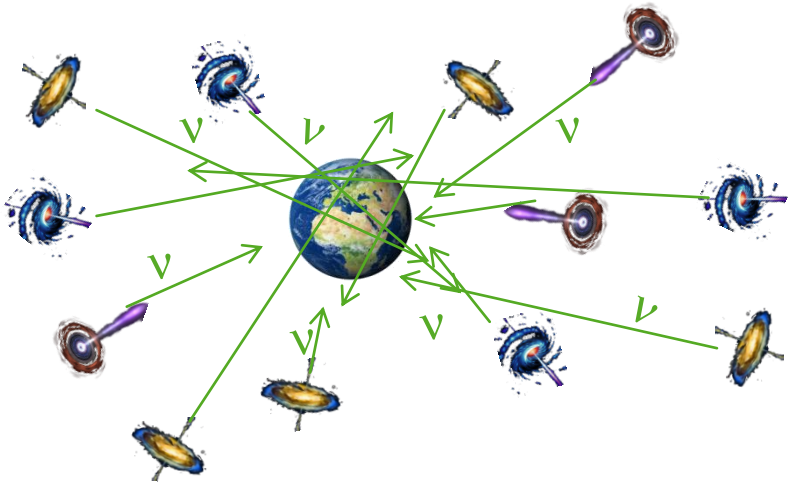
- just part of light in detector

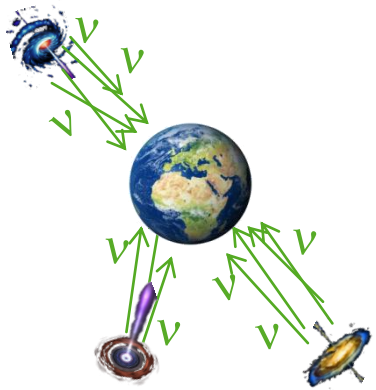
→ ~ 30% in $\log(E_\mu)$ resolution

- track-like geometry

→ ~ 0.6° angular resolution

Search for Astrophysical Neutrinos





Diffuse neutrino flux

More promising for:

- abundant extragalactic sources (e.g. AGN)

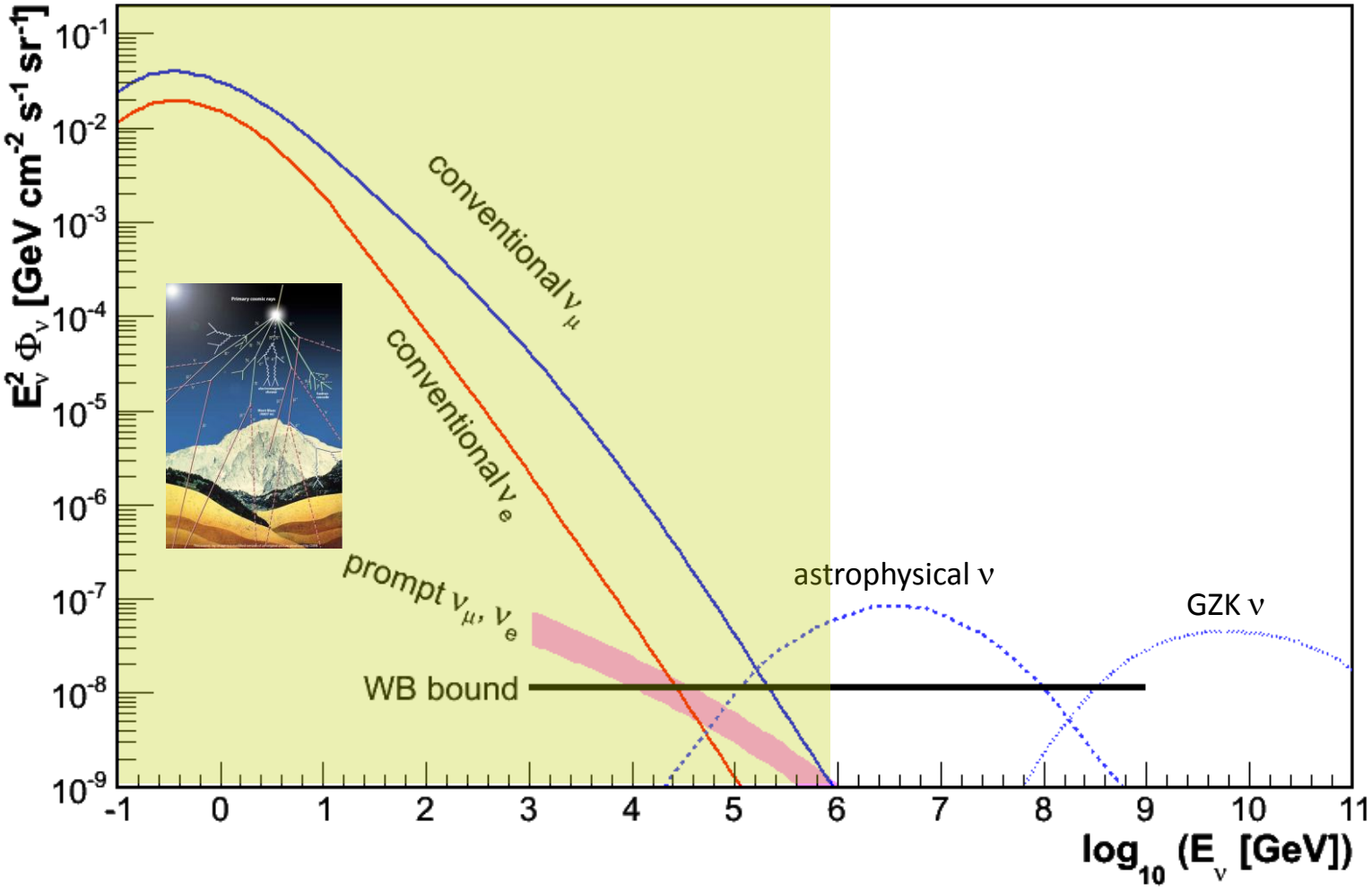
Point-like neutrino sources

More promising for:

- rare bright sources
- transient sources
- galactic sources

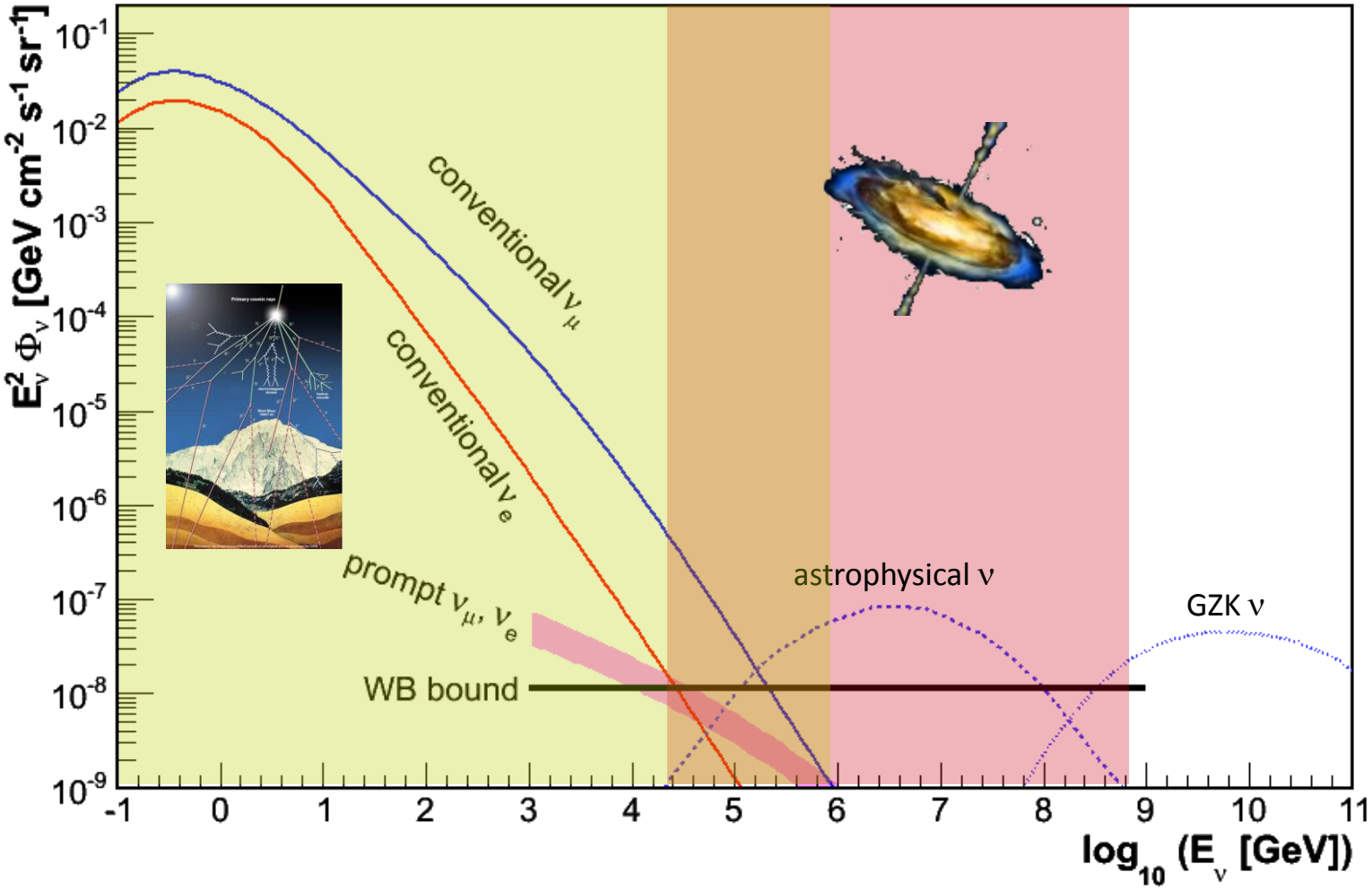
Diffuse Search

Search for excess in high-energy region



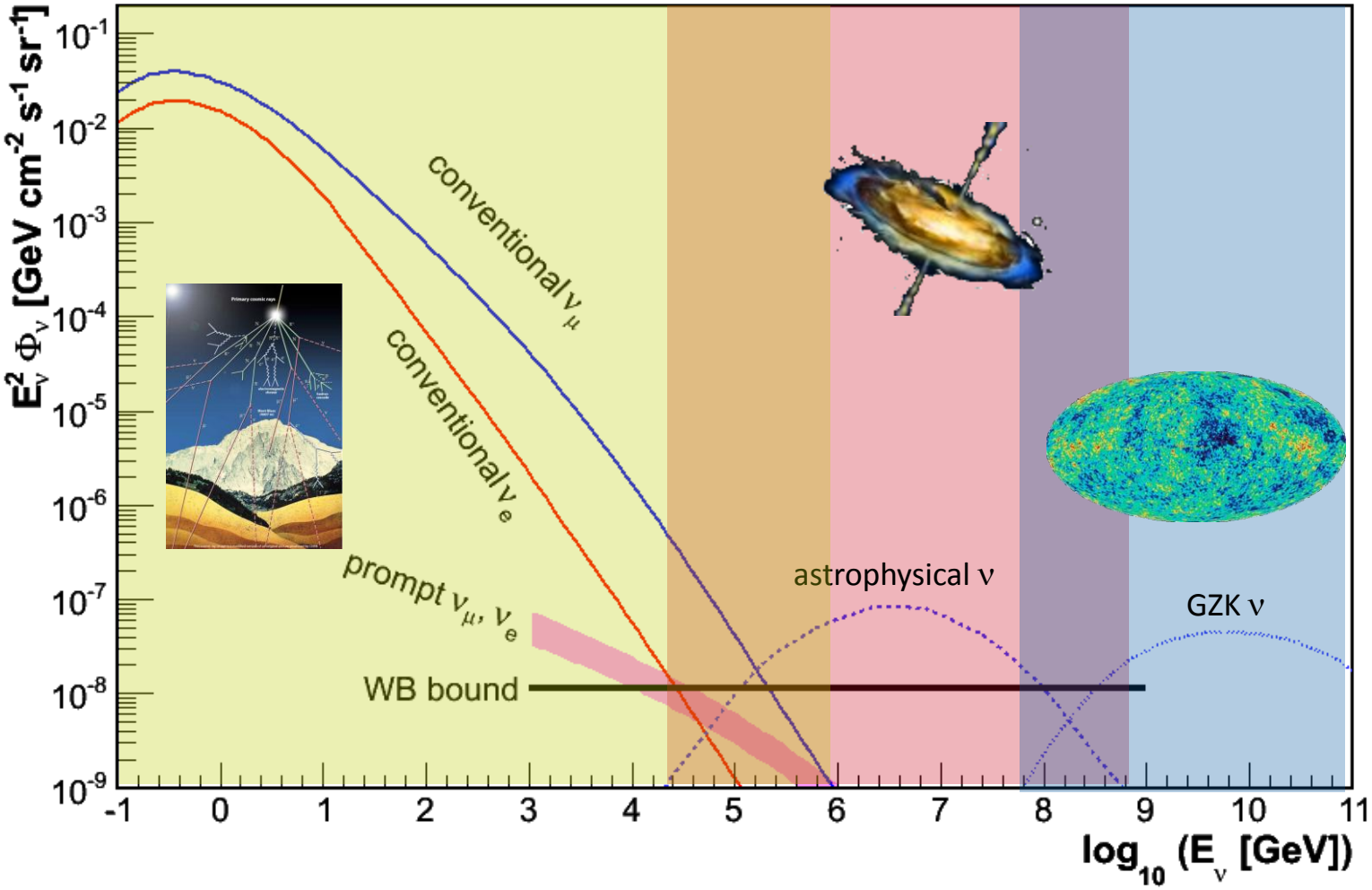
Diffuse Search

Search for excess in high-energy region



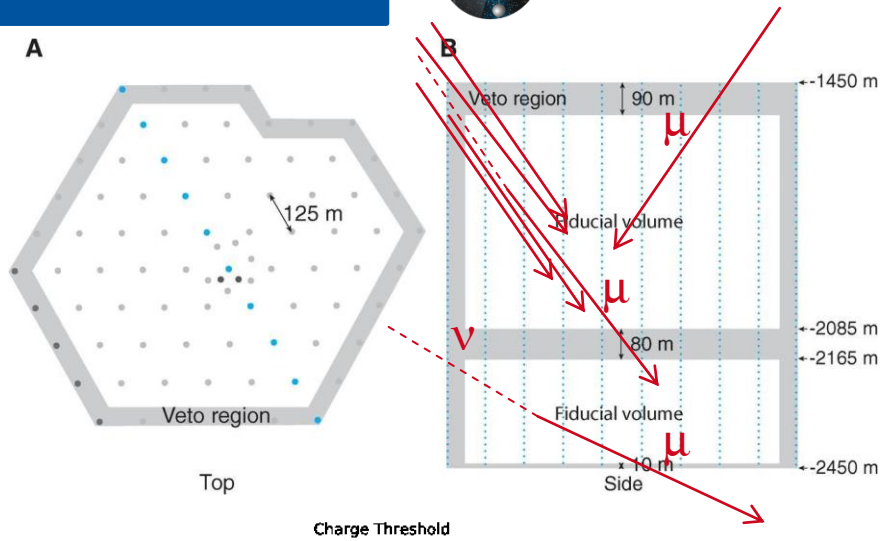
Diffuse Search

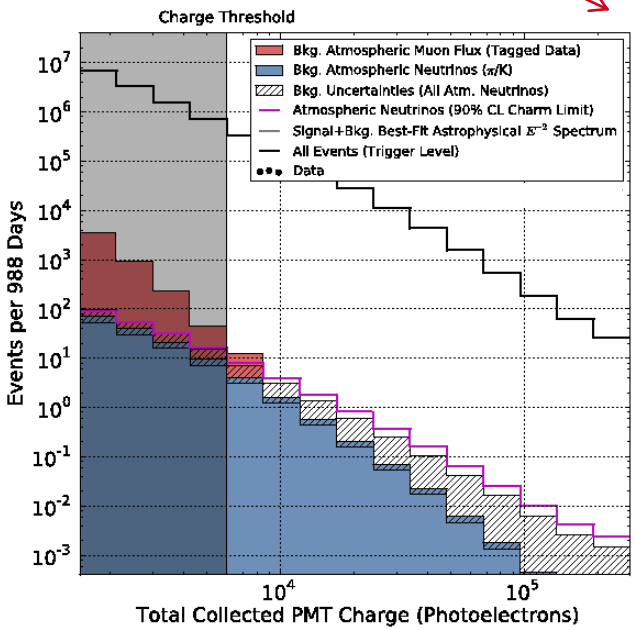
Search for excess in high-energy region



Starting Event Search

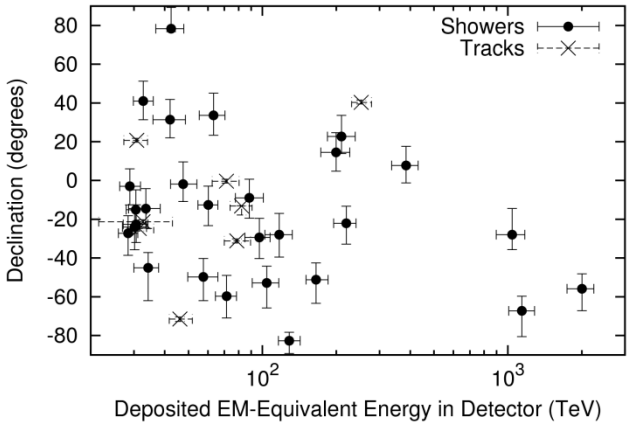
- Define veto region at detector borders to veto incoming atmospheric muons
- Down-going atmospheric neutrinos are accompanied by high-energy atm. muons
  → also vetoed
- To get good veto efficiency, require much light in detector
  → select high-energy events
- Selection is shower-dominated
- Get events from both hemispheres
- Selection has small effective volume

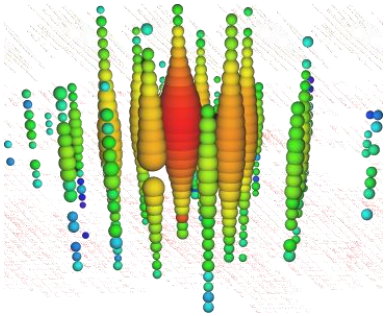


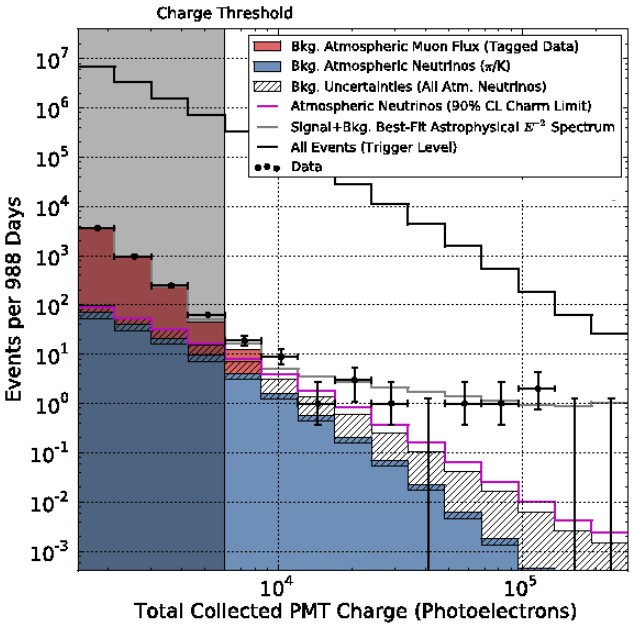


Starting Event Search

- In three years of data 37 high-energy neutrino events candidate found
- Estimated background
  $6.6^{+5.9}_{-1.6}$ atm. neutrinos
  8.4 ± 4.2 atm. muons
- Purely atmospheric flux rejected with 5.7σ
- 29 cascades and 8 tracks
  Consistent with 1:1:1 flavor ratio
- Best fit per flavor flux:
  $0.95 \pm 0.3 \cdot 10^{-8}\ E^{-2}\ \text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$
- One event with >2PeV energy







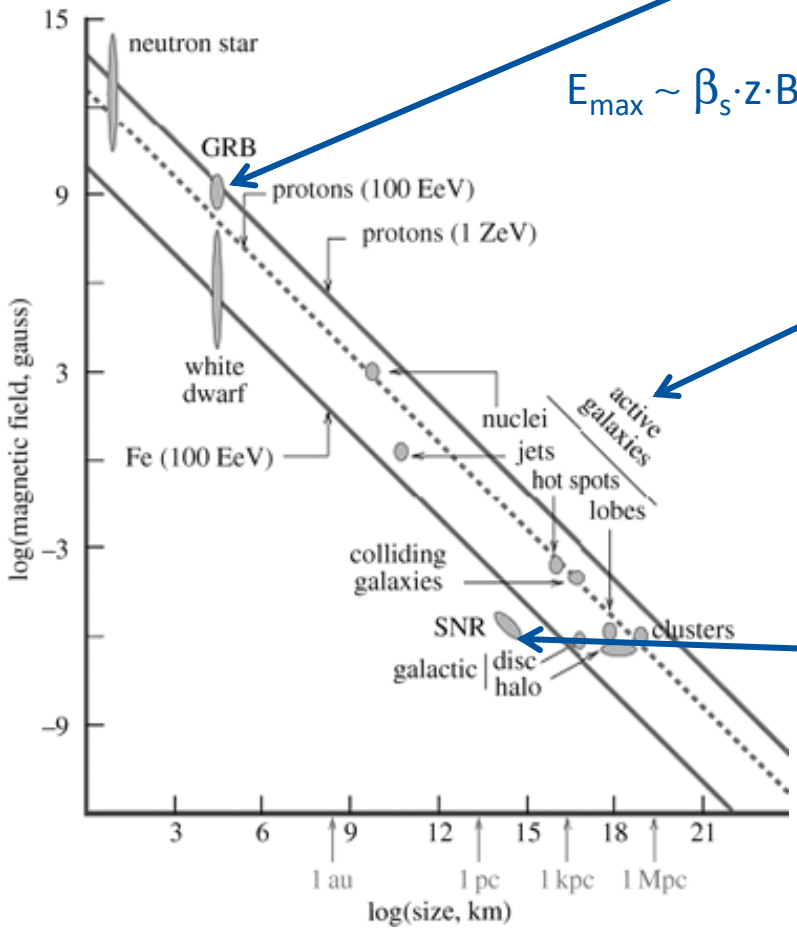
Search for the origin of astrophysical neutrinos

Where does this astrophysical neutrino flux come from?

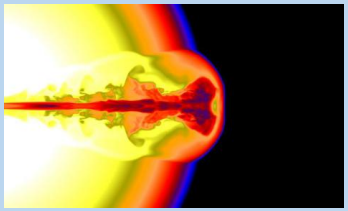
Candidate Sources of HE Cosmic Rays

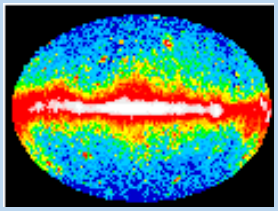
Maximum energy is constrained by magnetic field strength and size of object

$E_{max} \sim \beta_s \cdot z \cdot B \cdot L$

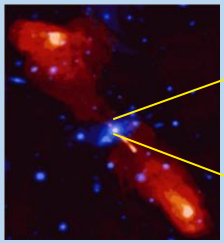


Extragalactic: **G**amma **R**ay **B**ursts





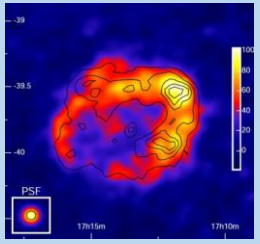
Extragalactic: **A**ctive **G**alactic **N**uclei



AGN 3C 219

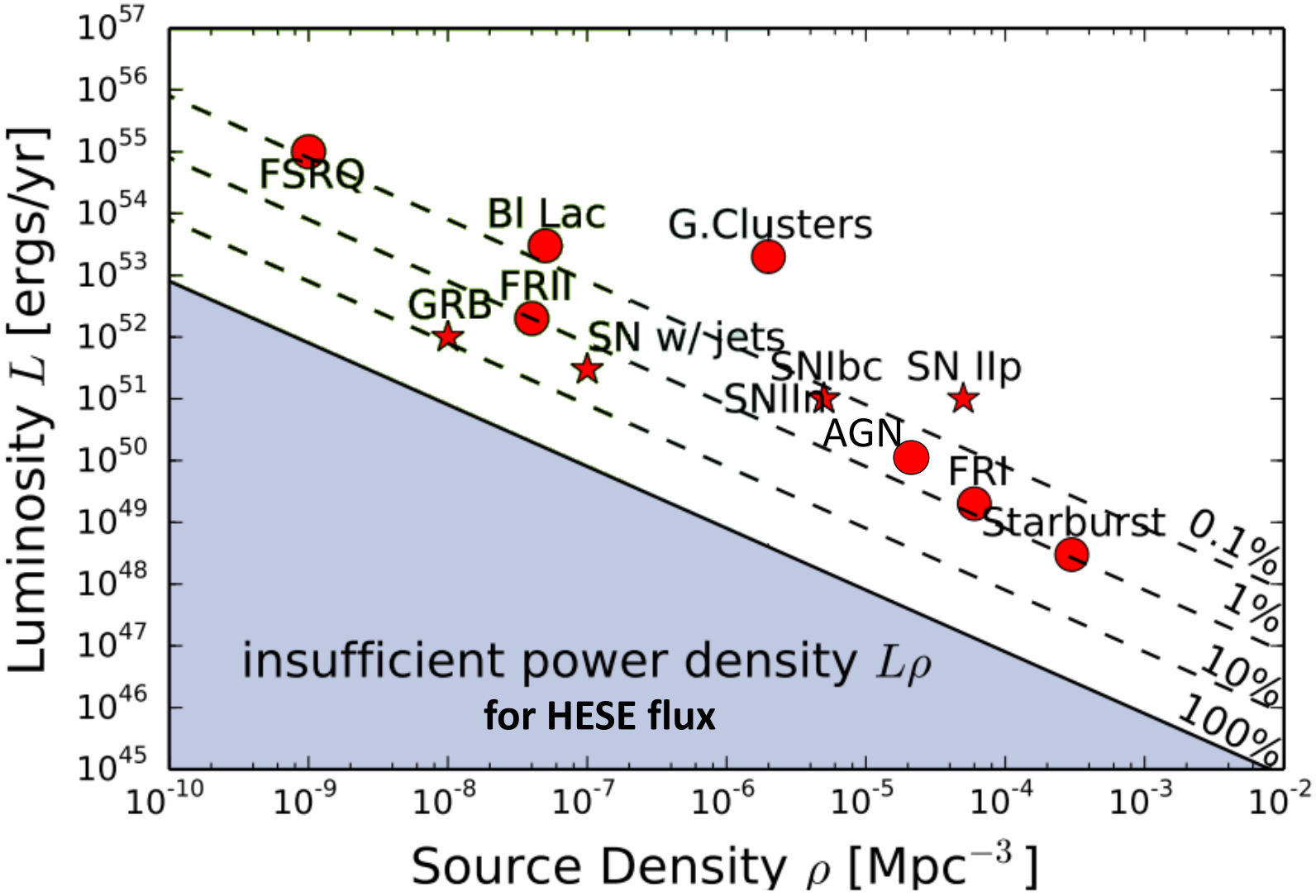
Galactic: **S**uper**n**ova **R**emnants

Crab nebular M1 (SN 1054)



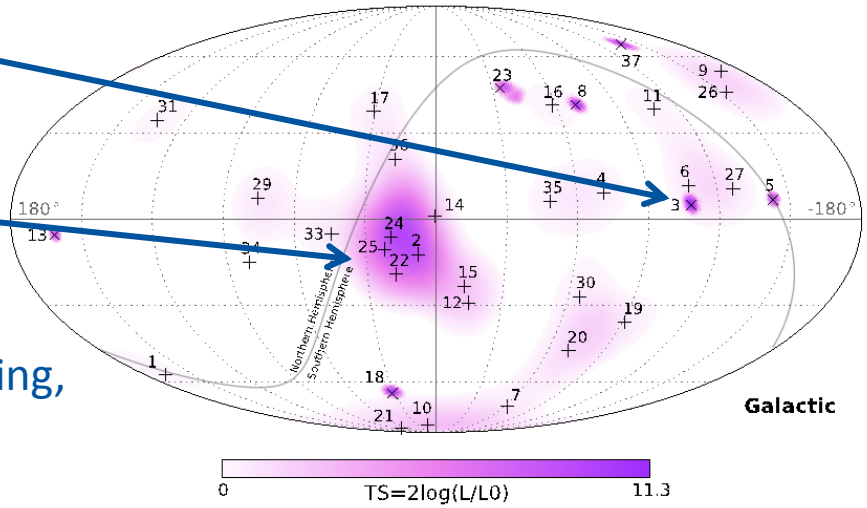
SN Remnant RX J1713 (x-ray)

Candidate Sources of HE Neutrinos



Starting Event Search

- No significant clustering observed
- All event hotspot
  Post trial p-value: 84%
- Shower event hotspot
  Post trial p-value: 7%
- Multi-clustering, galactic plane, time clustering, GRB correlation not significant either.



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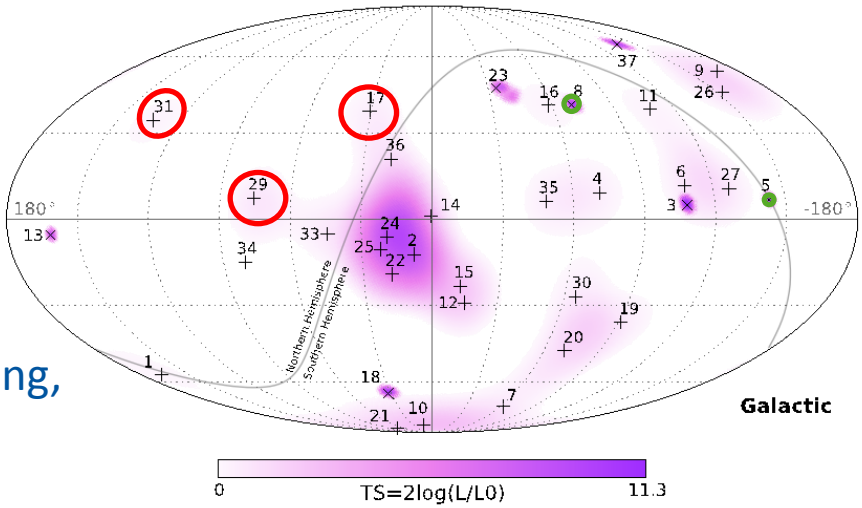

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  Post trial p-value: 84%
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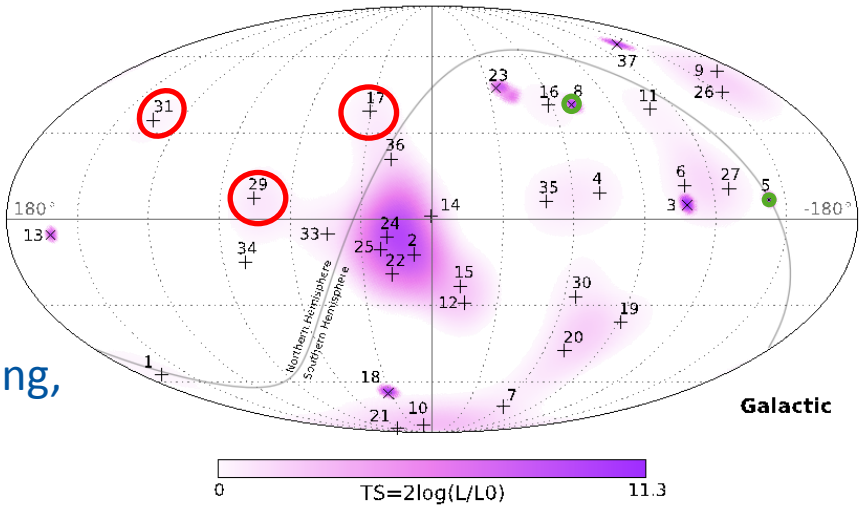
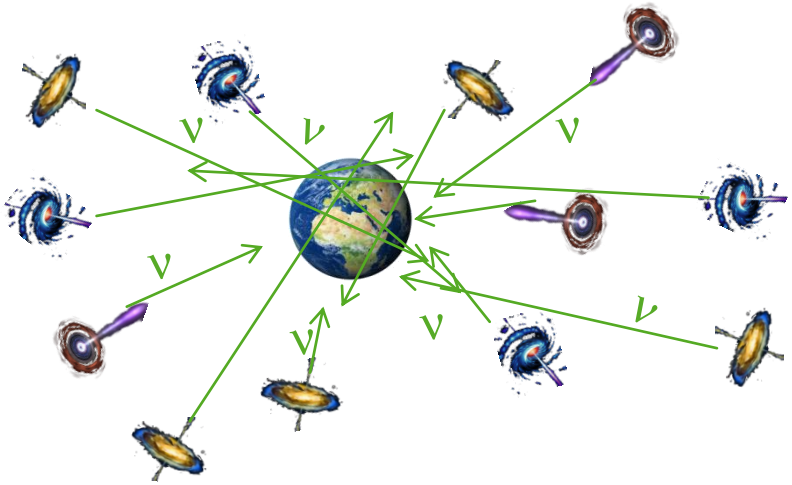
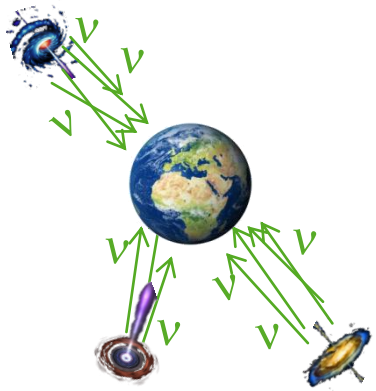
- Multi-clustering, galactic plane, time clustering, GRB correlation not significant either.
- Muon only diffuse search:
  IC59: 1.8σ
  IC79-IC86 I: 3.7σ
  IC59-IC86 (10xIC59): on going



Use only tracks to search for sources!

Search for Astrophysical Neutrinos





Diffuse neutrino flux

More promising for:

- abundant extragalactic sources (e.g. AGN)

Point-like neutrino sources

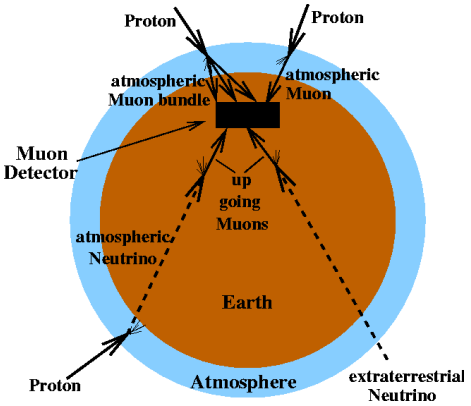
More promising for:

- rare bright sources
- transient sources
- galactic sources

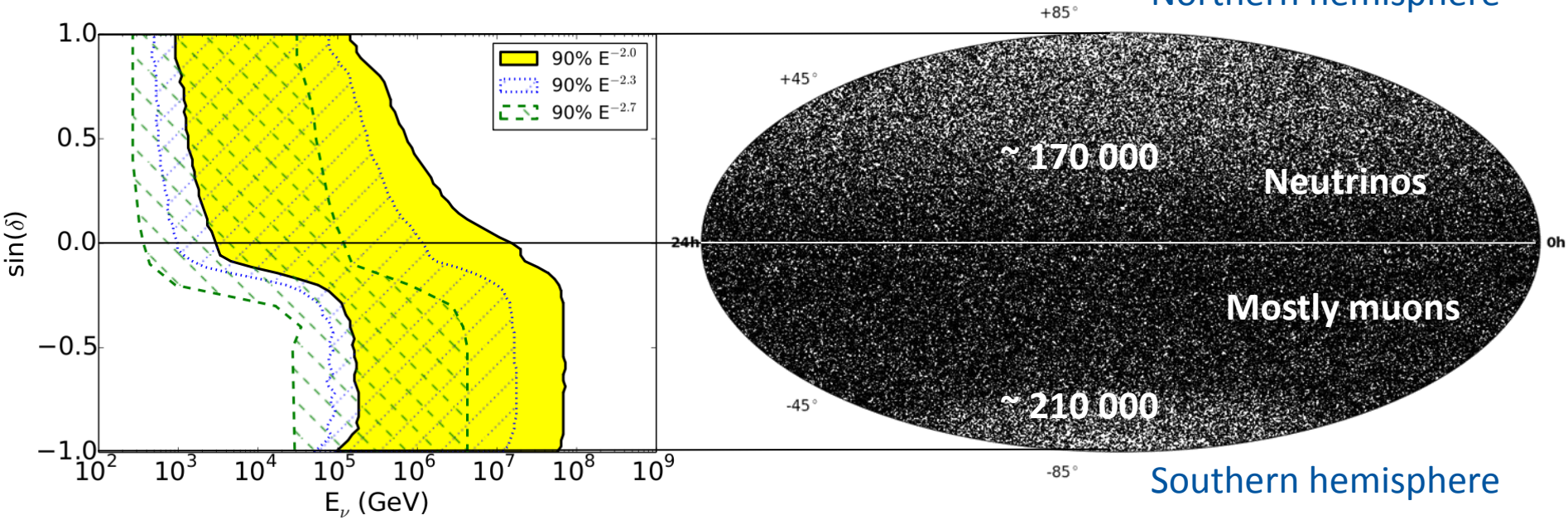
Point-source search with a lower energy threshold

- Selection of well reconstructed tracks
- 4 years of data

  IC40 + IC59 + IC79 + IC86

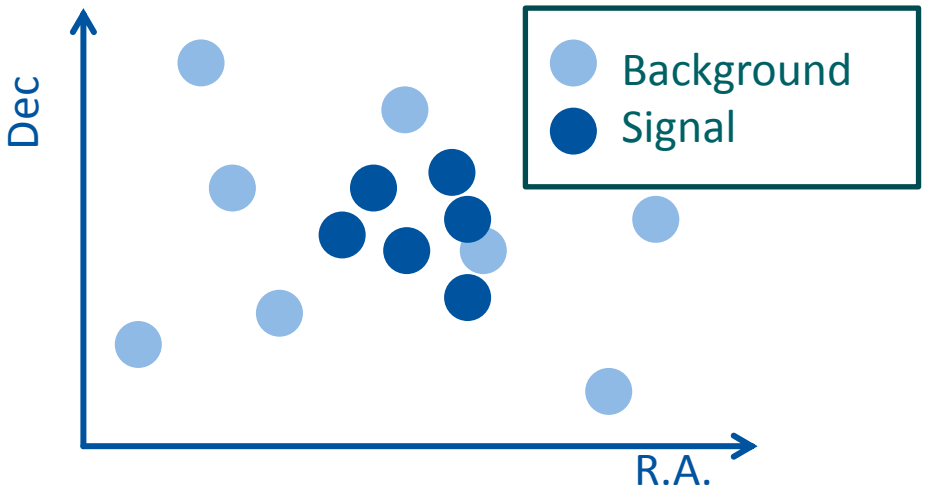


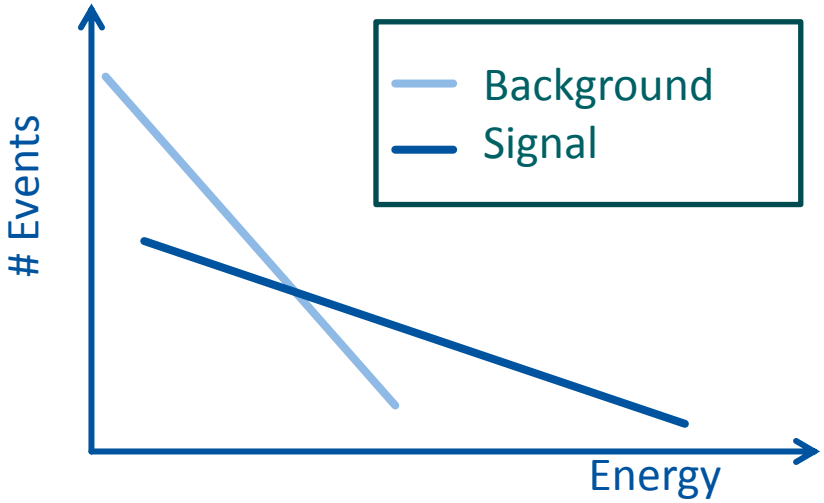
Northern hemisphere



Southern hemisphere

Point-source analysis





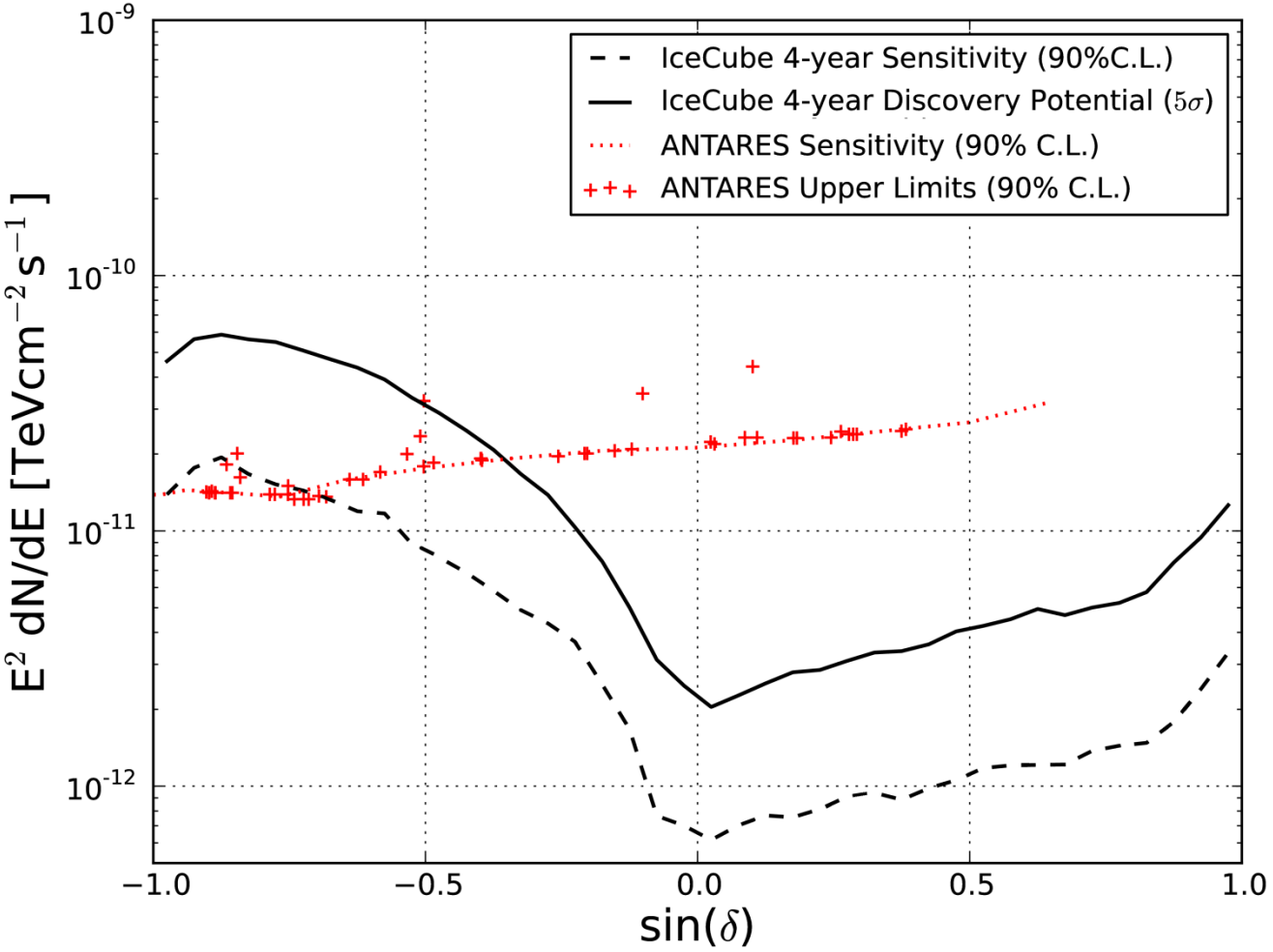
$$LLH = \sum_j \sum_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j \left(\left| \vec{x}_i - \vec{x}_s \right|, \sigma_i, E_i, \delta_i, \gamma \right) + \left(1 - \frac{n_s^j}{N^j} \right) B_i^j \left(E_i, \delta_i \right) \right]$$

$$S_i^j \left(\left| \vec{x}_i - \vec{x}_s \right|, \sigma_i, E_i, \delta_i, \gamma \right) = S_{i,spat}^j \left(\left| \vec{x}_i - \vec{x}_s \right|, \sigma_i, \delta_i \right) \cdot S_{i,ener}^j \left(E_i, \gamma \right)$$

$$B_i^j \left(E_i, \delta_i \right) = B_{i,spat}^j \left(\delta_i \right) \cdot B_{i,ener}^j \left(E_i \right)$$

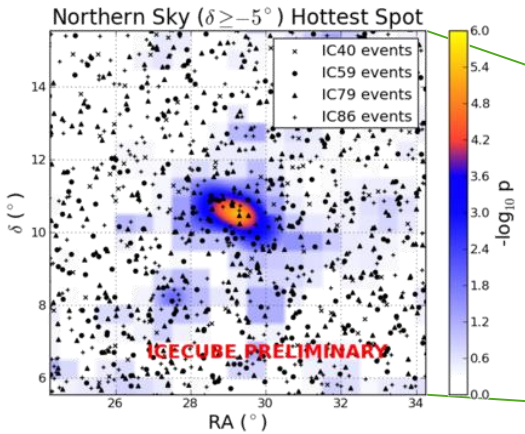
Unbinned likelihood analysis with spatial and energy pdfs

Point-Source Sensitivity

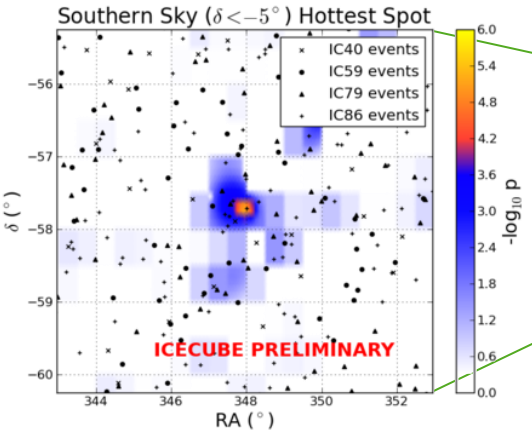


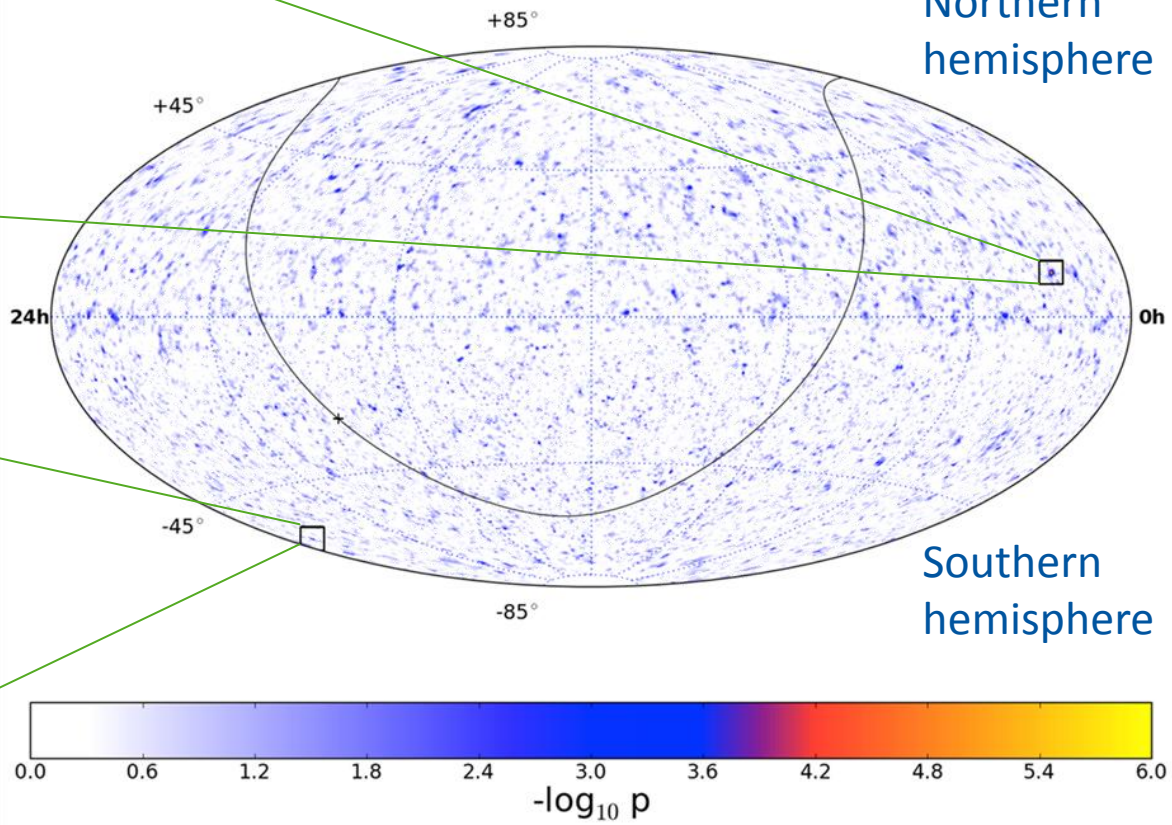
Point-source all-sky scan

Post trial p-value: 22.6%



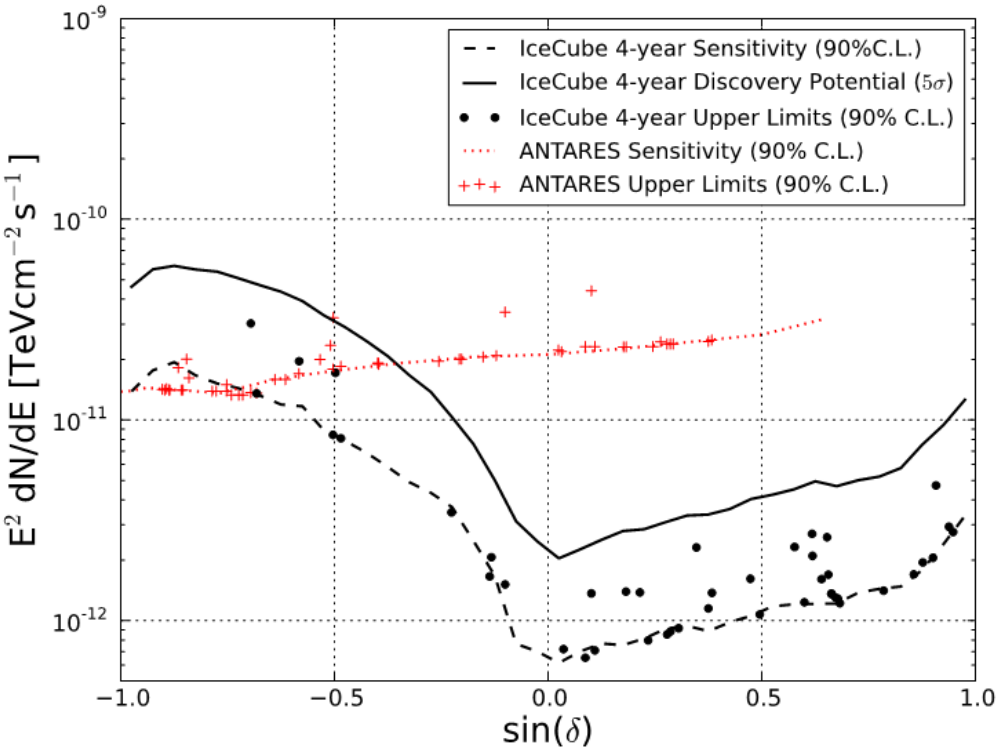
Post trial p-calue: 44.0%





Point-Source Search

- No significant excess was found
- Test physical motivated source catalogue
  - → No significant excess
  - → calculate UL for each source



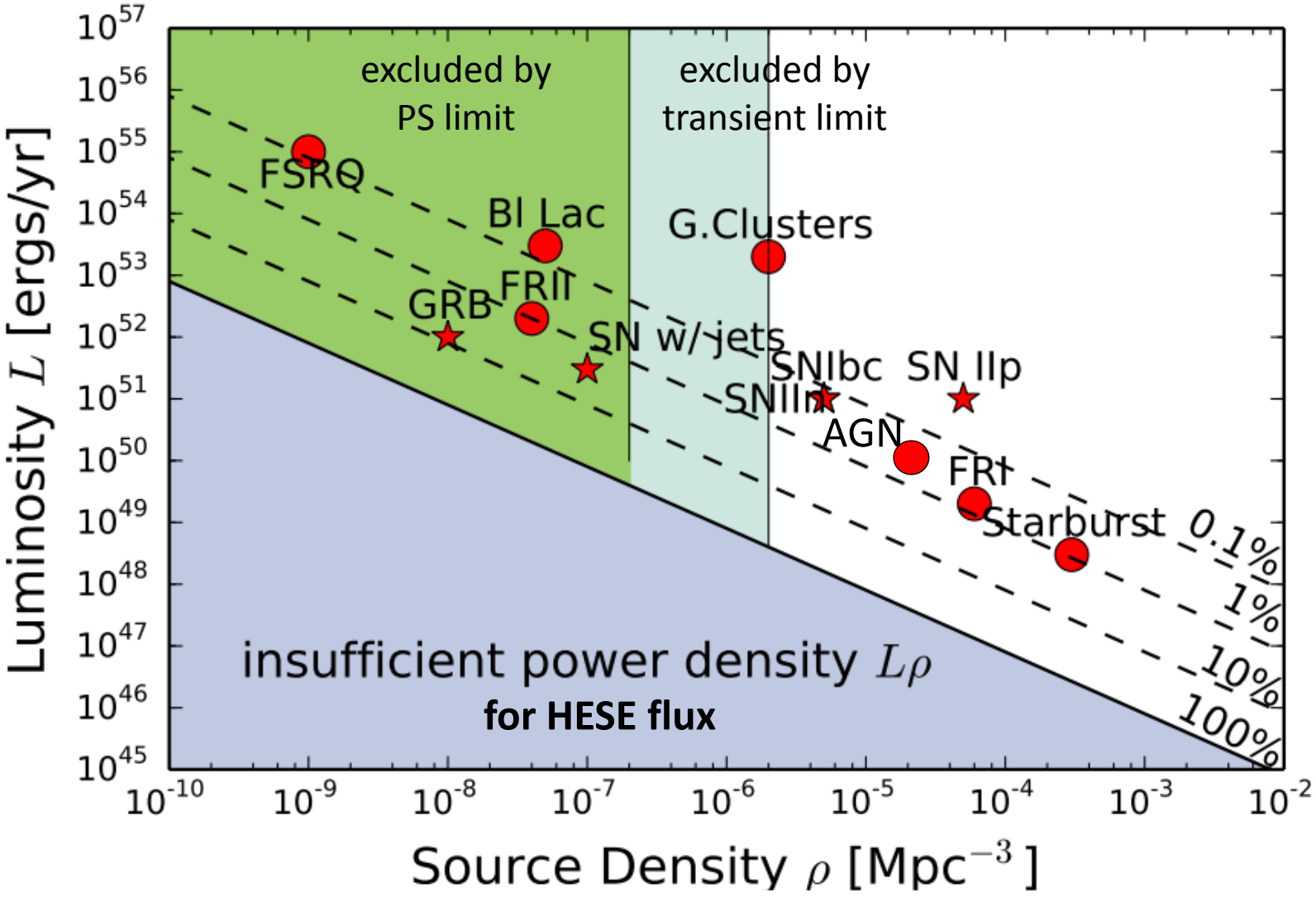
Source	RA (°)	Dec (°)	$\hat{n}_s$	$\hat{\gamma}$	B_{2°	p-value
S5 0716+71	110.47	71.34	0.00	3.93	66.1	–
M82	148.97	69.68	0.00	2.58	65.3	–
1ES 1959+650	300.00	65.15	9.85	3.16	70.8	0.0835
TYCHO	6.36	64.18	0.22	3.95	71.1	–
LSI 303	40.13	61.23	0.00	3.32	71.4	–
Cas A	350.85	58.81	0.00	2.76	71.3	–
1ES 2344+514	356.77	51.70	0.00	2.59	76.3	–
3C66A	35.67	43.04	0.00	2.55	82.0	–
H 1426+428	217.14	42.67	0.00	2.57	83.1	–
BL Lac	330.68	42.28	0.00	2.70	83.1	–
NGC 1275	49.95	41.51	0.00	3.24	83.9	–
Cyg OB2	308.08	41.51	0.00	3.27	83.9	–
Cyg X-3	308.11	40.96	3.59	3.95	85.9	0.418
Cyg A	299.87	40.73	0.00	2.92	85.9	–
Mrk 501	253.47	39.76	3.22	3.67	88.6	0.446
Mrk 421	166.11	38.21	3.76	1.85	89.5	0.264
4C 38.41	248.81	38.13	10.64	2.77	89.5	0.121
MGRO J2019+37	305.22	36.83	0.00	3.92	92.2	–
Cyg X-1	299.59	35.20	8.96	3.95	93.8	0.18
3C 123.0	69.27	29.67	1.85	3.95	102.6	0.488
W Comae	185.38	28.23	0.00	2.55	103.8	–
IC443	94.18	22.53	4.62	3.95	111.3	0.351
Crab Nebula	83.63	22.01	4.33	3.95	111.3	0.442
1ES 0229+200	38.20	20.29	15.99	3.65	114.5	0.0526
Geminga	98.48	17.77	0.00	1.02	122.8	–
PKS 0235+164	39.66	16.62	0.00	3.05	125.4	–
3C 454.3	343.49	16.15	0.00	2.71	125.4	–
PKS 0528+134	82.73	13.53	0.00	2.54	129.2	–
M87	187.71	12.39	8.85	3.95	129.7	0.26
PKS 1502+106	226.10	10.49	6.02	2.25	132.6	0.213
MGRO J1908+06	286.98	6.27	0.00	2.66	145.7	–
HESS J0632+057	98.25	5.80	13.43	3.35	147.9	0.144
SS433	287.96	4.98	0.00	2.54	150.2	–
3C 273	187.28	2.05	3.21	2.55	155.4	0.445

Source	RA (°)	Dec (°)	$\hat{n}_s$	$\hat{\gamma}$	B_{2°	p-value
3C279	194.05	-5.79	0.00	2.50	133.9	–
QSO 2022-077	306.42	-7.64	2.29	3.30	136.5	0.456
PKS 1406-076	212.24	-7.87	2.04	2.85	136.5	0.449
QSO 1730-130	263.26	-13.08	0.00	2.53	148.5	–
Sgr A*	266.42	-29.01	0.00	3.58	146.4	–
PKS 1622-297	246.53	-29.86	6.18	2.75	146.4	0.126
PKS 2155-304	329.72	-30.23	0.00	2.53	147.9	–
PKS 1454-354	224.36	-35.65	5.42	3.95	142.3	0.199
Cen A	201.37	-43.02	0.00	3.56	141.8	–
PKS 0537-441	84.71	-44.09	6.24	3.95	140.9	0.0829

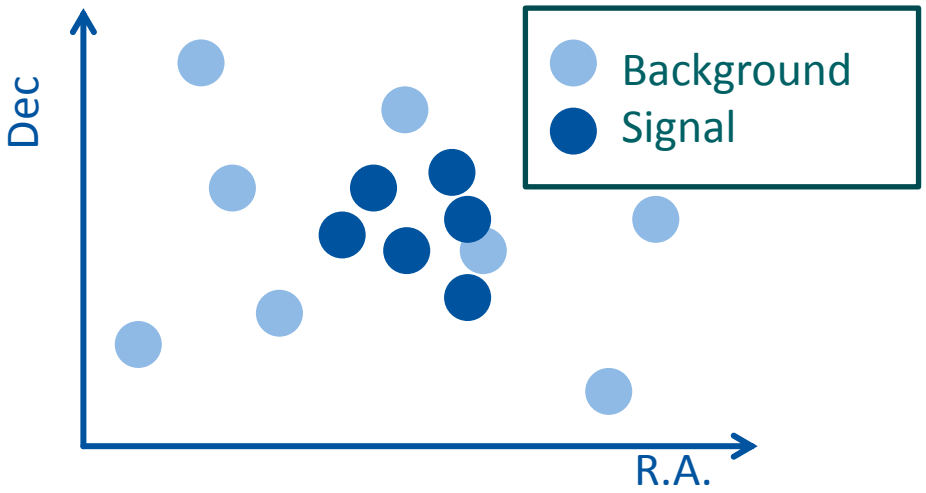
Point-Source Searches

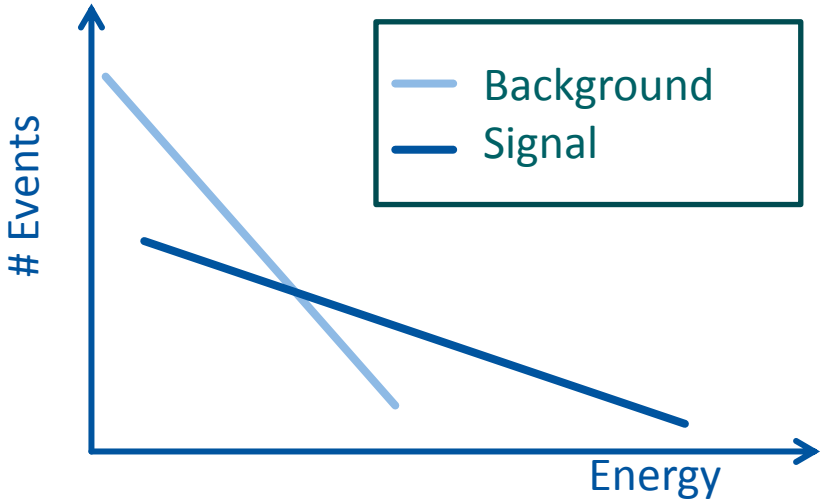
- Point-source scan
- Catalog search on physical motivated sources
- Stacked source analysis for source populations
- Time dependent searches

Candidate Sources of HE Neutrinos



Improve PS analysis





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$$B_i^j \left(E_i, \delta_i \right) = B_{i,spat}^j \left(\delta_i \right) \cdot B_{i,ener}^j \left(E_i \right)$$

Unbinned likelihood analysis with spatial and energy pdfs

Summary

- IceCube is a stable operating 1 km³ neutrino detector
- Found 37 high-energy starting neutrino events candidate, incompatible with atm. ν flux at 5.7σ
- Best fit per flavor flux near Waxman-Bahcall bound
- Found first >PeV energy neutrino candidates
- No significant PS found
- New idea: Use information from diffuse signal to be more sensitive to sources and source populations