Correlation studies of IceCube neutrinos with subcatalogs of Fermi's 3rd catalog

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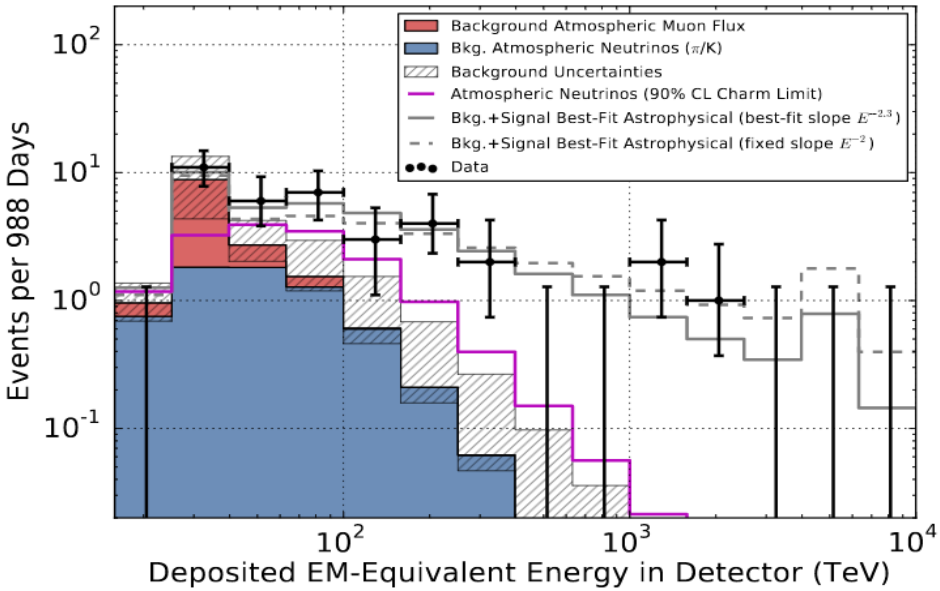
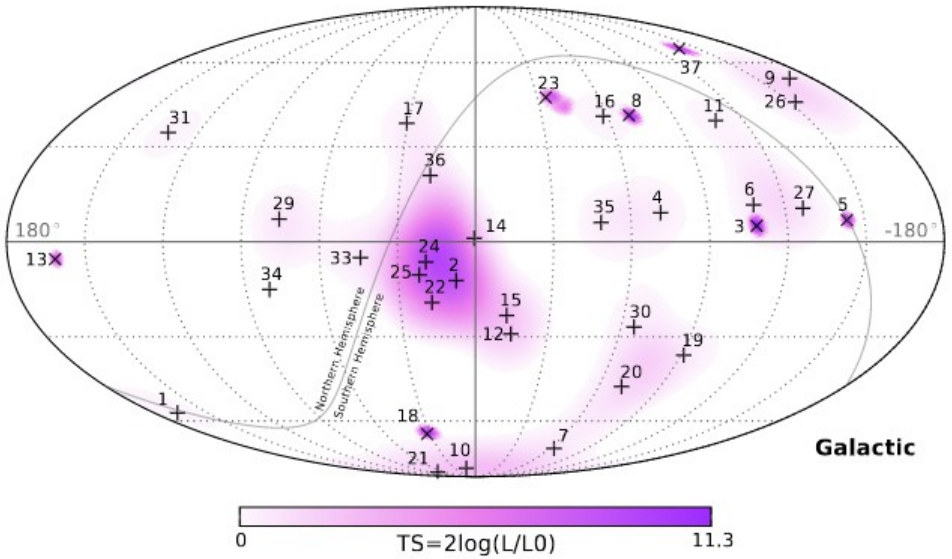
Motivation



- IceCube measured an extraterrestrial neutrino flux
- Neutrinos have energies up to the PeV regime

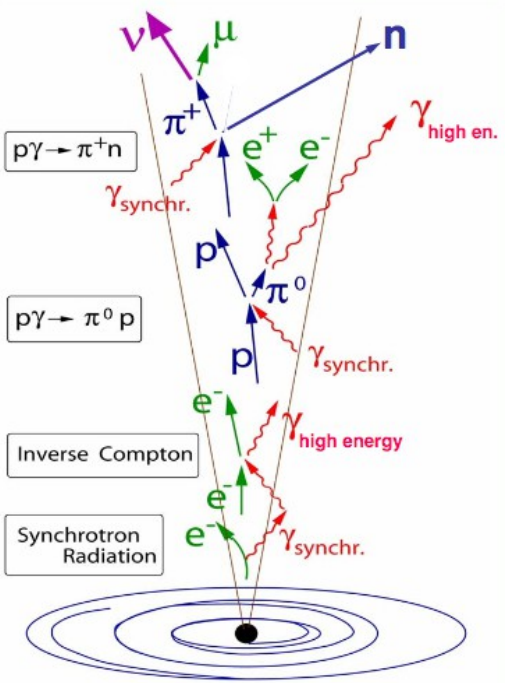
- Neutrino events have large directional errors
- No definite astrophysical counterparts were found yet



Credit: IceCube Collaboration, 2014

Flat-Spectrum Radio Quasars

- Most powerful active galactic nuclei (AGN) with relativistic jets
- Strong UV photon fields
- Brightest gamma-ray sources
- Hadronic models predict neutrino production via pion decay in PeV range for FSRQs



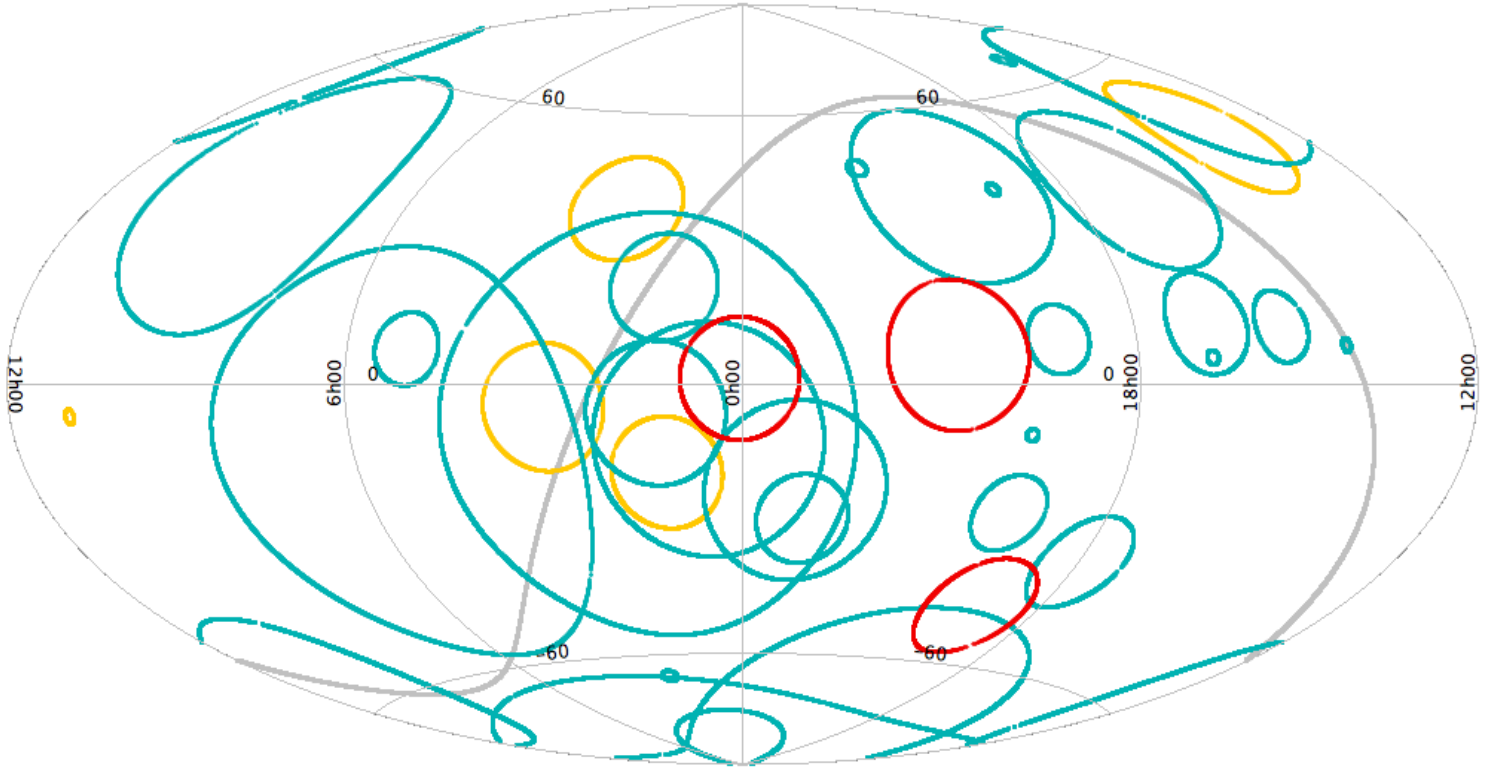
Credit: Katz & Spiering 2012

Credit: Aurore Simonnet, Sonoma State University

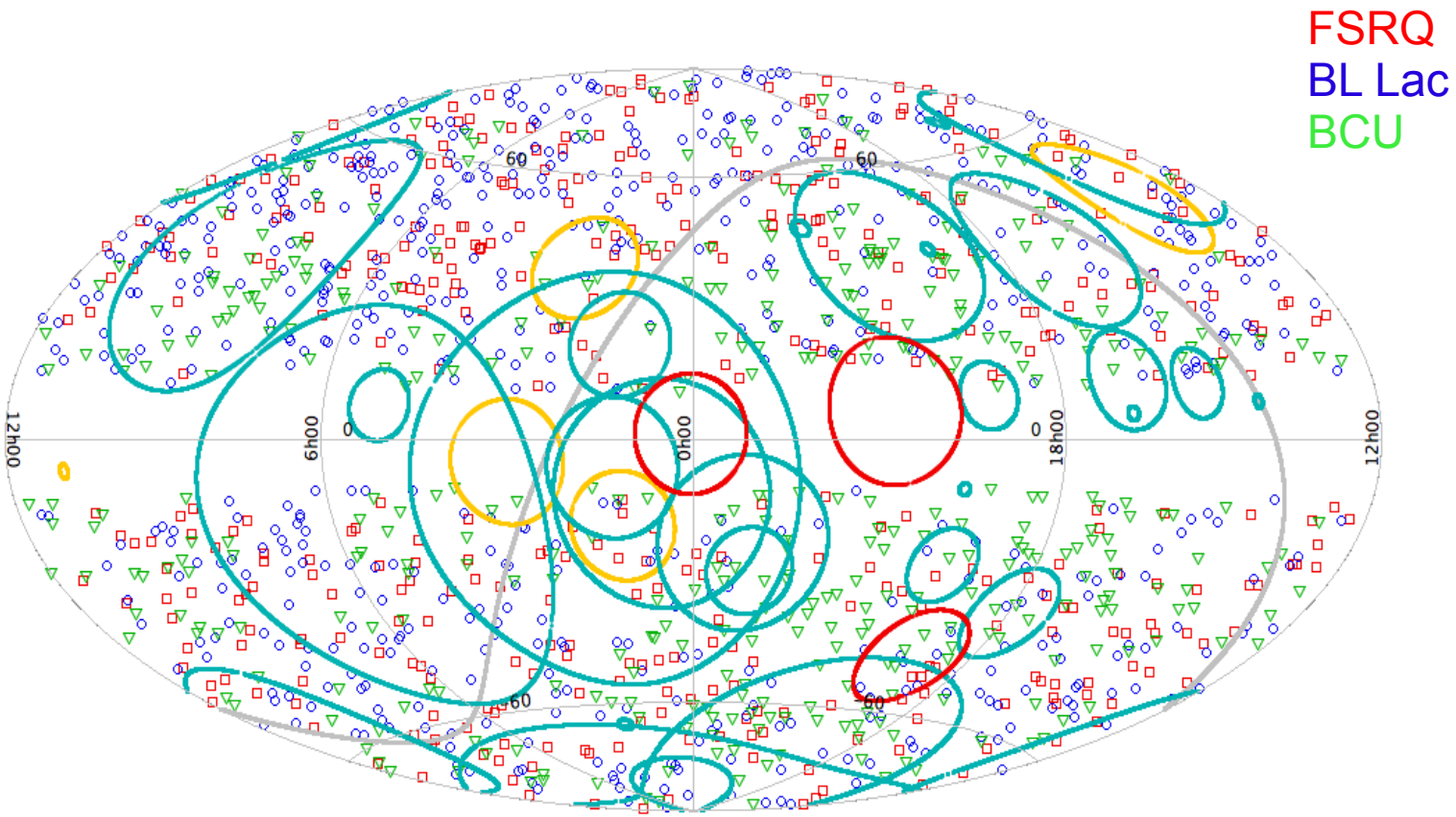
- Pion creation with UV photons possible
- Expected neutrino spectrum peaking in the PeV regime

See Kadler, M. et al. (2016)

Correlation with Fermi's 3rd catalog?



Correlation with Fermi's 3rd catalog?



Unbinned Maximum Likelihood Method

Maximisation of Likelihood with respect to the parameter n_s

$$\log(\mathcal{L}(n_s)) = \sum_{i=1}^{N} \log\left(\frac{n_s}{N} \cdot S_i + (1 - \frac{n_s}{N}) \cdot B_i\right)$$

Signal term

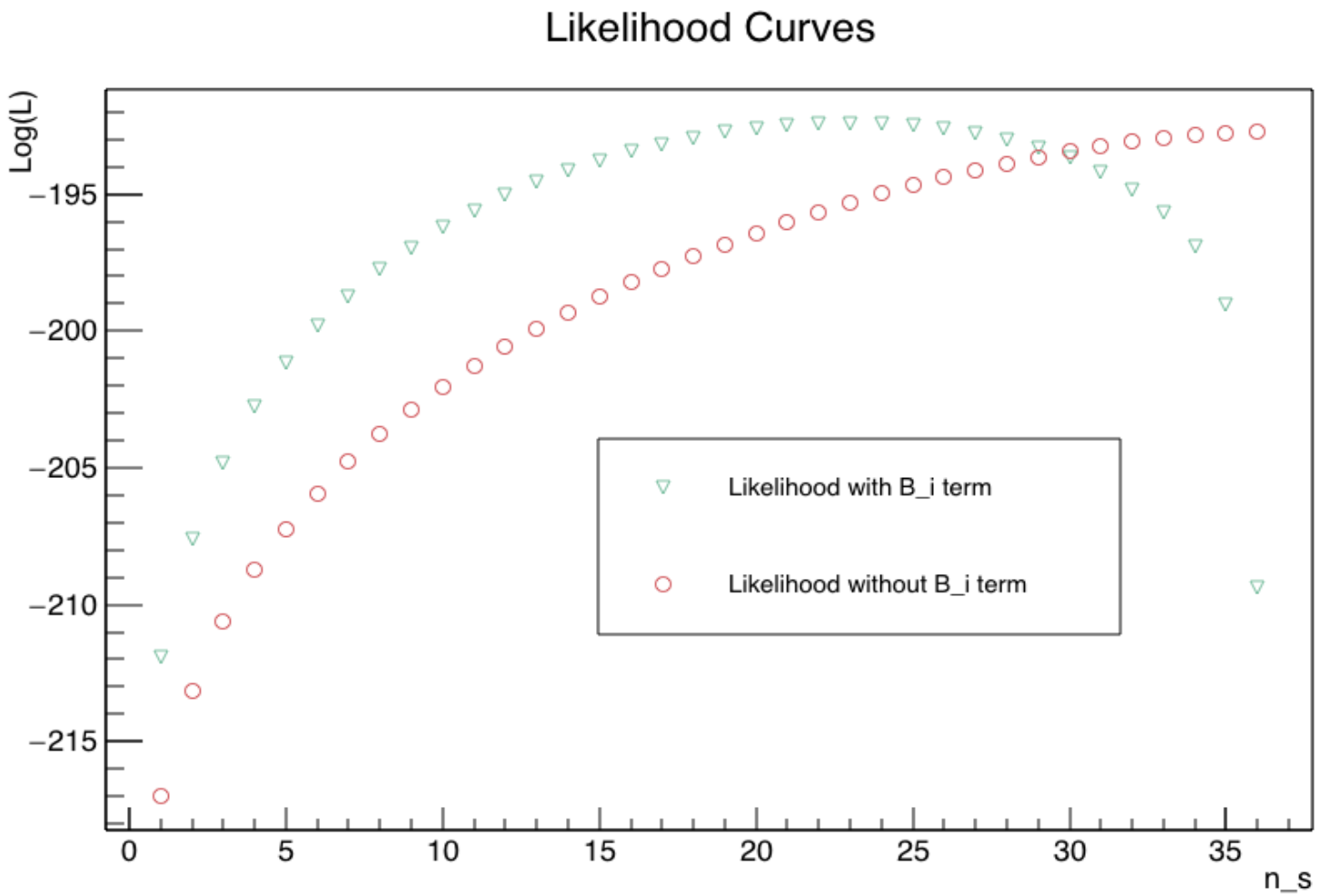
Background term

$$S_i = \frac{\sum_{j=1}^{N_{\text{sources}}} S_j(\vec{x}_i, \sigma_{\vec{x}_i}) \cdot \omega_j \cdot \epsilon_j^{s}(E_i)}{\sum_{j=1}^{N_{\text{sources}}} \omega_j}$$

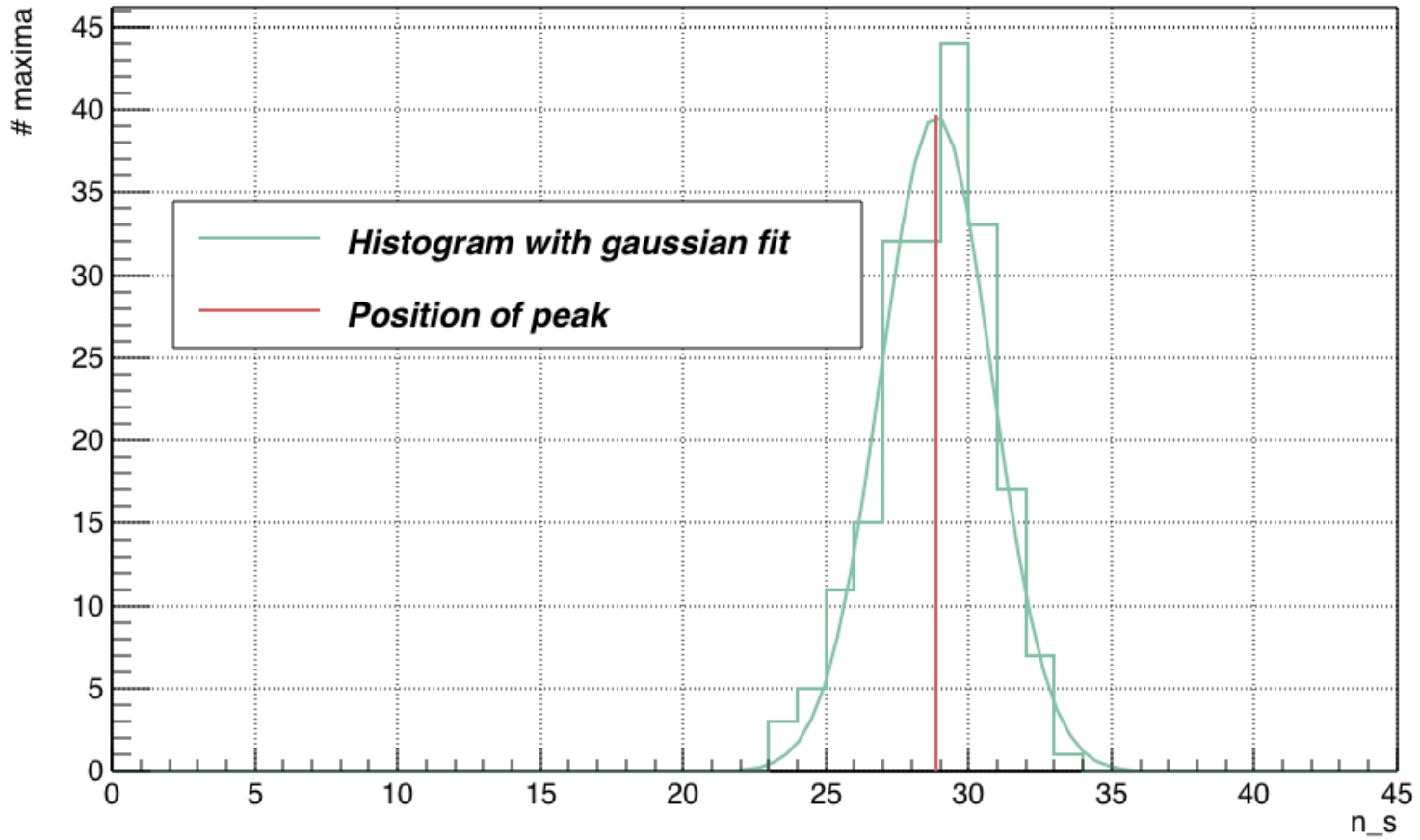
$$B_i = \frac{\sum_{j=1}^{N_{\text{Bck}}} B_j(\vec{x}_i, \sigma_{\vec{x}_i}) \cdot \epsilon_j^{B}(E_i)}{N_{\text{Bck}}}$$

See Glüsenkamp, T. (2016)

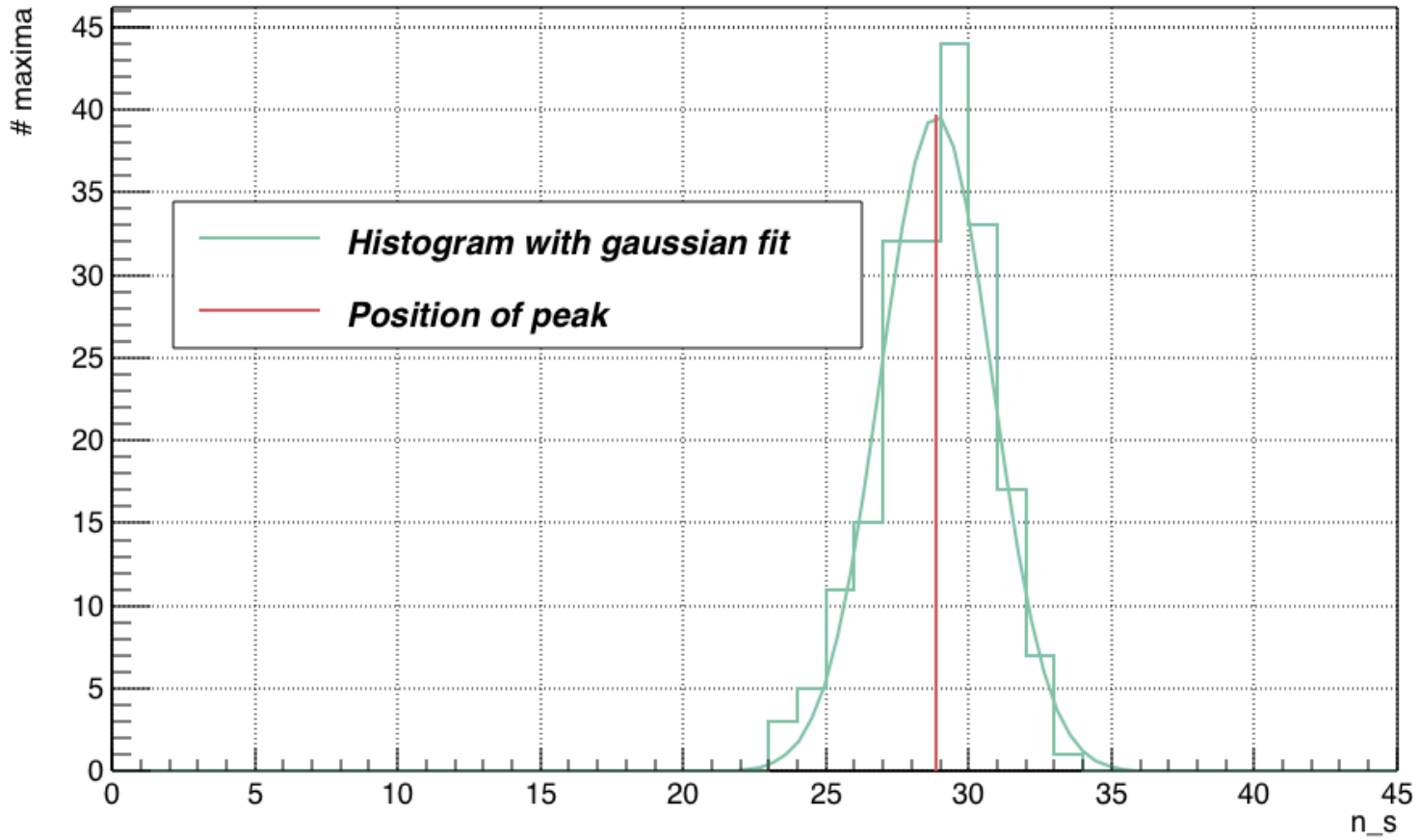
The algorithm creates likelihood curves similar to following plot:



- Calculations are repeated several times
- Likelihood maximum of each run is plotted in histogram
- Histogram is fitted with Gaussian

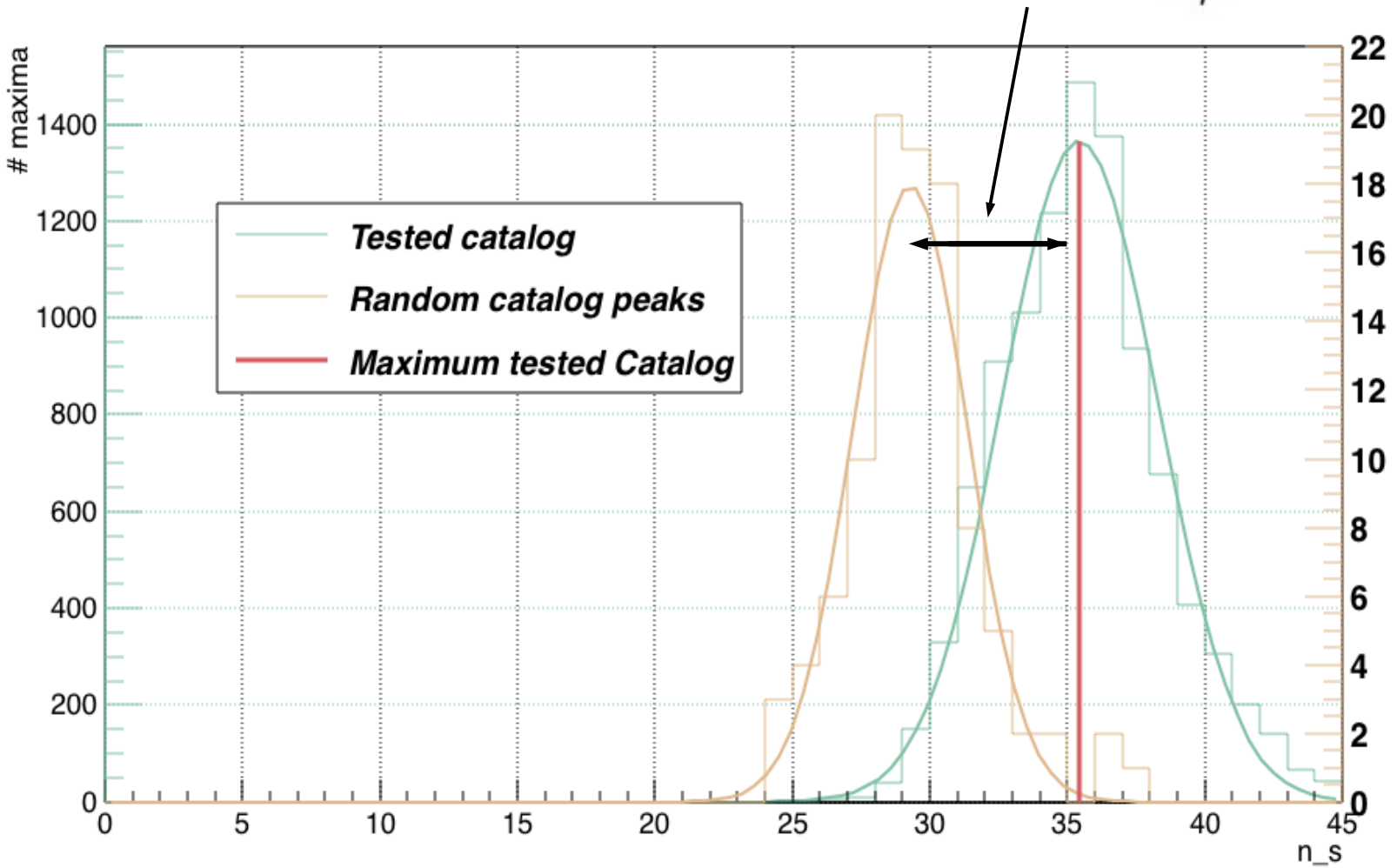


- Results strongly depend on the size of the catalog
- No meaningful comparison between different tested catalogs possible
- Solution: Perfoming tests on randomized catalogs and compare tested catalog to randomized catalogs



Distance between tested catalog and random catalogs gives a correlation probability

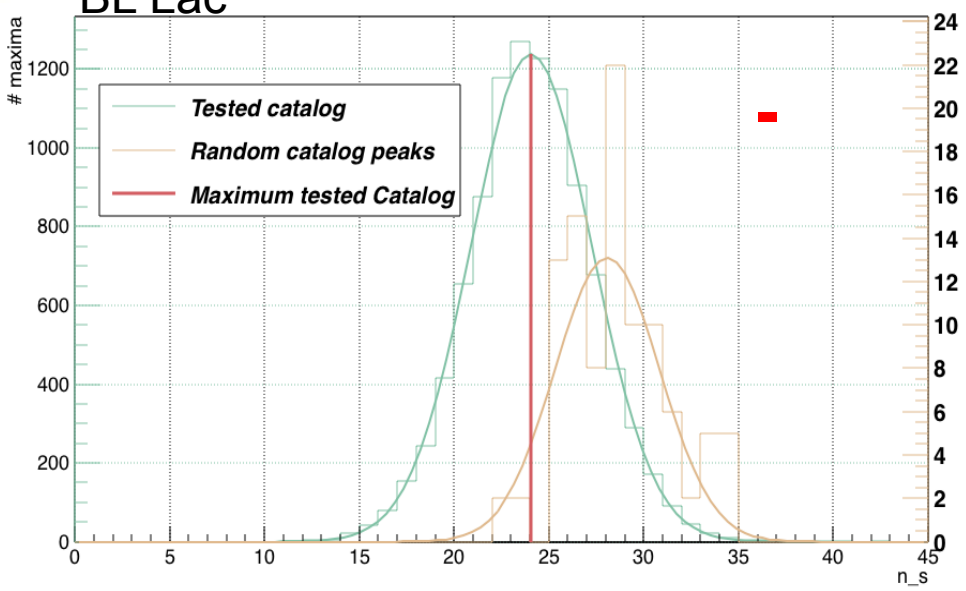
$$p = \int_{\mu}^{\tilde{\mu}} 2\hat{a} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



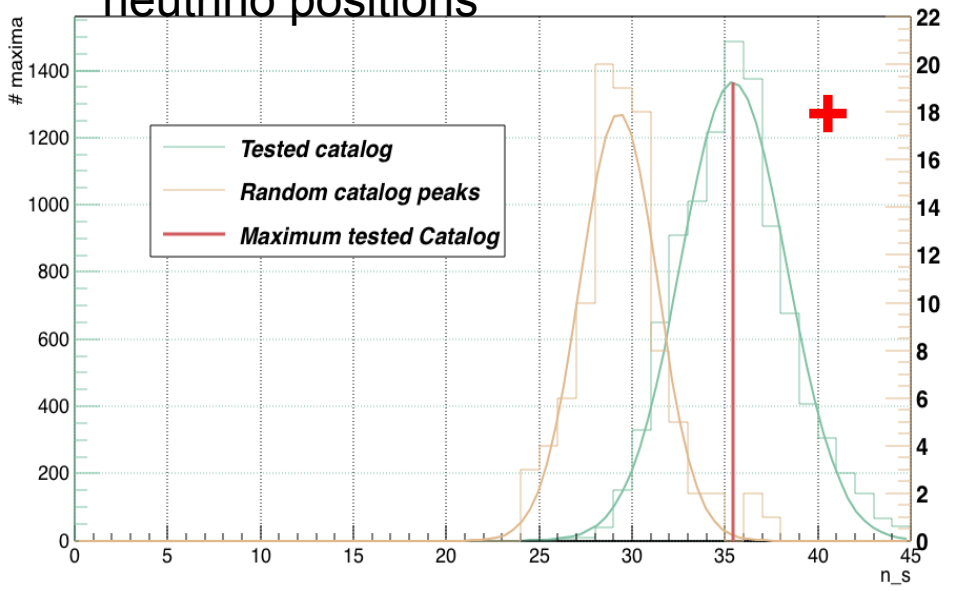
Results

Catalog	Probability p	Significance $[\sigma]$
FSRQ	0.475	0.64
BL Lac	-0.855	-1.46
BCU	-0.393	-0.51
REF-Nu	0.997	2.98

BL Lac



REF-Nu: Random positions + exact neutrino positions



Summary and Outlook

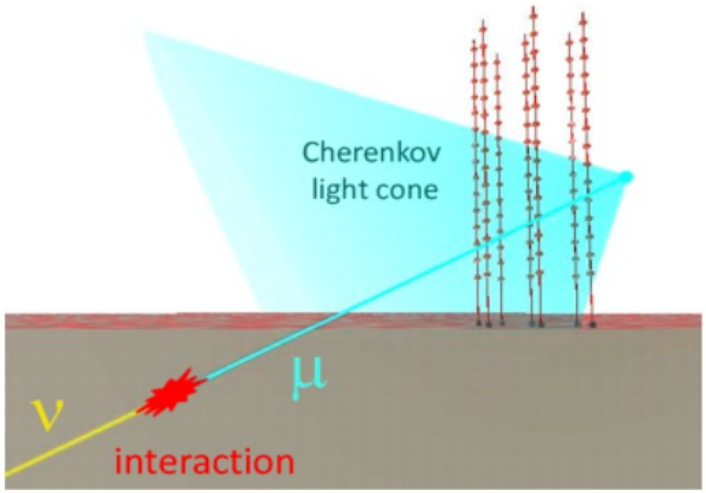
- Method allows to discriminate correlated and random catalogs
- Limitation: Large positional uncertainties of cascades
- Need more track events with energies above ~300 TeV

Thank You!

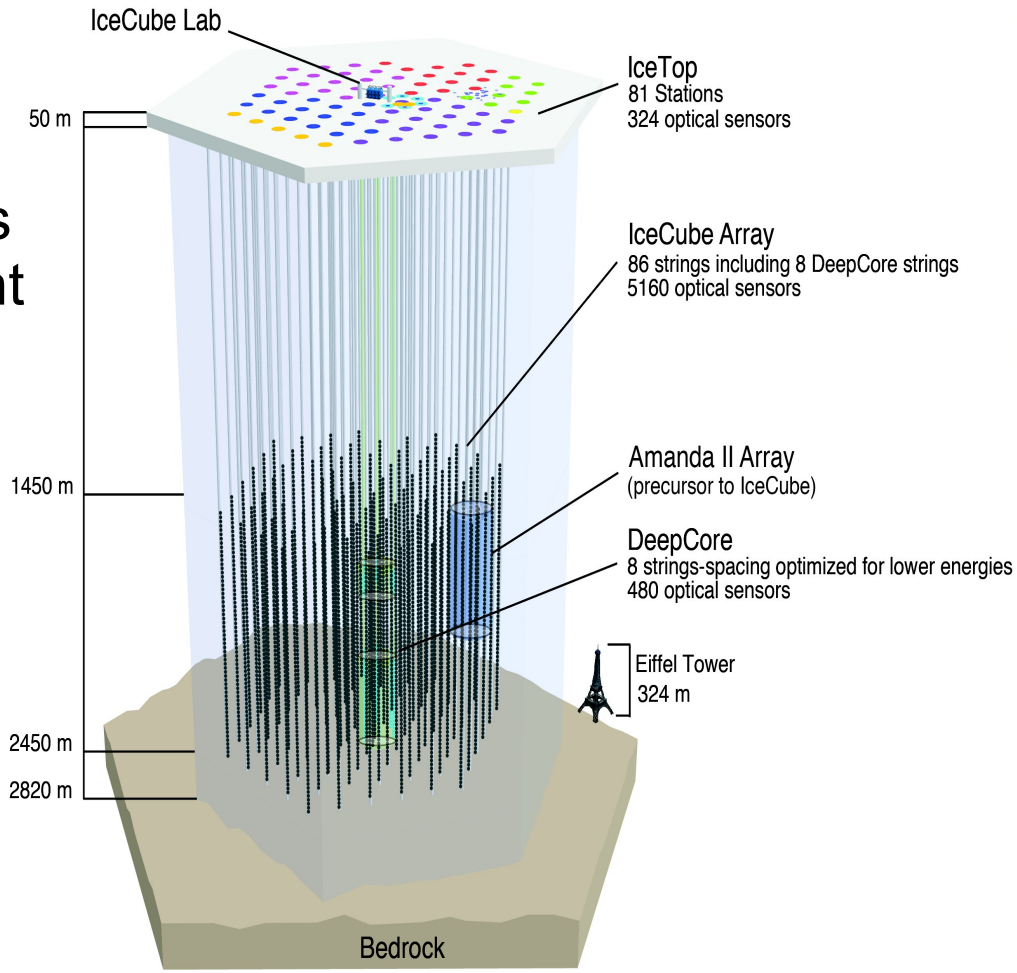
Backup Slides

IceCube

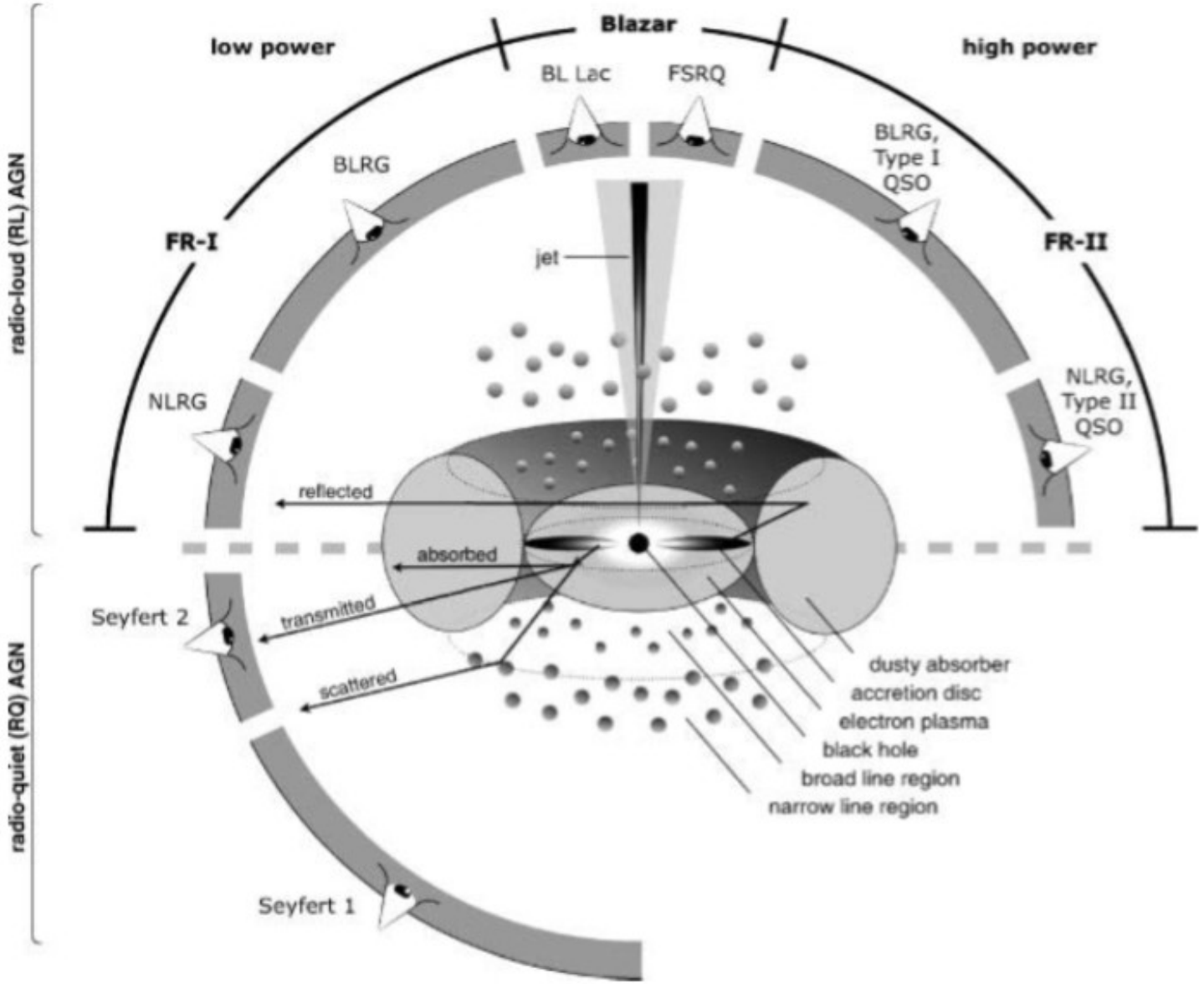
- Neutrino detector at the South Pole
- 86 strings with optical modules for detection of Cherenkov light from neutrino interaction products

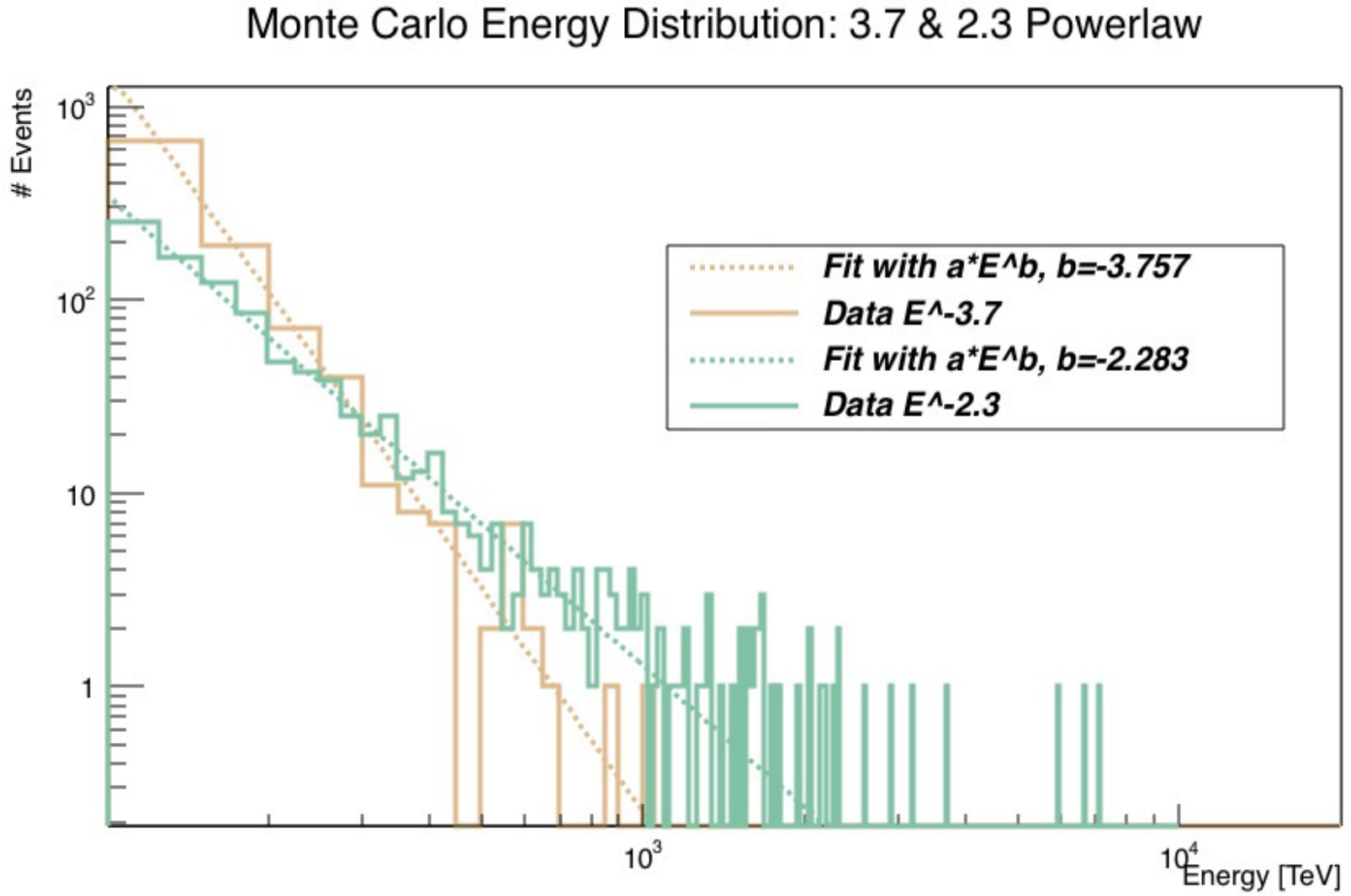


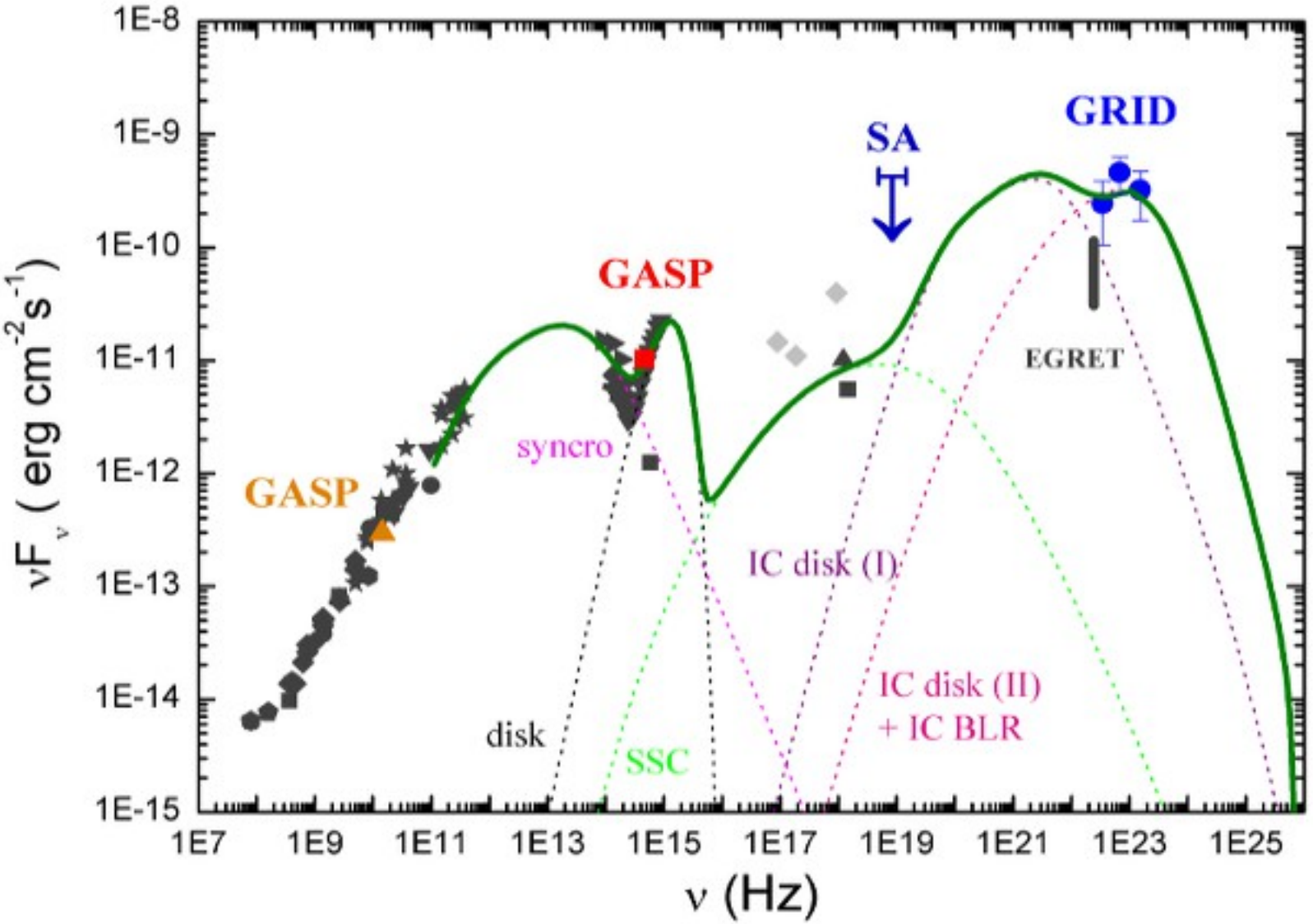
Credit: Ageron et al., 2011

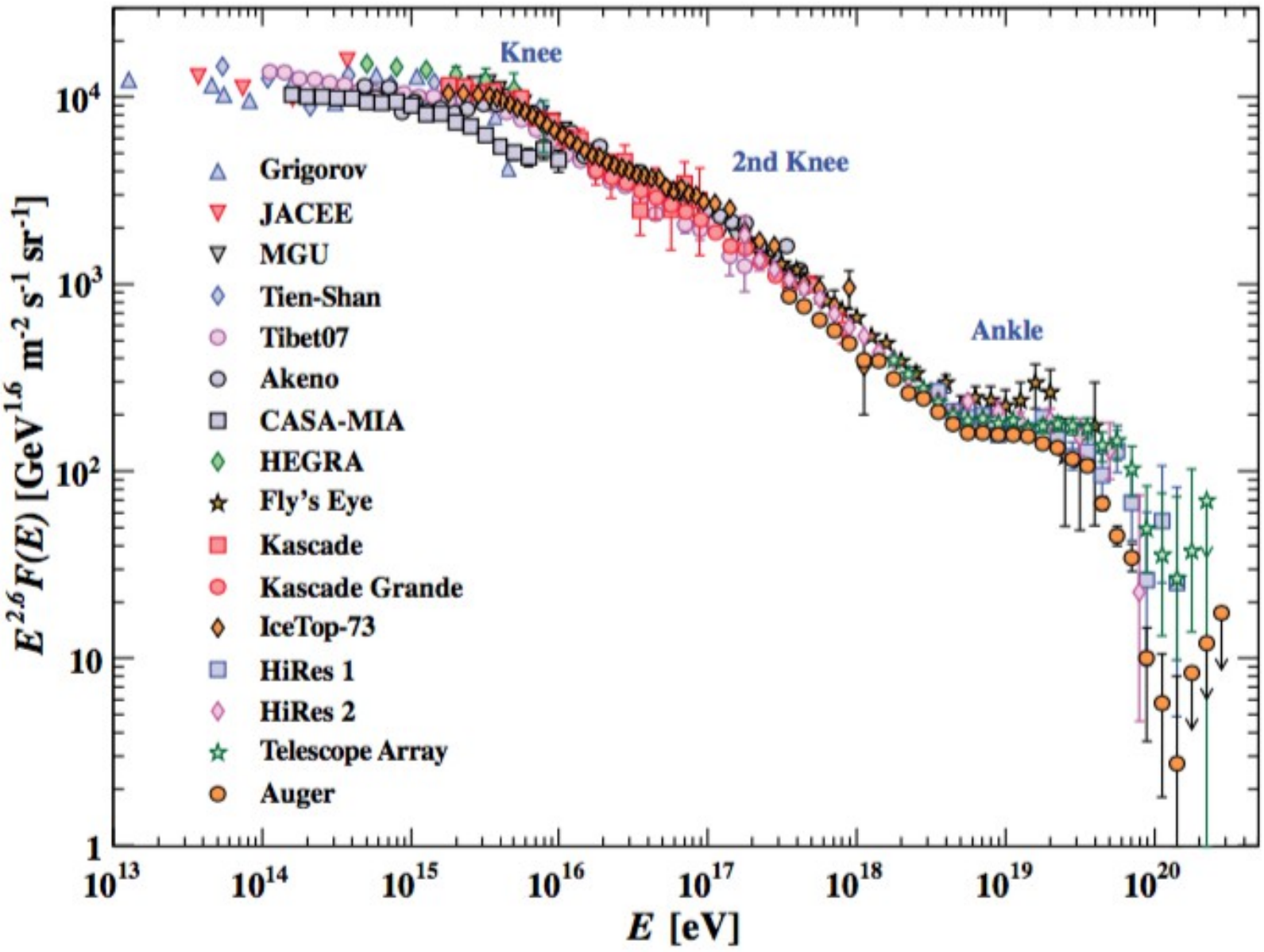


Credit: IceCube Collaboration


Blazar
low power
high power
BL Lac
FSRQ
BLRG
BLRG,
Type I
QSO
FR-I
FR-II
jet
NLRG
NLRG,
Type II
QSO
reflected
absorbed
transmitted
Seyfert 2
scattered
dusty absorber
accretion disc
electron plasma
black hole
broad line region
narrow line region
Seyfert 1
radio-loud (RL) AGN
radio-quiet (RQ) AGN


Monte Carlo Energy Distribution: 3.7 & 2.3 Powerlaw
Events
10^3
10^2
10
1
10^3
10^4
Energy [TeV]
Fit with a*E^b, b=-3.757
Data E^-3.7
Fit with a*E^b, b=-2.283
Data E^-2.3


GRID
SA
GASP
GASP
EGRET
syncro
IC disk (I)
IC disk (II)
+ IC BLR
disk
SSC
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
1E7
1E9
1E11
1E13
1E15
1E17
1E19
1E21
1E23
1E25
νF_ν (erg cm^-2 s^-1)
ν (Hz)


Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}