The Search for Cosmic Ray Sources and Recent IceCube Results

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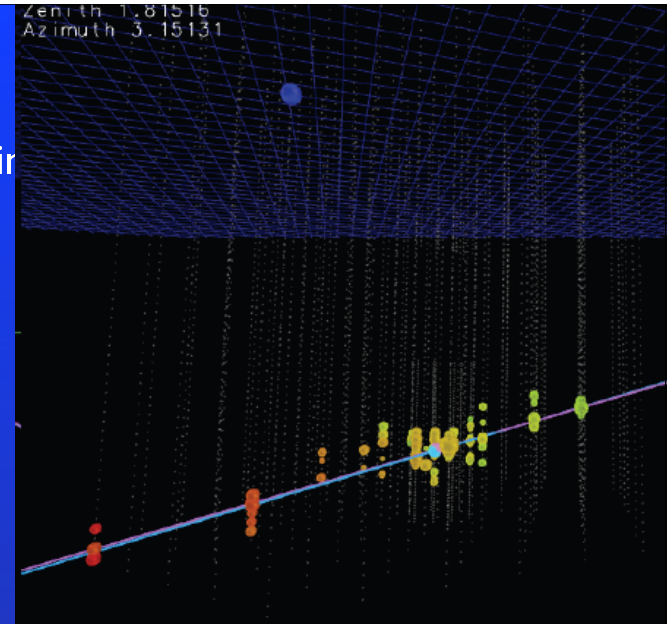
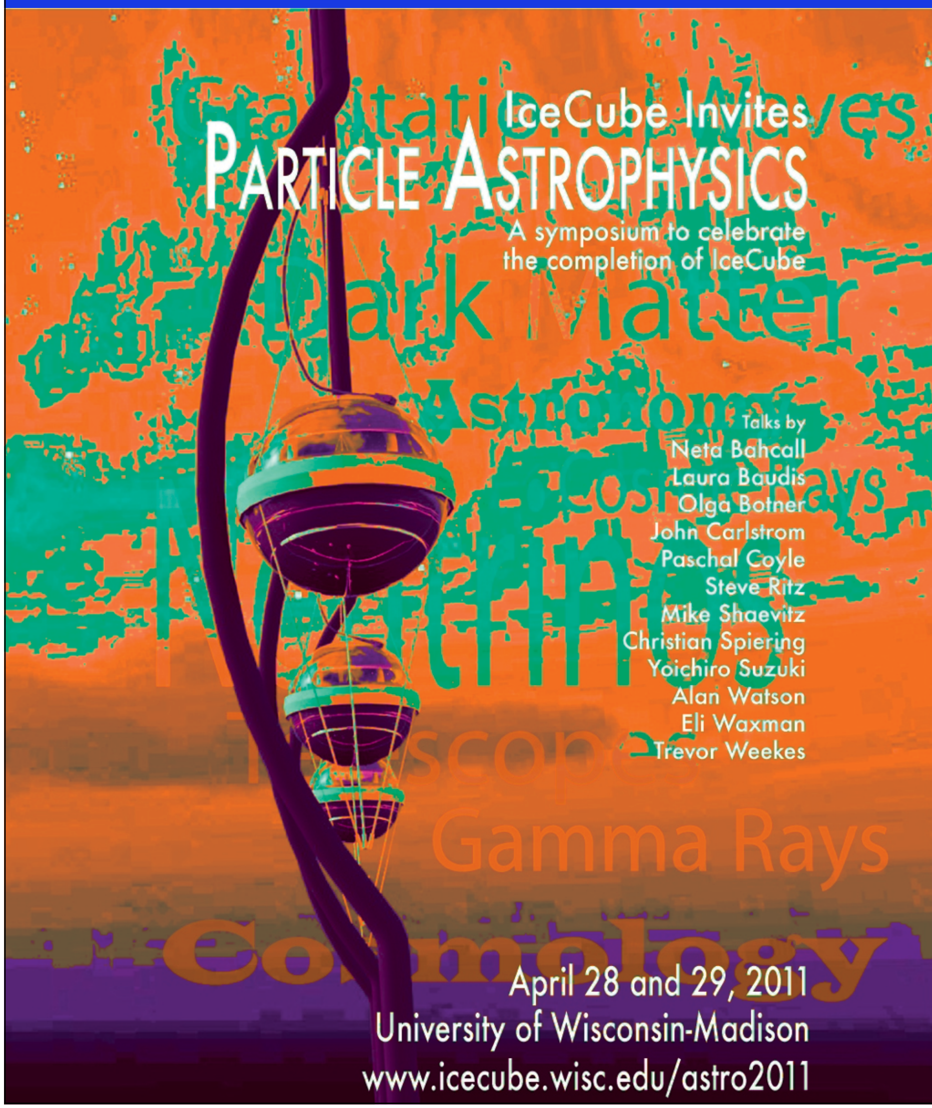
for the IceCube Collaboration

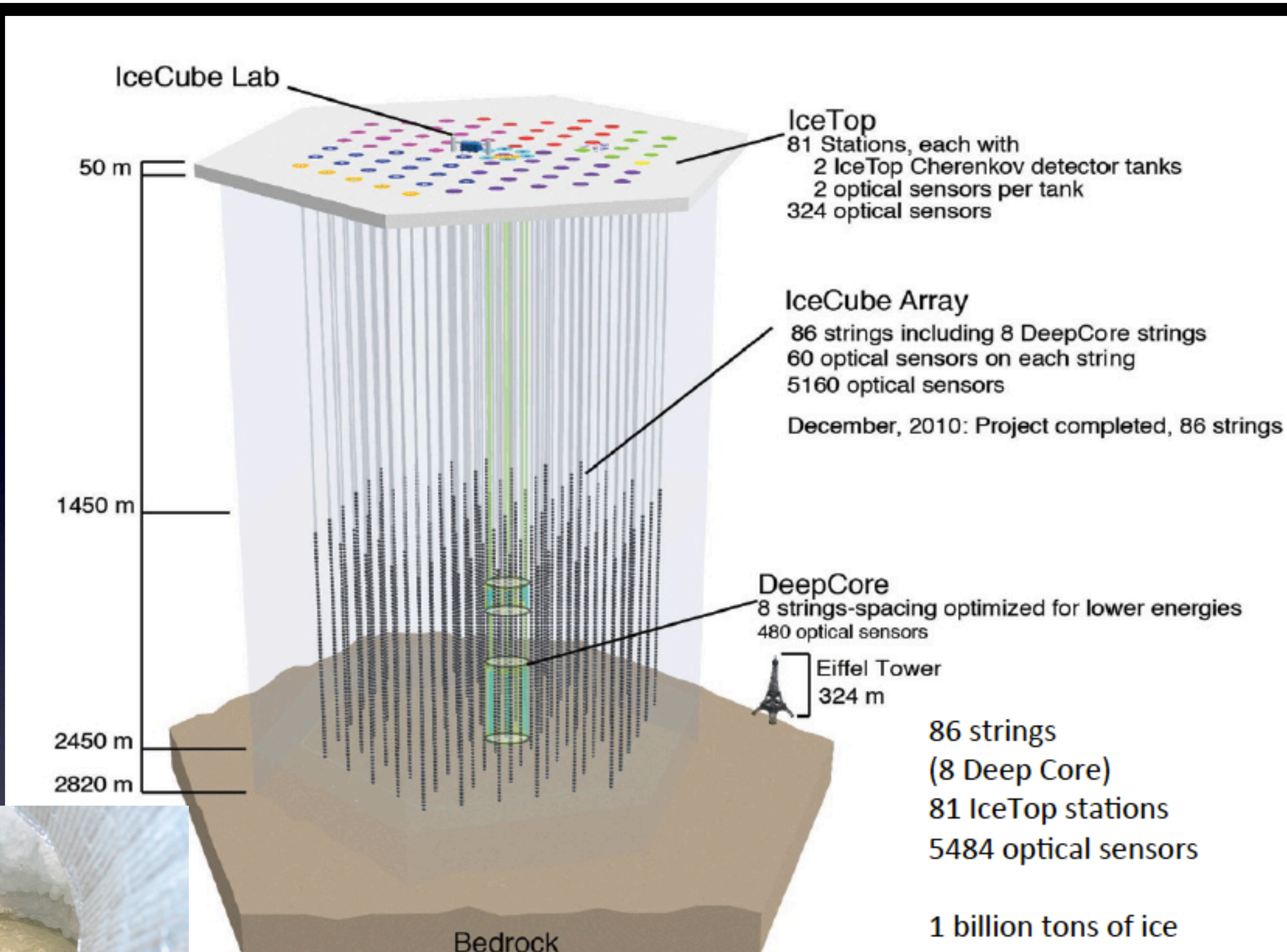
23rd Rencontres de Blois, Particle Physics and Cosmology
Jun 3, 2011

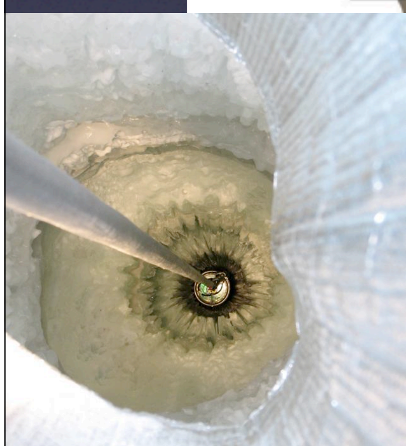
IceCube is complete!

First IceCube 86-string upgoing event in commissioning run





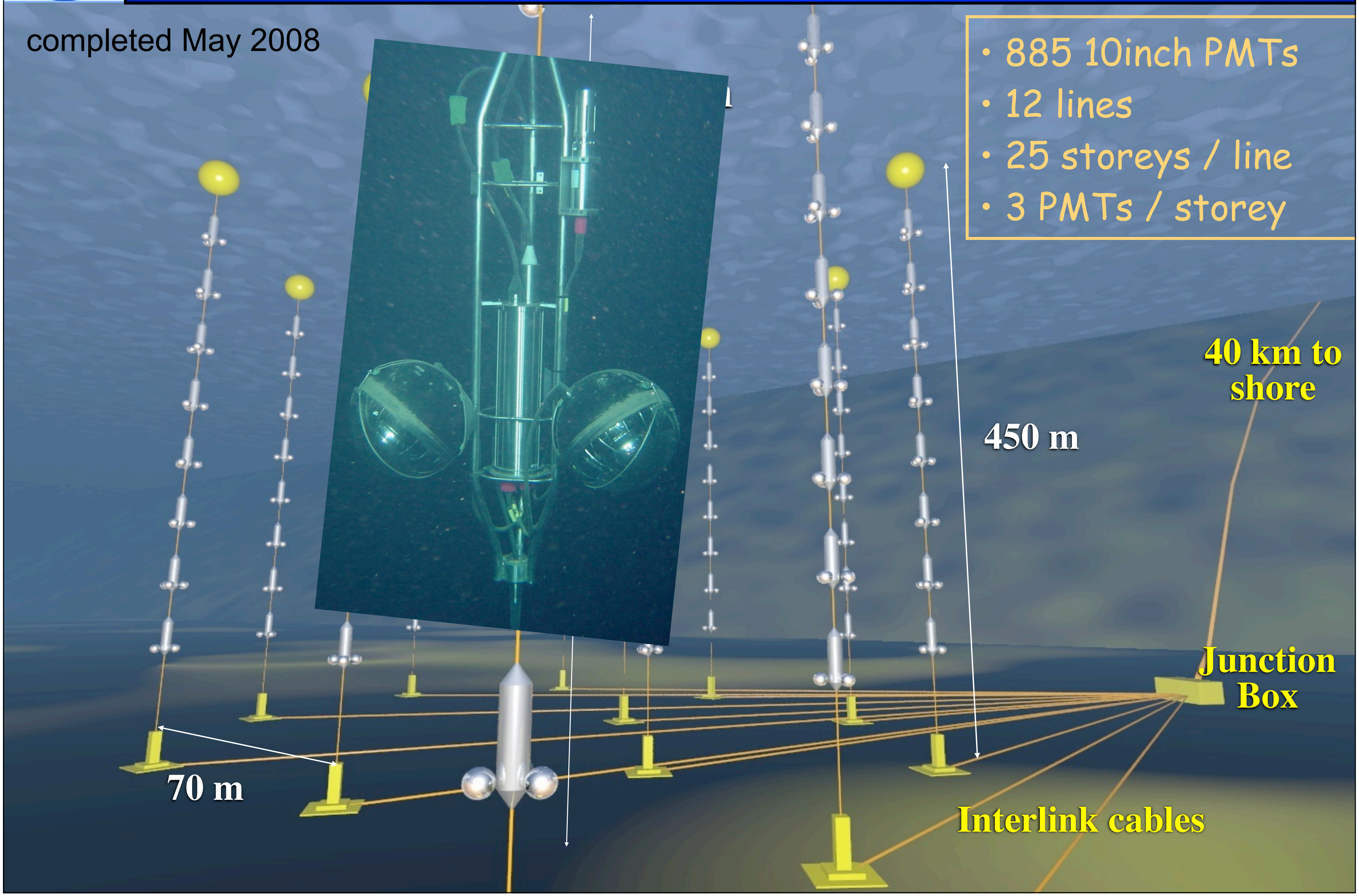

IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock
86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors
1 billion tons of ice



Another success in the sea: ANTARES

completed May 2008

- 885 10inch PMTs
- 12 lines
- 25 storeys / line
- 3 PMTs / storey



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- **Connections between Cosmic Rays - Neutrinos - Gammas**
- **Neutrino production in sources and Predicted fluxes**
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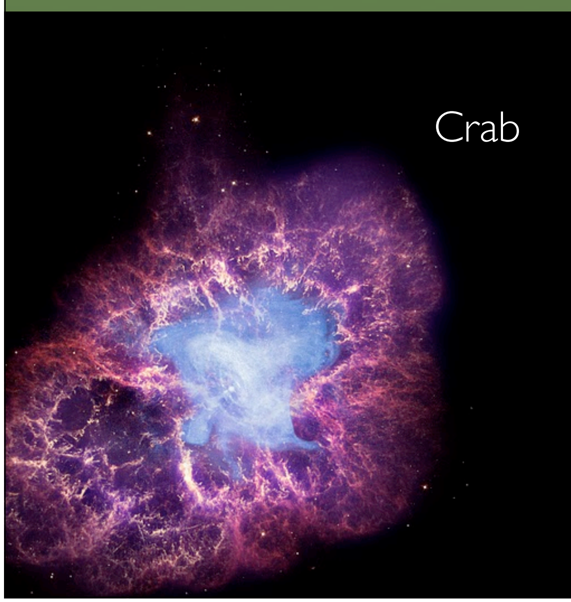
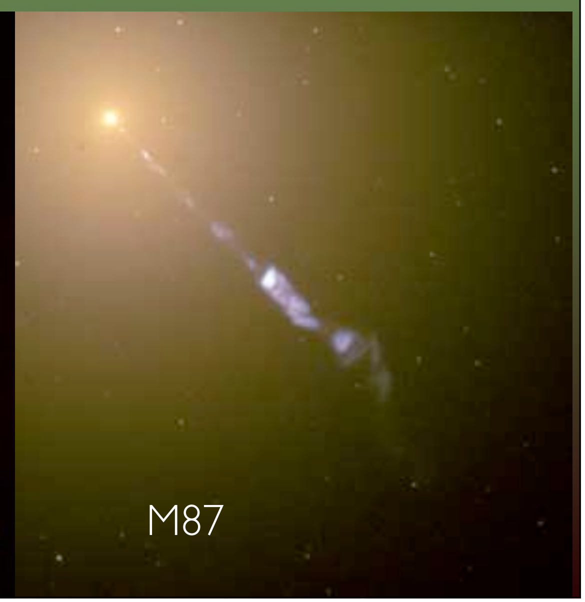
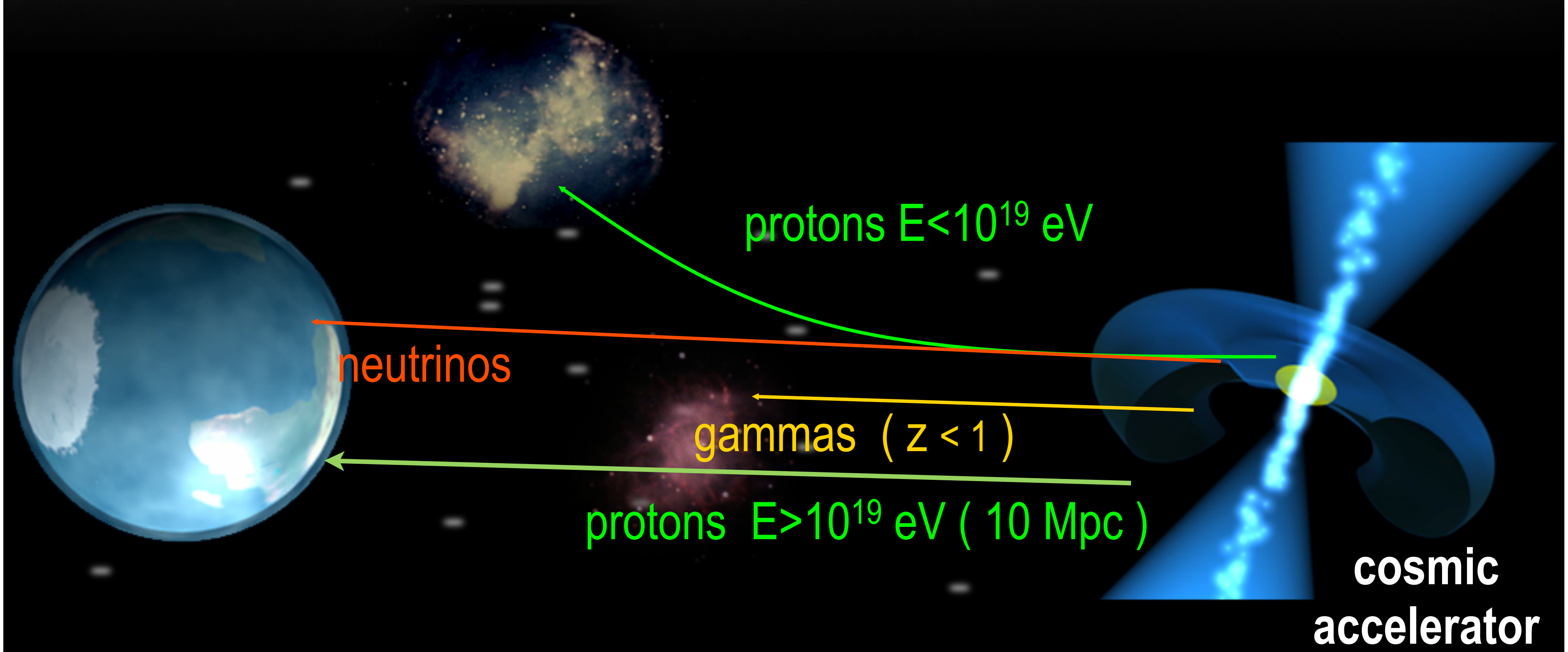




MESSENGERS FROM THE UNIVERSE

Discovery messengers: Neutrinos and Gravitational Waves

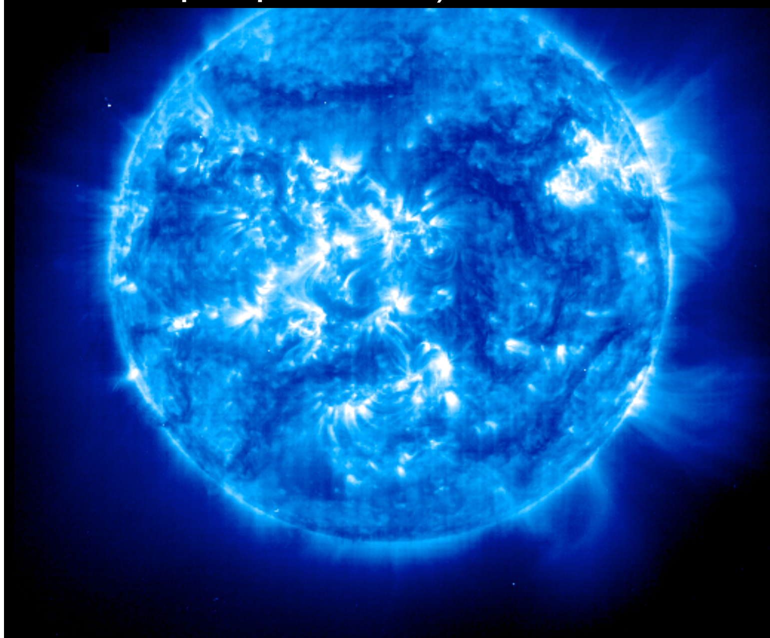


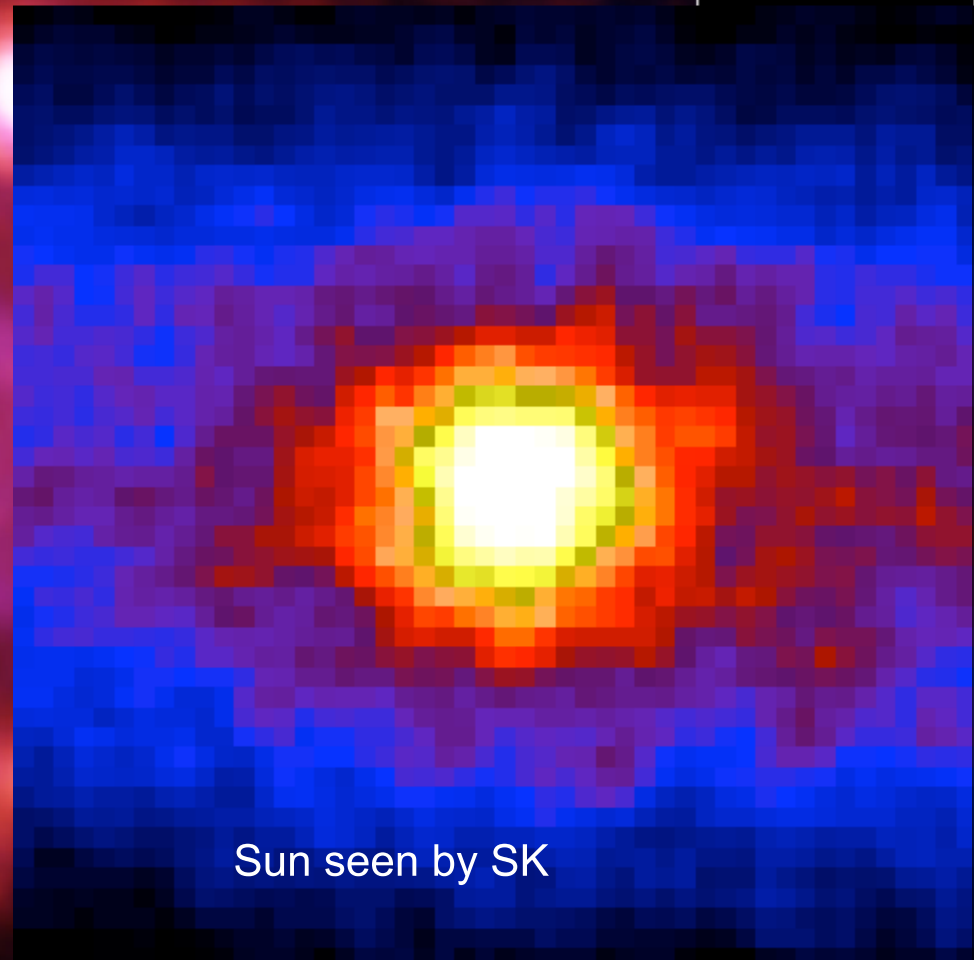
photons: absorbed on dust and radiation; reprocessed at source

protons/nuclei: deviated by magnetic fields, absorbed on radiation (GZK)

First Astrophysical Neutrino signals

Fusion reactions and magnetic reconnection solar flares accelerate CRs to about 10 GeV (one seen by IceTop, ApJL 2008)





Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC04-09a

OBSERVABLE UNIVERSE

10^3 TeV photons barely reach us from the Galactic Centre

$$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$$

Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \rightarrow \Delta^+ \rightarrow \pi^+ n$$

$$L_p = \frac{1}{\sigma_{p-\gamma CMB} n_\gamma} \sim \frac{1}{10^{-28}\text{cm}^2 \times 400\text{cm}^{-3}} \sim 10\ \text{Mpc}$$

The neutrino horizon is comparable to the universe!

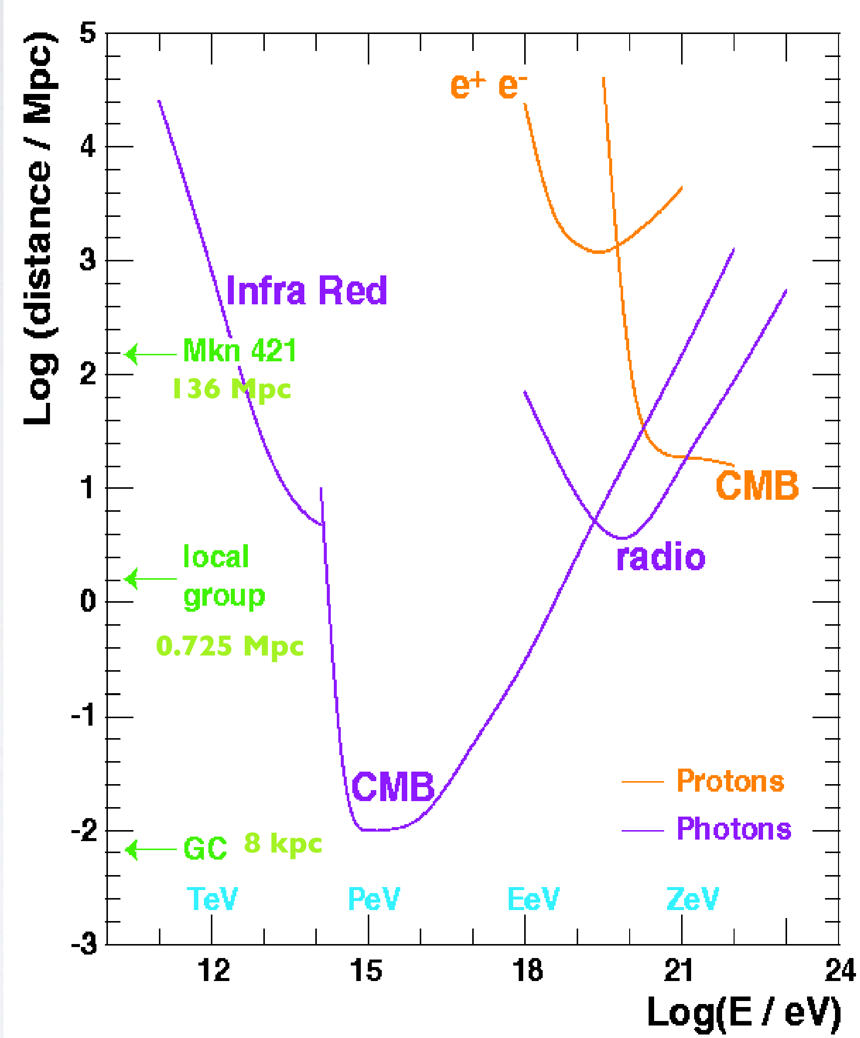
$$\bar{\nu}\nu_{1.95K} \rightarrow Z \rightarrow X$$

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4 \times 10^{21} \left(\frac{1\text{eV}}{m_\nu}\right)\text{eV}$$

$$L_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6Gpc$$

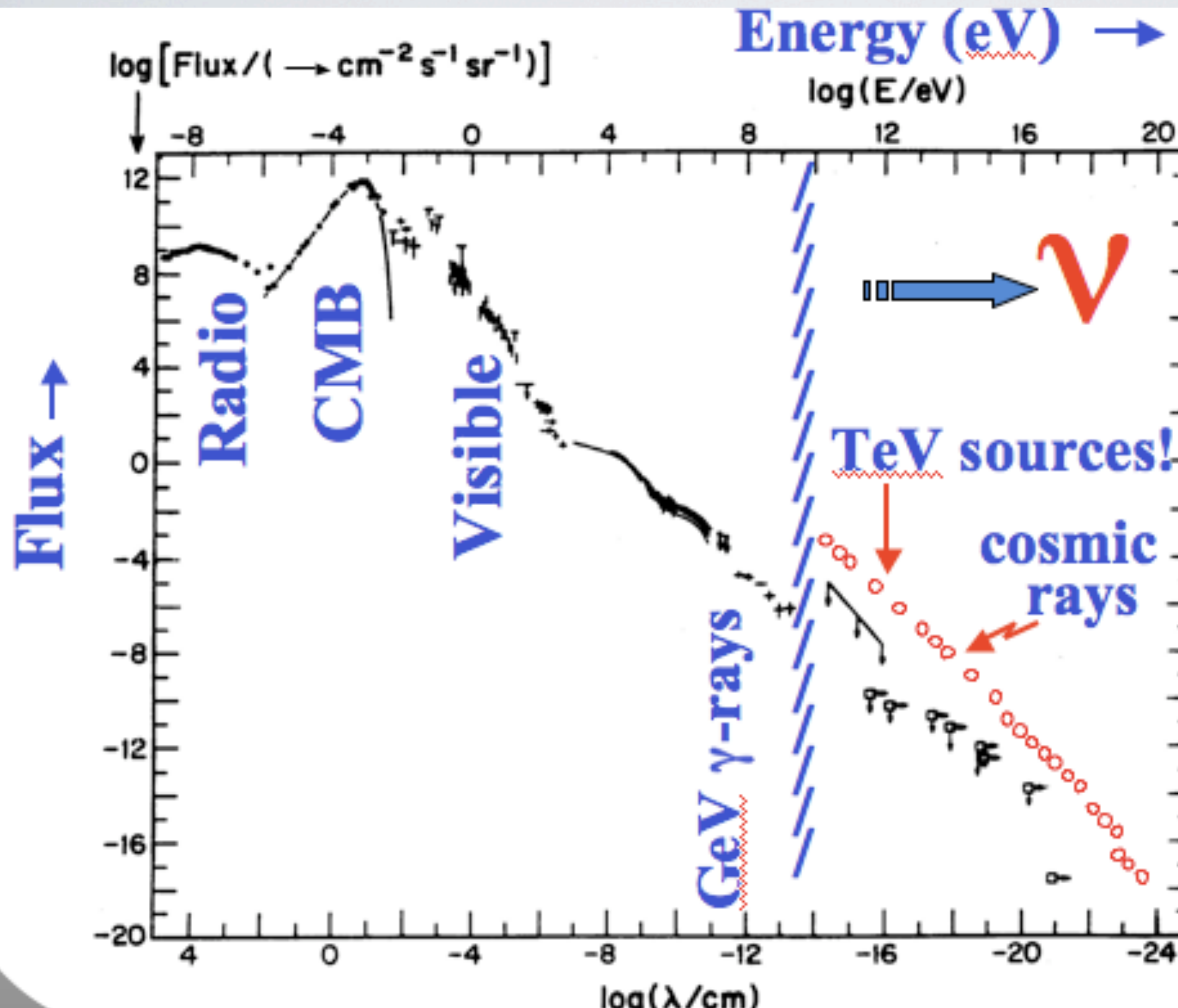
Particle horizon about 14 Gpc

1Mpc = 3.26 Mly = 3.1 10^{24} cm



T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)

UNDERSTANDING ACCELERATION PROCESSES IN THE UNIVERSE



Gamma astronomy

< 100 TeV

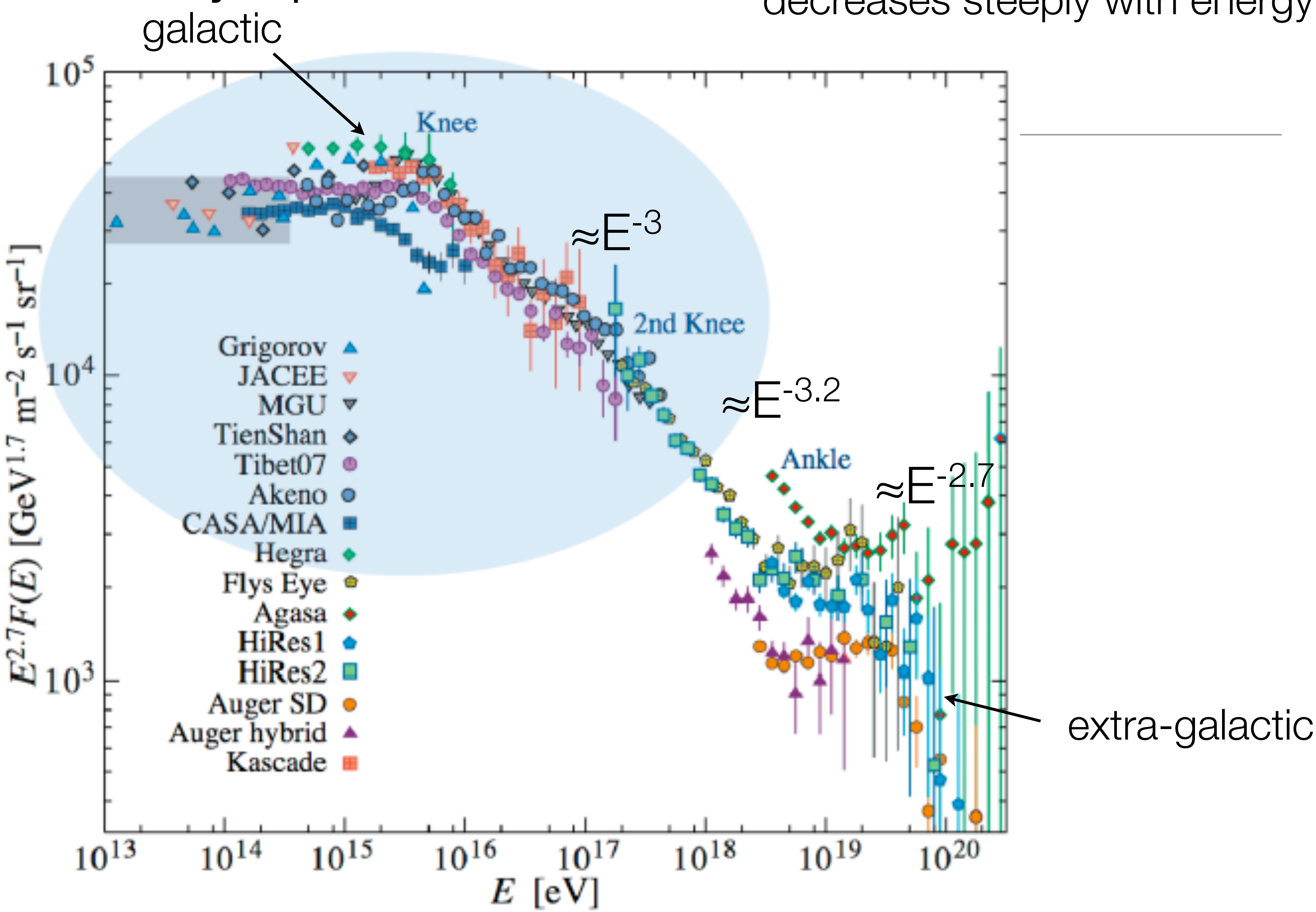
Neutrino astronomy

> 10 EeV

Proton astronomy

Cosmic Ray Spectrum

Luminosity of the CR beam decreases steeply with energy



Galaxy containment (B ~ 4 uG)

R ~ 400 pc @ 10^{18} eV
R ~ 0.4 pc @ 10^{15} eV

POWER OF SOURCES OF COSMIC RAYS

energy density flux = velocity x density

$$4\pi \int dE \left(E \frac{dN}{dE} \right) = c\, \rho_E$$

$1) p + \gamma \rightarrow \Delta^+ \rightarrow p\pi^0$

$2) p + \gamma \rightarrow \Delta^+ \rightarrow n\pi^+$

Waxman & Bahcall, PRD59, 1999 and PRD64, 2001)

Galactic

galactic CR: $\rho_E \sim 10^{-12}$ erg/cm^3
Power needed: $\rho_E / T_{esc} \approx 10^{-26}$ erg/cm^{3}s
$T_{esc} \approx 3 \times 10^6$ yrs escape time from Galaxy

10^{51} erg/SN every 30 years ~10^{-25} erg/cm^3 s for Galactic disk volume ~10^{67} cm^3

10% of SN provides the environment and energy to explain the galactic CRs!

1934 Baade and Zwicky
Acc mechanism then proposed by Fermi in 1949

Extragalactic

Above the ankle:

$$E\left\{E\frac{dN_{CR}}{dE}\right\} = \frac{3 \times 10^{10}\,\mathrm{GeV}}{(10^{10}\,\mathrm{cm}^2)(3 \times 10^7\,\mathrm{s})\,\mathrm{sr}} = 10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Energy density in extra-galactic CRs:

$$\rho_E = \frac{4\pi}{c}\int_{E_{min}}^{E_{max}} \frac{10^{-7}}{E} dE \frac{GeV}{cm^3} \sim 3 \times 10^{-19} \frac{erg}{cm^3}$$

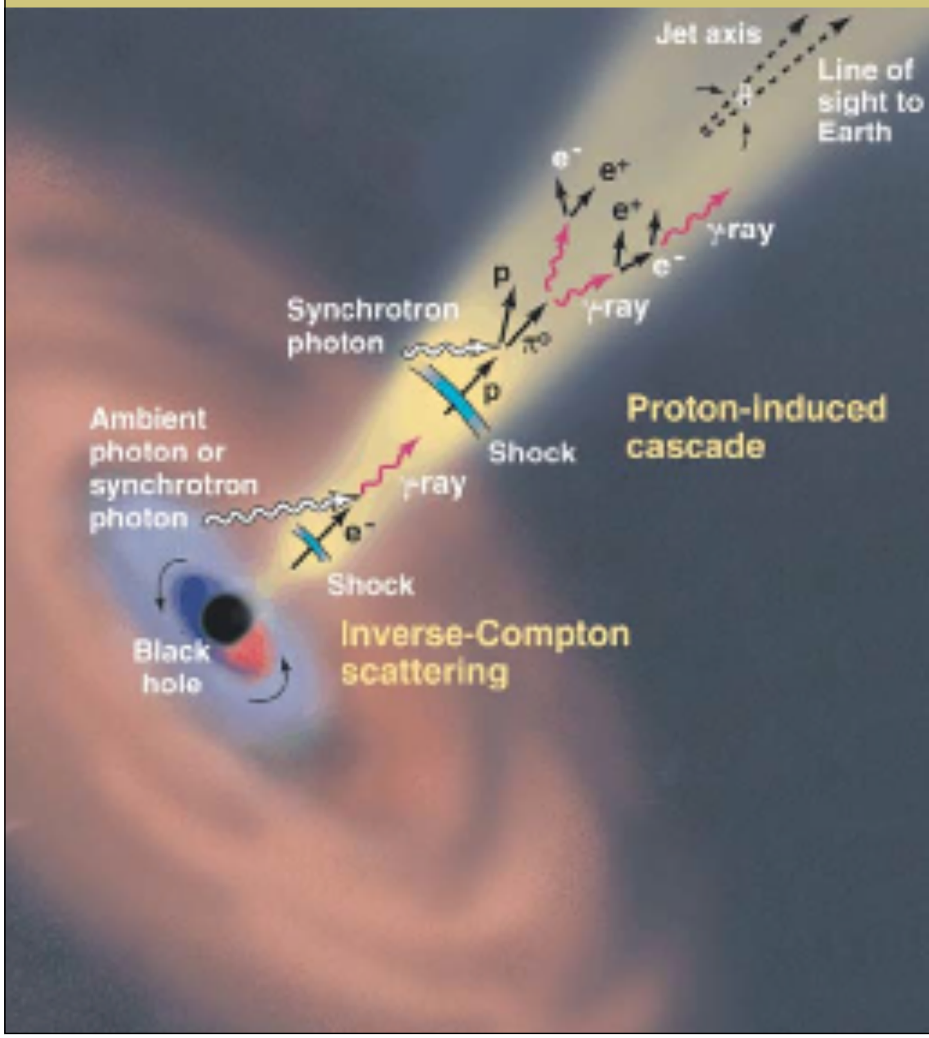
$$E_{max}/E_{min} \sim 10^3$$

Power needed by a population of sources of p with E^{-2} to generate ρ_E over the Hubble time = 10^{10} yrs $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}

3×19^{39} erg/s per galaxy
3×10^{42} erg/s per cluster of galaxies
2×10^{44} erg/s per AGN
2×10^{52} erg per cosmological GRB.

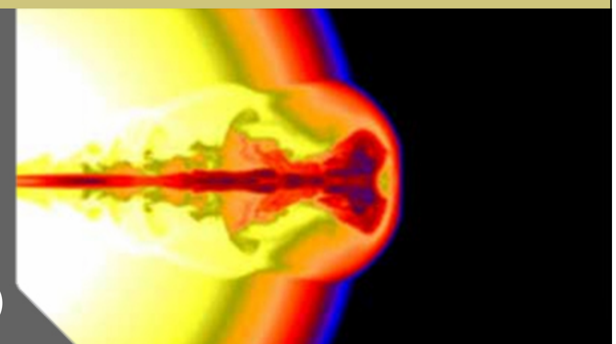
Extragalactic sources

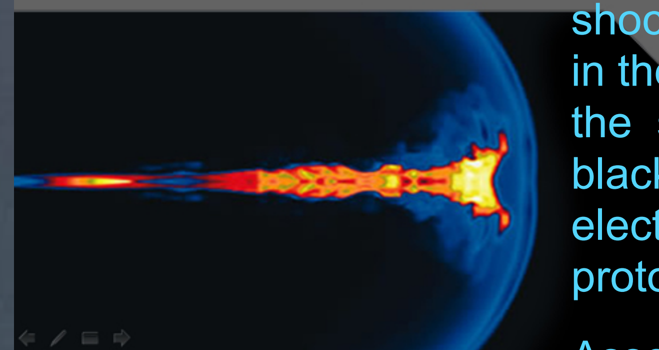
AGN's



gamma ray bursts

collapse of massive star produces a spinning black hole (long bursts)



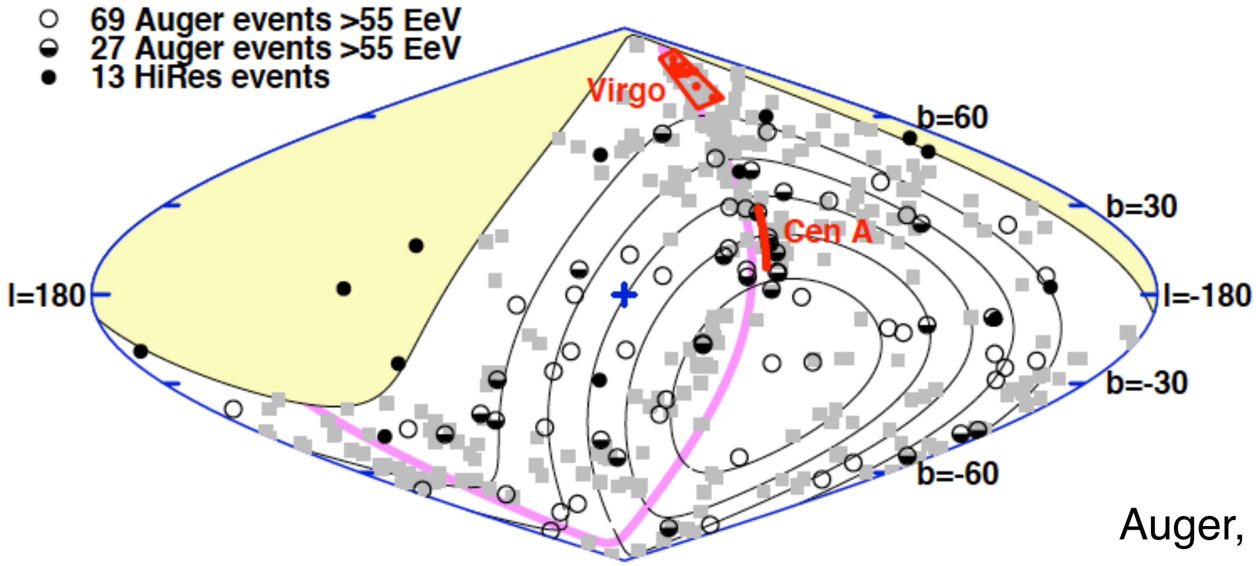


shocks produced in the outflow of the spinning black hole: electrons and protons ?

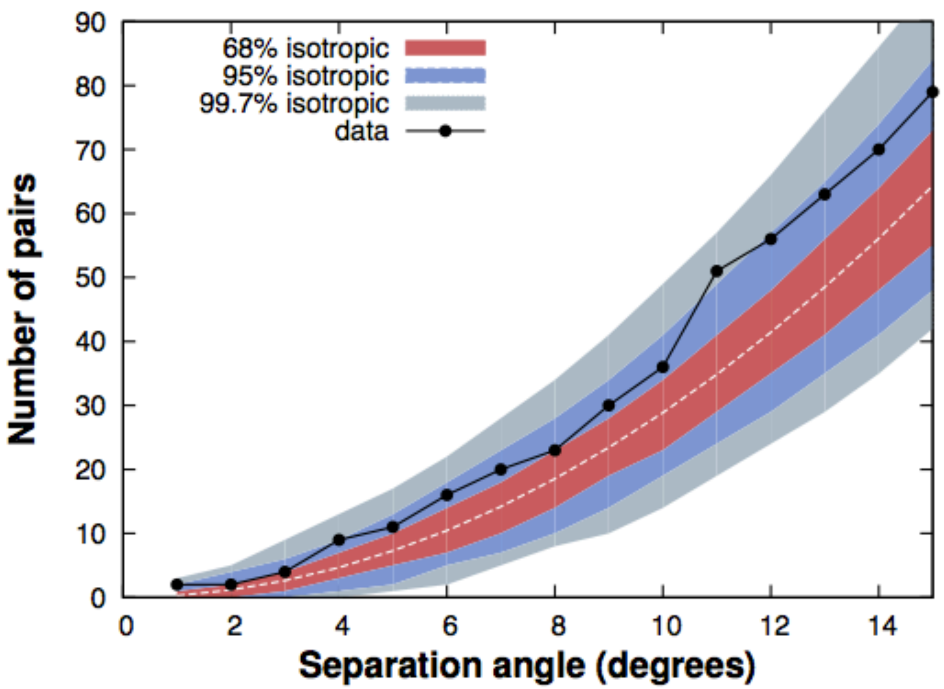
Associated to SN

compact binary mergers (short bursts)

The sources revealed?



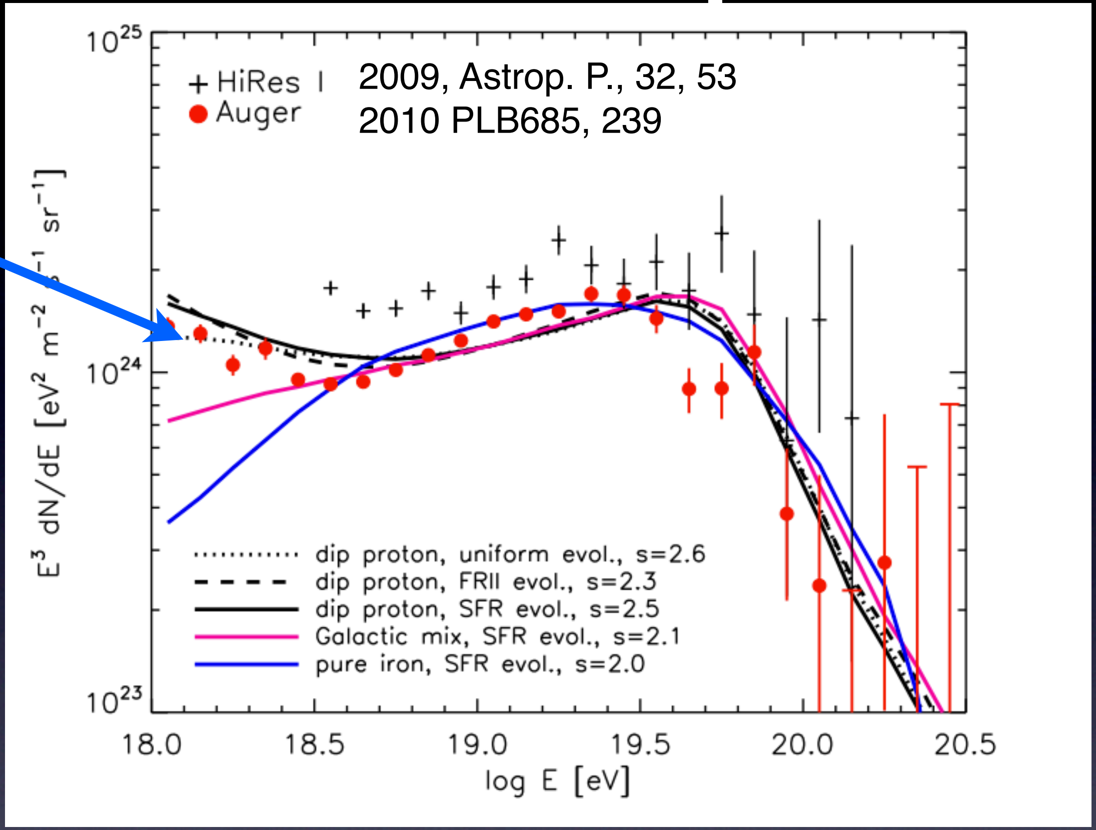
Auger, arXiv:1009.1855



Auger: correlating fraction of E>55 EeV events with AGN close-by catalogue decreased from 69% to 37% (21% expected to occur by chance for an isotropic flux).
18% of 69 events are inside 18^o from Cen A but no event from M87.
Autocorrelation function: largest deviation from isotropic distribution at 11^o.
For an isotropic distribution 1.3% pairs of the 69 events have 51 or more pairs inside 11^o.
The lack of knowledge of B-fields prevents to establish if UHECR astronomy is possible.

GZK-cut off proved

Where is the galactic - extra-galactic transition?

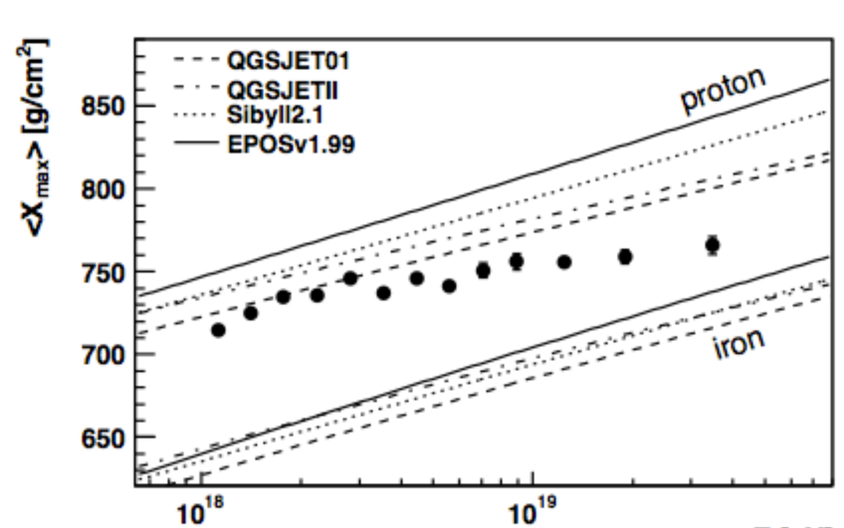


Nature trick: spectrum shows same feature for p and Fe.
While jets can easily accelerate Fe ($E_{max} \propto Z$), Fe would not survive photo-disintegrations when injected in extra-galactic accelerators such as a GRB fireball.

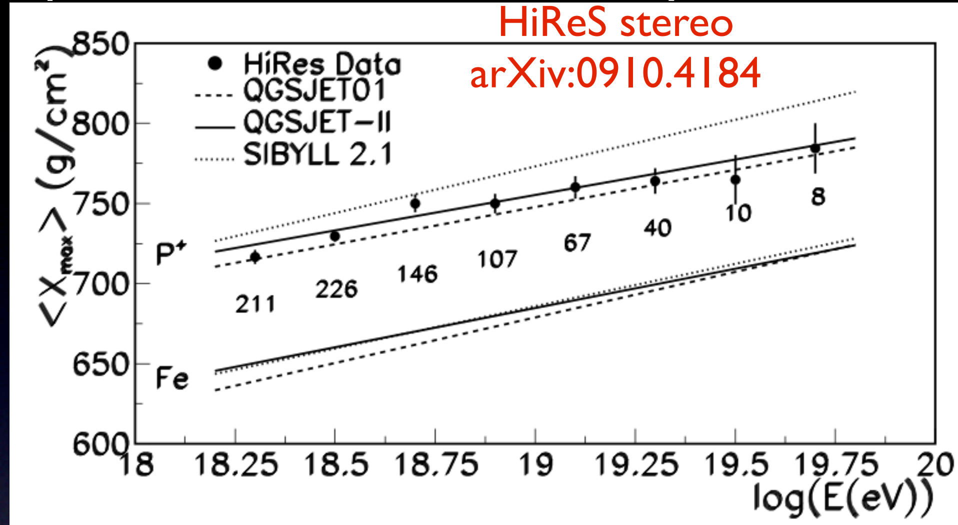
Kotera, Olinto's review arXiv: 1101.4256

Heavy/light composition?

In a heavy composition scenario anisotropies would be washed out by B-fields.

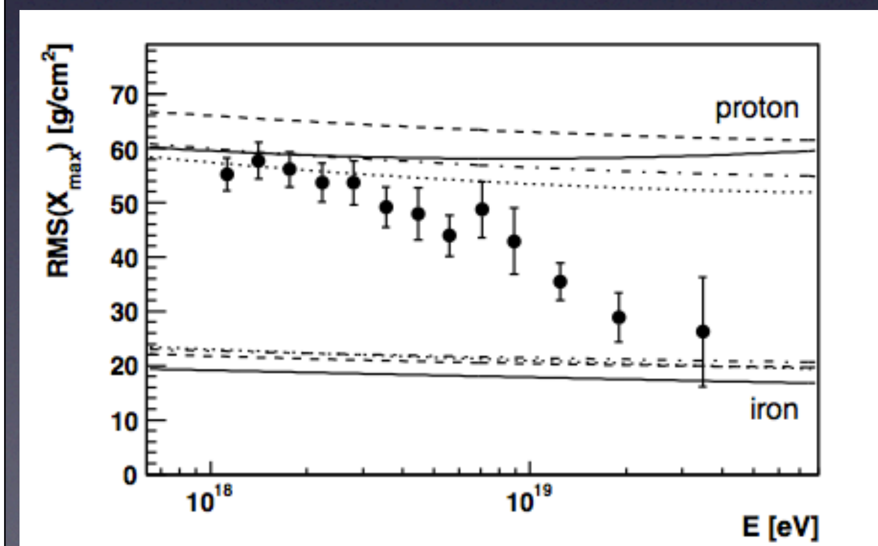


Auger arXiv:1002.0699



HiReS stereo
arXiv:0910.4184

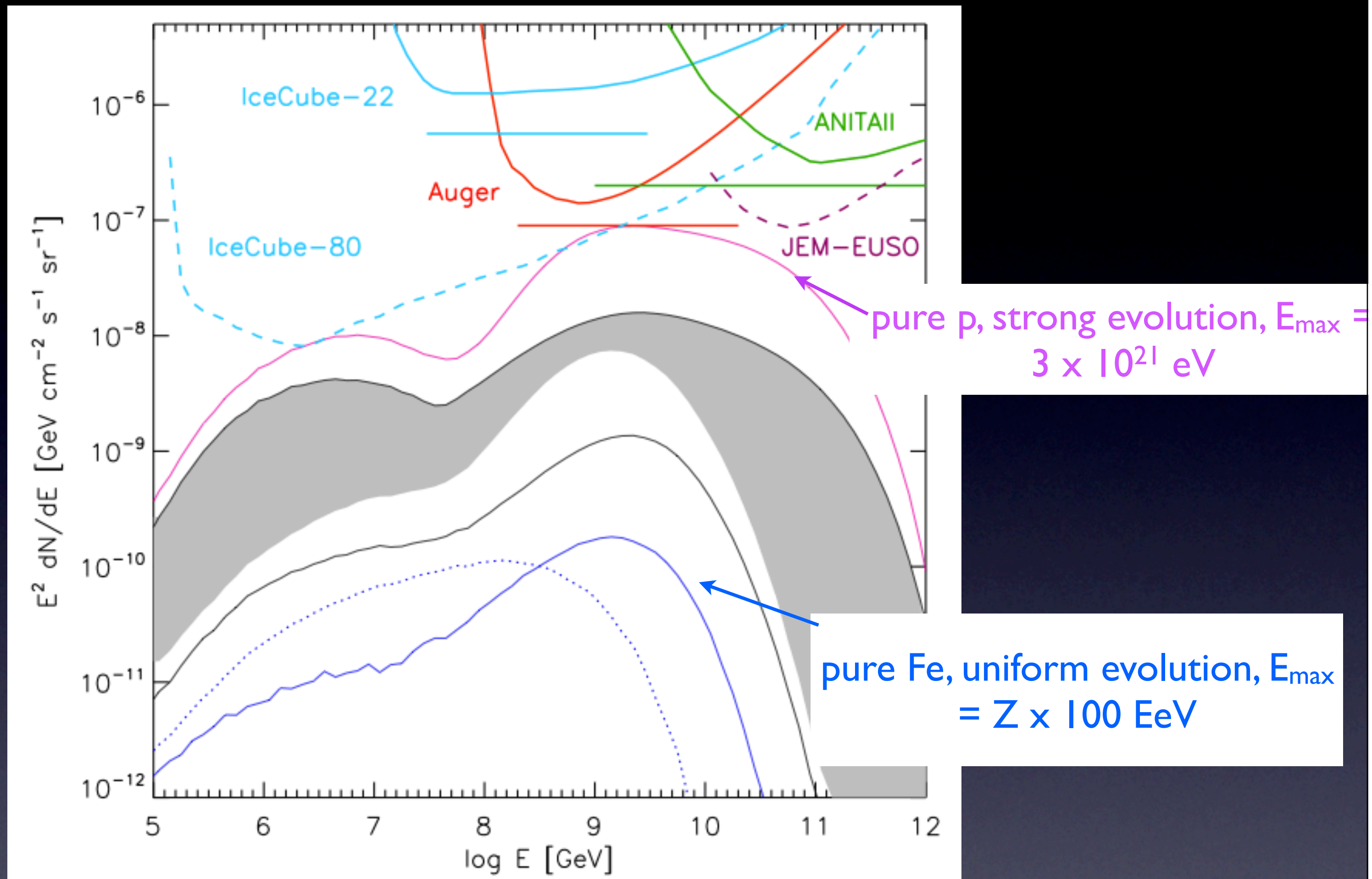
HiReS and Auger X_{max} are not directly comparable due to fiducial cuts.



An evidence of neutrinos in coincidence with UHECR would indicate that the extra-galactic sources are not GRBs because p take much longer than neutrinos. It would also indicate a p-dominated composition.

IceCube: no correlation evidence in 40-strings, 40+59 strings to be presented at ICRC 2011

Fluxes of UHECR neutrinos



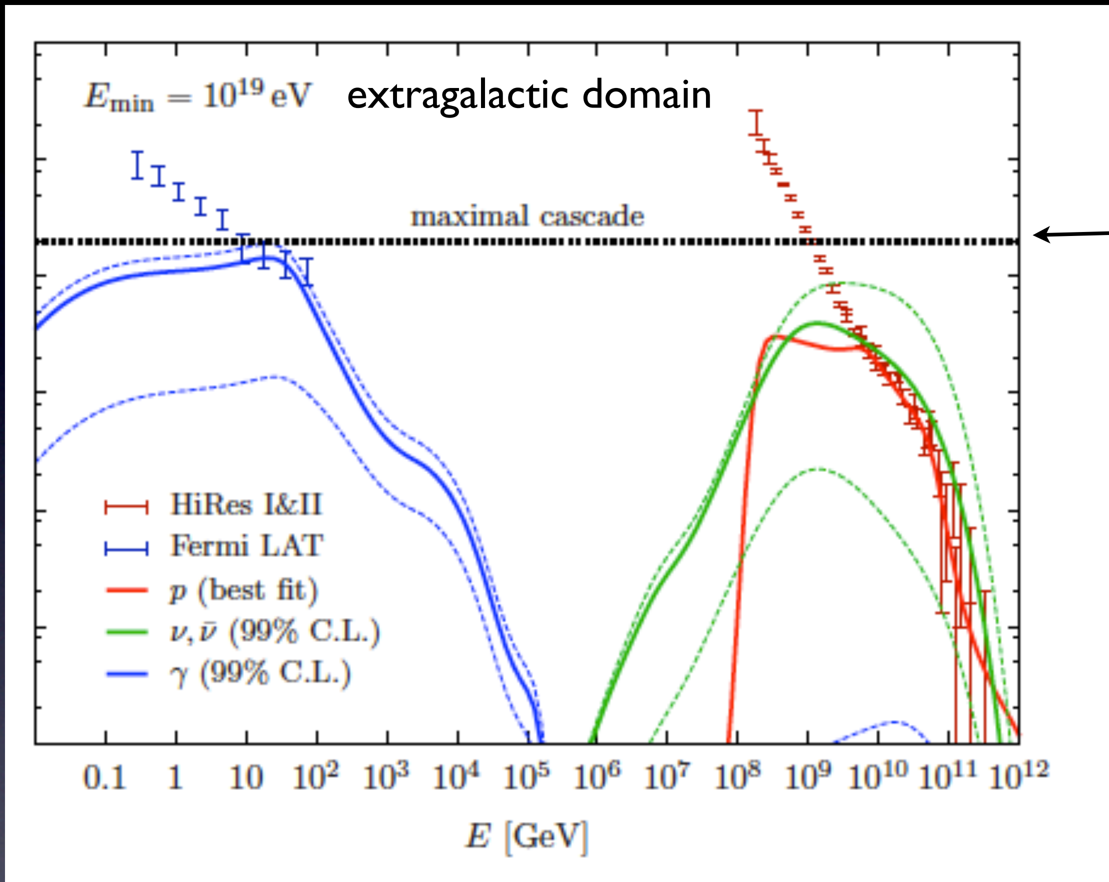
The diffuse extragalactic background measured by Fermi can be used as a constraint accounting for photon cascading.

UHECR neutrino fluxes depend on:

1) the transition energy between galactic and extra-galactic CRs
2) Emax
3) injection spectrum and source evolution

Kotera, Olinto's review arXiv: 1101.4256

Fermi-LAT extragalactic photon background - UHECR - neutrino connection



gamma flux in GeV-TeV saturating the total EM radiation energy density from proton energy losses

normalization to Fermi diffuse flux is tricky because gamma cascading and galactic point source flux subtraction.

$p + \gamma \rightarrow n + \pi^+$

$\rightarrow p + \pi^0$

~ cosmic ray + neutrino

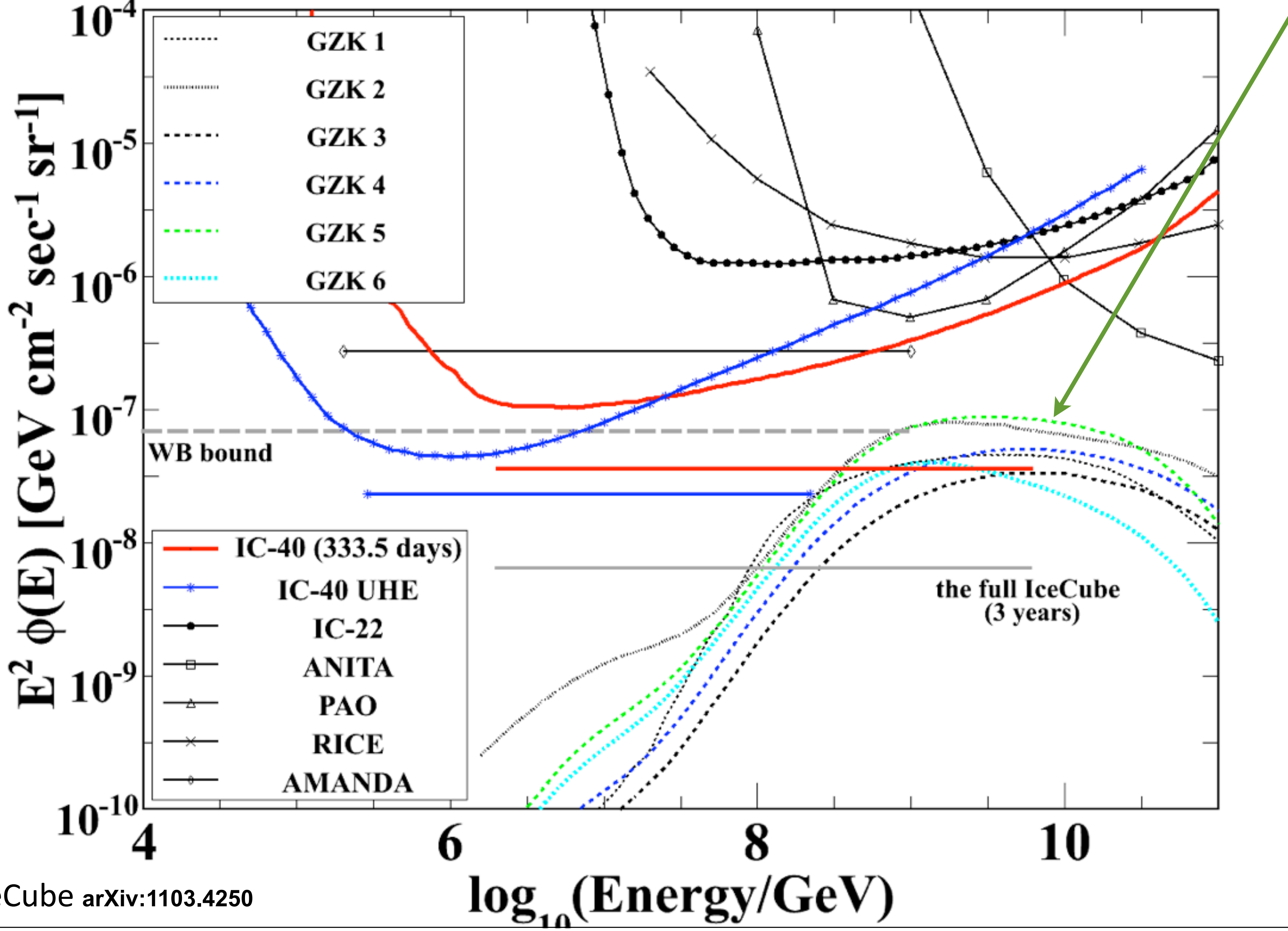
~ cosmic ray + gamma

Ahlers et al, arXiv:1005.2620

Cosmogenic Neutrinos in IceCube

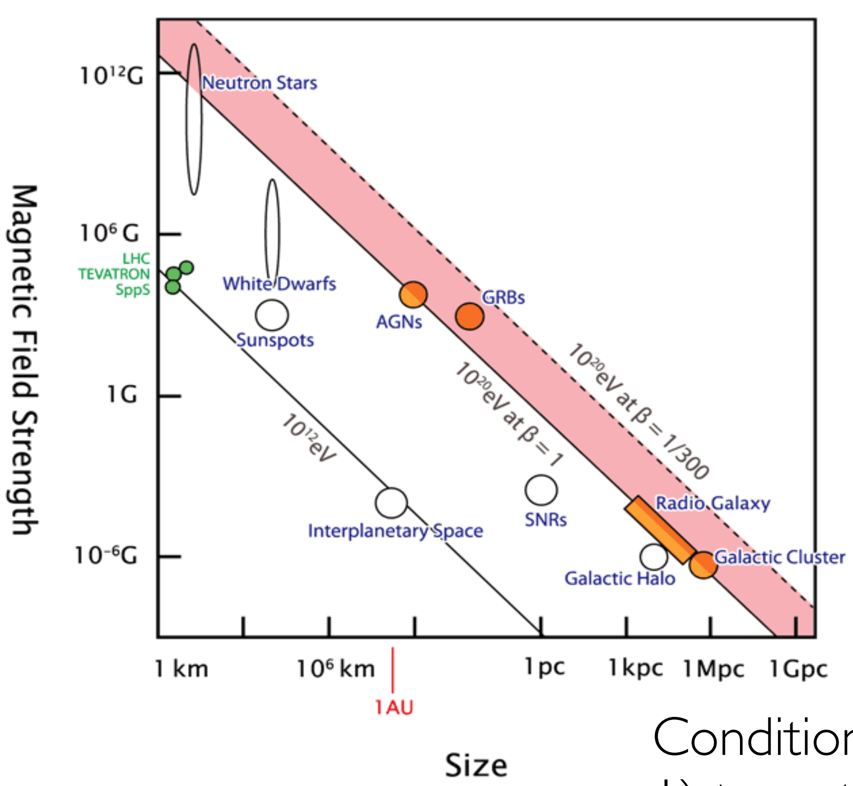
W&B with cosmological evolution: 24.5 events in IC86/3 yrs (4.5 in IC40)

GZK 5 (M. Ahlers, et al., 2010): 4.8 events in IC86/3 yrs (using constrain from Fermi diffuse gammas)



IceCube arXiv:1103.4250

ACCELERATION: HILLAS' PLOT



Basic acceleration condition: $R > r_L$

For jets $E_{obs} = \Gamma E_{source}$

$$E_{max} \sim \Gamma Z B R \sim \Gamma \times 1EeV \times Z \left(\frac{B}{1\mu \mathrm{G}}\right)\left(\frac{R}{1\ \mathrm{kpc}}\right)$$

More precisely the condition is:
$t_{acc} \lesssim t_{esc}, t_{age}, t_{energy\ loss}$

Conditions for GRBs to accelerate protons to 10^{20} eV:

1) $t_{acc} \lesssim t_{duration\ of\ burst}$

$$\frac{r_L}{c} \le \frac{1}{c}\frac{R}{\Gamma} \Rightarrow B \ge 10\mathrm{T} \left(\frac{E}{10^{20}\mathrm{eV}}\right)\left(\frac{10^{11}\mathrm{m}}{R}\right)$$

2) synchrotron energy lost ≲ energy gained in acceleration

$$\frac{r_L}{c} \le t_{syn} \Rightarrow B \le 10\mathrm{T}\left(\frac{\Gamma}{300}\right)^2\left(\frac{10^{20}\mathrm{eV}}{E}\right)^2 \qquad t_{syn} = \frac{\lambda_{int}}{\Gamma c} = \frac{1}{c\Gamma n_e \sigma_{Thompson}} \qquad n_e = \frac{m_e^2 c^4 B^2}{6\pi m_p^3}$$

this conditions sets the constrain: $\Gamma \ge 130 \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{3/4}\left(\frac{0.01\mathrm{s}}{\Delta t}\right)^{1/4}$

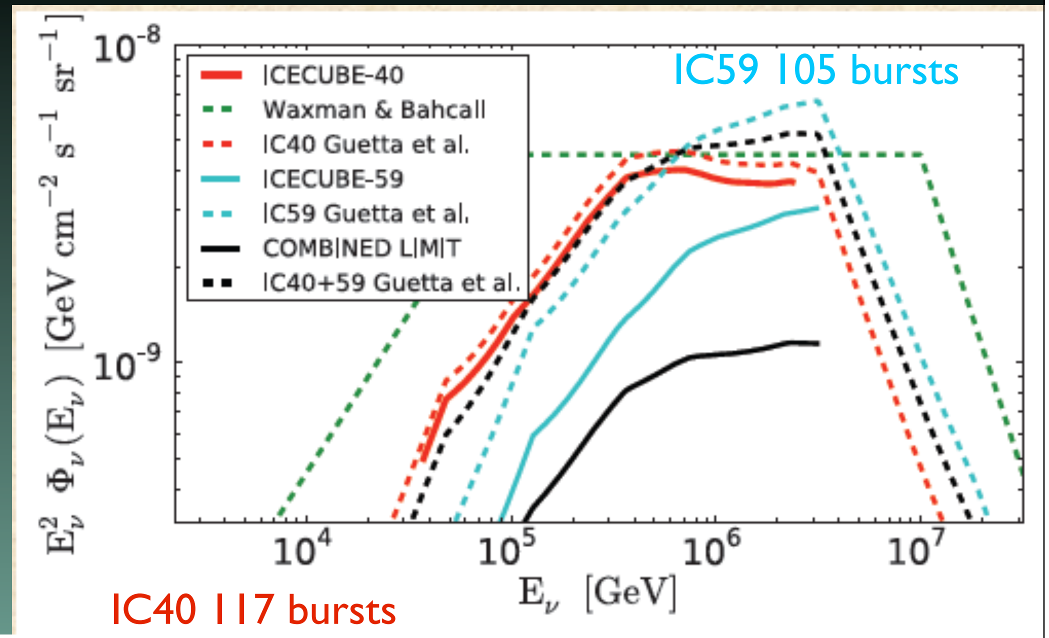
Waxman astro-ph/0303517

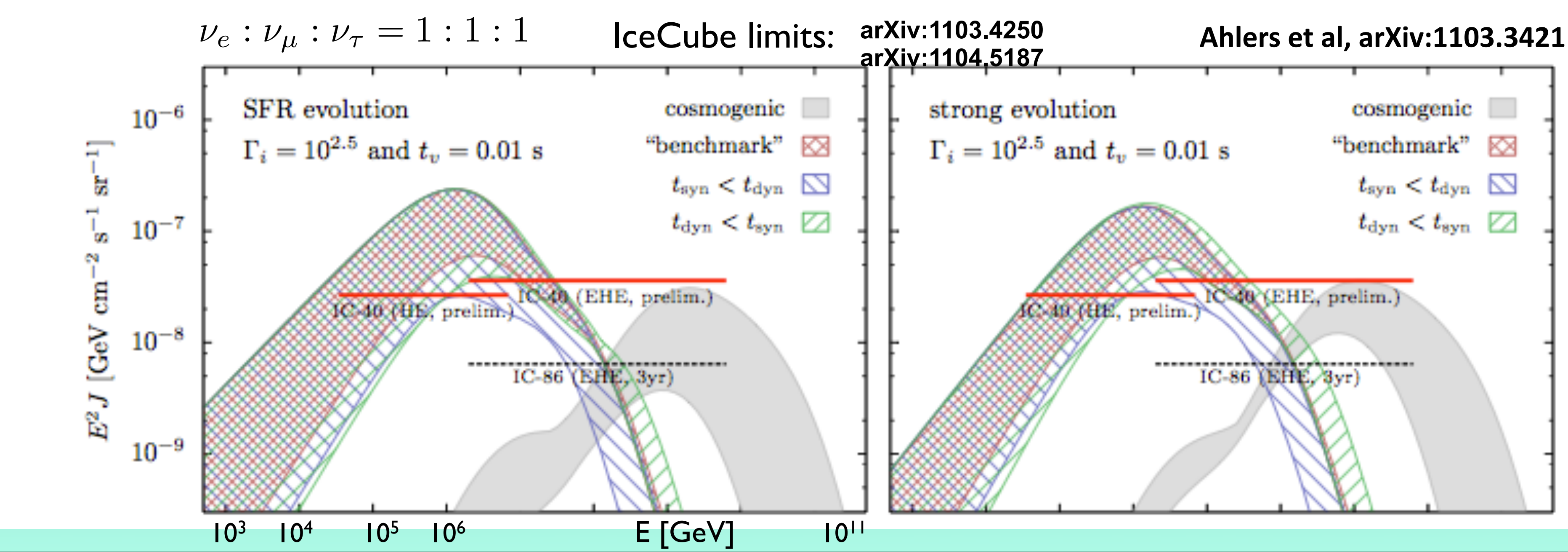
IceCube results for GRBs

40+59 strings: 8 events expected by W&B model, 0 observed
Combined limit is 0.22 modeled flux

Model parameters:
Bulk Lorentz factor and baryon loading in jet that determine the number of interactions of protons with photons, other extra-galactic CR sources?

In 3 yrs IceCube will rule out fireball model or establish GRBs are not only sources of UHECRs

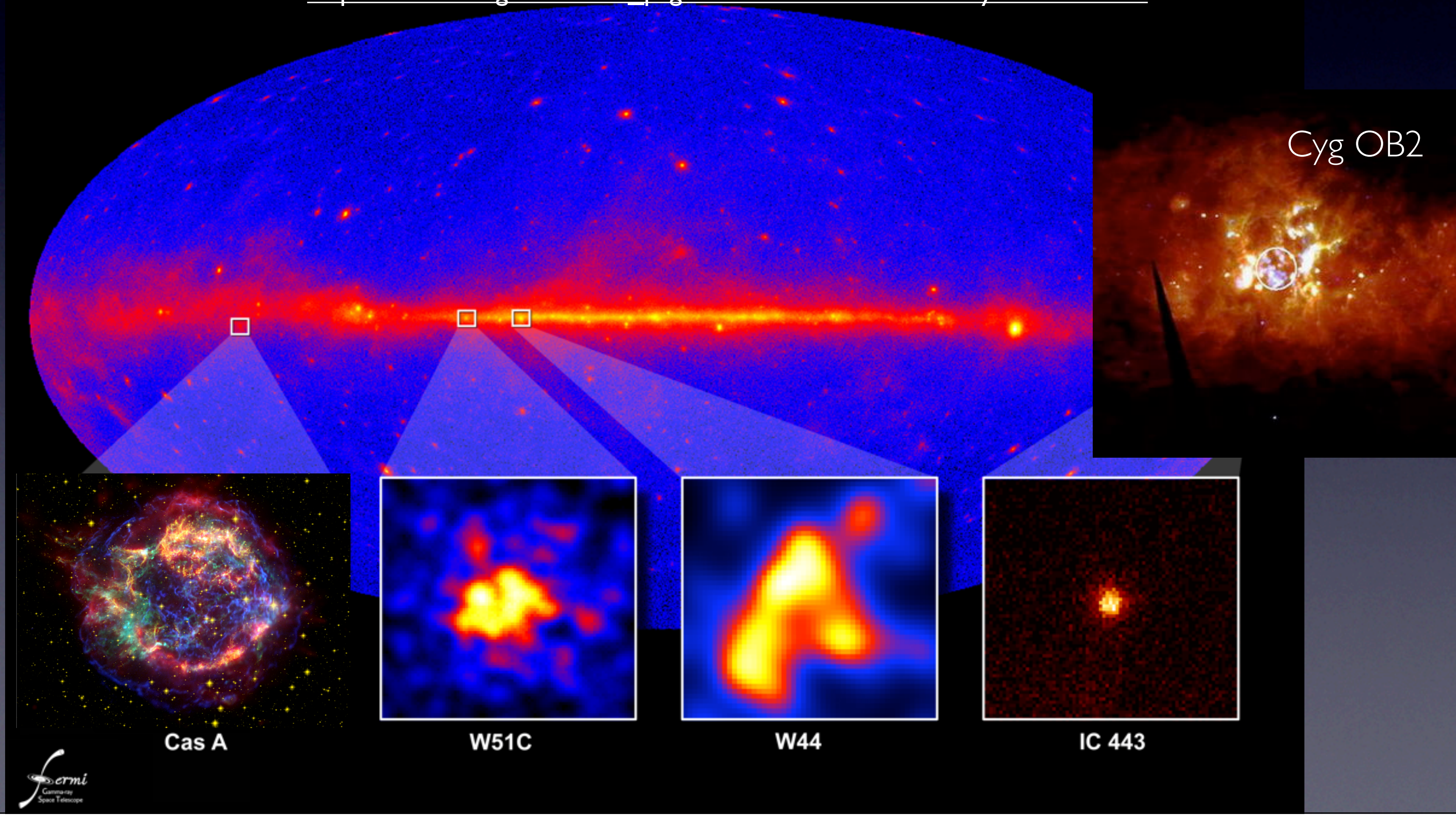




Galactic sources:

What PeVatrons accelerate CRs to the knee?

NASA's Fermi telescope resolves supernova remnants at GeV energies
http://www.nasa.gov/mission_pages/GLAST/news/cosmic-rays-source.html



SNR BEAM DUMP

Energy gain / cycle ΔE/E ~ β_{shock}

$dN/dE \sim E^{-\Gamma}$, $\Gamma = (R+2)/(R-1)$

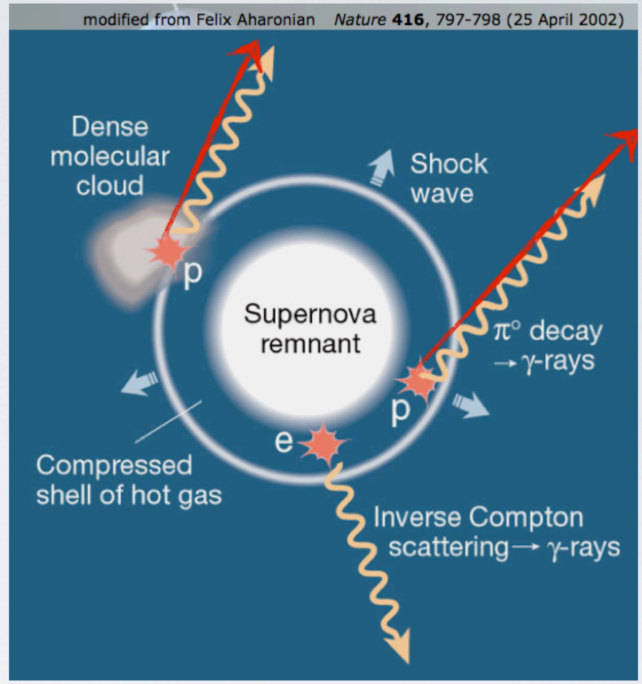
R = compression ratio

For strong shocks (Mach # >> 1): $R = 4 \rightarrow \Gamma = 2$

For weaker shocks: $R < 4 \rightarrow \Gamma > 2$

SNR maybe efficient accelerators during short periods when the shock speed is high and they transit from the free expansion (ejecta dominated phase) to the Sedov phase (adiabatic deceleration).

Eg. Bell & Lucek, 2001



$\pi^{\pm}$ decay $\rightarrow \nu$

ν NOT produced in leptonic interactions

$$p + p \rightarrow p + p + \pi^0$$

$$p + p \rightarrow p + n + \pi^+$$

$$p + A \rightarrow \pi^0 + \pi^+ + \pi^-$$

$\pi^0 \rightarrow \gamma\gamma$

$\pi^+ \rightarrow \mu\nu_\mu$, $e + 2\nu_\mu + \nu_e$

CRs +

2 γ's with $E_\gamma \approx E_\pi/2 \approx E_p/6$

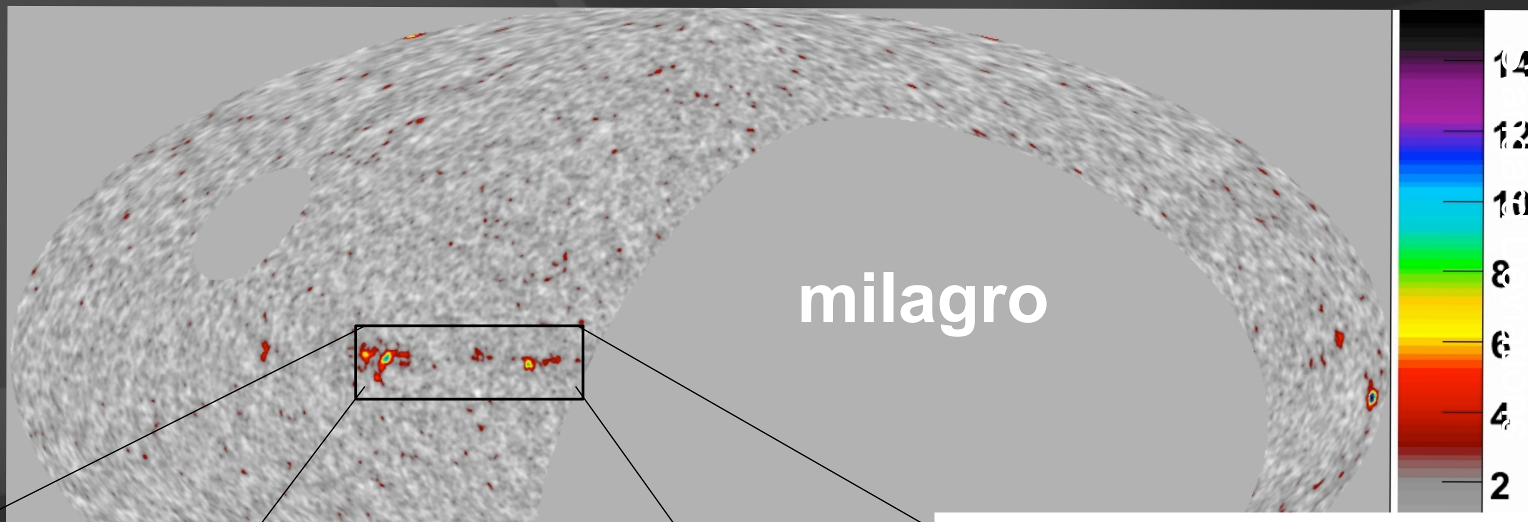
4 νμ with $E_\nu \approx E_\pi/4 \approx E_p/12$

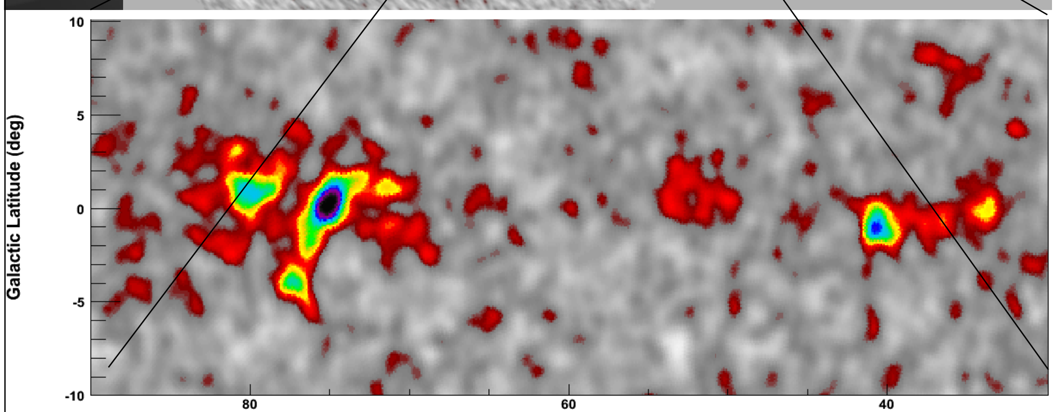
$$E_{p,th} = \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \sim 1.23 \text{ GeV}$$

K~0.5 after oscillations

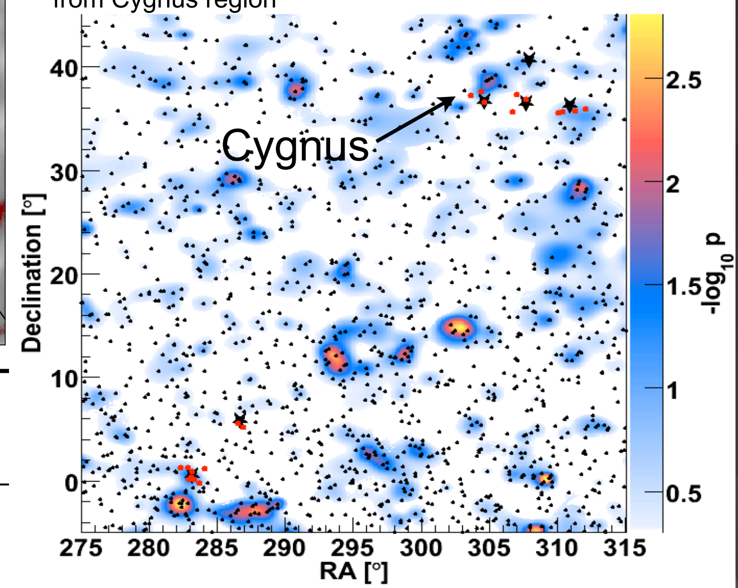
$$\int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{min}}^{E_\nu^{max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu,$$

Stacking the Milagro Pevatrons (SNR in molecular clouds)





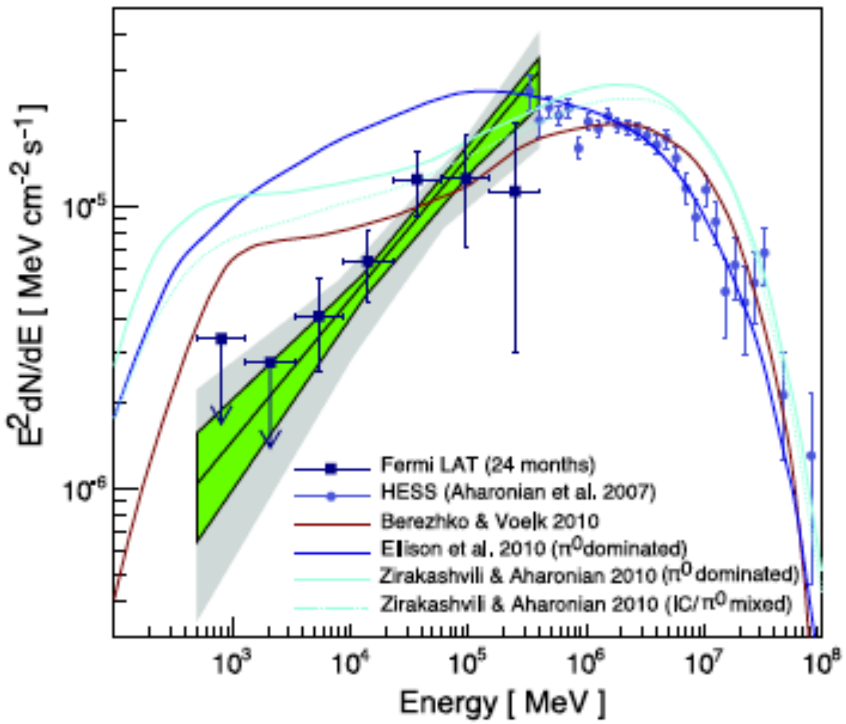
IC40+ AMANDA confirm only fluctuations of background from Cygnus region

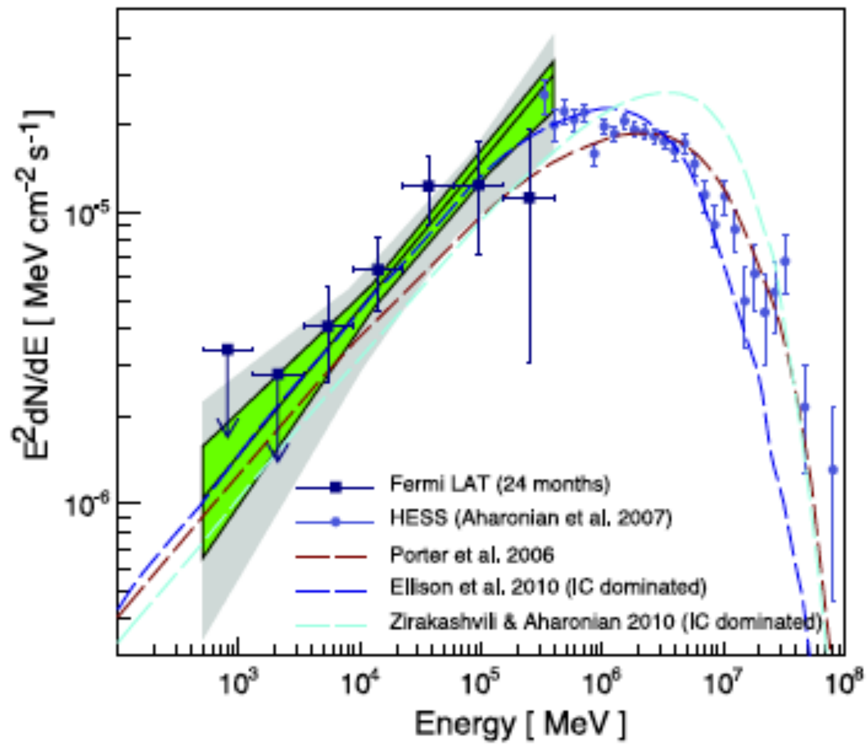


Catalogue	Med Sens	upper limit (90%cl)
6 Milagro SNR	2.9x prediction	7.2 x prediction

Model (Gonzalez-Garcia et al., arXiv:0902.1176): if E^{-2} cut-off at 300 TeV (10% of the knee of their CR primaries) => 5σ in 3 yr of IceCube

FERMI OBSERVATIONS OF RXJ 1713.7-3946





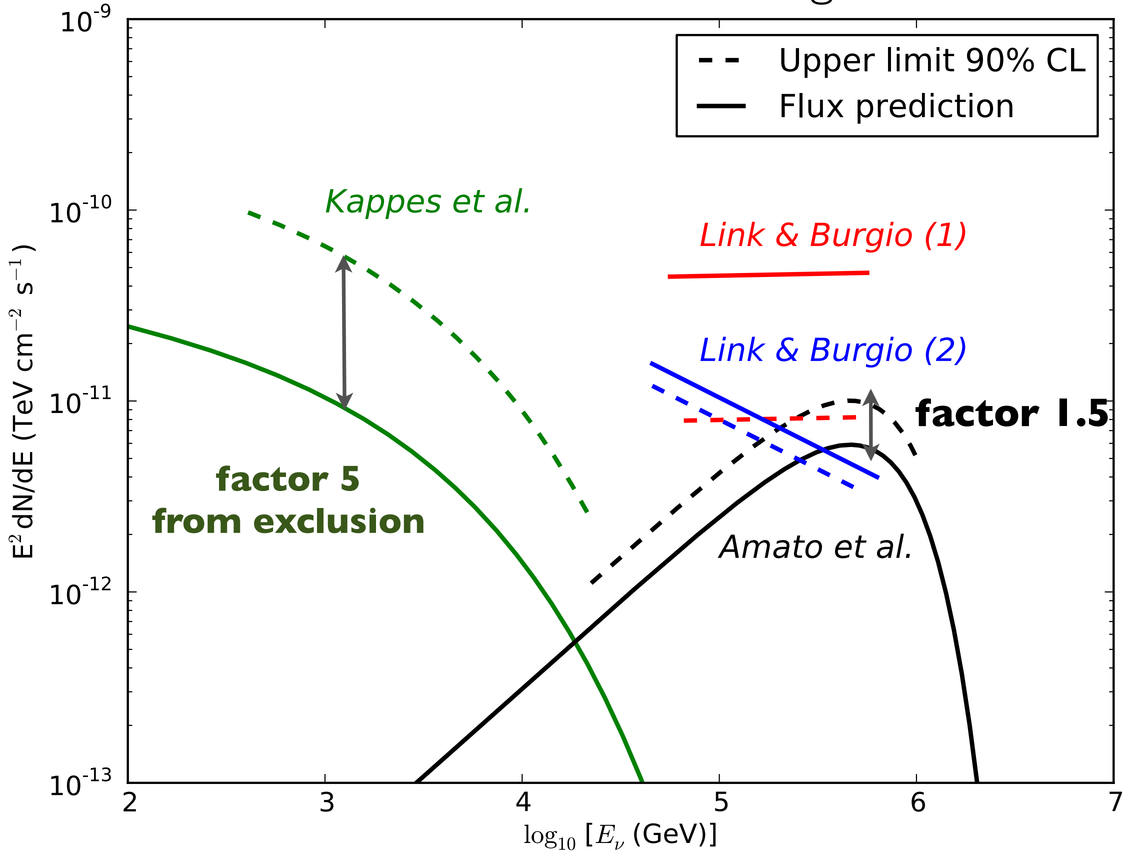
`The dominance of leptonic processes in explaining the gamma-ray emission does not mean that no protons are accelerated in this SNR, but that the ambient density is too low to produce a significant hadronic gamma-ray signal.' (arXiv:1103.5727).

Few neutrino events/km^2/yr in hadronic models

paper submitted to ApJ

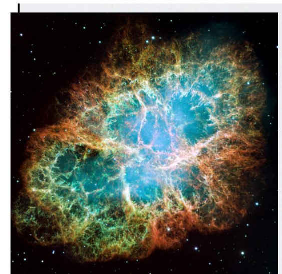
CRAB (STEADY EMISSION)

IceCube 40 strings



probe models assuming significant fraction of spin-down energy into neutrinos from p/nuclei acceleration.

L&B 2006: ions accelerated to Δ threshold with constant E-field (1) or linearly increasing E-field (2) with height above n star surface. Most optimistic predictions rejected @> 90% cl



Blasi & Amato 2003: close to exclude most optimistic values of the plerion wind Lorentz factor (10^7) and of effective target density for protons.

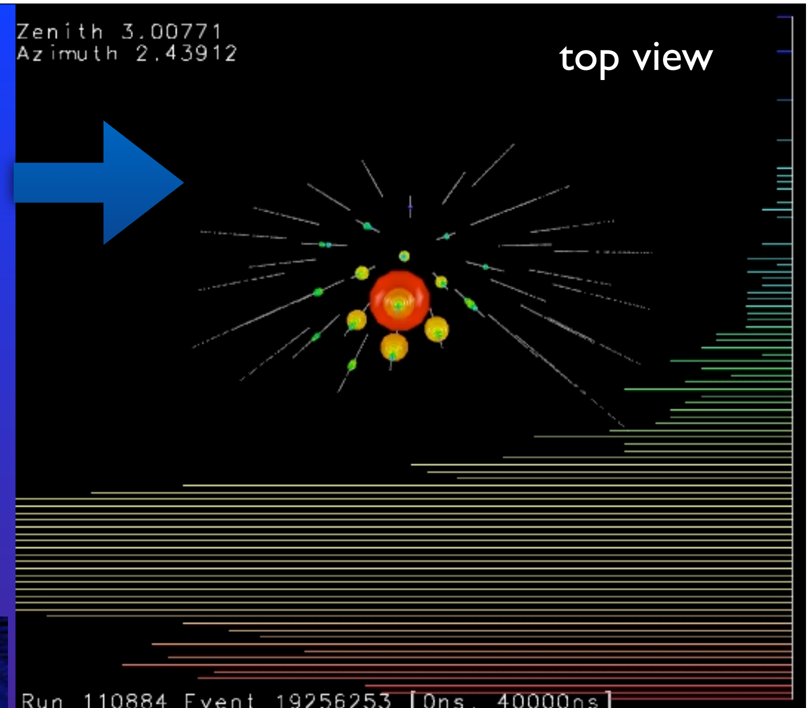
Kappes et al, 2007: protons and fit HESS gamma spectrum

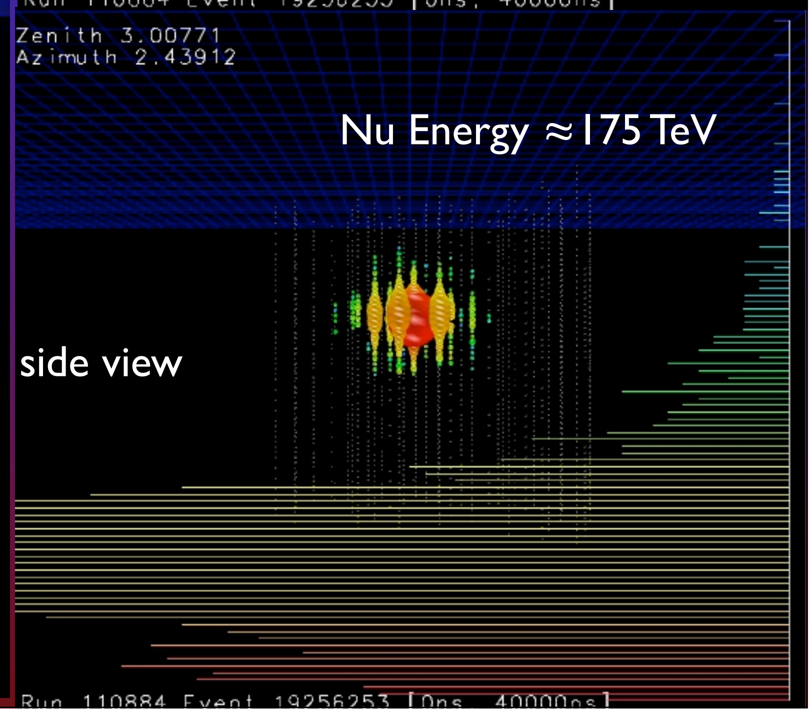
$$\frac{dN_p}{dE_p} = k_p \left(\frac{E_p}{1\,\mathrm{TeV}}\right)^{-\alpha} \exp\left(-\frac{E_p}{\epsilon_p}\right) \rightarrow \frac{dN_{\gamma/\nu}}{dE_{\gamma/\nu}} \approx k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1\,\mathrm{TeV}}\right)^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

Events of interest

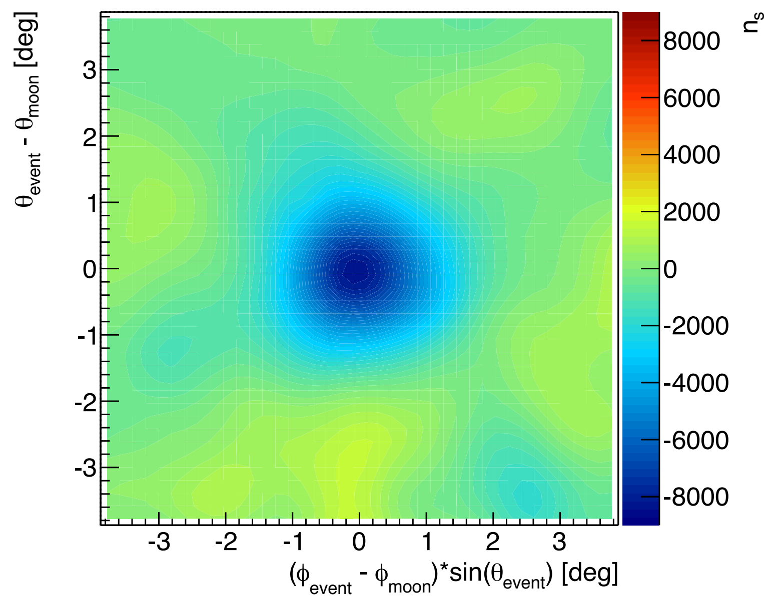
first > 100 TeV cascades in 40 strings!!

> 100 TeV muon neutrino event



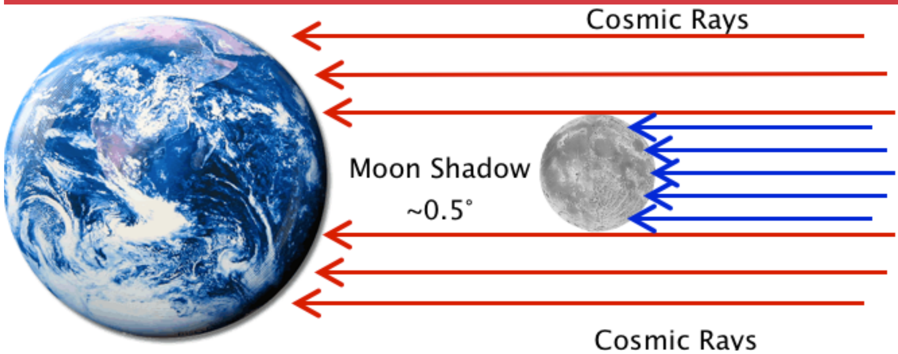


Sub-degree Pointing

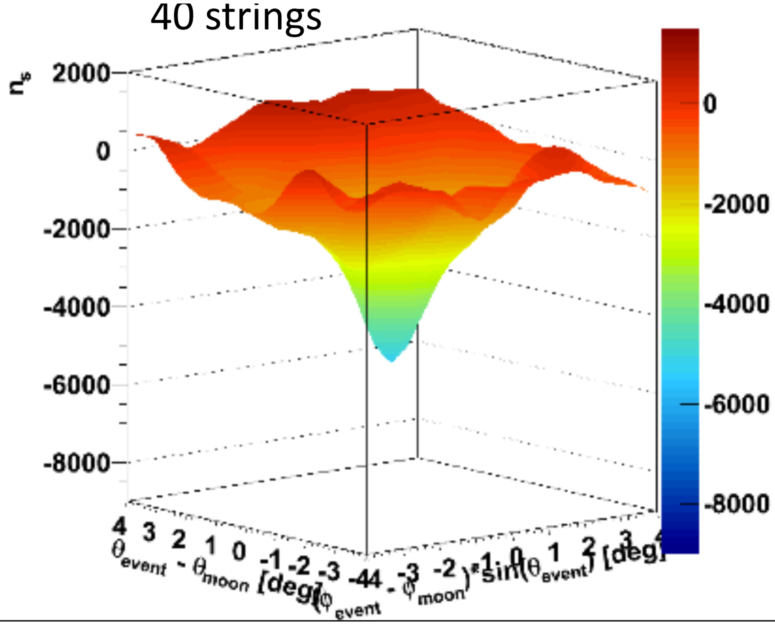


Moon shadow LH analysis (to be presented at ICRC2011):

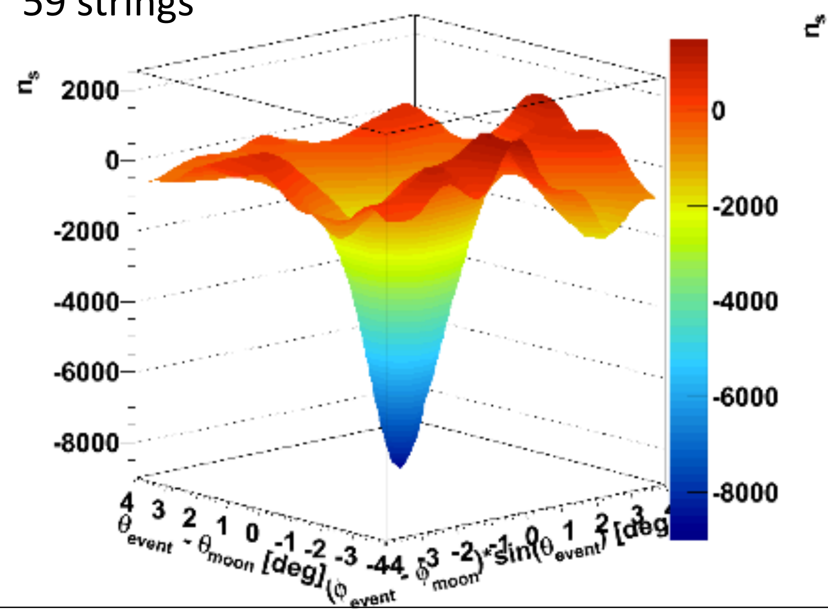
More than 12σ underfluctuation in 59-strings confirmed by binned analysis



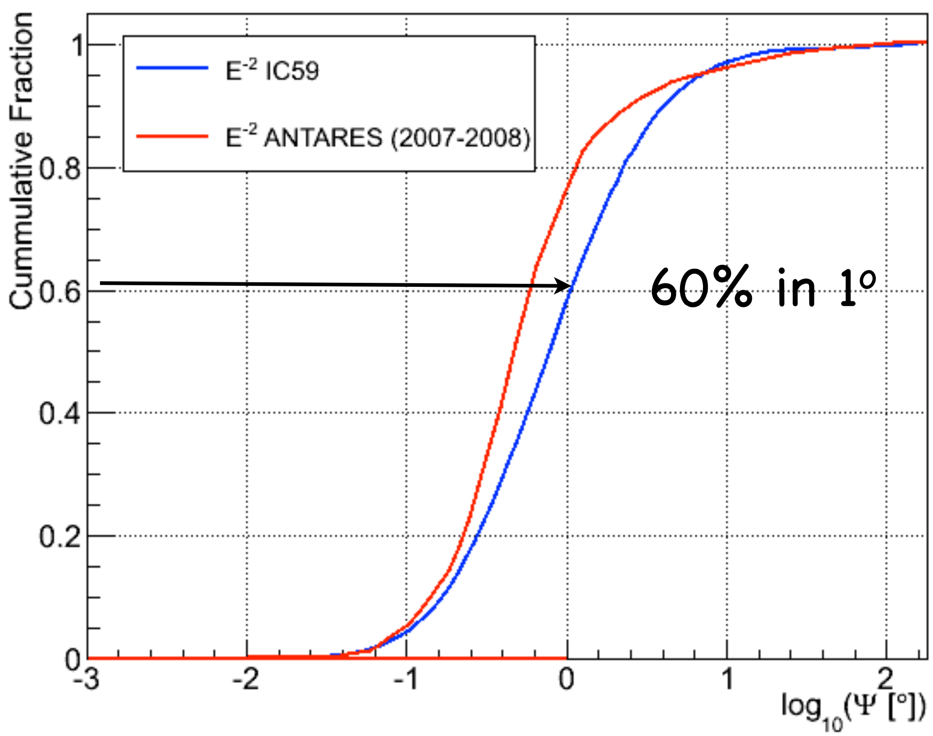
40 strings



59 strings

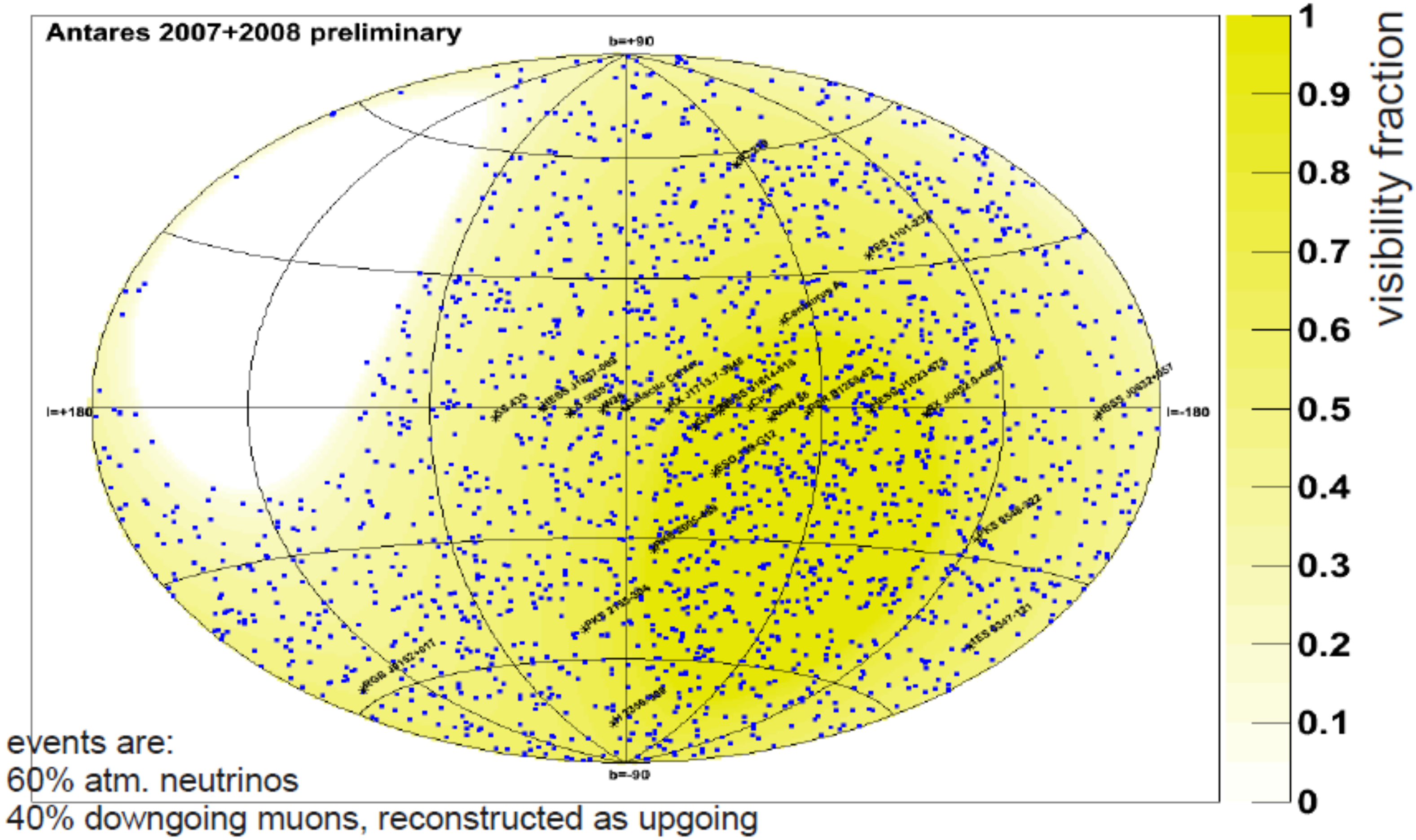


PSF in ANTARES and IceCube



ANTARES Sky Map

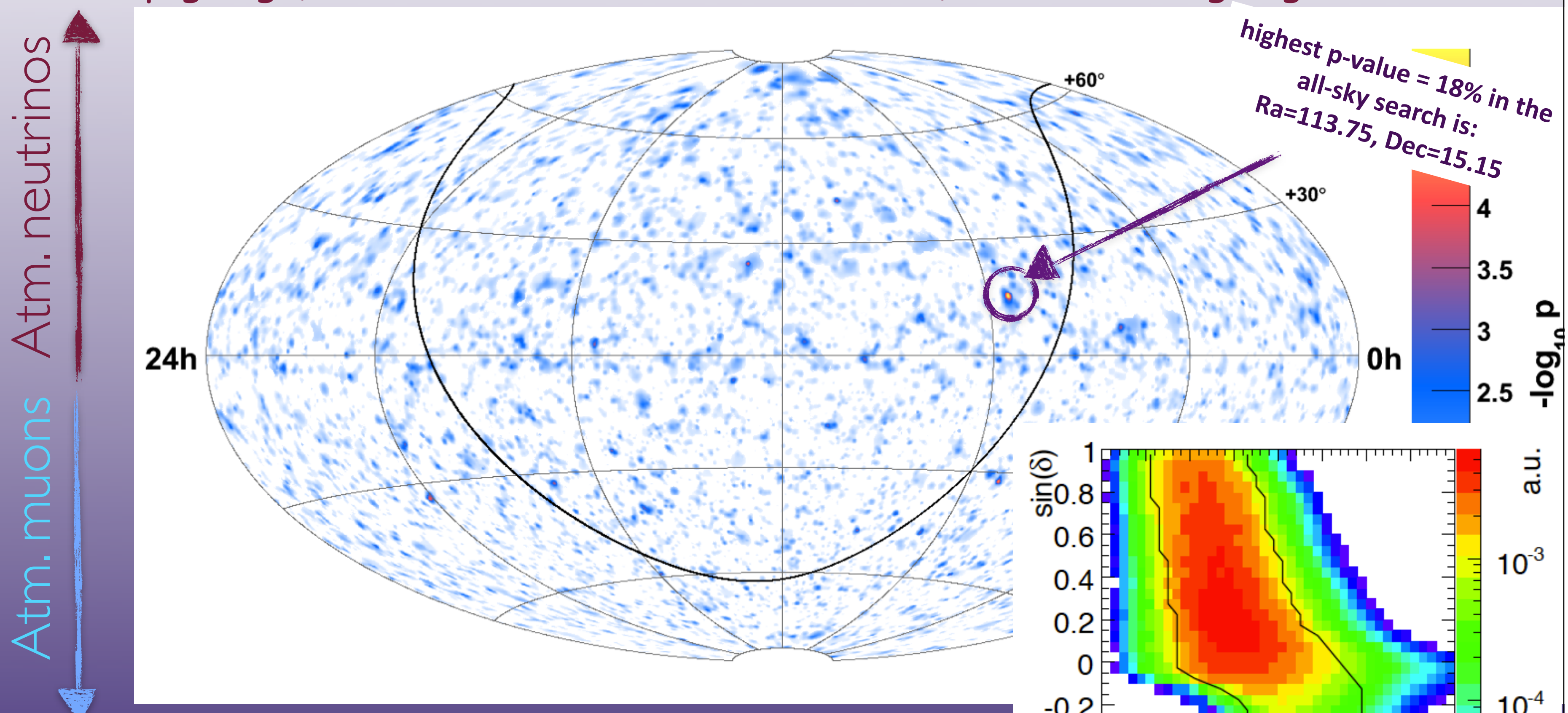
Selection optimized for Model Discover Potential (Λtrack > 5.4):
(Live time 2190 events in 304 days of 5-12 lines)

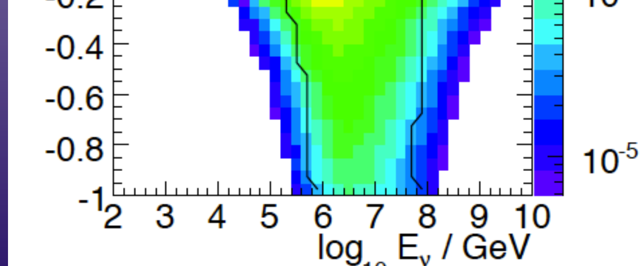


Most significant cluster located at: ra=134.6°, δ=13.4°
(post-trial probability to be background 2.4%)

...to 1/2 IceCube Map

14139 up-going (x2 from AMANDA in x3 less time), 23151 down-going in 375.5 d

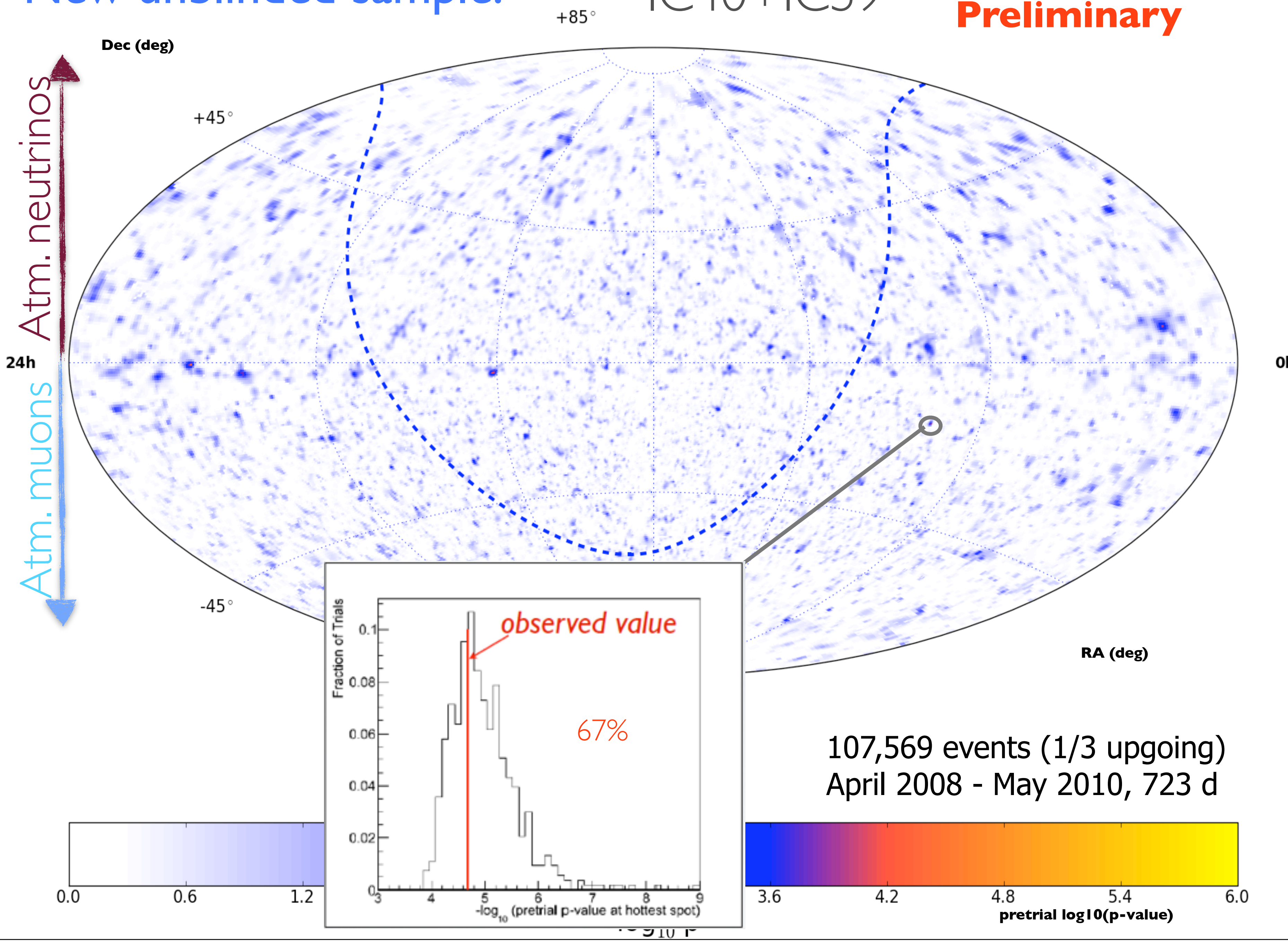




LH method using direction and energy in J. Braun et al. Astrop. Phys. 33 (2010) 175., J. Braun et al. Astrop.. Phys. 29 (2008) 299

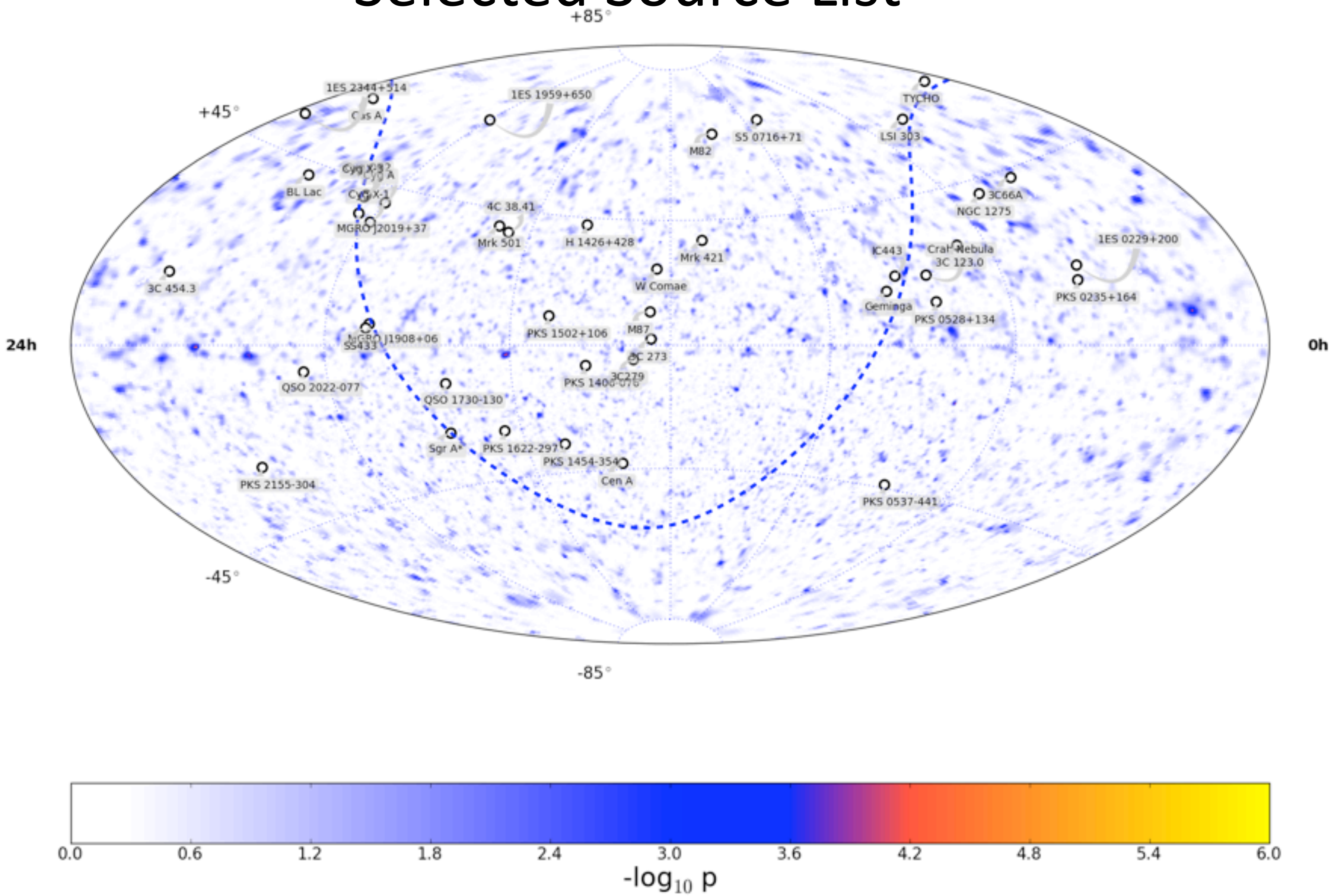
New unblinded sample: IC40+IC59

Preliminary



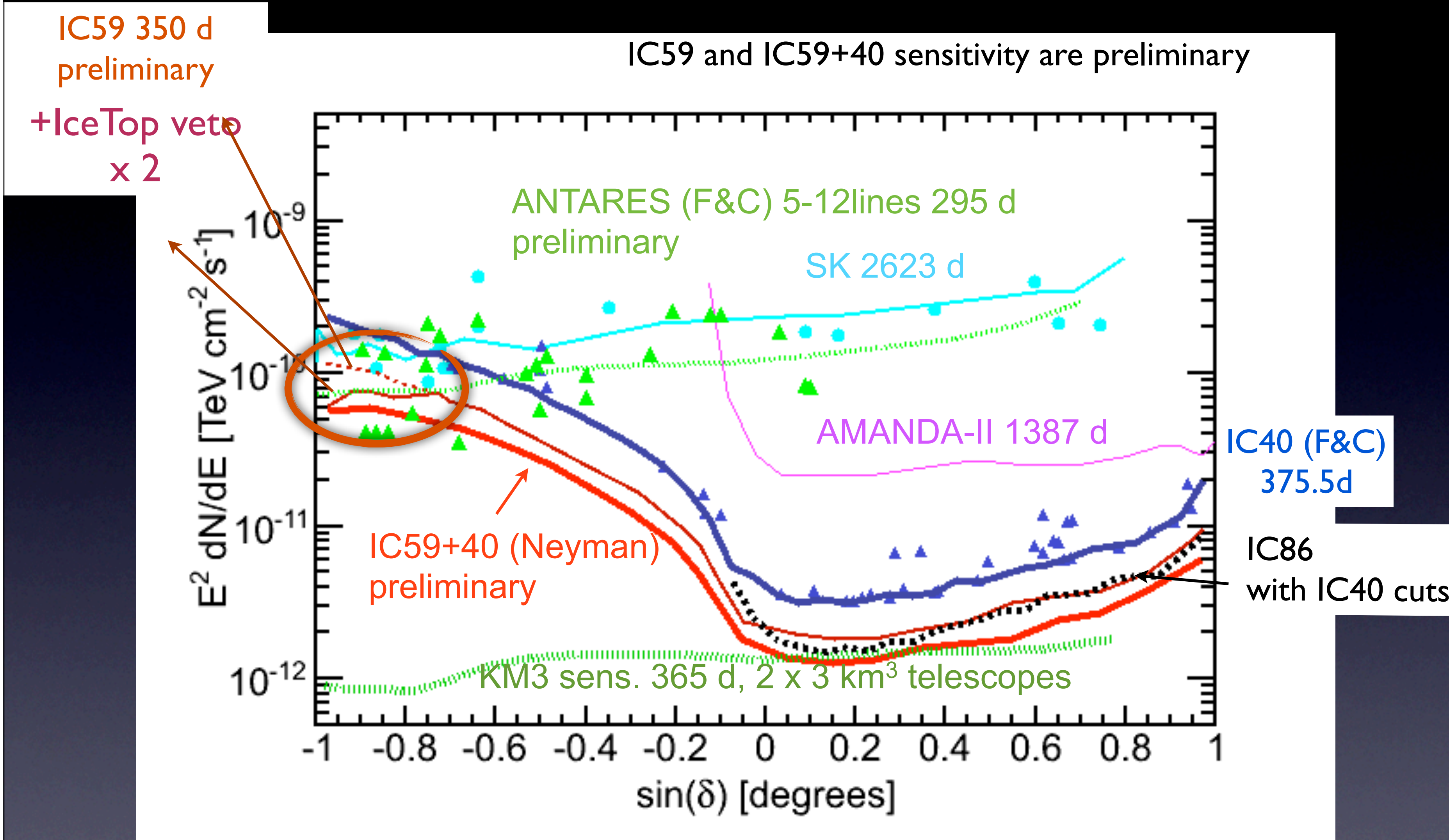
107,569 events (1/3 upgoing)
April 2008 - May 2010, 723 d

Selected Source List



No significant fluctuation: best pre-trial p-value = 0.14 pretrial in a list of 43 sources => 95% post-trial for PKS_1454-354

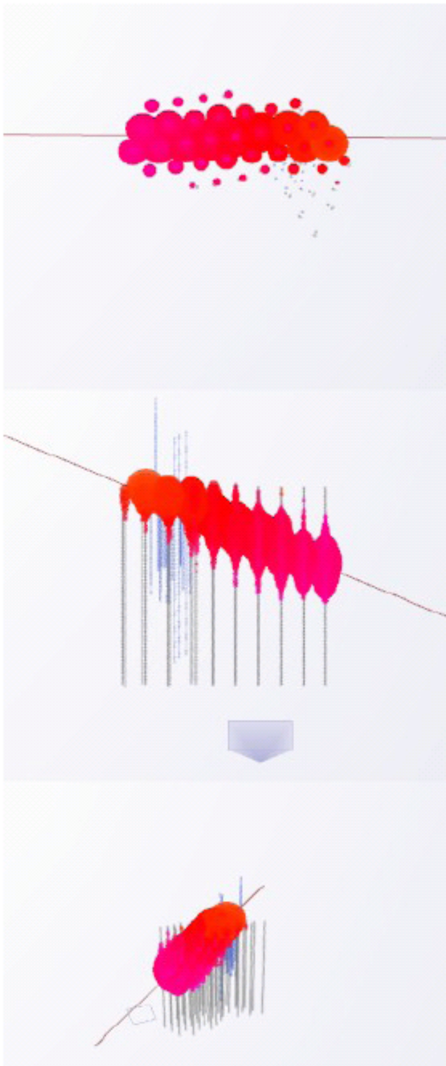
E^{-2} median sensitivity and upper limits (90%cl)

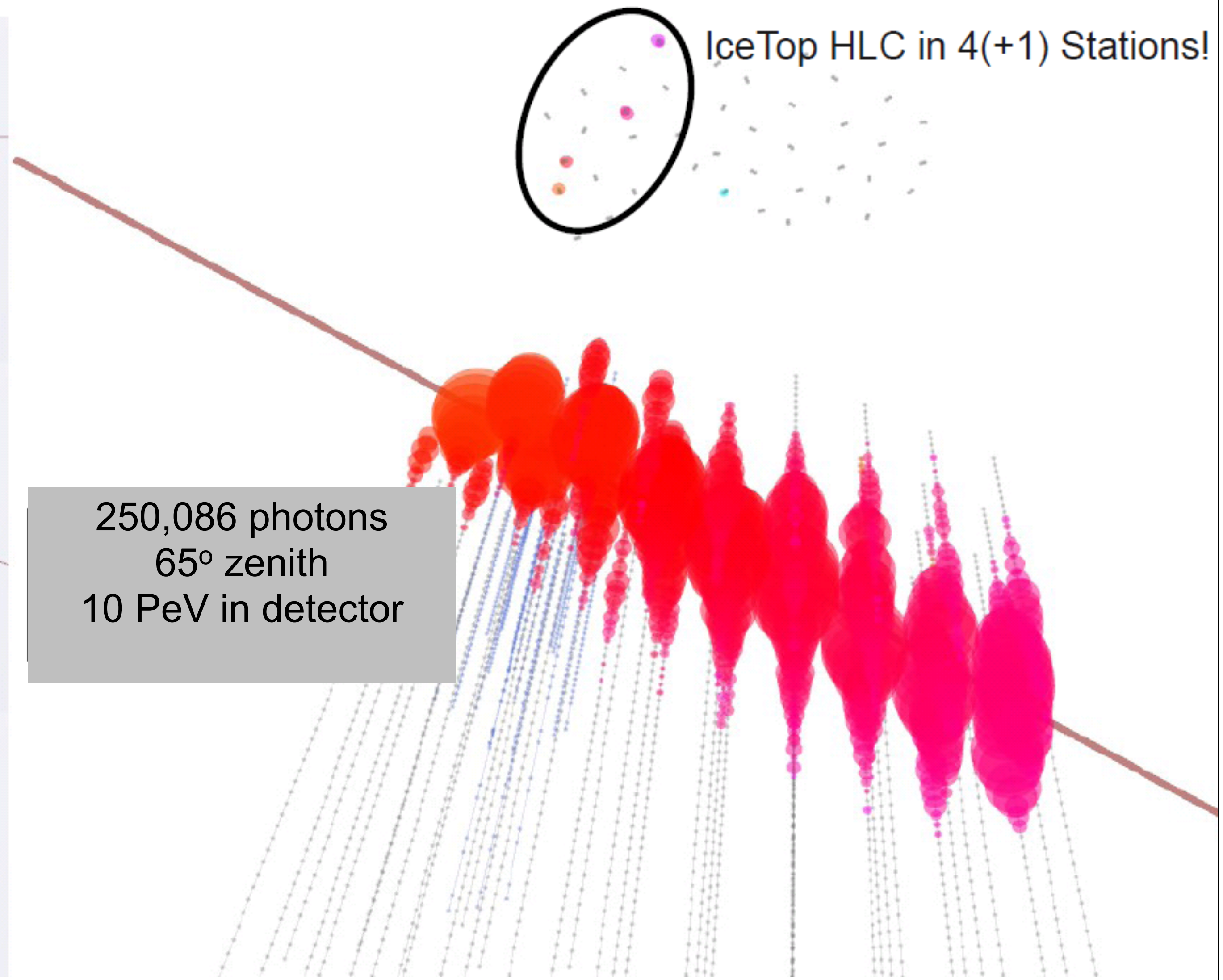


40+59 strings (x2.5 IC40) = better than preliminary estimates of full IceCube

IC40+IC59+IC79+IC86 = about factor of 5 from the blue curve (IC40)

Biggest Shower in IC40 EHE Analysis





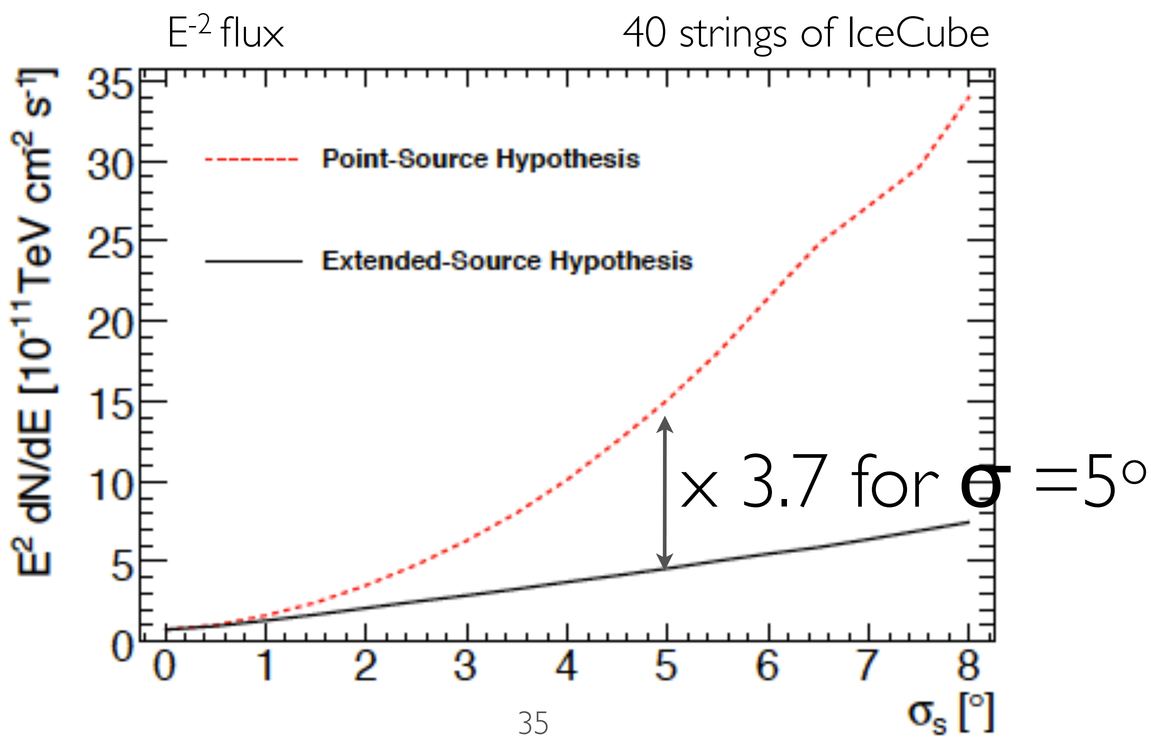
A. Ishihara, S. Yoshida
the event is rejected by blind cuts

EXTENDED SOURCES OF CRs?

Beyond the myth of the supernova-remnant origin of cosmic rays (Y. Butt Nature 2009)

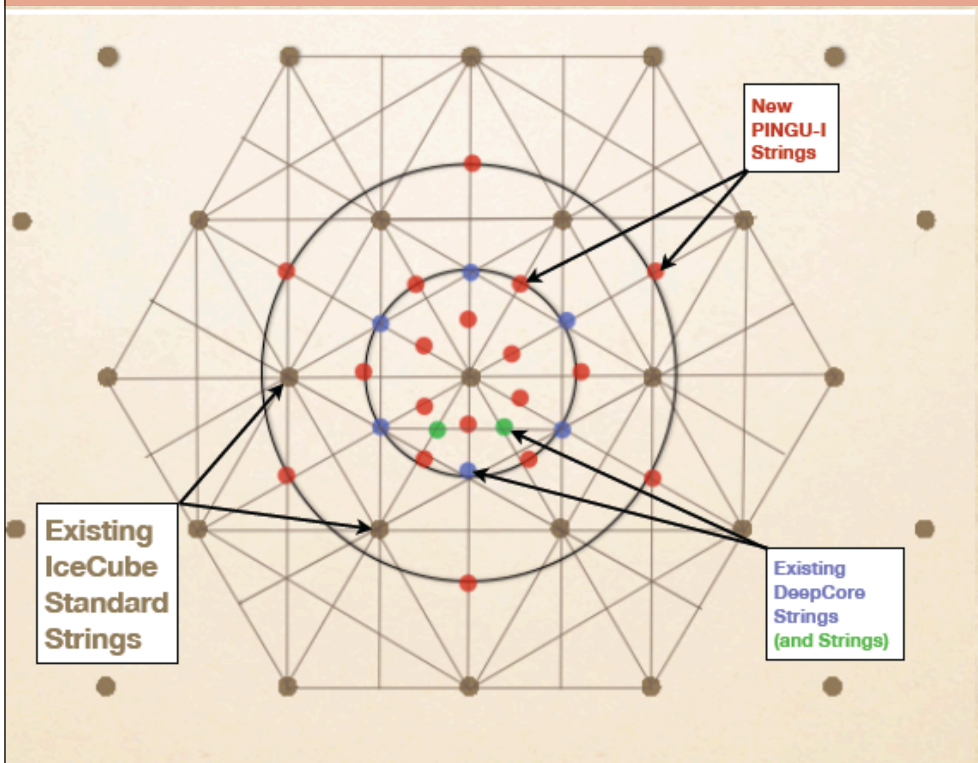
The origin of Galactic cosmic-ray ions has remained an enigma for almost a century. Although it has generally been thought that they are accelerated in the shock waves associated with powerful supernova explosions ...**we may be on the wrong track altogether in looking for isolated regions of cosmic-ray acceleration.**

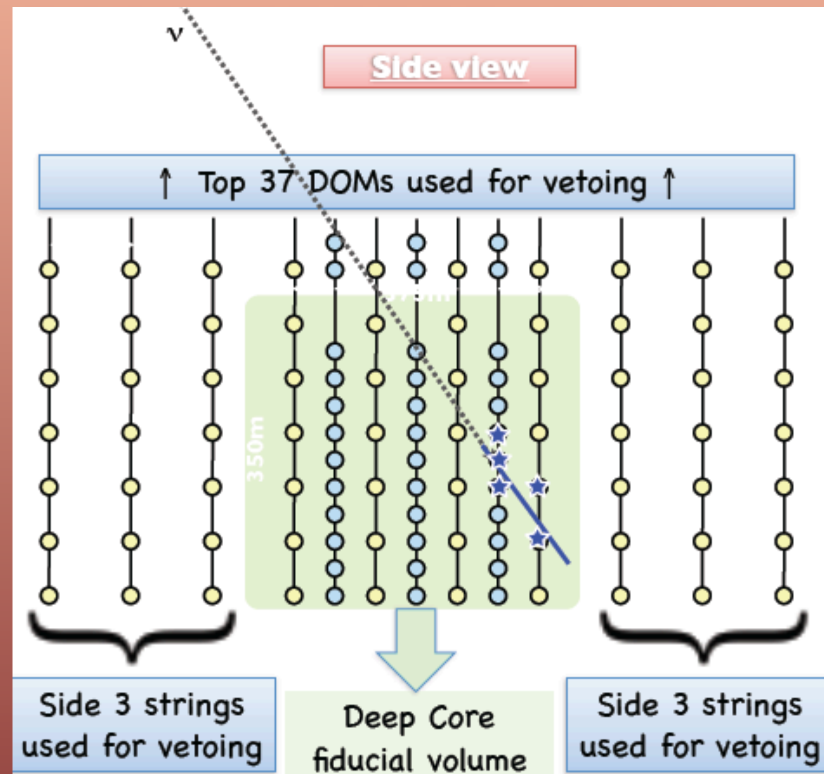
discovery potential flux at 5 σ , P = 50%



S. Toscano's talk on small scale anisotropies

I conclude by looking at the future: Pingu-I





18 additional strings with about 1000 DOMs in the 30 MT DeepCore volume to enhance low energy capabilities for:

- oscillations
- galactic sources
- dark matter
- SN neutrinos