Cosmic Neutrinos

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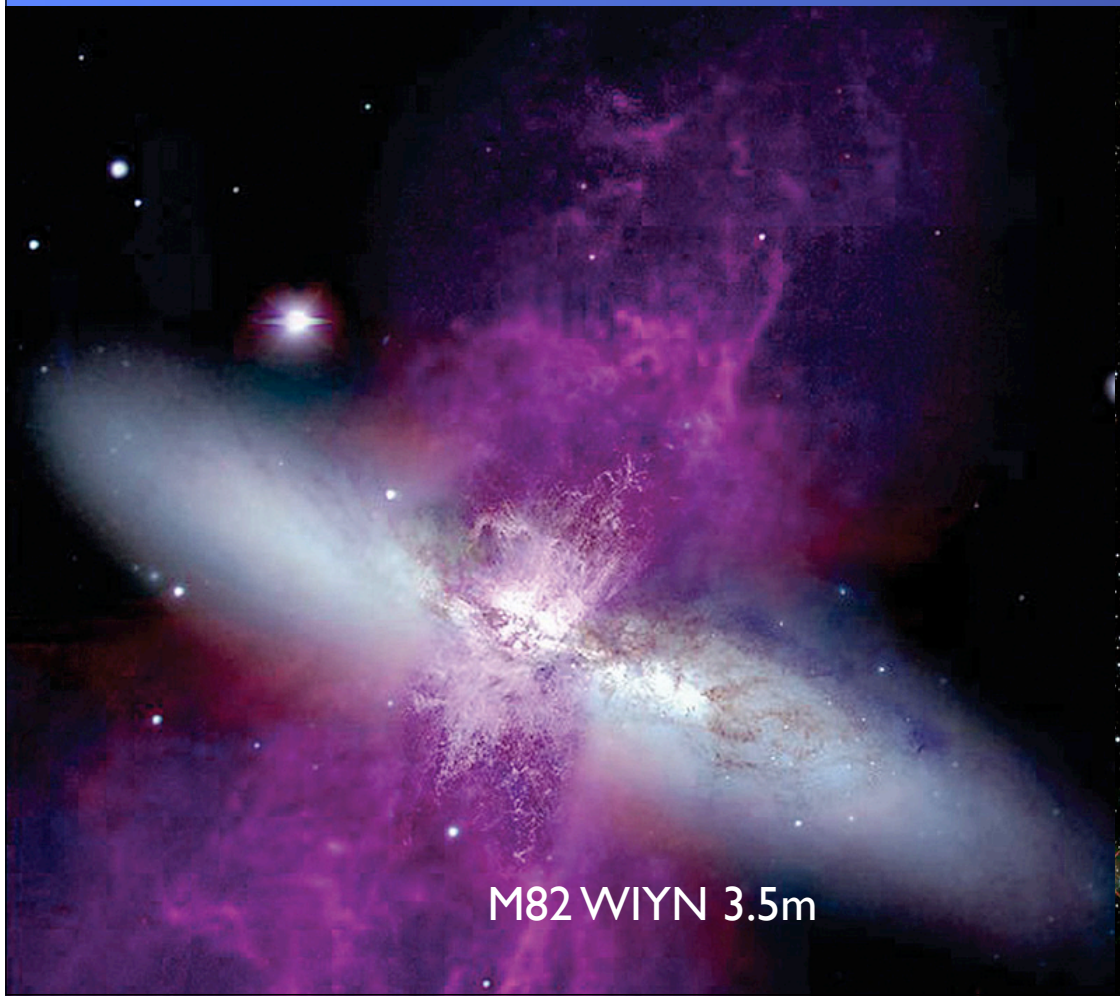
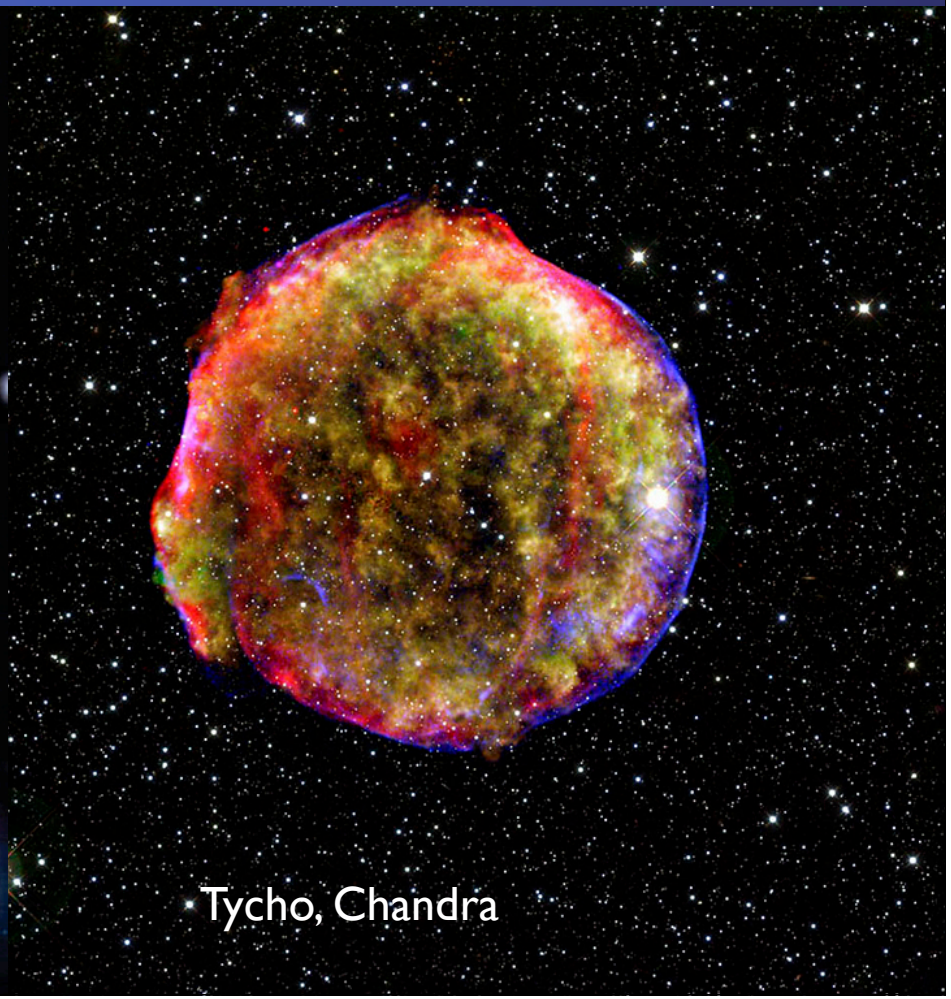
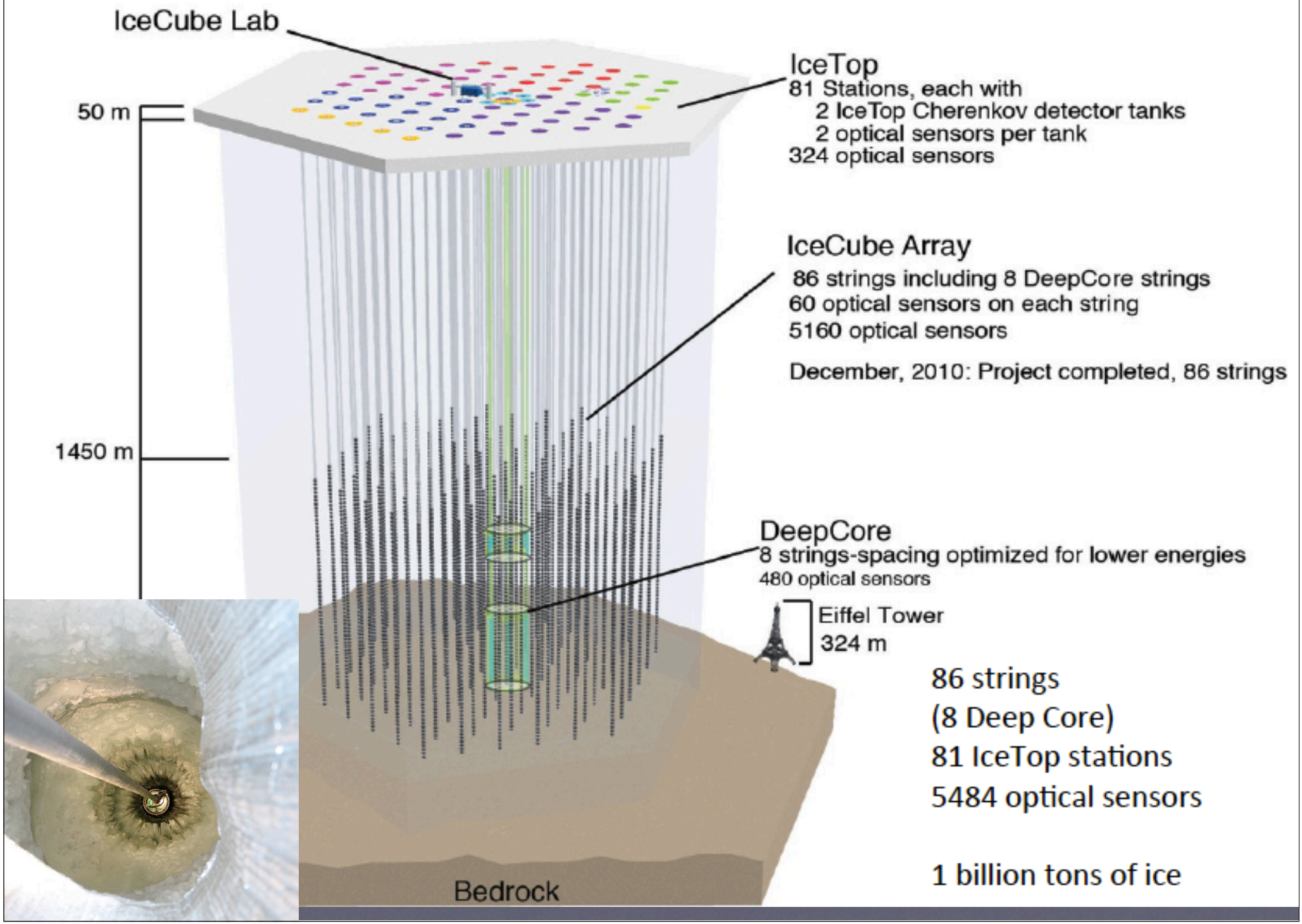
University of Wisconsin - Madison

Experimental results on behalf of the IceCube Collaboration

EPS-HEP 2011, Grenoble, July 26, 2011


M82 WIYN 3.5m

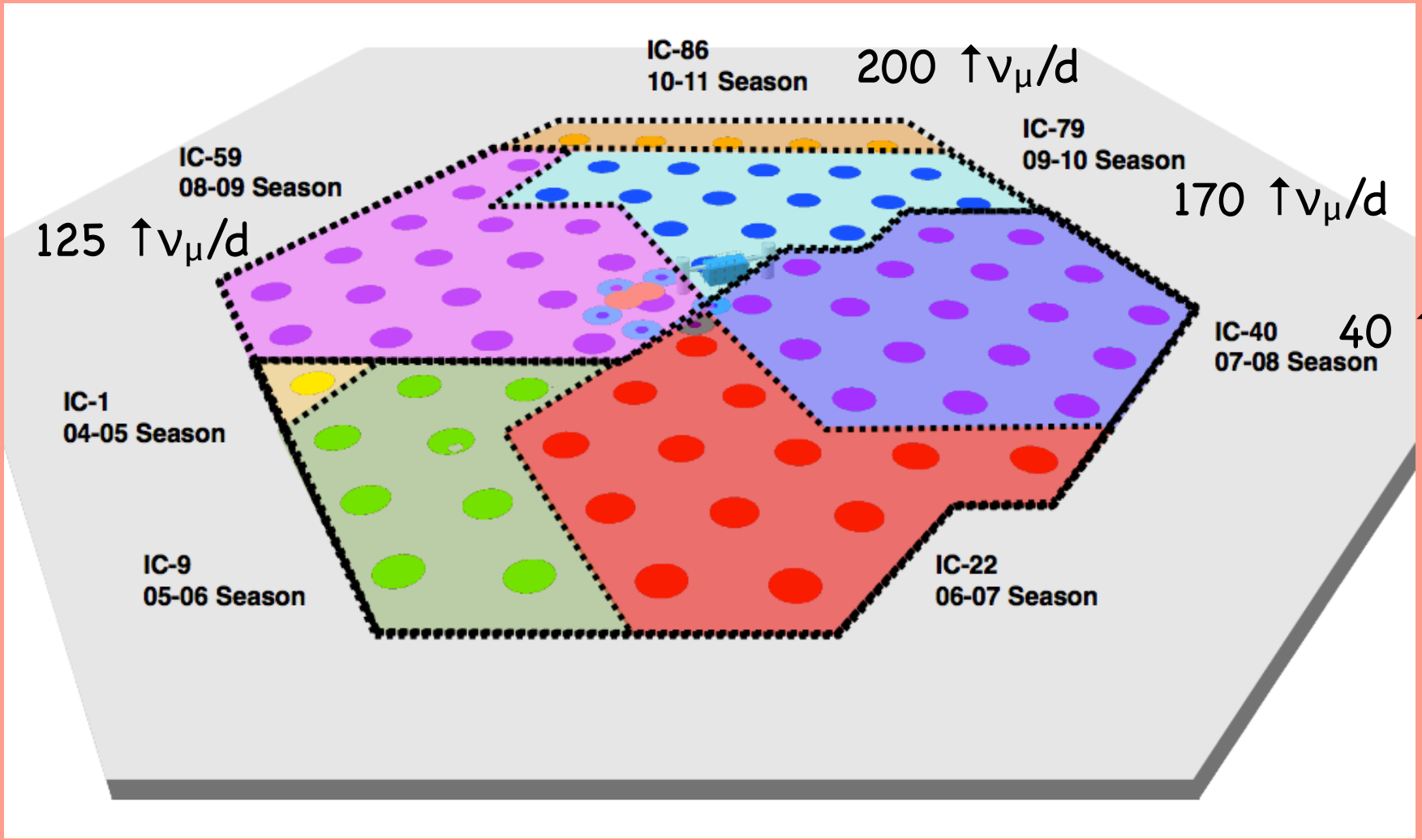

Tycho, Chandra



86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors

1 billion tons of ice

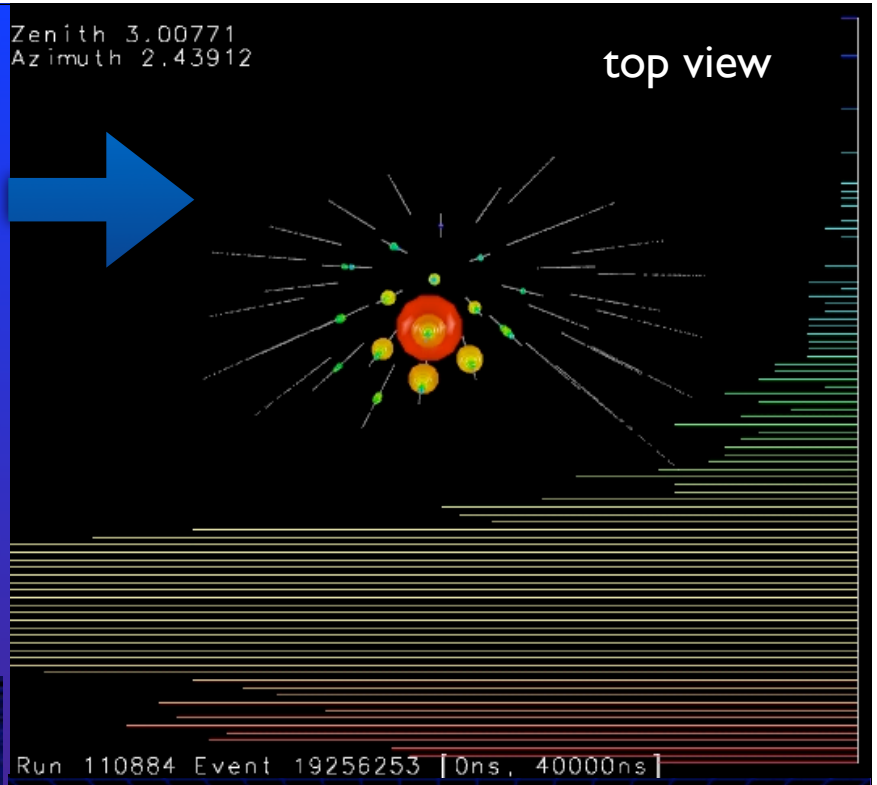
IceCube is complete!

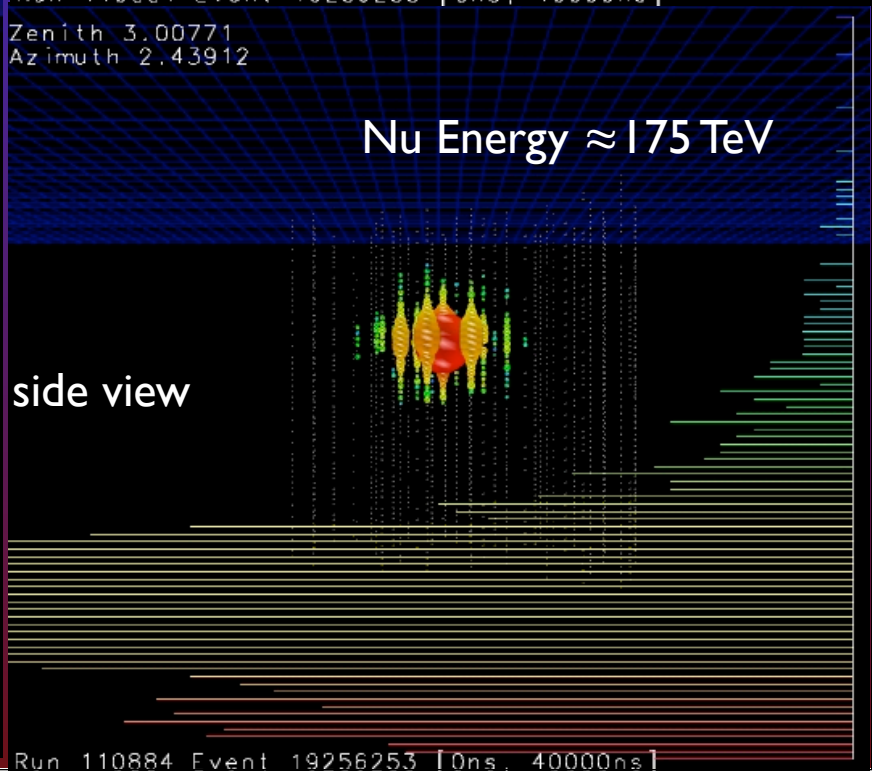


Events of interest

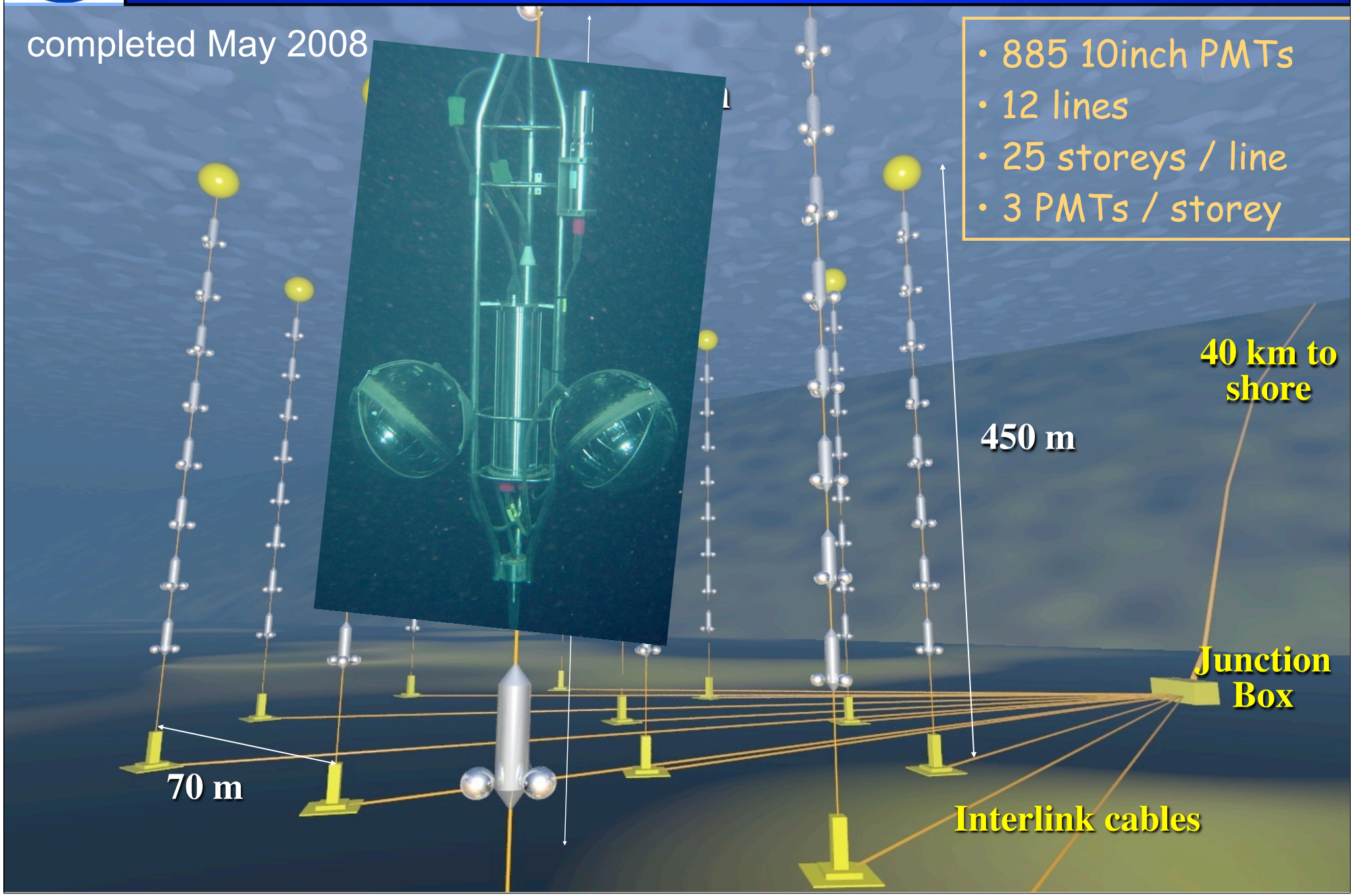
first > 100 TeV cascades in 40 strings!!

> 100 TeV muon neutrino event



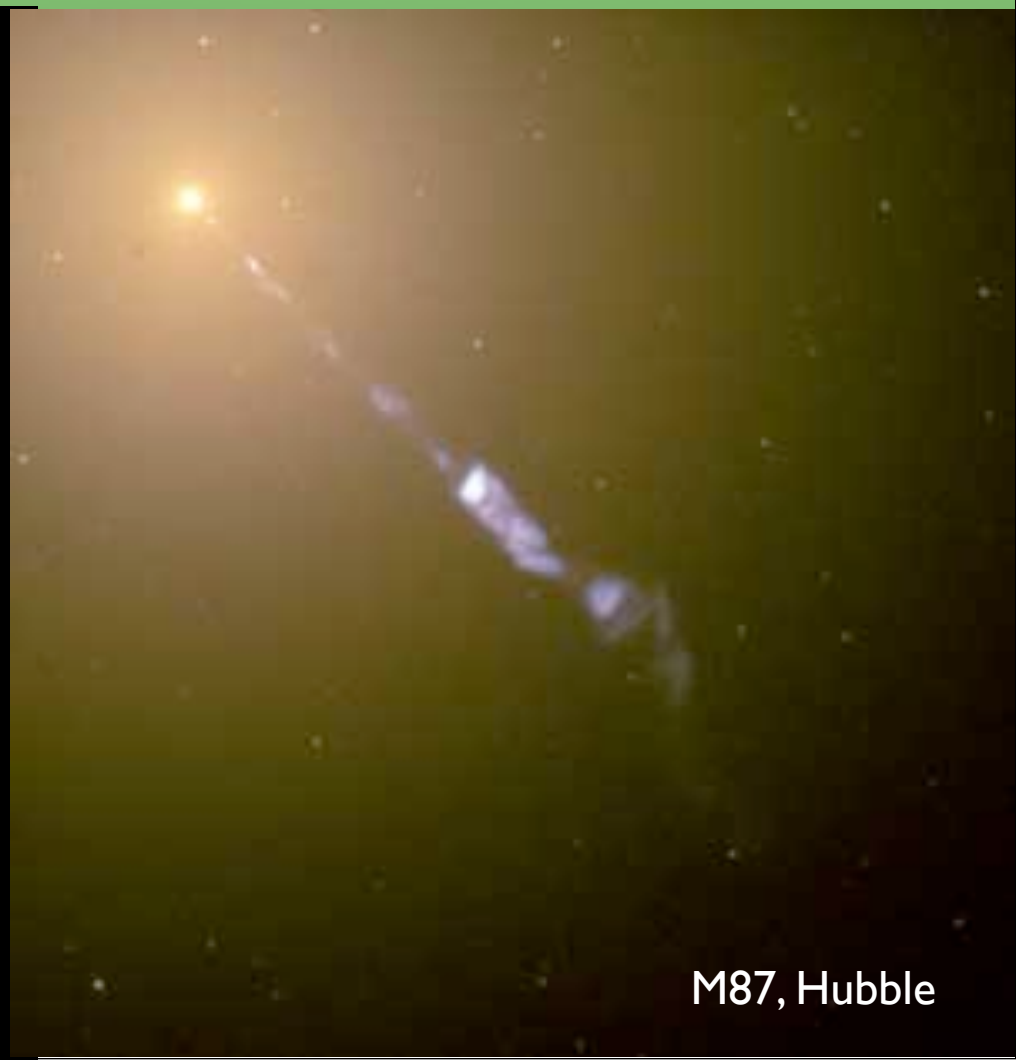


Another success in the sea: ANTARES



CONTENTS

- **Connection between Cosmic Rays - Neutrinos - Gammas**
- **Neutrino production in sources and Predicted fluxes**
- **Current results on extragalactic and galactic sources**



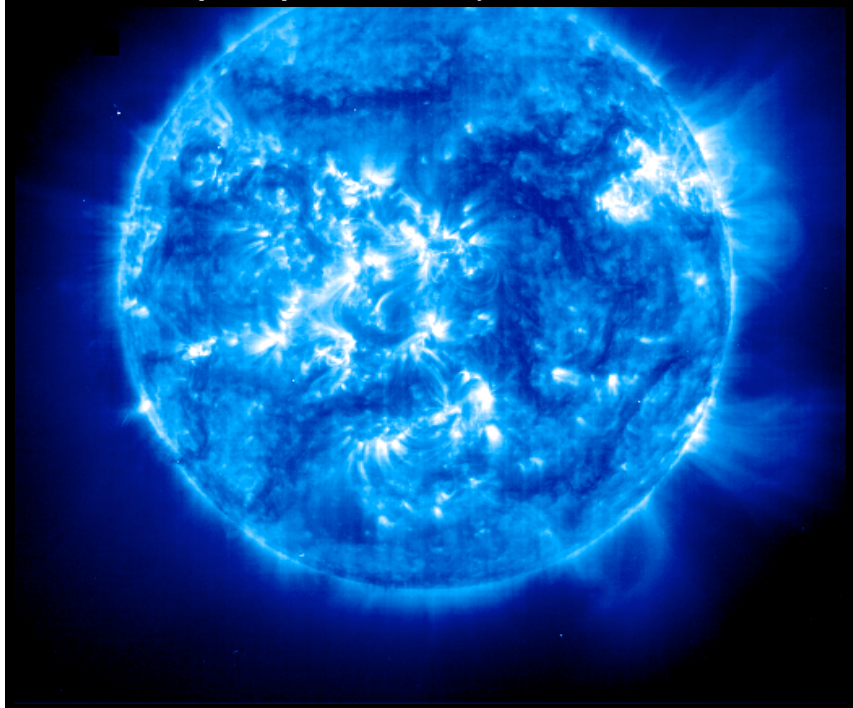
First Astrophysical Neutrino signals

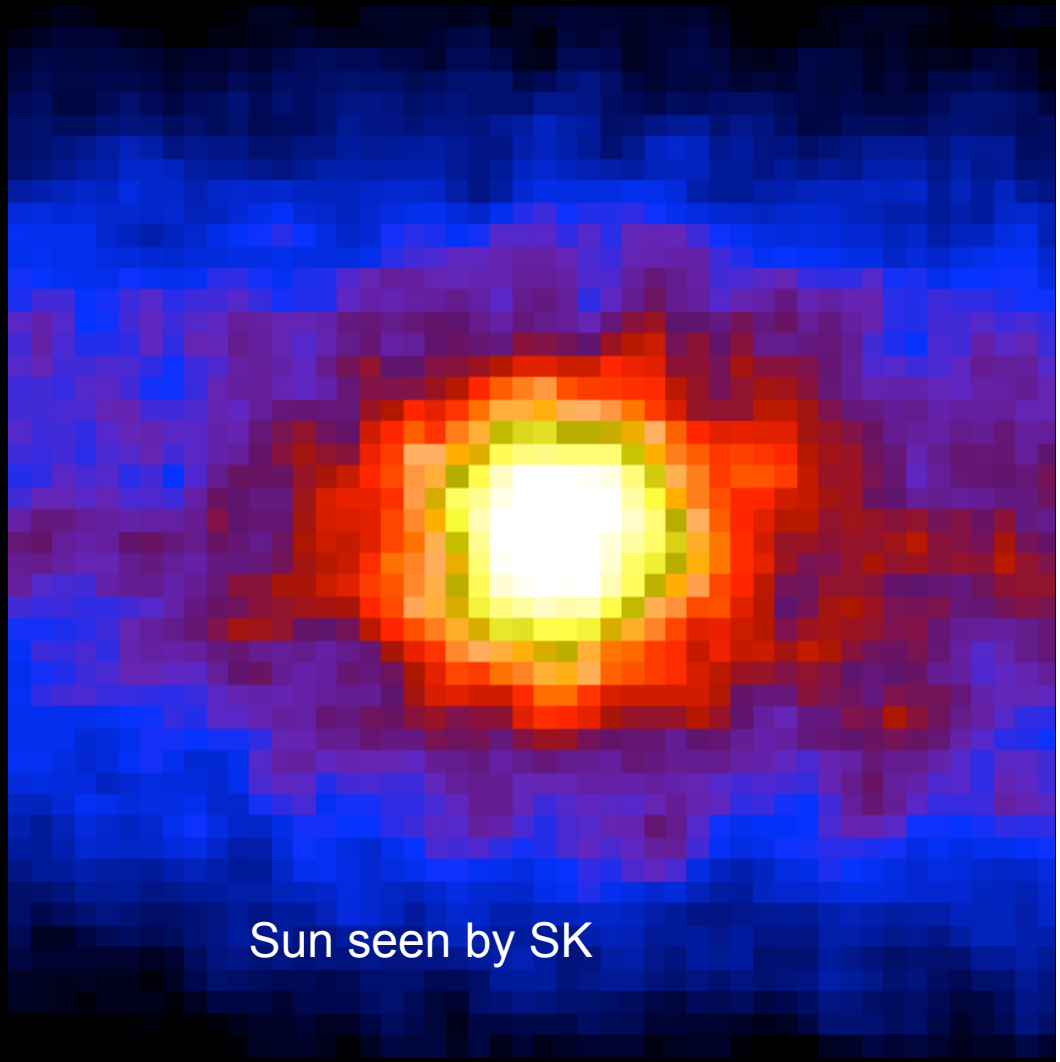
Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

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

First Astrophysical Neutrino signals

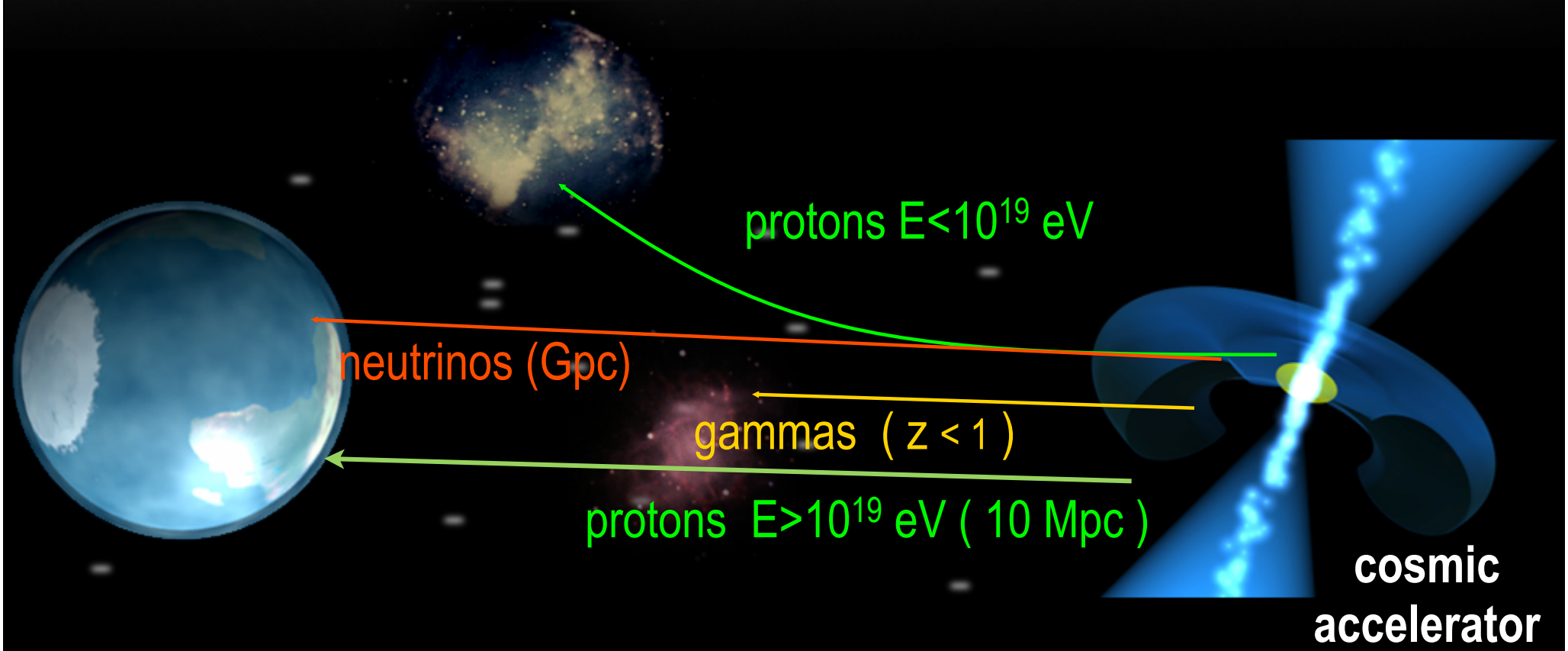
Fusion reactions and magnetic reconnection solar flares accelerate CRs to about 10 GeV (one seen by IceTop, ApJL 2008)





MESSENGERS FROM THE UNIVERSE

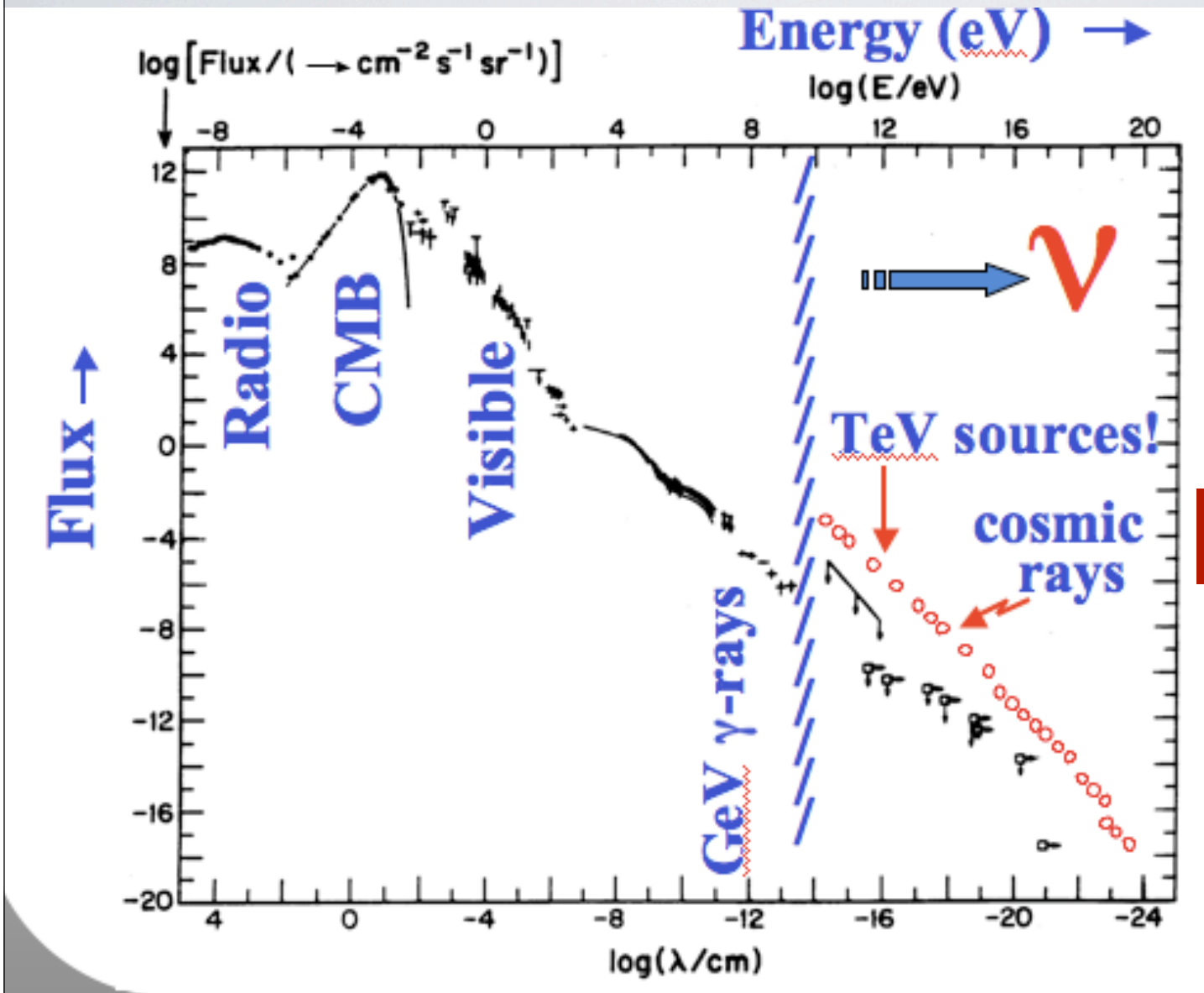
Discovery messengers: Neutrinos and Gravitational Waves



photons: absorbed on dust and radiation; reprocessed at source

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

UNDERSTANDING ACCELERATION PROCESSES IN THE UNIVERSE: THE CR PUZZLE



Gamma astronomy

< 100 TeV

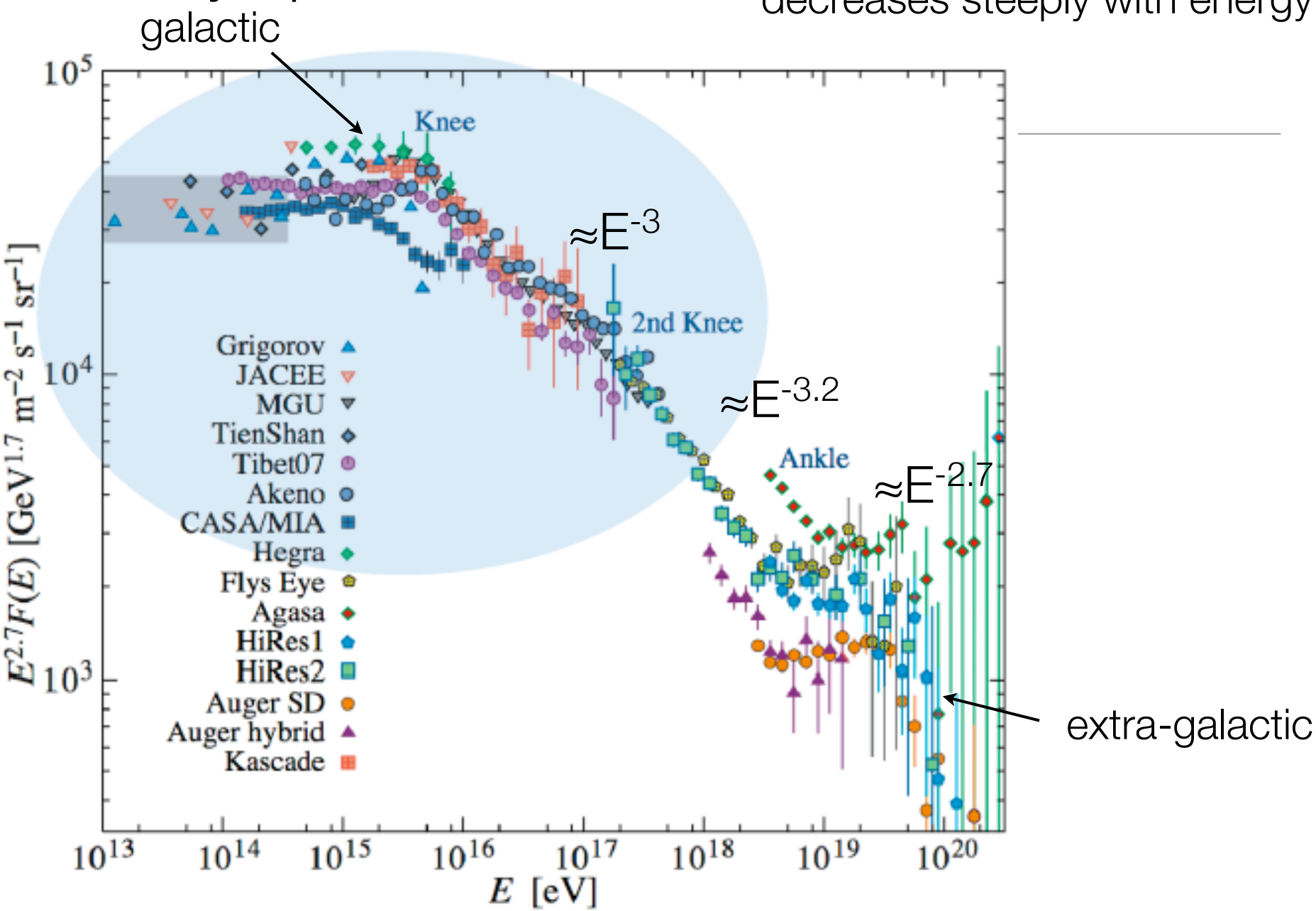
Neutrino astronomy

> 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: $\rho_E / \tau_{esc} \approx 10^{-26}$ erg/cm^{3}s
$\tau_{esc} \approx 3 \times 10^6$ yrs escape time from Galaxy

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

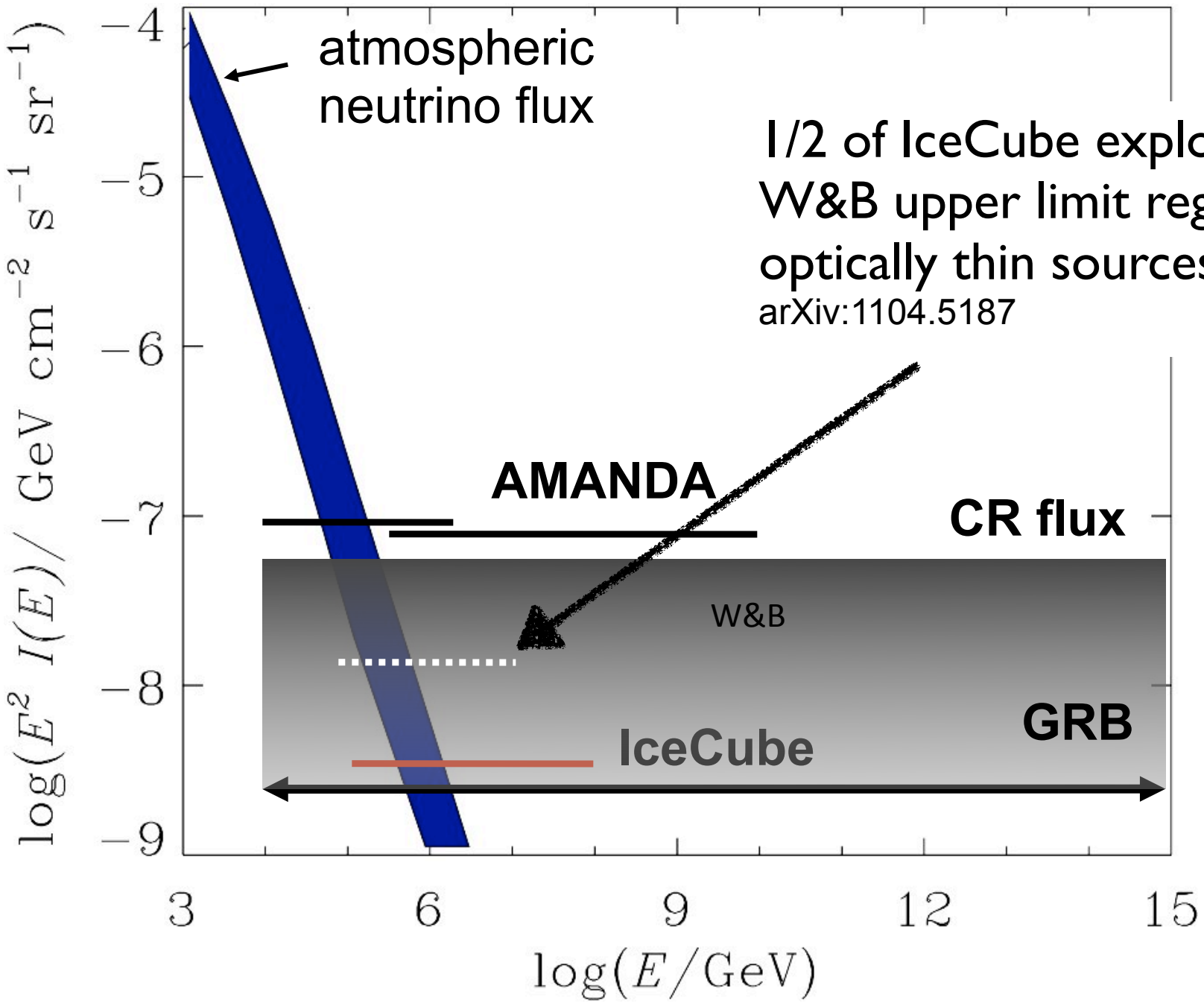
$$E\left\{E\frac{dN_{CR}}{dE}\right\} = \frac{3 \times 10^{10}\,\mathrm{GeV}}{(10^{10}\,\mathrm{cm}^2)(3 \times 10^7\,\mathrm{s})\,\mathrm{sr}} = 10^{-7}\,\mathrm{GeV\ cm^{-2}\,s^{-1}\,sr^{-1}}$$

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 of a population of sources of p with E^{-2} over the Hubble time $\rho_E = 10^{10}$ yrs $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}
Satisfied by:
300/Gpc^3 yr typical GRBs of 2 x 10^{53} erg
2 x 10^{44} erg/s per AGN into particle acceleration

No time-independent hidden sources (only seen in neutrinos)

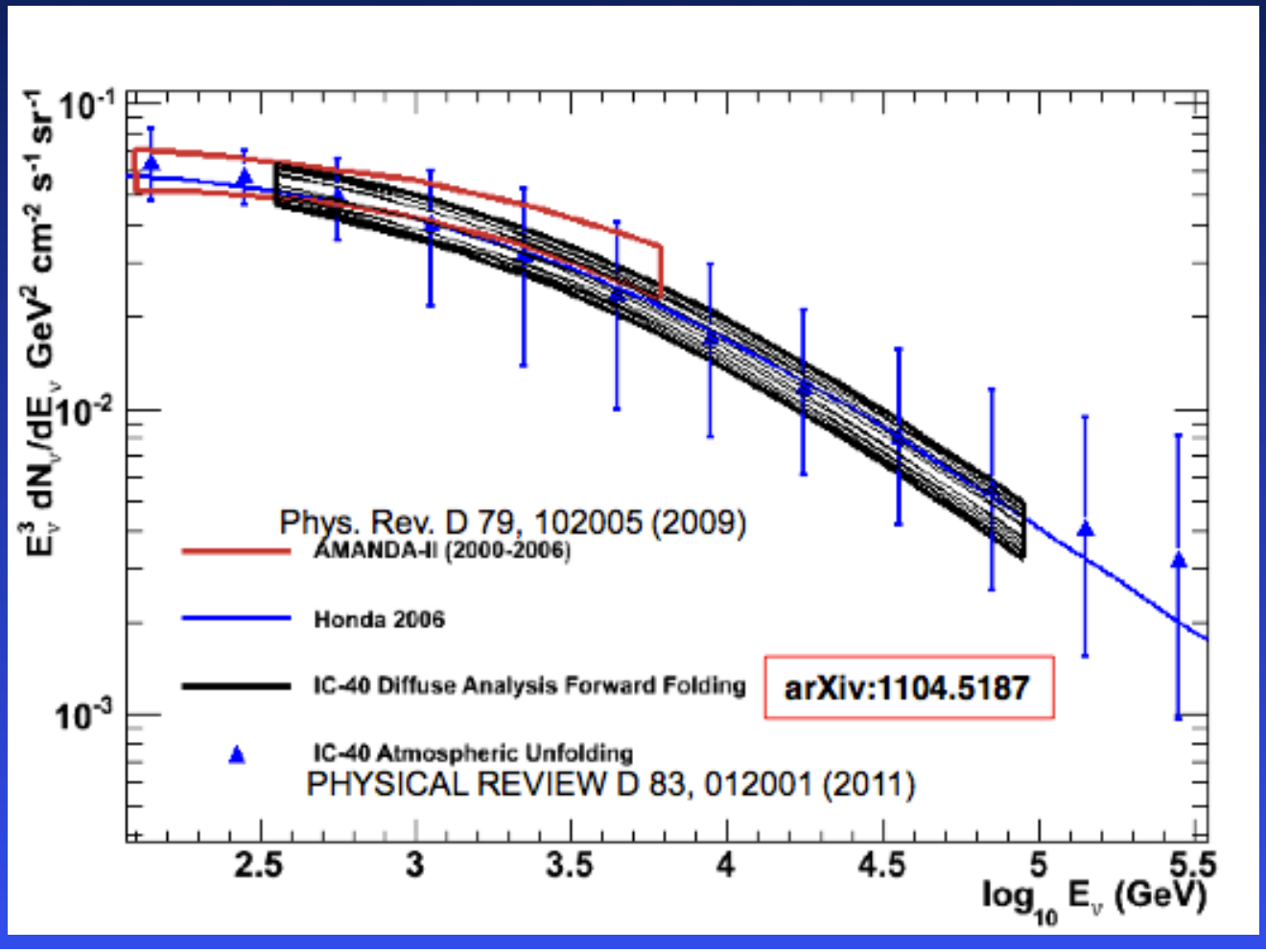


1/2 of IceCube explores the W&B upper limit region for optically thin sources.

arXiv:1104.5187

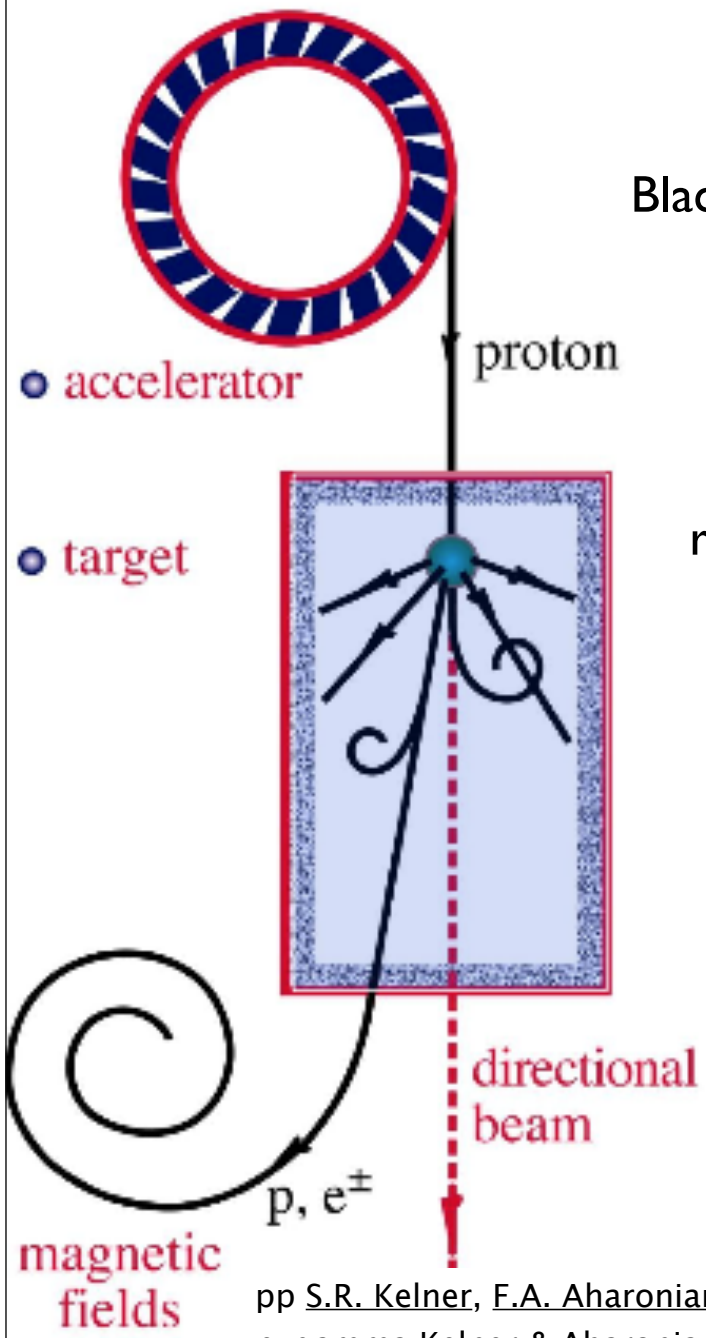
ATMOSPHERIC BACKGROUND

Anything we will see will be on top of an atmospheric background that needs to be well known (particle physics)



$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos(\theta)E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos(\theta)E_\nu/\epsilon_K} + \frac{A_{\mathrm{ch}\,\nu}}{1 + B_{\mathrm{ch}\,\nu}\cos(\theta)E_\nu/\epsilon_{\mathrm{ch}}} \right\}$$

MULTI-MESSENGER ASTRONOMY



Black Hole

radiation

matter

$p + \gamma \rightarrow \Delta \rightarrow n + \pi^+$ (1/3)

$\pi^+ \rightarrow \nu_\mu + (e + \nu_e + \nu_\mu)$ (1/4)

$p + \gamma \rightarrow \Delta \rightarrow p + \pi^0$ (2/3)

$\pi^0 \rightarrow \gamma + \gamma$ (1/2)

$x_\nu = E_\nu/E_p \sim 0.05$

$x_\gamma = E_\gamma/E_p \sim 0.1$

$$\frac{dN_\nu}{dE} = \frac{1}{2}\frac{dN_\gamma}{dE} \quad for\ p + p$$

$$\frac{dN_\nu}{dE} = \frac{1}{8}\frac{dN_\gamma}{dE} \quad for\ \gamma + p$$

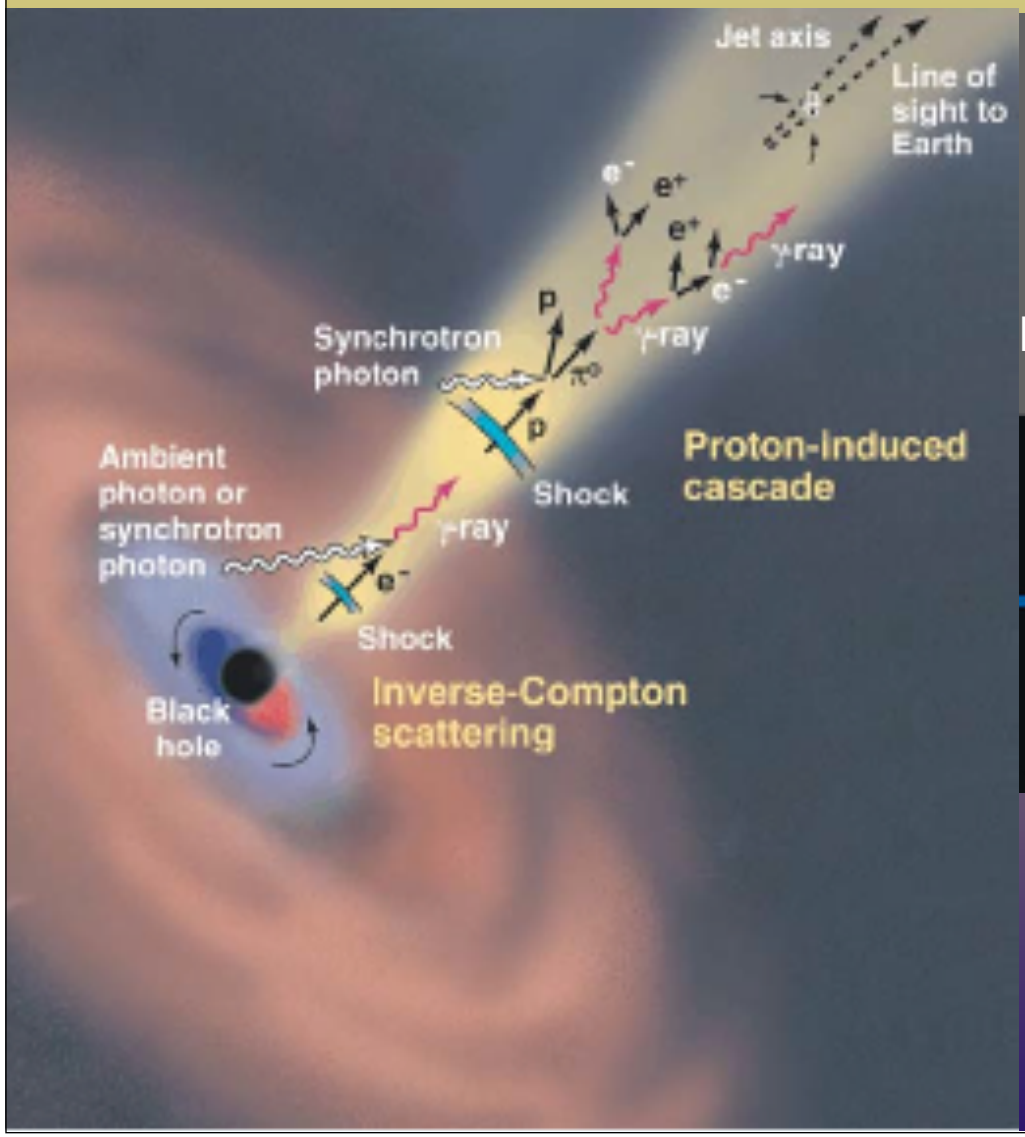
E^{-2} assumed

pp S.R. Kelner, F.A. Aharonian, V.V. Bugayov, 2006

p-gamma Kelner & Aharonian, 2008

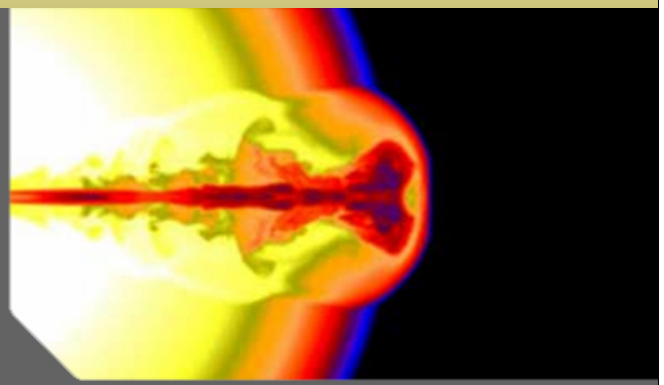
Extragalactic sources

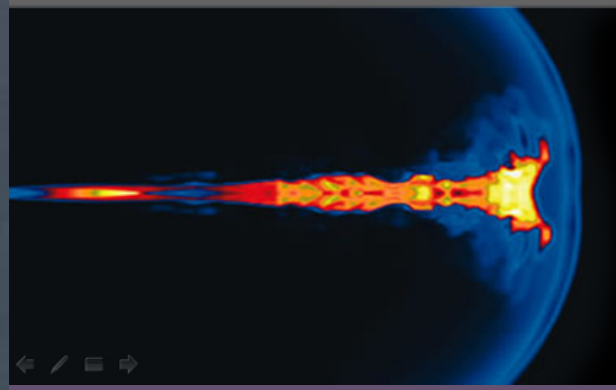
AGN's



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 ?

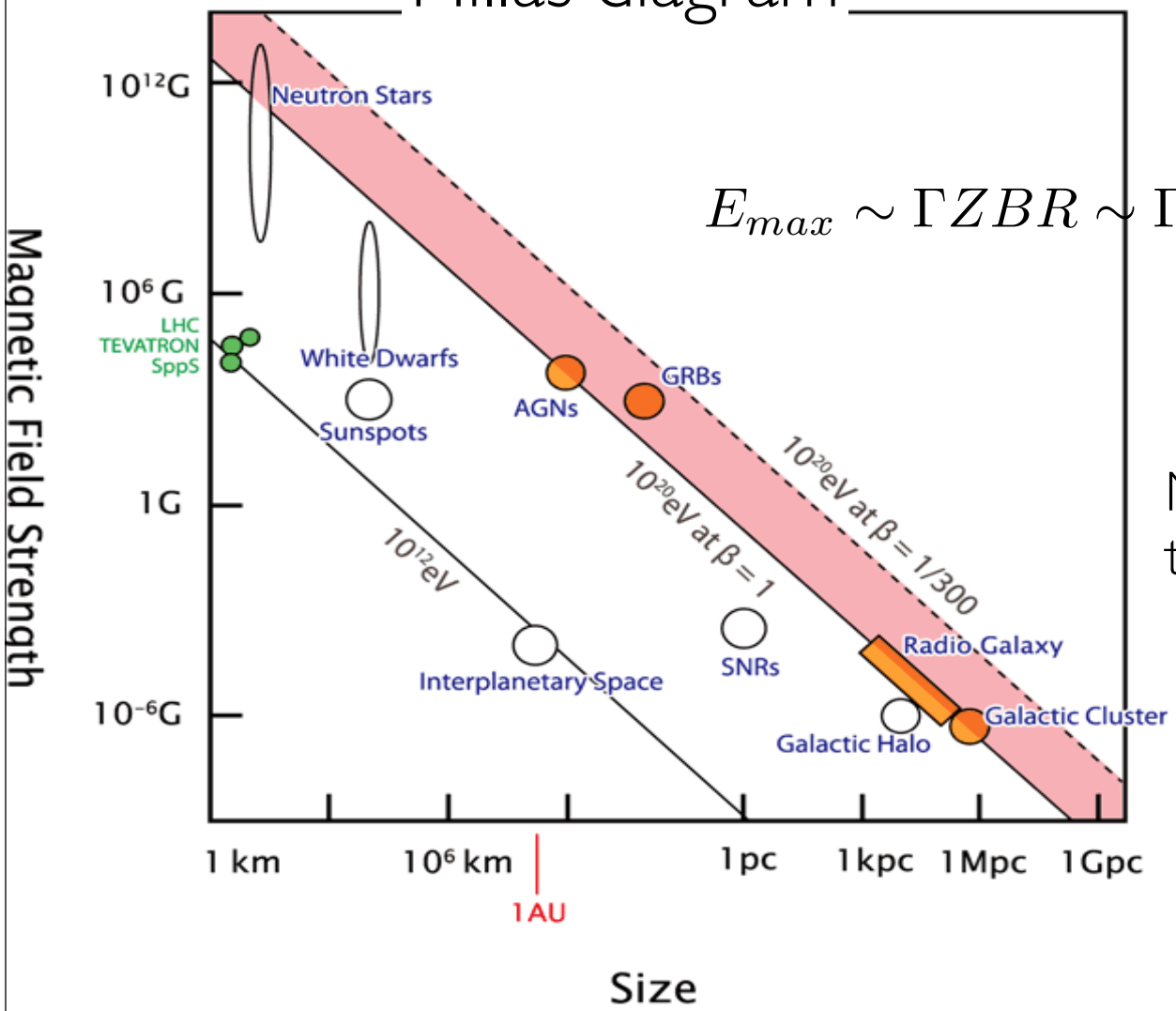
Associated to SN

compact binary mergers (short bursts)

Expanding fireball (containing γ, $e^{\pm}$, p) becomes optically thin and emits the observed radiation through the dissipation of particle kinetic energy into relativistic shocks

EFFICIENT ACCELERATORS

Hillas diagram



Basic acceleration condition:

$$r_L \leq R$$

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

More precisely the condition is:

$t_{acc} \lesssim t_{esc}, t_{age}, t_{energy\ loss}$

For GRBs:

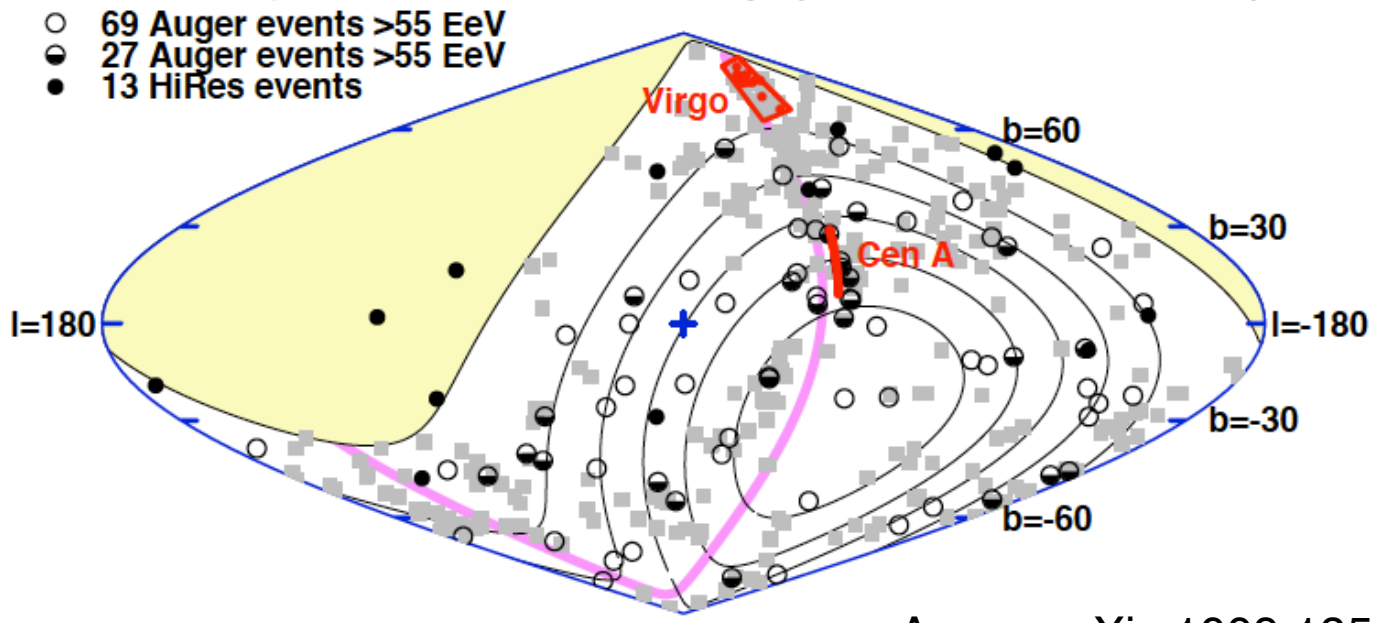
1) $t_{acc} \lesssim t_{duration\ of\ burst}$

2) synchrotron energy lost ≲ energy gained in acceleration

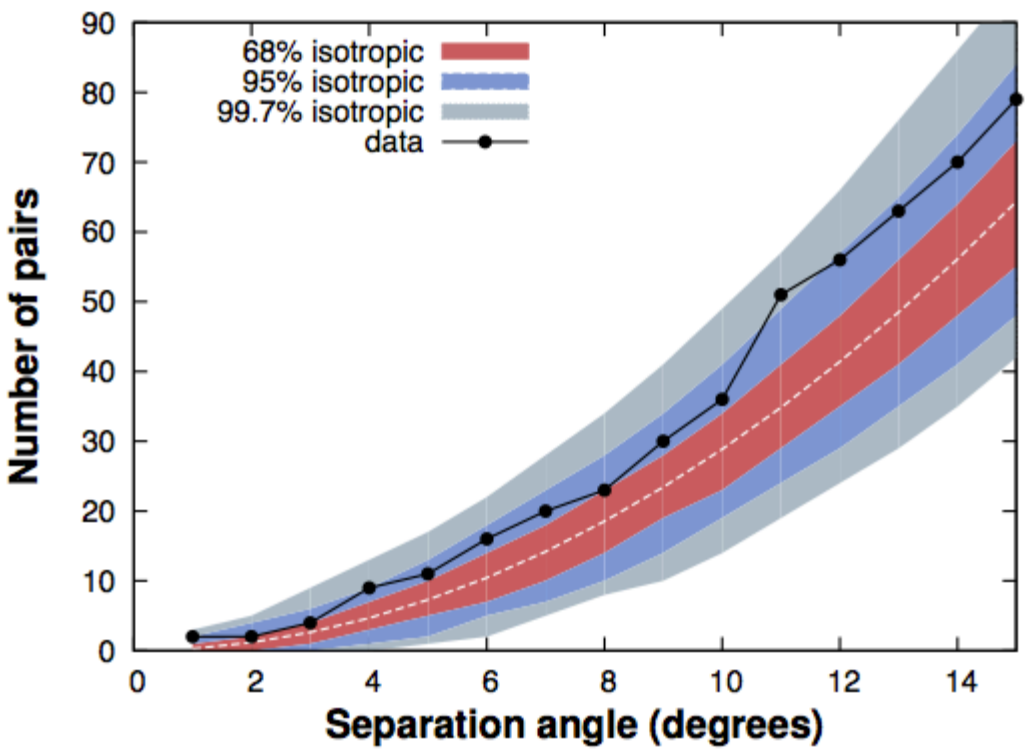
these conditions sets the constrain: $\Gamma \geq 130 \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{3/4} \left(\frac{0.01\mathrm{s}}{\Delta t}\right)^{1/4}$

Waxman astro-ph/0303517

AGNs: The sources revealed?

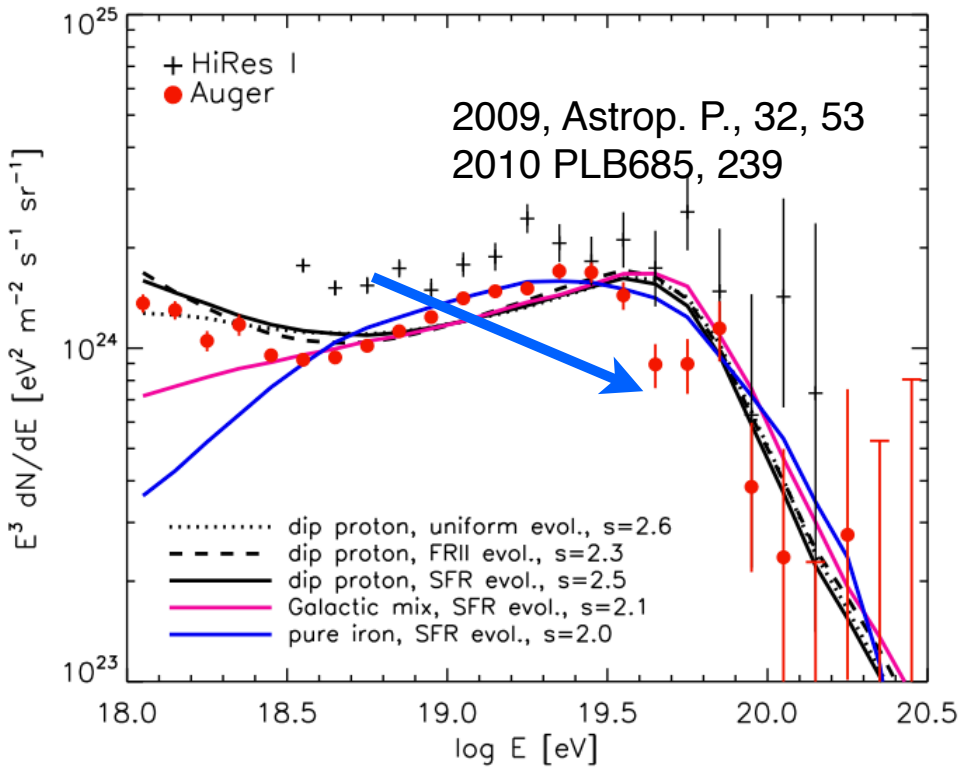


Auger, arXiv:1009.1855

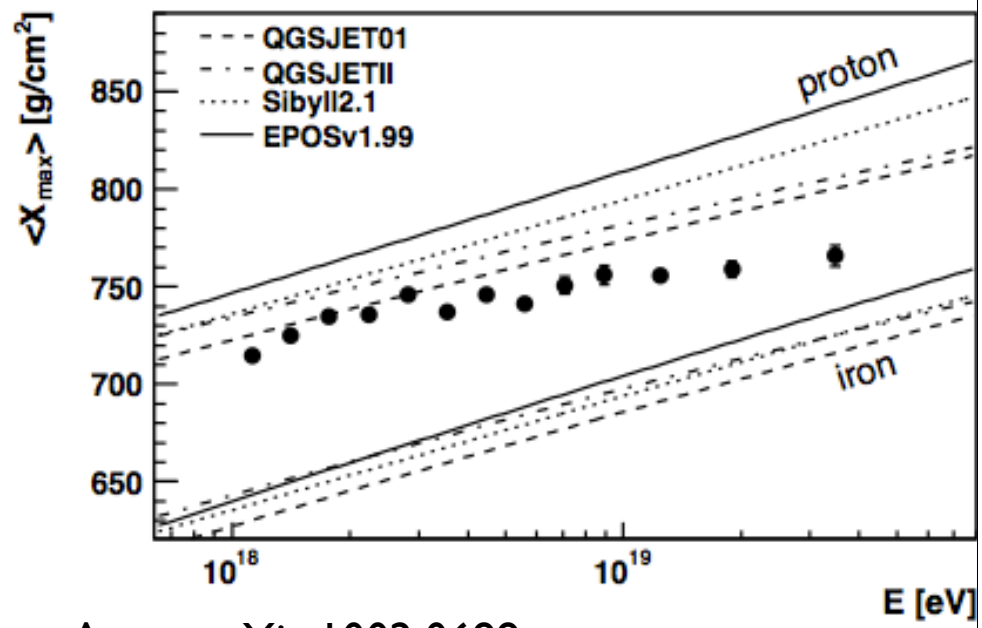


Anisotropy measured as fraction of arrival directions inside 3.1° from an AGN catalogue (<75 Mpc) with 69 E>55 EeV events: 37% (21% expected to occur by chance for an isotropic flux).
18% of 69 events are inside 18° from Cen A but no event from M87.
Autocorrelation function: largest deviation from isotropic distribution at 11°.
For an isotropic distribution 1.3% pairs of the 69 events have 51 or more pairs inside 11°.

Cut off proved, composition?



Where is the galactic - extra-galactic transition?



Auger arXiv:1002.0699

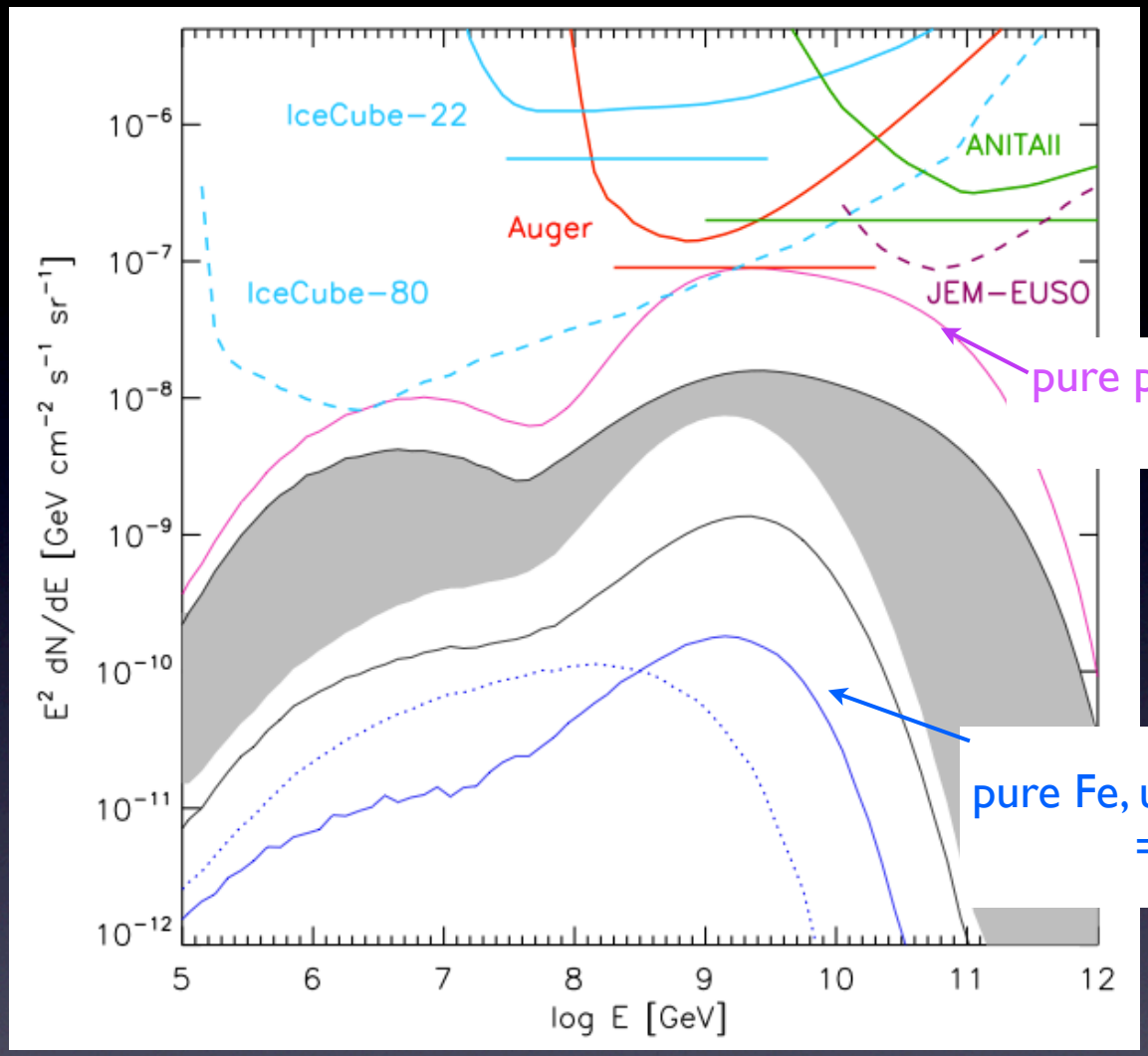
Auger hints towards heavy CR composition, unlike HiReS (arXiv:0910.4184)

Spectrum does not discriminate between p and Fe. If UHECRs are Fe => no anisotropies

Evidence of neutrinos in coincidence with UHECR => extra-galactic sources of CRs are not GRBs because protons cannot arrive at the same time as neutrinos.

IceCube: no correlation evidence in 40-strings, 40+59 strings (ICRC 2011)

Fluxes of UHECR neutrinos



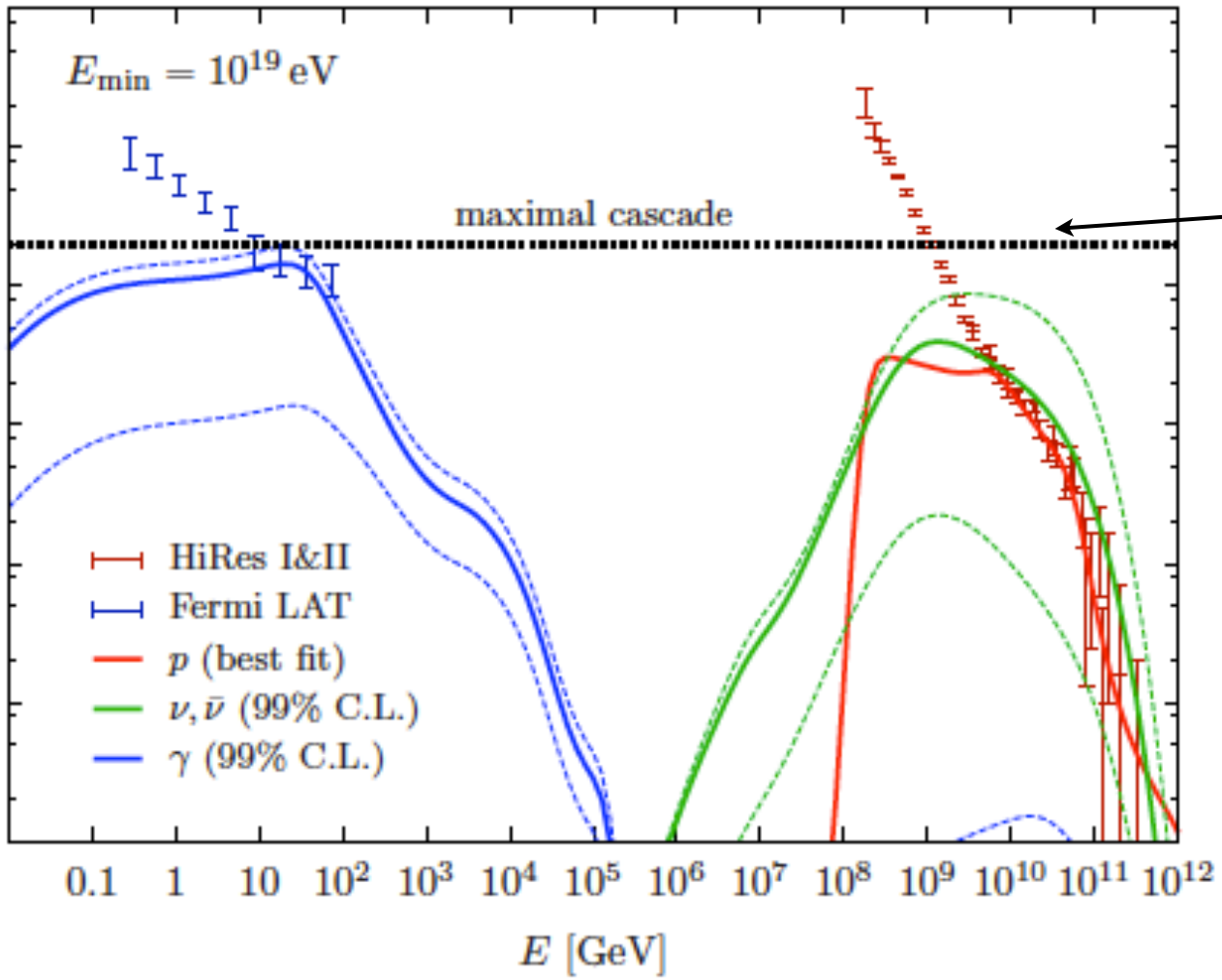
The diffuse extragalactic background measured by Fermi can be used as a constraint accounting for photon cascading.

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 + UHECR constrained predictions



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

Ahlers et al, arXiv:1005.2620

$$\frac{dN_\nu}{dE} \sim n_{int} \times \frac{1}{x_\nu} \times \frac{dN_{CR}}{dE}\left(\frac{E_{CR}}{x_\nu}\right)$$

~0.05

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

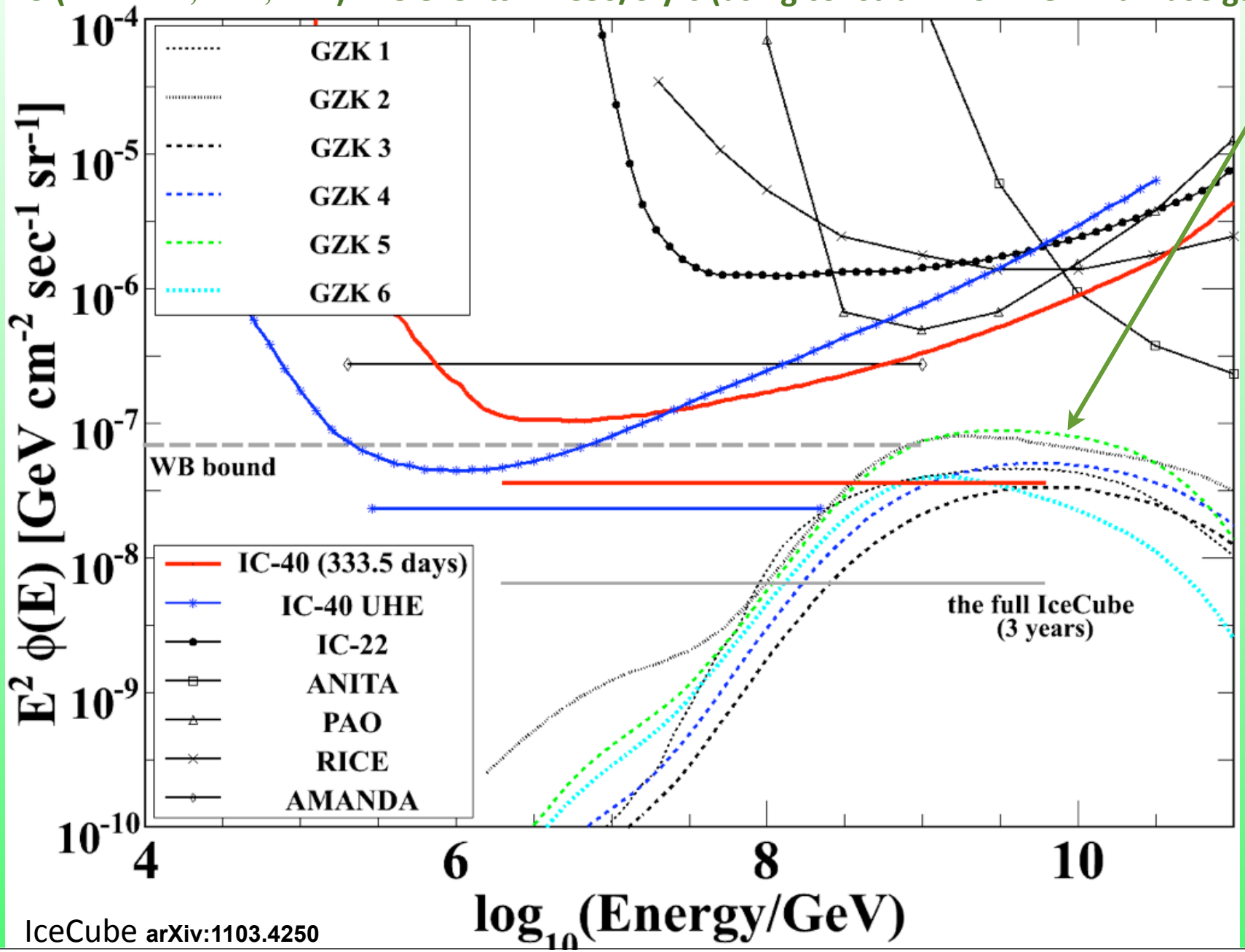
~ cosmic ray + gamma

Photon diffuse flux: uncertainties on gamma cascading, cosmic IR background, galactic point source flux subtraction from Fermi measurement.

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)

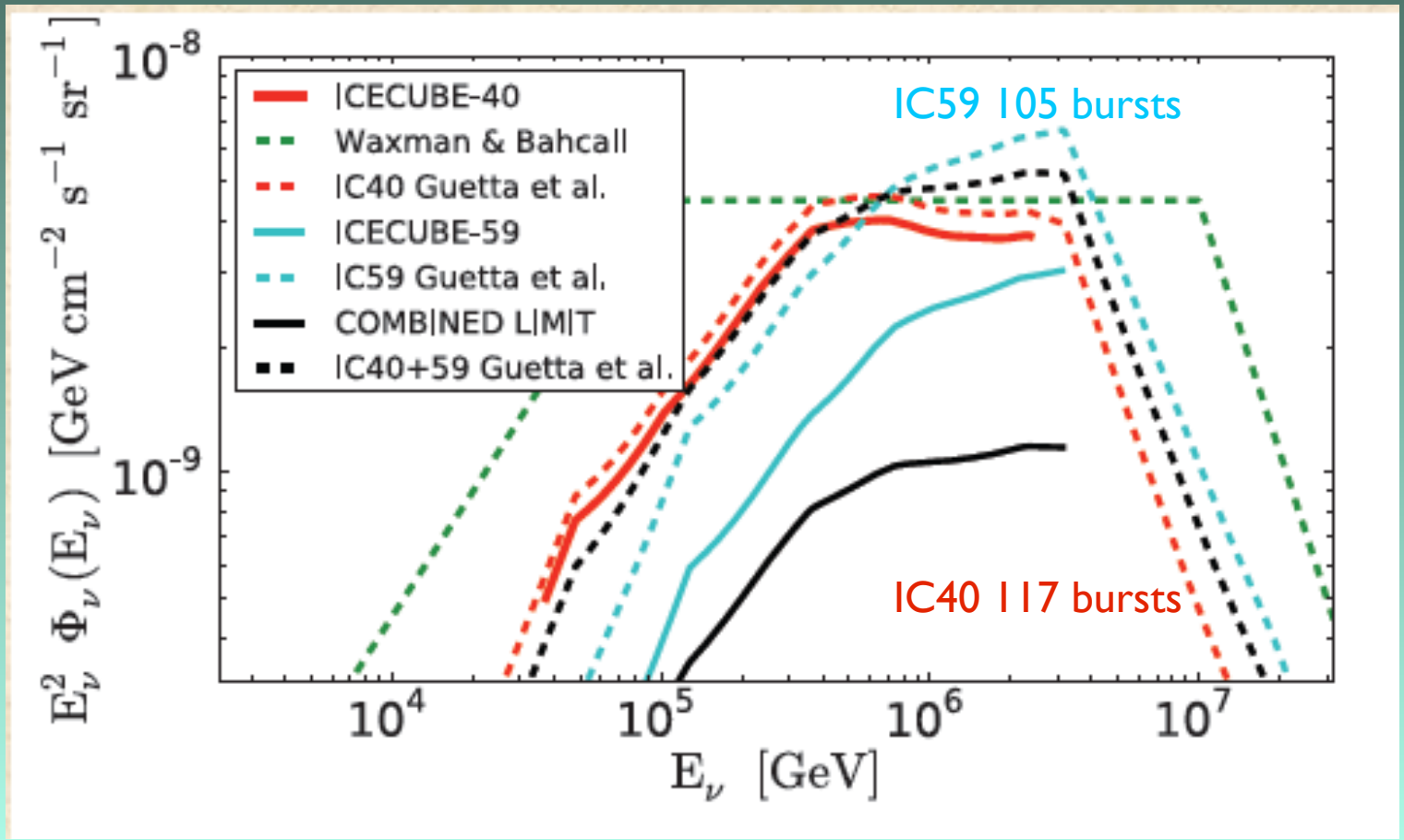


IceCube **arXiv:1103.4250**

IceCube results for GRBs

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

IceCube is in the **right range** to probe extragalactic sources
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?

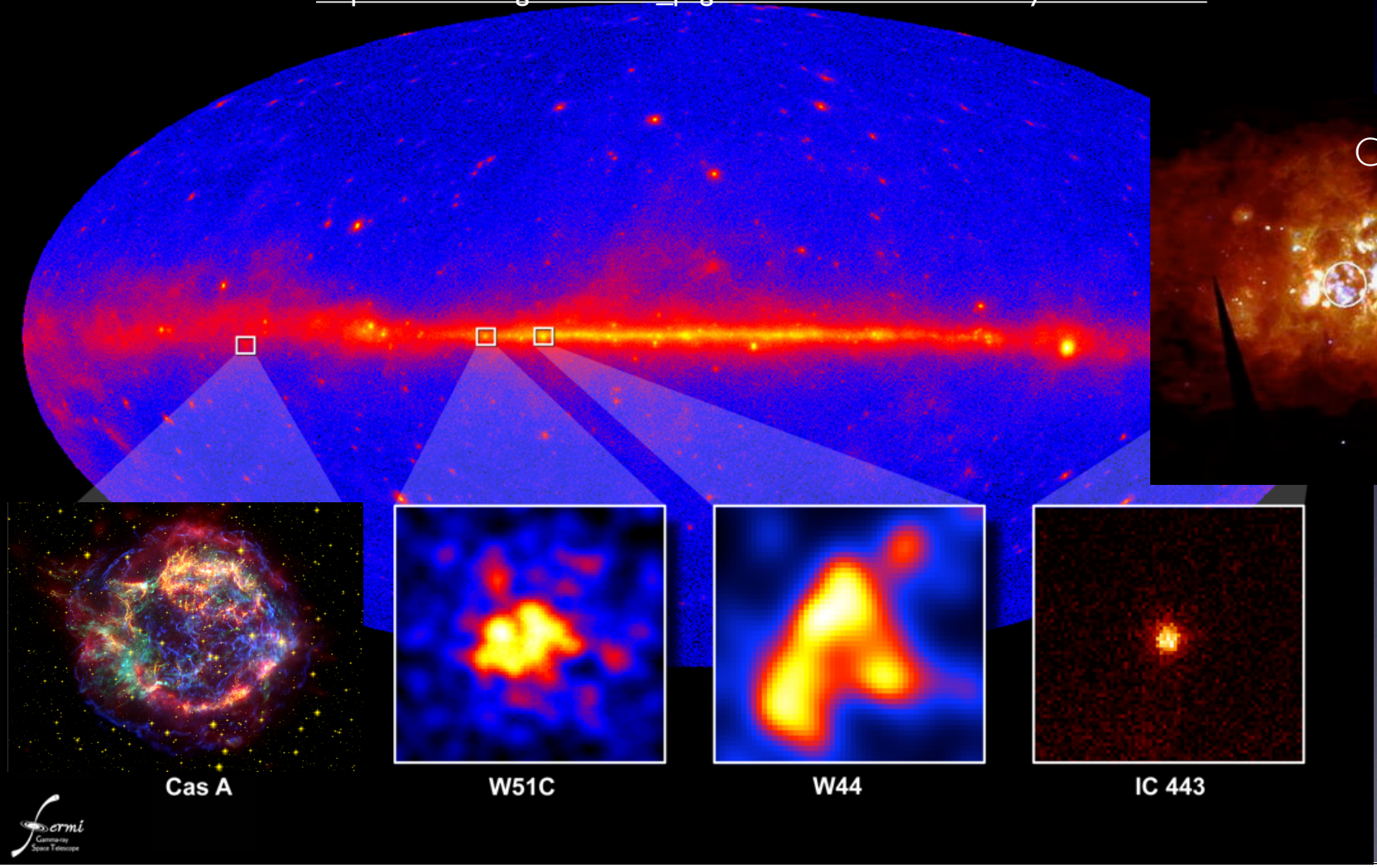


Galactic sources:

What PeVatrons accelerate CRs to the knee?

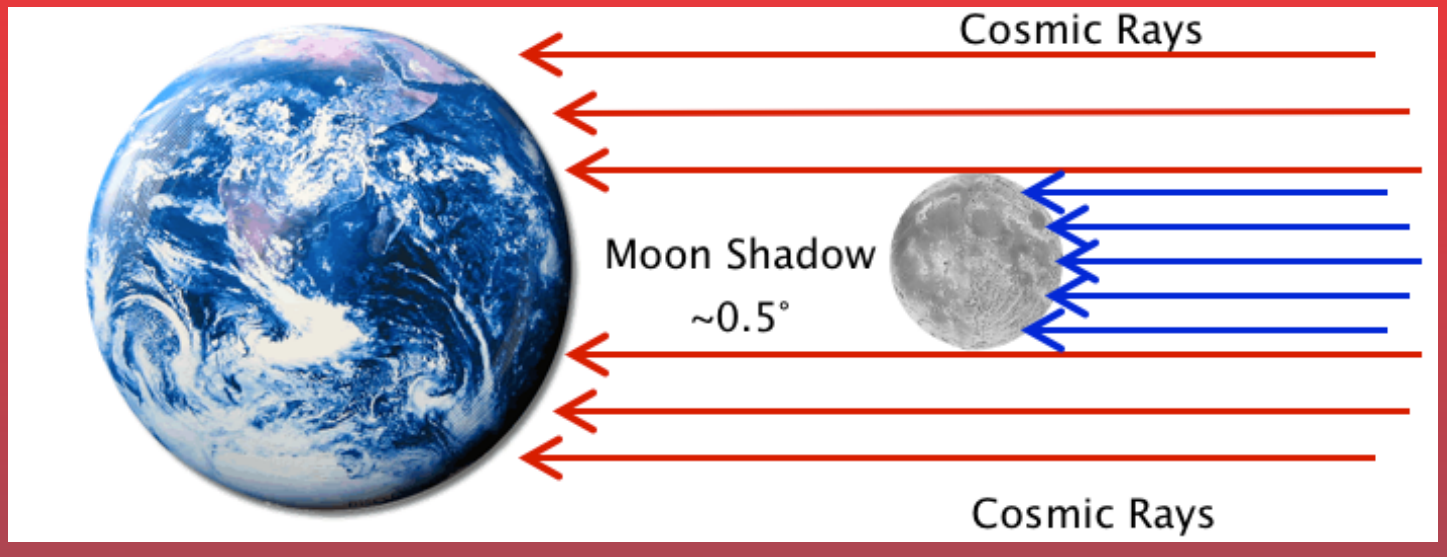
NASA's Fermi telescope resolves supernova remnants at GeV energies

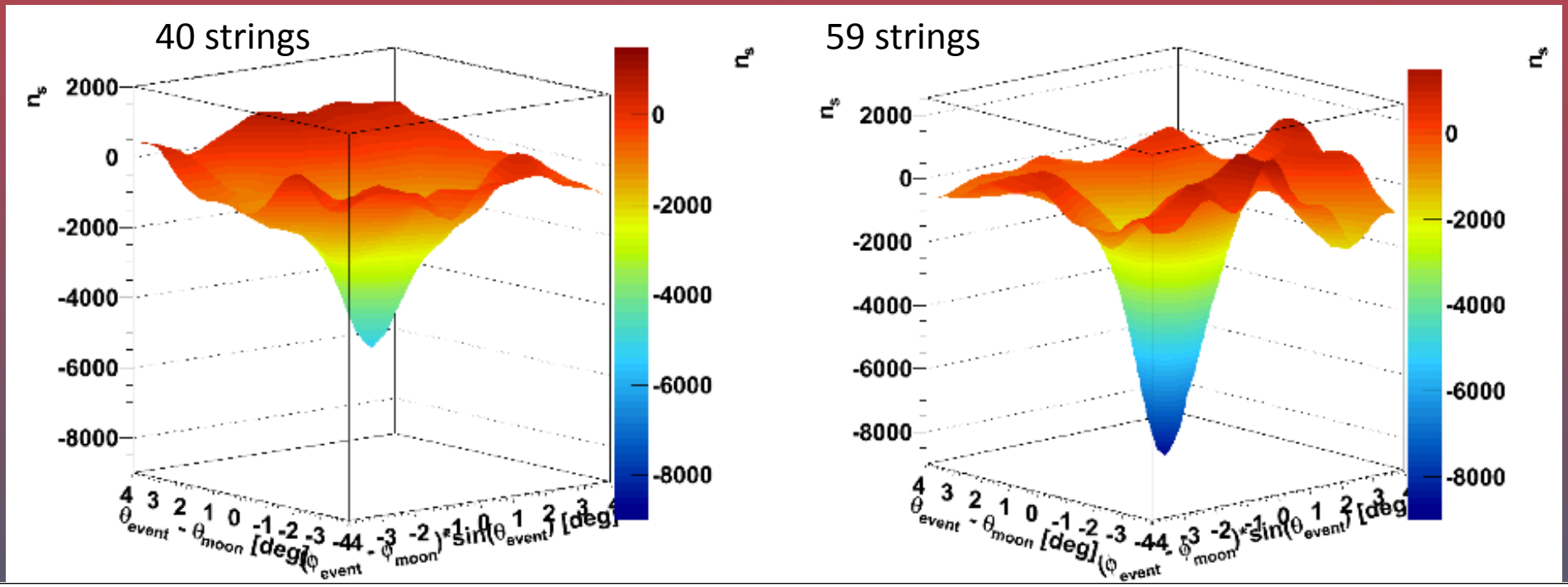
http://www.nasa.gov/mission_pages/GLAST/news/cosmic-rays-source.html



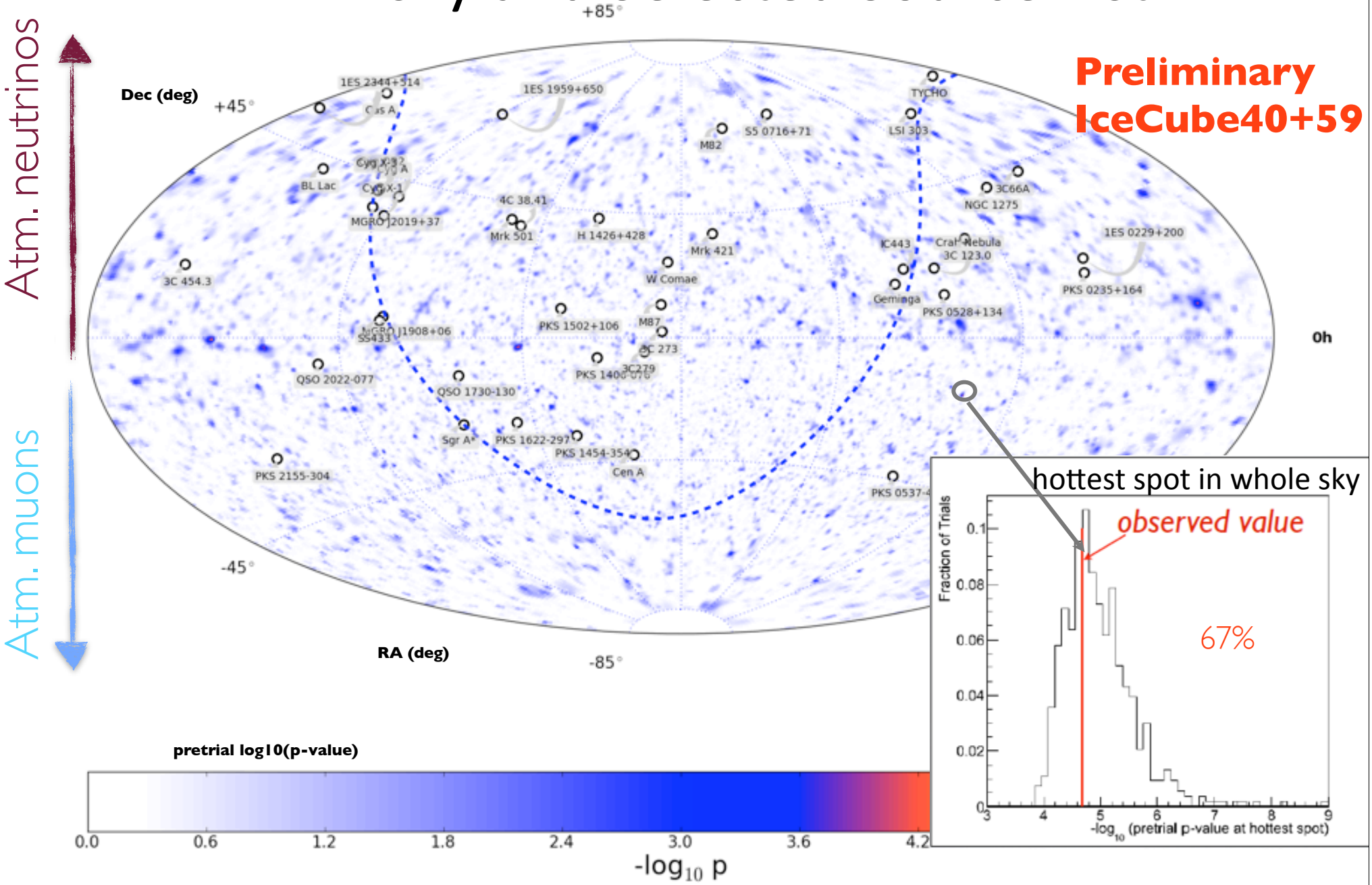
Sub-degree Pointing proved on the Moon

More than 12σ underfluctuation in 59-strings





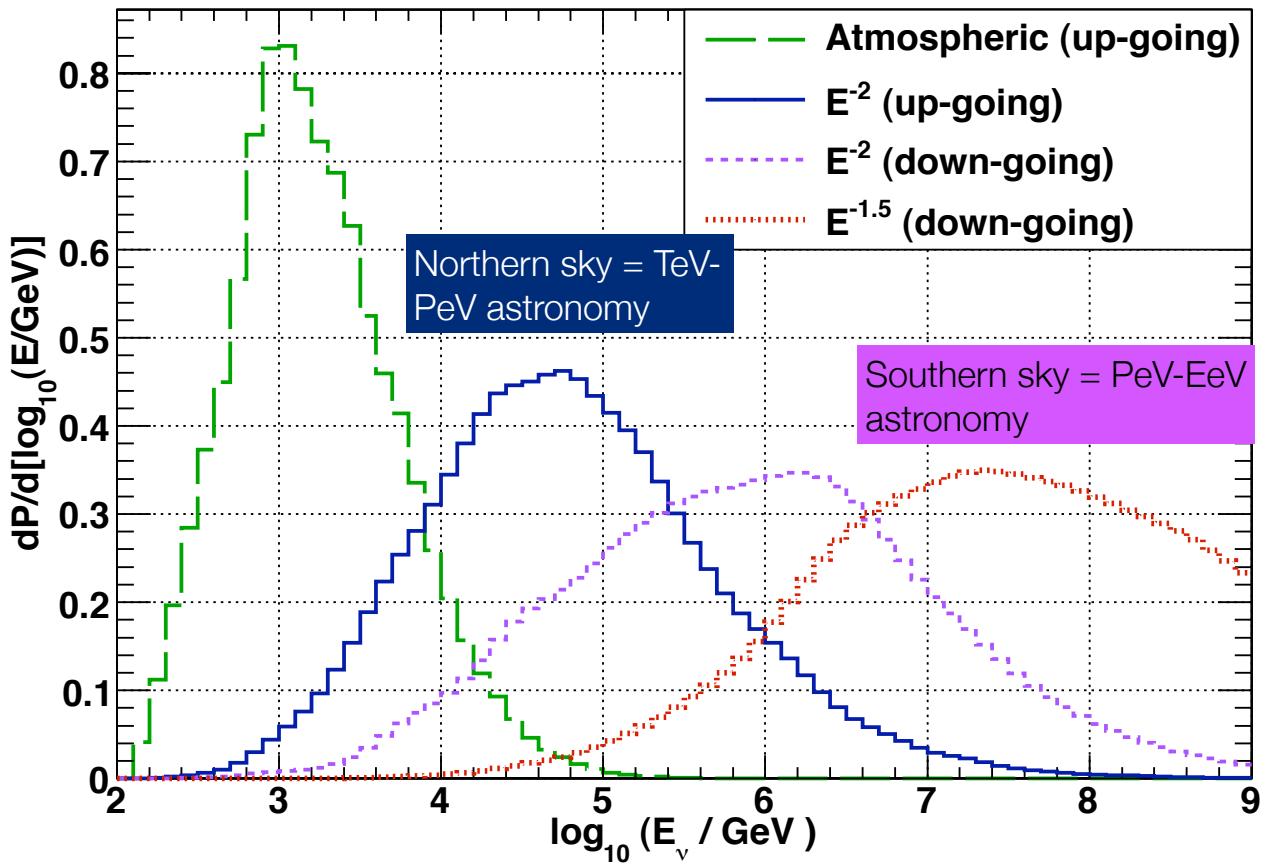
All sky and Selected Source List

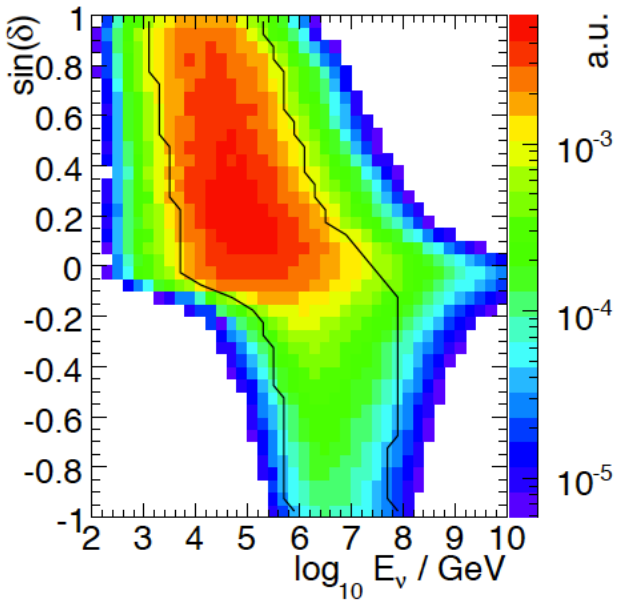


No significant fluctuation: best pre-trial p-value = 0.14 pretrial in a list of 43 sources => 95% post-trial for PKS_1454-354

Full Sky view

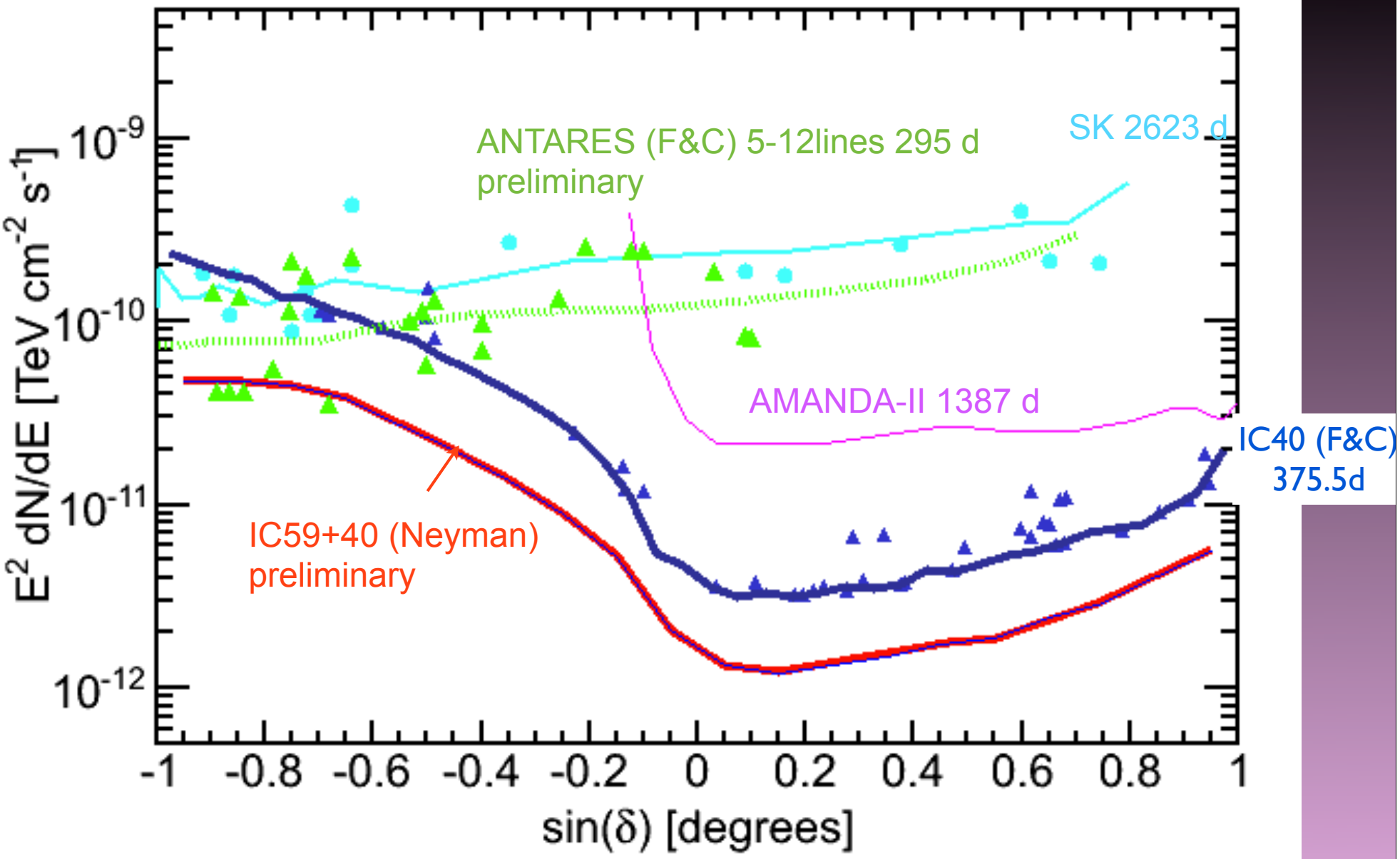
Data sample made of about 1/3 of upgoing neutrino induced muons and 2/3 of downgoing atmospheric muons (energy cut vs angle)
LH method to distinguish atmospheric background (random direction, soft spectrum) from signal (cluster around point-source, hard spectrum from 1st order Fermi shock acceleration E^{-2})





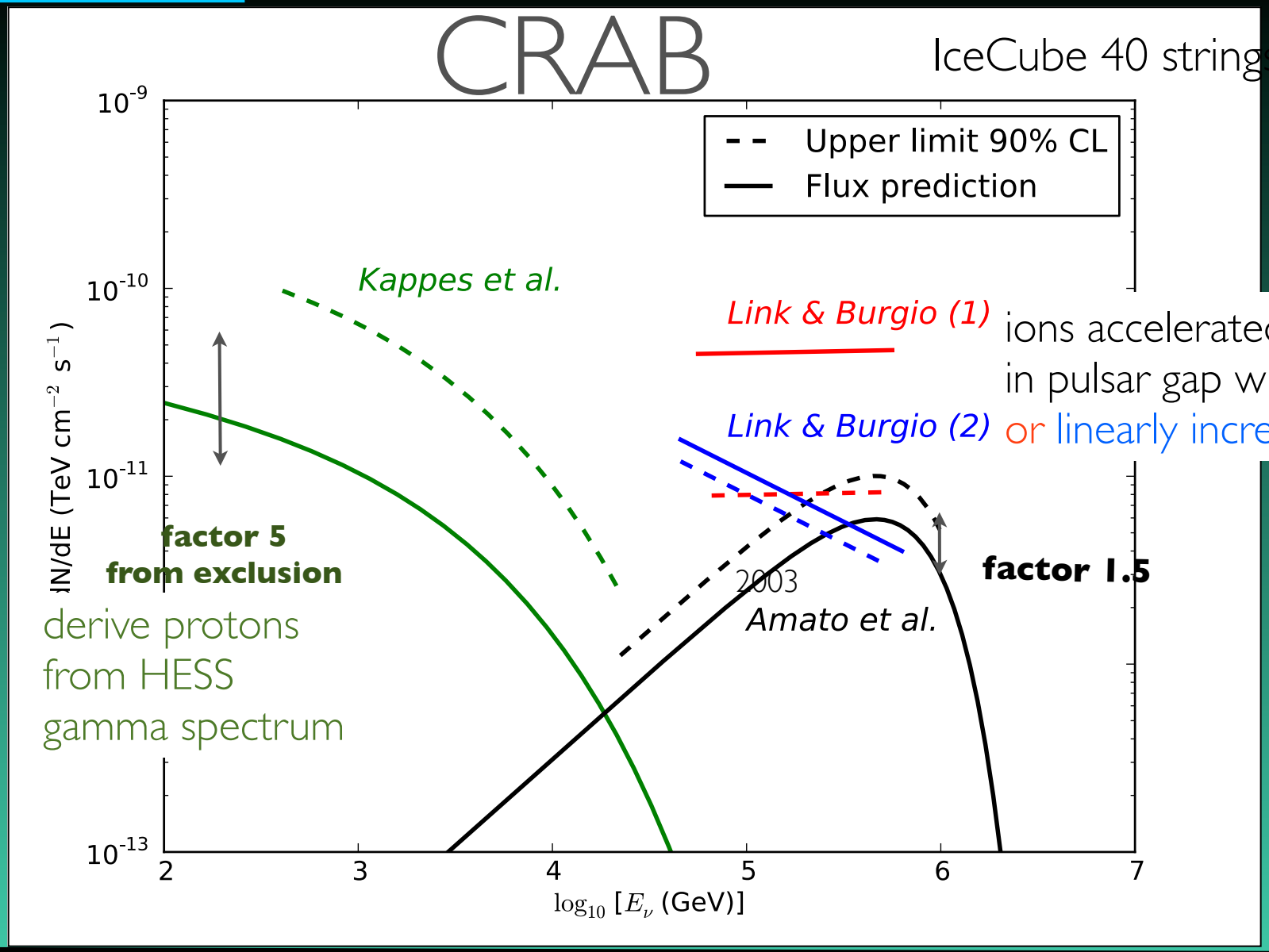
black lines: E^{-2} contour from 5% to 95%

Results for IceCube 40, Astrophys.J.732:18,2011



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

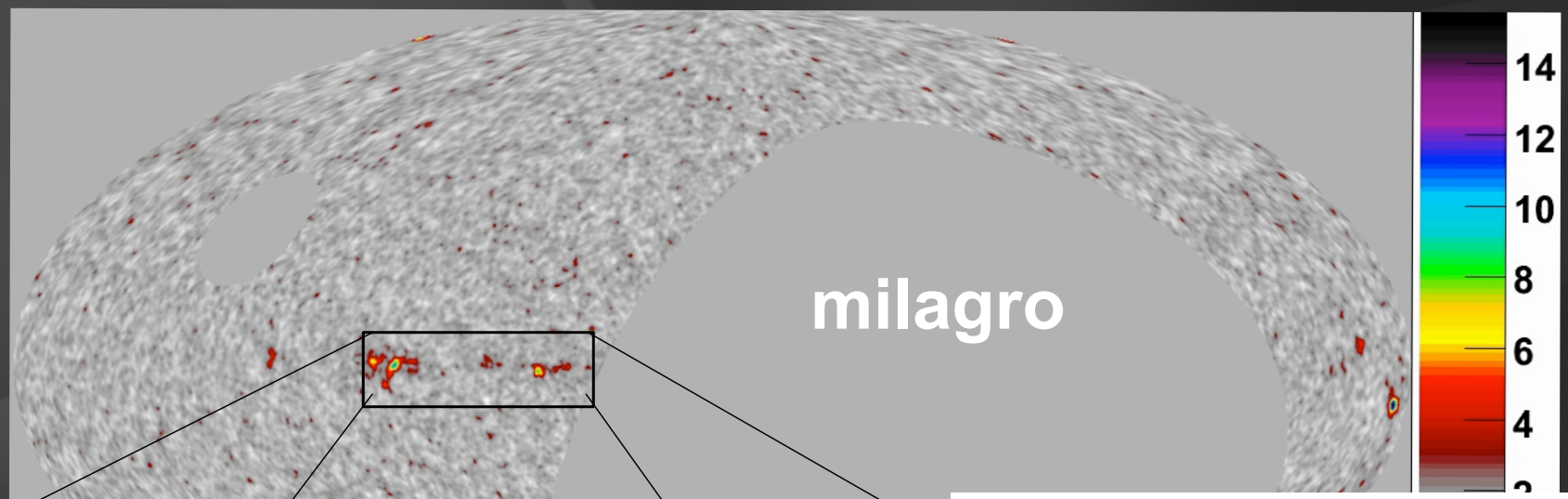
arXiv:1106.3484

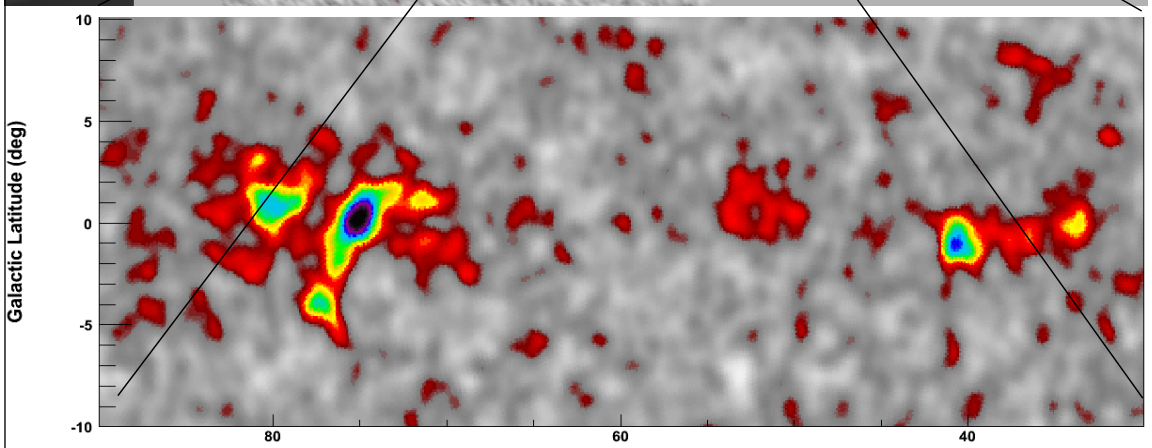


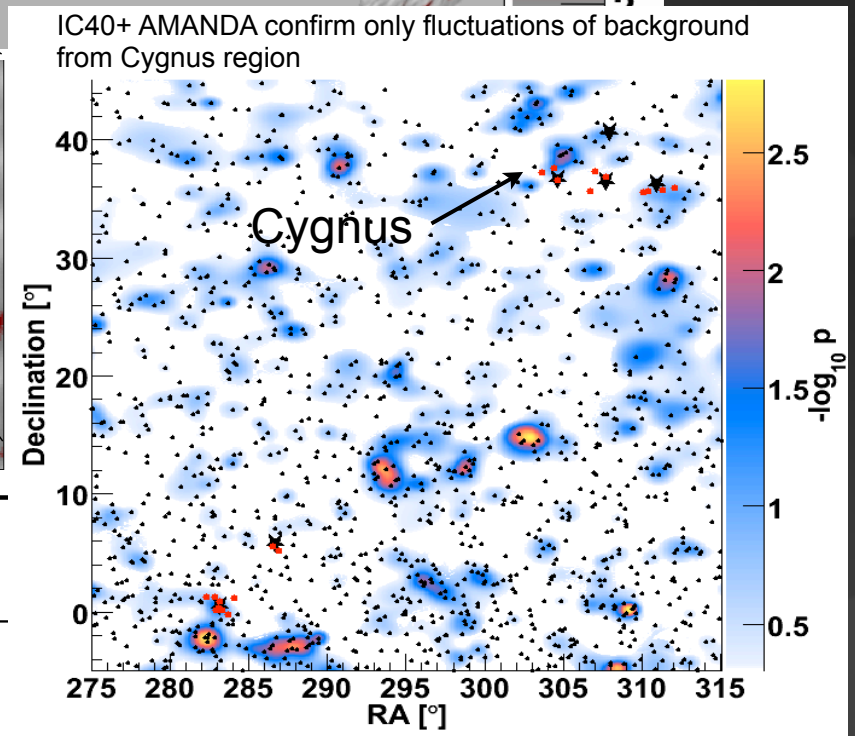
Region of shock acceleration in SNR being explored

For isotropic emission the E^{-2} IceCube limit corresponds to a nu luminosity constraint of 1 x 10^{35} erg s-1 ~1.7 luminosity between 0.4-40 TeV.

Stacking the Milagro Pevatrons (SNR in molecular clouds)



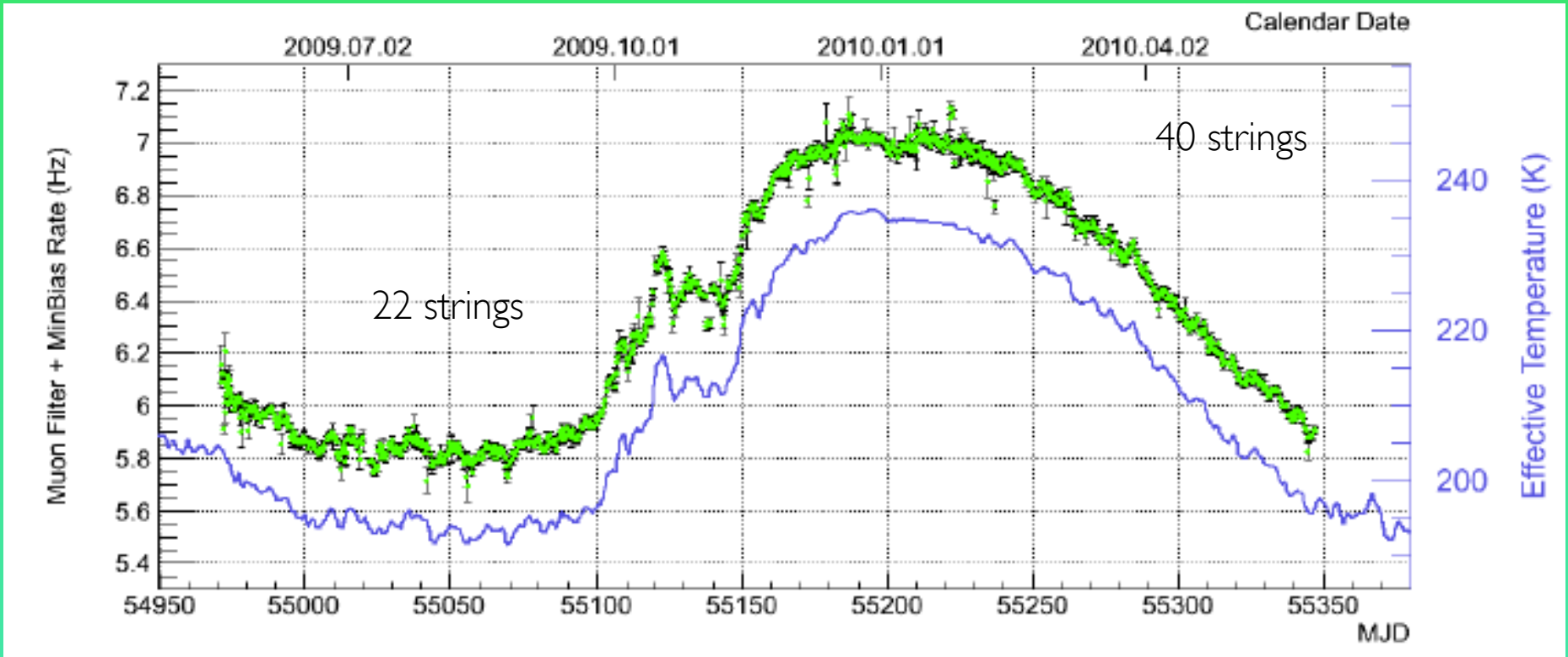




Catalogue	Med Sens	upper limit (90%cl)
6 Milagro SNR	2.9x prediction	7.2 x prediction

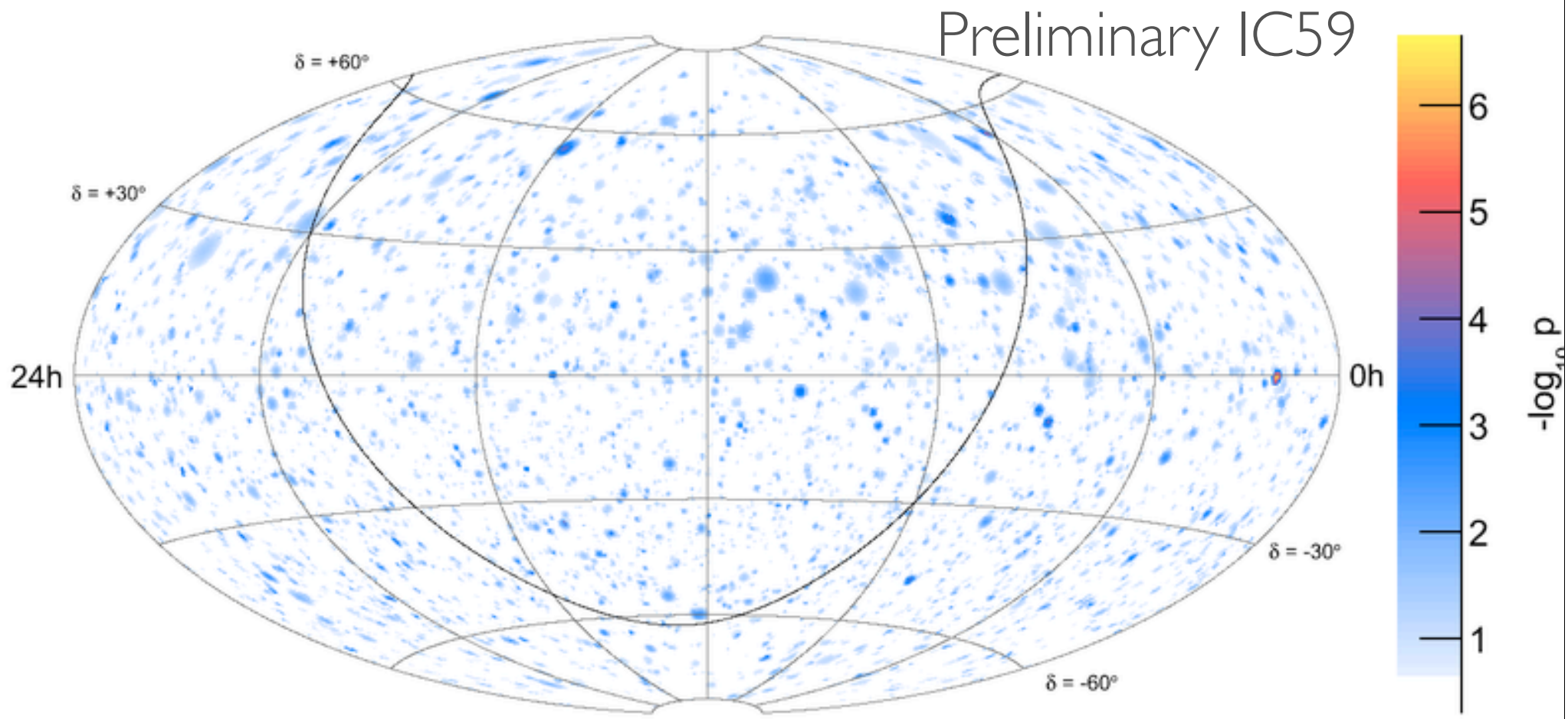
Model (Gonzalez-Garcia et al., arXiv:0902.1176): if E^{-2} cut-off at 300 TeV (10% of the knee of their CR primaries) => 5σ in 3 yr of IceCube

TIME DEPENDENT SEARCHES



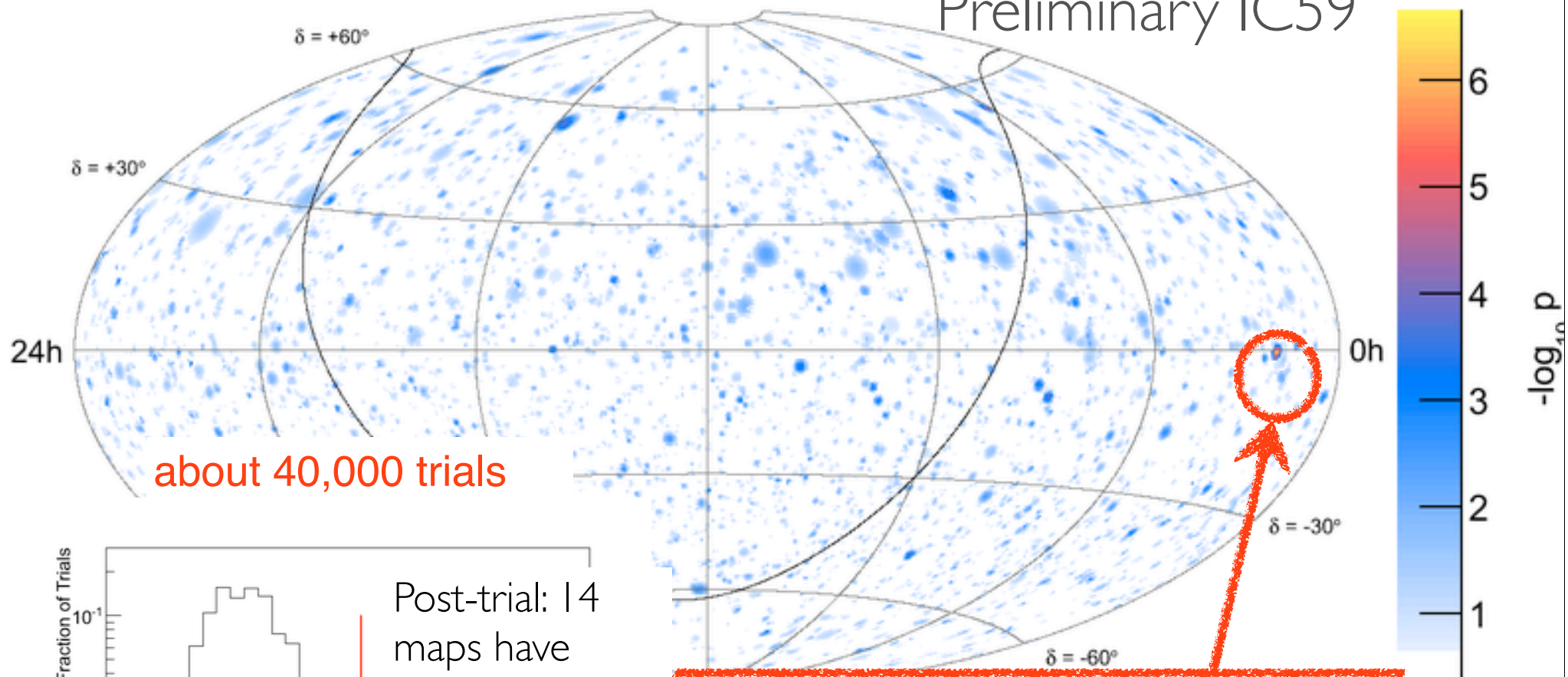
About a factor of 2-3 better discovery than time indep. searches for sigma of flare = 0.5 day and a direction thanks to atmospheric muon/neutrino background suppression.

ALL SKY SCAN IN TIME-ENERGY-SPACE

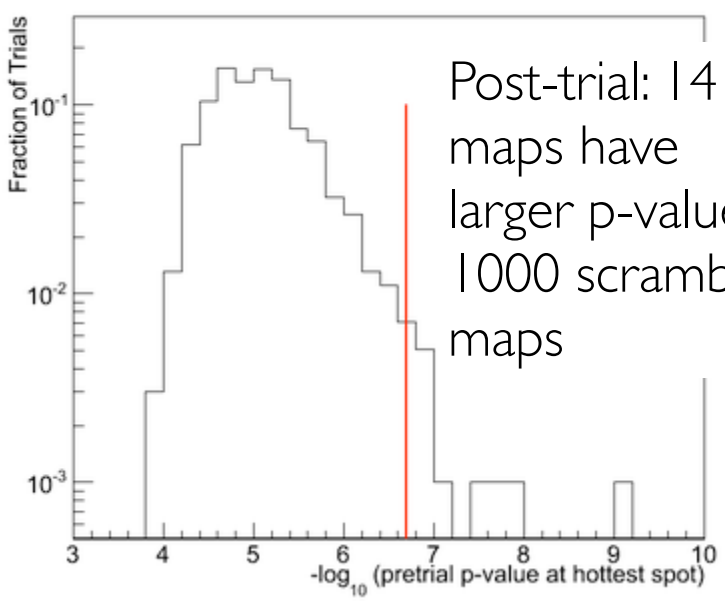


ALL SKY SCAN IN TIME-ENERGY-SPACE

Preliminary IC59



about 40,000 trials



Post-trial: 14 maps have larger p-value/ 1000 scrambled maps

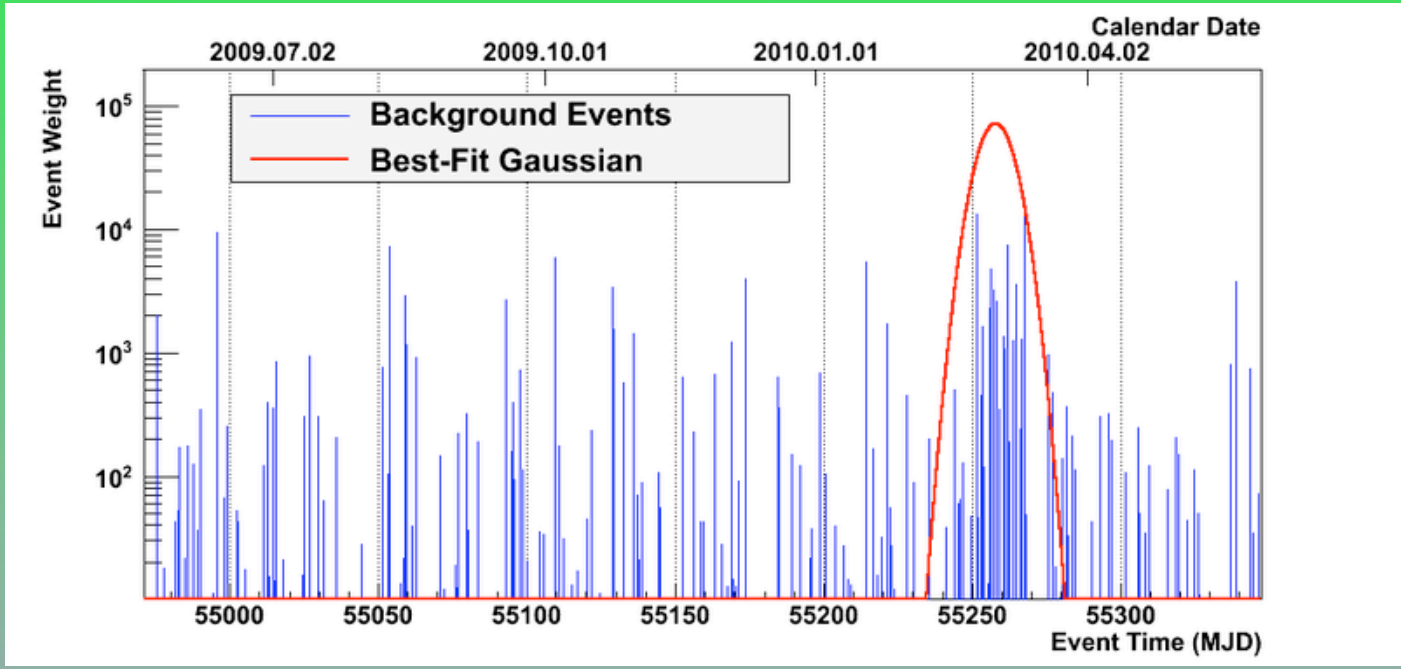
ra=21.35°, dec=-0.25°

n_s = 14.5 with $E^{-3.9}$

Flare peak on March 4, 2010

FWHM duration = 13 days -log10 (pretrial p-value) = **6.69**.

59 STRING UNTRIGGERED FLARE SEARCH



17 events in MJD 55251 to 55268 and within 3.5 degrees