# PEV NEUTRINOS FROM THE PROPAGATION OF ULTRA-HIGH ENERGY COSMIC RAYS

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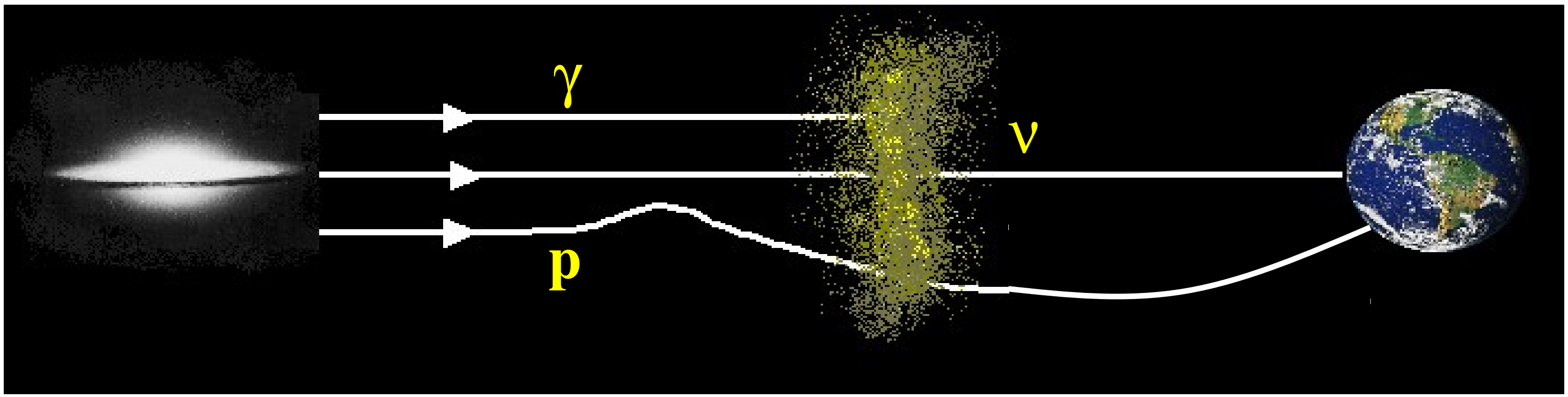
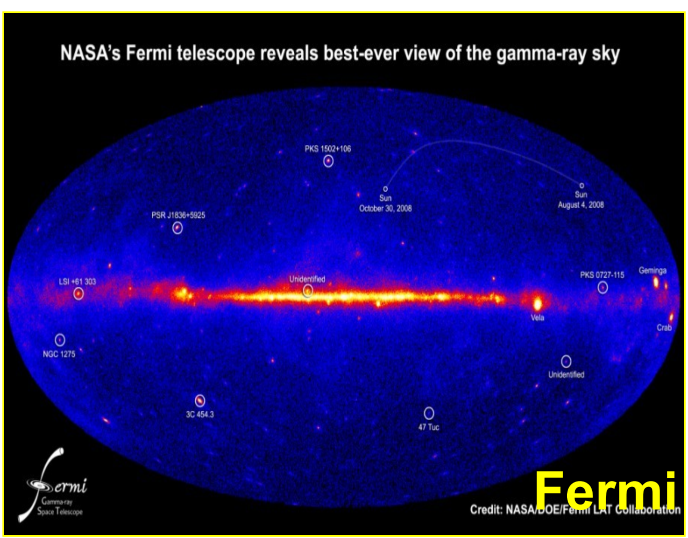
# THE ENERGETIC UNIVERSE

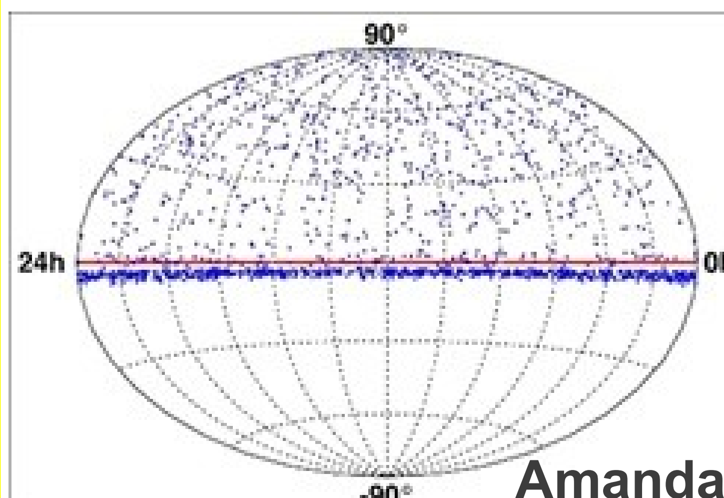
## multi-messenger astronomy



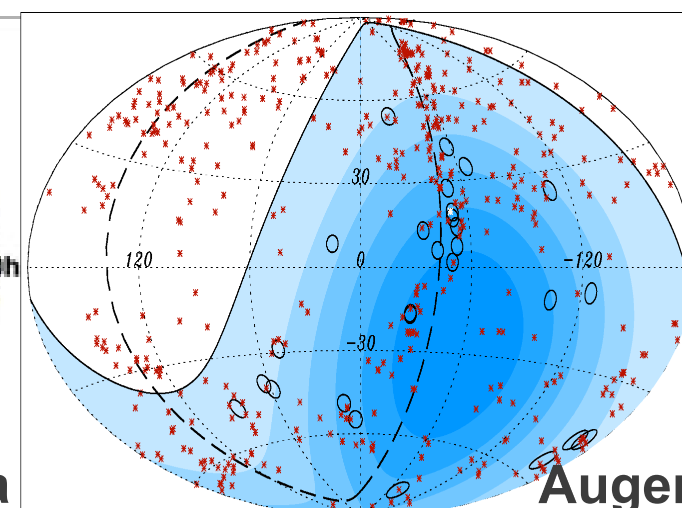

γ rays



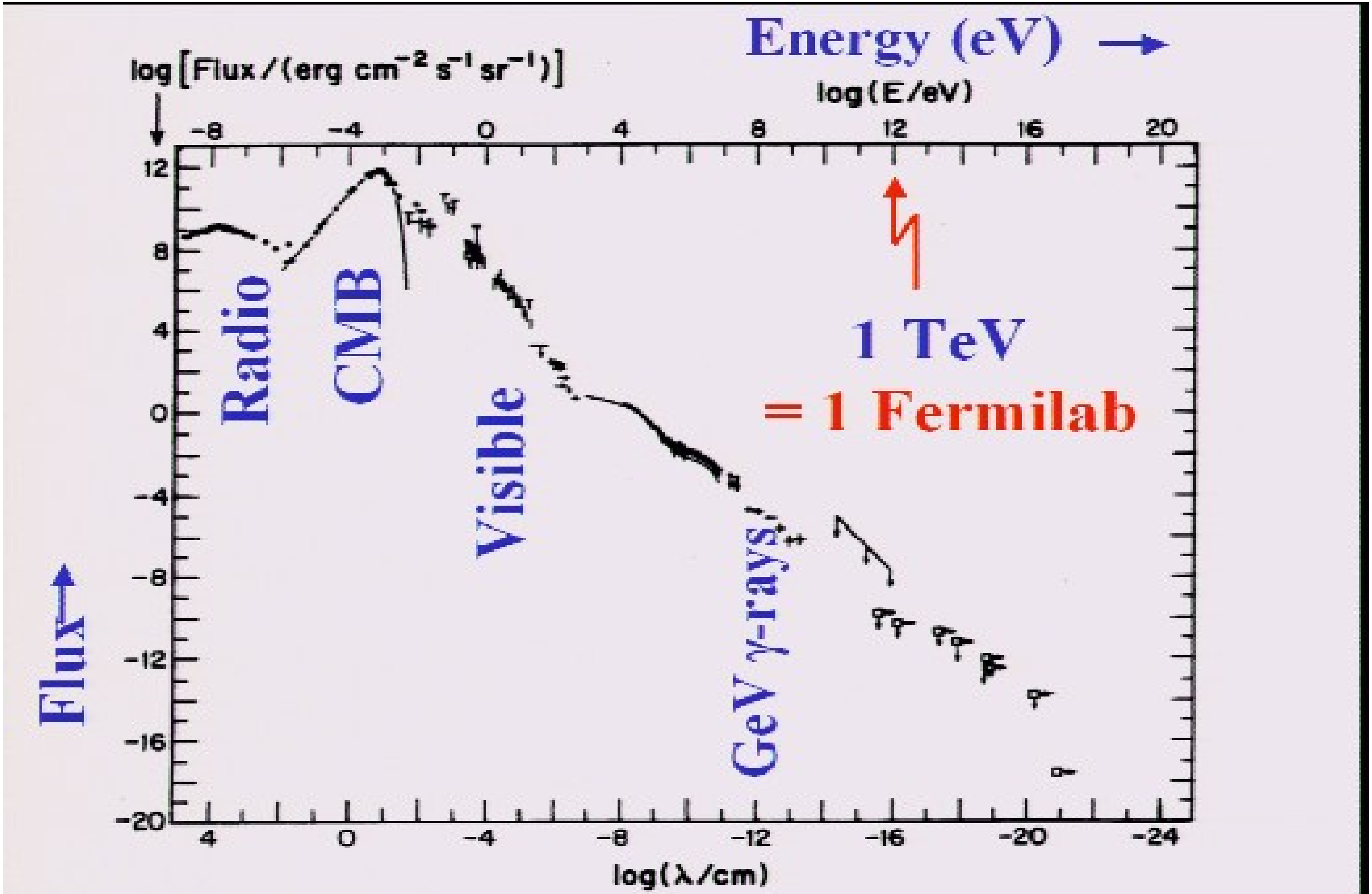

neutrinos



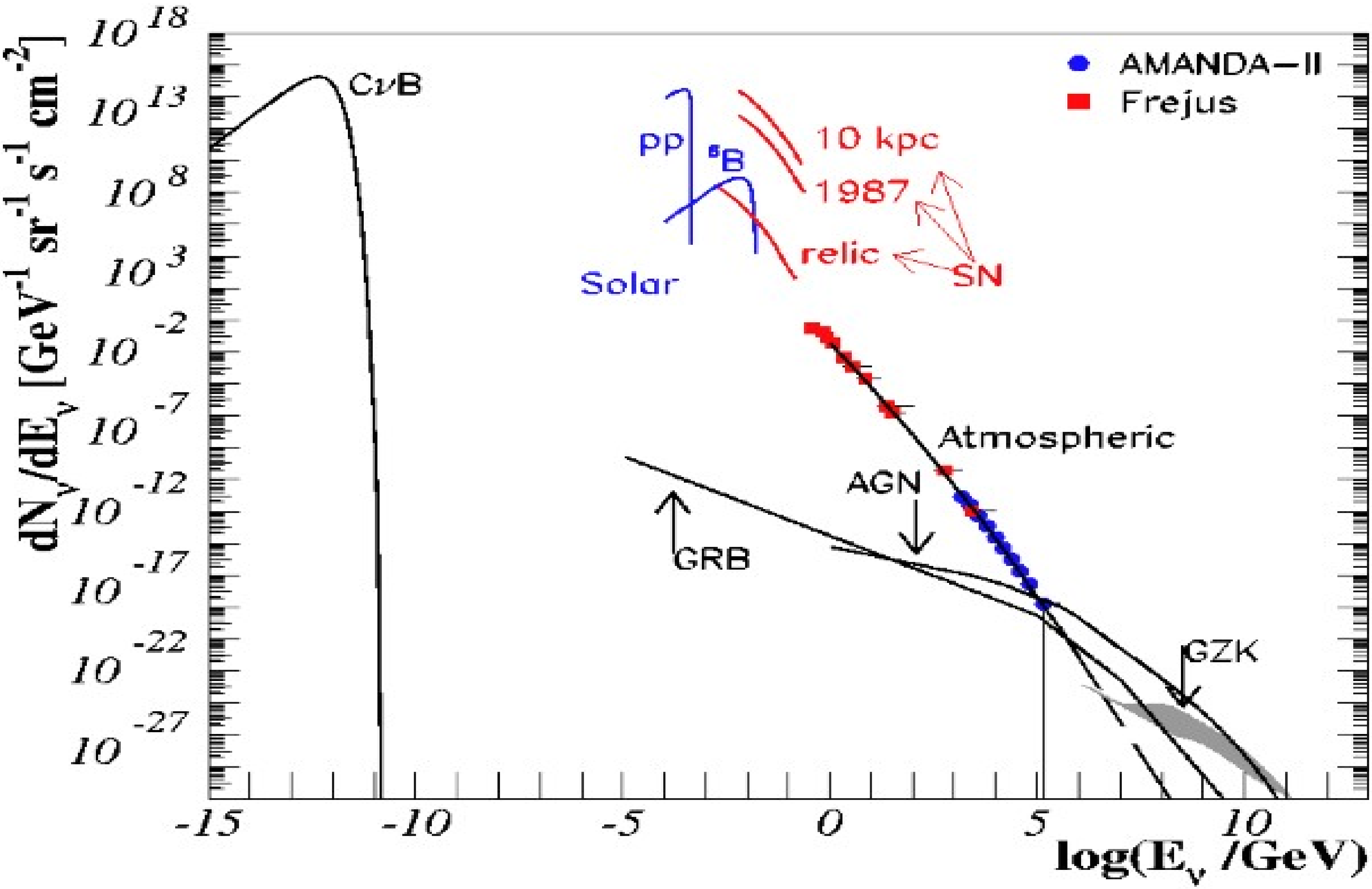

UHE Cosmic rays



# DIFFUSE PHOTON BACKGROUND

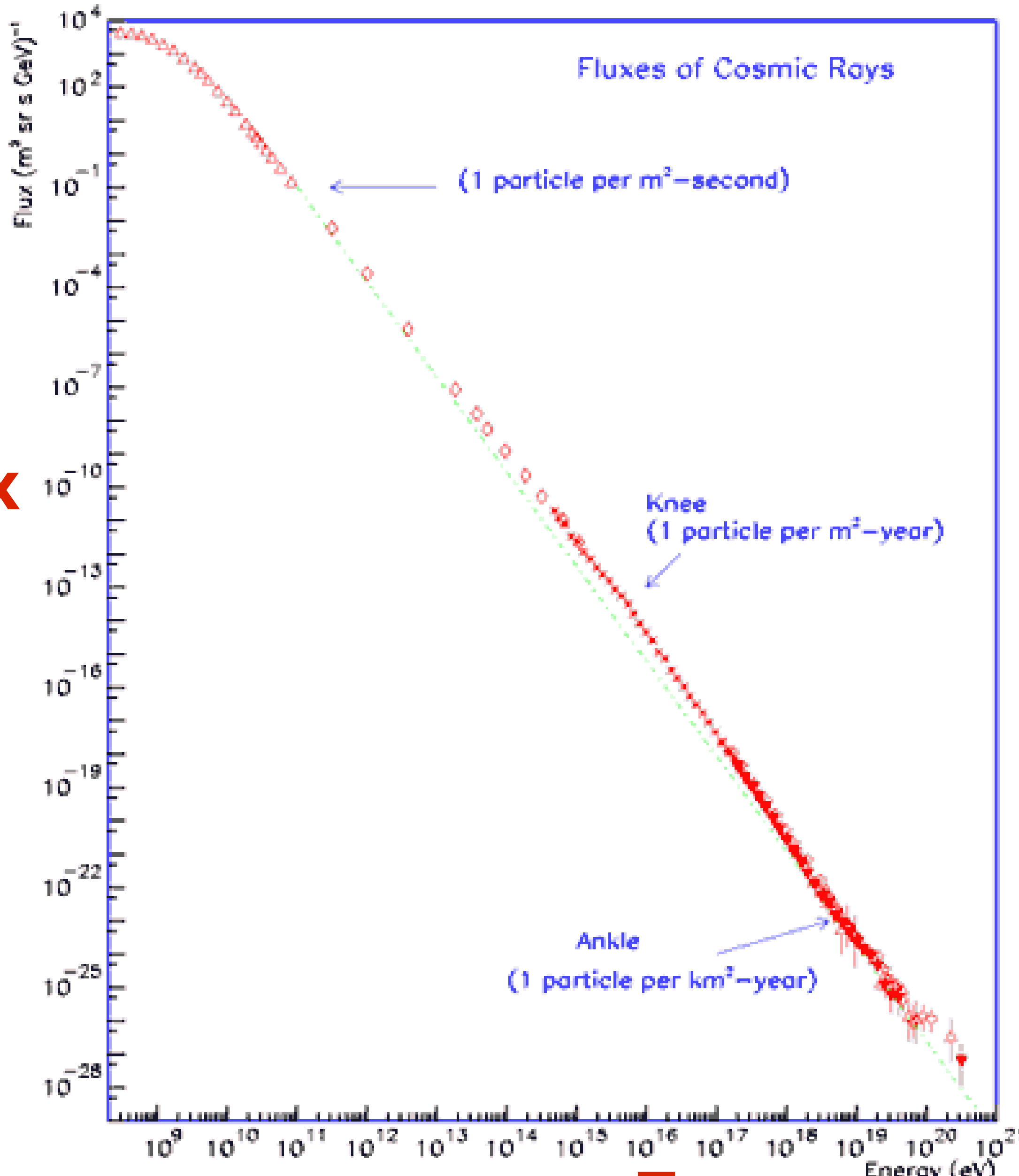


# THE NEUTRINO SKY



# COSMIC RAY SPECTRUM

flux



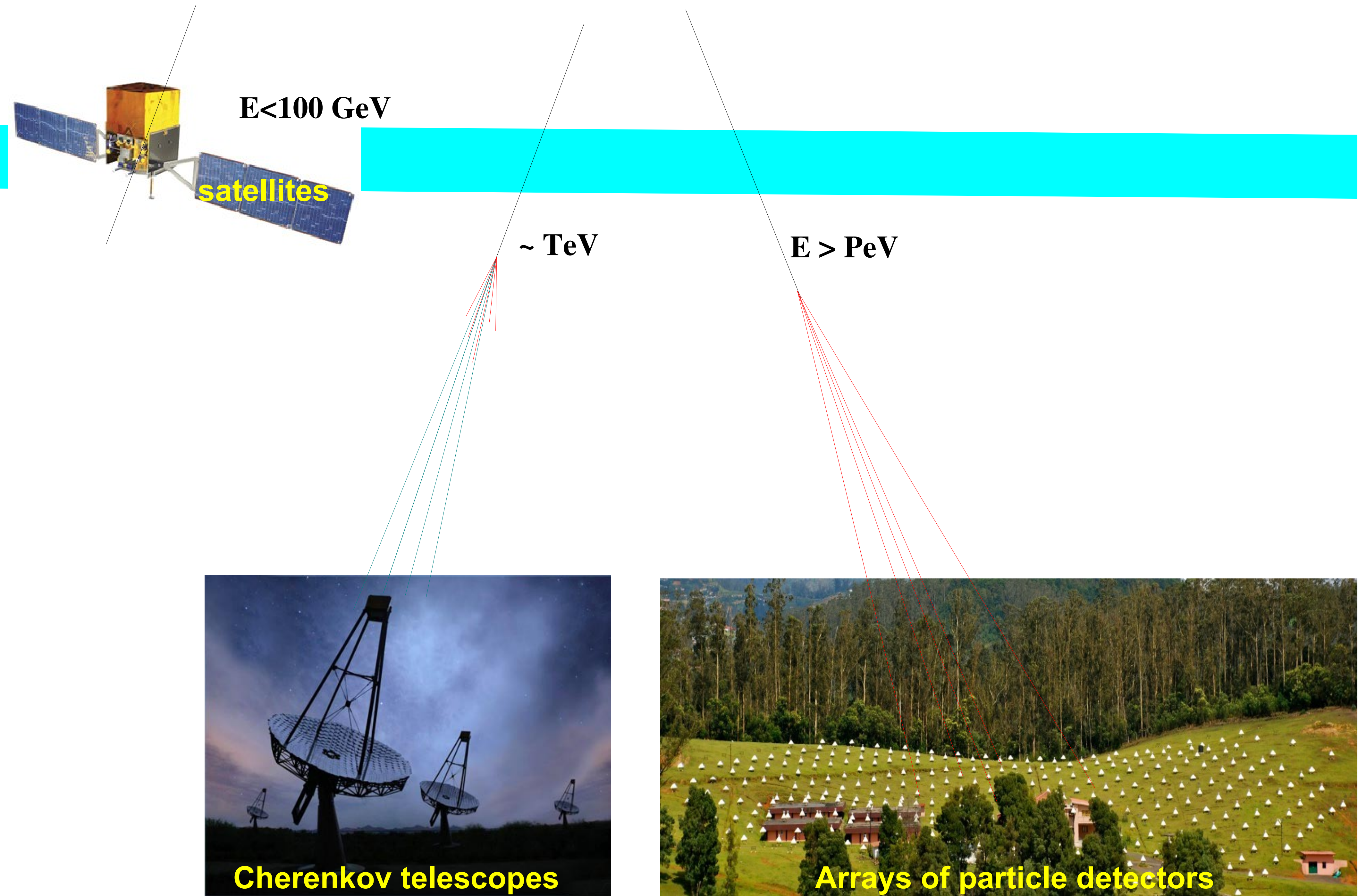

Energy

**Power law flux → stochastic (Fermi) acceleration in shocks**

**Small fractional energy gain after each shock crossing →**

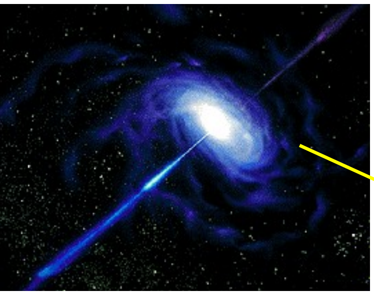
$$\frac{dN}{dE} \sim E^{-\alpha} \quad with\ \alpha \simeq 2-2.4$$

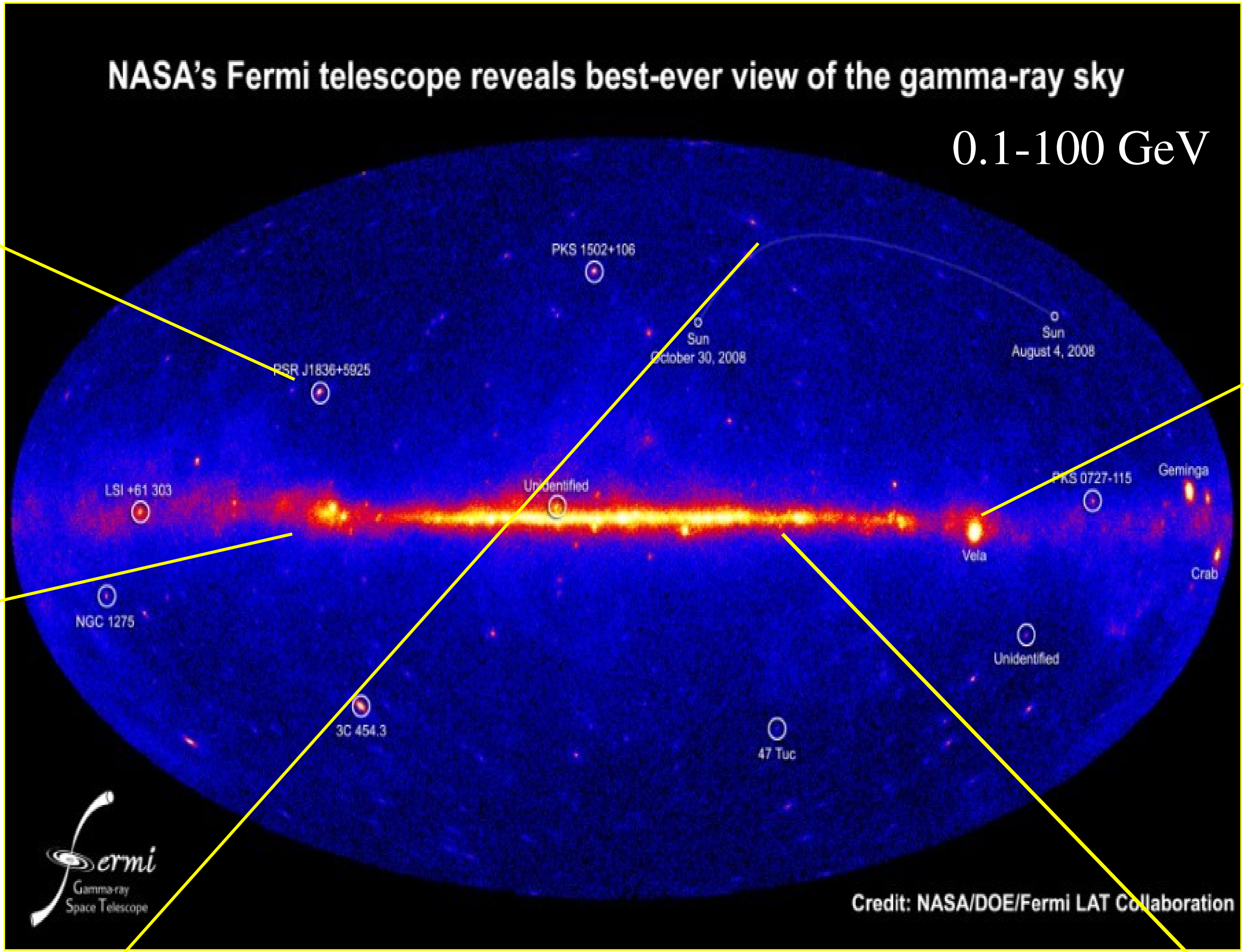
# TYPES OF COSMIC RAY DETECTORS



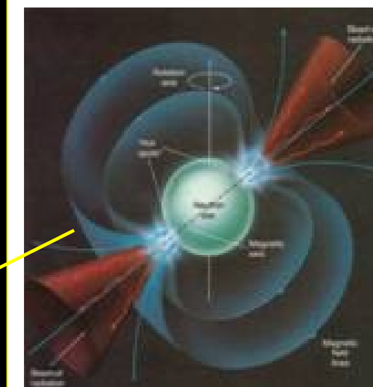
# Examples of powerful astrophysical Objects/potential CR accelerators

**AGN**

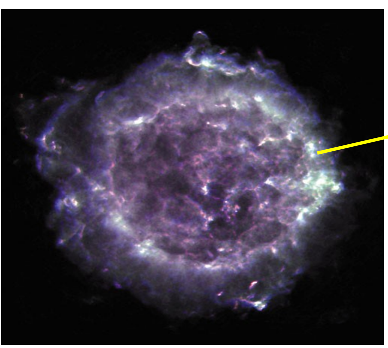




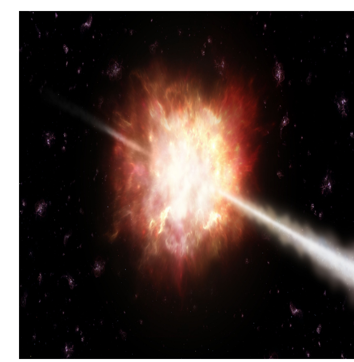

**Pulsar**



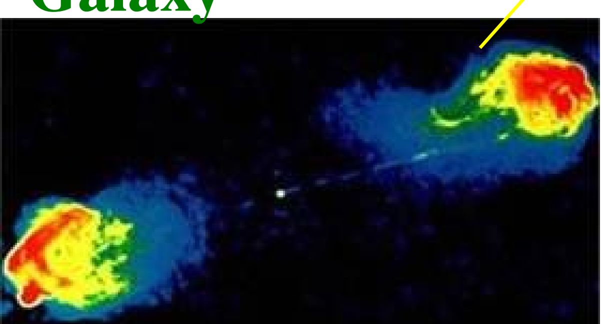
**SNR**



**GRB**



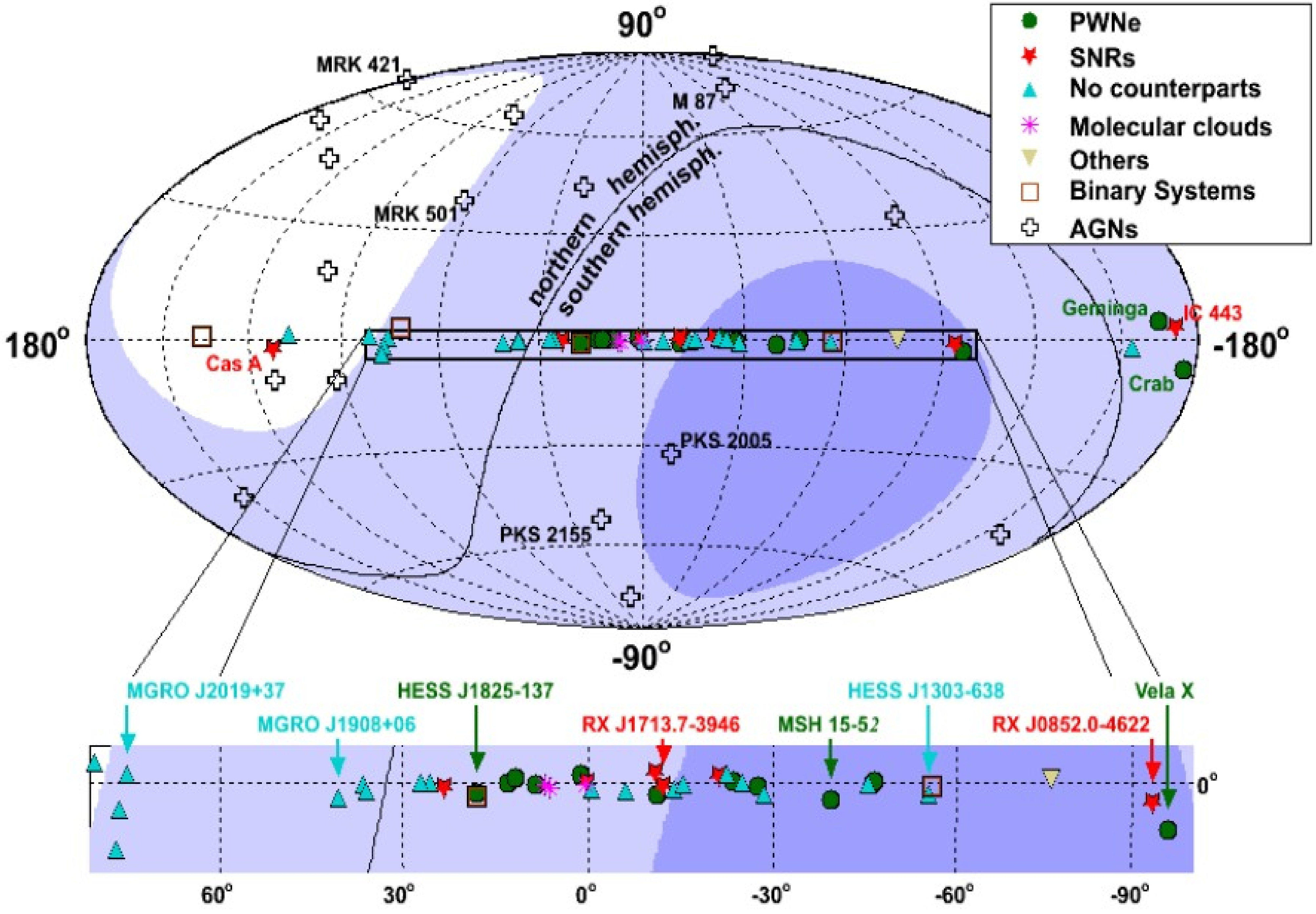
**Radio Galaxy**



**Colliding galaxies**

**Diffuse emission**

# TeV γ Astrophysical Sources



# Discriminating leptonic vs. hadronic scenarios

## (a way to know if protons are indeed accelerated in SNR)

**Brems:** $e + gas \rightarrow \gamma + \ldots$ **Synch:** $e + Bfield \rightarrow e + Xray$ **IC:** $e + Xray \rightarrow \gamma + e$

**Hadronic:** $CR + \gamma\,(p) \rightarrow \pi + X$ $\pi^0 \rightarrow \gamma\gamma\,,\ \pi^- \rightarrow e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$

## e.g. CasA γ spectrum

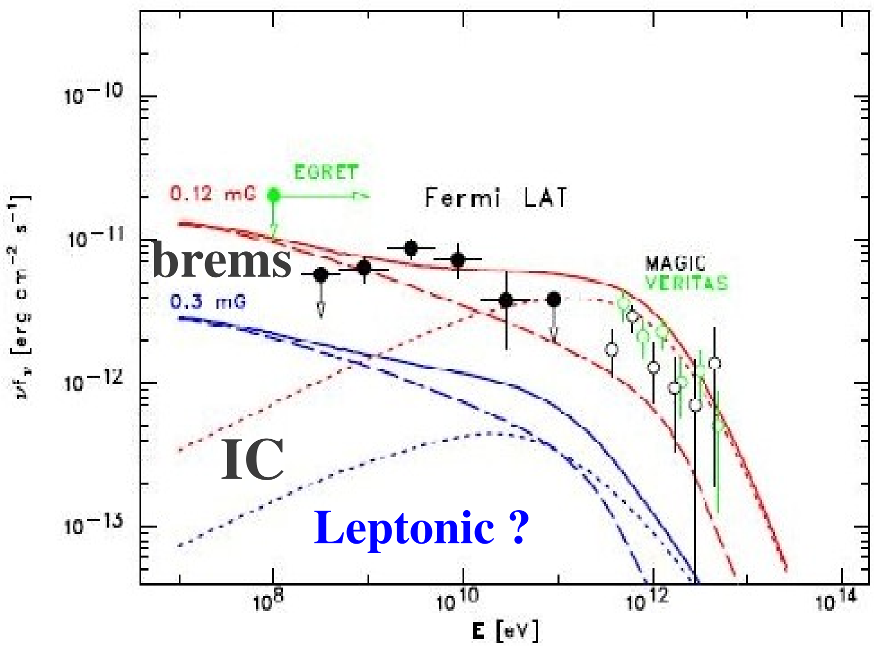



Fig. 3.— Energy spectrum of Cas A in a leptonic emission model. Shown is the Ferr
detected emission (filled circles) in comparison to the energy spectra detected by M
(black open circles; Albert et al. 2007) and VERITAS (green open circles; Humensky

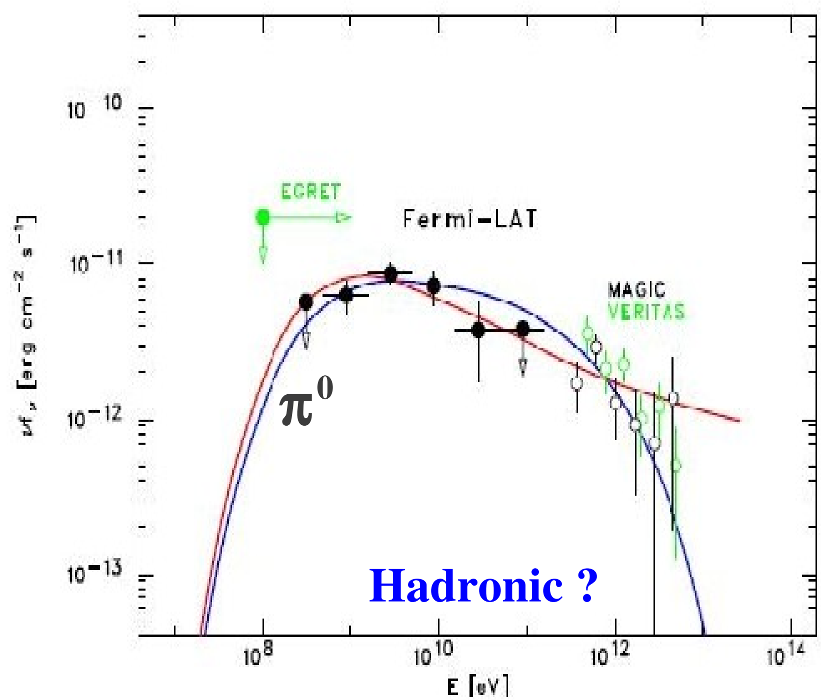
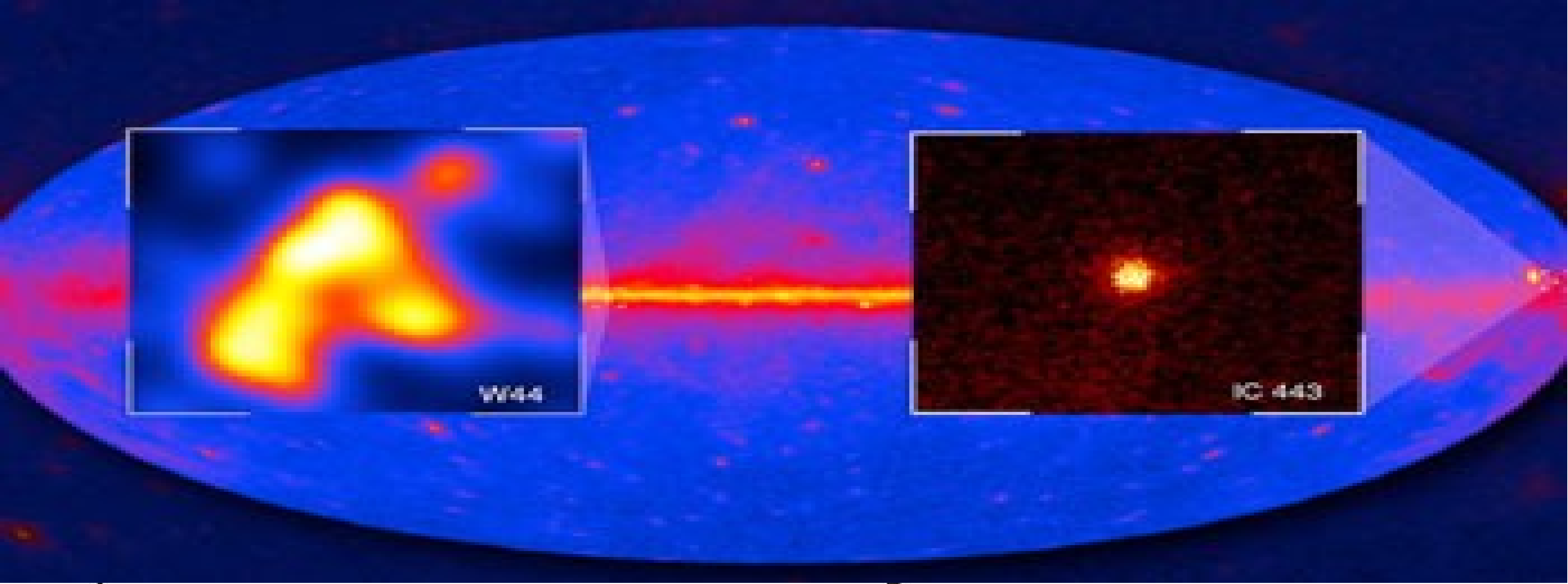
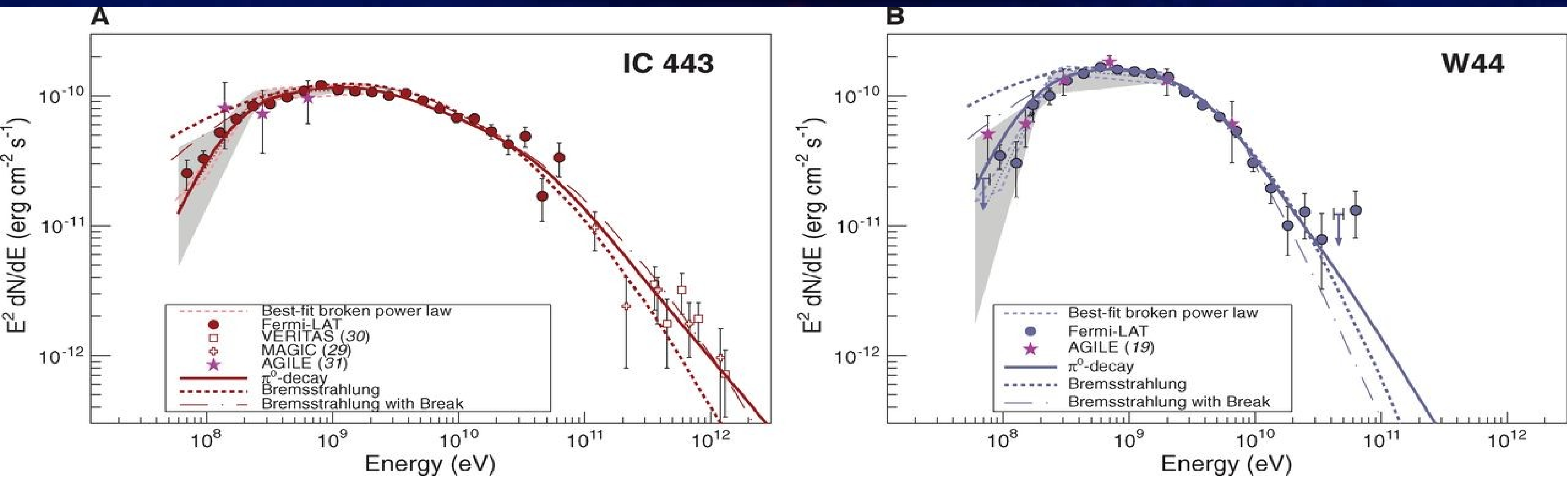



Fig. 4.— Same as Fig. 3 but in a hadronic emission model. Shown are $\pi^0$-decay spectra for

**Often inconclusive, observation of neutrinos would be unambiguous!**



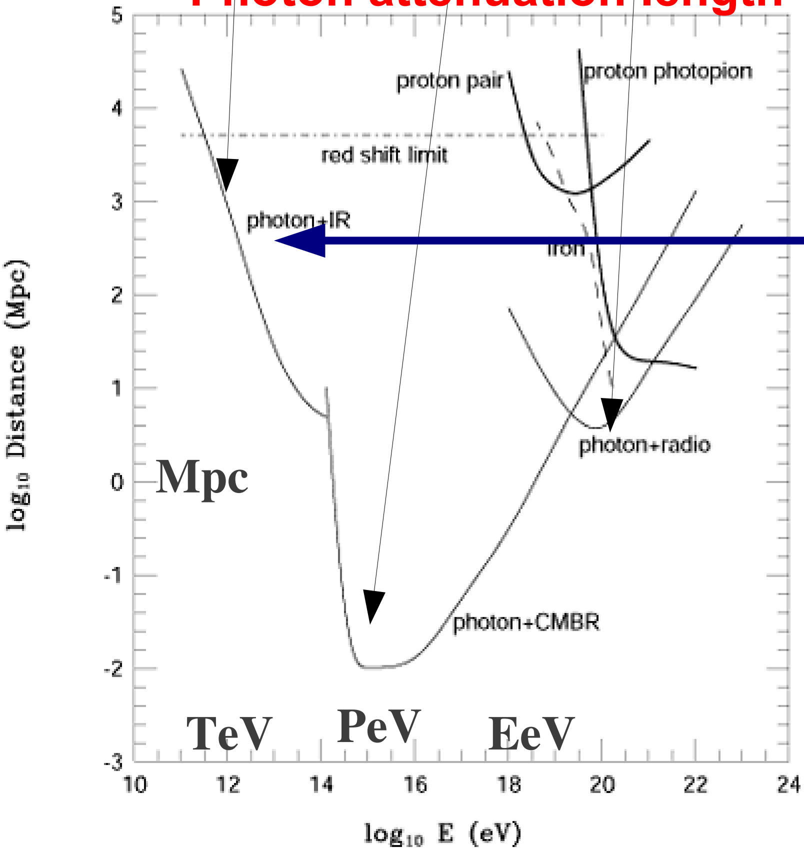




**FERMI found 2 SN remnants with clear signals of gammas from pion decays (low E supp.)**
**Proton acceleration in SuperNovae to beyond 10 TeV proved, associated ν flux expected**

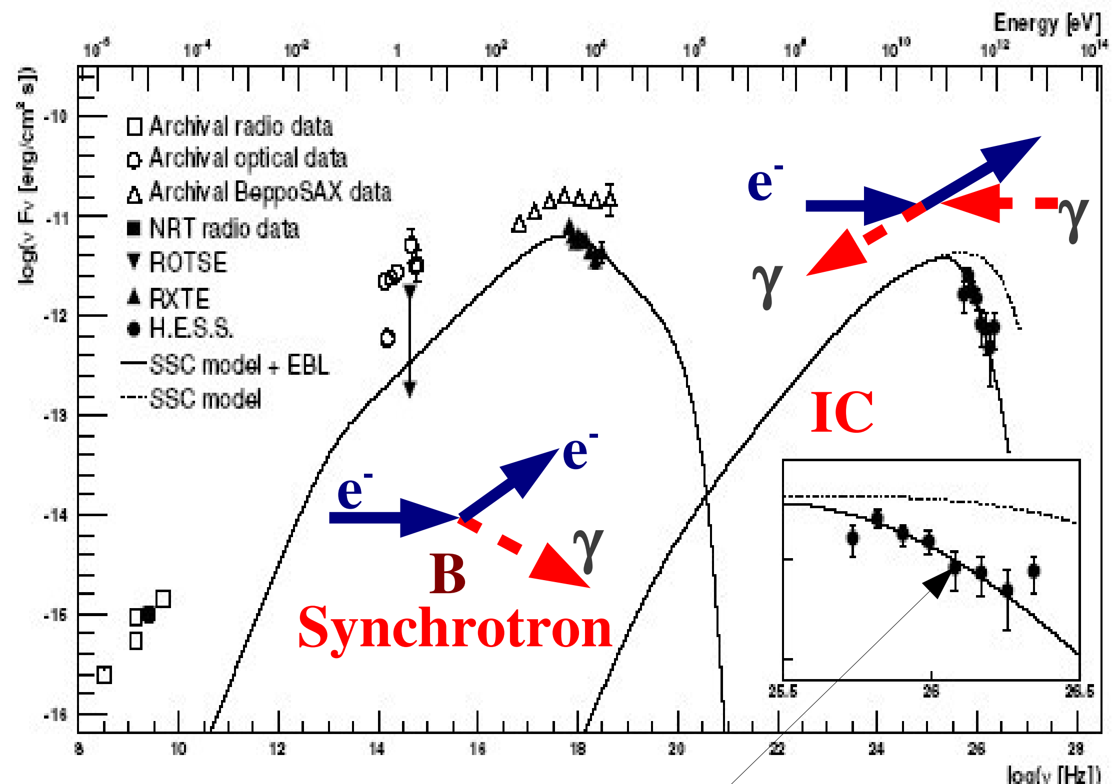
2013, Science, 339, 807

## Distant γ sources are strongly attenuated by background photons (starlight, CMB, radio, ...): $\gamma\gamma \rightarrow e^{+}e^{-}$

**Photon attenuation length**



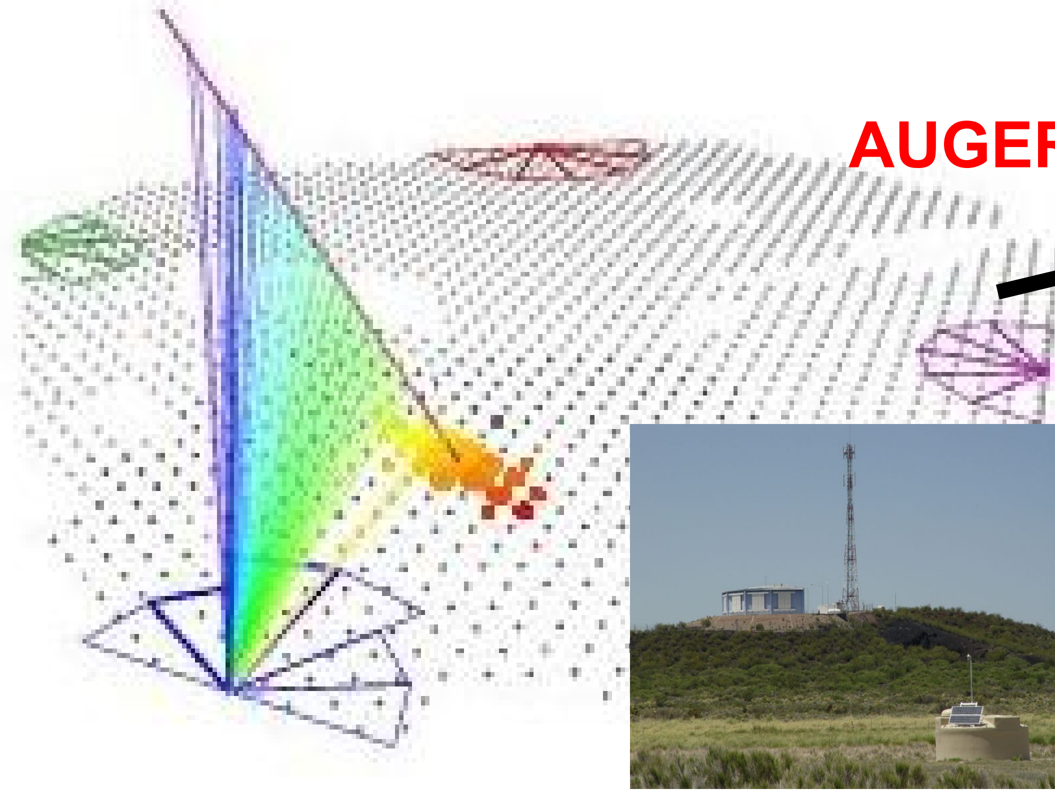

**z=0.165 BLLac (H2356-309 )**



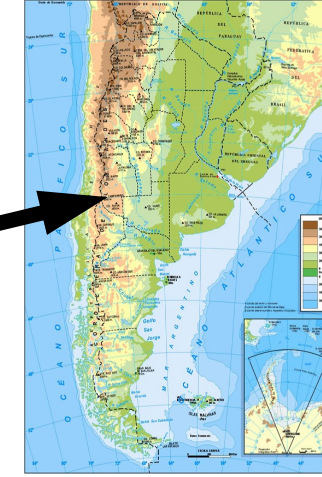

Can even measure IR background from observed attenuation

**beyond few TeV, high redshift Universe is unobservable with photons**

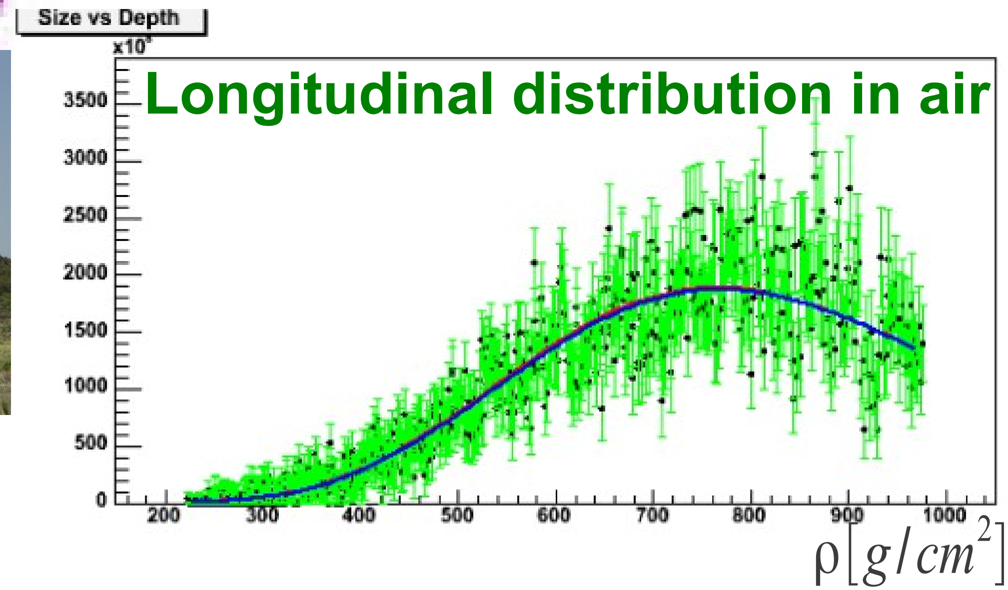
# CR AIR SHOWER DETECTORS



**AUGER, 3000 km$^2$**

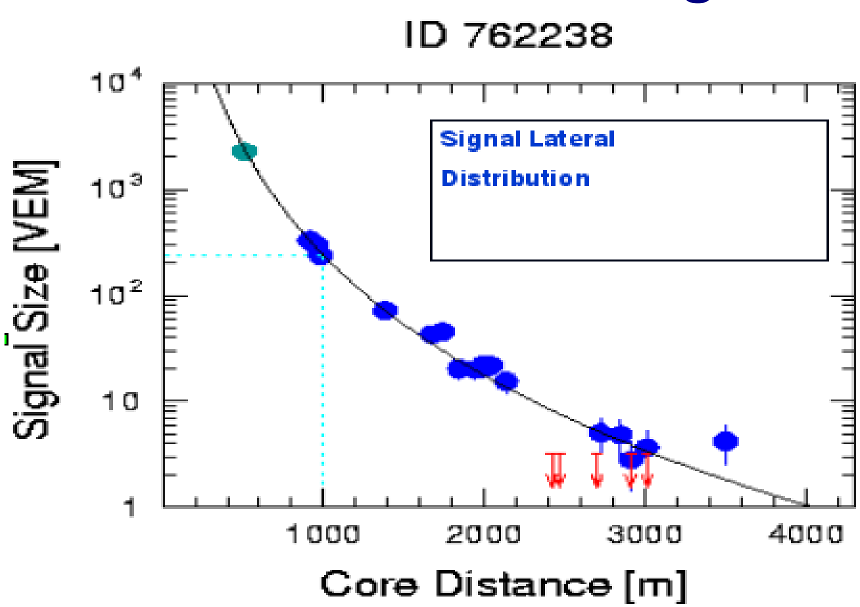


**Longitudinal distribution in air**



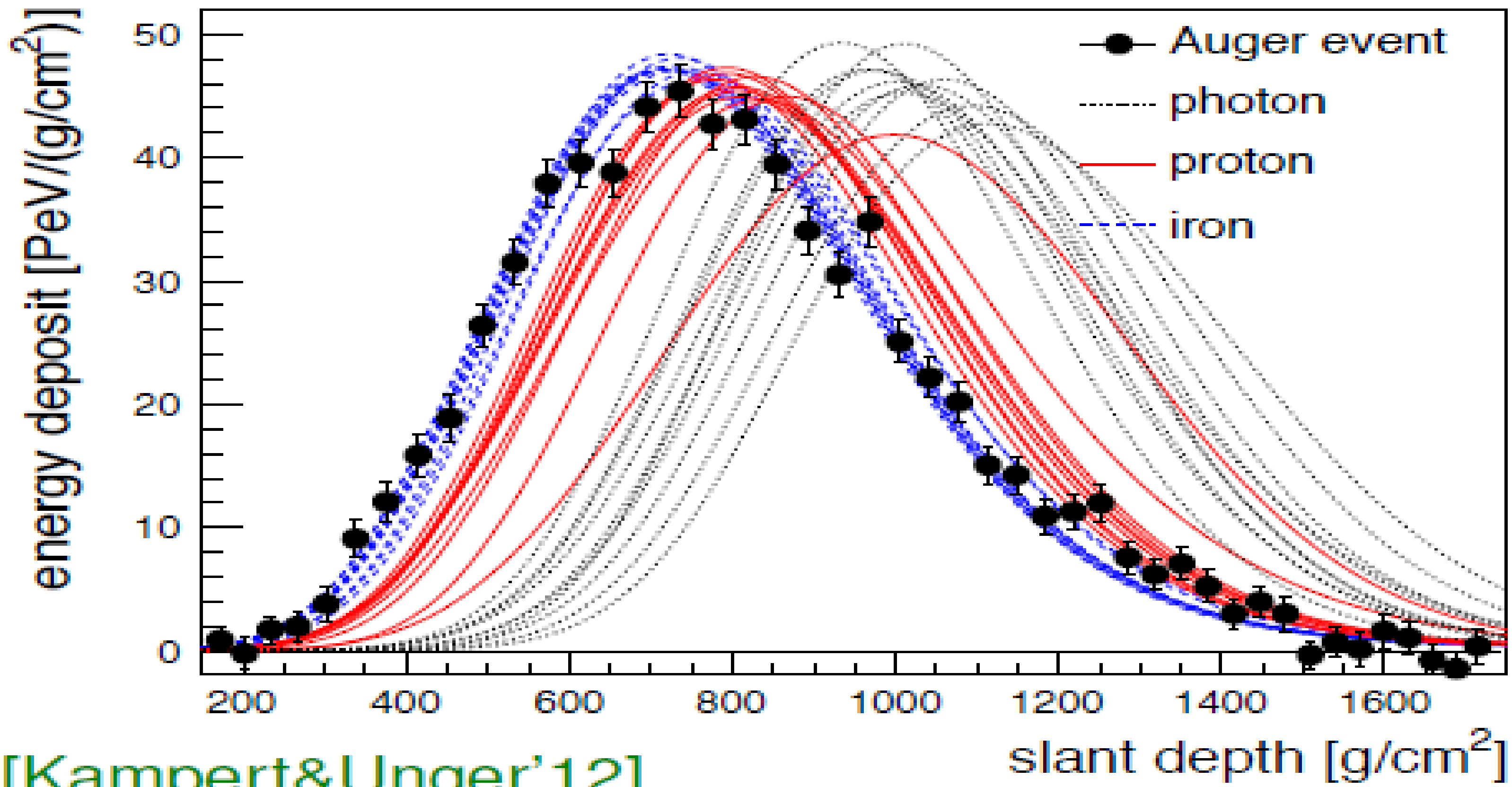

**(FD duty cycle ~15%)**

**Lateral distribution at ground**




**Measure Xmax**
**Energy calibration**
**angular resolution < 1°**

**(SD duty cycle ~100%)**

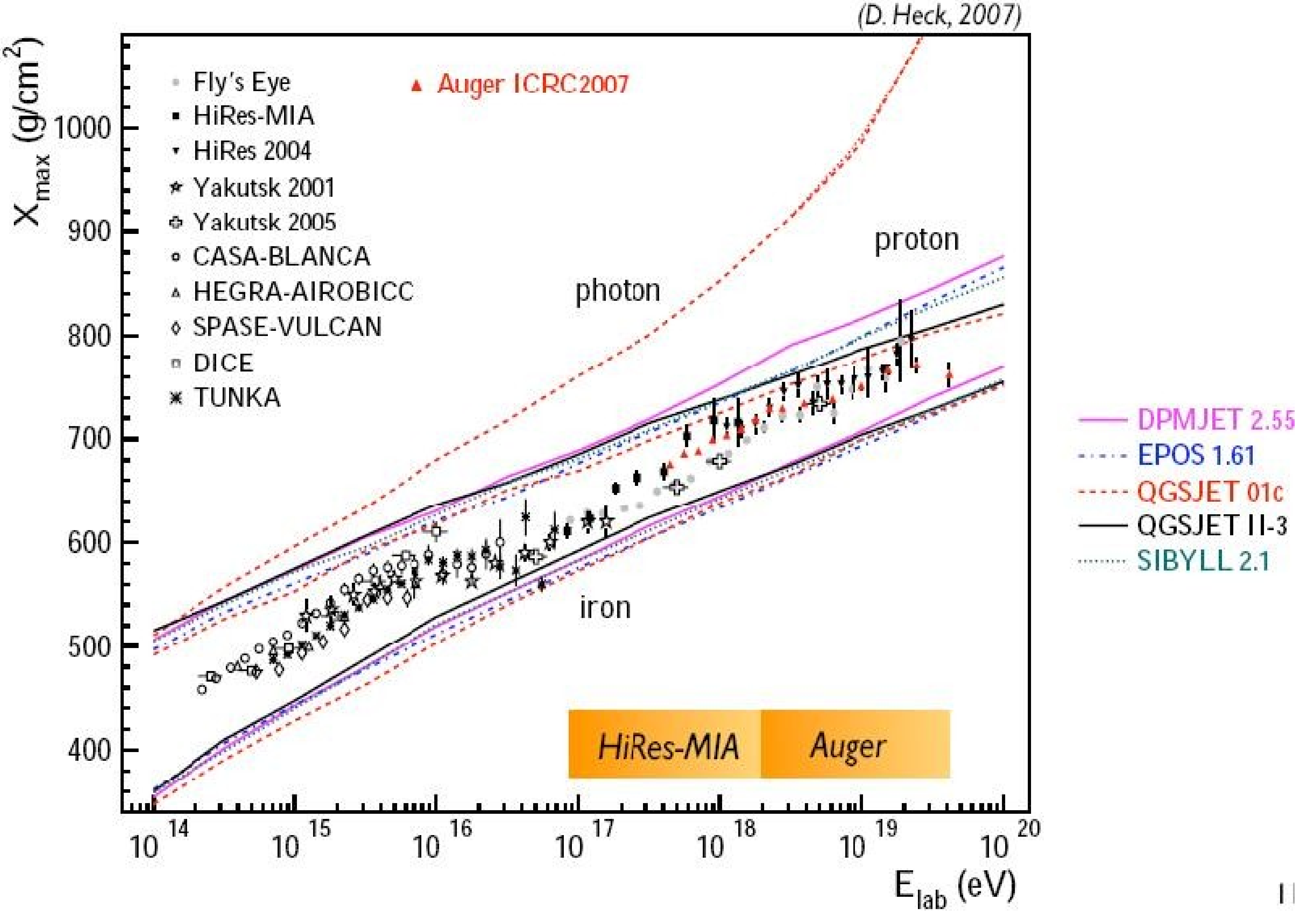



$n_{tot}$

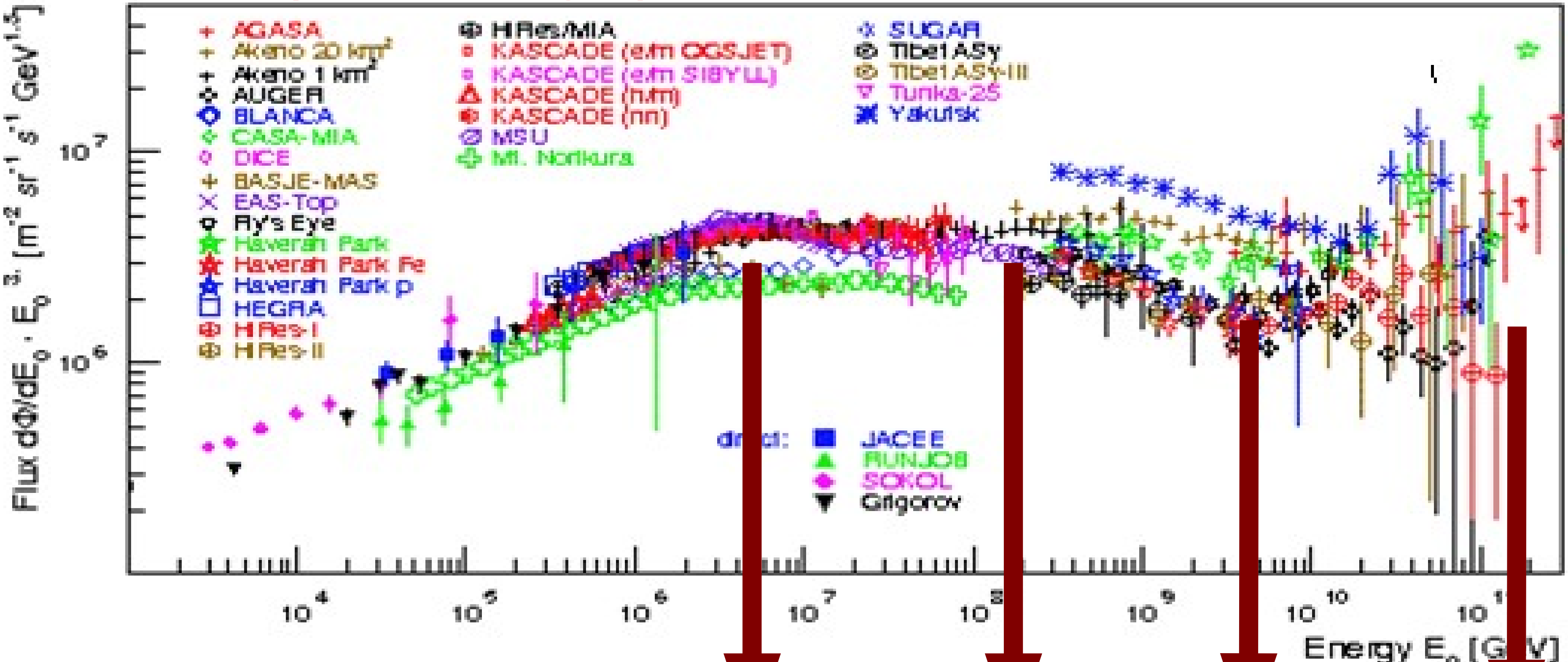
[Kampert&Unger'12]

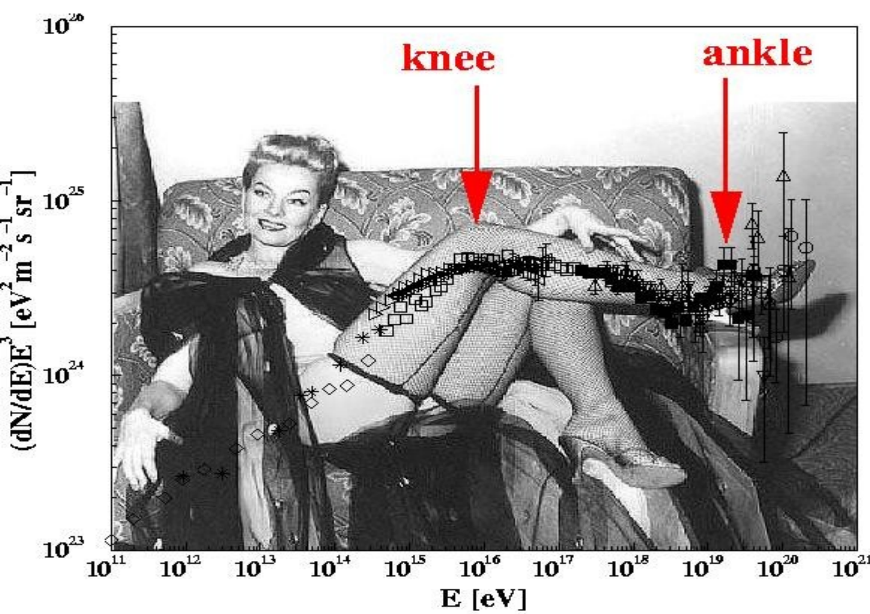
**Photons produce deep showers**
**nuclei of mass A behave as p with with E/A → shallower showers**

# COMPOSITION FROM $X_{max}$



# $E^3$ x FLUX (before Auger)

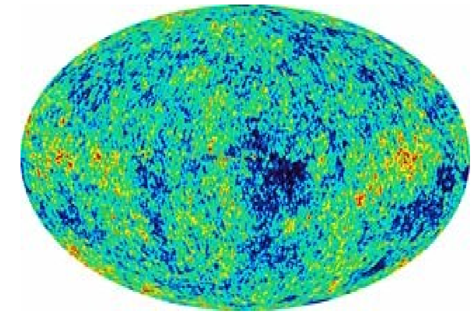


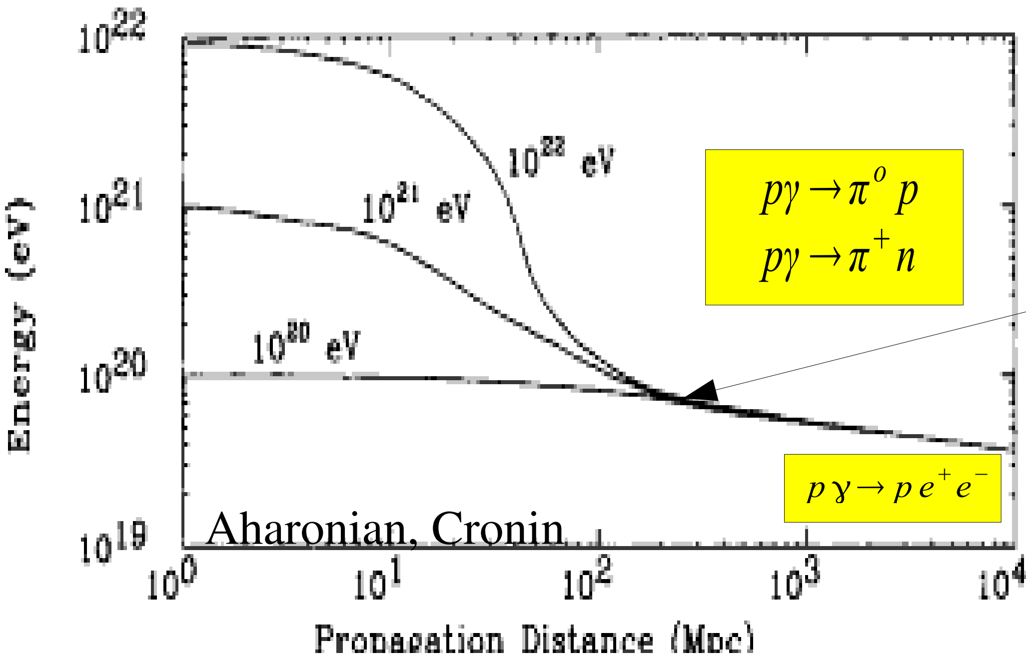




**knee** **2nd knee** **ankle** **GZK ?**

# the Greisen-Zatsepin-Kuzmin effect (1966)

**AT THE HIGHEST ENERGIES, PROTONS LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND**



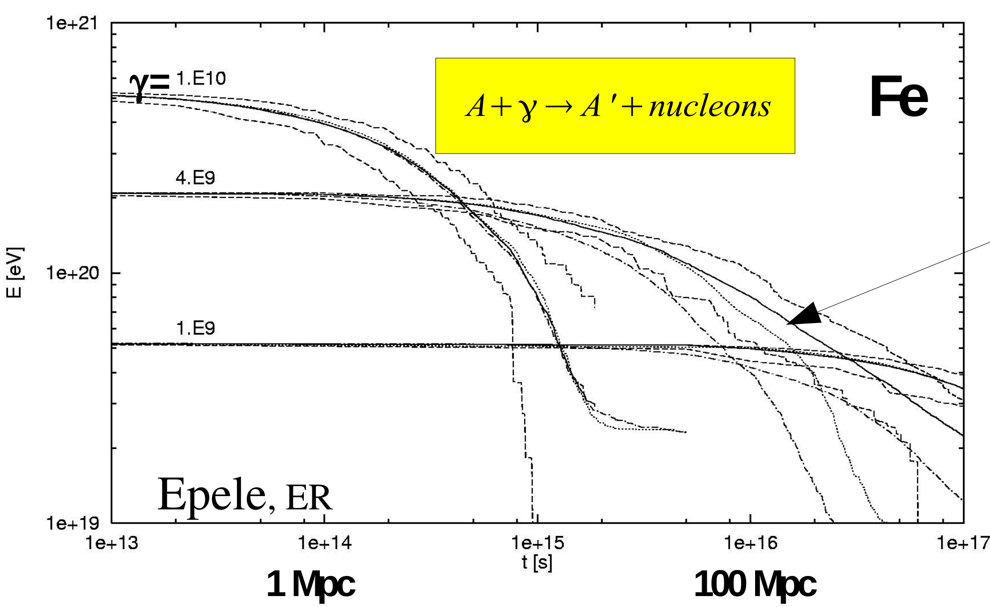



**PROTONS CAN NOT ARRIVE WITH E > 6x10[19] eV FROM D > 200 Mpc**

( $\pi^0$ produce GZK photons)

( $\pi^{\pm}$ produce cosmogenic neutrinos)

(Berezinsky & Zatsepin 69)

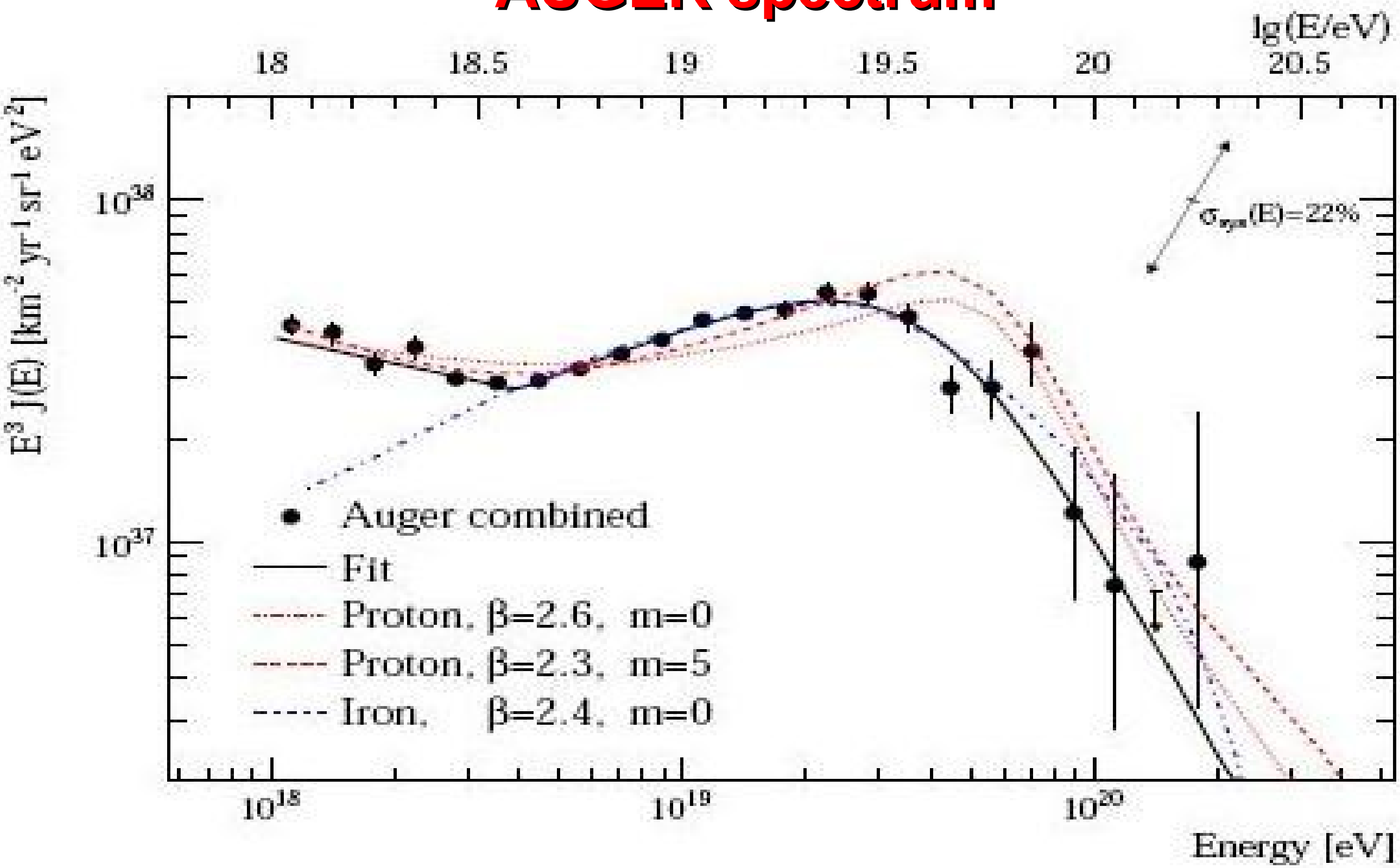



**For Fe nuclei: after ~ 200 Mpc the leading fragment has E < 6x10[19] eV**

**ligther nuclei get disintegrated on shorter distances**

(fewer neutrinos produced)

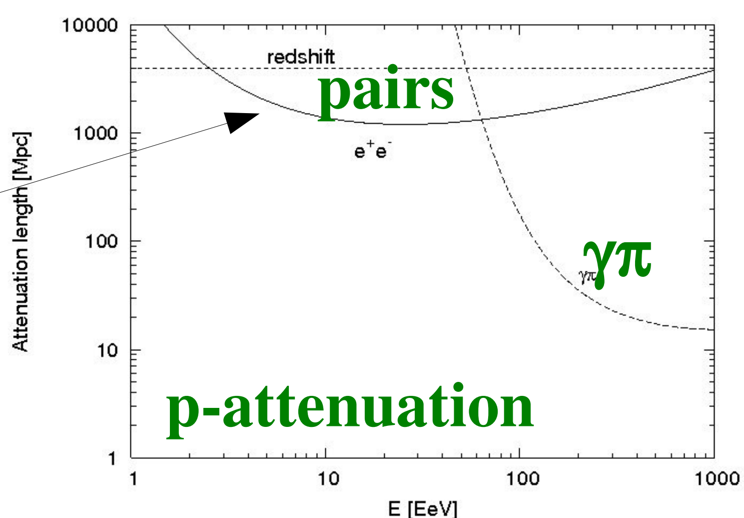
# AUGER spectrum




**Ankle:**

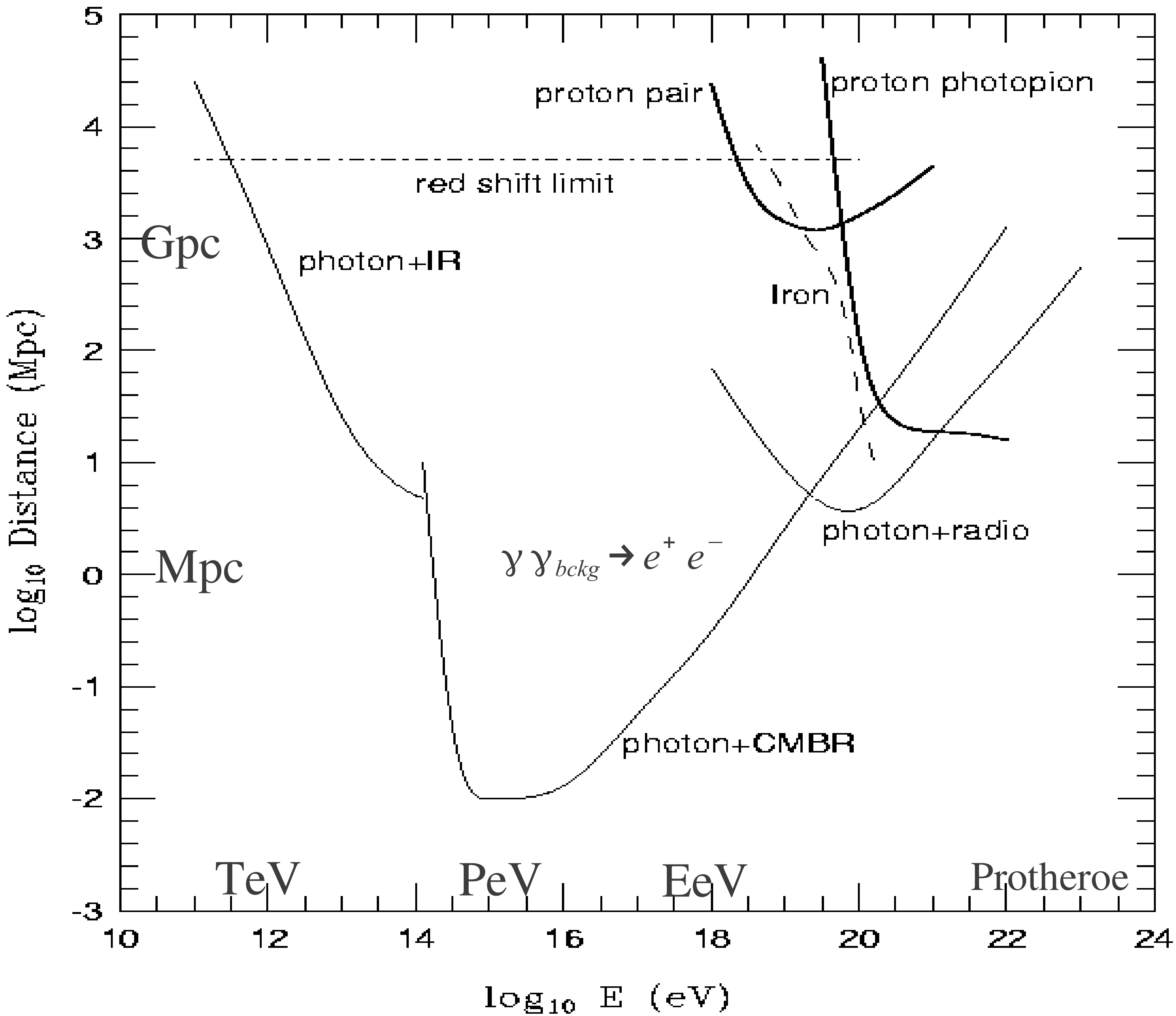
**1- Galactic–extragalactic transition? (ankle model)**

**2 - or $e^+e^-$ dip in Xgal protons? (dip model)**




**GZK: proton or Fe suppression ?**
**(and/or exhaustion of sources?)**

# Attenuation lengths vs E

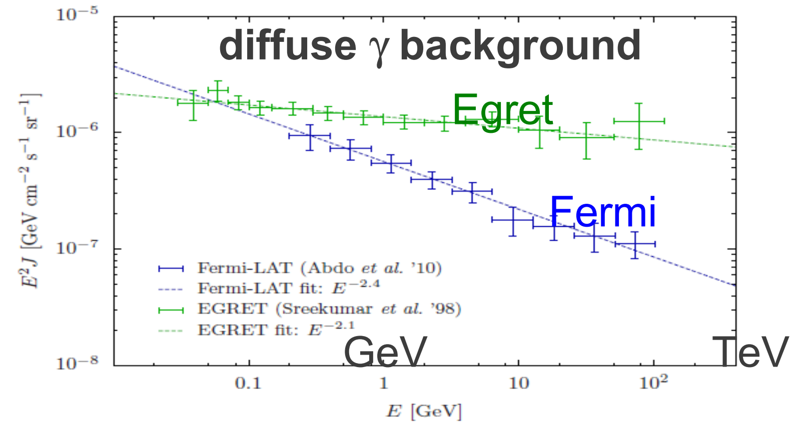


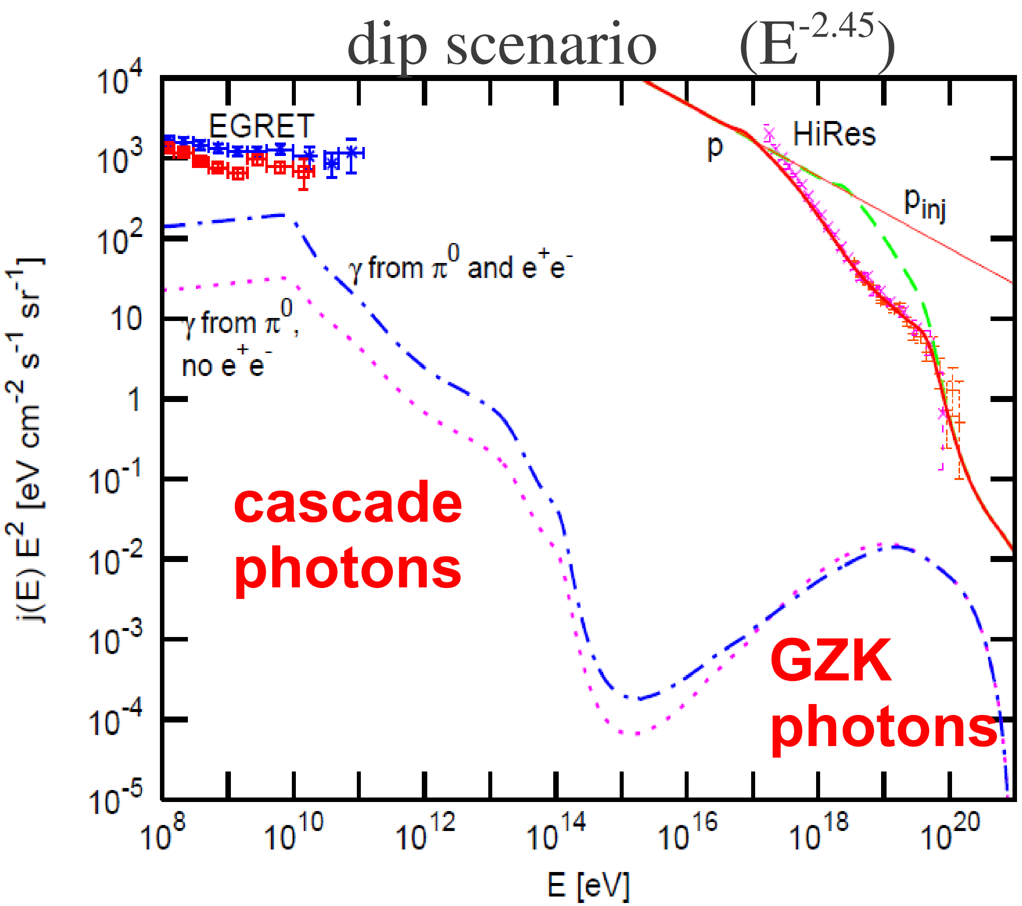
# ASSOCIATED PHOTON FLUXES

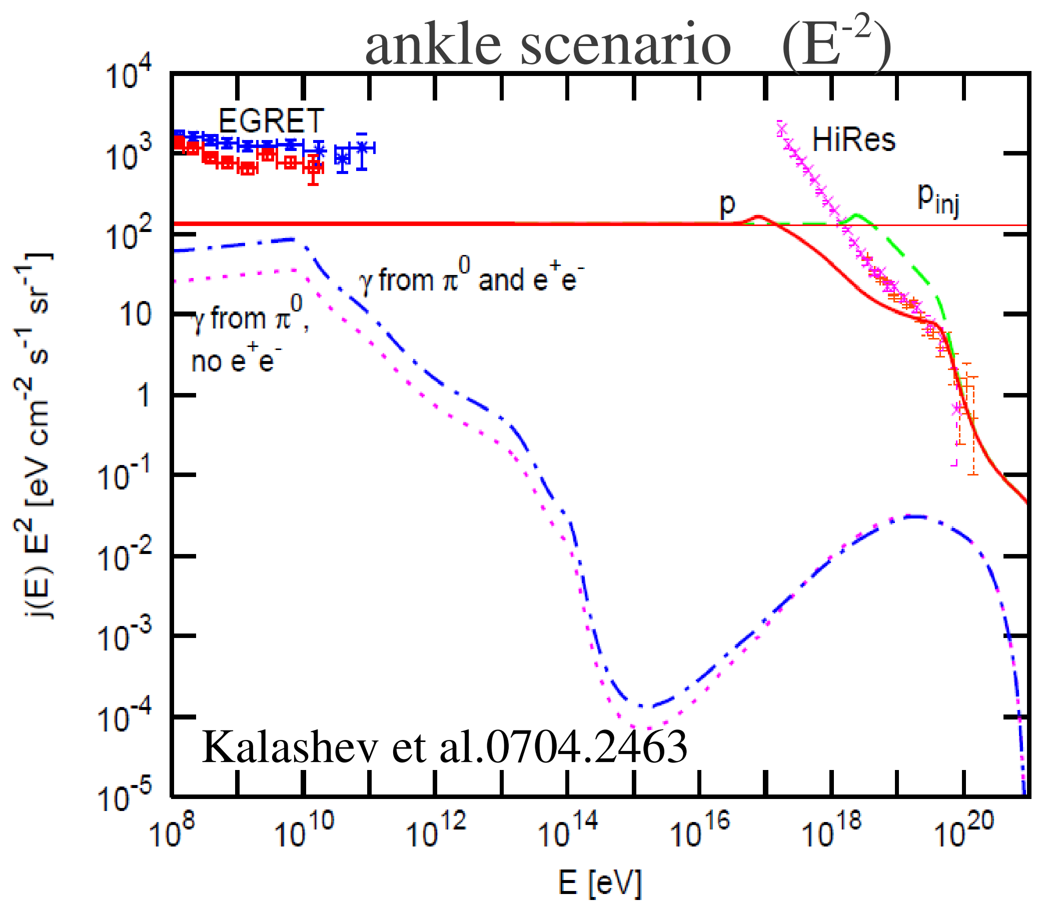
$p\,\gamma \rightarrow \pi^0\, p$ $\qquad \pi^0 \rightarrow \gamma\,\gamma$ $\qquad p\,\gamma \rightarrow p\, e^+ e^-$

$\gamma\,\gamma_{bckg} \rightarrow e^+ e^-$ $\qquad e\,\gamma_{bckg} \rightarrow e\,\gamma$

Cascades down to GeV-TeV



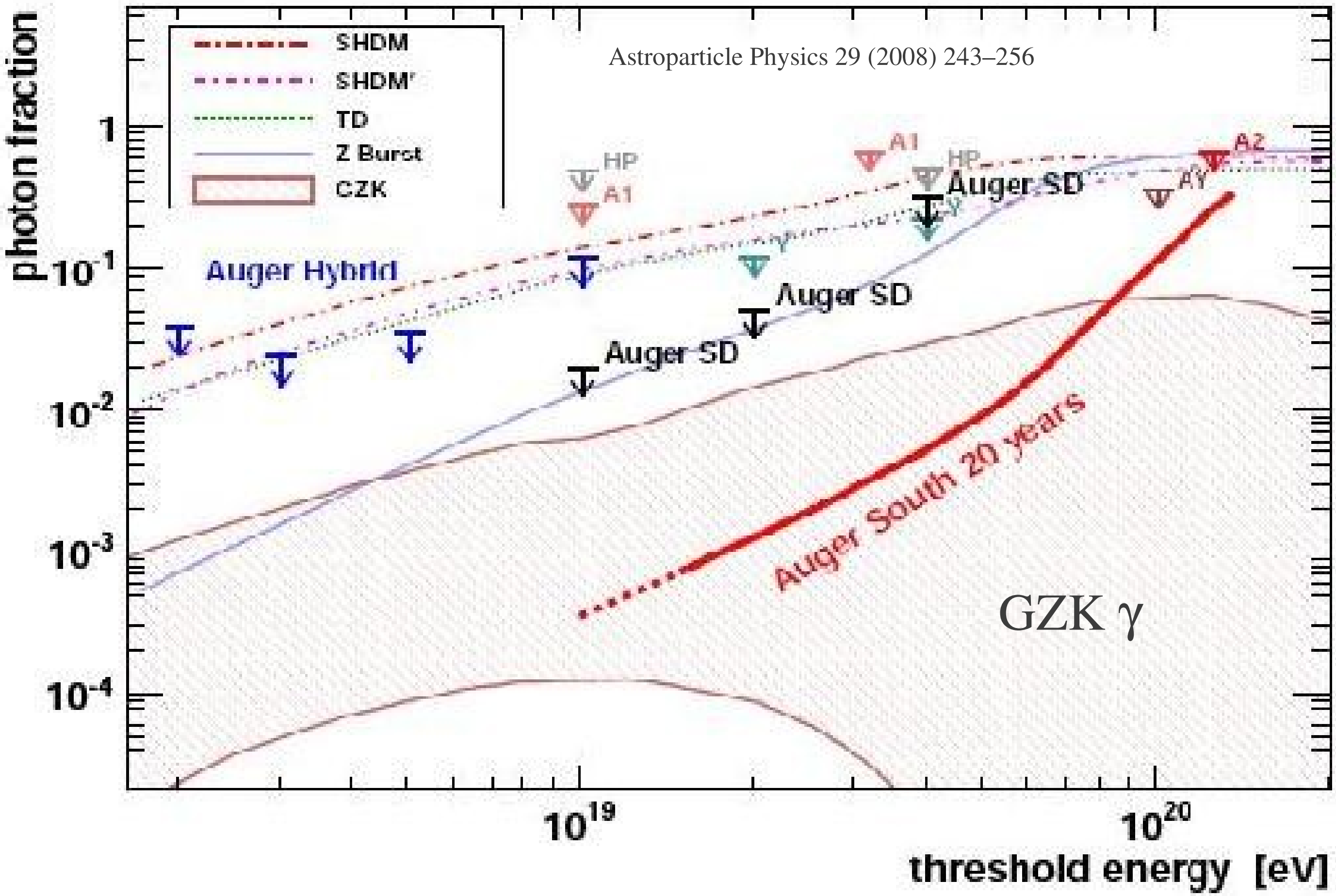




- **dip models lead to significant cascade fluxes from pair production**
- **ankle models (harder fluxes) lead to larger GZK photon fluxes**

# AUGER SD photon bound

**photon showers are quite penetrating (small curvature radius) and lack muons (electromagnetic signal in detectors have long rise times)**
**→ essentially no UHE photon candidates observed**



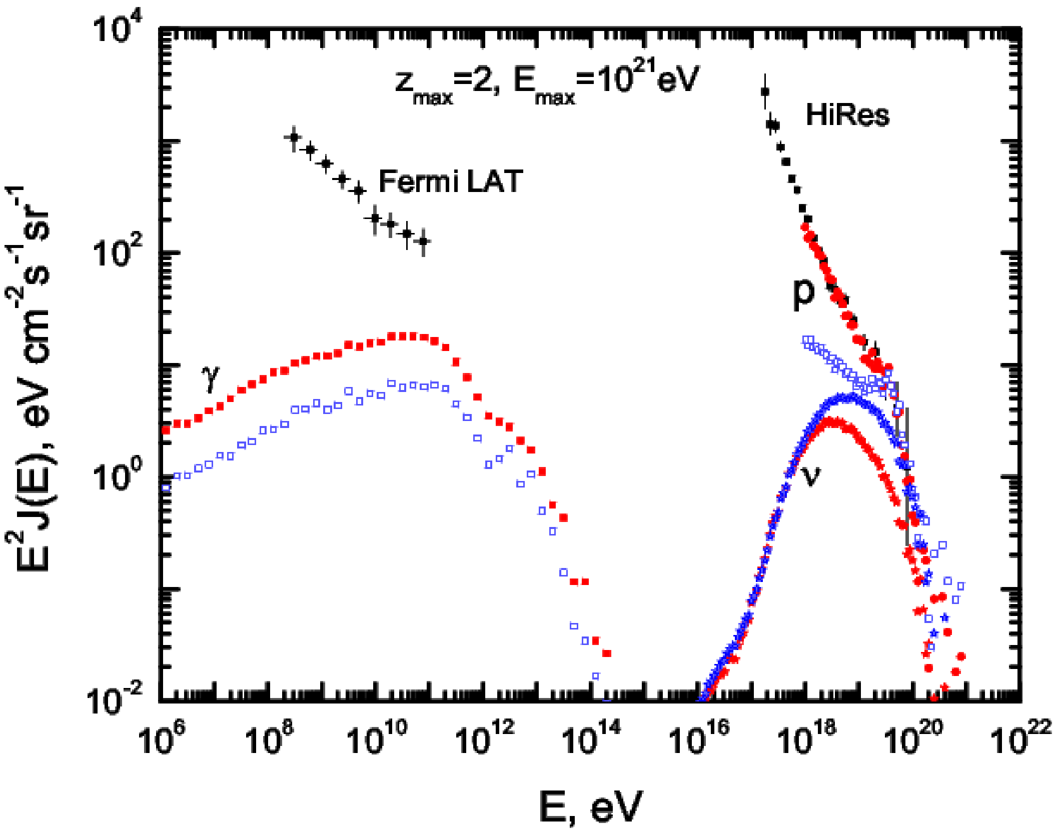

**photon fraction:**
**< 2% at E > 10 EeV**

**< 31% at E > 40 EeV**

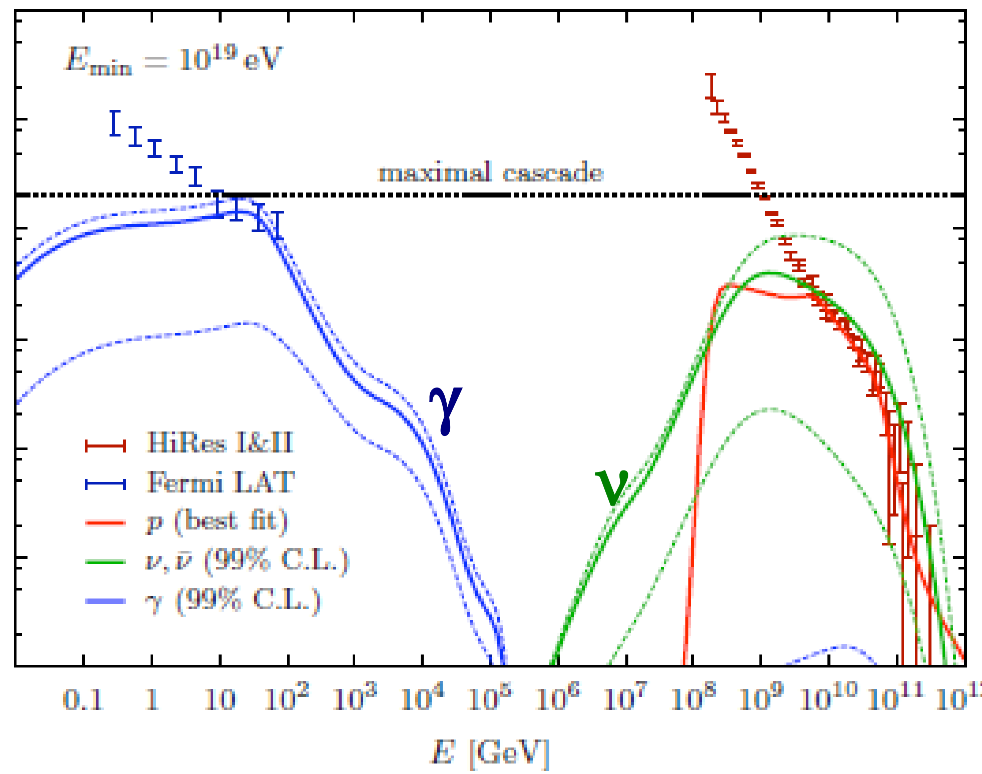
**excludes most top-down models, but still above optimistic GZK photons**

# COSMOGENIC NEUTRINO FLUXES:

Berezinsky et al., arXiv:1003.1496



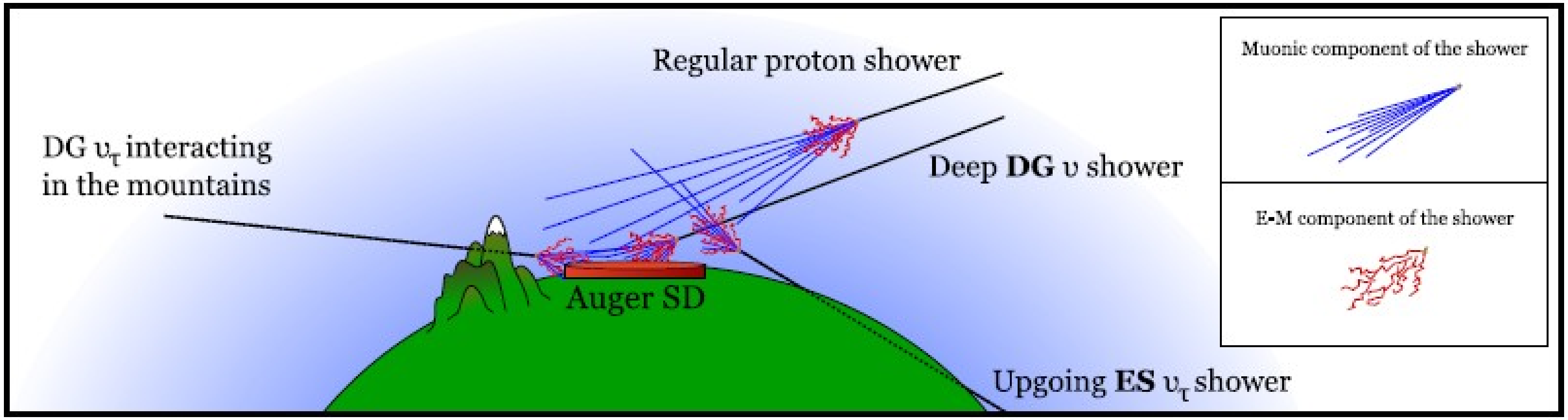

Ahlers et al., arXiv:1005.2620



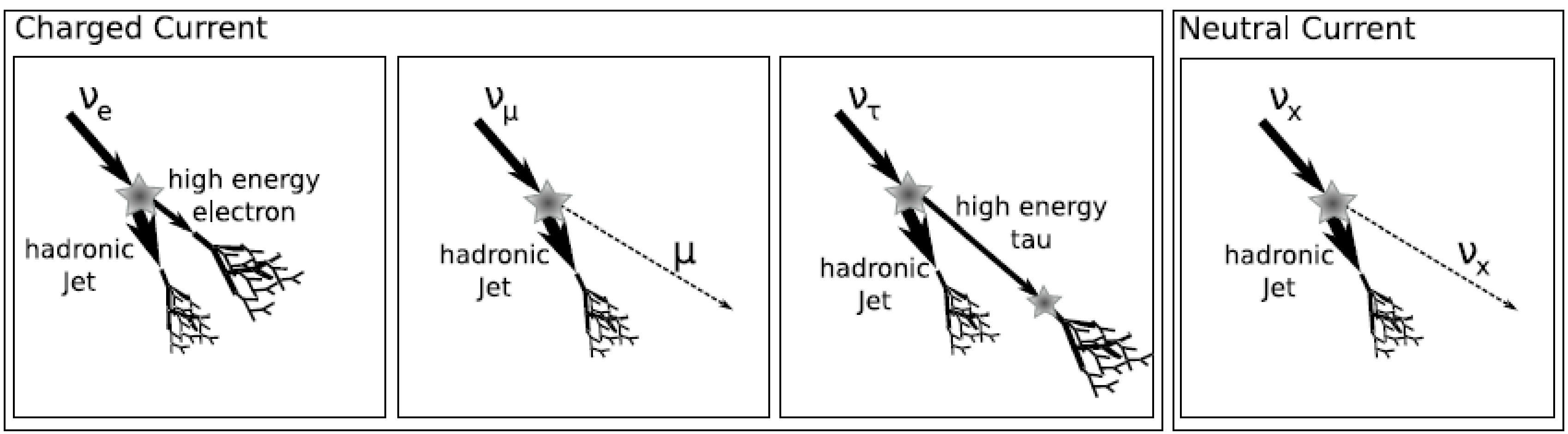

- ankle models (harder fluxes) lead to larger cosmogenic neutrino fluxes than dip models

- fluxes at EeV could be comparable to CR fluxes, but cross section tiny (~ 10 nb)
→ probability of interacting in atmosphere small (~$10^{-5}$ for vertical)

# Neutrino detection in AUGER




**Only neutrinos can produce young horizontal showers**




**For downgoing showers: (assuming 1:1:1 flavor ratios)**

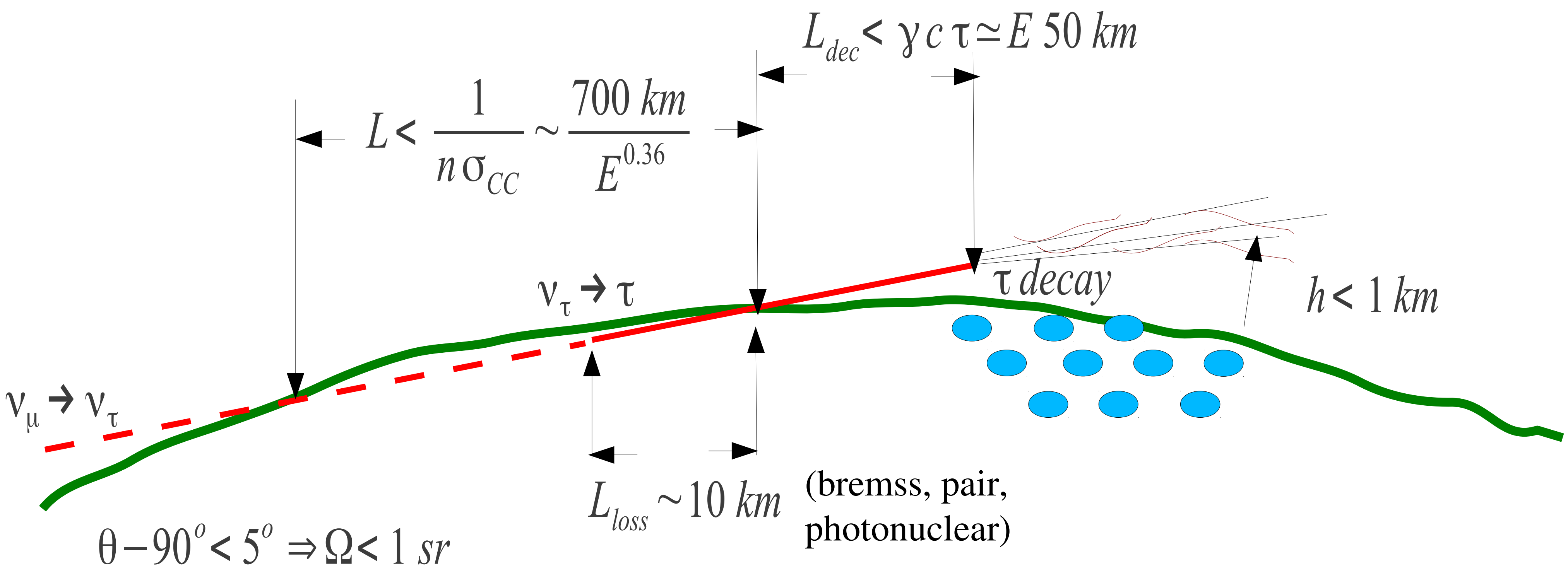
**38% from $\nu_e$, 18% from $\nu_\mu$, 29% from $\nu_\tau$ – air, 15% from $\nu_\tau$ – mountain**

**but Earth-skimming $\nu_\tau$ searches are more sensitive**

Fargion 2000,
Bertou et al '01
Feng et al. '02

# Up-going Earth-skimming $\nu_\tau$ showers

$$\sigma_{CC} \simeq 10^{-32}\, cm^2\, E^{0.36} \qquad (E\,[EeV])$$

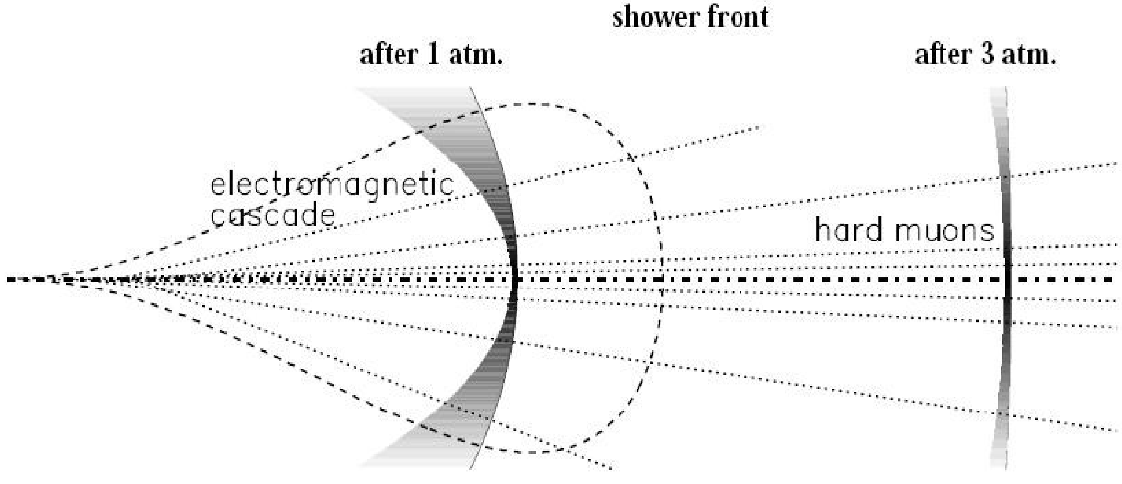


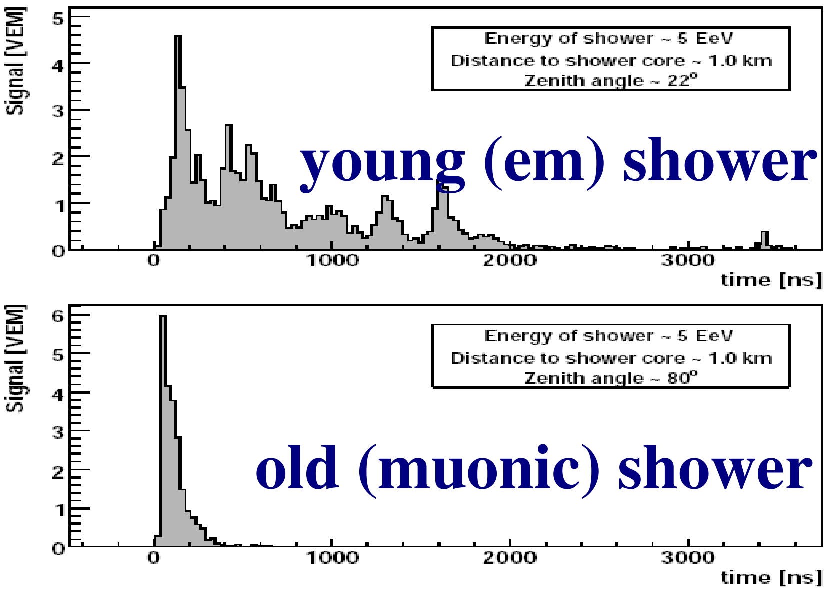

Probability of interacting
in the last 10 km ~ 0.01

→ Effective exposure ~ 0.1 km$^2$ sr
(c.f. ~ $10^4$ km$^2$ sr for UHECR)

# AUGER BOUNDS ON DIFFUSE NEUTRINO FLUX

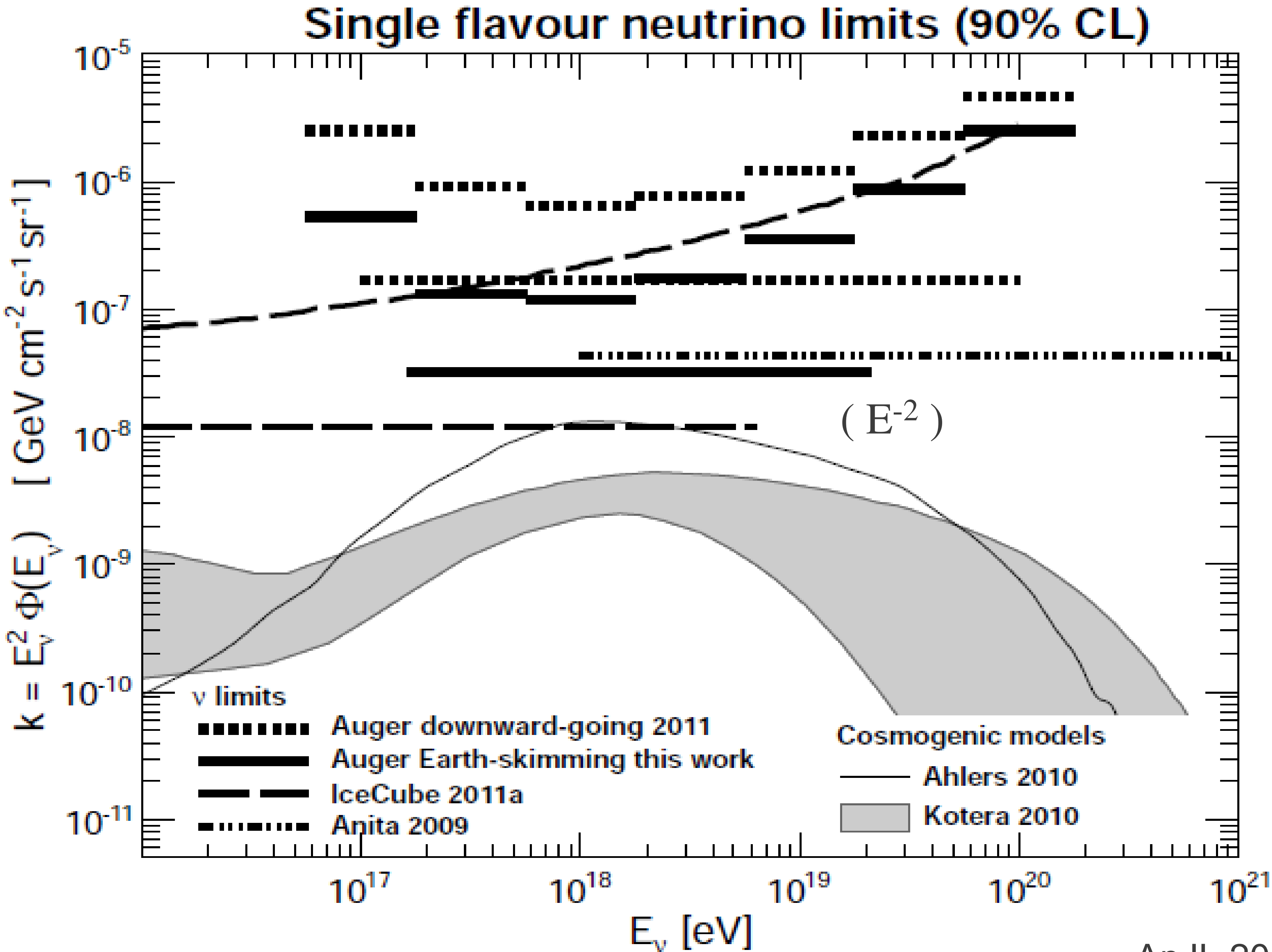
**unlike hadronic CRs, neutrinos can produce young horizontal showers above the detector (in particular from upcoming near horizontal tau lepton induced showers)**




**Horizontal young showers?**

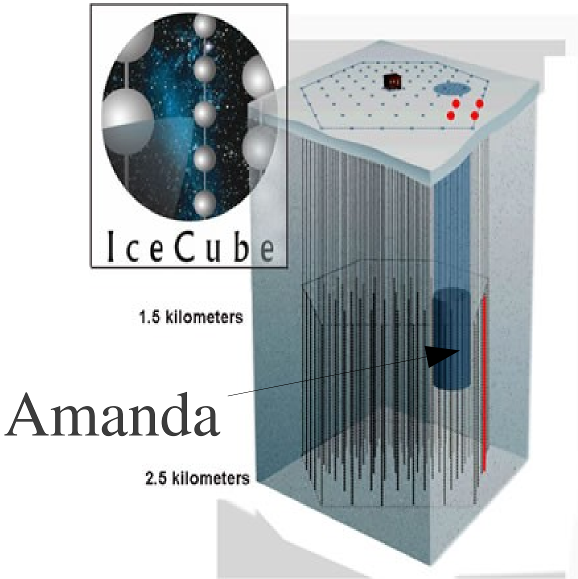
**ZERO CANDIDATES**




ApJL 2012

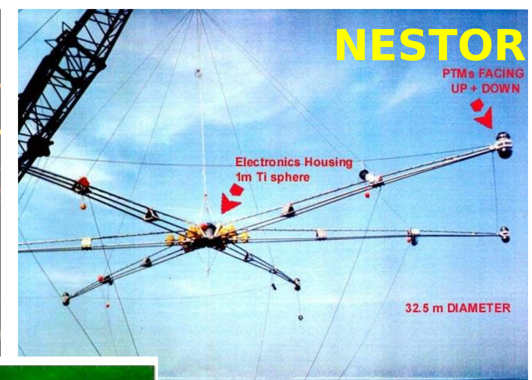
**0 events observed → bounds scale linearly with exposure**

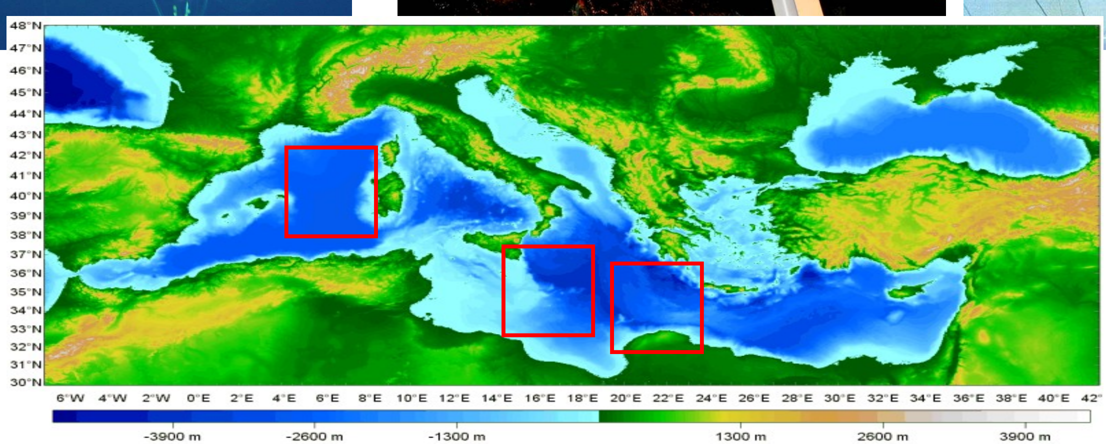
# NEUTRINO TELESCOPES (10 GeV to PeV and beyond)




km$^3$ detector at South Pole,
completed by 2011,
looking at northern ν sky
(and to southern sky above PeV)

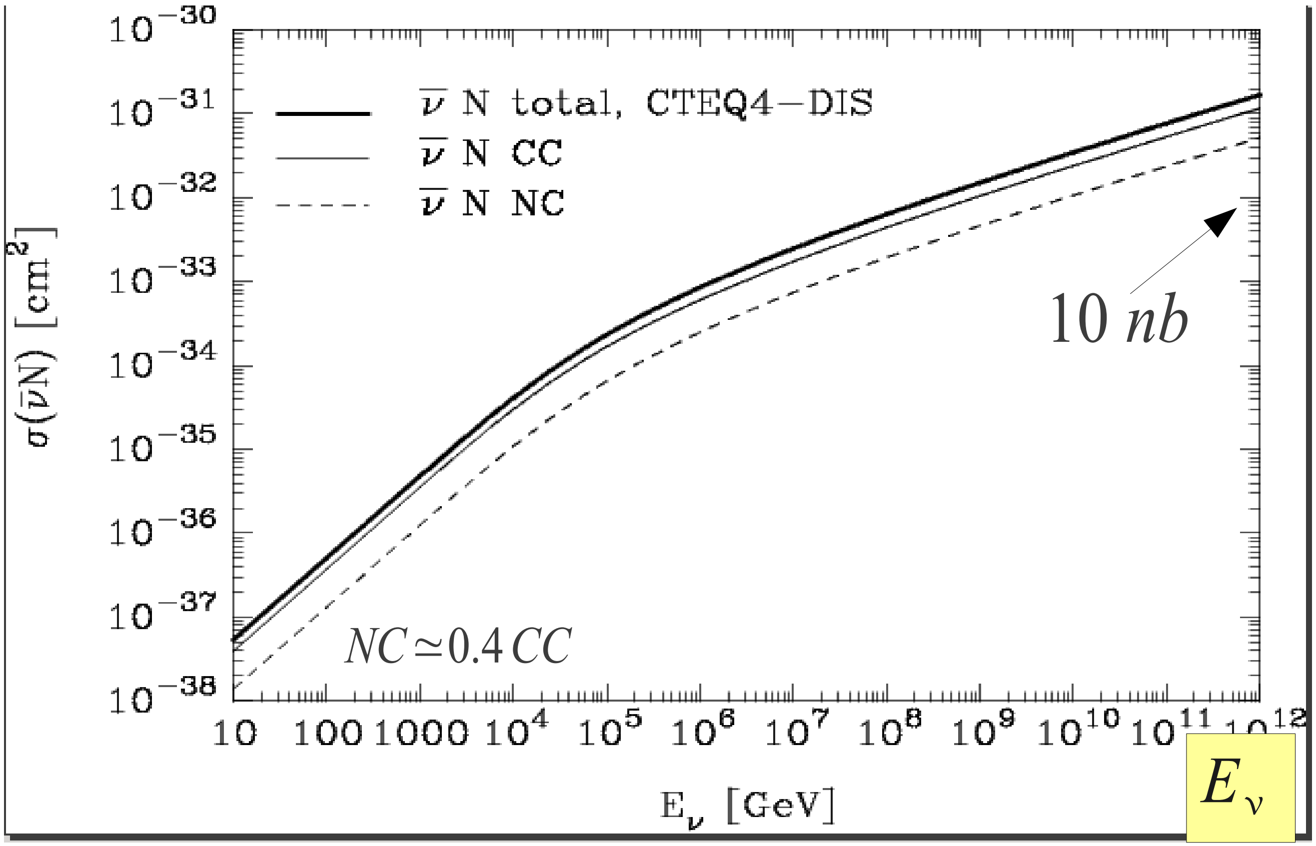




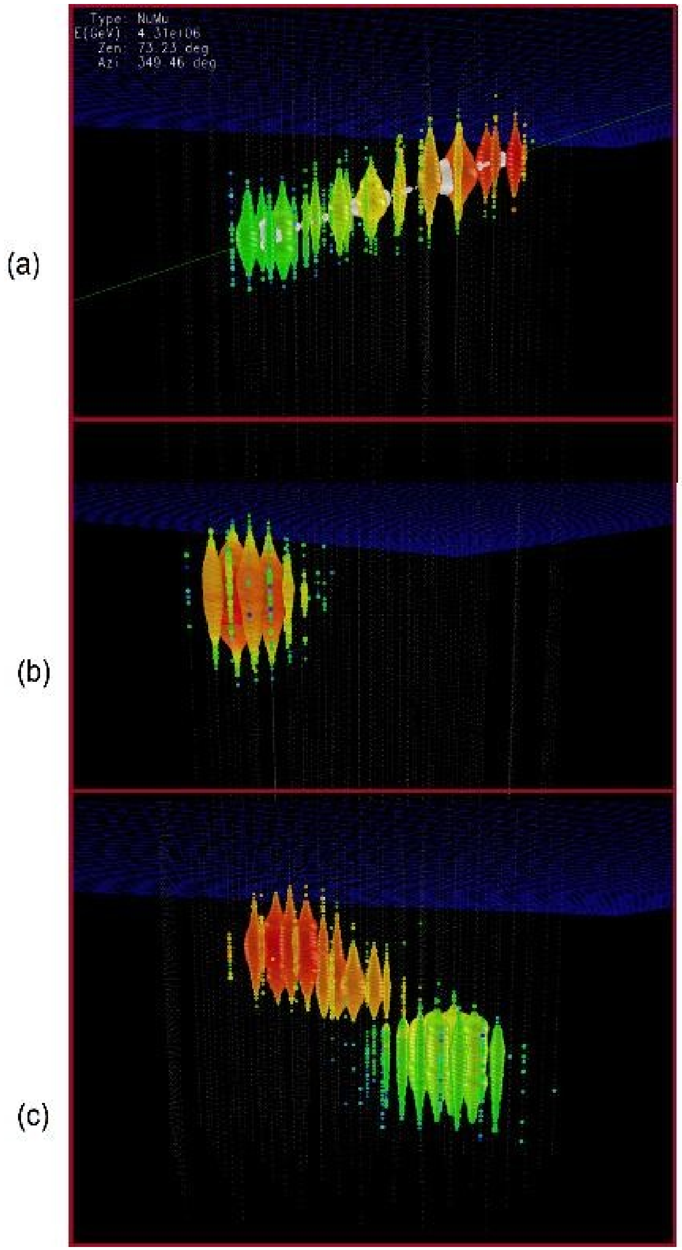

km$^3$ detector at Mediterranean
looking at southern neutrino
sky (proposed km3NET
& GVD in Baikal)

# Deep inelastic Neutrino nucleon interactions




**Earth opaque for E>40 TeV→ Need to look above horizon**

# One may even distinguish neutrino flavors



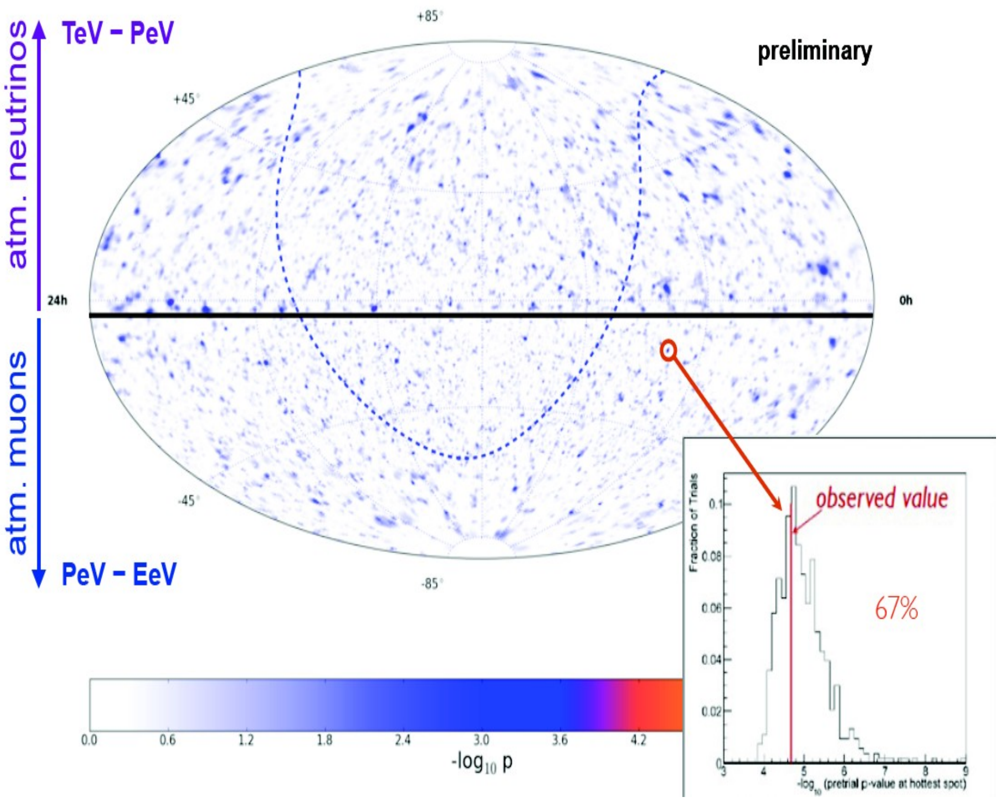

**muon neutrino (track)**

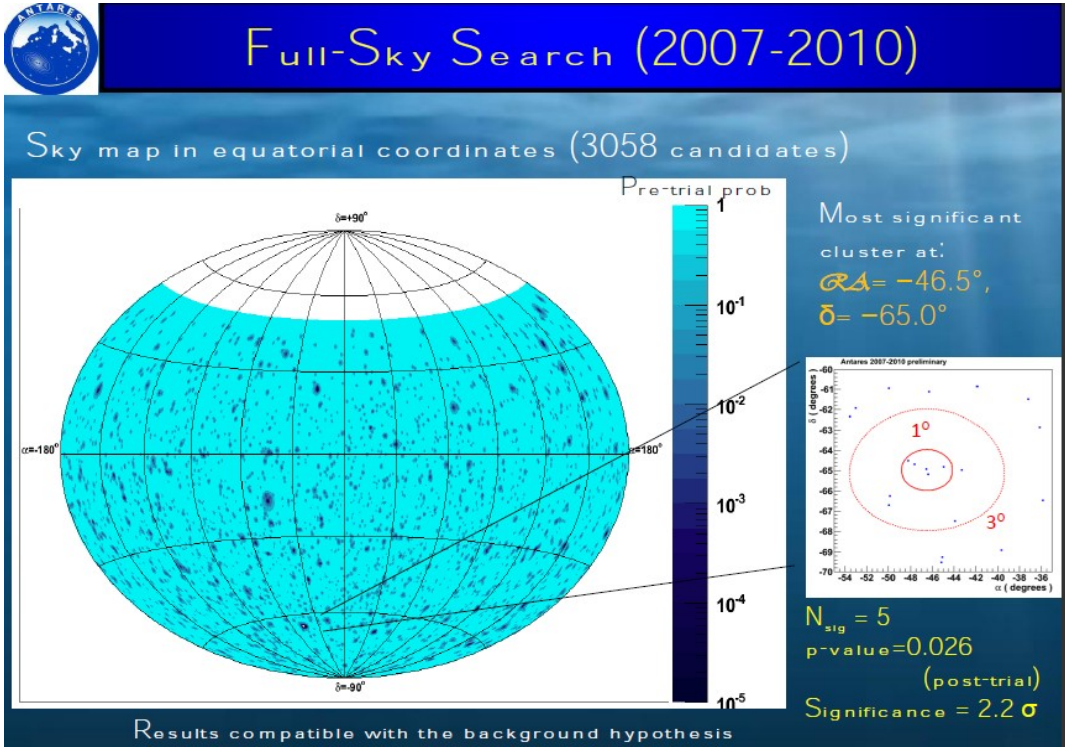
**electron neutrino (cascade, also from NC)**

**tau neutrino (double bang)**

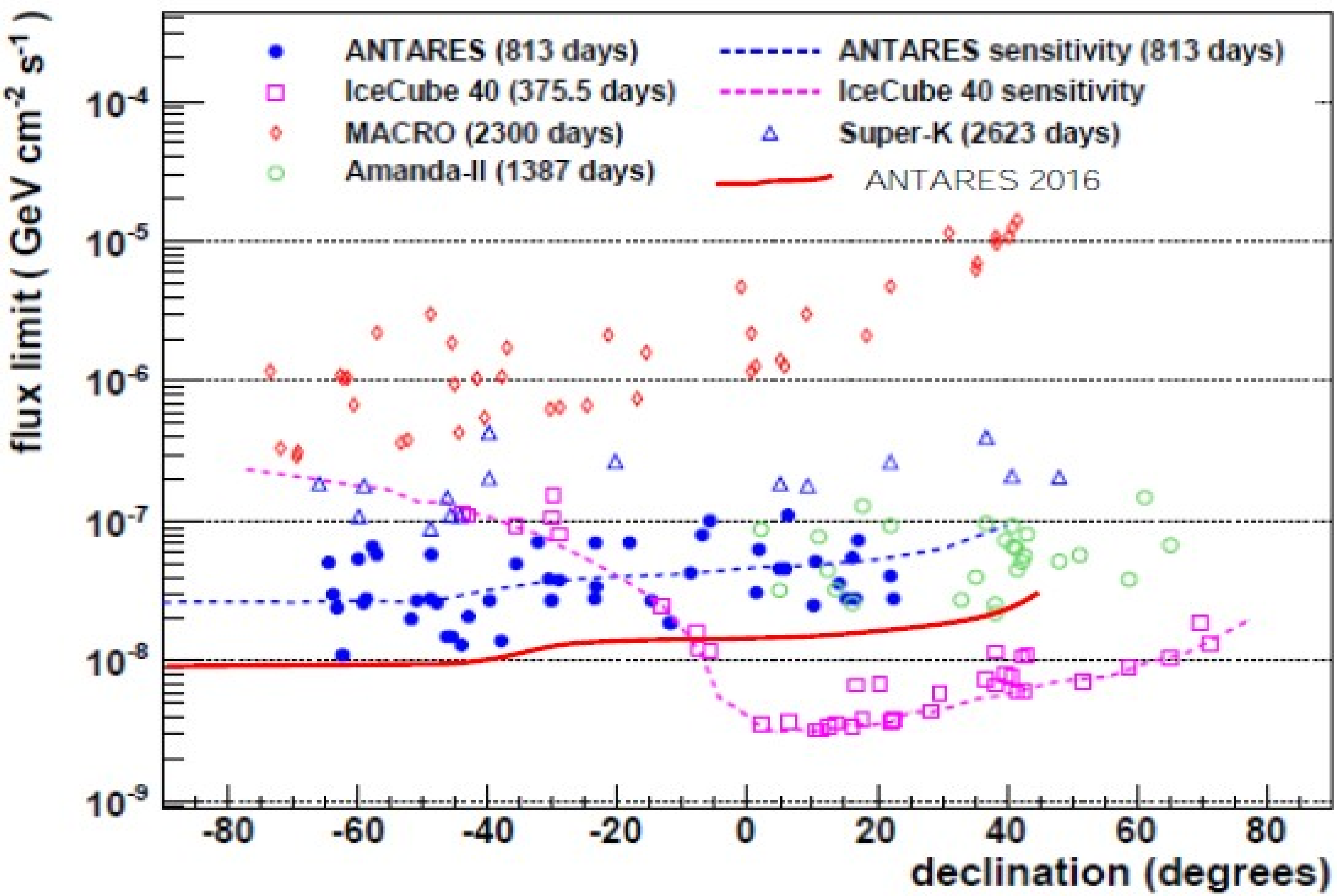
$$\gamma c \tau \simeq \frac{E}{PeV} 50\ m$$

## No point sources observed by Icecube nor Antares

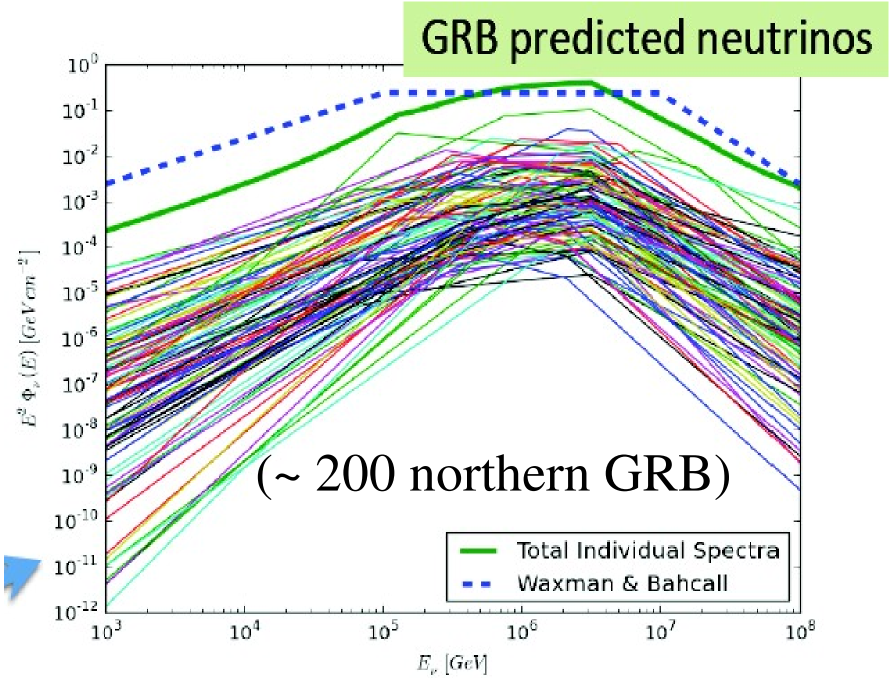


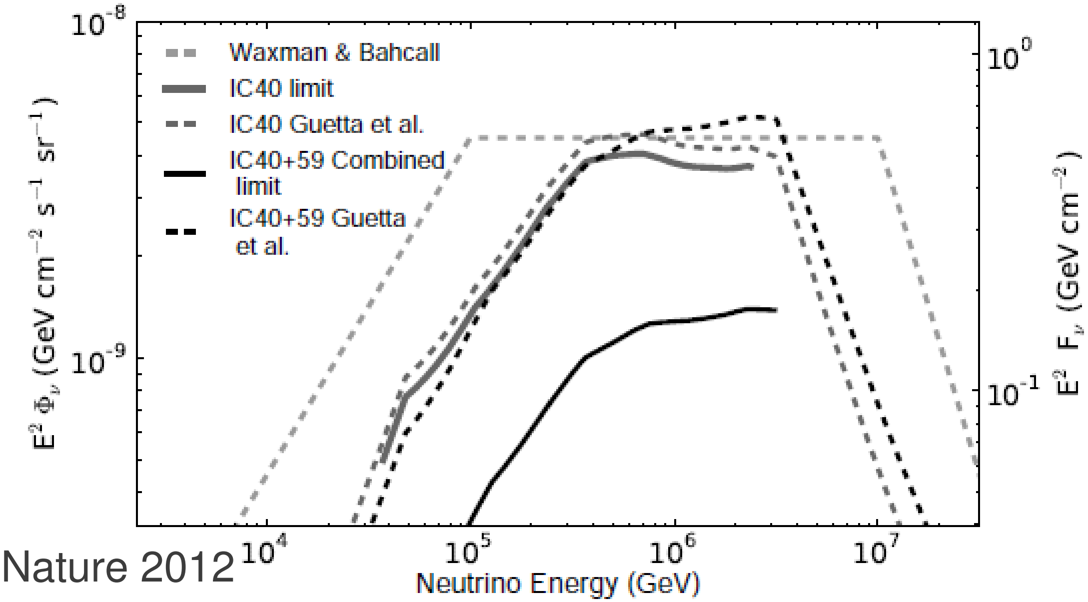



## Targeted searches  (galactic and extra-galactic candidates): SNR, AGN,...



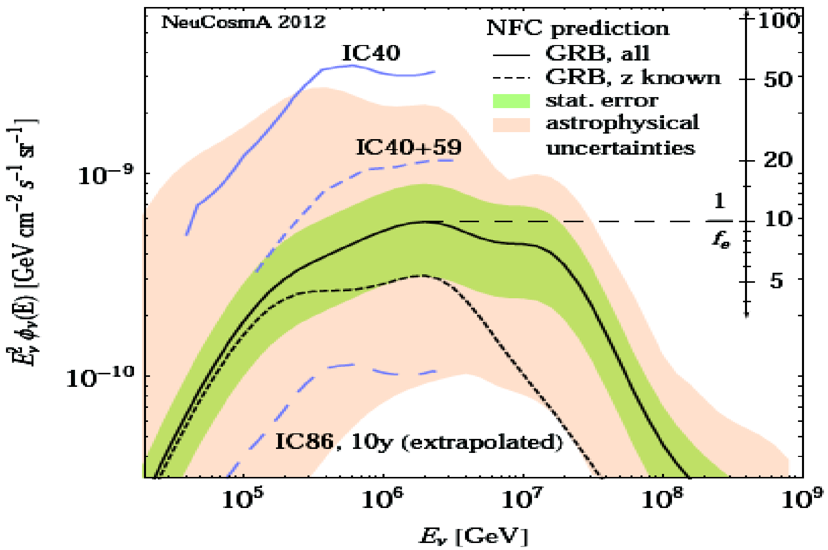
# ICECUBE stacked search for neutrinos coincident with observed GRB 2008/2010



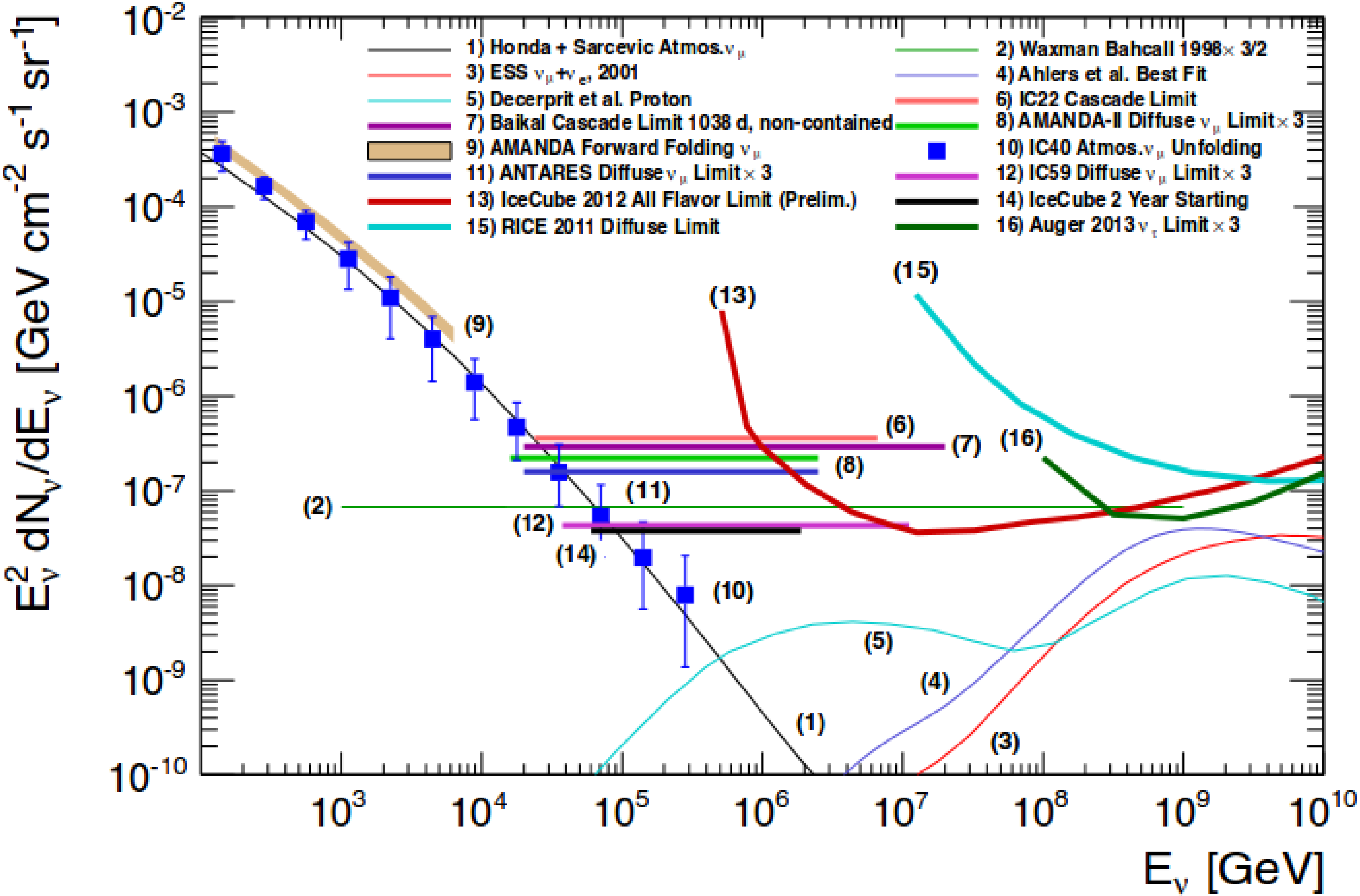

Nature 2012

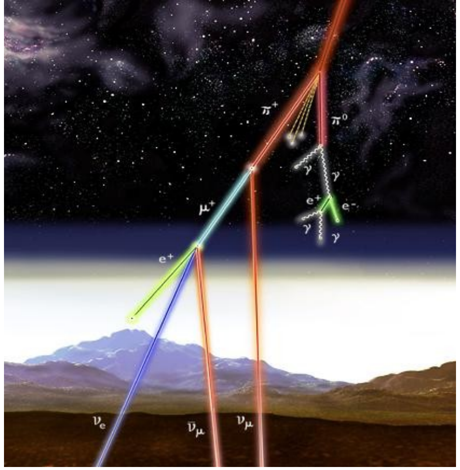
**Bound factor 4 below standard predictions**
**→ GRB are not main source of UHECRs**
**or production models need revision**




Revised model: (Hummer et al.):
E losses, flavor mix, spectral shapes...

# BOUNDS ON DIFFUSE NEUTRINO FLUXES





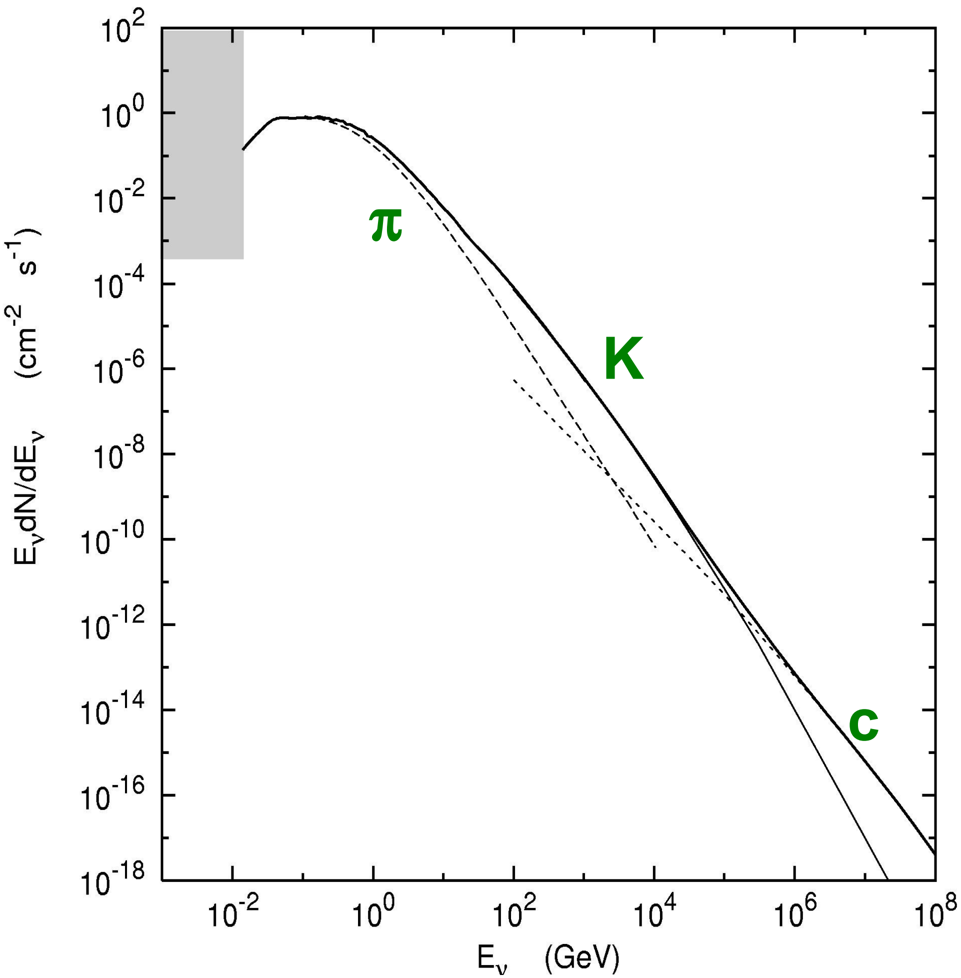
# High energy atmospheric neutrinos

**decay length** $L = \gamma c \tau$

$$L_\pi \simeq 6\, km \left( E_\pi / 100\, GeV \right)$$

$$L_K \simeq 7.5\, km \left( E_K / TeV \right)$$

$$L_D \simeq 2\, km \left( E_D / 10\, PeV \right)$$




**Atmospheric νs mainly from pion decays at low energies,**

**but above 100 GeV pions are stopped before decay → kaons become the main source,**

**but above ~100 TeV prompt charm decays dominate**

# Prompt charm production

Enberg et al. /0808.0418

For E > 200 TeV → ν mostly from c decays

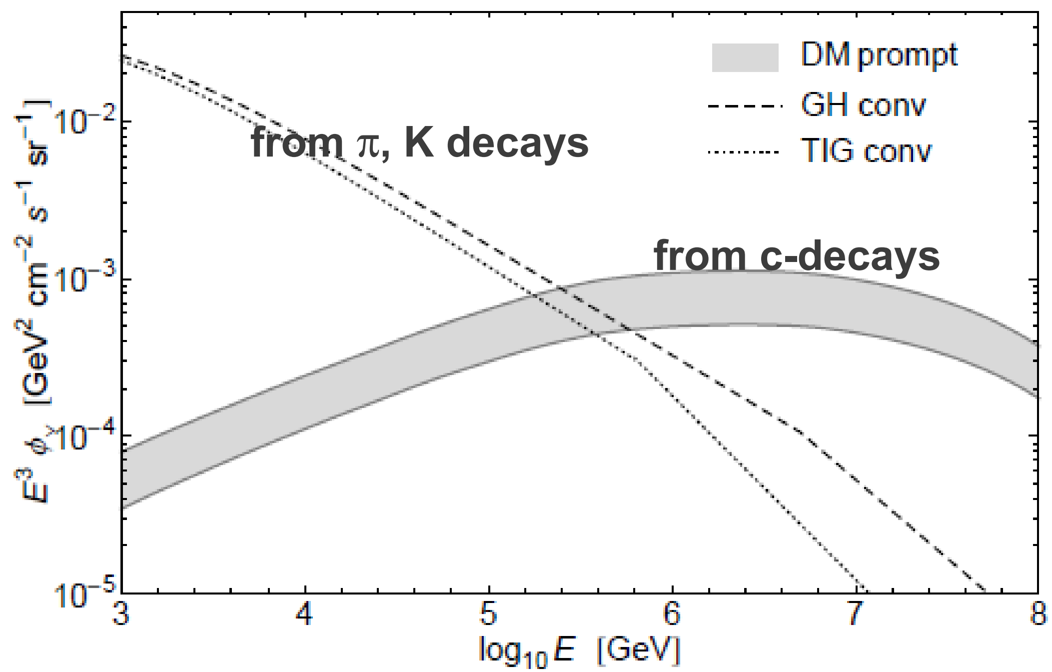
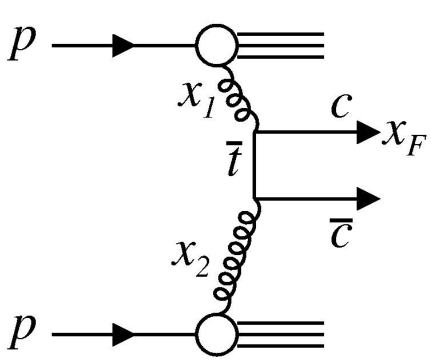



FIG. 5: Prompt and conventional $\nu_\mu + \bar{\nu}_\mu$ fluxes in the vertical




**sample gluon density distribution at** $x_2 \simeq \frac{M_{cc}^2}{2x_F s}$

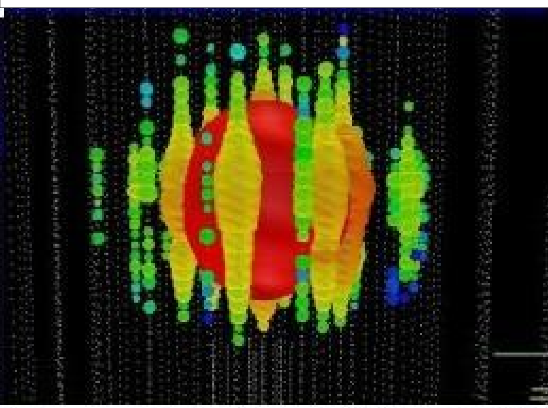
**→ $x_2 < 10^{-5}$ for E >$10^{15}$ eV**

**need to extrapolate from measured values**

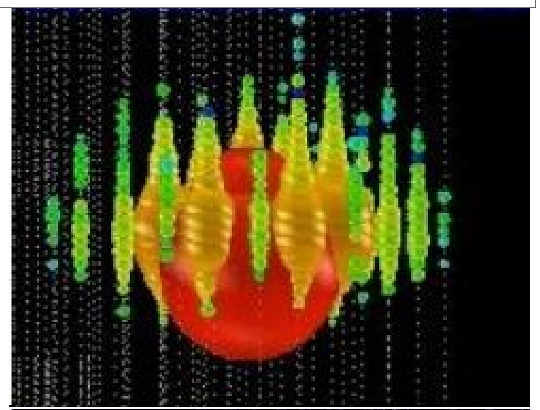
**also requires to include NLO processes**

## The two highest energy neutrino events observed by ICECUBE

E= 1.04 and 1.14 PeV (+-0.17)

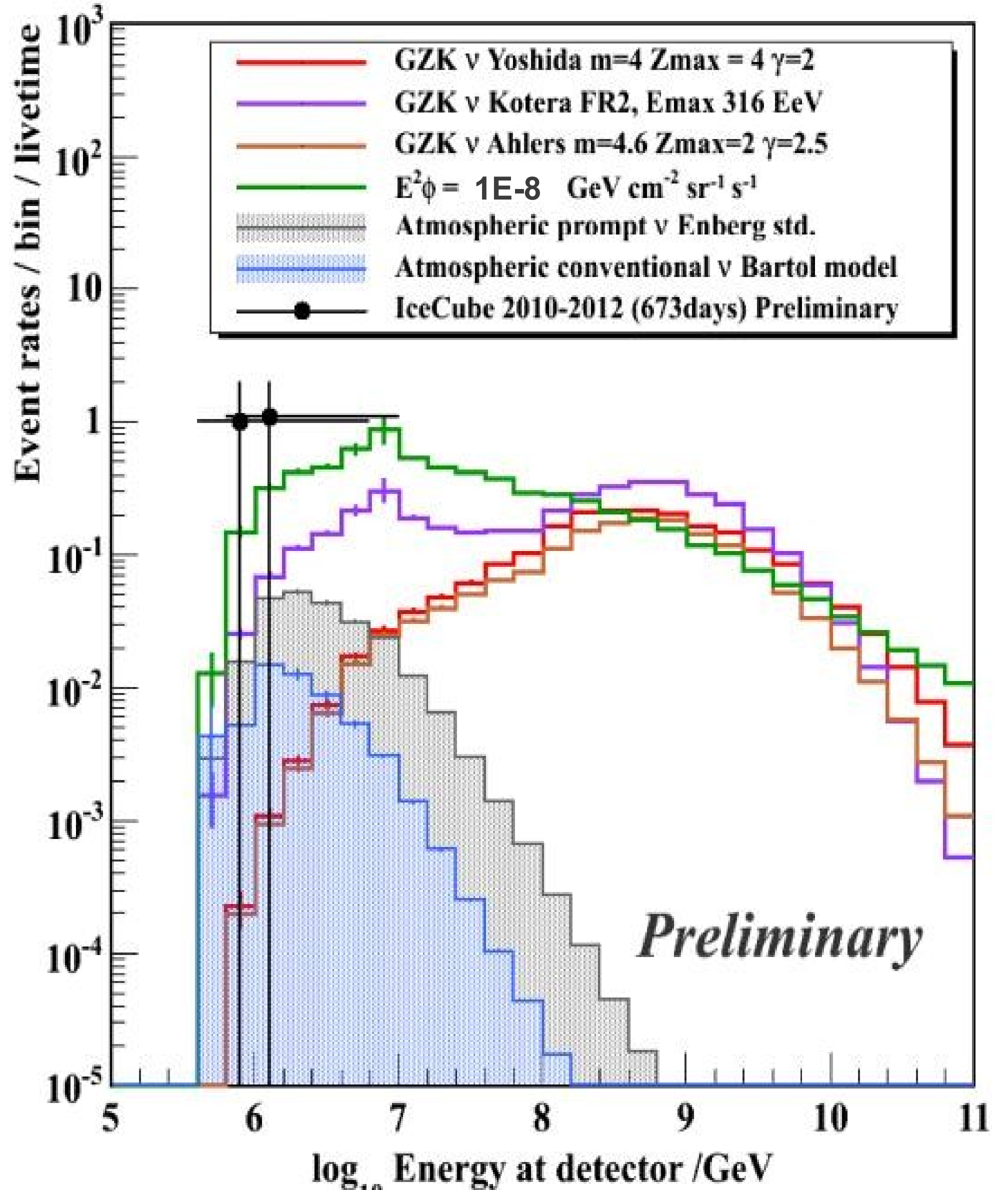


Run118545-Event63733662
August 9th 2011
NPE 6.9928x10⁴



Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10⁴

## Energy Distributions 2010-12

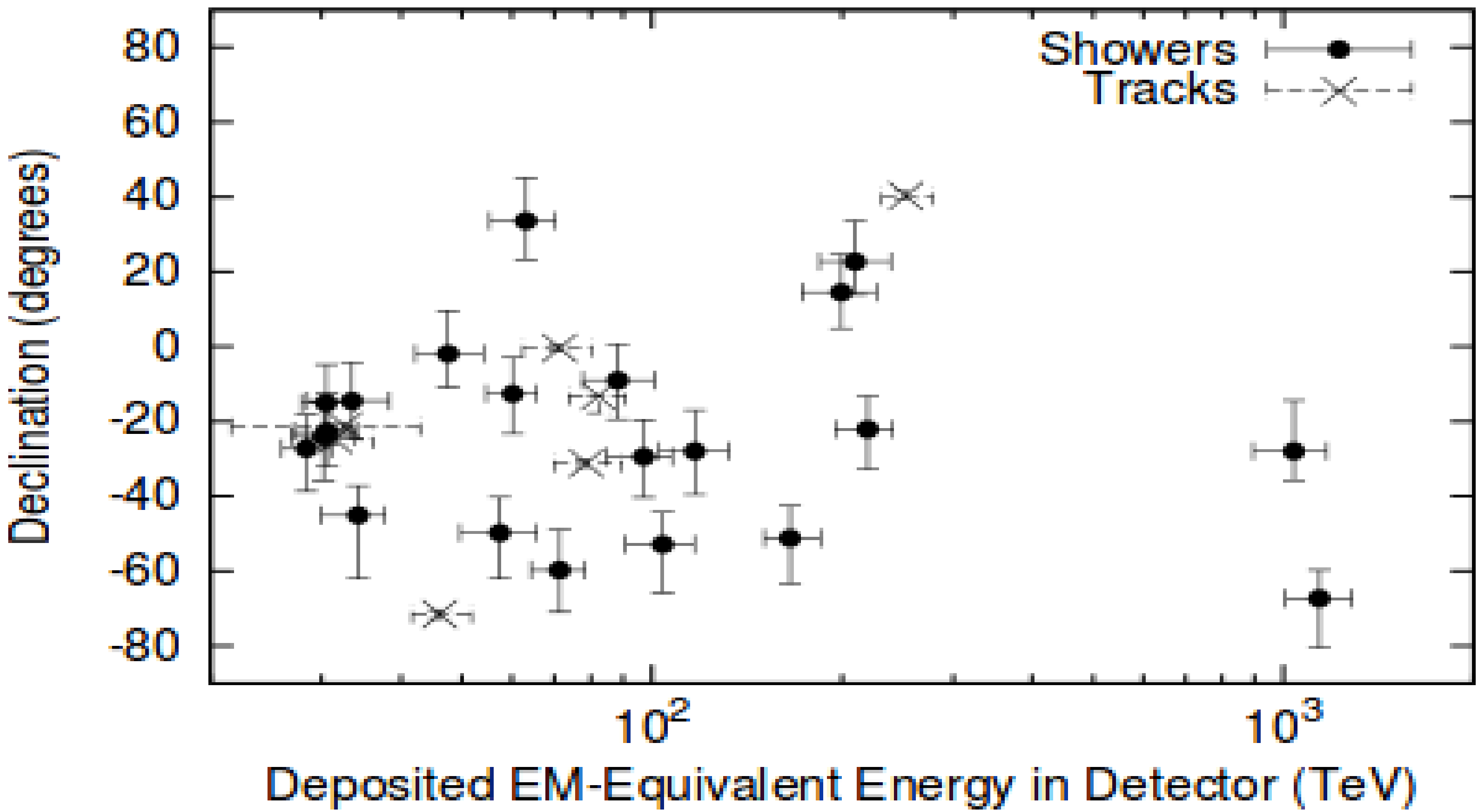



Possibility of the origin includes

- cosmogenic ν
- on-site ν production from the cosmic-ray accelerators
- atmospheric prompt ν
- atmospheric conventional ν

(PRD 2012)

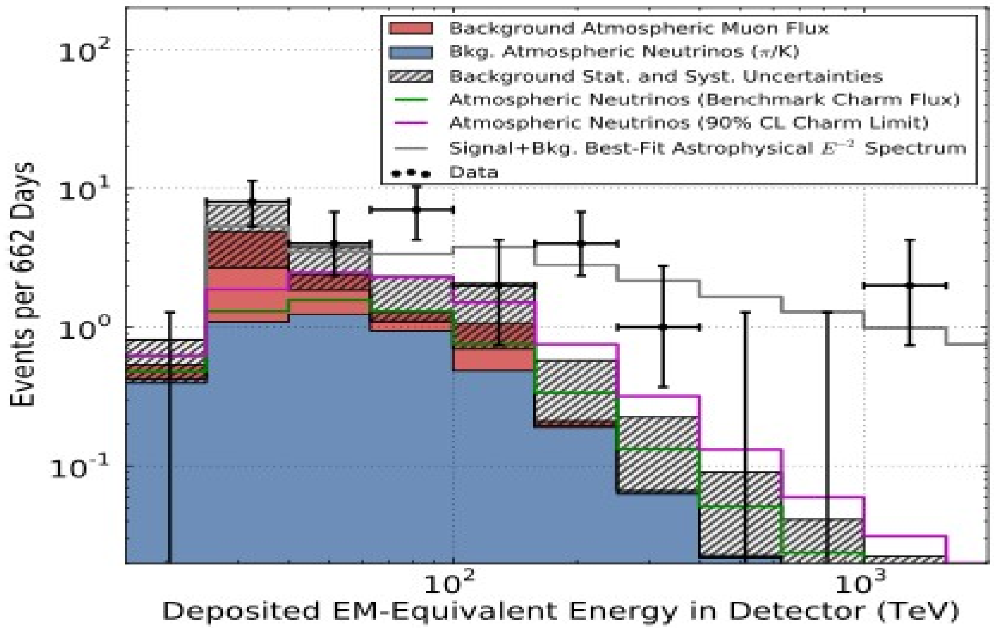
## Recently 26 additional events found above ~ 20 TeV

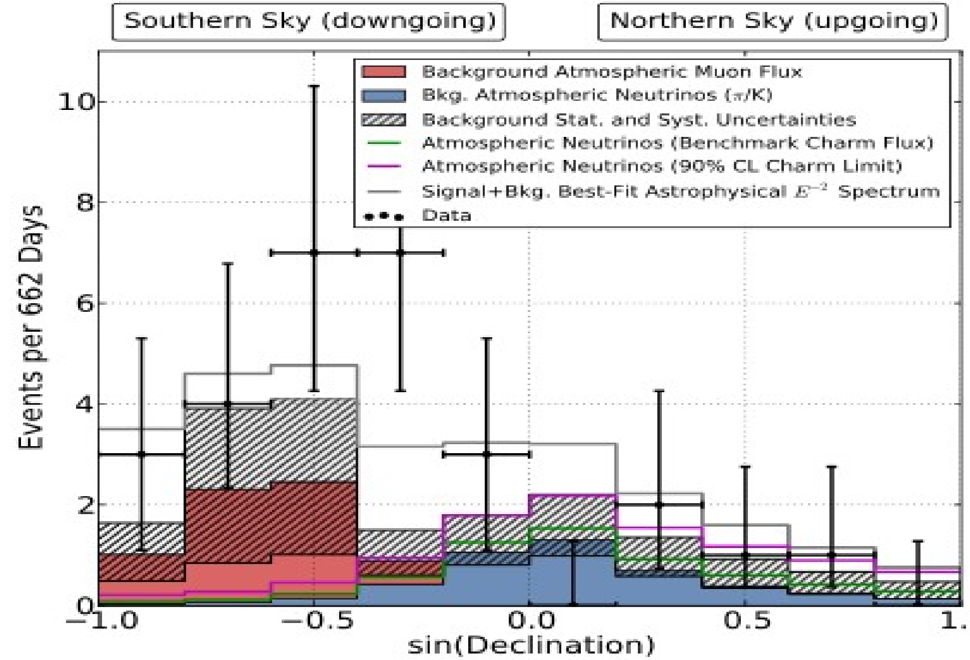



**21 showers and 7 tracks (consistent with 1:1:1 flavor ratios)**

**Only ~ $10.6^{+5}_{-3.6}$ expected from atmospheric background**

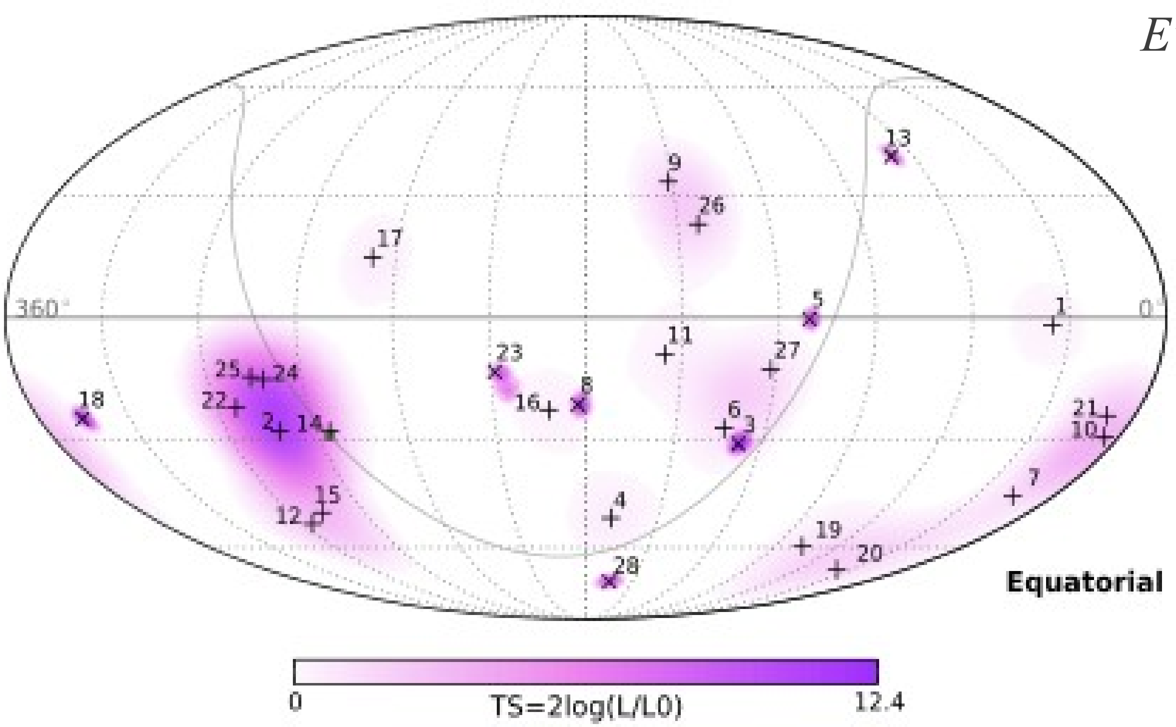
(Science 2013)




**Distribution in E and declination compatible with isotropic $E^{-2}$ flux with cutoff**

$$E^2\Phi(E) \sim 3\text{E-}8\, GeV/cm^2\, s\, sr,\ E < few\ PeV$$




# Cosmogenic neutrinos from proton sources:

**Threshold:** $p\,\gamma \to \pi^+\, n$

$$s=(p_p+p_\gamma)^2>(m_p+m_\pi)^2 \Rightarrow E_p>\frac{m_\pi(2m_p+m_\pi)}{4E_\gamma}\simeq\frac{70\ EeV}{E_\gamma/10^{-3}\,eV}$$

→ $10^{20}$ eV for CMB photons, $10^{17}$ eV for optical photons

**ν energies:**

$p\,\gamma \to \pi^+\, n$

$\pi^+ \to \mu^+\,\nu_\mu \to e^+\,\bar\nu_\mu\,\nu_\mu\,\nu_e$ → $E_{\bar\nu_\mu}\simeq E_{\nu_\mu}\simeq E_{\nu_e}\simeq E_\pi/4\simeq E_p/20$

$n \to p\,e\,\bar\nu_e$ → $E_{\bar\nu_e}\simeq\frac{m_n-m_p-m_e}{2\,m_n}E_n\simeq 4\ 10^{-4}\,E_n$

**Redshift** (production at 0<z<4) : $T_{CMB}=(1+z)\ 2.7$ K → redshifted threshold

Redshifted ν energy $E_\nu^{\pi-dec}\simeq\frac{E_p}{20(1+z)}$

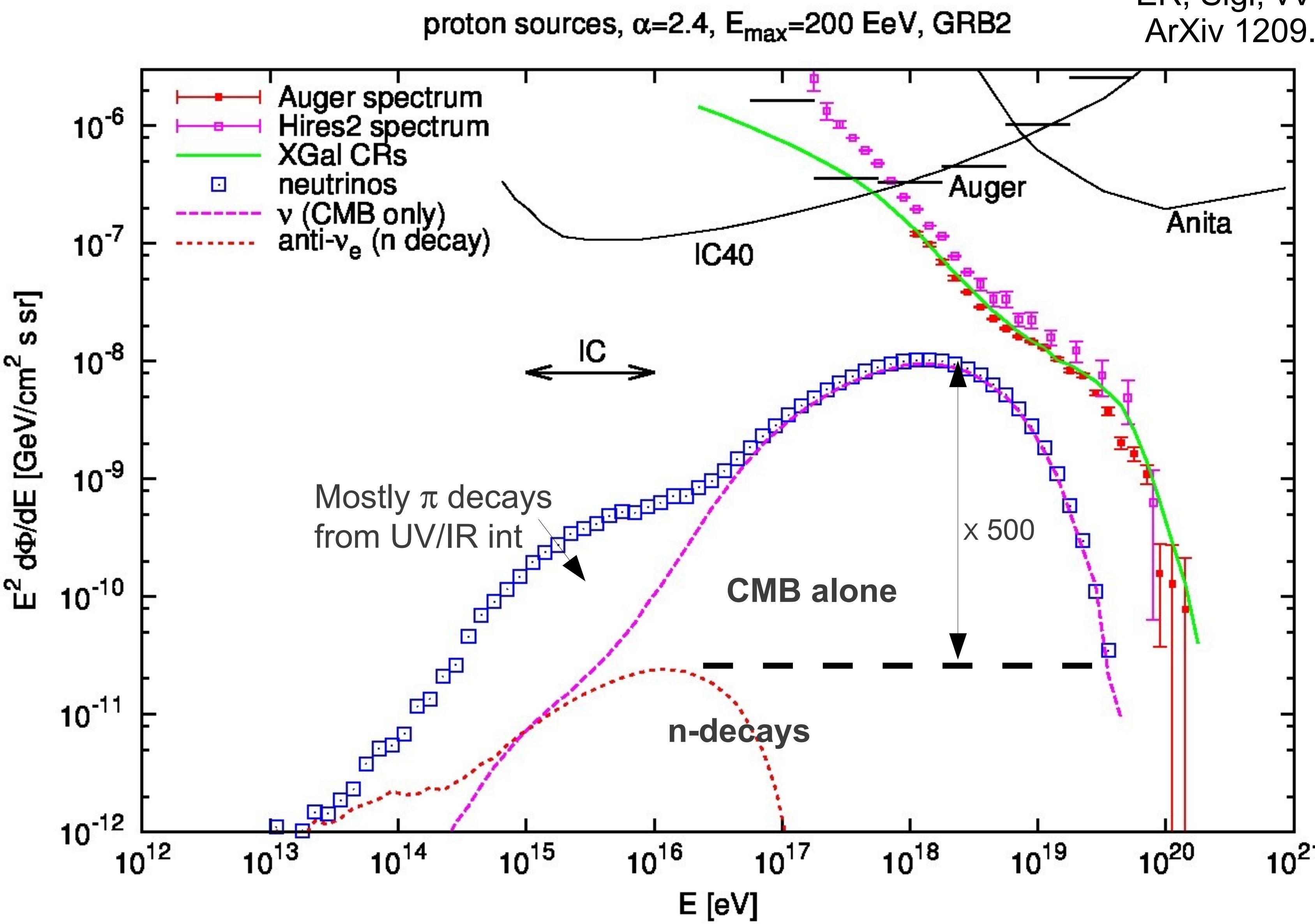
$$E_\nu^{\pi-dec}\simeq\frac{5\ EeV}{(1+z)(E_\gamma/10^{-3}\,eV)}$$

EeV ν from interactions with CMB photons

PeV ν from interactions with UV/O/IR photons

or PeV ν from n-decays from interactions with CMB?

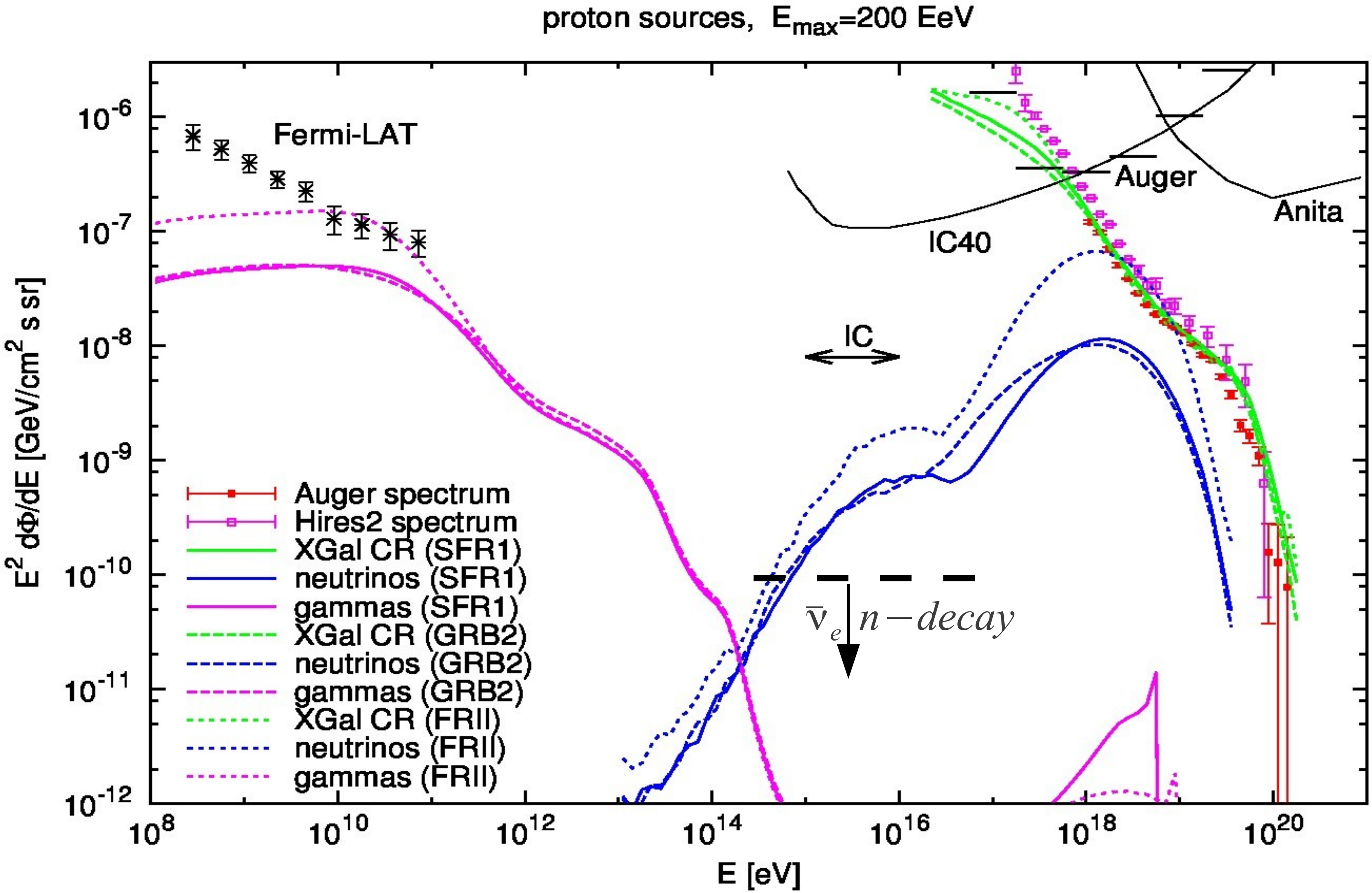
ER, Sigl, vVliet & Mollerach
ArXiv 1209.4033, JCAP 2013




**Height of PeV ν peak from n-decay related to height of EeV ν peak from π-decay**

$$\frac{d\,\Phi_{\bar{\nu}_e}}{d\,logE}\left(E_\nu^{n-decay}\right)\simeq\frac{d\,\Phi_{\nu_\mu}}{d\,logE}\left(E_\nu^{\pi-decay}\right)\;\Rightarrow\;\left[E_\nu^2\frac{d\,\Phi_{\bar{\nu}_e}}{d\,E}\right]^{n-dec}_{E_\nu=6\,10^{15}eV}\simeq\frac{E_{\bar{\nu}_e}^{n-d}}{E_\nu^{\pi-d}}\left[E_\nu^2\frac{d\,\Phi_{\nu_\mu}}{d\,E}\right]^{\pi-dec}_{E_{\nu_\mu}=10^{18}eV}$$

# $\nu$ and $\gamma$ for different source evolutions & cascade bound




**Allowed height of EeV $\nu$ flux implies bound on PeV $\nu$ peak from n-decay**

$$\left[E_\nu^2 \frac{d\,\Phi_{all\,\nu}}{d\,E}\right]_{E_\nu=10^{18}\,eV} < 5\times10^{-8}\,\frac{GeV}{cm^2\,s\,sr} \Rightarrow \left[E_\nu^2 \frac{d\,\Phi_{\bar{\nu}_e}}{d\,E}\right]^{n-dec}_{E_\nu=6\,10^{15}\,eV} < 10^{-10}\,\frac{GeV}{cm^2\,s\,sr}$$

$\rightarrow$ $\nu_e$ flux from n-decay tiny at PeV

# Cosmogenic neutrinos from nuclei:

**photo-disintegration:** $A\,\gamma \rightarrow A' + nucleons$

$A' \rightarrow A\, e\, \bar{\nu}_e$

$n \rightarrow p\, e\, \bar{\nu}_e$

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

$\pi^+ \rightarrow e^+\, \bar{\nu}_\mu \nu_\mu \nu_e$

Giant dipole resonance for $E'_\gamma \sim$ 10-30 MeV

**Threshold:**

$$s = (p_A + p_\gamma)^2 > (m_A + 10\,MeV)^2 \Rightarrow E_A > \frac{A}{56}\,\frac{2\times 10^{20}\,eV}{E_\gamma / 10^{-3}\,eV}$$

For Fe, similar cutoff as p

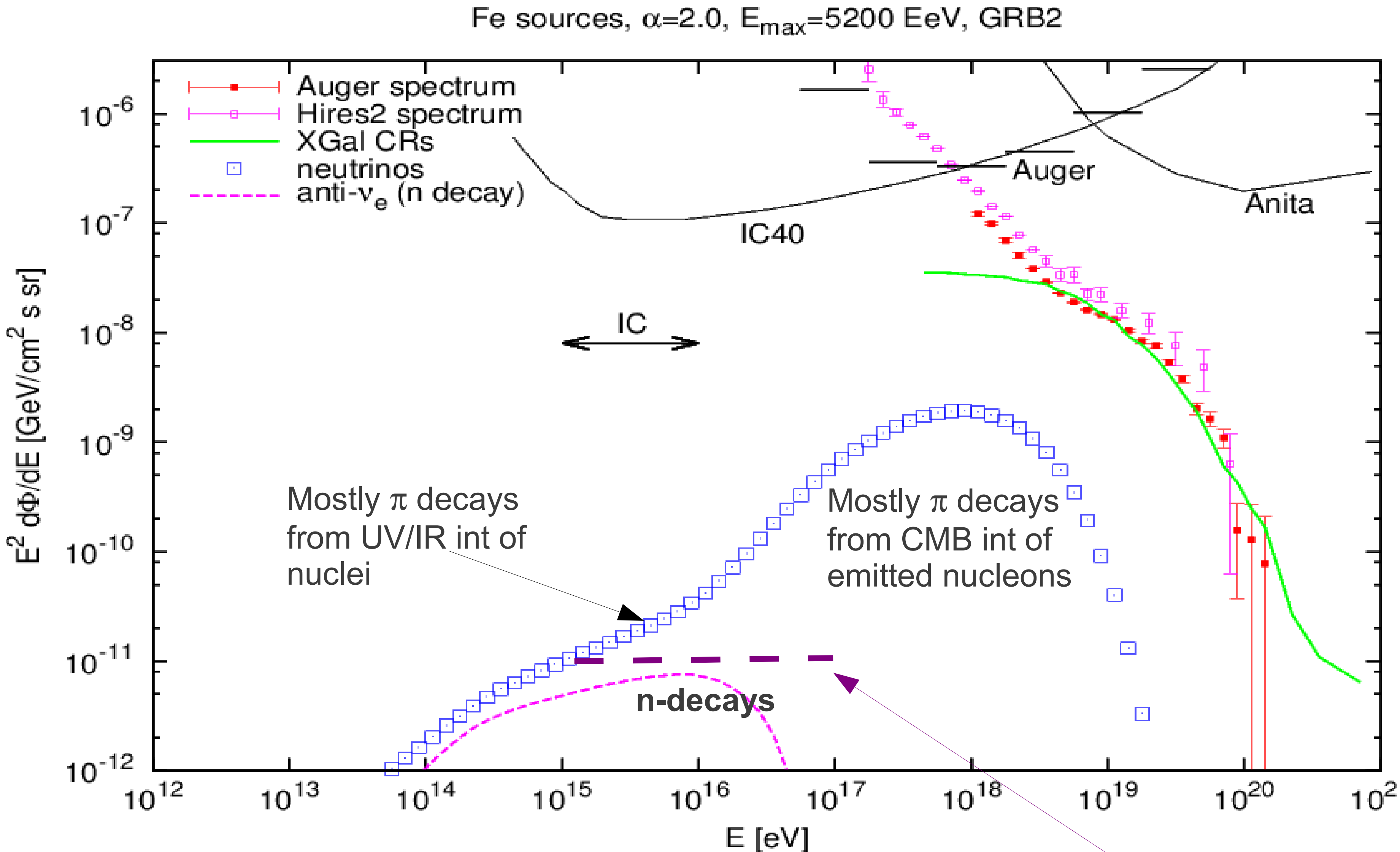
lighter nuclei → smaller cutoffs

**Photo-pion:** $A\,\gamma \rightarrow A' + \pi$ (need to account for nuclear suppression)

**For E/A > $10^{17}$ eV, nuclei disintegrate 'a lot' (from IR & CMB)**
**→ low energy neutrinos from n-decays (& beta decay)** $E_\nu \simeq 4\times 10^{-4}\, E/A$

**Secondary nucleons with E/A interact producing pions**

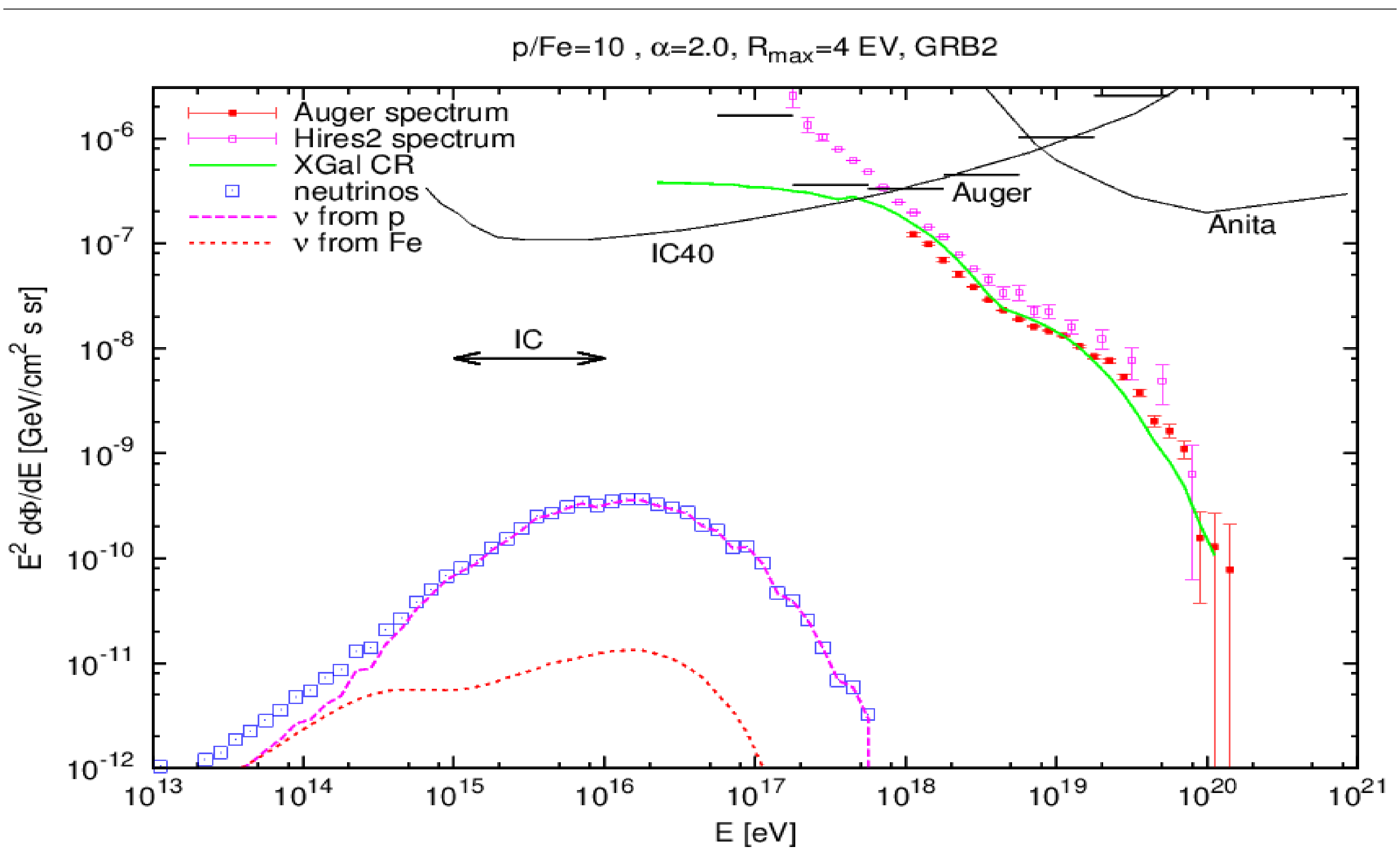
**for E/A < $10^{17}$ eV interaction probabilities small**
**→ few nuclei disintegrate, fewer nuclei emit pions, but those may still dominate PeV neutrino flux production**




**PeV ν from n-decays bounded by EeV neutrons, which are bounded by overall CR fluxes**

$$\left[\frac{d\,\Phi_{\bar{\nu}_e}}{d\log E}\right]^{n-dec}_{E_\nu=10^{15}eV} \simeq \left[\frac{d\,\Phi_{'n'}}{d\log E}\right]_{E=2\,10^{18}eV} < \left[\frac{1}{2}\frac{d\,\Phi_{CR}}{d\log E}\right]_{E=2\,10^{18}eV} \Rightarrow \left[E_\nu^2\frac{d\,\Phi_{\bar{\nu}_e}}{d\,E}\right]^{n-dec}_{E_\nu=10^{15}eV} < 10^{-11}\,\frac{GeV}{cm^2\,s\,sr}$$

# Mixed extragalactic p / Fe composition with low cutoff ($E_p$ < 4 EeV)




**p component below ankle leads to significant PeV ν fluxes from π-decay**
**no EeV ν due to low cutoff**

# Flavor oscillations

## Incoherent flavor conversions

(Pakvasa et al 2008)

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

π-decays:

$$(\nu_e : \nu_\mu : \nu_\tau) = (1:1:0) \rightarrow (0.78:0.61:0.61)$$

$$(\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = (0:1:0) \rightarrow (0.22:0.39:0.39)$$

n-decays:

$$(\nu_e : \nu_\mu : \nu_\tau) = (0:0:0) \rightarrow (0:0:0)$$

$$(\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = (1:0:0) \rightarrow (0.56:0.22:0.22)$$

(adopting TBM)

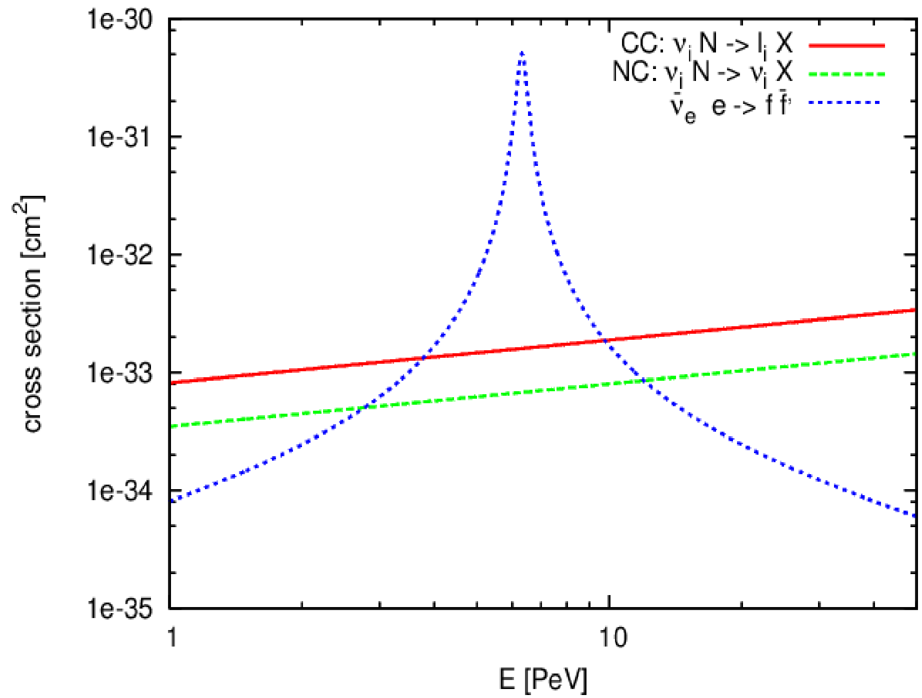
$$\sin^2\Theta_{23} \simeq 1/2$$

$$\sin^2\Theta_{12} \simeq 1/3$$

$$\sin^2\Theta_{13} \simeq 0$$

# THE GLASHOW RESONANCE

$$\bar{\nu}_e e \rightarrow W \rightarrow \bar{f}\, f'$$




**resonant for:** $$E = \frac{M_W^2}{2 m_e} = 6.3\ PeV$$

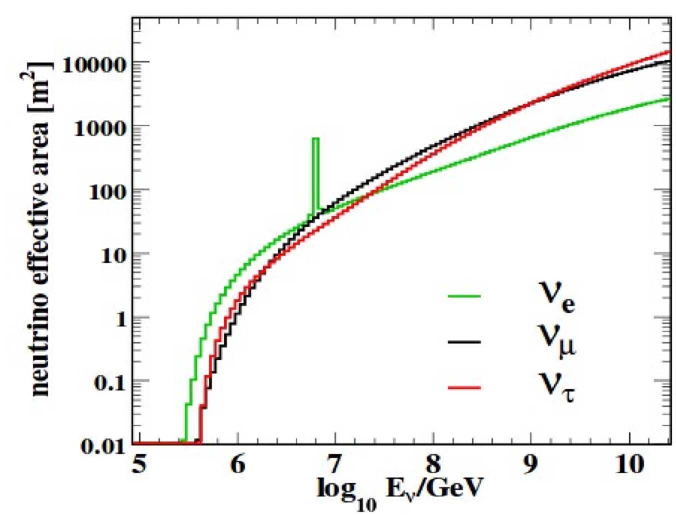
**at the peak,**

$$\sigma(\bar{\nu}_e e \rightarrow all) \simeq 350\, \sigma^{CC}(\nu_i N \rightarrow l_i X)$$

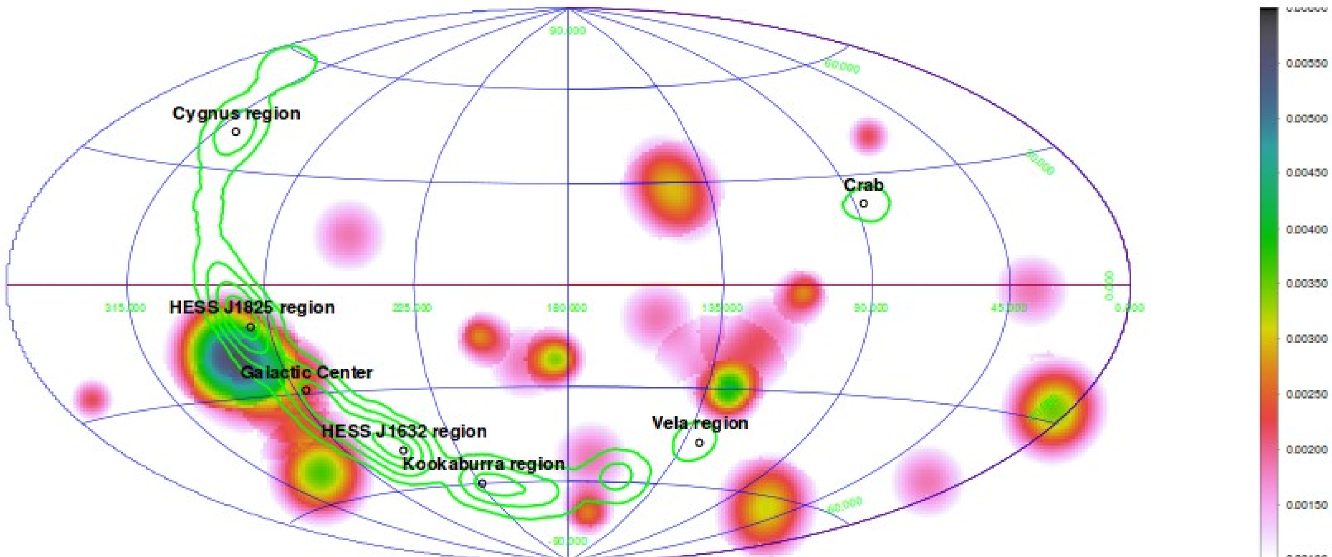
**but peak narrow (0.17 PeV), electron antineutrino flavor not dominant, $n_e/n_N$ = 5/9**

**→ overall contribution to the IceCube rates of ν from π−decays is similar to the CC+NC ones within 2.5 PeV of the resonance**

**→ does not allow to achieve strong enhancements**



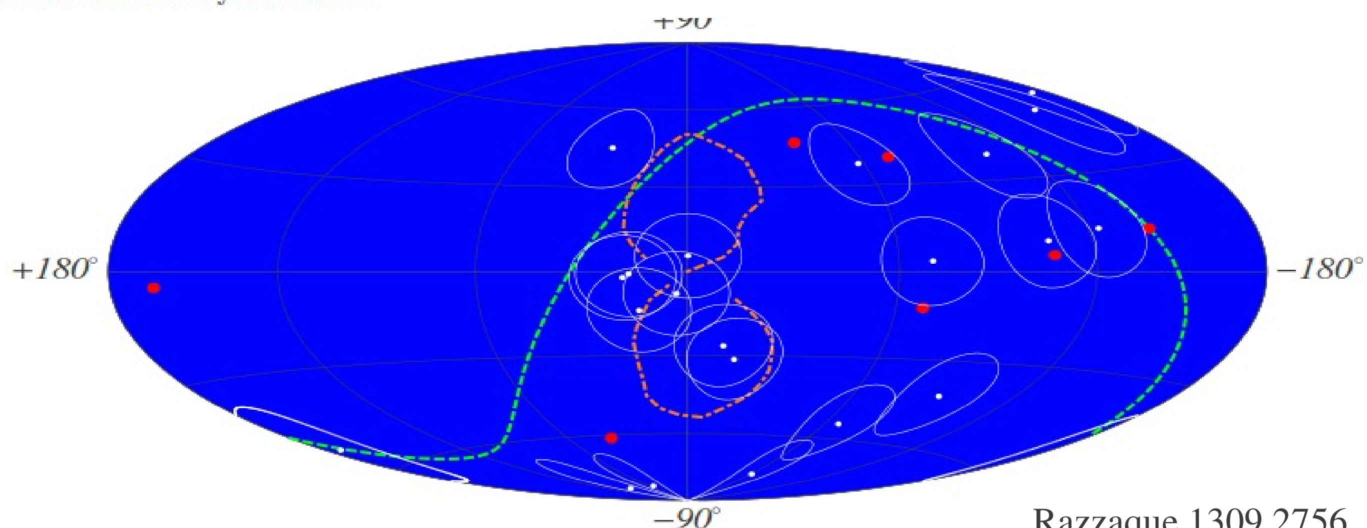
# PeV neutrinos of Galactic origin?




Neronov et al 1307.2158

IG. 1: IceCube count map in the energy range above 30 TeV (from Ref. [2]). Overlayed are contours from the Fermi/LAT ount map in the energy range above 500 GeV, smoothed with a 10 degrees Gaussian. The regions of excess $\gamma$-ray flux along he Galactic Plane are marked by their names.

**Correlated with Fermi diffuse gammas? produced by interaction with gas in galactic arms?**




Razzaque 1309.2756

FIG. 1: IceCube neutrino events in Galactic coordinates. The 21 shower-like events are shown with 15° error circles around the approximate positions (small white points) reported by IceCube [1]. The 7 track-like events are shown as larger red points. Also shown are the boundaries of the Fermi bubbles (dot-dashed line) and the Equatorial plane (dashed line).

**Correlated with Fermi Bubbles?**

**But: Composition becoming heavy above the knee, individual sources too faint, Bounds from CASA-MIA on 100 TeV gammas, ...**

## PeV neutrinos of extra-Galactic origin?

Sources could be AGN, GRBs, ….

Need about 10% of energy in few x$10^{16}$ CRs to go to pions

Optical photons at or around the source could be the target

Sources need not be too far away (unlike for cosmogenic nus)

## Is there a gap between 300 TeV and 1 PeV ?

PeV neutrinos from dark matter decay?

Need more data to test spectrum, cutoff, tracks/showers, arrival directions, …. IceCube will soon provide that

# CONCLUSIONS

**Detection of 2 PeV $\nu$ produced a revolution in the field of $\nu$ astronomy**

**- are they atmospheric ? (enhanced by charm production)**

**- are they cosmogenic ? (produced during propagation of CRs)**

**Significant PeV $\nu$ fluxes can arise from $10^{16}$ – $10^{17}$ eV protons producing $\pi$ in interactions with UV/IR (but probably not enough)**

**Cosmogenic neutrinos from n-decays tiny at PeV energies**

**Glashow resonance has moderate impact (narrow width, only anti-$\nu_e$)**

**- are they Galactic ? Produced by CR interaction with ISM**

**- are they produced at the sources ? (GRB, AGN, …)**

**We are at the dawn of the era of high energy neutrino astronomy**