

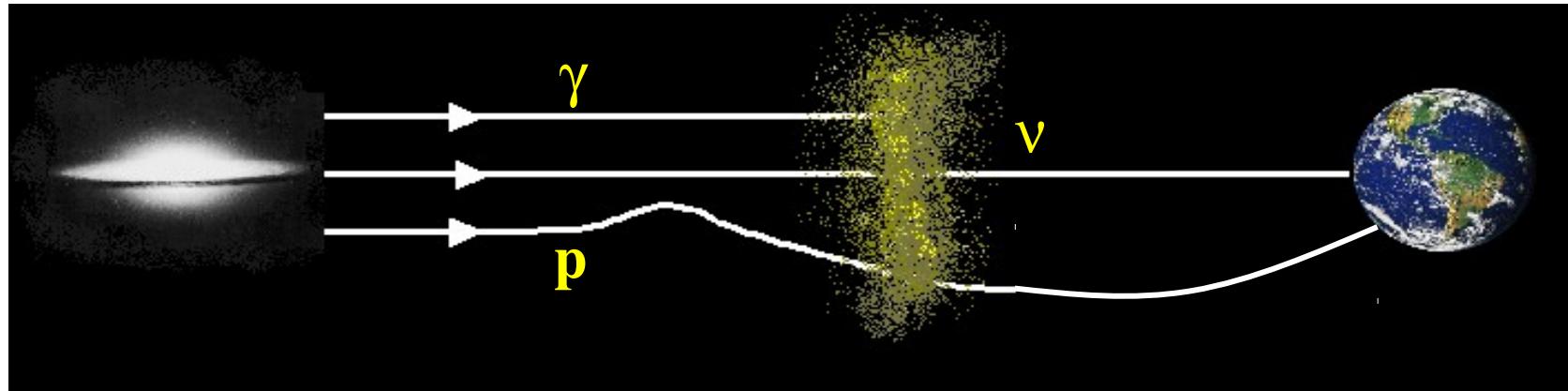
# **PeV NEUTRINOS FROM THE PROPAGATION OF ULTRA-HIGH ENERGY COSMIC RAYS**

Esteban Roulet  
CONICET, Centro Atómico Bariloche

Work with Mollerach, Sigl and van Vliet  
arXiv 1209.4033

# THE ENERGETIC UNIVERSE

multi-messenger astronomy

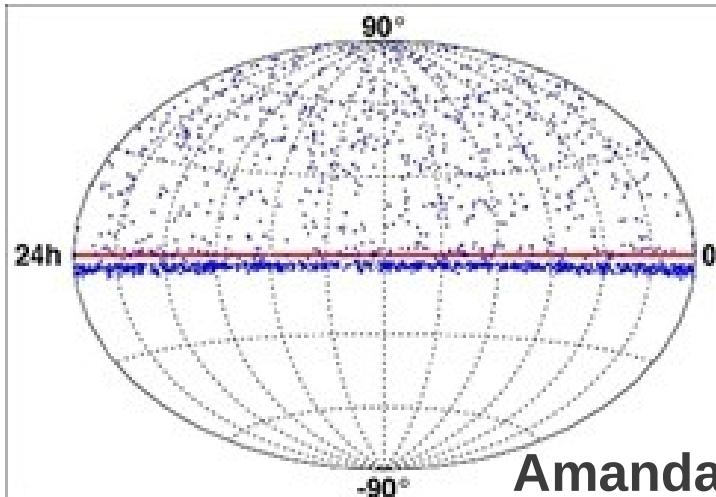
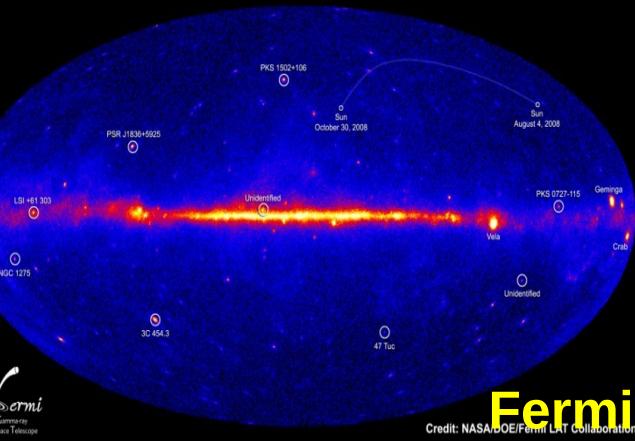


$\gamma$  rays

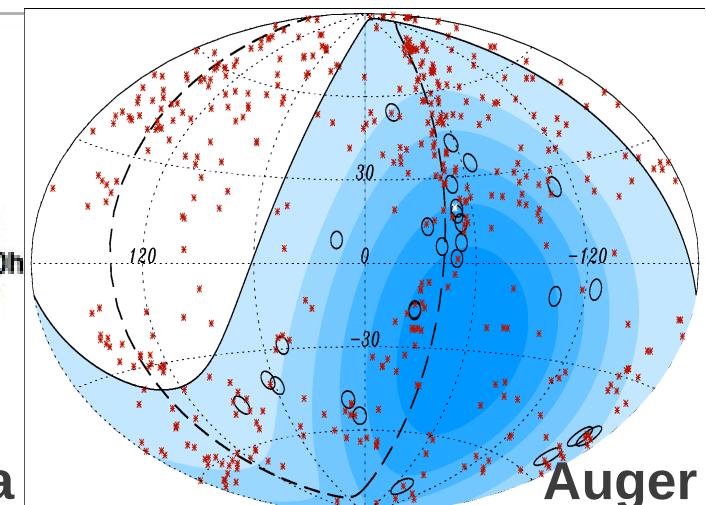
neutrinos

UHE Cosmic rays

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



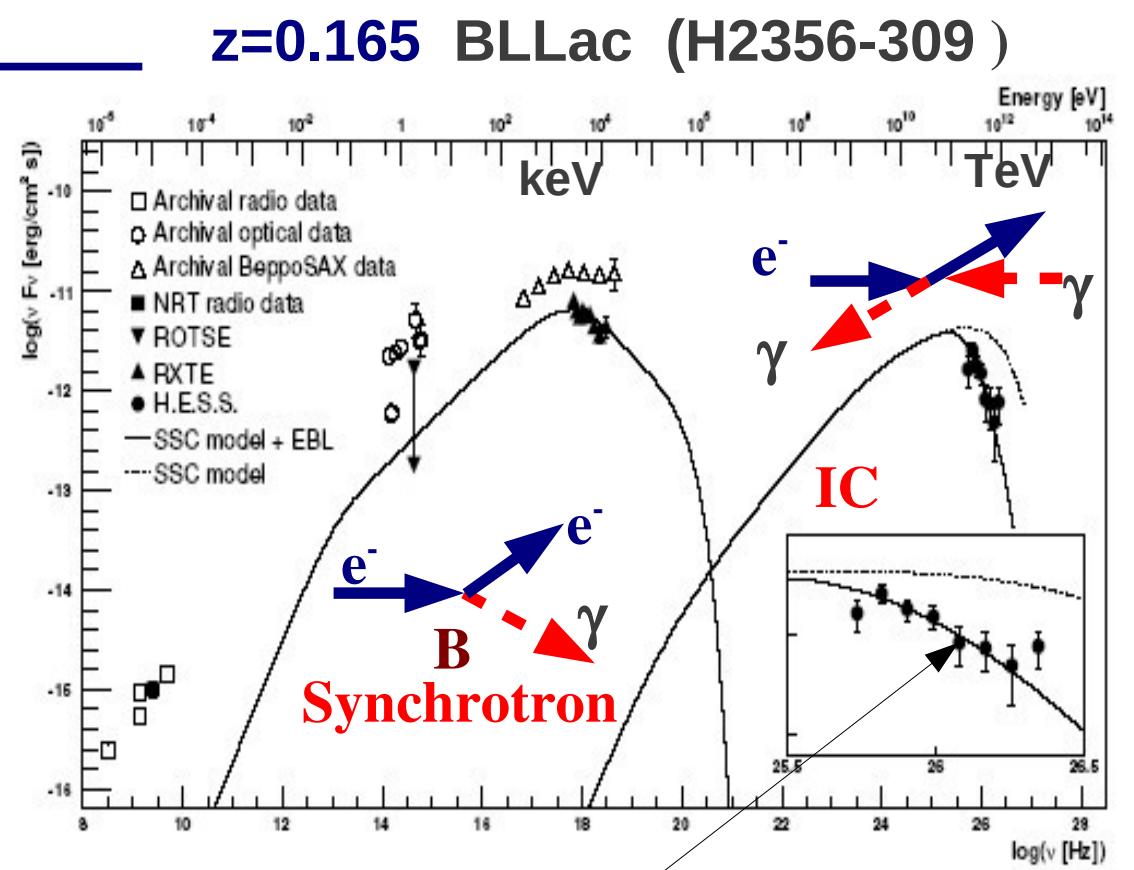
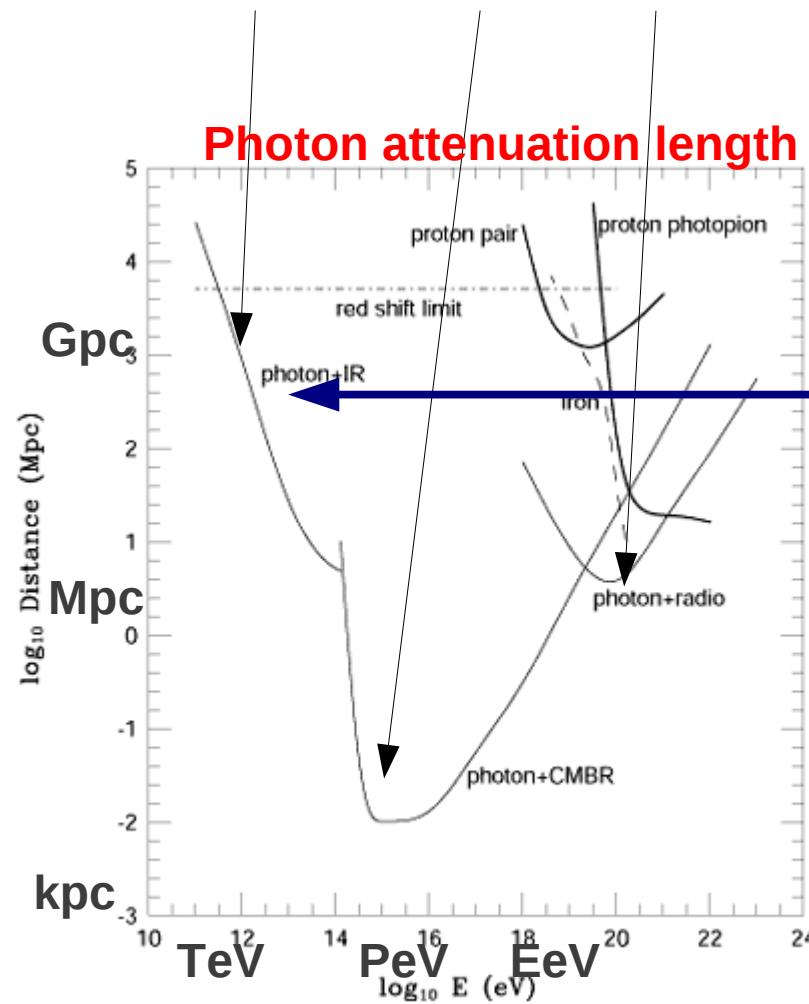
Amanda



Auger

But distant  $\gamma$  sources strongly attenuated by background photons

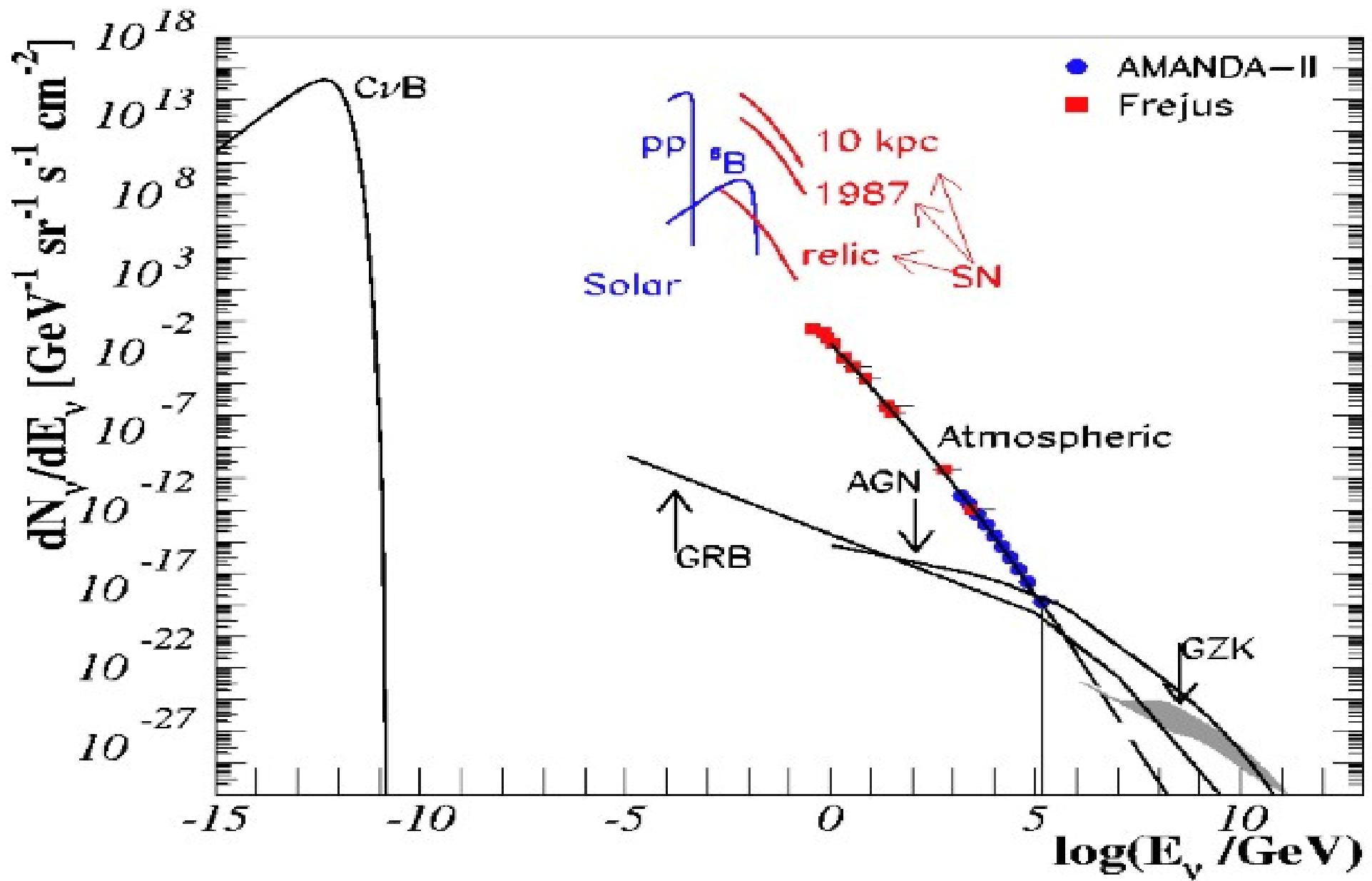
(starlight, CMB, radio, ...):  $\gamma\gamma_{bkg} \rightarrow e^+e^-$      $e\gamma_{bkg} \rightarrow e\gamma$     (em cascade)



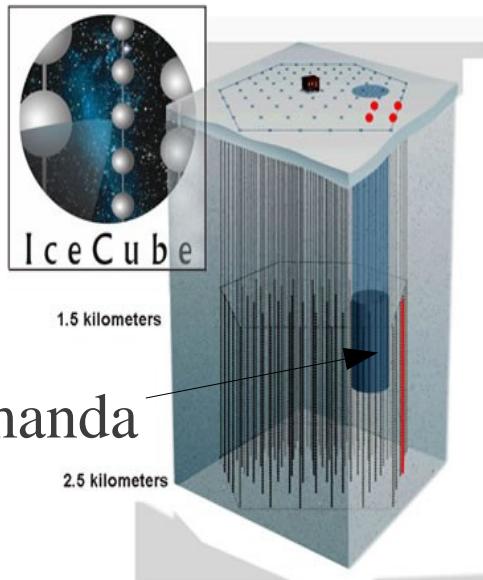
Can measure IR background from observed attenuation

beyond few TeV, high redshift Universe is unobservable with photons

# THE NEUTRINO SKY

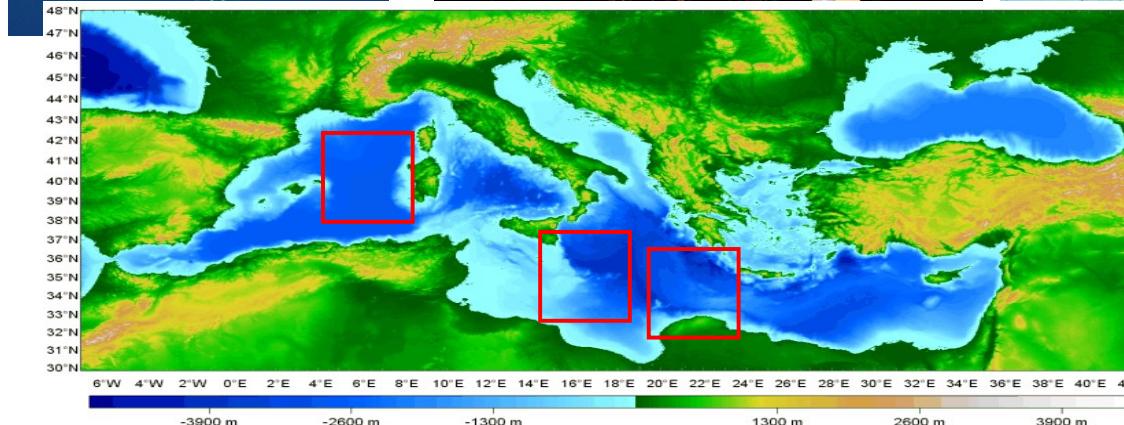


# NEUTRINO TELESCOPES (100 GeV to PeV and beyond)



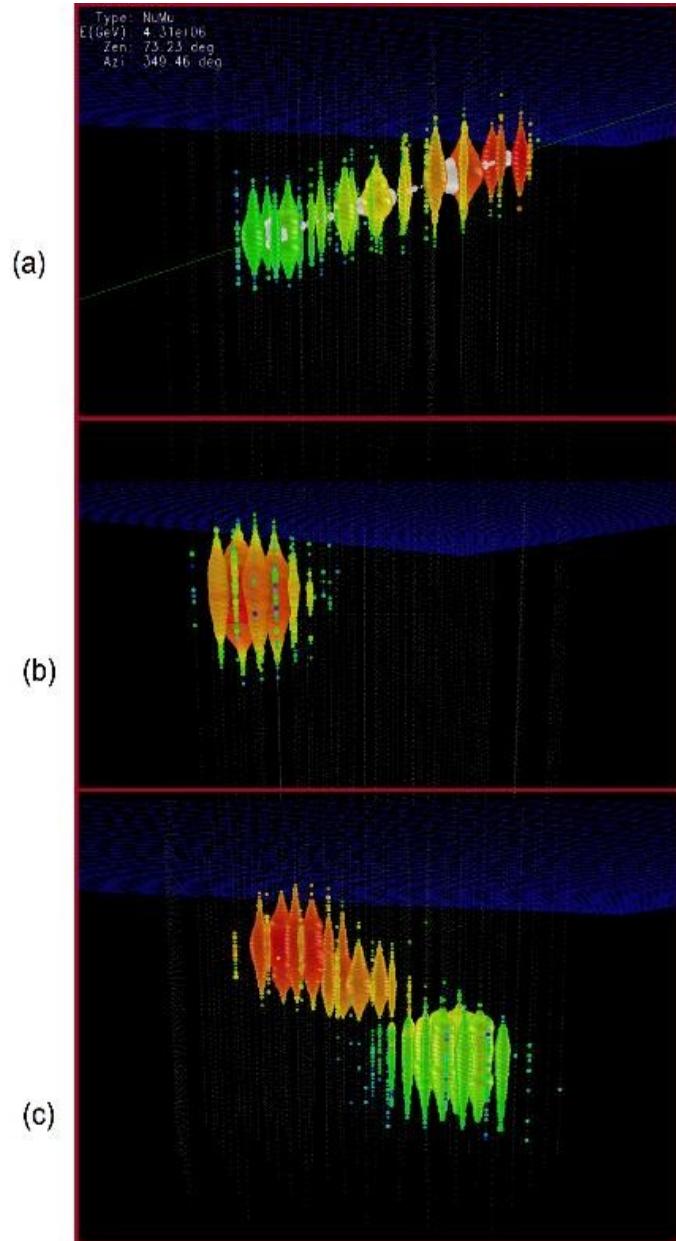
**km<sup>3</sup> detector at South Pole,  
completed by 2011,  
looking at northern  $\nu$  sky**

(and to southern sky above 40 TeV where Earth becomes opaque to  $\nu$ )



**km<sup>3</sup> detector at Mediterranean  
looking at southern neutrino  
sky (proposed km3NET  
& GVD in Baikal)**

# One may even distinguish neutrino flavors



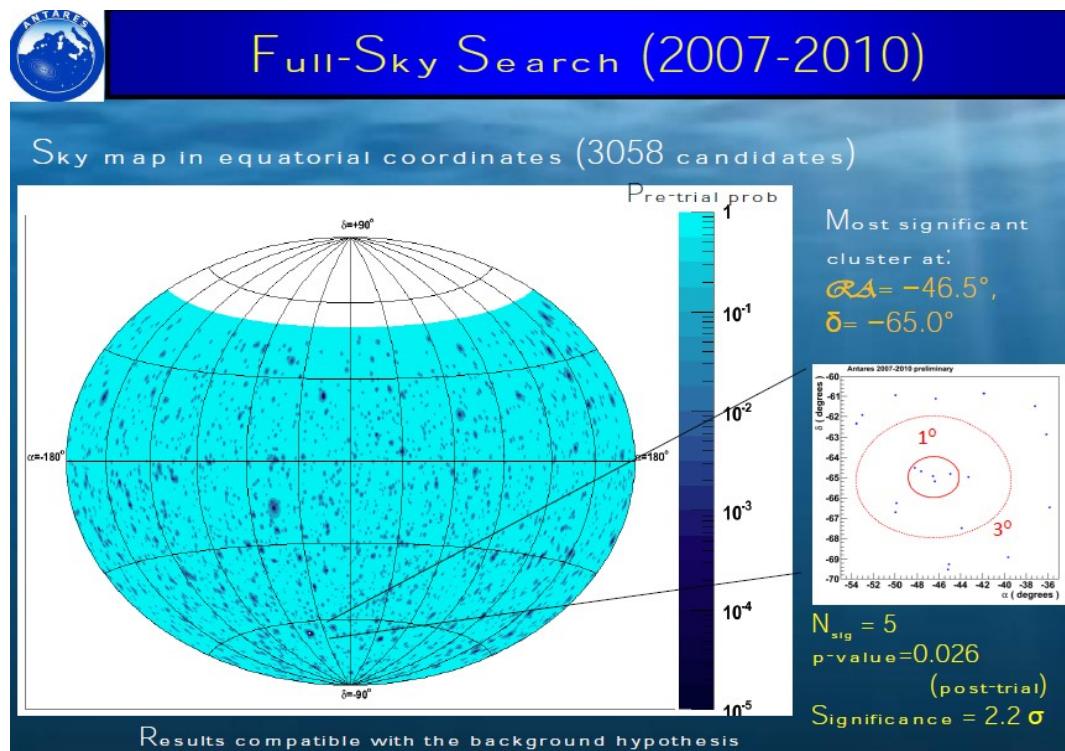
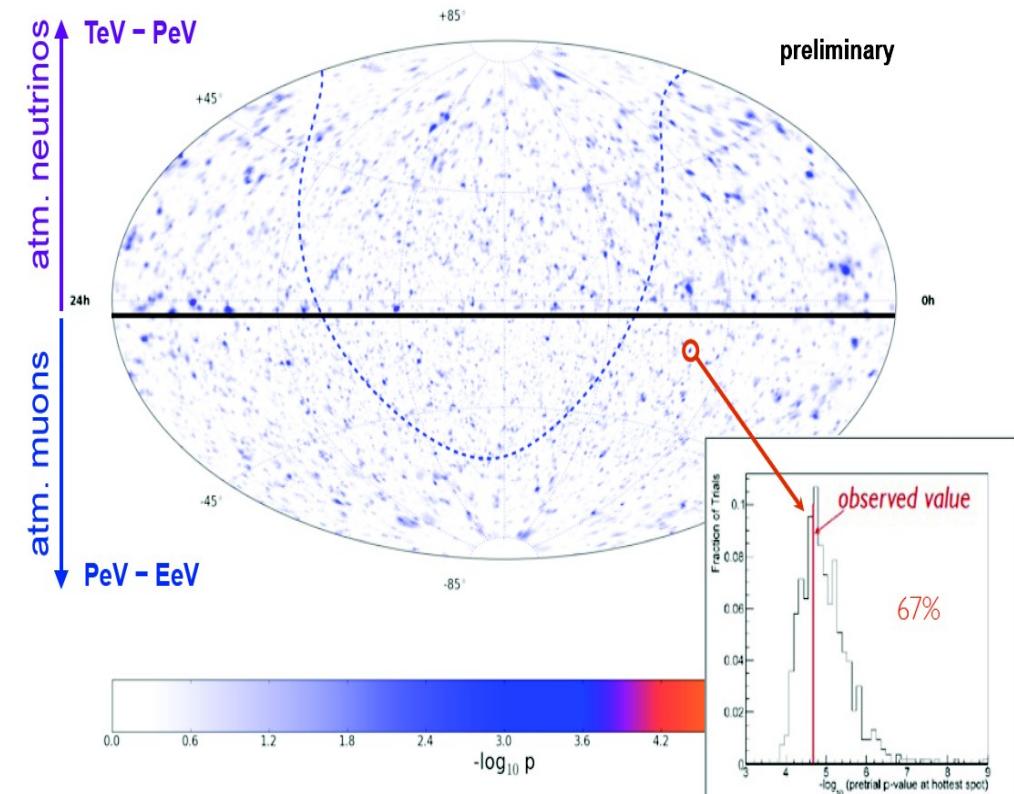
**muon neutrino (track)**

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

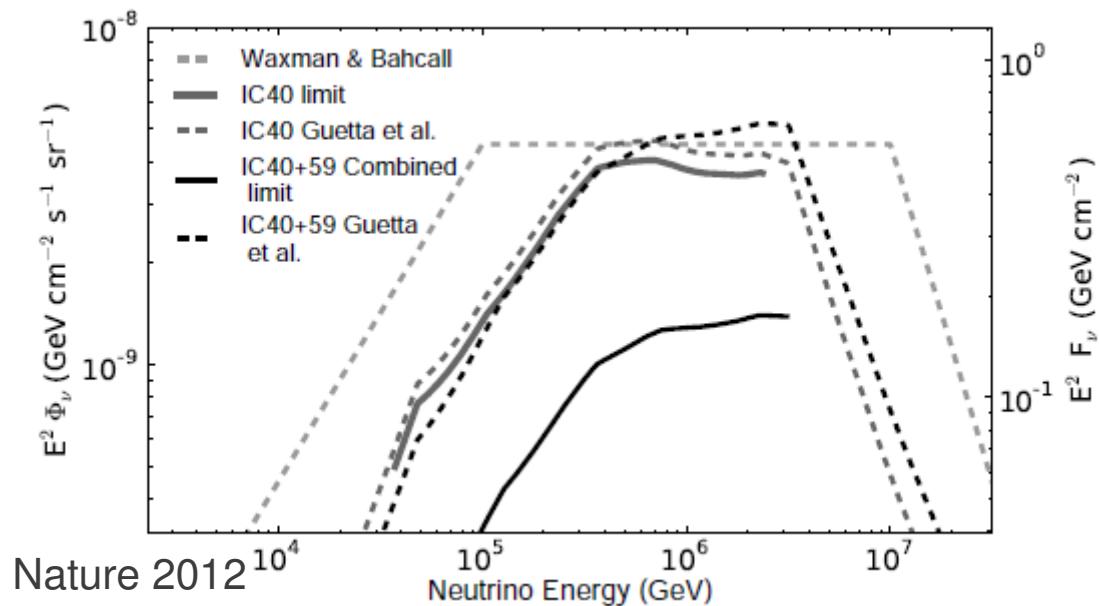
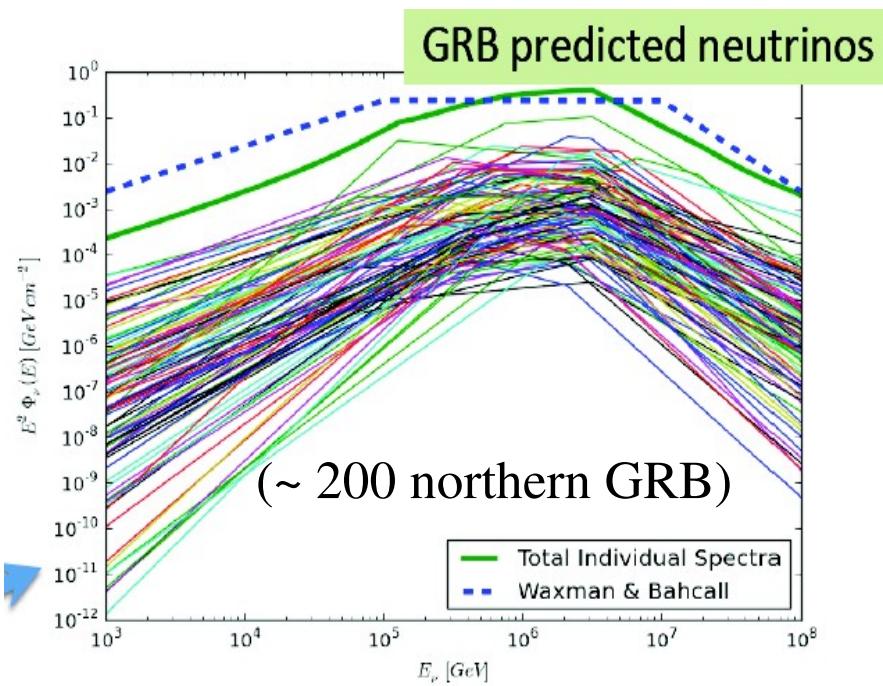
**tau neutrino (double bang)**



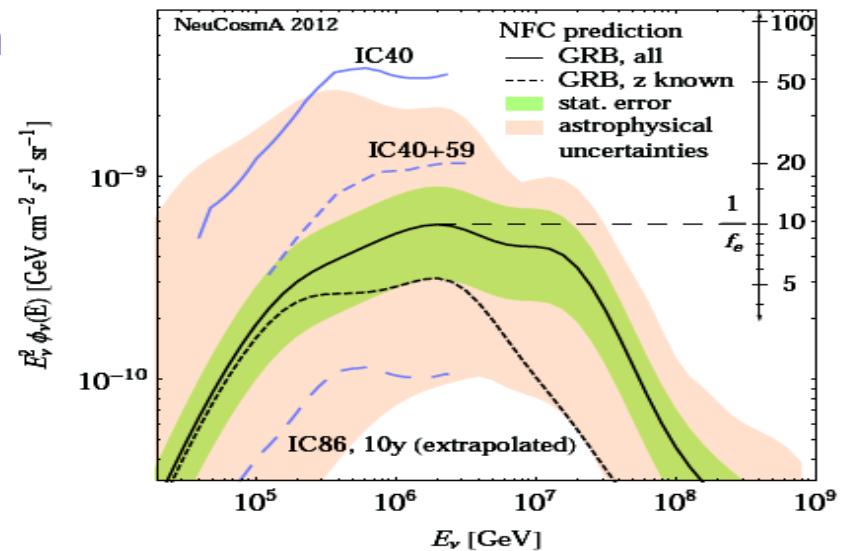
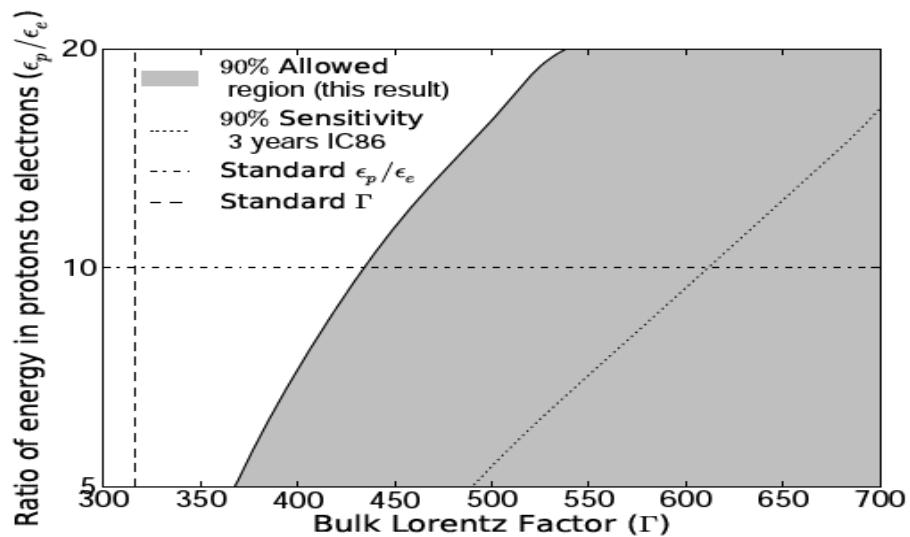
# No point sources observed by Icecube nor Antares



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

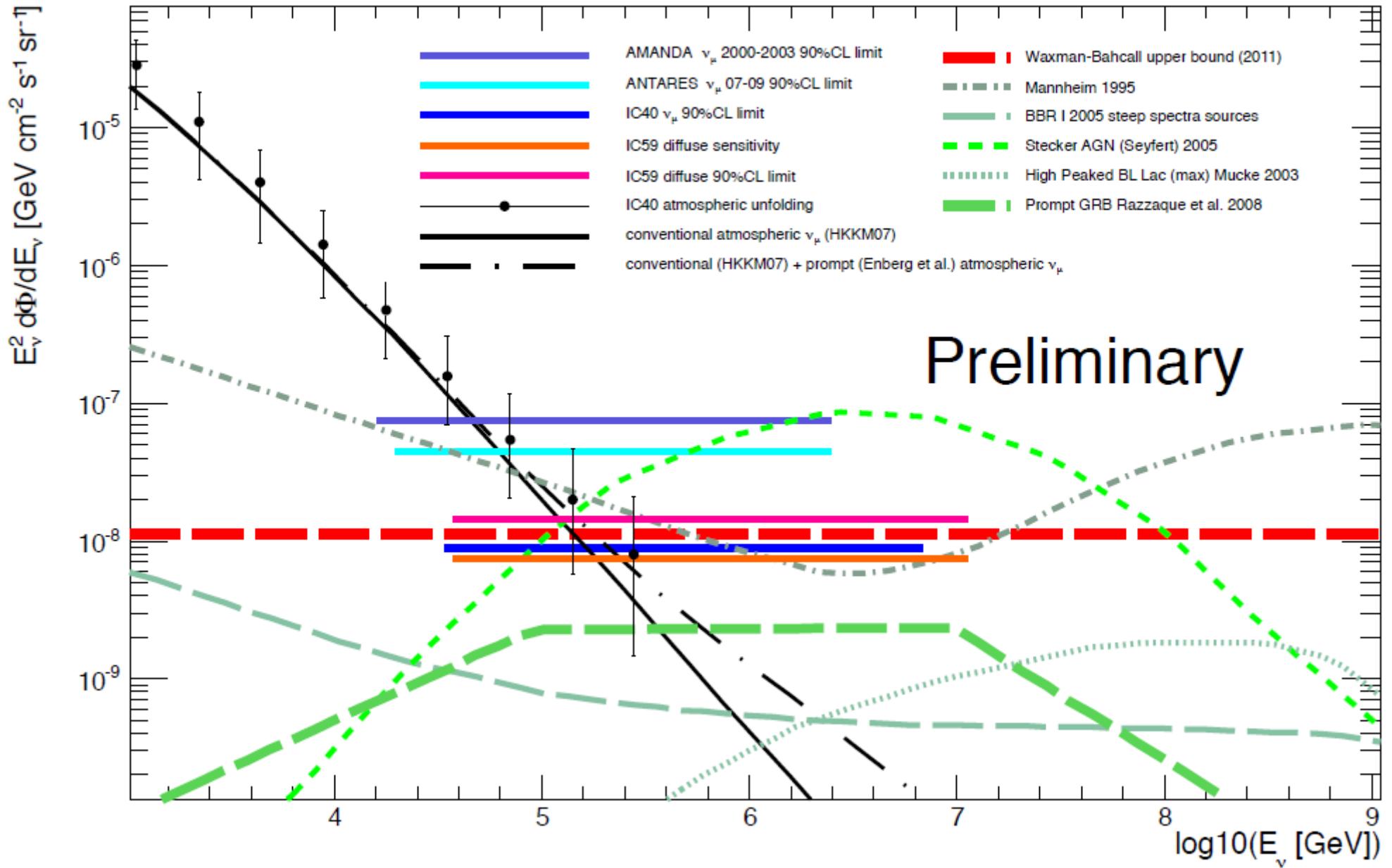


Bound factor 4 below standard predictions → GRB are not main source of UHECRs or production models need revision

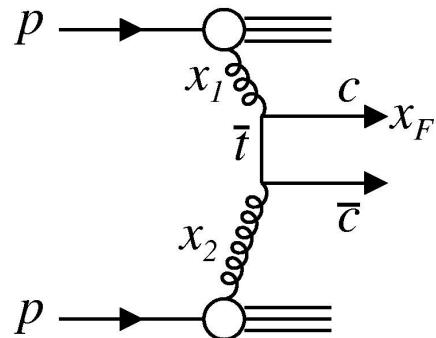


Revised model: (Hummer et al.):  
E losses, flavor mix, spectral shapes...

# ICECUBE 59 DIFFUSE BOUNDS 2012



# Prompt charm production



sample gluon density distribution at  $x_2 \simeq \frac{M_{cc}^2}{2x_F s}$   
 $\rightarrow x_2 < 10^{-5}$  for  $E > 10^{15}$  eV

need to extrapolate from measured values

also requires to include NLO processes

$E < \text{TeV} \rightarrow \nu$  mostly from  $\pi$  decays  
 $1 < E/\text{TeV} < 200 \rightarrow \nu$  mostly from K decays

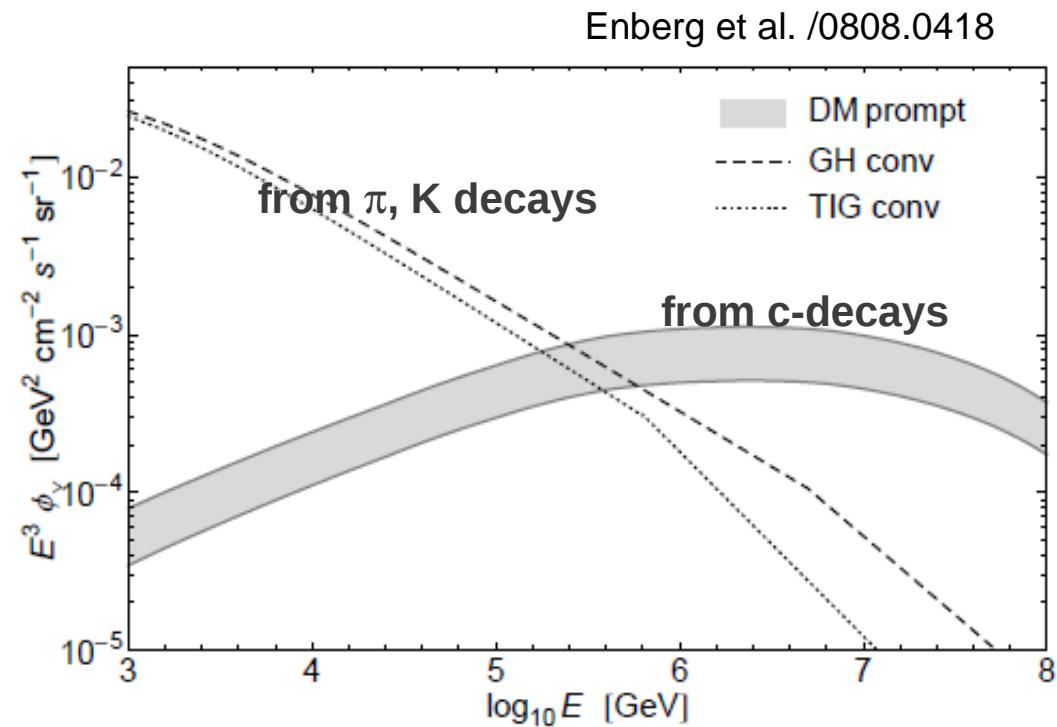
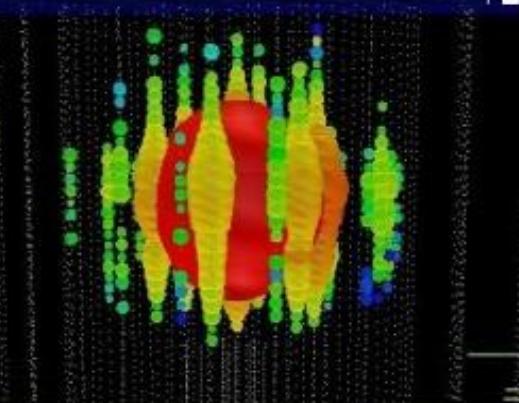


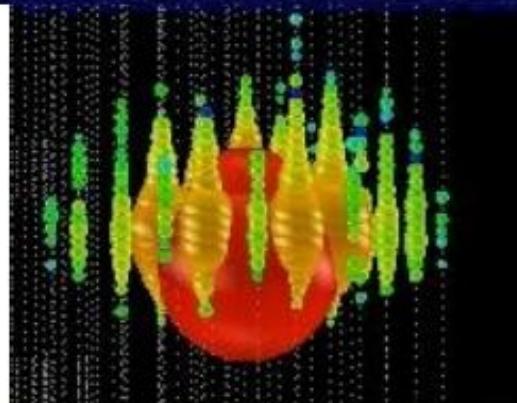
FIG. 5: Prompt and conventional  $\nu_\mu + \bar{\nu}_\mu$  fluxes in the vertical

# The two highest energy neutrino events observed by ICECUBE

Events are most likely neutrinos between 1 and 10 PeV



Run118545-Event63733662  
August 9<sup>th</sup> 2011  
NPE  $6.9928 \times 10^4$



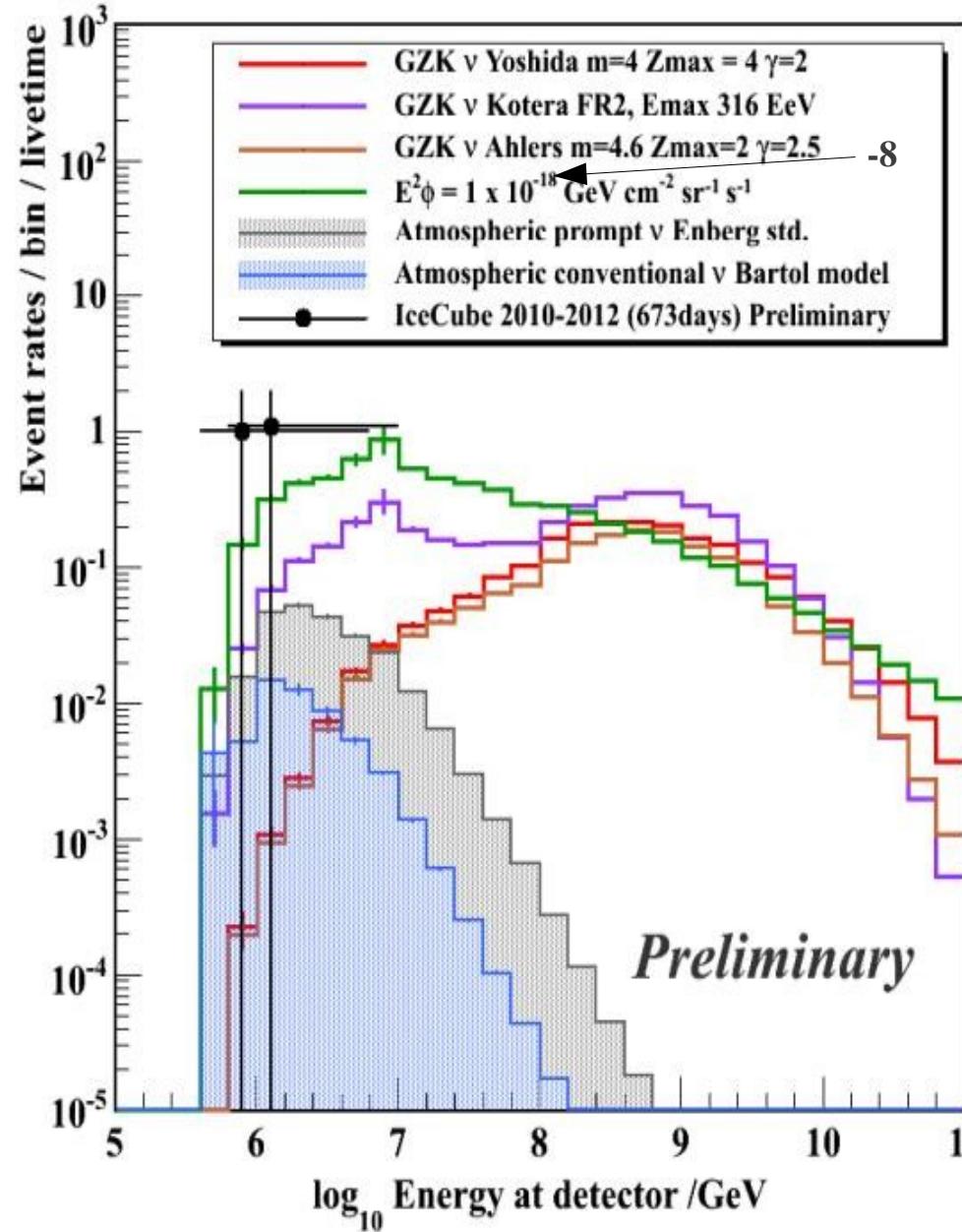
Run119316-Event36556705  
Jan 3<sup>rd</sup> 2012  
NPE  $9.628 \times 10^4$

## Possibility of the origin includes

- cosmogenic  $\nu$
  - on-site  $\nu$  production from the cosmic-ray accelerators
  - atmospheric prompt  $\nu$
  - atmospheric conventional  $\nu$
- but no coincident signals in ICE-Top

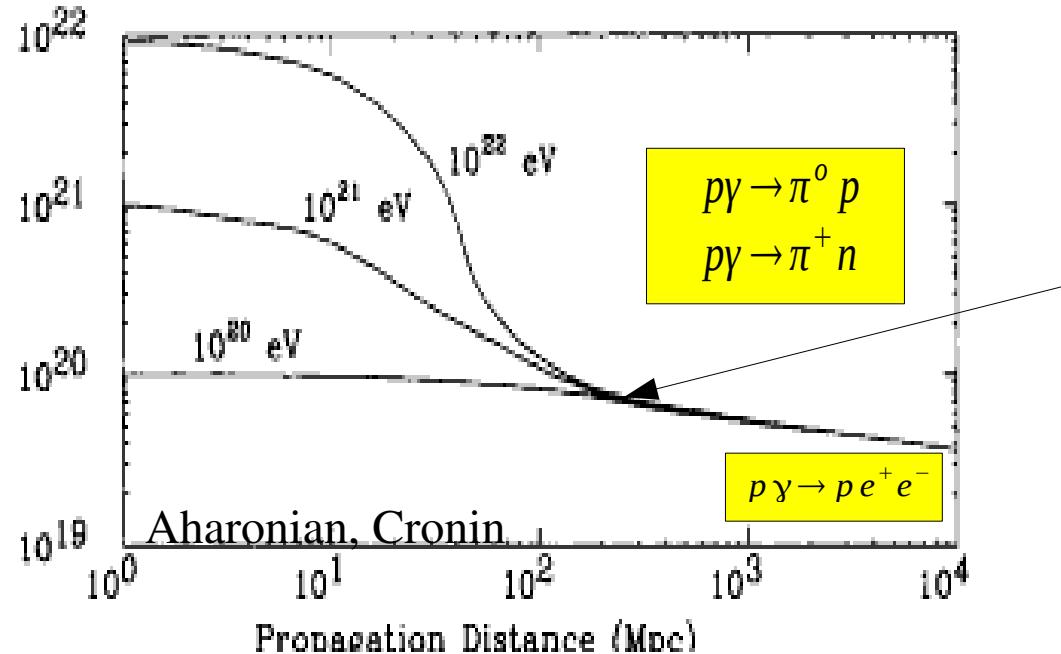
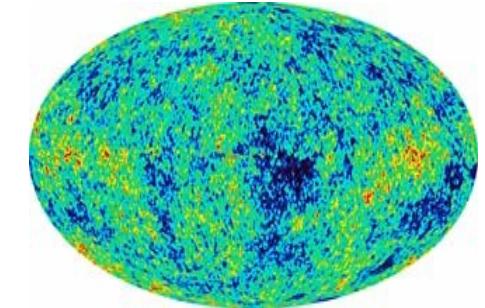
They are cascade events

## Energy Distributions 2010-12



# the Greisen-Zatsepin-Kuzmin effect (1966)

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

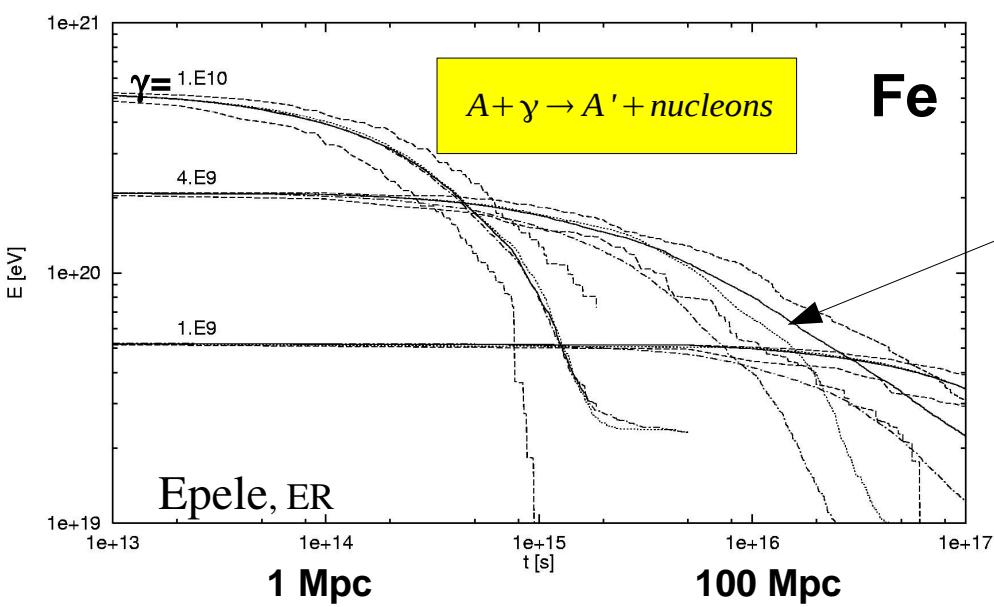


PROTONS CAN NOT ARRIVE WITH  
 $E > 6 \times 10^{19} \text{ eV}$  FROM  $D > 200 \text{ Mpc}$

( $\pi^0$  produce GZK photons)

( $\pi^+$  produce cosmogenic neutrinos)

(Berezinsky & Zatsepin 69)



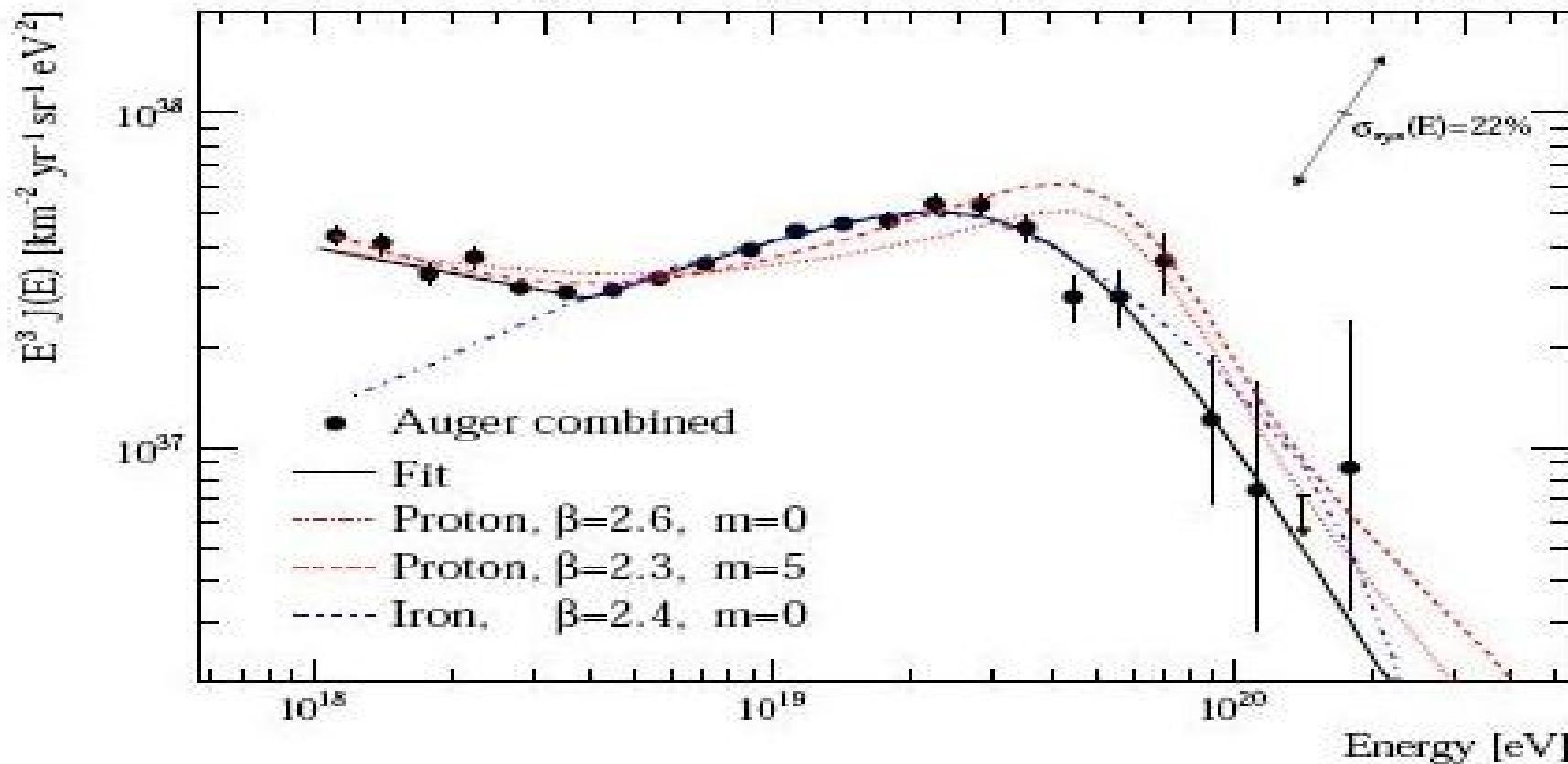
For Fe nuclei:  
after ~ 200 Mpc the leading  
fragment has  $E < 6 \times 10^{19} \text{ eV}$

lighter nuclei get disintegrated  
on shorter distances

# AUGER spectrum

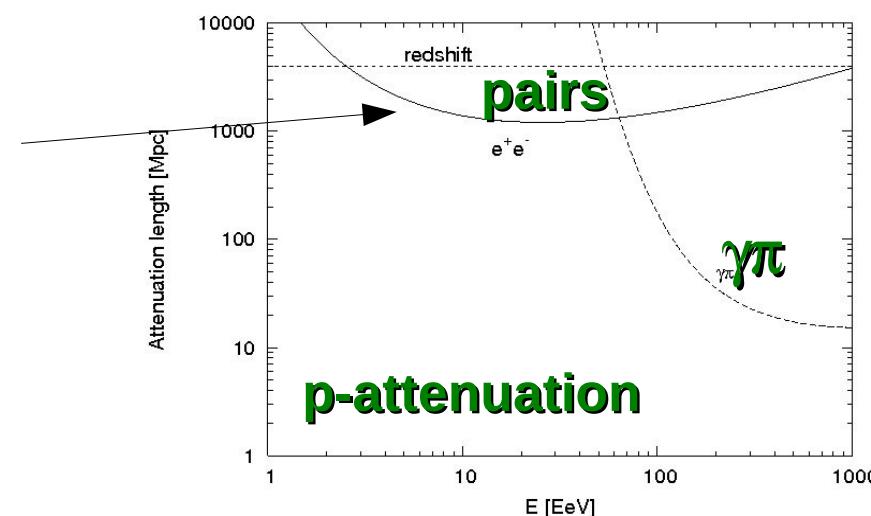
(ICRC09)

$\lg(E/\text{eV})$



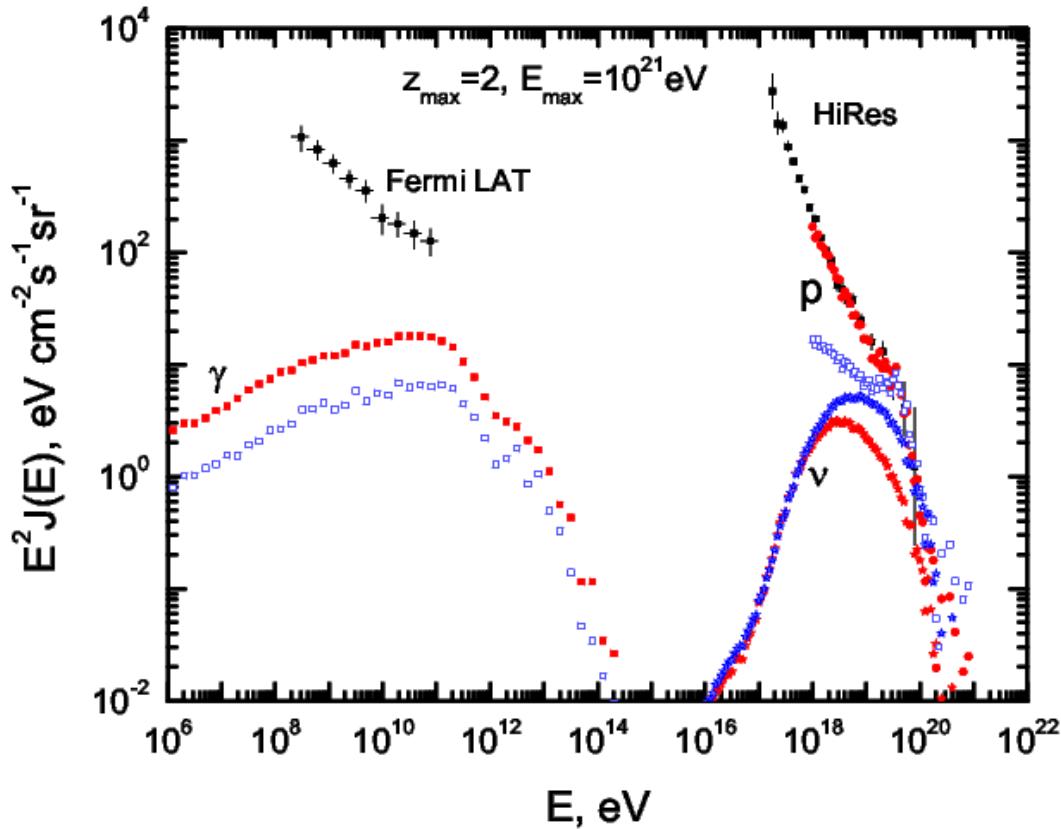
Ankle: Galactic – extragalactic transition  
or  $e^+e^-$  dip in Xgal protons ?

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

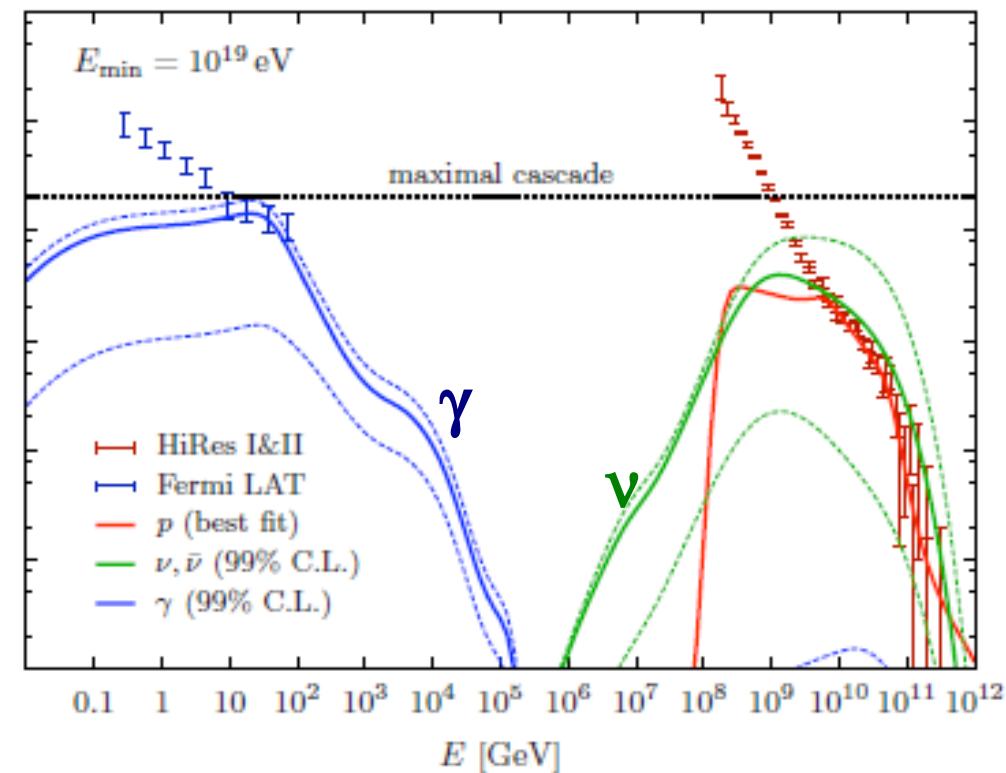


# COSMOGENIC NEUTRINO FLUXES:

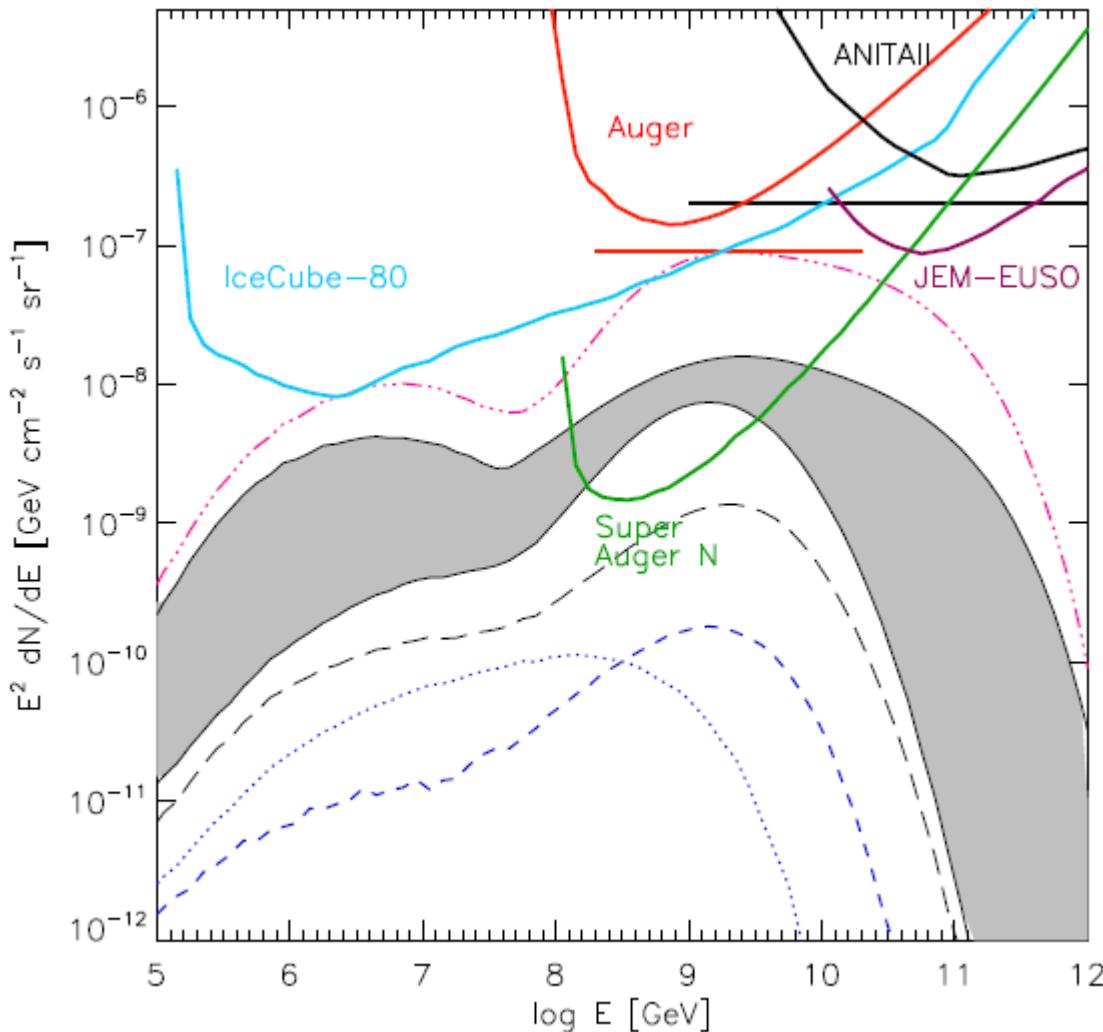
Berezinsky et al., arXiv:1003.1496



Ahlers et al., arXiv:1005.2620



- ankle models (harder fluxes) lead to larger cosmogenic neutrino fluxes than dip models
- fluxes at EeV comparable to CR fluxes, but cross section tiny ( $\sim 10 \text{ nb}$ )  $\rightarrow$  probability of interacting in atmosphere small ( $\sim 10^{-5}$  for vertical)



**Results depend on composition, spectral slope and cutoff, source redshift evolution UV/O/IR backg photons**

(Kotera, Allard & Olinto, 1009.1382)

# Cosmogenic neutrinos from proton sources:

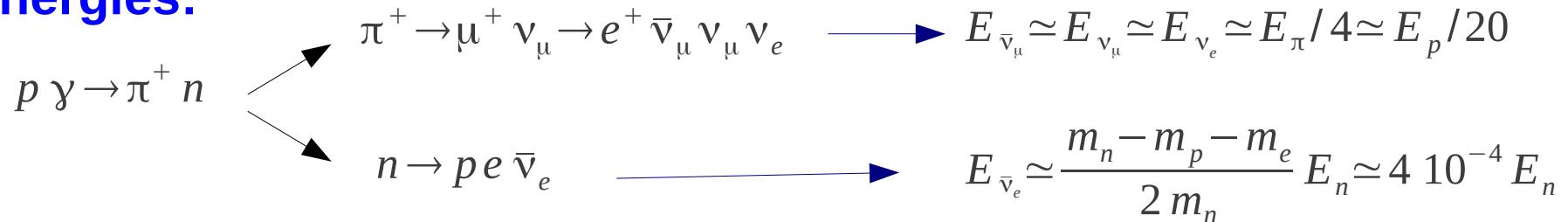
**Threshold:**  $p \gamma \rightarrow \pi^+ n$

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

→ **10<sup>20</sup> eV for CMB photons, 10<sup>17</sup> eV for optical photons**

strongly enhanced just above threshold: Δ resonance, steep spectrum

**ν energies:**



**Redshift (production at 0<z<4) :**

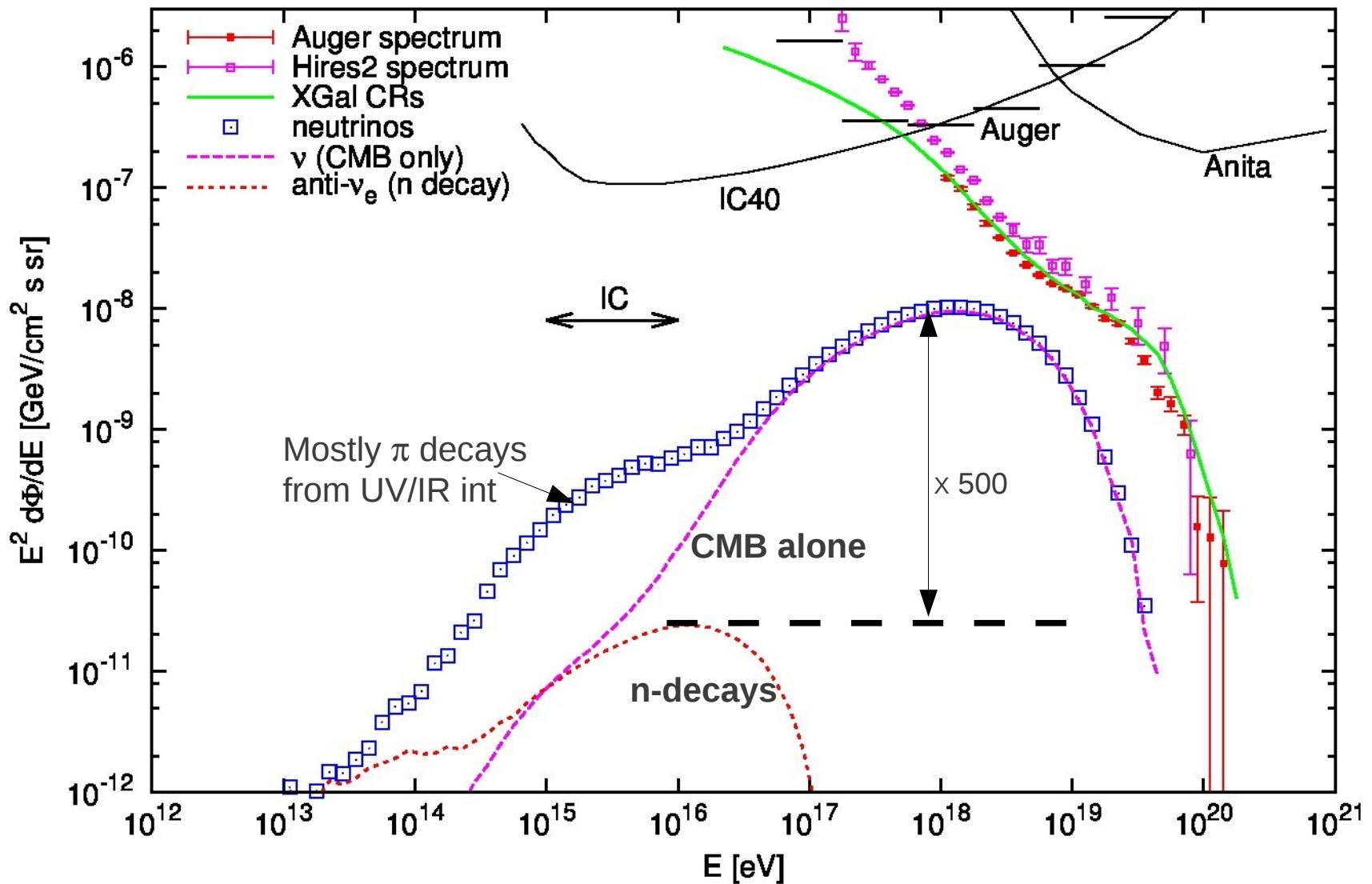
$$\text{Redshifted } \nu \text{ energy } E_\nu^{\pi-dec} \simeq \frac{E_p}{20(1+z)}$$

redshifted threshold: T<sub>CMB</sub> = (1+z) 2.7 K

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

**EeV ν from CMB photons**  
**PeV ν from UV/O/IR photons**

proton sources,  $\alpha=2.4$ ,  $E_{\text{max}}=200 \text{ EeV}$ , GRB2



Height of EeV  $\nu$  peak from  $\pi$ -decay related to height of PeV  $\nu$  peak from  $n$ -decay

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

# Cascade photon bound

(Berezinsky & Smirnov 1975)

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

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

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

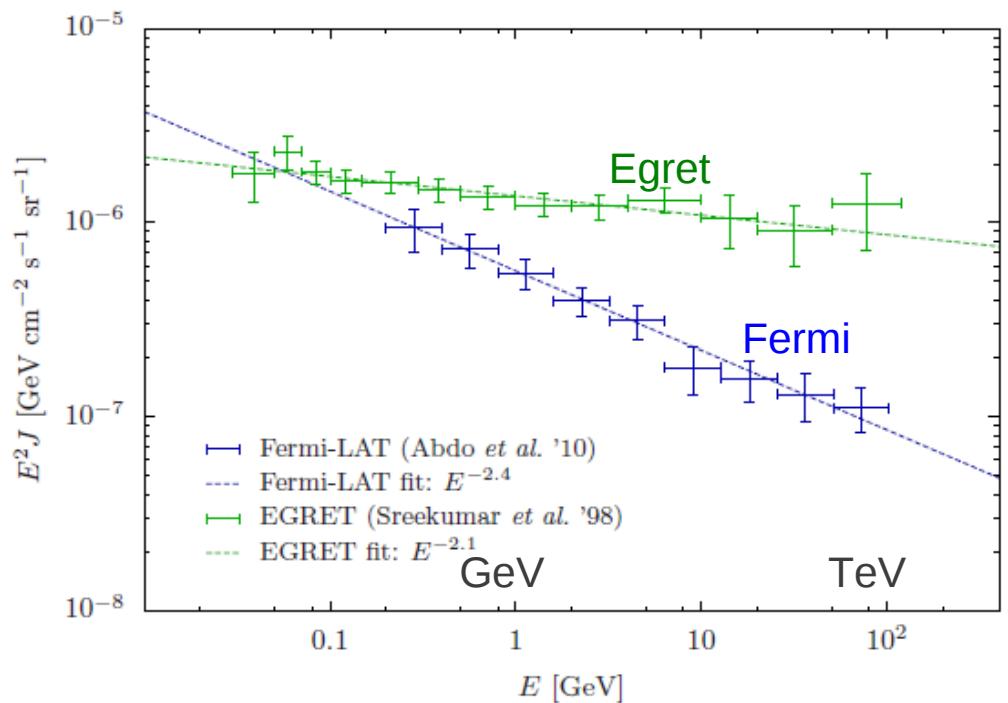
$$e \gamma_{bckg} \rightarrow e \gamma$$

Cascades down to GeV-TeV

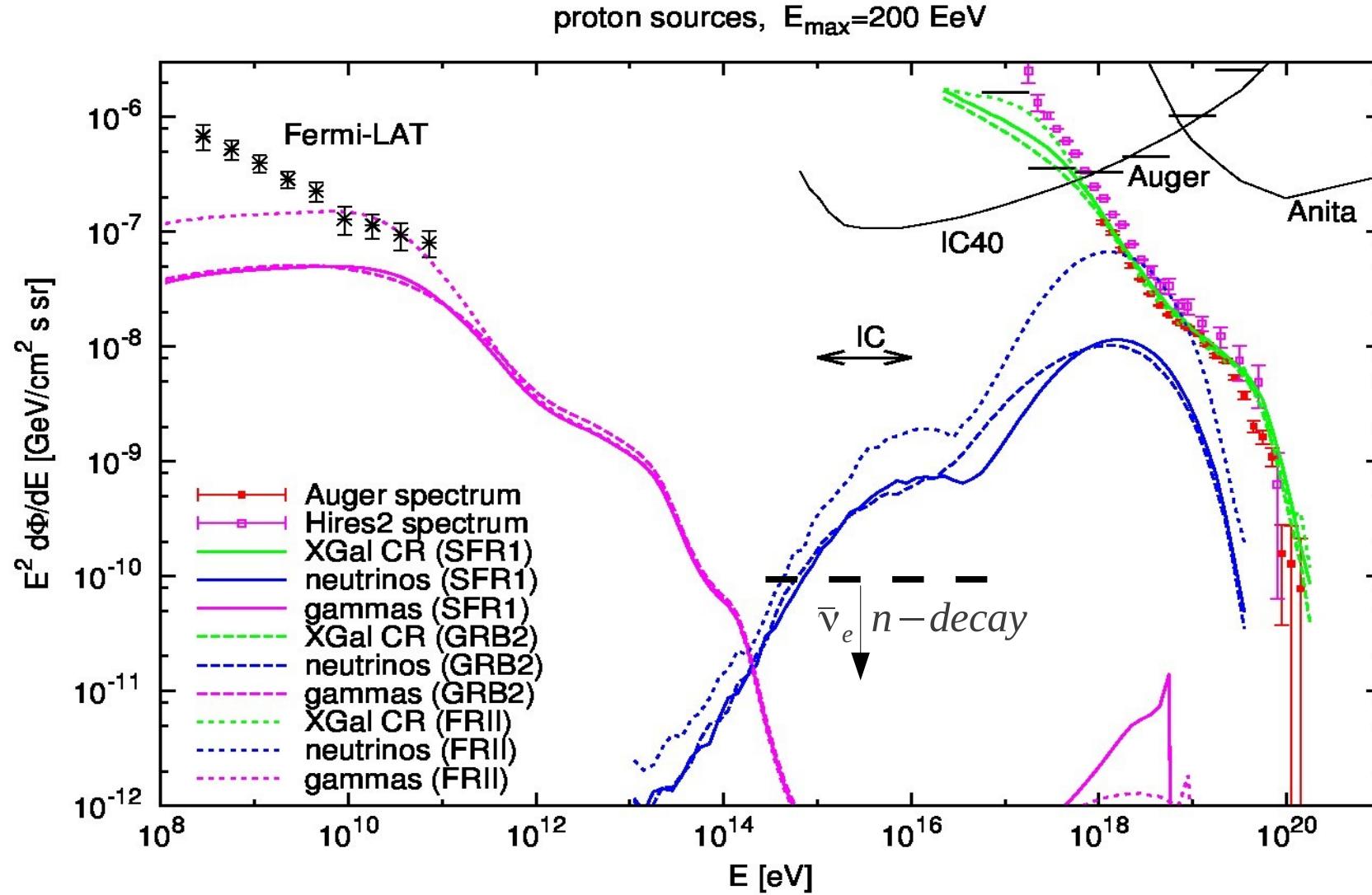
Total energy in GeV-TeV  $\gamma$  from  $\pi^0 \sim$  total energy in  $\nu$  from  $\pi^+$

Also:  $p \gamma \rightarrow p e^+ e^-$  this adds to GeV-TeV photons, specially in dip models

GeV diffuse  $\gamma$  background measured by Fermi-LAT



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

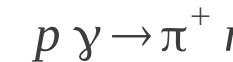
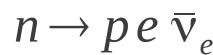


$$\left[ E_\nu^2 \frac{d\Phi_{all\nu}}{dE} \right]_{E_\nu=10^{18}\text{ eV}} < 5 \times 10^{-8} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}} \Rightarrow \left[ E_\nu^2 \frac{d\Phi_{\bar{\nu}_e}}{dE} \right]_{E_\nu=6 \times 10^{15}\text{ eV}}^{n-dec} < 10^{-10} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}$$

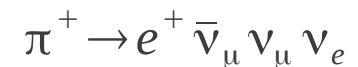
$\nu_e$  flux from n-decay tiny at PeV (contradicts arXiv 1207.4571)

## Cosmogenic neutrinos from nuclei:

**photo-disintegration:**  $A \gamma \rightarrow A' + \text{nucleons}$



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



**Threshold:**

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

For Fe, similar cutoff as p

lighter nuclei  $\rightarrow$  smaller cutoffs

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

For  $E/A > 10^{17} \text{ eV}$ , nuclei disintegrate 'a lot'

$\rightarrow$  many low energy neutrinos from n-decays

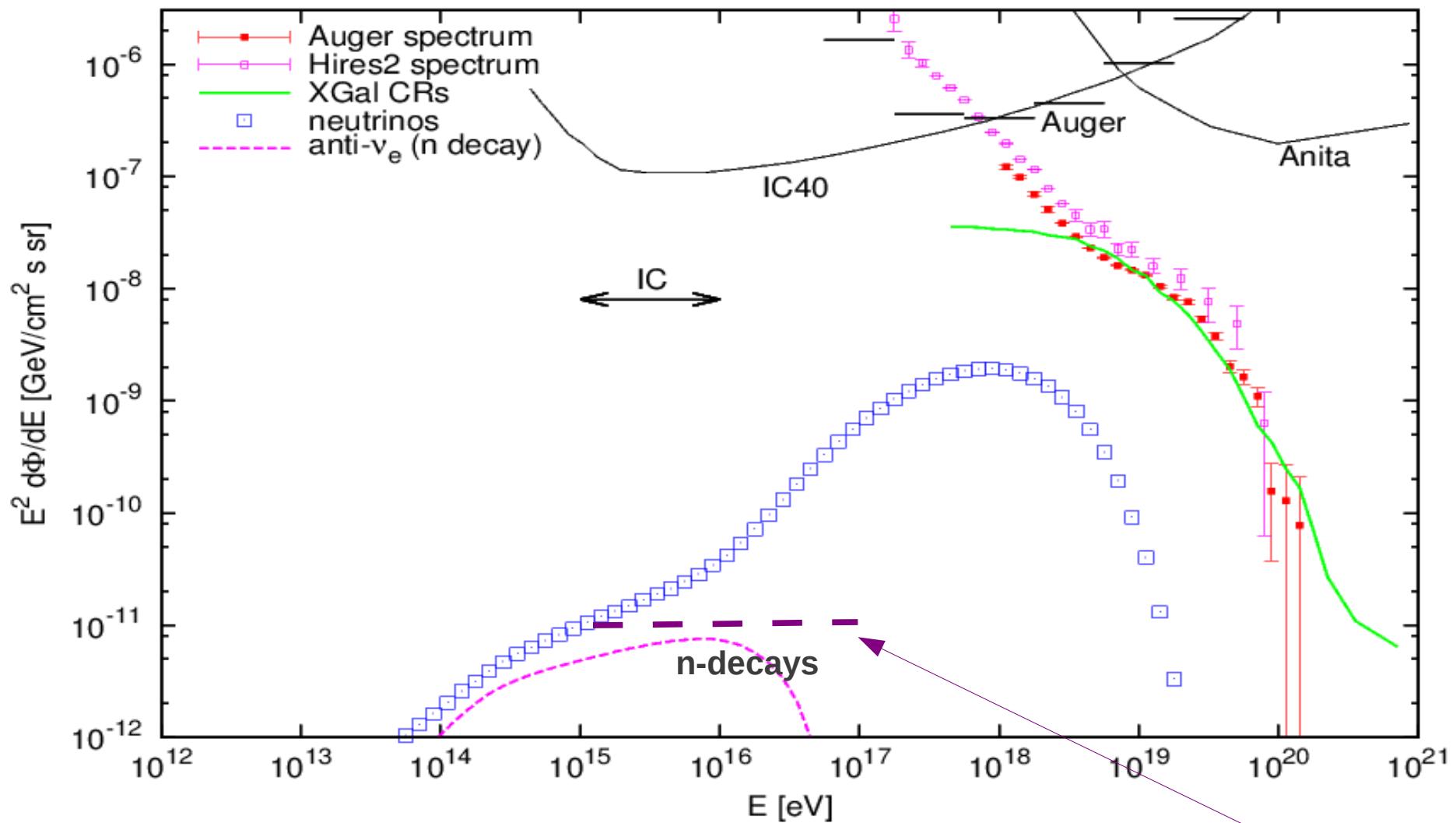
$$E_\nu \simeq 4 \cdot 10^{-4} E/A$$

Secondary nucleons with  $E/A$  interact producing pions

for  $E/A < 10^{17} \text{ eV}$ , even for  $z \sim 1$  interaction probabilities small

$\rightarrow$  few nuclei disintegrate, fewer nuclei emit pions, but those dominate neutrino PeV fluxes

Fe sources,  $\alpha=2.0$ ,  $E_{\text{max}}=5200 \text{ EeV}$ , GRB2

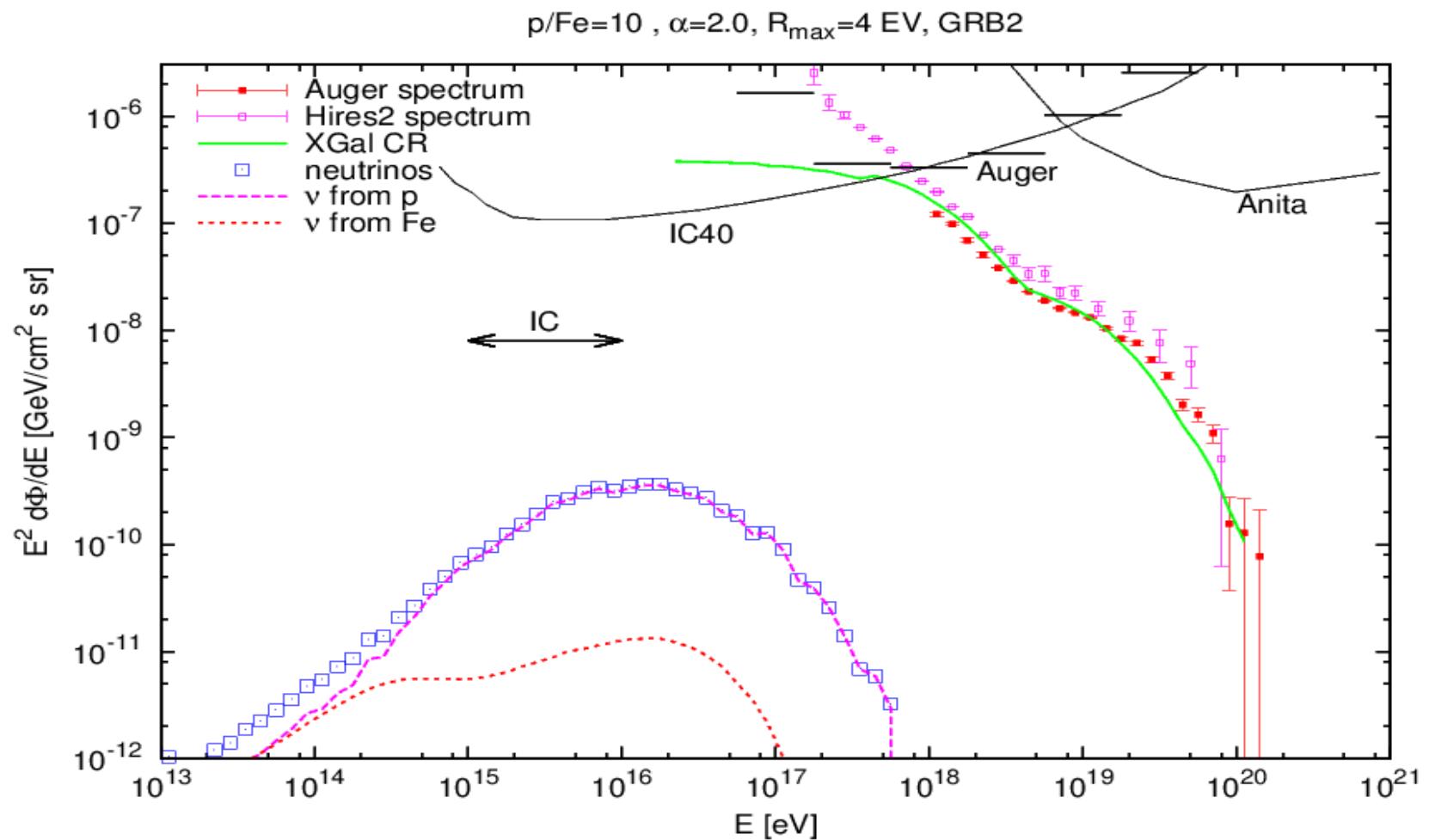


$$\left[ \frac{d\Phi_{\bar{\nu}_e}}{d\log E} \right]_{E_\nu=10^{15} \text{ eV}}^{n-\text{dec}} \gtrsim \left[ \frac{d\Phi_{n'}}{d\log E} \right]_{E=2 \cdot 10^{18} \text{ eV}} < \left[ \frac{1}{2} \frac{d\Phi_{CR}}{d\log E} \right]_{E=2 \cdot 10^{18} \text{ eV}} \Rightarrow \left[ E_\nu^2 \frac{d\Phi_{\bar{\nu}_e}}{dE}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

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

# Mixed p / Fe composition with low cutoff

(disappointing model,  
Aloiso et al. 2011)



**p component below ankle leads to significant PeV  $\nu$  fluxes from  $\pi$ -decay  
no EeV  $\nu$  due to low cutoff**

# Flavor oscillations

## Incoherent flavor conversions

(Pakvasa et al 2008)

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

$\pi$ - decays:  $(v_e : v_\mu : v_\tau) = (1:1:0) \rightarrow (0.78:0.61:0.61)$  (adopting TBM)  
 $(\bar{v}_e : \bar{v}_\mu : \bar{v}_\tau) = (0:1:0) \rightarrow (0.22:0.39:0.39)$   $\sin^2 \Theta_{23} \simeq 1/2$

$n$ - decays:  $(v_e : v_\mu : v_\tau) = (0:0:0) \rightarrow (0:0:0)$   $\sin^2 \Theta_{12} \simeq 1/3$   
 $(\bar{v}_e : \bar{v}_\mu : \bar{v}_\tau) = (1:0:0) \rightarrow (0.56:0.22:0.22)$   $\sin^2 \Theta_{13} \simeq 0$

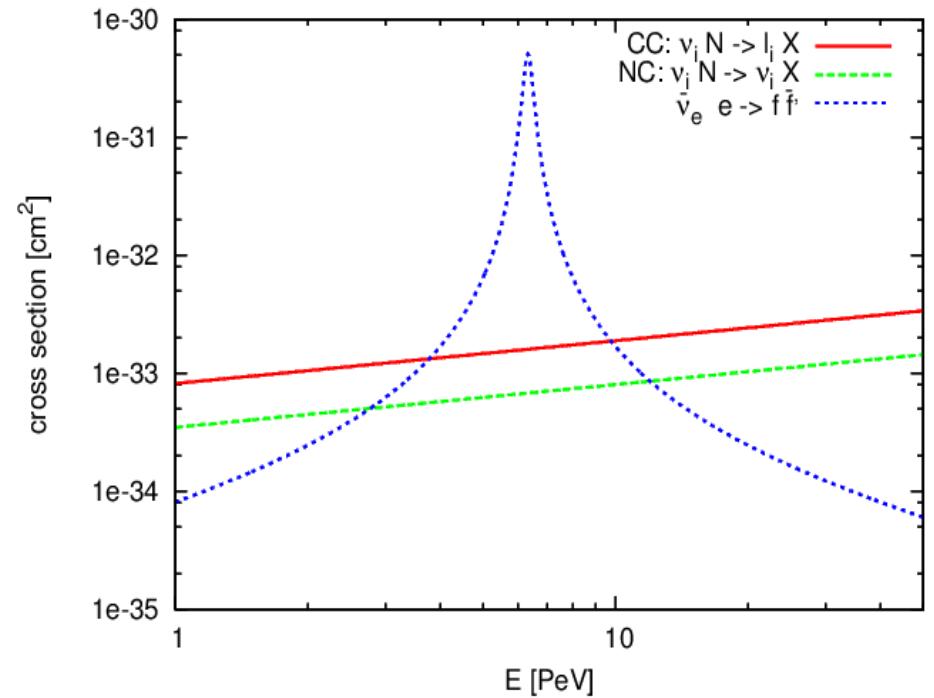
# THE GLASHOW RESONANCE

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

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

at the peak,

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



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

→ overall contribution to the IceCube rates of  $\nu$  from  $\pi$ -decays similar to the CC+NC ones within 2.5 PeV of the resonance

## CONCLUSIONS

Detection of  $2\nu$  with 1-10 PeV opened a new era for  $\nu$  astronomy

- are they atmospheric ? (enhanced by charm production)
- are they produced at the sources ? (GRB, AGN, ...)
- are they cosmogenic ? (produced during propagation of Crs)

Significant PeV fluxes can arise from  $10^{16} - 10^{17}$  eV protons producing  $\pi$  in interactions with UV/IR radiation

Cosmogenic neutrinos from n-decays tiny at PeV energies

Largest flux in p scenarios with steep spectra (more p with  $10^{17}$  eV)

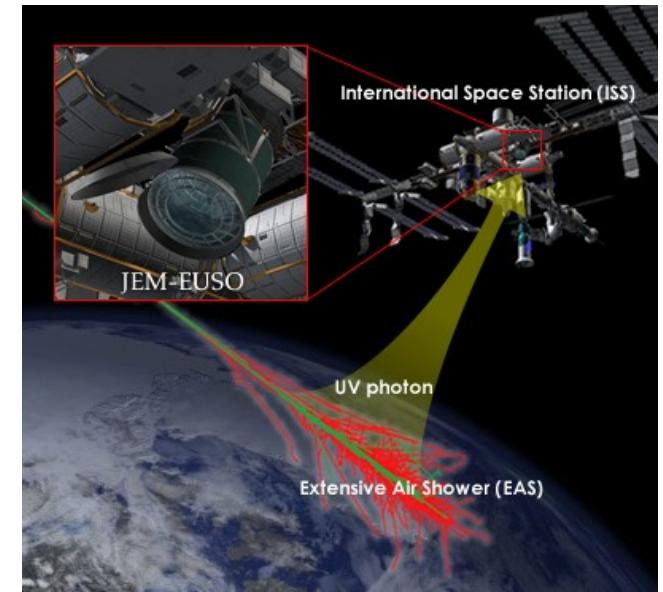
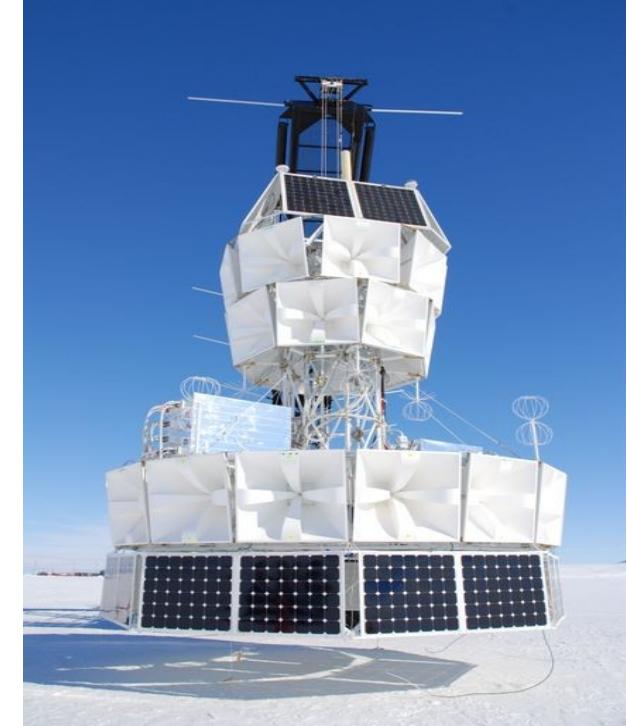
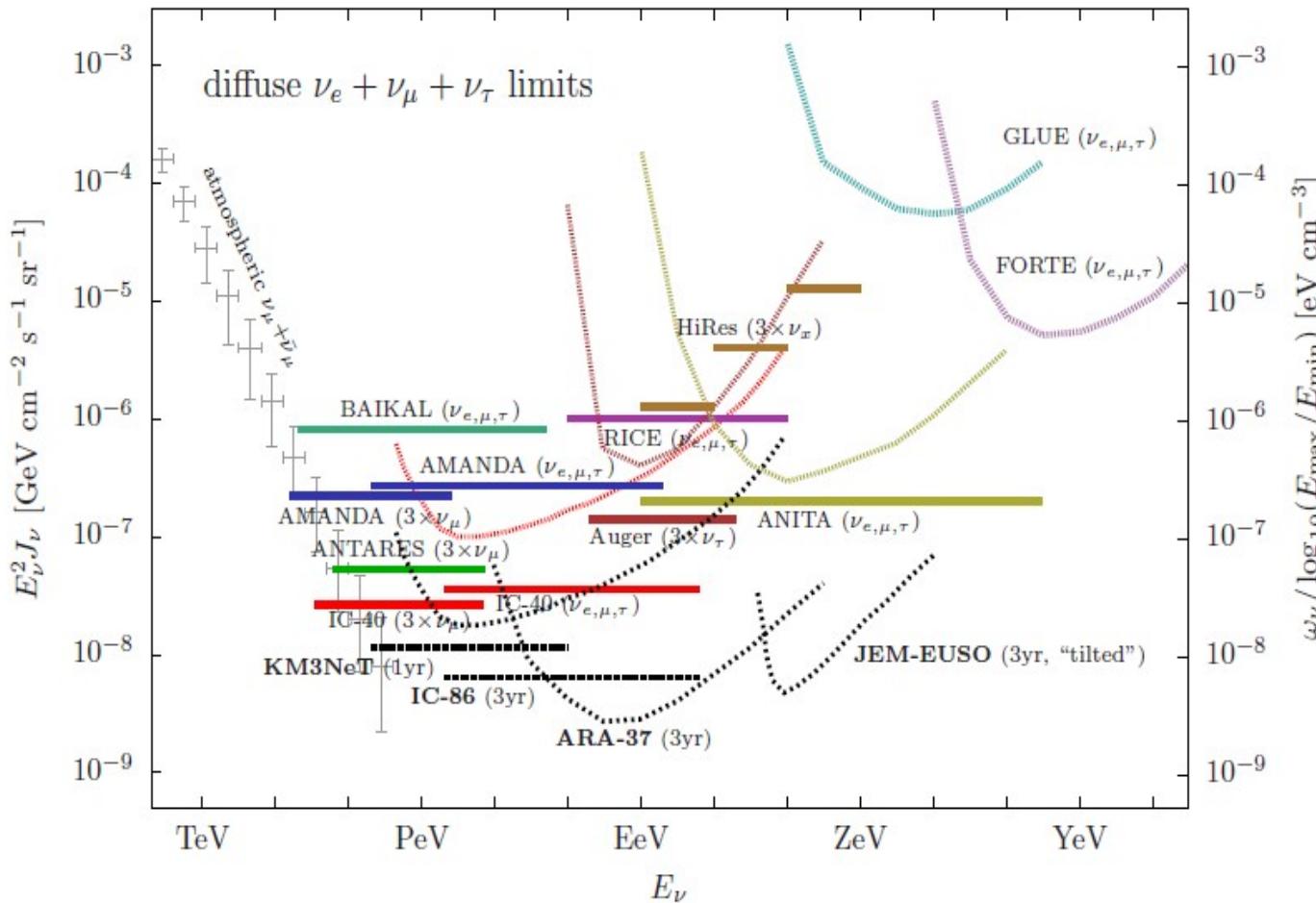
Glashow resonance has moderate impact (narrow width, only anti- $\nu_e$ )

Much larger data set expected soon (IC86)

# LOOKING TO $\nu$ FROM THE SKY

ANITA looked for up-going neutrino showers on ice producing radio coherent emission (Askaryan effect)  
 ~ 1 month balloon flights in Antarctica  
 → next generation: EVA ? (x 100 better)

**ARA: Askaryan Radio Array  
 (prototype deployment in 2011)**



or from the space station?  
 → JEM-EUSO