Unveiling the Origin of Neutrinos Observed by IceCube

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IAP Seminar
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Outline

Previous extraterrestrial neutrinos from SN1987A

MeV=10^6 eV neutrinos

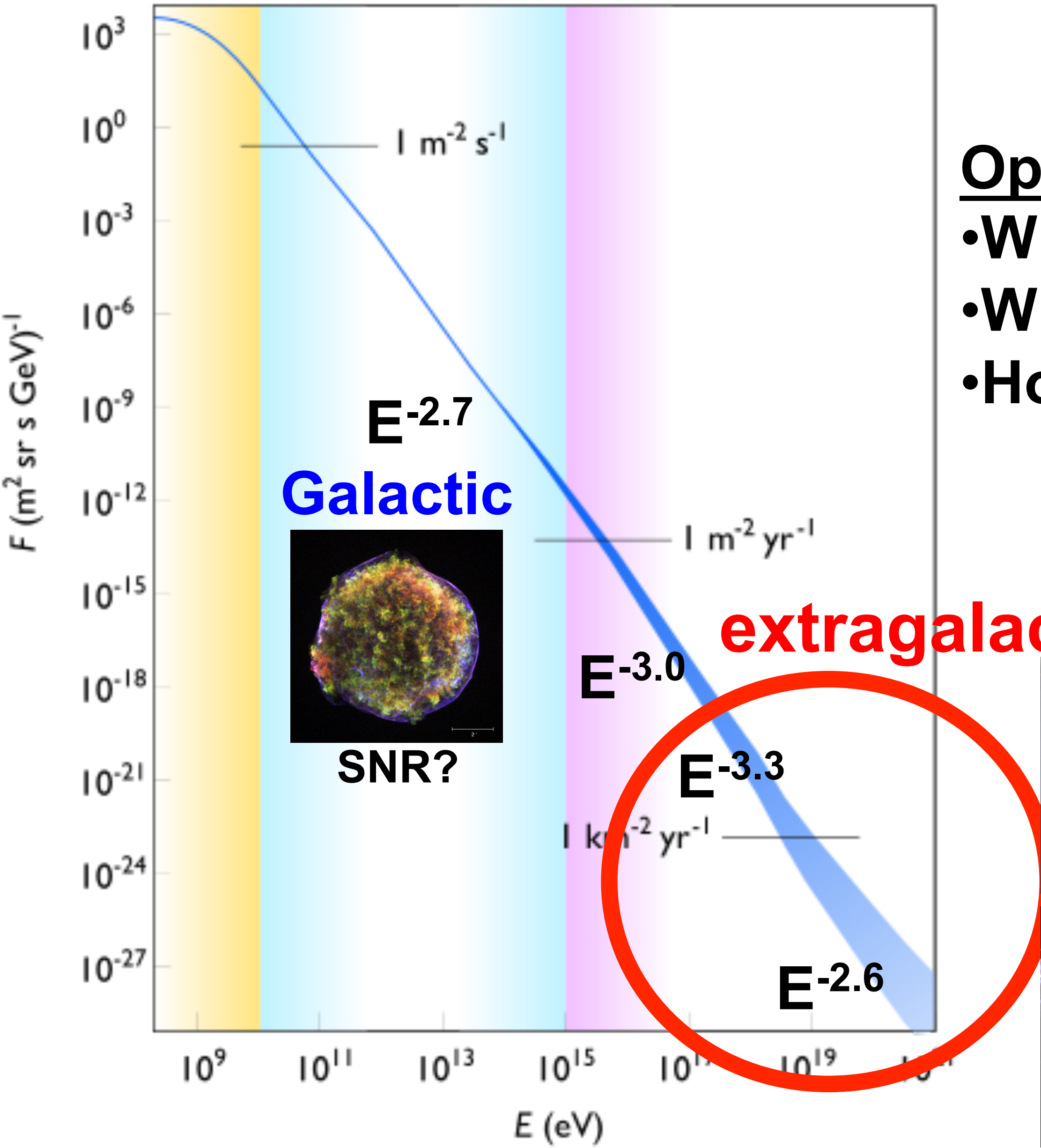
M. Koshiba
(Nobel prize)

Now PeV=10^{15} eV

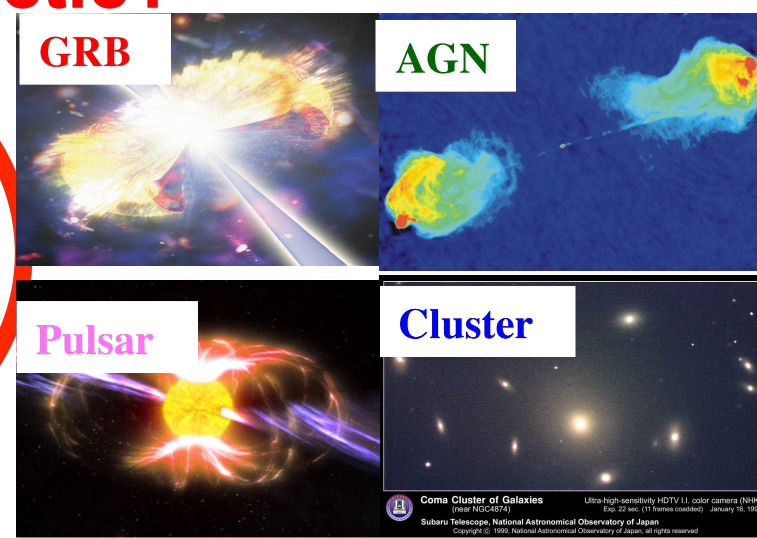
1. Introduction
2. Demystifying the PeV neutrino origin
3. Multi-messenger tests

Introductory talk (for details, directly ask me later)

Motivation: Identifying Cosmic-Ray Accelerators



<u>Open problems</u>
- **What is the origin?**
- **Where is the transition?**
- **How are CRs accelerated?**



- **Neutrinos**
  direct probe of ion acceleration (straight, negligible absorption)

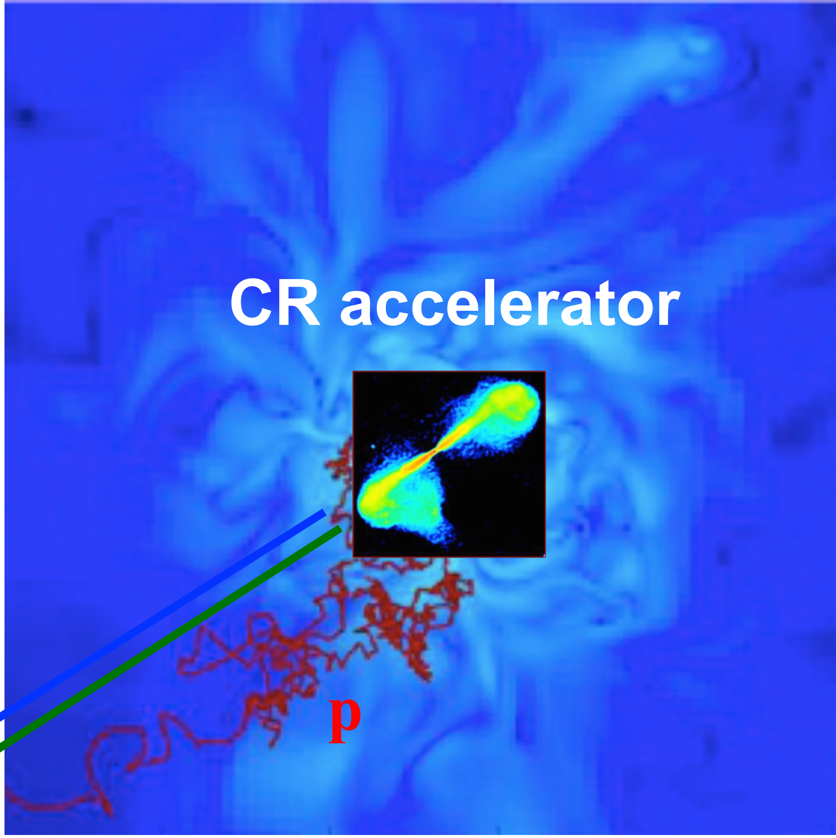
- **Gamma rays**
  interacting w. photons

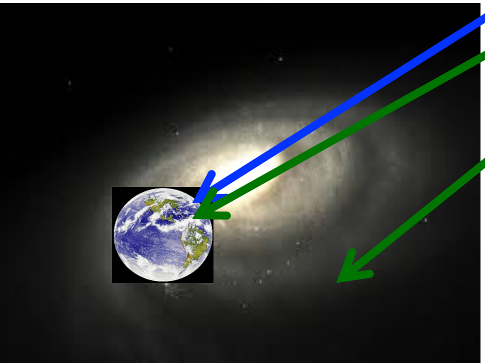
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

$$e + \gamma \rightarrow e + \gamma \ \text{(IC)}$$

$$e + B \rightarrow e + \gamma \ \text{(syn)}$$

es are deflected by magnetic fields



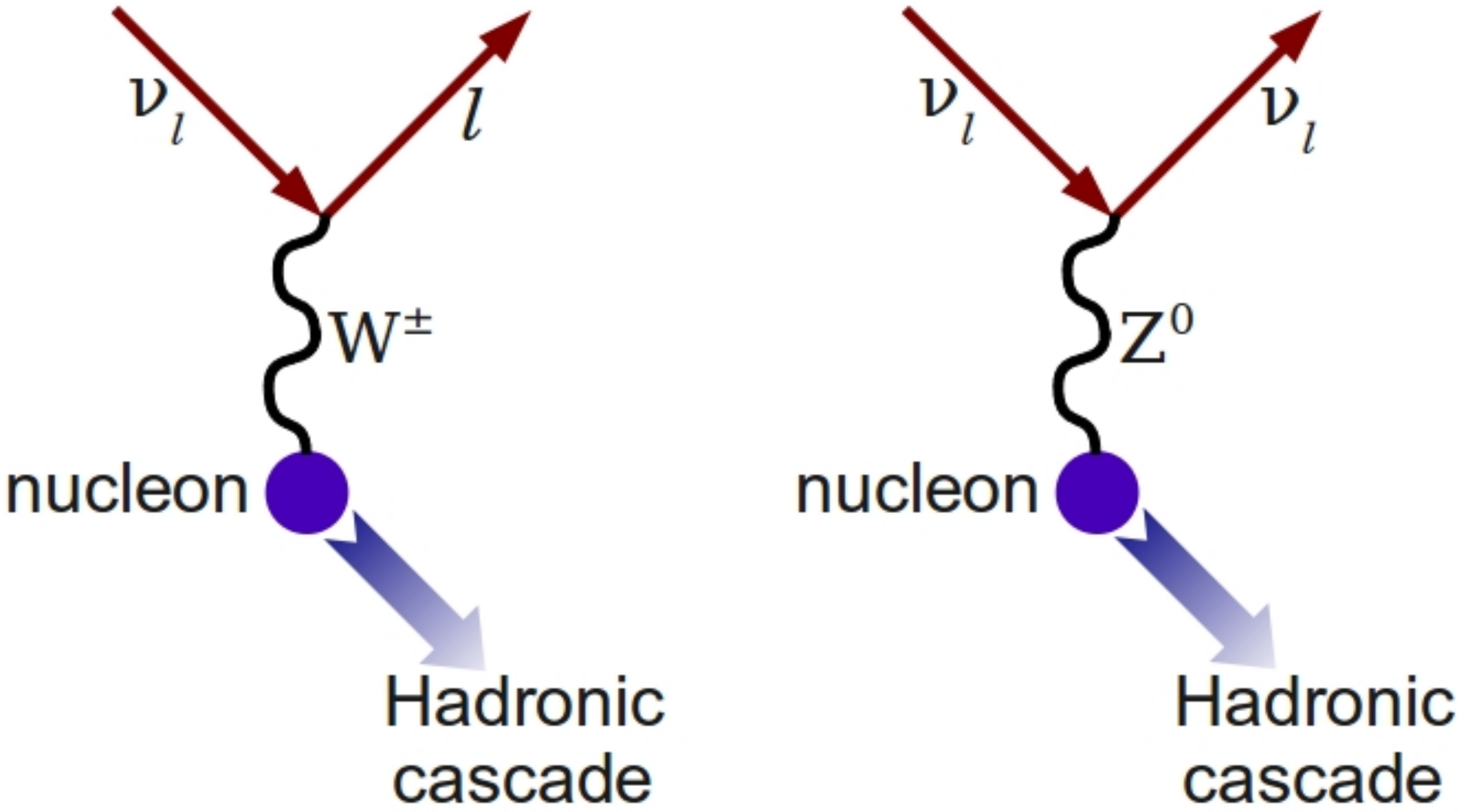


- **Cosmic rays**
  deflected by magnetic fields interacting w. photons/matter

$$p + \gamma \rightarrow p / n + N\pi$$

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

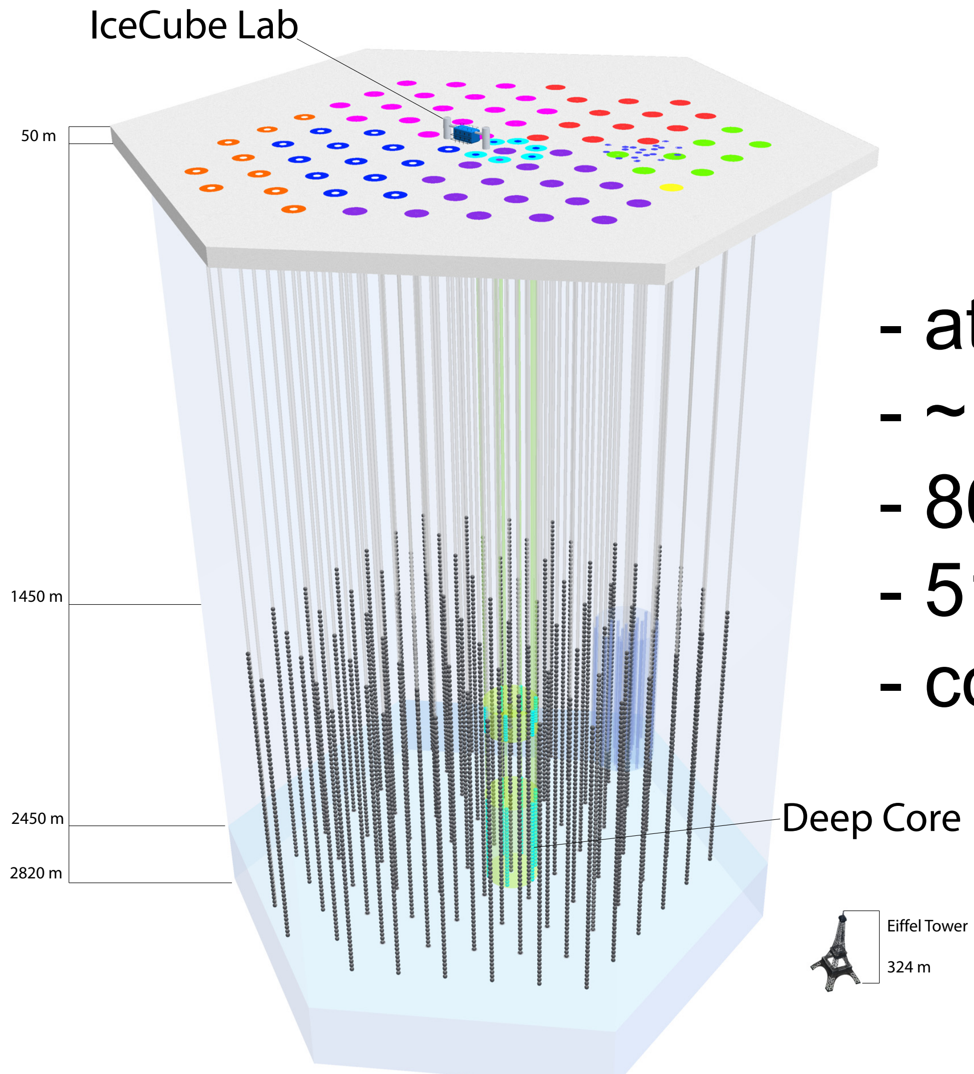
Neutrino: Weak Interaction



- $\sigma_{\nu N}$~10^{-33} cm^2 at 3 PeV → large volume needed

PeV=10^{15} eV

IceCube: Gton Neutrino Detector

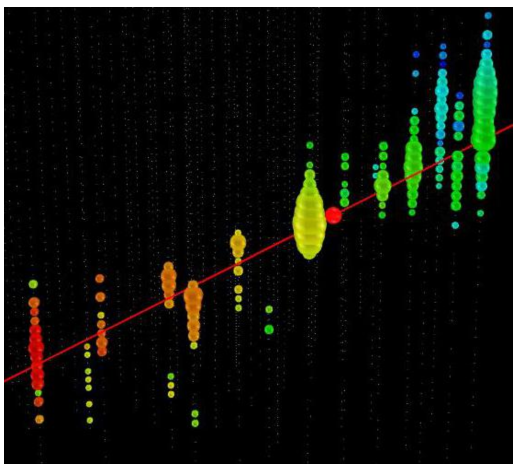


- at south pole
- ~ 1 km^3 volume ~ Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)
- completed 2010

How to Detect Neutrinos?

- 3 main event types

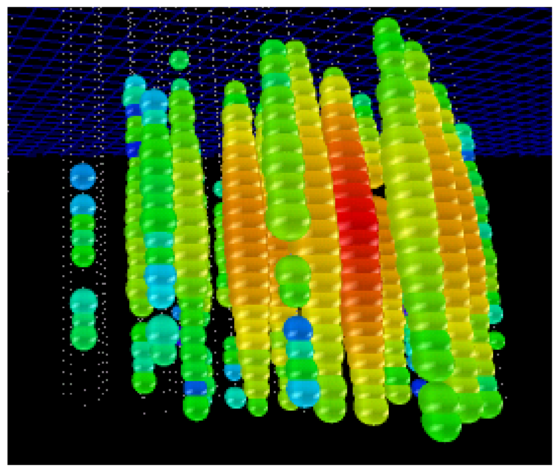
"Track" (detected)



ν_μ+N $\rightarrow$ μ+X

~2 energy res.
<1 deg ang res.

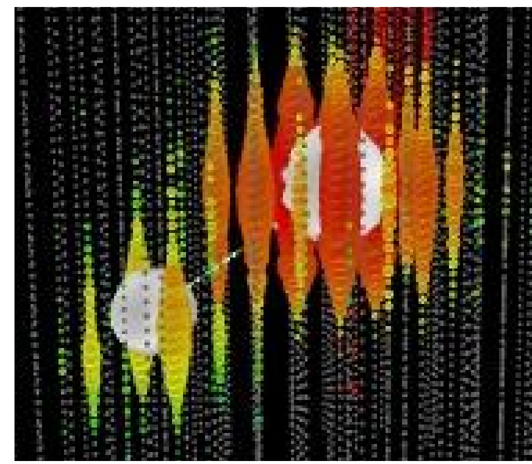
"Shower" (detected)



ν_e+N $\rightarrow$ e+X ν_X+N $\rightarrow$ ν_X+X

~15% energy res.
~10 deg ang res.
seen at >100 TeV

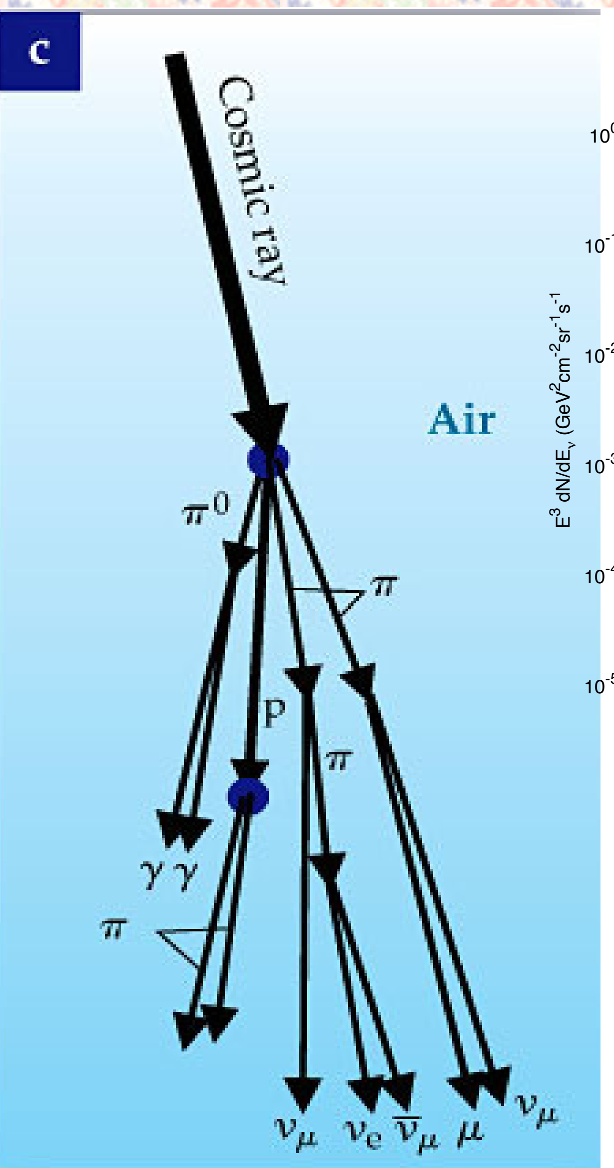
"Double-bang & others" (not detected)



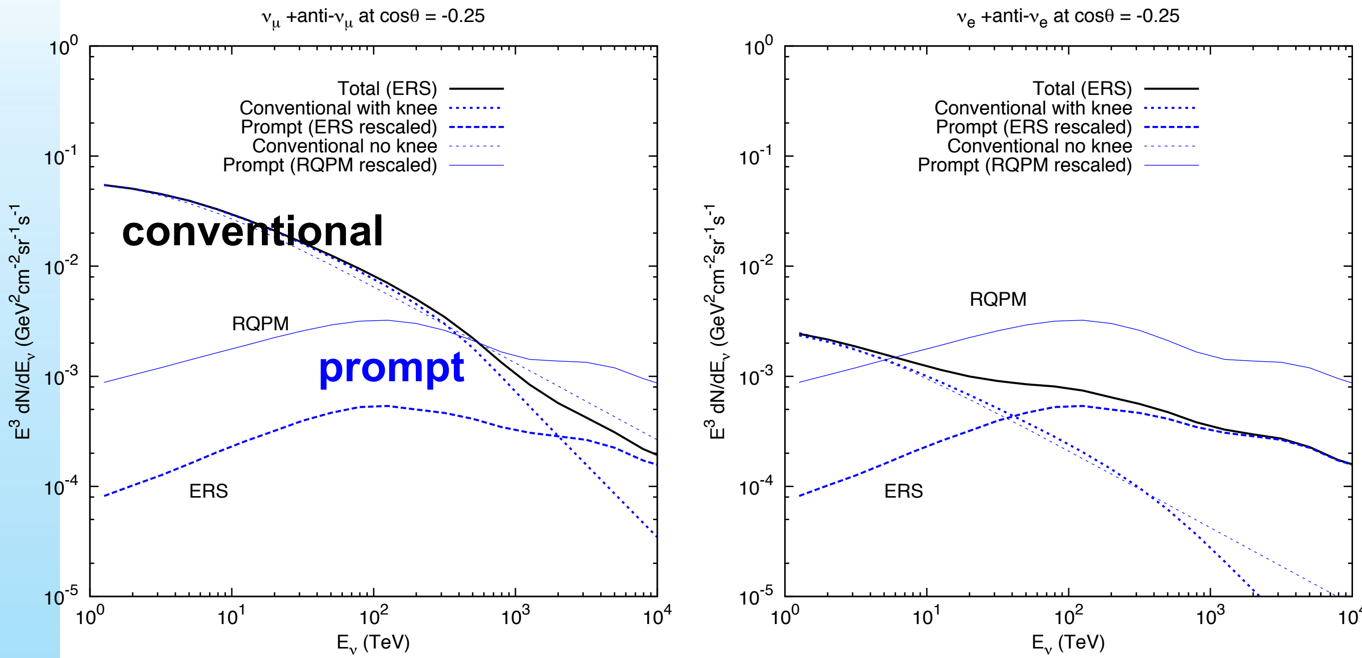
ν_τ+N $\rightarrow$ τ+X

observable at higher E

Background: Atmospheric (Terrestrial) Neutrinos



from Gaisser 13



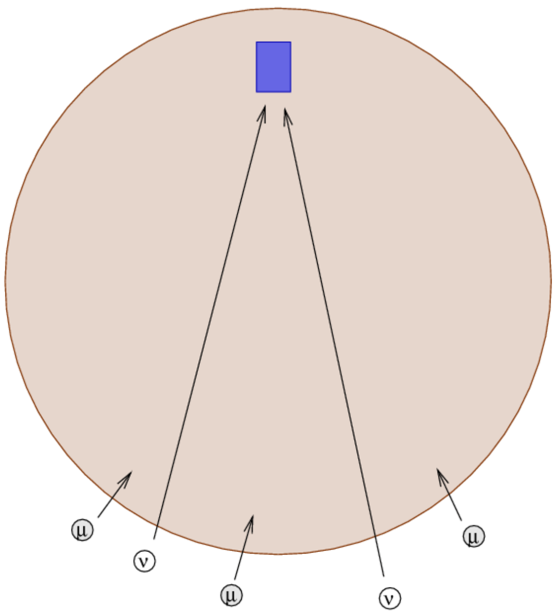
Conventional: neutrinos from pions and kaons

~ $E^{-3.7}$ due to hadronic cooling

Prompt: neutrinos from charmed mesons

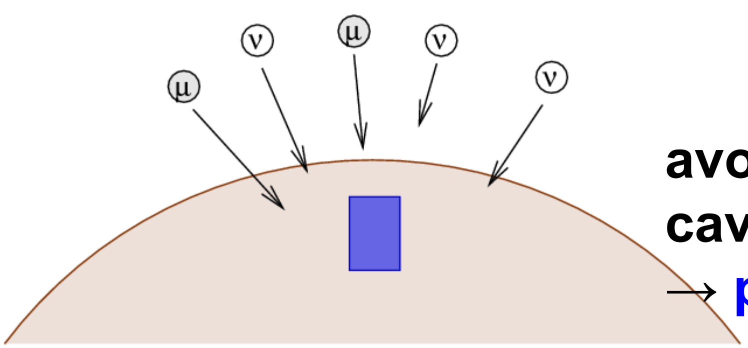
~ $E^{-2.7}$-$E^{-3.3}$ due to shorter lifetimes

Upgoing & Downgoing Neutrinos



Upgoing neutrinos

avoid atmospheric “muons”
caveat: attenuation by Earth at > 0.1-1 PeV
→ powerful at relatively low E



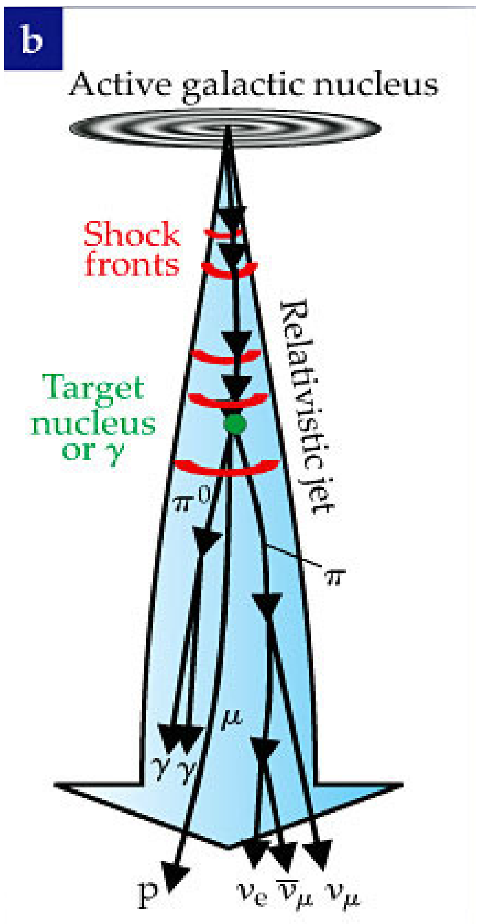
Downgoing neutrinos

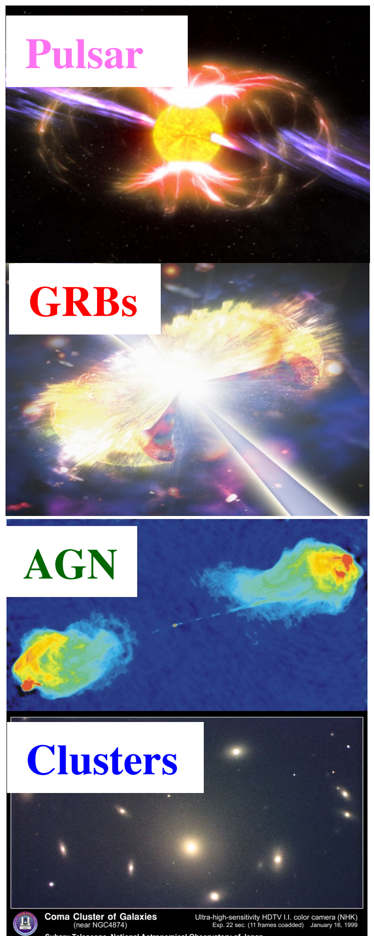
avoid attenuation by Earth
caveat: atm. muons (rapidly decreasing as E)
→ powerful at sufficiently higher E

Signal: Astrophysical (Extraterrestrial) Neutrinos

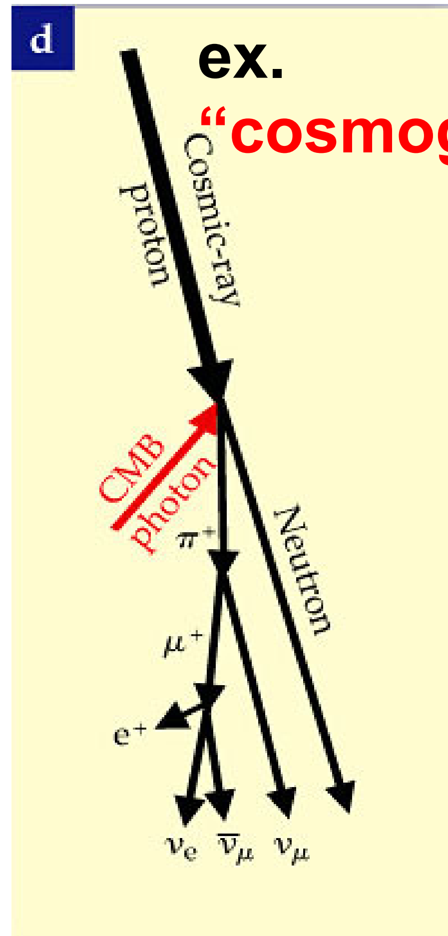
$E_\nu \sim 0.04\ E_p$: PeV neutrino ⇔ 20-30 PeV proton (or nucleon)

"on-source" neutrino





"off-source" neutrino



ex.

"cosmogenic" neutrinos

Benchmark Flux Level of Astrophysical Neutrinos

<u>Waxman-Bahcall bound</u> (Waxman & Bahcall 98 PRD)

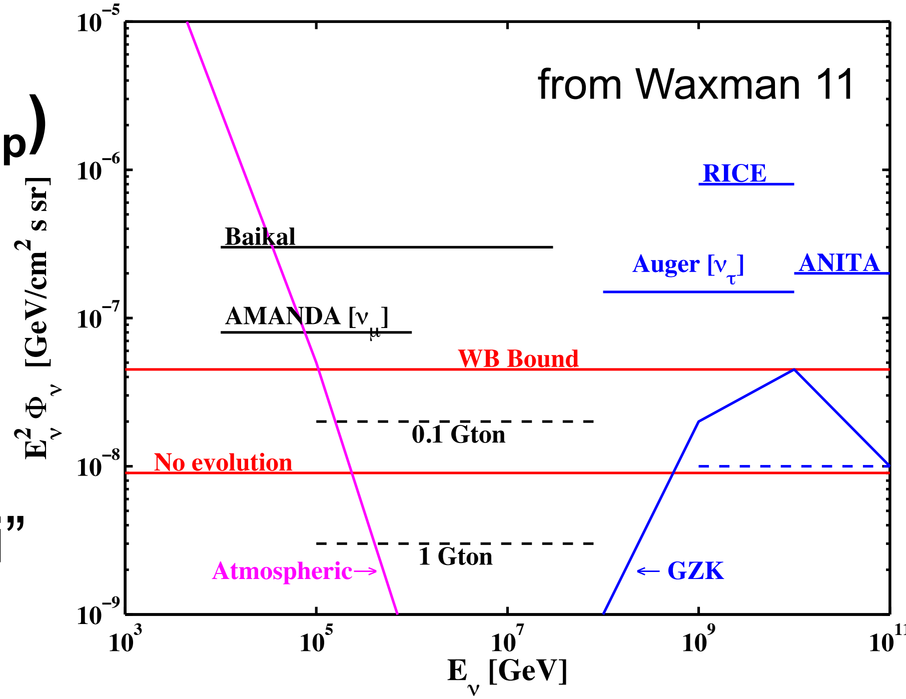
- meson production efficiency f_{mes} (< 1) → 1: "formal" limit
  (ex. $f_{mes} \sim n_\gamma \kappa_{p\gamma} \sigma_{p\gamma} (r/\Gamma)$ for $p\gamma$)
- reasonable bound for *cumulative* νs from UHECR sources
  (exceptions: non-UHECR sources, hidden neutrino sources)

ν flux: $\varepsilon_\nu^2 N(\varepsilon_\nu) \sim (1/4) f_{mes} \varepsilon_p^2 N(\varepsilon_p)$

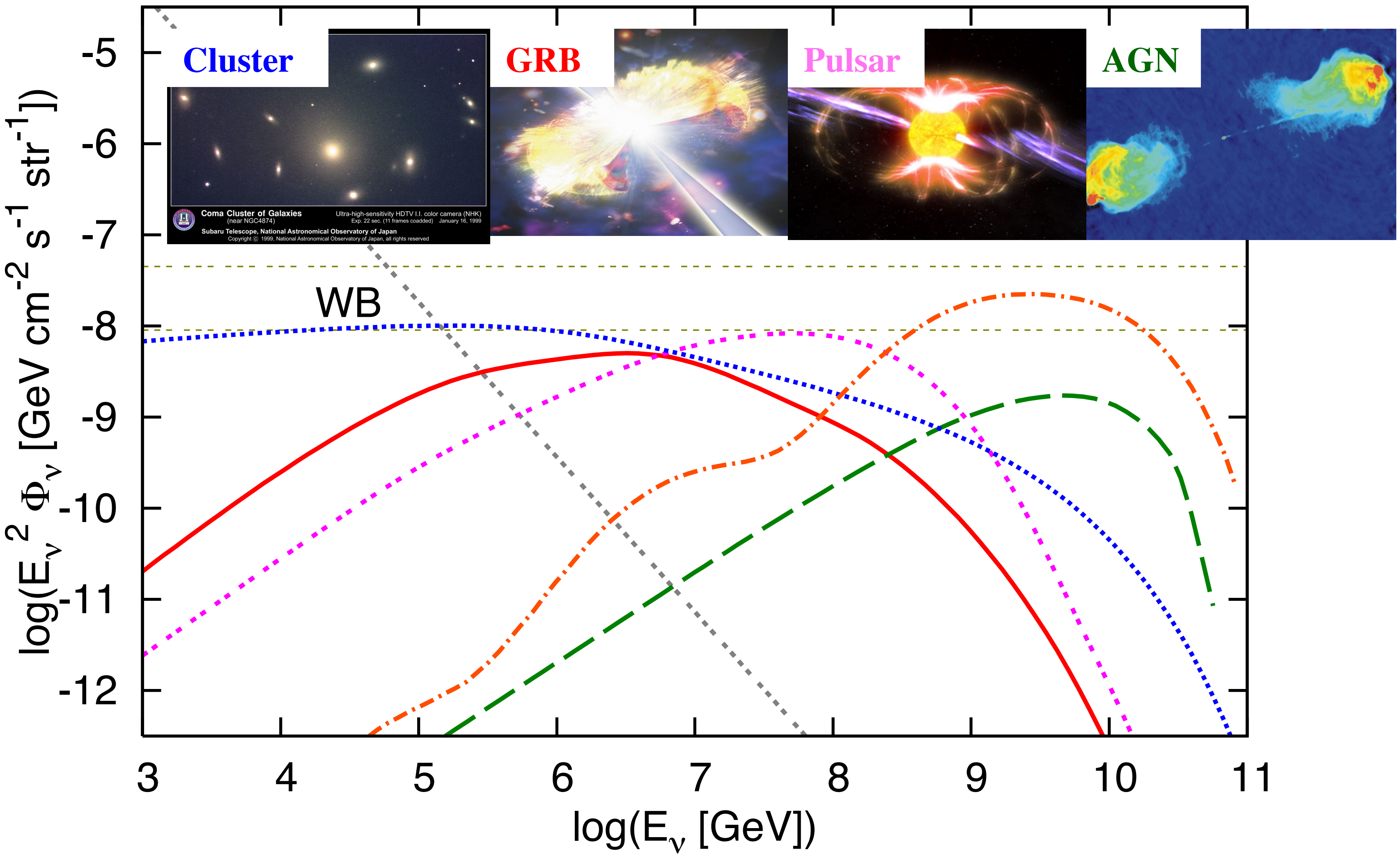
→ $(0.6\text{-}3)\times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

for CR spectrum $N(\varepsilon_p) \propto \varepsilon_p^{-2}$

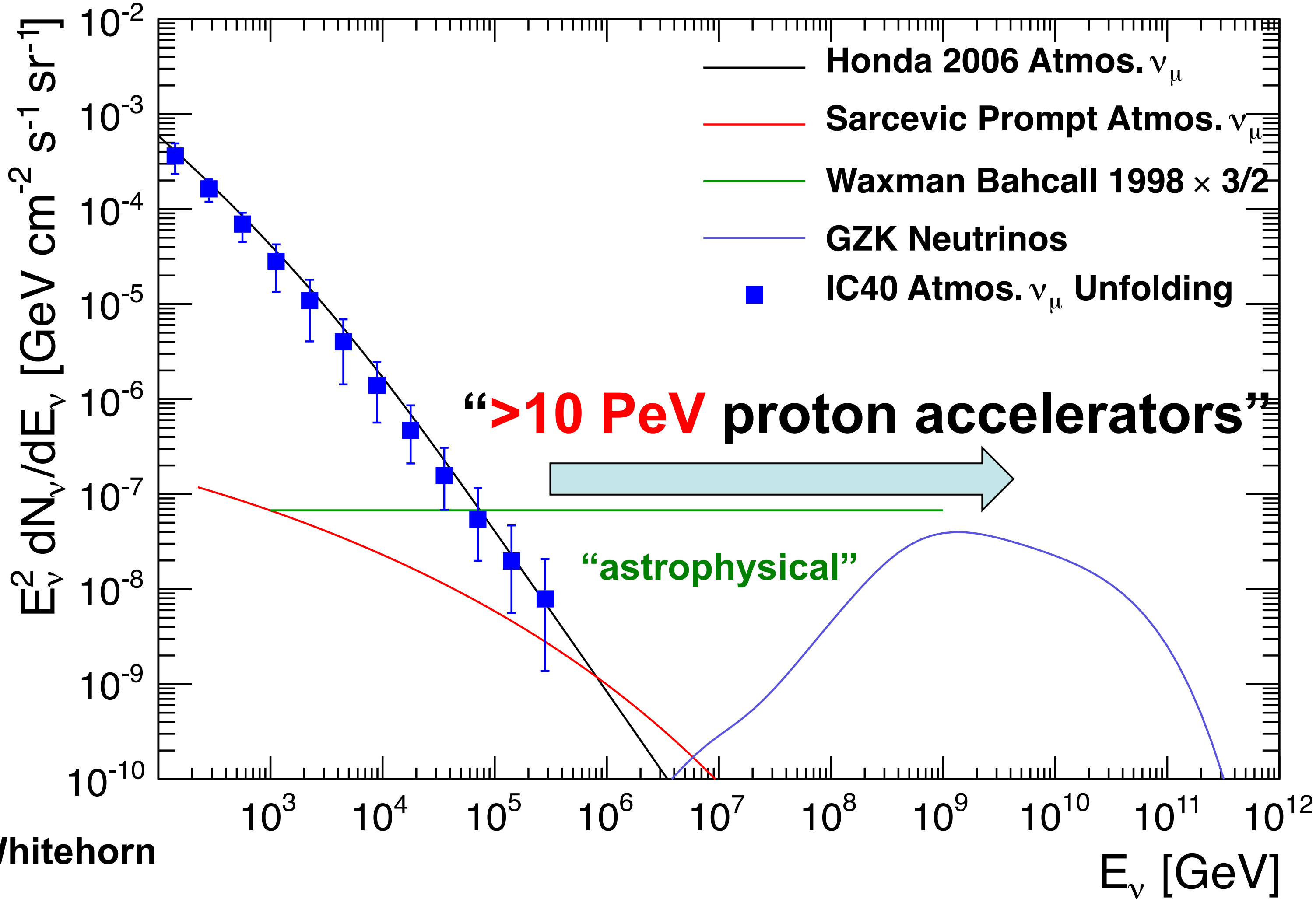
※>10 lower if UHECRs are "nuclei"
(KM & Beacom 10 PRD)



Various Astrophysical Predictions



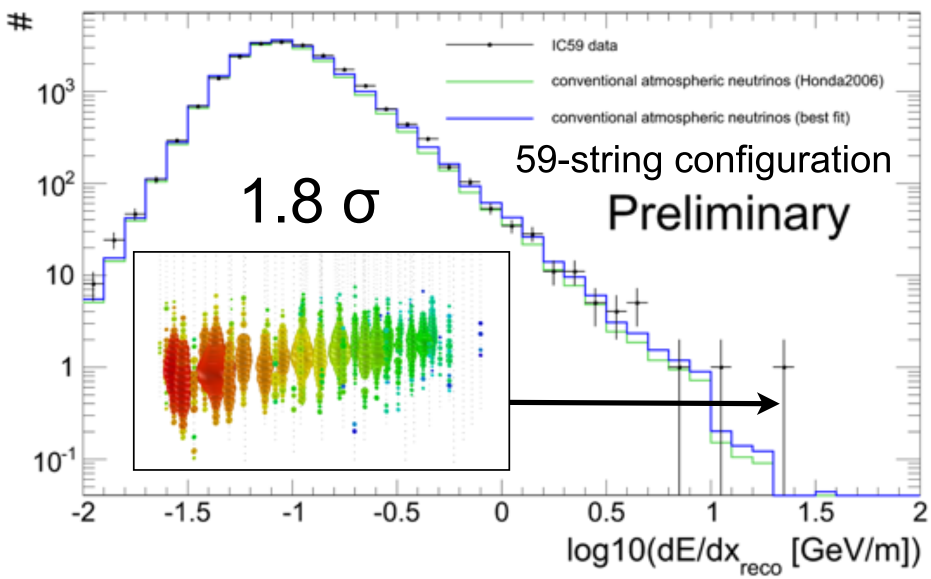
Classical Strategy



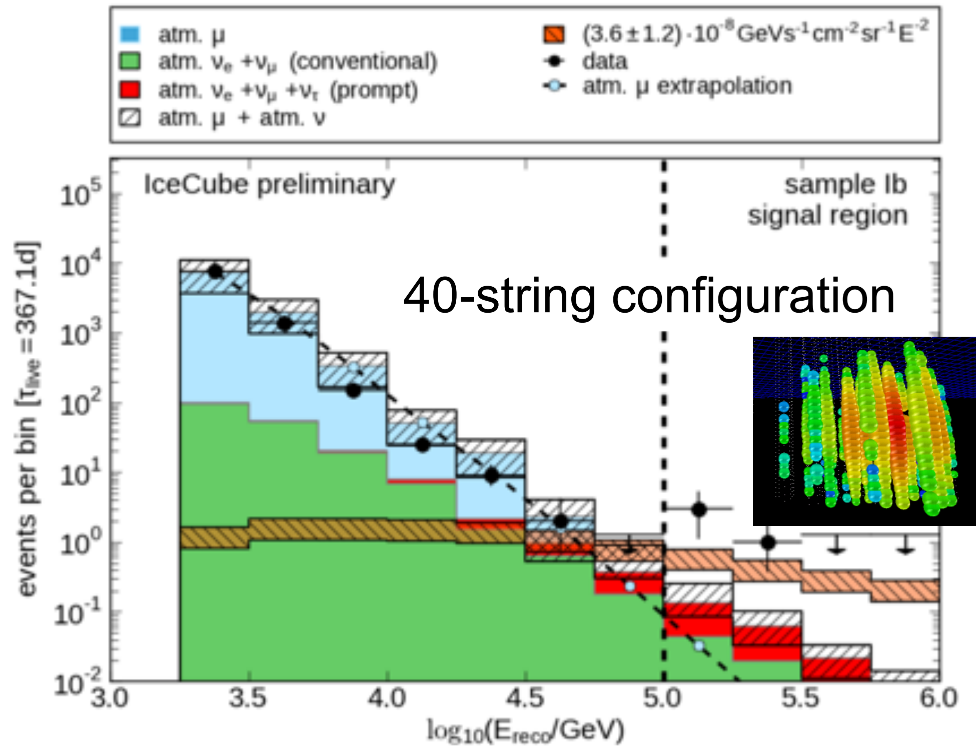
from Whitehorn

Hints from Classical Strategy

- IC59 upgoing track (1.8σ)
- IC40 shower (2.7σ)



IceCube 13 TAUP



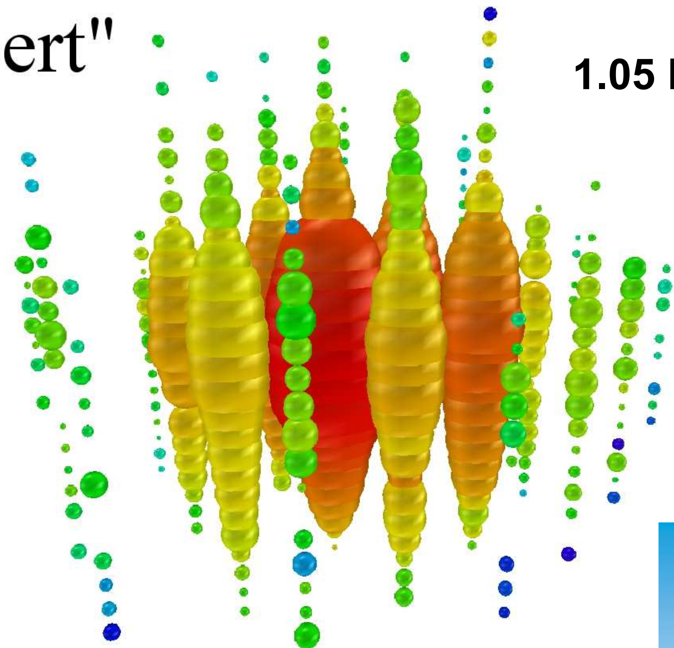
IceCube 13 TAUP

IC59 muon neutrino limit
higher than IC40 limit

PeV Events Reported in Neutrino 2012

- Two year data of IC-79/IC-86
- PeV downgoing **showers** in cosmogenic neutrino search

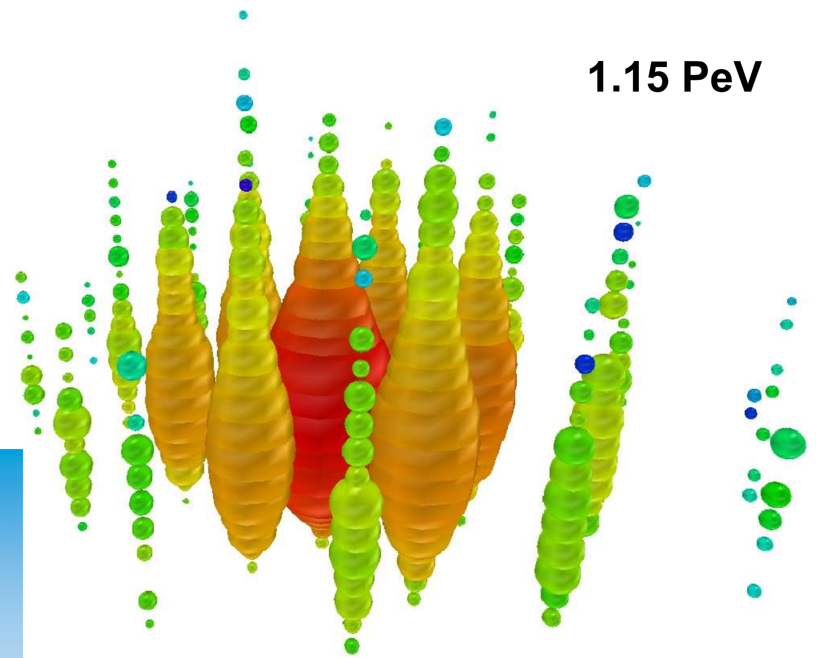
"Bert"



1.05 PeV

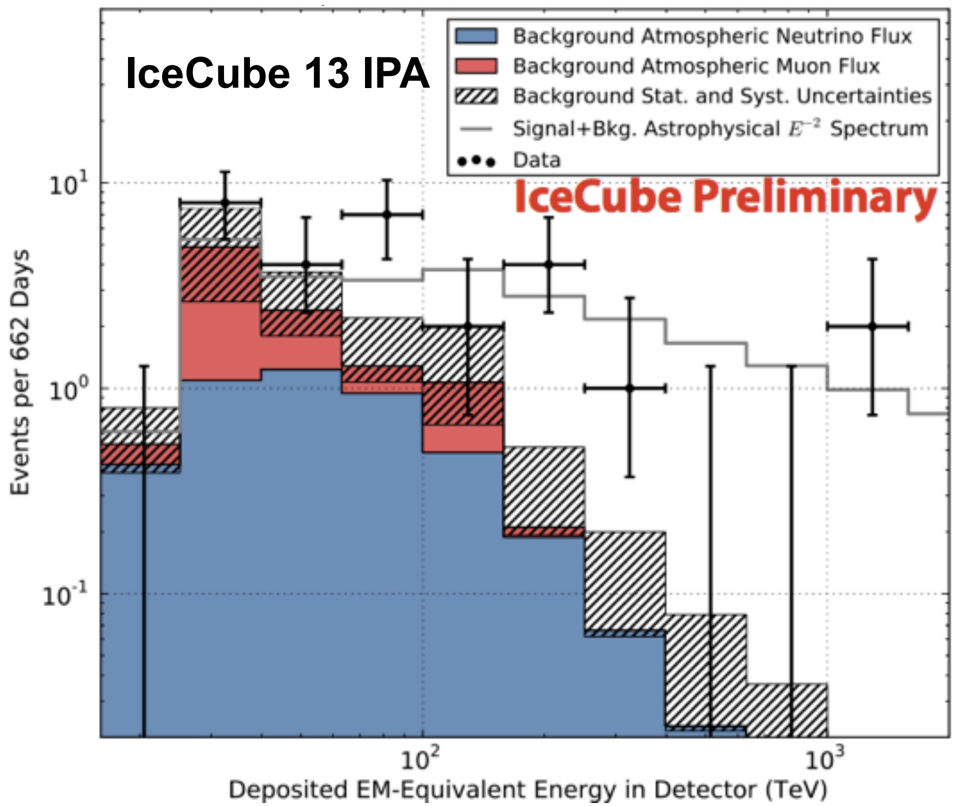
"Ernie"

1.15 PeV



IceCube 13 PRL

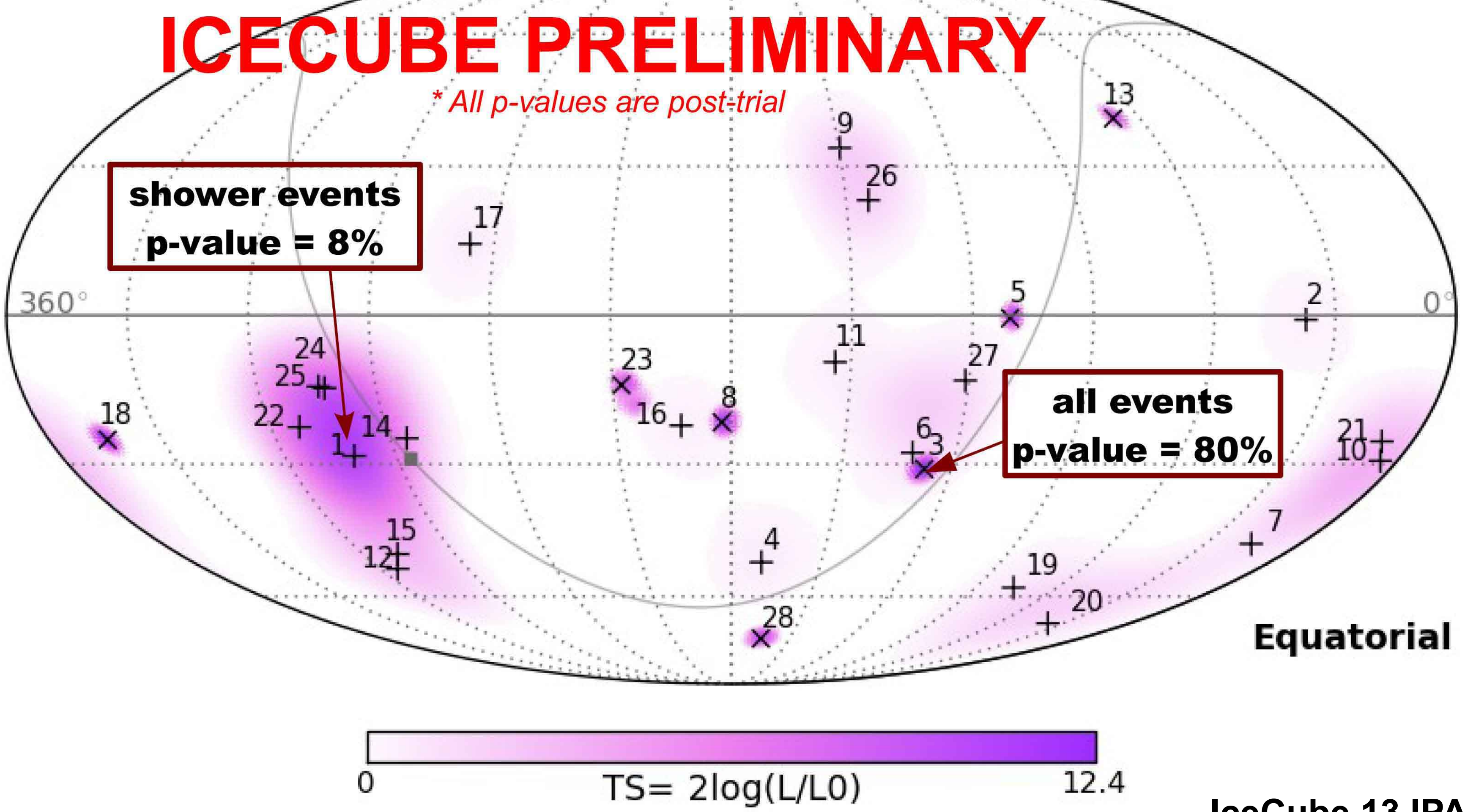
Follow-up Analysis: 2+26 Events (4.1σ)



- $E_\nu^2\ \Phi_\nu$=(1.2±0.4)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} (per flavor)
- Potential cutoff at 1.6 PeV for a E_ν^{-2} spectrum
- Consistent w. flavor ratio 1:1:1

After May 2013

consistent w. isotropic distribution



IceCube 13 IPA

2. Demystifying the PeV Neutrino Origin

Q. Where Do They Come from: Astrophysical or Not?

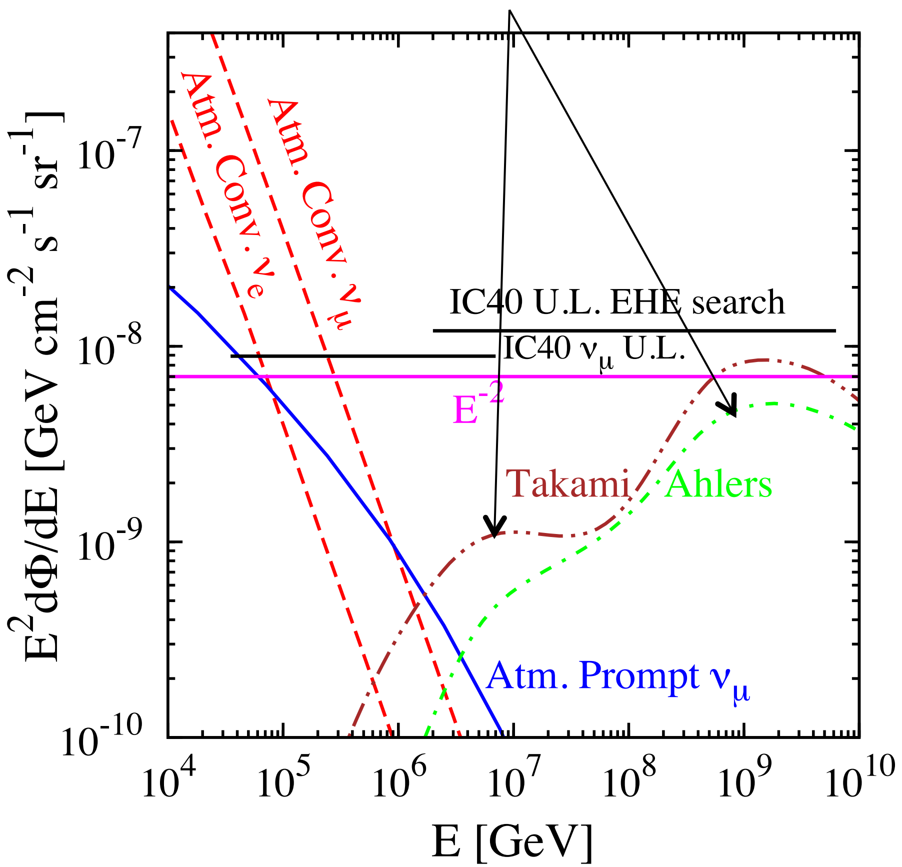
- Our (independent) analyses suggest
  conventional atm.: unlikely
  cosmogenic: unlikely
  prompt: disfavored

→ astrophysical (on-source): plausible
  hard spectra (like E^{-2}) w. a possible cutoff

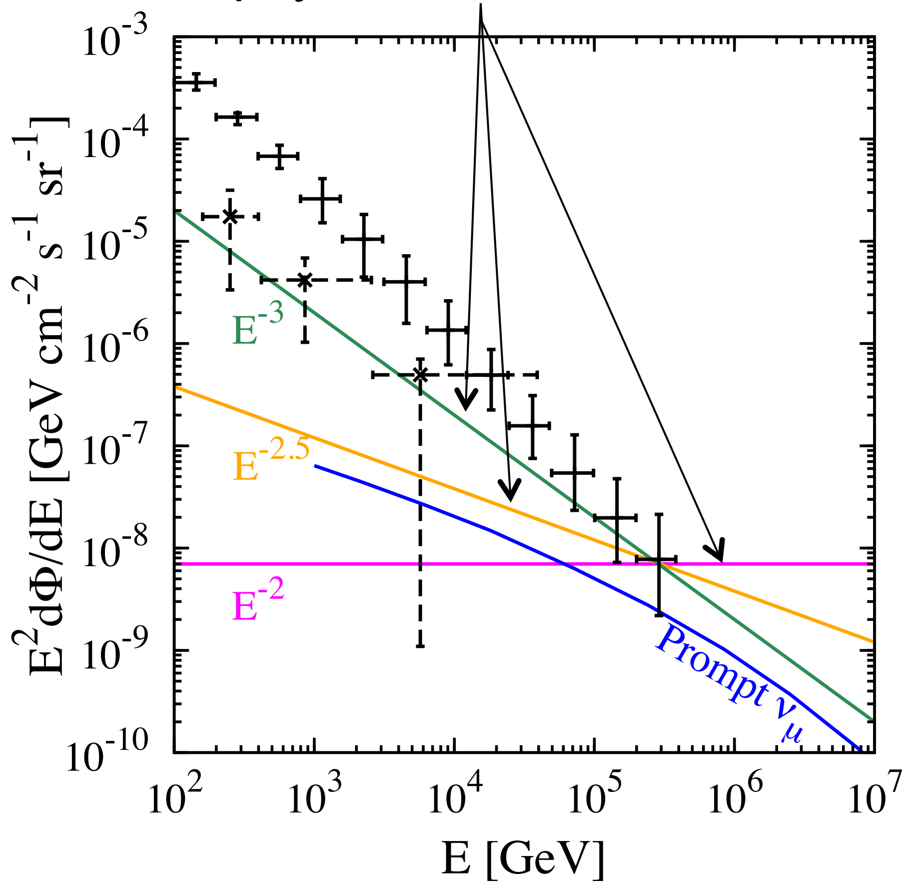
※ Of course more data are needed (still $< 5\sigma$)

Setup of Simple Analyses

cosmogenic neutrinos



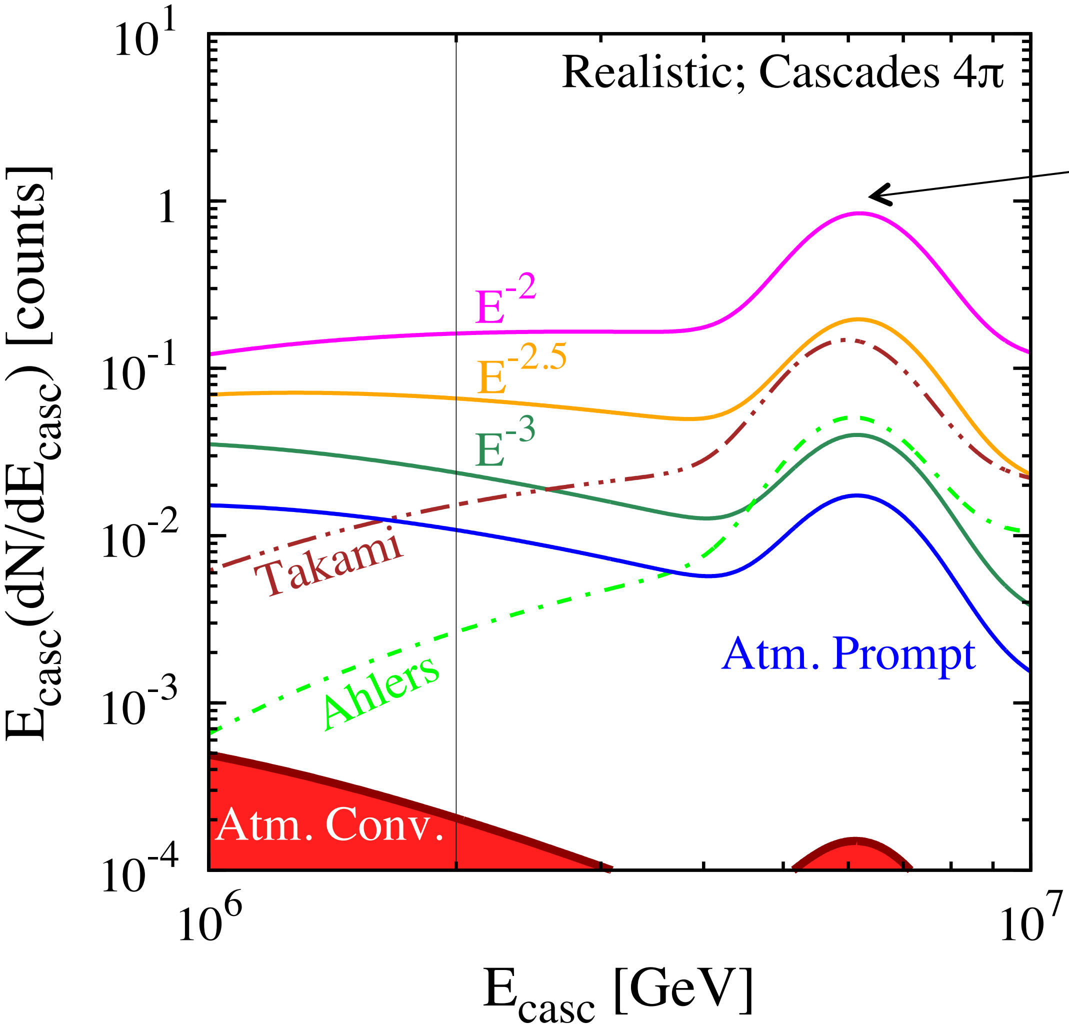
astrophysical on-source neutrinos



shower event rates

$$\frac{dN}{dE_{casc}} = 4\pi\, A_{\rm eff}\, T \times \frac{d\Phi}{dE_\nu}(E_\nu)$$

Shower Event Rates



Glashow resonance

$\bar{\nu}_e \, e^- \rightarrow W^-$

at E_ν=6.3 PeV

Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

2 events at PeV ⇔ $E_\nu^2 \, \Phi_\nu$ ~ (2-10)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

What It Cannot Be

- conventional atm.: unlikely
  - conventional atm. ν_e flux is too low
  - sneaking muons are not enough

- cosmogenic neutrinos: unlikely
  - neutrino flux at PeV is typically low
  - even if PeV events are explained, peak at EeV is inconsistent w. 0 events at >> 2 PeV

What It Could Be

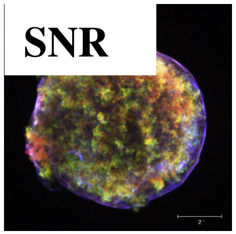
Too steep spectra: violating measured flux at < 0.3 PeV
Hard spectra: not extended to too high E due to large A_{eff}

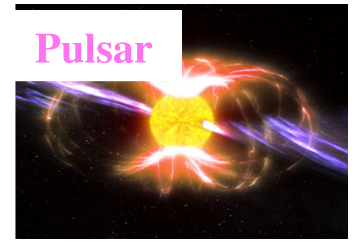
- prompt atm.: disfavored
  - too steep spectra & zenith-angle dependence
- astrophysical (on-source): plausible
  - disfavoring too steep spectra (like $E^{-2.5}$, E^{-3})
  - favoring hard spectra (like E^{-2}) w. a PeV cutoff
    or steep spectra (like $E^{-2.3}$) w.o. a cutoff

3. Multi-Messenger Tests

What is the Origin of the IceCube "Excess"?

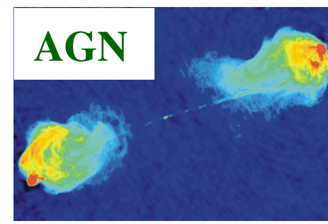
Galactic





vs

extragalactic



$$p + p \rightarrow N\pi + X$$

vs

$$p + \gamma \rightarrow N\pi + X$$

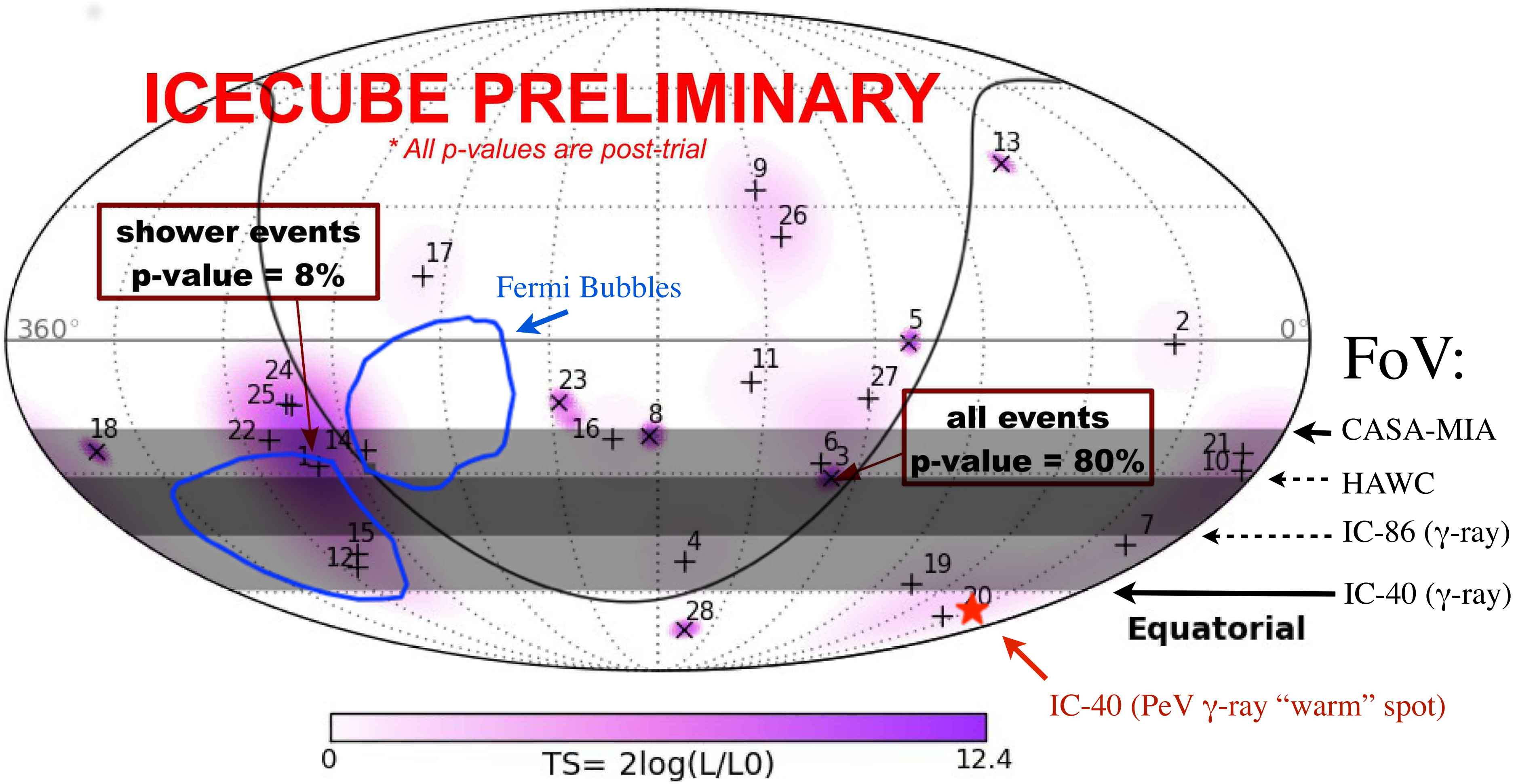
$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e) + e^{\pm} \qquad \pi^0 \rightarrow \gamma + \gamma$$

$E_\nu^2 \Phi_\nu \sim (1/6) f_{mes} E_{CR}^2 \Phi_{CR}$
$E_\gamma^2 \Phi_\gamma \sim (1/3) f_{mes} E_{CR}^2 \Phi_{CR}$
$\rightarrow E_\gamma^2 \Phi_\gamma = 2 E_\nu^2 \Phi_\nu$ (pp)

$E_\nu^2 \Phi_\nu \sim (1/8) f_{mes} E_{CR}^2 \Phi_{CR}$
$E_\gamma^2 \Phi_\gamma \sim (1/2) f_{mes} E_{CR}^2 \Phi_{CR}$
$\rightarrow E_\gamma^2 \Phi_\gamma = 4 E_\nu^2 \Phi_\nu$ (pγ)

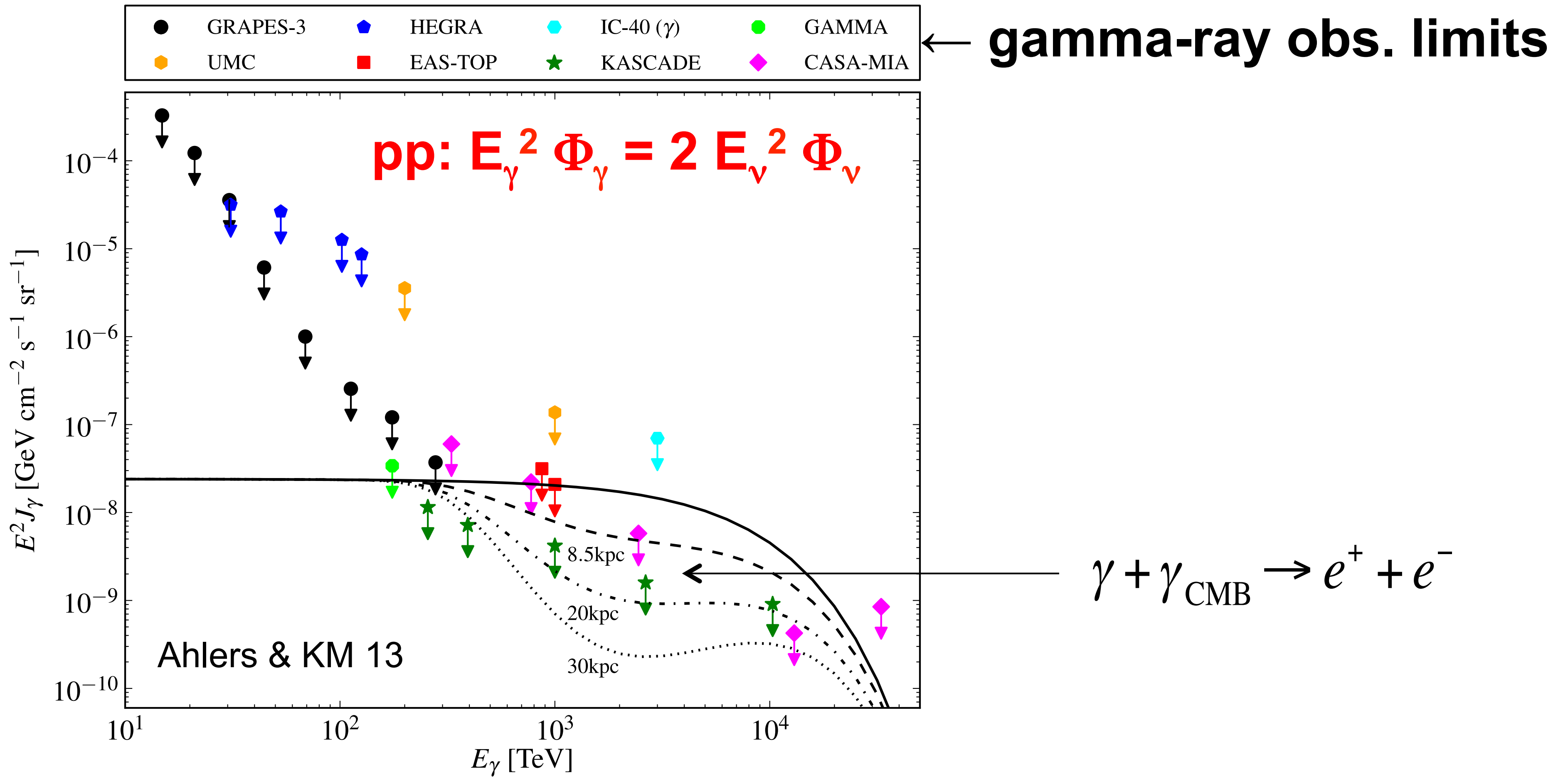
"multi-messenger connection"

Q1. Galactic or Extragalactic



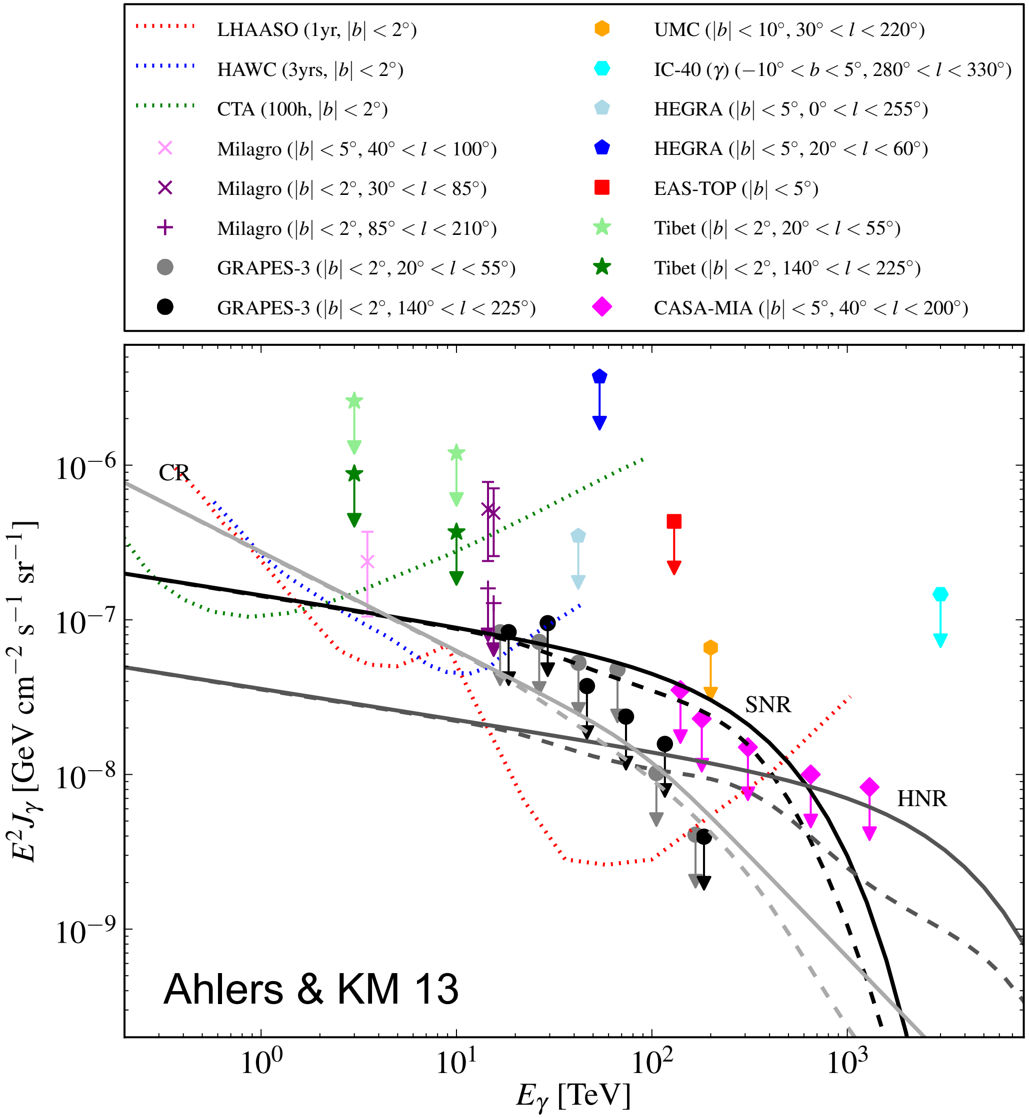
Proposed Galactic scenarios:
diffuse Galactic emission, hypernova remnants, Fermi bubbles

(Hypothetical) Isotropic Galactic Sources?



- Existing gamma-ray limits support extragalactic scenarios
- Galactic sources are probably subdominant

Subdominant Sources in the Galactic Plane?



For |b| < 2 deg,

~1/28 of the IceCube excess

⇔ 2x10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

proposed possibilities

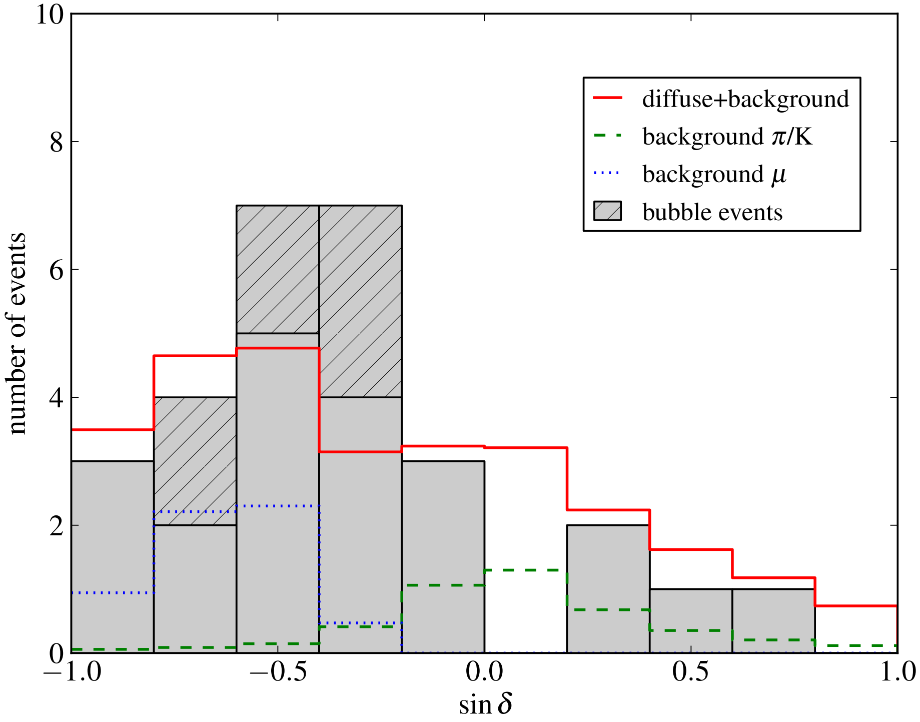
- diffuse Galactic emission consistent w. gamma limits but too steep for neutrino

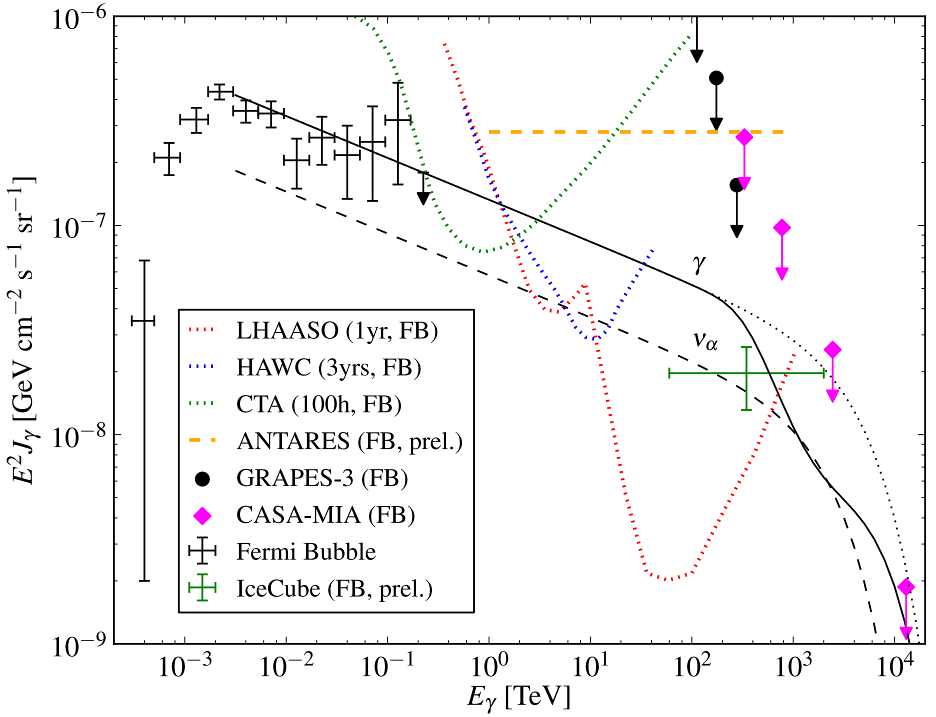
- hypernova remnants violating gamma limits

Association of IceCube events w. the Galactic plane is unlikely

Interesting Case: Fermi Bubbles?

Ahlers & KM 13





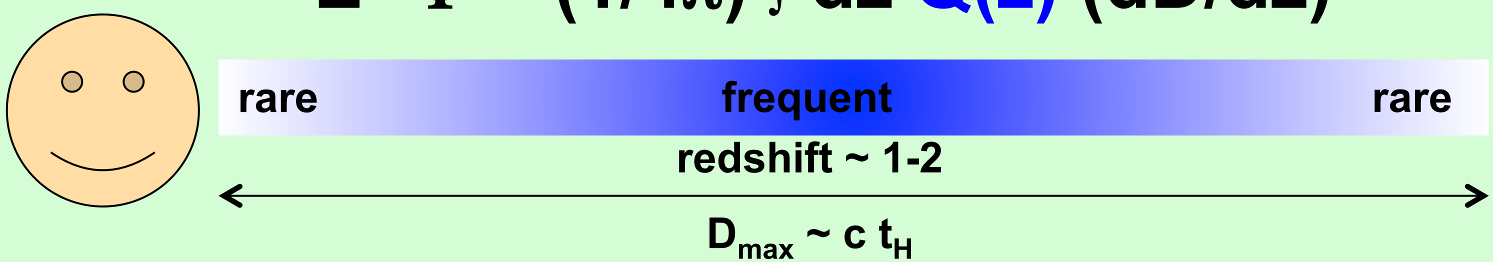
- up to 7 (among 28) can be associated w. Fermi bubbles
- consistent w. Γ=2.2 (giving better fits)
- testable w. future gamma-ray detectors (ex. CTA, HWC)

Which Extragalactic Sources are Viable?

Requirements: isotropic flux w. $E_\nu^2 \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
(break/cutoff around PeV for hard spectra)

Proposed "viable" extragalactic sources (as far as I know)
GRB, AGN, starburst galaxies, galaxy clusters/groups

$$E^2 \Phi = (1/4\pi) \int dz\, Q(z)\, (dD/dz)$$



Main contributions come from many distant sources

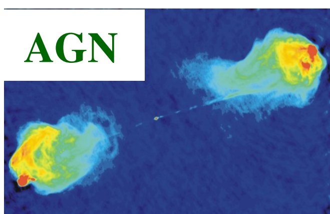
Q2. How to Get Clues to the Origin: pp or pγ?

There is difference between pp and pγ scenarios

$$p + p \to N\pi + X$$

- extending from GeV energies
- following CR spectra E_p^{-s}
- gamma rays can typically escape

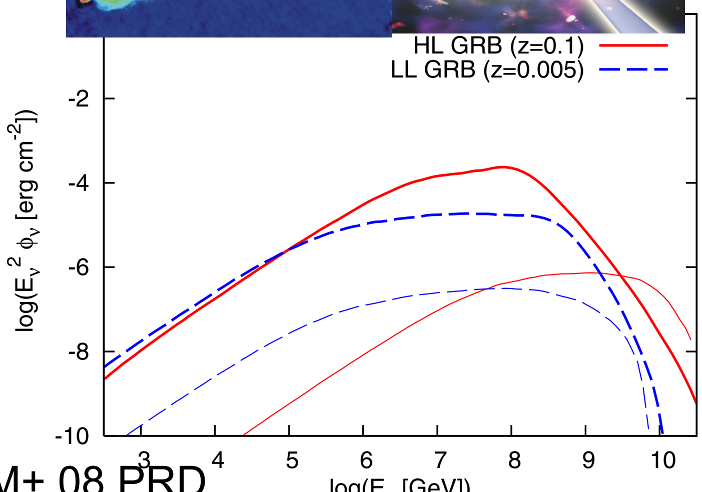
→ tight neutrino-gamma connection



$$p + \gamma \to N\pi + X$$

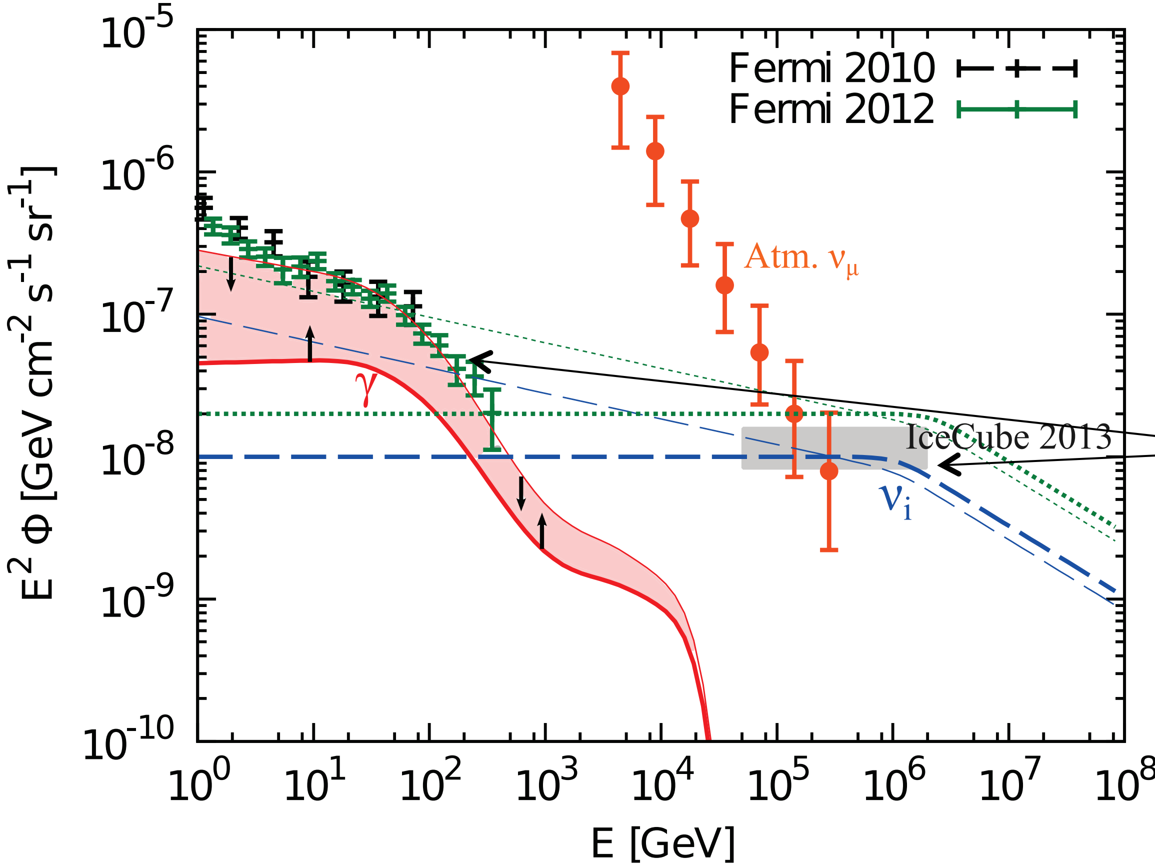
- threshold effect
  $E_\nu \sim 640$ PeV $(\Gamma_j/10)^2$ $(\varepsilon/1 \text{ eV})^{-1}$
  GRB: $\Gamma_j \sim 100$, $\varepsilon \sim 1$ MeV → ~ 0.6 PeV
  AGN: $\Gamma_j \sim 10$, $\varepsilon \sim 10$ eV → ~ 6 PeV
- depending on CR spectra E_p^{-s} as well as target photon spectra $\varepsilon^{-\alpha}$
- target photons for pγ cause $\gamma\gamma$ inside sources

→ connection is quite often lost



KM+ 08 PRD

First Multi-Messenger Tests with "Measured" Fluxes



KM, Ahlers & Lacki 13

pp: $E_\gamma^{\,2}\,\Phi_\gamma \sim 2\,E_\nu^{\,2}\,\Phi_\nu$

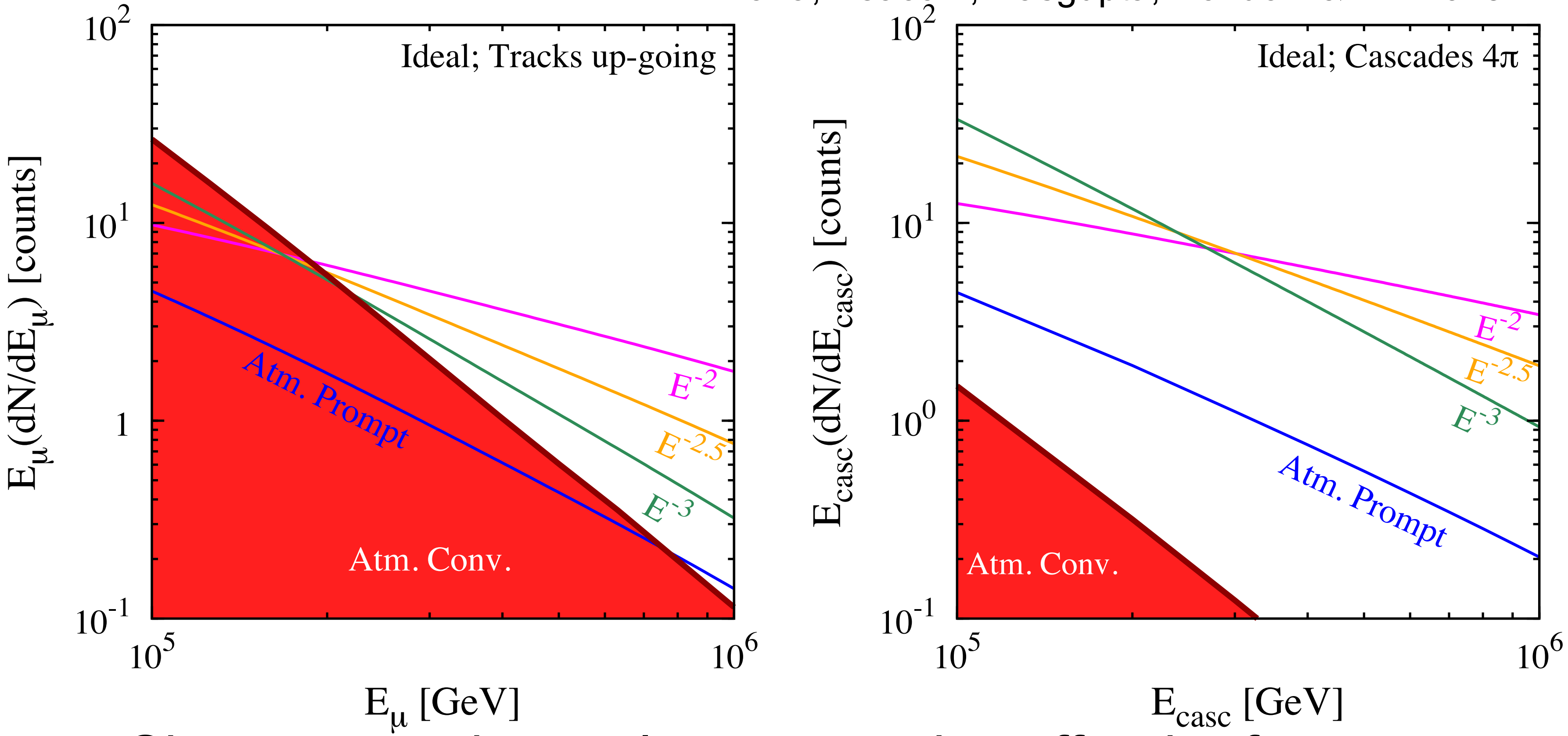
"comparable fluxes"

simple but important!

- Γ<2.1-2.2 (for extragalactic), Γ<2.0 (for Galactic)
- contribution to diffuse sub-TeV gamma-ray flux: >30-40%
- limits are insensitive to redshift evolution models

Implications for Further Neutrino Studies

Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

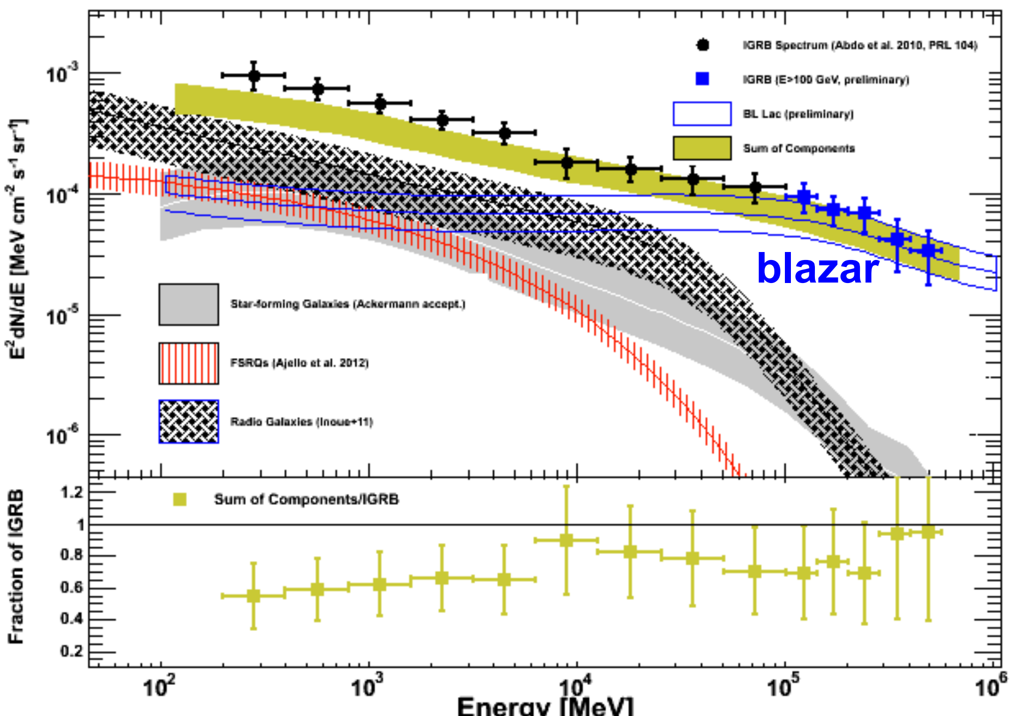


- Shower searches at lower energies offer the fastest way to distinguish between the spectra
  ex. if Γ>2.3 → pp scenarios will be disfavored

Implications for Further Gamma-Ray Studies

1. Gamma-ray spectra should be hard (Γ<2.1-2.2)
   → deep obs. by future TeV gamma-ray detectors is crucial

2. Contributing >30-40% of diffuse sub-TeV gamma-ray flux
   → improving and understanding the Fermi data are crucial



ex.
If >60-70% come from blazars
→ no room for pp scenarios!

If >50% come from blazars
→ Γ<2.0-2.1

from Fermi collaboration 13

Summary

PeV neutrinos may start to be detected by IceCube

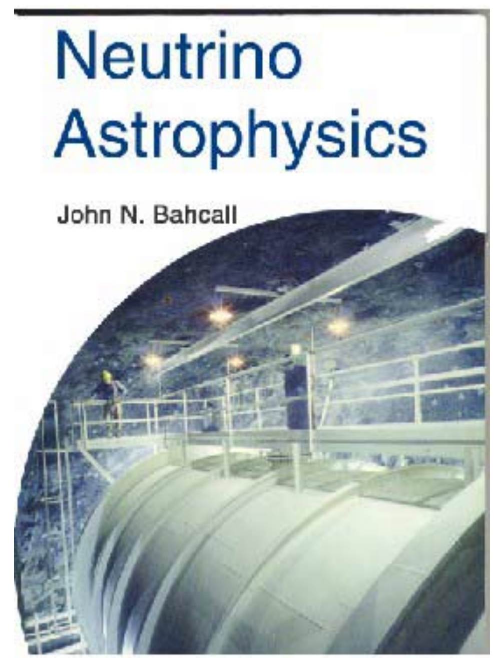
- (Likely) first evidence for extraterrestrial HE neutrinos favoring astrophysical “on-source” neutrinos (not cosmogenic)

Multi-messenger tests with the measured neutrino flux

- Galactic or extragalactic?
  → supporting extragalactic scenarios but still interesting
  Galactic sources can be tested by sub-PeV gamma rays
- pp or pγ?
  → most pp sources can be tested in the next several years
  1. determination of Γ in the sub-PeV range (IceCube)
  2. understanding the diffuse sub-TeV gamma-ray flux (Fermi)
  3. deep obs. of individual pp sources w. TeV gamma rays
- Need for more studies on pγ sources such as AGN and GRBs

J.N. Bahcall (IAS), Neutrino Astrophysics (1989)

"The title is more of an expression of hope than a description of the book's contents....the observational horizon of neutrino astrophysics may grow ... perhaps in a time as short as one or two decades"



Remarks on pγ Scenarios

- Viable pp scenarios can be tested w. IceCube (sub-PeV), Fermi (sub-TeV) and TeV gamma-ray telescopes
- pγ scenarios can be favored by disfavoring pp scenarios

Viable pγ scenarios?

GRB: independent limit from stacking analysis for bright GRBs

strong limit $E_\nu^2 \Phi_\nu < 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

→ undetected low-luminosity GRBs (KM & Ioka 13)

AGN: jet models predict ~ 100-1000 PeV peak

inconsistent w. 0 neutrino events at >> PeV

→ hidden AGN core scenario (Stecker et al. 93)