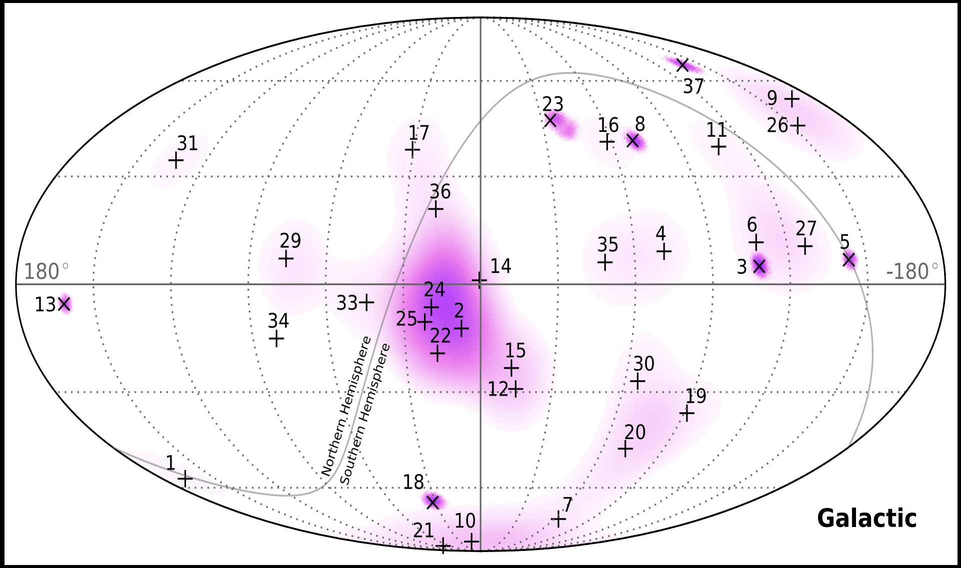
Multimessenger Approaches to the Origin of High-Energy Neutrinos

Kohta Murase (Institute for Advanced Study)



IceCube
arXiv:1405.5303

HEM 2014

Talk Outline

The first discovery of HE cosmic ν signals by IceCube

Q. What is the origin?

A. Not known yet. Many possibilities. Need more data.
But intriguing implications are obtained.

0. Brief introduction
1. Theoretical models for PeV neutrinos
2. Multimessenger tests and future perspectives

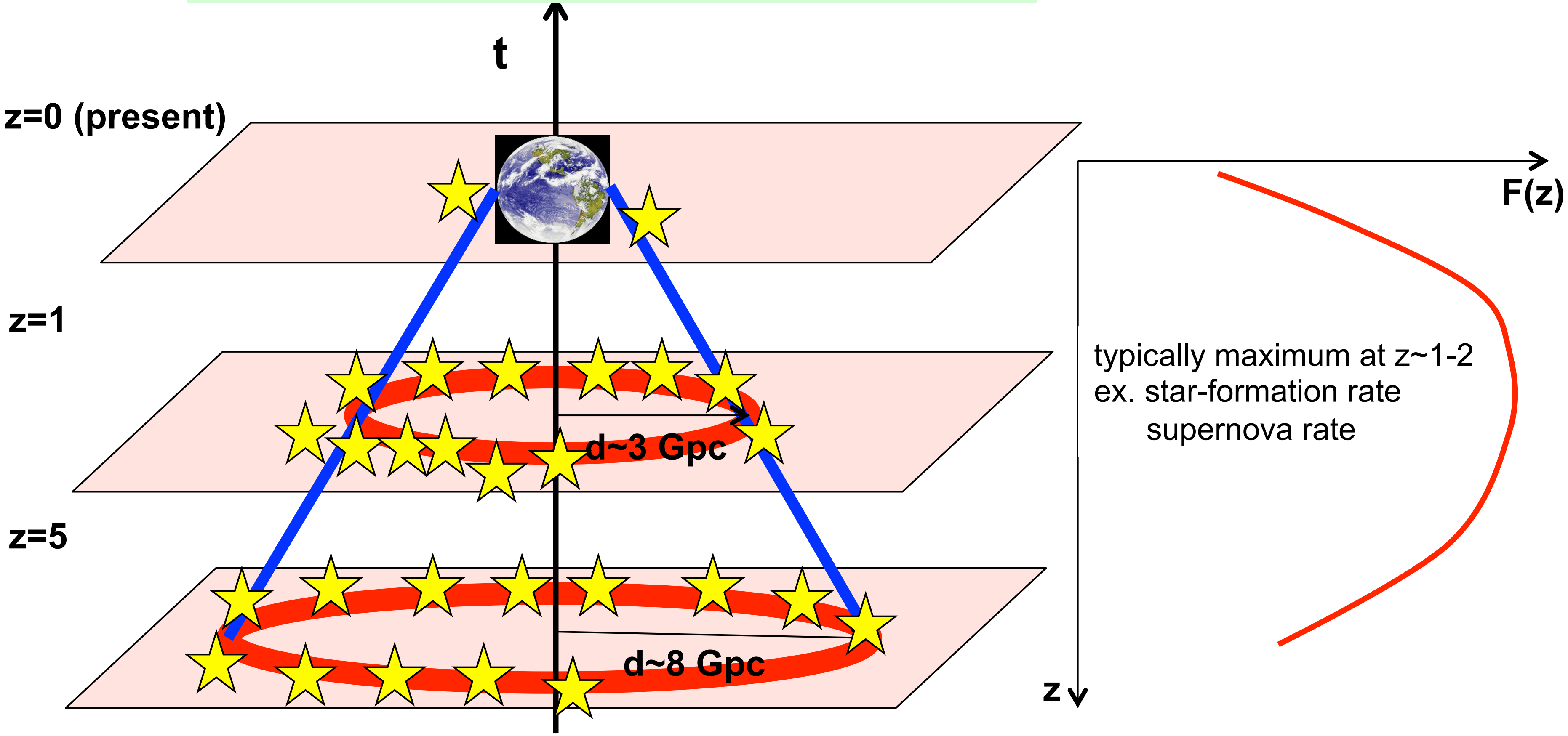
Astrophysical "Isotropic" Neutrino Background – Mean Diffuse Intensity

diffuse ν intensity of extragalactic sources (cf. DSNB) ← consistent w. isotropic distribution

$$\varepsilon_\nu^2 \Phi_\nu = \frac{c}{4\pi}\int dz \left|\frac{dt}{dz}\right| \varepsilon_\nu^2 q_\nu(\varepsilon_\nu) F(z)$$

$\varepsilon_\nu^2 q(\varepsilon_\nu)$: ν emissivity at z=0
(source physics)

F(z): redshift evolution



typically maximum at z~1-2
ex. star-formation rate
supernova rate

Most contributions come from unresolved distant sources, difficult to see each

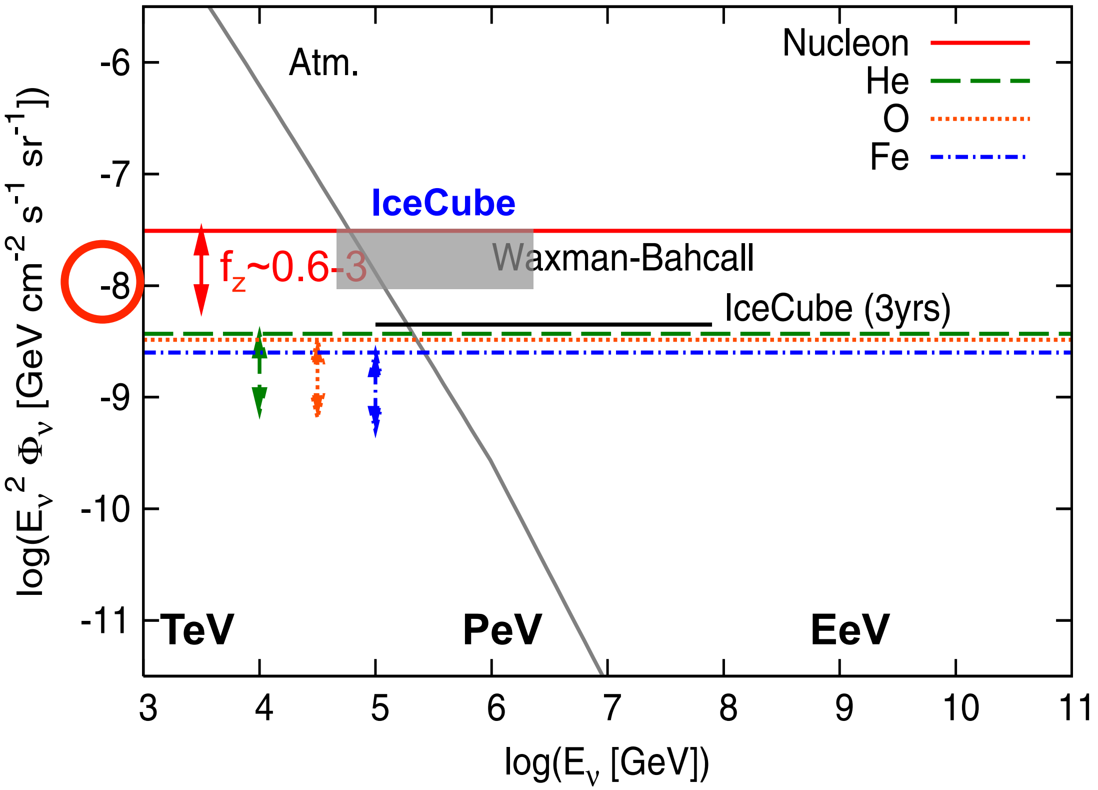
What does $E_\nu{}^2\Phi_\nu$~3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} Imply?: Cosmic-Ray Connection

$$E_\nu^2\Phi_\nu \approx \frac{ct_H}{4\pi}\left[\frac{3}{8} f_{\rm mes}\varepsilon_{\rm CR}^2 q_{\rm CR}\right] f_z$$

$f_{\rm mes}$ (<1): efficiency (energy fraction of πs)
$\varepsilon_{\rm CR}{}^2\, q_{\rm CR}$: CR emissivity at z=0
f_z: averaged F(z)

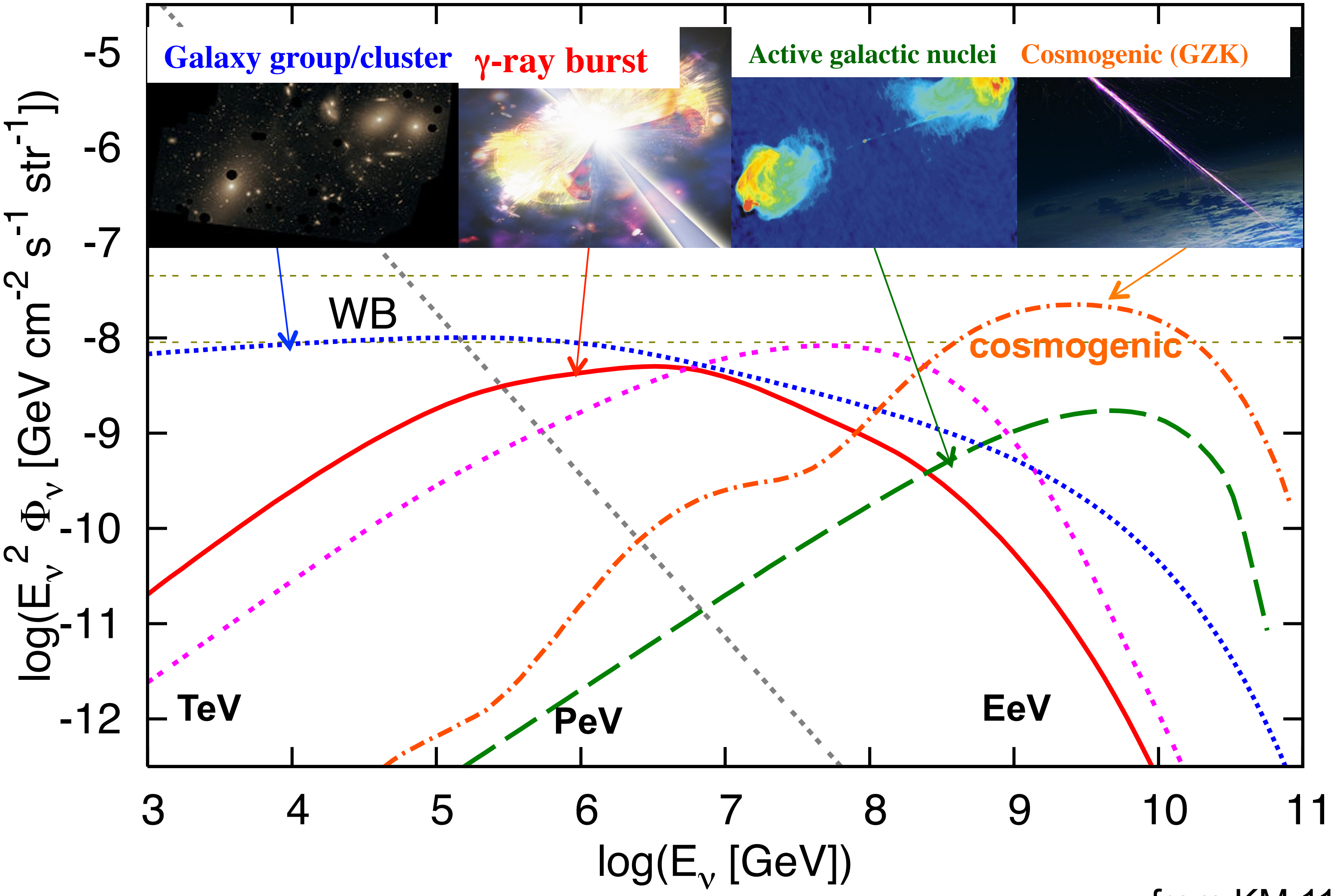
Waxman-Bahcall landmark ($s_{\rm CR}$=2 assumed) (Waxman & Bahcall 98 PRD)

1) $\varepsilon_{\rm CR}{}^2 q_{\rm CR}$: normalized by the obs. UHECR flux, 2) $f_{\rm mes}$→1 limit



← **“nucleus-survival” landmarks**
(KM & Beacom 10 PRD)
∵ $\sigma_{A\gamma} >> \sigma_{p\gamma}$

Now is Time to Test Models



from KM 11 NuPhS

Theoretical Models for PeV Neutrinos

Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)

Active galactic nuclei

accretion to massive black hole

γ-ray burst

core-collapse of massive stars

Cosmic-ray Reservoirs

Starburst galaxy

higher star-formation → more supernovae

Galaxy group/cluster

gigantic reservoirs w. AGN, galaxy mergers

- γ-ray bursts

  ex. Waxman & Bahcall 97, KM et al. 06
  after Neutrino 2012:
  Cholis & Hooper 13, Liu & Wang 13
  KM & Ioka 13, Laha et al. 13, Winter 13

- Active galactic nuclei

  ex. Stecker et al. 91, Atoyan & Dermer 01
  after Neutrino 2012:
  Kalashev, Kusenko & Essey 13, Stecker 13,
  KM, Inoue & Dermer 13, Winter 13

- Starburst galaxies (not Milky-Way-like)

  ex. Loeb & Waxman 06, Thompson et al. 07
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Katz et al. 13,
  Liu et al. 14, Tamborra, Ando & KM 14,
  Anchordoqui et al. 14

- Galaxy groups/clusters

  ex. Berezinsky et al. 97, KM et al. 08
  after Neutrino 2012:
  KM, Ahlers & Lacki 13

Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)

Active galactic nuclei

γ-ray burst

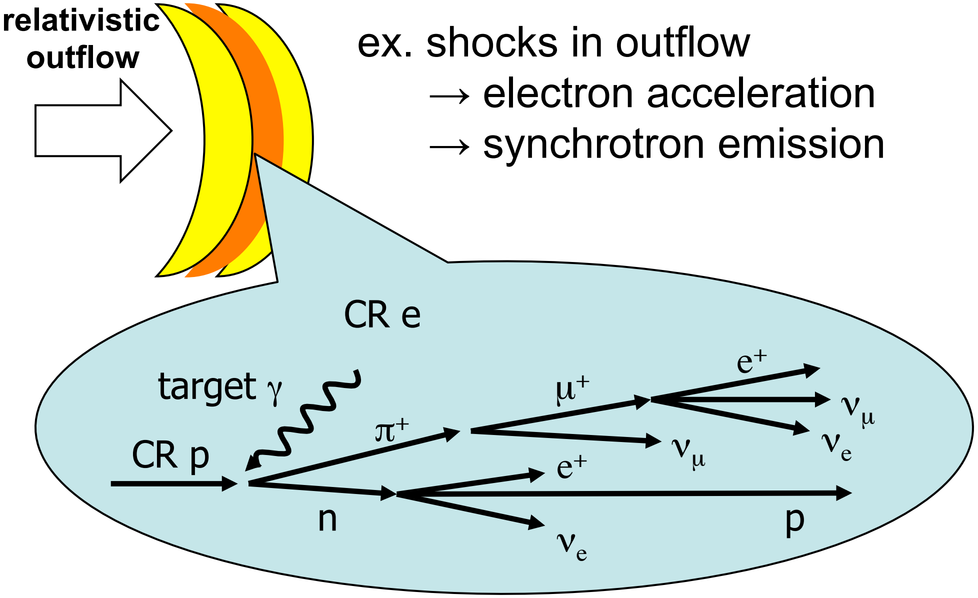
$$p + \gamma \rightarrow N\pi + X$$

Cosmic-ray Reservoirs

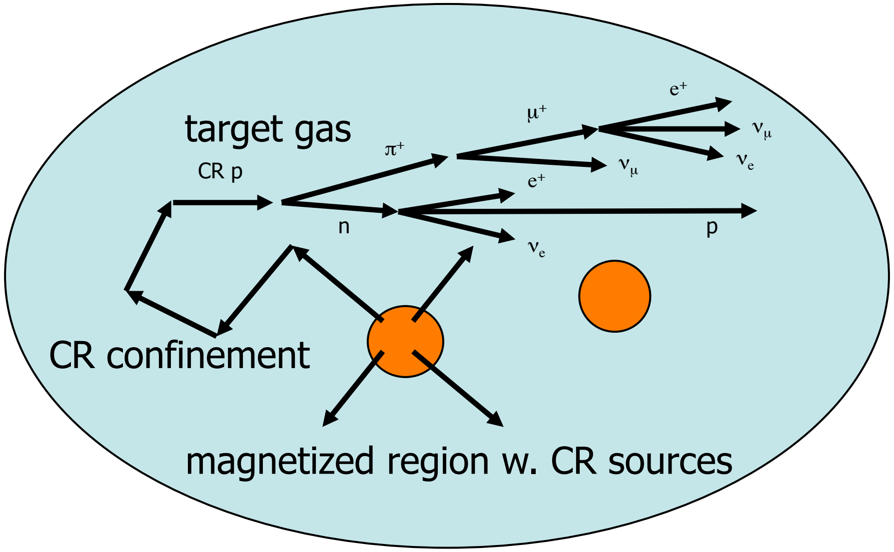
Starburst galaxy

Galaxy group/cluster

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



ex. shocks in outflow
→ electron acceleration
→ synchrotron emission



Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)

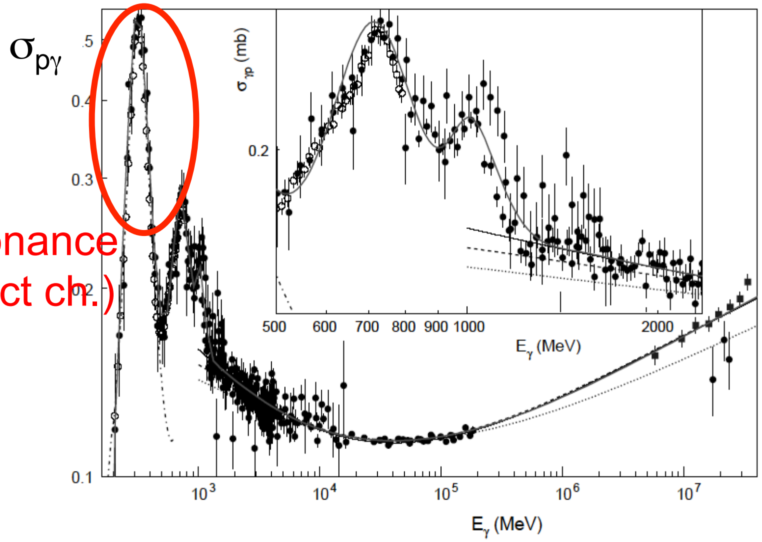
Active galactic nuclei

accretion to massive black hole

γ-ray burst

core-collapse of massive stars

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



Δ-resonance
(+ direct ch.)

$$\sigma_{p\gamma} \sim \alpha\sigma_{pp} \sim 0.5 \text{ mb}$$

$$\varepsilon'_p\varepsilon'_\gamma \sim (0.34 \text{ GeV})(m_p/2) \sim 0.16 \text{ GeV}^2$$

Cosmic-ray Reservoirs

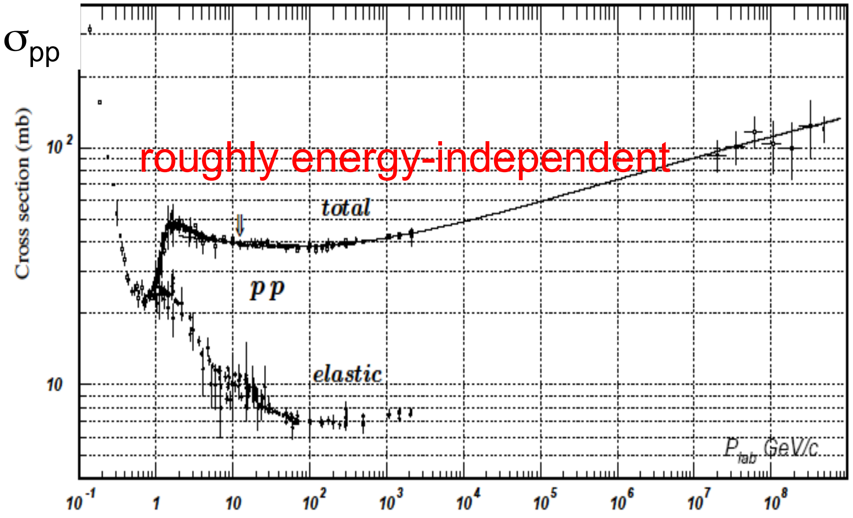
Starburst galaxy

higher star-formation → more supernovae

Galaxy group/cluster

gigantic reservoirs w. AGN, galaxy mergers

$$p+p \longrightarrow N\pi + X$$



roughly energy-independent

$$\sigma_{pp} \sim 1/m_\pi^2 \sim 30 \text{ mb}$$

Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)

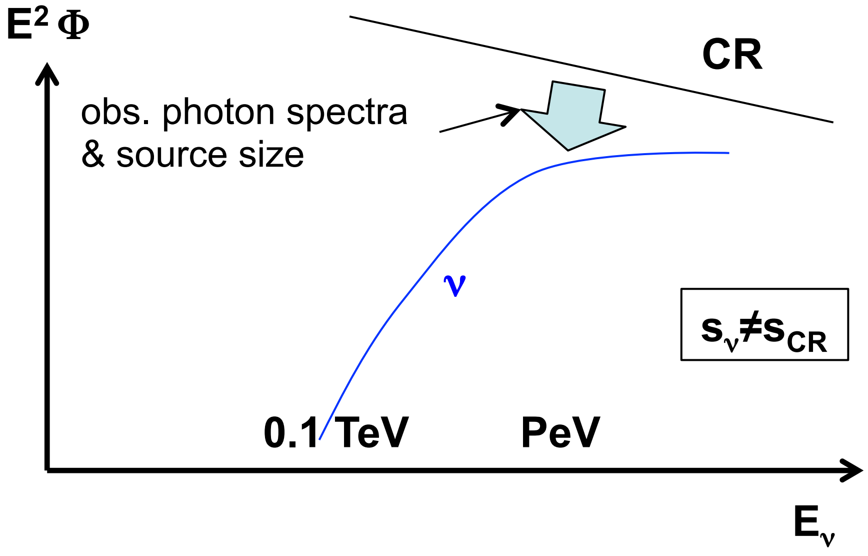
Active galactic nuclei

accretion to massive black hole

γ-ray burst

core-collapse of massive stars

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



Cosmic-ray Reservoirs

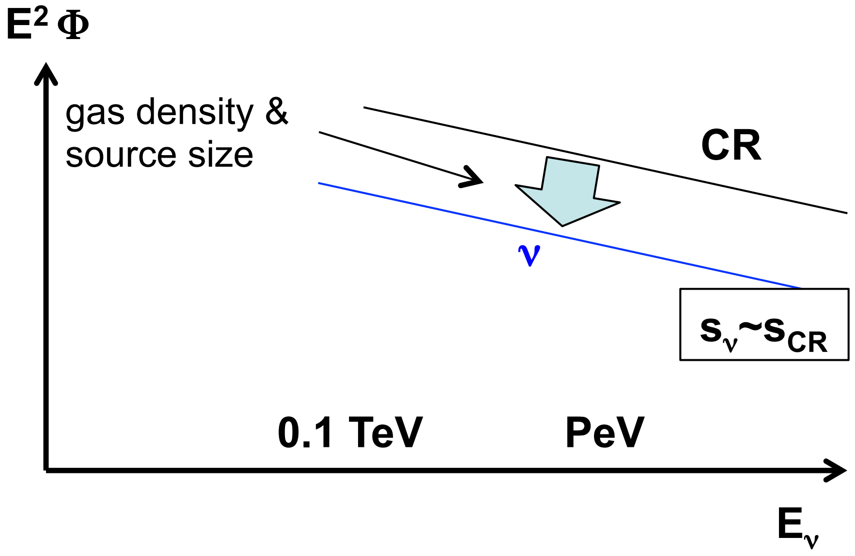
Starburst galaxy

higher star-formation → more supernovae

Galaxy group/cluster

gigantic reservoirs w. AGN, galaxy mergers

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



$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)

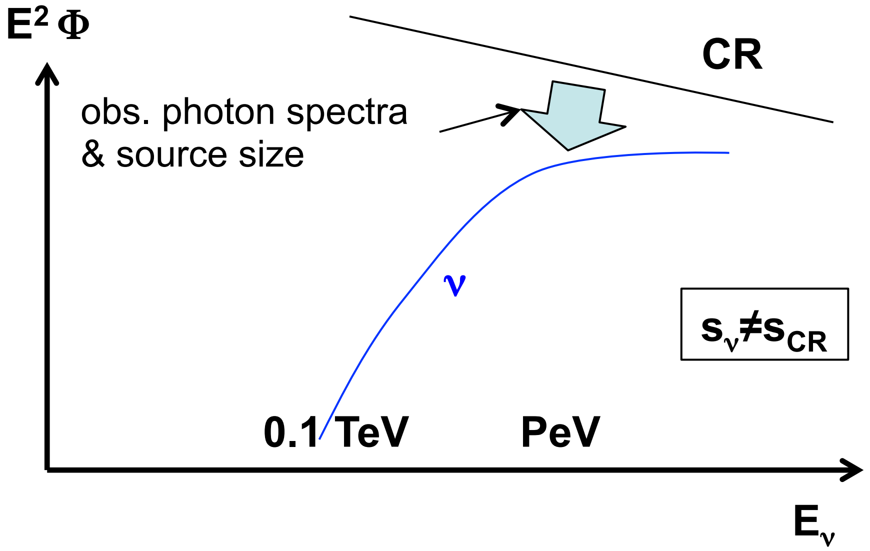
Active galactic nuclei

accretion to massive black hole

γ-ray burst

core-collapse of massive stars

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



Cosmic-ray Reservoirs

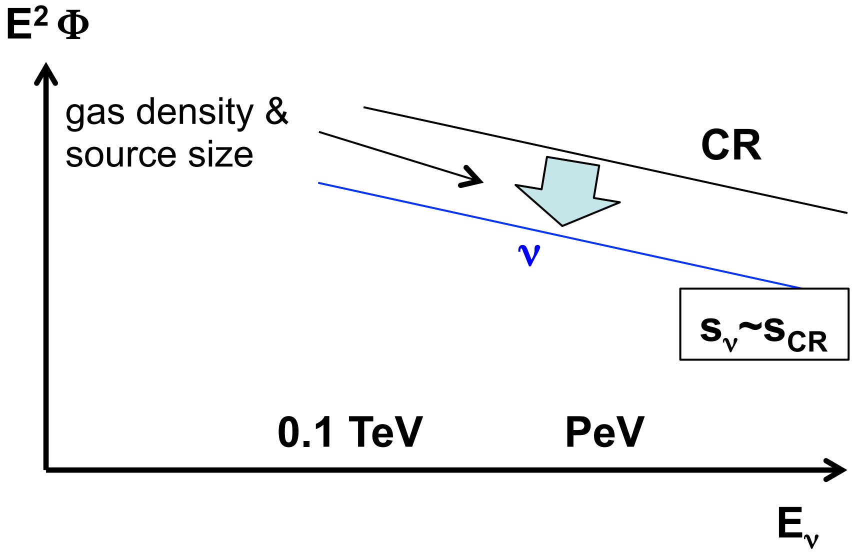
Starburst galaxy

higher star-formation → more supernovae

Galaxy group/cluster

gigantic reservoirs w. AGN, galaxy mergers

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

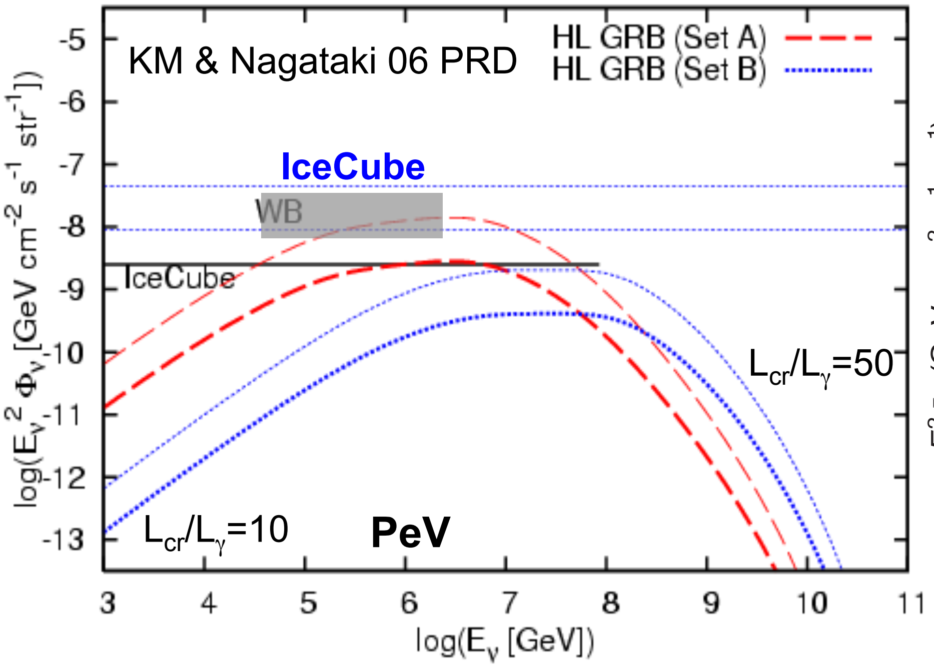


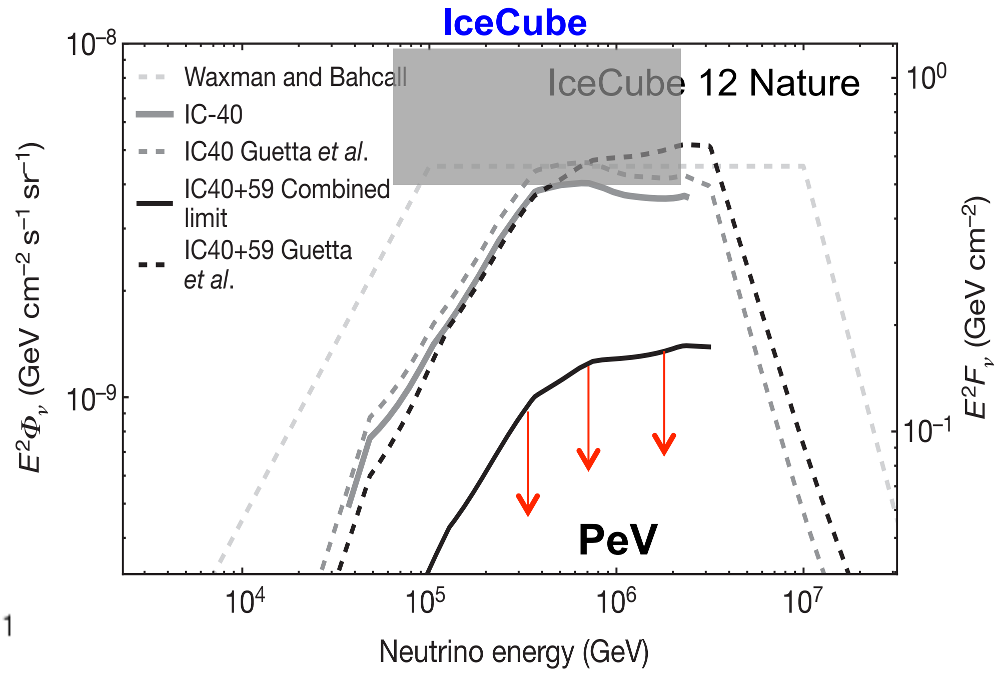
$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

$p\gamma$ Neutrinos from Gamma-Ray Bursts

- Popular candidate sources of PeV νs and ultrahigh-energy cosmic rays

typical energy $\varepsilon_\nu \sim 0.05\varepsilon_p \sim 0.01\ \mathrm{GeV}^2\ \Gamma_j^2/\varepsilon_{\gamma,pk} \sim$ 1 PeV ($\leftarrow \varepsilon_{\gamma,pk} \sim$ 1 MeV & $\Gamma_j \sim 300$)





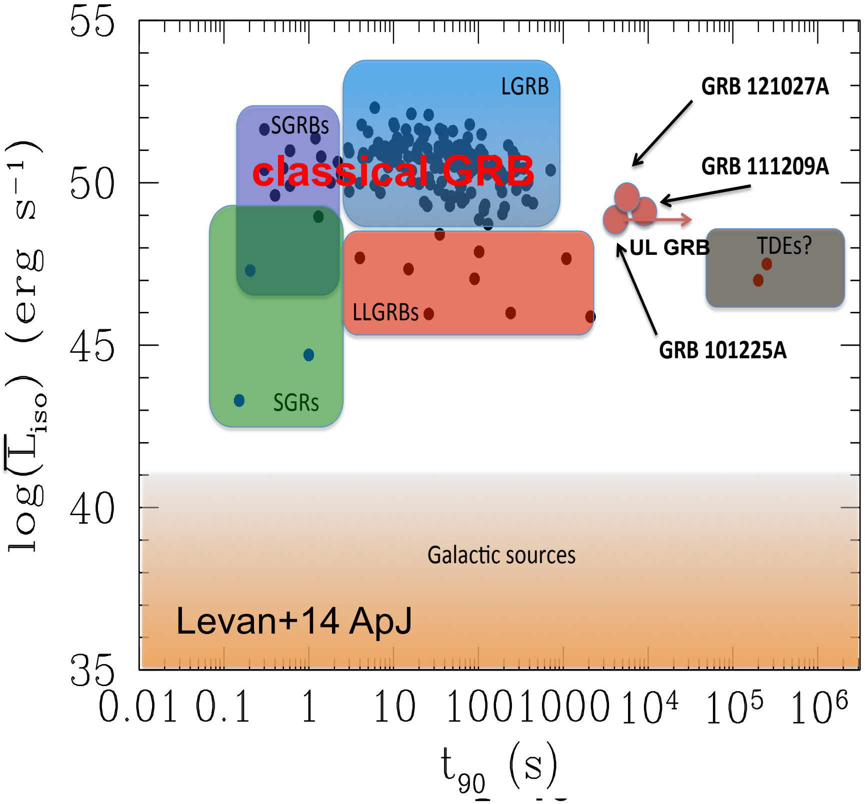
- GRBs are special: stacking analyses (ex. IceCube coll. 12 Nature)

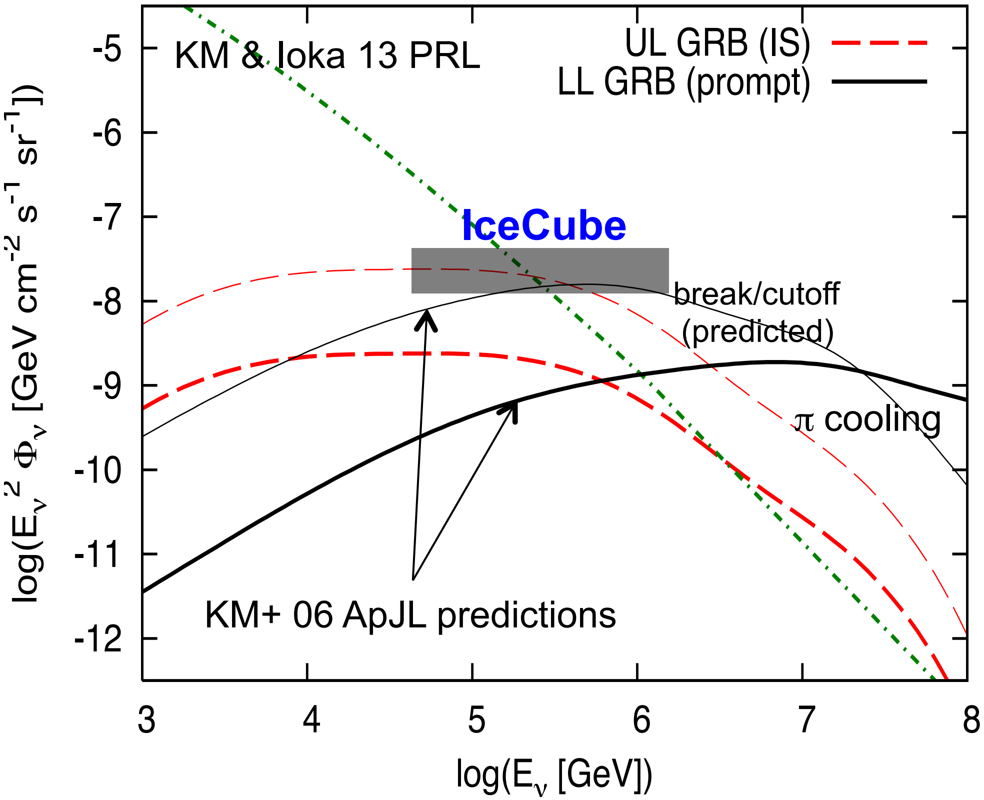
duration (~10-100 s) & localization → atm. bkg. is practically negligible

- IC40+59 limits: <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} (and stronger w. IC79)

→ disfavored as the main origin of observed PeV neutrinos

Exceptions: Low-Power Gamma-Ray Burst Jets



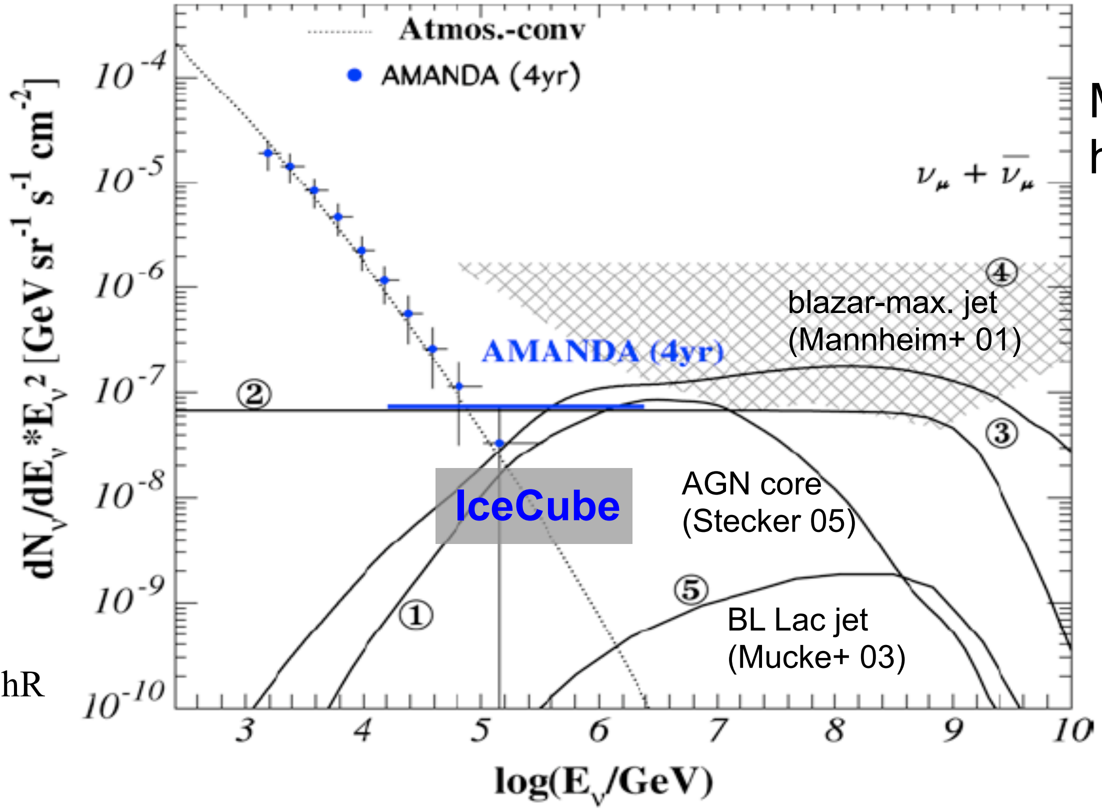


See also: Cholis & Hooper 13, Liu & Wang 13

- Low-luminosity (LL) & ultralong (UL) GRB jets are largely missed
  consistent w. ν data without violating stacking limits
- Uncertain so far, but relevant to understand the fate of massive stars
  → Better (next-generation) wide-field sky monitors are required

pγ Neutrinos from Active Galactic Nuclei

- Considered as powerful HE ν emitters for more than 20 years
- Popular candidate sources of ultrahigh-energy cosmic rays



Becker 06 PhR

Many of original models have been constrained

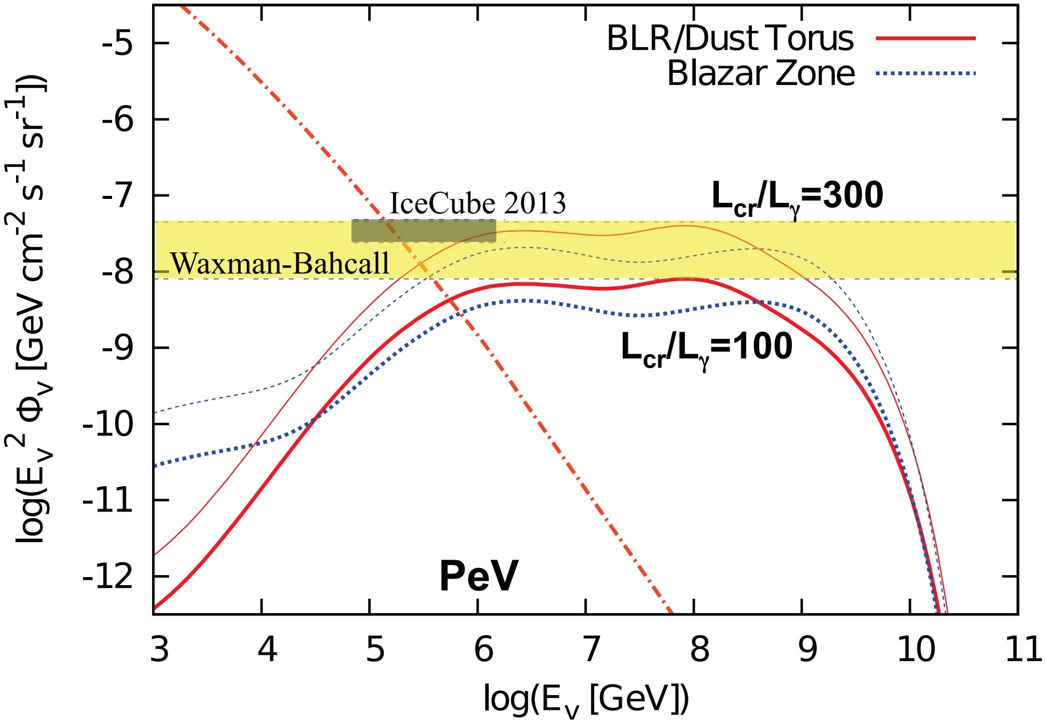
※ For jet emission, pp interactions are unimportant (ex. Atoyan & Dermer 03)

See also:
Kalashev, Kusenko & Essey13
Stecker 13
Winter 13
KM, Inoue & Dermer 14,
Dermer, KM & Inoue 14

- Difficult to explain sub-PeV ν flux since ν spectra are too hard
  → Standard inner jet model has some difficulty in explaining ν data ☹
- Observed νs may correlate with known (<100) γ−ray bright AGN ☺

Blazars as Powerful EeV ν Sources

- Quasar-hosted blazars: efficient ν production, UHECR damped
- BL Lac objects: less efficient ν production, UHE nuclei sources



KM, Inoue & Dermer 14

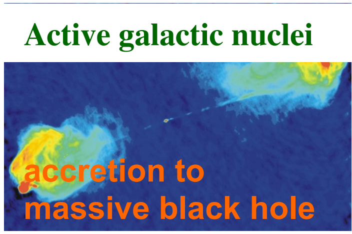
- UHECR acc. is the same and their spectrum is a power law
- Strong prediction: cross-corr. w. known <100 FSRQs → ARA
- Overwhelming cosmogenic neutrinos

for details, Chuck's talk

Astrophysical Extragalactic Scenarios

Relativistic Jets

(UHECR candidate sources)

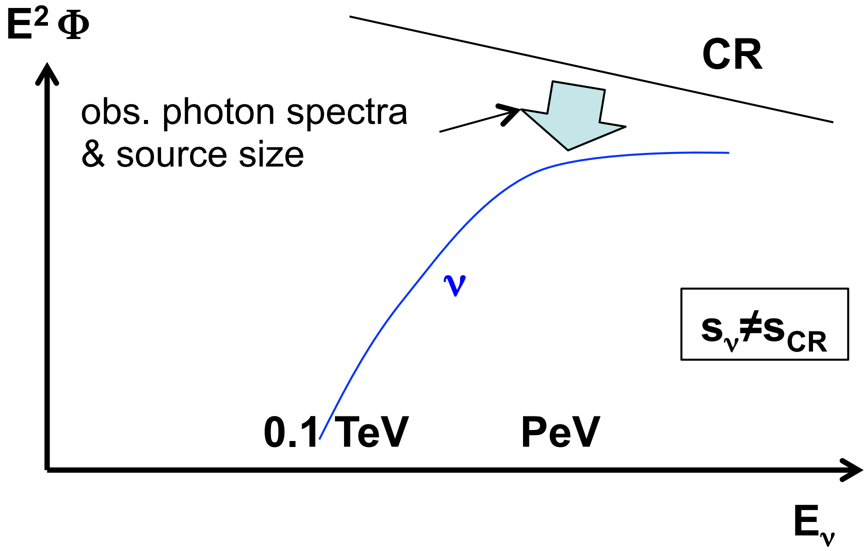

Active galactic nuclei

accretion to massive black hole


γ-ray burst

core-collapse of massive stars

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



Cosmic-ray Reservoirs

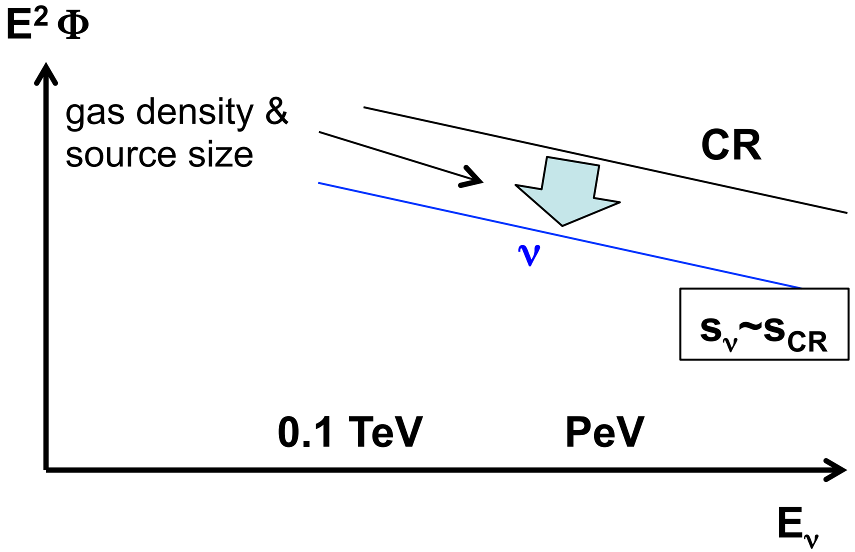

Starburst galaxy

higher star-formation → more supernovae


Galaxy group/cluster

gigantic reservoirs w. AGN, galaxy mergers

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



$E_\nu \sim 0.04\,E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

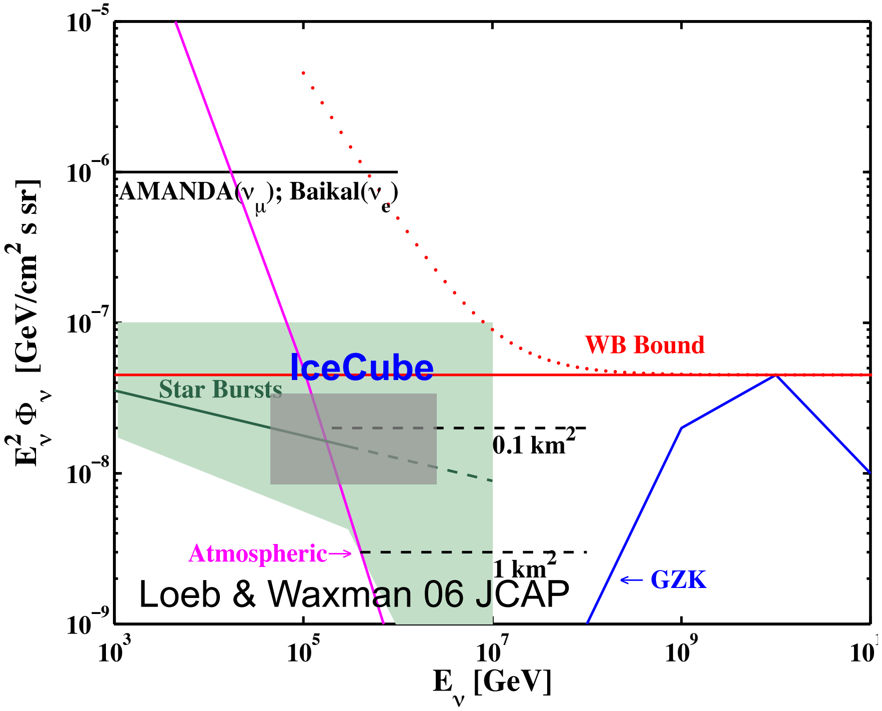
pp Neutrinos from Cosmic-Ray Reservoirs

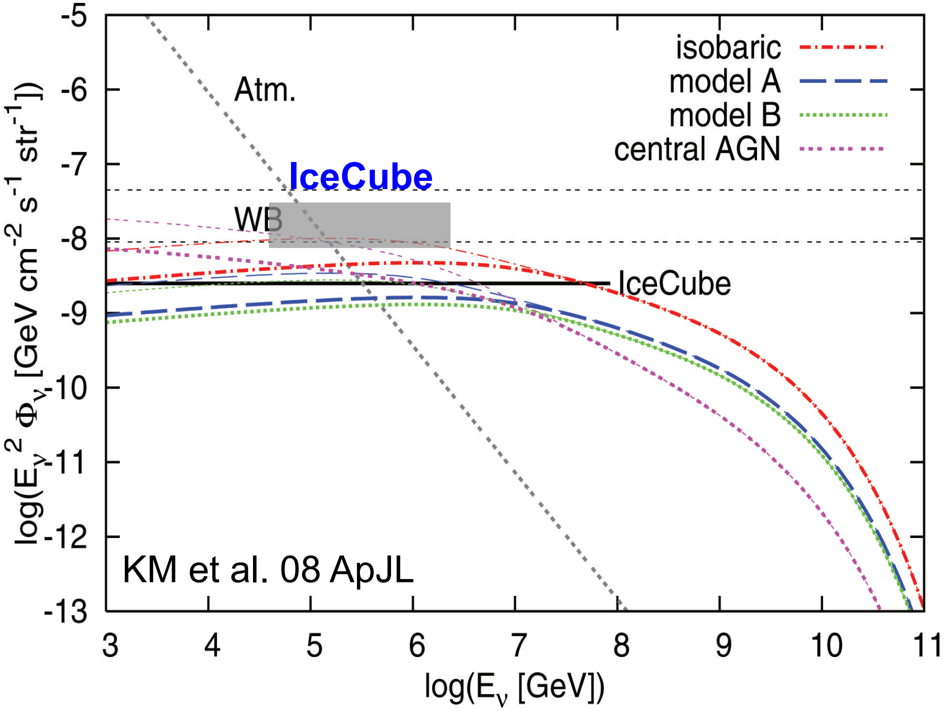
Starburst galaxy
size~0.1-1 kpc, B~0.1-1 mG

CR sources: peculiar supernovae, AGN

Galaxy group/cluster
size~3 Mpc, B~0.1-1 μG

CR sources: AGN, galaxy mergers, virial shocks

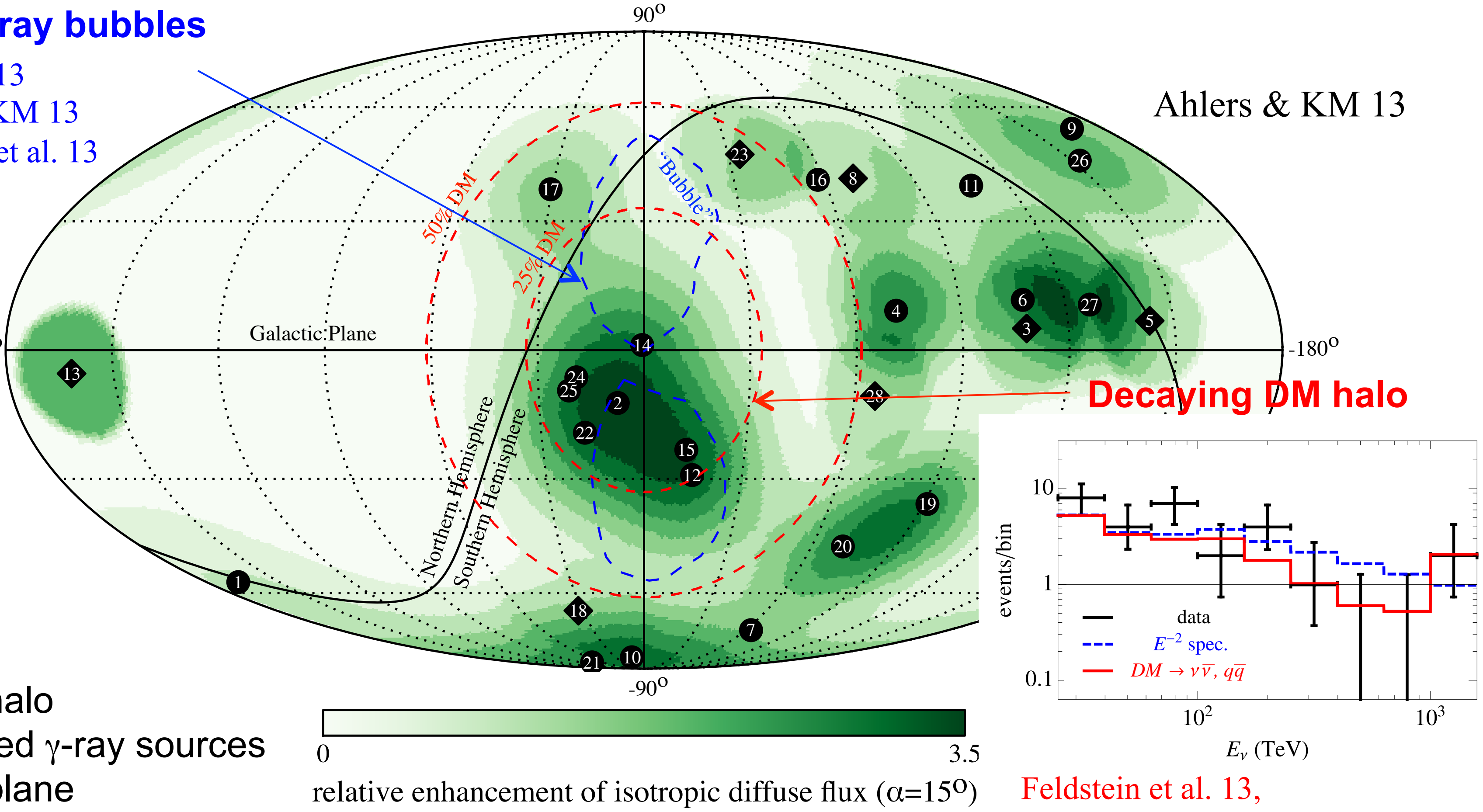




- ν data are consistent w. pre-IceCube calculations (within uncertainty) ☺
- CR diffusive escape naturally makes a ν spectral break (predicted)
- Various theoretical issues, a single source is too faint to detect ☹

Galactic Contributions?

So far, more papers about Galactic sources
(a fraction of νs are explained except the Galactic halo model)



Fermi γ-ray bubbles

Razzaque 13
Ahlers & KM 13
Lunardini et al. 13

Ahlers & KM 13

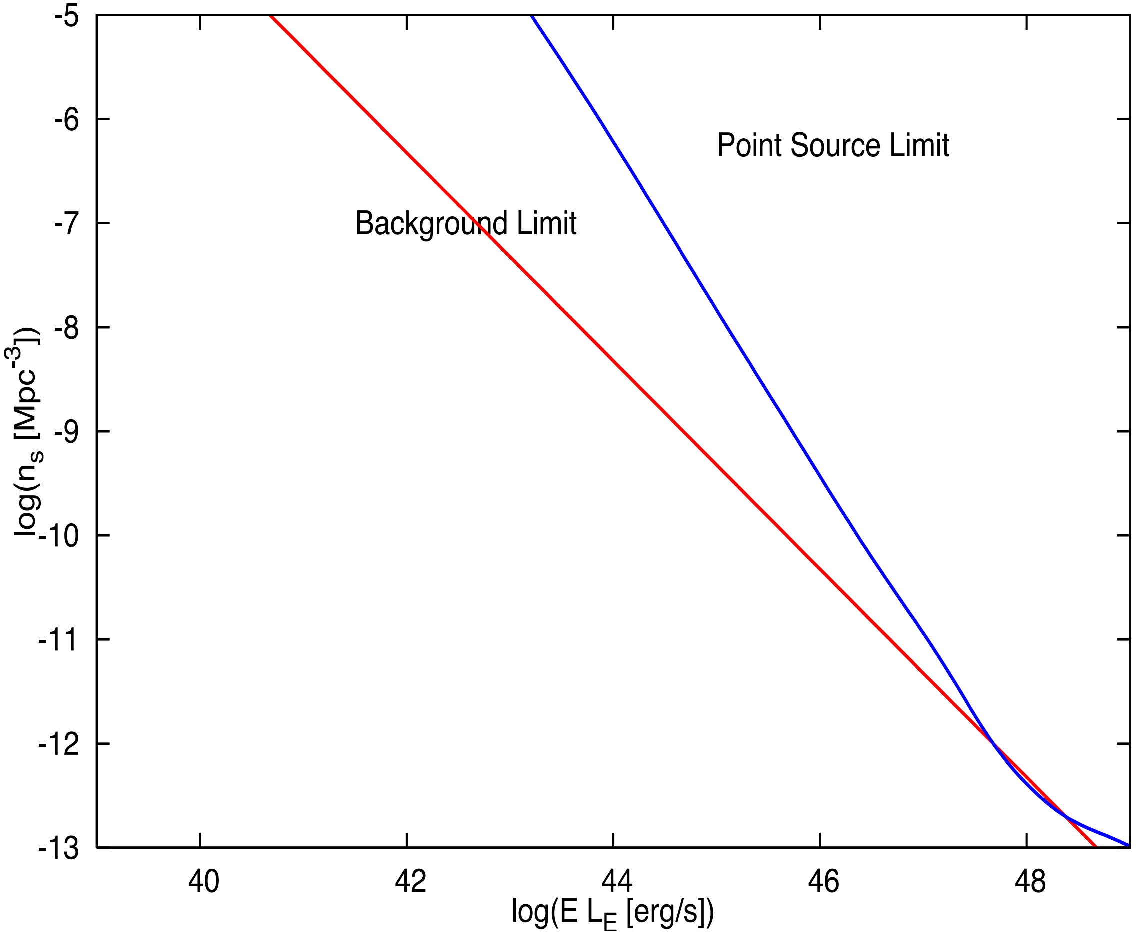
Decaying DM halo

Feldstein et al. 13,
Esmaili & Serpico 13, Bai et al. 14

Others:
Galactic halo
Unidentified γ-ray sources
Galactic plane
Local spiral arms…

Multi-Messenger Tests and Perspectives

Point Source Flux vs Diffuse Flux



cf.
KM, Beacom & Takami 12 JCAP

It is hard to difficult to see a single source

Constraints from clustering & cross-correlation, see Ahlers & Halzen 13

How to Test?: Multi-Messenger Approach

$$\boxed{\pi^0 \to \gamma + \gamma}$$

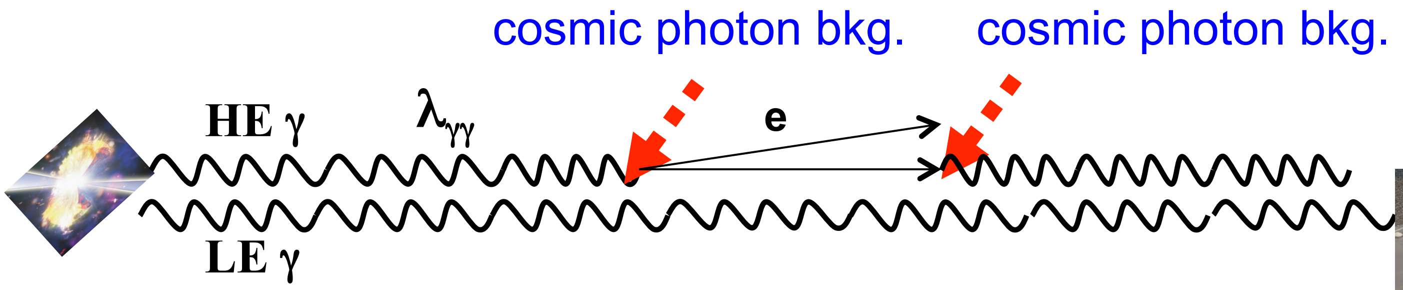
$p + \gamma \to N\pi + X$ $\quad$ $\pi^{\pm}:\pi^0 \sim 1:1 \to$ **$E_\gamma^2\ \Phi_\gamma \sim (4/3)\ E_\nu^2\ \Phi_\nu$**

$p + p \to N\pi + X$ $\quad$ $\pi^{\pm}:\pi^0 \sim 2:1 \to$ **$E_\gamma^2\ \Phi_\gamma \sim (2/3)\ E_\nu^2\ \Phi_\nu$**

>TeV γ rays interact with CMB & extragalactic background light (EBL)

$\gamma + \gamma_{\mathrm{CMB/EBL}} \to e^+ + e^-$ $\quad$ ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc

$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center



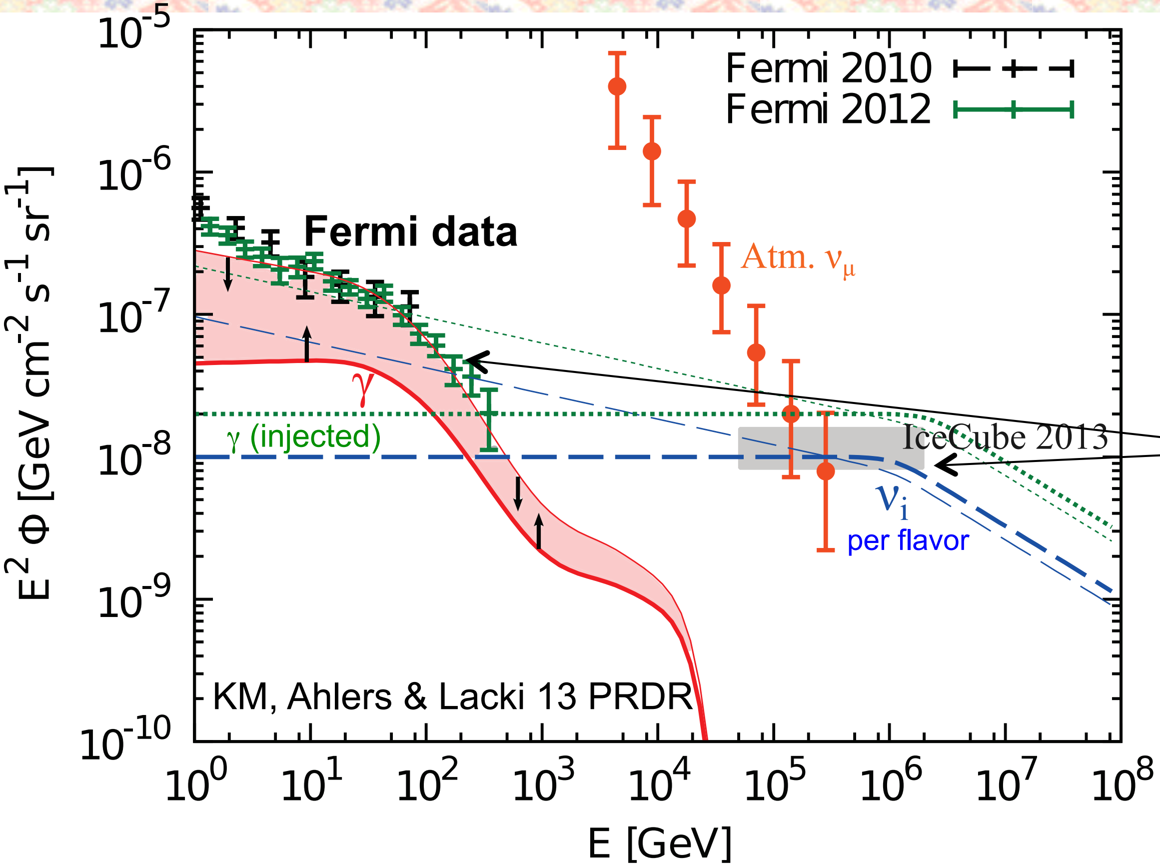

Fermi satellite


airshower detectors

realistic fate of γ rays=electromagnetic cascades

crucial for extragalactic γ rays

New Multimessenger Implications from "Measured" Fluxes



pp scenario

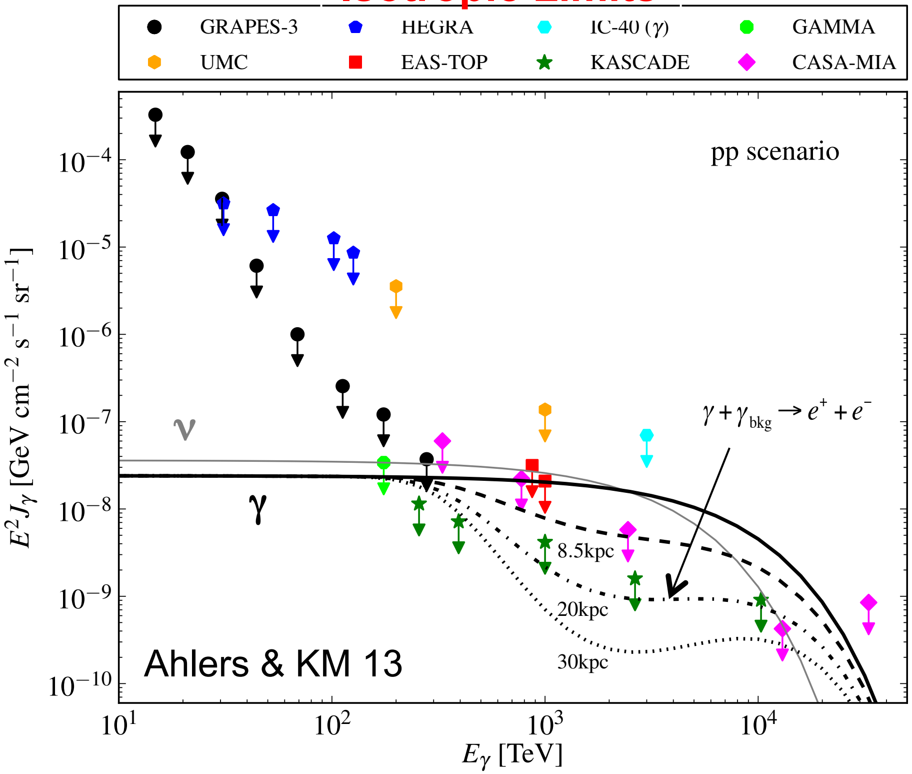
"comparable fluxes"

simple but profound

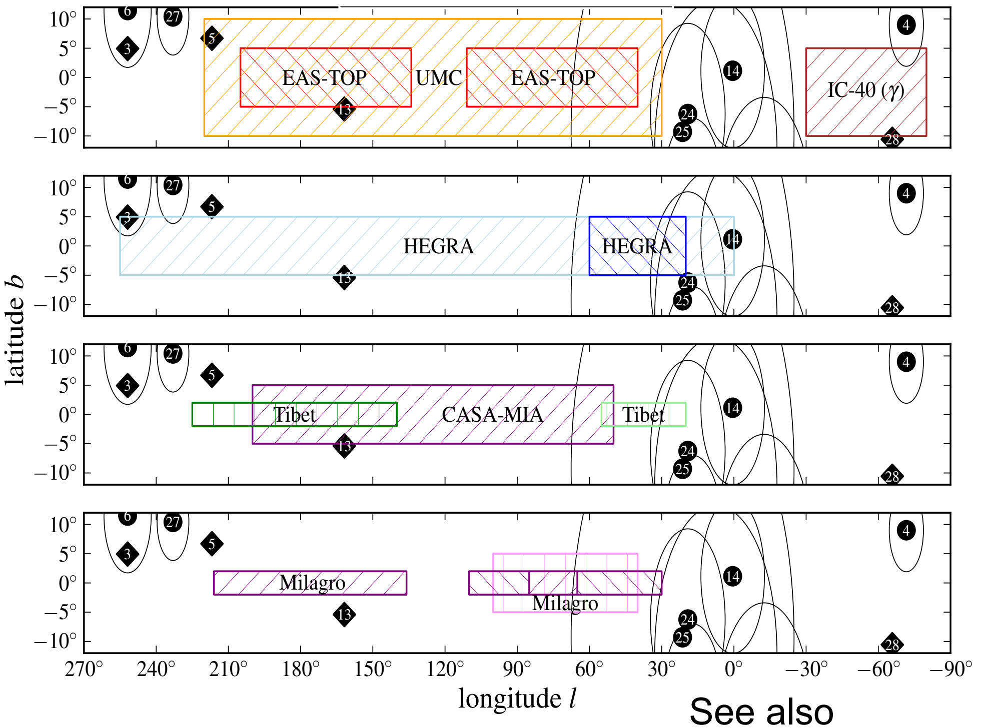
- s_ν<2.1-2.2 (for extragal.), s_ν<2.0 (Gal.) (cf. Milky Way: s_γ~2.7)
  (pp scenarios will be disfavored if future ν data at sub-PeV lead to s_ν>2.2)
- contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)
  (almost excluded if >60-70% of diffuse γ is made by AGN leptonic emission)
- IceCube & Fermi data could be explained simultaneously

Importance of Future TeV-PeV Limits on Galactic Sources

Airshower arrays have placed diffuse γ-ray limits at TeV-PeV



Isotropic Limits



Galactic Plane

See also
Spantisky 14
Joshi+ 14
Anchodoqui+ 14

- Existing TeV-PeV γ-ray limits are close to predicted fluxes
- No significant overlap between νs and search regions
- Need deeper TeV-PeV γ-ray obs. in the Southern Hemisphere

Summary: Implications

Origin of PeV neutrinos: Need more data, no strong preference so far…

- Relativistic jets (GRBs & AGN)
  - possible but their standard jet models have some difficulty for PeV νs
  - need careful studies on γ rays including EM cascades in the sources

- Cosmic-ray reservoirs (starbursts & galaxy groups/clusters)
  consistent w. previous expectations but $s_\nu<2.1$-2.2 from γ-ray data
  1. determination of s_ν in the sub-PeV range (IceCube)
  2. understanding diffuse sub-TeV γ-ray origins (Fermi & γ-ray telescopes)
  (pp models are good in the sense that they can be tested in a simple way.)

- Galactic sources (many possibilities)
  - some of observed ν events may be Galactic
  - diffuse TeV-PeV γ-ray searches in the Southern Hemisphere are useful

- Cosmological PeV neutrinos can be used for constraining new physics
  (for recent studies, ν decay: ex. Baerwald+ 13, Pakvasa+ 13, Lorentz invariance violation: ex. Borriello+ 13, Anchordoqui+ 14, $\nu\nu$ interactions: ex. Ioka & KM 14, Ng & Beacom 14)

Questions for Future

- Spectral features: is the possible ν spectral break/cutoff real?

- Flavor ratio: consistent w. 1:1:1?
  0.57:1:1 (μ damp), 2.5:1:1 (neutron decay), others (exotic),
  looking for τ-appearance, Glashow-res. etc. (ex. Pakvasa 0803.1701, Anchordoqui+ 1312.6587)

- Connection w. ultrahigh-energy cosmic-ray origins?
  PeV ν ⇔ ~20-30 PeV p or ~(20-30)A PeV nuclei (cf. “knee”~3 PeV)

  Is $E_\nu^2 \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} coincident with the WB bound?
  a. UHECR sources have $s_{CR} \sim 2$ & $f_{mes} \sim 1$
  b. UHECR sources have $s_{CR} >> 2$ & $f_{mes} << 1$
  (may be better if observed UHECRs are heavy nuclei)

※injected/confined CR spectra ≠ escaping CR spectra

WANTED

~~Diffuse or~~ Associated

ν

- Source identification may not be easy
  (ex. starbursts: horizon of an average source ~ 1 Mpc)
- promising cases: “bright transients (GRBs, AGN flares)”,
  “rare bright sources (powerful AGN)”, “Galactic sources”
- Not guaranteed but remember the success of γ-ray astrophysics