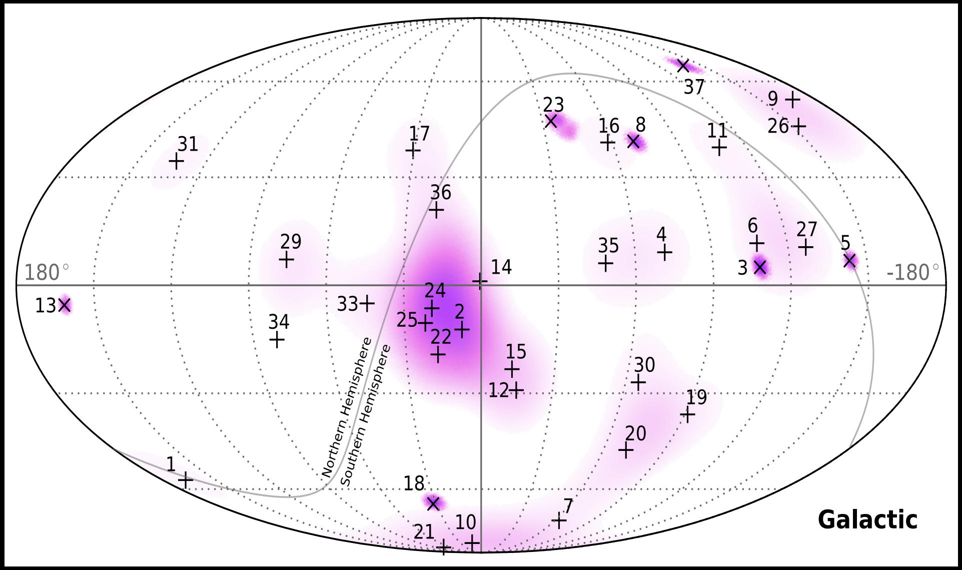
Origin of High-Energy Cosmic Neutrinos

Kohta Murase (Institute for Advanced Study)



IceCube
arXiv:1405.5303

ISVHECRI @ CERN, August 20 2014

Talk Outline

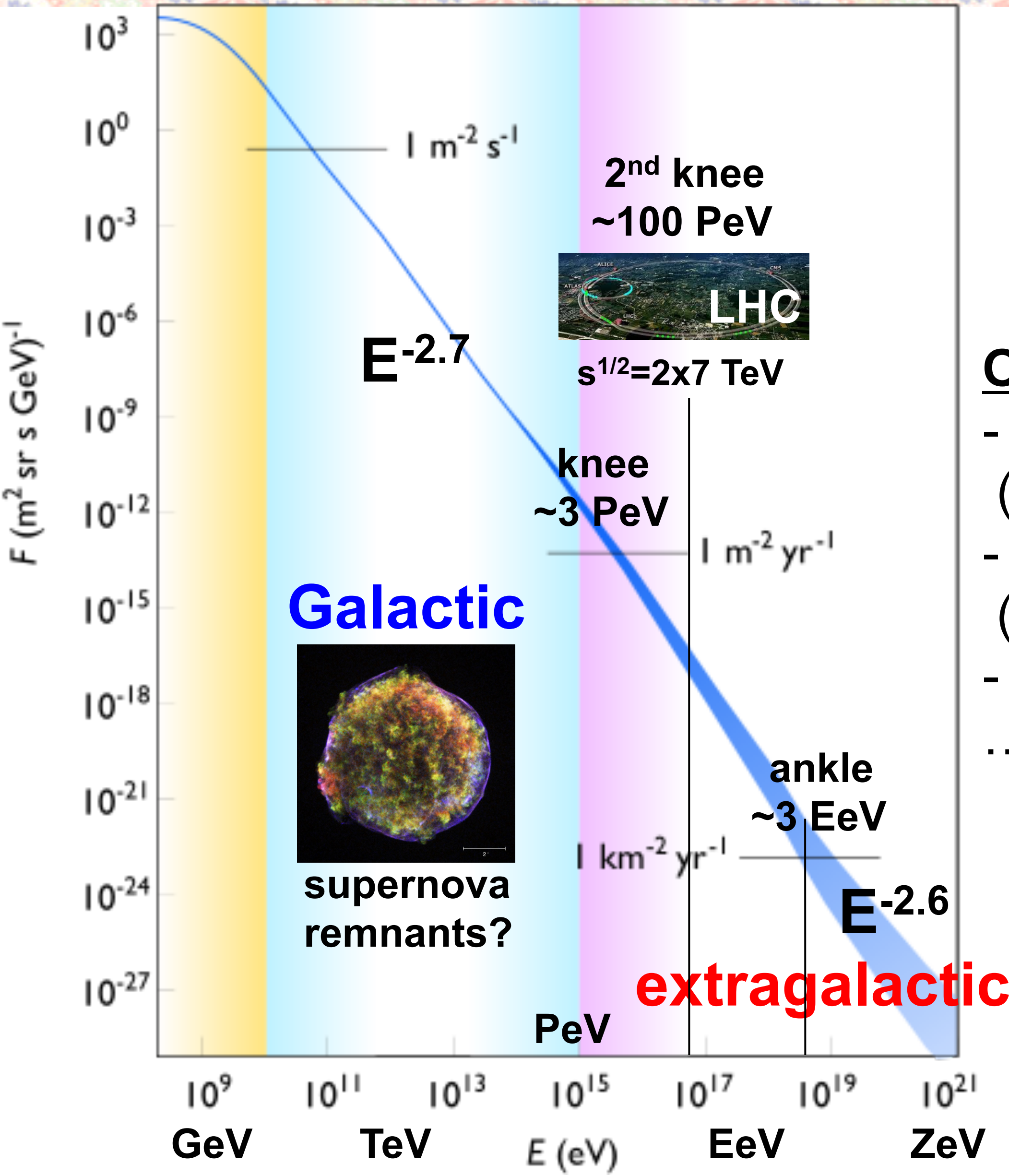
The first discovery of HE cosmic ν signals by IceCube

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

Motivation I: Cosmic Rays – A Century Old Puzzle



$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

Open problems

- How is the spectrum formed?
 (ex. transition to extragalactic)
- How are CRs accelerated?
 (ex. Fermi mechanism: s_{CR}~2)
- How do CRs propagate?

…

The key question

"What is the origin?"

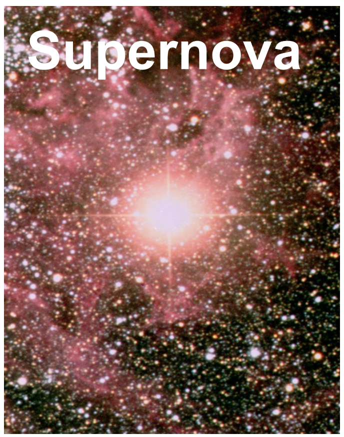
extreme energy (EeV-ZeV)

→ extreme sources

see Eli's & Andrew's talks

Motivation II: Probe of Astrophysics & Neutrino Physics

Neutrinos can probe dense environments like the stellar interior
→ detecting even a few events can give definitive answers
→ will open new windrows of HE astrophysics & ν physics



~10 MeV neutrinos from supernova 1987A
thermal ν: stellar core's grav. binding energy

- explosion mechanisms, progenitor properties, nucleosynthesis, ν oscillation etc.

> GeV neutrinos from jets (ex. γ-ray bursts)
nonthermal ν: dissipation in relativistic jets

- relativistic jet properties, relationship with supernovae, new physics (ex. LIV, νν interactions) etc.

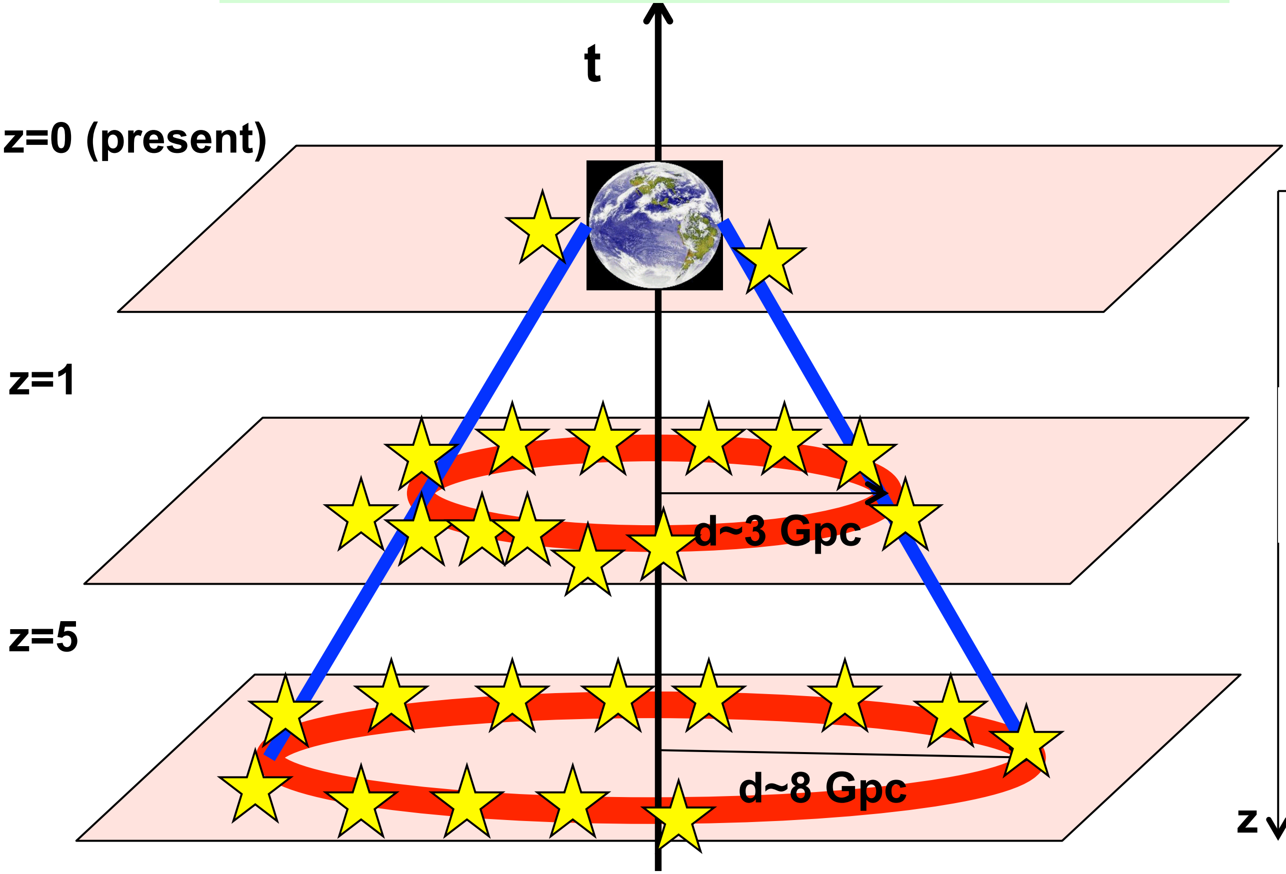
Astrophysical "Isotropic" Neutrino Background – Mean Diffuse Intensity

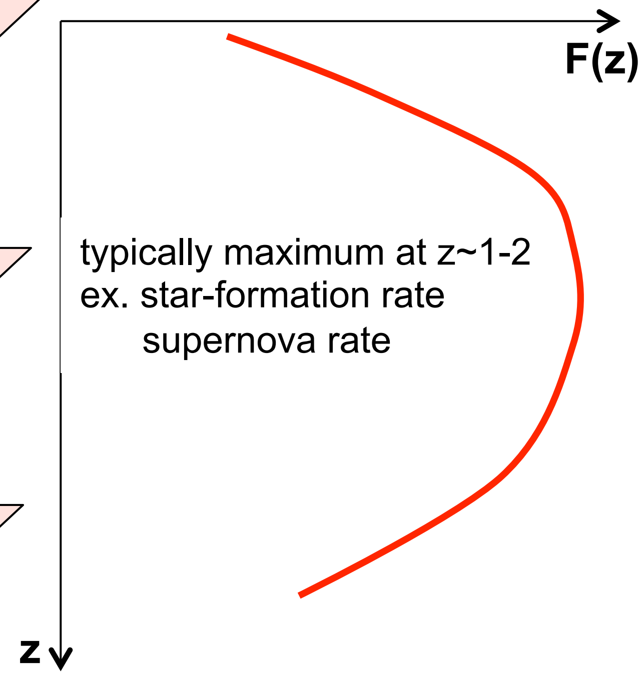
diffuse ν intensity of extragalactic sources (cf. supernova ν bkg.) ← consistent w. isotropic distribution

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

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

F(z): redshift evolution





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

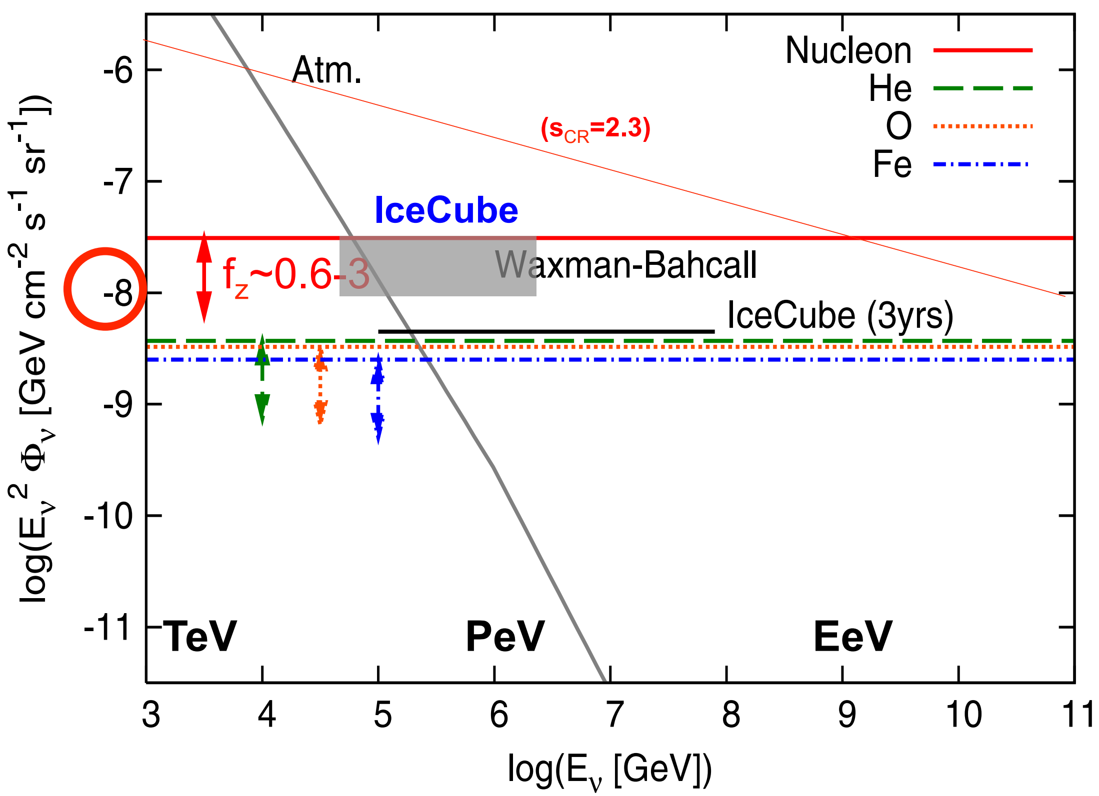
What does $E_\nu^2\Phi_\nu$~3x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} Imply?: Cosmic-Ray Connection

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

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

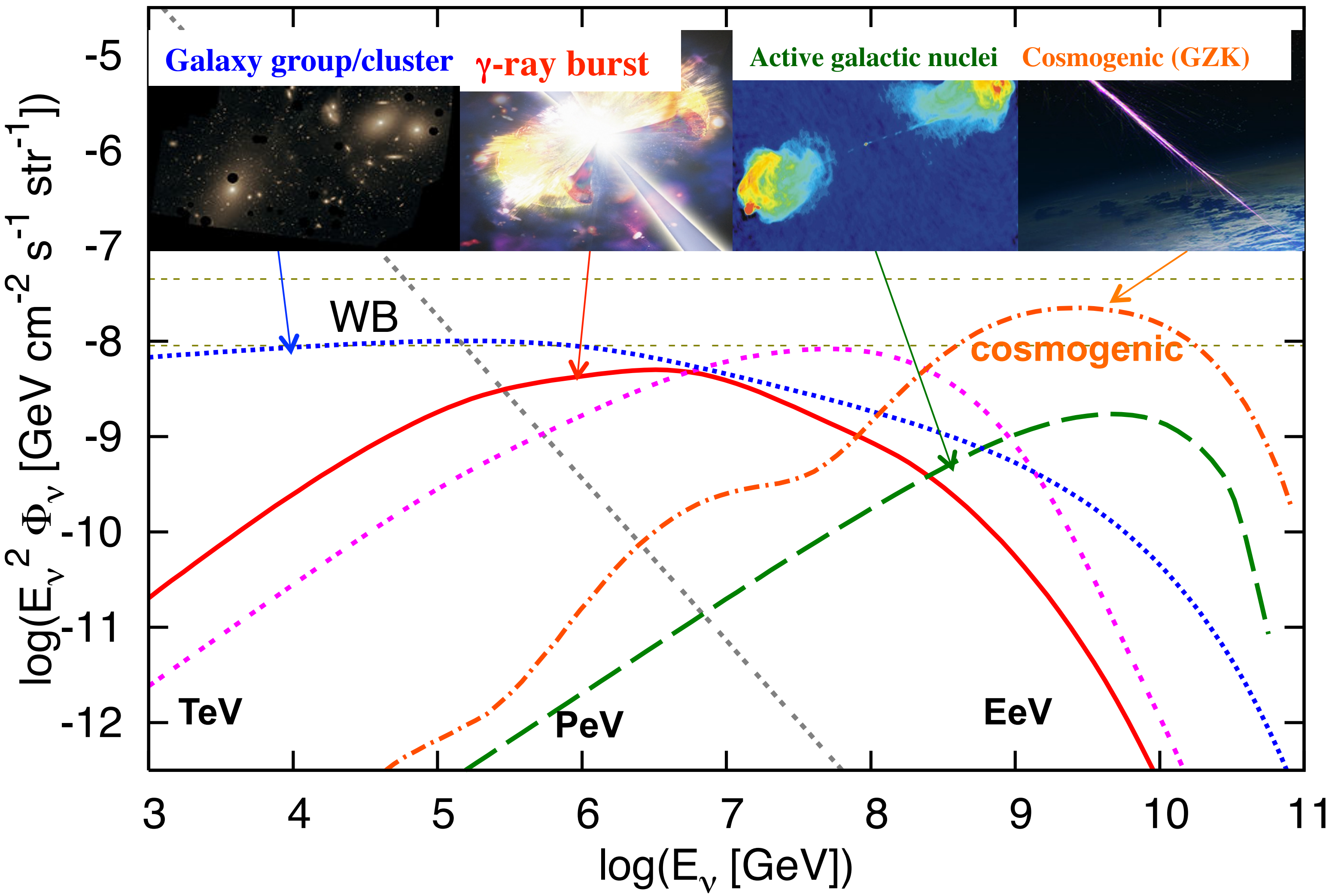
Waxman-Bahcall landmark (s_{CR}=2 assumed) (Waxman & Bahcall 98 PRD)

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



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

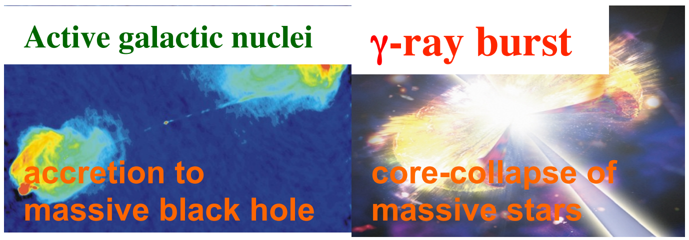
Now is Time to Test Models



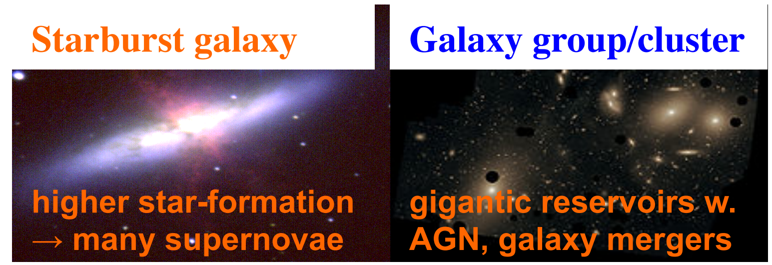
Theoretical Models for PeV Neutrinos

Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)



Cosmic-ray Reservoirs



- 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, Mannheim 95
after Neutrino 2012:
Kalashev, Kusenko & Essey 13, Stecker 13,
KM, Inoue & Dermer 14, Dermer et al. 14

- 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

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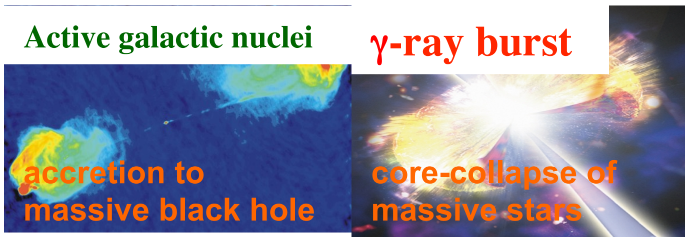
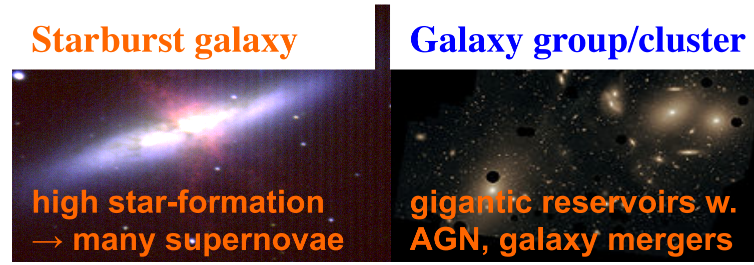


$$p + \gamma \rightarrow N\pi + X$$

Cosmic-ray Reservoirs



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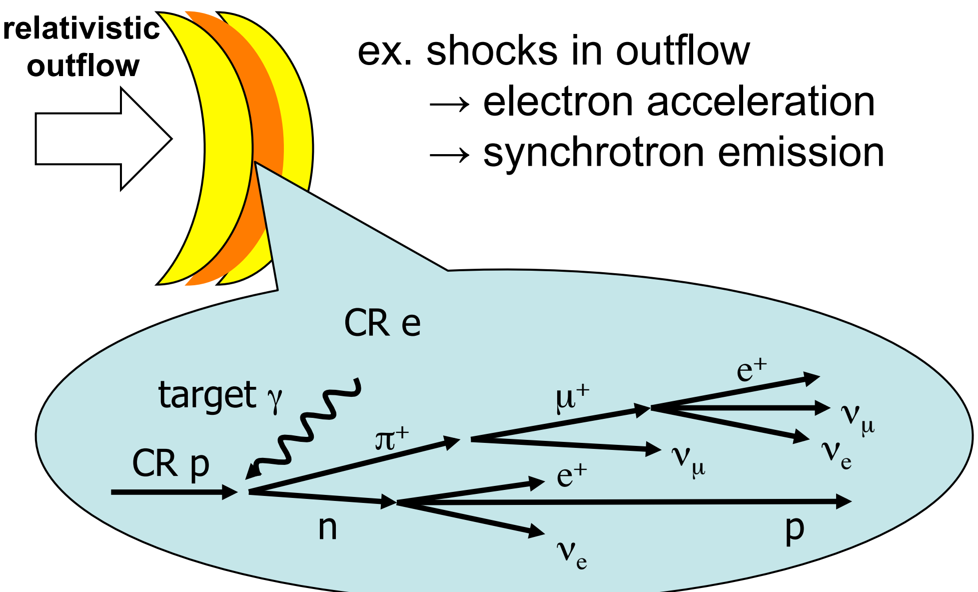

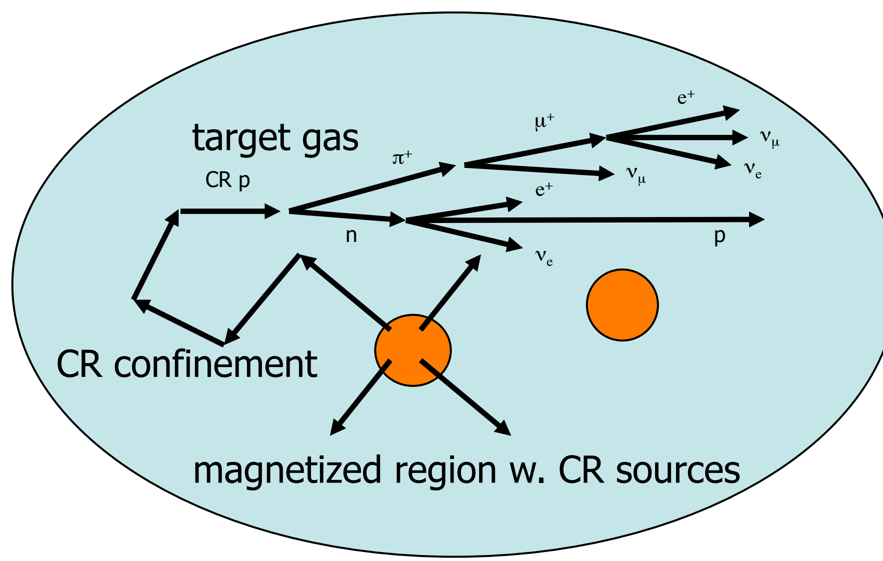

Astrophysical Extragalactic Scenarios

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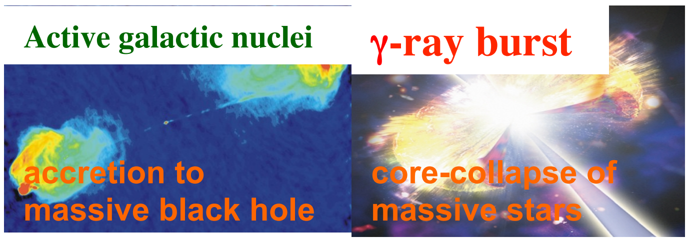
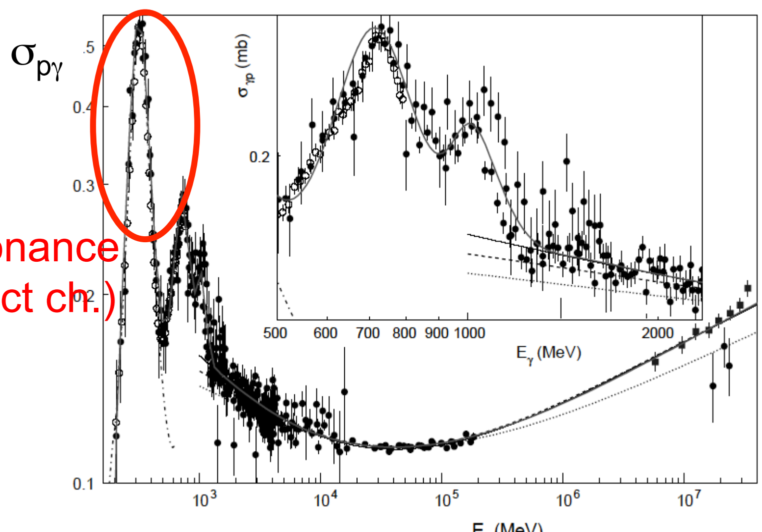


$$p+\gamma \rightarrow N\pi + X$$

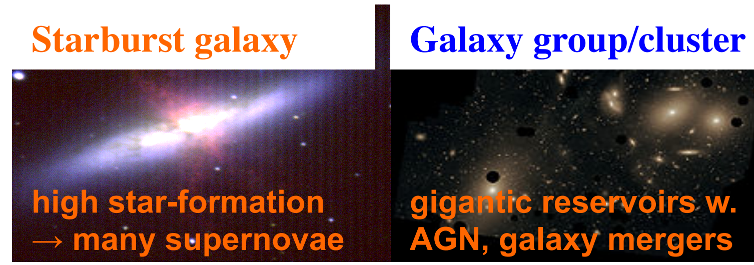


Δ-resonance
(+ direct ch.)

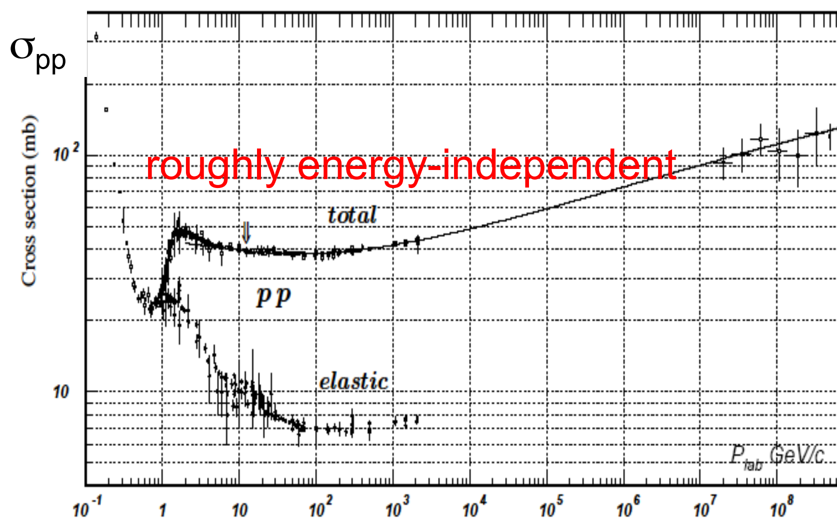
$\sigma_{p\gamma} \sim \alpha \sigma_{pp} \sim 0.5$ mb

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

Cosmic-ray Reservoirs



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



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

Astrophysical Extragalactic Scenarios

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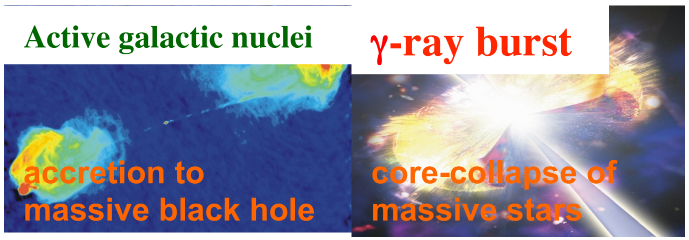
(UHECR candidate sources)



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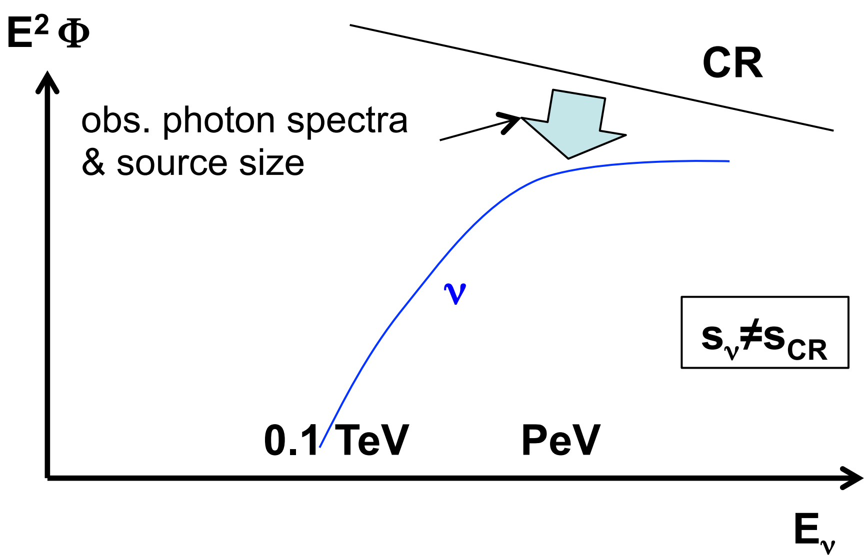
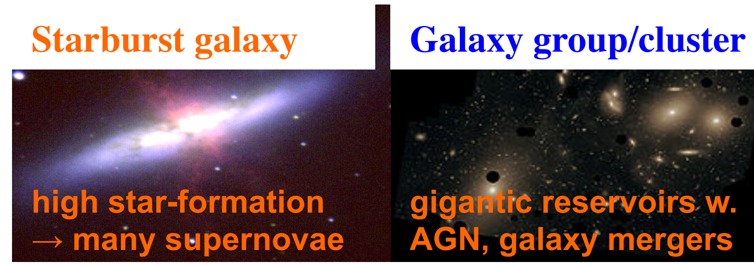


Cosmic-ray Reservoirs



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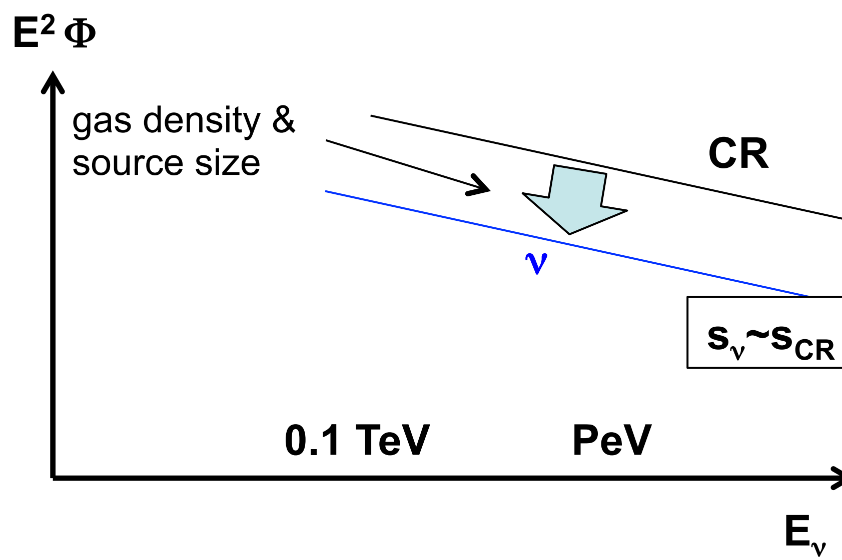

$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Astrophysical Extragalactic Scenarios

Relativistic Jets
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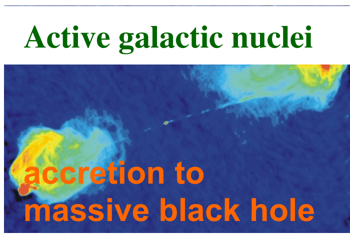
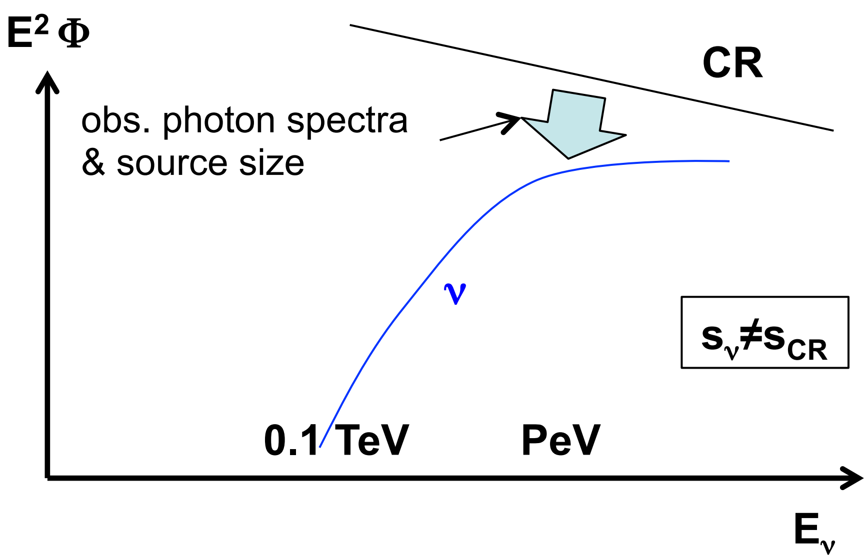
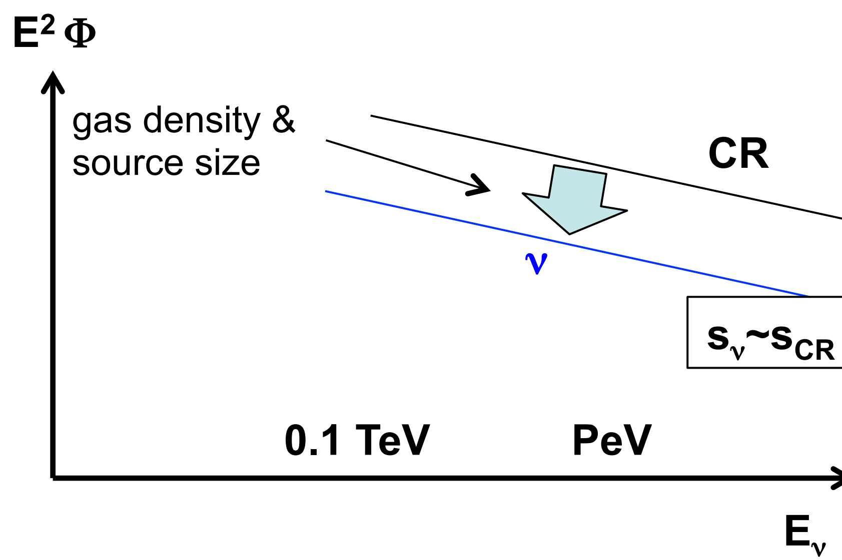


$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs

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



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

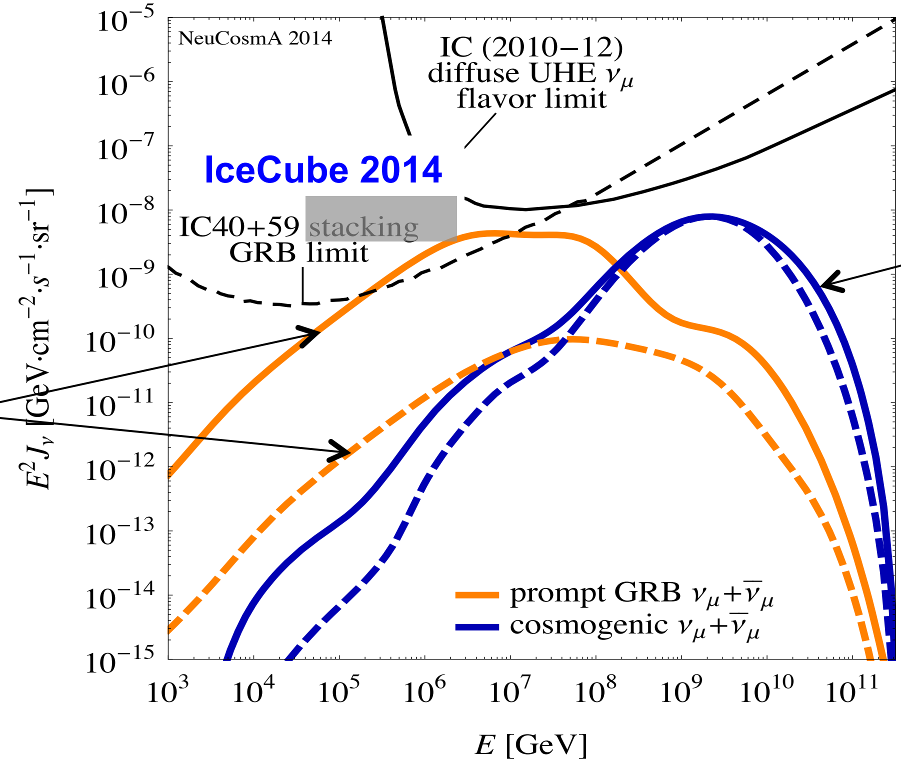
$p\gamma$ Neutrinos from Gamma-Ray Burst Jets

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

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

"classical" GRB ν

Cholis & Hooper 13
but implausible, see
KM & Ioka 13
Laha et al. 13
Liu & Wang 13 etc.



cosmogenic ν
(difficult to explain PeV νs)
ex.
Roulet et al. 13
Laha et al. 13
IceCube coll. 13

taken from Baerwald et al. 14

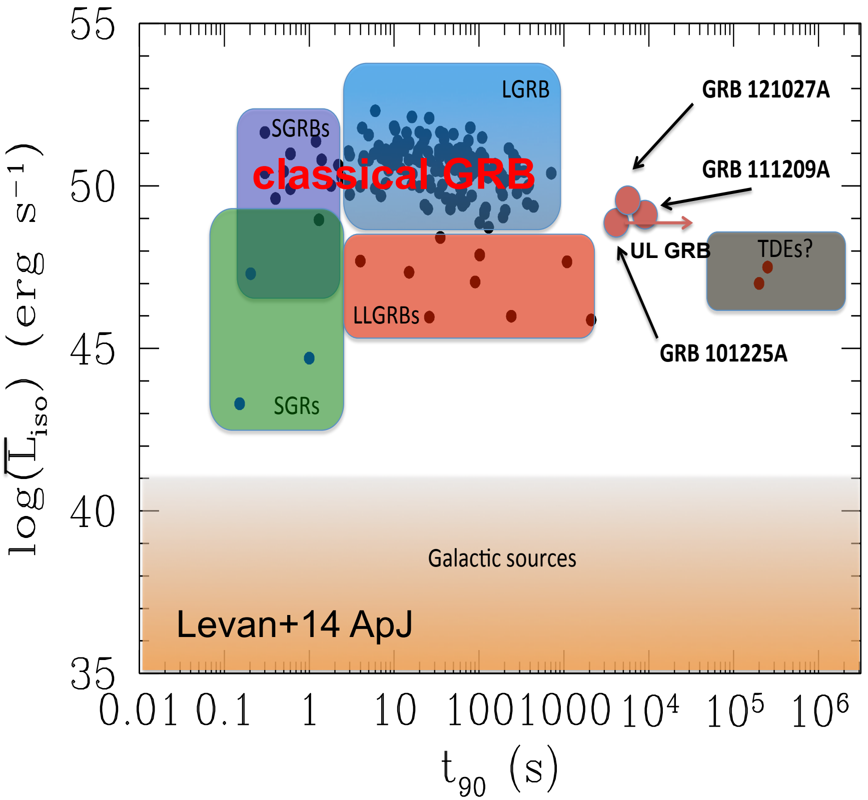
- GRBs are special: stacking analyses (ex. IceCube coll. 12 Nature)

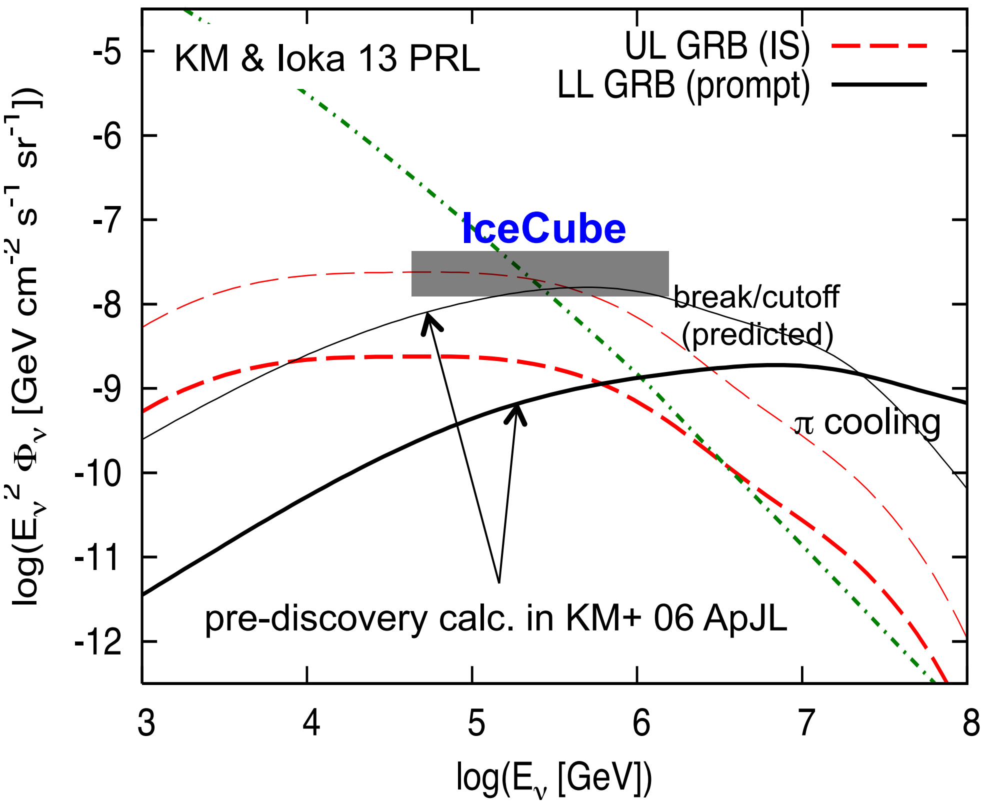
duration (~10-100 s) & localization → atm. bkg. is practically negligible

- IC40+59 limits: <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} (and stronger w. IC79+86)

→ Classical GRBs are not the main origin of observed PeV neutrinos

Exceptions: Low-Power Gamma-Ray Burst Jets



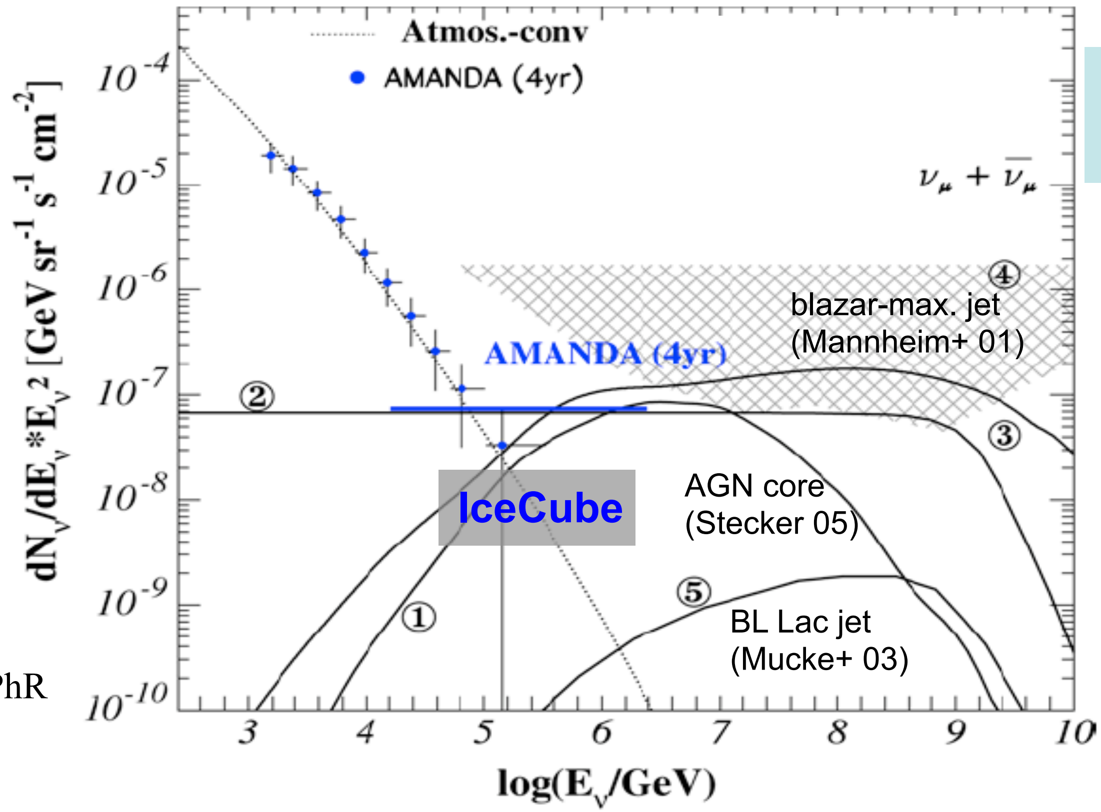


cf. Cholis & Hooper 13

- Low-luminosity (LL) & ultralong (UL) GRB jets are largely missed
  Compatible w. IceCube 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

$p\gamma$ 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"

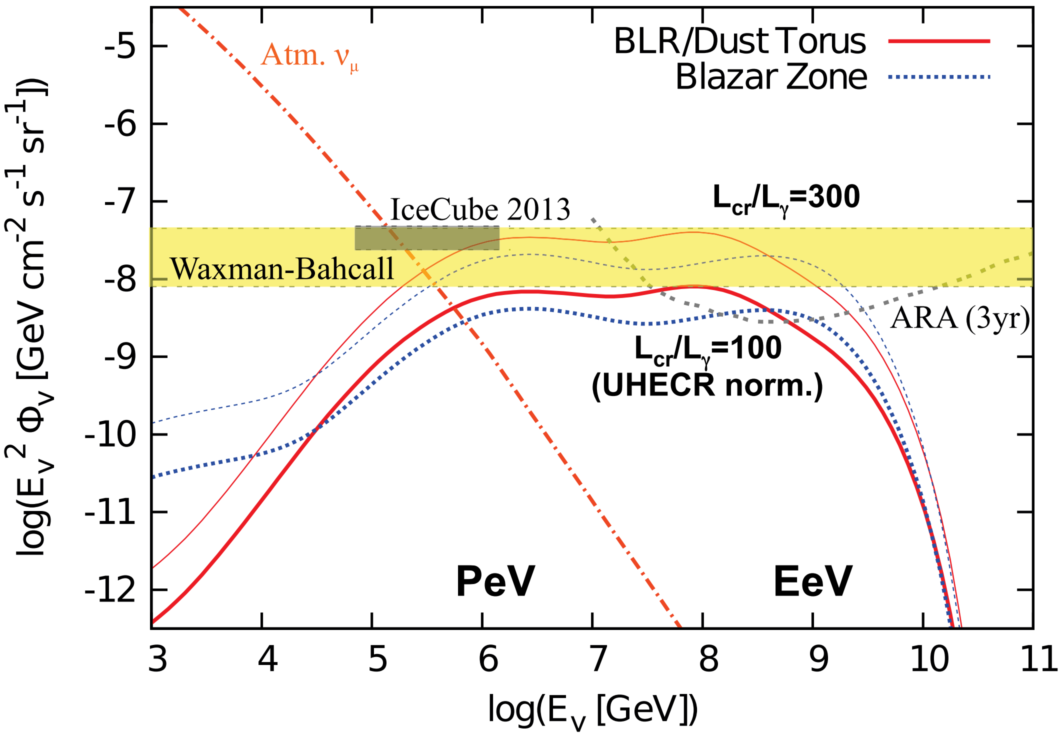
※ For jet emission, pp interactions are unimportant (ex. Atoyan & Dermer 03)

see:
Kalashev, Kusenko & Essey13
Stecker 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 difficulty in explaining ν data

Blazars as Powerful EeV ν Sources

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



- luminosity function is now provided by Fermi satellite
- target photon spectra of all types of blazars w. external radiation fields

KM, Inoue & Dermer 14 PRD

- PeV-EeV ν: pγ w. BLR & dust-torus photons → unique shape
- Strong prediction: cross-corr. w. known <100 bright quasars
- UHECR norm. → below WB but detectable in the EeV range

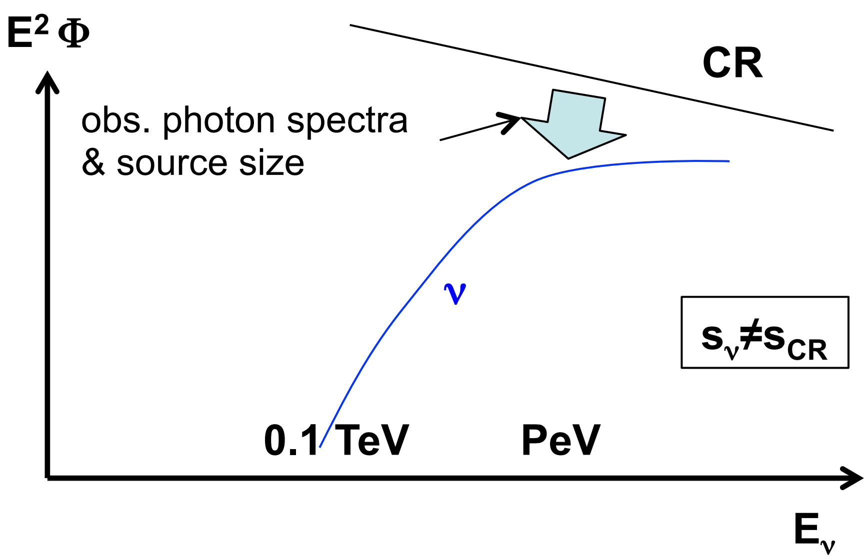
Astrophysical Extragalactic Scenarios

Relativistic Jets
(UHECR candidate sources)

Active galactic nuclei

γ-ray burst

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

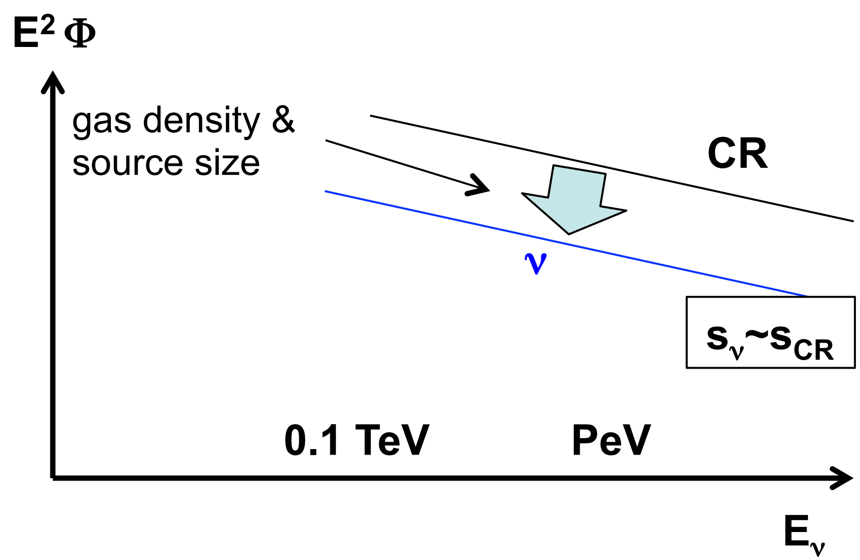


Cosmic-ray Reservoirs

Starburst galaxy

Galaxy group/cluster

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

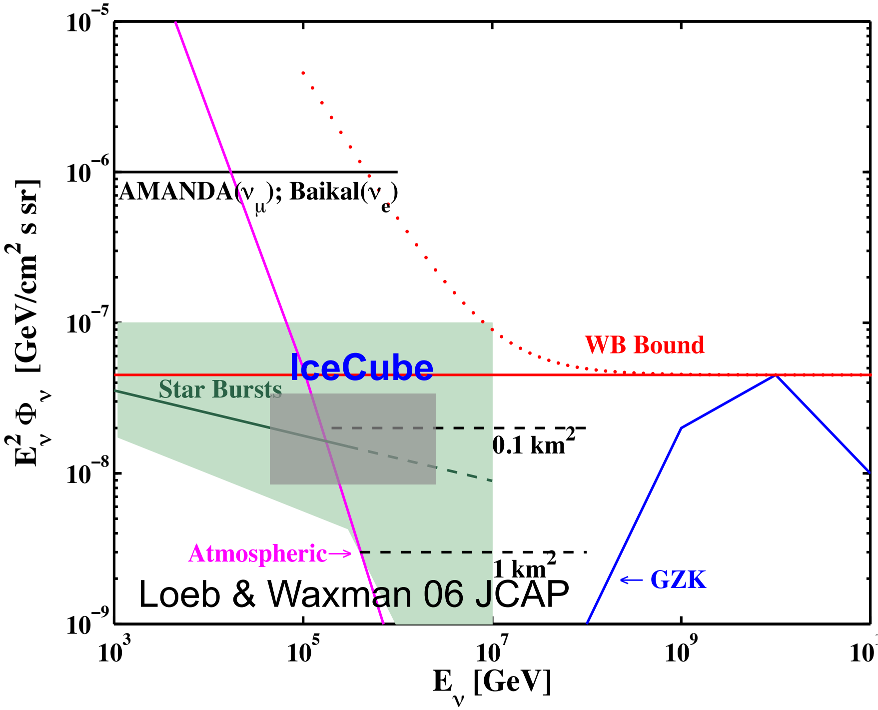


$E_\nu \sim 0.04\ E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

pp Neutrinos from Cosmic-Ray Reservoirs

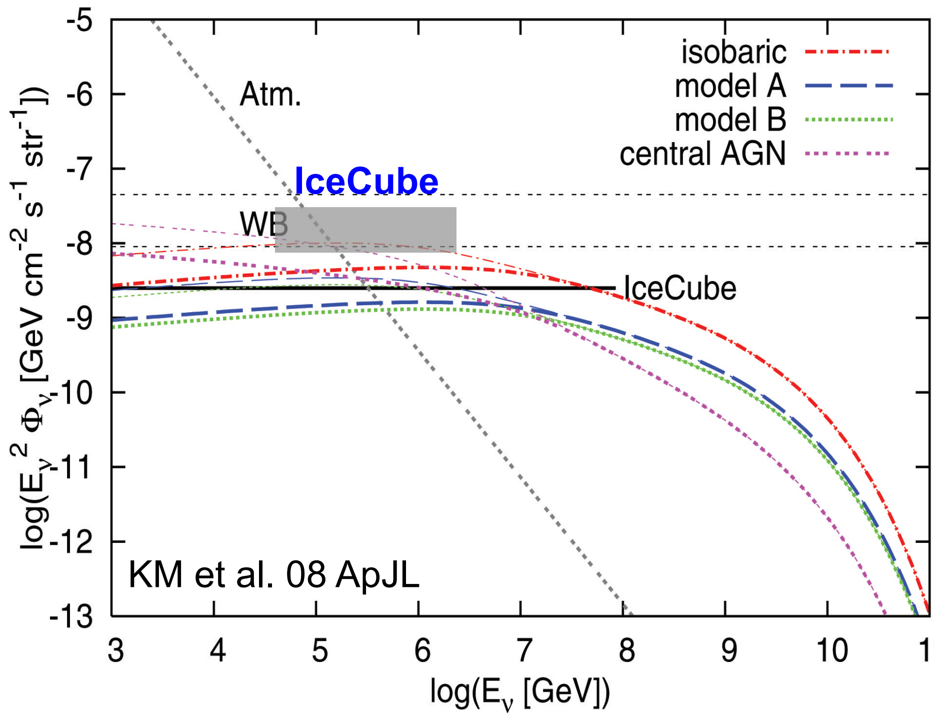
Starburst galaxy
size~0.1-1 kpc, B~0.1-1 mG

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-discovery* calculations (within uncertainty)
- CR diffusive escape naturally makes a ν spectral break (predicted)
- Uncertain (ex. how $E_p^{max} > E_{knee}$?), a single source is too faint to detect

Galactic Contributions?

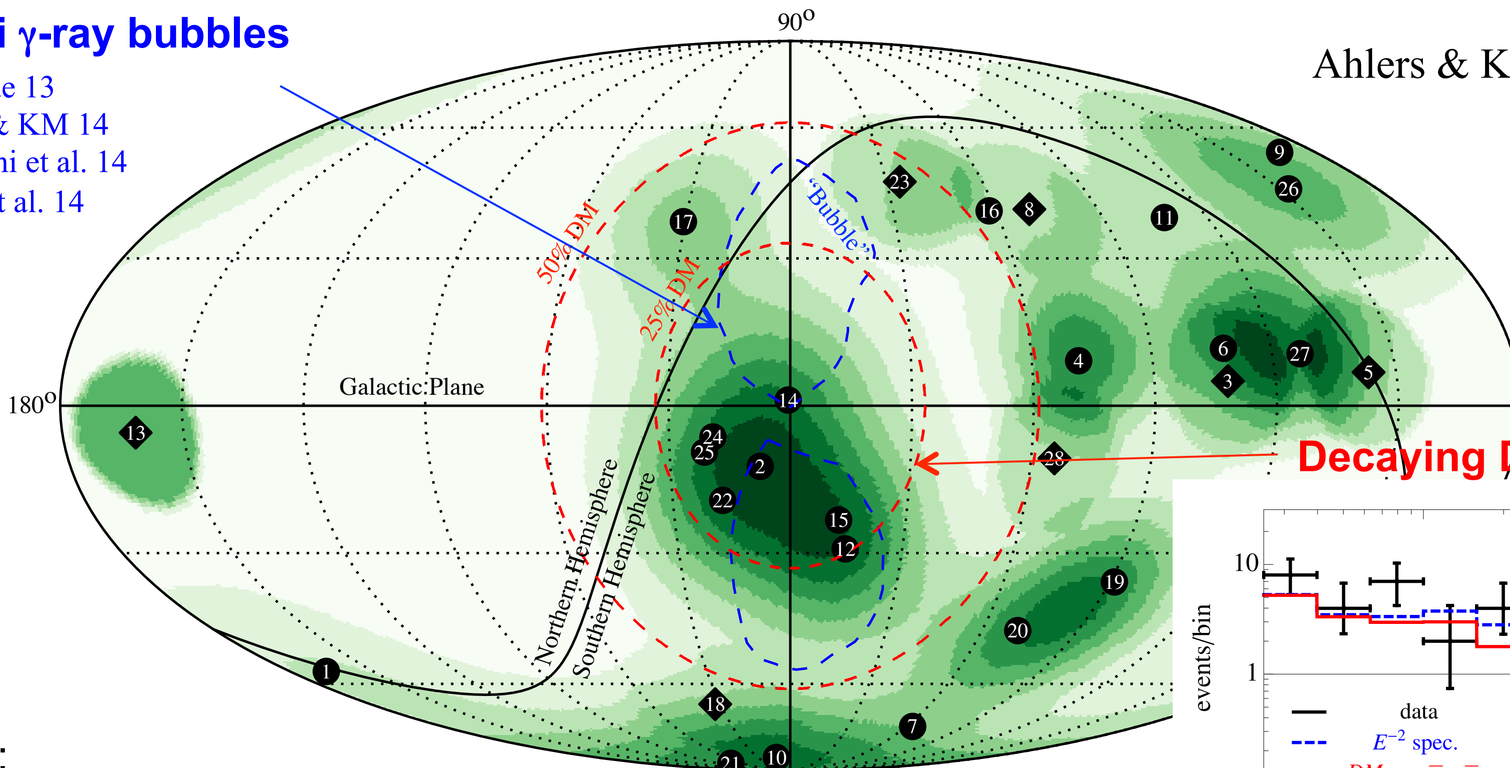
So far, more papers about Galactic sources

(a fraction of νs are explained except Galactic halo models)

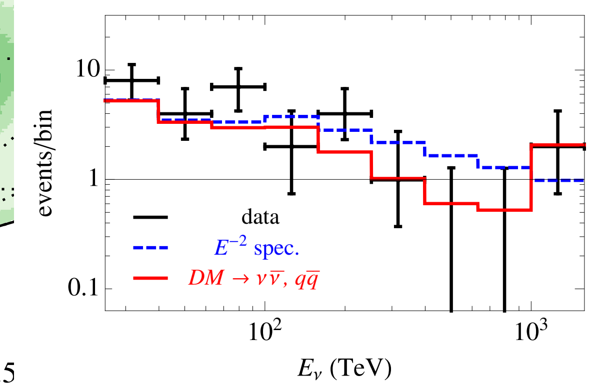
Fermi γ-ray bubbles

Razzaque 13
Ahlers & KM 14
Lunardini et al. 14
Taylor et al. 14

Ahlers & KM 14 PRD



Decaying DM halo



KM & Beacom 12, Feldstein et al. 13,
Esmaili & Serpico 13, Bai et al. 14

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

Multi-Messenger Tests and Perspectives

How to Test?: Multi-Messenger Approach

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

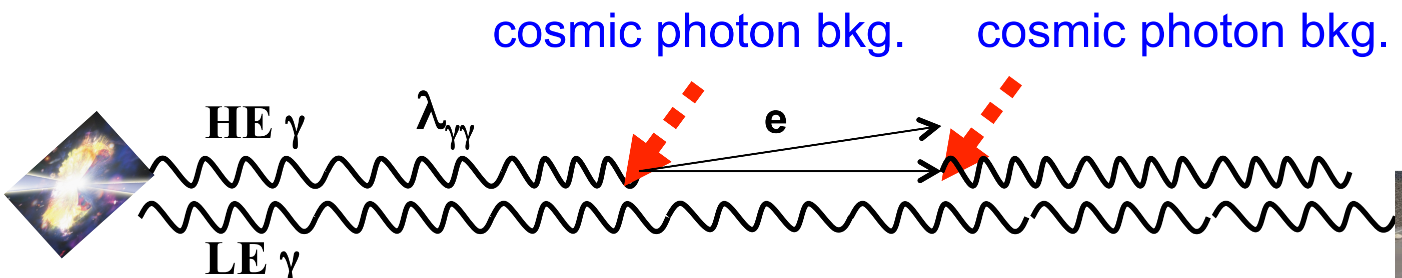
$p + \gamma \rightarrow N\pi + X$ $\quad \pi^{\pm}:\pi^0 \sim 1:1 \rightarrow$ **$E_\gamma^2 \Phi_\gamma \sim (4/3) E_\nu^2 \Phi_\nu$**

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

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

$\gamma + \gamma_{\mathrm{CMB/EBL}} \rightarrow e^+ + e^-$

ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center

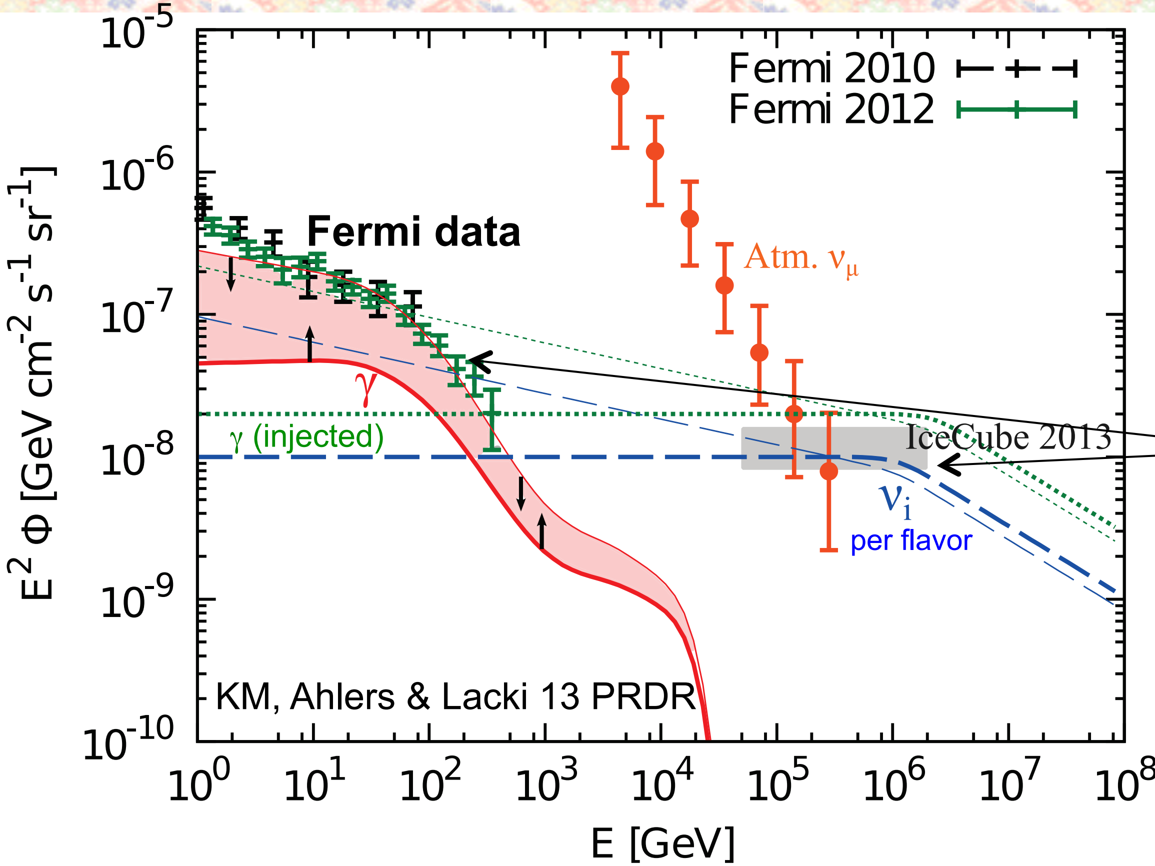


Fermi satellite

airshower detectors

realistic fate of γ rays=electromagnetic cascades
crucial for extragalactic γ rays

New Multimessenger Implications from “Measured” Fluxes



pp scenario

cosmic-ray reservoir models
(starbursts, galaxy assemblies etc.)

“comparable fluxes”

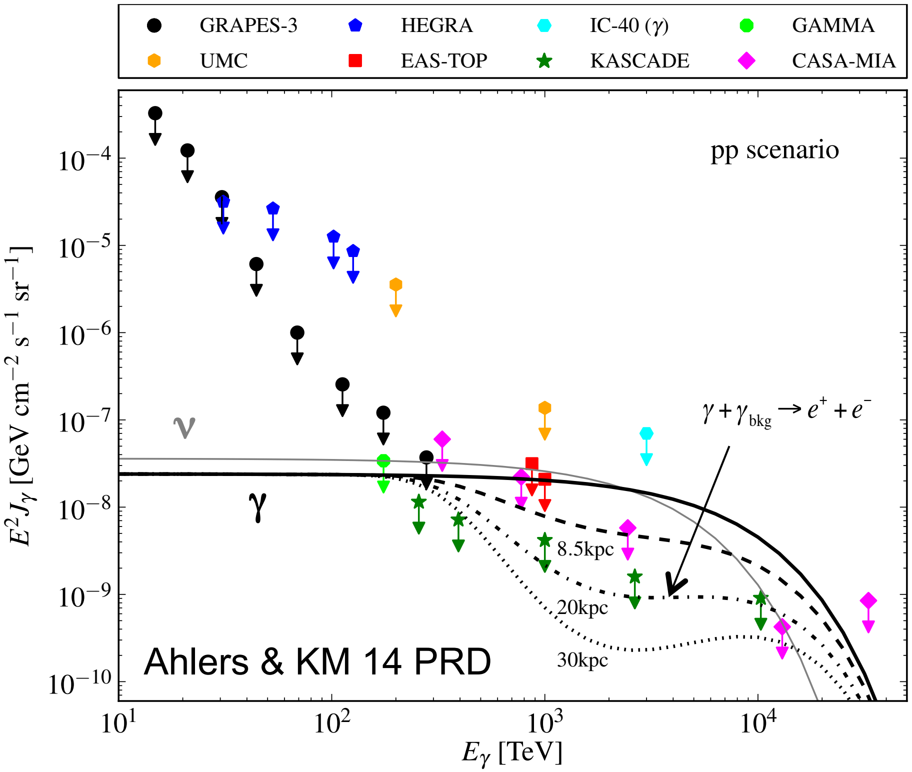
quite model-independent

- 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 can be explained simultaneously

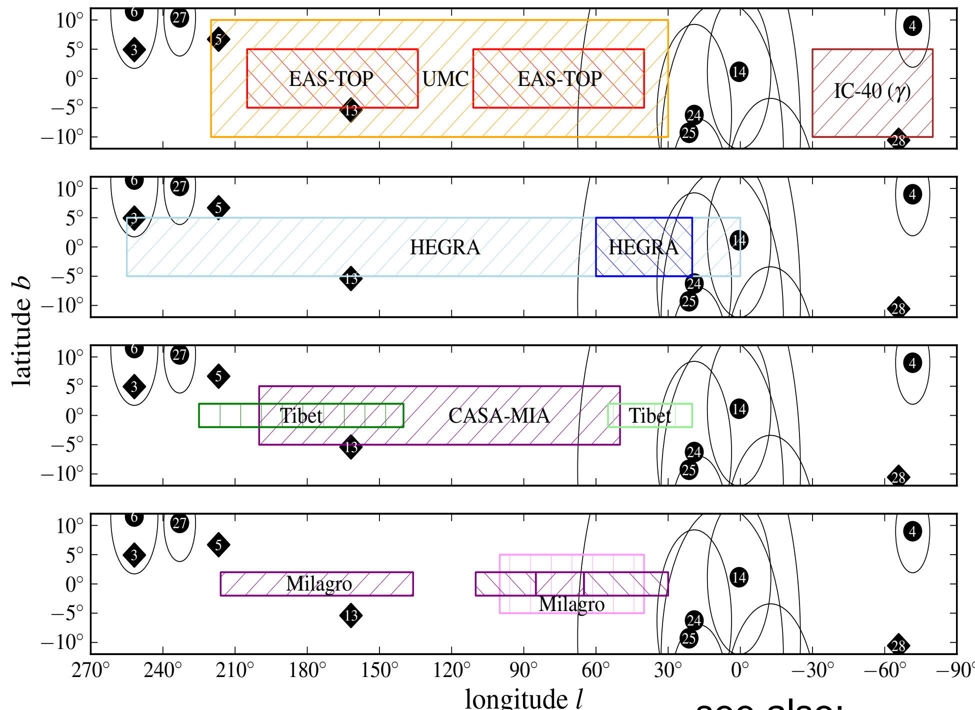
Importance of TeV-PeV γ-ray Limits on Galactic Sources

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

Isotropic limits (ex. Galactic halo models)



Galactic Plane (ex. supernova remnants)



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

<u>Origin of PeV neutrinos</u>: Need more data, no strong preference so far…

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

- Cosmic-ray reservoirs (starbursts & galaxy groups/clusters)
  consistent w. pre-discovery 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)
  3. observing individual sources w. hard TeV γ-ray spectra → e.g., CTA

- Galactic sources (many possibilities as subdominant sources)
  - could be seen especially at $E_\nu<0.05E_{knee}\sim200$ TeV
  - diffuse TeV-PeV γ-ray searches in the Southern Hemisphere are useful

- Cosmological PeV neutrinos as a probe of ν physics beyond SM
  (**ν decay**: ex. Baerwald+ 13, Pakvasa+ 13, **Lorentz inv. violation**: ex. Borriello+ 13, Anchordoqui+ 14,
  new $\nu\nu$ interactions: ex. Ioka & KM 14, Ng & Beacom 14, Blum, Hook & KM 14)

Questions for Future

- Spectral features: is the possible ν spectral break/cutoff real?
- Flavor ratio: consistent w. 1:1:1? (more data!)
  0.57:1:1 (μ damp), 2.5:1:1 (neutron decay), others (exotic),
  looking for τ-appearance, anti-ν_e Glashow-resonance at 6.3 PeV etc.
- Cross-corr. & auto-corr. (much more data! → DecaCube?)
- 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 $s_{CR}>>2$ & $f_{mes}<<1$
     (maybe 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

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

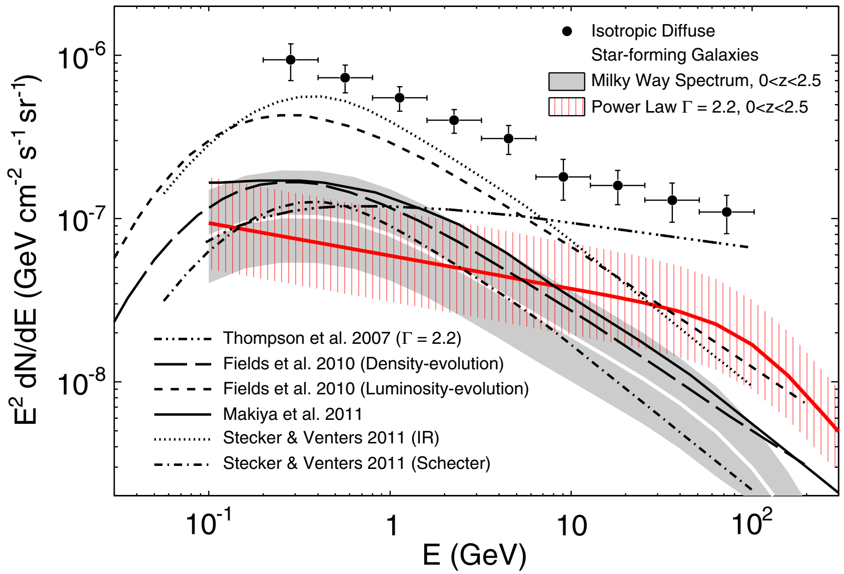
"The title is more of an expression of hope than a description of the book's contents"
"The observational horizon of neutrino astrophysics may grow perhaps in a time as short as one or two decades"

Hope that first HE ν sources are reported in the next decade

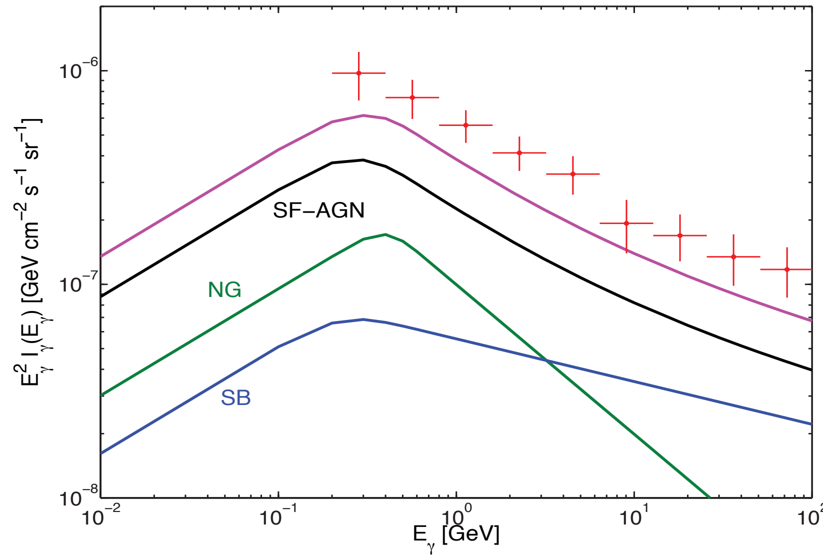
Backup Slides

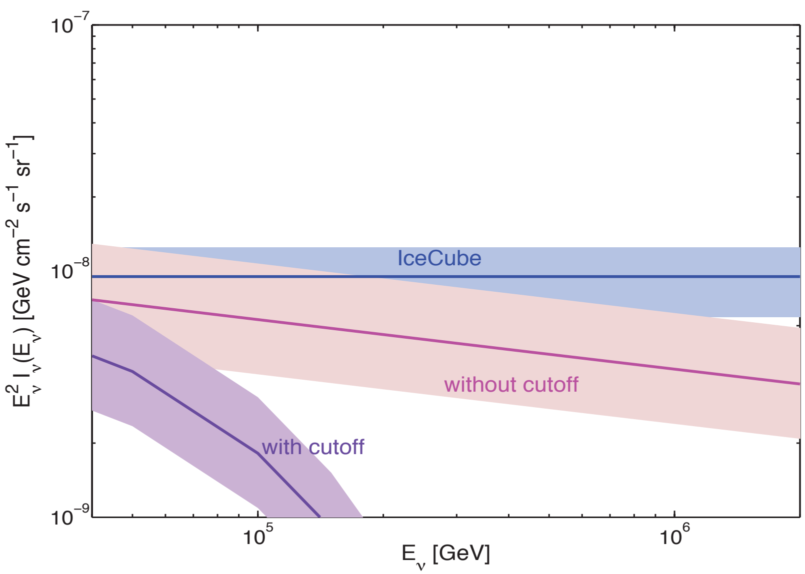
Requirements in Star-Forming Galaxies

Fermi collaboration 12 ApJ



Tamborra et al. 14





- ~20% of diffuse γ bkg. → s_ν~2 but including SF-AGN can help (<~50 % can be explained)
- E_{knee}~E_p^{max} (rather than E_p^{esc}) → cutoff at 100 TeV transients powerful than SNRs?

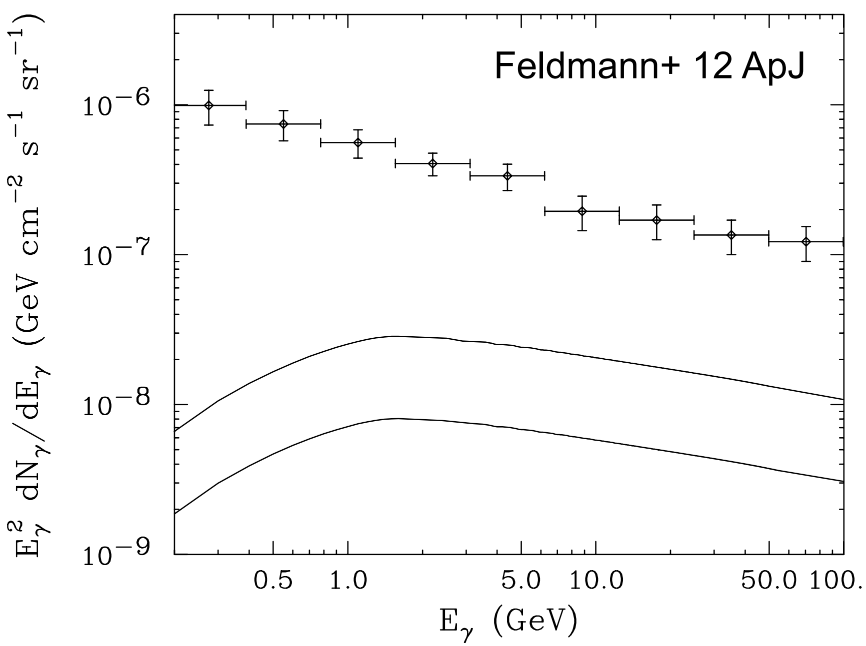
Galactic Halo

CRs should interact w. circumgalactic gas

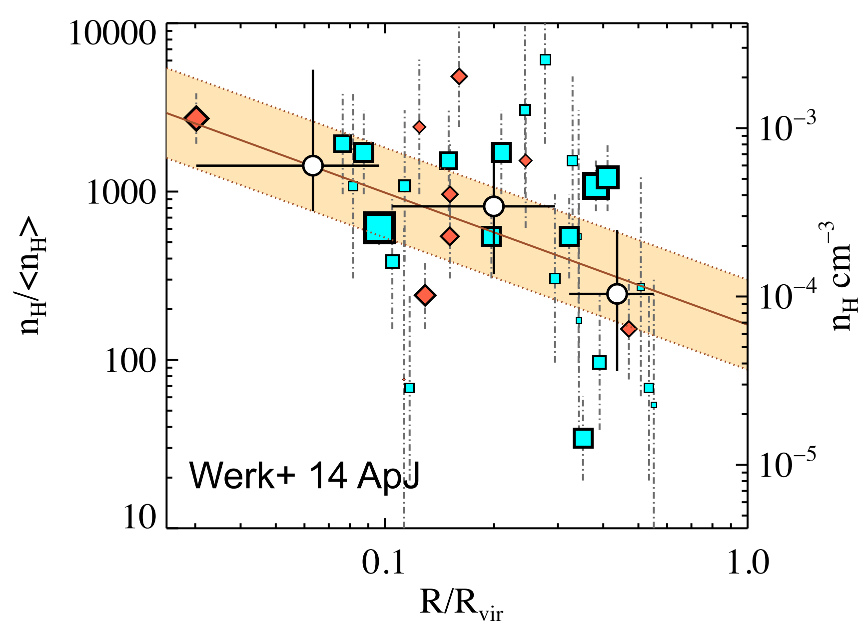
$$E_\nu^2 J_{\nu_\alpha}^{\rm halo} \simeq \frac{N_{\rm SNR}}{4\pi V_{\rm halo}} \int_0^{R_{\rm vir}} dr E_\nu^2 Q_{\nu_\alpha}$$
$$\simeq 2.4 \times 10^{-9}\ {\rm GeV cm^{-2} s^{-1} sr^{-1}} \epsilon_{p,-1} \mathcal{E}_{\rm ej,51} \times \left(\frac{R_{\rm vir}}{260\ {\rm kpc}}\right)^{-2} \left(\frac{f_{\rm past}}{3}\right) \left(\frac{R_{\rm SN}}{0.03\ {\rm yr^{-1}}}\right) \left(\frac{t_{\rm inj}}{10\ {\rm Gyr}}\right)$$

not enough (typically)

pre-IceCube predictions



$$n_H = (10^{-4.2\pm0.25})(R/R_{\rm vir})^{-0.8\pm0.3}$$



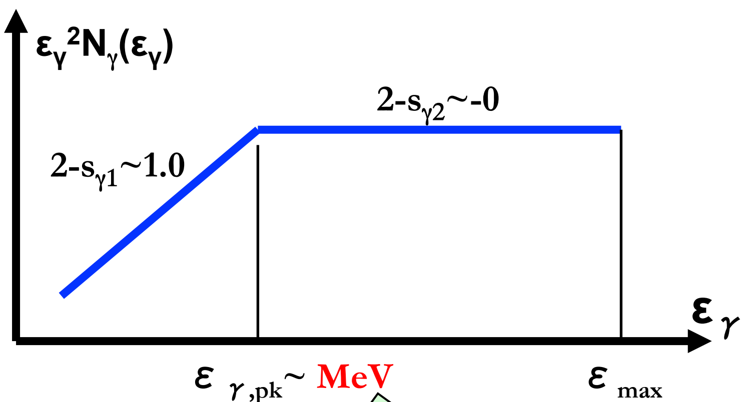
※ **PeV γ rays should be expected (~60 % come from <26 kpc or higher if CR dist. has gradient)**

An Example of Calculation: Gamma-Ray Burst Jets

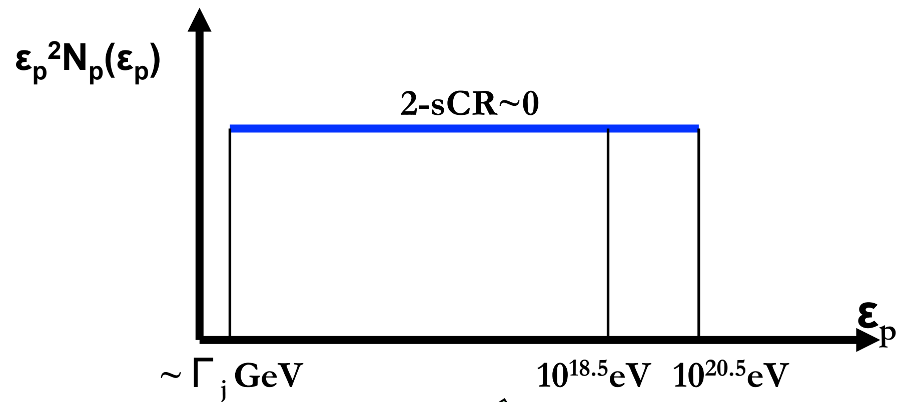
GRB: brightest γ-ray transient

Popular candidate sources of UHECRs

Photon Spectrum (observed)



CR Spectrum (Fermi mechanism)



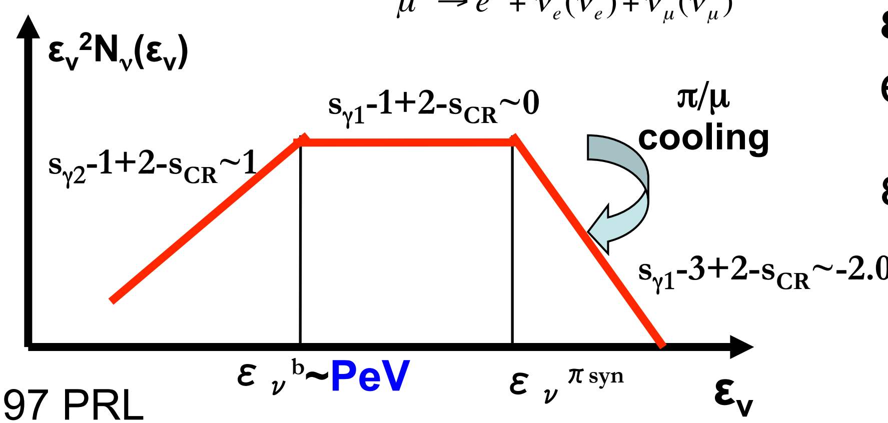
$\varepsilon_p \varepsilon_\gamma \sim 0.2\Gamma_j^2$ GeV^2

at Δ-resonance

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

Neutrino Spectrum



$\varepsilon_\nu^2 N_\nu(\varepsilon_\nu)\sim(1/4) f_{p\gamma}\,\varepsilon_p^2 N_p(\varepsilon_p)$

efficiency: $f_{p\gamma}\sim 0.2 n_\gamma \sigma_{p\gamma}\Delta$

$\varepsilon_\nu^b \sim 0.05\varepsilon_p^b$

~ 0.01 GeV^2 $\Gamma^2/\varepsilon_{\gamma,pk}$

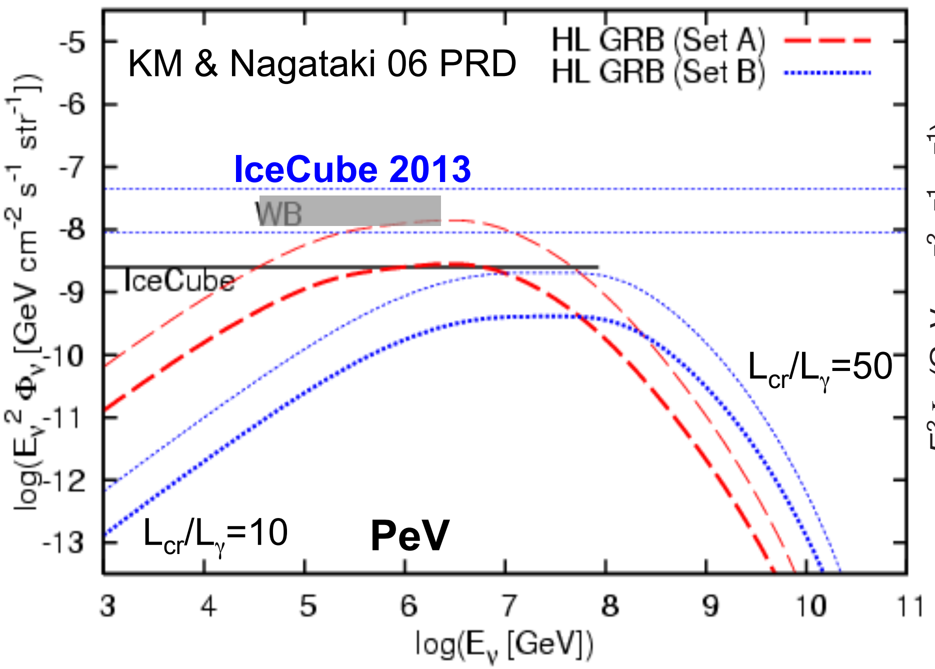
~1 PeV (w. $\varepsilon_{\gamma,pk}\sim 1$ MeV)

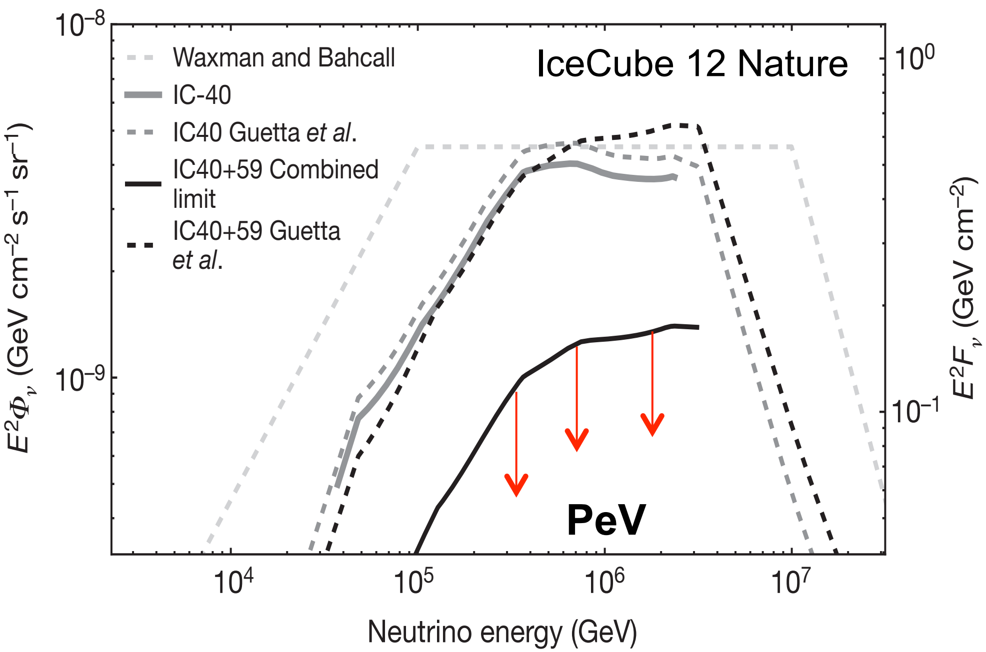
Waxman & Bahcall 97 PRL

$\Gamma_j\sim 300$: jet Lorentz factor

Gamma-Ray Bursts ($p\gamma$)

numerical results w. detailed microphysics





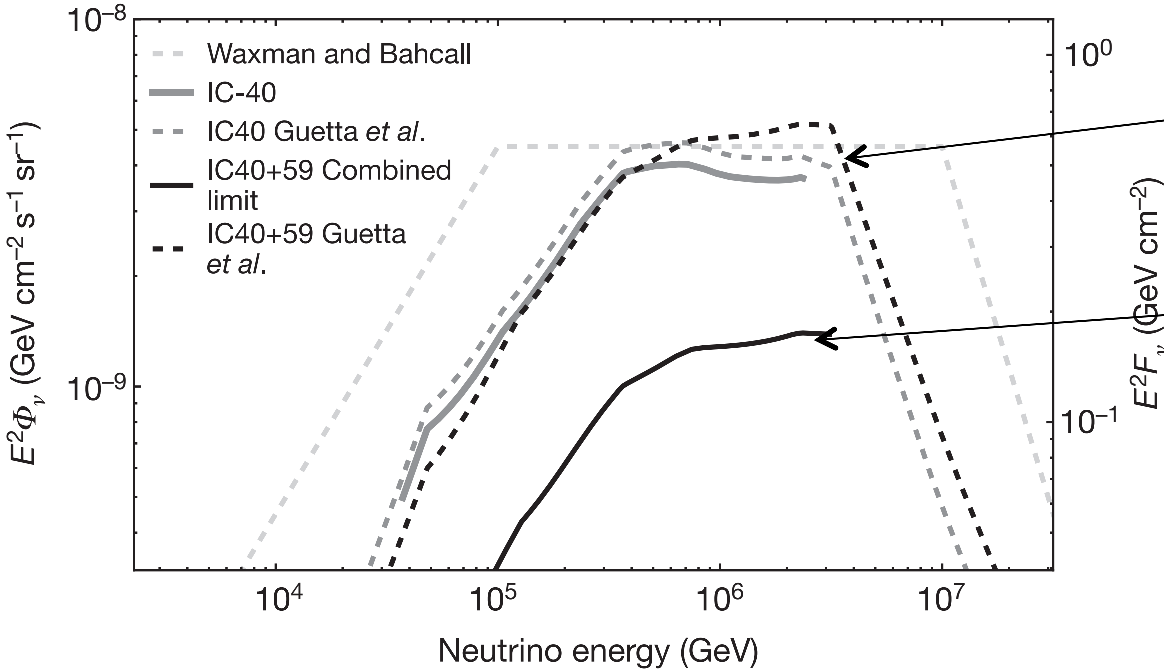
GRBs are special since stacking analyses are possible

duration~10-100 s → atm. bkg. is negligible for typical GRBs

Stacking analyses imply <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

→ disfavored as the origin of observed diffuse neutrinos

Recent IceCube Limits on Prompt ν Emission



IceCube collaboration 12 Nature

Obs. limits start to be powerful but be careful

1. $f_{p\gamma}$ is energy-dependent, π-cooling → ~ 4 ↓ (Li 11 PRD, Hummer et al. 12 PRL)

2. ($\varepsilon_\gamma^2\ \phi_\gamma$ at $\varepsilon_{\gamma,pk}$) ≠ ($\int d\varepsilon_\gamma\ \varepsilon_\gamma\ \phi_\gamma$) → ~3-6 ↓ (Hummer et al. 12 PRL, He et al. 12 ApJ)

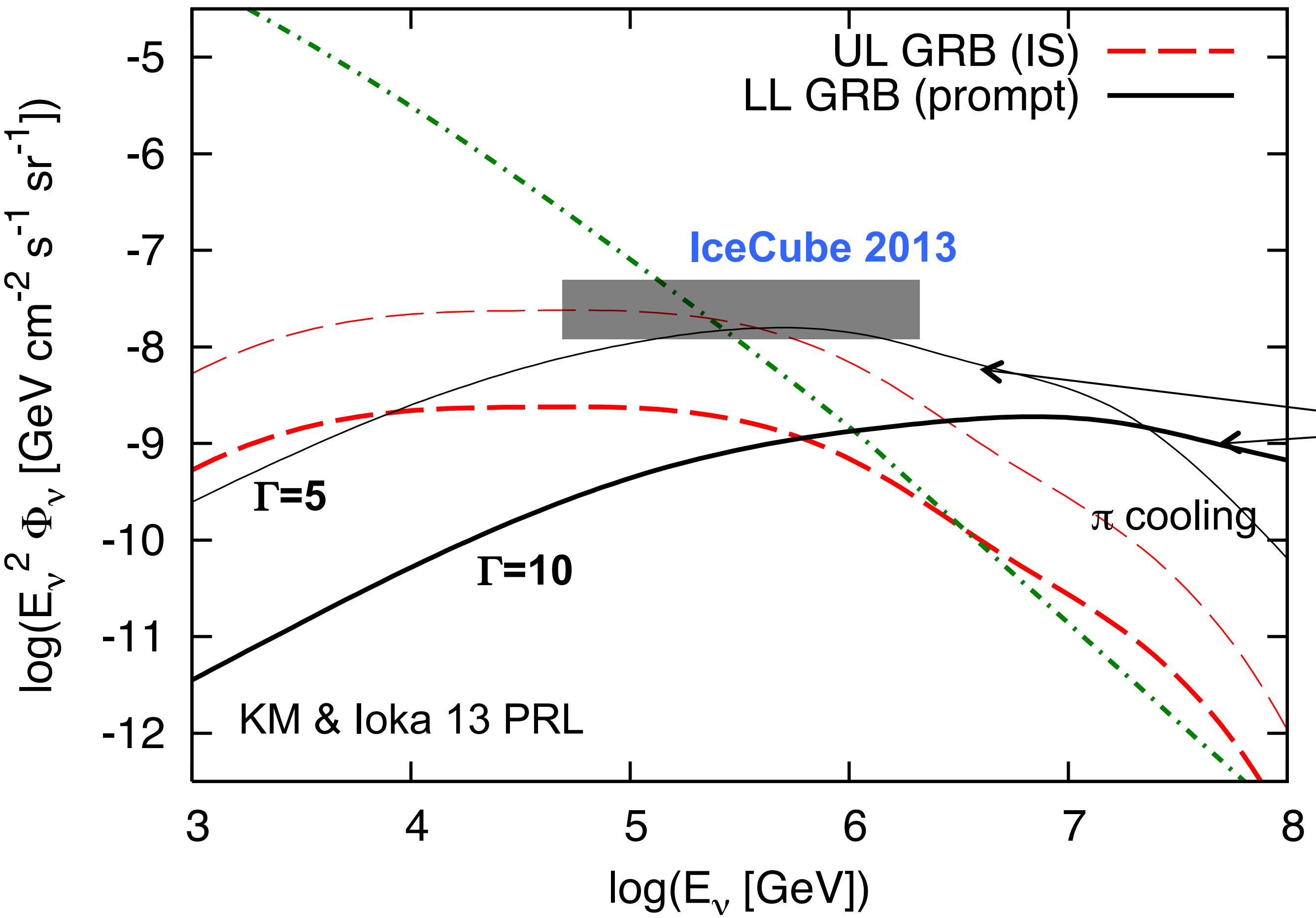
3. details (multi-π, ν mixing etc.) → ex., multi-π ~2-3 ↑ (KM & Nagataki 06 PRD)

- Different from "astrophysical" model-uncertainty in calculating $f_{p\gamma}$
- Taken account of in earlier calculations for given parameters (ex. Dermer & Atoyan 03 KM & Nagataki 06)

Exceptions: Low-Power Gamma-Ray Burst Jets

- Low-power jets (LL GRBs, ultralong GRBs etc.) are missed
- Viable without violating IceCube stacking limits

e.g., KM & Ioka 13 PRL, Cholis & Hooper 13 JCAP



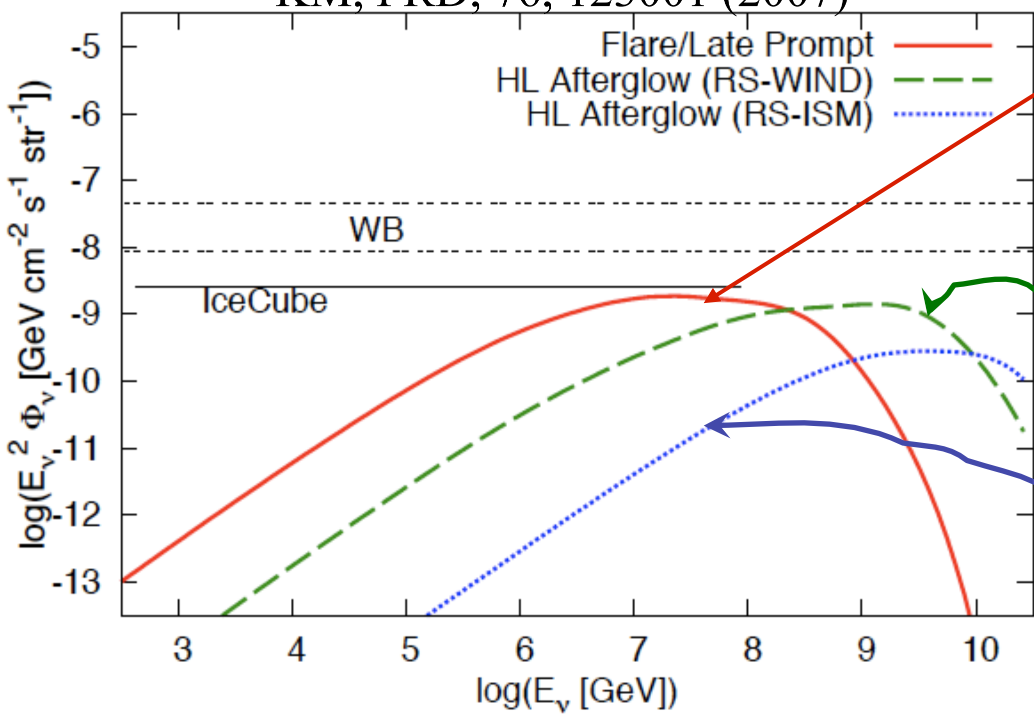
predictions by KM+ 06 ApJL

large uncertainty but intriguing

GRB Early Afterglow Emission

- Most νs are radiated in **~0.1-1 hr** (physically max[T, T_{dec}])
- Afterglows are typically explained by **external shock scenario**
- But flares and early afterglows may come from **internal dissipation**

KM, PRD, 76, 123001 (2007)



Inner jet protons + flare x rays
(normalized by 10% of UHECR budget)

KM & Nagataki, PRL, 97, 051101 (2006)

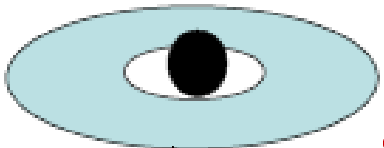
ES protons + ES opt-x rays
stellar wind medium
(normalized by UHECR budget)

ES protons + ES opt-x rays
interstellar medium
(normalized by UHECR budget)

- **Flares – efficient meson production ($f_{p\gamma}$ ~ 1-10), maybe detectable**
- **External shock – not easy to detect both νs and hadronic γ rays**

Active Galactic Nuclei (AGN)

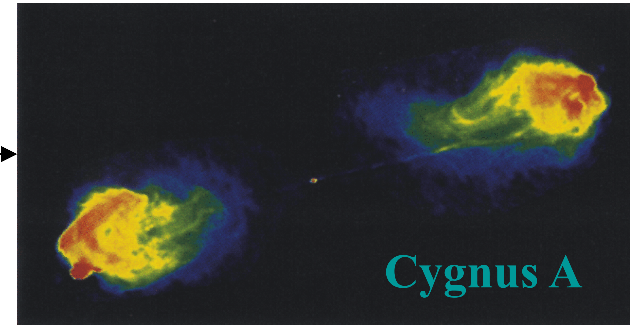
BH + accretion disk



~ 10%
Jets
(Γ~1-10)
elliptical gal.

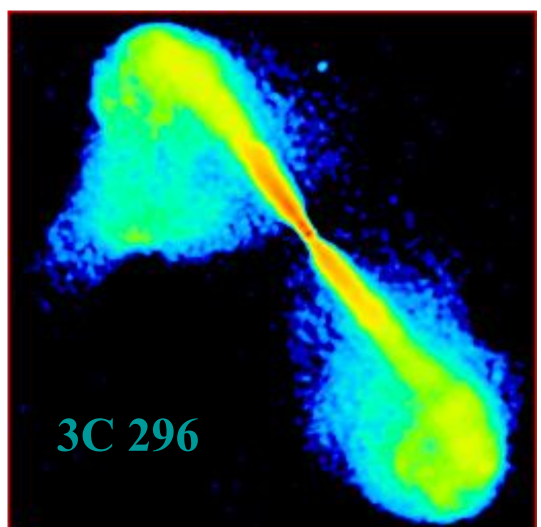
~ 1 %
$L_{radio} > 5\times10^{41}$ erg/s

FR-II radio galaxy
Flat spectrum radio quasar (FSRQ)
Steep spectrum radio quasar (SSRQ)



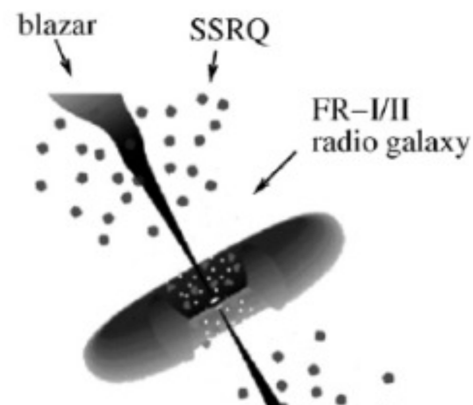
~ 9 %
$L_{radio} < 5\times10^{41}$ erg/s

FR-I radio galaxy
BL Lacertae object (BL Lac)



~ 90%
No jets
spiral gal.

Seyfert galaxy
Radio quiet quasar
Radio intermediate quasar

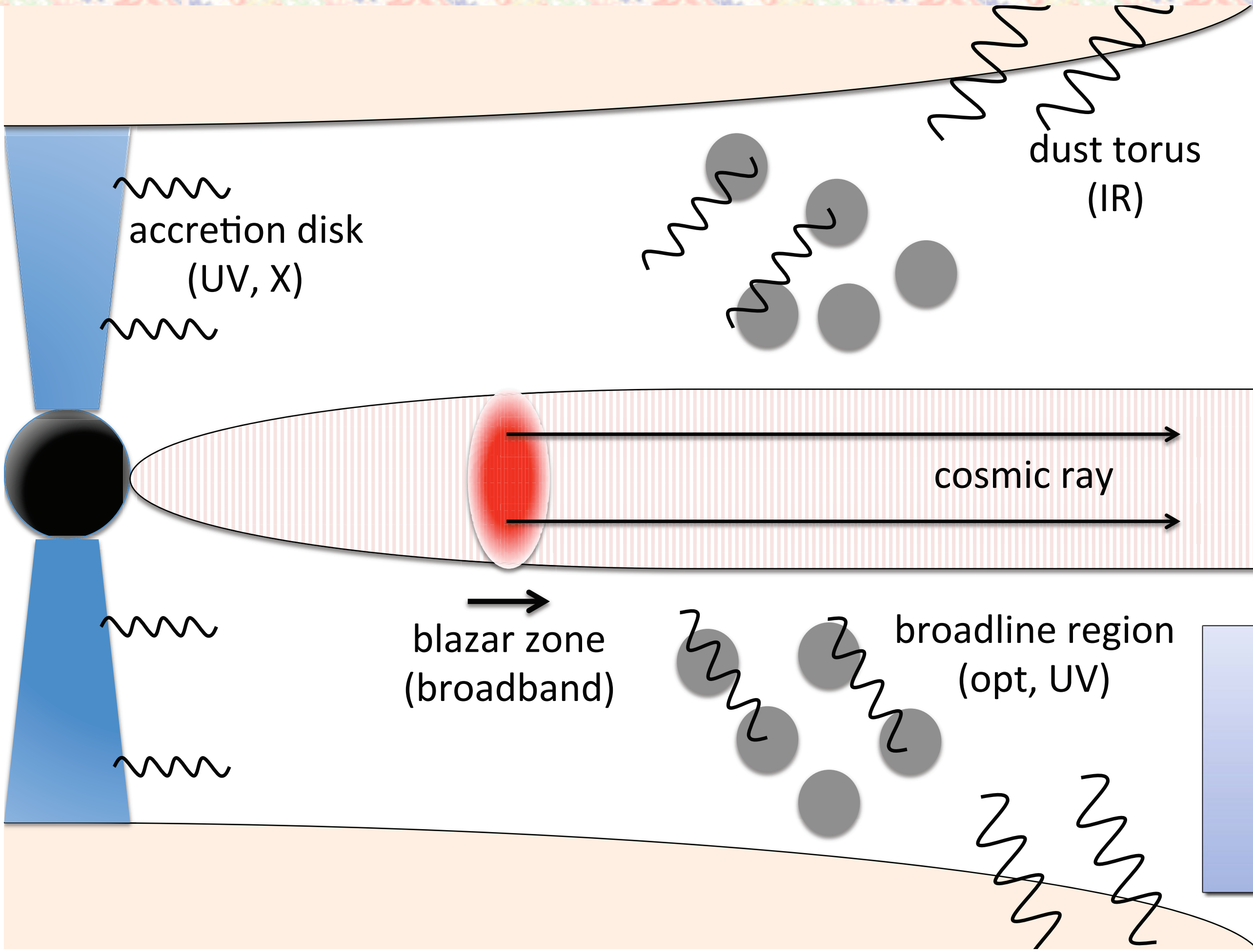


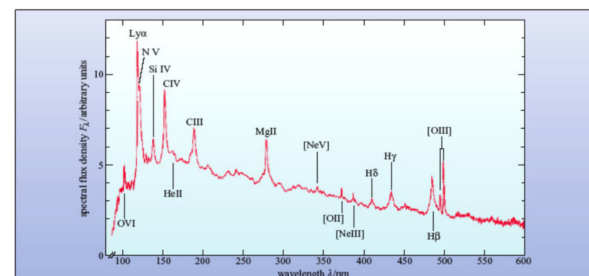
"blazar" (FSRQ+BL Lac)
= on-axis jets
•Flares (e.g., T ~ day)

FR=Fanaroff-Riley

External Radiation Fields

KM, Inoue & Dermer 14

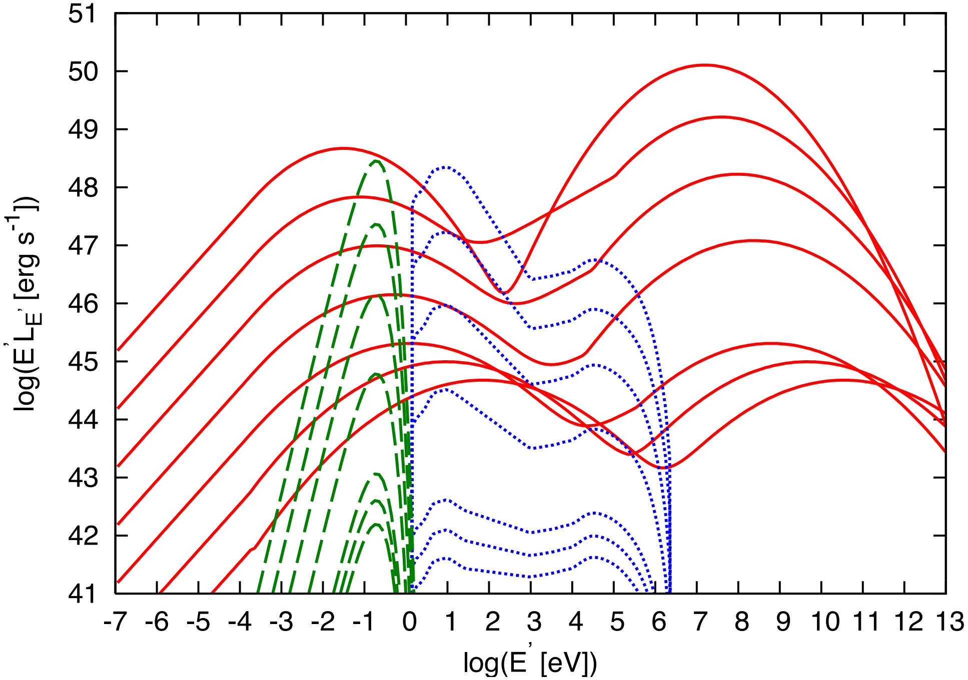




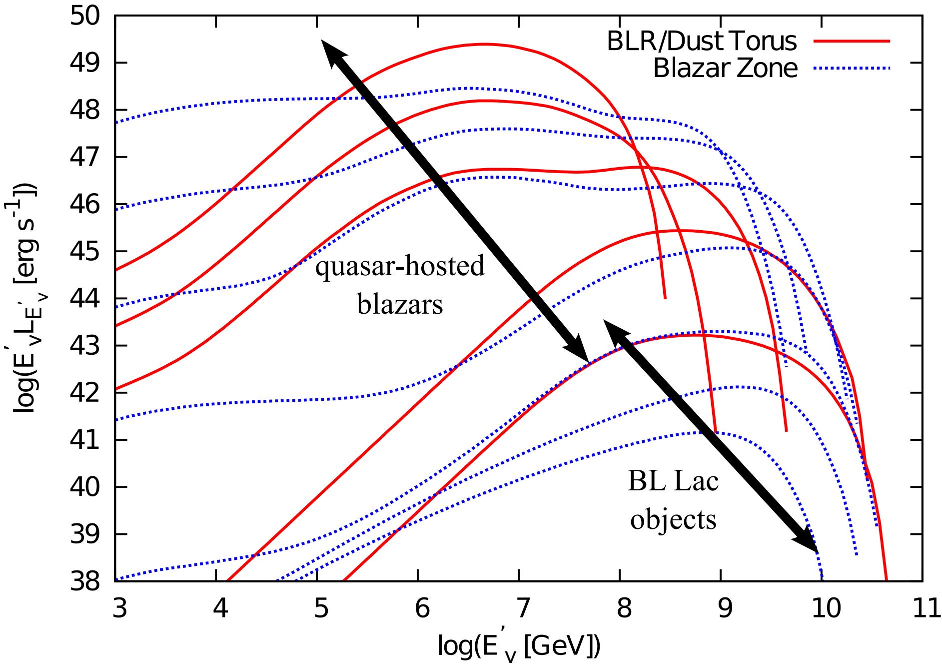
$$f_{p\gamma} \approx \hat{n}_{\rm BL} \sigma_{p\gamma}^{\rm eff} r_{\rm BLR} \simeq 5.4 \times 10^{-2}\ L_{\rm AD,46.5}^{1/2} \qquad r_{\rm BLR} \approx 10^{17}\ {\rm cm}\ L_{\rm AD,45}^{1/2}$$

cf. $f_{p\gamma} \approx \hat{n}_{\rm EBL} \sigma_{p\gamma}^{\rm eff} d \simeq 1.9 \times 10^{-4}\ \hat{n}_{\rm EBL,-4} d_{28.5}$

Blazar Sequence



"Blazar sequence"
softer spectra at higher L



Neutrino blazar sequence

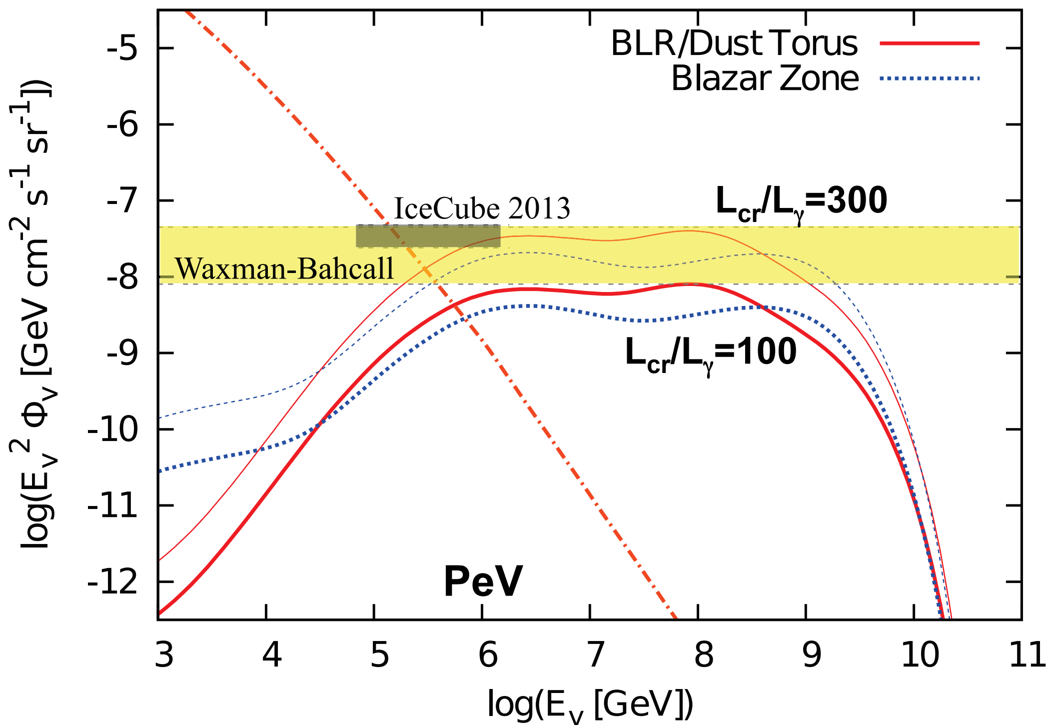
$L_{cr} \propto L_\gamma$, $f_{p\gamma} \propto L_\gamma^{1/2}$

$\rightarrow L_\nu \propto L_\gamma^{1.5}$

KM, Inoue & Dermer 14

AGN Inner Jet (pγ)

- Active galaxies are known powerful γ-ray sources
- One of the most popular ultrahigh-energy cosmic-ray origins

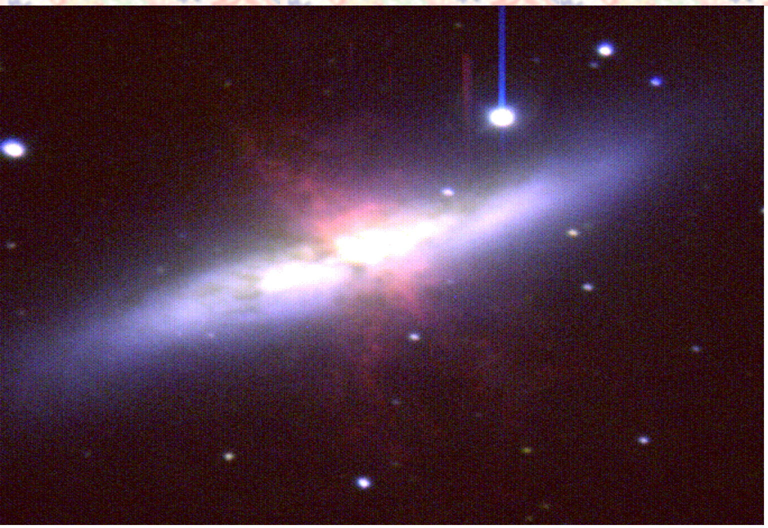


KM, Inoue & Dermer 14

Sub-PeV ν flux is insufficient and ν spectra are too hard
→ The inner jet model has difficulty

Strong prediction: cross-corr. w. known <80 FSRQs → ARA

Starburst/Star-Forming Galaxies



- High-surface density

  M82, NGC253: Σ_g~0.1 gcm^{-3} → n~200 cm^{-3}

  high-z MSG: Σ_g~0.1 g cm^{-3} → n~10 cm^{-3}

  submm gal. Σ_g~1 gcm^{-3} → n~200 cm^{-3}
- Many SNRs

  known CR accelerators

energy budget

$$Q_{\rm cr} \sim 8.5 \times 10^{45}~{\rm erg~Mpc^{-3}~yr^{-1}}~\epsilon_{{\rm cr},-1} \varrho_{{\rm SFR},-2}$$

ρ_{SFR}~10^{-2} Mpc^{-3} yr^{-1} (MSG), ρ_{SFR}~10^{-3} Mpc^{-3} yr^{-1} (SBG)

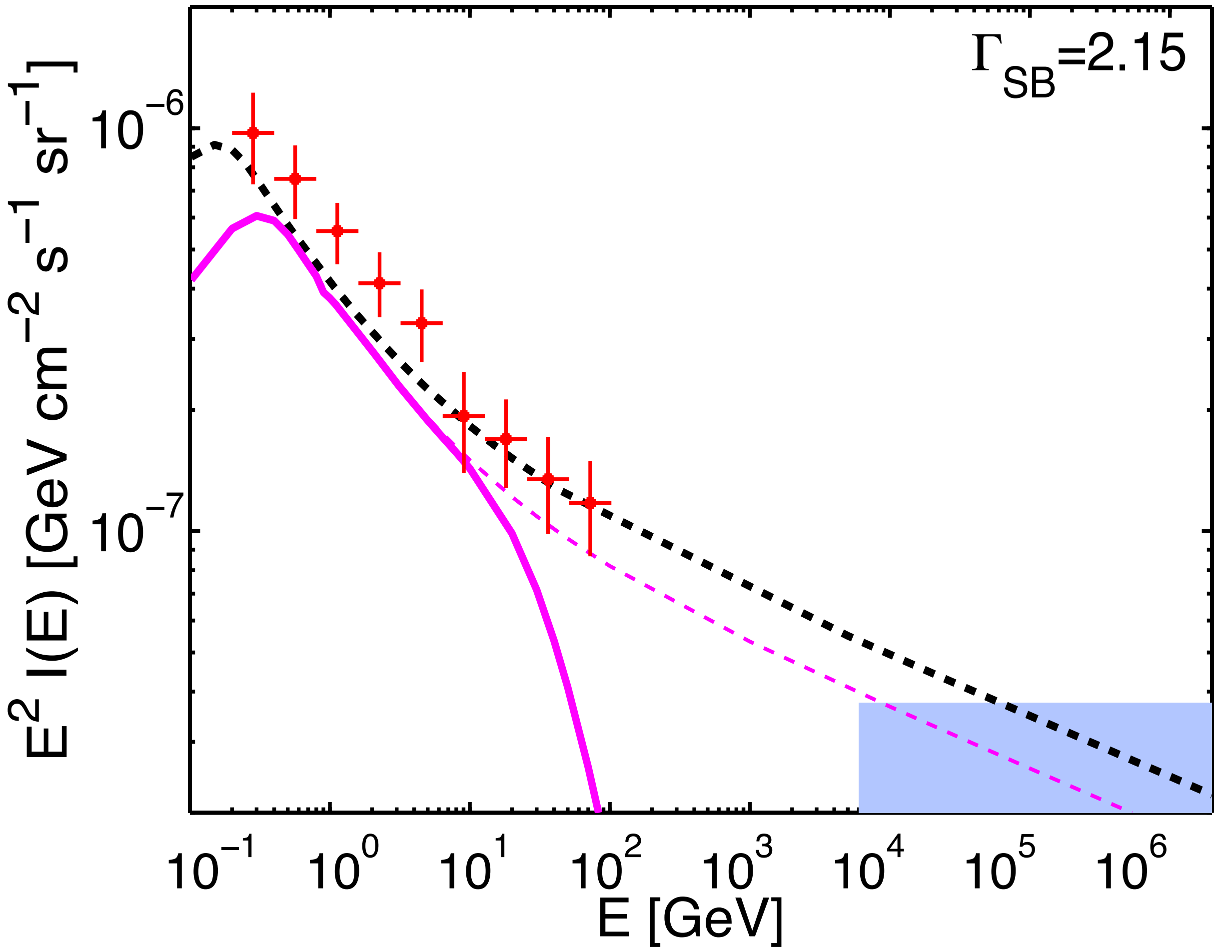
advection time

$$t_{\rm esc} \approx t_{\rm adv} \approx h/V_w \simeq 3.1~{\rm Myr}~(h/{\rm kpc}) V_{w,7.5}^{-1}$$

pp efficiency

$$f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm esc} \simeq 1.1~\Sigma_{g,-1} V_{w,7.5}^{-1} (t_{\rm esc}/t_{\rm adv})$$

Starburst/Star-Forming Galaxies (pp)

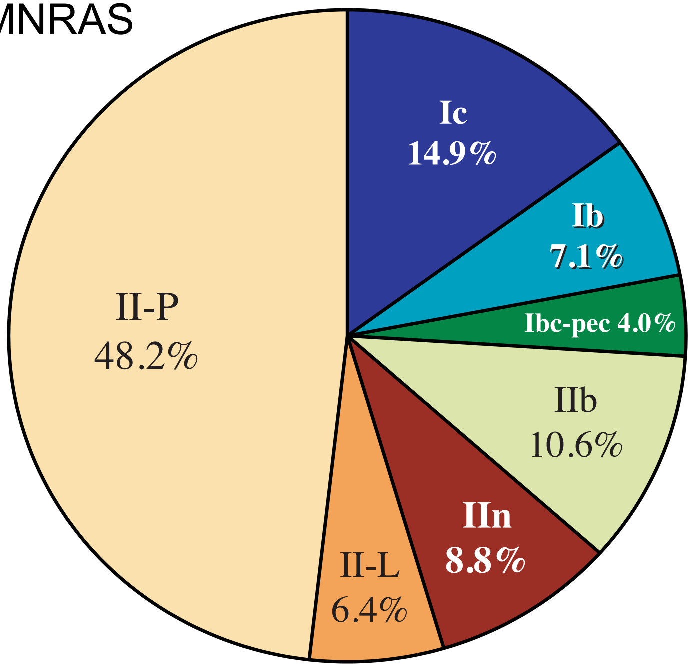


Tamborra+ 14 JCAP

- Consistent w. obs. & a PeV break was predicted!
- How can CRs get accelerated above 100 PeV?

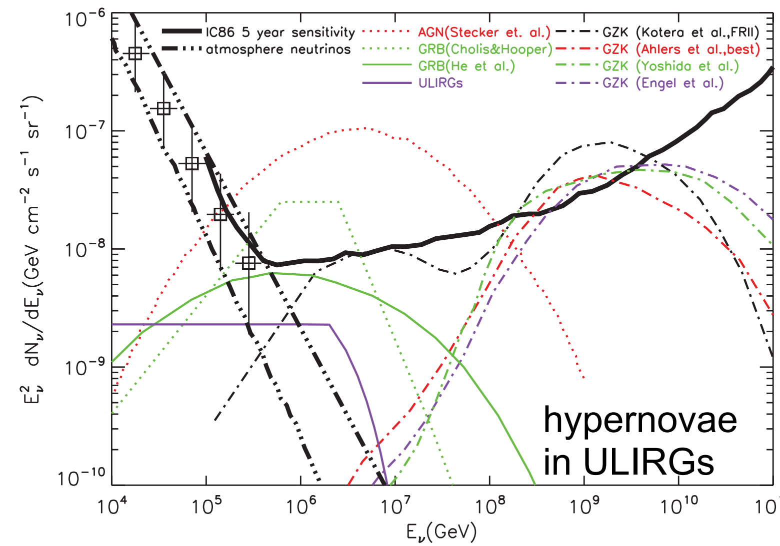
Speculations about Accelerators

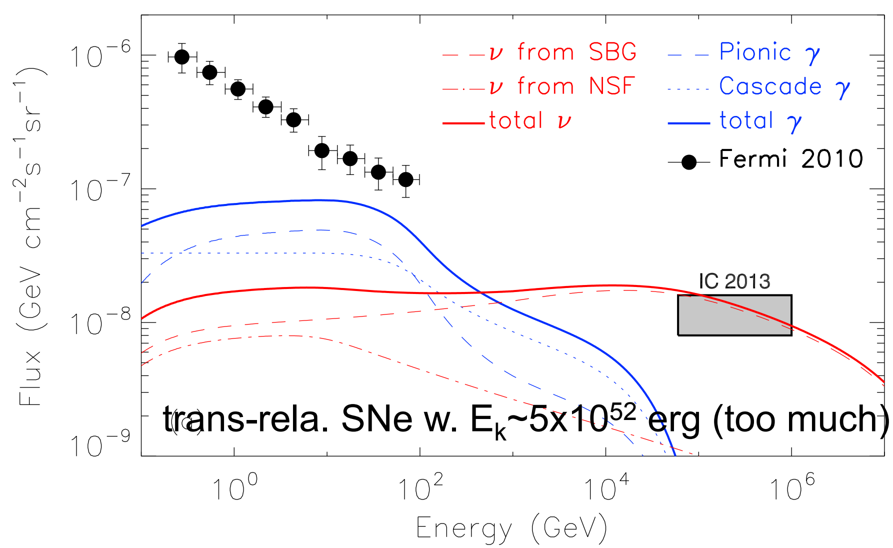
Smith+ 11 MNRAS



Core-Collapse SN Fractions

ULIRG: He+ 12 PRD, Type IIn: KM et al. 11 PRD
Hypernova: KM et al. 13 PRDR, TRSNe: Liu+13

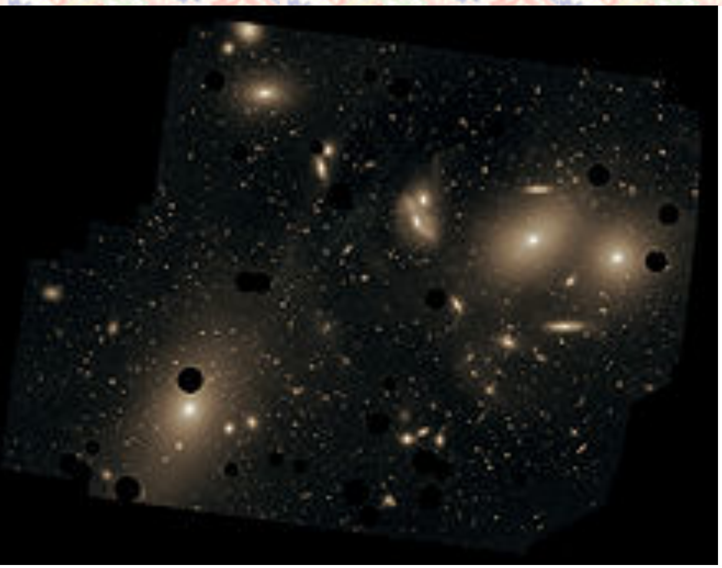




Issues

- Why is Milky way special?
- Normal SNRs are more dominant
- Can B-field be amplified sufficiently?
- Trans-relativistic SNe ≠ hypernovae (ex. GRB060218 E_k~2×10^{51} erg)

Galaxy Groups and Clusters



- intracluster gas density
  n~10^{-4} cm^{-3}, a fewx10^{-2} cm^{-3} (center)
- Many CR accelerators
  AGN, galaxy mergers, galaxies
- accretion shocks

$$\varepsilon_p^{\max} \approx (3/20)(V_s/c)eBr_{\rm sh} \sim 1.2 \text{ EeV } B_{-6.5}V_{s,8.5}M_{15}^{1/3}$$

energetics

$$Q_{\rm cr} \sim 1.0 \times 10^{47} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \ \epsilon_{{\rm cr},-1}L_{{\rm ac},45.5}\rho_{{\rm GC},-5}$$

$$Q_{\rm cr} \sim 3.2 \times 10^{46} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \ \epsilon_{{\rm cr},-1}L_{j,45}\rho_{{\rm GC},-5}$$

ρ_{GC}~10^{-6} Mpc^{-3} for M>10^{15} M_{sun}, ρ_{GC}~10^{-5} Mpc^{-3} for M>a fewx10^{14} M_{sun}

pp efficiency

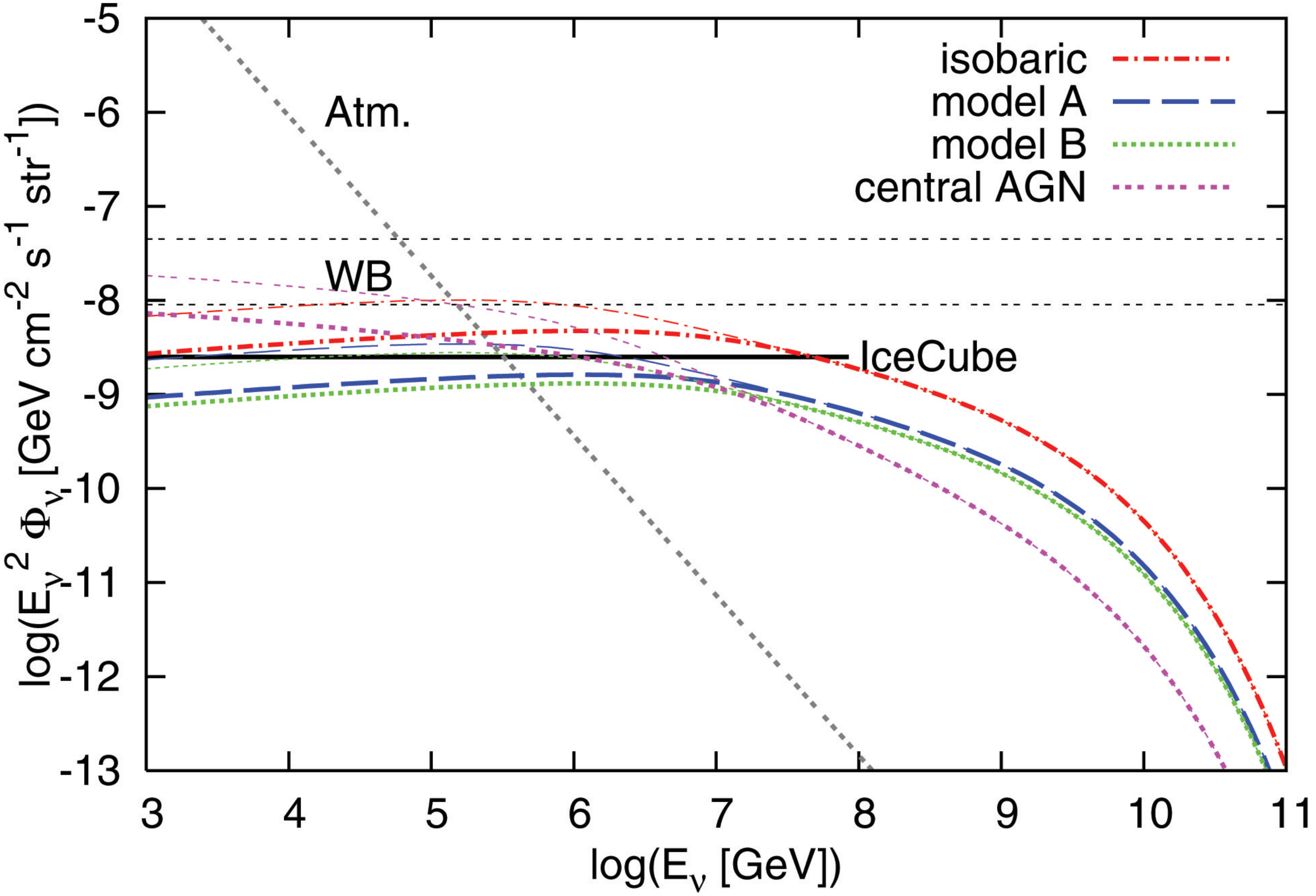
$$f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm int} \simeq 0.76 \times 10^{-2} \ g\bar{n}_{-4}(t_{\rm int}/2 \text{ Gyr})$$

diffusion time

$$t_{\rm diff} \approx (r_{\rm vir}^2/6D) \simeq 1.6 \text{ Gyr } \varepsilon_{p,17}^{-1/3}B_{-6.5}^{1/3}(l_{\rm coh}/30 \text{ kpc})^{-2/3}M_{15}^{2/3}$$

$$t_{\rm diff} = t_{\rm inj} \Longrightarrow \varepsilon_p^b \approx 51 \text{ PeV } B_{-6.5}(l_{\rm coh}/30 \text{ kpc})^{-2}M_{15}^2(t_{\rm inj}/2 \text{ Gyr})^{-3}$$

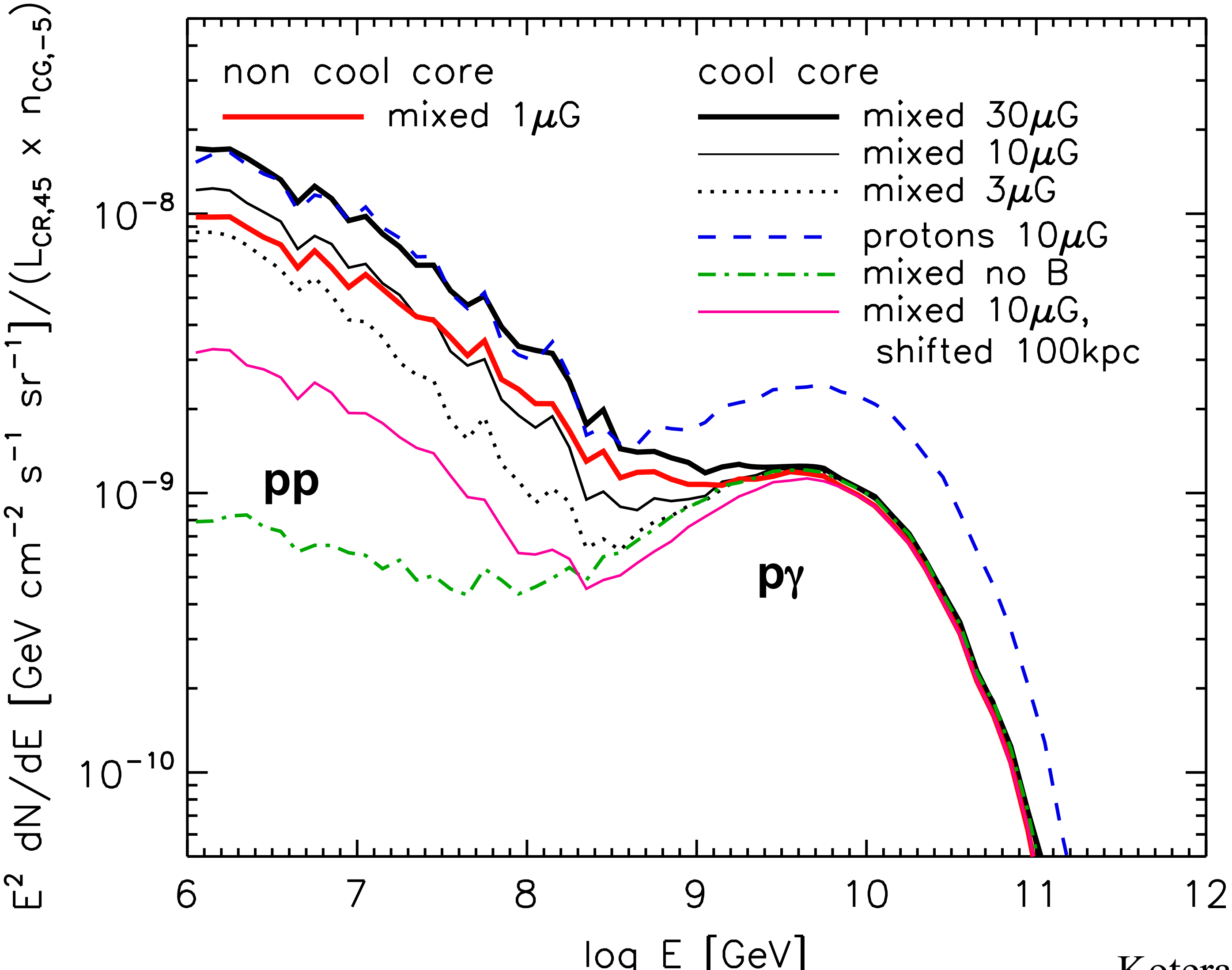
Galaxy Clusters and Groups (pp)



KM et al. 08 ApJL

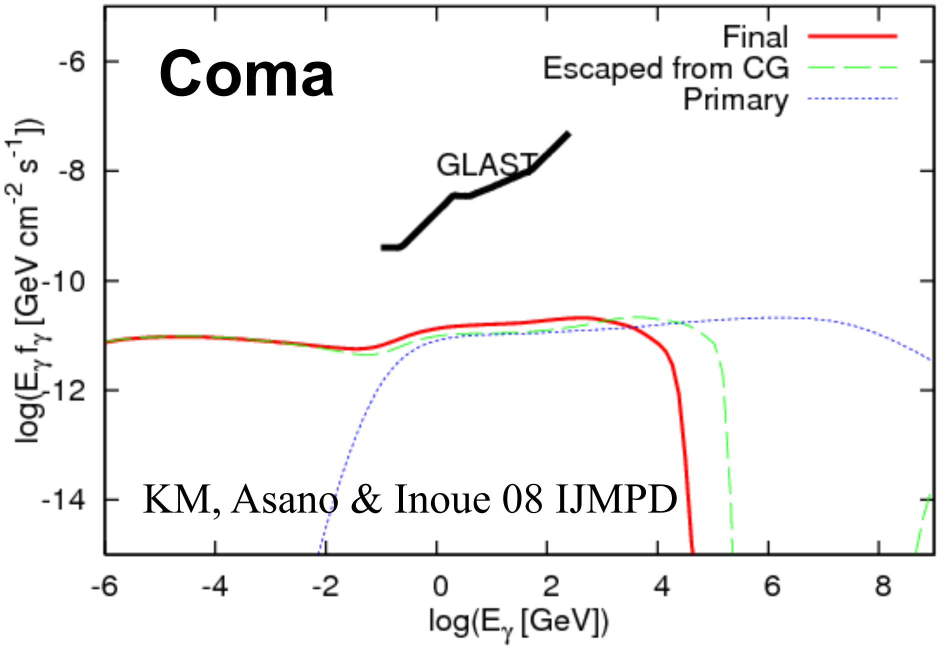
- Consistent w. obs. & a PeV break was predicted!
- No firm gamma-ray detection, Normalization?

AGN in Galaxy Clusters and Groups



Kotera, Allard, KM+ 09 ApJ

Gamma-Ray Limits?

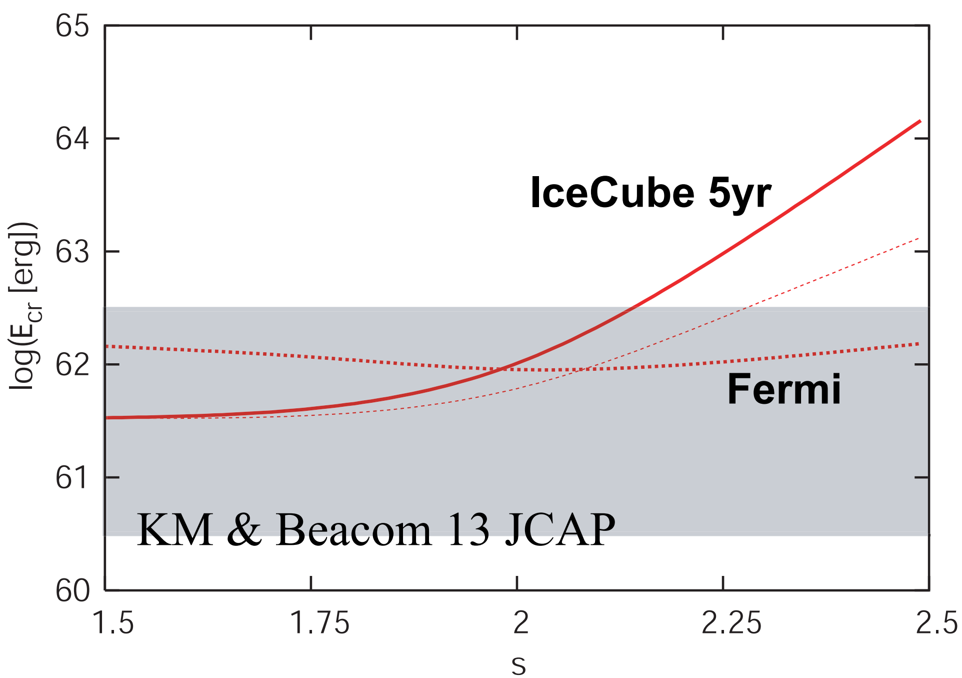


consistent with nondetection of gamma rays

(but connection to the diffuse flux is actually not trivial)

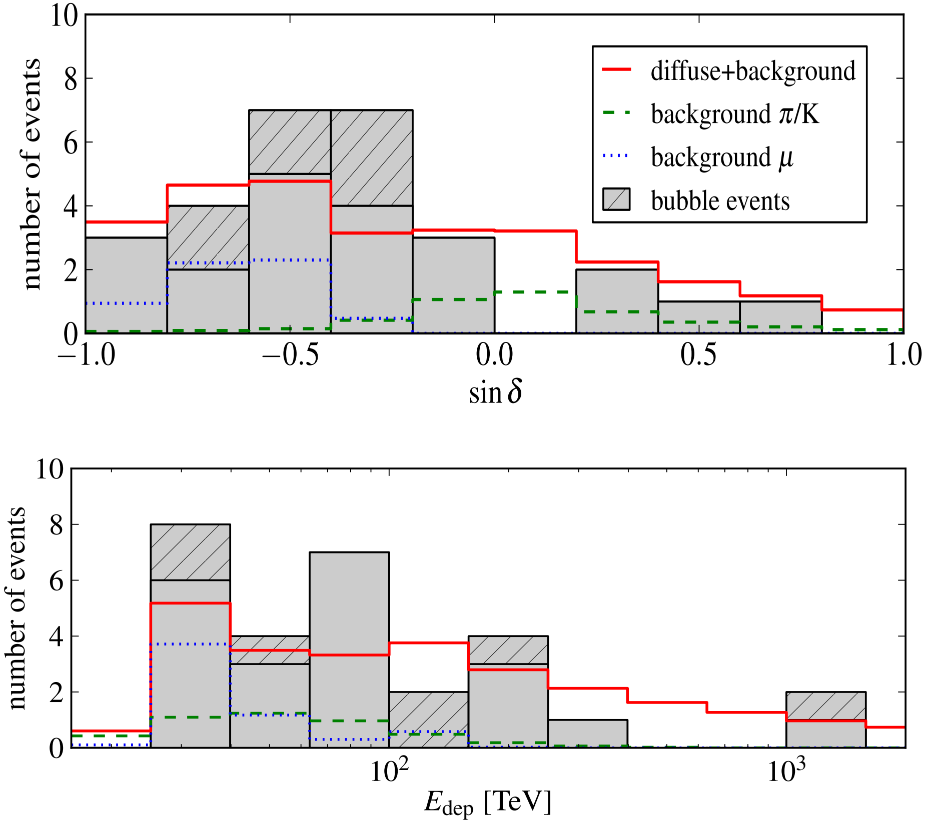
L_{cr}~0.5x10^{45} erg s^{-1} (Virgo)

→ E_{cr}=$L_{cr}t_{inj}$~3x10^{61} erg

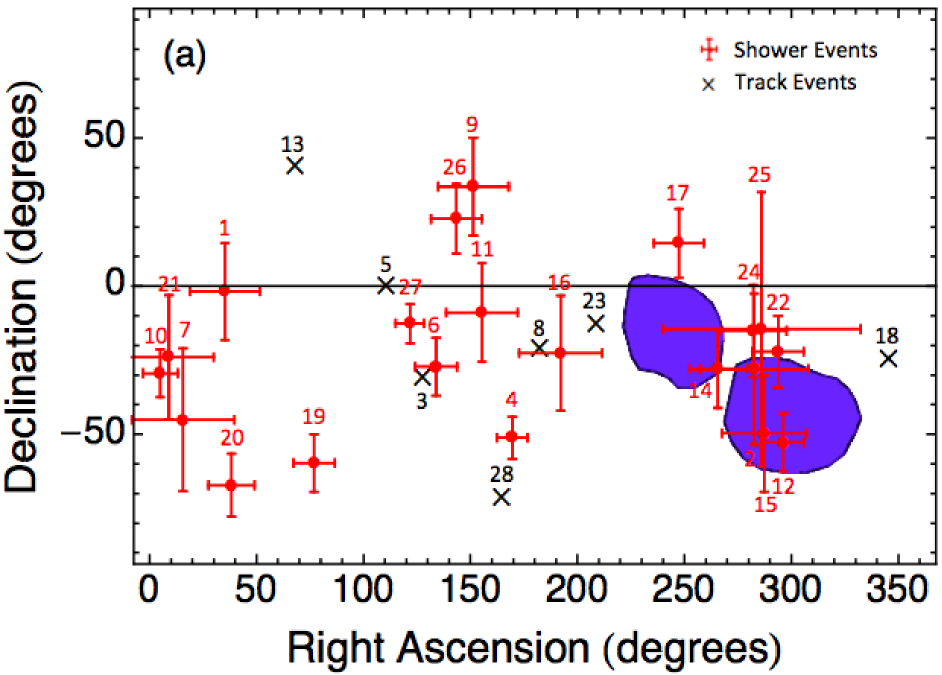


Fermi Bubbles

Ref. Ahlers & KM 13, Razzaque 13, Lunardini+ 13



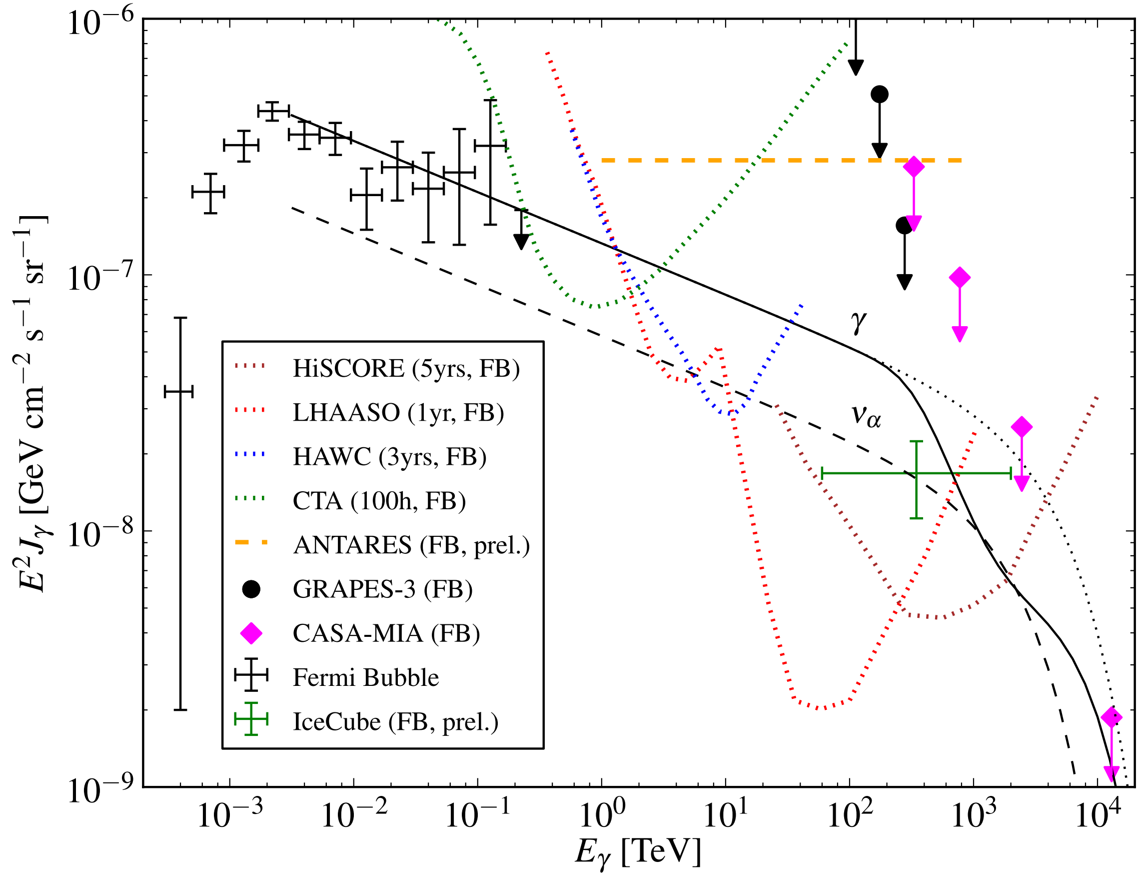
Ahlers & KM 13



Lunardini et al. 13

up to 7 (among 28) can be associated w. Fermi bubbles

Contributions from Fermi Bubbles?

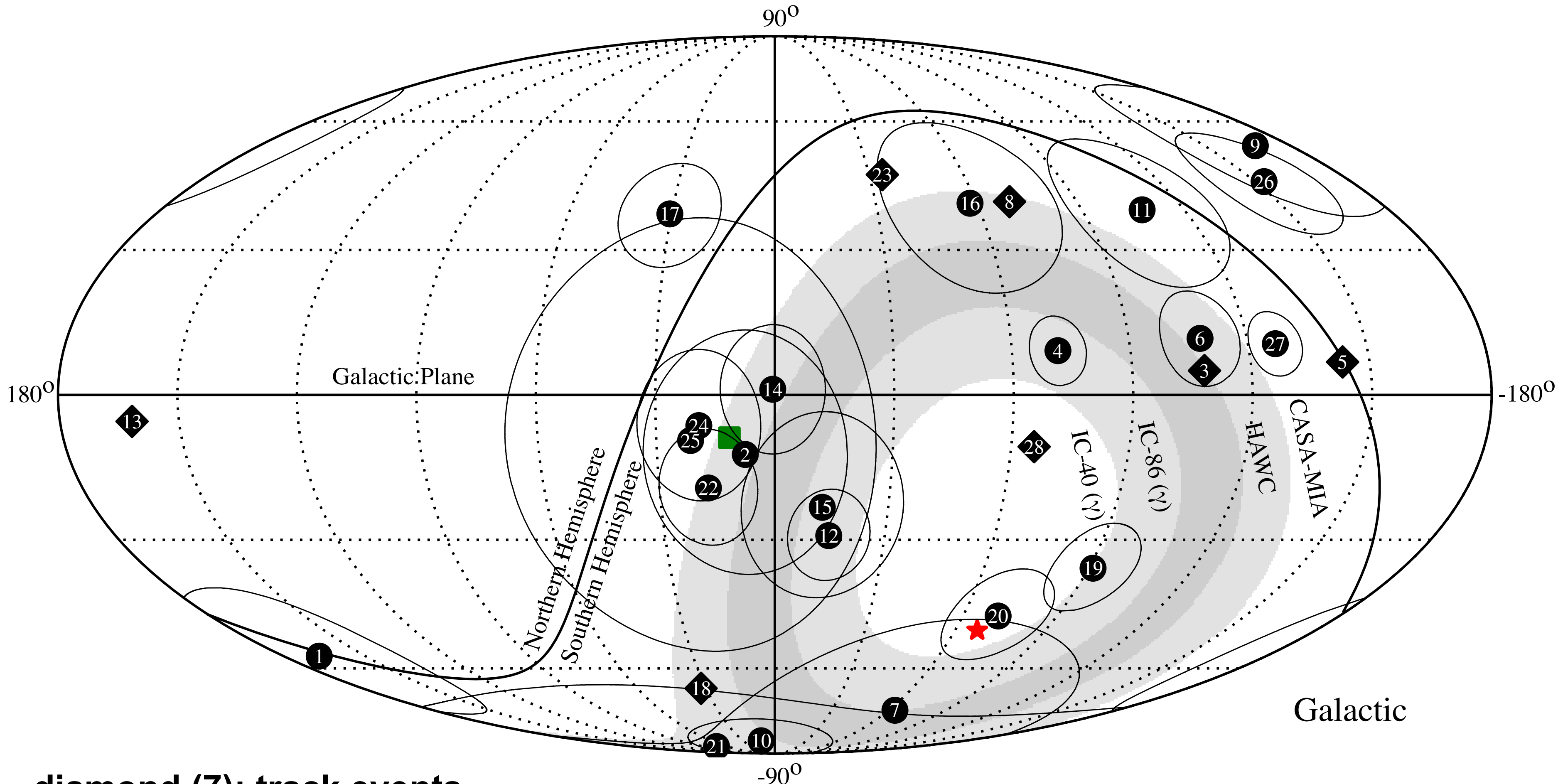


Ahlers & KM 13

- consistent w. Γ=2.2 (while the cutoff is indicated by Fermi)
- testable w. future gamma-ray detectors (ex. CTA, HAWC)

Need for Gamma-Ray Detectors in the Southern Hemisphere

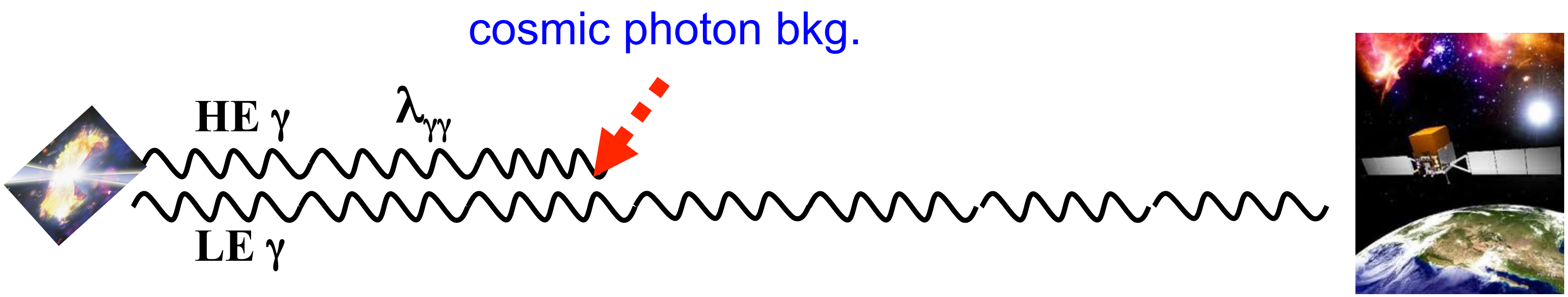
Many HE νs come from the sky region

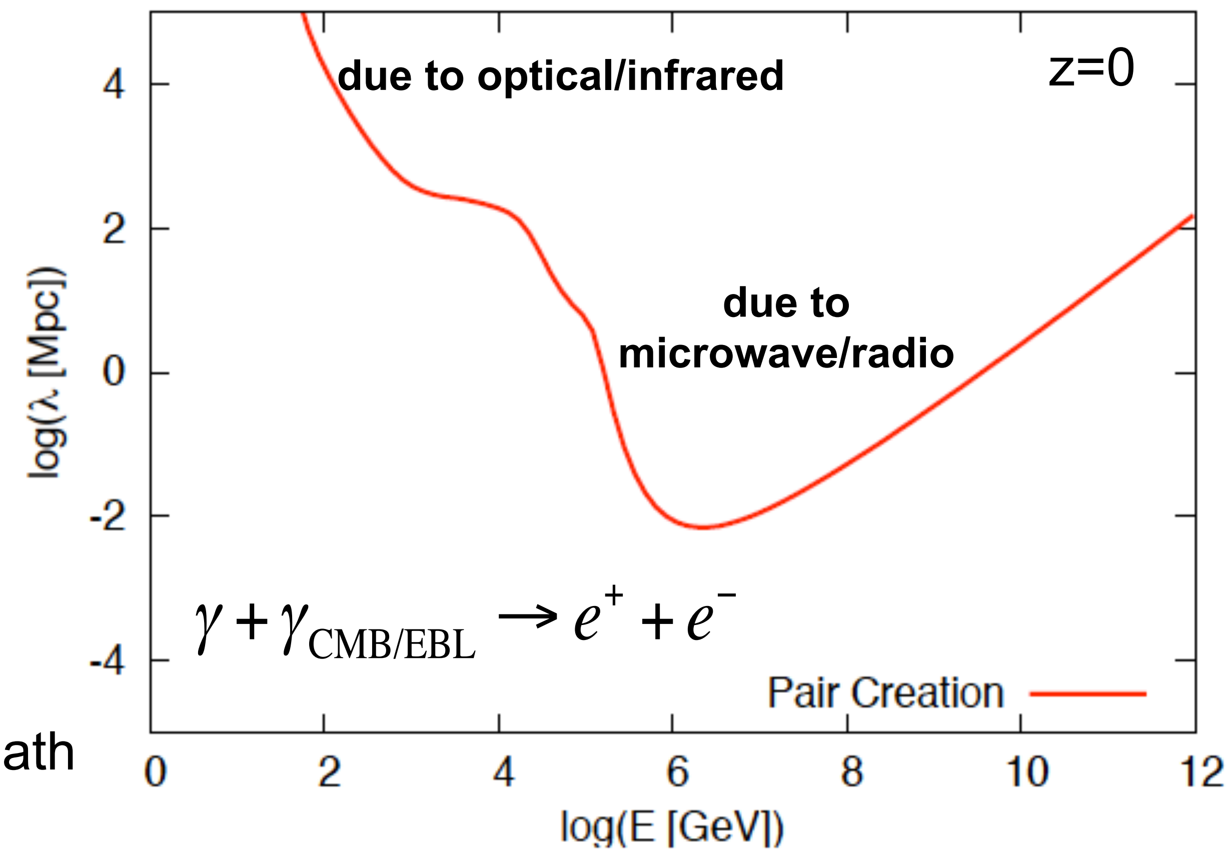


diamond (7): track events
circle (21): shower event

Ahlers & KM 13; complied from IceCube 13 Science

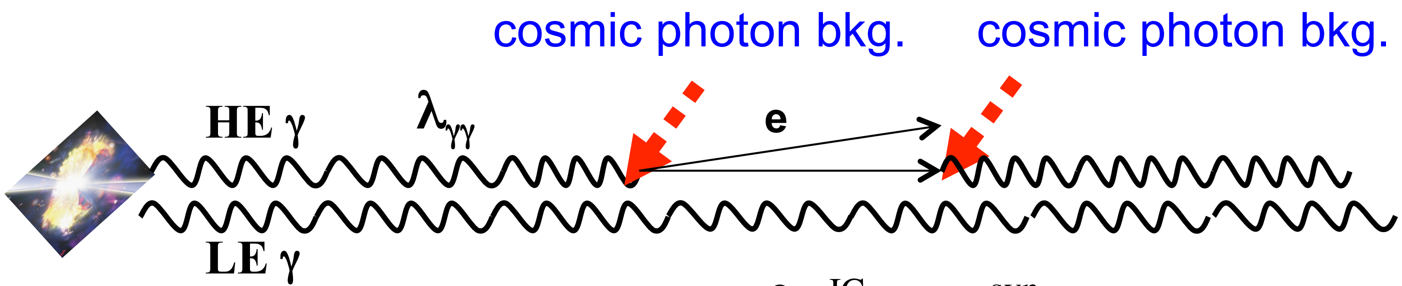
Fate of Extragalactic Gamma Rays





mean free path

Effects of Electromagnetic Cascades



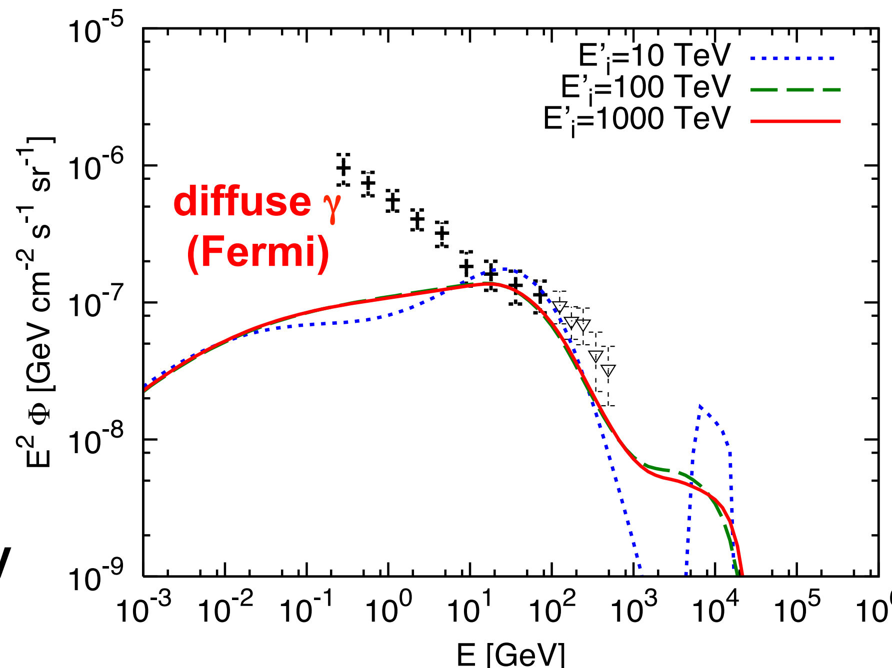
Boltzmann equation

$$\frac{\partial N_\gamma}{\partial x} = -N_\gamma R_{\gamma\gamma} + \frac{\partial N_\gamma^{\rm IC}}{\partial x} + \frac{\partial N_\gamma^{\rm syn}}{\partial x} - \frac{\partial}{\partial E}[P_{\rm ad} N_\gamma] + Q_\gamma^{\rm inj},$$

$$\frac{\partial N_e}{\partial x} = \frac{\partial N_e^{\gamma\gamma}}{\partial x} - N_e R_{\rm IC} + \frac{\partial N_e^{\rm IC}}{\partial x} - \frac{\partial}{\partial E}[(P_{\rm syn} + P_{\rm ad}) N_e] + Q_e^{\rm inj},$$

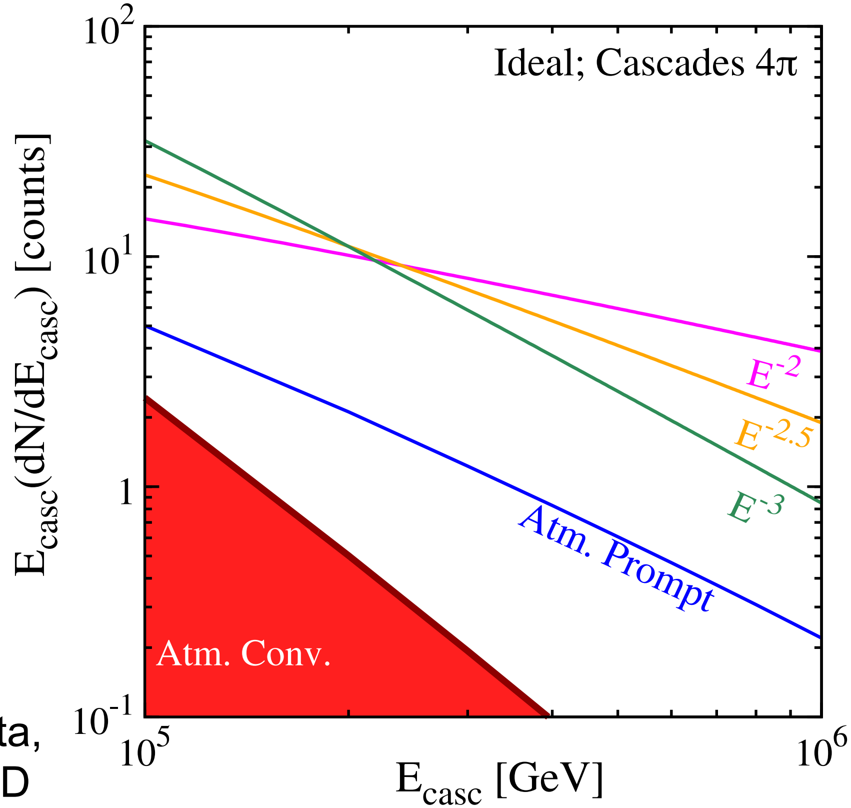
γ-ray spectra

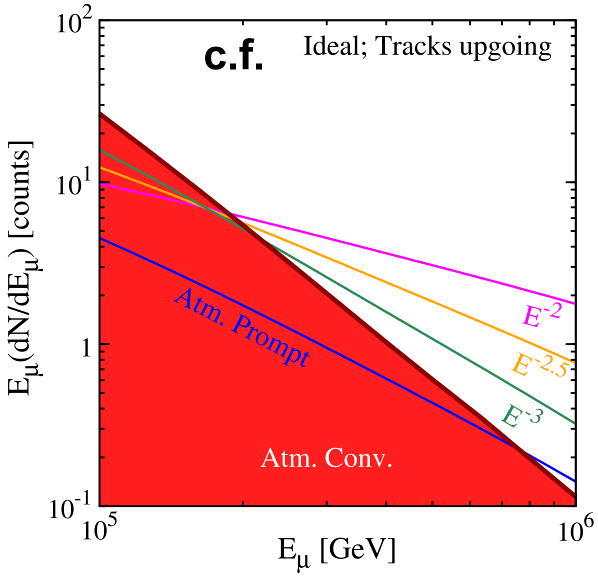
"near-universal" at < TeV



KM et al. 12 JCAP

Implications for Further Neutrino Studies





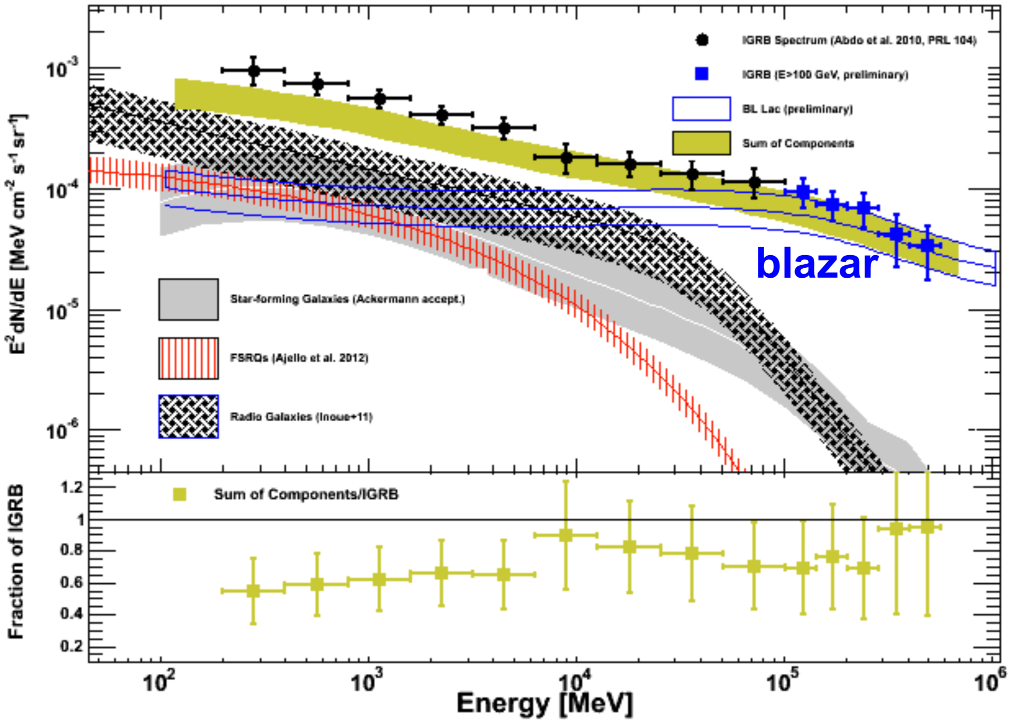
Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

Shower searches at lower energies offer the fastest way to distinguish between the neutrino 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 >50% come from blazars
→ Γ<2.0-2.1

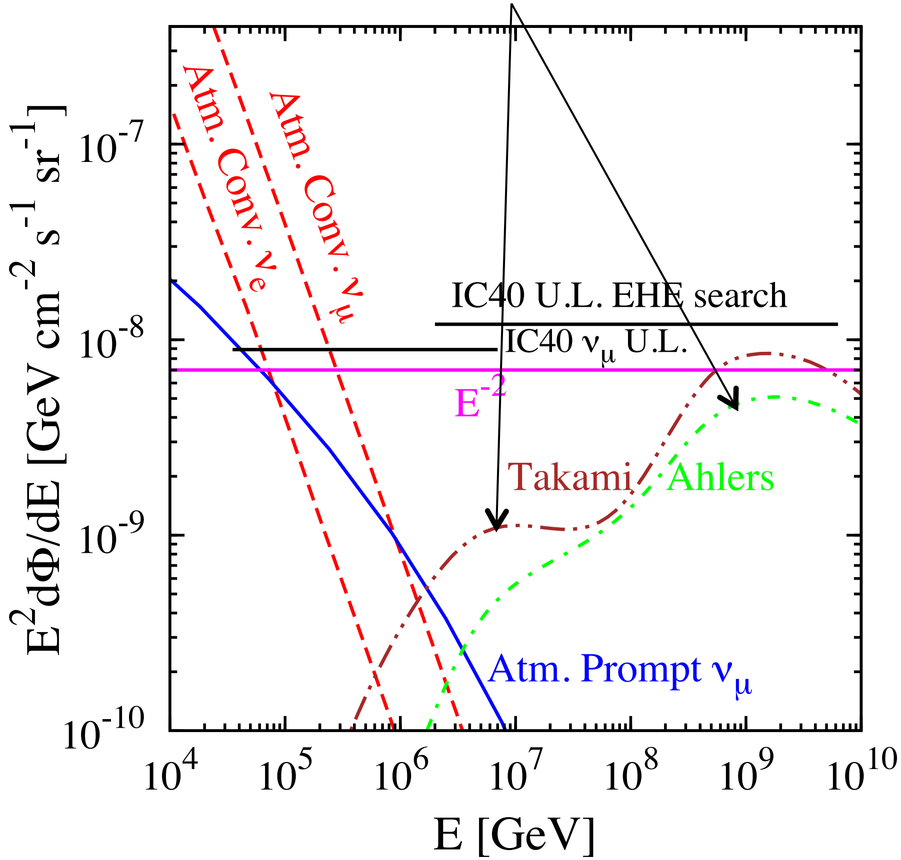
If >60-70% come from blazars
→ no room for pp scenarios!

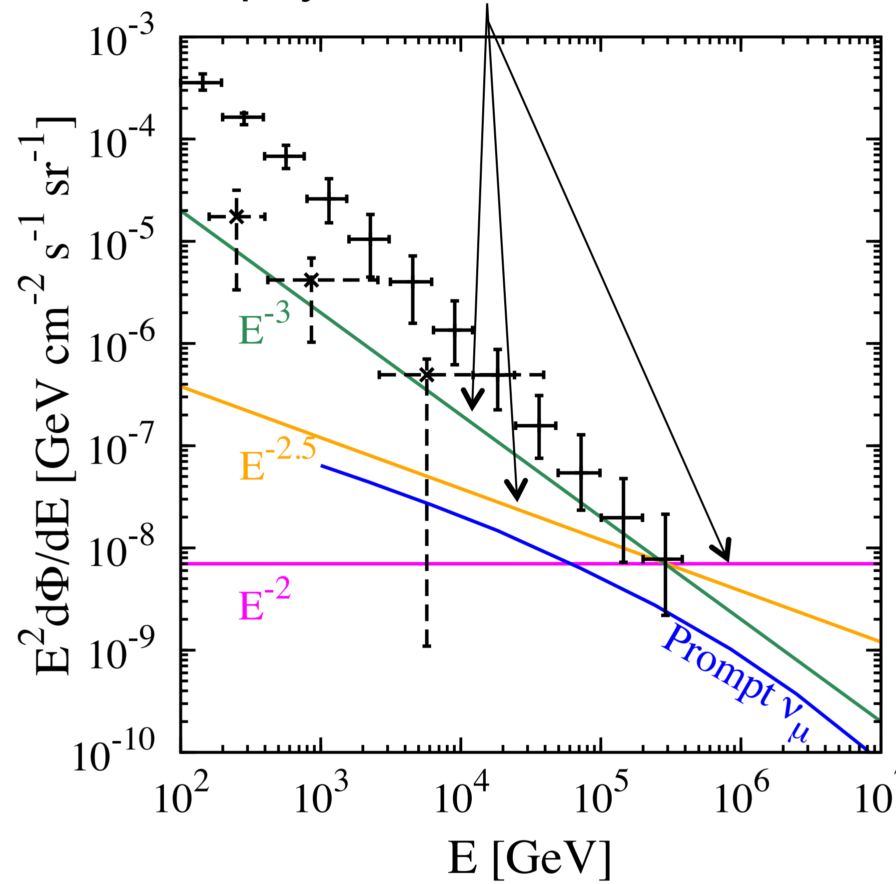
from Fermi collaboration 13

Simple Analyses for Intuitive Understanding

cosmogenic neutrinos

astrophysical on-source neutrinos



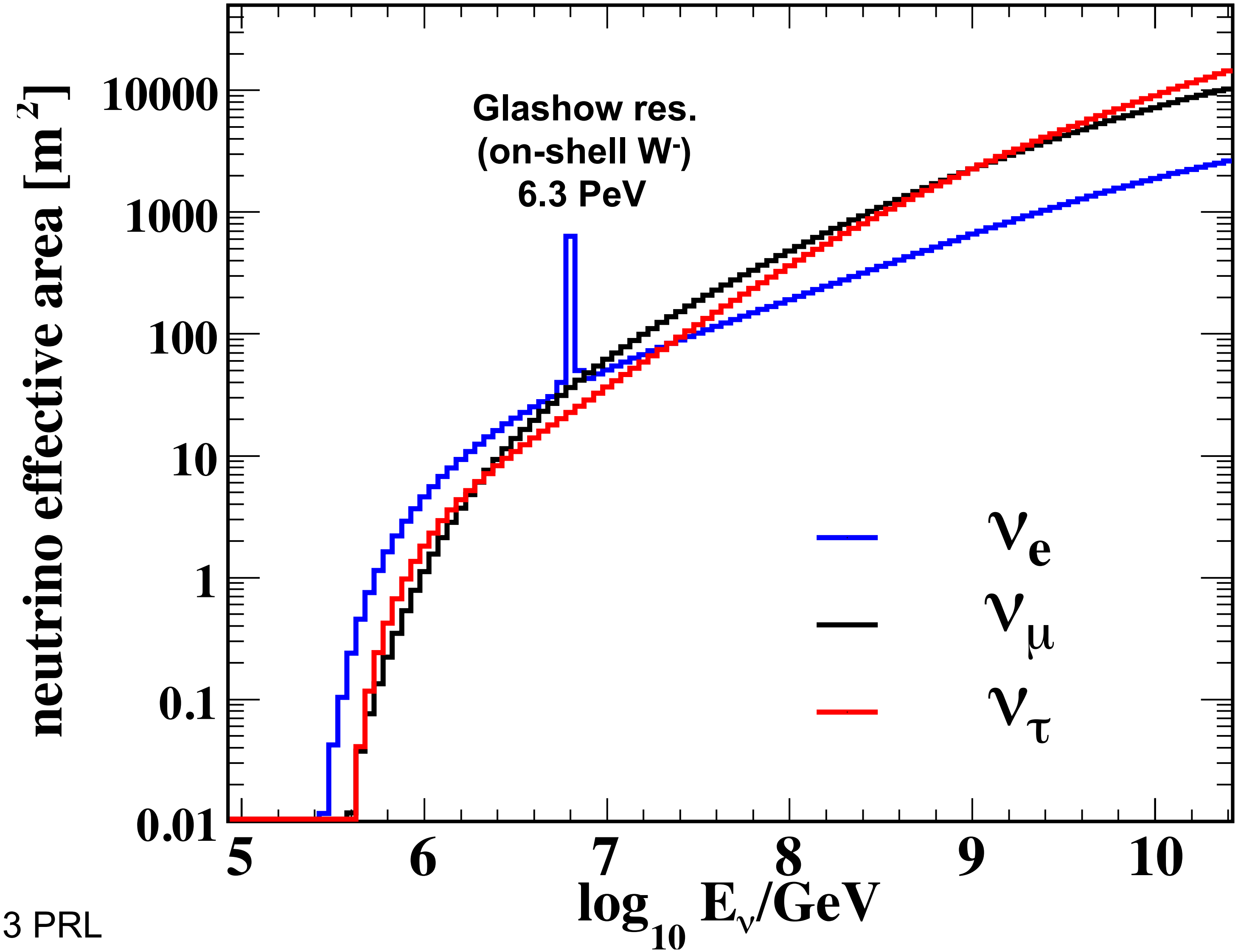


shower event rates

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

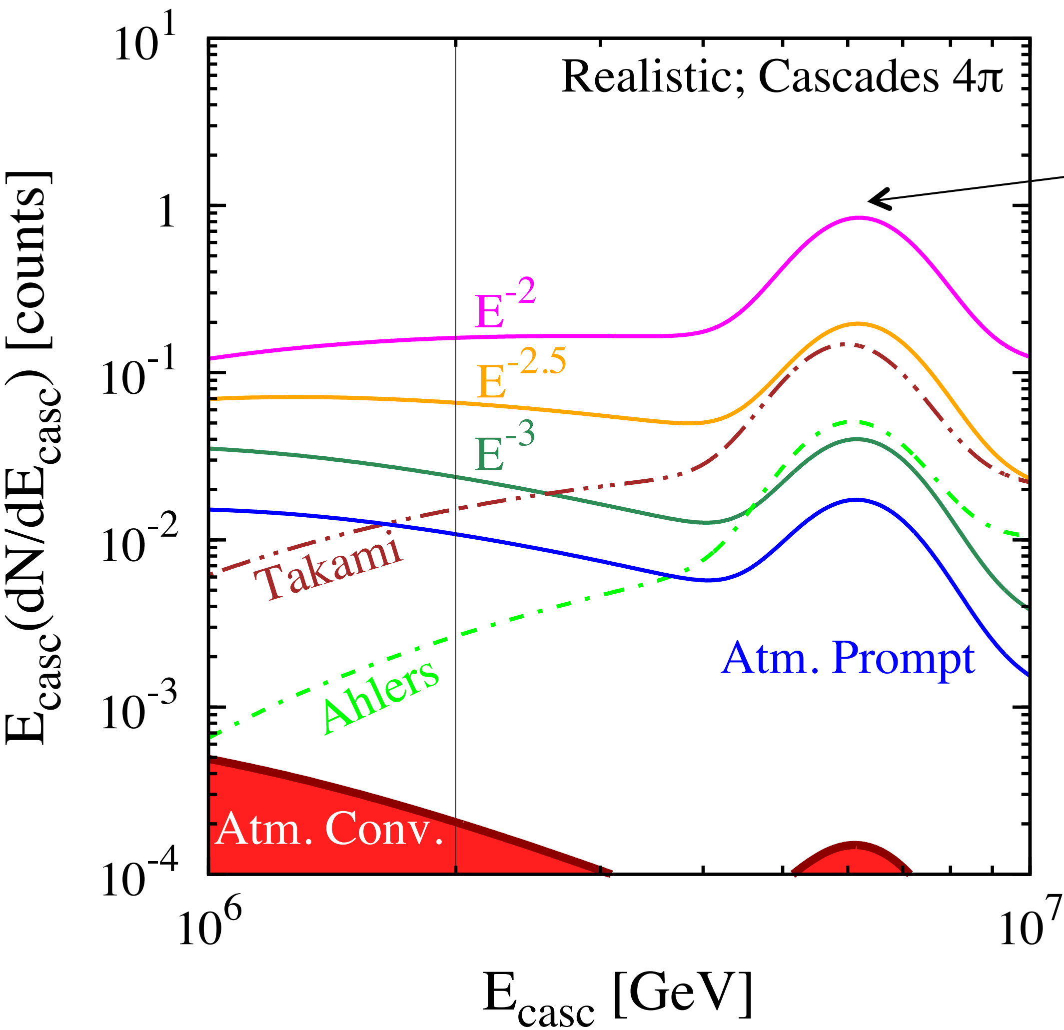
T=615.9 d

Neutrino Effective Area



IceCube 13 PRL

Shower Event Rates



Glashow resonance

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

at E_ν=6.3 PeV

Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

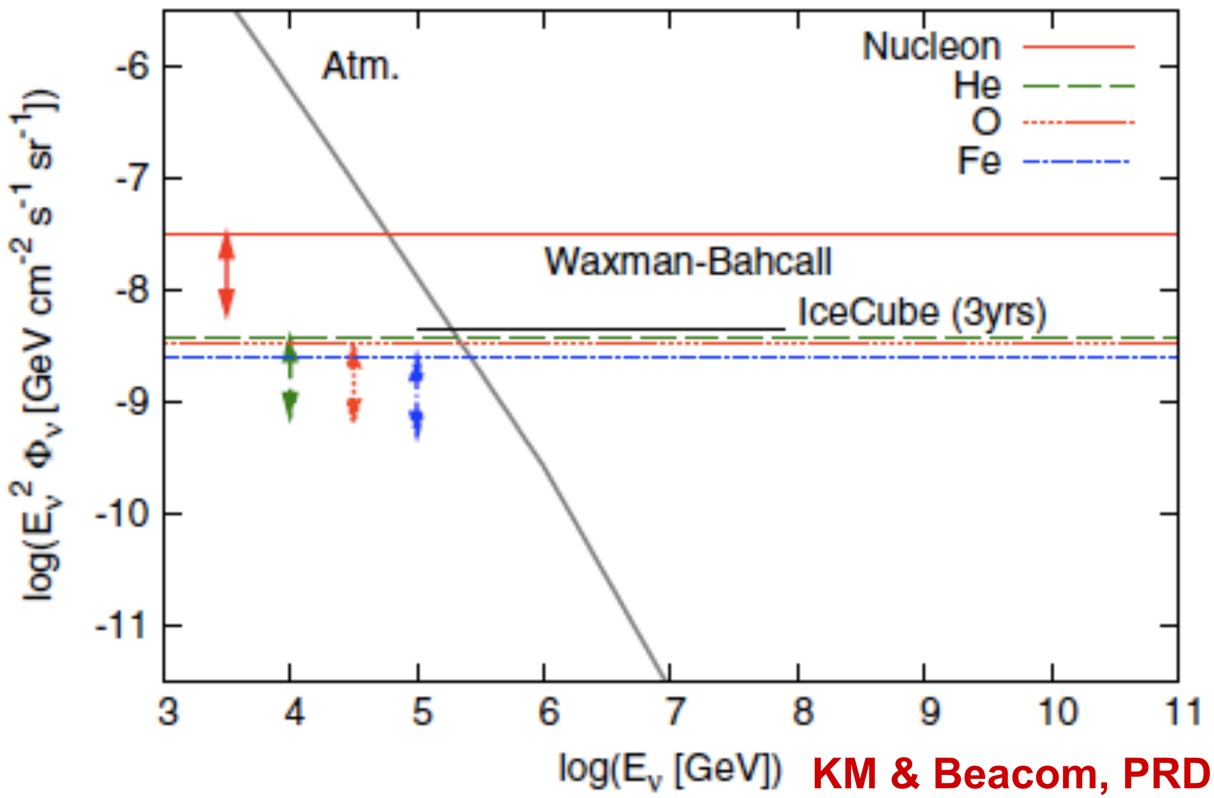
2 events at PeV ⇔ $E_\nu^2 \Phi_\nu$ ~ a fewx10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

Landmarks from "UHE" Nuclei Sources

Conservative requirement: $f_{A\gamma} \sim \kappa\, n_\gamma\, \sigma_{A\gamma}\, \Delta < 1$

$f_{mes} \sim (0.2/A)\, n_\gamma\, A\, \sigma_{p\gamma}\, (r/\Gamma) \sim f_{A\gamma}\, (0.2\, \sigma_{p\gamma}/\kappa\sigma_{A\gamma}) < 10^{-1}$

$\rightarrow \varepsilon_\nu^{\,2}\, \Phi(\varepsilon_\nu) \sim 0.25\, f_{mes}\, \varepsilon_A^{\,2}\, \Phi(\varepsilon_A) < (0.5\text{-}3)\times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}



KM & Beacom, PRD, 81, 123001 (2010)