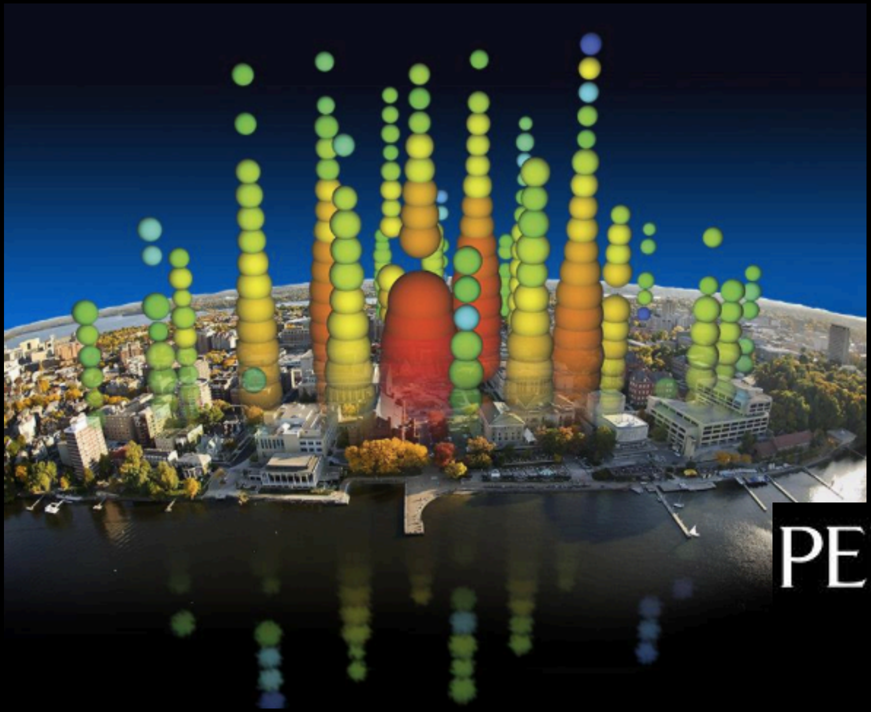
Mysteries of Cosmic High-Energy Neutrinos



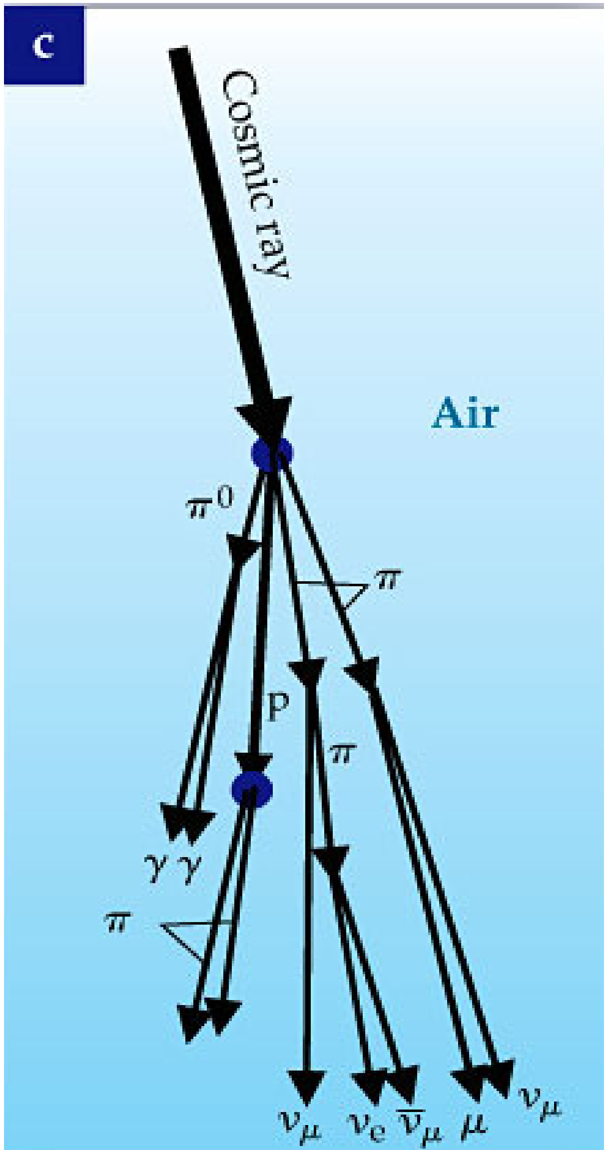
Kohta Murase (Penn State)

July 7 2016 @ KIAA, Beijing

PENNSTATE

1855

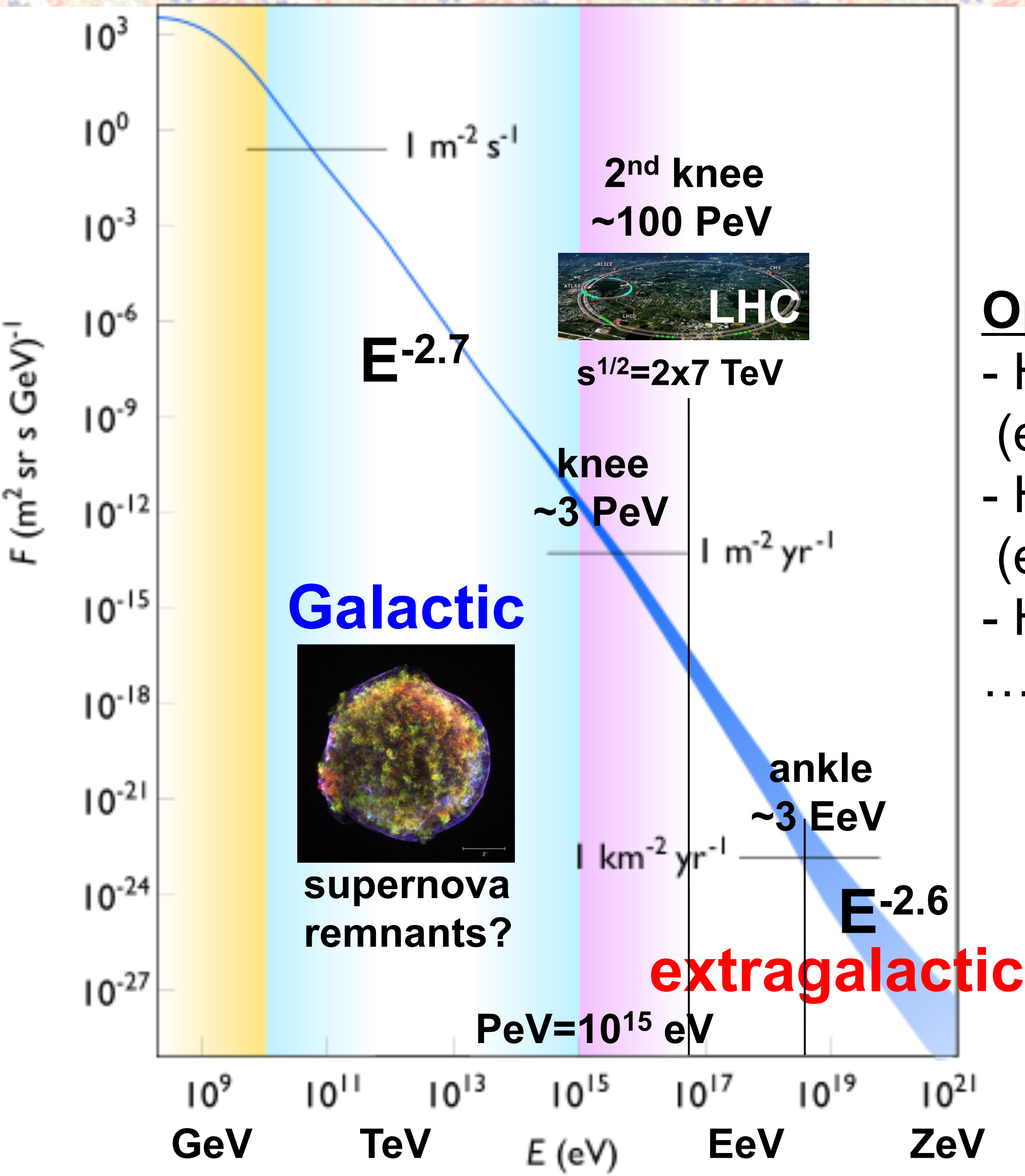
A 2015 Nobel Laureate in Physics Said…



"I want to thank the neutrinos, of course. And since neutrinos are created by cosmic rays, I want to thank them, too."

But we do not know well about "them"…

Motivation: Cosmic Rays – A Century Old Puzzle



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

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

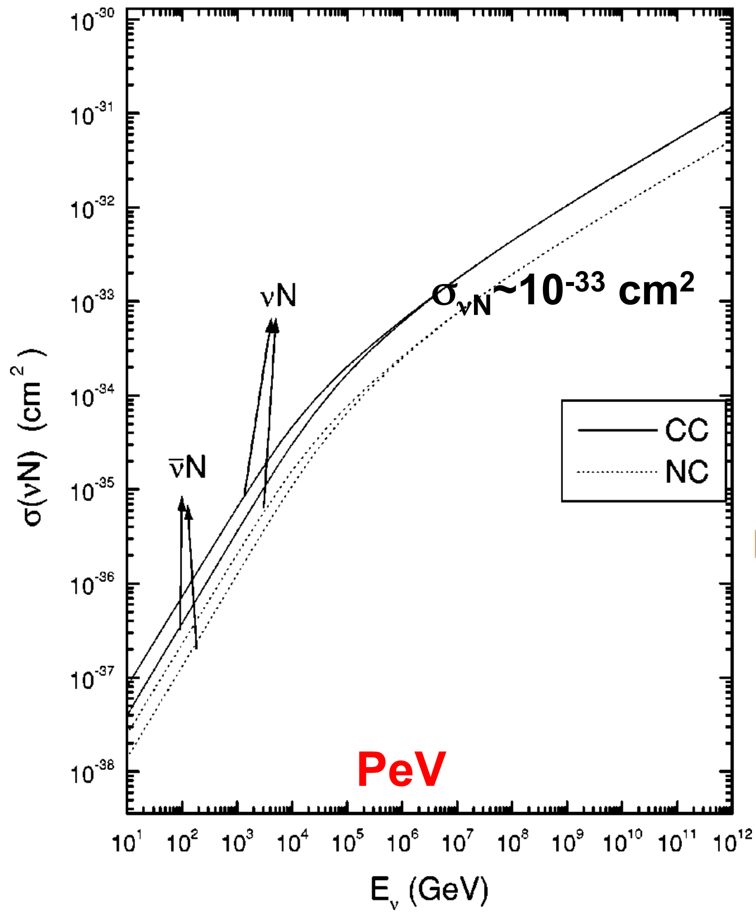
"What is the origin?"

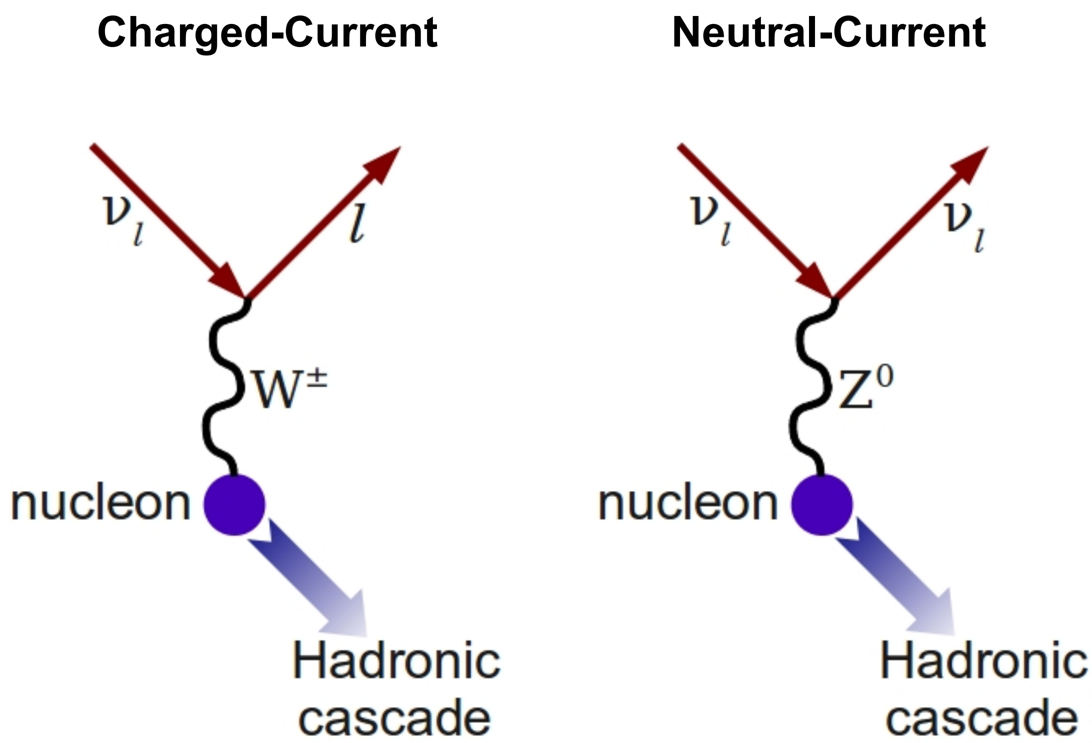
extreme energy (EeV-ZeV)

→ extreme sources

Multi-Messenger Approach

Neutrino: Weak Interaction

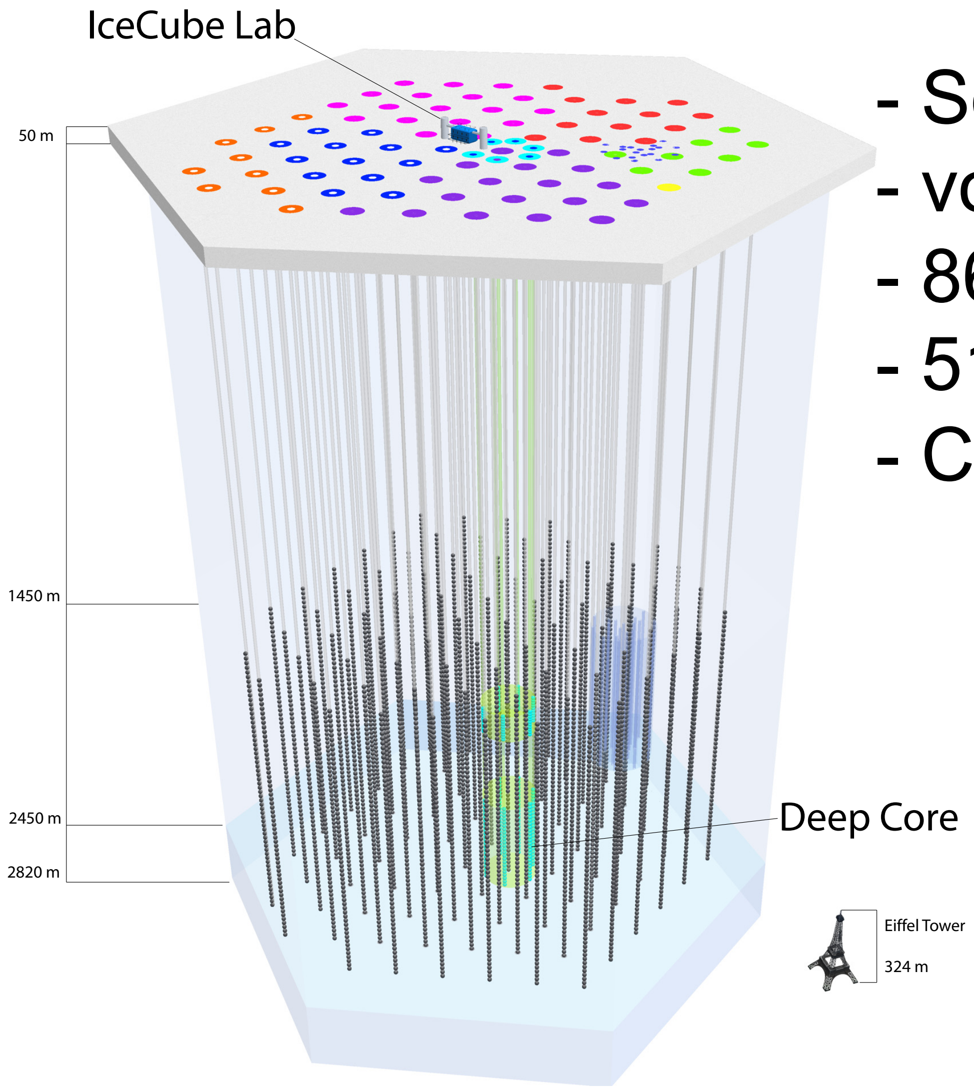




crude estimate at PeV energies

$$\mathcal{N} \sim (\varepsilon_\nu \Phi_\varepsilon)\sigma_{\nu N}(2\pi N_A \rho V) \simeq 10 \text{ yr}^{-1} \left(\frac{\varepsilon_\nu^2 \Phi_\varepsilon}{10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}}\right)\left(\frac{V}{\text{km}^3}\right)$$

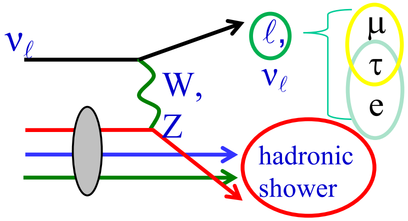
IceCube: Gton Neutrino Detector

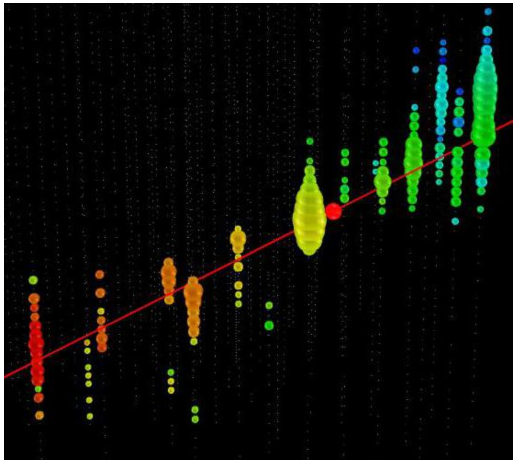
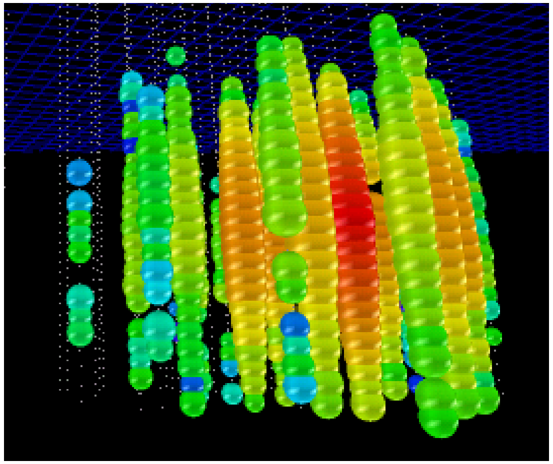
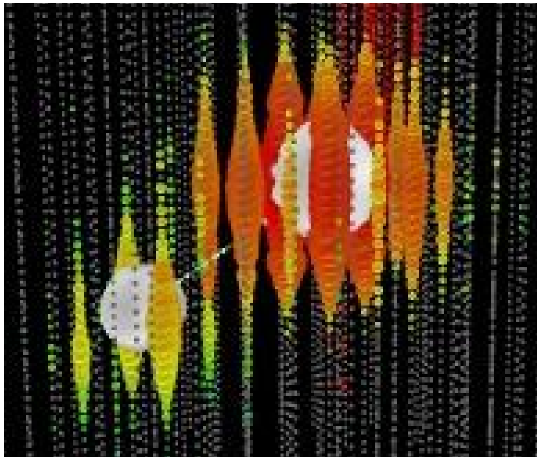


- South pole
- volume~1 km^3, mass~Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)
- Completed in 2010

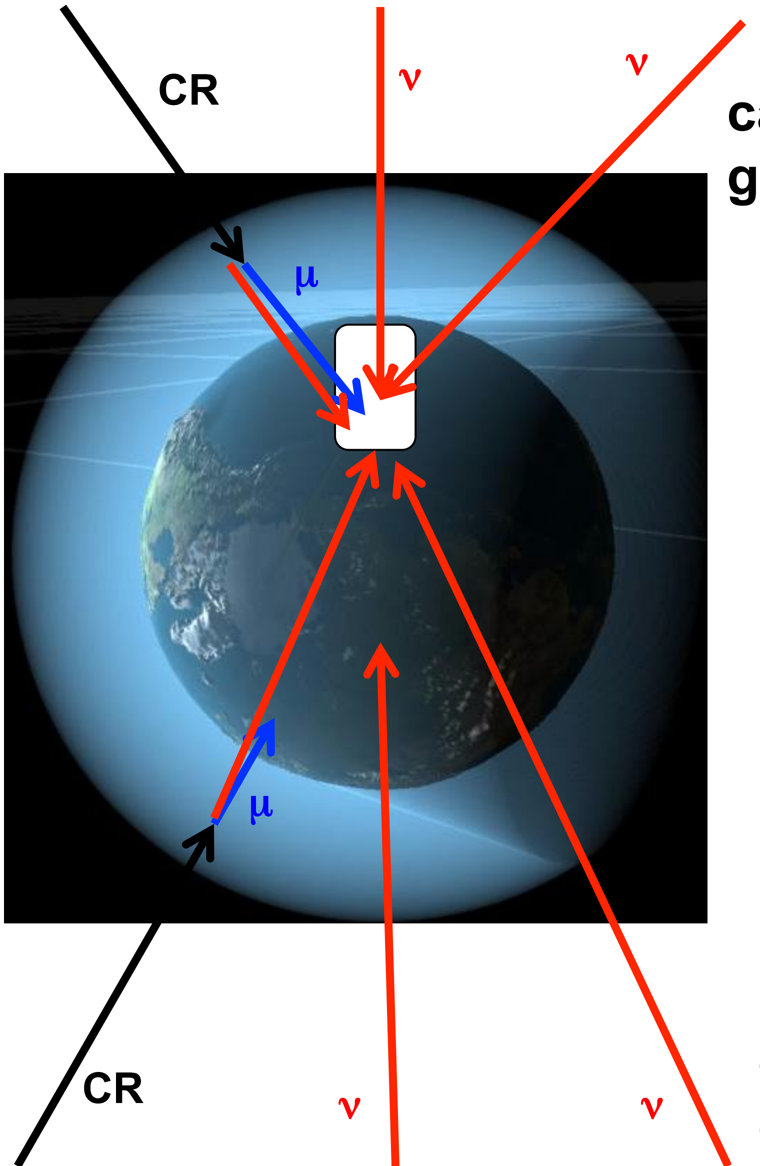
How to Detect Neutrinos?

- 3 main event types



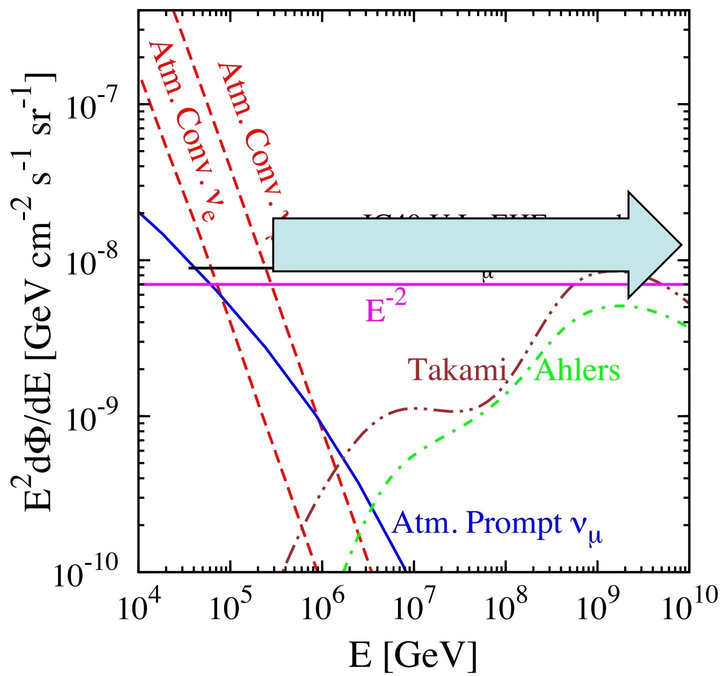
"Track" (detected)	"Shower" (detected)	"Double-bang & others" (not detected)
		
ν_μ+N → μ+X	ν_e+N → e+X ν_X+N → ν_X+X	ν_τ+N → τ+X
~2 energy res. <1 deg ang res.	~15% energy res. ~10 deg ang res. seen at >100 TeV	observable at higher E

Upgoing & Downgoing Neutrinos



Downgoing neutrinos

caveat: atm. muons (rapidly decreasing as E)
good: avoid attenuation by Earth

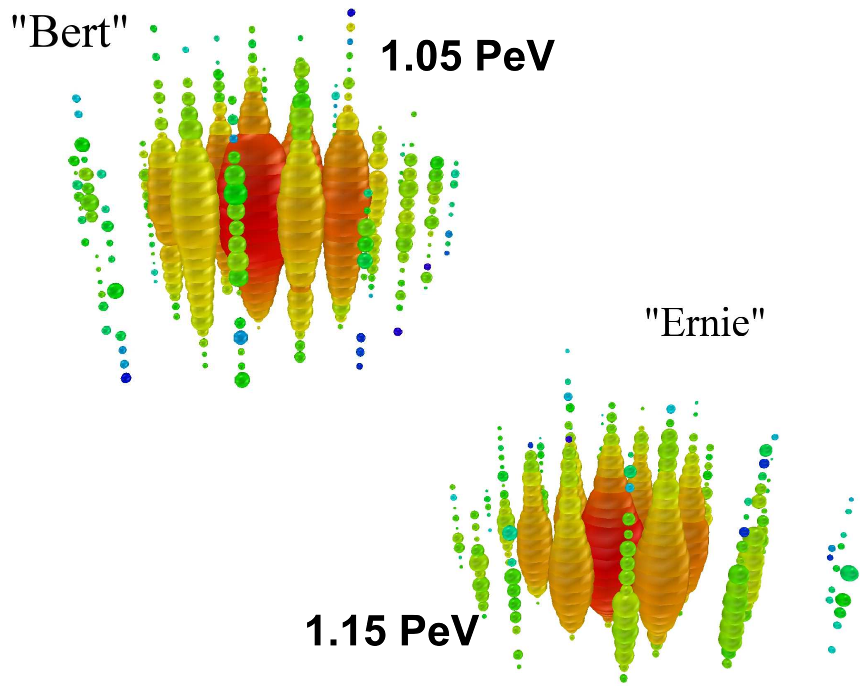


Upgoing neutrinos

good: avoid atmospheric “muons”
caveat: attenuation by Earth at > 0.1-1 PeV

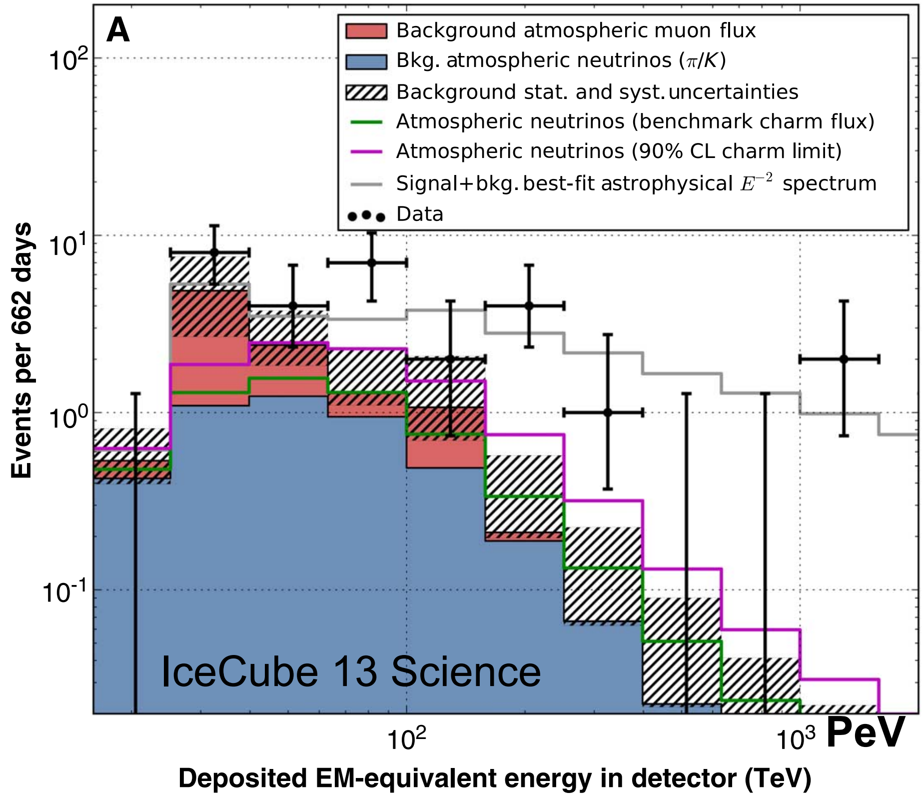
Discovery: Early Results in 2012-2013

First detection of PeV events (~3σ)



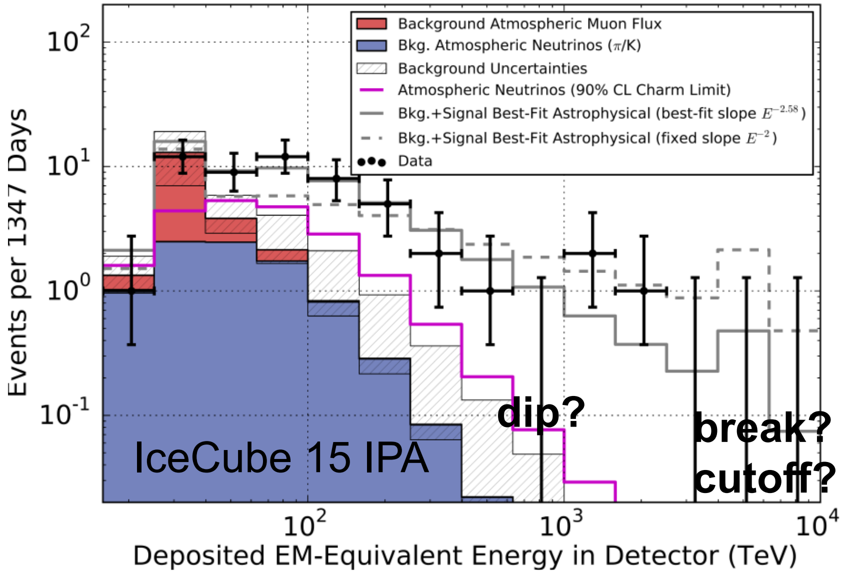
IceCube 13 PRL

Follow-up analysis (~4σ)



- $E_\nu^2\ \Phi_\nu$=(1.2±0.4)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} (per flavor)
- Consistent w. flavor ratio ν_e:ν_μ:ν_τ=1:1:1
- Favoring cutoff at ~2 PeV for E_ν^{-2} or steeper than $E_\nu^{-2.2}$

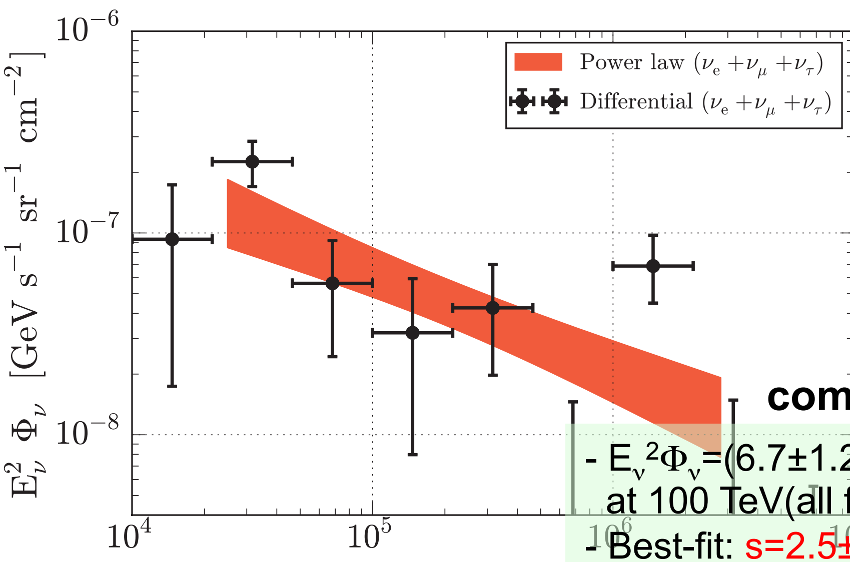
IceCube Neutrinos: Updates in 2015



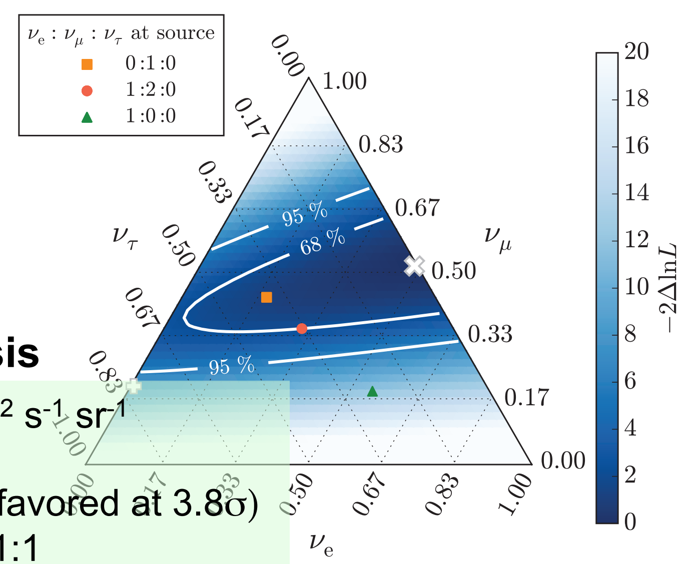
IceCube 15 IPA

- 4-yr HESE data: 54 events (6.5 σ)
  E_{dep}: 20 TeV-2 PeV
  - Best fit (no cutoff): s_ν=2.58+-0.25
  - $E_\nu^2\ \Phi_\nu$=(2.2±0.7)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV (per flavor)

cf. 3-yr HESE data: 37 events (5.7 σ)
E_{dep}: 30 TeV-2 PeV
- Best fit (no cutoff): s_ν=2.3+-0.3



IceCube 15 ApJ

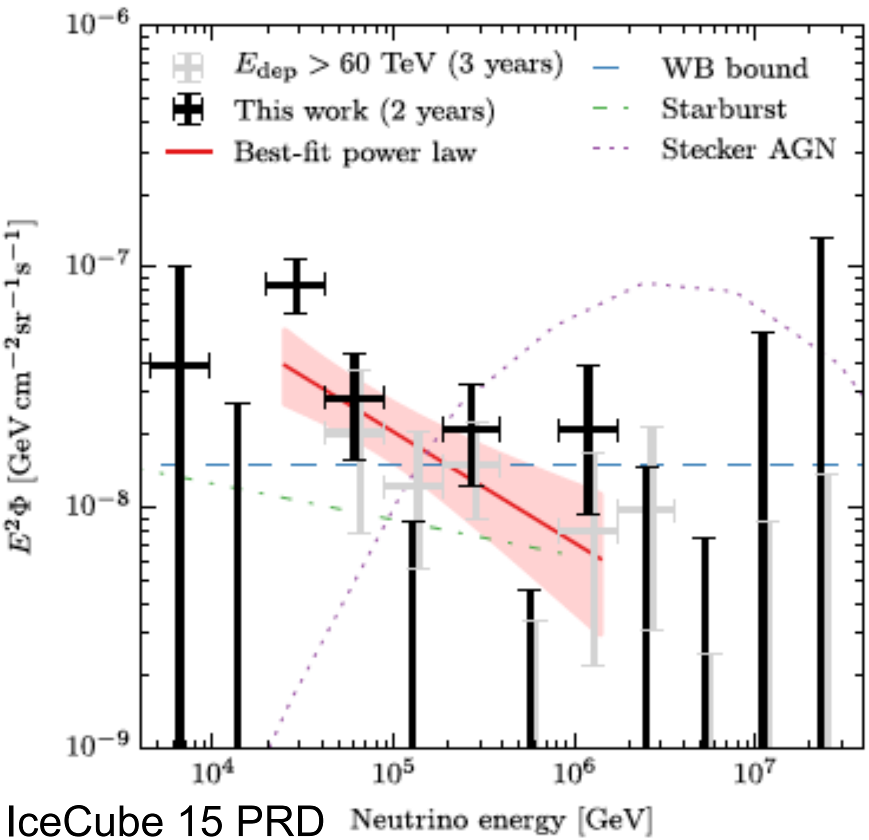


combined analysis

- $E_\nu^2\Phi_\nu$=(6.7±1.2)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV(all flavor)
- Best-fit: s=2.5±0.09 (s=2.0 disfavored at 3.8σ)
- Flavor ratio is consistent w. 1:1:1

Lowering the Threshold: Steep Spectra?

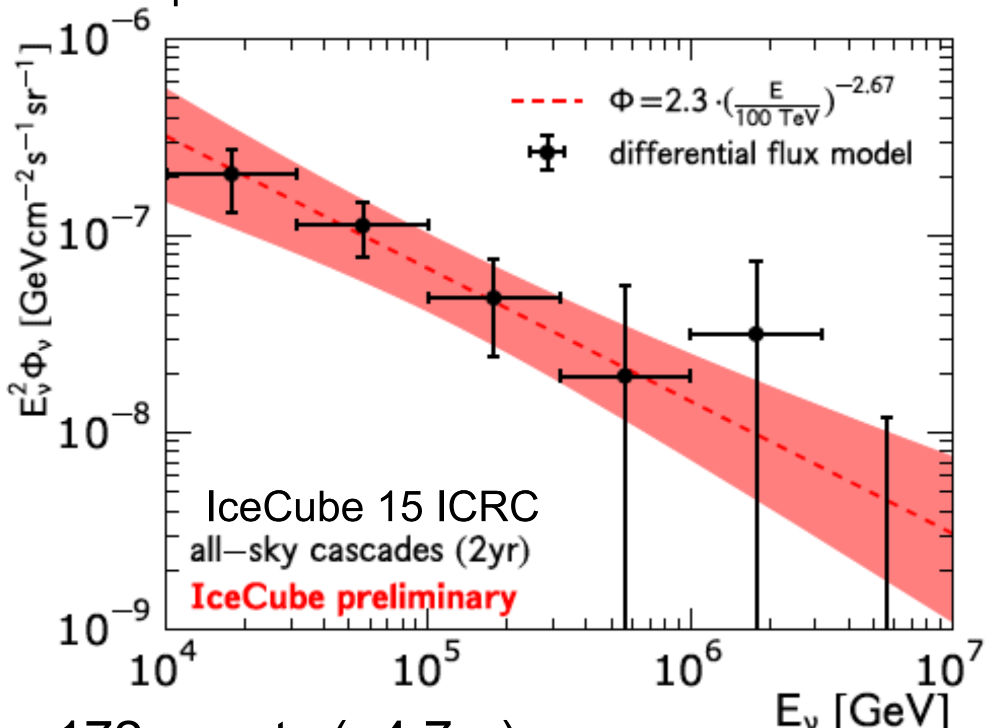
- Including lower-energy νs E_{dep}>~1 TeV (2010-2012)



IceCube 15 PRD

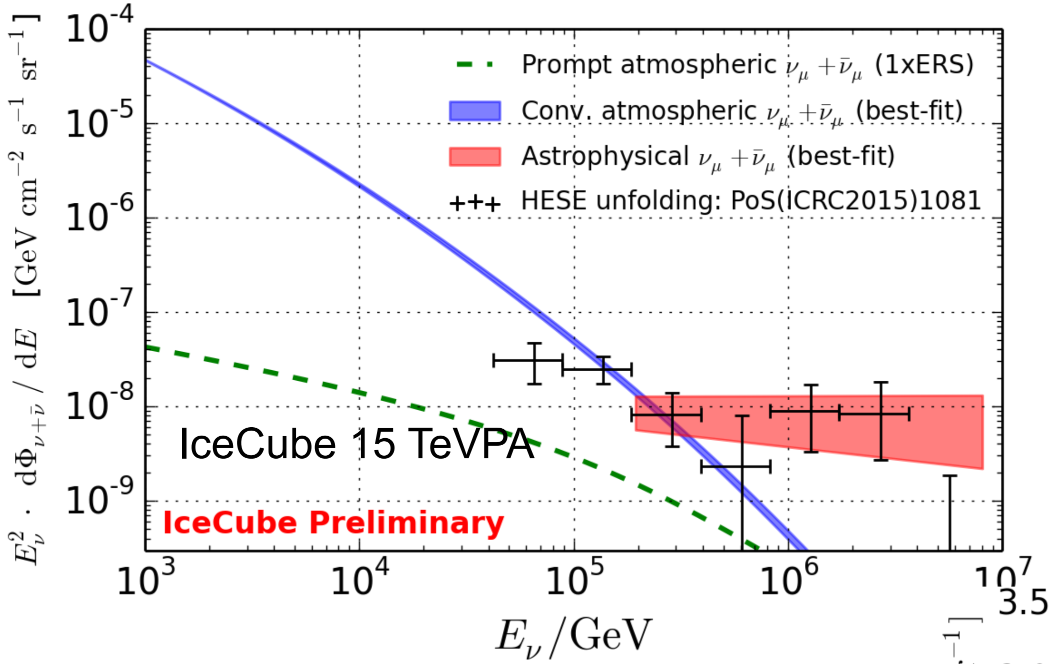
best-fit simple PL: s=2.46±0.12

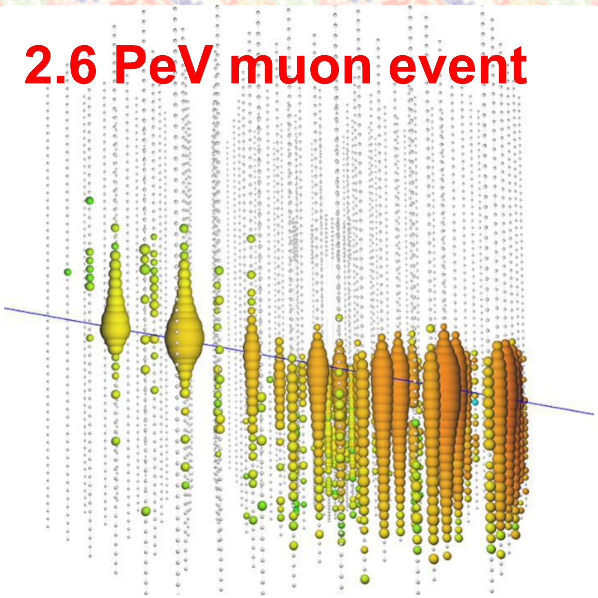
- Shower analyses E_{dep}: 10 TeV-1 PeV (2010-2012)

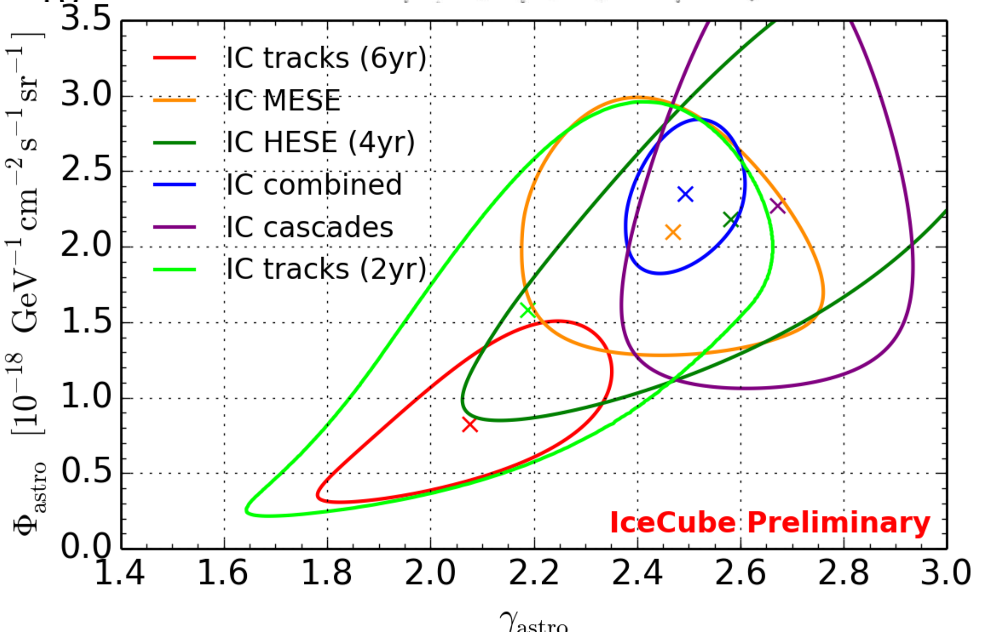


172 events (~4.7 σ)
s=2.67+0.12-0.13
atm. prompt (90%CL)
< 3.8×10^{-9} cm^{-2} s^{-1} sr^{-1}
No evidence for north-south asymmetry

Upgoing Muon Tracks: Hard Spectra?





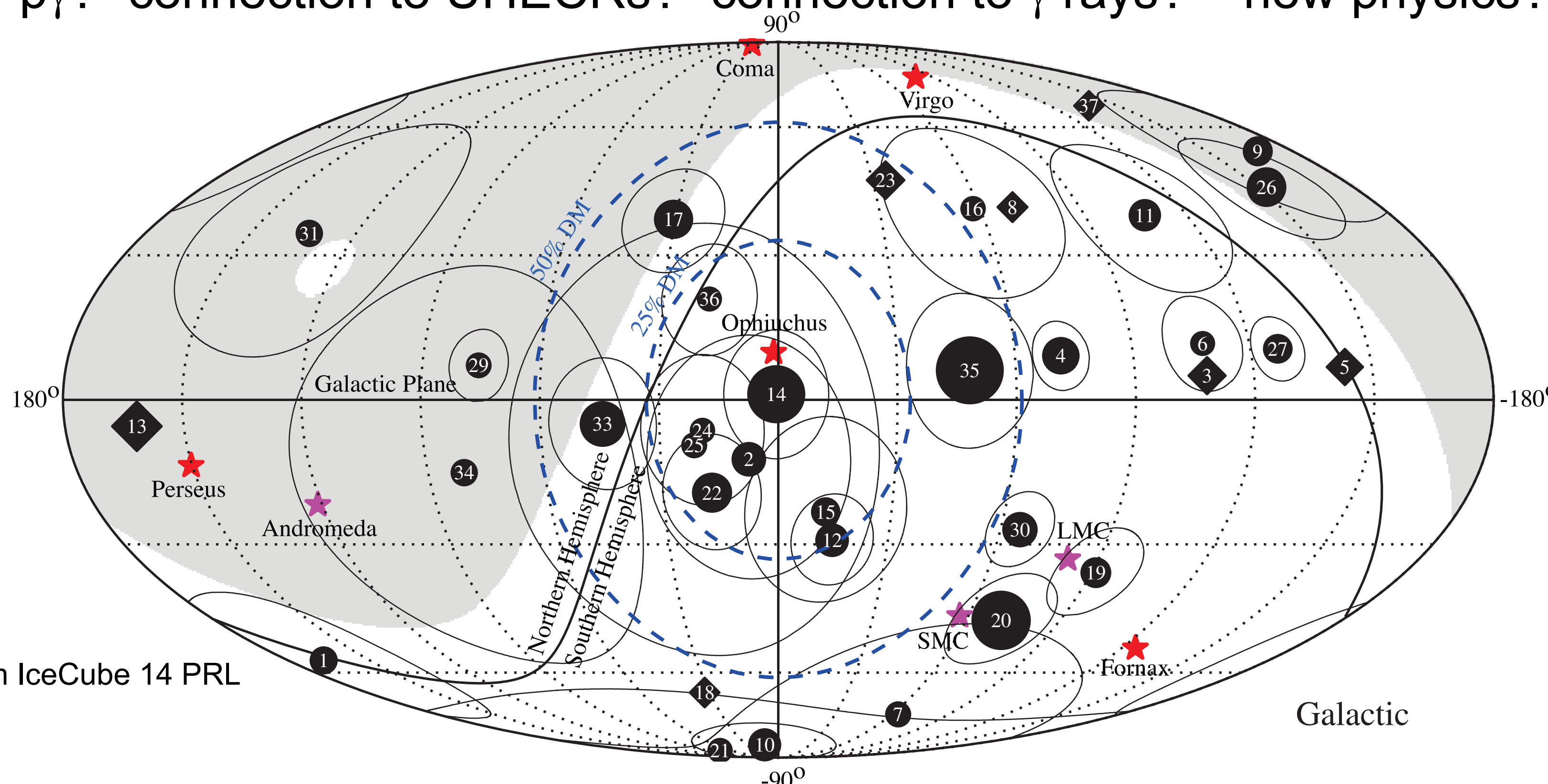


- 6-yr Upgoing muon ν (>220 TeV): only bkg. rejected at 5.9σ
- Best-fit index: s=2.07±0.13
- Muon ν flux at 100 TeV: $E_\nu^2\Phi_\nu$=(0.82+0.3-0.26) x10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
- Consistent w. low-energy analyses but there is a 2σ tension

HE Neutrino Astrophysics Started

Origins and mechanism of cosmic neutrinos?

-pp or pγ? -connection to UHECRs? -connection to γ rays? – new physics?



complied from IceCube 14 PRL

No single source detection & no significant clustering

Easy to see: mostly isotropic → extragalactic sources

(supported by diffuse gamma-ray searches:
KM, Ahlers & Lacki 13 PRDR, Ahlers & KM 14 PRD)

Astrophysical "Isotropic" Neutrino Background – Mean Diffuse Intensity

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

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

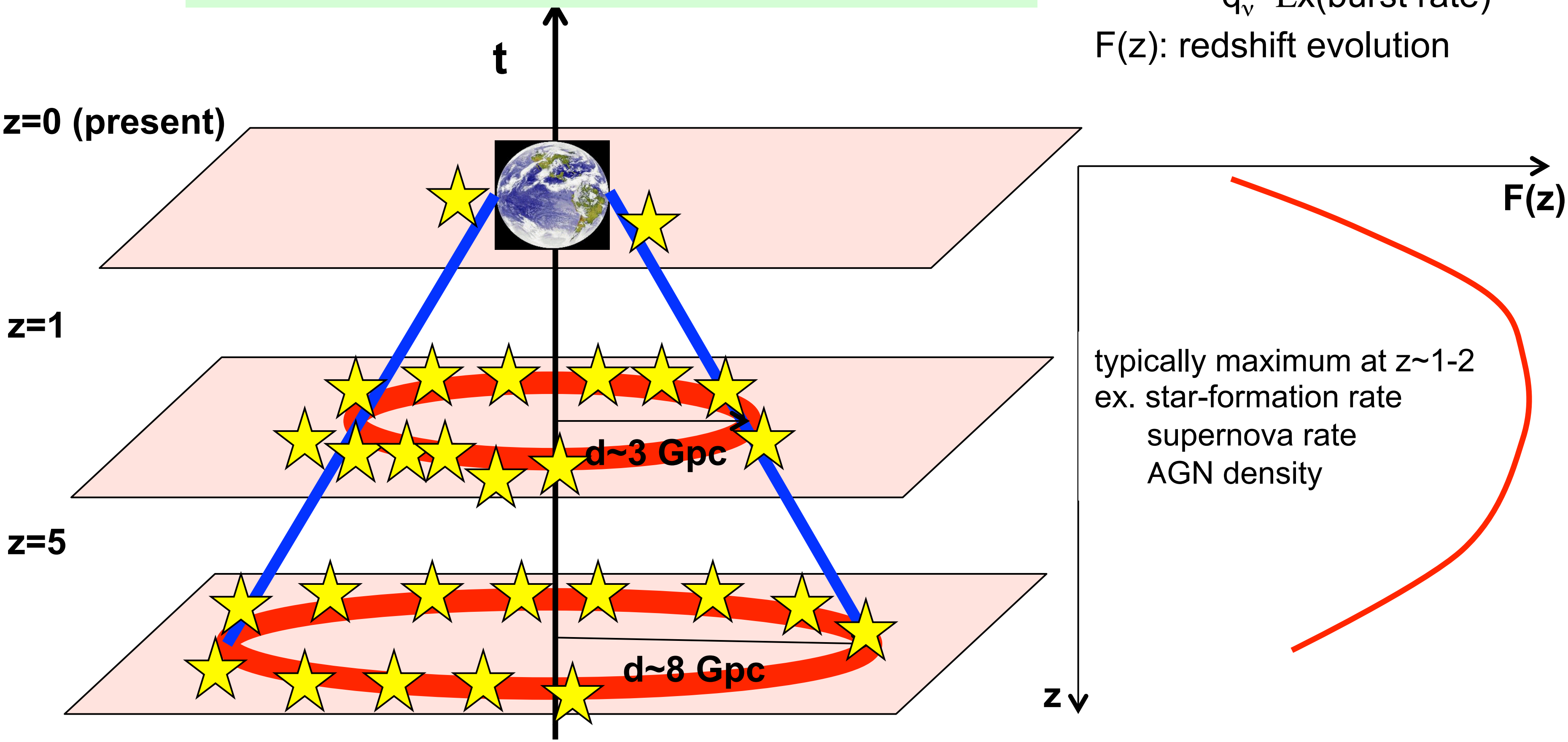
$\varepsilon_\nu^2 q_\nu(\varepsilon_\nu)$: ν emissivity at z=0

"source physics"

q_ν=Lx(source density)

q_ν=$\mathcal{E}$x(burst rate)

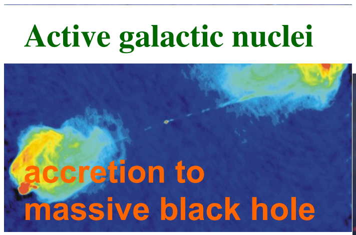
F(z): redshift evolution



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

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators
(ex. UHECR candidate sources)



Cosmic-ray Reservoirs

- <u>γ-ray bursts</u>

  ex. Waxman & Bahcall 97, KM et al. 06
  after Neutrino 2012:
  Cholis & Hooper 13, Liu & Wang 13
  KM & Ioka 13, Winter 13, Senno, KM & Meszaros 16

- <u>Active galactic nuclei</u>

  ex. Stecker et al. 91, Mannheim 95
  after Neutrino 2012:
  Kalashev, Kusenko & Essey 13, Stecker 13,
  KM, Inoue & Dermer 14, Dermer, KM & Inoue 14,
  Tavecchio et al. 14, Kimura, KM & Toma 15,
  Padvani et al. 15, Wang & Liu 16

- <u>Starburst galaxies (not Milky-Way-like)</u>

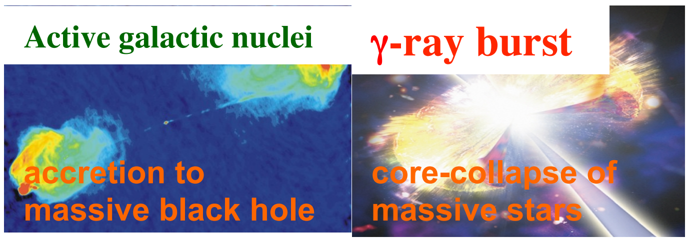
  ex. Loeb & Waxman 06, Thompson et al. 07
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Katz et al. 13,
  Liu et al. 14, Tamborra, Ando & KM 14,
  Anchordoqui et al. 14, Senno et al. 15

- <u>Galaxy groups/clusters</u>

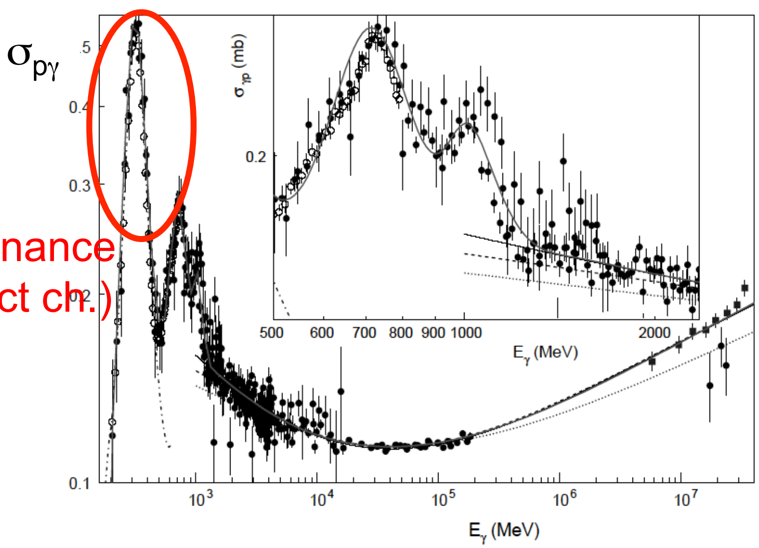
  ex. Berezinsky et al. 97, KM et al. 08, Kotera et al. 09
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Fang & Olinto 16

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



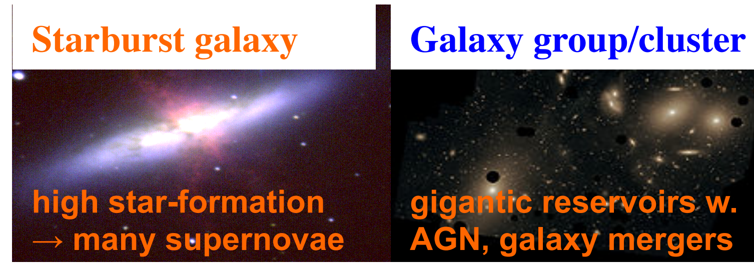
$$p + \gamma \rightarrow N\pi + X$$



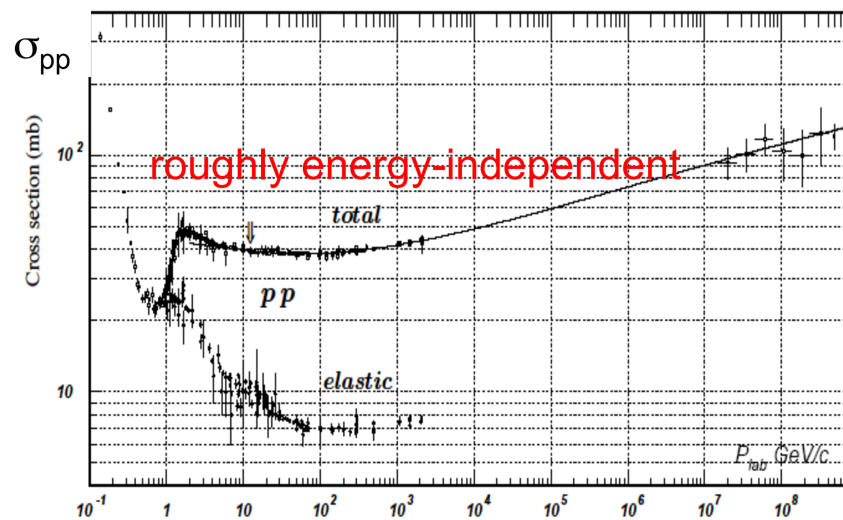
$\sigma_{p\gamma} \sim \alpha \sigma_{pp} \sim 0.5$ mb

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

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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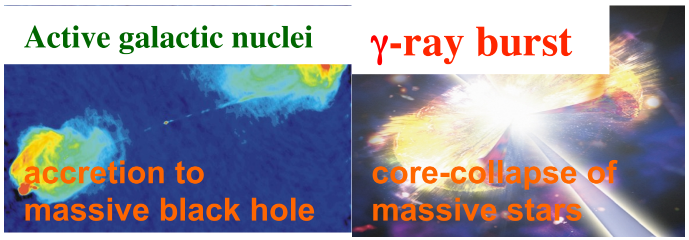
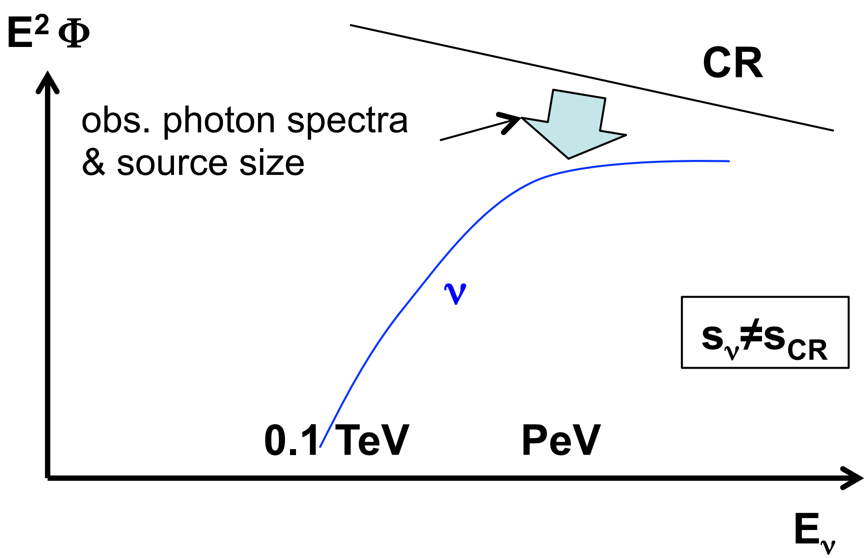
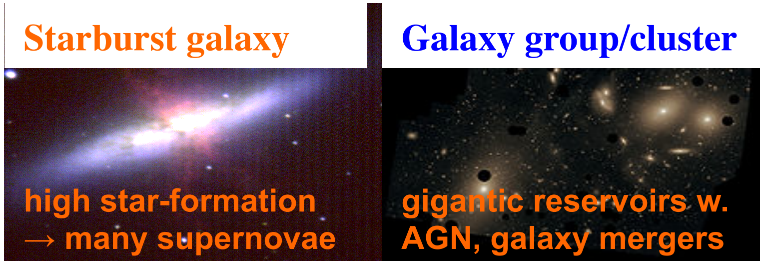


$$p + \gamma \rightarrow N\pi + X$$

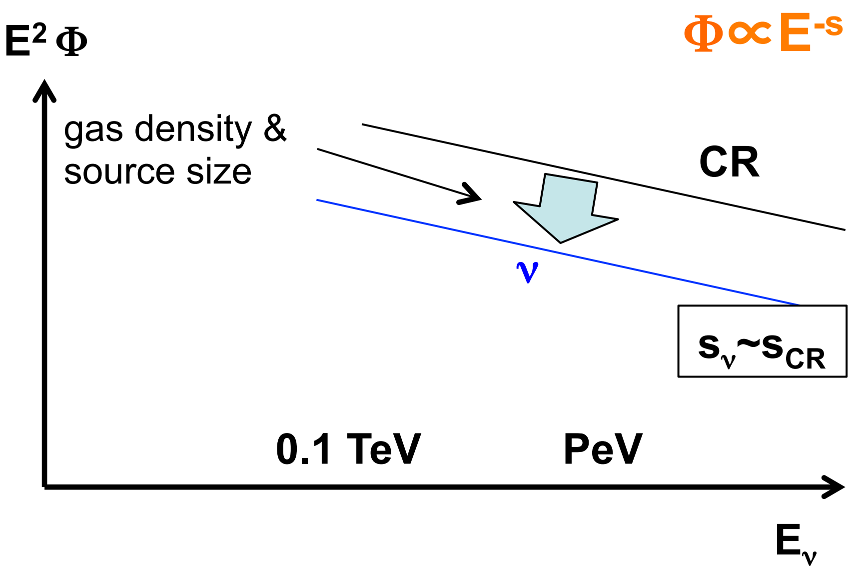


Cosmic-ray Reservoirs



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

$\Phi \propto E^{-s}$



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

Astrophysical Extragalactic Scenarios

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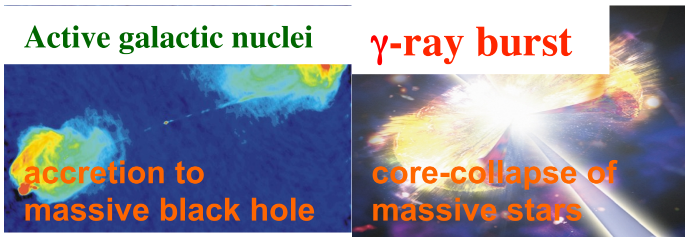
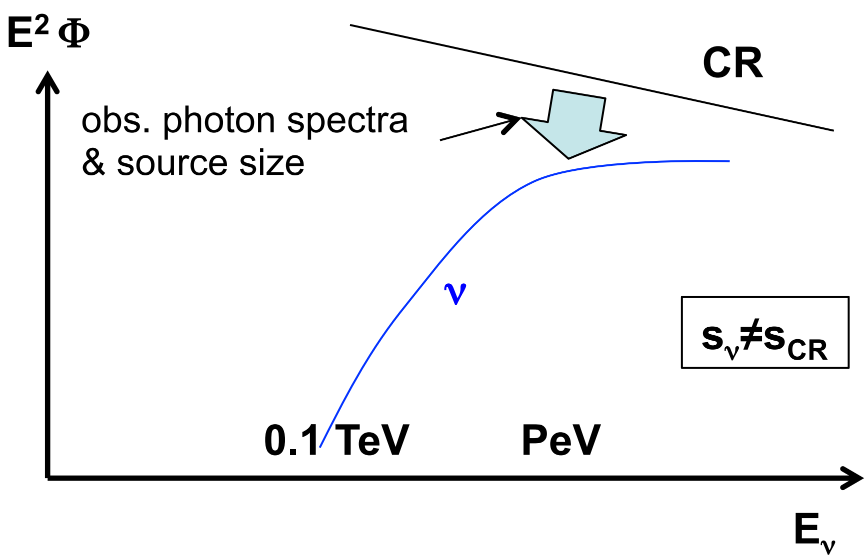
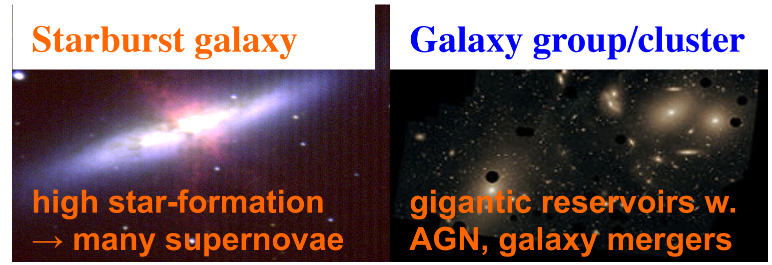
(ex. UHECR candidate sources)



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



Cosmic-ray Reservoirs



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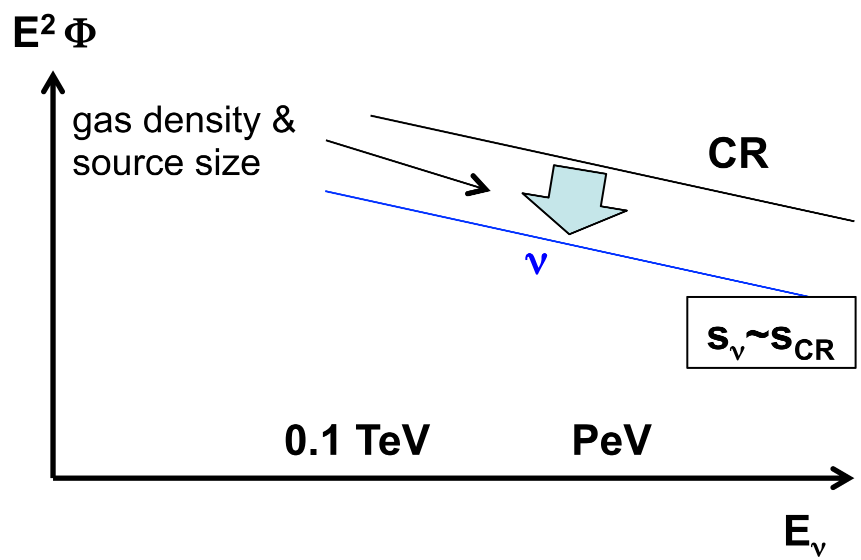
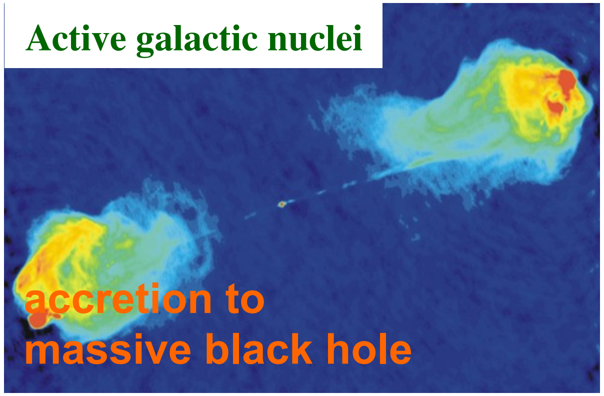
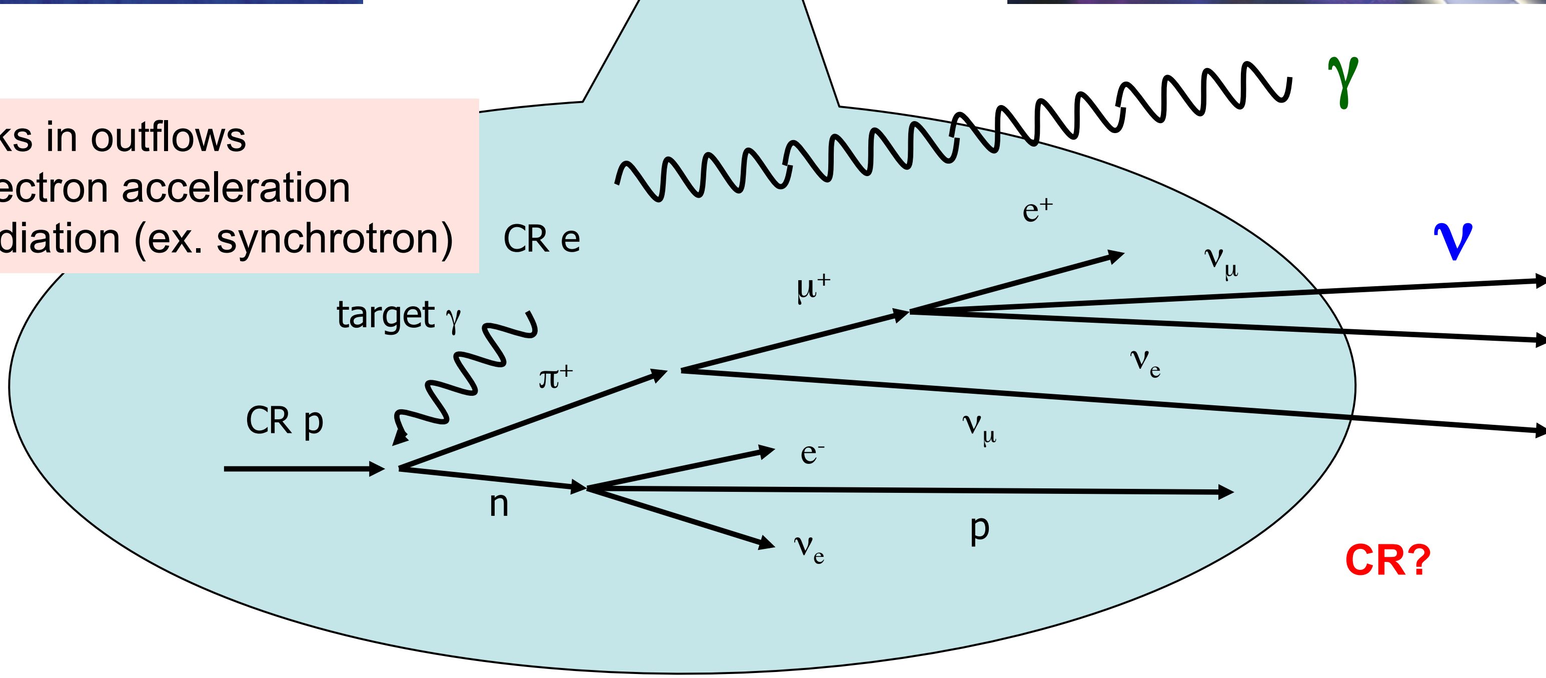


$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-Ray Accelerators





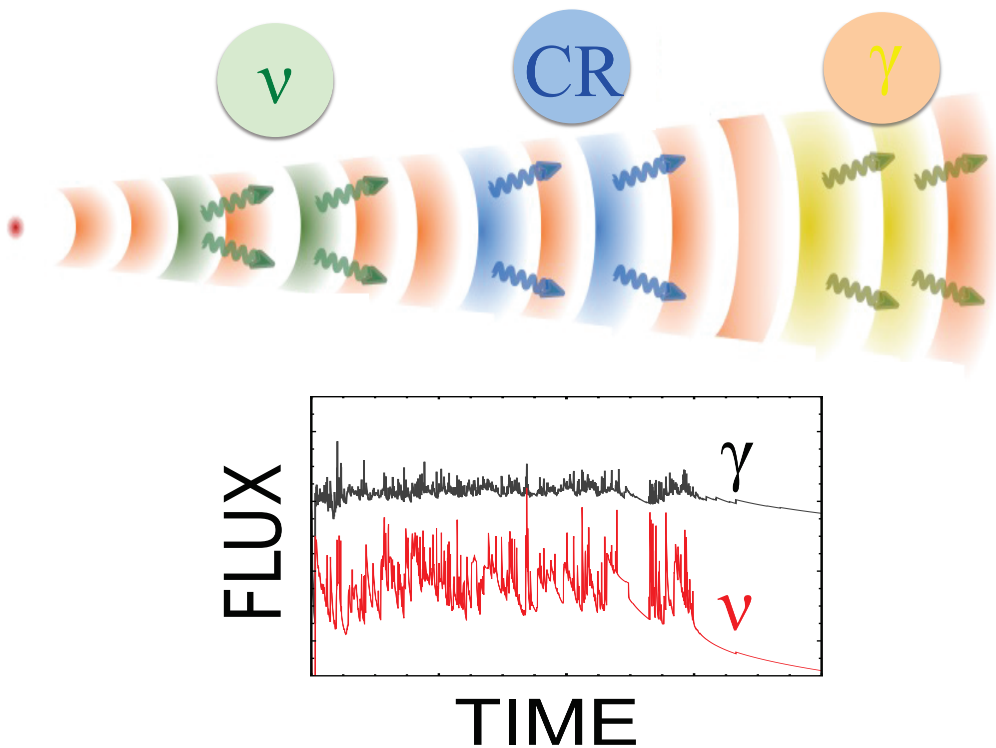
CRs may or may not escape

HE Neutrinos from Classical GRBs

Standard jet models as the cosmic ν origin: excluded by multimessenger obs.

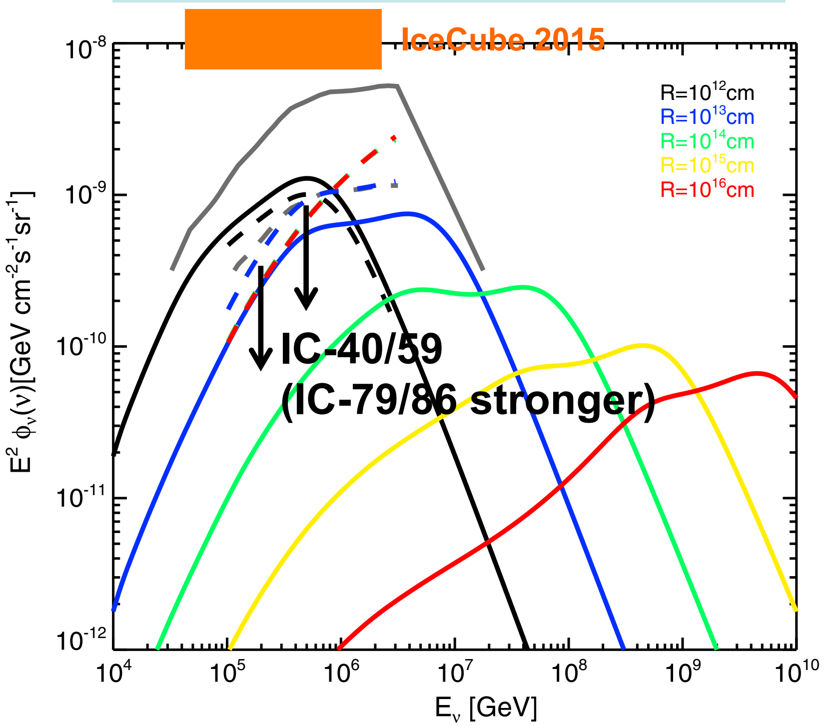
- Classical GRBs: constrained by stacking analyses **<~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}**

※ space- and time-coincidence (duration~30 s → background free)



Bustamante, Baerwald, KM, & Winter 15 Nature Comm.

Classical GRBs (prompt)

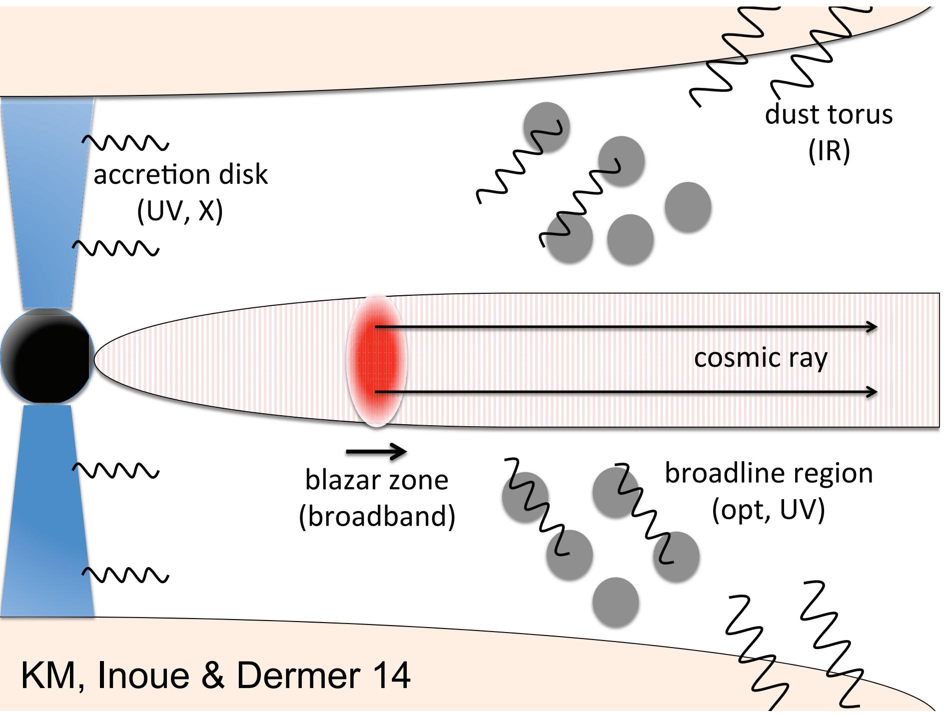


He+ KM 12 ApJ

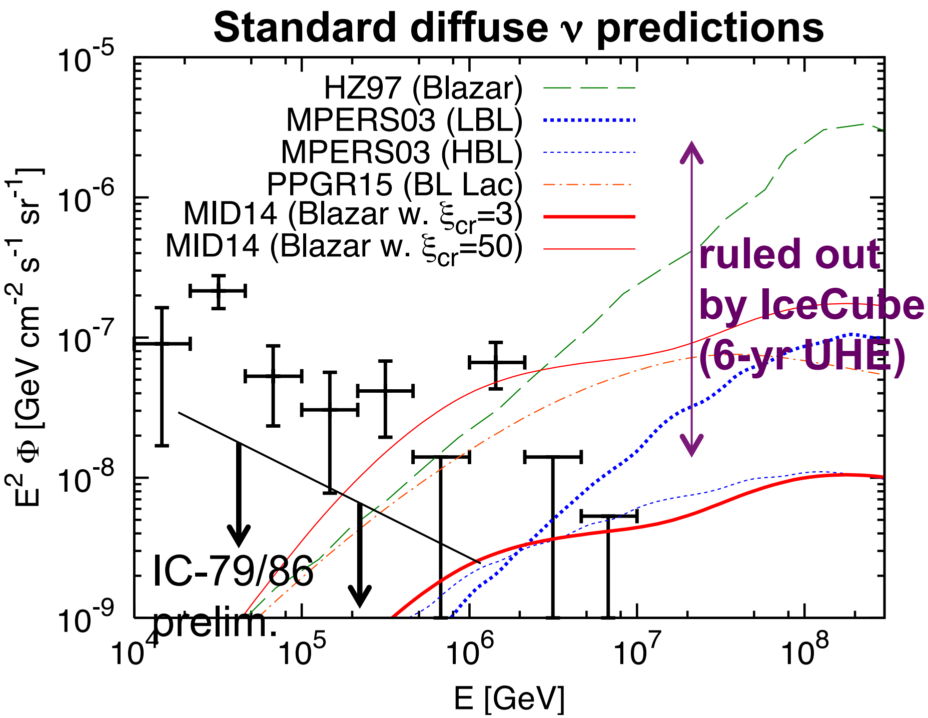
HE Neutrinos from AGN Jets

Standard jet models as the cosmic ν origin: disfavored by multimessenger obs.

- Blazars: 1. obs. SEDs (int. & ext.) → hard spectral shape (KM, Inoue & Dermer 14)
  2. no clustering (KM & Waxman 16) 3. no source association (IceCube Coll. 15)



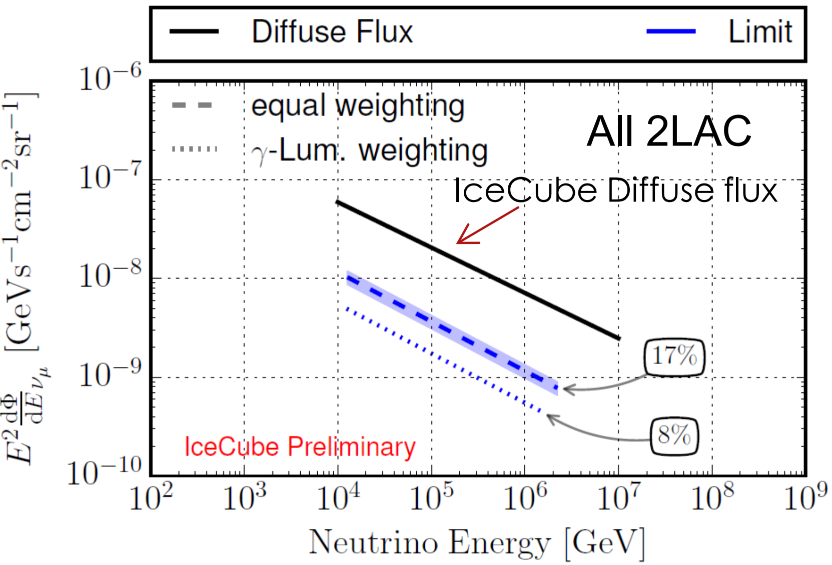
Blazars



- Very hard spectra: a general trend of one-zone models
- Many of them (including a leptonic-hadronic model) are excluded by IceCube

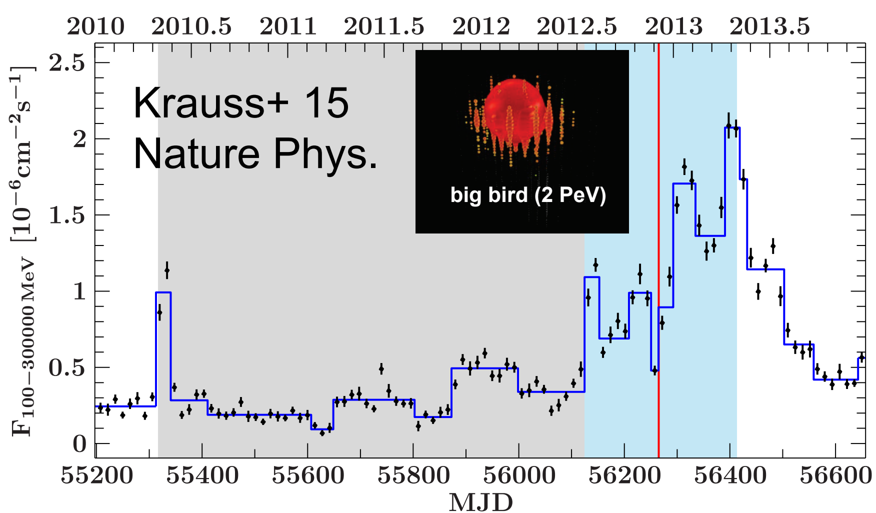
Controversy: Blazars as the Origin of IceCube's Neutrinos?

IceCube 15



NO! (IceCube 15, Wang & Li 15, KM & Waxman 16)

- Comparison w. FSRQs' γ-ray bkg. (Ajello+ 13 ApJ)
  → average ratio: L_ν/L_γ~0.1 (for all-flavor L_ν)
- Blazars are rare objects in the Universe
  L_γ/L_ν~0.1 → nearby blazars should be seen but unobserved
- Some model-dependence but quite reasonable (e.g., power-law assumption, γ-dim population of blazars)

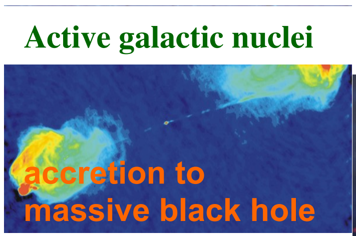


YES! (Padovani & Resconi 14, Krauss+ 15)

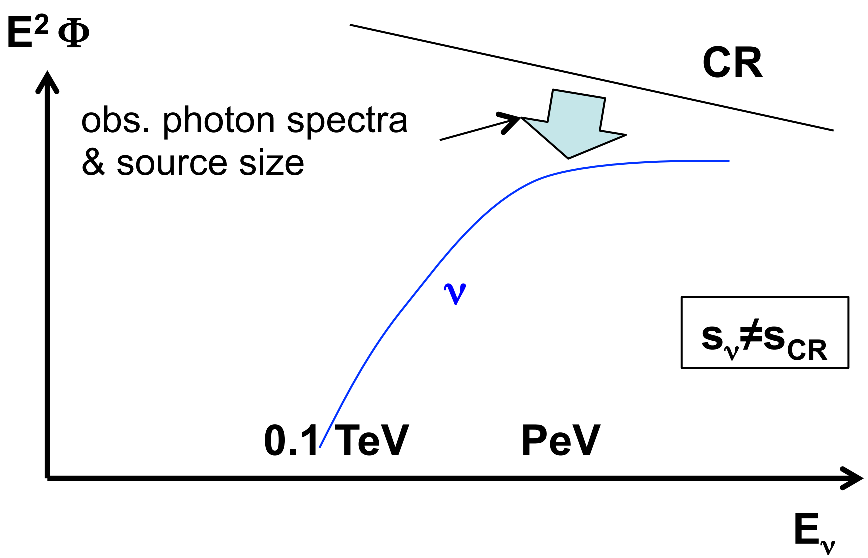
- Three PeV events may be associated with distant blazars
- Low significance
  (~2σ association of the 2 PeV event w. a FSRQ)
- Association w. a HESE event can be explained if L_γ~L_ν

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)

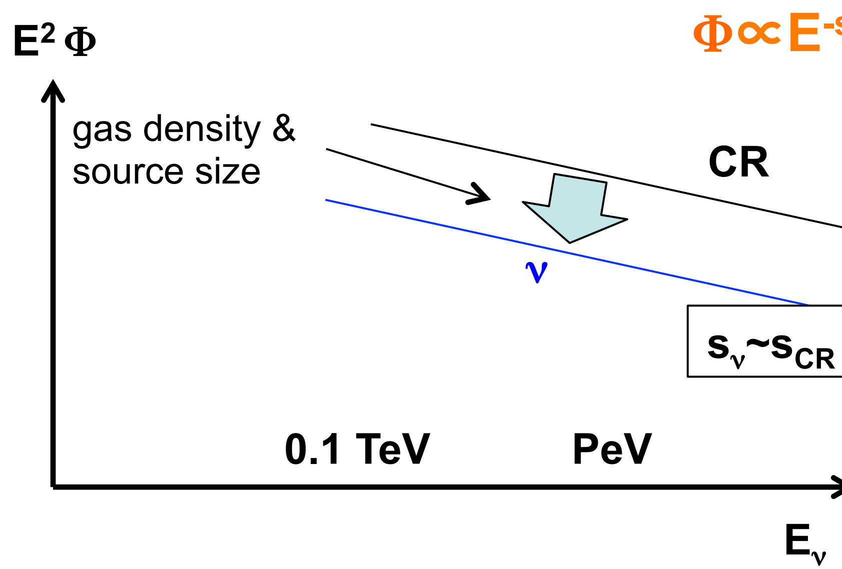


$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs

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



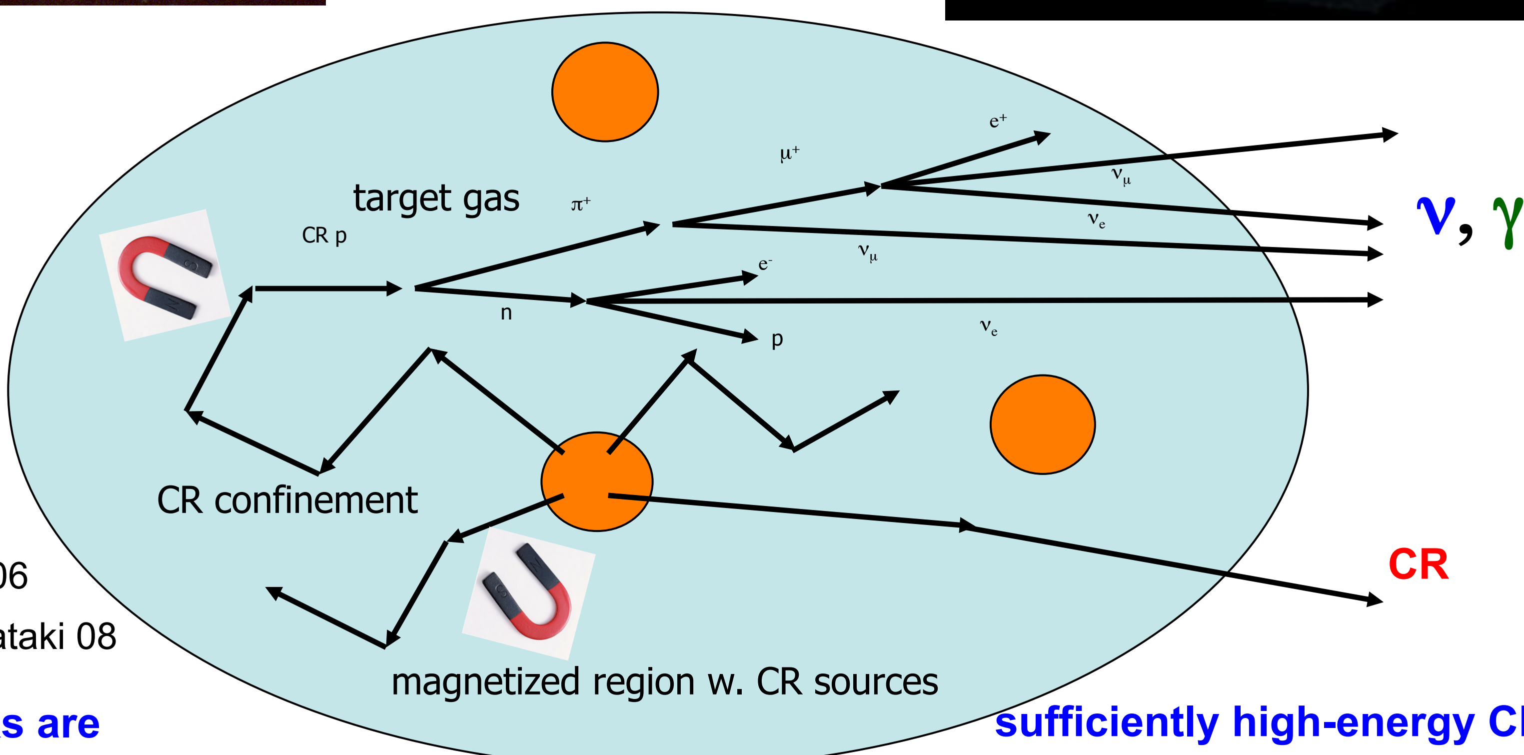
$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-Ray Reservoirs

Starburst galaxies

"cosmic-ray reservoirs"

Galaxy clusters/groups

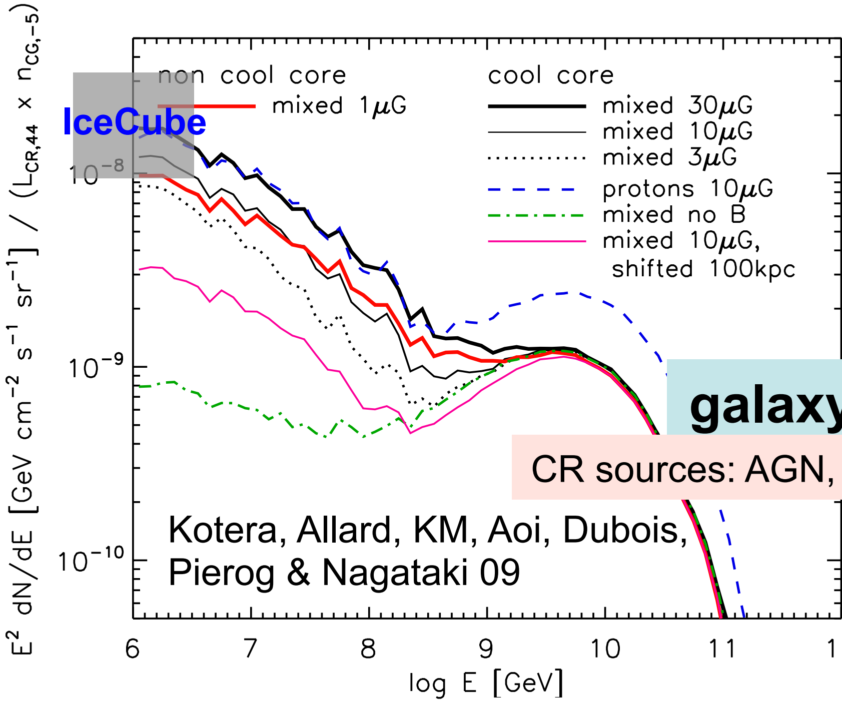


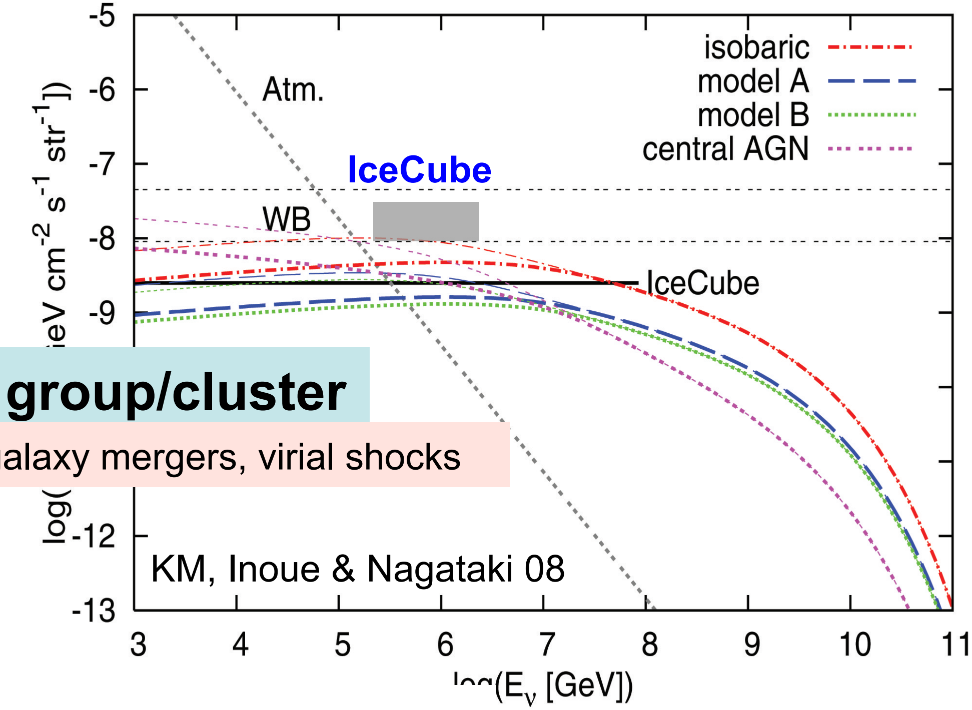
Loeb & Waxman 06

KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

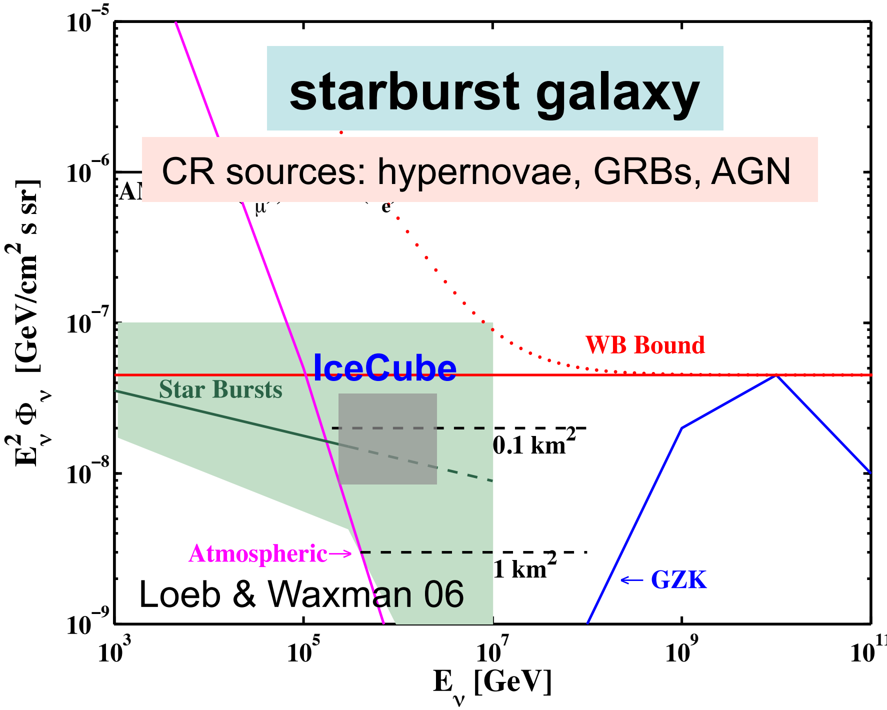
sufficiently high-energy CRs escape without interactions





galaxy group/cluster

CR sources: AGN, galaxy mergers, virial shocks

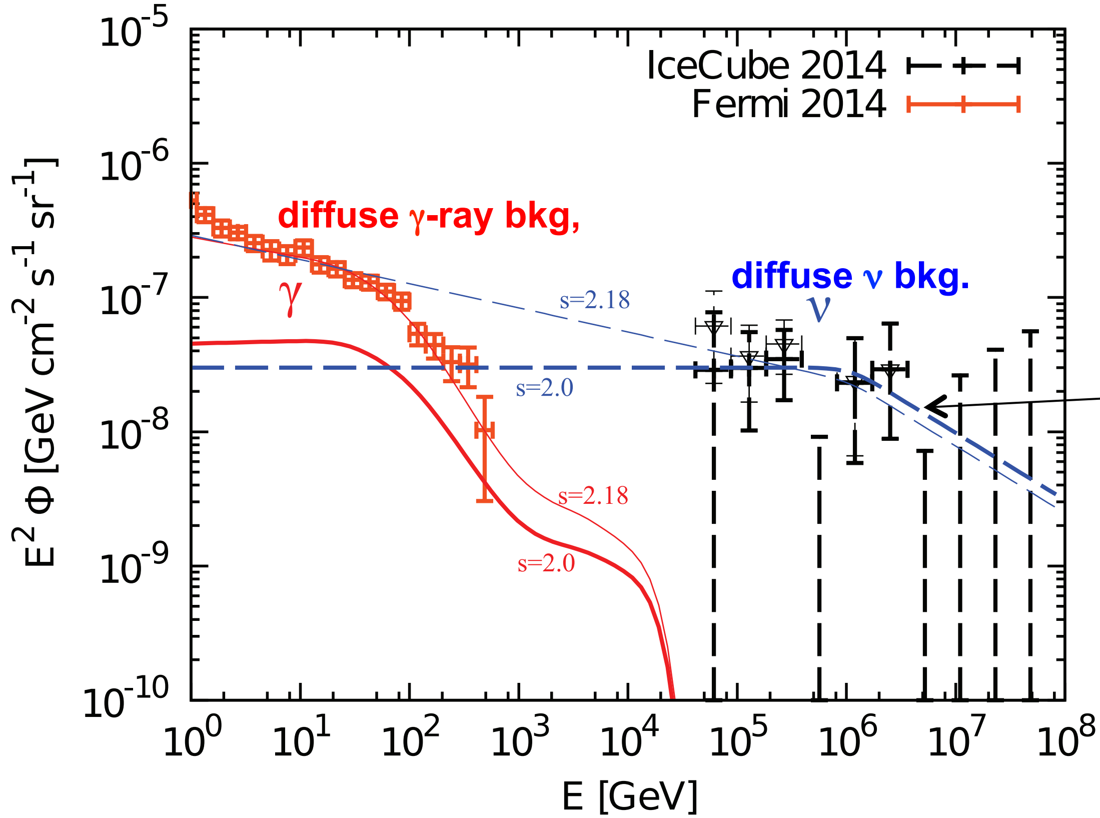


starburst galaxy

CR sources: hypernovae, GRBs, AGN

Inelastic pp Neutrinos from CR Reservoirs

- Explain >0.1 PeV ν data with a few PeV break (theoretically predicted)



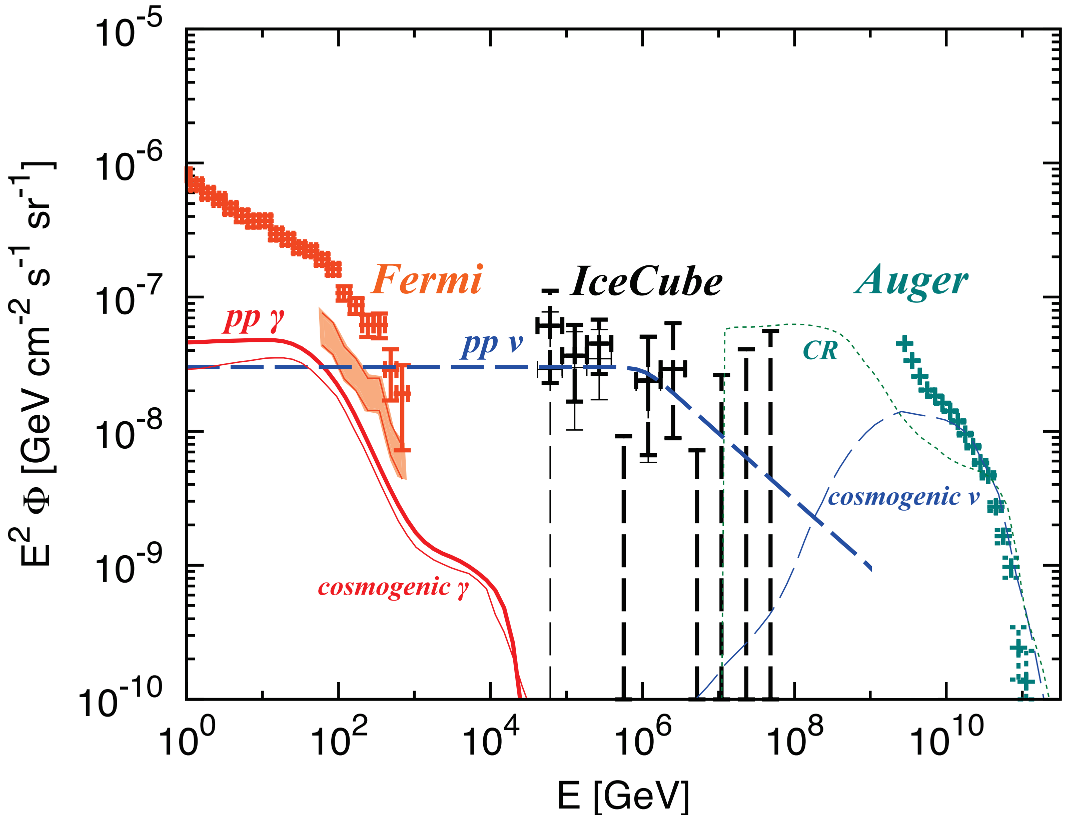
KM, Ahlers & Lacki 13 PRDR
updated @ Neutrino 2014

diffusive escape of CRs

Common origin for neutrinos and gamma rays?

Inelastic pp Neutrinos from CR Reservoirs

- Explain >0.1 PeV ν data with a few PeV break (theoretically predicted)
- Escaping CRs may contribute to the CR flux (theoretically predicted)



KM & Waxman 16
see also Katz et al. 13

Common origin for neutrinos, gamma rays & UHECRs?

How to Test?: Multi-Messenger Approach

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

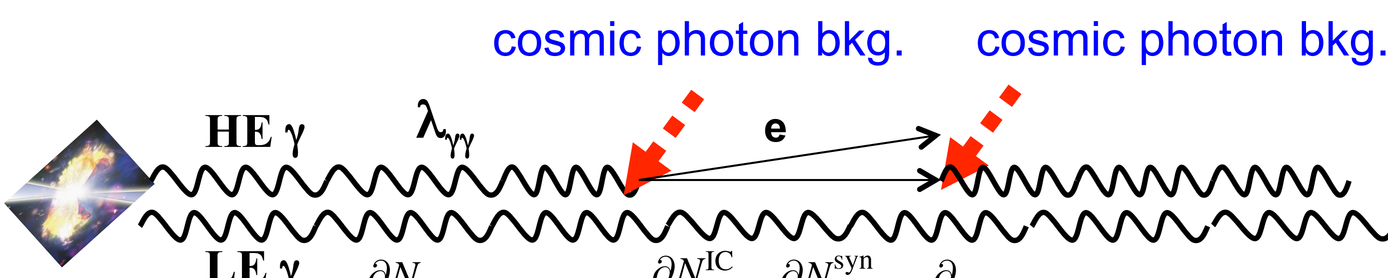
$p + \gamma \rightarrow N\pi + X$ $\pi^\pm:\pi^0 \sim 1:1$ $\rightarrow$ **$E_\gamma^2\ \Phi_\gamma \sim (4/3)\ E_\nu^2\ \Phi_\nu$**

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

>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

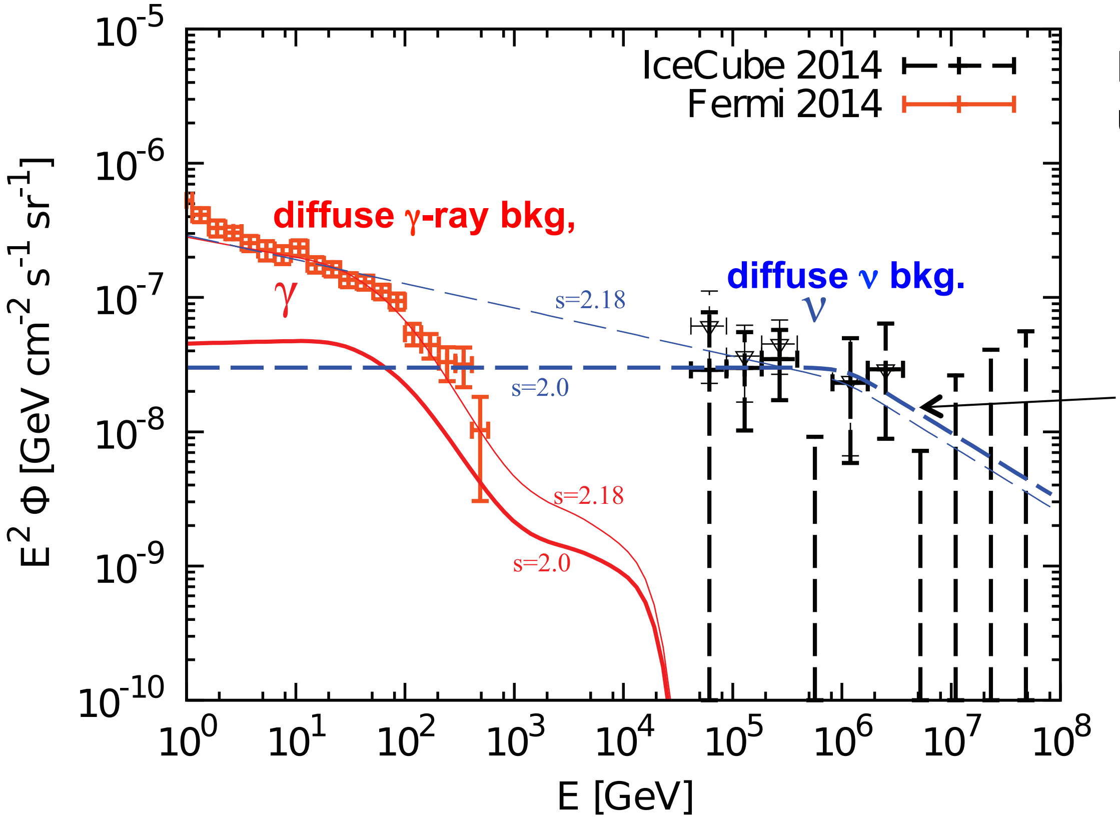
airshower detectors

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

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

Inelastic pp Neutrinos from CR Reservoirs

- Explain >0.1 PeV ν data with a few PeV break (theoretically predicted)
- Must largely contribute to diffuse γ-ray bkg. (perhaps "common" origins?)



KM, Ahlers & Lacki 13 PRDR
updated by KM 1410.3680

diffusive escape of CRs

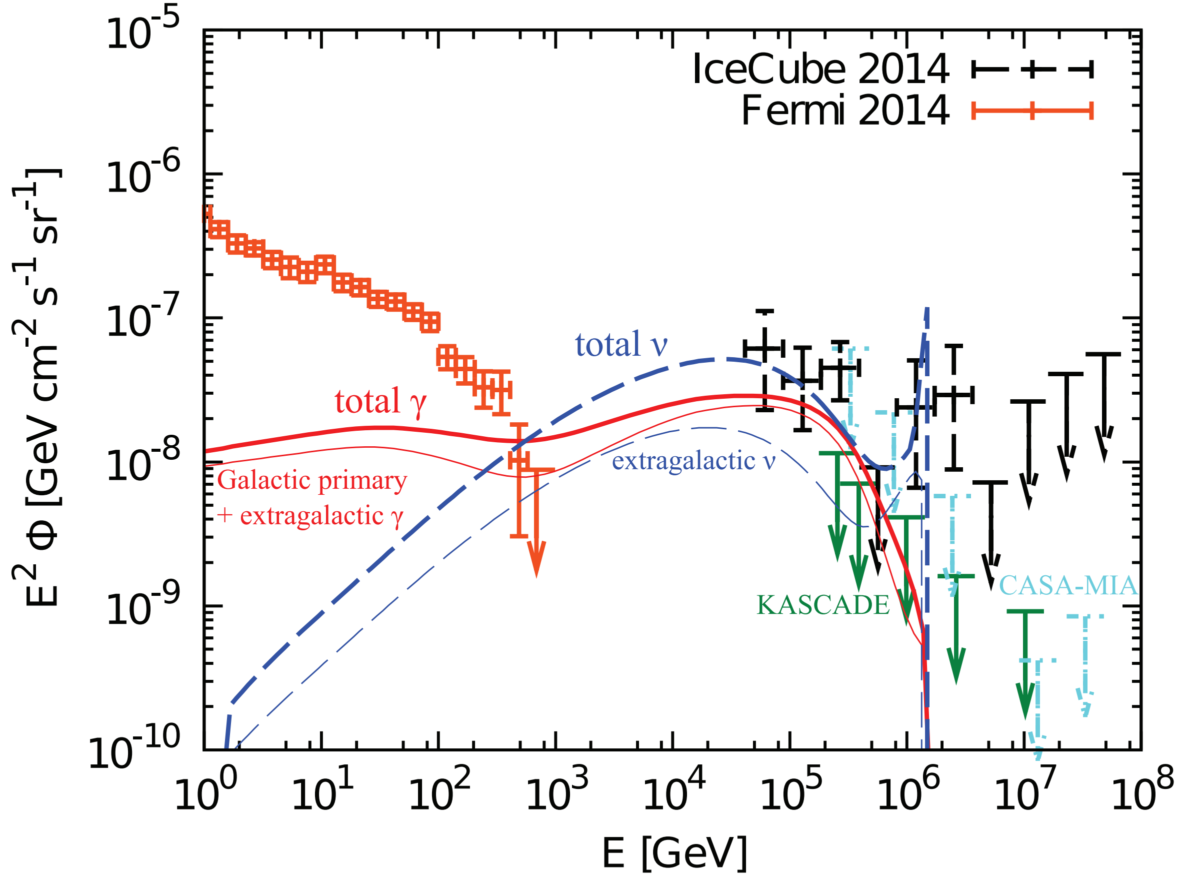
- Strong predictions: spectral index s<2.1-2.2, >30-40% to diffuse γ-ray bkg.

Proposed tests: 1. Measurements of neutrino data below 100 TeV

2. Decomposing the diffuse γ-ray bkg.

Application: Gamma Rays Challenge Dark Matter Models

Quasi-isotropic emission from the Galactic halo (e.g., DM) can be constrained



KM, Laha, Ando & Ahlers 15 PRL

ex. Feldstein et al. 13,
Esmaili & Serpico 13,
Higaki+ 14, Fong+ 15,
Bai+ 14, Rott+ 15

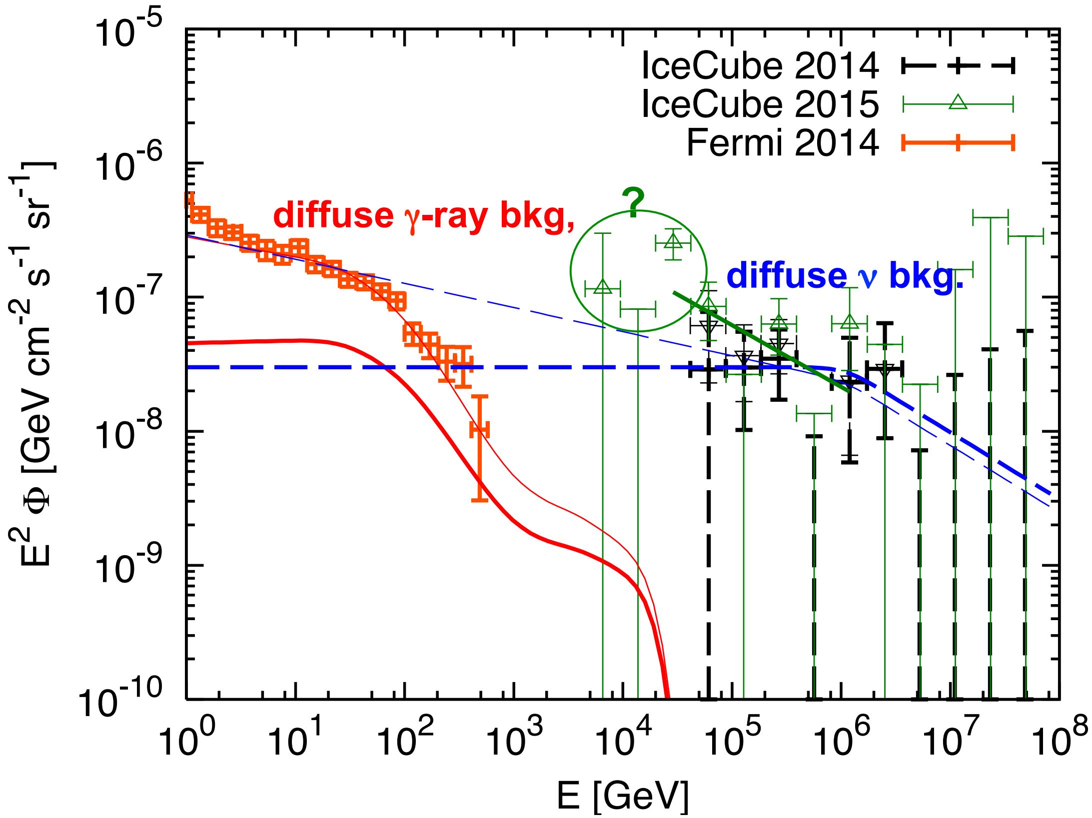
DM → $\nu_e + \bar{\nu}_e$ (12%)
DM → $b + \bar{b}$ (88%)

(similar results in other models that are proposed)

- Galactic: γ → direct (w. some attenuation), $e^{\pm}$ → sync. + inv. Compton
- Extragalactic → EM cascades during cosmological propagation

Inelastic pp Neutrinos from CR Reservoirs

- Explain >0.1 PeV ν data with a few PeV break (theoretically predicted)
- Must largely contribute to diffuse γ-ray bkg. (perhaps "common" origins?)

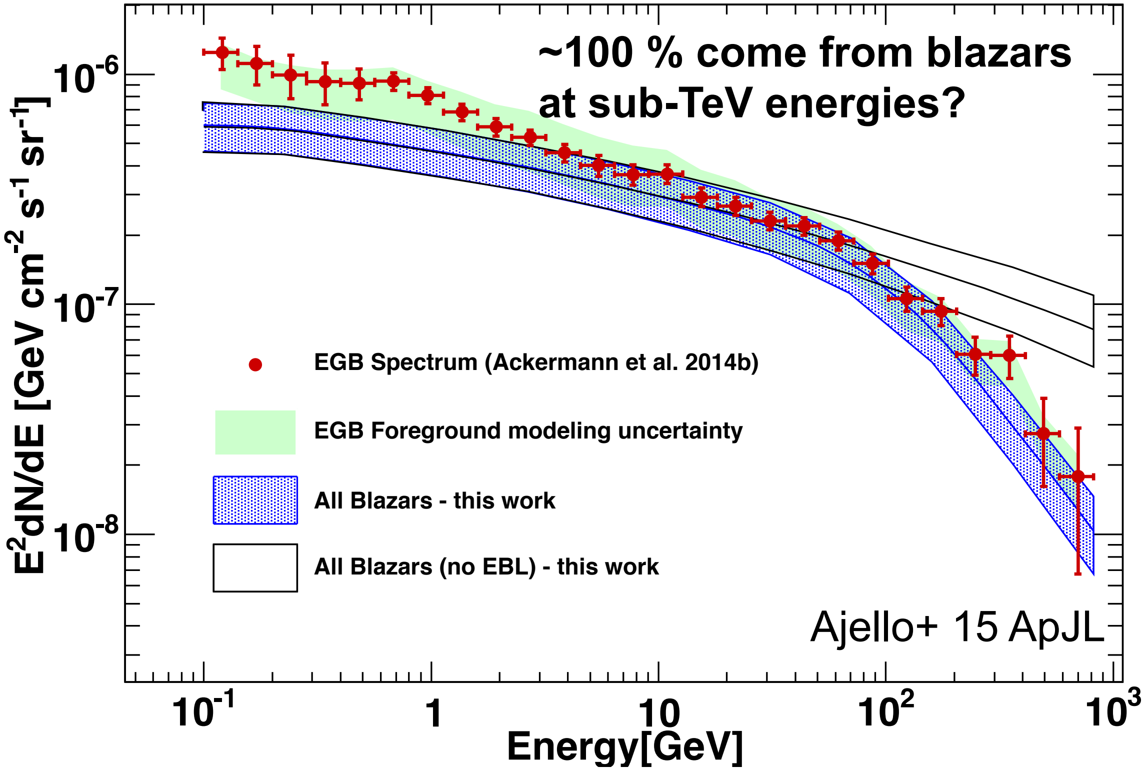


KM, Ahlers & Lacki 13 PRDR
updated by KM 1410.3680

- Strong predictions: spectral index s<2.1-2.2, >30-40% to diffuse γ-ray bkg.
- If steep (s~2.5)→ ruling out a single origin & another component is required
  pγ sources (KM & Ioka 13 PRL, Kimura, KM & Toma 15 ApJ), Galactic (Ahlers & KM 14 PRD)

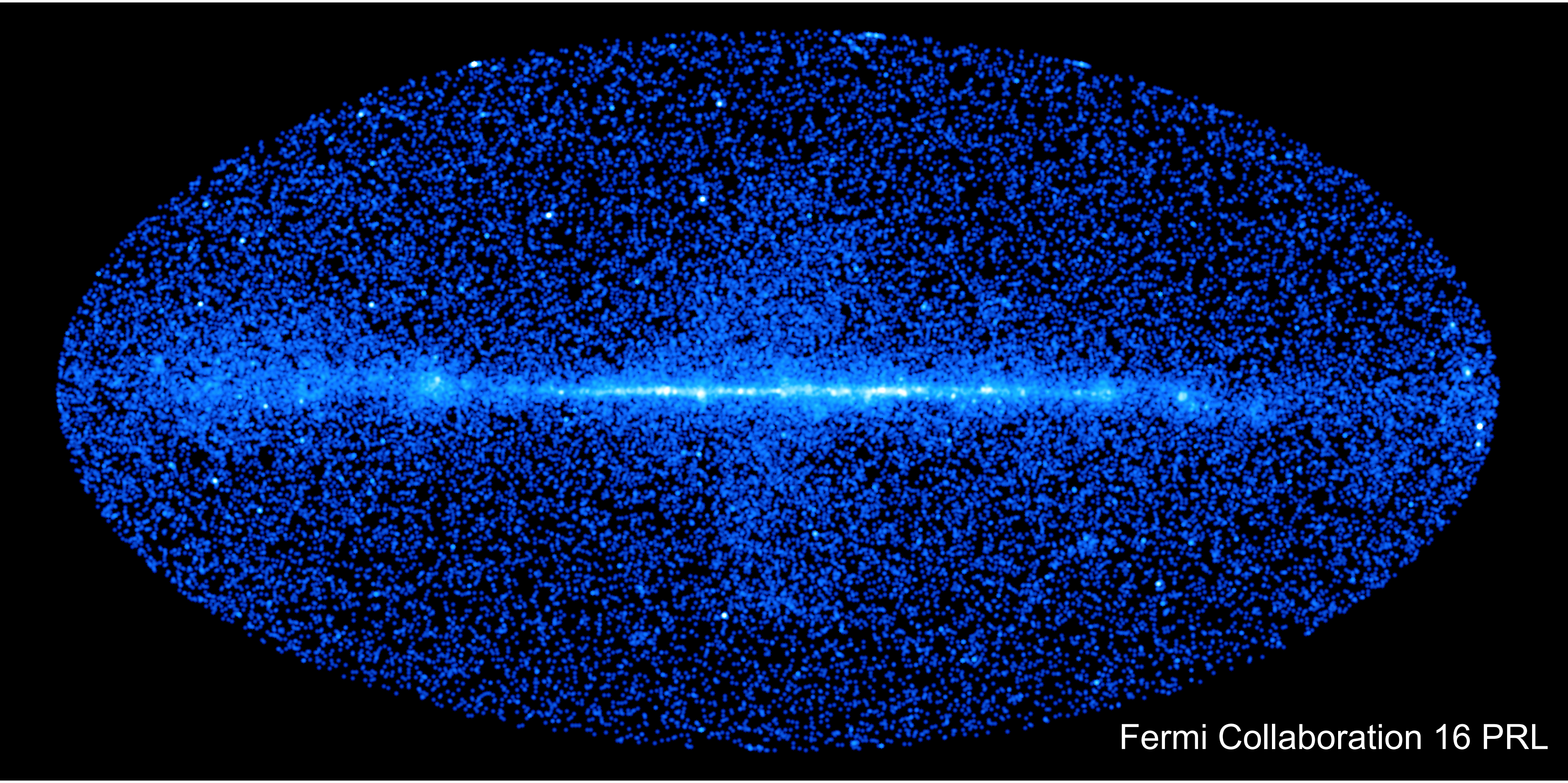
Implications of Detailed Gamma-Ray Studies

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



Be cautious but
If >50% come from blazars → **tighter constraints: s<2.0-2.1**
If >60-70% come from blazars → **insufficient room for pp scenarios!**

Implications of Detailed Gamma-Ray Studies



Photon fluctuation analyses (Poisson term of angular power spectra)

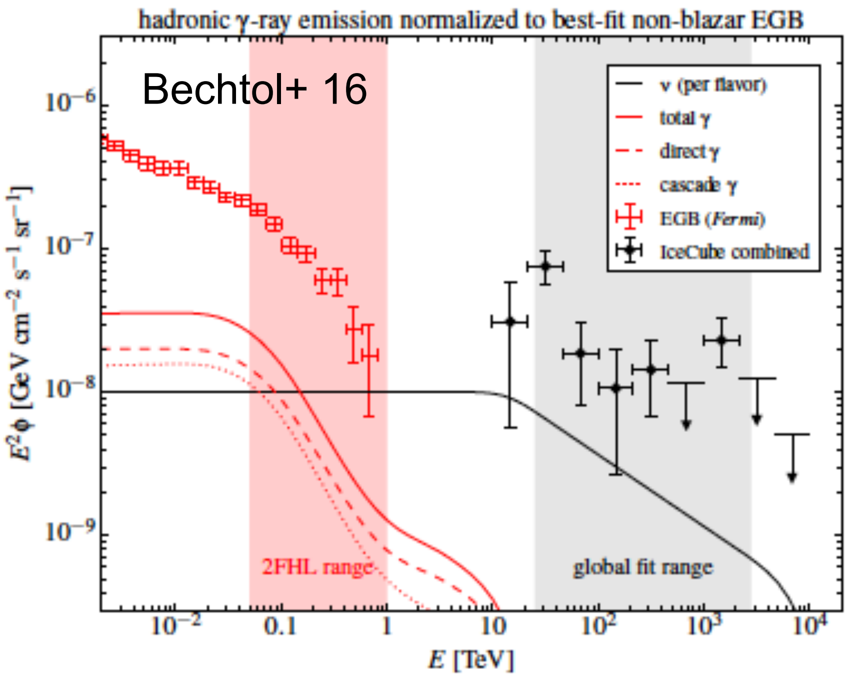
$$C_P = \int_0^{S_{\max}} (1 - \omega(S'))\, S'^2 \frac{dN}{dS'} dS' [(\mathrm{ph\ cm^{-2}\ s^{-1}})^2 \mathrm{sr}^{-1}]$$

Non-blazar contribution < 14±14%

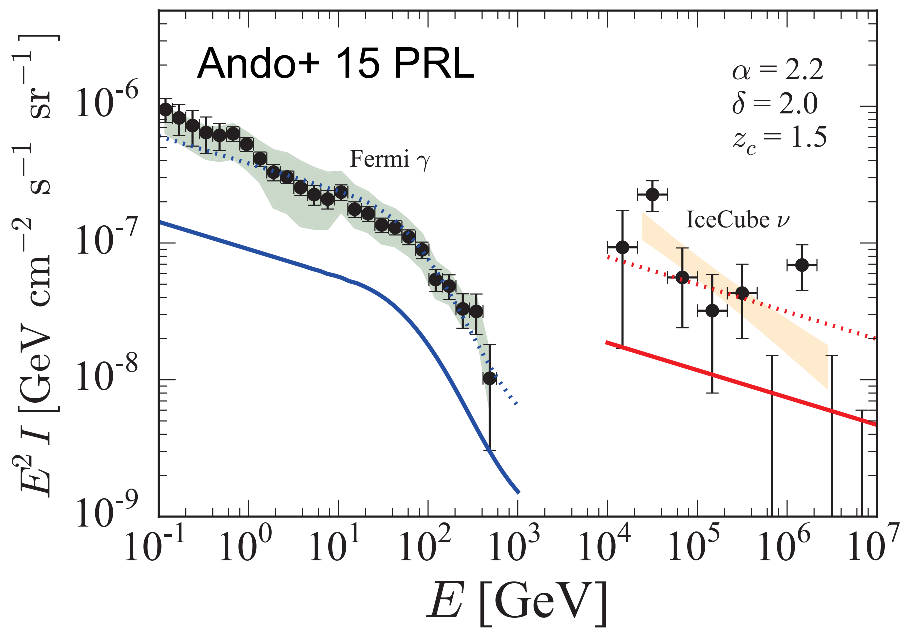
Implications of Detailed Gamma-Ray Studies

The proposed tests for pp scenarios have been done

shot-noise in diffuse γ-ray bkg.



cross corr. between galaxy catalogues



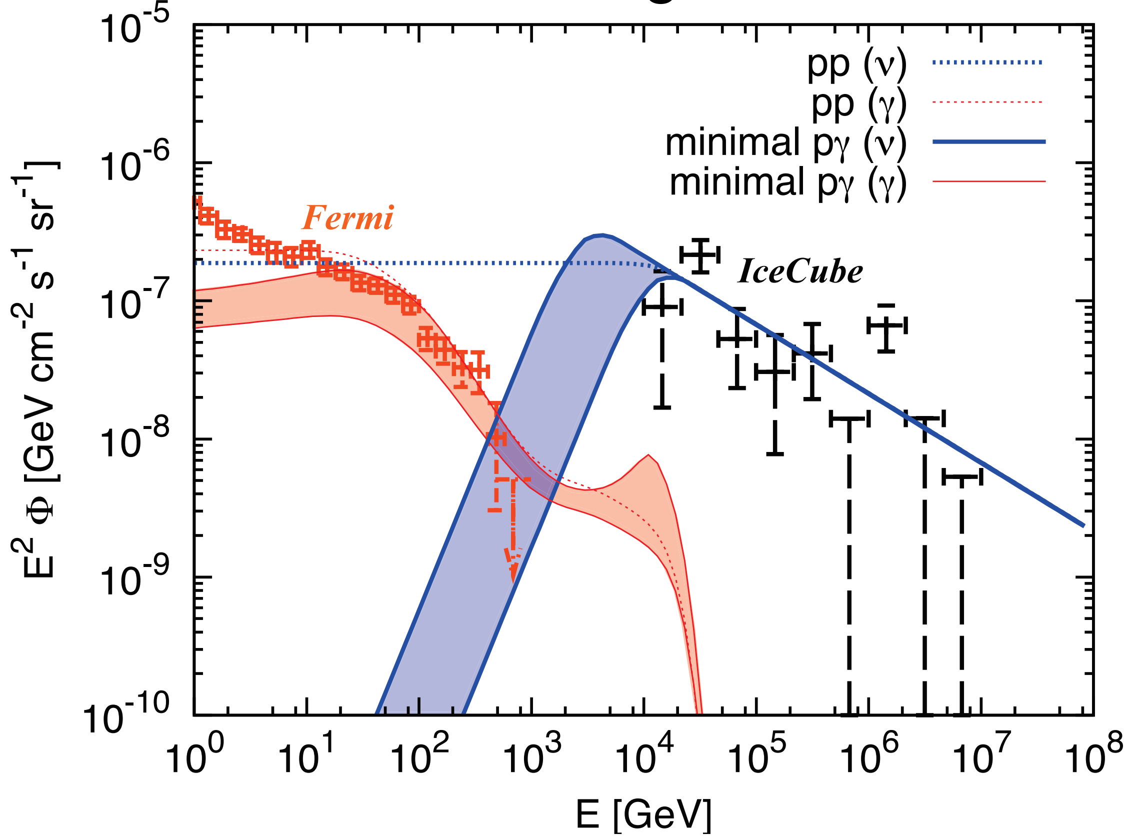
Given that IceCube's data above 100 TeV are explained…

Decomposition of extragalactic γ-ray bkg. gives tighter limits: s<2.0-2.1

Insufficient room for pp scenarios to explain the 10-100 TeV neutrino data

Two Components?: Low-Energy "Excess" Problem

- Best-fit spectral indices tend to be as soft as s~2.5
- 10−100 TeV data: large fluxes of $\sim 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}



KM, Guetta & Ahlers 16 PRL

$$\varepsilon_\nu Q_{\varepsilon_\nu} \propto \begin{cases} \varepsilon_\nu^{2-s} & (\varepsilon_\nu \le \varepsilon_\nu^b) \\ \varepsilon_\nu^{2-s'} & (\varepsilon_\nu^b < \varepsilon_\nu) \end{cases} \quad (pp)$$

$$\varepsilon_\nu Q_{\varepsilon_\nu} \propto \begin{cases} \varepsilon_\nu^{2} & (\varepsilon_\nu \le \varepsilon_\nu^b) \\ \varepsilon_\nu^{2-s'} & (\varepsilon_\nu^b < \varepsilon_\nu) \end{cases} \quad (\text{minimal } p\gamma)$$

minimum pγ:
~30 TeV is just around energy due to the pion production threshold

- If γ-ray transparent → strong tensions w. diffuse γ-ray bkg. for both pp & pγ

pp → ~100% of diffuse γ-ray bkg. even w. s~2.0
minimal pγ → >50% diffuse γ-ray bkg. (via EM cascades)

contrary to standard AGN interpretation!

$p\gamma/\gamma\gamma$ Optical Depth Correspondence

- $\gamma\gamma \rightarrow e^+e^-$: unavoidable in **$p\gamma$ sources** (ex. GRBs, AGN)

- **Same target photons prevent γ-ray escape**

$$f_{p\gamma} \approx n_\gamma \sigma_{p\gamma}^{\rm eff} \Delta$$
$$\tau_{\gamma\gamma} \approx n_\gamma (0.1\sigma_T) \Delta$$

$$\Rightarrow \quad \tau_{\gamma\gamma} \approx \frac{0.1\sigma_{\gamma\gamma}}{\sigma_{p\gamma}^{\rm eff}} f_{p\gamma} \sim 1000 f_{p\gamma}$$

$$\varepsilon_p \approx 20\varepsilon_\nu \approx 0.5\Gamma^2 m_p c^2 \bar{\varepsilon}_\Delta {\varepsilon_t}^{-1}$$
$$\varepsilon_\gamma \approx \Gamma^2 m_e^2 c^4 {\varepsilon_t}^{-1}$$

$$\Rightarrow \quad \varepsilon_\gamma^c \approx \frac{2m_e^2c^2}{m_p\bar{\varepsilon}_\Delta}\varepsilon_p \sim {\rm GeV} \left(\frac{\varepsilon_\nu}{25\ {\rm TeV}}\right)$$

30 TeV-3 PeV ν constrains 1-100 GeV γ

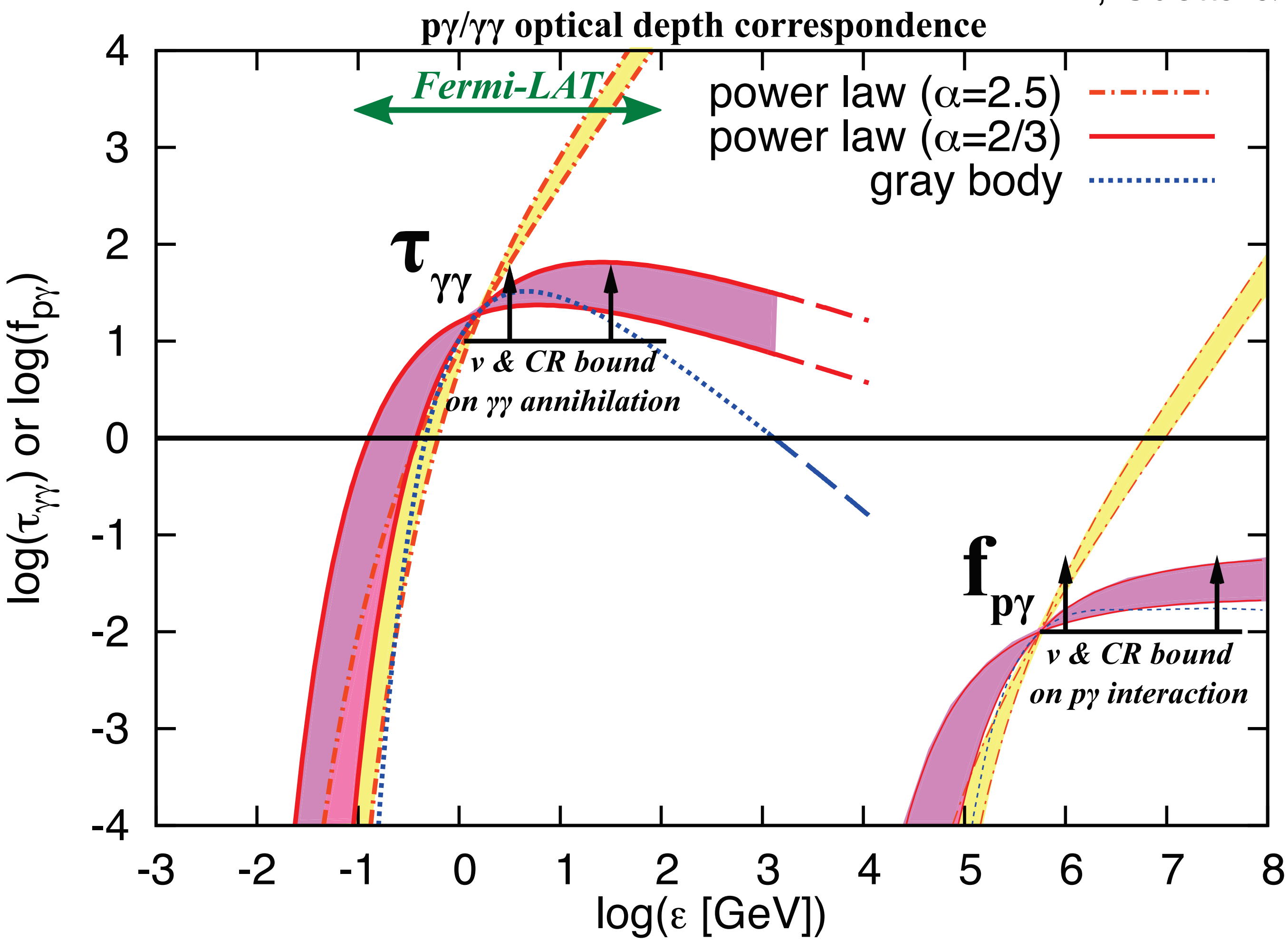
- Neutrino production efficiency $f_{p\gamma}$ cannot be too small

1. $f_{p\gamma}$ << 1 unnatural (requiring fine tuning), Do not overshoot the observed CR flux
2. Comparison w. non-thermal energy budgets of known objects (galaxies, AGN, cluster shocks etc.)

$$\Rightarrow \quad f_{p\gamma} \gtrsim 0.01 \quad \Rightarrow \quad \tau_{\gamma\gamma} \gtrsim 10$$

Indication of Gamma-Ray Dark Cosmic-Ray Accelerators

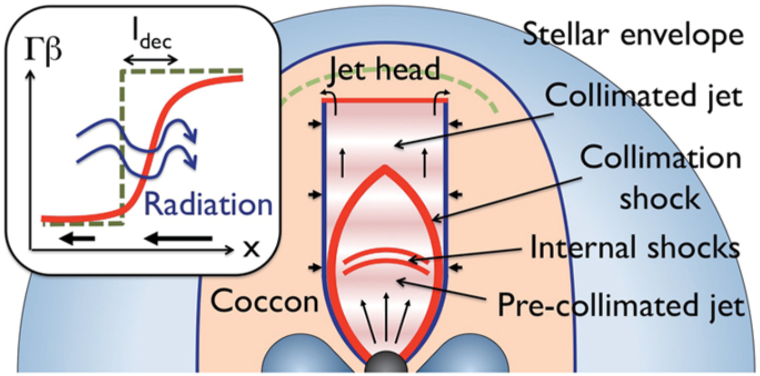
KM, Guetta & Ahlers 16 PRL

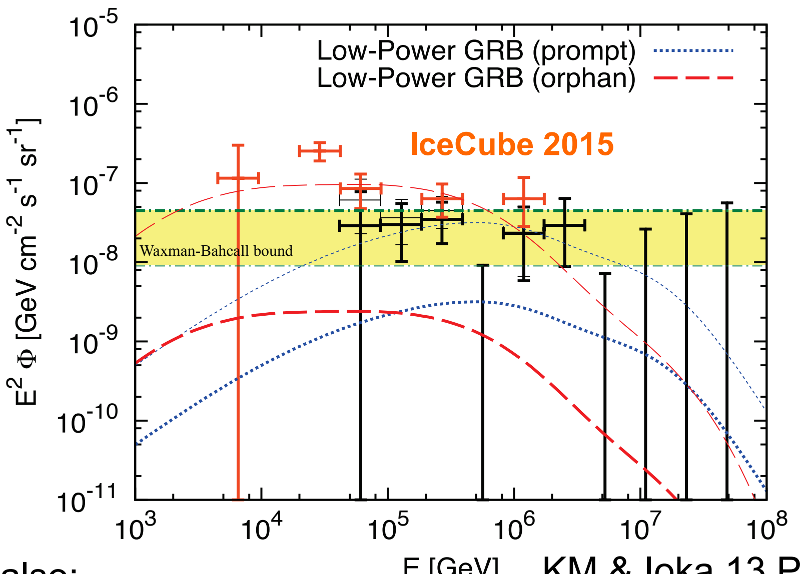


- Bounds on $\tau_{\gamma\gamma}$ hold for both thermal and nonthermal photon targets
- $p\gamma$ mechanism: ν sources should naturally be obscured in GeV-TeV γ rays

GRBs and AGN as Hidden Neutrino Factories?

Low-power GRBs (choked jets)

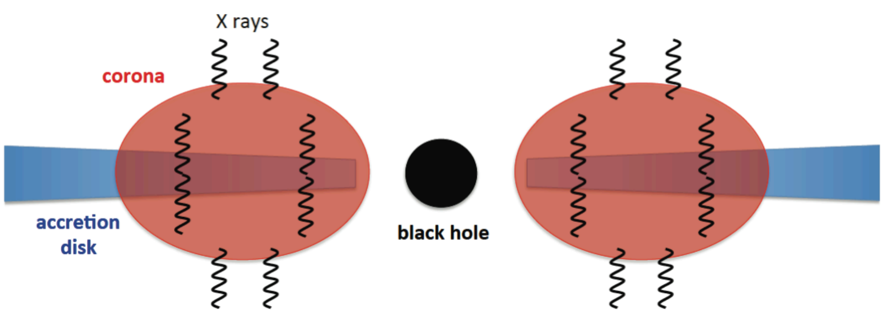


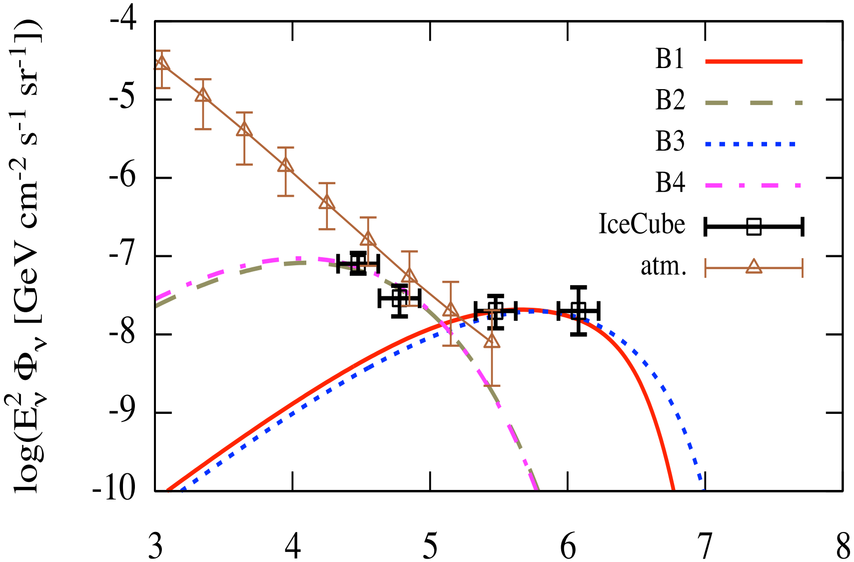


see also:
Bhattacharya+ 15
Nakar 15

KM & Ioka 13 PRL
Senno+ 15
cf. KM+ 06 ApJL

Supermassive blackhole cores

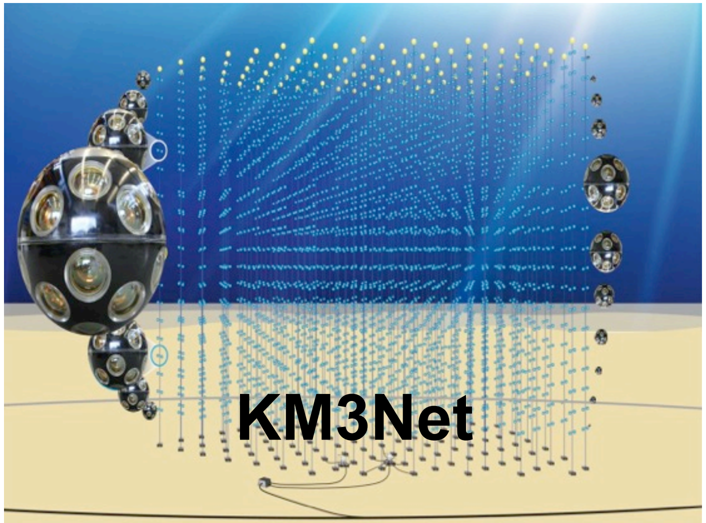


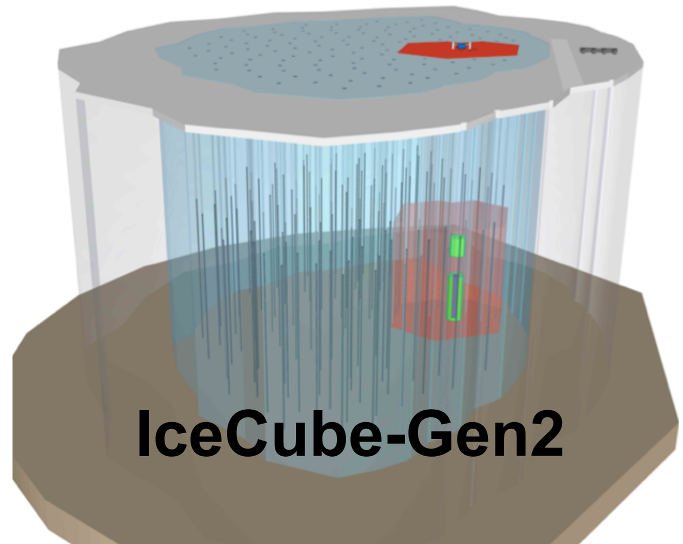


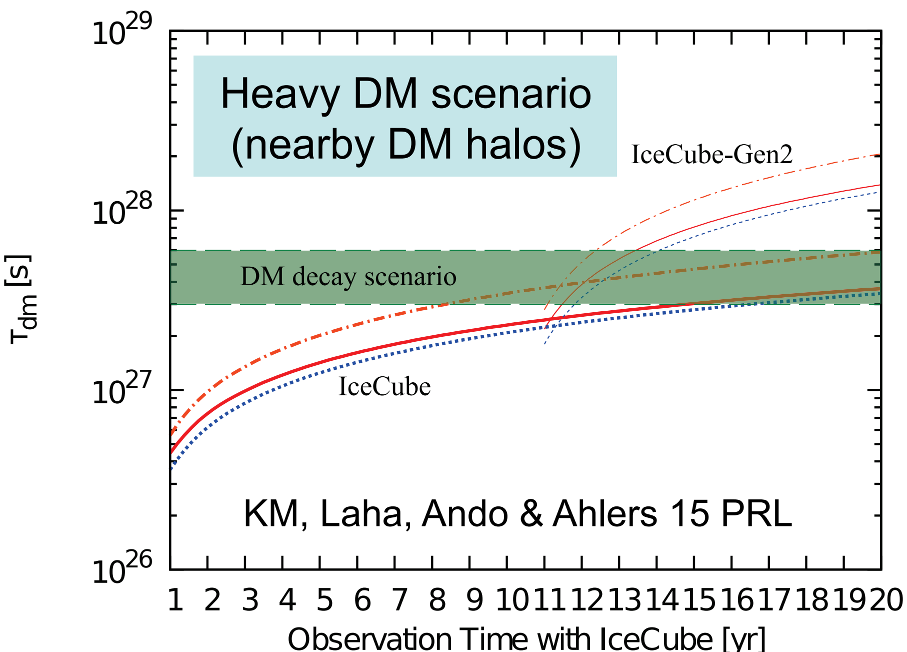
see also:
Stecker 13
Kalashev+ 15

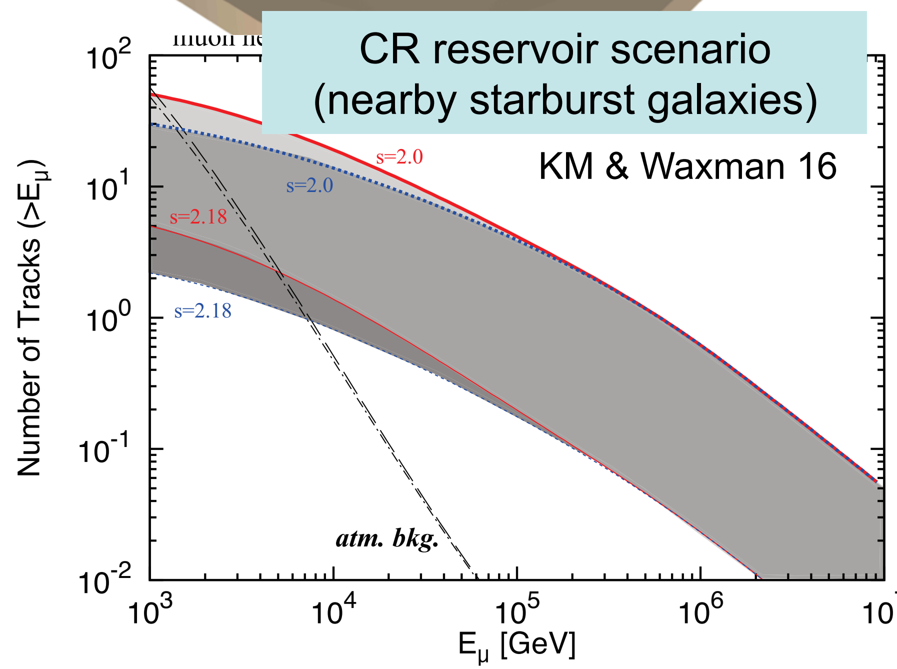
Kimura, KM & Toma 15 ApJ

What's Next?: Need to Detect Individudal Sources









Summary

What is the origin of cosmic ν signals?

mostly isotropic & diffuse TeV-PeV γ-ray limits → extragalactic component
pp scenarios: theoretical predictions & may consistently explain the CR data
s<2.1-2.2 & >30% to the diffuse sub-TeV γ-ray bkg.
pγ scenarios: classical GRBs & blazars (most powerful jets) are subdominant
(although they can still be the sources of UHECRs)
dim CR accelerators (ex. low-power GRBs/AGN cores) allowed

LE excess: atm. bkg.? magical combination w. Gal. comp.? or something new?
pp scenarios: strong tensions w. detailed studies of the diffuse γ-ray bkg.
pγ scenarios: natural in hidden CR accelerators (ex. low-power GRBs/AGN)
Are cosmic-ray connections coincident?

Toward identifying individual sources

- IceCube-Gen2: almost all (reasonable) models can be tested
- Gal. sources: ν_μ search by KM3Net & sub-PeV γ in the Southern Hemisphere
- X-ray/soft γ-ray detectors for hidden sources, UHE (>10 PeV) ν searches

Appendix

Galactic Contributions?

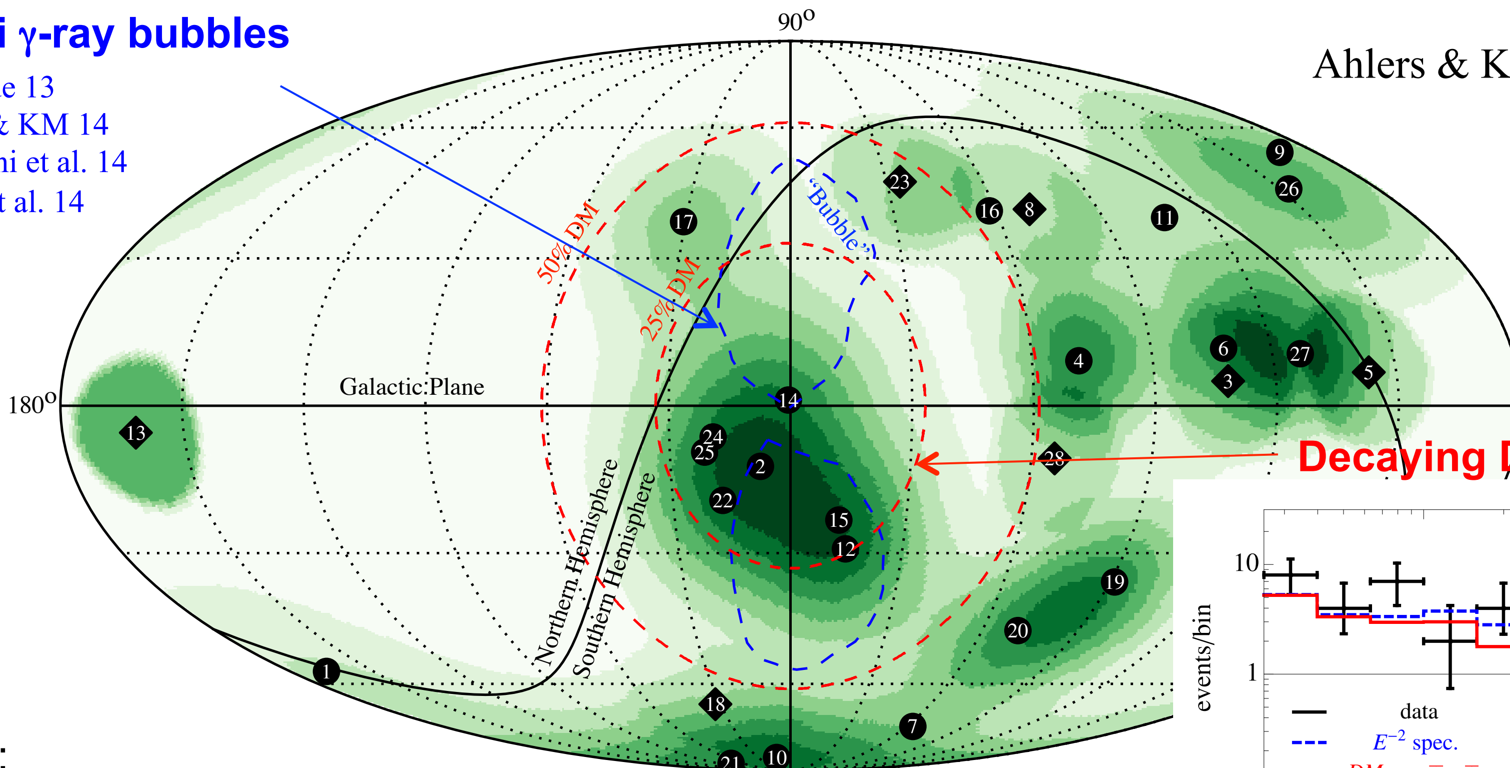
So far, more papers about Galactic sources

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

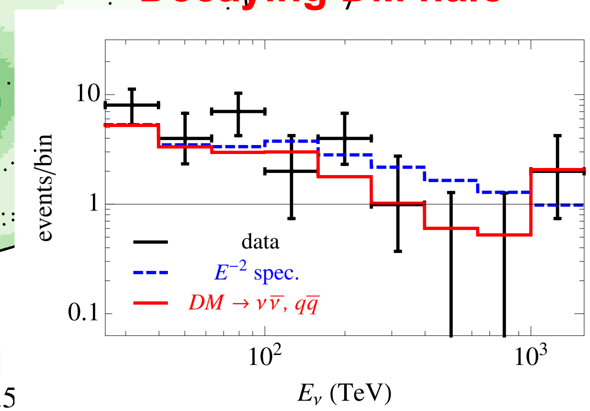
Fermi γ-ray bubbles

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

Ahlers & KM 14 PRD



Decaying DM halo



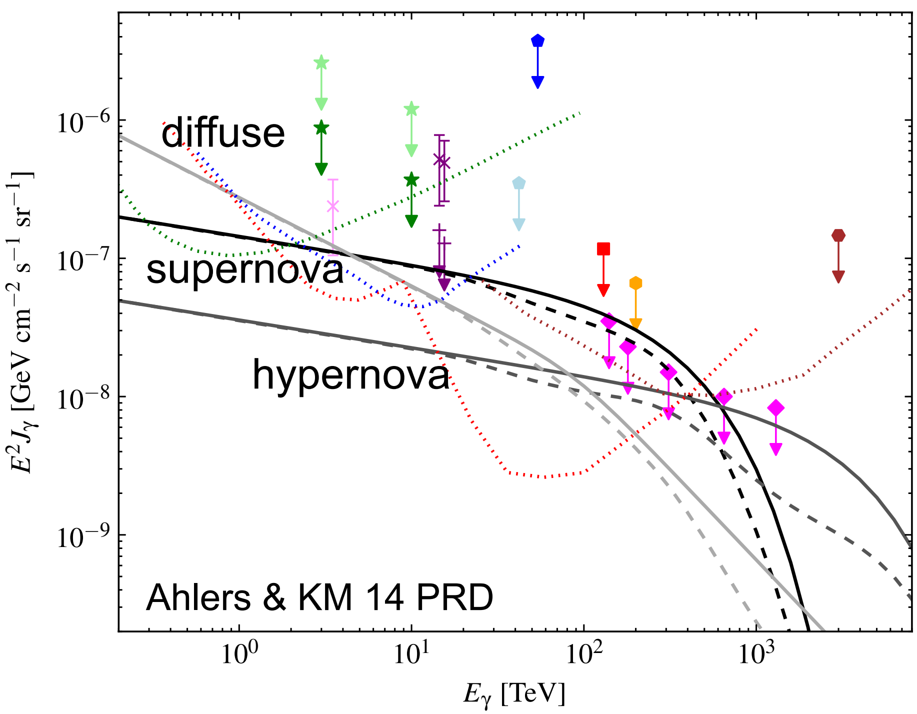
KM & Beacom 12, Feldstein et al. 13,
Esmaili & Serpico 13, Bai et al. 14

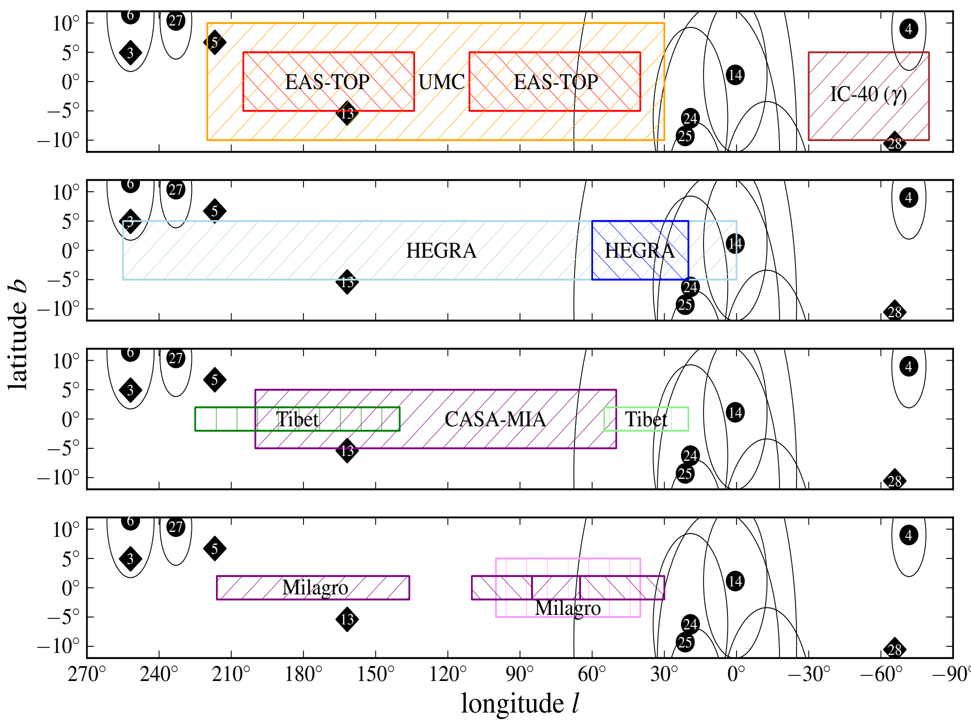
Others:
Galactic CR halo
Unidentified γ-ray sources
Galactic plane
Local spiral arms…

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

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

Galactic Plane (ex. diffuse Galactic cosmic rays, supernova remnants, SF regions)





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

Secret Neutrino Interactions

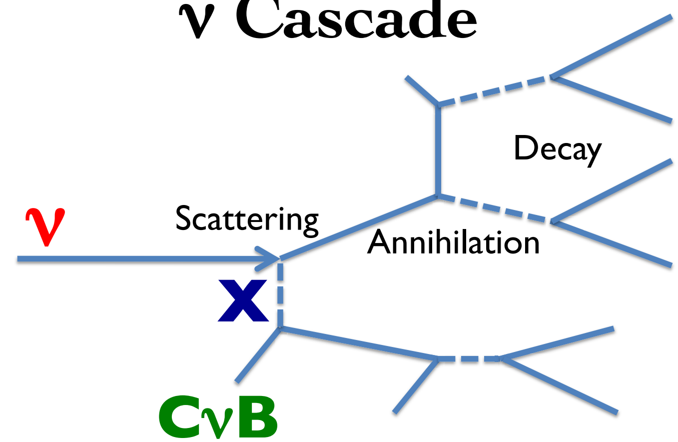
Majorna neutrino self-interactions via a scalar

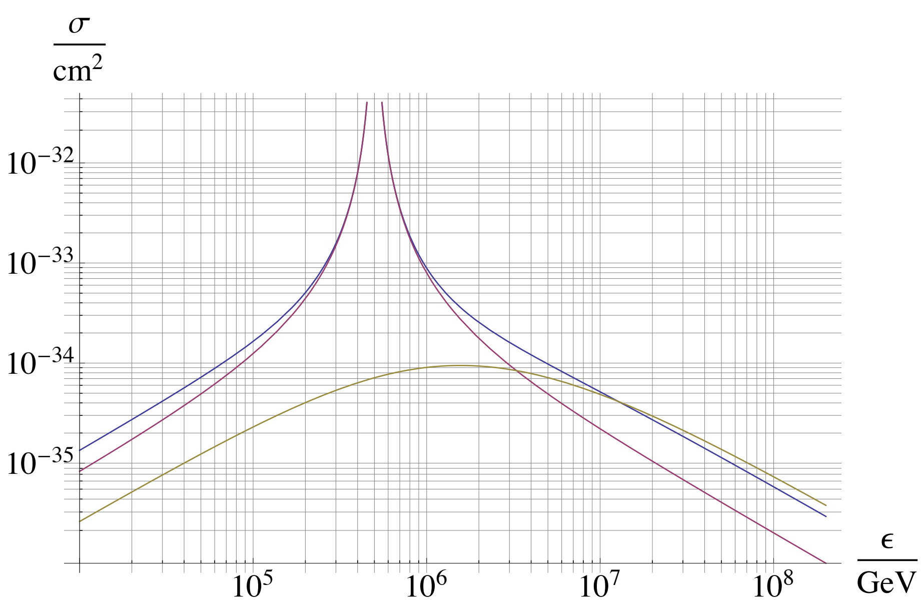
$$\mathcal{L} = -\frac{1}{2}\sum_i \left(m_{\nu_i} + \mathcal{G}_i\phi\right)\nu_i\nu_i + cc + ...,$$

SSB, LNV ⇧ $m_{\nu_i} = \frac{g_i \mu v^2}{\Lambda^2}$

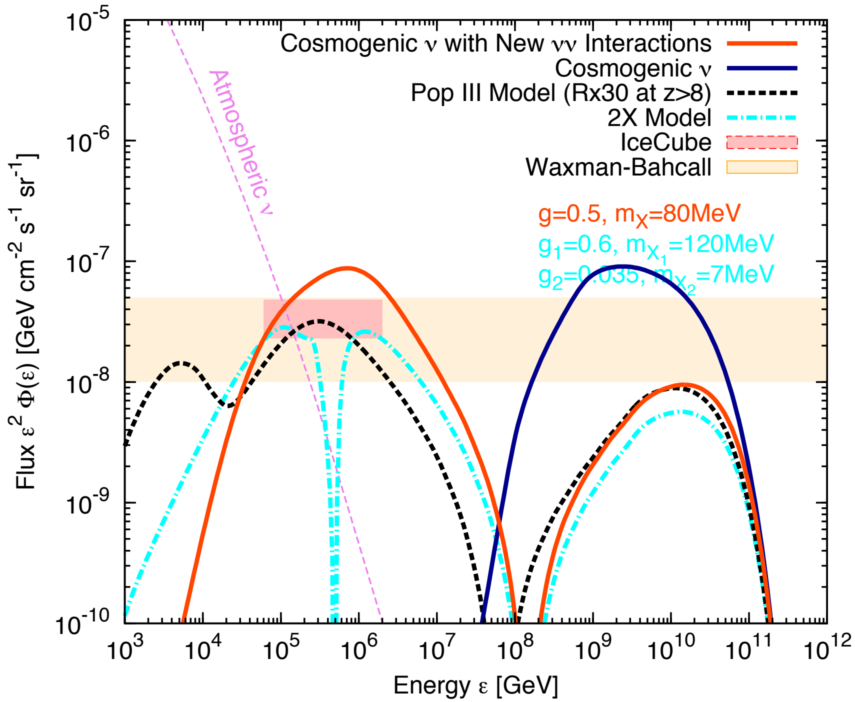
$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc.$$

ν Cascade

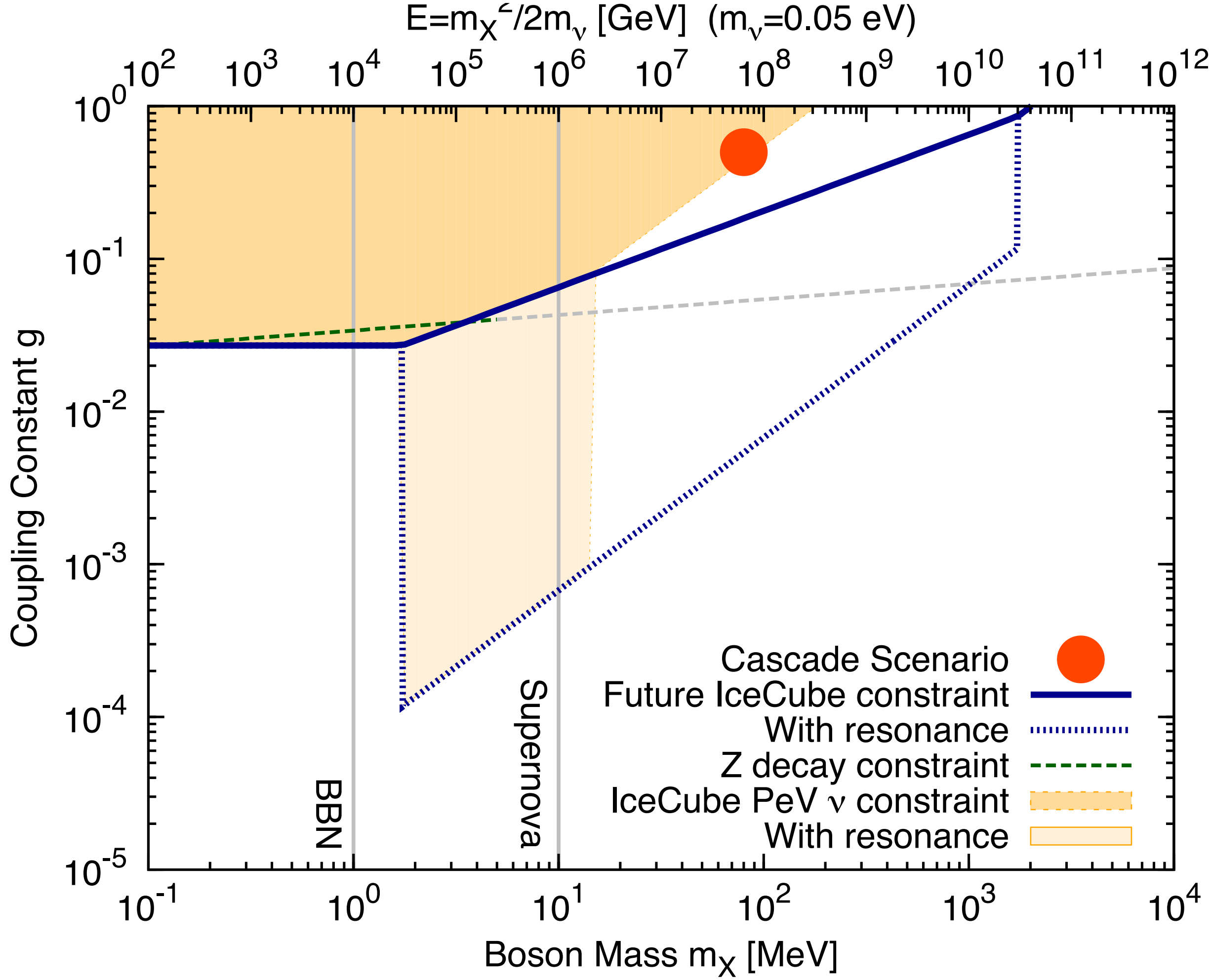




Blum. Hook & KM 14, Ioka & KM 14 PTEP



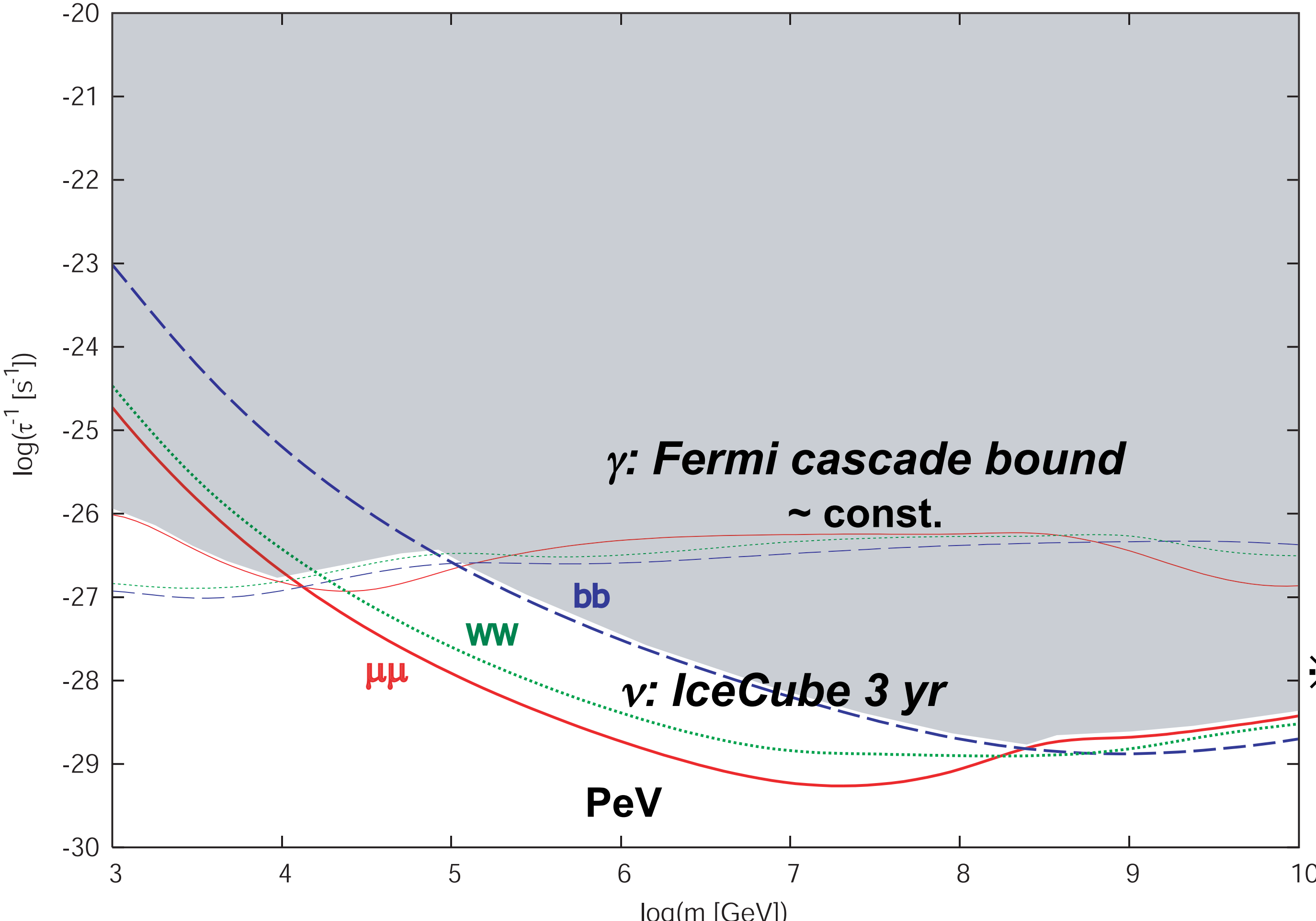
Constraints on Self-Interactions



ex. s-channel resonance:
$s=2m_\nu E_\nu \sim m_X^2$

- An example that IceCube can be used for testing nonstandard interactions
- Can be more powerful than laboratory tests

Neutrino Constraints on Dark Matter Decay



KM & Beacom 12 JCAP

※Annihilating heavy dark matter scenarios are difficult due to the unitarity bound

- Neutrino bound is very powerful at high energies
- Cascade γ-ray bound: more conservative/robust at high m_{dm}