Cosmic-ray Reservoirs as Multi-Messenger Sources

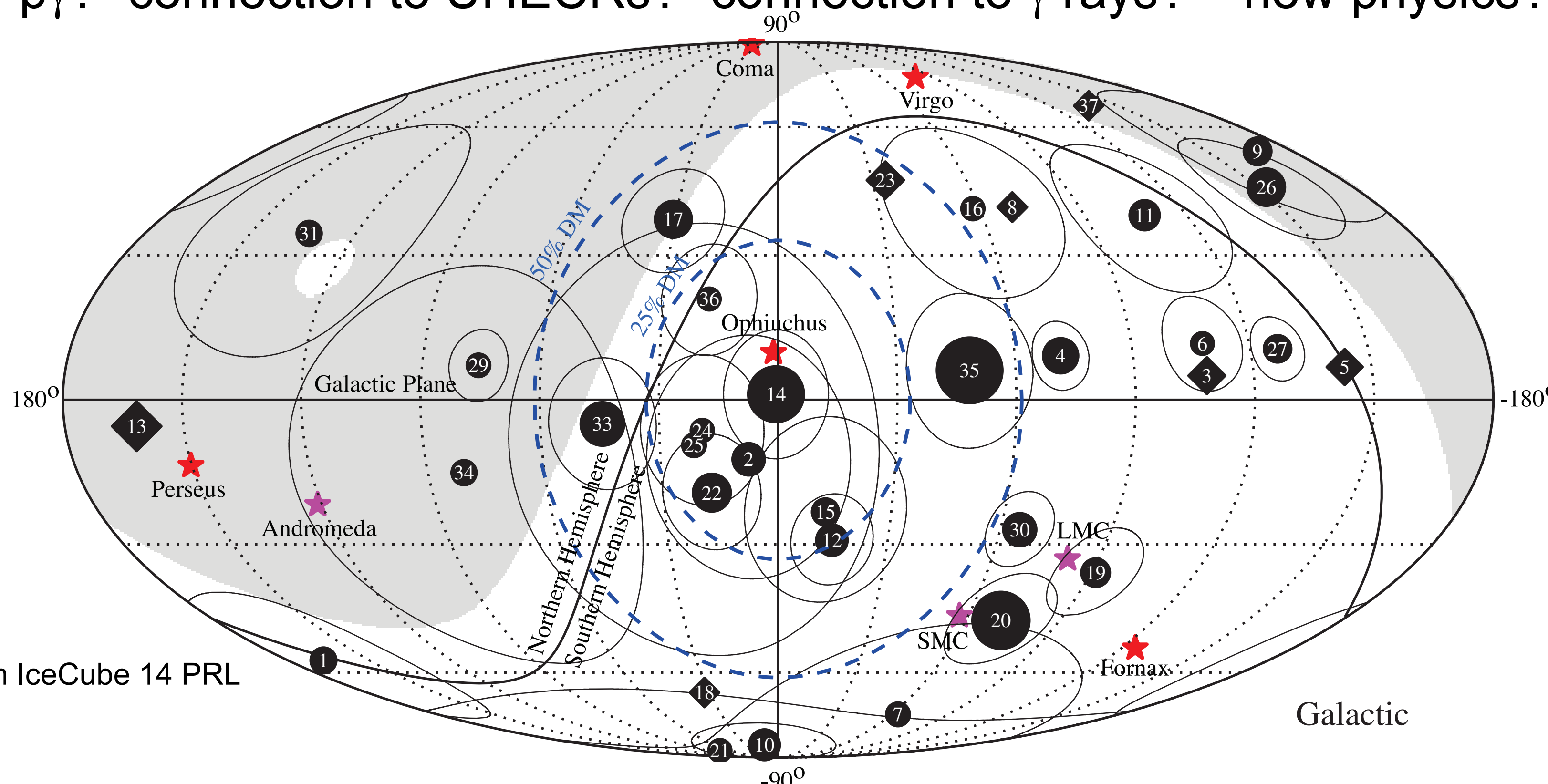
Kohta Murase (Penn State)

July 25 2016 @ Chiba Univ.

HE Neutrino Astrophysics Started

Origins and mechanism of cosmic neutrinos?

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

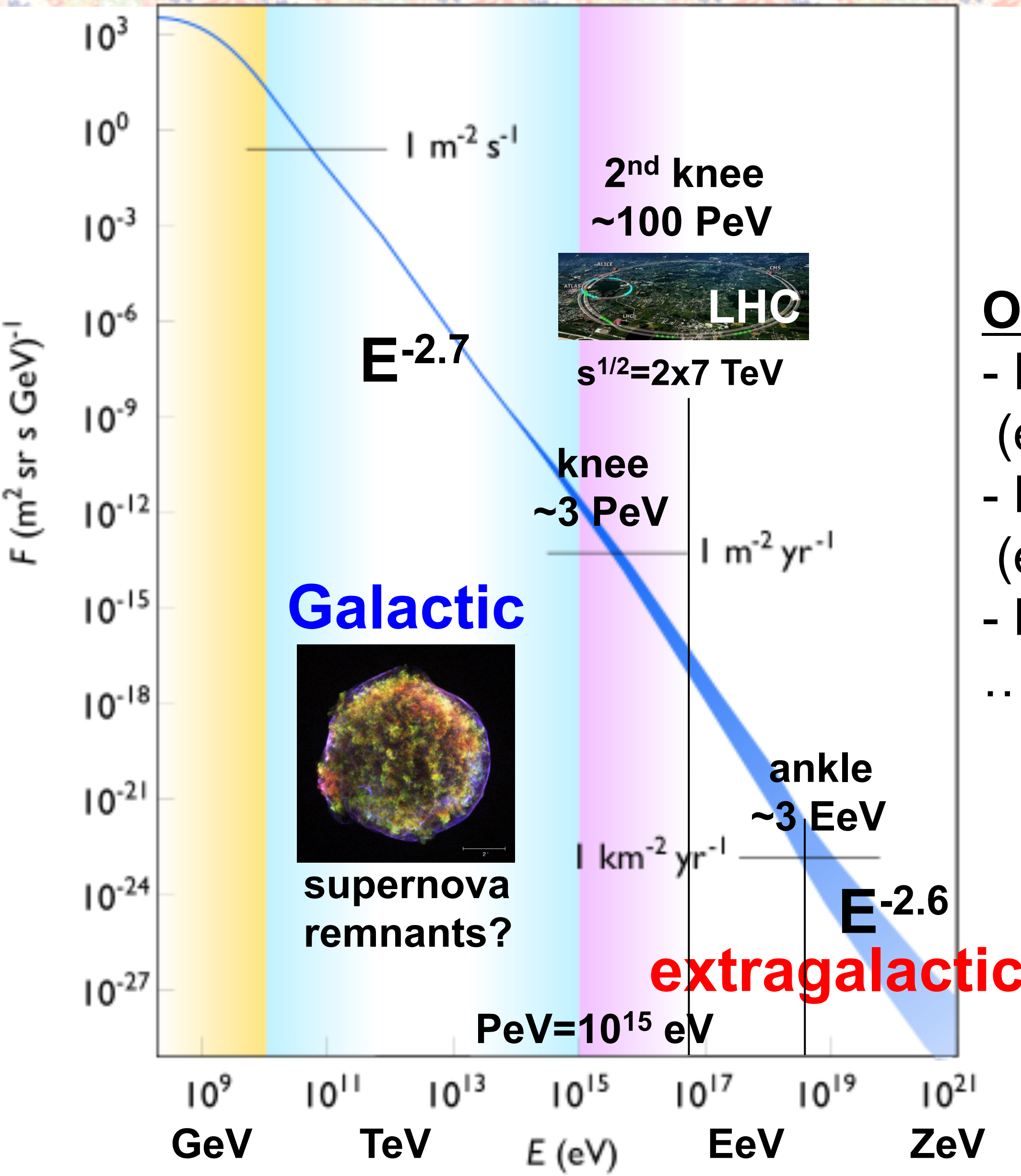


complied from IceCube 14 PRL

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)

Motivation: 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?

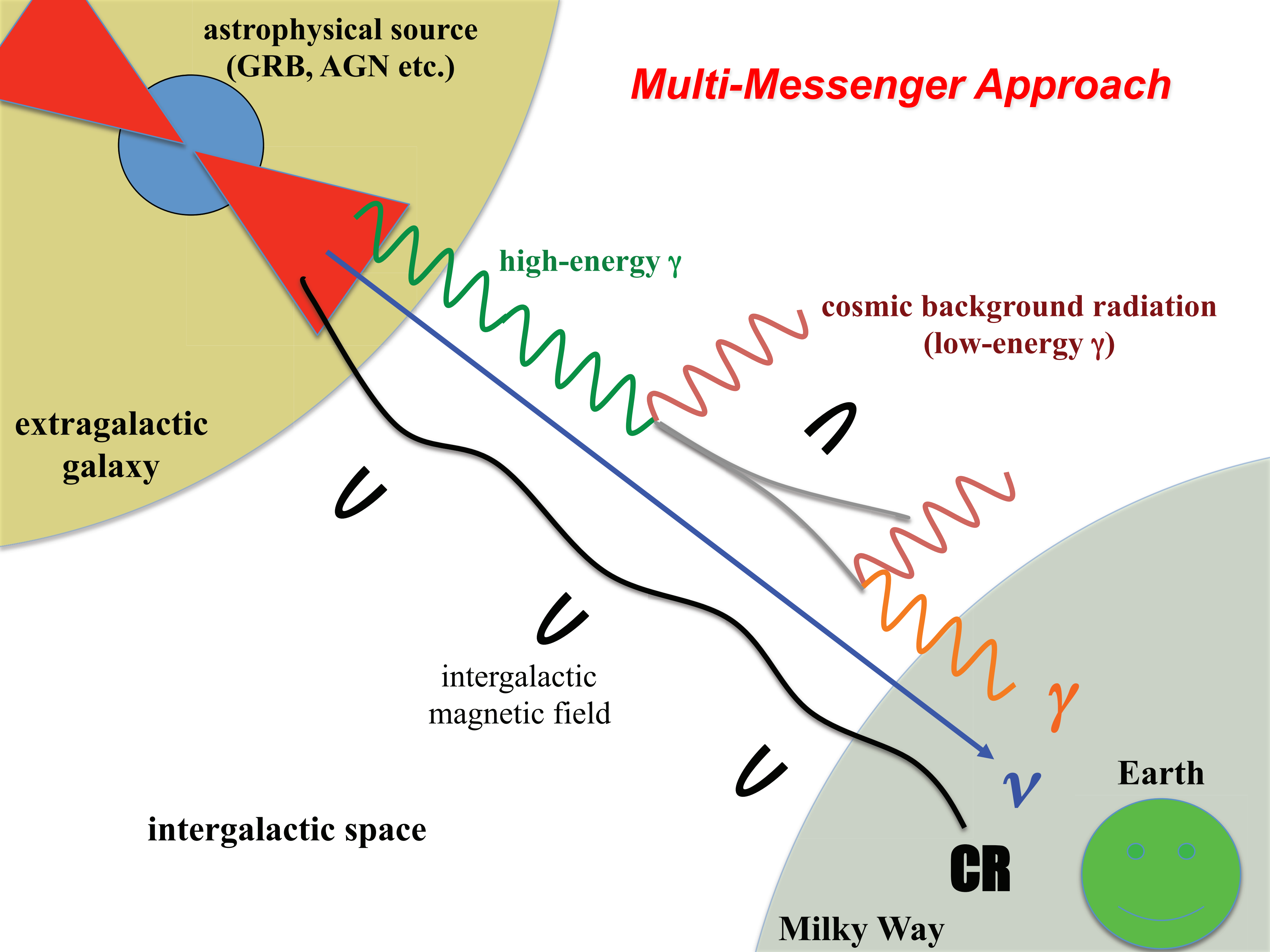
…

The key question

"What is the origin?"

extreme energy (EeV-ZeV)

→ extreme sources


astrophysical source
(GRB, AGN etc.)
Multi-Messenger Approach
high-energy γ
cosmic background radiation
(low-energy γ)
extragalactic
galaxy
intergalactic
magnetic field
γ
ν
Earth
intergalactic space
CR
Milky Way

Astrophysical "Isotropic" Neutrino Background – Mean Diffuse Intensity

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

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

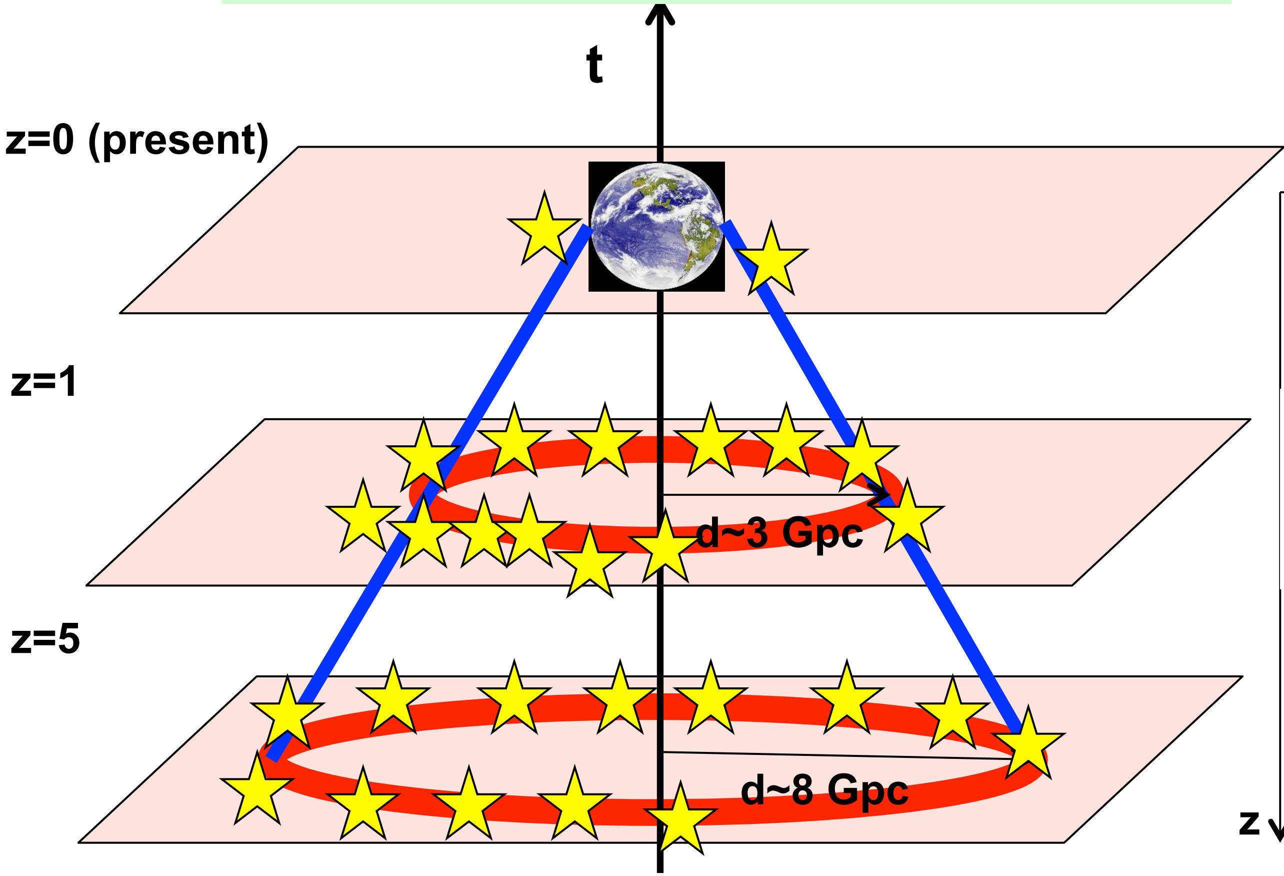
$\varepsilon_\nu^2 q_\nu(\varepsilon_\nu)$: ν emissivity at z=0

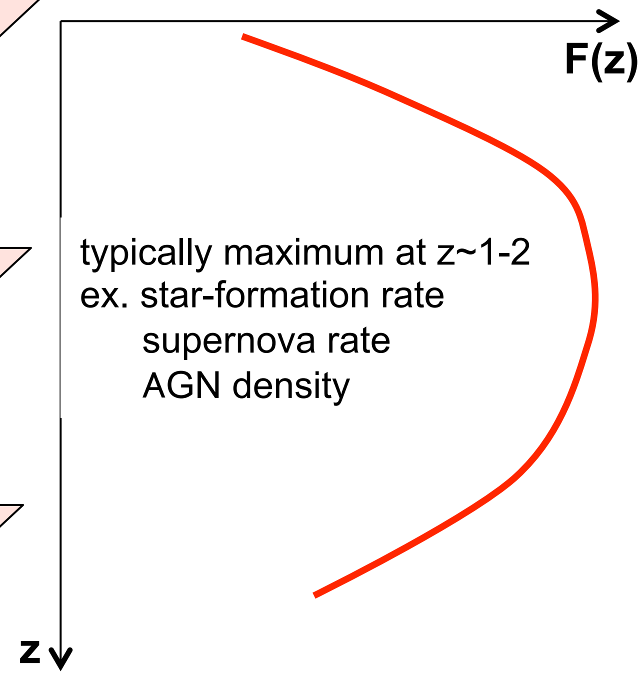
"source physics"

q_ν=Lx(source density)

q_ν=Ex(burst rate)

F(z): redshift evolution





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

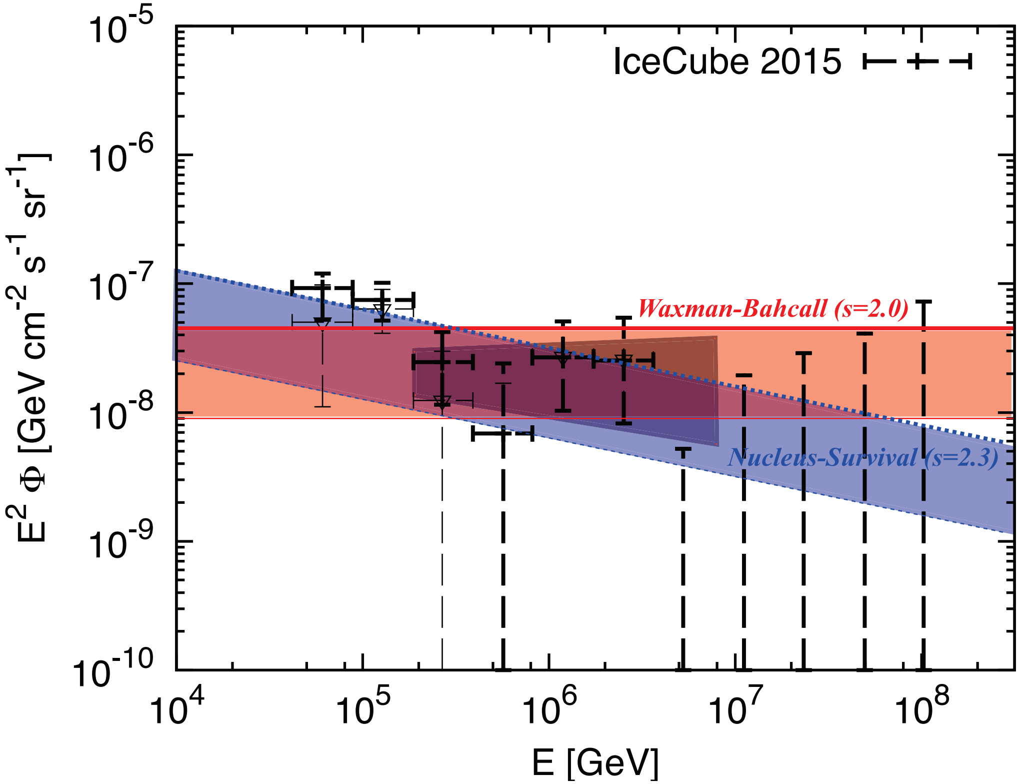
Cosmic-Ray Connection: Hint or Conspiracy?

$$\varepsilon_\nu^2 \Phi_\nu = \frac{c}{4\pi} \int dz \left| \frac{dt}{dz} \right| \varepsilon_\nu^2 q_\nu(\varepsilon_\nu) F(z) \Longrightarrow E_\nu^2 \Phi_\nu \approx \frac{c t_H}{4\pi} \left[\frac{f_{\rm mes}}{4} \varepsilon_p^2 q_p(\varepsilon_p) \right] f_z$$

f_{mes} (<1): meson production efficiency (ex. $f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} \Delta$)
f_z (~0.6-5): source redshift evolution
$\varepsilon_p^2 q(\varepsilon_p)$: CR energy generation rate per volume

obs. UHECR flux: $\varepsilon_p^2 q(\varepsilon_p) = 0.6 \times 10^{44}$ erg Mpc^{-3} yr^{-1} & $f_{mes} \rightarrow 1$ limit

(Waxman & Bahcall 98 PRD)



Attempts to make a ν-CR connection have been made but may not be easy
(Katz et al. 13, Kistler+ 14,
Yoshida & Takami 14, KM & Waxman 16)

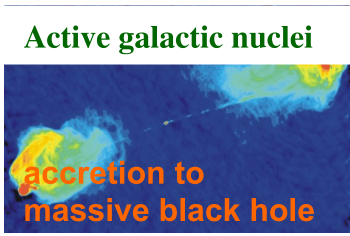
← **"nucleus-survival" bounds**
(KM & Beacom 10 PRD)

$$\sigma_{p\gamma}^{\rm eff} = \kappa_{p\gamma} \sigma_{p\gamma} \sim 10^{-28}\ {\rm cm}^2$$
$$\sigma_{A\gamma}^{\rm eff} = \kappa_{A\gamma} \sigma_{A\gamma} \sim 10^{-27}\ {\rm cm}^2$$

$$\Longrightarrow f_{p\gamma} \approx (\sigma_{p\gamma}^{\rm eff} / \sigma_{A\gamma}^{\rm eff}) f_{A\gamma} \lesssim 0.1$$

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. 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, Winter 13, Senno, KM & Meszaros 16

- Active galactic nuclei

  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 & Li 16

- 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, Senno et al. 15

- Galaxy groups/clusters

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

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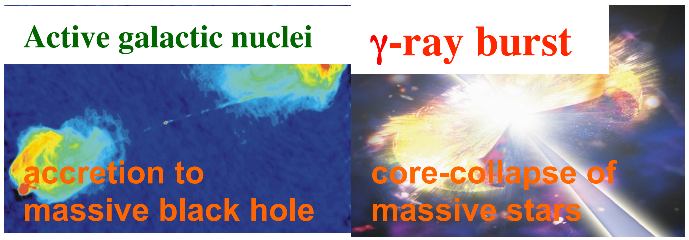
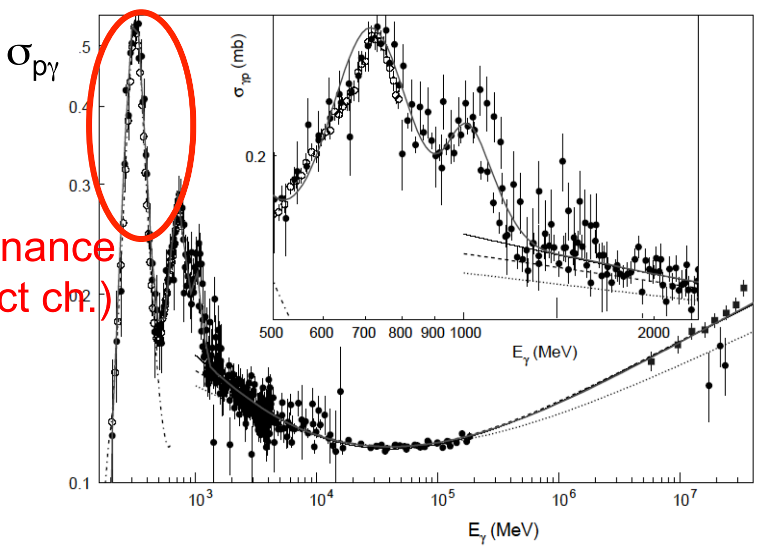


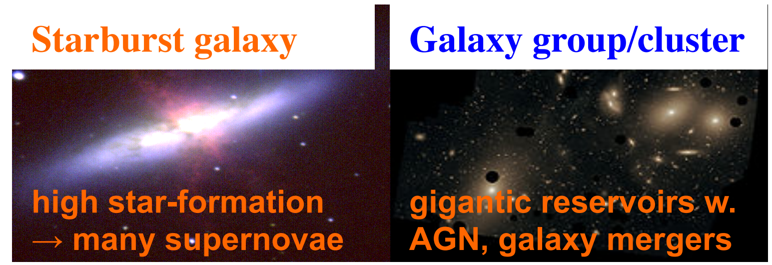
$$p+\gamma \rightarrow N\pi + X$$



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

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

Cosmic-ray Reservoirs



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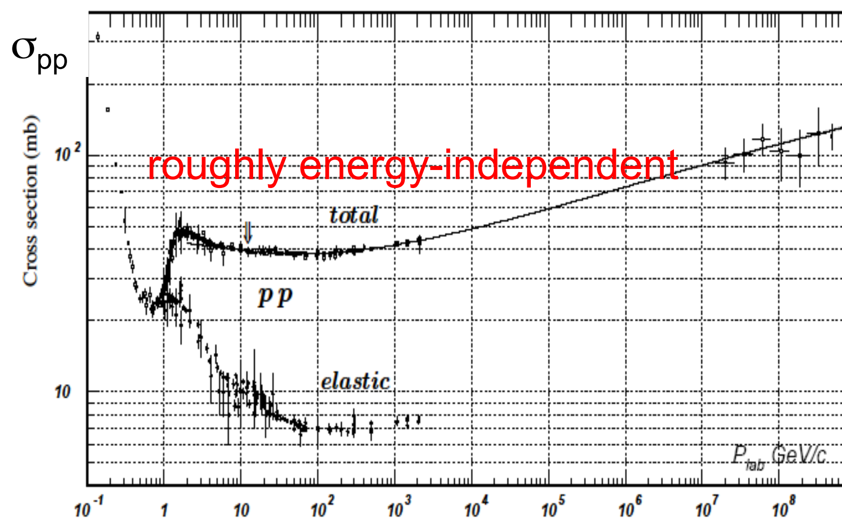

$\sigma_{pp} \sim 1/m_\pi^2 \sim 30$ mb

Astrophysical Extragalactic Scenarios

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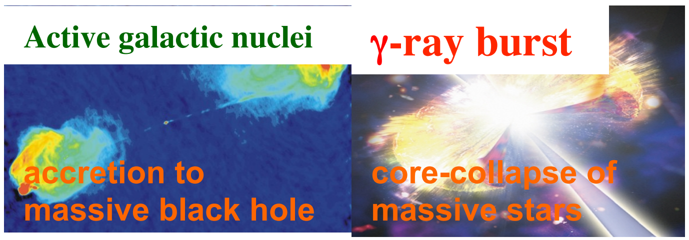

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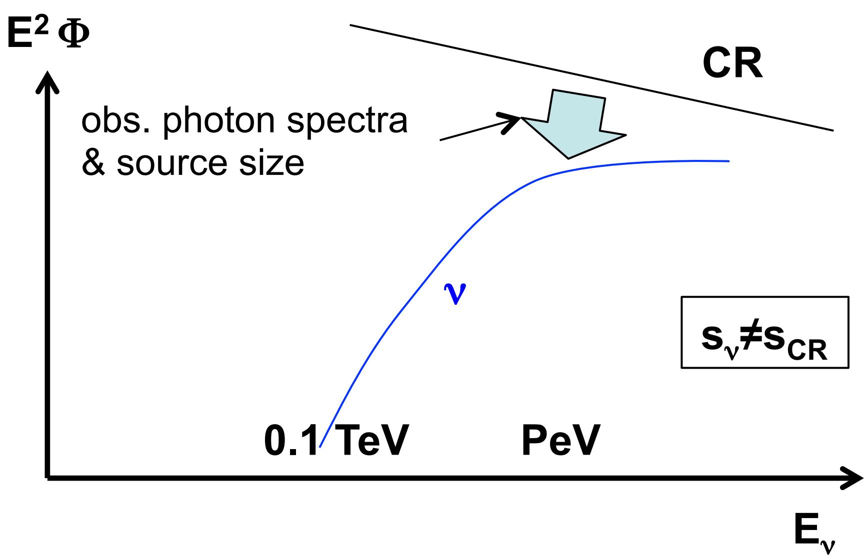
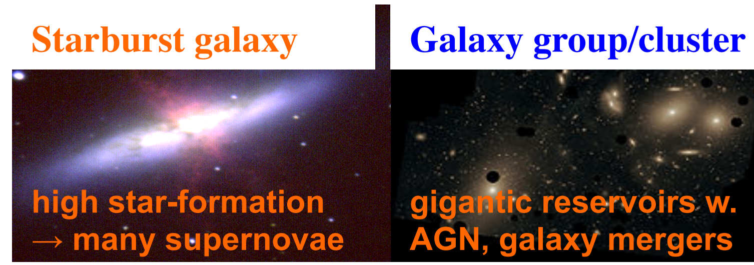
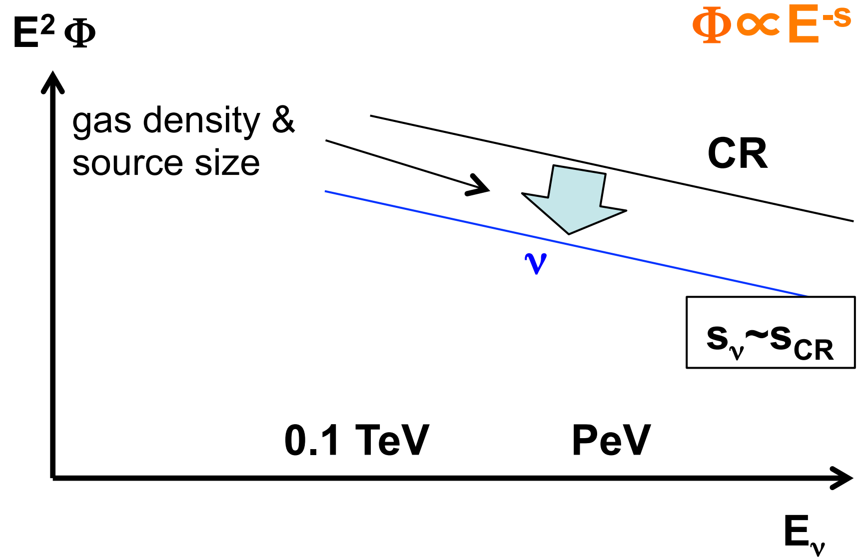


Cosmic-ray Reservoirs



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

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



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

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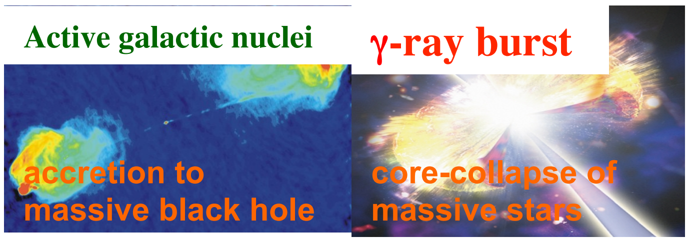

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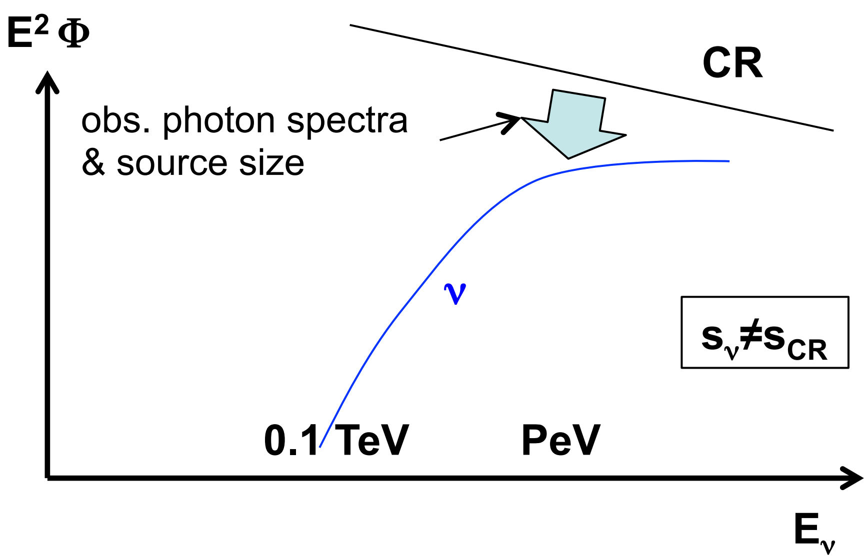
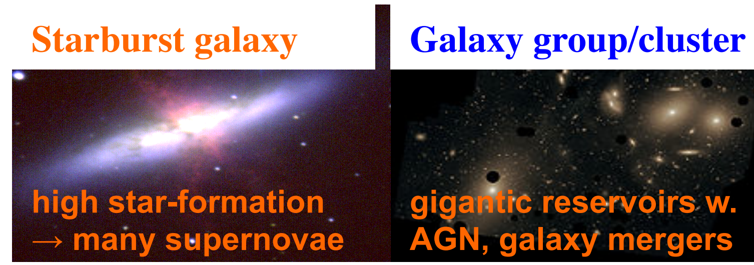


Cosmic-ray Reservoirs



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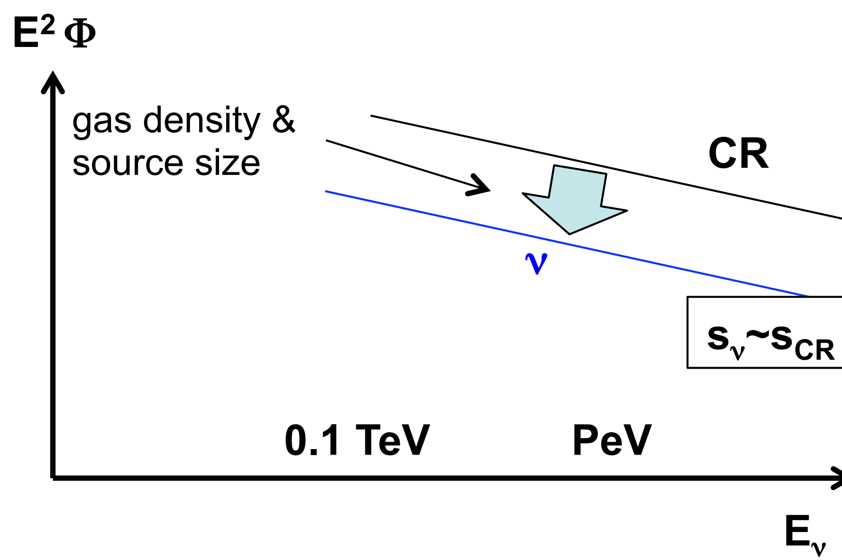

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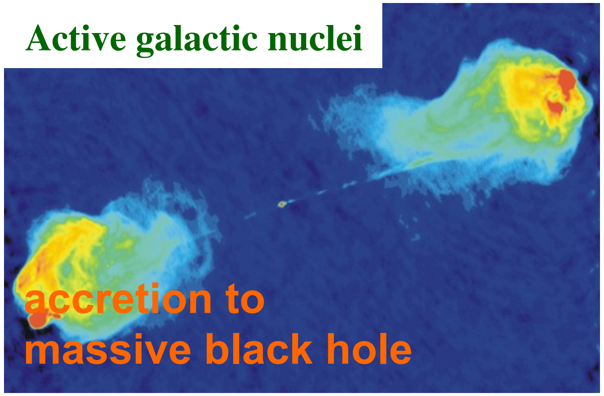
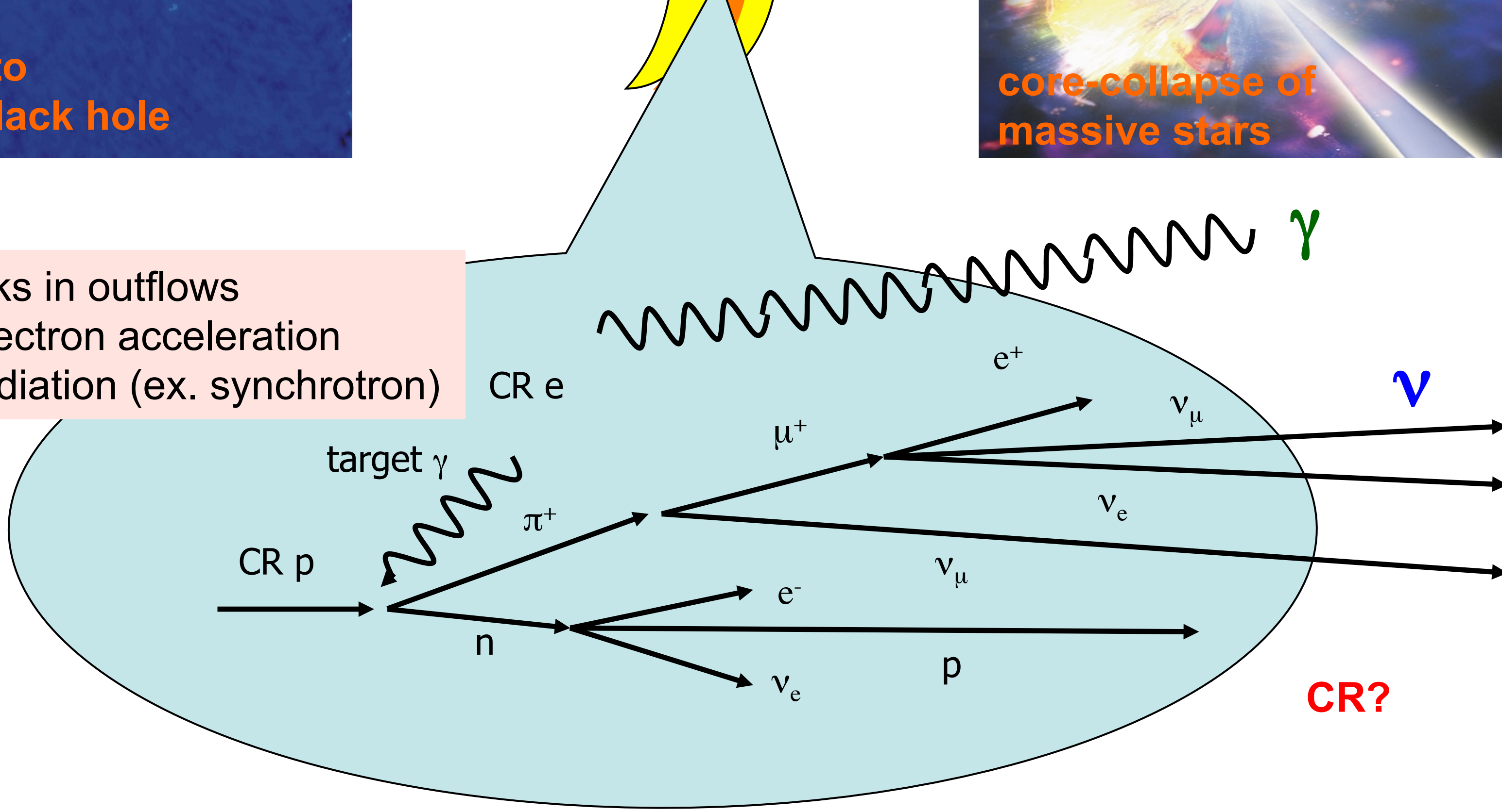
Cosmic-Ray Accelerators





ex. shocks in outflows
→ electron acceleration
→ radiation (ex. synchrotron)

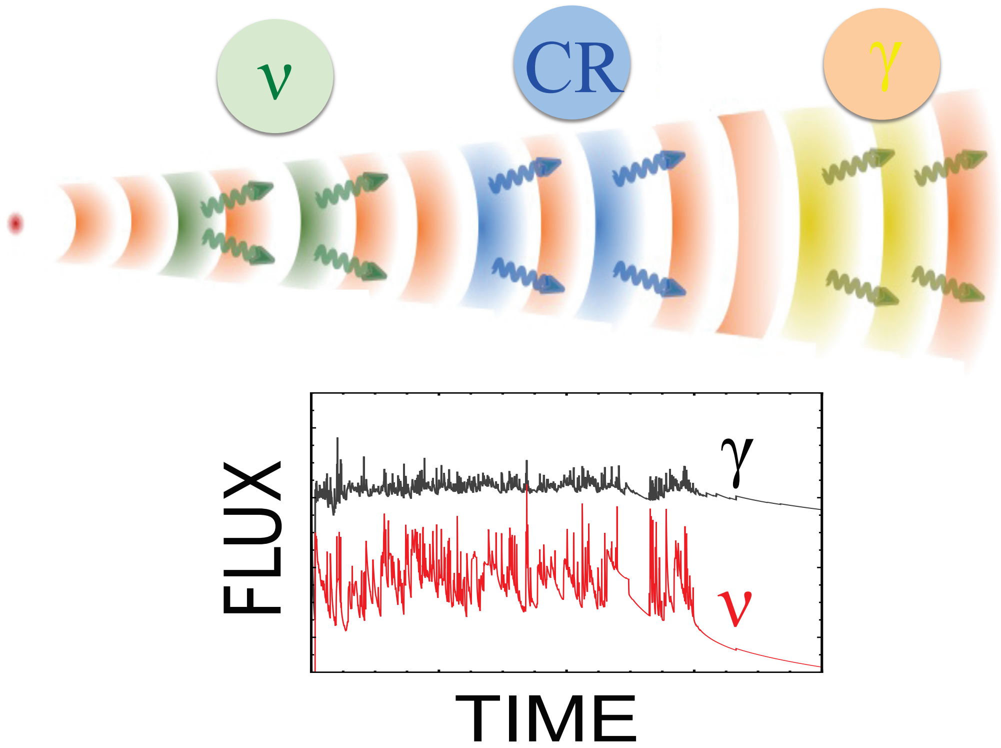
CRs may or may not escape

HE Neutrinos from Classical GRBs

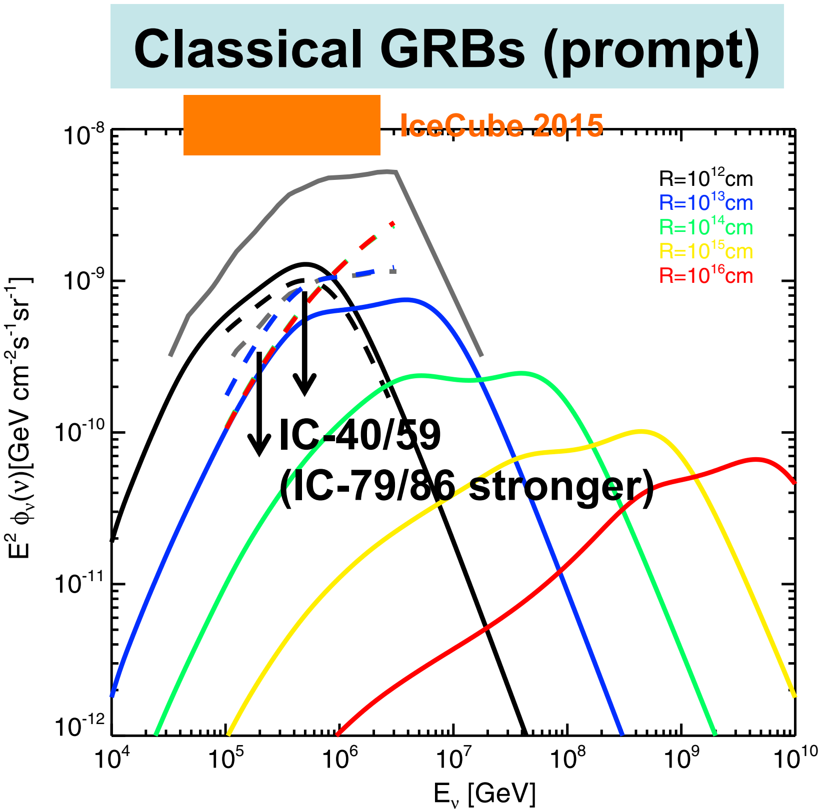
Standard jet models as the cosmic ν origin: excluded by multimessenger obs.

- 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.



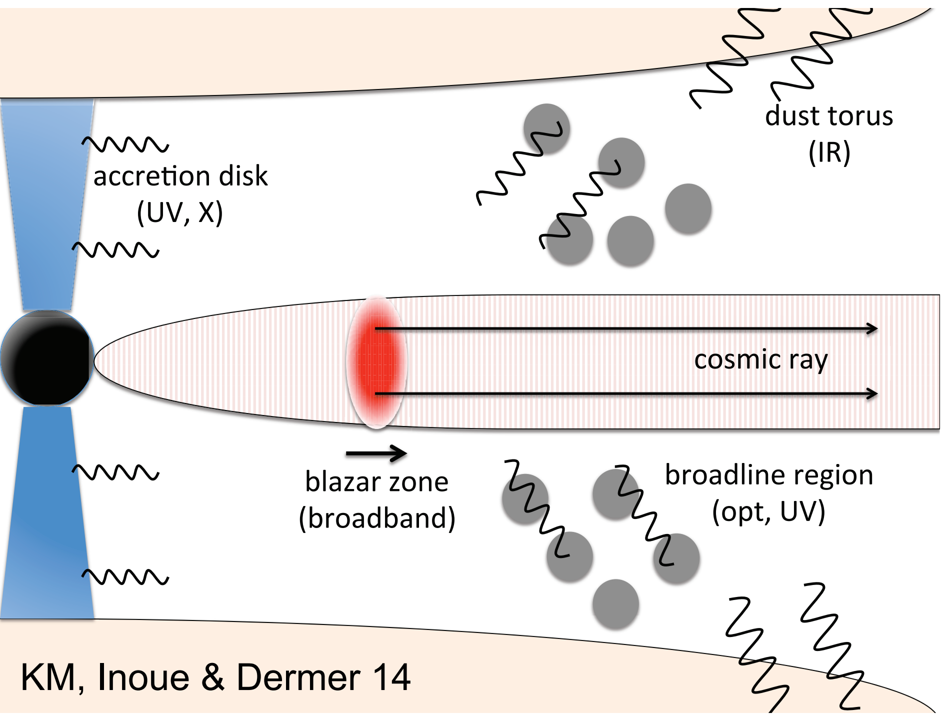
He+ KM 12 ApJ

HE Neutrinos from AGN Jets

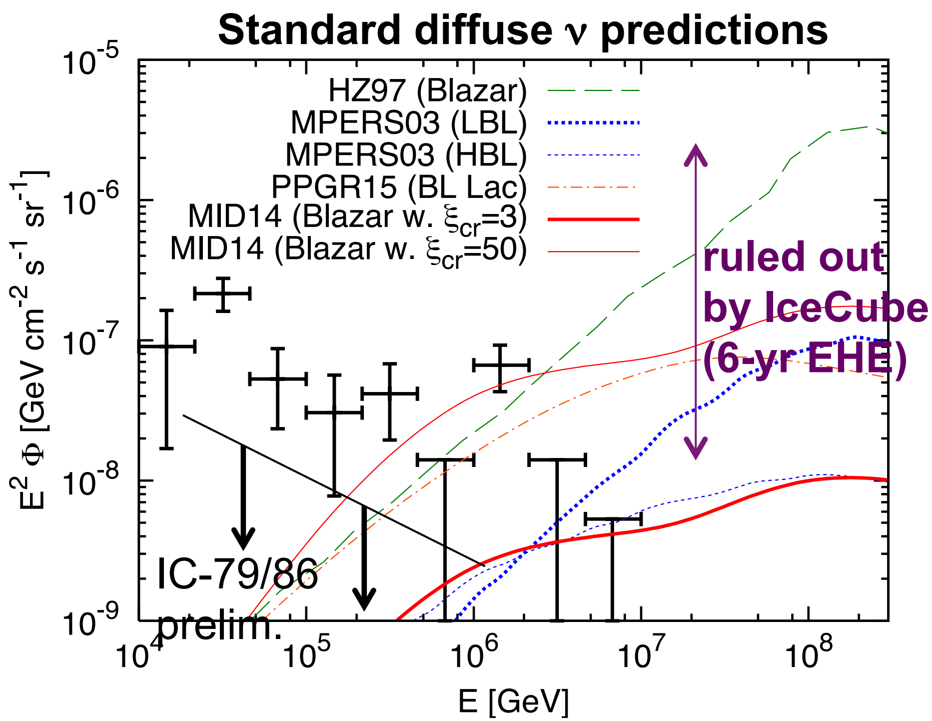
Standard jet models as the cosmic ν origin: disfavored by multimessenger obs.

- 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)



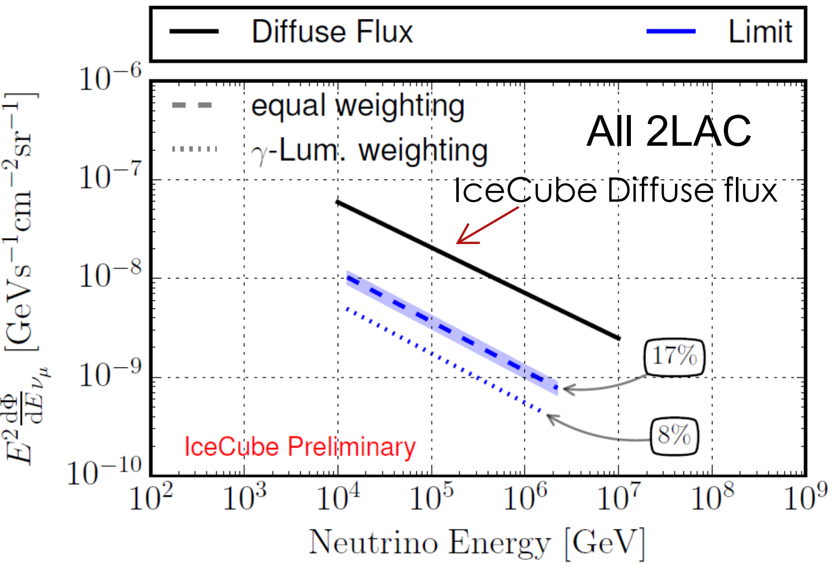
Blazars



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

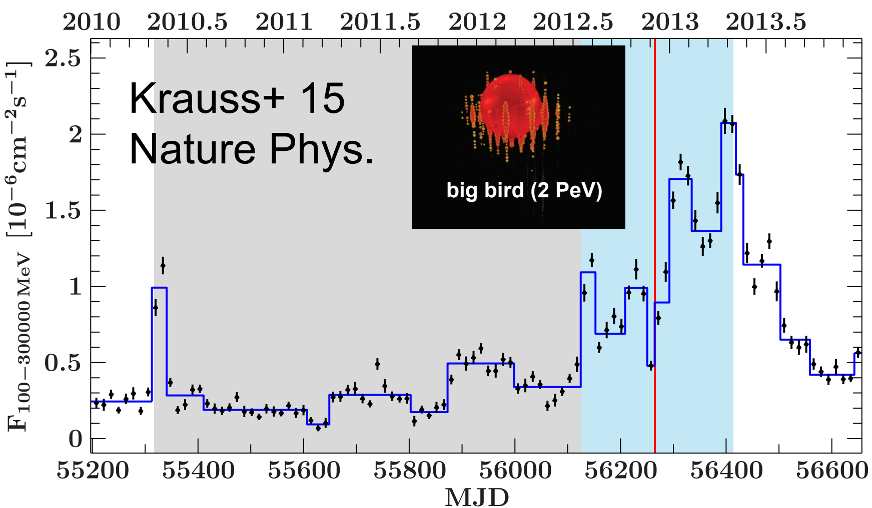
Controversy: Blazars as the Origin of IceCube's Neutrinos?

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)

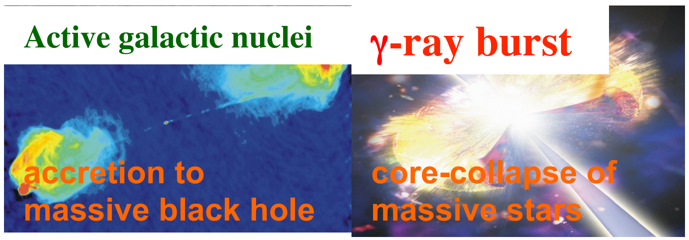


YES! (Padovani & Resconi 14, Krauss+ 15)

- 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)



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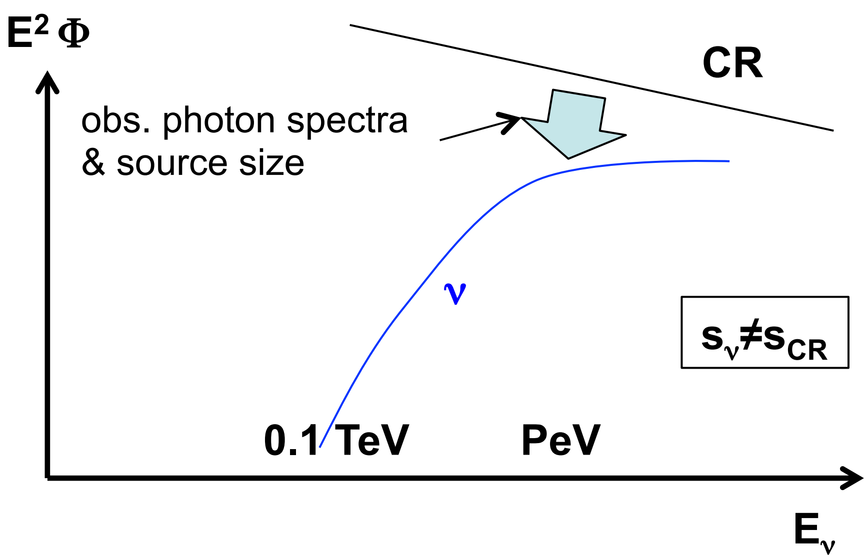
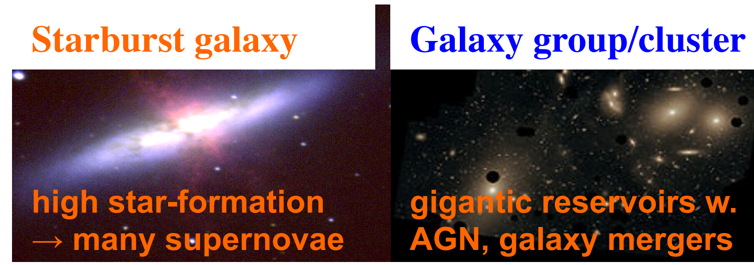


Cosmic-ray Reservoirs



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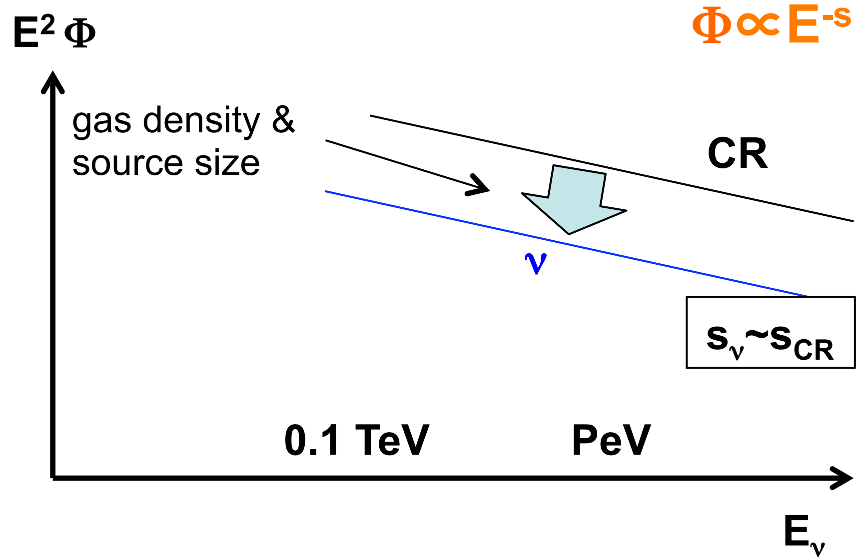

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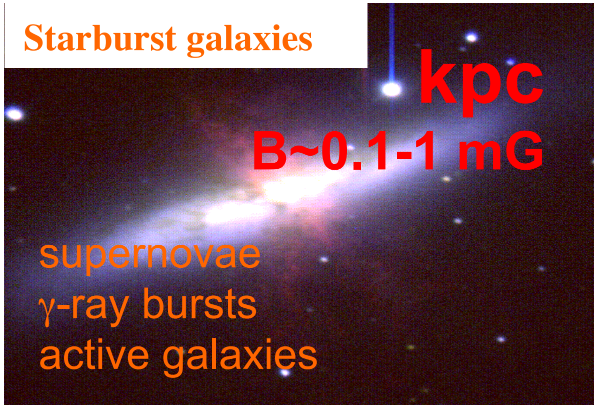
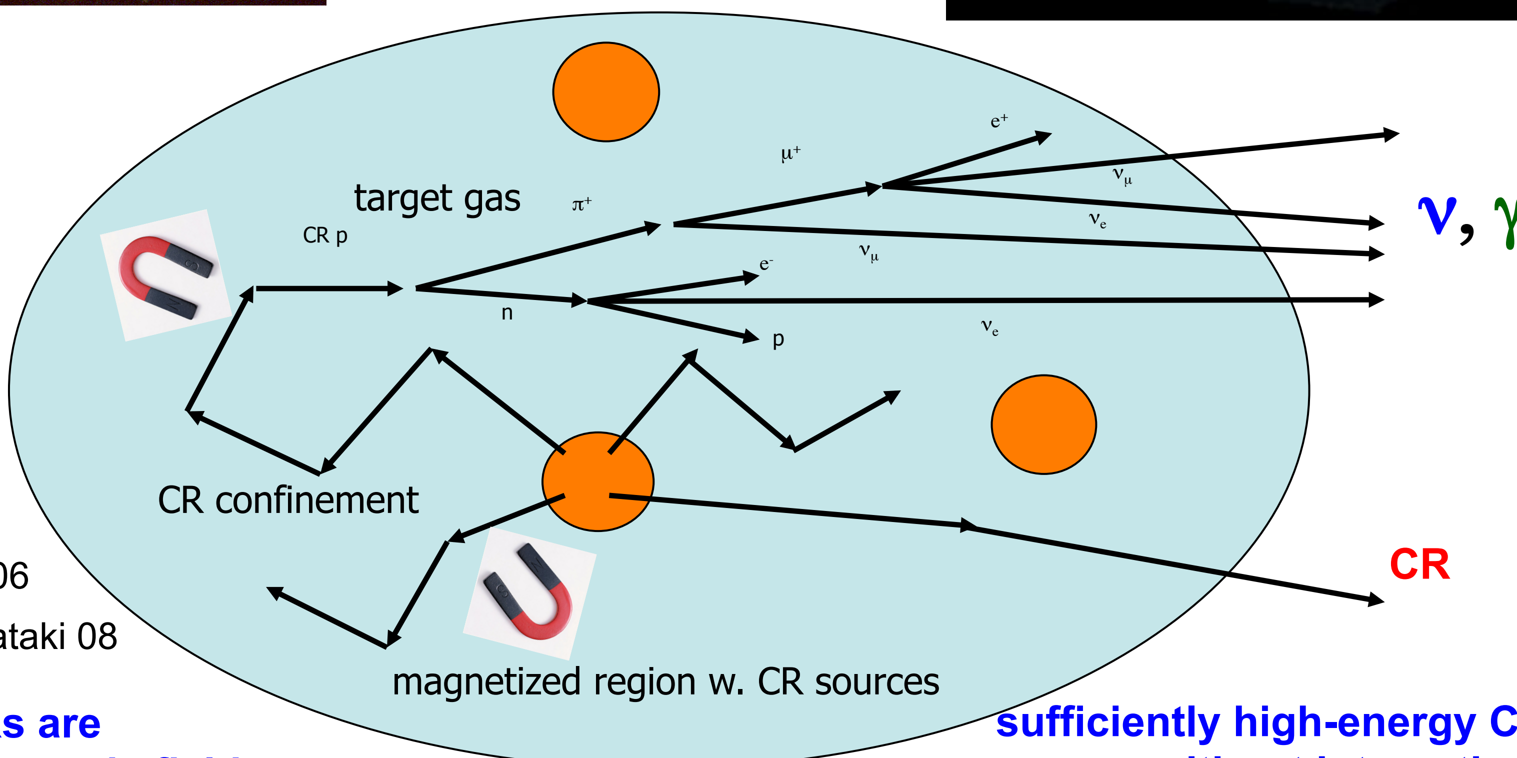
Cosmic-Ray Reservoirs



"cosmic-ray reservoirs"



Loeb & Waxman 06

KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions

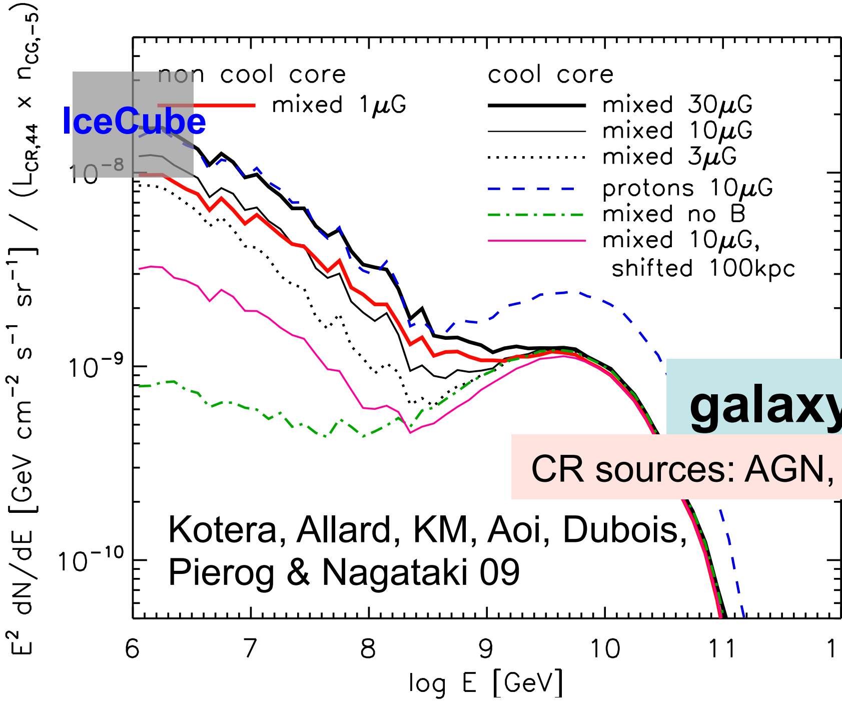
Points of CR Reservoir Models

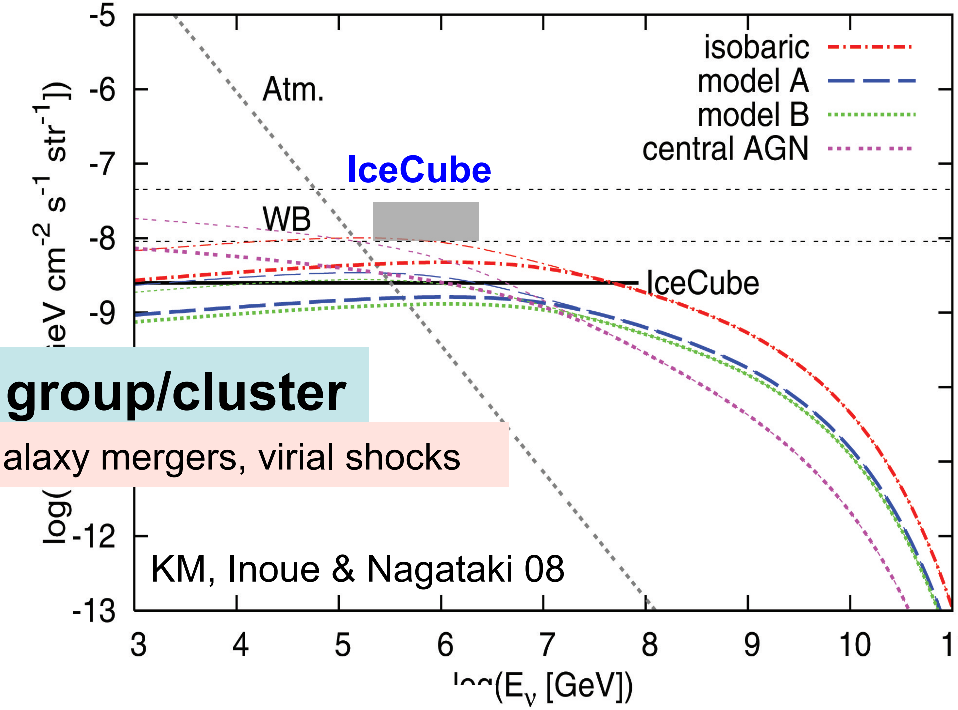
- Some contributions must exist: very natural (galaxies contain CRs & gamma rays are detected)
- Predicted before IceCube's discovery (a multi-PeV break/cutoff has been expected)
  (Berezinsky et al. 97, Loeb & Waxman 06, KM et al. 08 ApJ, Kotera, Allard, KM et al. 09)
- "Unification" of multi-messengers is possible
  (KM, Ahlers & Lacki 13, Katz et al. 13, Dado & Dar 14, KM & Waxman 16)

Issue: tension w. Fermi gamma-ray limits?
relevance of "low-energy excess problem"
(KM, Ahlers & Lacki 13, Senno, Meszaros, KM+ 15
KM, Guetta & Ahlers 16, Ando, Tamborra & Zandanel 16, Bechtol+ 16)

galaxy group/cluster

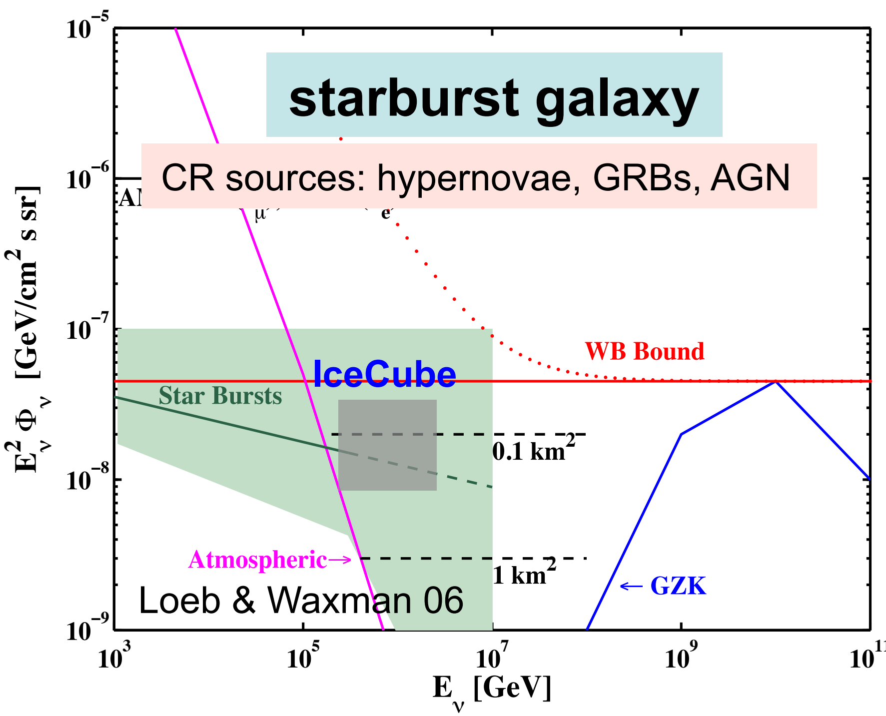
CR sources: AGN, galaxy mergers, virial shocks





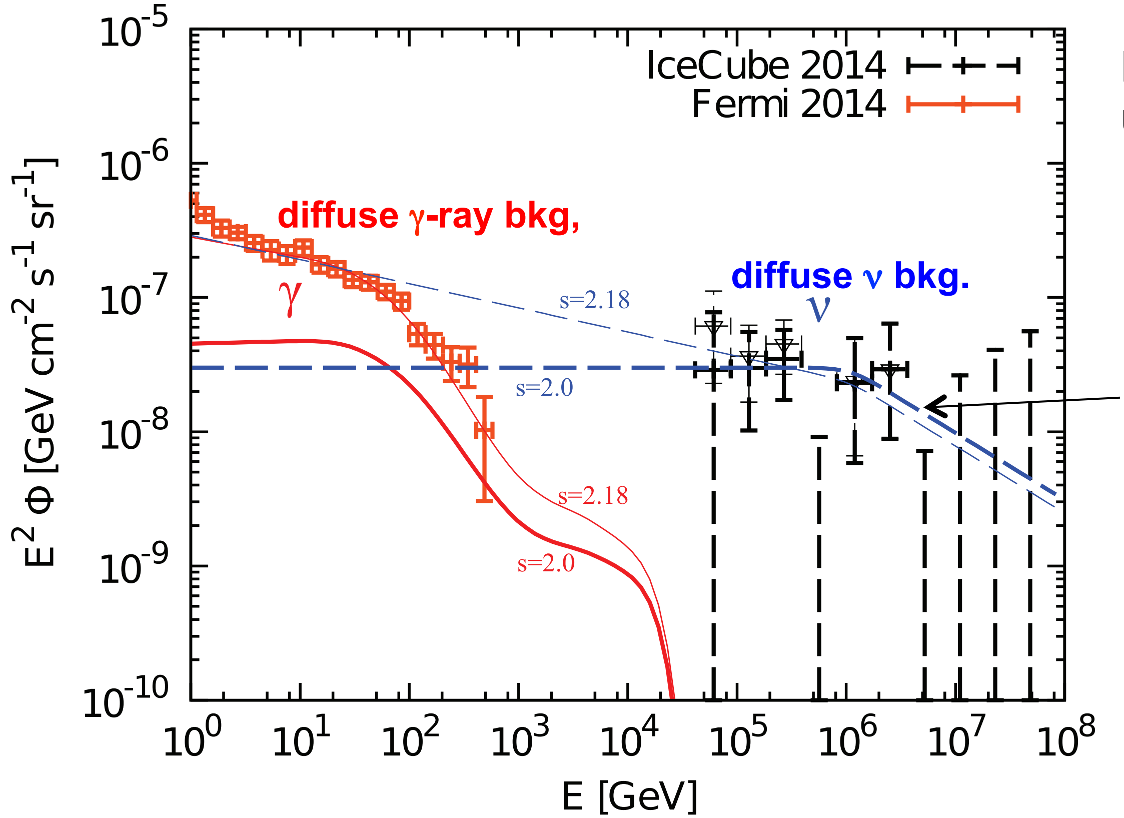
starburst galaxy

CR sources: hypernovae, GRBs, AGN



Inelastic pp Neutrinos from CR Reservoirs

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



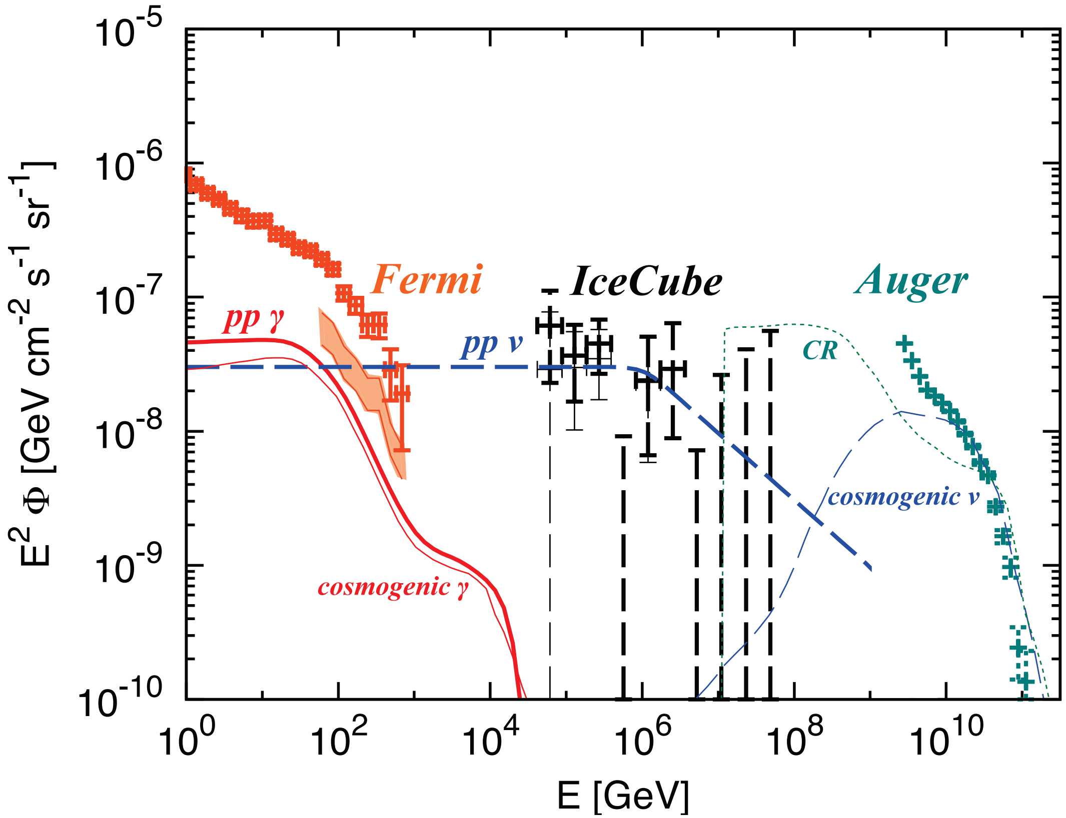
KM, Ahlers & Lacki 13 PRDR
updated @ Neutrino 2014

diffusive escape of CRs

Unification of 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)



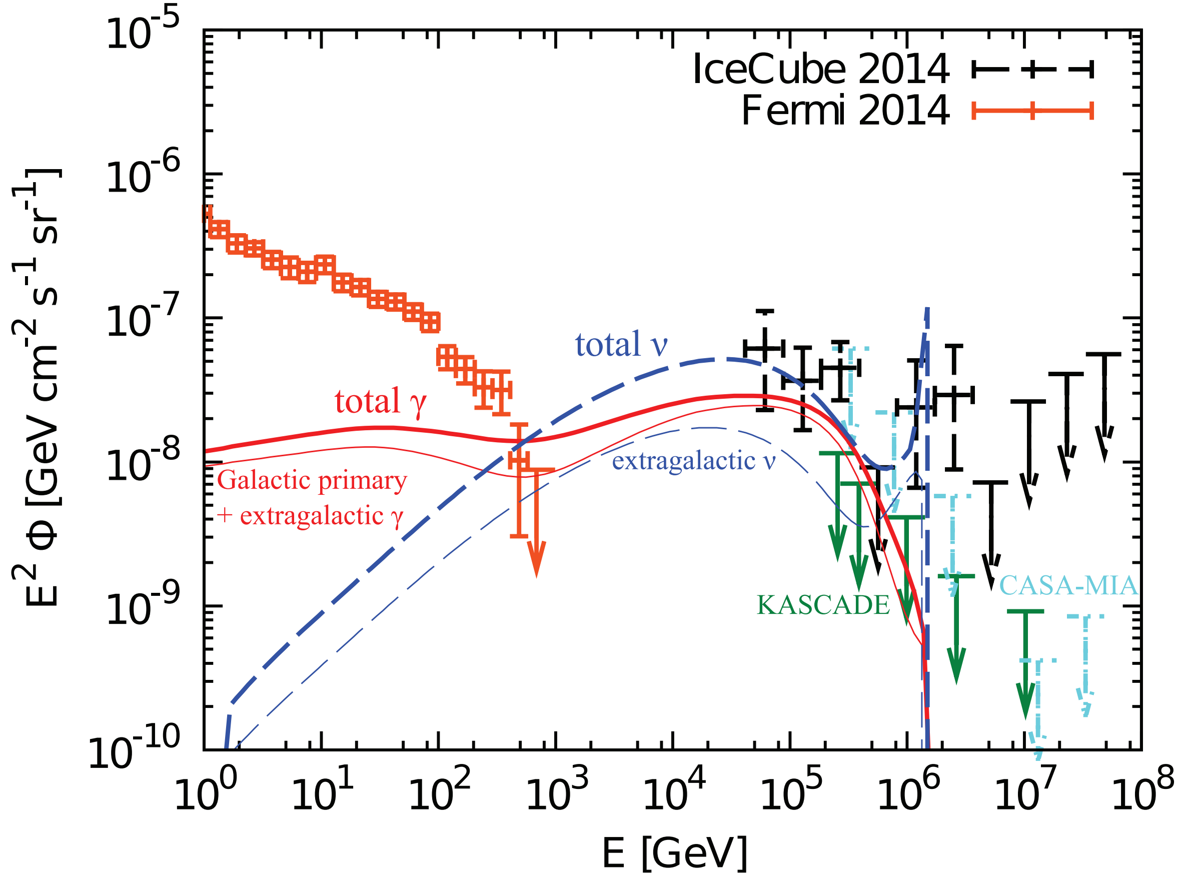
KM & Waxman 16
see also Katz et al. 13

Grand-unification of neutrinos, gamma rays & UHECRs

※cosmogenic ν flux does not violate the latest EHE limit by IceCube

Neutrinos from Dark Reservoirs

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



KM, Laha, Ando & Ahlers 15 PRL

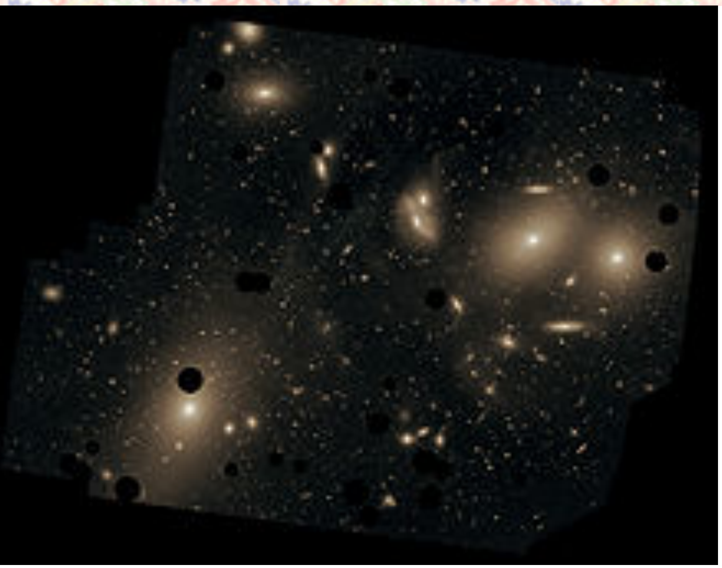
ex. Feldstein et al. 13,
Esmaili & Serpico 13,
Higaki+ 14, Fong+ 15,
Bai+ 14, Rott+ 15

DM → ν_e+ν_e (12%)
DM → b+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

Galaxy Groups and Clusters: Basics



- intracluster gas density
  n~10^{-4} cm^{-3}, a fewx10^{-2} cm^{-3} (center)
- CR accelerators
  AGN (~a few), galaxy mergers,
  normal galaxies (~100-1000)
  UHECR acceleration possible in AGN
- accretion shocks

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

CR injection occurs for ~1-10 Gyr over a cluster/group

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

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

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

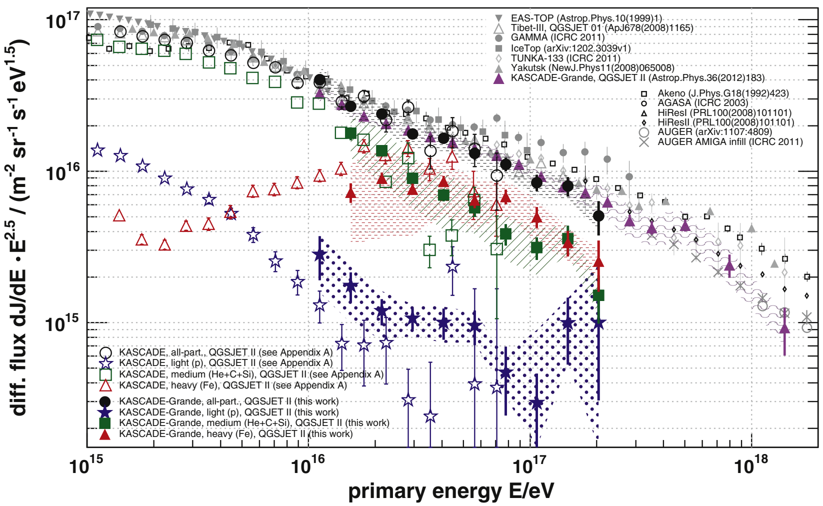
$$E_\nu^2 \Phi_{\nu_i} \sim 10^{-9}\text{–}10^{-8} \, {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Diffusion Break & Second Knee

- Maximum energy of CRs is expected to be high enough (which is not the case in normal/starburst galaxies)
- Big! → confining CRs is easy (E<eBR~10^{21} eV)

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

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



Apel et al. 13 APh

- CR break compatible w. 2nd knee
- Escaping CRs naturally contribute to the observed CR flux above 2nd knee

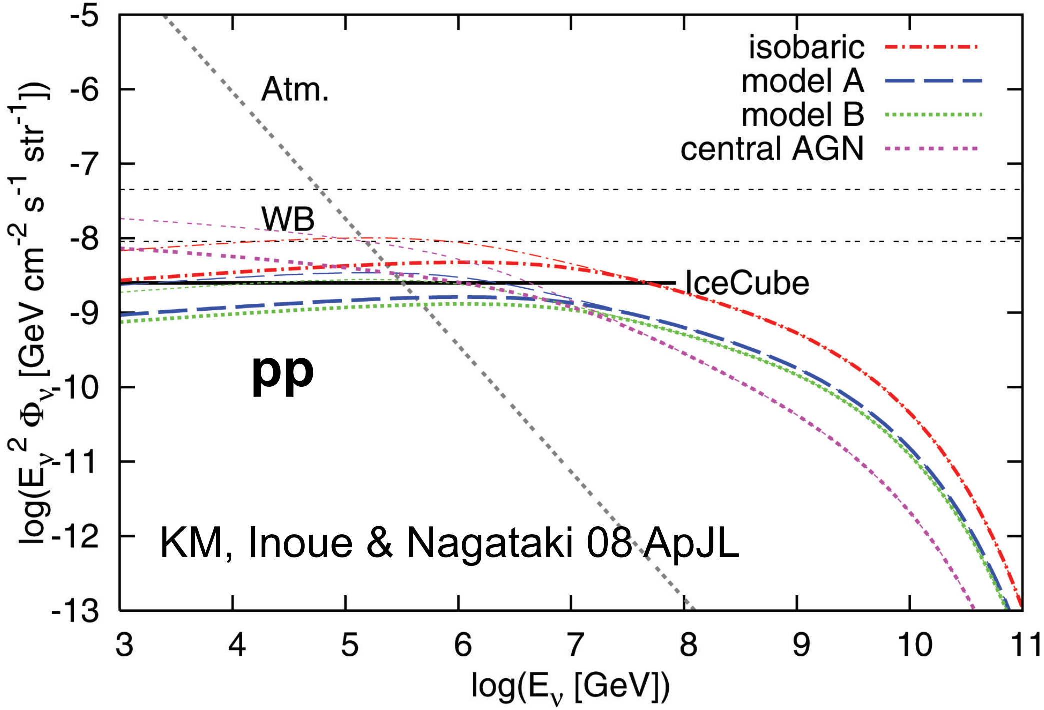
⇨ ν break $\varepsilon_\nu^b \approx 0.04 \varepsilon_p^b \simeq 2.0\ {\rm PeV}\ B_{-6.5} (l_{\rm coh}/30\ {\rm kpc})^{-2} M_{15}^2 (t_{\rm inj}/2\ {\rm Gyr})^{-3}$

KM, Inoue & Nagataki 08 ApJL

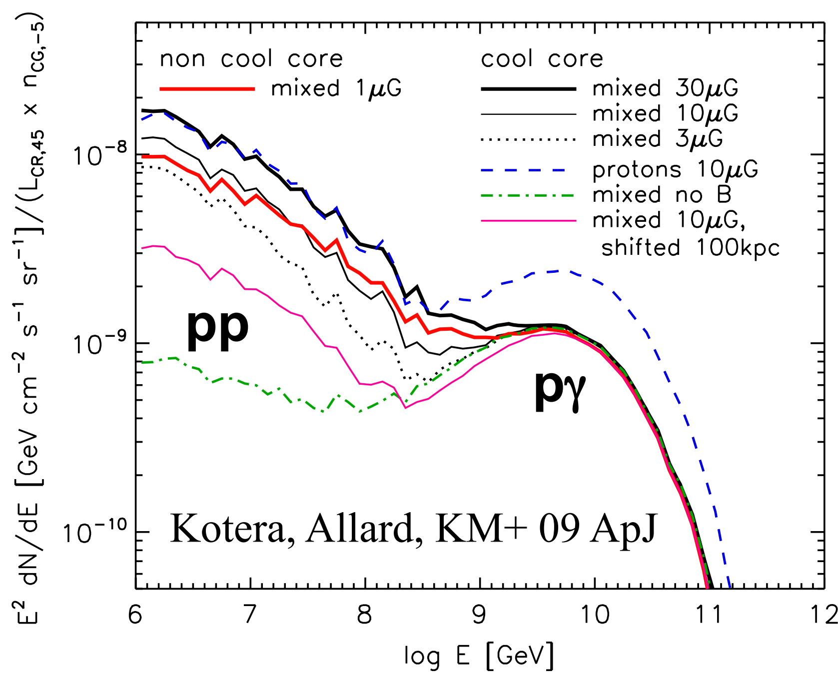
Galaxy Clusters/Groups, CRs, νs

Pre-IceCube predictions motivated by the explanation of observed CRs

Normalized by CRs above 2nd knee (s=2.0)
(only massive clusters included)



Normalized by UHECRs (s=2.3)
(low-mass clusters included)



- Consistent w. obs. & a multi-PeV break was predicted
- No firm gamma-ray detection, low-mass clusters needed

Neutrino Limits

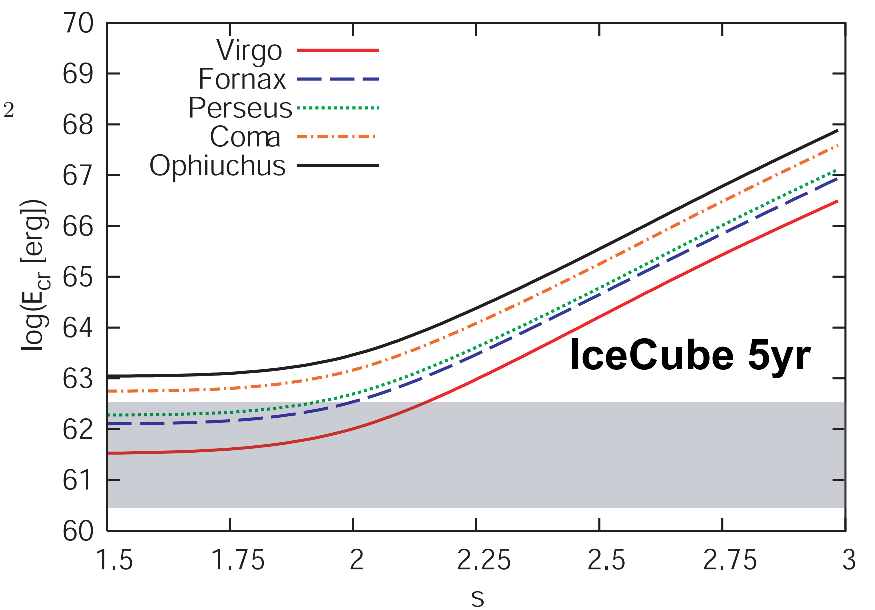
Cosmic-ray confined in one cluster

$$\mathcal{E}_{\rm cr} \sim L_{\rm cr} \times \min[t_{\rm inj}, t_{\rm diff}]$$
$$\simeq 10^{61.5}\ {\rm erg} \left(\frac{L_{\rm cr}}{10^{45}\ {\rm erg\ s^{-1}}}\right) \left(\frac{\min[t_{\rm inj}, t_{\rm diff}]}{\rm Gyr}\right)$$

~10^{61}-10^{62} erg needed to explain CRs or νs

KM & Beacom 13 JCAP

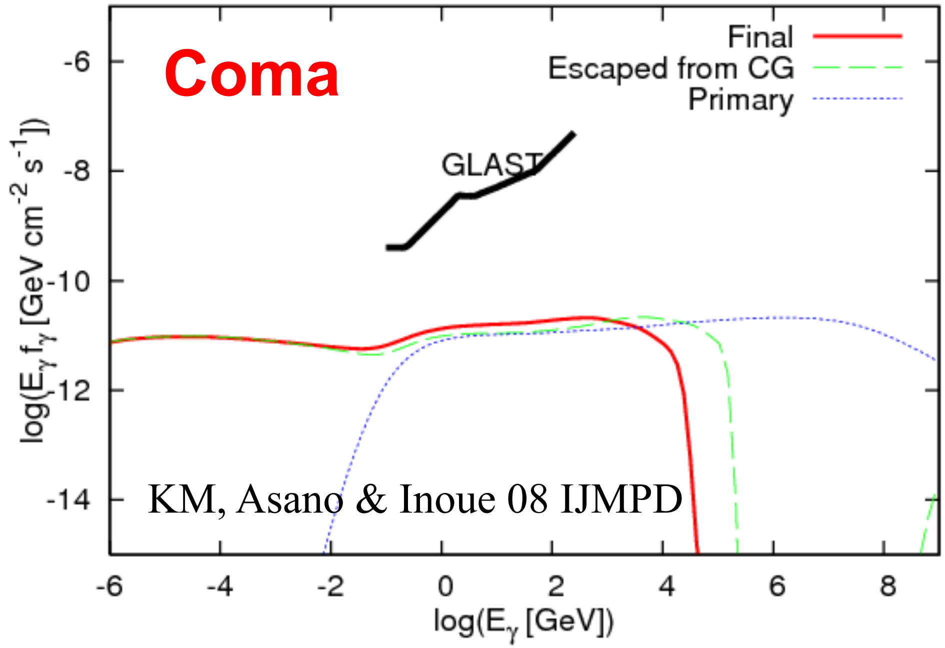
$$E^2 F_E \approx \frac{1}{8\pi d^2} f_{pp} \frac{L_{\rm cr}}{\mathcal{R}_{\rm cr}} \approx \frac{1}{8\pi d^2} \bar{n}_N \kappa_\pi \sigma_{pp} c \frac{\mathcal{E}_{\rm cr}}{\mathcal{R}_{\rm cr}}$$
$$\simeq 1.5 \times 10^{-10}\ {\rm GeV\ cm^{-2}\ s^{-1}} \left(\frac{\bar{n}_N}{10^{-4}\ {\rm cm^{-3}}}\right) \left(\frac{\mathcal{E}_{\rm cr}}{10^{61}\ {\rm erg}}\right) \left(\frac{20}{\mathcal{R}_{\rm cr}}\right) \left(\frac{16\ {\rm Mpc}}{d}\right)^2$$



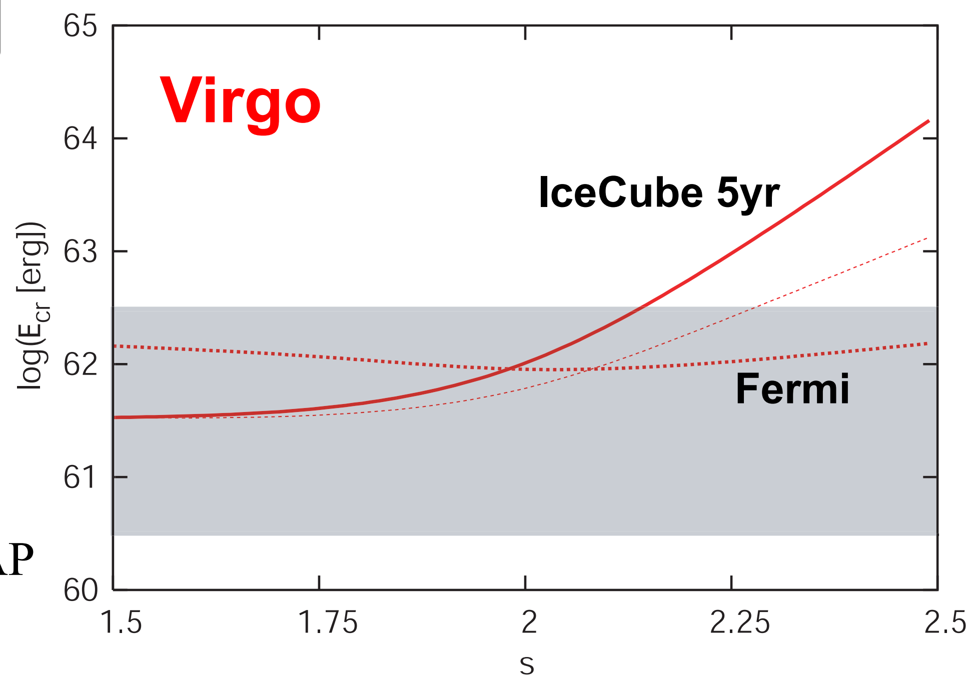
IceCube started to constrain the relevant parameter space!

(seen in the IceCube point source paper 2014)

Gamma-Ray Limits?



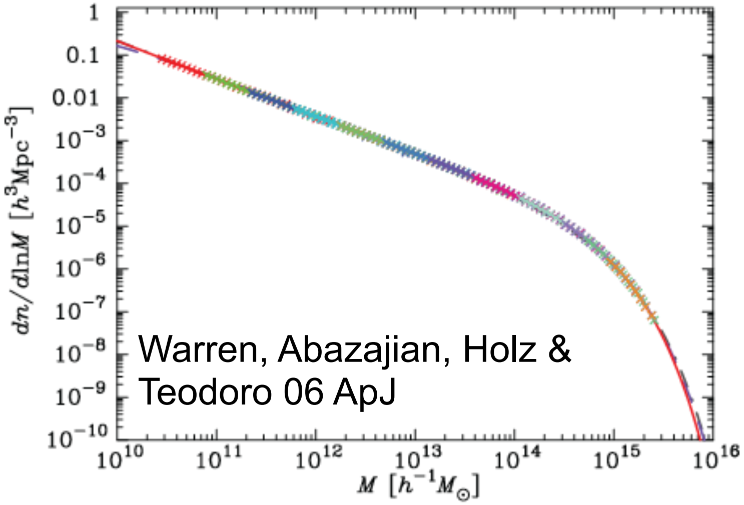
models have to be consistent with non-detection by Fermi (but connection to the diffuse flux is actually not trivial)



KM & Beacom 13 JCAP

Application to Dark Matter

- Clusters are also storage rooms of dark matter (DM)

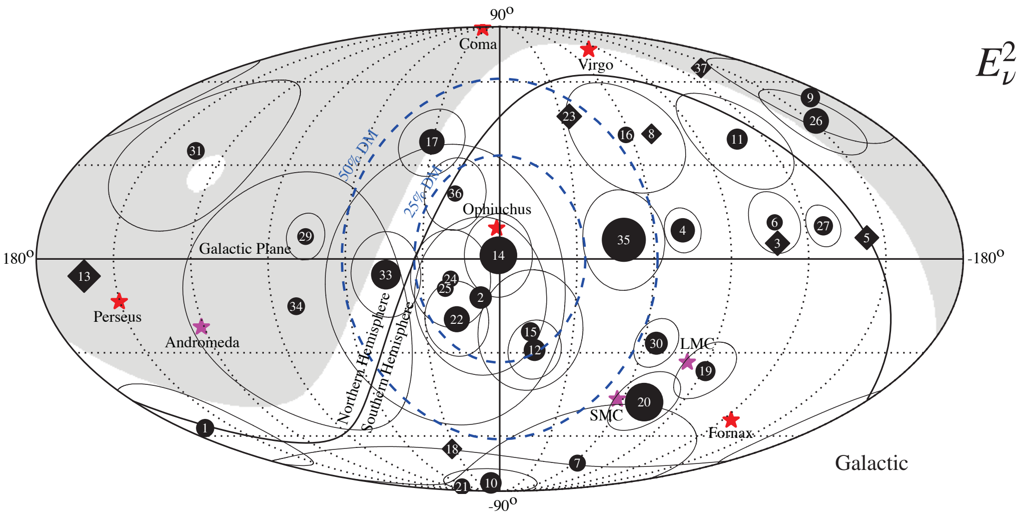


Warren, Abazajian, Holz & Teodoro 06 ApJ

τ_{dm} ~ a fewx10^{27} s

needed in the DM decay scenario

nearby DM halos (galaxies, clusters) enable us to test DM models

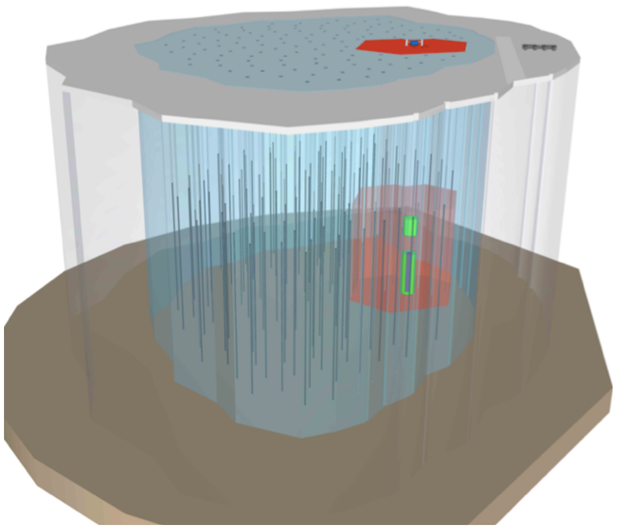


$$E_\nu^2 \phi_{\nu_\mu} \approx \frac{1}{12\pi d^2} \frac{M_{\rm dm} c^2}{\tau_{\rm dm} \mathcal{R}_\nu}$$
$$\simeq 1.3 \times 10^{-10}\ {\rm GeV\,cm^{-2}\,s^{-1}}\ \tau_{\rm dm,27.5}^{-1} (\mathcal{R}_\nu/15)^{-1}$$
$$\times \left(\frac{M_{\rm dm}}{5\times 10^{14} M_\odot}\right) \left(\frac{d}{16\ {\rm Mpc}}\right)^{-2},$$

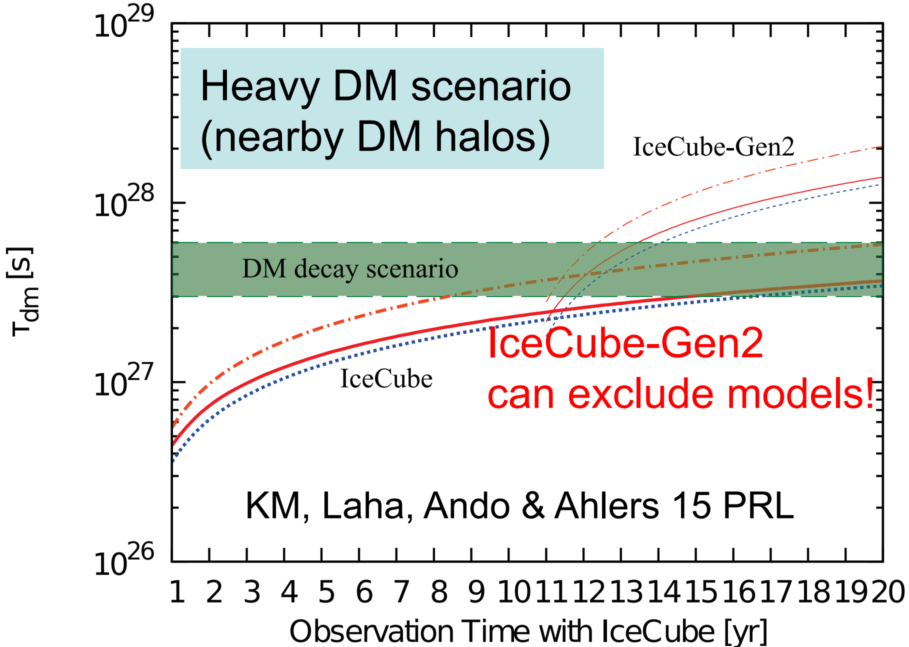
flux ∝ M_{dm}/D^2

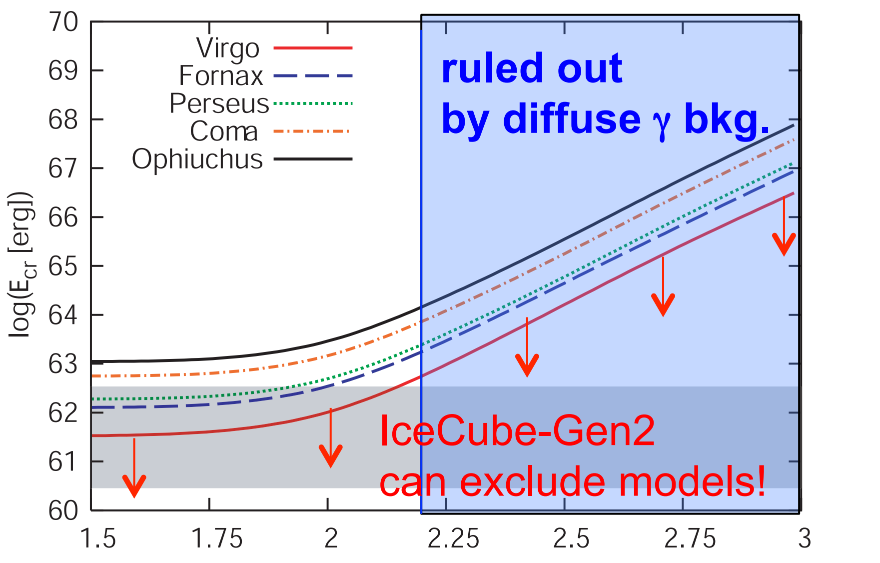
KM, Laha, Ando & Ahlers 15 PRL

What's Next?: Need to Identify the Sources



IceCube-Gen2





KM & Beacom 13 JCAP

Multiplet Searches are Independently Powerful

Non-detection of point sources give "upper" limits on the number density

For early (quasi-ignored) papers, Lipari 08, Silvestri & Barwick 10, KM, Beacom & Takami 12

$$N_s = b_{m,L}\left(\frac{\Delta\Omega}{3}\right) n_0^{\rm eff} d_{\rm lim}^3 < 1 \qquad d_{\rm lim} \approx \left(\frac{E_\nu L^{\rm eff}_{E_{\nu_\mu}}}{4\pi F_{\rm lim}}\right)^{1/2} \simeq 72\ {\rm Mpc}\left(\frac{E_\nu L^{\rm eff}_{E_{\nu_\mu}}}{10^{42}{\rm erg\,s^{-1}}}\right)^{1/2}\left(\frac{F_{\rm lim}}{10^{-9}\ {\rm GeV\,cm^{-2}\,s^{-1}}}\right)^{-1/2}$$

$$\Rightarrow\quad n_0^{\rm eff} \lesssim 2.5\times10^{-7}\ {\rm Mpc^{-3}}\left(\frac{E_\nu L^{\rm eff}_{E_{\nu_\mu}}}{10^{42}{\rm erg\,s^{-1}}}\right)^{3/2}\left(\frac{F_{\rm lim}}{10^{-9}\ {\rm GeV\,cm^{-2}\,s^{-1}}}\right)^{-3/2}\left(\frac{b_{m,L}}{5}\right)^{-1}\left(\frac{\Delta\Omega}{2\pi}\right)^{-1}$$

IceCube measurements fix the normalization

$$n_0^{\rm eff}\left(\frac{E_\nu L^{\rm eff}_{E_{\nu_\mu}}}{10^{42}{\rm erg\,s^{-1}}}\right) \simeq 1.6\times10^{-7}\ {\rm Mpc^{-3}}\left(\frac{\xi_z}{3}\right)^{-1}\left(\frac{E_\nu^2\Phi_{\nu_\mu}}{10^{-8}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}}\right)$$

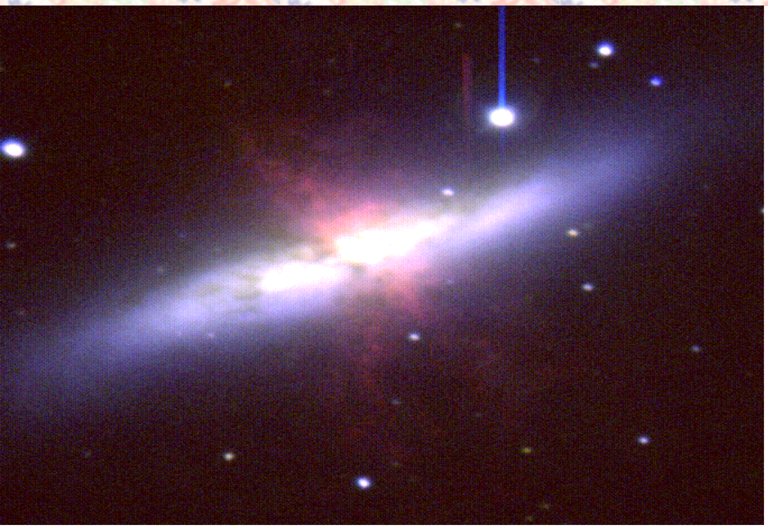
$$\Downarrow$$

"lower" limits $\quad n_0^{\rm eff} \gtrsim 0.8\times10^{-5}\,{\rm Mpc^{-3}}\left(\frac{b_{m,L}}{5}\right)^2\left(\frac{\xi_z}{0.6}\right)^{-3}\left(\frac{F_{\rm lim}}{10^{-9}\ {\rm GeV\,cm^{-2}\,s^{-1}}}\right)^{-3}\left(\frac{\Delta\Omega}{2\pi}\right)^2$

cluster accretion shock model: weak (even negative) evolution, $n_0^{\rm eff}\sim10^{-6}$ Mpc^{-3}
cluster/group internal accelerator model: positive evolution, $n_0^{\rm eff}\sim10^{-5}$ Mpc^{-3}

For discussion after IceCube's discovery, Ahlers & Halzen 14, Kowarski 15, KM & Waxman 16

Starburst/Star-Forming Galaxies



- High-surface density

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

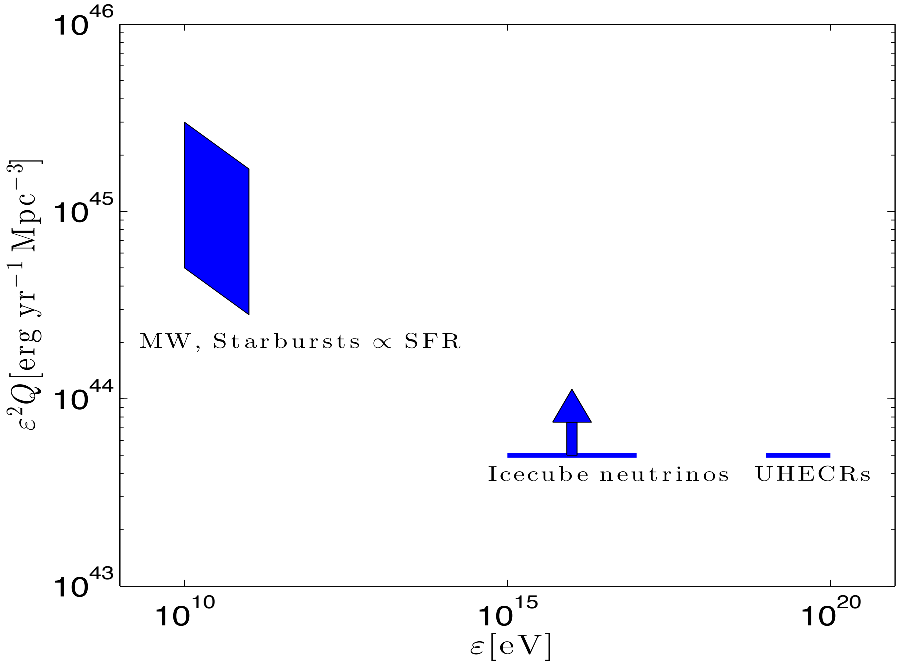
  high-z MSG: Σ_g~0.1 g cm^{-3} → n~10 cm^{-3}

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

- Supernovae, hypernovae, GRBs, AGN etc.

  SNR shock

$$\varepsilon_p^{\rm max} \approx (3/20)(V_{\rm ej}/c)eBR_{\rm Sed} \simeq 3.1\,{\rm PeV}\,B_{-3.5}\mathcal{E}_{\rm ej,51}^{1/3}V_{\rm ej,9}^{1/3}n^{-1/3}$$



SFG CR energy budget ~ Milky Way CR budget

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

SBG CR energy budget

$$Q_{\rm cr} \sim 8.5 \times 10^{44}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1}\varrho_{{\rm SFR},-3}$$

UHECR energy budget integrated over UHE

$$Q_{\rm uhecr} \sim {\rm a\ few} \times 10^{44}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}$$

CR Confinement and Escape

- Low-energy CRs are advected by starburst-driven winds

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

f_{pp}>~1 ↔ "calorimetric": almost all CR energy is used for ν & γ

$$E_\nu^2 \Phi_{\nu_i} \sim 10^{-9}\text{–}10^{-7} \ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

(Loeb & Waxman 06 JCAP)

- Diffusive escape is more important for high-energy CRs
  (a) $f_{pp}>1$ → a break is determined by $t_{diff}=t_{pp}$
  (b) $f_{pp}<1$ → a break is determined by $t_{diff}=t_{adv}$

(KM, Ahlers & Lacki 13 PRDR)

In case (a) $\varepsilon_p^b \approx 21 \ {\rm PeV} \ D_{0,26}^{-3} \Sigma_{g,-1}^3 (h/{\rm kpc})^3$

⇨ $\varepsilon_\nu^b \approx 0.04 \varepsilon_p^b \simeq 0.80 \ {\rm PeV} \ D_{0,26}^{-3} \Sigma_{g,-1}^3 (h/{\rm kpc})^3$

※ diffusion coefficient D_0 must be smaller than the Galactic one ($D_0 \sim 10^{28}$ cm^2 s^{-1})

Luminosity Function & Calorimetry

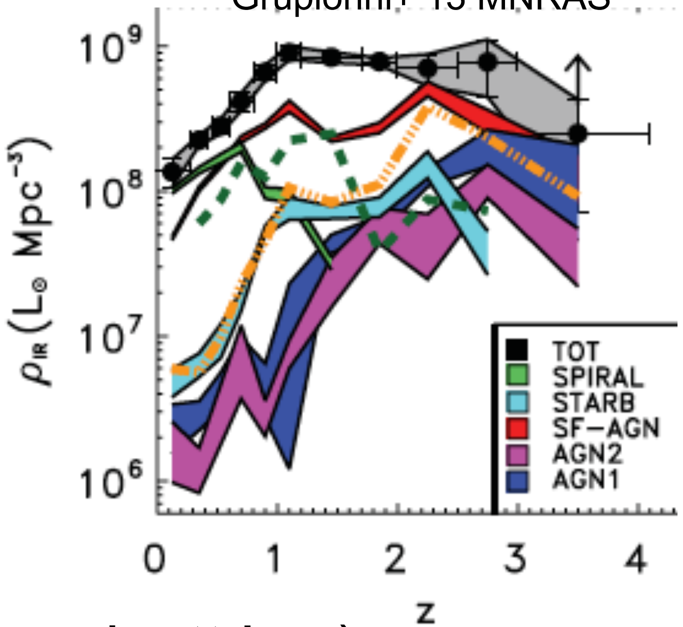
LF is described by the Schechter function

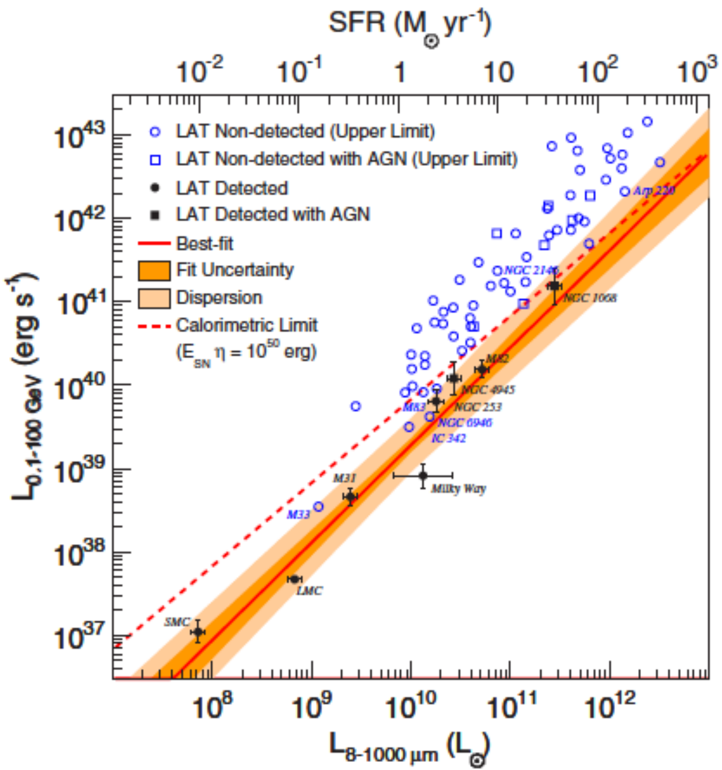
$$\Phi(L)\mathrm{d}\log L = \Phi^* \left(\frac{L}{L^*}\right)^{1-\alpha} \exp\left[-\frac{1}{2\sigma^2}\log_{10}^2\left(1+\frac{L}{L^*}\right)\right]\mathrm{d}\log L$$

$\alpha\sim1$, $L^*\sim10^{11}\ L_{sun}$: typical infrared luminosity

Redshift evolution: m~3-4 up to z~1 for $(1+z)^m$

Grupionni+ 13 MNRAS





SFR ∝ L_{IR} (Kennicutt law)

$L_\gamma \propto L_{IR}^{1.17}$ (Fermi collaboration 12 ApJ)

(basic agreement w. calorimetry)

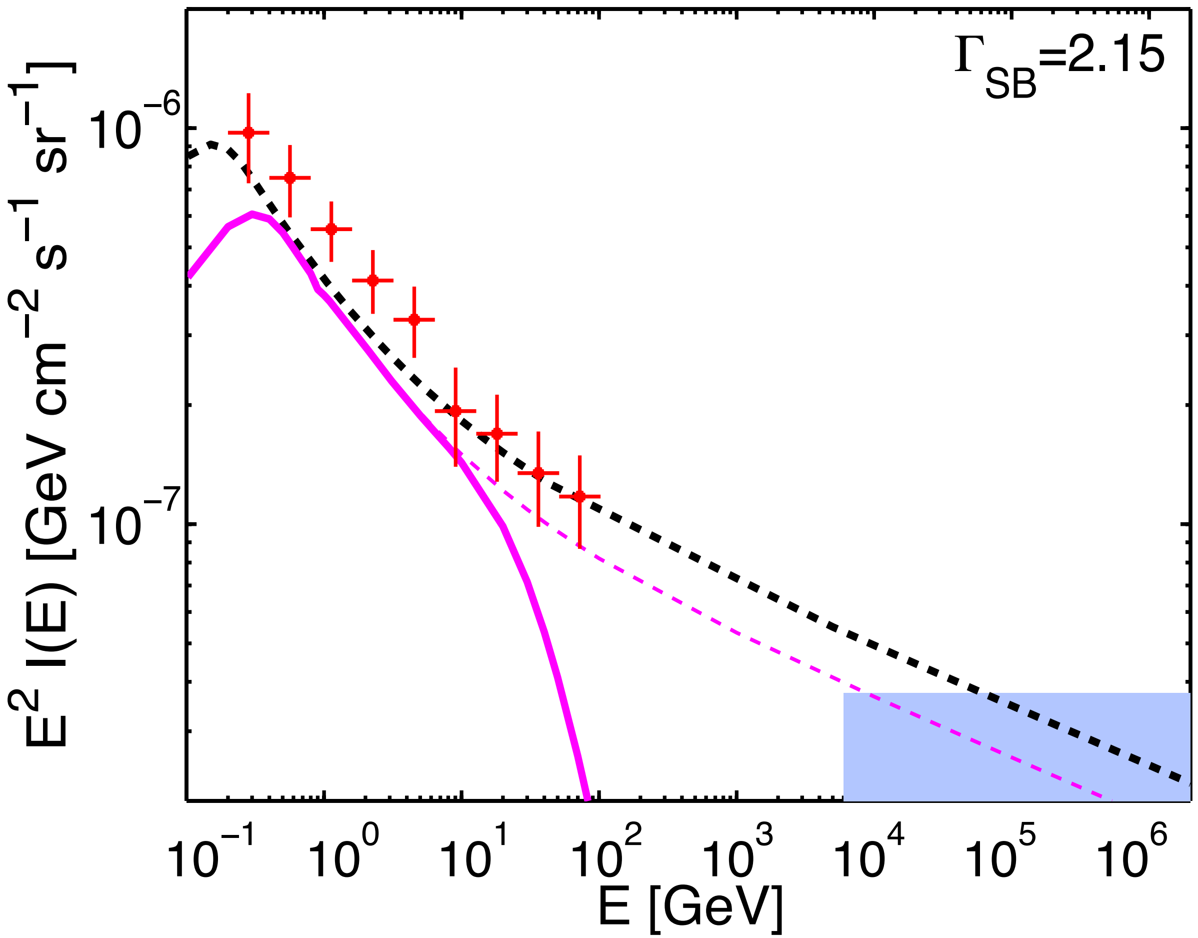
→ "typical" muon neutrino luminosity:

$EL_E \sim 2\times10^{40}$ erg s^{-1}

"effective" density: $n_0\sim10^{-5}$ Mpc^{-3}

can be reached by Gen2 (KM & Waxman 16)

Star-Forming/Starburst Galaxies, νs, γs



Tamborra, KM & Ando
14 JCAP

- Consistent w. obs. & a multi-PeV break is possible
- How can CRs get accelerated above 100 PeV?

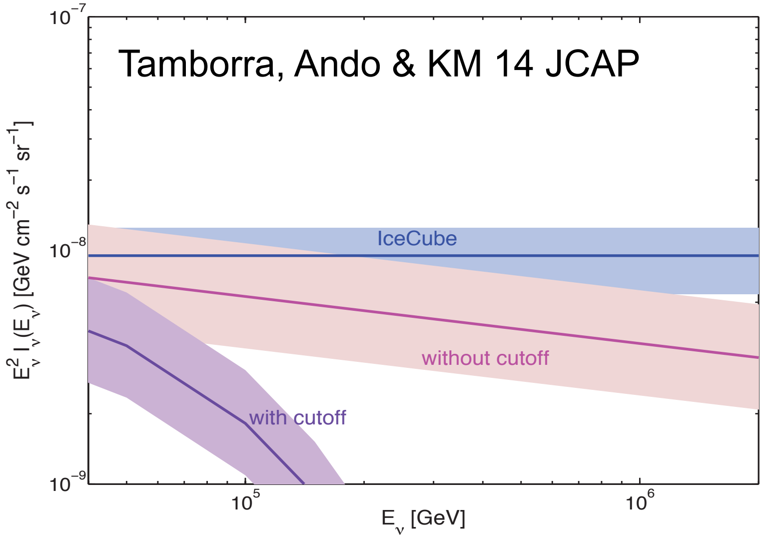
Necessity of Super-Pevatrons

Our Galaxy's CR spectrum

Knee at 3 PeV

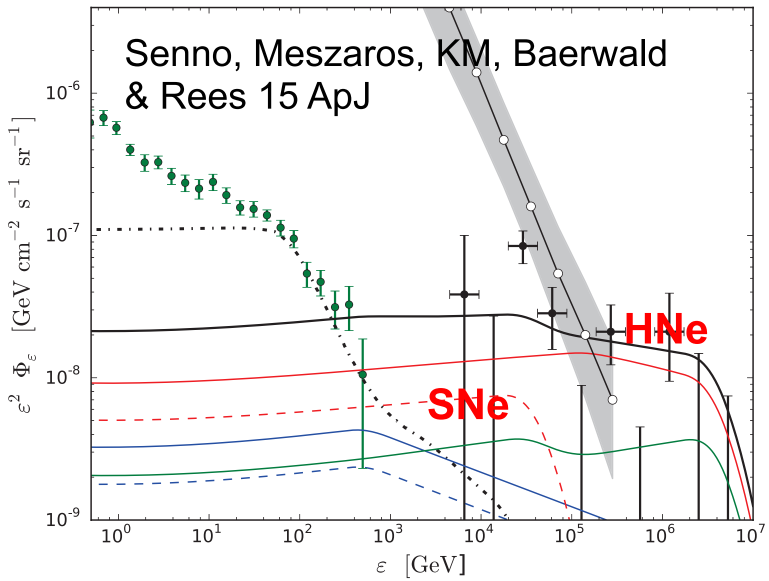
→ neutrino knee at ~ 100 TeV

So ordinary supernovae (SNe) are not sufficient to explain >0.1 PeV data



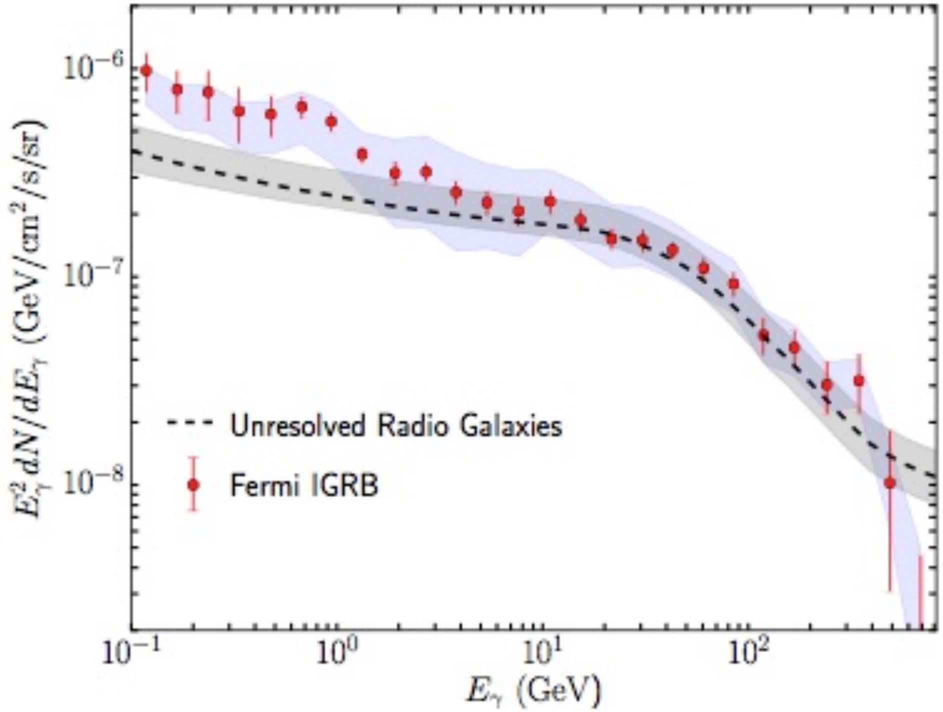
Possible solutions

1. Hypernovae (HNe) KM+ 13, Liu+ 14, Senno+ 15
2. Gamma-ray bursts Dado & Dar 14, Wang+ 15
3. Low-luminosity gamma-ray bursts/ Trans-relativistic supernovae
4. Type IIn supernovae Zirakashvilli & Ptuskin 16
5. AGN jets/disk outflows KM+ 14, Tamborra+ 14
6. B fields amplified to ~mG KM+ 13



How about Radio Galaxies?

Detected by Fermi & possible origin of the diffuse γ-ray bkg.
Q. Can they explain the IceCube flux like starbursts?



Hooper, Linden & Lopez 16

f_{pp} in elliptical galaxies: $f_{pp} \simeq 1.2 \times 10^{-3}\ n_{-1} D_{0,27.5}^{-1} \varepsilon_{p,17}^{-1/3} (R/3\ \mathrm{kpc})^2$ non-calorimetric!

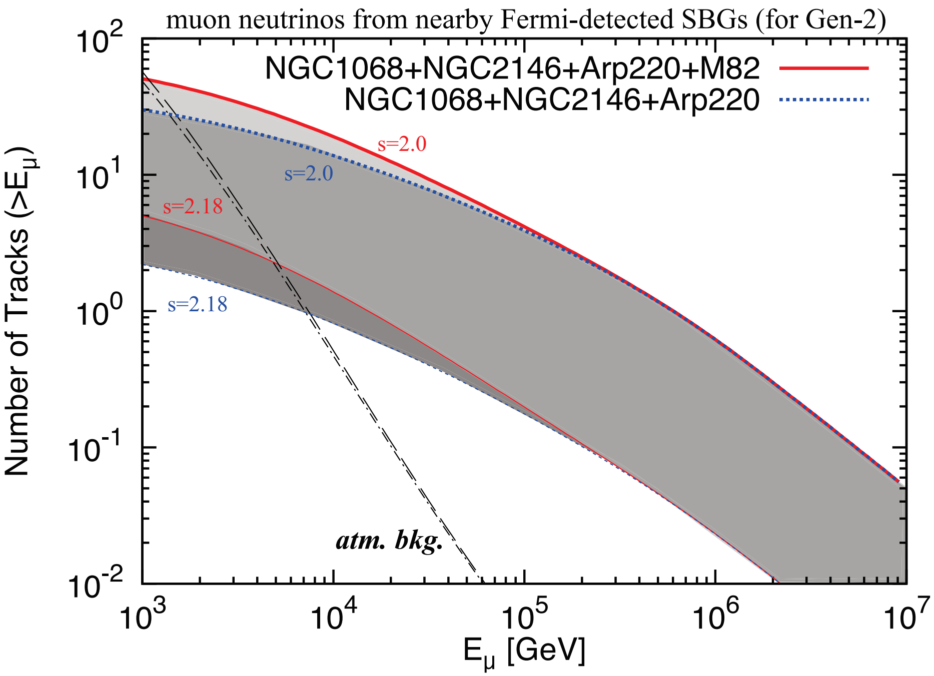
Many of radio galaxies show time variablity → more compact
Efficient pp inside jets leads to the energetics crisis (Atoyan & Dermer 01)
But AGN core emission is possible (Kimura, KM & Toma 15, Tjus et al. 14)

What's Next?: Need to Identify the Sources

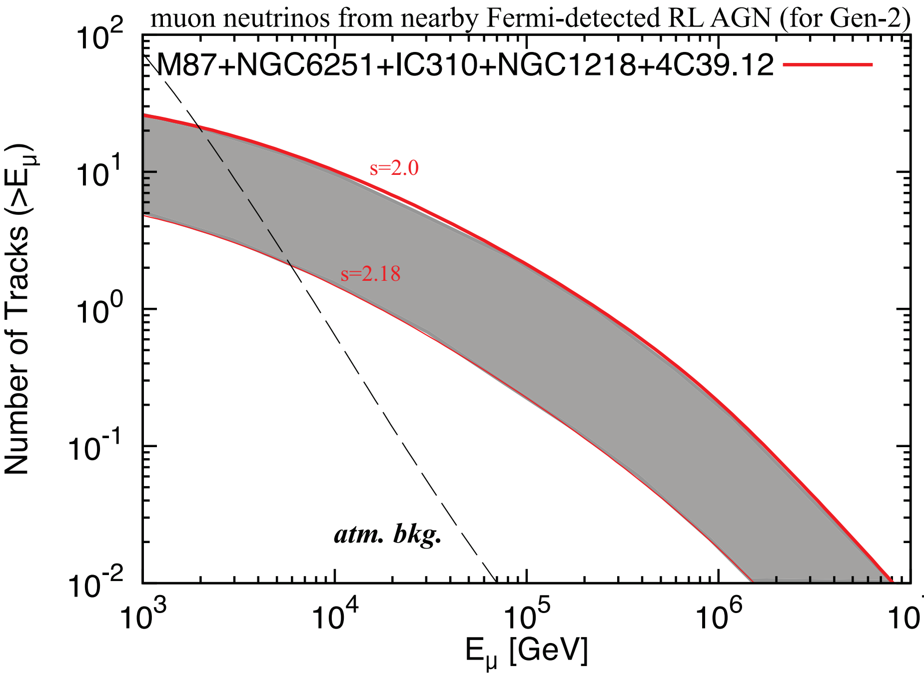
Starbursts and radio galaxies are already detected by Fermi

For pp scenarios, we have strong predictions for IceCube-Gen2

nearby starburst galaxies
in the northern hemisphere



nearby radio galaxies
in the northern hemisphere

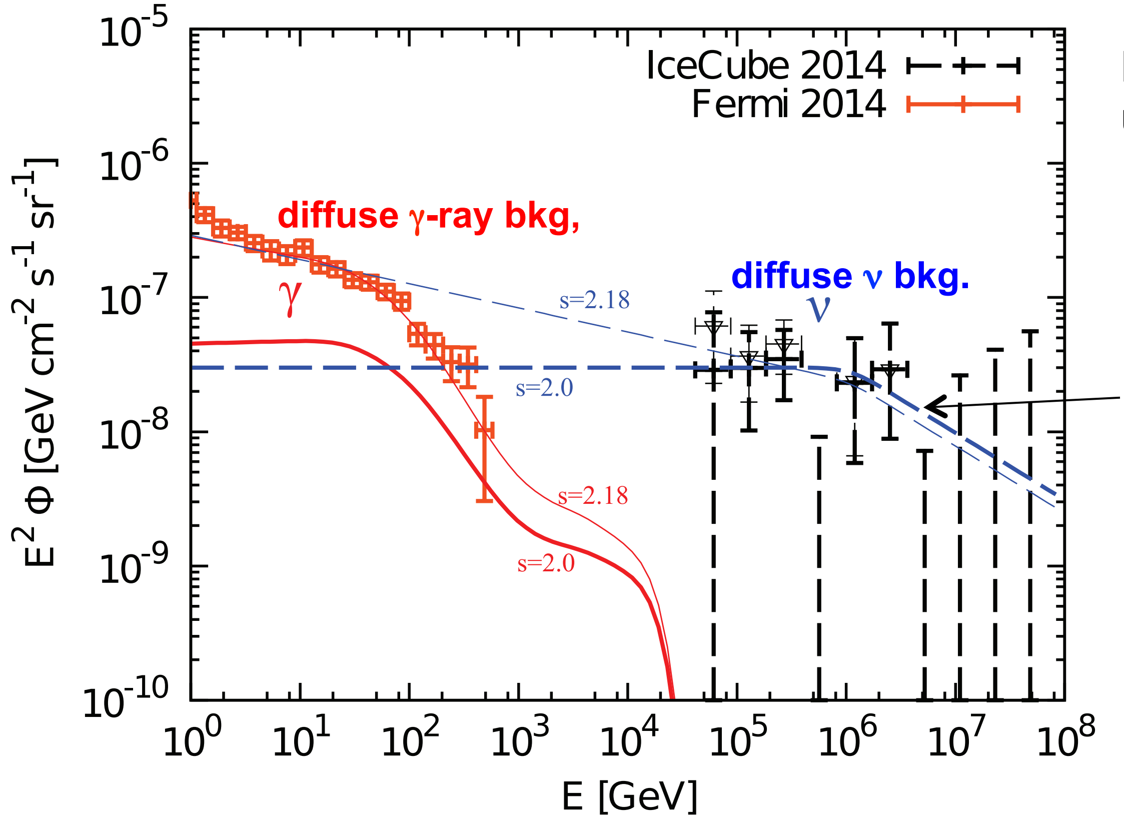


V=10 km3 & best ang. res.=0.1 deg & 5 yr obs. assumed

KM & Waxman 16

Wrap up: Predictions of CR Reservoir Models

- 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

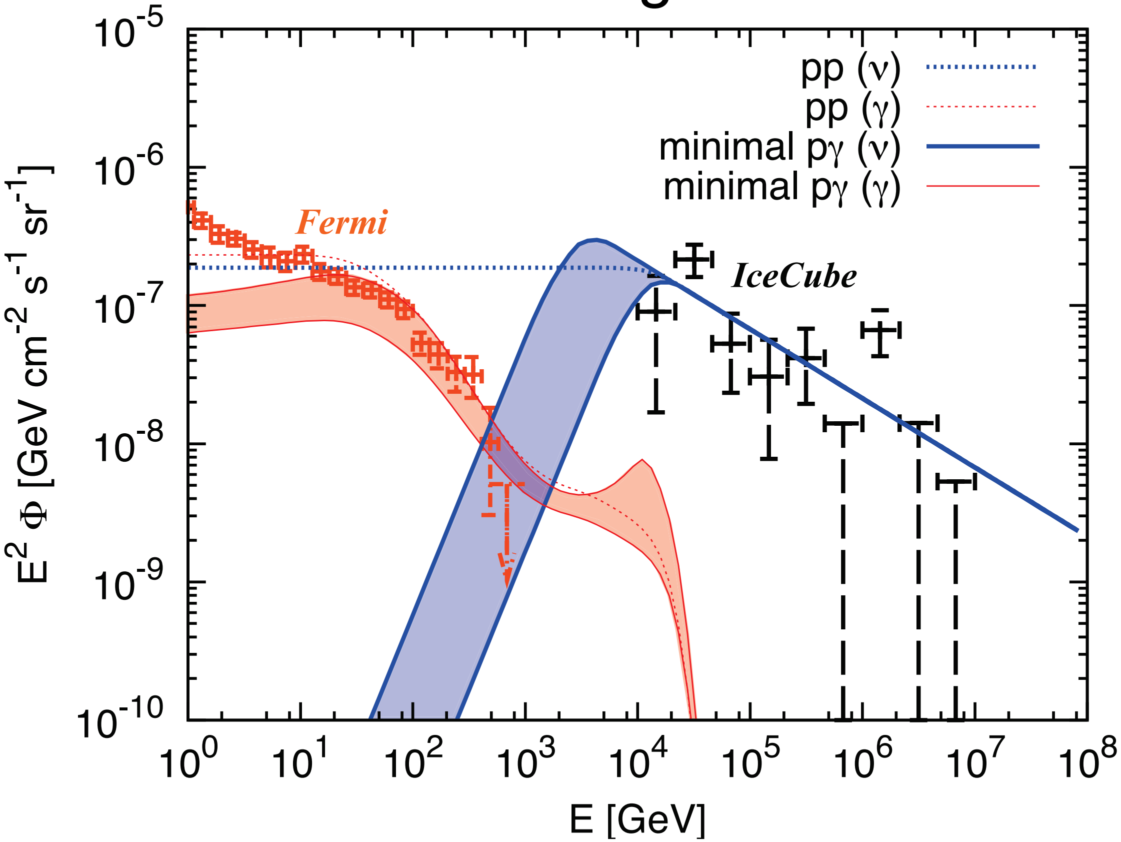
diffusive escape of CRs

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

Proposed tests: 1. (Stacking) searches for neutrinos & γ rays from nearby reservoirs
2. Decomposing the diffuse γ-ray bkg.
3. Measurements of neutrino data below 100 TeV

Beyond Waxman-Bahcall?: Low-Energy "Excess" Problem

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



KM, Guetta & Ahlers 16 PRL

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

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

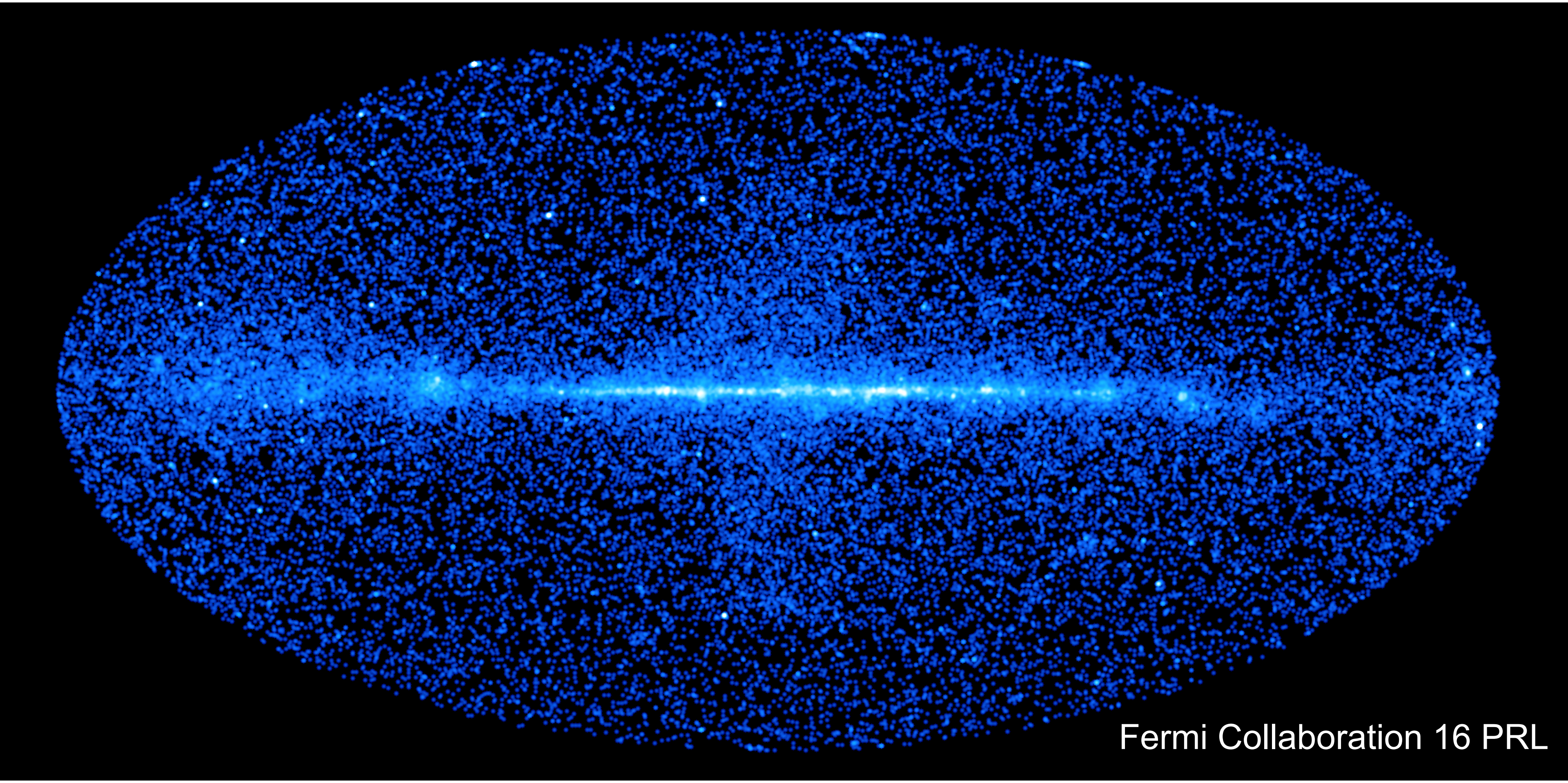
minimum pγ:
~30 TeV is just around energy due to the pion production threshold

- 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!

Implications of Detailed Gamma-Ray Studies



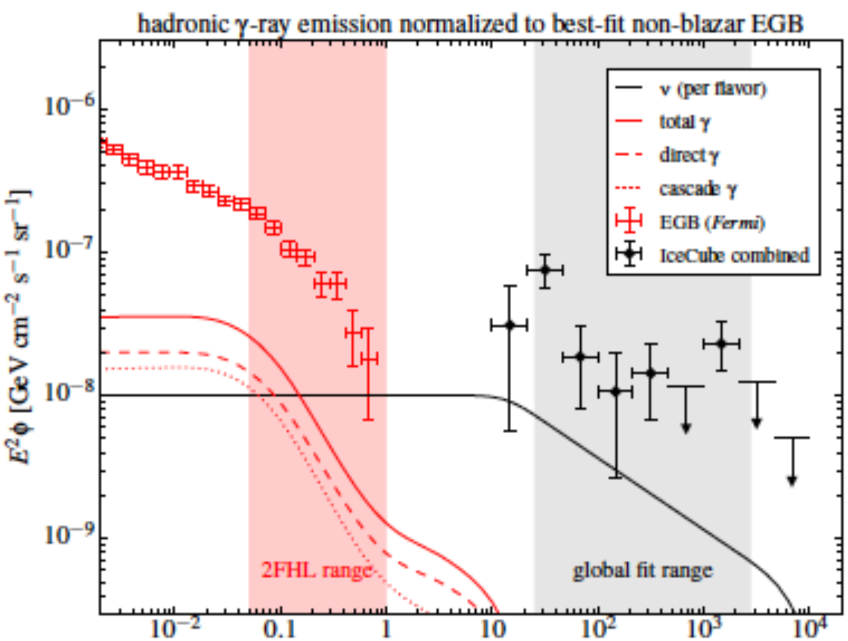
Photon fluctuation analyses (Poisson term of angular power spectra)

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

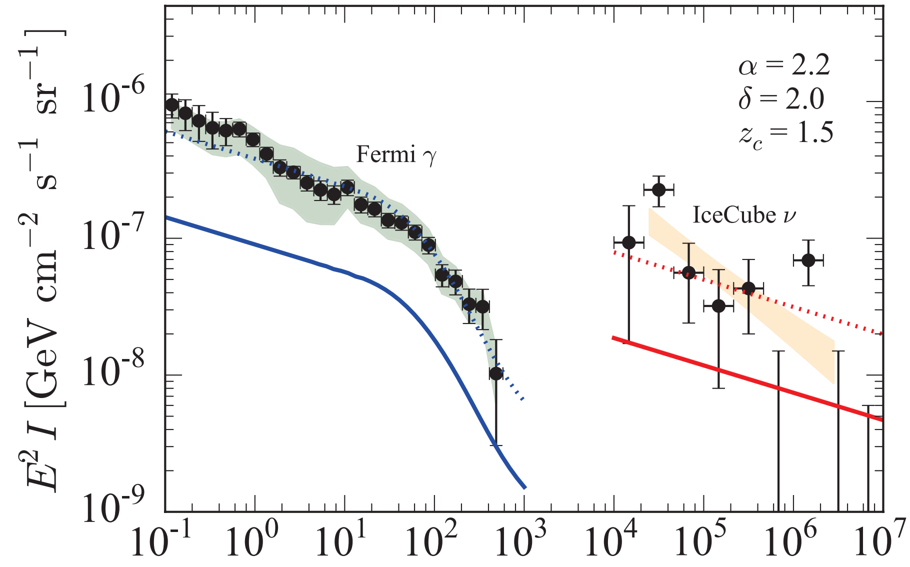
Non-blazar contribution < 14±14%

Implications of Detailed Gamma-Ray Studies

Our conclusion has been confirmed by subsequent papers



Bechtol+ 16 ApJ



Ando+ 15 PRL

shot-noise in diffuse γ-ray bkg.

cross corr. between galaxy catalogues

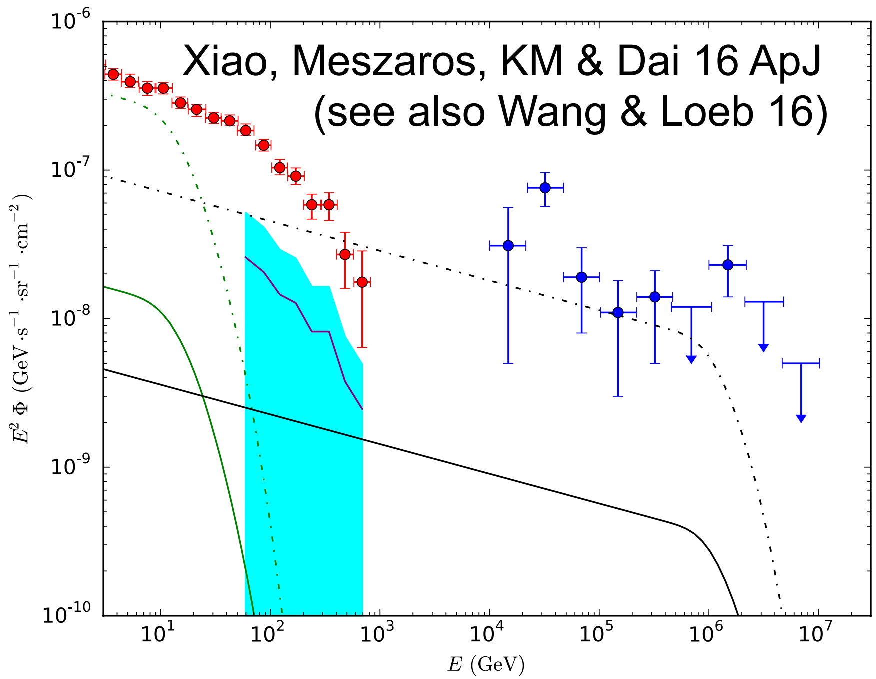
Given that IceCube's data above 100 TeV are explained…

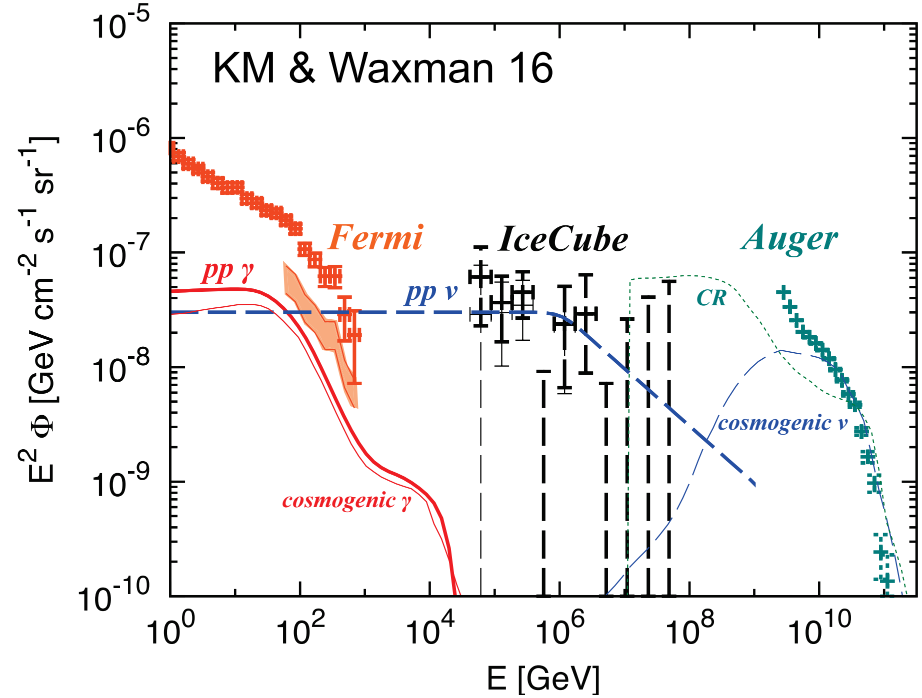
Decomposition of extragalactic γ-ray bkg. gives tighter limits: s<2.0-2.1

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

Implications of Detailed Gamma-Ray Studies

Our conclusion has been confirmed by subsequent papers





- This conclusion is driven by the interpretation of 10-100 TeV data
  could be alleviated by possible high-z only contributions
- The model (s=2.0) in MAL2013 does not contradict the Fermi data
  (non-blazar EGB is well-explained by combination w. cosmogenic γ!)
- But galactic CR production should be dominated by super-Pevatrons

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

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

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

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

→

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

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

→

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

30 TeV-3 PeV ν constrains 1-100 GeV γ

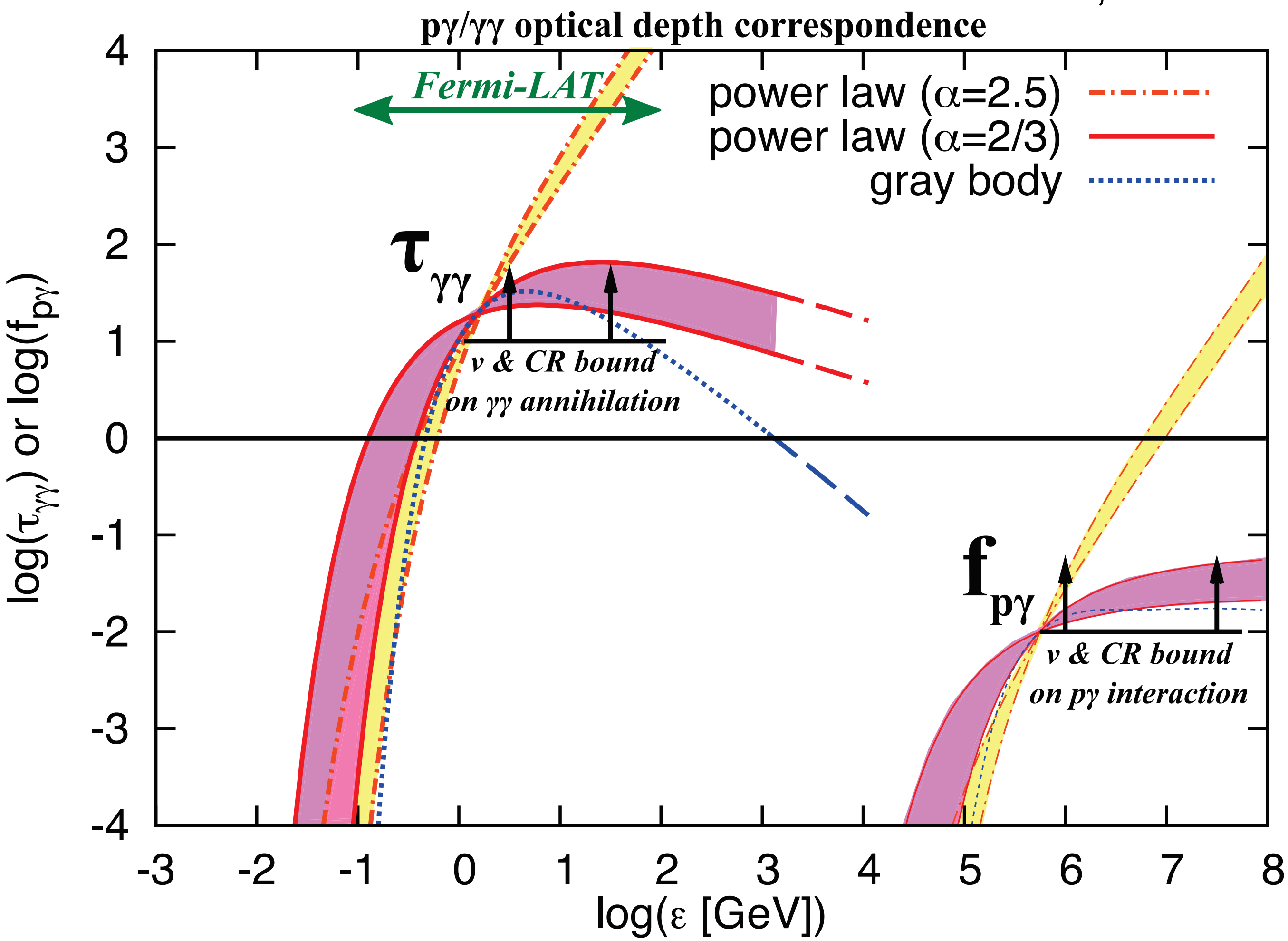
- Neutrino production efficiency $f_{p\gamma}$ cannot be too small

1. $f_{p\gamma}$ << 1 unnatural (requiring fine tuning), Do not overshoot the observed CR flux (Yoshida & Takami 14 PRD)
2. Comparison w. non-thermal energy budgets of known objects (galaxies, AGN, cluster shocks etc.)

→ $f_{p\gamma} \gtrsim 0.01$ → $\tau_{\gamma\gamma} \gtrsim 10$

Indication of Gamma-Ray Dark Cosmic-Ray Accelerators

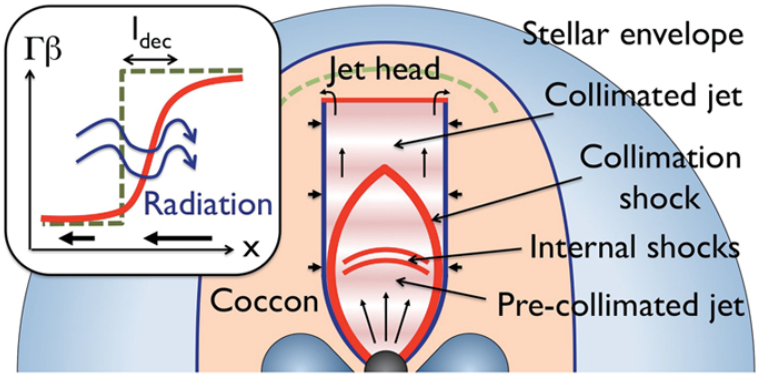
KM, Guetta & Ahlers 16 PRL

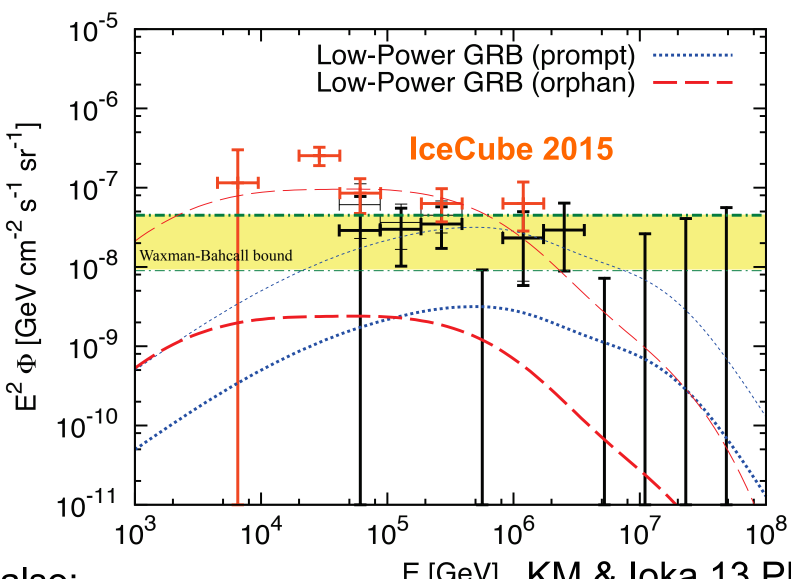


- Bounds on $\tau_{\gamma\gamma}$ hold for both thermal and nonthermal photon targets
- pγ mechanism: ν sources should naturally be obscured in GeV-TeV γ rays

GRBs and AGN as Hidden Neutrino Factories?

Low-power GRBs (choked jets)

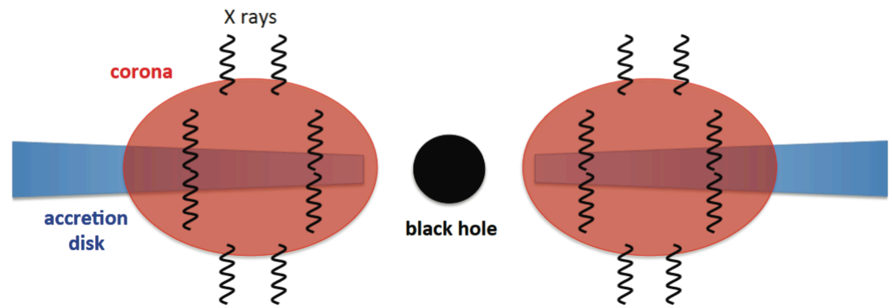


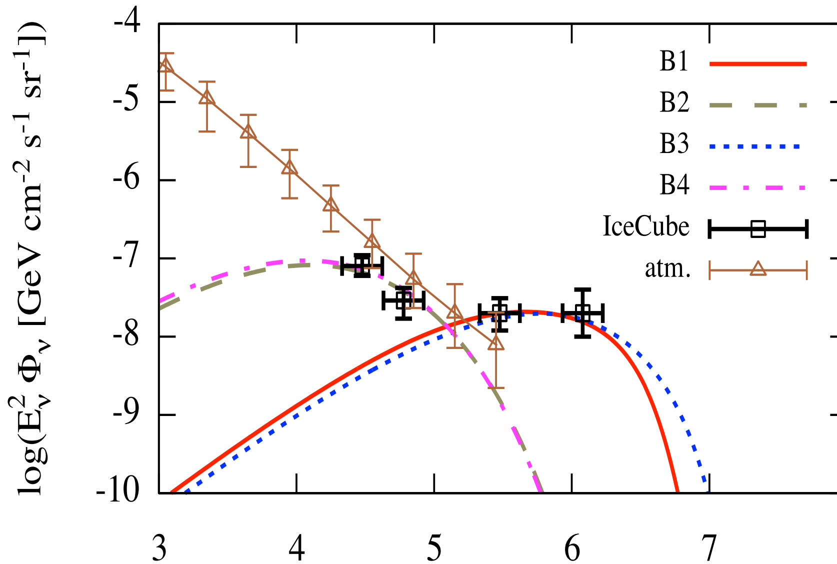


see also:
Bhattacharya+ 15
Nakar 15

KM & Ioka 13 PRL
Senno, KM & Meszaros 16
cf. KM+ 06 ApJL

Supermassive blackhole cores





Kimura, KM & Toma 15 ApJ

see also:
Stecker 13
Kalashev+ 15

Summary

CR reservoirs are promising multi-messenger sources

Nice features: theoretical predictions including a multi-PeV break
UHECRs may be explained simultaneously
Even the diffuse γ-ray bkg. can be explained (grand-unification)

Strong predictions that can be tested (KM, Ahlers & Lacki 13)

1. s<2.1-2.2
2. >30% to the diffuse sub-TeV γ-ray bkg.
3. IACTs should observe them as hard γ-ray sources

Source identification is possible w. IceCube-Gen2 (stacking, event clustering)

Understanding the 10-100 TeV data is important

LE excess: fluctuation? magical combination w. Gal. comp.? or new physics?

pp scenarios: most models suffer from tensions w. the diffuse γ-ray bkg.

pγ scenarios: hidden CR accelerators needed & tensions are naturally avoided
X-ray/MeV γ-ray counterparts (ex. low-power GRBs/AGN)
Are cosmic-ray connections just coincident?


Thank You!