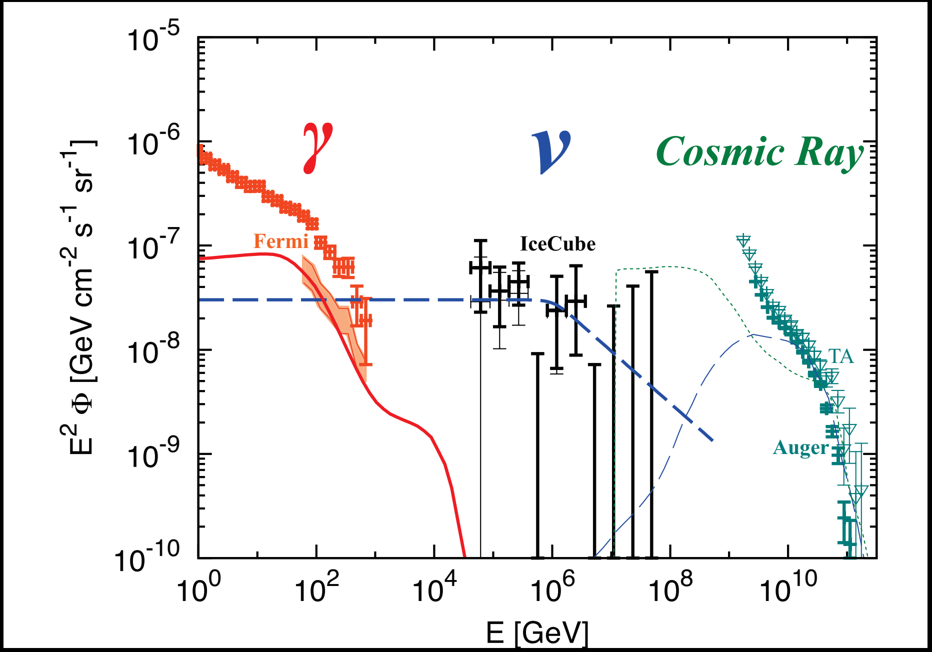
Cosmic-Ray Reservoirs as Non-Thermal Neutrino Sources



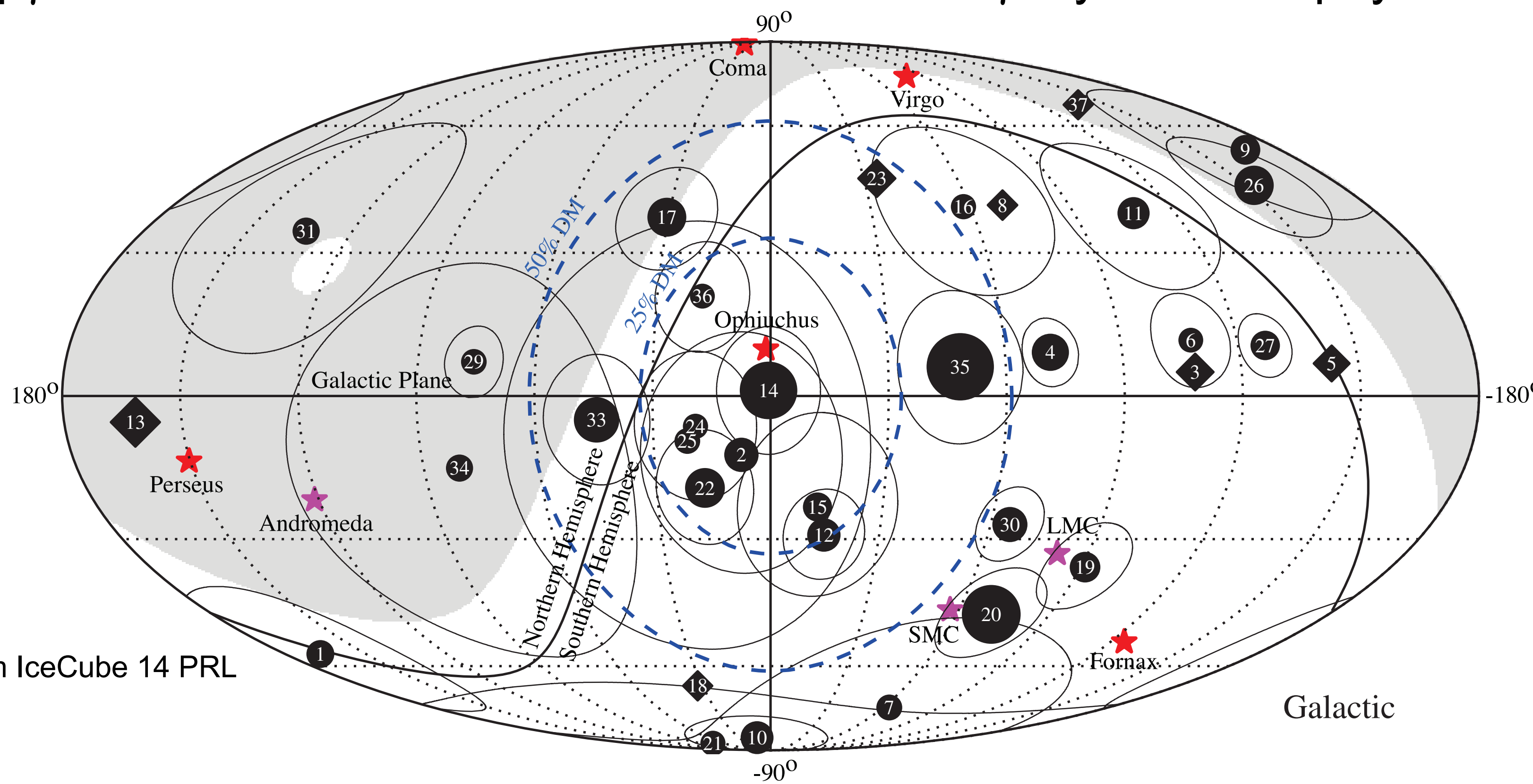
Kohta Murase (Penn State)

IPA 2017: May 10 @ WI-Madison

New Mystery in Particle Astrophysics

Origins and mechanism of cosmic neutrinos?

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



complied from IceCube 14 PRL

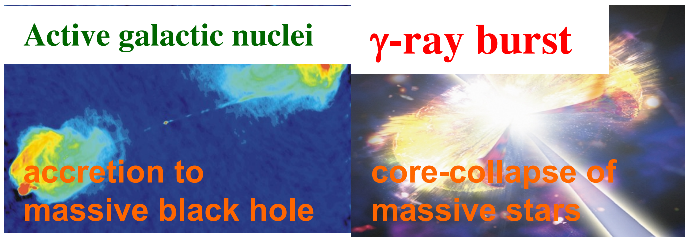
No single source detection & no significant clustering

Easy to see: mostly isotropic → extragalactic sources

(supported by sub-PeV diffuse γ-ray searches)

Astrophysical Extragalactic Scenarios

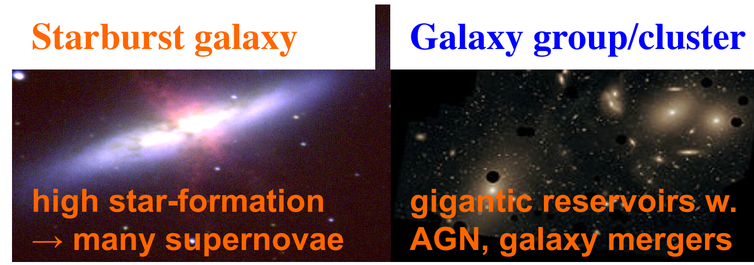
Cosmic-ray Accelerators (ex. UHECR candidate sources)



- 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, Bustamante+ 14
  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, Hooper 16

Cosmic-ray Reservoirs

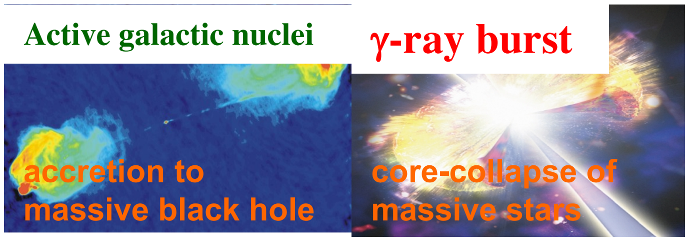


- Starburst galaxies (not Milky-Way-like)
  ex. Loeb & Waxman 06, Thompson et al. 07
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Katz et al. 13,
  Liu et al. 14, Tamborra, Ando & KM 14,
  Anchordoqui et al. 14, Senno et al. 15, Xiao+ 16

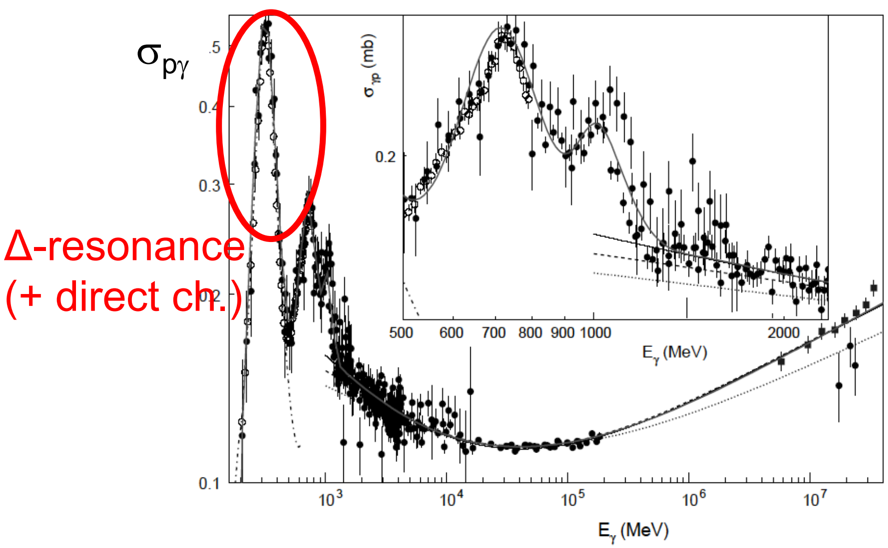
- Galaxy groups/clusters
  ex. Berezinsky et al. 97, KM et al. 08, Kotera et al. 09
  after Neutrino 2012:
  KM, Ahlers & Lacki 13, Zandanel+ 14
  Fang & Olinto 16, Fang & KM 17

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



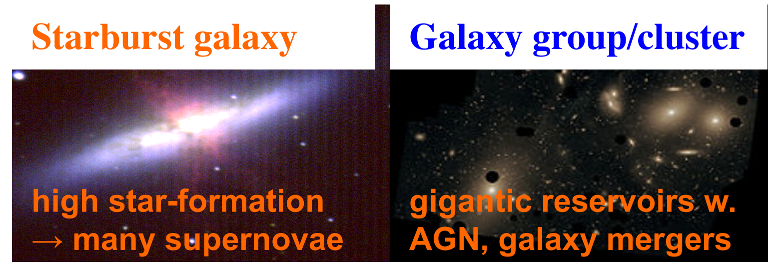
$$p+\gamma \rightarrow N\pi + X$$



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

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

Cosmic-ray Reservoirs



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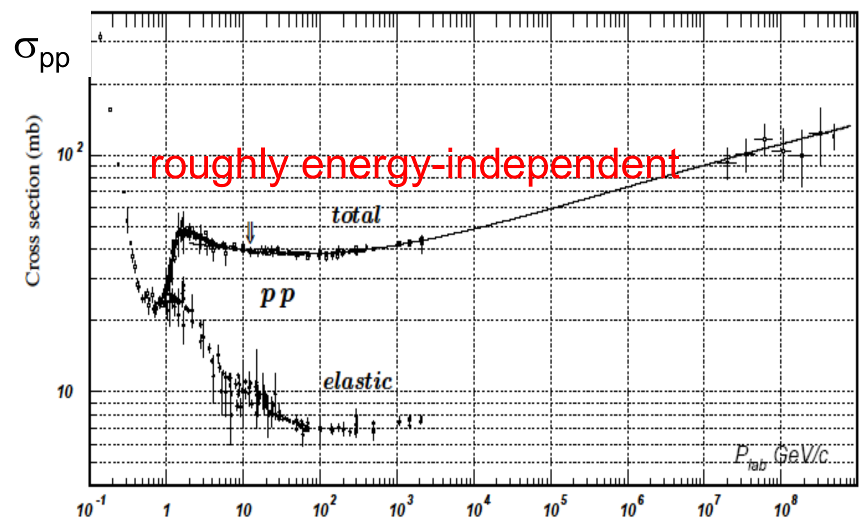

$\sigma_{pp} \sim 1/m_\pi^2 \sim 30$ mb

Astrophysical Extragalactic Scenarios

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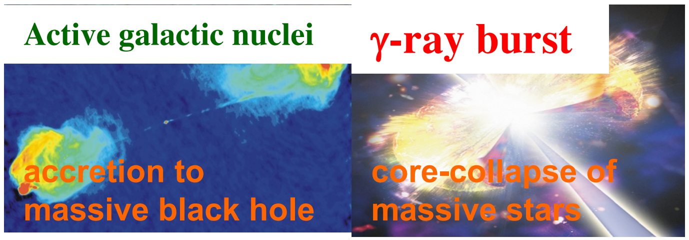

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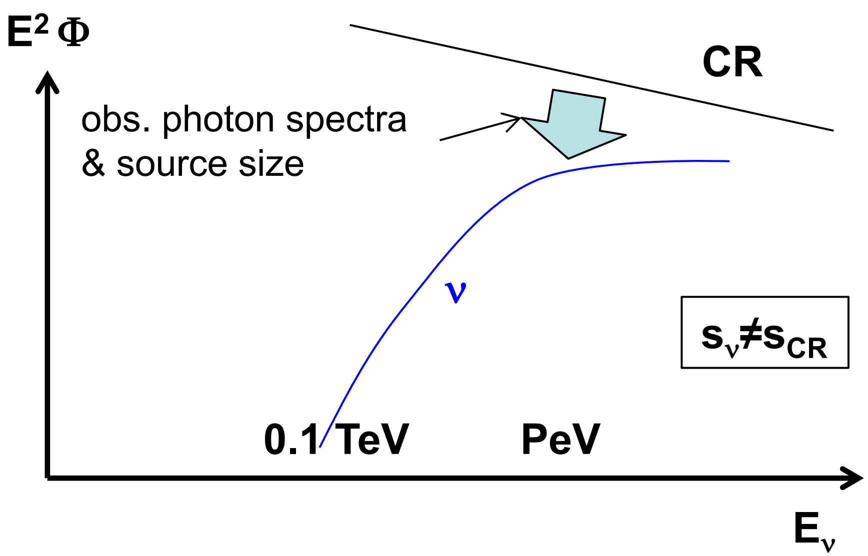
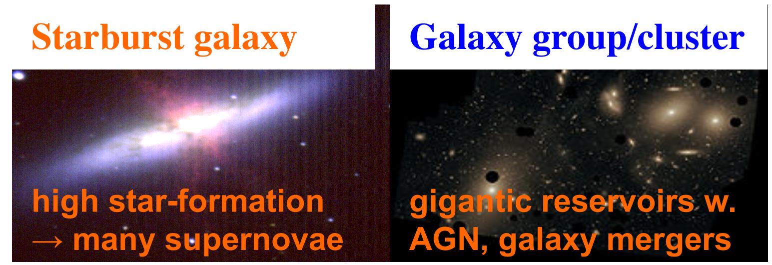


Cosmic-ray Reservoirs



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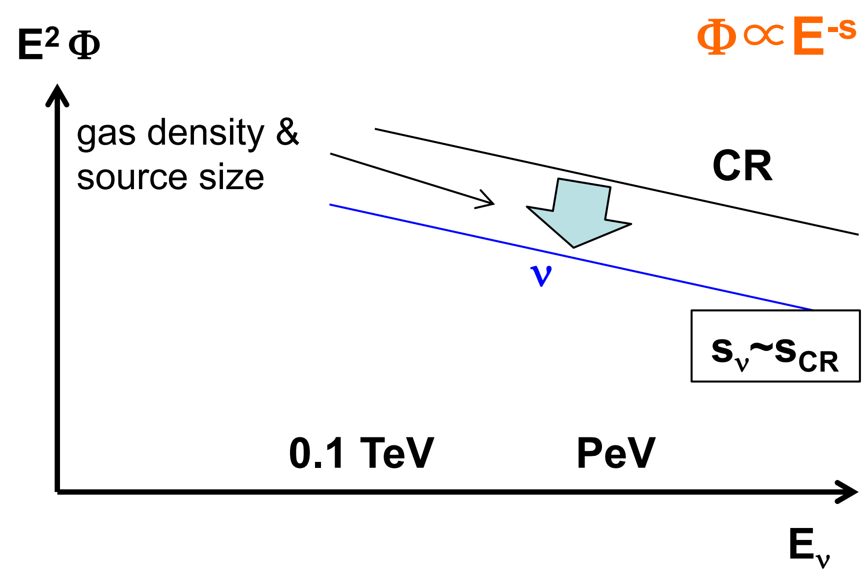

$E_\nu \sim 0.04\ E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Astrophysical Extragalactic Scenarios

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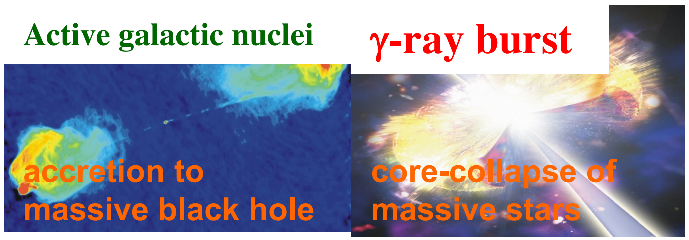
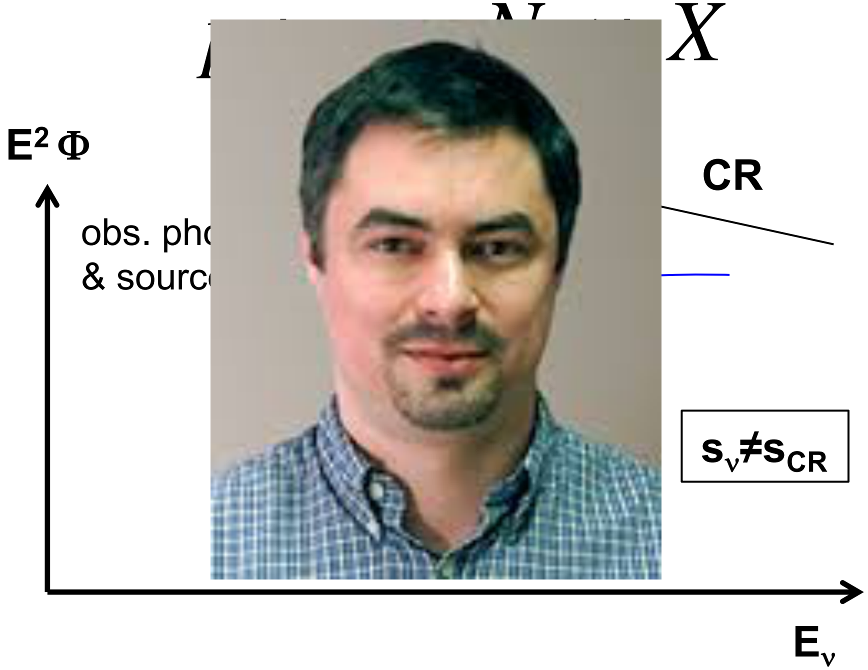
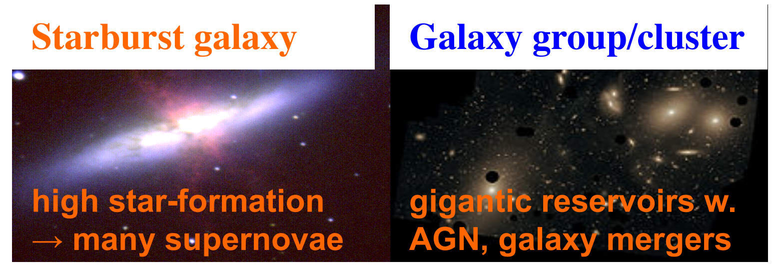
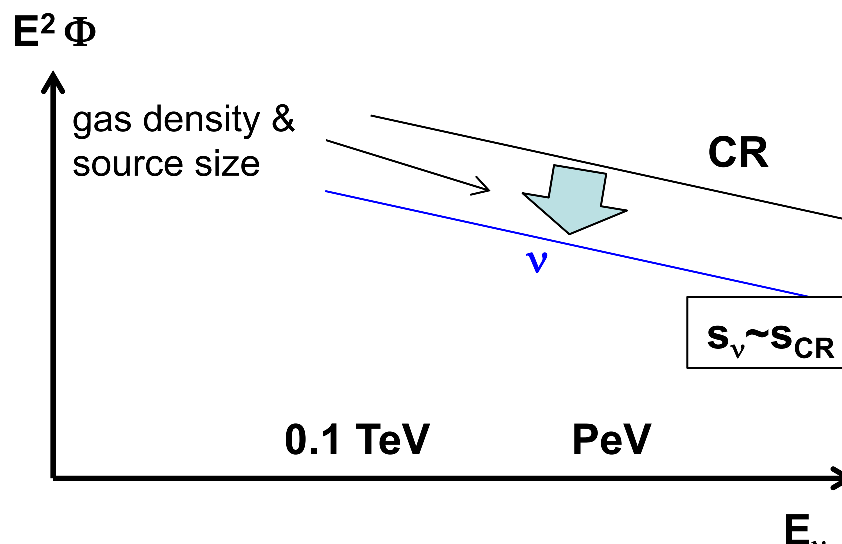




Cosmic-ray Reservoirs



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



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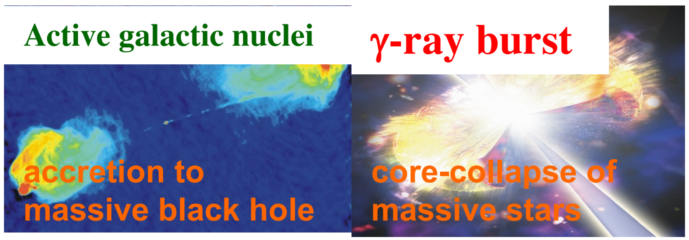

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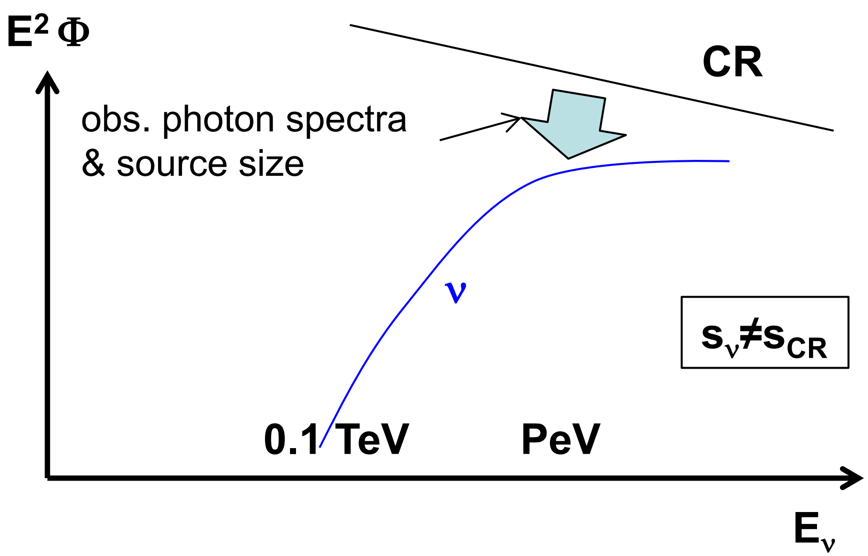
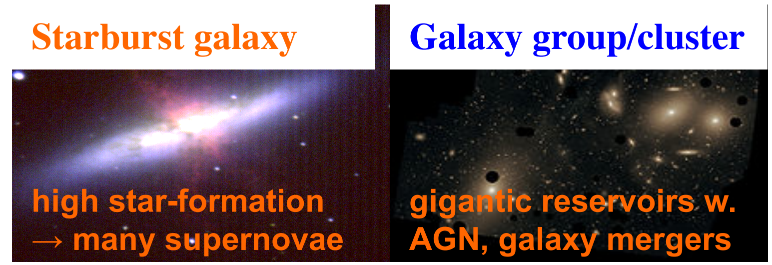
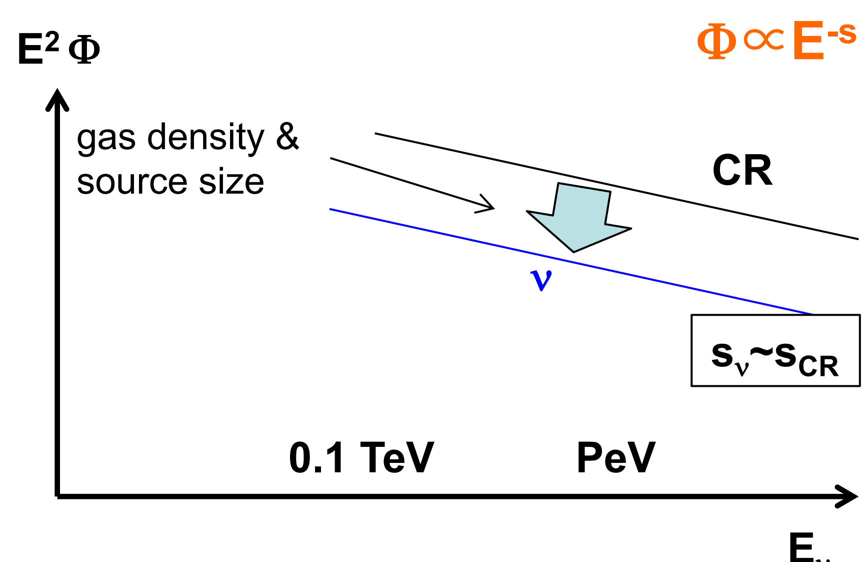


Cosmic-ray Reservoirs



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

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



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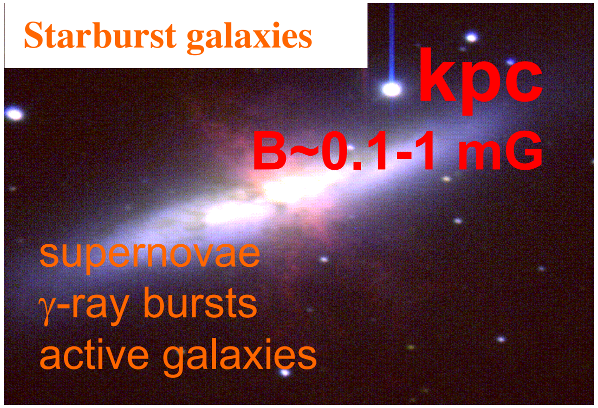
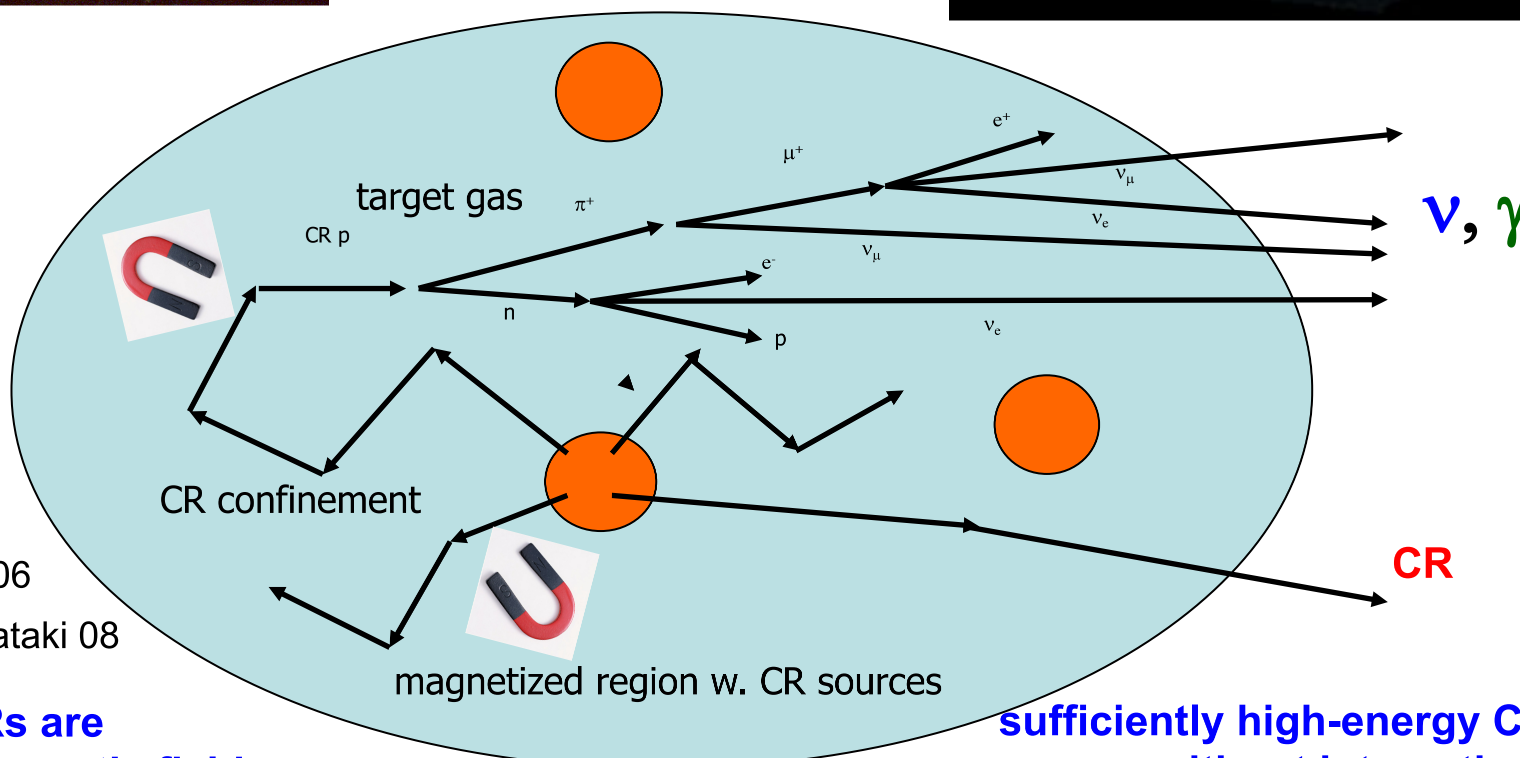
Cosmic-Ray Reservoirs



"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

Key Points of CR Reservoir Models

- Some contributions must exist: very natural (galaxies contain CRs & gamma rays are detected)

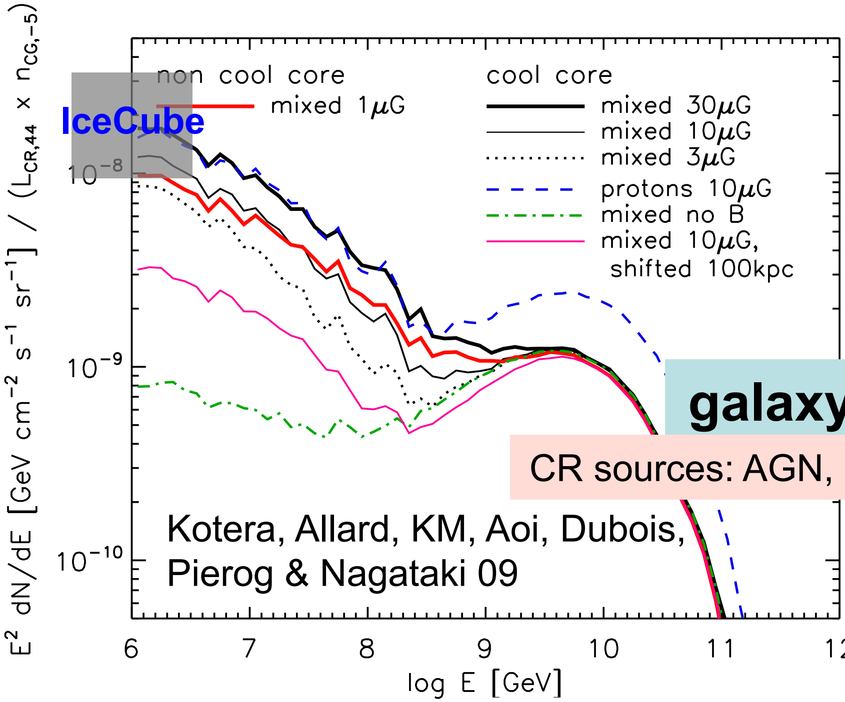
1. Expected before IceCube's discovery
   (a multi-PeV break/cutoff has been expected)
   (Loeb & Waxman 06, KM et al. 08 ApJ, Kotera, Allard, KM et al. 09)

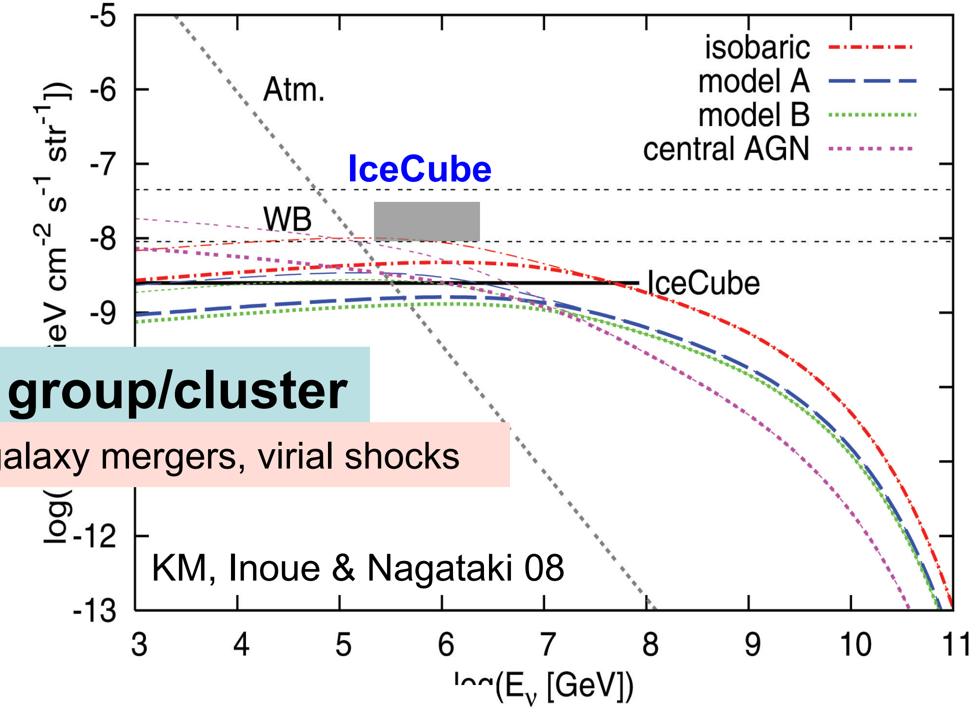
2. "Unification" of multi-messengers is possible
   (KM, Ahlers & Lacki 13, Katz et al. 13, Dado & Dar 14, Giancinti+ 15, KM & Waxman 16)

Issue: tension w. Fermi gamma-ray limits?
relevance of "medium-energy neutrino data"
(KM, Guetta & Ahlers 1509.00805, Kistler 1511.01530, Bechtol+ 1511.00688)

galaxy group/cluster

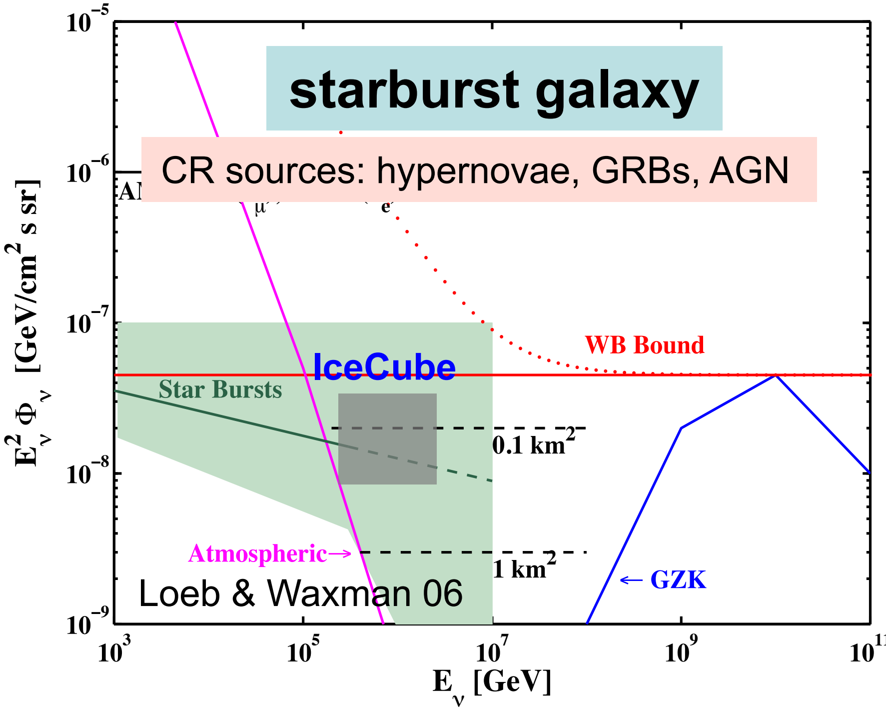
CR sources: AGN, galaxy mergers, virial shocks





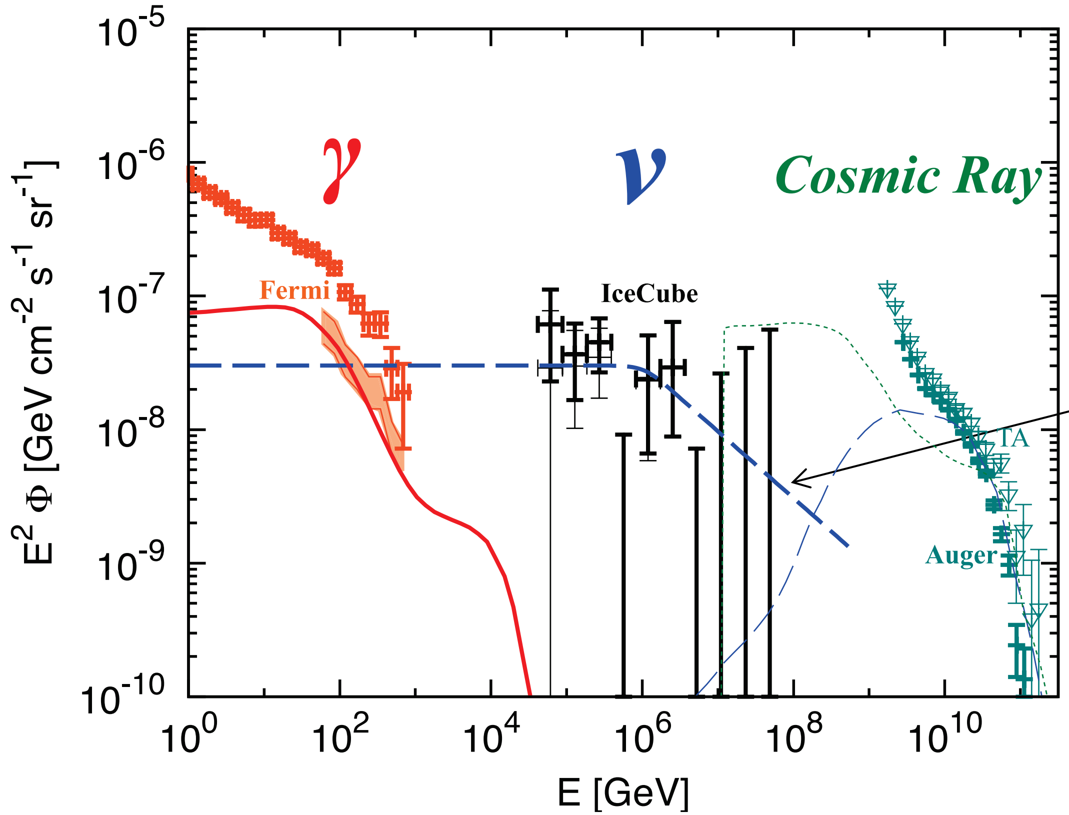
starburst galaxy

CR sources: hypernovae, GRBs, AGN



Multi-Messenger Connection?

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



KM & Waxman 16 PRD

diffusive escape of CRs

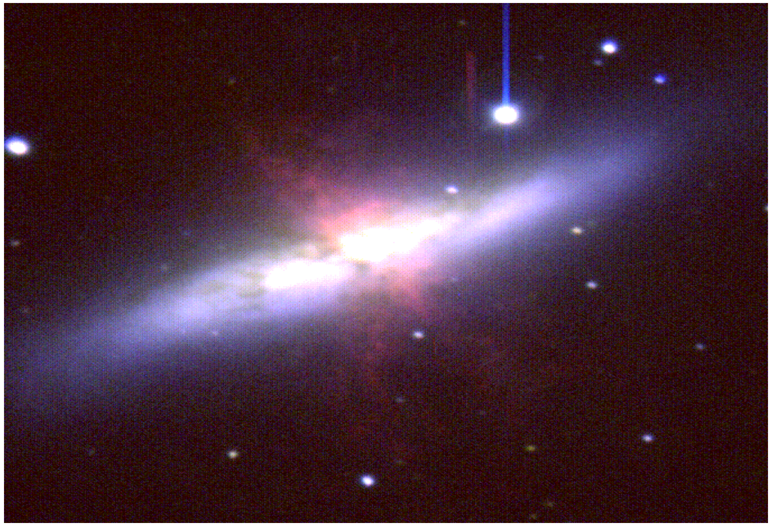
PeVν – confined CR
UHECR – escaping CR
sub-TeVγ – "both"

Grand-unification of neutrinos, gamma rays & UHECRs?

"cosmic particle-convergence"

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

Starburst/Star-Forming Galaxies: Basics



- High-surface density

  M82, NGC253: Σ_g~0.1 gcm^{-2} → n~200 cm^{-3}

  high-z gal.: Σ_g~0.1 g cm^{-2} → n~10 cm^{-3}

  submm gal. Σ_g~1 gcm^{-2} → n~200 cm^{-3}

- CR accelerators

  Supernovae, hypernovae, GRBs,
  Super-bubbles (multiple SNe)
  Galaxy mergers, AGN

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

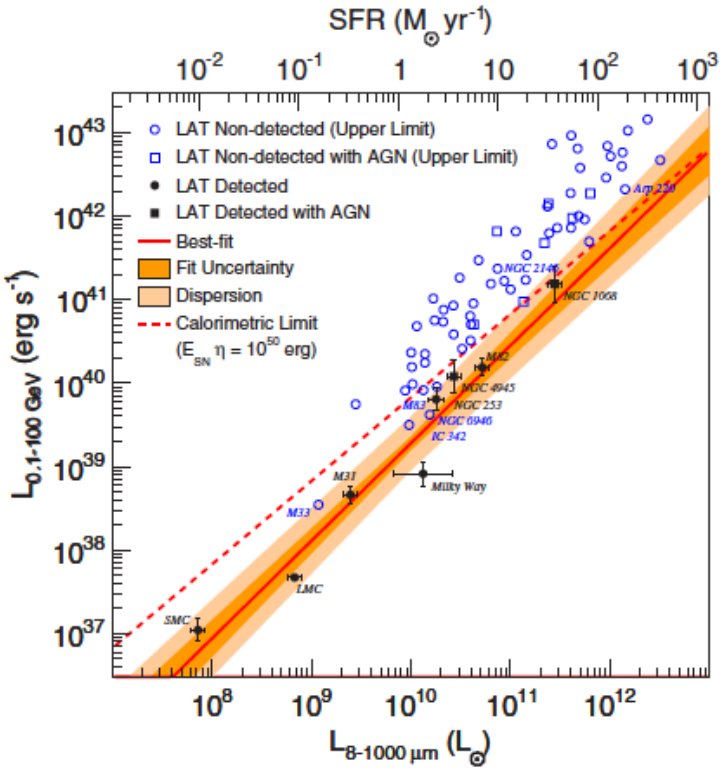
(SFG cosmic-ray energy budget ~ Milky Way CR budget is ~10 times larger)

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

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

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

Infrared – Gamma – Neutrino Connection



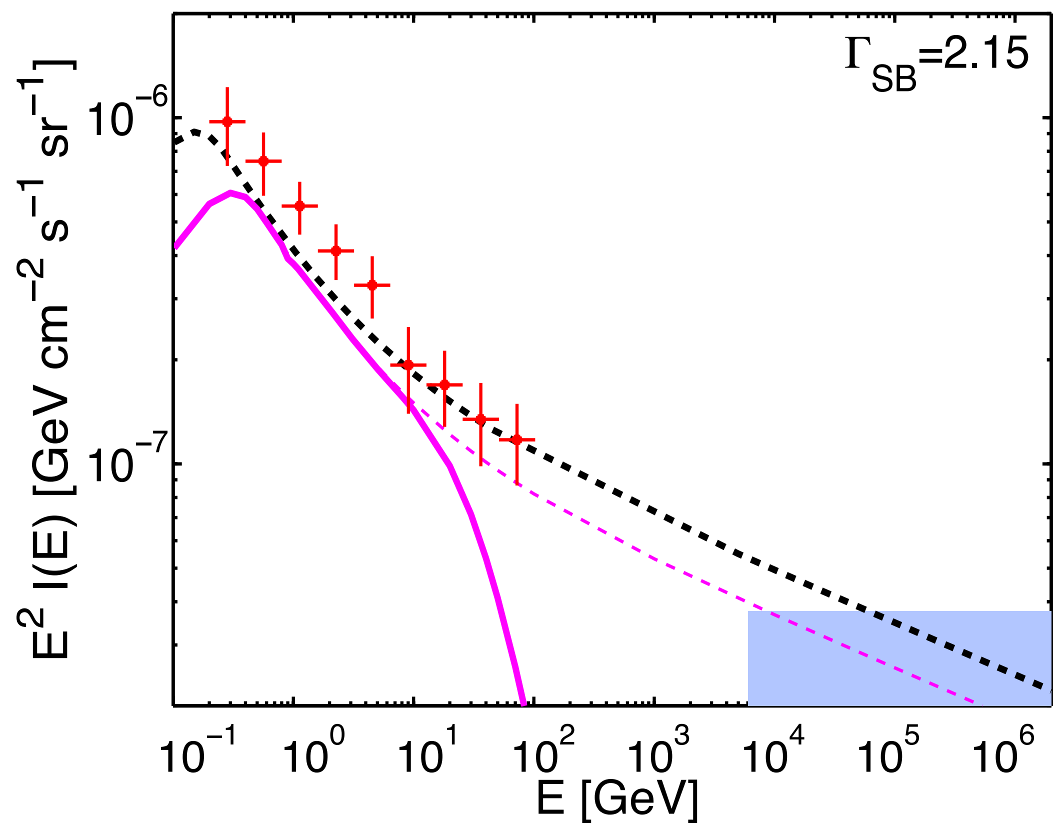
(Fermi collaboration 12 ApJ)

SFR ∝ L_{IR} (Kennicutt law)

$L_\gamma \propto L_{IR}^{1.17}$

(basic agreement w. calorimetry)

Tamborra, KM & Ando 14 (see also Bechtol et al. 17)



- Harshel IR luminosity function
- Redshift evolution:
  m~3-4 up to z~1 for $(1+z)^m$
- Need to include starbursts
  w. AGN (mostly Seyferts)

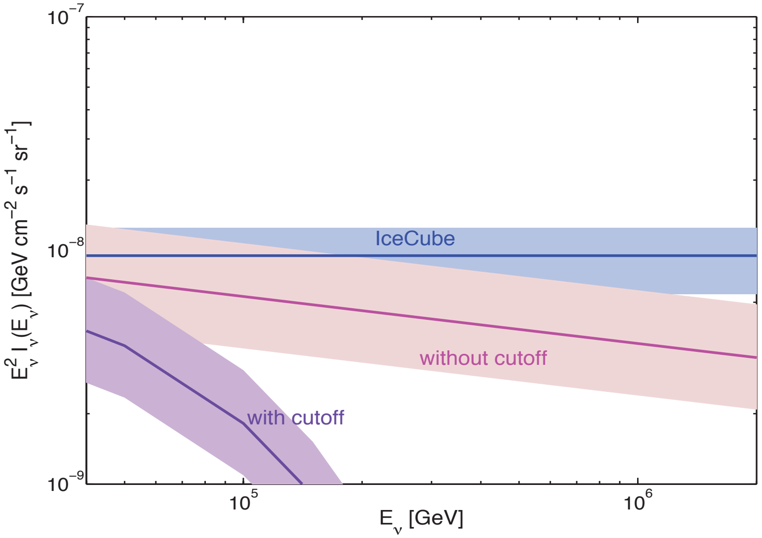
Necessity of Super-Pevatrons

Our Galaxy's CR spectrum

Knee at 3 PeV

→ neutrino knee at ~100 TeV

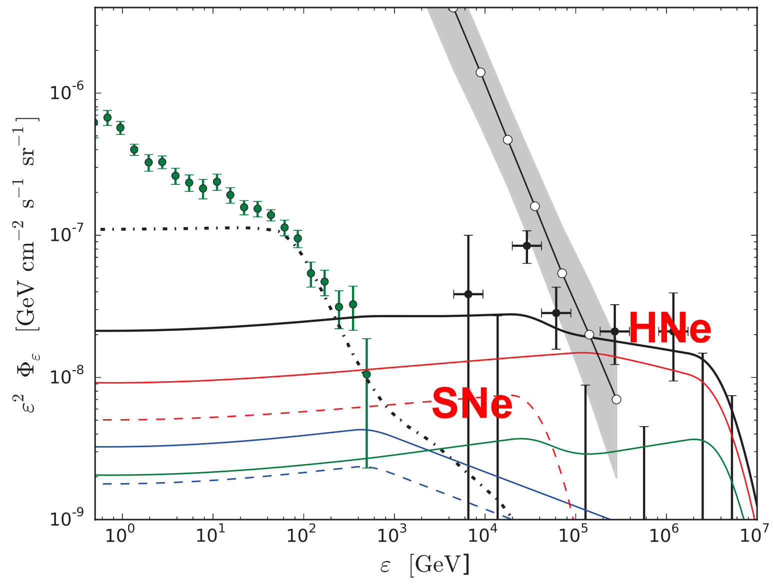
Normal supernovae (SNe) are not sufficient to explain >0.1 PeV data



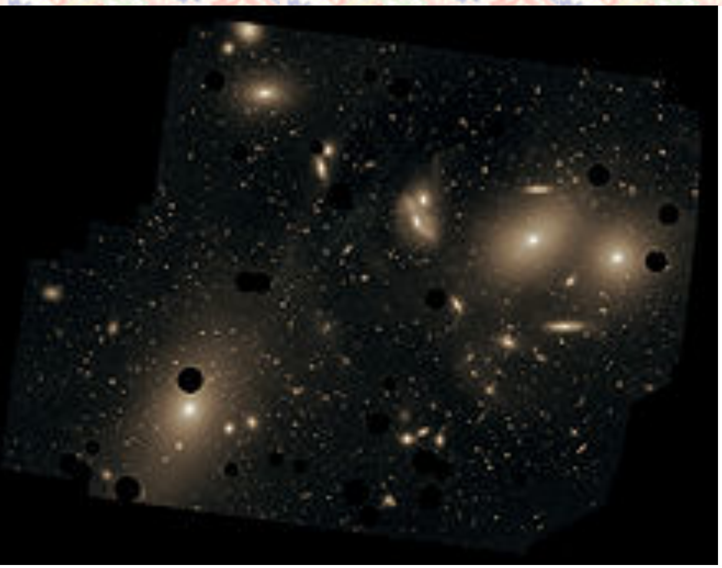
Possible solutions

1. B fields amplified to ~ mG KM+ 13
2 .Hypernovae (HNe) KM+ 13, Liu+ 14, Senno+ 15
3. Trans-relativistic supernovae gamma-ray bursts Dado & Dar 14, Wang+ 15
4. Type IIn/IIb supernovae Zirakashvilli & Ptuskin 16
5. Super-bubbles
6. AGN disk-driven outflows Tamborra+ 14
7. Galaxy mergers Kashiyama & Meszaros 14

Senno, Meszaros, KM, Baerwald & Rees 15



Galaxy Groups and Clusters: Basics



- Intracluster gas density (known)
  n~10^{-4} cm^{-3}, a fewx10^{-2} cm^{-3} (center)
- CR accelerators
  AGN (~a few) "active"
  accretion shocks (massive clusters)
  galaxy/cluster mergers
  normal galaxies (~100-1000)

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

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

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

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

Advantages & Disadvantages

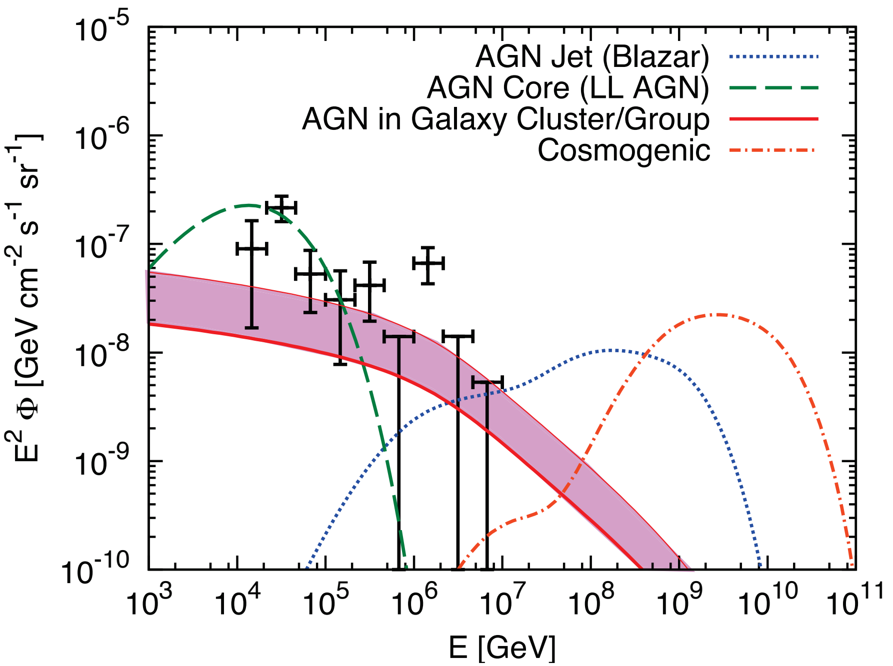
- Maximum energy of CRs is expected to be high enough (which is not the case in normal/starburst galaxies)
- Gigantic! → confining CRs is easy (E < eBR~10^{21} eV)

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

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

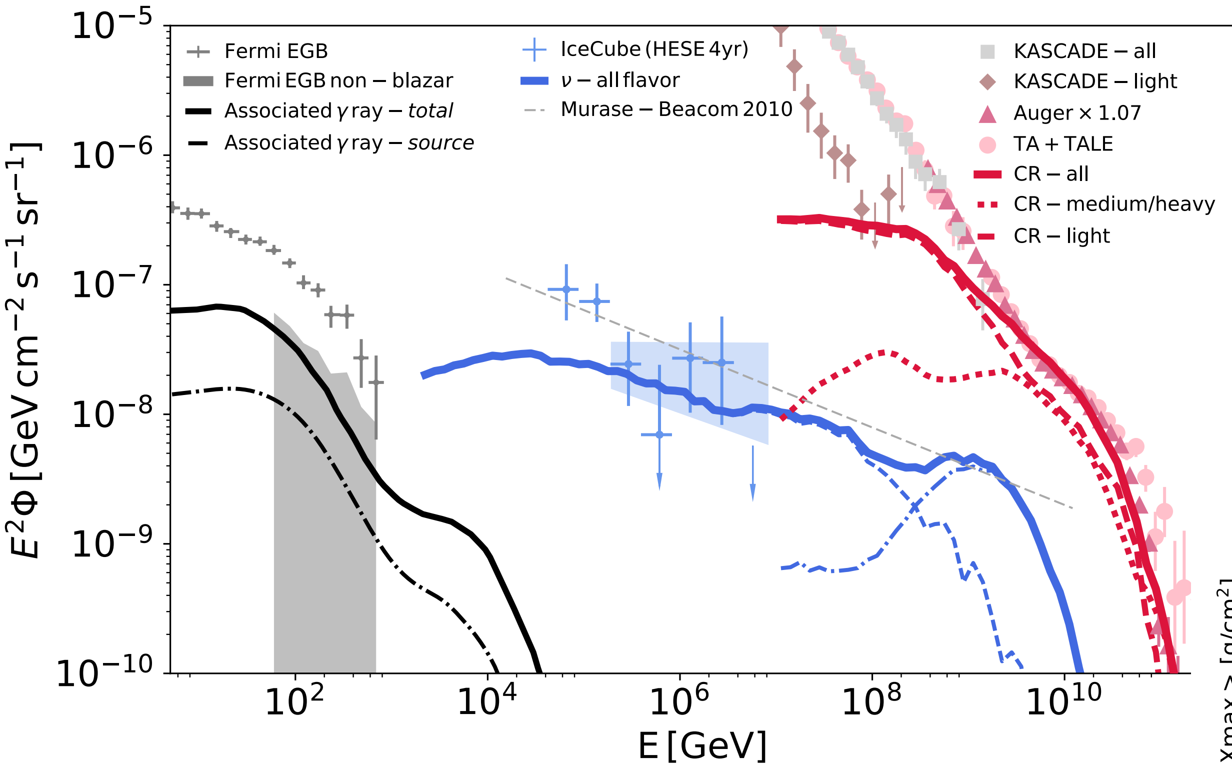
ν break

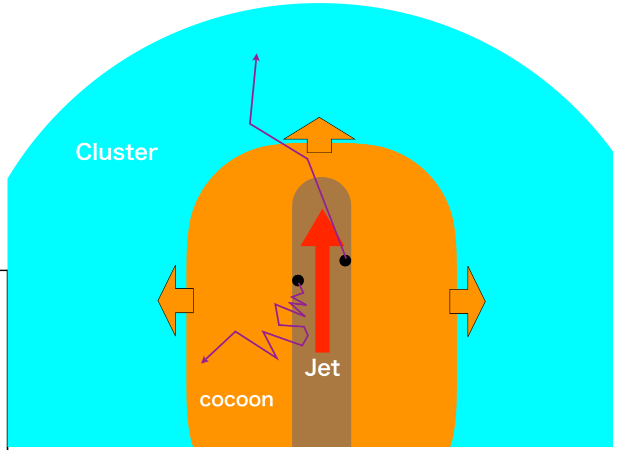
Issues
- γ-ray overshooting?
- “accretion shock” scenario already disfavored (neutrino, γ-ray & radio)



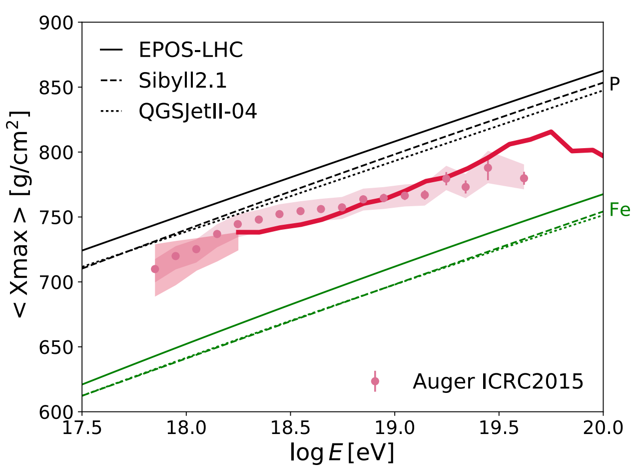
AGN Embedded in Galaxy Clusters/Groups

- AGN as "UHECR" accelerators
- confinement in cocoons & clusters
- Escaping CR nuclei may have s < 2





Fang & KM 17



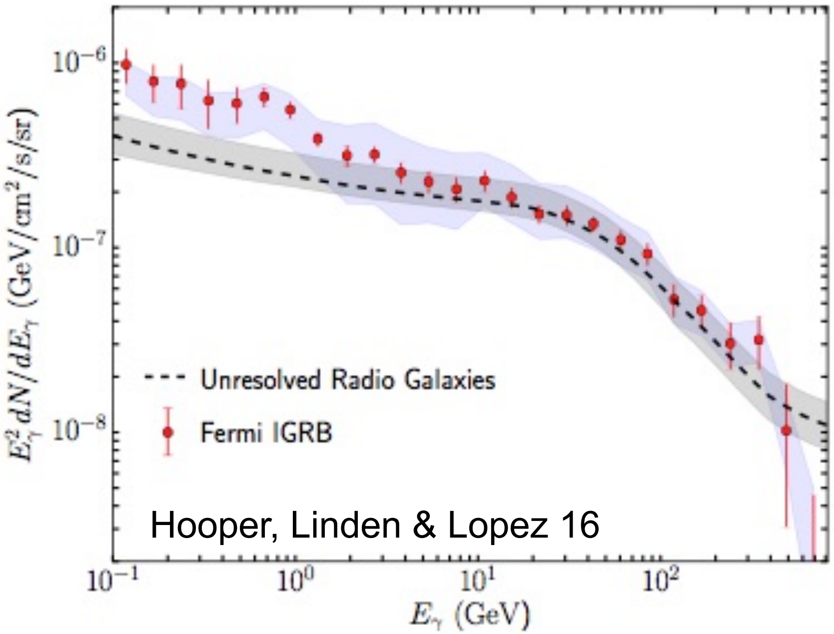
"cosmic particle-unification"

neutrino, gamma-ray, UHECR (sub-ankle & composition)

Other Possibilities?

Radio galaxies

Becker et al. 14, Hooper 16



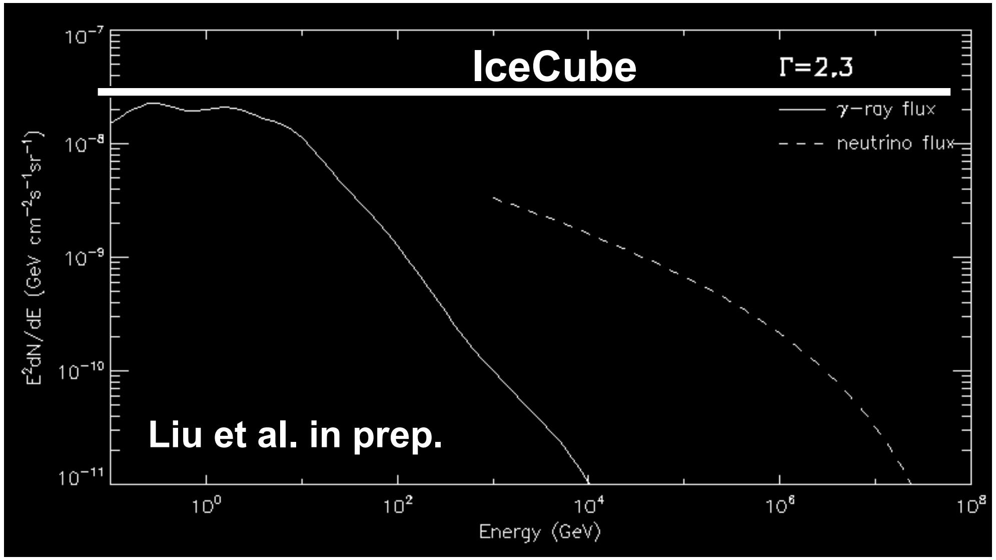
- Leptonic vs hadronic
- Variablity? → compact region?
- pp efficiency? → compact region?

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

not inside jets (Atoyan & Dermer 01)

AGN outflows

AGN outflows w. starbursts (Tamborra, Ando & KM 14)
Quasar outflows (Wang & Loeb 16)



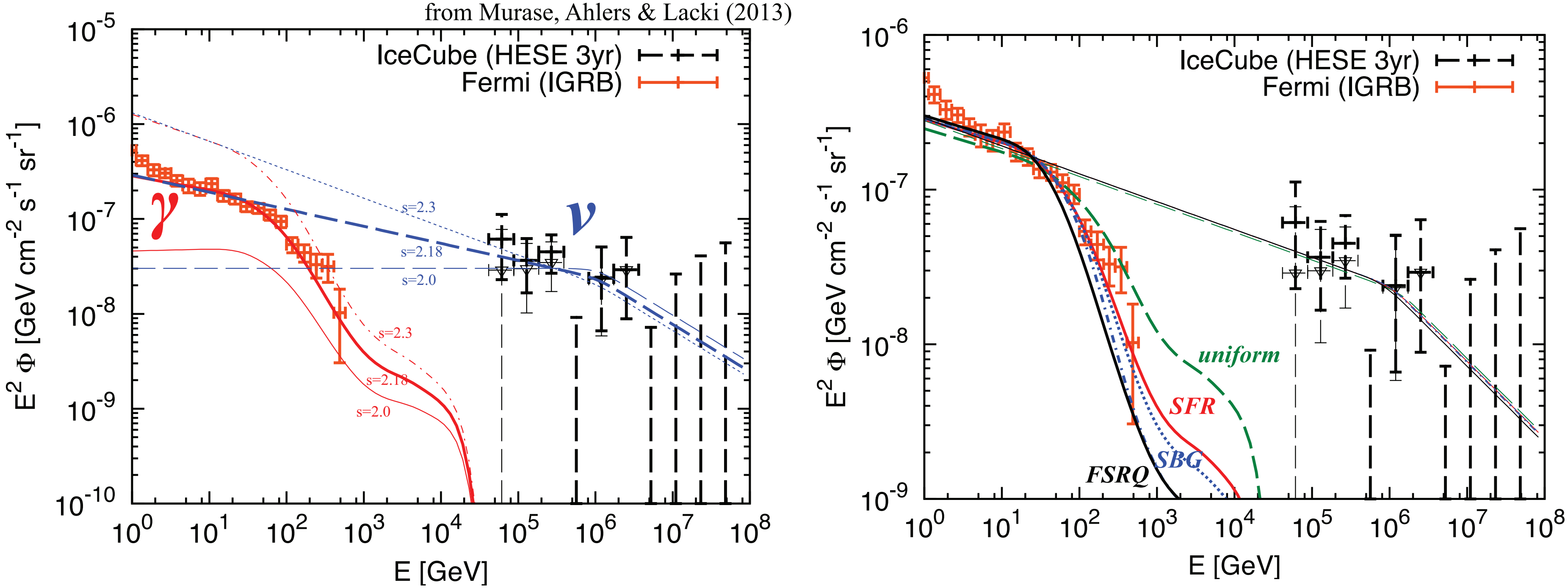
- Normalization of CR luminosity?
  kinetic luminosity vs thermal luminosity
- Column density?
  X-ray obs.: N_H ~ 10^{20-24} cm^{-2}
- Model degeneracy?

Predictions of CR Reservoir Models and Issues

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

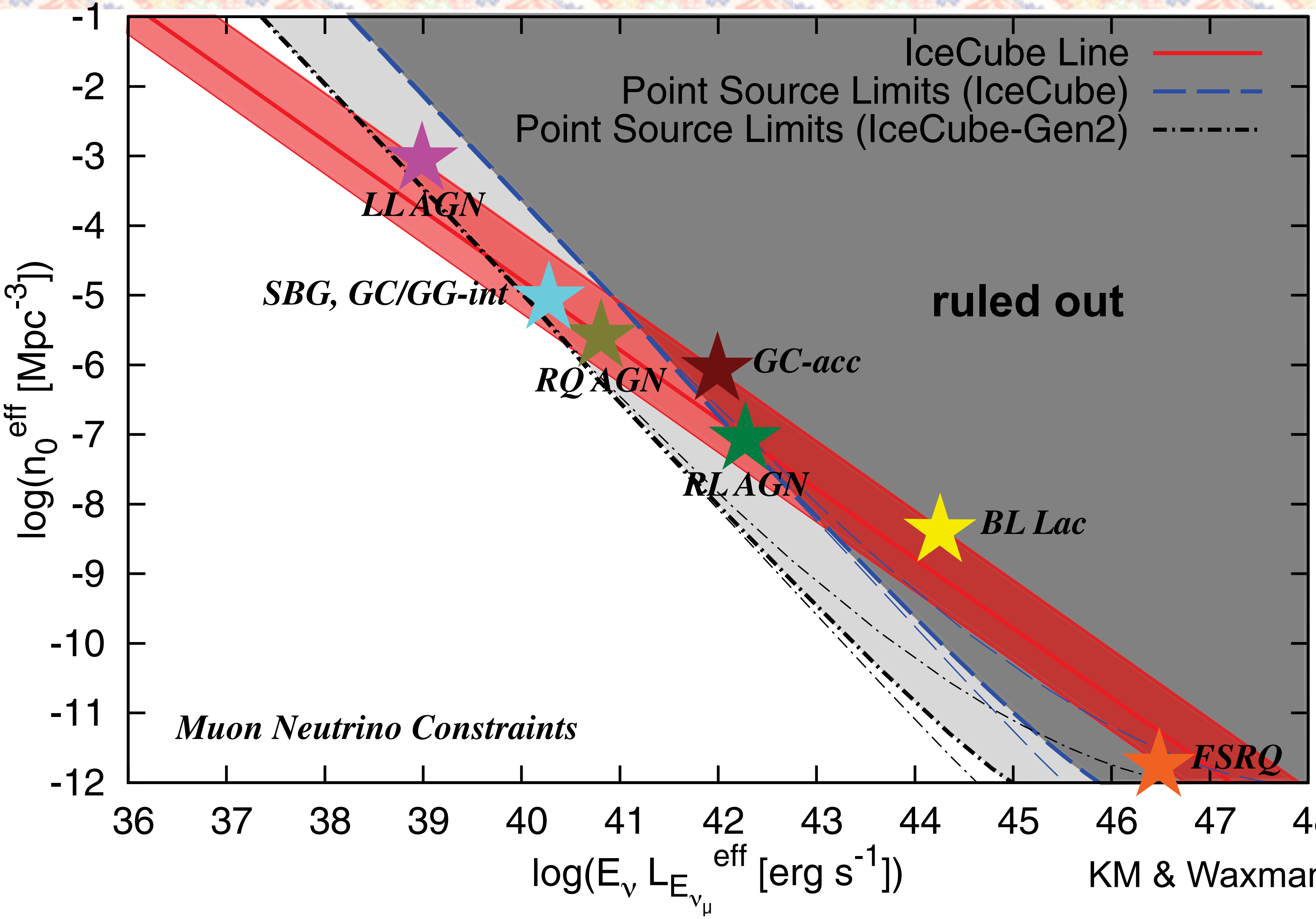
※ **insensitive to redshift evolution and EBL models**

from Murase, Ahlers & Lacki (2013)



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

General Clustering Limits



KM & Waxman 16 PRD

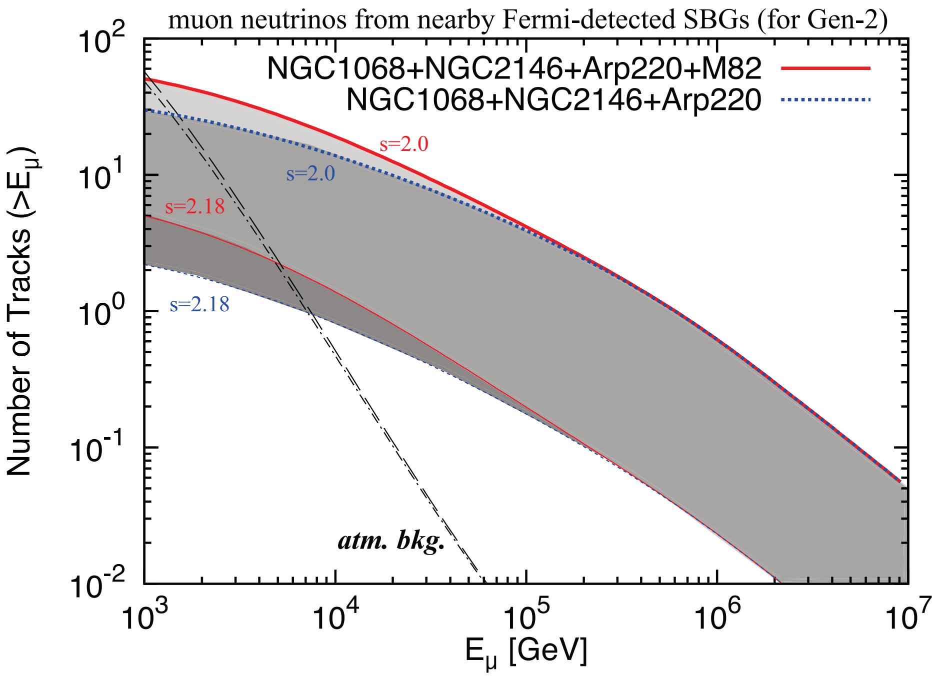
Non-detection of multiplet sources give “upper” limits on the number density

(Lipari 08, Silvestri & Barwick 10, KM, Beacom & Takami 12, Ahlers & Halzen 14, Kowarski 15)

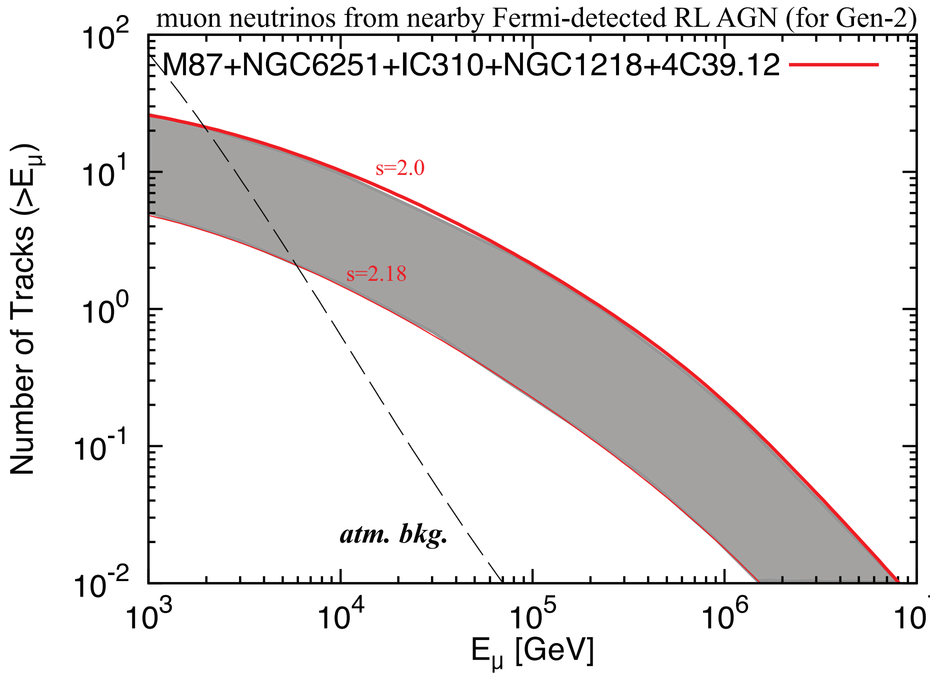
Need to Identify the Sources: Stacking?

Cross-correlation - powerful but complete catalogues may not be available
Starbursts and radio galaxies are detected by Fermi -> **"ν–γ connection"**
For pp scenarios w. s<2.2, we have strong predictions for IceCube-Gen2

nearby starburst galaxies in the northern hemisphere



nearby radio galaxies in the northern hemisphere

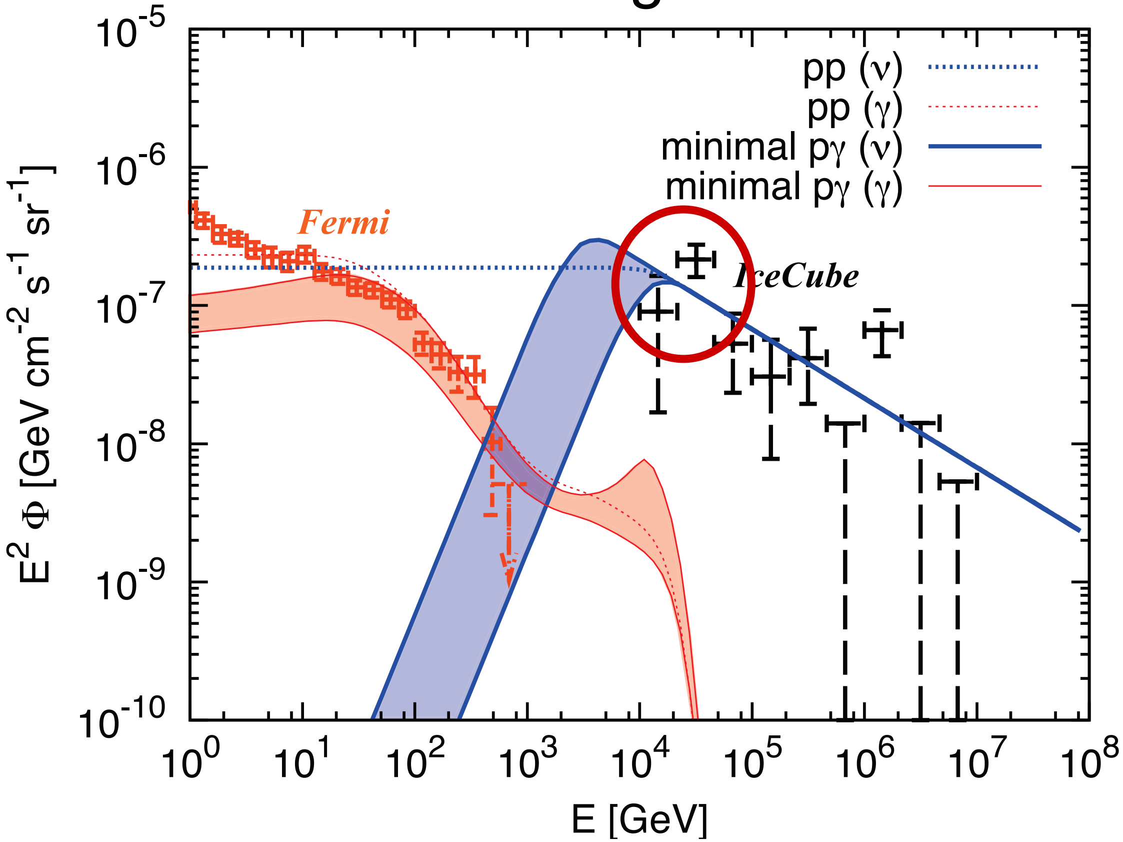


V=10 km3 & best ang. res.=0.1 deg & 5 yr obs. assumed

KM & Waxman 16

Beyond Waxman-Bahcall?: MESE “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

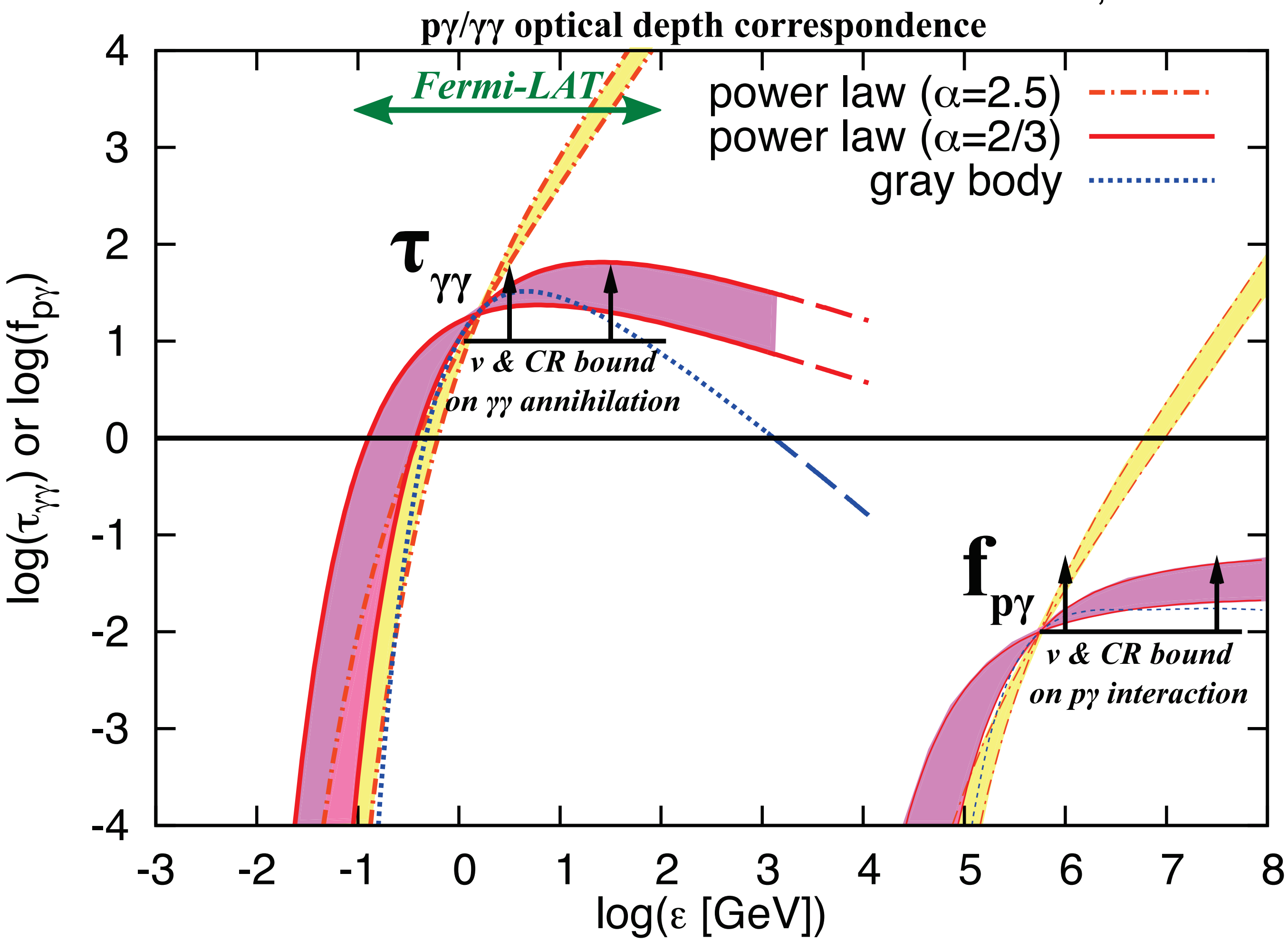
If γ-ray transparent strong tensions w. Fermi for both pp & pγ

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

contrary to sub-threshold source & cross-corr. analyses

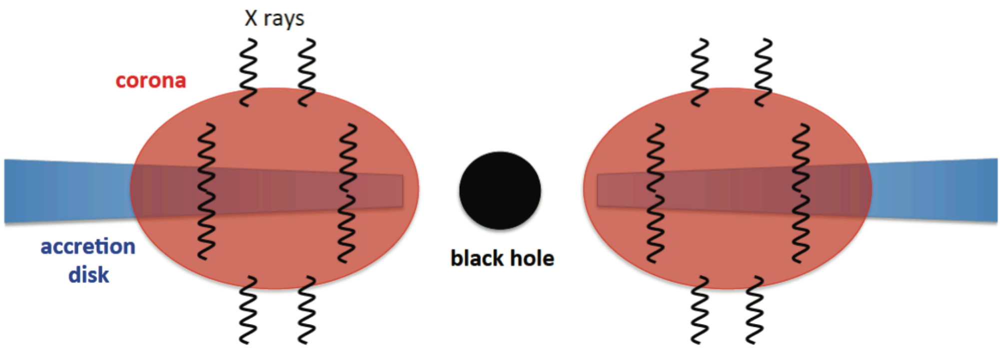
Indication of Gamma-Ray Dark Cosmic-Ray Accelerators

KM, Guetta & Ahlers 16 PRL



- $\gamma\gamma \rightarrow e^+e^-$: unavoidable in pγ sources (ex. GRBs, AGN)
- ν sources should naturally be obscured in GeV-TeV γ rays

AGN Cores as Hidden Neutrino Factories?



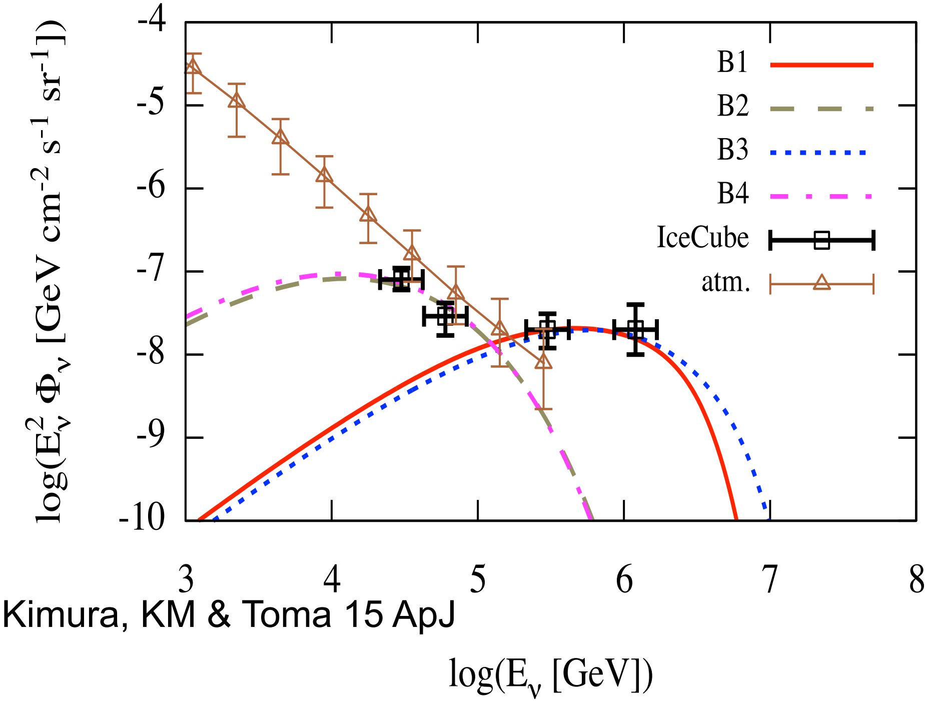
Seyfert/Quasar AGN

standard accretion disk -> collisional
CR acceleration does not occur

Low-luminosity AGN

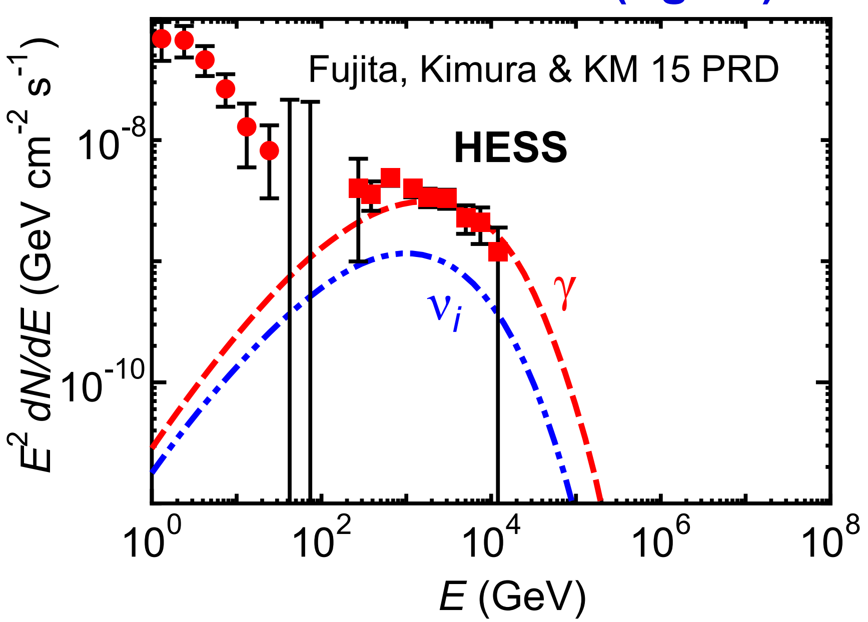
accretion disk is "radiatively inefficient"
collisionless flow -> CR acceleration
Non-thermal emission from Sgr A*, Cen A?

diffuse neutrino flux

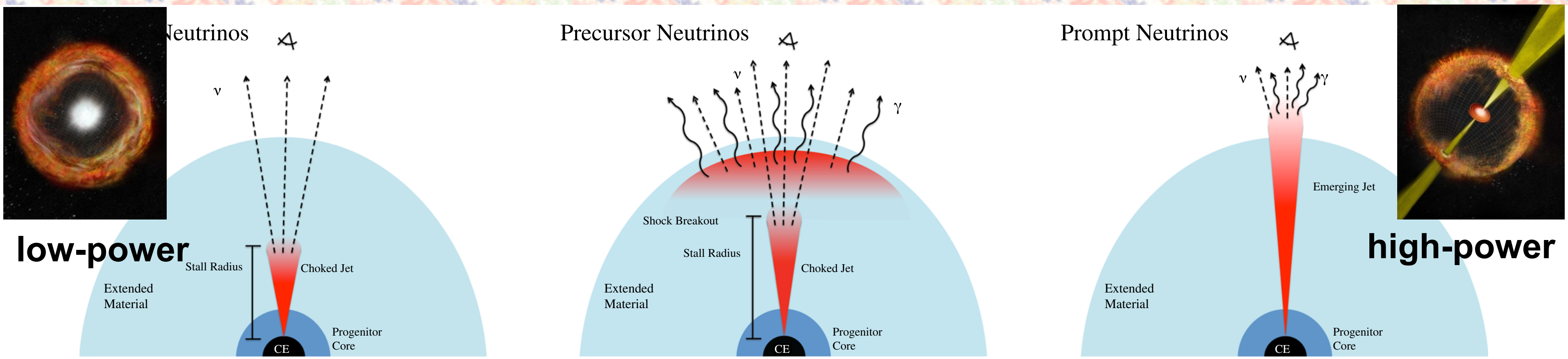


Kimura, KM & Toma 15 ApJ

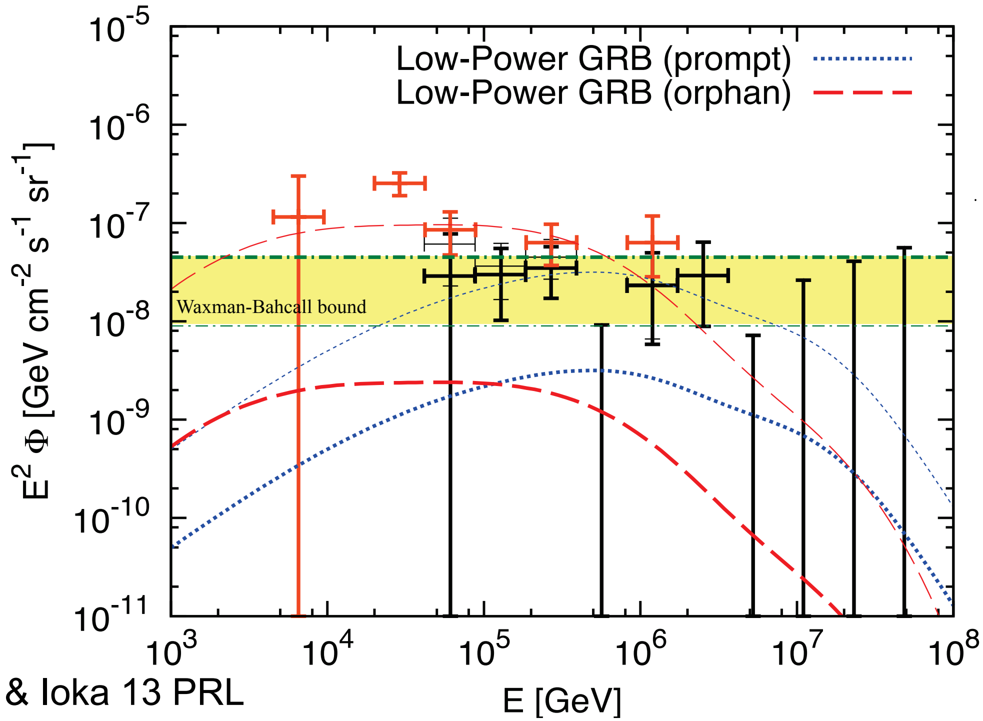
Galactic center (SgrA*)



Choked Jets as Hidden Neutrino Factories?



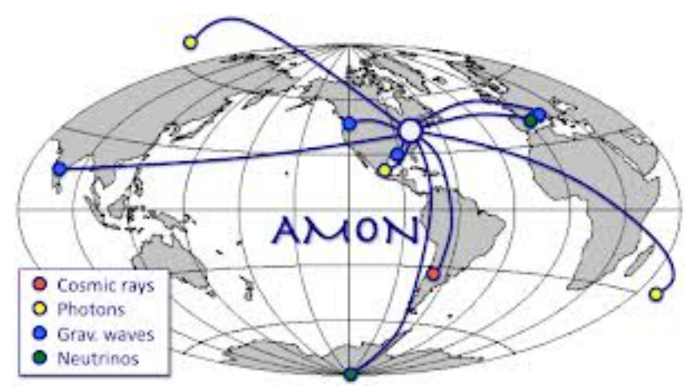
Senno, KM & Meszaros 16 PRD



KM & Ioka 13 PRL

Lower-power jets are better for CR acc.

Neutrinos from LL GRBs
-> X-ray coincidence
Neutrinos from SNe Ibc
-> optical follow-ups



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 likely w. IceCube-Gen2 (stacking, event clustering)

Understanding the 10-100 TeV data is important

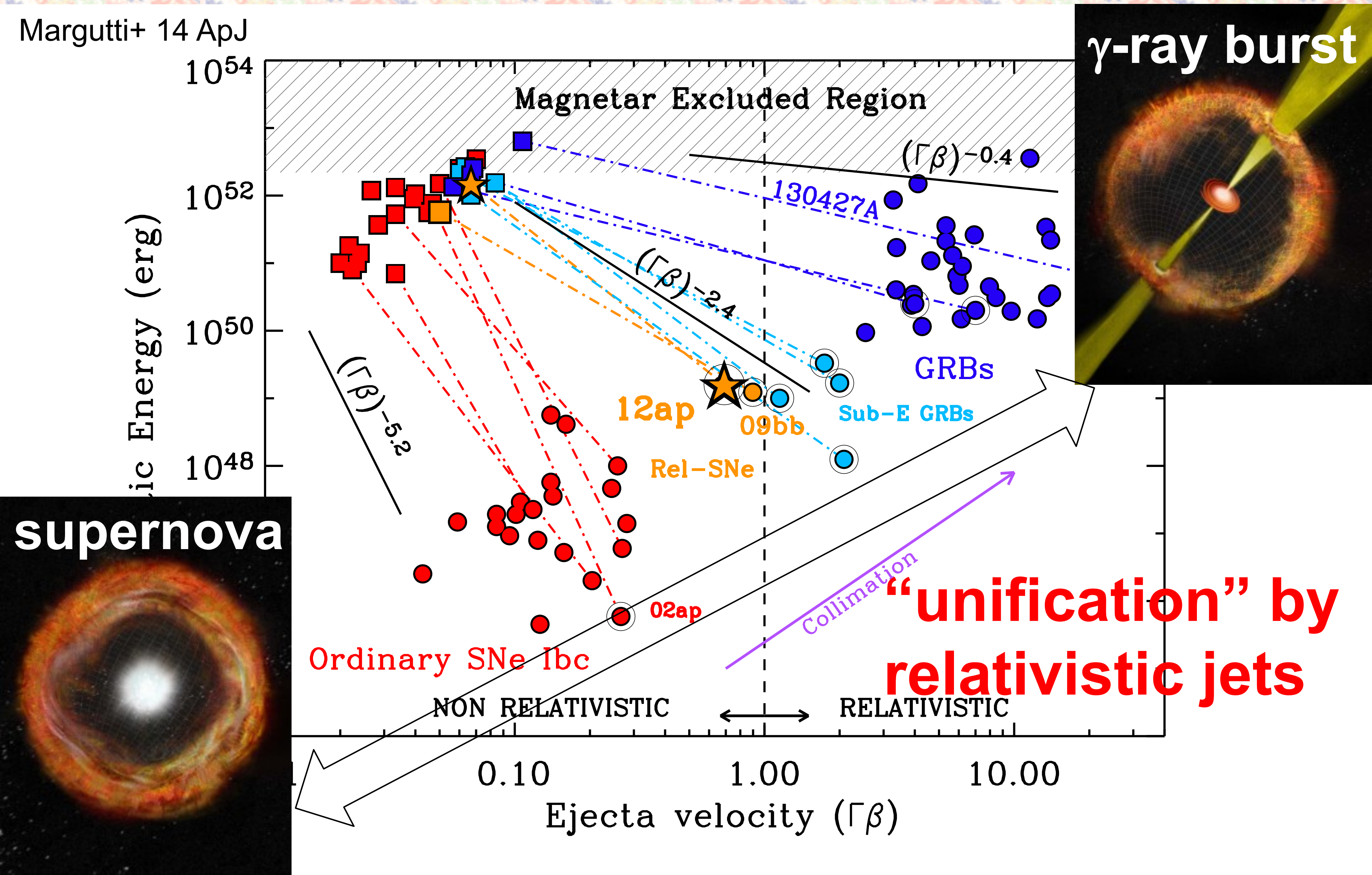
medium-energy excess: background? special Gal. sources? or new physics?

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?

Gamma-Ray Burst – Supernova Connection

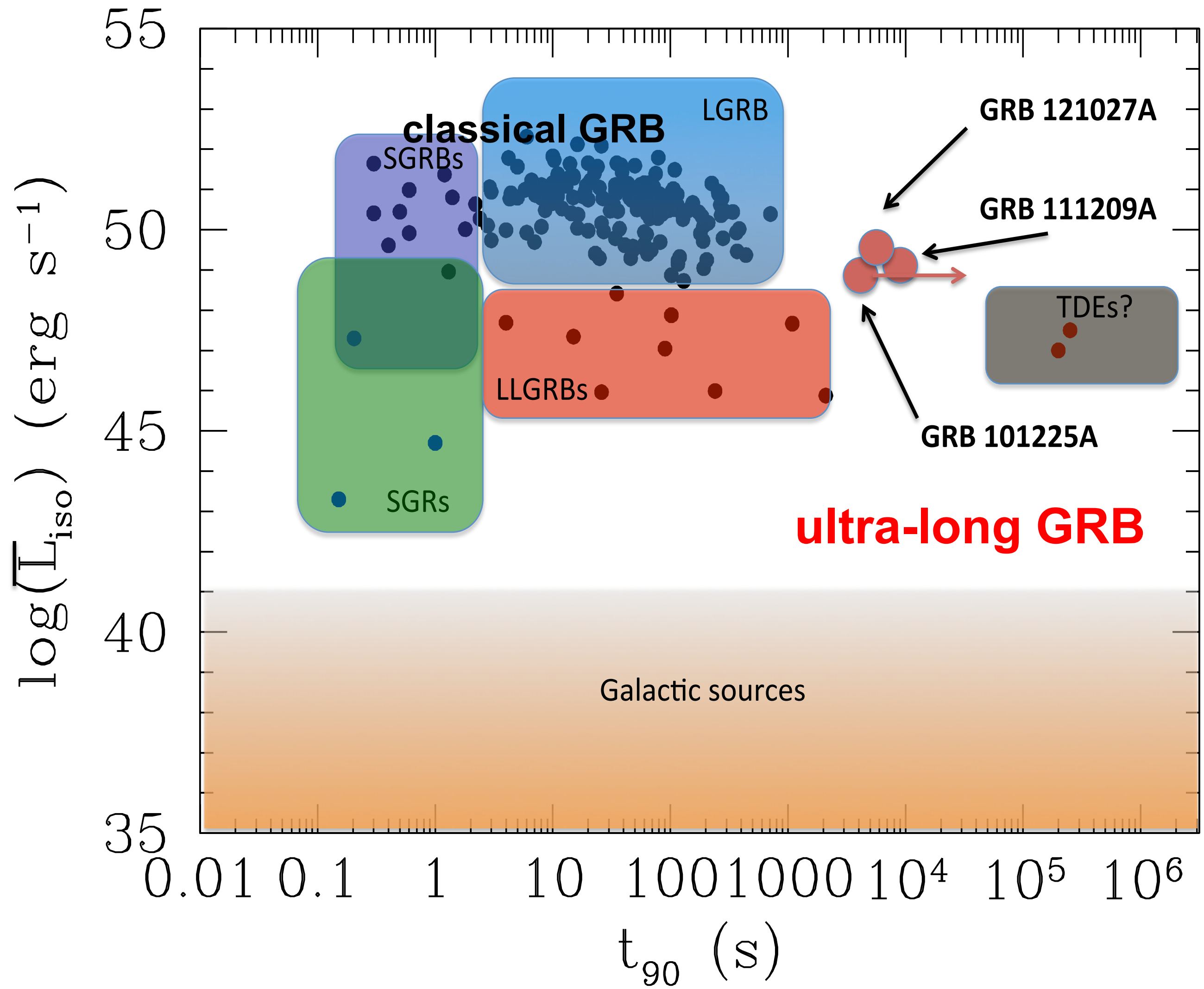
Margutti+ 14 ApJ



“unification” by relativistic jets

Gamma-Ray Transients' Zoo

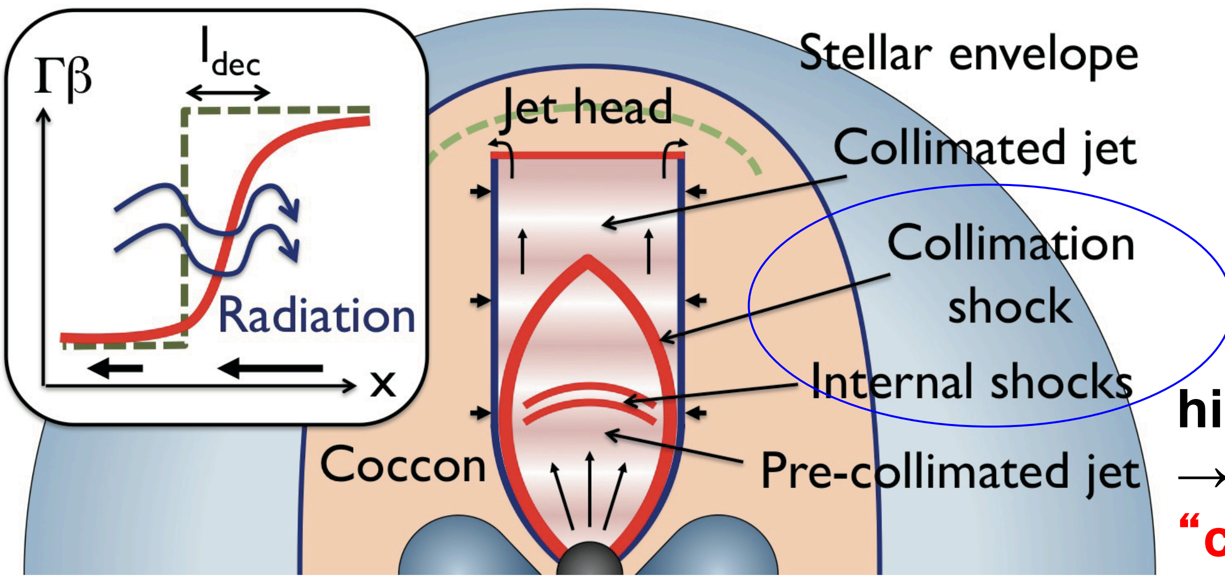
$E_\gamma \sim L_\gamma T$ - longer is dimmer (→ untriggered)



Levan+14 ApJ

Choked Jets as "Hidden" Neutrino Sources

Neutrinos: smoking gun of rel. jets that cannot be directly seen by γ



hydrodynamic jet assumed

e.g., Meszaros & Waxman 01 PRL
Razzaque+04 PRL,
Levinson & Bromberg 08 PRL
KM & Ioka 13 PRL

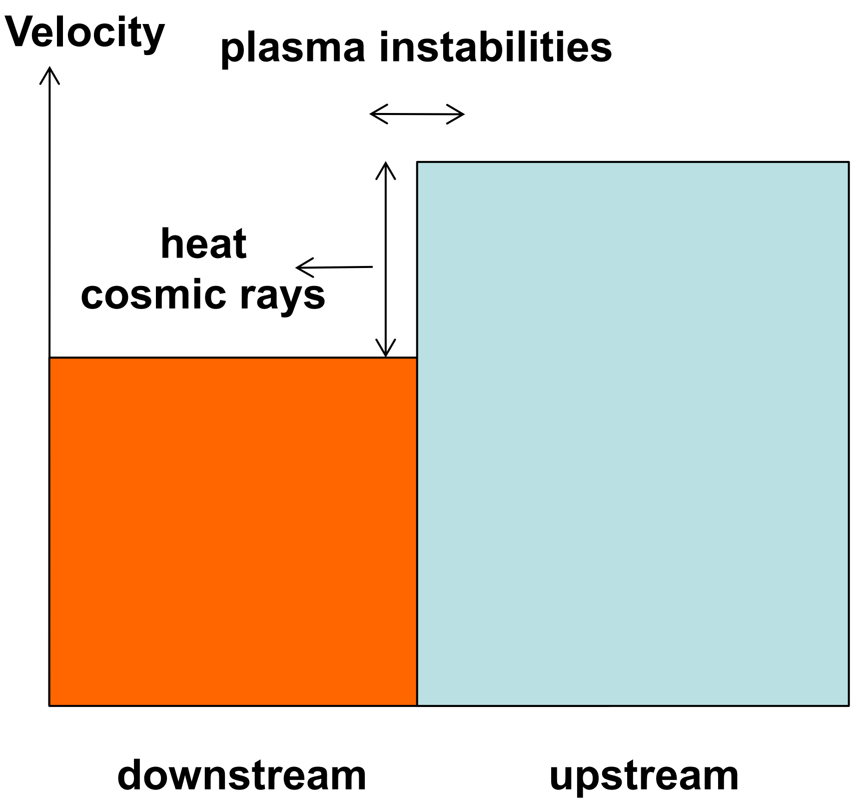
mildly relativistic shocks

high density
→ all CRs are used for ν&γ
"calorimetric"
→ ν escape
no γ escape

1. Ballistic jets inside stars?
   → collimation shock & collimated jet
2. Cosmic-ray acceleration?
   → inefficient at radiation-mediated shocks

Limitation of Shock Acceleration

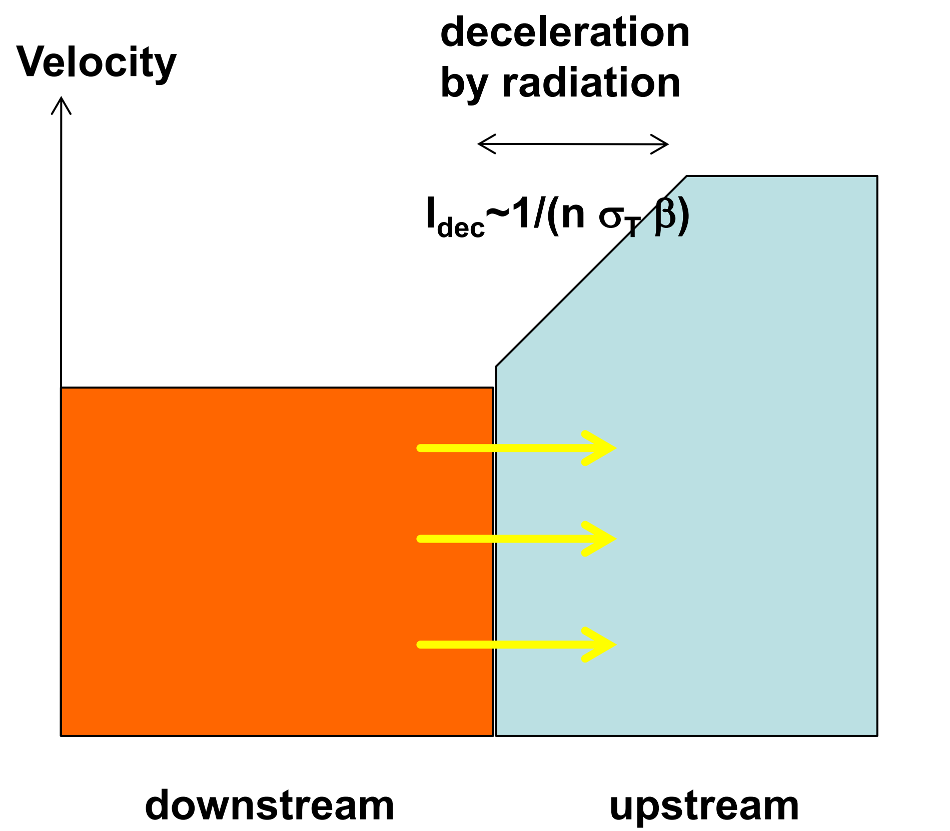
Collisionless shock



(m.f.p.) ~ $r_L(\varepsilon_p)$ > (shock width)

allowed CR acceleration

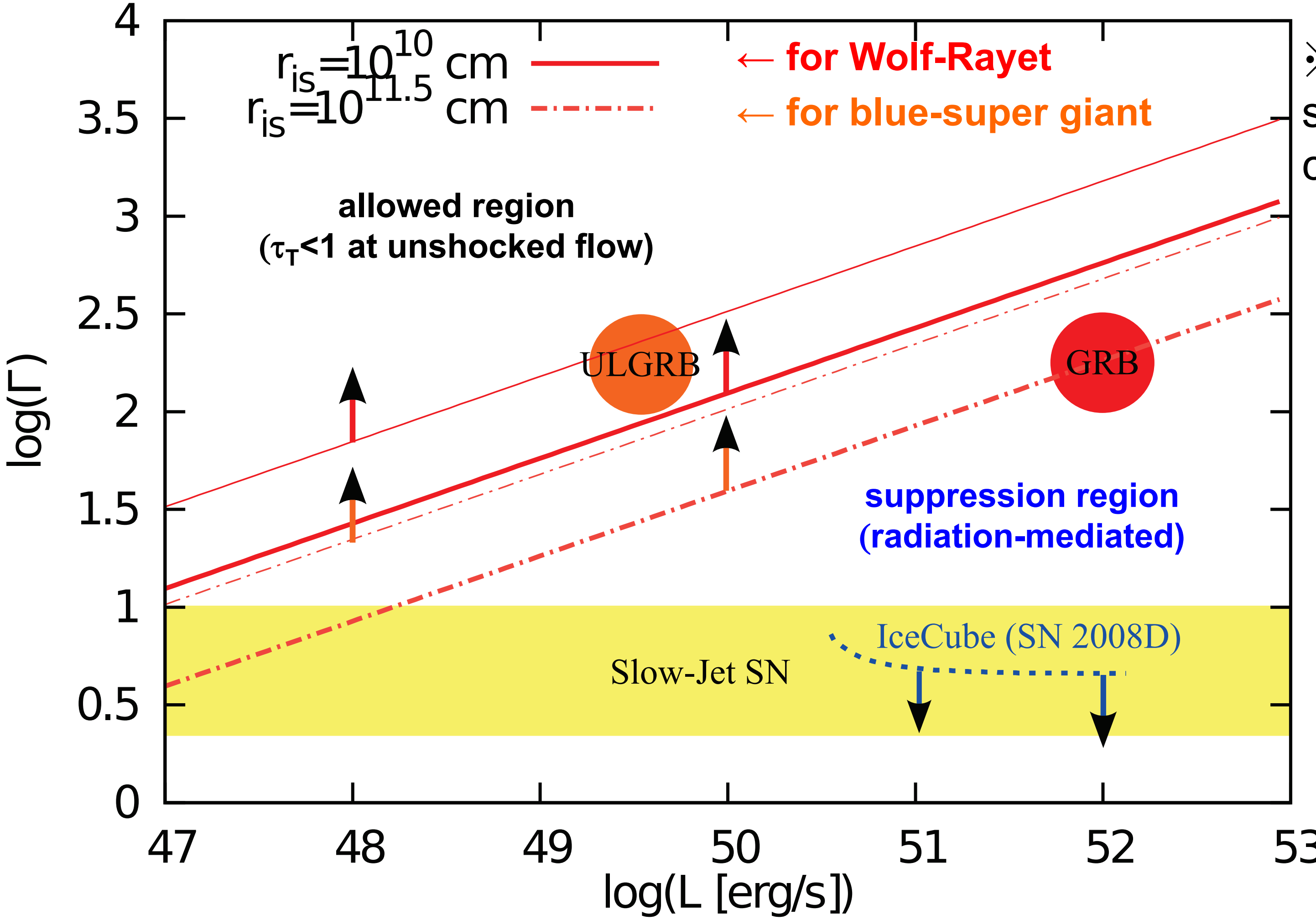
Radiation-mediated shock



(m.f.p.) ~ $r_L(\varepsilon_p)$ < (shock width)

suppressed CR acceleration

“Radiation Constraints” on Non-thermal Neutrino Production



※ A bit different but similar derivation for collimation shock

KM & Ioka 13 PRL

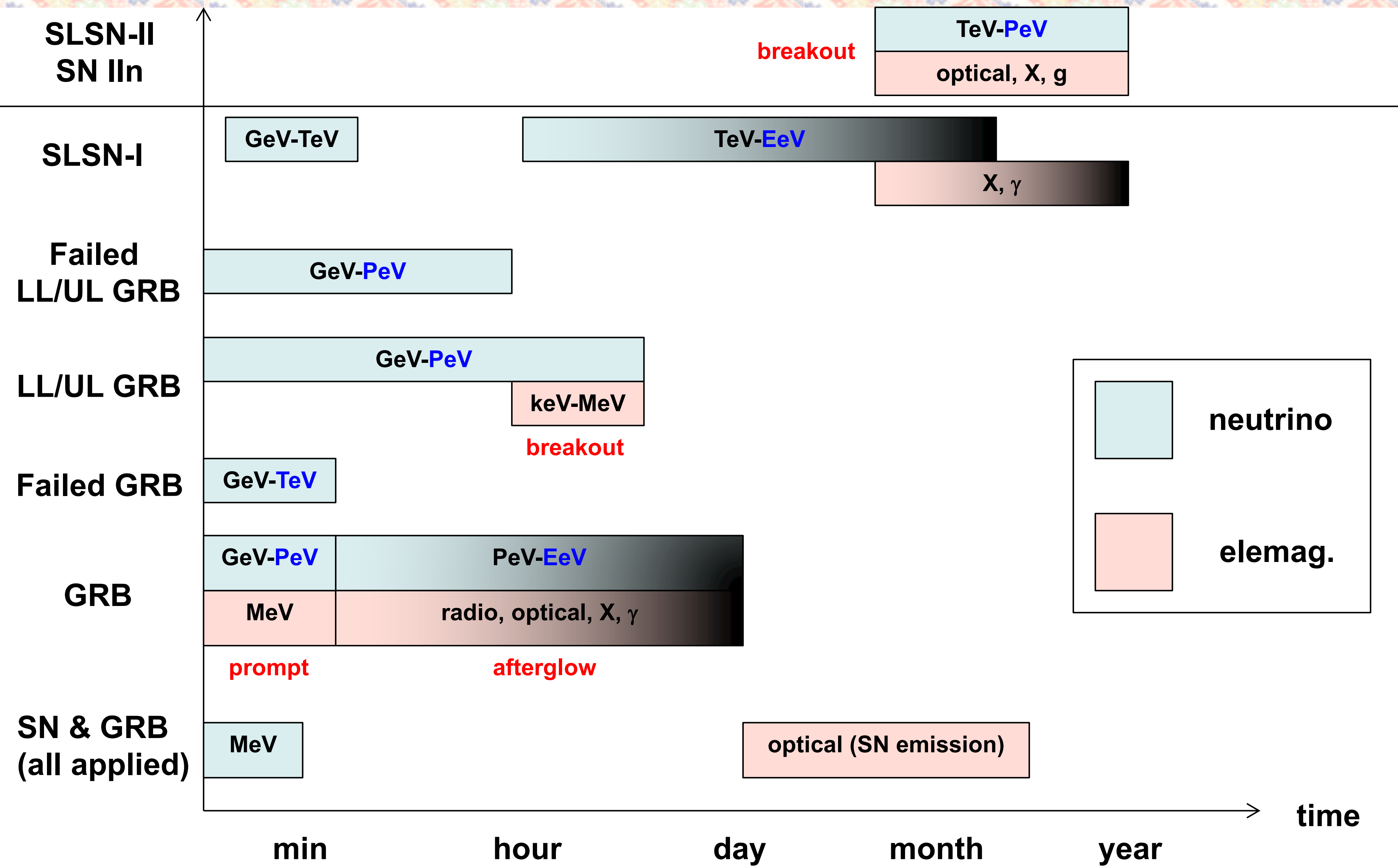
Thomson optical depth

$$\tau_T = n_e \sigma_T \Delta \propto L\Gamma^{-2}$$

L: kinetic luminosity

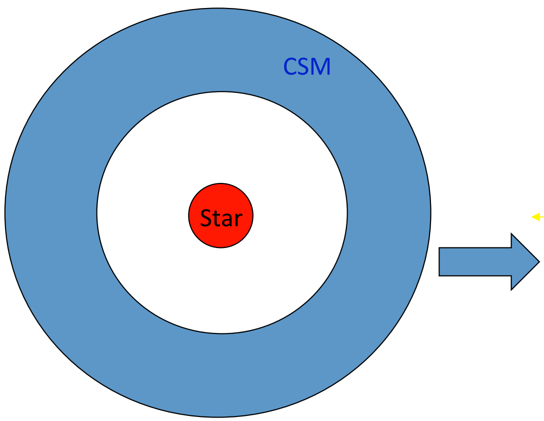
Γ: Jet Lorentz factor

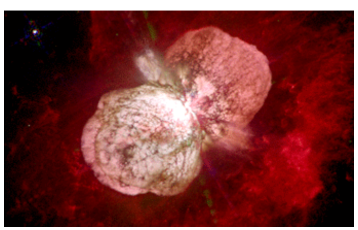
Time & Energy Scales



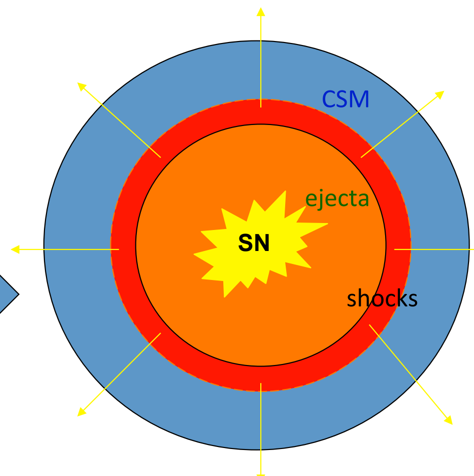
Neutrinos from Interaction-Powered SNe

CSM eruption(s) before explosion

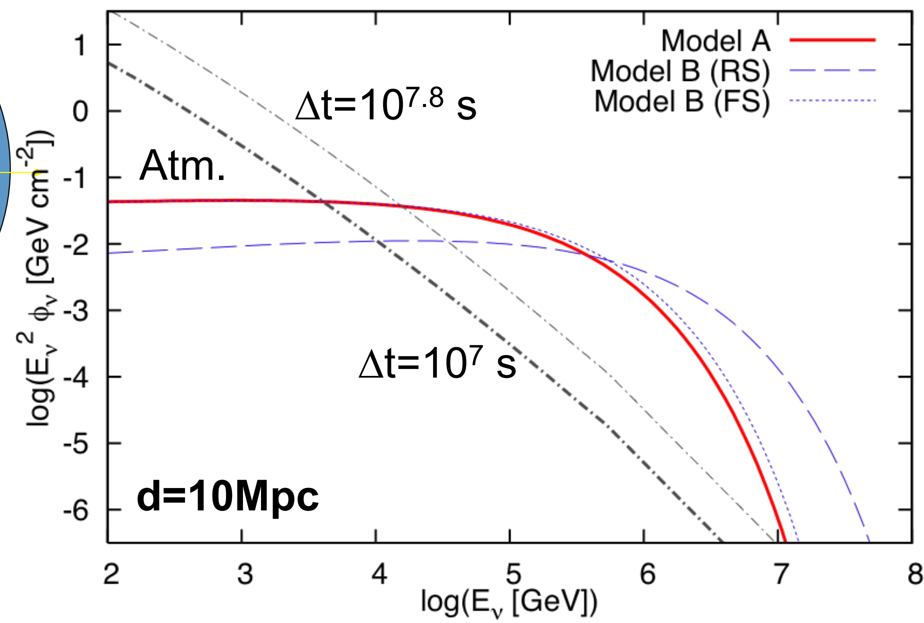




True SN explosion



KM, Thompson, Lacki & Beacom 11 PRD



CR acc. efficiency ~10% → # of μs expected in IceCube
~a few events for SN@10Mpc

Multiplet Searches are Independently Powerful

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

For early papers, Lipari 08, Silvestri & Barwick 10, KM, Beacom & Takami 12

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

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

IceCube measurements fix the normalization

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

$$\Downarrow$$

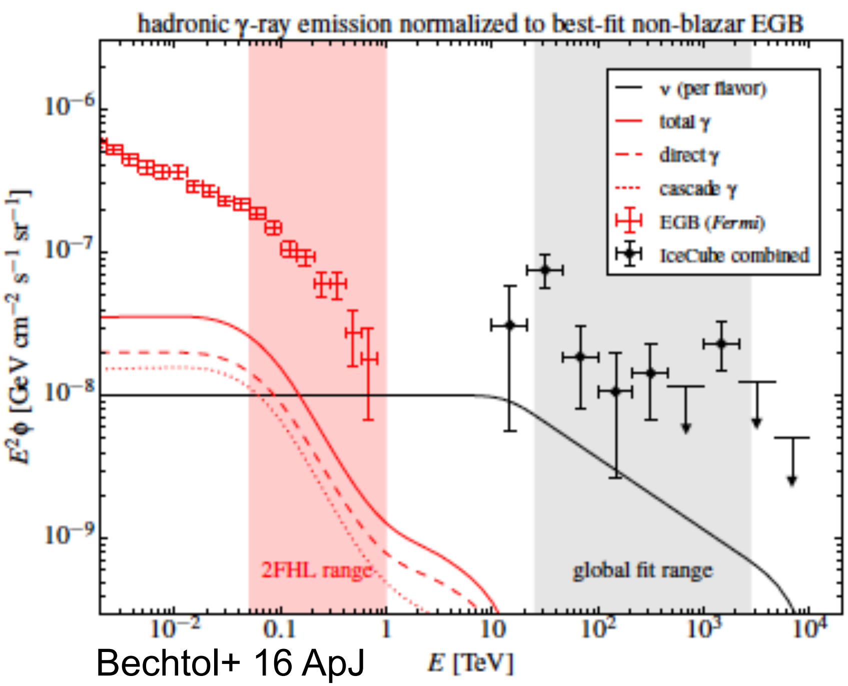
"lower" limits $\quad n_0^{\rm eff} \gtrsim 0.8\times 10^{-5}\,{\rm Mpc^{-3}}\left(\frac{b_{m,L}}{5}\right)^{2}\left(\frac{\xi_z}{0.6}\right)^{-3}\left(\frac{F_{\rm lim}}{10^{-9}\ {\rm GeV\,cm^{-2}\,s^{-1}}}\right)^{-3}\left(\frac{\Delta\Omega}{2\pi}\right)^{2}$

cluster accretion shock model: weak (even negative) evolution, $n_0^{\rm eff} \sim 10^{-6}$ Mpc^{-3}
cluster/group internal accelerator model: positive evolution, $n_0^{\rm eff} \sim 10^{-5}$ Mpc^{-3}

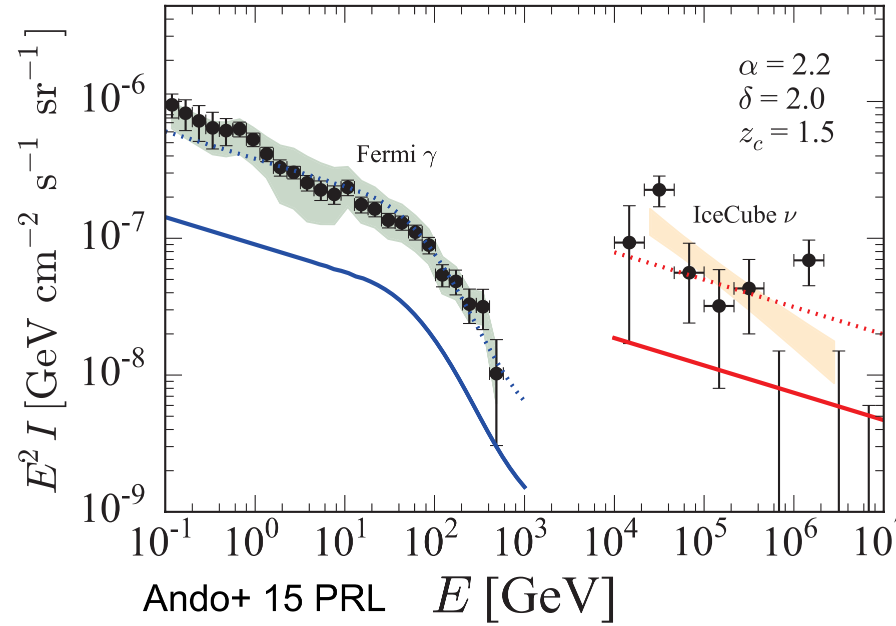
For discussion after IceCube's discovery, Ahlers & Halzen 14, Kowarski 15, KM & Waxman 16

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

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

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

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

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

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

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

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

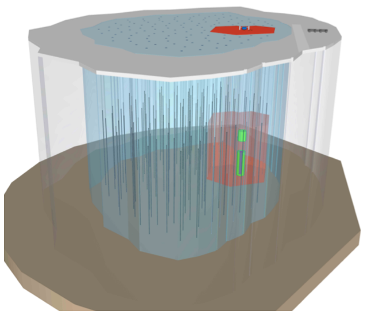
30 TeV-3 PeV ν constrains 1-100 GeV γ

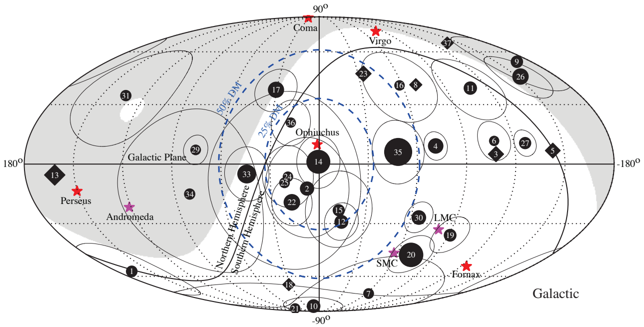
- Neutrino production efficiency $f_{p\gamma}$ cannot be too small

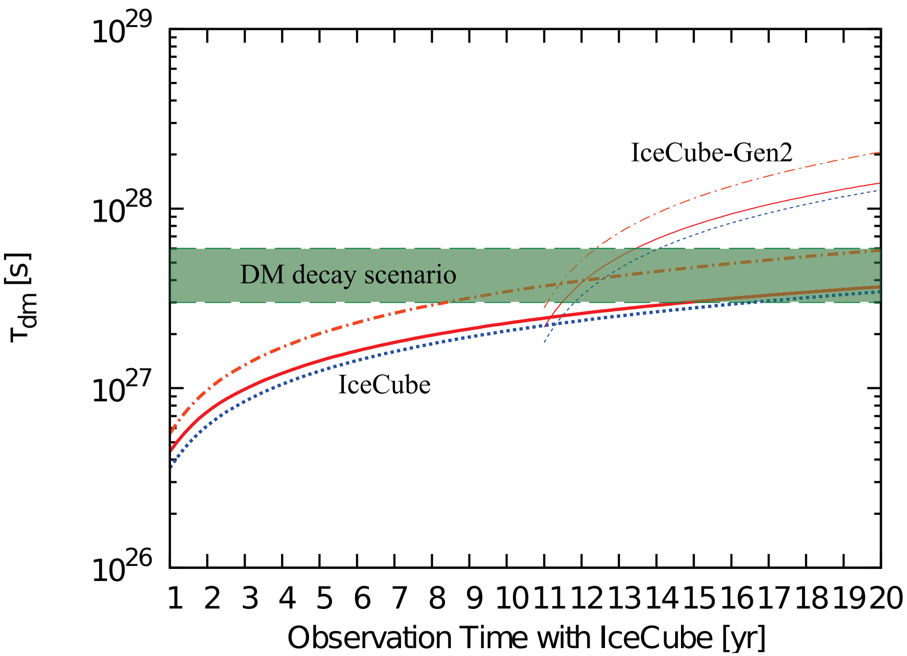
1. $f_{p\gamma}$ << 1 unnatural (requiring fine tuning), Do not overshoot the observed CR flux (Yoshida & Takami 14 PRD)
2. Comparison w. non-thermal energy budgets of known objects (galaxies, AGN, cluster shocks etc.)

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

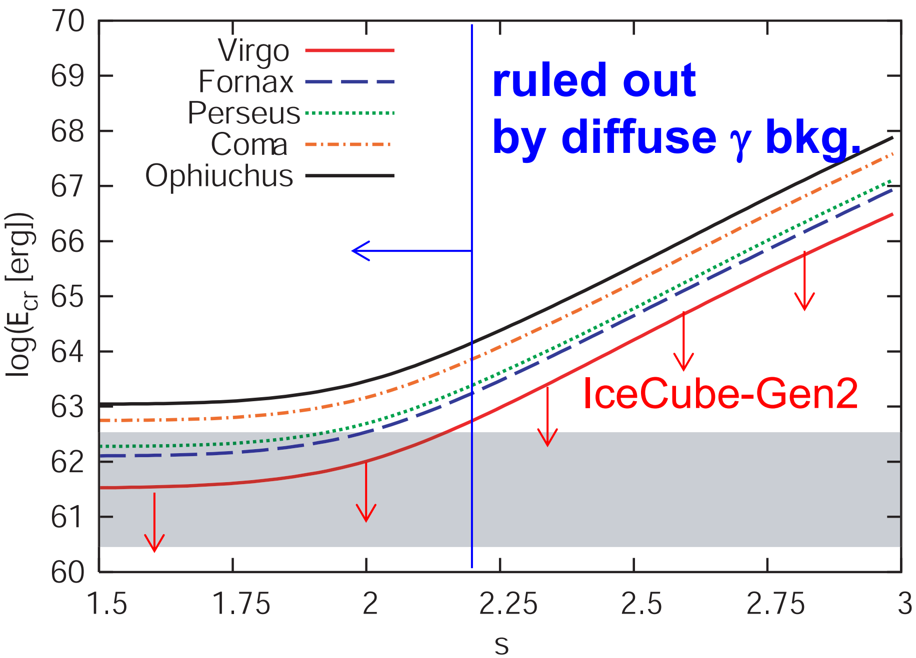
Testing Galaxy Clusters w. Neutrinos







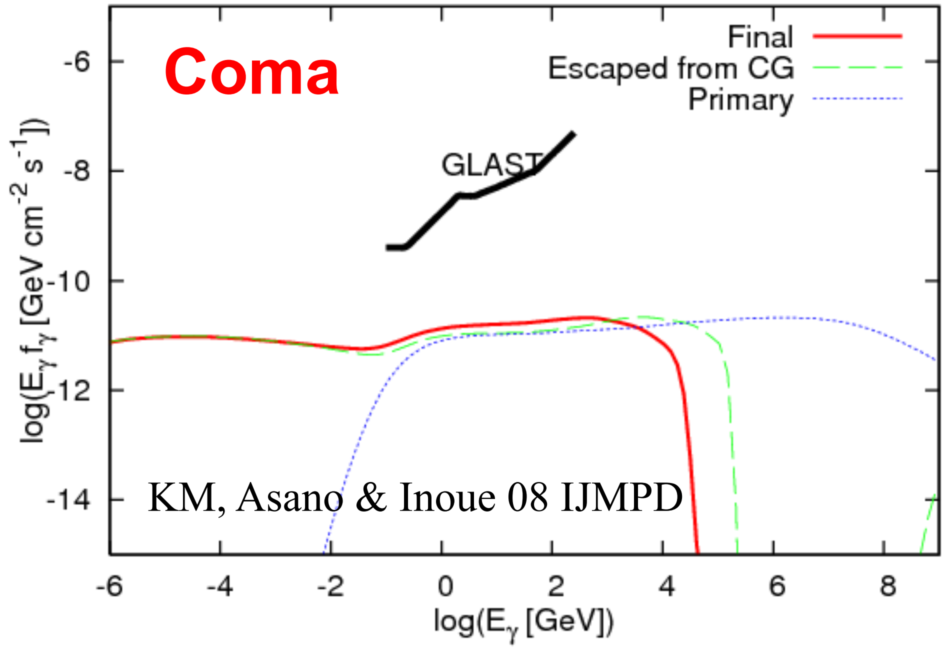
KM, Laha, Ando & Ahlers 15 PRL



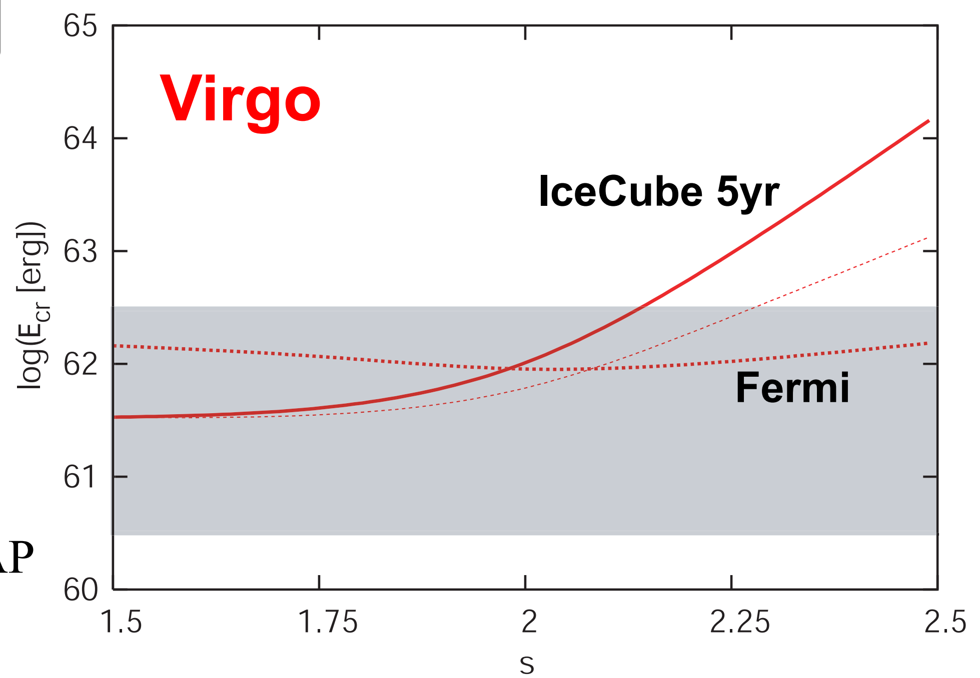
KM & Beacom 13 JCAP

Good chances to see neutrinos if CR reservoir models are correct

Gamma-Ray Limits?



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



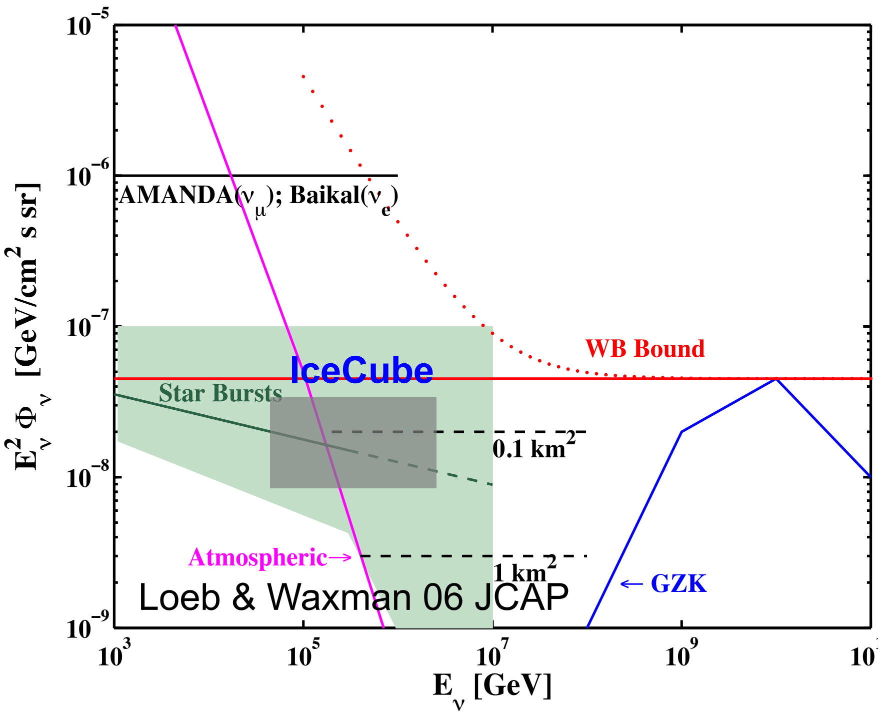
KM & Beacom 13 JCAP

Backup Slides

pp Neutrinos from Cosmic-Ray Reservoirs

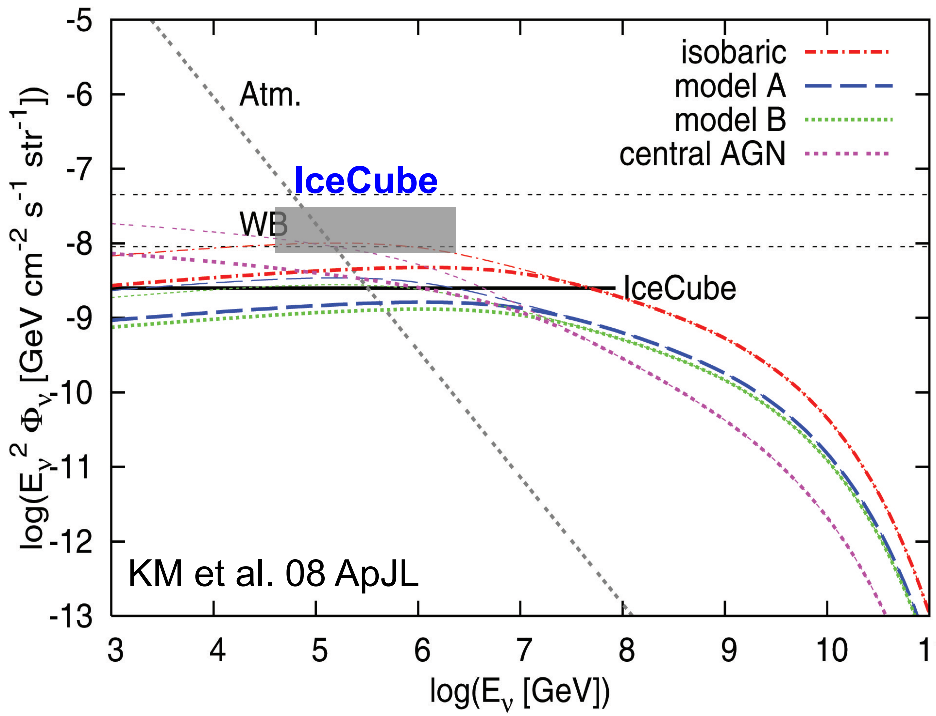
Starburst galaxy
size~0.1-1 kpc, B~0.1-1 mG

CR sources: peculiar supernovae, AGN



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

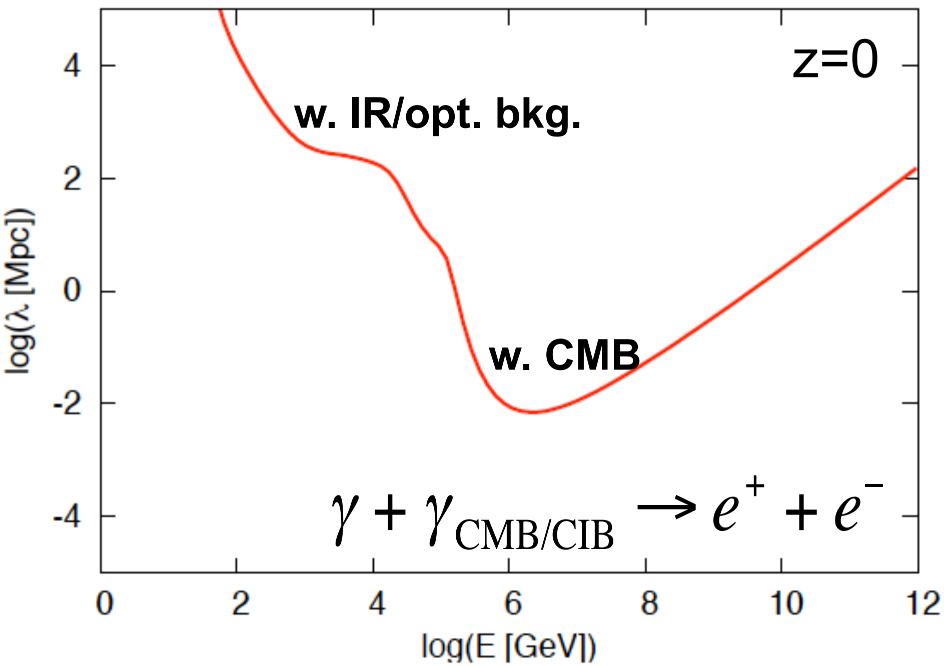
CR sources: AGN, galaxy mergers, virial shocks



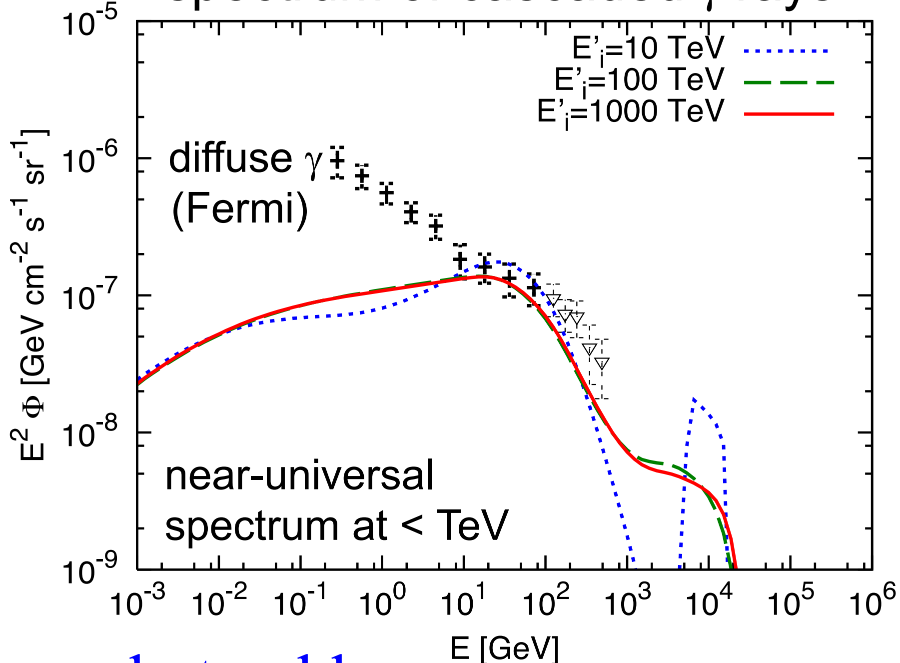
- ν data are consistent w. *pre-discovery* calculations (within uncertainty)
- CR diffusive escape naturally makes a ν spectral break (predicted)
- Uncertain (ex. how $E_p^{max} > E_{knee}$?) but models look simple and natural

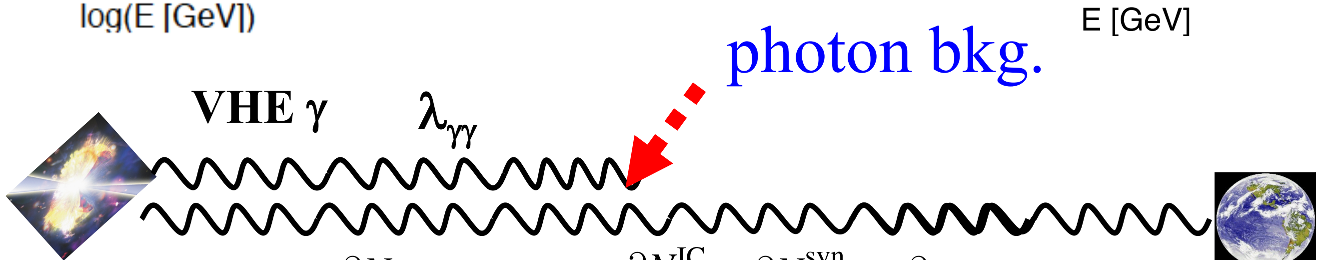
Fate of Extragalactic Gamma Rays

γ-ray mean free path



spectrum of cascaded γ rays





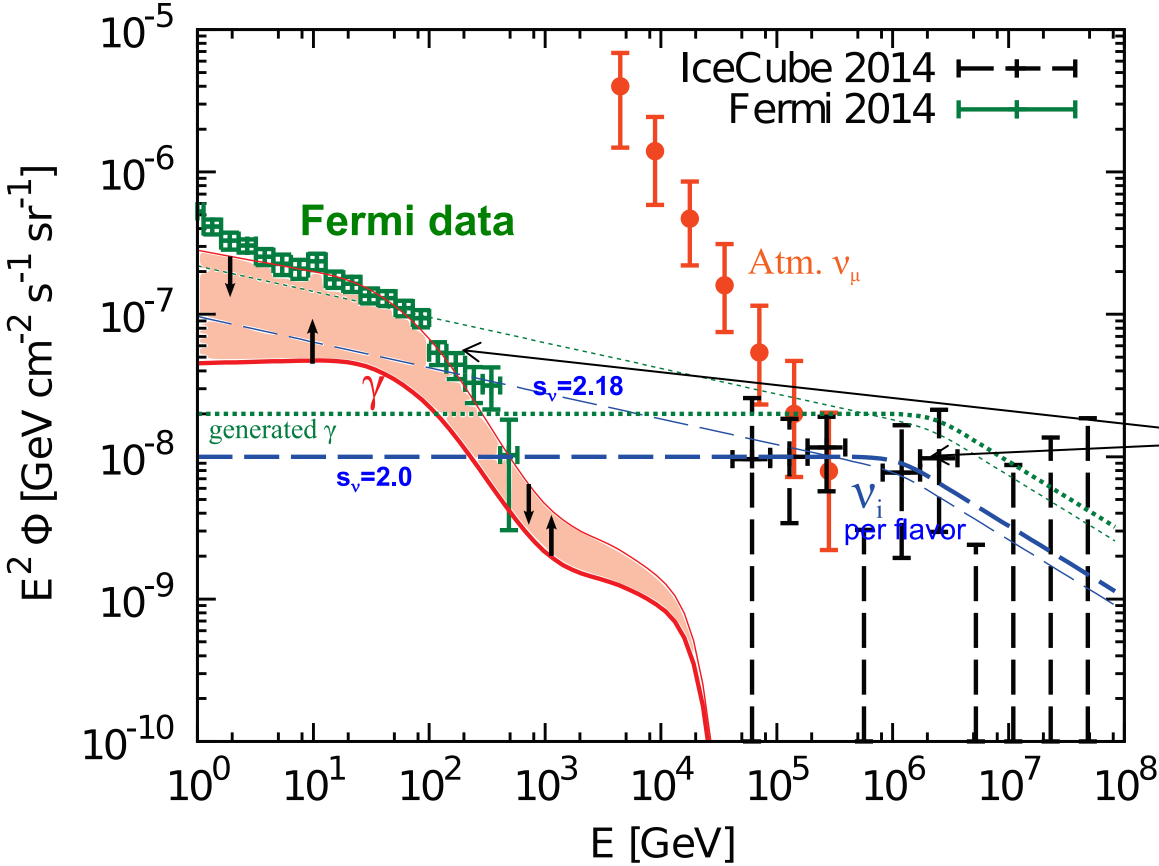
LE γ

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

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

First Multimessenger Constraints from "Measured" Fluxes

KM, Ahlers & Lacki 13 PRDR



pp scenario

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

"comparable fluxes"

quite model-independent

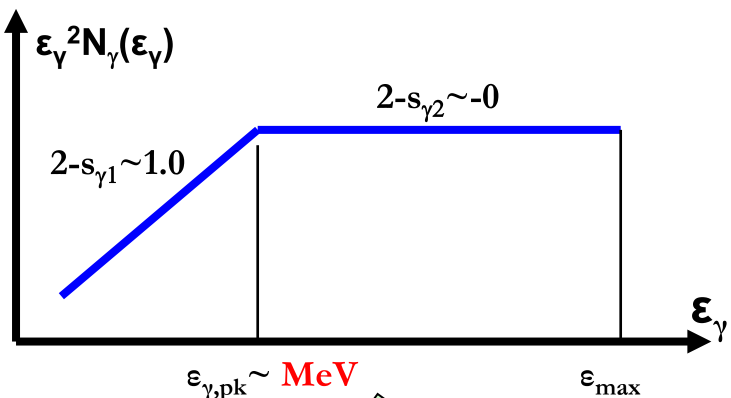
- s_ν<2.1-2.2 (for extragal.), s_ν<2.0 (Gal.) (cf. Milky Way: s_γ~2.7)
- contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)
- IceCube & Fermi data can be explained simultaneously

An Example of Calculation: Gamma-Ray Burst Jets

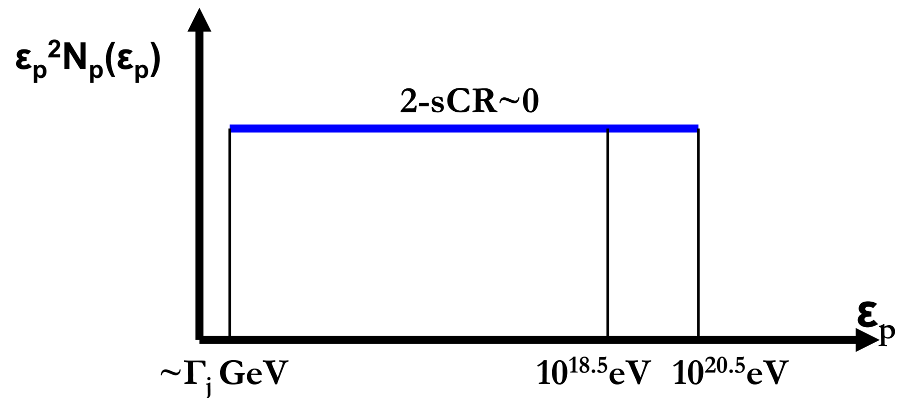
GRB: brightest γ-ray transient

Popular candidate sources of UHECRs

Photon Spectrum (observed)



CR Spectrum (Fermi mechanism)



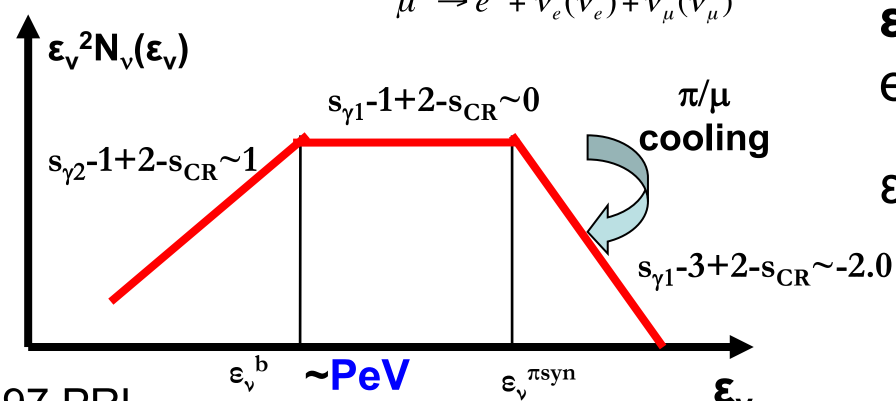
$\varepsilon_p \varepsilon_\gamma \sim 0.2\Gamma_j^2$ GeV^2

at Δ-resonance

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

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

Neutrino Spectrum



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

efficiency: $f_{p\gamma}\sim0.2 n_\gamma \sigma_{p\gamma} \Delta$

$\varepsilon_\nu^b\sim0.05\varepsilon_p^b$

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

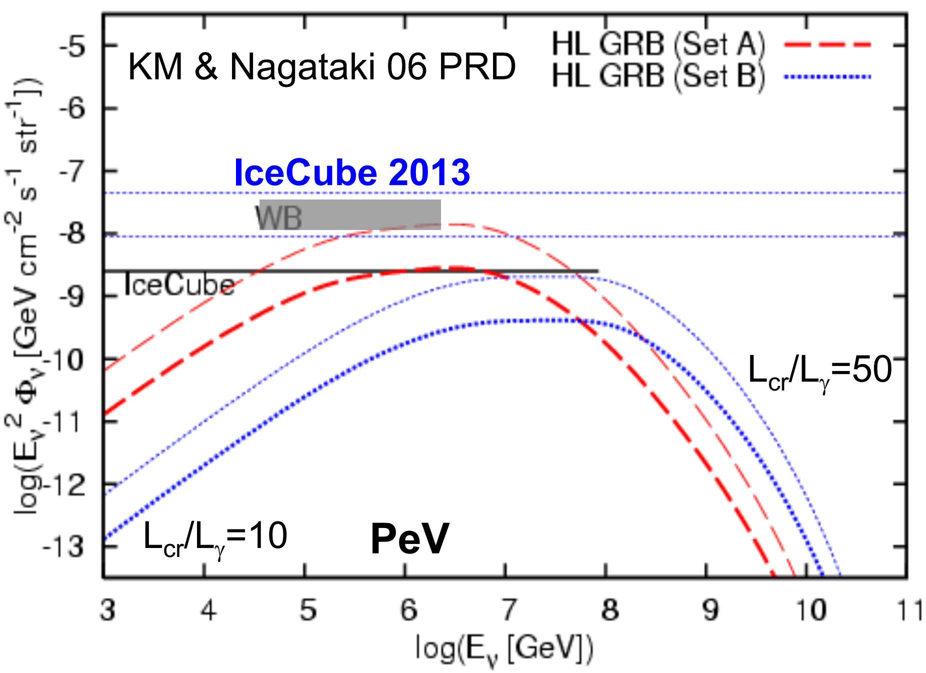
~1 PeV (w. $\varepsilon_{\gamma,pk}\sim1$ MeV)

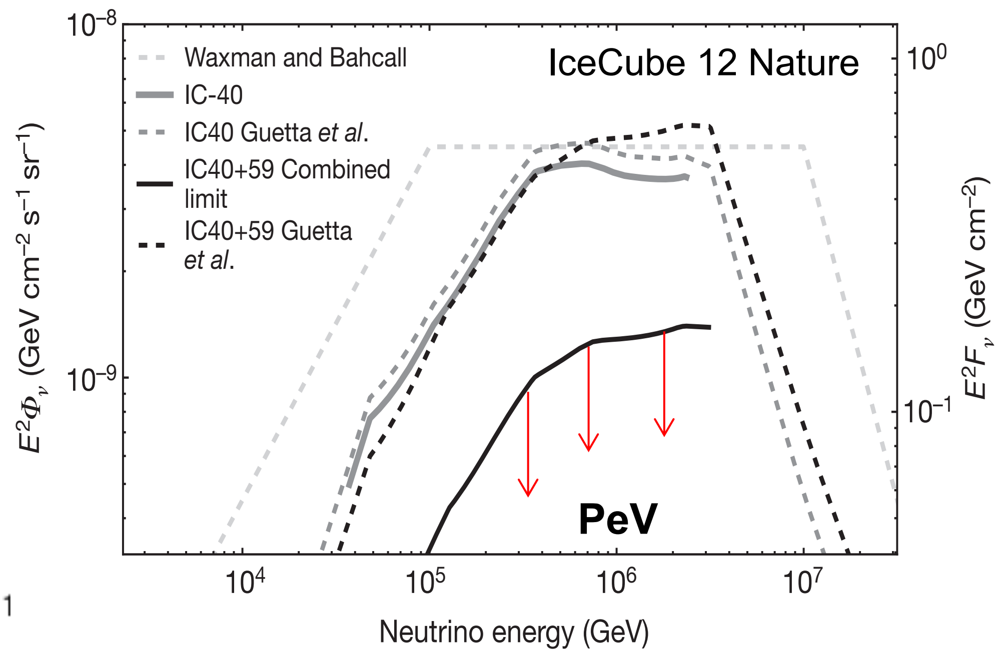
$\Gamma_j\sim300$: jet Lorentz factor

Waxman & Bahcall 97 PRL

Classical Long Gamma-Ray Bursts (pγ)

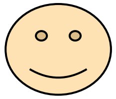
numerical results w. detailed microphysics





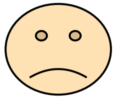
- GRBs are special: stacking analyses

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

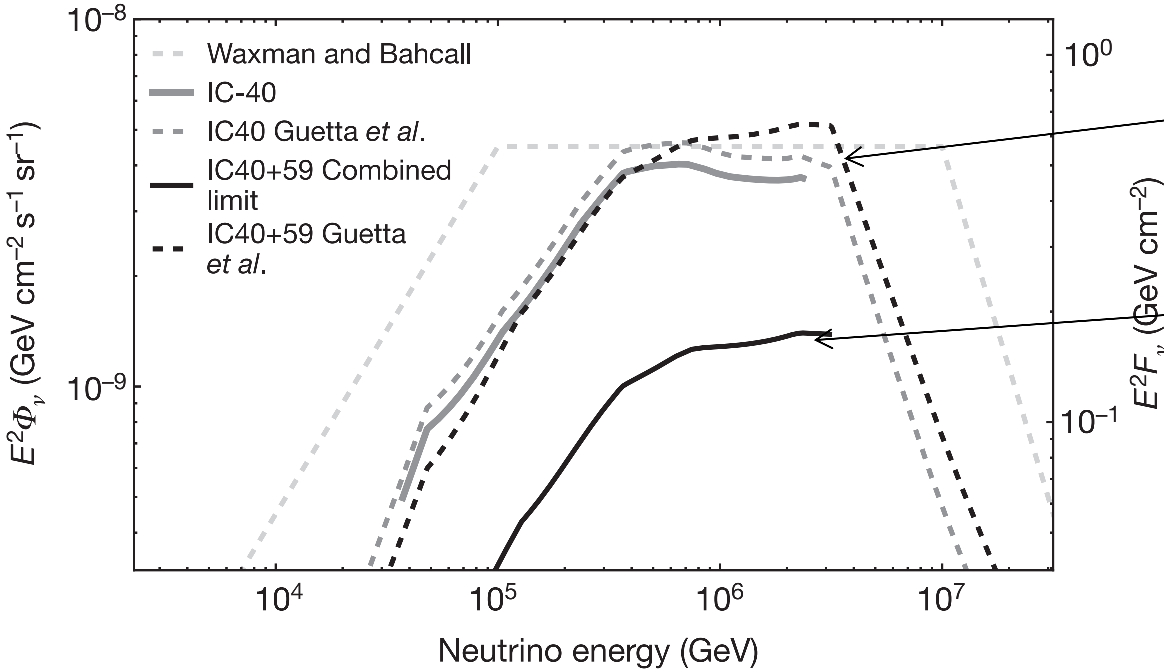


- IC40+59 limits: <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} (and stronger w. IC79+86)

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



Recent IceCube Limits on Prompt ν Emission



Theor. prediction (but see below)

Obs. limit (based on stacking)

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)

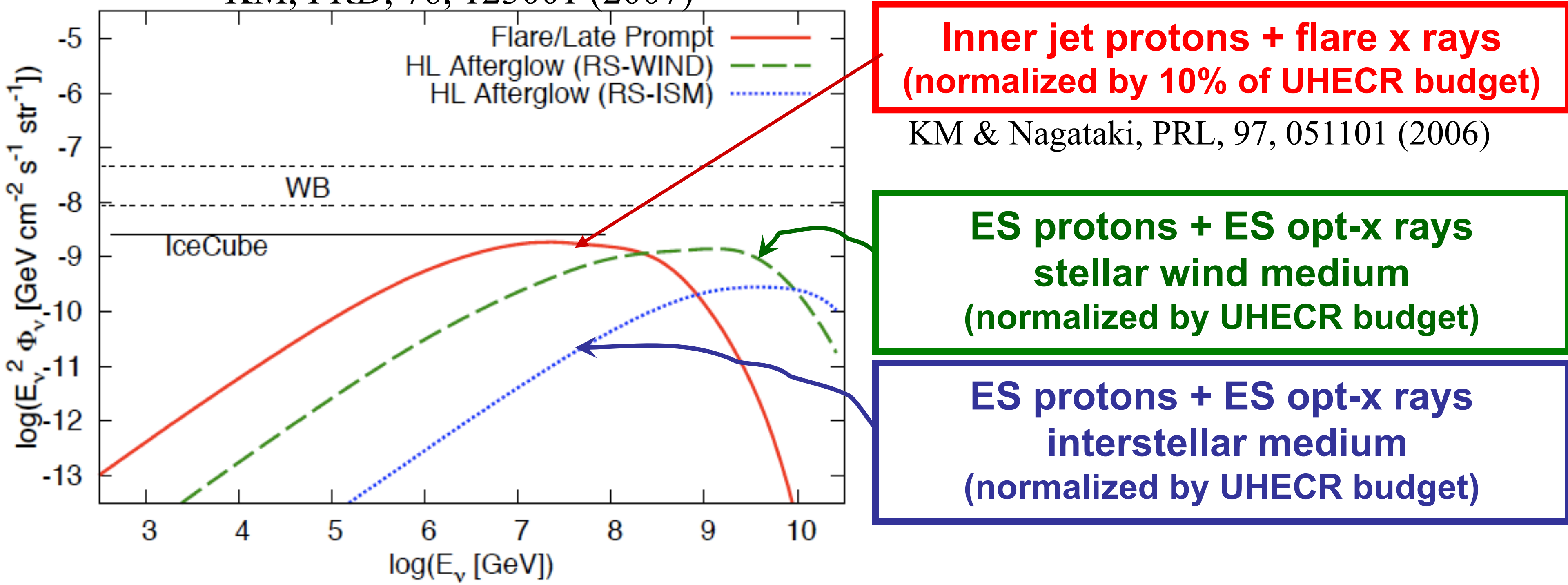
3. details (multi-π, ν mixing etc.) → ex., multi-π ~2-3 ↑ (KM & Nagataki 06 PRD)

- 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)

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

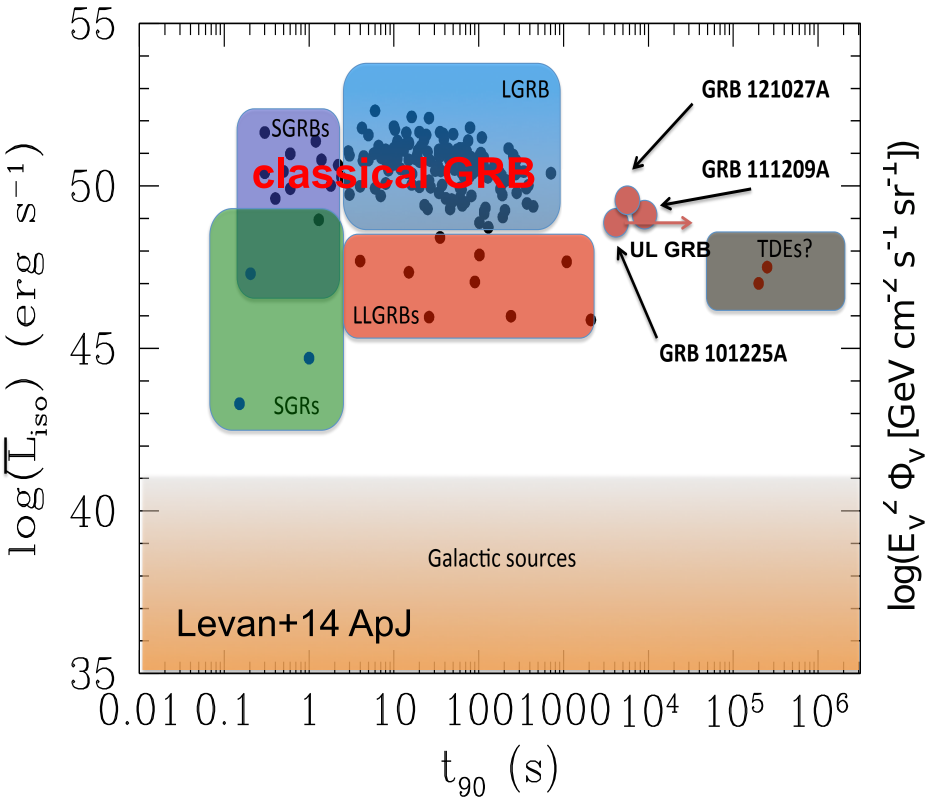
KM, PRD, 76, 123001 (2007)

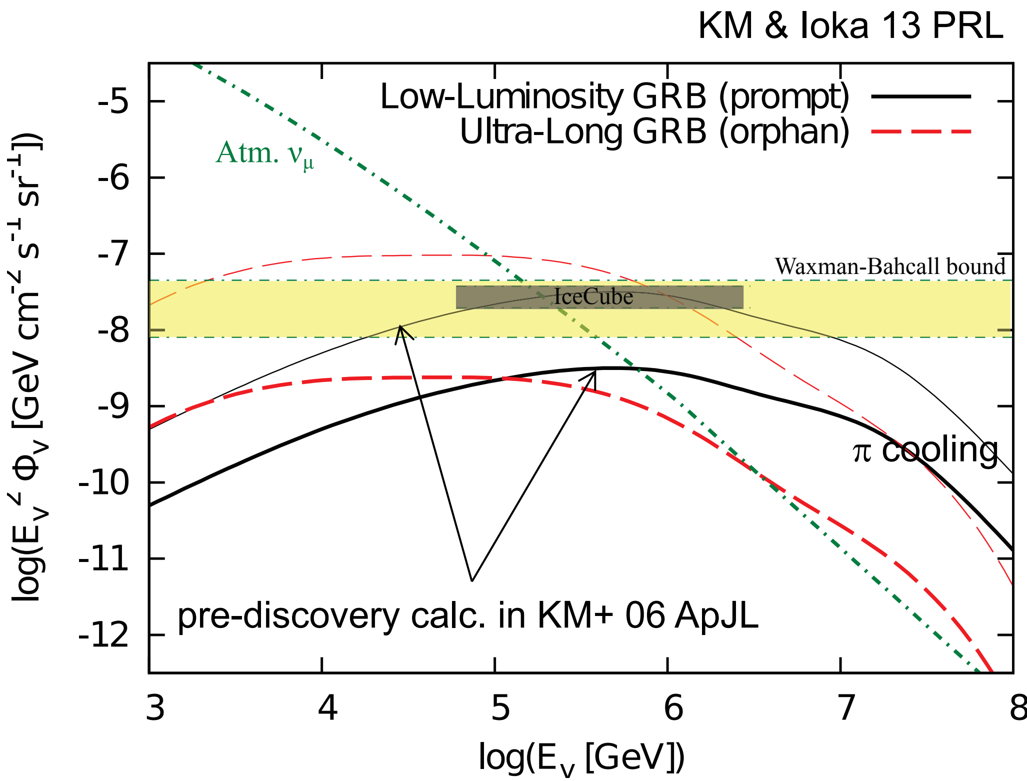


KM & Nagataki, PRL, 97, 051101 (2006)

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

Exceptions: Low-Power Gamma-Ray Burst Jets

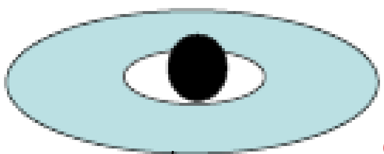




- Low-luminosity (LL) & ultralong (UL) GRB jets are largely missed
  may explain IceCube ν data without violating stacking limits
- Uncertain so far, but relevant to understand the fate of massive stars
  → Better (next-generation) wide-field sky monitors are required

Active Galactic Nuclei (AGN)

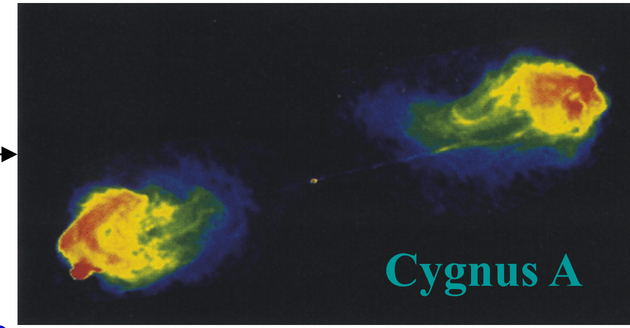
BH + accretion disk



~ 10%
Jets
(Γ~1-10)
elliptical gal.

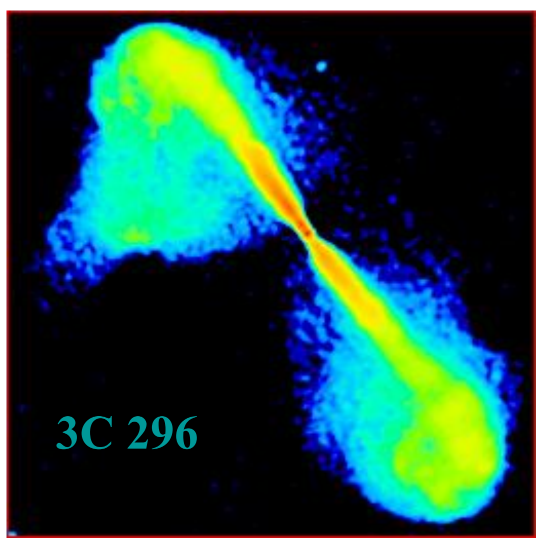
~ 1 %
$L_{radio} > 5 \times 10^{41}$ erg/s

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



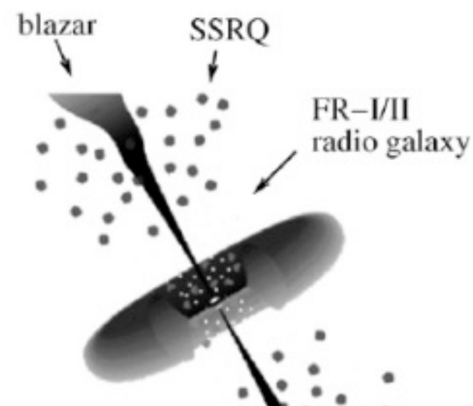
~ 9 %
$L_{radio} < 5 \times 10^{41}$ erg/s

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



~ 90%
No jets
spiral gal.

Seyfert galaxy
Radio quiet quasar
Radio intermediate quasar



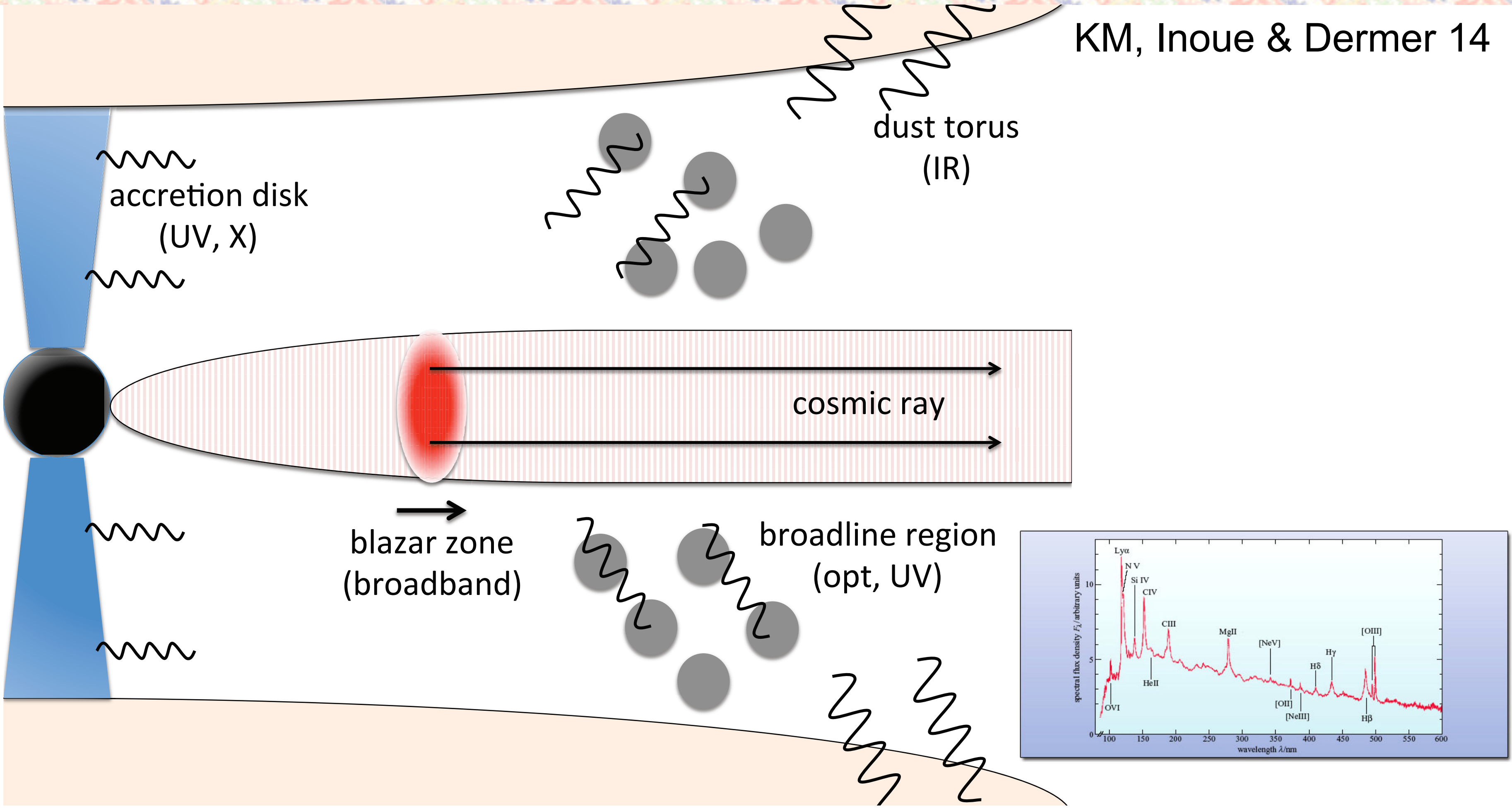
"blazar" (FSRQ+BL Lac)
= on-axis jets

- Flares (e.g., T ~ day)

FR=Fanaroff-Riley

External Radiation Fields

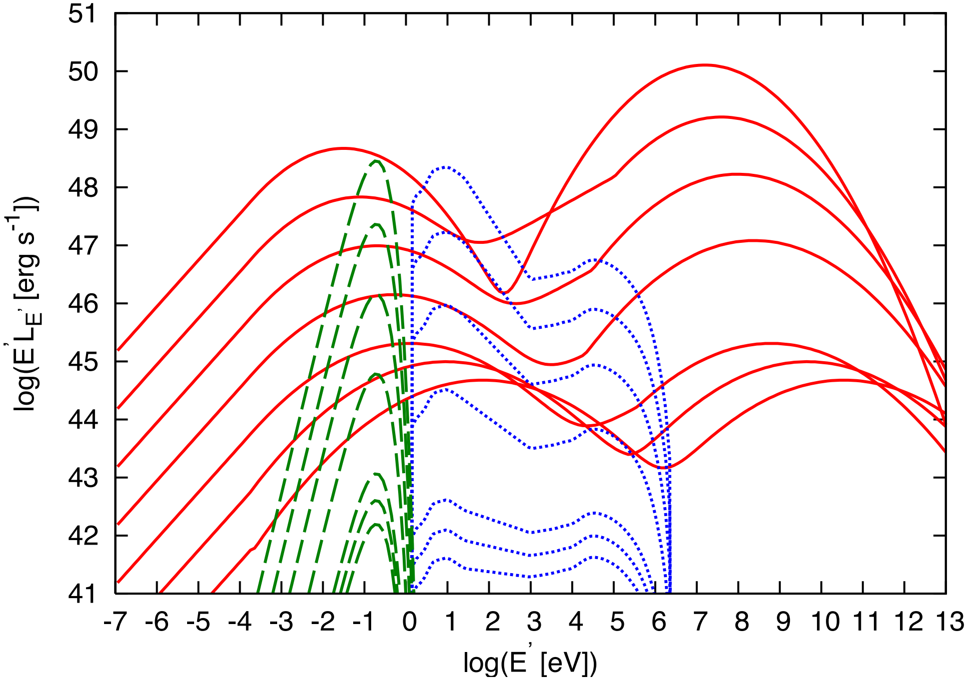
KM, Inoue & Dermer 14



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

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



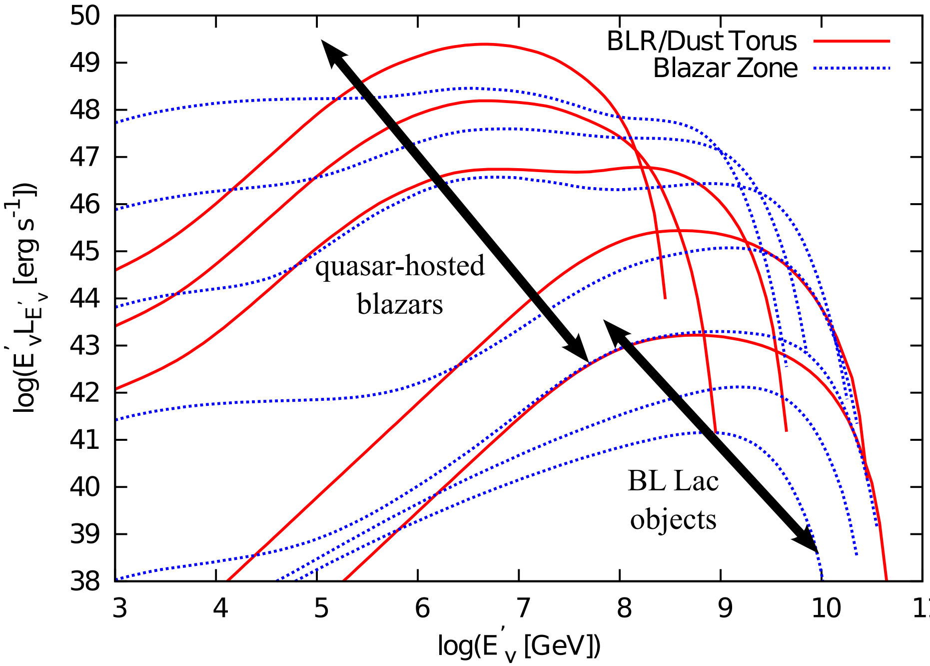
"Blazar sequence"

softer spectra at higher L

Neutrino blazar sequence

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

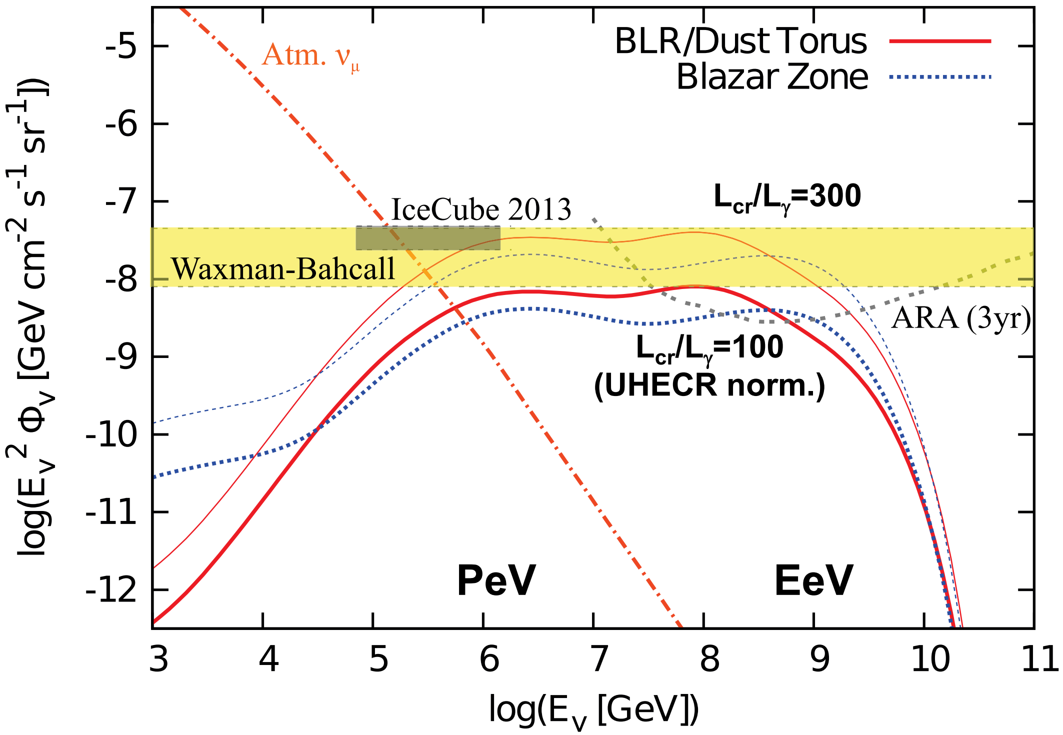
$\rightarrow L_{\nu} \propto L_{\gamma}^{1.5}$



KM, Inoue & Dermer 14

Blazars as Powerful EeV ν Sources

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

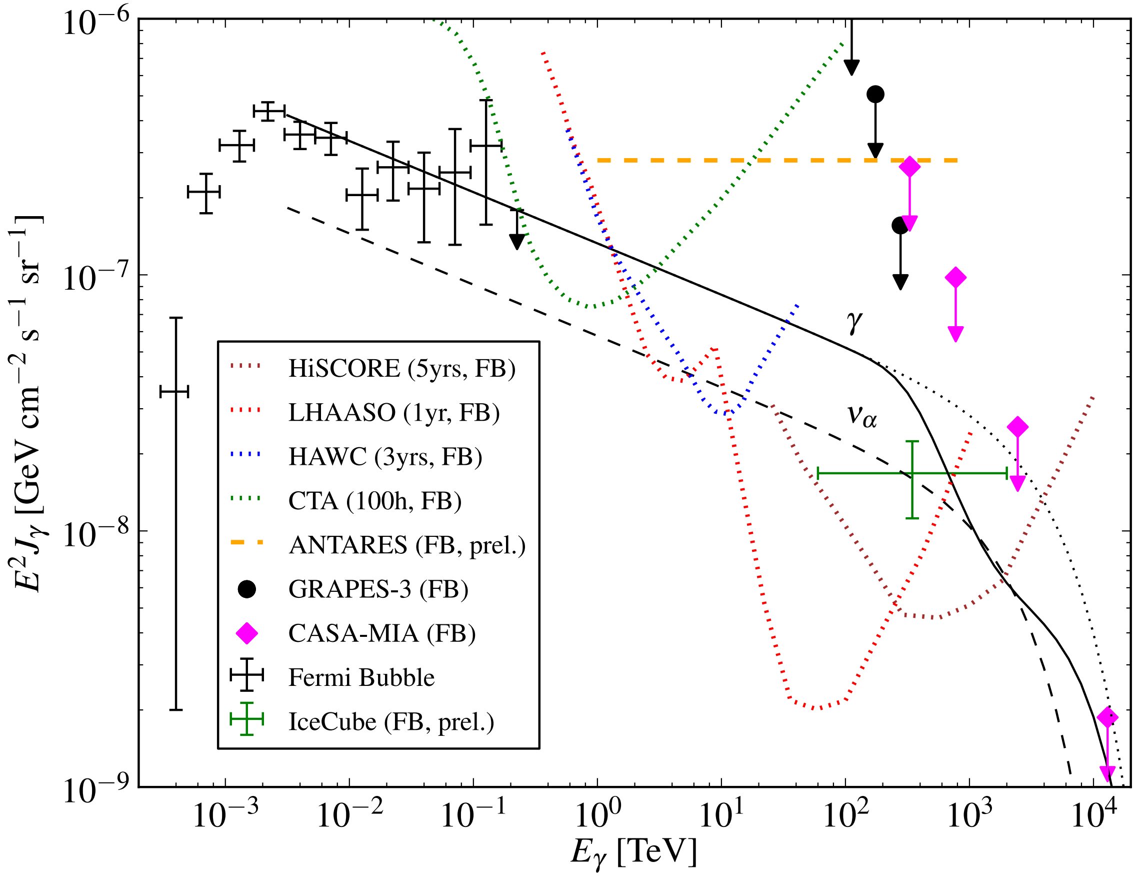


- luminosity function is now provided by Fermi satellite
- target photon spectra of all types of blazars w. external radiation fields

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 EeV ν detectable by ARA

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)