Toward the Identification of the Cosmic Neutrino Origin

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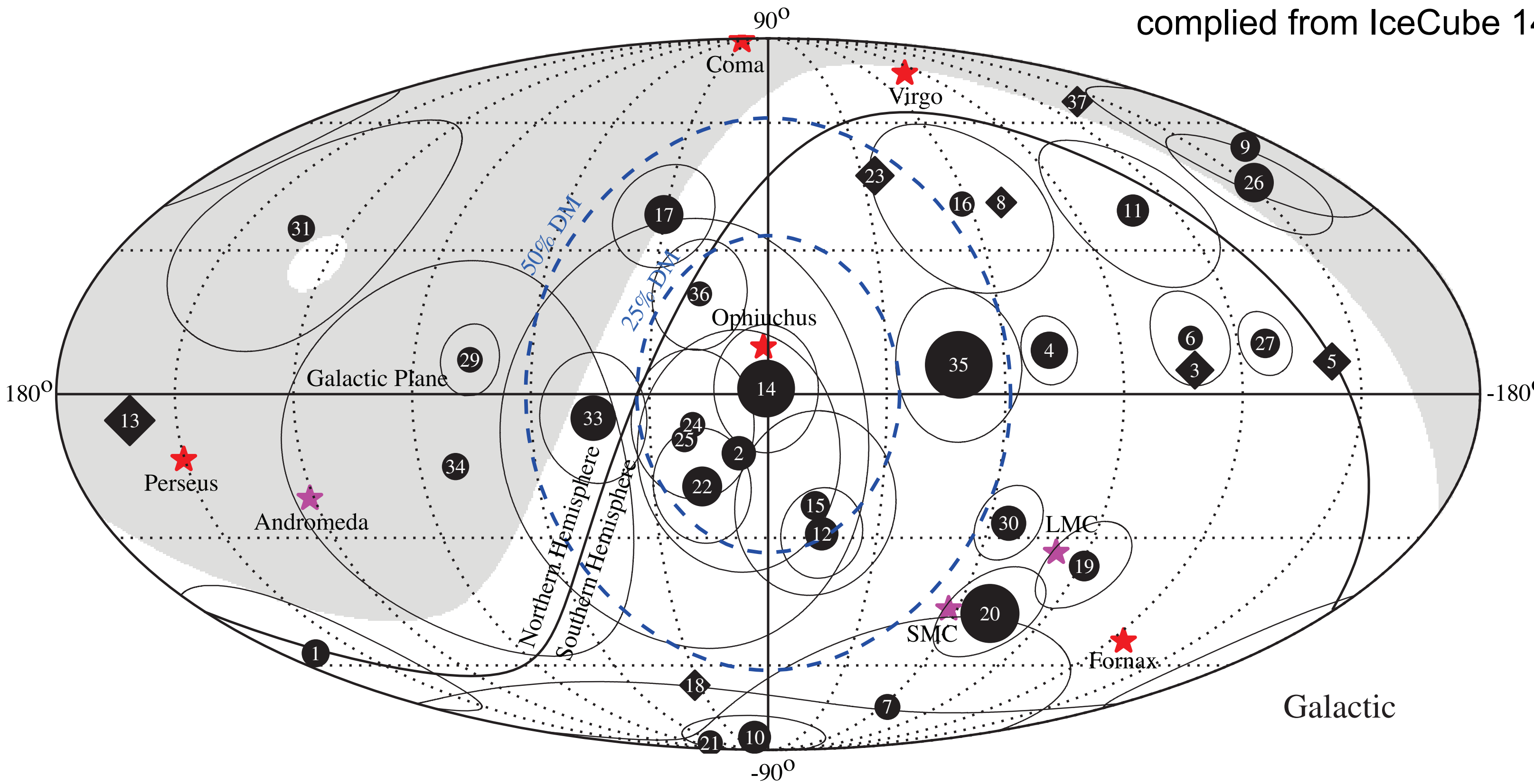
PENNSTATE
1855

IPA 2015 @ Madison

HE Neutrino Astrophysics Started

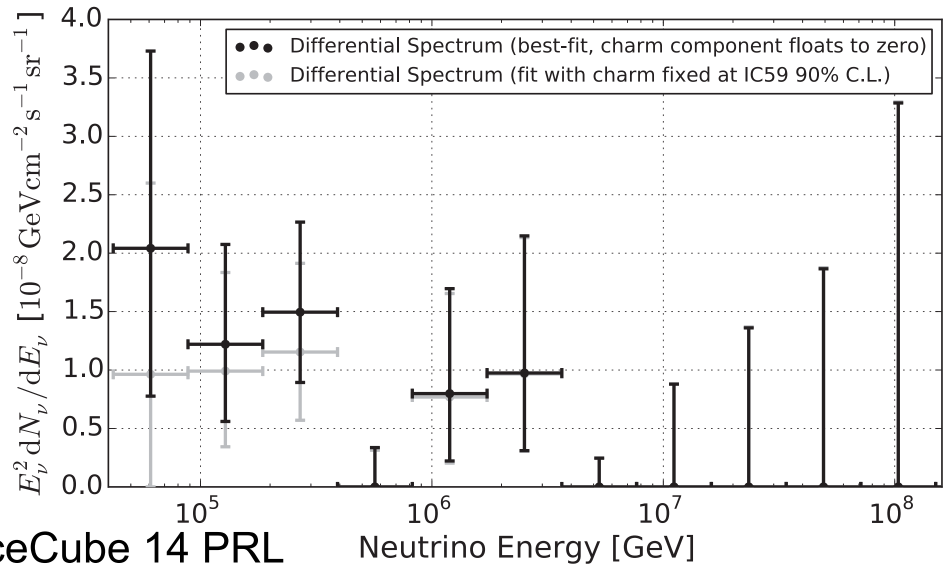
Ahlers & KM 14 PRD, KM+ 15
complied from IceCube 14 PRL



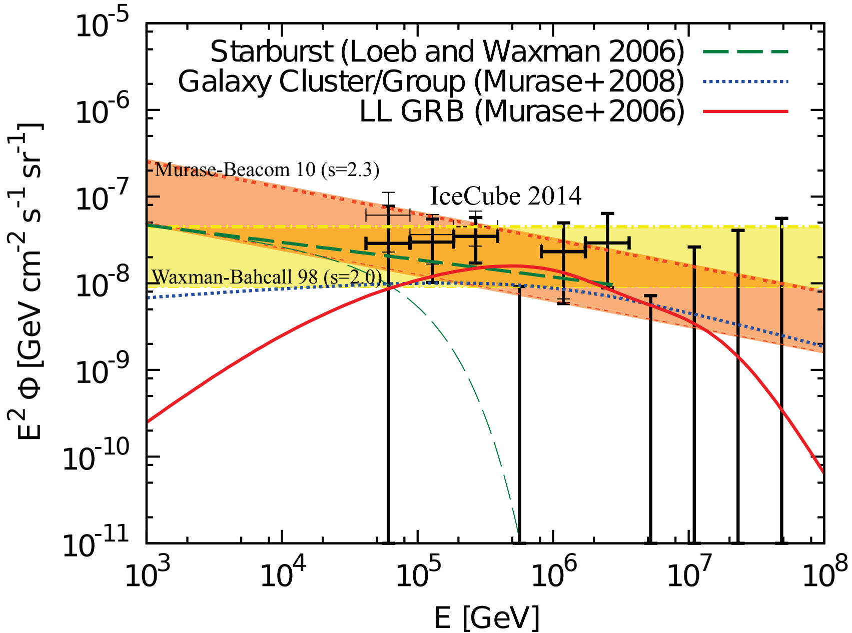
- Easy to see: mostly isotropic, extragalactic events
- Galactic halo? absence of sub-TeV/sub-PeV γ rays

(KM, Ahlers & Lacki 13 PRDR, Ahlers & KM 14 PRD)

Open Questions

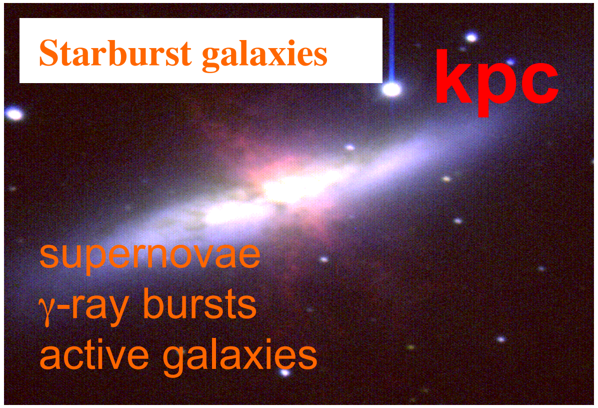


IceCube 14 PRL

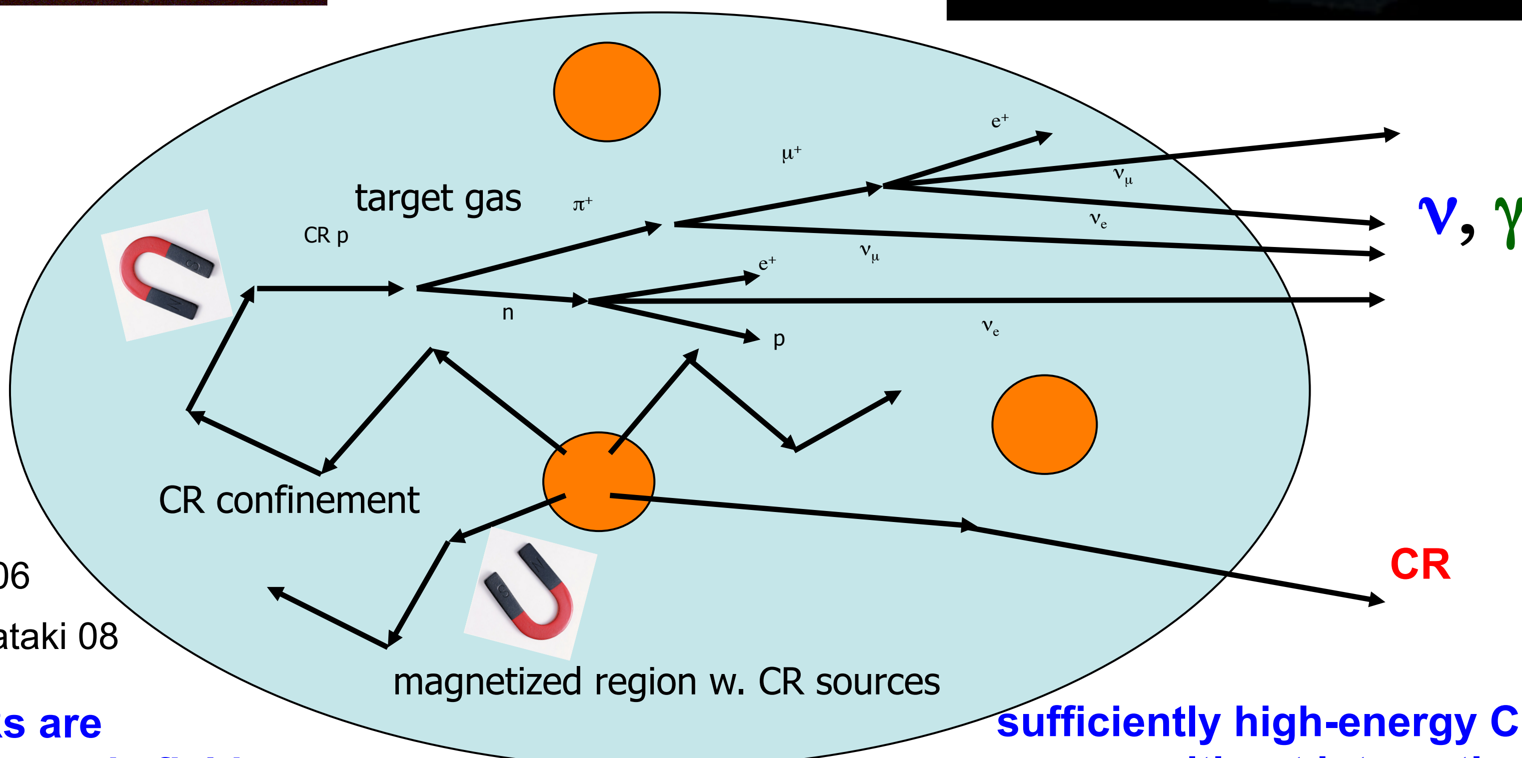


- Cosmic ν origin?
  starbursts
  galaxy clusters/groups
  active galaxies
  gamma-ray bursts
  supernovae/pulsars…
- pp or pγ?
- UHECR connection?
  Waxman-Bahcall bound?
  nucleus-survival bound?
- γ-ray connection?
- Flavor ratios?
- New physics?

Cosmic-Ray Reservoirs



"cosmic-ray reservoirs"



Loeb & Waxman 06

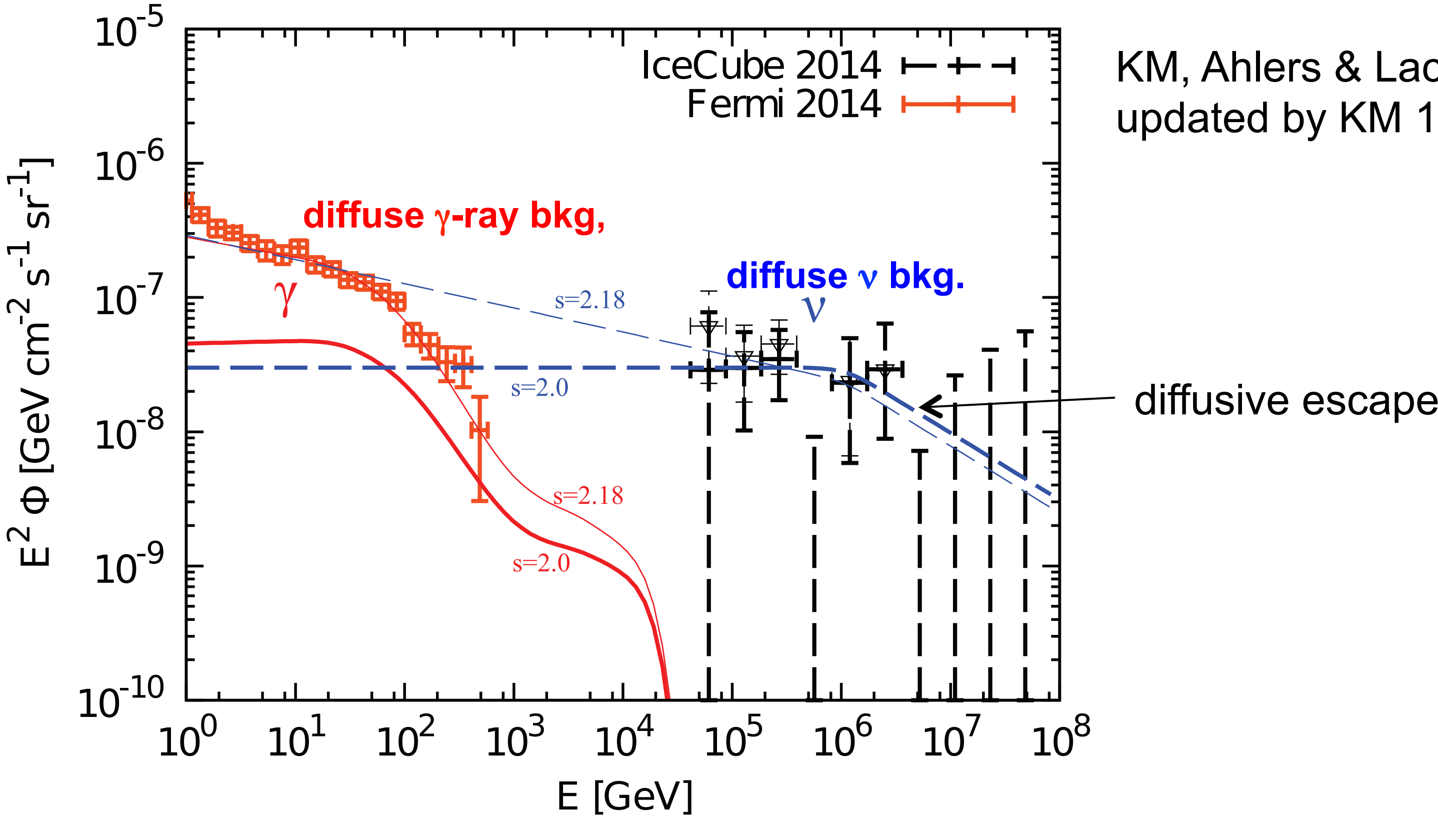
KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions

pp Neutrinos from CR Reservoirs

- CR reservoirs explain >0.1 PeV neutrino data with a few PeV break
- 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<2.2, >30% to the diffuse γ-ray bkg.

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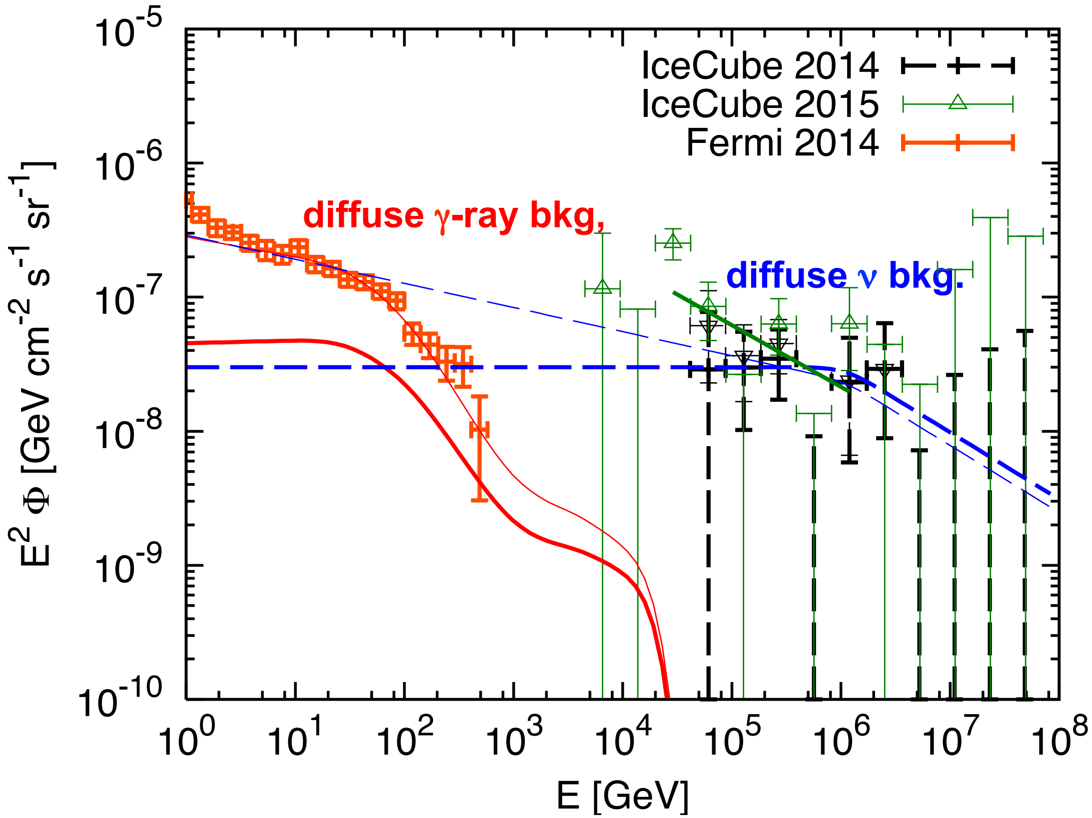


KM, Ahlers & Lacki 13 PRDR
updated by KM 1410.3680

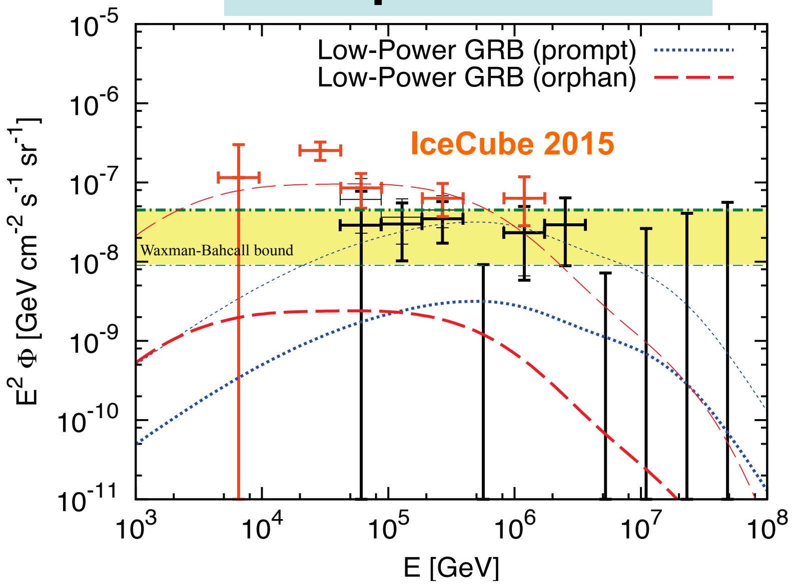
- Strong predictions: spectral index s<2.2, >30% to the diffuse γ-ray bkg.
- If steep (s~2.5)→ ruling out a single origin & another component is required
  GRB (KM & Ioka 13 PRL), AGN (Kimura, KM & Toma 15 ApJ), Galactic (Ahlers & KM 14 PRD)

$p\gamma$ Neutrinos from GRBs and AGN

Standard jet models as the cosmic ν origin: ruled out by multi-messenger obs.

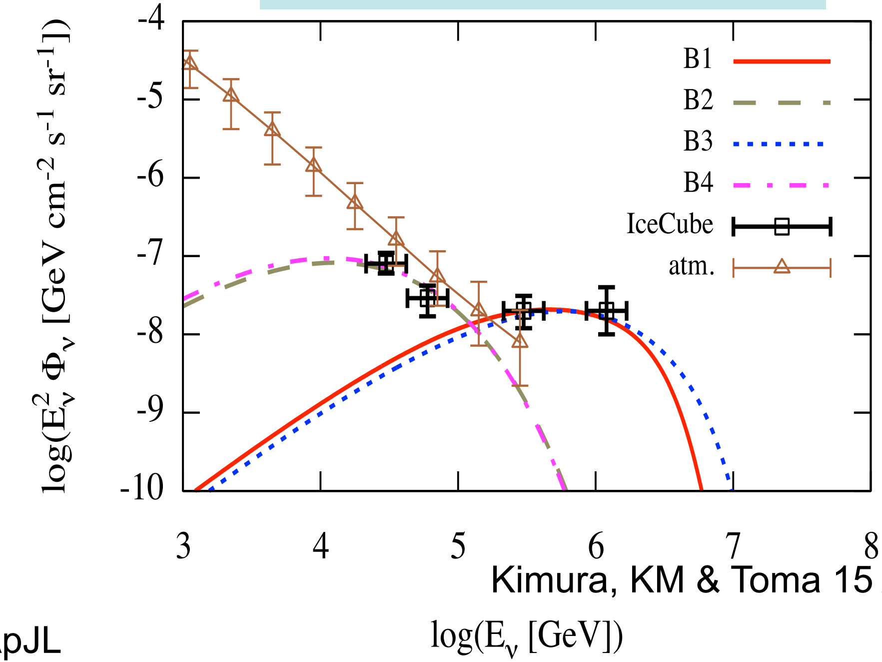
- Classical GRBs: constrained by stacking analyses **<~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}**
- Blazars: spectral shape (KM, Inoue & Dermer 14), point-source limits (KM & Waxman 15)

Low-power GRBs



KM & Ioka 13 PRL
see also KM+ 06 ApJL

Low-luminosity AGN

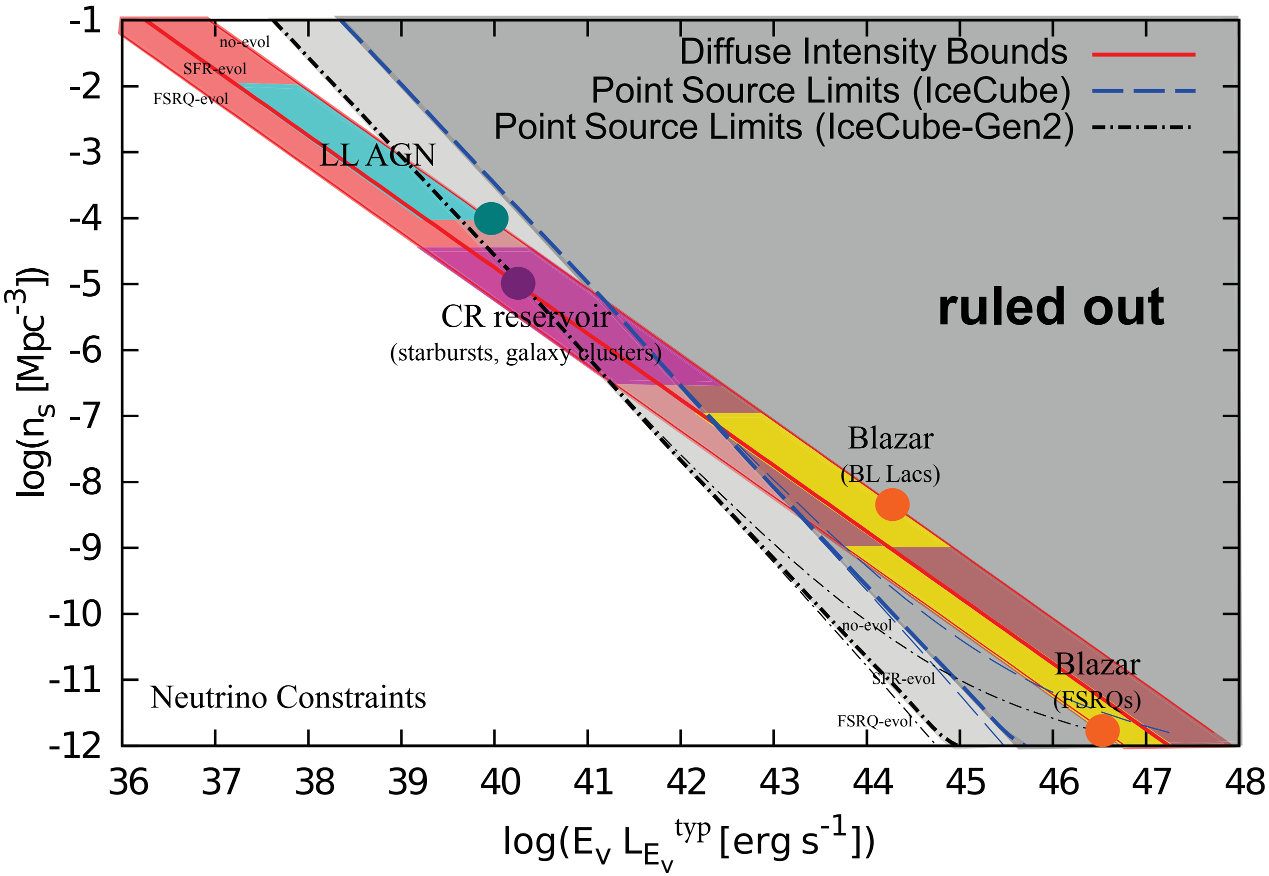


Kimura, KM & Toma 15 ApJ

- **"hidden neutrino sources?"** (invisible in γ rays but maybe in X rays or optical)
- Uncertain but multi-messenger data should help (need theoretical work)

Muon Neutrino Constraints

- Present data give limits: $n_0 > 10^{-8}$-10^{-5} Mpc^{-3}
  $E_\nu L_{E\nu} < 10^{41}$-10^{43} erg/s
- Testing CR reservoirs: need a detector like IceCube-Gen2



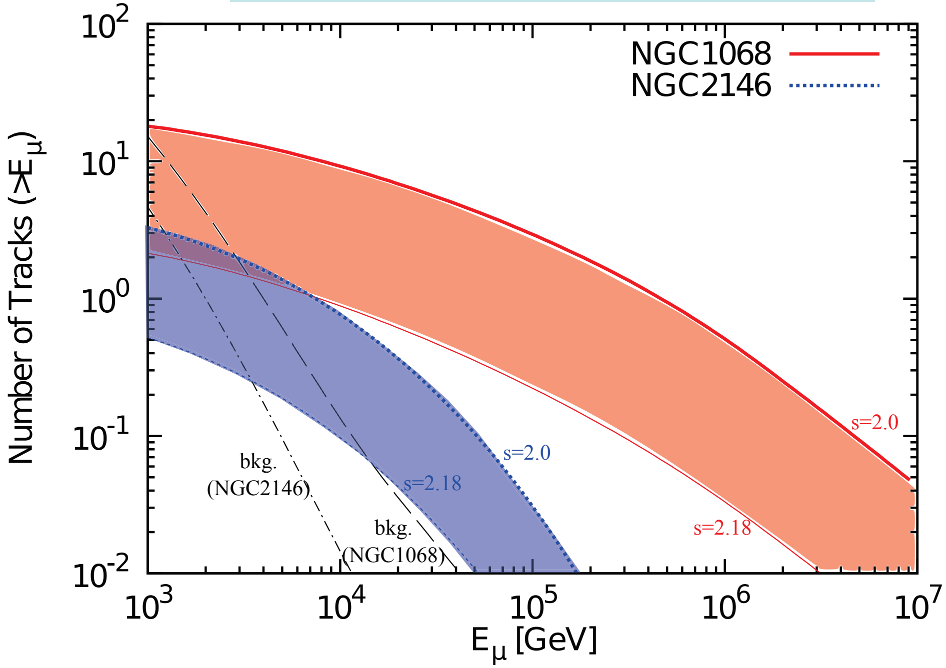
KM & Waxman 14 @JSI
see also
Silvestri & Barwick 10
KM, Beacom & Takami 12
Ahlers & Halzen 14

Testing CR Reservoir Models w. Neutrinos

Starburst galaxies: n_0~10^{-5} Mpc^{-3} (calorimetric or L_γ-L_{IR} corr.)

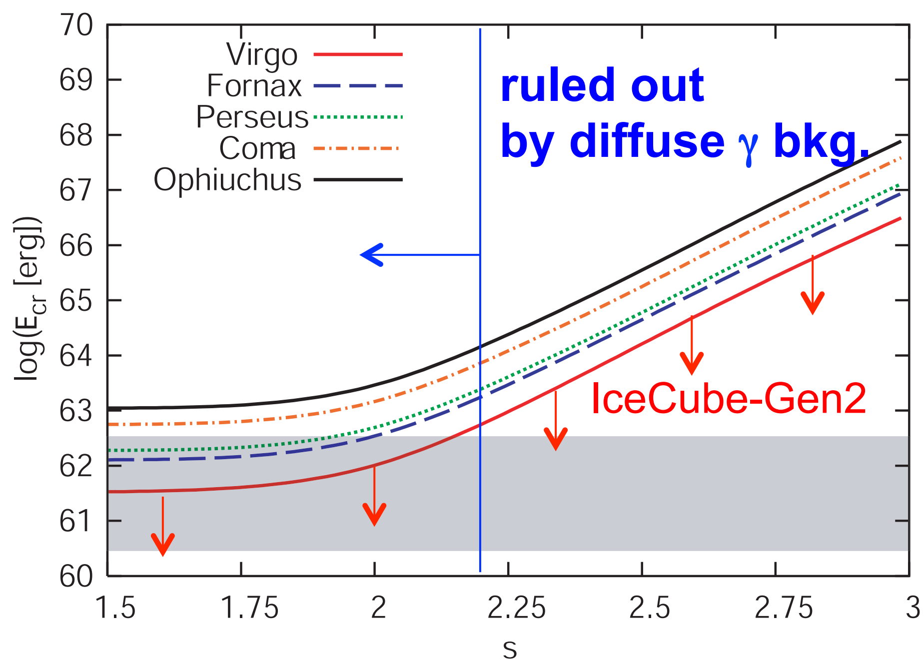
Galaxy clusters: n_0~10^{-5} Mpc^{-3}, n_0~10^{-6} Mpc^{-3} (massive clusters)

Muon neutrino event rates from nearby starbursts



KM & Waxman 15

Muon neutrino constraints from nearby galaxy clusters

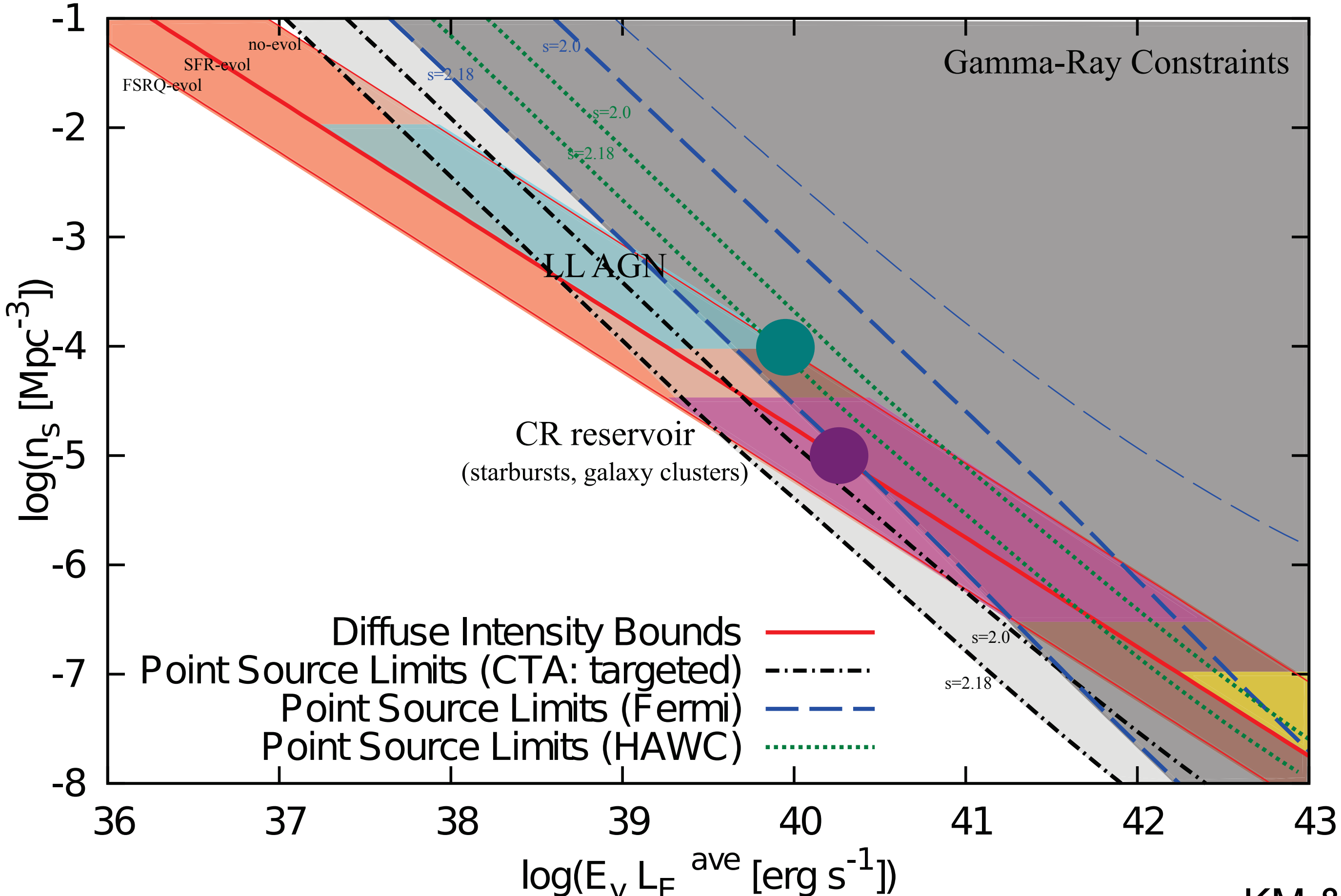


KM & Beacom 13 JCAP

Good chances to see neutrinos if CR reservoir models are correct

Testing CR Reservoir Models w. γ Rays

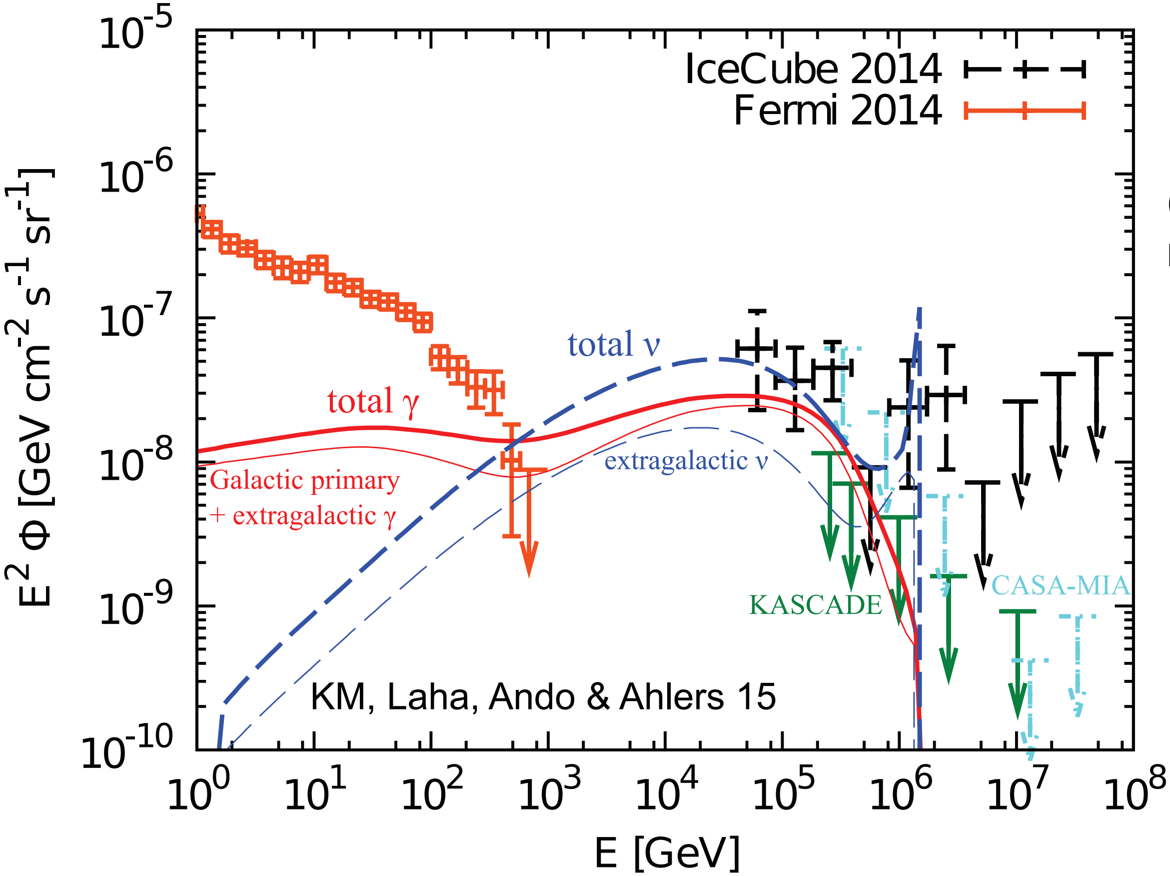
- Fermi results → γ-ray spectra should be hard (s<2.1-2.2)
- Nearby CR reservoirs should be seen as hard multi-TeV γ-ray sources
- Deep observations by future TeV γ-ray detectors (ex. CTA) is crucial



KM & Waxman 15

γ-ray Limits Challenge the Dark Matter Scenario

Many authors tried to explain by DM… ex. Feldstein et al. 13, Esmaili & Serpico 13, Bai+ 14, Higaki+ 14, Fong+ 15, Rott+ 15

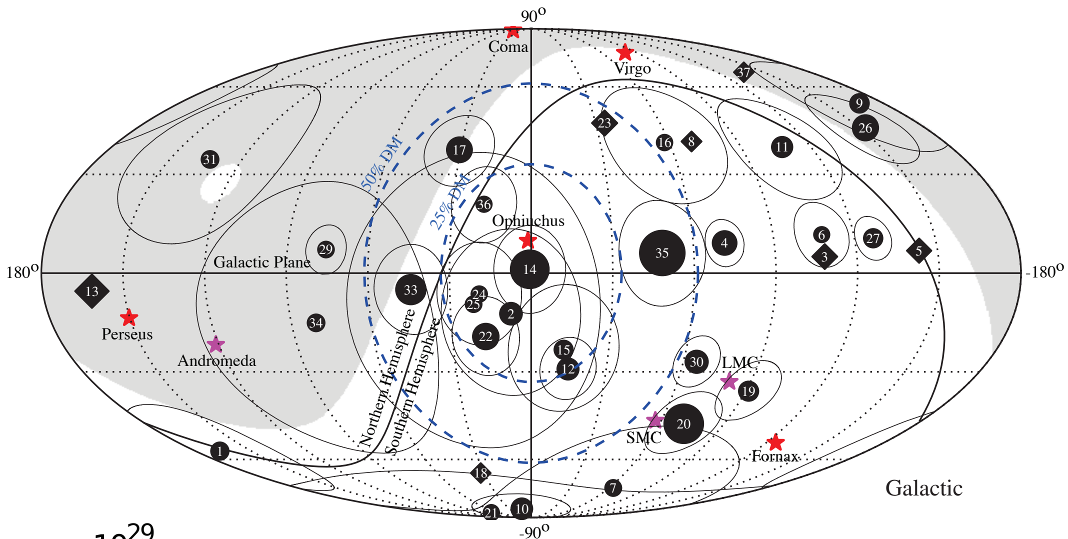


DM → $\nu_e+\nu_e$ (12%)
DM → b+b (88%)

(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

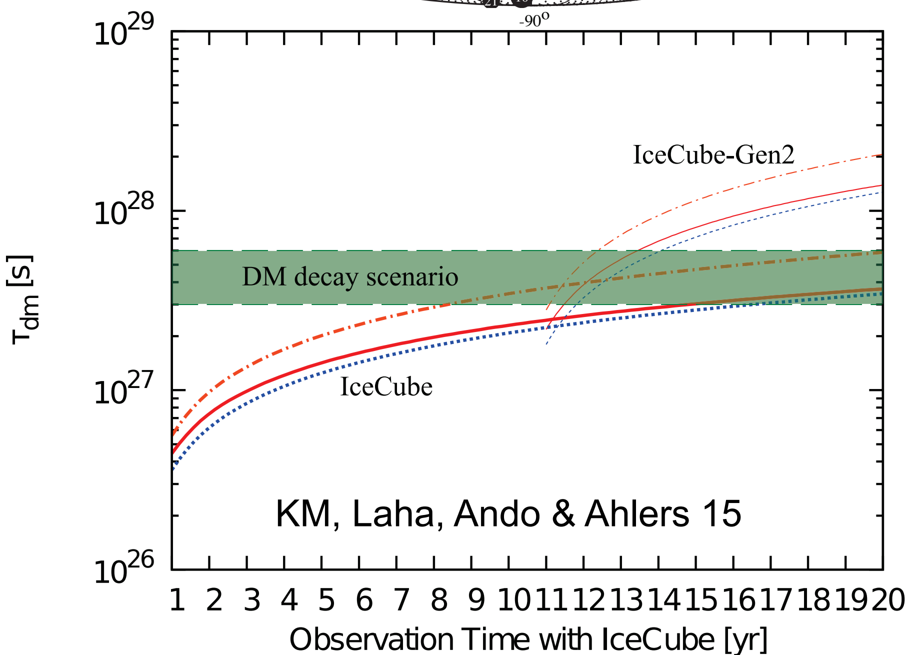
DM Scenarios can be Killed by IceCube-Gen2



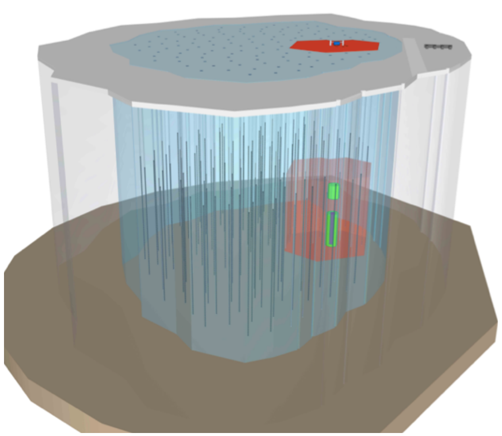
τ_{dm} ~ a fewx10^{27} s

flux ∝ $M_{dm}/\tau_{dm}/D^2$

→ nearby DM halos (galaxies & clusters) give us a critical test



Again, IceCube-Gen2 is crucial



Summary

What is the origin of cosmic ν signals?

Implications:

mostly isotropic & diffuse TeV-PeV γ-ray limits → extragalactic
pp scenarios: s<2.2 & >30% to the diffuse sub-TeV γ-ray bkg.
s~2.5 → another component below ~100 TeV?

pγ scenarios: not explained by classical GRBs & blazars
→ hidden sources (ex. low-power GRBs/AGN)?

Requests for future:

IceCube-Gen2: $n_0 > 10^{-5}$ Mpc^{-3}, testing CR reservoirs & PeV DM

Fermi: ~2-3 improvements can rule out or support pp scenarios & PeV DM

CTA: CR reservoirs as s<2.2 γ-ray sources, DM emission from galaxy clusters

HAWC/air-shower arrays: γ-ray counterparts if significant Galactic contributions

Importance of theories: "multi-messenger" approach (ex. AMON)
especially for pγ scenarios (ex. low-power GRBs w. hard X-ray sky monitors)

Backup Slides

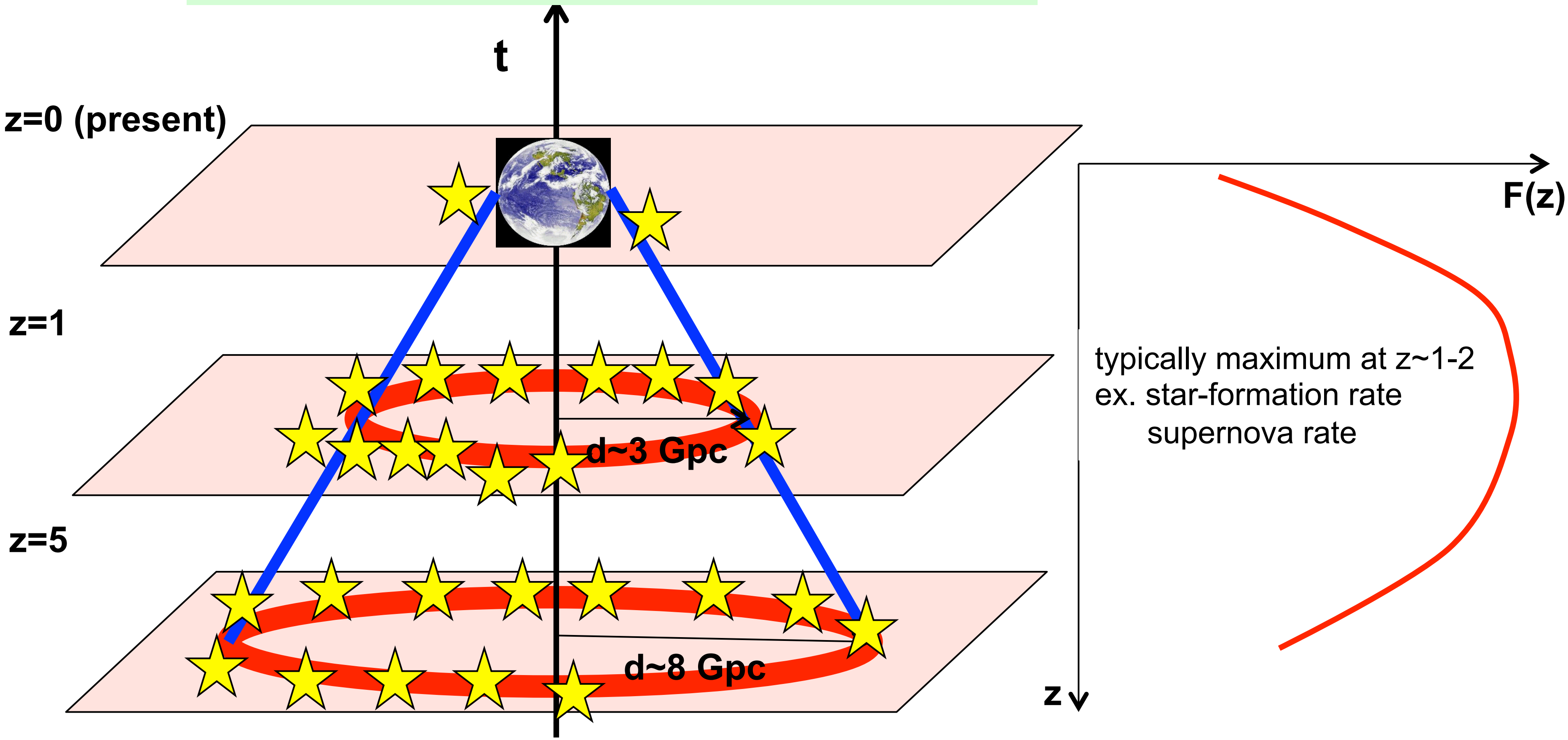
Astrophysical "Isotropic" Neutrino Background – Mean Diffuse Intensity

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

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

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

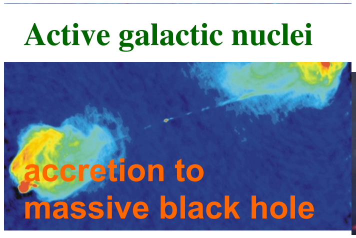
F(z): redshift evolution



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

Astrophysical Extragalactic Scenarios

Cosmic-Ray Accelerators
(UHECR candidate sources)



Cosmic-ray Reservoirs

- <u>γ-ray bursts</u>
  ex. Waxman & Bahcall 97, KM et al. 06
  after Neutrino 2012:
  KM & Ioka 13, Laha et al. 13, Winter 13
  Cholis & Hooper 13, Liu & Wang 13

- <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 et al. 14

- <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

- <u>Galaxy groups/clusters</u>
  ex. Berezinsky et al. 97, KM et al. 08
  after Neutrino 2012:
  KM, Ahlers & Lacki 13

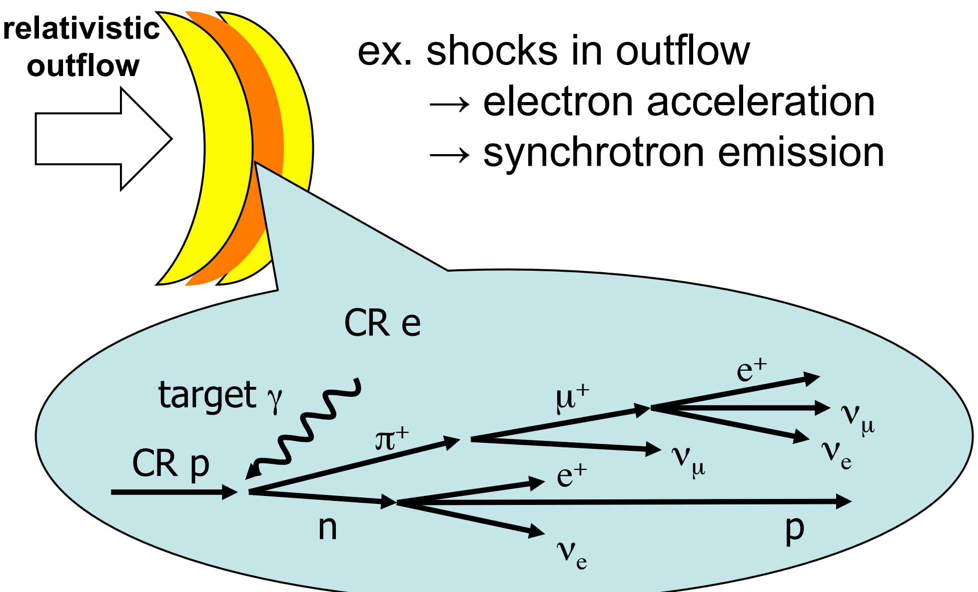
Astrophysical Extragalactic Scenarios

Cosmic-Ray Accelerators
(UHECR candidate sources)

Active galactic nuclei

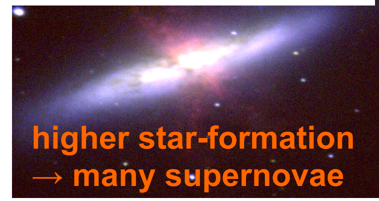
γ-ray burst

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



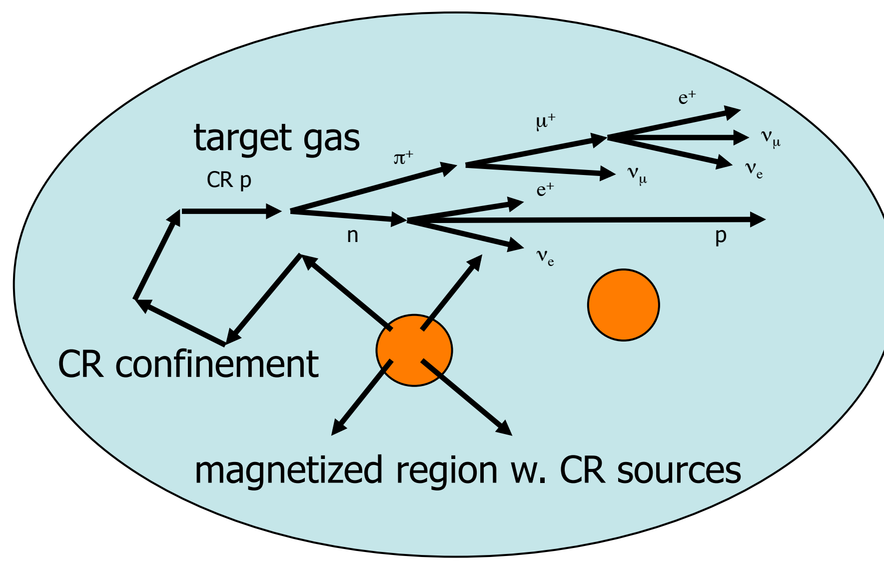
Cosmic-ray Reservoirs

Starburst galaxy



Galaxy group/cluster

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



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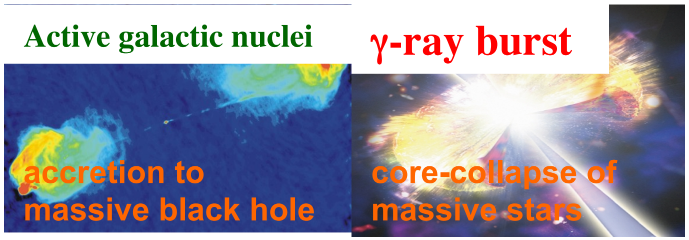
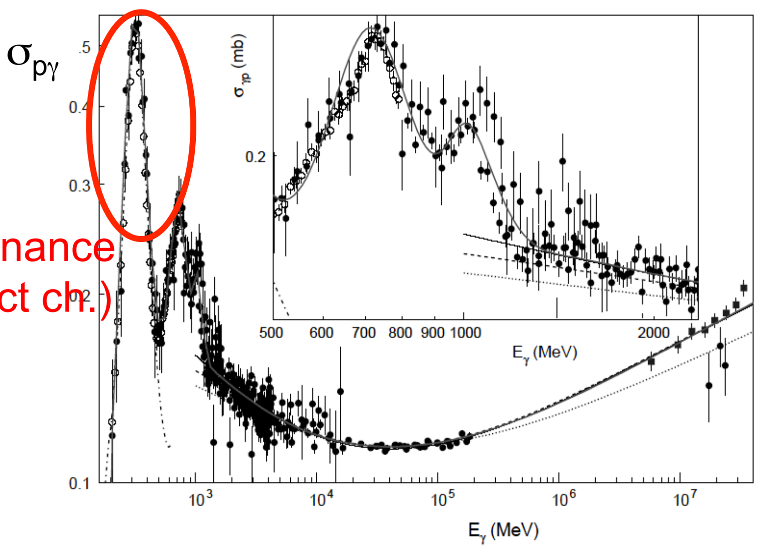


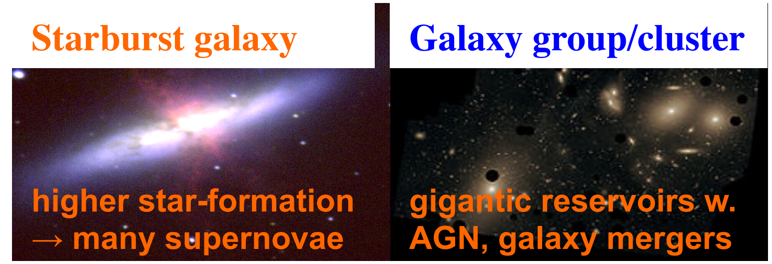
$$p + \gamma \rightarrow N\pi + X$$



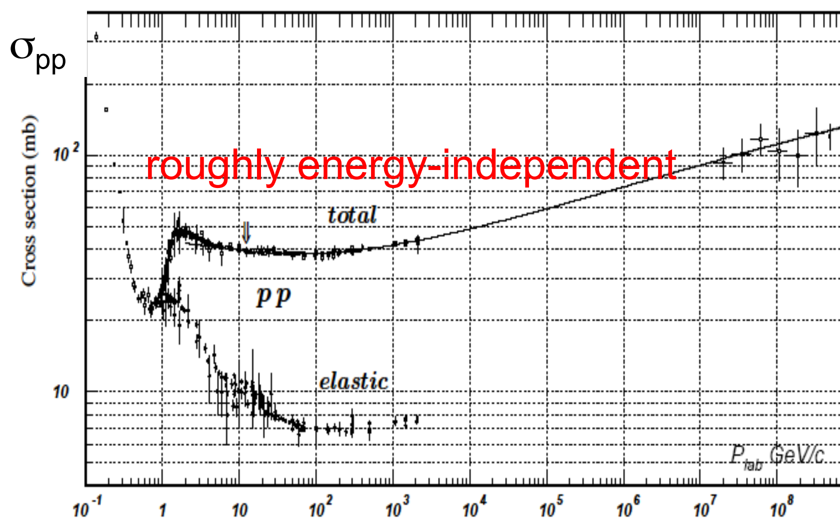
$\sigma_{p\gamma} \sim \alpha\sigma_{pp} \sim 0.5$ mb

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

Cosmic-ray Reservoirs



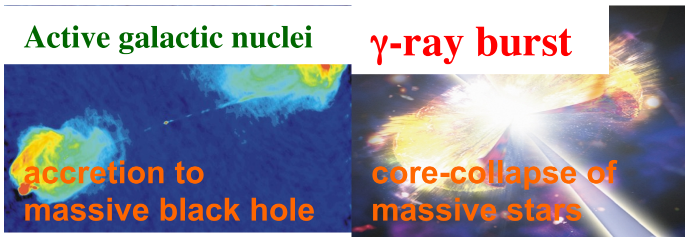
$$p + p \rightarrow N\pi + X$$



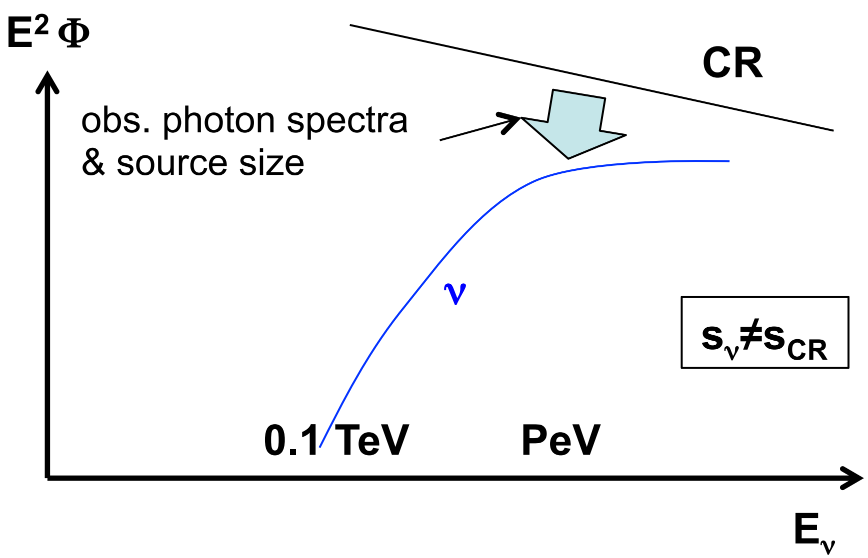
$\sigma_{pp} \sim 1/m_\pi^2 \sim 30$ mb

Astrophysical Extragalactic Scenarios

Cosmic-Ray Accelerators
(UHECR candidate sources)



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



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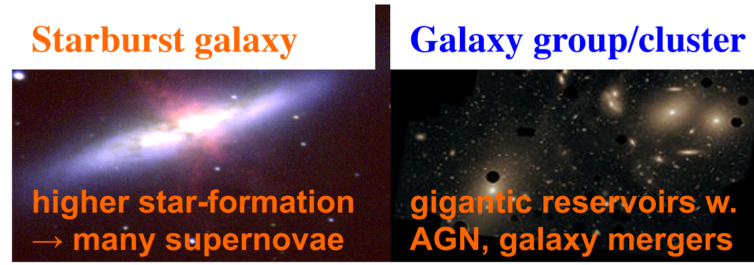
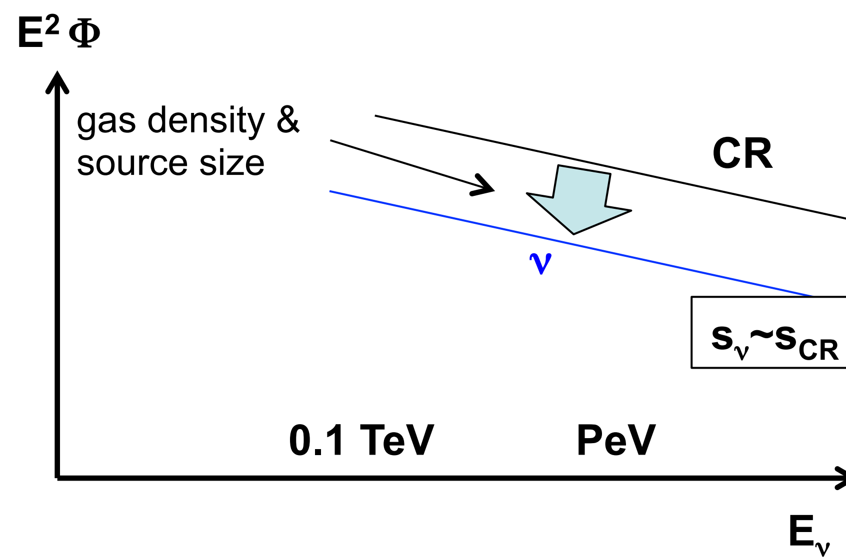


$$p+p \rightarrow N\pi + X$$

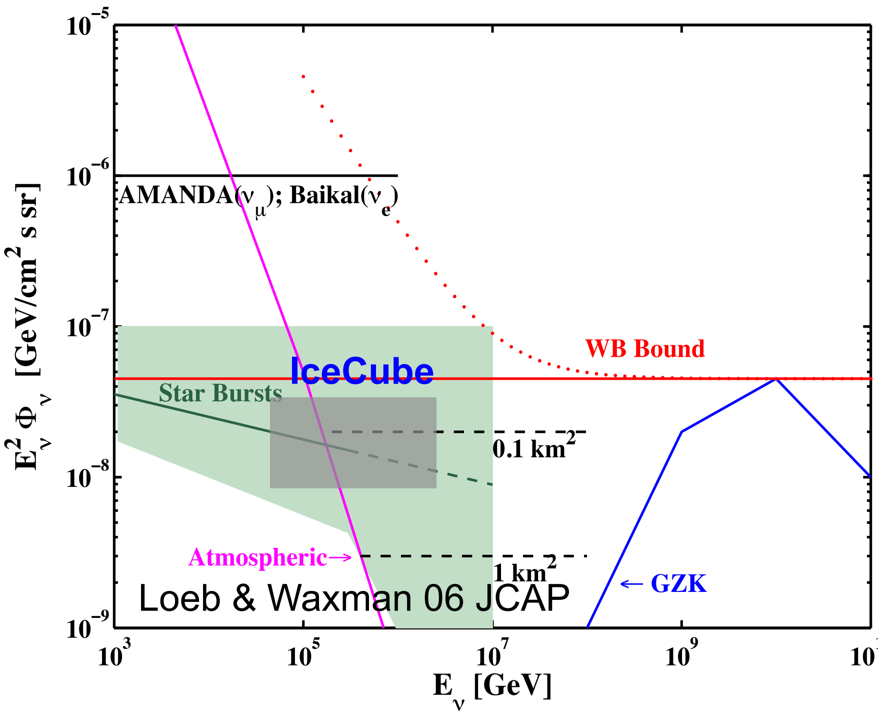


$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

pp Neutrinos from Cosmic-Ray Reservoirs

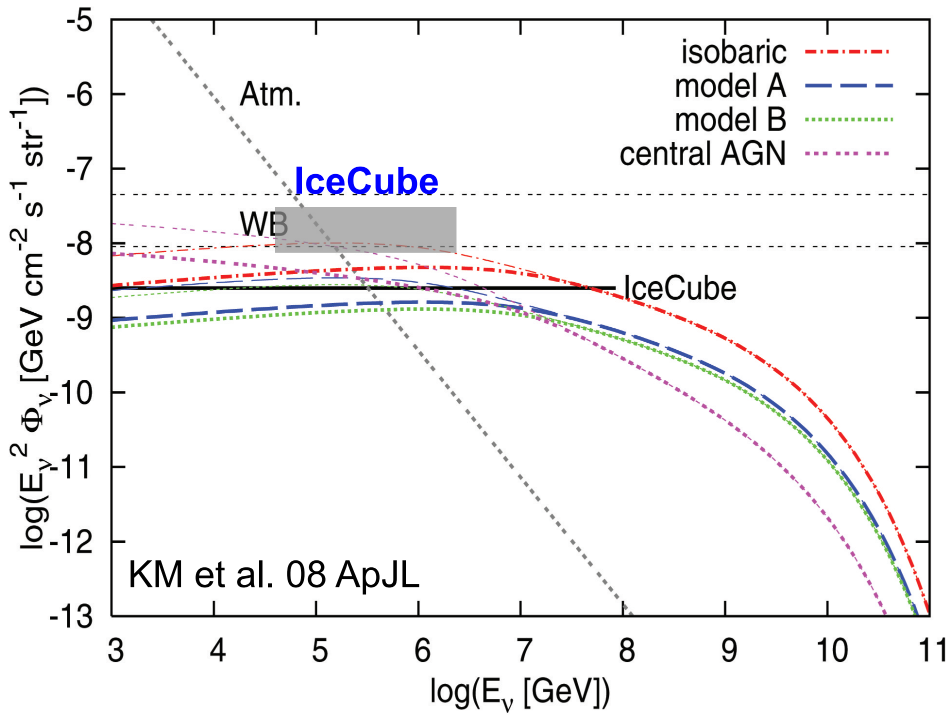
Starburst galaxy
size~0.1-1 kpc, B~0.1-1 mG

CR sources: peculiar supernovae, AGN



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

CR sources: AGN, galaxy mergers, virial shocks



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

How to Test?: Multi-Messenger Approach

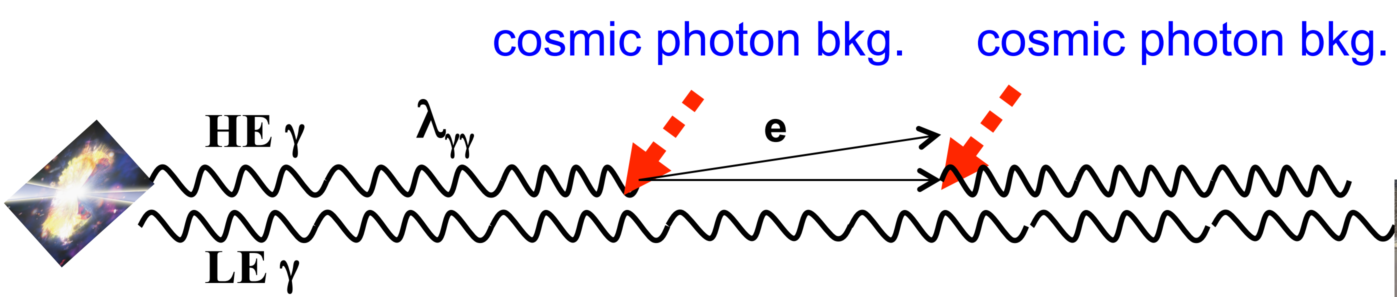
$$\boxed{\pi^0 \rightarrow \gamma + \gamma}$$

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

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

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

$\gamma + \gamma_{\mathrm{CMB/EBL}} \rightarrow e^+ + e^-$ ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center



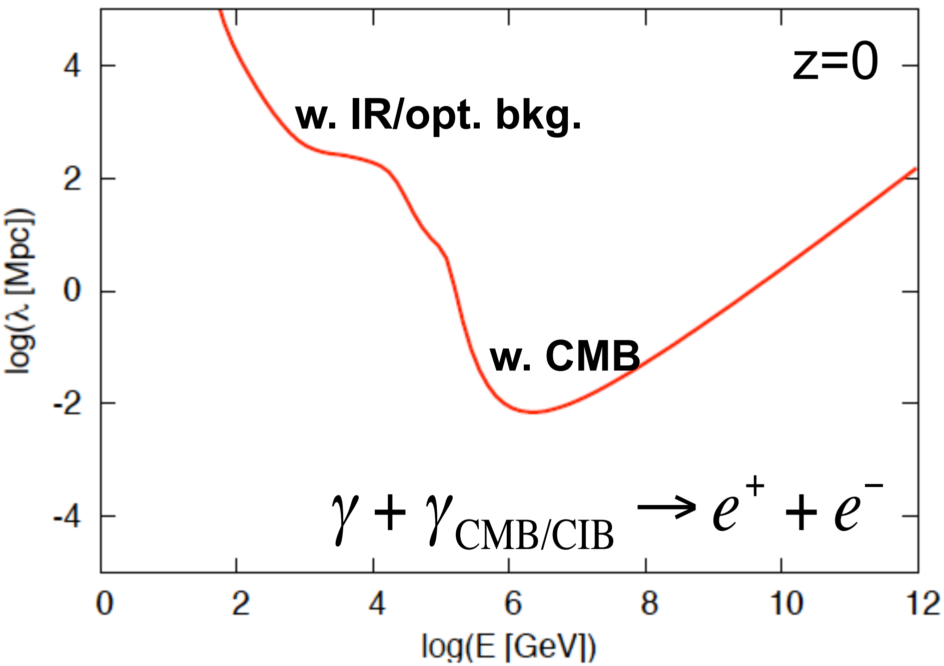
Fermi satellite

airshower detectors

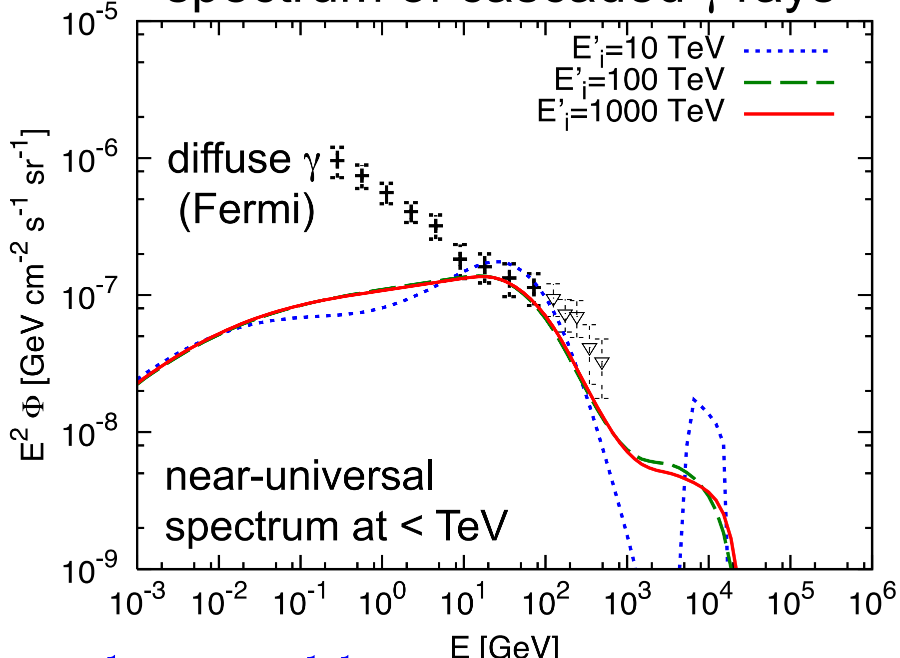
realistic fate of γ rays=electromagnetic cascades
crucial for extragalactic γ rays

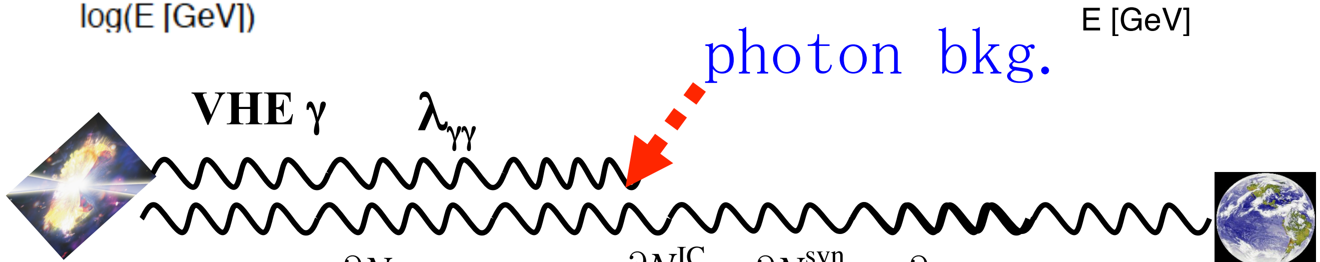
Fate of Extragalactic Gamma Rays

γ-ray mean free path



spectrum of cascaded γ rays





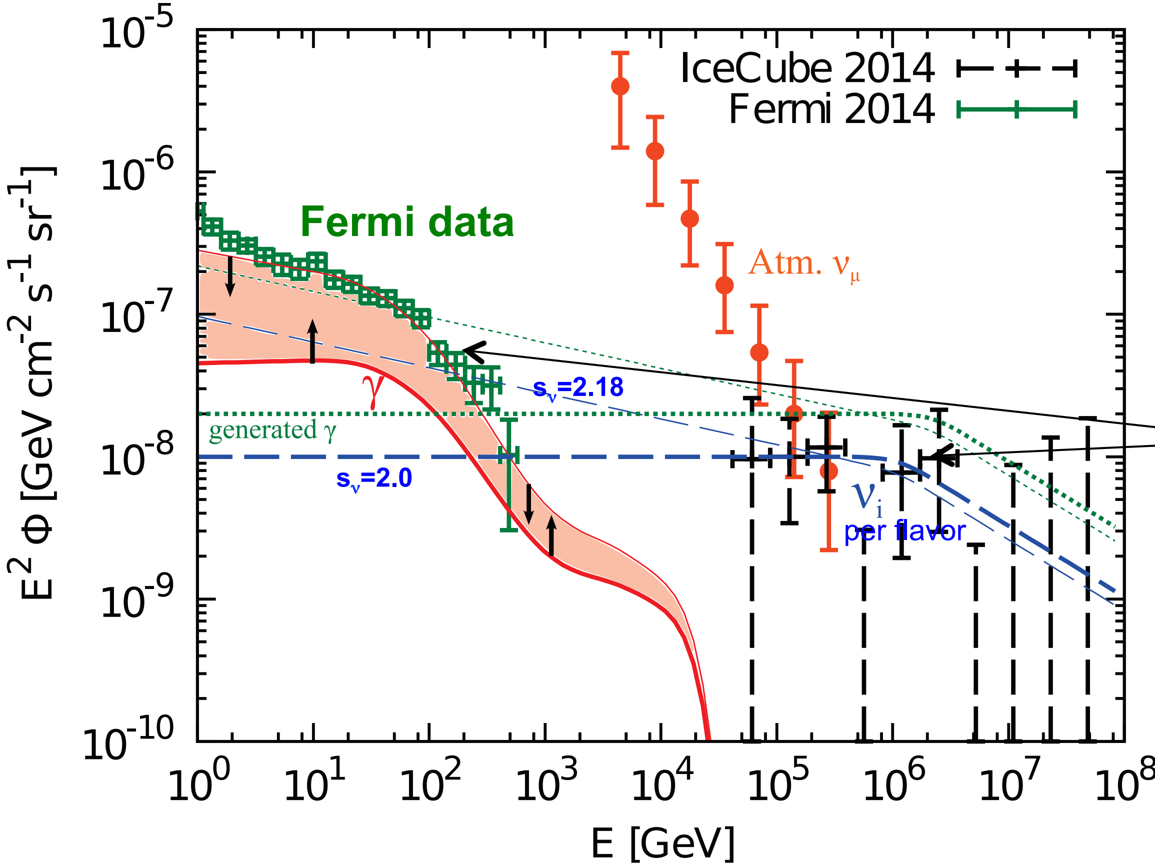
LE γ

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

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

First Multimessenger Constraints from "Measured" Fluxes

KM, Ahlers & Lacki 13 PRDR



pp scenario

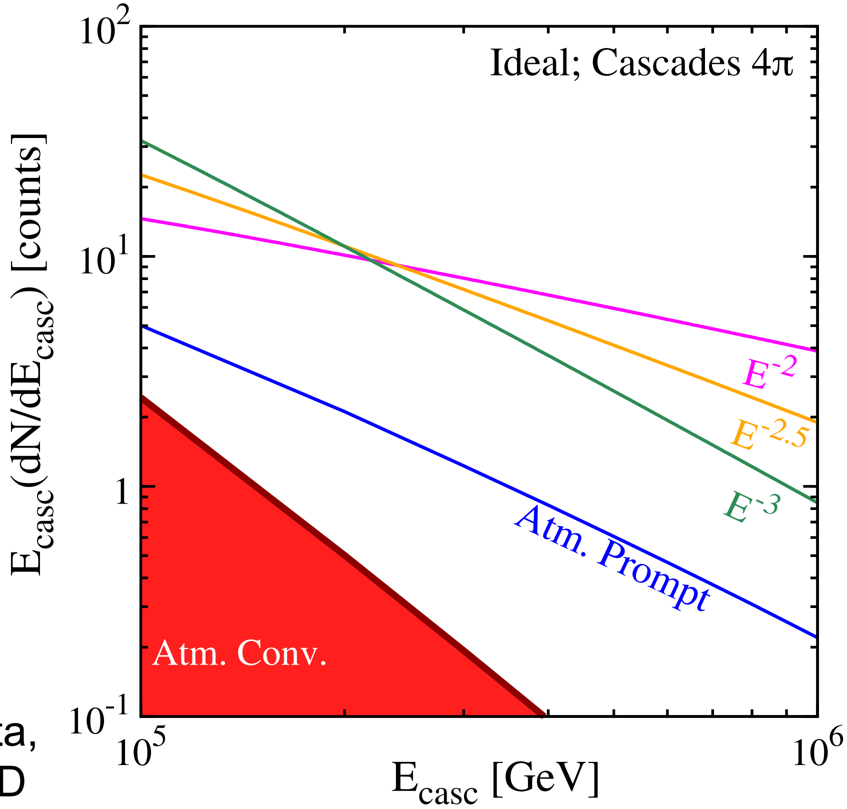
cosmic-ray reservoir models
(starbursts, galaxy clusters etc.)

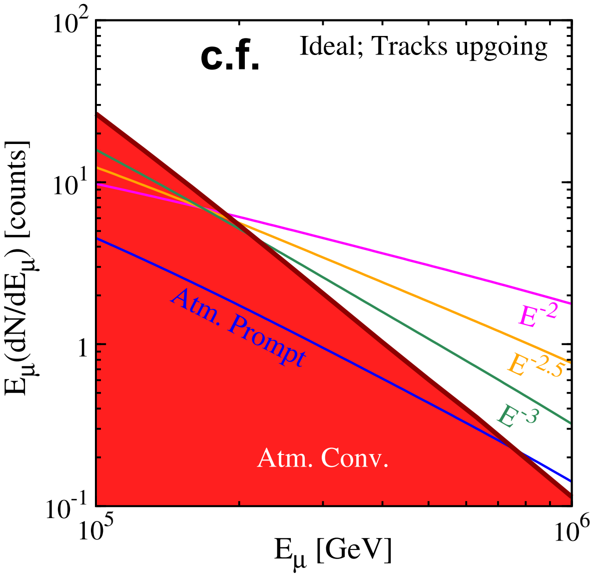
"comparable fluxes"

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

Implications for Further Neutrino Studies





Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

Shower searches at lower energies offer the fastest way to distinguish between the neutrino spectra

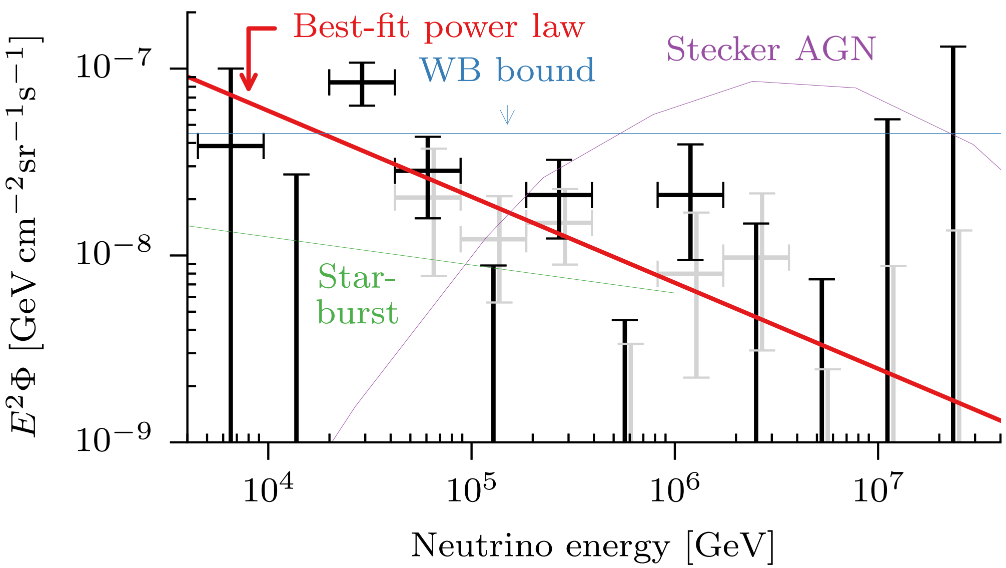
ex. if s_ν>2.3 → pp scenarios will have a trouble

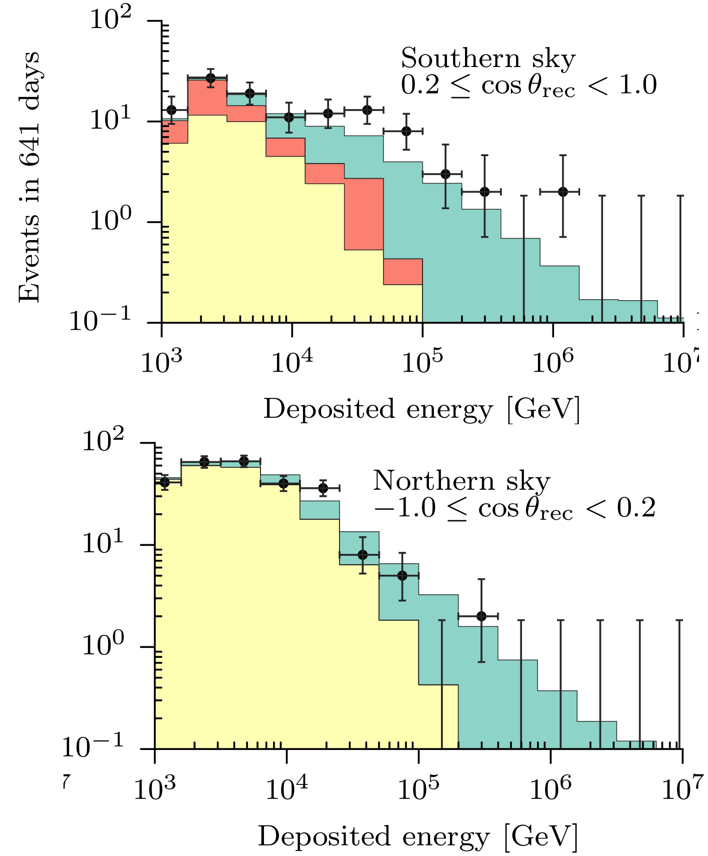
So measurements of s_ν at low energies have been waited for

New Results Announced in 2014

- LE extension down to <10 TeV

IceCube 1410.1749





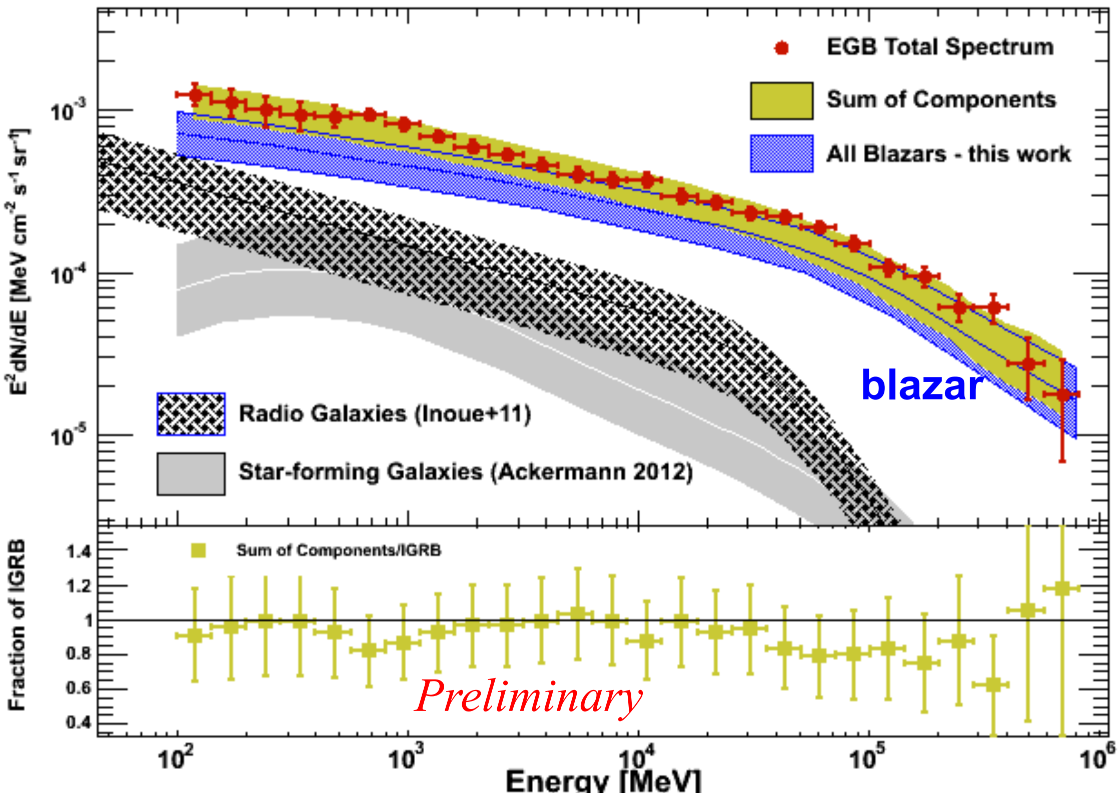
best-fit $\Phi_\nu = 2.06^{+0.4}_{-0.3} \times 10^{-18} \left(E_\nu/10^5\ \mathrm{GeV}\right)^{-2.46\pm0.12} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$

2.46 is too steep & 10^{-7} is too high → 1. Galactic components at LE?
2. favoring pγ scenarios?

It may be premature: wait for more results from shower analyses….

Implications for Further Gamma-Ray Studies

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



from Fermi collaboration 14

~100 % come from blazars at sub-TeV energies?

Be cautious but

If >50% come from blazars → **s_ν<2.0-2.1**

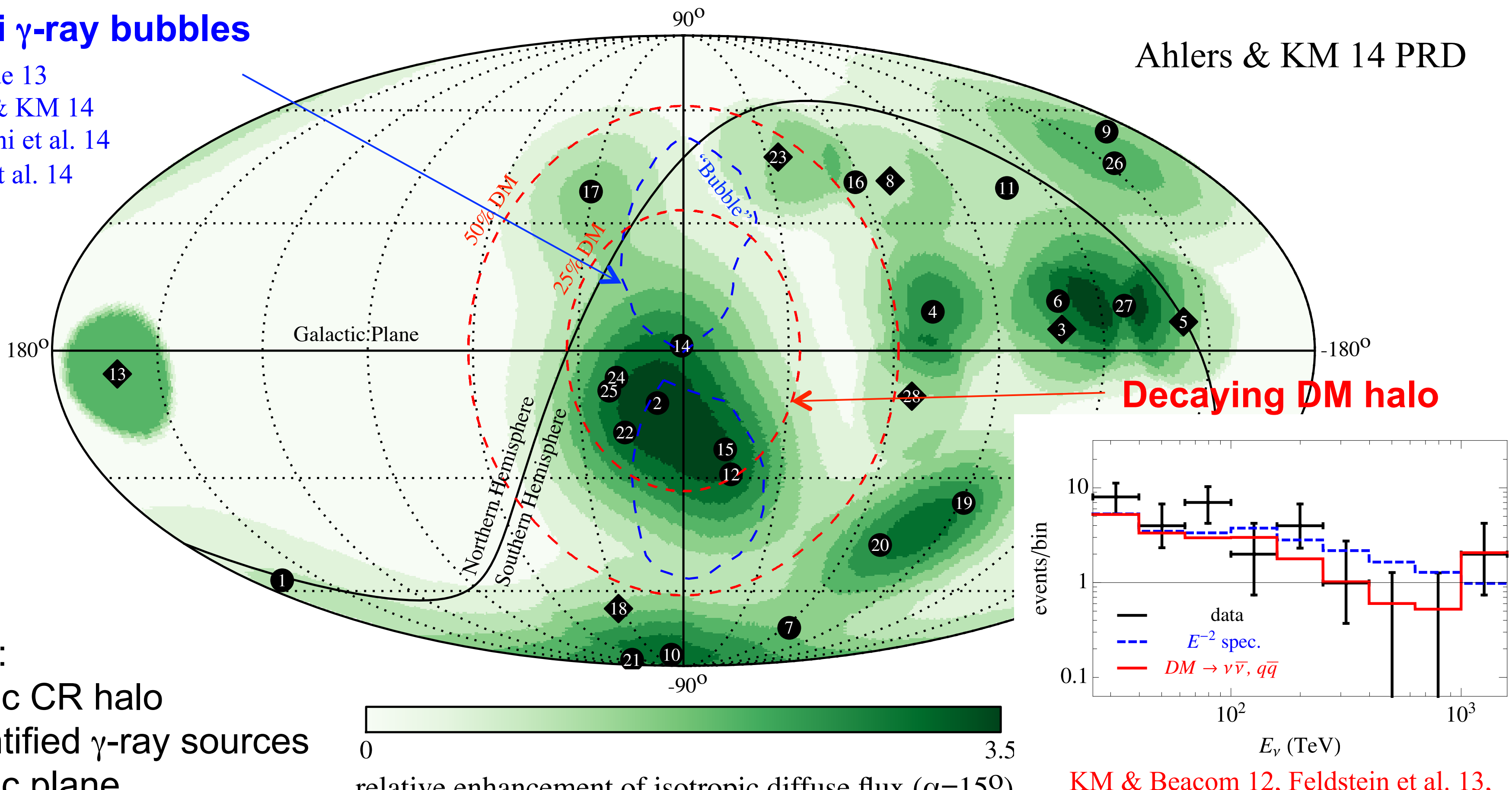
If >60-70% come from blazars → **no room for pp scenarios!**

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



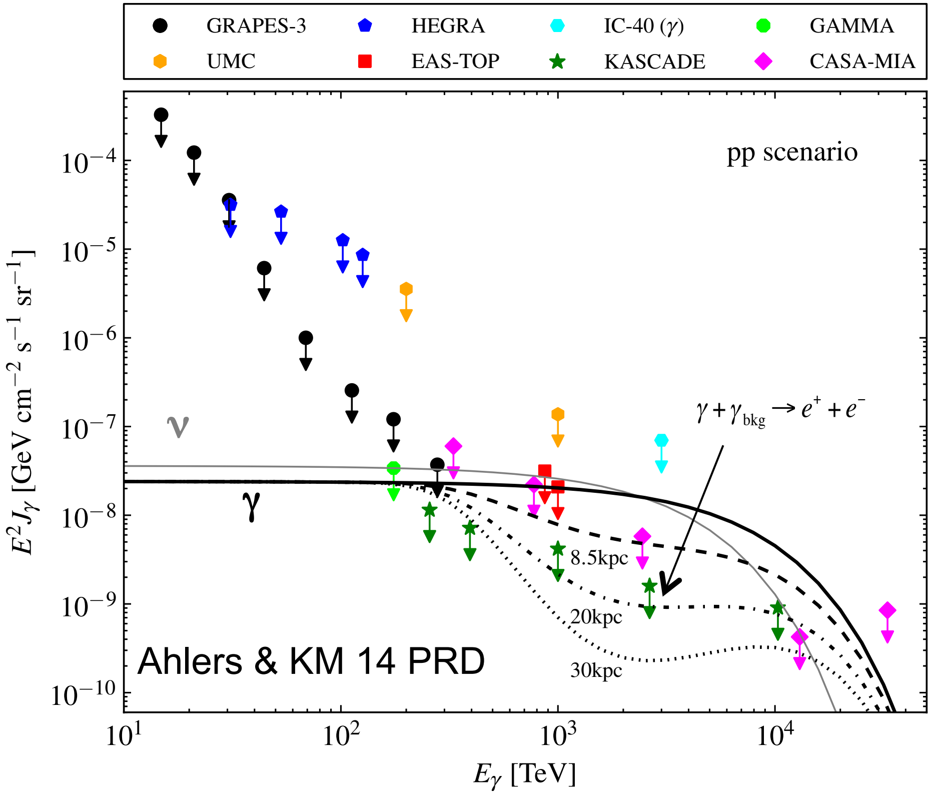
KM & Beacom 12, Feldstein et al. 13,
Esmaili & Serpico 13, Bai et al. 14
Ahlers & KM 14, Rott et al. 14

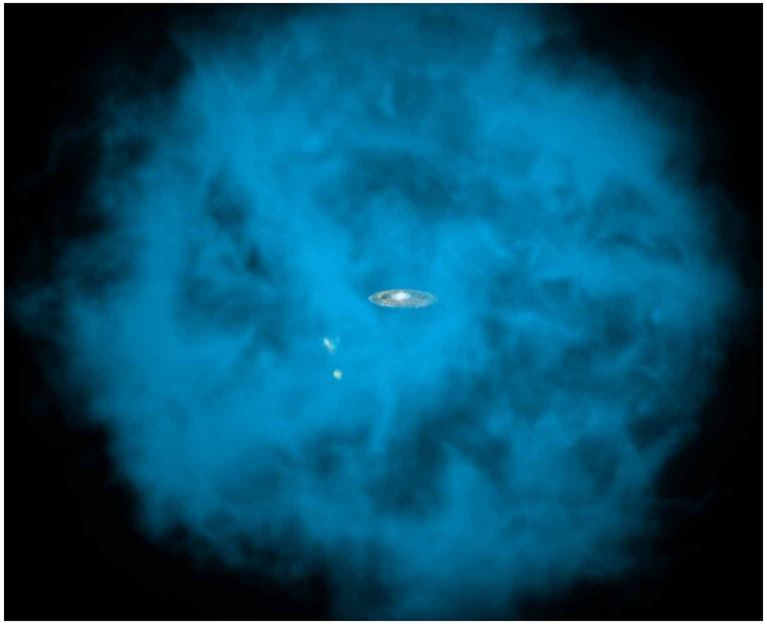
Others:
Galactic CR halo
Unidentified γ-ray sources
Galactic plane
Local spiral arms…

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

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

Isotropic limits (Galactic halo CR model)





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

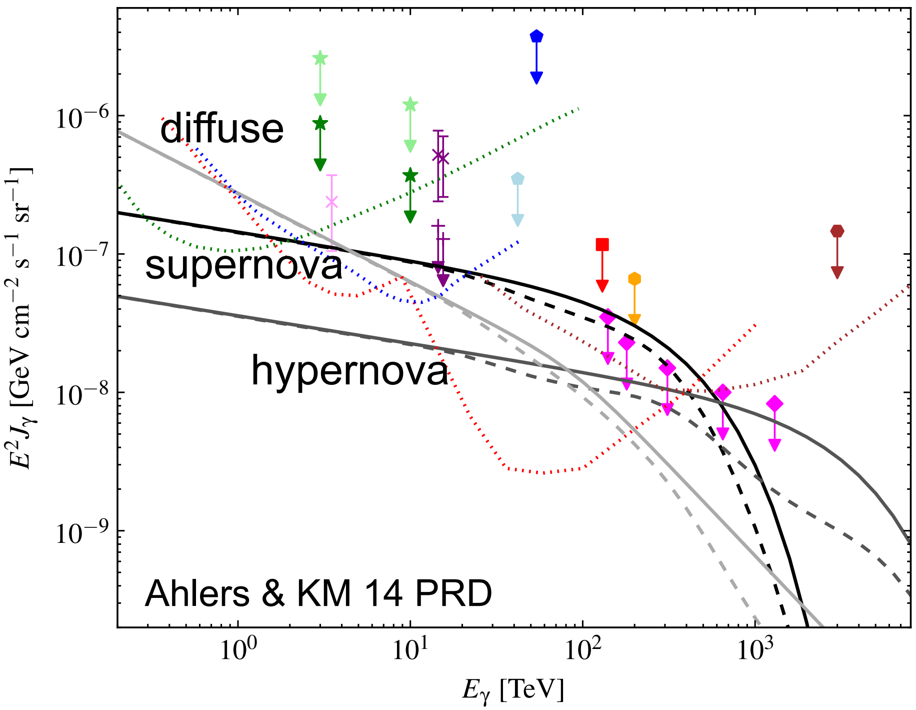
- Existing old TeV-PeV γ-ray limits are close to predicted fluxes
  → Need deeper TeV-PeV γ-ray observations (relatively not expensive)

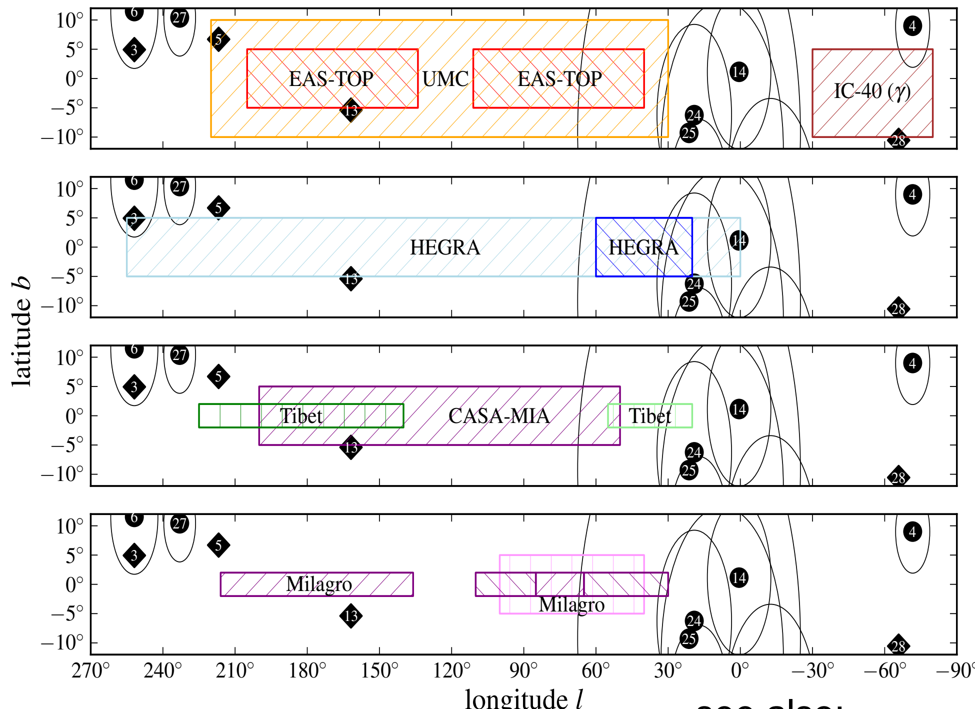
※ Fermi γ-ray data imply $s_\nu < 2.0$ → support extragalactic scenarios

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)





see also:
Spantisky 14
Joshi+ 14
Anchodoqui+ 14

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

WANTED

~~Diffuse or~~ Associated

ν

- Source identification may not be easy
  (ex. starbursts: horizon of an average source ~ 10 Mpc)
- promising cases: “bright transients (GRBs, AGN flares)”,
  “rare bright sources (powerful AGN)”, “Galactic sources”
- Not guaranteed but remember the success of γ-ray astrophysics

Questions for Future

- Spectral features: is the possible ν spectral break/cutoff real?
- Flavor ratio: consistent w. 1:1:1? (more data!)
  0.57:1:1 (μ damp), 2.5:1:1 (neutron decay), others (exotic),
  looking for τ-appearance, anti-ν_e Glashow-resonance at 6.3 PeV etc.
- Cross-corr. & auto-corr. (much more data! → 10xIceCube?)
- Connection w. ultrahigh-energy cosmic-ray origins?
  PeV ν ⇔ ~20-30 PeV p or ~(20-30)A PeV nuclei (cf. "knee"~3 PeV)

  Is $E_\nu^2 \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} coincident with the WB bound?
  a. UHECR sources have $s_{CR}\sim2$ & $f_{mes}\sim1$
  b. UHECR sources have $s_{CR}>>2$ & $f_{mes}<<1$
  (maybe better if observed UHECRs are heavy nuclei)

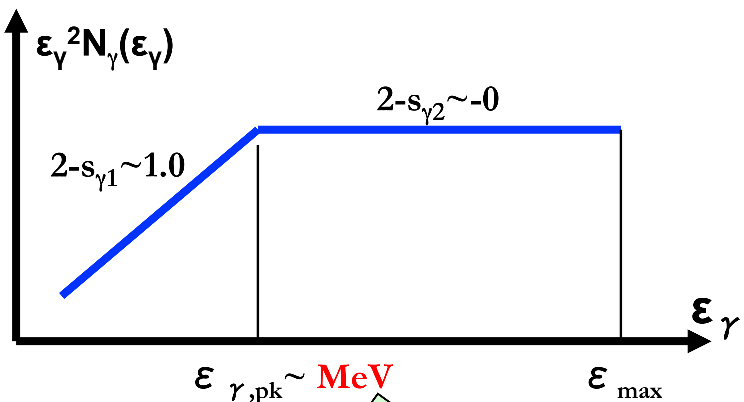
※injected/confined CR spectra ≠ escaping CR spectra

An Example of Calculation: Gamma-Ray Burst Jets

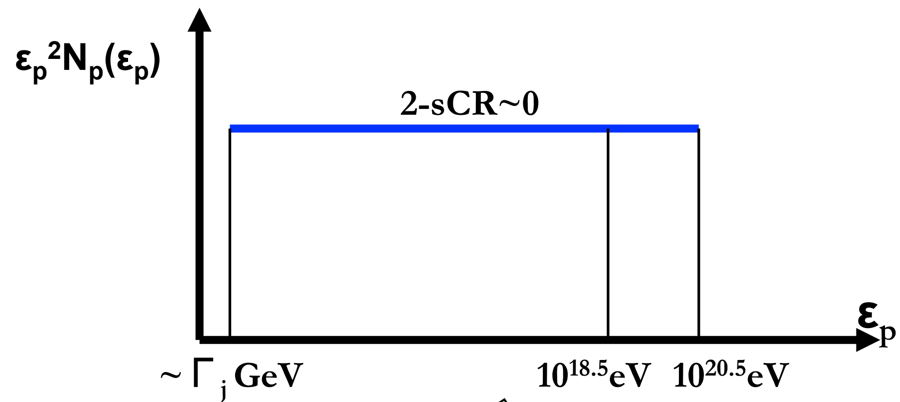
GRB: brightest γ-ray transient

Popular candidate sources of UHECRs

Photon Spectrum (observed)



CR Spectrum (Fermi mechanism)

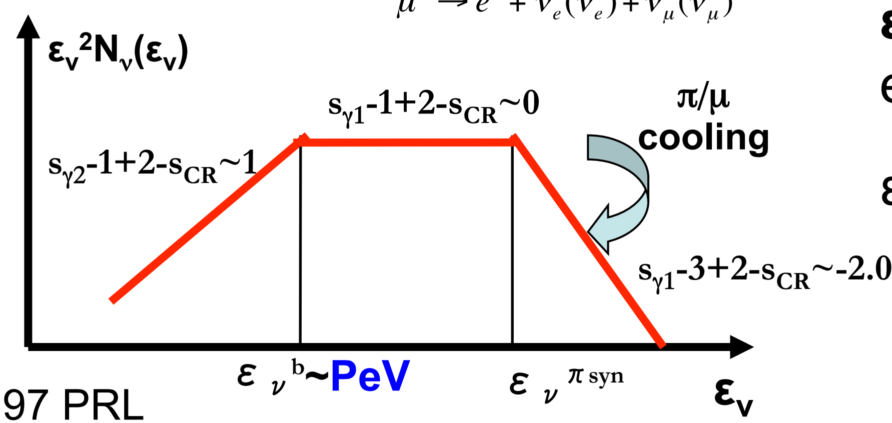


$\varepsilon_p \varepsilon_\gamma \sim 0.2\Gamma_j^2\ \mathrm{GeV}^2$
at Δ-resonance

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

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

Neutrino Spectrum



Waxman & Bahcall 97 PRL

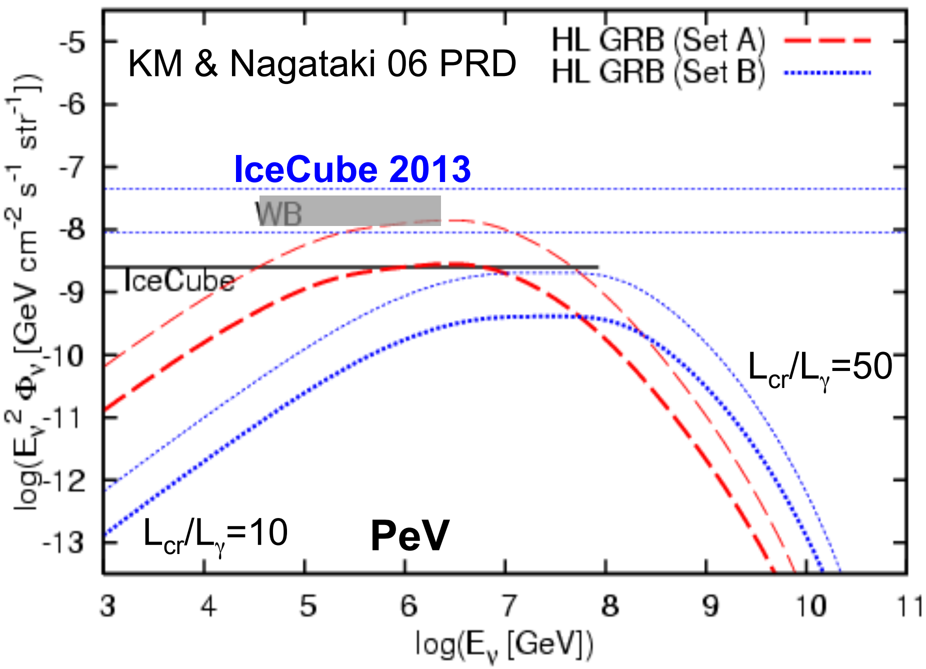
$\varepsilon_\nu^2 N_\nu(\varepsilon_\nu) \sim (1/4) f_{p\gamma} \varepsilon_p^2 N_p(\varepsilon_p)$
efficiency: $f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} \Delta$

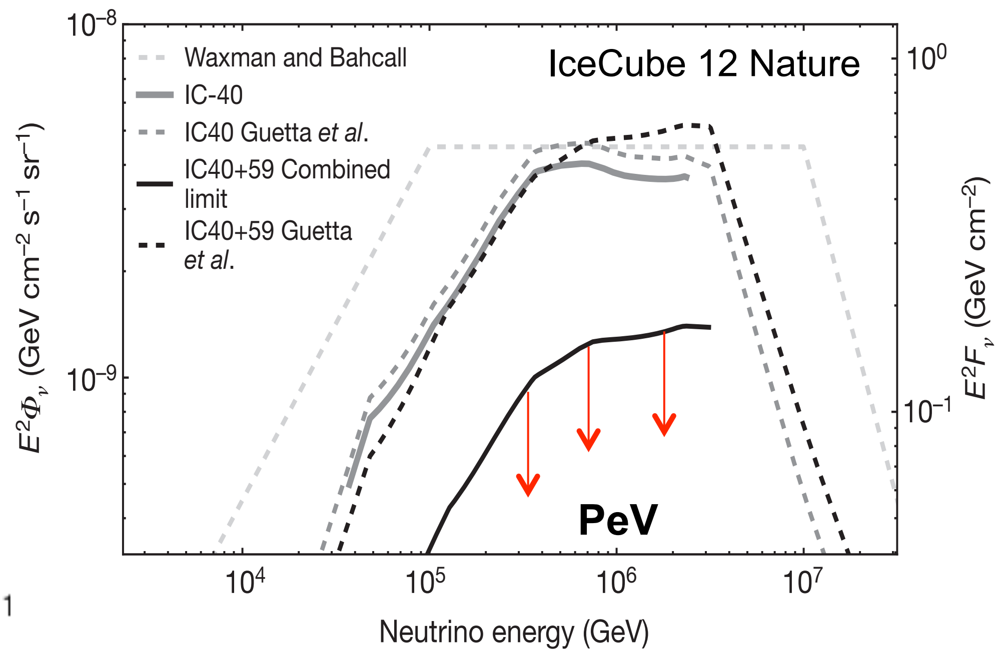
$\varepsilon_\nu^{\,b} \sim 0.05 \varepsilon_p^{\,b}$
$\sim 0.01\ \mathrm{GeV}^2\ \Gamma^2/\varepsilon_{\gamma,pk}$
$\sim$1 PeV (w. $\varepsilon_{\gamma,pk} \sim 1$ MeV)

$\Gamma_j \sim 300$: jet Lorentz factor

Classical Long Gamma-Ray Bursts (pγ)

numerical results w. detailed microphysics

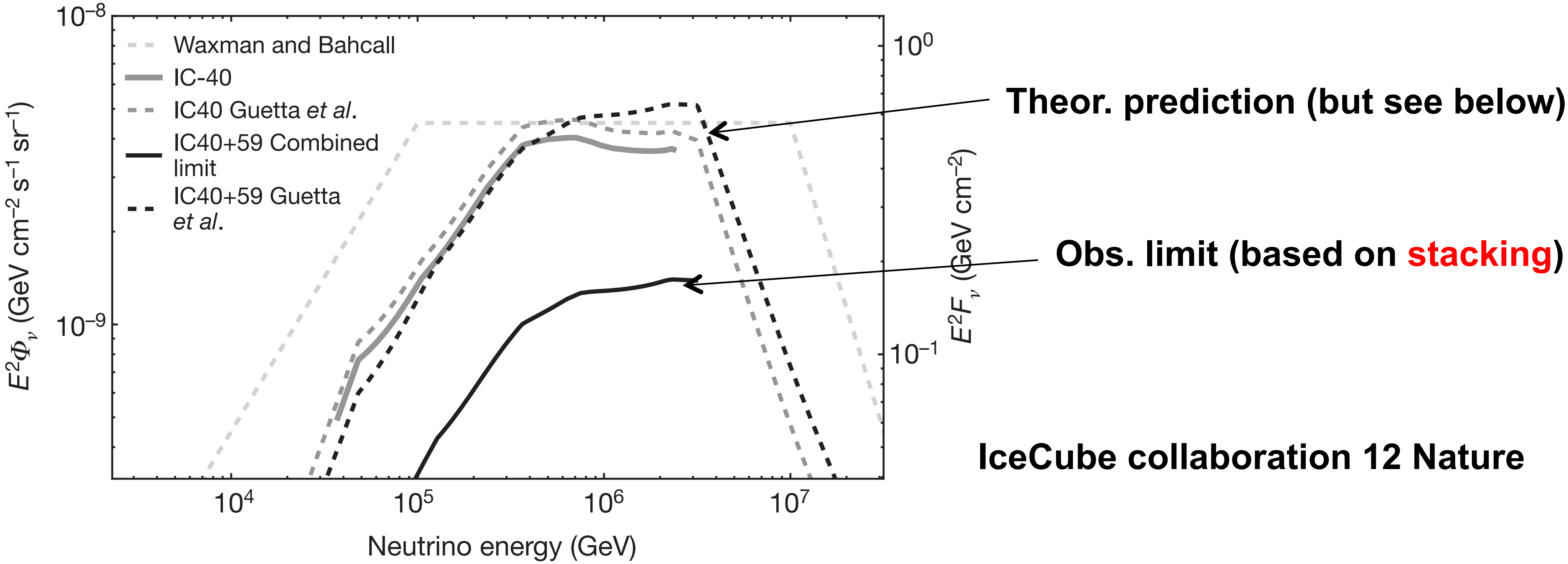




- GRBs are special: stacking analyses
duration (~10-100 s) & localization → atm. bkg. is practically negligible

- 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



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)

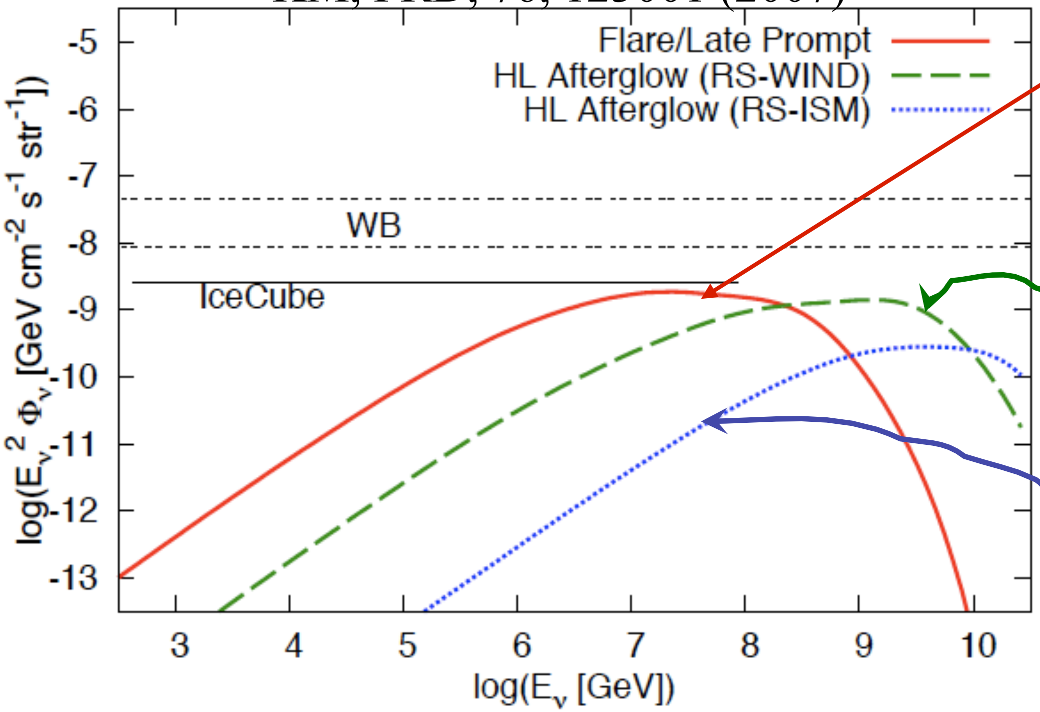
3. details (multi-π, ν mixing etc.) → ex., multi-π ~2-3 ↑ (KM & Nagataki 06 PRD)

- 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)



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

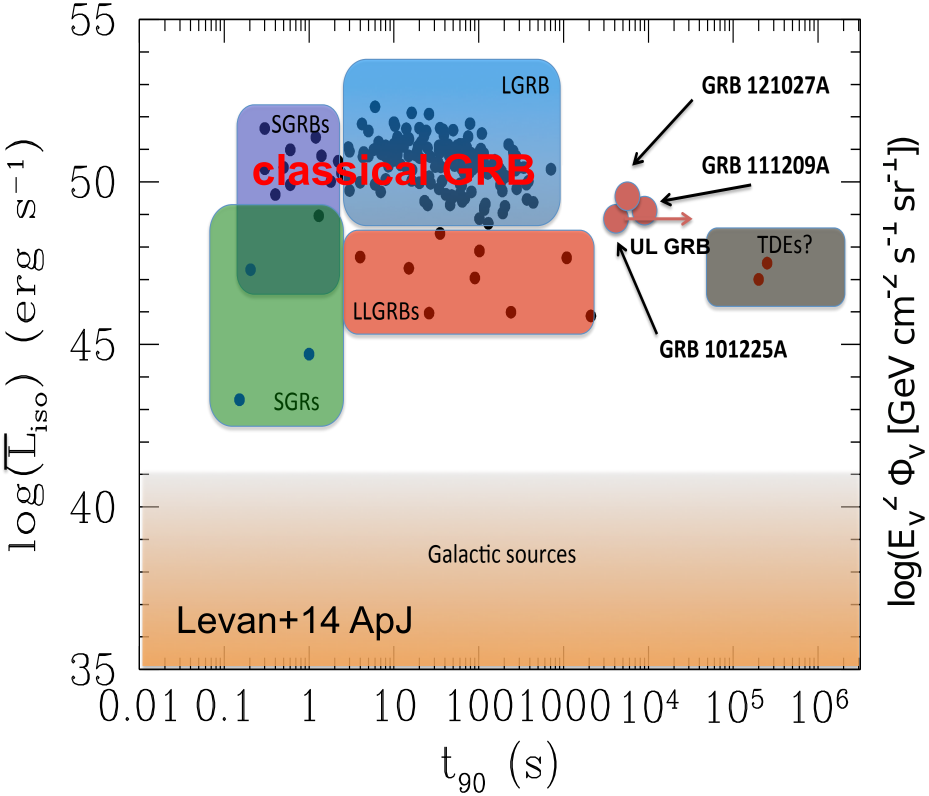
KM & Nagataki, PRL, 97, 051101 (2006)

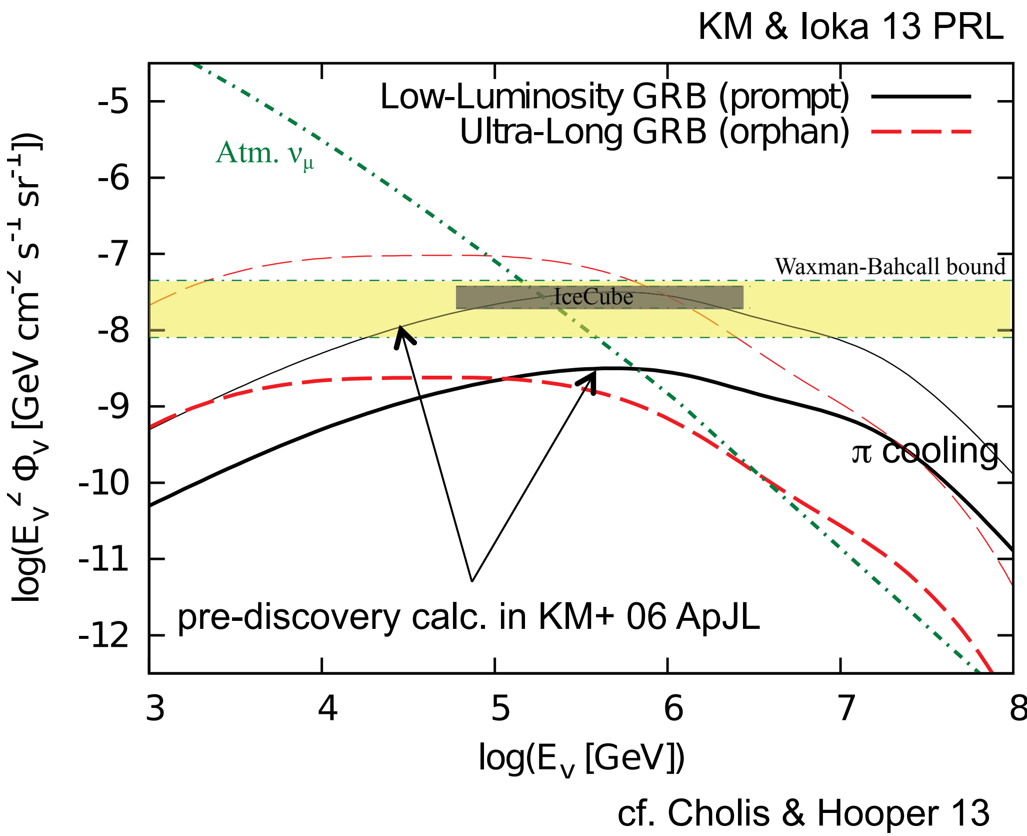
ES protons + ES opt-x rays stellar wind medium (normalized by UHECR budget)

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

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

Exceptions: Low-Power Gamma-Ray Burst Jets

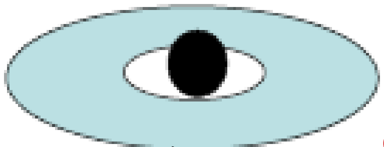




- Low-luminosity (LL) & ultralong (UL) GRB jets are largely missed
  may explain IceCube ν data without violating stacking limits
- Uncertain so far, but relevant to understand the fate of massive stars
  → Better (next-generation) wide-field sky monitors are required

Active Galactic Nuclei (AGN)

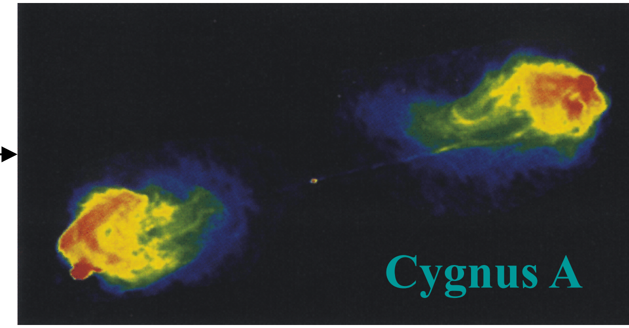
BH + accretion disk



~ 10%
Jets
(Γ~1-10)
elliptical gal.

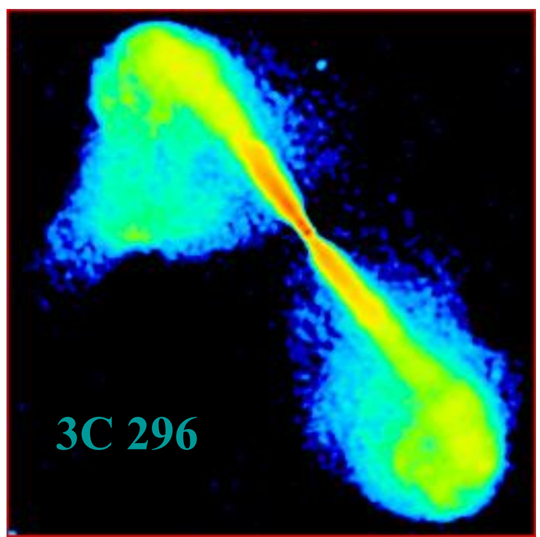
~ 1 %
$L_{radio} > 5\times10^{41}$ erg/s

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



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

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



~ 90%
No jets
spiral gal.

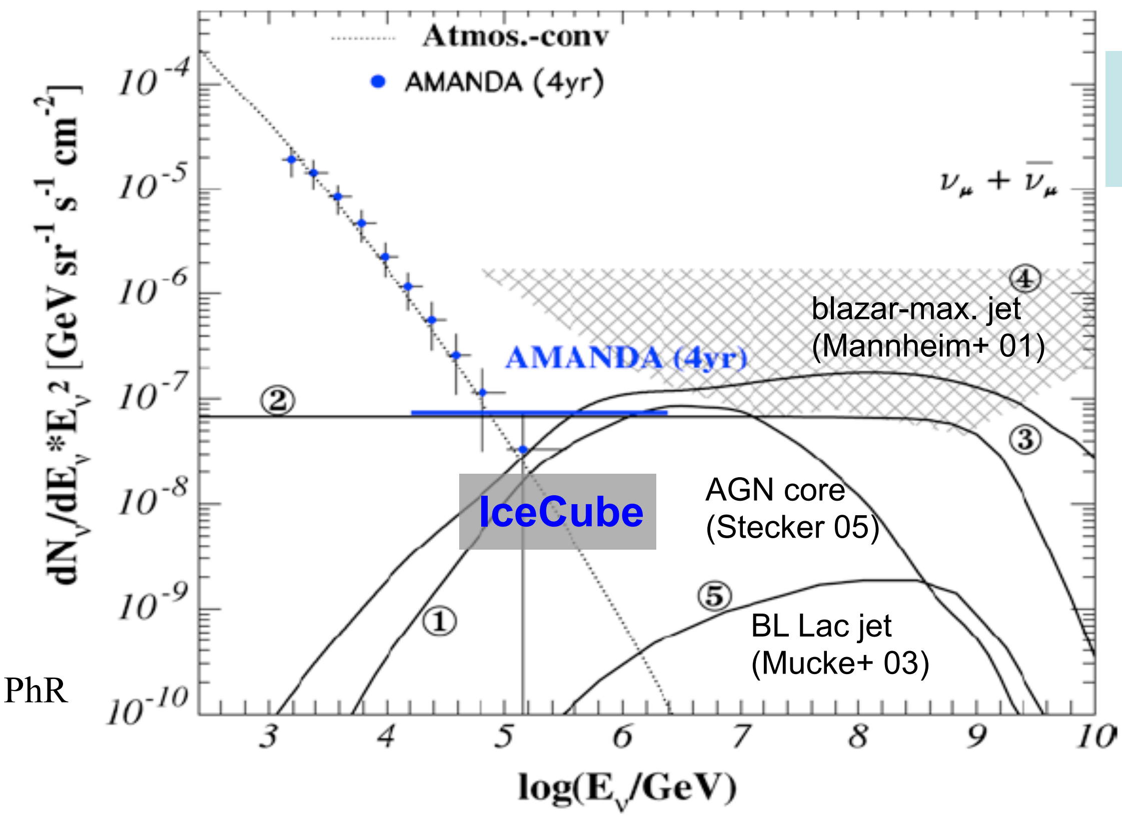
Seyfert galaxy
Radio quiet quasar
Radio intermediate quasar

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

FR=Fanaroff-Riley

$p\gamma$ Neutrinos from Active Galactic Nuclei

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



Becker 06 PhR

"Many of original models have been constrained"

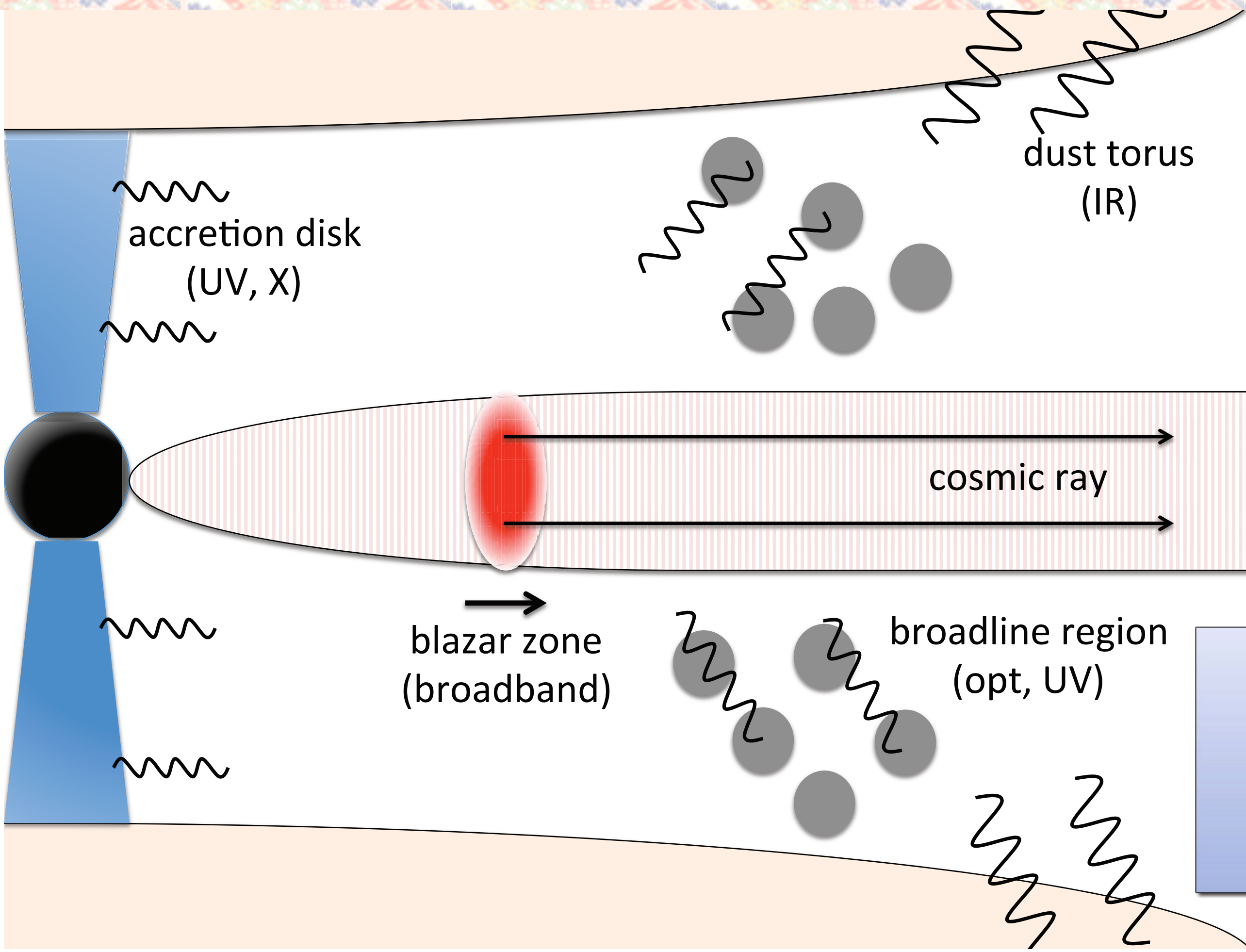
※ For jet emission, pp interactions are unimportant (ex. Atoyan & Dermer 03)

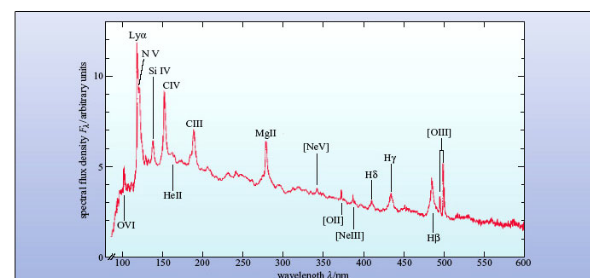
see:
Kalashev, Kusenko & Essey13
Stecker 13
KM, Inoue & Dermer 14
Dermer, KM & Inoue 14

- Difficult to explain sub-PeV ν flux since ν spectra are too hard
→ Standard inner jet model has difficulty in explaining ν data

External Radiation Fields

KM, Inoue & Dermer 14

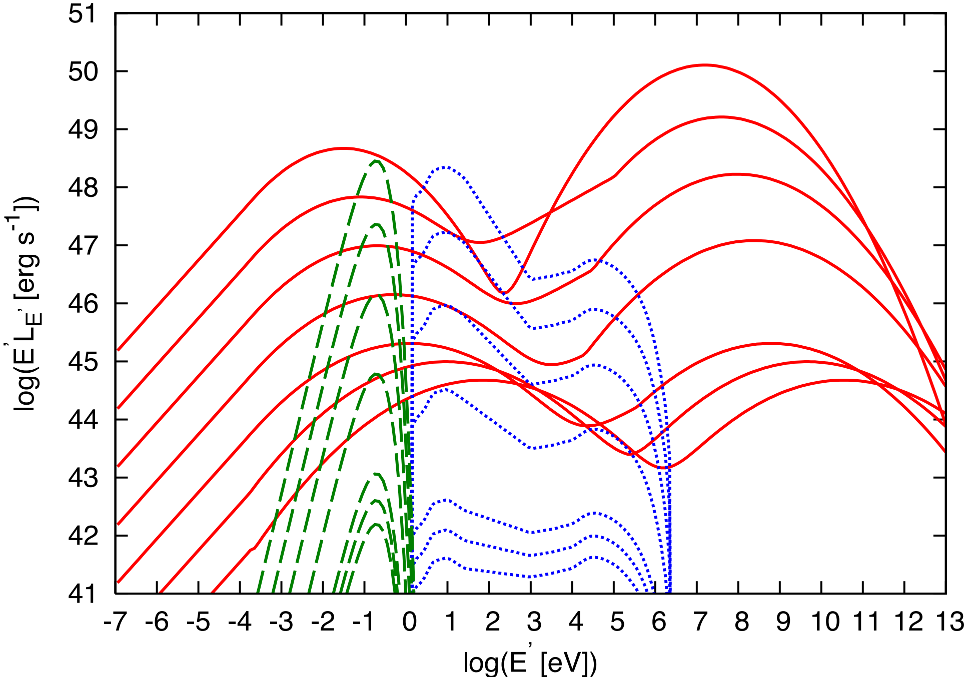




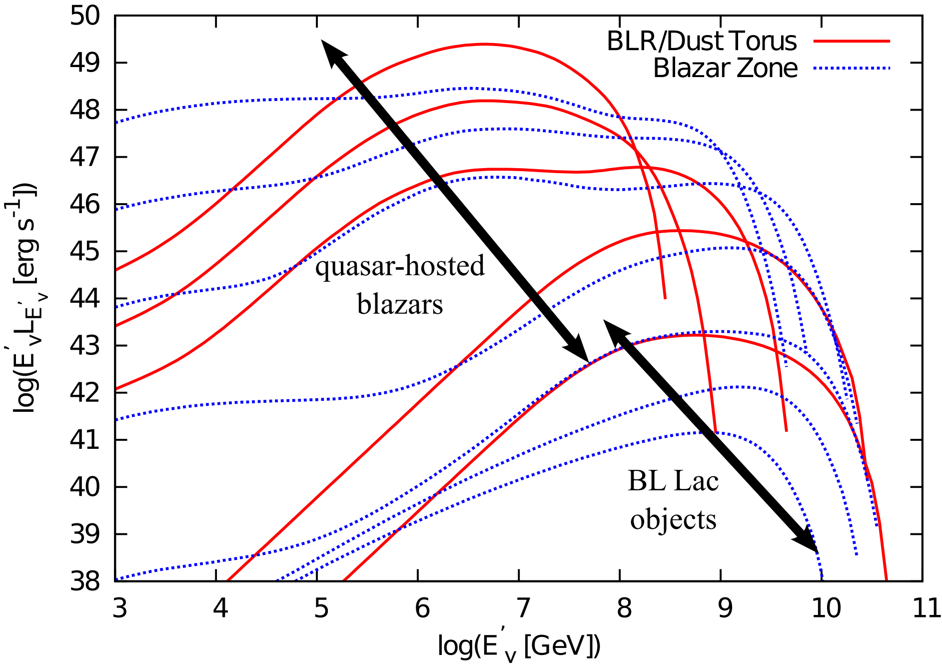
$$f_{p\gamma} \approx \hat{n}_{\rm BL}\sigma_{p\gamma}^{\rm eff} r_{\rm BLR} \simeq 5.4 \times 10^{-2} \ L_{\rm AD,46.5}^{1/2} \qquad r_{\rm BLR} \approx 10^{17} \ {\rm cm} \ L_{\rm AD,45}^{1/2}$$

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

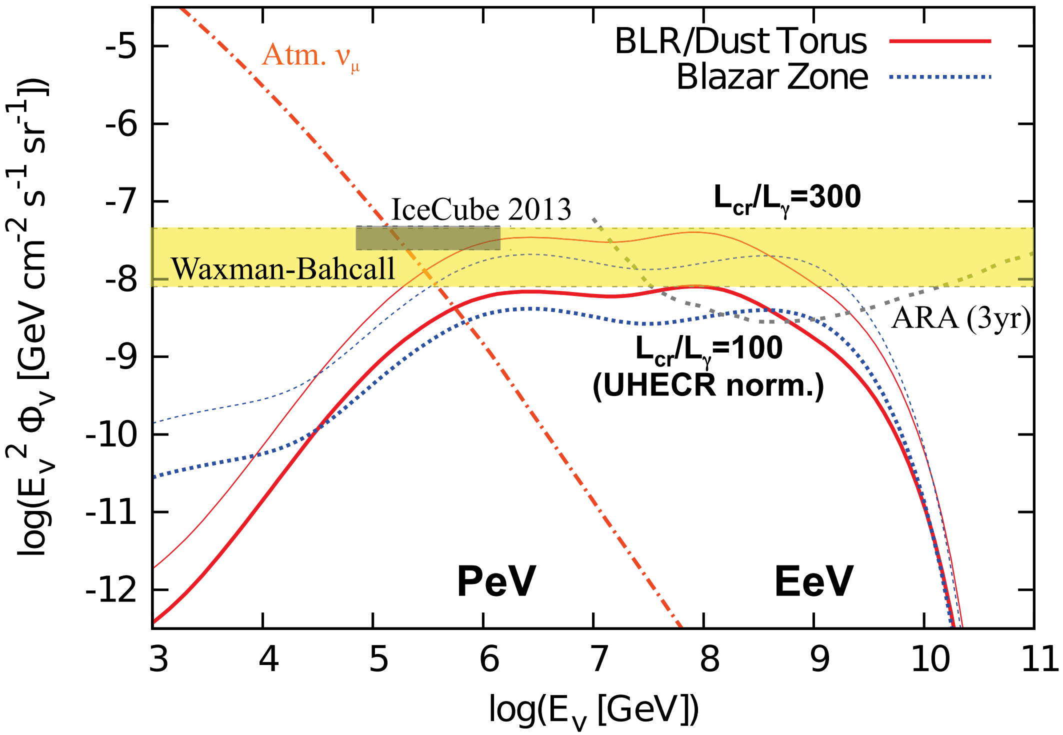
$L_{cr} \propto L_\gamma$, $f_{p\gamma} \propto L_\gamma^{1/2}$

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

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

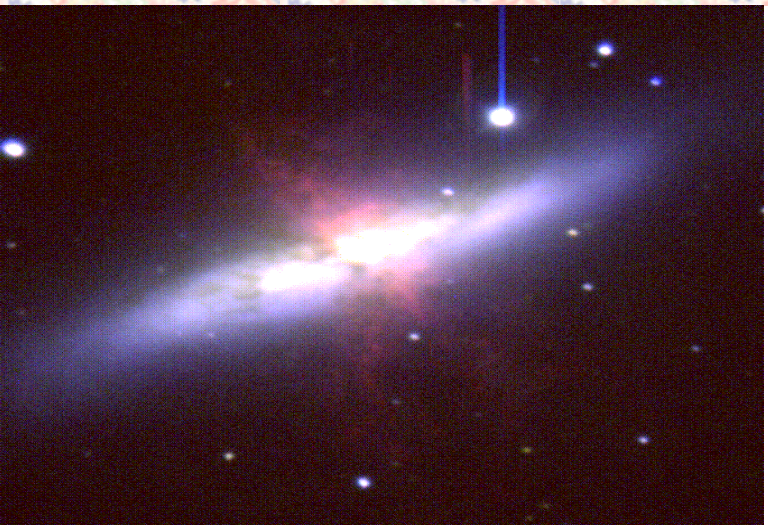


- luminosity function is now provided by Fermi satellite
- target photon spectra of all types of blazars w. external radiation fields

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

Starburst/Star-Forming Galaxies



- High-surface density

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

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

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

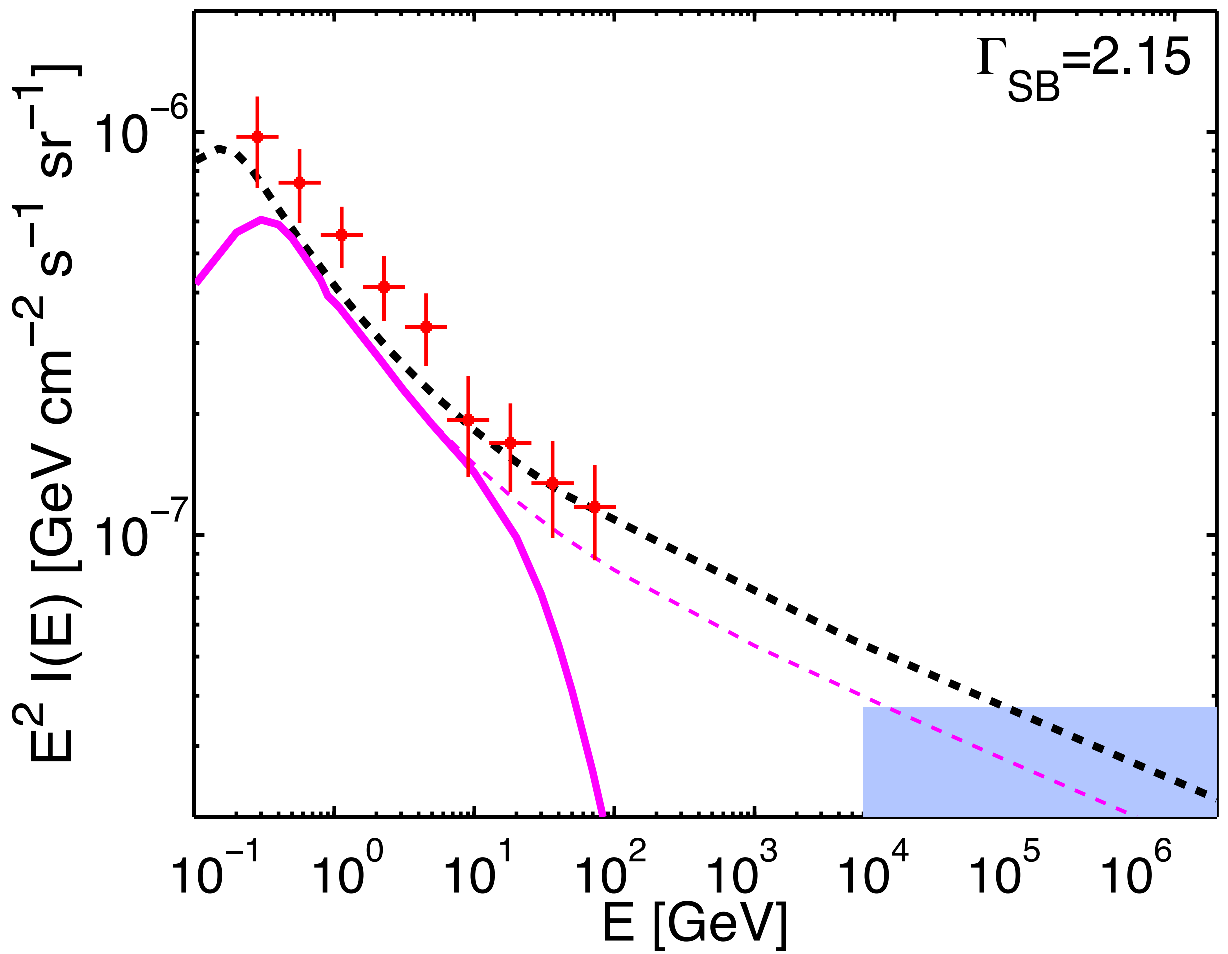
  known CR accelerators

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

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

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

Starburst/Star-Forming Galaxies (pp)

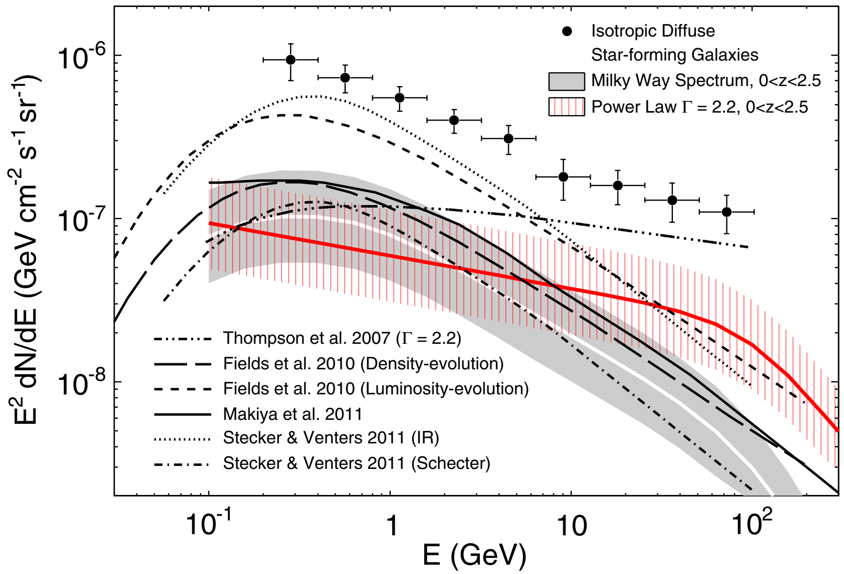


Tamborra, KM & Ando
14 JCAP

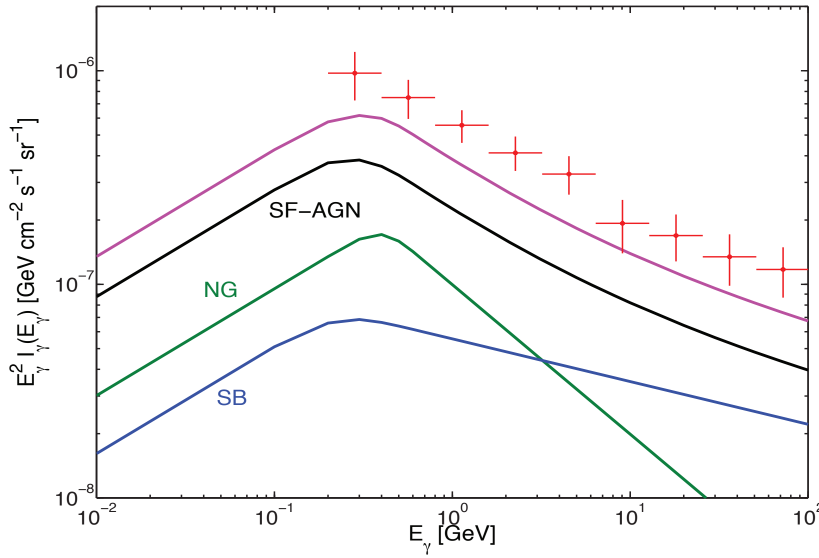
- Consistent w. obs. & a PeV break was predicted!
- How can CRs get accelerated above 100 PeV?

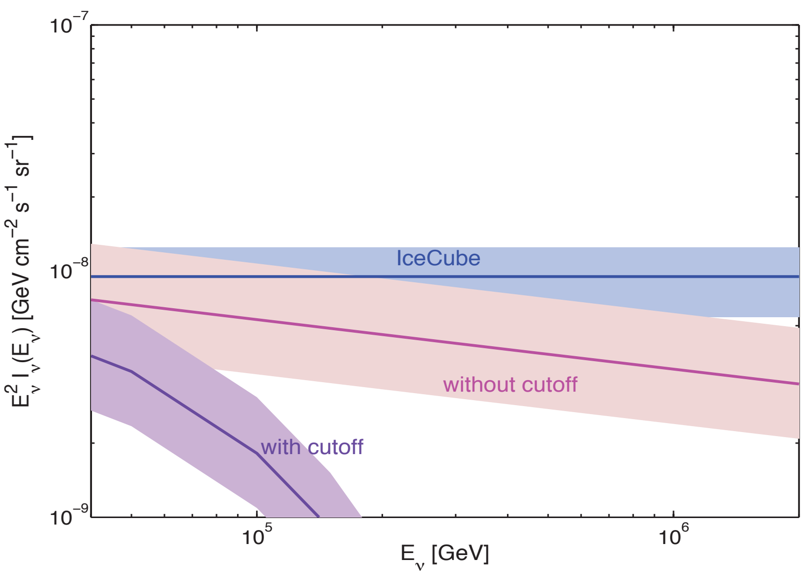
Requirements in Star-Forming Galaxies

Fermi collaboration 12 ApJ



Tamborra, KM & Ando 14

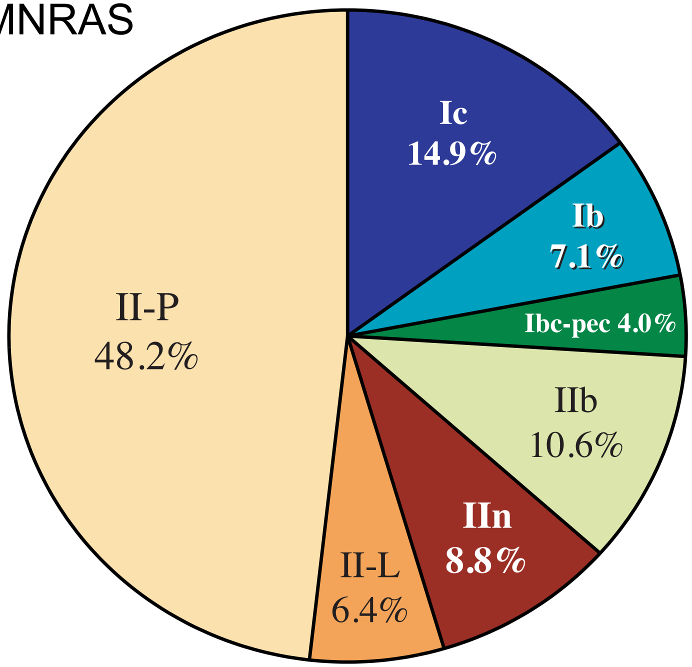




- ~20% of diffuse γ bkg. → s_ν~2 but including SF-AGN can help (<~50 % can be explained)
- E_{knee}~E_p^{max} (rather than E_p^{esc}) → cutoff at 100 TeV transients powerful than SNRs?

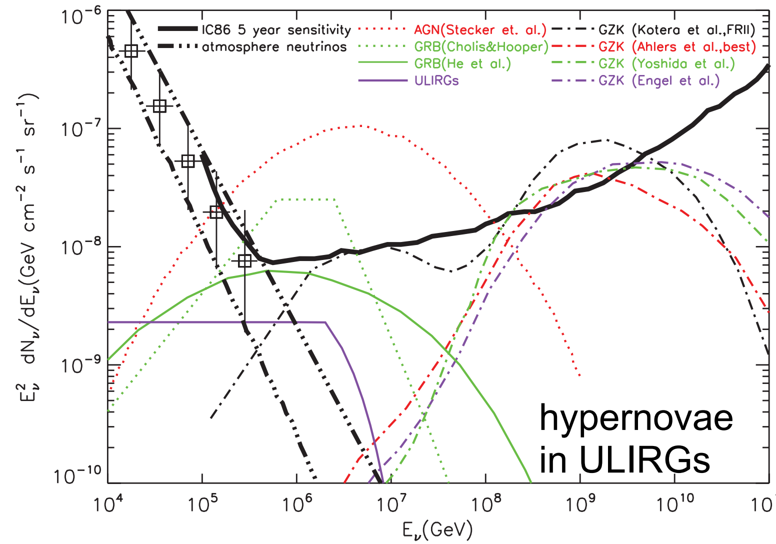
Speculations about Accelerators

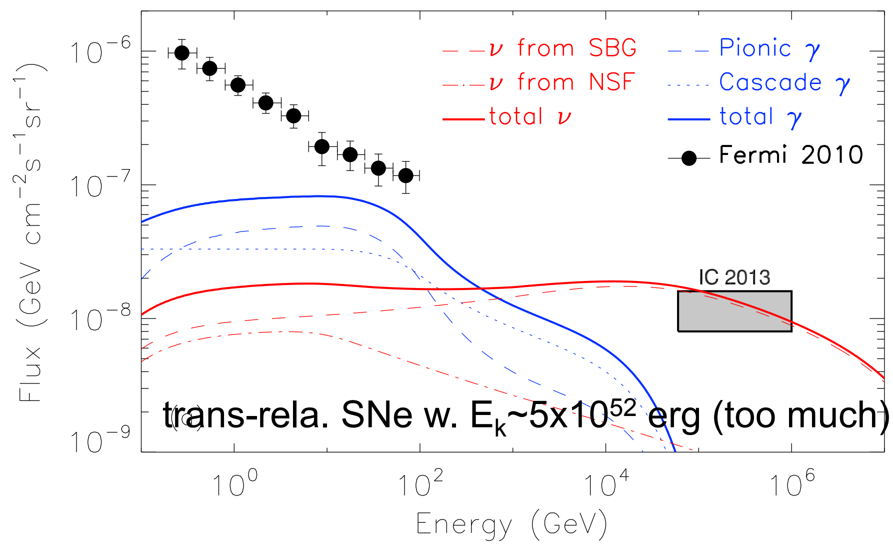
Smith+ 11 MNRAS



Core-Collapse SN Fractions

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

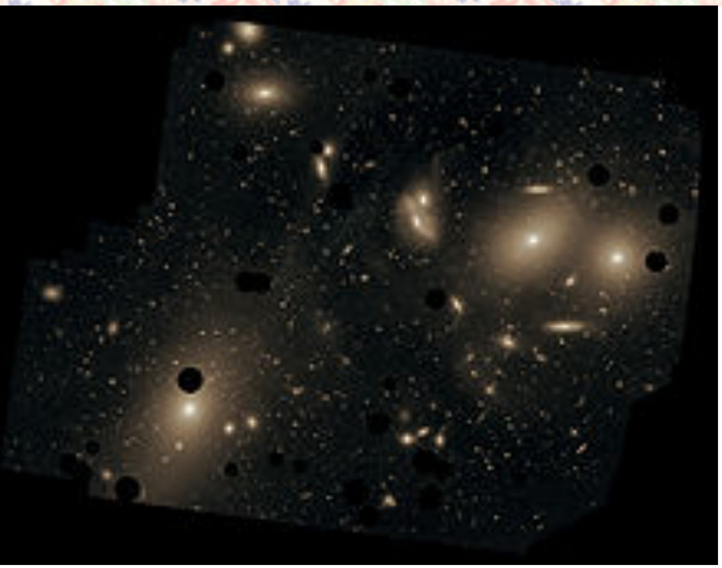




Issues

- Why is Milky way special?
- Normal SNRs are more dominant
- Can B-field be amplified sufficiently?
- Trans-relativistic SNe ≠ hypernovae (ex. GRB060218 E_k~$2x10^{51}$ erg)

Galaxy Groups and Clusters



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

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

energetics

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

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

pp efficiency

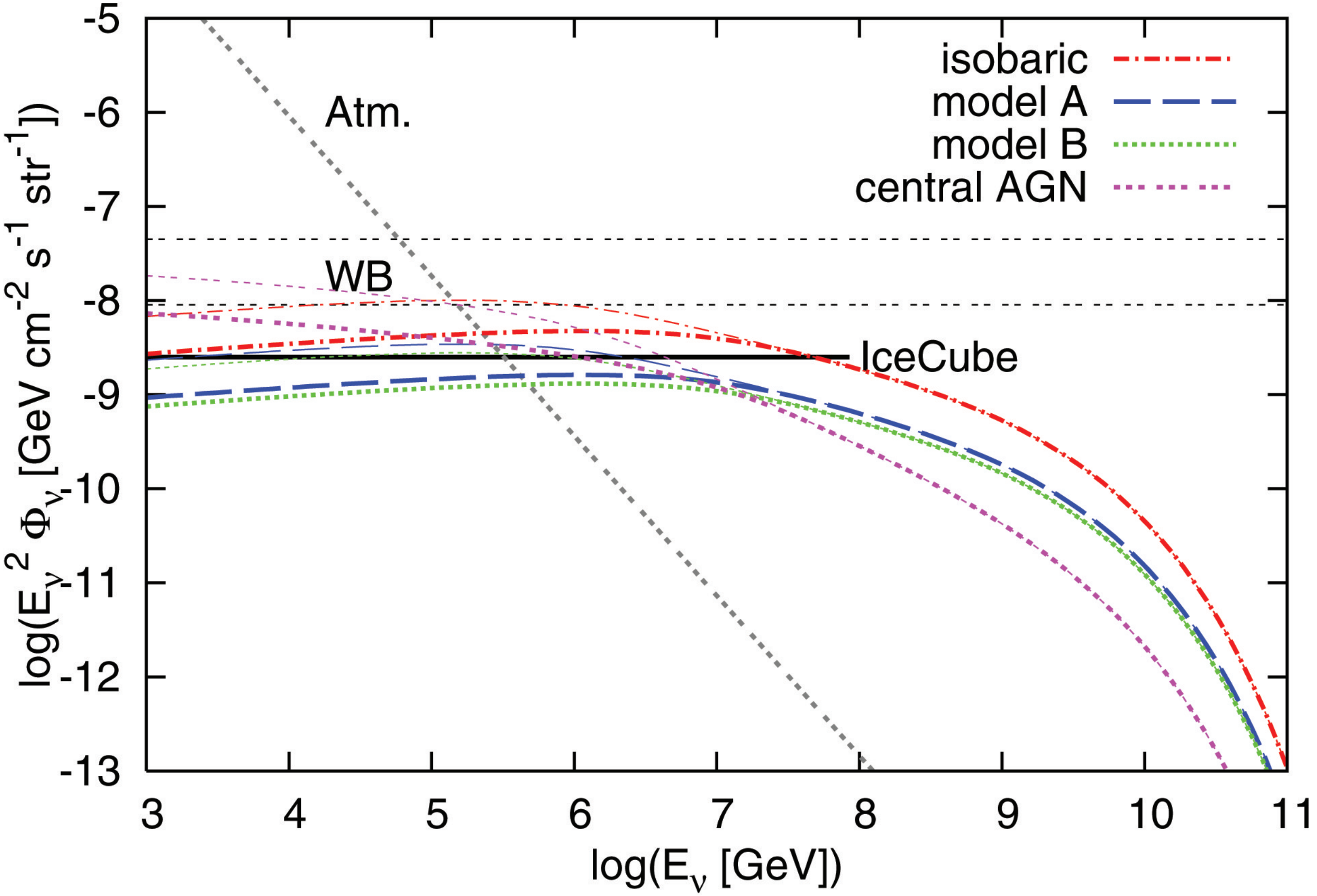
$$f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm int} \simeq 0.76 \times 10^{-2} \ g\bar{n}_{-4}(t_{\rm int}/2 \text{ Gyr})$$

diffusion time

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

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

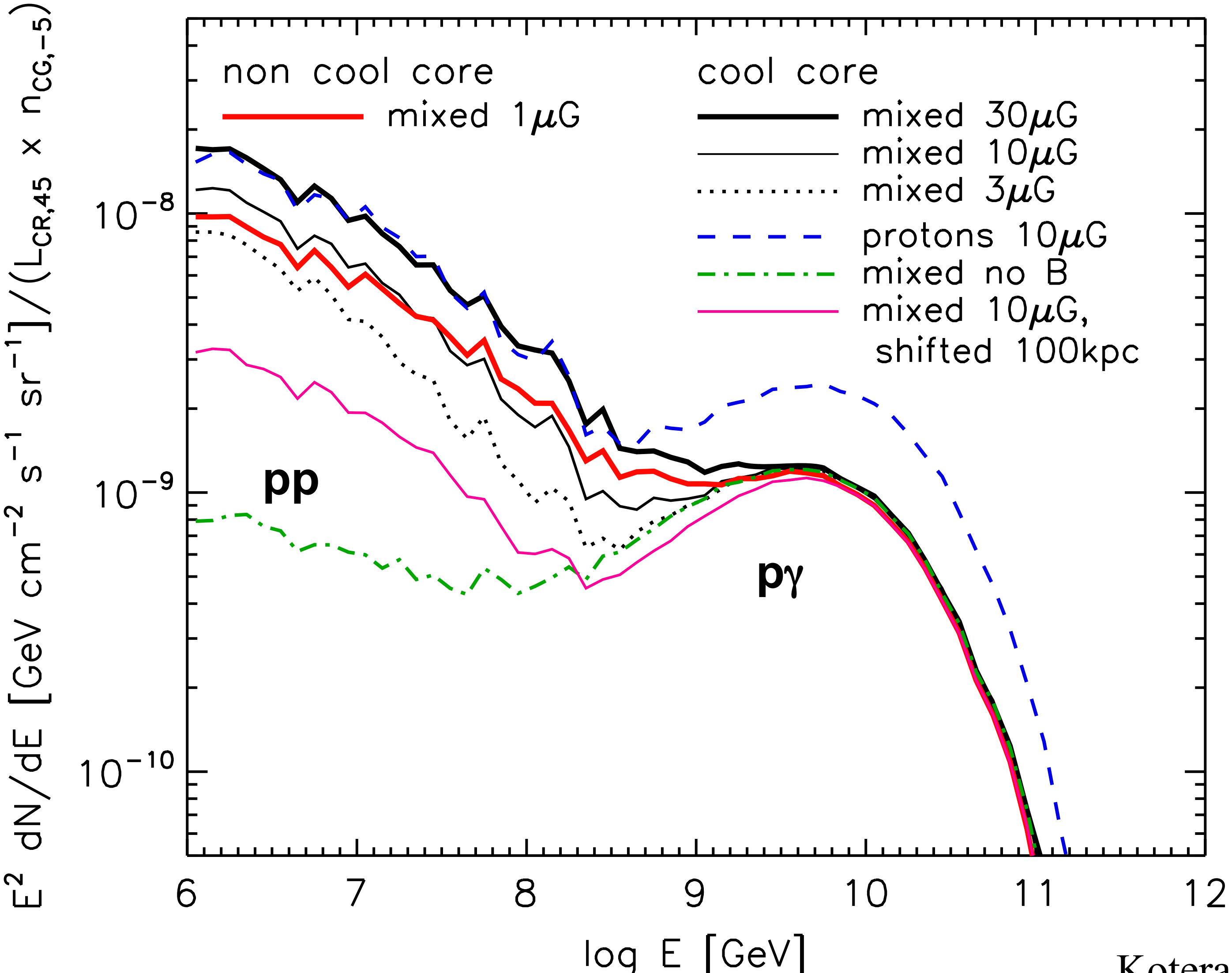
Galaxy Clusters and Groups (pp)



KM et al. 08 ApJL

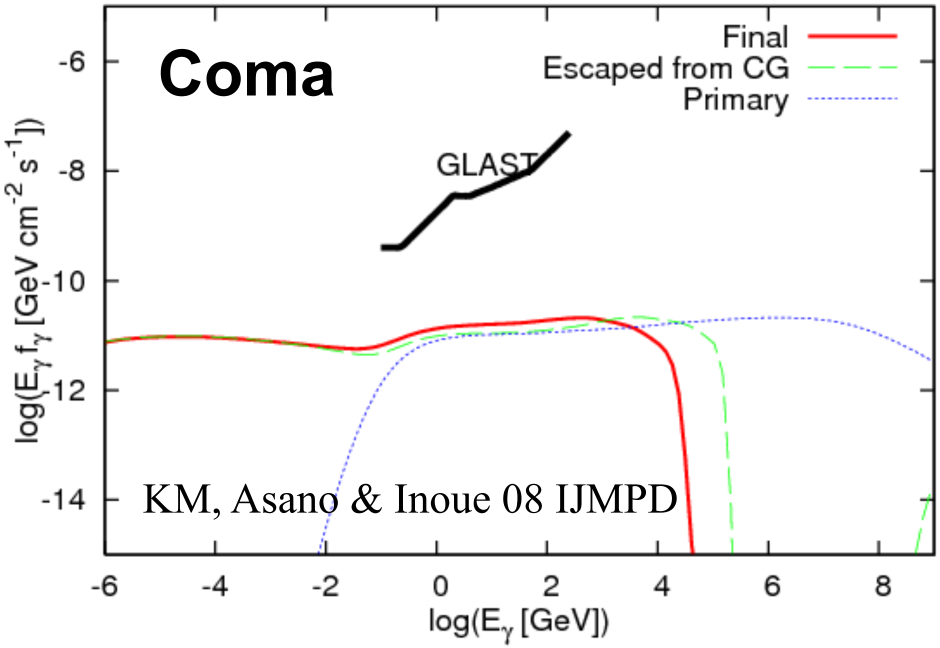
- Consistent w. obs. & a PeV break was predicted!
- No firm gamma-ray detection, Normalization?

AGN in Galaxy Clusters and Groups



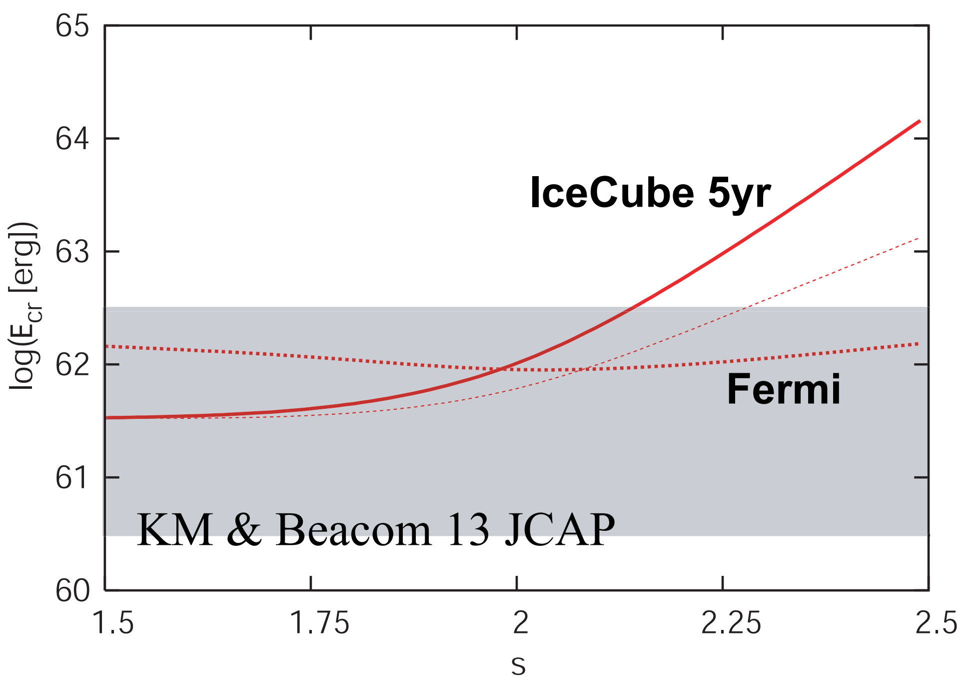
Kotera, Allard, KM+ 09 ApJ

Gamma-Ray Limits?



consistent with nondetection of gamma rays

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



$L_{cr} \sim 0.5\times10^{45}$ erg s^{-1} (Virgo)

$\rightarrow E_{cr}=L_{cr}t_{inj} \sim 3\times10^{61}$ erg

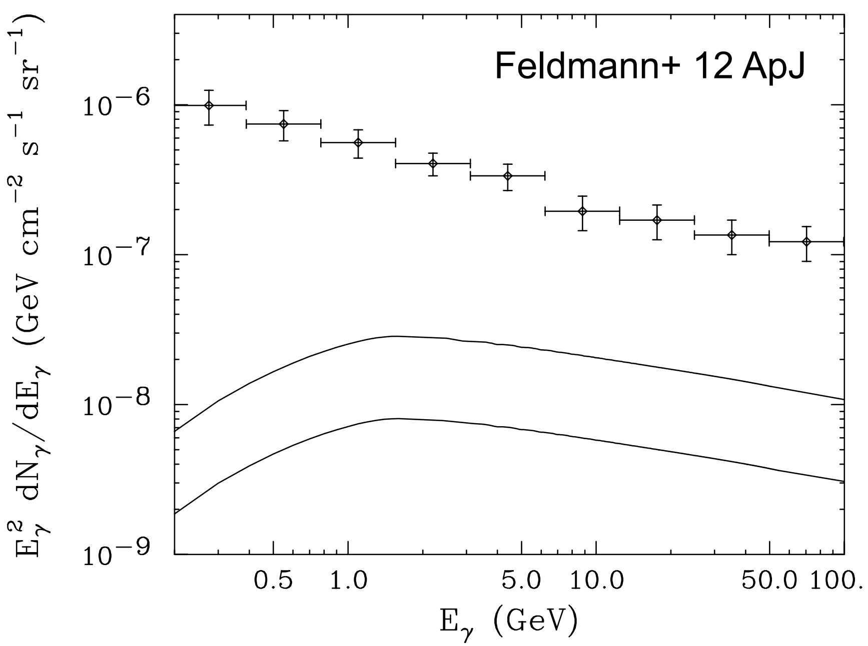
Galactic Halo

CRs should interact w. circumgalactic gas

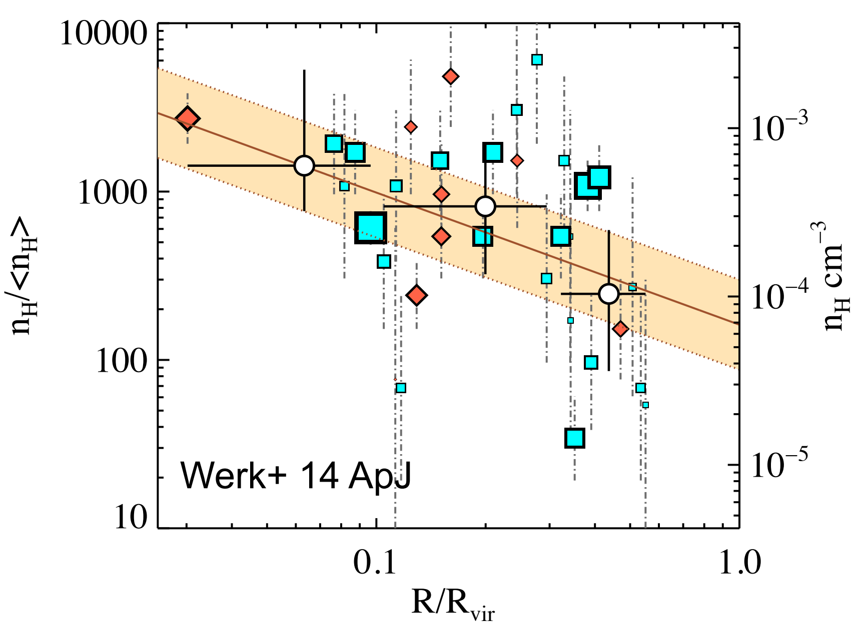
$$E_\nu^2 J_{\nu_\alpha}^{\rm halo} \simeq \frac{N_{\rm SNR}}{4\pi V_{\rm halo}} \int_0^{R_{\rm vir}} dr E_\nu^2 Q_{\nu_\alpha}$$
$$\simeq 2.4 \times 10^{-9}\ {\rm GeV cm^{-2} s^{-1} sr^{-1}} \epsilon_{p,-1} \mathcal{E}_{\rm ej,51}$$
$$\times \left(\frac{R_{\rm vir}}{260\ {\rm kpc}}\right)^{-2} \left(\frac{f_{\rm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

not enough (typically)

pre-IceCube predictions



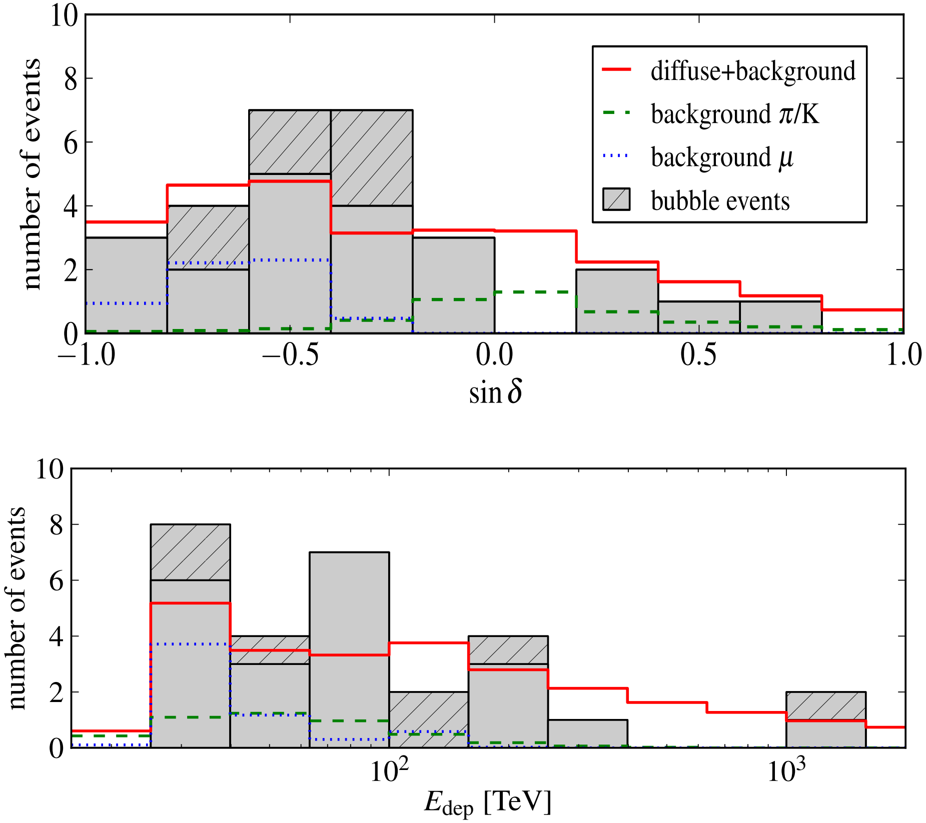
$$n_H = (10^{-4.2\pm0.25})(R/R_{\rm vir})^{-0.8\pm0.3}$$



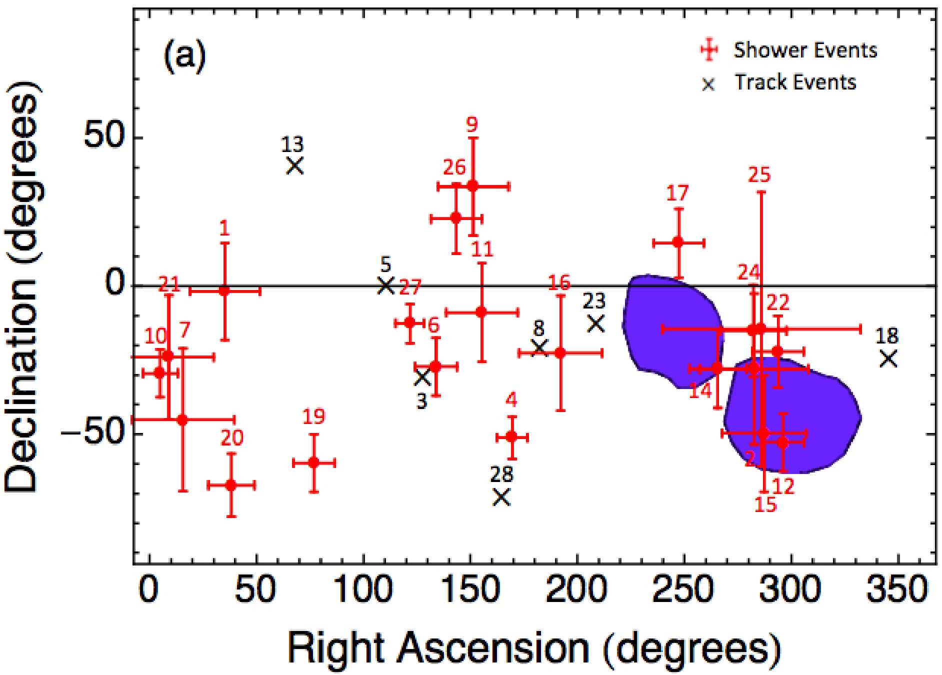
※ **PeV γ rays should be expected (~60 % come from <26 kpc or higher if CR dist. has gradient)**

Fermi Bubbles

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



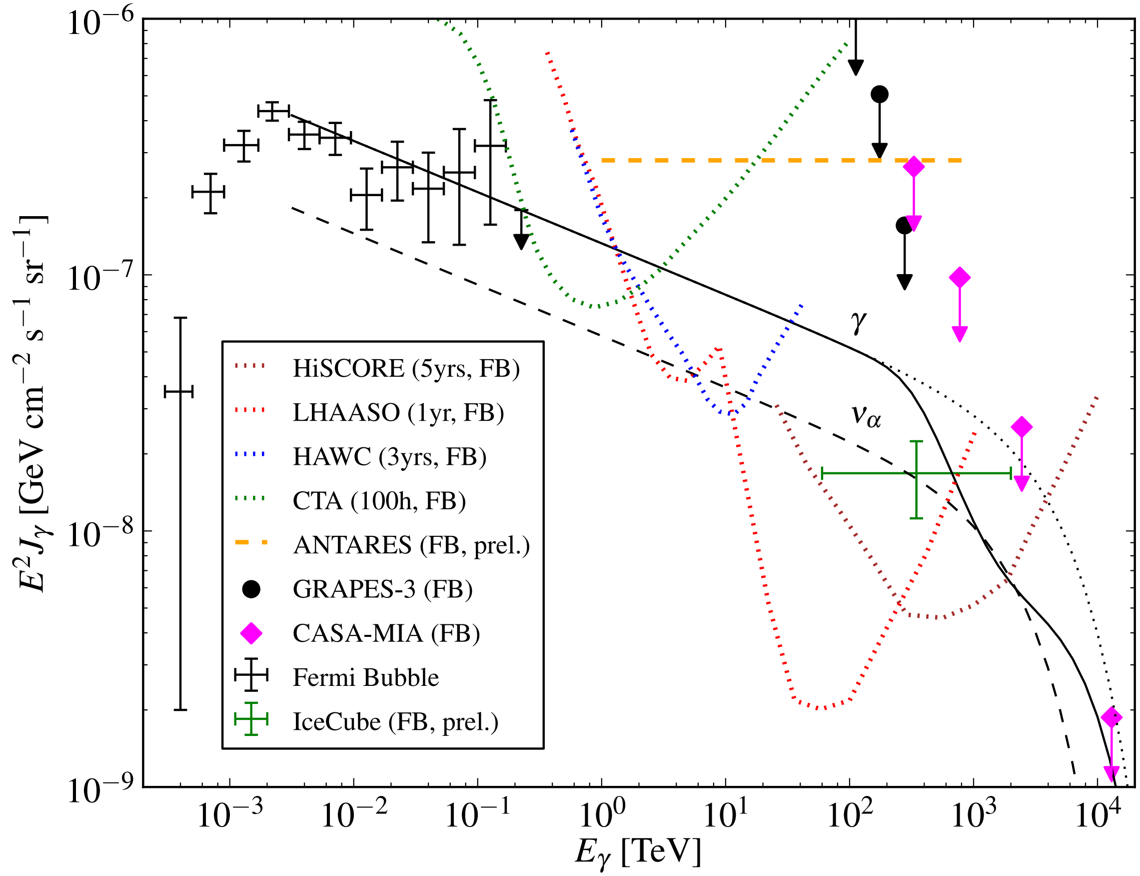
Ahlers & KM 13



Lunardini et al. 13

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

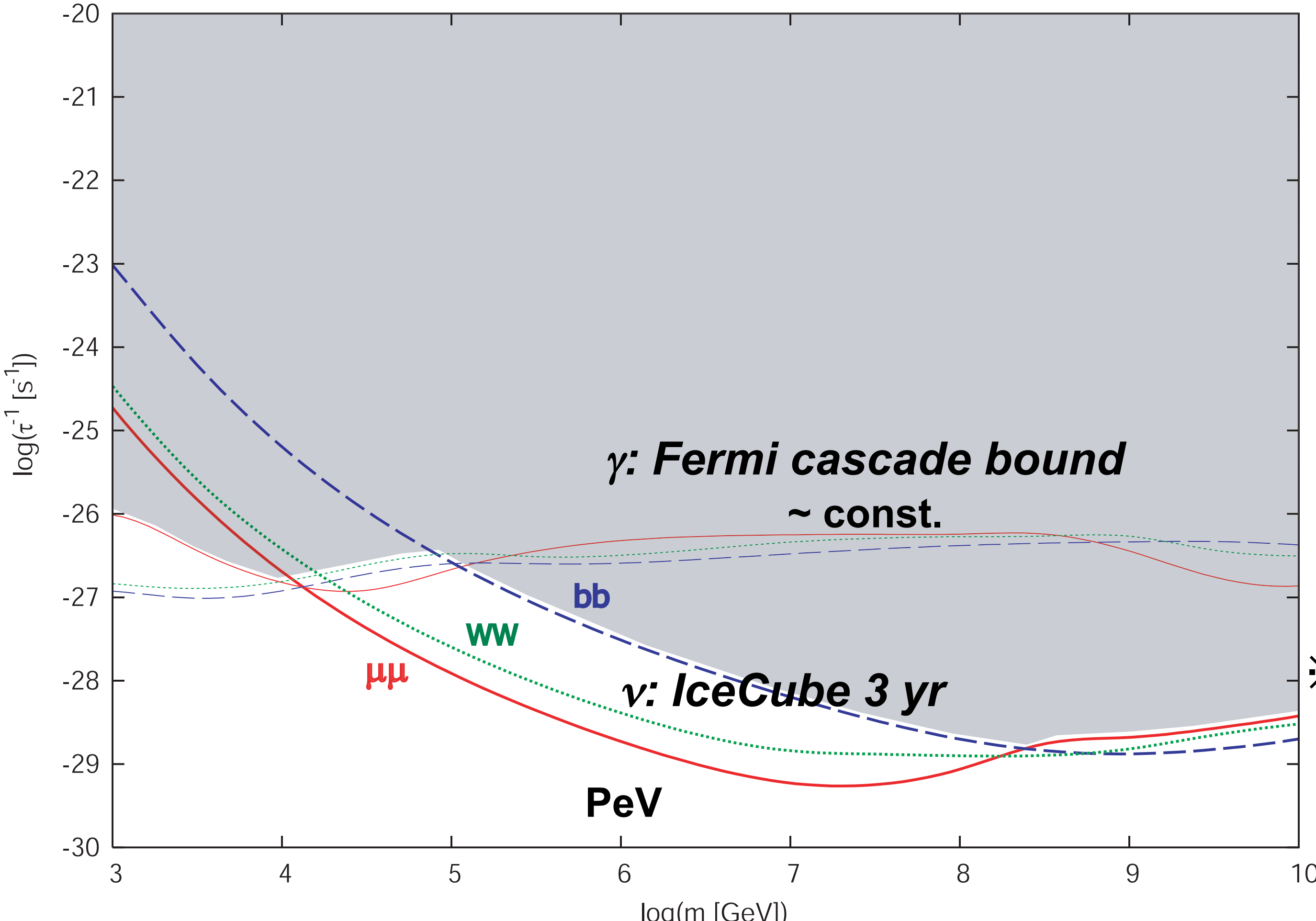
Contributions from Fermi Bubbles?



Ahlers & KM 13

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

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}

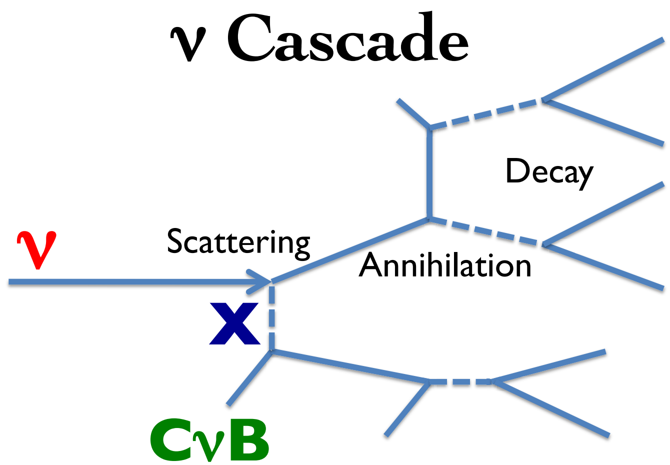
Secret Neutrino Interactions

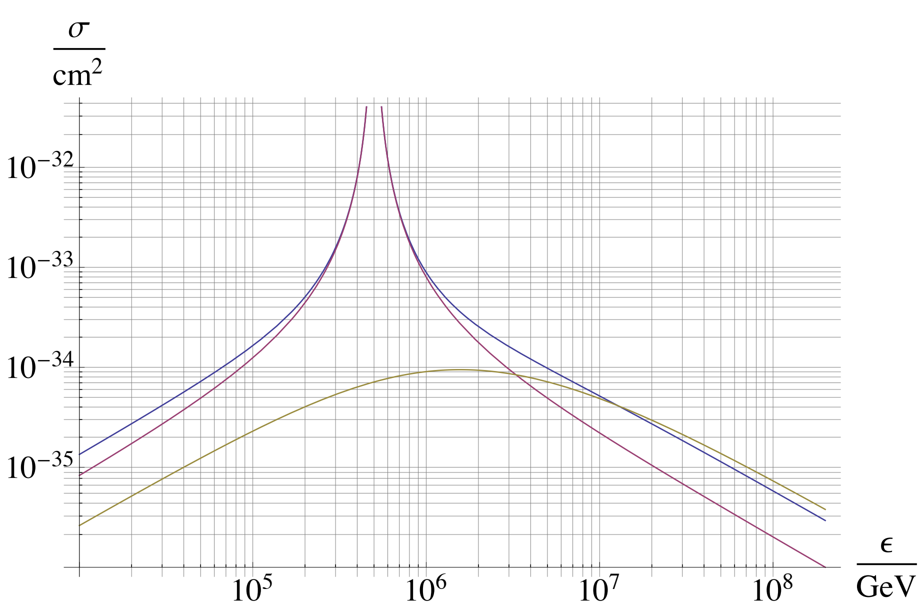
Majorna neutrino self-interactions via a scalar

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

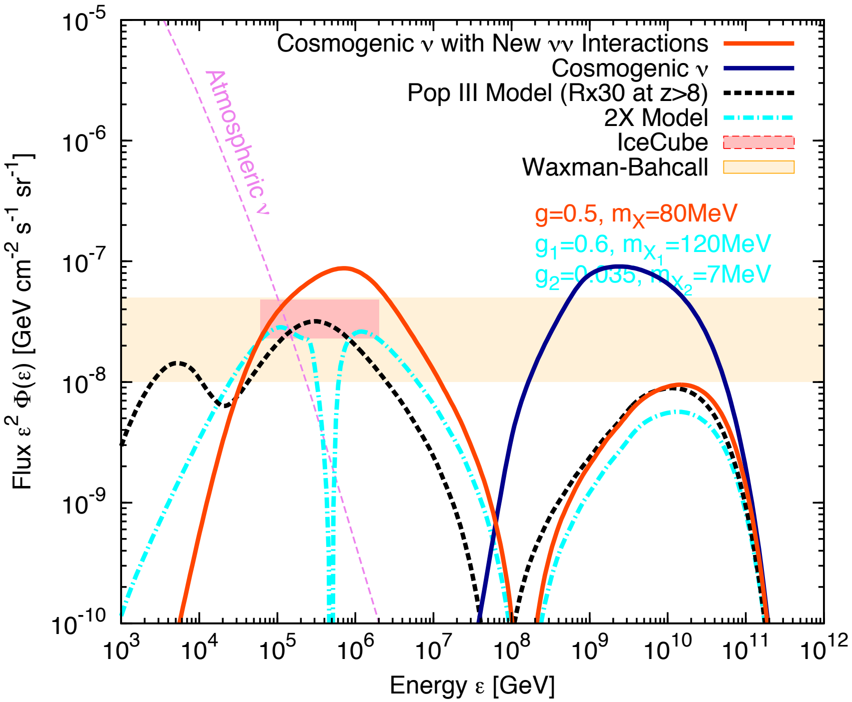
SSB, LNV $\quad m_{\nu_i} = \frac{g_i \mu v^2}{\Lambda^2}$

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

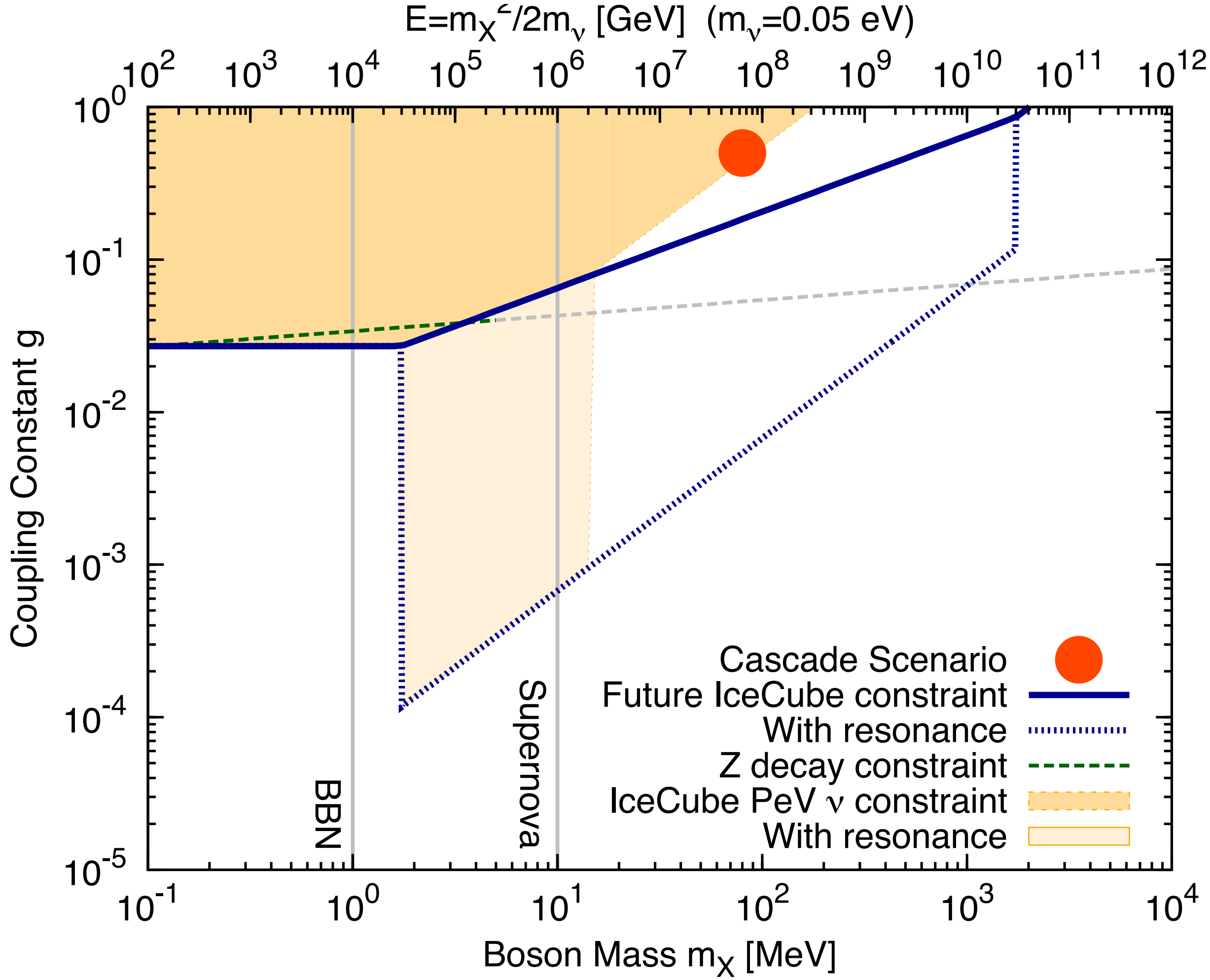




Blum. Hook & KM 14, Ioka & KM 14 PTEP



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