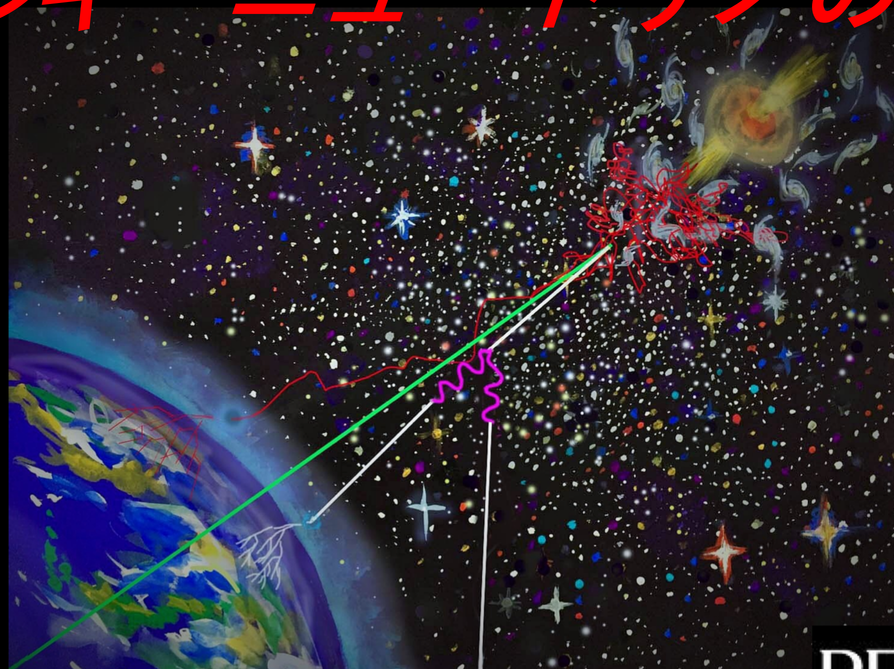
マルチメッセンジャー観測で迫る高エネルギーニュートリノの起源天体

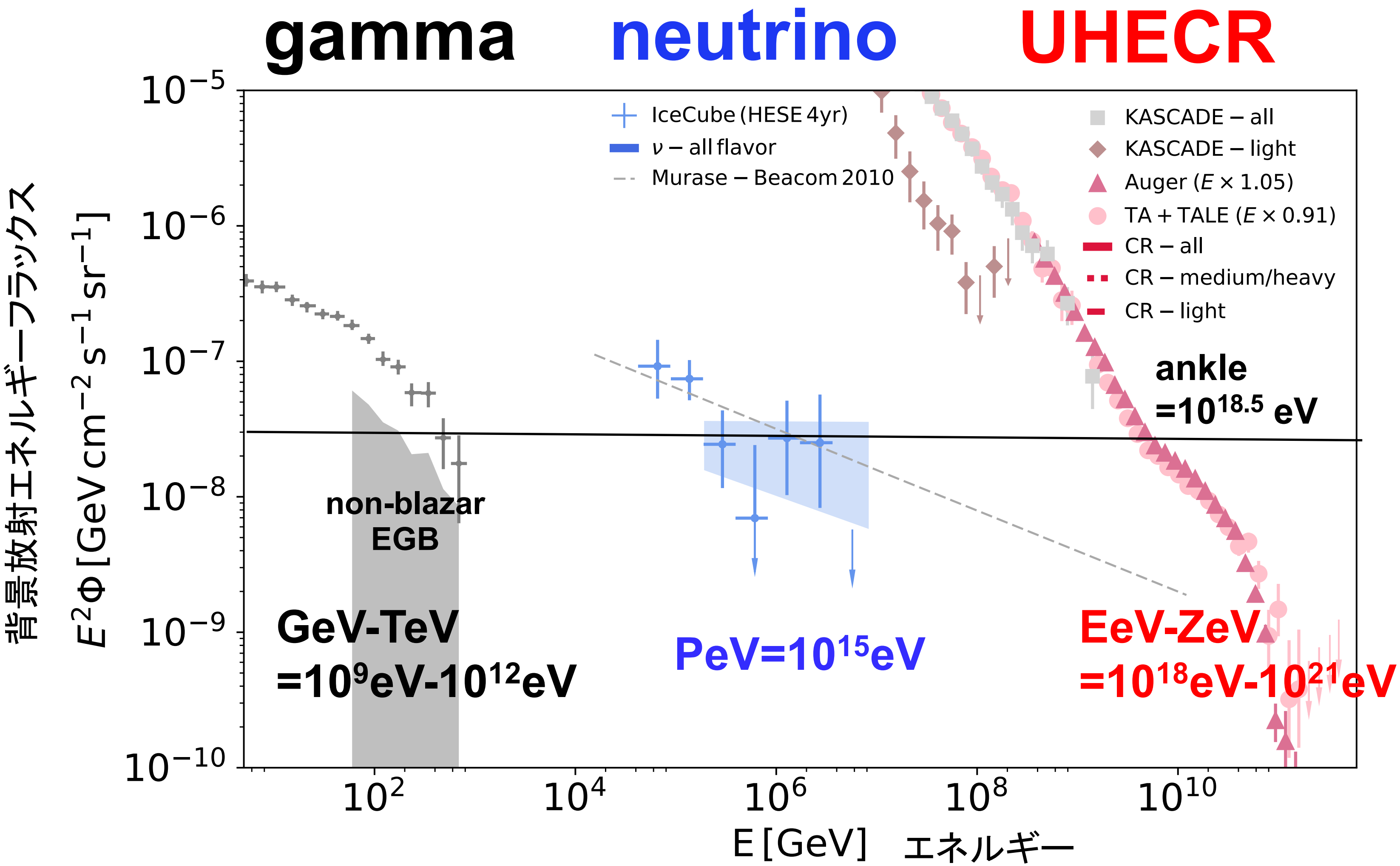


Kohta Murase

Penn State University

天文学会 @ 兵庫県立大学

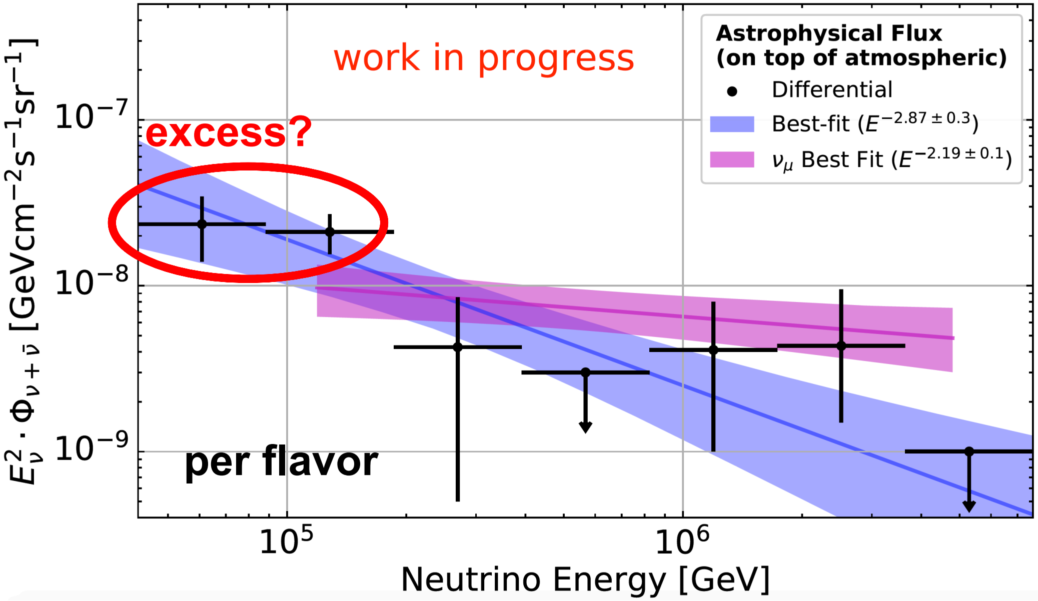
Multi-Messenger View of Cosmic Particle "Backgrounds"



Energy budgets are all comparable (10^{43} -10^{44} erg Mpc^{-3} yr^{-1})

e.g., KM & Fukugita 18

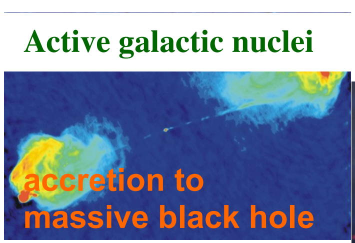
Diffuse Neutrino Intensity & Candidate Sources



- **7.5 year HE starting events**
  103 events
  (60 events > 60 TeV)
  best-fit: s=2.87±0.3
- **8 year upgoing ν_μ "track"**
  36 events at >200 TeV (6.7σ)
  best-fit: s=2.19±0.10

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

Cosmic-ray Accelerators
(ex. UHECR candidate sources)

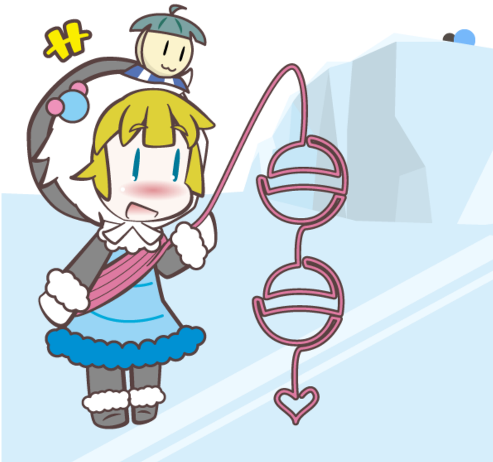


$$p + \gamma \rightarrow N\pi + X$$

Cosmic-ray Reservoirs

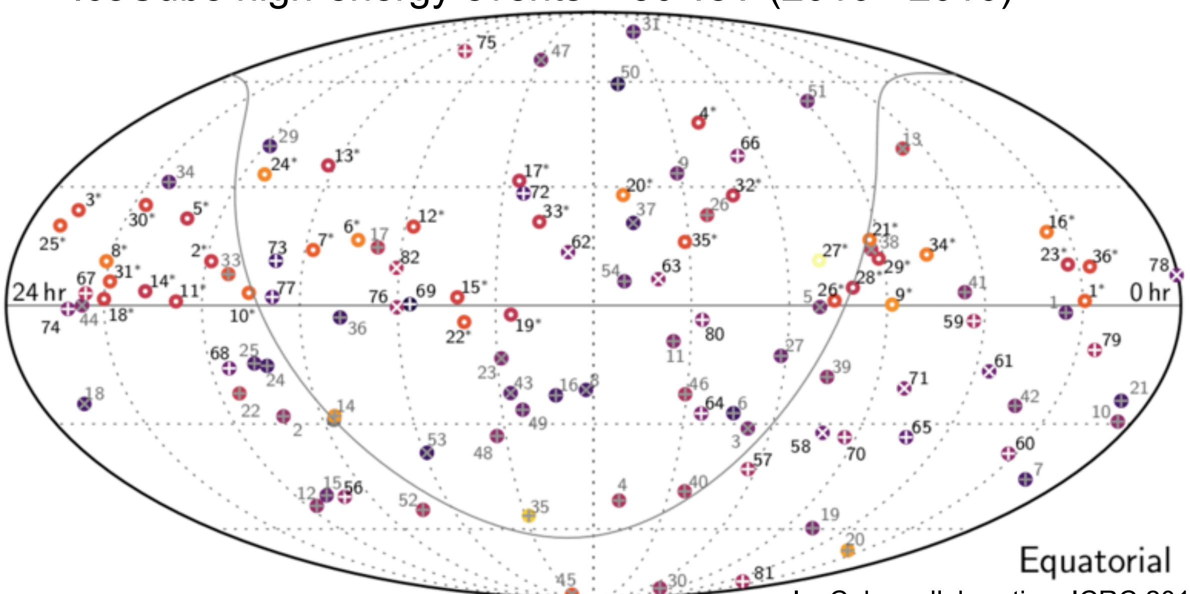
$$p + p \rightarrow N\pi + X$$

Fishing Neutrino Sources



- compatible w. isotropic distribution
- no significant clustering at >30 TeV
- some (fishy) sources?
  TXS 0506+056, PKS B-1424-41

IceCube high-energy events > 30 TeV (2010 - 2016)

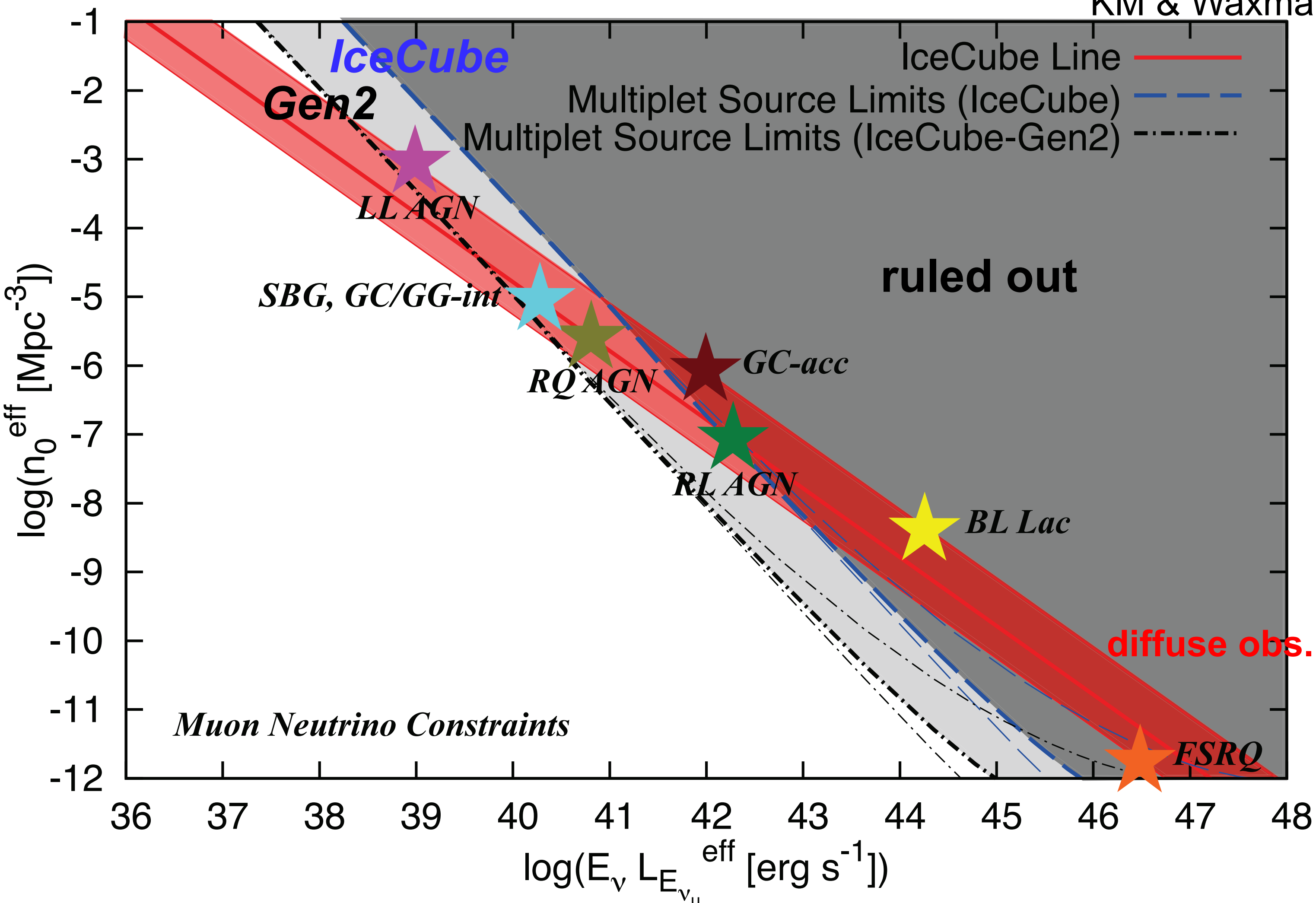


IceCube Preliminary

IceCube collaboration, ICRC 2017

What Have We Learned from the Neutrino Sky?

KM & Waxman 16 PRD



- Rare sources cannot be the dominant origin (n_s>10^{-7}-10^{-6} Mpc^{-3})
- Most models can be tested by next-generation detectors (Gen2)

Fate of High-Energy Gamma Rays

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

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

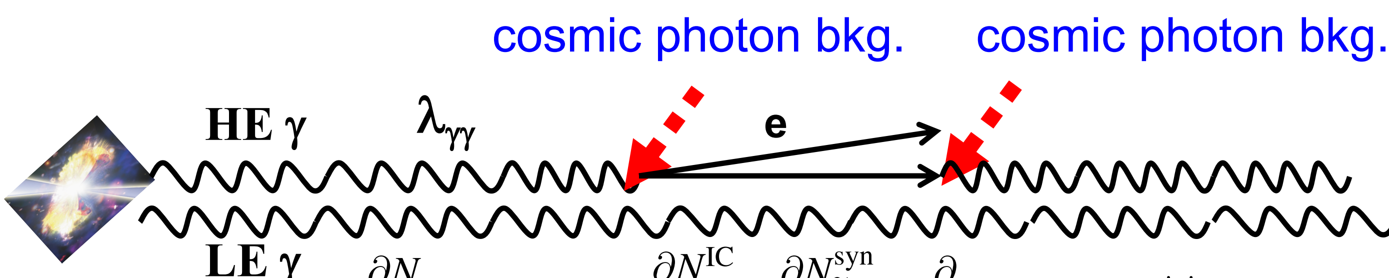
$p + p \rightarrow N\pi + X$ $\quad\pi^{\pm}:\pi^0 \sim 2:1 \rightarrow$ **$E_\gamma^2\,\Phi_\gamma \sim (2/3)\,E_\nu^2\,\Phi_\nu$**

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

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

ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc

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



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

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

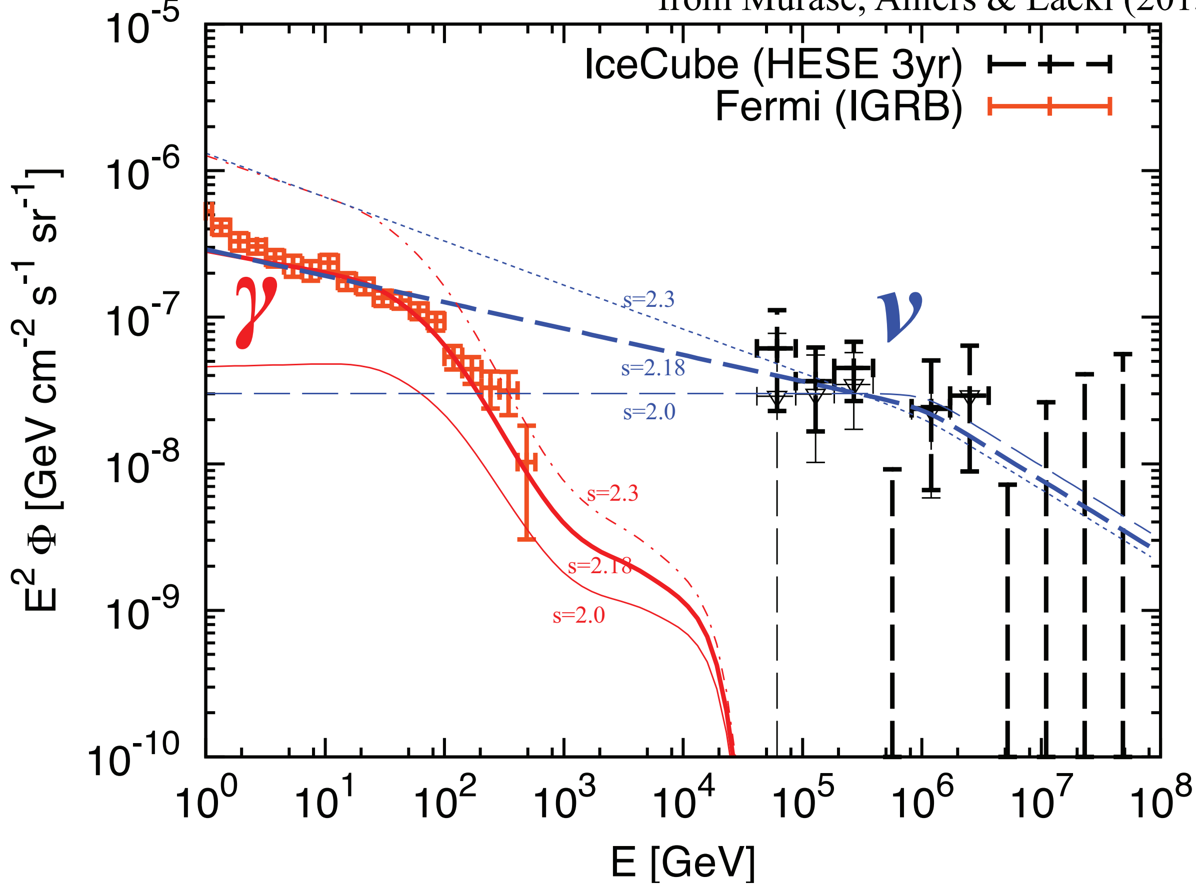
Fermi satellite

airshower detectors

Multi-Messenger Constraints on the >0.1 PeV ν Origin

- Generic power-law spectrum $\varepsilon Q_\varepsilon \propto \varepsilon^{2-s}$, transparent to GeV-TeV γ

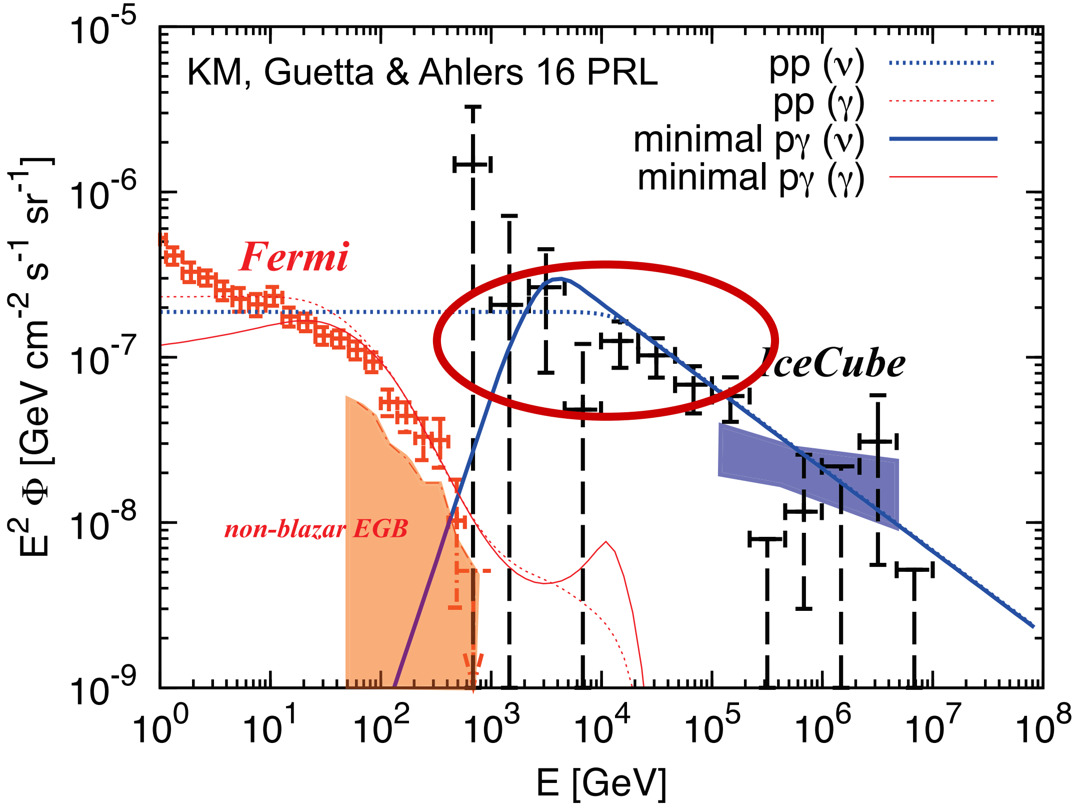
from Murase, Ahlers & Lacki (2013)

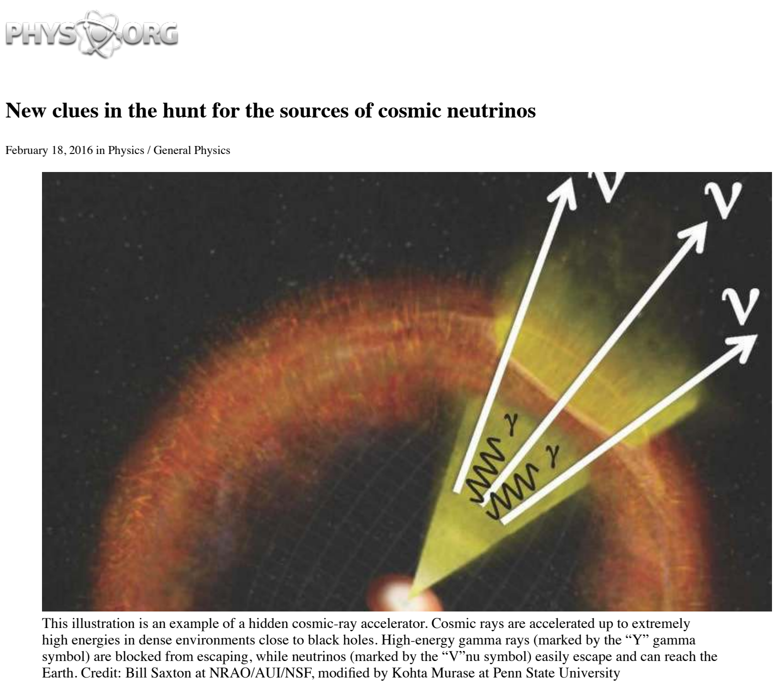


- **s < 2.1-2.2 (for extragal.); insensitive to evolution & EBL models**
- **contribution to diffuse sub-TeV γ–ray bkg.: >30-40%**
- s < 2.0 for nearly isotropic Galactic emission (e.g., Galactic halo)

New Component?: Medium-Energy "Excess"?

- 10-100 TeV data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1} (best-fit spectral indices tend to be as soft as s~2.5-2.9)





Violation of Fermi diffuse γ-ray bkg. if ν sources are γ-ray transparent

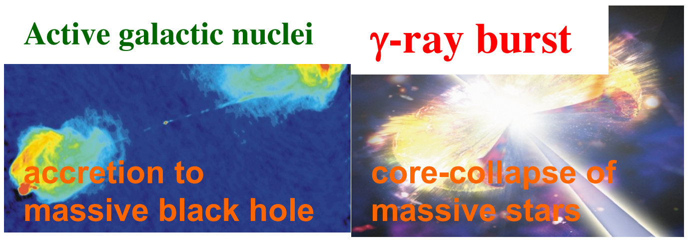
→ "hidden neutrino sources (i.e. γ-ray attenuation)"

In this talk we focus on general classes of >0.1 PeV neutrino sources

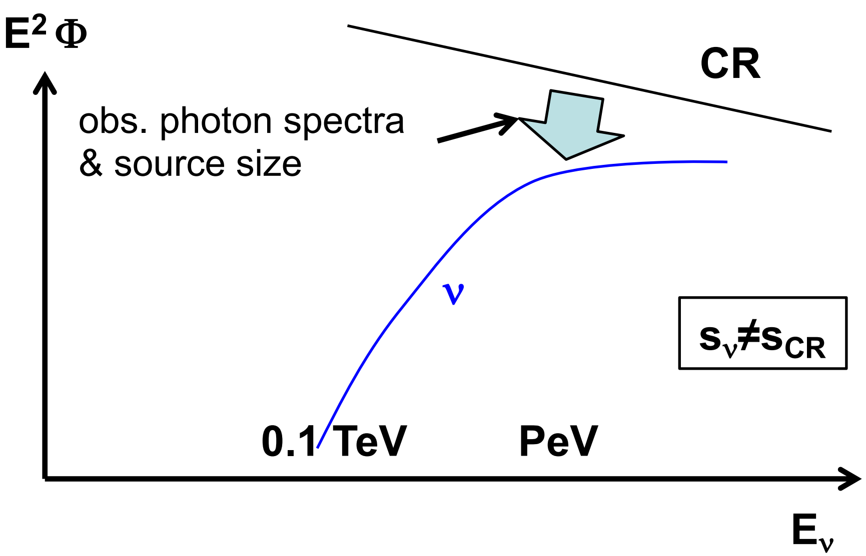
Astrophysical Extragalactic Scenarios

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

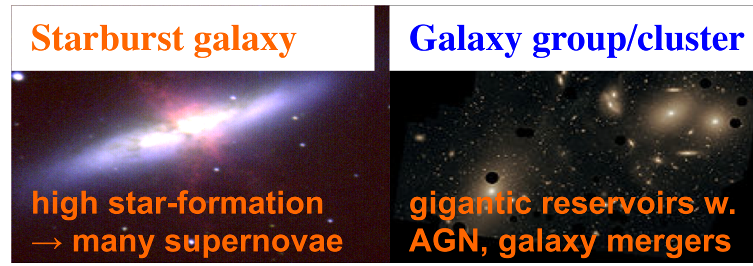
Cosmic-ray Accelerators (ex. UHECR candidate sources)



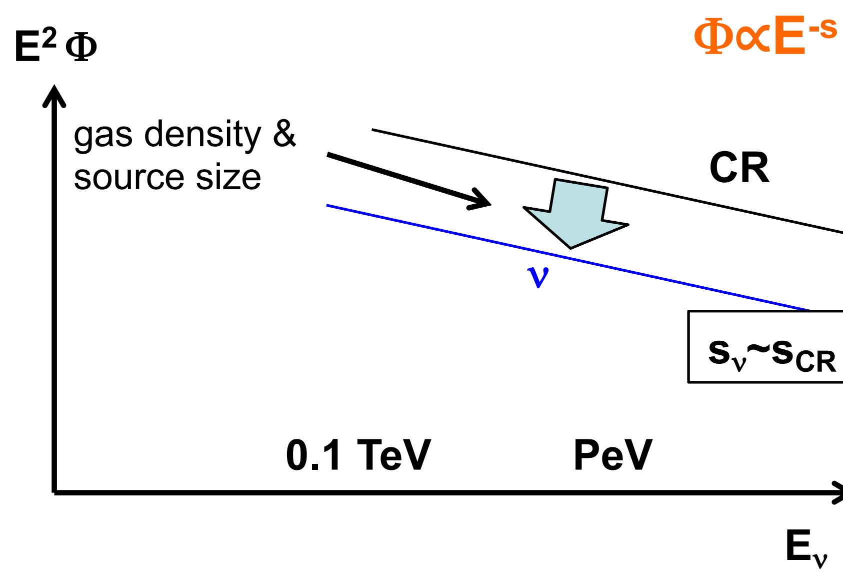
$$p + \gamma \rightarrow N\pi + X$$



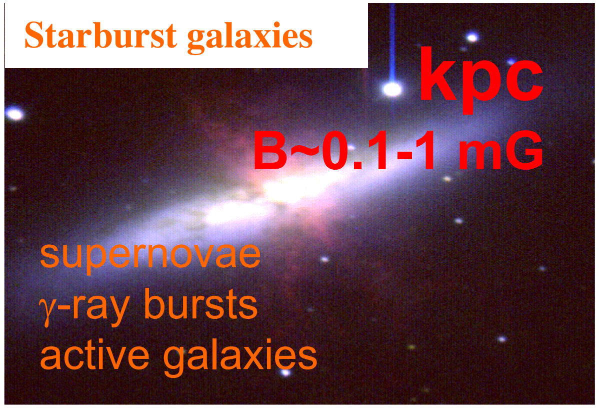
Cosmic-ray Reservoirs



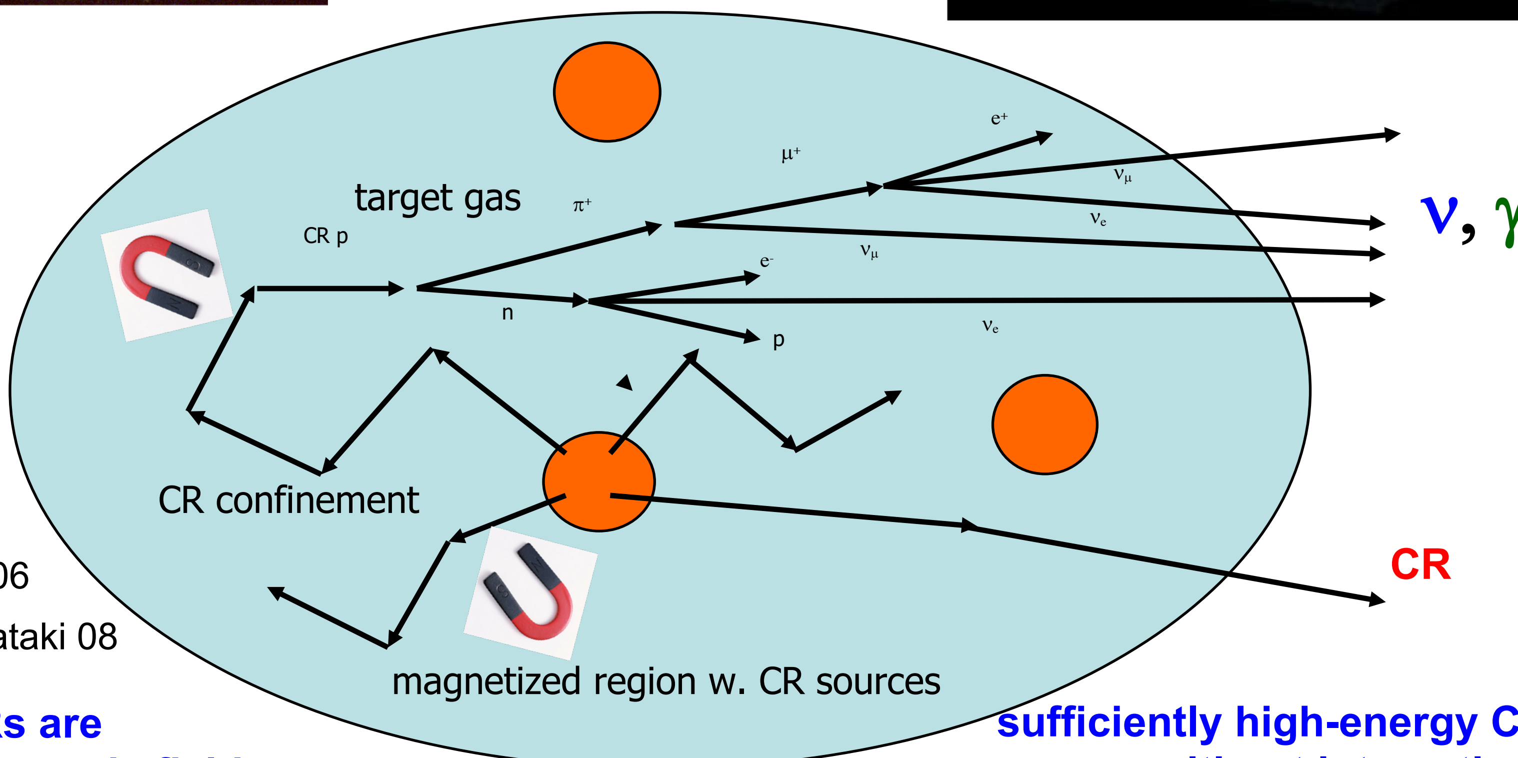
$$p + p \rightarrow N\pi + X$$



Cosmic-Ray Reservoirs



“cosmic-ray reservoirs”

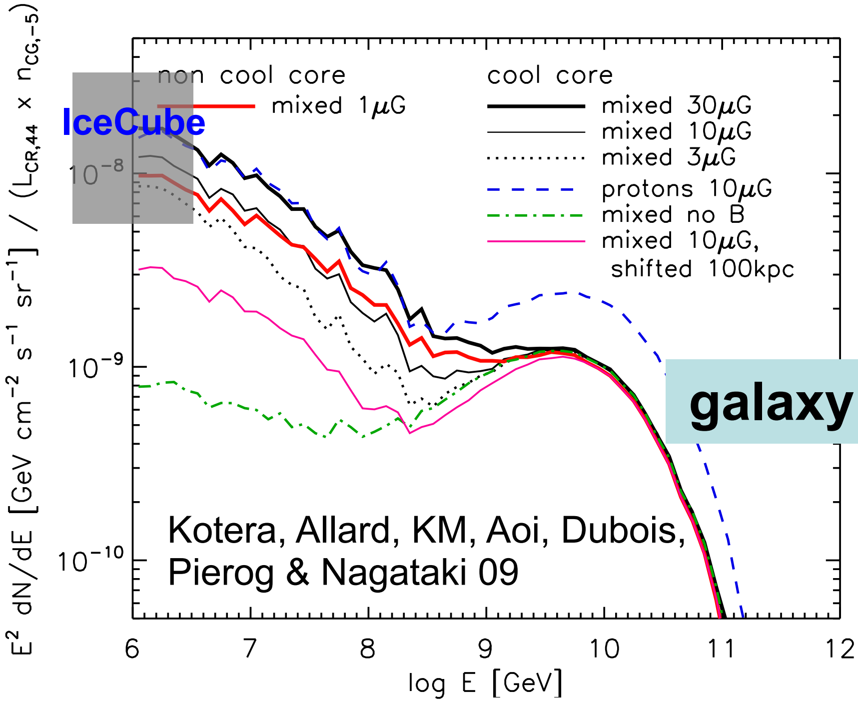


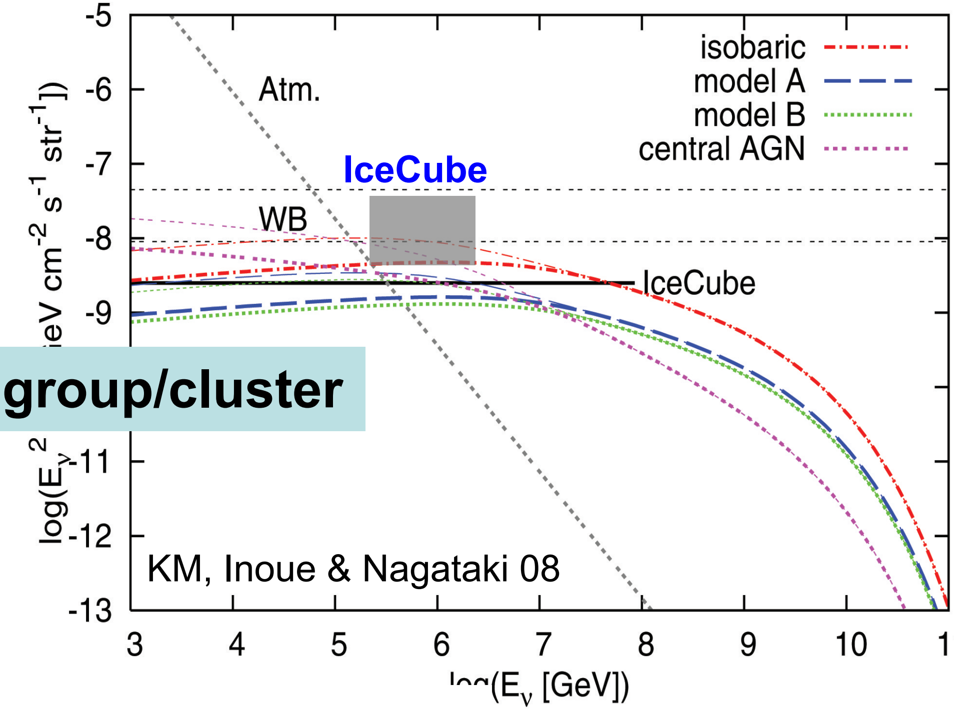
Loeb & Waxman 06

KM, Inoue & Nagataki 08

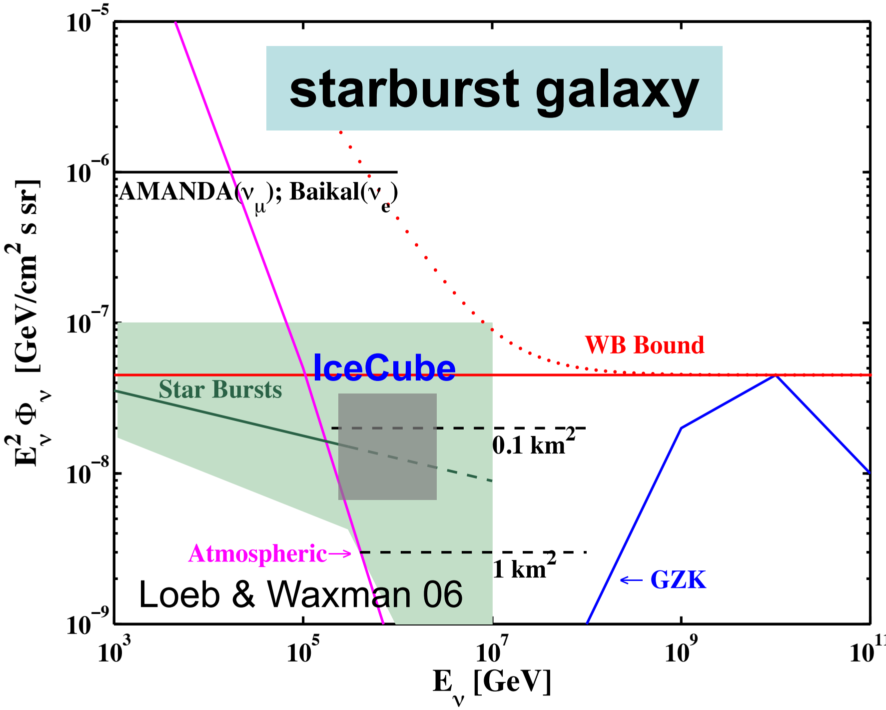
low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions





galaxy group/cluster

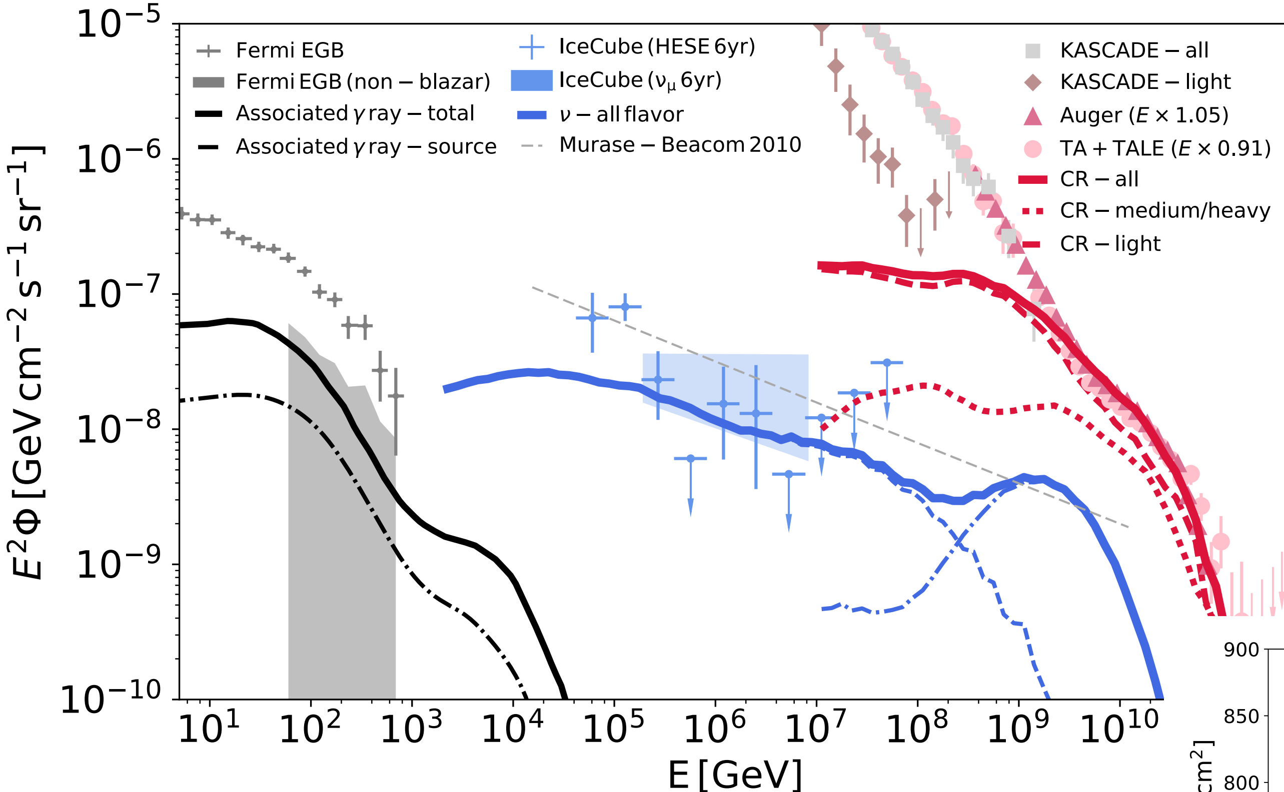


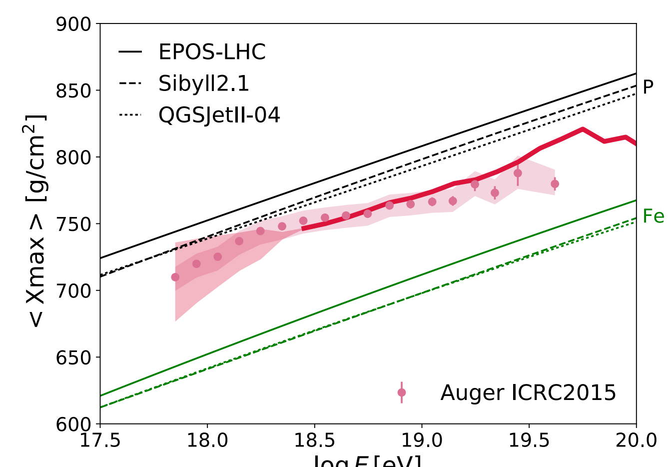
starburst galaxy

consistent w. predictions

Grand-Unification of High-Energy Cosmic Particles?

Fang & KM 18 Nature Physics (see also KM & Waxman 16 PRD)



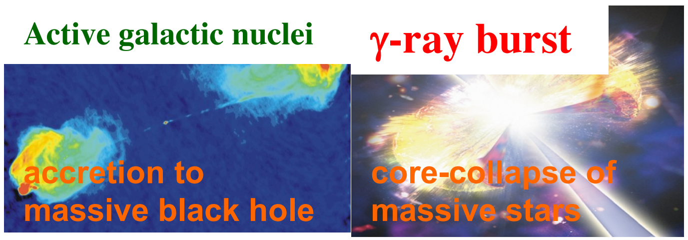


- AGN="UHECR" accelerators
  Galaxy clusters/groups="CR" reservoirs
- LE CRs: confinement in AGN & clusters
  HE CRs: escape into intergalactic space

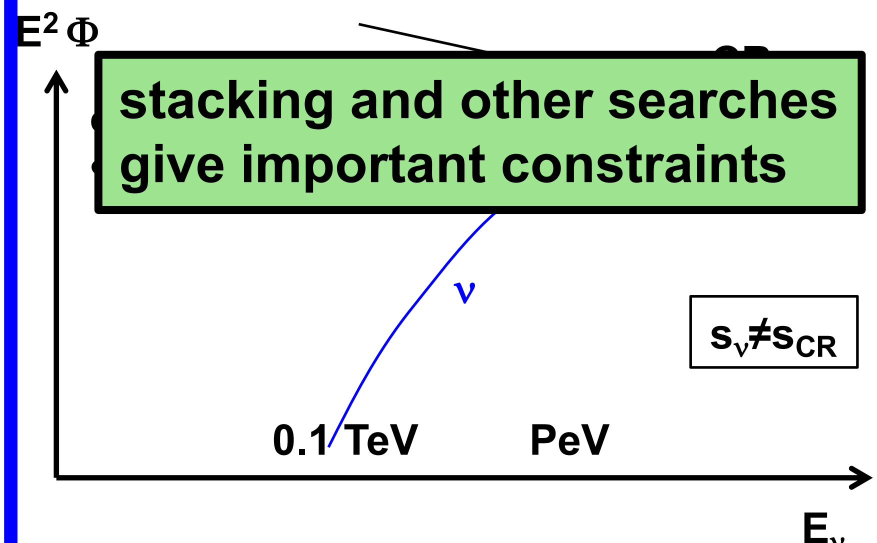
Astrophysical Extragalactic Scenarios

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

Cosmic-ray Accelerators
(ex. UHECR candidate sources)

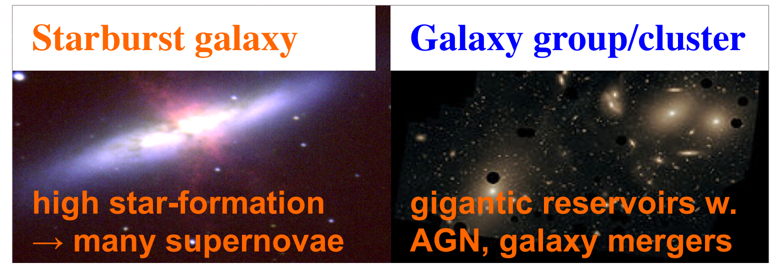


$$p + \gamma \rightarrow N\pi + X$$



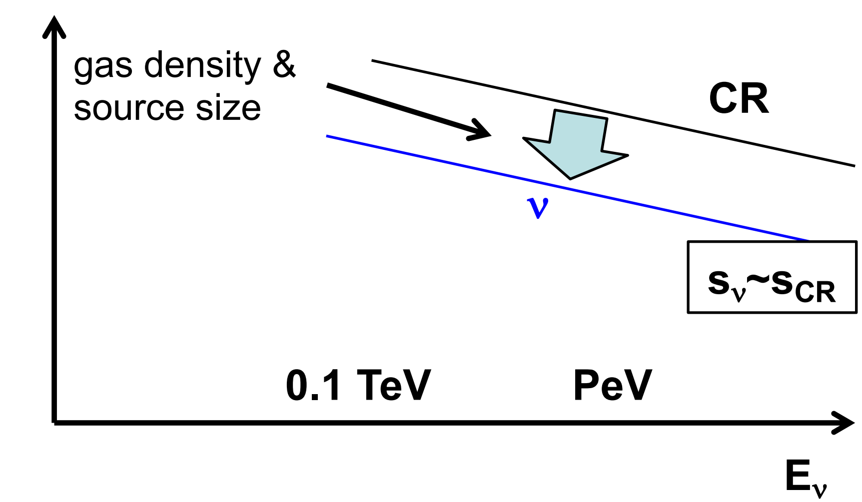
stacking and other searches give important constraints

Cosmic-ray Reservoirs



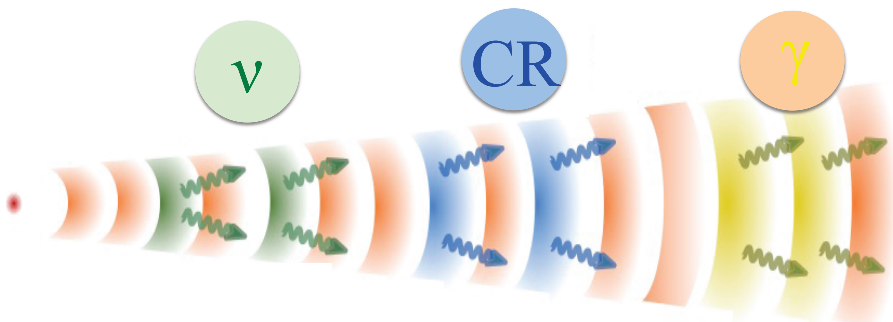
$$p + p \rightarrow N\pi + X$$

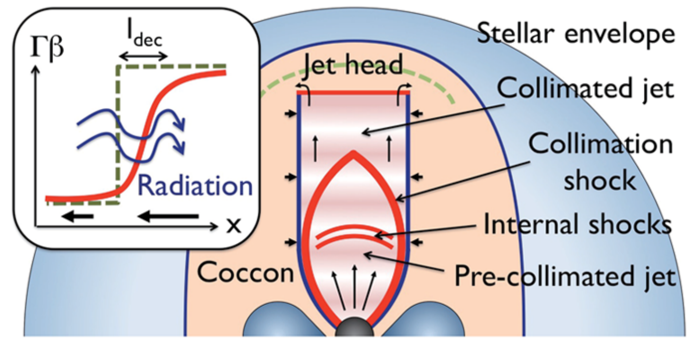
$\Phi \propto E^{-s}$

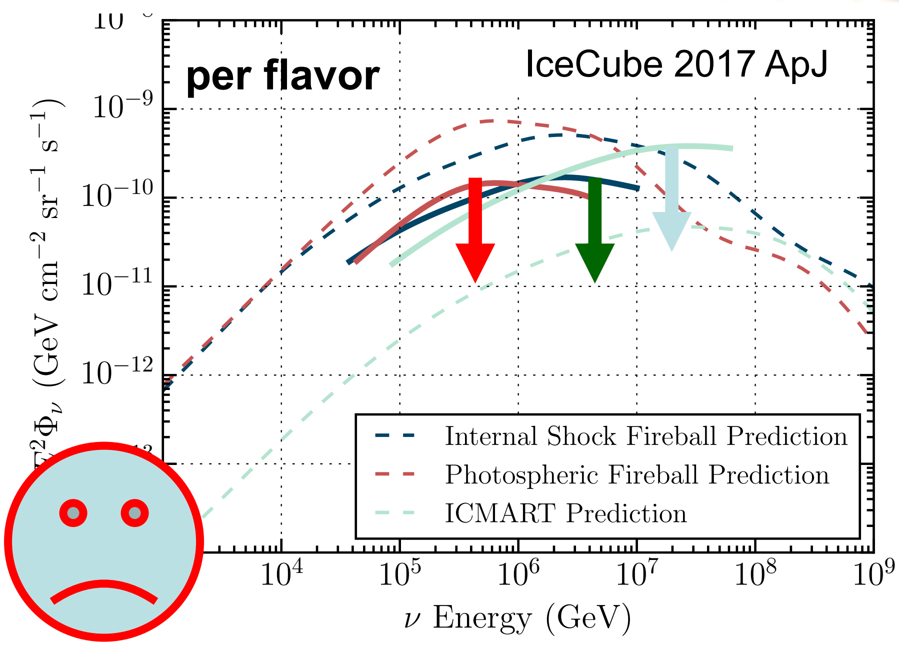


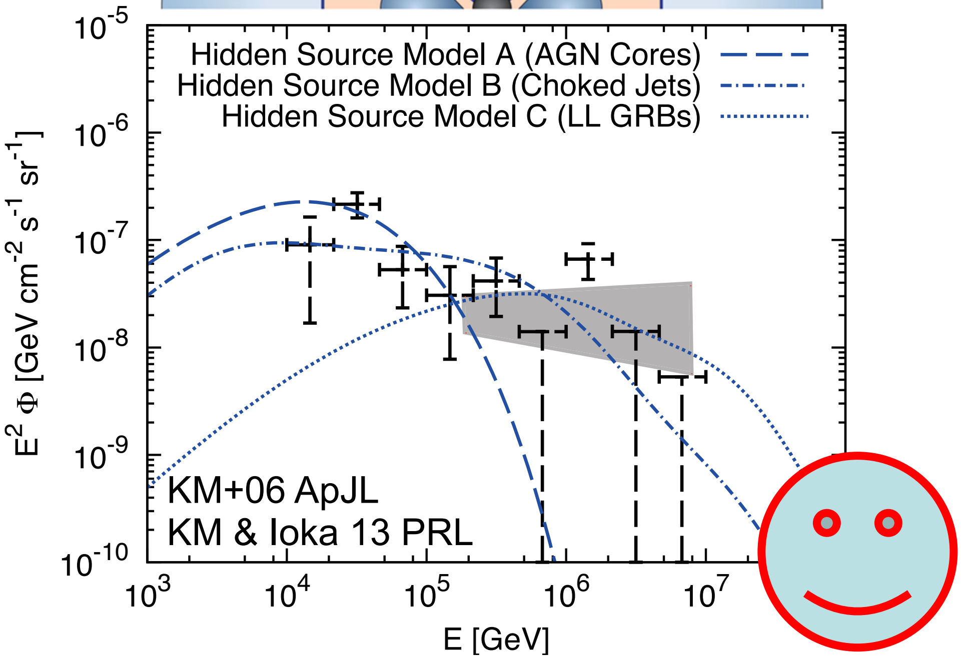
Diffuse Neutrino Intensity from GRBs

- Classical GRBs as the dominant origin: excluded by multimessenger obs.
  constrained by stacking analyses **<~ 10^{-10} GeV cm^{-2} s^{-1} sr^{-1}**
- Low-luminosity GRBs and choked-jet SNe: viable as the dominant sources



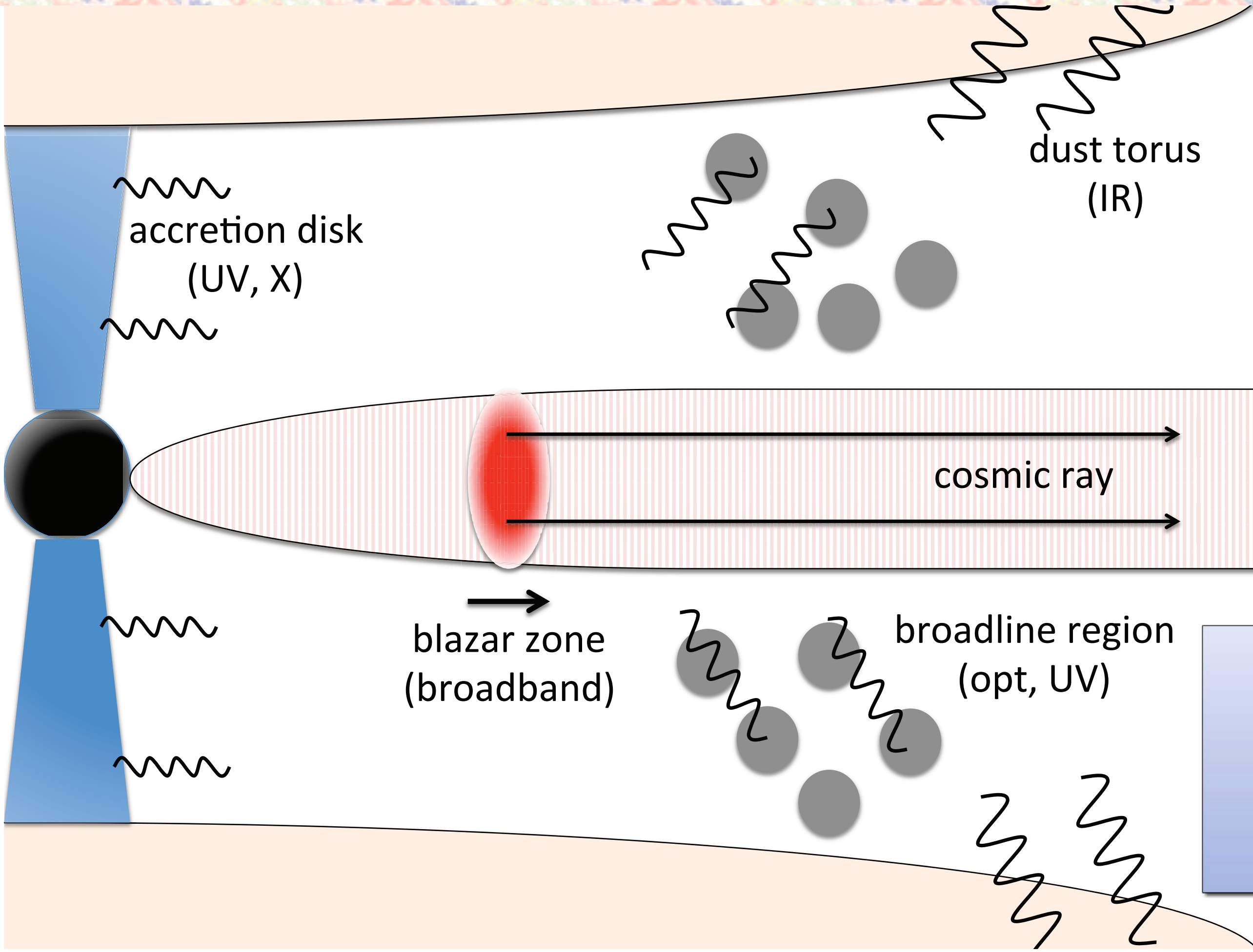




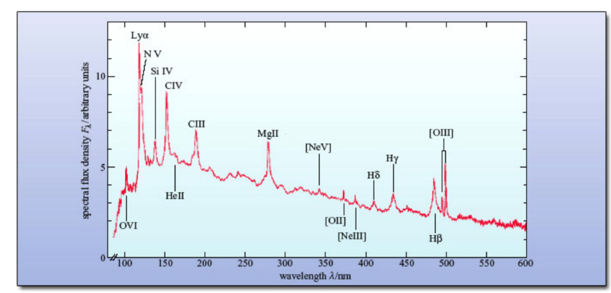


Photomeson Production in Blazars

KM, Inoue & Dermer 14



neutrinos
“beamed”



$$E'_\nu \approx 0.05 E'_p \simeq 0.8 \text{ PeV } \Gamma_1^2 (E'_s/1 \text{ keV})^{-1}$$ **inner jet photons**

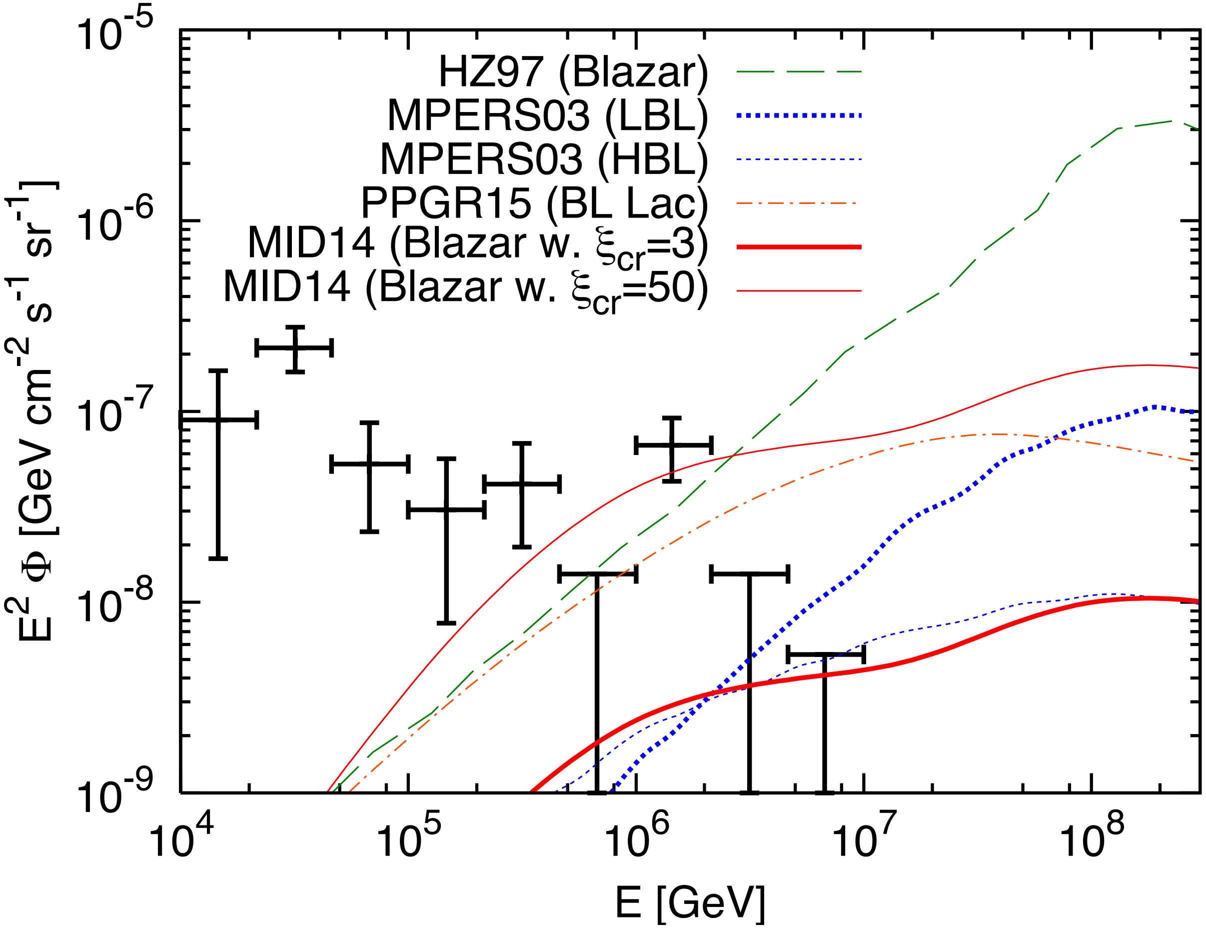
p$\gamma \rightarrow \Delta^+ \rightarrow \pi$ + N

$$E'^b_\nu \approx 0.05(0.5 m_p c^2 \bar{\varepsilon}_\Delta / E'_{\rm BL}) \simeq 0.78 \text{ PeV}$$ **broadline (UV) photons**

$$E'^b_\nu \simeq 0.066 \text{ EeV} (T_{\rm IR}/500 \text{ K})^{-1}$$ **dust torus (IR) photons**

Diffuse Neutrino Intensity from Blazars

Blazars: if UHECR accelerators → promising EeV neutrino emitters



various diffuse ν predictions

leptonic w. IceCube norm.
BL Lacs + FSRQ

lepto-hadronic w. γ-ray norm.
BL Lacs (w.o. external fields)

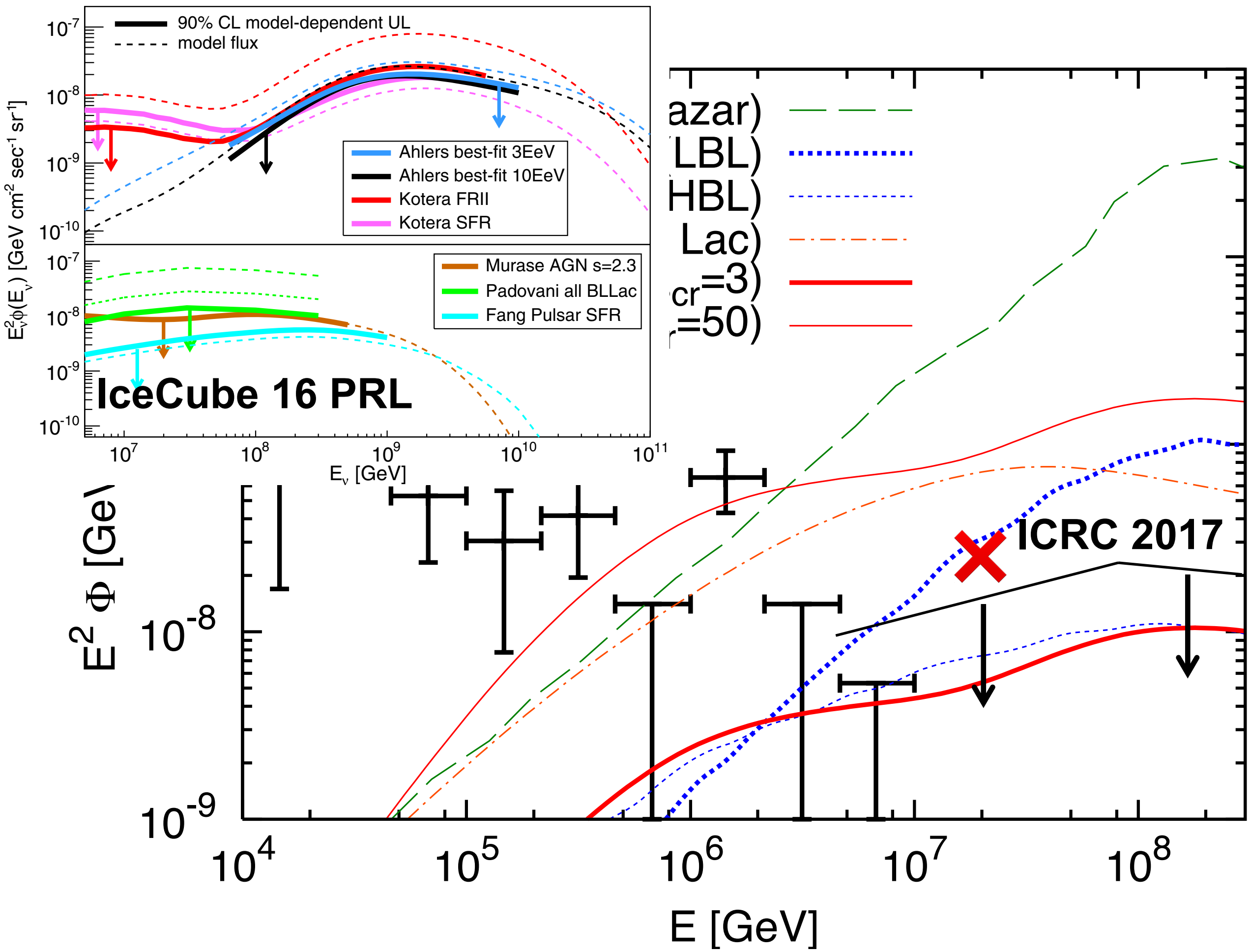
leptonic w. UHECR norm.
BL Lacs + FSRQ

Diffuse Neutrino Intensity from Blazars

Blazars: if UHECR accelerators → promising EeV neutrino emitters

IceCube 9-yr EHE analyses give a limit of <10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 10 PeV

many existing models have been constrained



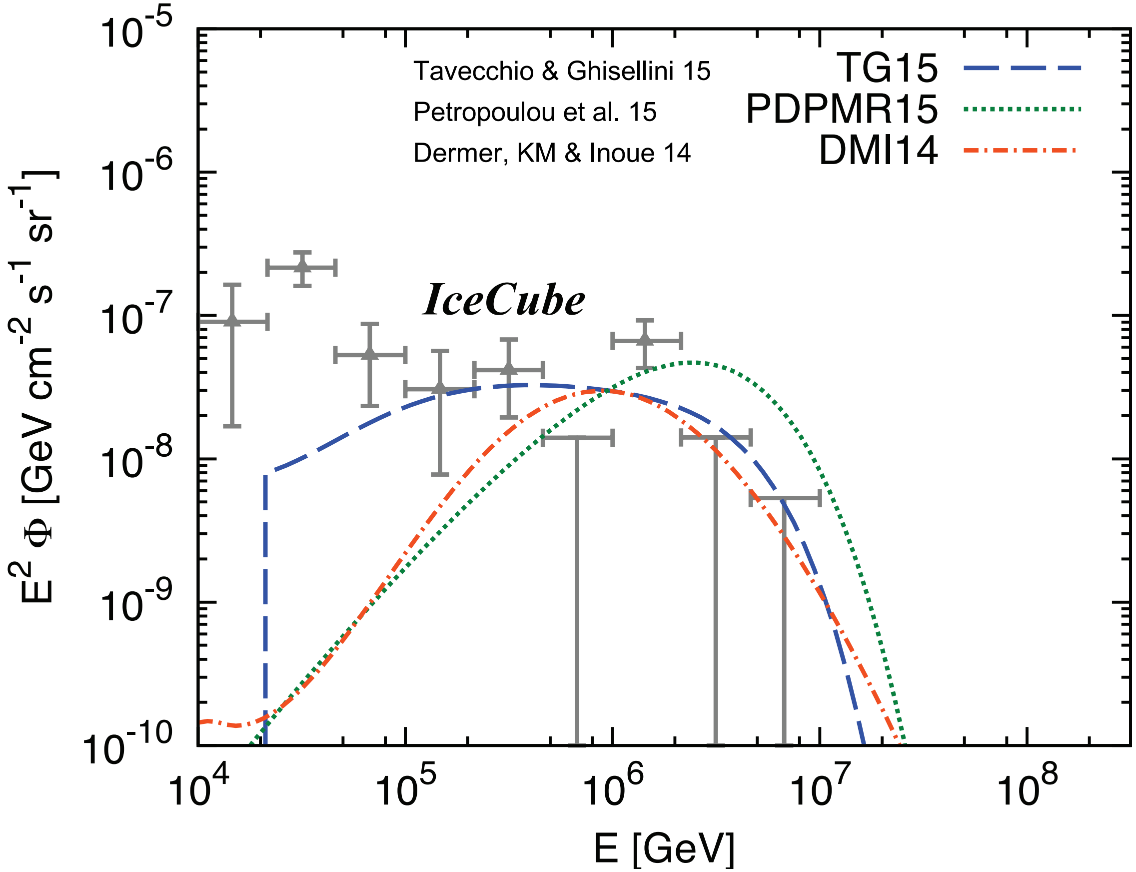
various diffuse ν predictions

leptonic w. IceCube norm.
BL Lacs + FSRQ

lepto-hadronic w. γ-ray norm.
BL Lacs (w.o. external fields)

leptonic w. UHECR norm.
BL Lacs + FSRQ

Can Blazars Explain the IceCube Data?



BL Lac – spine-sheath

BL Lac – one-zone

FSRQ – w. external field

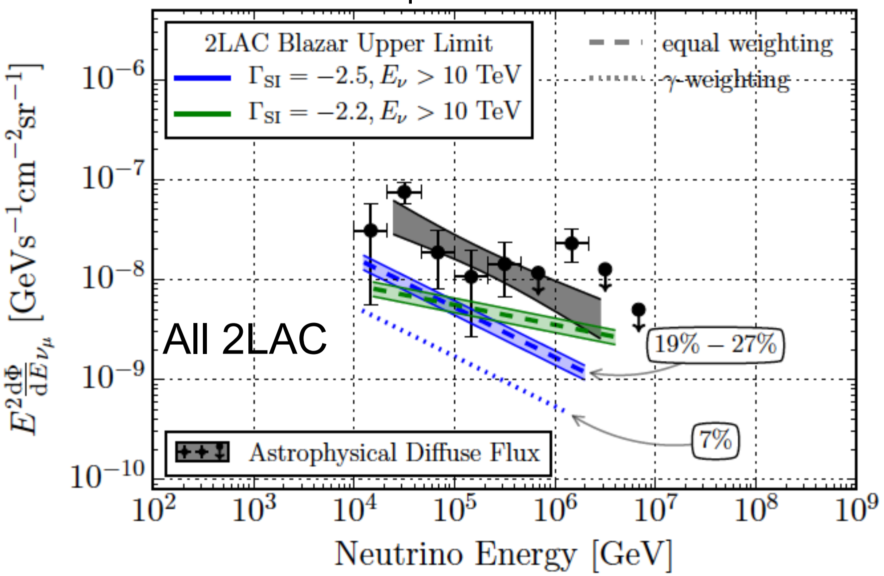
from KM & Waxman 16 PRD

<u>Challenging</u>

- Cutoff or steepening around a few PeV seems required (e.g., stochastic acceleration? Dermer, KM & Inoue 14)
- The models give up the simultaneous explanation of UHECRs

Statistical Constraints on Blazar Contribution

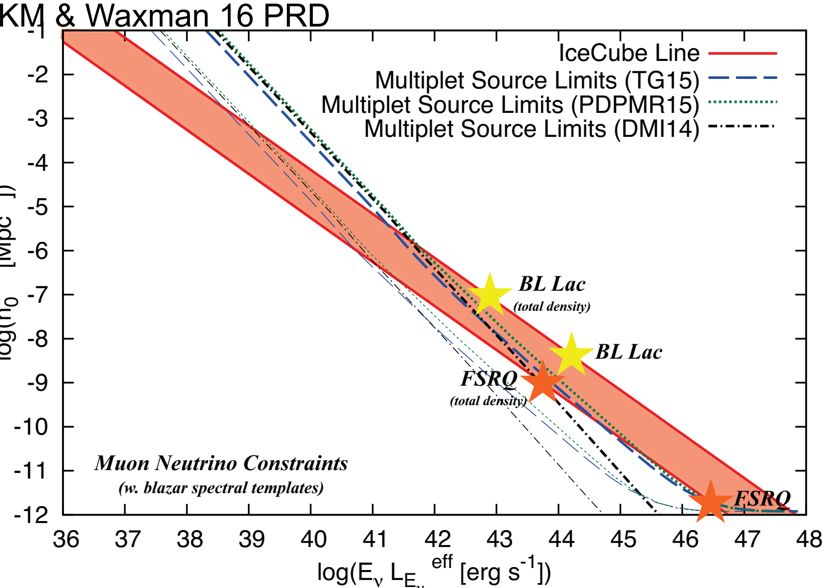
IceCube Collaboration 17 ApJ



γ-ray bright blazars are largely resolved
-> stacking/cross-correlation analyses

- 2LAC: **<7-27%** of the diffuse ν flux
  2FHL: **<4-6%** of the diffuse ν flux

KM & Waxman 16 PRD

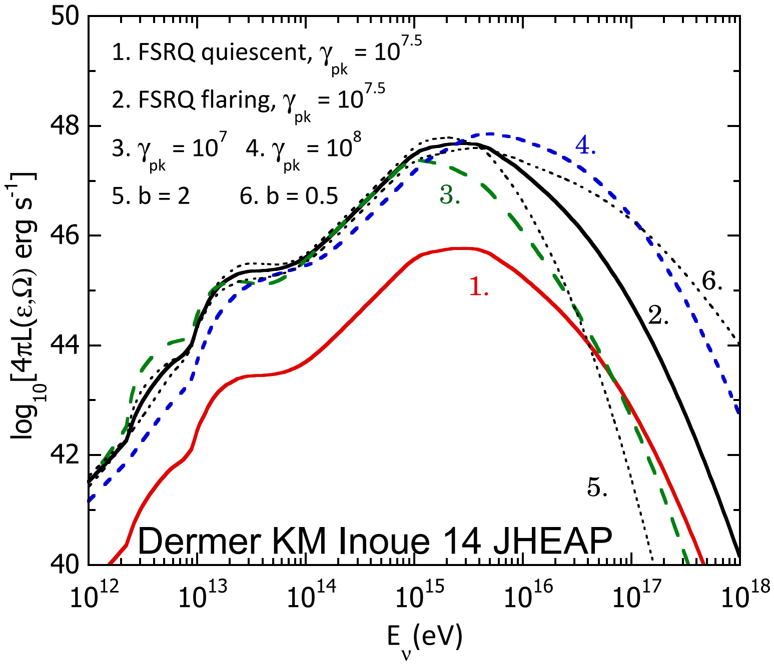


Blazars are rare objects in the universe
-> neutrino clustering/auto-correlation

- **< 10%** of the diffuse ν flux at 100 TeV
  (but can be more at higher energies)

Caution!: unavoidable model dependence

Transient Sources & Blazar Flares

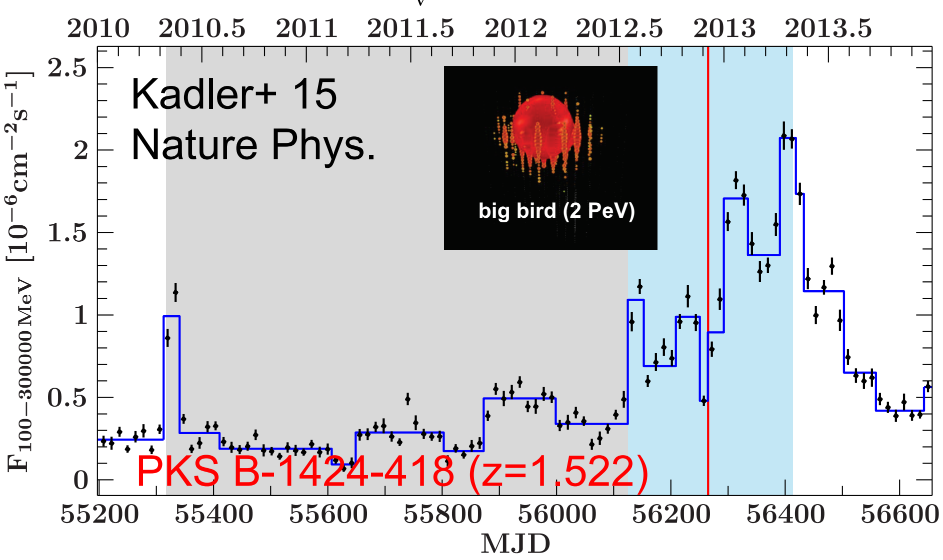


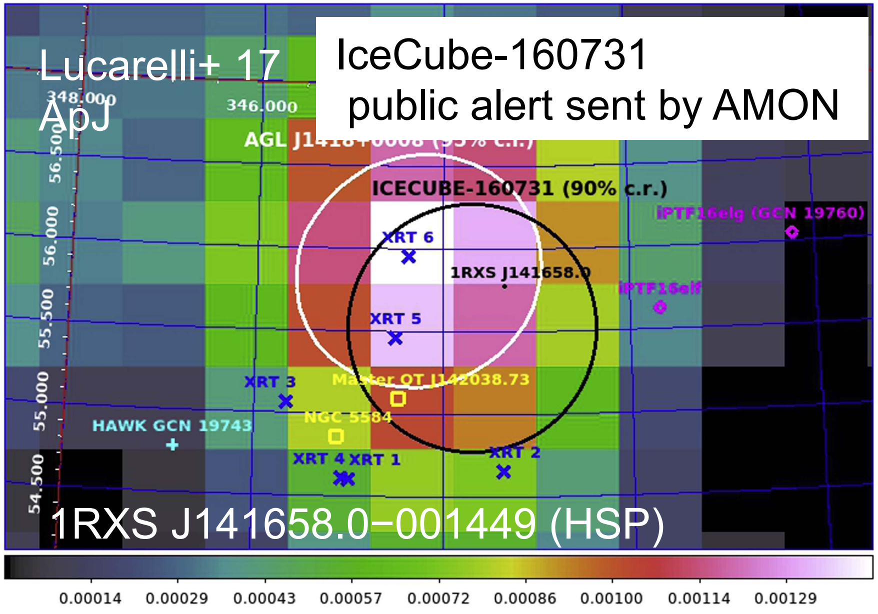
Good chances to detect them even if subdominant in the diffuse ν sky

(story is similar for GRBs!)

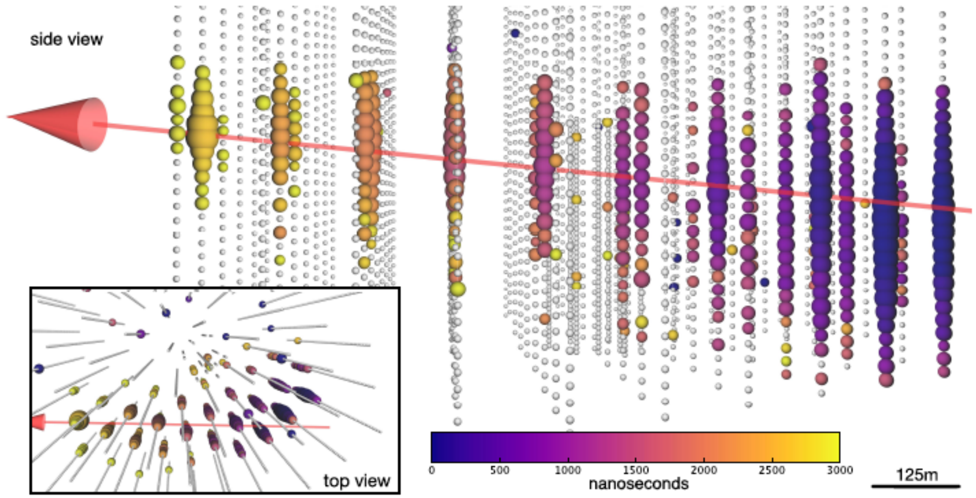
1. Observational reason:
   temporal & spatial coincidence
2. Theoretical reason
   "enhanced" jet power + target photons

(see e.g., KM & Waxman 16, KM et al.18)



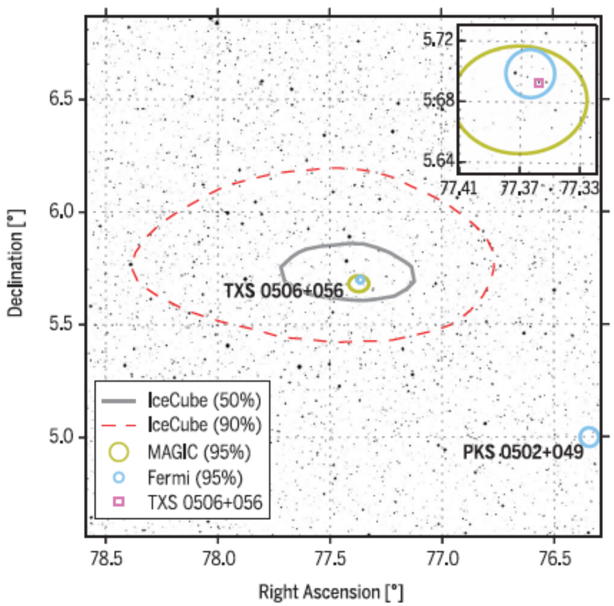


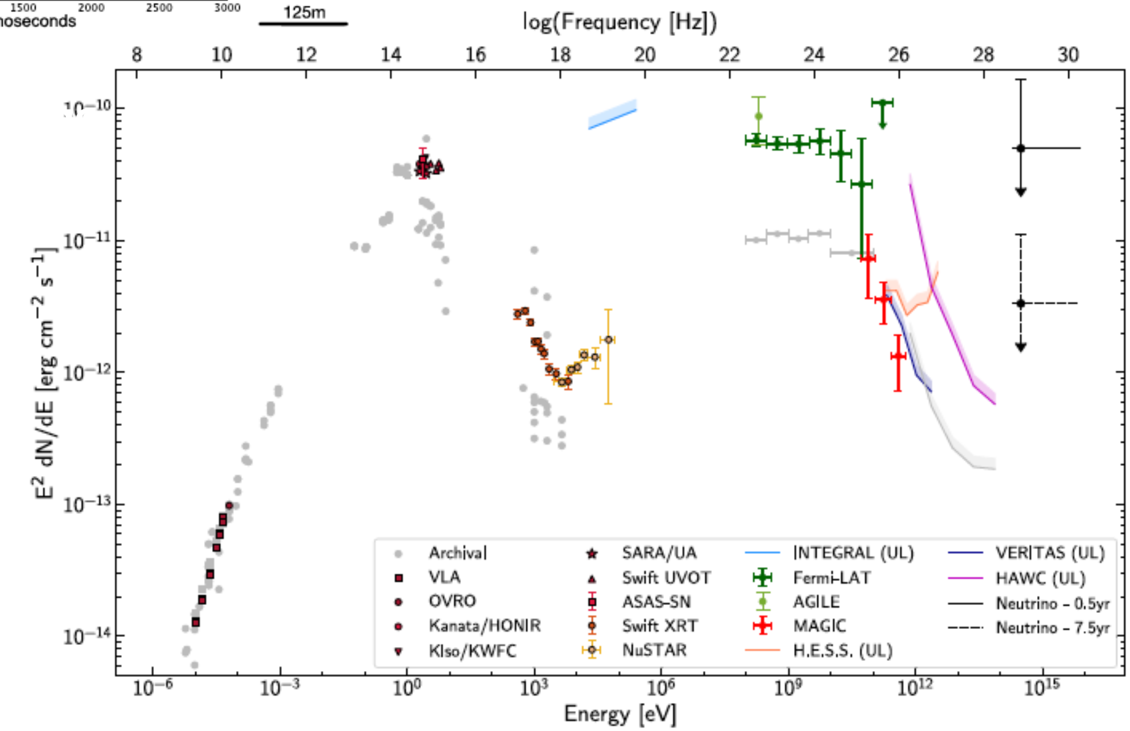
IceCube 170922A & TXS 0506+056



- IceCube EHE alert pipeline
- Automatic public alert (through AMON/GCN)
- Kanata observations of blazars -> Fermi-LAT (Tanaka et al.) ATel #10791 (Sep/28/17)

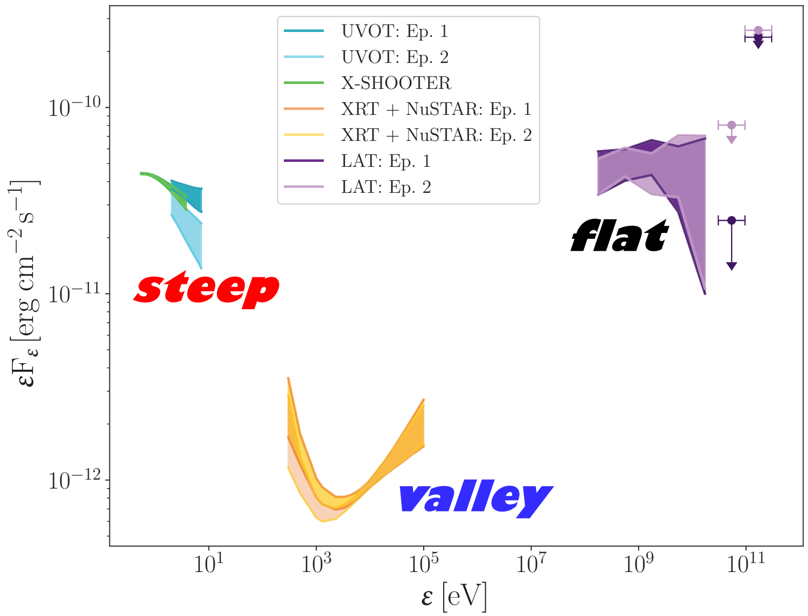
IceCube 2018 Science

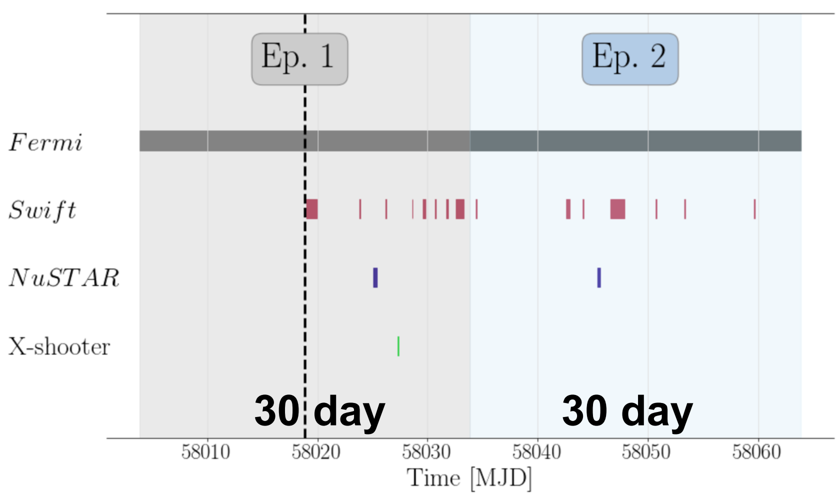




TXS 0506+056: Detailed Observations

Keivani, KM, Petropoulou, Fox et al. (for AMON) 2018 ApJ





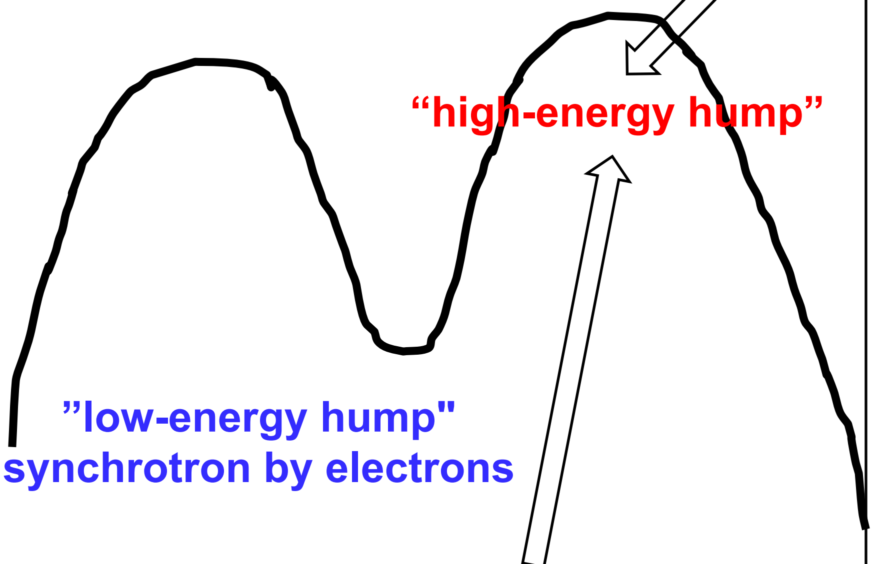
- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data

- UVOT/X-Shooter ν_{syn}<3x10^{14} Hz: ISP/LSP

- X-ray observations reported by members of AMON
- Swift (Keivani et al.) GCN #21930, ATel #10942 NuSTAR (Fox et al.) ATel #10861

Emission Mechanisms

spectral energy distribution (SED)



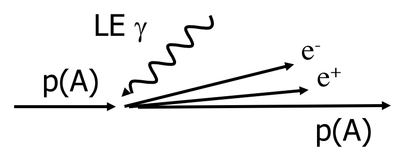
<u>Leptonic components</u>

1. synchrotron self-Compton
   (seed=synchrotron emission)
2. external inverse-Compton
   (seed=disk, broadline, dust…)

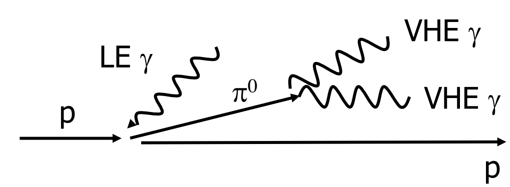
<u>Hadronic components</u>

1. synchrotron radiation from UHECRs
   $p+B \rightarrow p+\gamma$
2. **proton-induced cascades** (ν-related)
   $p+\gamma \rightarrow p/n, \pi \rightarrow p/n, \nu, \gamma, e$

Bethe-Heitler process



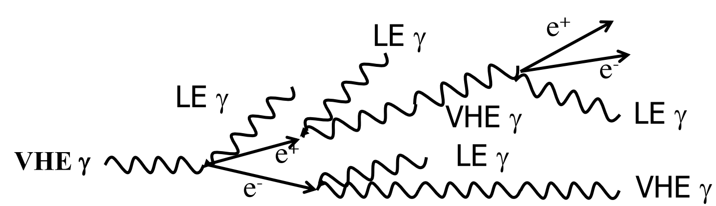
photomeson production



cascades $\gamma+\gamma \rightarrow e^+ + e^-$

$e+\gamma \rightarrow e+\gamma$ (IC)

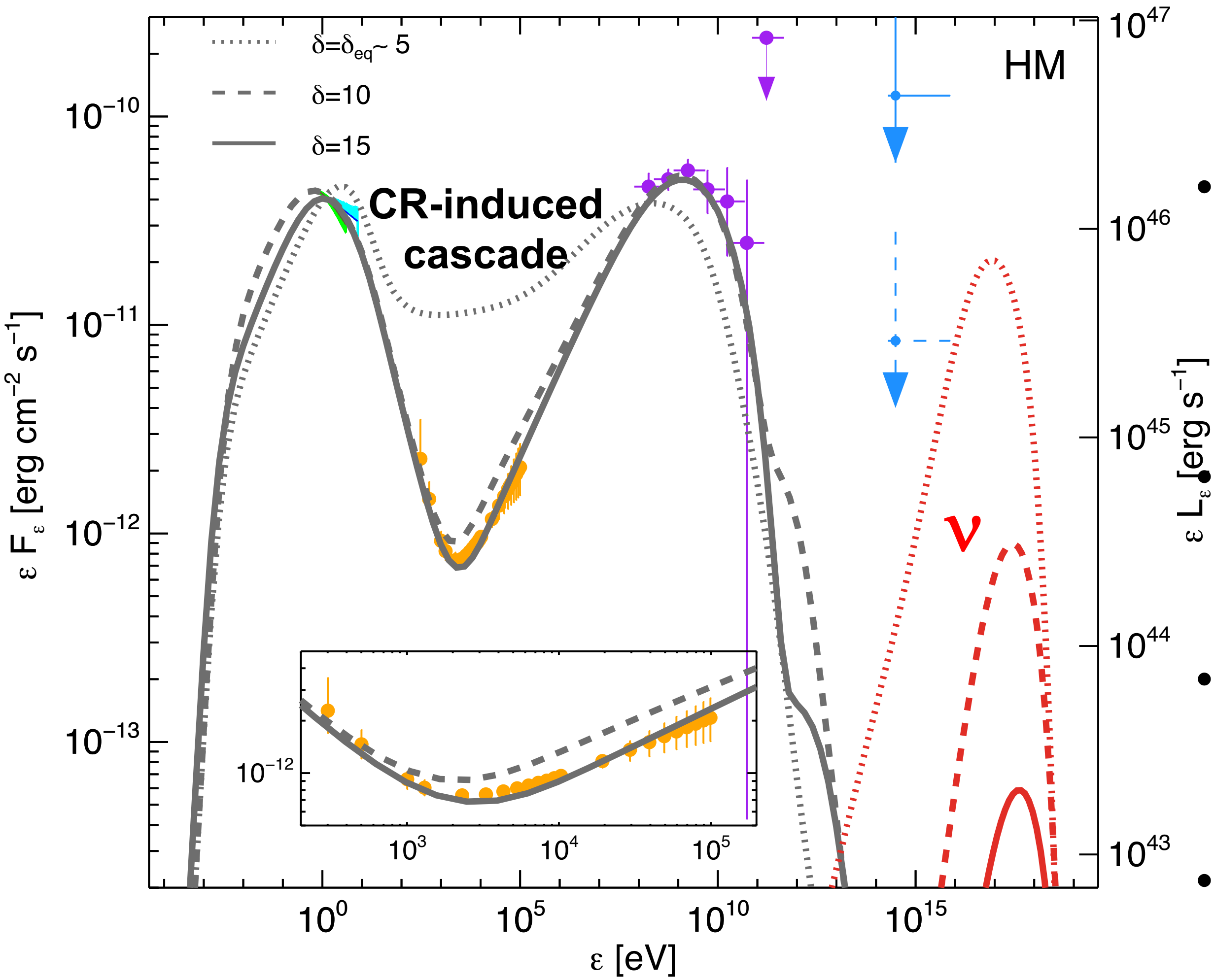
$e+B \rightarrow e+\gamma$ (syn)



“cascades”: unavoidable (energy conservation)
generically broad spectrum

TXS 0506+056 SED Modeling: Hadronic

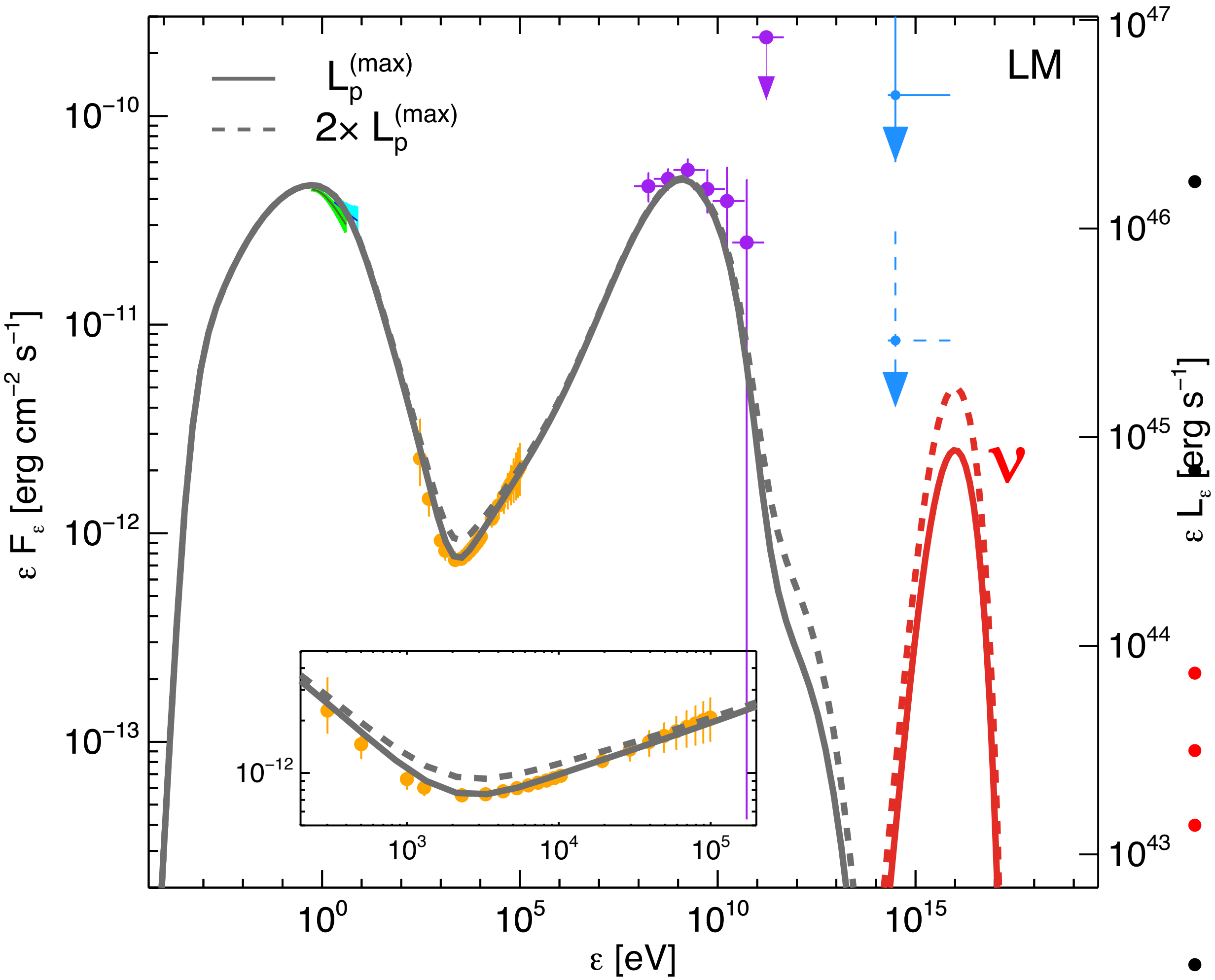
Keivani, KM, Petropoulou, Fox et al. (for AMON) 2018 ApJ



- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data
- UVOT/X-Shooter ν_{syn}<3x10^{14} Hz: ISP/LSP
- γ = π-induced cascade $F_\nu \sim F_\gamma$: ruled out
- γ = p-syn. from UHECRs very low F_ν at 0.1-1 PeV
- IC-170922A event CANNOT be explained by the hadronic scenario

TXS 0506+056 SED Modeling: Leptonic

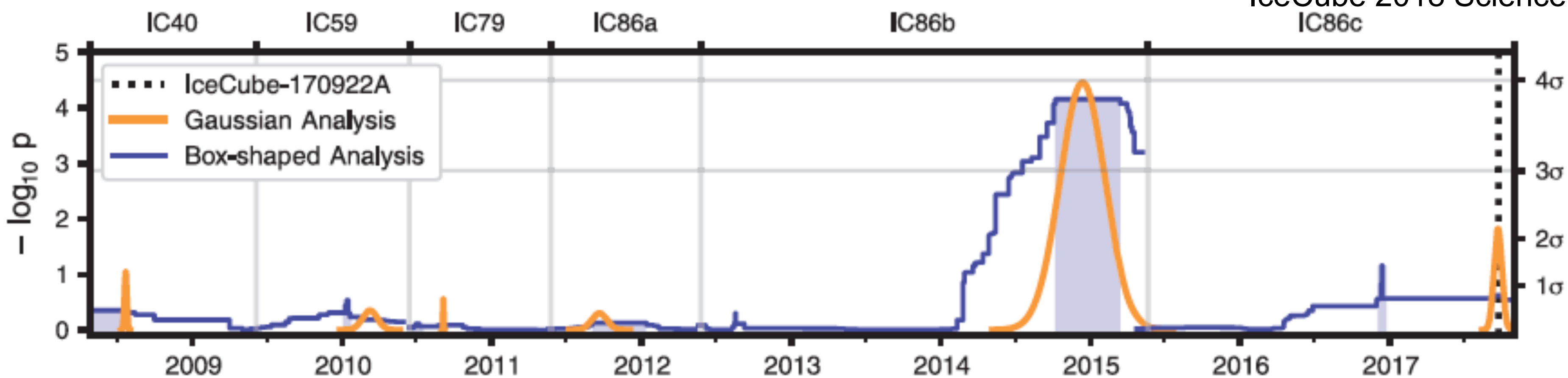
Keivani, KM, Petropoulou, Fox et al. (for AMON) 2018 ApJ



- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data
- UVOT/X-Shooter ν_{syn}<3x10^{14} Hz: ISP/LSP
- Leptonic scenario γ = external IC emission
- F_ν < (1-2)x10^{-12} erg/cm^2/s
- $\varepsilon_p/\varepsilon_e$ > 300
- E_{max} < 0.3 Z EeV
- N_ν~0.02/yr (real-time) N_ν~0.2/yr (point-source)

2014-2015 Neutrino Flare

IceCube 2018 Science



If association is physical $E_\nu L_{E\nu} \sim (3\text{-}10)\times 10^{46}$ erg/s

X-ray luminosity due to cascades by synchrotron from Bethe-Heitler pairs

$$\varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon^{\rm BH}_{\rm syn}} \approx \frac{4g[\beta]}{3(1+Y_{\rm IC})}\varepsilon_\nu L_{\varepsilon_\nu}$$

$$\varepsilon^{\rm BH}_{\rm syn} \simeq 6 \ {\rm keV} \ B'_{-0.5}(\varepsilon_p/6\ {\rm PeV})^2(20/\delta)$$

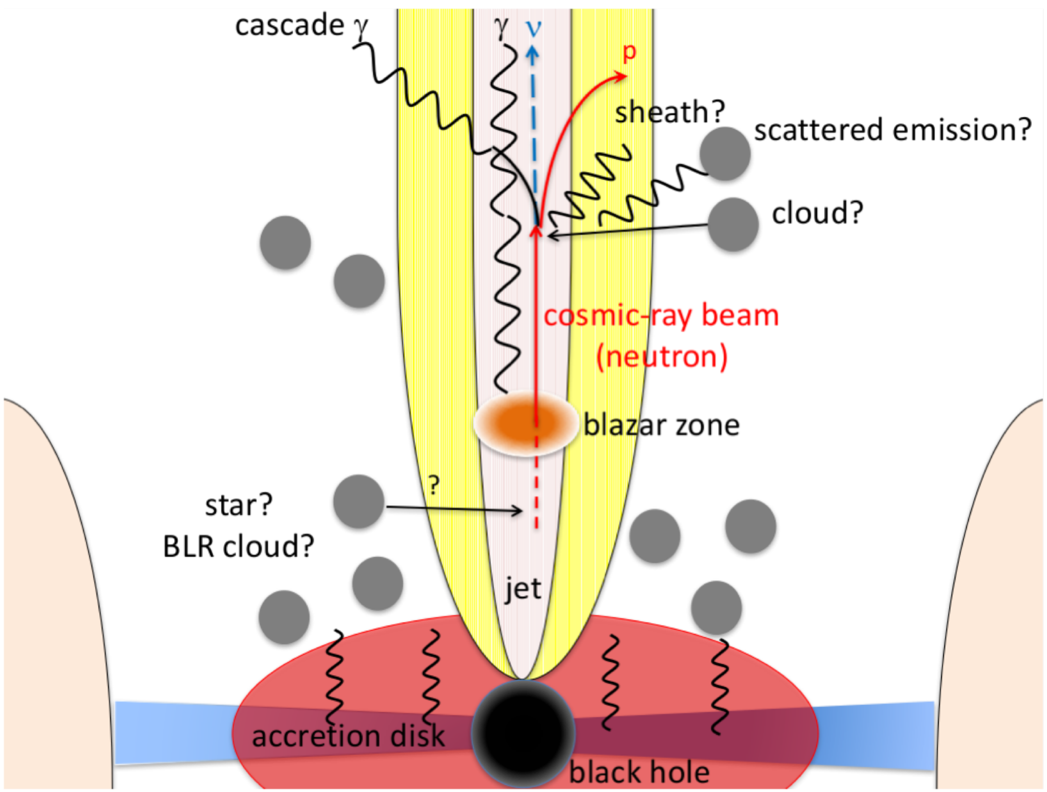
Single-zone models predict $F_x \sim 10^{-10}$ erg/cm^2/s that violates the Swift-BAT limit

(KM, Oikinomou & Petropoulou 18 ApJ)

TXS 0506+056: Implications

No convincing picture (especially with the 2014-2015 ν flare)

Single-zone models (either pγ or pp models)
- Suggesting the leptonic γ–ray origin & disfavoring UHECR acceleration
- Real-time detection was lucky (lower-energy ν were not detected)
- Challenging energetics (P_{cr}>>L_{Edd}), dark accelerator (L_p>>300 L_e)



cascades are crucial

How to avoid X-ray limits?
1. Anisotropic cascades
   (isotropization & time delay)
2. Avoiding Bethe-Heitler by neutrons
3. Compton scattering of X rays
   (requiring N_H>10^{25} cm^{-2})

Neutron beam model?
OR…

(KM, Oikinomou & Petropoulou 18 ApJ)

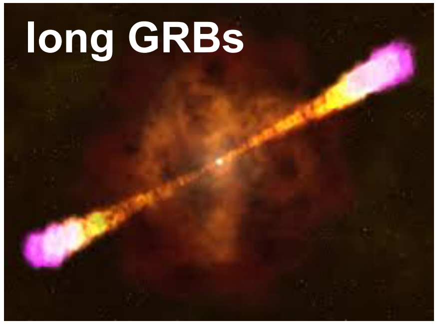
Other Neutrino Transients?

If TXS story is true we should see more blazar flares (up to 1 events/yr)

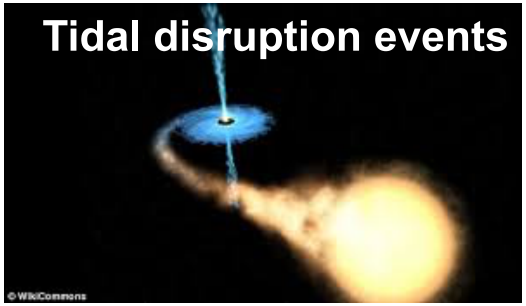
Remember: UHECR accelerators have to be powerful

$$L_B \equiv \epsilon_B L \gtrsim 2 \times 10^{45} \frac{\Gamma^2 {E_{20}}^2}{Z^2 \beta} \text{ erg s}^{-1}$$

PeV-EeV ν



TeV-PeV ν (prompt)
EeV ν (afterglow)



PeV-EeV ν

TeV-EeV ν

TeV-EeV ν

- Gen2/KM3Net: ν alerts w. ~0.1 deg, AMON: ν–γ, ν-GW alerts
- UV/X-ray/MeV γ-ray monitoring is ***critically important!!!***

Summary

Multi-messenger approaches are now critical for *"ν" questions*

Origin of the diffuse neutrino intensity?

γ-ray flux ~ ν flux ~ CR flux

pp scenarios: s<2.1-2.2 & significant contribution to Fermi γ-ray bkg.
cosmic particle unification is possible
10-100 TeV data are NOT explained by CR reservoirs
pγ scenarios: 10-100 TeV data suggest hidden CR accelerators

Brightest neutrino sources including neutrino "transients"?

TXS 0506+056: encouraging, successful example of ν-triggered campaigns
cascade bounds: **X-ray flux ~ ν flux**

No convincing picture: luck? multi-zone (ex. n-beam) models?, need more..

Future?

diffuse ν origin: likely to be common sources, need for Gen2/KM3Net
ν transients: big potential due to time/space-coincidence, need more efforts…

Backup Slides

Astrophysical Extragalactic Scenarios

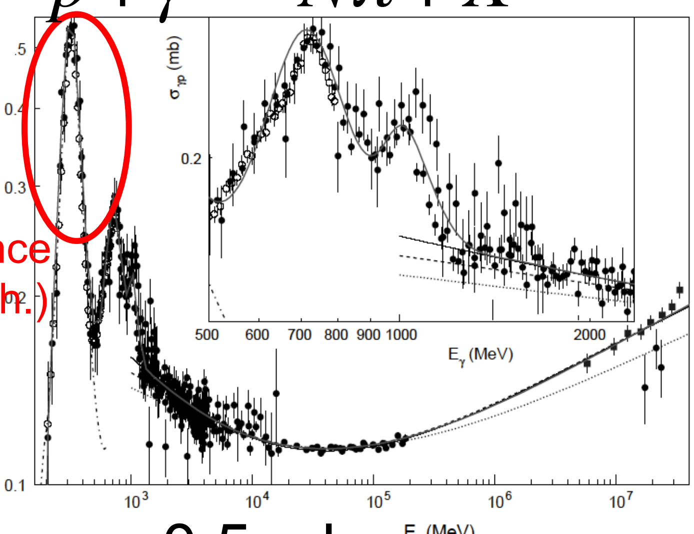
$E_\nu \sim 0.04\ E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)

Active galactic nuclei

γ-ray burst

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

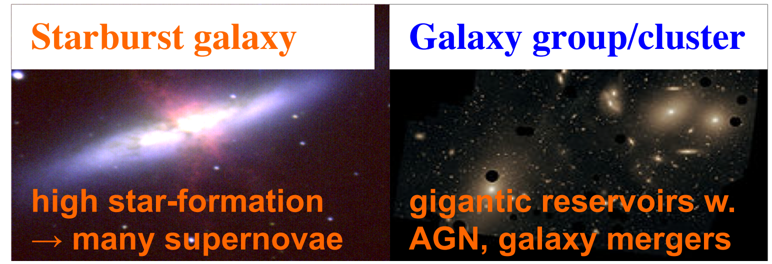


Δ-resonance
(+ direct ch.)

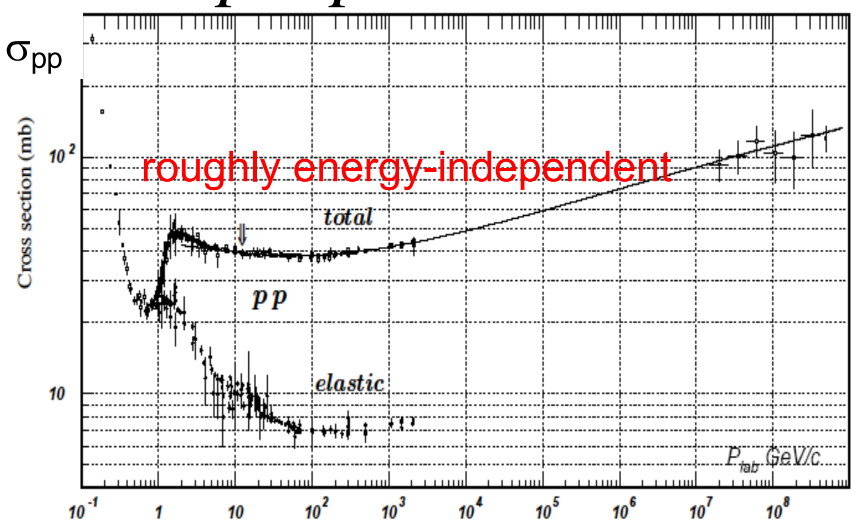
$\sigma_{p\gamma} \sim \alpha \sigma_{pp} \sim 0.5$ mb

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

Cosmic-ray Reservoirs

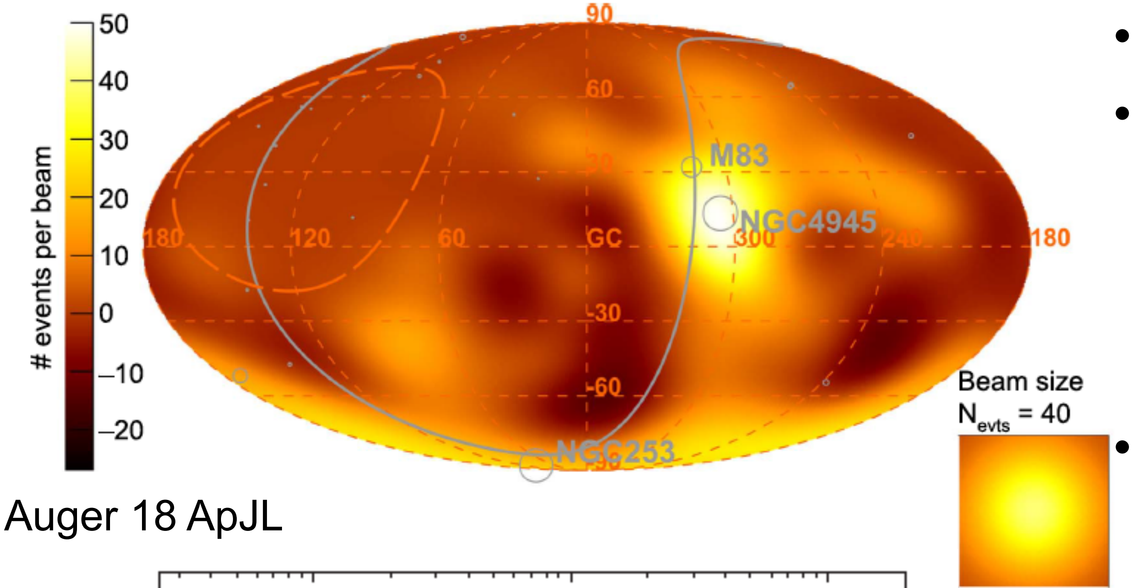


$$p + p \rightarrow N\pi + X$$

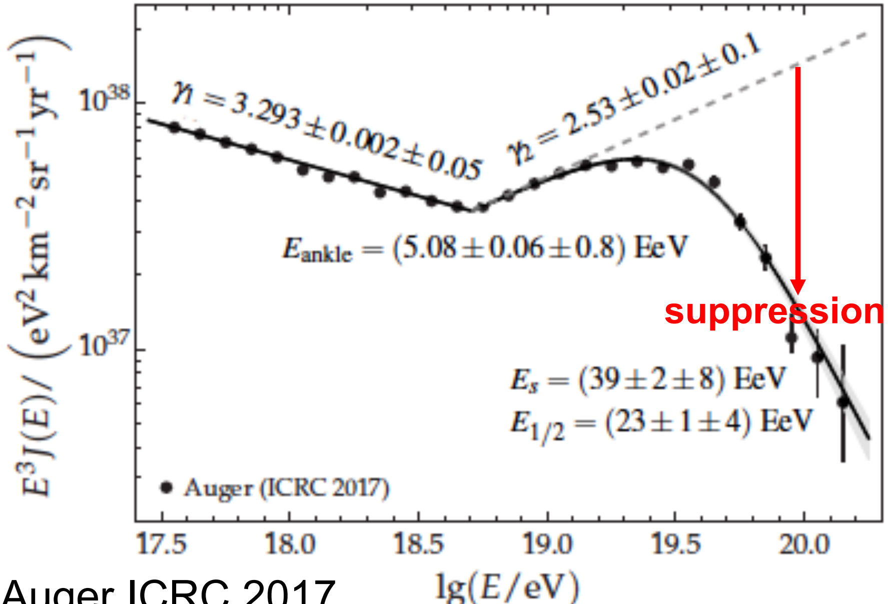


$\sigma_{pp} \sim 30$ mb

UHECR Sky: Unknown (but Hint?)



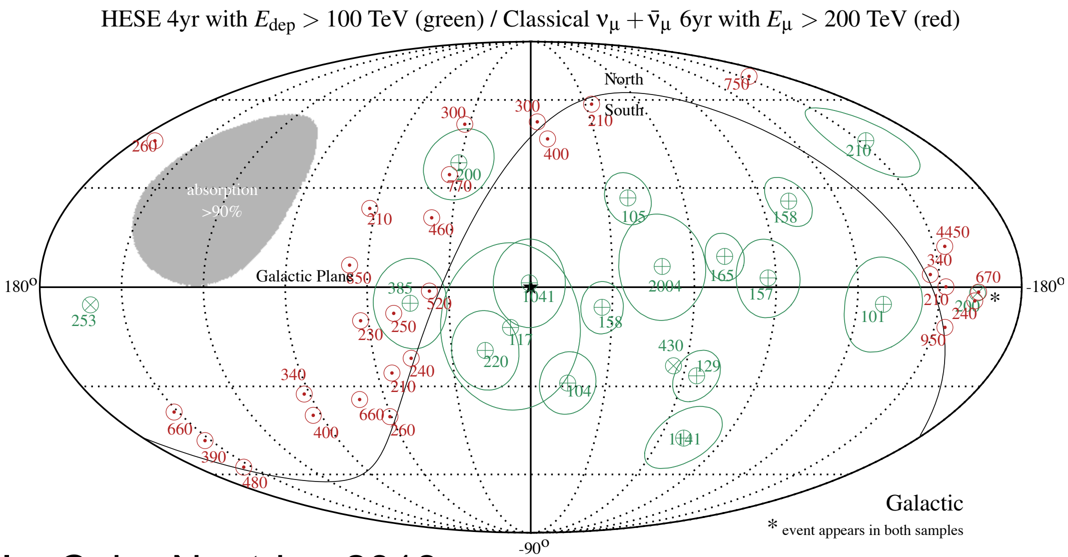
Auger 18 ApJL



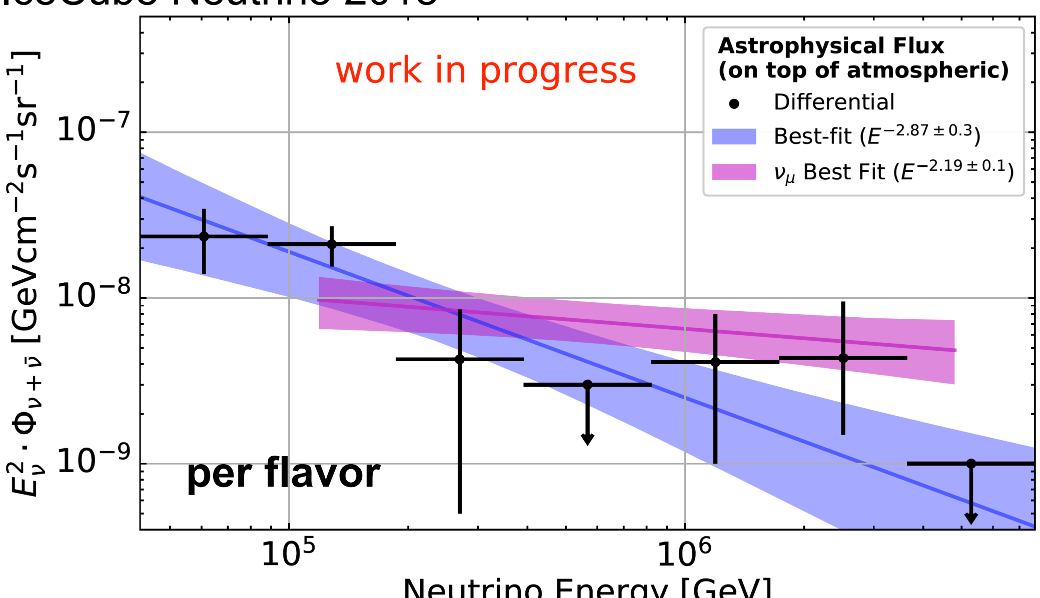
Auger ICRC 2017

- No established source yet
- Tentative correlation?
  starbursts: ~4σ
  AGN: ~3σ
  TA hotspot: ~3σ
- Dipole anisotropy established
  -> supporting extragalactic
  (Auger 17 Science)
- Spectrum:
  suppression at ~40 EeV can be explained by interactions with CMB during the propagation OR maximum energy at the sources
- Composition:
  heavier nuclei beyond the ankle?

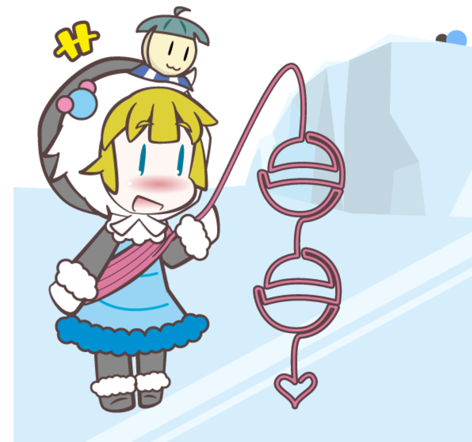
High-Energy Neutrino Sky: Unknown



IceCube Neutrino 2018

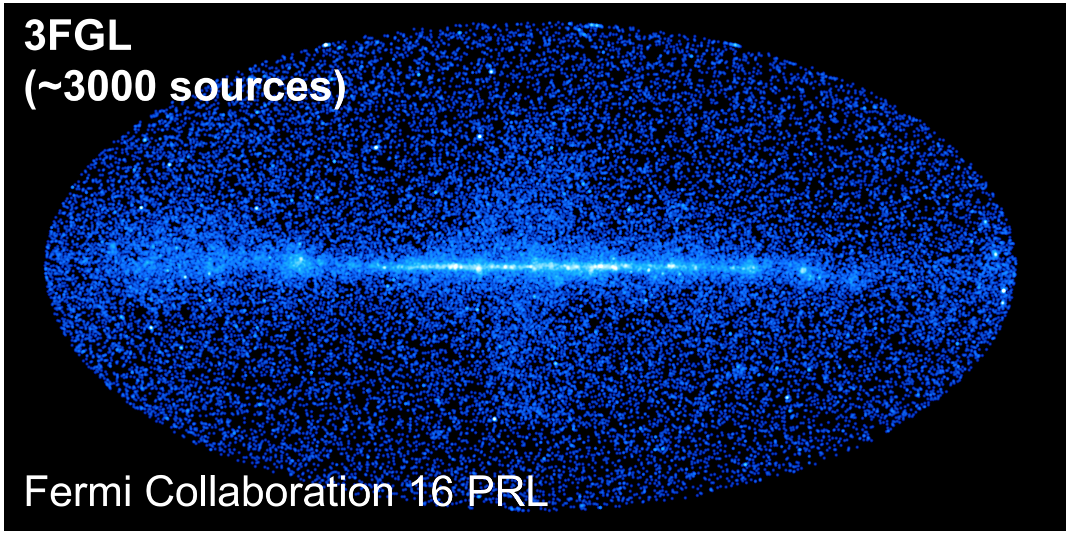


No established source yet (except fishy event)

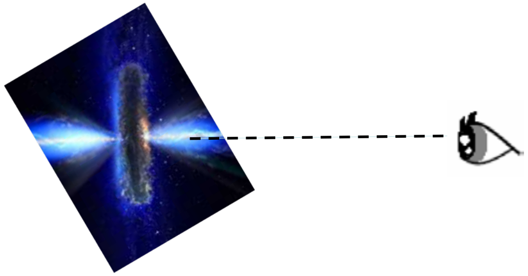


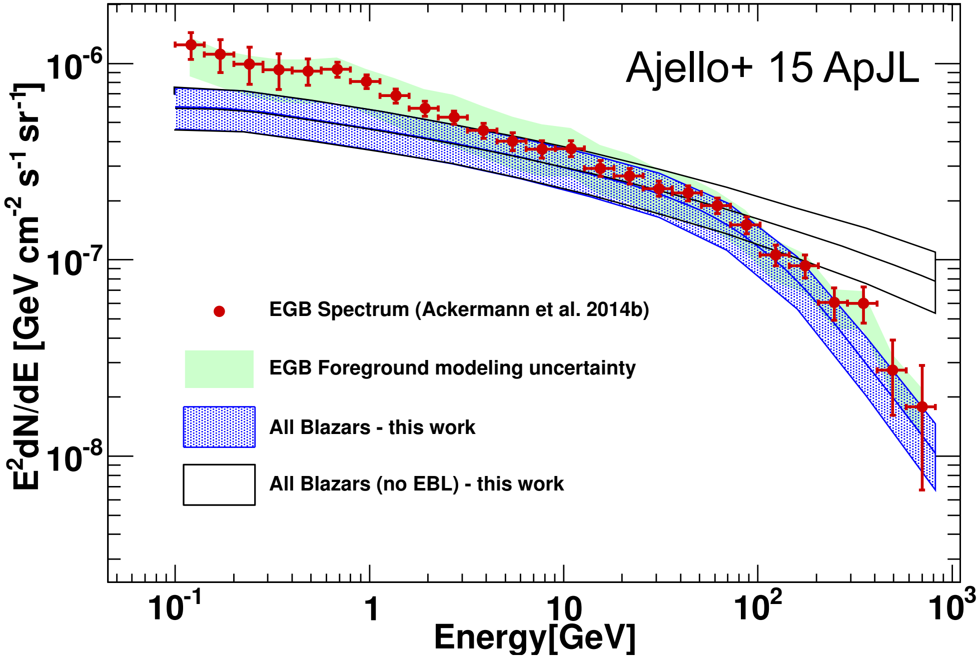
- 7.5 year HE starting events
  103 events
  (60 events > 60 TeV)
  best-fit: s=2.87±0.3
- 8-yr upgoing ν_μ “track”
  36 events at >200 TeV (6.7σ)
  best-fit: s=2.19±0.10

Extragalactic Gamma-Ray Sky: Dominated by Blazars



48 months of observations :
3LAC: 1563 sources
1444 AGNs in the clean sample
most of them are blazars





Blazar (point-source) contribution to extragalactic γ-ray background (EGB)

86%+16%-14% (Fermi 16 PRL)

68%+9%-8% (Lisanti+ 16 ApJ)

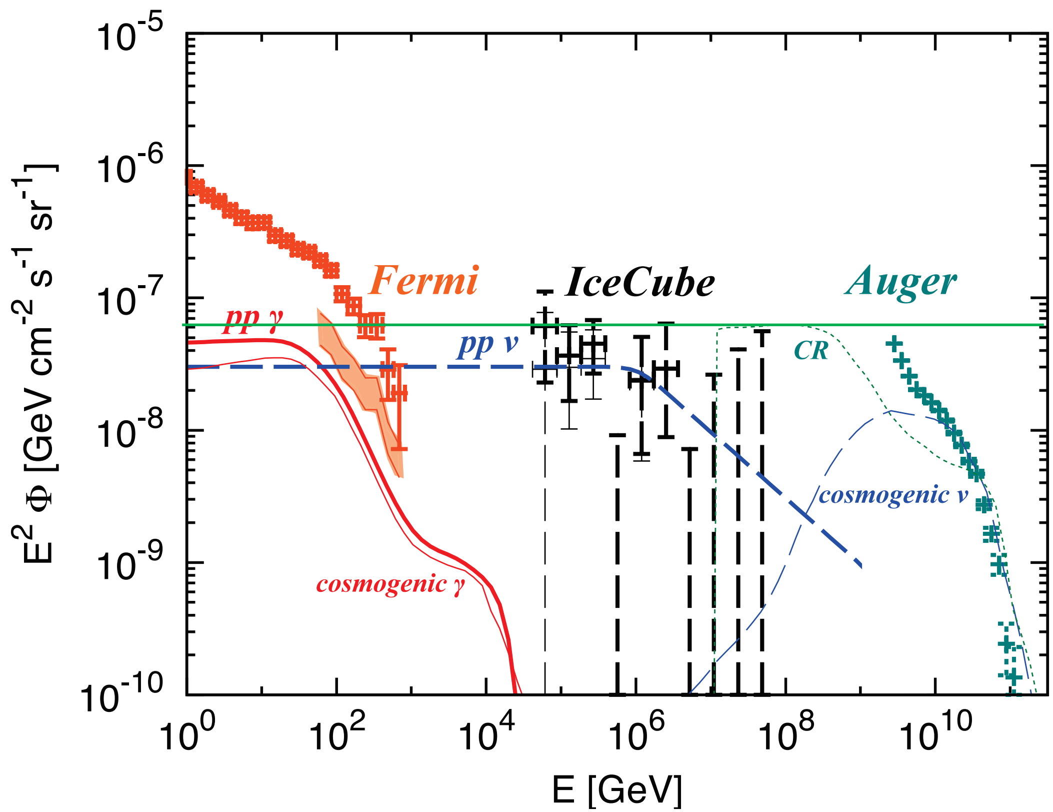
~15-30% of the EGB at > 50 GeV may come from something else (and more rooms at lower energies)

Neutrino-Gamma-UHECR Connection?

(grand-)unification of neutrinos, gamma rays & UHECRs

simple flat energy spectrum w. s~2 can fit all diffuse fluxes

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



KM & Waxman 16 PRD

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

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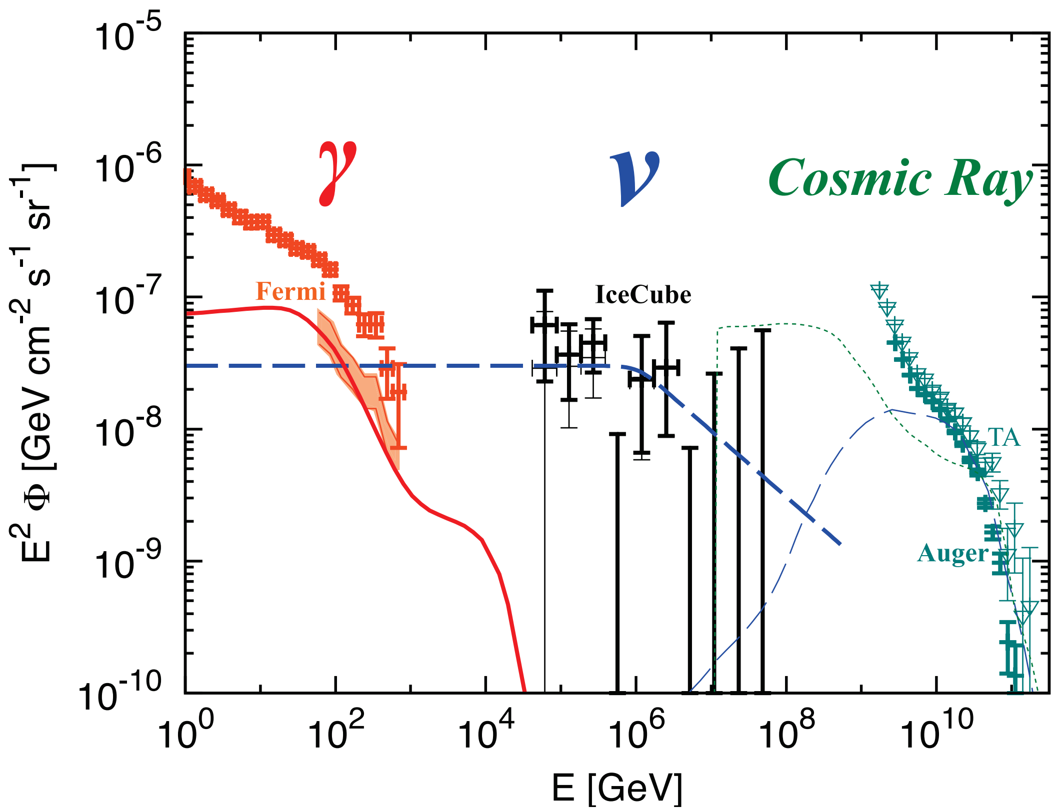
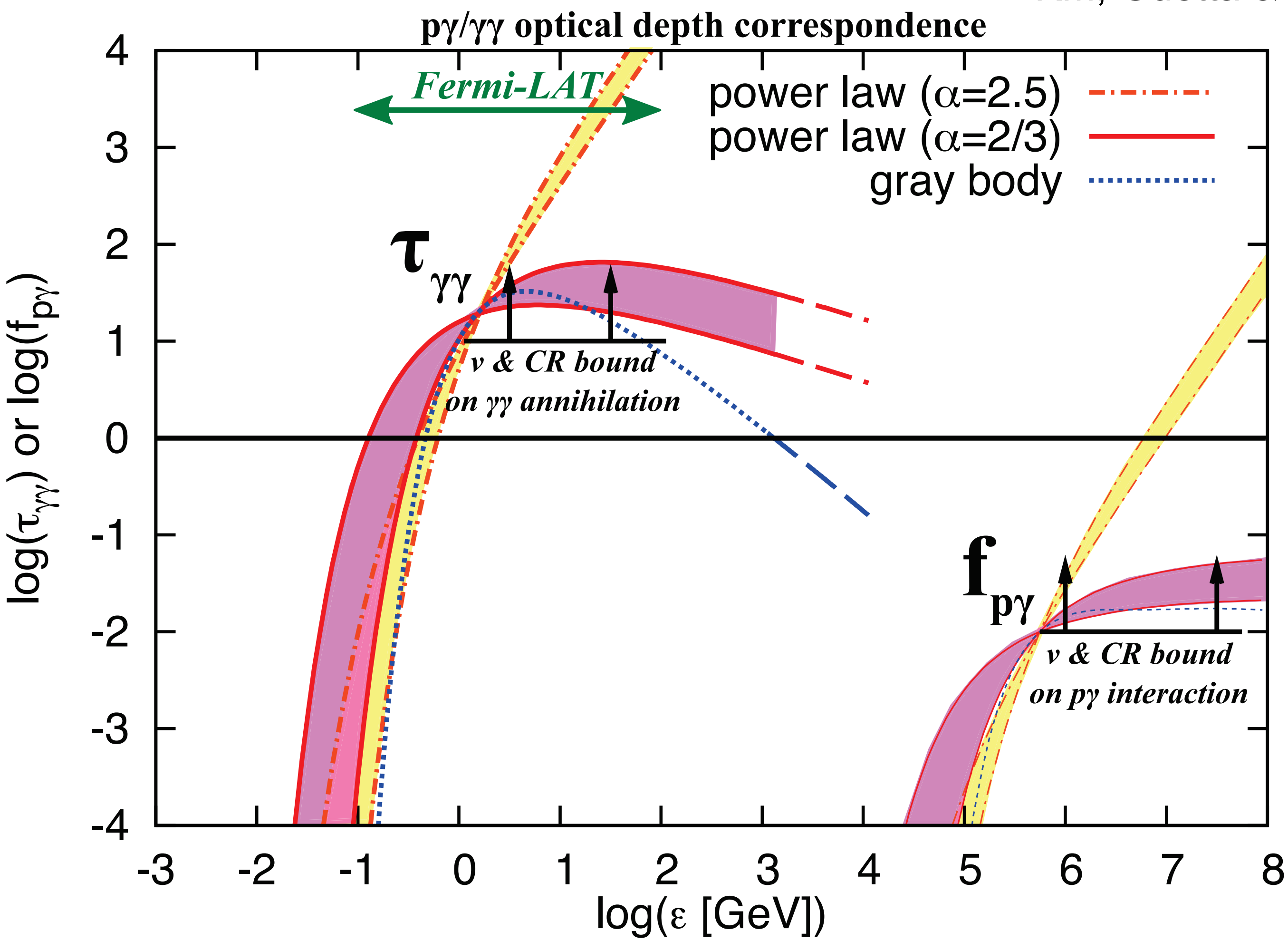


KM & Waxman 16 PRD

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

Indication of Gamma-Ray Dark Cosmic-Ray Accelerators

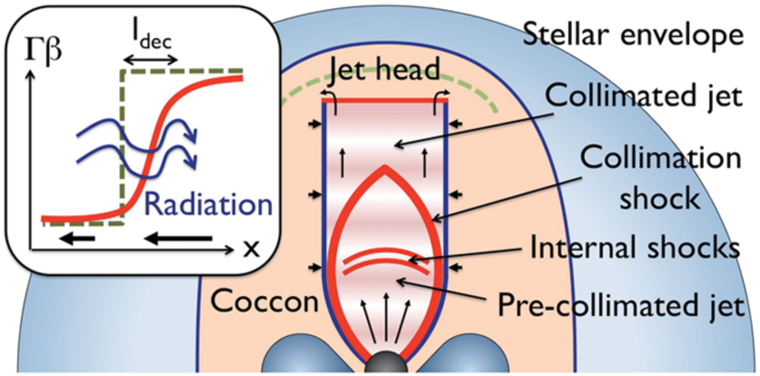
KM, Guetta & Ahlers 16 PRL



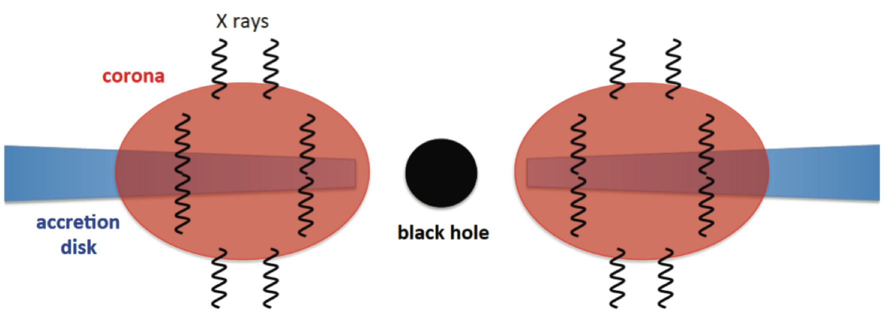
- $\gamma\gamma \rightarrow e^+e^-$ inside the sources: unavoidable in $p\gamma$ sources
- ν sources naturally become obscured in GeV-TeV γ rays

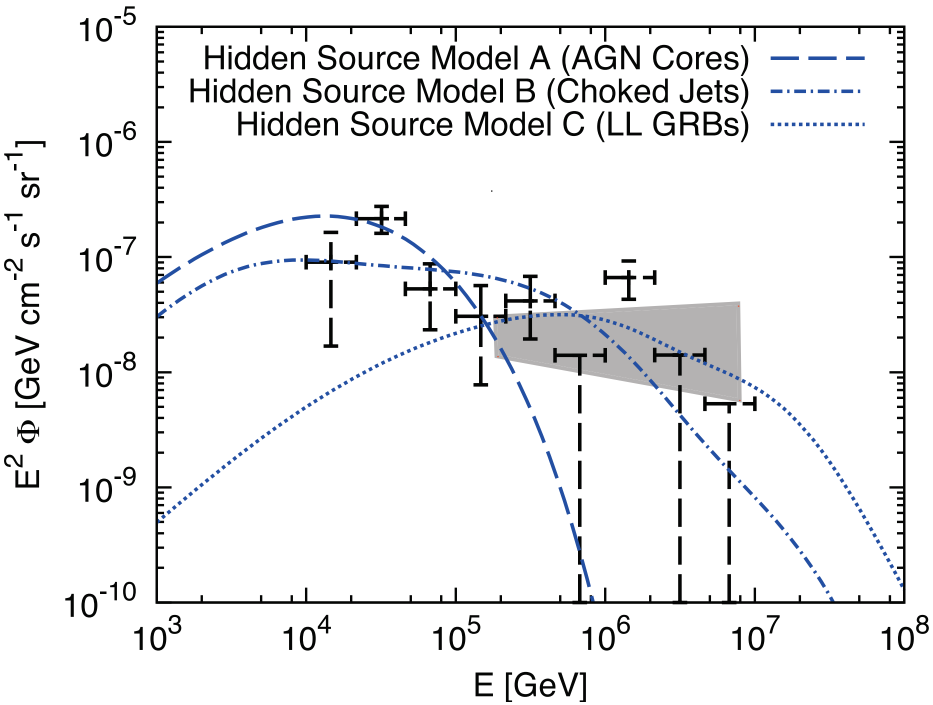
GRBs and AGN as Hidden Neutrino Factories?

Low-power GRBs (choked jets)



Supermassive blackhole cores





KM & Ioka 13 PRL
Senno, KM & Meszaros 16

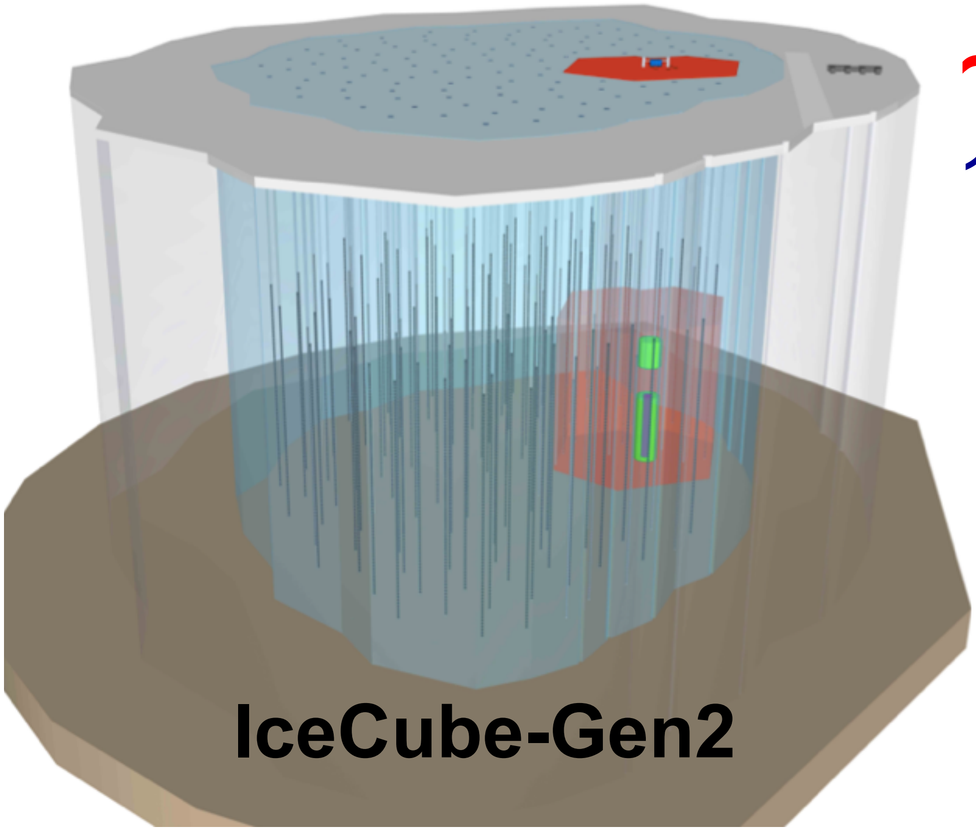
cf. KM+ 06 ApJL

see also:
Bhattacharya+ 15
Nakar 15

Kimura, KM & Toma 15 ApJ

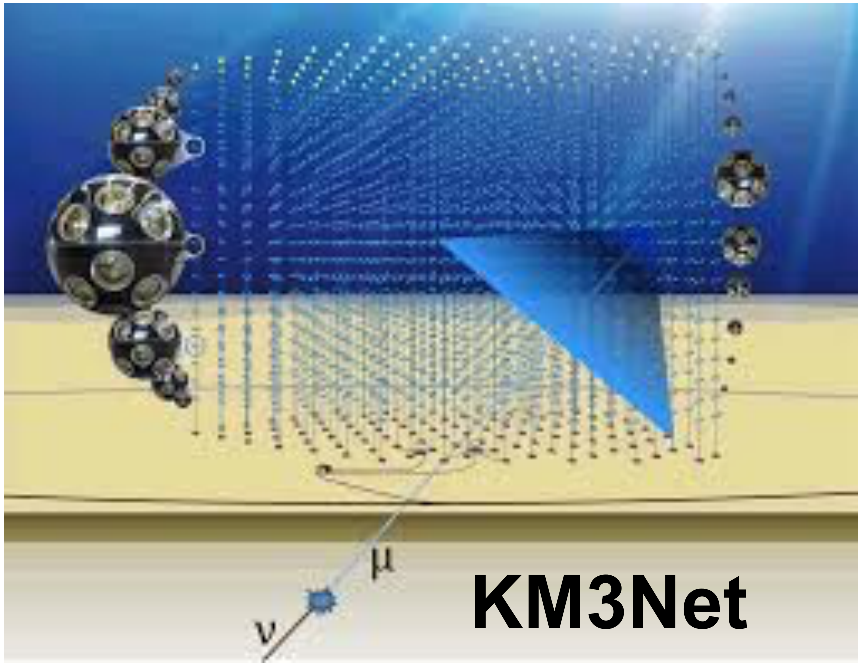
see also:
Stecker 13
Kalashev+ 15

Future Detectors



~10 km^3

120m→240m spacing

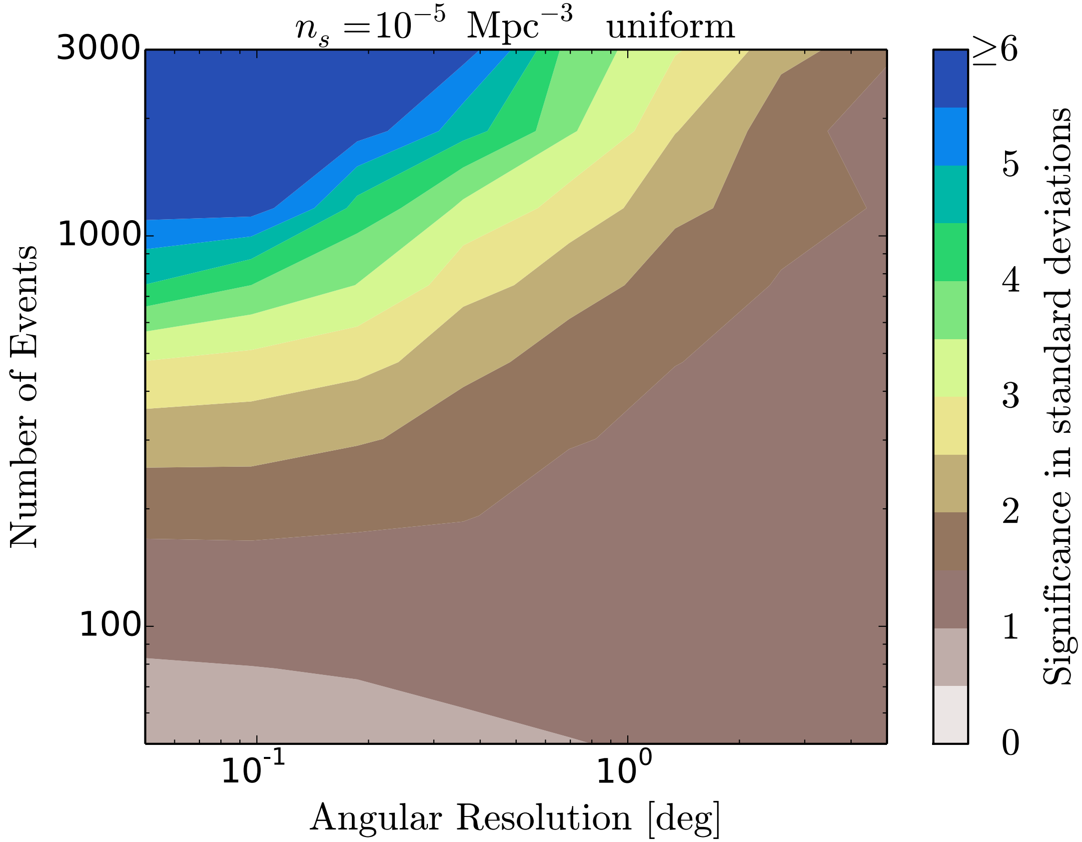


~1 km^3

better angular resolution

Multiplet Searches

Fang, Kotera, Miller, KM & Oikonomou 16 JCAP

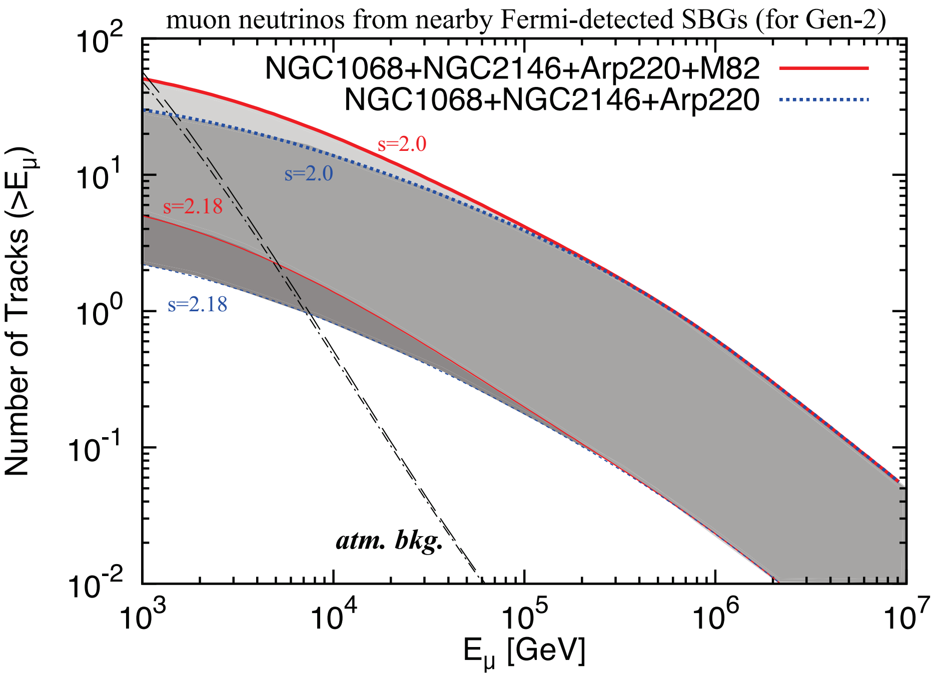


- N~100-1000 events are needed for 5σ discovery
- Angular resolution is important (confusion limit)
- Agree well w. analytical estimates by KM & Waxman 16

What's Next?: Need to Identify the Sources

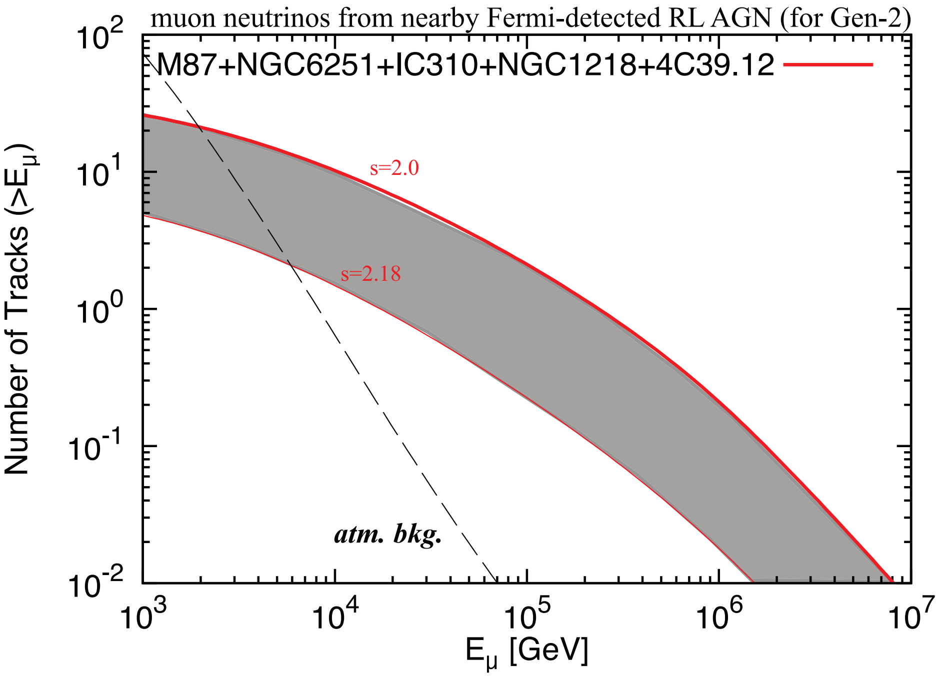
Starbursts and radio galaxies are already detected by Fermi w. γ rays
For pp scenarios, s<2.2 leads to strong predictions for Gen2/KM3Net

nearby starburst galaxies in the northern hemisphere



※M82 is not a representative SBG

nearby radio galaxies in the northern hemisphere

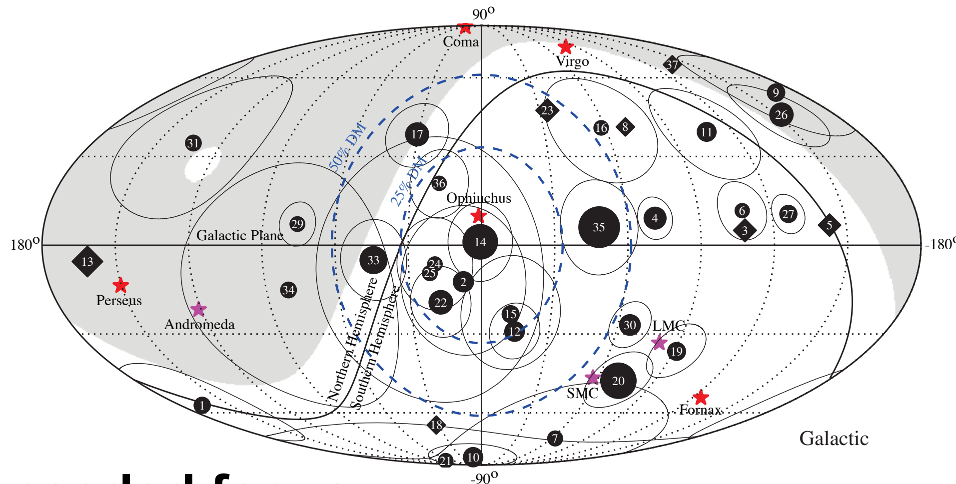


※variable AGN such as NGC 1275 are removed

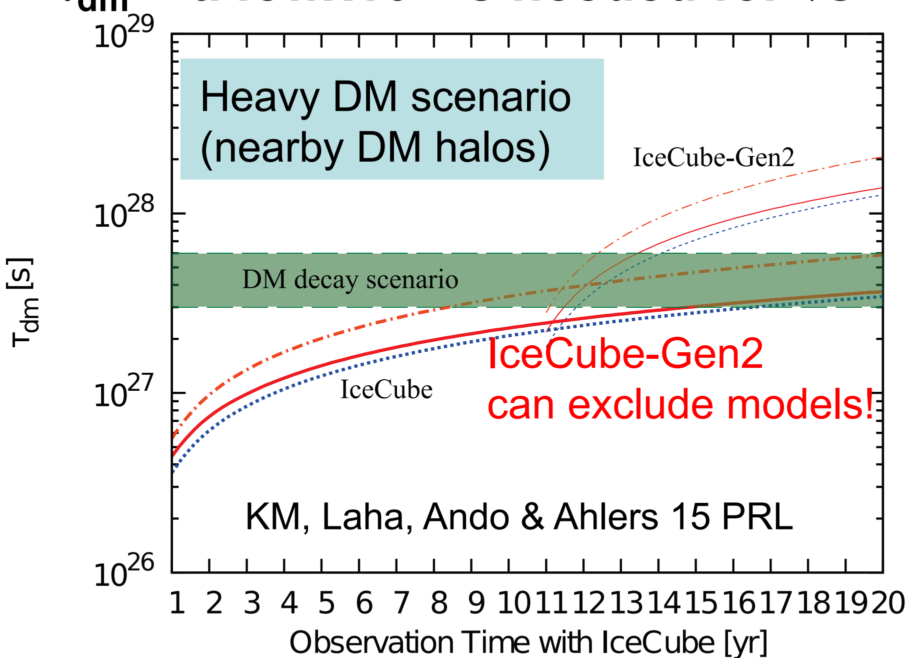
V=10 km^3 & best ang. res.=0.1 deg & 5 yr obs. assumed

KM & Waxman 16 PRD

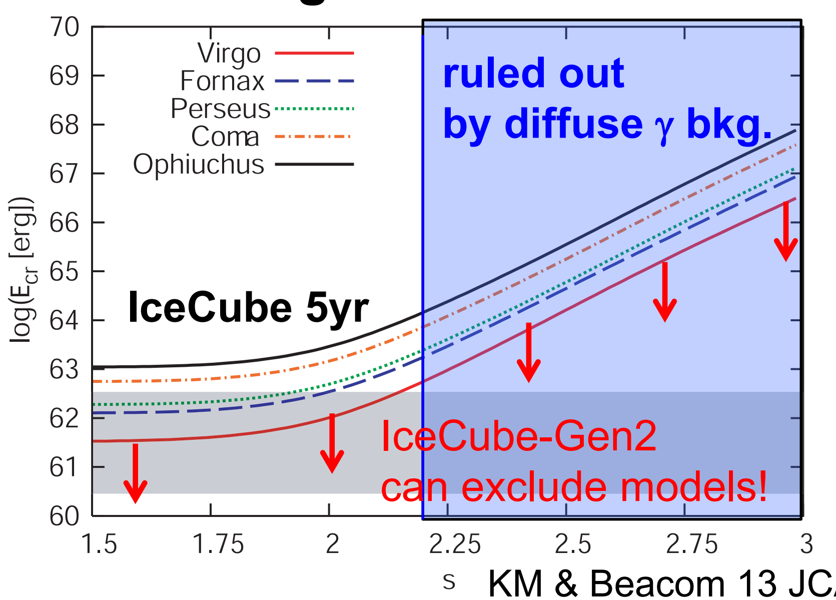
How about Galaxy Clusters?



τ_{dm} ~ a fewx10^{27} s needed for νs



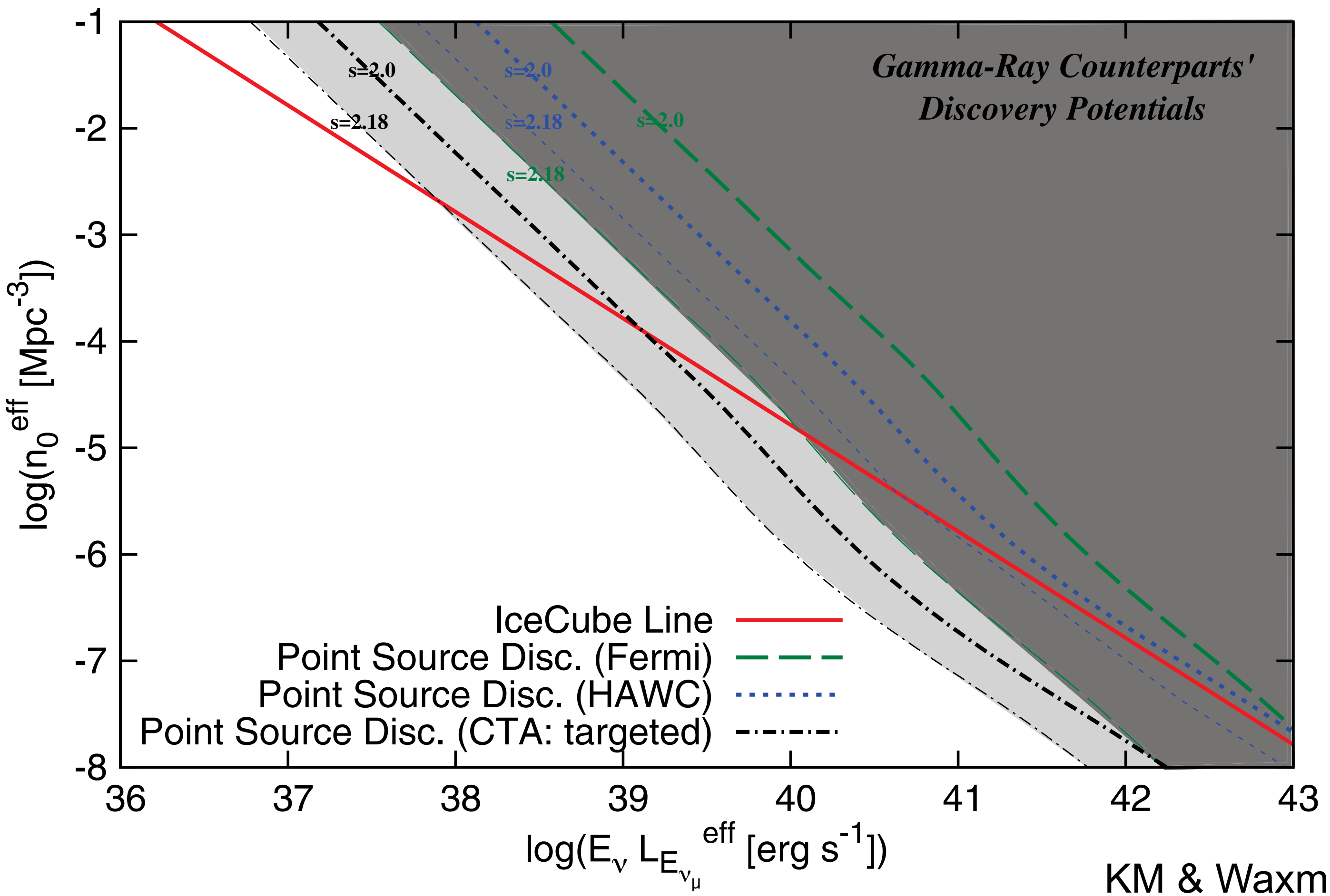
~10^{60}-10^{62} erg needed for CRs or νs



KM & Beacom 13 JCAP

Relevance of γ rays for Testing CR Reservoir Models

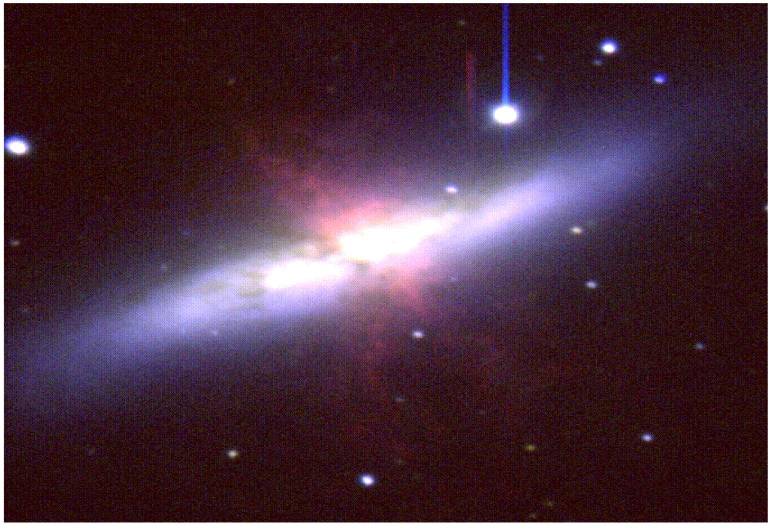
- Fermi results → γ-ray spectra of pp sources should be hard (s<2.1-2.2)
- For a given complete catalogue, γ-ray searches are powerful
- Neutrino point-source candidates should be clearly seen in γ rays



KM & Waxman 16 PRD

CR Reservoirs

Starburst/Star-Forming Galaxies: Basics



- 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}
- CR accelerators

  Supernovae, hypernovae, GRBs,

  Super-bubbles (multiple SNe)

  Galaxy mergers, AGN

SBG CR 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 CR energy budget ~ Milky Way CR budget is ~10 times larger)

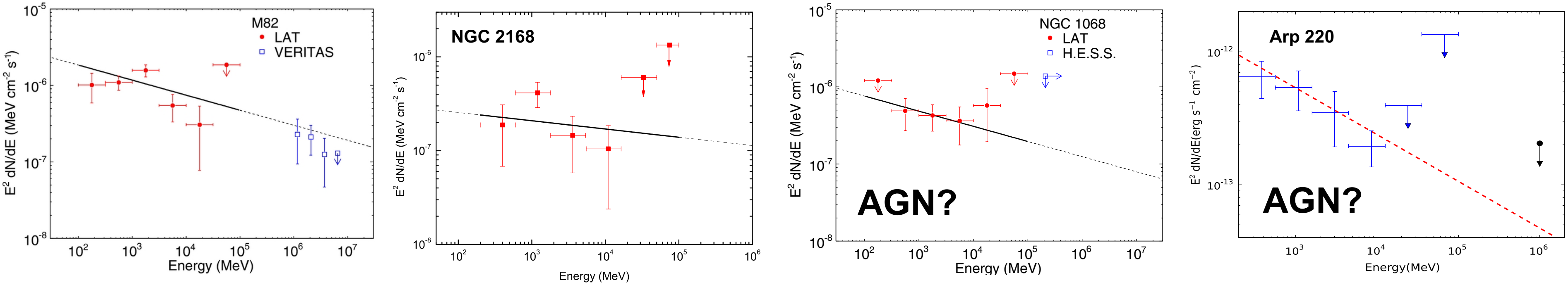
advection time (Gal. wind) $t_{\rm esc} \approx t_{\rm adv} \approx h/V_w \simeq 3.1\ {\rm Myr}\ (h/{\rm kpc}) V_{w,7.5}^{-1}$

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

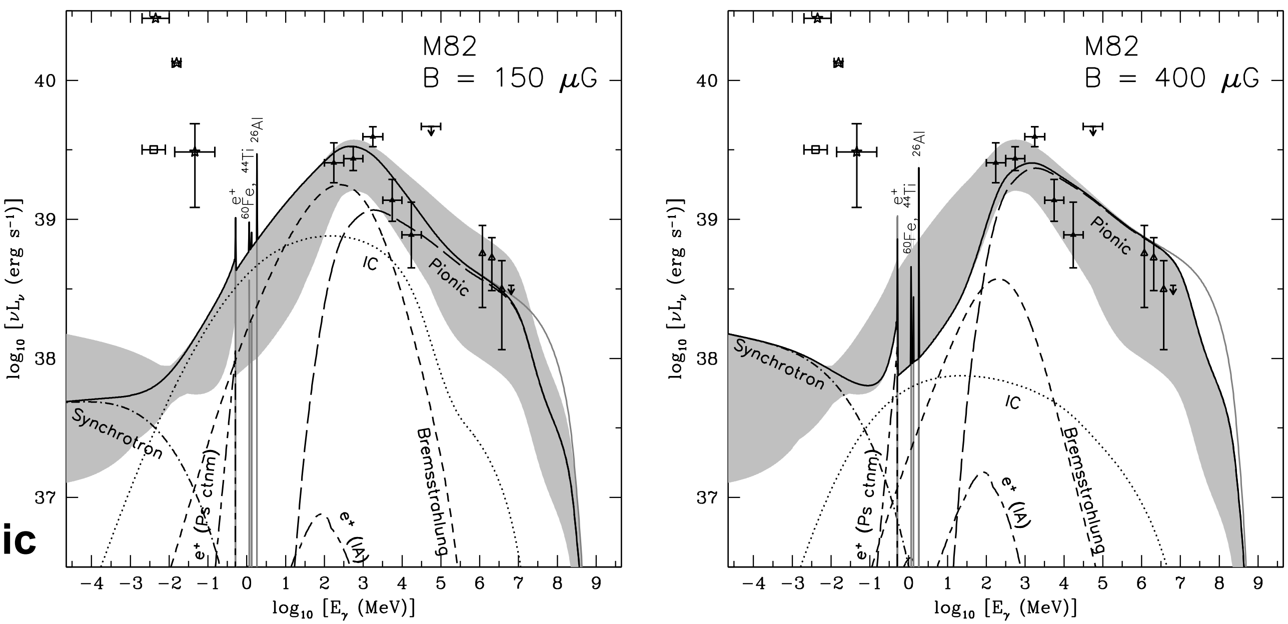
$$E_\nu^2 \Phi_{\nu_i} \sim 10^{-9}\text{–}10^{-7}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Gamma-Ray Detection from Starbursts

Starbursts have been detected in GeV-TeV gamma rays



Ackermann+ 12 ApJ, Tang+ 14 ApJL, Peng+ 16 ApJL, Griffin+ 16 ApJL



leptonic+hadronic

hadronic

Lacki, Horiuchi & Beacom 14 ApJ

Luminosity Function & Calorimetry

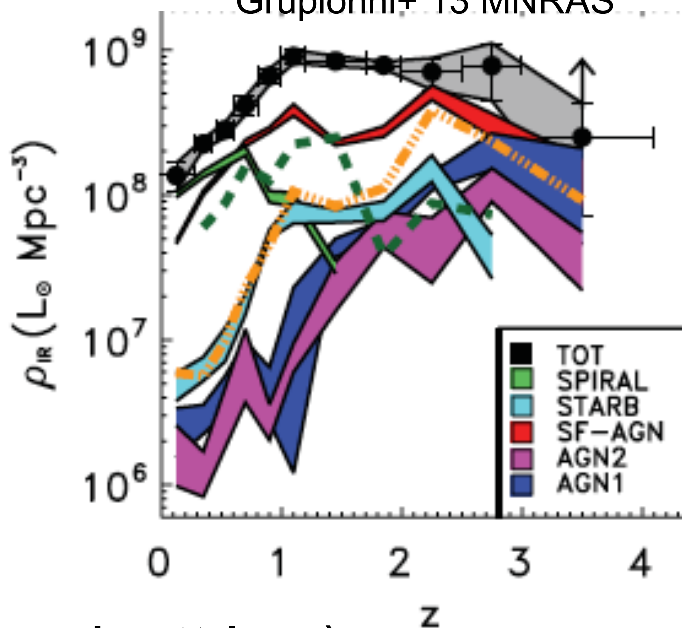
LF is described by the Schechter function

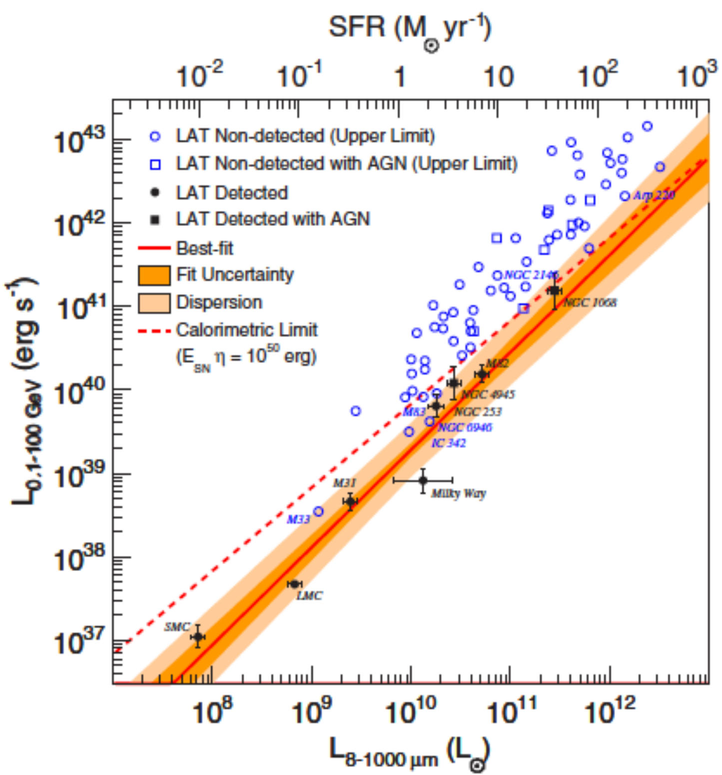
$$\Phi(L)\mathrm{d}\log L = \Phi^* \left(\frac{L}{L^*}\right)^{1-\alpha} \exp\left[-\frac{1}{2\sigma^2}\log_{10}^2\left(1+\frac{L}{L^*}\right)\right]\mathrm{d}\log L$$

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

Redshift evolution: $m\sim3\text{-}4$ up to $z\sim1$ for $(1+z)^m$

Grupionni+ 13 MNRAS





SFR $\propto L_{IR}$ (Kennicutt law)

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

(basic agreement w. calorimetry)

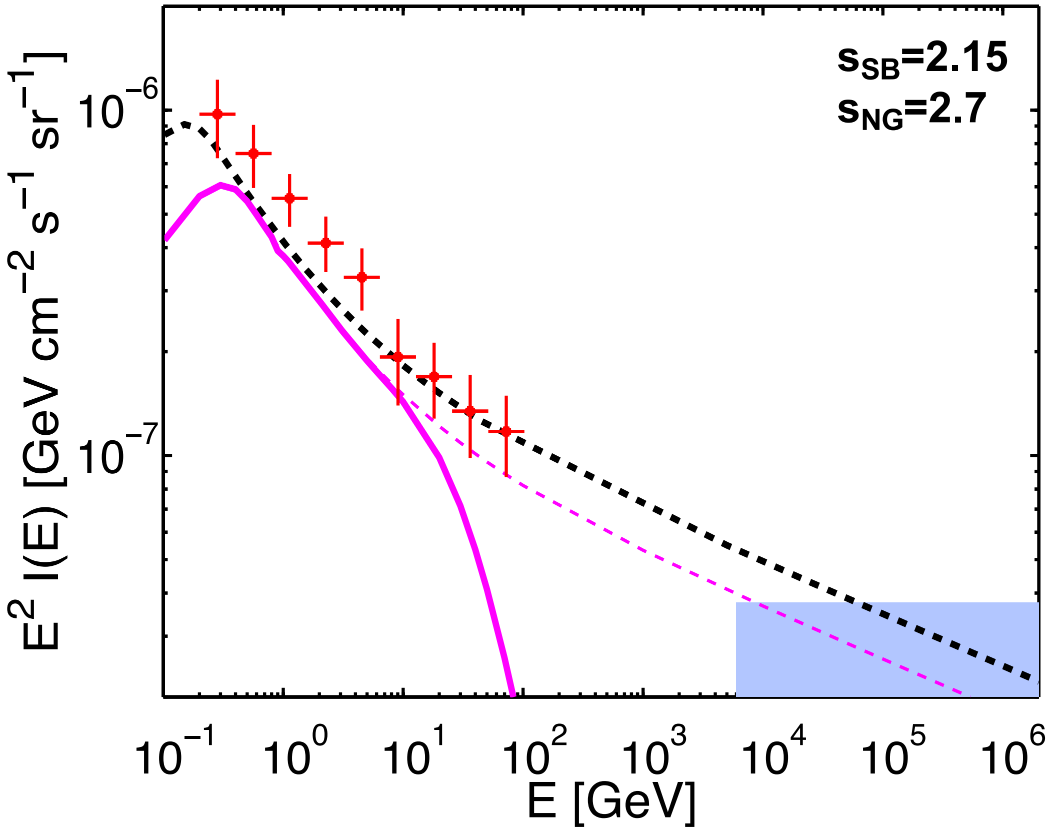
→ "typical" muon neutrino luminosity:

$EL_E\sim2\times10^{40}$ erg s^{-1}

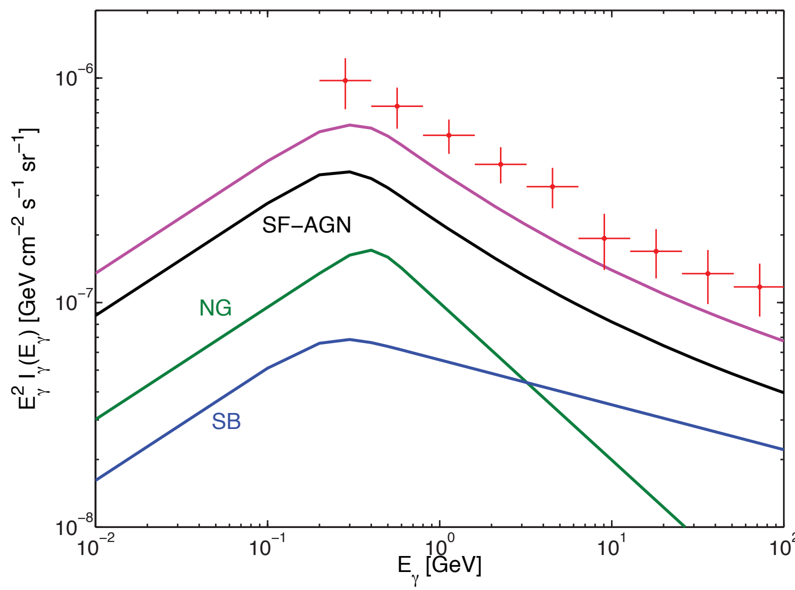
"effective" density: $n_0\sim10^{-5}$ Mpc^{-3}

can be reached by Gen2 (KM & Waxman 16)

Star-Forming/Starburst Galaxies, νs, γs



Tamborra, Ando & KM 14 JCAP



Starbursts can potentially explain ν and γ simultaneously, but keep in mind

- Normalization is uncertain (L_γ-L_{IR}, uncertain AGN contribution)
- Spectral indices are uncertain (could be s_{SB}=2.0 at high energies)

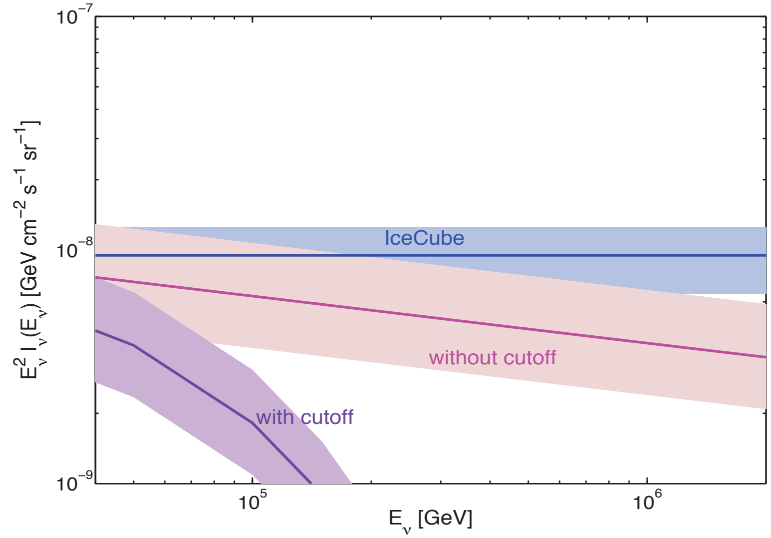
Necessity of Super-Pevatrons

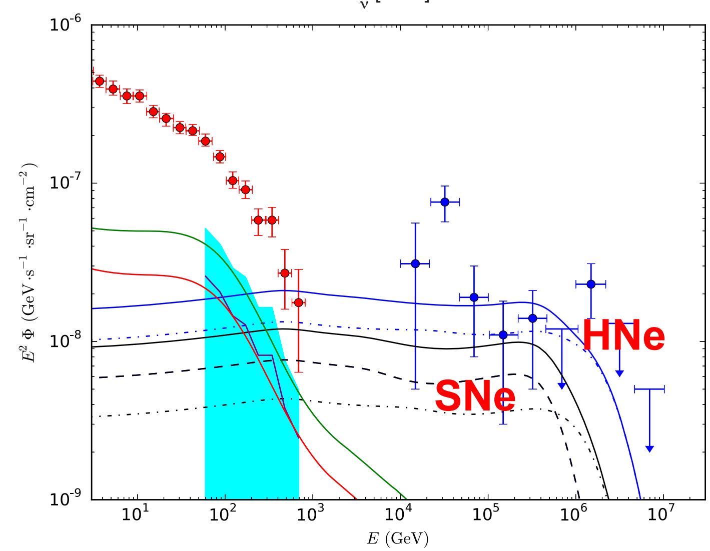
Our Galaxy's CR spectrum

Knee at 3 PeV

→ neutrino knee at ~100 TeV

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



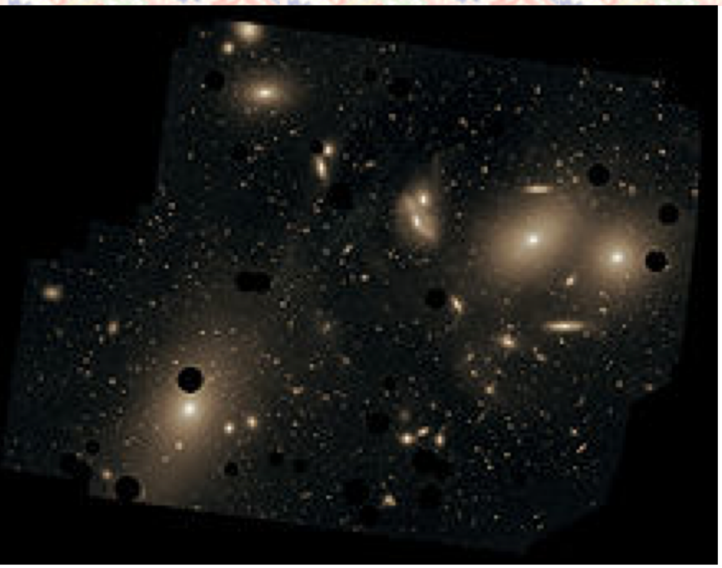


Senno, Meszaros, KM, Baerwald & Rees 15 ApJ
Xiao, Meszaros, KM & Dai 16 ApJ

<u>Possible solutions</u>

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, Yuan+ 18

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)

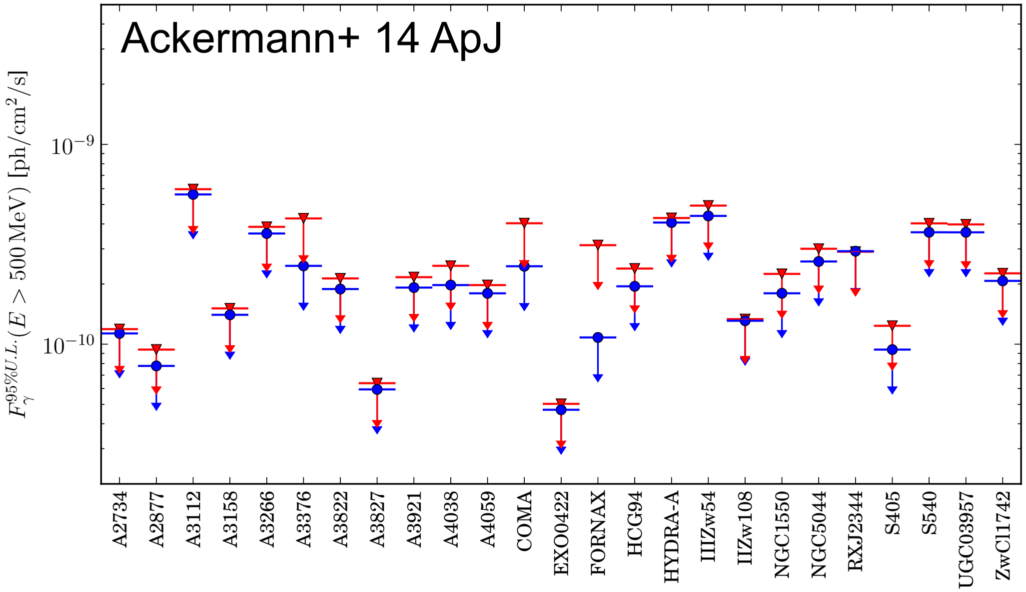
AGN jet luminosity density $Q_{\rm cr} \sim 3.2 \times 10^{46}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1} L_{j,45} \rho_{{\rm GC},-5}$

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

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

Gamma-Ray Limits on Galaxy Clusters



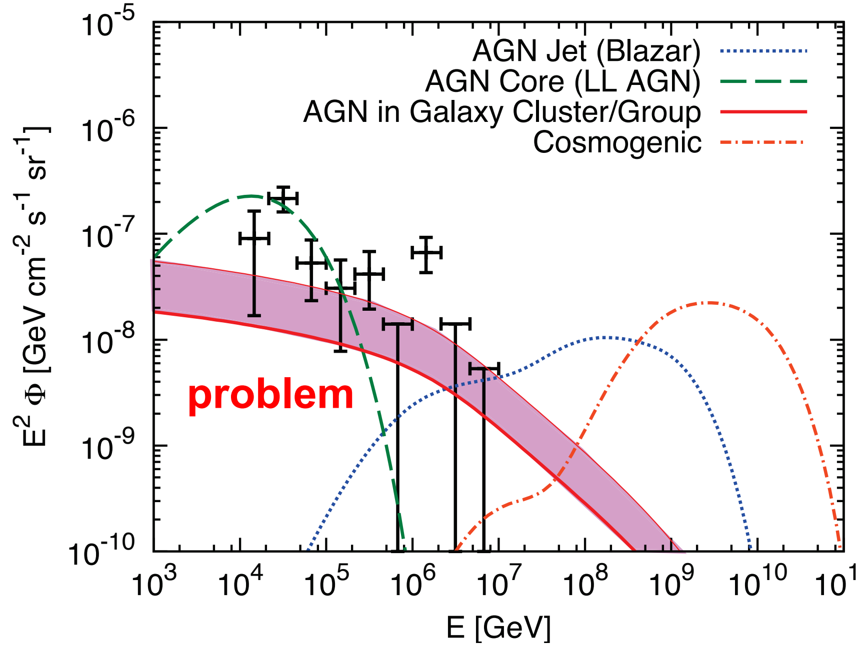
γ rays from virial shocks have been constrained

- CR pressure:
  < 1% of thermal pressure
- CR efficiency: < 15%

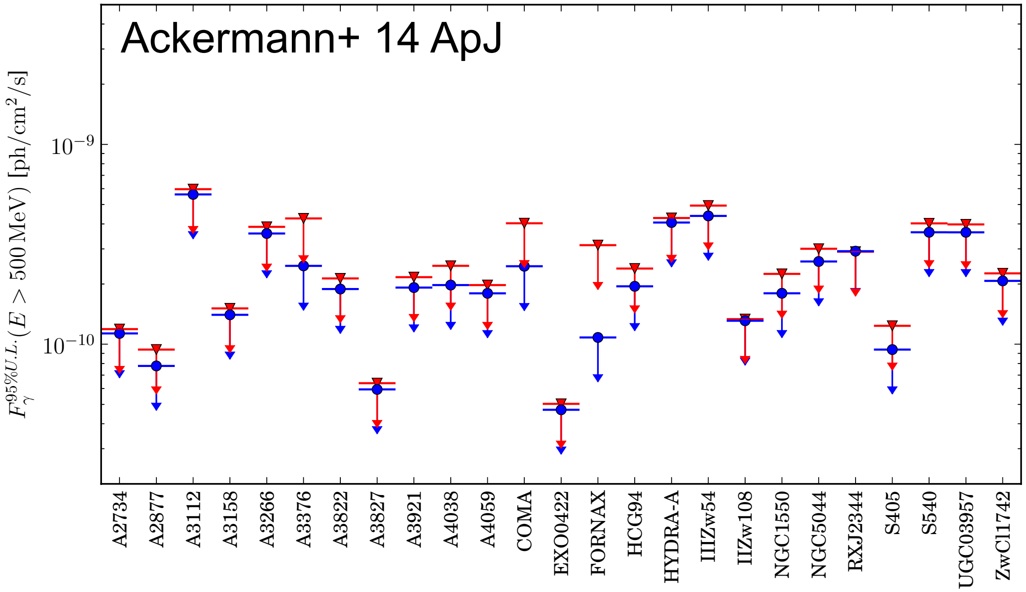
but see: Ackermann+ 16 ApJ
Reiss+ 17

Issues:
- γ-ray limits from nearby clusters
- overshooting diffuse γ-ray bkg.
- radio constraints for massive clusters

-> spectral indices cannot be steep
accretion shock scenario is disfavored



Gamma-Ray Limits on Galaxy Clusters



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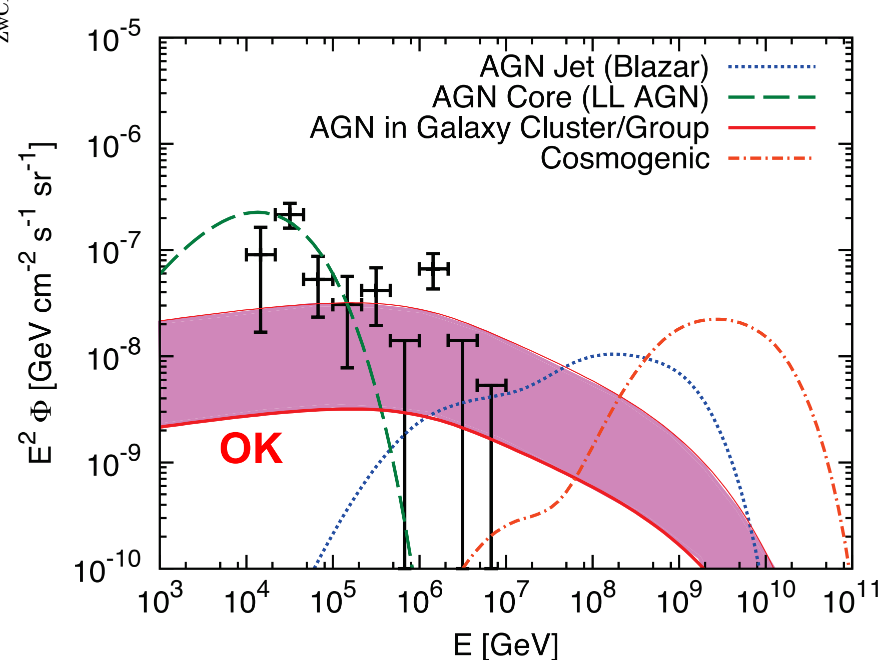


Issues:
- γ-ray limits from nearby clusters
- overshooting diffuse γ-ray bkg.
- radio constraints for massive clusters

-> spectral indices cannot be steep
   accretion shock scenario is disfavored

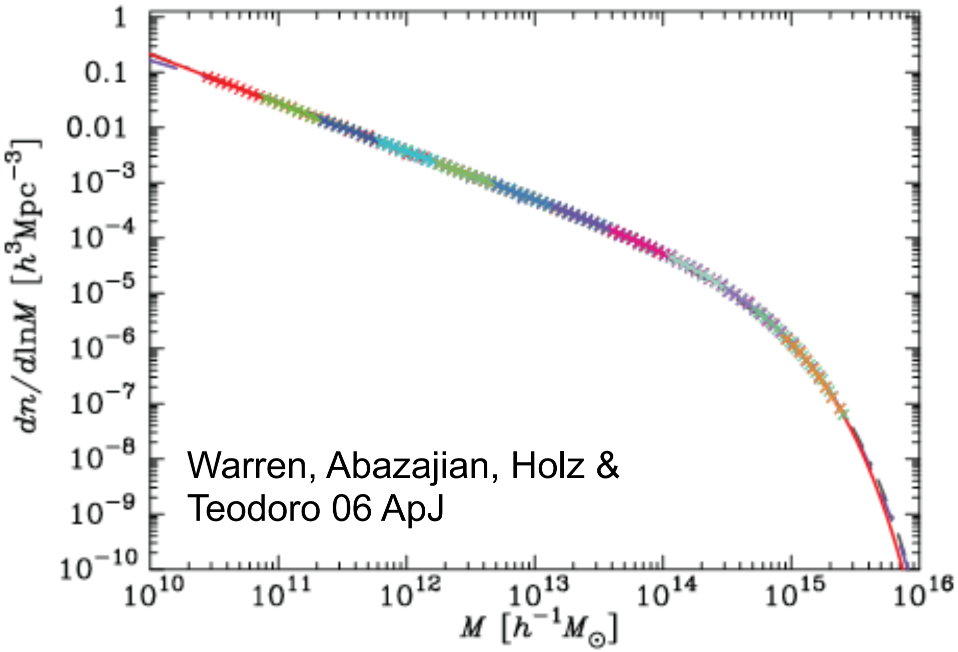
AGN with Galaxy Clusters

- Maximum energy of CRs is expected to be high enough (if AGN are the sources of UHECRs)
- Gigantic! → CR confinement 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

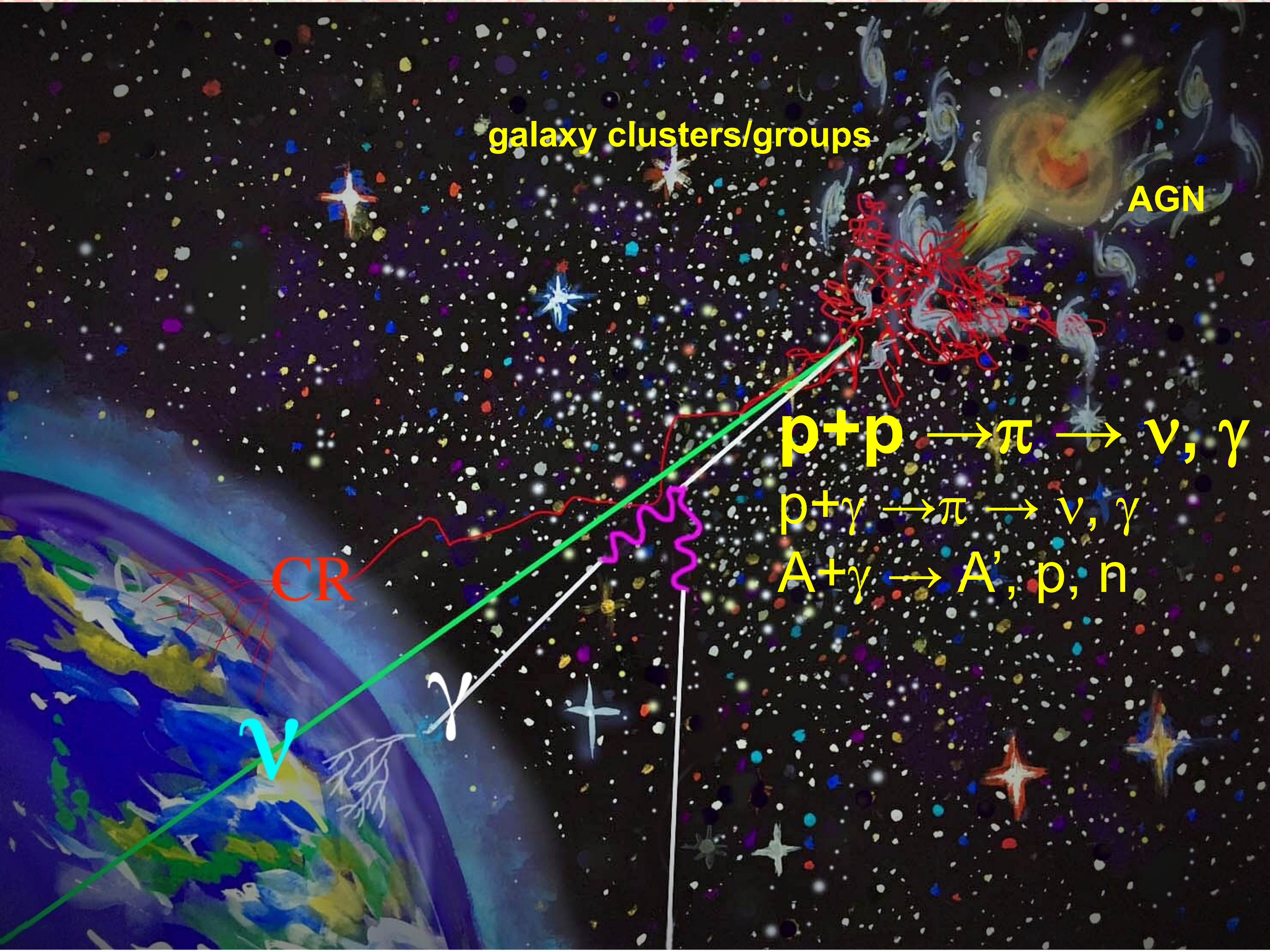


- cluster mass function: known (low-mass clusters are important)

- AGN evolution: $(1+z)^{3\text{-}4}$

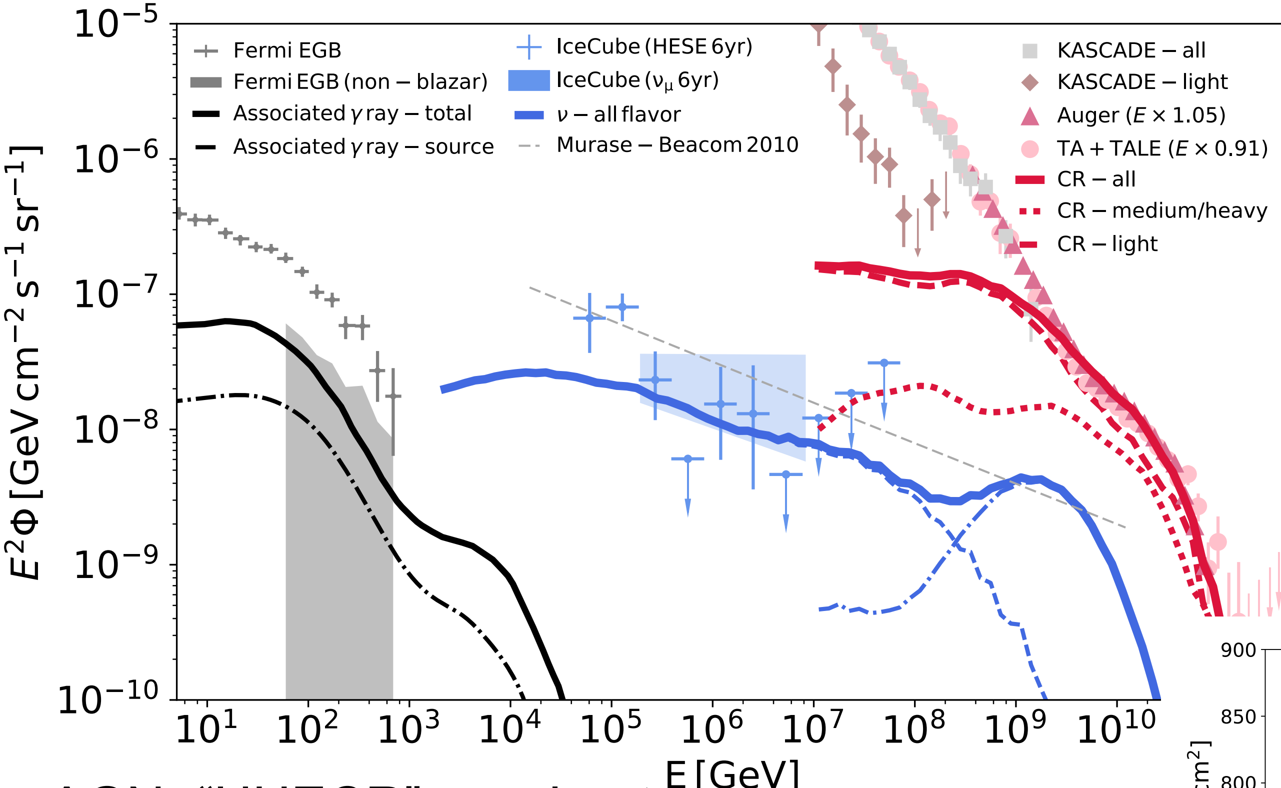
- gas density: relatively known (β profile)

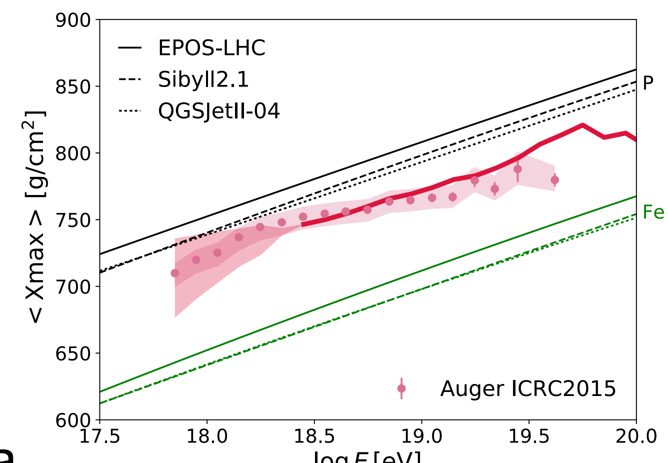
→ reasonable predictions


galaxy clusters/groups
AGN
p+p →π → ν, γ
p+γ →π → ν, γ
A+γ → A', p, n
CR
ν
γ

Unification of High-Energy Cosmic Particles?

Fang & KM 18 Nature Physics (see also KM & Waxman 16 PRD)

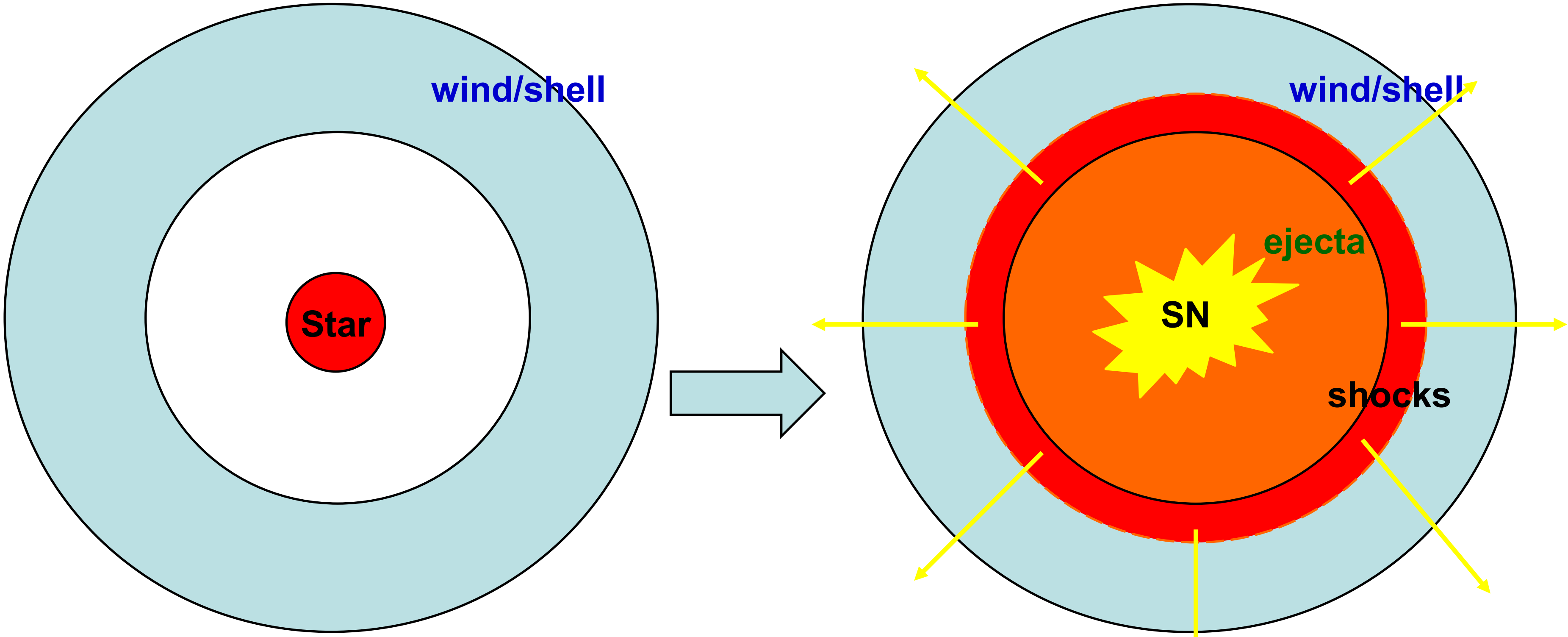




- AGN="UHECR" accelerators
  Galaxy clusters/groups="CR" reservoirs
- LE CRs: confinement in AGN & clusters
  HE CRs: escape into intergalactic space
- CR nuclei: photodisintegration -> harder spectra

GRBs and SNe

High-Energy Emission from Interacting SNe



kinetic energy → thermal + non-thermal via shock

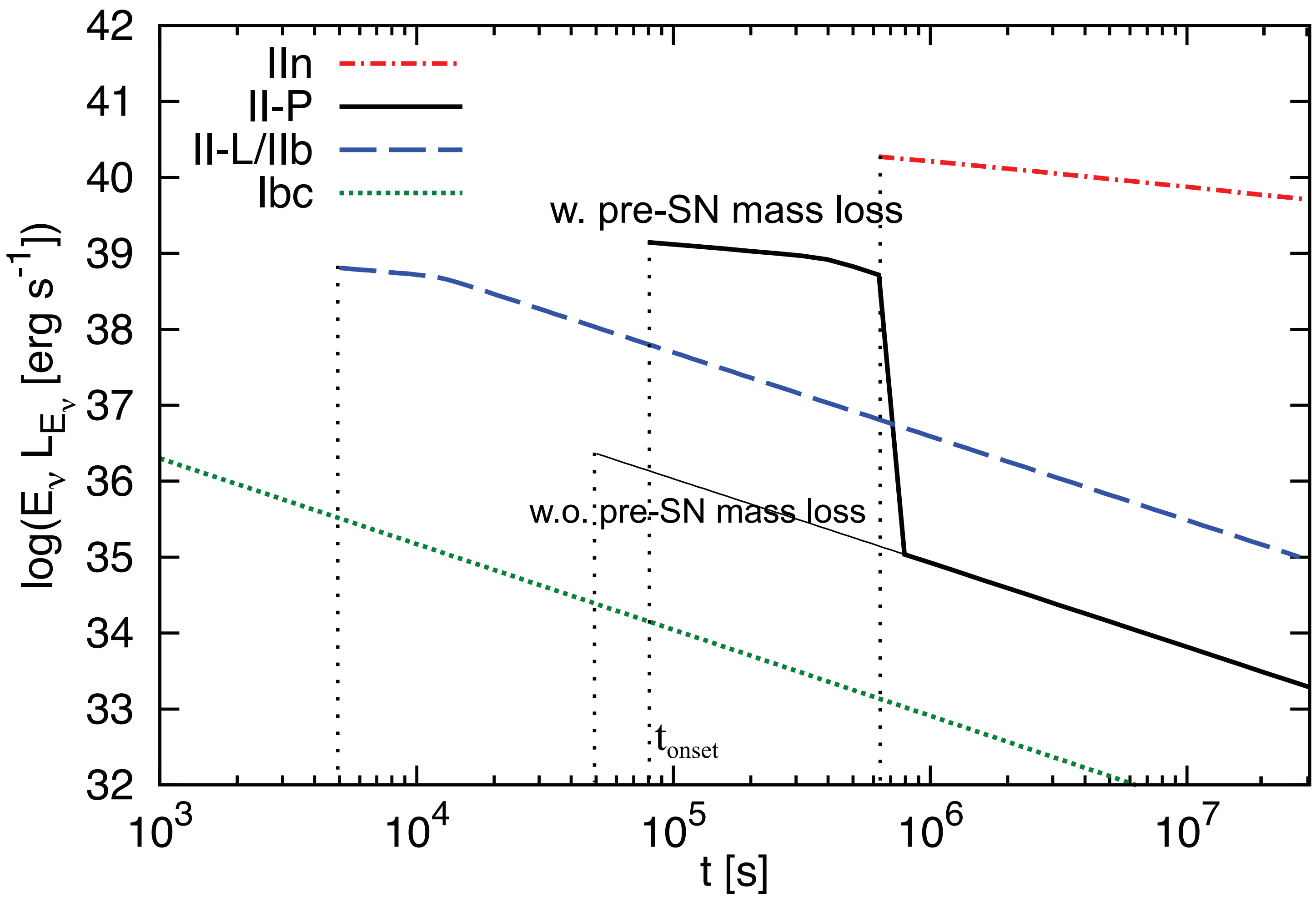
$$p + p \longrightarrow N\pi + X$$

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

$$\pi^{0} \longrightarrow \gamma + \gamma$$

Neutrino Light Curve

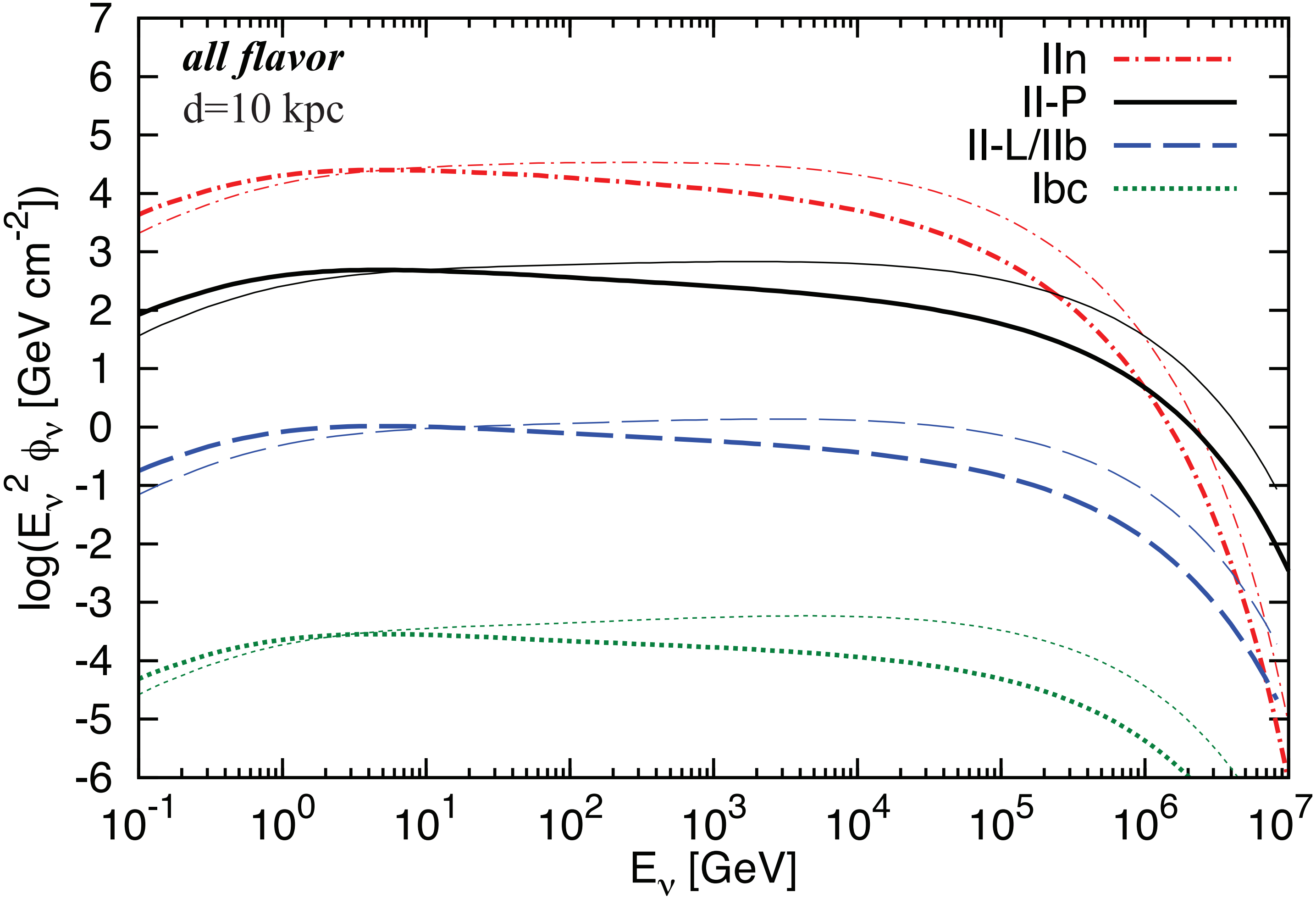
KM 18 PRDR



t_{onset} ~ time leaving the star (typical) or breakout time (IIn)

slowly declining light curve while pion production efficiency ~ 1

Neutrino Fluence



thick: s=2.2

thin: s=2.0

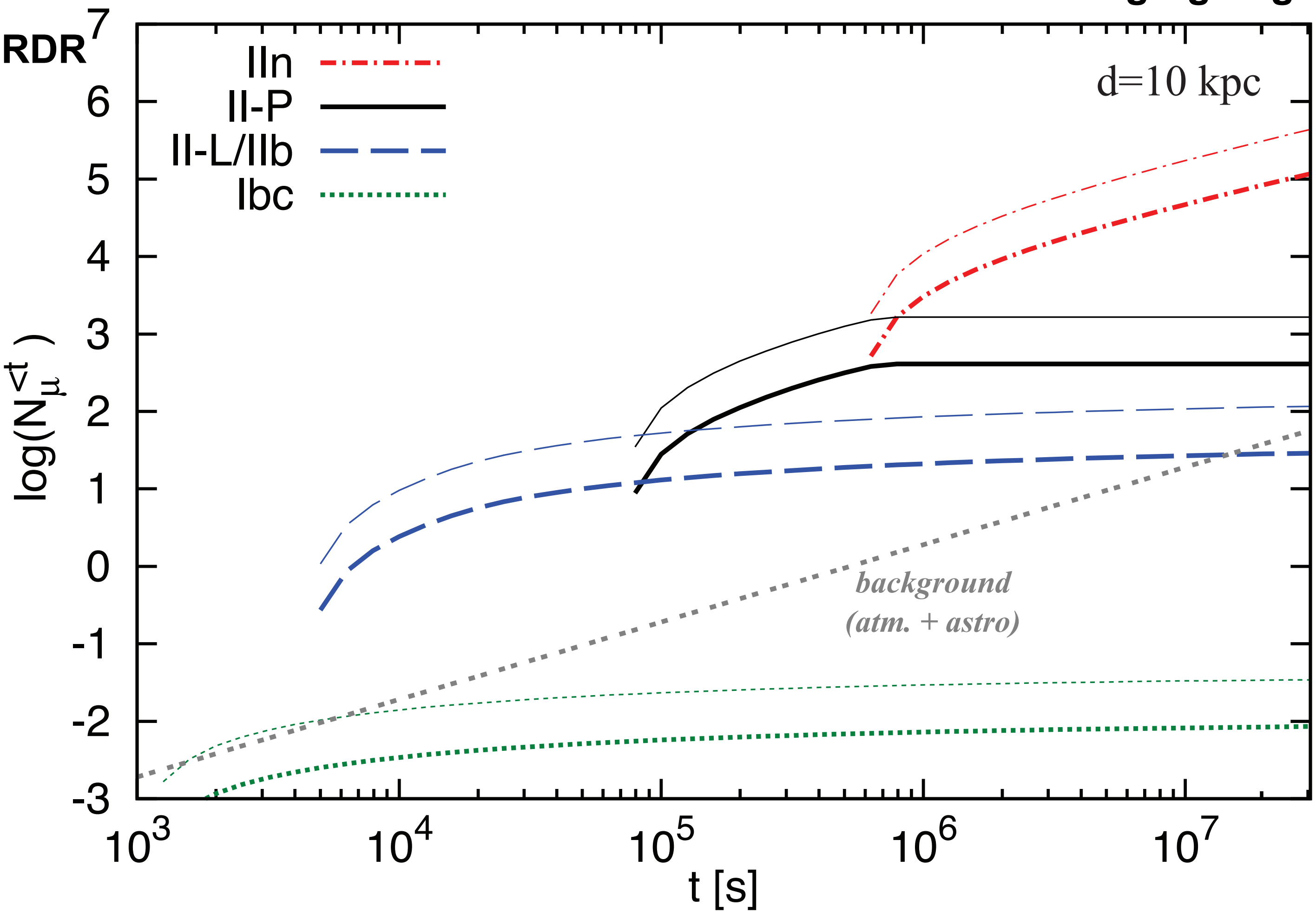
KM 18 PRDR

Fluence for an integration time when S/B$^{1/2}$ is maximal
(determined by the time-dependent model due to atm. bkg.)

Prospects for Neutrino Detection

through-going muon events

KM 18 PRDR

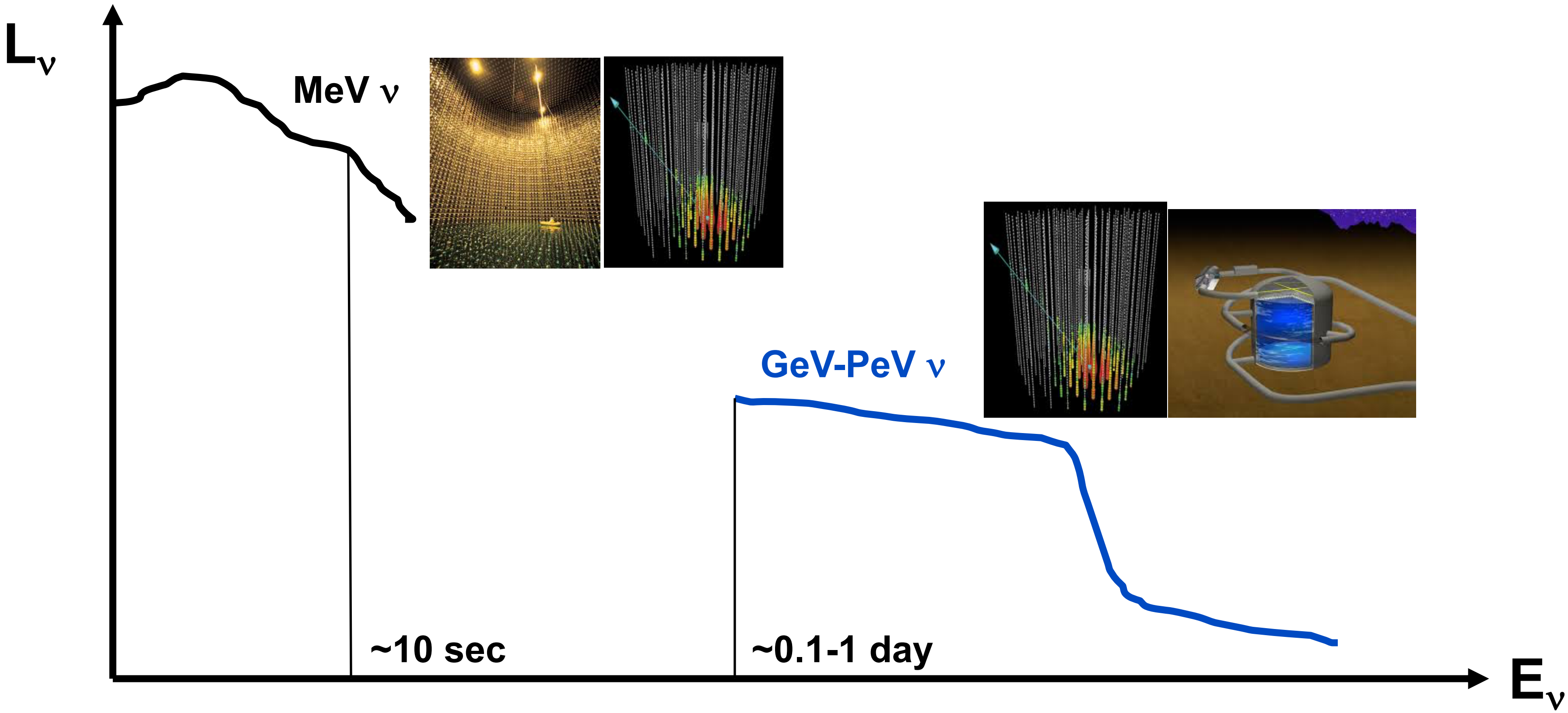


~ 10-1000 events for Type II supernovae at 10 kpc

~ 0.01-0.1 events for Ibc (but there would be exceptions)

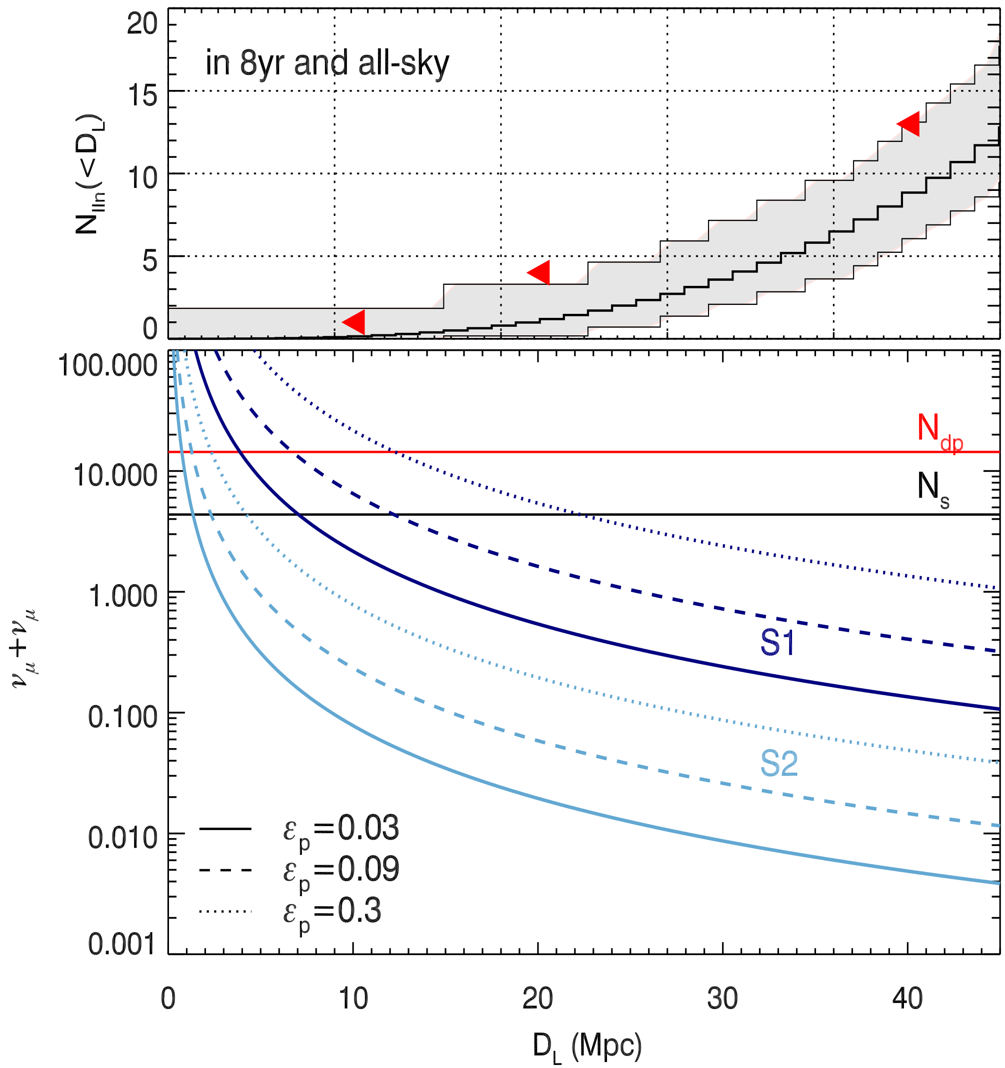
Multi-Energy Neutrino View of the Next Galactic Supernova?

- Type II: ~100-1000 events of TeV ν from the next Galactic SNe!!!
  ex. Betelgeuse: ~10^3-3×10^6 events!!!, Eta Carinae: ~10^5-3×10^6 events!!!
- SNe as "multi-messenger" & "multi-energy" neutrino source
- Real time obs. of CR ion acceleration
- Probes of neutrino physics (e.g., non-standard interactions)



How about Extragalactic SNe?

Petropoulou et al. 17 MNRAS



typical Type II-P, II-L/IIb: detection of extragalactic SNe is hard

$N \sim 0.01\text{-}0.1\ (d/1\ \mathrm{Mpc})^{-2}$

A single SN IIn is detectable up to ~10 Mpc

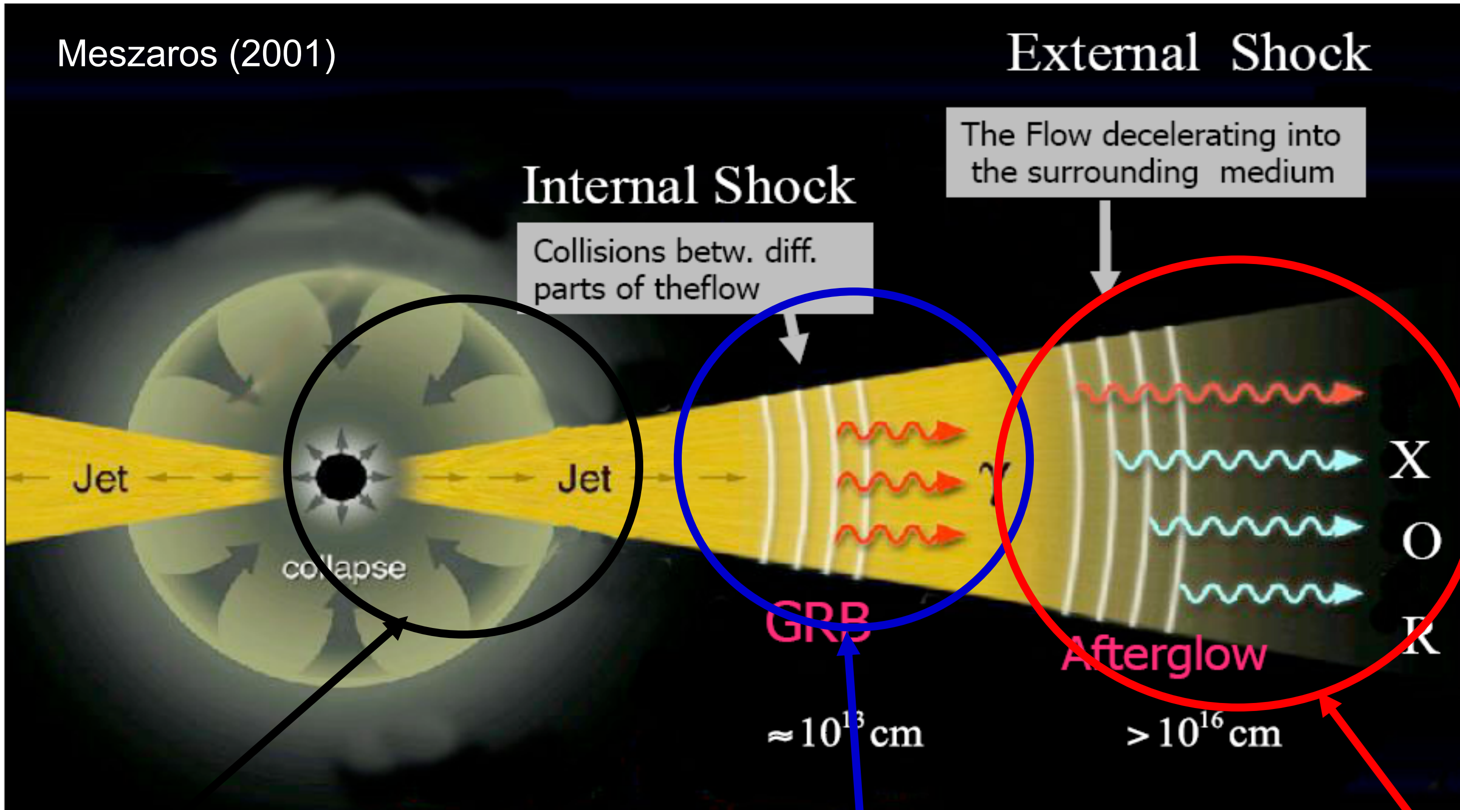
(KM+ 11 PRD, Petropoulou+ 17 MNRAS)

statistical search

ex. stacking analysis

auto-correlation analysis

Possible Neutrino Production Sites



Inner jet inside a star
$r < 10^{12}$ cm, $B > 10^{6}$ G
TeV-PeV ν, no γ

Meszaros & Waxman 01 PRL
Razzaque et al. 03 PRL
KM & Ioka 13 PRL

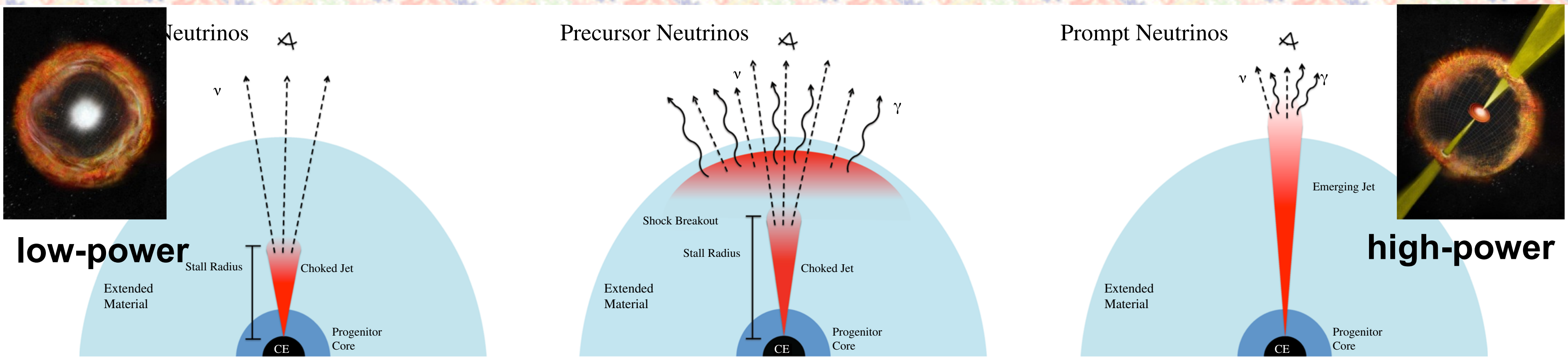
Inner jet (prompt/flare)
$r \sim 10^{12}$-10^{16} cm $B \sim 10^{2\text{-}6}$ G
PeV ν, GeV-TeV γ

Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL
KM & Nagataki 06 PRL

Afterglow
$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G
EeV ν, GeV-TeV γ

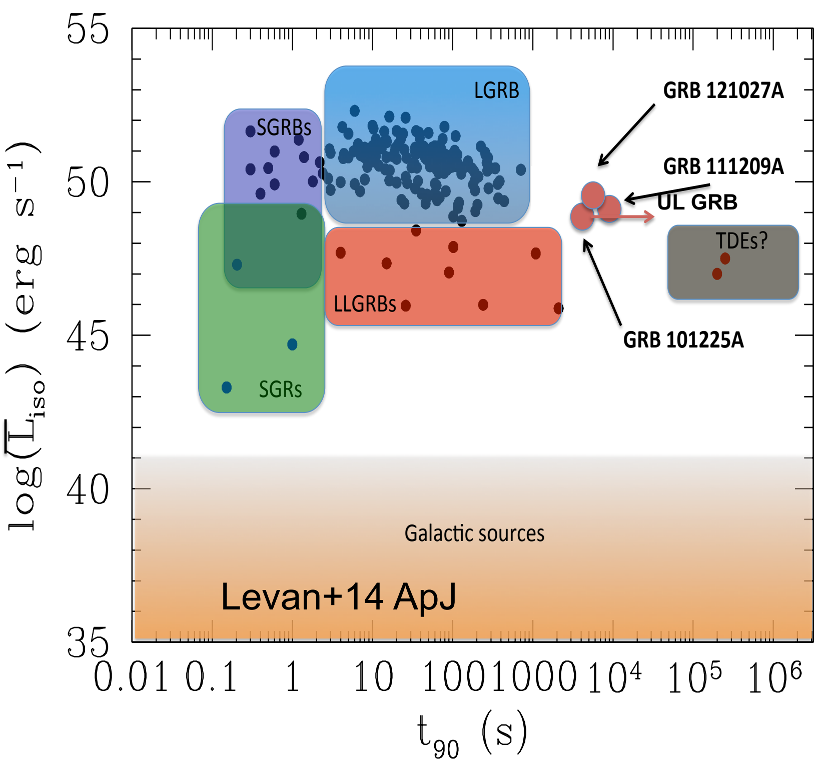
e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

Choked Jets as Hidden Neutrino Factories?



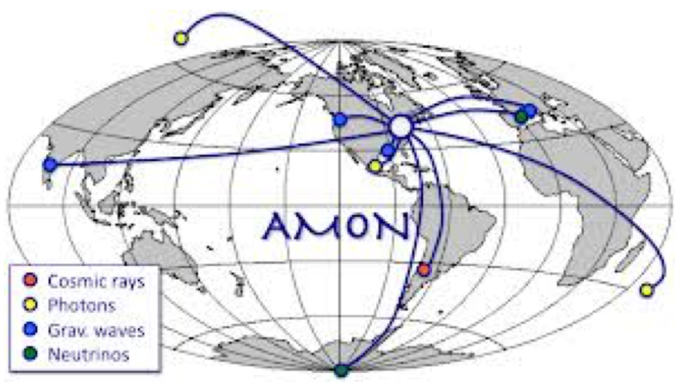
low-power

high-power



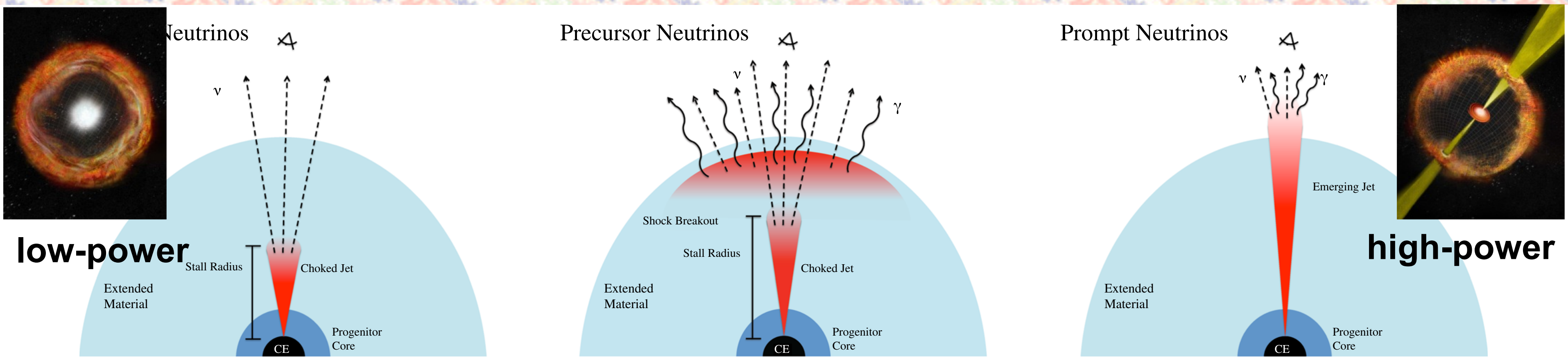
Senno, KM & Meszaros 16 PRD

Multi-messenger targets



stacking limits on canonical GRBs are not applied!
LL GRBs can be seen up to ~150 Mpc

Choked Jets as Hidden Neutrino Factories?

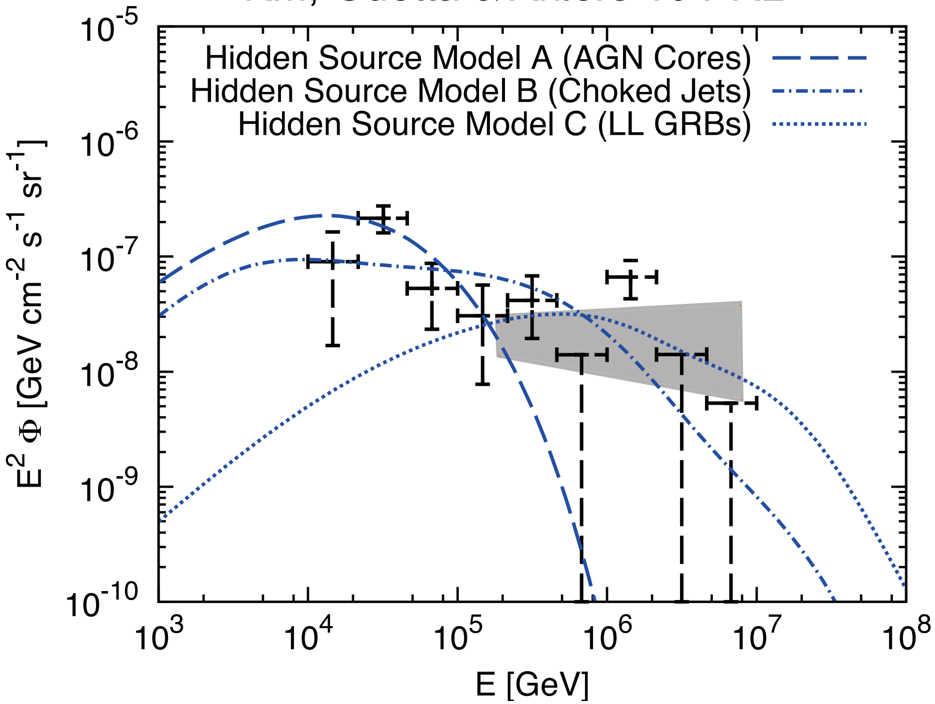


low-power

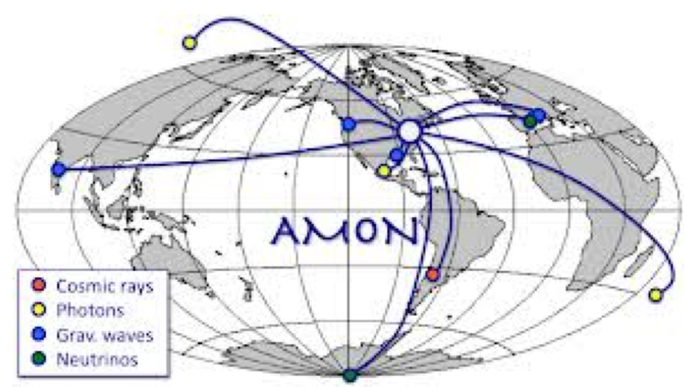
high-power

KM, Guetta & Ahlers 16 PRL

Senno, KM & Meszaros 16 PRD



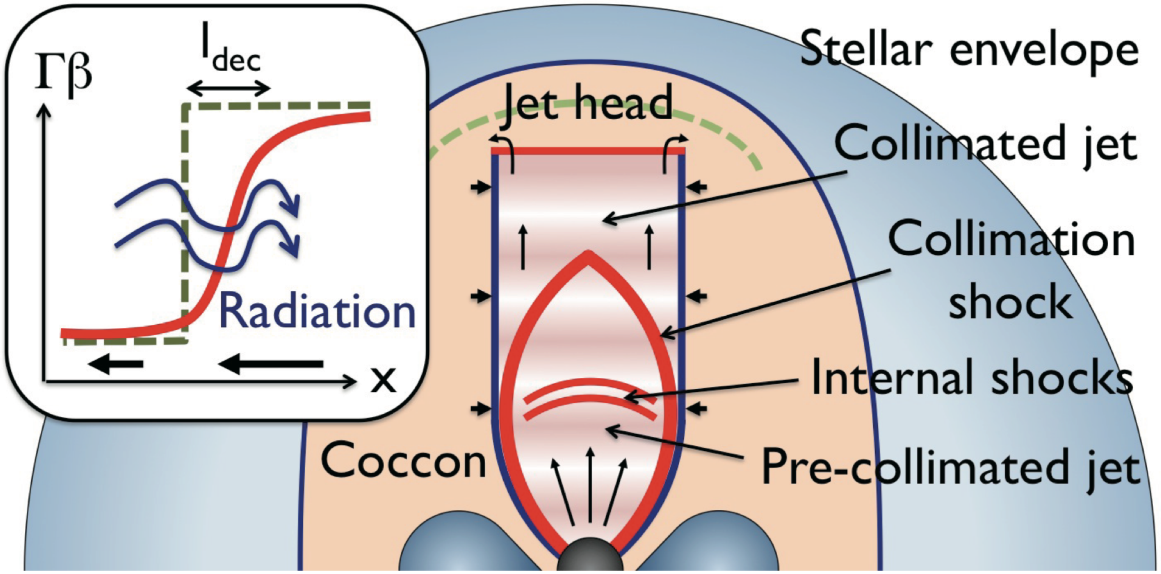
Multi-messenger targets



stacking limits on canonical GRBs are not applied!
LL GRBs can be seen up to ~150 Mpc

Realistic Picture

Two pieces of important physics were overlooked

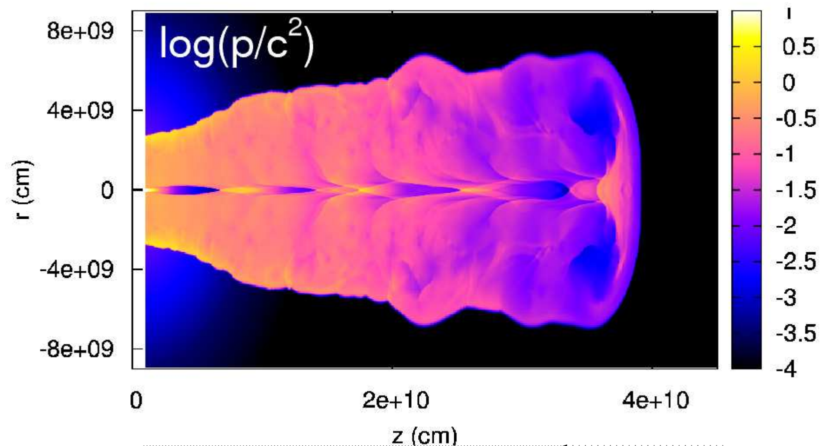


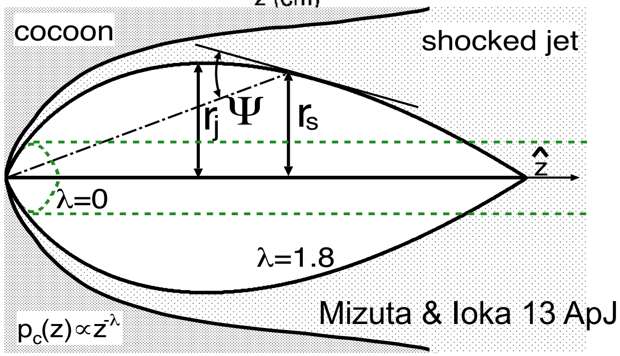
KM & Ioka 13 PRL

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

Jet Propagation inside a Star

- Jet propagation has been understood (cannot be ignored) controlled by luminosity, duration, opening angle, and $\rho(r)$





1. ram pressure balance at jet head
2. cocoon dynamics
3. collimation shocks

(Bromberg+ 11 ApJ, Mizuta & Ioka 13 ApJ)

jet head radius

$$r_h \approx 8.0 \times 10^9 \text{ cm}\, t^{3/5} L_{j0,52}^{1/5} (\theta_j/0.2)^{-4/5} \varrho_{a,4}^{-1/5}$$

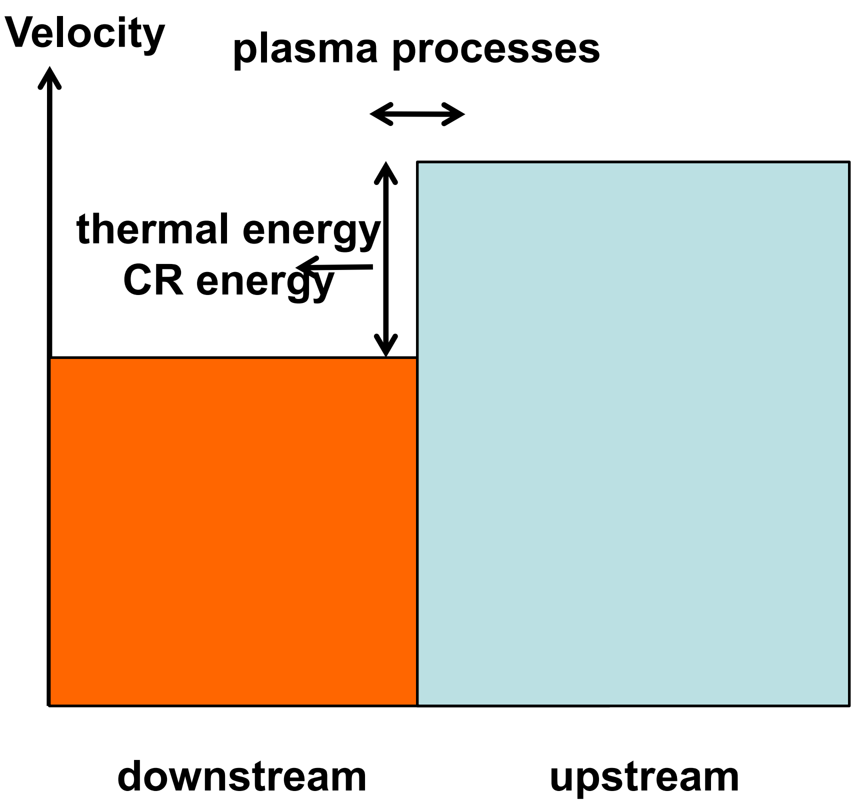
cf. uncollimated shock

$$r_h \approx 2\Gamma_h^2 ct \simeq 2.3 \times 10^{13} \text{ cm} L_{0,52}^{1/2} \rho_{\rm ext}^{-1/2} r_{\rm ext,13.5}^{-1} t_{1.5}$$

- Collimation is crucial for jets propagating in high-density environments
- **Must be taken into account for neutrino emission from choked jets**
  jet-stalling condition L < L_{JS}: change by many order of magnitudes

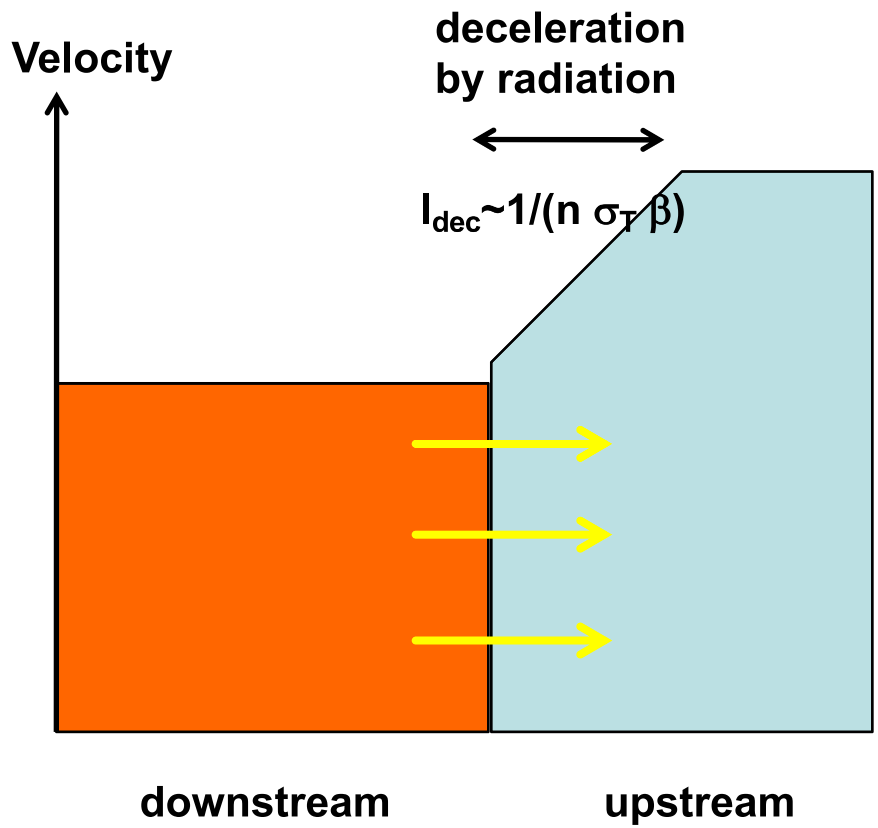
Limitation of Shock Acceleration

Collisionless shock



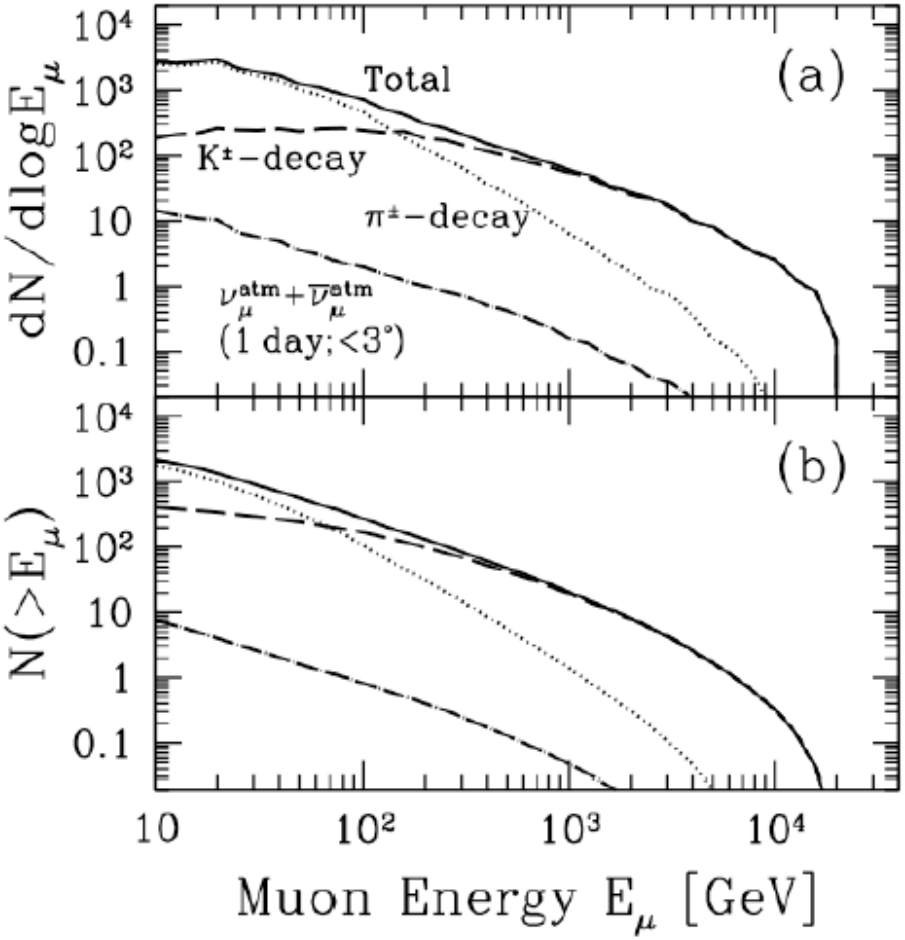
(m.f.p.) ~ $r_L(\varepsilon_p)$ > (shock width)

Radiation-mediated shock



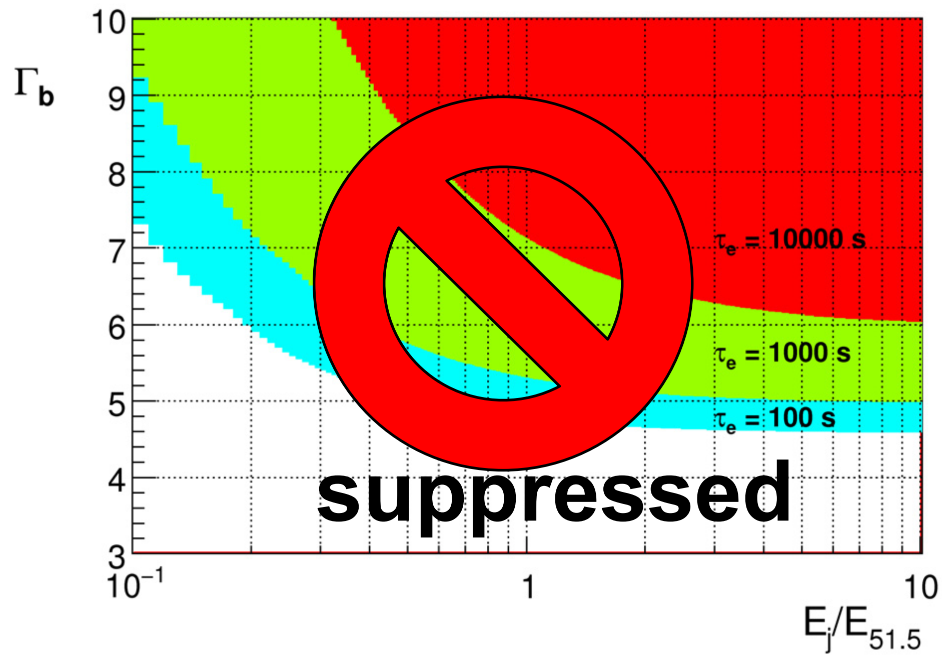
(m.f.p.) ~ $r_L(\varepsilon_p)$ < (shock width)

SNe with Slow Jets (Failed GRBs)



Ando & Beacom 05 PRL

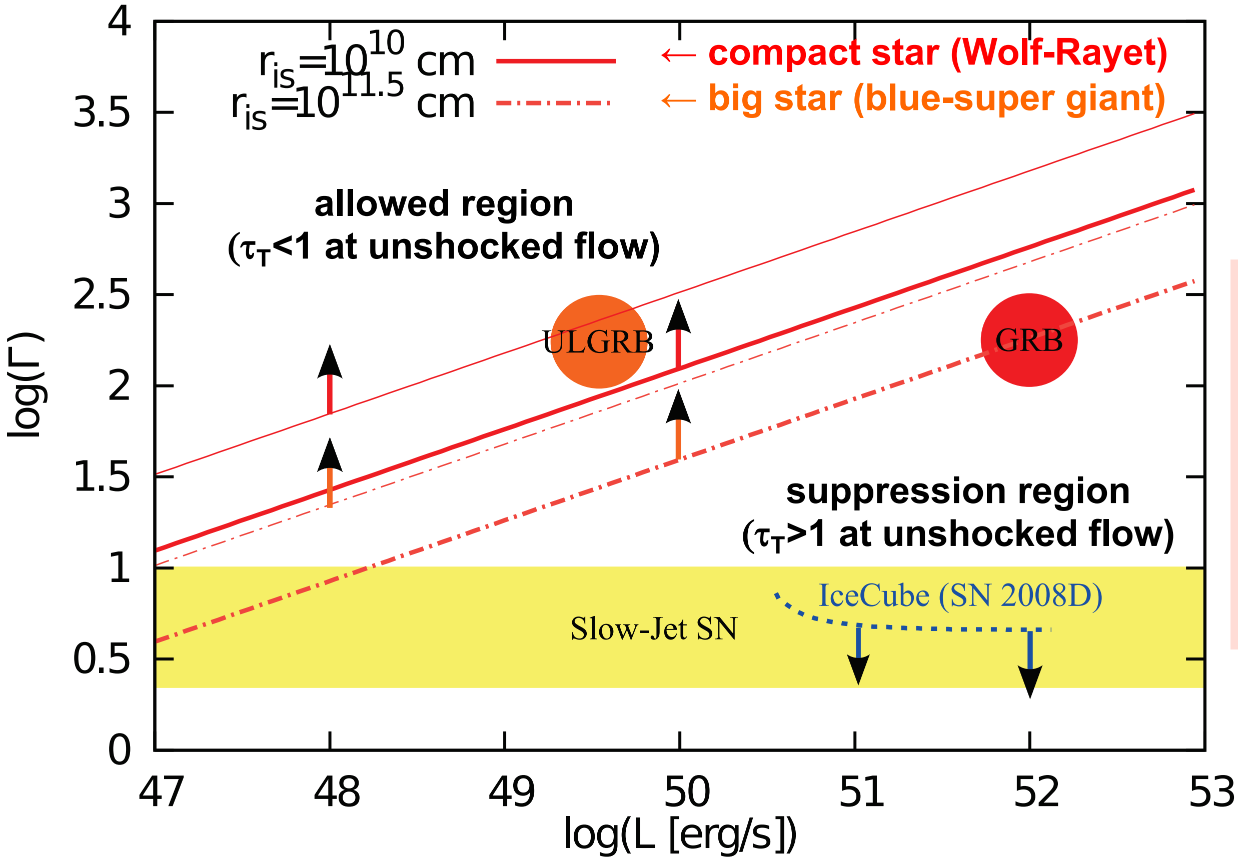
SN 2008D
constraints on Γ and E_j



IceCube 11 A&A

If CRs carry E_{CR}^{iso}~0.5x10^{53} erg (GRB)
→ # of μs ~ **0 events (due to radiation mediated shocks)**

"Radiation Constraints" on Non-thermal Neutrino Production



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

- Lower-power is better
- Bigger progenitor is better

⇨

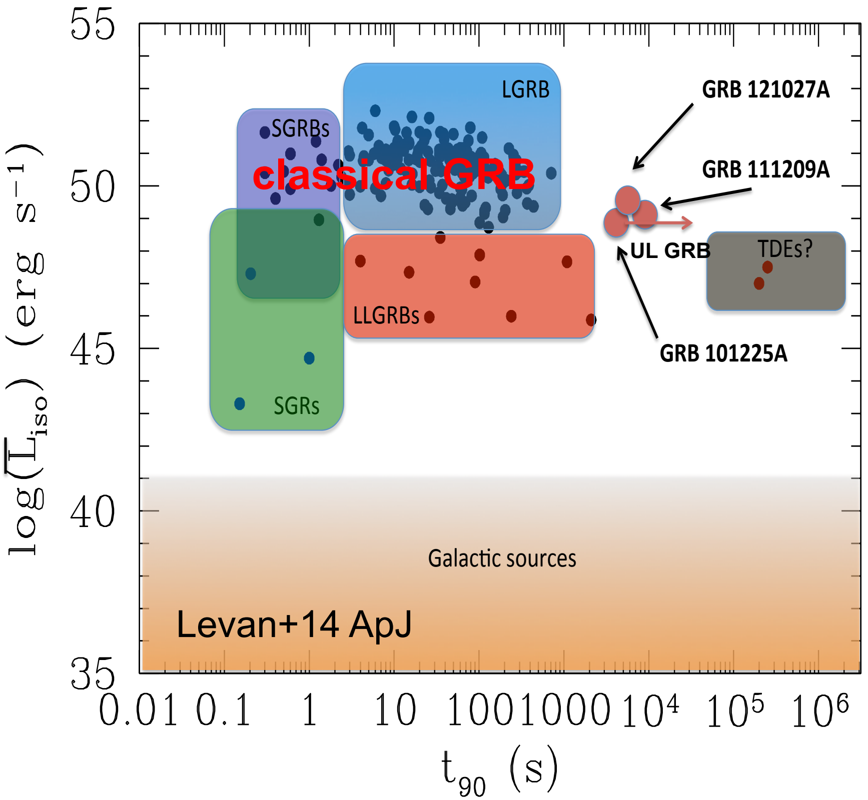
- **suppressed in typical GRBs and powerful slow-jet SNe**
- **favoring choked jets (difficulty of penetration)**

Basic Picture

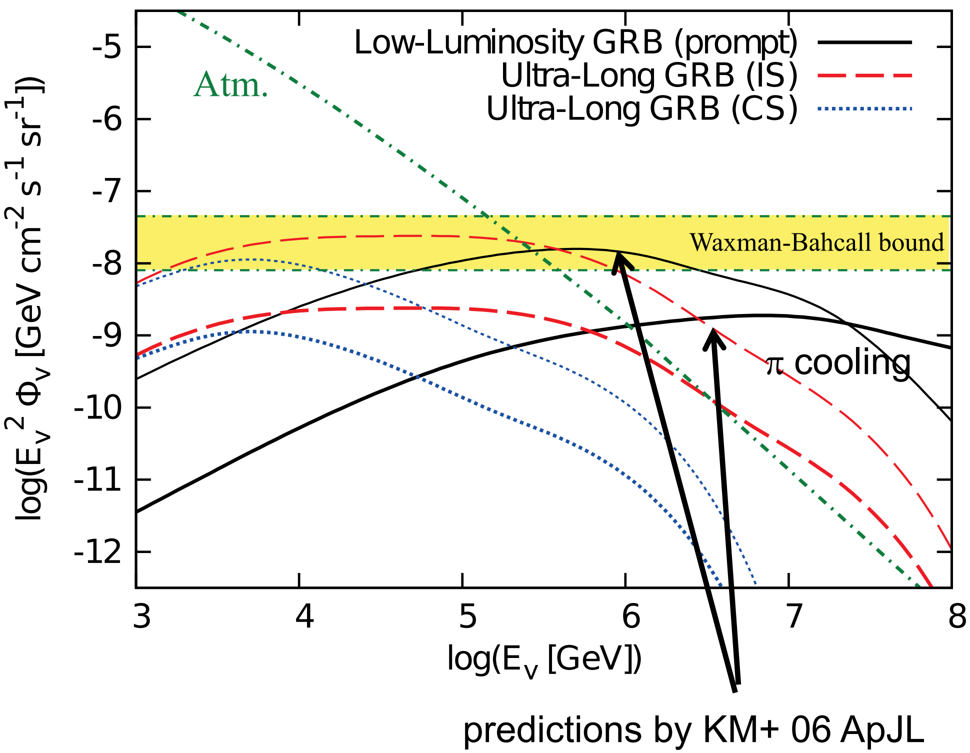
Story of high-energy neutrino production

- Internal shock scenario
  maybe CR acceleration (if collisionless)
  pγ interactions in inner jets, pp interactions are inefficient $f_{pp} \lesssim \frac{\kappa_{pp}\sigma_{pp}}{\sigma_T} \simeq 0.04$
  target photons by collimation-shocked jet (w. screening) & inner jets
  adiabatic losses during the expansion of the emission region and
  will not interact w. stellar material (hot spot and cocoon)
- Collimation shock scenario
  possible CR acceleration (if collisionless)
  pγ interactions in collimation-shocked jets
  target photons by collimation-shocked jet
  little adiabatic losses due to the collimation and
  pp interactions should occur during the advection
- Reverse shock scenario
  CR acceleration is usually difficult
- Forward shock scenario
  No CR acceleration (collisional)

Examples of Neutrino Spectra for Choked Jets

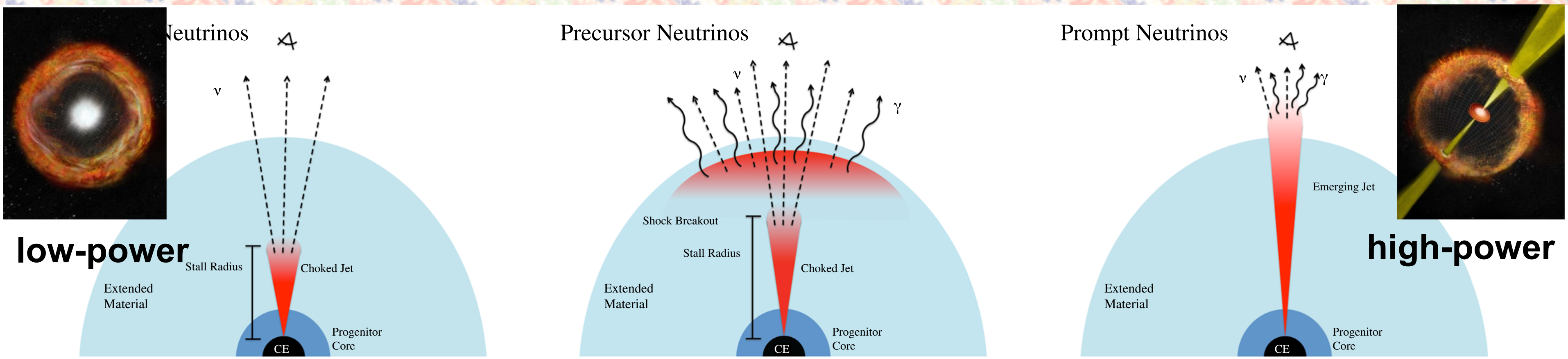


KM & Ioka 13 PRL

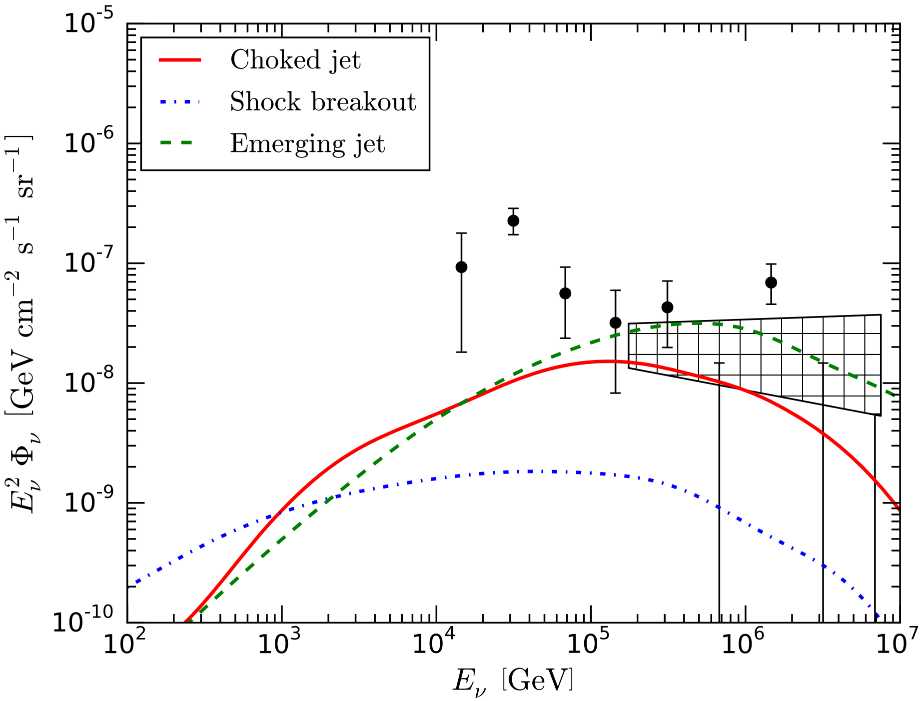


- Low-luminosity (LL) & ultra-long (UL) GRB jets are largely missed
- Compatible w. IceCube ν data without violating stacking limits (by introducing contributions from choked jets)
- Non-detection of νs from GRBs already supports radiation constraints (If ν production occurred inside a star for HL GRBs, we could detect them)

Type Ibc Supernovae & Low-Luminosity GRBs



Senno, KM & Meszaros 16 PRD



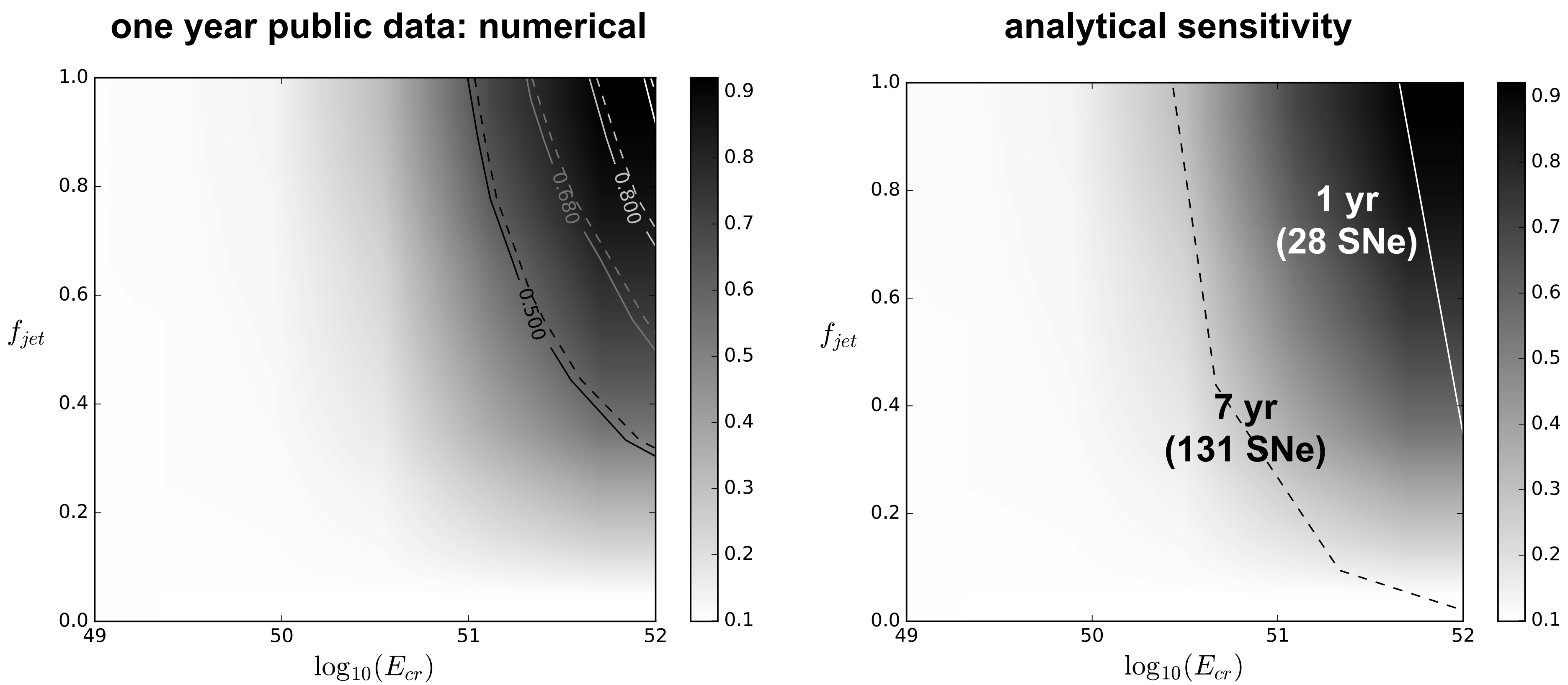
- **Trans-relativistic SNe such as may come from shock breakout**
  (Campana+ 07, Waxman+ 07)
- **Successful or failed?**
  (Toma+07, Nakar 15, Irwin & Chevalier 16)
- **They could significantly contribute to the IceCube flux (stacking limits on canonical GRBs are not applied)**

Name	Max Mag (MJD)	RA (rad)	Dec (rad)	D_L (Mpc)	Type
SN2011ep	55750.5	4.47	0.57	1490	Ic
PTF11ixk	55765.5	3.50	0.55	95	Ic
PTF11izq	55767.5	3.61	0.70	289	Ib
PTF11ilr	55771.5	6.05	0.27	—	Ib
SN2011ee	55773.5	6.14	0.15	137	Ic
PTF11kaa	55775.5	4.57	0.82	184	Ib
SN2011gd	55790.5	4.34	0.38	44	Ib
PTF11klg	55810.5	5.79	0.11	120	Ic
PFT11kmb	55820.5	5.86	0.63	77	Ib-Ca
SN2011fl	55829.5	0.21	0.49	71	Ib
SN2011ft	55829.5	4.68	0.51	78	Ib
SN2011gh	55829.5	1.97	0.45	85	Ib
PFT11qcj	55866.5	3.46	0.83	127	Ib
SN2011fz	55888.5	6.01	0.04	73	Ib
LSQ11jw	55909.5	0.54.	0.01	90	Ic
SN2011jm	55918.5	3.38	0.05	14	Ic
SN2011it	55919.5	5.77	0.55	72	Ic
SN2011kf	55925.5	3.83	0.29	1280	Ic
SN2012C	55939.5	2.52	0.57	65	Ic
SN2012F	55930.5	0.15	0.07	137	Ib
SN2011kg	55937.5	0.44	0.52	976	SLSN-I
SN2012il	55941.5	2.56	0.35	878	SLSN-I
SN2012aa	55954.5	3.89	-0.04	376	Ic
SN2012ap	55975.5	1.31	-0.05	55	Ic BL
PTF12bwq	56007.5	3.61	0.44	184	Ib
PS1-12sk	56013.5	2.29	0.75	251	Ibn
LSQ12bph	56017.5	4.13	0.4	207	Ic
SN2012bw	56039.5	4.25	0.57	141	Ic
PTF12cde	56068.5	3.66	0.63	56	Ib/c

- **29 Ibc SNe (Open SN catalog)**
- Limited number of SN Ibc samples because only 1 year data are public for through-going ν
- We need more data on SNe & neutrinos

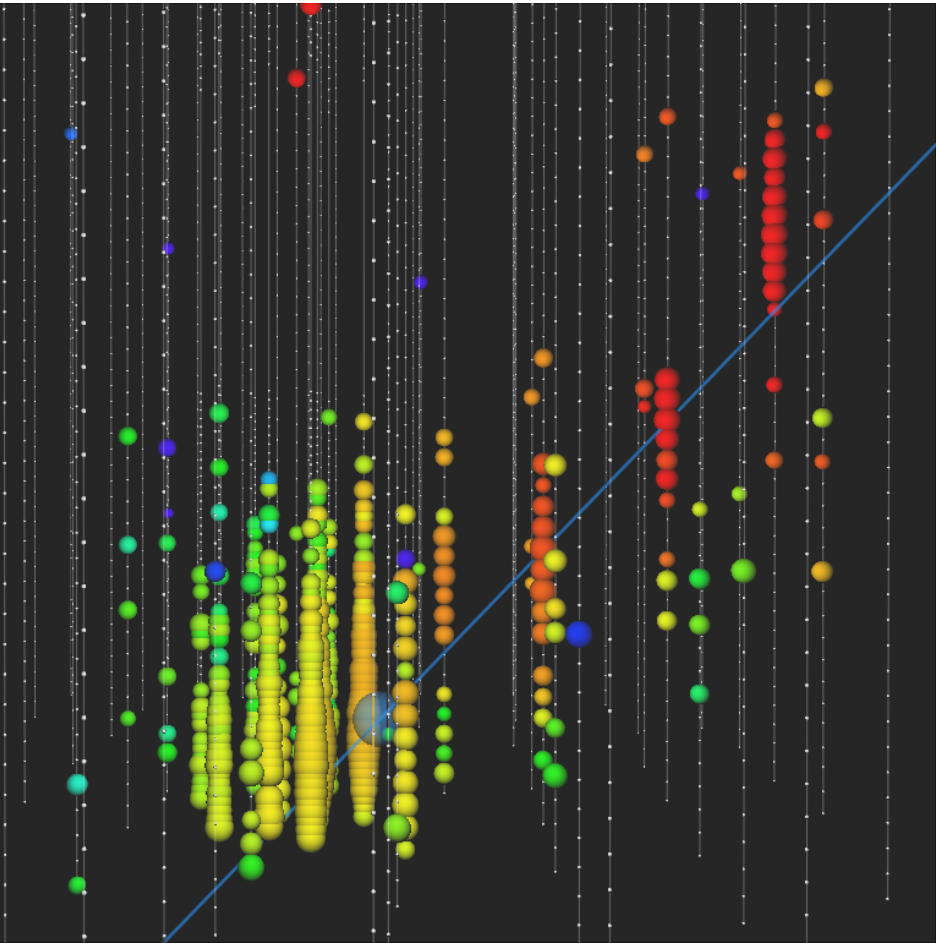
Type Ibc Stacking

Senno, KM & Meszaros 18 JCAP



- Consistent w. no correlation: $E_{cr}<10^{51}$-10^{52} erg
- Will be updated by the IceCube Collaboration

Another Idea: Neutrino Follow-Up



Neutrinos are not attenuated:
Rare SN ransients can be found

(ex. KM et al. 06 ApJL)

A few (even ~1) neutrinos can tell us where the source is

Neutrino detection

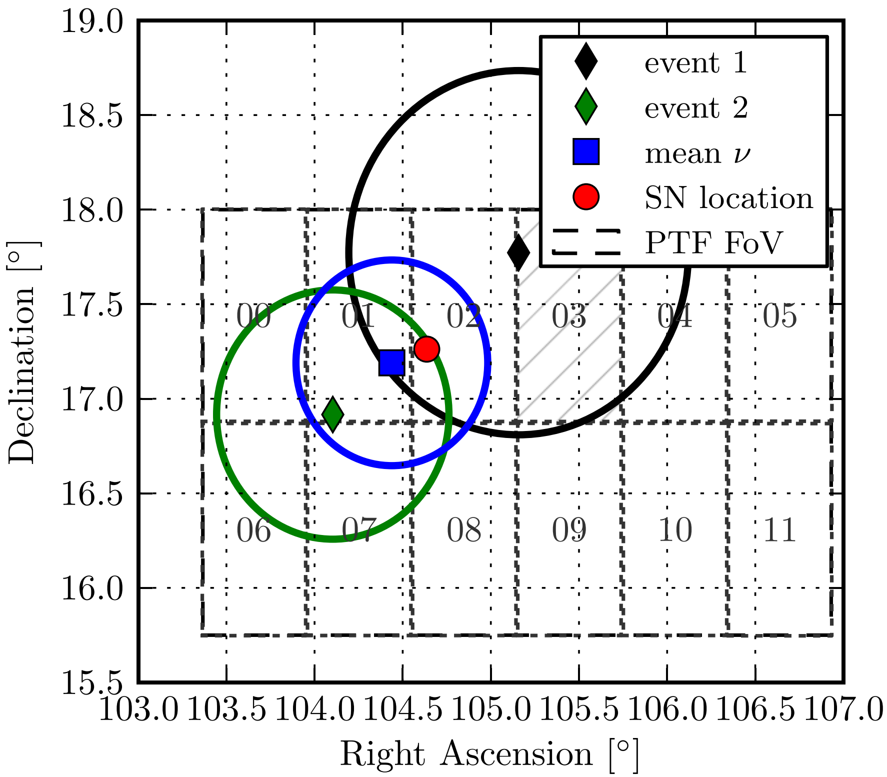
↓

EHE localization (~0.2-0.8 deg)
HESE localization (~2-9 deg)

↓

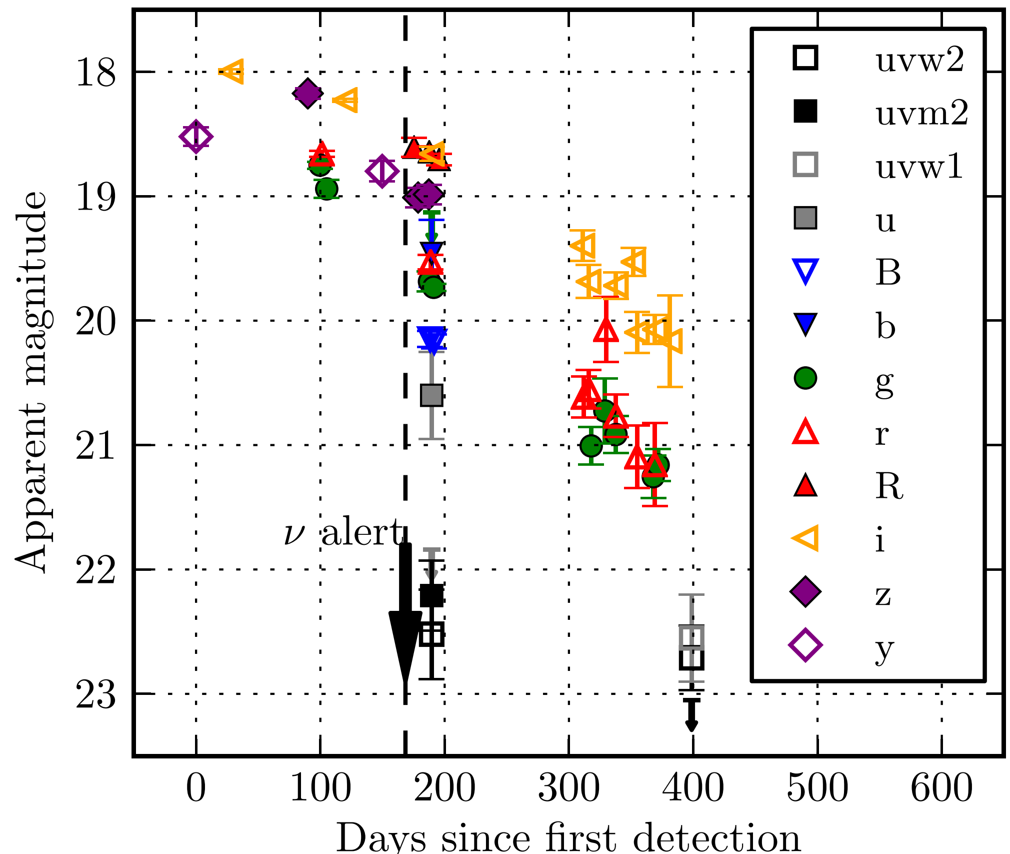
follow up observations
AS SOON AS POSSIBLE
for transients

Example of Multiplet Follow-Up: PTF12csy



A pair of two neutrinos

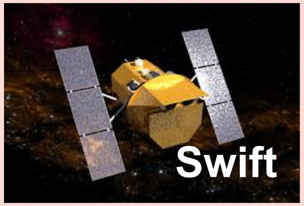
→ Type II supernova is found (PTF12csy)



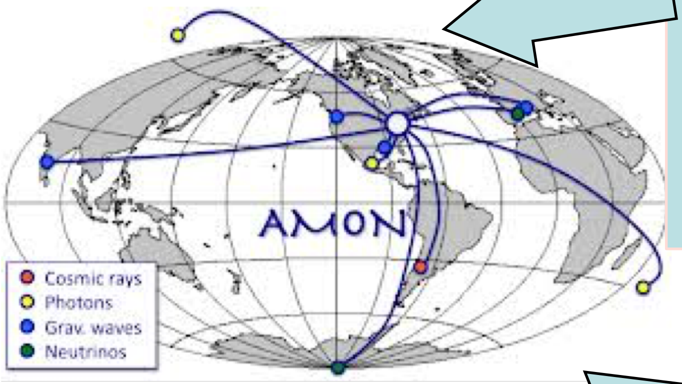
- Weak correlation
- Probability that it happens by accident ~ 3% (not significant)

Astrophysical Multi-Messenger Observatory Network (AMON)

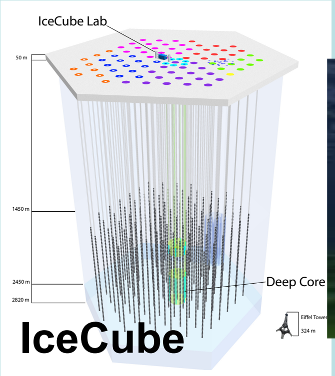
Light (elemag)



- send "public" alerts
- $\nu - \gamma$ subthreshold events



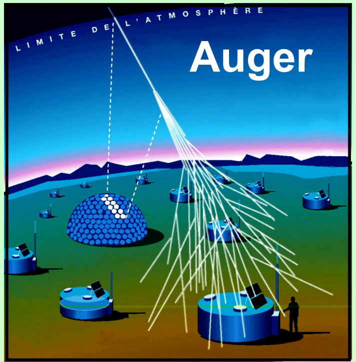
Neutrino (weak force)



AMON/GCN (present pipeline)
HESE track: 2-9 deg (90%)
HESE/EHE: 0.4-1.6 deg (50%)

Gravitational wave (gravity)

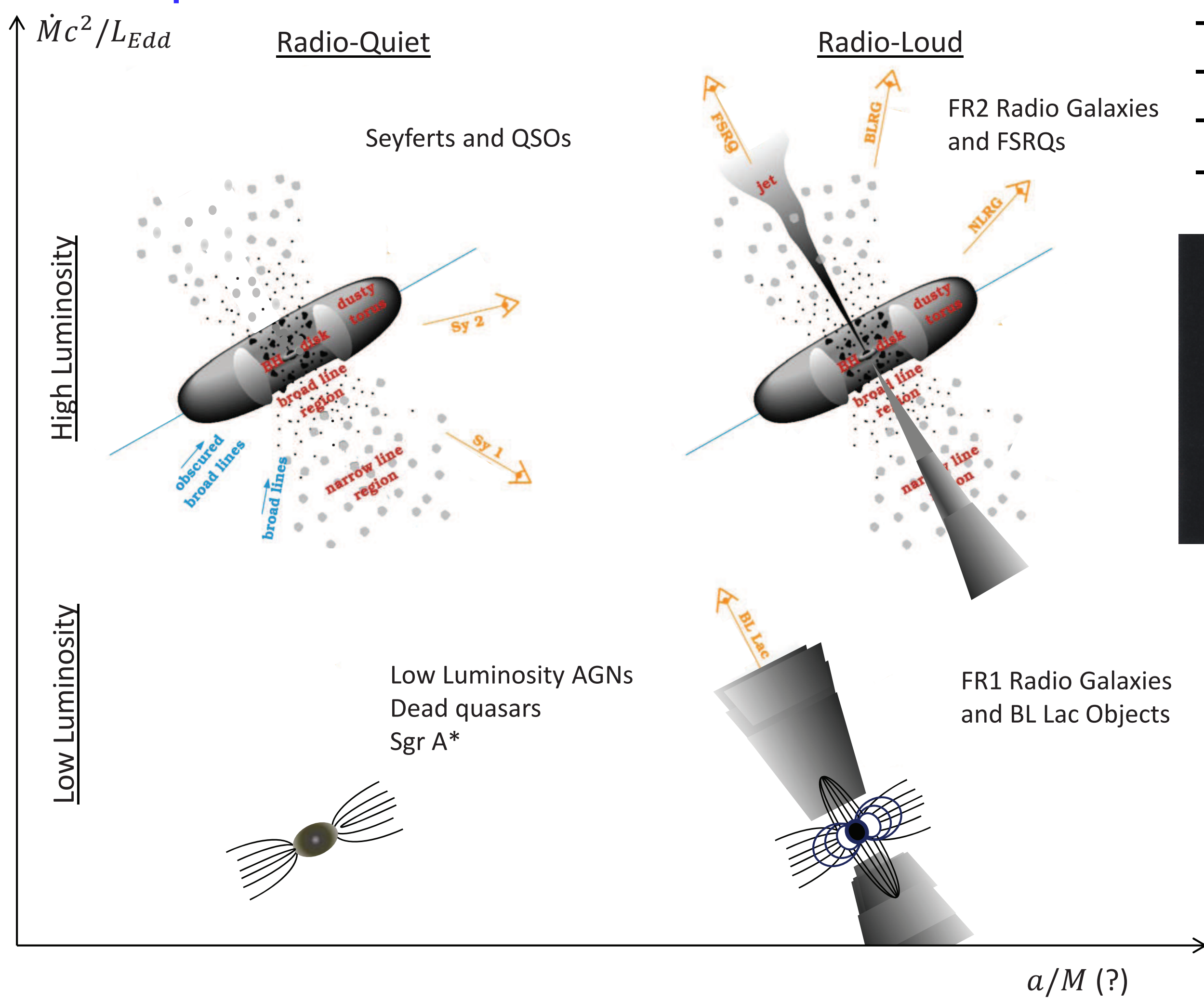
Cosmic-ray (strong force)



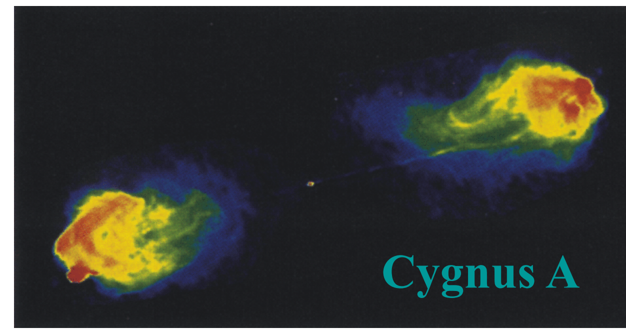
AGN

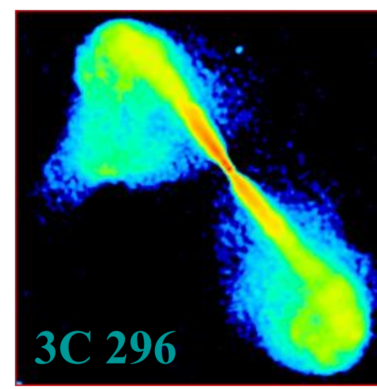
Active Galactic Nuclei & Diversity

- jets of radio-loud AGN (including blazars)
- weak jets of radio-quiet AGN
- disk-driven outflows
- accretion disk/corona
- black hole magnetosphere

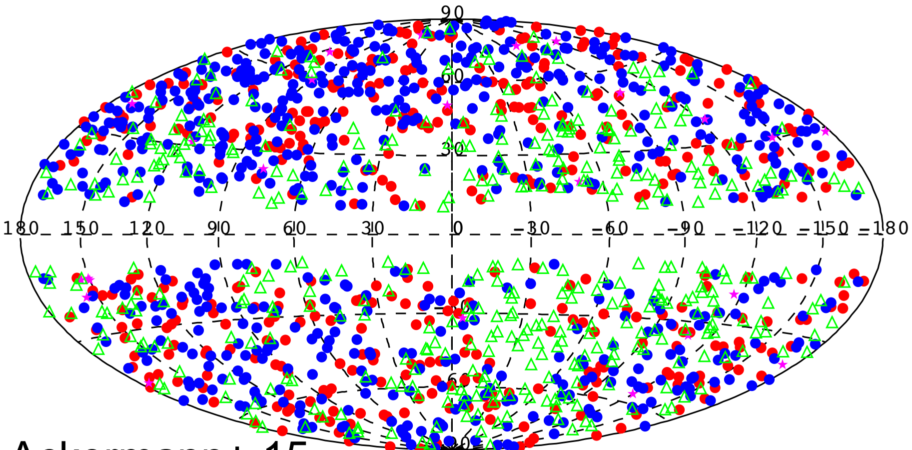


from Dermer

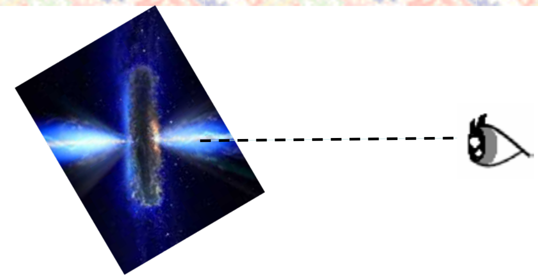




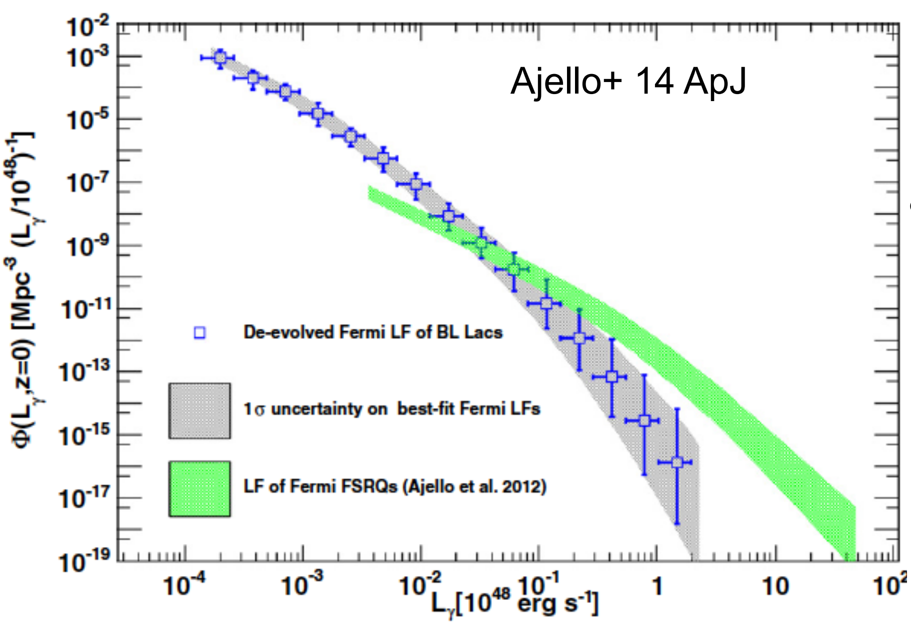
Extragalactic Gamma-Ray Sky Dominated by Blazars

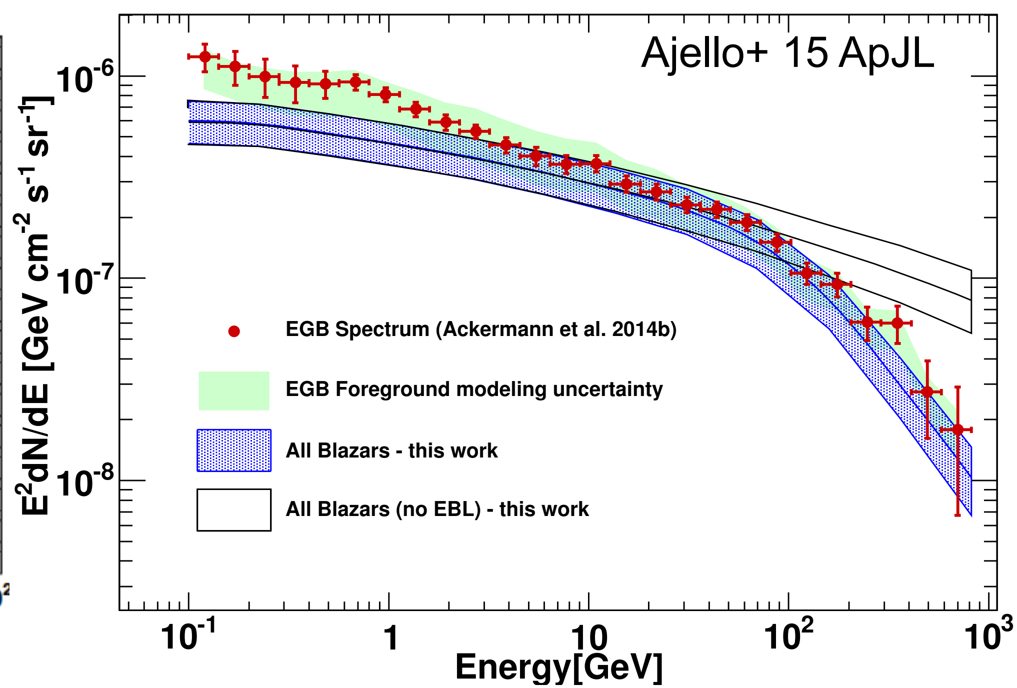


Ackermann+ 15

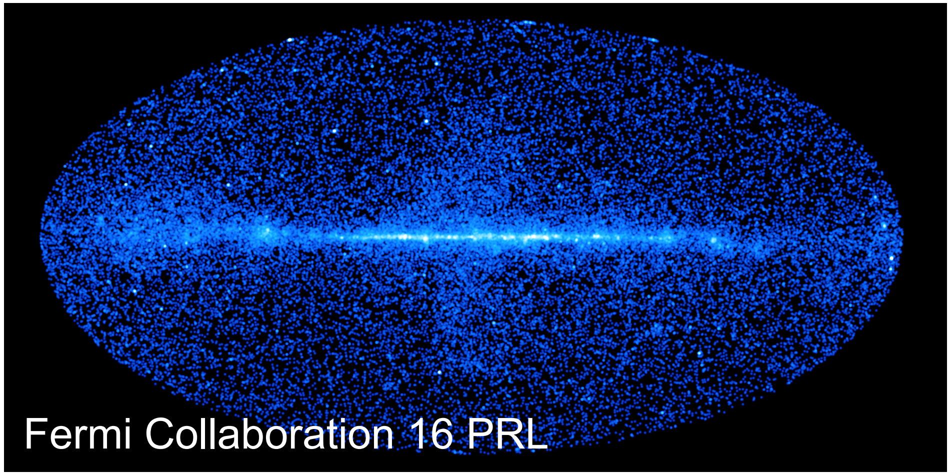


48 months of observations :
3LAC: 1563 sources
1444 AGNs in the clean sample
most of them are blazars





Digging Sub-Threshold Sources



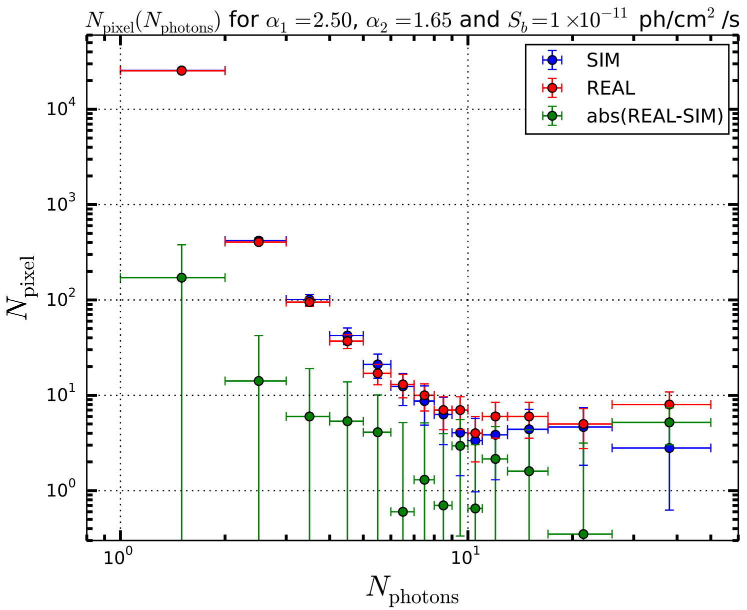
Data-driven approach

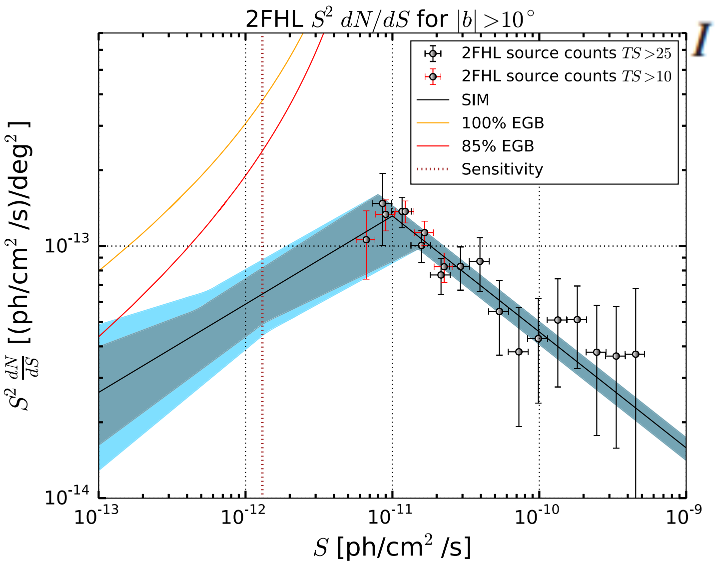
pixel-photon count distribution

⇩ **profile-based fitting**

source-count distribution

(# used in X-ray astronomy)





$$I = \int_0^{S_{\max}} S' \frac{dN}{dS'} dS'$$

PS contribution to total γ-ray bkg.

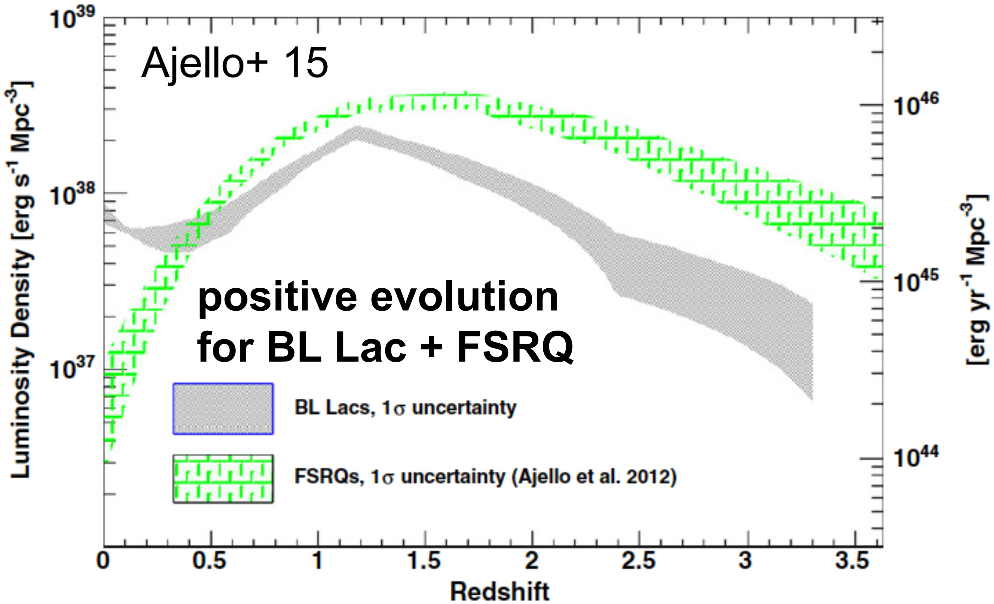
86%+16%-14%

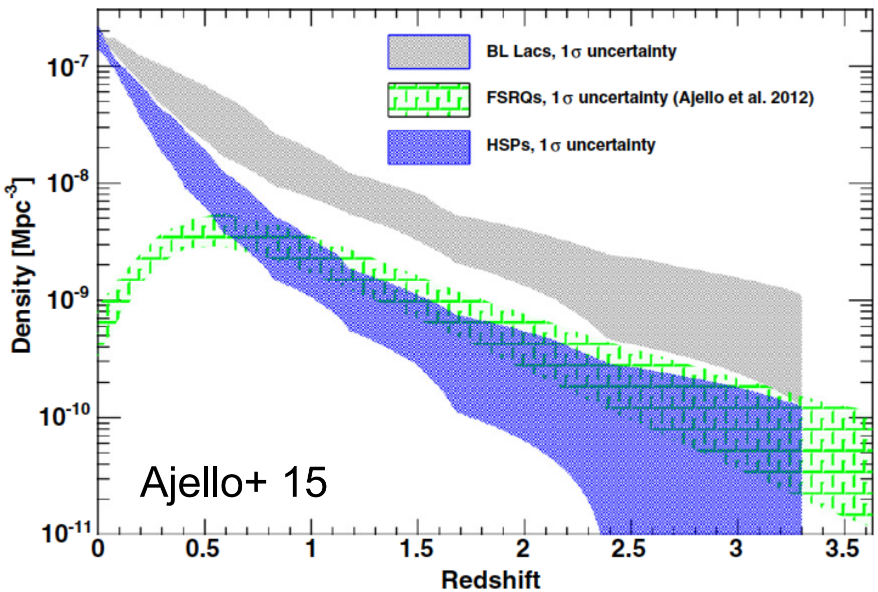
(Fermi 16 PRL)

68%+9%-8%

(Lisanti+ 16 ApJ)

Energy Budget & Redshift Evolution





Luminosity density

BL Lacs:

2×10^{45} erg Mpc^{-3} yr^{-1}

FSRQs:

$\sim(1\text{-}4)\times10^{44}$ erg Mpc^{-3} yr^{-1}

⇕

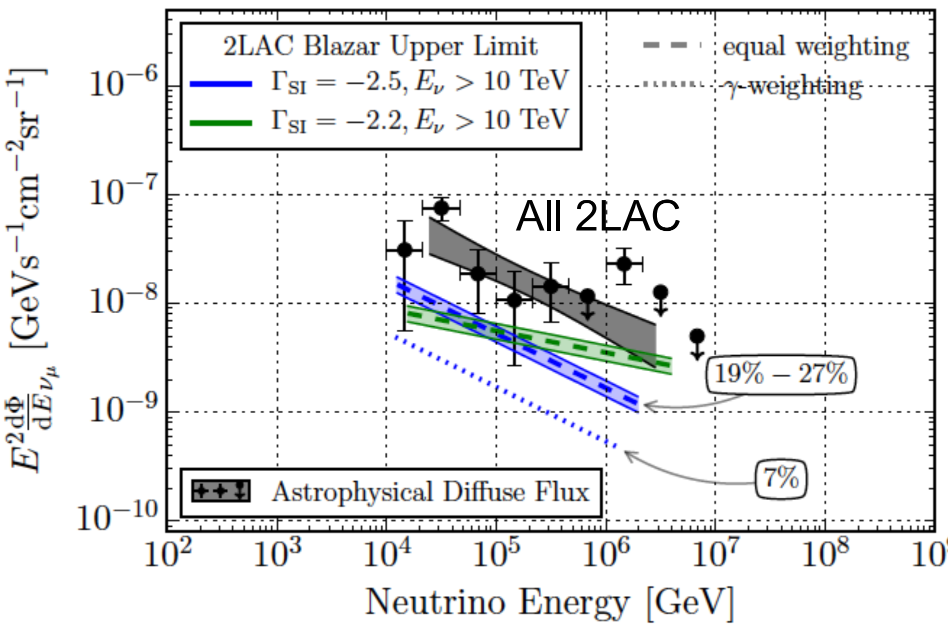
UHECR:

$\sim10^{44}$ erg Mpc^{-3} yr^{-1}

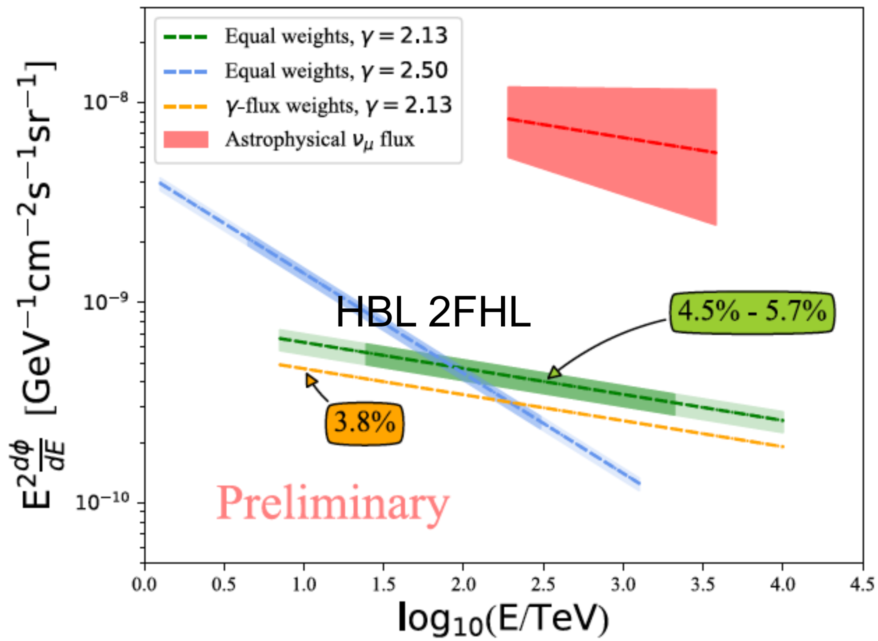
Candidate sources of UHECRs

Stacking Constraints on Blazars?

IceCube Collaboration 17 ApJ



IceCube Collaboration 17 ICRC



γ-ray bright blazars are largely resolved -> stacking analyses are powerful

- All 2LAC, FSRQ 3LAC, HBL 2FHL catalogues
  2LAC: blazar contribution < 7-27 % of the diffuse neutrino flux
  2FHL: blazar contribution < 4-6 % of the diffuse neutrino flux
  # some model-dependence (e.g., spectral templates)
- Important for theoretically-predicted luminosity relationships: $L_\nu \propto L_\gamma - L_\gamma^2$

(ex. Palladino, Rodrigues, Gao & Winter 18)

Multiplet & Auto-Correlation Constraints?

Blazars are rare objects in Universe -> search for event clustering is powerful

1. No more than one source of high-energy (E_μ>30-50 TeV) "multiplets"

$$N_s = b_{m,L} \left(\frac{\Delta\Omega}{3} \right) n_0^{\rm eff} d_{\rm lim}^3 < 1$$

$d_{\rm lim}$: horizon for a source with L

$b_{m,L}$: depends on analysis details

"upper" limits $\mathbf{n_0 < 10^{-7}\text{-}10^{-6}\ Mpc^{-3}\ (L_\nu/10^{42}\ erg/s)^{-3/2}}$

(Lipari 08, KM+ 12, Kowalski 14, Ahlers& Halzen 14, KM & Waxman 16, Ando+ 17, IceCube Collaboration 1807.11492 etc.)

2. IceCube flux ($E_\nu^2\Phi_\nu$ ~ 3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}) tells us the ν energy generation rate

$\mathbf{n_0\ L_\nu \sim 10^{44}\ erg\ Mpc^{-3}\ yr^{-1}}$ (for no redshift evolution)

3. Lower limits can be placed from the information 1+2

"lower" limits $\mathbf{n_0 > 10^{-5}\text{-}10^{-6}\ Mpc^{-3}}$

 # auto-corr. E^4C_P<4×10^{-19} GeV cm^{-2} s^{-2} s^{-1} -> similar limits within one order of magnitude

<~ 10% of the IceCube flux at 0.1 PeV (and more at higher energies)

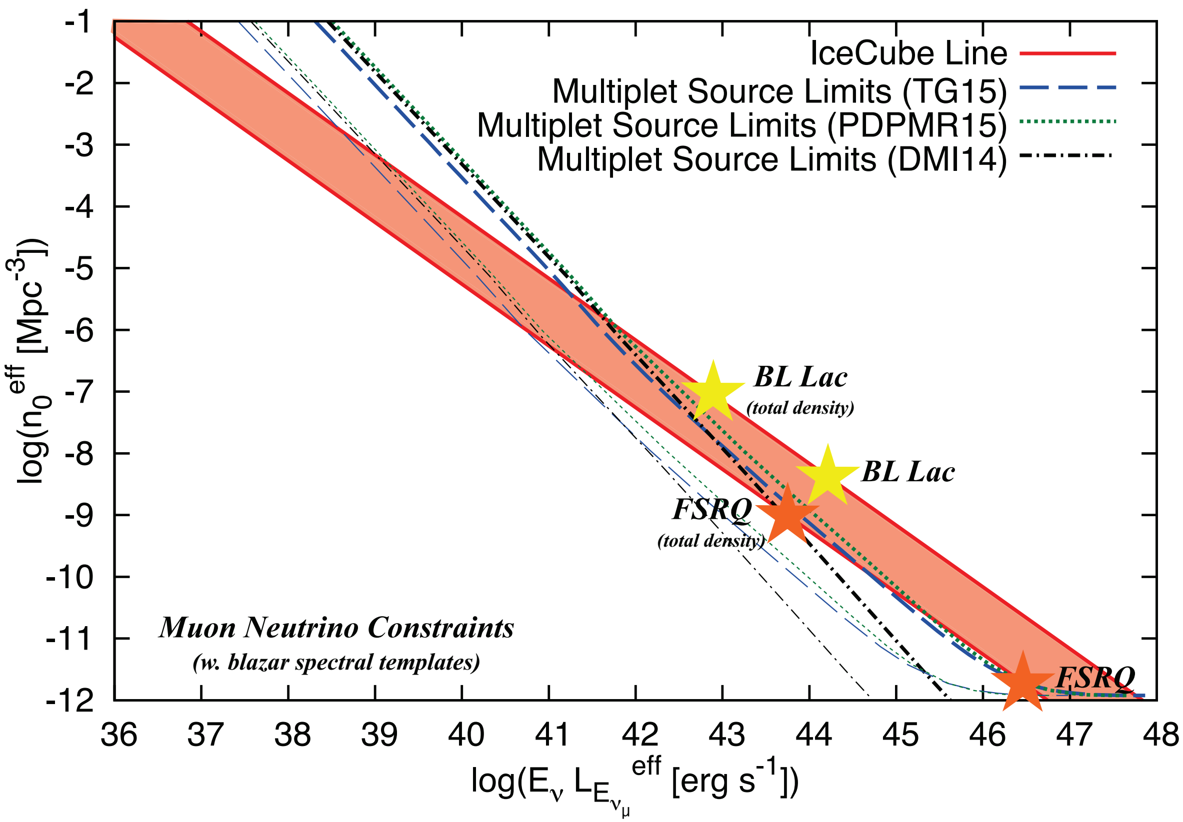
some model-dependence (e.g., spectral templates)

relevant for weaker redshift evolution (complementary to stacking limits)

Multiplet & Auto-Correlation Constraints?

Blazars are rare objects in Universe -> search for event clustering is powerful

(Lipari 08, KM+ 12, Kowalski 14, Ahlers& Halzen 14, KM & Waxman 16, Ando+ 17, IceCube Collaboration 1807.11492 etc.)



no more than one source of multiplets w. E_μ>30-50 TeV (auto-correlation gives similar constraints within ~10)

KM & Waxman 16 PRD

<~ 10% of the IceCube flux at 0.1 PeV (and more at higher energies)

some model-dependence (e.g., spectral templates)

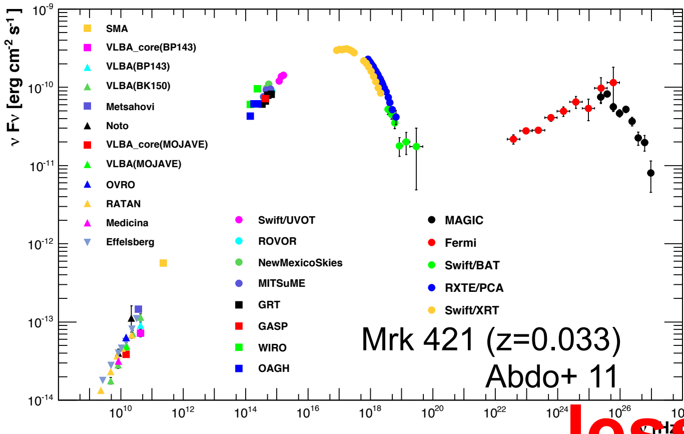
relevant for weaker redshift evolution (complementary to stacking limits)

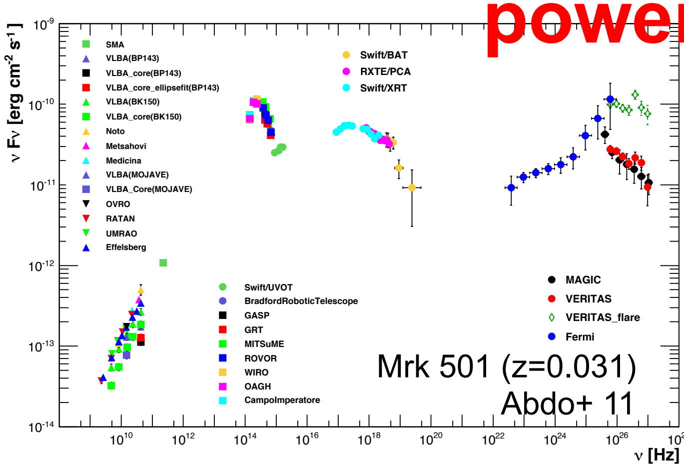
Blazars: Success of Multiwavelength Observations

Spectral energy distribution (SED): typically "two hump" structure

BL Lac objects (BL Lacs)

γ emission up to TeV energies

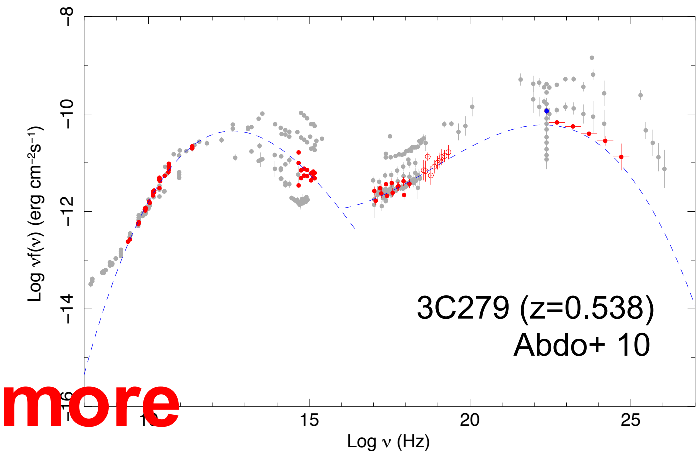


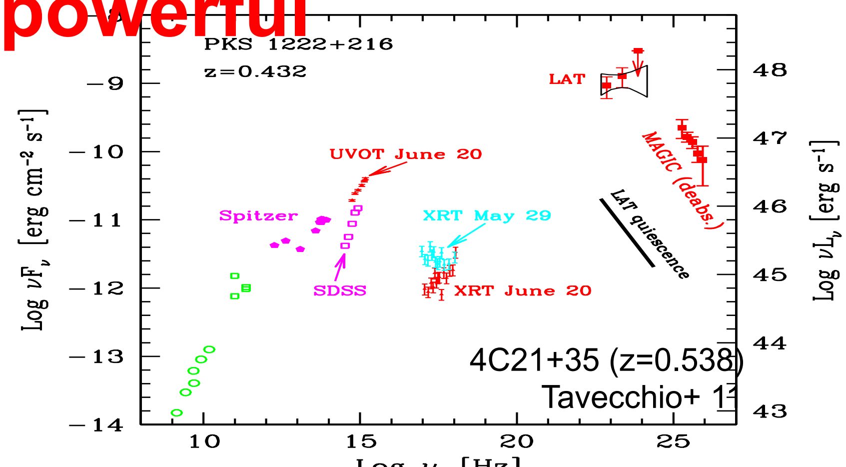


less powerful ⟺ **more powerful**

Flat-spectrum quasars (FSRQs)

mostly ν_{syn}<10^{14} Hz, GeV break





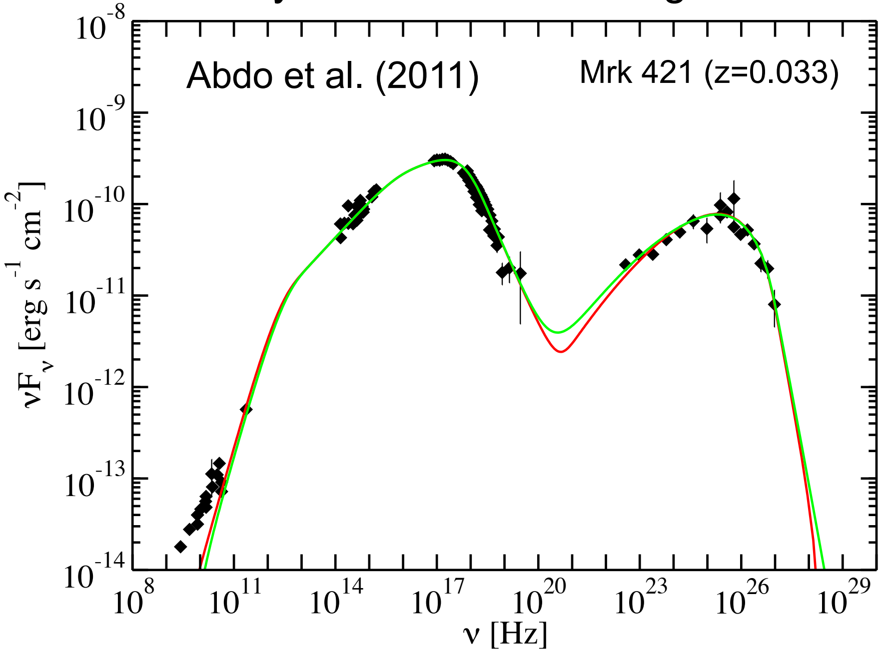
Leptonic Scenario

Broadband HE radiation: relativistic electrons accelerated in magnetized jets

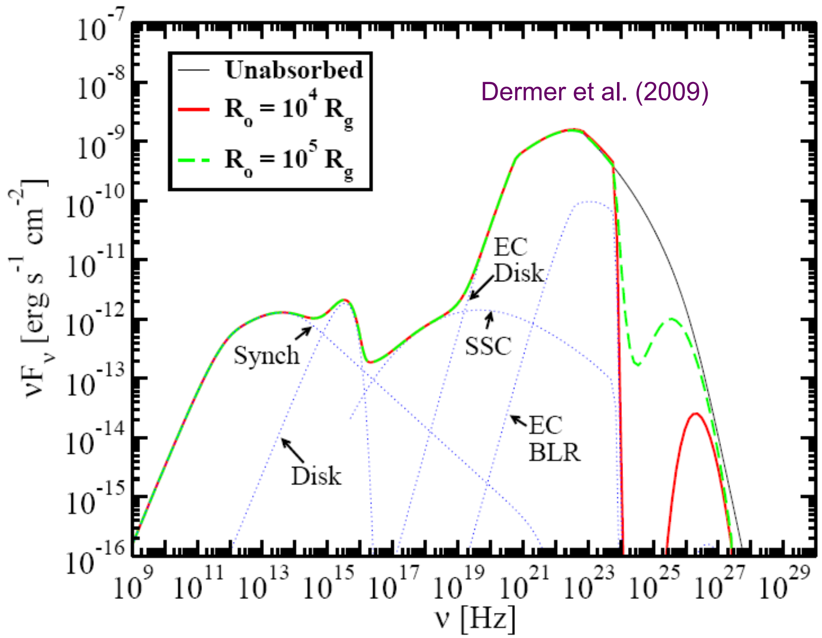
LE hump = synchrotron emission

HE hump = synchrotron self-Compton (SSC) or external inverse-Compton (EIC)

BL Lacs
synchrotron/SSC fitting

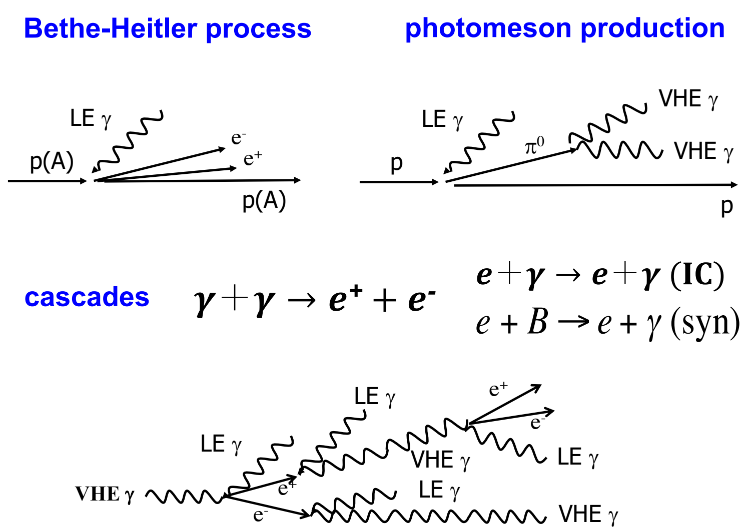


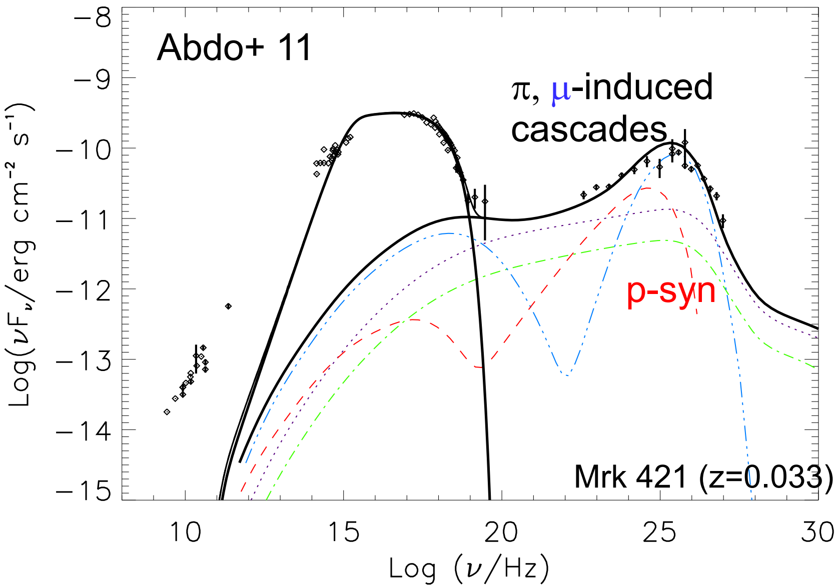
FSRQs
synchrotron/SSC+EIC model fits



- Basic tool: one-zone syn./SSC model w. syn. self-absorption and internal $\gamma\gamma$
- For EIC: bloadline regions (BLR), dust torus, (scattered) accretion disk

(Lepto-)Hadronic Scenario?





- Low-energy hump:
  synchrotron radiation from primary e

- High-energy hump:
  1. proton and ion synchrotron radiation
     $p+B \to p+\gamma$
  2. proton-induced cascades
     $p+\gamma \to p/n, \pi \to p/n, \nu, \gamma, e$

"SEDs can usually be fitted by both leptonic and leptohadronic scenarios"

common problems:
- large CR power is often necessary ($L_{cr} > L_{Edd}$, $\varepsilon_p > 100\text{-}1000\varepsilon_e$)
- more free parameters

smoking gun? -> neutrinos!

Open Questions

Source physics

- Gamma-ray origin: leptonic vs hadronic?
- CR acceleration process & magnetic fields?
- Jet properties (total power composition etc.)
- What can we learn about engines (jet-disk connection)?

Origins of extragalactic background emissions

- Can AGN jets be the dominant origin of UHECRs?
- Can be blazars be the dominant origin of HE neutrinos?
- Interplay of BL Lacs, FSRQs, FR I galaxies & FR galaxies etc.?

Ions? Maximum CR Energy

~10% of AGN have powerful jets: “radio-loud AGN”
~0.1-1% of them are FR II galaxies and FSRQs (on-axis)

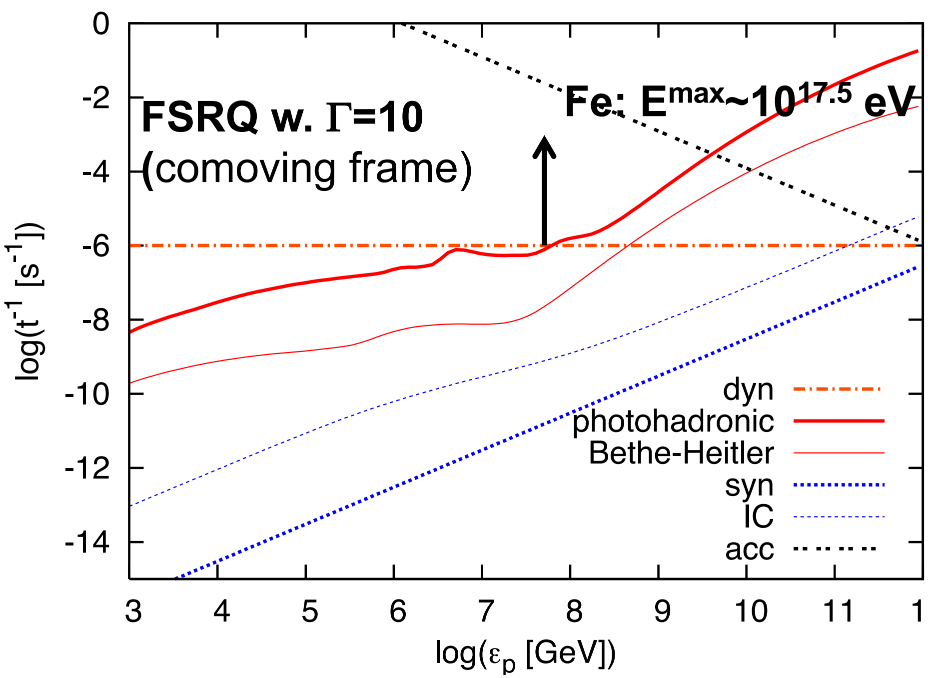
Hillas condition: $E_A^{max}=ZeB'\Gamma R'$
nearby FR I & blazars seen by Fermi

ID	Source	d_L [Mpc]	$E_A^{max\,(\dagger)}/Z[10^{19}]$ [eV]
1	CenA(core)	3.7	0.004-3.3
2	M87	16.7	0.040
3	NGC1275	75.3	4.6
4	NGC6251	104	0.27
5	Mrk421	130.0	0.29
6	Mrk501 (h.[g],1997)	146.0	0.17-1.5
7	Mrk501 (l.[g],1997)	146.0	0.28-1.5
8	Mrk501 (l.[g],2007)	146.0	0.2
9	Mrk501 (l.[g],2009)	146.0	0.12-0.6
10	1ES1959+650(h.[g])	206	0.12-2.9
11	1ES1959+650(l.[g])	206	1.3
12	PKS2200+420/BL Lac	307.0	1.1
13	PKS2005-489	316.0	3.1
14	WComae	464.0	0.37-0.57
15	PKS2155-304	533.0	0.23

KM, Dermer, Takami, & Migliori 2012 ApJ

$E^{max} < Z10^{19}$ eV for FSRQs
$p\gamma/A\gamma$ losses are very important

FSRQs cannot be 10^{20} eV nuclei sources



Ions? Maximum CR Energy

~10% of AGN have powerful jets: "radio-loud AGN"
Most of them are FR I galaxies and BL Lacs (on-axis)

Hillas condition: $E_A^{max}=ZeB'\Gamma R'$
nearby FR I & blazars seen by Fermi

ID	Source	d_L [Mpc]	$E_A^{max\,(f)}/Z[10^{19}]$ [eV]
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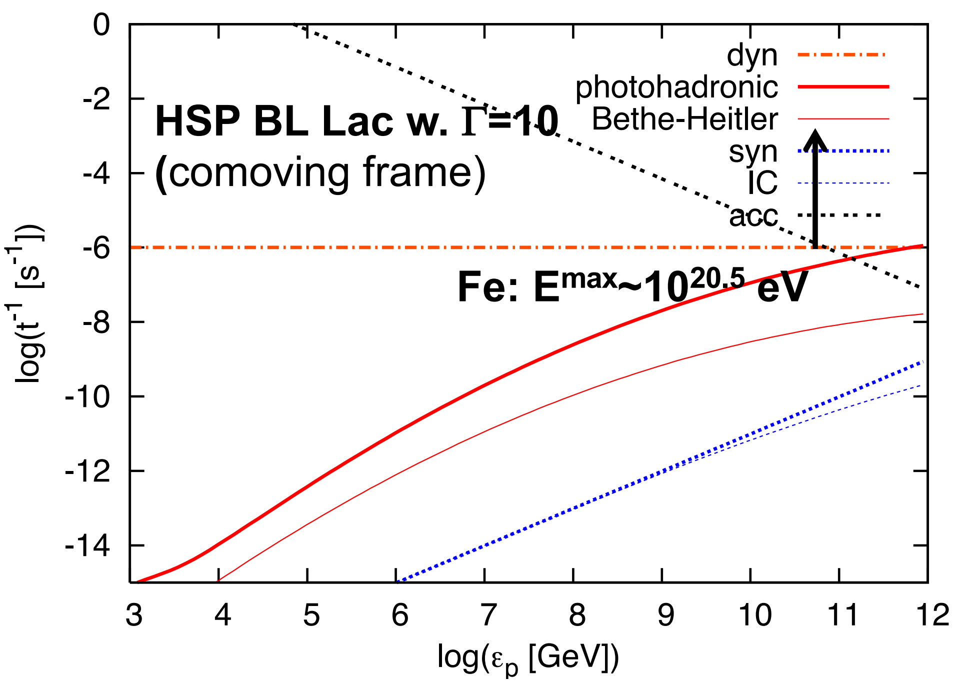
KM, Dermer, Takami, & Migliori 2012 ApJ

$E^{max} \sim Z\mathrm{x}(10^{18}\text{-}10^{19})$ eV for BL Lacs
$p\gamma/A\gamma$ losses are irrelevant

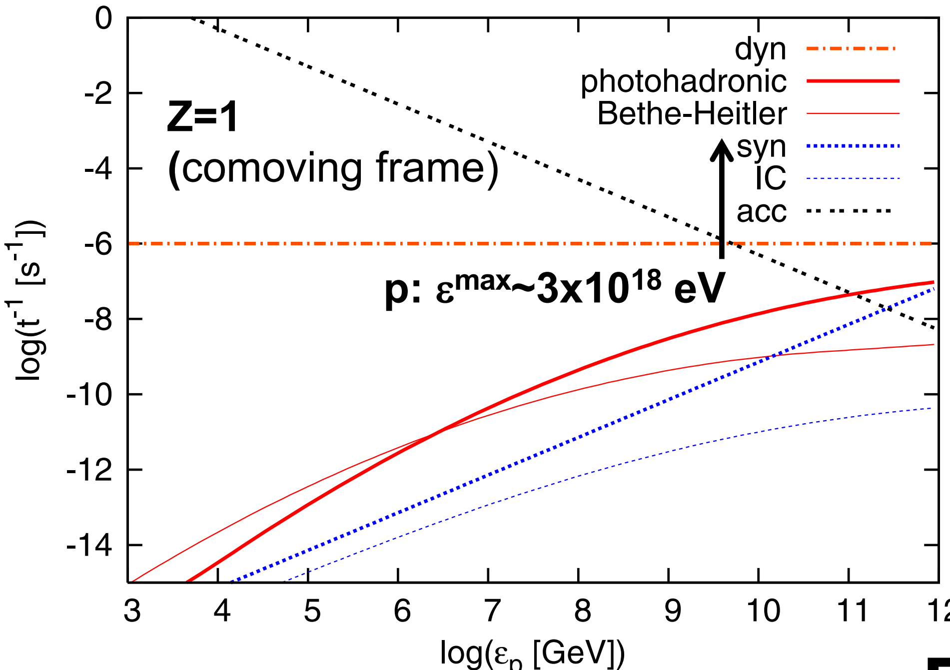
BL Lacs could be 10^{20} eV nuclei sources



Proton Maximum Energy?

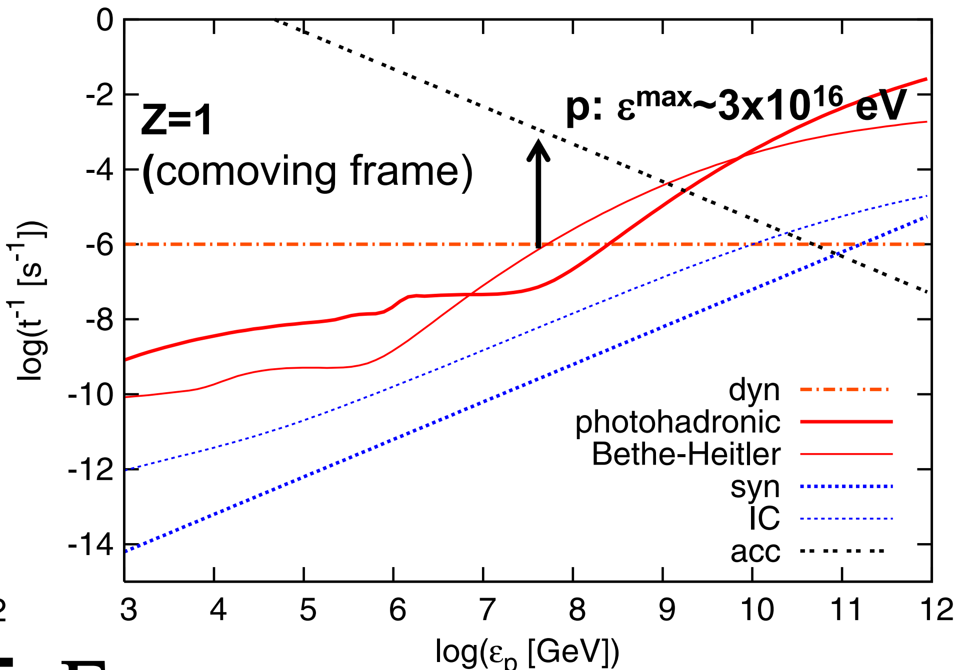
Some AGN have powerful jets: “radio-loud AGN”
On-axis objects are called “blazars = BL Lacs + FSRQs”

BL Lac (low-power blazar)



E^{max} ~ 3x10^{19} eV
limited by dynamical time

FSRQ (high-power blazar)

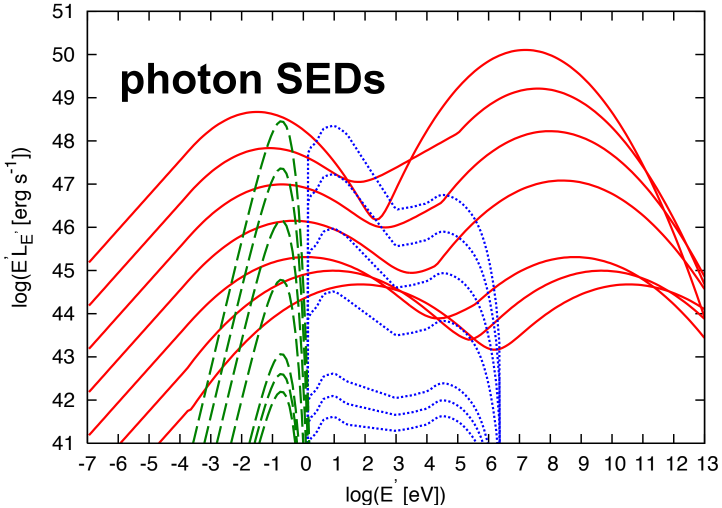


E^{max} ~ 3x10^{17} eV
limited by $p\gamma$ losses

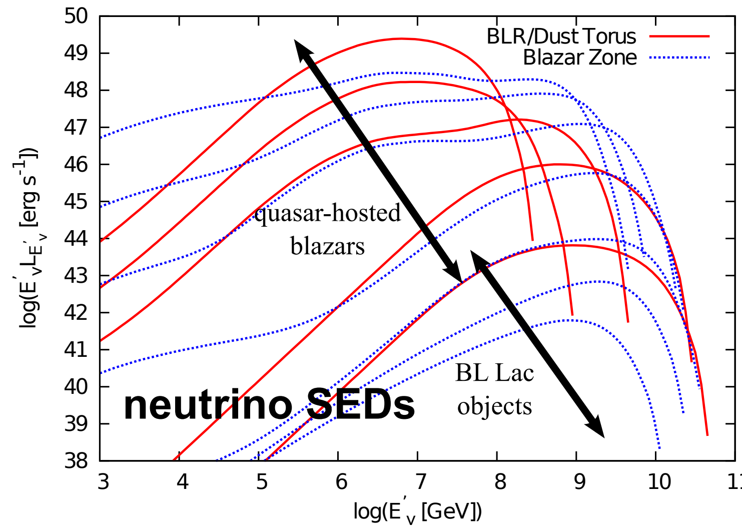
$E \sim \Gamma\varepsilon$

Such consideration is now possible thanks to the multi-wavelength data

Neutrino SEDs



power-law
CR spectrum
(s=2.)



effective optical depth for pγ:

$\mathbf{f_{p\gamma} \sim n_\gamma(\kappa_p \sigma_{p\gamma})(\Gamma c \delta t)}$

L_ν increases w. L_γ
(positive luminosity weight)

interactions w. internal radiation field (Δ-res.+direct prod.)

$$f_{p\gamma}(E'_p) \simeq \underline{7.8 \times 10^{-4}} L^s_{\mathrm{rad},45} \Gamma_1^{-4} \delta t'^{-1}_5 (E'_s/10\ \mathrm{eV})^{-1} \begin{cases} (E'_\nu/E'^b_\nu)^{\beta_h - 1} \\ (E'_\nu/E'^b_\nu)^{\beta_l - 1} \end{cases}$$

interactions w. external radiation fields (Δ-res.+multi-pion)

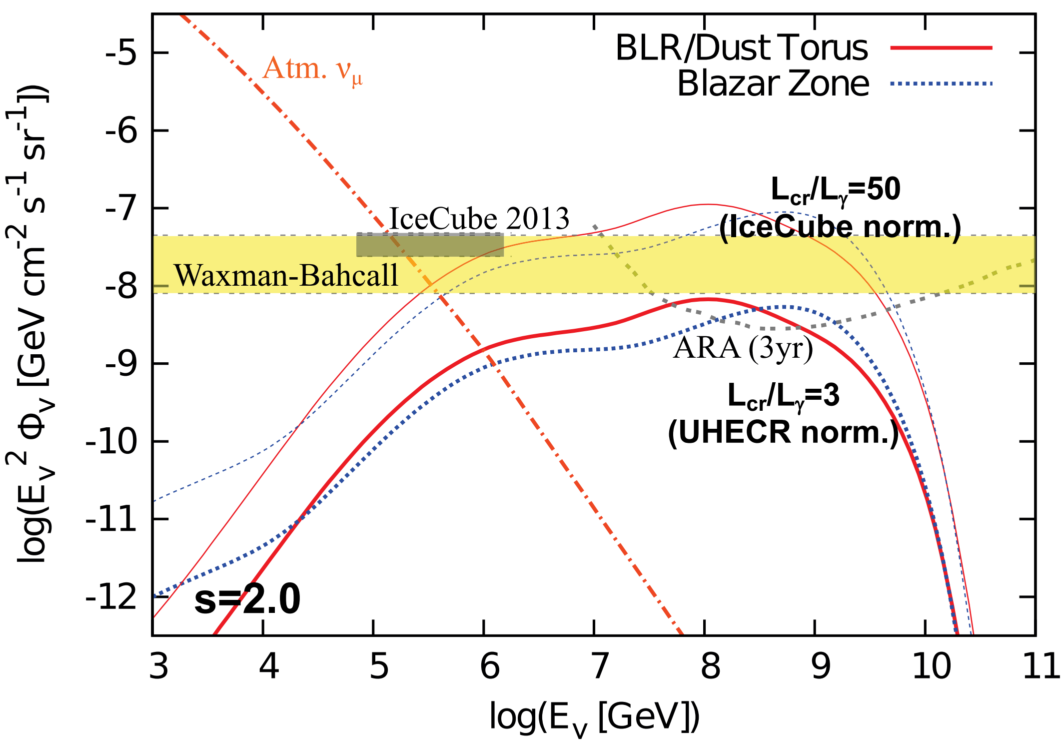
$$f_{p\gamma} \approx \hat{n}_{\mathrm{BL}} \sigma^{\mathrm{eff}}_{p\gamma} r_{\mathrm{BLR}} \simeq \underline{5.4 \times 10^{-2}}\ f_{\mathrm{cov},-1} L^{1/2}_{\mathrm{AD},46.5}$$

$$f_{p\gamma} \simeq \underline{0.89}\ L^{1/2}_{\mathrm{AD},46.5} (T_{\mathrm{IR}}/500\ \mathrm{K})^{-1}$$

independent of Γ

Blazars as Powerful EeV ν Sources

- FSRQs: efficient ν production, UHECRs largely destroyed
- BL Lac objects: less efficient ν production, UHE nuclei survive



KM, Inoue & Dermer 14 PRD

- PeV-EeV ν: pγ w. BLR & dust-torus photons → unique shape
- Strong prediction: cross-correlation w. known <100 bright quasars
- UHECR norm. → lower than the IceCube flux but EeV ν detectable

Neutron Beam Model for Two Flares of TXS 0506+056

1. CR neutrons are produced in the blob by e.g., disintegration of nuclei
2. Neutrinos are produced in the extended region via np or nγ interactions
   Gamma-ray emission in the GeV range is mostly leptonic (Keivani, KM+ 18)
   Associated hadronic cascades are "triply" suppressed in the X-ray range

In principle, this model can explain both 2017 and 2014-2015 flares with the single picture as a natural extension of the single-zone modeling (R_{ext} ~ typical scale of the collimation shock and giant molecular clouds)

$$\varepsilon_\nu L_{\varepsilon_\nu} \simeq 3.8 \times 10^{46}\ \mathrm{erg\ s^{-1}} \left(\frac{2K}{1+K}\right)\left(\frac{f_{n\gamma/np}\varepsilon_n L_{\varepsilon_n}}{10^{47}\ \mathrm{erg\ s^{-1}}}\right)$$

$$L_n^{\rm fl} \simeq 3.0 \times 10^{49}\ \mathrm{erg\ s^{-1}}\ f_{A\gamma}(\theta_{\rm beam}/0.05)^{-2}(\epsilon_{\rm cr}/0.2)(b_{\rm fl} f_{\rm fl}^{-1}/10)\ (P_j/0.3L_{\rm Edd})(M_{\rm BH}/10^9\ M_\odot)$$

- 2017 flare
  CR beam production occurs at large radii such that $\tau_{\gamma\gamma}<1$ (ν–γ flare)
  ex. $f_{A\gamma}$ ~ 0.1 → real-time N_ν ~ 0.1 yr^{-1} & point-source N_ν ~ 1 yr^{-1}
- 2014-2015 flare
  CR beam production occurs at small radii such that $\tau_{\gamma\gamma}>1$ (orphan flare)
  ex. $f_{A\gamma}$ >~ 1 → point-source N_ν ~ 10 yr^{-1}

KM, Oikinomou & Petropoulou 18 ApJ

Issues in Jet-Cloud Models

Neutrinos could be produced by pp interactions if jet-cloud collisions occur

- Isotropization problem

  unavoidable for the system w. the CR beam & non-relativistic target
  - jets must form a relativistic shock with dense clouds
  - magnetic fields: Γ B ~ Γ $10^3(R_s/R)$ G ~ 10 G at 10^{17} cm for Γ~10
  - $r_L << R \rightarrow$ CR ions must be isotropized

  serious energetics issue! (but n-beam model can overcome this issue)

- Heavy-jet problem
  unavoidable if pp interactions occur inside the relativistic jet
  - required luminosity largely exceeds the Eddington luminosity

- Origin?
  ad hoc: stars may be OK but stellar clusters or BLR clouds are speculative

- Survival?
  jet-cloud interactions easily cease (pushed by the jet or crossing the jet)

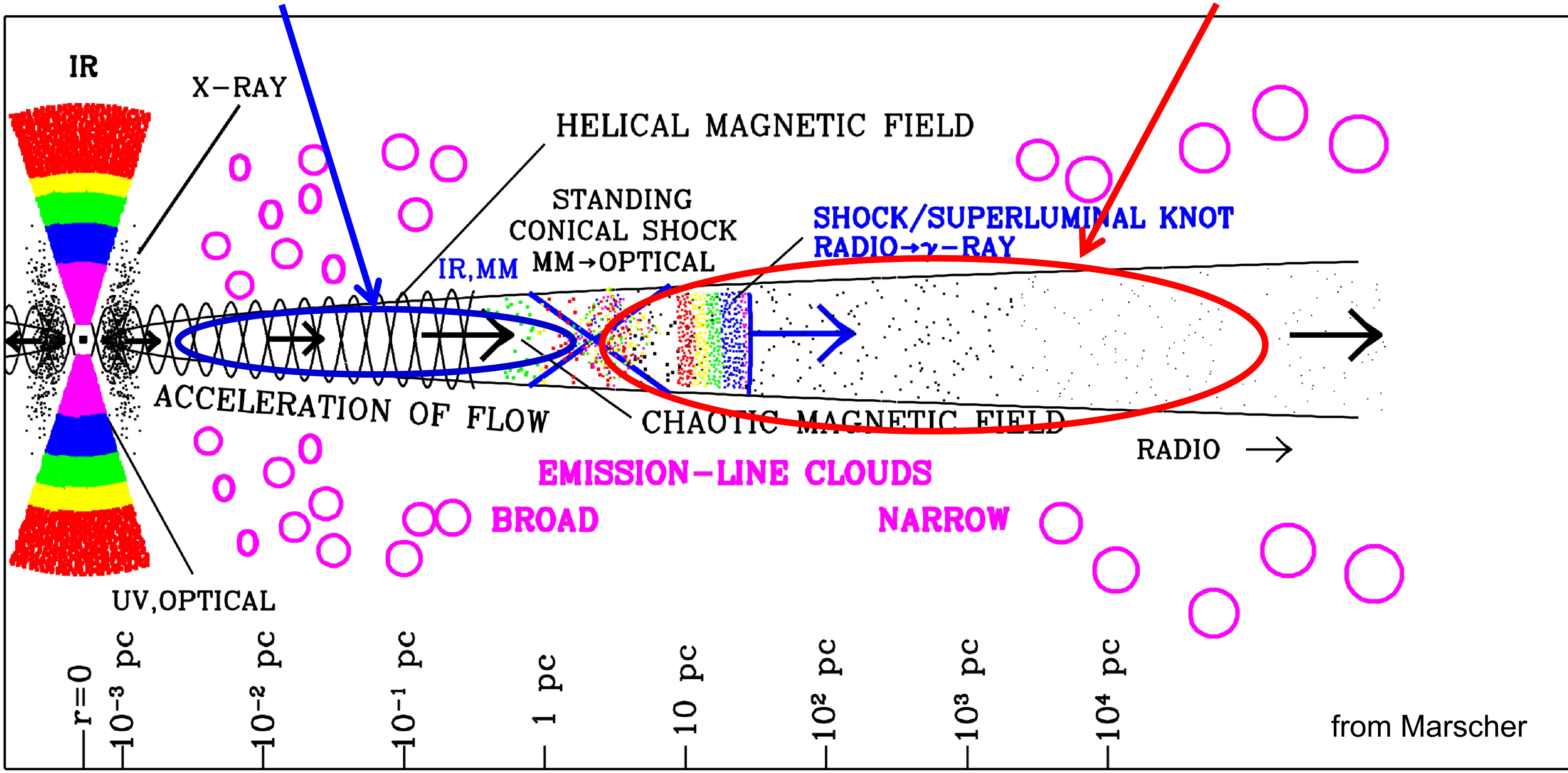
Particle Acceleration in AGN Jets?

Inner jet (blazar zone)

r ~ 10^{16}-10^{17} cm, B ~ 0.1-100 G, Γ ~ 10

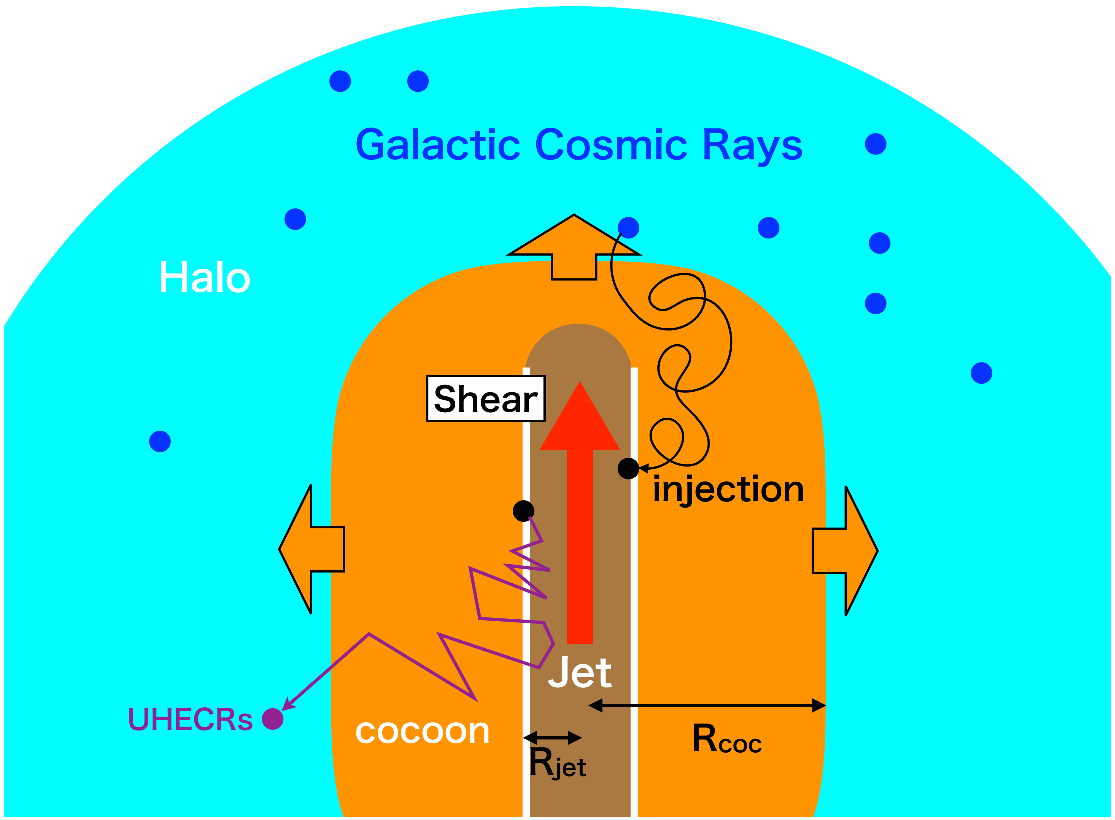
Large-scale jet, cocoon, hot spot

r ~ 10^{20}-10^{21} cm, B ~ 1μG -1 mG, Γ ~ 1

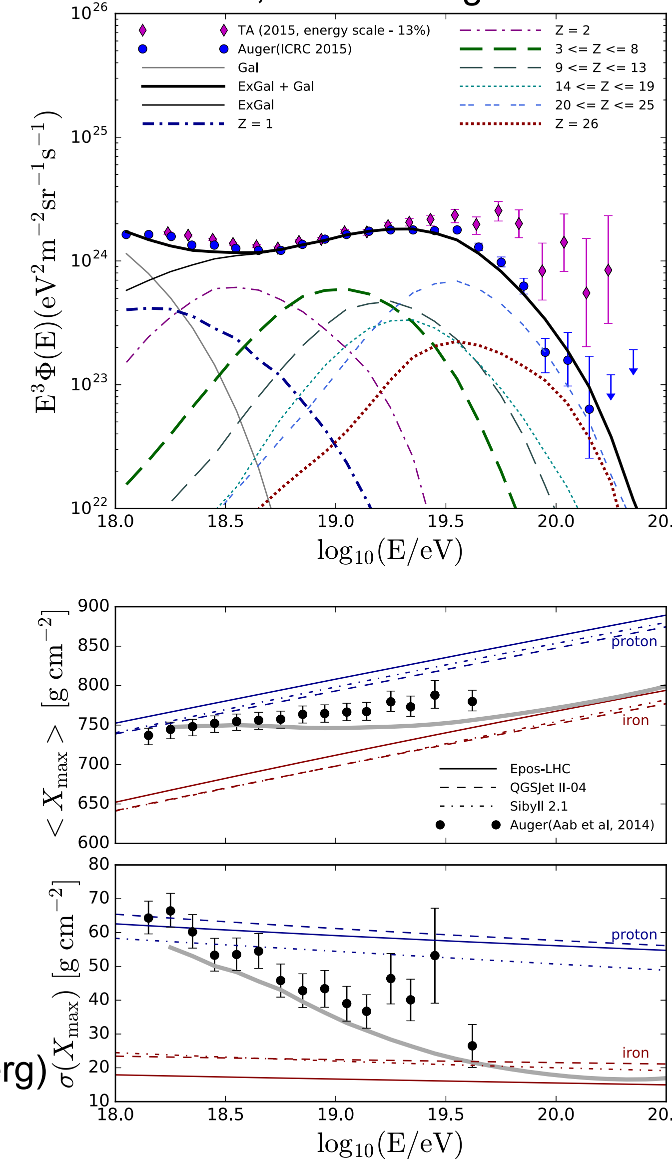


Hillas condition: E_{max} ~ZeBrΓ ~ 3x10^{19} eV Z (Γ/10) (B/0.1 G) (r/10^{17} cm)

Example: Shear Acceleration at Kpc Scale Jets



Kimura, KM & Zhang 18 PRD



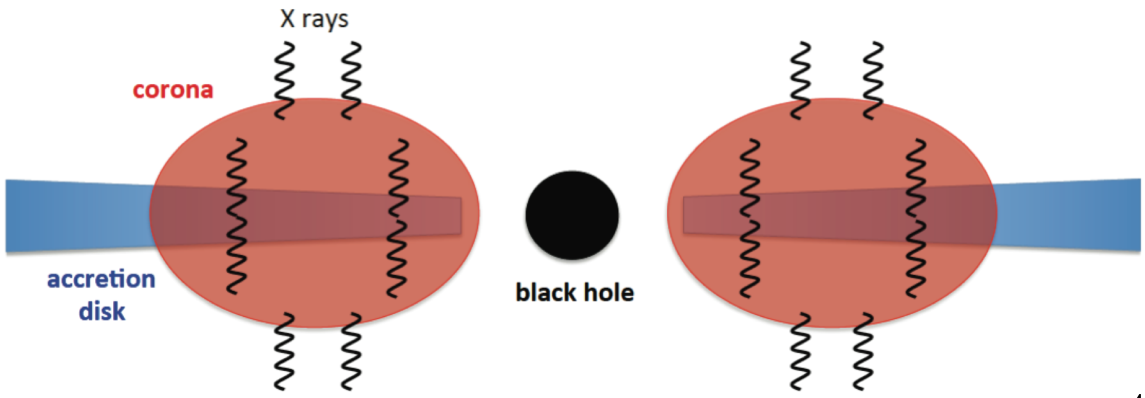
- High abundance of nuclei is challenging
- Re-acceleration of “galactic” CRs by AGN jets

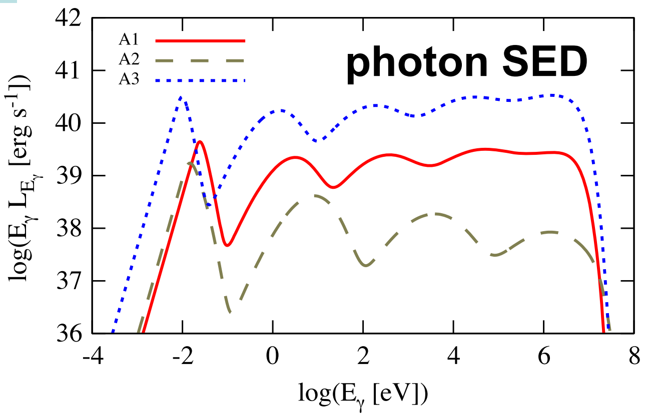
shear acc. (ex. Stawarz & Ostrowski), one-shot acc. (Gallant & Achterberg)

Neutrino Emission from Cores of Active Galactic Nuclei

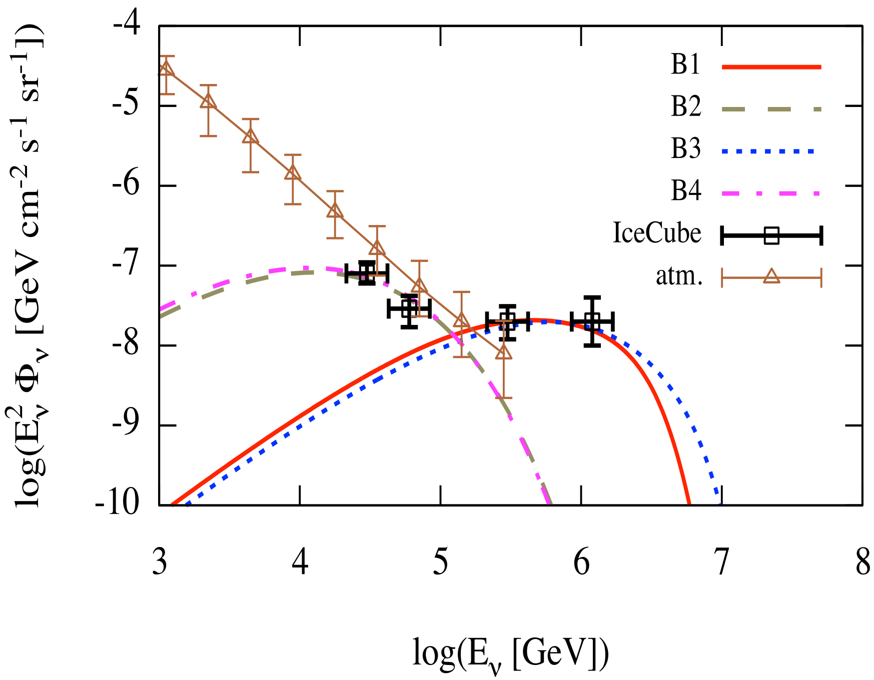
Radiatively Inefficient Accretion Flow (RIAF)

Kimura, KM & Toma 15 ApJ



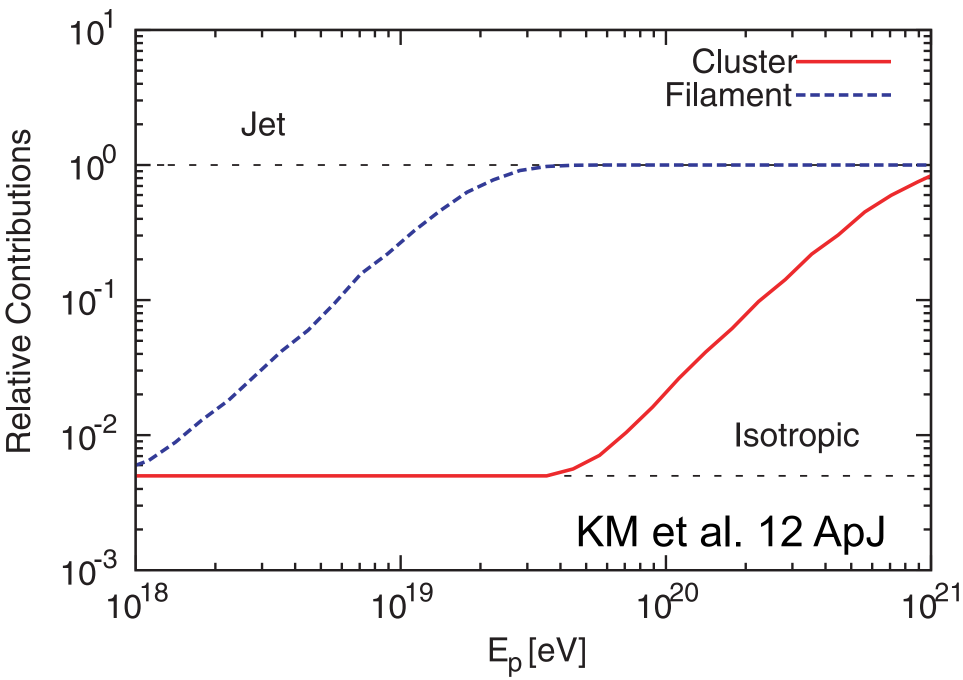


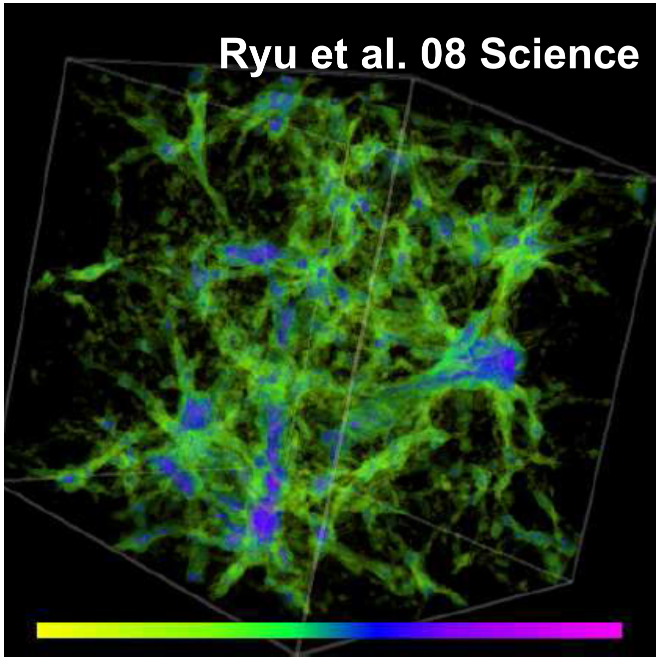
- RIAF plasma can be collisionless -> CR acceleration in disk/corona
- CR acceleration processes: magnetic reconnection, shear, turbulence, accretion shocks, potential gap in the BH magnetosphere
- Both pp & pγ interactions should occur
- >10 GeV γ rays do not escape



Fate of Beamed Cosmic Rays

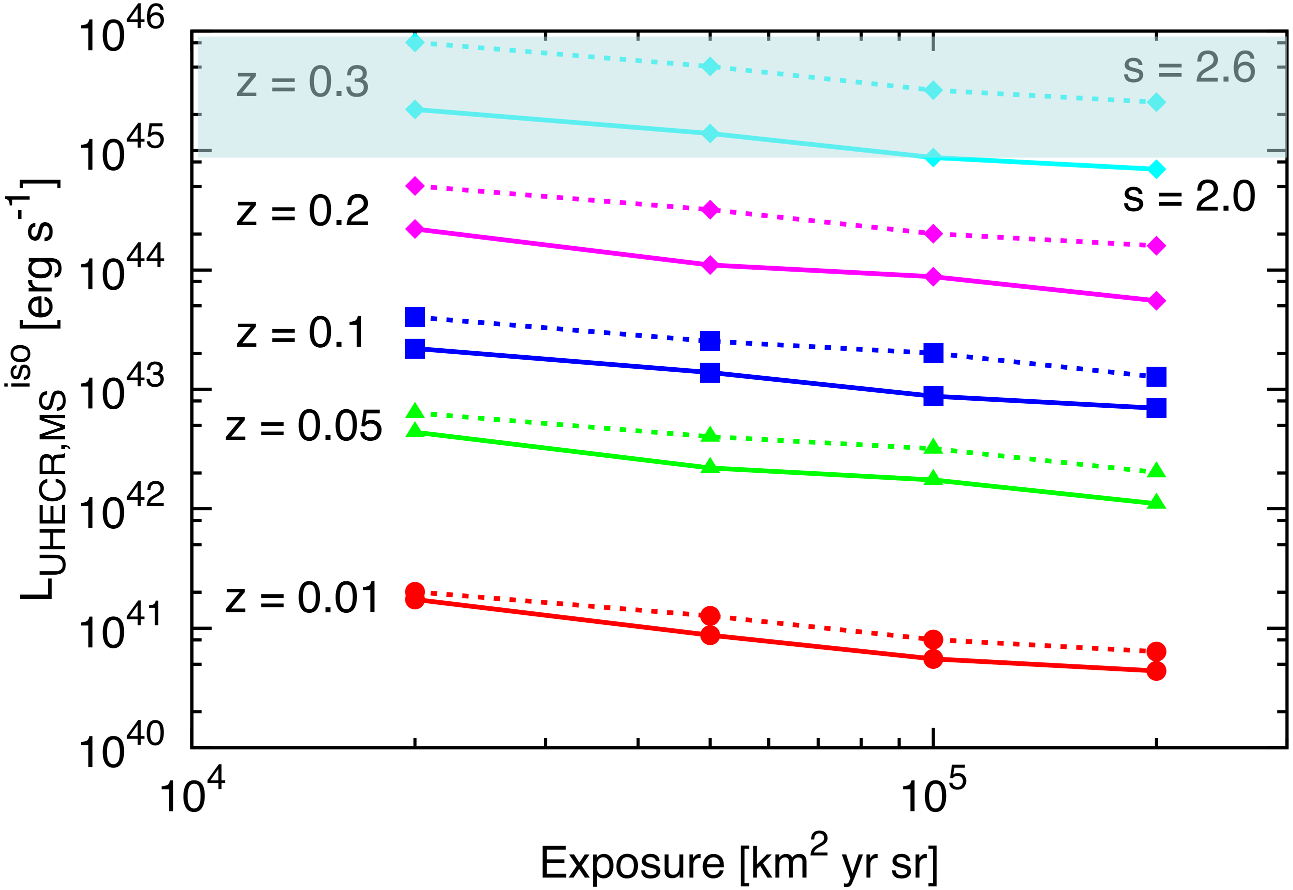
UHECR beams should be "isotropized" by many reasons
- No blazars within the GZK horizon (~100 Mpc)
- structured extragalactic magnetic fields (clusters: ~1-10 μG, filament: ~10-100 nG) (KM et al. 12 ApJ)
- radio bubbles/lobes of AGN (~ 1-10 μG) (Dermer et al. 09, Fang & KM 18)
- These magnetic fields also affect the observed CR spectra





“Isotropy” Constraints

Takami, Murase & Dermer 16 ApJ

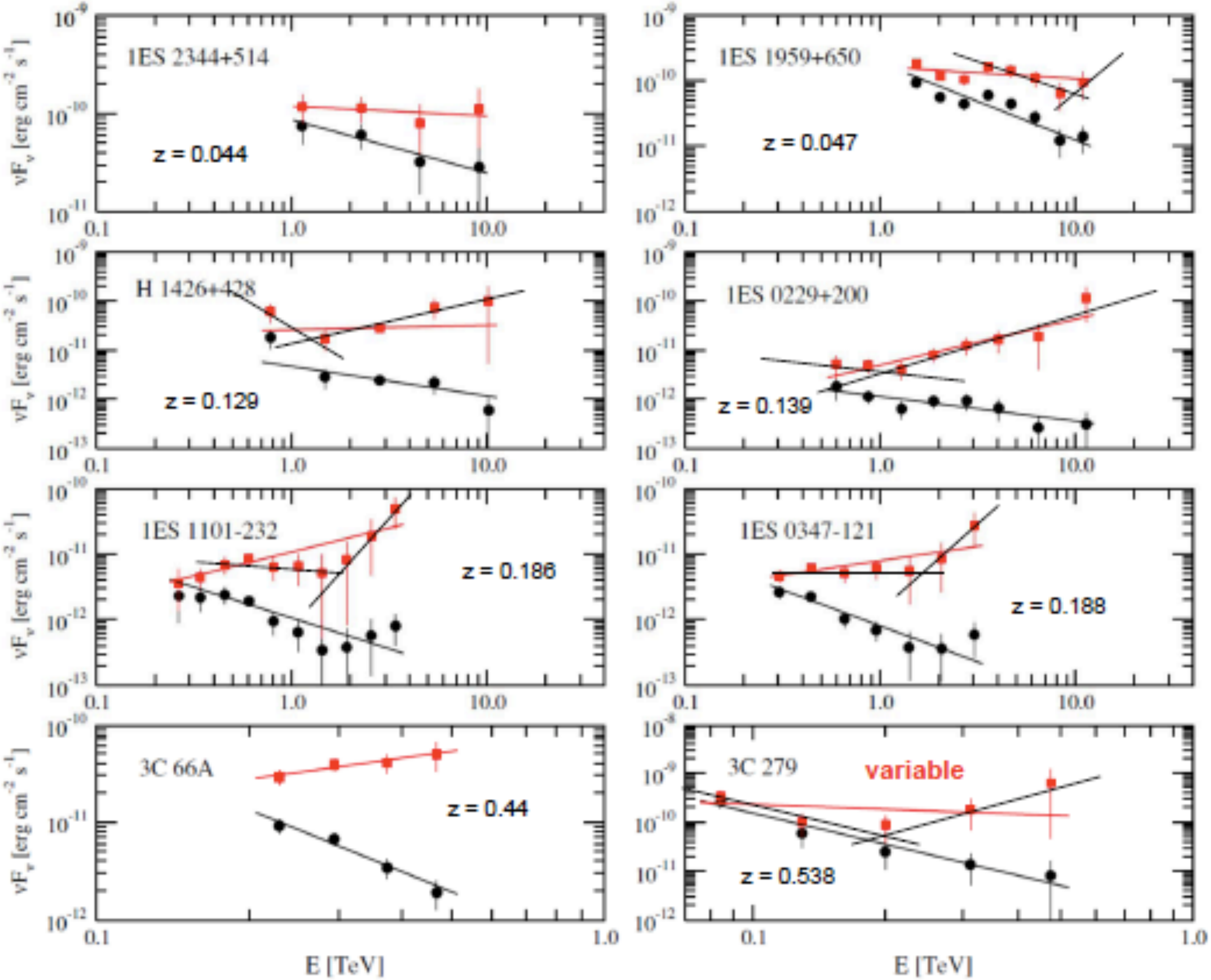


$E_{max} \sim Z\ 10^{19}$ eV

No small-scale anisotropy → $n_s > 10^{-4}$-10^{-3} Mpc^{-3} at 10^{19} eV

No powerful UHECR emitters -> support “isotropization”

Possible Hardening in Weakly Variable Blazars?



Weak Fermi LAT fluxes

1ES 0229+200	z = 0.14
1ES 0347-121	z = 0.186
1ES 1101-232	z = 0.14
1ES 0548-322	z = 0.069
RGB J0152+0.17	z = 0.08

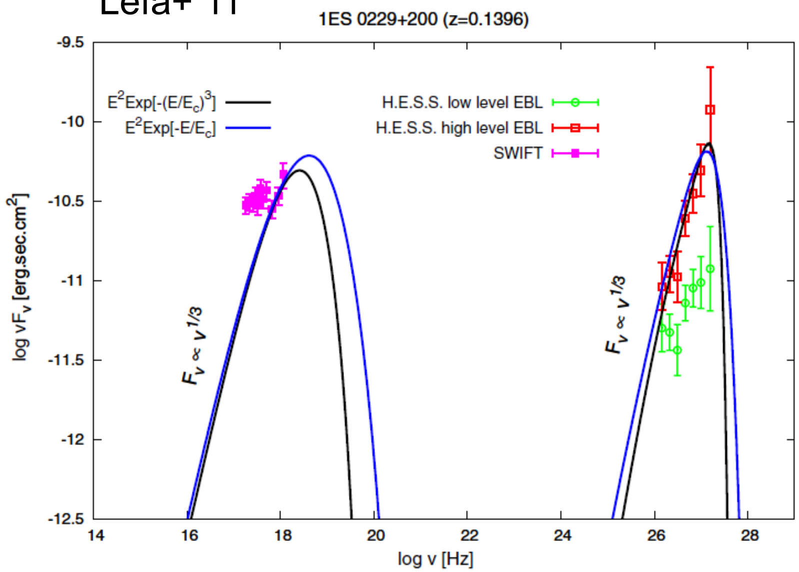
Finke et al. 2010 ApJ

Extreme VHE Blazars: Challenge?

De-absorbed spectrum is as hard as s~1-1.5
Almost mono-energetic electron distribution is needed
Suggested values of B seem much smaller (e.g., Tavechhio+ 11)

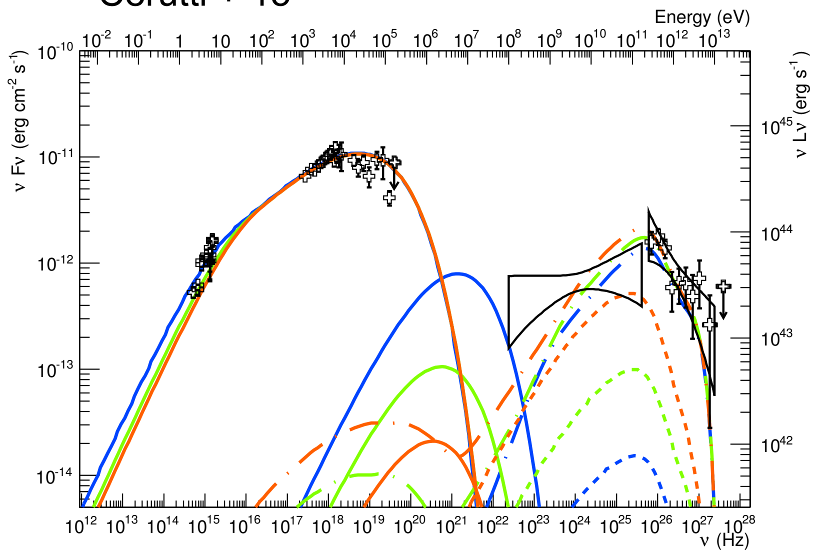
Have been used to constrain intergalactic fields in voids
Cascade component appear as a GeV excess? (e.g., Vovk+ 12)

Lefa+ 11



stochastic acceleration (leptonic)

Cerutti + 15

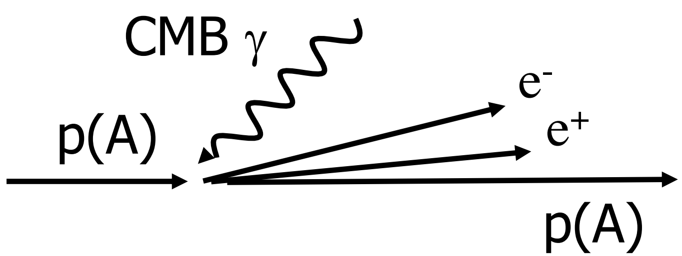


lepto-hadronic

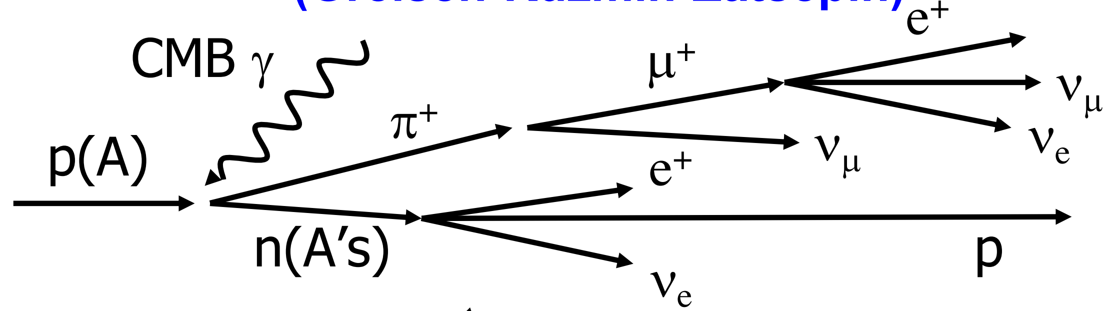
Intergalactic Cascade Emission?

Alternative explanation for gamma rays from blazars:
neutrino and hadronic gamma-ray production *outside* sources

Bethe-Heitler process



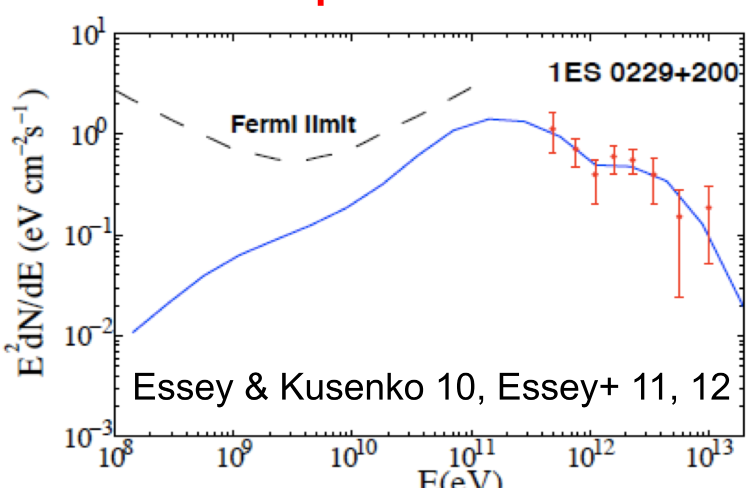
pγ meson production
(Greisen-Kuzmin-Zatsepin)

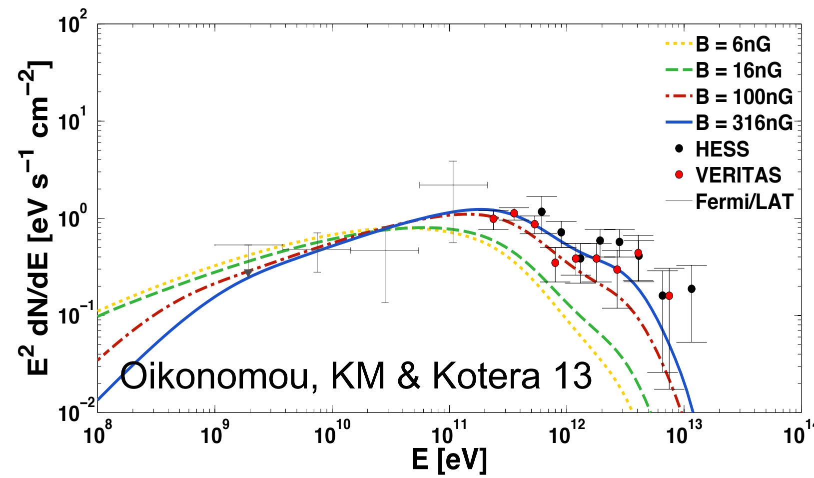


$e+\gamma \rightarrow e+\gamma$ (IC) $\quad \gamma+\gamma \rightarrow e^{+}+e^{-}$

$e+B \rightarrow e+\gamma$ (syn)

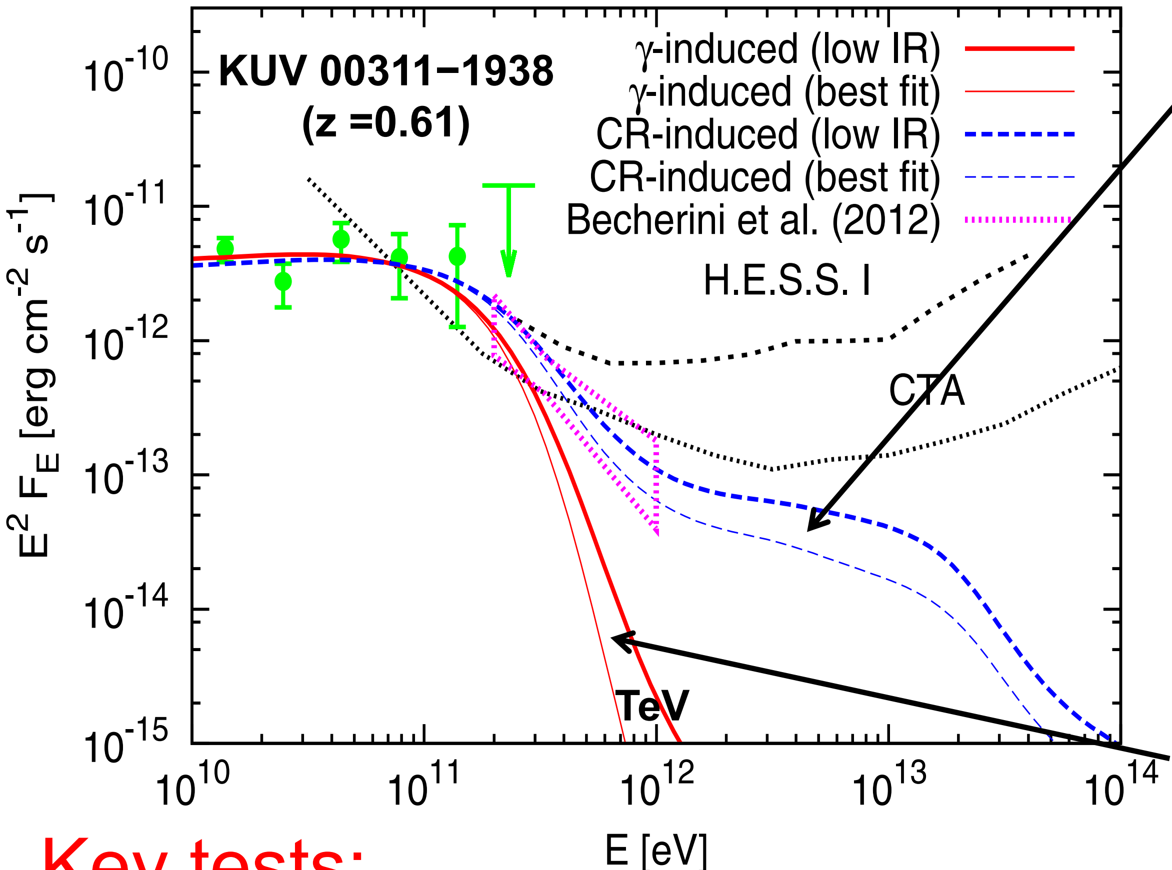
Inverse-Compton cascades in voids | **Synchrotron cascades in filaments/clusters**





Smoking Gun: High-Energy Tail of Distant Blazars

Takami, KM & Dermer 13 ApJL
see also KM, Dermer, Takami & Migliori 12 ApJ, Aharonian+ 13 PRD



Primary UHECR-induced:

$dI_\gamma \sim -(1/\lambda_{\gamma\gamma})\, I_\gamma\, dr + (1/\lambda_{BH})\, I_{CR}\, dr$
$\rightarrow \propto (1-\exp(-\tau_{\gamma\gamma}))/\tau_{\gamma\gamma}$

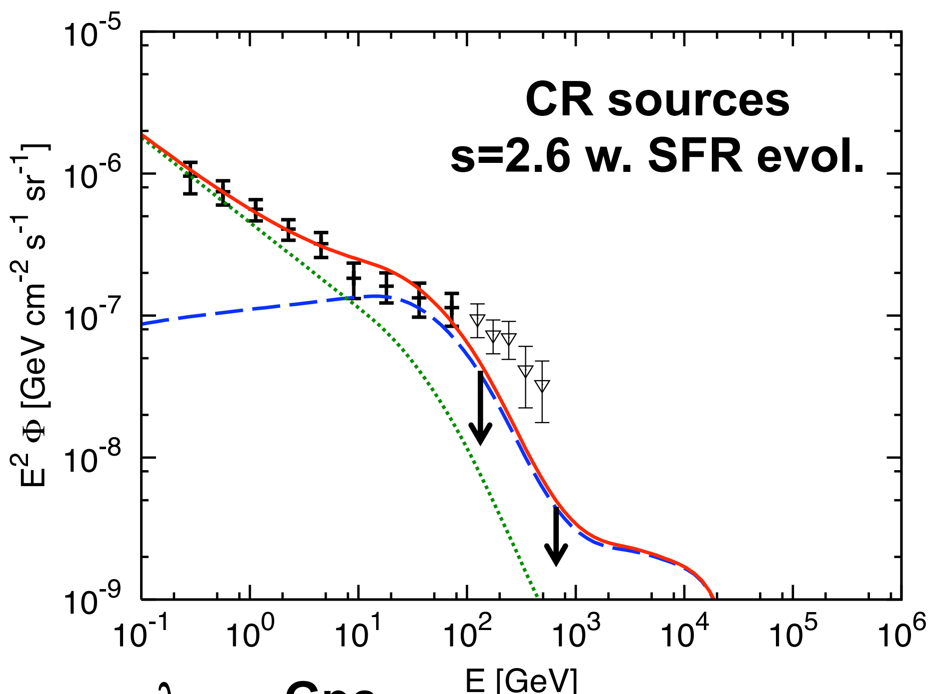
Primary γ-induced:

$dI_\gamma \sim -(1/\lambda_{\gamma\gamma})\, I_\gamma\, dr$
$\rightarrow \propto \exp(-\tau_{\gamma\gamma})$

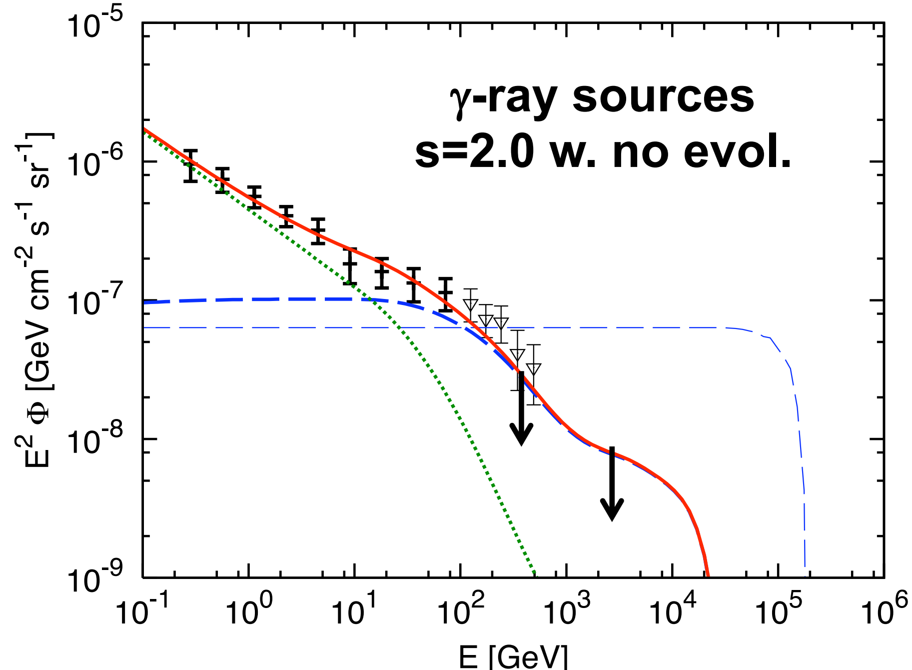
Key tests:

- go to higher energies and/or higher redshifts (→ CTA)
- weak variability $\Delta t_{\rm IGV} \simeq 14\,{\rm yr}\; E_{\gamma,11}^{-2}\, B_{{\rm IGV},-17}^{2} (\lambda_{\rm BH}/{\rm Gpc})(1+z)^{-1}$

Cosmogenic γ can contribute to diffuse γ-ray background
Steeper than spectra of preliminary Fermi data



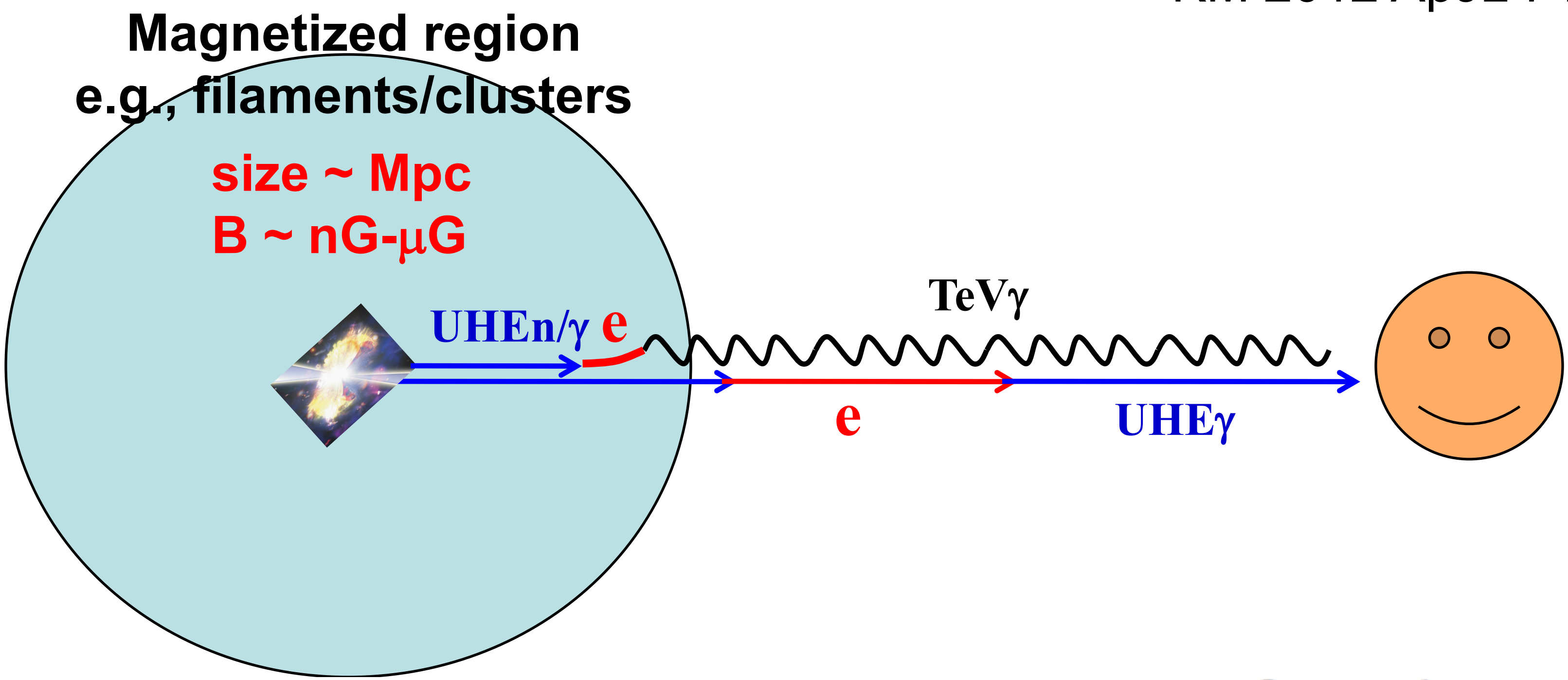
KM, Beacom & Takami 12 JCAP



λ_{BH} ~ Gpc
→ importance of distant sources
→ effective evolution is stronger

Variable Hadronic Cascade Emission: UHE Neutral Beams

KM 2012 ApJL 745 L16



$$\theta_{\rm EG} \approx \sqrt{2}\lambda_{\rm syn}/\sqrt{3}r_L \simeq 3.5\times10^{-4}\gamma_{e,13.5}^{-2}B_{\rm EG,-7.5}^{-1}$$

CMB/CRB/EBL $\Delta t_{\rm EG} \approx \theta_{\rm EG}^2(l/2c) \simeq 0.27\,{\rm yr}\,E_{{\rm syn},11.5}^{-2}l_{\rm Mpc}$ **~month**

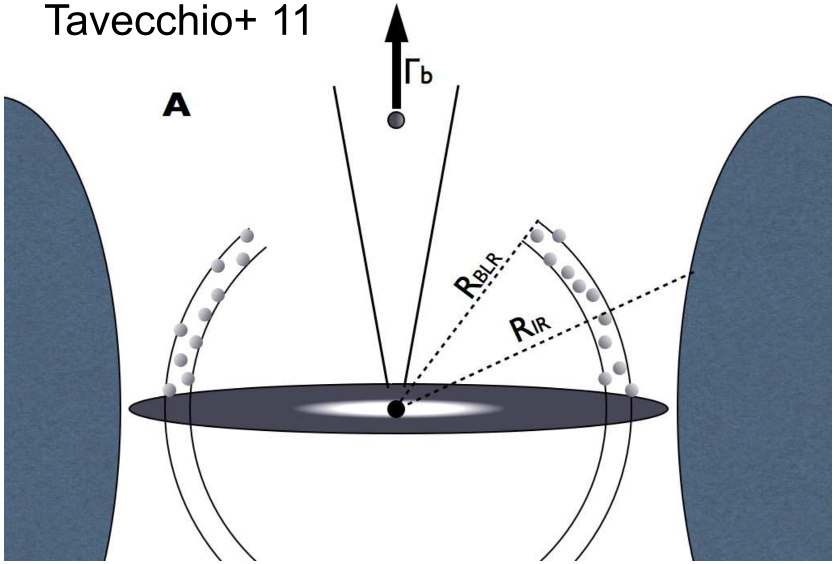
w. additional fields

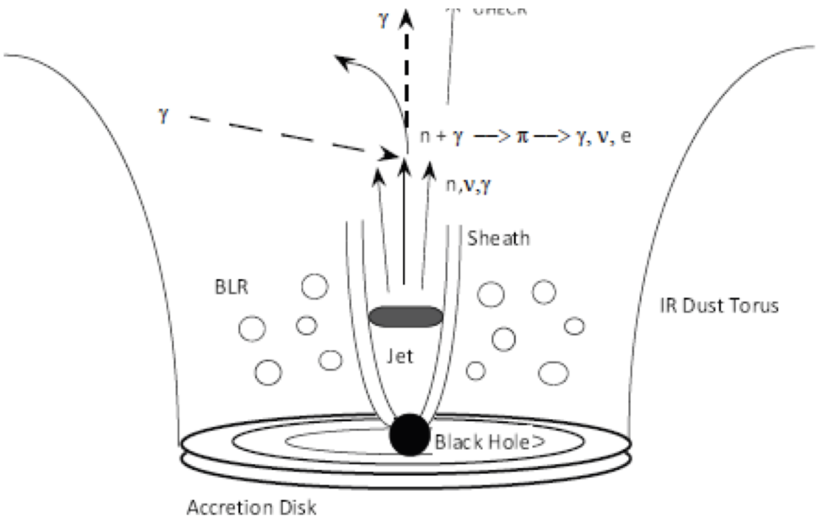
galaxy scale (~kpc) ⇔ ~day

dust torus scale (~pc) ⇔ ~minute

Application to Blazars

Tavecchio+ 11





Dermer, KM & Takami 12

FSRQ 4C+21.35 (z=0.432)
>30 GeV γ rays (made inside BLR)
are damped (e^{-30}~10^{-13})

but fast variability w. ~10 min

(Tanaka+ 11, MAGIC Coll. +11)

"a very compact emission region outside BLR"

$R' \sim 10^{15}$ (Γ/100) cm << 10^{17} cm

Alternative explanations:

- Minute-scale echo produced by UHE neutral beams

(Dermer, KM & Takami 12)

- Axion-like particles (Tavecchio+ 12)