Blazars as Cosmic-Ray Sources

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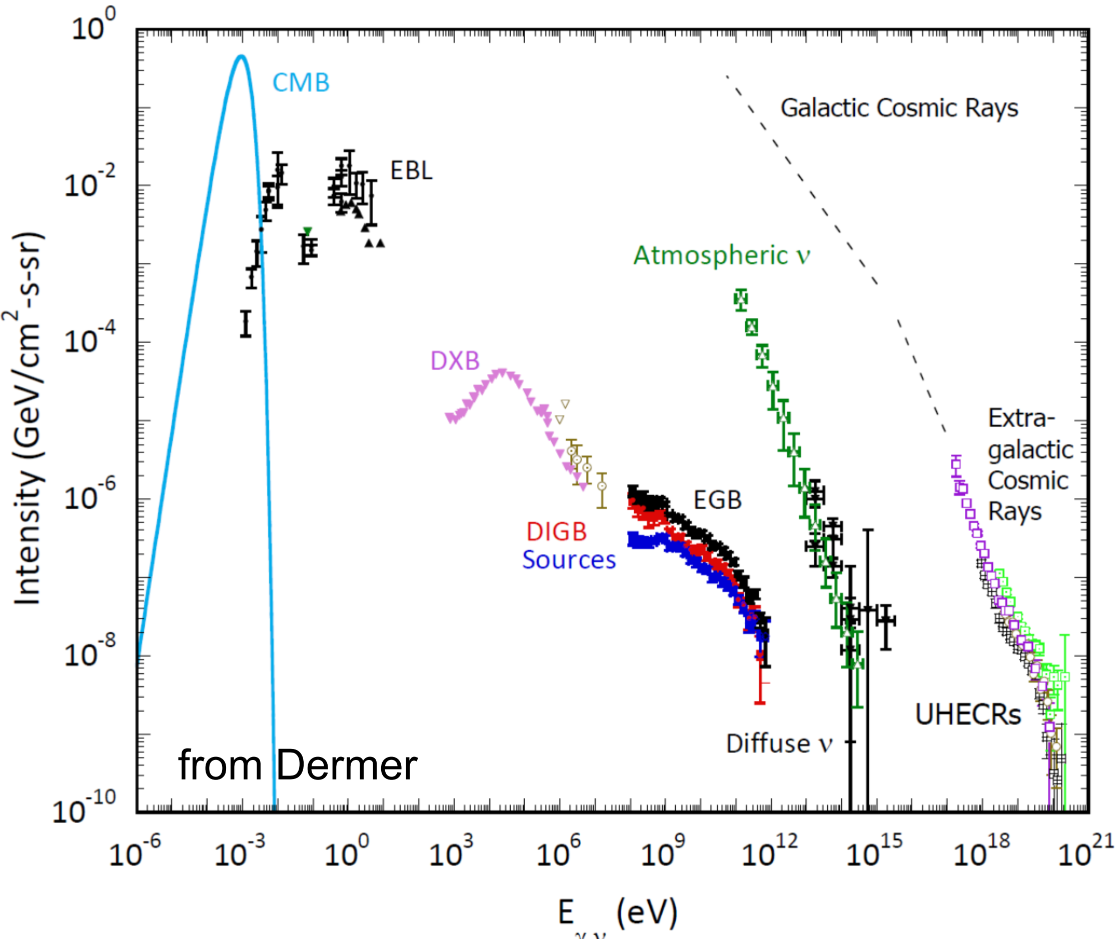
TeVPA 2015 @ Kashiwa

Cosmic Background Radiation

Cosmic non-thermal budgets?

- cosmic-ray origin, cosmic ν origin, cosmic γ origin



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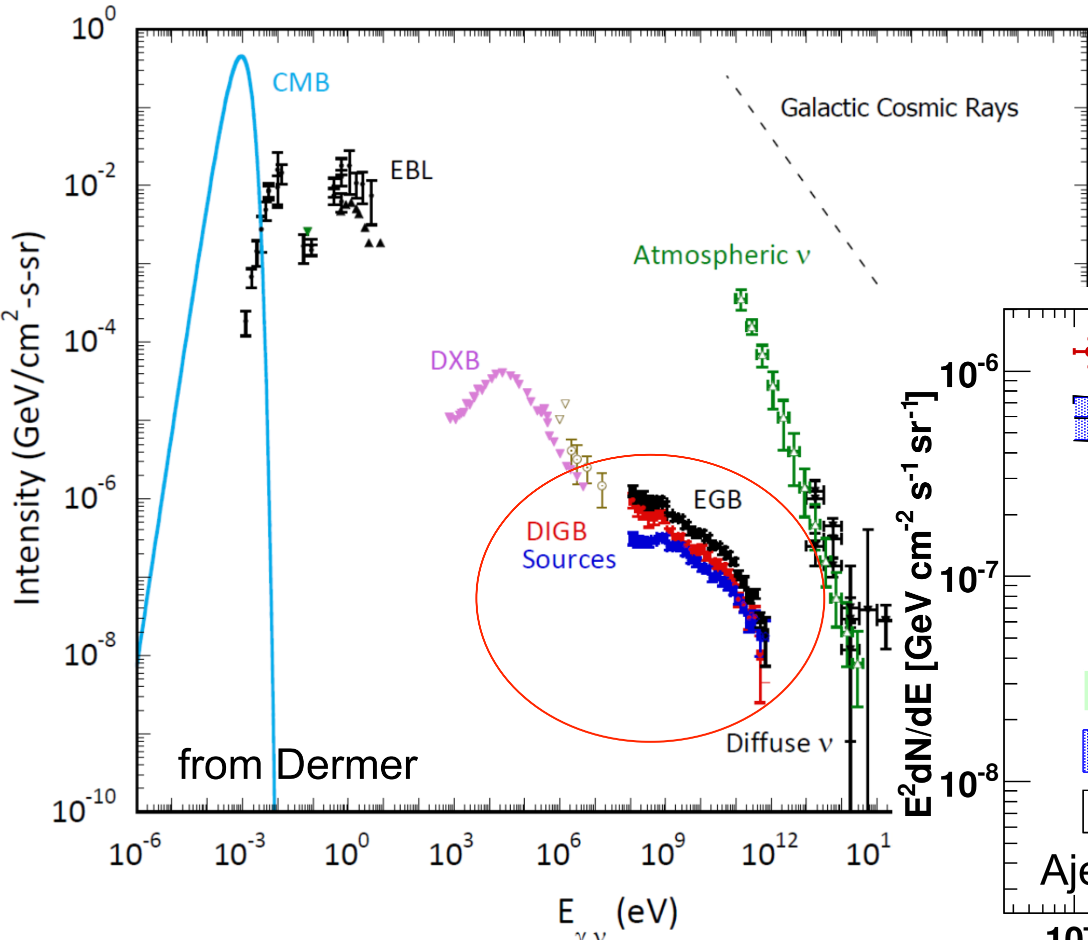
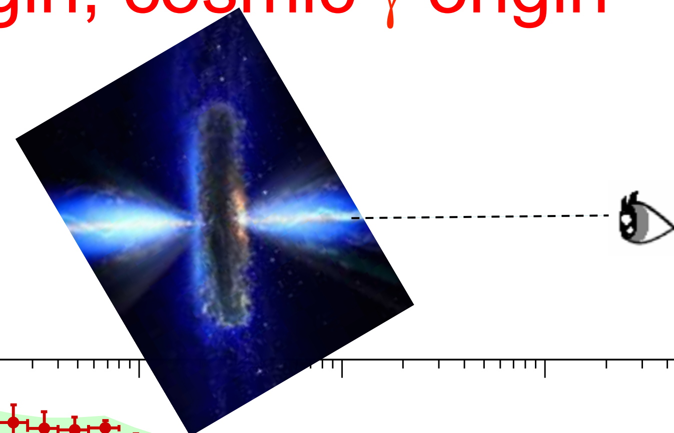
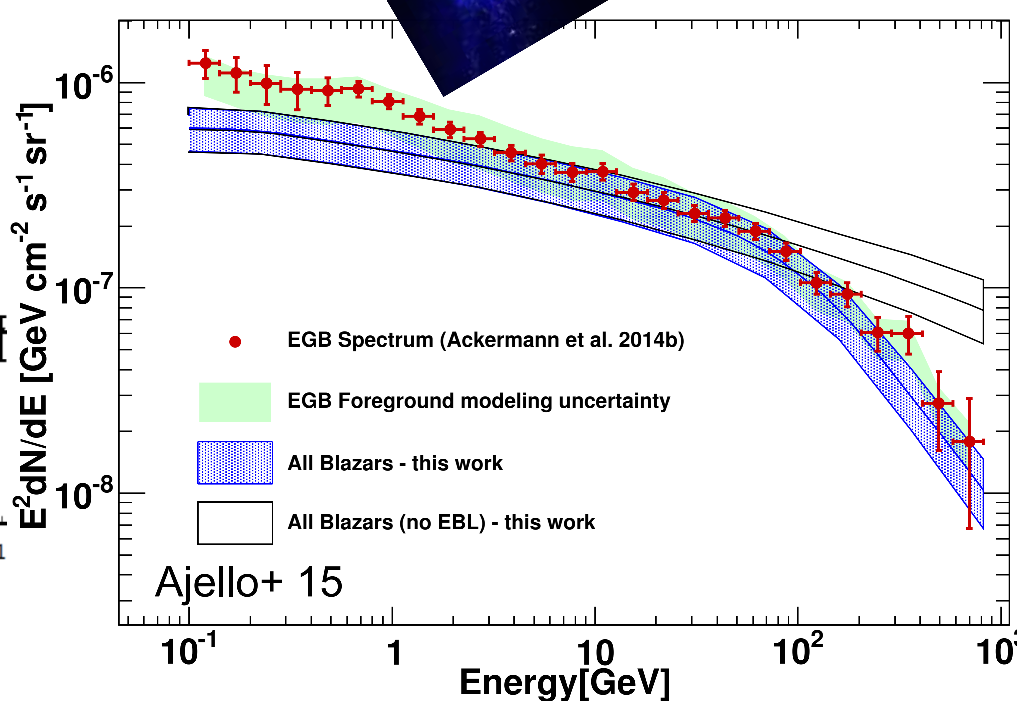
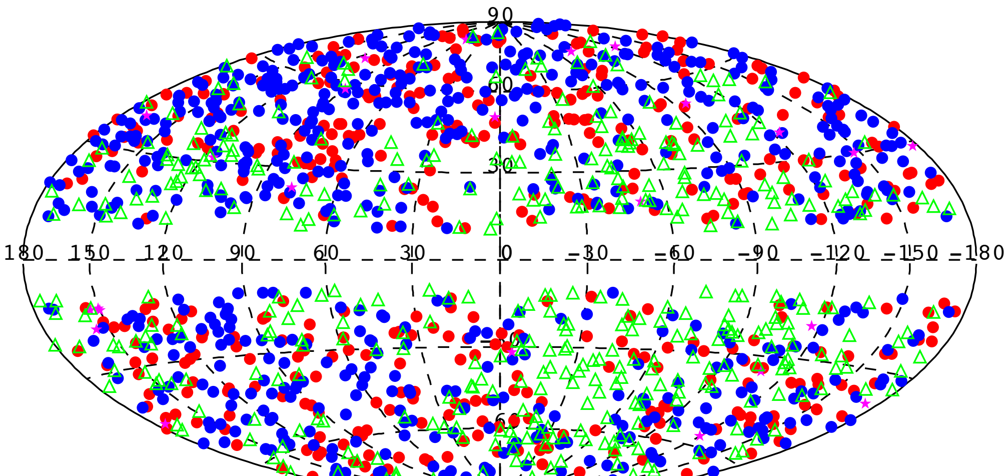






Blazars: Main Extragalactic Sources in the γ-ray Sky



Ackermann+ 15

48 months of observations :

2192 TS>25, |b|>10° sources

3LAC: 1563 sources

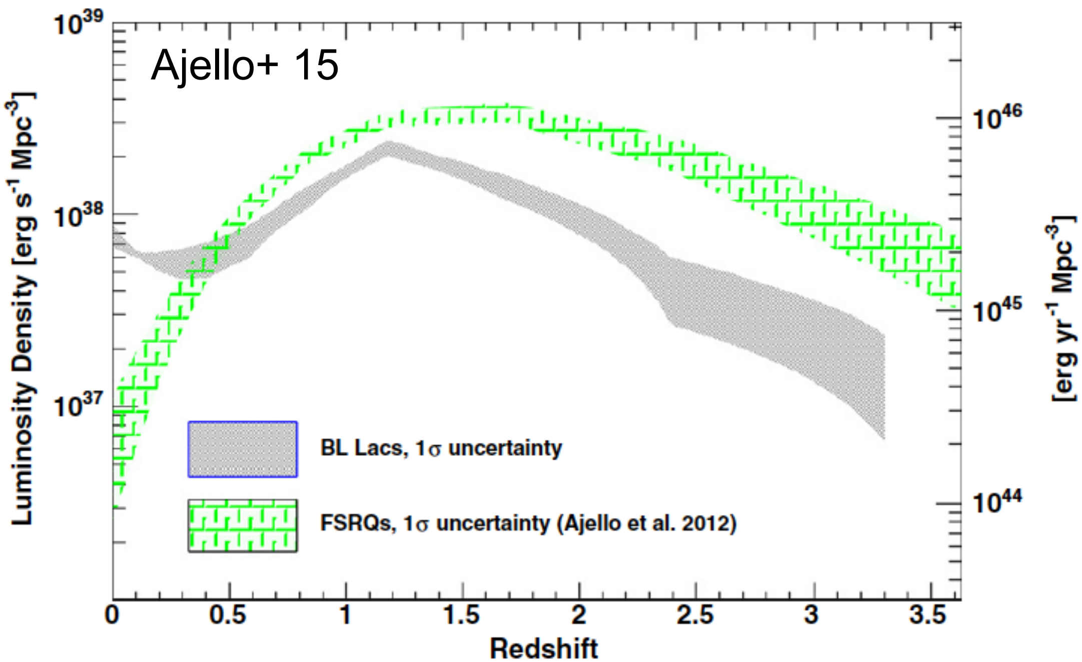
1444 AGNs in the clean sample

415 FSRQs

602 BL Lacs

413 of unknown type

23 other AGNs



Local (z=0) 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}

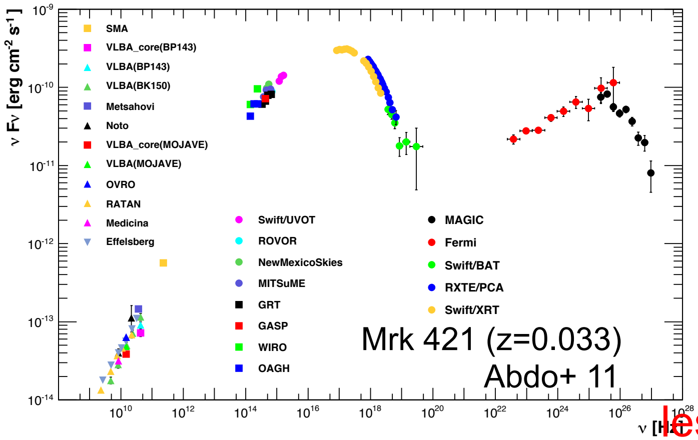
Candidate sources of UHECRs

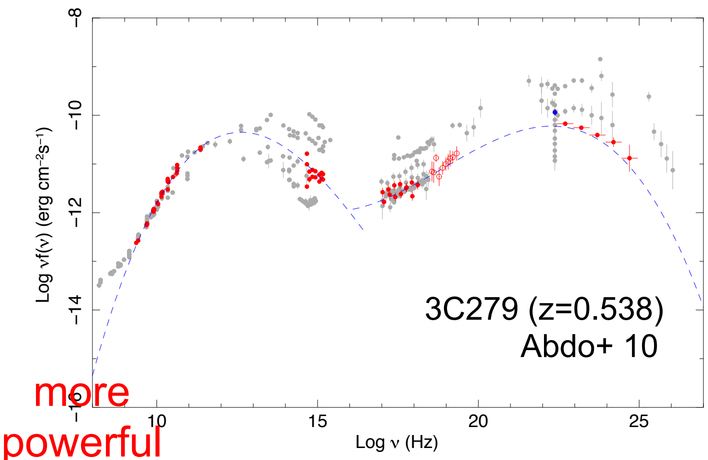
Blazars: Success of Multiwavelength Observations

Spectral energy distribution (SED): “two hump” structure

BL Lac objects (BL Lacs)
emission to VHE/TeV energies

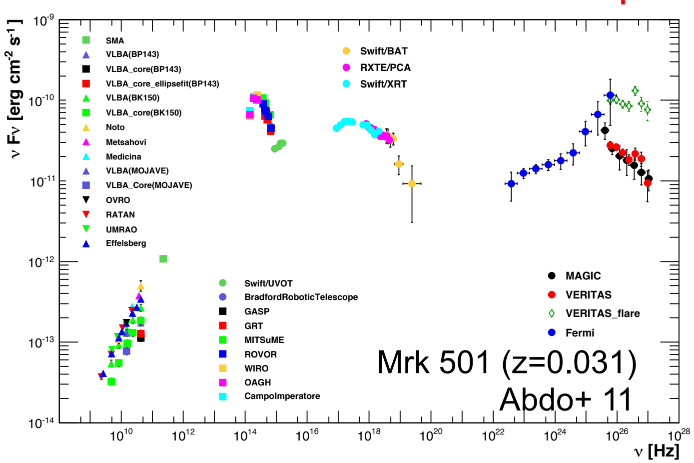
Flat-spectrum quasars (FSRQs)
(or quasar-hosted blazars (QHBs))
mosty LSPs (ν_{pk}<10^{14} Hz), GeV break

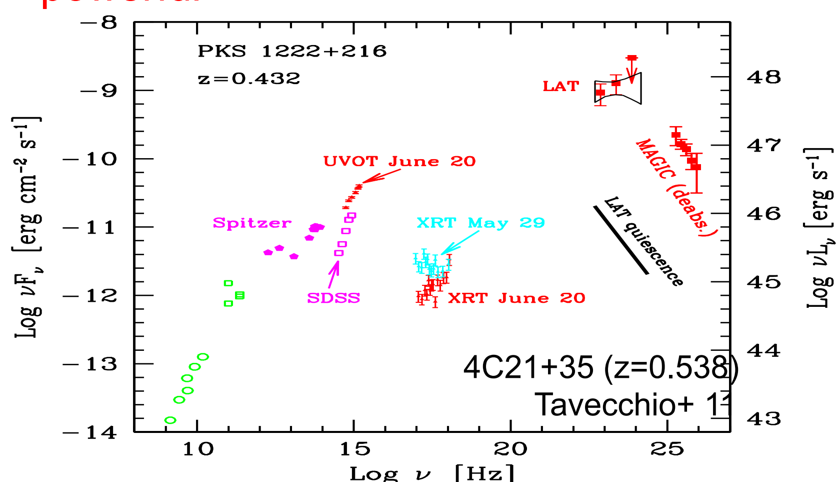




less powerful

more powerful

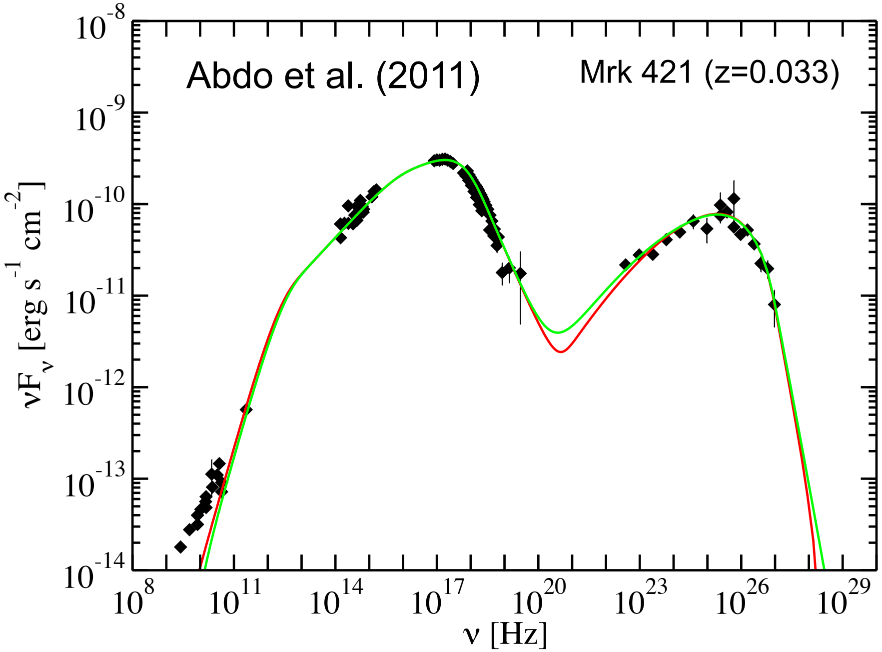




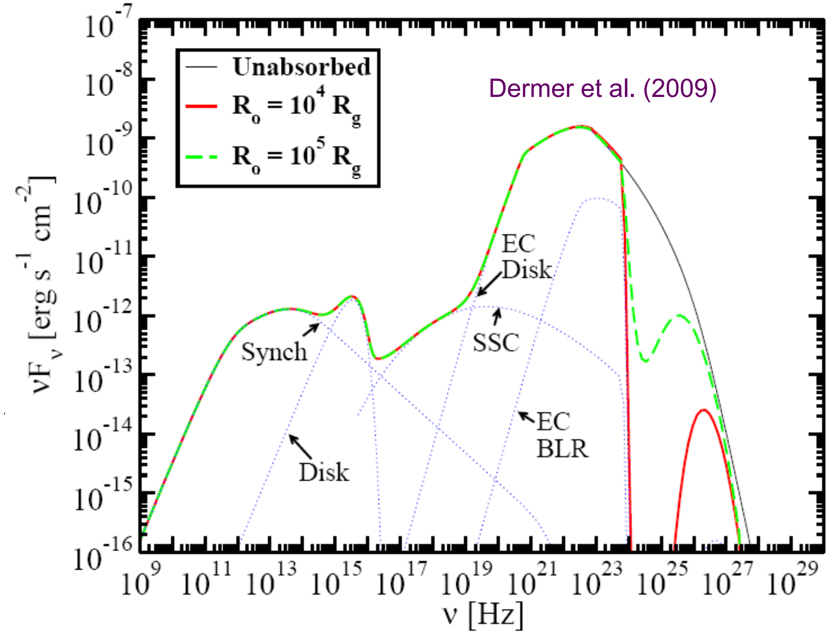
Leptonic Scenario

HE radiation: relativistic electrons accelerated in inner jets
(magnetic reconnection, shock acc., shear acc., turbulence etc.)

BL Lacs
synchrotron/SSC fitting

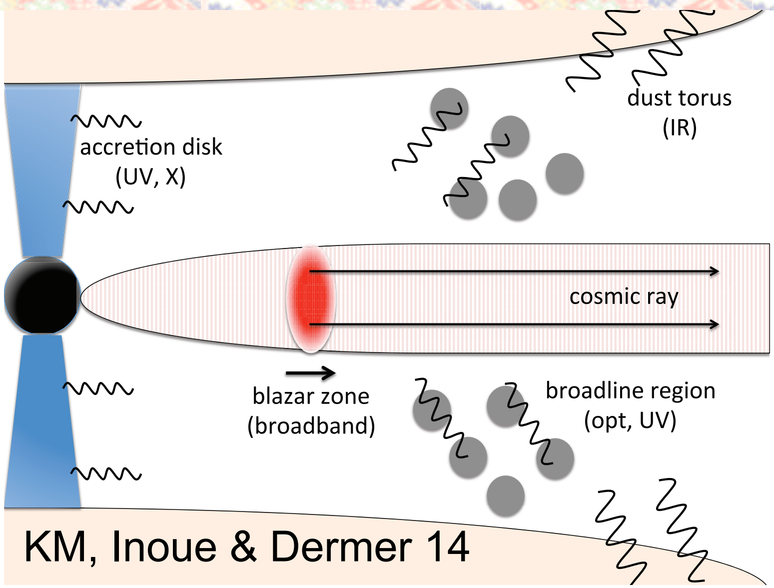


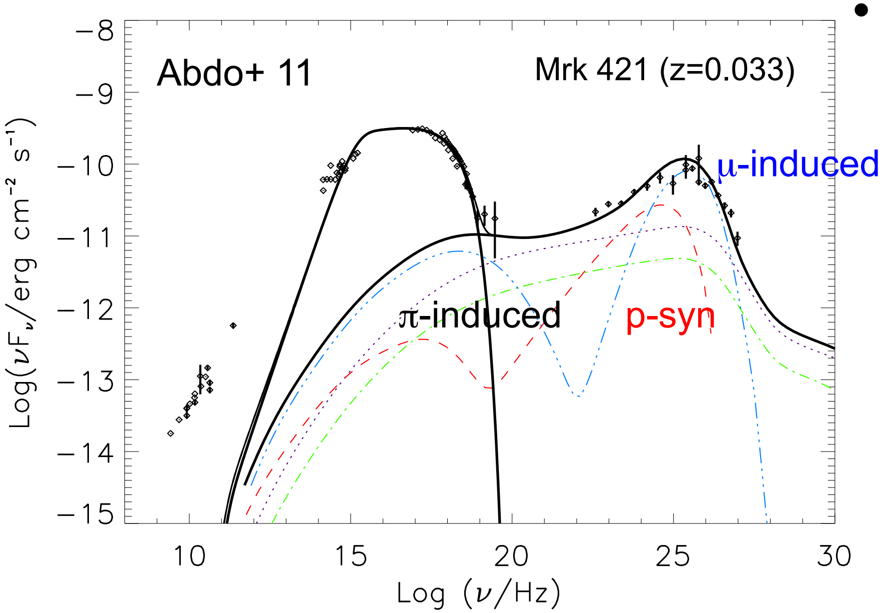
FSRQs or QHBs
synchrotron/SSC+EIC model fits



- 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
- Complicated injection spectrum (intrinsic spectral break & low max. energy)
- Log-parabolic function works well: stochastic acc.? (ex. Tramacere+ 11)

Lepto-Hadronic Scenario





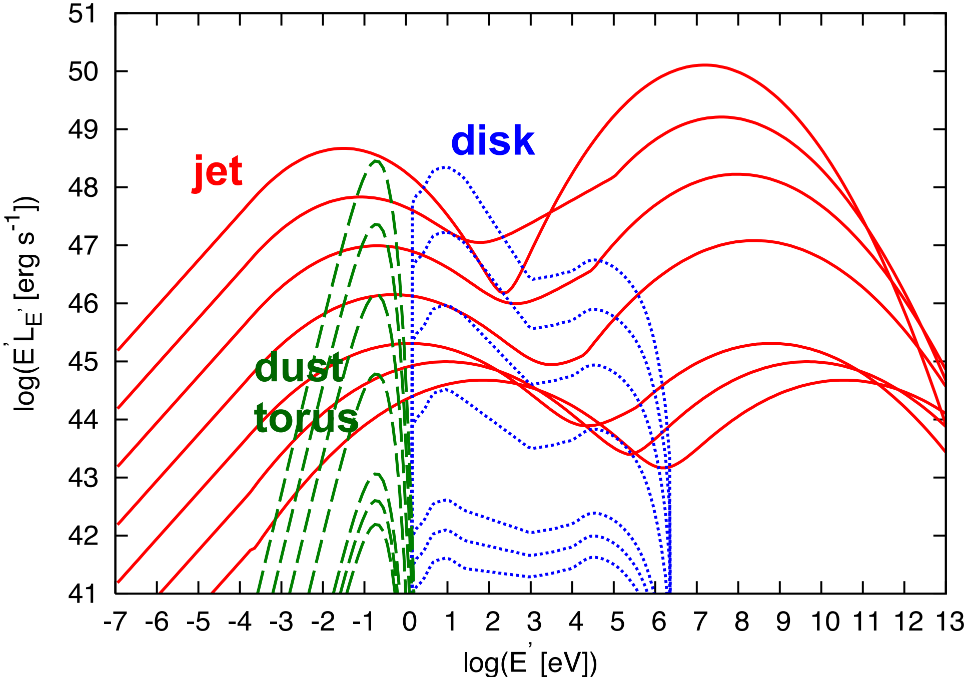
- Nonthermal synchrotron radiation from primary electrons for radio through optical (low-energy hump)
- Proton and ion synchrotron radiation
  $p+B \rightarrow \gamma$
- Photomeson production
  $p\gamma \rightarrow \pi^0,\pi^\pm \rightarrow \gamma, \nu, n, e^\pm$
- Neutrons escape to become UHECRs
- Hadronuclear process
  $p+N \rightarrow \pi^0, \pi^\pm \rightarrow \gamma, \nu, n, e^\pm$
  (“heavy” jet problem; Atoyan & Dermer 03)

“SEDs can be fitted by both leptonic and lepto-hadronic scenarios”

Smoking gun?

- neutrinos
- detailed studies of γ-ray spectra
- X-ray & γ-ray polarization (Zhang& Bottcher 13)

Blazar Sequence & pγ Efficiency



"Blazar sequence" (Fossati+ 98)

softer spectra at higher L

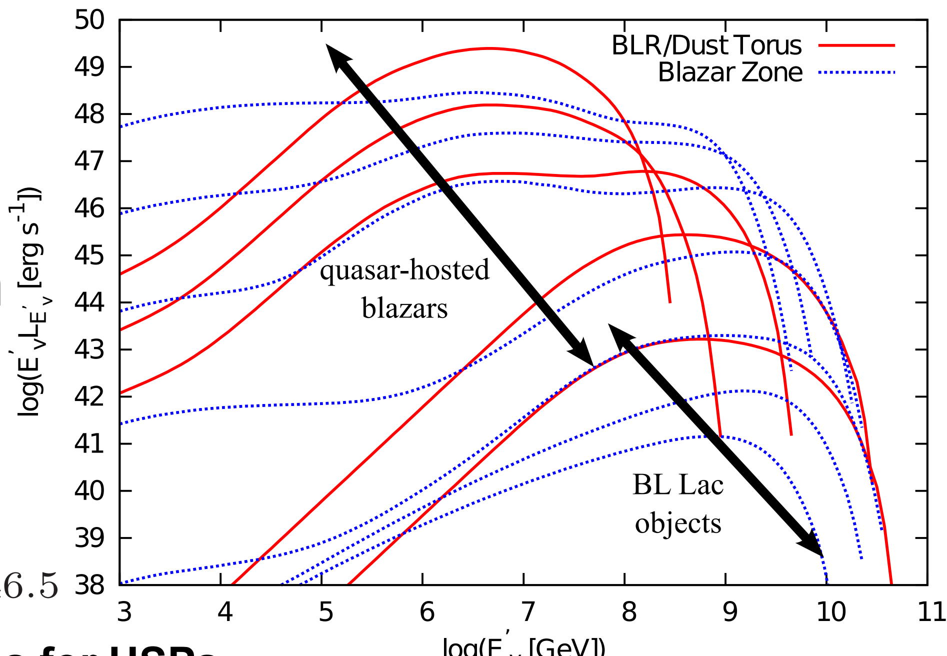
LSP: powerful ⇆ HSP: weak

Stronger sequence in pγ emission

$L_{cr} \propto L_\gamma$, $f_{p\gamma} \propto L_\gamma^{1/2}$ (for ext. rad.)

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

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



large CR power in lepto-hadronic interpretations for HSPs

(L_{cr}~10^{47}-10^{49} erg/s; see Bottcher+ 12)

KM, Inoue & Dermer 14

Maximum CR Energy

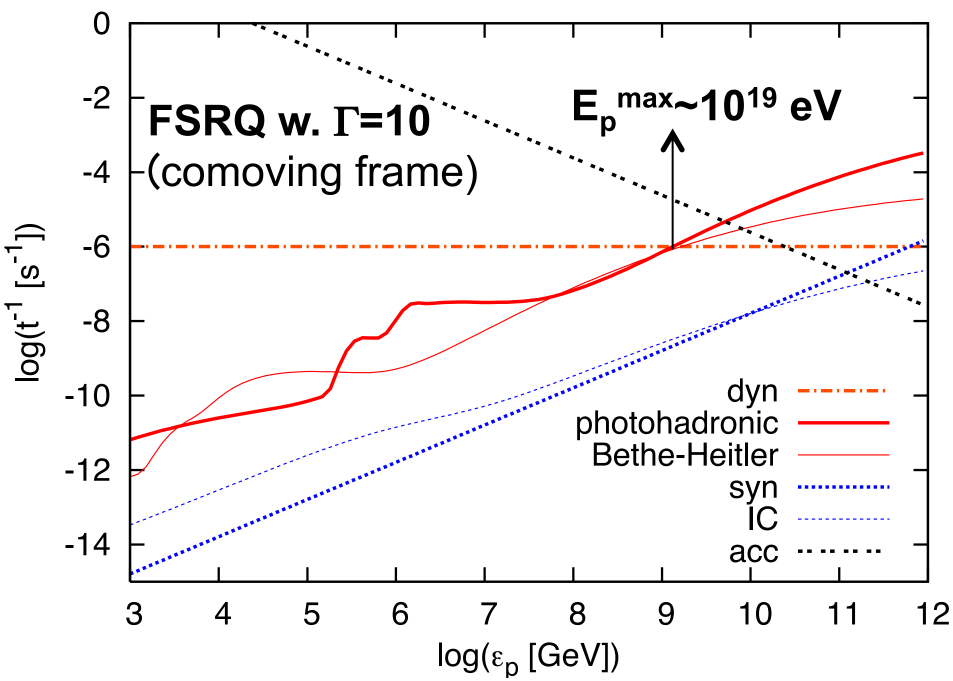
~10% of AGN have powerful jets (radio-loud): $n_s \sim 10^{-4}$ Mpc^{-3}
Most of them are FR I galaxies and BL Lacs

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]
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

Hillas condition typically gives
$E_p^{max} \sim 10^{18}$-10^{19} eV for BL Lacs
$E_p^{max} \sim 10^{20}$ eV for FSRQs
but pγ losses are relevant for FSRQs



Some Remarks on CR Acc. in Blazars

- BL Lacs can accelerate heavy nuclei up to ~10^{20} eV
  FSRQs are more powerful but pγ cooling limits the max. energy

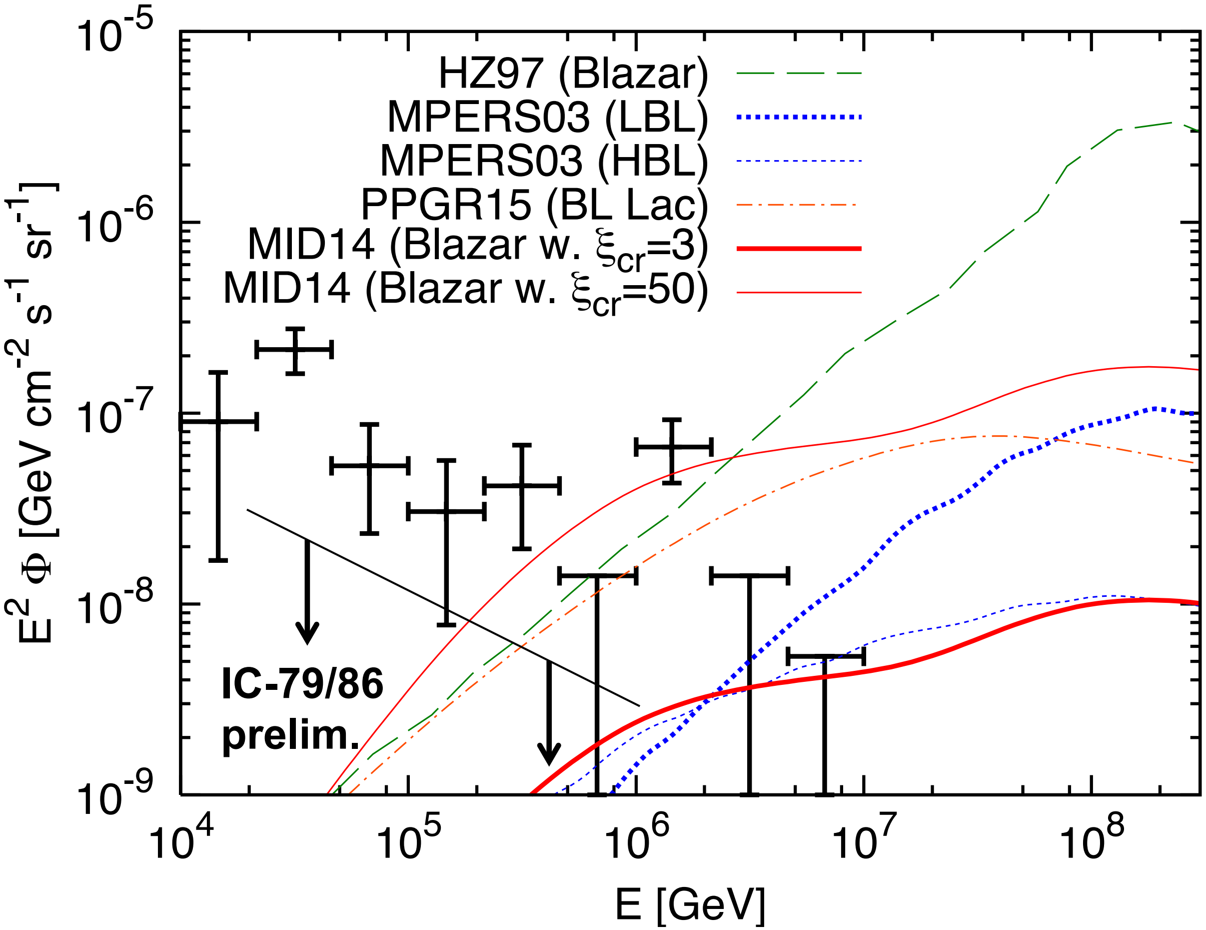
- Auger results suggest heavy nuclei at UHE energies
  nucleus survival: OK in BL Lacs but not in FSRQs (KM+ 12, 14)
  open question: how heavy nuclei are loaded in AGN jets
  hard injection spectra (s<2) are suggested (Taylor+ 15)

- UHECRs from most blazars should be largely isotropized
  otherwise strong anisotropy was observed (Takami, KM & Dermer 14)
  (or acceleration region is not beamed as in radio galaxies)

- UHECR-AGN hypothesis
  does not mean the lepto-hadronic scenario
  does not mean they give the main origin of IceCube neutrinos

HE Neutrinos from AGN Jets

Standard jet models as the cosmic ν origin: difficult, many constraints…
- Blazars: power-law CR spectra → hard spectral shape (KM, Inoue & Dermer 14)
  point-source limits & correlation studies (KM & Waxman 15, IceCube Coll. 15)



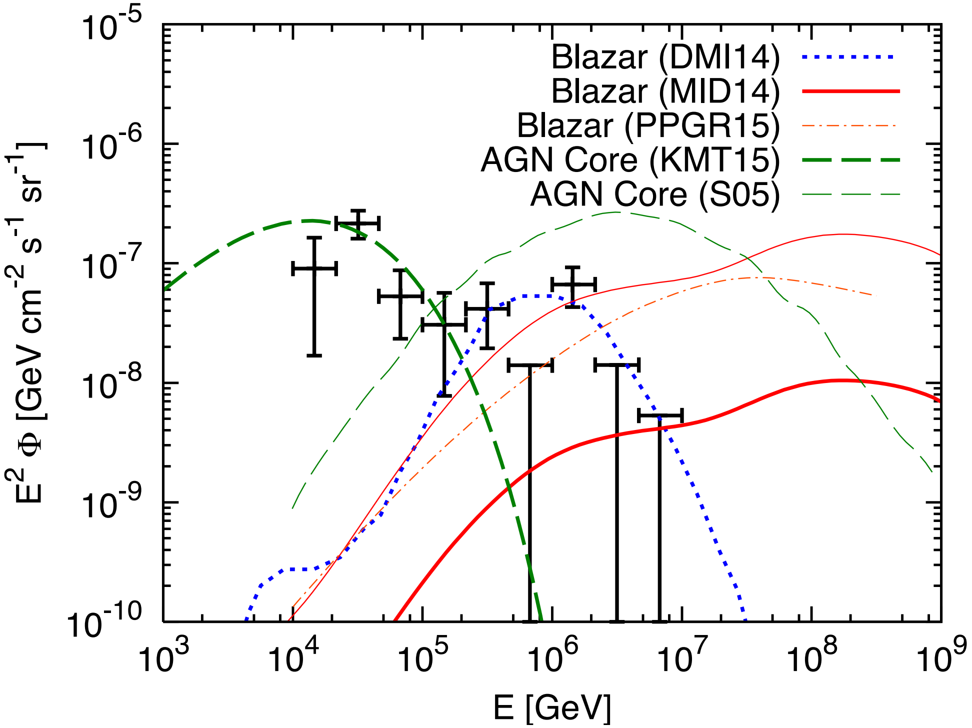
Various diffuse ν predictions

leptonic
BL Lacs + FSRQ

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

leptonic w. UHECR norm.
BL Lacs + FSRQ

Can We Play a Game?

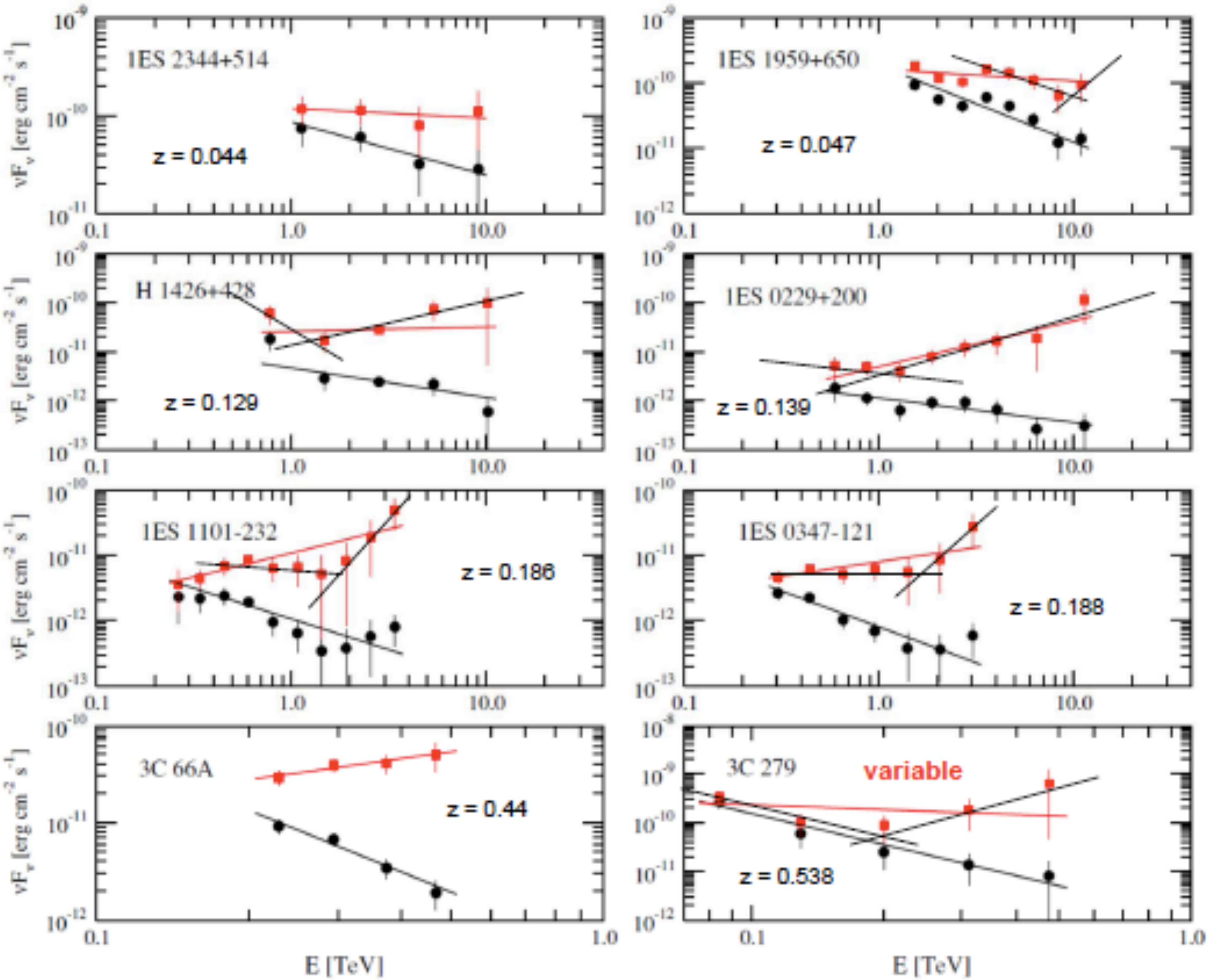


Kalashev, Kusenko & Essey
Dermer, KM & Inoue 14
Tavechhio & Ghisellini 14

Can blazars explain IceCube data? Yes but…
- Only PeV data unless multi-zone models are invoked
- Need cutoff at 10^{17} eV to avoid UHE upper limits (stochastic acc.?)

Can blazars explain UHECRs? Yes but IceCube νs have a different origin
- $p\gamma$ w. BLR & dust-torus photons: cross-corr. w. known <100 bright quasars
- UHECR norm. (reasonable) → EeV ν detectable by ARA & GRAND

Possible VHE Anomaly 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

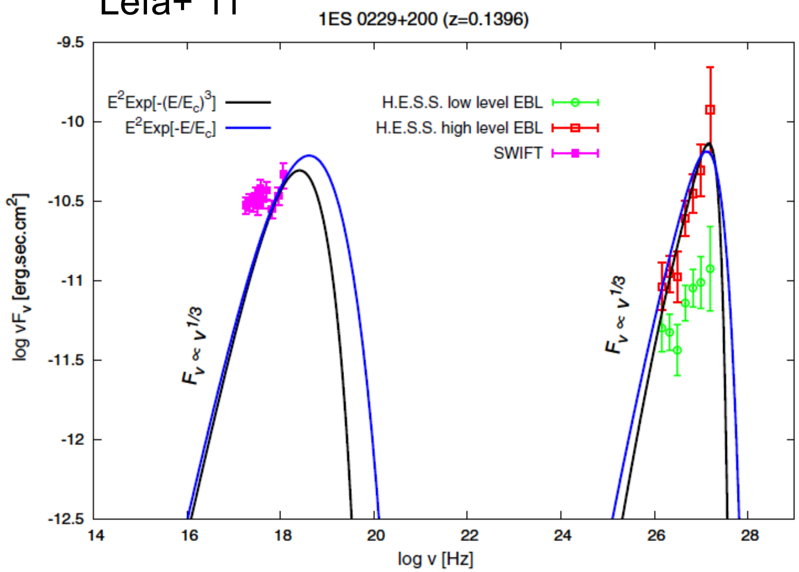
Finke et al. 2010 ApJ

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)

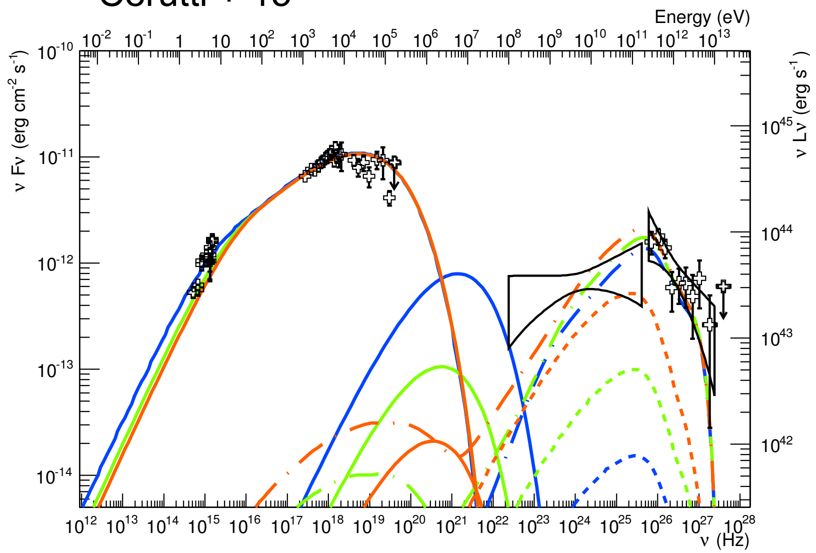
Have been used to constrain intergalactic fields in voids
Cascade component appear as a GeV excess? (e.g., Vovk+ 12)

Lefa+ 11



stochastic acceleration (leptonic)

Cerutti + 15

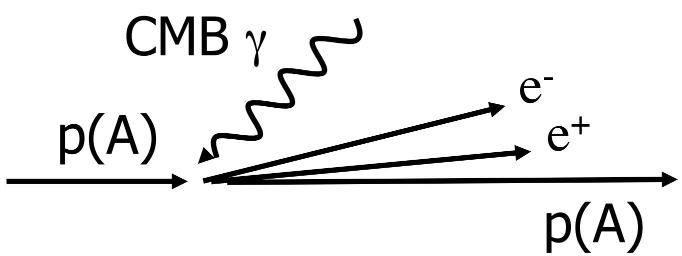


lepto-hadronic

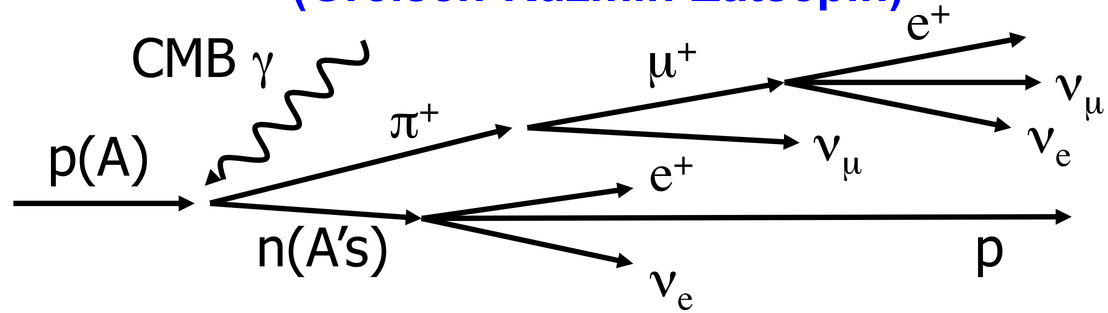
Intergalactic Cascade Emission?

Alternative scenario:
neutrino and hadronic gamma-ray production *outside* sources

Bethe-Heitler process



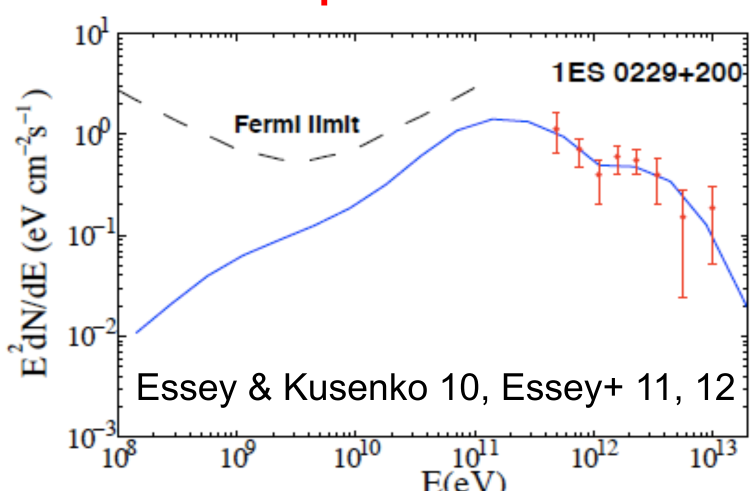
pγ meson production
(Greisen-Kuzmin-Zatsepin)



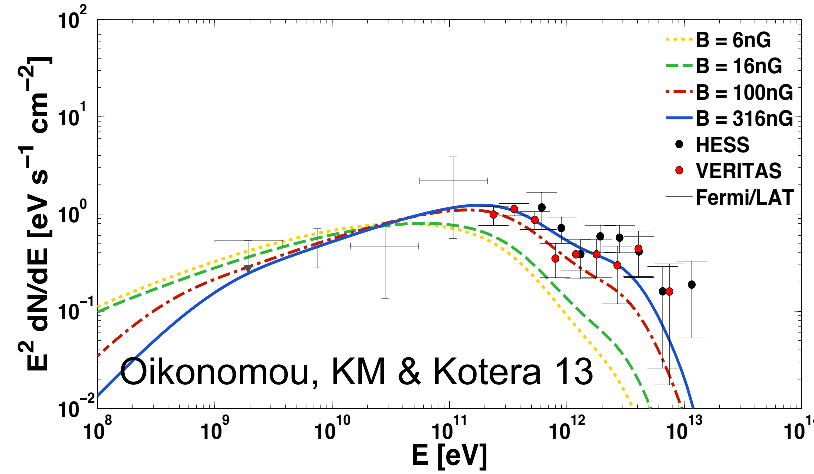
$e+\gamma \rightarrow e+\gamma$ (IC) $\quad \gamma+\gamma \rightarrow e^+ + e^-$

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

Inverse-Compton cascades in voids

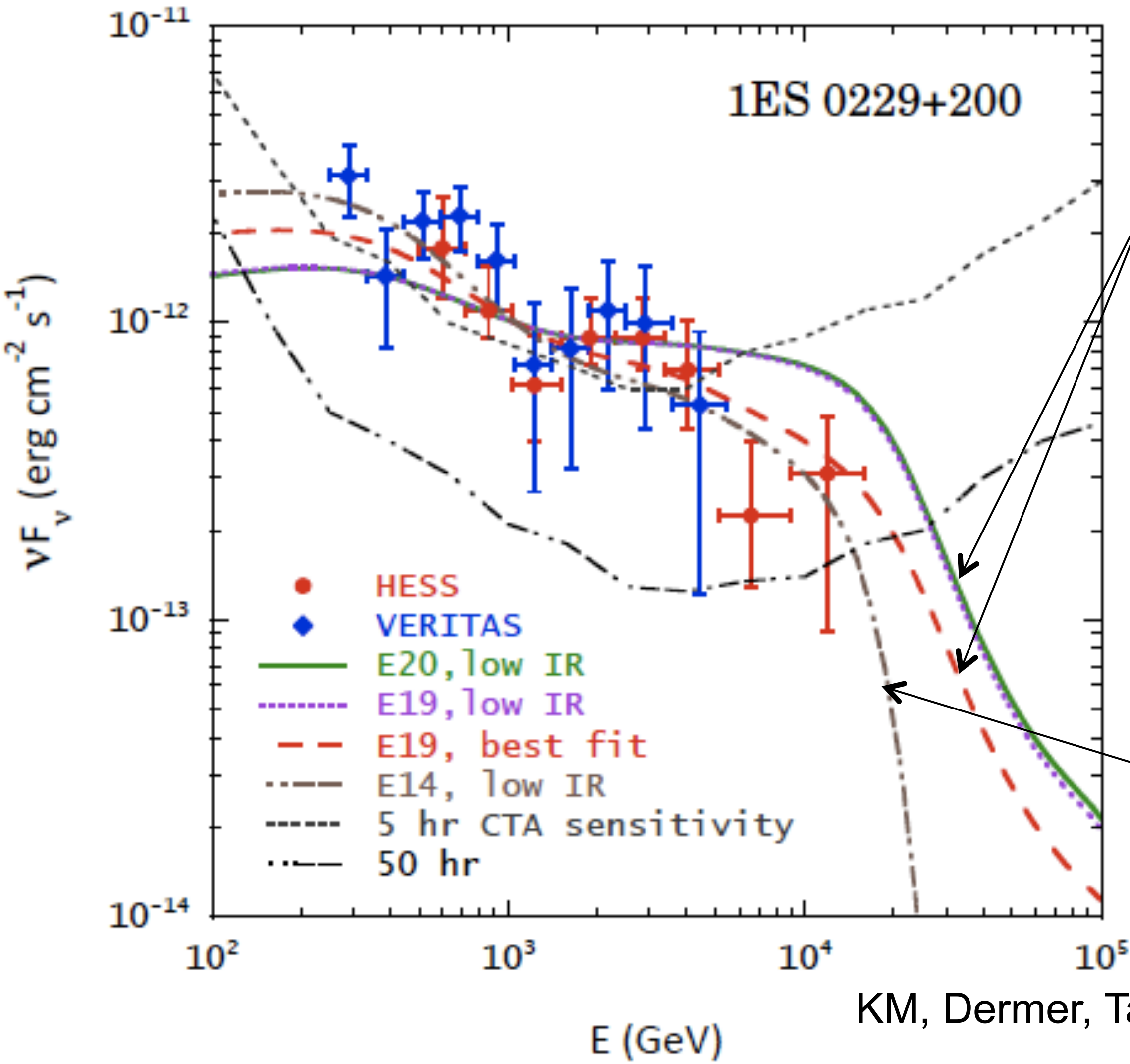


Synchrotron cascades in filaments/clusters



Predictions for VHE Gamma-Ray Spectra

Many models: buy classified into two distinct features in VHE spectra



Primary CR-induced:
Intergalactic IC cascades
Intergalactic syn. cascades

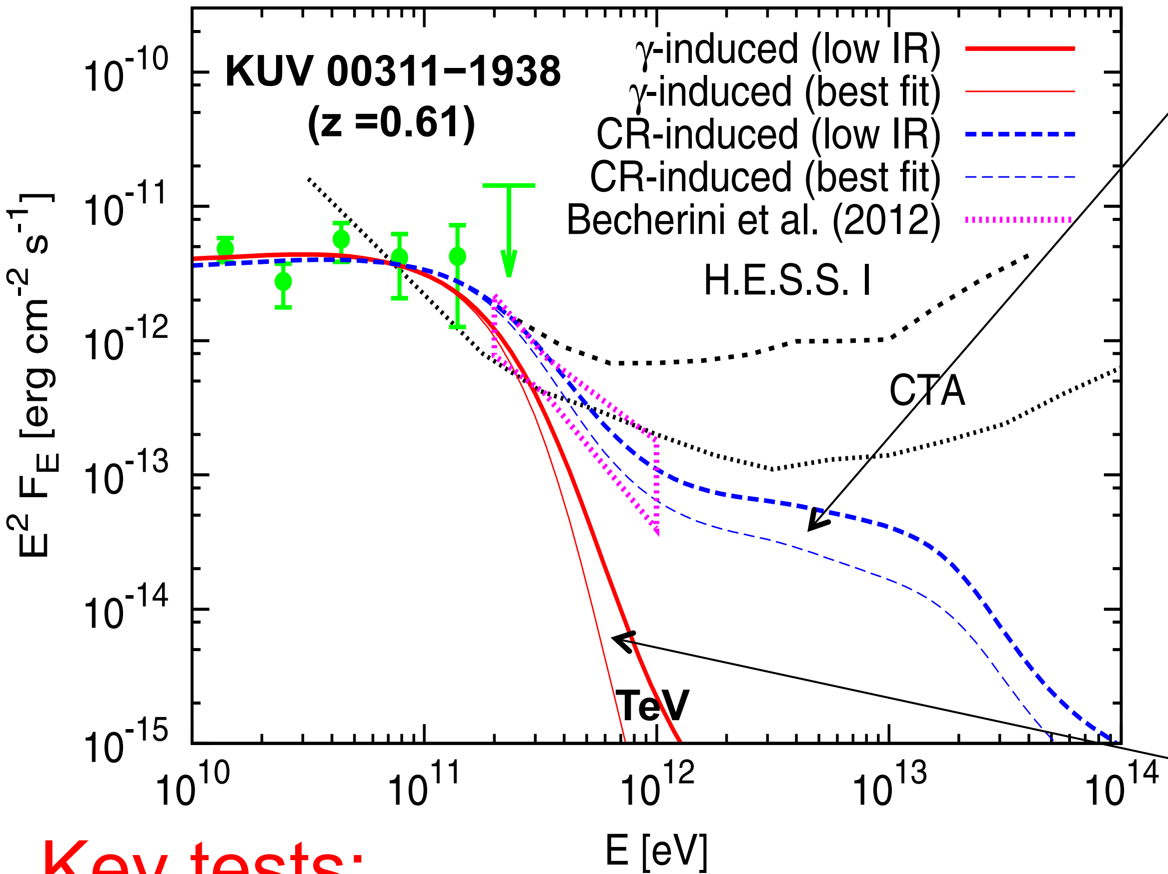
discrimination by CTA

Primary γ-induced:
leptonic
lepto-hadronic
Intergalactic syn. cascades

KM, Dermer, Takami, & Migliori 12 ApJ 749 63

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:

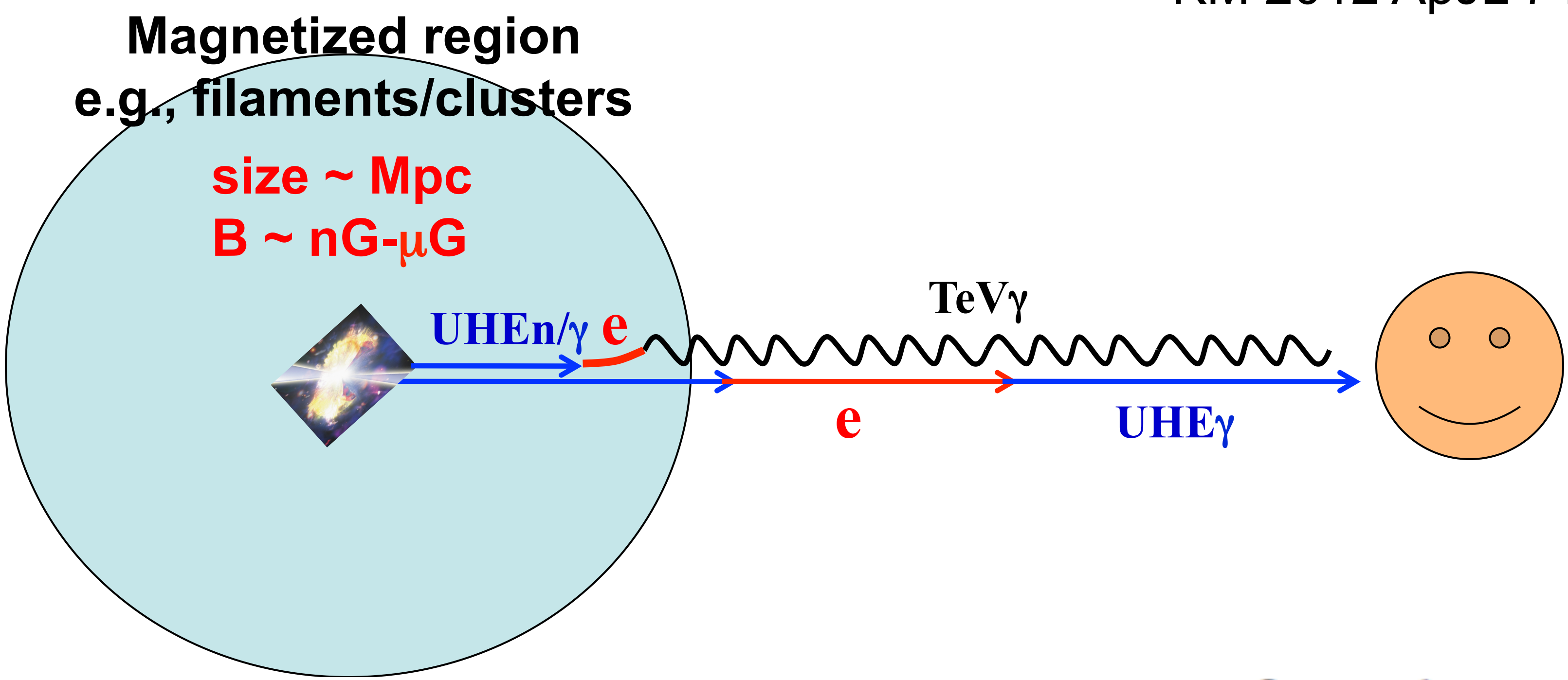
$dI_\gamma \sim -(1/\lambda_{\gamma\gamma})\, I_\gamma\, dr$
$\rightarrow \propto \exp(-\tau_{\gamma\gamma})$

Key tests:

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

Variable Hadronic Cascade Emission: UHE Neutral Beams

KM 2012 ApJL 745 L16



$$\theta_{\rm EG} \approx \sqrt{2}\lambda_{\rm syn}/\sqrt{3}r_L \simeq 3.5\times 10^{-4}\gamma_{e,13.5}^{-2}B_{\rm EG,-7.5}^{-1}$$

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**

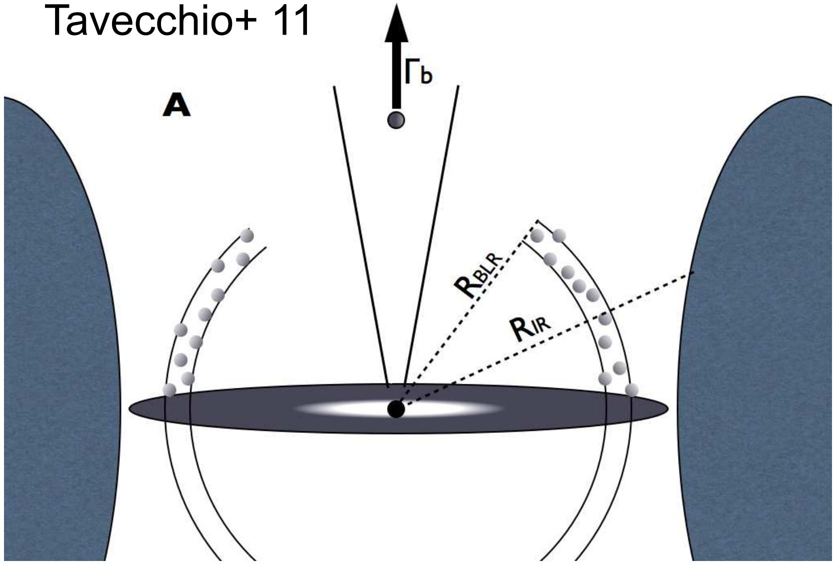
w. additional fields

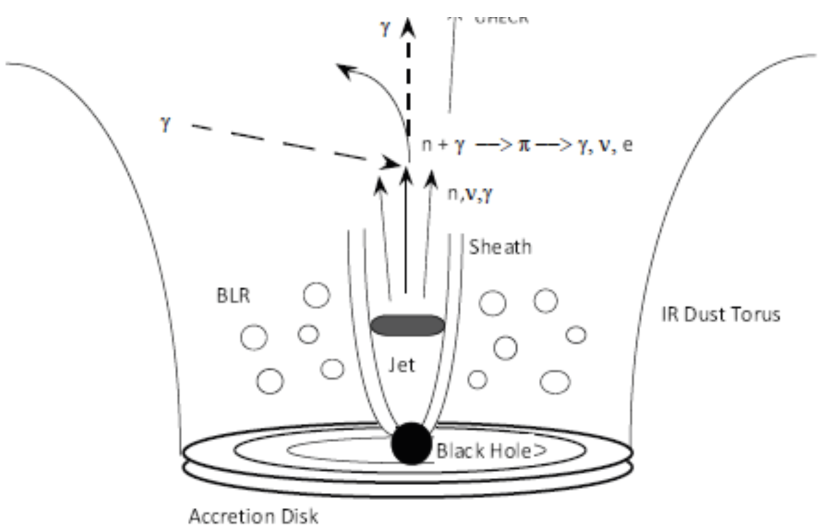
galaxy scale (~kpc) ⇔ ~day

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)

Summary

- Blazars & radio-loud AGN have been promising UHECR sources
  dominant sources of the luminosity density in the γ-ray band

- Leptonic vs lepto-hadronic
  both can explain SEDs (though more literature in leptonic)

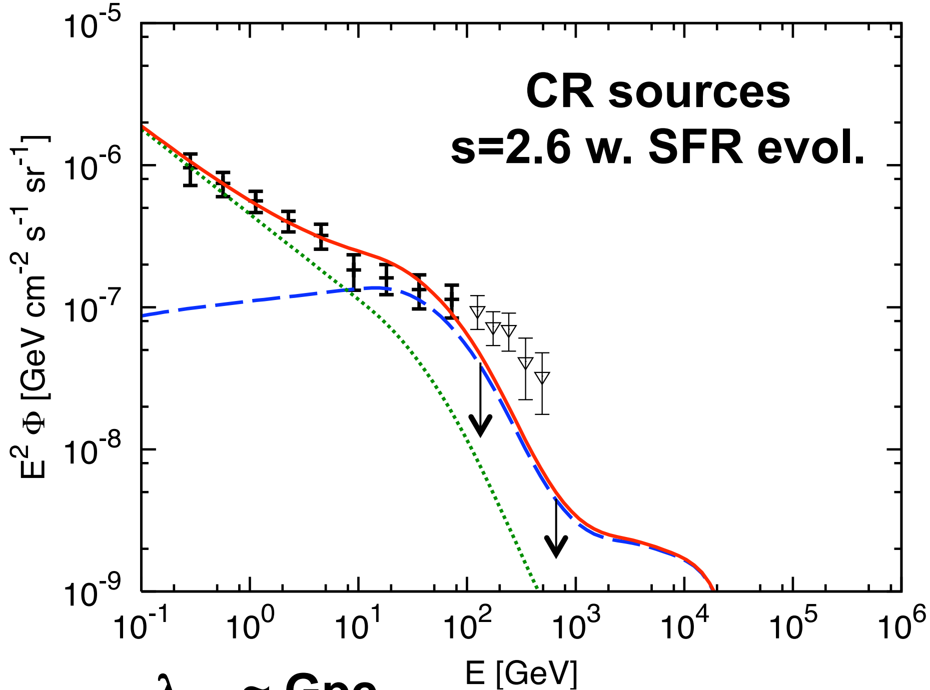
- HE neutrinos start to give crucial tests for CR ion acc. in AGN
  explaining the IceCube data w. blazars seems challenging
  simultaneous UHECR explanation: tough in standard models

- Extreme blazars: hints of intergalactic cascade emission?
  CTA, HESS-II: crucial tests for primary γ-ray vs CR-induced

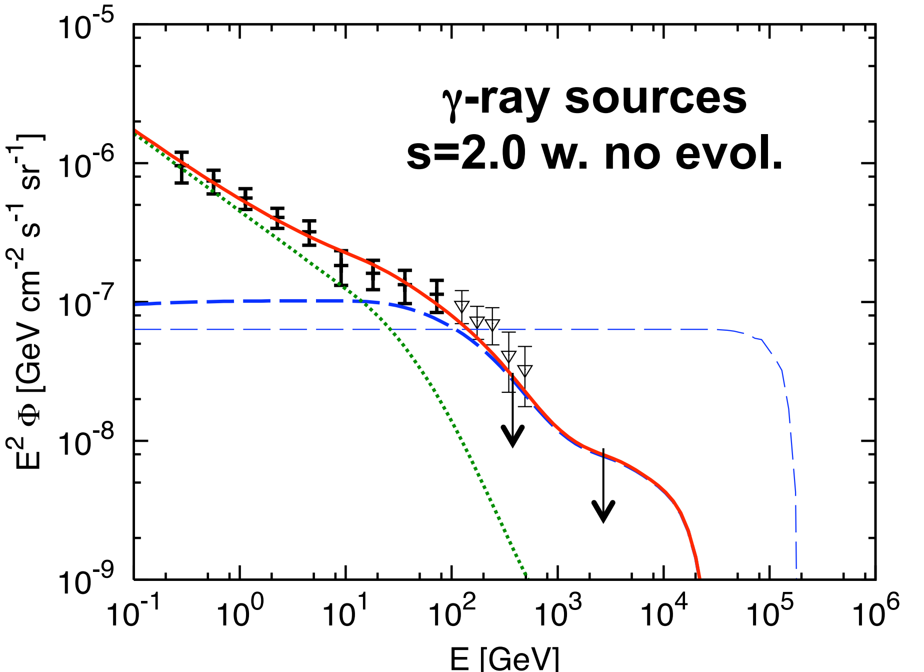
- Fast-variability could be produced by UHE neutral beams

Cosmogenic γ can contribute to diffuse γ-ray background

Steeper than spectra of preliminary Fermi data



KM, Beacom & Takami 12 JCAP

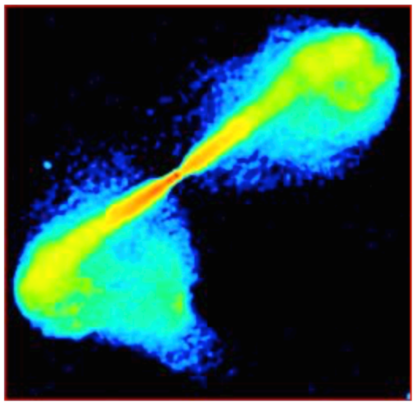


λ_{BH} ~ Gpc

→ importance of distant sources

→ effective evolution is stronger

$$E_{\rm pri} = 1\ \mathrm{TeV}$$



CIB

$$\lambda_{\rm IC} = 400\mathrm{kpc}\left(\frac{E_{\rm pri}}{1\mathrm{TeV}}\right)^{-1}$$

CMB, CIB

$$E_{\rm sec} = 3\mathrm{GeV}\left(\frac{E_{\rm pri}}{1\mathrm{TeV}}\right)^{2}$$

$$\lambda_{\gamma\gamma} = 200\mathrm{Mpc}\left(\frac{n_{\rm IR}}{0.01\mathrm{cm}^{-3}}\right)^{-1}$$

"IC pair halo" ex. Neronov & Semikoz 08

$$\theta_{\rm ext} = 0.07^\circ\left(\frac{E_{\rm sec}}{3\mathrm{GeV}}\right)^{-1/2}\left(\frac{B}{10^{-17}\mathrm{G}}\right)\left(\frac{n_{\rm IR}}{0.01\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{D}{\mathrm{Gpc}}\right)^{-1}$$

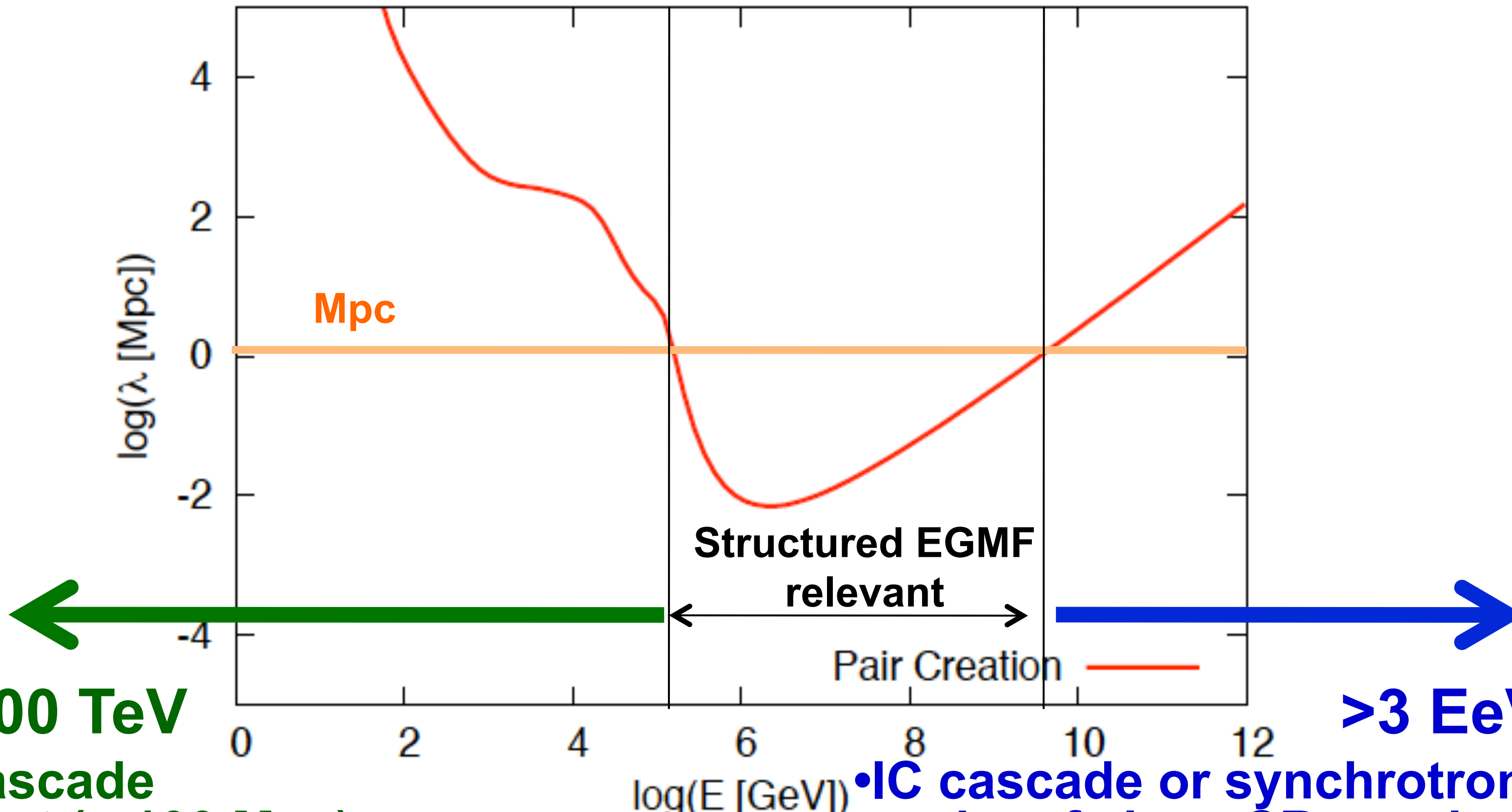
"IC pair echo" ex. KM+ 08

$$\Delta t_B = 60\mathrm{day}\left(\frac{E_{\rm sec}}{3\mathrm{GeV}}\right)^{-2}\left(\frac{B}{10^{-19}\mathrm{G}}\right)^{2}\left(\frac{n_{\rm IR}}{0.01\mathrm{cm}^{-3}}\right)^{-1}$$

blazar no halo → B > 10^{-16} G, blazar flare no echo → B > 10^{-20} G

The Fate of Gamma Rays

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



< 100 TeV

- IC cascade
- distant (> 100 Mpc) sources can be observed (either hadronic or leptonic)

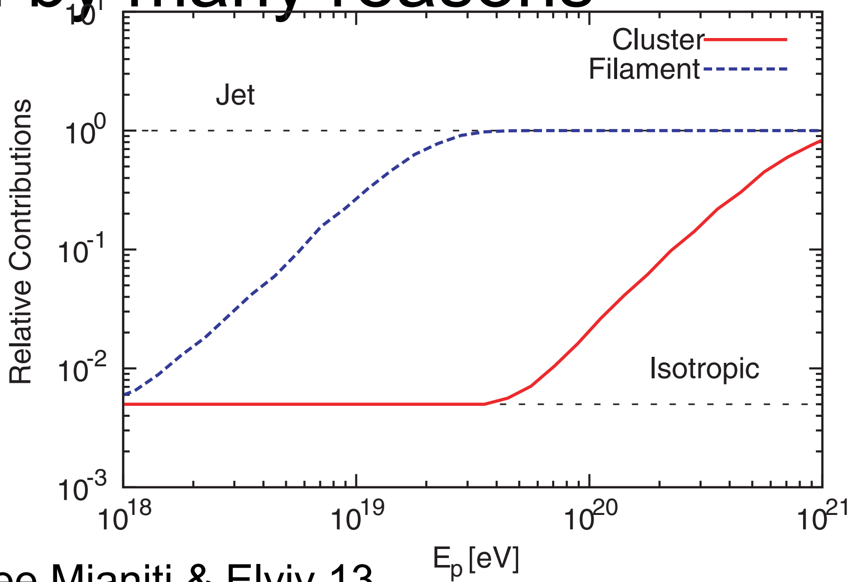
>3 EeV

- IC cascade or synchrotron
- probe of close CR accelerators (hadronic)

Issues: Assumption on CR Beaming

CR beams can be isotropized by many reasons

- structured magnetic fields
  (cluster: ~ μG)
  (filament: ~ 10 nG)
- radio bubbles/lobes (~ mG)
- plasma instabilities
  oblique Broderik+ 12, Shlickeiser+ 13 but see Mianiti & Elyiv 13
  CR streaming KM+ 12

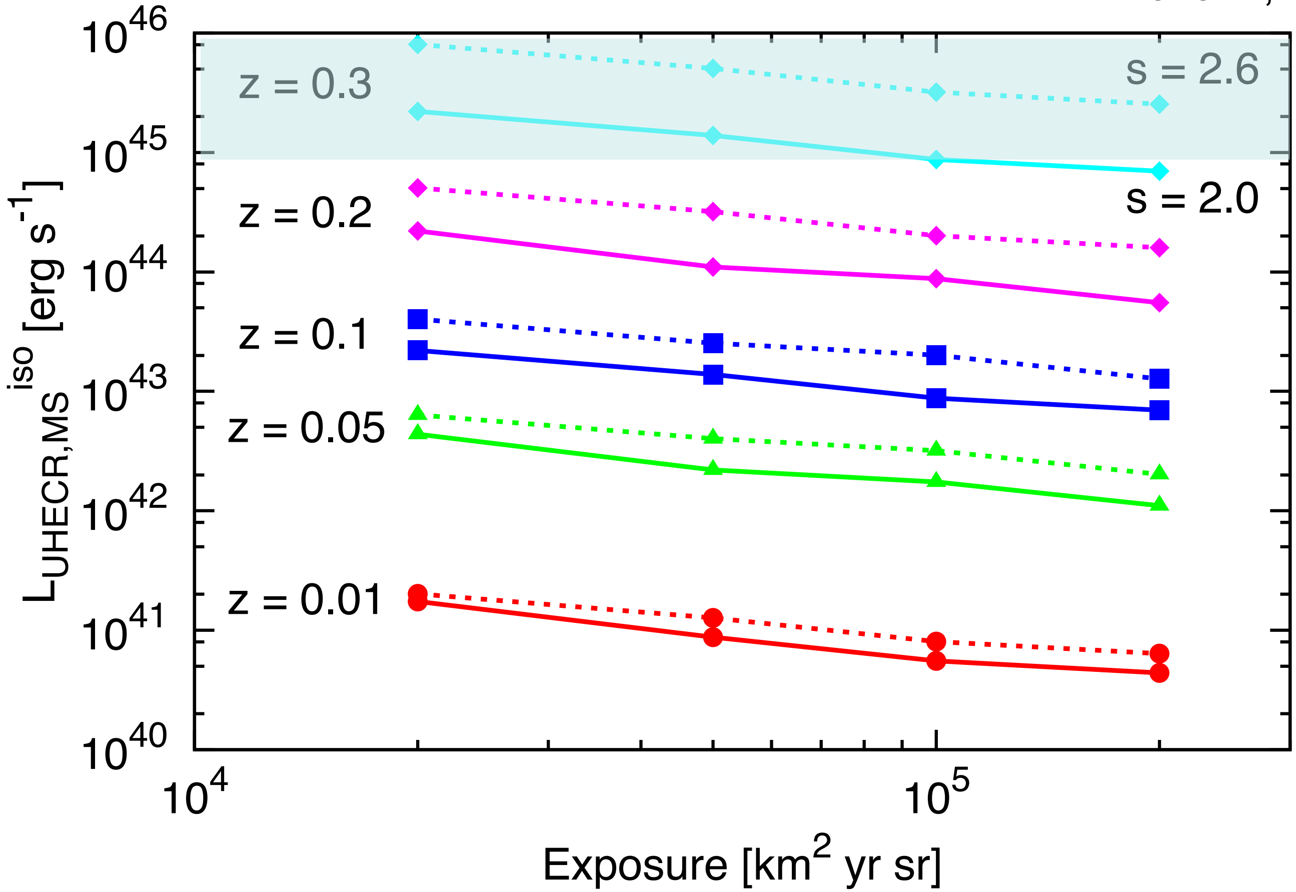


If isotropized, CR luminosity exceeds

$$L_{\rm Edd,abs} = \frac{4\pi G M_{\rm BH} m_p c}{\sigma_T} \simeq 1.3 \times 10^{46}\,{\rm erg\,s^{-1}} \left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)$$

UHECR "Isotropy" Problem

Takami, Murase & Dermer 14



E_{max} ~ 10^{19} eV

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

Extreme blazars are not UHECR sources or weird EGMF