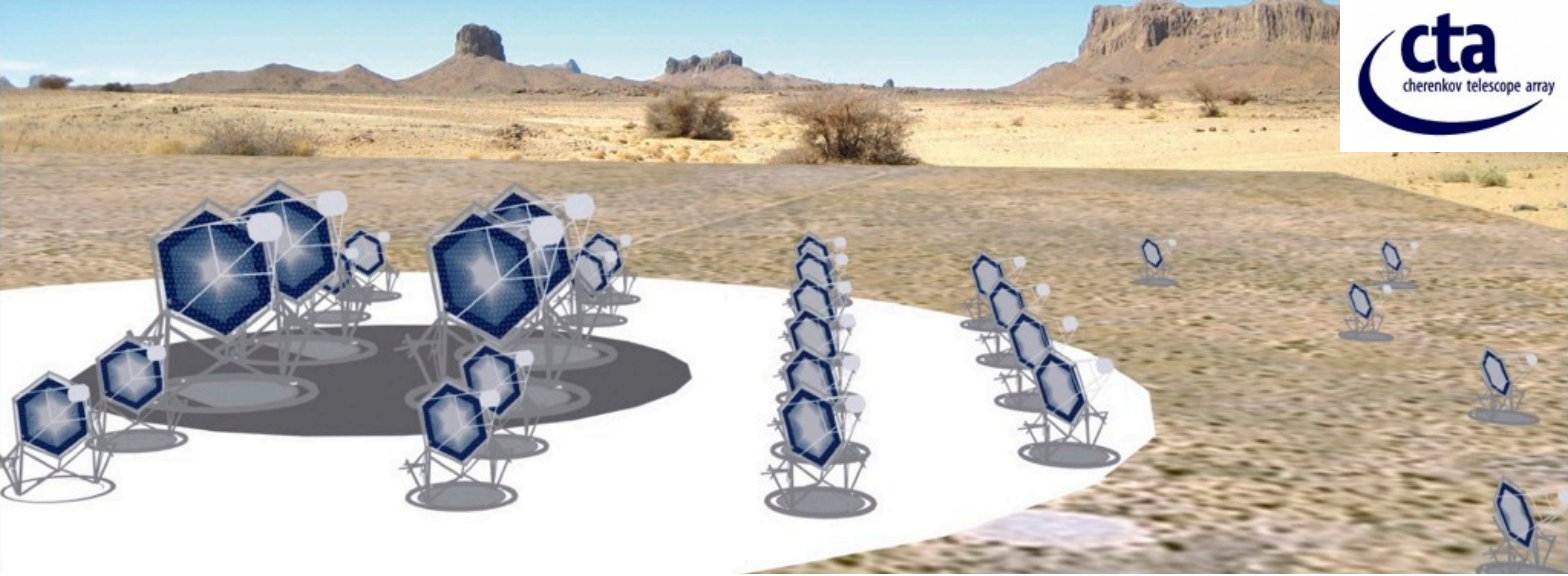

cta
cherenkov telescope array

CTA Science Cases for Ultra-high-energy Cosmic Rays

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KEK, JSPS Fellow

JSPS 独立行政法人 日本学術振興会
Japan Society for the Promotion of Science

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KEK Theory Center Cosmophysics Group

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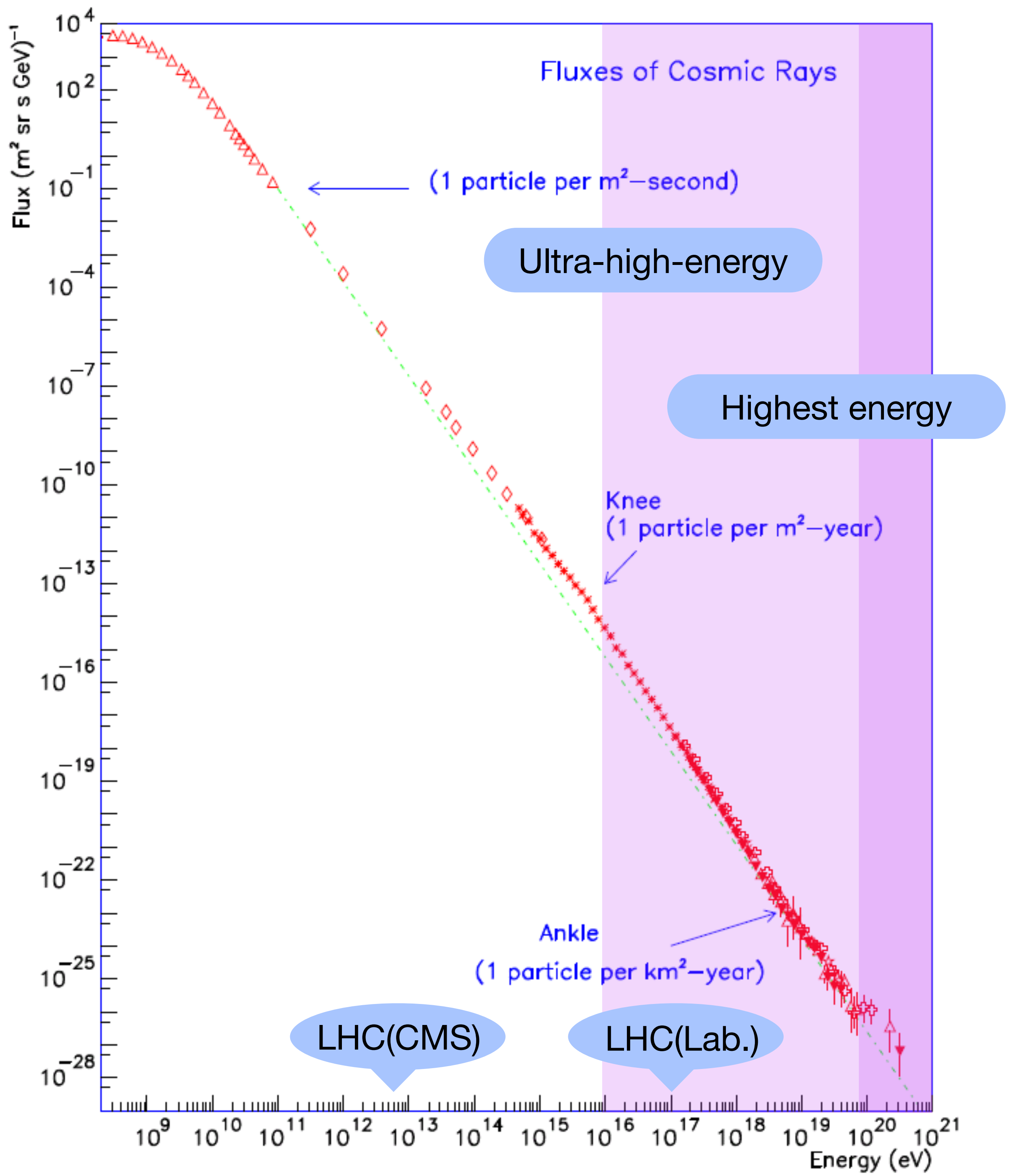
Outline

- Current understandings on ultra-high-energy cosmic rays
- Multi-messenger approaches to UHECRs
- Gamma-ray emission accompanying UHECR acceleration
  - Hadronic gamma-ray emission from blazars / AGN
  - Cosmic-ray-induced cascades
  - Neutron-star-binary mergers -- connection to GW

Cosmic rays



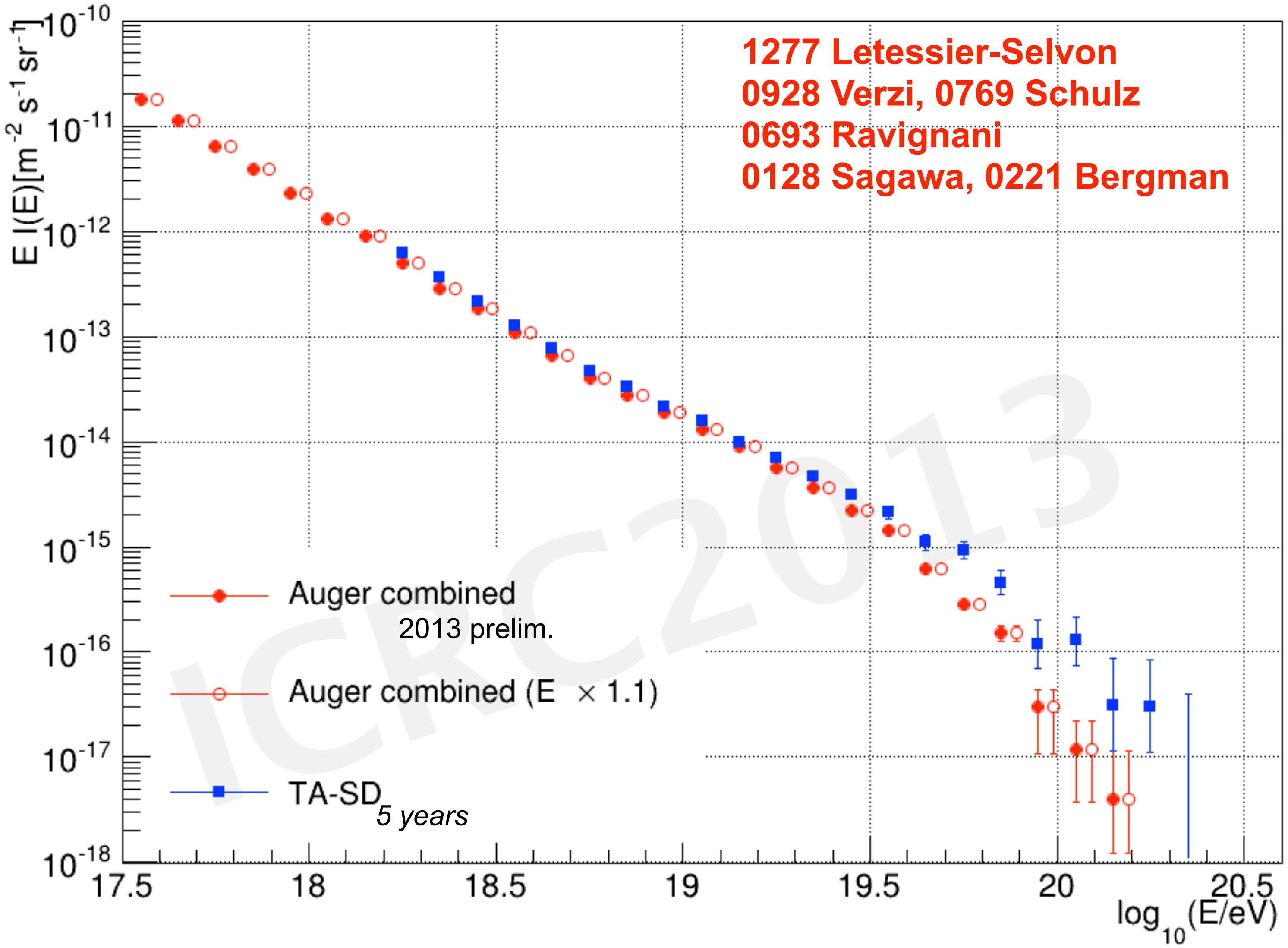
Bhattacharjee & Sigl (2000),
originally from S. Swordy

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

UHECR Spectra



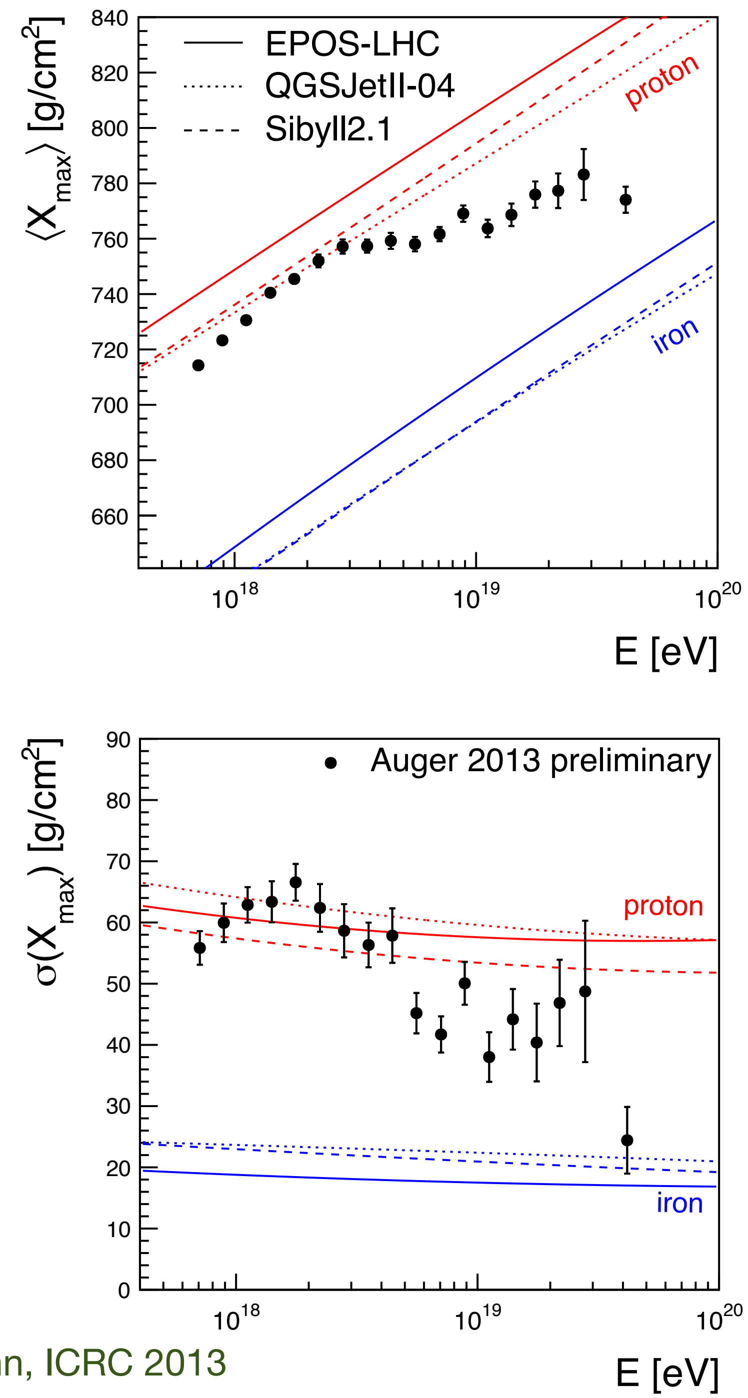
Tsunesada, ICRC 2013

- Auger energy-scale updated by (10-16)%
- Auger energy uncertainty improved to 14%
- Marginally consistent between Auger and TA
  - Steepening at $\sim 10^{20}$ eV
  - Dip at $\sim 10^{18.5}$ eV

UHECR Composition

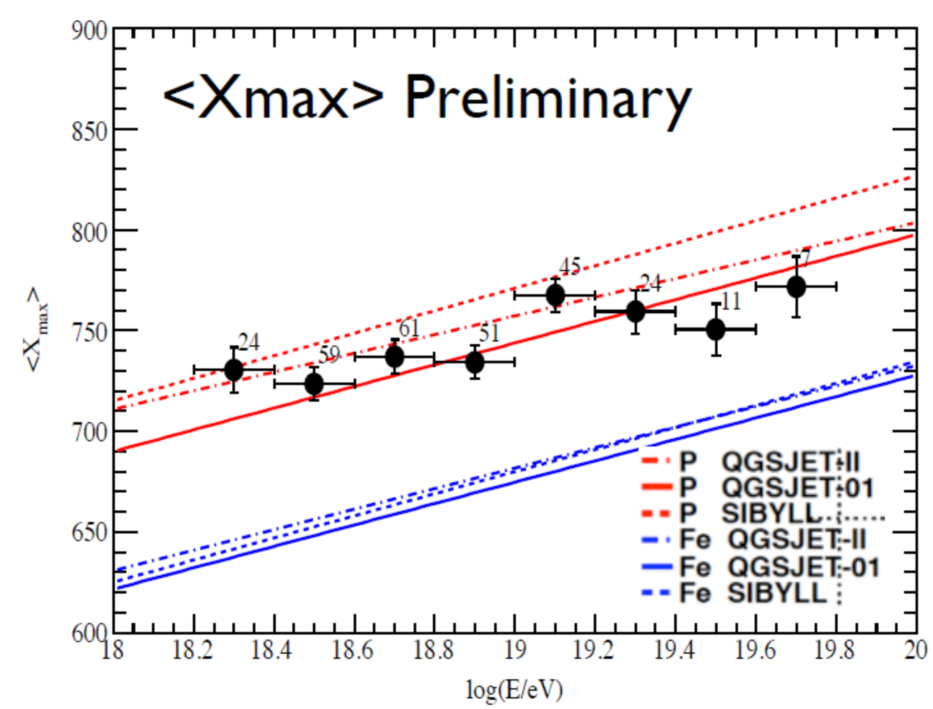
Still inconsistent between Auger and TA

Auger



Ahn, ICRC 2013

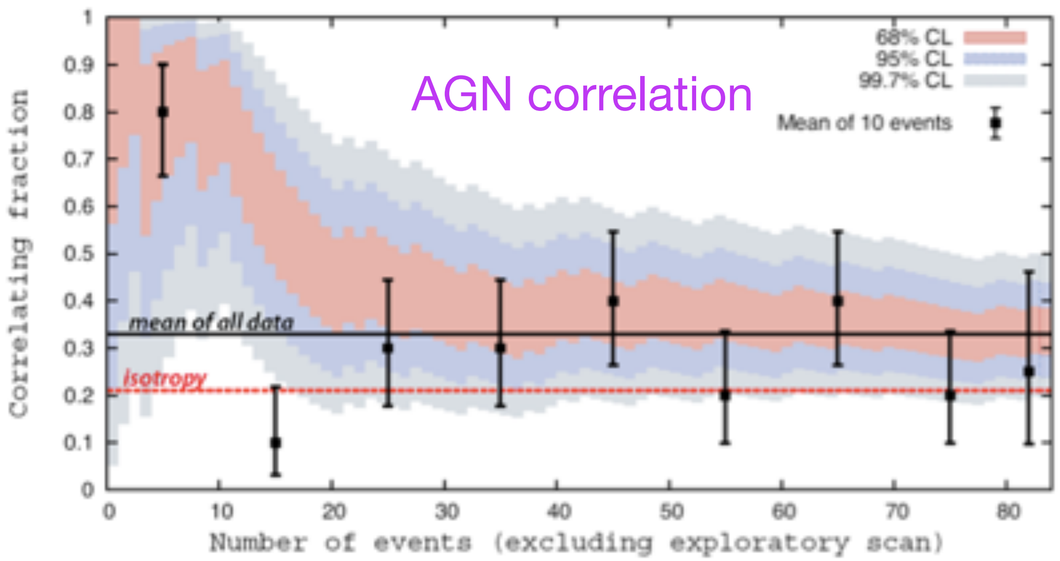
TA

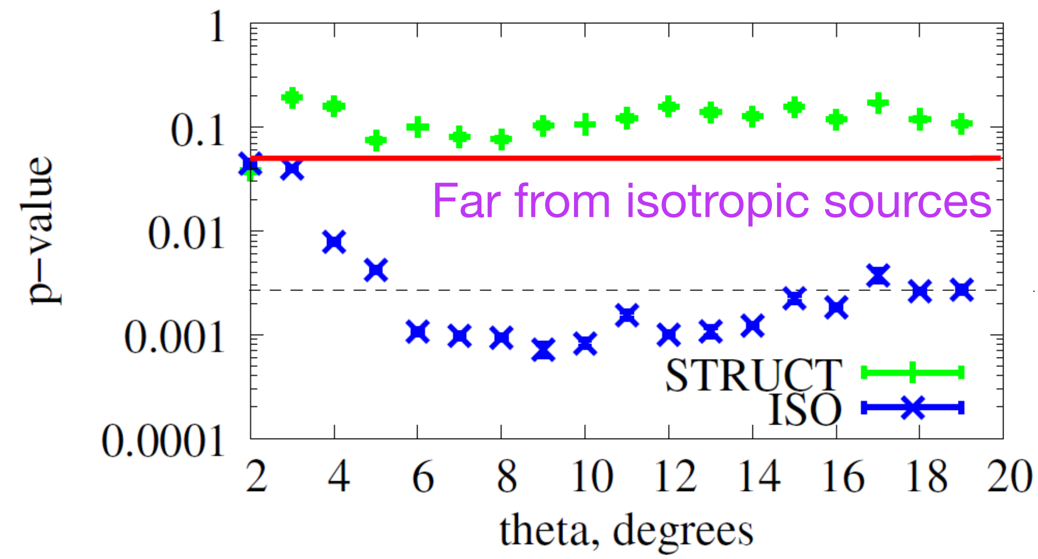


Sagawa, ICRC 2013

Anisotropy

Small-scale

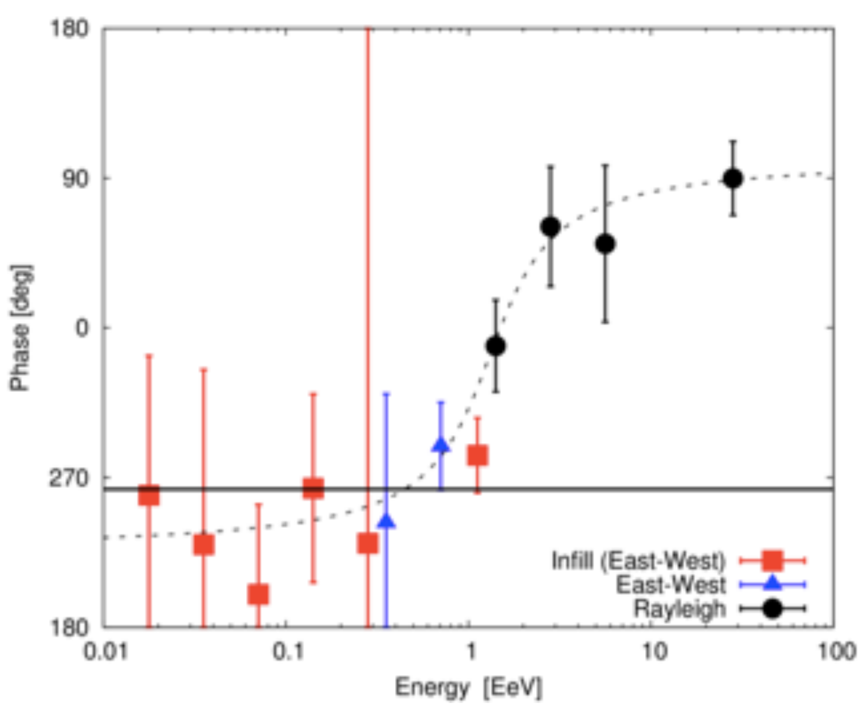


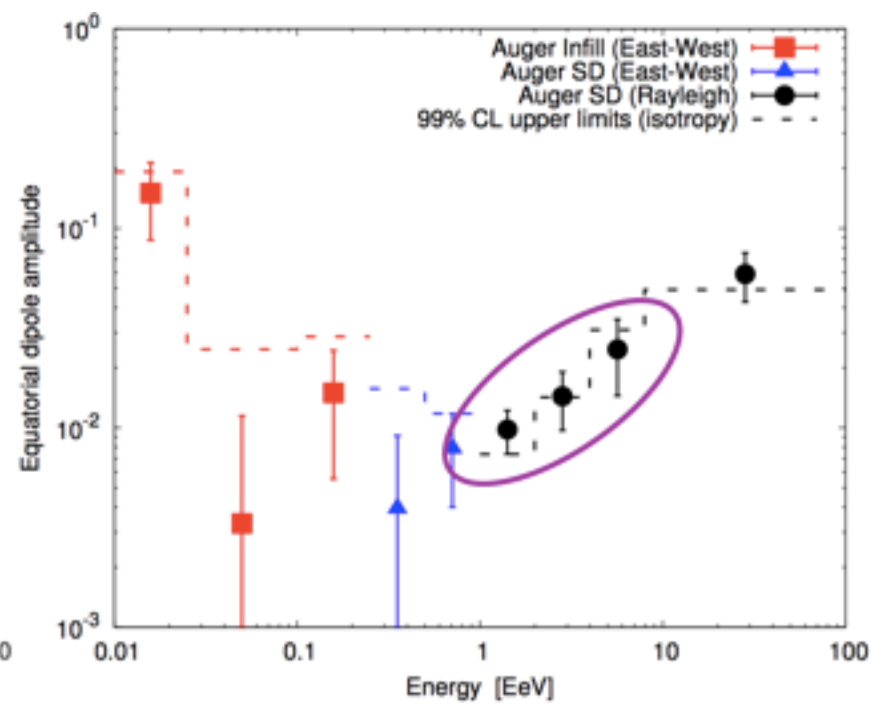


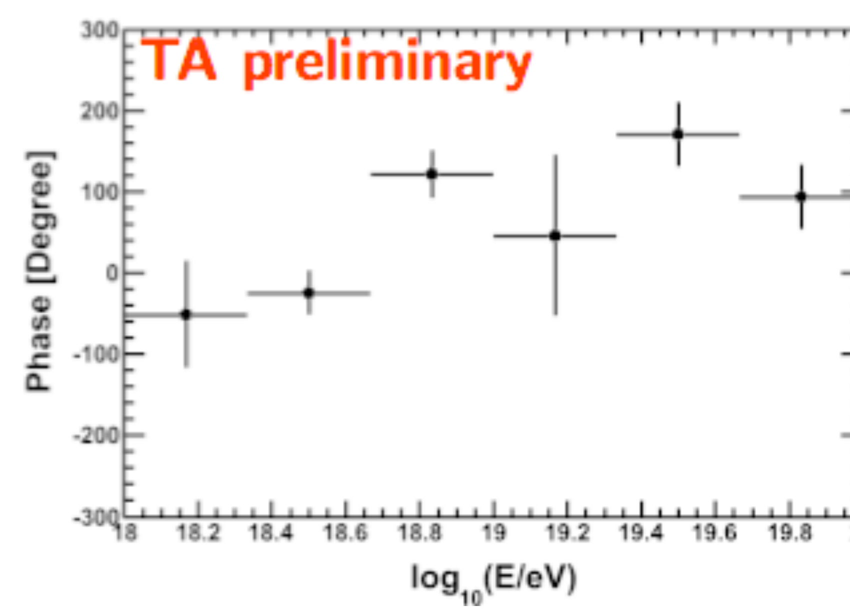
Roth, TeVPA 2013

Sagawa, ICRC 2013

Large-scale: first harmonics







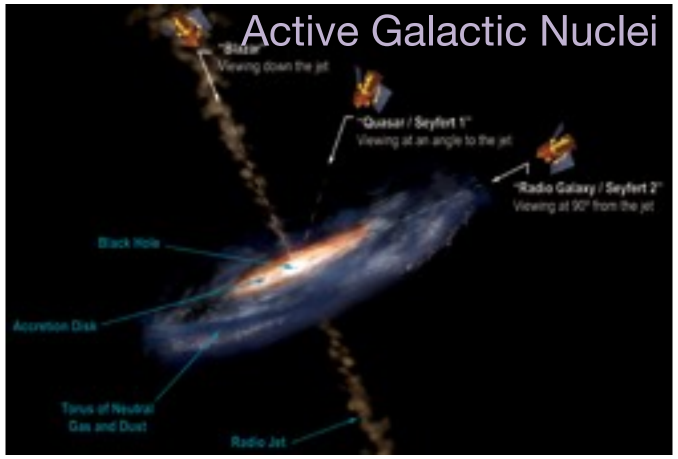
Remaining Problems on UHECRs

- What is the maximum energy of UHECRs?
- What is the composition of UHECRs?

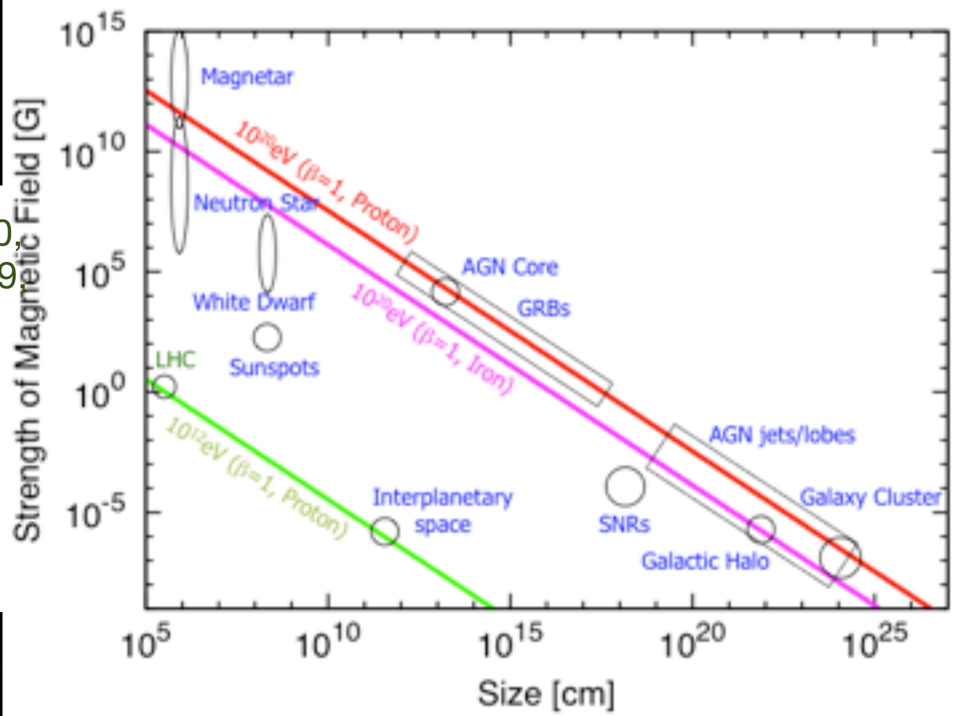
What is the sources of UHECRs?

Possible Highest-energy CR Sources

Only extreme phenomena in the Universe can produce UHECRs.

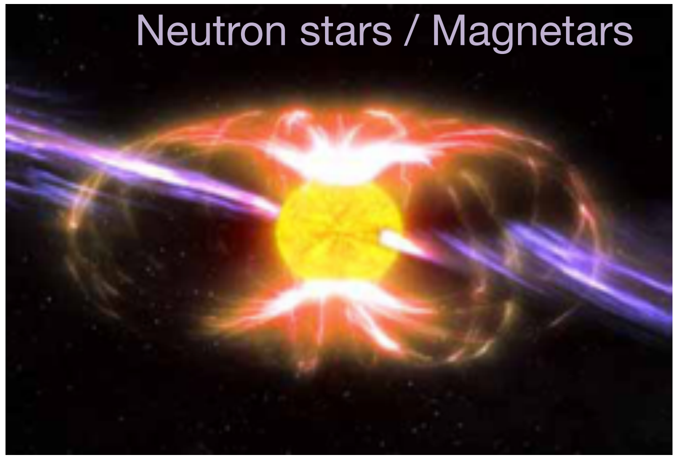


e.g., Biermann & Stritmatter ‘87, Takahara ‘90,
Rachen & Biermann ‘93, Farrar & Gruzinov ‘09,
Dermer et al. ’09, Pe’er et al. ‘09,
HT & Horiuchi ’11, Murase et al. ‘11



JEM-EUSO Purple book

e.g., Waxman ‘95, Vietri ’95,
Murase et al. ’08, Wang et al. ‘08



e.g., Blasi et al. ’00, Arons ‘03,
Kotera ‘11, Fang et al. ‘12

e.g., Norman et al. ‘95, Kang et al. ‘96, Inoue et al. ‘07

What we have learned from UHECR measurements

- Some (extreme) composition models have not been favored (spectrum, composition)

  Allard et al. 2008, Hooper et al. 2009, ...

- Apparent local source number density
  - (>)~ 10^{-4} Mpc^{-3} for small deflection (~protons)

    HT& Sato 2009, Cuoco et al. 2009, Abreu et al. 2013

  - >~ 10^{-7} Mpc^{-3} for heavy nuclei (highly dependent on B models)

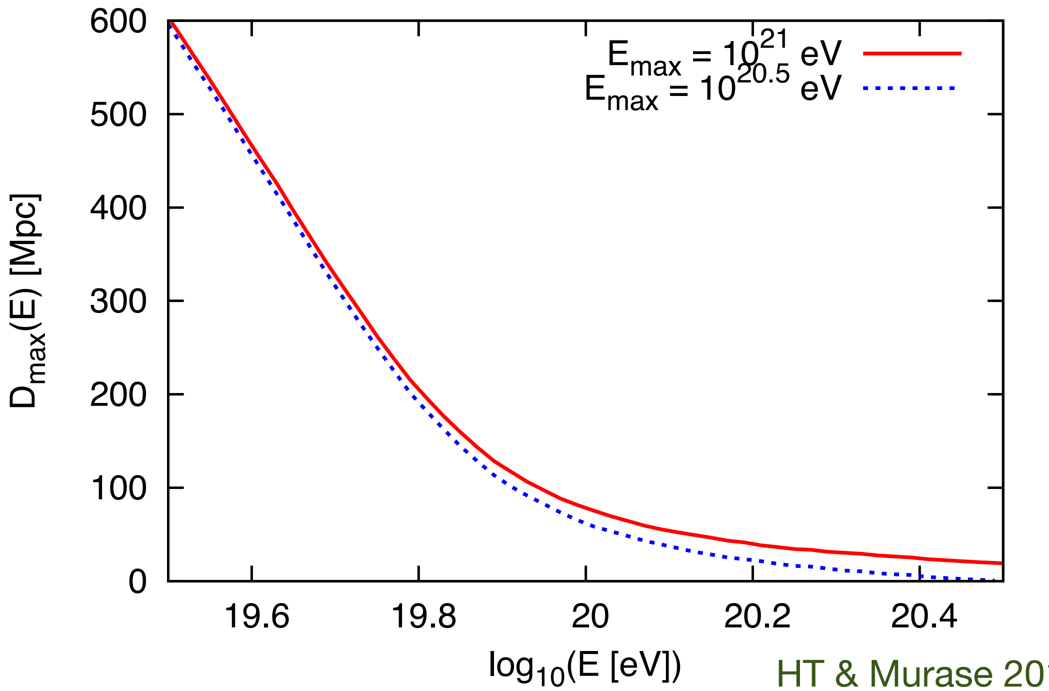
    HT, Inoue, Yamamoto 2012

Objects	n_s [Mpc^{-3}]
Major galaxies	~ 10^{-2}
Bright galaxies	1.3 x 10^{-2}
Seyfert galaxies	1.25 x 10^{-2}
Dead quasars	5 x 10^{-4}
Fanaroff-Riley I	8 x 10^{-5}
Cluster of galaxies	1 x 10^{-6}
Bright quasars	1.4 x 10^{-6}
Colliding galaxies	7 x 10^{-7}
BL Lac objects	3 x 10^{-7}
Fanaroff-Riley II	3 x 10^{-8}

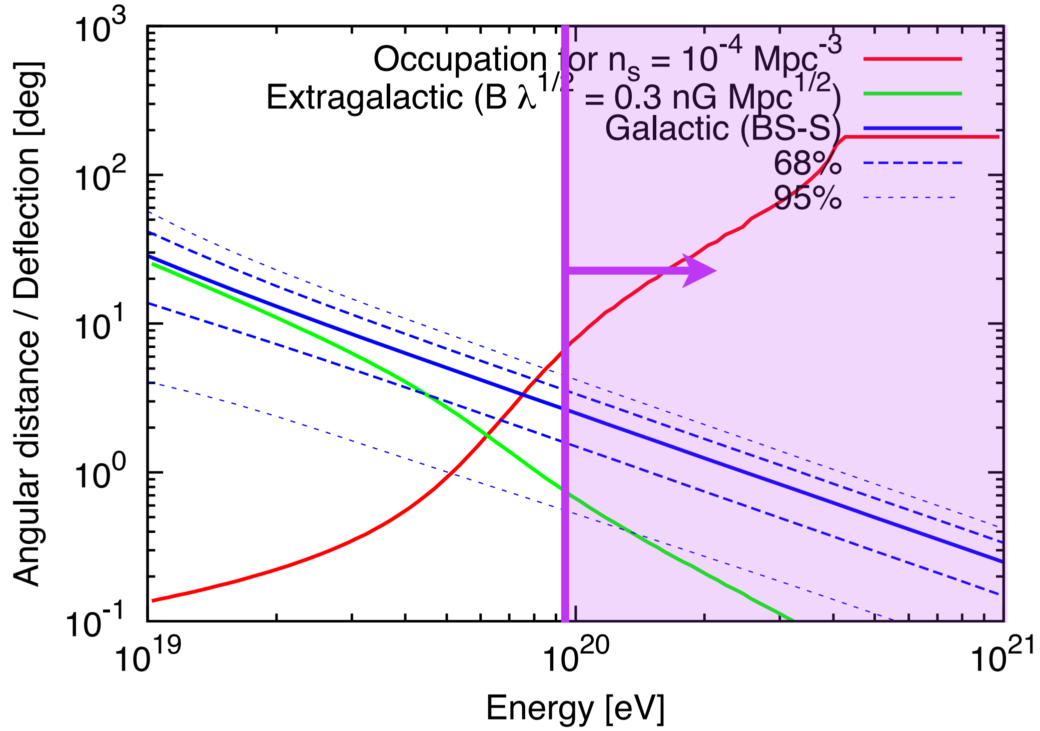
See Yoshida & Ishihara (2012) for a neutrino constraint

Source-identification ability of UHECRs

Averaged occupation of UHECR sources in the sky > Deflection angles



HT & Murase 2012



D_{max}(E)

- 99% cosmic rays included
- Uniform distribution

Occupation

$$\frac{4\pi}{3} D_{\rm max}^3(E) n_s \Delta\Omega = 4\pi$$

Deflection (extragalactic)

$$\theta(E) = 2.5^\circ \left(\frac{E}{10^{20}\ \rm eV}\right)^{-1} \left(\frac{D_{\rm max}(E)}{100\ \rm Mpc}\right)^{1/2} \left(\frac{B}{1\ \rm nG}\right) \left(\frac{\lambda}{1\ \rm Mpc}\right)^{1/2}$$

$B\lambda^{1/2} \sim 0.3\ \rm nG\ Mpc^{1/2}$ from Ryu et al. (2008) simulations

HT & Murase 2012

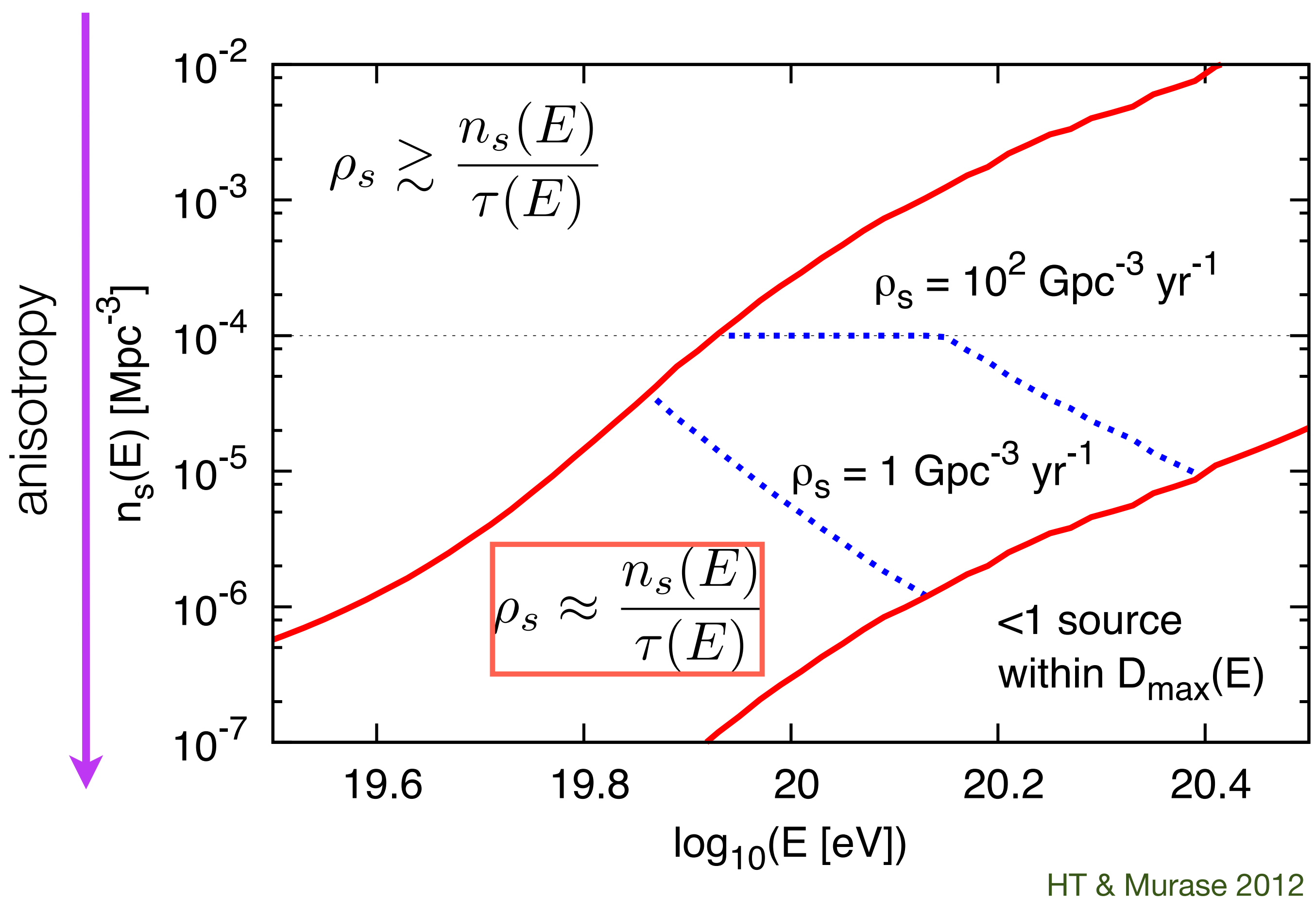
1. Huge statistics at E > 10^{20} eV
   JEM-EUSO, TA2, Auger-next, ...

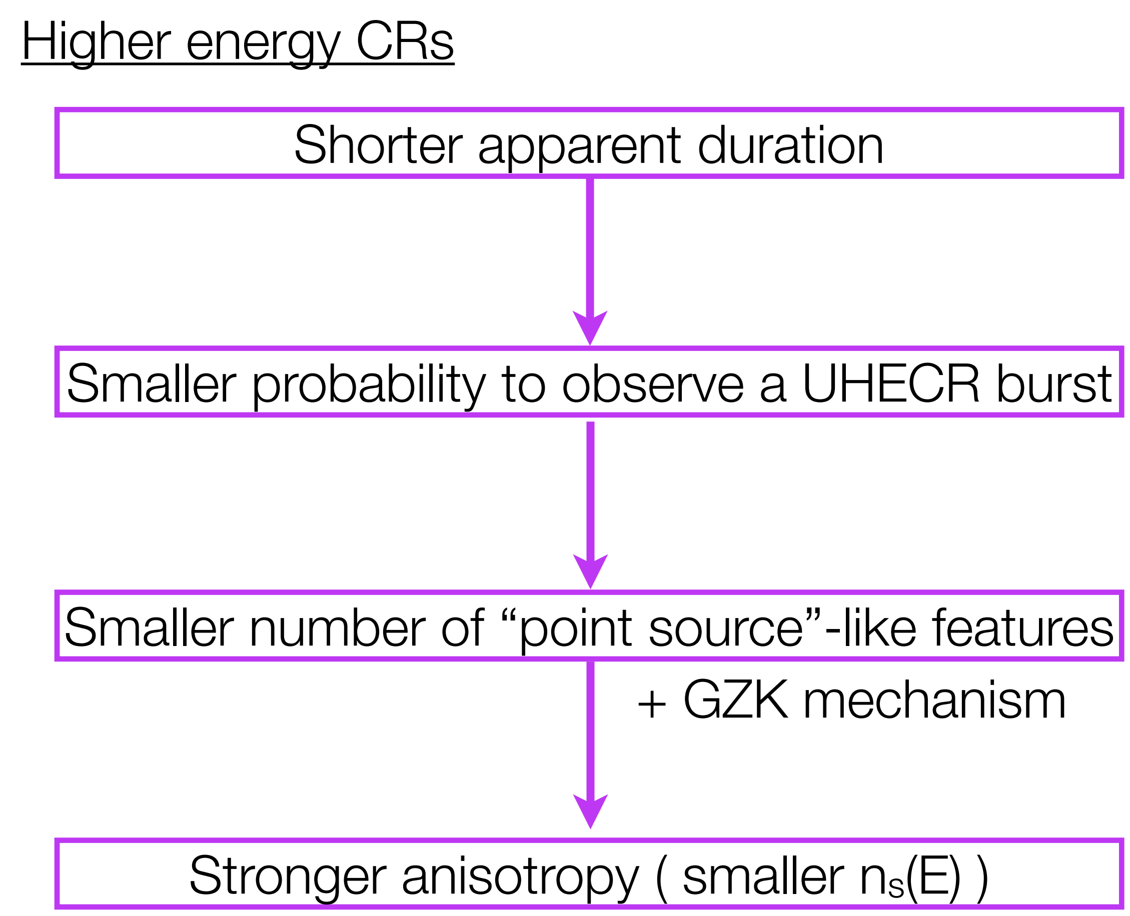
2. Other messengers
   Gamma rays, neutrinos, ...

Transient Sources

A stronger anisotropy appears at higher energies .

· $n_s(E)$ ~ source number density estimated on the assumption of steady sources
· ρ_s : UHECR burst rate (source property instead of n_s in steady source cases)





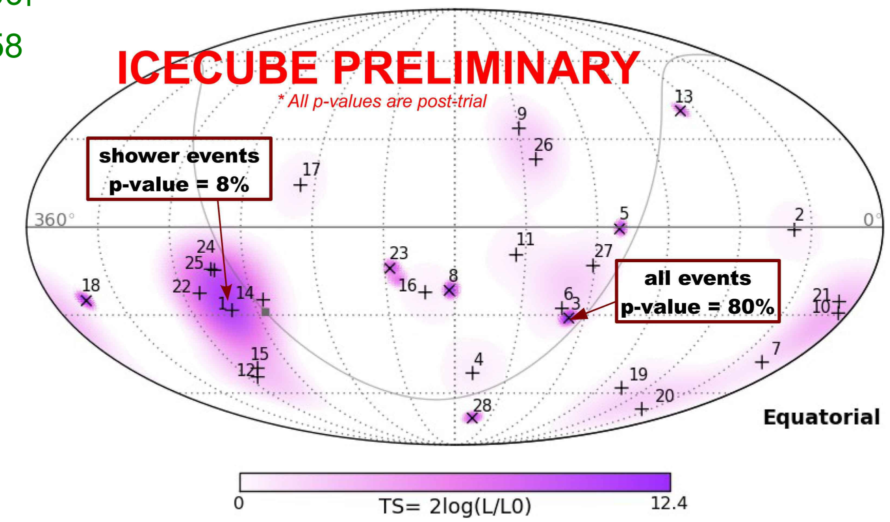
The dependence of $n_s(E)$ is evidence of transient generation of UHECRs.

$n_s(E)$ should be estimated in at least two energy ranges.

PeV neutrinos

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [Loeb&Waxman'06; He *et al.* 1303.1253; Murase, MA & Lacki 1306.3417]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]
- **Galactic sources:**
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase (in prep.)]
  - diffuse Galactic γ-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase (in prep.)]
- **γ-ray association:**
  - unidentified Galactic TeV γ-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic γ-ray emission [Neronov, Semikoz & Tchernin 1307.2158

$E_p \sim 20\ E_\nu \sim 10^{16}$ - 10^{17} eV



Markus Ahlers, TeVPA 2013

- Gamma-ray emission accompanying UHECR acceleration
    - Hadronic gamma-ray emission from blazars / AGN
    - Cosmic-ray-induced cascades (AGN)
    - (Neutron-star-binary mergers if time is allowed)

Active Galactic Nuclei

- Luminous nucleus comparable with the whole galaxy
- Powered by accretion onto supermassive black holes
- Some AGN (radio galaxies) have jets.

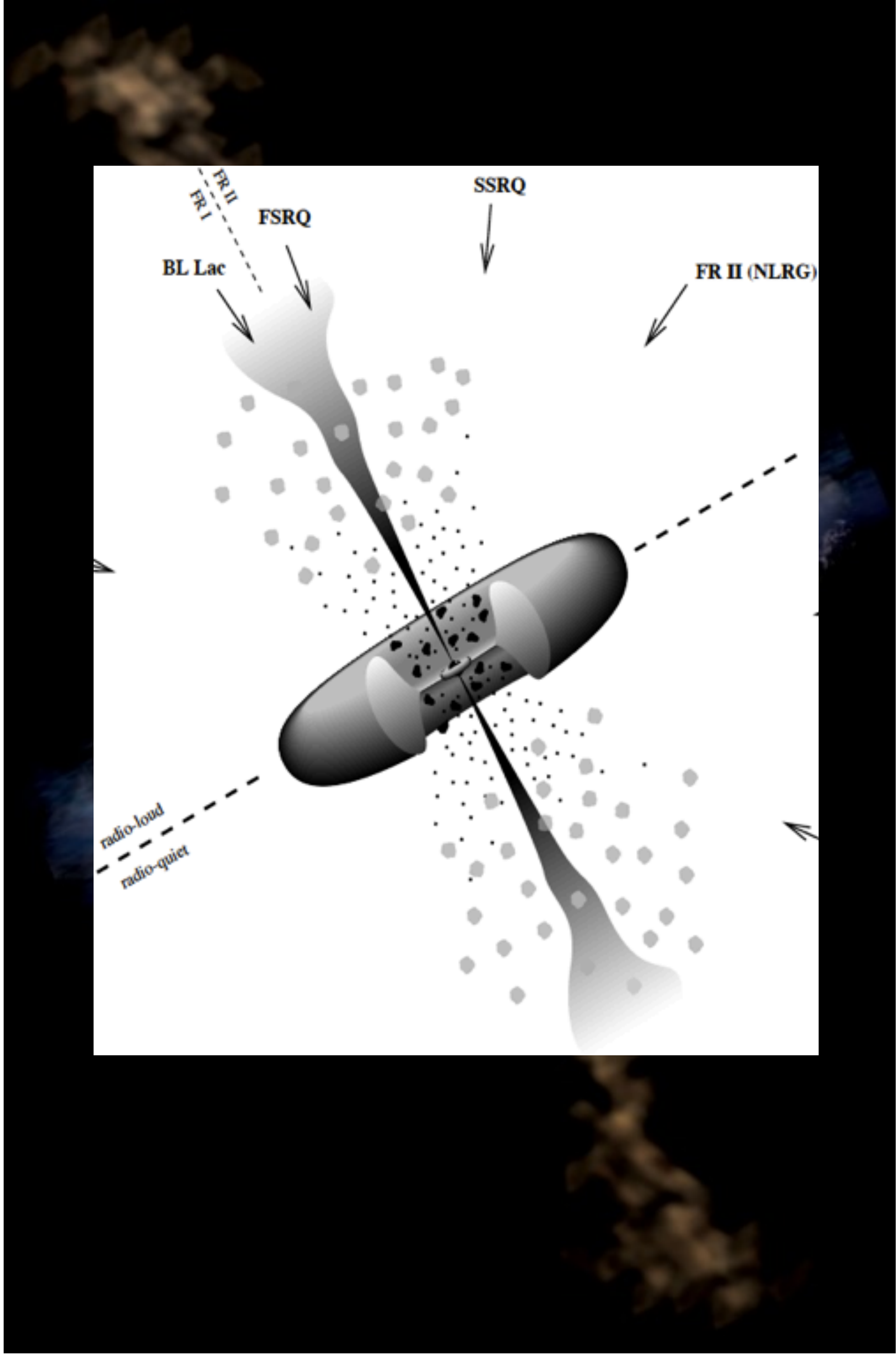
Unification Hypothesis

The diversity of AGN originates from the viewing angle of observers.

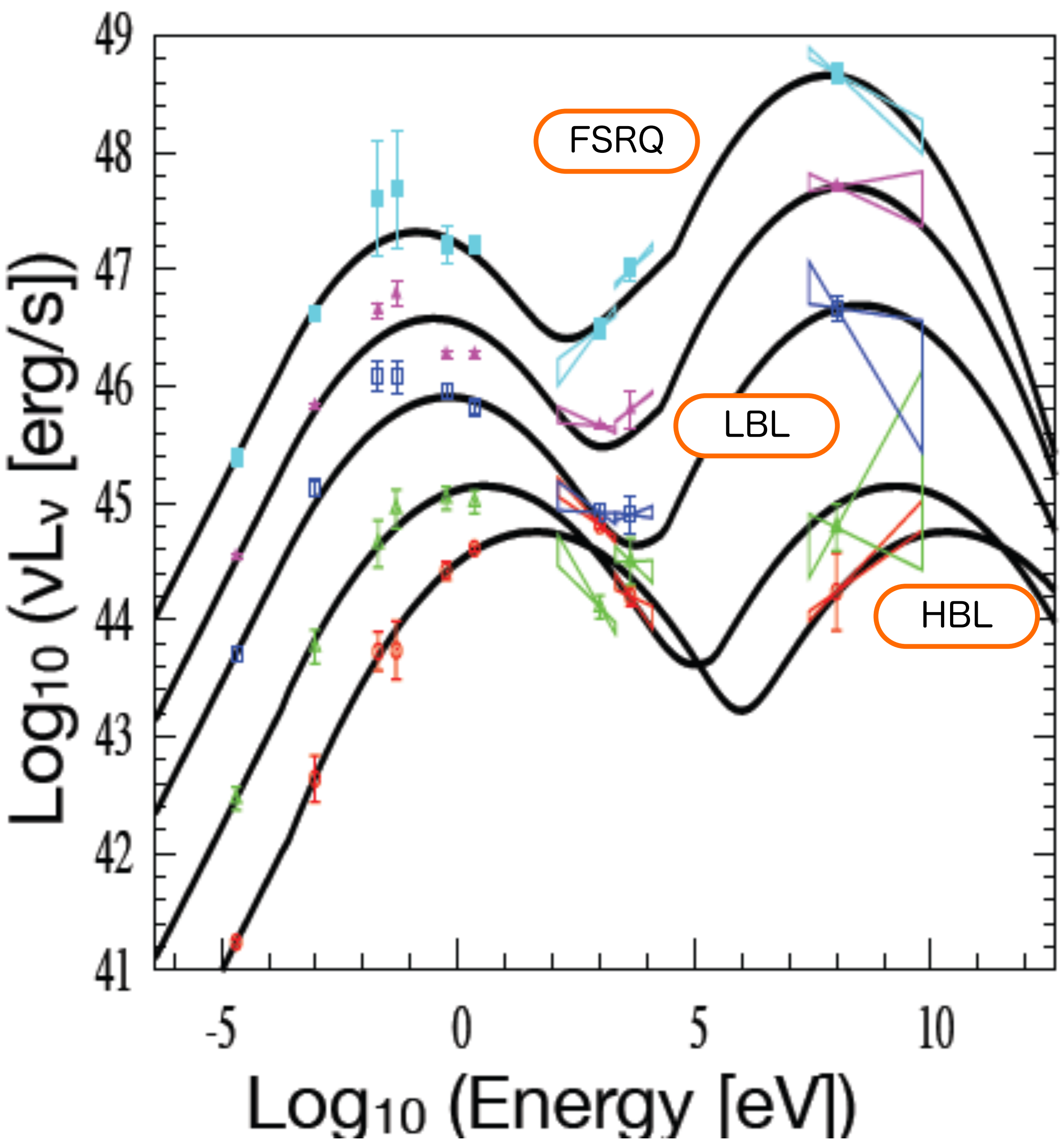
Urry & Padovani 1995

Blazars - AGN with jets directed to observers

Relativistic jets
--> Relativistic beaming is essentially important.



Typical SED and Blazar Sequence



Fossati+ 1998

Spectral Energy Distribution

Two humps

- Lower freq. - Electron synchrotron radiation
- Higher freq. - Inverse Compton / Hadronic

Blazar sequence

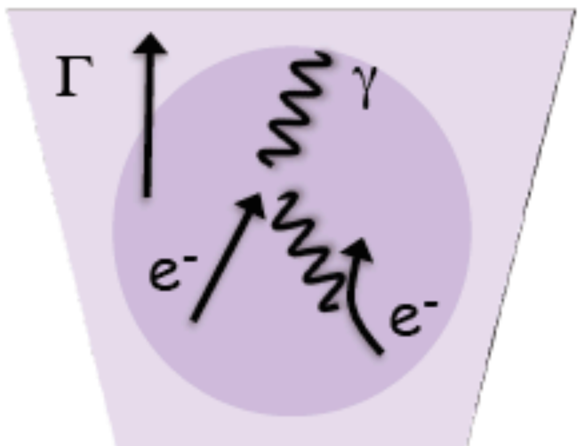
Empirical relation:

The lower peak frequency is, the higher luminosity is.

Emission Models of Blazars

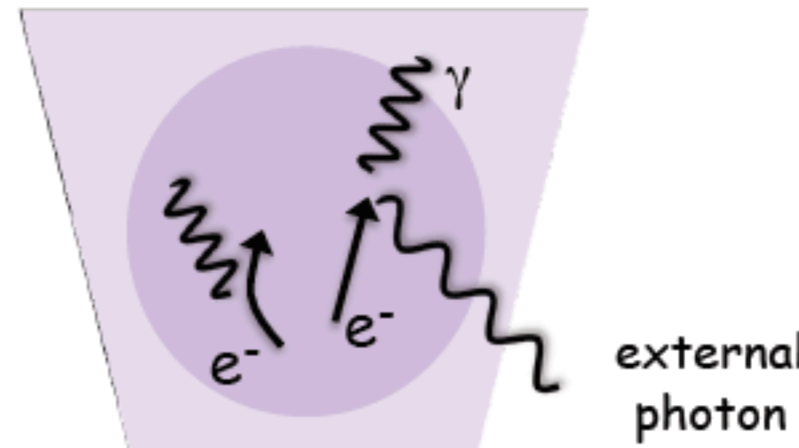
Leptonic Model

Synchrotron self-compton model



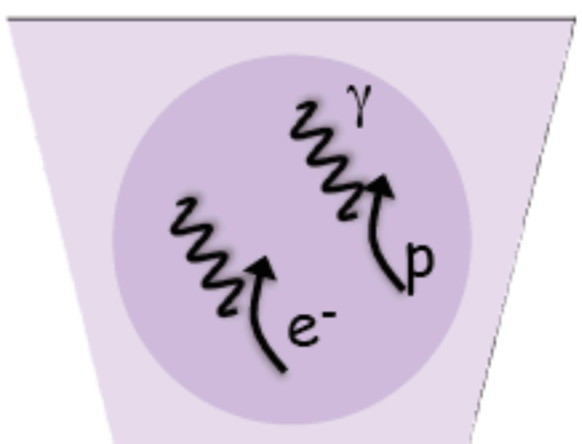
B ~ 10 - 100 mG

External compton model



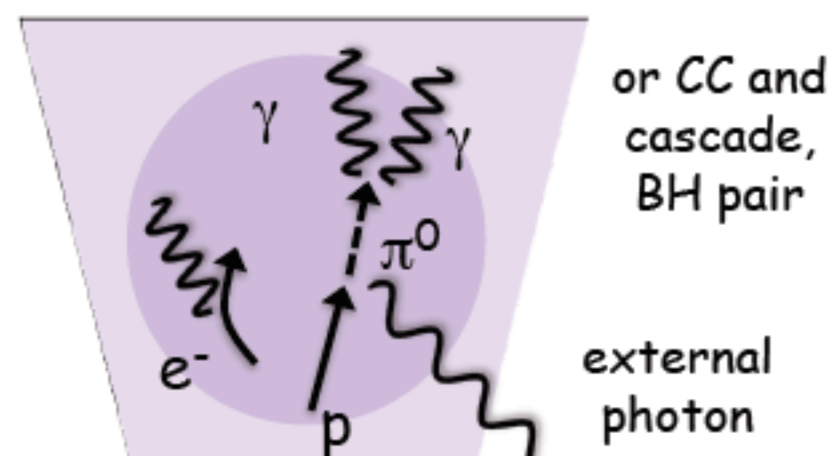
Hadronic Model

Proton synchrotron model



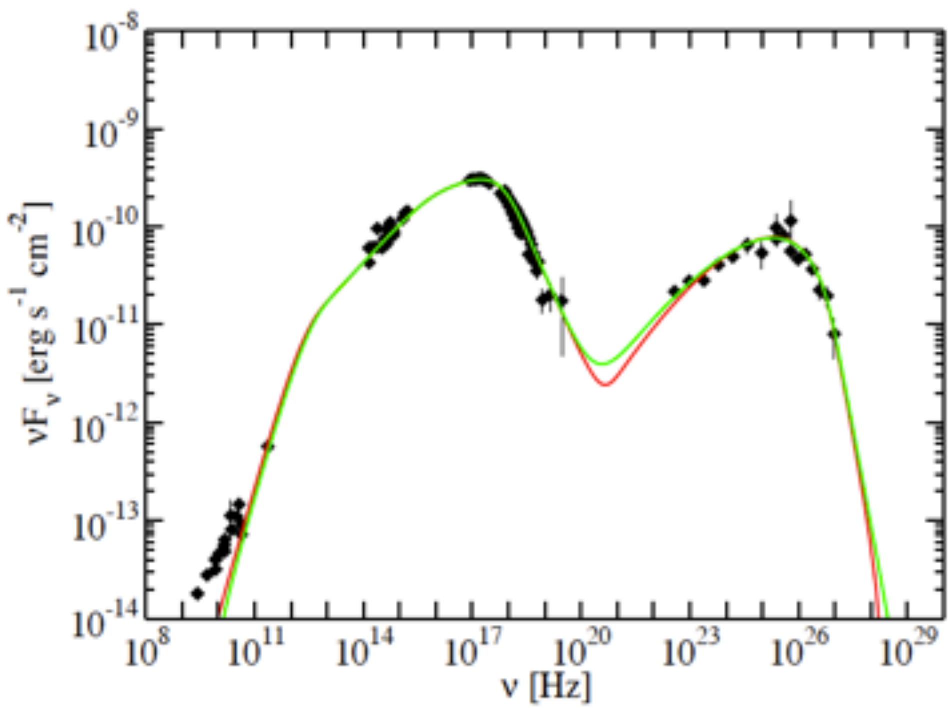
B ~ 10 – 100 G
UHECRs ($E>10^{18}$eV)

photohadronic model

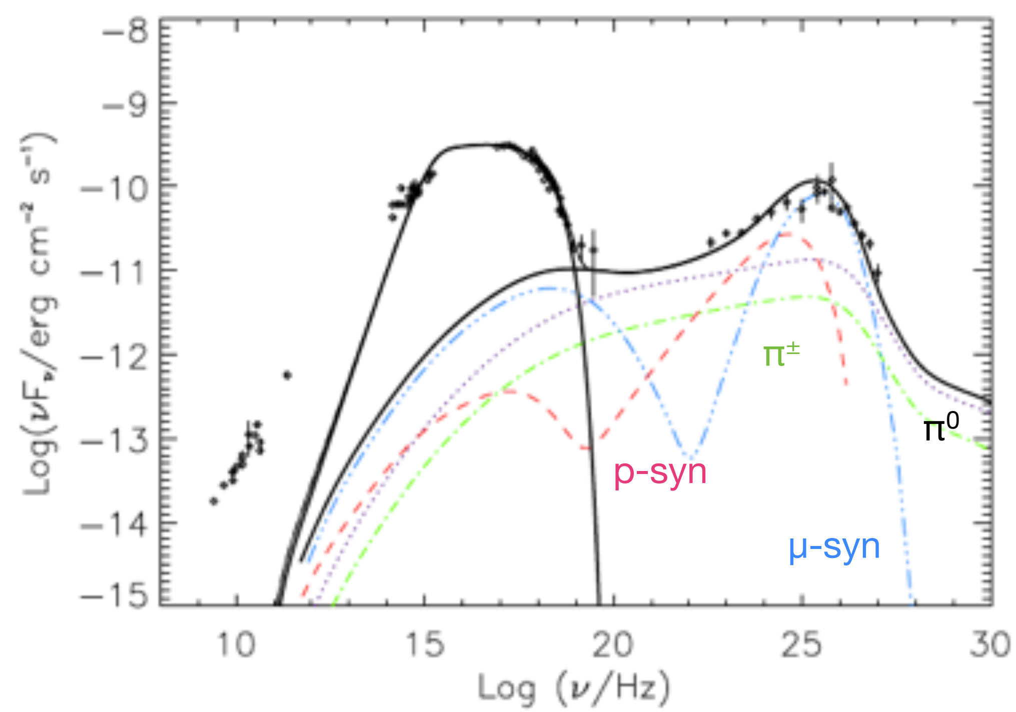


SED Modeling of Mrk 421

<u>Leptonic model</u>



<u>Hadronic model</u>



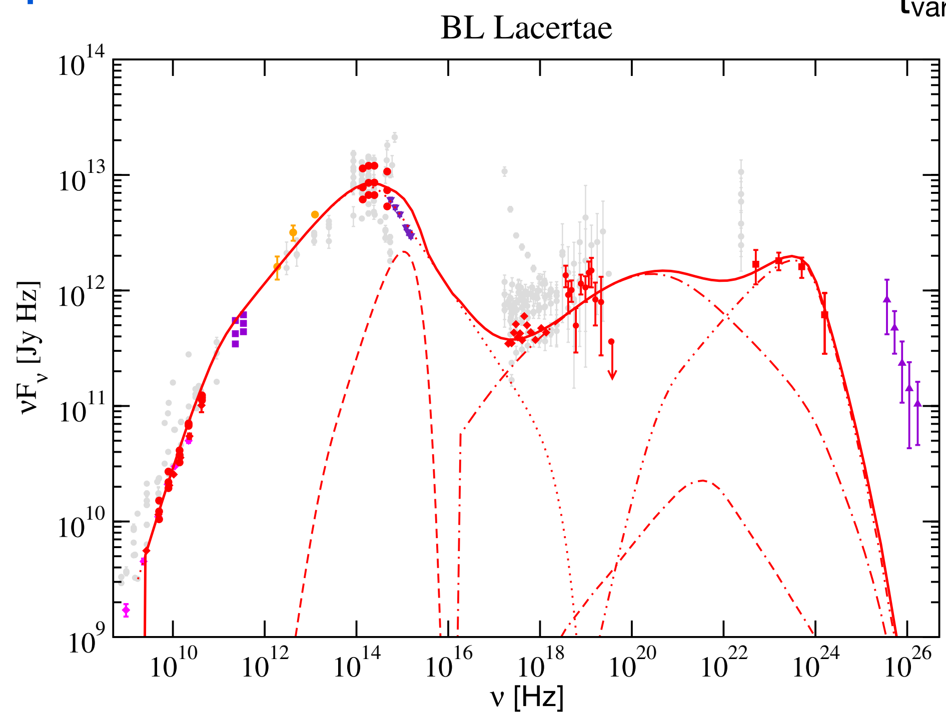
Abdo+ 2011

- Spectral fit → Physical parameters
- Both models can reproduce the SED.
- Hadronic models usually require UHECRs.

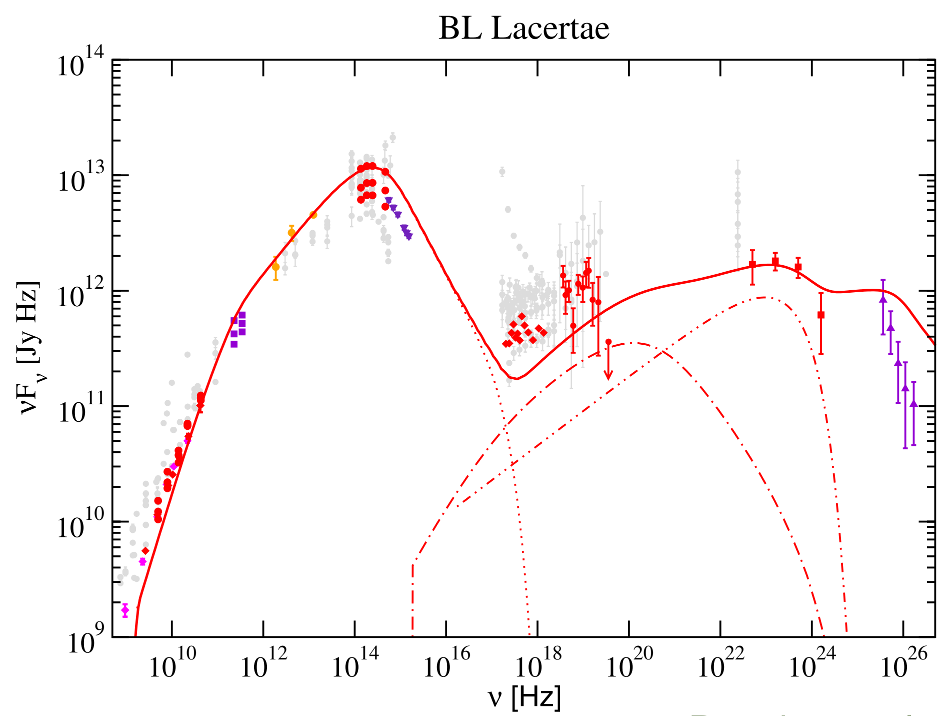
(Lepto-)Hadronic Model for BL Lac

Leptonic model

t_{var} ~ 1.5 hr



Hadronic model



	Leptonic	Hadronic
L_e [erg/s]	4.4×10^{43}	-
L_p [erg/s]	8.7×10^{42}	9.8×10^{48}
B [G]	2.5	10
δ	15	15
γ_{min}	1.1×10^3	7×10^2
γ_{max}	1×10^5	1.5×10^4
q_e	3.2	3.5
E_{max}	-	2×10^{18}
q_p	-	2.4

Hadronic model

- $L_p = \pi R^2 \beta c n_p m_p c^2$
- μ-synchrotron, π-synchrotron are neglected.
  - Simpler semi-analytical method --- parameter fits
  - Only available cases are considered
- Cascade in the emission region

Böttcher et al. 2013

UHECR Acceleration in SSC blobs

Hadronic scenarios --> hint of unknown UHECR sources

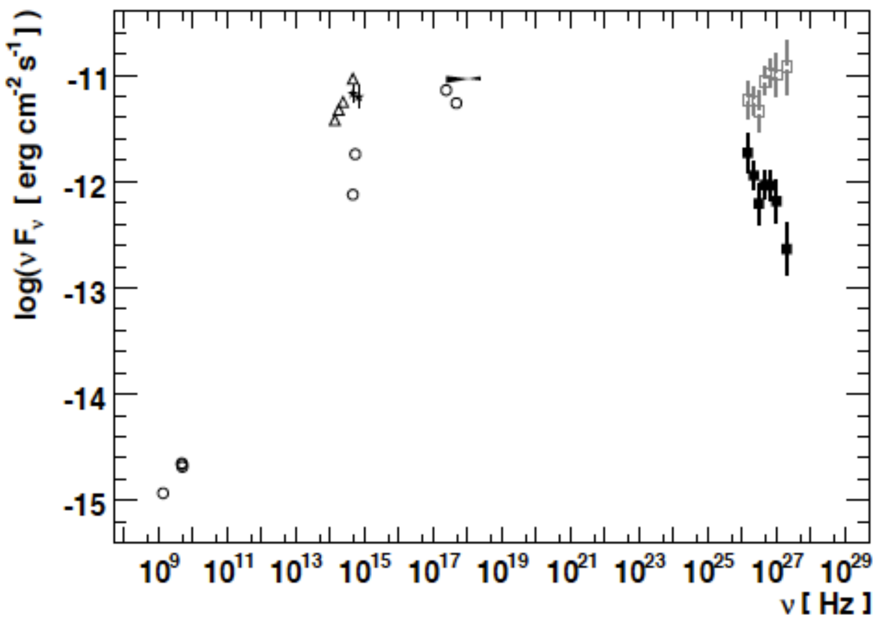
ID	Source	z	Epoch	t_{var} (s)	δ^{a}	$R'^{a}(10^{15})$ (cm)	B'^{a} (G)	$E^{max}{}_{A}/Z(10^{19})^{f}$ (eV)
1	CenA(core)	0.00183	2009	$\leqslant 1.0 \times 10^{5}$	1.0–3.9	3.0–11.0	0.02–6.2	0.01–4
2	M87	0.00436	2009	1.7×10^{5}	3.9	14.0	0.055	0.05
3	NGC1275	0.0179	2010 Oct	8.6×10^{4}	2.3	2×10^{3}	0.05	5
4	NGC6251	0.024	...	...	2.4	120	0.037	0.3
5	Mrk421	0.03	2001 Mar 19	1.0×10^{3}	80	3.0	0.048	0.3
6	Mrk501 (h.[c],1997)	0.0337	1997 Apr 16	7×10^{3}	14–20	1.0–5.0	0.15–0.8	0.1–2
7	Mrk501 (l.[c],1997)	0.0337	1997 Apr 7	...	15	5.0	0.8	2
8	Mrk501 (l.[c],2007)	0.0337	2007	...	25	1.0	0.31	0.2
9	Mrk501 (l.[c],2009)	0.0337	2009	3.5×10^{5}	12–25	1.0–130	0.015–0.34	0.2–0.7
10	1ES1959+650(h.[c])	0.047	2001 Sep–2002 May	$(2.2–7.2) \times 10^{4}$	18–20	5.8–9	0.04–0.9	0.1–3
11	1ES1959+650(l.[c])	0.047	2006 May 23–25	8.64×10^{4}	18	7.3	0.25–0.4	1–2
12	PKS2200+420/BL Lac	0.069	...	...	15	2.0	1.4	1
13	PKS2005−489	0.071	...	...	22	8.0	0.7	4
14	WComae	0.102	2008 Jun 7–8	5400	20–25	3.0	0.24–0.3	0.4–0.7
15	PKS2155−304	0.116	2006 Jul 28–30	300	110	0.86	0.1	0.3

Dermer, Murase, HT, Migliori 2012

The highest energy CRs are difficult to be accelerated in the SSC blobs of BL Lac objects / FR I galaxies.

Extreme HBL

Highest-frequency-end of the blazar sequence



Aharonian et al. 2007

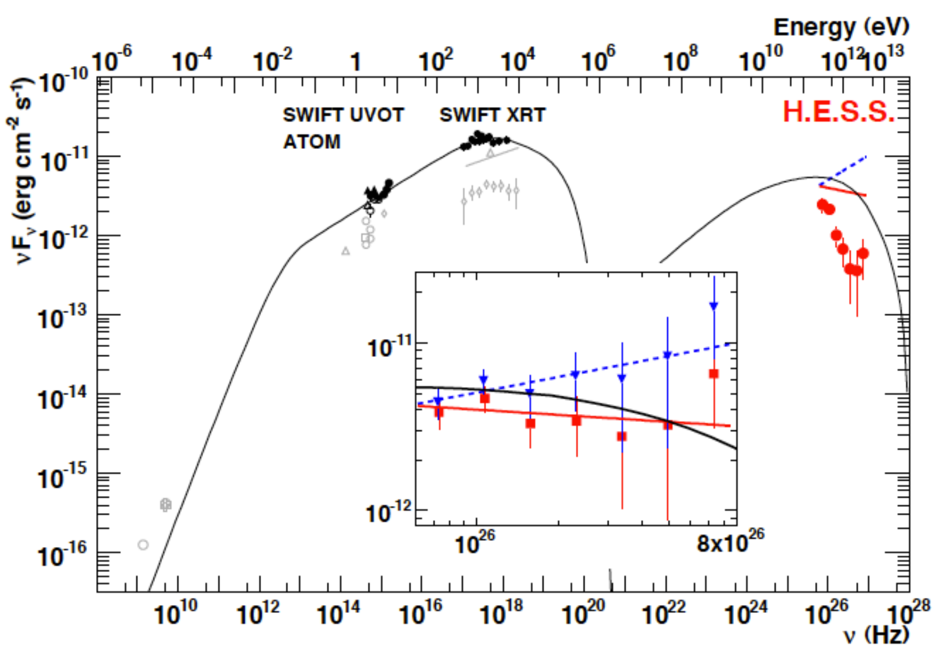
<u>1ES 0229+200</u> (z = 0.14)
$\Gamma = 2.50 \pm 0.19_{stat} \pm 0.10_{sys}$
(500 GeV - 15 TeV)

z ~ 0.2

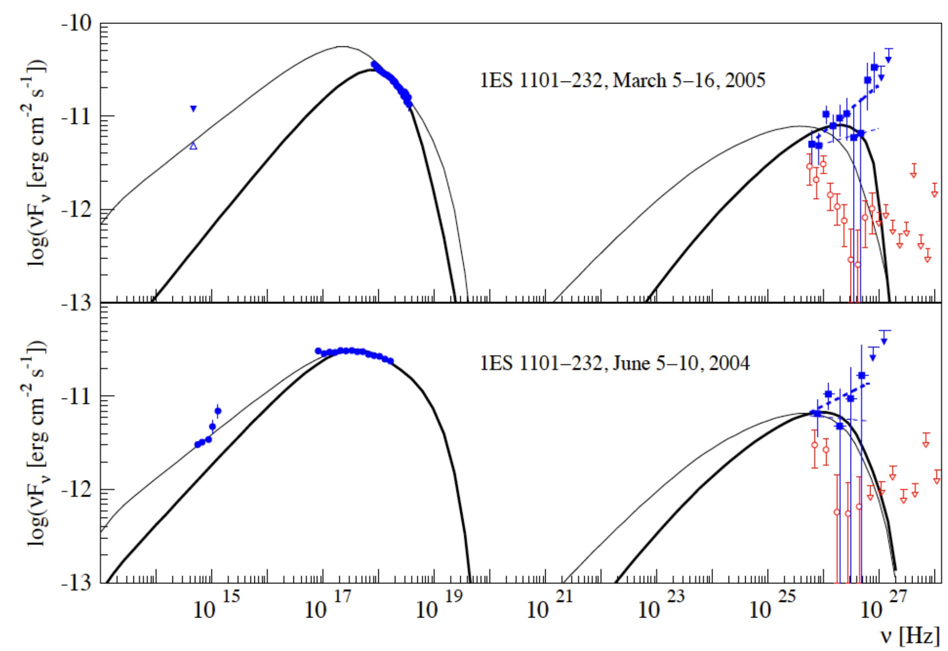
- Very hard TeV spectra beyond ~10 TeV
- No significant variability
- Faint in the Fermi range

<u>1ES 0347-121</u> (z = 0.188)
$\Gamma = 3.10 \pm 0.23_{stat} \pm 0.10_{sys}$
(250 GeV - 3 TeV)

<u>1ES 1101-232</u> (z = 0.186)
$\Gamma = 2.94 \pm 0.20$
(> 225 GeV)



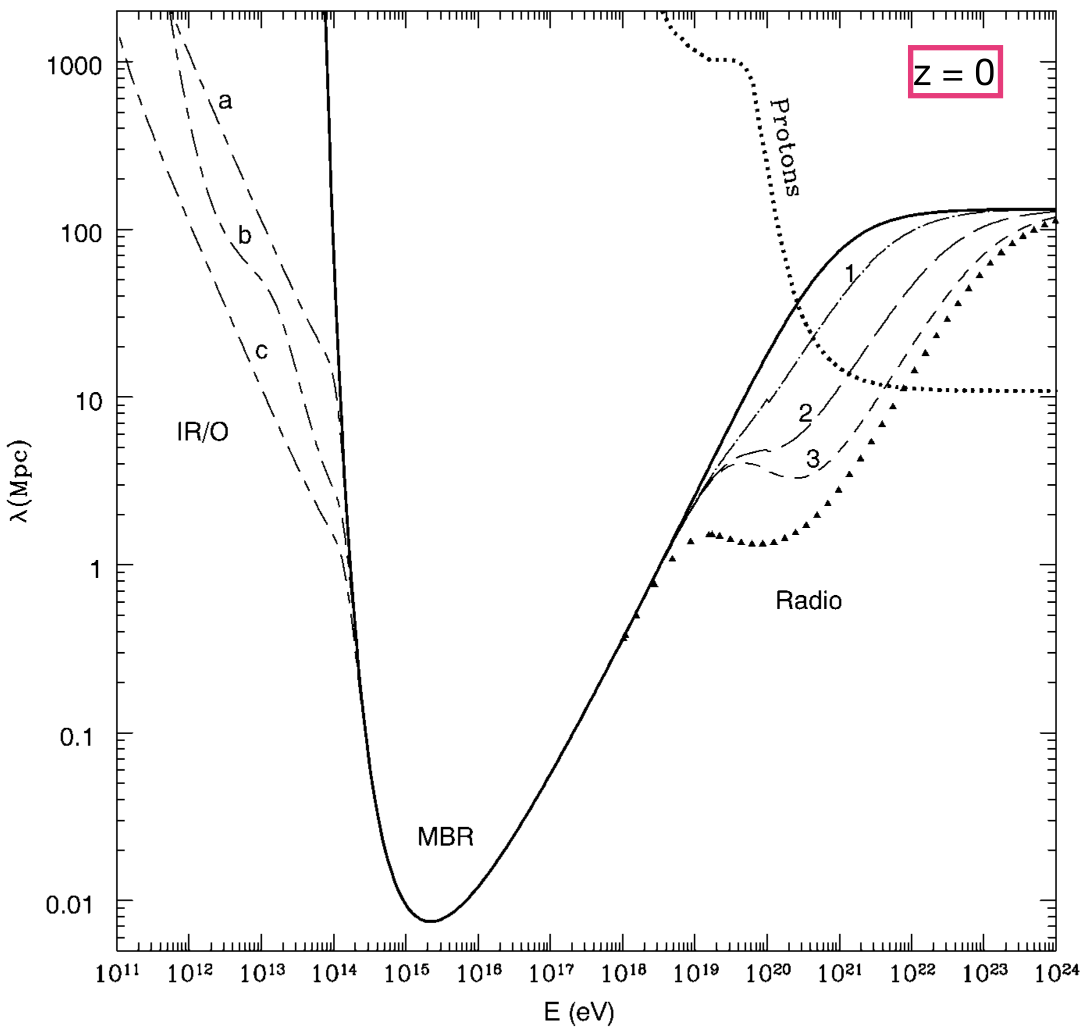
Aharonian et al. 2007



Aharonian et al. 2007

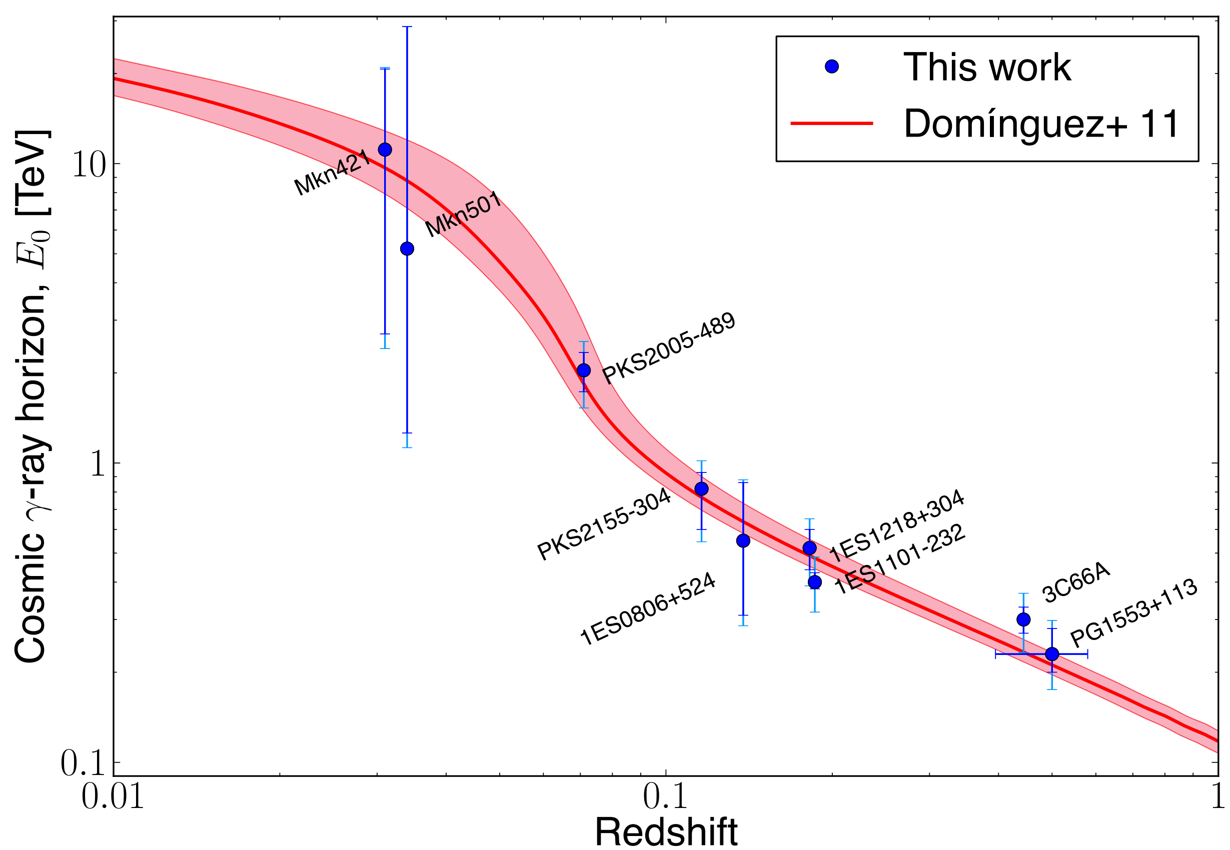
Mean free path and optical depth of gamma rays

Mean free path



Coppi & Aharonian 1997

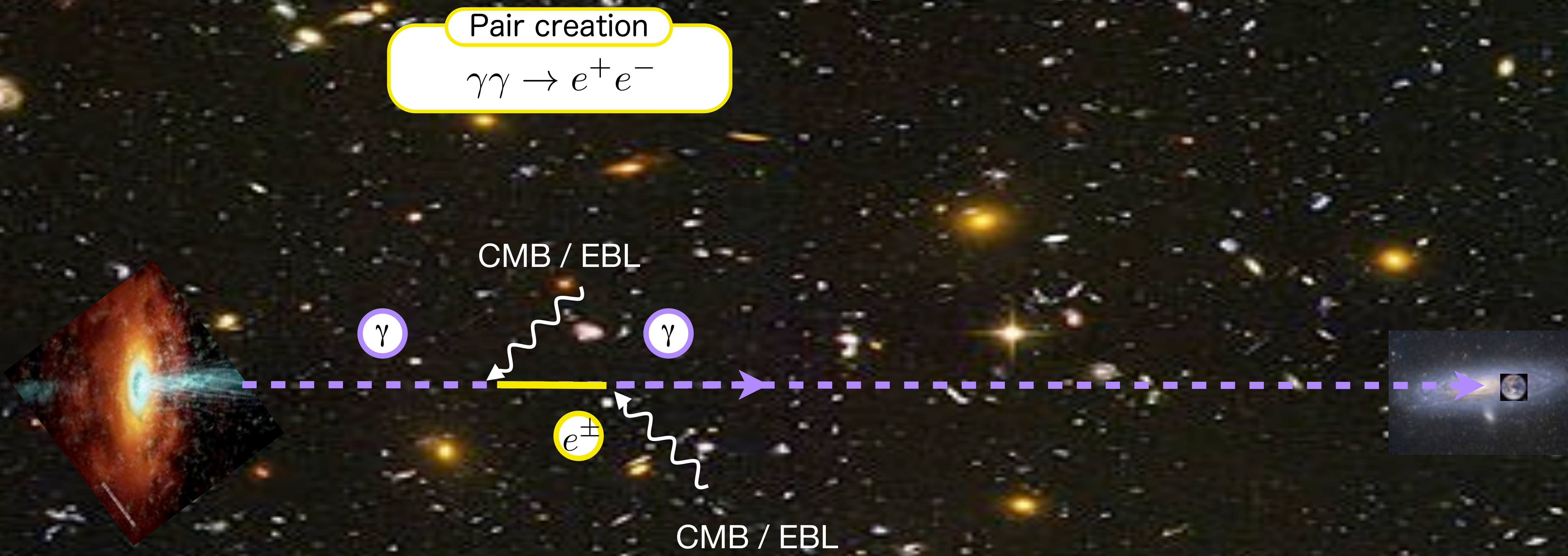
Attenuation energy [τ(E,z)=1]



Dominguez et al. 2013

Very-high-energy photons (>100 GeV) are absorbed via pair creation, depending on source redshift, by extragalactic background light.

Gamma-ray-induced Cascade

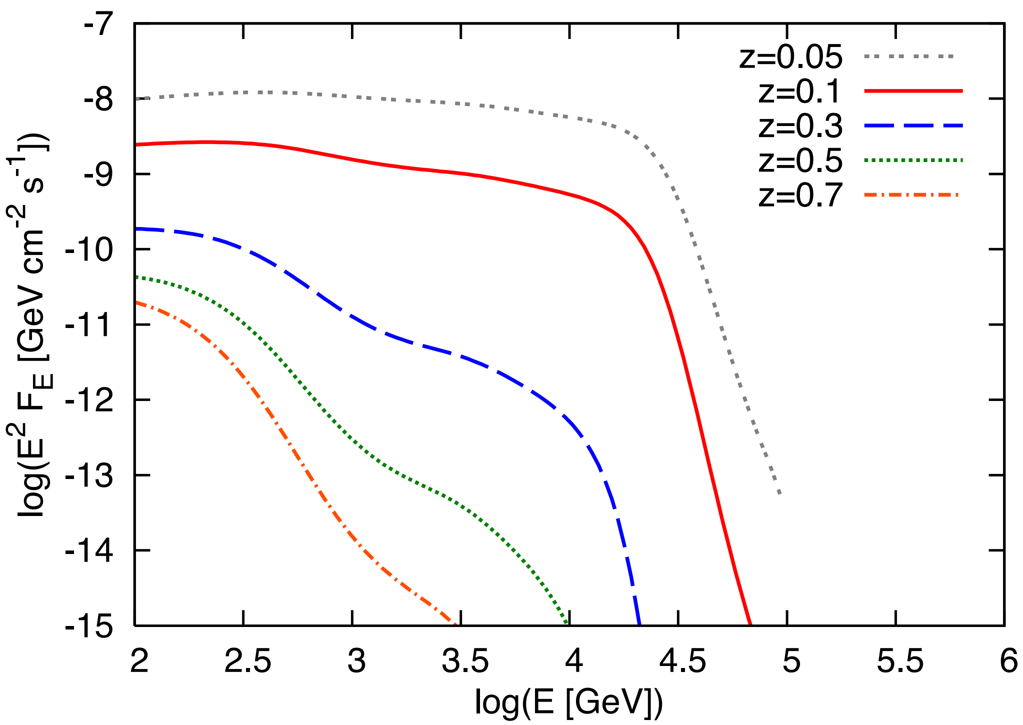


Created pairs are affected by intergalactic magnetic magnetic fields if they are strong enough.

- Pair-halo : image spread (e.g., Aharonian Coppi, Völk 1994, Elyiv et al. 2009)
- Pair-echo : delayed secondary gamma rays (e.g., Plaga 1995, Murase et al. 2008, Ichiki et al. 2008)

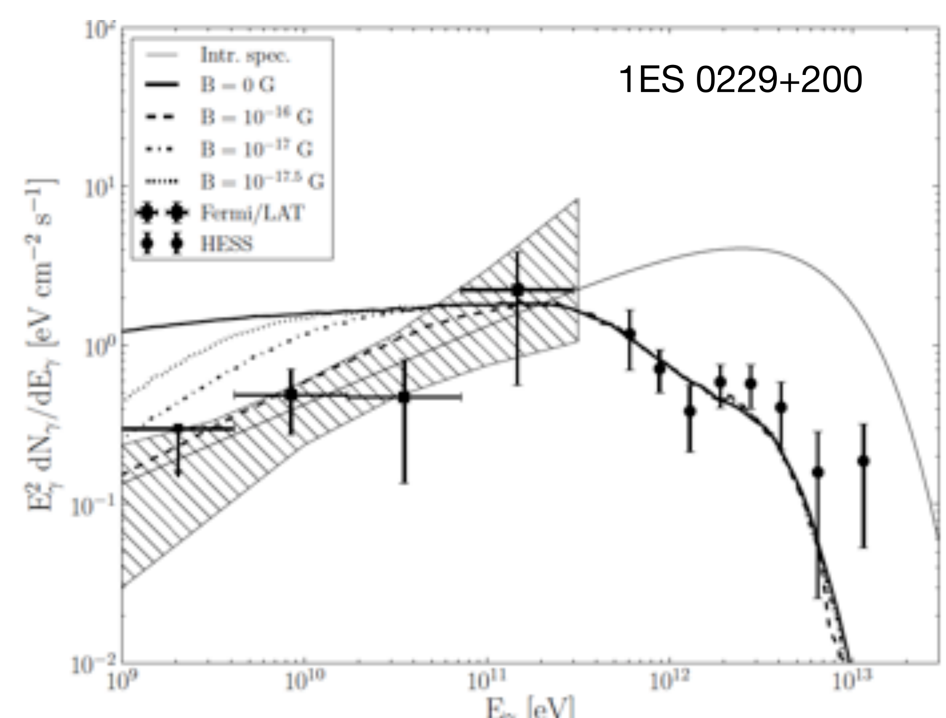
- IGMF study : gamma rays from deflected pairs do not reach the earth if IGMF is sufficiently strong (e.g., Neronov et al. 2009, Dermer et al. 2011, Dolag et al. 2011), but possible plasma instability causes the deflection (under debate; e.g., Schlickeiser et al. 2013 for a recent discussion)

Gamma-ray-induced Cascade



Murase, Dermer, HT, Migliori 2012

- The cascaded spectra are strongly attenuated above energies defined from $\tau_{\gamma\gamma}(E,z) = 1$.
- A spectral shape at around the characteristic EBL absorption energy is essentially determined by the spectral shape of EBL.



Vovk et al. 2012

- The hard spectra of extreme HBLs can be well reproduced even after strong EBL absorption.
- A lot of >10 TeV photons are required to compensate the absorption.

Cosmic-ray-induced Cascade

Photomeson production

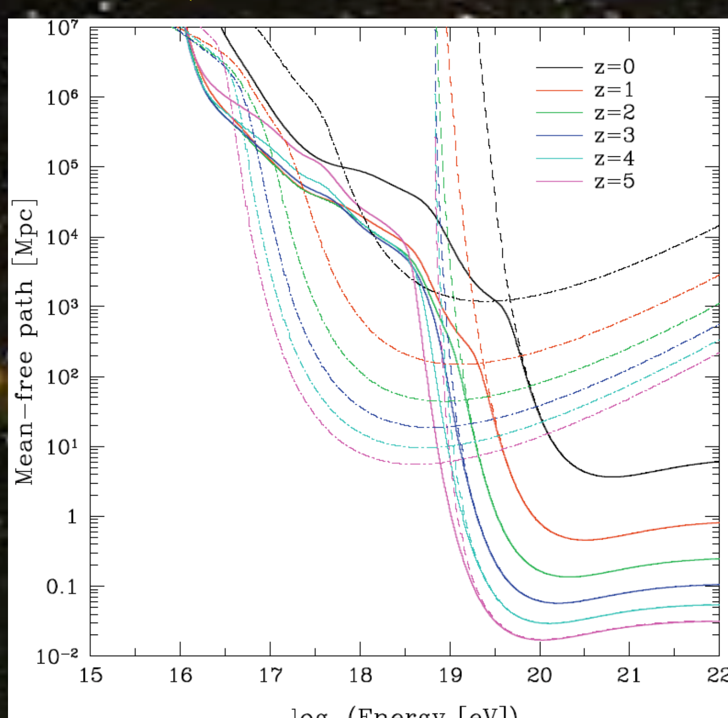
$$p\gamma \rightarrow p\pi^0 \rightarrow p + 2\gamma$$
$$p\gamma \rightarrow n\pi^+ \rightarrow ne^+\nu_\mu\nu_e\bar{\nu}_\mu$$

E > 6 x 10^{19} eV for CMB

Bethe-Heitler Pair Creation

$$p\gamma \rightarrow pe^+e^-$$

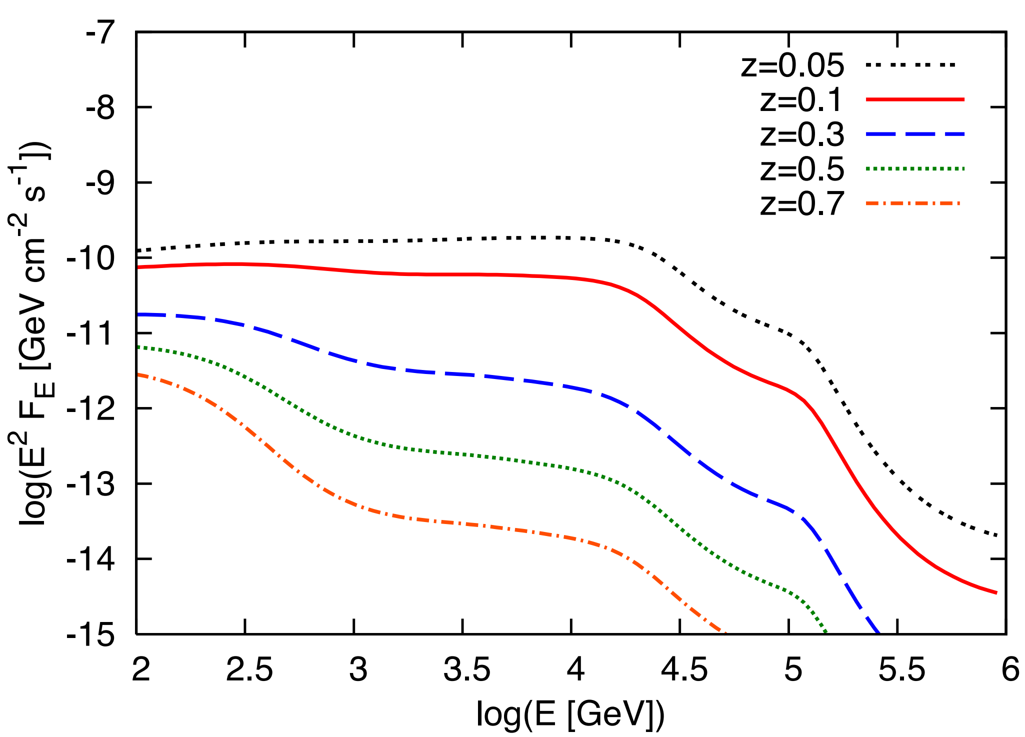
E > 6 x 10^{16} eV for CMB



Higher energy photons than EBL attenuation remain because of e± supply even near observers.

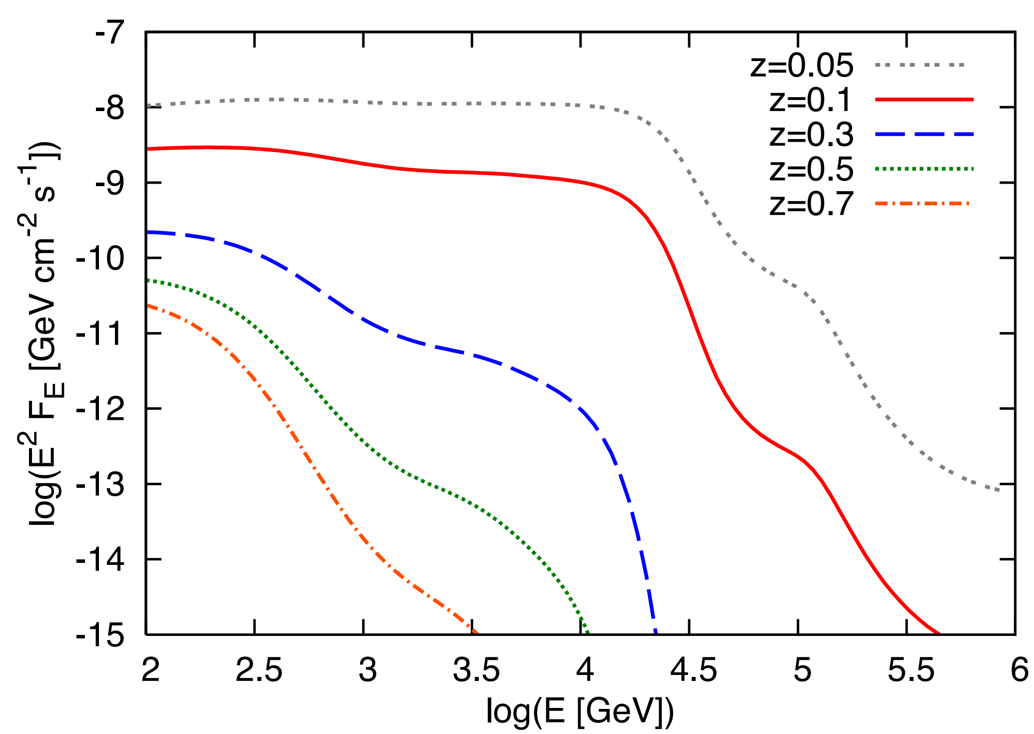
Gamma rays induced by cosmic rays

Cosmic-ray-induced cascade



- $dN/dE \propto E^{-2}$; $10^{18} < E < 10^{19}$ eV
- No IGMF is assumed.

Gamma-ray-induced cascade

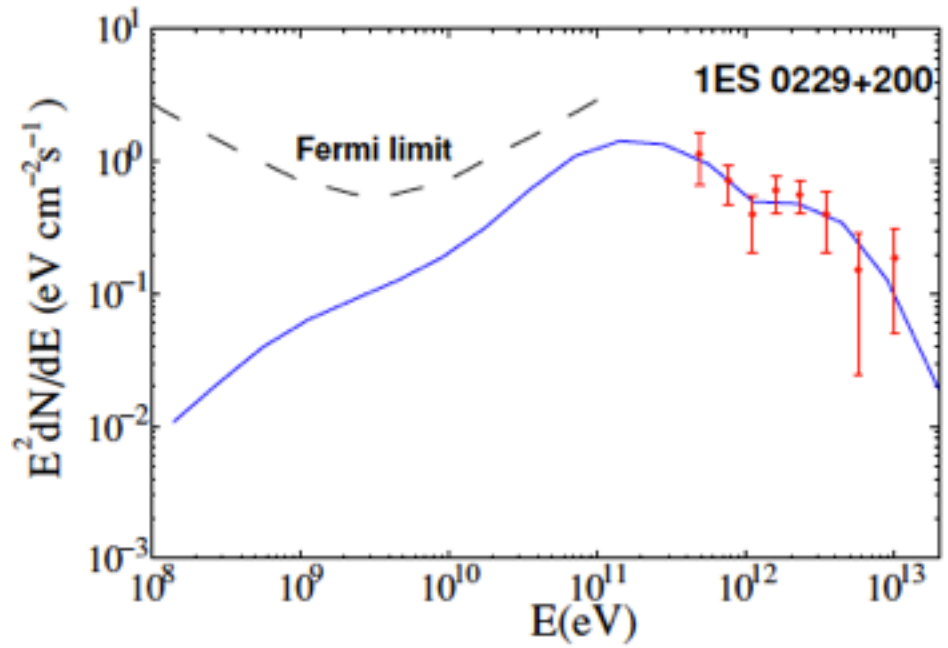


Murase, Dermer, HT, Migliori 2012

- Gamma-rays with 10^{19} eV induces the cascades.
- No IGMF is assumed.

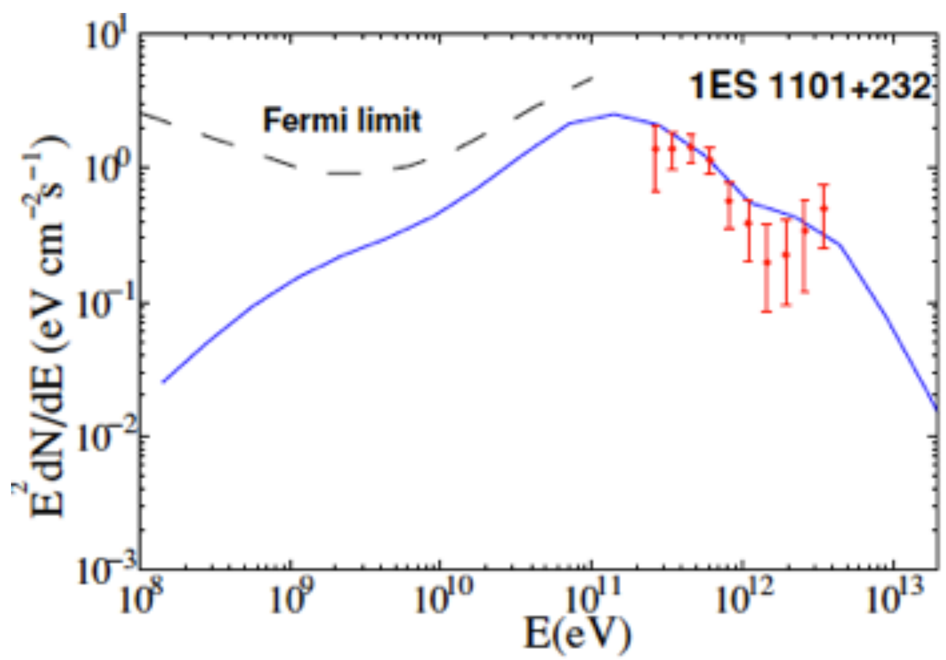
Hard spectra are predicted above energies defined from $\tau_{\gamma\gamma}(E,z) = 1$ from cosmic-ray-induced cascade due to the long energy-loss length of Bethe-Heitler pair creation.

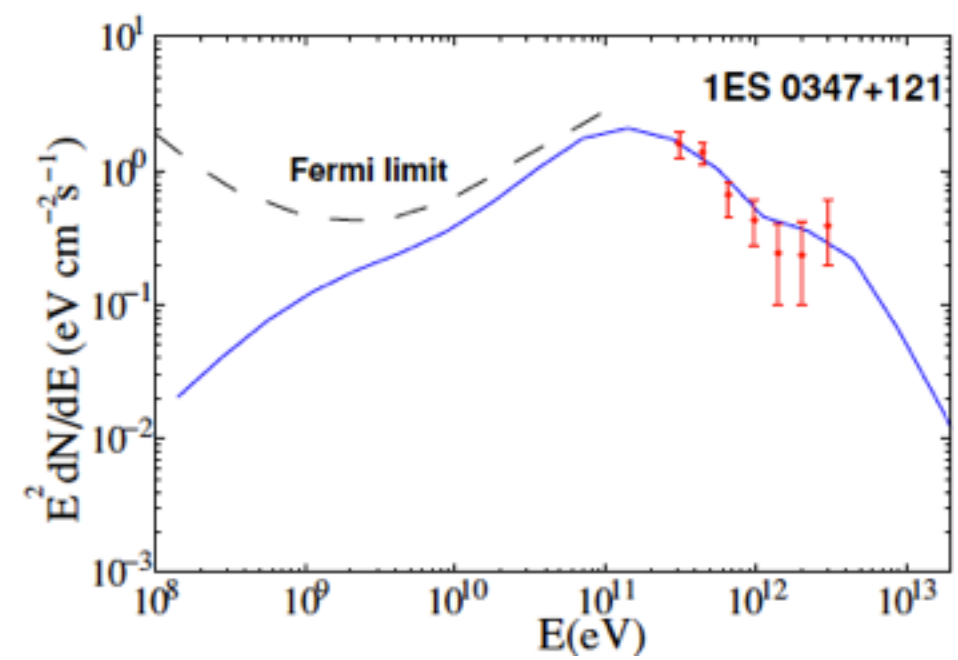
γ-rays from Line-of-sight Cascade



• The observed spectra are well reproduced.

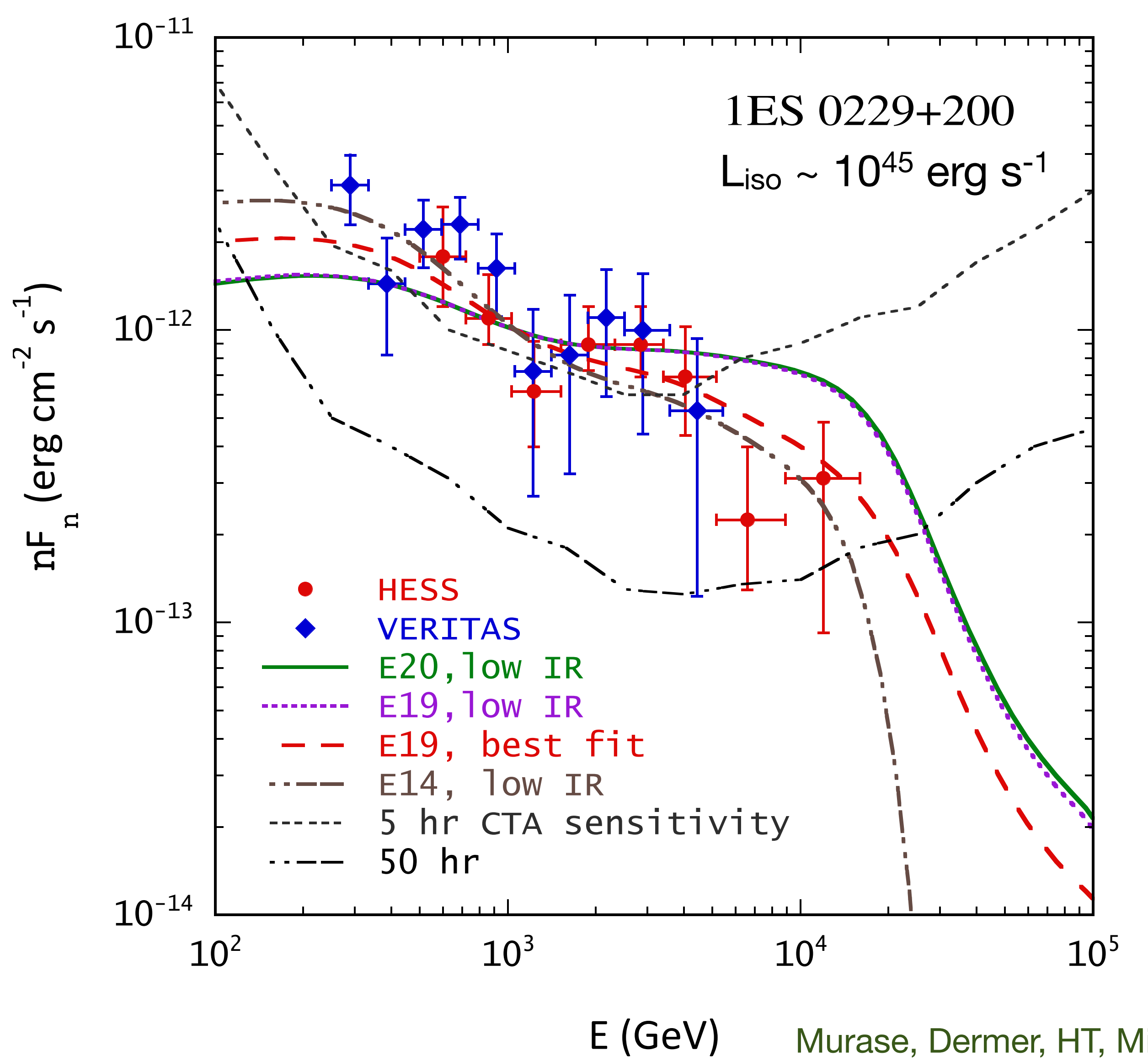
• Intergalactic magnetic field reduces γ-ray flux at the Fermi energy range.





Essey et al. 2011

SED Modeling of a Extreme HBL

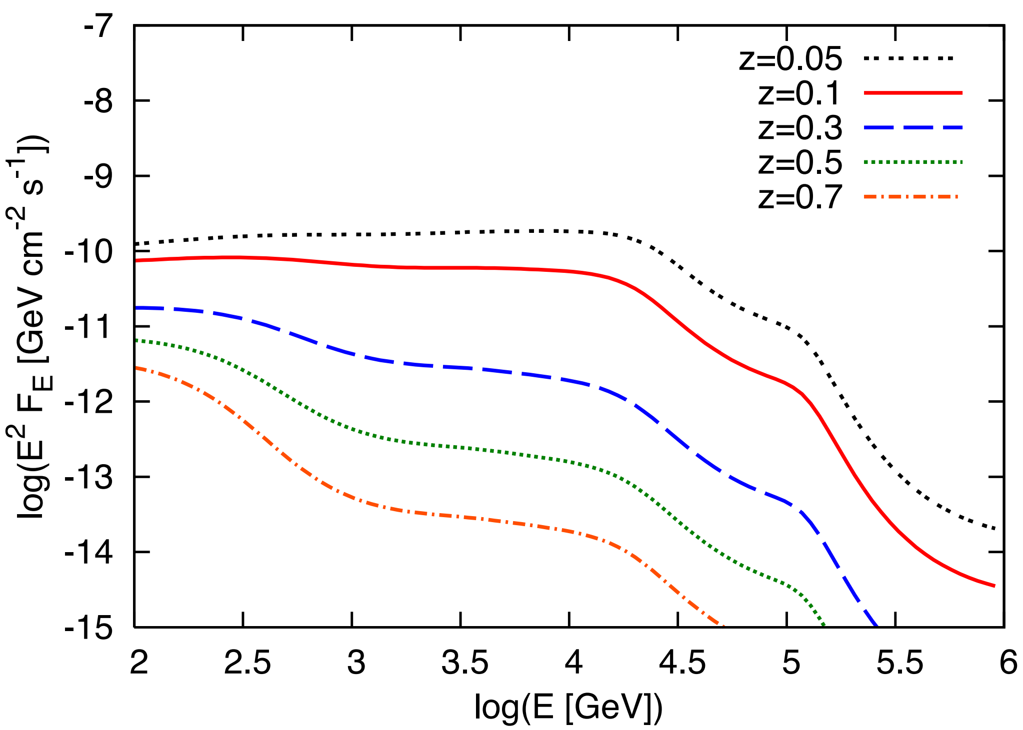


Murase, Dermer, HT, Migliori 2012

- Spectral shape is essentially determined by the spectral shape of EBL.
- 100 TeV γ-ray emitter can also reproduce the observed spectrum.
- Difference between hadronic cascade scenarios and leptonic cascade scenarios appears above 20 TeV
- CTA and HAWK have a potential to distinguish these scenarios.

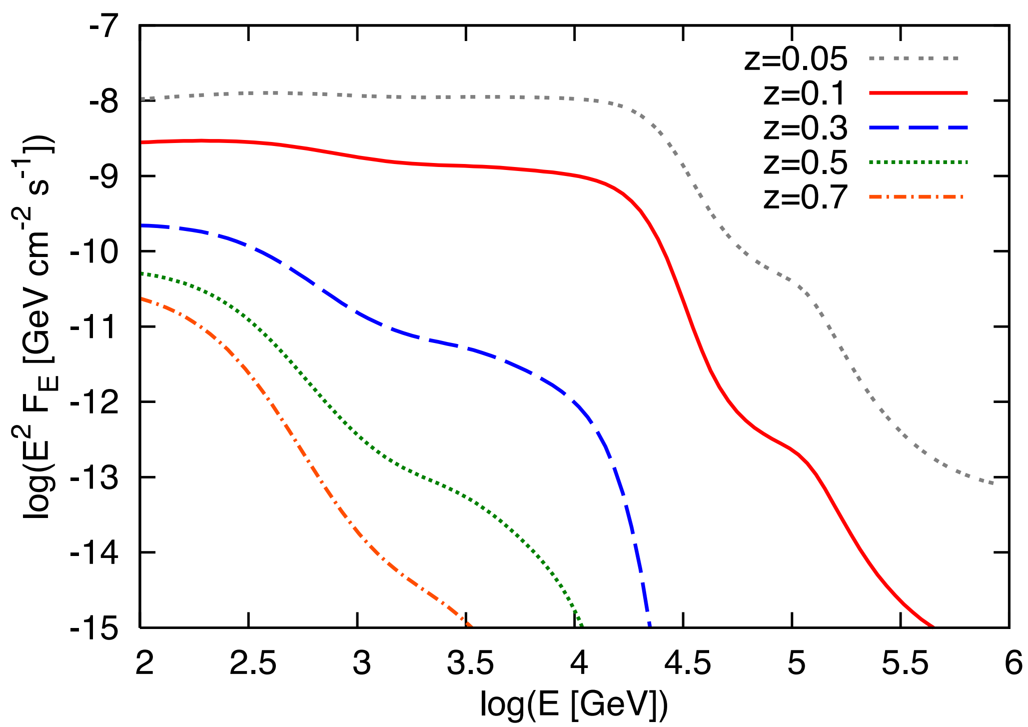
Gamma rays induced by cosmic rays

Cosmic-ray-induced cascade



- dN/dE ∝ E^{-2}; $10^{18} < E < 10^{19}$ eV
- No IGMF is assumed.

Gamma-ray-induced cascade



Murase, Dermer, HT, Migliori 2012

- Gamma-rays with 10^{19} eV induces the cascades.
- No IGMF is assumed.

Distant hard gamma-ray spectrum blazars may result from cosmic-ray-induced cascades, which become evidence for ultra-high-energy cosmic-ray sources.

List of distant VHE gamma-ray emitters

Fermi sources associated with VHE photons, but not identified by IACTs (z>0.5)

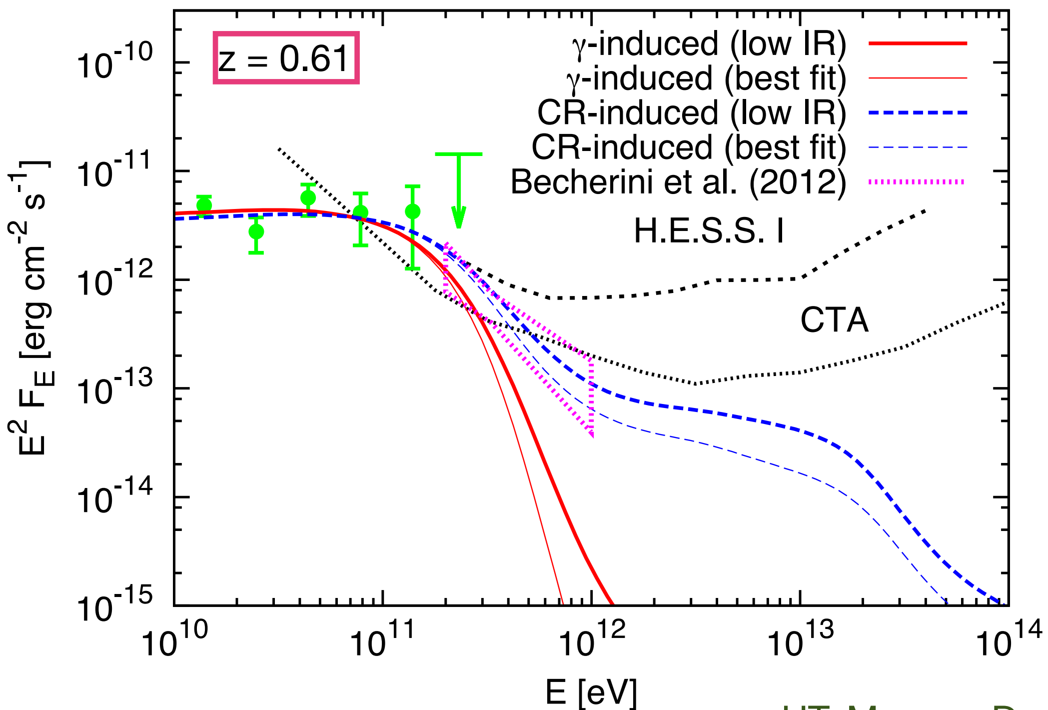
	Name	RA	DEC	Type	z	N_{30-100}	$N_{0.1}$	$N_{0.2}$	E_{max}	L/L_{Mrk421}	P	Index
1	TXS 0138-097	25.3576	-9.4788	BL	0.733	2	1f	0	138	44.5	1.1e-3	2.033
2	PKS 0426-380	67.1685	-37.9388	BL	1.11	13	1f	0	134	151	0.9e-3	1.946
3	B2 0912+29	138.9683	29.5567	BL	1.521	5	1f	0	126	405	0.7e-3	1.875
4	Ton 116	190.8031	36.4622	BL	1.065	11	1b	0	114	133	0.7e-3	1.698
5	PG 1246+586	192.0783	58.3413	BL	0.847	9	1b	0	104	67.5	1.2e-3	1.949
6	B3 1307+433	197.3563	43.0849	BL	0.69	4	1f	0	104	37.5	0.8e-3	1.839
7	4C +55.17	149.4091	55.3827	FSRQ	0.8955	14	1b	0	141	84.0	1.6e-3	Log PB
8	TXS 1720+102	260.6857	10.2266	FSRQ	0.732	0	1f	0	168	46.8	1.9e-3	2.23
9	PKS 1958-179	300.2379	-17.8160	FSRQ	0.65	2	1b	0	118	33.5	2.3e-3	2.38
10	PKS 2142-75	326.8030	-75.6037	FSRQ	1.139	1	1f	0	135	173	1.5e-3	2.517
11	KUV 00311-1938	8.3933	-19.3594	BL	0.61	11	0	2b	152	53.2	8e-6	1.758
12	RGB J0250+172	42.6567	17.2067	BL	1.1	3	0	1b	358	147	7.6e-3	1.836
13	PKS 1130+008	173.190067	0.5744	BL	1.223	1	0	1f	140	204	4.4e-3	2.178

Neronov et al. 2012

(The 1FHL catalog may include more sources with VHE photons.)

- They have rather hard spectra.
- The hard spectra motivates possible hadronic origin.

Example: KUV 00311-1938



HT, Murase, Dermer 2013

KUV 00311-1938

- Distant hard-source in the Fermi-LAT
- Recently detected by H.E.S.S. Becherini et al. 2012
- z=0.61 is quoted, but recent optical spectroscopy indicates only z>0.506. Pita et al. 2012

Models

EBL: Kneiske et al. (2004) for low and best-fit EBL

Leptonic model

- $dN/dE \propto E^{-s}$; $E > 10^{9.75}$ eV, $E_{max} = 10^{14}$ eV
- No suppression from IGMF (10^{-20} G < B < 10^{-15} G)

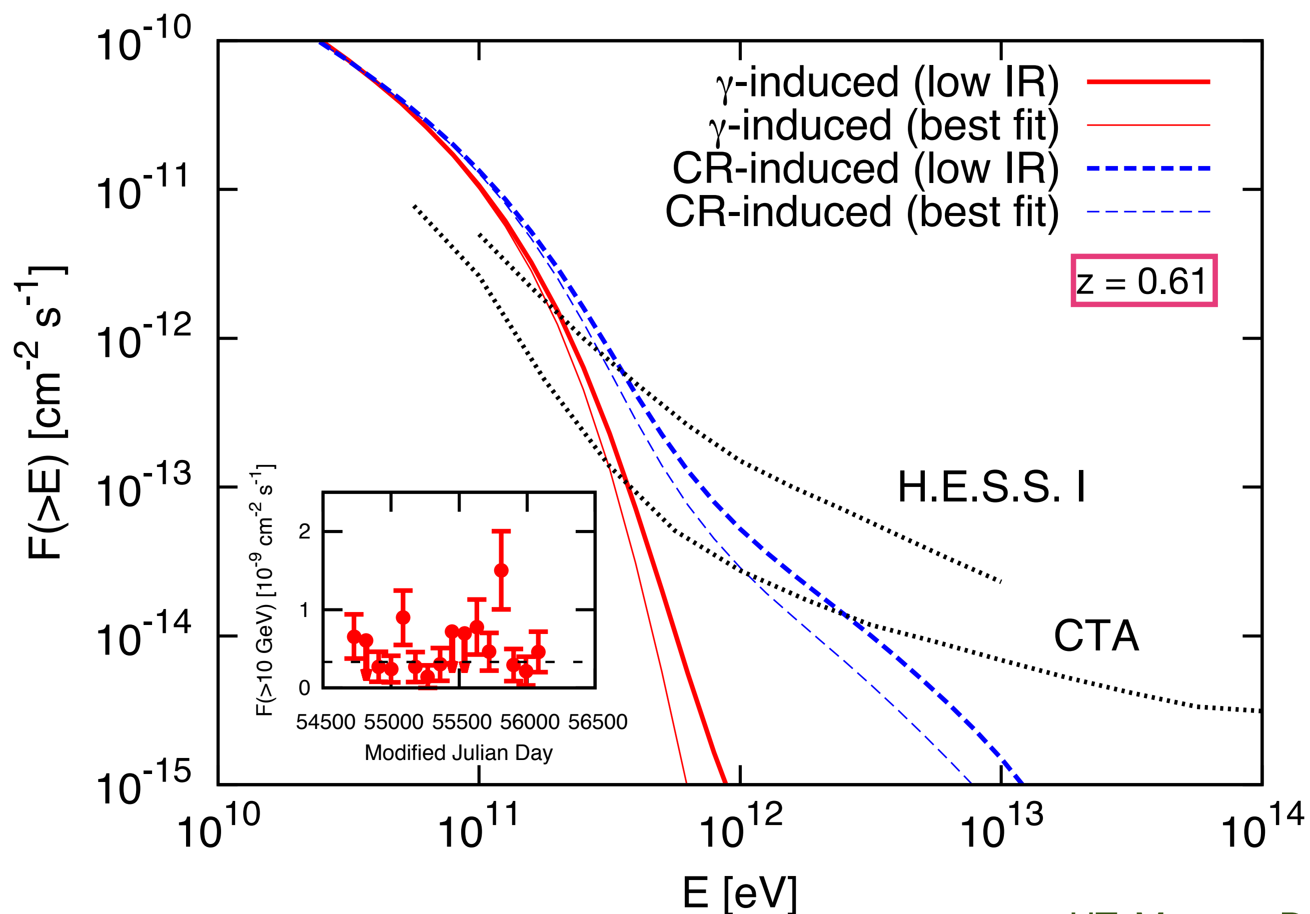
Hadronic model

- $dN/dE \propto E^{-2.6} \exp(-E/E_c)$; $E > 10^{18}$ eV, $E_c = 10^{19}$ eV
- No suppression from IGMF (B < 10^{-14} G for protons)

- Both models reproduce the Fermi spectrum.
  - The sources in the sample except PKS 0426-380 and 2142 are also reproduced.
- These models are distinguishable above ~500 GeV even considering the uncertainty of EBL models.
- The hadronic model is favored if z = 0.61 is correct.
  - Redshift measurement is important for confirmation.

Example: KUV 00311-1938 ~ integral flux ~

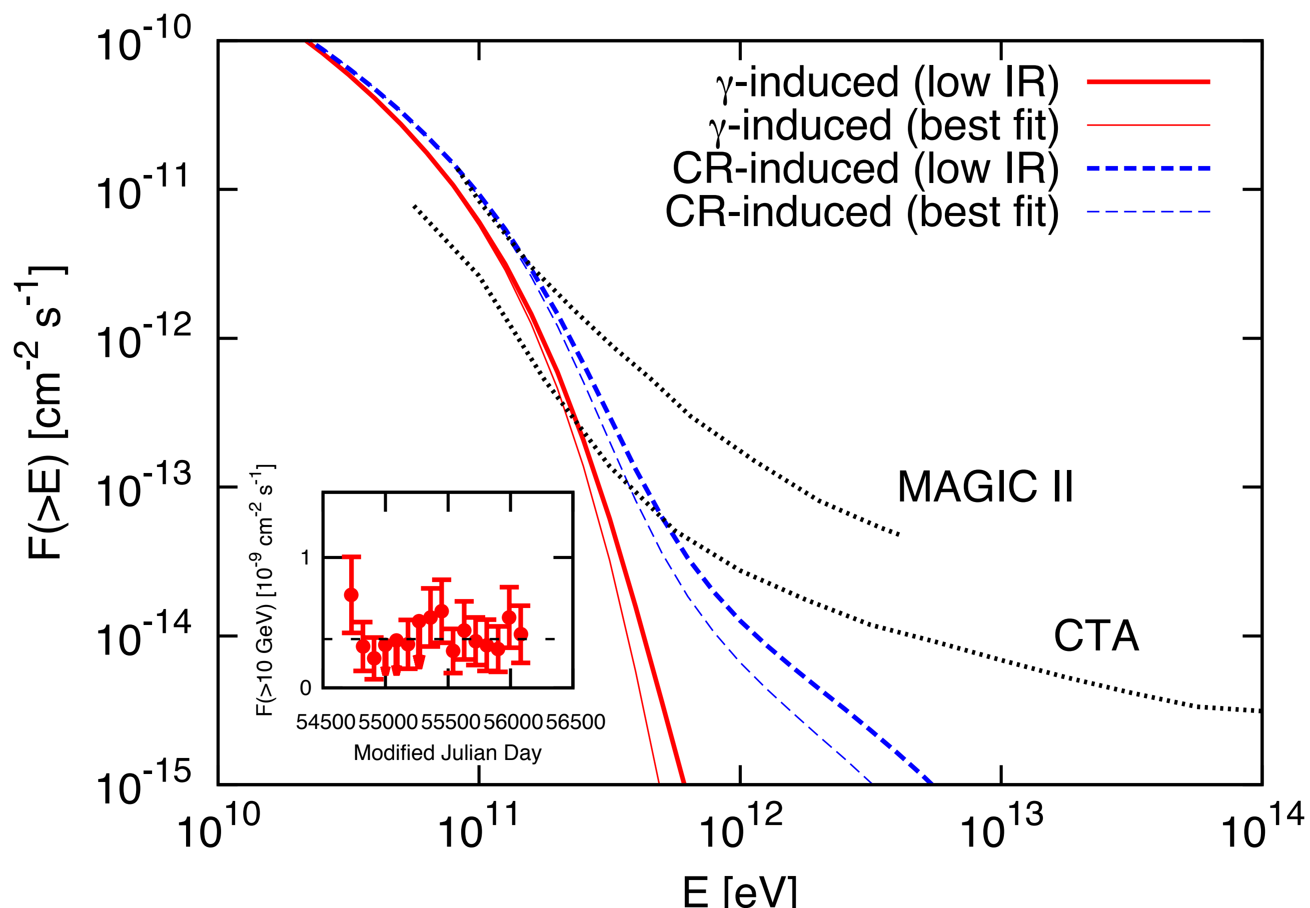
Integral flux is sensitive to the hard component in the hadronic model.



HT, Murase, Dermer 2013

- Integral flux above ~500 GeV can clearly distinguish these two scenarios.
- The light curve (with ~3 month bins) is consistent with constant flux (χ^2/d.o.f. = 0.94)

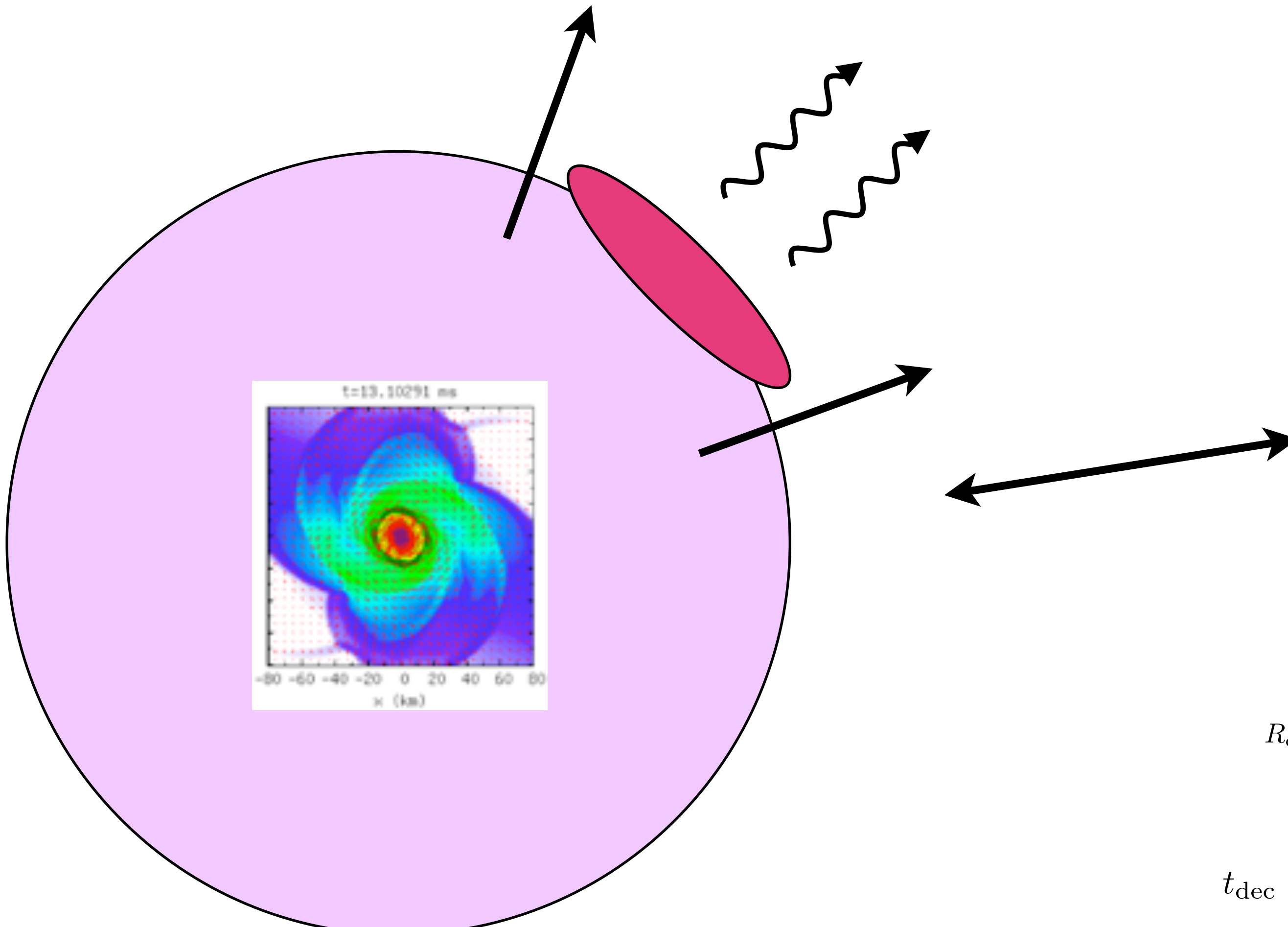
Example: PG 1246+586 (z=0.847)

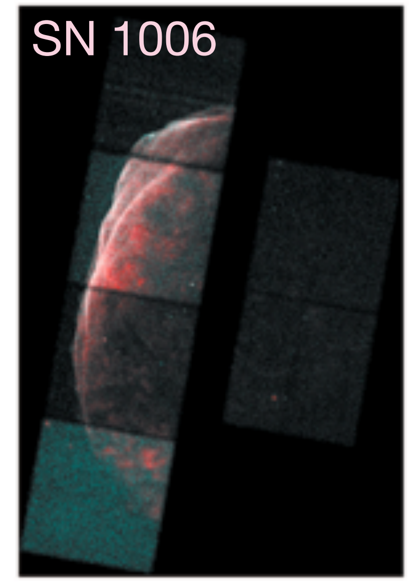


HT, Murase, Dermer 2013

- Even for z~0.85 sources, hadronic origin can be investigated by CTA.
- The light curve (with ~3 month bins) is consistent with constant flux (χ^2/d.o.f. = 0.40)

Ejecta - ISM Shock from NS Binary Mergers

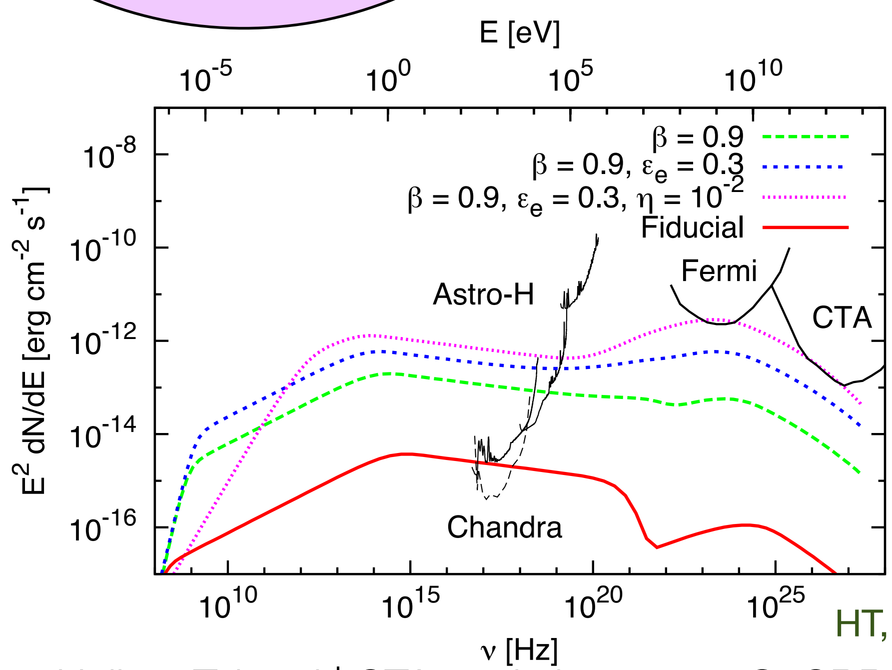




Bamba+ 2003

$$R_{\rm dec} = \left(\frac{3E_0}{4\pi n m_p c^2 {\beta_0}^2}\right)^{1/3} = 1.1\times10^{18}\left(\frac{M}{10^{-2}\ M_\odot}\right)^{1/3}\left(\frac{n}{1\ {\rm cm}^{-3}}\right)^{-1/3}\ [{\rm cm}]$$

$$t_{\rm dec} = \frac{R_{\rm dec}}{\beta_0 c} = 1.2\times10^{8}\left(\frac{M}{10^{-2}\ M_\odot}\right)^{1/3}\left(\frac{n}{1\ {\rm cm}^{-3}}\right)^{-1/3}\left(\frac{\beta_0}{0.3}\right)\ [{\rm s}]$$



$$\gamma_{\rm CR,max} = 1\times10^{8}\xi^{-1}ZA^{-1}\epsilon_{B,-2}^{1/2}M_{-2}^{1/3}n_0^{1/6}\beta_{0.3}^{2}\ \ (\xi \geq \xi_{\rm b,CR})$$

HT, Kyutoku, Ioka 2013

Summary

- The origin of UHECRs are still under debate, although some essential constraints have been obtained from UHECR and neutrino experiments.
    - Towards source identification
        - Huge statistics above 10^{20} eV --- JEM-EUSO, TA2, AugerNext, ...
        - Multi-messenger approaches --- CTA, IceCube, ARA, ...
- Gamma-ray connection to UHECRs
    - Hadronic gamma-ray emission
    - Cosmic-ray-induced cascade
    - (Inference from physical parameters constrained by leptonic emission)