Blazars as the source of ultrahigh-energy cosmic rays

— Implications for multi-TeV gamma ray observation in the LHAASO era

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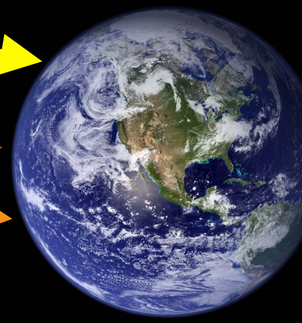
Source ⟷ Propagation ⟷ Detection

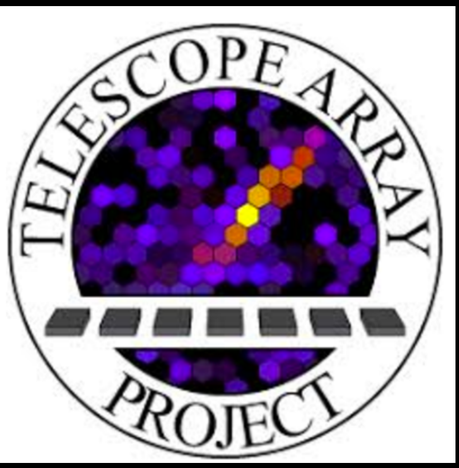
LHAASO can test the UHECR scenario

UHECRs

Gamma ray induced cascade γ

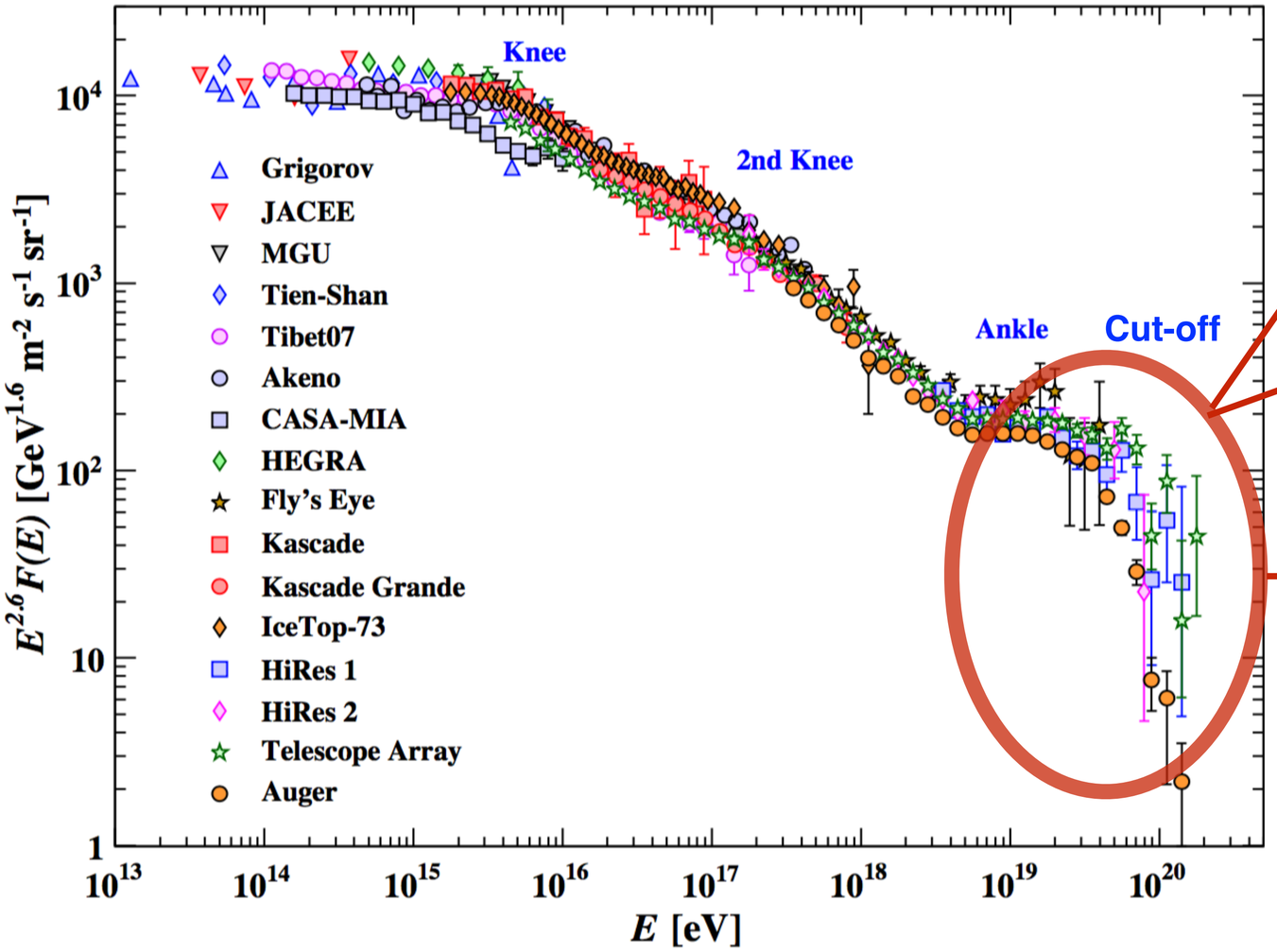
UHECRs induced cascade γ





Ultrahigh-Energy Cosmic Rays - Spectrum

UHECRs: cosmic rays with energy larger than $\sim 10^{18}$ eV



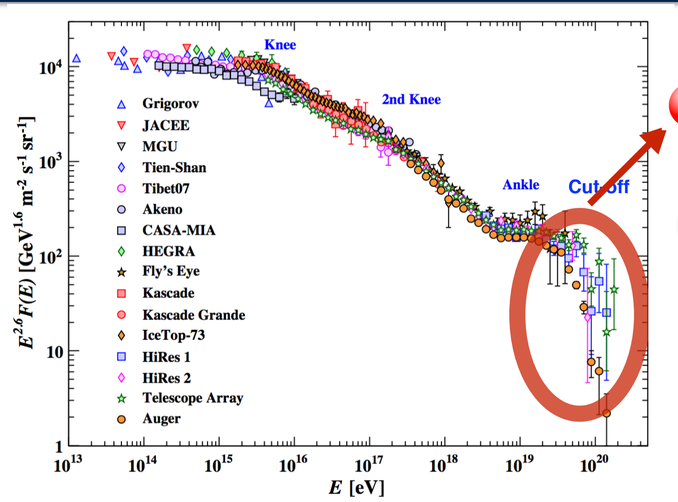
What is the composition?

Where are the sources?

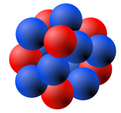
How can they be accelerated to ultrahigh energy?

Review of Particle Physics, Chin. Phys., 2016

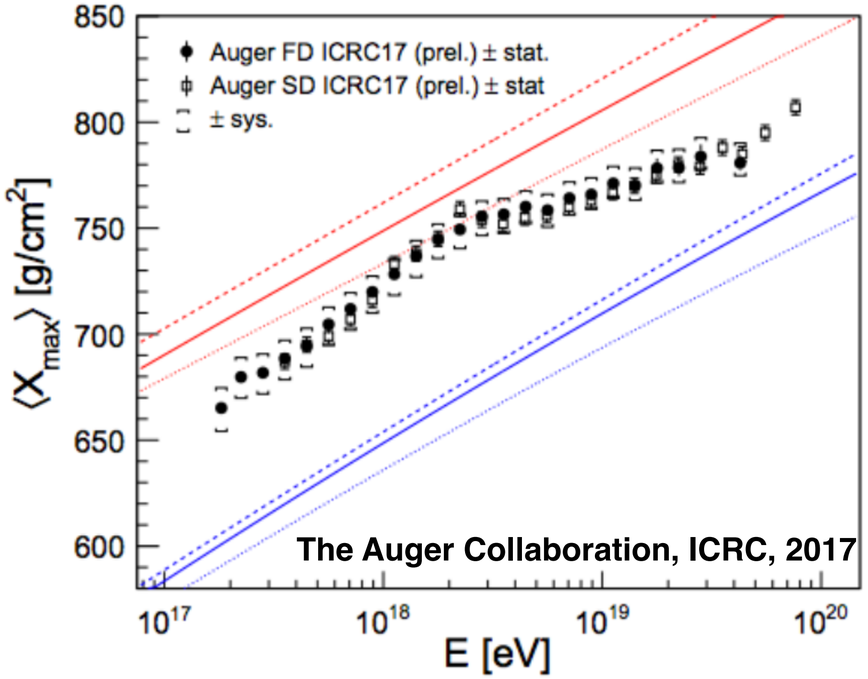
What is the composition?

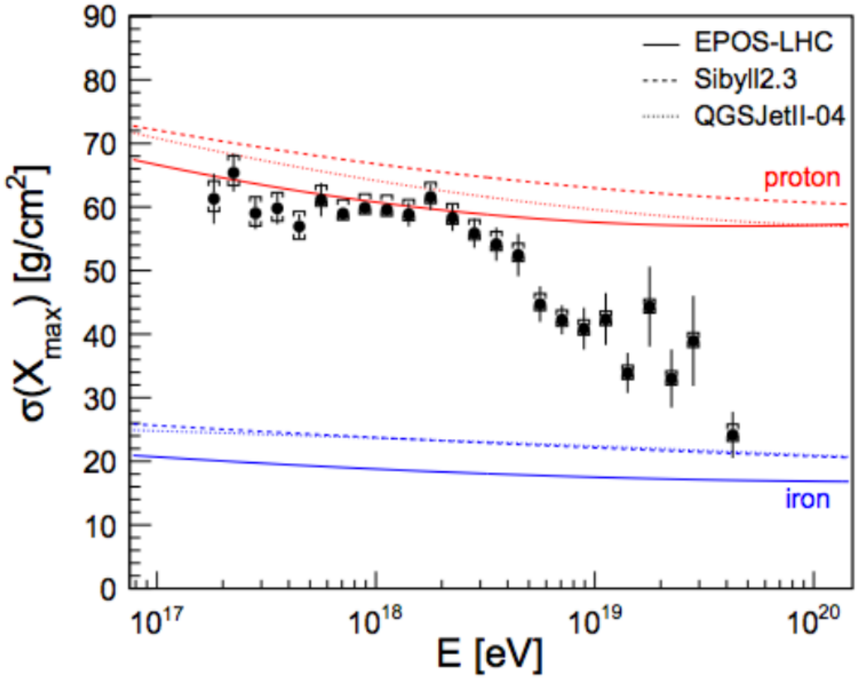


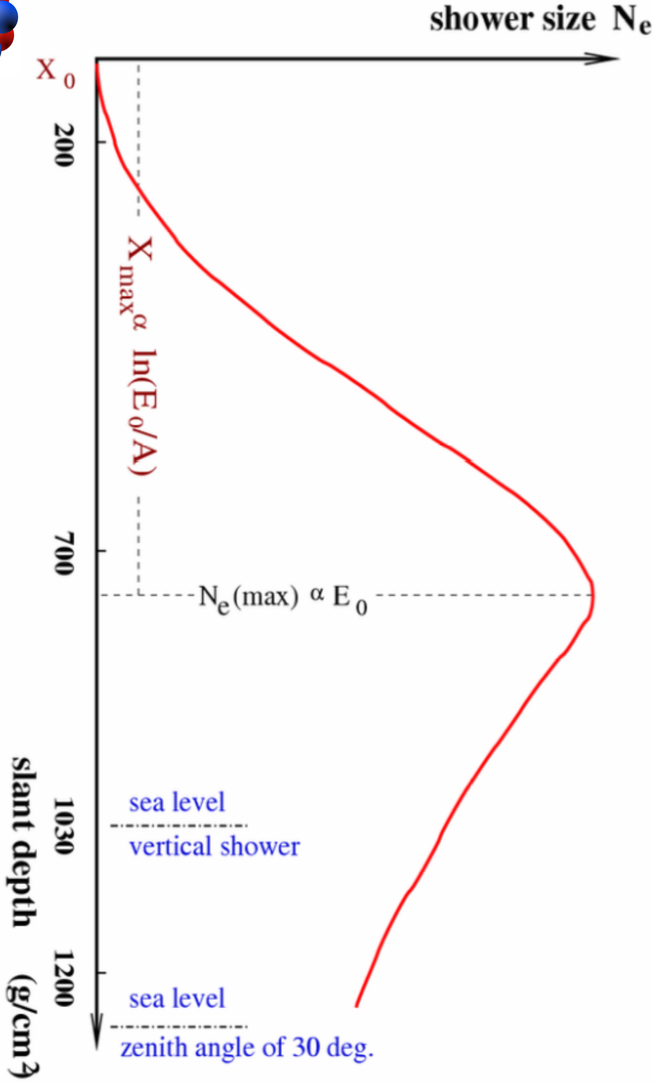
H He C N O Ne Mg Si Fe



A trend toward heavy nuclei !!!

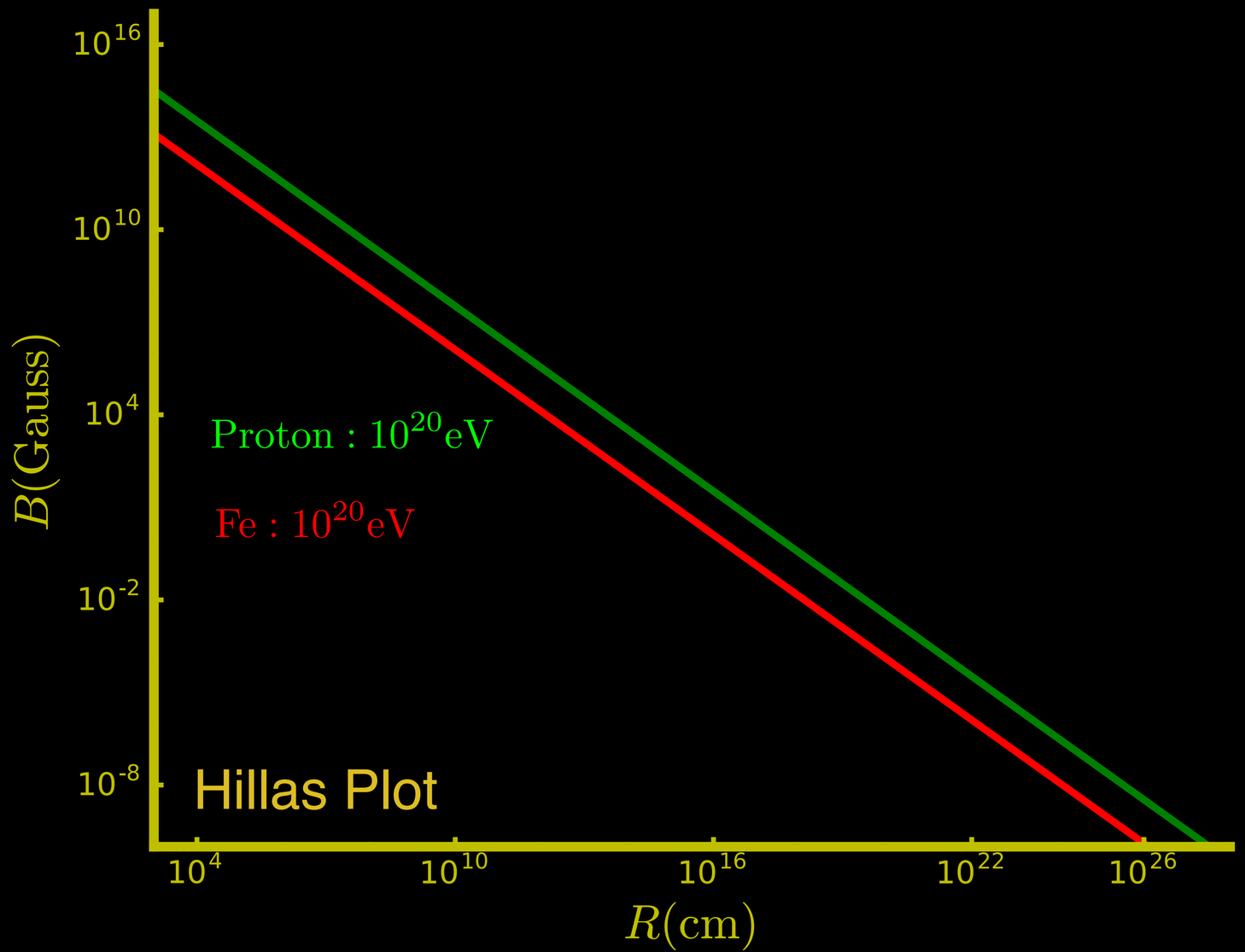






From Ralph Engel, 2017

Where are the sources ?



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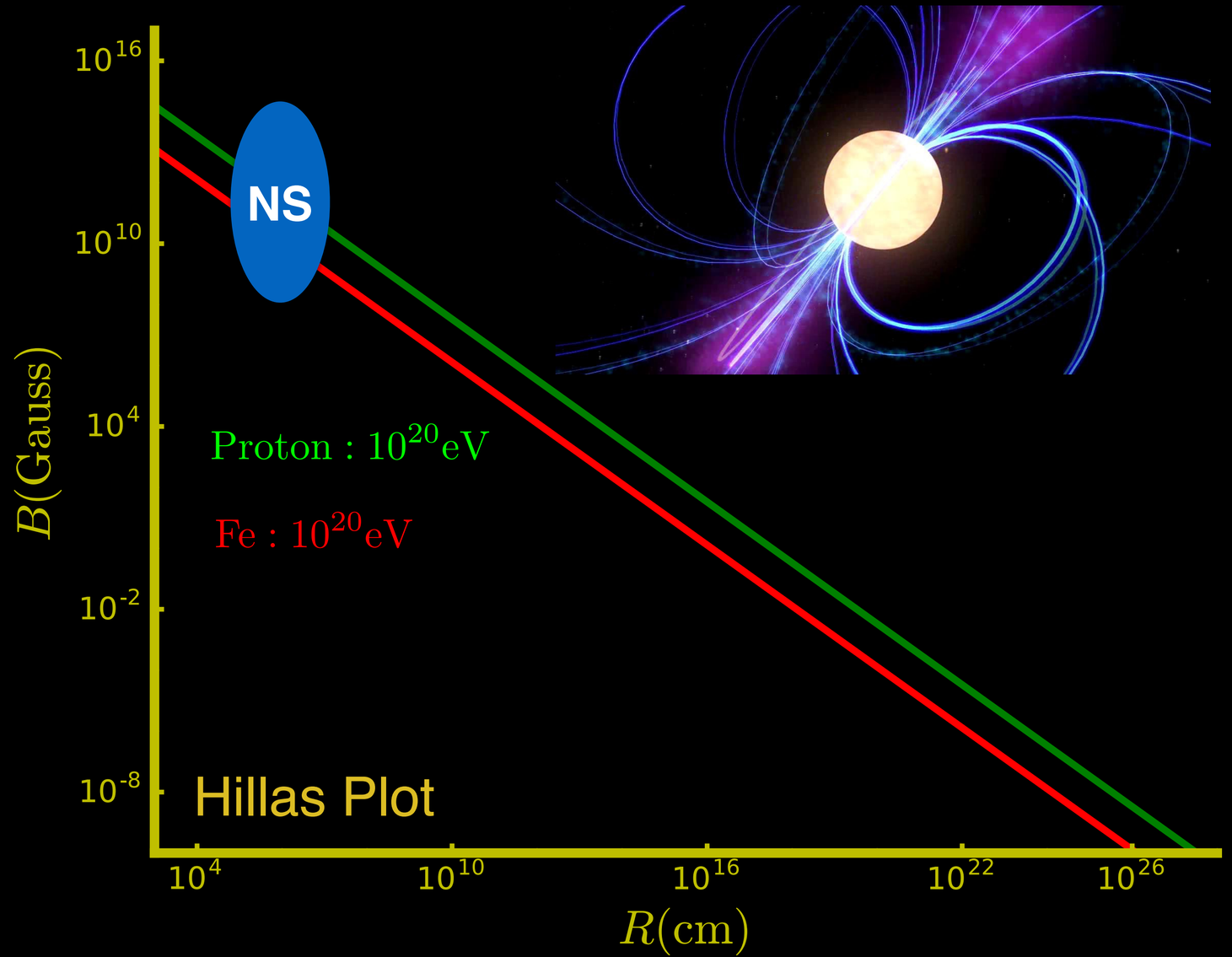


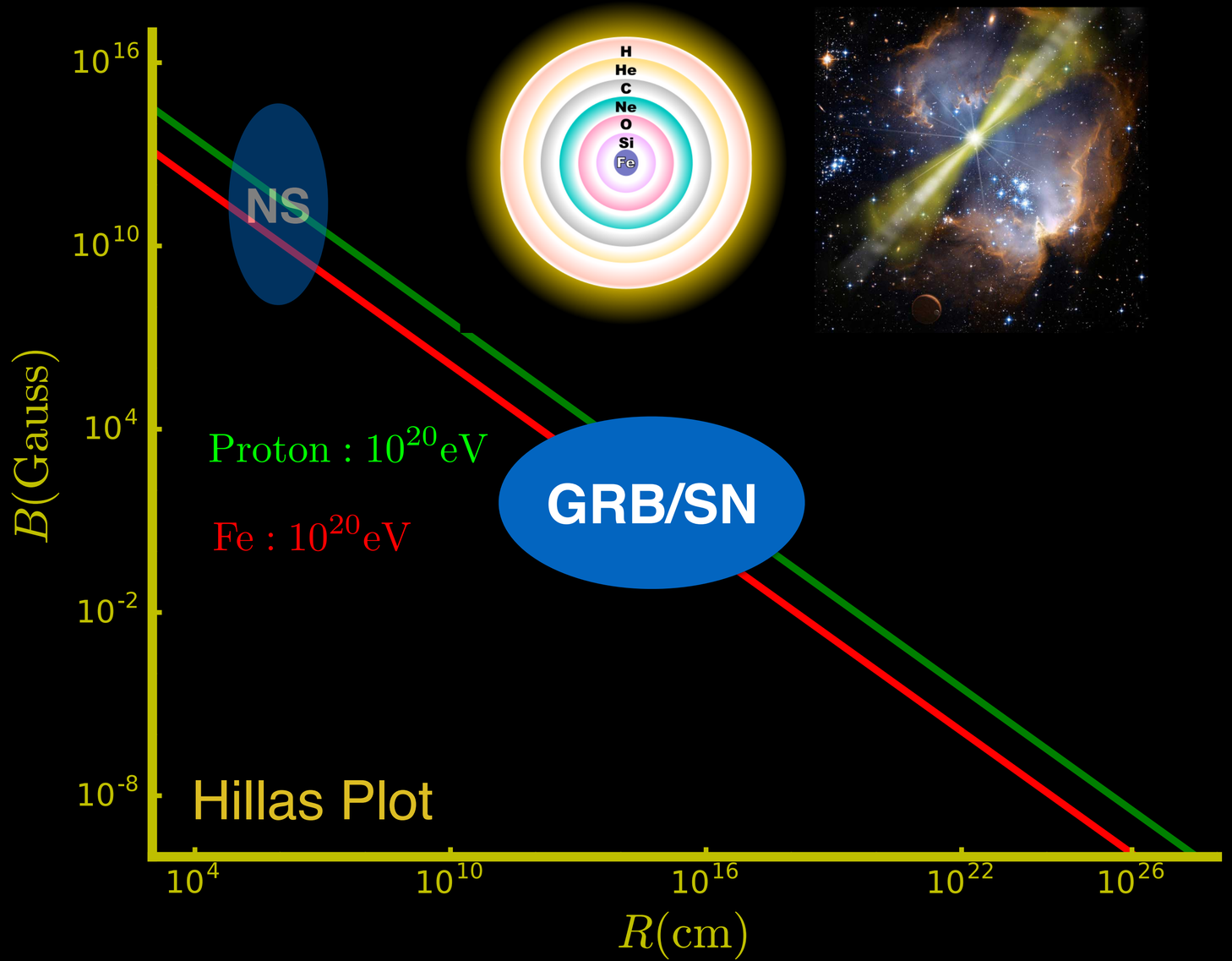
New born pulsars

Kotera et al. 2011, 2015; Fang et al. 2012, 2013;

Acceleration by Unipolar Induction

Heavy nuclei from neutron star wind

Where are the sources ?



New born pulsars

Gamma ray bursts / Hypernova

Waxman 1995; Vieri 1995;

Murase et al. 2006, 2008; Wang et al. 2007, 2008;

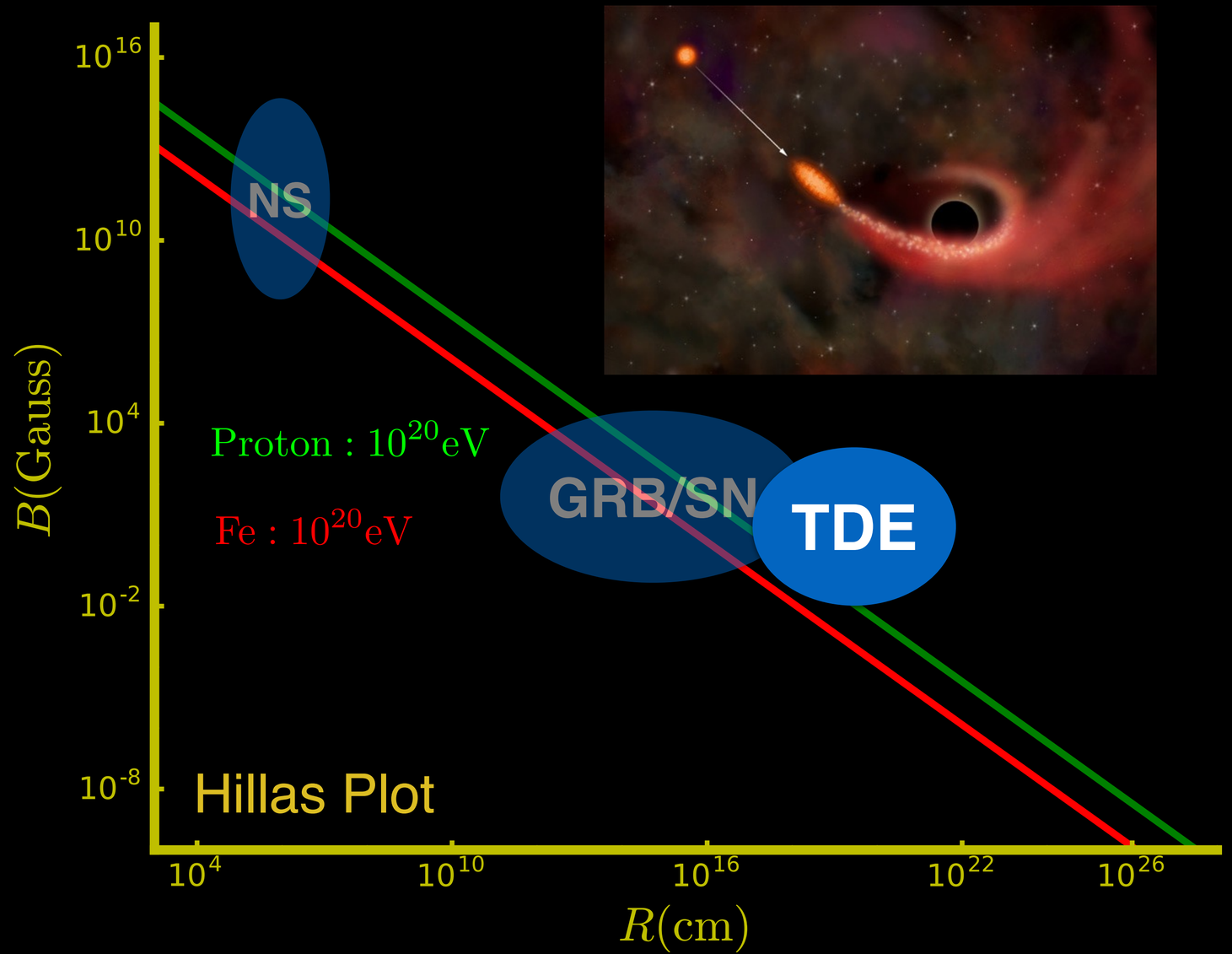
Chakraborty et al. 2011; Liu et al. 2012;

Globus et al. 2015; Biehl et al. 2017;

Acceleration in the jet / outflow

Heavy nuclei from the inner region of progenitor stars or outflow

Where are the sources ?



New born pulsars

Gamma ray bursts / Hypernova

Tidal disruption events

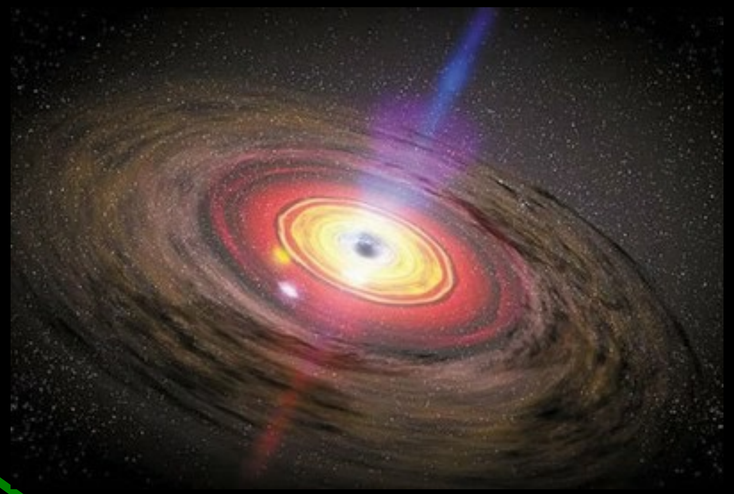
Farrar & Piran. 2014;

Bastia & Silk. 2017; BTZ, Murase, Oikonomou, Li. 2017;

Acceleration in the jet / outflow

Heavy nuclei from the disrupted white dwarfs

Where are the sources ?



New born pulsars

Gamma ray bursts / Hypernova

Tidal disruption events

Active galactic nuclei

Norman et al. 1995; Peer et al. 2009;

Dermer & Razzaque. 2010; Murase et al. 2012;

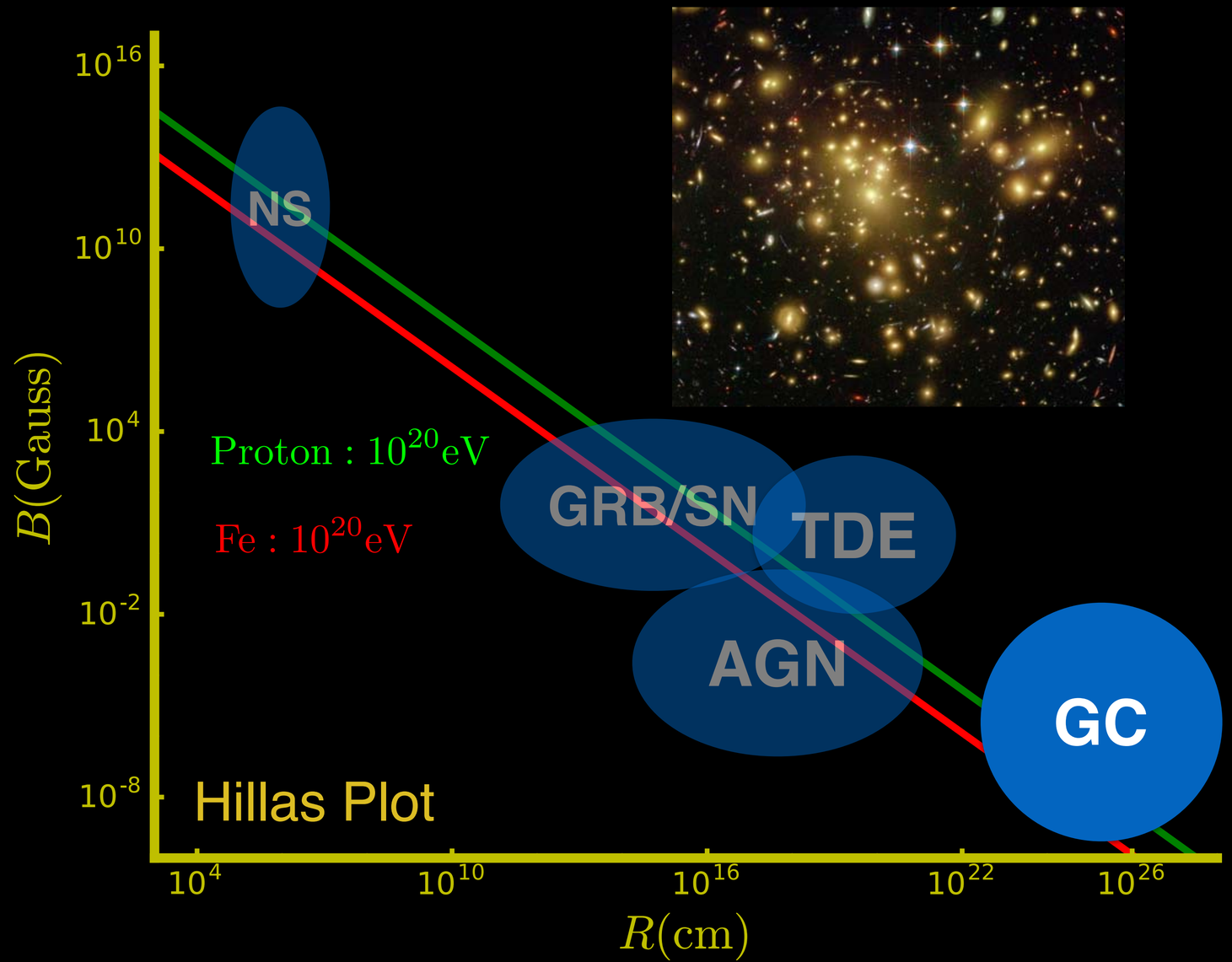
Caprioli. 2015; Fang & Murase. 2017;

Kimura, Murase, BTZ. 2017;

Acceleration in the jet / outflow

Heavy nuclei from ISM or re-acceleration galactic cosmic rays

Where are the sources ?



New born pulsars

Gamma ray bursts / Hypernova

Tidal disruption events

Active galactic nuclei

Structure formation shocks

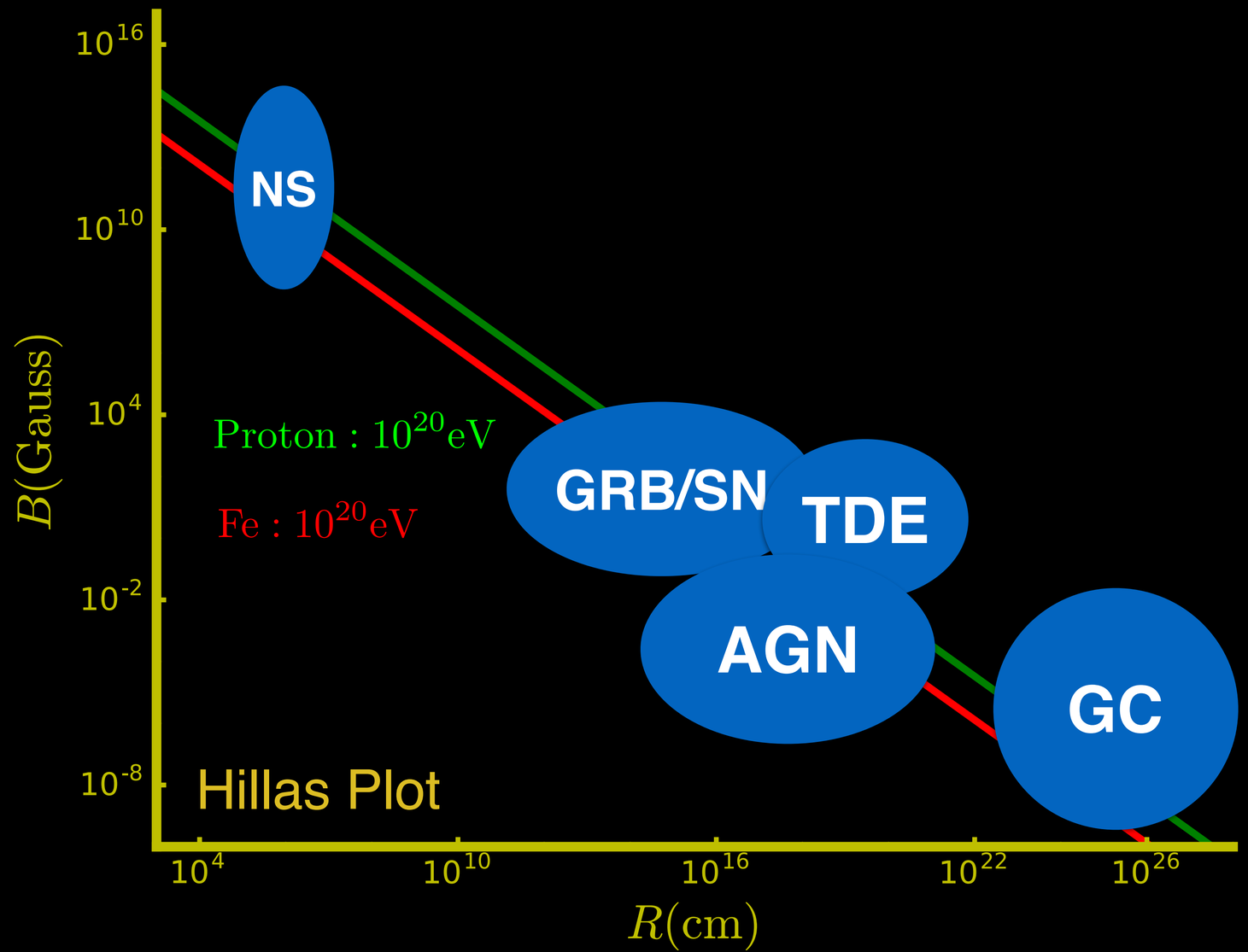
Norman et al. 1995; Kang et al. 1996;

Inoue et al. 2007;

Acceleration in the shocks

Heavy nuclei from ISM

Where are the sources ?



New born pulsars

Gamma ray bursts / Hypernova

Tidal disruption events

Active galactic nuclei

Structure formation shocks

Various source candidates

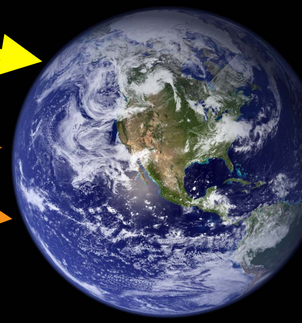
Source ⟷ Propagation ⟷ Detection

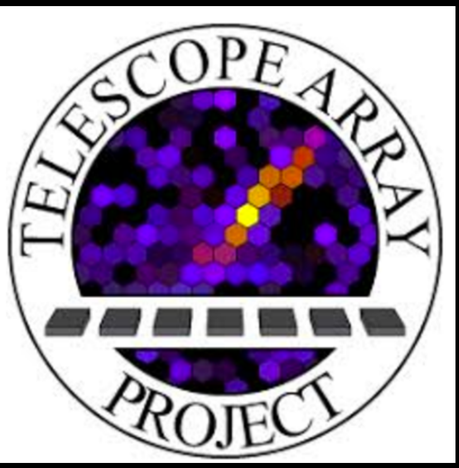
LHAASO can test the UHECR scenario

UHECRs

Gamma ray induced cascade γ

UHECRs induced cascade γ





Propagation of ultrahigh-energy cosmic rays

Photopion production $p + \gamma \to p + \pi^0 \quad p + \gamma \to n + \pi^+$

Photodisintegration

$$^{A}_{Z}X + \gamma \to ^{A-1}_{Z}X + n$$
$$^{A}_{Z}X + \gamma \to ^{A-1}_{Z-1}X + p$$

Pair production $^{A}_{Z}X + \gamma \to ^{A}_{Z}X + e^+ + e^-$

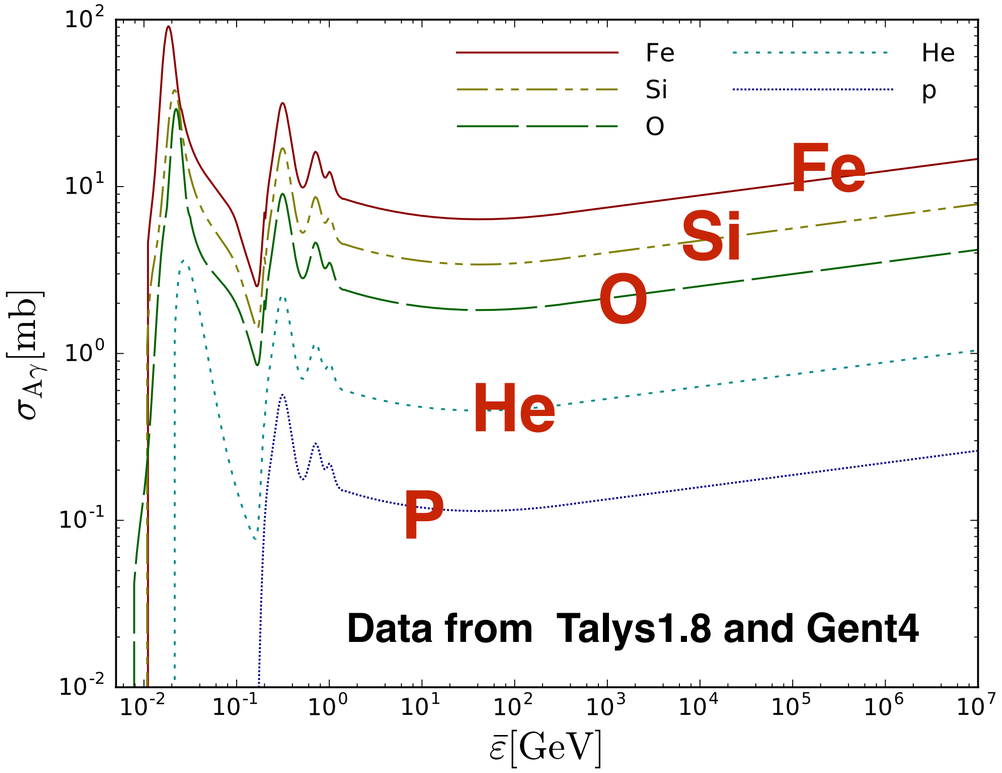
Continues injection at larger distance

Important for secondary photons

Nuclear decay

Adiabatic losses

Giant dipole resonance



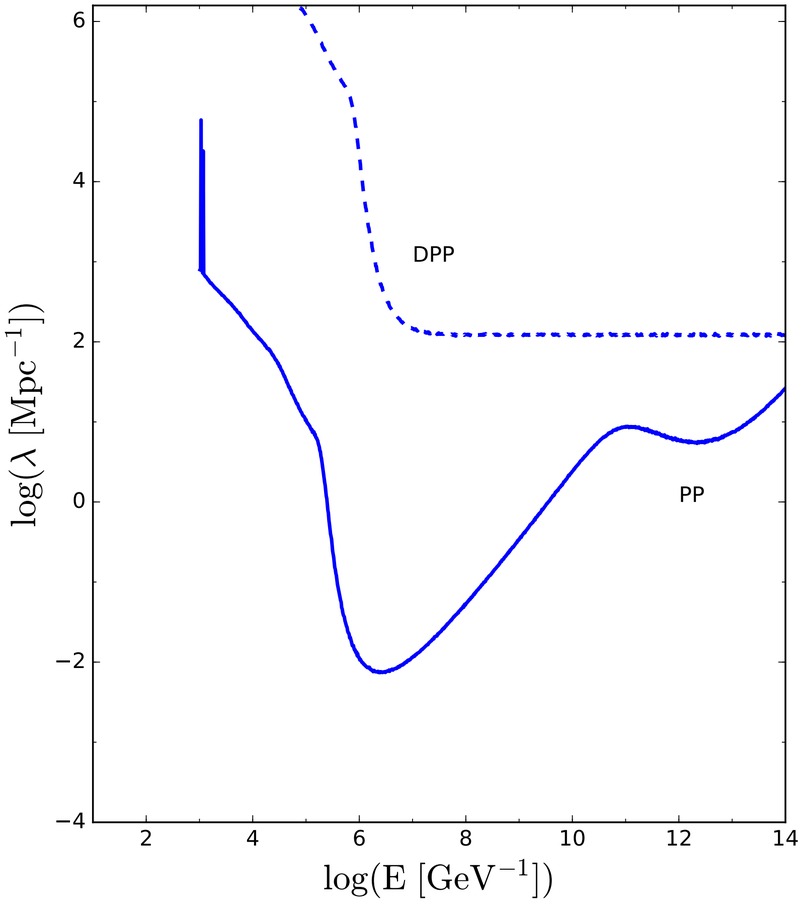
Public code for the propagation of UHECRs:

CRPropa: 3D propagation, magnetic field deflection

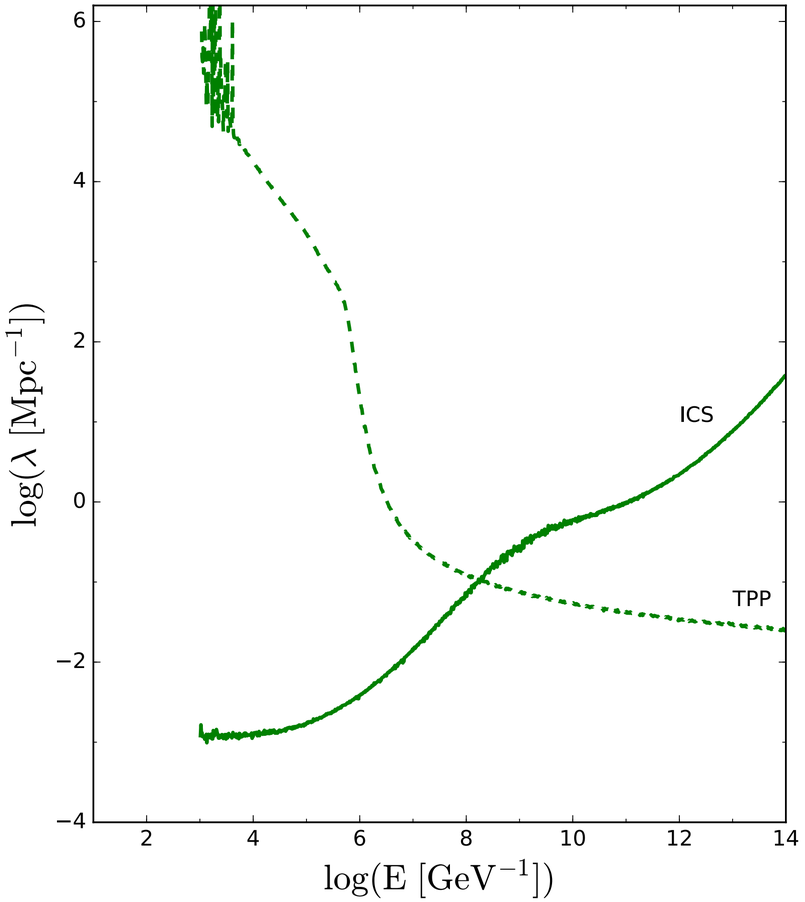
Simprop: 1D propagation

Propagation of high energy photons and electrons/positrons

photons



electrons/positrons



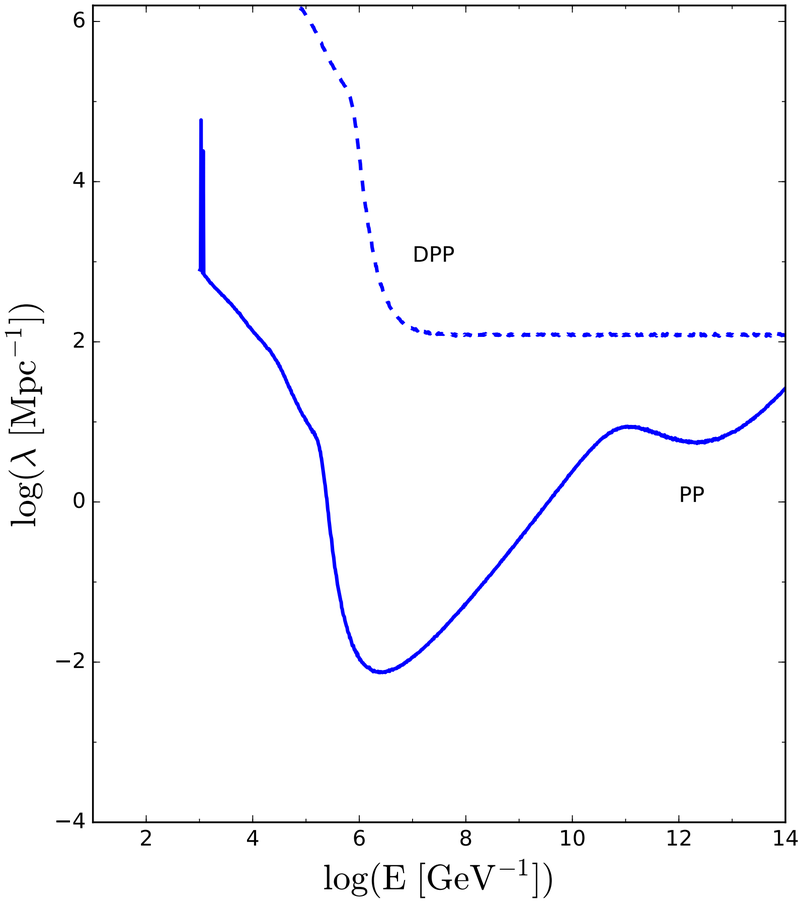
Electromagnetic cascade

$$\gamma + \gamma_b \rightarrow e^+ + e^- \,(\mathrm{PP})$$
$$\rightarrow e^+ + e^- + e^+ + e^- \,(\mathrm{DPP})$$
$$e + \gamma_b \rightarrow e + \gamma \,(\mathrm{ICS})$$
$$\rightarrow e + e^- + e^+ \,(\mathrm{TPP})$$

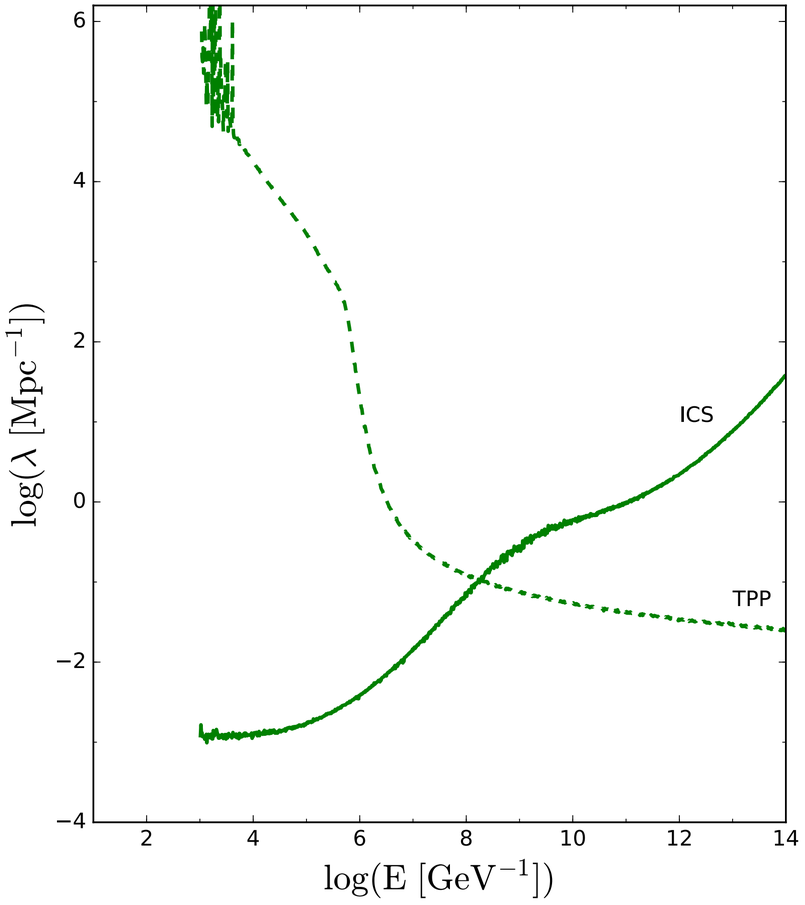
Mean interaction lengths

Propagation of high energy photons and electrons/positrons

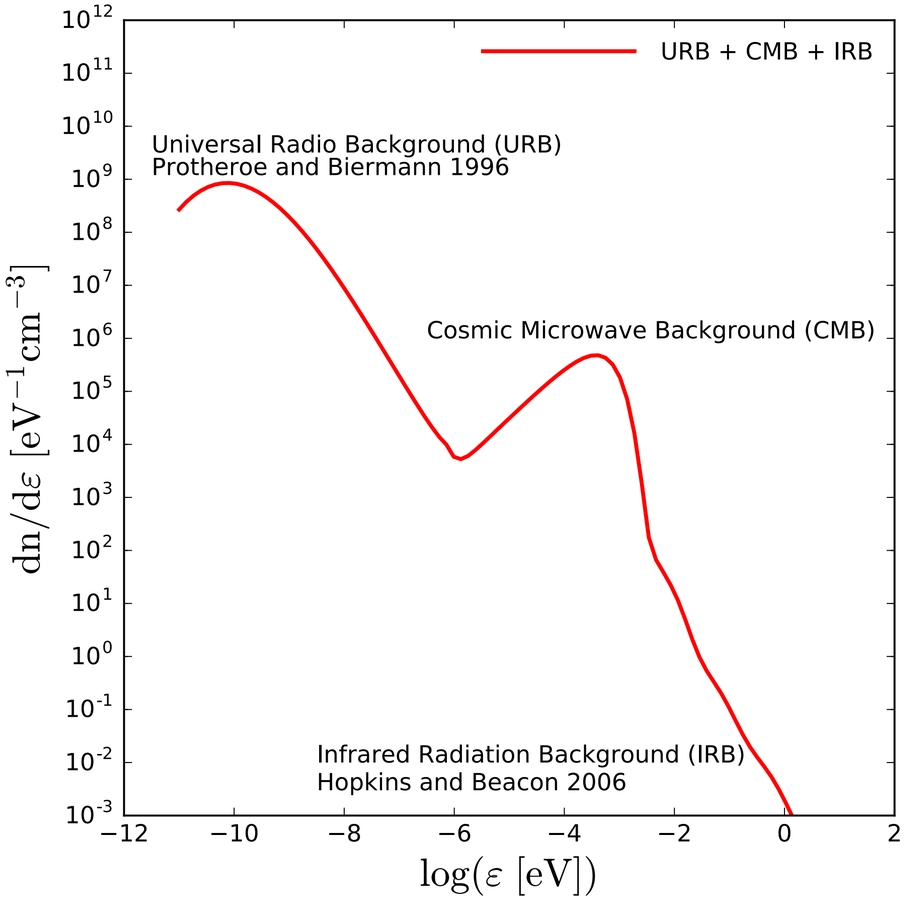
photons



electrons/positrons



Cosmic radiation background



Mean interaction lengths

Propagation of high energy photons and electrons/positrons

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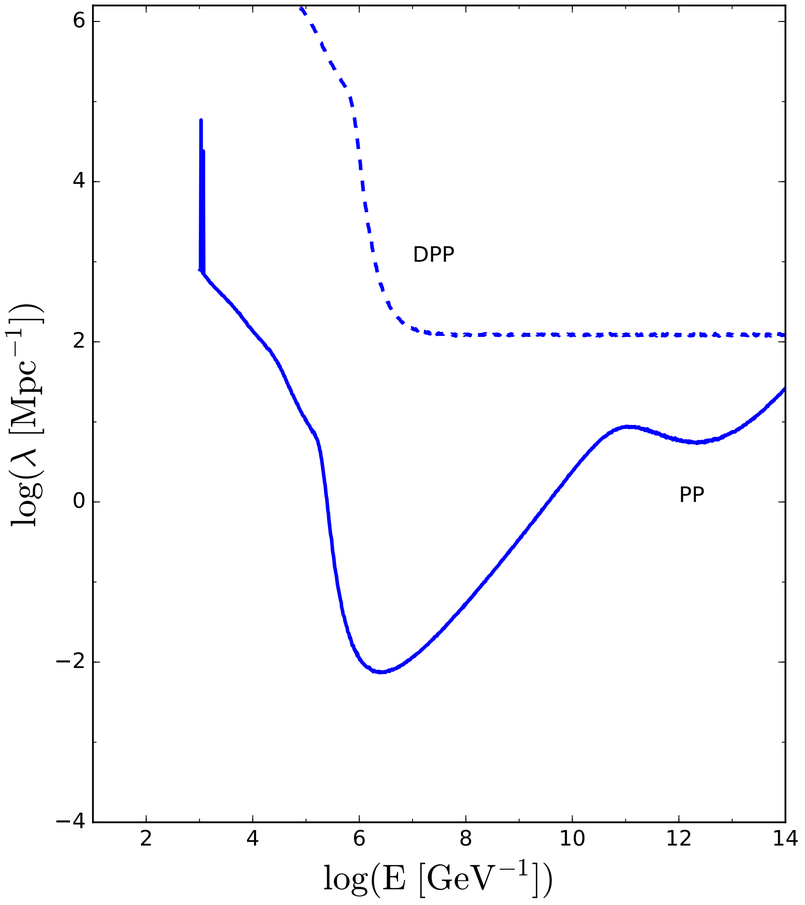
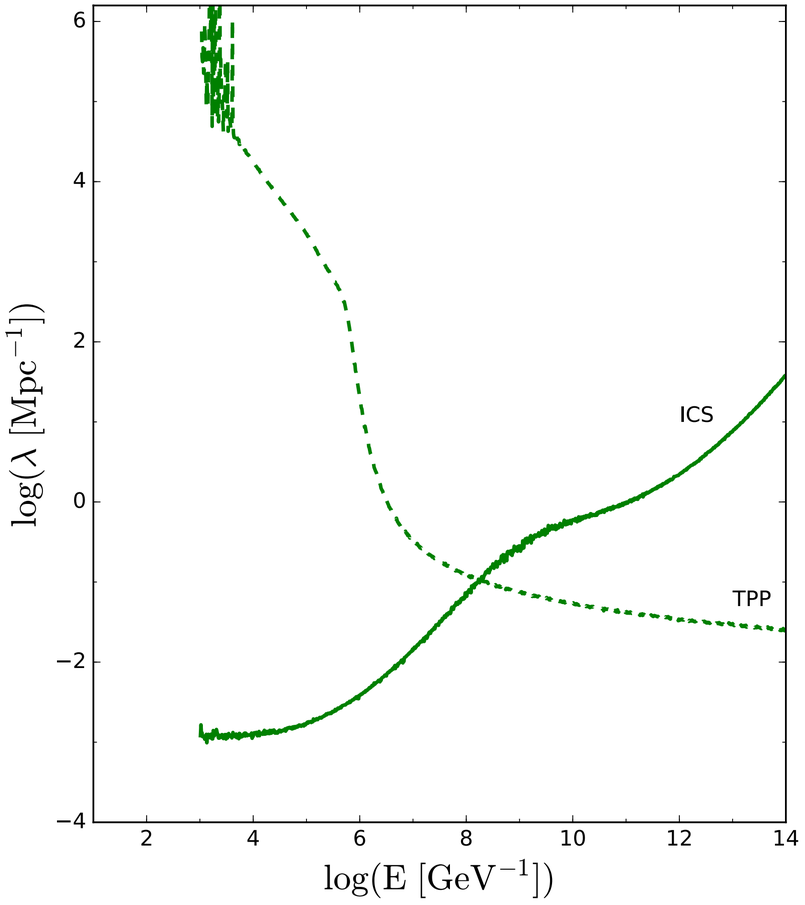


electrons/positrons



Mean interaction lengths

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$$e + \gamma_b \rightarrow e + \gamma \,(\mathrm{ICS})$$
$$\rightarrow e + e^- + e^+ \,(\mathrm{TPP})$$

Numerical simulation is needed

Monte Carlo simulation

e.g. EleCa $E > 10^{17}$ eV

Boltzmann kinetic equations

e.g. Dint $E < 10^{17}$ eV

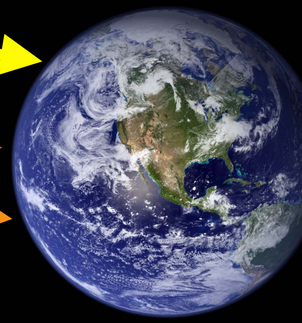
Source ⟷ Propagation ⟷ Detection

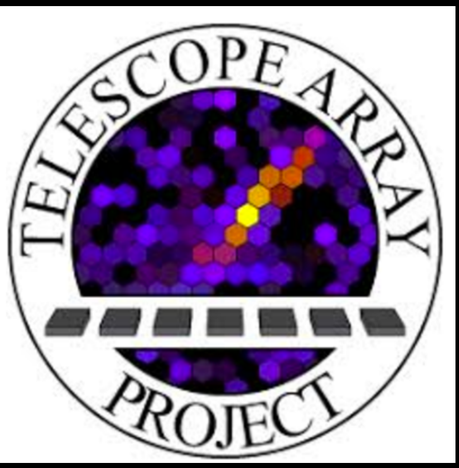
LHAASO can test the UHECR scenario

UHECRs

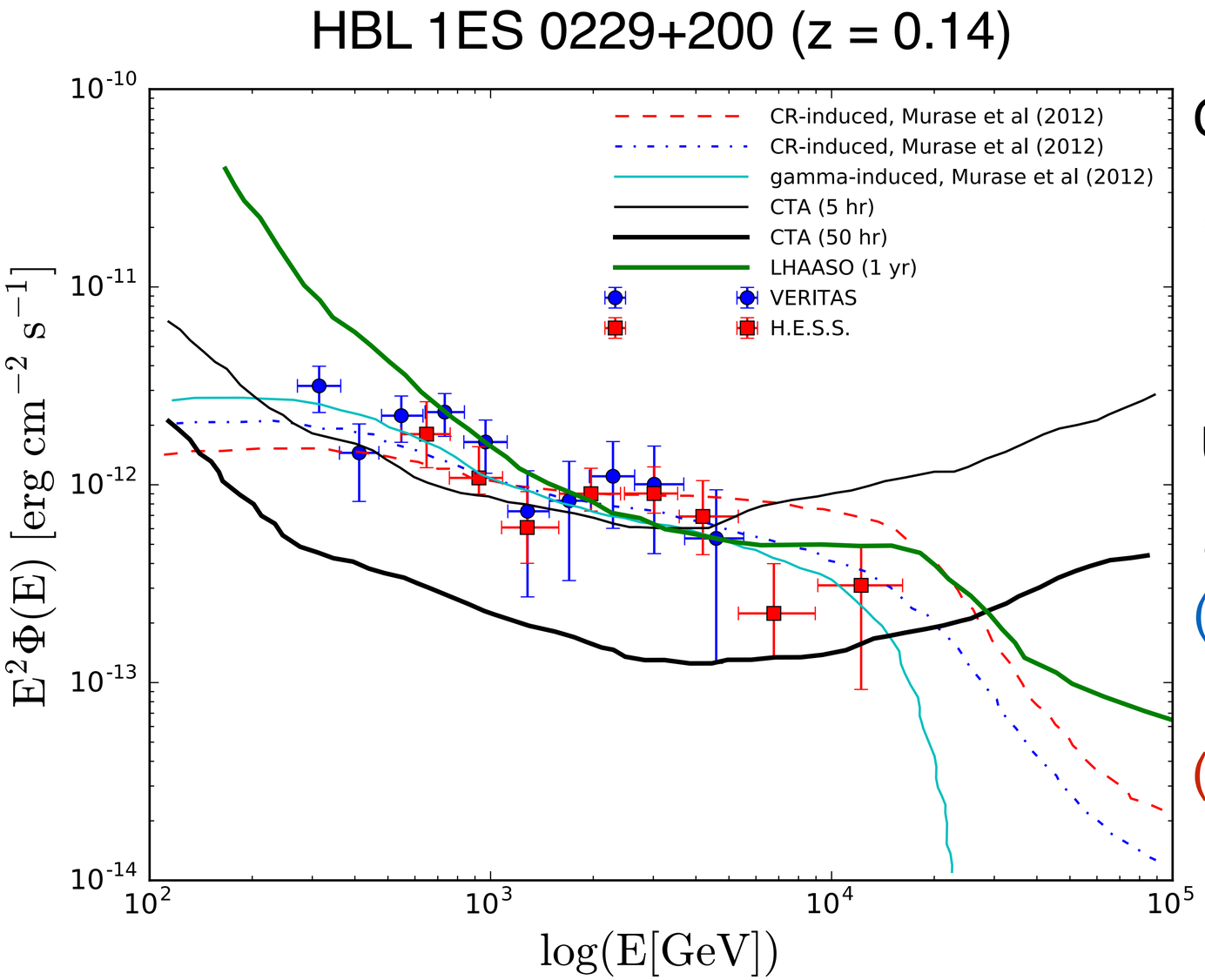
Gamma ray induced cascade γ

UHECRs induced cascade γ





UHECR induced cascade or gamma induced cascade ?



Gamma-ray induced cascade (solid cyan line)

$dN/dE \propto E^{-s}$

$E_c \simeq 100\ \mathrm{TeV} \quad s = 1.25 \quad L_\gamma \simeq 10^{45}\ \mathrm{erg\ s^{-1}}$

UHECR induced cascade

$dN/dE \propto E_p^{-p} \exp(-E_p/E_{p,c})$

(dot-dash blue line)

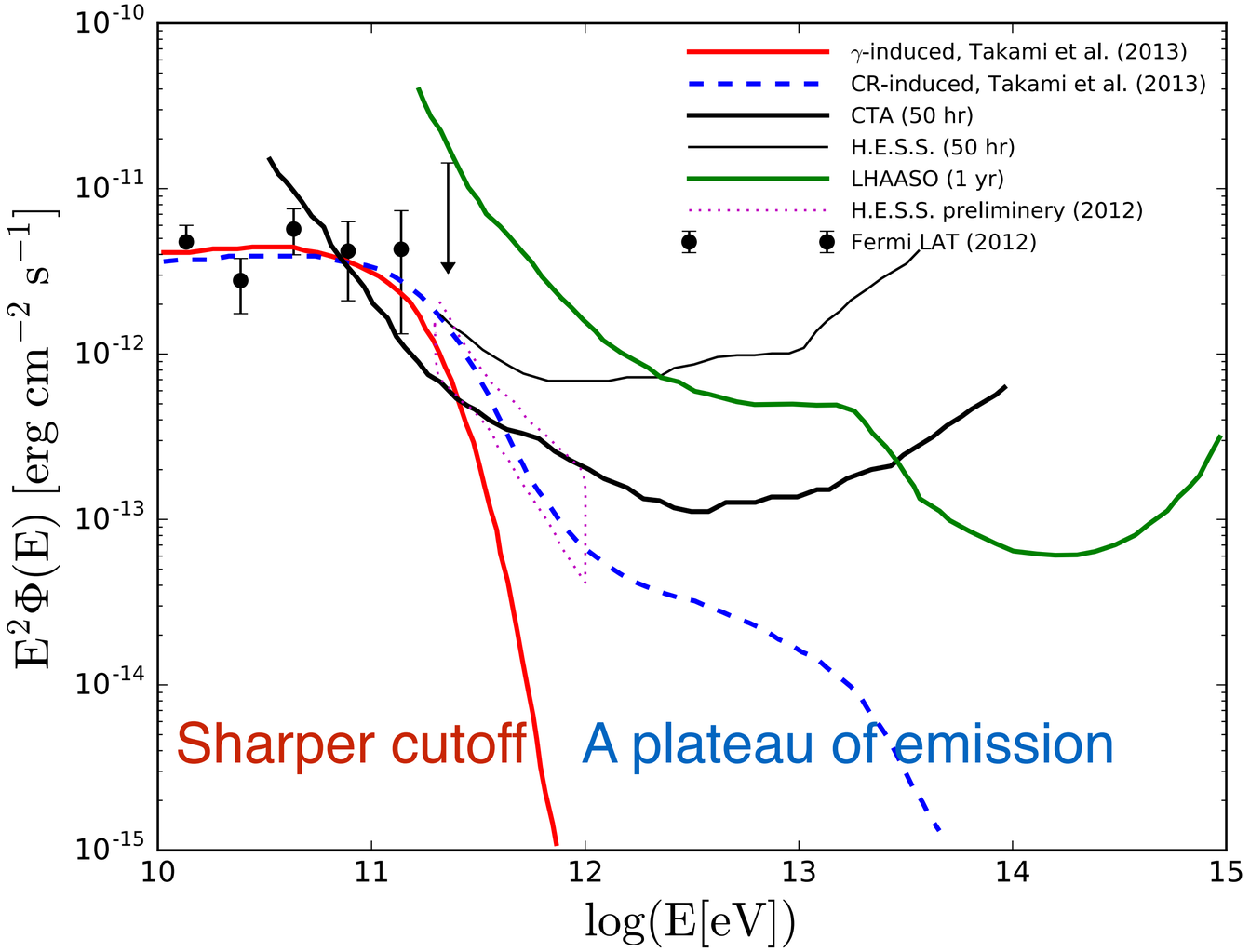
$E_{\mathrm{p,c}} \simeq 10^{19}\ \mathrm{eV} \quad p = 2 \quad L_{\mathrm{UHECR}} \simeq 10^{46}\ \mathrm{erg\ s^{-1}}$

(red-dash blue line)

$E_{\mathrm{p,c}} \simeq 10^{20}\ \mathrm{eV}$

UHECR induced cascade or gamma induced cascade ?

BL Lac object KUV 00311-1938 (z = 0.61)



Gamma-ray induced cascade (solid red line)

$$dN/dE \propto E^{-s}$$

$$E_c \simeq 100\ \mathrm{TeV} \qquad s = 1.76 \qquad L_\gamma^{\mathrm{iso}} = 3.5 \times 10^{46}\ \mathrm{erg\ s^{-1}}$$

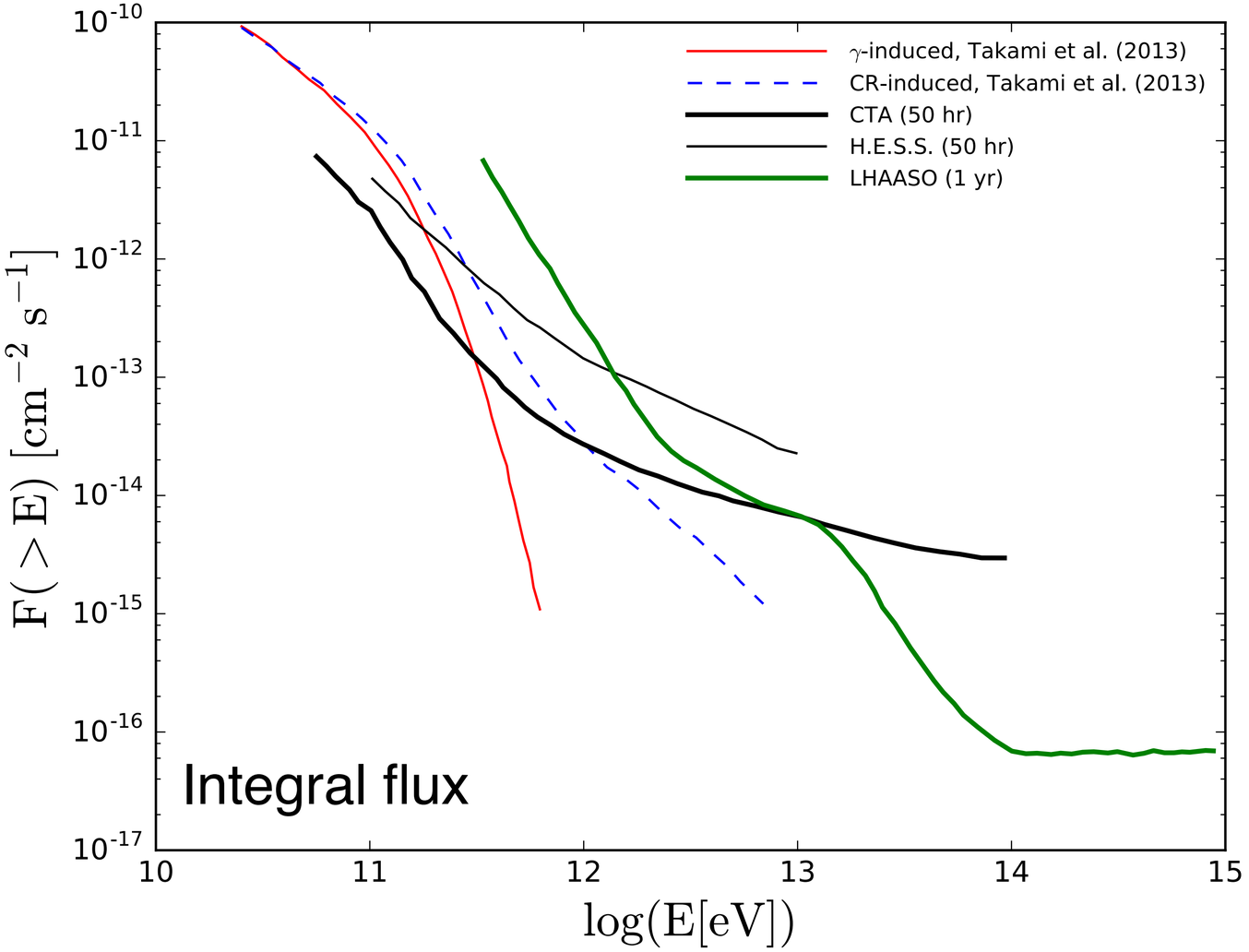
UHECR induced cascade (dashed blue line)

$$dN/dE \propto E_p^{-p} \exp(-E_p/E_{p,c})$$

$$E_{\mathrm{p,c}} \simeq 10^{19}\ \mathrm{eV} \qquad p = 2.6 \qquad L_p^{\mathrm{iso}} = 1.1 \times 10^{47}\ \mathrm{erg\ s^{-1}}$$

UHECR induced cascade or gamma induced cascade ?

BL Lac object KUV 00311-1938 (z = 0.61)



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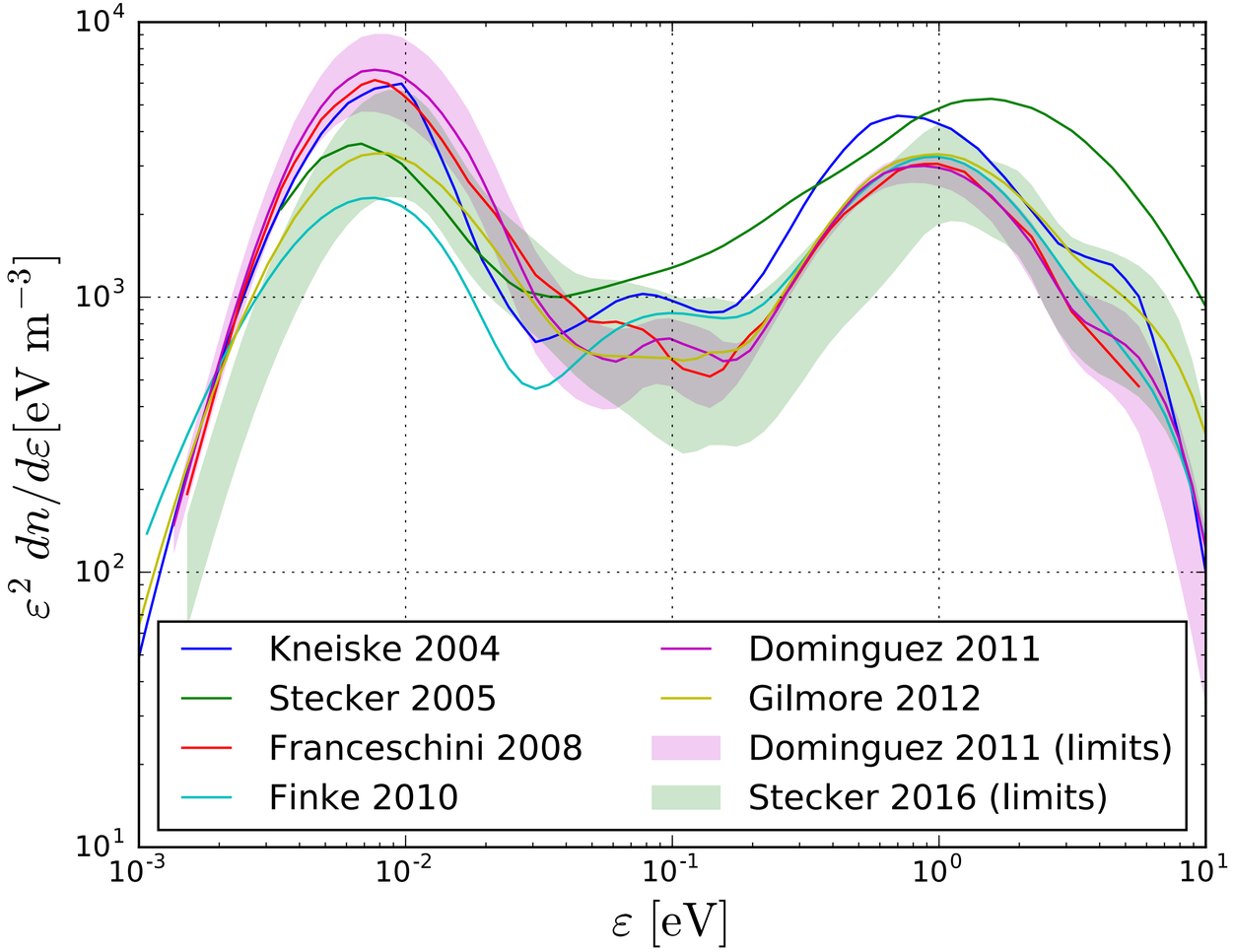
Future plan and improvements

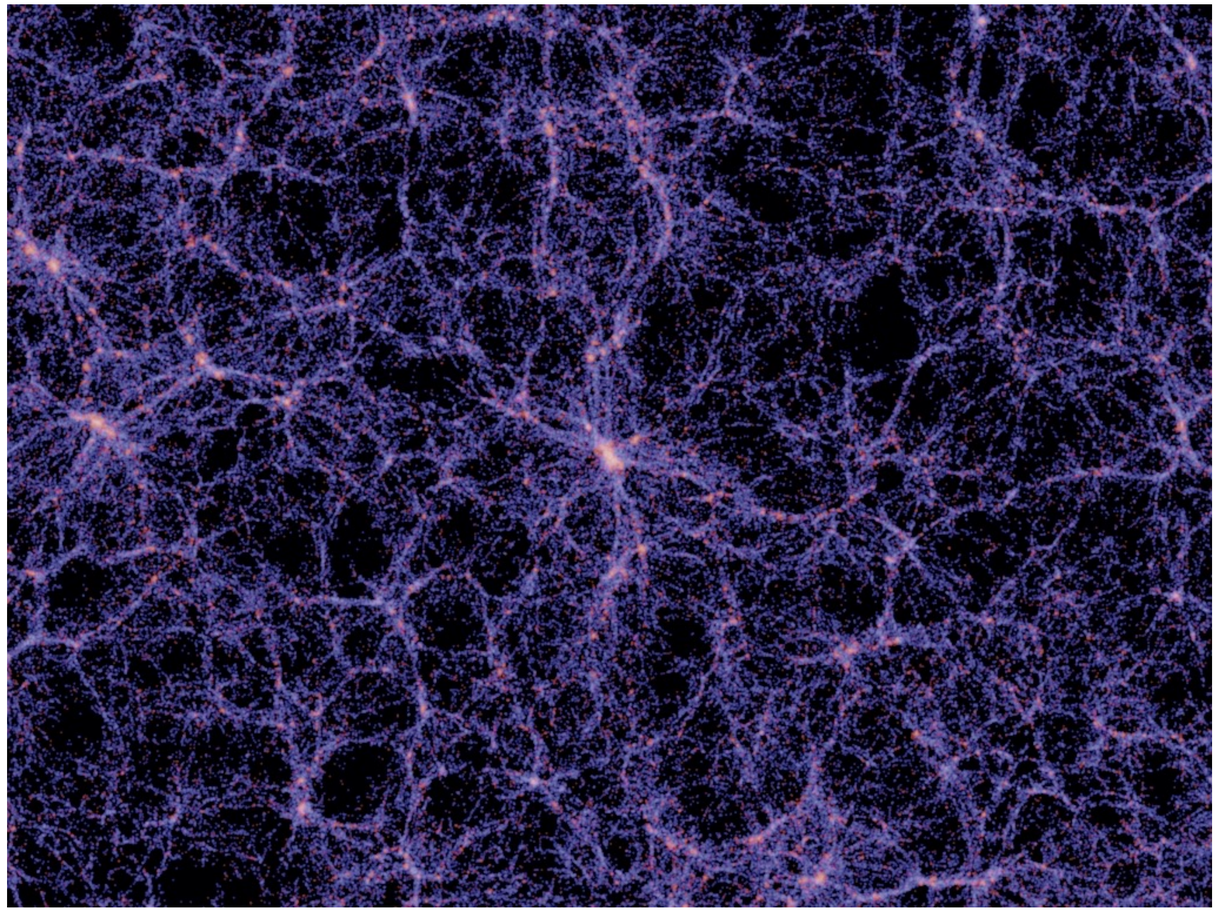
Extragalactic background light



Future plan and improvements

Larger scale magnetic field

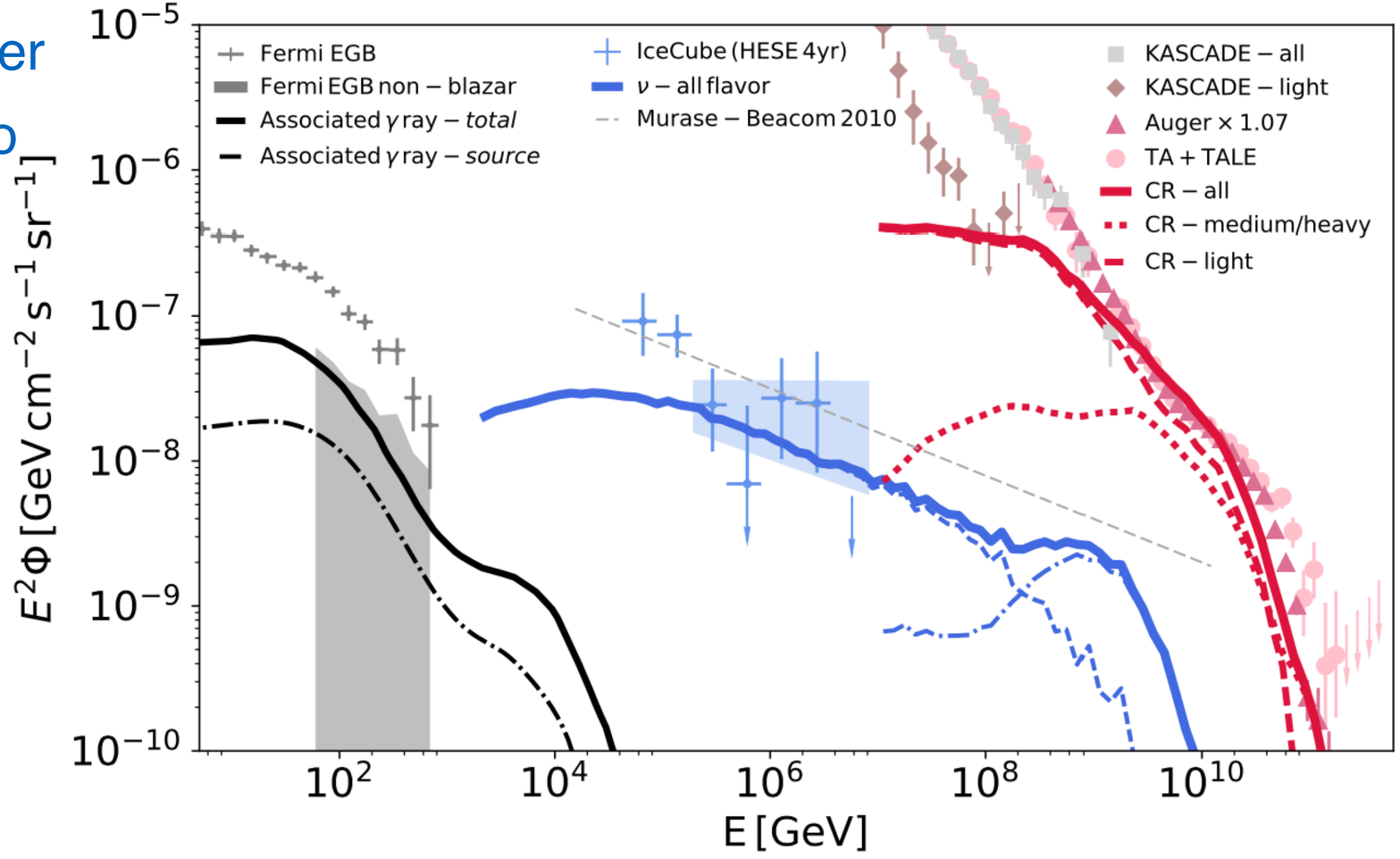
- EGMFs in clusters, filaments, voids
- Deflection and delay charged particles
- 3D simulation implemented magnetic field is needed



Future plan and improvements

UHECR composition (heavy nuclei?)

- Heavy nuclei suggested by Auger
- More easier to be accelerated to ultrahigh-energy



Fang and Murase, 2017

Future plan and improvements

Extragalactic background light — Accurate EBL model

Larger scale magnetic field — 3D simulation implemented magnetic field is needed

UHECR composition (heavy nuclei?) — C N O Ne Mg Si Fe

Source ⟷ Propagation ⟷ Detection

LHAASO can test the UHECR scenario

UHECRs

Gamma ray induced cascade γ

UHECRs induced cascade γ