Ultra-High-Energy Cosmic Ray Outburst from GRB 221009A

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2023/10/23 合肥

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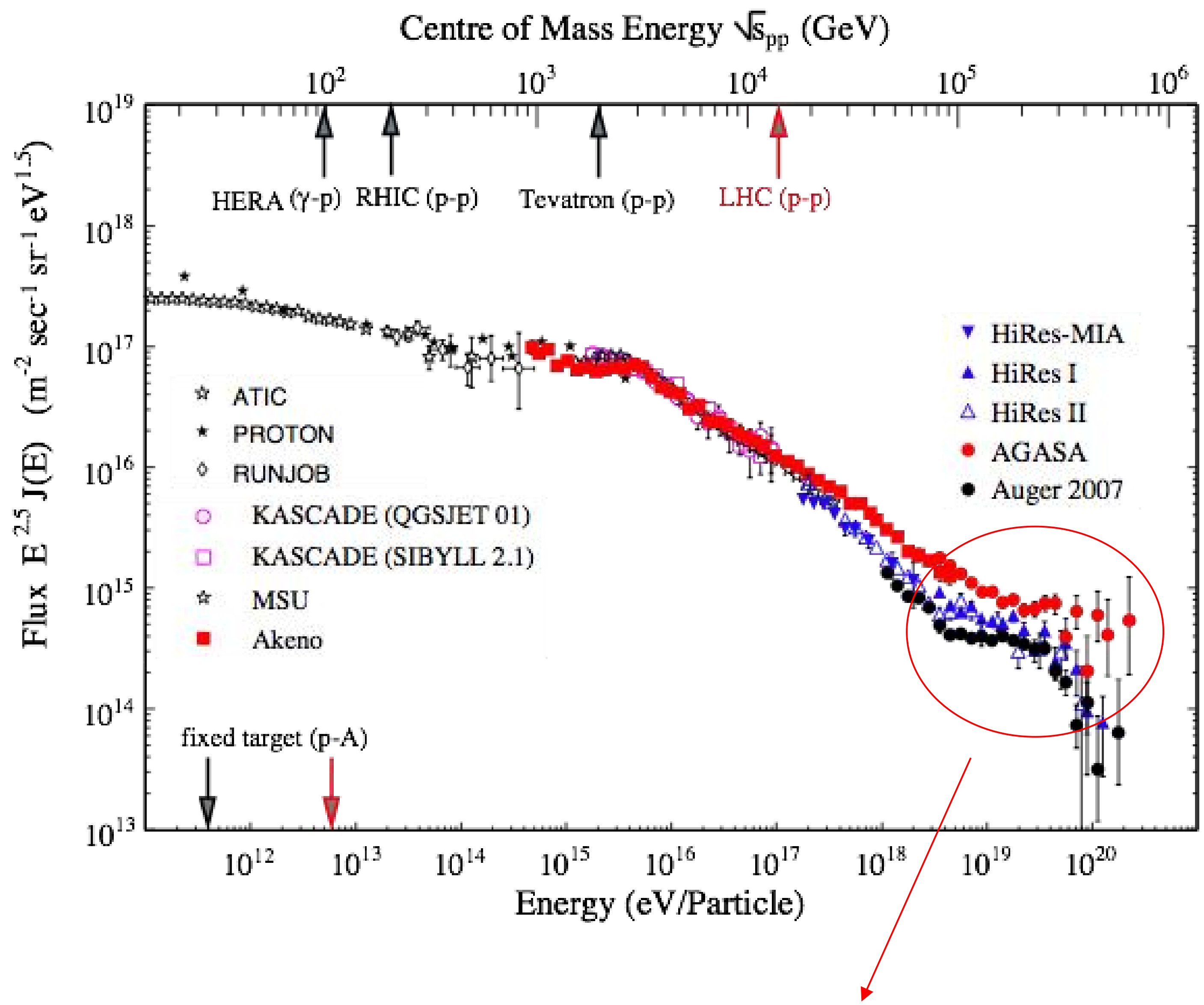
2023弥散伽马射线与宇宙线研讨会暨“宇宙线起源”青年团队年度总结会议
2023年10月21日-10月24日 安徽 合肥

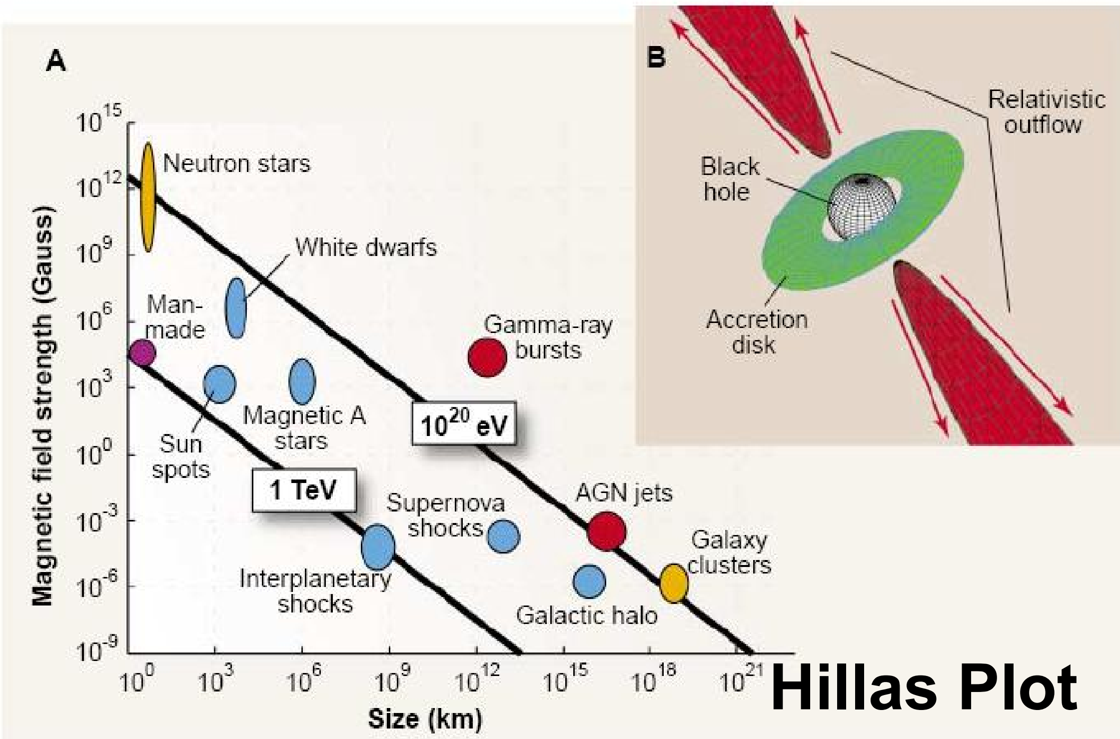
Origins of Cosmic rays
—— 111 years mystery

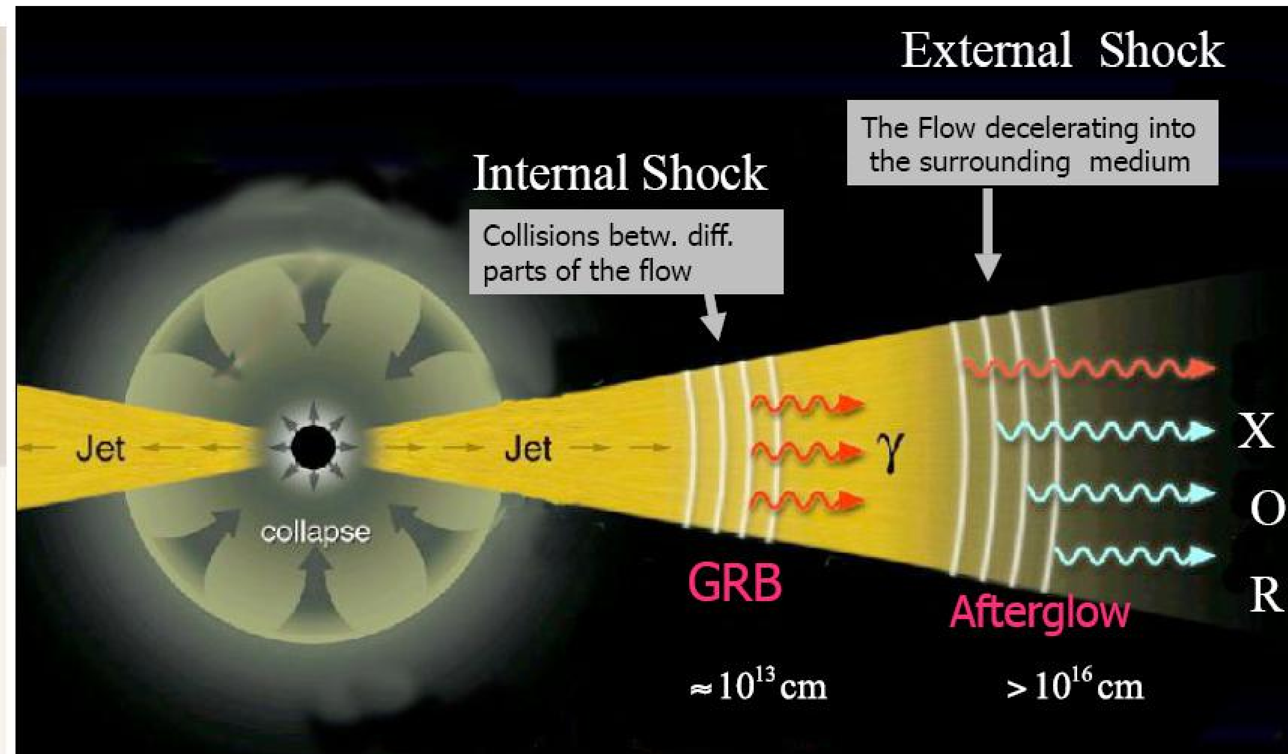
Hess bei Ballonlandung (1912).



Ultra-high energy cosmic rays (UHECRs, E>1EeV,1962)

CR acceleration in GRBs





Credit: P. Meszaros

R_L<R → B*R>E/Zqv

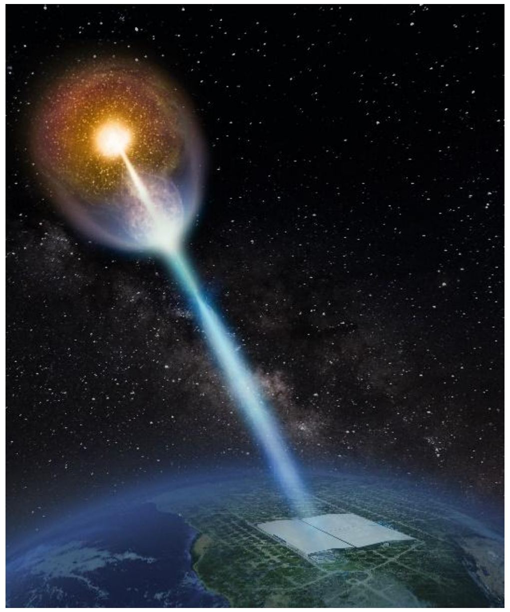
Internal shocks (Waxamn 1995)

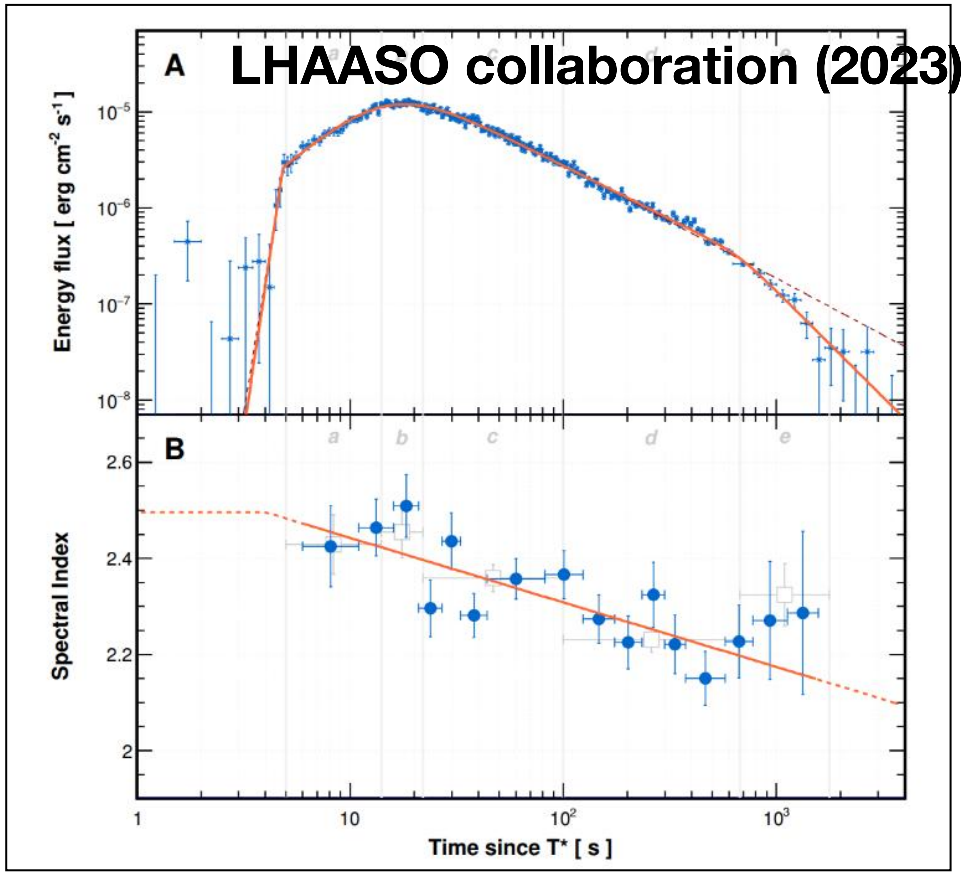
External shocks (Vietri 1995)

GRBs have been proposed as one of promising sources of UHECRs since 1995, but there is no direct observational evidence yet.

GRB 221009A

- **GRB 221009A** was detected as the B.O.A.T. (“brightest of all time”) GRB, a rare event once in 1000 years, locating at z=0.151 (745 Mpc).
- LHAASO reported the detection of the very high energy photon with energy up to ~ 18 TeV from the GRB within ~ 2000 s after the trigger (Huang et al. 2022).
- High statistics: >60,000 photonsabove 0.2TeV (LHAASO WCDA) (LHAASO collaboration 2023,LHAASO Collaboration, Science 380, 1390 (2023)).
- The open angle of the jet is $\theta_{\rm j} \simeq 0.6^{\circ} E_{\rm k,55}^{-1/8} n_0^{1/8}$, and the core of the jet is pointing to Earth (LHAASO collaboration 2023).
- The features of the host galaxy is consistent with those of typical long GRB host galaxy at low redshift (Levan et al. 2023; Malesani et al. 2023).

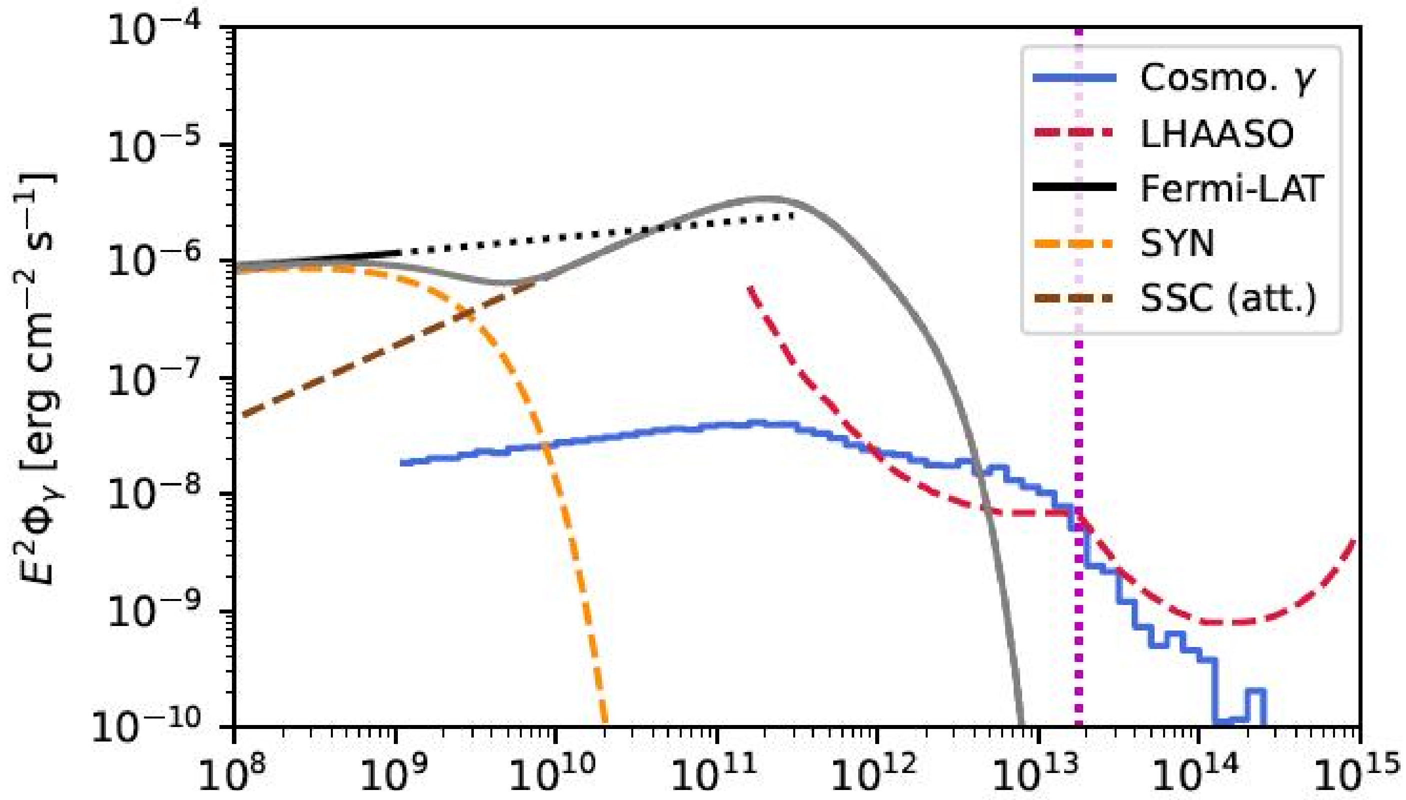




Possible explanations on the high energy photon detection

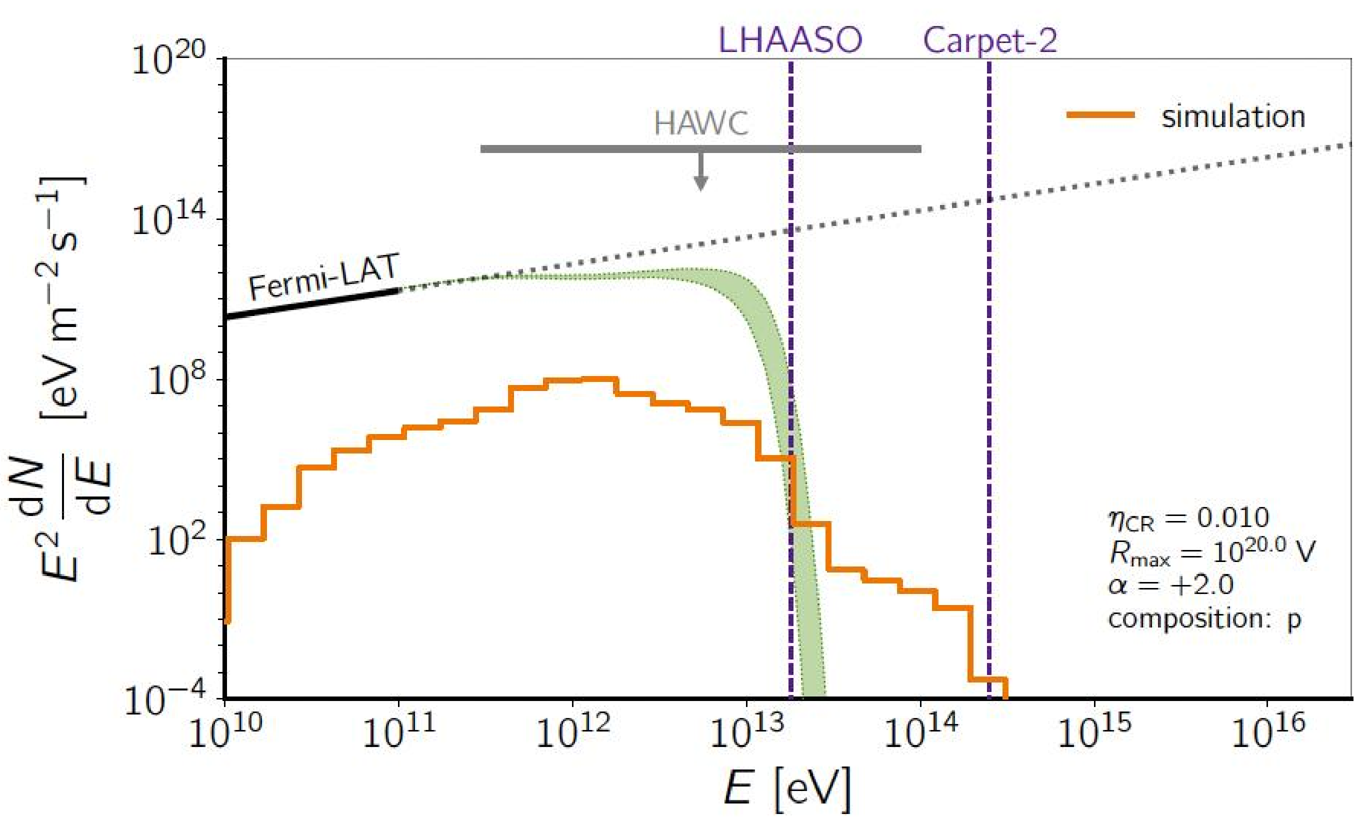
- The existence of axion-like-particles and two-photon coupling or the Lorentz-invariance violation (Galanti et al. 2022; Baktash et al. 2022; Troitsky 2022; Dzhappuev et al. 2022; Li & Ma 2023; Finke & Razzaque 2023)
- EM cascade initiated by the photomeson production process of high energy protons or by the SSC photons from electrons in the burst (Wang et al. 2023).
- Electromagnetic (EM) cascade initiated by UHECRs propagating in the inter-galactic space(Mirabal 2023; Das & Razzaque 2023; Alves Batista 2022).

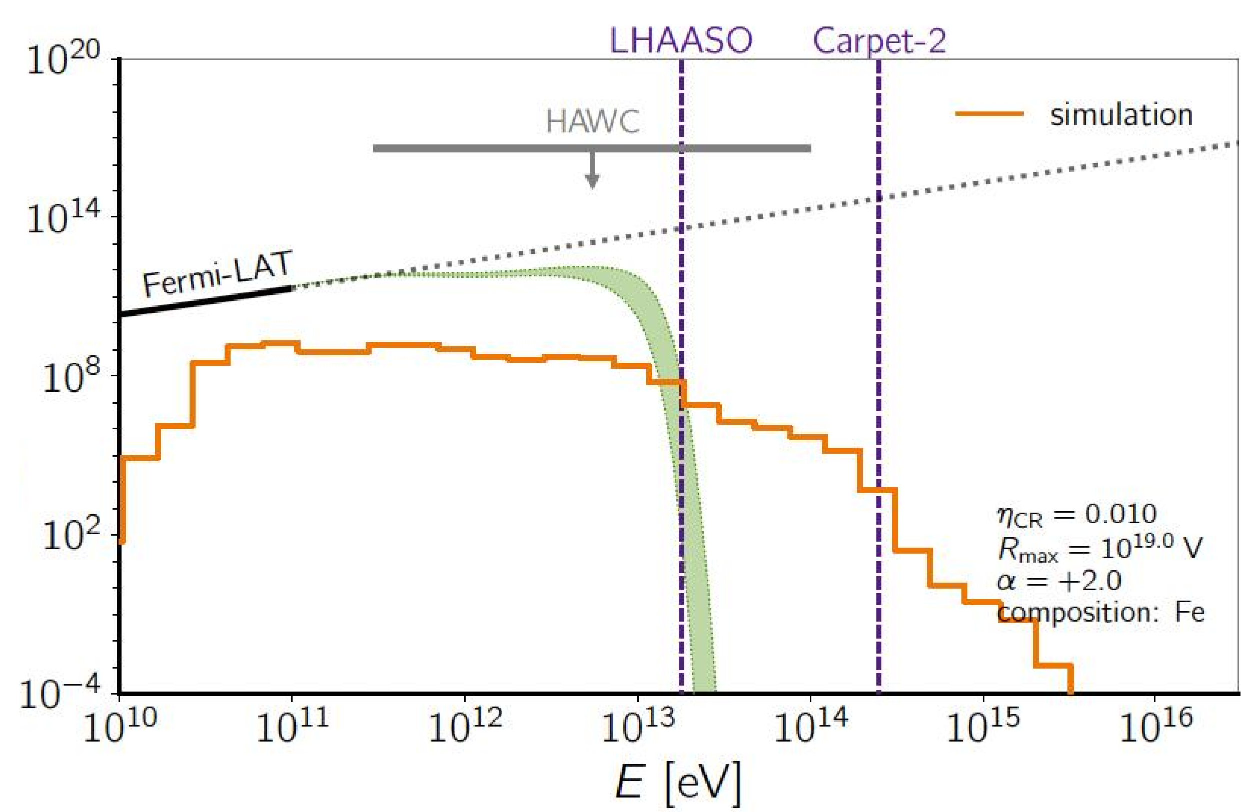
Cosmogenic Photons



Das & Rezzaque 2023

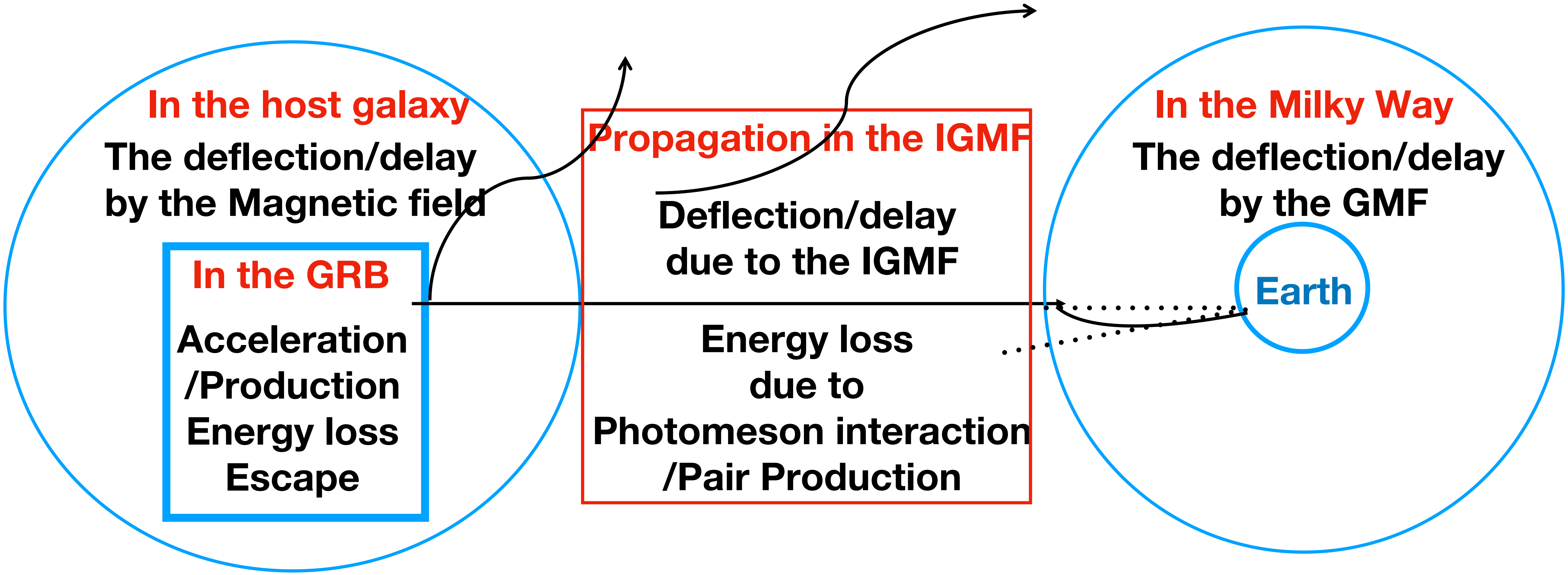
Rafael Alves Batista 2023





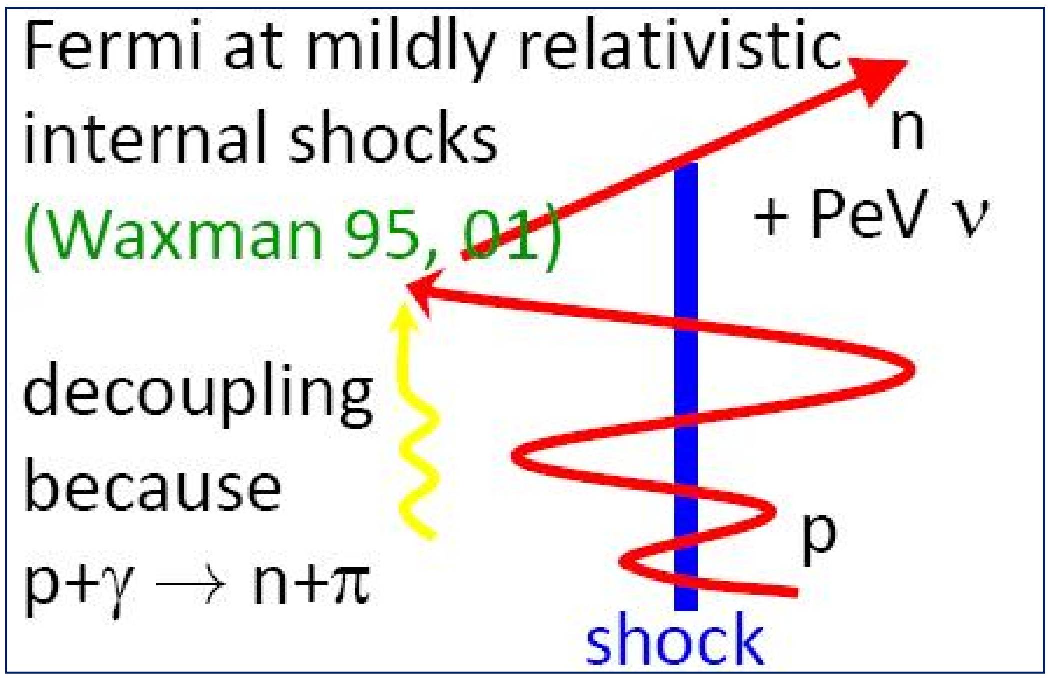
Heavier Nuclei Composition might lead to photons with energy extended to higher energy.

UHECRs from GRB 221009A



IGMF: Inter-galactic Magnetic Field
GMF: Galactic Magnetic Field

Proton Acceleration and Energy Loss in the GRB



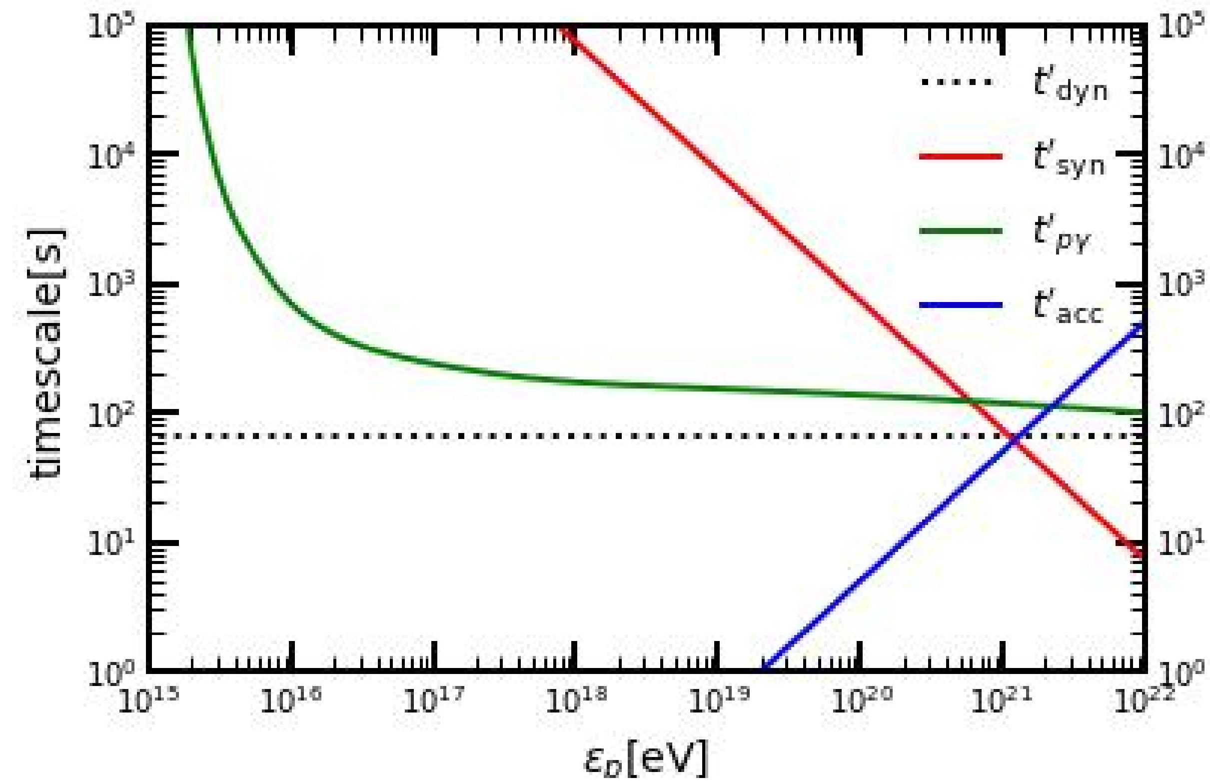


Table 1. The Adopted Parameters.

Descriptions	Symbols	Values
Redshift	z	0.151
Dissipation radius	R	10^{15}cm
Low energy photon index	α	0.76
High-energy photon index	β	2.13
Minimum energy of photon spectrum	$\varepsilon_{\gamma,\min}$	20 keV
Maximum energy of photon spectrum	$\varepsilon_{\gamma,\max}$	10 MeV
Peak energy of photon spectrum	$\varepsilon_{\gamma,b}$	3 MeV
Proton index	p	2
Calibration luminosity	L_γ [a]	$1 \times 10^{54}\,{\rm erg\,s^{-1}}$
Bulk Lorentz factor	Γ	500
Baryonic loading factor	ξ_p	1
Fraction of magnetic field energy	ϵ_B	0.01
Fraction of electron energy	ϵ_e	0.1
Total radiation energy	$E_{\gamma,\rm iso}$	10^{54} erg

[a] The luminosity at 20 keV–10 MeV.

$$\min[t'_{\rm dyn},\ t'_{\rm syn}(\varepsilon_{p,\max}),\ t'_{p\gamma}(\varepsilon_{p,\max})] = t'_{\rm acc}(\varepsilon_{p,\max}).$$

$$R = 2\Gamma^2 c t_{\rm v}/(1+z) = 10^{15}\ {\rm cm}\ (1+z)^{-1}\Gamma_{2.7}^2 \frac{t_{\rm v}}{0.082{\rm s}},$$

$$B' = 5.2\times10^3\ {\rm G}\,\epsilon_{e,-1}^{-\frac{1}{2}}\epsilon_{B,-2}^{\frac{1}{2}}\Gamma_{2.7}^{-1}R_{15}^{-1}L_{\gamma,54}^{\frac{1}{2}},$$

$$\varepsilon_{p,\max} = 1.2\times10^{21}{\rm eV}(1+z)^{-1}\Gamma_{2.7}^{3/2}\eta_0^{1/2}\epsilon_{e,-1}^{1/4}\epsilon_{B,-2}^{-1/4}R_{15}^{1/2}L_{\gamma,54}^{-1/4},$$

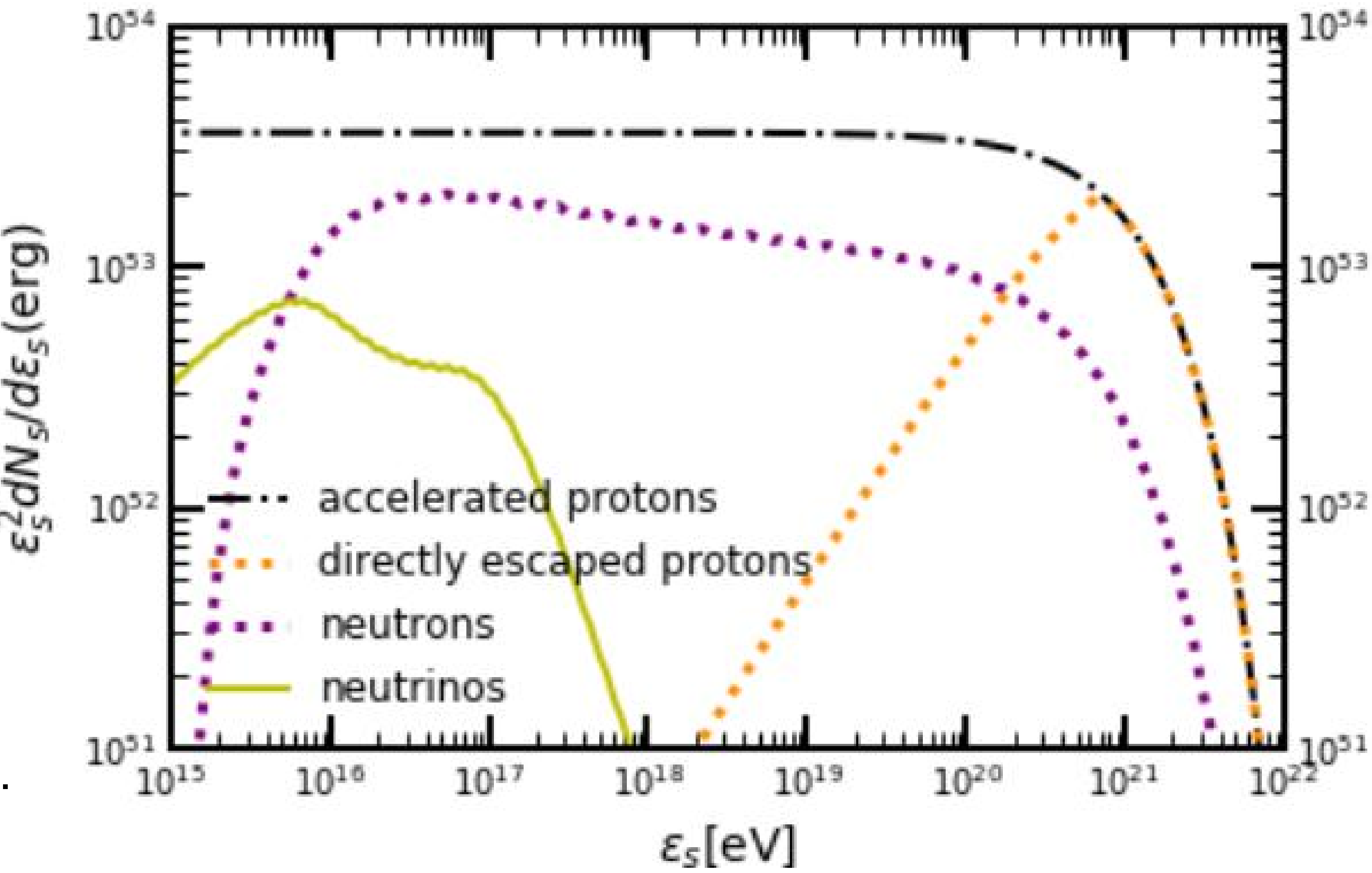
Neutron and Neutrino Production in the GRB

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0. \end{cases}$$

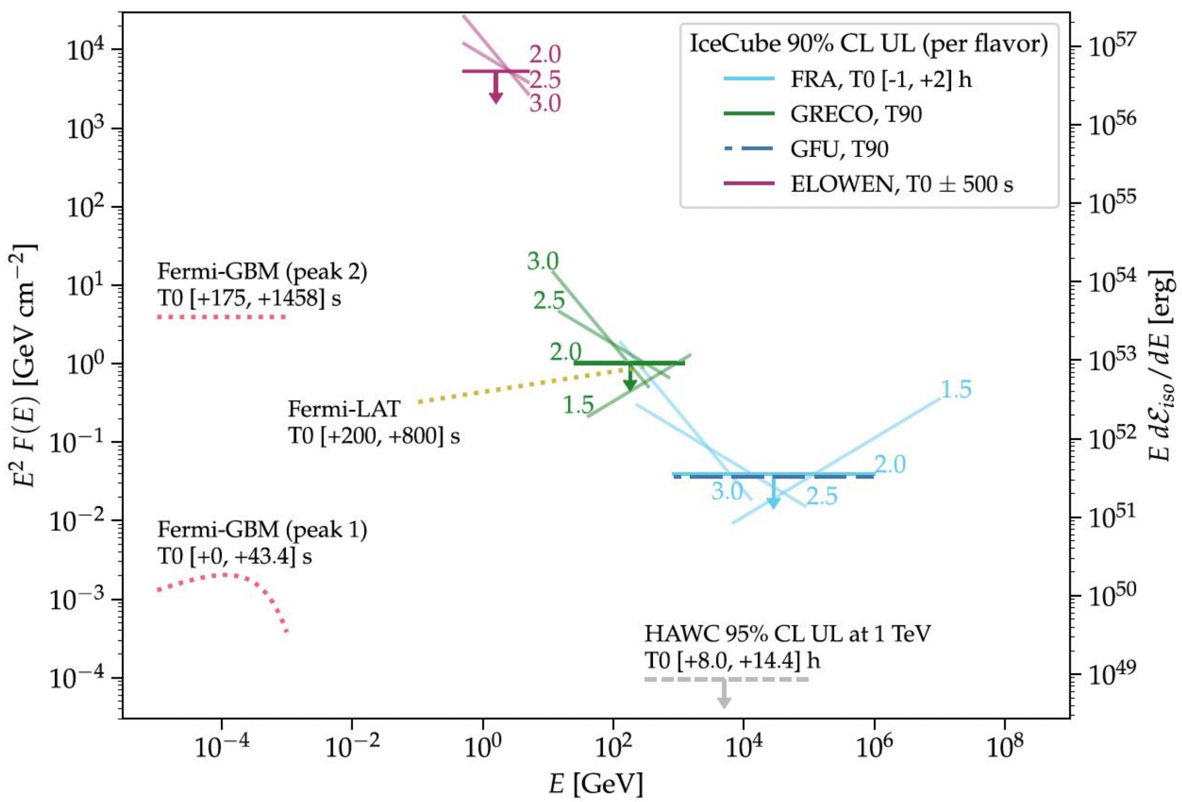
$$n \rightarrow p + e^- + \bar{\nu}_e,$$
$$\pi^\pm \rightarrow \nu_\mu(\bar{\nu}_\mu)\mu^\pm \rightarrow \nu_\mu(\bar{\nu}_\mu)e^+(e^-)\nu_e(\bar{\nu}_e)\bar{\nu}_\mu(\nu_\mu)$$

$$Q(\varepsilon'_s) = \int \frac{d\varepsilon'_p}{\varepsilon'_p}\frac{dn_p}{d\varepsilon'_p}\int d\varepsilon'_\gamma \frac{dn_\gamma}{d\varepsilon'_\gamma}\mathcal{R}(\varepsilon'_s, \varepsilon'_p),$$

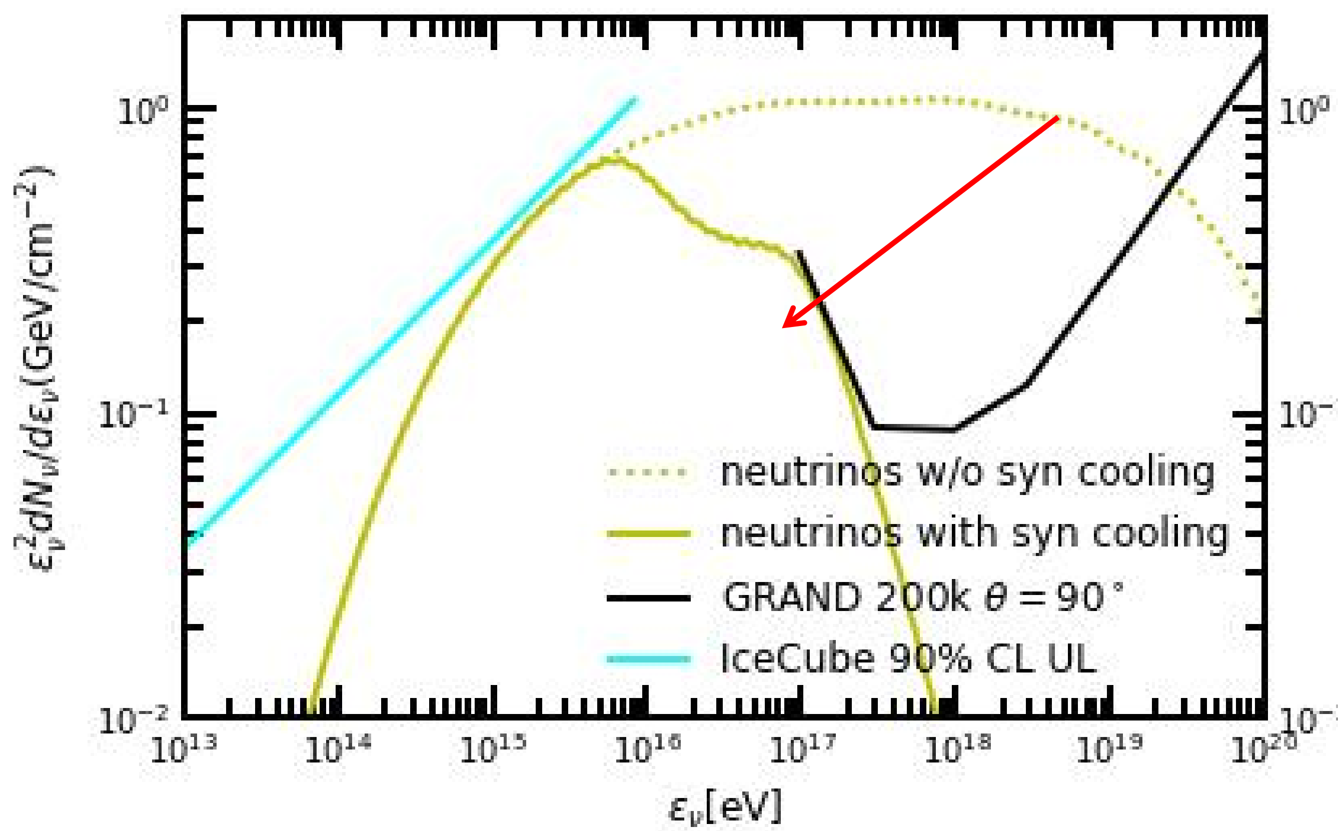
Adopting SOPHIA numerical code.



Neutrinos from GRB 221009A



IceCube upper limit on neutrinos
from GRB 221009A
The IceCube collaboration (2023)



Synchrotron cooling of muons and pions

CR Escape from the GRB

Proton Direct Escape:

The length of the mean free path:

$$\lambda'_{p,\mathrm{mfp}}(E') = \min[\Delta r', R'_L(E'), c\, t'_{p\gamma}(E')],$$

$$R'_L = \frac{E'_p}{e\, B'} \simeq 33.3\,\mathrm{cm} \times \left(\frac{E'_p}{\mathrm{GeV}}\right) \times \left(\frac{10^5\,\mathrm{G}}{B'}\right)$$

shell thickness as $\Delta r' \simeq \Gamma c t_v/(1+z)$.

The fraction of escape particles:

$$f_{\mathrm{esc}} \equiv \frac{V'_{\mathrm{direct}}}{V'_{\mathrm{iso}}} \simeq \frac{1}{2} \times \frac{4\pi\,(r^2 + (r-\Delta r')^2)\,\lambda'_{\mathrm{mfp}}}{4\pi\, r^2\, \Delta r'} \simeq \frac{\lambda'_{\mathrm{mfp}}}{\Delta r'}.$$

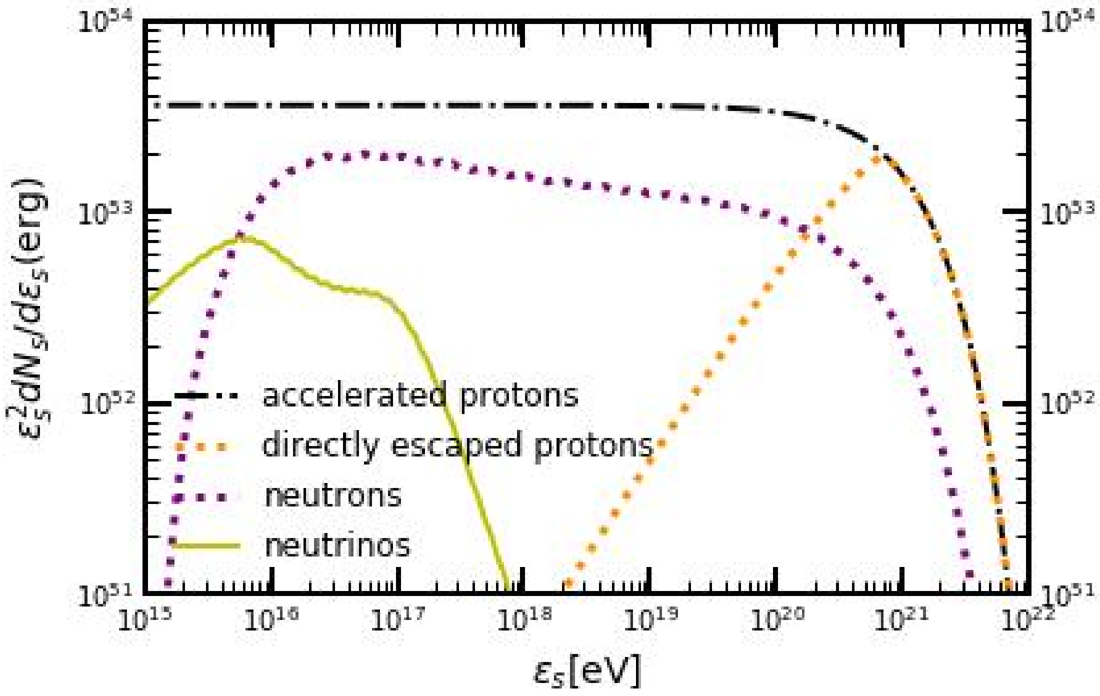
Neutron Escape:

$$\tau_n \simeq (t'^{-1}_{n\gamma} + t'^{-1}_{n})/t'^{-1}_{\mathrm{dyn}} \simeq t'_{\mathrm{dyn}}/t'_{p\gamma}$$

$$\tau_n < 1$$

Neutronsphere:

The remaining neutrons will escape at a certain radius where the target photon density is low enough, since photon density drops as r^-3. (Barewald et al. 2013)



Escape from the Host Galaxy

Protons with E> 300 EeV are still pointing to Earth, after escape from the host galaxy.

$$\theta_{\rm reg,hg} \simeq 4.1^\circ \varepsilon_{p,19.5}^{-1} \frac{B_{\rm reg,hg}}{1\ \mu{\rm G}} \frac{R_{\rm e}}{2.45\ {\rm kpc}},$$

$$\theta_{\rm rms,hg} \simeq 1.5^\circ \varepsilon_{p,19.5}^{-1} \frac{B_{\rm rms,hg}}{2\mu{\rm G}} \left(\frac{\lambda_{B,\rm hg}}{50\ {\rm pc}}\right)^{1/2} \left(\frac{L_{\rm hg}}{10\ {\rm kpc}}\right)^{1/2}$$

$$\Delta t_{\rm rms,hg} \simeq \frac{L_{\rm hg}\theta_{\rm rms,hg}^2}{12c} \simeq 1.9\ {\rm yr}\, \varepsilon_{p,19.5}^{-2} \left(\frac{B_{\rm rms,hg}}{2\ \mu{\rm G}}\right)^2 \frac{\lambda_{B,\rm hg}}{50\ {\rm pc}} \left(\frac{L_{\rm hg}}{10\ {\rm kpc}}\right)^2$$

Neutrons with energy larger than 10 EeV can escape from the host galaxy with no deflection and delay, before beta-decay.

$$n \to p + e^- + \bar{\nu}_e$$

$$L_n = ct'_n \frac{\varepsilon_n(1+z)}{m_n} \simeq 88\ {\rm kpc}\ \varepsilon_{n,19}(1+z)$$

Hereafter, we study the propagation of protons with E>300 EeV, and neutron-induced protons in the IGMF.

Proton Propagation in the IGMF

Deflection:

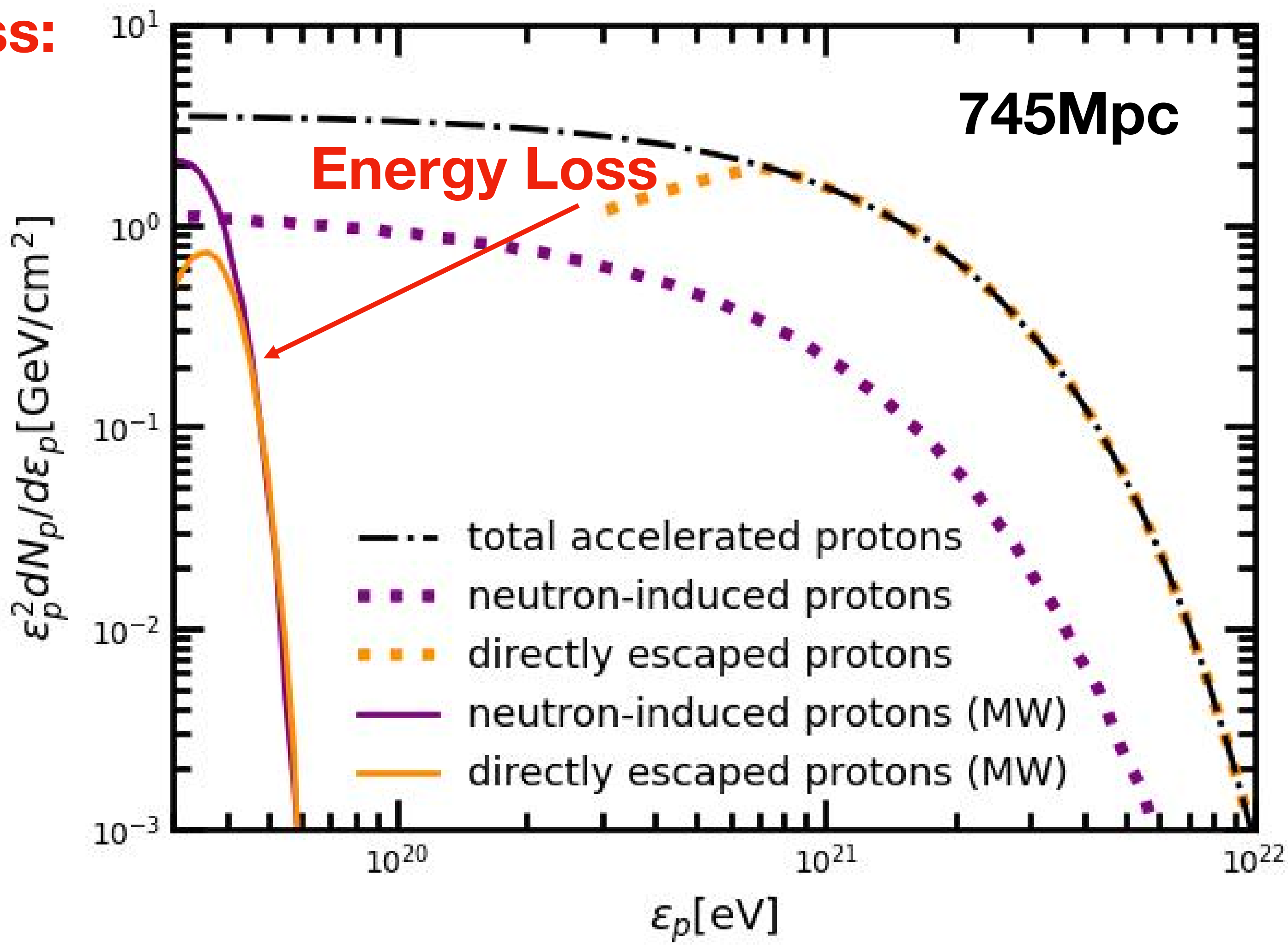
$$\theta_{\rm rms,IG} \simeq 2.9\times10^{-6\circ}\varepsilon_{p,19.5}^{-1}B_{\rm IG,-16}\left(\frac{\lambda_{\rm IG}}{1\,{\rm Mpc}}\right)^{1/2}\left(\frac{D_{\rm L}}{745\,{\rm Mpc}}\right)^{1/2}$$

Time delay:

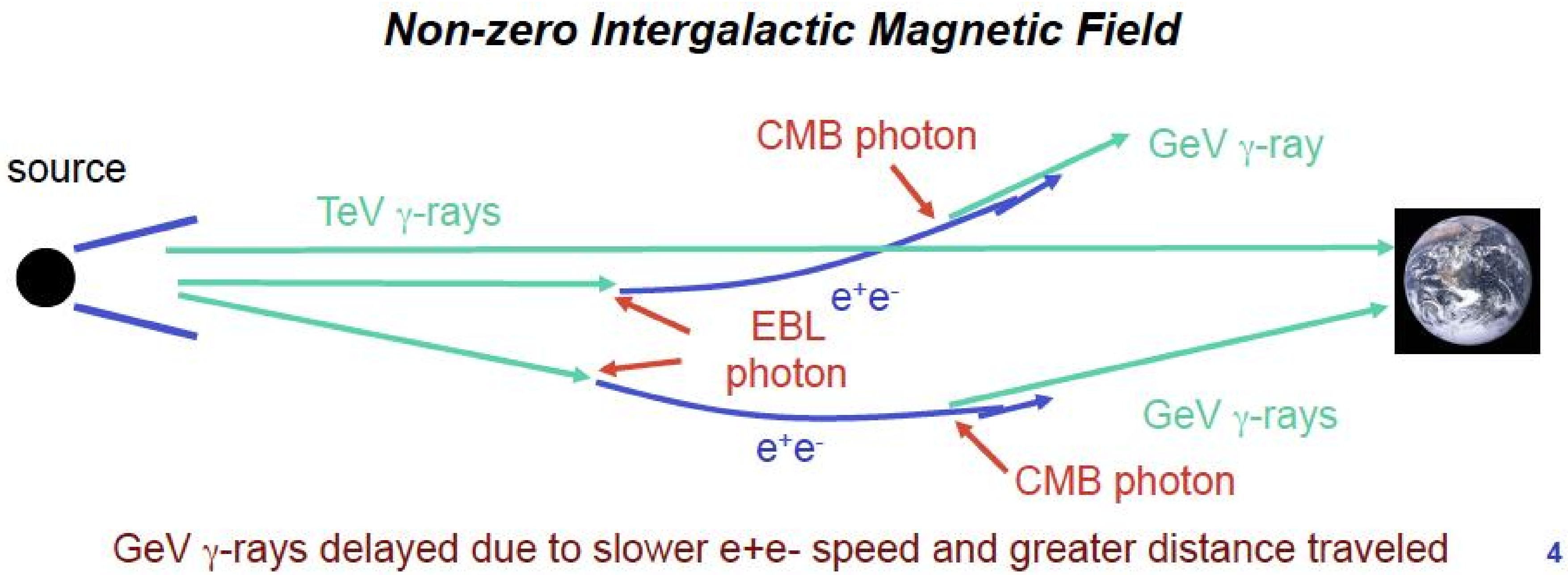
$$\Delta t_{\rm IG} \simeq 16\,{\rm s}\,\varepsilon_{p,19.5}^{-2}B_{\rm IG,-16}^{2}\frac{\lambda_{\rm IG}}{1\,{\rm Mpc}}\left(\frac{D_{\rm L}}{745\,{\rm Mpc}}\right)^{2}$$

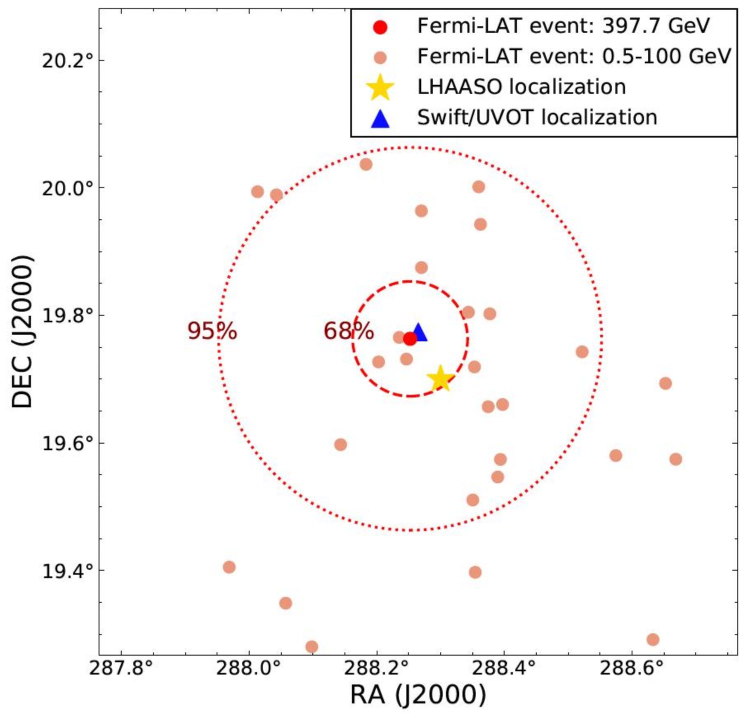
If $B_{\rm IG} \lesssim 3\times10^{-13}$G and $\lambda_{\rm IG} \lesssim 1$Mpc, there are $\theta_{\rm rms,IG} \ll \theta_{\rm j}$ and $\Delta t_{\rm IG} < 5$yr for protons with energy larger than 30 EeV, hence the fluence of protons arriving at the MW within 5 years would not be suppressed by the deflection of the IGMF significantly.

Energy Loss:



The Constraint on the IGMF





At 33554 s after the Fermi-GBM trigger,
there came a gamma ray with an energy of 400 GeV.

$$\epsilon_\gamma \approx 19 \left(\frac{\epsilon_{\gamma,2\mathrm{nd}}}{400\,\mathrm{GeV}}\right)^{1/2} \left(\frac{1+z}{1.151}\right)^{-1} \mathrm{TeV}.$$

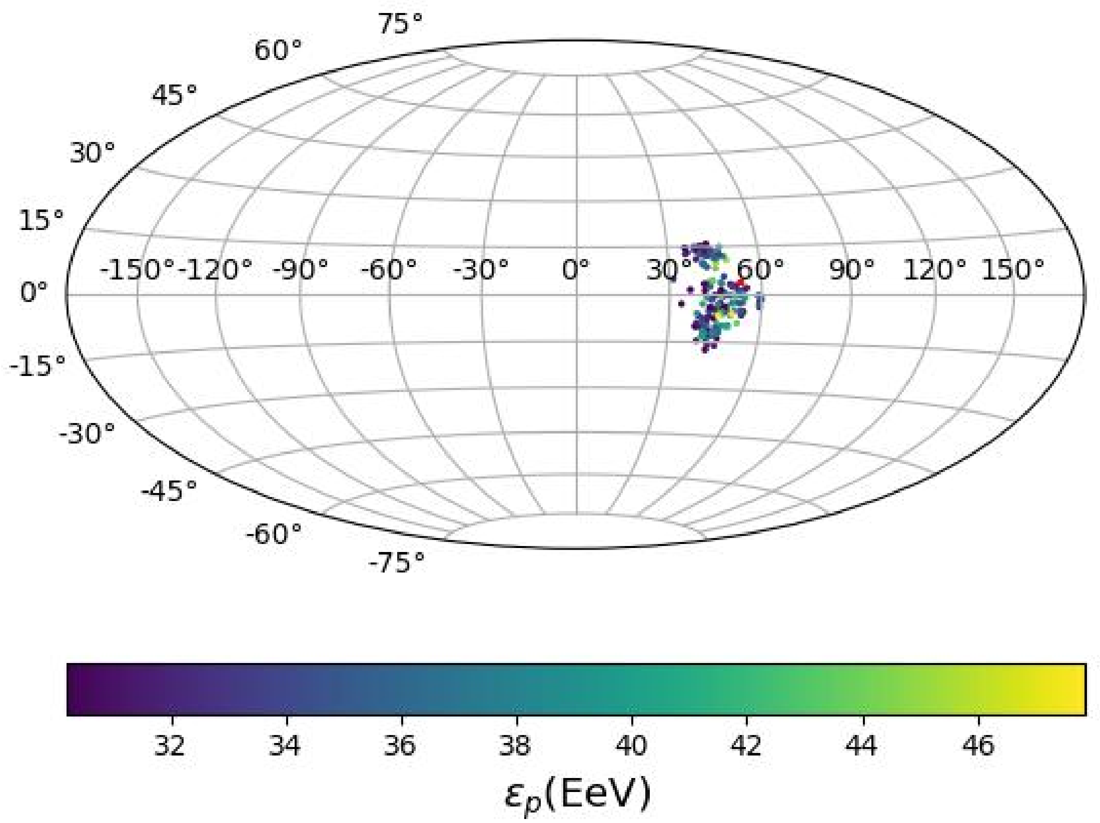
$$B_{\mathrm{IGMF}} \approx 1.2\times10^{-16} \left(\frac{\epsilon_{\gamma,2\mathrm{nd}}}{400\,\mathrm{GeV}}\right)^{5/2} \left(\frac{\Delta t_{\mathrm{B}}}{0.4\,\mathrm{day}}\right)^{1/2} \left(\frac{1+z}{1.151}\right)^{11/2} \mathrm{G}.$$

Xia ZQ et al. 2023

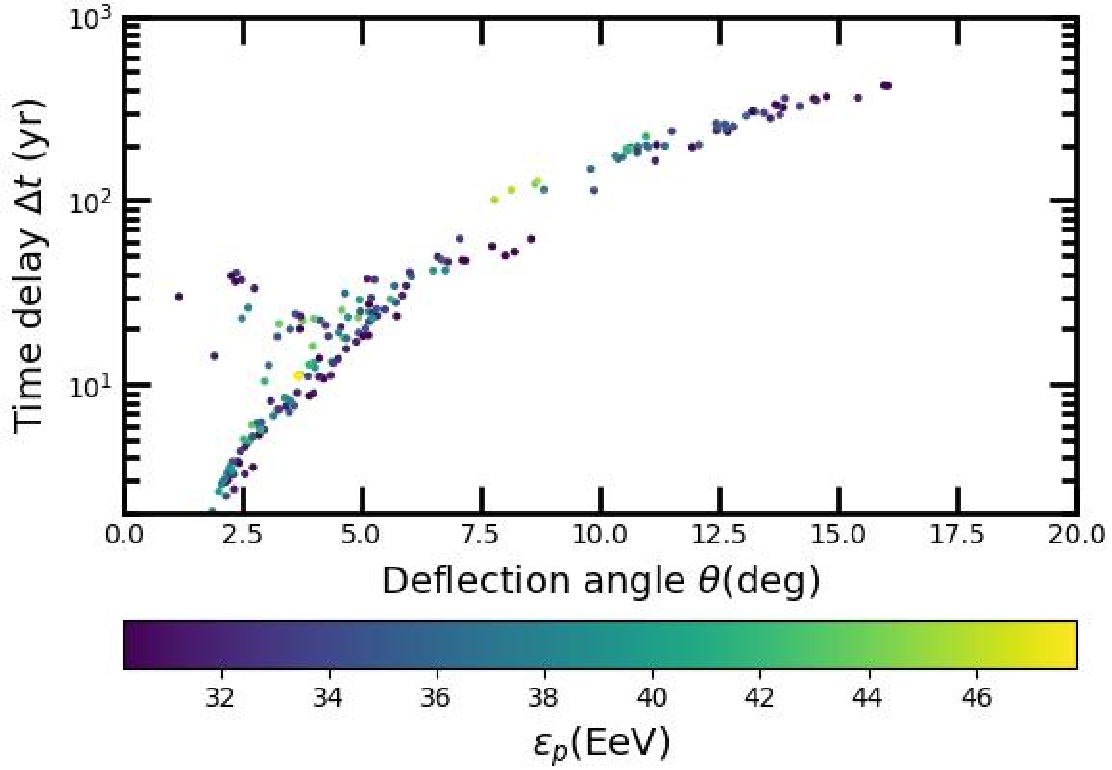
This is consistent with the constraint made from TeV blazars in Dermer et al. 2011; Taylor et al. 2011; Vovk et al. 2012; Finke et al. 2015; Podlesnyi et al. 2022.

UHECRs Propagation in the Milky Way

The Lensed Map

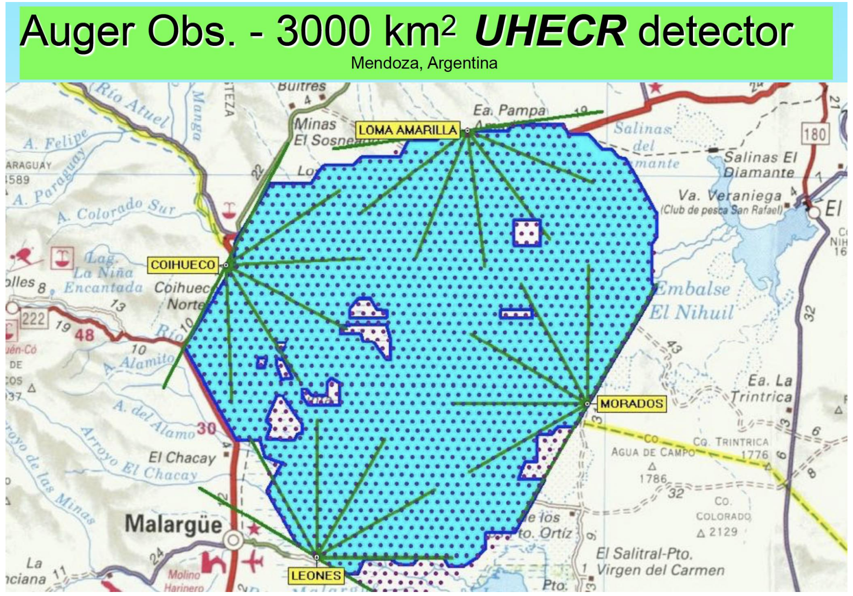


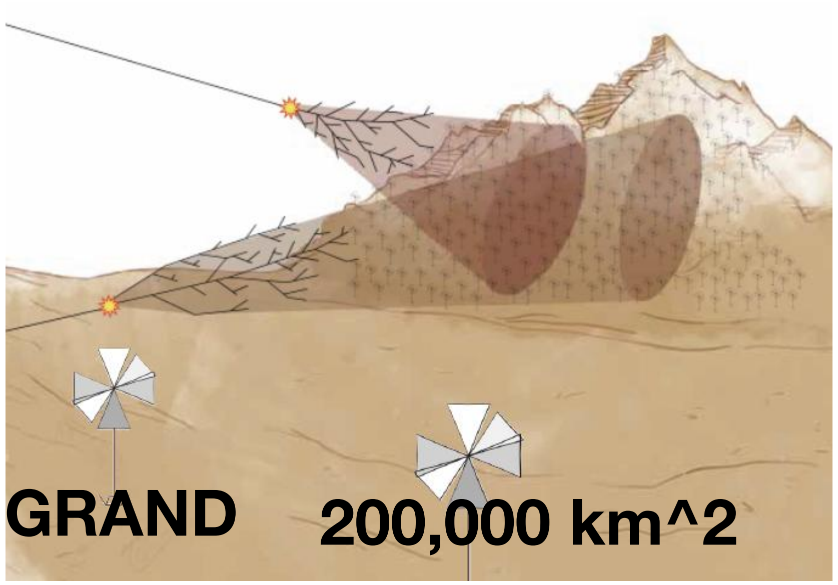
Time Delay and Deflection Angle

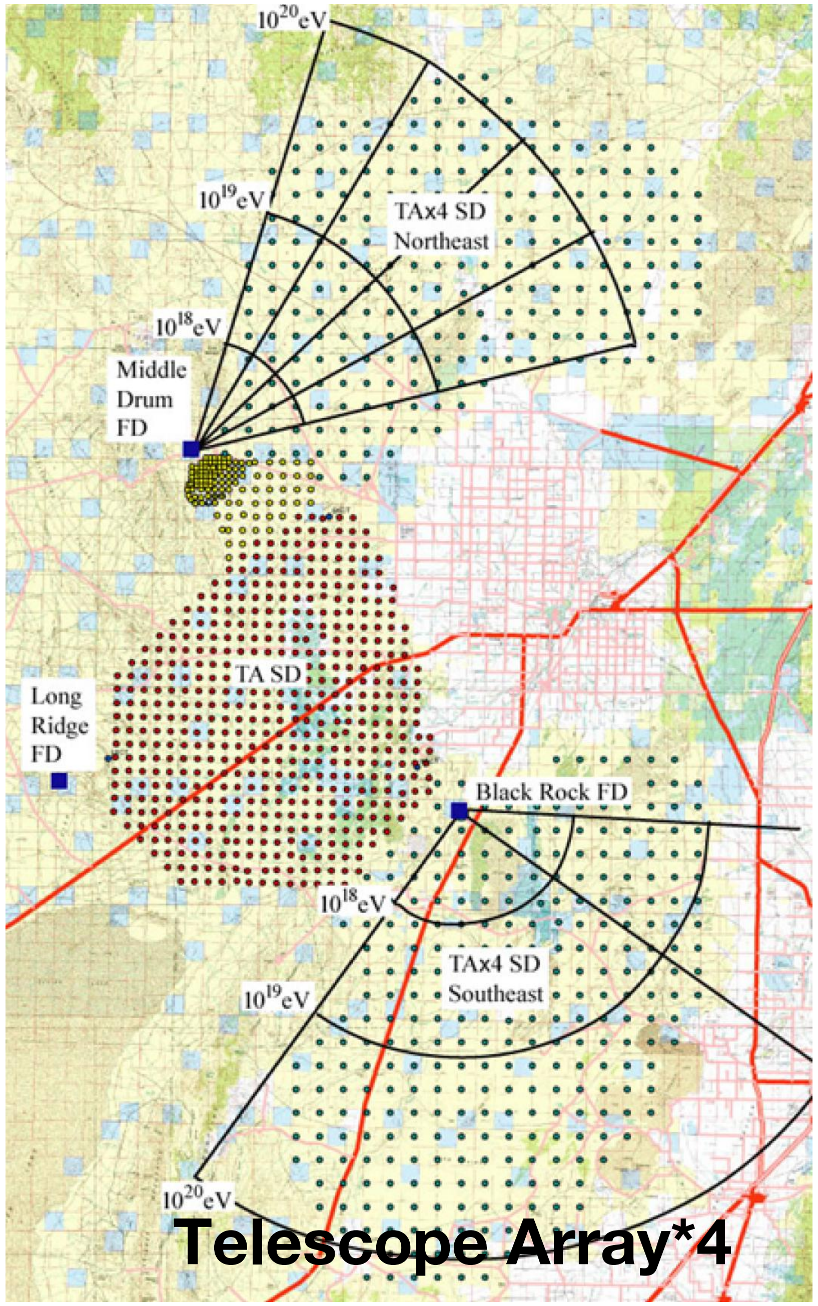


Calculated via CRpropa, adopting Jansson &Farrar (2012) GMF model

UHECR Observatories

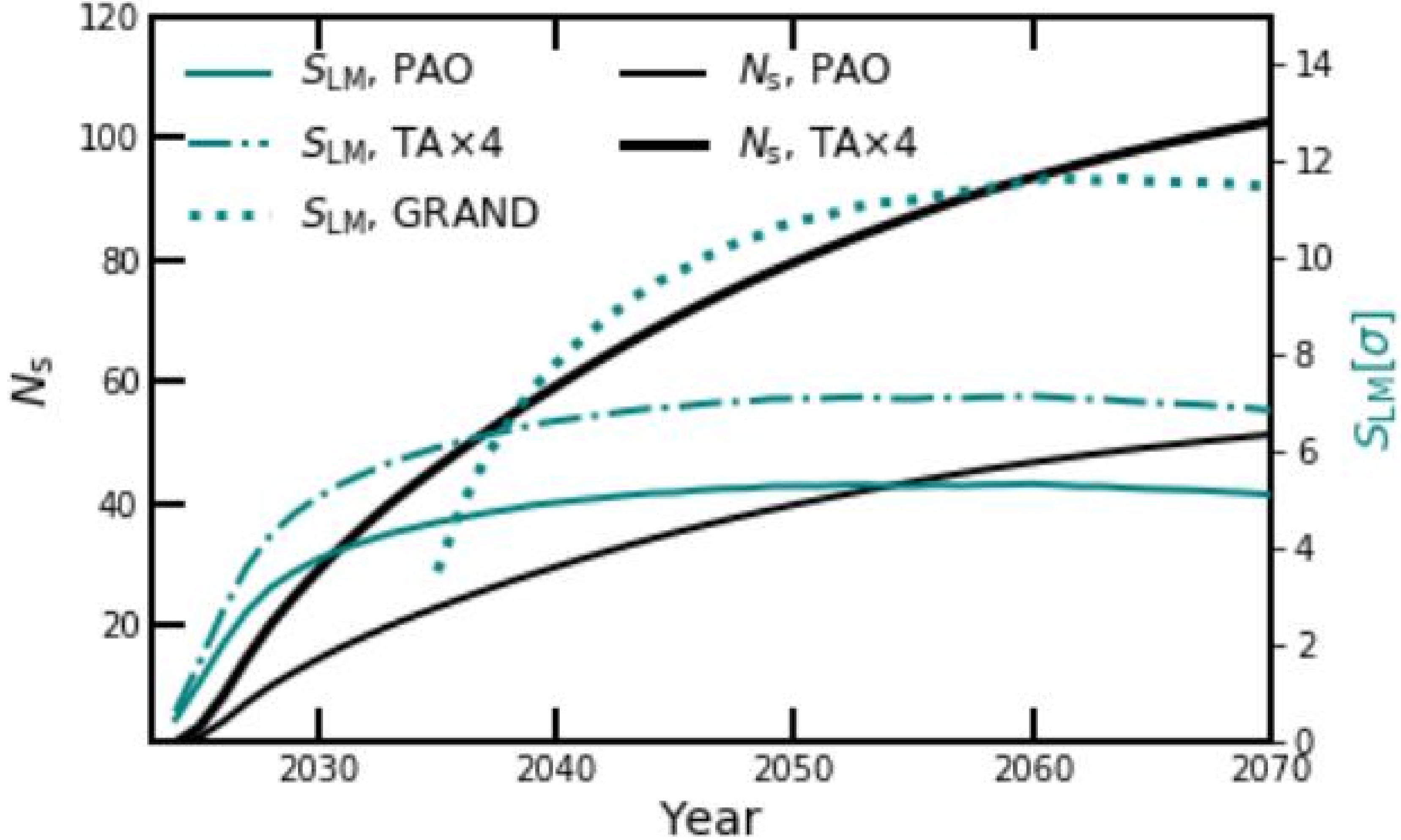






GRB221009A: RA = 288.3deg, Dec = 19.7deg
PAO: ~400km^2
TA*4: ~720km^2
GRAND: ~4000km^2

Expected Significance of the UHECR Burst



$$S_{\rm LM} = \sqrt{2}\left[N_{\rm on}\ln\left(\frac{2N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right) + N_{\rm off}\ln\left(\frac{2N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]^{1/2}$$

Uncertainties:
The magnetic deflection effect
The baryon loading factor: eta=1

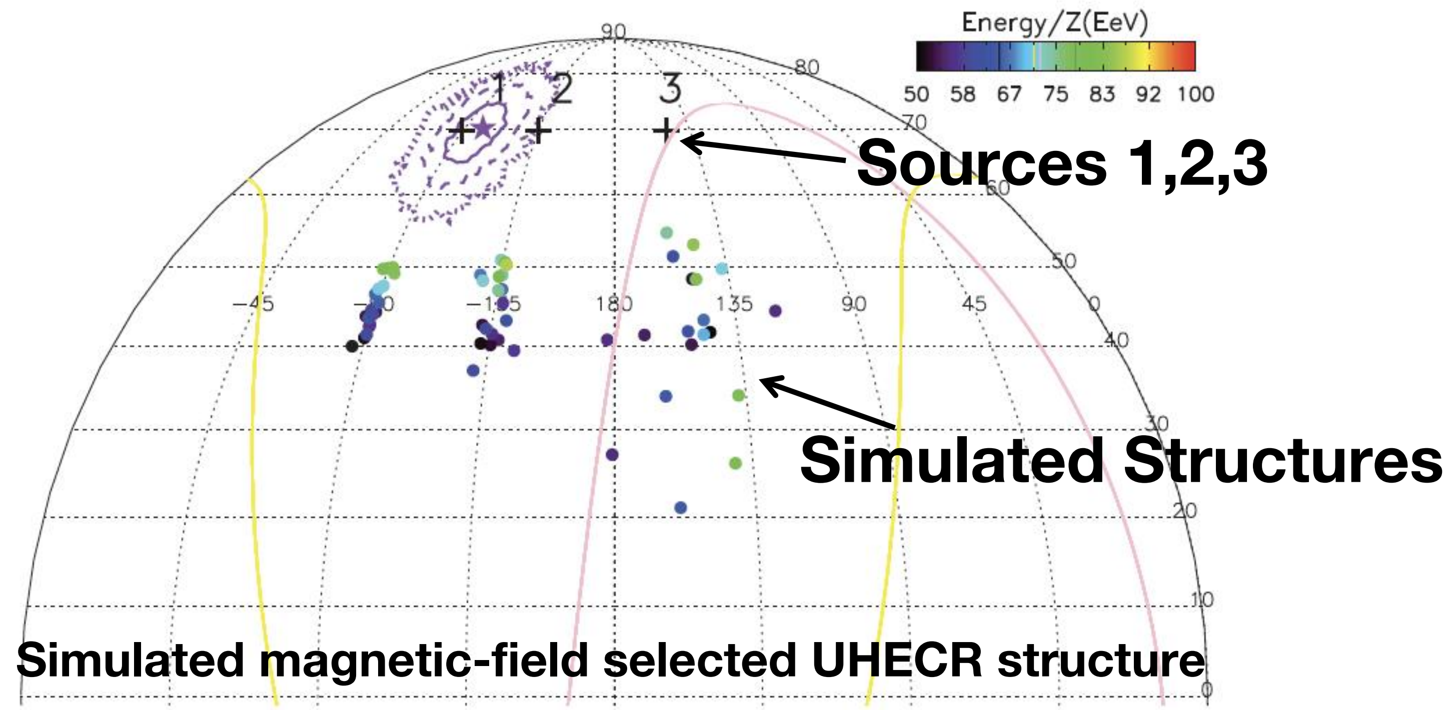
A New Method Searching for Magnetic-Field Selected UHECR Structure

Magnetic Field Model Independent
Assumptions: 1. Single source
2. Pure composition
3. Steady mangetic-field effect

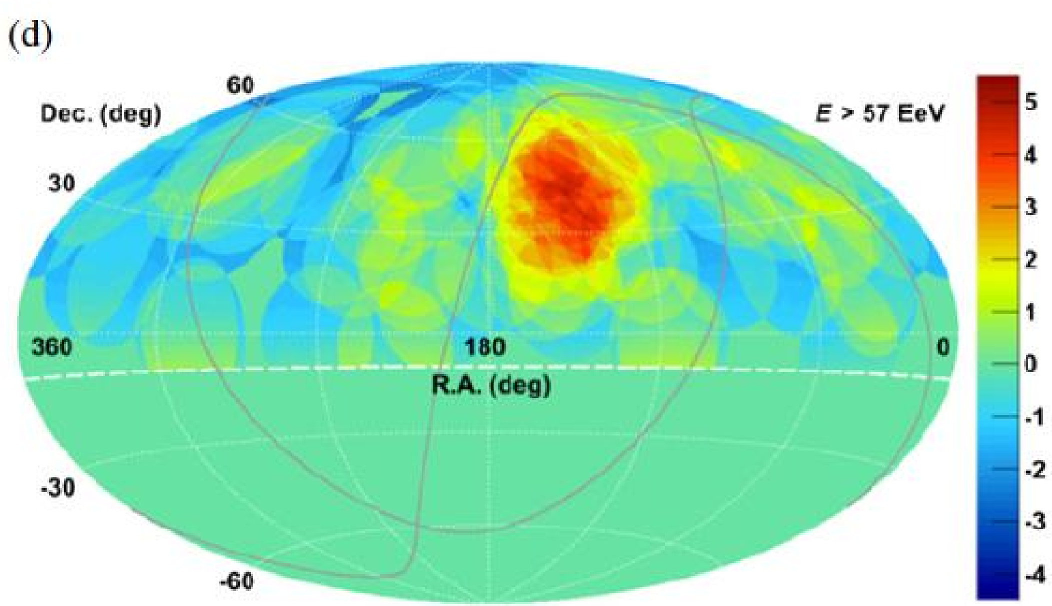
$$\delta_{\rm reg} \simeq 0.5°Z \frac{100\ {\rm EeV}}{E} \frac{D_{\rm reg}}{1\ {\rm Mpc}} \frac{B_{{\rm reg},\perp}}{1\ {\rm nG}} = A_1 \times \frac{100\ {\rm EeV}}{E}$$

$$\delta_{\rm rms} \simeq 0.36°Z \frac{100\ {\rm EeV}}{E} \left(\frac{D_{\rm dif}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{D_{\rm c}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}} \frac{B_{\rm rms}}{1\ {\rm nG}} = A_2 \times \frac{100\ {\rm EeV}}{E},$$

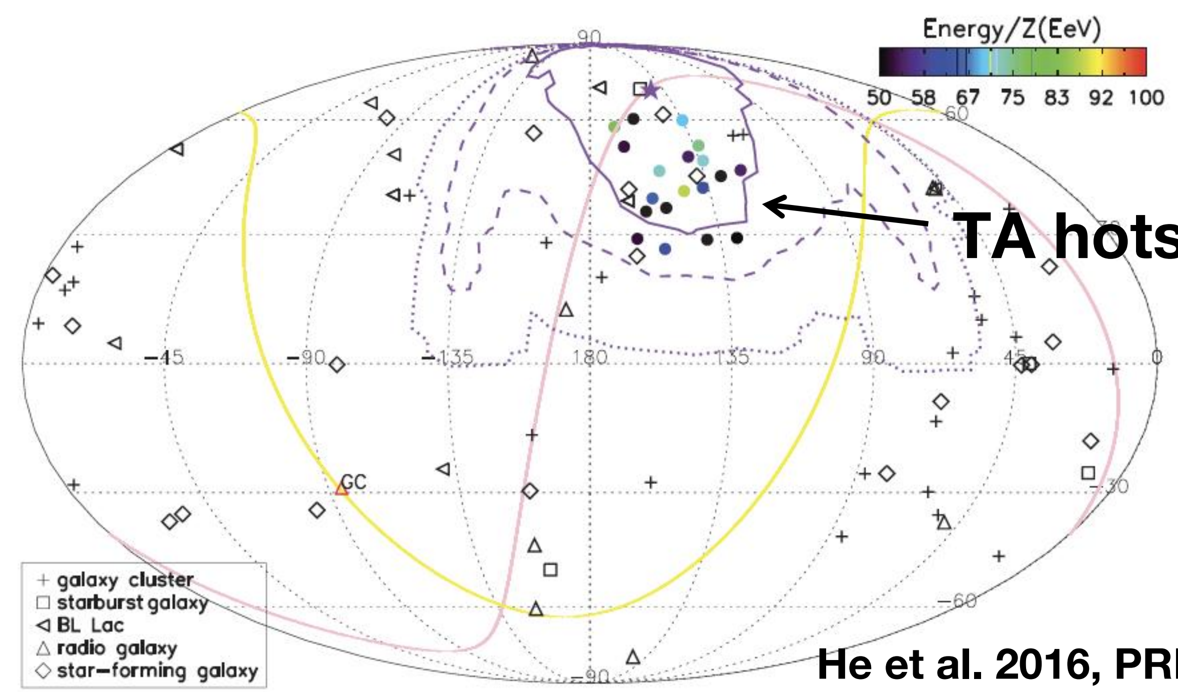
$$f(\delta_{\rm dif}, \delta_{\rm rms}) = \frac{1}{\delta_{\rm rms}\sqrt{2\pi}} \exp\left(-\frac{\delta_{\rm dif}^2}{2\delta_{\rm rms}^2}\right).$$



Simulated magnetic-field selected UHECR structure



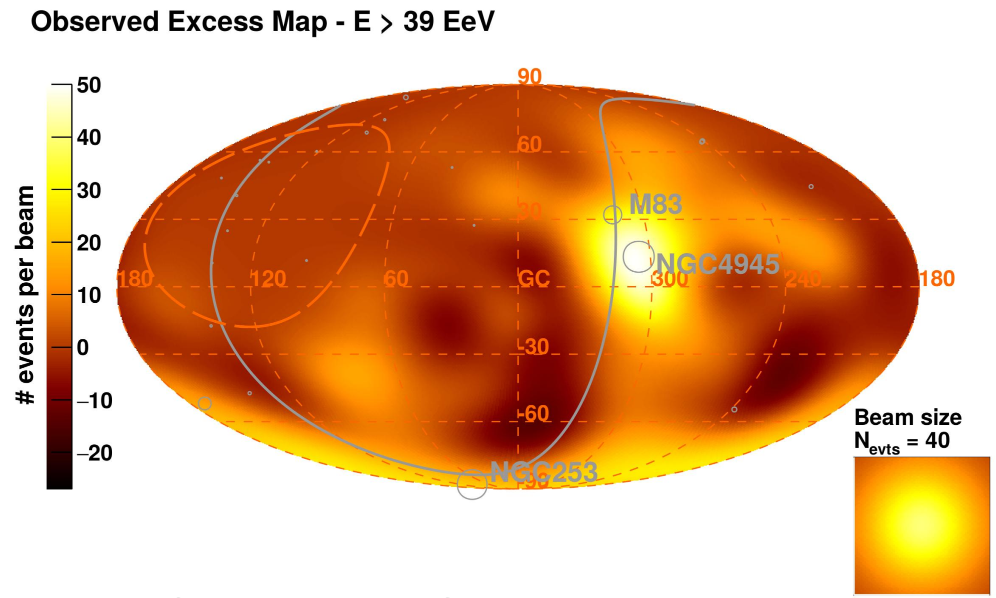
TA hotspot (TA collaboration, 2014)



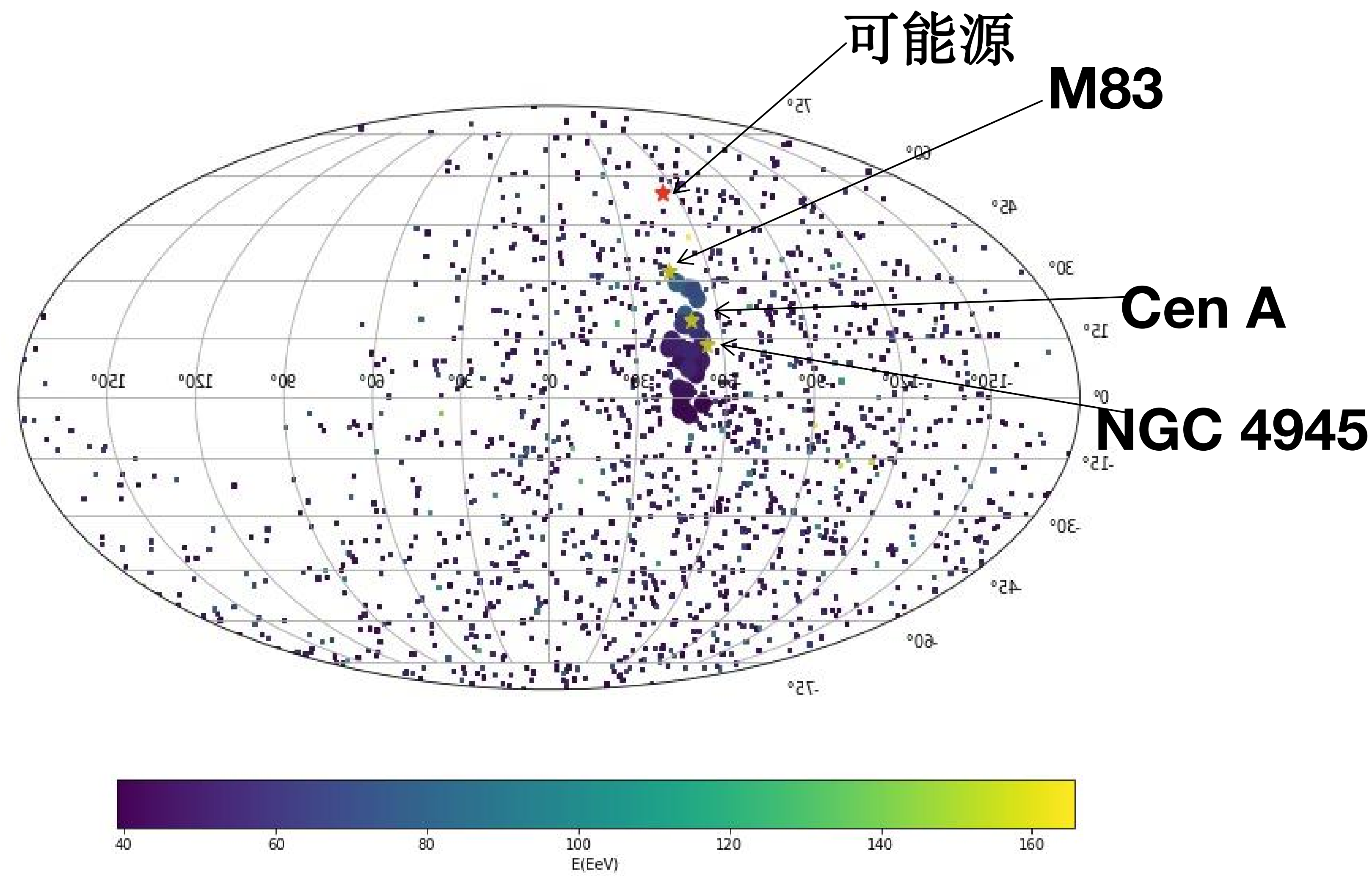
He et al. 2016, PRD 93, 043011

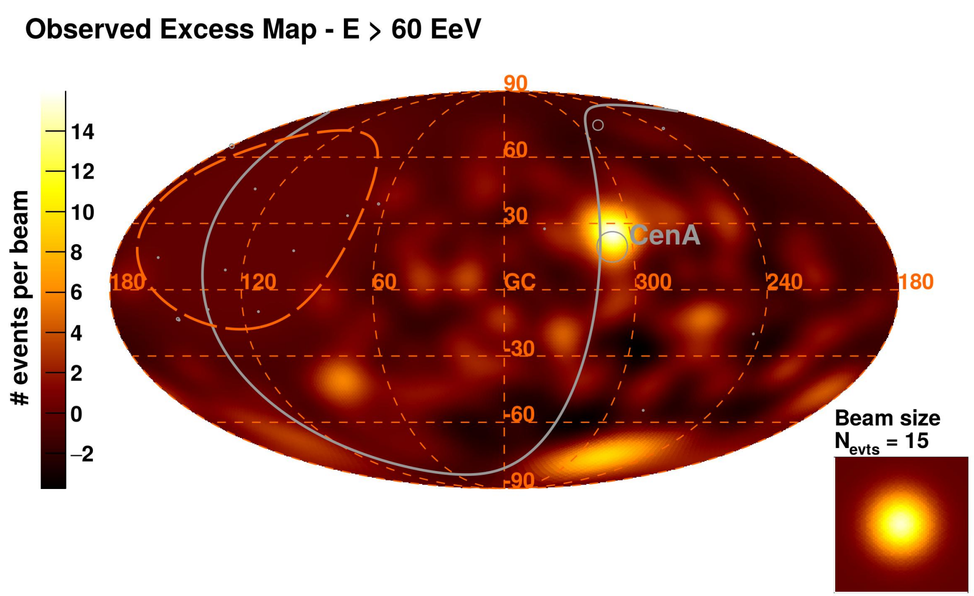
Application on TA hotspot

Magnetic-Field Selected UHECR Structures



Galactic Coordinate





PAO's Analysis
(PAO collaboration, 2020)

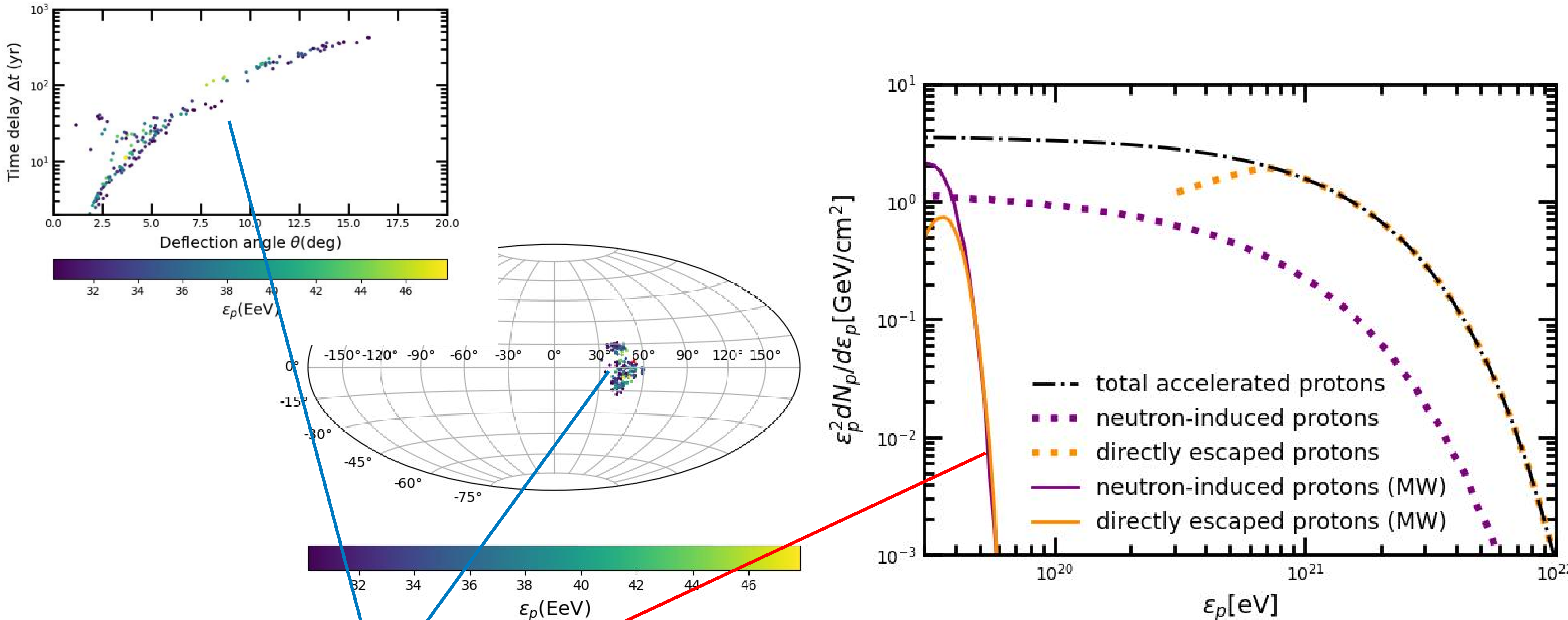
Our Analysis on PAO's 2635 UHECRs

$$S_i = \frac{1}{2\pi\delta^2_{\mathrm{rms}}(E_i)} exp\left(-\frac{\delta^2_{\mathrm{diff,i}}}{2\delta^2_{\mathrm{rms}}(E_i)}\right)\frac{\delta_{\mathrm{diff,i}}}{sin\delta_{\mathrm{diff,i}}}$$

$$B_i^{\mathrm{spatial}} = \frac{N_{\mathrm{obs}}(\beta_i)}{\sum_k N_{\mathrm{obs}}(\beta_k)\Delta\Omega}$$

$$L = \prod_{i=0}^{N_{\mathrm{tot}}}\left(\frac{n_s}{N_{\mathrm{tot}}}S_i + \frac{N_{\mathrm{tot}}-n_s}{N_{\mathrm{tot}}}B_i^{\mathrm{spatial}}\right)$$

Application on
UHECR Burst from GRB 221009A



$$L = \prod_{i=0}^{N_{\rm tot}} \left(\frac{n_s}{N_{\rm tot}} S_i(\Delta t) S_i^{\rm energy} + \frac{N_{\rm tot} - n_s}{N_{\rm tot}} B_i^{\rm spatial} B_i^{\rm energy} \right)$$

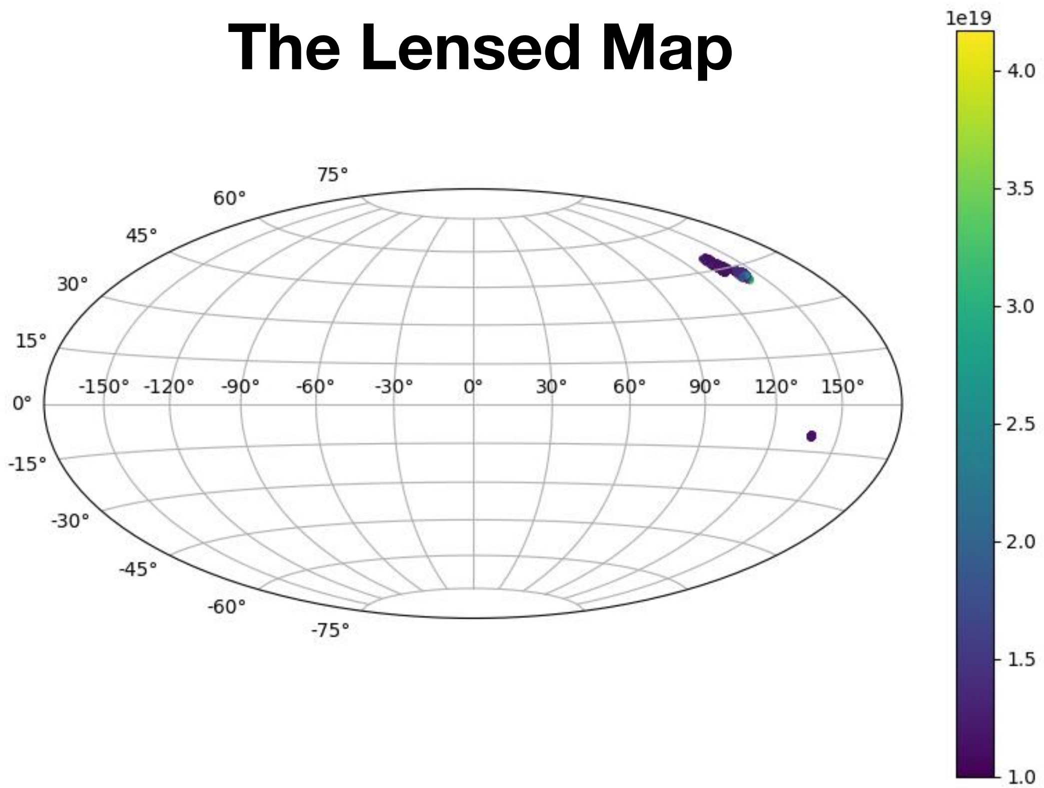
Via adopting the modified method on the UHECR burst from GRB 221009A in the future, adding the temporal information and spectral information, we expect to get higher significance than using Li&Ma method.

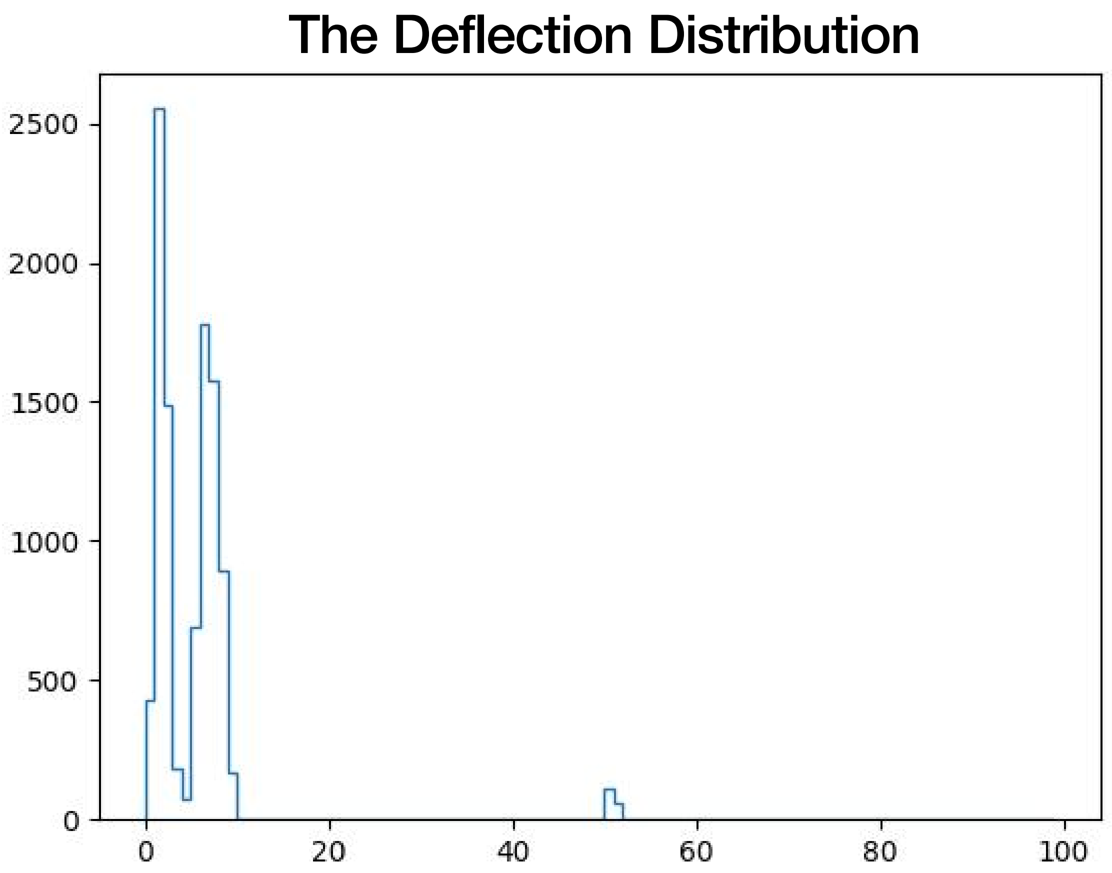
Conclusions & Discussions

- GRB UHECR burst are dominated by the neutron-induced protons.
- There are uncertainties on the magnetic field and the baryon loading factor.
- Auger and TAX4 can constrain the model soon in future few years.
- GRAND is a good detector for UHECR burst from GRB 221009A as long as the construction is completed in 2030s.
- Our method searching for magnetic-field selected UHECR structures can be modified and used to study the future observed UHECR burst, and finally check the correlation between UHECRs and the GRB.

Thank you!

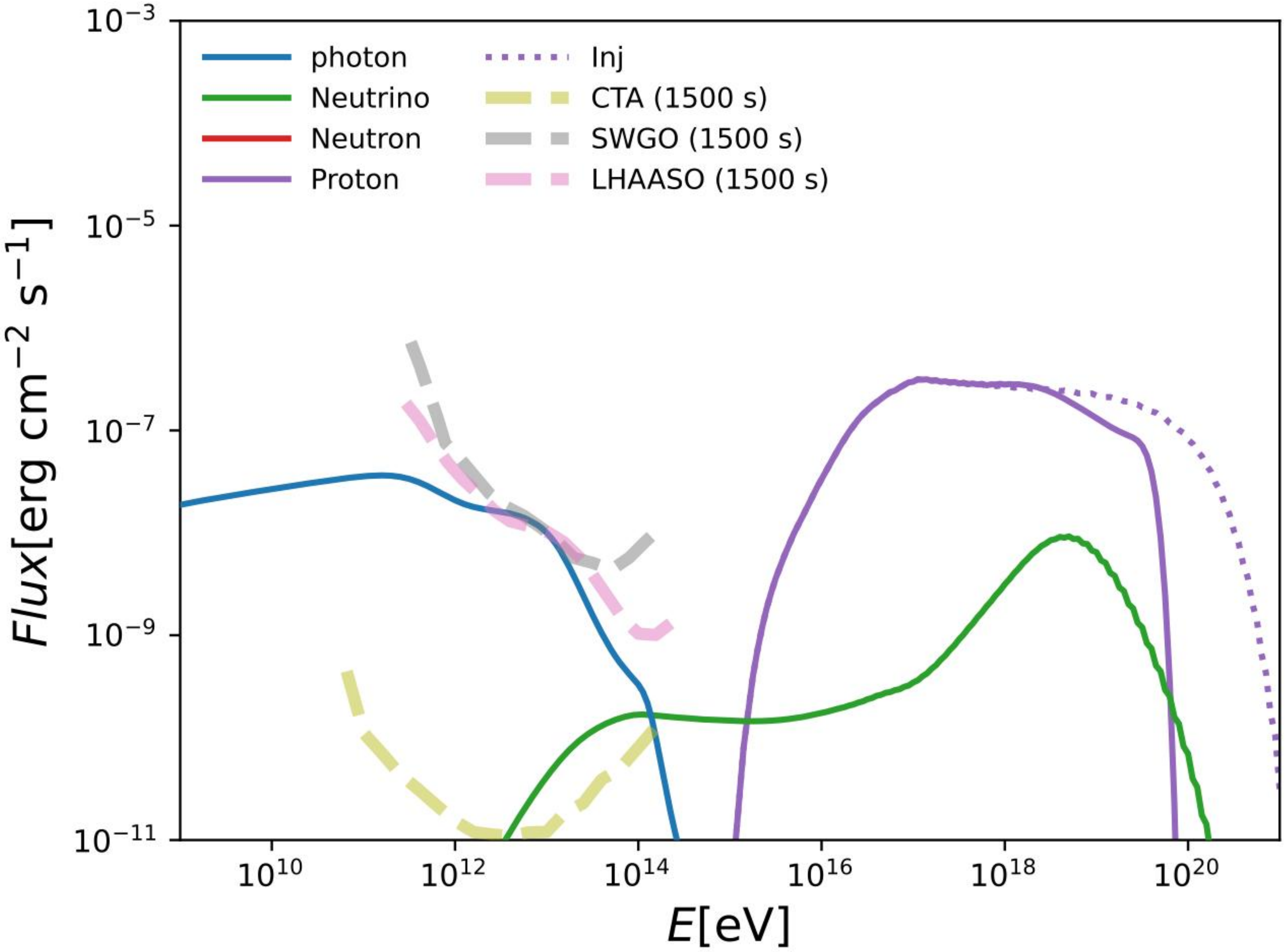
If we put the GRB in another direction





The UHECRs is less deflected and more protons arrive within 1 degree.
The Magnetic Selected Structure will help us to distinguish the UHECR multiplets.

Cosmogenic Photons



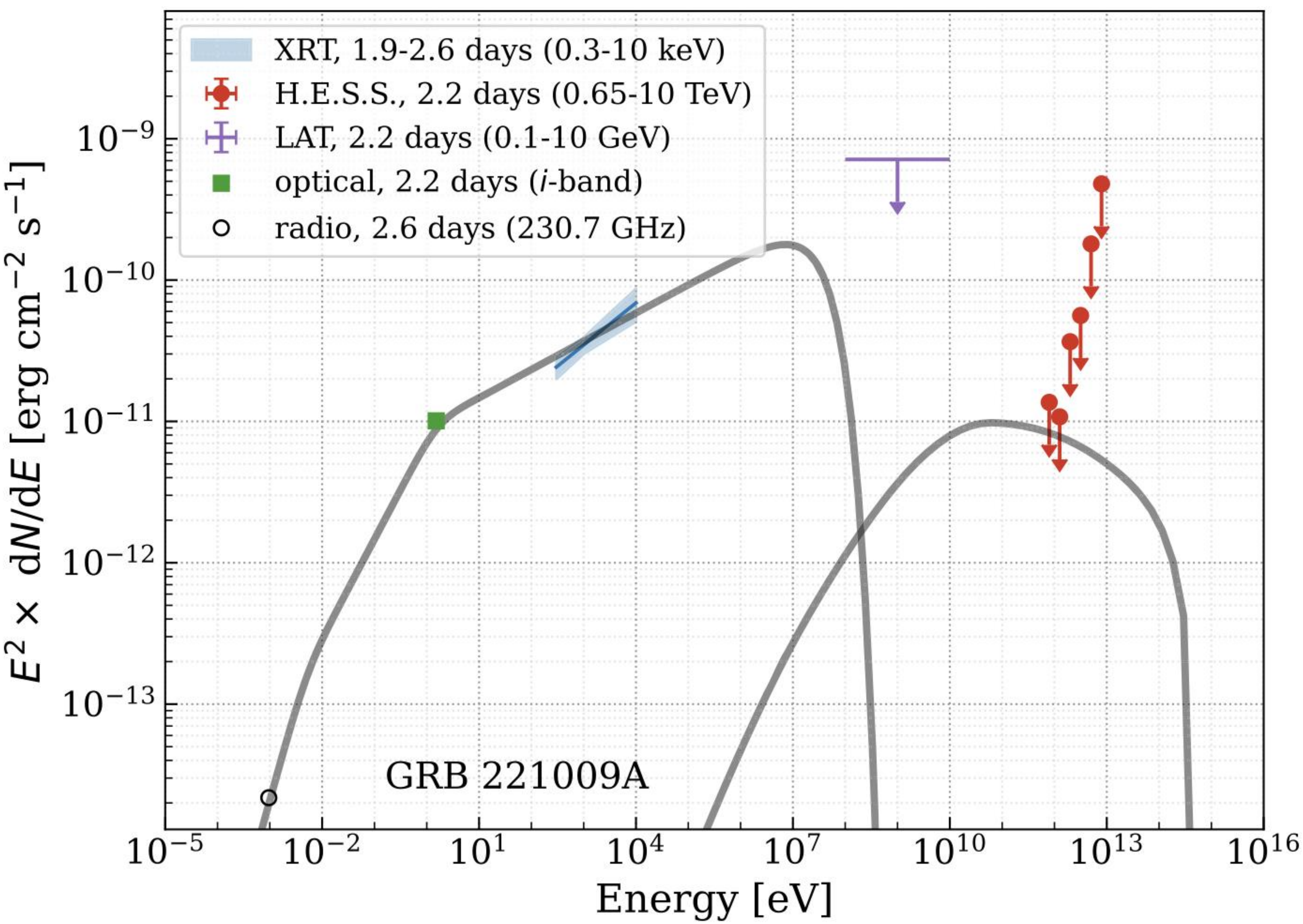
Baryon Loading factor=0.1

We simulate the propagation of protons and photons in the Inter-galactic field.

Here we ignored the effect of the IGMF.

More details need to be checked.

- Cosmogenic photons from such a bright GRB might be observed LHAASO, SWGO and CTA.



XRT, 1.9-2.6 days (0.3-10 keV)
H.E.S.S., 2.2 days (0.65-10 TeV)
LAT, 2.2 days (0.1-10 GeV)
optical, 2.2 days (i-band)
radio, 2.6 days (230.7 GHz)
GRB 221009A
$E^2 \times \mathrm{d}N/\mathrm{d}E$ [erg cm^{-2} s^{-1}]
Energy [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-5}
10^{-2}
10^{1}
10^{4}
10^{7}
10^{10}
10^{13}
10^{16}

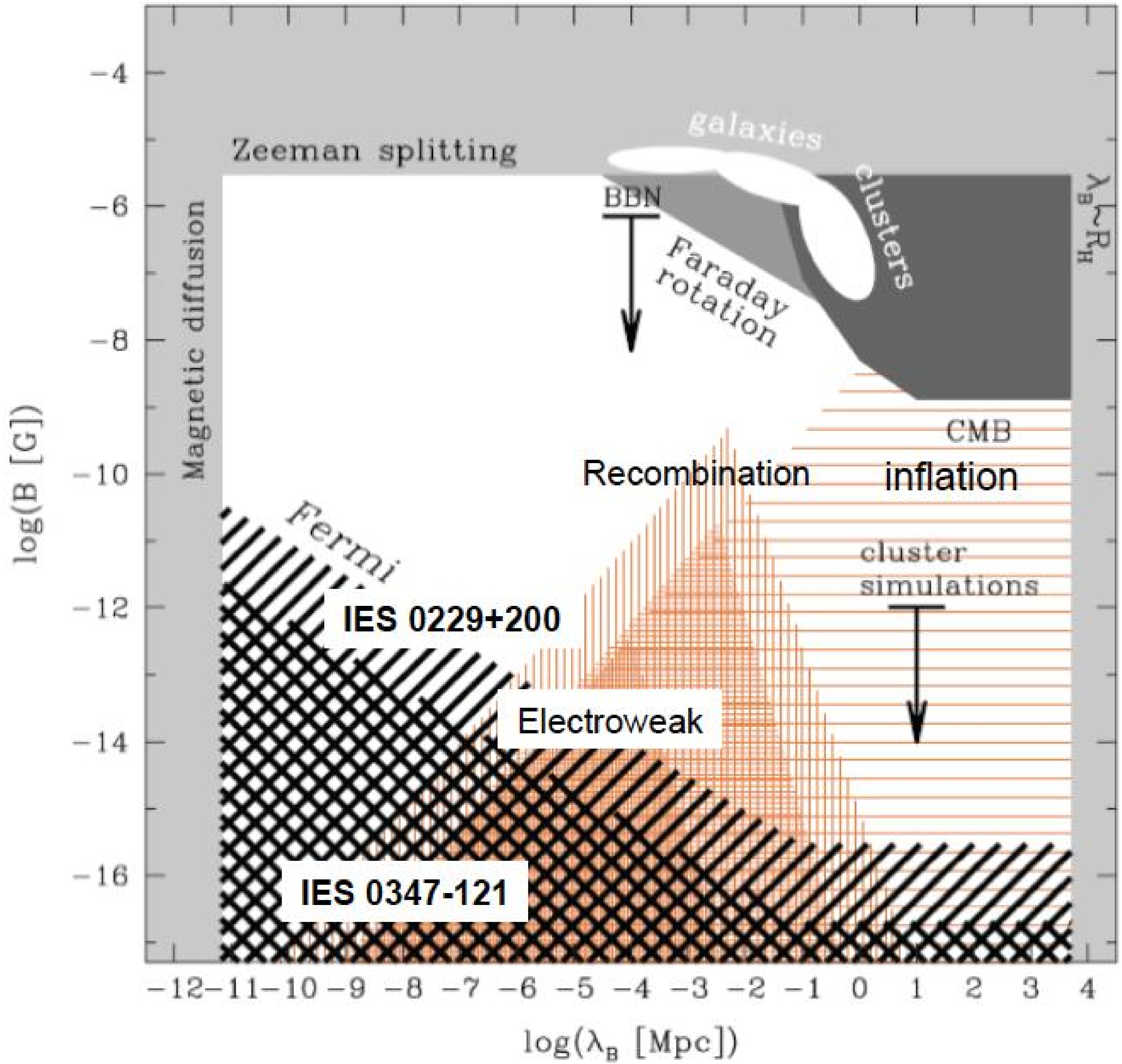
/**

@class PlanckJF12bField

@brief PlanckJF12bField: the JF12 galactic magnetic field model with corrections suggested by the Planck Collaboration

See: Planck Collaboration, "Planck intermediate results. XLII. Large-scale Galactic magnetic fields", A&A 596 (2016) A103; arXiv:1601.00546

Intergalactic Magnetic Field



Orange: Allowed by a variety of ways of generating the IGMF.

More interesting ways: phase transitions in the early universe, or inflationary magnetogenesis

Black/gray: ruled out.

Neronov & Vovk (2010, Science, 328, 73)

Neutrino production in GRBs

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} n + \pi^{+} \\ p + \pi^{0} \end{cases}$$

$$pp/pn \rightarrow \pi^{\pm}/K^{\pm}$$

Conditions:

1. protons acceleration

2. targets: photons or matter

$$\gamma + p \rightarrow n + \pi^{+} \; ; \quad \pi^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \overline{\nu}_{\mu}$$

Delta Resonance Approximation: $(\varepsilon_p / \Gamma)(\varepsilon_\gamma / \Gamma) \geq 0.3 \ \mathrm{GeV}^2$

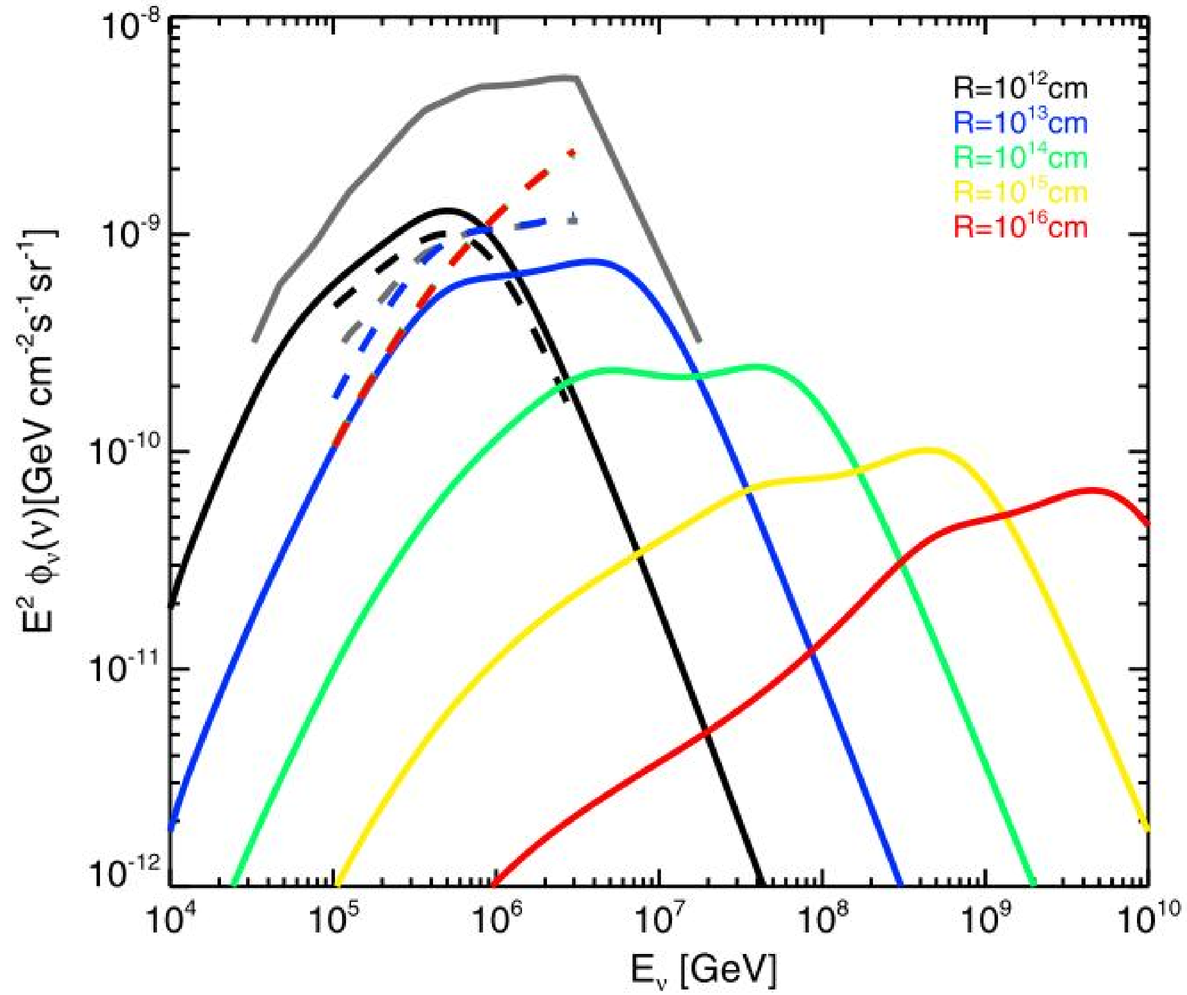
$$\varepsilon_\gamma = 1 \ \mathrm{MeV}, \Gamma = 10^{2.5} \Rightarrow \quad \varepsilon_p \geq 10^{16} \ \mathrm{eV}, \ \varepsilon_\nu \geq 10^{14.5} \ \mathrm{eV}$$

General dissipation scenario ——constrain the dissipation radius and the baryon loading factor

The fraction of proton energy converted into pions:

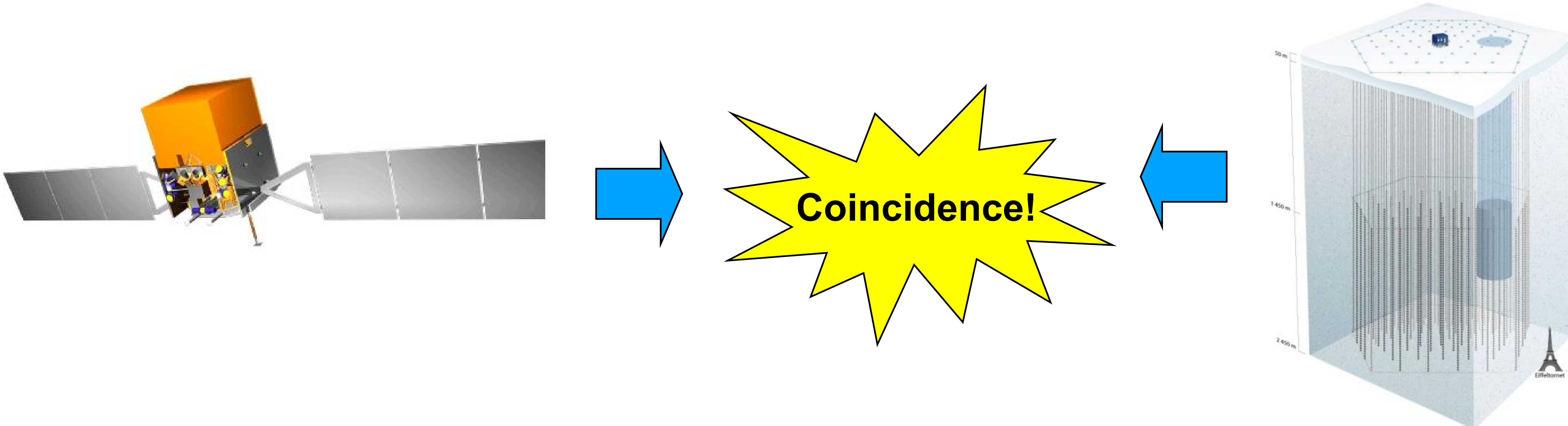
$$f_{p\gamma}(\epsilon_p^{\rm ob}) \simeq \frac{0.11}{y_1}\left(\frac{2}{\alpha+1}\right)\left(\frac{1}{1+z}\right)\frac{L_{\gamma 52}}{\epsilon_{\gamma b,{\rm MeV}}^{\rm ob}\Gamma_{2.5}^2 R_{14}} \times \begin{cases} k_1\left(\frac{\epsilon_p^{\rm ob}}{\epsilon_{p,b}^{\rm ob}}\right)^{\beta-1}, & \epsilon_p^{\rm ob} \leqslant \epsilon_{p,b}^{\rm ob} \\ \left(\frac{\epsilon_p^{\rm ob}}{\epsilon_{p,b}^{\rm ob}}\right)^{\alpha-1} + k_p, & \epsilon_p^{\rm ob} > \epsilon_{p,b}^{\rm ob}, \end{cases}$$

The baryon loading factor $E_p/E_\gamma = 10$



He H.N. et al. (2012) ApJ 752:29

Search for GRB neutrinos by IceCube



IceCube

Good information on timing and direction——> background reduction

No evidence of correlation between neutrino events and GRBs was found.

Prompt neutrino emission from GRBs is limited to <=1% of the observed diffuse neutrino flux.

The IceCube Collaboration (2022)

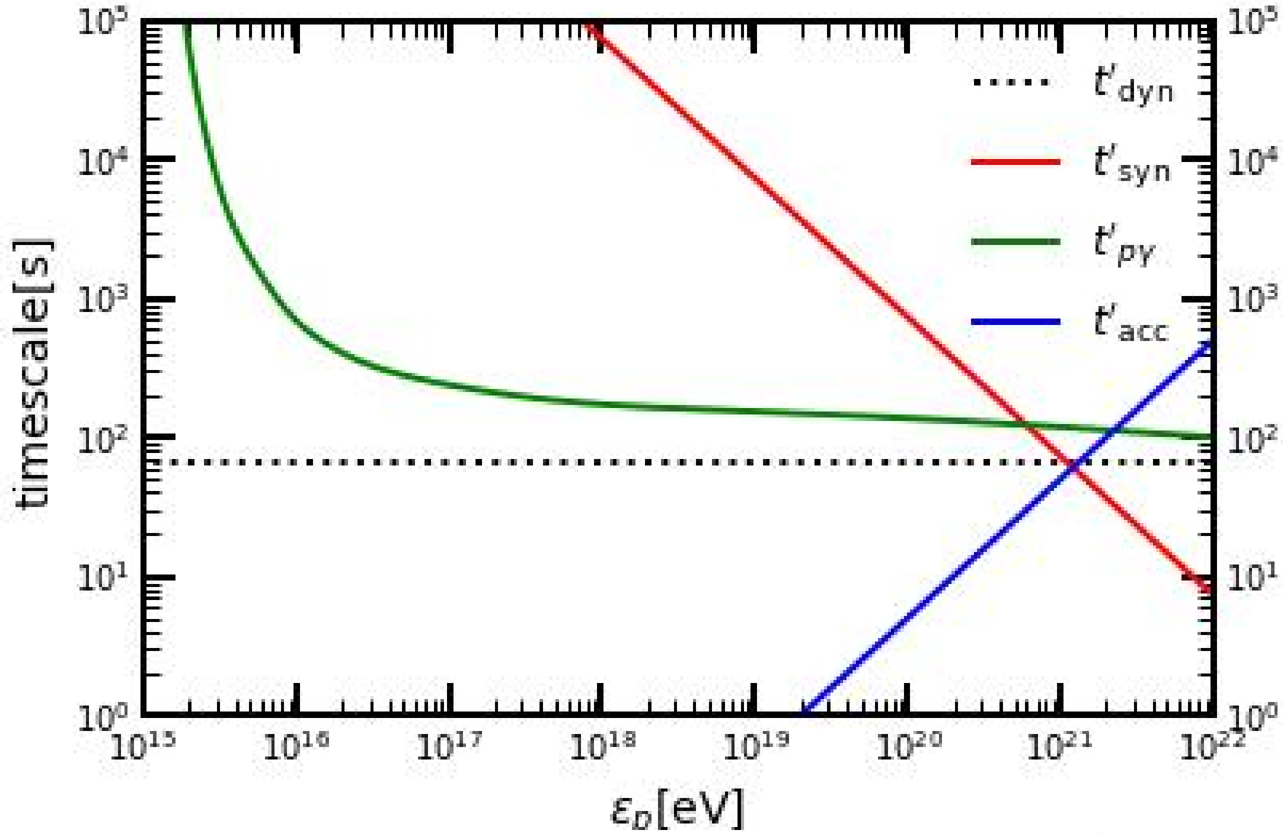
Possible Contributions from other GRB populations:

Untriggered GRBs (Liu & Wang 2013)

Low-luminosity GRBs (Murase & Nagataki 2006, Liu, Wang, Dai 2011)

Pop III GRBs (Gao & Meszaros 12)

Proton Acceleration and Energy Loss in the GRB



$$\min(t'_{\rm dyn}, t'_{\rm syn}(\varepsilon_{p,\rm max}), t'_{p\gamma}(\varepsilon_{p,\rm max})) = t'_{\rm acc}(\varepsilon_{p,\rm max})$$

$$\varepsilon_{p,\rm max} = 1.2 \times 10^{21}\,\mathrm{eV} \times (1+z)^{-1}\Gamma_{2.7}^{3/2}\eta_0^{1/2}\epsilon_{e,-1}^{1/4}\epsilon_{B,-2}^{-1/4}R_{15}^{1/2}L_{\gamma,54}^{-1/4},$$

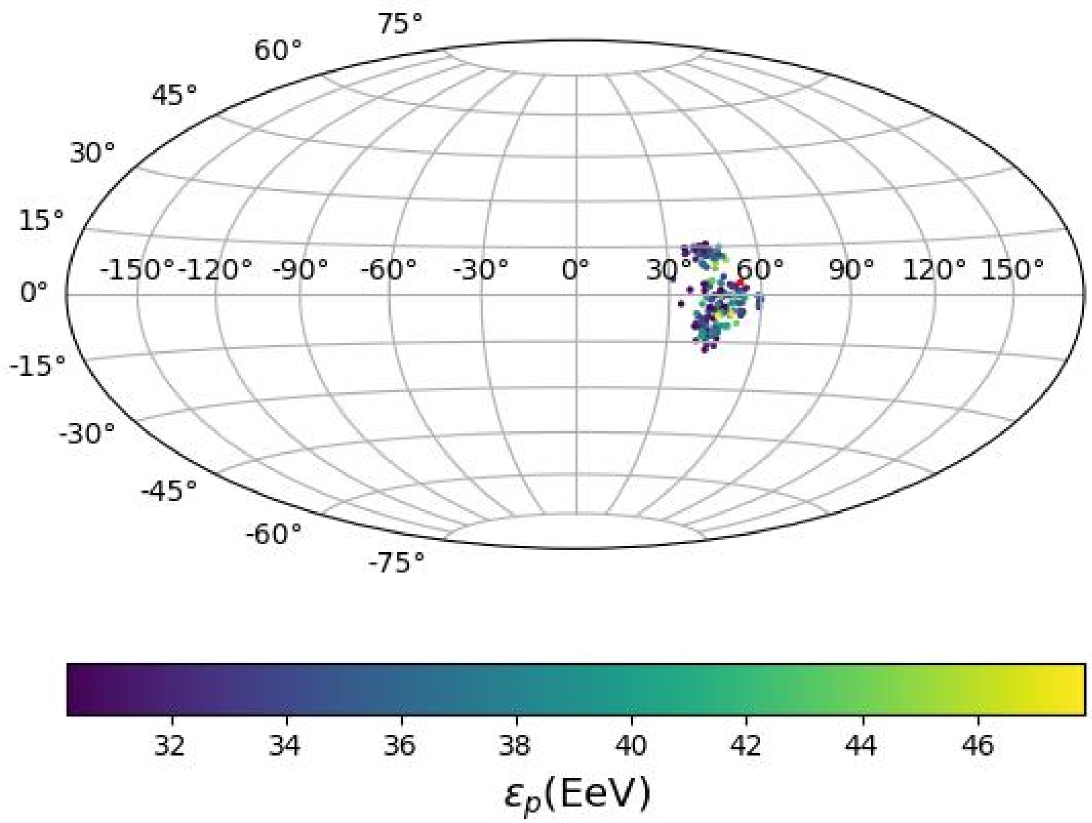
Table 1. The Adopted Parameters.

Descriptions	Symbols	Values
Redshift	z	0.151
Dissipation radius	R	10^{15}cm
Low energy photon index	α	0.76
High-energy photon index	β	2.13
Minimum energy of photon spectrum	$\varepsilon_{\gamma,\rm min}$	20 keV
Maximum energy of photon spectrum	$\varepsilon_{\gamma,\rm max}$	10 MeV
Peak energy of photon spectrum	$\varepsilon_{\gamma,\rm b}$	3 MeV
Proton index	p	2
Calibration luminosity	L_γ [a]	1×10^{54} erg s^{-1}
Bulk Lorentz factor	Γ	500
Baryonic loading factor	ξ_p	1
Fraction of magnetic field energy	ϵ_B	0.01
Fraction of electron energy	ϵ_e	0.1
Total radiation energy	$E_{\gamma,\rm iso}$	10^{54} erg

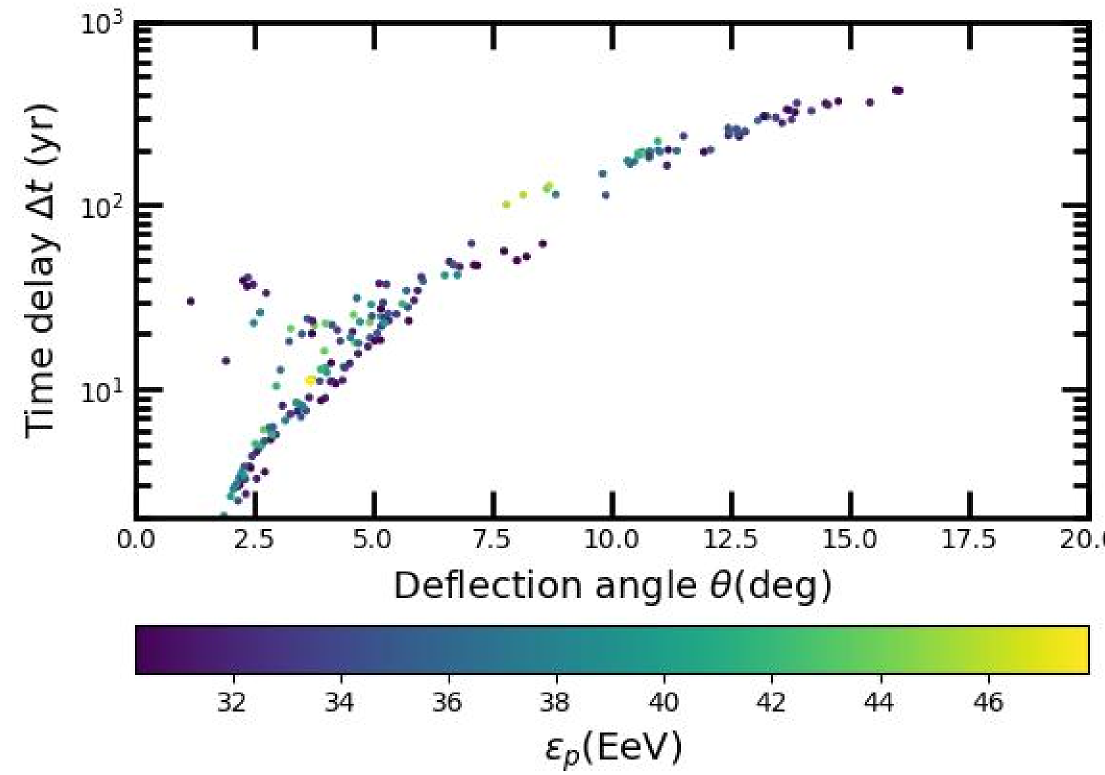
[a] The luminosity at 20 keV–10 MeV.

UHECRs Propagation in the Milky Way

The Lensed Map



Time delay and Deflection Angle



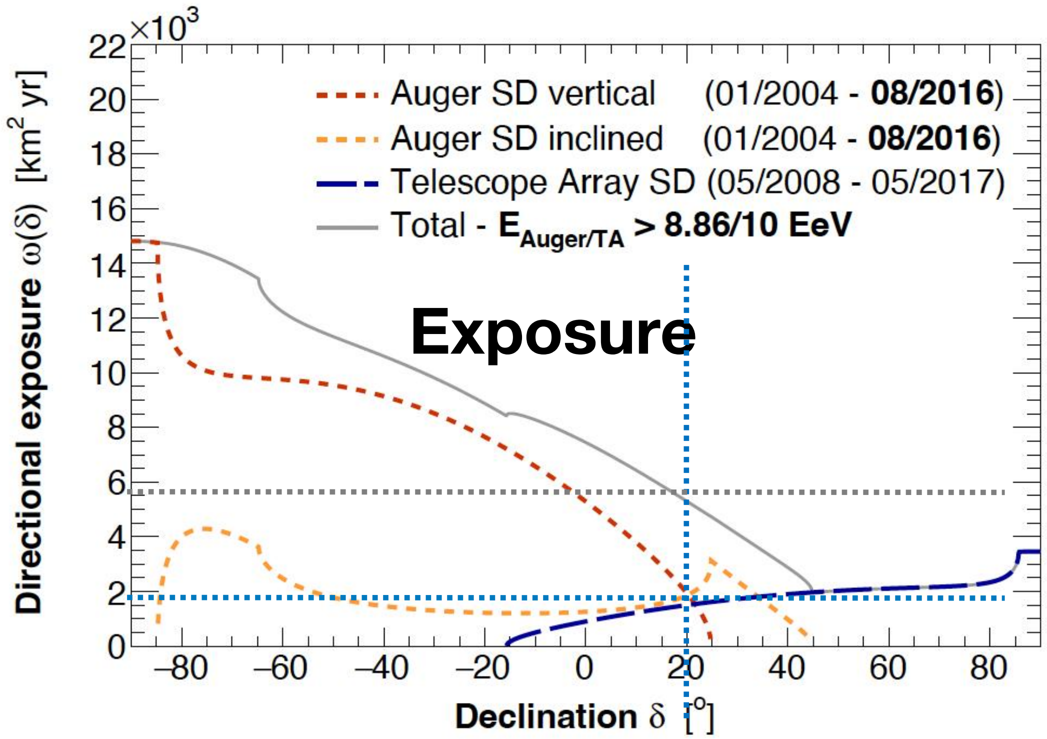
Calculated via CRpropa, Jansson &Farrar (2012) GMF model

$$\Delta t_{\rm reg,MW} \simeq \frac{L_{\rm reg,MW}\theta^2_{\rm reg,MW}}{6c} = 0.8{\rm yr}\frac{L_{\rm reg,MW}}{5\,{\rm kpc}}\left(\frac{\theta_{\rm reg,MW}}{1^\circ}\right)^2$$

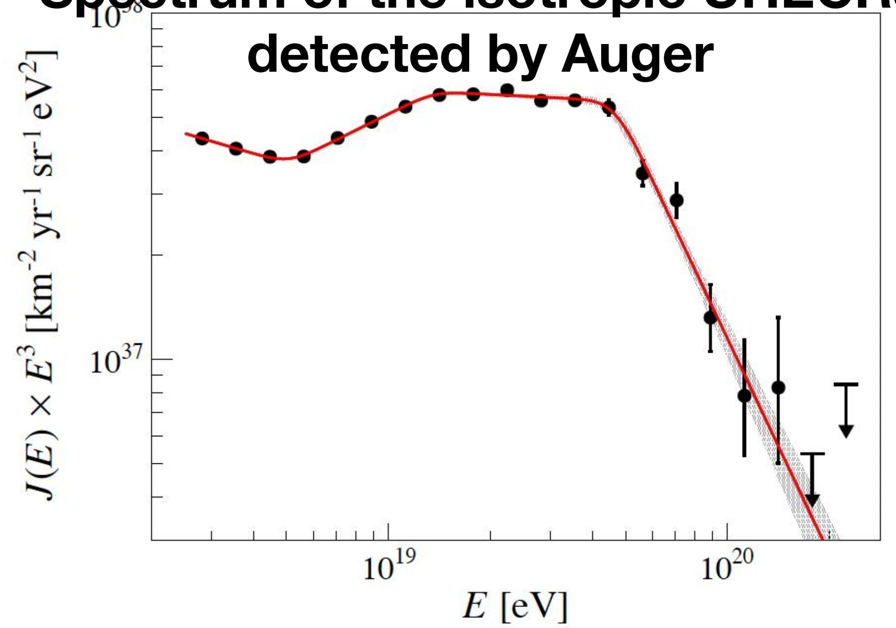
$$\Delta t_{\rm rms,MW} \simeq 6.3\,{\rm yr}\,\varepsilon^{-2}_{p,19.5}\frac{\lambda_{\rm MW}}{50\,{\rm pc}}\left(\frac{L_{\rm tur,MW}}{10kpc}\right)^2\left(\frac{B_{\rm rms,MW}}{5\mu{\rm G}}\right)^2$$

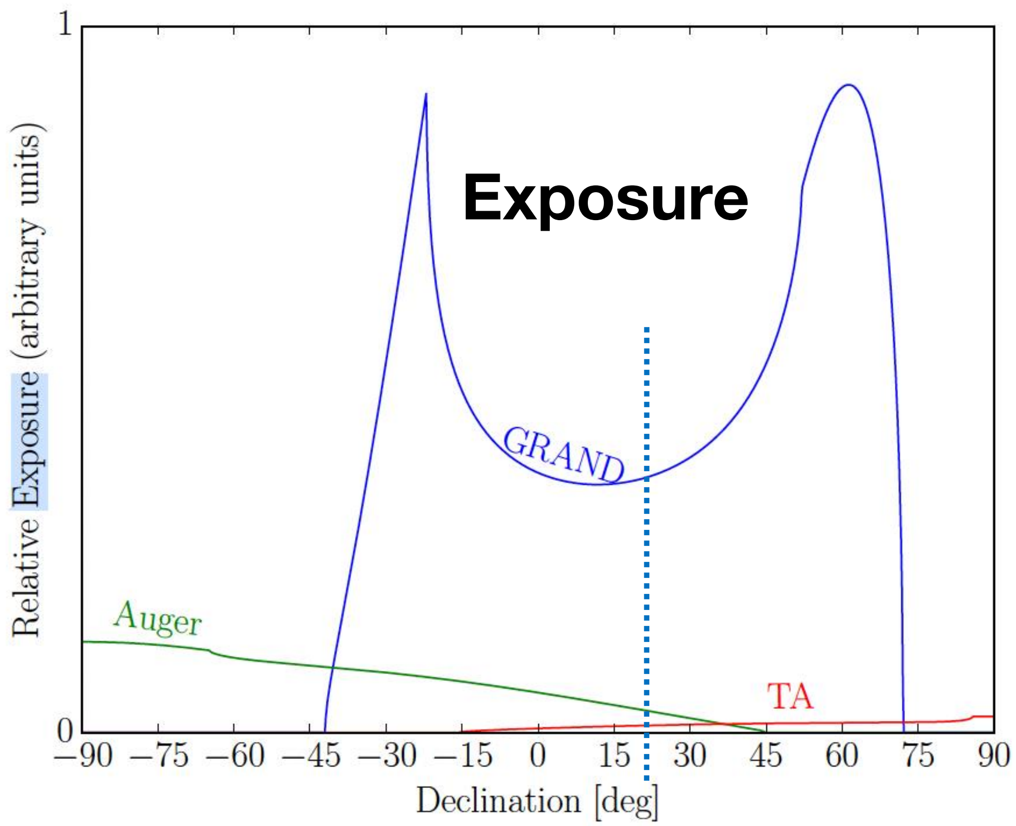
Expected UHECRs from GRB 221009A

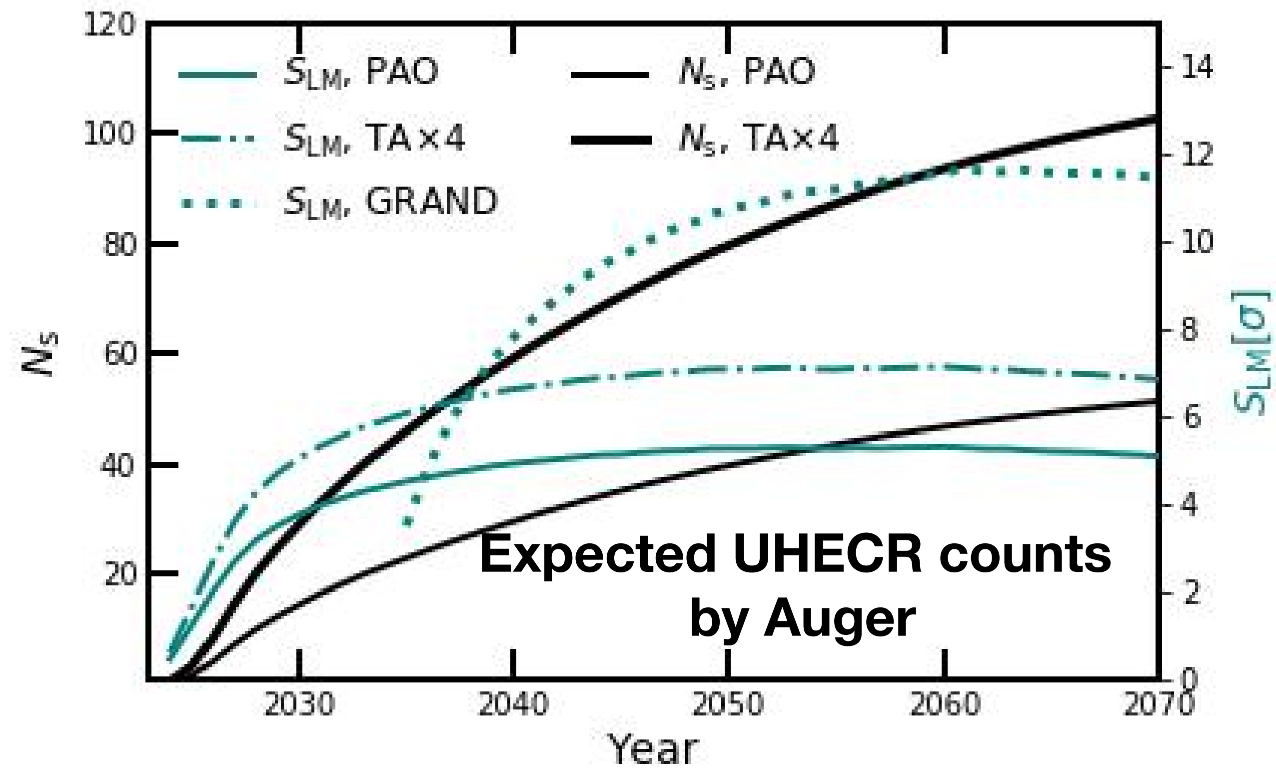
(RA = 288.3deg, Dec = 19.7deg)



Spectrum of the isotropic UHECRs detected by Auger







The signal to background ratio peaks around 2028.

A Rough Estimation on the Detection Rate of UHECRs

	Annual Exposure (km^2)	N_total (30-50EeV, theta<4.8deg) by 2028	N_b (30-50EeV, theta<4.8deg) by 2028	Significance (sigma)
TAX4	720	29	2.5	5.0
Auger	400	16	1.4	3.8
	Annual Exposure (km^2)	N_total (30-50EeV, theta<5.8deg) by 2036	N_b (30-50EeV, theta<5.8deg) by 2036	Significance (sigma)
GRAND	4000	34	5.2	3.5

Uncertainties:

The magnetic deflection effect

The baryon loading factor: eta=1

Consistent with the Galactic Magnetic Field