INVESTIGATION OF MULTI-MESSENGER PROPERTIES OF FR-0 RADIO GALAXY EMITTED ULTRA-HIGH ENERGY COSMIC RAYS

JON PAUL LUNDQUIST

UNIVERSITY OF NOVA GORICA

JLUNDQUIST@UNG.SI

University of Nova Gorica

www.ung.si/en/research/cac/

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Jon Paul Lundquist[1],Lukas Merten[2], Serguei Vorobiov[1], Margot Boughelilba[2], Anita Reimer[2], Paolo Da Vela[2], Fabrizio Tavecchio[3], Giacomo Bonnoli [4], Chiara Righi[3]

[1]Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia
[2]Institute for Astro and Particle Physics, University of Innsbruck, Innsbruck, Austria
[3]Astronomical Observatory of Brera, Milano, Italy
[4]Instituto de Astrofísica de Andalucía (CSIC), Granada, Spain

University of Nova Gorica

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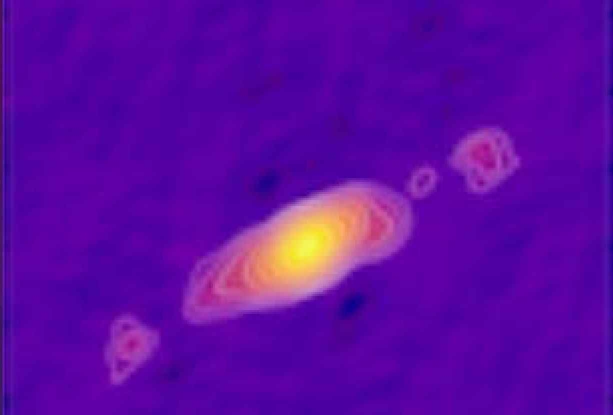
INTRODUCTION

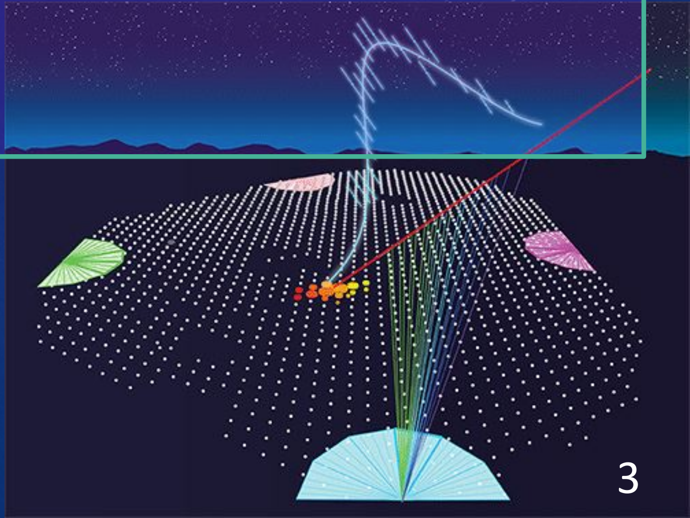


Cheng et al. 2021. MNRAS

- Low luminosity Fanaroff-Riley (FR0) radio galaxies [1] are potentially significant UHECR sources capable of acceleration to the highest energies [2]. High local density (~5 × FR1s) allows for emission of a large UHECR energy density fraction.

[Reimer, et al, TAUP2023]

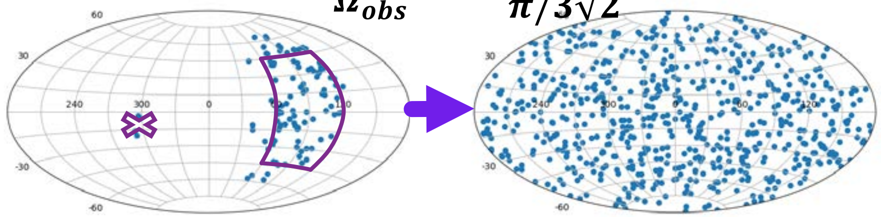
- FR0 simulations include an approximately isotropic distribution and various intergalactic magnetic fields (including random and structured fields).
- To determine FR0 UHECR emission composition and energy spectrum, simulations from CRPropa3 are fit to Pierre Auger Observatory data.
- Cosmogenic photon and neutrino fluxes are also predicted.



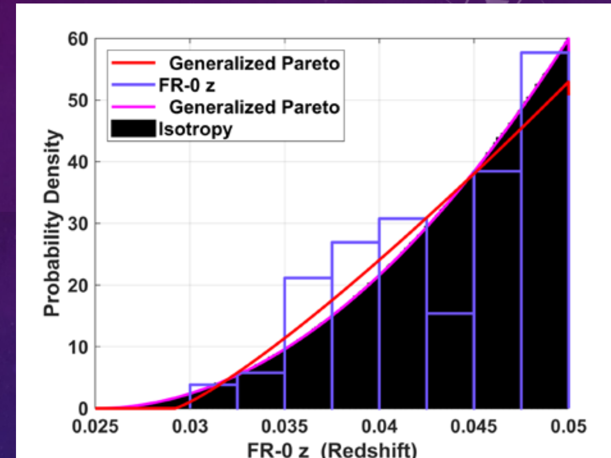
[1] Baldi, R. D. et al., FR0CAT: a FIRST catalog of FR 0 radio galaxies, A&A 609 (2018) A1.
[2] Merten, L. et al., Scrutinizing FR 0 radio galaxies as ultra-high-energy cosmic ray source candidates, Astropart. Phys. 128 (2021) 102564.

ISOTROPIC FR-0 SIMULATION

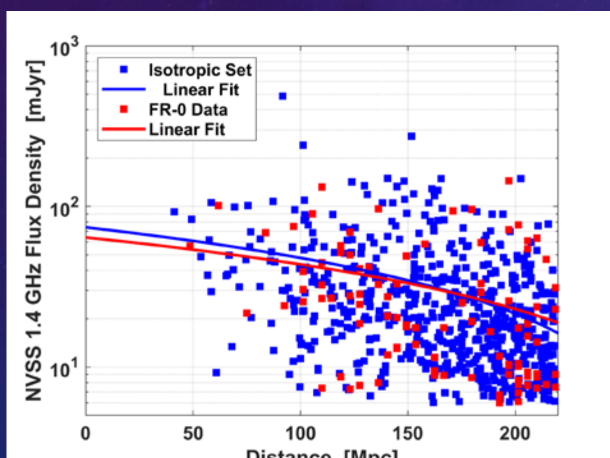
$$N_{iso} = N_{obs}\frac{\Omega_{iso}}{\Omega_{obs}} = 74\frac{4\pi}{\pi/3\sqrt{2}} \approx 628$$



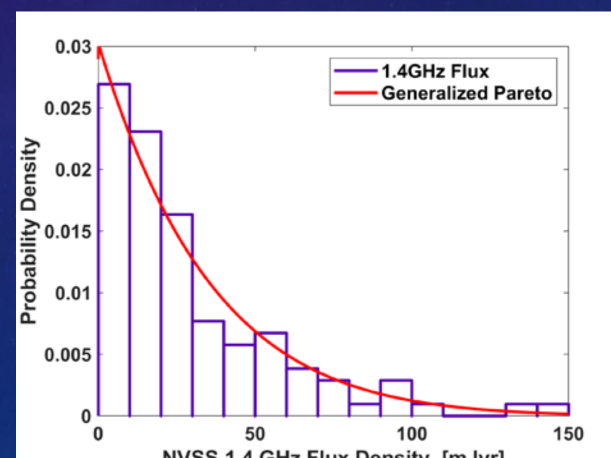
Isotropic FR-0 radio galaxy density estimated from well-sampled FR0CAT[1] catalog section.



Simulated FR-0 redshift distribution from Pareto fit to catalog data[1]. Isotropy probability of ~16%.



$z \leq 0.05$



Local source evolution modeled by preserving correlation between radio output and redshift distance (Kendall's correlation coeff.: -0.28, p-Value: 4.6e-5)[1].

FR-0 UHECR flux proportional to radio output. Generated by Pareto fit to NVSS data[1].

INTERGALACTIC PROPAGATION

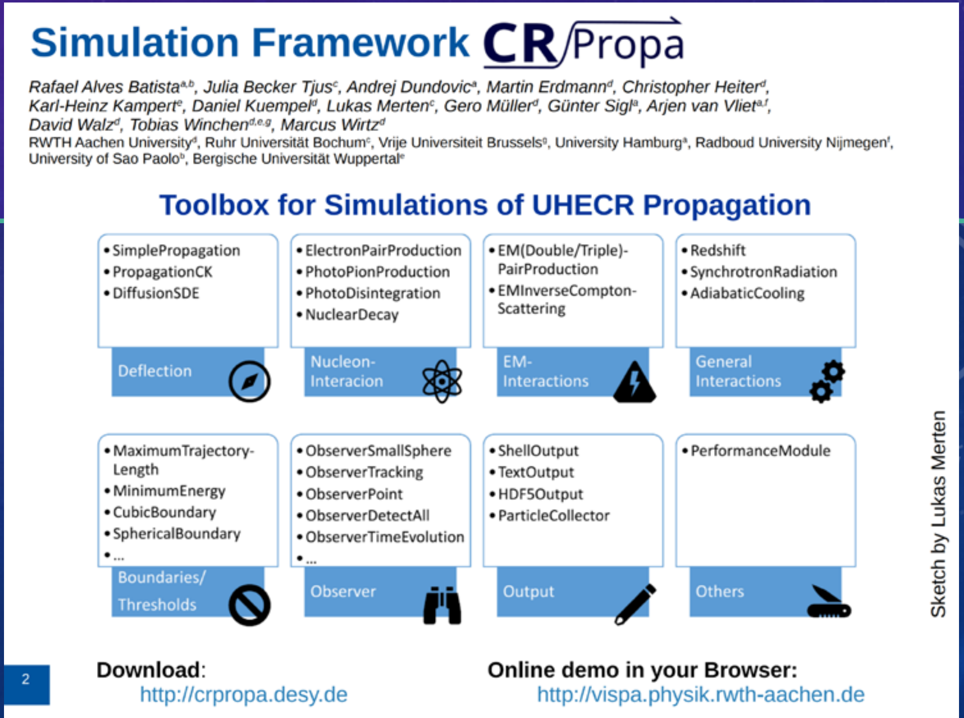
CRPropa 3 used to simulate propagation of five nucleon (proton, helium, nitrogen, silicon, and iron) UHECR primaries through the intergalactic medium.

Interactions with the CMB, IRB, and URB include:

- **Photo-pion production (GZK effect).**
- **Pair-production (including double and triple).**
- **Inverse Compton scattering.**

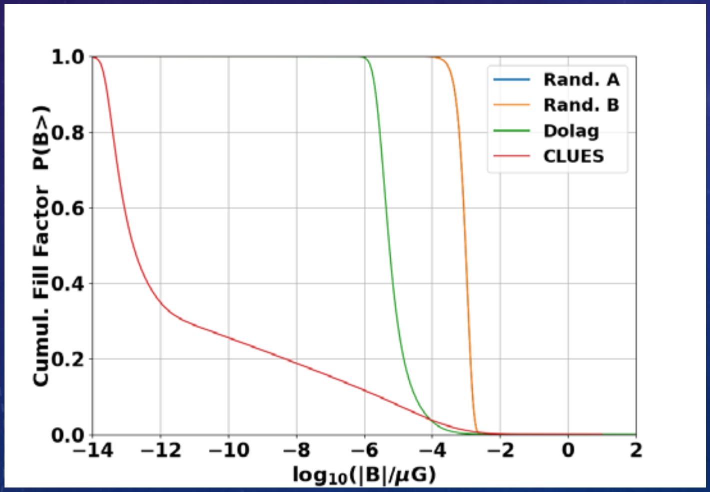
General interactions include:

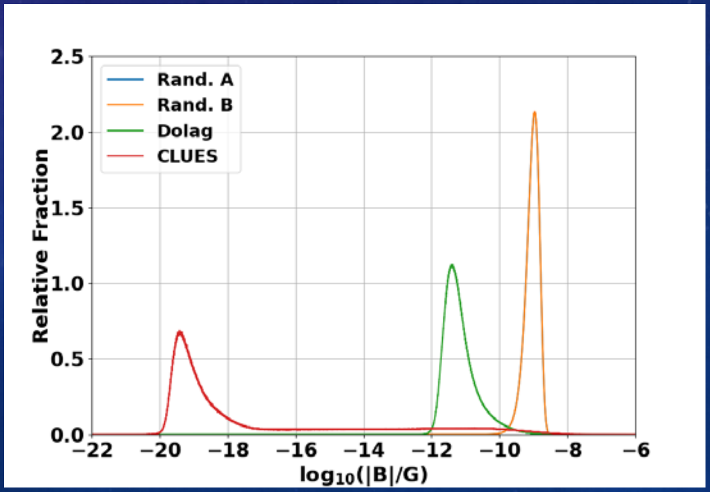
- **Redshift adiabatic cooling.**
- **Nuclear decay.**



MAGNETIC FIELD AND COMPOSITION MODELS

- **Two Extensive Air-Shower Composition Models: EPOS-LHC and QGSJETII-04**
- **Four Magnetic Fields:**
  - **Structured Fields:**
    - **Dolag et al.** arXiv:astro-ph/0410419v2
    - **Hackenstein et al. (CLUES) Astro_1B:** arXiv:1710.01353v2
  - **1 nG Random Fields (-11/3 Kolmogorov spectrum):**
    - **(A)** $\langle l_{\mathrm{corr}} \rangle = 234$ kpc **(60 kpc to 1 Mpc)**
    - **(B)** $\langle l_{\mathrm{corr}} \rangle = 647$ kpc **(60 kpc to 3 Mpc)**
- **And no magnetic Field**
- **10 models total.**





AUGER FIT MODEL

- CRPropa3 sim. power law $\gamma = 1$
- Fits done by reweighting simulated events (weighted sums/means…)

$$w_1 = E_0^{-(\gamma_{new}-1)}$$

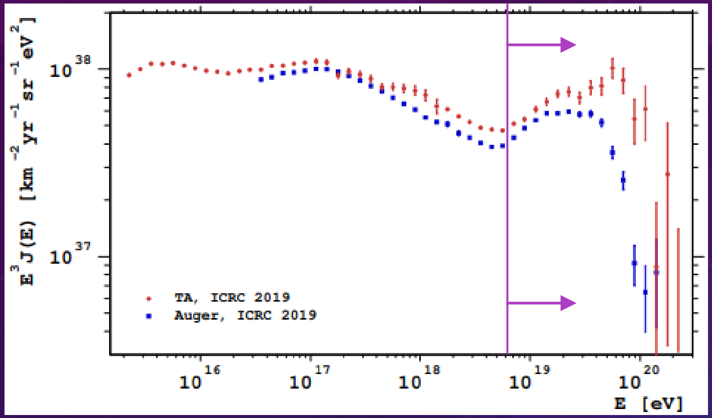
$$w_2[E_0 > ZR_{cut}] = w_1[E_0 > ZR_{cut}] * e^{\left(1-\frac{E_0[E_0>ZR_{cut}]}{ZR_{cut}}\right)}$$

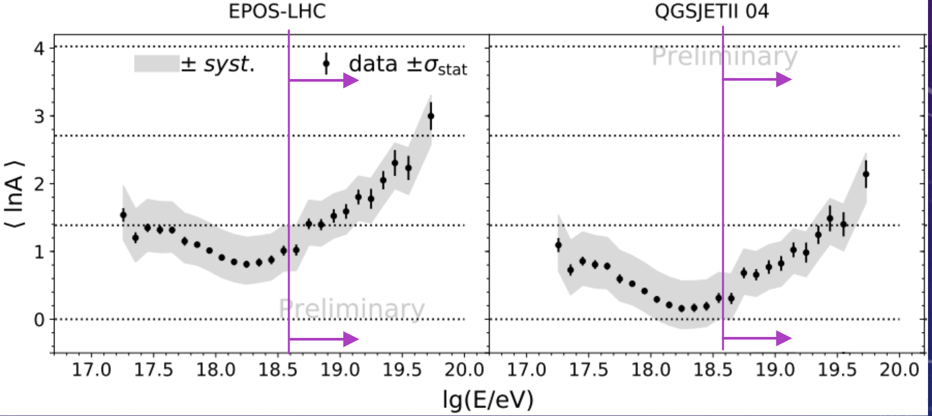
- Auger JCAP04(2017)038 arXiv:1612.07155v3
- One constant nucleon fraction: f_A
- Rigidity dependent cutoff: ZR_{cut}

$$\frac{\mathrm{d}N_A}{\mathrm{d}E} = J_A(E) = f_A J_0 \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}})$$

$$f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}}) = \begin{cases} 1 & (E < Z_A R_{\mathrm{cut}}) \\ \exp\left(1 - \frac{E}{Z_A R_{\mathrm{cut}}}\right) & (E > Z_A R_{\mathrm{cut}}) \end{cases}$$

COMBINED FIT





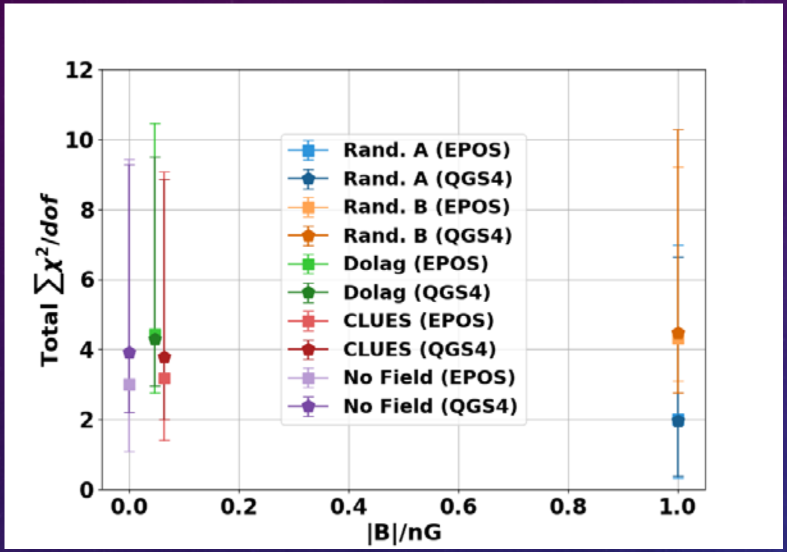
Minimize: $\sum \chi^2_{tot}/dof = \sum \chi^2_E/dof_E + \sum \chi^2_C/dof_C$

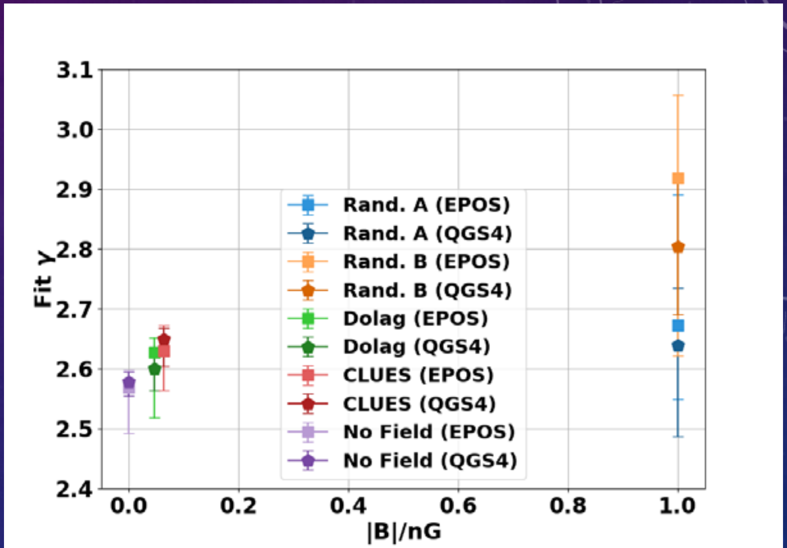
$$= \sum \chi^2_E/8 + \sum \chi^2_C/4$$

16 energy and 11 composition bins

- **8 Parameters:**
  - **Power law:** γ
  - **Spectrum normalization:** n
  - **Rigidity dependent exponential cut off:** ZR_{cut}
  - **5 nucleon fit: Hydrogen, Helium, Nitrogen, Silicon, Iron.**
    - **Fractions sum to one – 4 parameters.**
  - **Maximum trajectory** D

FIT PARAMETER RESULTS



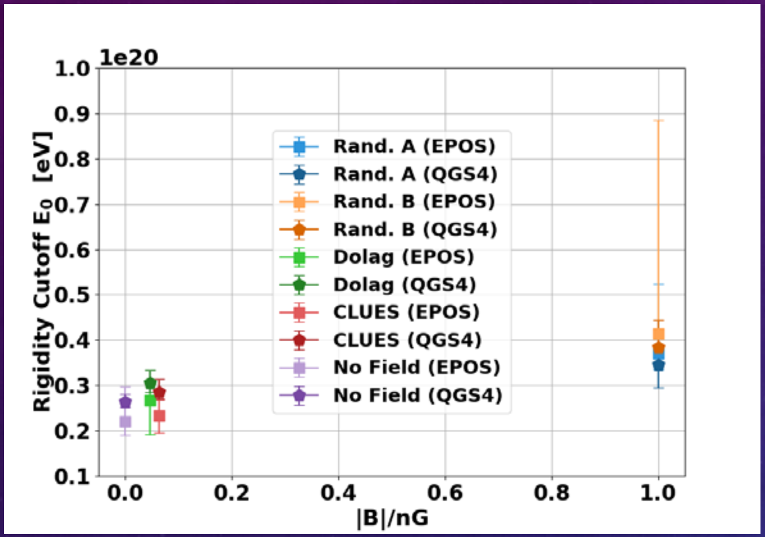


Goodness-of-fit Versus Magnetic Field

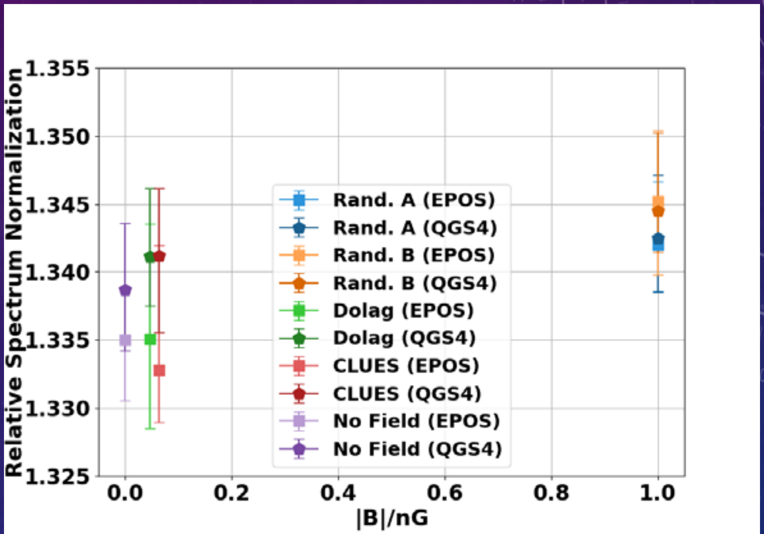
Power law Spectral Index γ Versus Magnetic Field

- **x-axis is average magnetic field in nanogauss.**
- **Error bars: 1 Gaussian σ confidence intervals around best fit for bootstrapped simulations and bootstrapped data.**

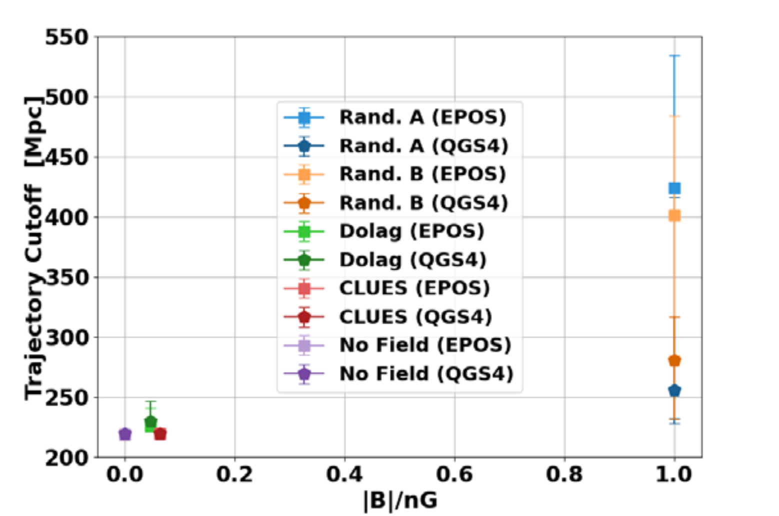
FIT PARAMETER RESULTS



Rigidity cutoff R_{cut} Versus Magnetic Field

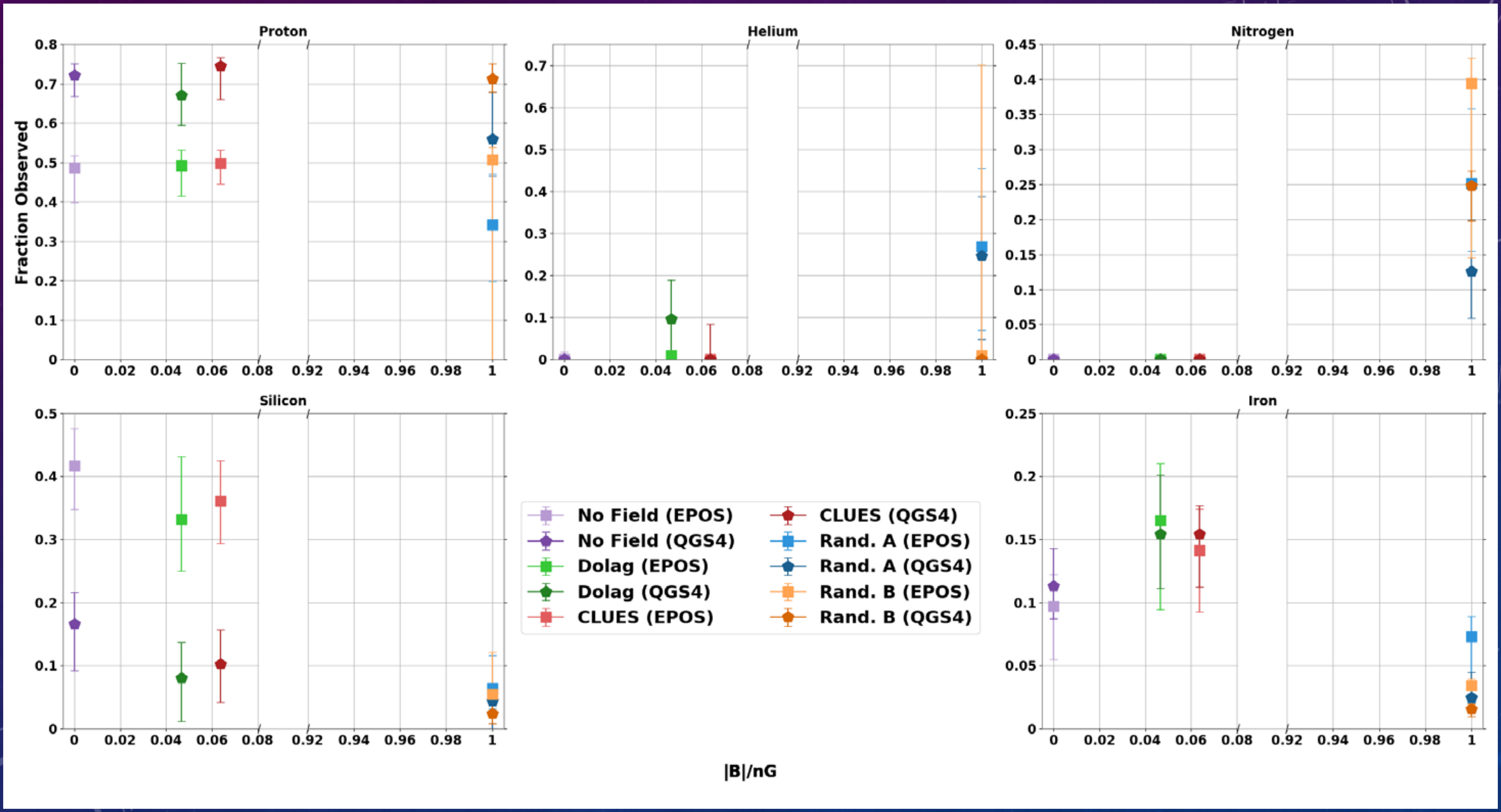


Spectrum Normalization Versus Magnetic Field



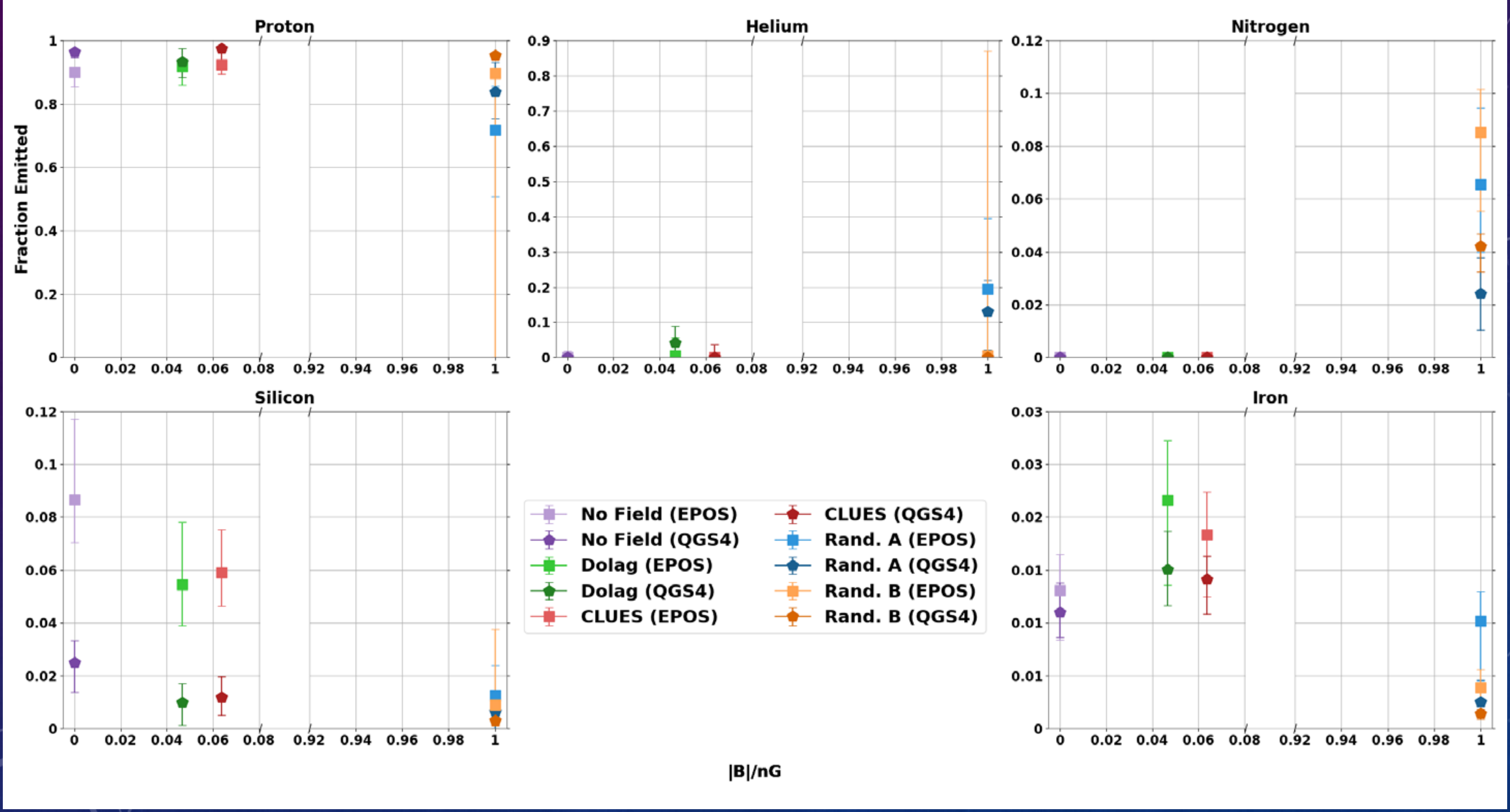
Trajectory cutoff D_{cut} Versus Magnetic Field

NUCLEON FRACTION RESULTS



Observed **Nucleon Fraction Versus Magnetic Field**

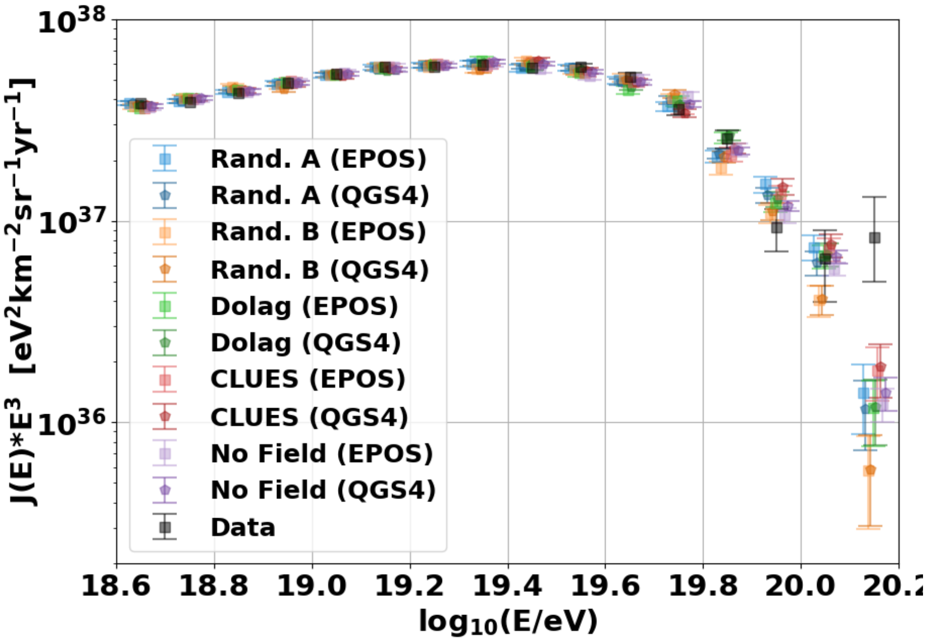
NUCLEON FRACTION RESULTS



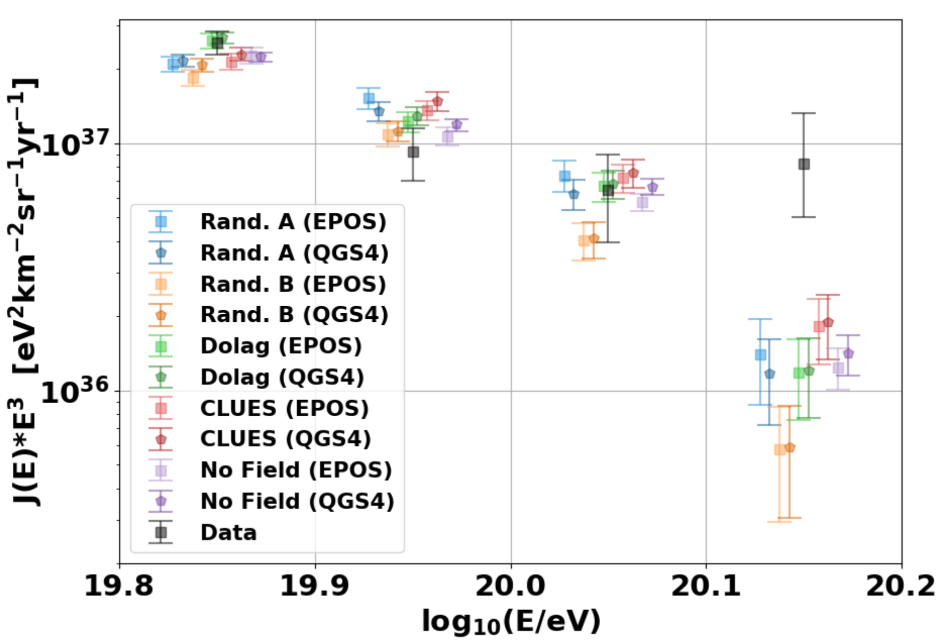
***Emitted* Nucleon Fraction Versus Magnetic Field**

ENERGY SPECTRUM FITS

Data: Deligny, O. et al., The energy spectrum of ultra-high energy cosmic rays measured at the Pierre Auger Observatory and at the Telescope Array, *PoS ICRC2019 (2020) 234*.



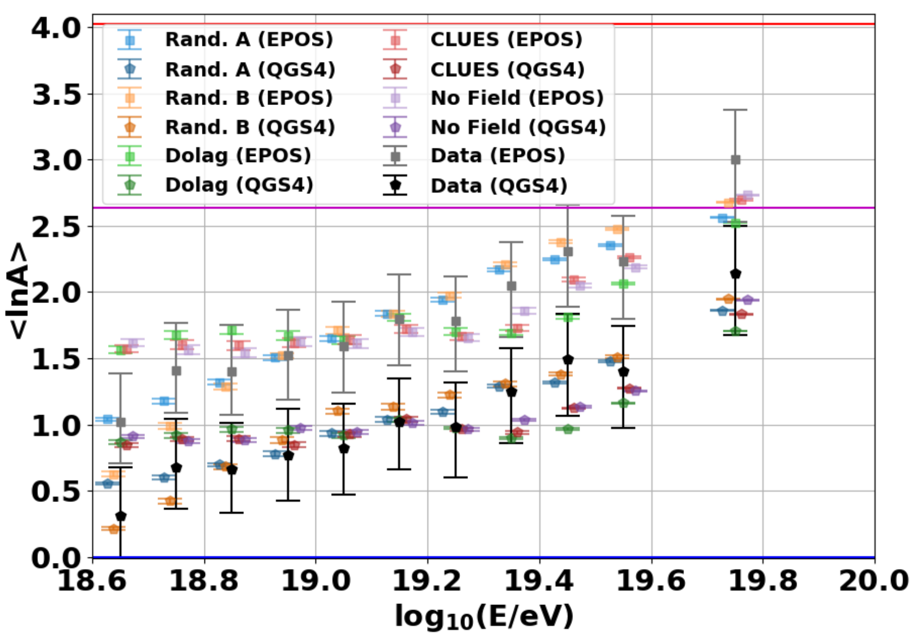
Zoomed In

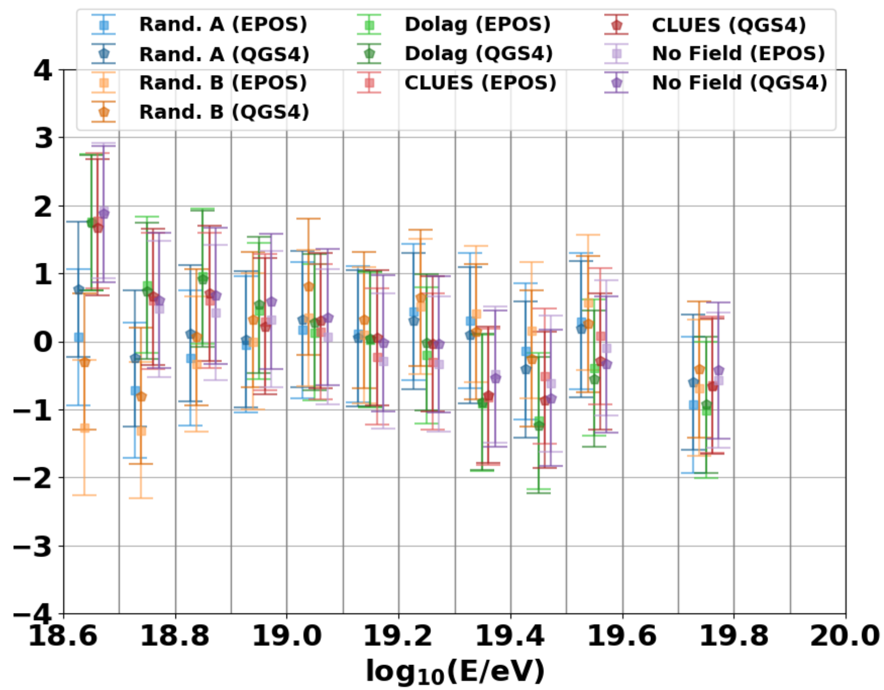


- Energy Spectra for all models
- Highest energies are (of course) not fit.
- FR0 not expected as a significant contributor.

MEAN LOG MASS <lnA> FITS

Data From: Yushkov, A. et al., Mass Composition of Cosmic Rays with Energies above $10^{17.2}$ eV from the Hybrid Data of the Pierre Auger Observatory, *PoS* ICRC2019 (2020) 482





<lnA> for all models

<lnA> Residuals for all models

PHOTONS – (1 nG – 234 kpc QGSJETII-04 MODEL)

The Astrophysical Journal, 933:125 (11pp), 2022 July 10 Abreu et al.

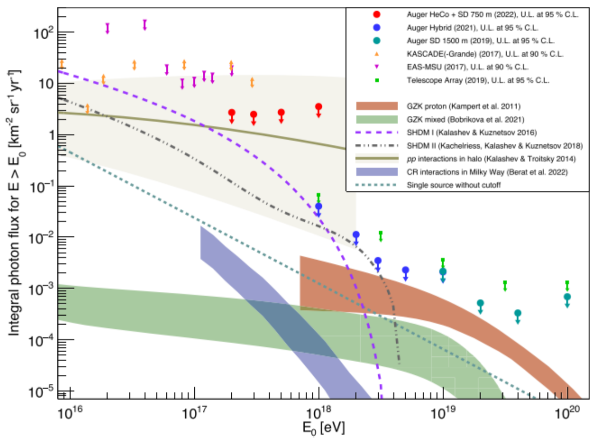
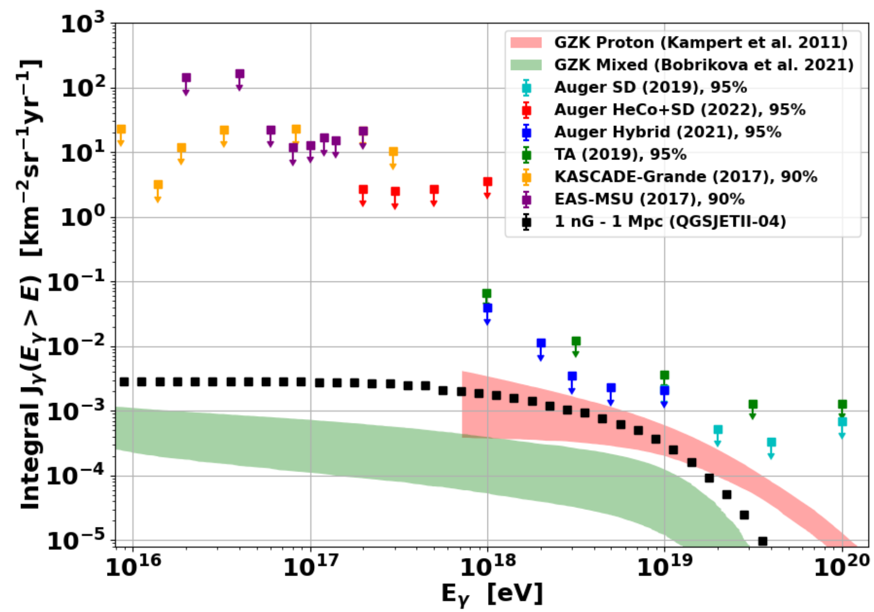


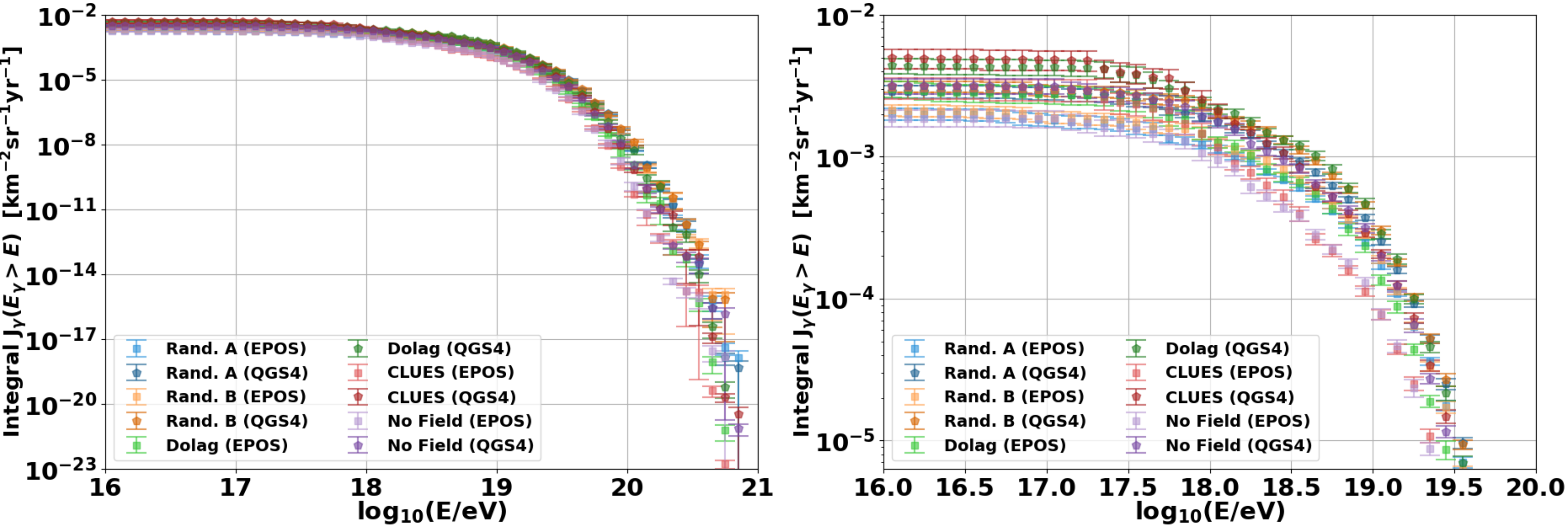
Figure 5. Upper limits (at 95% C.L.) on the integral photon flux above 2×10^{17} eV determined here (red circles). Shown are also previous upper limits by various experiments: Pierre Auger Observatory (hybrid: blue circles, taken from Savina & Pierre Auger Collaboration 2021; SD: cyan circles, taken from Rautenberg & Pierre Auger Collaboration 2019), KASCADE/KASCADE-Grande (orange triangles, taken from Apel et al. 2017), EAS-MSU (magenta diamonds, taken from Fomin et al. 2017), and Telescope Array (green squares, taken from Abbasi et al. 2019). The red band denotes the range of expected GZK photon fluxes under the assumption of a pure-proton scenario (Kampert et al. 2011). The green band shows the expected GZK photon flux assuming a mixed composition that would fit the Auger data (Bobrikova et al. 2021). In addition, the expected photon fluxes from the decay of SHDM particles are included (decay into hadrons: dashed violet line, based on Kalashev & Kuznetsov 2016; decay into leptons: dotted–dashed gray line, based on Kachelriess et al. 2018; the exact lines have been obtained through personal communication with one of the authors). The photon fluxes that would be expected from *pp* interactions in the Galactic halo (Kalashev & Troitsky 2014, olive-green line) or from cosmic-ray interactions with matter in the Milky Way (Bérat et al. 2022, blue band) are shown as well. Also included is the expected flux of photons from a single, putative source without a cutoff in its spectrum (dotted turquoise line, modeled after HAWC J1825-134, Albert et al. 2021, where we extrapolated the measured flux to the highest energies), ignoring its directionality as if its flux were distributed over the full sky.



A Search for Photons with Energies Above 2×10^17 eV Using Hybrid Data from the Low-Energy Extensions of the Pierre Auger Observatory
P. Abreu et al 2022 ApJ 933 125
arXiv:2205.14864

Red/green areas are no magnetic field and GZK only.

PHOTON COMPARISONS

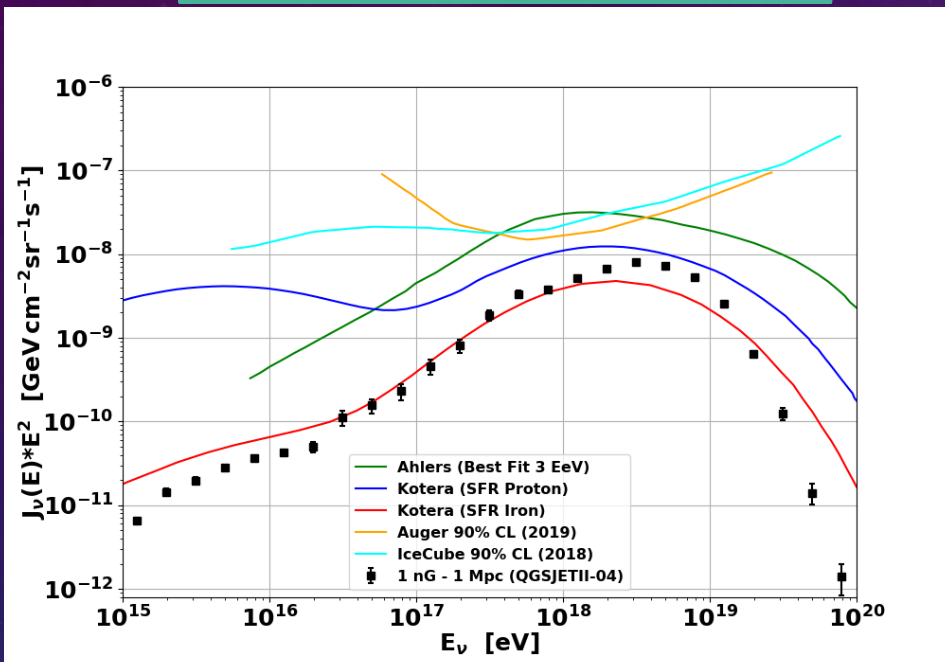


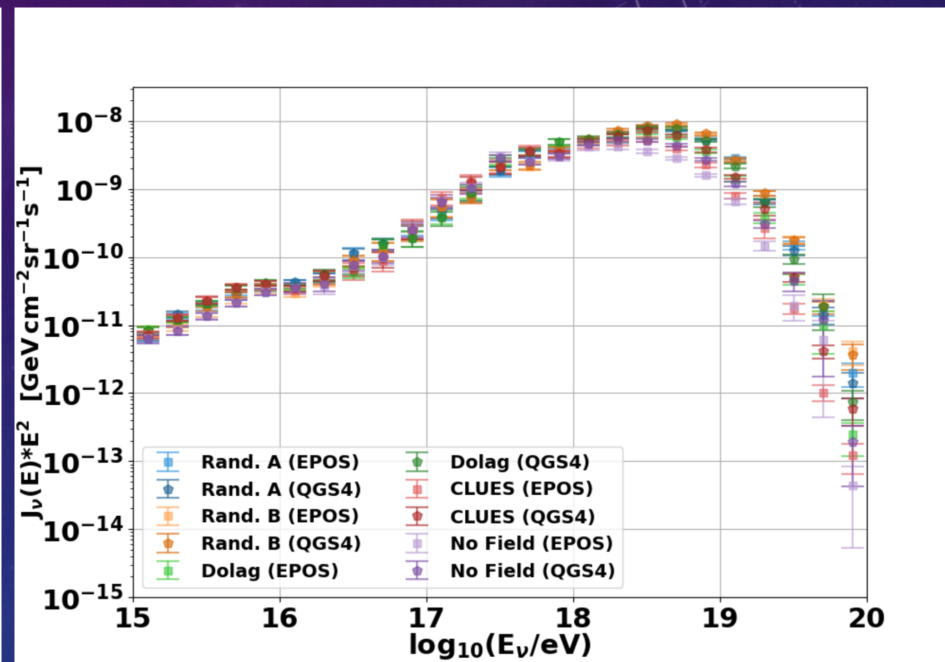
Zoomed In

Integral photon flux for all models

NEUTRINOS

1 nG – 234 kpc QGSJETII-04





Kotera et al: JCAP (2010) arXiv:1009.1382
Ahlers et al: Astropart.Phys.(2010) arXiv:1005.2620v2
IceCube: Phys.Rev.D(2018) arXiv:1807.01820v2
Auger: JCAP10 (2019) arXiv:1906.07422v2

Neutrino flux for all models

CONCLUSIONS

Best Fit: 1 nG – 234 kpc QGSJETII-04 (or EPOS)

- Possibly due to effective additional fit parameter (trajectory cutoff D_{cut})
- Next best: No Field and CLUES structured field with EPOS composition.

Trends with increasing magnetic field strength:

- γ, R_{cut}, D_{cut}, and Norm all tend to increase.
- Stable: Proton emission.
- Increases: Helium and Nitrogen emission.
- Decreases: Silicon and Iron emission.

Photon spectra: higher flux than expected for mixed composition from GZK only.

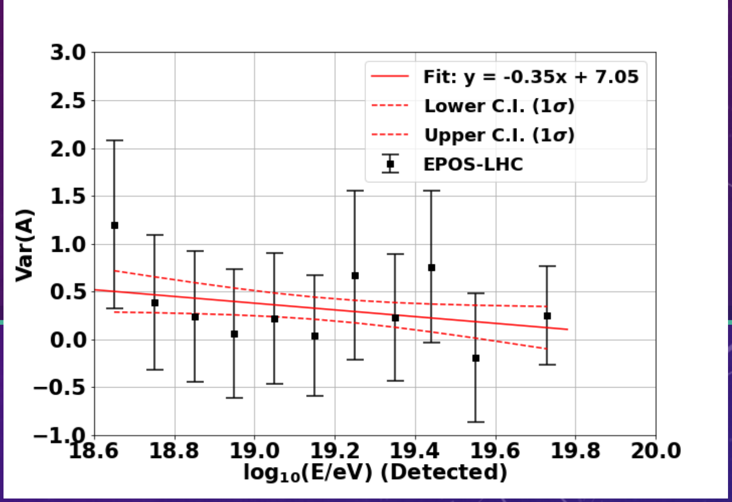
- Increases with magnetic field strength.

Neutrino spectra lower flux than expected **from Kotera model for mixed composition.**

- Increases with magnetic field strength. $z \leq 0.05$

COMMENT RESPONSES

ADDING Var(lnA)



- *EPOS-LHC $Var(lnA)$*
  - *Invalid values*
  - Slope -0.29 +/- 0.30
    - *Not significant with uncertainties in A transform.*
    - *Transforming A to $X_{\max}$ transfers uncertainty to simulation.*

- *Adding more rigid constraint than $Var(lnA)$ χ^2:*
  - *Constrain simulation variance slope +/- 1σ.*
    - χ^2 : 2.67 to 7.45
    - Gamma γ: 2.67 to 3.14
    - Rigidity cutoff: 37×10^{18} to 21×10^{18}
    - Trajectory cutoff: 424 Mpc to 225 Mpc
    - Observed nucleon fractions:
      - Proton: 34% to 52%
      - Helium: 27% to 0%
      - Nitrogen: 25% to 34%
      - Silicon: 6% to 8.3%
      - Iron: 7% to 5.4%

- *1 nG 234 kpc magnetic field*

EFFECT OF EXTENDING MAXIMUM Z

- **Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory**
  - ***JCAP04(2017)038 [arXiv:1612.07155v3]()***

- ***One constant nucleon fraction: f_A***
- ***Rigidity dependent cutoff: ZR_{cut}***

source evolution		γ	$\log_{10}(R_{cut}/V)$	D	$D(J)$	$D(X_{max})$
$(1+z)^m$	$m = +3$	$-1.40^{+0.35}_{[illegible]}$	$18.22^{+0.05}_{[illegible]}$	179.1	7.5	171.7
	$m = 0$	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
	$m = -3$	$+1.42^{[illegible]}_{-0.07}$	$18.85^{[illegible]}_{-0.07}$	173.9	19.3	154.6
	$m = -6$	$+1.56^{+0.06}_{-0.07}$	18.74 ± 0.03	182.4	19.1	163.3
	$m = -12$	$+1.79 \pm 0.06$	18.73 ± 0.03	182.1	18.1	164.0
	$z \leq 0.02$	$+2.69 \pm 0.01$	$19.50^{+0.08}_{-0.07}$	178.6	15.3	163.3

Table 10. Best fit parameters (reference model) corresponding to different assumptions on the evolution or spatial distribution of sources.

- **Limiting z results in**
  - **Softer emission spectrum.**
  - **Higher rigidity cutoff.**

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- **Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory**
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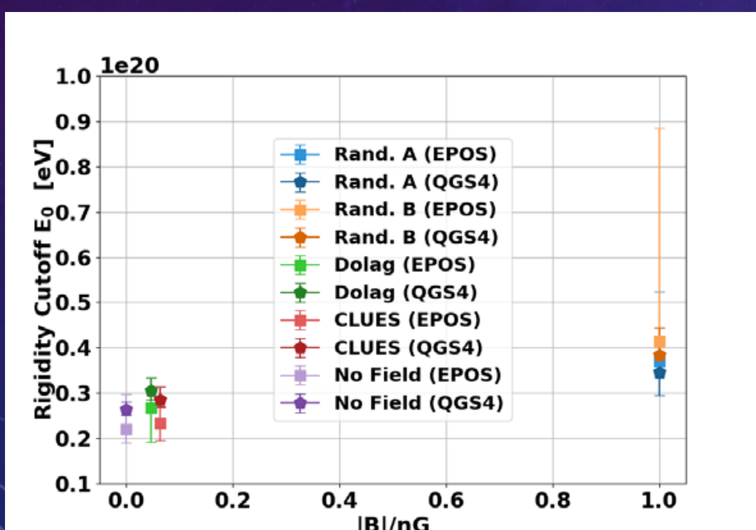
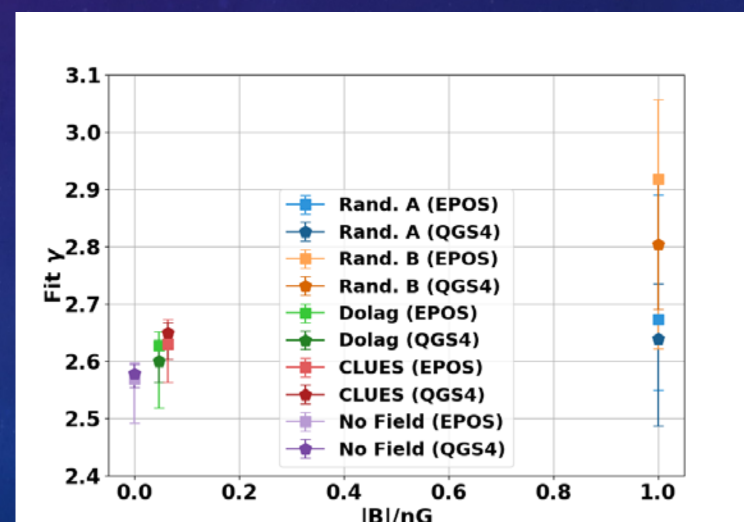
$z \leq 0.02$	$+2.69{\pm}0.01$	$19.50^{+0.08}_{-0.07}$	178.6	15.3	163.3

- **Limiting z results in**
  - **A softer emission spectrum.**
  - **A higher rigidity cutoff.**



Power law Spectral Index γ Versus Magnetic Field



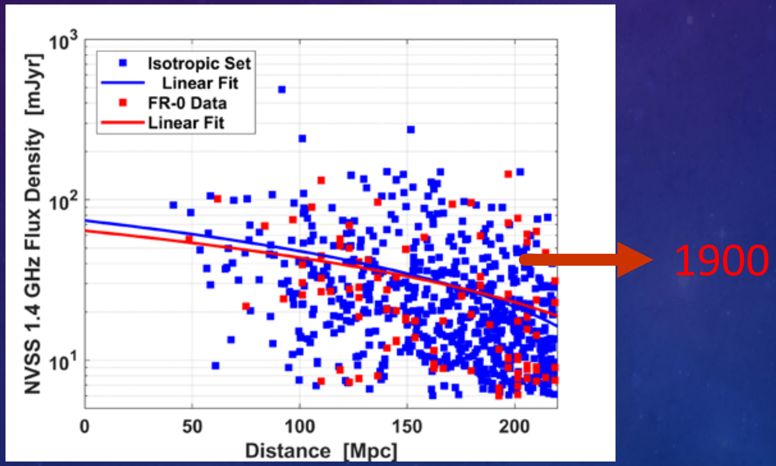
Rigidity cutoff R_{cut} Versus Magnetic Field

EFFECT OF EXTENDING MAXIMUM Z

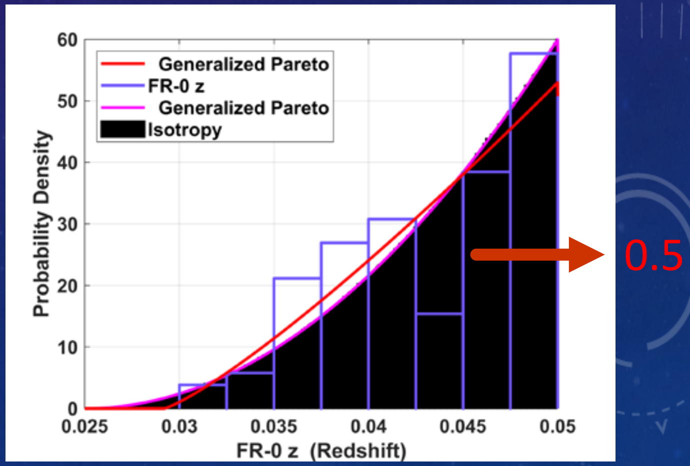
– 1 nG 234 kpc MAGNETIC FIELD

Extrapolating **to FR0 sources** ***z = 0.05 to 0.5*** **(simulate 0 to 0.5):**

- **Proton ratio (detected nucleons)/(emitted nucleons) is ~1/24th that of z = 0 to 0.05.**
  - **Neutrinos (detected neutrinos)/(emitted nucleons) is ~1/68th .**
- **Iron ratio is ~1/51th .**
  - **Neutrinos is ~1/26th.**
- **A significant computing penalty** ***(small sampling above…).***



Local source evolution modeled by preserving correlation between radio output and redshift distance (Kendall's correlation coeff.: -0.28, p-Value: 4.6e-5)[1].



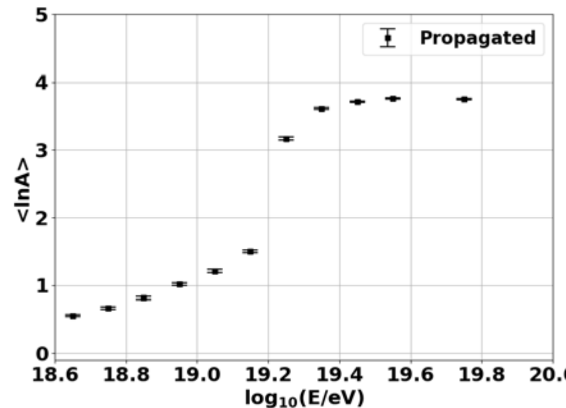
Simulated FR-0 redshift distribution from Pareto fit to catalog data[1].
Isotropy probability of ~16%.

EFFECT OF EXTENDING MAXIMUM Z

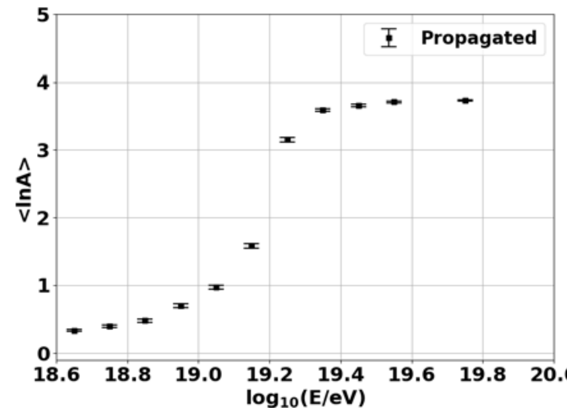
– IRON: 1 nG 234 kpc MAGNETIC FIELD

- **Updated CRPropa 3**
- **Extrapolating to FR0 sources z = 0.05 up to 0.5 (simulate 0 to 0.5)**

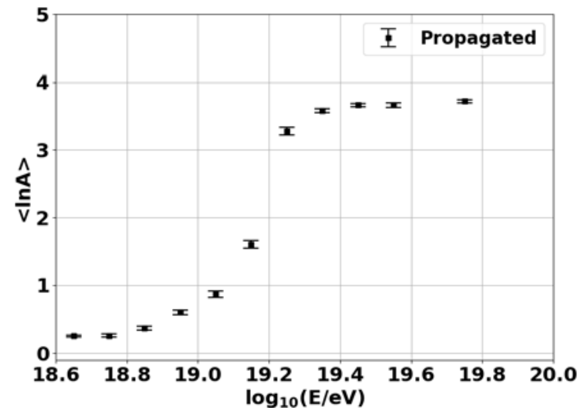
IRON



Up to z = 0.05

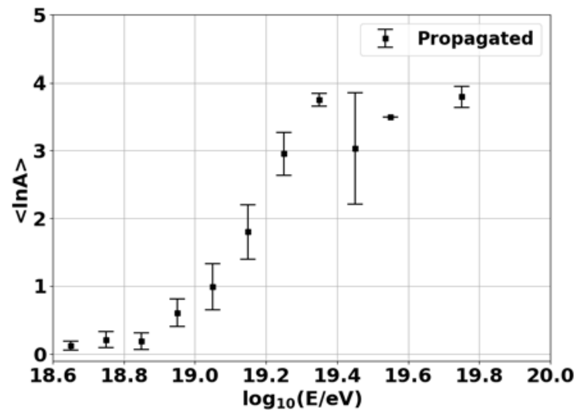


Up to z = 0.1



Up to z = 0.2

- **Iron propagation does not change significantly past z = 0.1**
- **Up to z = 0.5 has too high computation cost.**
- **Currently generating z = 0.2.**

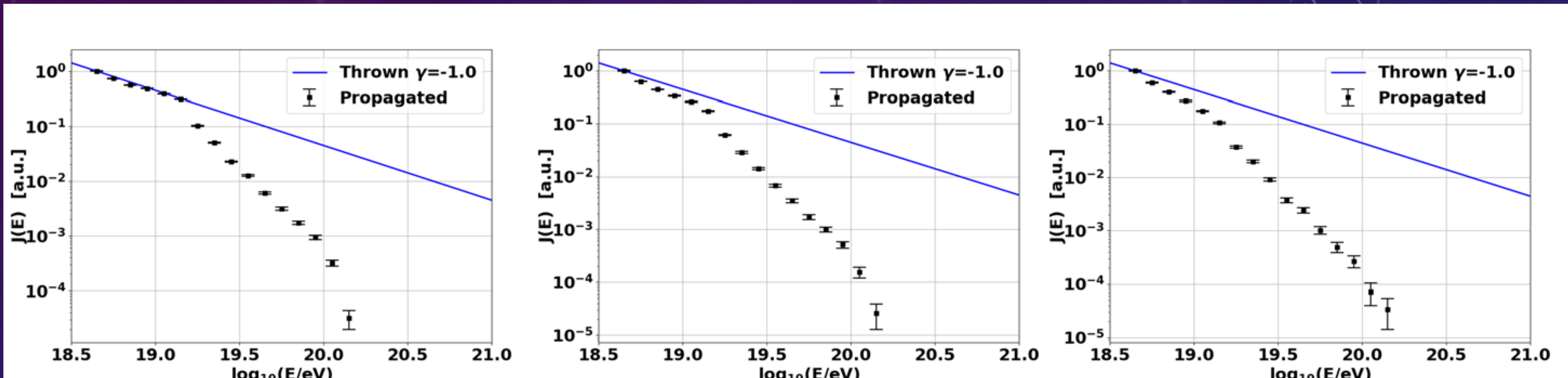


Up to z = 0.5 (smaller stats)

EFFECT OF EXTENDING MAXIMUM Z

– IRON: 1 nG 234 kpc MAGNETIC FIELD

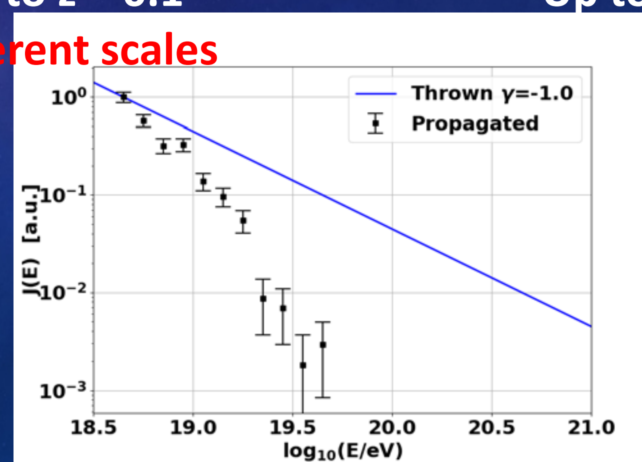
- **Updated CRPropa 3**
- **Extrapolating to FR0 sources z = 0.05 up to 0.5 (simulate 0 to 0.5)**



Up to z = 0.05 **Up to z = 0.1** **Up to z = 0.2**

Different scales

- **Iron propagation does not change significantly past z = 0.1**
- **Up to z = 0.5 has too high computation cost.**
- **Currently generating z = 0.2**

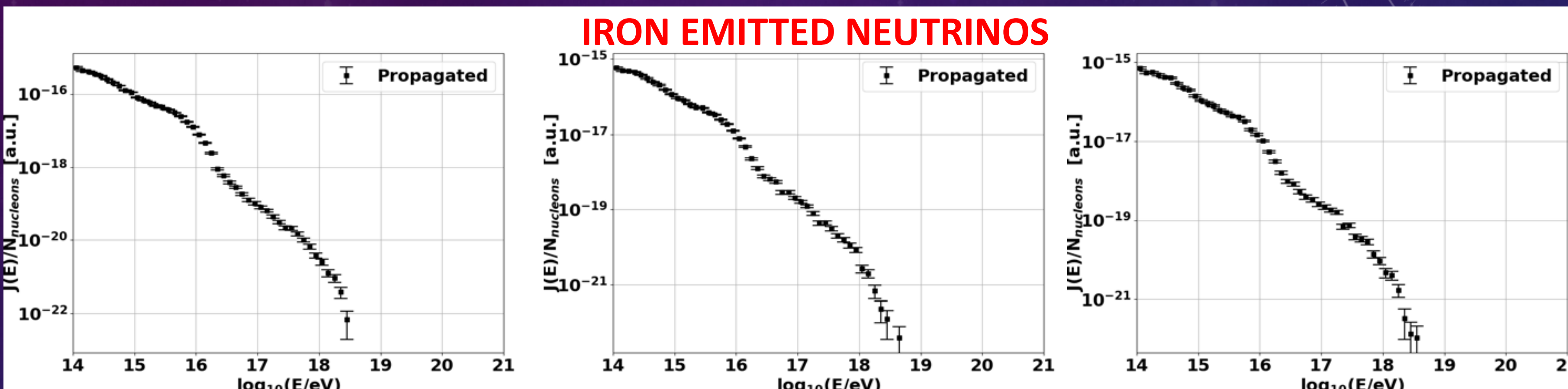


Up to z = 0.5 (smaller stats)

EFFECT OF EXTENDING MAXIMUM Z

– IRON EMITTED NEUTRINOS: 1 nG 234 kpc MAGNETIC FIELD

- Updated CRPropa 3
- Extrapolating to FR0 sources z = 0.05 up to 0.5 (simulate 0 to 0.5)

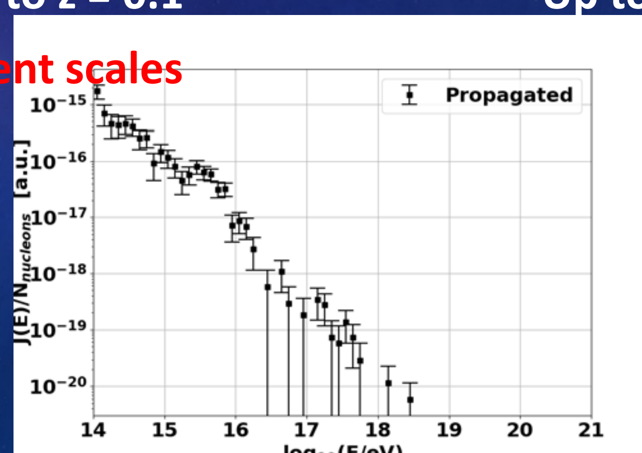


Up to z = 0.05

Up to z = 0.1

Up to z = 0.2

Different scales



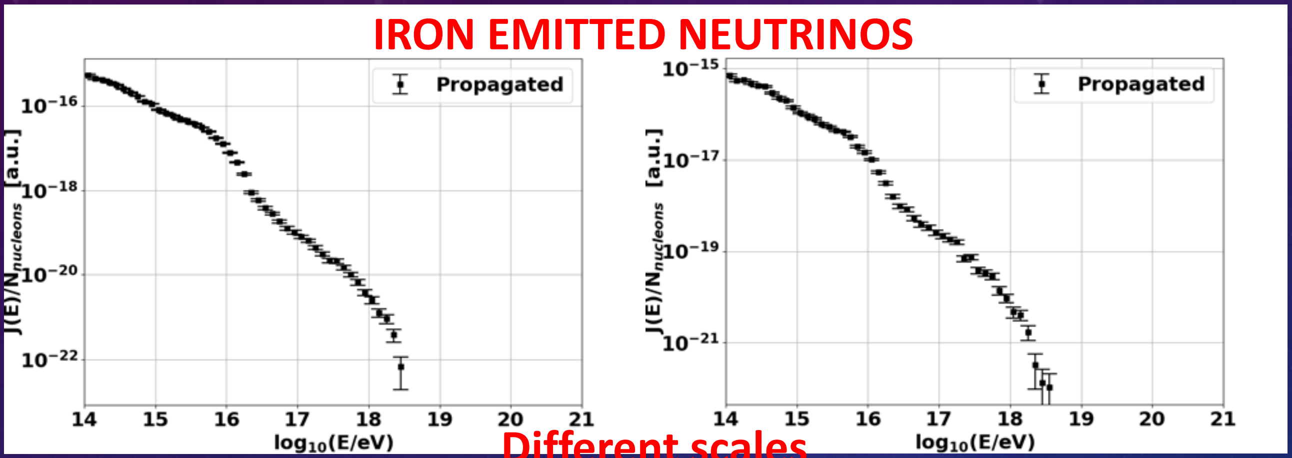
Up to z = 0.5
(smaller stats)

- Iron propagation does not change significantly past z = 0.1
- Up to z = 0.5 has too high computation cost.
- Currently generating z = 0.2

EFFECT OF EXTENDING MAXIMUM Z

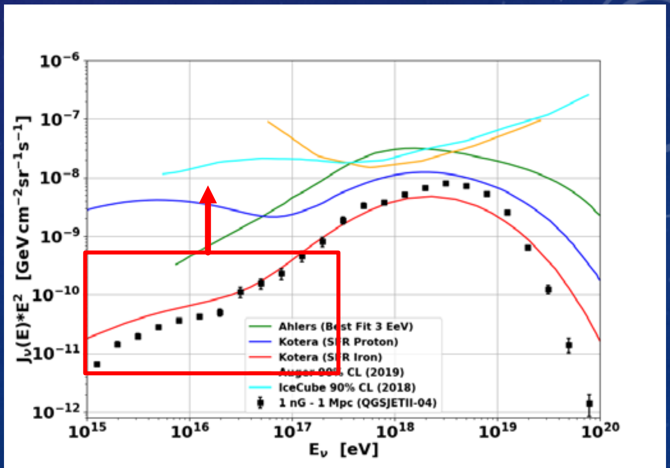
- IRON EMITTED NEUTRINOS: 1 nG 234 kpc MAGNETIC FIELD

- **Updated CRPropa 3**
- **Extrapolating to FR0 sources z = 0.05 up to 0.5 (simulate 0 to 0.5)**



Up to z = 0.05

Up to z = 0.2



- **More neutrinos.**
  - **Seems to affect lower energy more.**

CONCLUSIONS

- New simulations with new version of CRPropa 3
  - Changes in mean log A and energy spectrum.

- Adding variance of lnA not possible (negative values).
  - A flat line is compatible within 1sigma of linear fit.
  - Converting simulation to Xmax transfers lnA large error bars to simulation.
    - Would seem to not contribute much to chi-square.

- Extending maximum redshift z.
  - Increases neutrino flux.
  - Softens emitted spectrum.
    - Fitted gamma will decrease.
  - Does not significantly change $z > 0.1$.

ADDITIONAL

SECONDARY RATIOS