Origin of Ultra-high Energy* Cosmic Rays in Binary Neutron Star Collisions

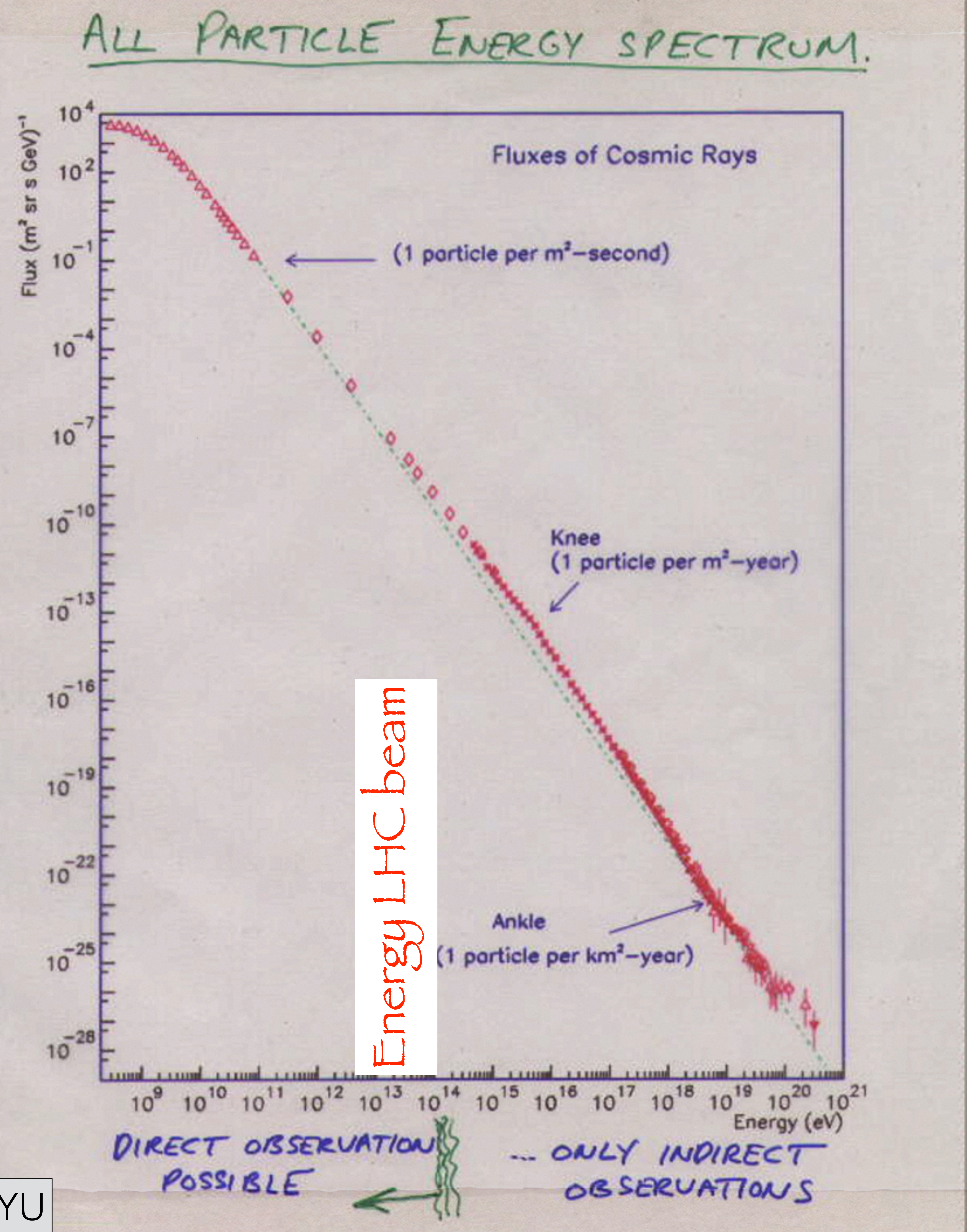
and the crucial role of nuclear physics

Glennys R. Farrar, New York University
EuNPC25, Sept. 23, 2025

* <E per nucleon> ~ 2 EeV ➜ γ >10^9

Today

- Review of UHECR essentials
- Why BNS mergers are likely to be the site of UHECR production
- UHECR acceleration in the magnetized turbulent outflow of a BNS merger
- Predicting the UHECR spectrum and composition
- Tests
- ***New(?) nuclear physics questions***



Cosmic Rays

- 32 decades of flux
- 12 decades of energy
- Highest energy particles ever observed:
  - 10^8 times higher energy than LHC beams
  - E_{CM} of collision with air nucleus is ~ 100 times higher than at the LHC.

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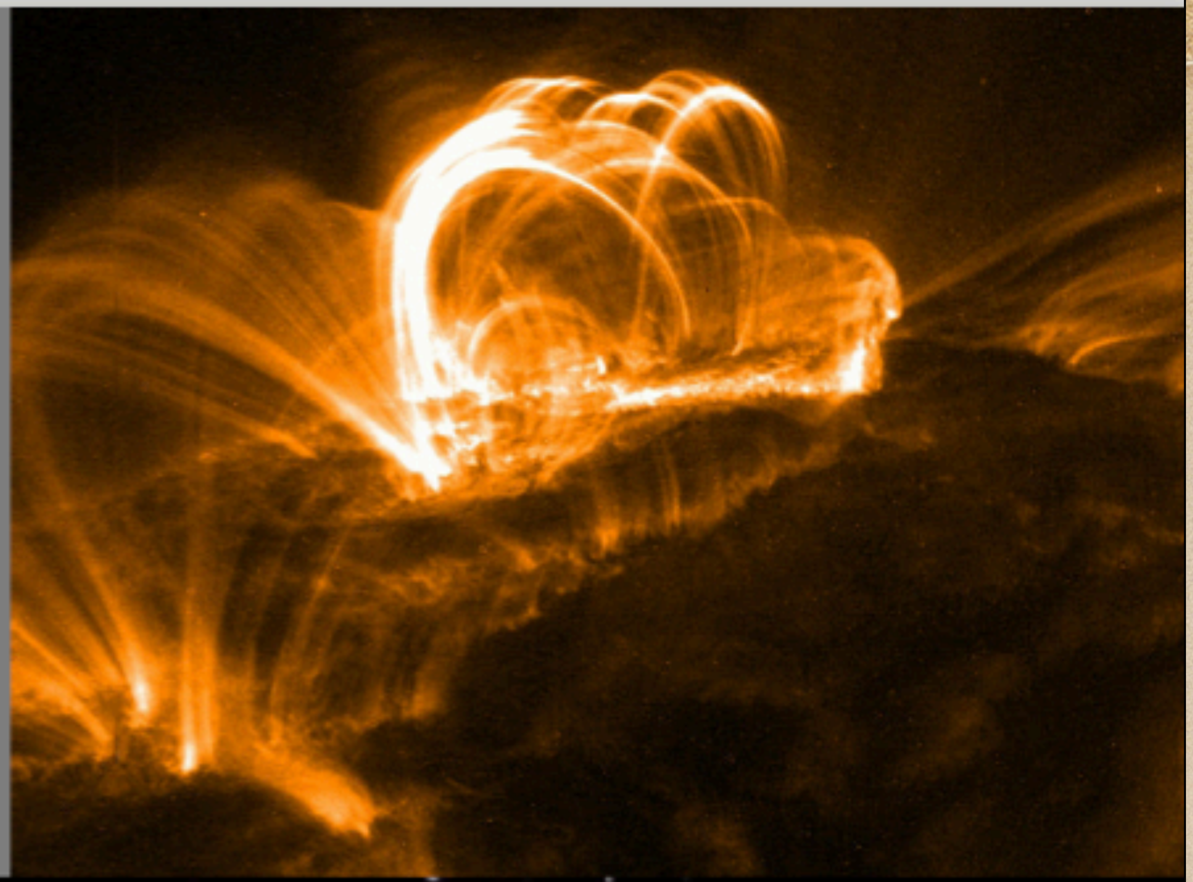
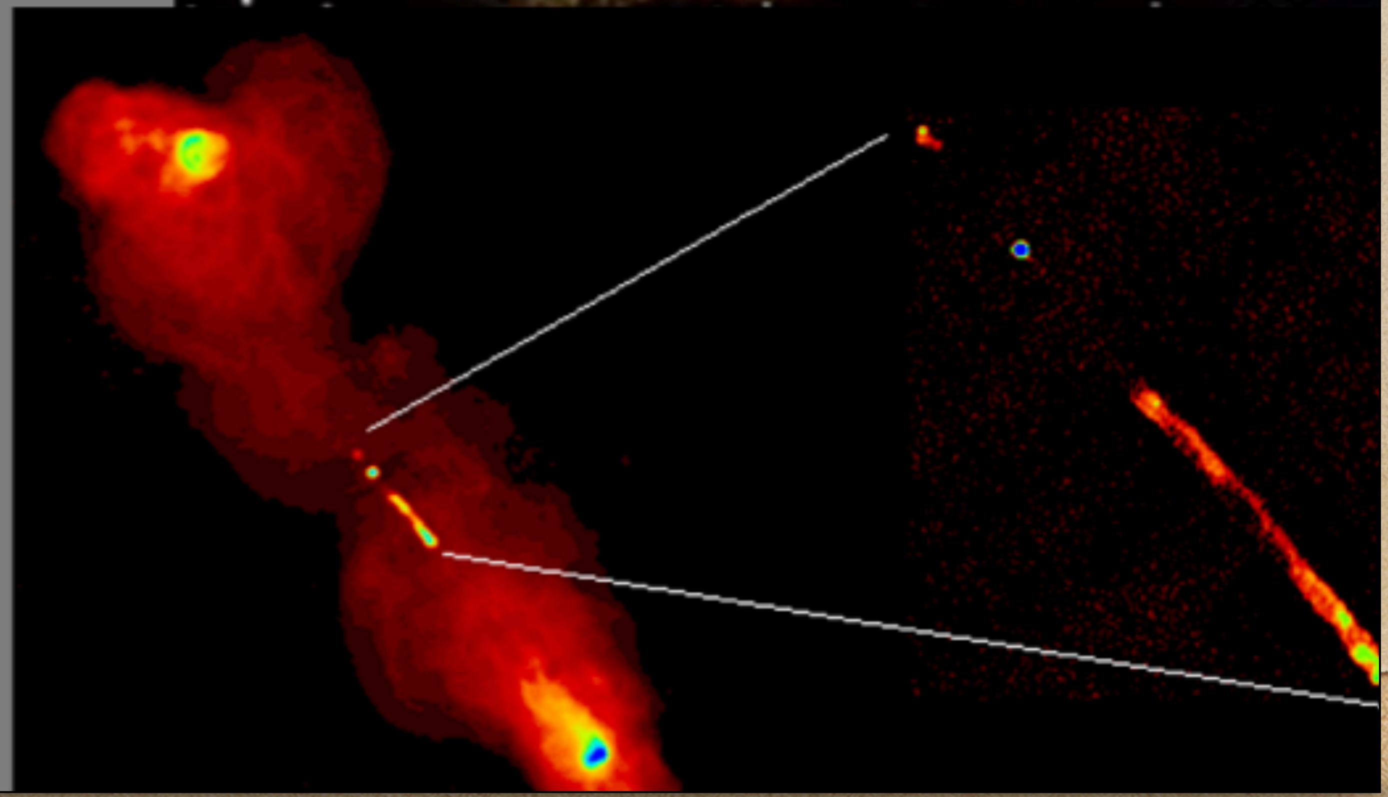
Cosmic Rays



- Low energy CR's: from sun

- Medium energy: Milky Way
  - accelerated in supernovae remnants (Fermi mechanism)
  - Confined by Galactic magnetic fiel
    Larmour radius = 1 $E_{18}/(Z\ B_{\mu G})$ kpc



- High energy: Extragalactic
  - What are they? (protons, nuclei,...)
  - What are their sources?
  - How are they accelerated?

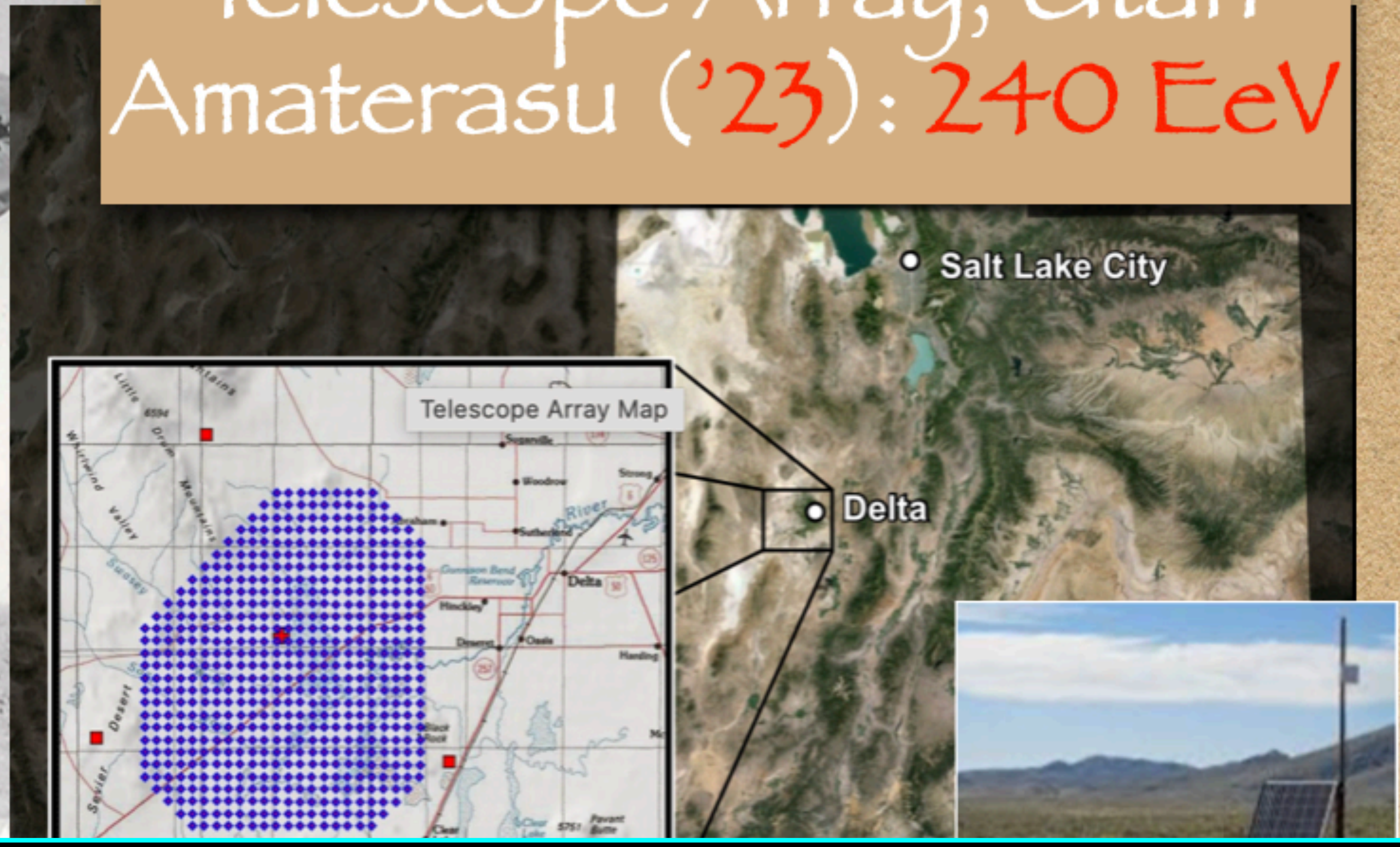
Discovery of CRs: Hess 1912

Hess: CRs
1911 or 1912

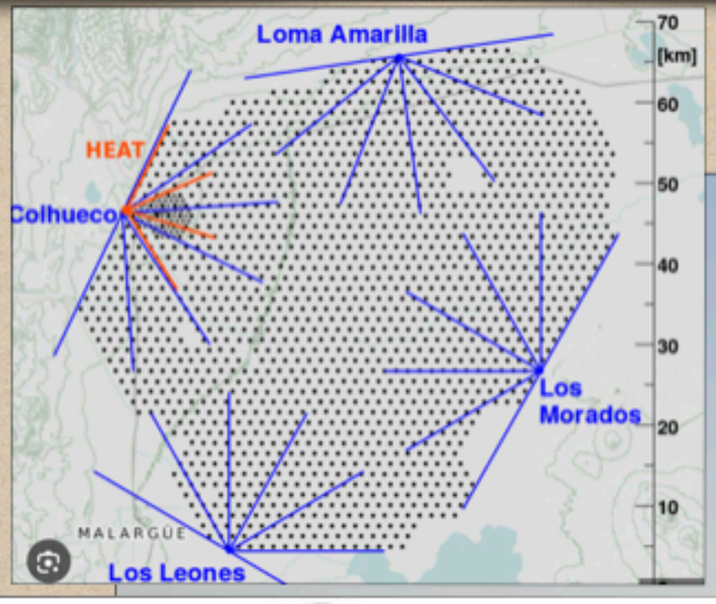
1st UHECR: Linsley 1962

Linsley: 1st evt > 100 EeV
Volcano Ranch, NM ~1962

Telescope Array, Utah
Amaterasu ('23): 240 EeV

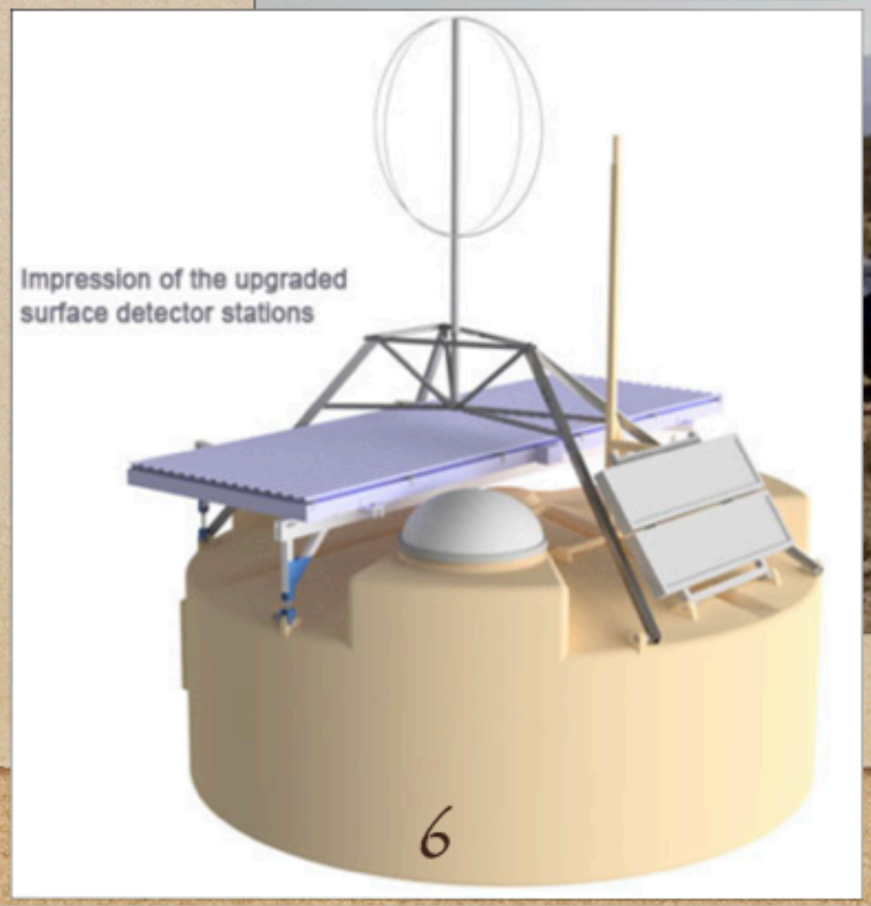


Contemporary UHECR observatories
TA ↑
Auger ↓



Pierre Auger Obs., Argentina
~50 evts > 100 EeV

1700 stations, 3000 km^2



Highest E (>250 EeV) 1991

Fly's Eye Utah 1991
OMG: 320 (250) EeV

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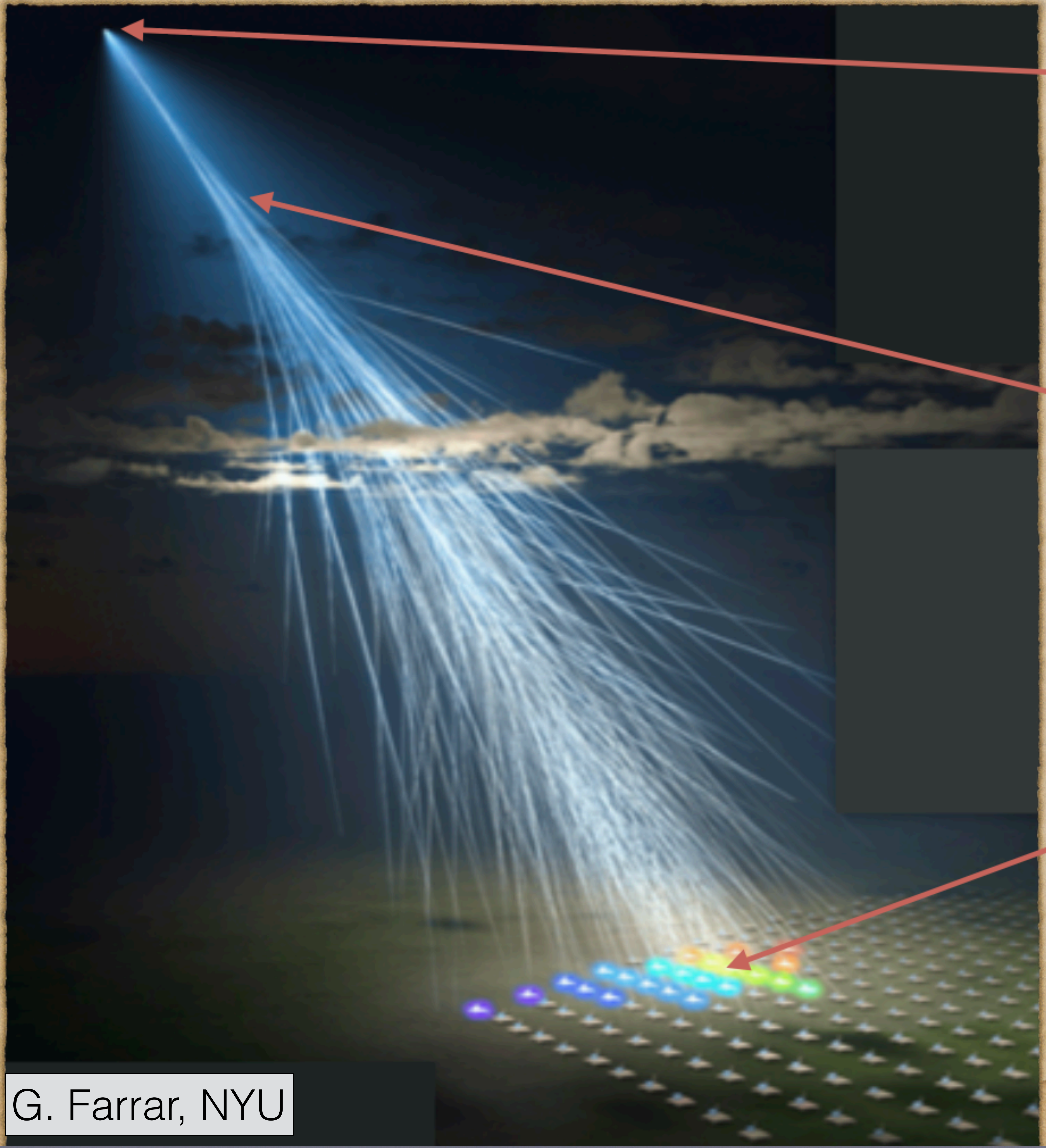
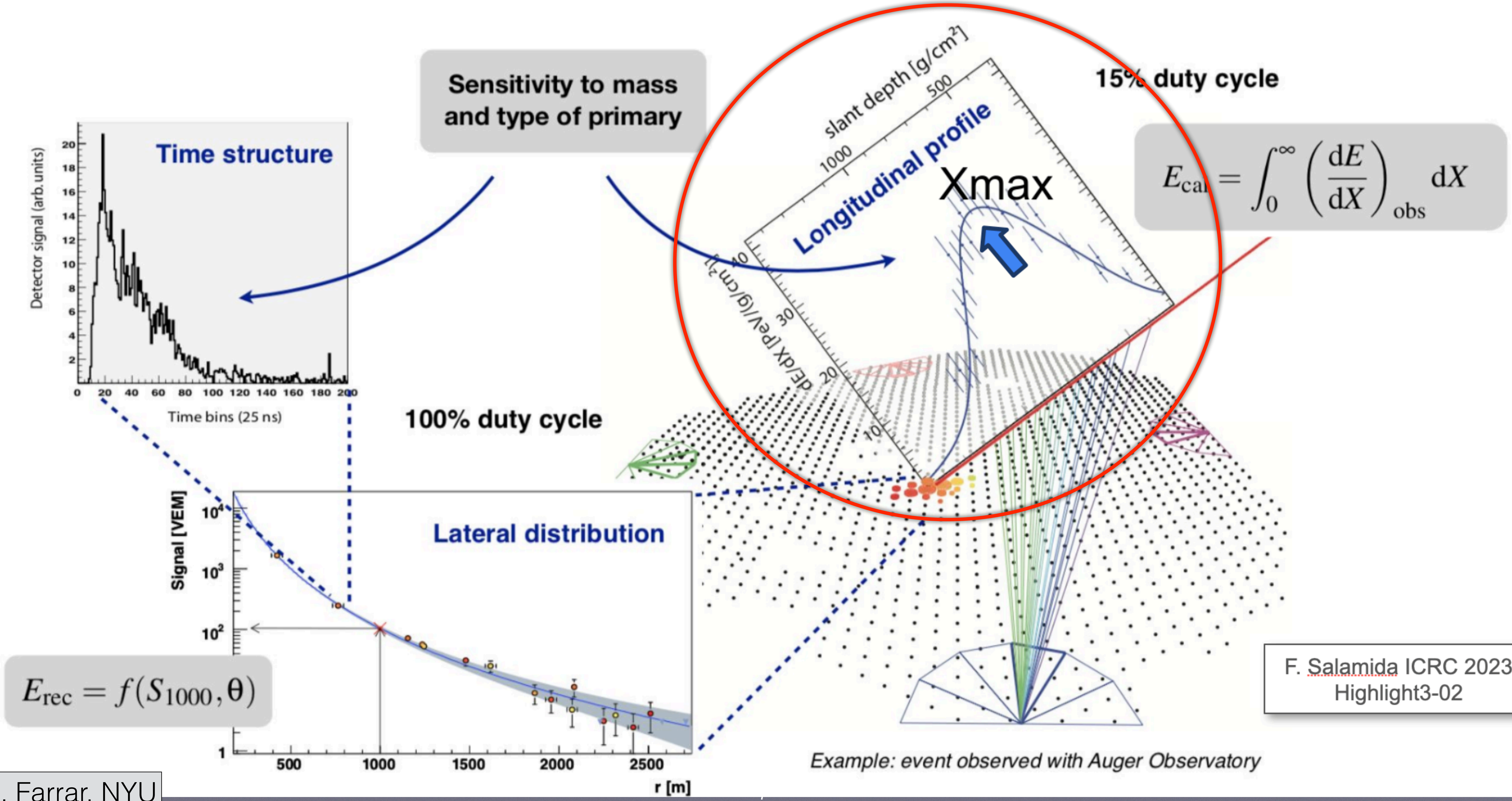
How to deduce the mass and energy of a UHECR



- Depth of first interaction:
  - heavy nucleus: interacts quickly (starts high)
  - proton: 1st interaction is deep or shallow
- Shower development:
  - heavy nucleus: shower develops quickly
  - proton: more interactions needed to reach shower max
  - primary energy from integrated fluorescence emission
- Ground signal:
  - EM vs muon components ⇒ nuclear mass
  - primary energy from total signal

The Hybrid Observation Method of Auger



F. Salamida ICRC 2023
Highlight3-02

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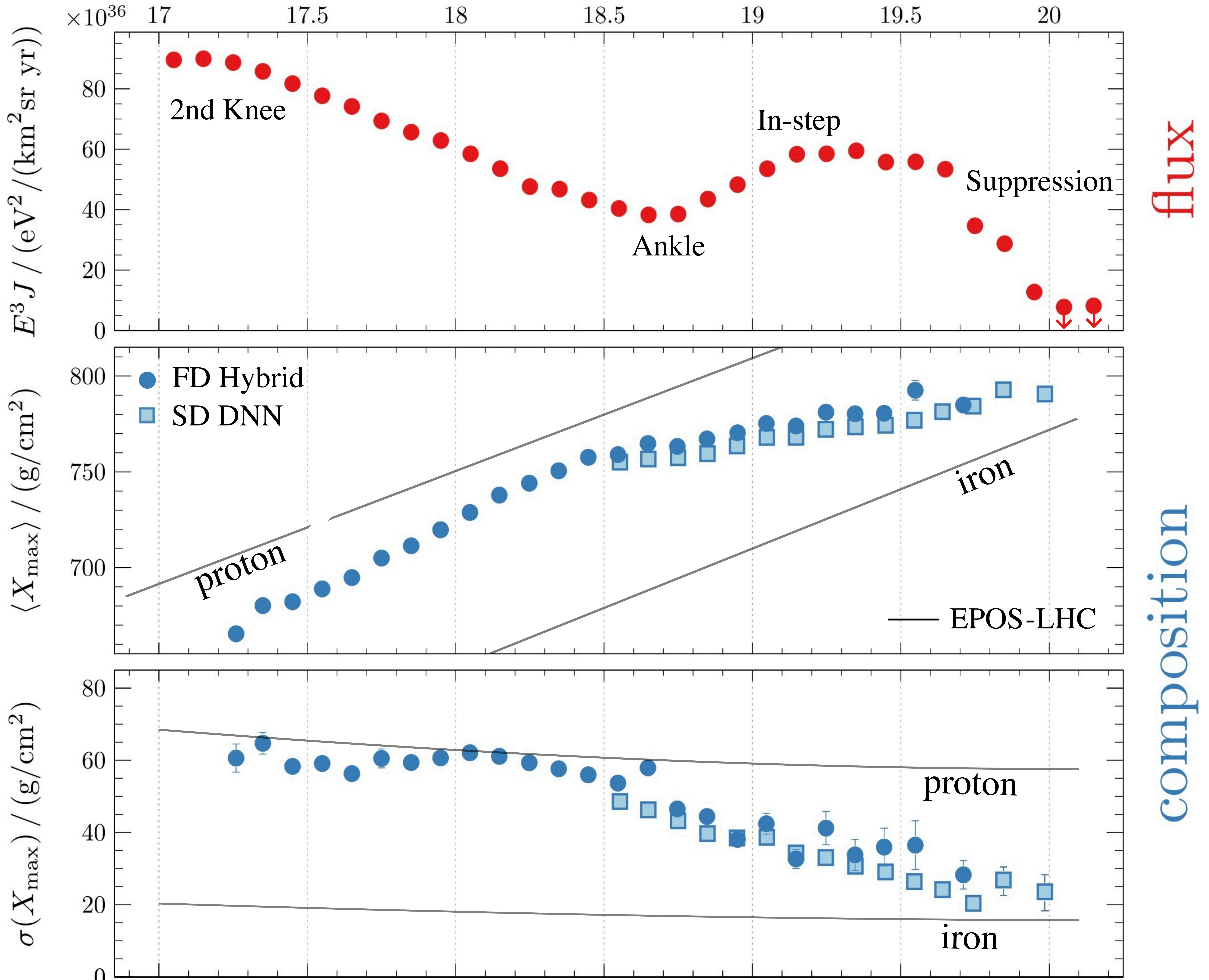
Auger Spectrum
<Xmax>
σ(Xmax)

Composition gets heavier with energy

A single mass group dominates at each E



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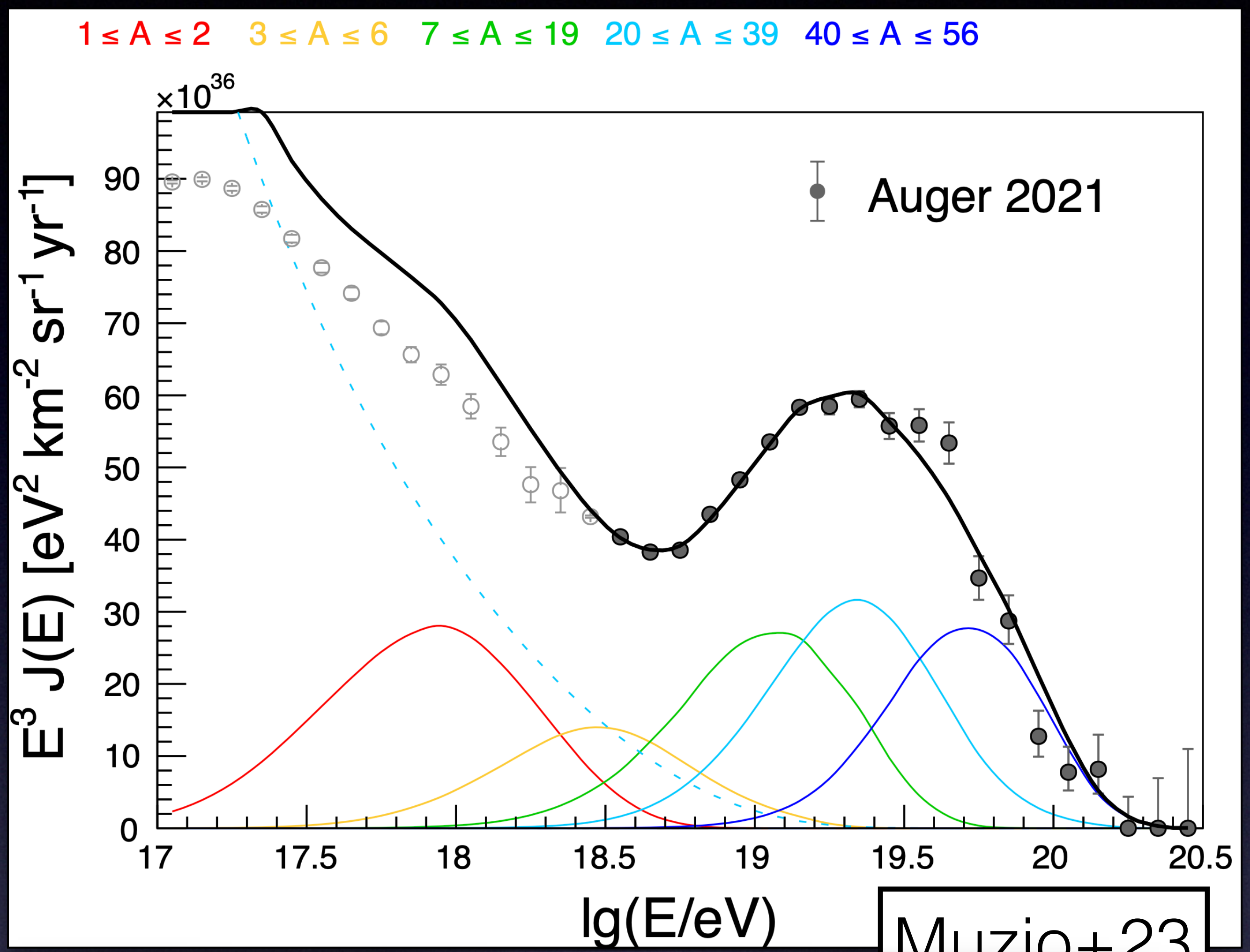
Implications of the observations

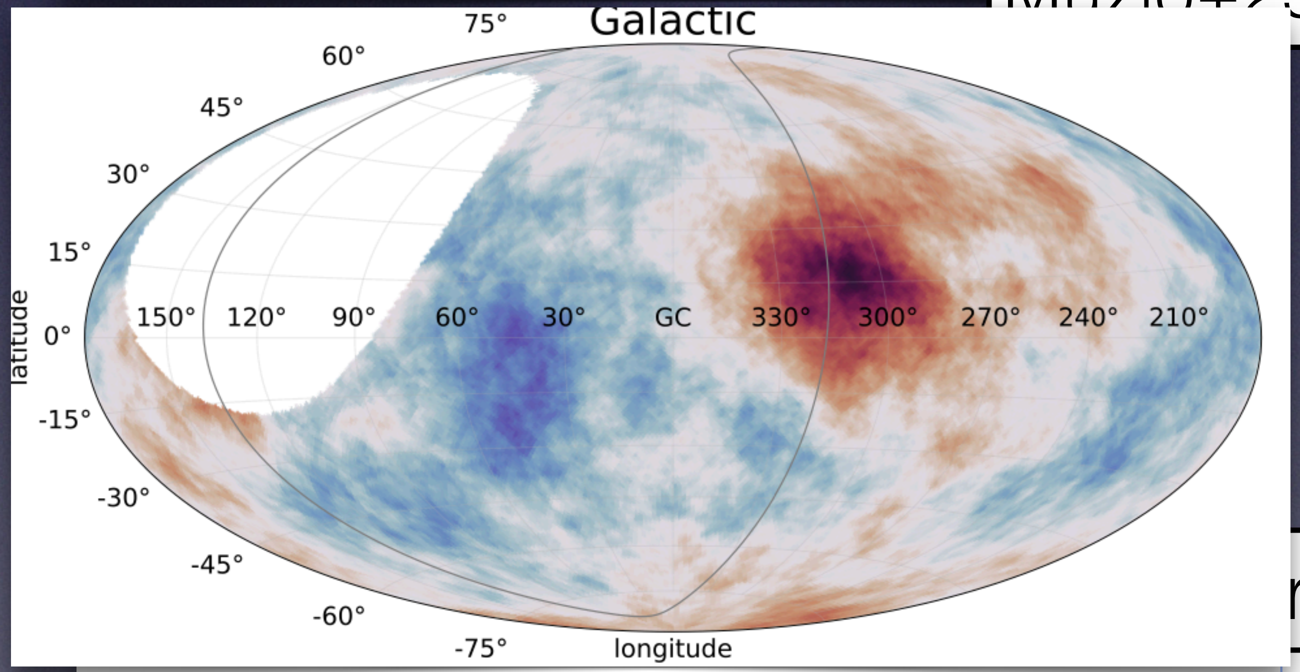
- Composition is mixed, mass increases with E
- *Narrow range of masses at each E:*

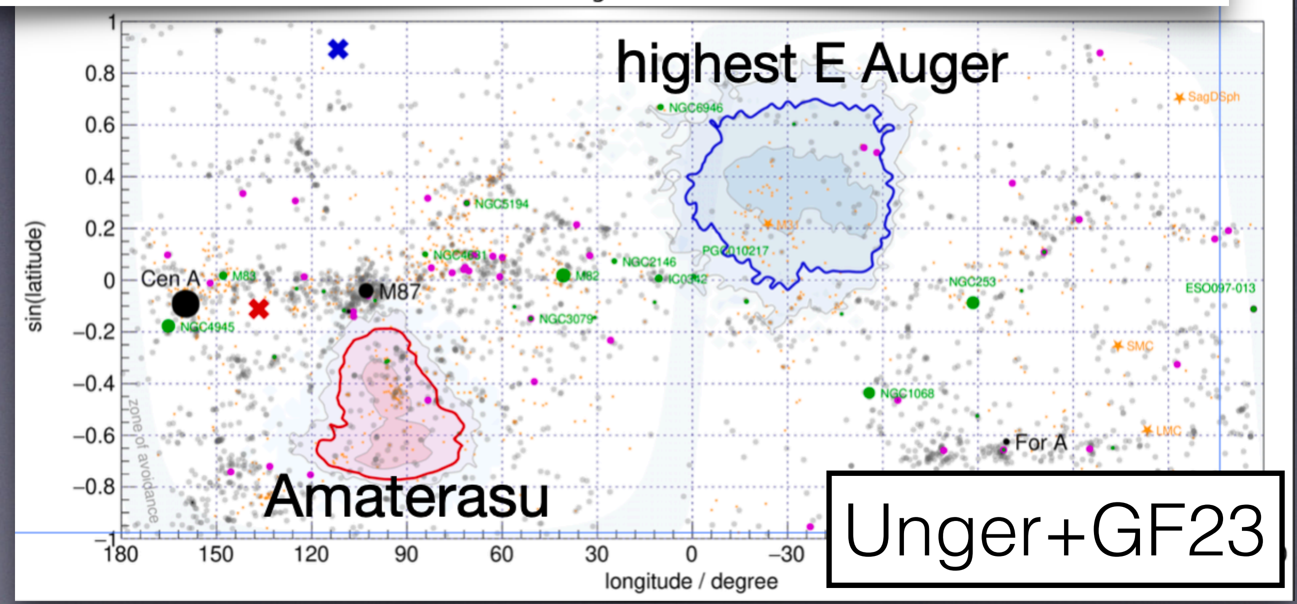
  ***Rigidity spectrum is narrow**: <**R**≡E/Ze>≈4 EV*

- Arrival directions: *Sources are abundant*
- No prominent sources for highest E events:

  Sources are transients







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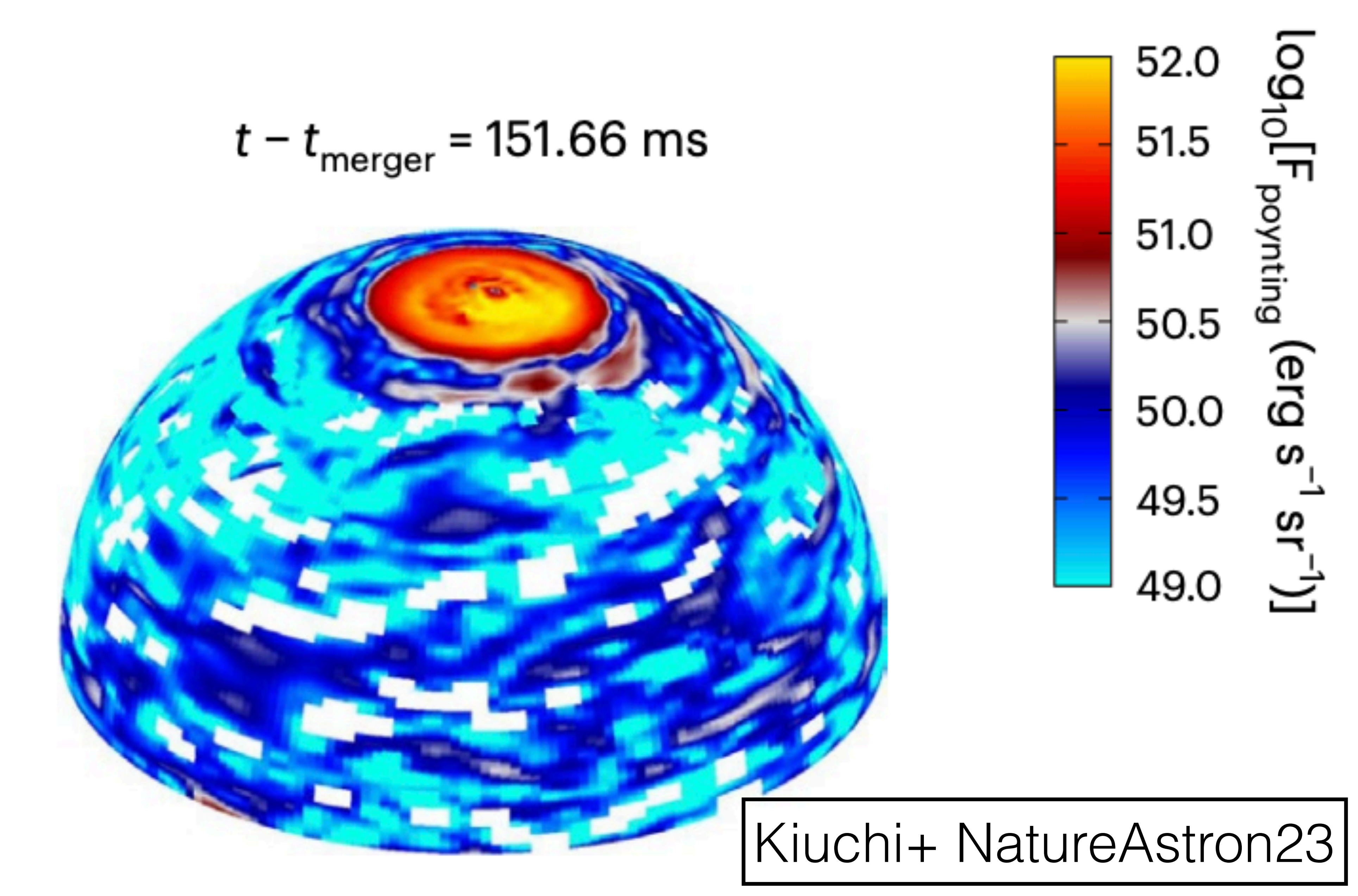
Binary Neutron Star Mergers

only (currently known) source candidate satisfying all criteria

- Universal rigidity spectrum explained:
  1. Magnetic field is generated by *gravitational* dynamo 💕
  2. Mass range of BNS is narrow 💕
     Known BNS's: M= 2.64±0.14 (5%) $M_\odot$



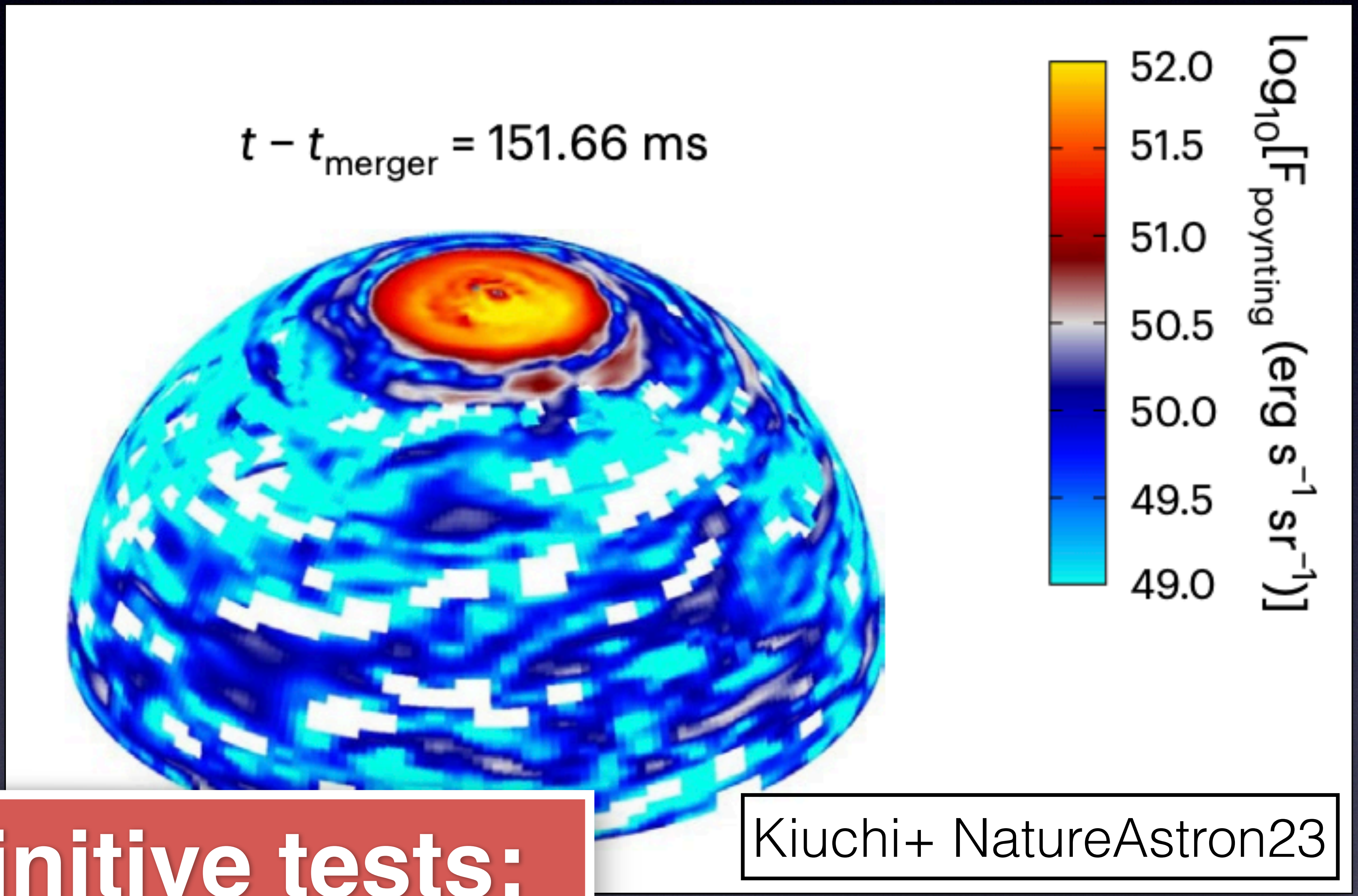
Kiuchi+ NatureAstron23

- UHECR energy injection rate promising:
  - need UHECR energy per merger ≈ 10^{50} erg (<1% of total energy emitted)

arXiv: 2405.112004 [astro-ph.HE] & PRL 2025

Binary Neutron Star Mergers

only (currently known) source candidate satisfying all criteria



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  1. Magnetic field is generated by *gravitational* dynamo 💕
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     Known BNS's: M= 2.64±0.14 (5%) M⊙

- UHECR ener
  - need UHEC … emitted)

Unique predictions enable definitive tests:

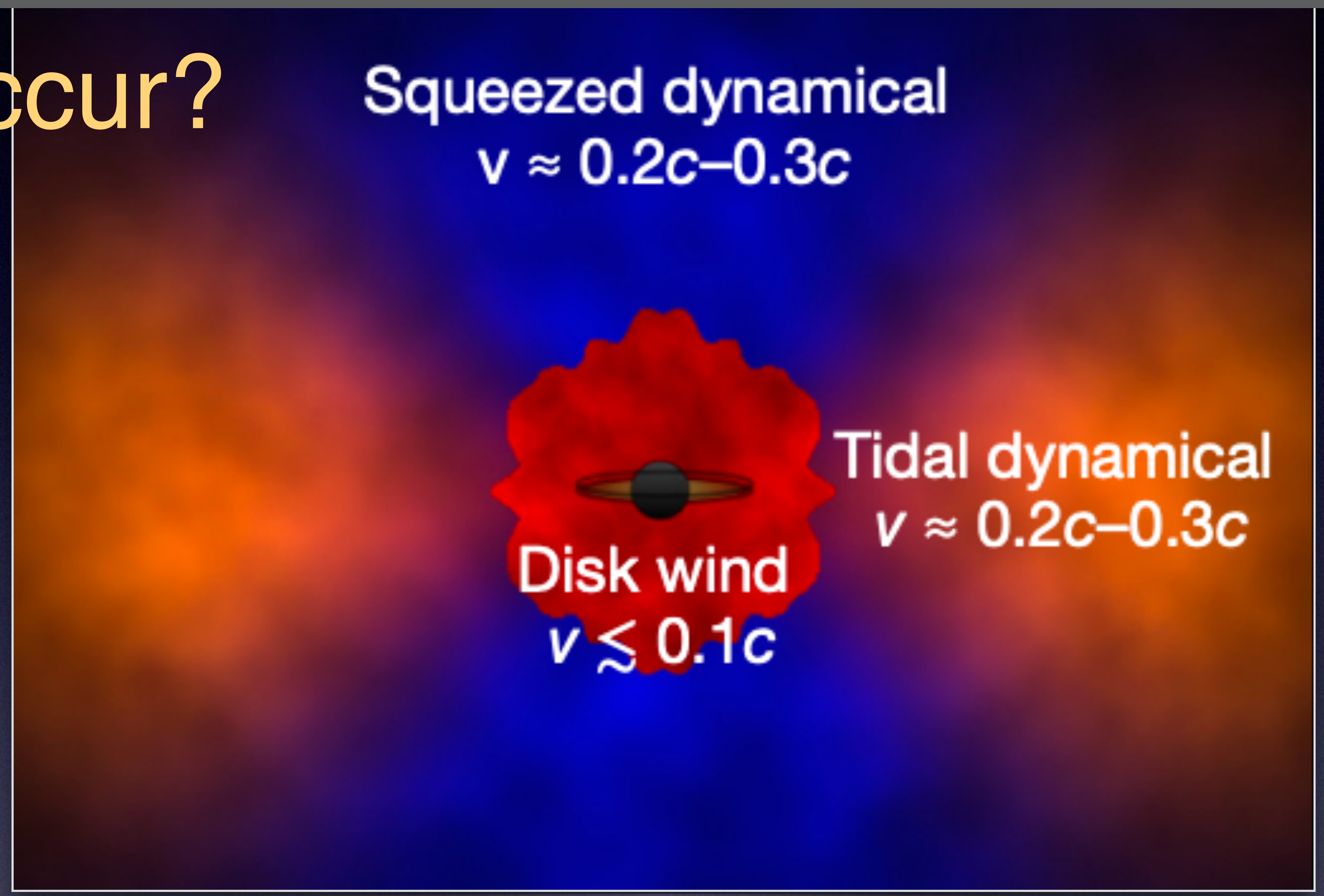
- EHE ν's ↔ gravitational waves
- Highest energy UHECRs: Z>26
- BNS merger ➜ initial B ➜ predict spectrum

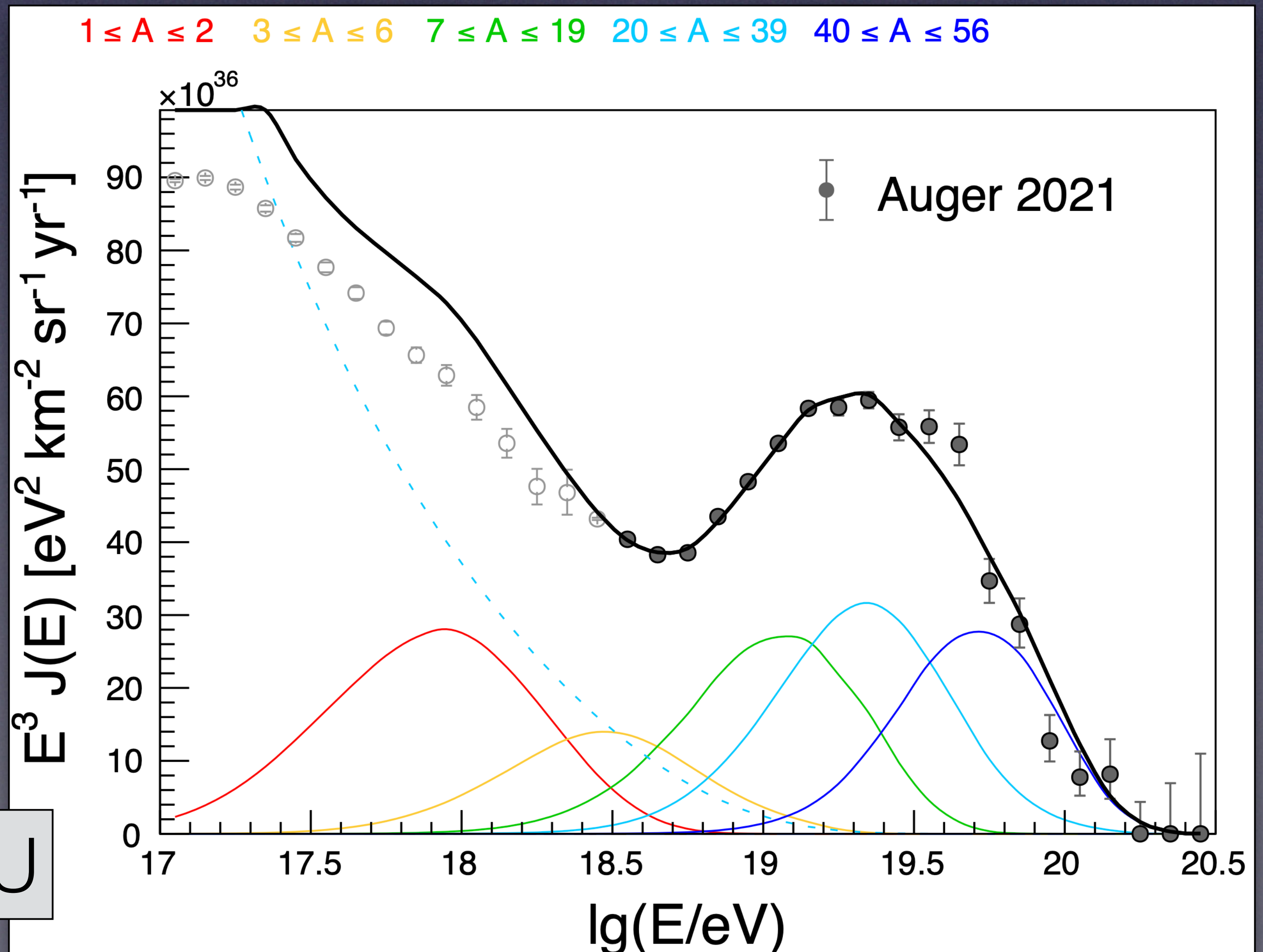
arXiv: 24… [astro-ph.HE] & PRL 2025

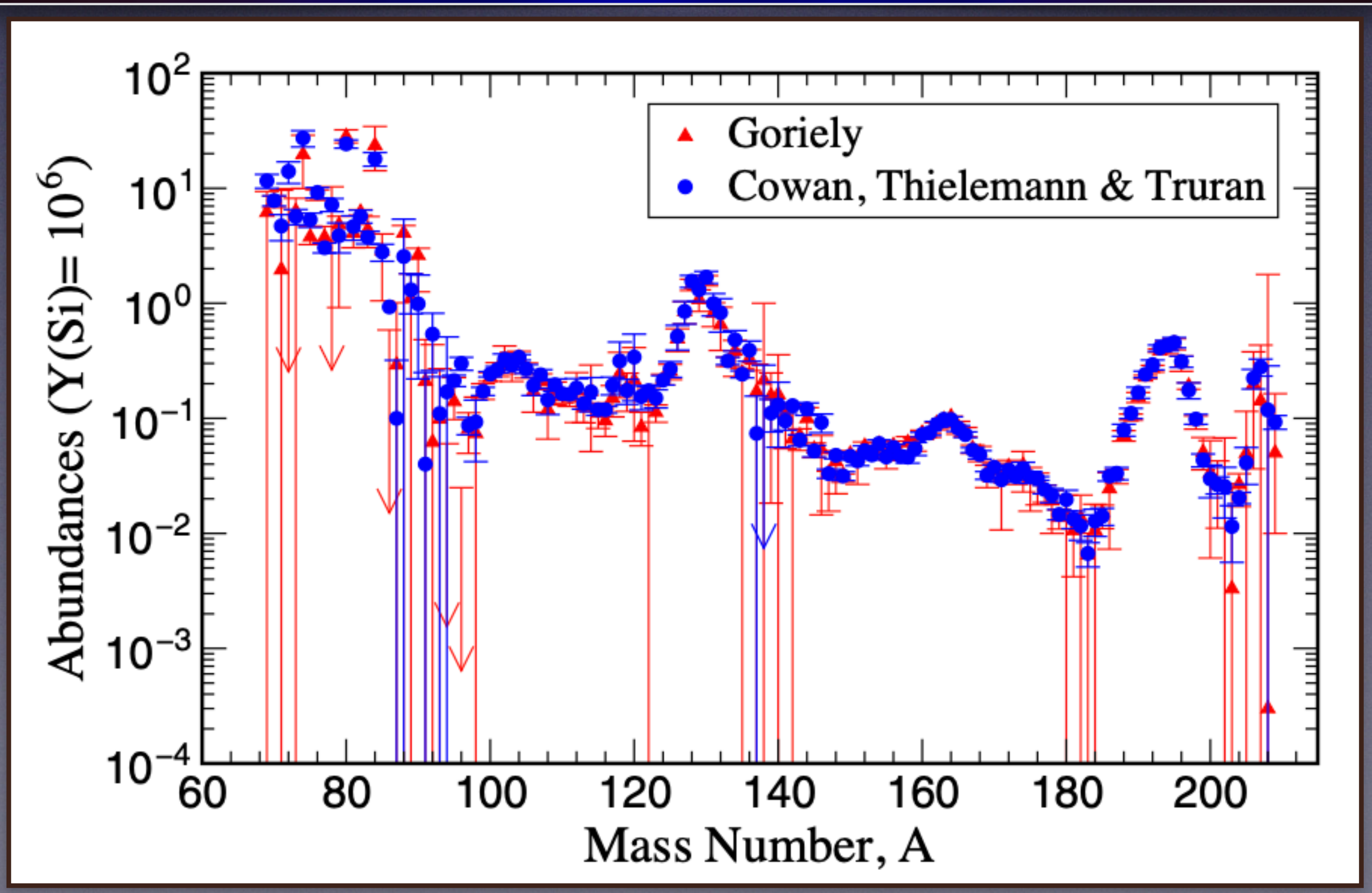
Topics for today

- Where in the merger ejecta does UHECR acceleration occur?
- What is the time profile for UHECR production?
  (coincidences between GW and EHE ν's?)
- Abundances of different UHECR nuclei?

Outflow after merger (Kasen+2017)







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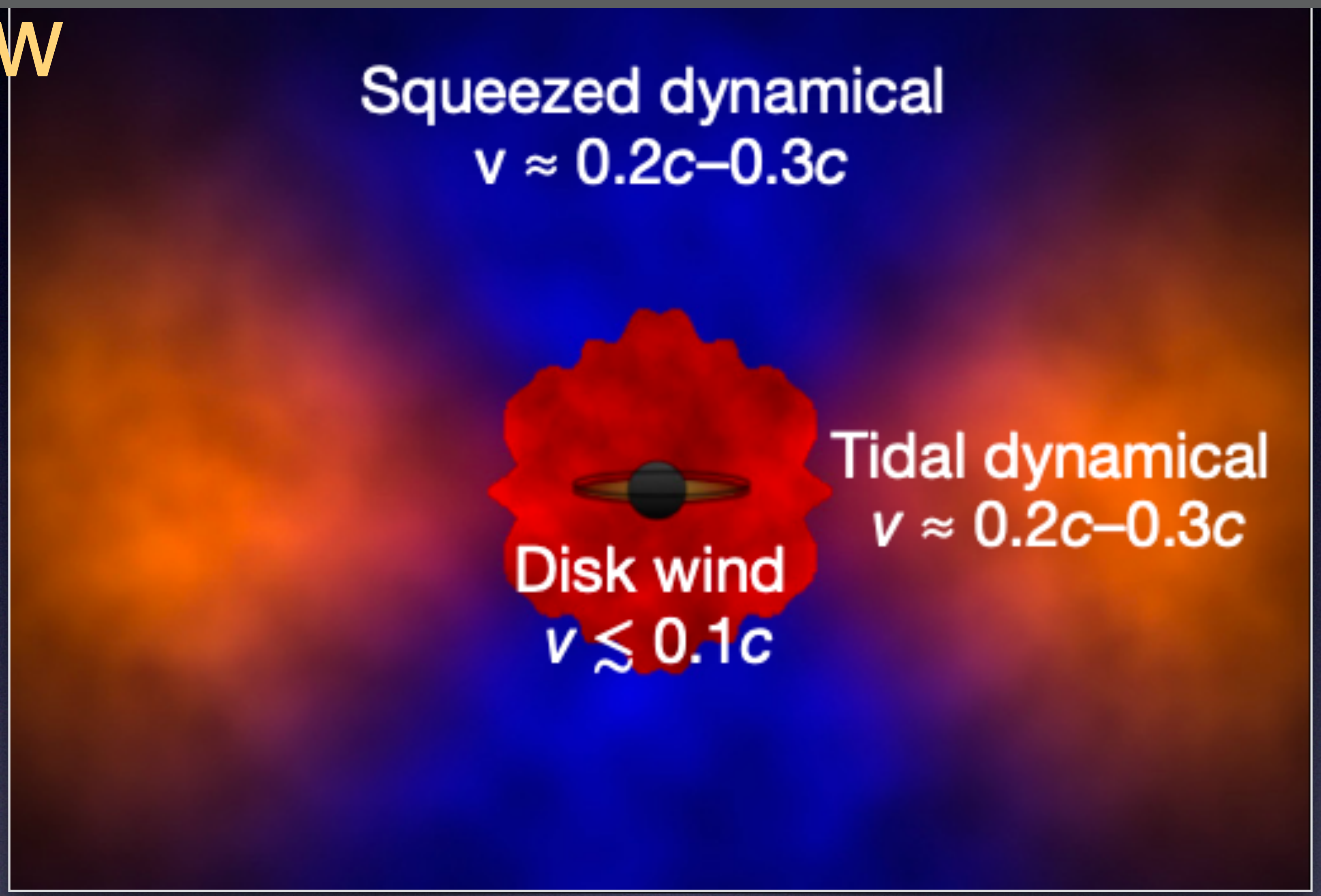
Topics for today

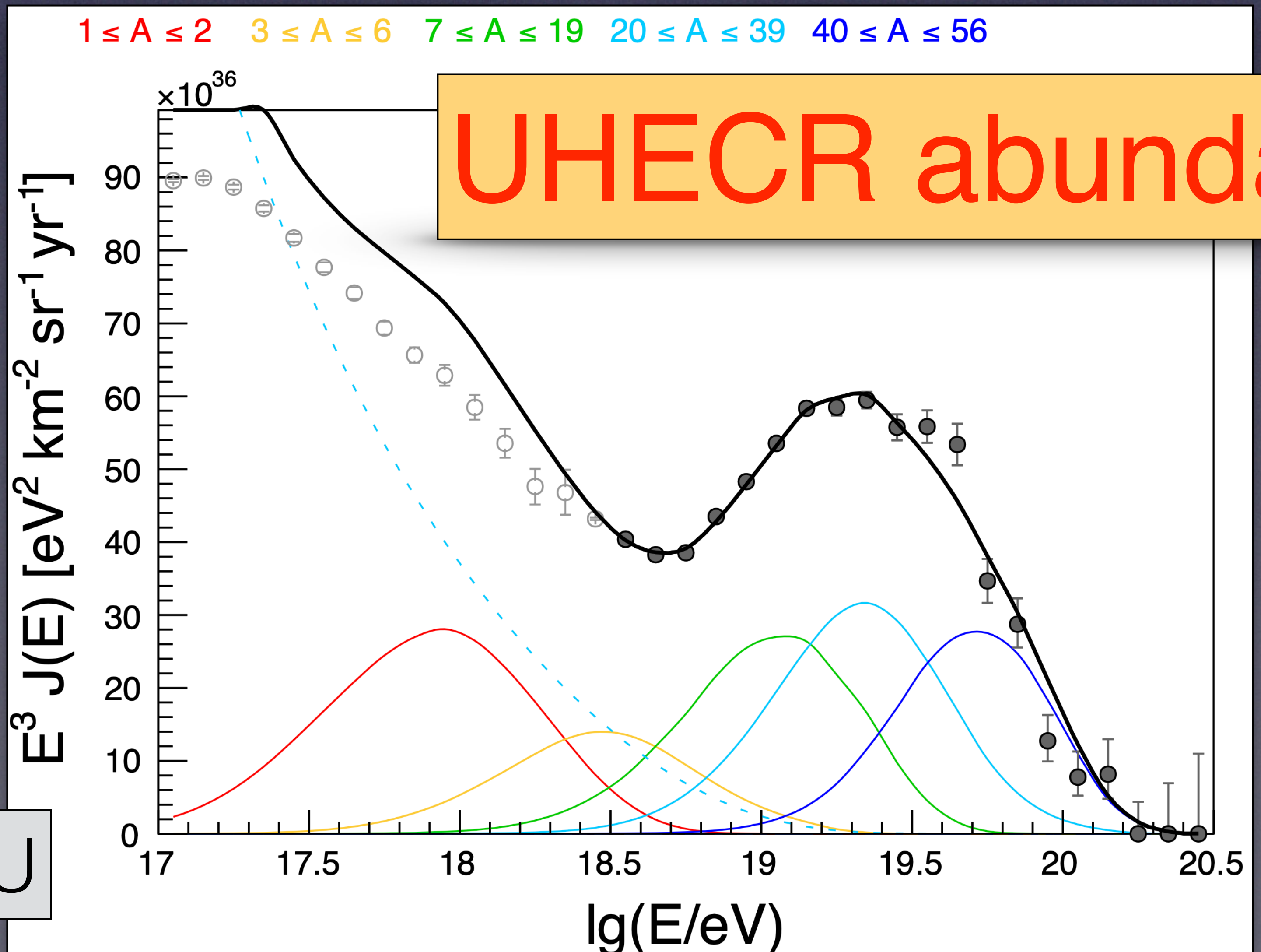
✓ UHECR acceleration occurs in the magnetized outflow
➜ Predicts rigidity cutoff R_{cut} and spectral shape

✓ UHECR production occurs ~ 1 day after merger
(coincidences between GW and EHE ν's…)

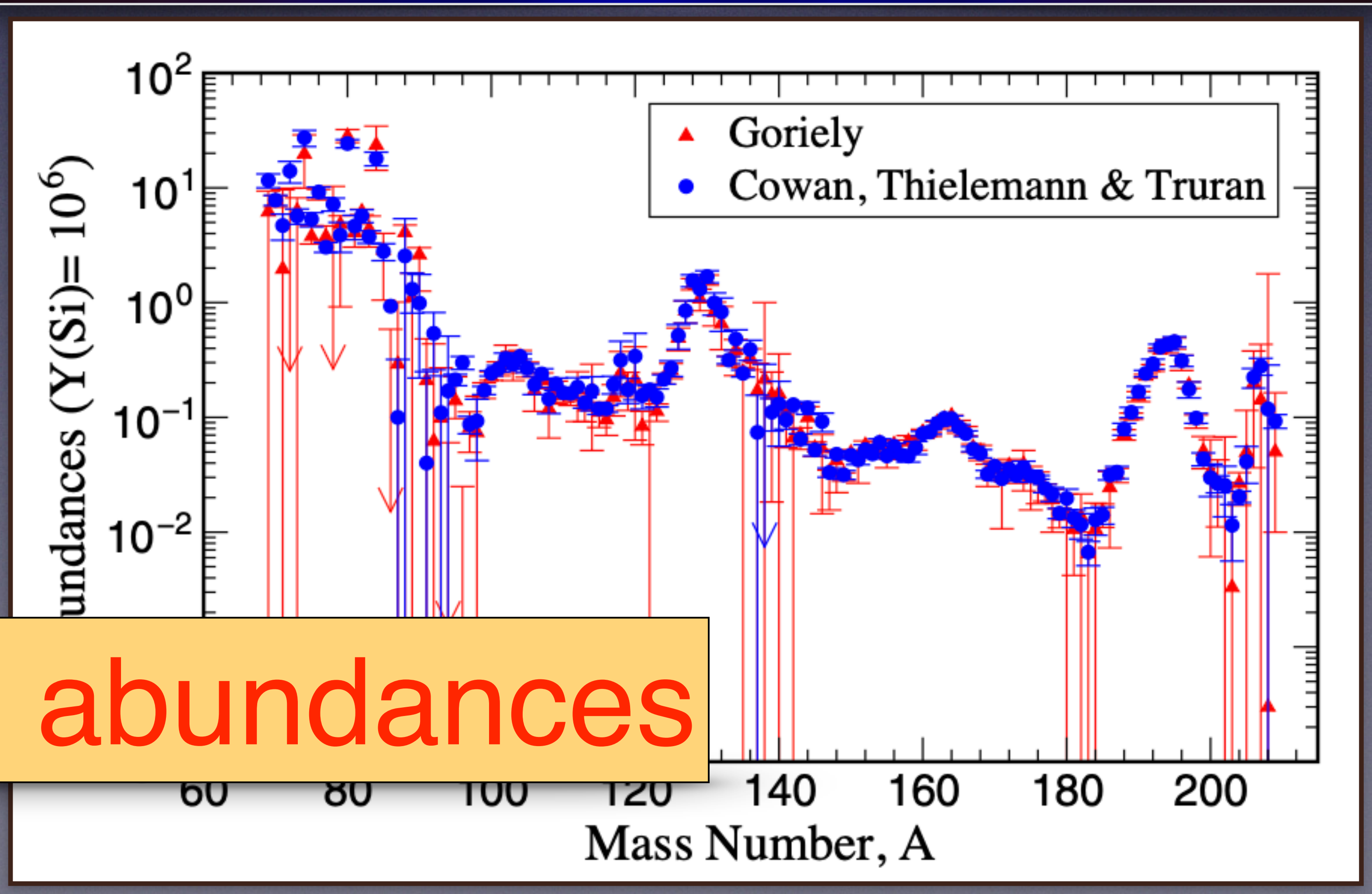
- **Abundances of different UHECR nuclei**

Outflow after merger (Kasen+2017)





UHECR abundances



r-process abundances

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Big Picture

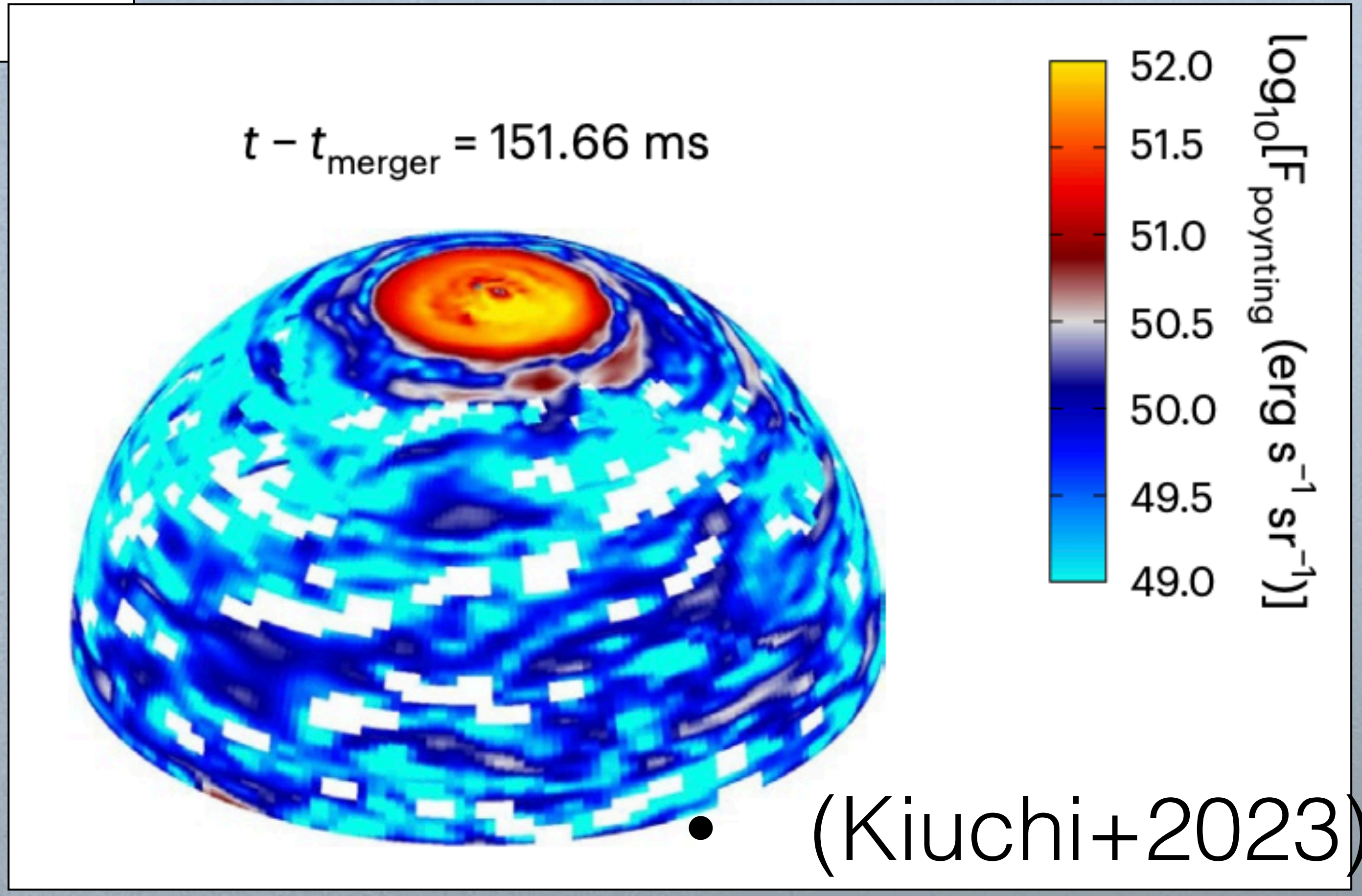
time

Gravitational Wave Emitted

grav-driven dynamo➜B
t=150ms, 500 km

cools to ~ 1 MeV
nucleosynthesis
~1 s: r~10^{10} cm

B drops till synch losses are subdominant
UHECR accel
~1 day: 10^{14} cm



• (Kiuchi+2023)

$\tau_{accel} / \tau_{synch\text{-}loss} \sim 1$

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Big Picture

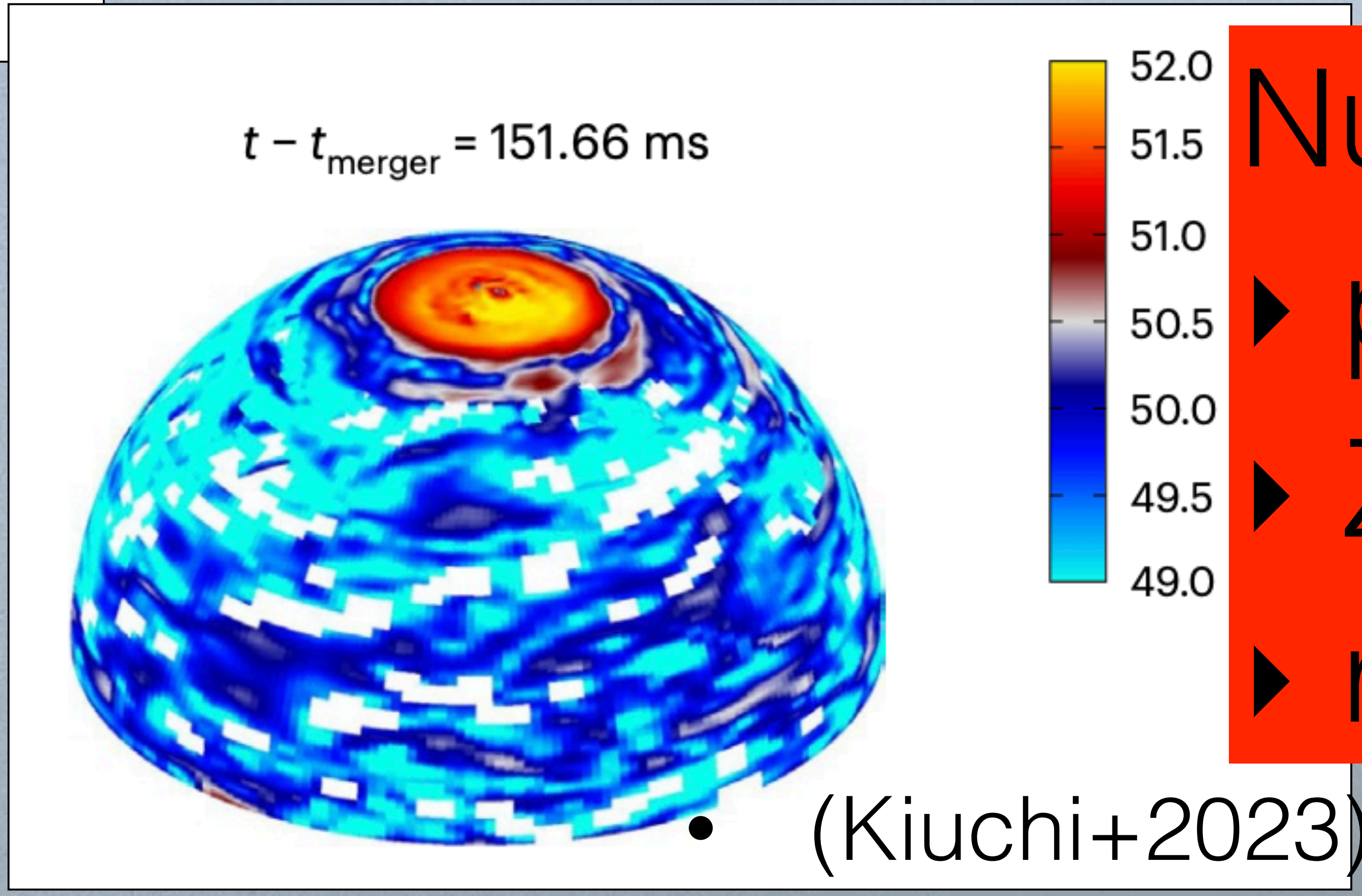
time →

Expands at v~ 0.1 c

Gravitational Wave Emitted

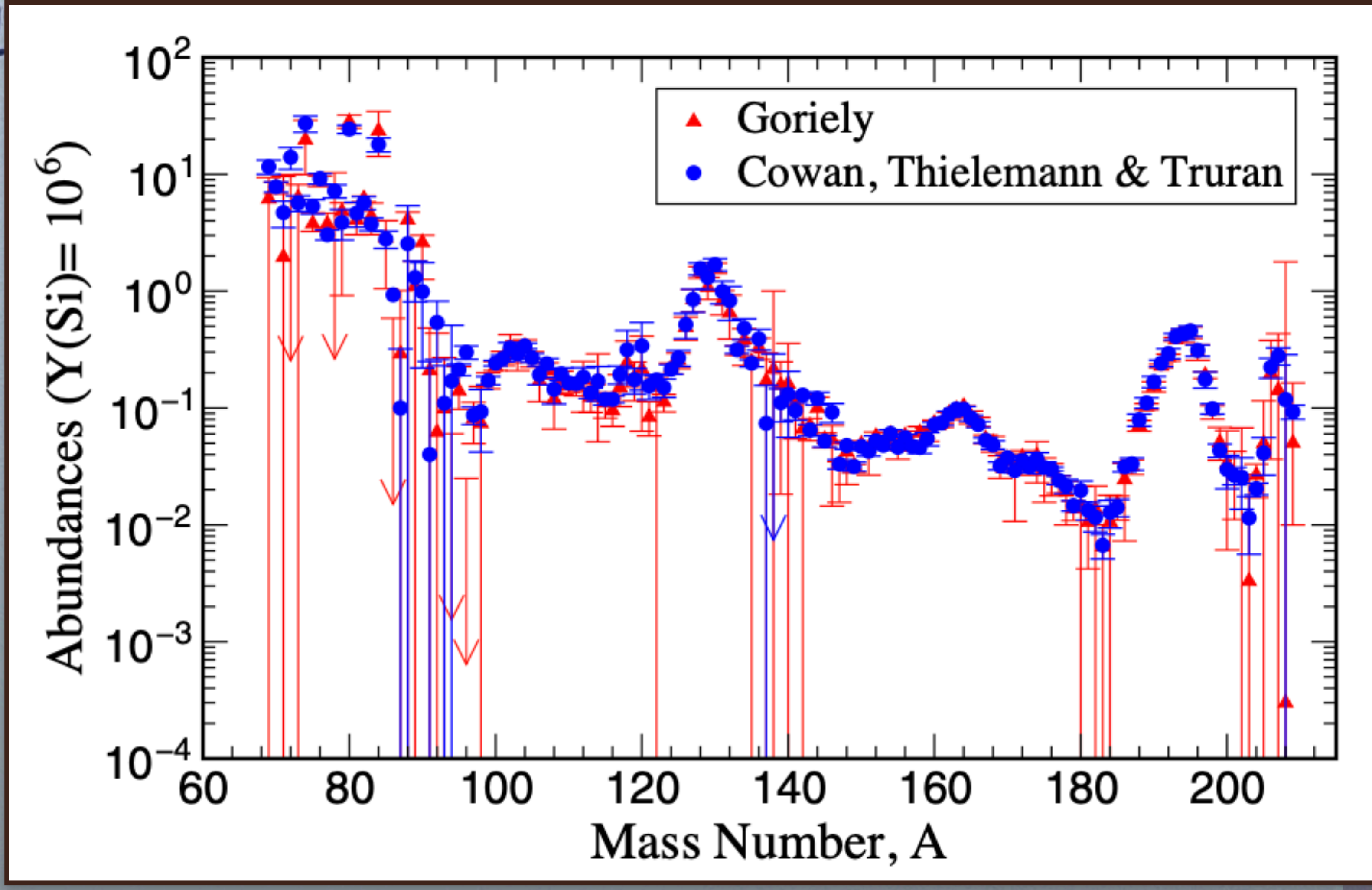
initialization of B
150ms, 500 km

cools to ~ 1 MeV nucleosynthesis
~1 s: r~10^{10} cm



- (Kiuchi+2023)

Nucleosynthesis:
- p,He in jet
- Z,N≥20 elsewhere
- r-process nuclei



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Big Picture

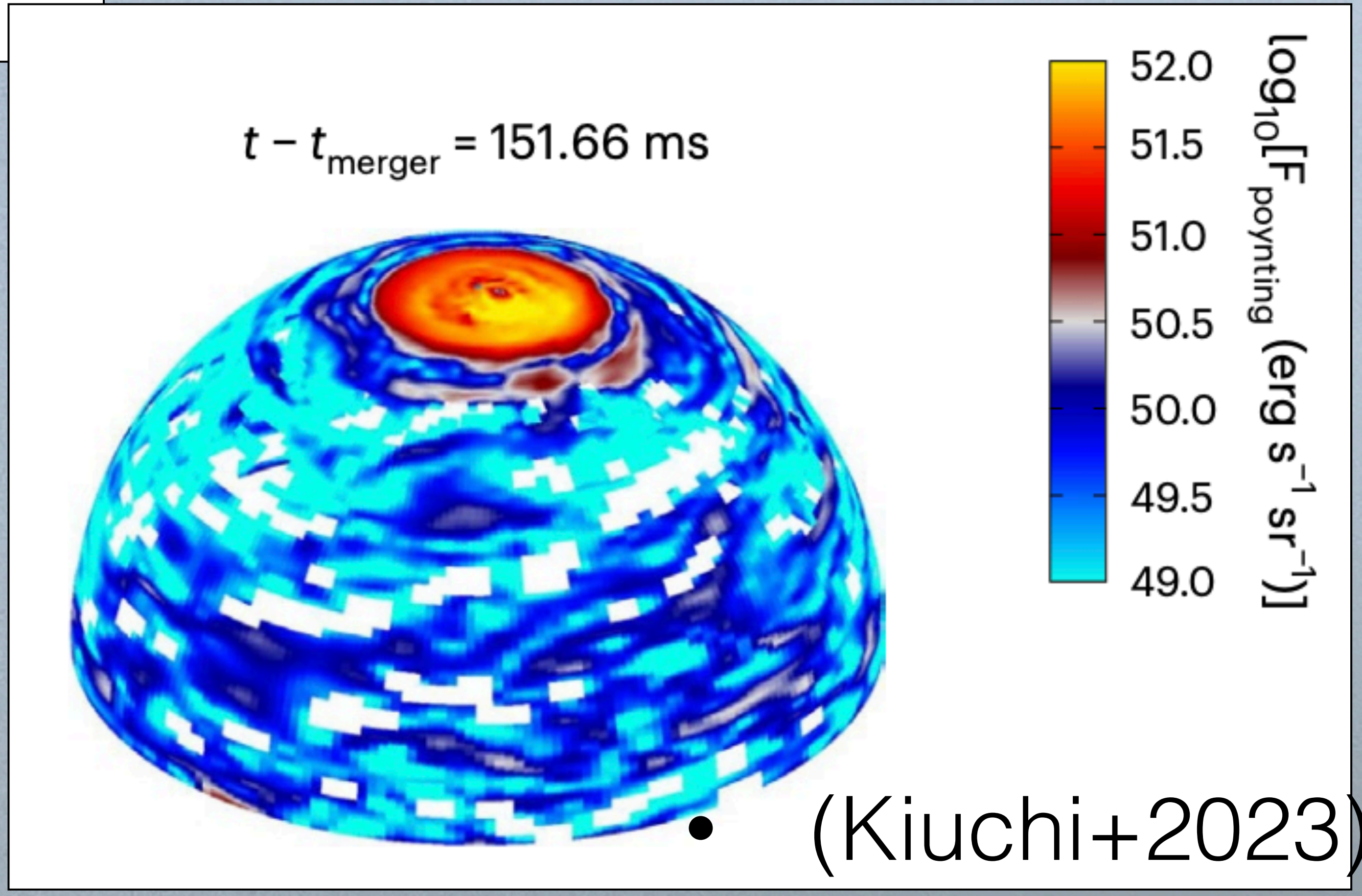
time → Expands at v~ 0.1 c

Gravitational Wave Emitted

initialization of B
150ms, 500 km

cools to ~ 1 MeV
nucleosynthesis
~1 s: r~10^{10} cm

UHECRs produced
~1 day: 10^{14} cm



- (Kiuchi+2023)

- some nuclei accelerated to KE > 100 MeV
- collisions ➜ breakup
  - range of A's
  - ***determines composition***

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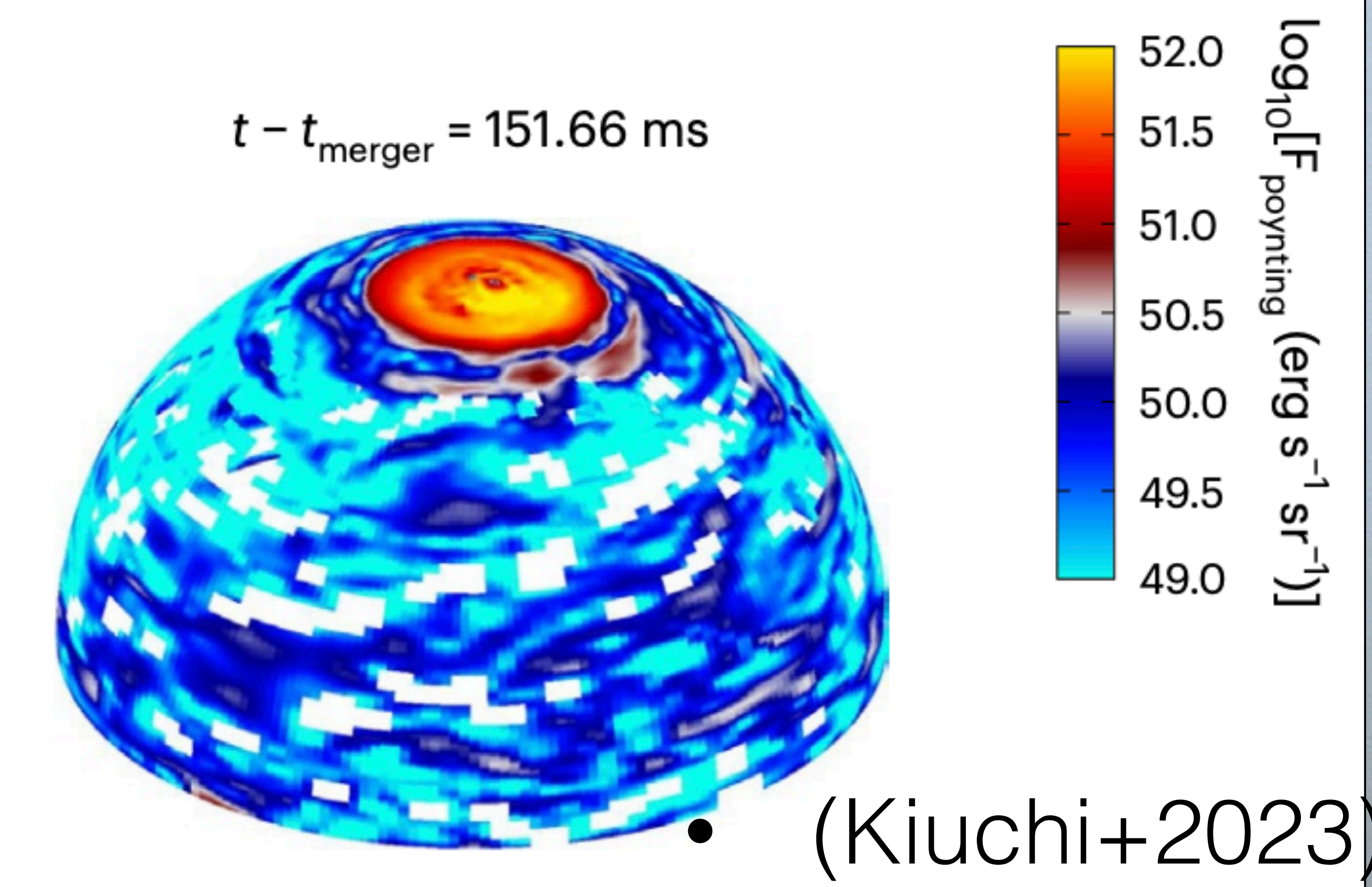
Big Picture

time →

Expands at v~ 0.1 c

Gravitational Wave Emitted

initialization of B
150ms, 500 km



- (Kiuchi+2023)

cools to ~ 1 MeV
nucleosynthesis
~1 s: r~10^{10} cm

B drops till
$\tau_{accel} / \tau_{synch\text{-}loss} \sim 1$
UHECR accel
~1 day: 10^{14} cm

Predict R_{cut} for different {Z,A}

Next: Predict UHECR composition given nuclear physics breakup cross sections

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Big Picture

time →

Expands at v~ 0.1 c

Gravitational Wave Emitted

initialization of B
150ms, 500 km

• (Kiuchi+2

UHECRs produced
~1 day: 10^{14} cm

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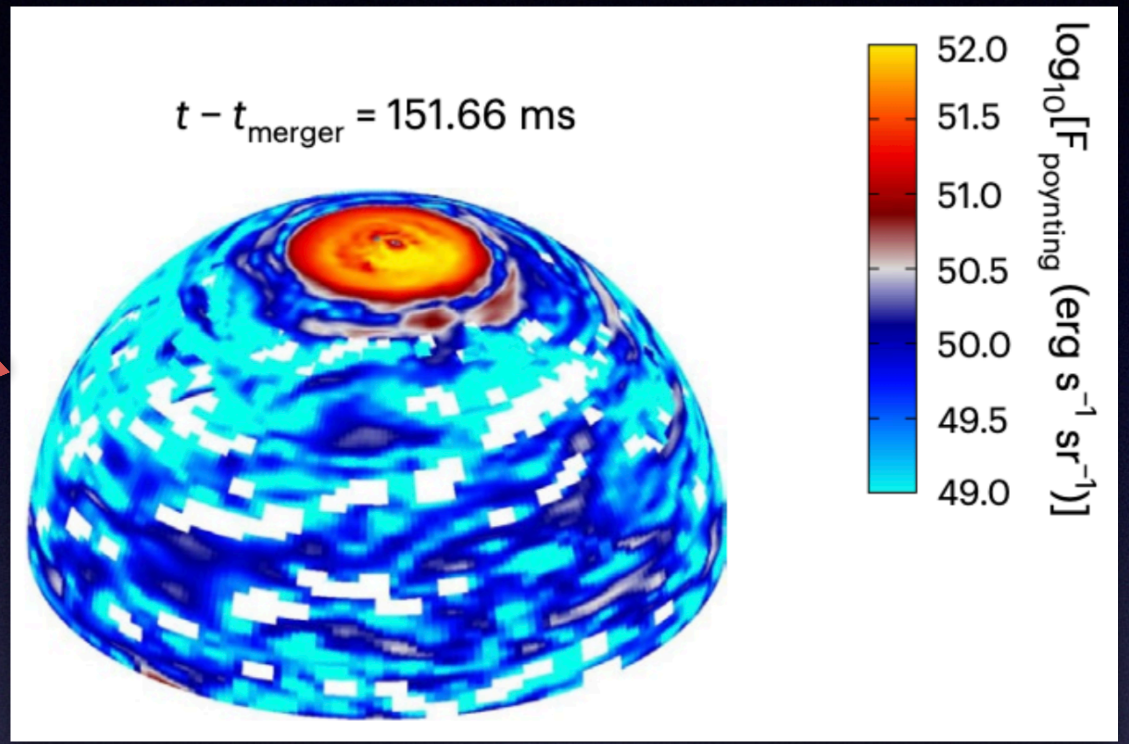
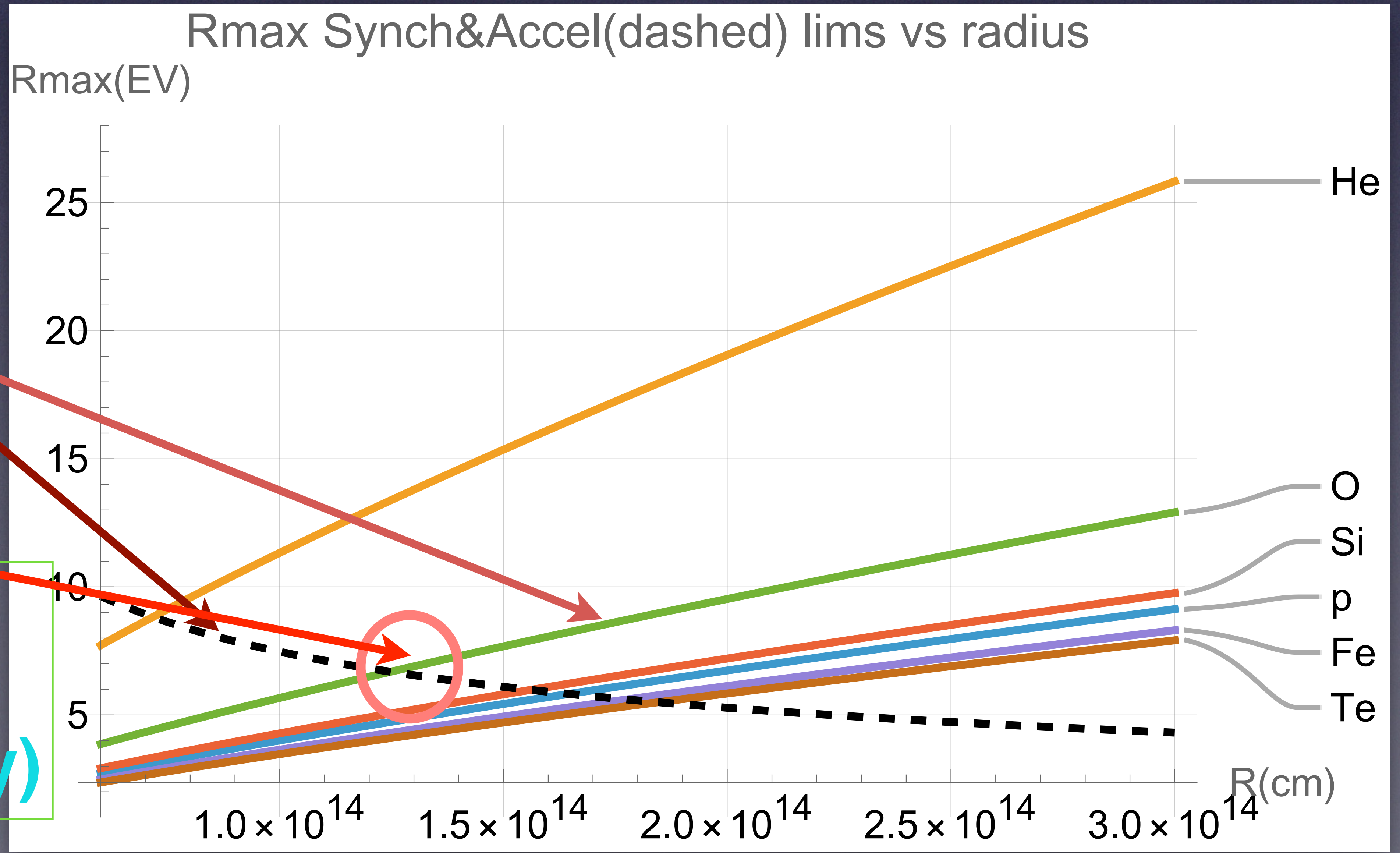
Predicting R_{cut} for in the magnetized turbulent outflow

- Initialize $B(r=500\text{ km}) = 3.3\ 10^{12}$ G; $L_{coh} \approx r/3$ (Kiuchi+2023)



- Homologous expansion: $B(r) = B_0\,(r/r_0)^{-3/2}$ (Rosswog+2014)
- Maximum rigidity CRs at radius r:
  - $R_{max}(r) = 0.65\ B(r)\ L_{coh}(r)$ (turb. accel. CFM24)
  - but require $\tau_{synch\text{-}loss}(A,Z,R,r) \gtrsim \tau_{accel}(R,B)$
  - ***➜ $R_{cut}(Z, A, r)$ is intersection***



R_{cut} {p,He,O,Si,Fe,Te} ≈ {6.2, 9.4, 7.1, 6.3, 6.0, 5.9} EV

agrees wtih Auger fit! (R_{cut} = 6.8 EV; factor-1.5 uncertainty)

Tests of BNS merger scenario

- ✓ Eroded r-process nuclei among UCRs (A>56)
- ✓ Successful prediction of R_{cut}
- Characteristic pattern of R_{cut} slightly varying with A reflecting synchrotron-limited acceleration
- flux of EHE neutrinos
- GW-ν coincidences for EHE ν's (E> PeV) - time delay ≈1 day

Test 1: E>150 EeV events are from r-process primaries

$E = R\, Z_{Te\text{-}Xe} \approx 4.5$ EV x (52-54) = 240 EeV

- $E_{OMG} \approx 250 \pm 70$ EeV, $E_{Amaterasu} \approx 212 \pm 25$ EeV
- Two highest energies observed are consistent with r-process expectation

$E_{cut,Fe} \approx 5$ EV x 26 = 130 EeV +1-σ E uncertainty ➜ 150 EeV

- Auger should look closely at the ~10 events with E > 150 EeV, to see i they favor A > 56.

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Test 2: EHE Neutrino production

- Neutrinos come from UHECRs:
  - spallation neutrons beta decay: $E_\nu \approx 10^{-3} (E_n \approx \boldsymbol{R}/2) \sim 2$ PeV
  - photo-pion production: $E_\nu \lesssim (E/A)/20 \sim \boldsymbol{R}/40 \sim 100$ PeV
- Time delay for $\boldsymbol{\nu}$ is > time for ejecta to expand to 10^{14} cm where UHECRs form:
  - $< v_{ej} > = 0.1$ c ➜ delay of O(day)

To do: make better estimate of rate of observing GW-nu coincidences

very crude: 1/yr with Cosmic Explorer, Einstein telescope & ICGen2

Path to predict UCR composition

- Initialize from r-process simulations
  - Depends on NS EoS & … but will improve
  - Beyond ~ 30^{o}, most nuclei are heavier than ~Fe
- Follow expansion as outflow radius increases
  - CRs accelerated to $\gtrsim$100 MeV collide, producing breakup
  - Lighter nuclei are formed
- Need PIC simulations
  - Expanding magnetized turbulence
  - “Uptake probability” into acceleration chain, to calculate absolute magnitude of CR component.

Need to know…

- BNS merger (simulation) community:
  - photon field at large radii, to calculate spallation
  - nucleosynthesis abundances
- Nuclear physics community:
  - breakup cross sections for reaction networks to predict UHECR composition
- Particle Acceleration/Plasma Physics community:
  - PIC simulation for spherically expanding system
  - PIC simulations to understand uptake

In sum: BNS mergers explain essential features of UHECRs

- **Spectrum from magnetized turbulence:** $\sim E^{-2.1}\ \mathrm{sech}[(E/E_{cut})^2]$
  - Minimal source-to-source variation
  - $R_{cut} \approx$ 6-9 EV (observed: $R_{cut} = 6.3^{+6.3}_{-2.3}$ EV)
- **First explanation for highest energy events:** EXCELLENT interpretation as originating in A~130 Tellurium/Xenon peak.

$$E = R\, Z_{Te\text{-}Xe} \approx 4.5\ \text{EV} \times (52\text{-}54) = 240\ \text{EeV}$$

$$E_{OMG} \approx 250 \pm 70\ \text{EeV},\quad E_{Amaterasu} \approx 212 \pm 25\ \text{EeV}$$

Thank you!

Source candidates vs key constraints

	$n_S \gtrsim 10^{-3.5}$ Mpc^{-3}	energy injection	ordinary galaxy	Universal R_{max}	Highest energy events
Powerful AGN	[✘]	✔	✘	✘	✘
Long GRBs	[✘]	✘	✘	✘	✘
TidalDistruption Events	?	?	✔	✘	✘
Accretion Shocks	?	?	[✘]	✘	✘
BNS mergers	✔	[✔]	✔	✔	✔

(All can satisfy Hillas size > Larmor radius)

ENERGY LOSS IN PROPAGATION ⇒ GZK Horizon

Greisen, Zatsepin, Kuzmin (GZK) bound

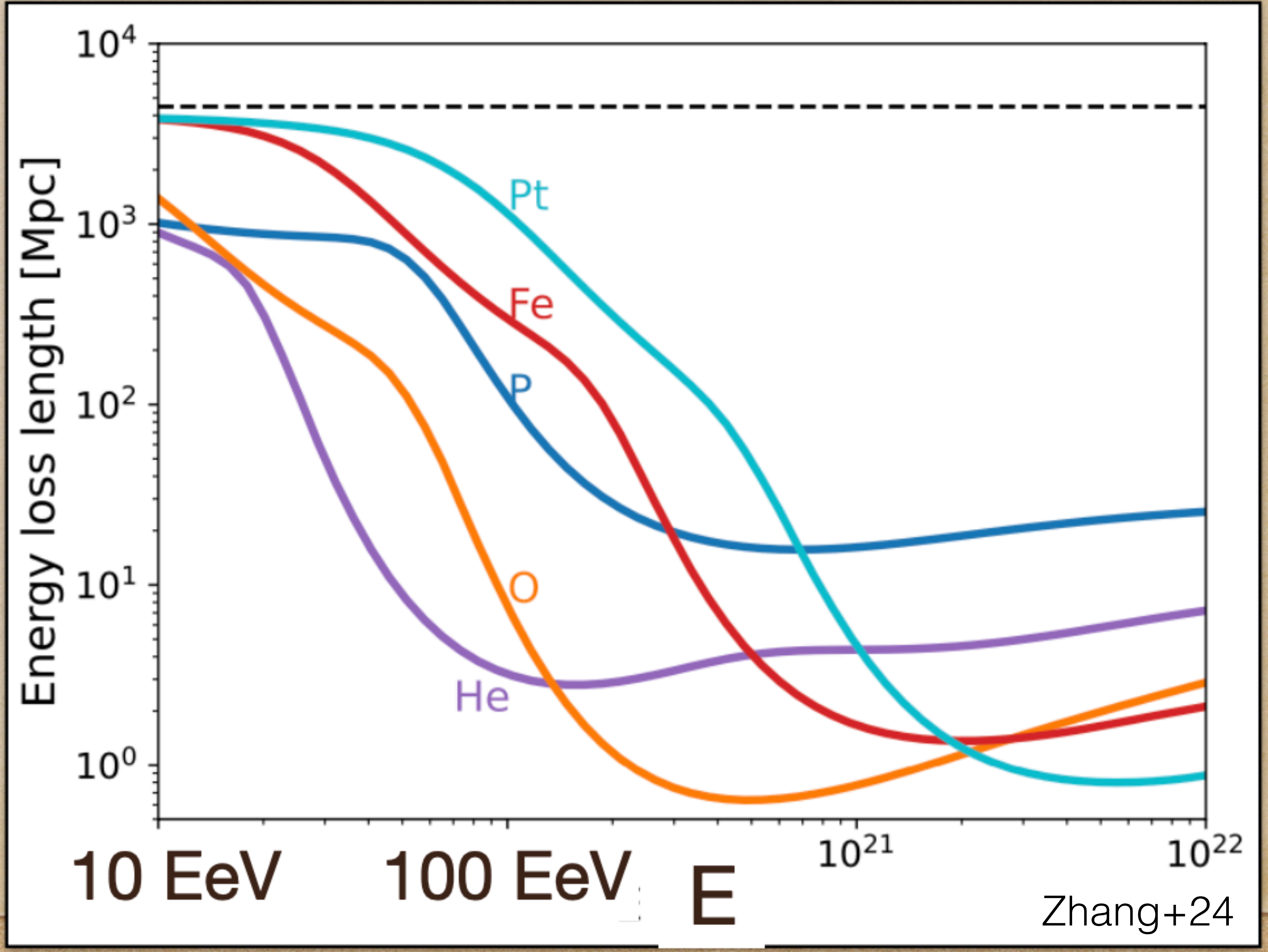
$p + \gamma_{CMB} \rightarrow \pi + N$; $p + \gamma_{CMB} \rightarrow e^+e^- p$

$A + \gamma_{EBL} \rightarrow (A\text{-}1) + N$; ...

$\langle dist \rangle_{E>8EeV} \approx 210$ Mpc

$\langle dist \rangle_{E>32EeV} \approx 70$ Mpc

(for ref: M87 is 16 Mpc away)



Spectrum for Magnetized Turbulence

$\sigma > 1$

Ultra-High-Energy Cosmic Rays Accelerated by Magnetically Dominated Turbulence

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ABSTRACT

Ultra-High-Energy Cosmic Rays (UHECRs), particles characterized by energies exceeding 10^{18} eV, are generally believed to be accelerated electromagnetically in high-energy astrophysical sources. One promising mechanism of UHECR acceleration is magnetized turbulence. We demonstrate from first principles, using fully kinetic particle-in-cell simulations, that magnetically dominated turbulence accelerates particles on a short timescale, producing a power-law energy distribution with a rigidity-dependent, sharply defined cutoff well approximated by the form $f_{\rm cut}(E, E_{\rm cut}) = {\rm sech}\left[(E/E_{\rm cut})^2\right]$. Particle escape from the turbulent accelerating region is energy-dependent, with $t_{\rm esc} \propto E^{-\delta}$ and $\delta \sim 1/3$. The resulting particle flux from the accelerator follows $dN/dEdt \propto E^{-s}{\rm sech}\left[(E/E_{\rm cut})^2\right]$, with $s \sim 2.1$. We fit the Pierre Auger Observatory's spectrum and composition measurements, taking into account particle interactions between acceleration and detection, and show that the turbulence-associated energy cutoff is well supported by the data, with the best-fitting spectral index being $s = 2.1^{+0.06}_{-0.13}$. Our first-principles results indicate that particle acceleration by magnetically dominated turbulence may constitute the physical mechanism responsible for UHECR acceleration.

Fully kinetic treatment of the plasma

- The evolution of the particle density $f_s(\boldsymbol{x}, \boldsymbol{p}, t)$ of species s in a collisionless plasma is described by the Vlasov equation

$$\frac{\partial f_s}{\partial t} + \frac{\boldsymbol{p}}{m_s \gamma_s} \cdot \nabla_{\boldsymbol{x}} f_s + \boldsymbol{F} \cdot \nabla_{\boldsymbol{p}} f_s = 0$$

where $\gamma_s^2 = 1 + \dfrac{|\boldsymbol{p}|^2}{m_s^2 c^2}$ and $\boldsymbol{F} = q_s \left(\boldsymbol{E} + \dfrac{\boldsymbol{p}}{\gamma_s m_s c} \times \boldsymbol{B} \right)$.

- $\boldsymbol{E}(\boldsymbol{x}, t)$ and $\boldsymbol{B}(\boldsymbol{x}, t)$ are determined from Maxwell's equations

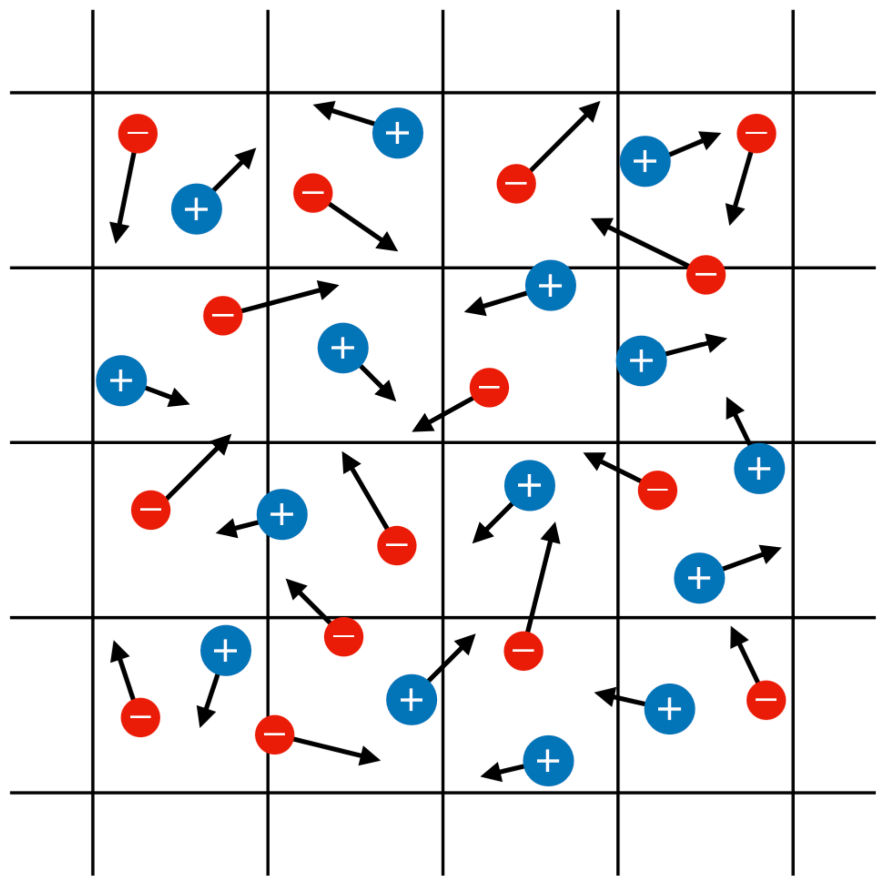
$$\frac{\partial \boldsymbol{E}}{\partial t} - c\,{\rm curl}\boldsymbol{B} = -4\pi \boldsymbol{J}\,, \qquad {\rm div}\boldsymbol{E} = 4\pi\rho\,,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + c\,{\rm curl}\boldsymbol{E} = 0\,, \qquad {\rm div}\boldsymbol{B} = 0\,,$$

where the source terms are computed by

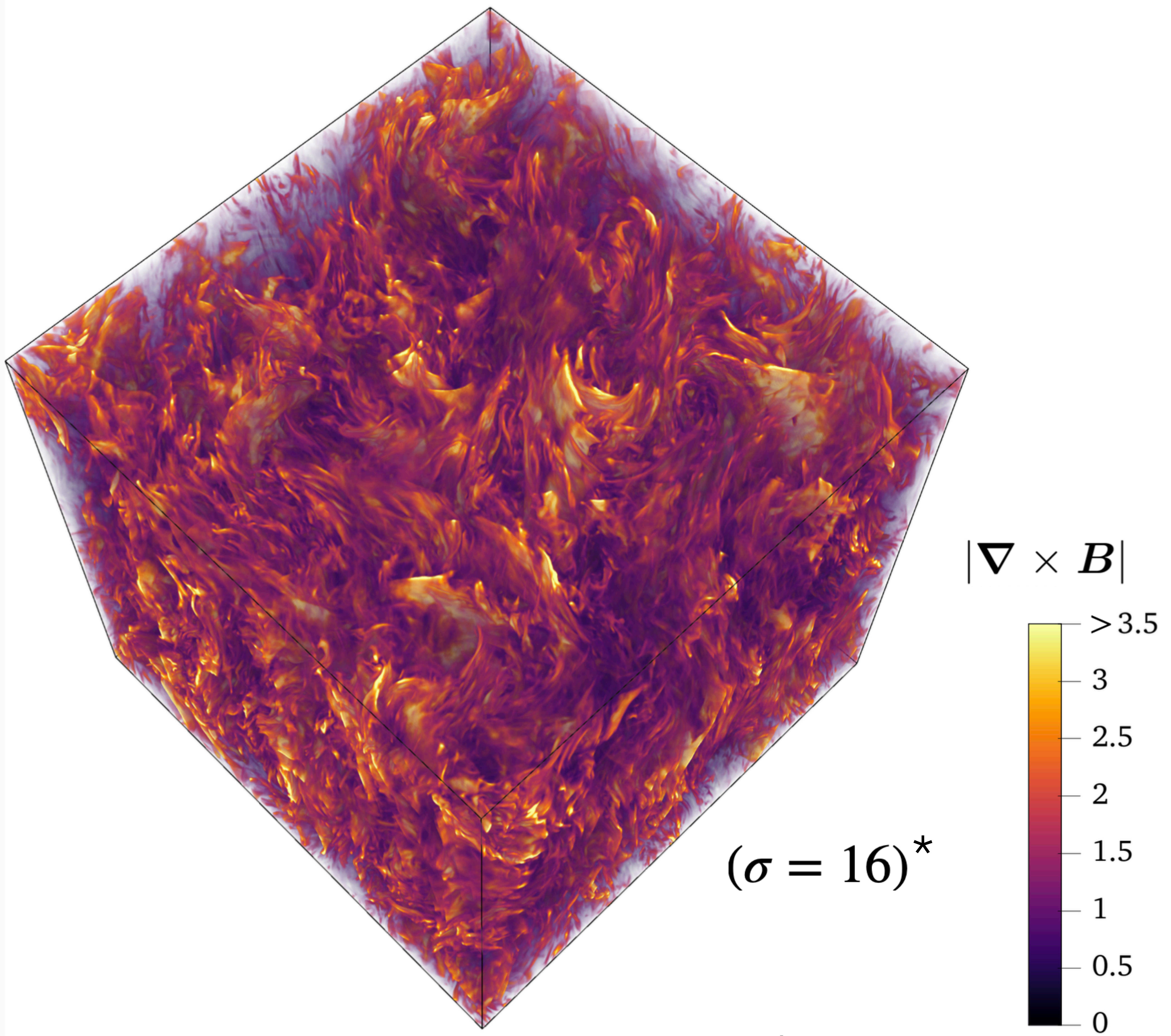
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\boldsymbol{p}\,, \qquad \boldsymbol{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\boldsymbol{p}}{\gamma_s} d\boldsymbol{p}\,.$$

- Solution via particle-in-cell method

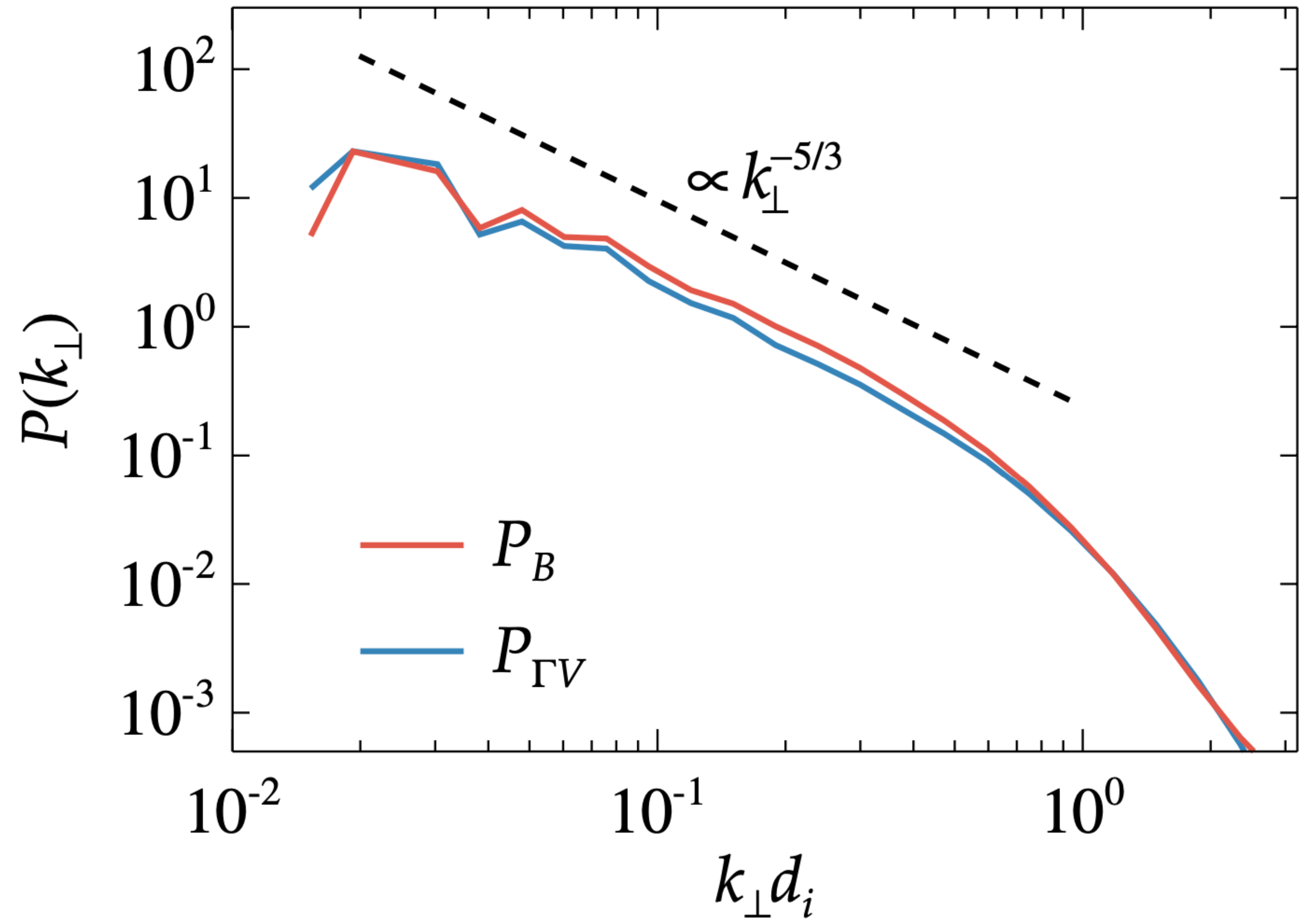


PIC code: TRISTAN-MP (Spitkovsky 2005)

Magnetically dominated turbulence from first-principles PIC simulations

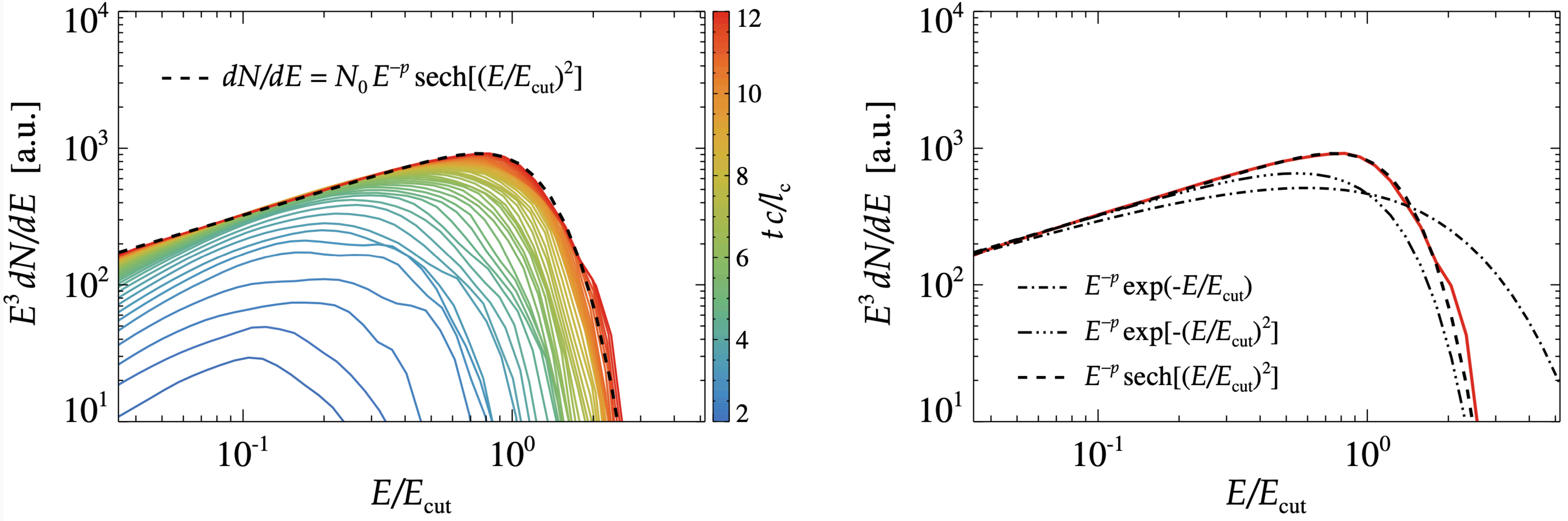


*σ ≈ U_{mag}/KEden



- The large computational domain allow us to capture both the MHD cascade at large scales and the kinetic cascade at small scales

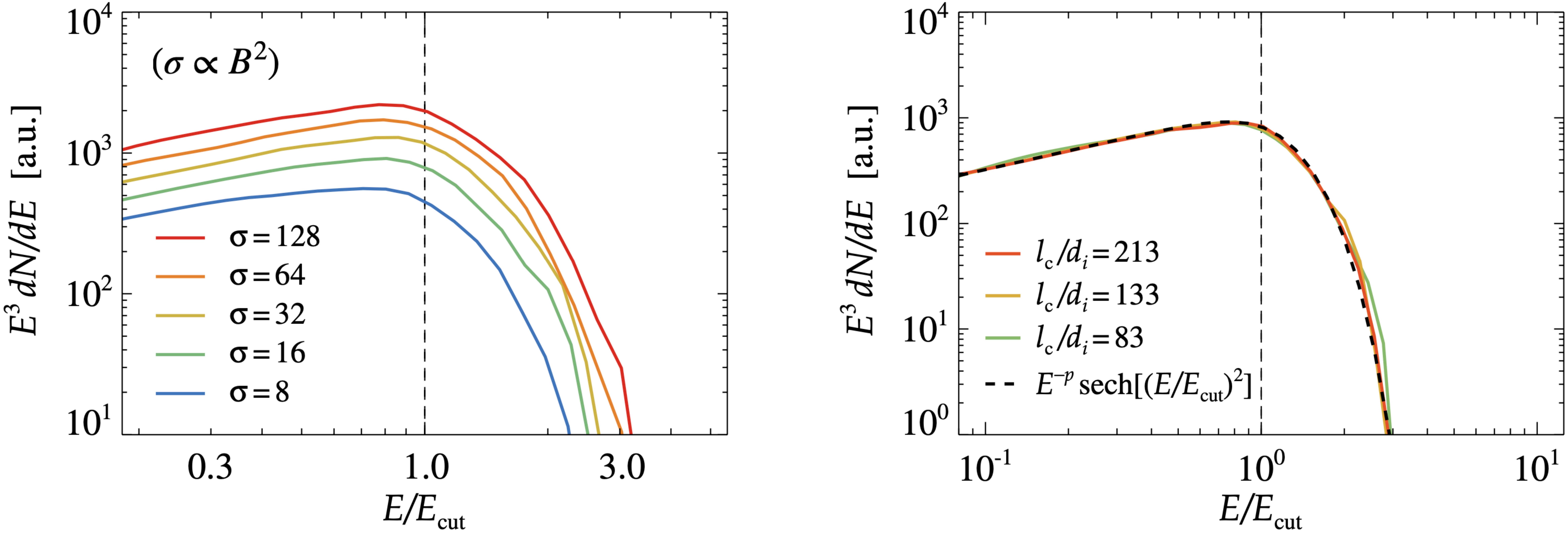
Particle acceleration via magnetized turbulence: nonthermal particle spectrum



- magnetized turbulence accelerates particles into a spectrum of the form:

$$\frac{dN}{dE} = N_0 E^{-p} f_{\rm cut}\left(E, E_{\rm cut}\right) \quad \text{with} \quad f_{\rm cut}\left(E, E_{\rm cut}\right) = \text{sech}\left[\left(E/E_{\rm cut}\right)^2\right]$$

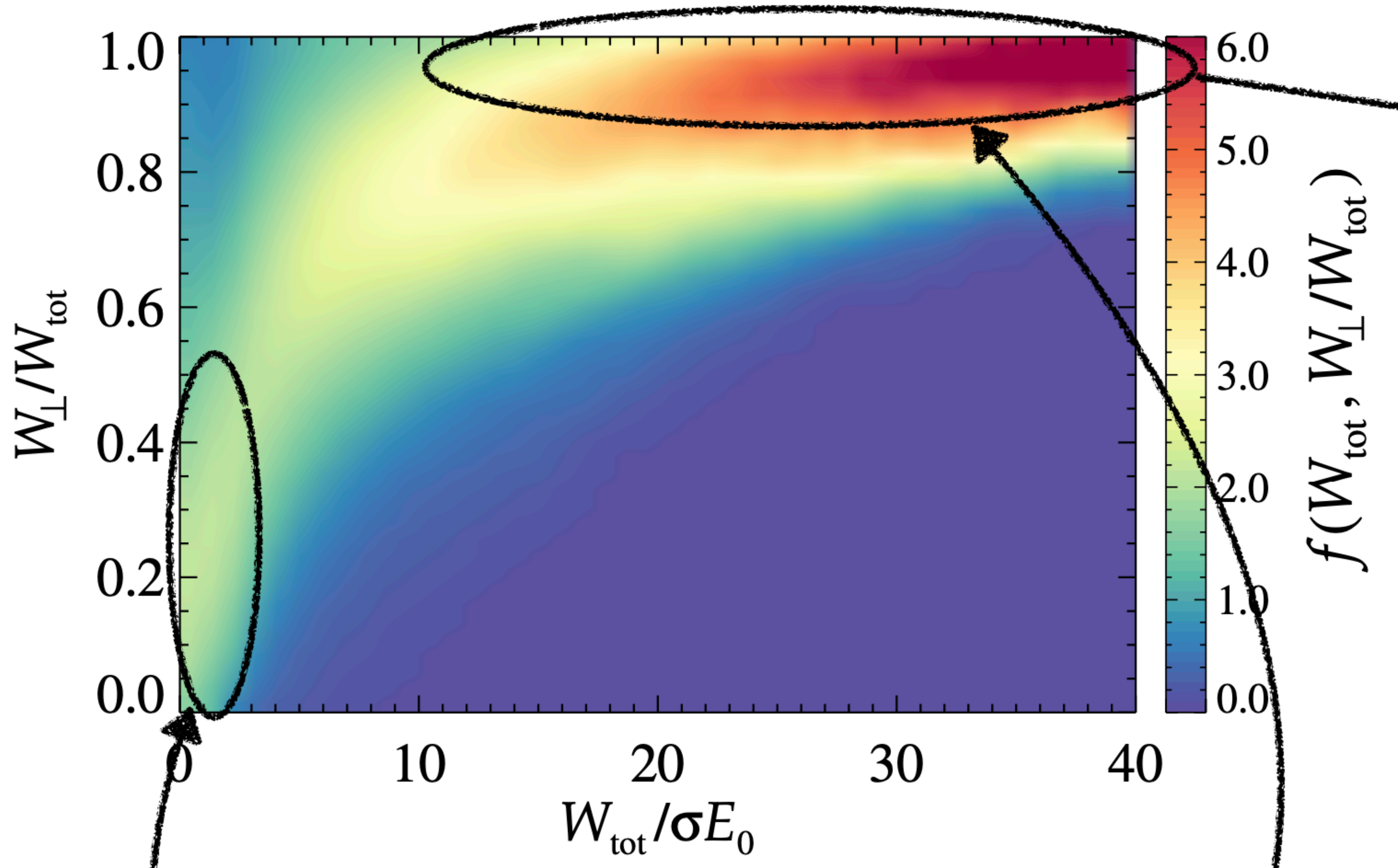
Particle acceleration via magnetized turbulence: cutoff energy

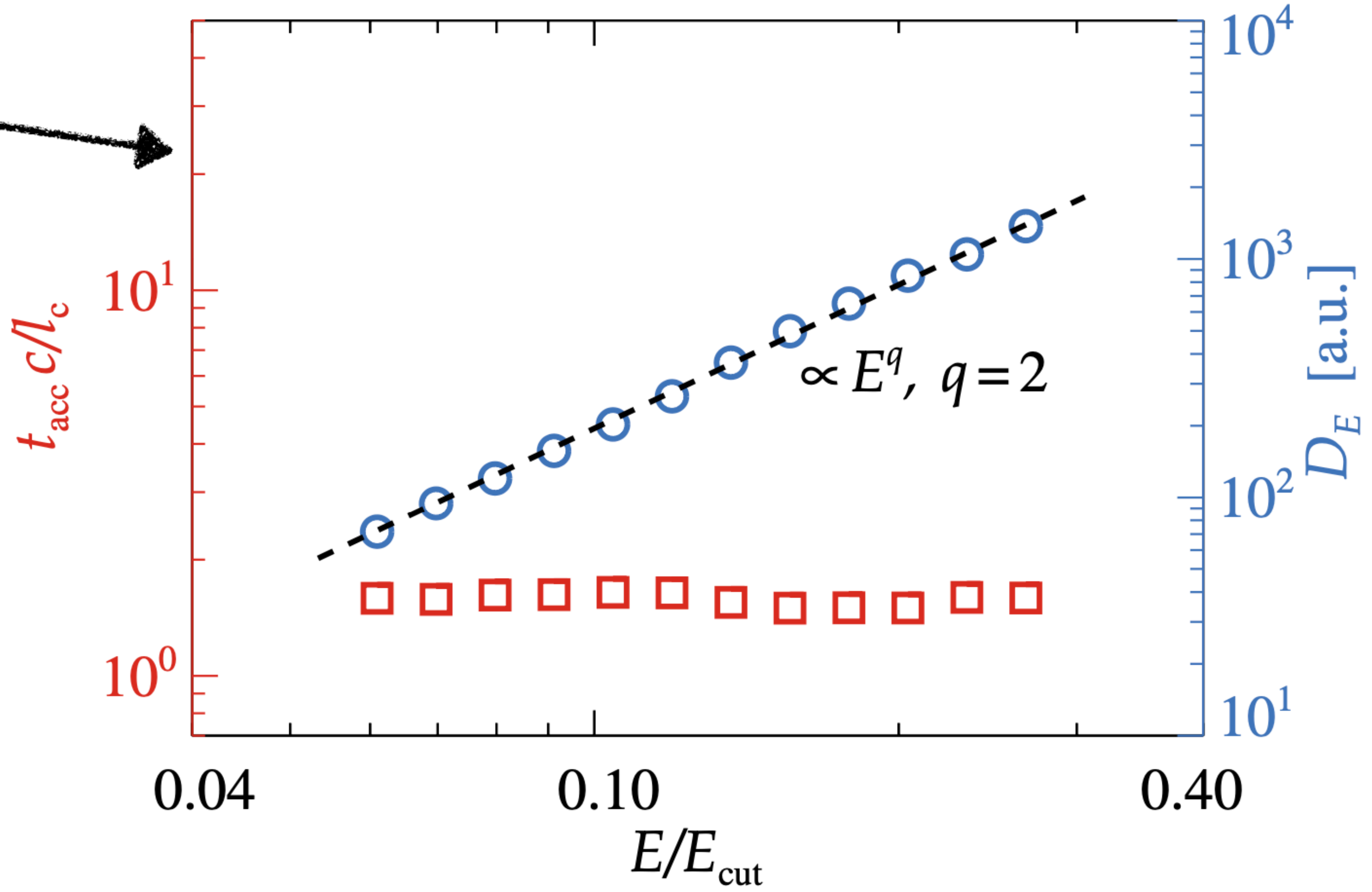


- cutoff $\boxed{\mathrm{sech}[(E/E_{cut})^2]}$ scales with $\boxed{E_{cut} = ZeR_{cut} = Ze(B_{rms}\kappa l_c)}$, where $\boxed{\kappa = 0.65}$ from the fits
- magnetized turbulence does accelerate particles to the "Hillas limit" if one assumes $R_{size} = l_c$

$R_{cut} = 0.65\ B\ L_{coh}$

Particle acceleration via magnetized turbulence: particle acceleration elements





$$W_{\parallel,\perp}(t) = q\int_0^t \mathbf{E}_{\parallel,\perp}(t')\cdot\mathbf{v}(t')\,dt'$$

$$\mathbf{E}_\parallel = (\mathbf{E}\cdot\mathbf{B})\mathbf{B}/B^2$$

$$\mathbf{E}_\perp = \mathbf{E} - \mathbf{E}_\parallel \simeq -(\mathbf{V}/c)\times\mathbf{B}$$

$$t_{acc} = \frac{E^2}{4D_E} \simeq \frac{1}{4\kappa_{acc}\delta u^2}\frac{B_{rms}^2}{\delta B_{rms}^2}\frac{l_c}{c}$$

$\kappa_{acc} \simeq 0.1$ from PIC simulations (see Comisso & Sironi 2019)

Particle acceleration via magnetized turbulence: spactrum out o

- residence time within the accelerator:

$$t_{esc} \simeq \frac{L^2}{\lambda_s c} \simeq \frac{L^2}{l_c c}\left(\frac{E_{cut}}{E}\right)^{\delta} \propto E^{-\delta}$$

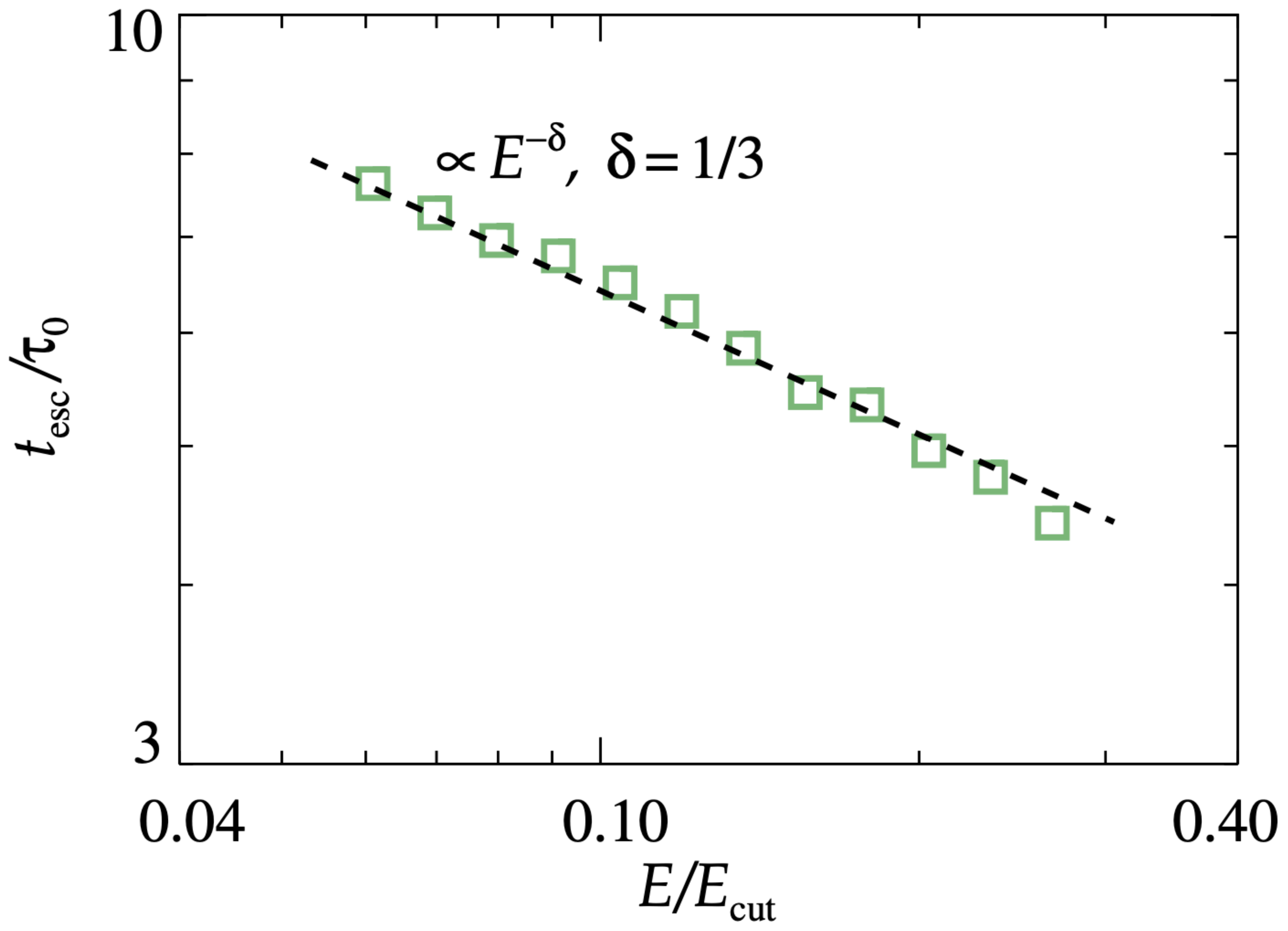
- flux of particles escaping the accelerator is given by

$$\phi(E) = \frac{dN}{dEdt} = \frac{1}{t_{esc}}\frac{dN}{dE} \propto E^{-s}\,\mathrm{sech}\left[\left(E/E_{cut}\right)^2\right]$$

with $s = p + \delta \sim 2.1$

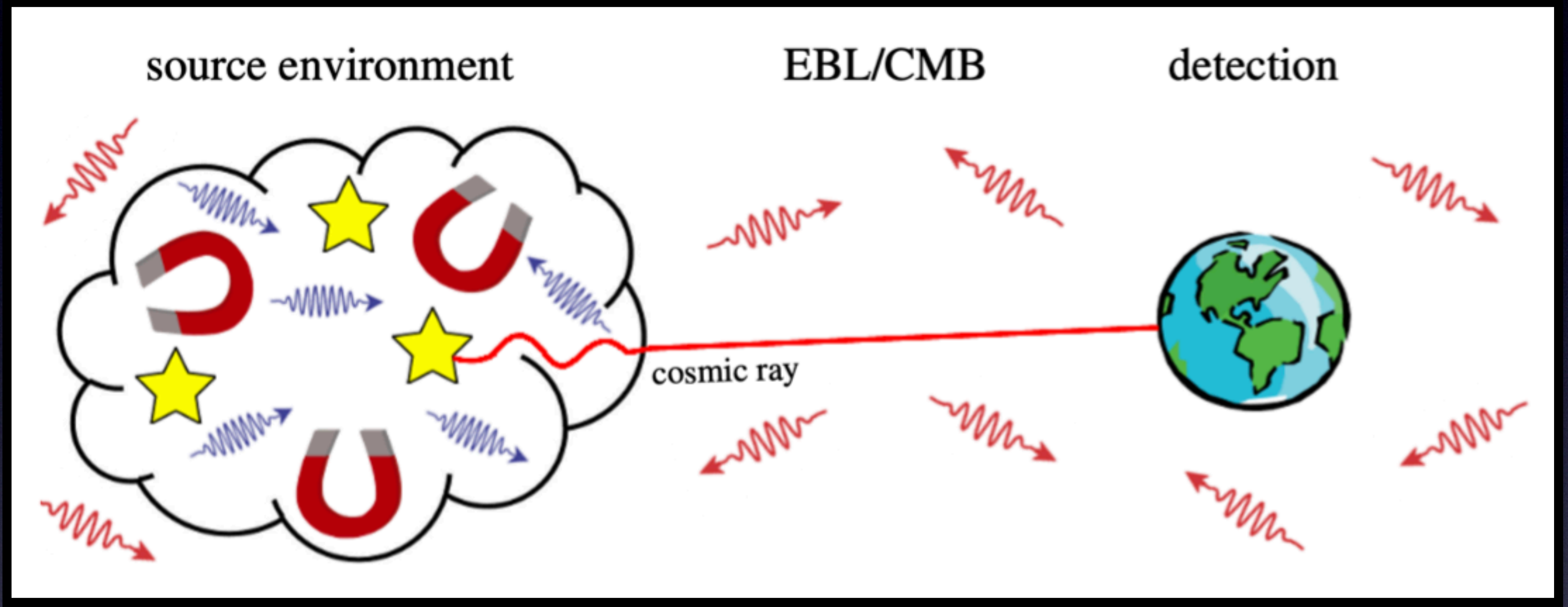
$p \sim 2.4$

$\delta \sim 1/3$

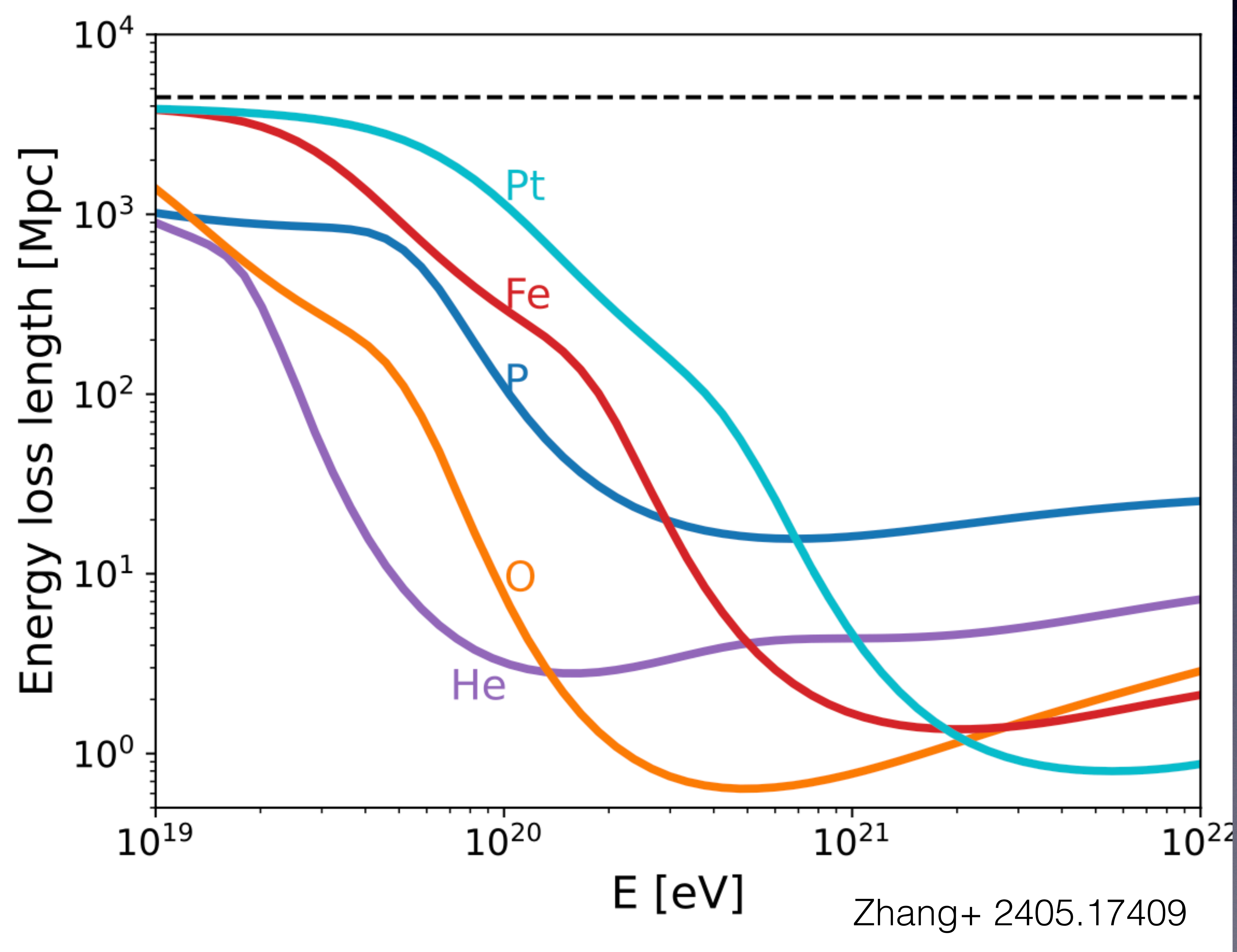


from PIC simulations of highly magnetized ($\sigma \gg 1$) turbulence

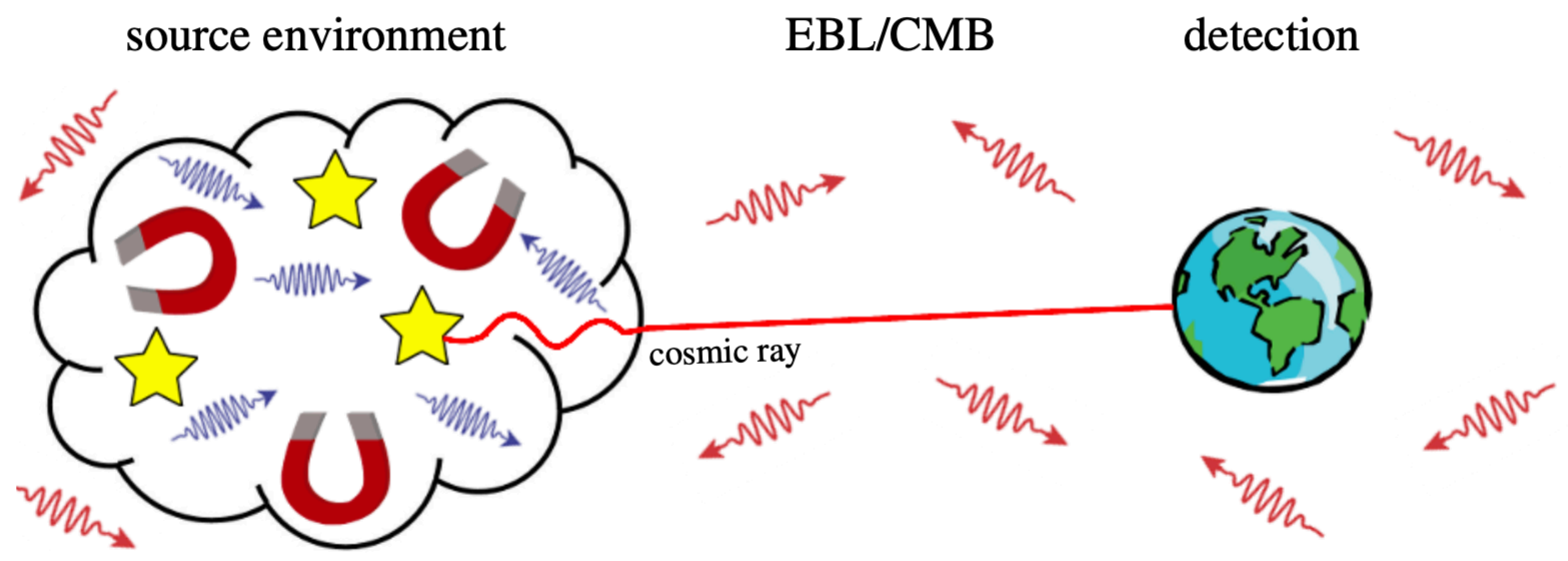
Interactions in surroundings and propagation from source



- Flexible treatment of processing leaving source Unger, GF, Anchordoqui 2015, Muzio+GF 2023
- Hardens the spectrum, since highest rigidity particles escape more readily
- UCRs spallate in source environment, CMB and EGBL: E/A (thus E/Z) approximately constant



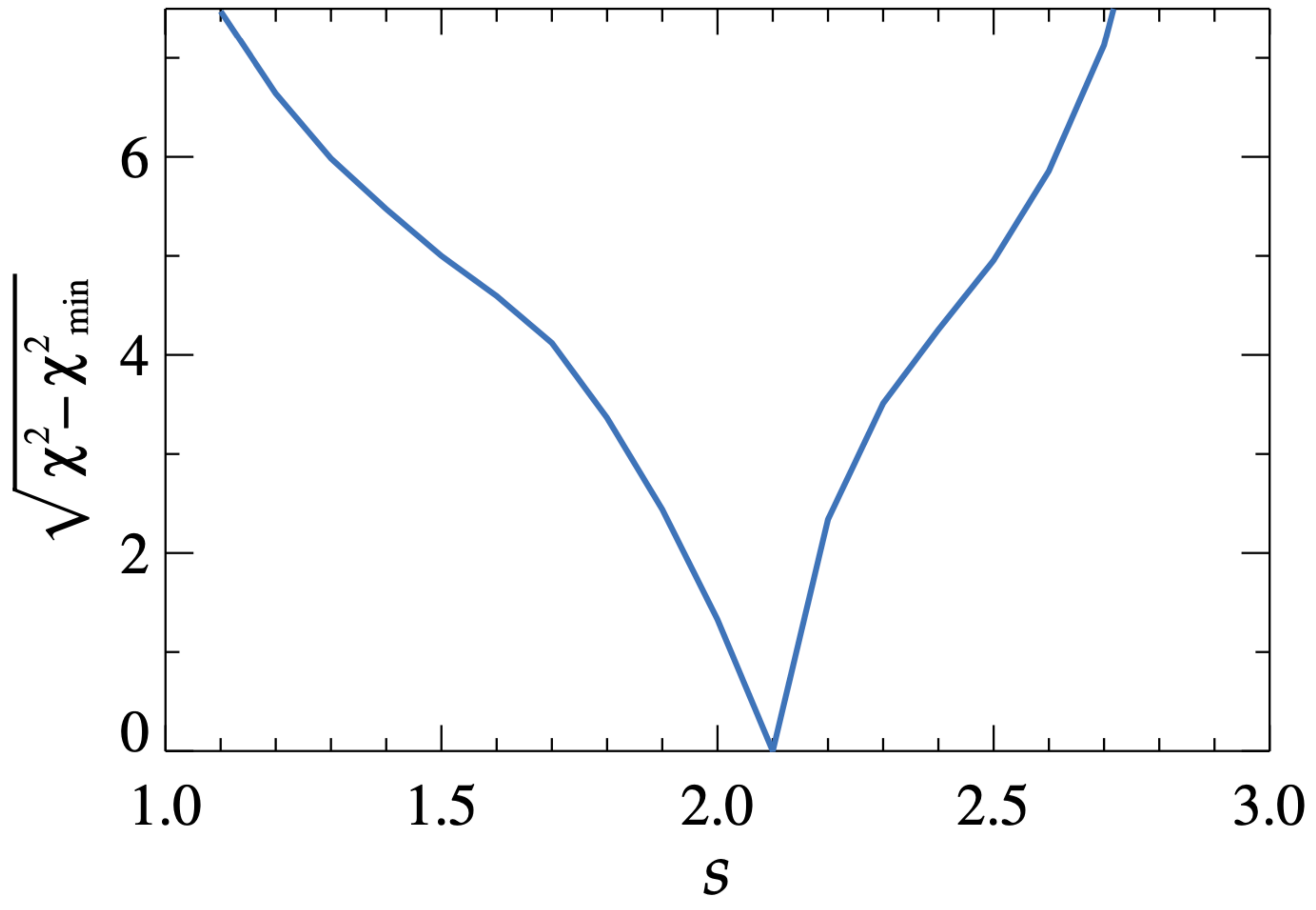
Particle injected by the accelerator: spectral index from fit to data



- We computed particle interaction and propagation according to Unger, Farrar, Anchordoqui 2015 (see also Muzio and Farrar 2023)

$$\chi^2 = \sum_i^{N_{\rm spec}} \frac{(J_{m,i} - J_i)^2}{\sigma^2_{J,i}} + \sum_j^{N_{\rm comp}} \frac{(\langle \ln A\rangle_{m,j} - \langle \ln A\rangle_j)^2}{\sigma^2_{\langle \ln A\rangle,j}}$$

$$+ \sum_j^{N_{\rm comp}} \frac{(\mathrm{Var}(\ln A)_{m,j} - \mathrm{Var}(\ln A)_j)^2}{\sigma^2_{\mathrm{Var}(\ln A),j}}$$



- **Best fit to data return** $s = 2.1^{+0.06}_{-0.13}$

$E^{-s} \exp(-E/E_{cut})$ require s ≈ 1 *and* get much worse fit

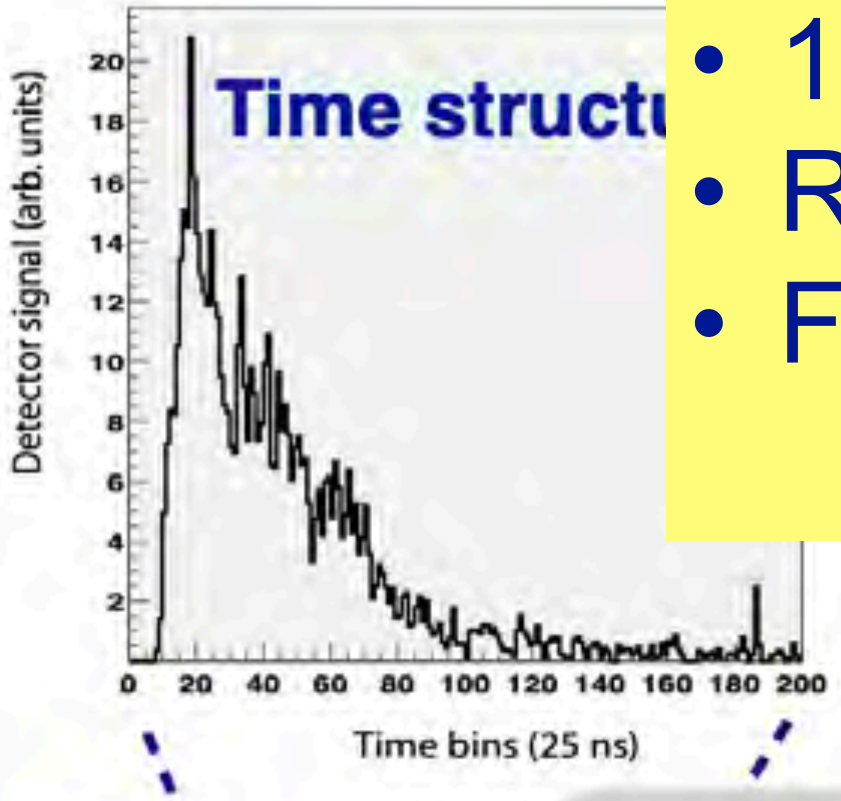
Does spectral cutoff discriminate between acceleration mechanisms?

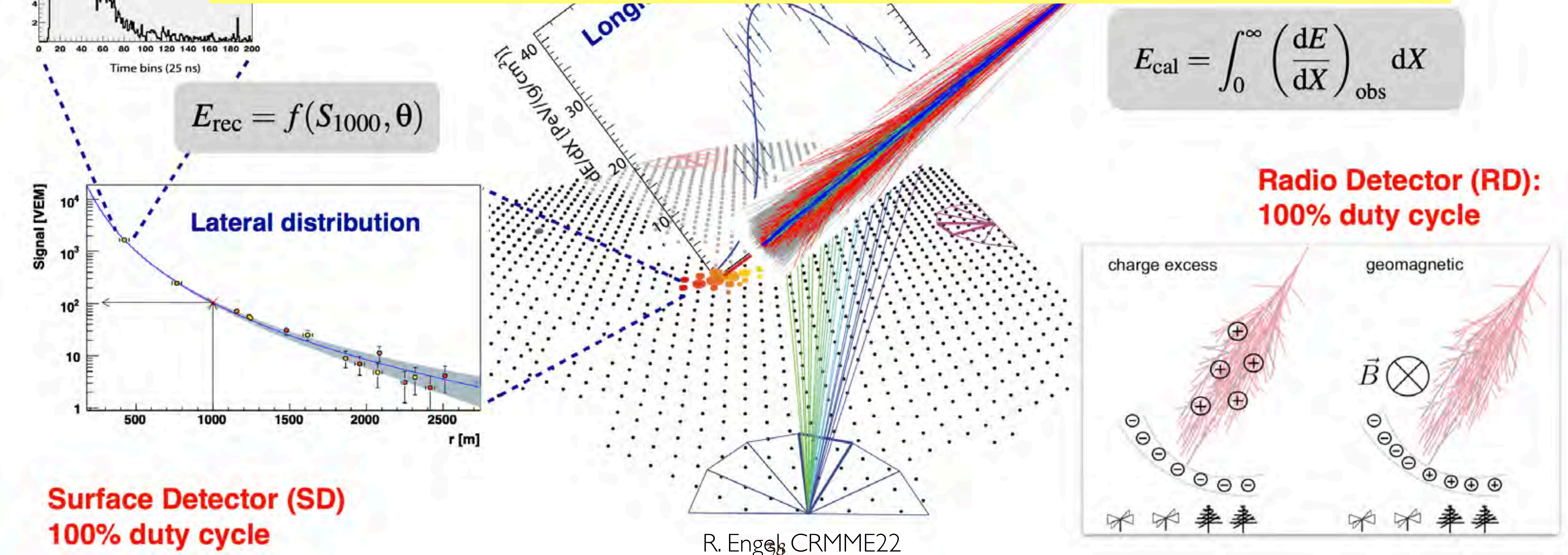
- The sech[$(E/E_{cut})^2$] spectral cutoff of magnetized turbulence fits well, but is it generic?
  - Analytic treatment (Protheroe+Stanev 1999): DSA ➜ E^{-2} exp($-E/E_{cut}$) or softer
    - exp($-E/E_{cut}$) cutoff gives poor fit to UCR data while sech[$(E/E_{cut})^2$] cutoff fits well (Comisso, GRF, Muzio ApJL 2024)
  - Must measure spectral cutoff in PIC simulations, for other acceleration mechanisms!
- Should also measure:
  - ``Uptake efficiency" versus Z & A ~(Z/A), $(Z/A)^2$, …???
  - What is the low energy (rigidity) cutoff? What governs it?
  - Evolution of U_B while CRs are accelerated? Does CR acceleration sap U_B and "shut down"?

Air shower observables (hybrid observation)

<u>Key components of UHECR observatory:</u>

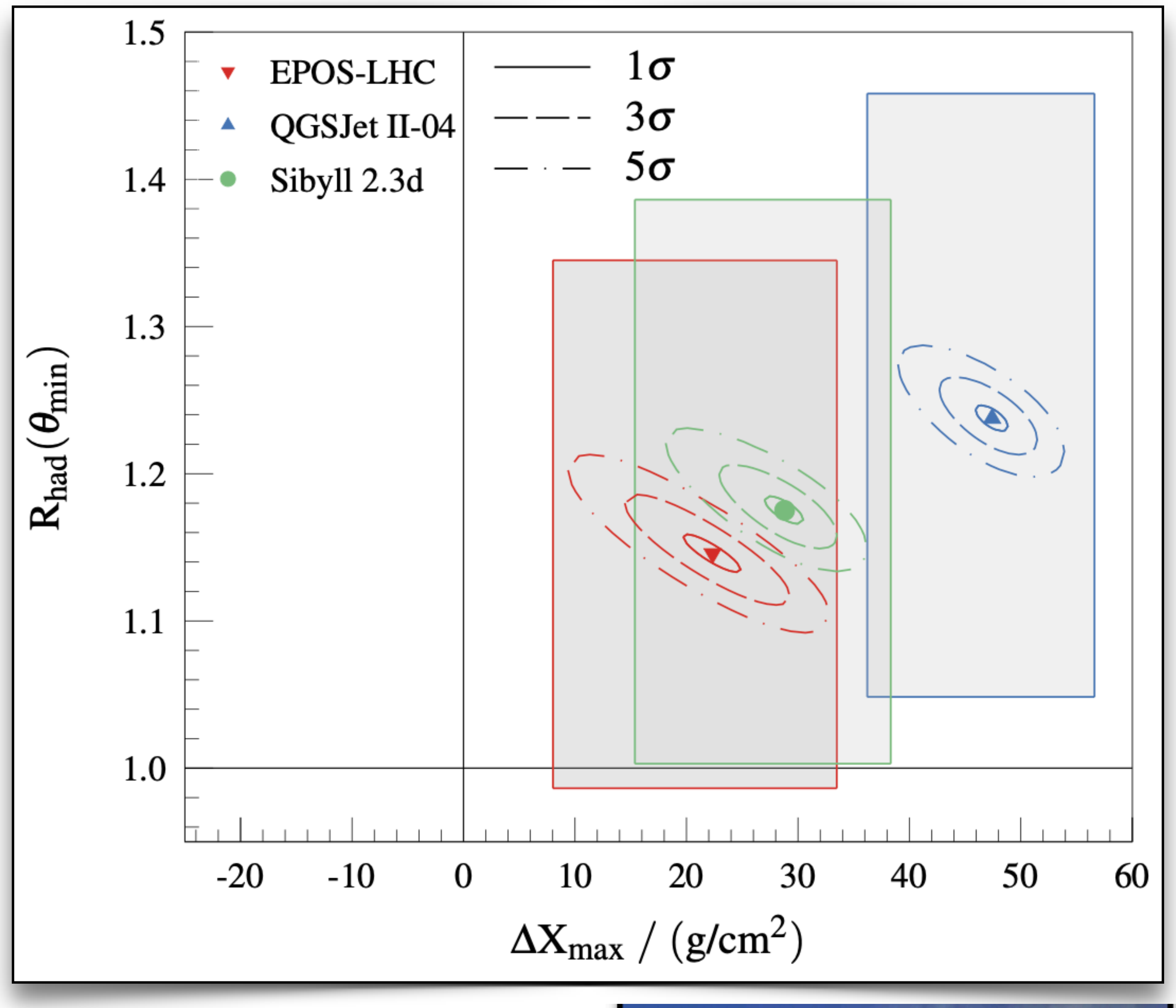
- 1600 (ea) Water Cherenkov & Scintillator Detectors, 1.5 km spacing (100%)
- Radio (100%, best for large zenith angle)
- Fluorescence Detector ➜ Longitudinal profile (15%)





Achieving correct hadronic interaction models (HIMs)

Auger *Phys.Rev.D* 109 (2024) 10, 102001



- No accelerator-tuned HIM accurately describes the muon content and X_{max} seen in UHECR shower observations
- Phase II tools should identify source of the problem
  - Underground muons ➜ *muon spectral info*
  - SSD/RD ➜ more precise *EM/hadronic separation*
- WCD + SSD/RD + FD + UMC ➜ **MULTI-HYBRID** composition assignment
  - Phase II + Machine Learning *enables quality composition estimation for all Phase I data* *(>60k events above the ankle)*
- ***Accurate HIMs + multi-hybrid composition ➜ robust A, Z inference***

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“Muon Problem”

- Ground signal (S_{38}) & X_{max} distribution should not depend on zenith
- **Muon problem ➜ muon AND X_{max} problems**

We found that for the best description of the data distributions in the energy range $10^{18.5}$ to $10^{19.0}$ eV for $\theta < 60°$ the MC predictions of X_{max} should be deeper in the atmosphere by about 20 to 50 g/cm^2, and the hadronic signal should be increased by about 15 to 25% in all three models. These modifications reduce the differences between the models in X_{max} and $S(1000)$, and as a consequence, lead to smaller uncertainties on the estimated fractions of the primary nuclei. Due to the deeper MC X_{max} scale and, correspondingly, a heavier mass composition inferred from the data compared with non-modified models, the scaling factors for the hadronic signal are found to be smaller than in previous estimations not considering any modifications to the MC X_{max} scales. The

- After shift, composition determination agrees between models, and becomes heavier than before.

Testing Hadronic-Model Predictions of Depth of Maximum of Air-Shower Profiles and Ground-Particle Signals using Hybrid Data of the Pierre Auger Observatory

The Pierre Auger Collaboration
The Pierre Auger Observatory, Av. San Martín Norte 306, 5613 Malargüe, Mendoza, Argentina;
http://www.auger.org

(Dated: February 19, 2024)
PRD2024

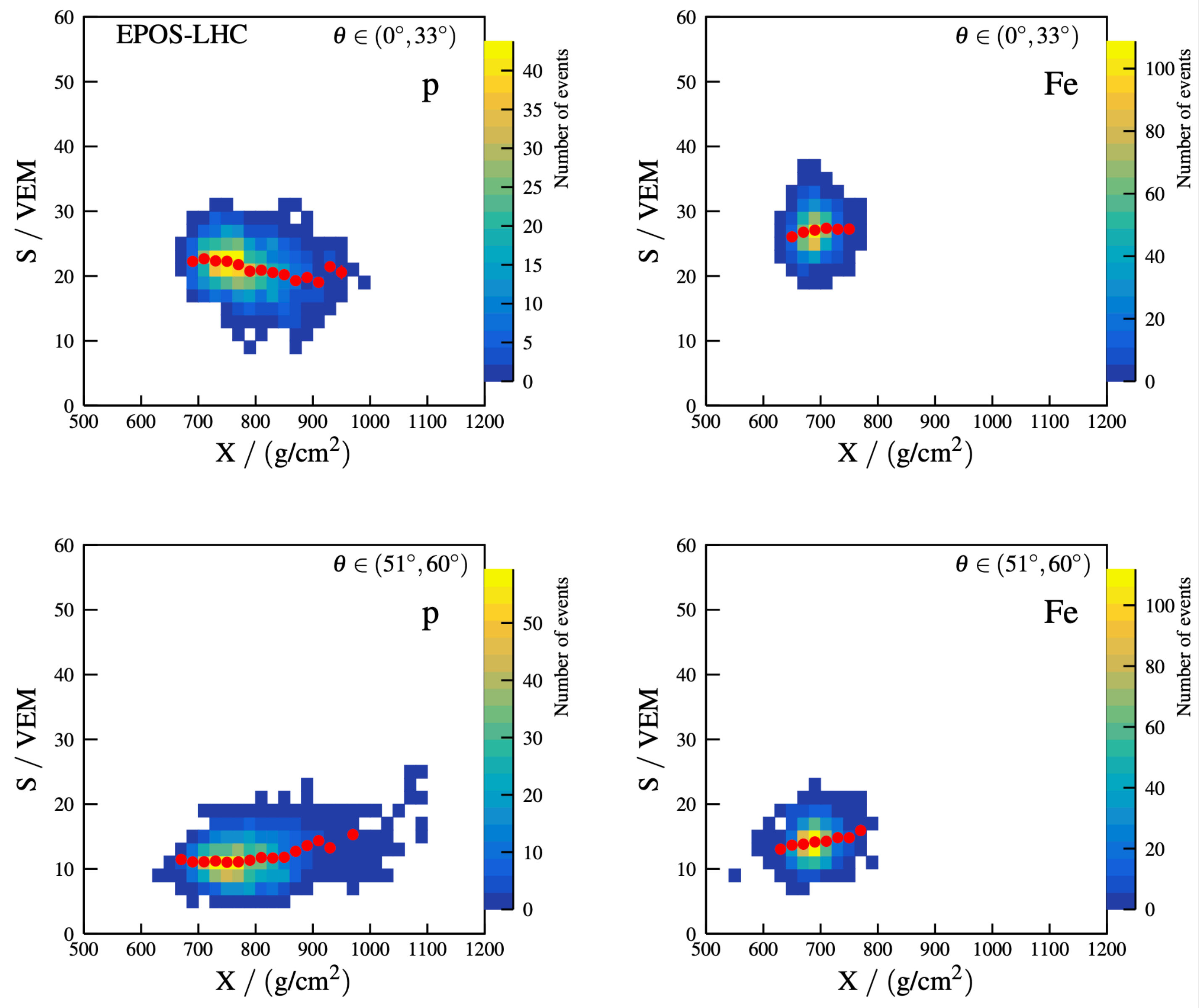


FIG. 1: Examples of two-dimensional distributions of S and X for protons (left) and iron nuclei (right) generated with EPOS-LHC for zenith angles between 0° and 33° (top) and 51° and 60° (bottom). The red points indicate the mean values of S. $E = 10^{18.5}$ to $10^{19.0}$ eV.

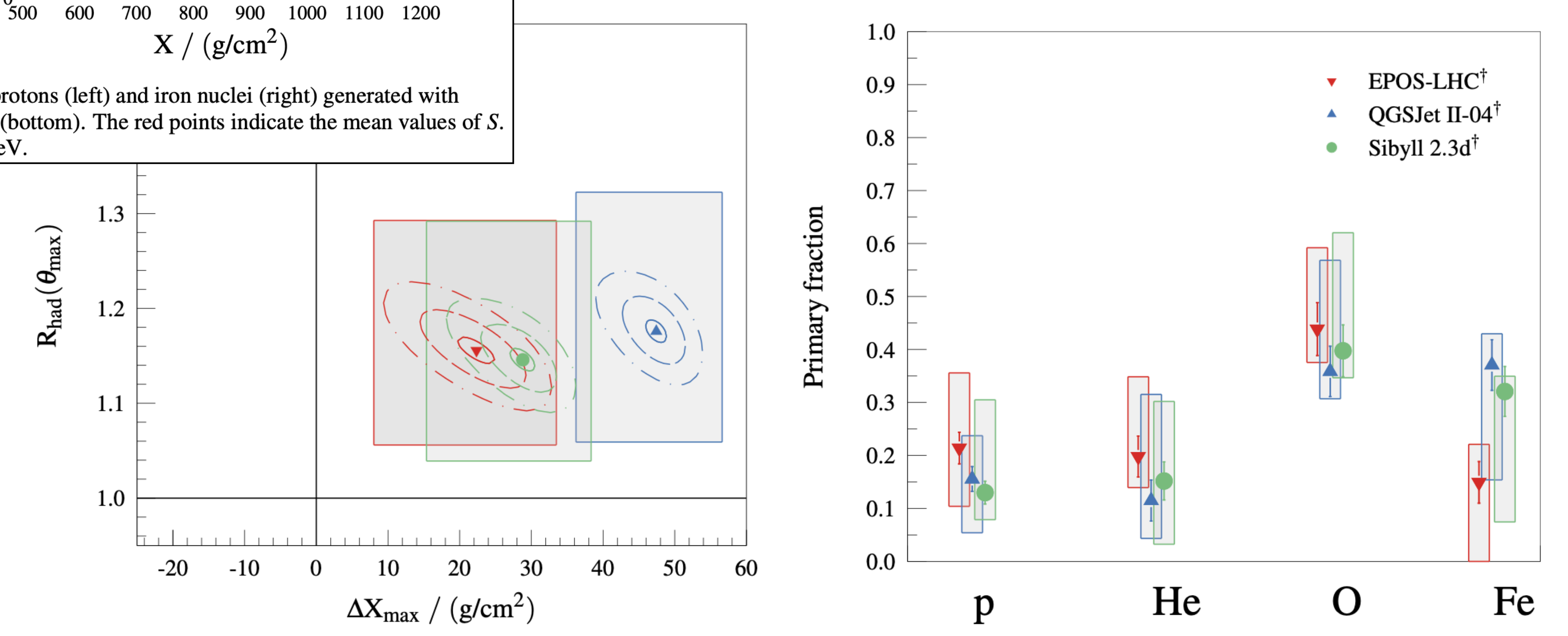
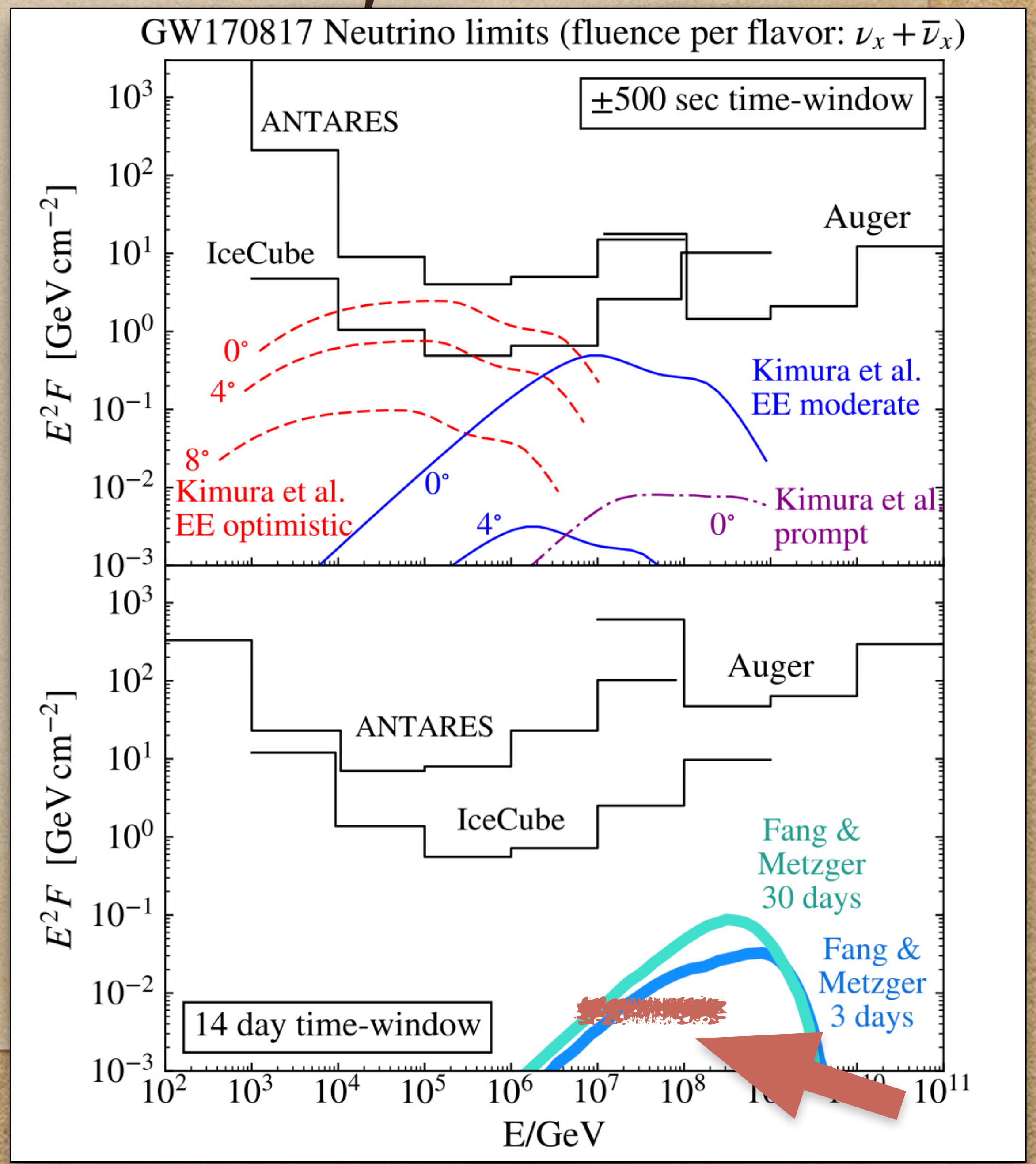


FIG. 6: *Left:* Correlations between ΔX_{max} and $R_{had}(\theta_{max} \approx 55°)$ modifications of the model predictions obtained from the data fits. The contours correspond to 1σ, 3σ, and 5σ statistical uncertainties. The gray rectangles are the projections of the total systematic uncertainties. *Right:* The most likely primary fractions of the four components from the data fits using ΔX_{max} and $R_{had}(\theta)$. The height of the gray bands shows the size of projected total systematic uncertainties.

Future test of BNS-merger origin: EHE neutrino ≈coincident with GW from BNS merger

- EVERY EHE **ν** should be accompanied by a gravitational wave from the NS merger.
- Cosmic Explorer+Einstein Telescope+IceCube-Gen2 x few yrs: very promising
- GW170817 also accompanied by EHE neutrinos but estimated fluence for favorable case of aligned jet << 0.15 GeV cm^{-2} per flavor.
  <u>Sensitivity not adequate by orders of magnitude</u>



Antares, IceCube, Auger, LVK '17