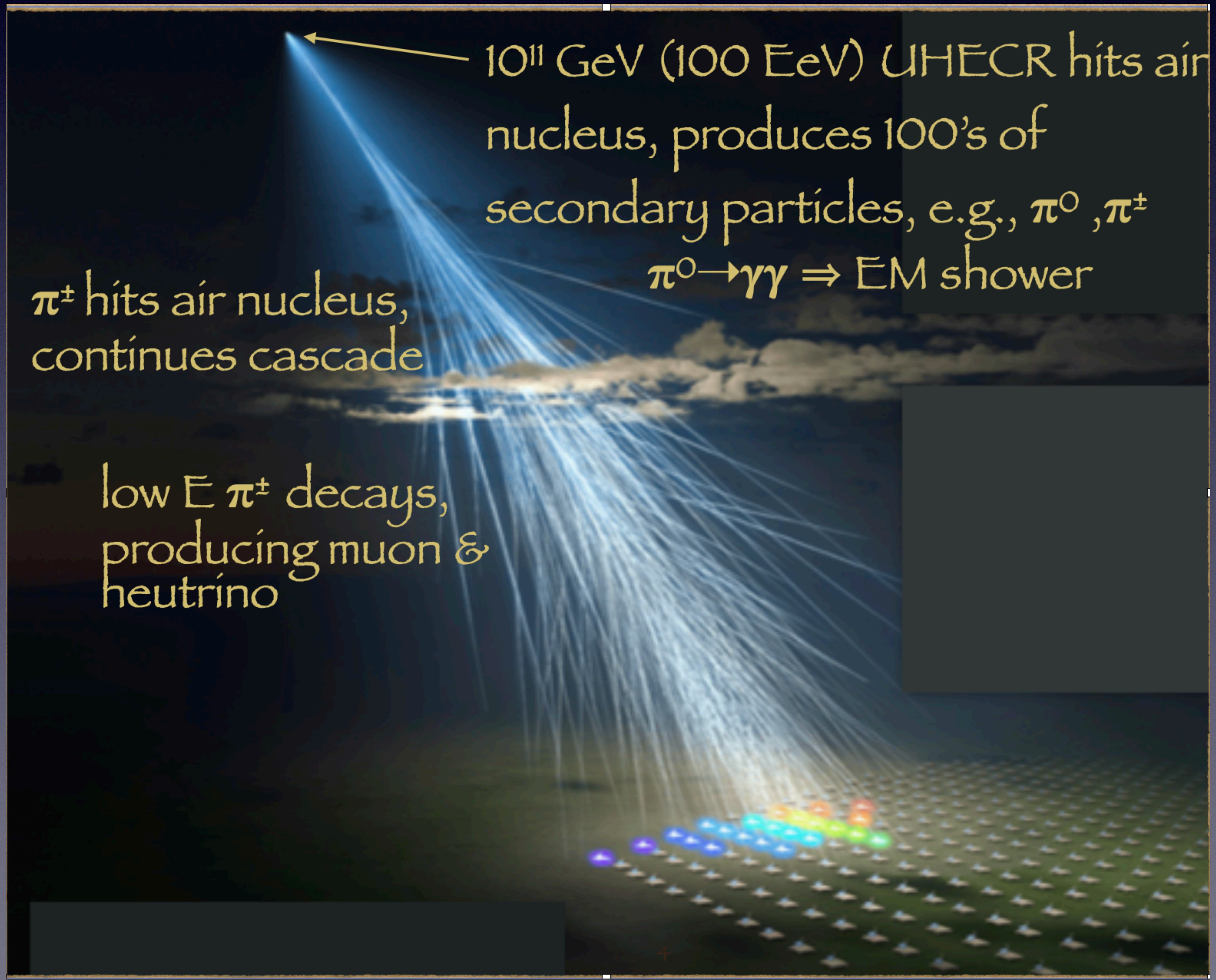
# The Origin of Ultra-high Energy* Cosmic Rays





Glennys R. Farrar, New York University

INT workshop, Sept.10, 2025

<E per nucleon> ~ 2 EeV ➜ $\gamma$ >$10^9$

# 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
- What we need from YOU!

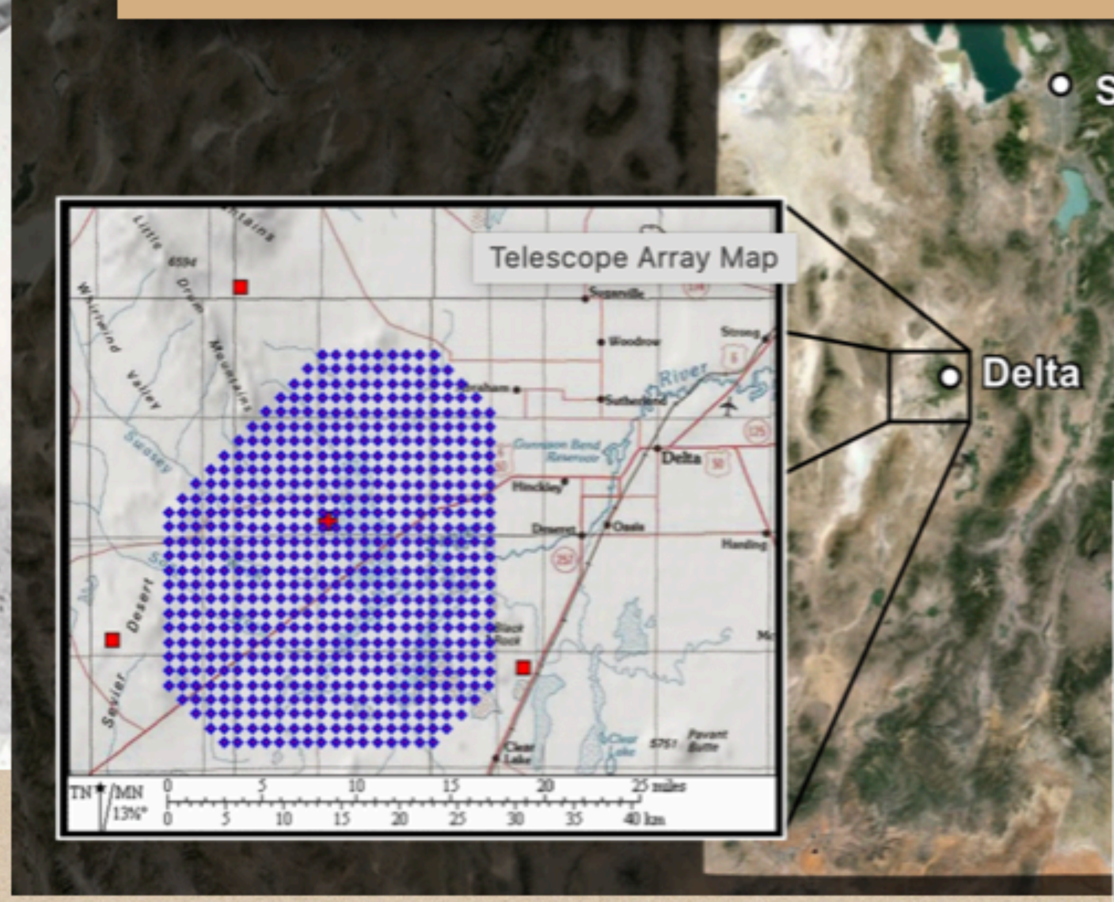
# It's been a long, hard search

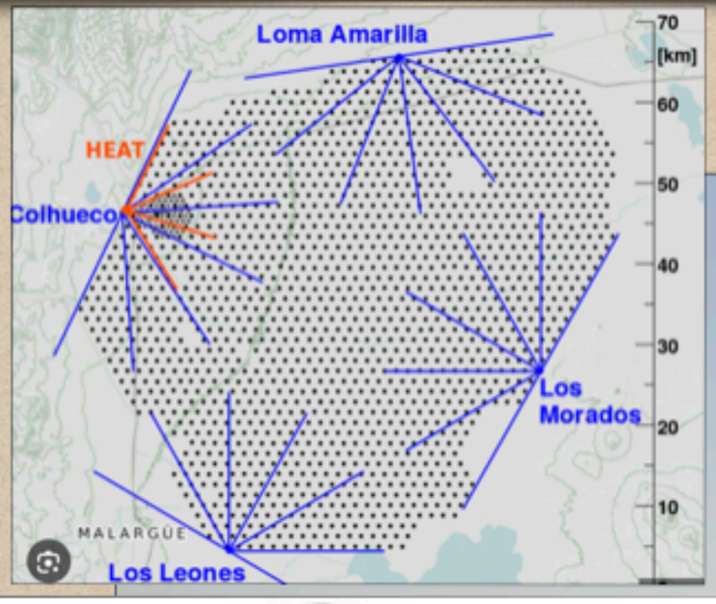


Hess: CRs
1911 or 1912

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

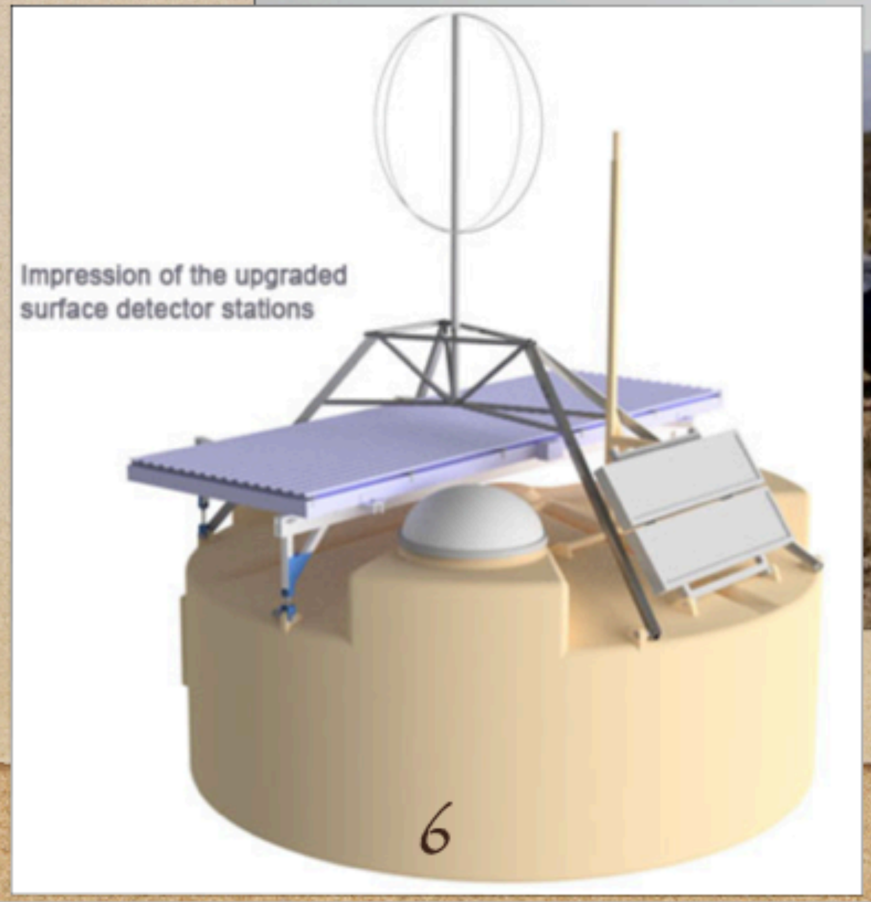
Telescope Array, Utah
Amaterasu ('23): 240 EeV



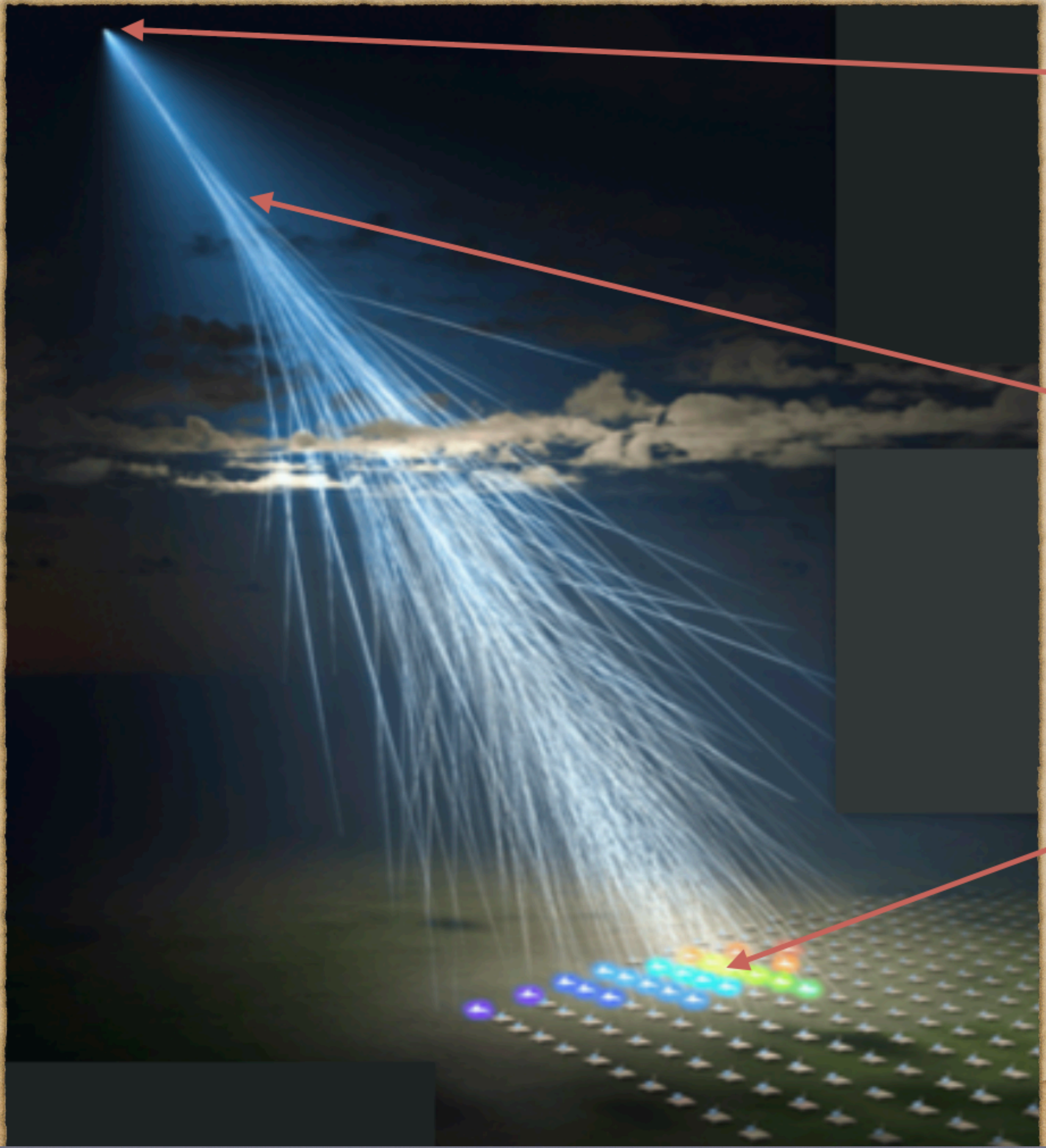

Pierre Auger Obs., Argentina
~50 evts > 100 EeV

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



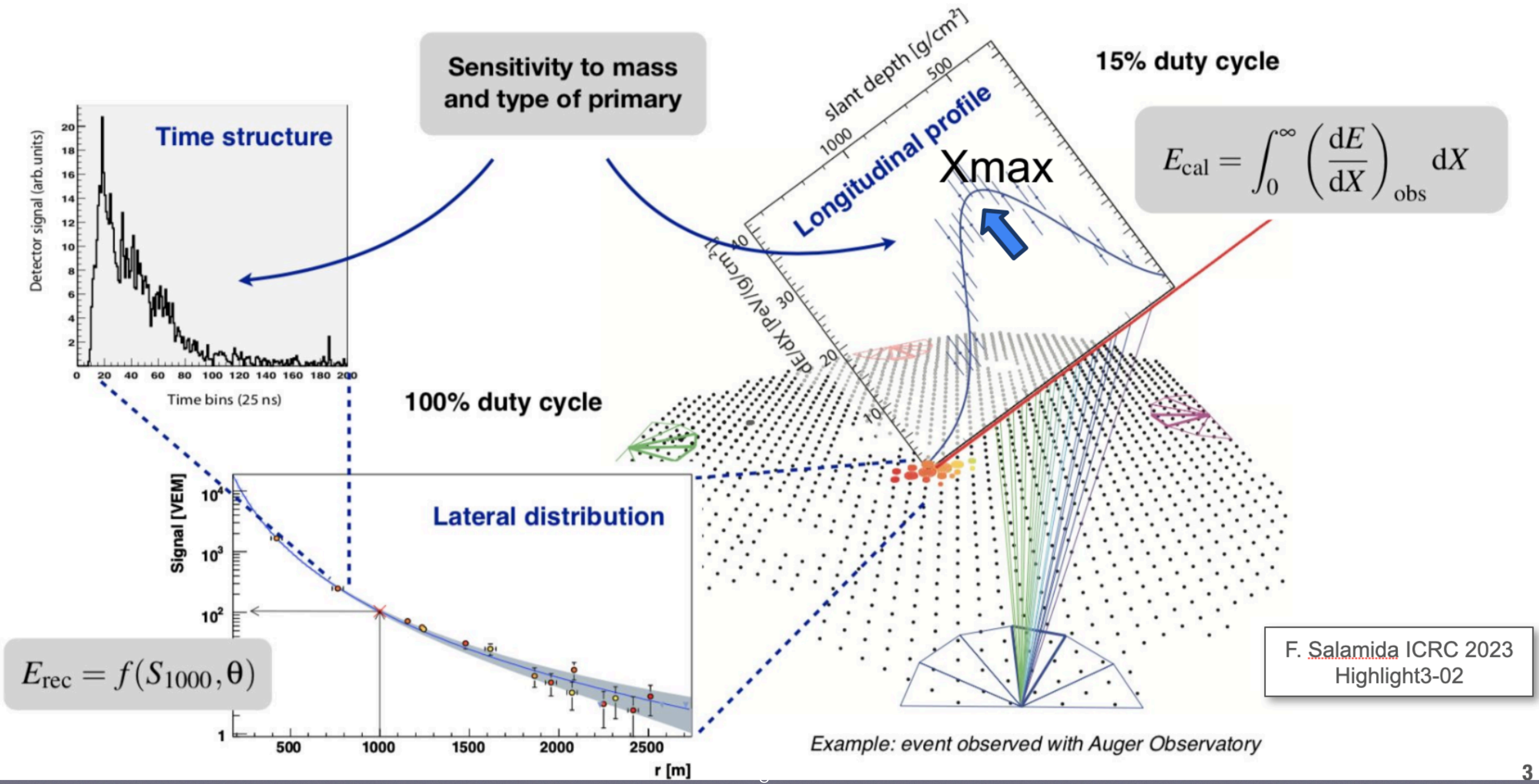

1700 stations, 3000 km$^2$

# 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

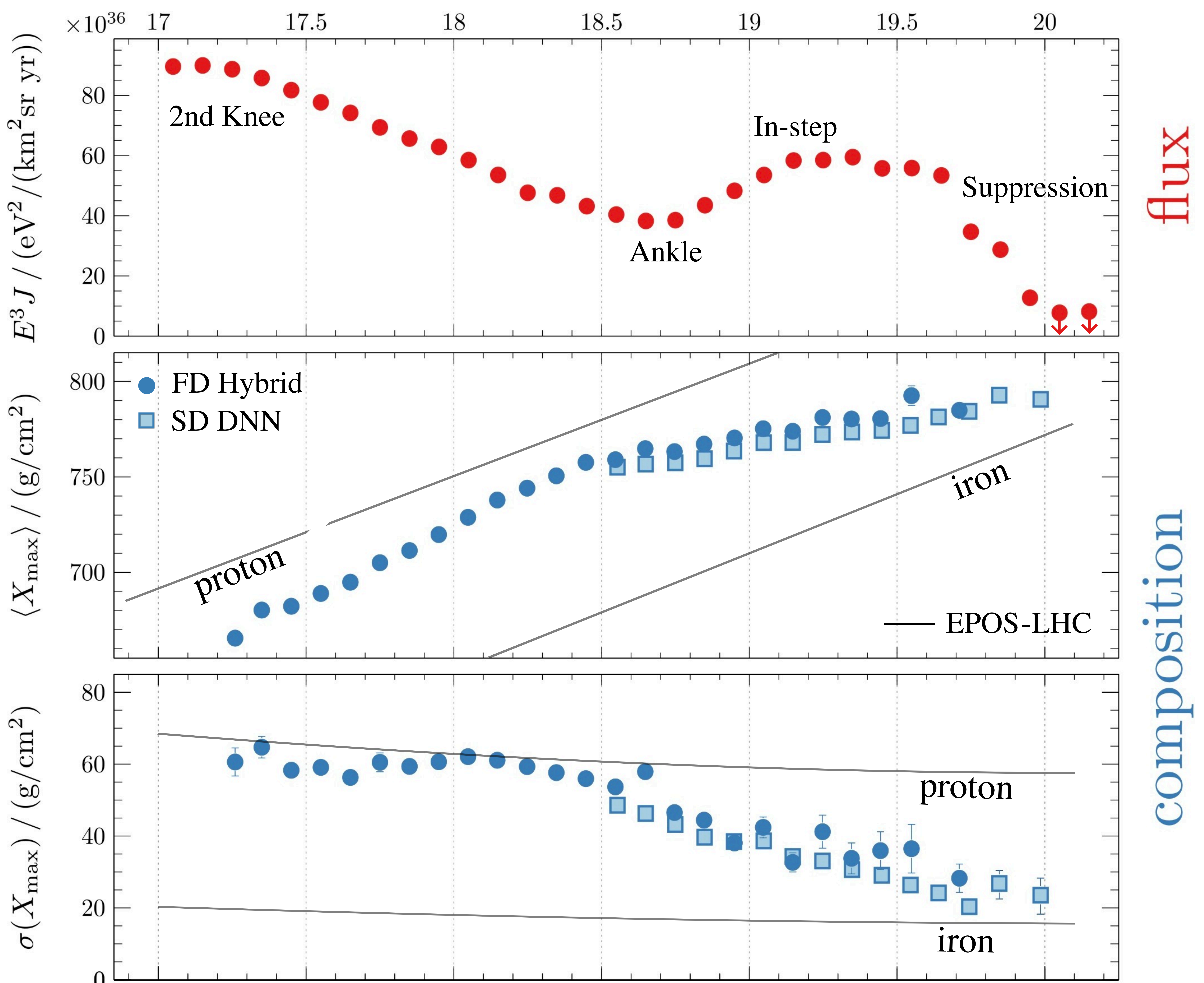
# The Hybrid Observation Method of Auger



# Spectrum, <$X_{max}$> $\sigma(X_{max})$

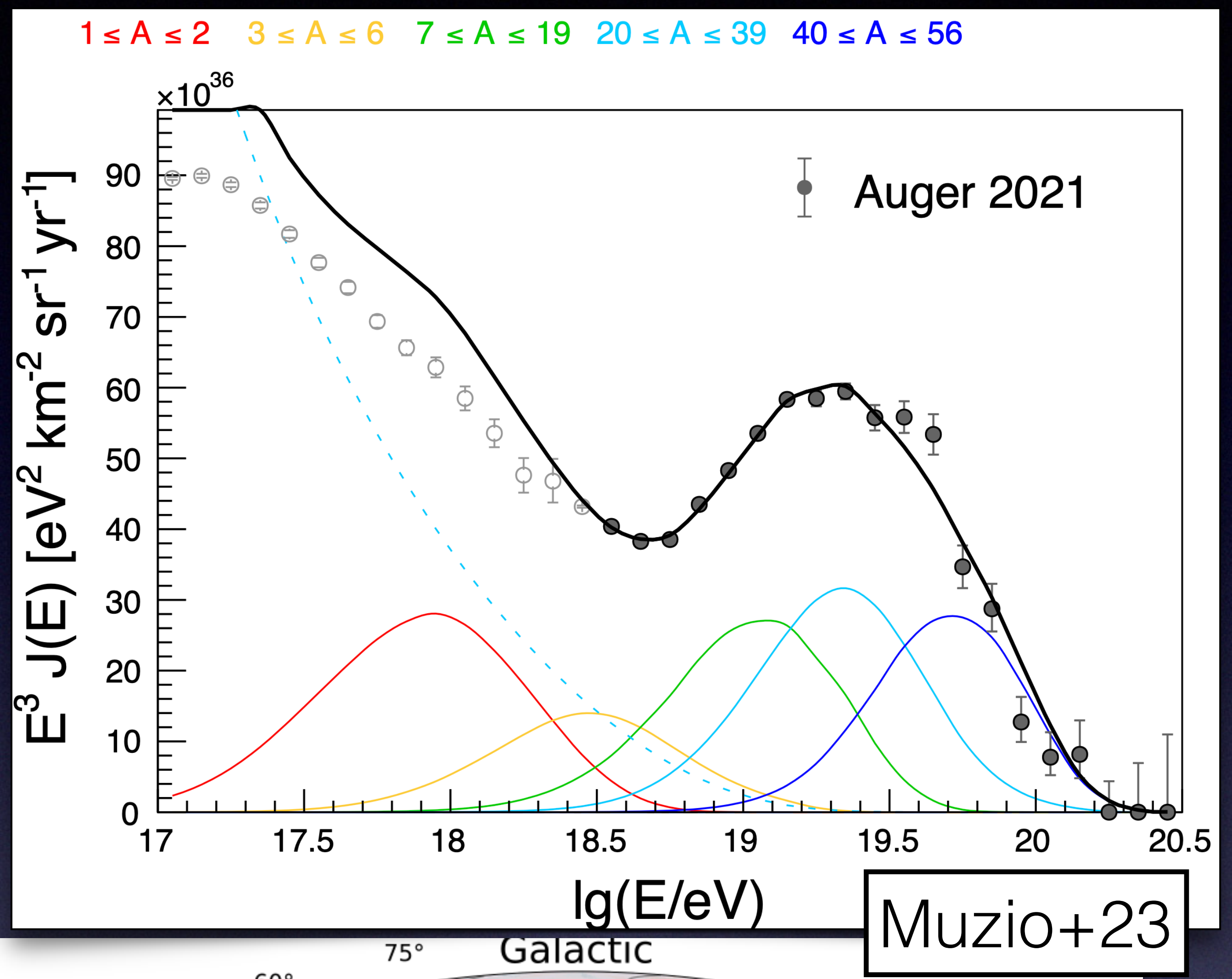
Composition gets heavier with energy

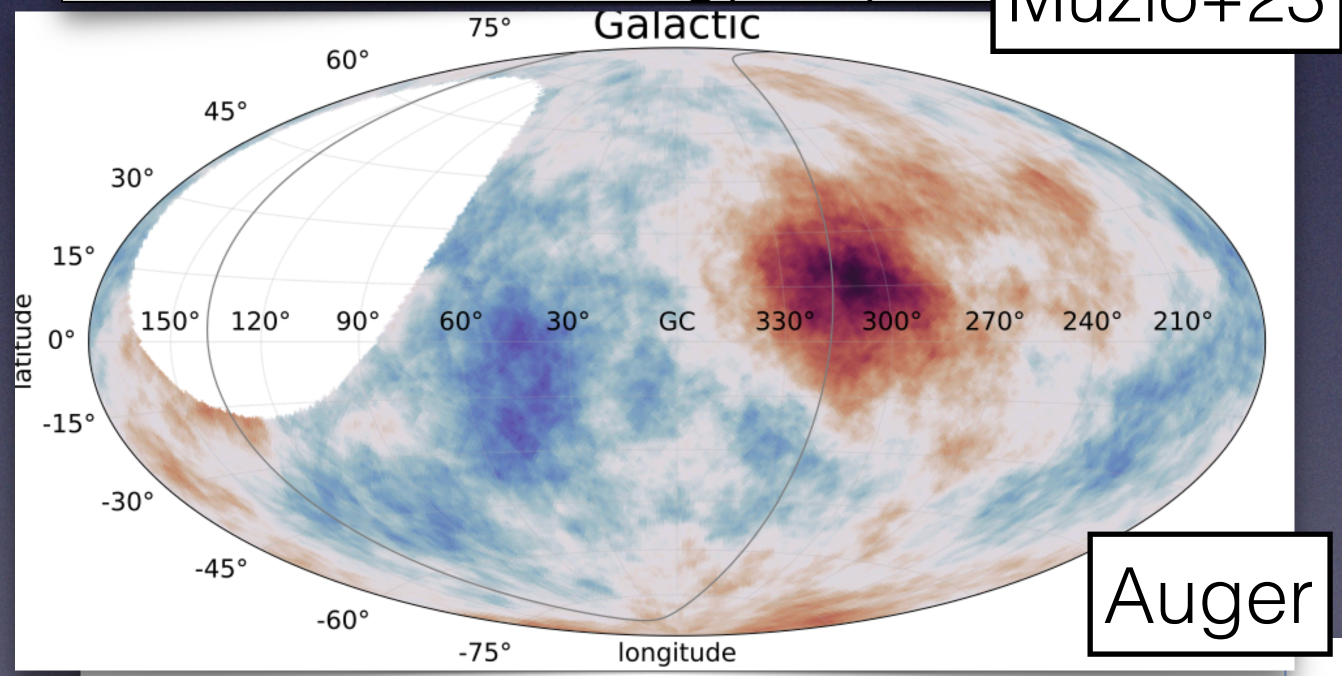
A single mass group dominates at each E

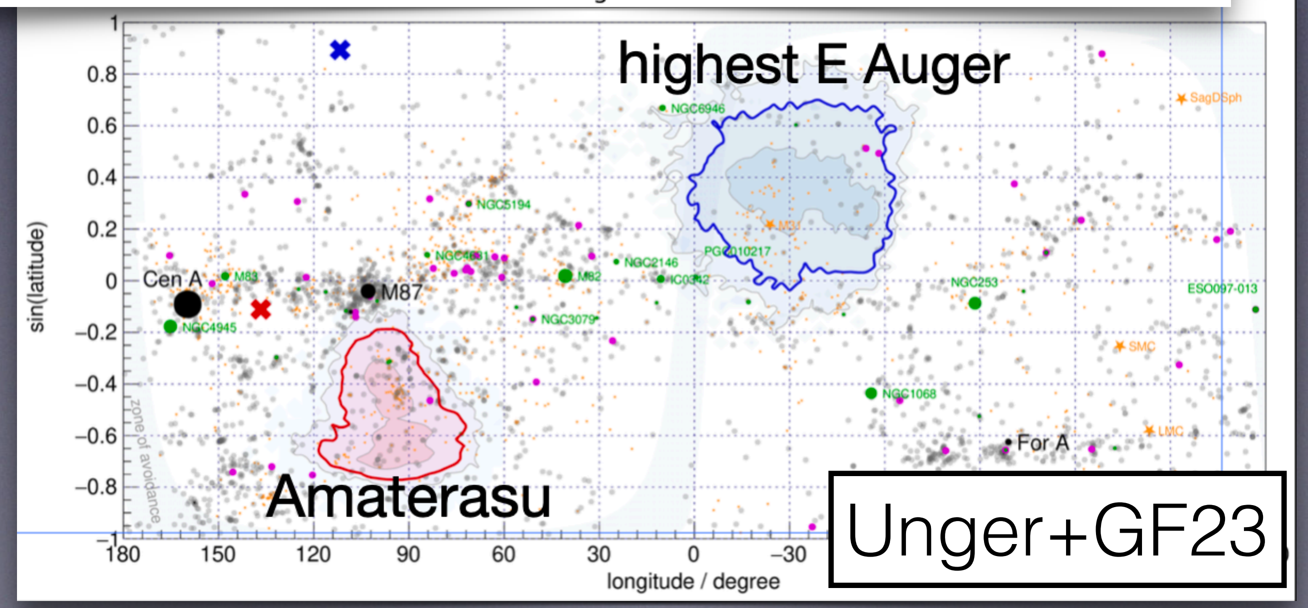


# Essential results from observations

- Mixed composition
- *Narrow range of mass at each E:*
  - Rigidity spectrum is narrow. <R≡E/Ze> ≈ 4 EV
- Only significant multipole is dipole ➜ sources are not rare.
- No prominent sources ➜ sources are transients.



# Correct Source model must explain

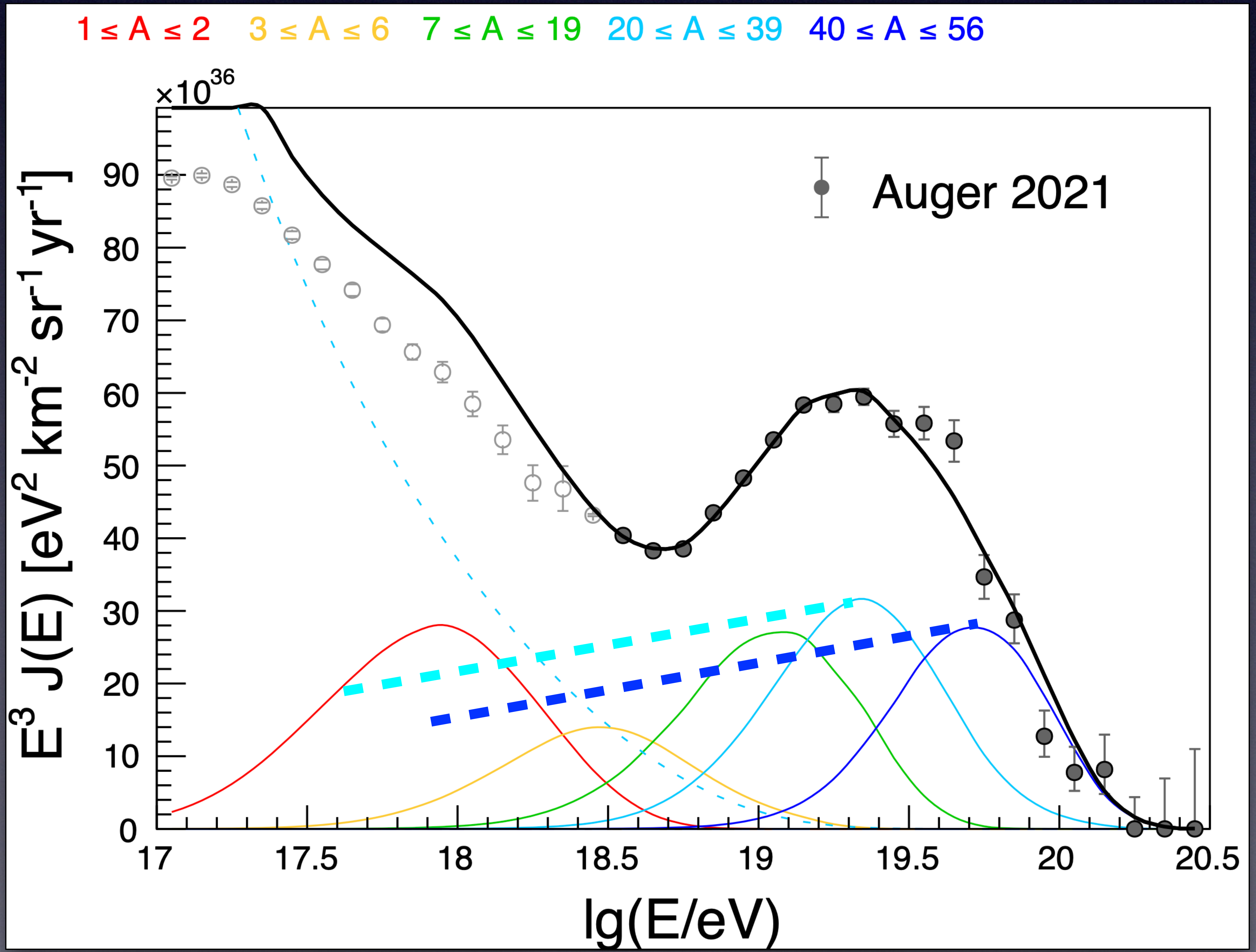
- Tight mass-energy relation requires minimal population variance. Excludes AGNs, long GRBs & TDEs. *(Ehlert, Oikonomou, Unger 2023)*

- Energy injection rate; source number density

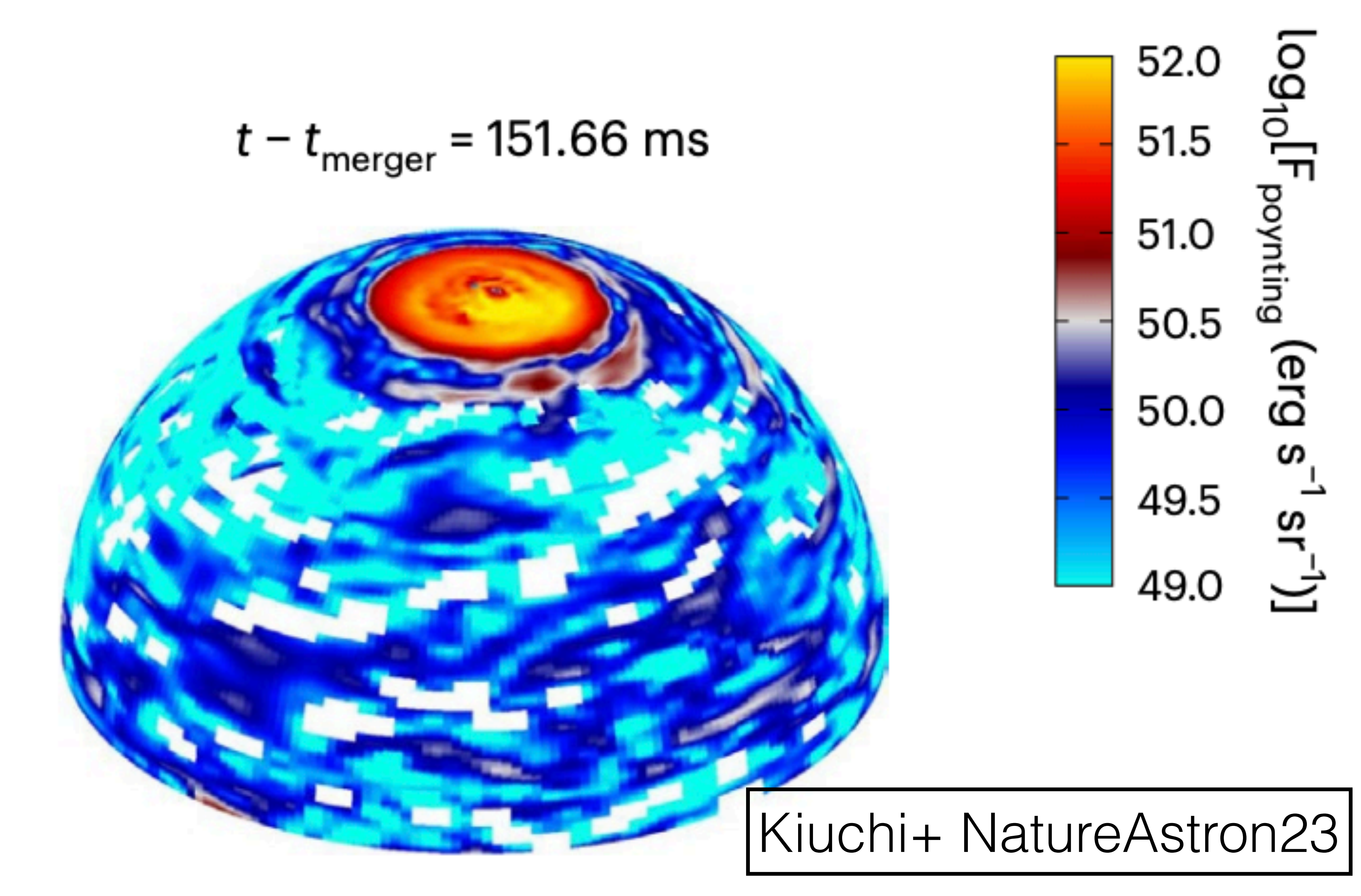
- Maximum rigidity (Hillas criterion)

- Highest energy events: 150-250 EeV
  (Amaterasu, Fly's Eye, >10 Auger above150 EeV)

- The highest energy events are from transients.



# Binary Neutron Star Mergers: the only (currently known) source satisfying all criteria




- Universal rigidity spectrum explained because:
  1. Magnetic field is generated by *gravitational* dynamo.
  2. Mass range of BNS is narrow:
     💕 known BNS's: M= 2.64±0.14 (5%) $M_\odot$
     3.2 $M_\odot$ → 10% (negligible) spread
- UHECR energy injection rate promising:

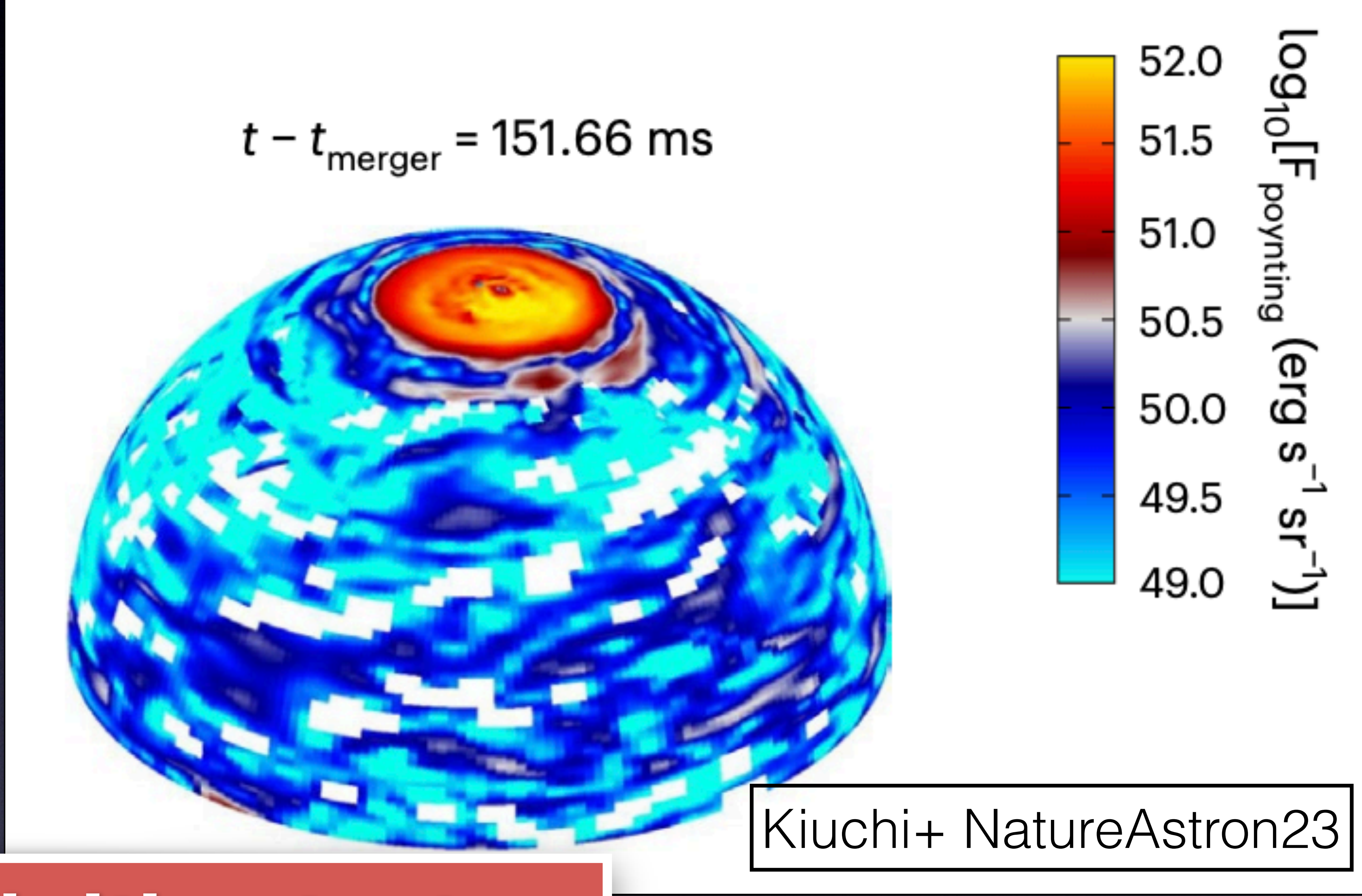
  - $\Gamma_{merger}$ = (0.3-1.7)$10^{-6}$ $Mpc^{-3}$ $yr^{-1}$ ; need UHECR energy per merger ≈ $10^{50}$ erg (total energy emitted > $10^{52.5}$ erg).



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

# Binary Neutron Star Mergers: the only (currently known) source satisfying all criteria

- Universal peak rigidity explained because:
  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 energ

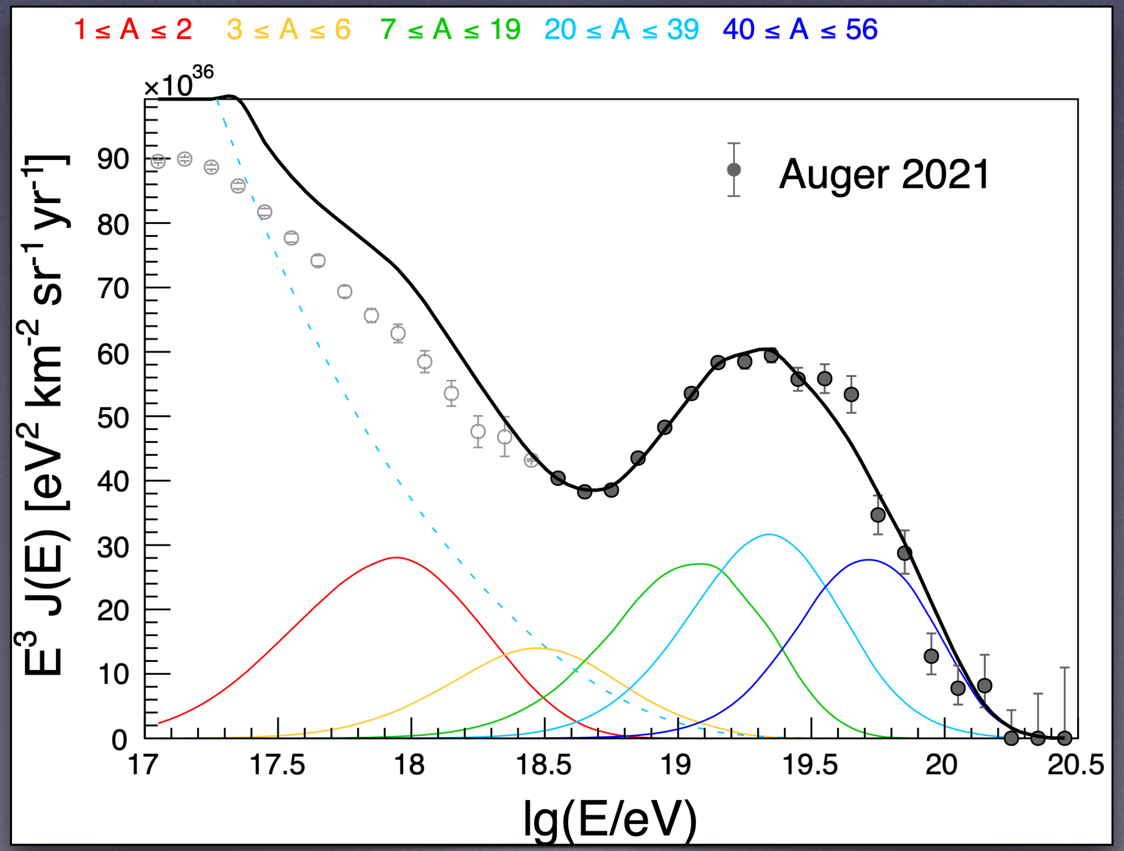
  - $\Gamma_{merger}$ = (0.3 … rger ≈ $10^{50}$ erg (total ene

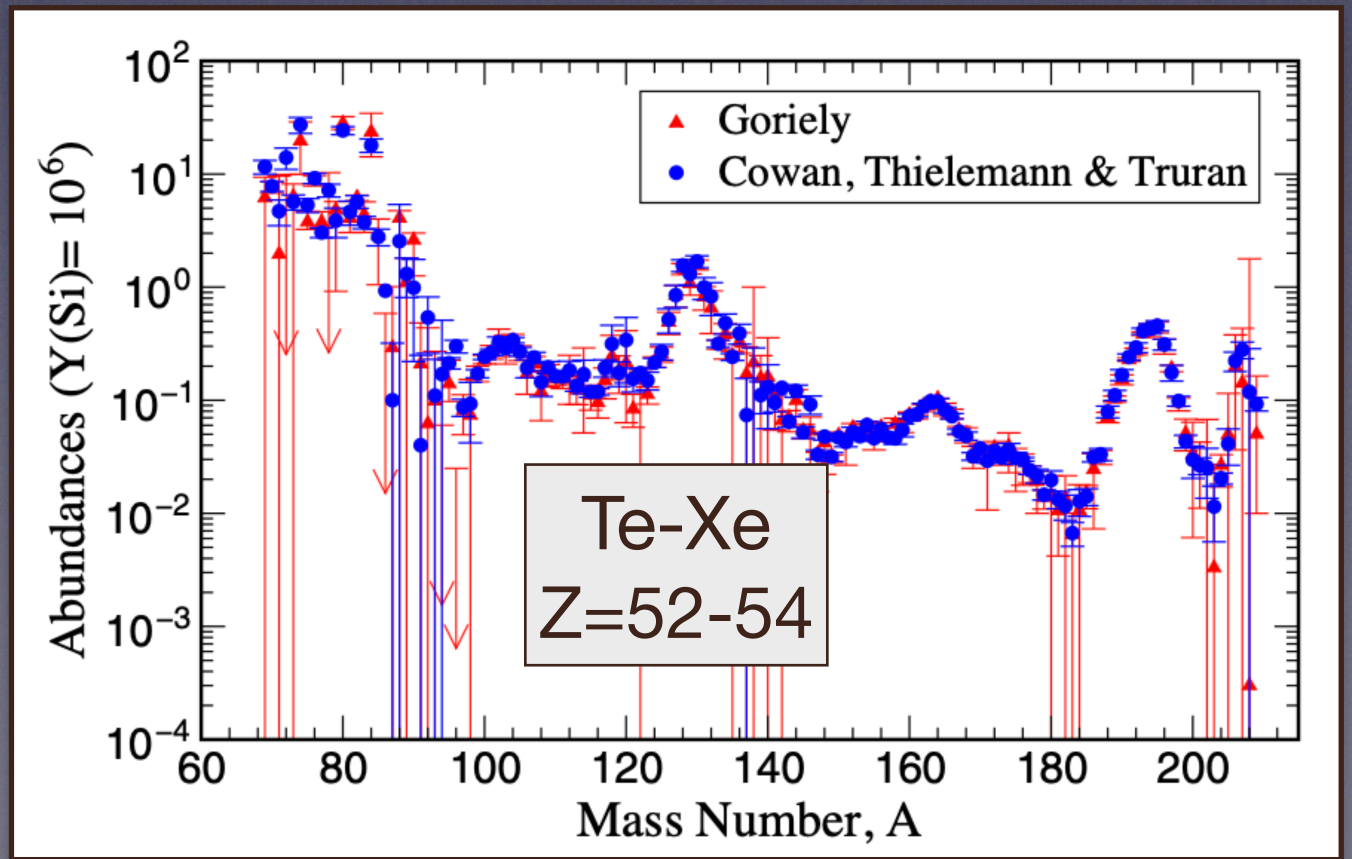
**Unique predictions enable definitive tests:**

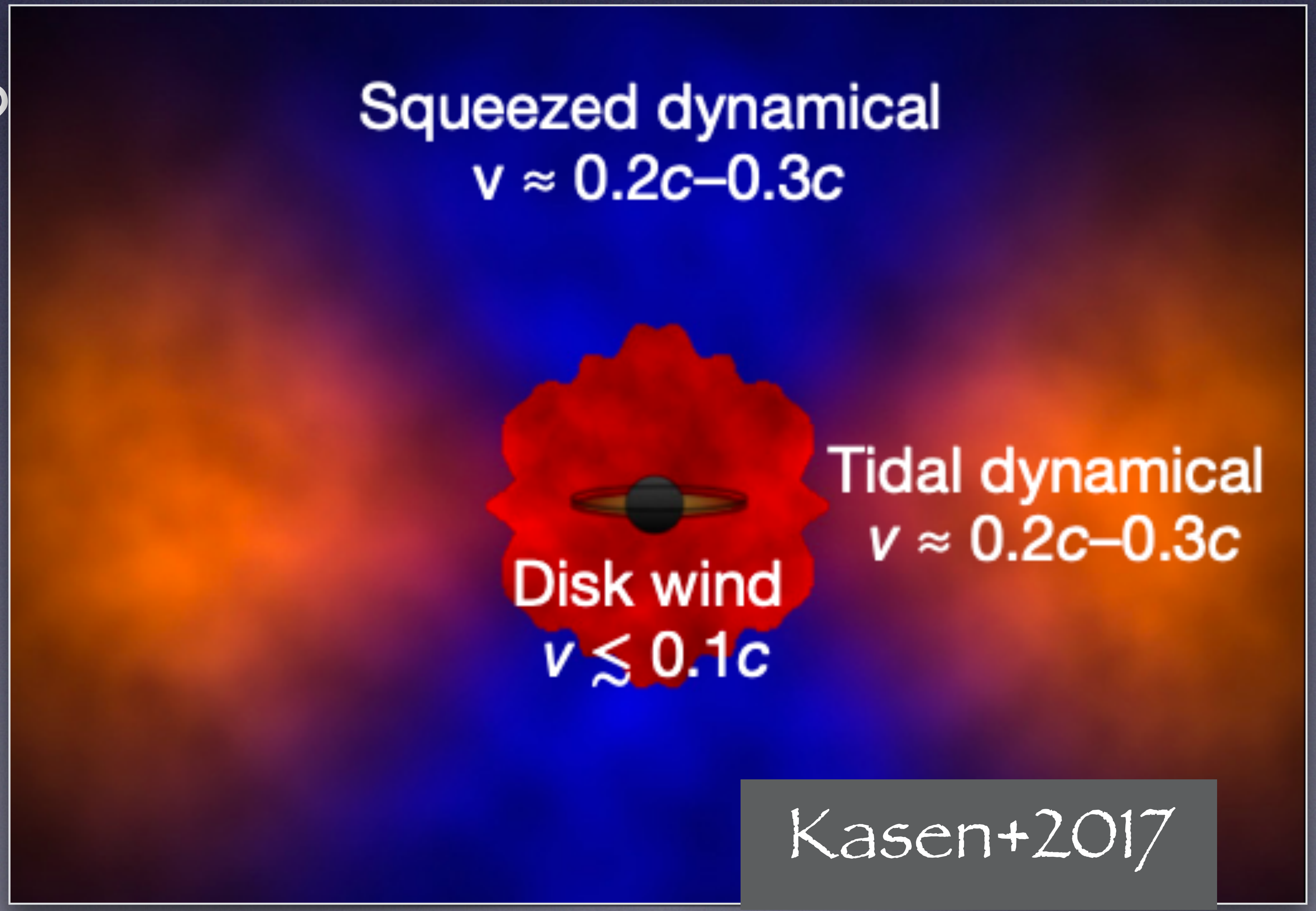
- EHE $\nu$'s ↔ gravitational waves
- Highest energy UHECRs: Z>26
- BNS merger ➔ initial B ➔ predict spectrum

# Topics for today

- Where in the merger ejecta does UHECR acceleration occur? ➜ **Predict rigidity cutoff $R_{cut}$ and spectral shape**
- What is the time profile for UHECR production? **(coincidences between GW and EHE $\nu$'s…)**
- What are the relative abundances of different nuclei?



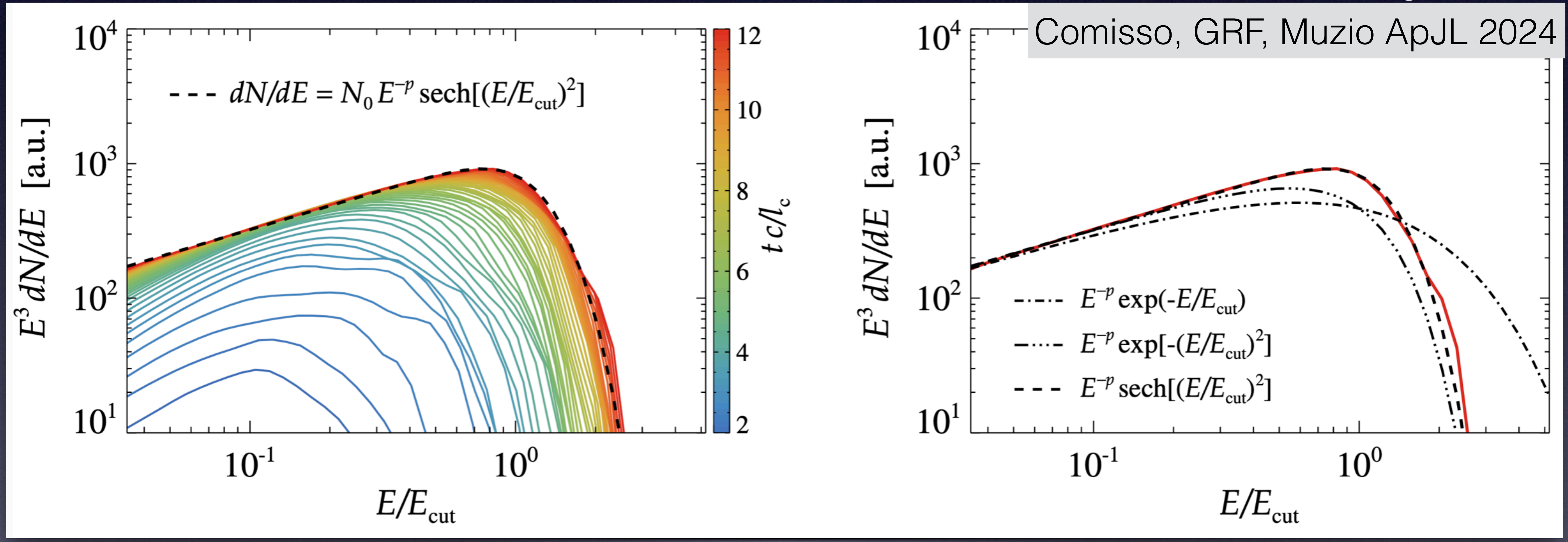



# UHECRs mainly produced in the turbulent outflow (maybe some UHECRs also from jets)

- *Composition*: UHECRs have masses up to (at least) Fe, but jets only have p,He (Perego+22)

- *Spectrum*: $E^{-2.x}$ × function of $(E/E_{cut})$




  - Outflow: Magnetized turbulence cutoff: sech[ $(E/E_{cut})^2$] (Comisso, GRF, Muzio ApJL 2024)
  - Jets: Diffusive Shock Acceleration cutoff: exp($-E/E_{cut}$) ??? (Protheroe+Stanev 1997)

**UHECR data strongly favor sech[$(E/E_{cut})^2$] cutoff**

# Big Picture

time →


**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 synch losses are subdominant

**UHECR accel**
~1 day: $10^{14}$ cm

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

# Big Picture

**time** →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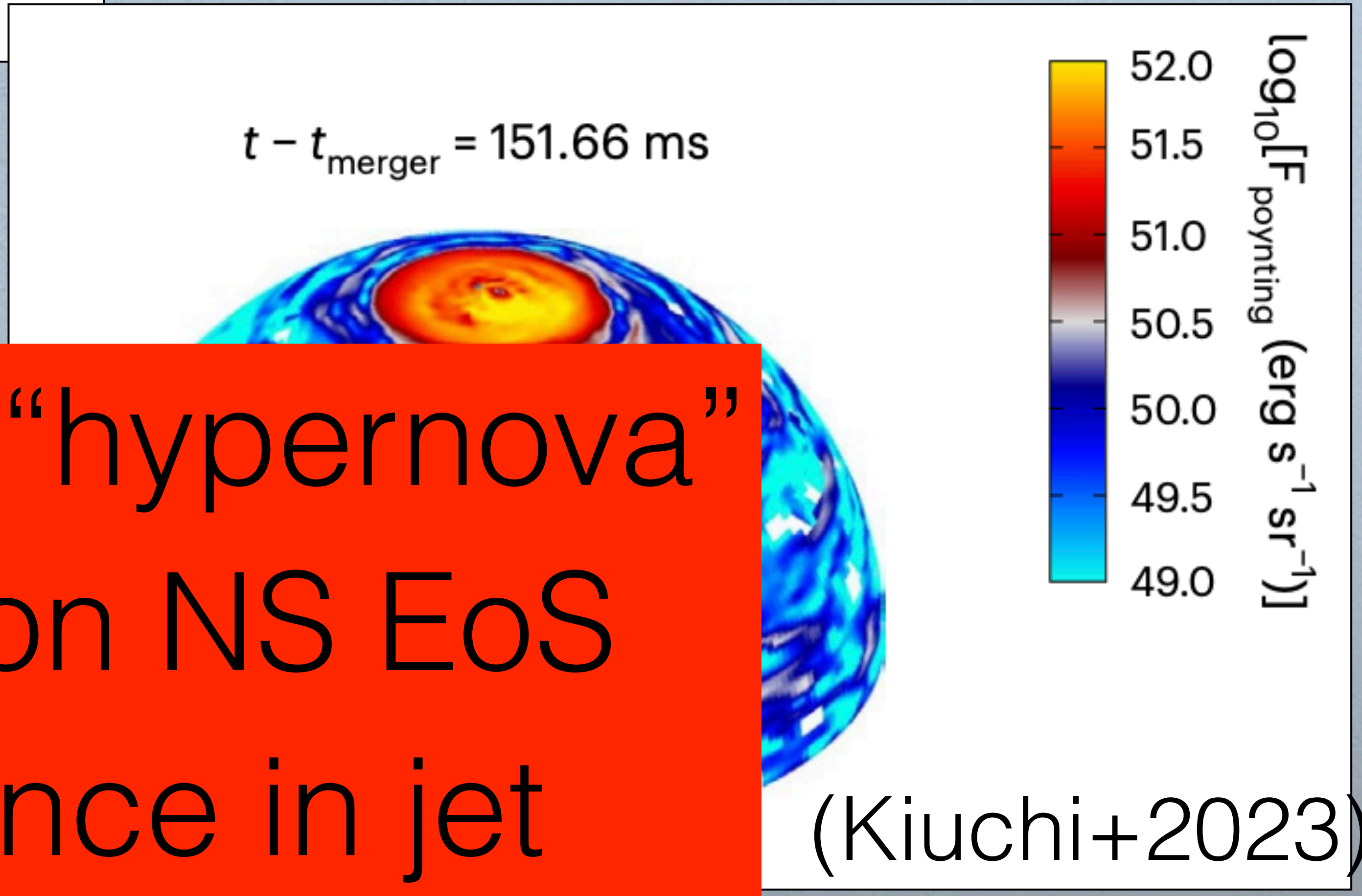


(Kiuchi+2023)

**Duration of "hypernova"**
- depends on NS EoS
  - p,He balance in jet
  - total energy output

# Big Picture

time


Gravitational Wave Emitted

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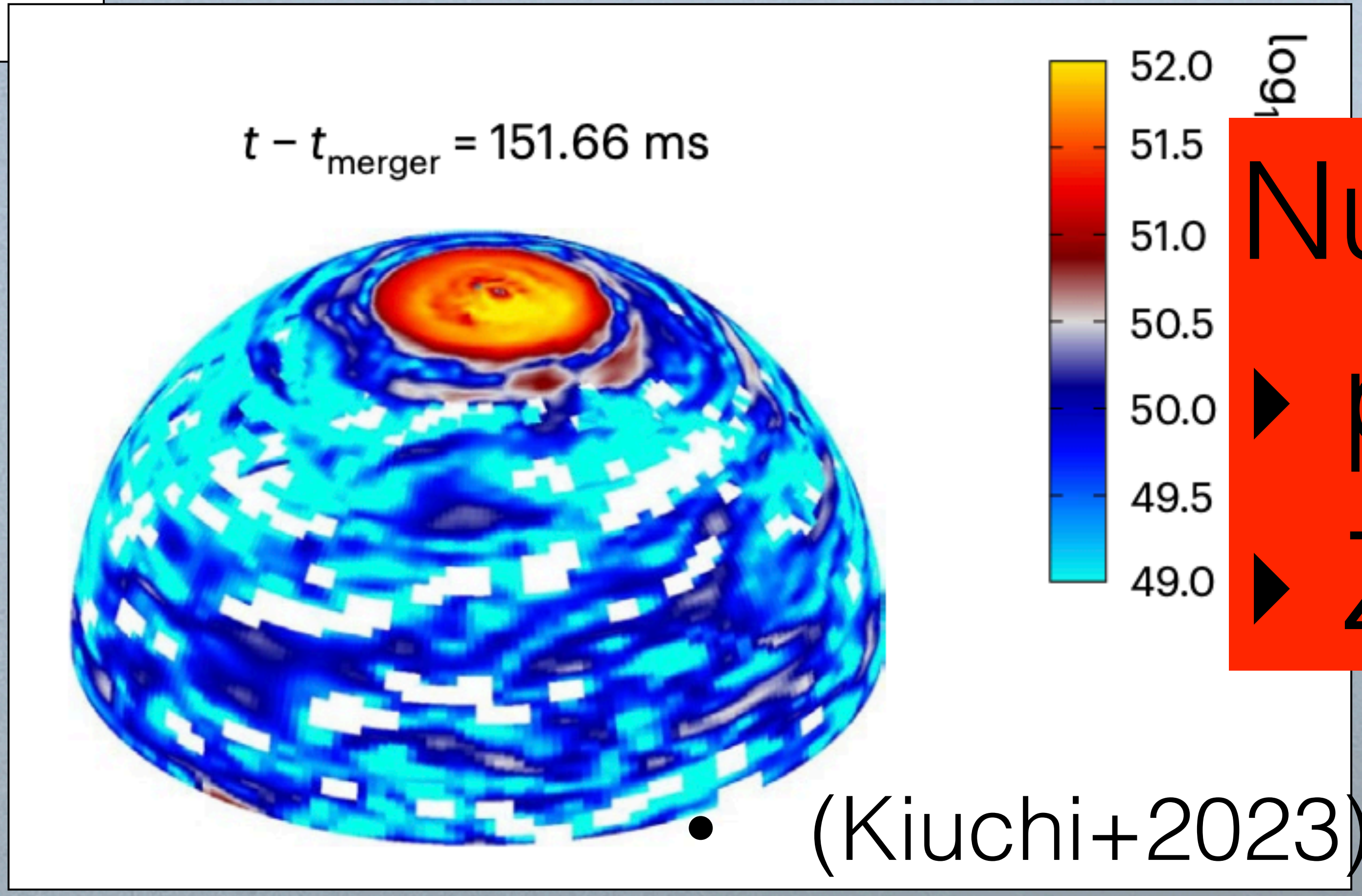
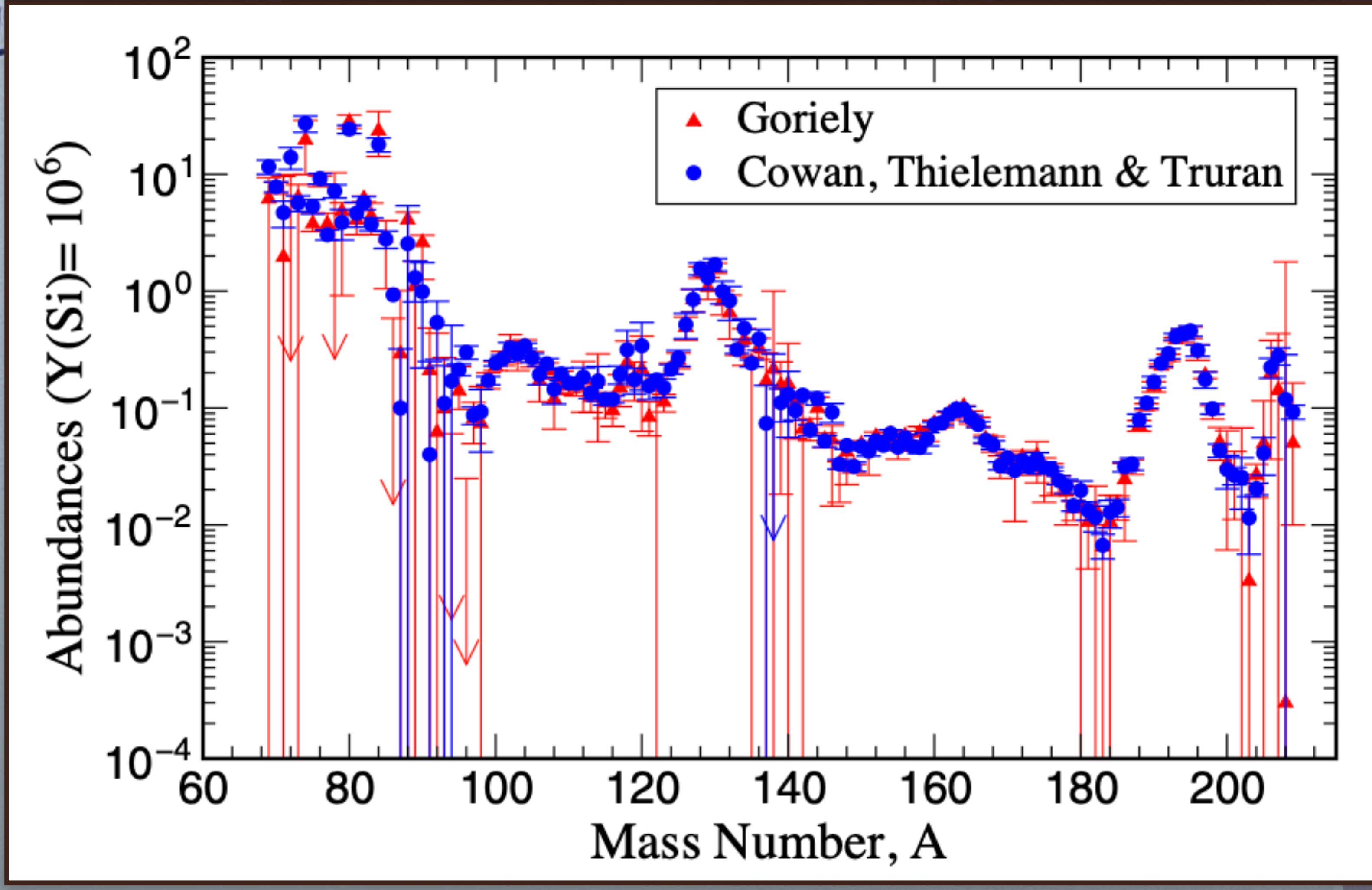



• (Kiuchi+2023)

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



# Big Picture

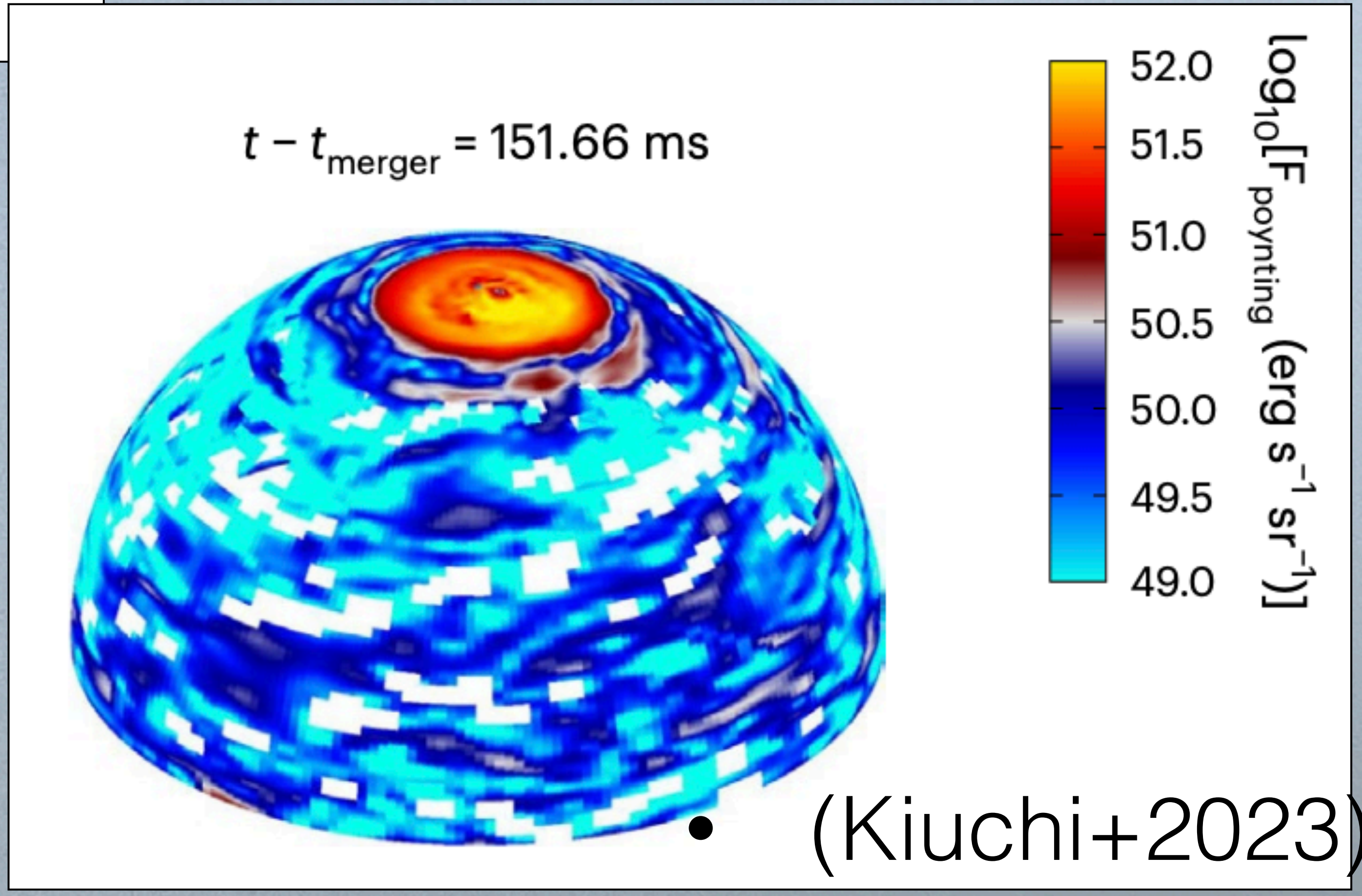
**time** →


Gravitational Wave Emitted

initialization of B
150ms, 500 km

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

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




• (Kiuchi+2023)

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

# Big Picture

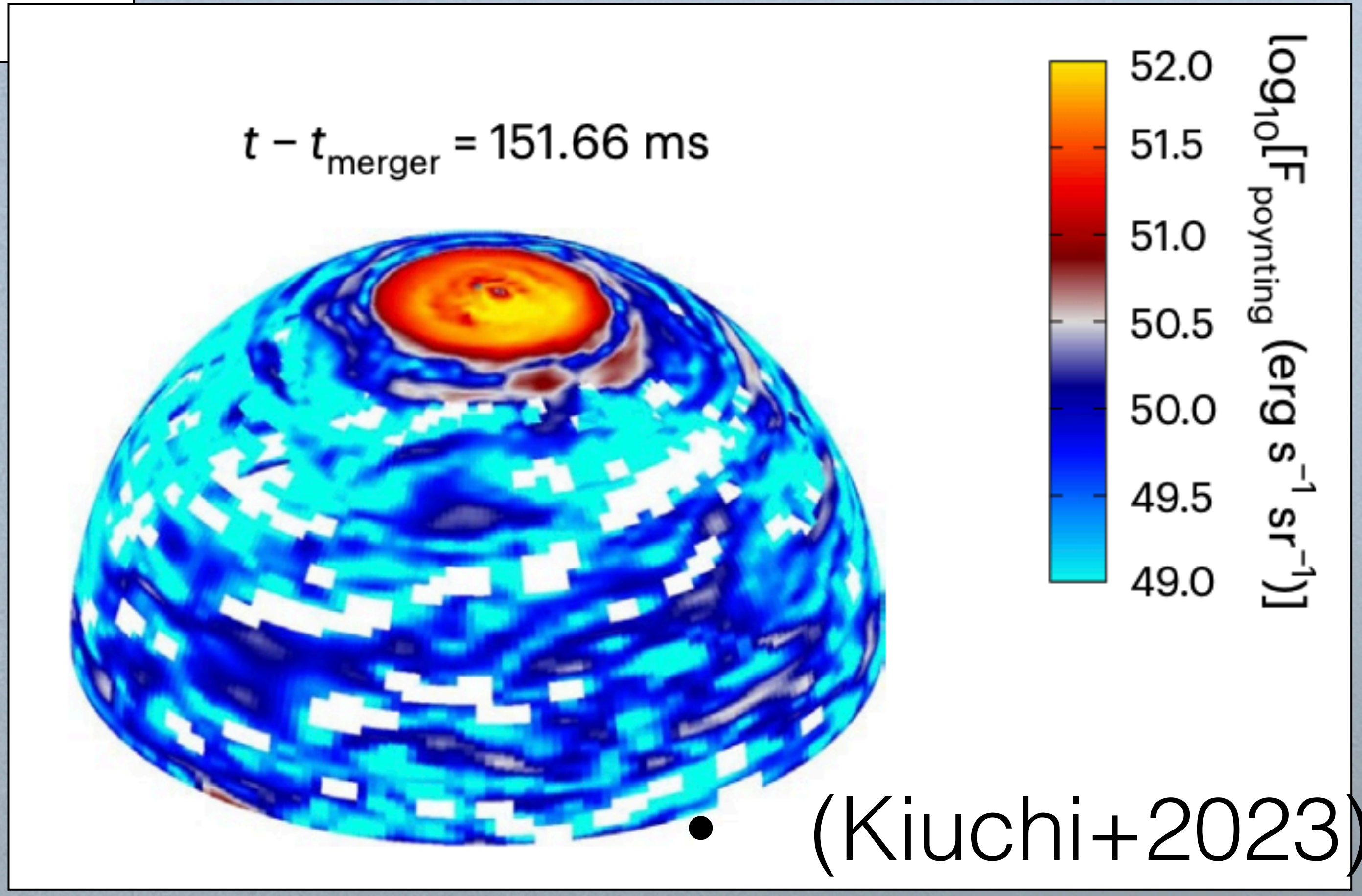
time →


**Gravitational Wave Emitted**

**initialization of B**
150ms, 500 km

cools to ~ 1 MeV
**nucleosynthesis**
~1 s: $r \sim 10^{10}$ cm

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




- (Kiuchi+2023)

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

# Predicting the UHECR spectral cutoff, $R_{cut}$, in the BNS magnetized turbulent outflow (1)

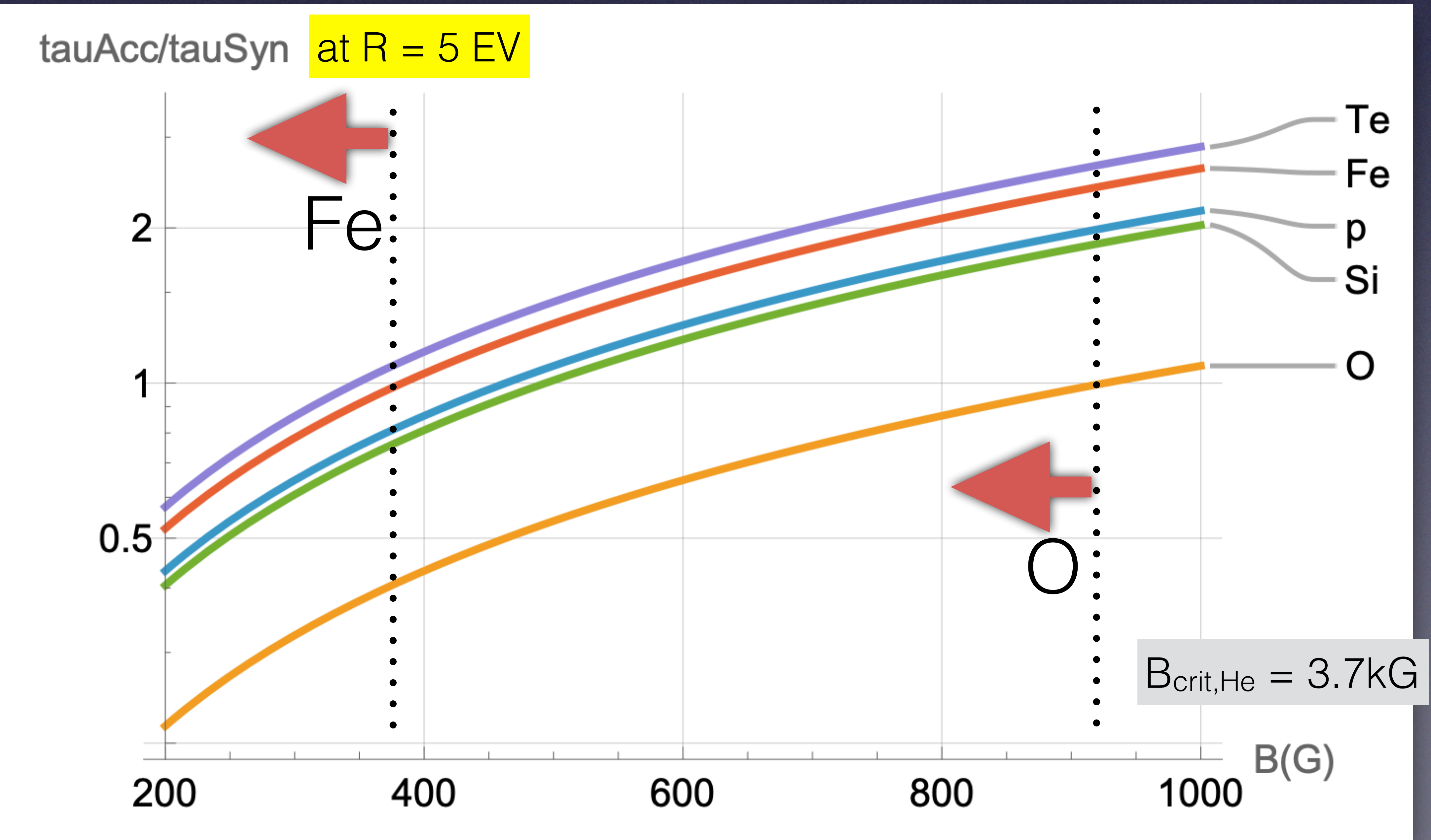
For a given B field, maximum energy of CR is set by $\tau_{synch\text{-}loss} \approx \tau_{accel}$

- $\tau_{synch\text{-}loss}$ depends on A, Z, B, & ***R***igidity (= $\gamma$ A/Z $m_p$):

$$\dot{E}_{\rm synch} = \frac{4}{9} c \left( \frac{m_e r_0}{m_p} \right)^2 (\gamma \beta B)^2 \, \frac{Z^4}{A^2}$$

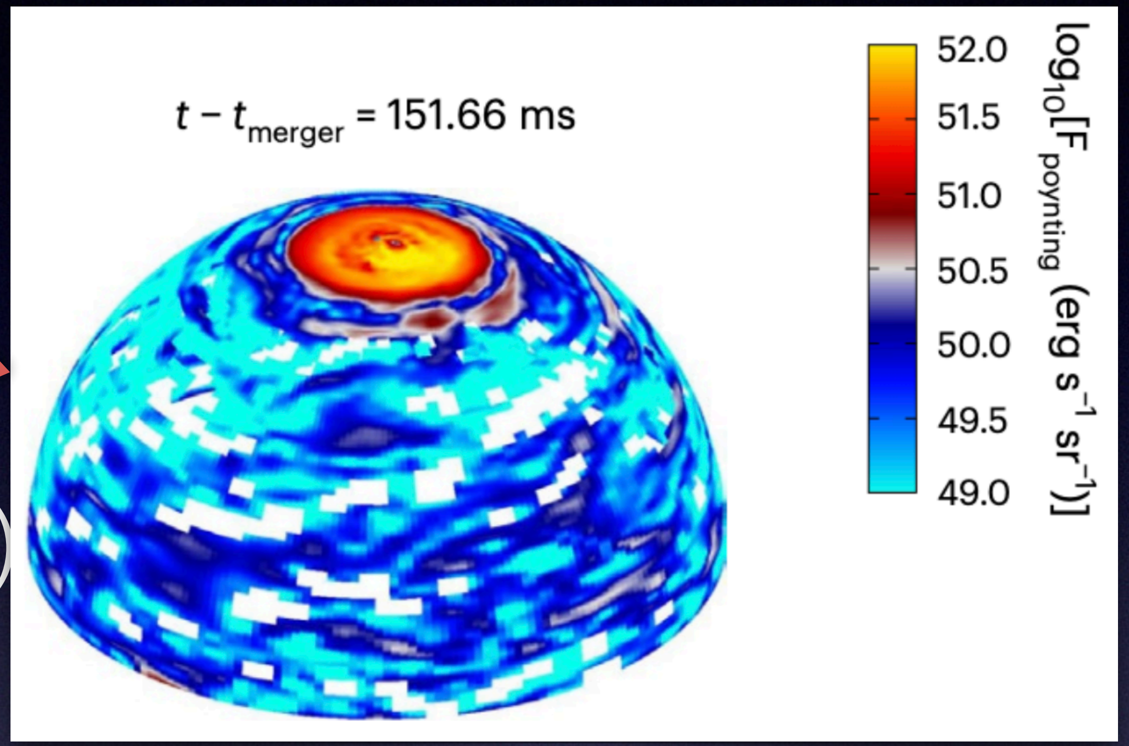
- $\tau_{accel} \approx r_{Lar}/c \sim (E/Z = \boldsymbol{R}) / B$

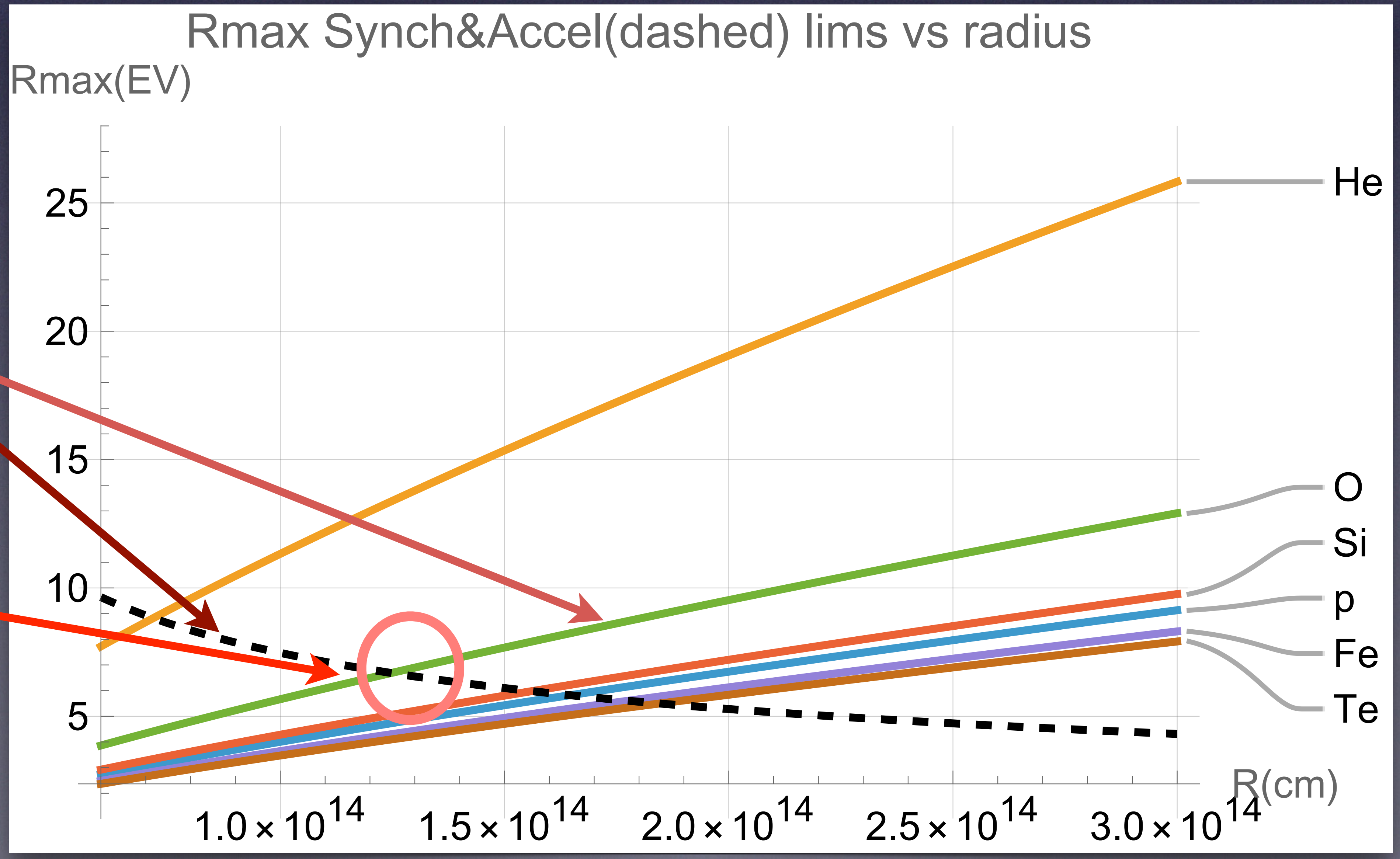
$\tau_{accel} / \tau_{synch\text{-}loss} \sim 1 \Rightarrow$ max B for given ***R***



# Predicting $R_{cut}$ in the BNS magnetized turbulent outflow (2)

- Initialize $B(r{=}500\ \text{km}) = 3.3\ 10^{12}$ G; $L_{coh} \approx r/3$ (Kiuchi+2023)
- Assume that $B(r) = B_0\ (r/r_0)^{-3/2}$ ; homologous expn (Rosswog+2014)
- Maximum rigidity of CR when radius is 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

fit to Auger data assuming common ➜ $R_{cut}$ = 6.8 EV

# Essential UHECR facts explained!

- Spectrum from magnetized turbulence: $\sim E^{-2.1}\,\mathrm{sech}[(E/E_{cut})^2]$
- At each E, the range of masses is narrow:
  - Minimal source-to-source variation
  - Rigidity spectrum of individual sources is narrow (sech)
  - $R_{cut} \approx$ 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.

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

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

# 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-$\nu$ coincidences for EHE $\nu$'s (E> PeV) - time delay ≈1 day

# EHE Neutrino production

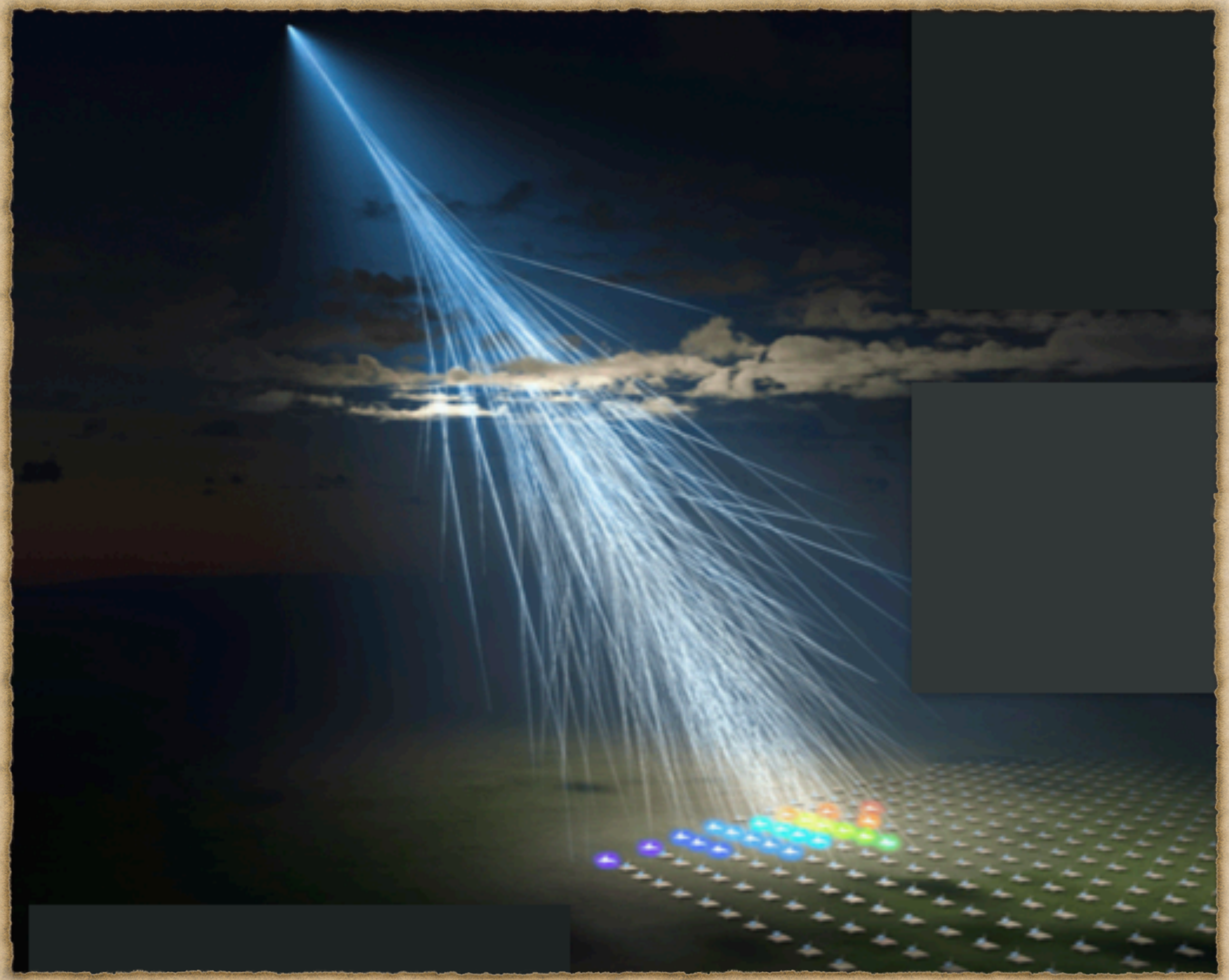
- Neutrinos come from UHECRs:
  - spallation neutrons beta decay: $E_{\nu} \approx 10^{-3} (E_n \approx \boldsymbol{R}/2) \sim 2$ PeV
  - photo-pion production: $E_{\nu} \lesssim (E/A)/20 \sim \boldsymbol{R}/40 \sim 100$ PeV
- Time delay for $\boldsymbol{\nu}$ is > time for ejecta to expand to $10^{14}$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

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

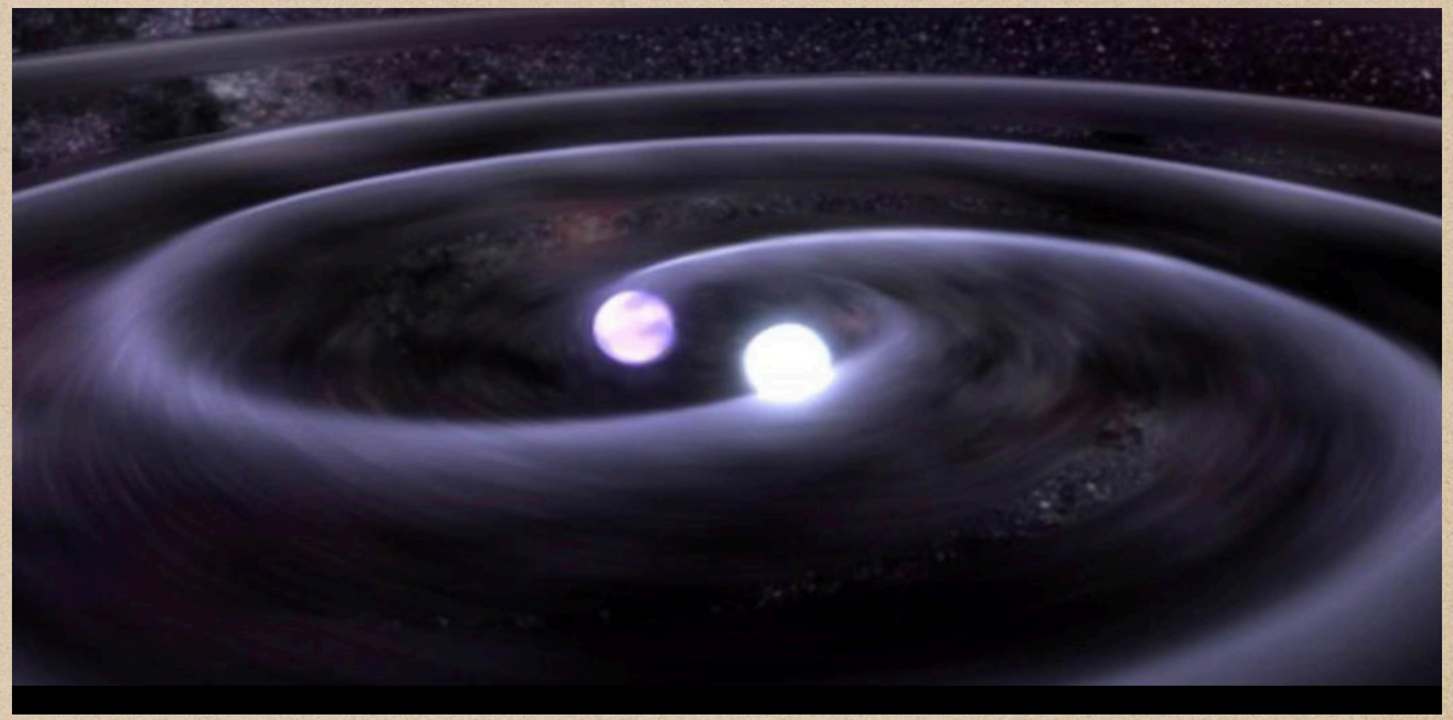
very crude: 1/yr with Cosmic Explorer, Einstein telescope & ICGen2

# 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 ≳100 MeV collide, producing spallation
  - lighter nuclei are formed
- Need PIC simulations
  - Expanding magnetized turbulence
  - “Uptake probability” into acceleration chain, to calculate absolute magnitude of CR component.



# Summary



**New suggestion: UHECRs are produced in binary NS mergers.**

- Uniquely, potentially satisfies all requirements:
  * Universal Maximum Rigidity explained — predicted value agrees with data.
  * TBD: Total UHECR power (depends on BNS merger rate & power in CRs)
- Highest energy events are r-process nuclei — testable by Auger
- EHE neutrinos, and coincidences with GWs or sGRBs from BNS-merger

# Needed from YOU!!!

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

# Backup slides

# 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)

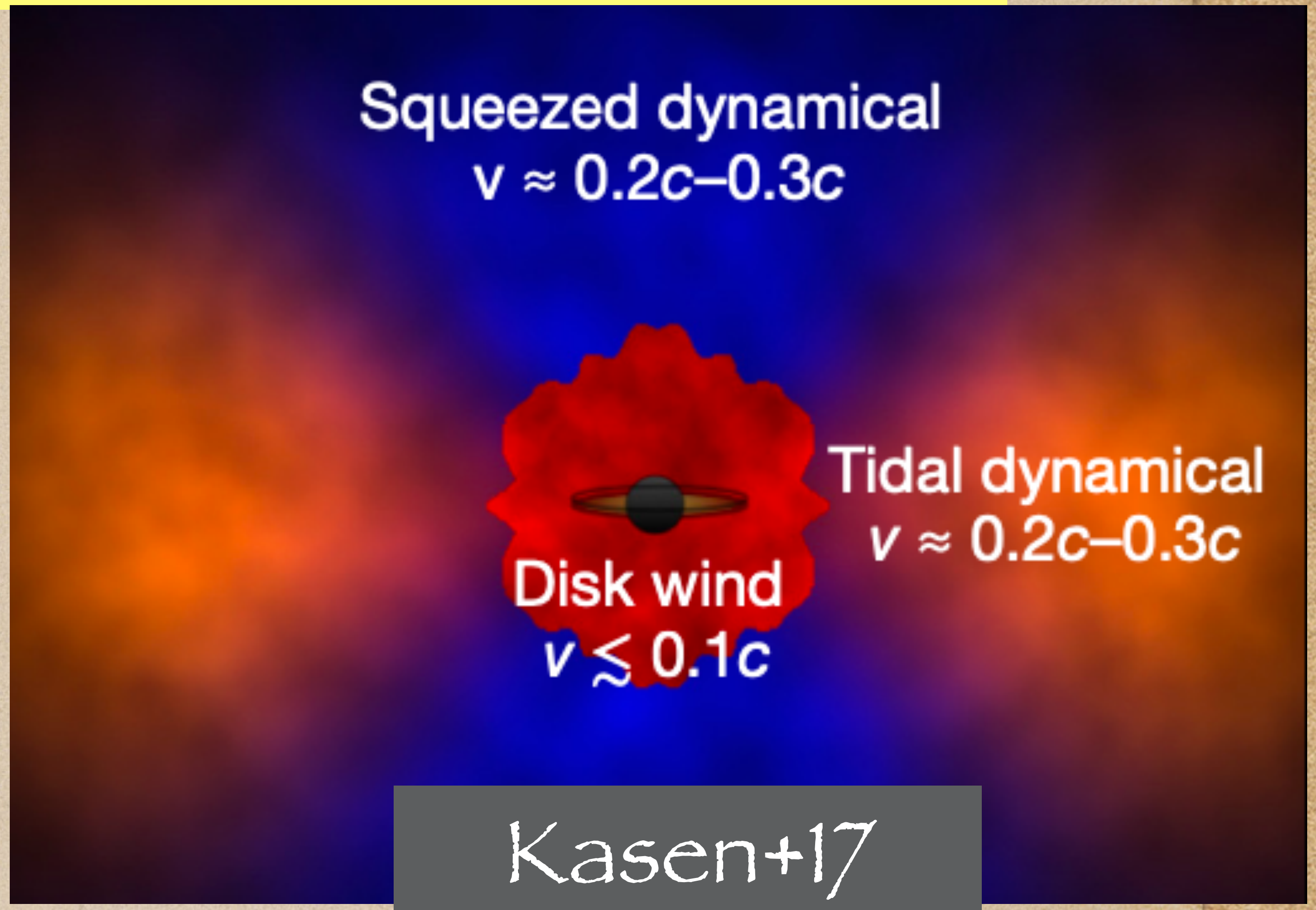
# Very highest energy UHECRs explained!

## (with narrow Rigidity ≈ 4.5 EV, where do UCR's above 100 EeV come from?)

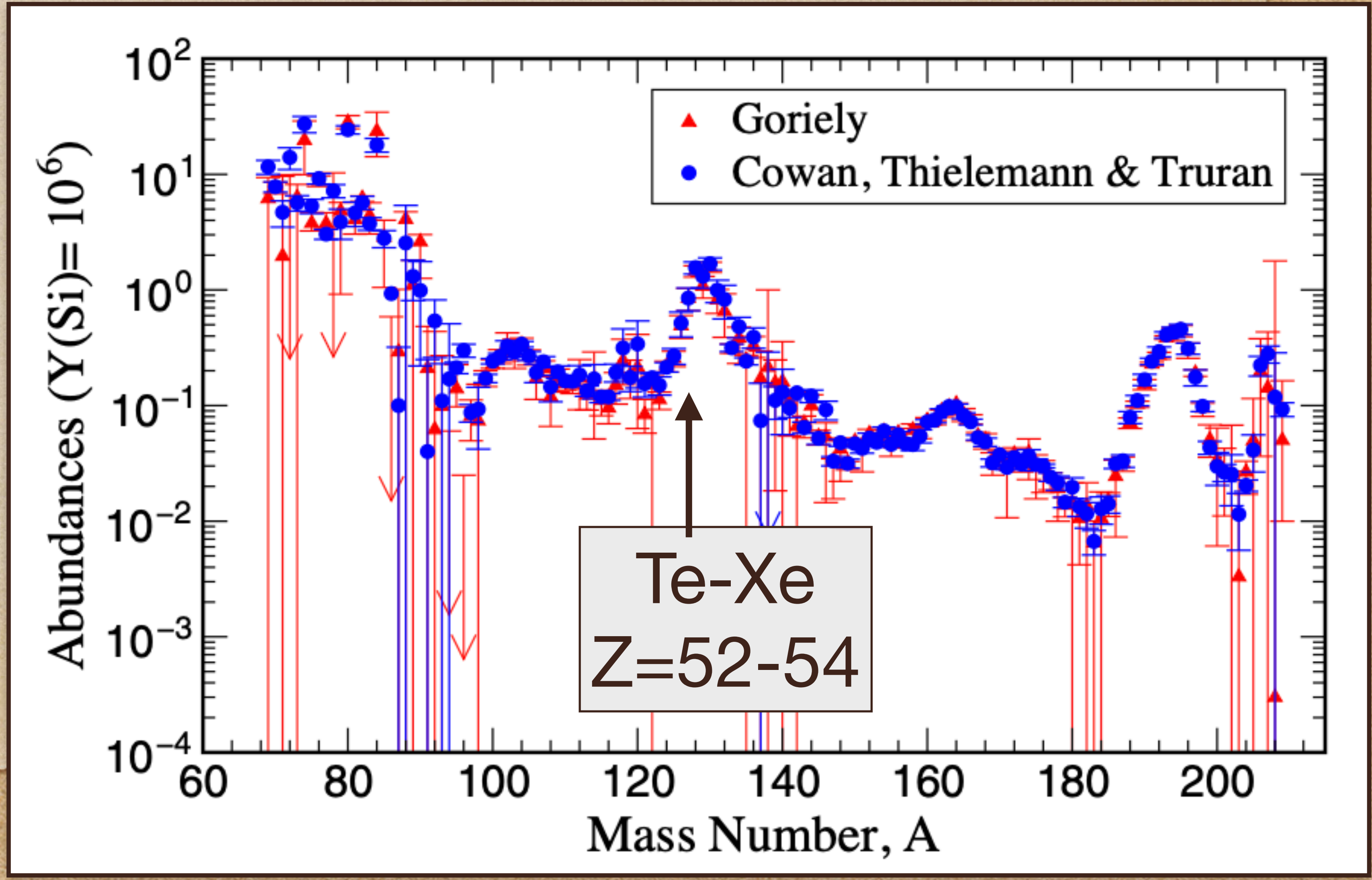
- r-process nucleosynthesis takes place in BNS mergers
- sometimes an r-nucleus is swept up and accelerated

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

- Excellent agreement with OMG and Amaterasu!
- $E_{OMG} \approx 250 \pm 70$ EeV*, $E_{Amaterasu} \approx 212 \pm 25$ EeV**




Kasen+17




*with modern air fluorescence yield **higher if a proton

# ENERGY LOSS IN PROPAGATION ⇒ GZK Horizon

Greisen, Zatsepin, Kuzmin (GZK) bound

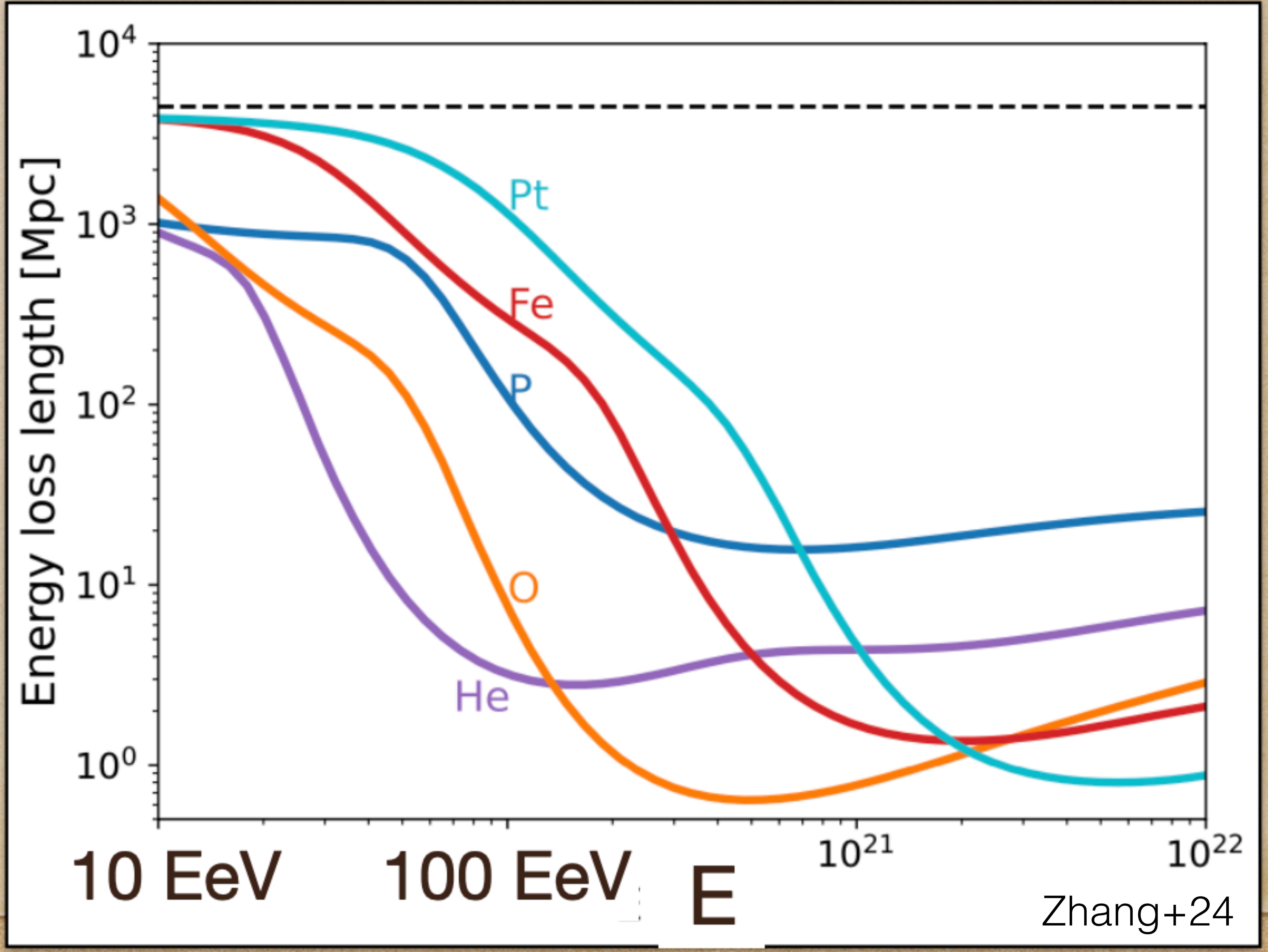
$p + \gamma_{CMB} \rightarrow \pi + N$ ; $p + \gamma_{CMB} \rightarrow e^+e^- p$

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

$\langle dist \rangle_{E>8EeV} \approx 210$ 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 $\gamma_s^2 = 1 + \frac{|\boldsymbol{p}|^2}{m_s^2 c^2}$ and $\boldsymbol{F} = q_s \left( \boldsymbol{E} + \frac{\boldsymbol{p}}{\gamma_s m_s c} \times \boldsymbol{B} \right)$.

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

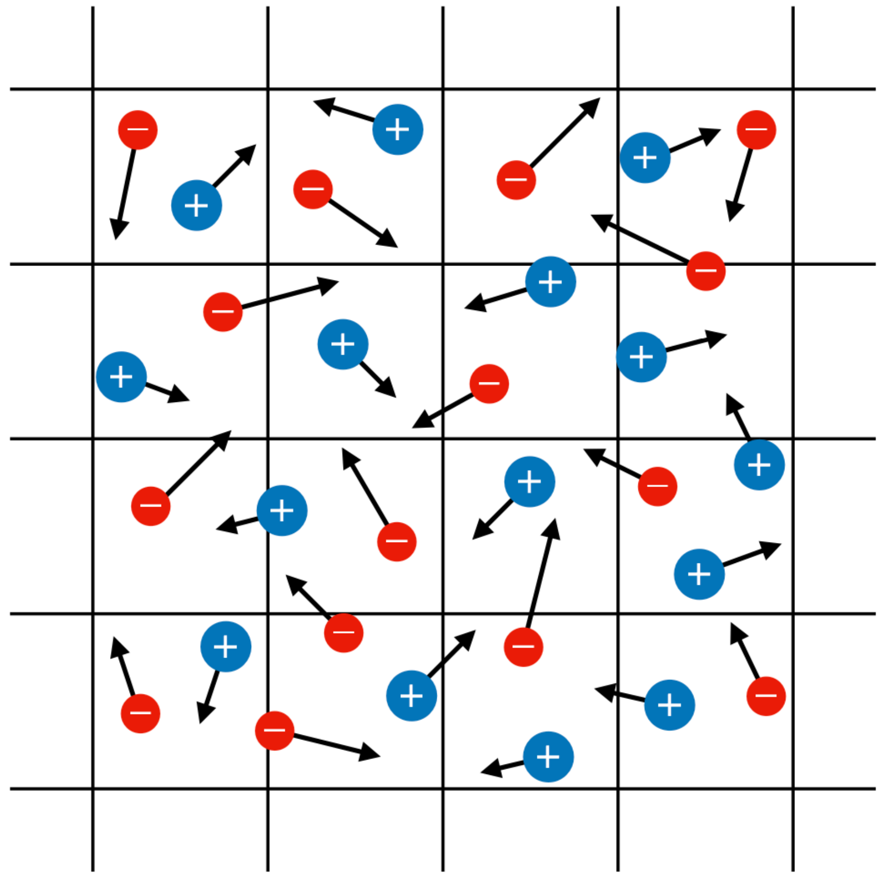
$$\frac{\partial \boldsymbol{E}}{\partial t} - c\,{\rm curl}\boldsymbol{B} = -4\pi \boldsymbol{J}, \qquad {\rm div}\boldsymbol{E} = 4\pi\rho,$$

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

where the source terms are computed by

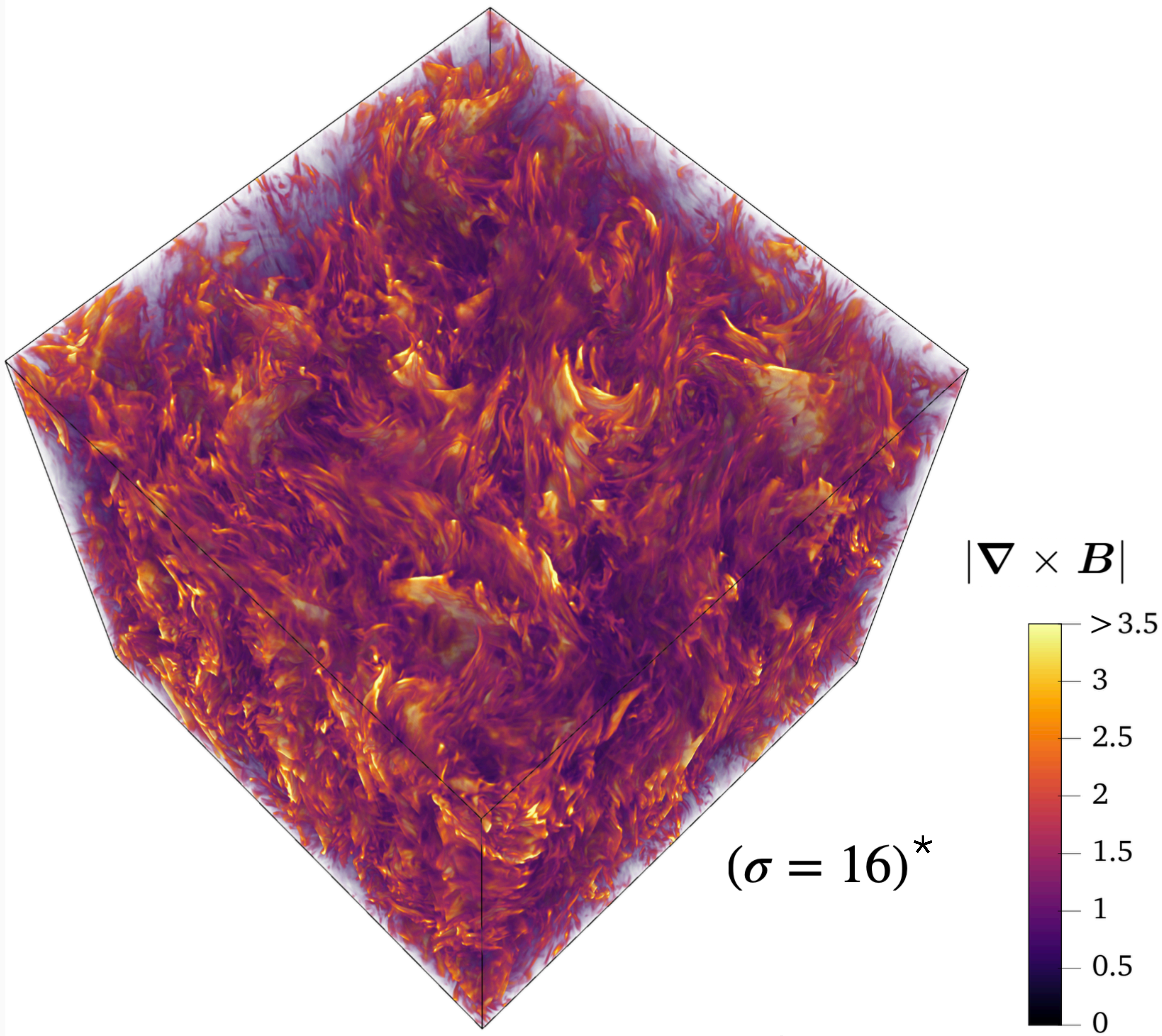
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\boldsymbol{p}, \qquad \boldsymbol{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\boldsymbol{p}}{\gamma_s} d\boldsymbol{p}.$$

- Solution via particle-in-cell method

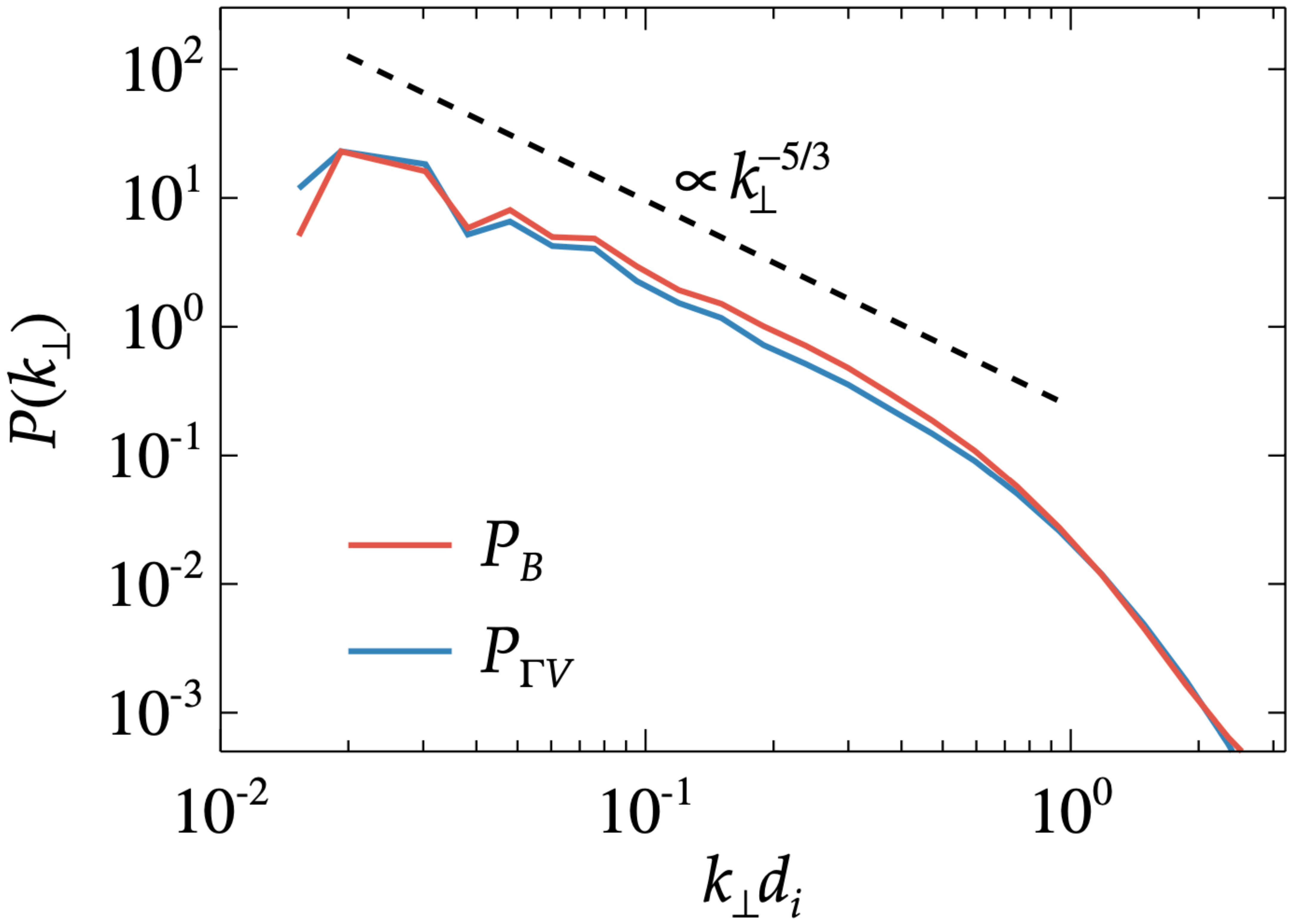


PIC code: TRISTAN-MP (Spitkovsky 2005)

# Magnetically dominated turbulence from first-principles PIC simulations

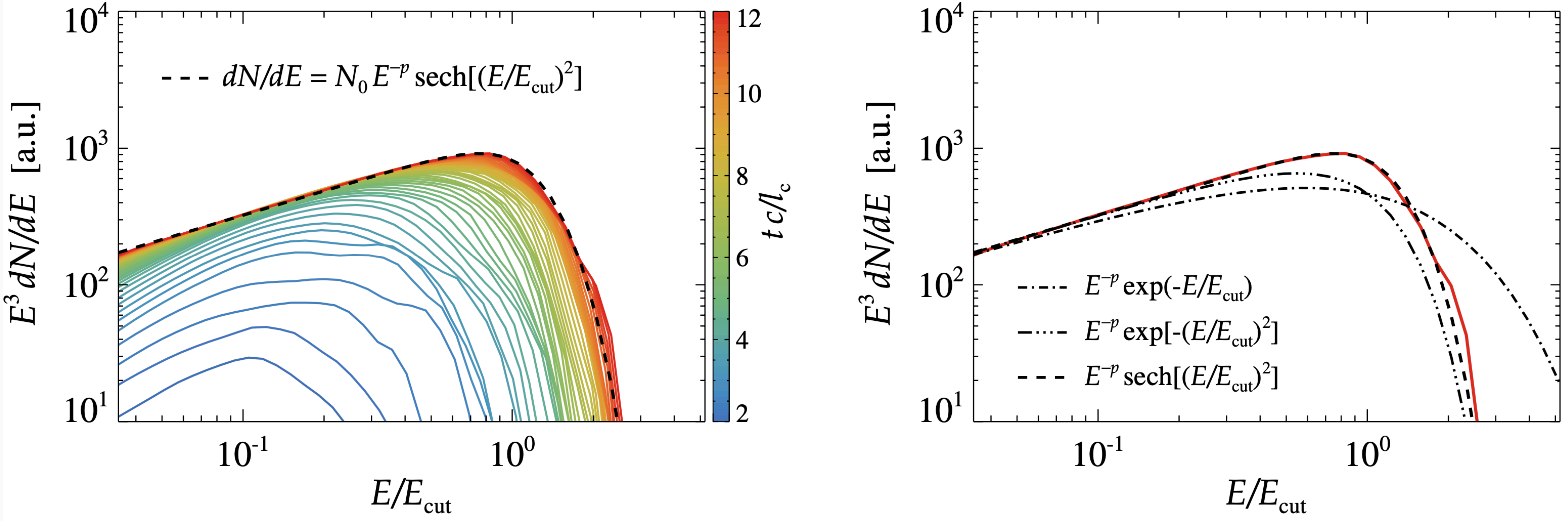



*σ ≈ $U_{mag}$/KEden




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

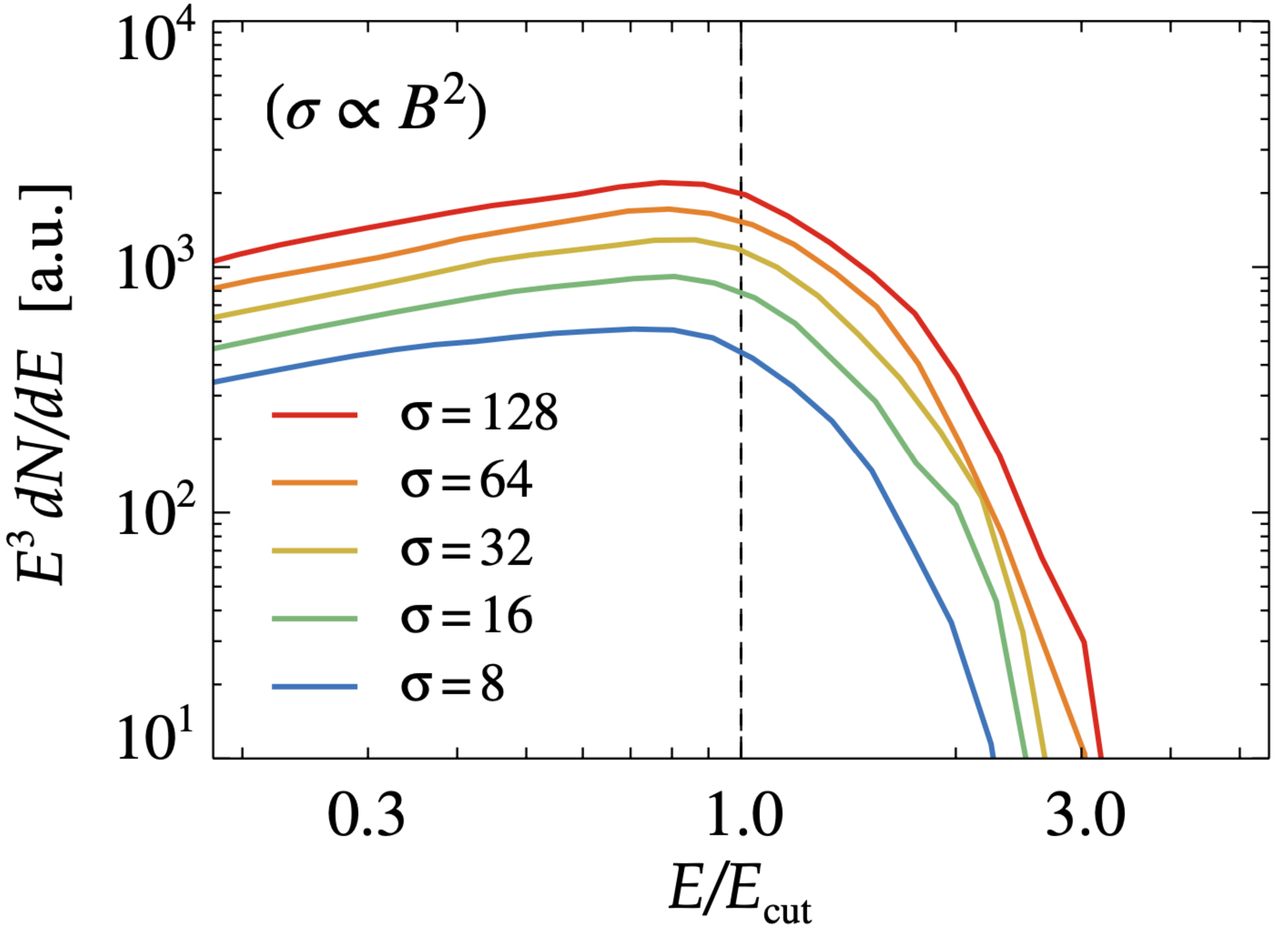
# Particle acceleration via magnetized turbulence: nonthermal particle spectrum

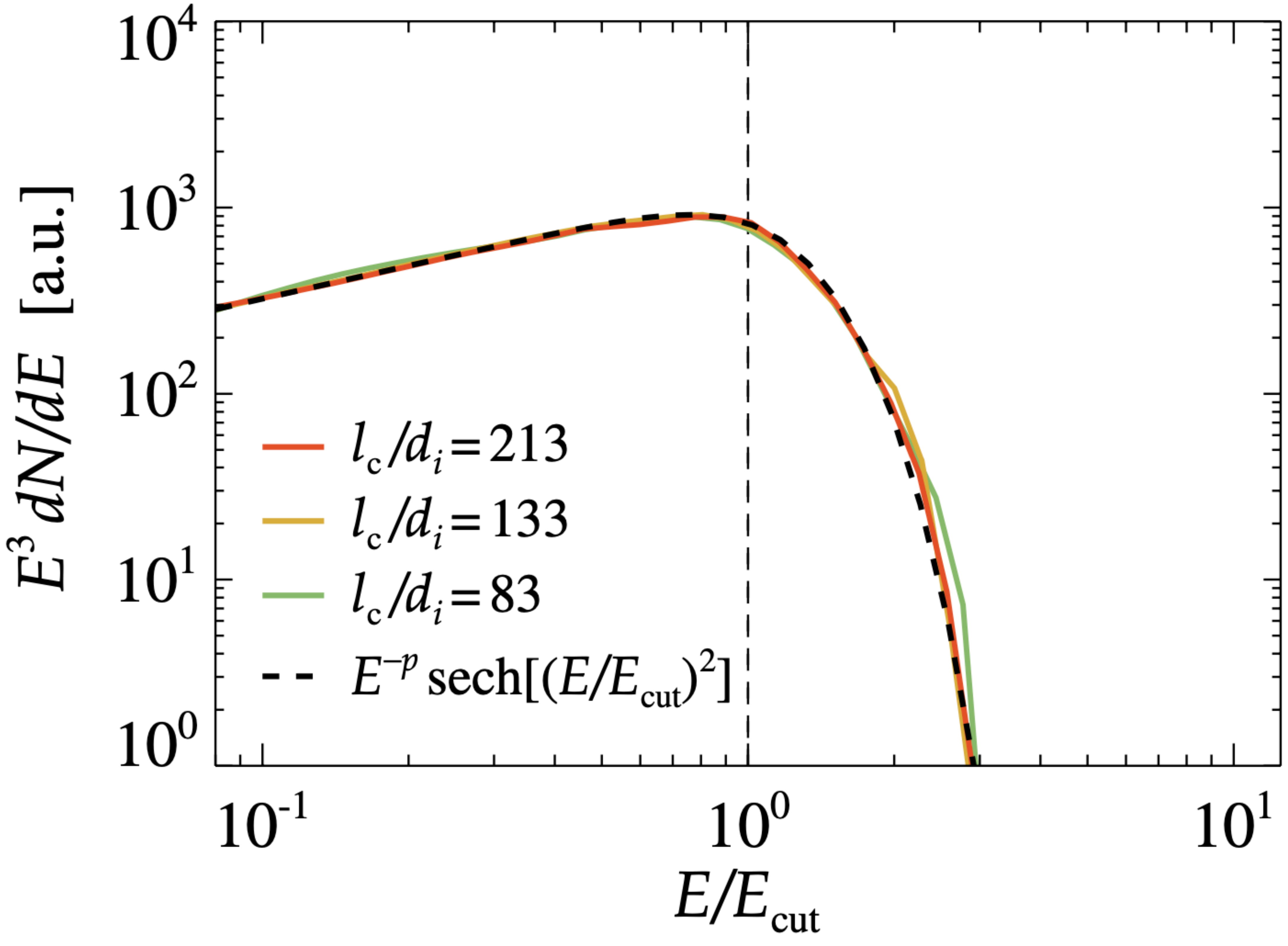



- magnetized turbulence accelerates particles into a spectrum of the form:

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

# Particle acceleration via magnetized turbulence: cutoff energy

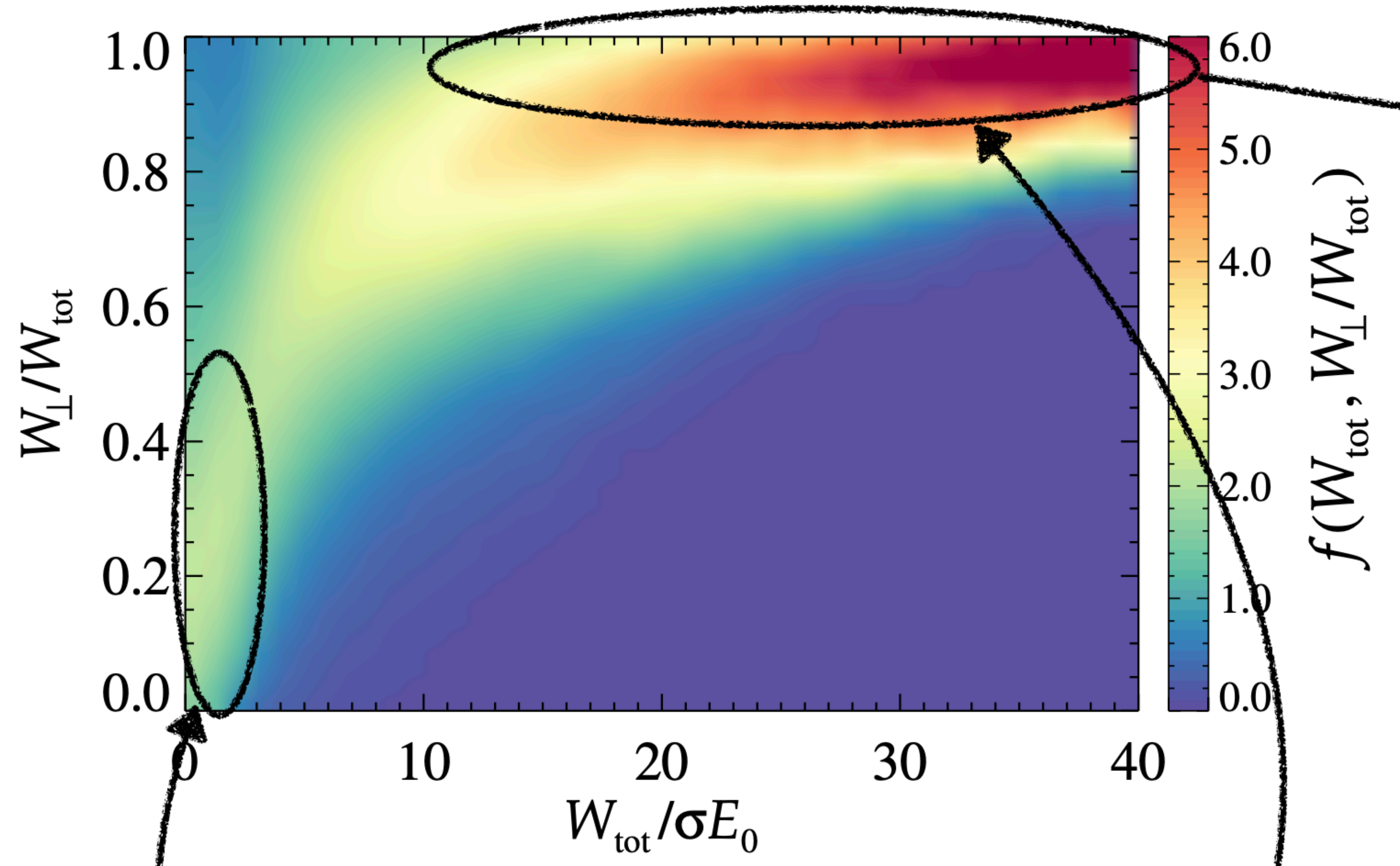


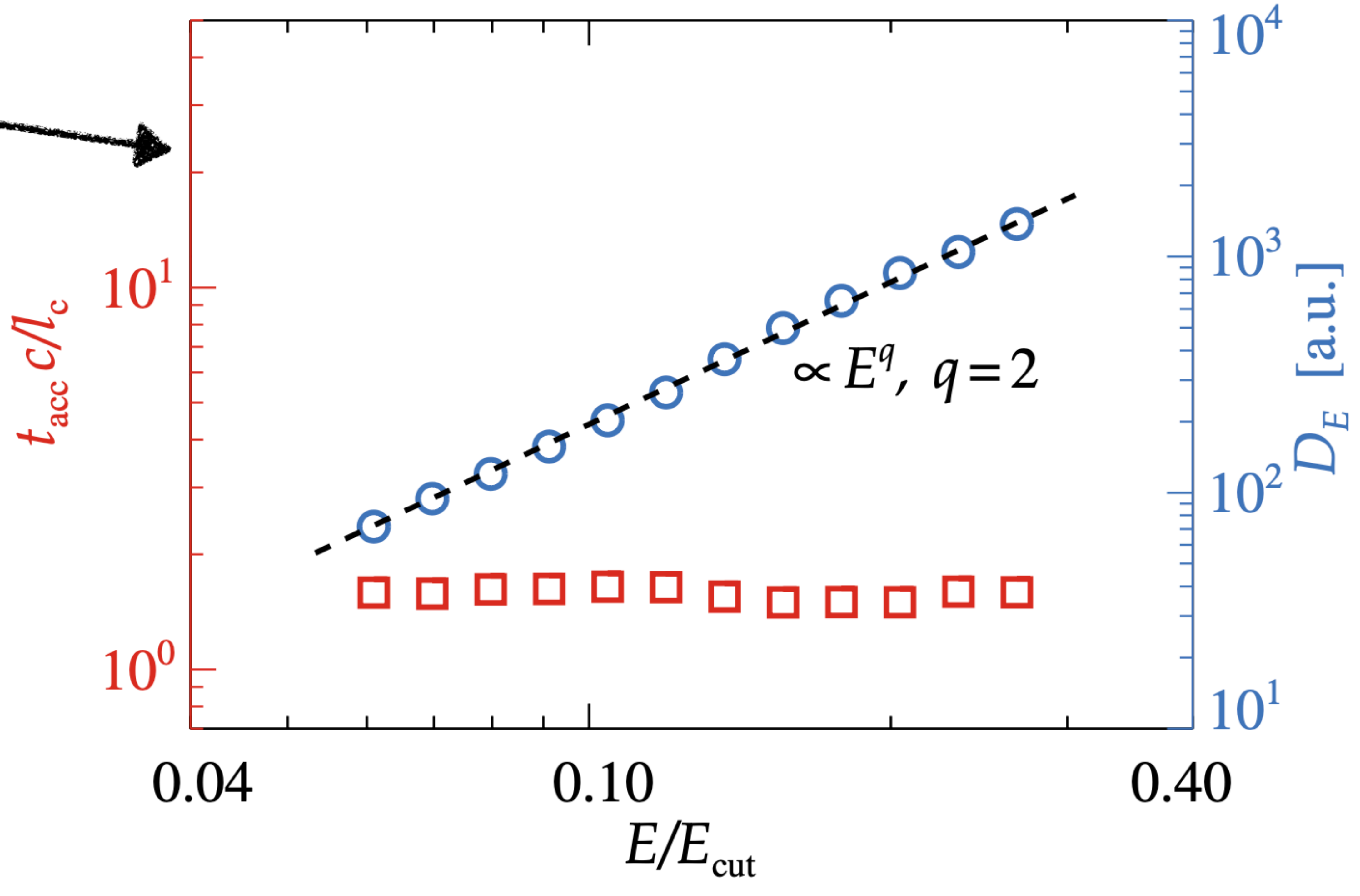




- cutoff $\text{sech}[(E/E_{\rm cut})^2]$ scales with $E_{\rm cut} = ZeR_{\rm cut} = Ze(B_{\rm rms}\kappa l_c)$, where $\kappa = 0.65$ from the fits
- magnetized turbulence does accelerate particles to the "Hillas limit" if one assumes $R_{\rm size} = l_c$

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

# 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:

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

- flux of particles escaping the accelerator is given by

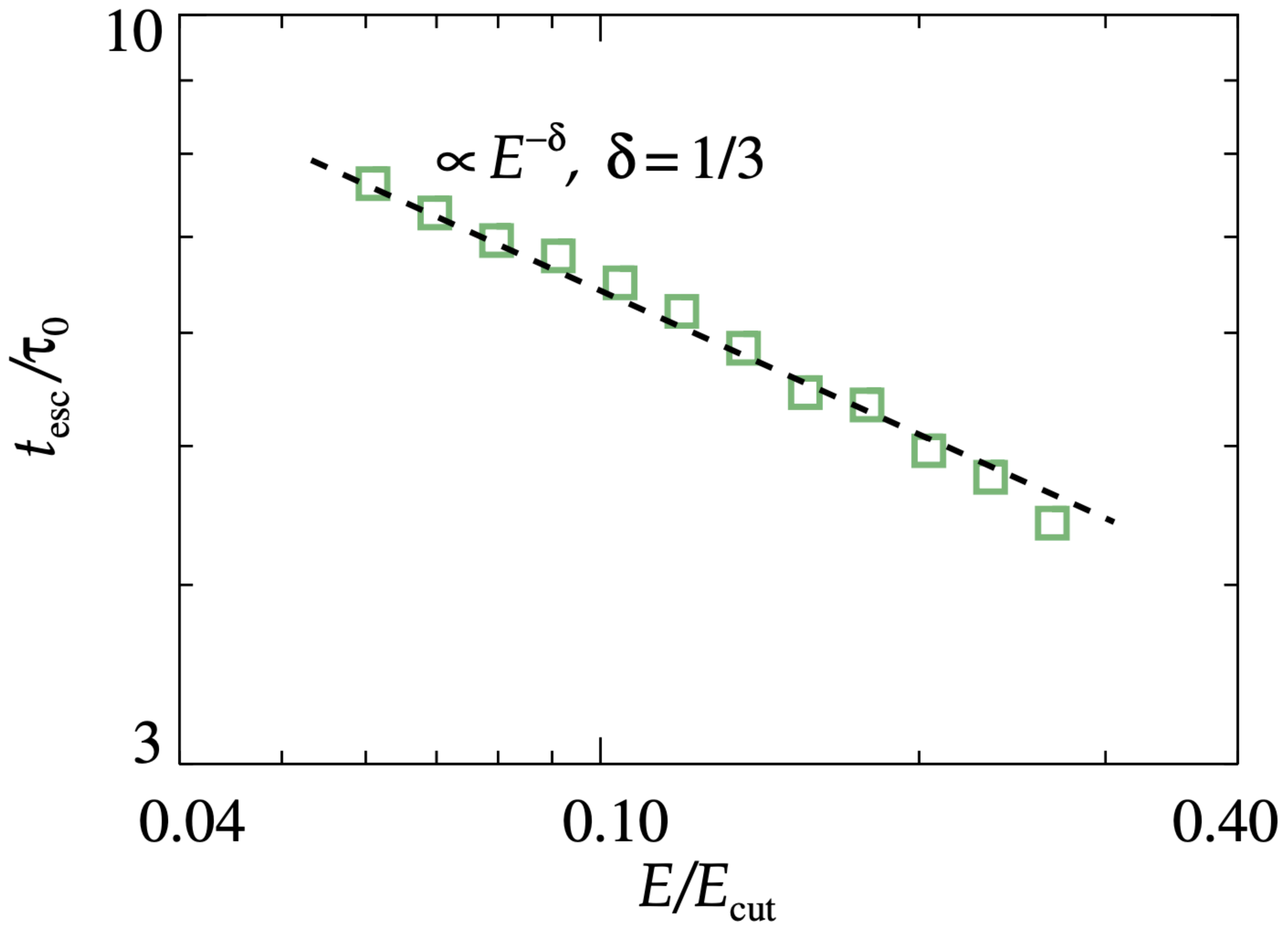
$$\phi(E) = \frac{dN}{dE dt} = \frac{1}{t_{\rm esc}}\frac{dN}{dE} \propto E^{-s}\,\mathrm{sech}\left[\left(E/E_{\rm cut}\right)^2\right]$$

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

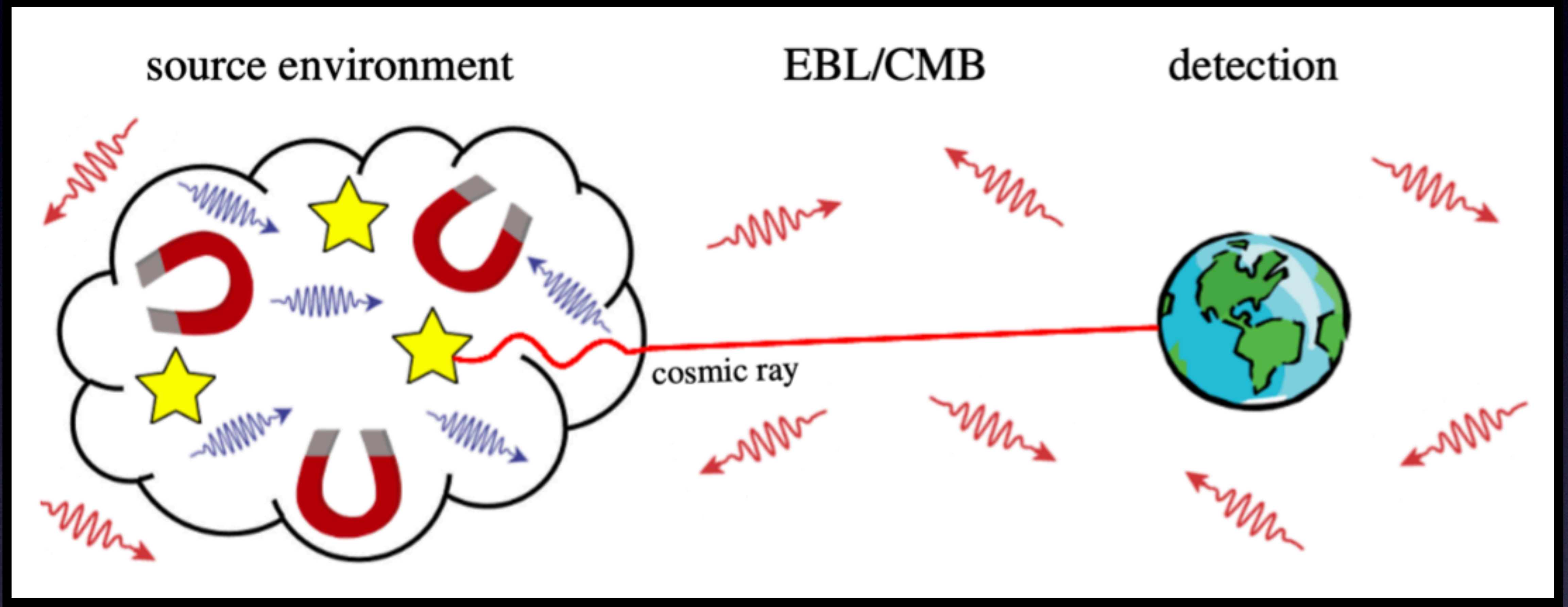
$p \sim 2.4$

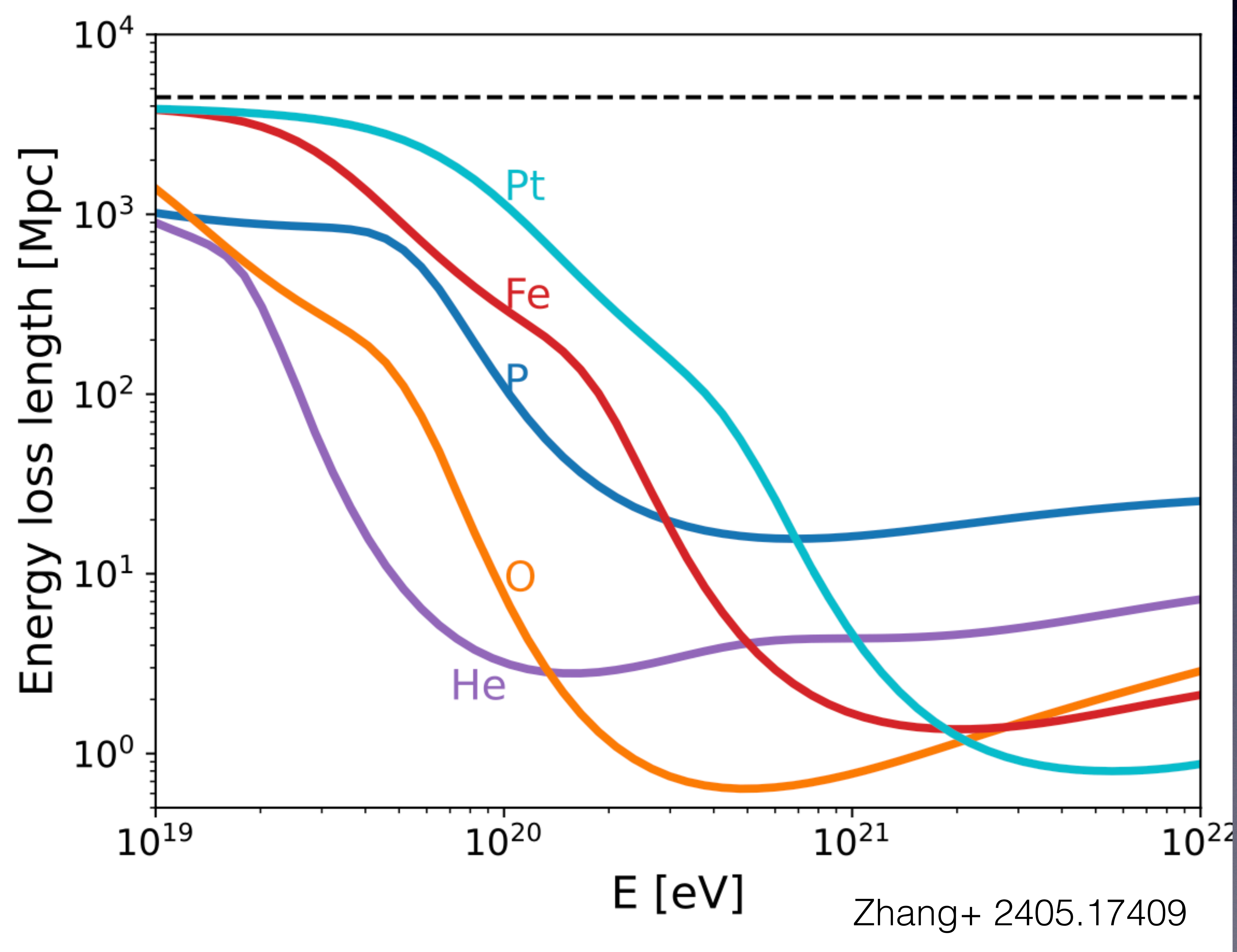
$\delta \sim 1/3$

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



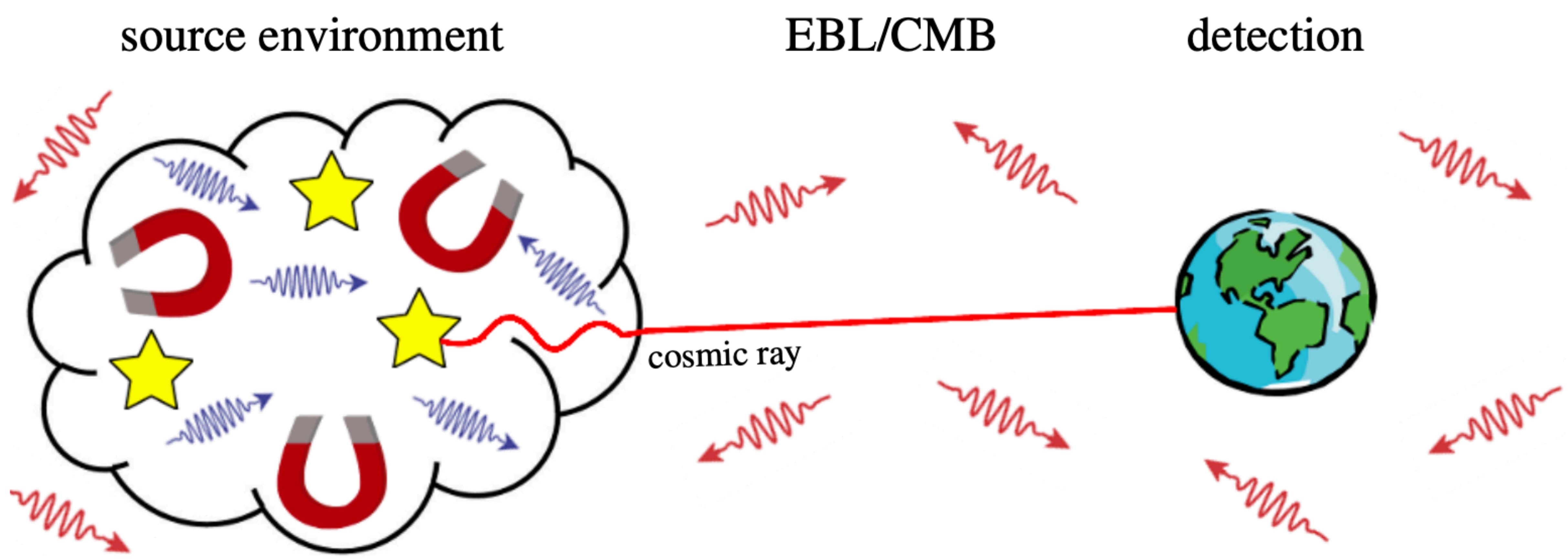
# Interactions in surroundings and propagation from source




- 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

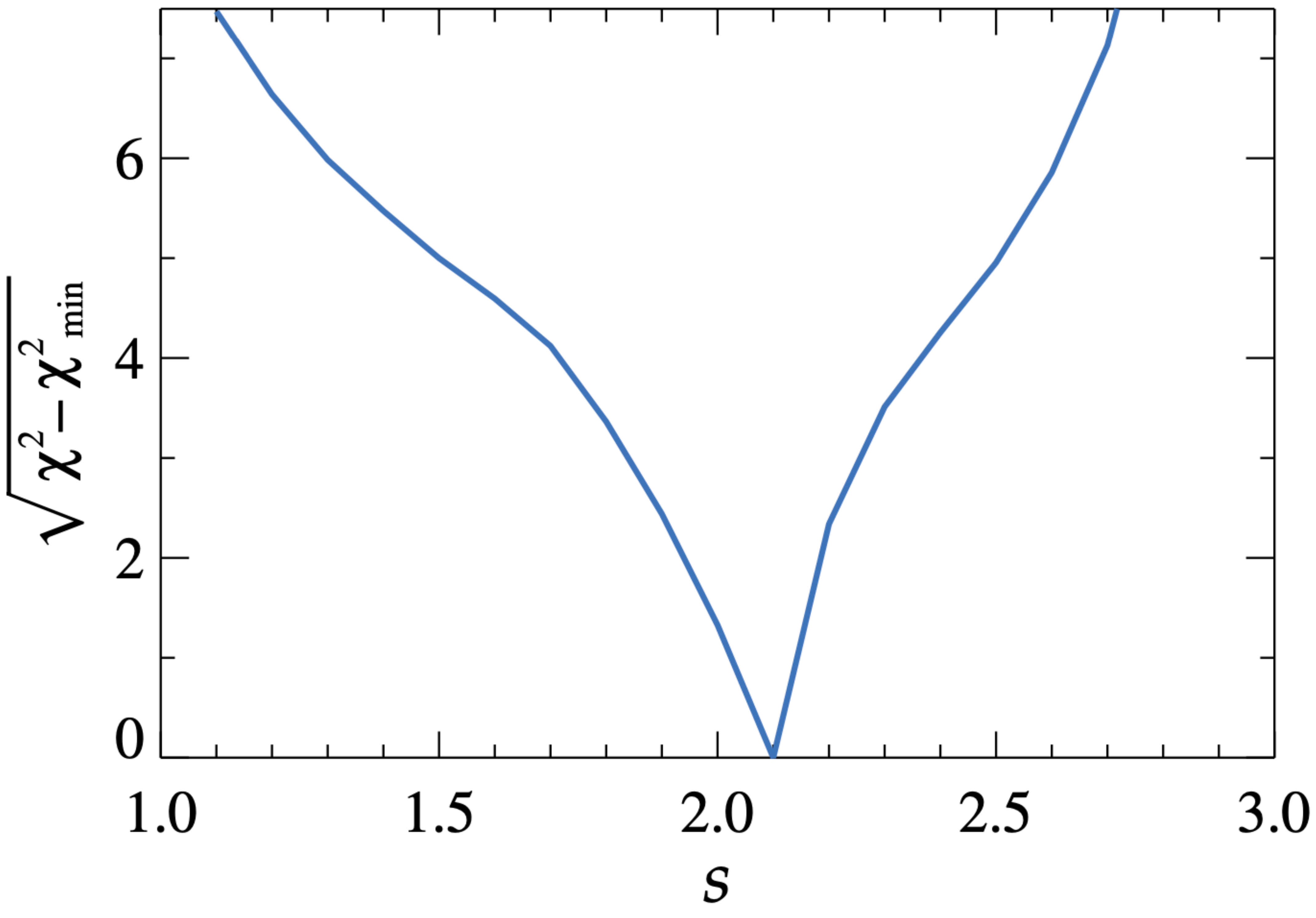
# Particle injected by the accelerator: spectral index from fit to data




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

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

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




- 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

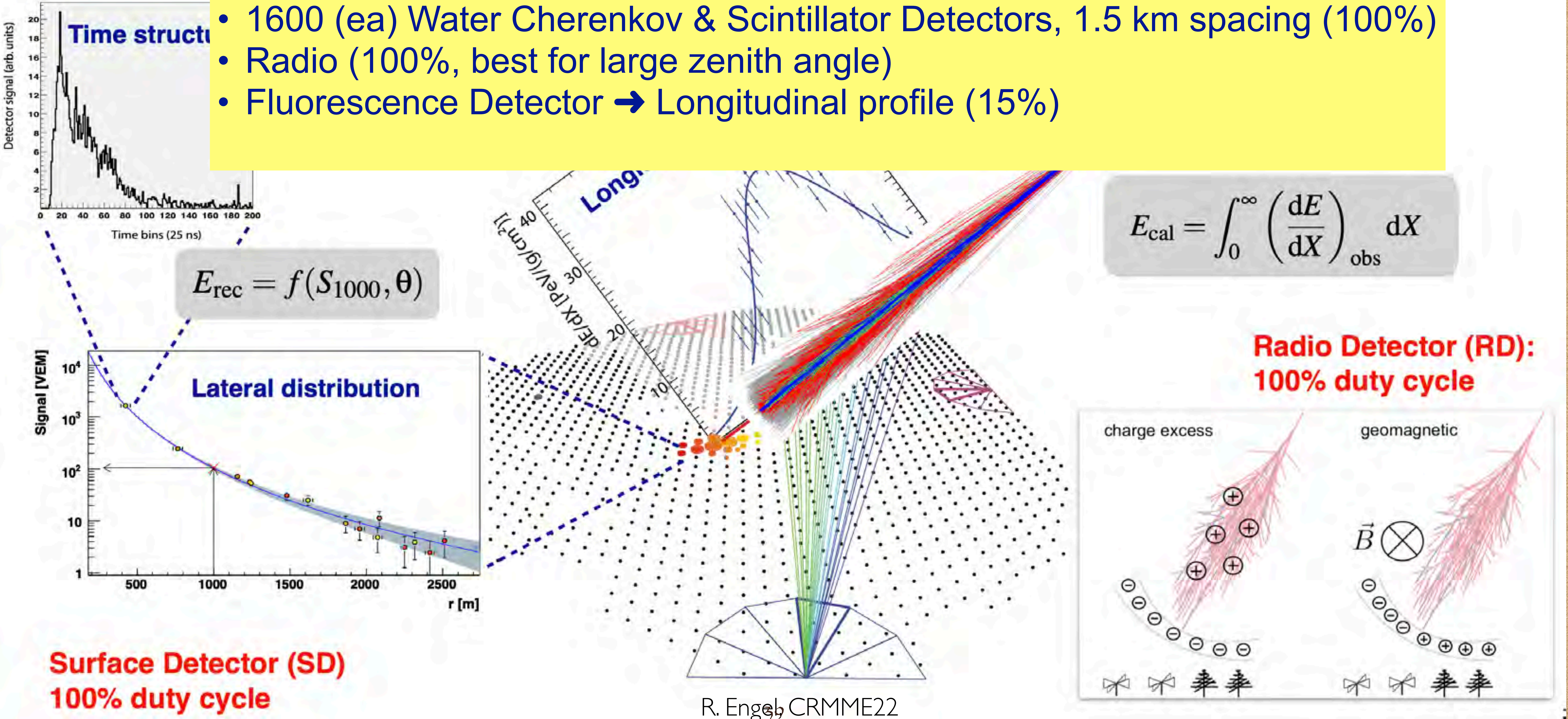
# Does spectral cutoff discriminate between acceleration mechanisms?

- 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)

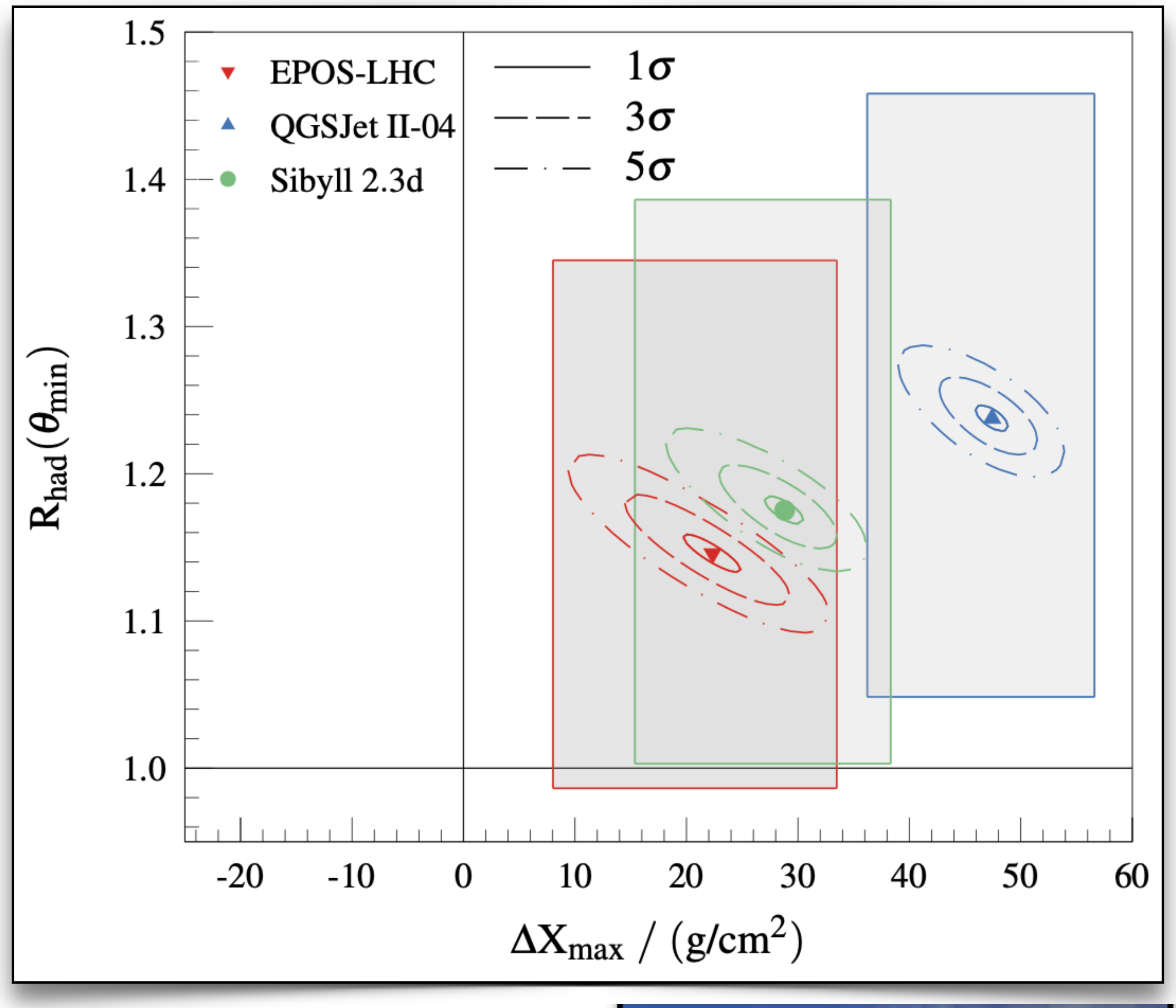
<u>Key components of UHECR observatory:</u>

- 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

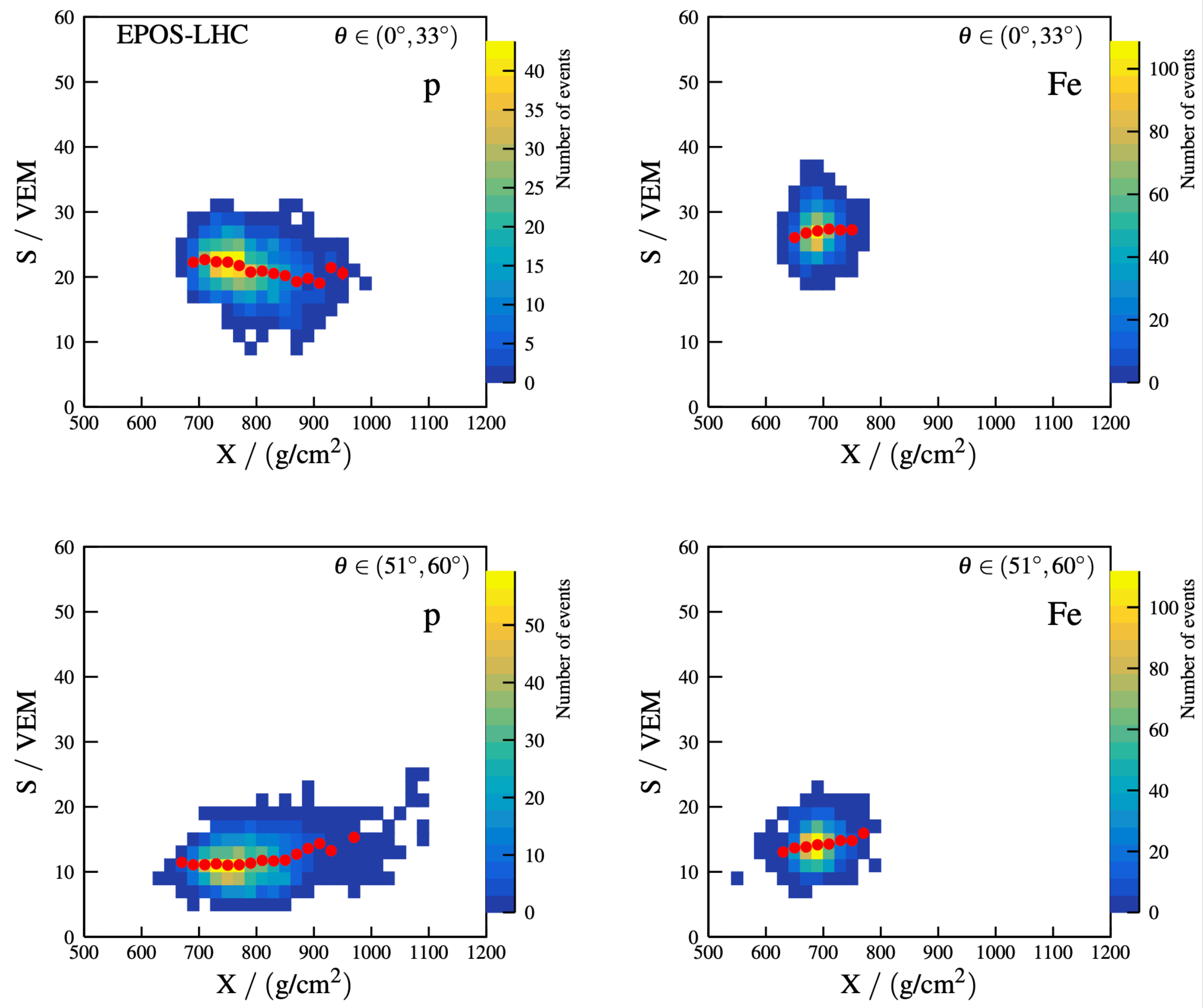



FIG. 1: Examples of two-dimensional distributions of $S$ and $X$ for protons (left) and iron nuclei (right) generated with EPOS-LHC for zenith angles between 0° and 33° (top) and 51° and 60° (bottom). The red points indicate the mean values of $S$. $E = 10^{18.5}$ to $10^{19.0}$ eV.

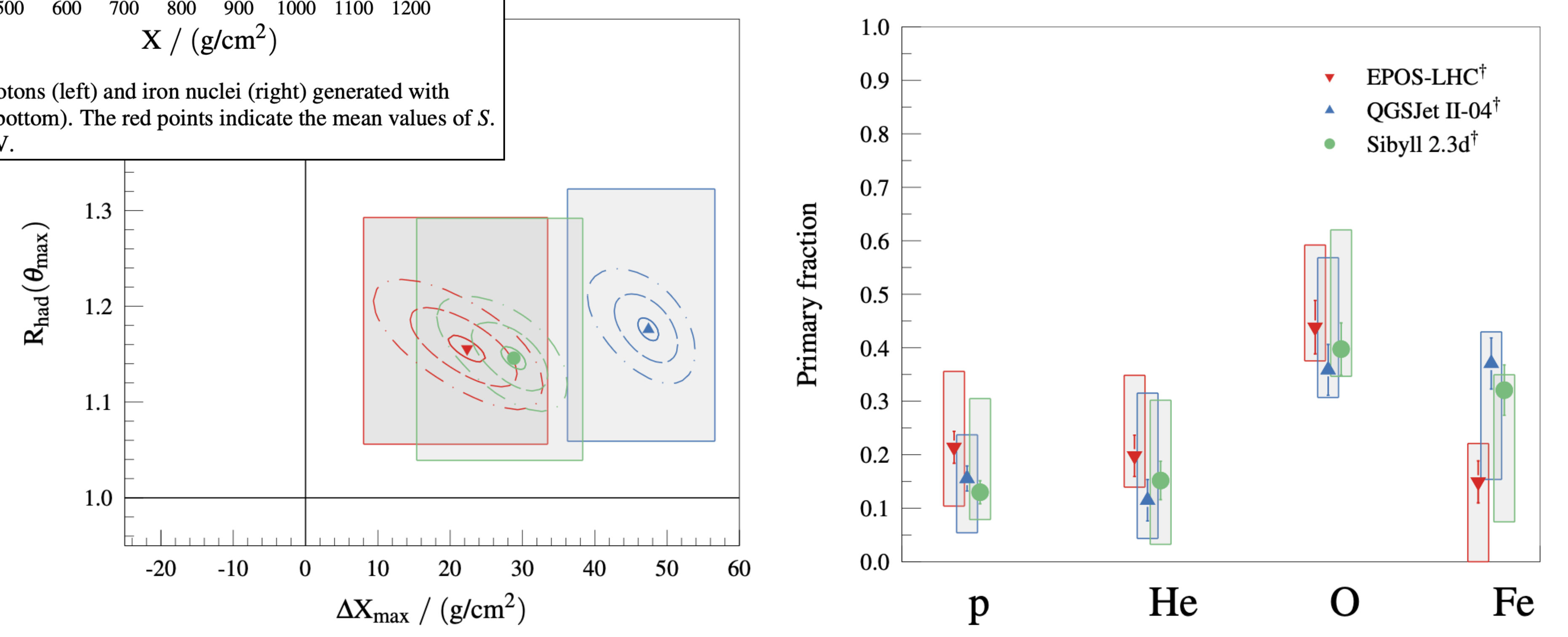
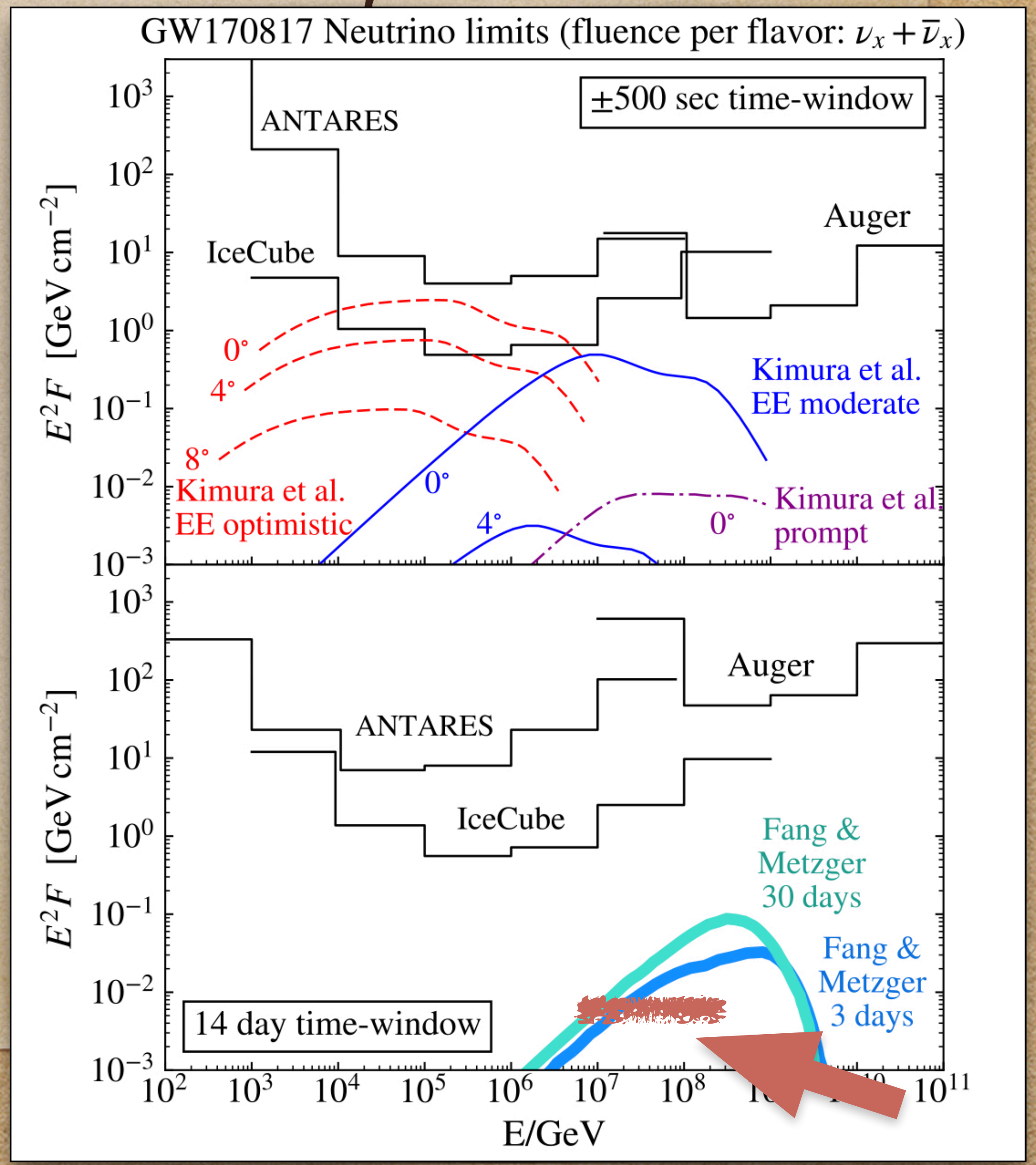



FIG. 6: *Left:* Correlations between $\Delta X_{max}$ and $R_{had}(\theta_{max}{\approx}55°)$ modifications of the model predictions obtained from the data fits. The contours correspond to $1\sigma$, $3\sigma$, and $5\sigma$ statistical uncertainties. The gray rectangles are the projections of the total systematic uncertainties. *Right:* The most likely primary fractions of the four components from the data fits using $\Delta X_{max}$ 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+EinsteinTelescope+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.
  Sensitivity not adequate by orders of magnitude




Antares, IceCube, Auger, LVK '17

# r-process nucleosynthesis B²FH

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

## Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

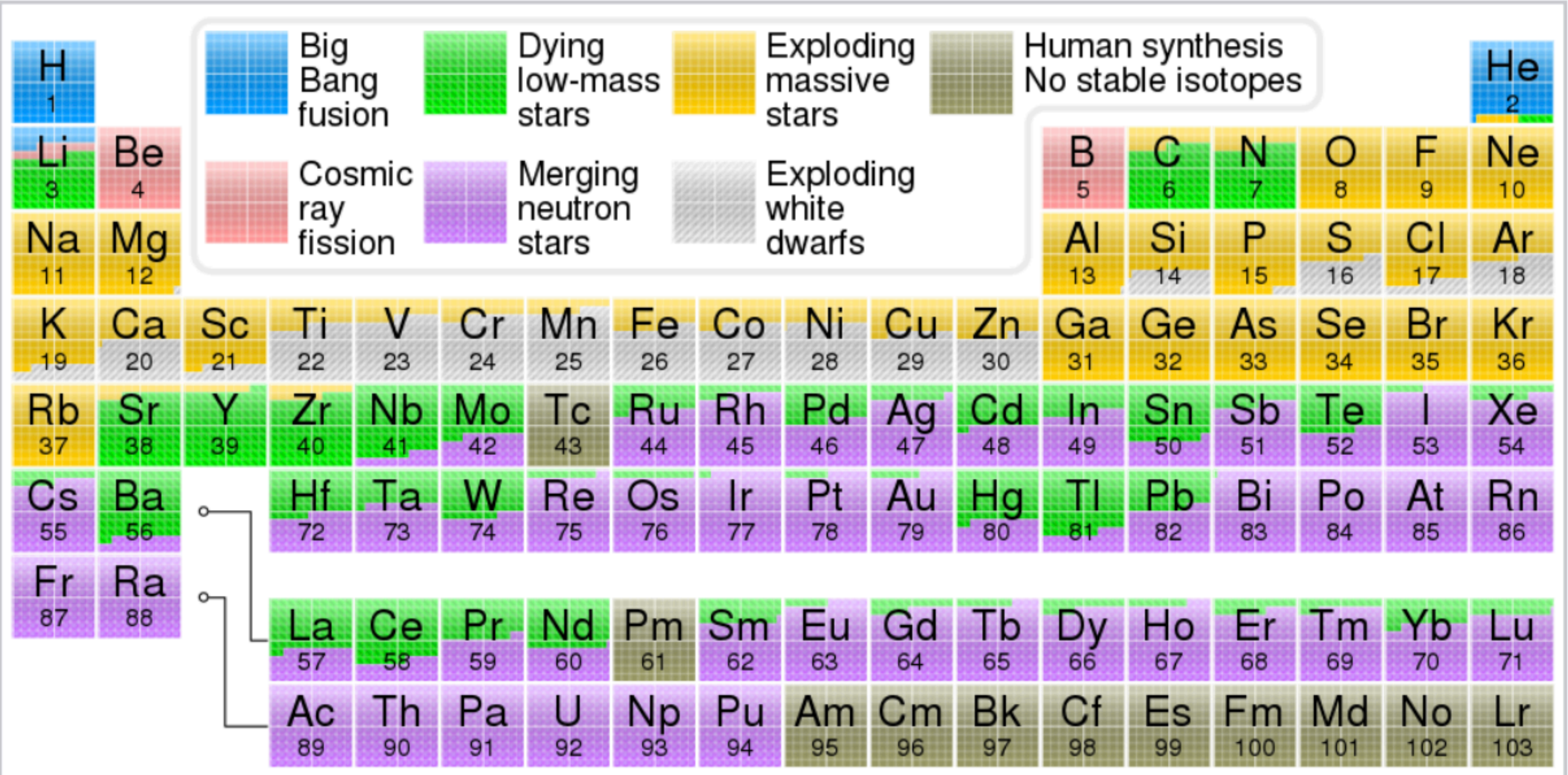
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

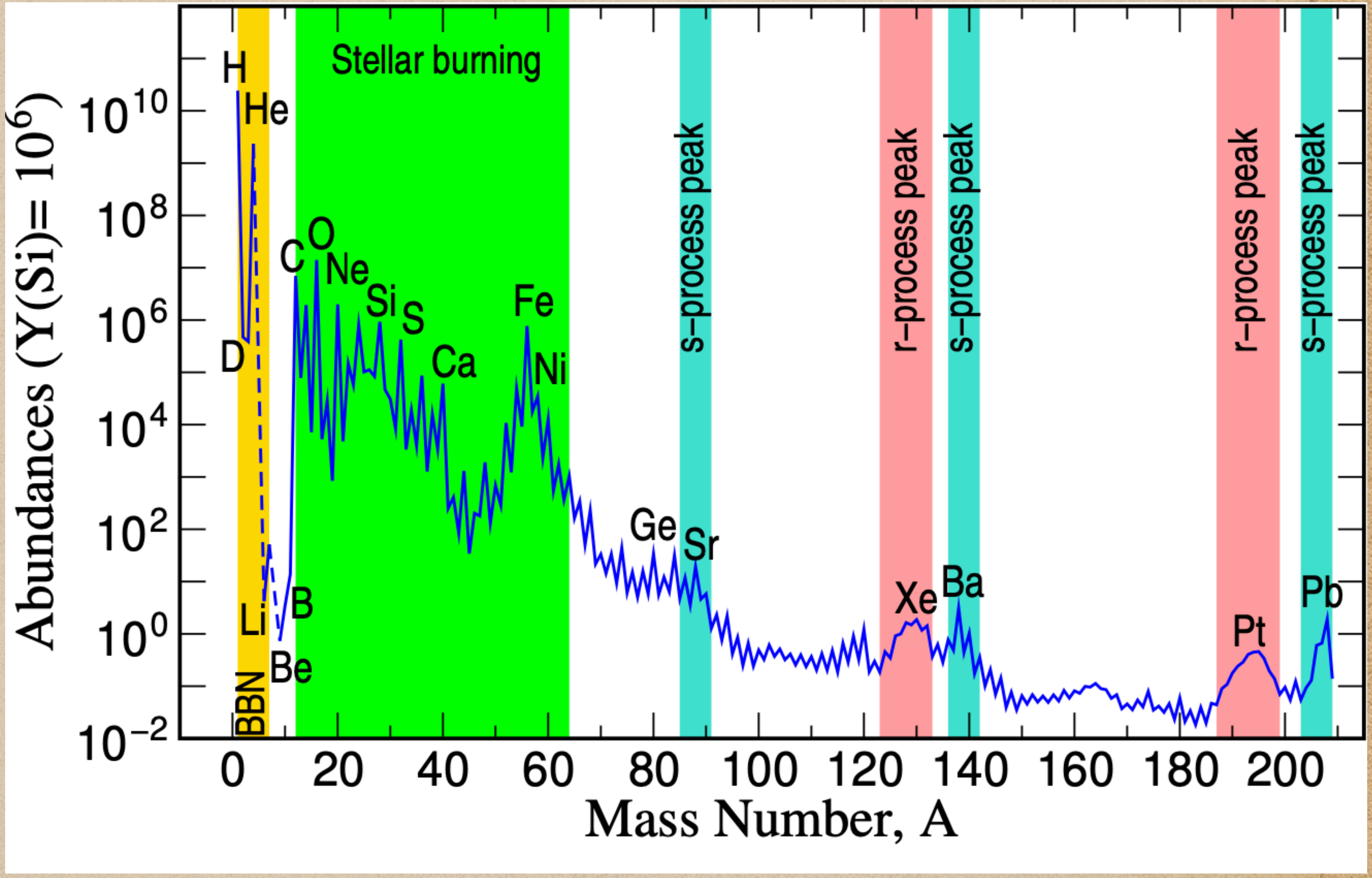
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

*r process*.—The nuclear physics of this process demands that neutrons be added extremely rapidly, so that the total time-scale for the addition of a maximum of about 200 neutrons per iron nucleus is ∼10–100 sec.

# Merging NS's produce "r-process" elements




Periodic table showing the cosmogenic origin of each element. The elements heavier than iron with origins in supernovae are typically those produced by the *r*-process, which is powered by supernova neutron bursts



# The $r$ process

B$^2$FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

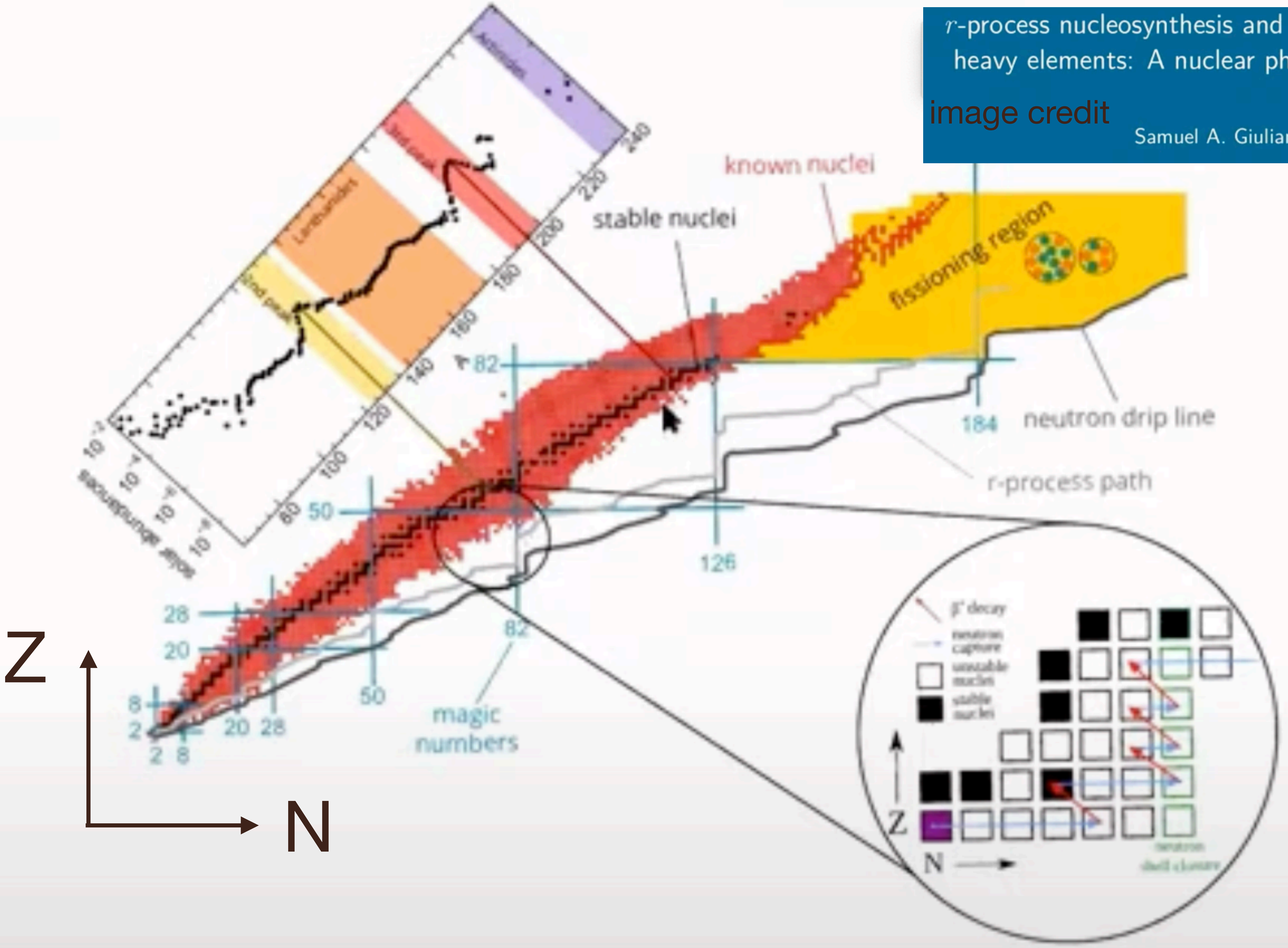
$r$(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta-}$

And see Nicole Vassh movie https://www.google.com/search?client=safari&rls=en&q=r-process+nucleosynthesis+movie&ie=UTF-8&oe=UTF-8#fpstate=ive&vld=cid:94d4d99d,vid:P1tHGLdXRTw,st:361

$r$-process nucleosynthesis and the production of heavy elements: A nuclear physics perspective

image credit

Samuel A. Giuliani




- The path to heavier nuclei goes through neutron-rich nuclei.

# Major Upgrades Underway

V.Versi, UHECR22

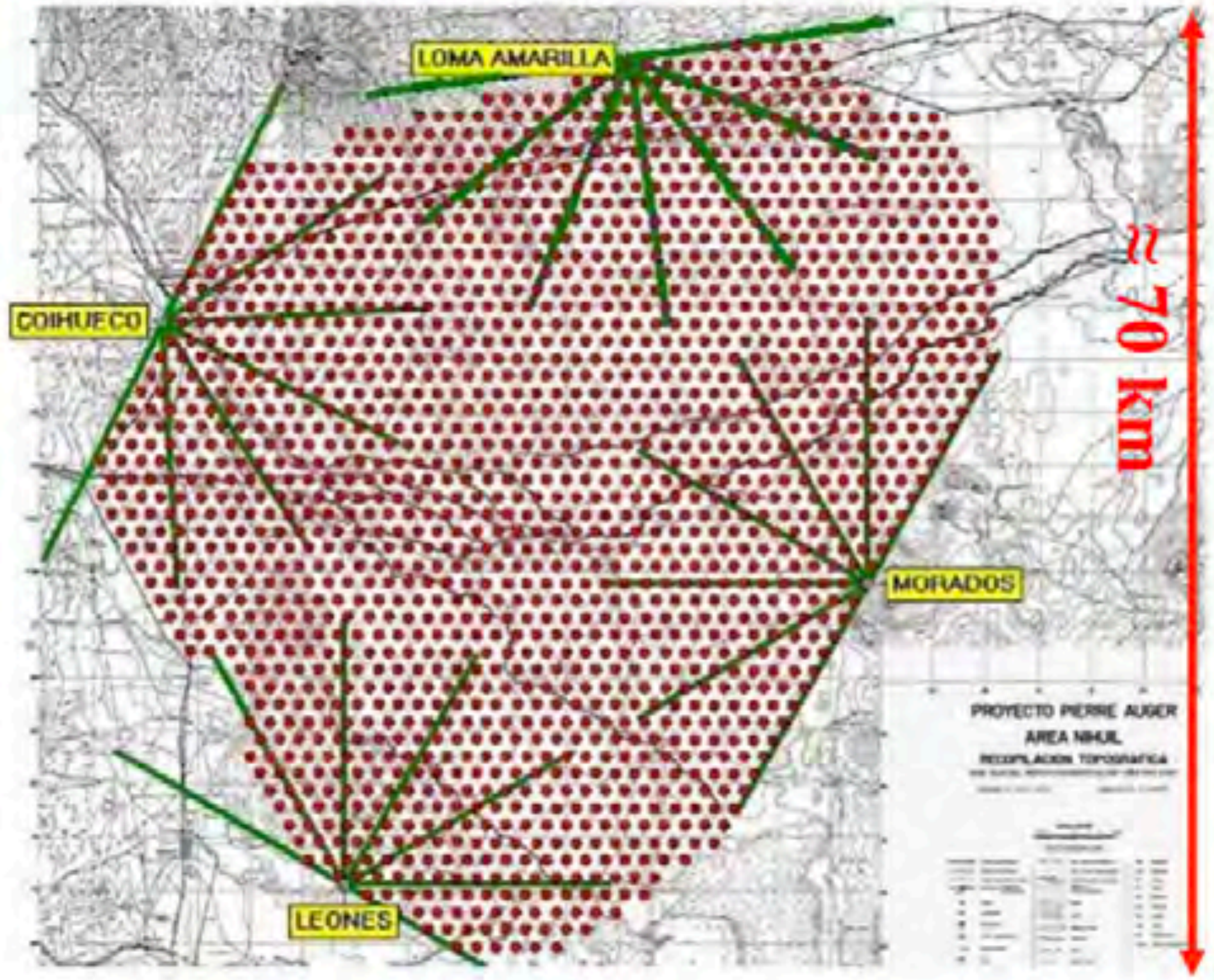
## AugerPrime

**Malargüe Mendoza (Argentina)**
**$35^0$ S latitude**

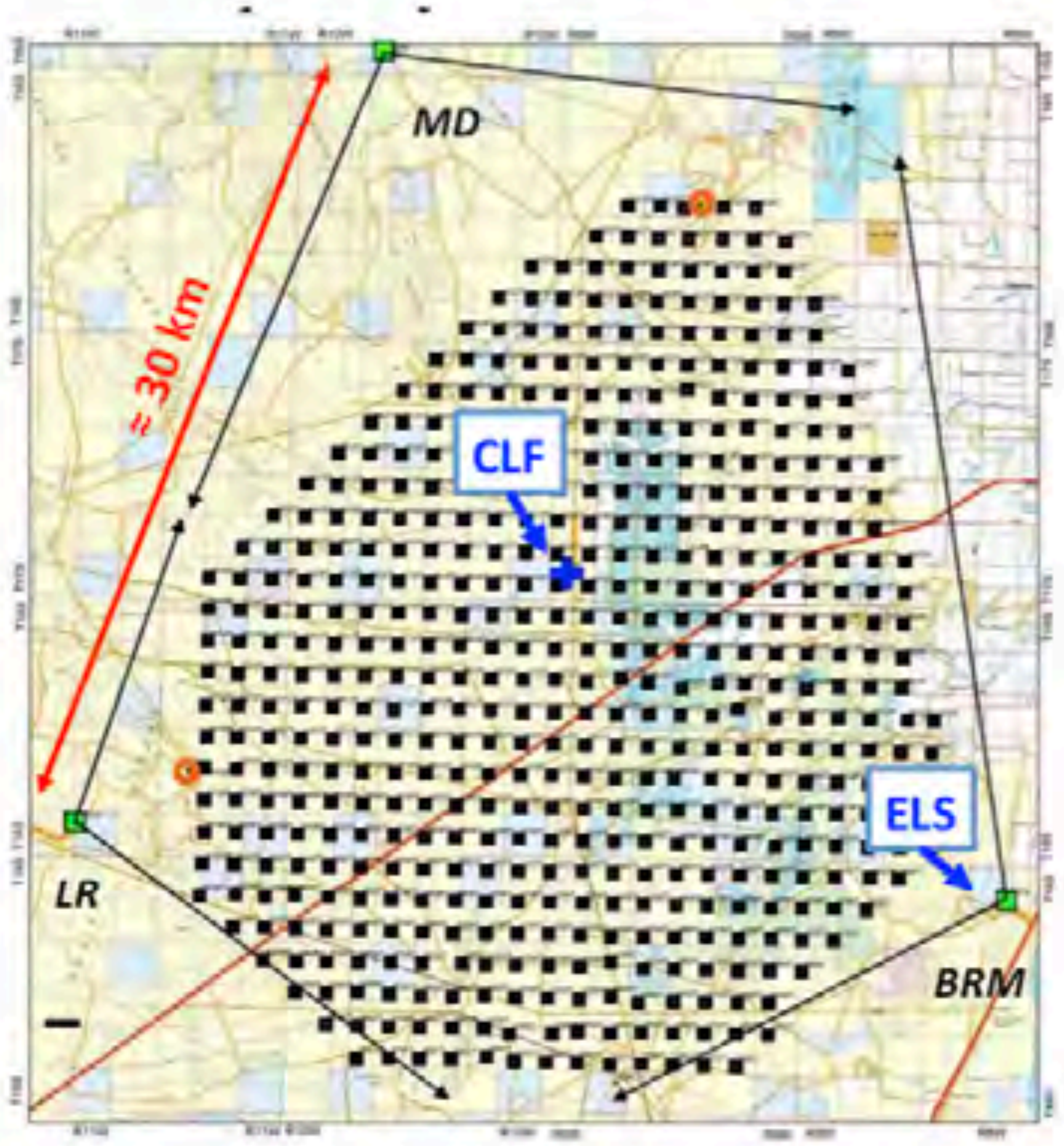
**3000 km$^2$**

**1660 WCDs**
**1500 m spacing**
**triangular grid**

**4 FD sites**




## TA x 4




**Millard County Utah (USA)**
**$39^0$ N latitude**

**700 km$^2$**

**507 scintillators**
**1200 m spacing**
**square grid**

**3 FD sites**

WCD = water Cherenkov detector; FD = fluorescence detector

Adding capability for better particle ID:
Scintillators; underground muon detectors...