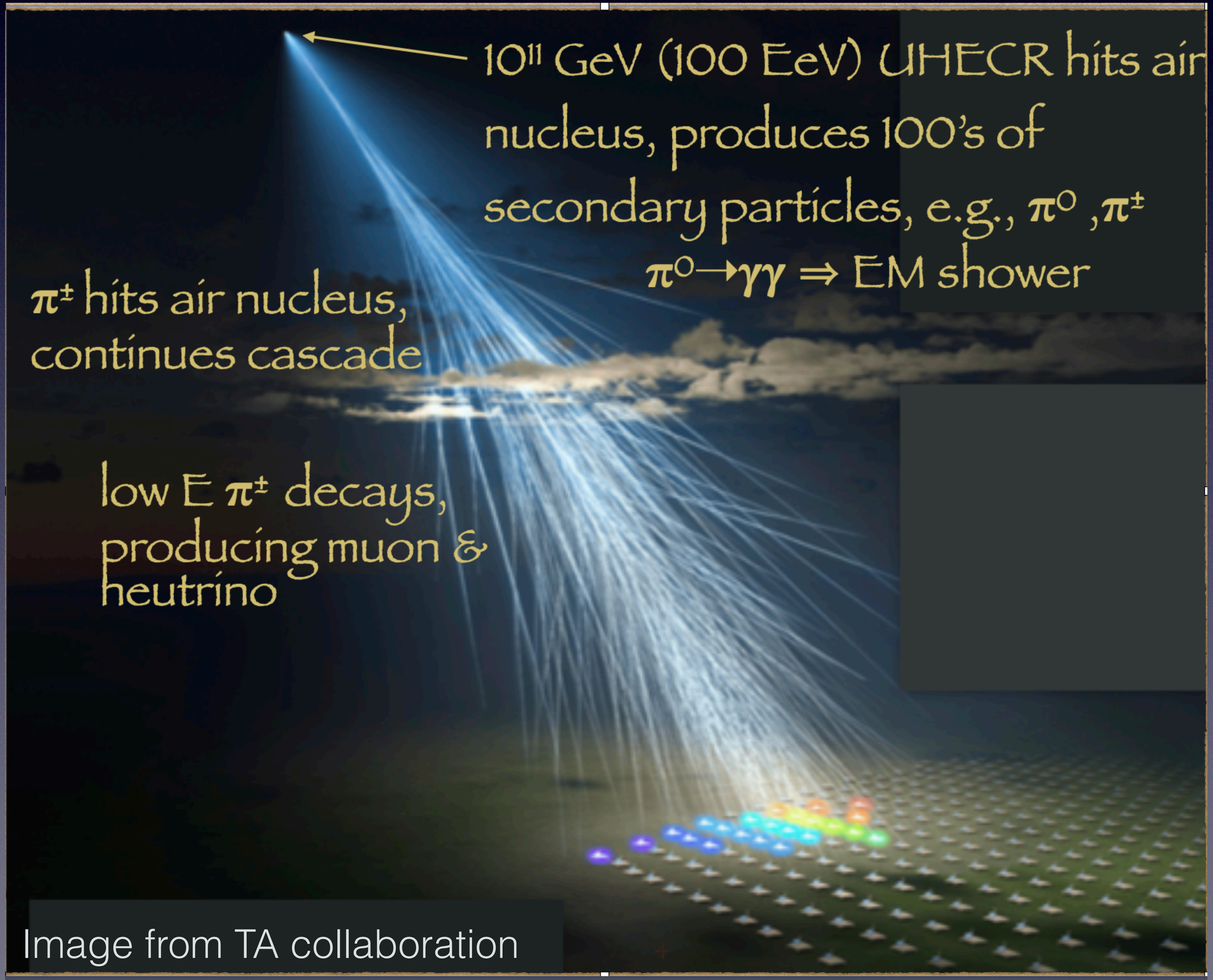
Origin of Ultra-high Energy* Cosmic Rays in Binary Neutron Star Collisions



Glennys R. Farrar
New York University

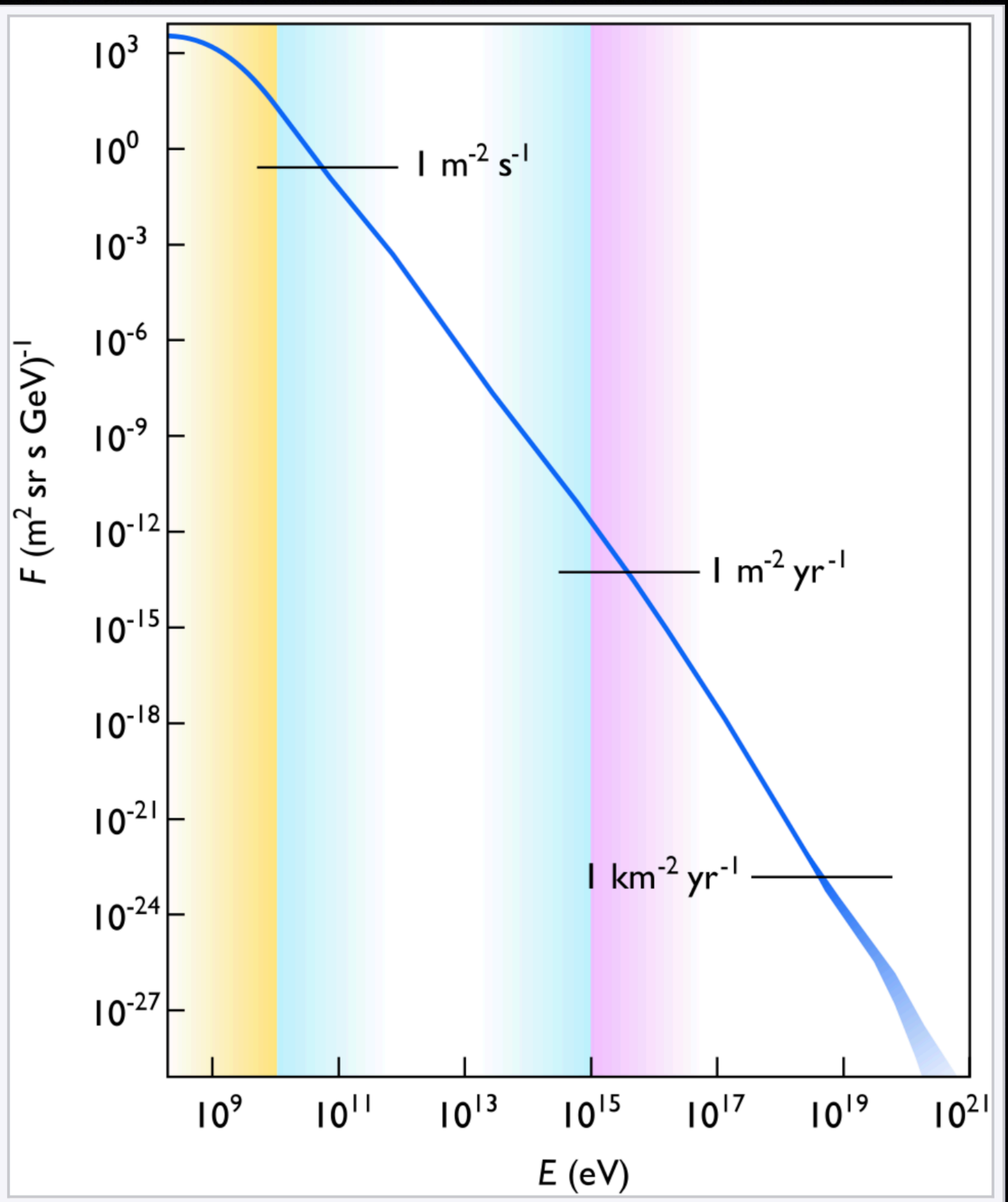
FZU, Prague, June 15, 2026

* <E per nucleon> ~ 2 EeV~ 6M erg
➔ $\gamma > 10^9$

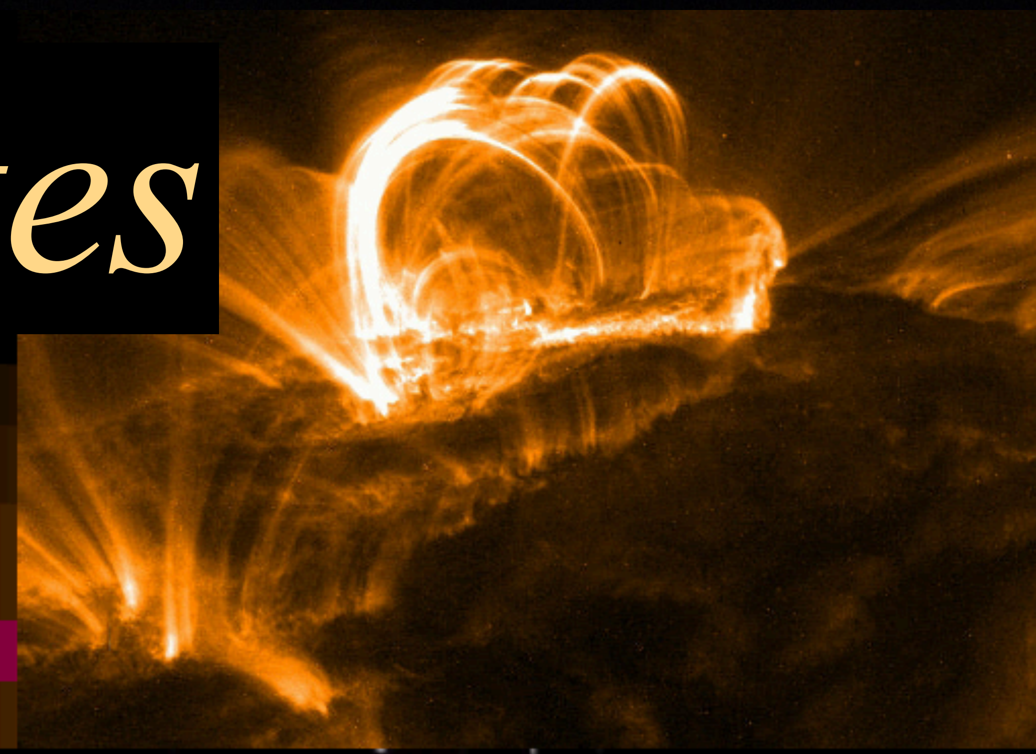
Ultrahigh Energy Cosmic Rays are

- Very rare: <1 per square km *per century*
- Very energetic: up to 30 million times higher energy than the Large Hadron Collider at CERN in Switzerland.
- Atomic nuclei: including protons, helium, oxygen, silicon, iron and probably higher masses up to xenon & maybe gold, platinum …
- likely produced when binary neutron stars merge

Spectrum



Acceleration Sites

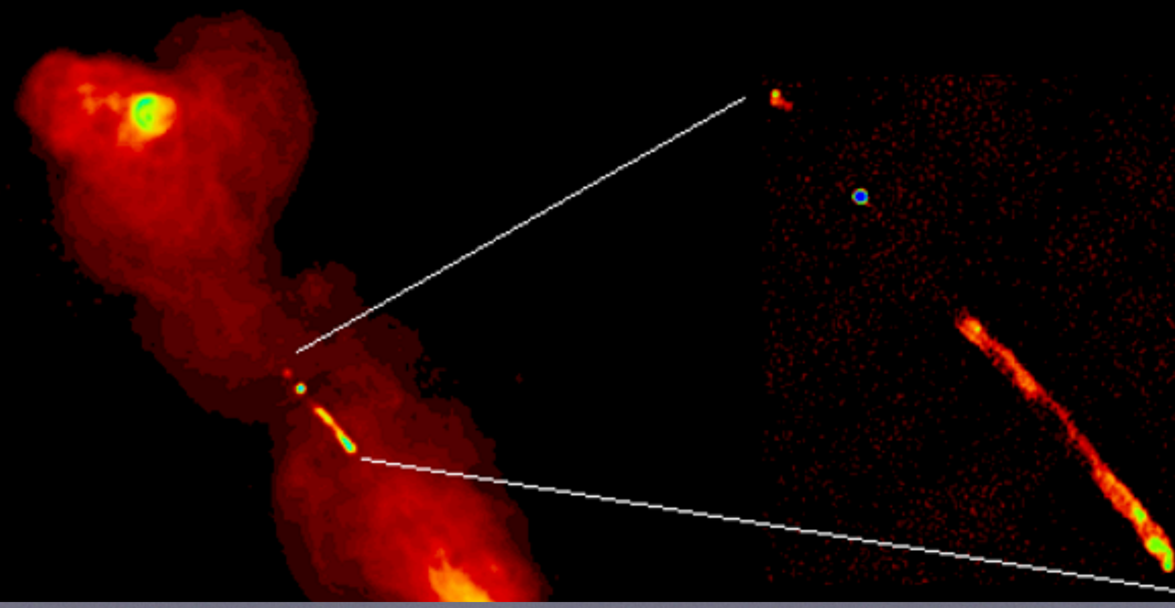


- Low energy CR's: from sun

- Medium energy: Milky Way
  - accelerated in supernovae remnants (Fermi mechanism)
  - Confined by Galactic magnetic field

    Larmour radius = 1 $E_{18}/(Z\ B_{\mu G})$ kpc

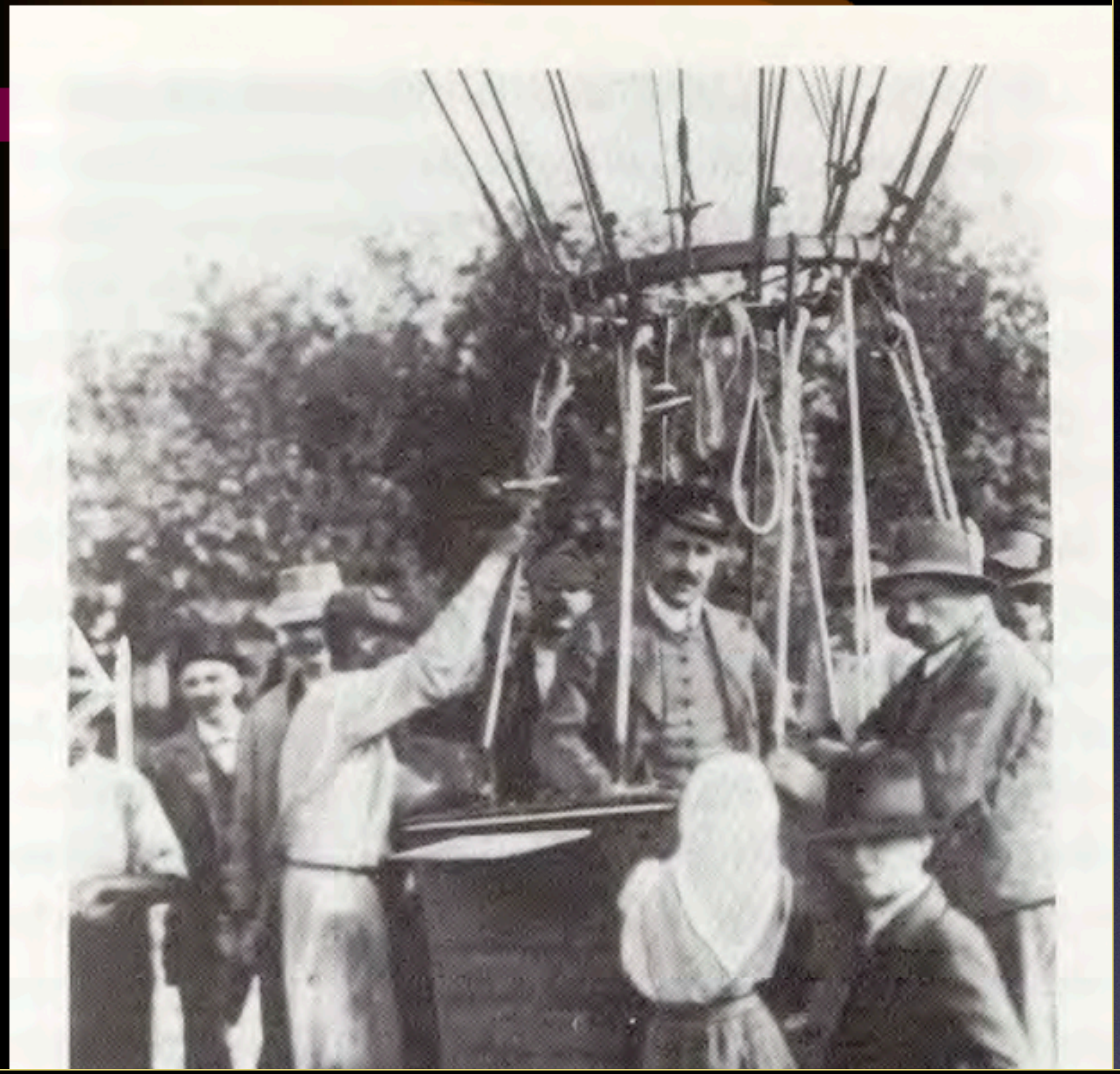
    (~size of Milky Way)

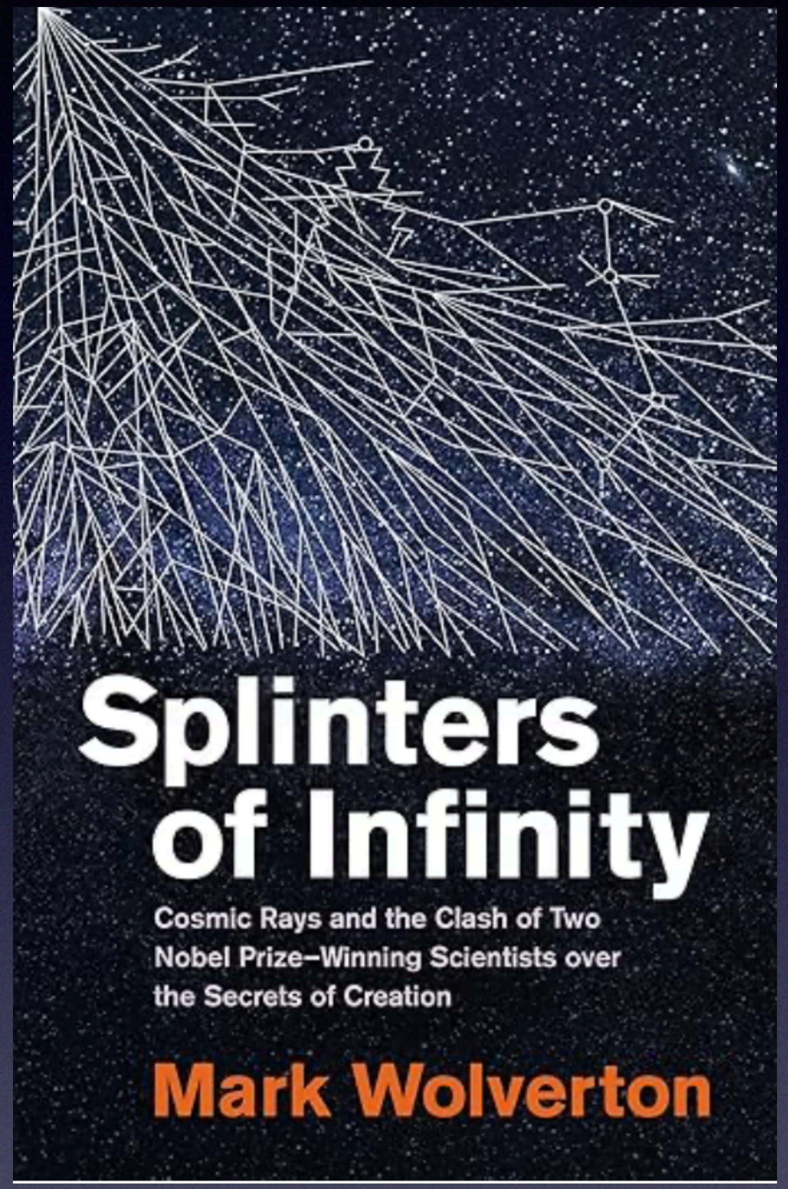


- High energy: Extragalactic
  - What are they? (protons, nuclei,…)
  - What are their sources?
  - How are they accelerated?

1911-1912
Victor Hess discovers cosmic rays

- Becquerel: Electroscope discharge rate measures ambient radiation.
- Residual radiation in absence of apparent source!
- Hess set out in hot-air balloon to map fall off of radiation with altitude. Flies to 4880m
  - up to 1 km, flux drops with increasing altitude
  - above 1 km, flux *increases!*





1912~1930's: Intense debate re. CR identity & origin

- Millikan: "birth cries of atomic nuclei" (gamma-ray)
- Rossi, Compton: charged particles

1932: positron (anti-electron)

1937: muon (heavy electron)

1940's: pions, kaons … first unstable particles containing quarks

Ultrahigh Energy Cosmic Rays: 1961

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

cleon–nucleon scattering see, for example, M. L. Goldberger, M. T. Grisaru, S. W. MacDowell, and D. Y. Wong, Phys. Rev. 120, 2250 (1960). Other methods of calculating phase shifts in terms of scalar and vector particle exchanges have been considered by a number of authors. See, for example, R. Bryan, C. Dismukes, and W. Ramsay (to be published).
[3]R. Blankenbecler and M. L. Goldberger, Phys. Rev. 126, 766 (1962); G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 7, 394 (1961); S. Frautschi, M. Gell-Mann, and F. Zachariasen, Phys. Rev. 126, 2204 (1962); D. Wong, Phys. Rev. 126, 1220 (1962).
[4]H. Stapp (private communication).
[5]M. Hull, K. Lassila, H. Ruppel, F. McDonald, and G. Breit, Phys. Rev. 122, 1606 (1961).
[6]C. de Vries, R. Hofstadter, and R. Herman, Phys. Rev. Letters 8, 381 (1962).
[7]J. Ball and D. Wong (to be published).

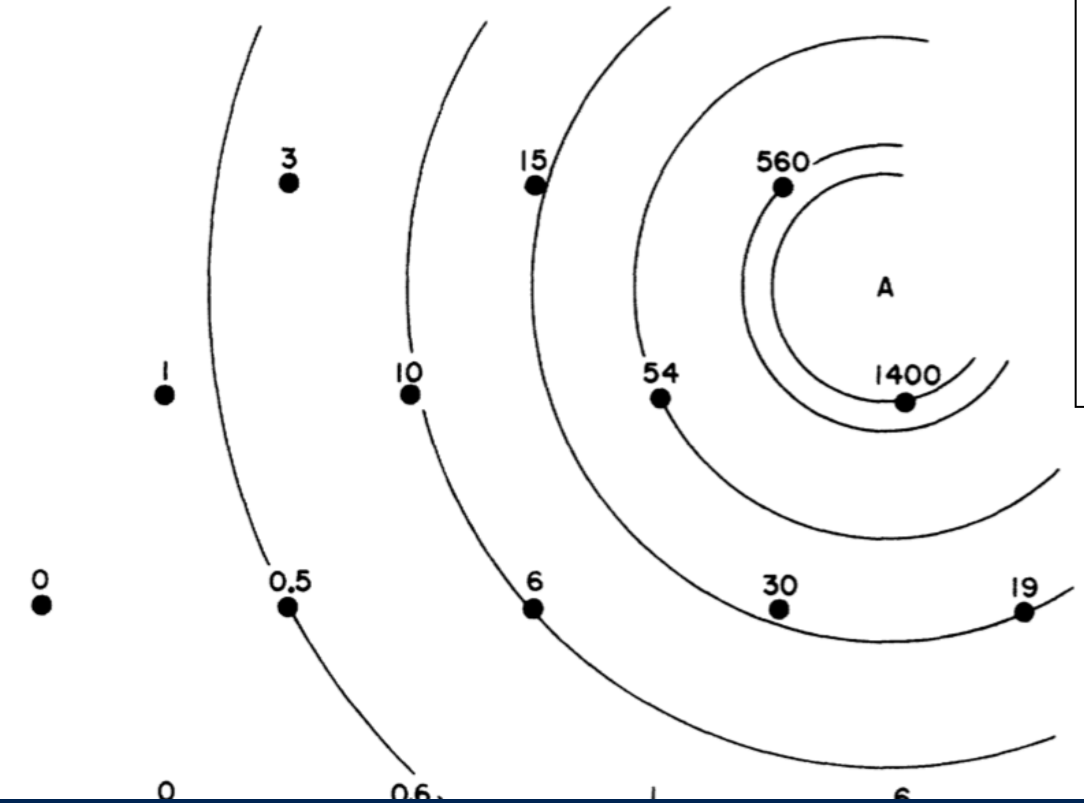
EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February 1962 indicates that the total number of particles in the shower (Serial No. 2-4834) was 5×10^{10}. The total energy of the primary particle which produced the shower was 1.0×10^{20} eV. The shower was about twice the size of the largest we had reported previously (No. 1-15832, recorded in March 1961).[1]

The existence of cosmic-ray particles having such a great energy is of importance to astrophysics because such particles (believed to be atomic nuclei) have very great magnetic rigidity. It is believed that the region in which such a particle originates must be large enough and possess a strong enough magnetic field so that $RH \gg (1/300)\times(E/Z)$, where R is the radius of the region (cm) and H is the intensity of the magnetic field (gauss). E is the total energy of the particle (eV) and Z is its charge. Recent evidence favors the choice $Z=1$ (proton primaries) for the region of highest cosmic-ray energies.[2] For the present event one

point marked "A," assuming only (1) that shower particles are distributed symmetrically about an axis (the "core"), and (2) that the density of particles decreases monotonically with increasing distance from the axis. The observed densities



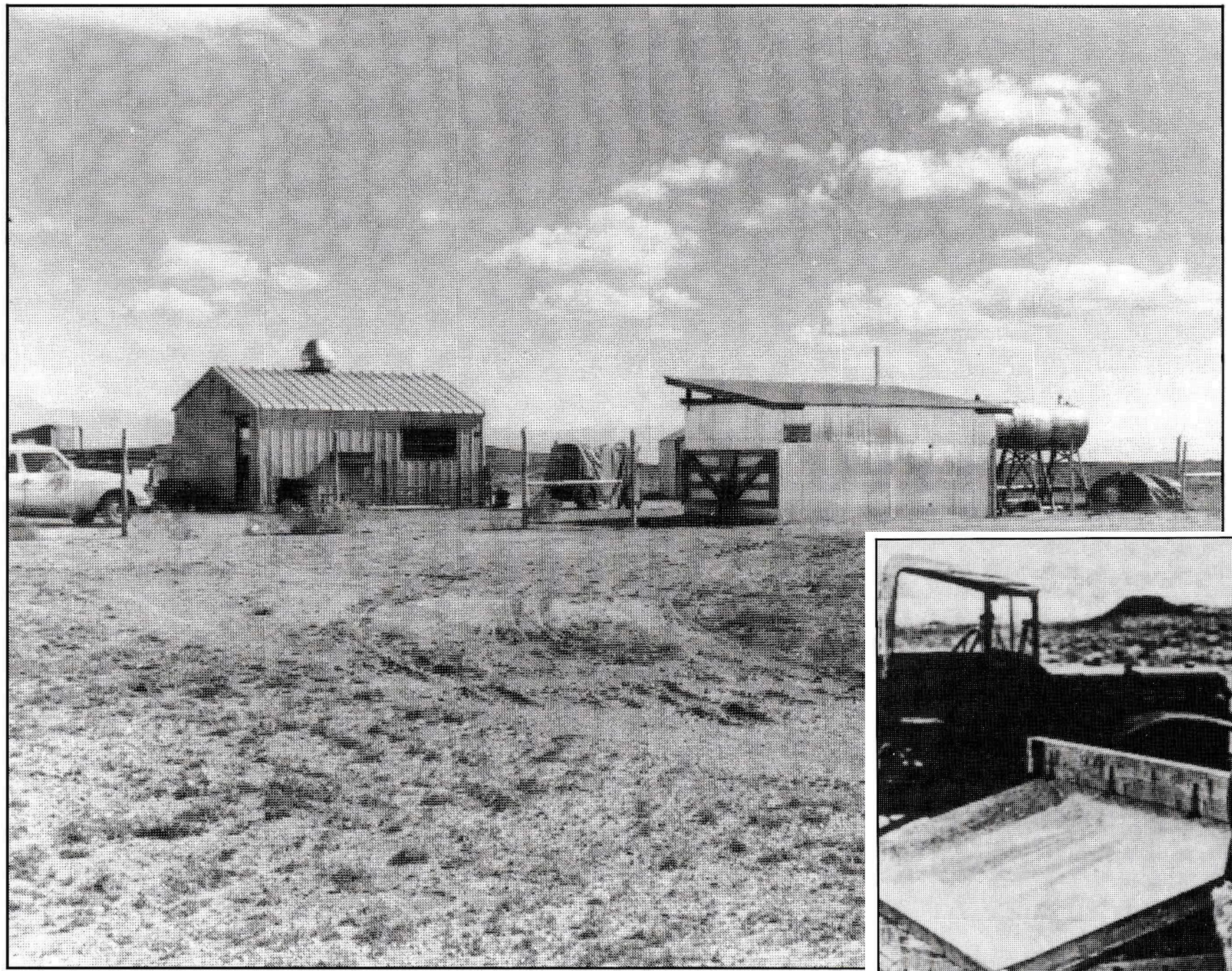
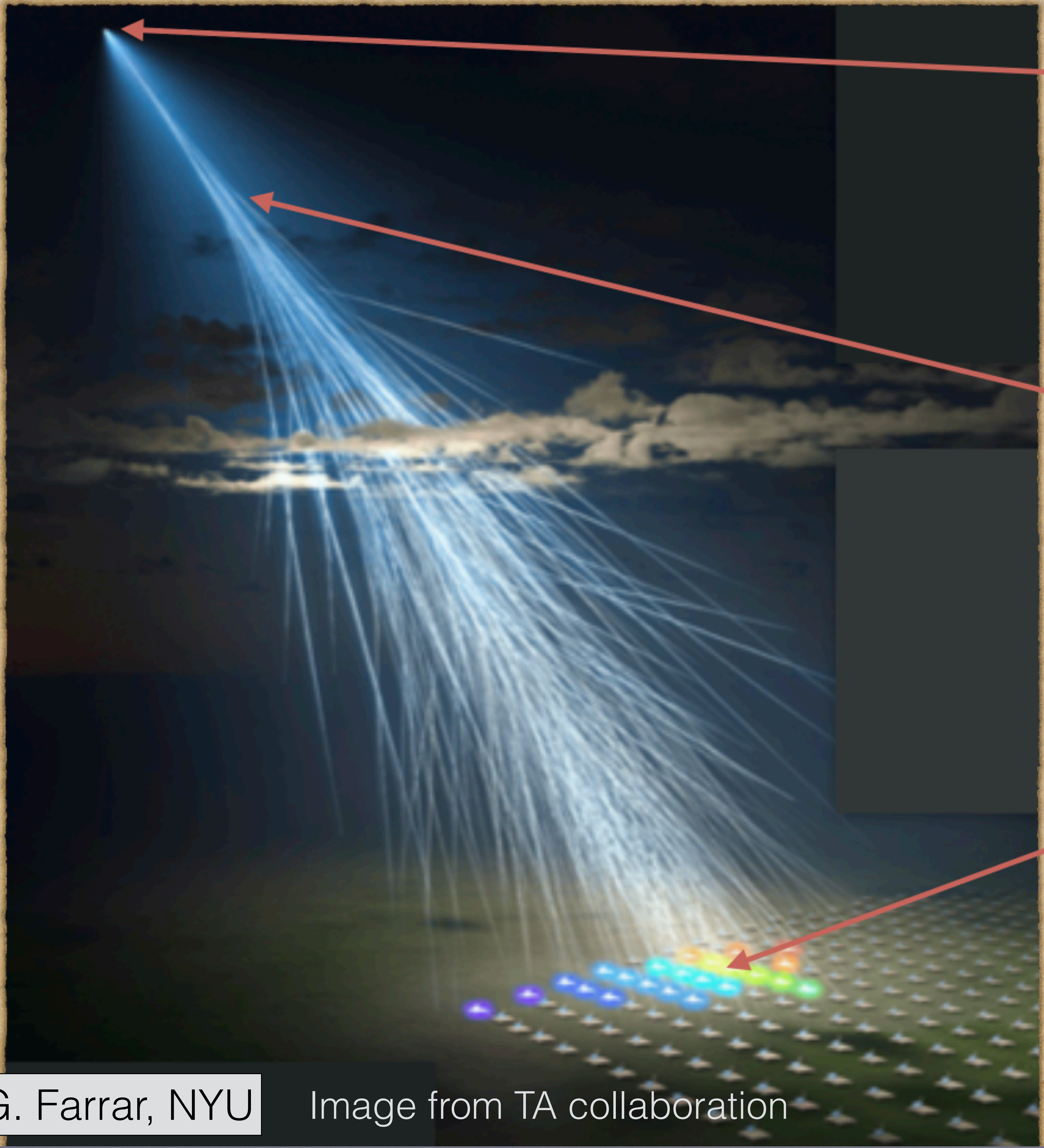


Plate 54. Volcano Ranch; the laboratory and the control r

1st event > 100 EeV


Hess discovered CRs
1911-12
Highest Energy Ever:
Fly's Eye ~250 EeV 1991
Telescope Array, Utah
Amaterasu ('23): 240 EeV
Salt Lake City
Telescope Array Map
Delta
Fly's Eye Utah 1991
OMG: 320(250) EeV
Linsley: first UHECR
> 100 EeV 1962
today: Auger ⬇ TA ⬆
Pierre Auger Obs., Argentina
~50 evts > 100 EeV
Rcut
HEAT
Coihueco
Los Morados
Los Leones
MALARGUE
mpression of the upgraded
urface detector stations
1700 stations, 3000 km²
Plate 54. Volcano Ranch; the laboratory and the control room.

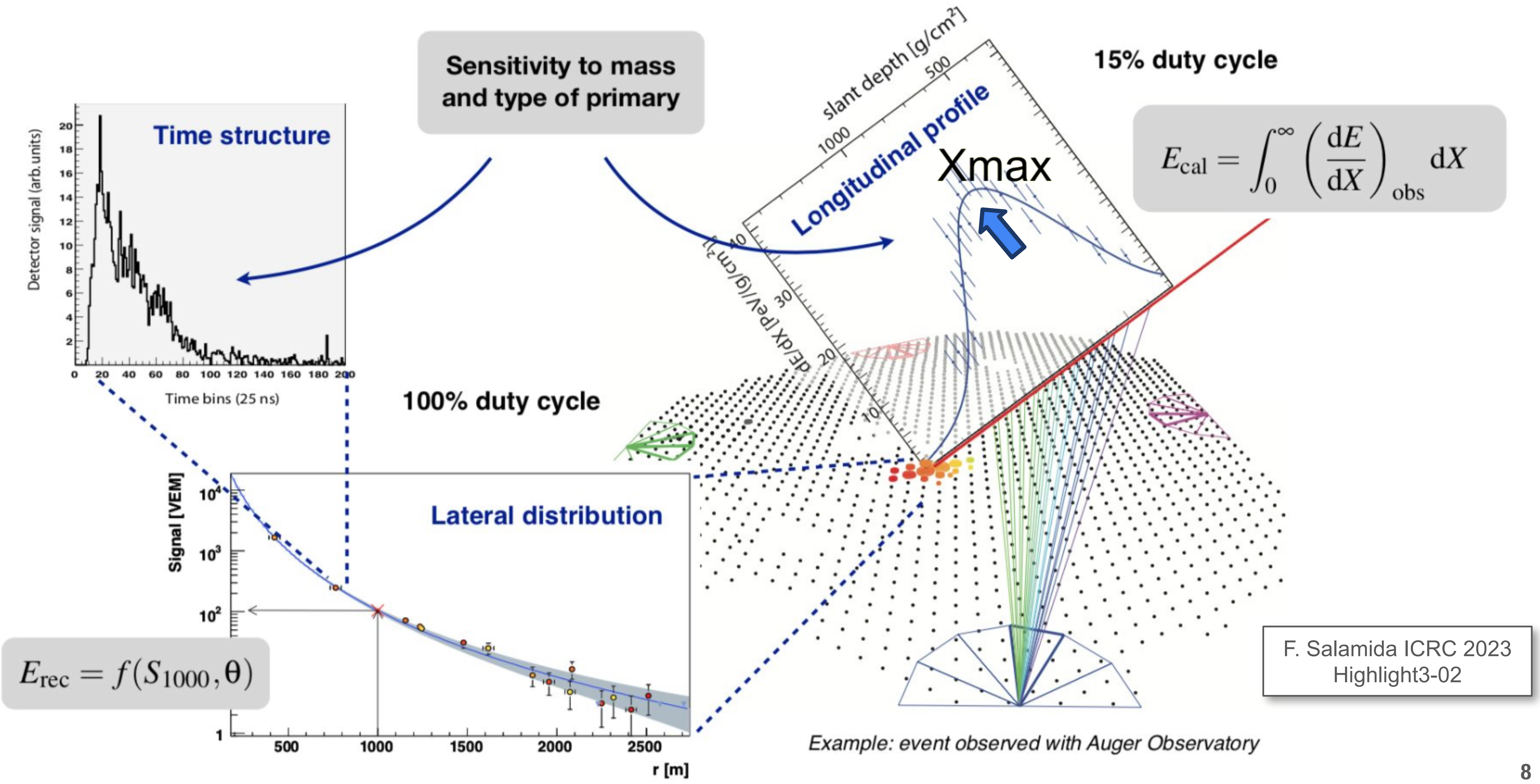
How to deduce the mass and energy of a UHECR



- 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

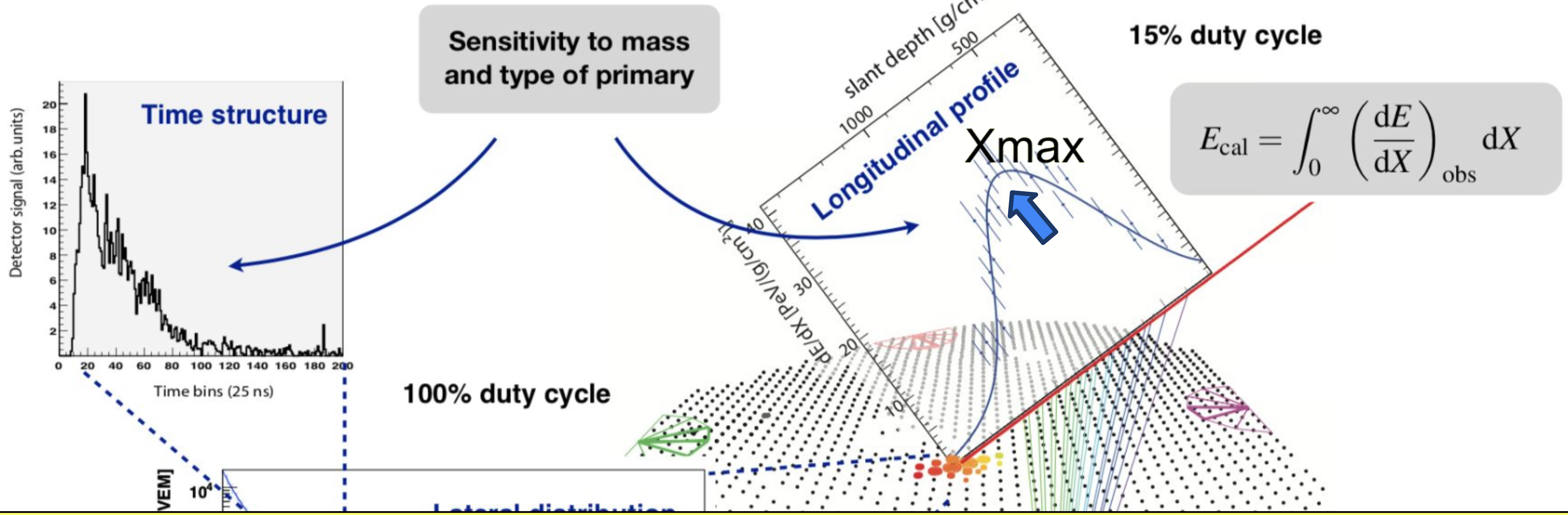
Image from TA collaboration

The Hybrid Observation Method of Auger



The Hybrid Observation Method of Auger

Phase II: absolute composition & neutrinos from UHECRs



Key components of upgraded Auger observatory:

- 1600 Water Cherenkov tanks@1.5 km spacing (100%); Fluorescence Telescopes (15%)
- *+1600 Scintillator Detectors ➜ EM/had separation for low & moderate zenith*
- *+1600 Radio detectors ➜ EM/had separation at large zenith angles*
- *+1600 upgraded electronics ➜* ***sensitivity to 100 PeV neutrinos from UHECRs***

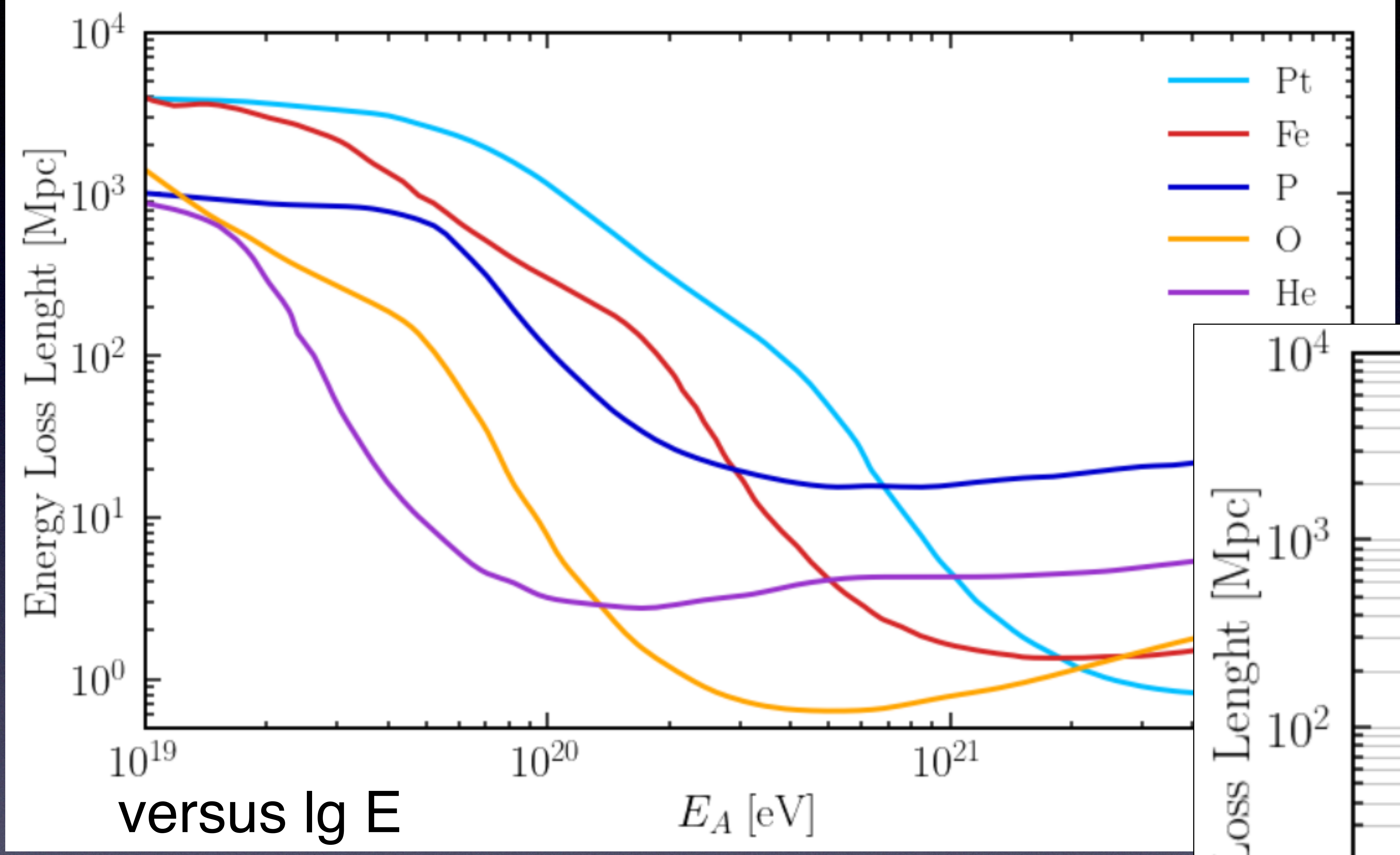
top 109 events: https://opendata.auger.org/catalog/

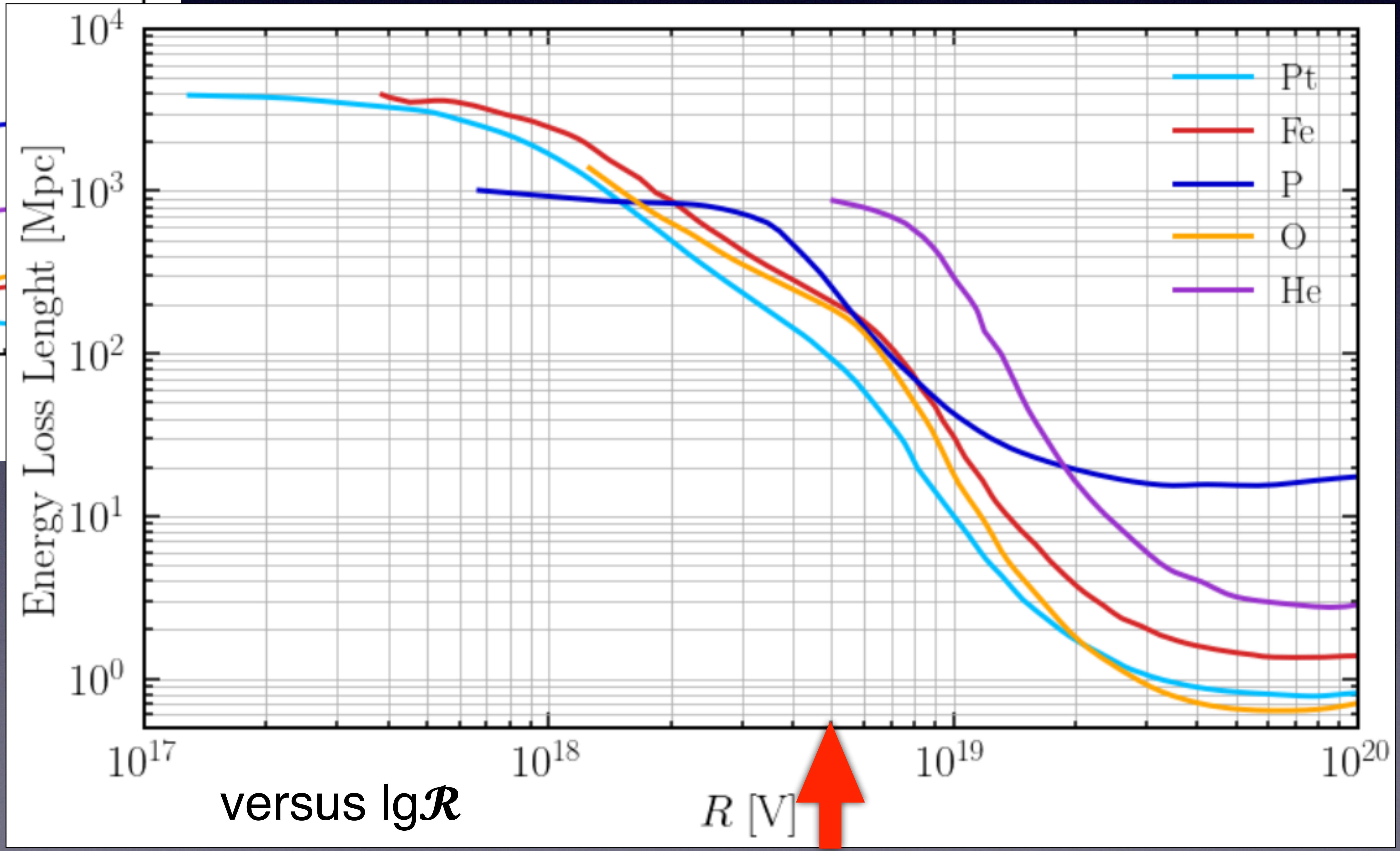
Basics: GZK & Hillas

- **Greisen, Zatsepin & Kuzmin** 1966 "**GZK bound**":
  - UHECR "horizon" drops dramatically when E_{CM} is sufficient for photopion production on CMB ($p + \gamma \rightarrow \pi + N$; $A + \gamma \rightarrow A\text{-}1 + N$)
- **Hillas Condition** 1984**:**
  - If Larmor radius > source size, CR escapes
  - **Define Rigidity $\mathcal{R} \equiv E/Ze$. Larmor radius = $\mathcal{R}$ B ➜ *Hillas condition:***

$$\mathcal{R}_{\rm max,EV} \lesssim 3 \times 10^{-16} \Gamma R_{\rm cm} B_{\rm G}$$

Propagation energy loss length (“GZK”)





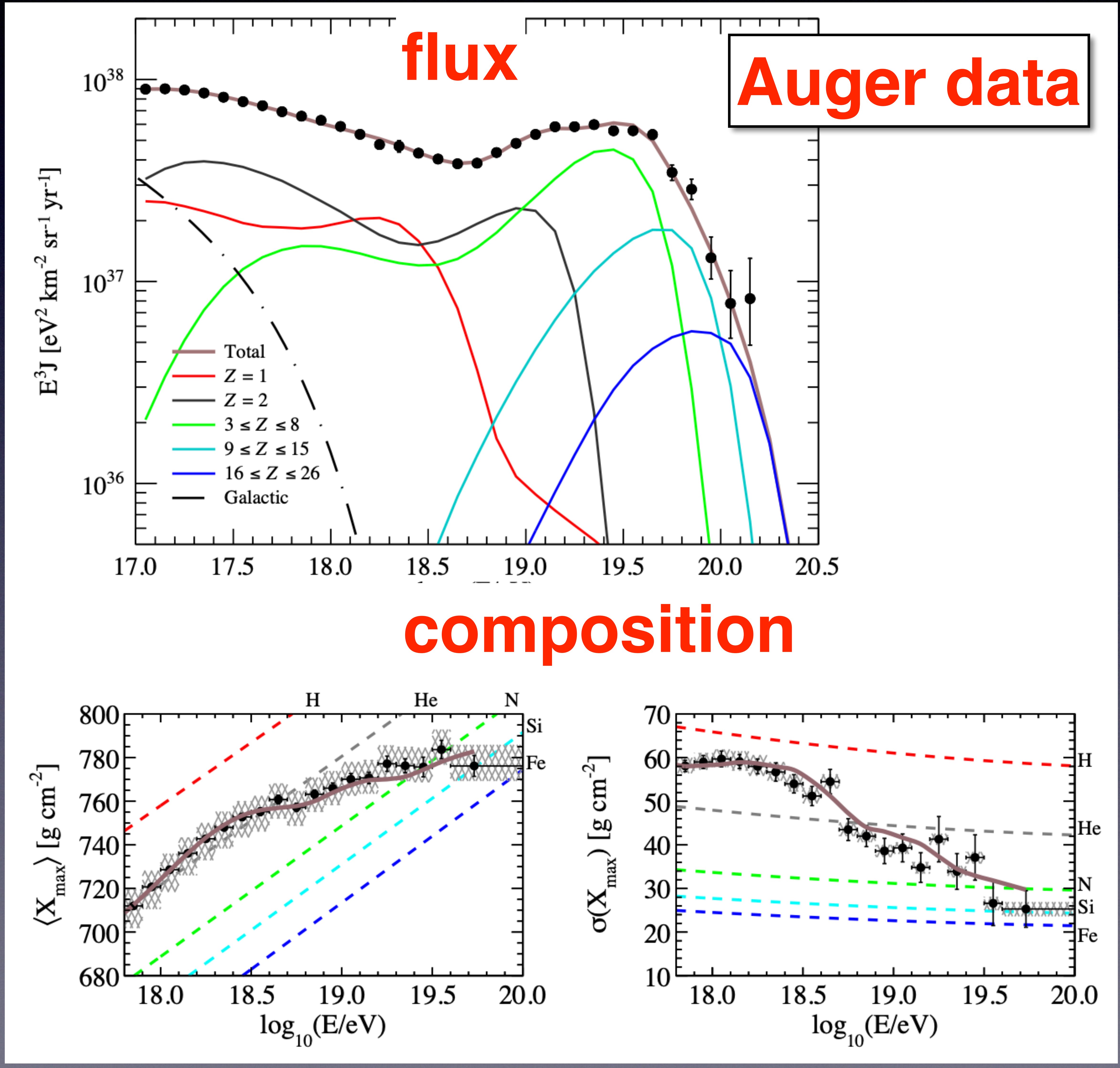
For $\mathcal{R}$ = 5 EV

Z,A={36,80} ➜ <E_n>= 2.25 EeV
Z,A={14,28} ➜ <E_n>= 2.50 EeV

- **Rigidity $\mathcal{R}$≡E/Ze**

Implications of the observations (1)

- Composition is mixed, mass increases with E
- *Narrow range of masses at each E*
- ***Rigidity spectrum is narrow***
  $<\mathcal{R} \equiv E/Ze> \approx 4$ EV
- ***Cutoff is sharp :*** $\mathcal{R}_{cut} \approx$ 6-7 EV



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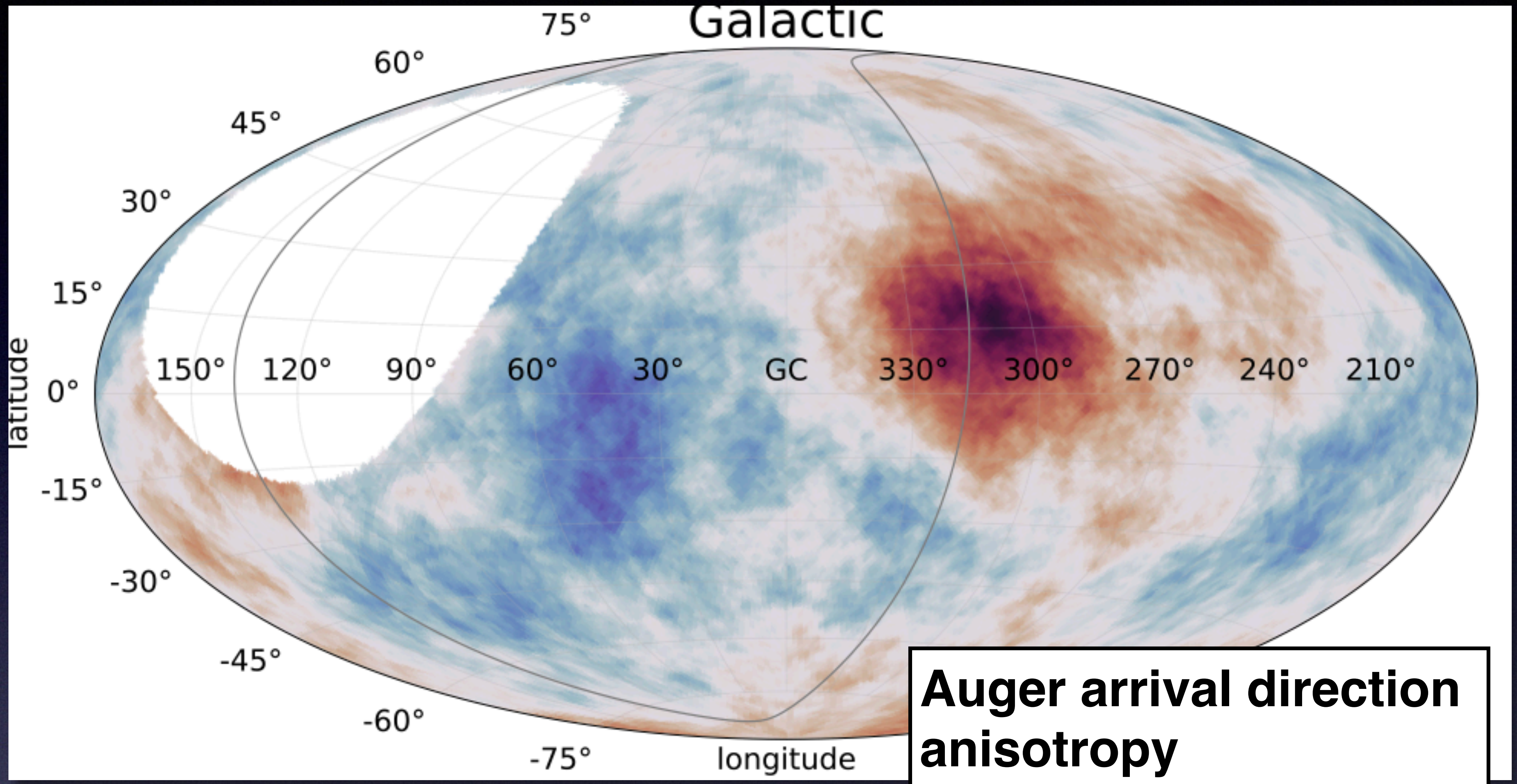
Implications of the observations (2)

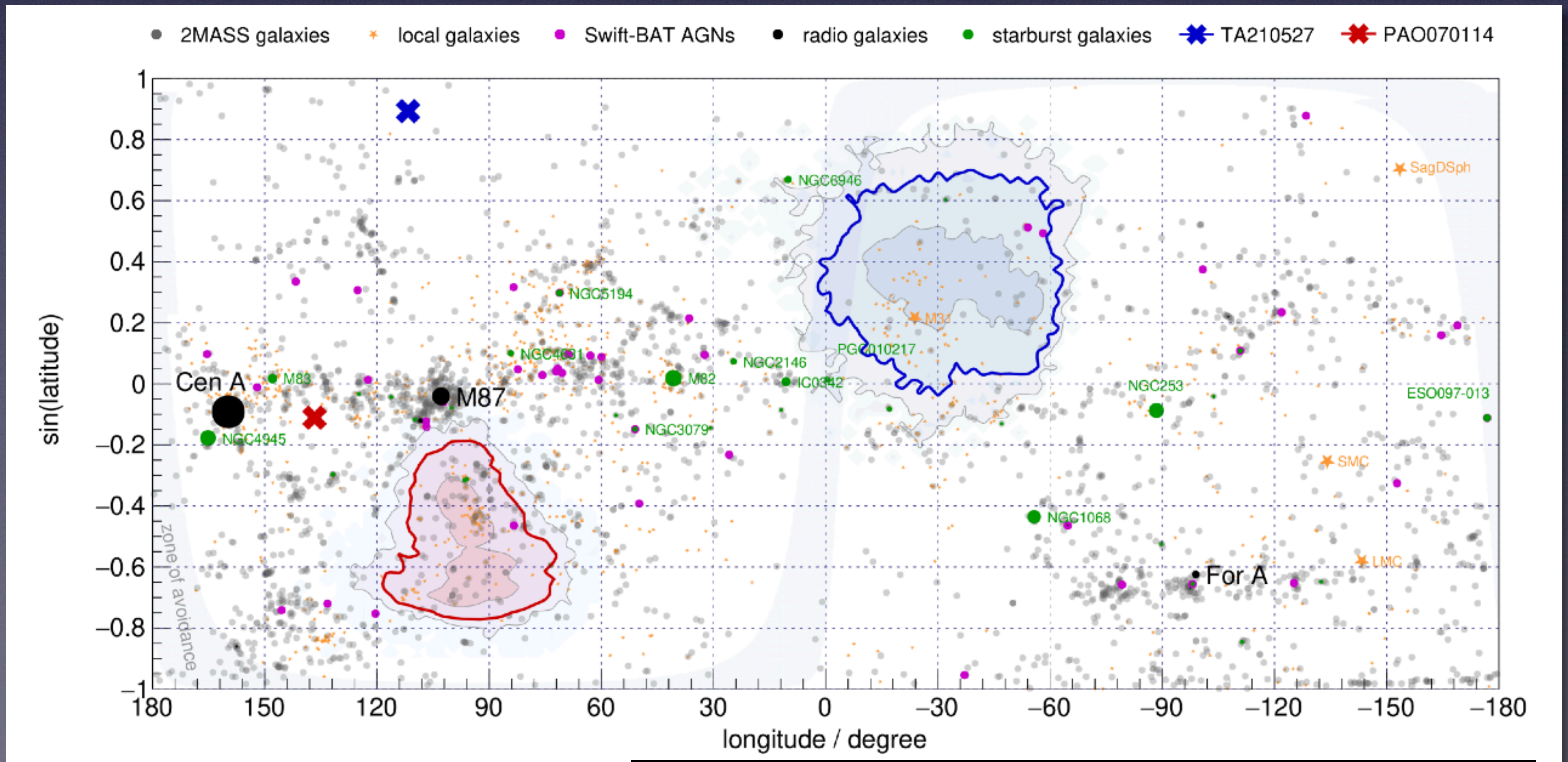
- ***Rigidity spectrum is narrow:***
  $< \mathcal{R} \equiv E/Ze > \approx 4$ EV, $\mathcal{R}_{\mathrm{cut}} \approx$ 6-7 EV

- Arrival directions: ***Sources are abundant***

- No prominent sources for highest E events: ***Sources are transients***



Auger arrival direction anisotropy



Unger+GF23, **backtracking thru GMF**

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Correct Source model must explain:

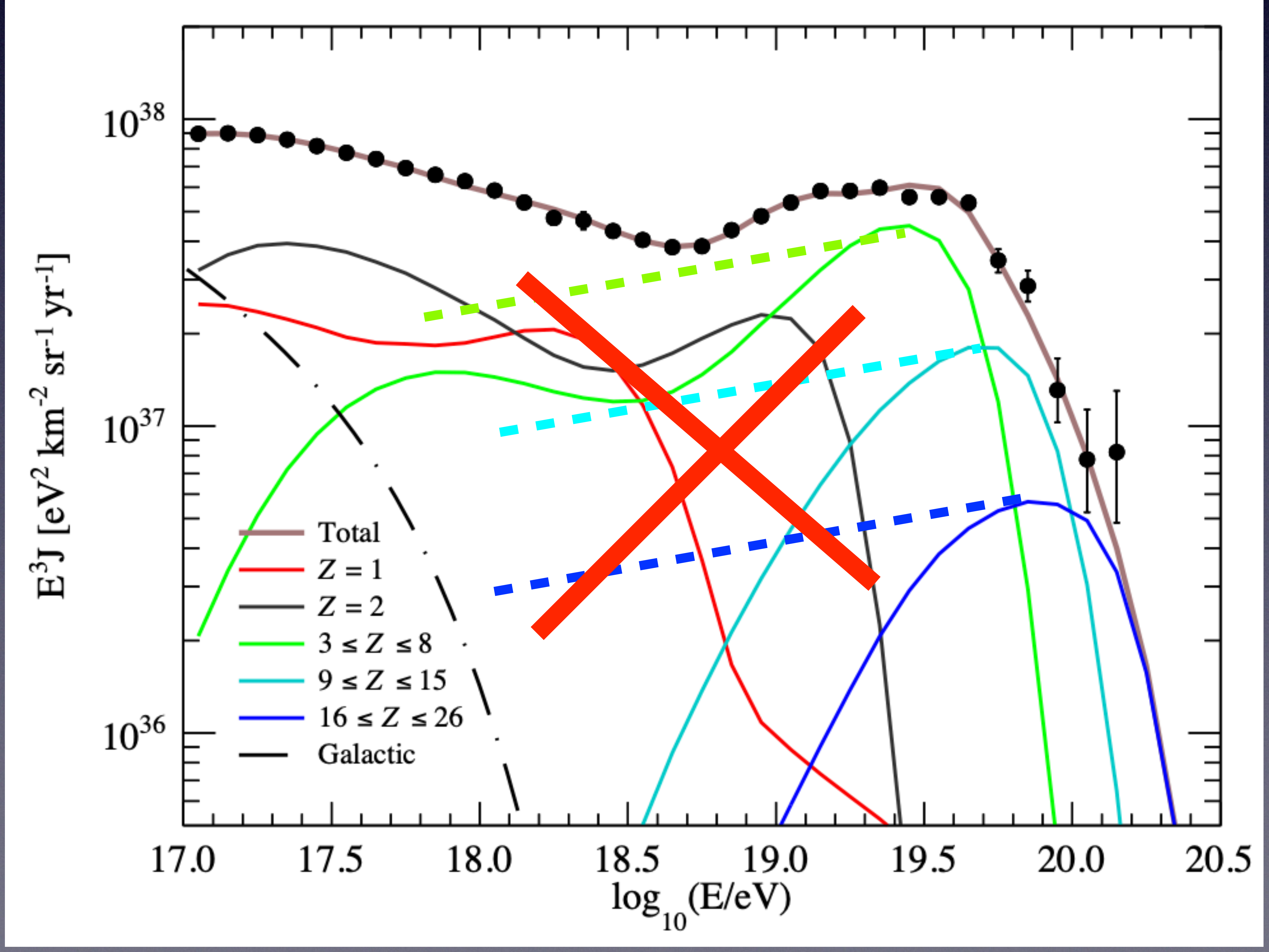
- **Tight mass-energy relation, requires minimal population variance. "Seems to exclude AGNs, long GRBs & TDEs."**
  (Ehlert, Oikonomou, Unger 2023)

- Energy injection rate; source number density

- Value of rigidity cutoff

- Existence of event energies 150-250 EeV
  (Amaterasu, Fly's Eye, ≳10 Auger above150 EeV)

- The highest energy events are from transients.



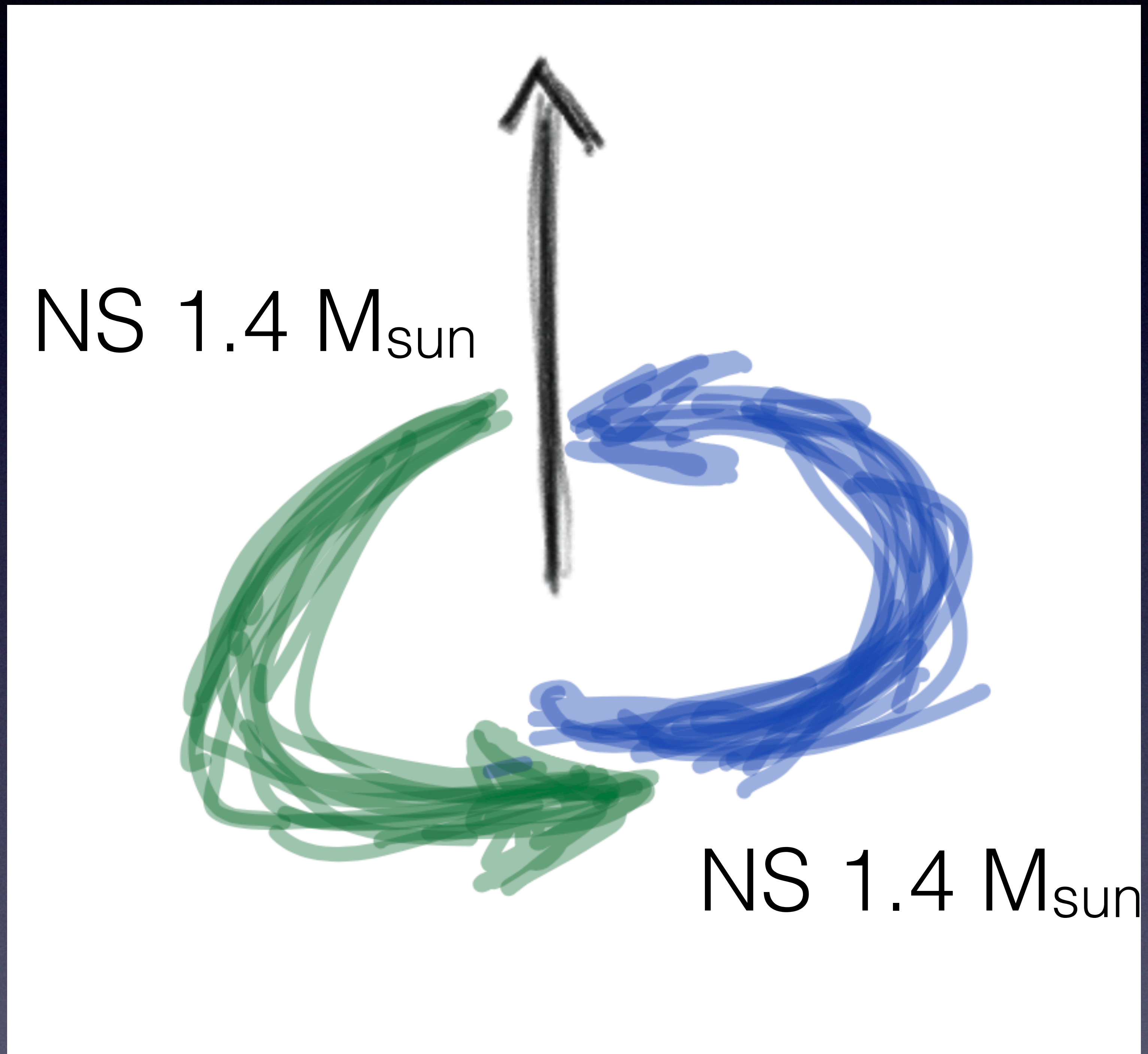
Source candidates vs key constraints

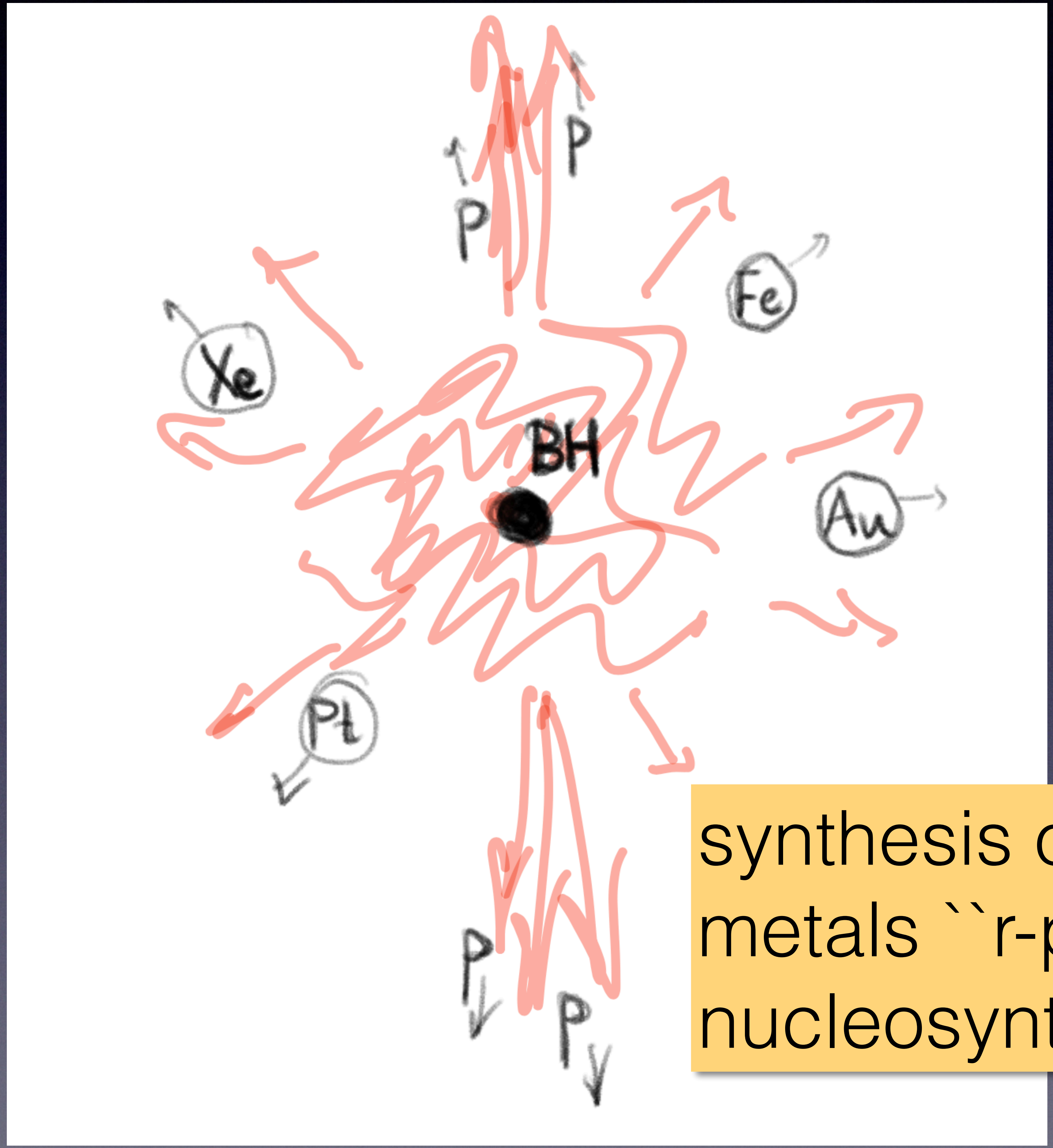
	$n_S \gtrsim 10^{-3.5}$ Mpc^{-3}	energy injection	ordinary galaxy	Universal R_{max}	Highest energy events
Powerful AGN	[✘]	✔	✘	✘	✘
Long GRBs	[✘]	✘	✘	✘	✘
TidalDistruption Events	?	?	✔	✘	✘
Accretion Shocks	?	?	[✘]	✘	✘
BNS mergers	✔	[✔]	✔	✔	✔

(All can satisfy Hillas size > Larmor radius)

Binary Neutron Star Mergers

only (currently known) source candidate satisfying all criteria





synthesis of precious metals ``r-process nucleosynthesis"

Ligo-Virgo GW170817: binary neutron star merger ➜ Black Hole +

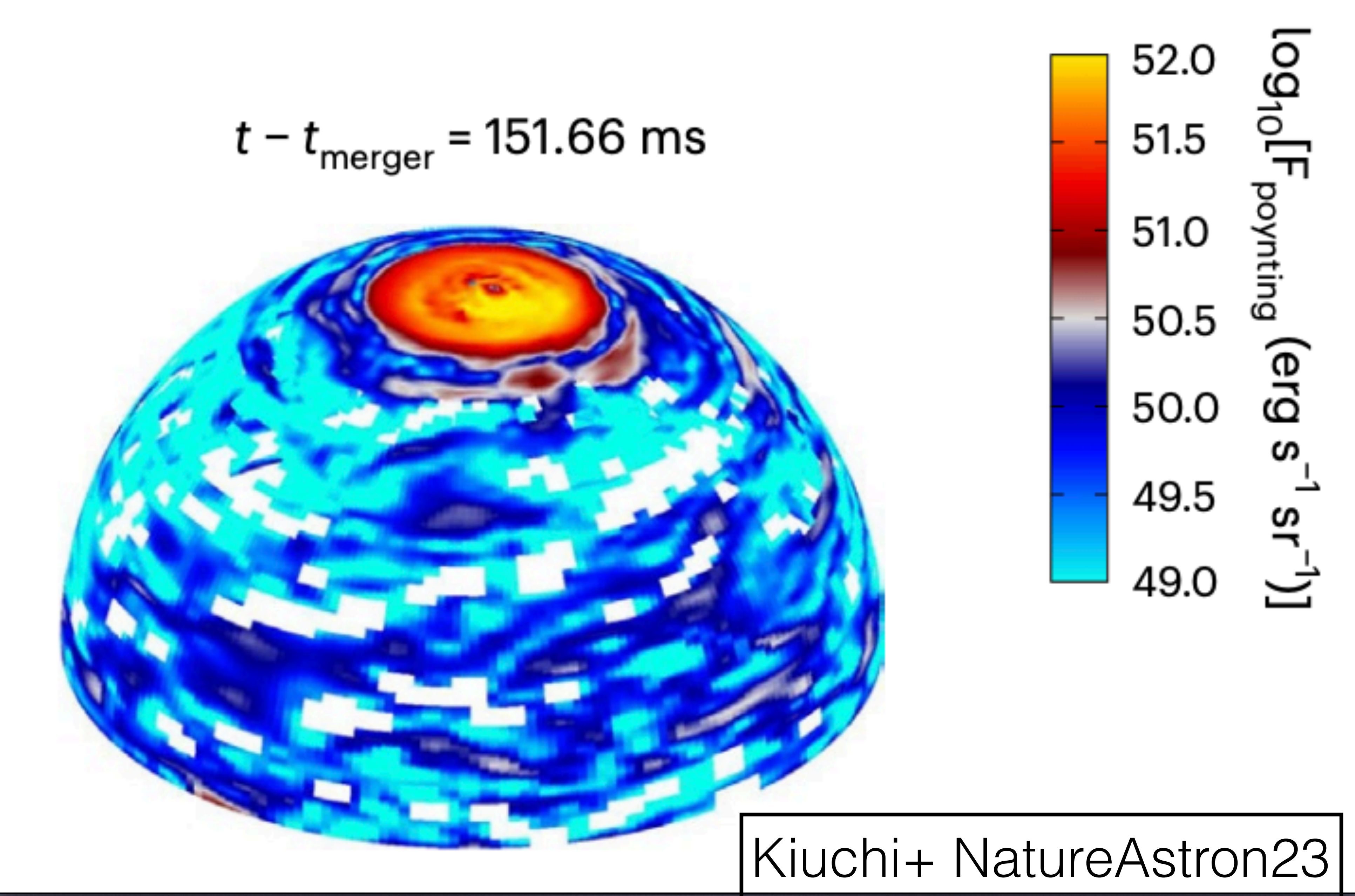
G. Farrar, NYU

Binary Neutron Star Mergers

only (currently known) source candidate satisfying all criteria

- Universal rigidity spectrum explained:
  1. Magnetic field is generated by gravitational dynamo 💕 Kiuchi+ NatureAstron23
  2. Mass range of binary NS's is narrow 💕

2.6-3.2 M$_\odot$ → 10% (negligible) spread in $\mathcal{R}_{max}$



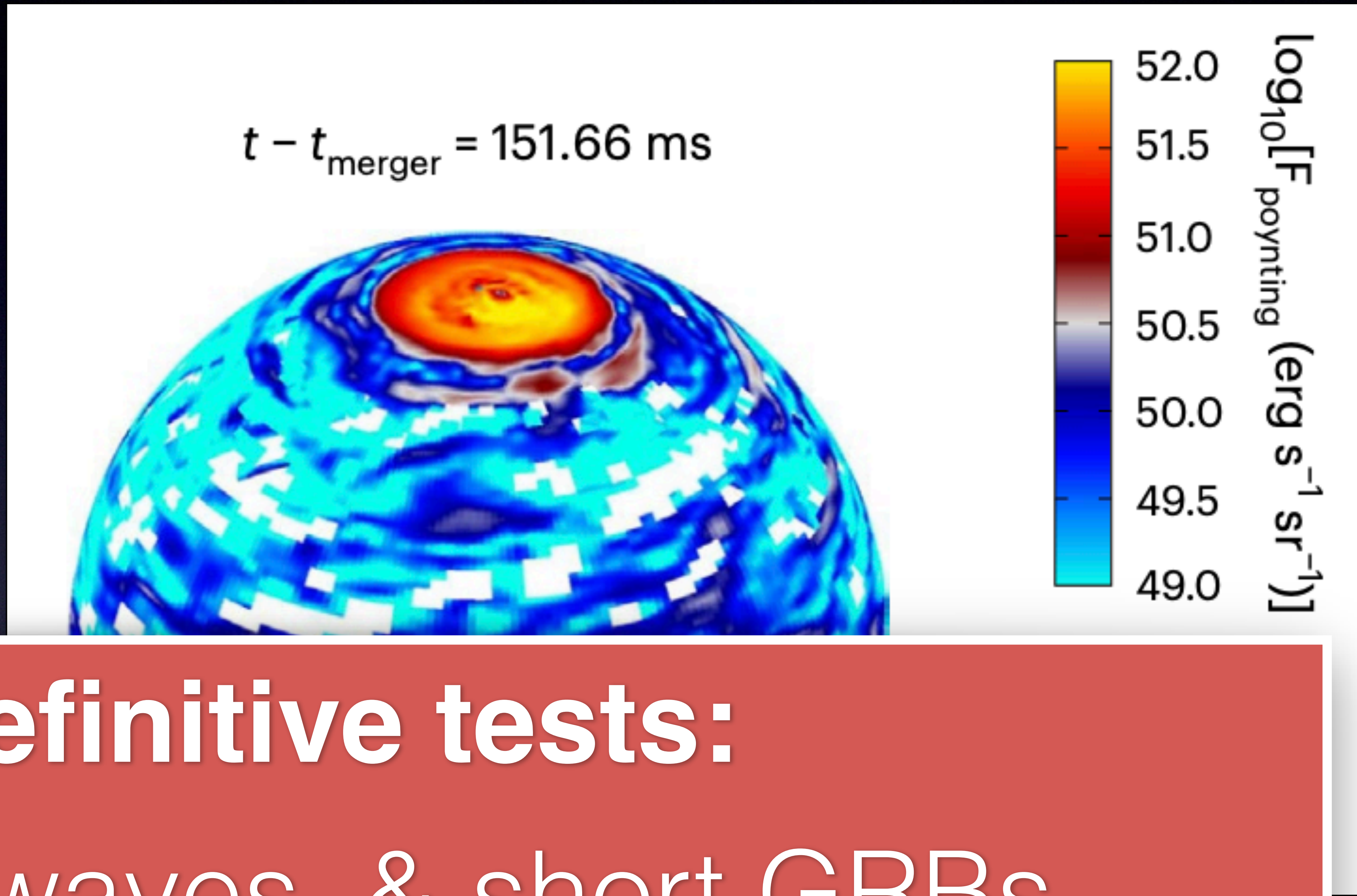
Kiuchi+ NatureAstron23

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

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

Binary Neutron Star Mergers

Initial condition is known!

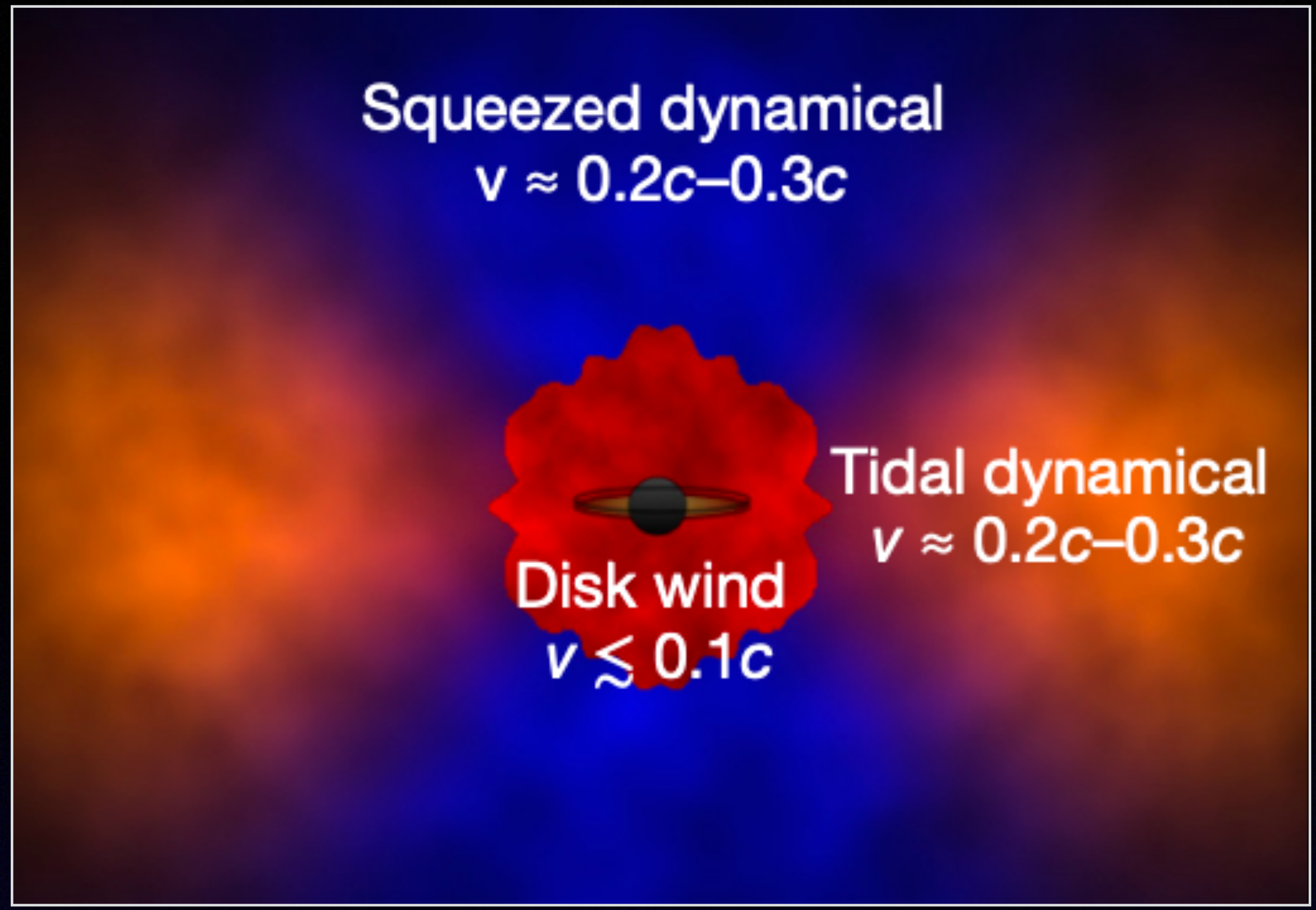


Clean predictions enable definitive tests:

- EHE ν's correlating with gravitational waves & short GRBs
- Highest energy UHECRs: Z>26
- BNS merger ➜ initial B ➜ predicts spectrum & cutoff (correctly)

arXiv: 2405.112004 & PRL 2025
arXiv: 2506.22625 & ApJL 2025

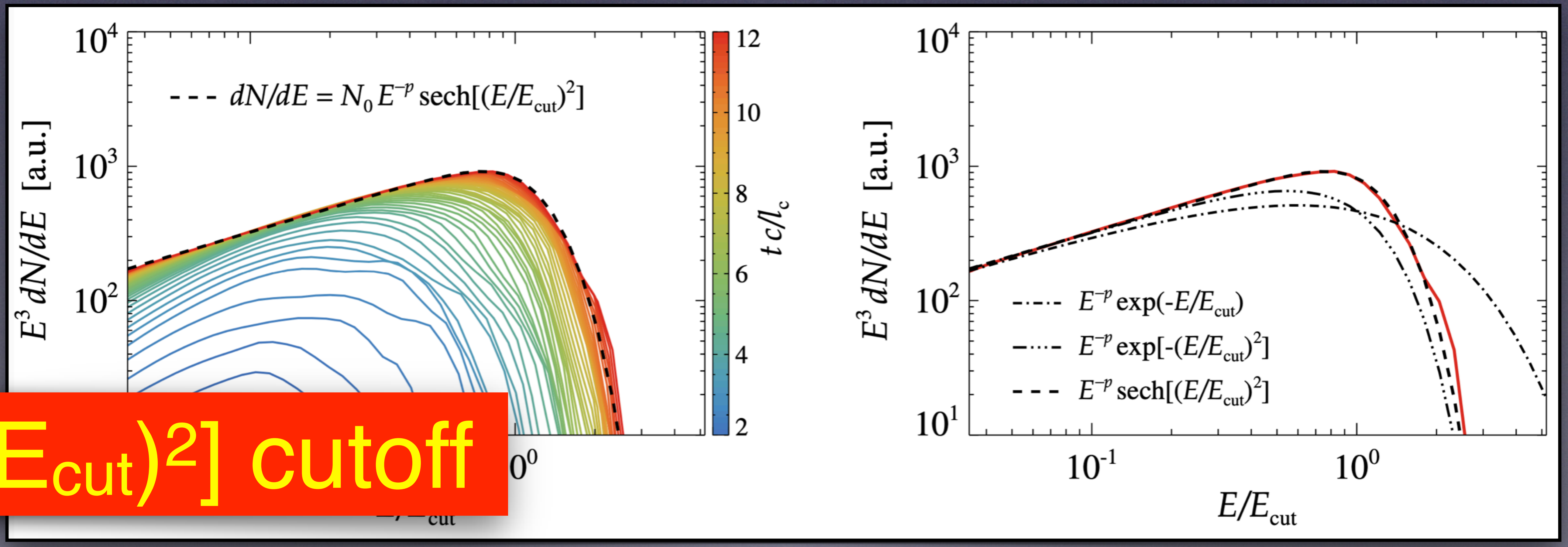
Empirically, UHECRs are mainly produced in the turbulent outflow



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

2. Spectrum: $E^{-2.x}$ × cutoff func(E/E_{cut})
   - Magnetized turbulence cutoff is sech[$(E/E_{cut})^2$]
   - *Diffusive shock acceleration said to produce exponential cutoff (Protheroe & Stanev, 1998)*

Comisso, GRF, Muzio 2024



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

Big Picture

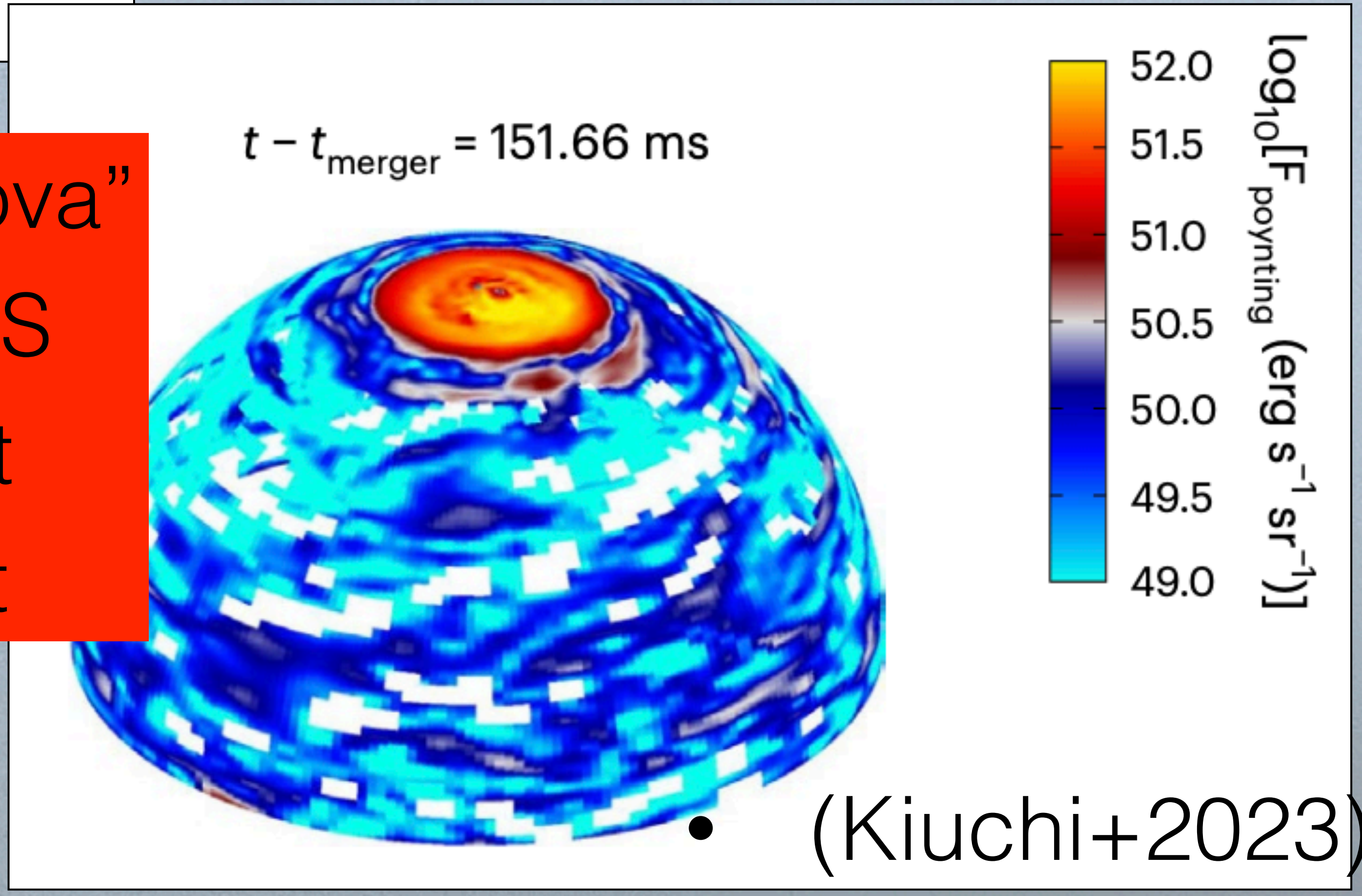
time →

bulk outflow: homologous expansion at v~ 0.1c

grav-driven dynamo➜B
t=150ms, 500 km

Gravitational Wave Emitted

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



- (Kiuchi+2023)

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

Nucleosynthesis (1s)
- p,He in jet
- Z,N≥20 elsewhere
- r-process nuclei

B drops till synch losses are subdominant

UHECRs are accelerated when r~ 10^{14} cm (≈1 day)

Big Picture

time

Expands at v~ 0.1 c

Gravitational Wave Emitted

initialization of B
150ms, 500 km

r-process nucleosynthesis
1 MeV ~1 s: 10^{10} cm

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

- (Kiuchi+

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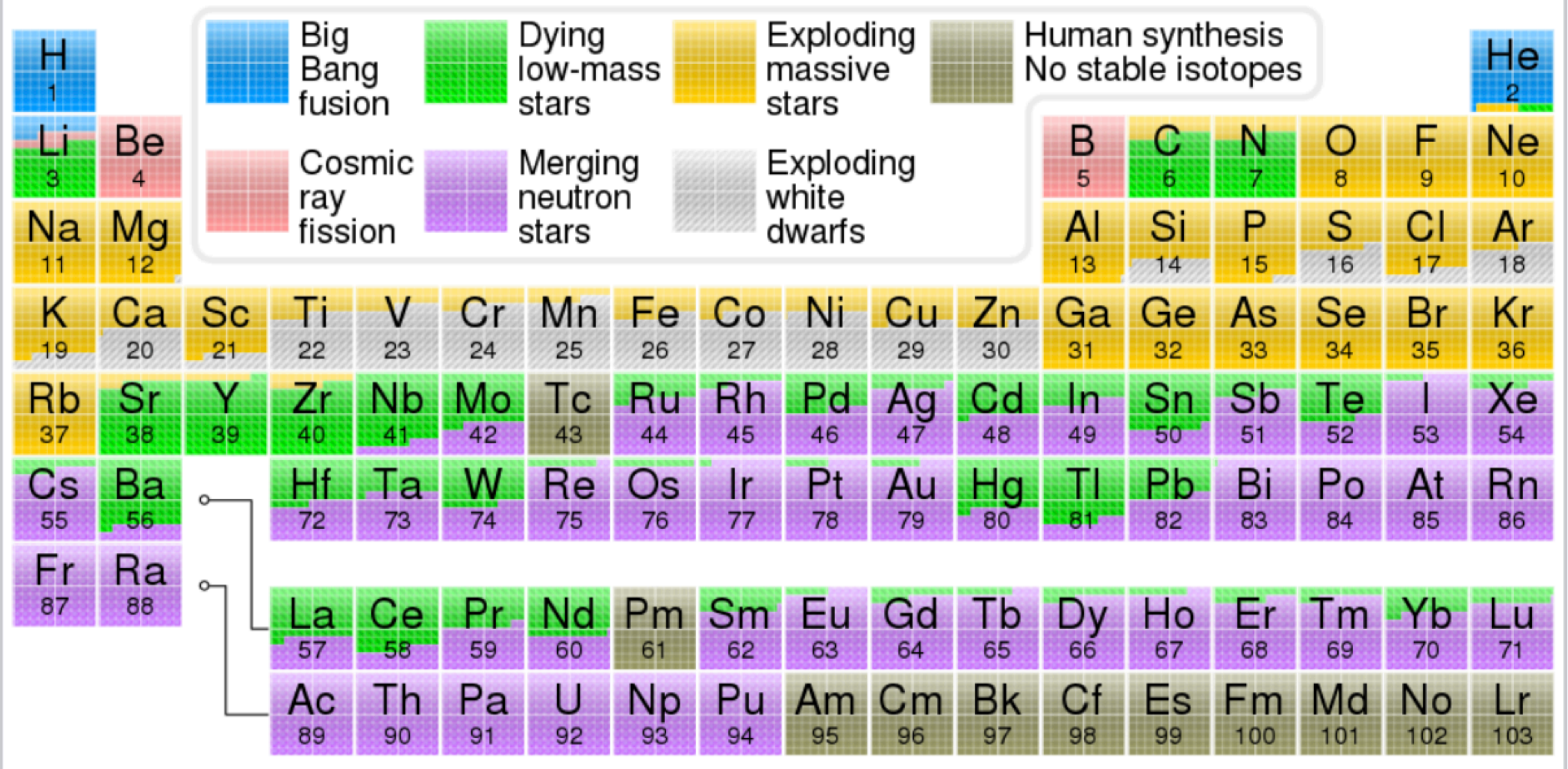
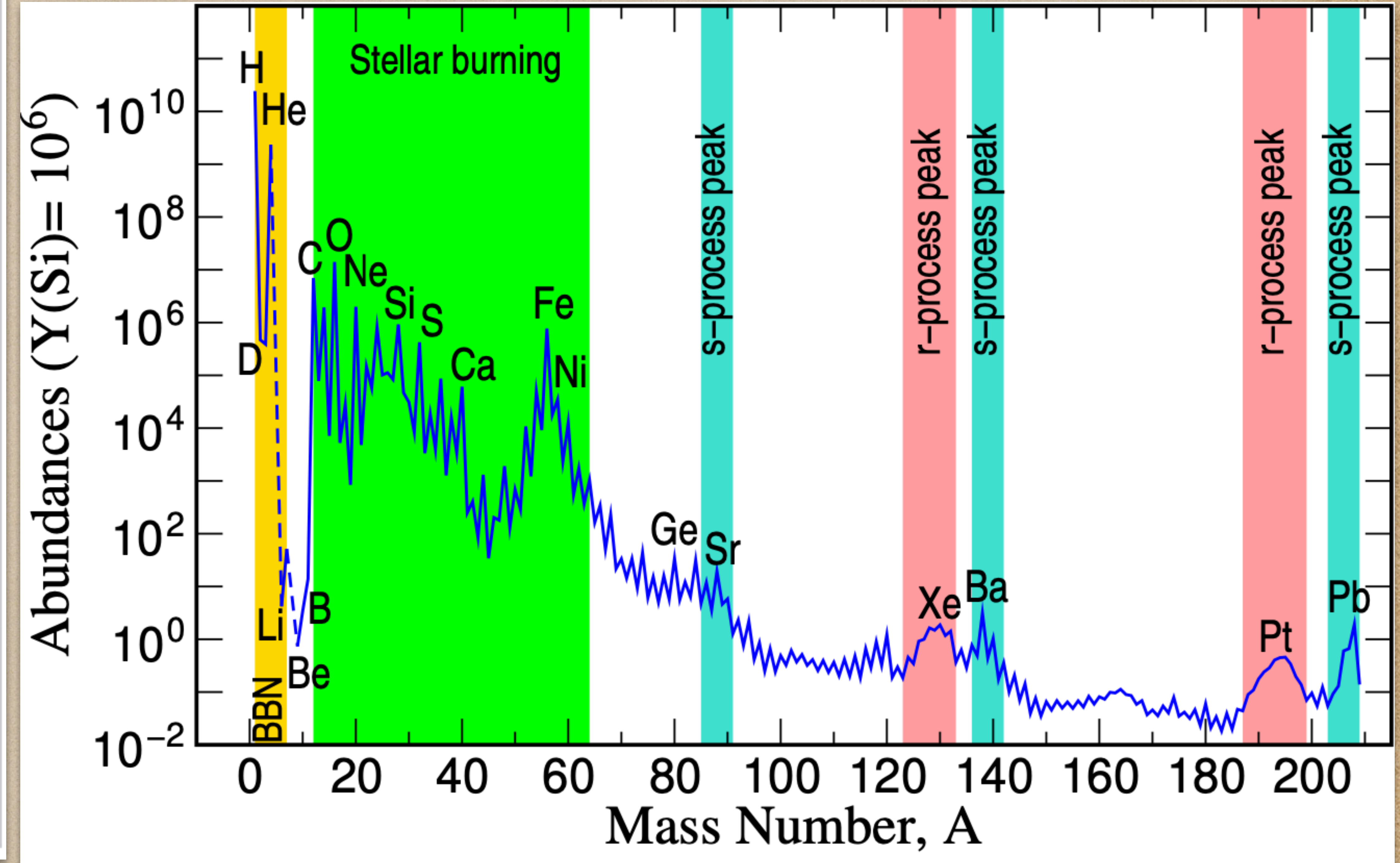
r-process nucleosynthesis 1957 B²FH



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

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 Neutron Stars produce "r-process" elements

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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

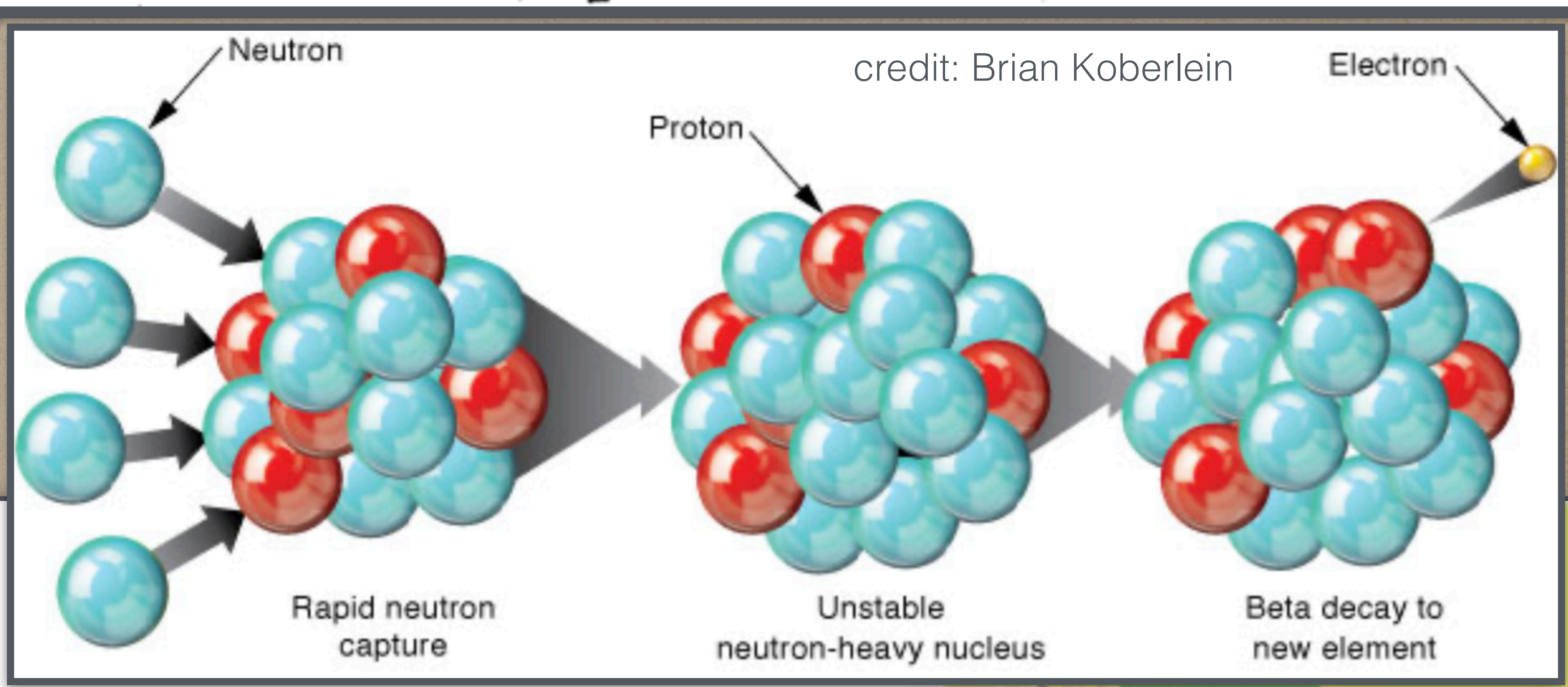
Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

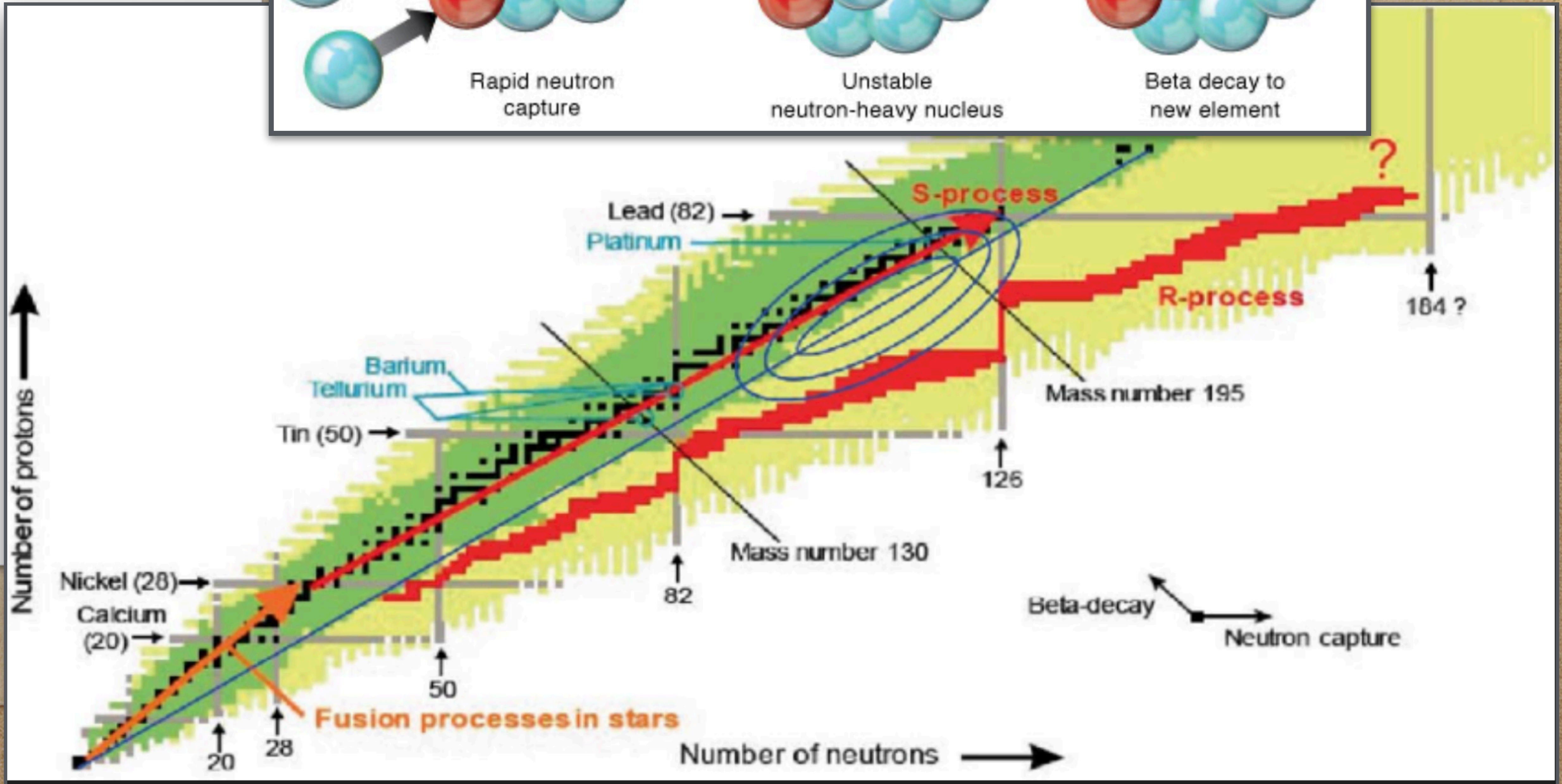
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

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

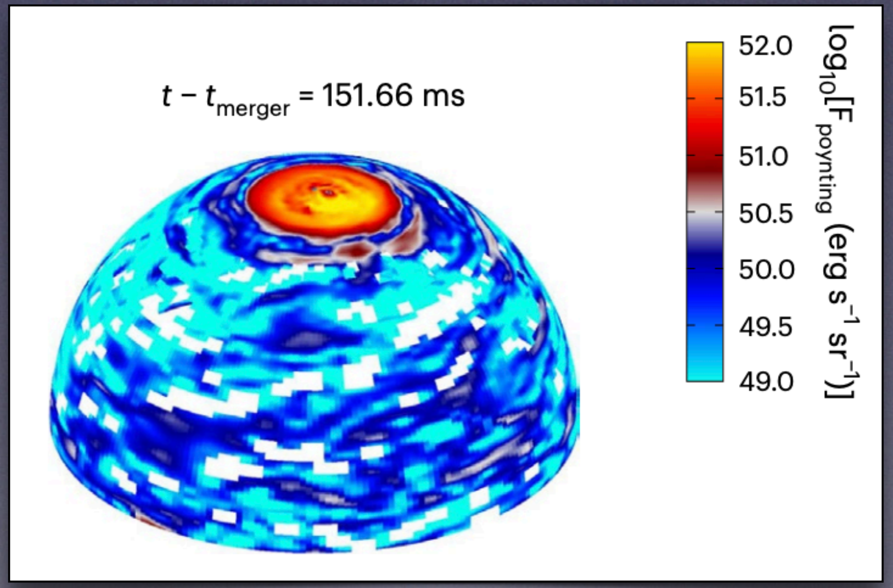
r process.—The nuclear physics of this process demands that neutrons be added extremely rapidly, so that the total time-scale for the addition of a maximum of about 200 neutrons per iron nucleus is ~10–100 sec.



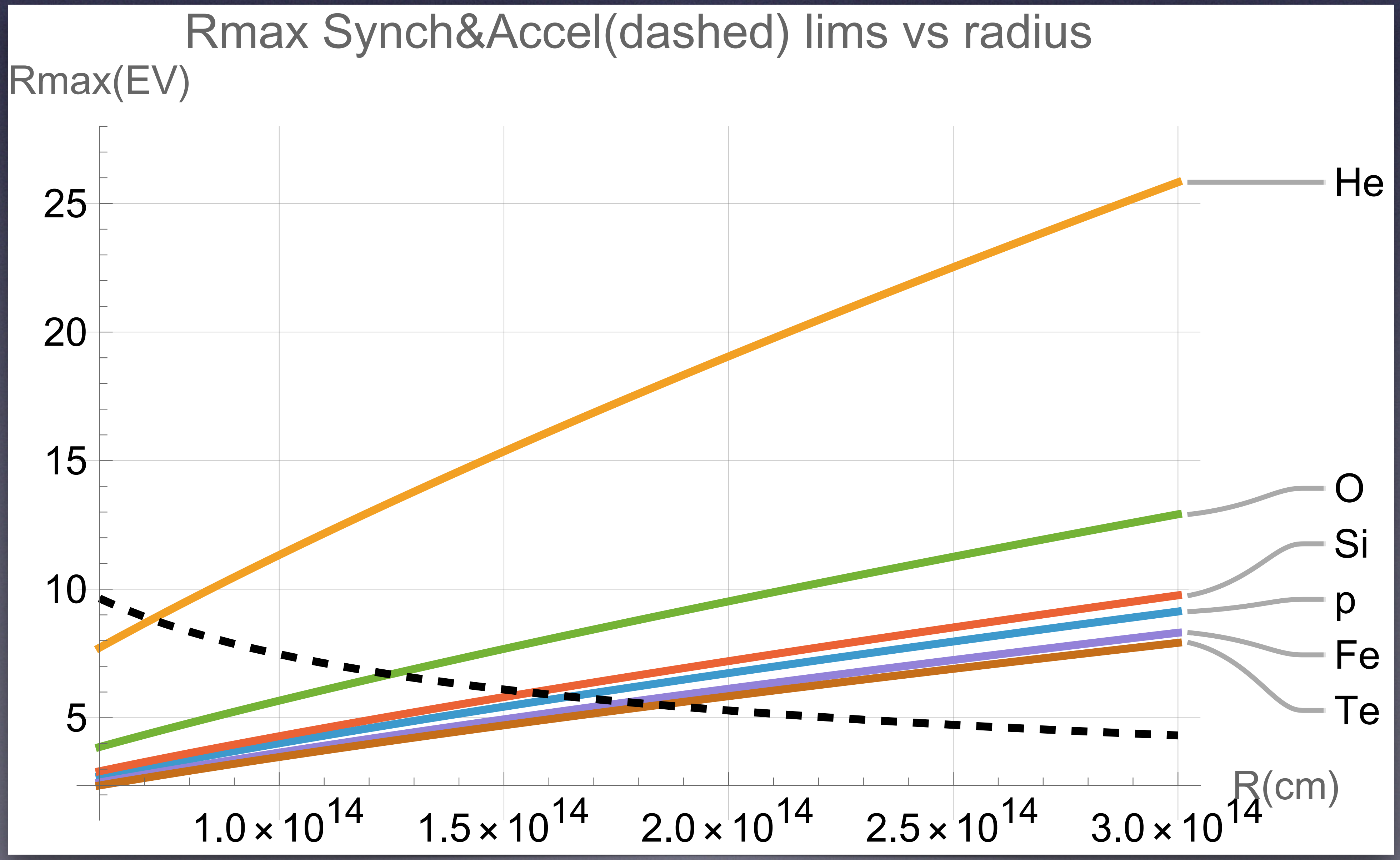


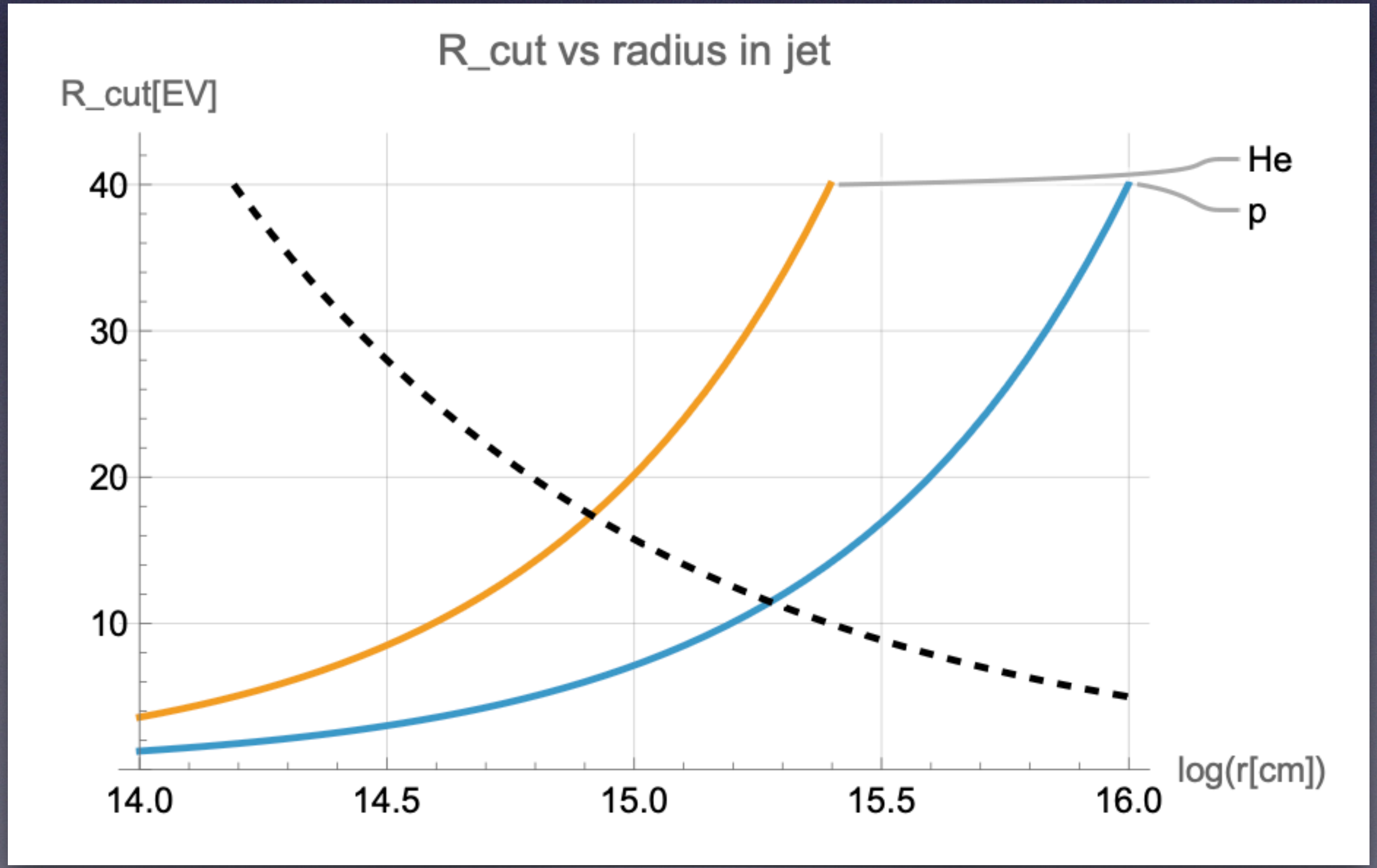
Knowing B ➜ no-free-parameter *prediction* of spectral cutoff

- $\tau_{accel} / \tau_{synch\text{-}loss} \sim 1 \Rightarrow$ radius maximizing $\mathcal{R}_{cut}$
- **Turbulent outflow:** R_{cut} 6-7 EV (9 EV for He)
- Auger Peters cycle fit: R_{cut} = 6.3 EV (systematics ⇒ factor-2 uncertainty)
- **Jet:** (possible direct proton and/or He) $E_{cut} \approx$ 11 EeV (proton), $E_{cut} \approx$ 35 EeV (He)



➜





And on observational grounds…

The Astrophysical Journal Letters, 986:L34 (15pp), 2025 June 20 https://doi.org/10.3847/2041-8213/add536

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A Heavy-metal Scenario of Ultra-high-energy Cosmic Rays

Jakub Vícha[1], Alena Bakalová[1], Ana L. Müller[1], Olena Tkachenko[1], and Maximilian K. Stadelmaier[2,3]
[1] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic; vicha@fzu.cz
[2] Università degli Studi di Milano, Dipartimento di Fisica & INFN, Sezione di Milano, Milano, Italy
[3] Karlsruhe Institute of Technology, Institut für Astroteilchenphysik, Karlsruhe, Germany
Received 2025 April 15; revised 2025 May 6; accepted 2025 May 7; published 2025 June 19

Abstract

The mass composition of ultra-high-energy cosmic rays is an open problem in astroparticle physics. It is usually inferred from the depth of the shower maximum (X_{max}) of cosmic-ray showers, which is only ambiguously determined by modern hadronic interaction models. We examine a data-driven scenario, in which we consider the expectation value of X_{max} as a free parameter. We test the novel hypothesis of whether the cosmic-ray data from the Pierre Auger Observatory can be interpreted in a consistent picture, under the assumption that the mass composition of cosmic rays at the highest energies is dominated by high metallicity, resulting in pure iron nuclei at energies above ≈40 EeV. We investigate the implications on astrophysical observations and hadronic interactions, and we discuss the global consistency of the data assuming this heavy-metal scenario. We conclude that the data from the Pierre Auger Observatory can be interpreted consistently if the expectation values for X_{max} from modern hadronic interaction models are shifted to larger values.

Unified Astronomy Thesaurus concepts: Ultra-high-energy cosmic radiation (1733); Nuclear abundances (1128); Spectral energy distribution (2129); Cosmic ray showers (327)

Predictions of BNS merger scenario

✓ Narrow rigidity distribution

✓ Correct spectral slope and shape of cutoff

✓ Observed maximum energy of each nuclear type

➡ Eroded r-process nuclei (Z>26): first explanation for CRs above 150 EeV

- Flux of extremely high energy neutrinos ($E \gtrsim 10$ PeV)
- GW-ν coincidences for EHE ν's with time delay ≈1 day

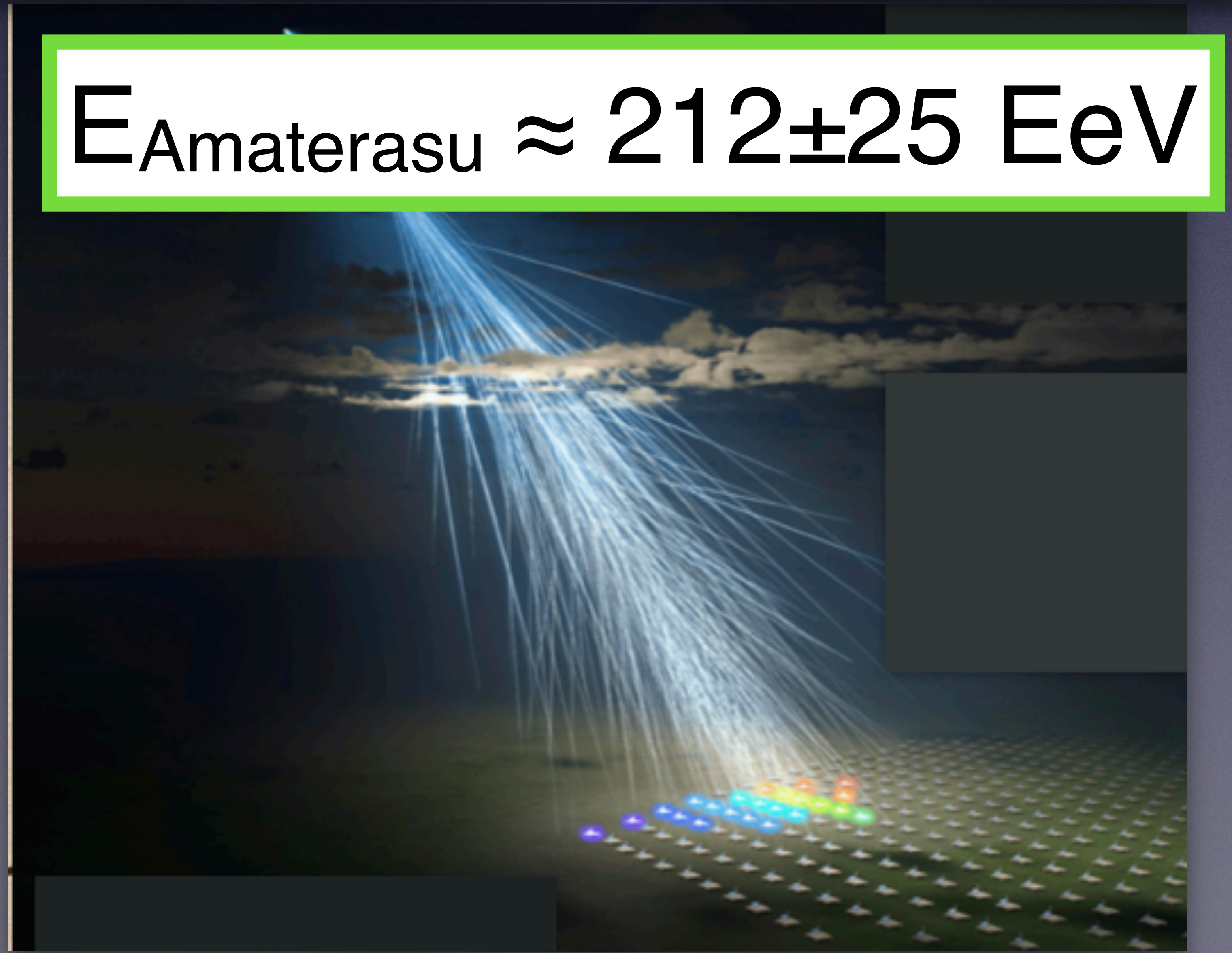
Events above 150 EeV are (finally!) naturally explained

- $E_{cut,Fe} \approx$ 6 EV x 26 ≈ 150 EeV
- But ~ 1 dozen events seen above 150 EeV:
  - Fly's Eye OMG event: 250 EeV
  - TA's Amaterasu event: 215 EeV
  - Auger has ~ 10 events > 150 EeV

★ $Z_{Te} = 52$ ➜ $< E_{Te\text{-}Xe} > = 235$ EeV

★ $Z_{Kr} = 36$ ➜ $< E_{Kr} > = 165$ EeV

Auger Phase II: measure these masses!



G. Farrar, NYU

Prediction: Every EHE Neutrino is accompanied by a Gravitational Wave

- Neutrinos come from UHECRs
  - **spallation neutrons** beta decay: $\mathbf{E_\nu} \approx 10^{-3}\,(E_n \approx \boldsymbol{R}/2) \sim$ **2 PeV**
  - **photo-pion** production: $\mathbf{E_\nu} \lesssim (E/A)/20 \sim \boldsymbol{R}/40 \sim$ **100 PeV** (KM3NeT)

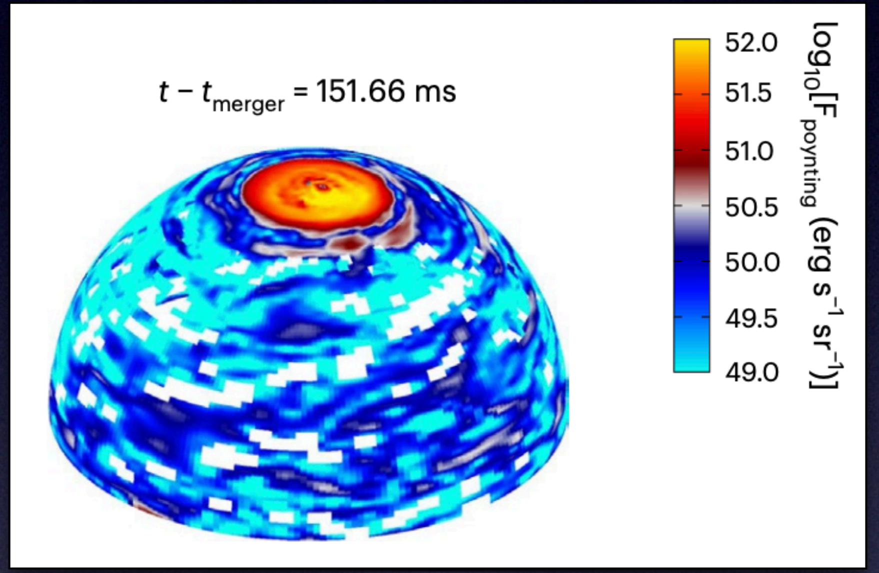
- Time delay for $\boldsymbol{\nu}$: $\gtrsim$ time for ejecta to expand to 10^{14} cm (where UHECRs form)
  - $\langle v_{ej} \rangle = 0.1\,c$ ➜ **delay ≈ O(day)**

Crude estimate: 1ν per yr with Cosmic Explorer, Einstein telescope & ICGen2

Coming soon: better estimate of rate of observing GW-nu coincidences.

Summary

- BNS merger scenario for UCR production is promising. Explains "standard candle" aspect.



- Acceleration mainly occurs in magnetized turbulent outflow.
    - Correct spectrum with no free parameters, initializing **B** to Kiuchi+24 dynamo simulation

- PIC simulations in expanding outflow are needed for high (and low?) E cutoff, escape spectral index, total energy in UHECRs per merger

- UHECR & multi-messenger data will give a new probe of BNS mergers.

What a next-generation UHECR observatory can do for you

- *If you're an astrophysicist:*
  - Unique new probe of binary neutron star mergers, sensitive to details of nucleosynthesis, large-distance outflow and merger-rate evolution.
  - Test theories of magnetic field generation, r-process nucleosynthesis.
  - Highly complementary to Gravitational Wave probes
- *If you're a nuclear or particle physicist:*
  - Determine equation of state of densest matter. Is the interior of a neutron star filled with a quark liquid? Exciting new arena of post-nucleosynthetic fragmentation. Tests understanding of nuclei in a new regime.
- *If you're a plasma physicist:*
  - Unique tests of field generation & particle acceleration in expanding medium
  - *Measure* "uptake" probability as a function of A & Z

BACKUP SLIDES

and see

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

GRF arXiv: 2506.22625 [astro-ph.HE] == ApJL 2025

Path to predict UCR composition

- Initialize from r-process simulations

- Follow expansion as outflow radius increases
  - CRs accelerated to $\gtrsim$100 MeV collide & fragment
  - Lighter nuclei are formed

- Need more PIC simulations of acceleration
  - Expanding magnetized turbulence; escape
  - “Uptake probability” into acceleration chain, to calculate absolute magnitude of CR component.

To predict composition & spectrum need info from:

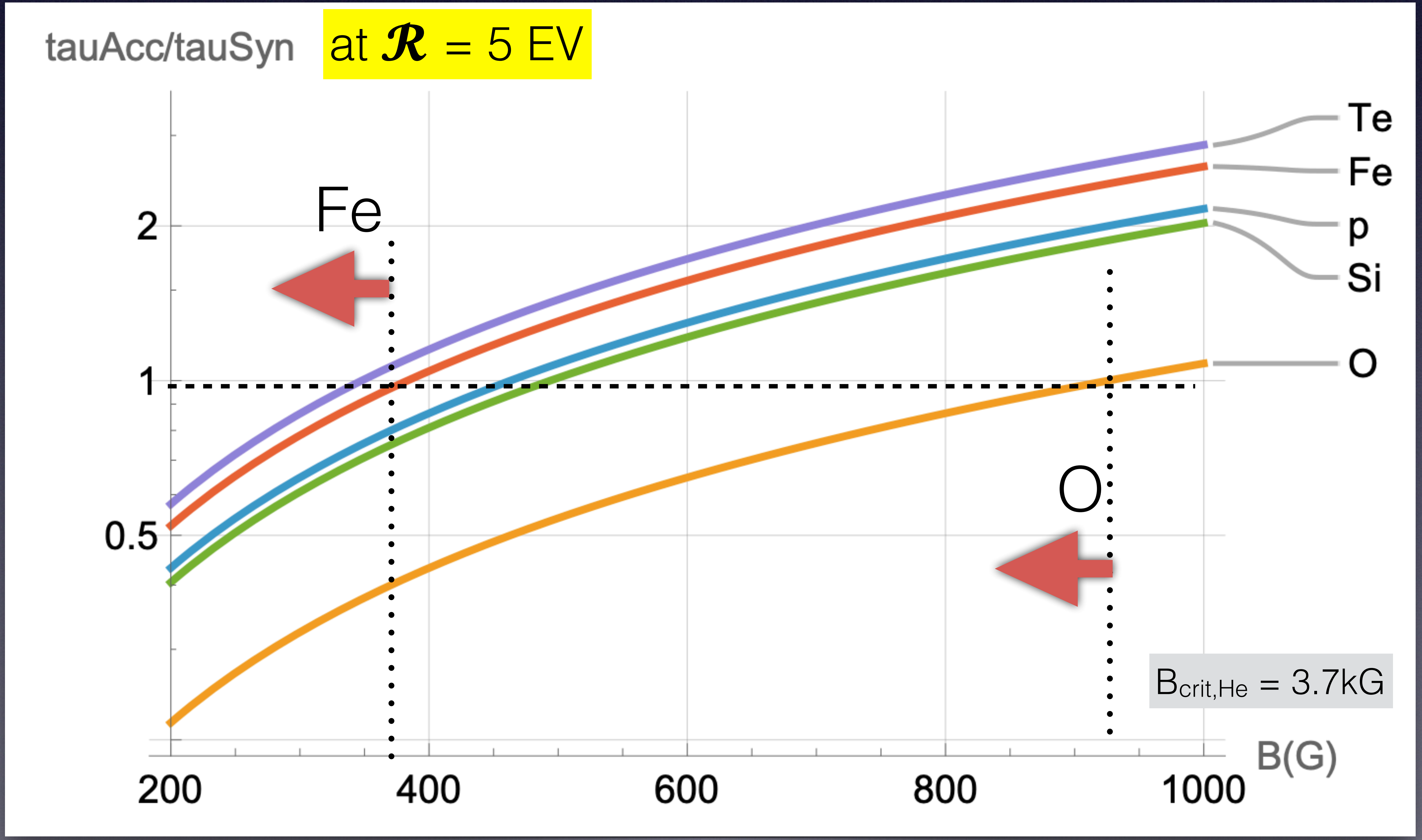
- BNS merger (simulation) community:
  - photon field at large radii, to calculate spallation (Kiuchi group, in prep.)
  - nucleosynthesis abundances
- Nuclear physics community:
  - fragmentation cross sections for reaction networks, to predict UHECR composition
- Particle Acceleration/Plasma Physics community:
  - PIC simulations of spectrum for spherically expanding system, including escape
  - PIC simulations to understand uptake (total energy in UHECRs)

Predicting the UHECR spectral cutoff, $\mathcal{R}_{cut}$, in the BNS magnetized turbulent outflow (1)

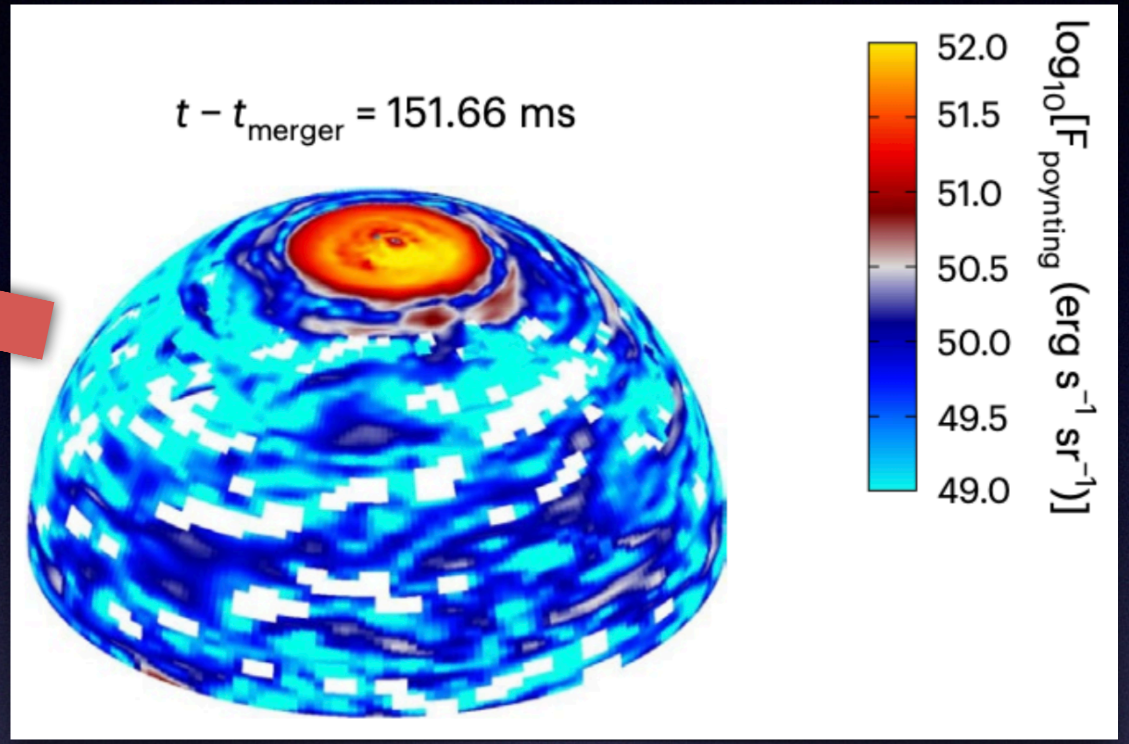
For a given B field, maximum energy of CR is set by $\tau_{synch\text{-}loss} \approx \tau_{accel}$

- $\mathcal{R}$igidity = E/Z = γ A/Z m_p
- $\tau_{accel} \approx r_{Lar}/c \sim \mathcal{R}$ / B
- $\tau_{synch\text{-}loss}$ depends on $\mathcal{R}$, A, Z, & B

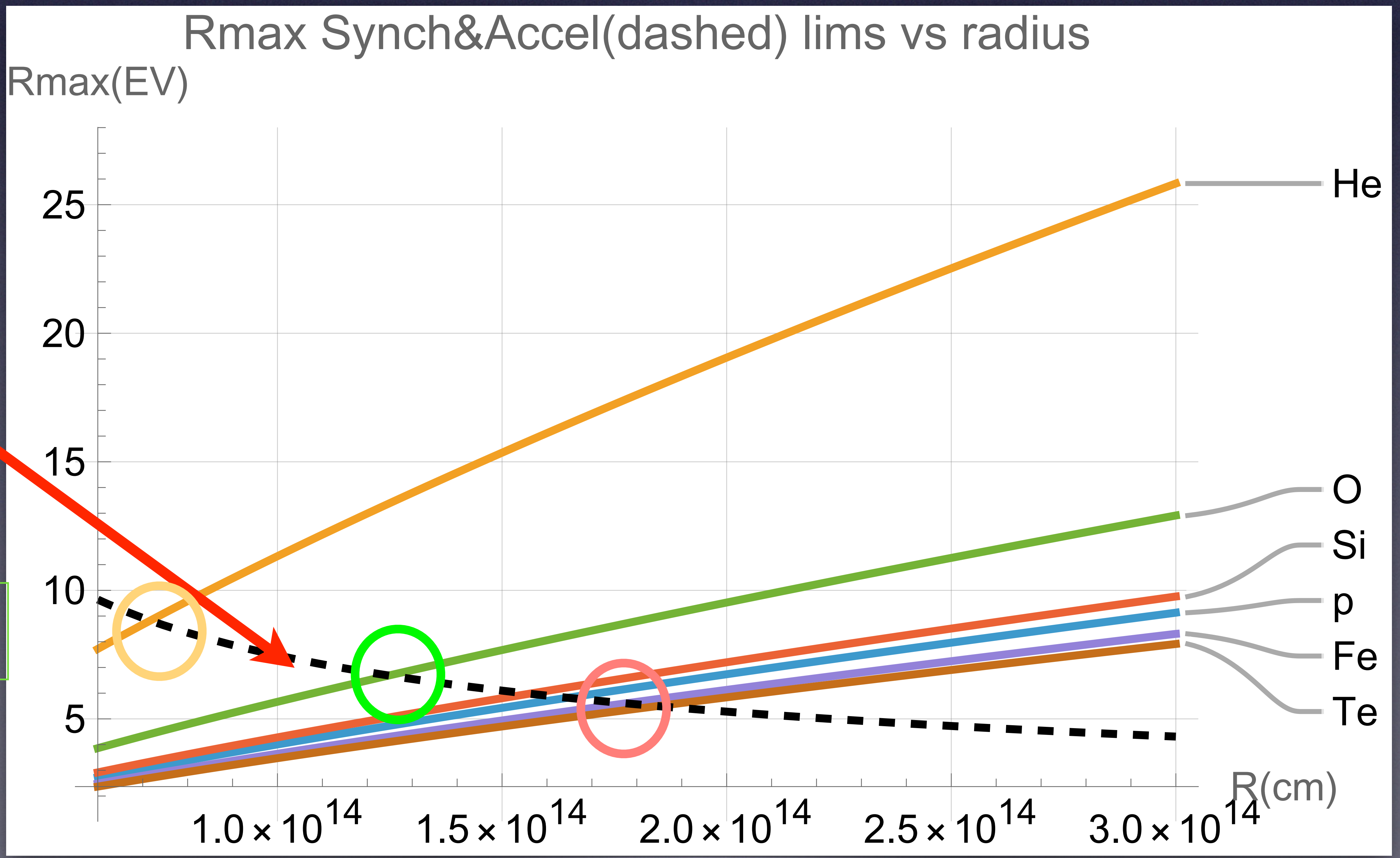
$$\dot{E}_{\rm synch} = \frac{4}{9} c \left(\frac{m_e r_0}{m_p}\right)^2 (\gamma\beta B)^2 \frac{Z^4}{A^2}$$



Predicting $\mathcal{R}_{cut}$ in the magnetized turbulent outflow (2)



- 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:
  - $\mathcal{R}_{cut}(r) = 0.65\ B(r)\ L_{coh}(r) \sim r^{-1/2}$
  - $\tau_{synch\text{-}loss}(A,Z,\mathcal{R},r) \gtrsim \tau_{accel}(\mathcal{R},B)$
  - **→ $\mathcal{R}_{cut}(Z, A, r)$ *is intersection***



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

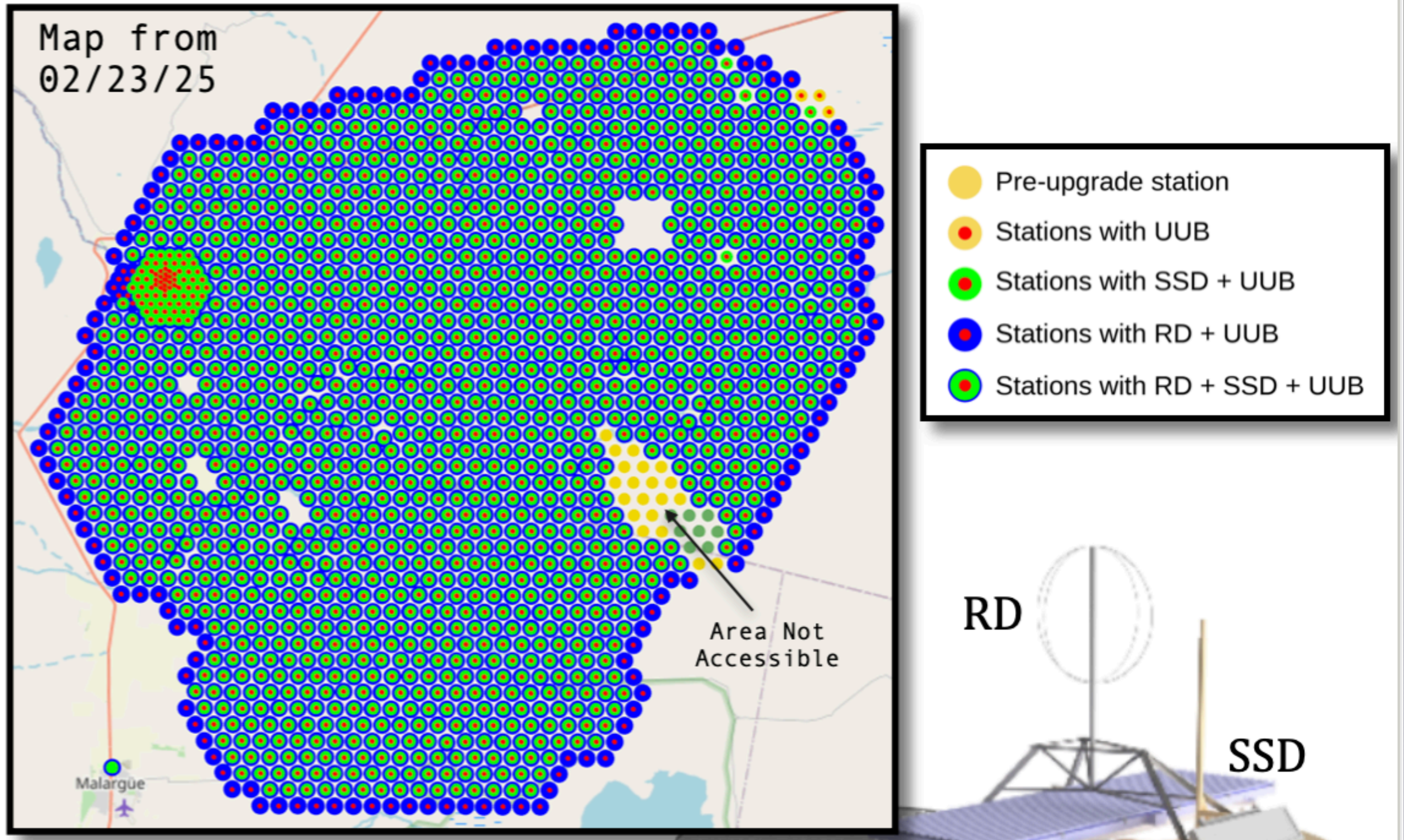
Auger fit: R_{cut} = 6.8 EV with factor-1.5 uncertainty)

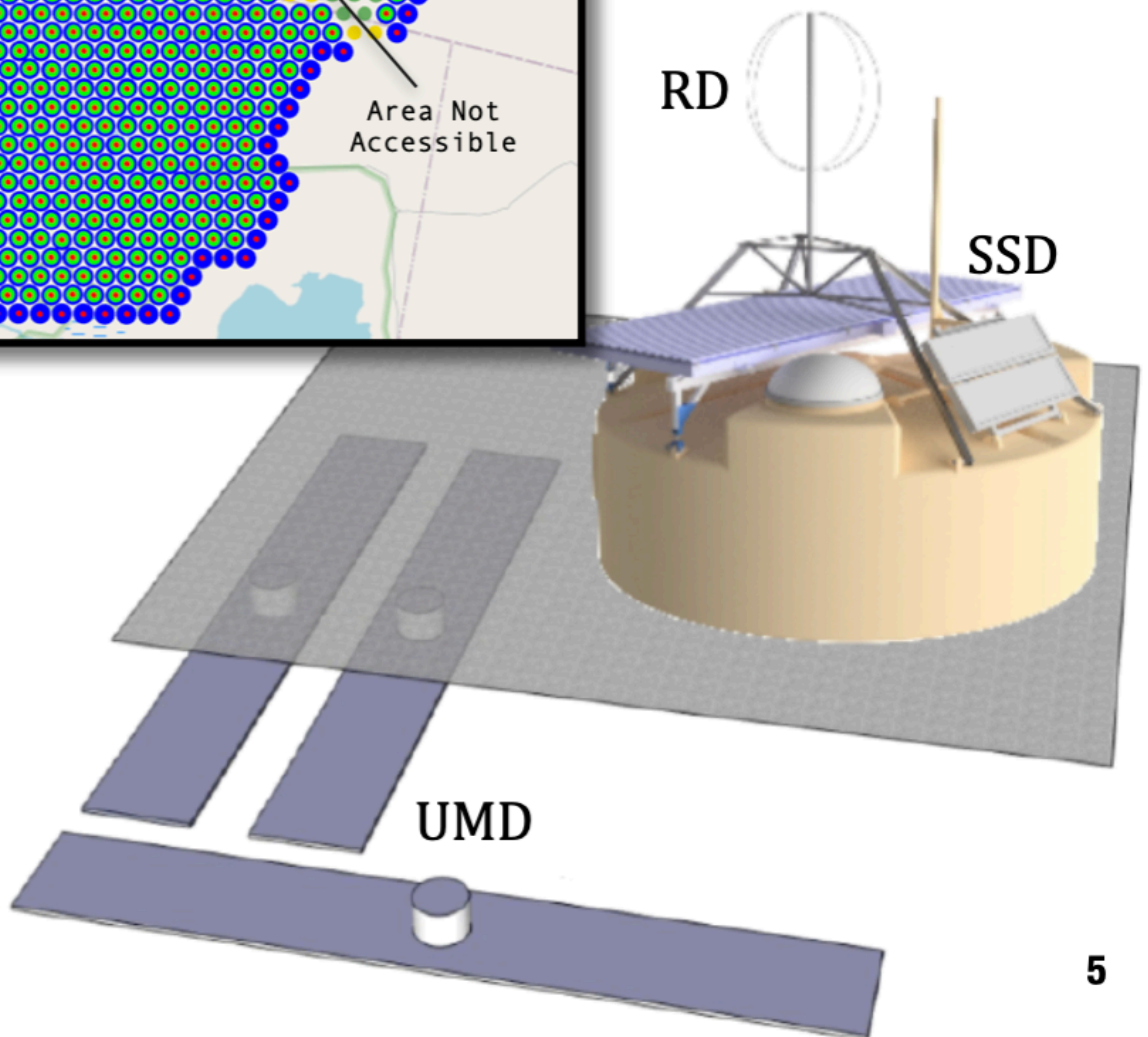
Auger Phase II: upgrade completed 2023

Auger Phase II: Status

The instrumentation upgrade to improve composition sensitivity is complete

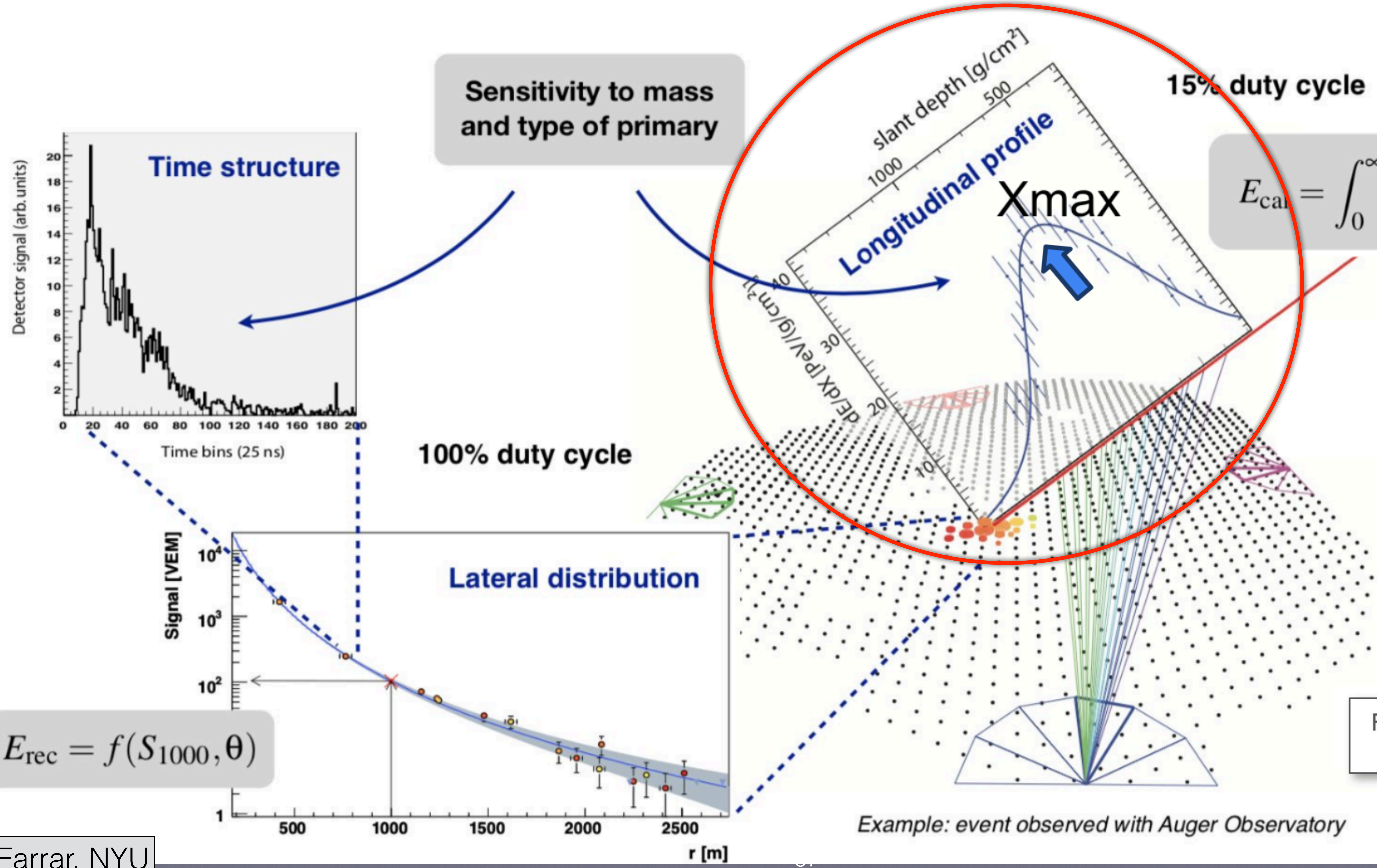
- Surface Scintillator detectors (SSD)
- Radio Detectors (RD)
- Underground Muon Detectors (UMD)
- Small PMT to expand dynamic range
- New faster electronics
- Increased FD duty-cycle





Auger Phase II data-taking is underway, and all equipment is performing to spec

The Hybrid Observation Method of Auger



$$E_{cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{obs} dX$$

$$E_{rec} = f(S_{1000}, \theta)$$

F. Salamida ICRC 2023 Highlight3-02

G. Farrar, NYU

BNS mergers explain essential features of UHECRs

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

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

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

G. Farrar, NYU

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	✔	[✔]	✔	✔	✔

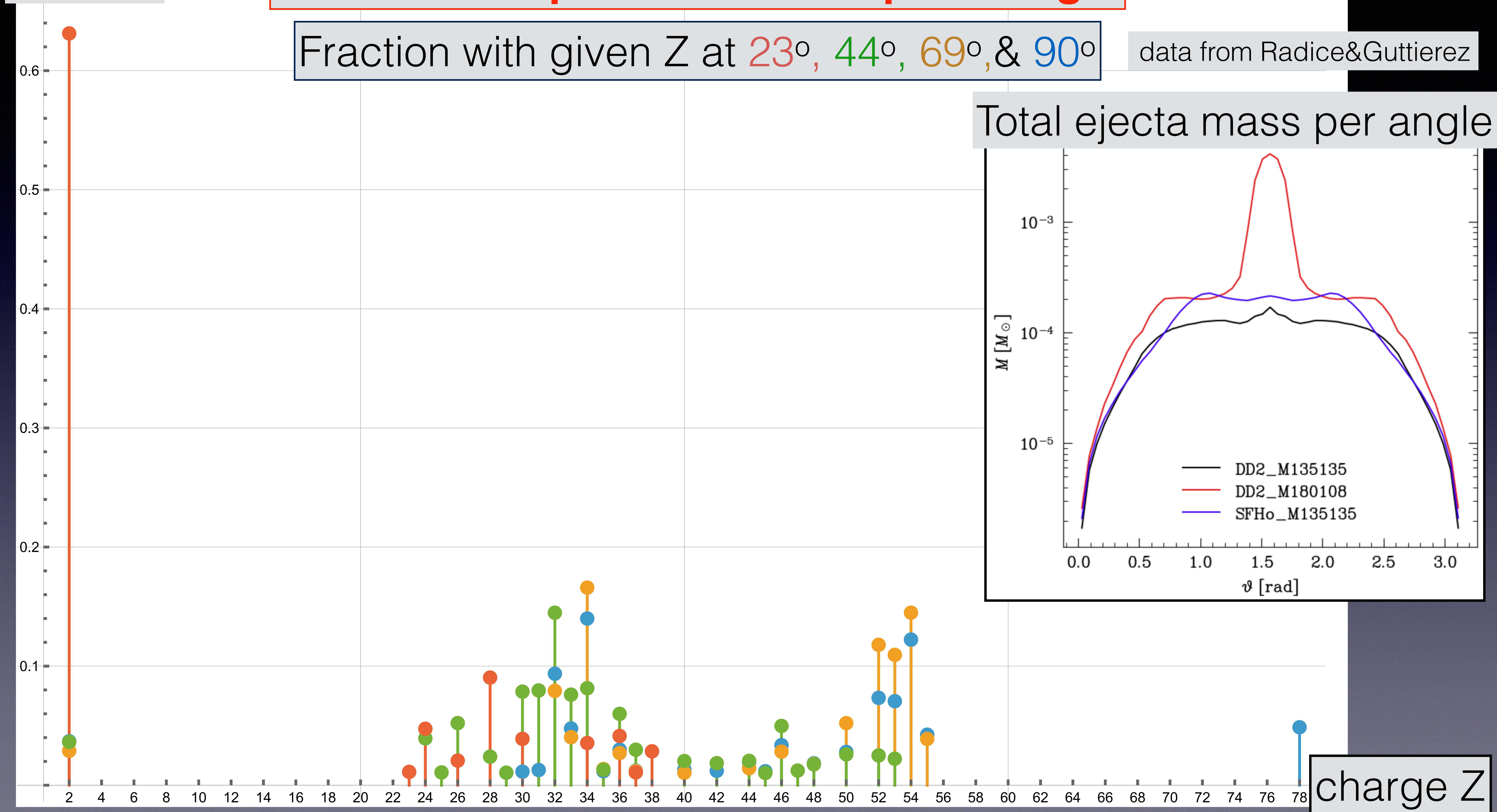
(All can satisfy Hillas size > Larmor radius)

Nuclear Composition Mix vs polar angle

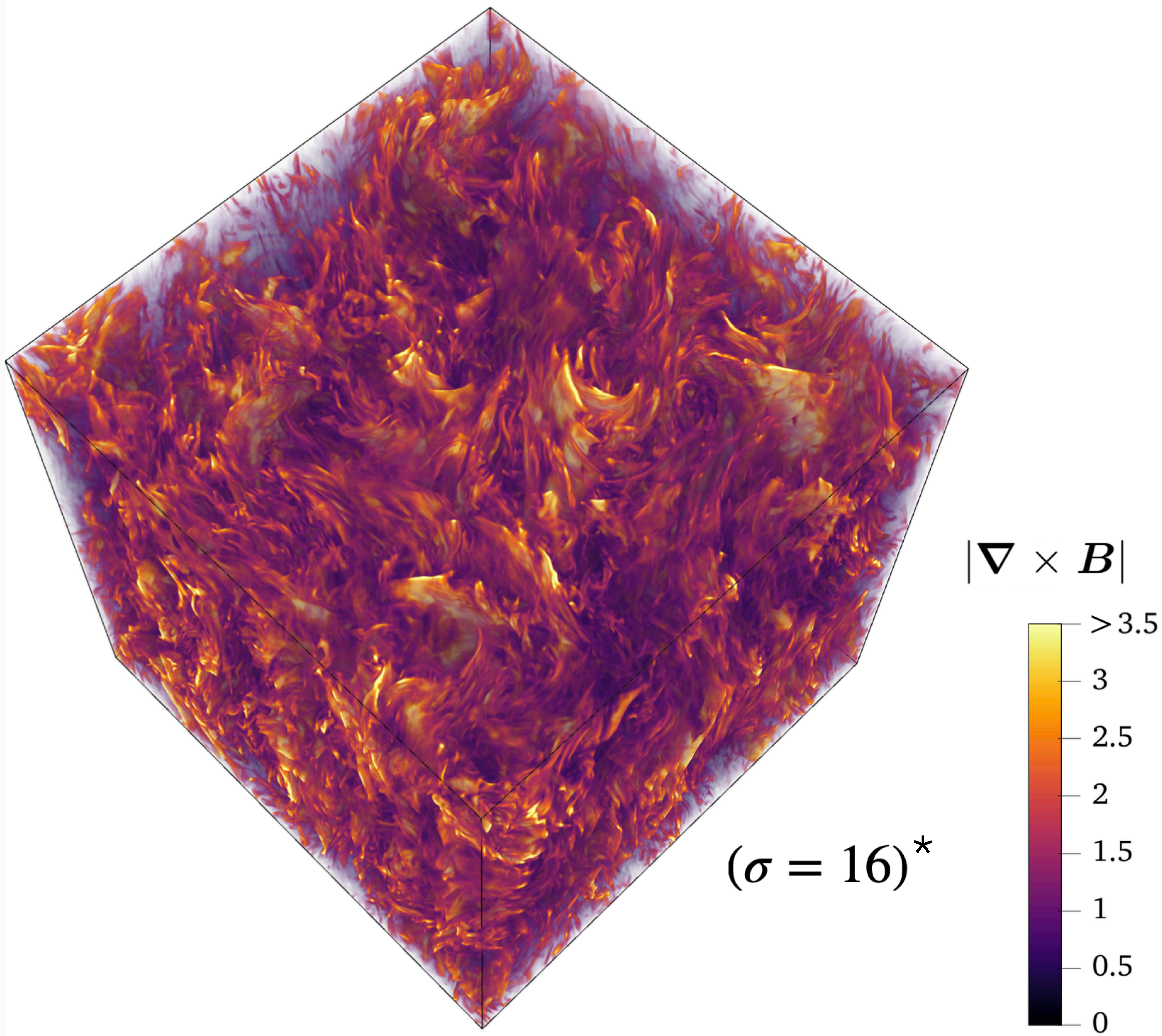
Fraction with given Z at 23°, 44°, 69°,& 90°

data from Radice&Guttierez

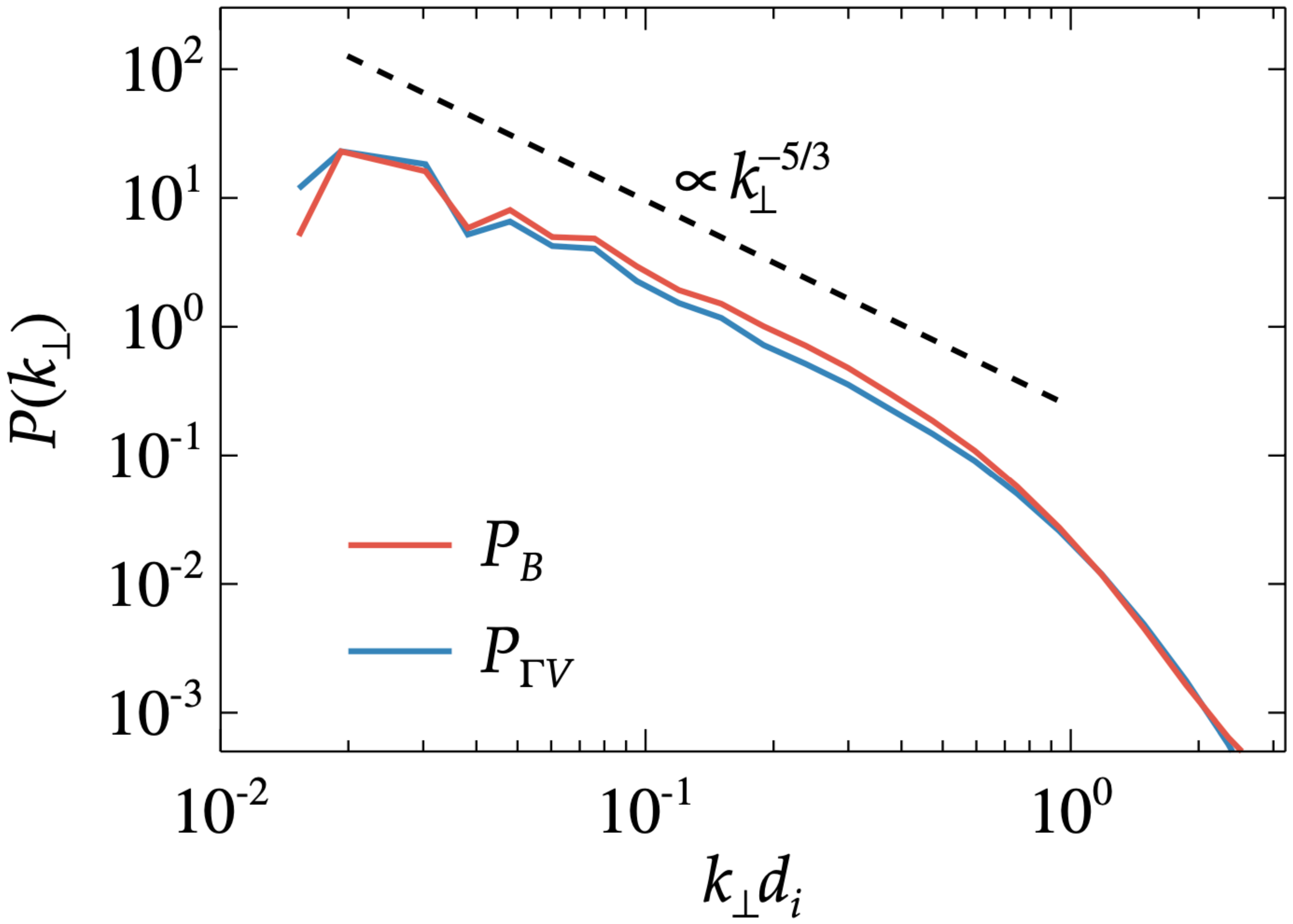
Total ejecta mass per angle



Magnetically dominated turbulence from first-principles PIC simulations



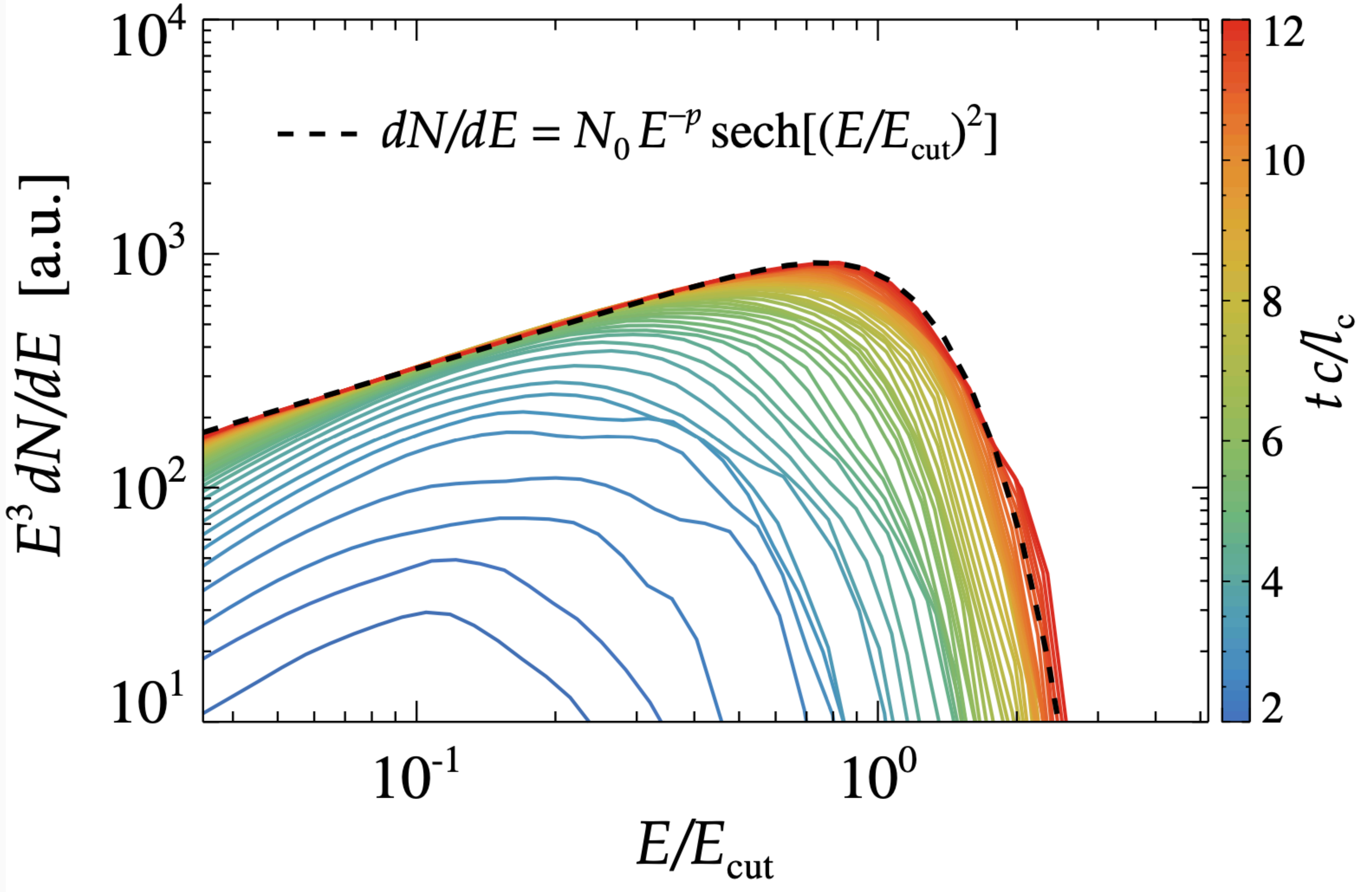
*σ ≈ U_{mag}/KEden

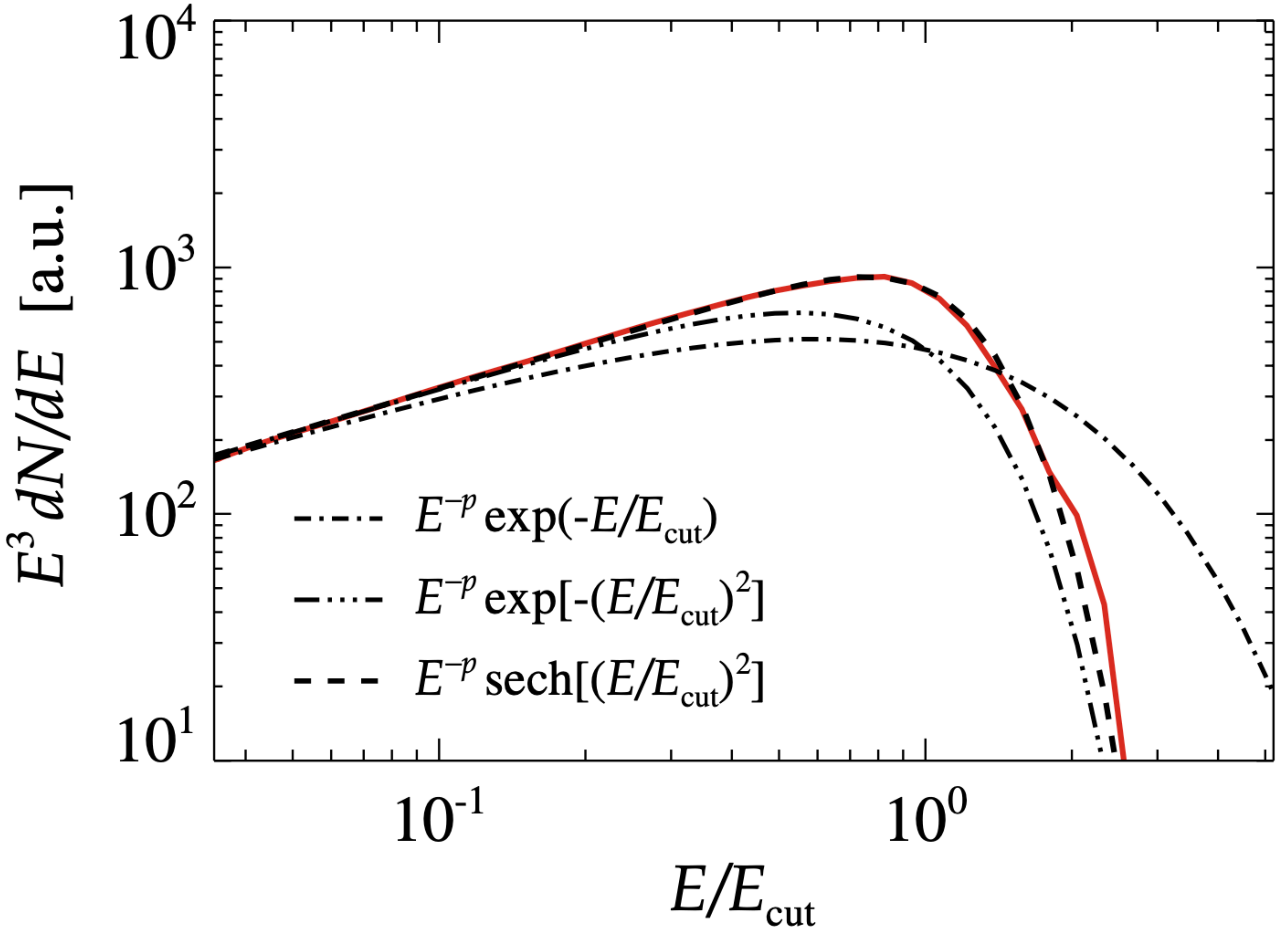


- The large computational domain allow us to capture both the MHD cascade at large scales and the kinetic cascade at small scales

L. Comisso, GRF, M. Muzio, ApJL2024

Particle acceleration via magnetized turbulence: nonthermal particle spectrum





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

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

L. Comisso, GRF, M. Muzio, ApJL2024

Spectrum for Magnetized Turbulence

$\sigma > 1$

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

LUCA COMISSO,[1,2,3] GLENNYS R. FARRAR,[4] AND MARCO S. MUZIO[5,6,7]

[1] *Department of Physics, Columbia University, New York, NY 10027, USA*
[2] *Department of Astronomy, Columbia University, New York, NY 10027, USA*
[3] *Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA*
[4] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[5] *Department of Physics, Pennsylvania State University, University Park, PA 16802, USA*
[6] *Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA*
[7] *Institute of Gravitation and the Cosmos, Center for Multi-Messenger Astrophysics, Pennsylvania State University, University Park, 16802, USA*

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

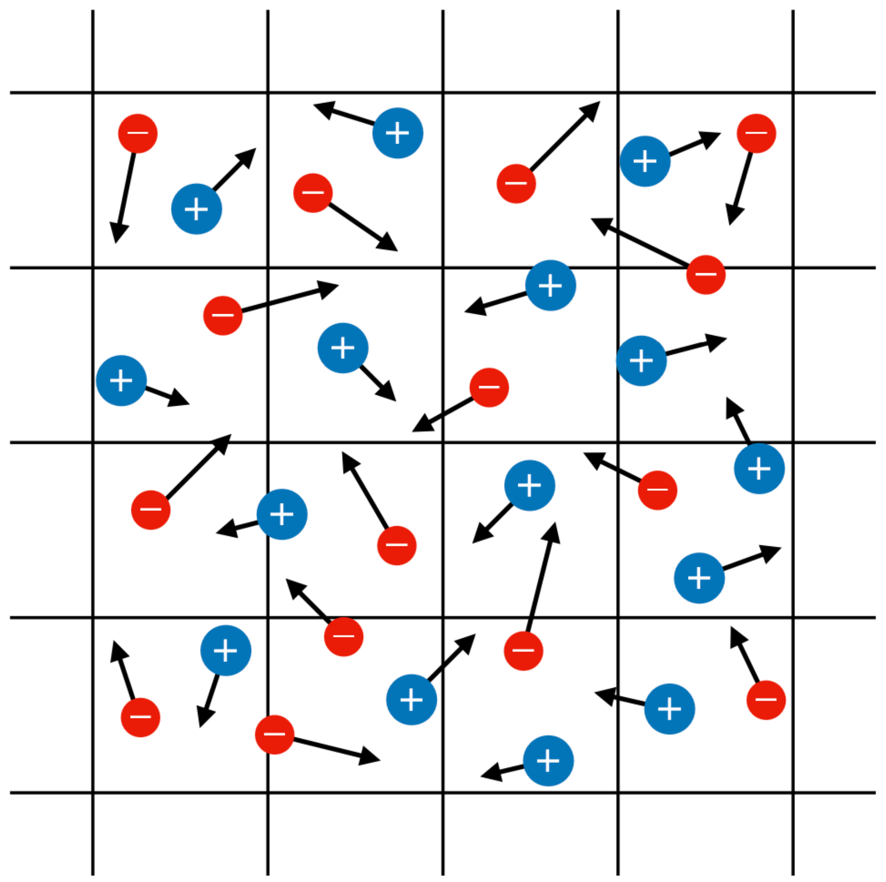
$$\frac{\partial \boldsymbol{E}}{\partial t} - c\,{\rm curl}\boldsymbol{B} = -4\pi \boldsymbol{J}\,, \qquad {\rm div}\boldsymbol{E} = 4\pi\rho\,,$$

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

where the source terms are computed by

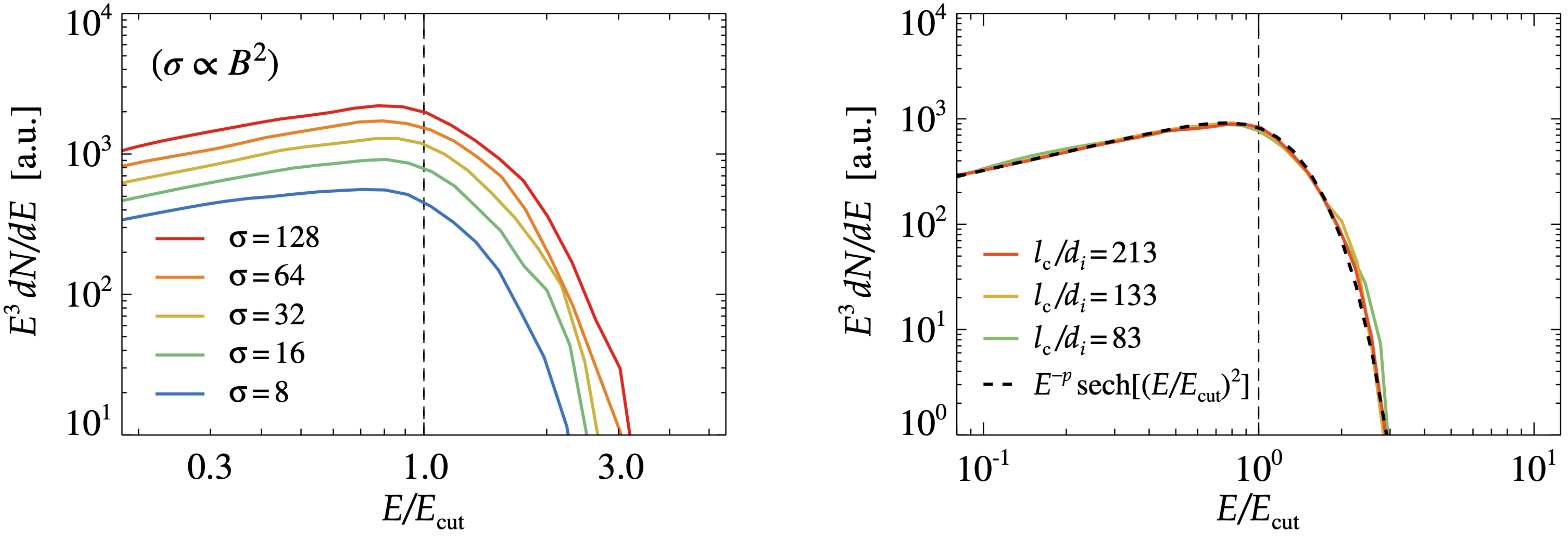
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\boldsymbol{p}\,, \qquad \boldsymbol{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\boldsymbol{p}}{\gamma_s} d\boldsymbol{p}\,.$$

- Solution via particle-in-cell method



PIC code: TRISTAN-MP
(Spitkovsky 2005)

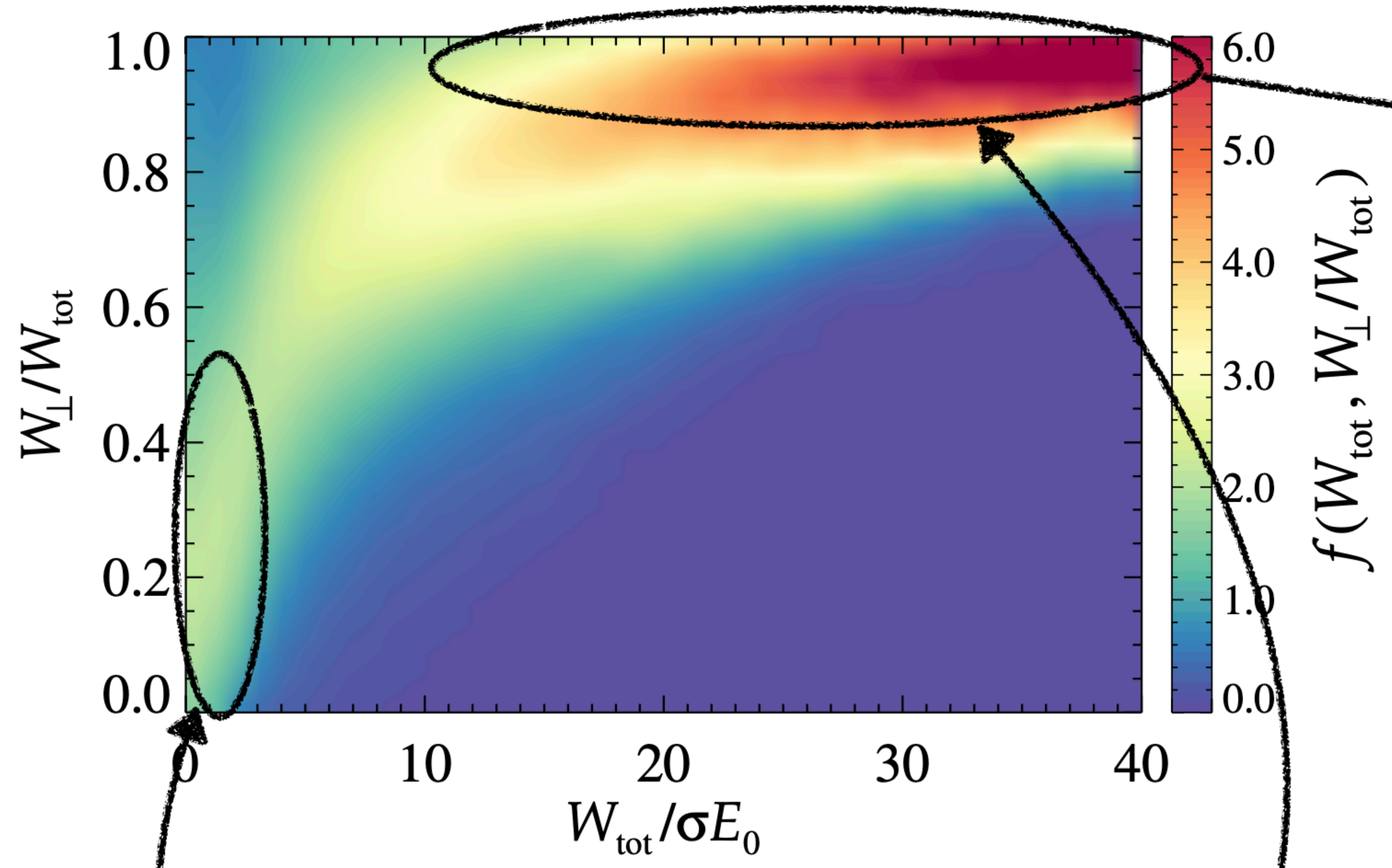
Particle acceleration via magnetized turbulence: cutoff energy

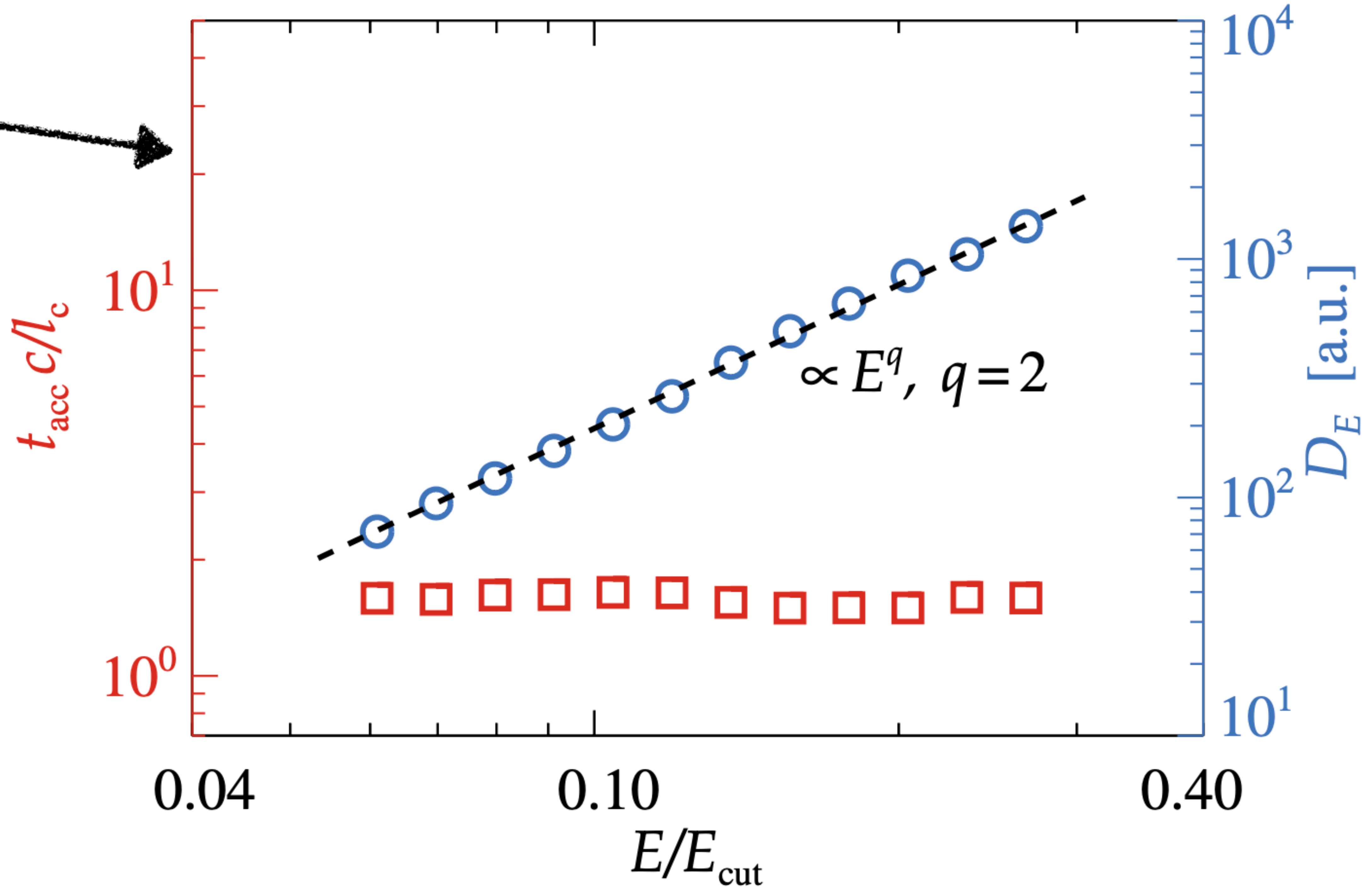


- cutoff $\mathrm{sech}[(E/E_{\rm cut})^2]$ scales with $E_{\rm cut} = ZeR_{\rm cut} = Ze(B_{\rm rms}\kappa l_c)$, where $\kappa = 0.65$ from the fits
- magnetized turbulence does accelerate particles to the "Hillas limit" if one assumes $R_{\rm size} = l_c$

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

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)

L. Comisso, GRF, M. Muzio, ApJL2024

Particle acceleration via magnetized turbulence: spactrum out o

- residence time within the accelerator:

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

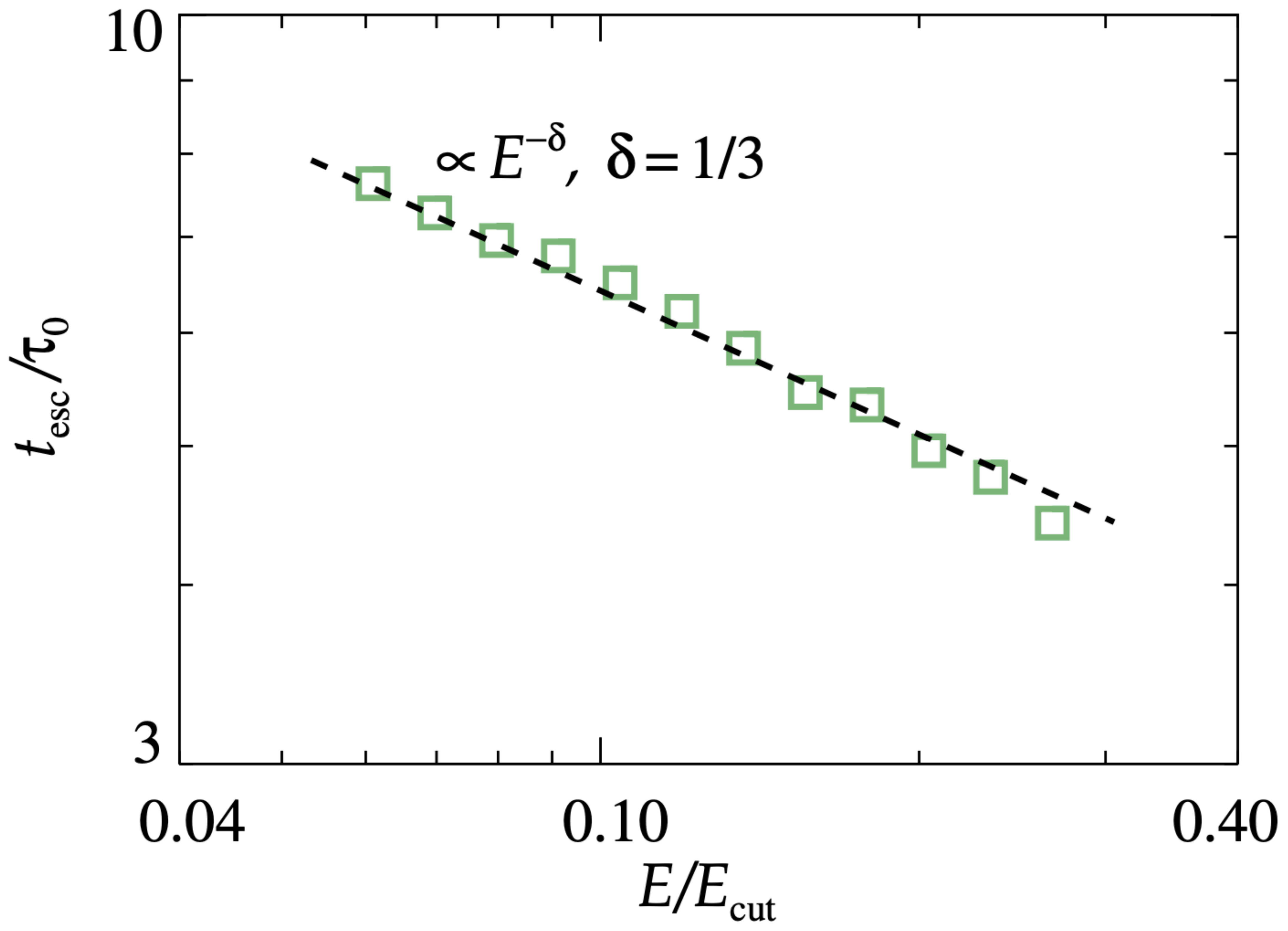
- flux of particles escaping the accelerator is given by

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

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

$p \sim 2.4$ $\quad$ $\delta \sim 1/3$

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

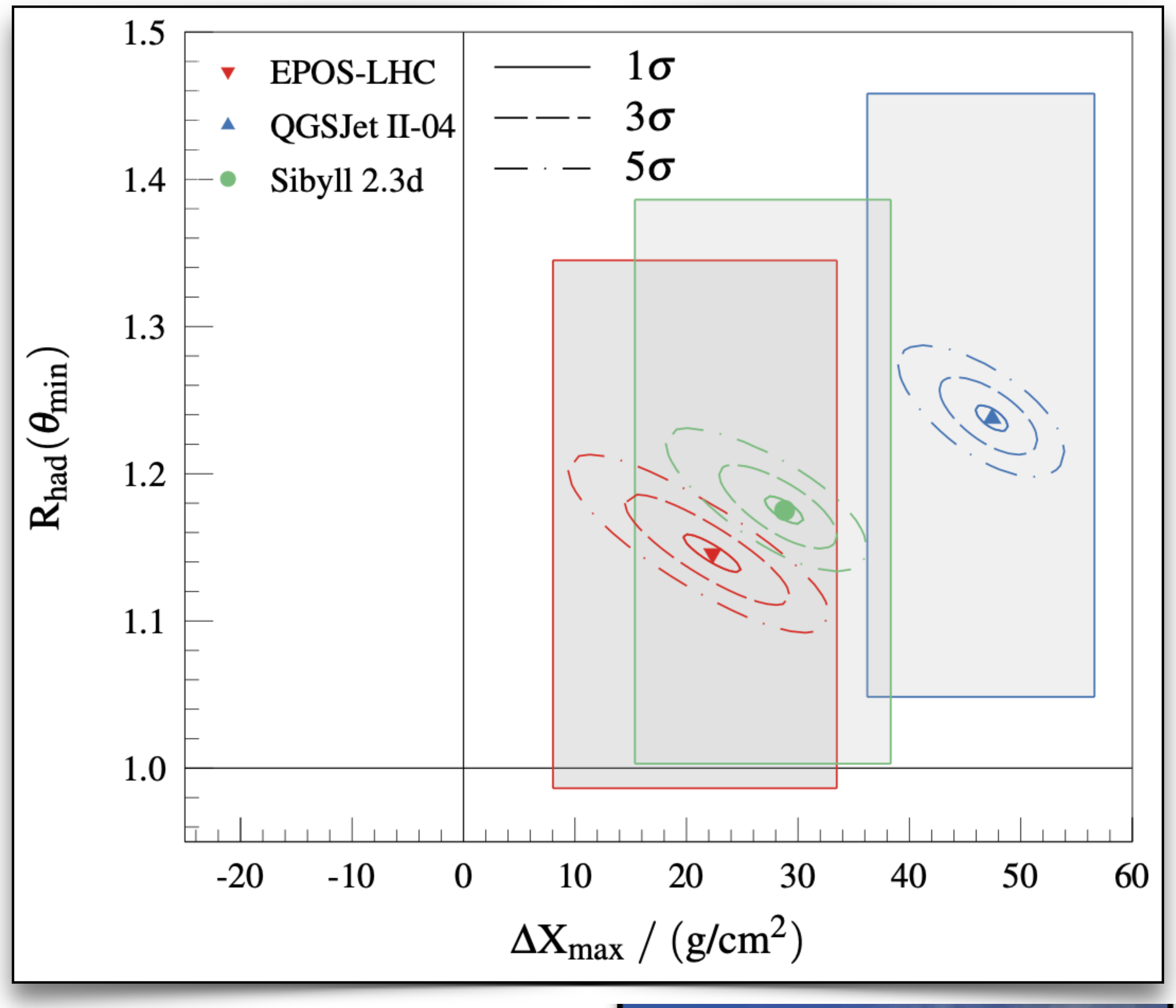


Does spectral cutoff discriminate between acceleration mechanisms?

- 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"?

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

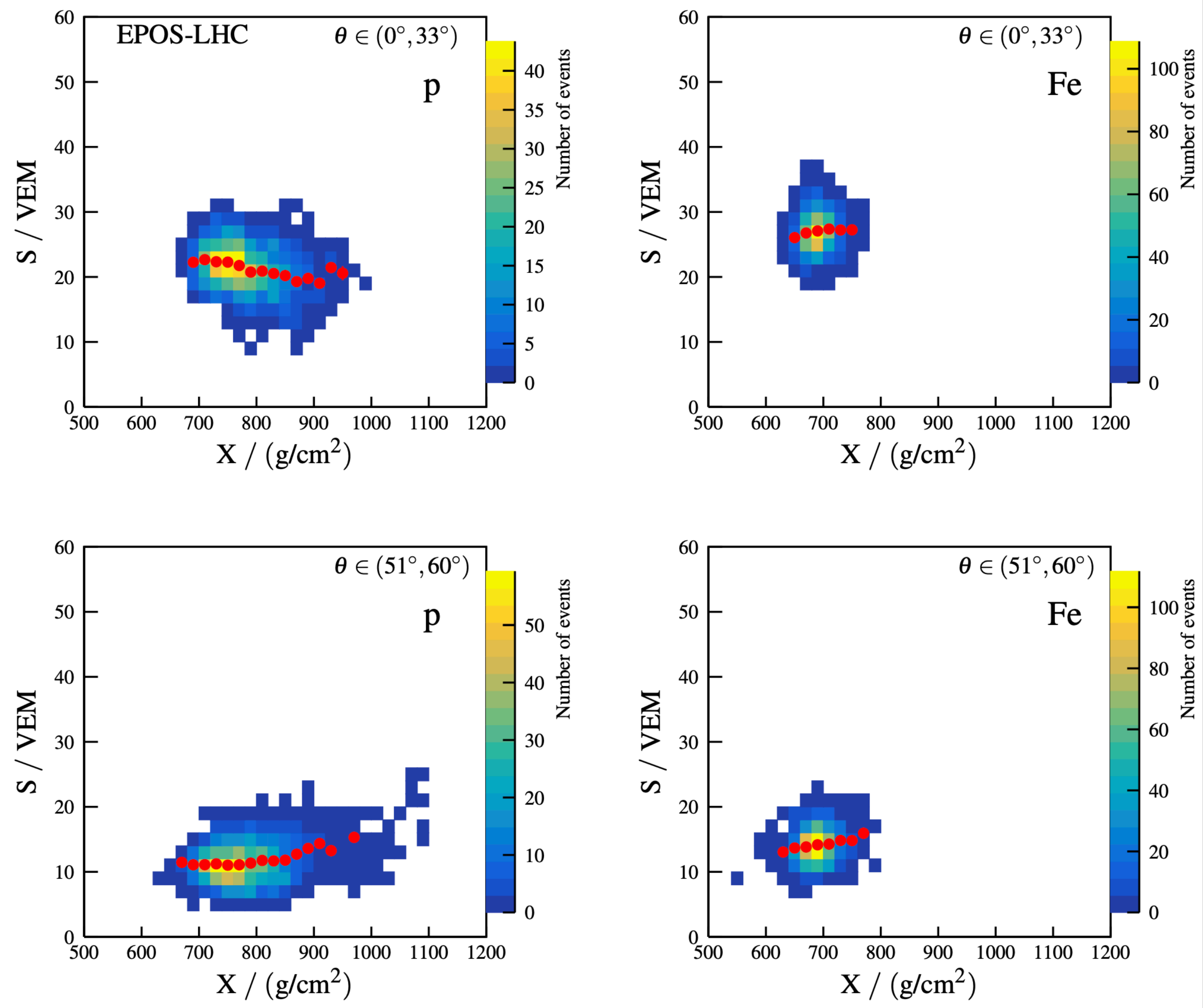


FIG. 1: Examples of two-dimensional distributions of S and X for protons (left) and iron nuclei (right) generated with EPOS-LHC for zenith angles between 0° and 33° (top) and 51° and 60° (bottom). The red points indicate the mean values of S. $E = 10^{18.5}$ to $10^{19.0}$ eV.

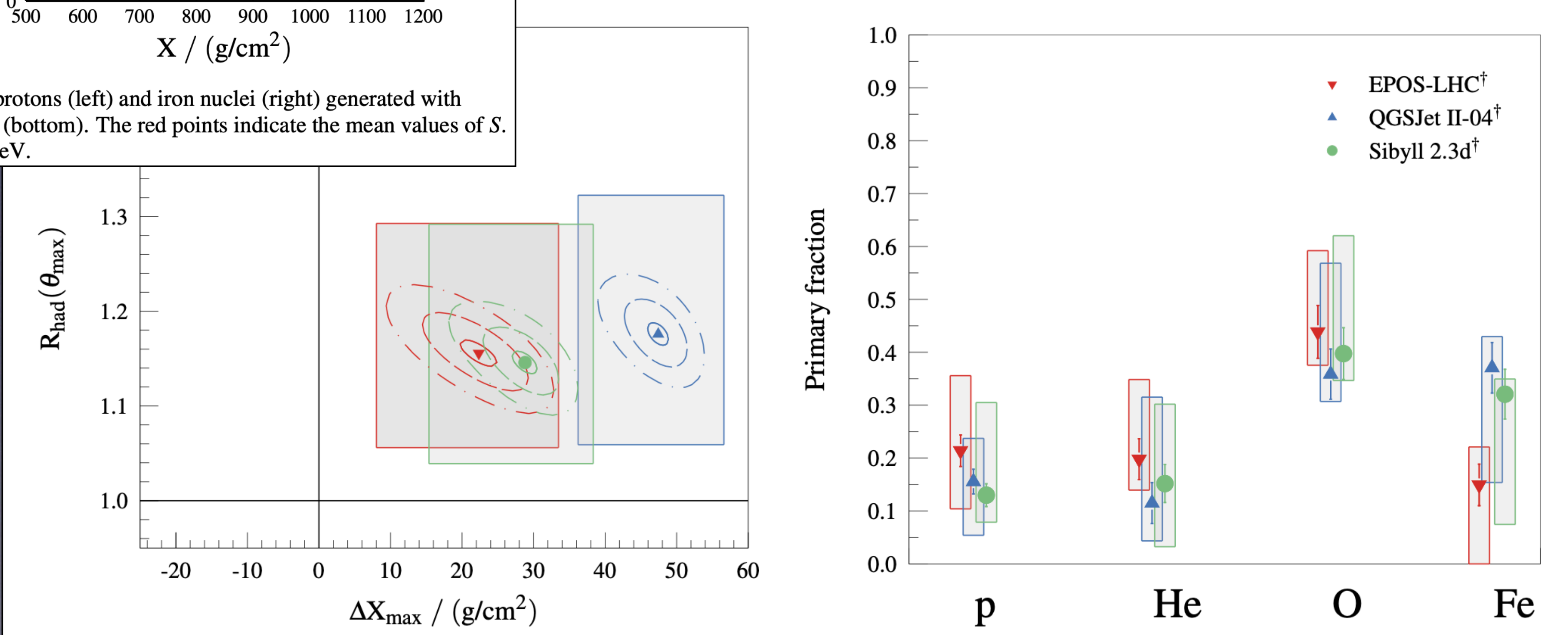
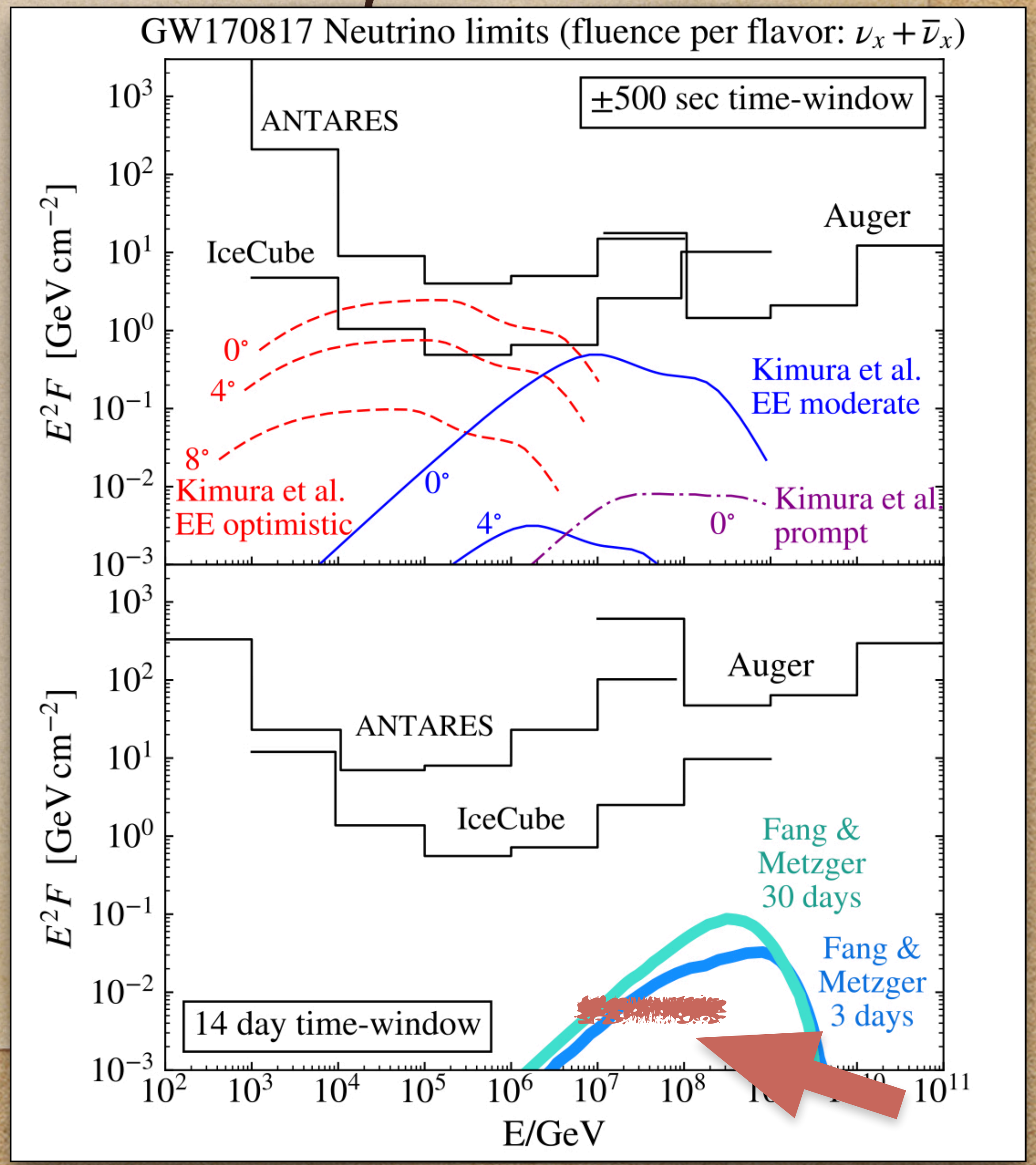


FIG. 6: *Left:* Correlations between ΔX_{max} and $R_{had}(\theta_{max}{\approx}55°)$ modifications of the model predictions obtained from the data fits. The contours correspond to 1σ, 3σ, and 5σ statistical uncertainties. The gray rectangles are the projections of the total systematic uncertainties. *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+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