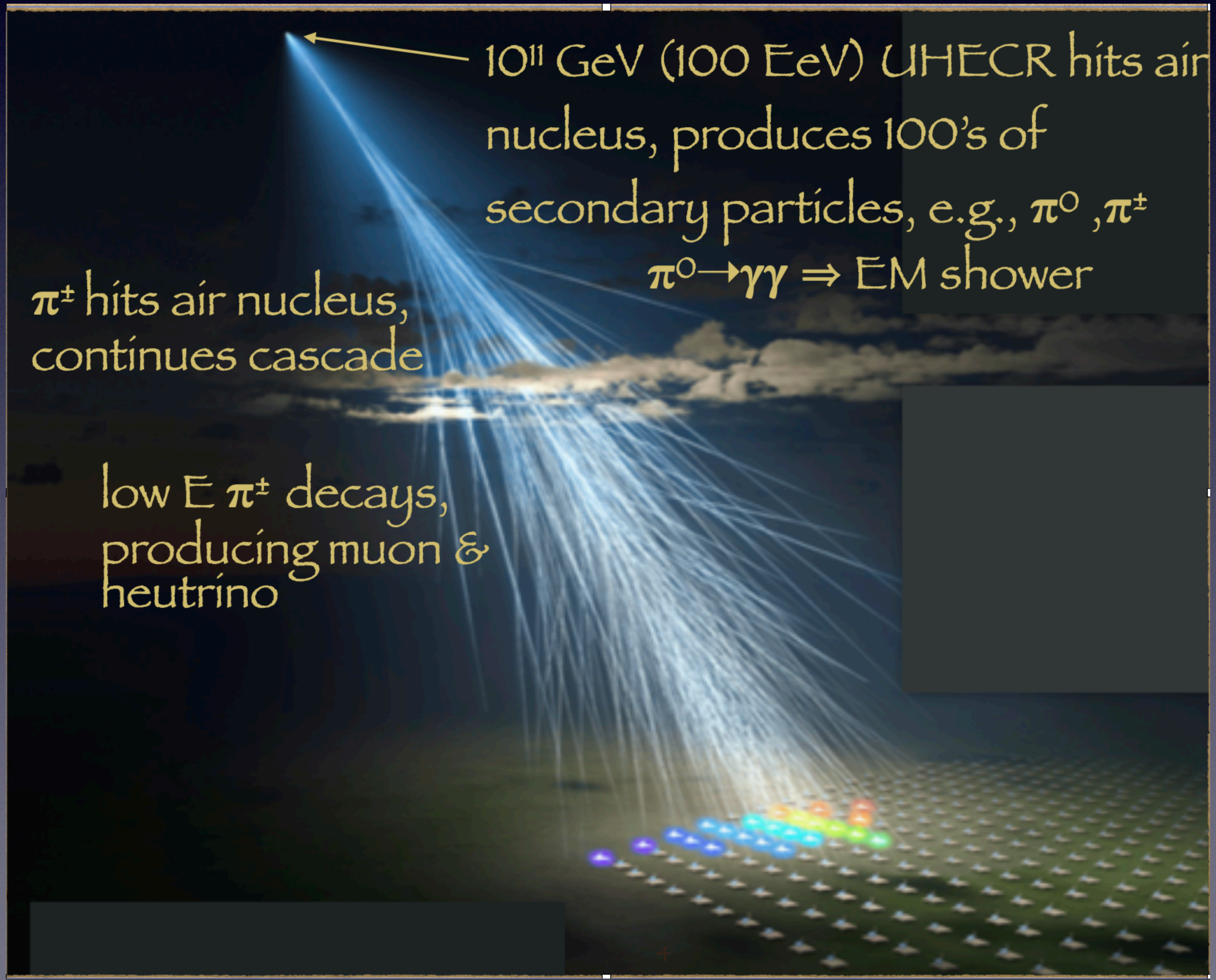
The Origin of Ultra-high Energy* Cosmic Rays



Glennys R. Farrar, New York University
BNL, Oct. 23, 2025

<E per nucleon> ~ 2 EeV ➜ γ >10^9

UHECR trivia

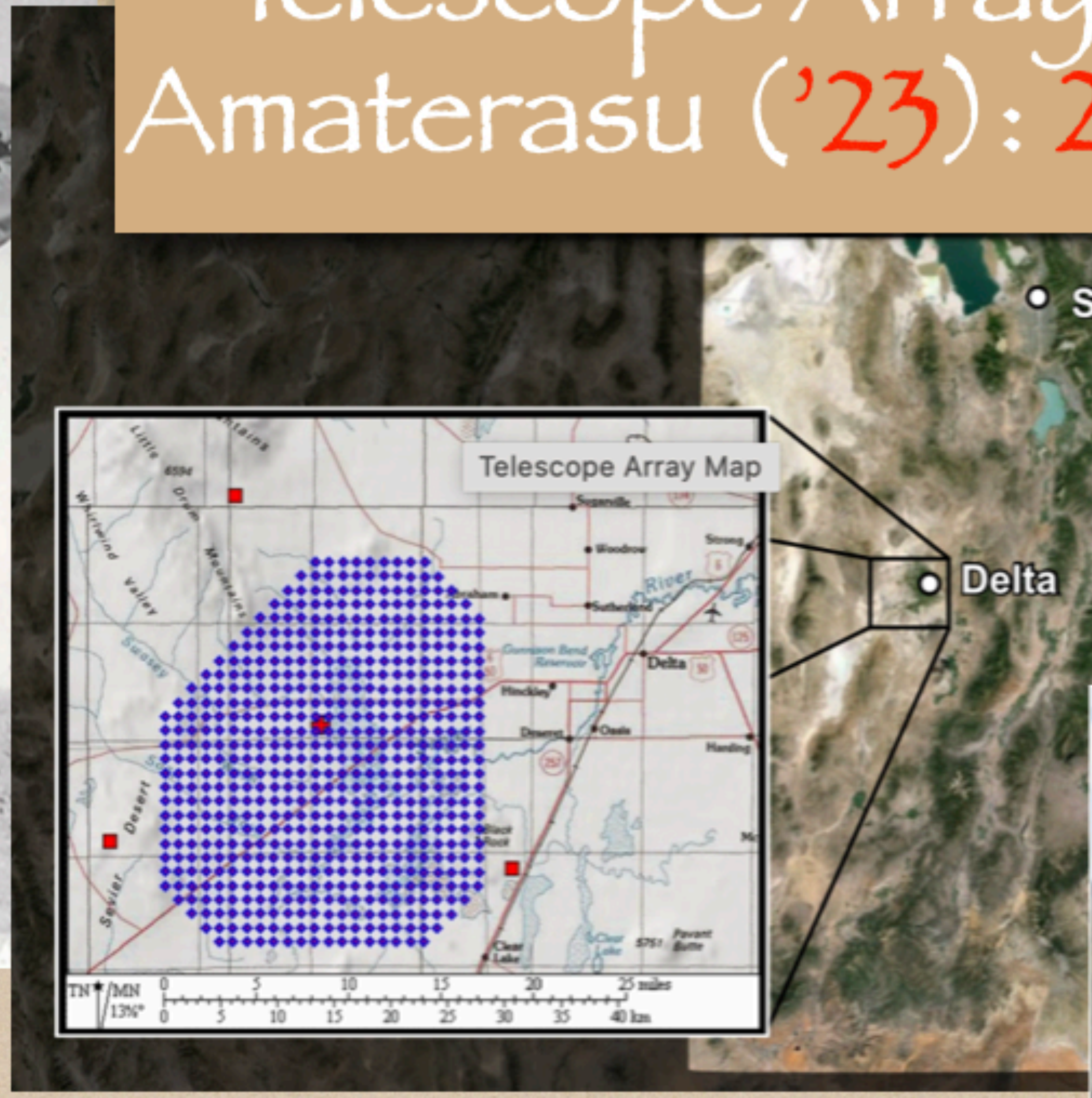
- Highest energy CR > 200 EeV ≡ 2×10^{20} eV — a single nucleus with the kinetic energy of the highest energy pro golf ball
- 100 EeV neutron: Relativistic time dilation ($\gamma = E/mc^2 = 10^{11}$) ⇒ lifetime is a million years ⇒ can travel across a galaxy without decaying
- Flux of CRs above 150 EeV ≈ 0.2 / km^2 / millennium

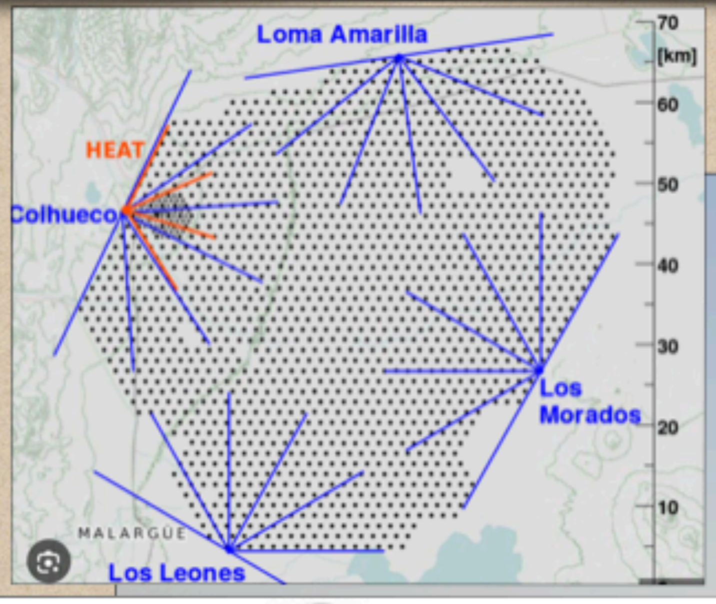
It's been a long, hard search

Hess: CRs
1911 or 1912

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

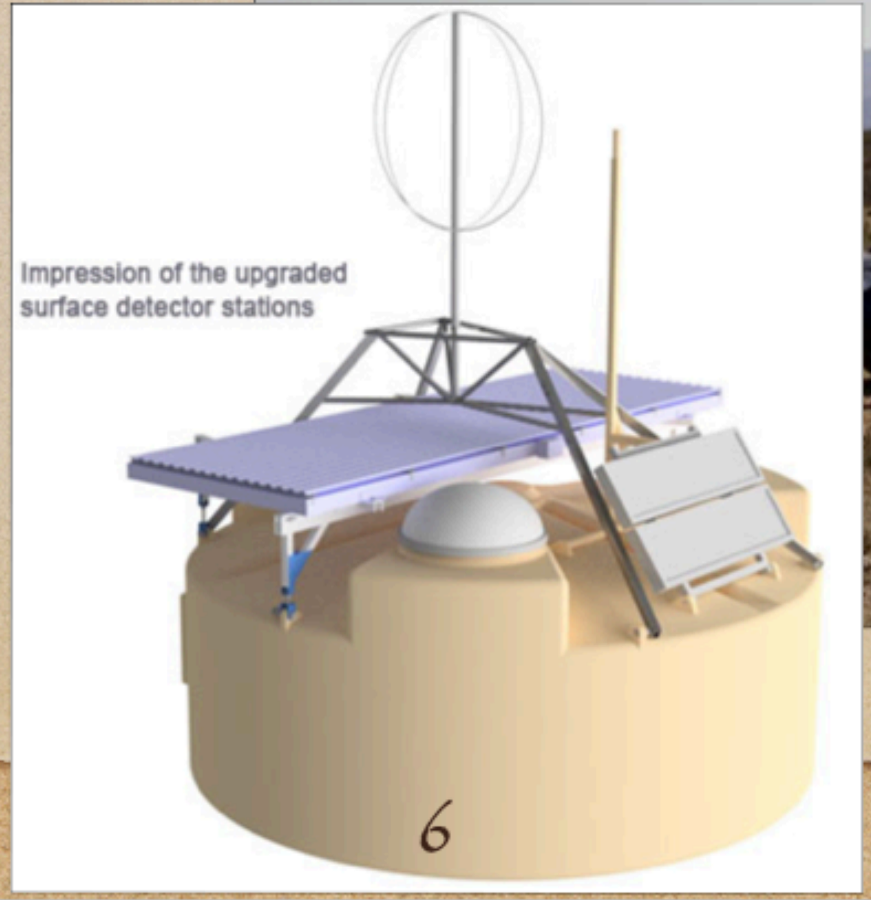
Telescope Array, Utah
Amaterasu ('23): 240 EeV





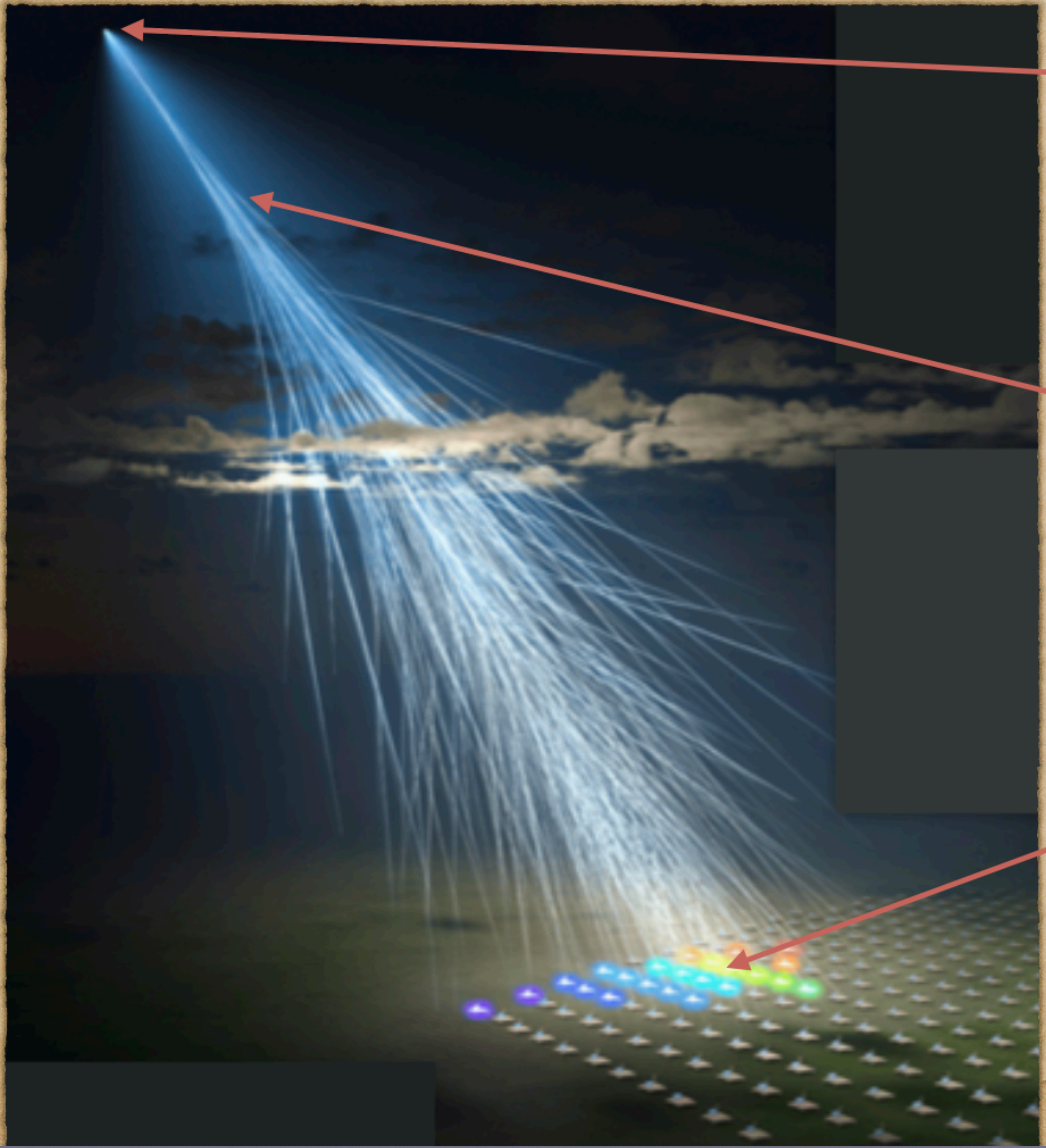
Pierre Auger Obs., Argentina
~50 evts > 100 EeV

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



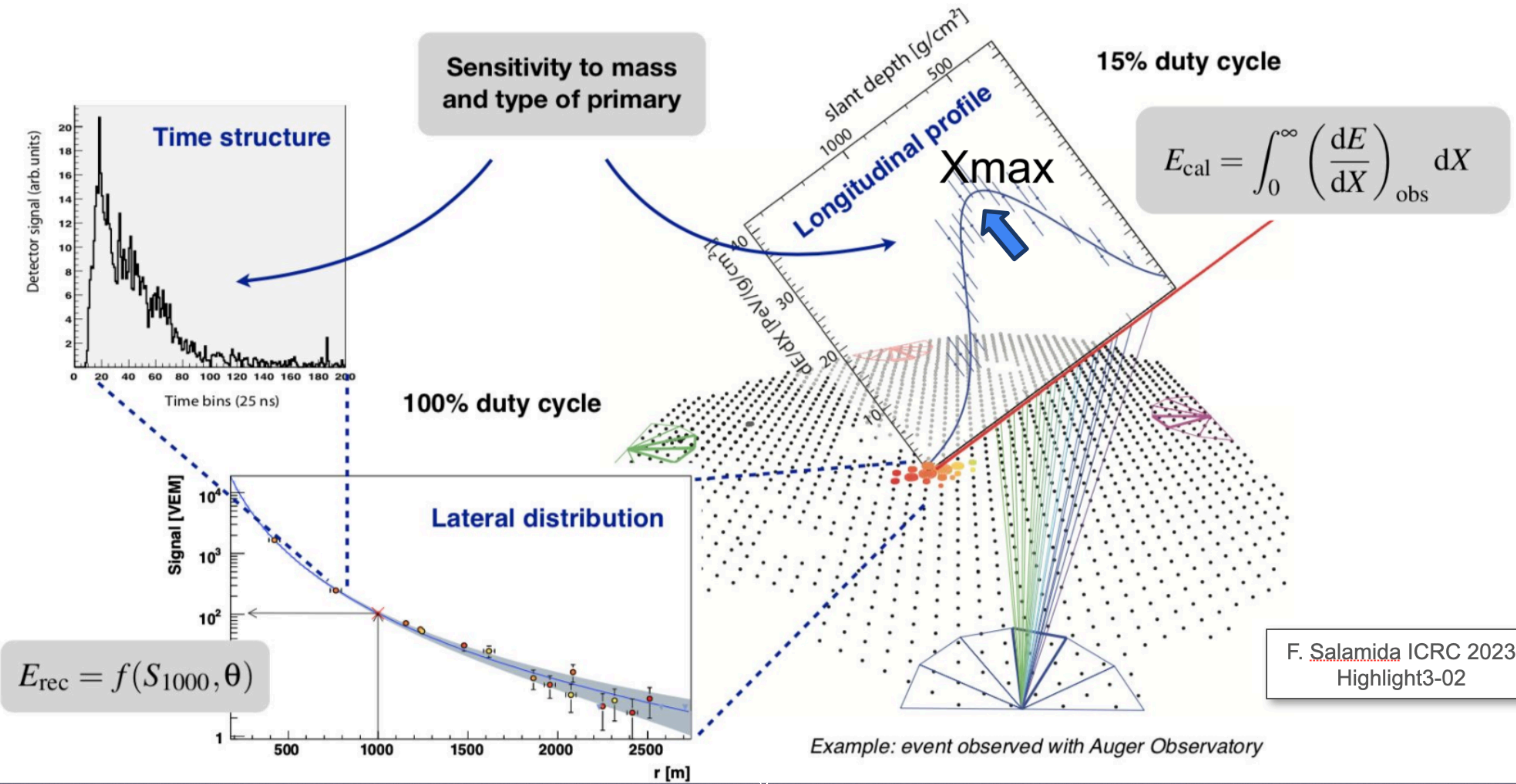
1700 stations, 3000 km^2

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



F. Salamida ICRC 2023
Highlight3-02

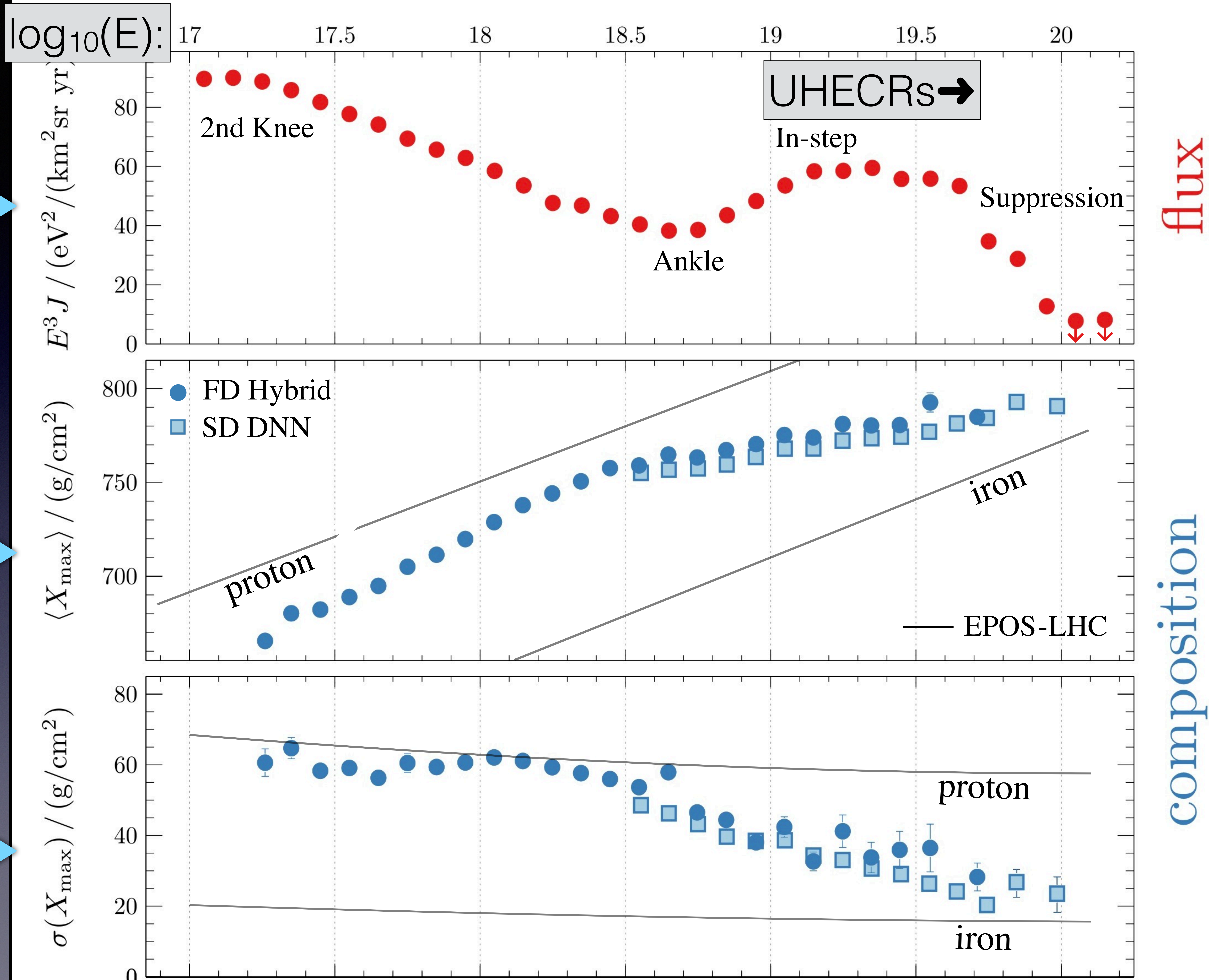
E³ x Spectrum

Composition gets heavier with energy

<X_{max}>

A single mass group dominates at each E

$\sigma(X_{max})$



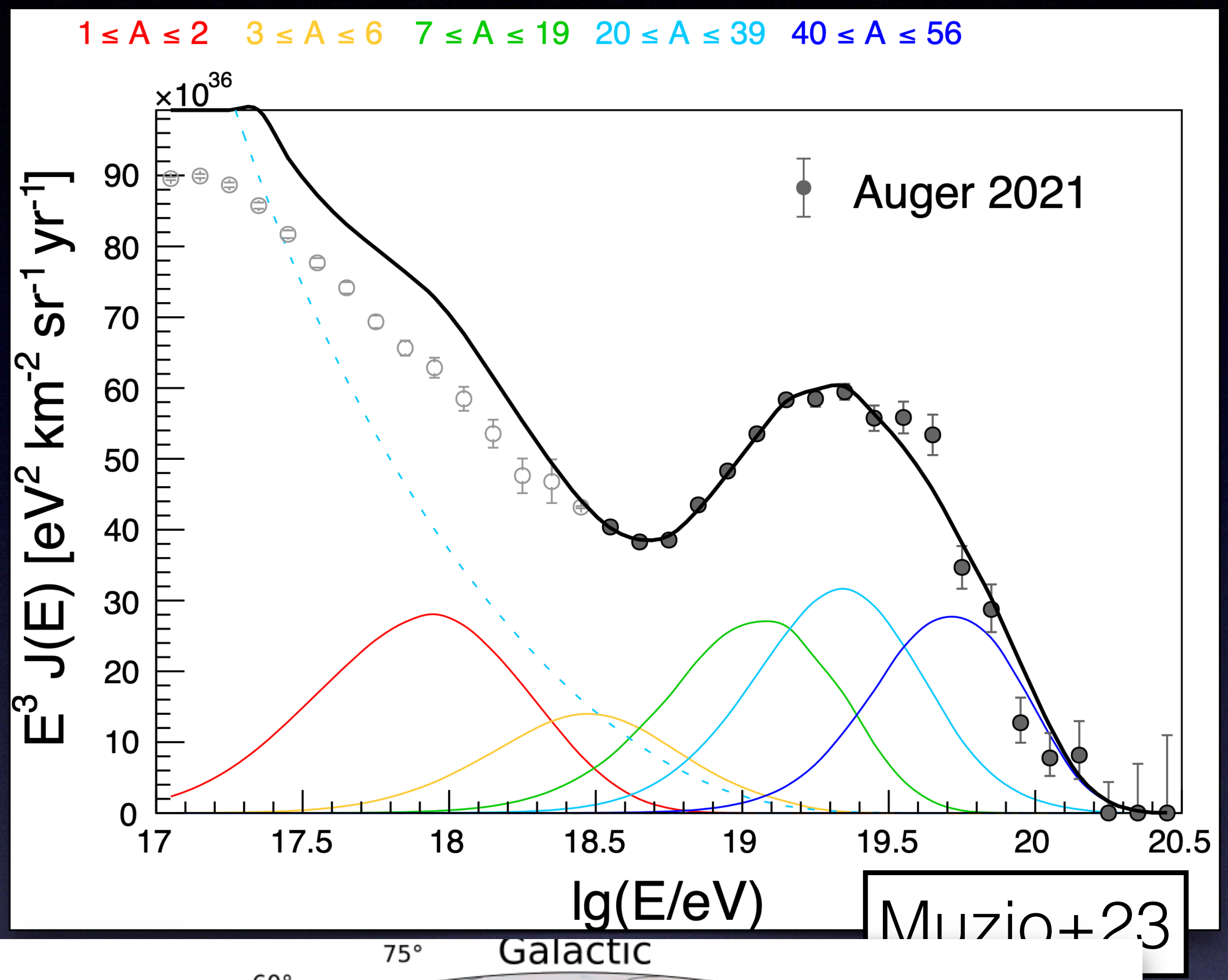
Implications of the observations

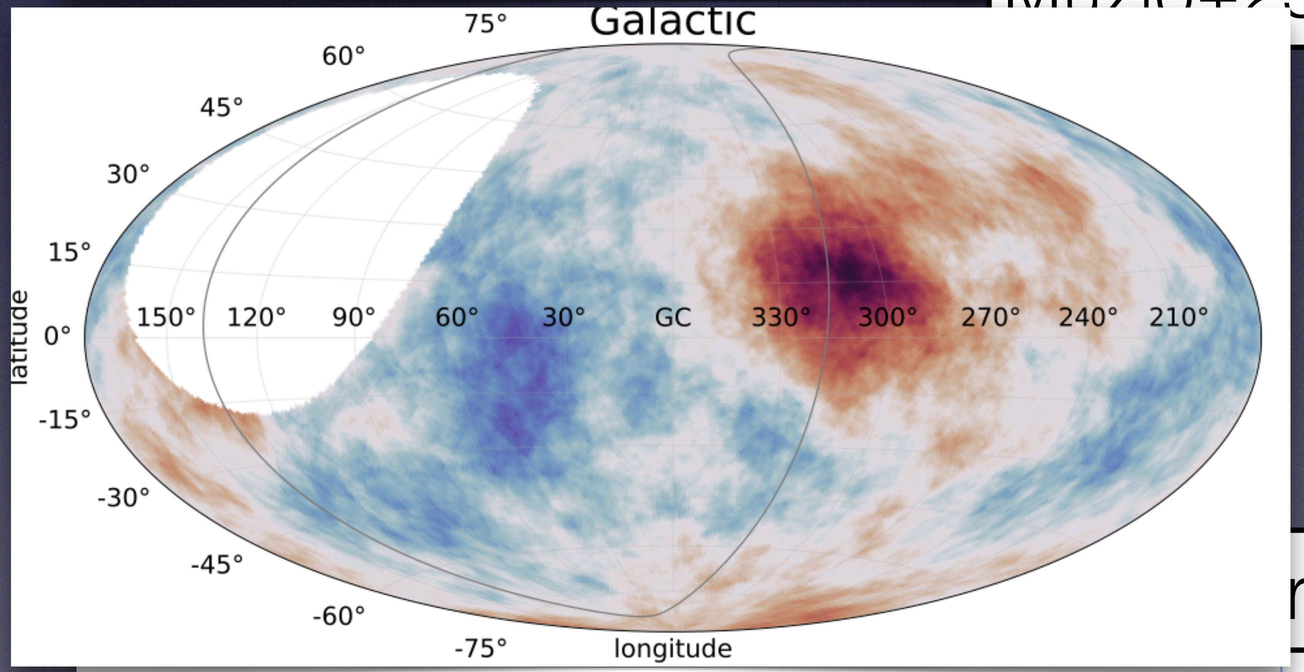
- Composition is mixed, mass increases with E
- *Narrow range of masses at each E:*

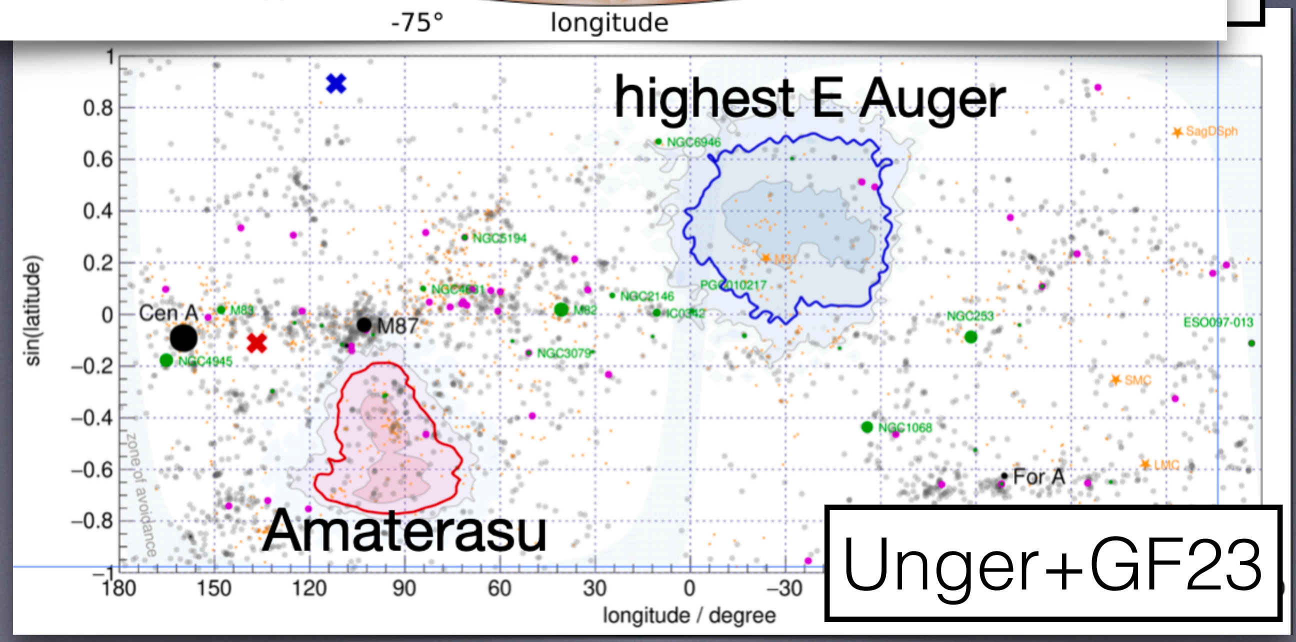
  Rigidity spectrum is narrow: $\langle \boldsymbol{R} \equiv E/Ze \rangle \approx 4$ EV

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

  Sources are transients







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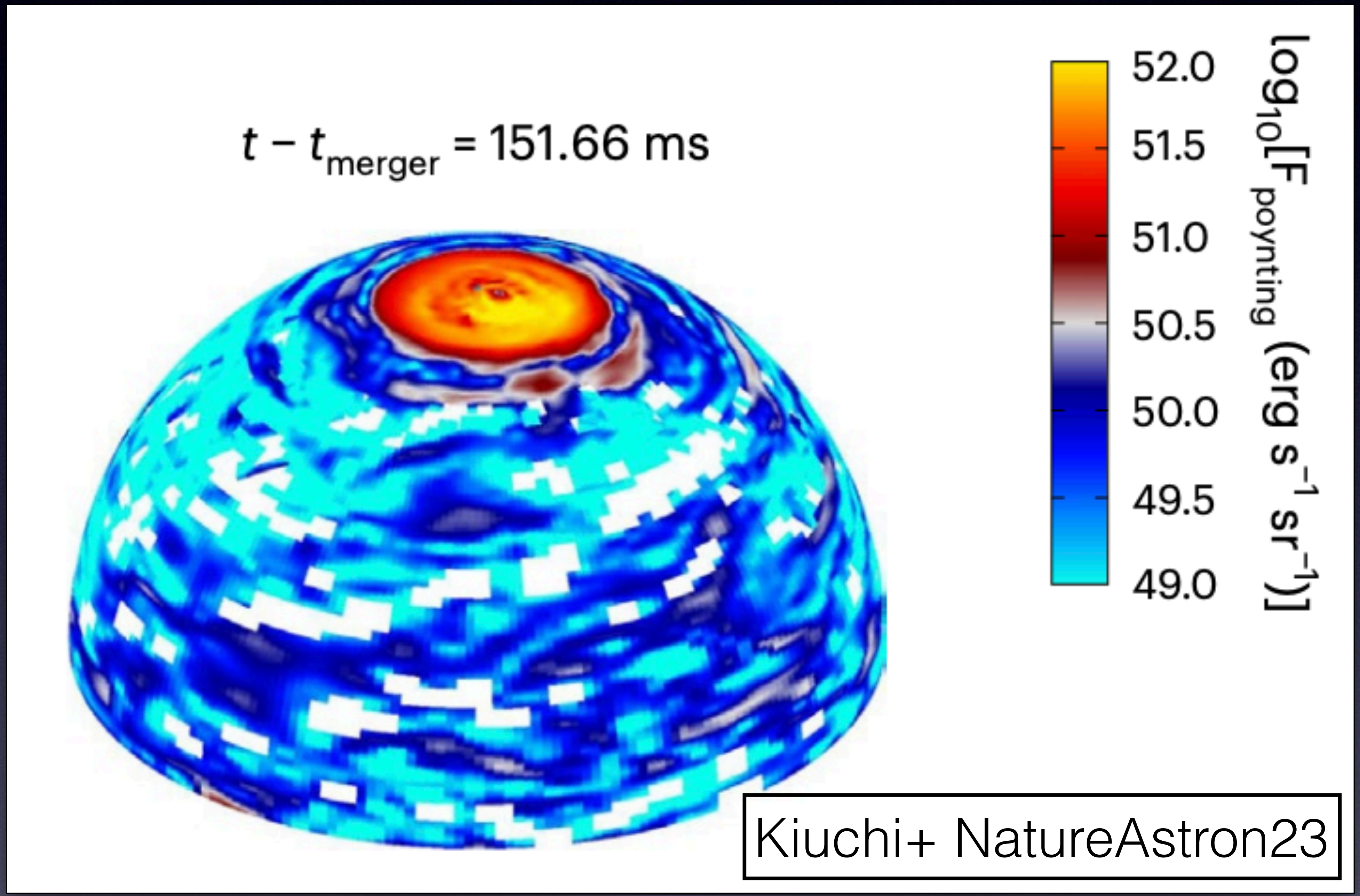
Binary Neutron Star Mergers

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⊙
     (3.2 M⊙ → 10% (negligible) spread)



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

Binary Neutron Star Mergers

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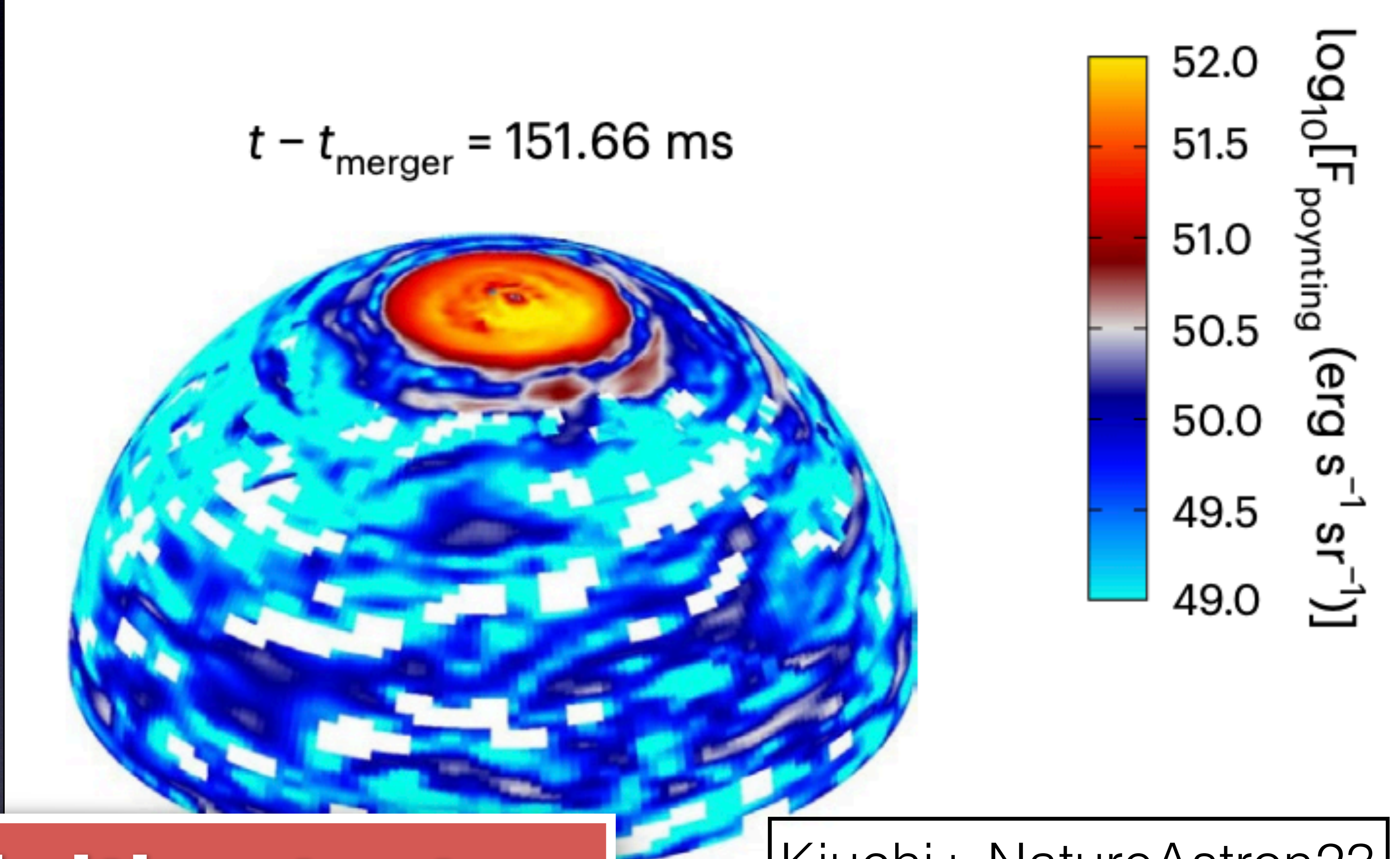


Kiuchi+ NatureAstron23

- UHECR ener

  - need UHEC … emitted)

Unique predictions enable definitive tests:

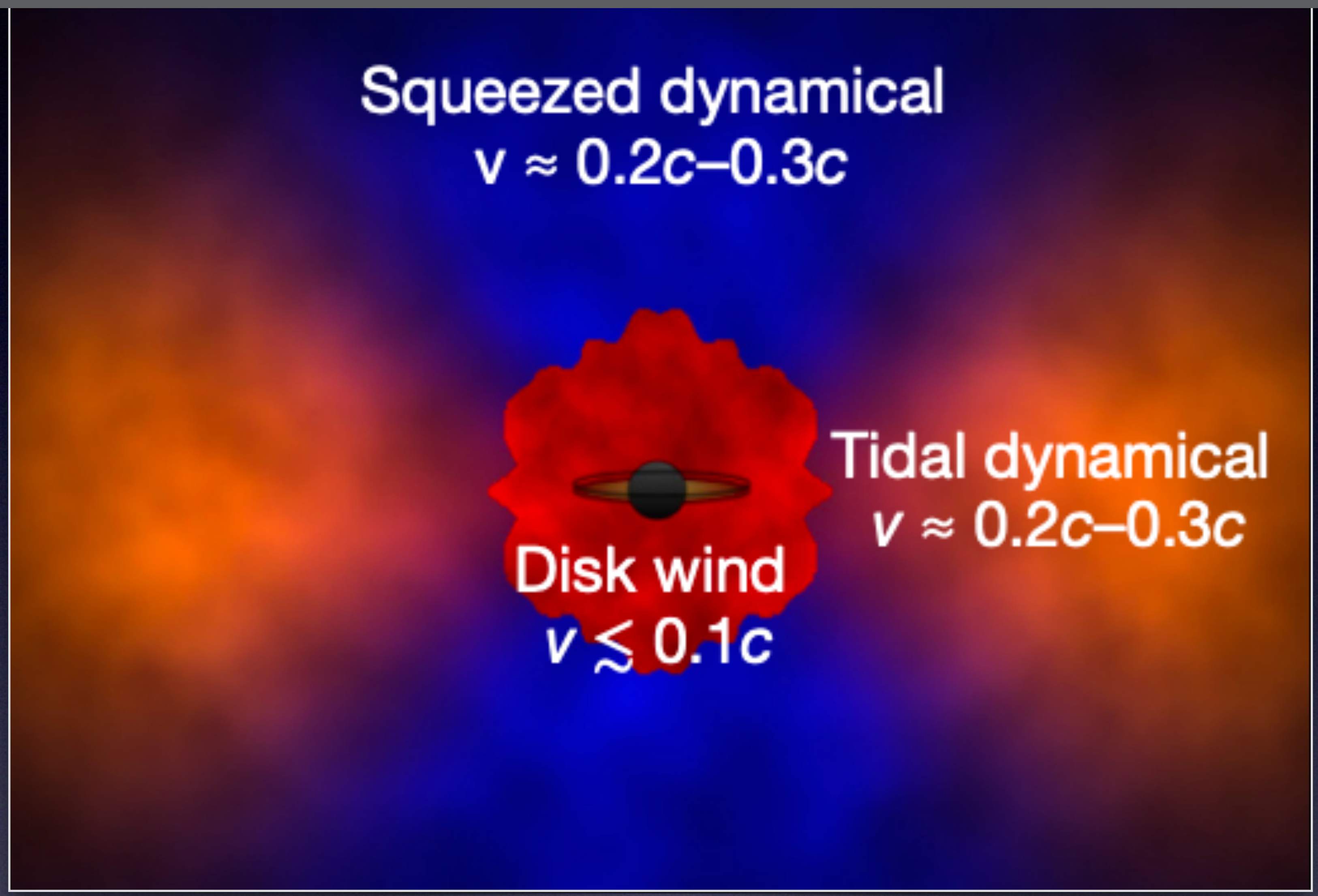
- EHE 𝝂's ↔ gravitational waves
- Highest energy UHECRs: Z>26
- BNS merger ➜ initial B ➜ predict spectrum

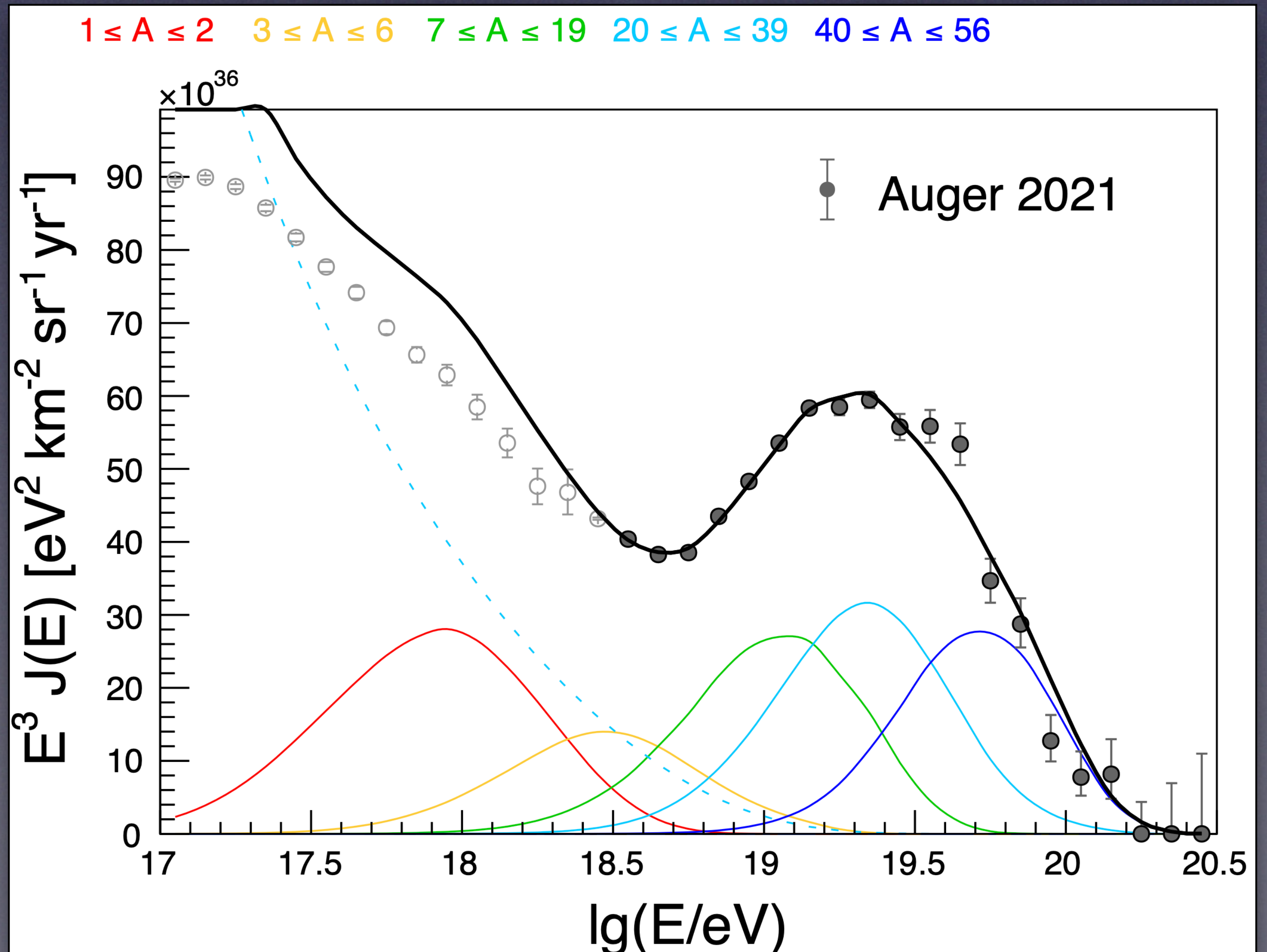
[astro-ph.HE] & PRL 2025

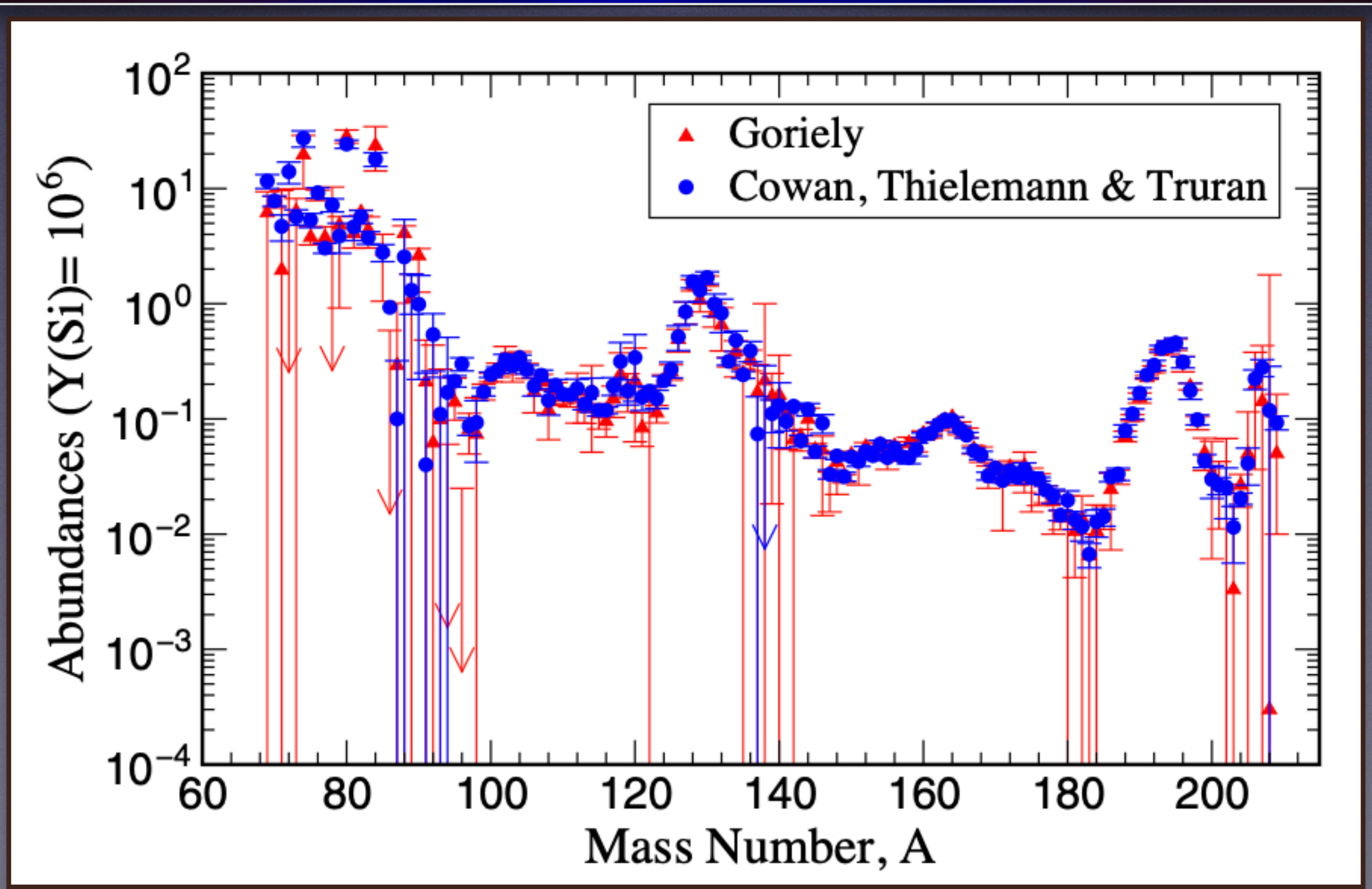
Questions we can answer now

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

Outflow after merger (Kasen+2017)







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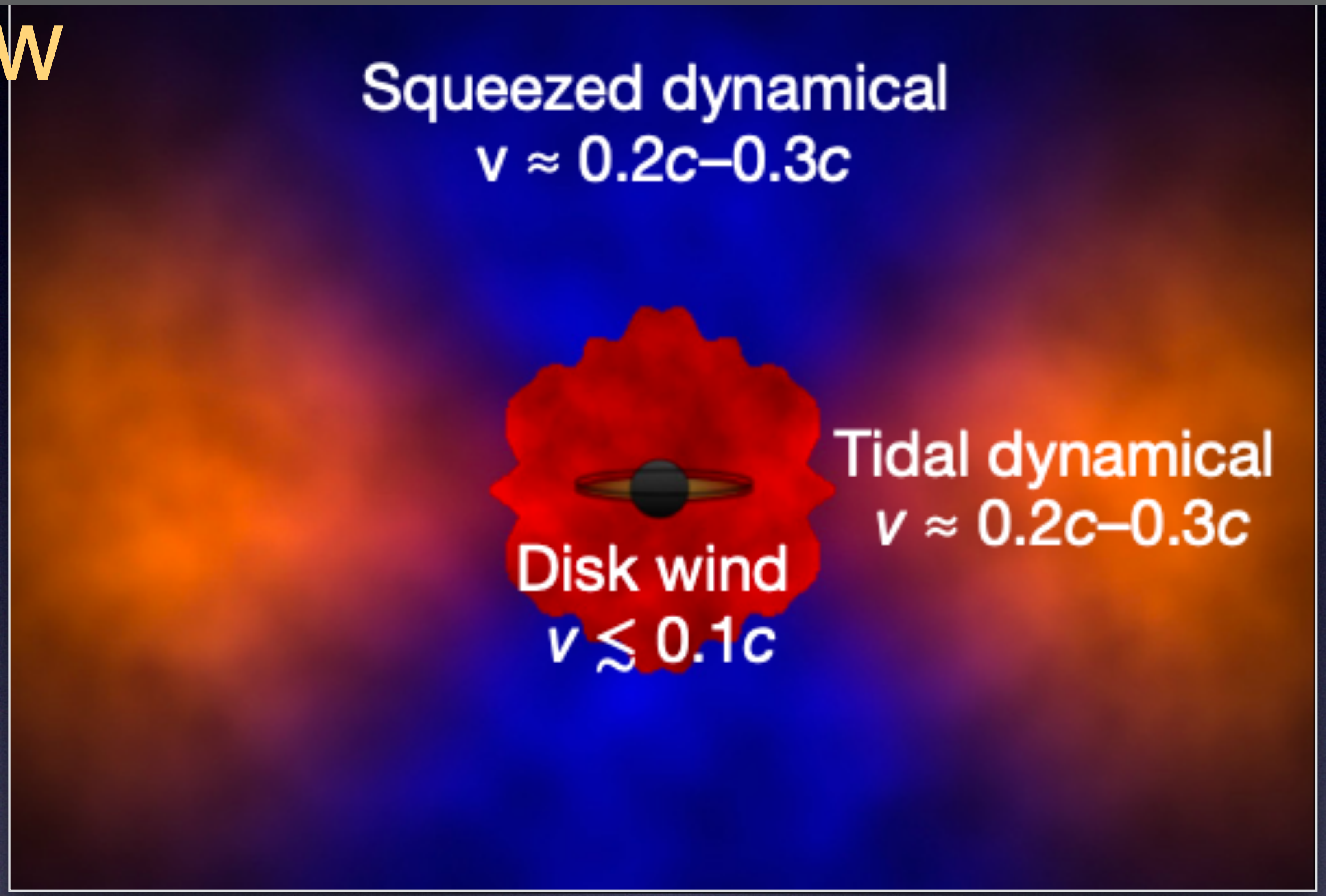
Topics for today

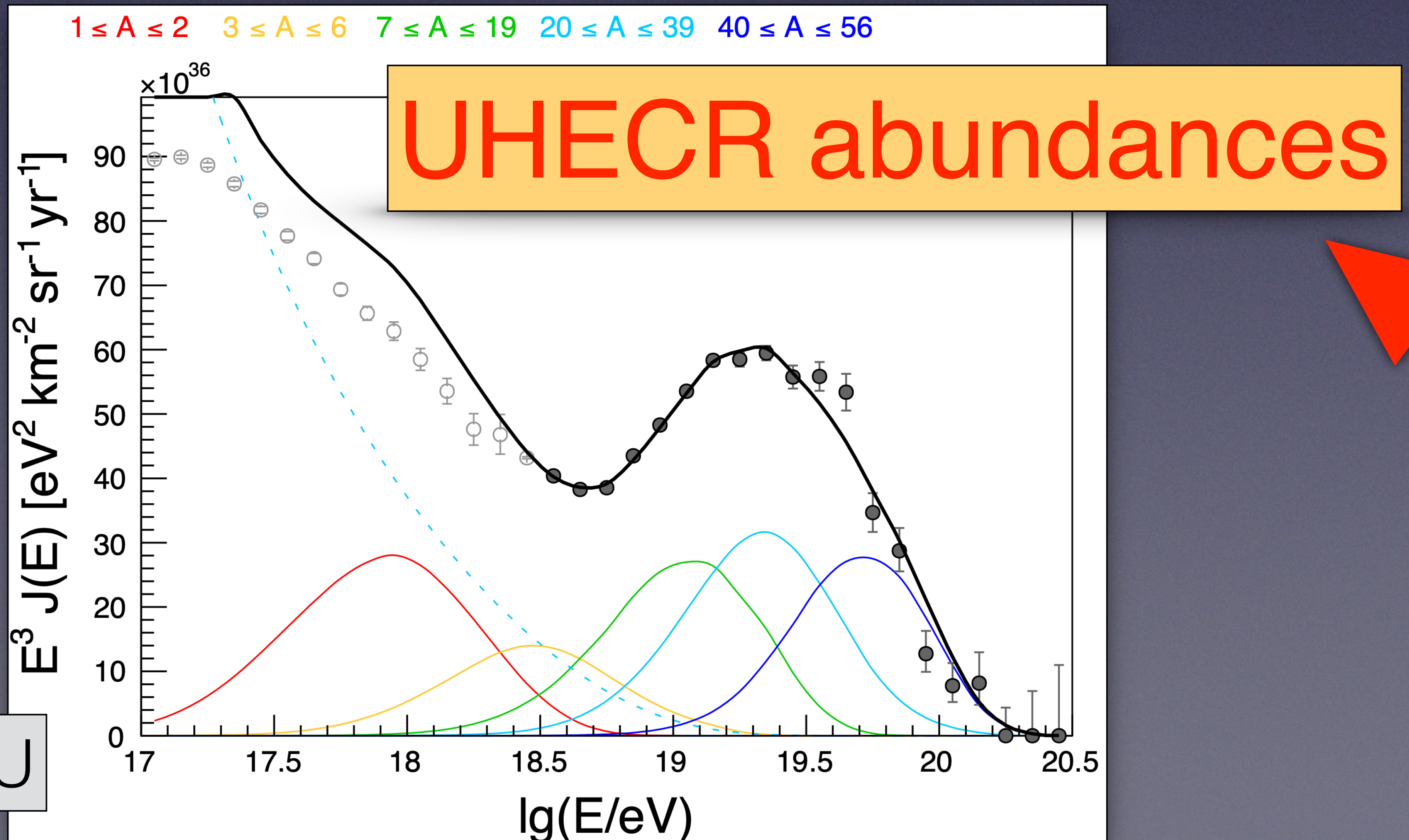
- ✓ UHECR acceleration occurs in the magnetized outflow
  ➜ Predicts rigidity cutoff R_{cut} and spectral shape

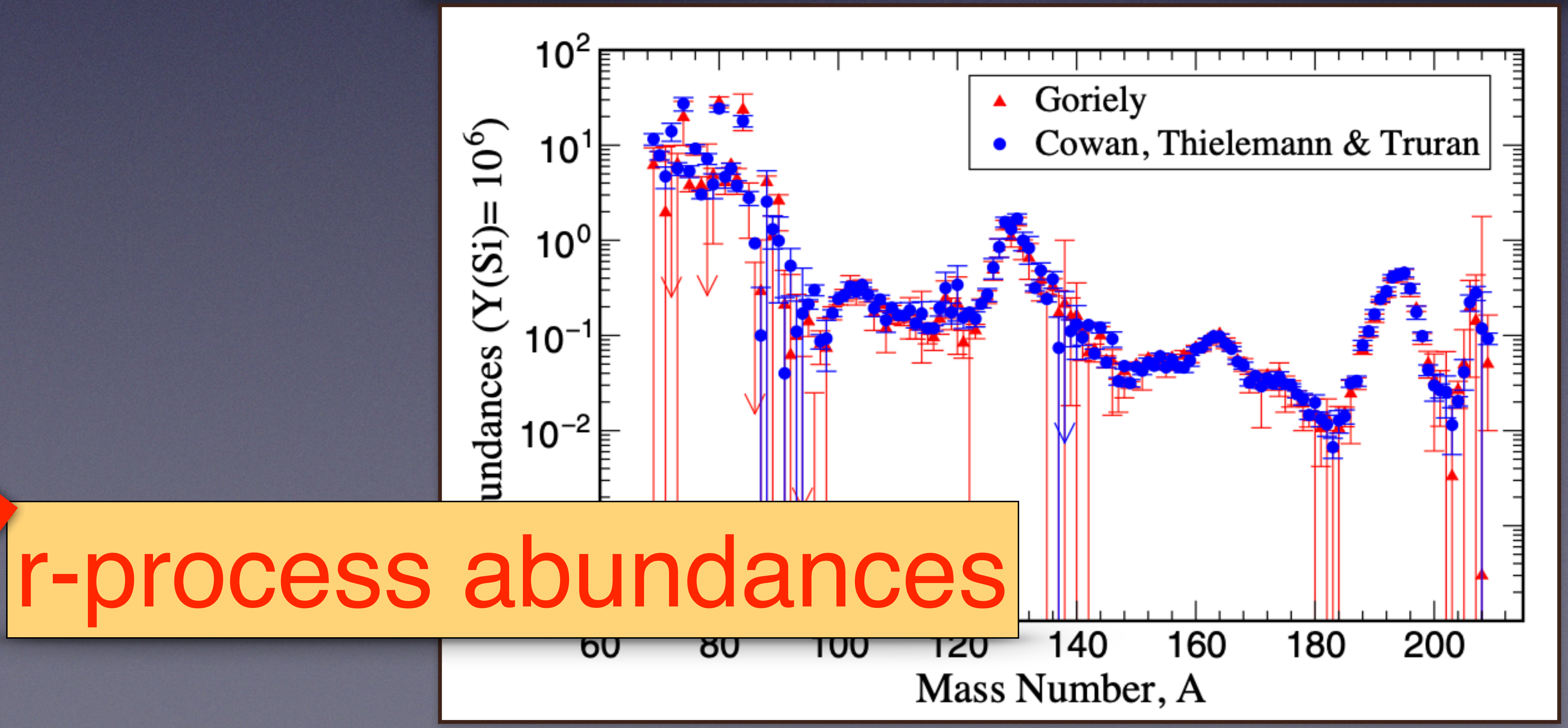
- ✓ UHECR production occurs ~ 1 day after merger
  (coincidences between GW and EHE ν's…)

- **Abundances of different UHECR nuclei**

Outflow after merger (Kasen+2017)





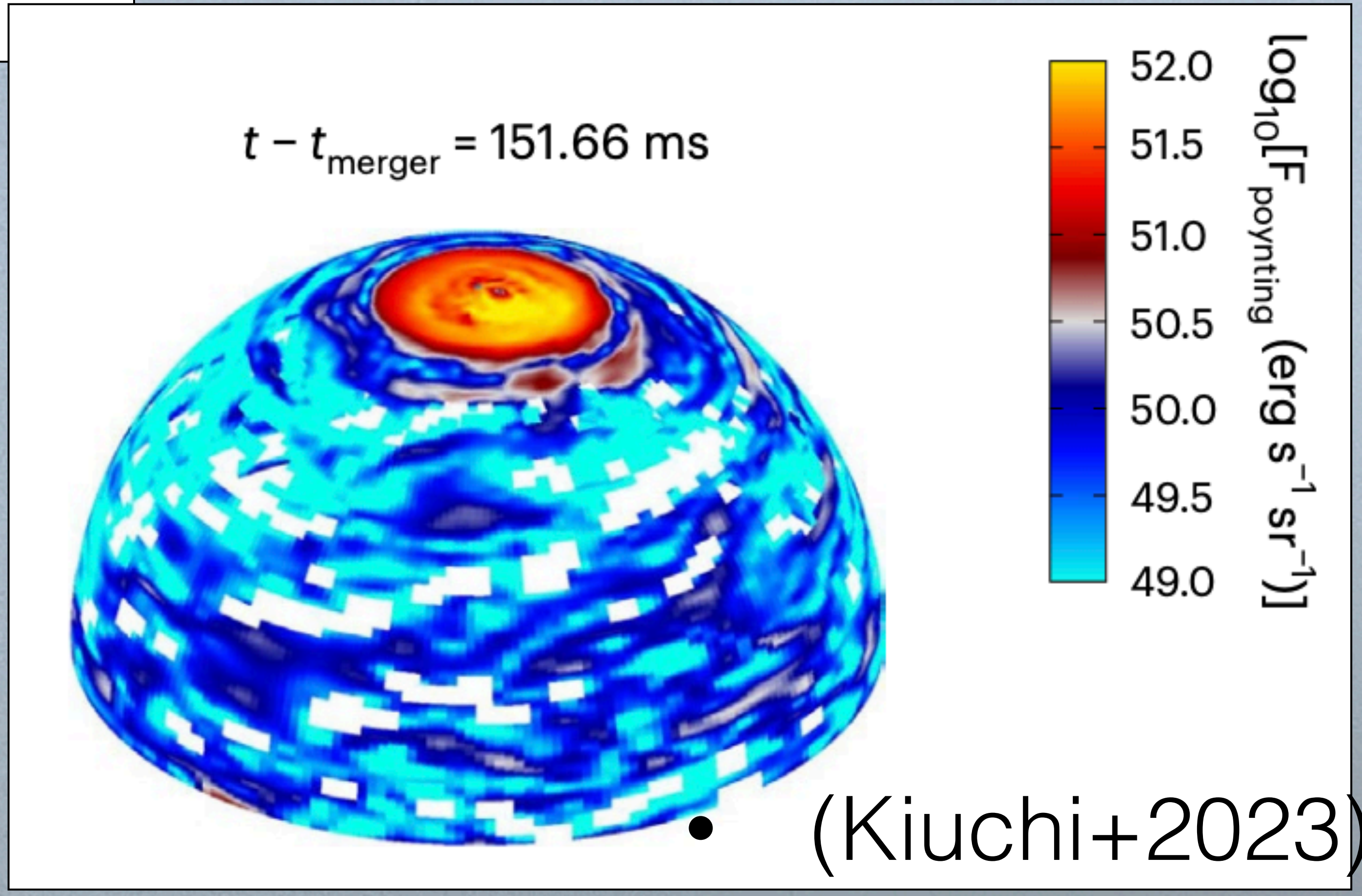


Big Picture

time

Gravitational Wave Emitted

grav-driven dynamo➜B
t=150ms, 500 km



- (Kiuchi+2023)

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

B drops till synch losses are subdominant

UHECR acceleration
~1 day: 10^{14} cm

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

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Big Picture

time →

Expands at v~ 0.1 c

jet

v~0.1c

"outflow"

10°

inspiral

GRMHD dynamo

→ huge B

"Hypernova"

0-few sec

Gravitational Wave Emitted

initialization of B
150ms, 500 km

Kiuchi+23 → B_{ini}

r~10^{10} cm

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

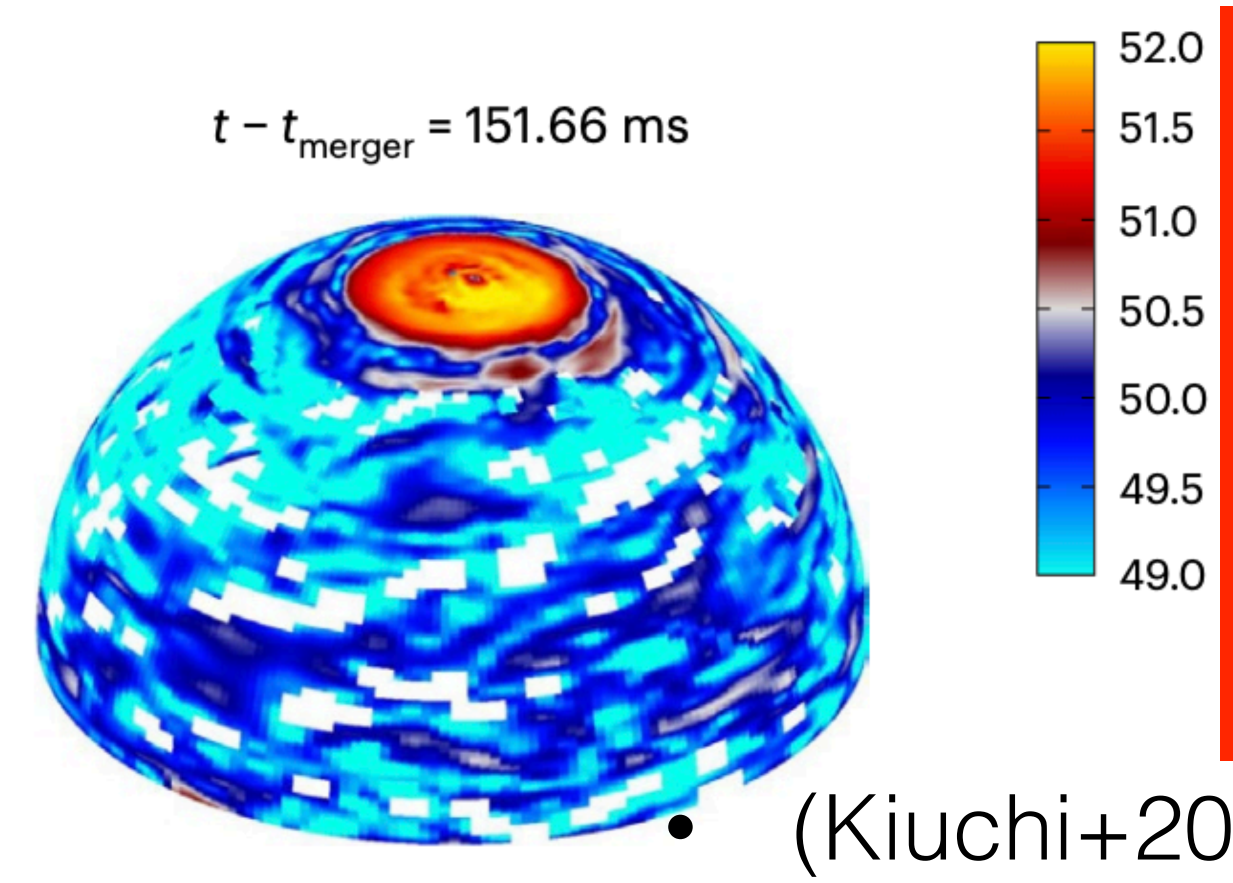
r-process

r~10^{14} cm

B≈400G

UHECR's accelerated

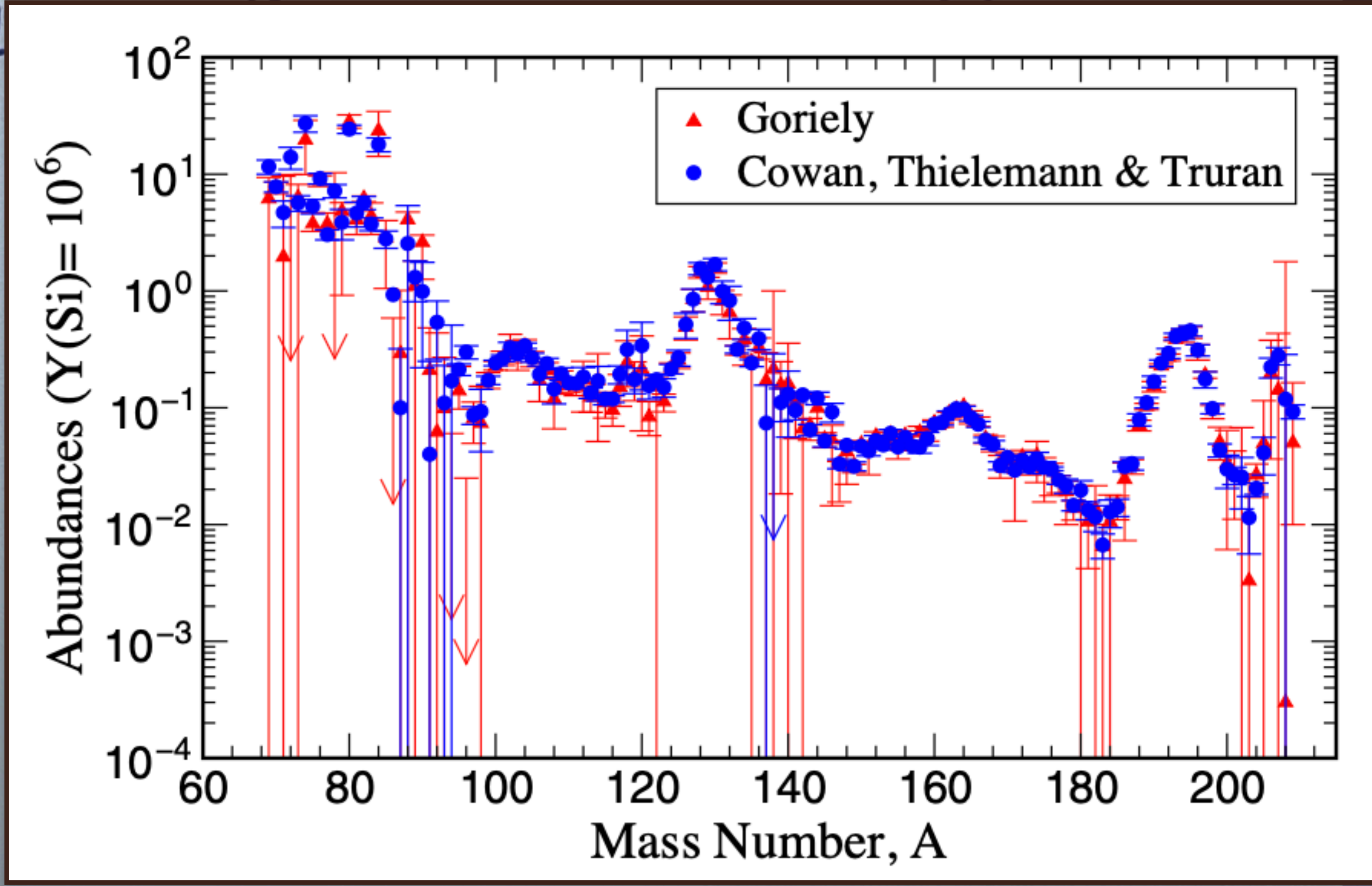
~1 day



- (Kiuchi+2023)

Nucleosynthesis:

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



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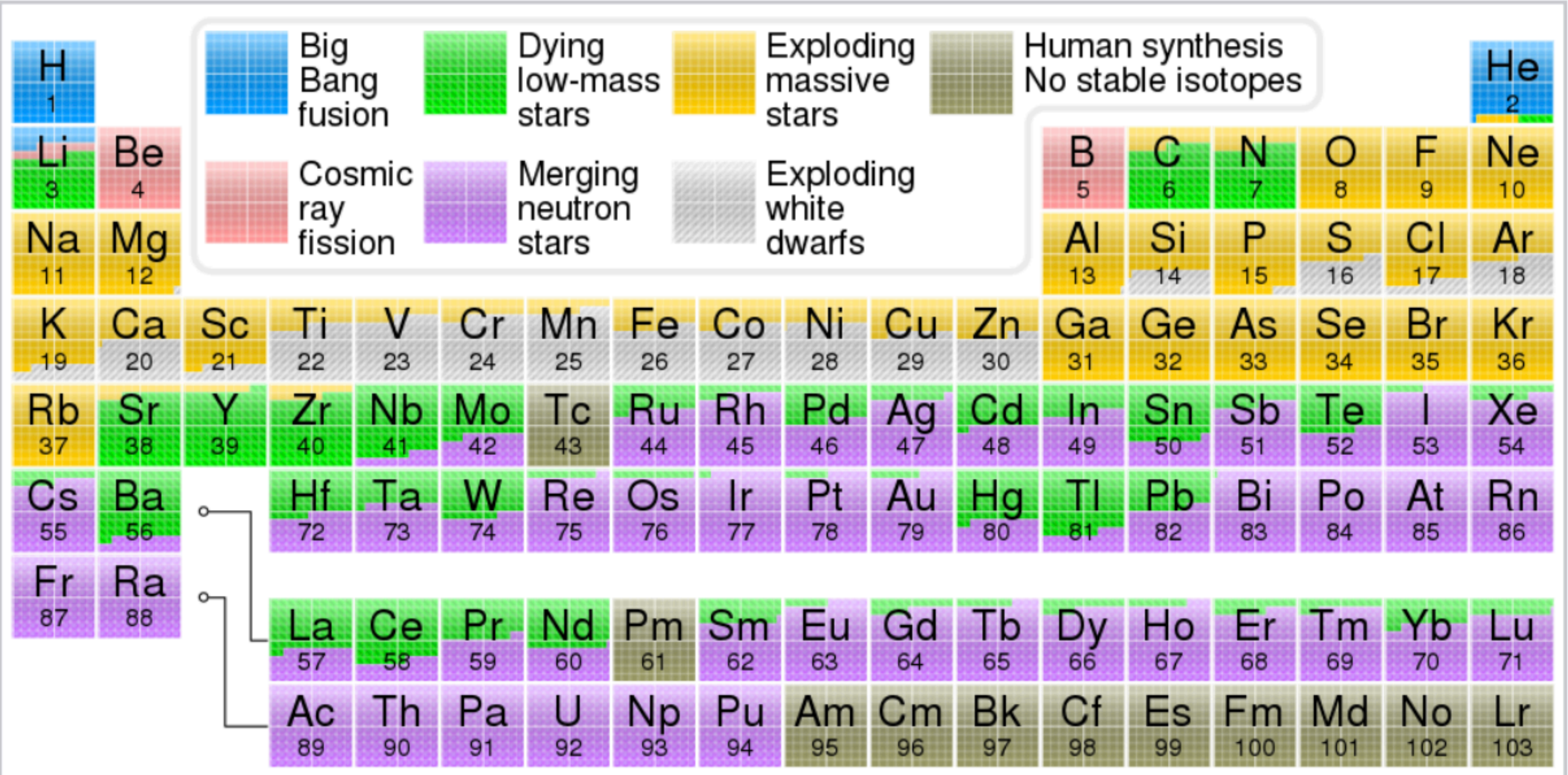
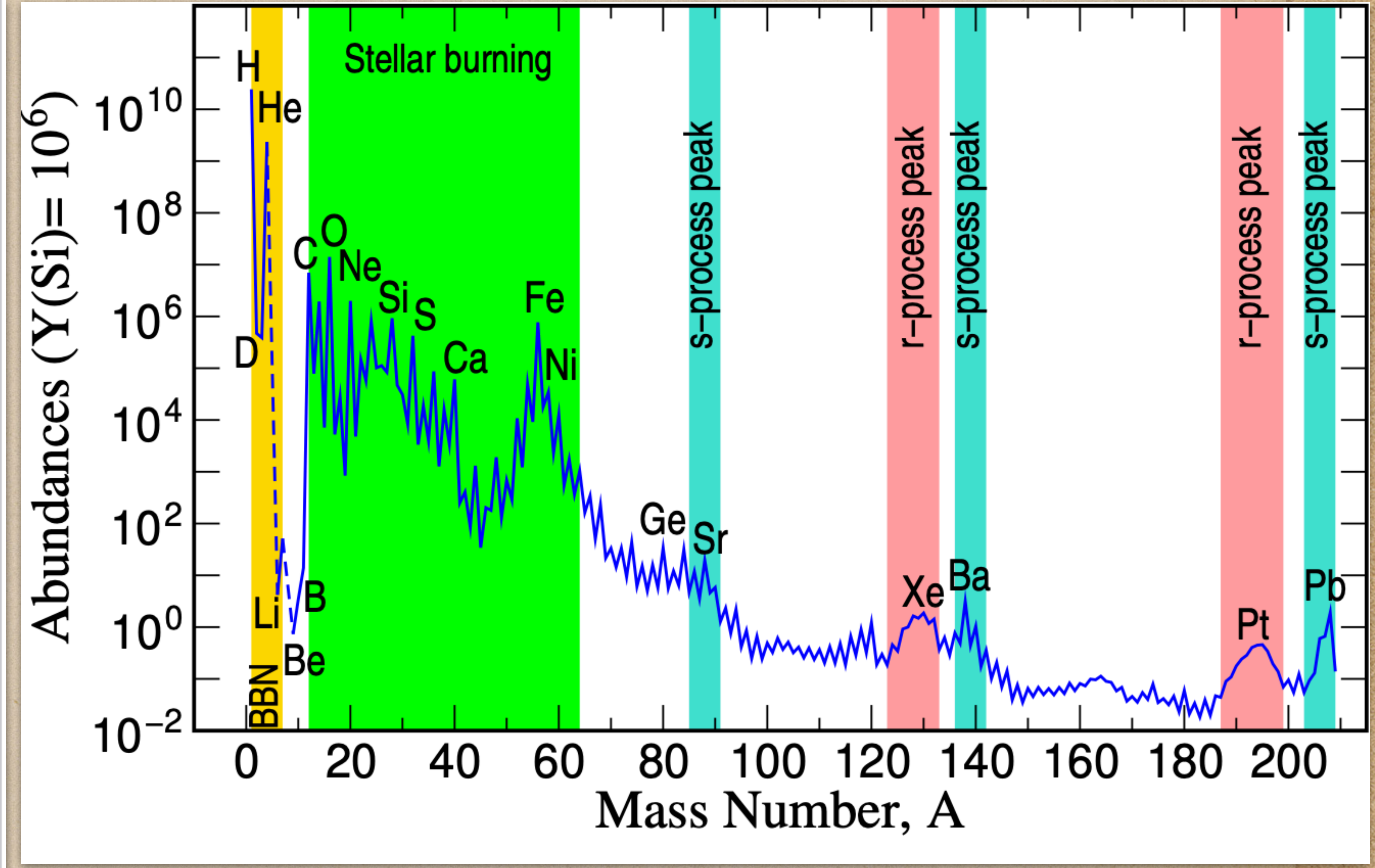
Merging NS's produce "r-process" elements



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



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r-process nucleosynthesis B^{2}FH

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.

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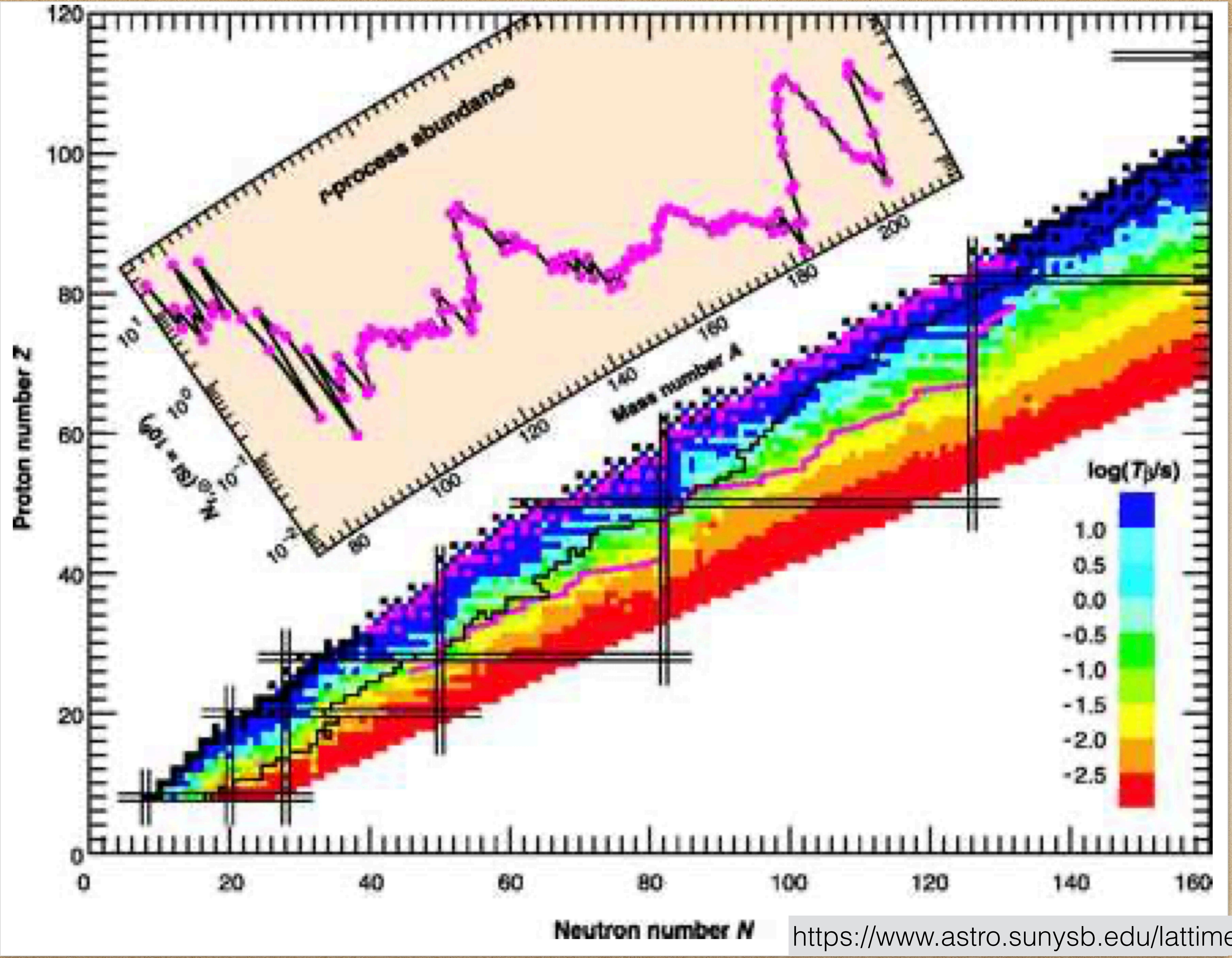

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https://www.astro.sunysb.edu/lattimer/PHY521/nucleo.pdf

Big Picture

time

Expands at v~ 0.1 c

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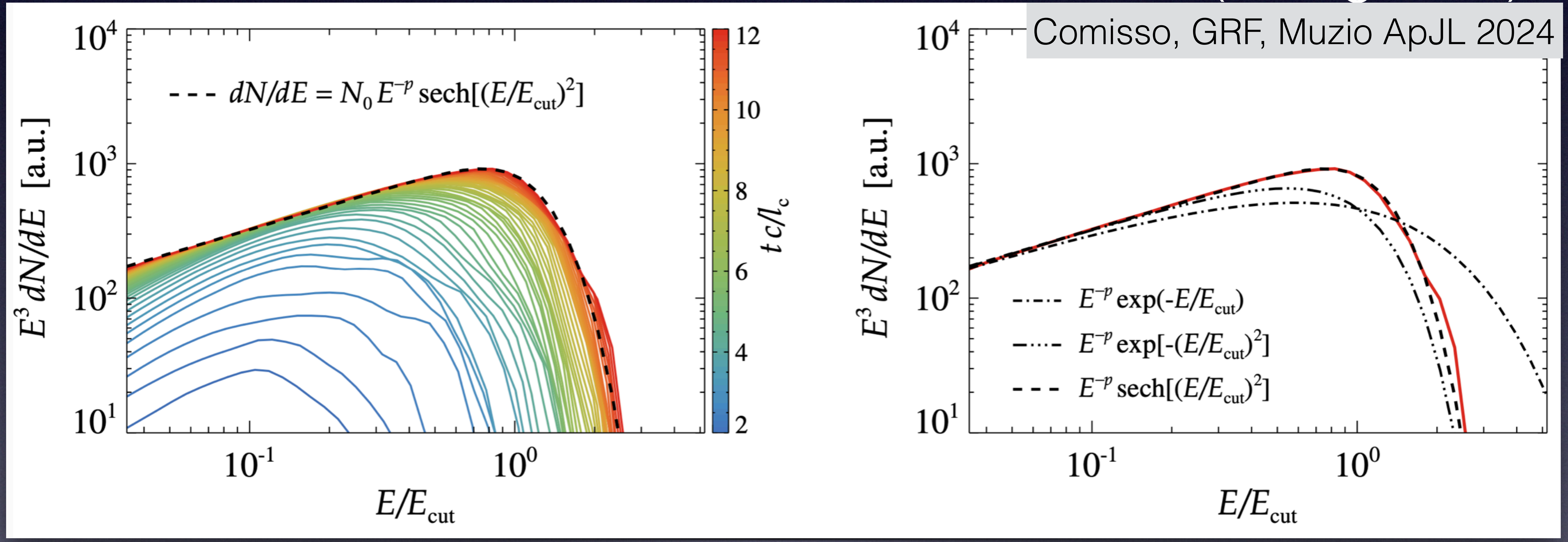
UHECRs mainly produced in the turbulent outflow (maybe some UHECRs also from jets)

- 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})

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

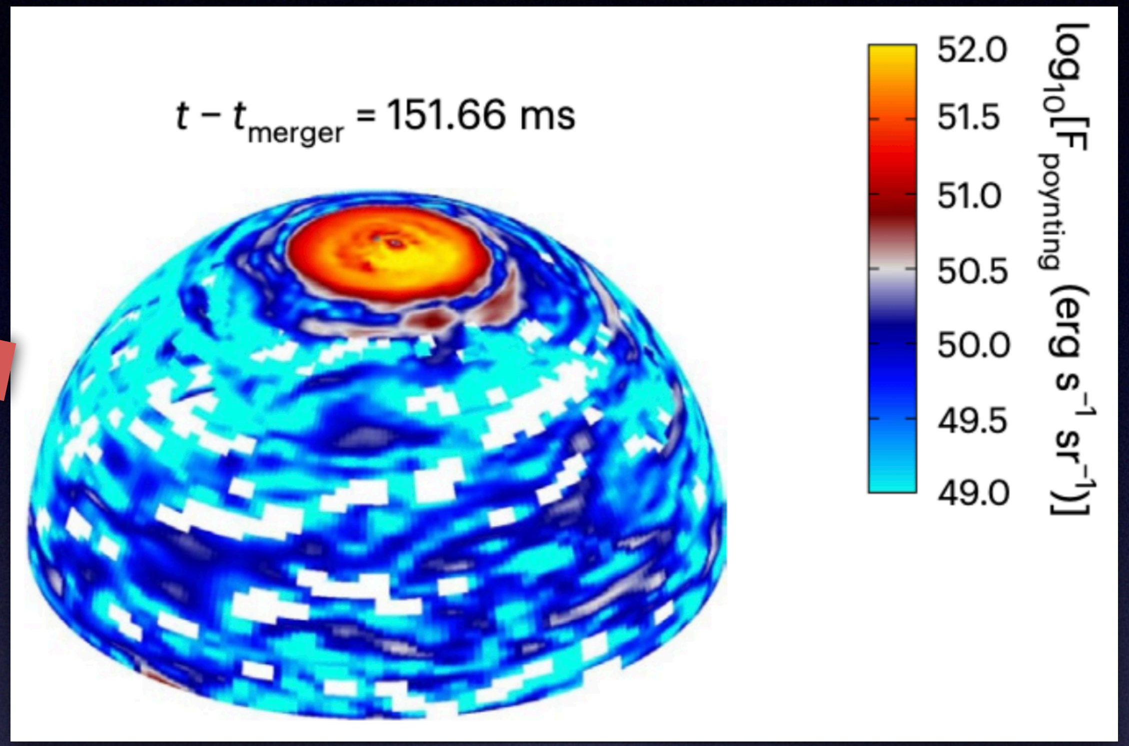


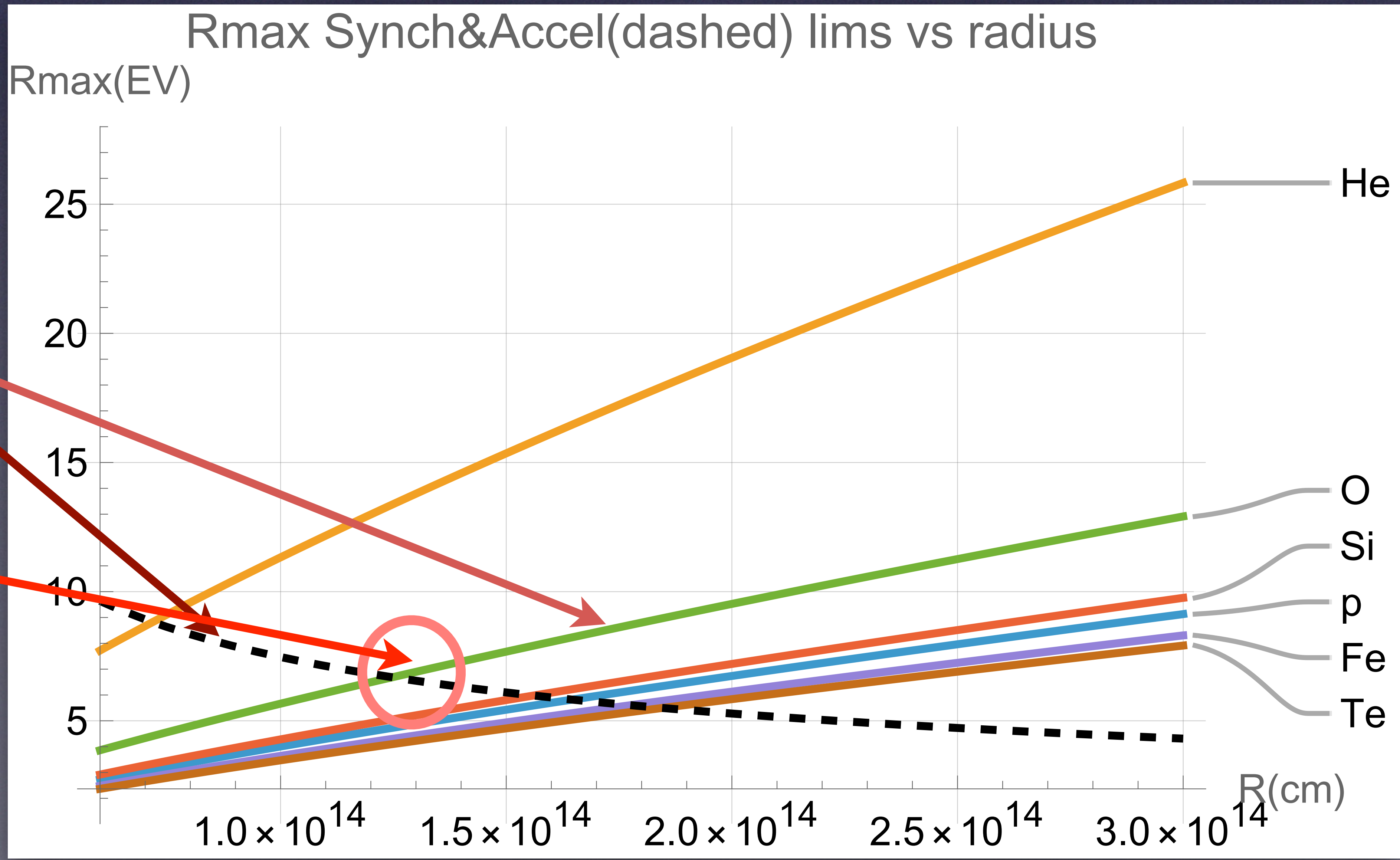
- Outflow: Magnetized turbulence ➜ cutoff sech[$(E/E_{cut})^2$] (Comisso, GRF, Muzio ApJL 2024)
- Jets: Diffusive Shock Acceleration cutoff: exp($-E/E_{cut}$) ??? (Protheroe+Stanev 1997)

Peak energy when acceleration = loss

- Initialize $B(r{=}500\ \mathrm{km}) = 3.3\ 10^{12}$ 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: Rigidity R≡E/Z
  - $R_{max}\ (r) = 0.65\ B(r)\ L_{coh}\ (r)$ (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***

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





BNS initialization ➜ no-free-parameter *predictions* of R_{cut}

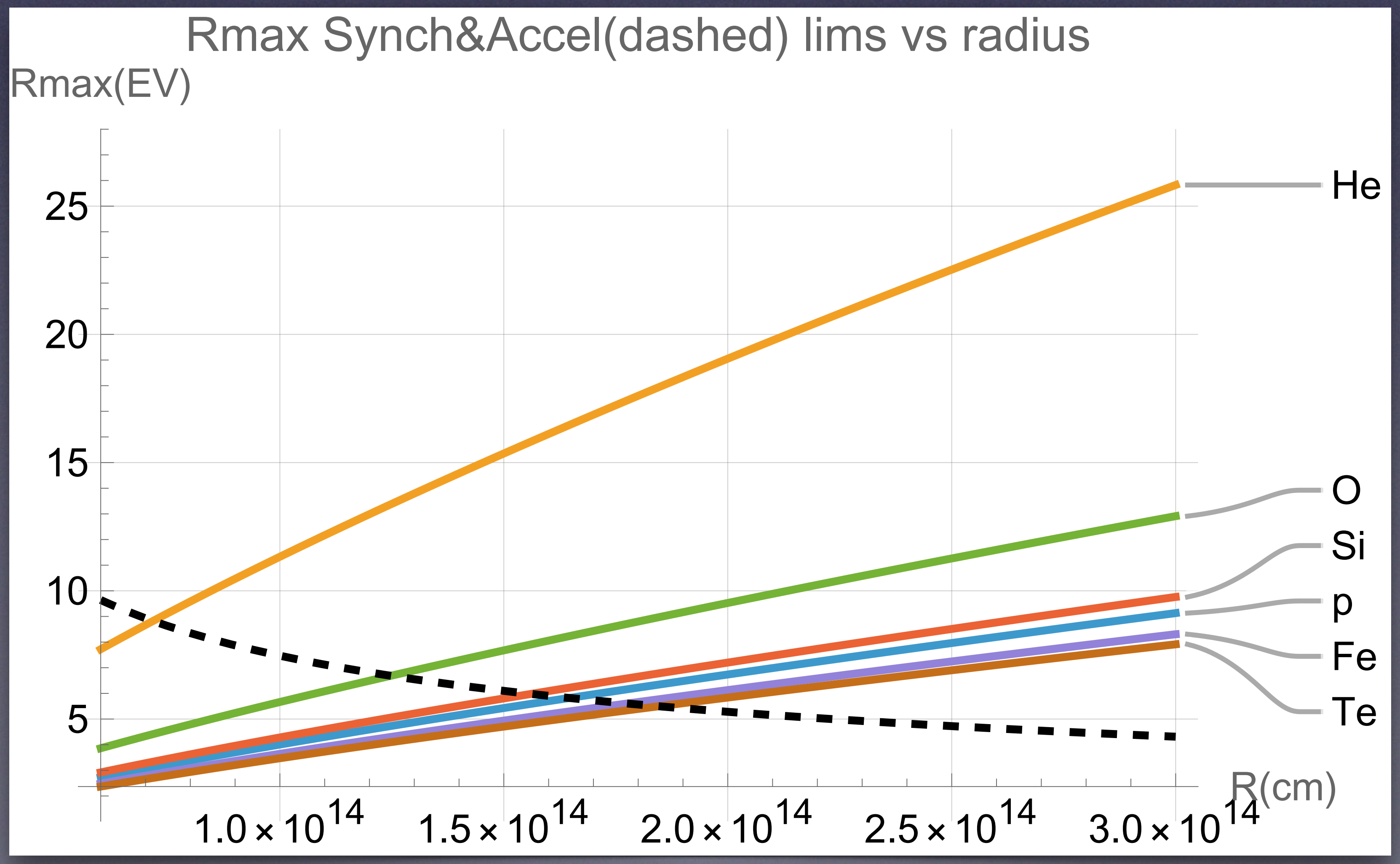
rigidity R≡E/Z

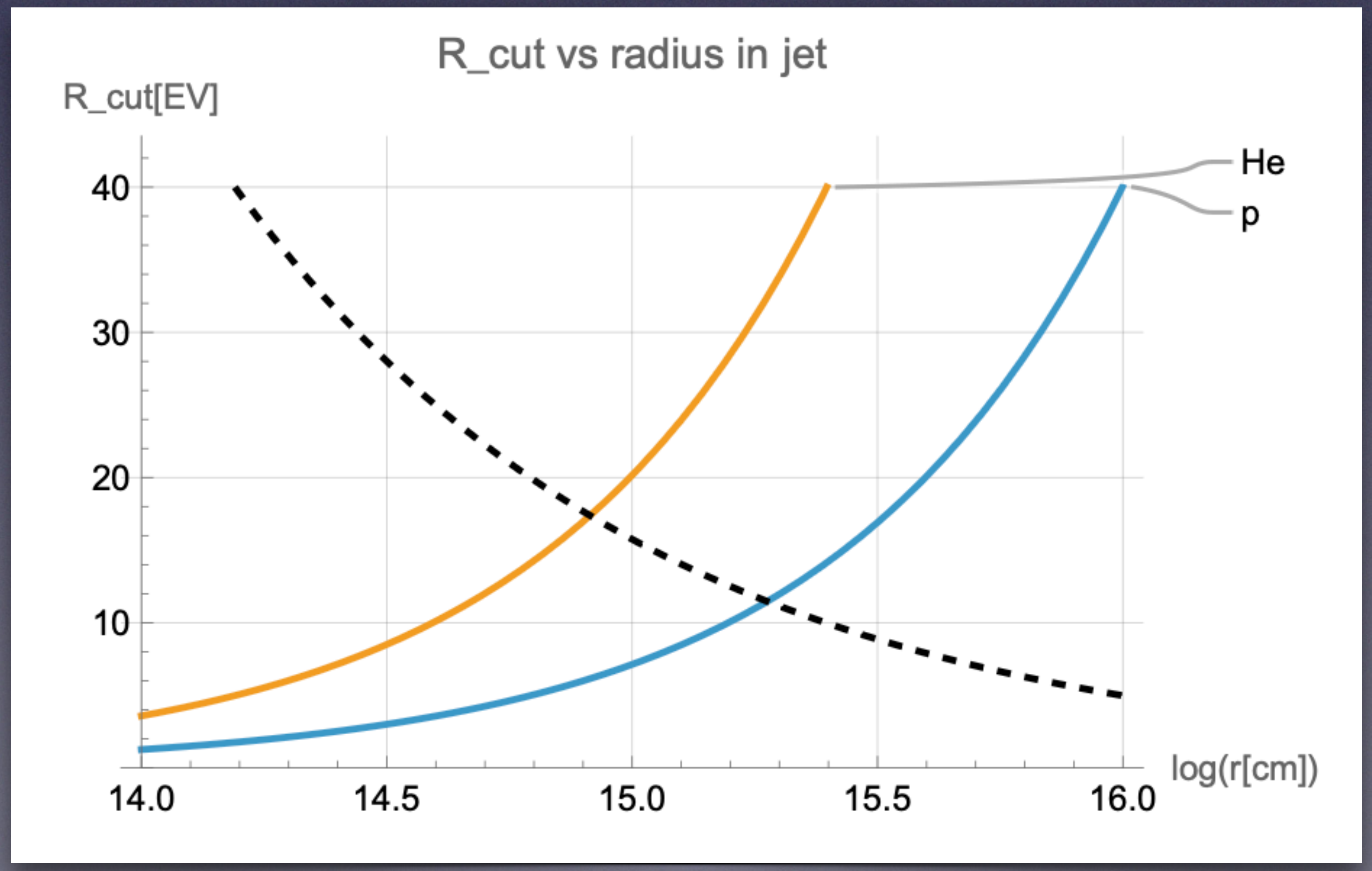
- **Turbulent outflow:** R_{cut} {p,He,O,Si,Fe,Te} ≈ {6.2, 9.4, 7.1, 6.3, 6.0, 5.9} EV

Auger fit: R_{cut} = 6.3 EV (has factor-2 uncertainty)

- **Jet:** some proton and/or He; E_{cut} ≈ 11 EeV for proton, E_{cut} ≈ 35 EeV for He

Additional light component improves Auger fit by 5σ (Muzio+2019)





Tests of BNS merger scenario

- ✓ Successful prediction of R_{cut}
- ✓ Eroded r-process nuclei among UCRs ($A>56$)
- Possible characteristic pattern of R_{cut} slightly varying with A, reflecting synchrotron-limited acceleration
- Flux of EHE neutrinos
- GW-$\boldsymbol{\nu}$ coincidences for EHE $\boldsymbol{\nu}$'s ($E>$ PeV) - time delay $\approx$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

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

★ Auger should look closely at the ~10 events with E > 130 EeV, to see if they favor A > 56.

Test 2: EHE Neutrino ↔ Grav. Wave

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

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)

Summary: BNS mergers explain essential features of UHECRs

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

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

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

G. Farrar, NYU

Thank you!