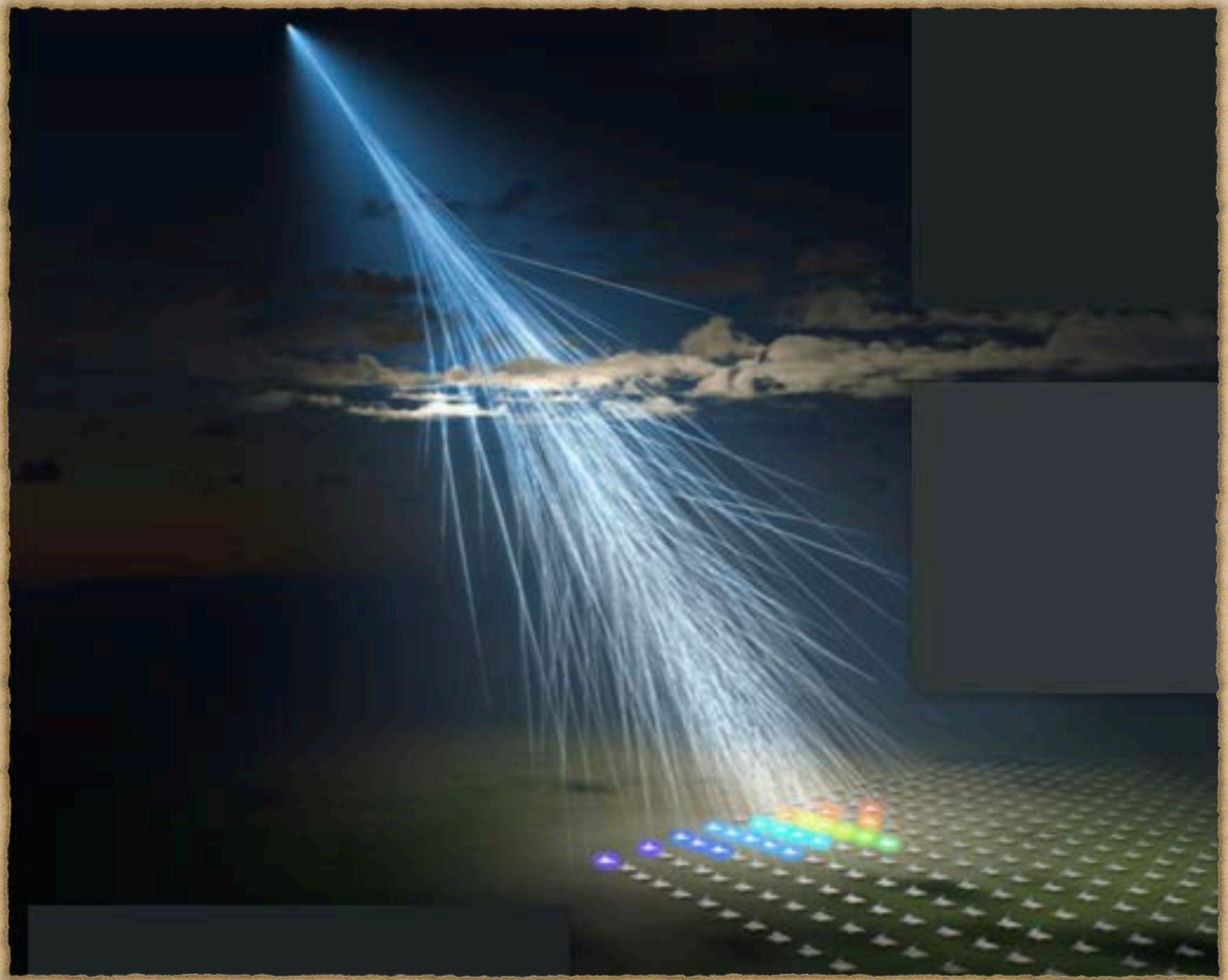
# An EHE neutrino accompanied by a Gravitational Wave would reveal the origin of Ultrahigh Energy Cosmic Rays

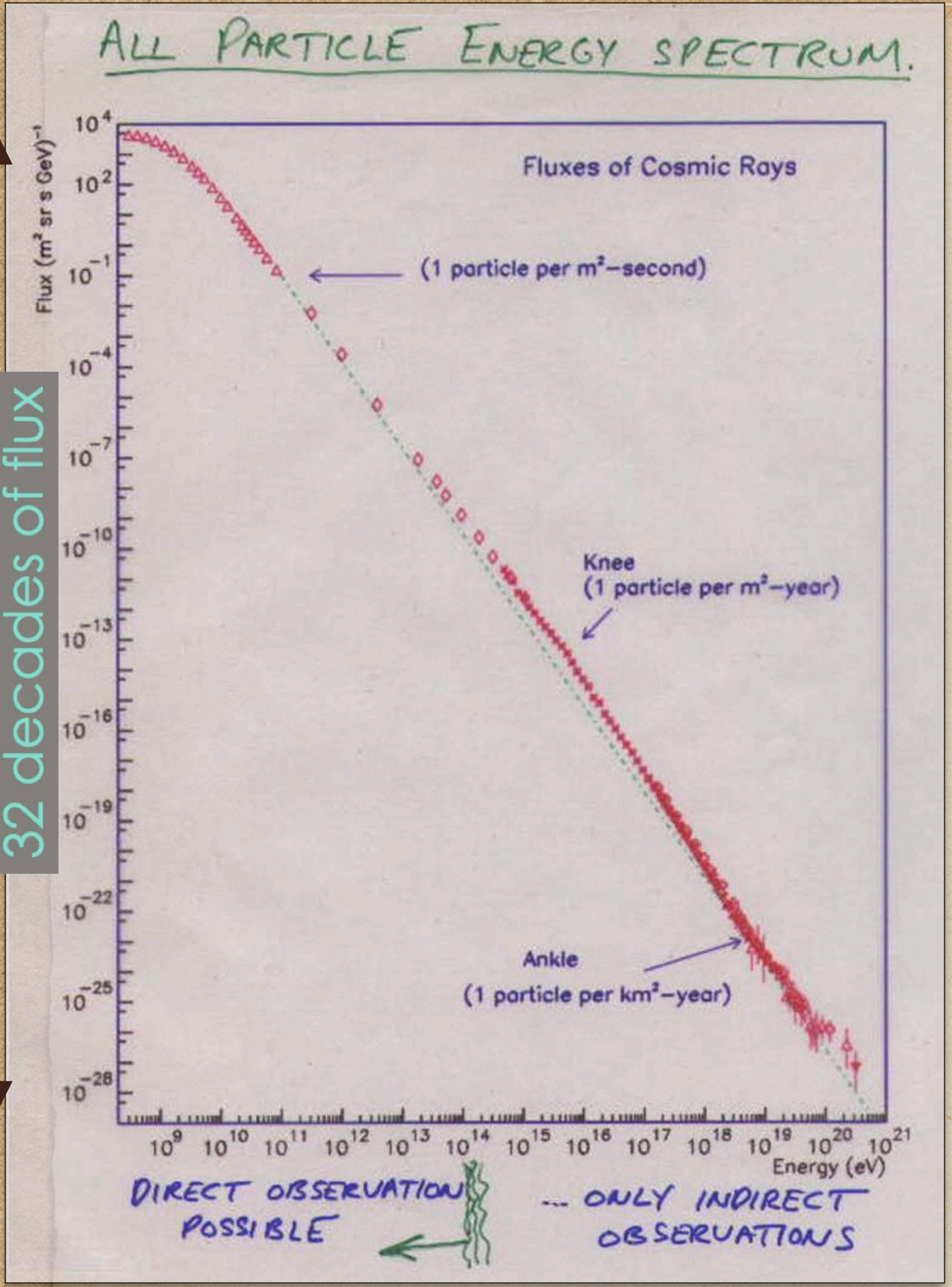
## or “UHECRs from Binary Neutron Star Mergers”



Glennys R. Farrar, New York University

Baha/George Fest, Berkeley, Jan. 17, 2025

arXiv: 2405.112004 [astro-ph.HE]



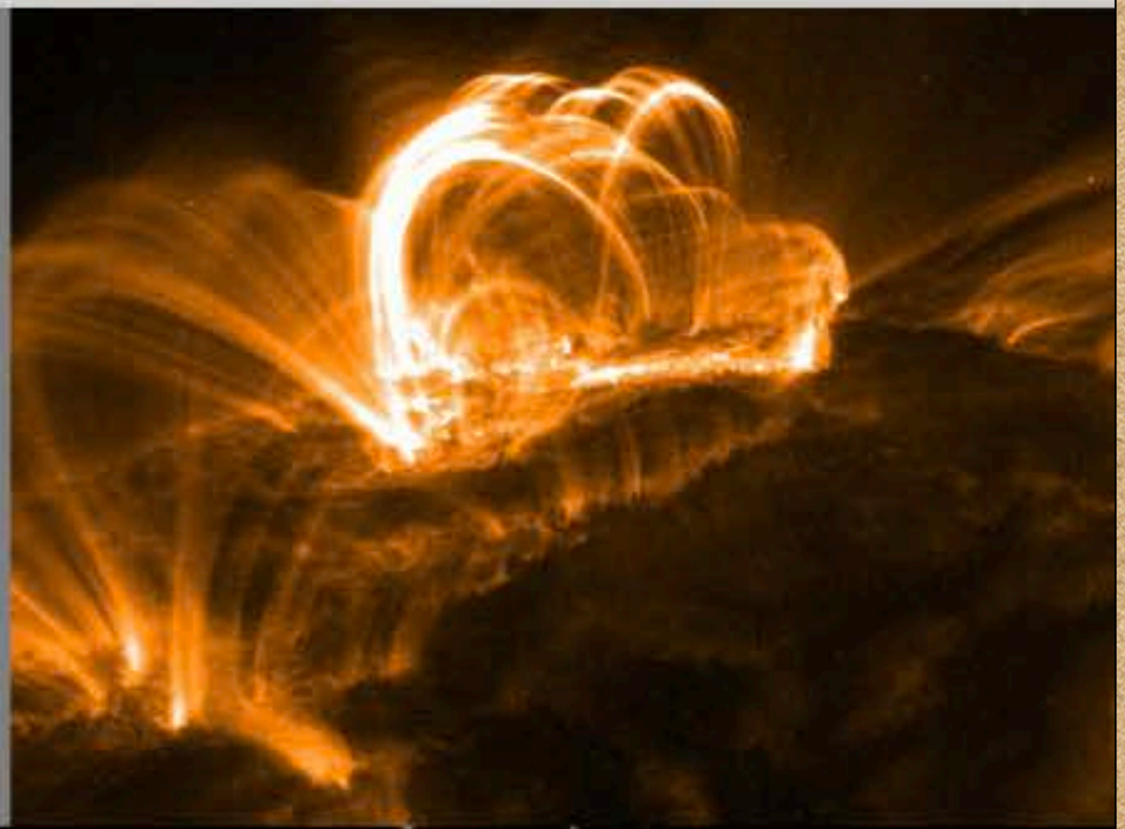

32 decades of flux

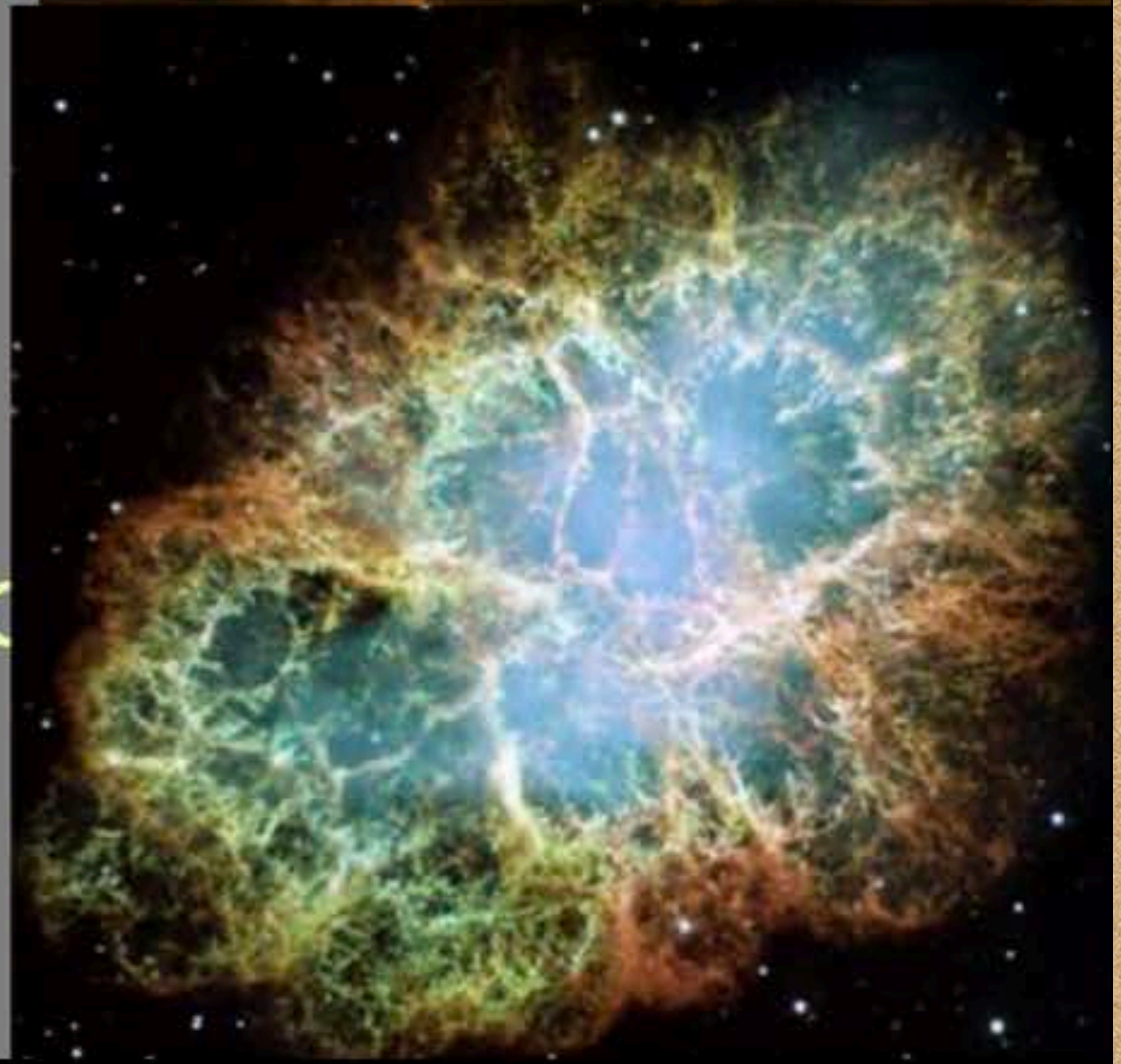
12 decades of energy

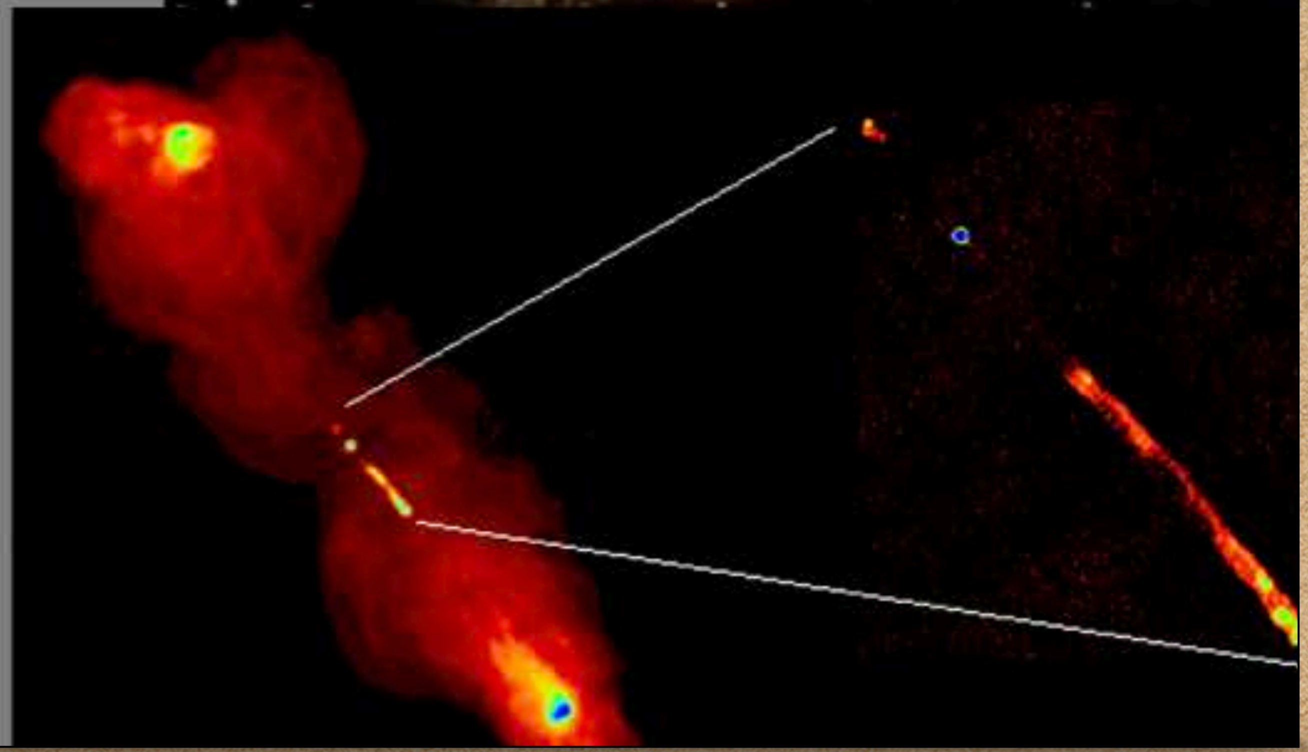
32 decades of flux

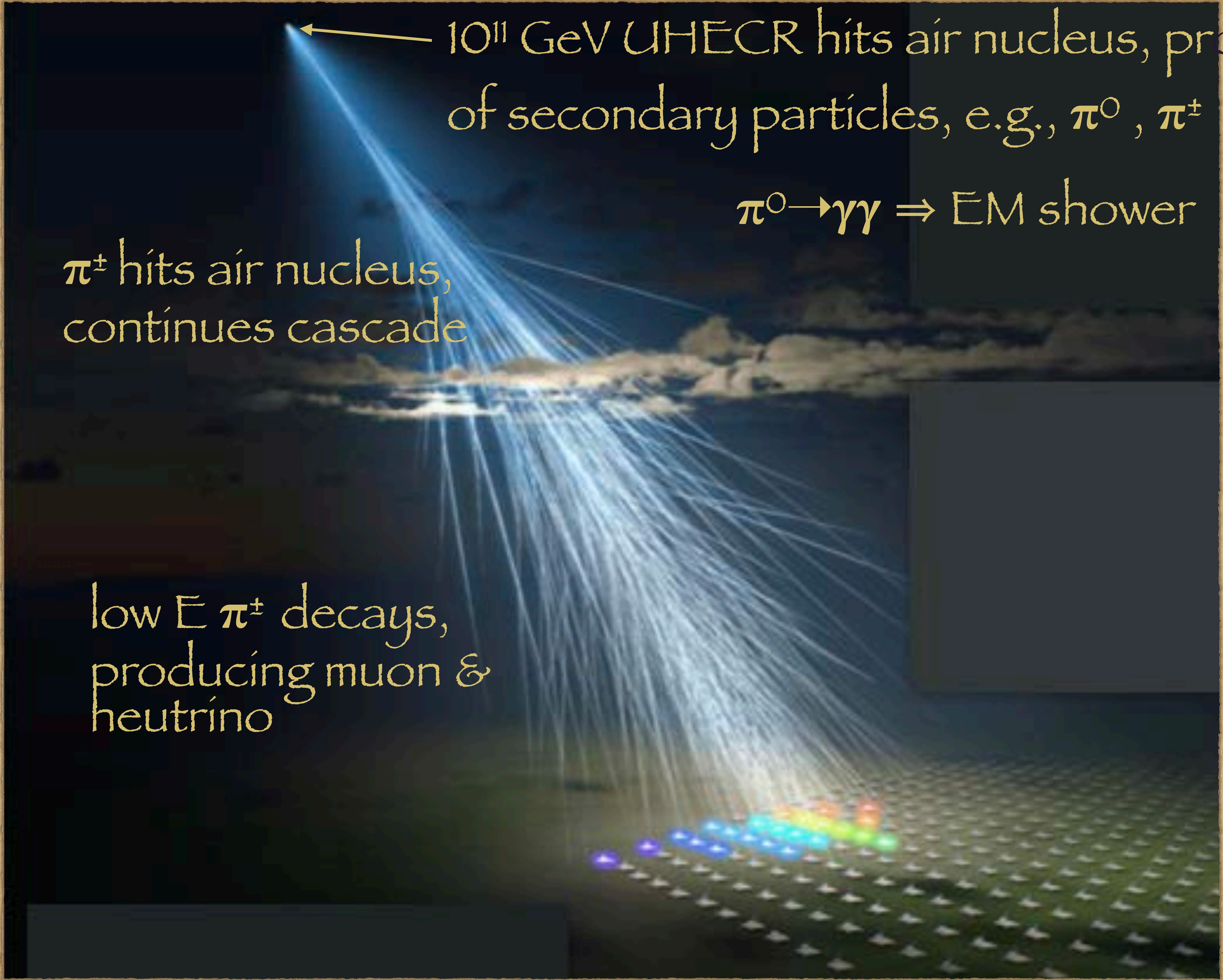
# Cosmic Rays

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



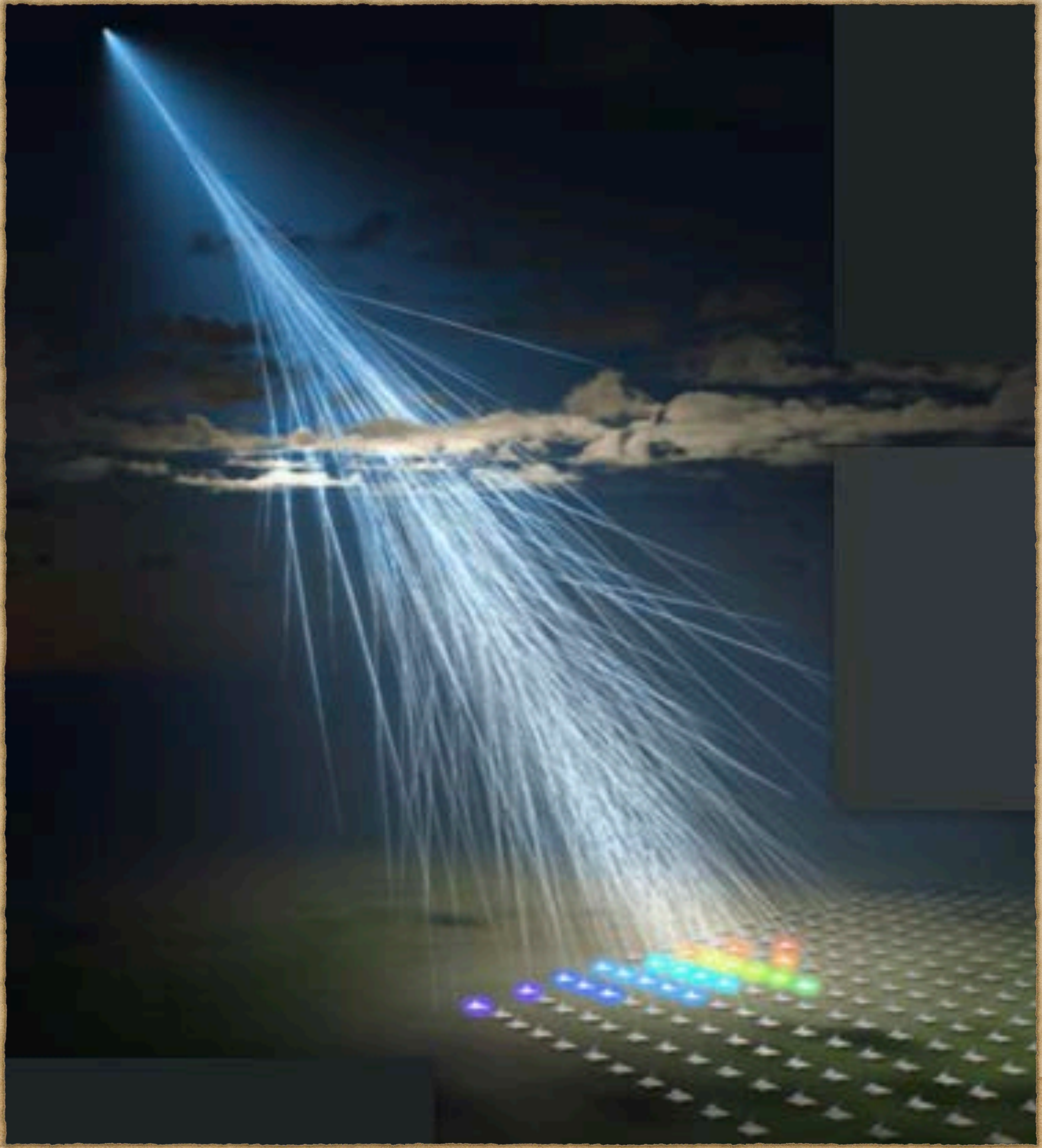




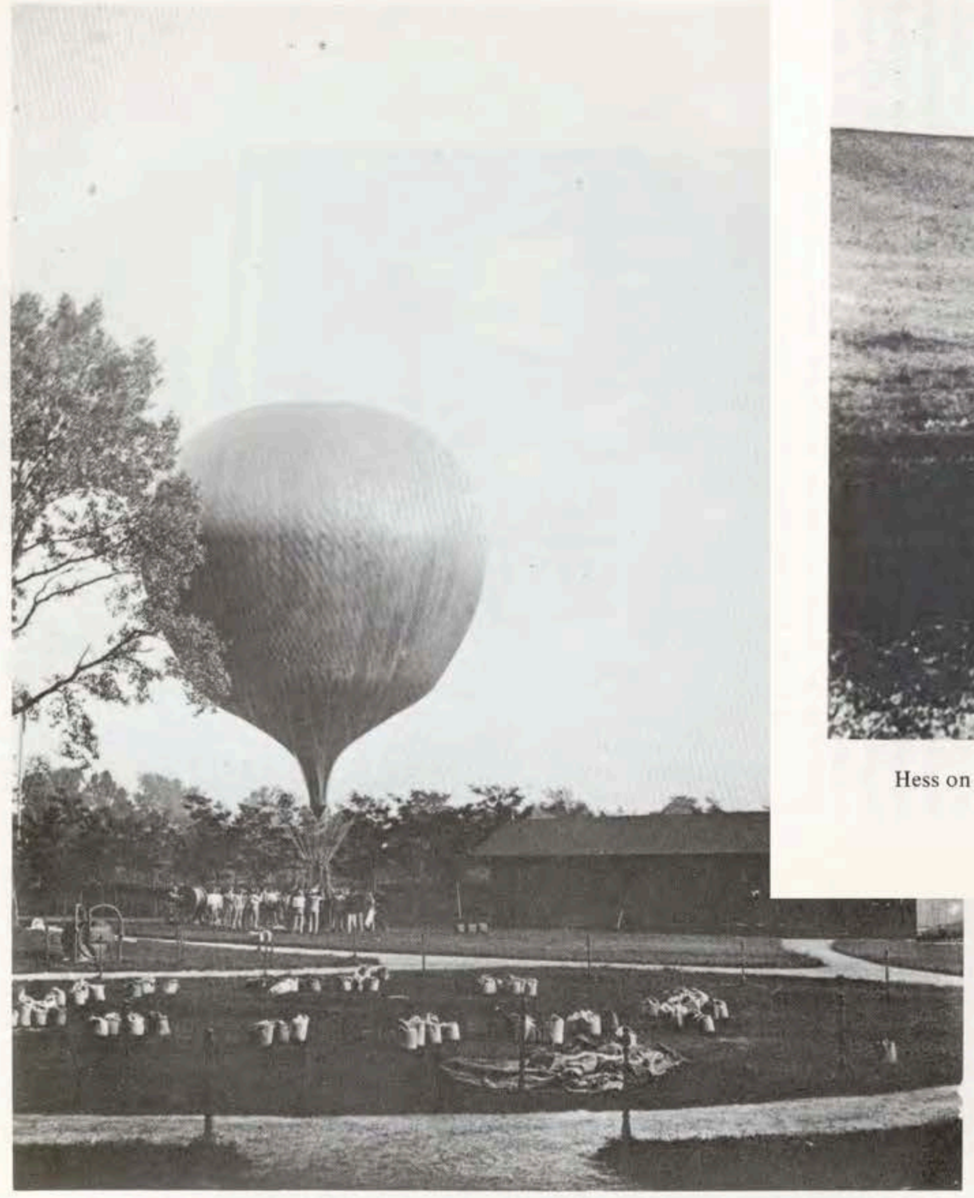


$10^{11}$ GeV UHECR hits air nucleus, producing 1000s of secondary particles, e.g., $\pi^0$ , $\pi^\pm$
$\pi^0 \rightarrow \gamma\gamma \Rightarrow$ EM shower
$\pi^\pm$ hits air nucleus, continues cascade
low E $\pi^\pm$ decays, producing muon & neutrino

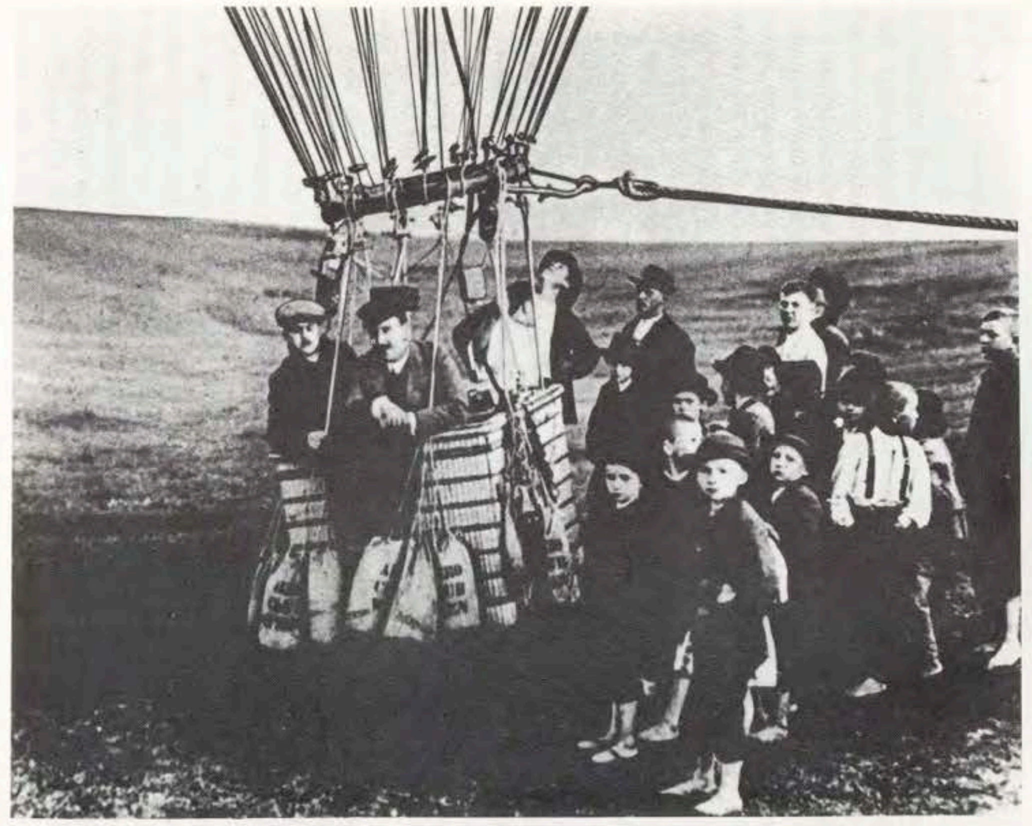
# How to deduce the mass and energy of a UHECR



- 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



Aeronautisches Gelände im Wiener Prater, von dem aus V. F. Hess in den Jahren 1911/12 seine ersten Freiballon-Forschungsfahrten unternommen hatte. (Courtesy of Heeresgeschichtliche Museum, Vienna)
<Ed> Contributed by R. Steinmaurer. See p. 17.



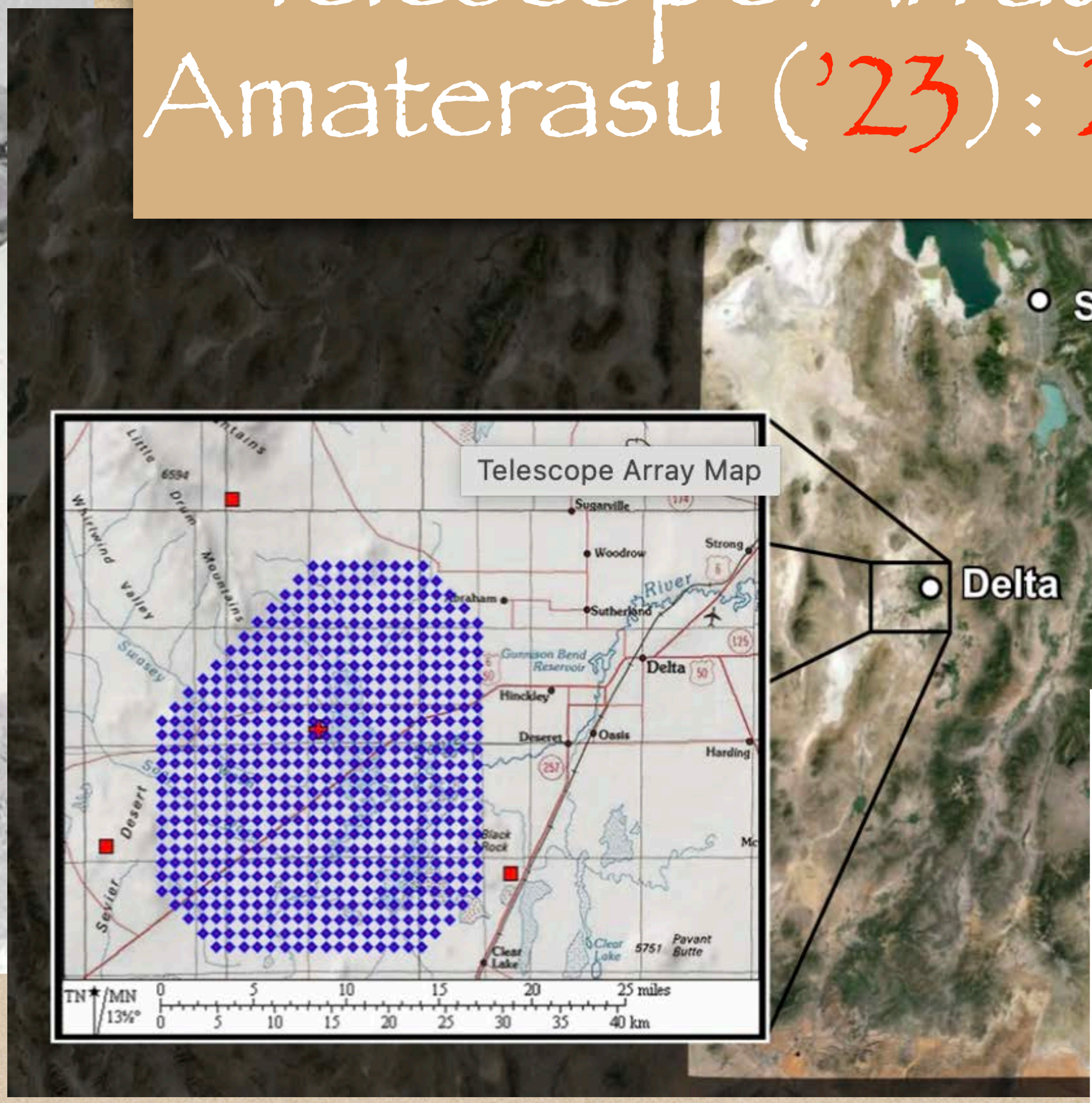
Hess on gondola in 1912 probably in test flight. The date and place is not clear at present.
<Ed> Contributed by R. Steinmaurer. See p. 17.

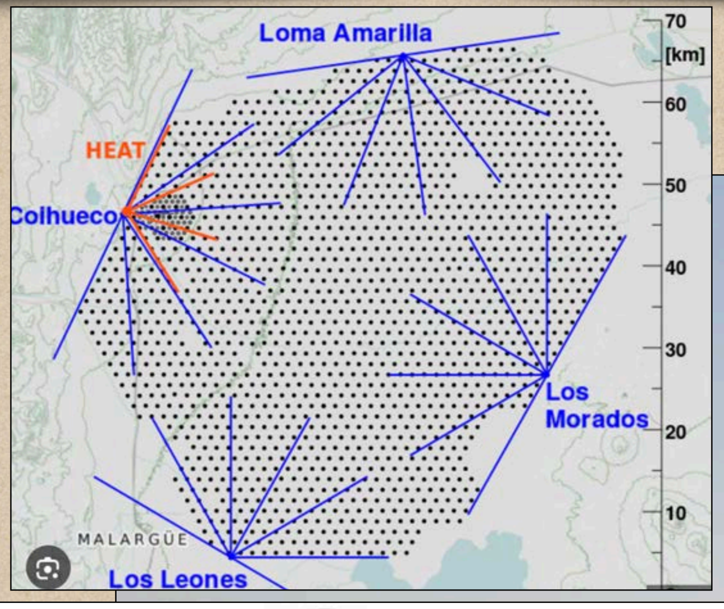
Hess: CRs
1911 or 1912

3

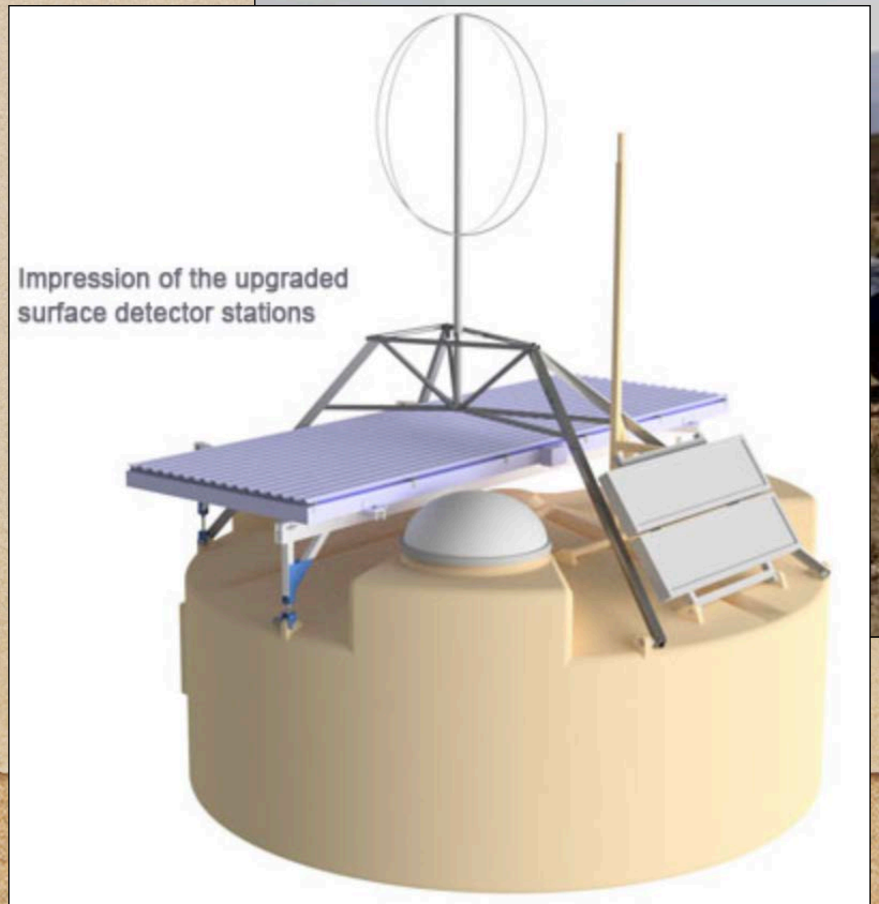
Linsley: 1st evt > 100 EeV
Volcano Ranch, NM ~1962

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




# Pierre Auger Obs., Argentina
40 evts > 100 EeV




Fly's Eye Utah 1991
OMG: 320 EeV

1700 stations, 3000 km$^2$

# Plan of talk

Observations & status of UHECRs:

- Modern data is very constraining; no GZK violation; "usual suspects" sources — AGNs, Gamma Ray Bursts (collapse of massive star) — all have problems

NEW PROPOSAL: UHECRs are produced in jets of binary neutron star mergers.

- This is first scenario which potentially satisfies all requirements
- Can account for all UHECRs with a single mechanism.
- Fascinating prediction: Highest energy UHECRs are r-process nuclei.
- EVERY EHE neutrino is accompanied by a Gravitational Wave

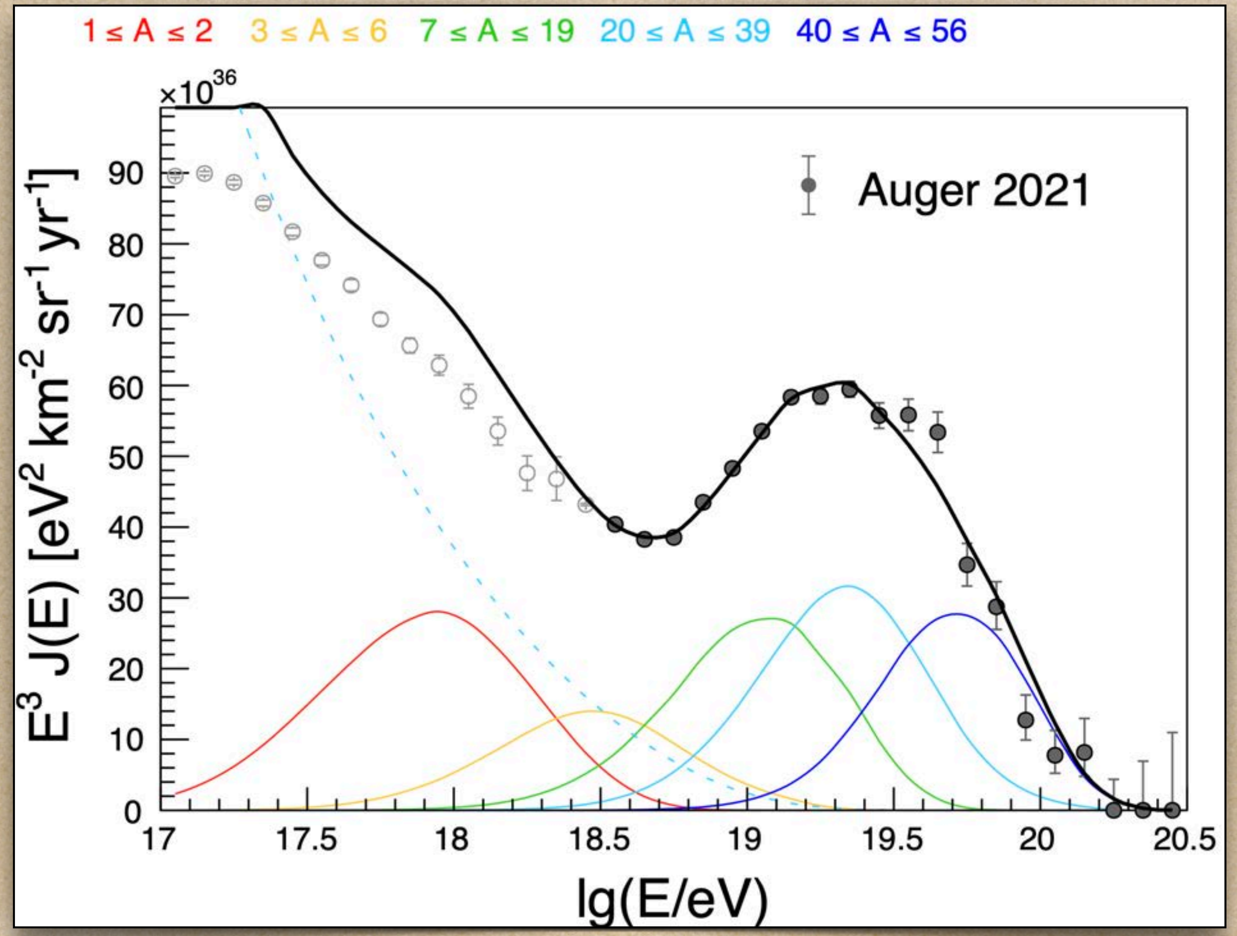
# Constraints from Spectrum and Composition

- Energy injection in UHECRs > 10 EeV: $\approx 6 \times 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$
- Mixed composition; hard spectrum, depends on <u>Rigidity</u>: $R \equiv E/(Z\,e)$
- Peak rigidity ≈4.5 EV ➜ <u>Factor-few spread in rigidities</u>

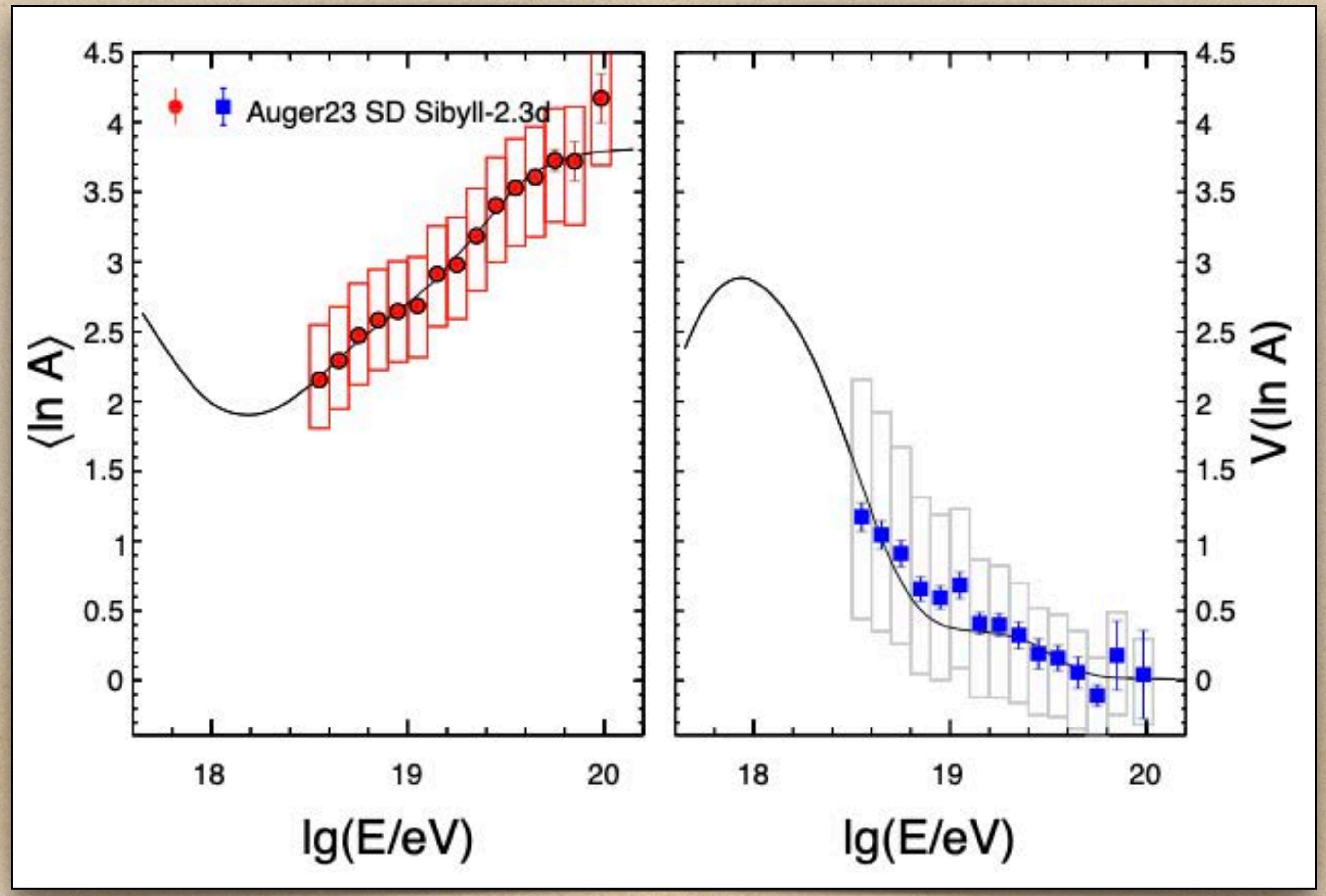
  How can spread be so narrow ??? Ehlert,Oikonomou,Unger+23

> 40 events above 100 EeV ($10^{20}$eV); ~50,000 events above 10 EeV

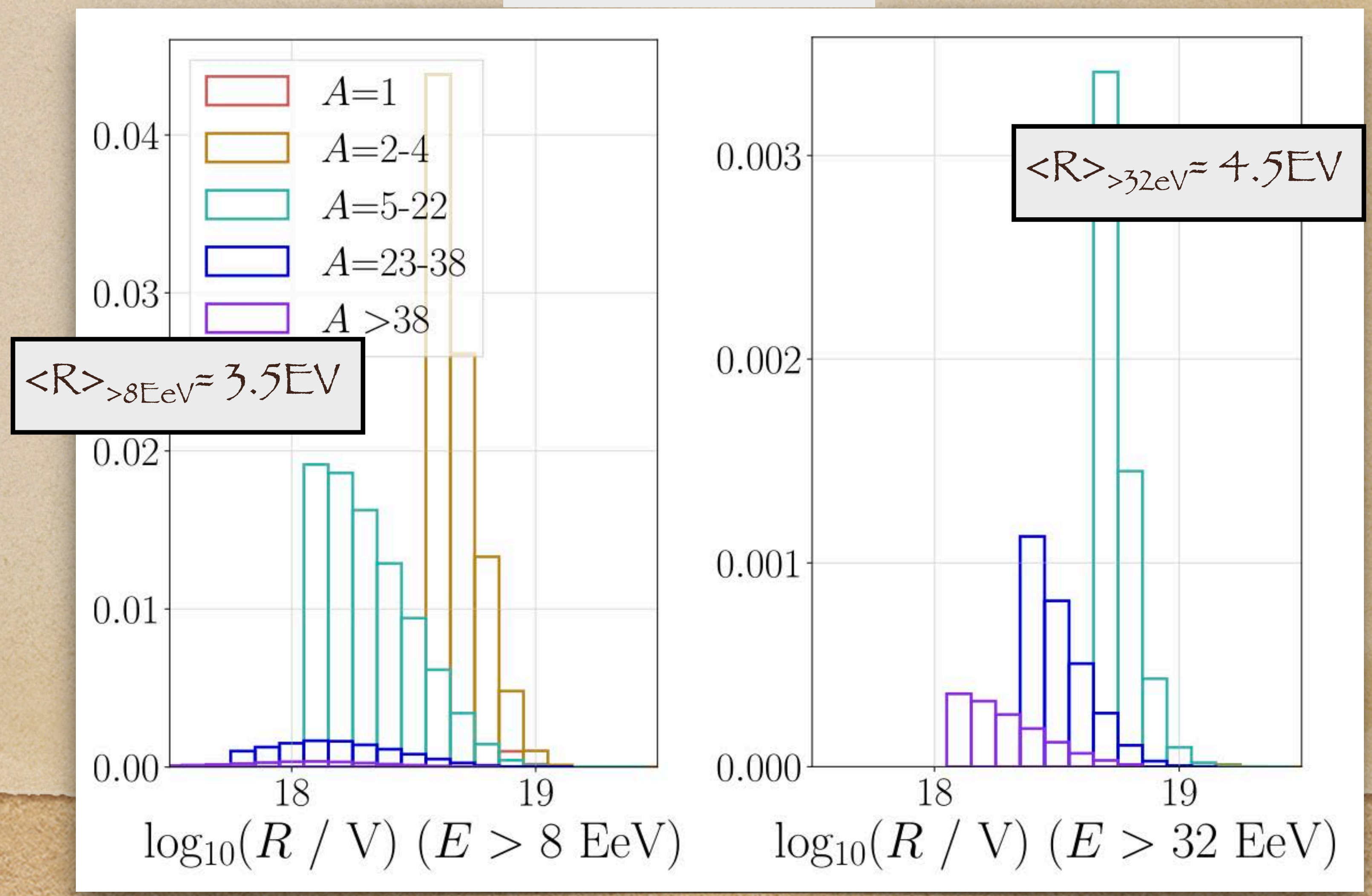
*Bister,GF+23



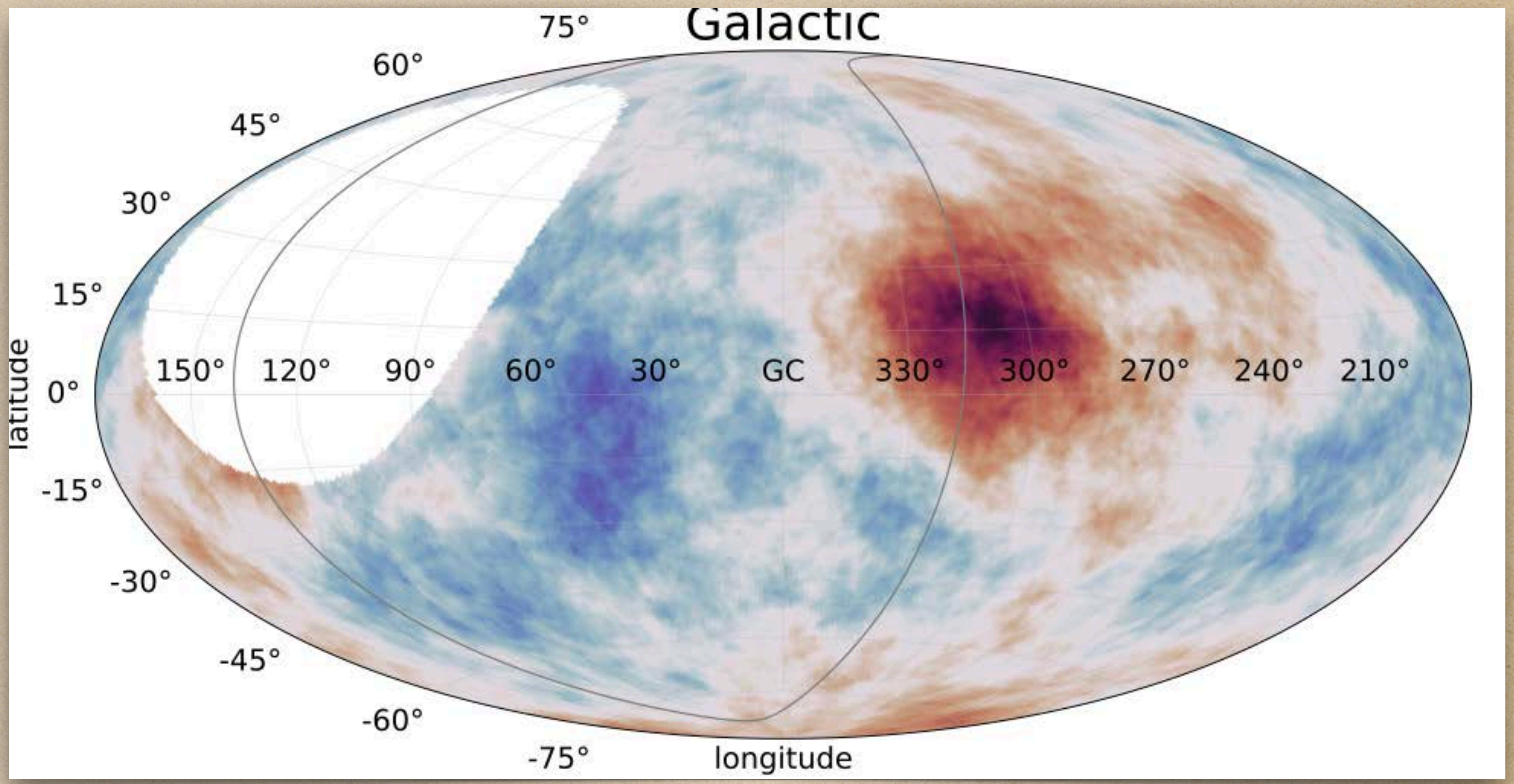

Spectrum




Composition



# Constraints from Arrival Directions

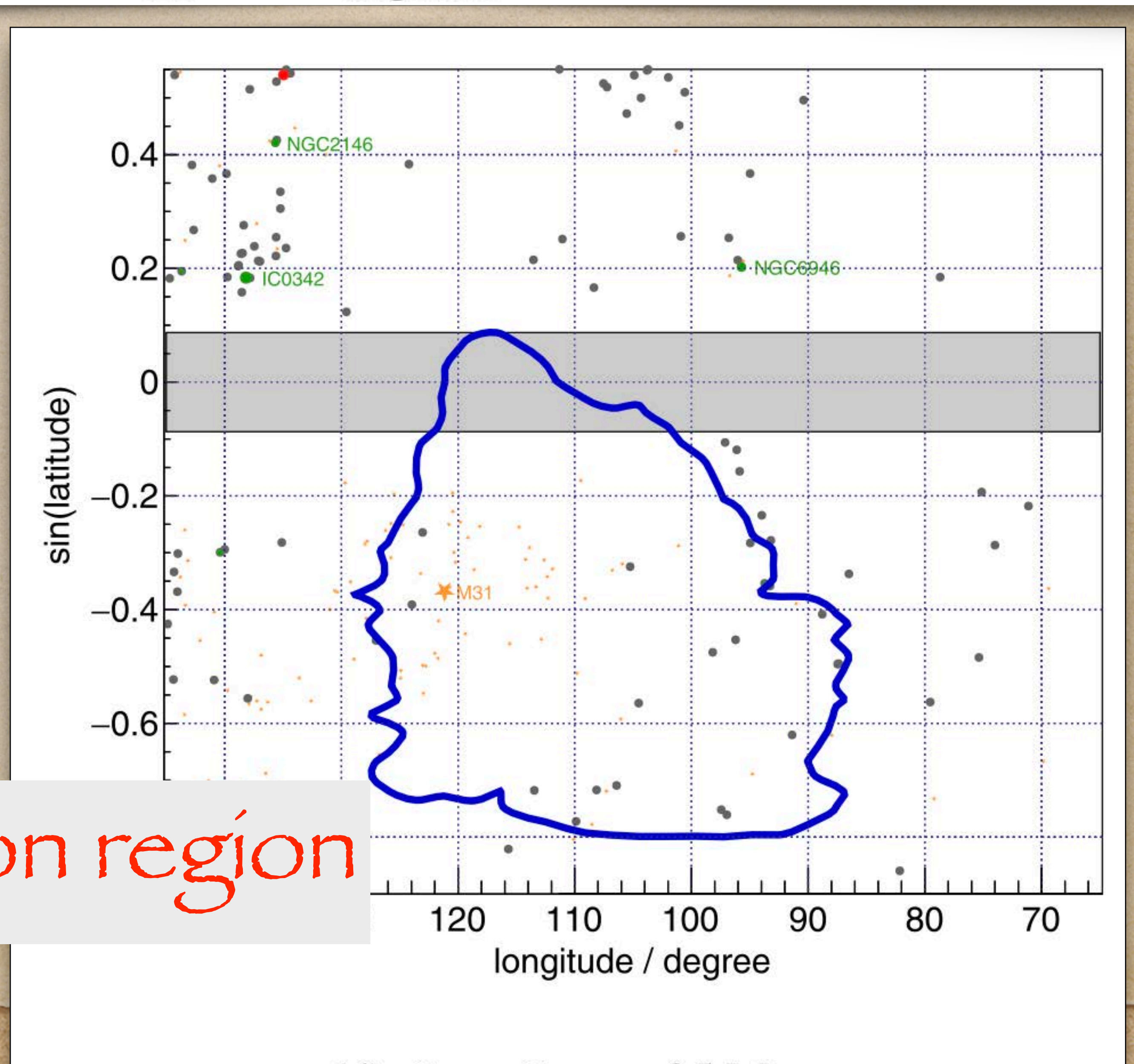



- Sources fairly abundant

  T. Bister and GRF, ApJ 2024

- HIGHEST ENERGY UHECRs are produced in TRANSIENTS (TA's Amaterasu, Fly's Eye OMG)

  M. Unger and GRF, ApJL 2024



(d) $E_{\rm low}, D_{0.1} = 25$ Mpc

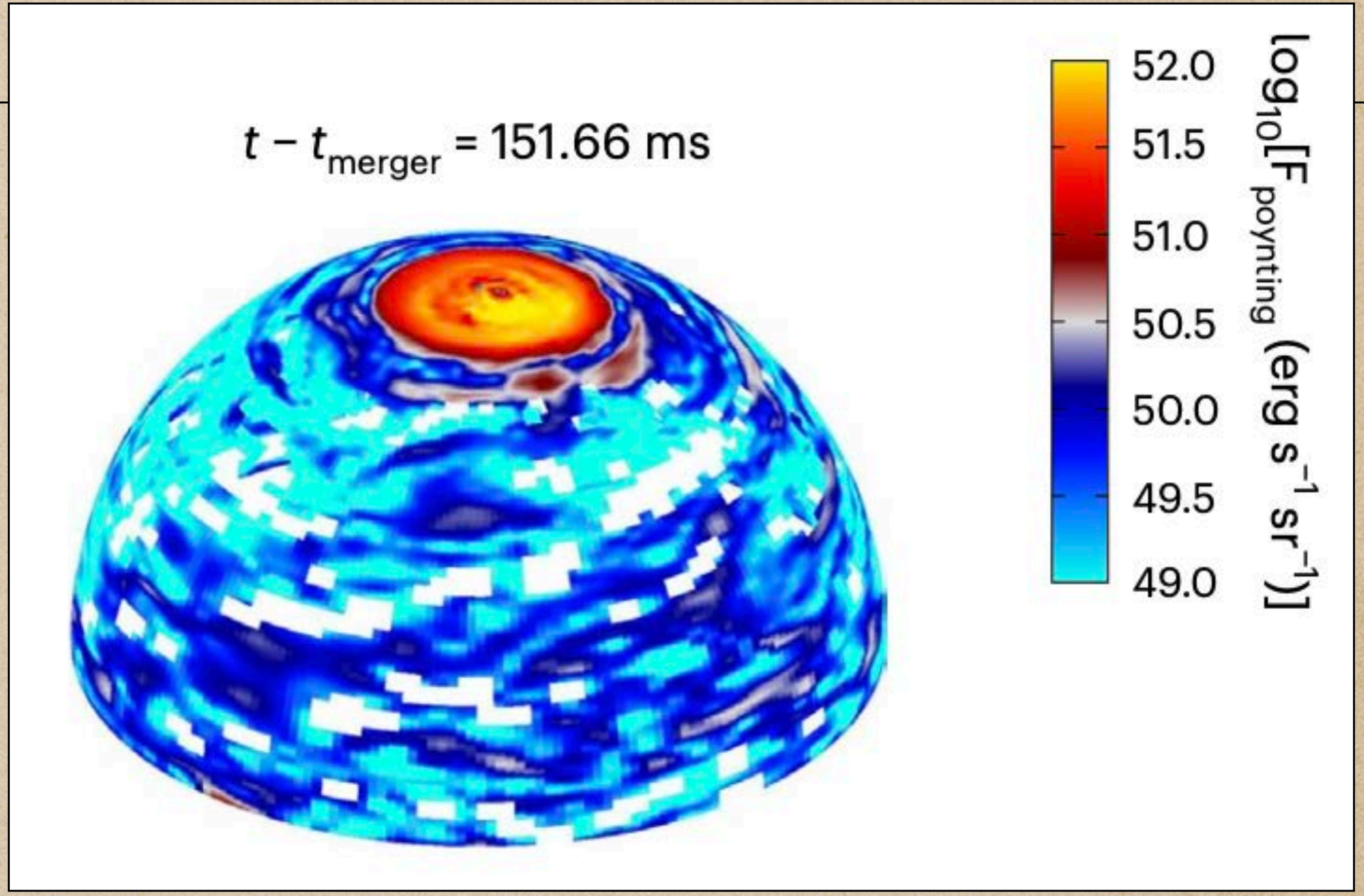
NO powerful AGN or starburst galaxies (long GRB) in localization region

# Key conditions on UHECR sources

- Hillas criterion: CR escapes unless its Larmor radius is < source size ➜ $R_{max,EV} \approx 3 \times 10^{-11}\, \Gamma_{jet}\, L_{km}\, B_G$
- Source number density and energy injection rate:
  - $n_S \gtrsim 10^{-3.5}$ Mpc$^{-3}$ and $dQ/dt \approx 6 \times 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$ for $E_{CR} > 10$ EeV
- Highest energy UHECRs are produced in TRANSIENTS
- Universal maximum rigidity (little source-to-source variation)
- Anomalously high energy of "OMG" & Amaterasu (250 EeV & 220 EeV)

New Proposal:

# Binary Neutron Star Mergers




- Universal Maximum Rigidity is natural
  - $M_{BNS} \approx (2.64 \pm 0.14) M_\odot$
  - Gravitationally-driven dynamo — Kiuchi+ NatureAstron23
  - km-scale fields > $10^{15}$ G ✔ Hillas
- Energy injection rate: (obs ≈ $6 \times 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$)
  - BNS rate $\Gamma_{NSmerg} \approx$ 10–1700 Gpc$^{-3}$ yr$^{-1}$ ✔ if $\Gamma_{NSmerg} \gtrsim 100$ Gpc$^{-3}$ yr$^{-1}$
  - Energy in jet and outflow ✔ (Kiuchi+23)
- Effective source density ✔ magnetic smearing $\beta_{EGMF} > 0.04$

$\beta_{\rm EGMF} \equiv B_{\rm EGMF}/{\rm nG}\sqrt{L_c/{\rm Mpc}}$ (expected range 0.1-1)

arXiv: 2405.112004 [astro-ph.HE]

# Potential challenges to Binary Neutron Star merger scenario

- Factor-few universality, merger-to-merger, in $R_{max}$
  - Understand detailed origin of $R_{max}$
  - More hi-res simulations of BNS merger jets to understand $R_{max}$ sensitivity to NS spins
  - UHECR pheno: how much "pollution" from other sources is ok?

- Sufficient UHECR production ?
  - Is the BNS merger rate sufficient?
  - UHECR acceleration is efficient: ~50-50 energy balance between $L_{Poynting}$ & $L_{UCR}$ (Comisso, GF & Muzio 2410.05546)

## Binary Neutron Star Mergers as the source of UHECRs:

# Two important consequences

# & tests

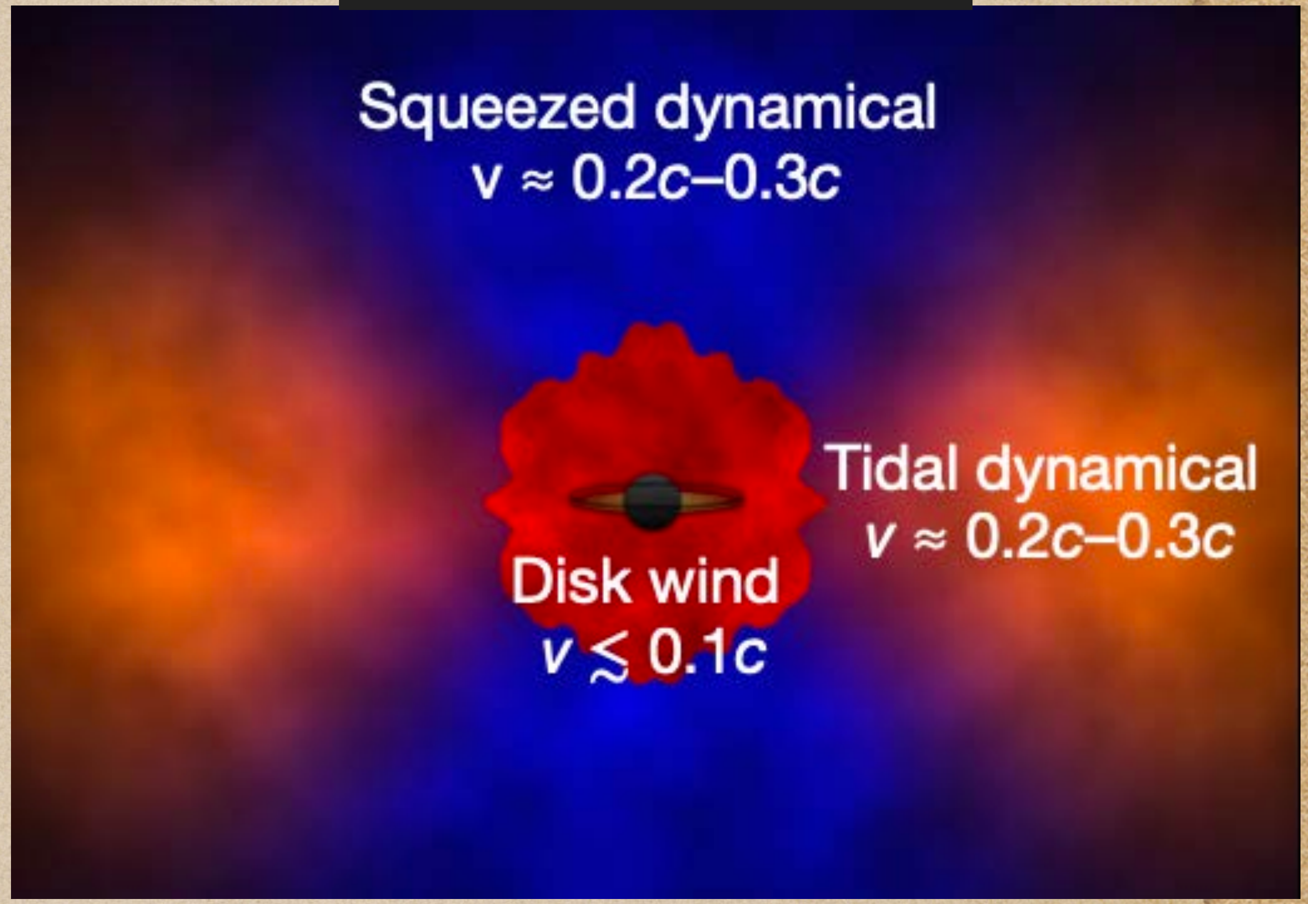
# Very highest energy events explained!

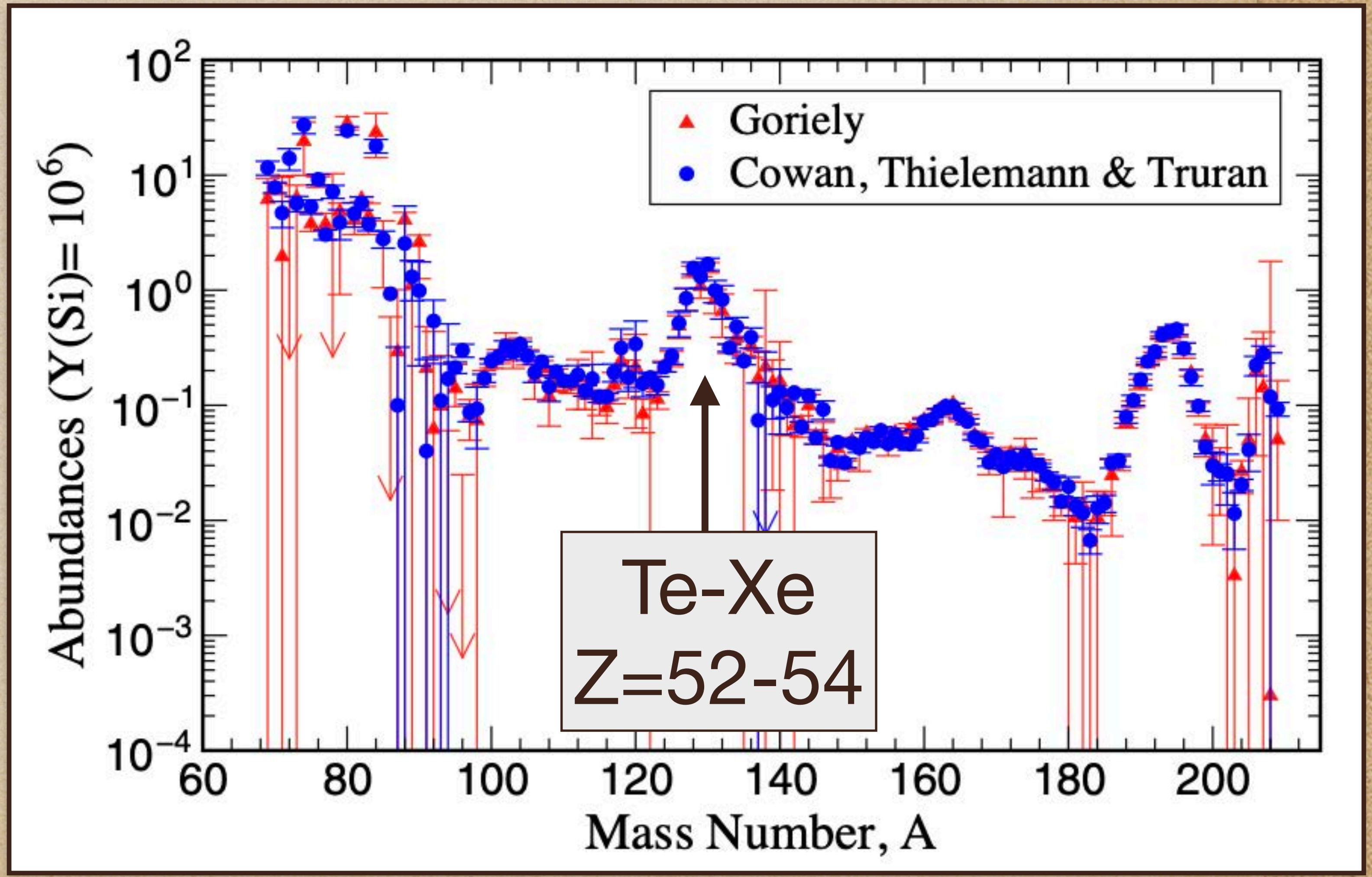
- r-process nucleosynthesis takes place in BNS mergers
- sometimes an r-nucleus is swept up and accelerated

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

# 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*

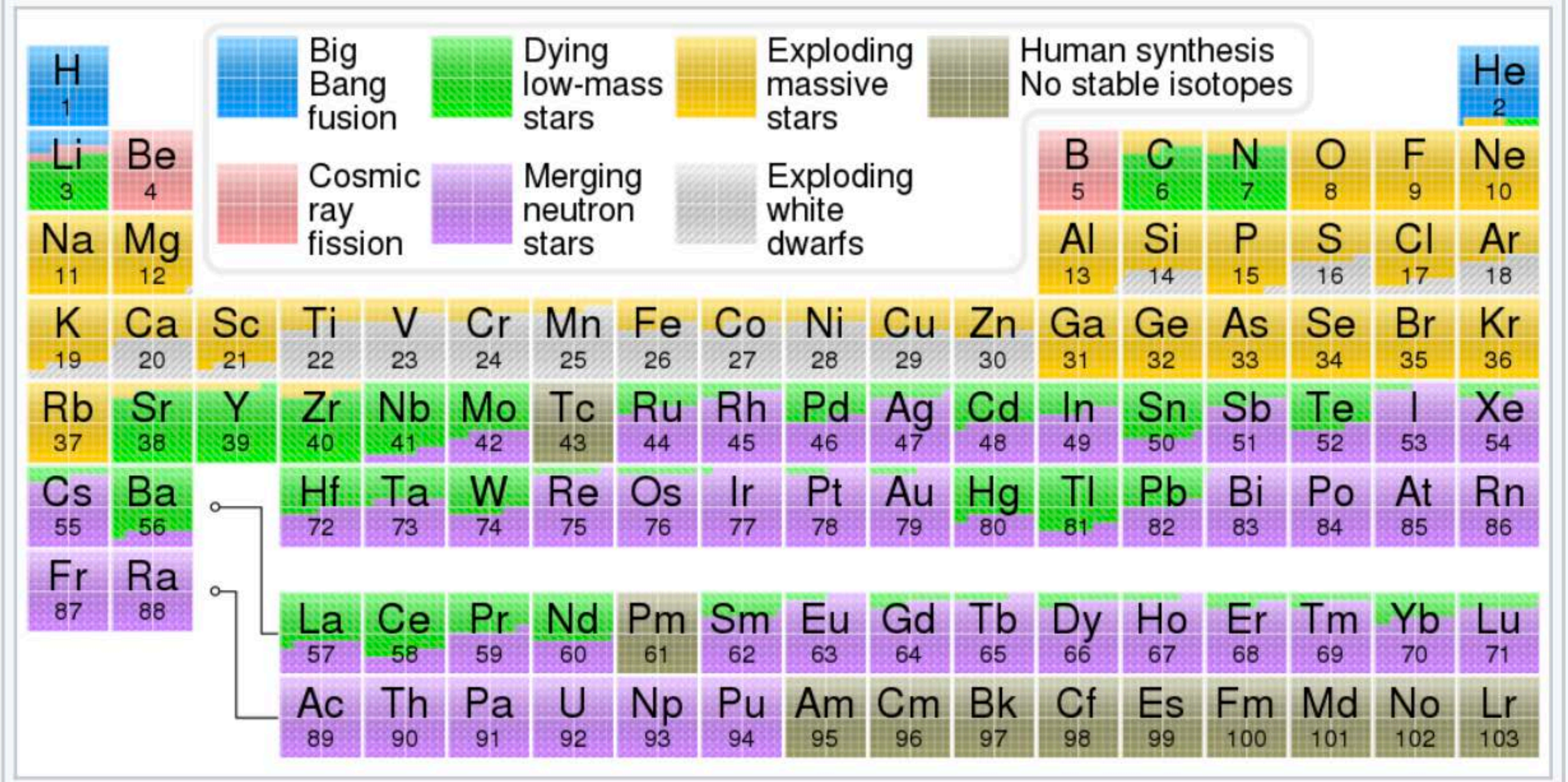
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

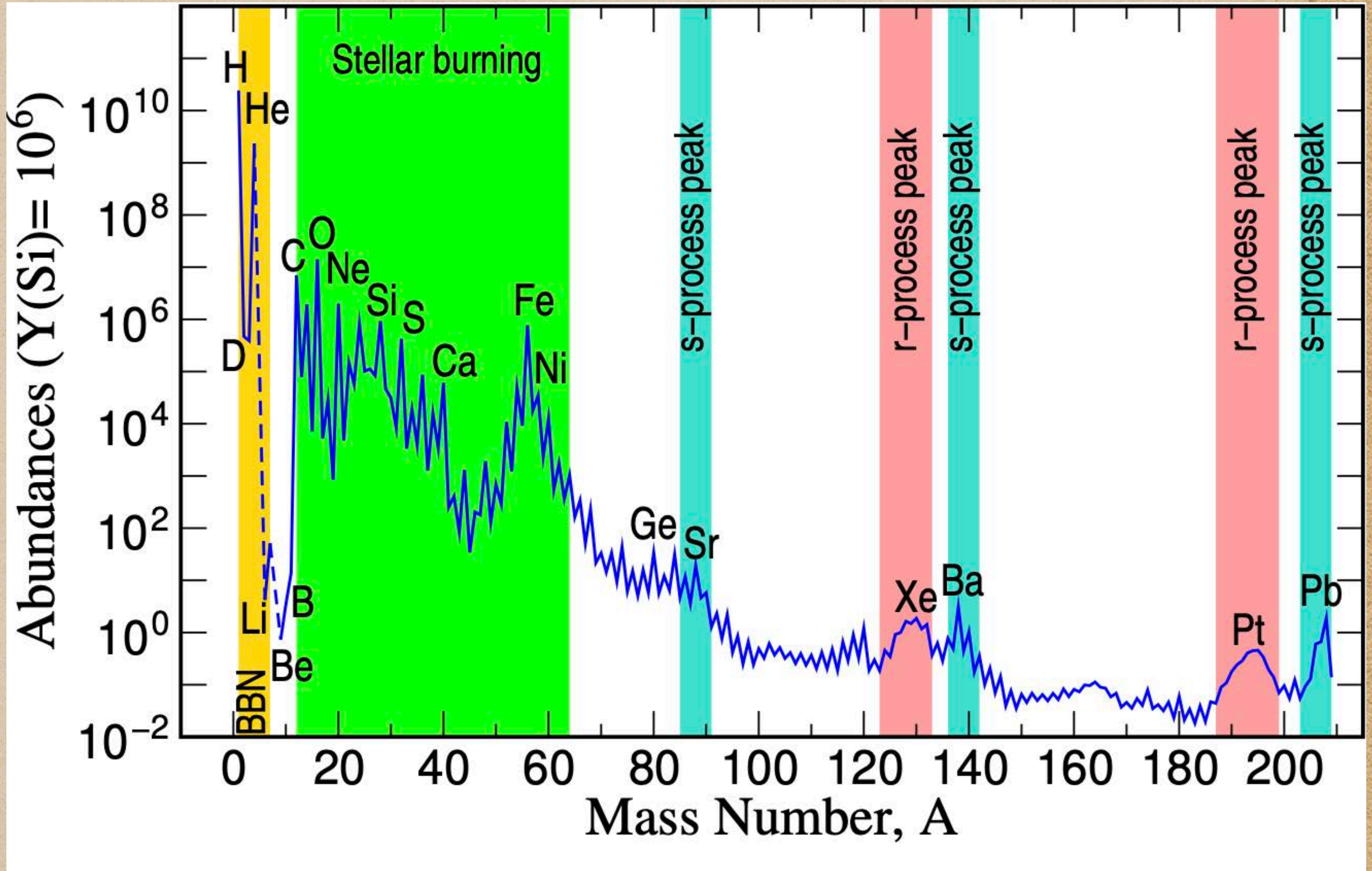
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

*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.

# 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

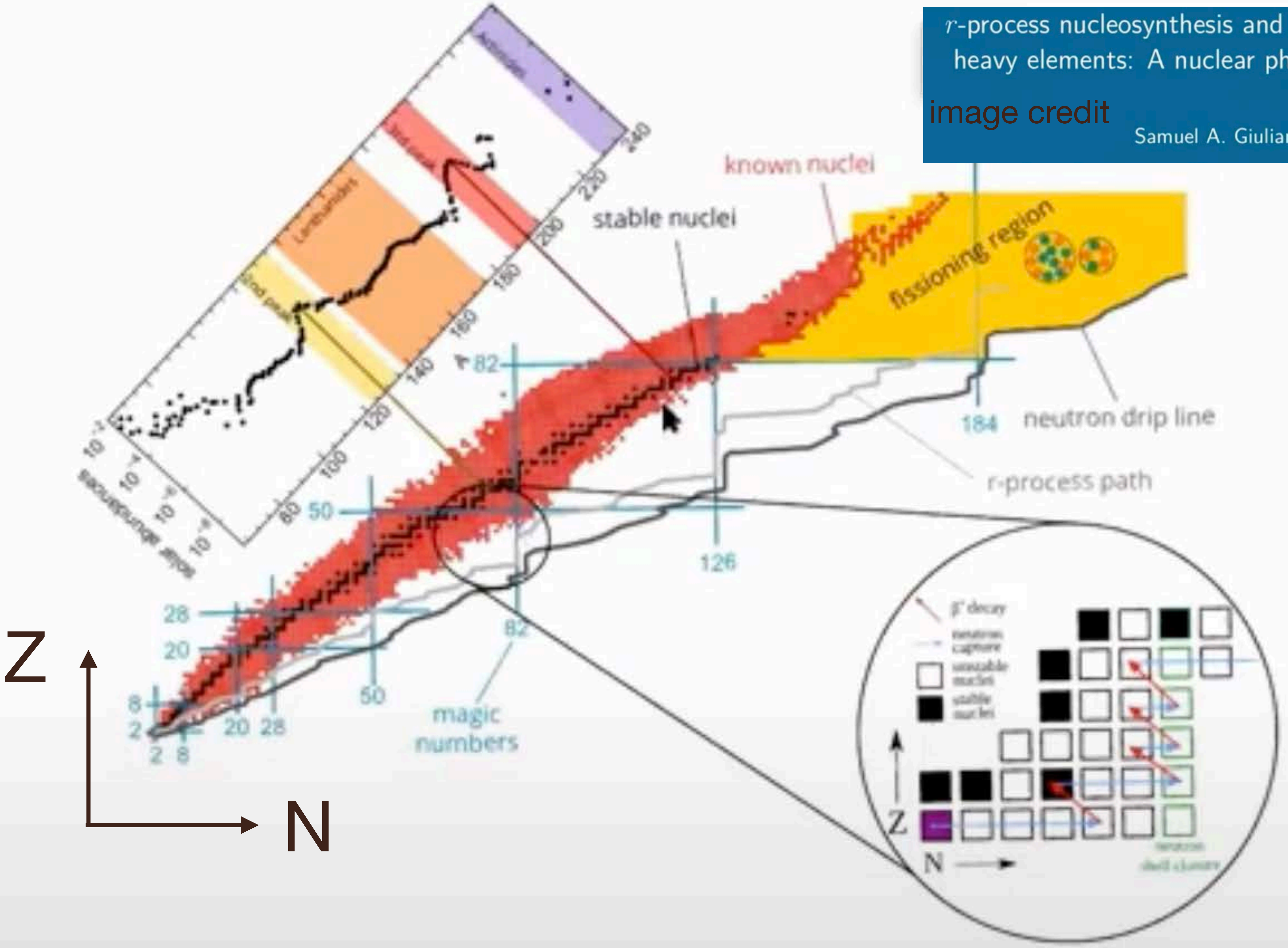
B$^2$FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

$r$(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

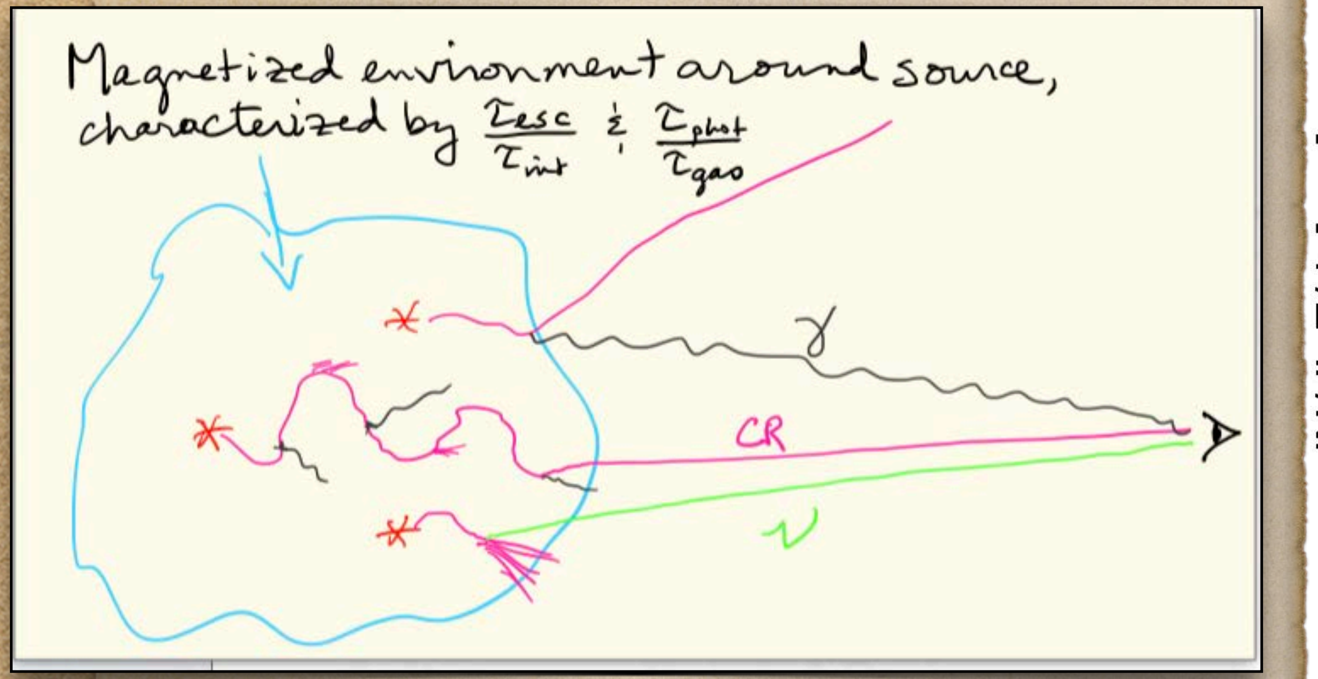
$r$-process nucleosynthesis and the production of heavy elements: A nuclear physics perspective

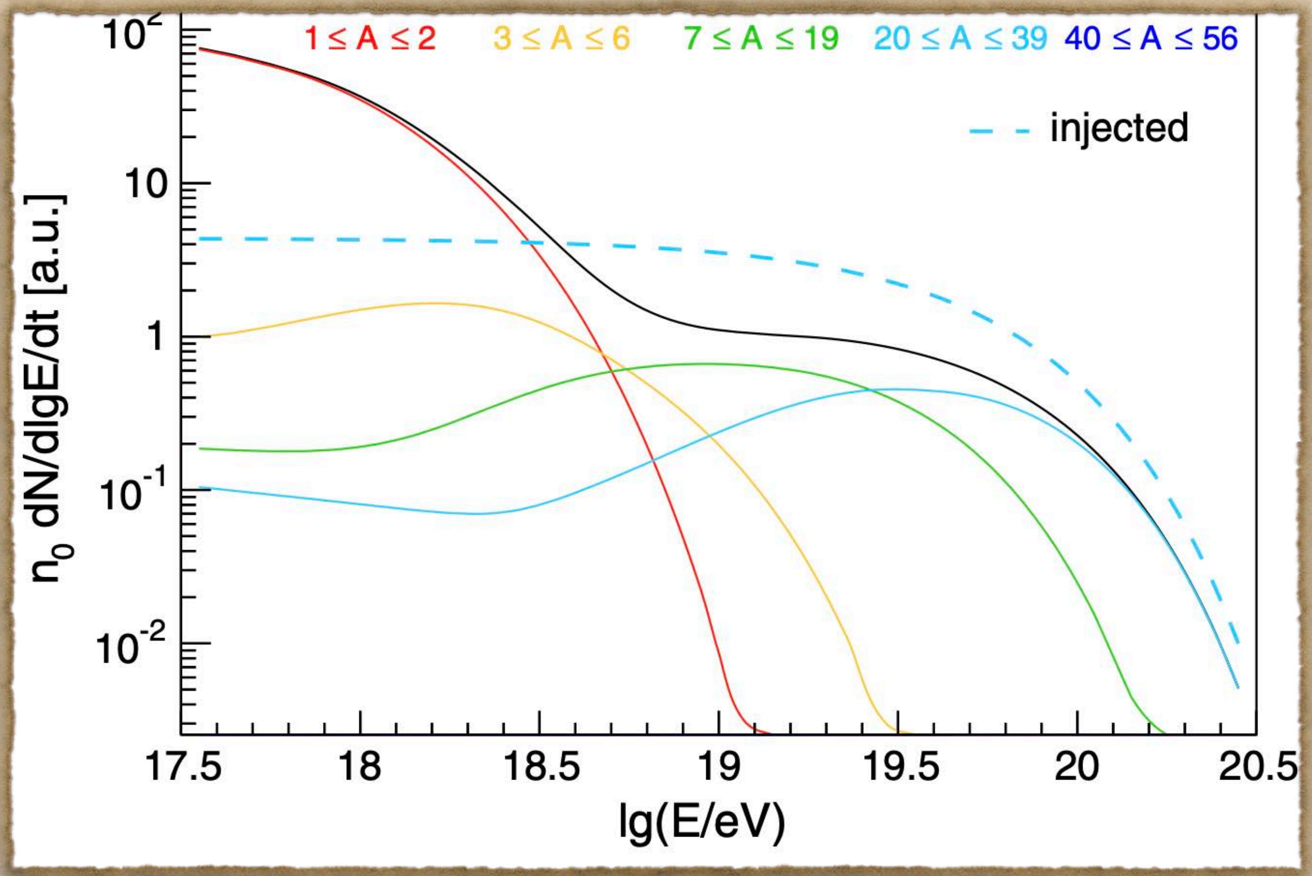
image credit Samuel A. Giuliani

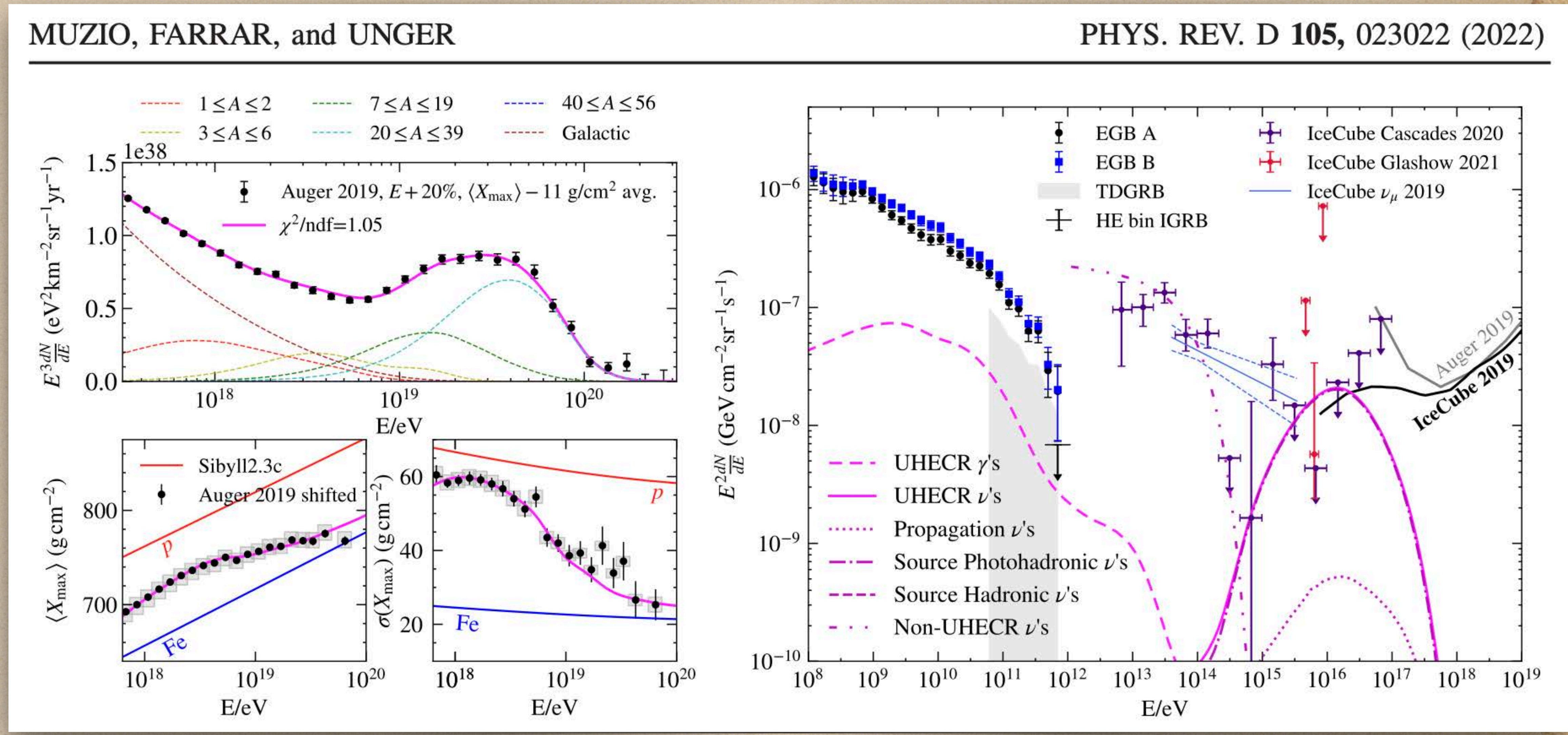



- The path to heavier nuclei goes through neutron-rich nuclei.

# 20 PeV neutrinos come from UHECRs




- "UFA" mechanism* gives good fit to spectrum & composition
- Each nucleon in UHECR carries E ≈ 4 x Ze/ A EV ≈ 2 EeV
- Interacts with photon in the environment of accelerator → **π**

with E ≈ 80 PeV → $E_\nu$ ≈ 20 PeV

*Unger, GF, Anchordoqui 2015

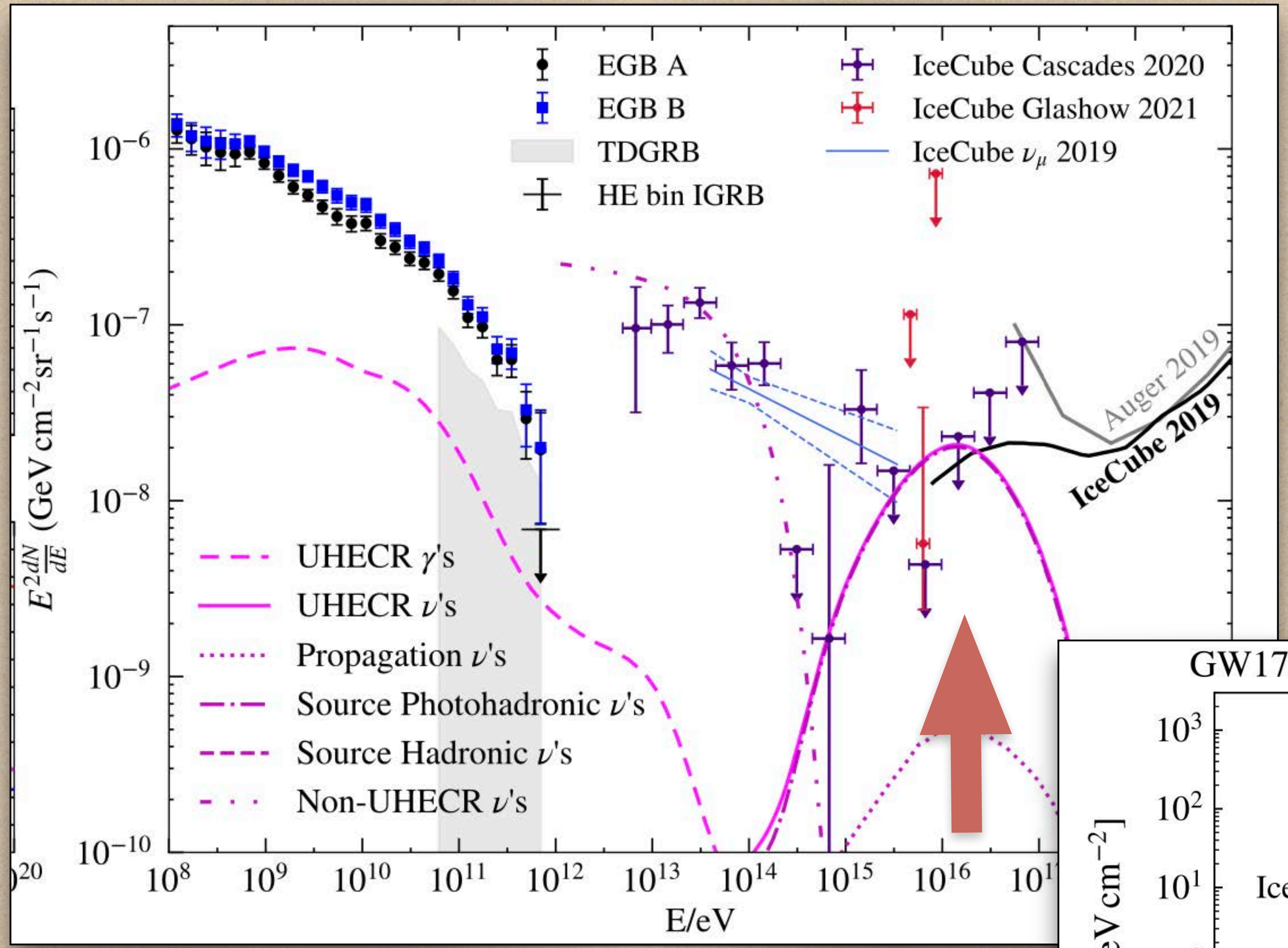
# Future test of BNS-merger origin:

## ≈20 PeV neutrinos coincident with GW from BNS mergers

- UHECRs interact while escaping the source, producing $\nu$'s with $E_\nu \approx 20$ PeV

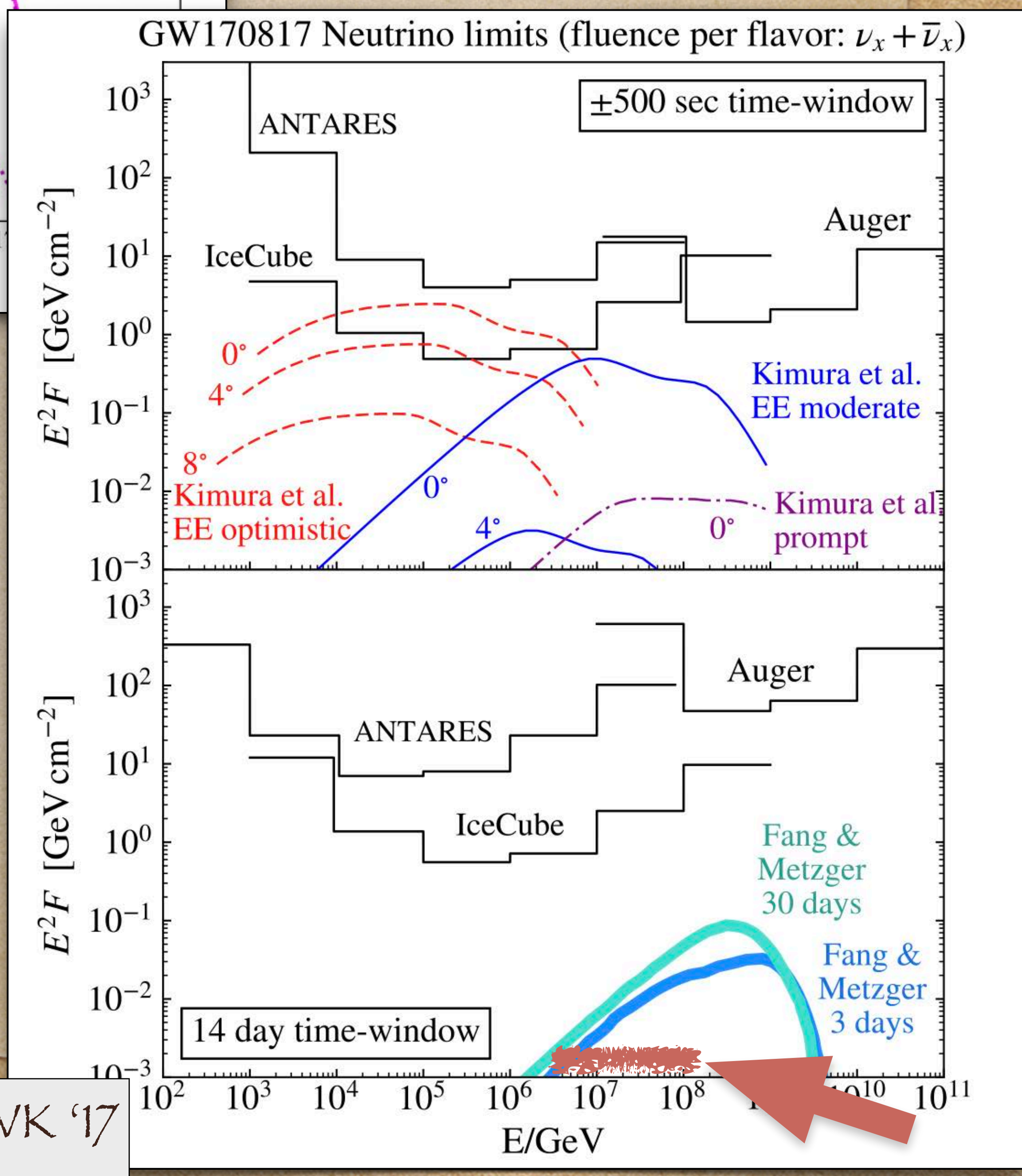
⇒ Every ≈ 20 PeV $\nu$ should be accompanied by a gravitational wave from the NS merger.

CE+ET+IC-Gen2 x few yrs: very promising.




Muzio, GF, Unger '22

- GW170817 should also have been accompanied by 20 PeV neutrinos but estimated fluence for most favorable case of aligned jet << 0.15 GeV cm$^{-2}$ per flavor. Sensitivity not adequate by orders of magnitude



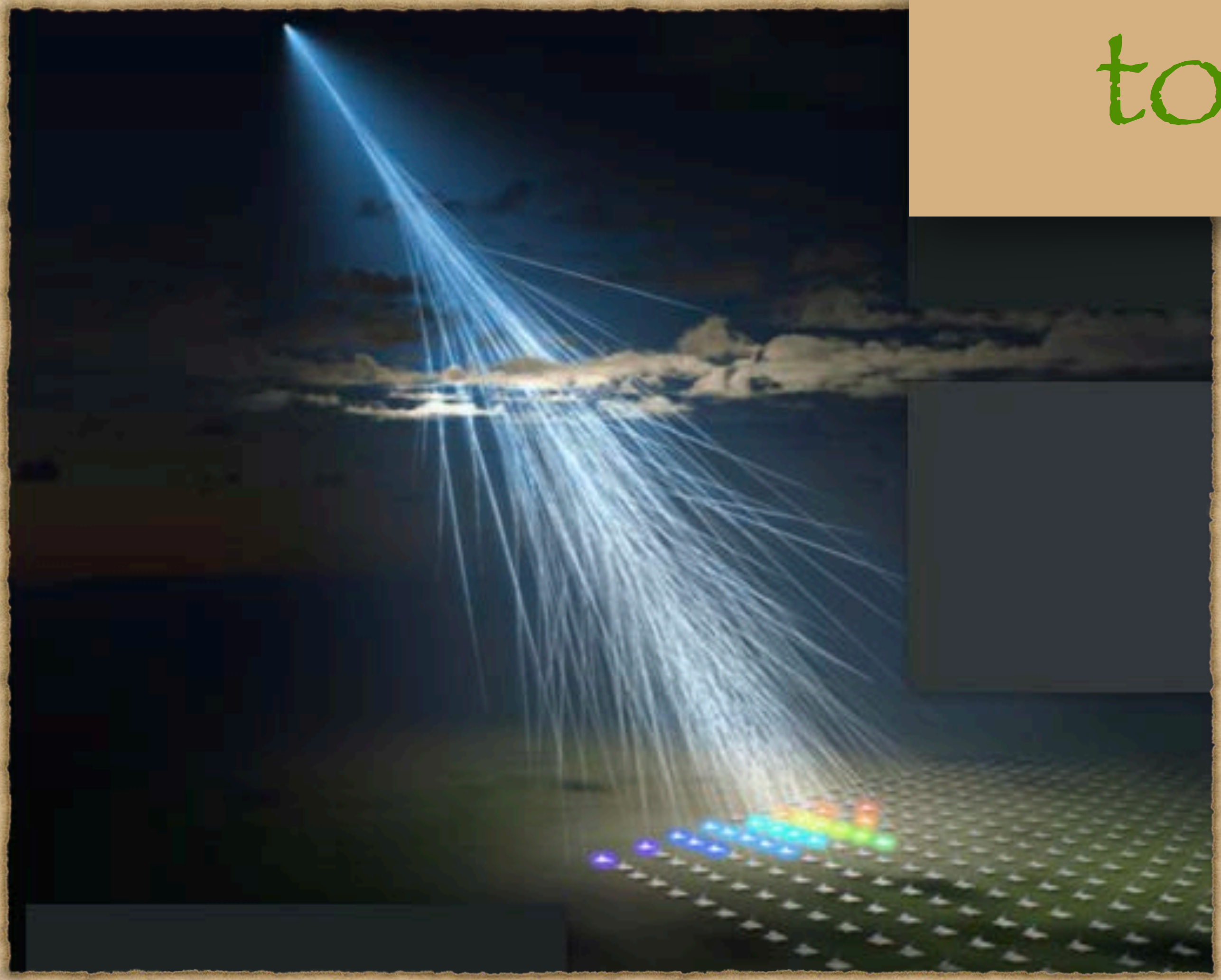

Antares, IceCube, Auger, LVK '17

# Review: Source candidates vs key constraints

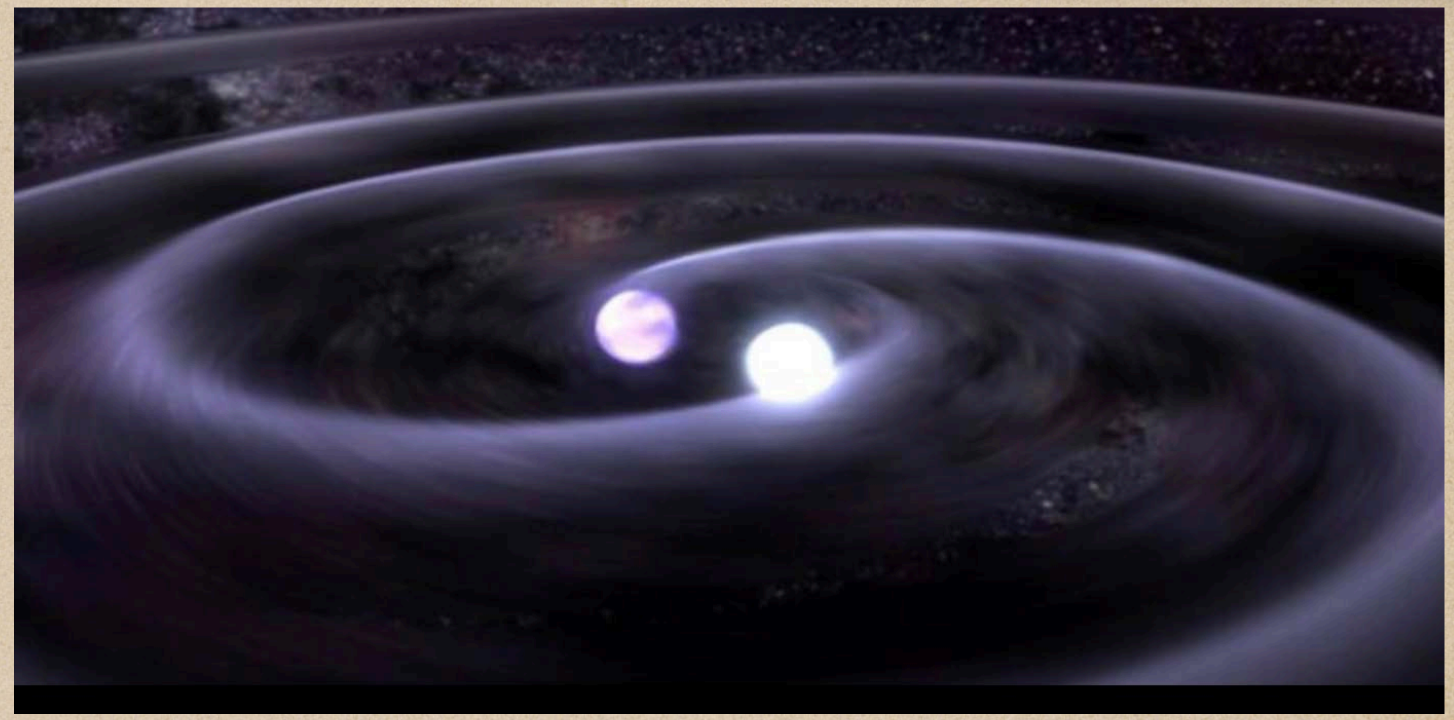
| | $n_S \gtrsim 10^{-3.5}$ $Mpc^{-3}$ | energy injection | ordinary galaxy | Universal $R_{max}$ | Highest energy events |
|---|---|---|---|---|---|
| Powerful AGN | [✘] | ✔ | ✘ | ✘ | ✘ |
| Long GRBs | [✘] | ✘ | ✘ | ✘ | ✘ |
| TidalDistruption Events | ? | ? | ✔ | ✘ | ✘ |
| Accretion Shocks | ? | ? |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

All can satisfy Hillas size > Larmor radius

Congratulations, George & Baha! — looking forward to your many more great future accomplishments!!!



# Summary

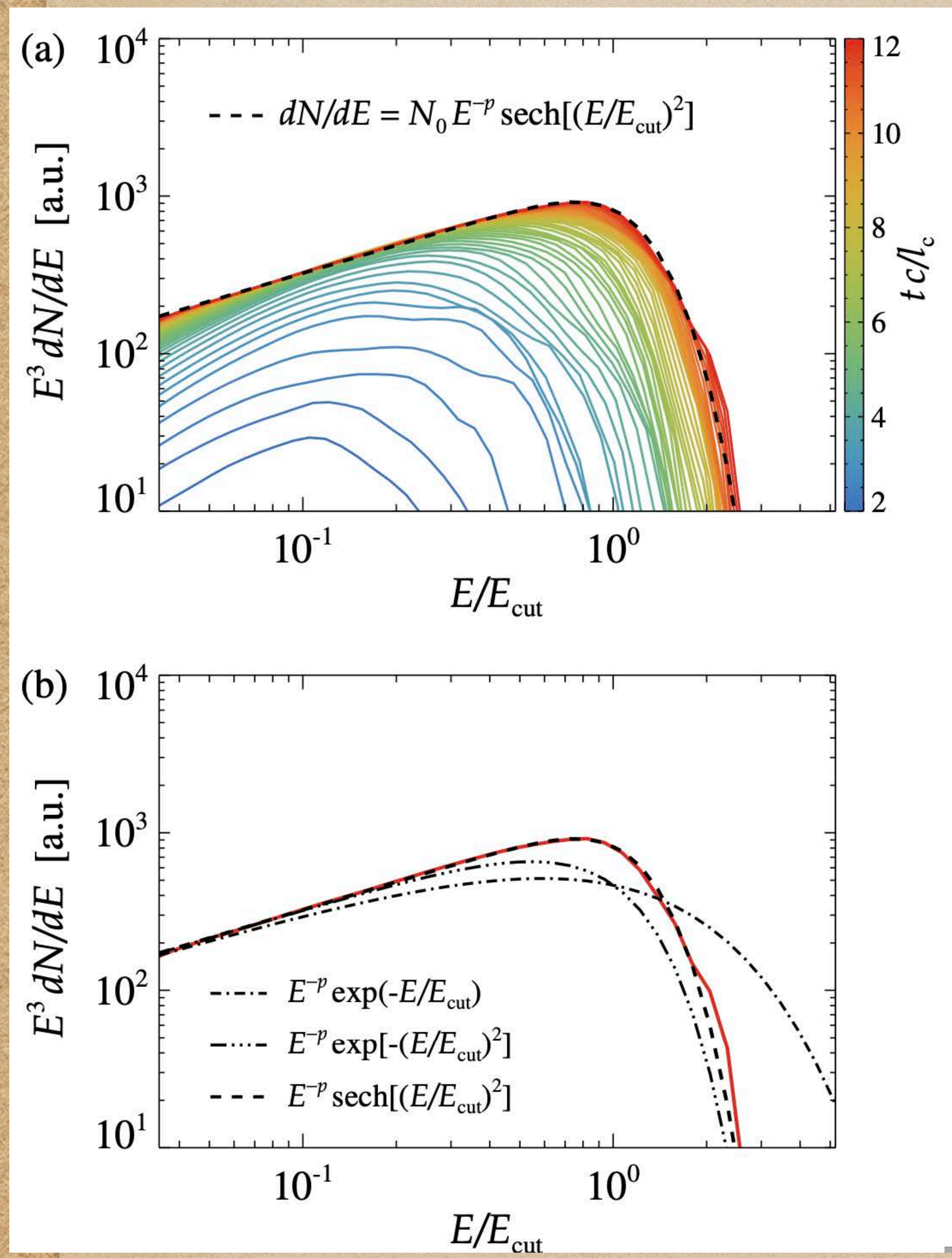


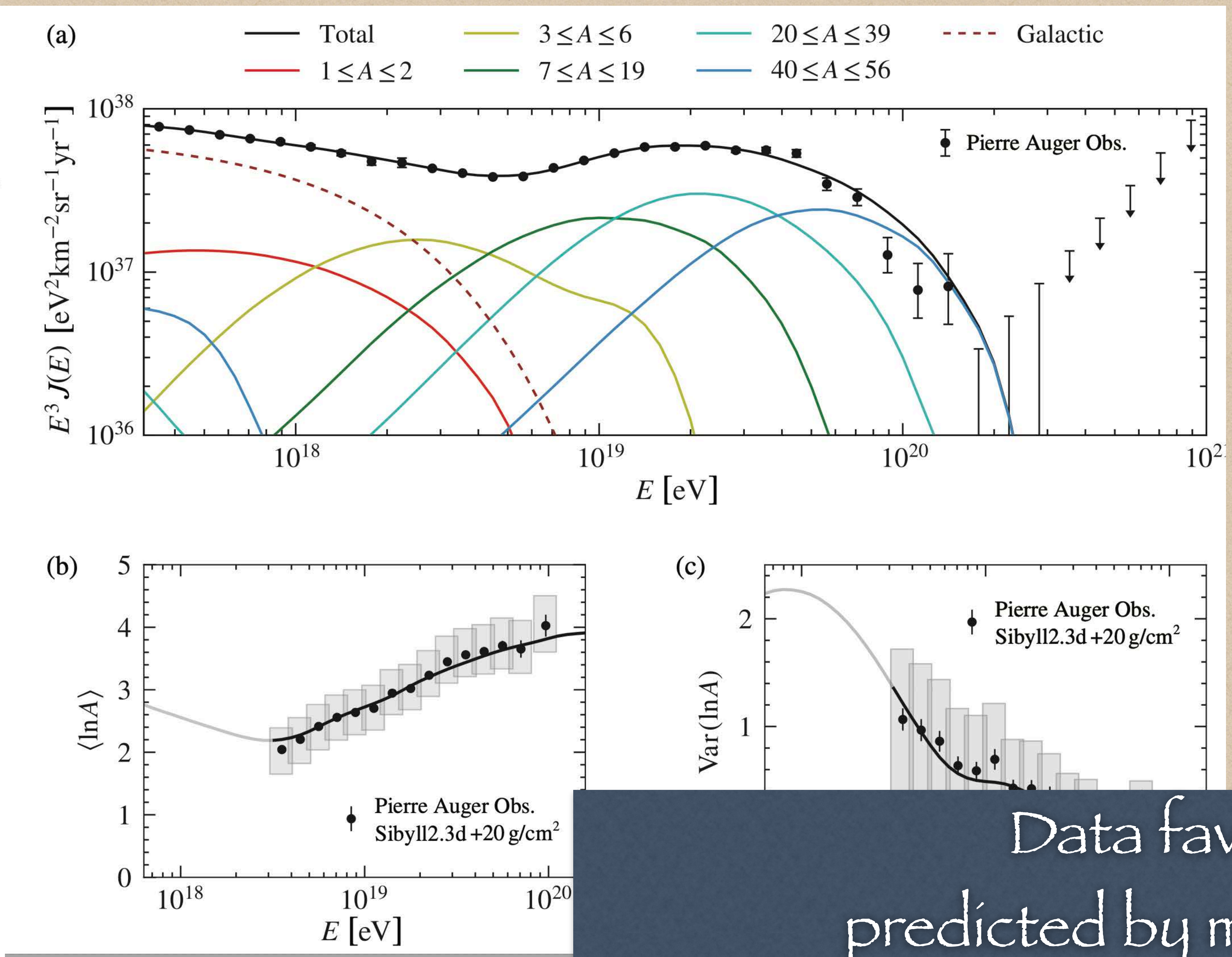
## New suggestion: UHECRs are produced in binary NS mergers.

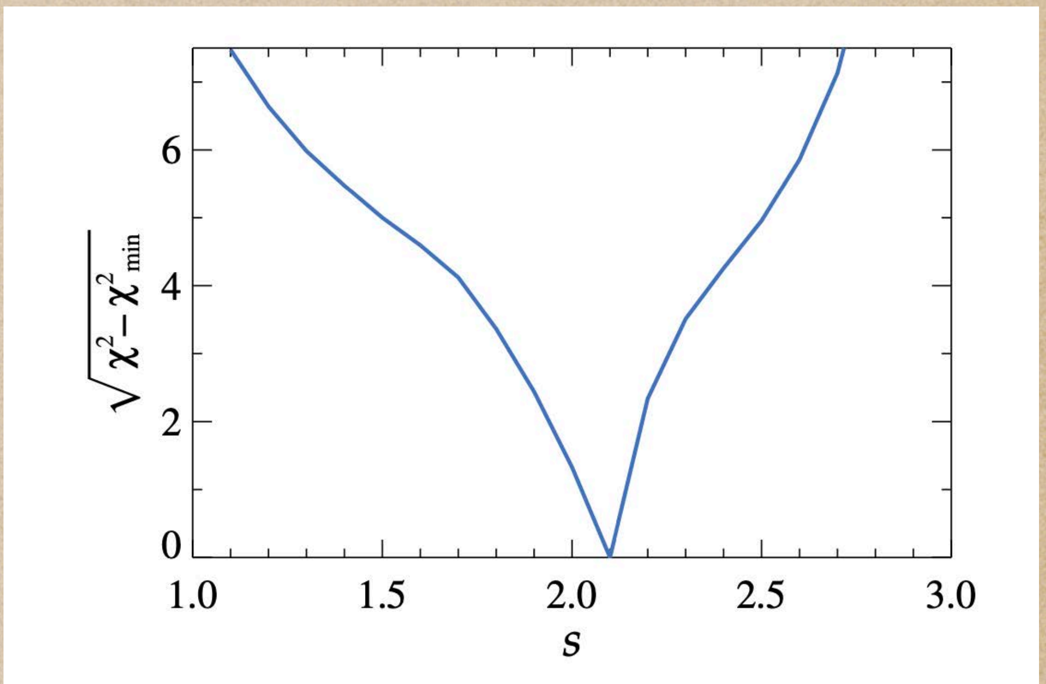
- Uniquely, can probably satisfy all requirements:
  - Universal Maximum Rigidity explained.
  - Can produce all CRs (dependent on BNS merger rate & power in CRs)
- Highest energy events are r-process nuclei
- Should see coincidences between ≈20 PeV neutrinos and GWs from BNS-merger

# UHECR data can discriminate between Acceleration Mechanisms!

L. Comisso, GRF, M. Muzio 2410.05546




Data favor the cutoff
predicted by magnetic turbulence
acceleration over that of diffusive shock acceleration
sech$(E/E_{cut})$^2 rather than exp$(-E/E_{cut})$