

The Power of Neutrinos

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arXiv: 2405.112004 & PRL 2025
arXiv: 2506.22625 & ApJL 2025
to appear soon: A. Suliga+GRF



Bravo and thanks to Francis,
the colleagues who worked so hard
and well to make IceCube, and NSF!!!

Strong indirect evidence →

***UHECRs are produced in
Binary Neutron Star Mergers***

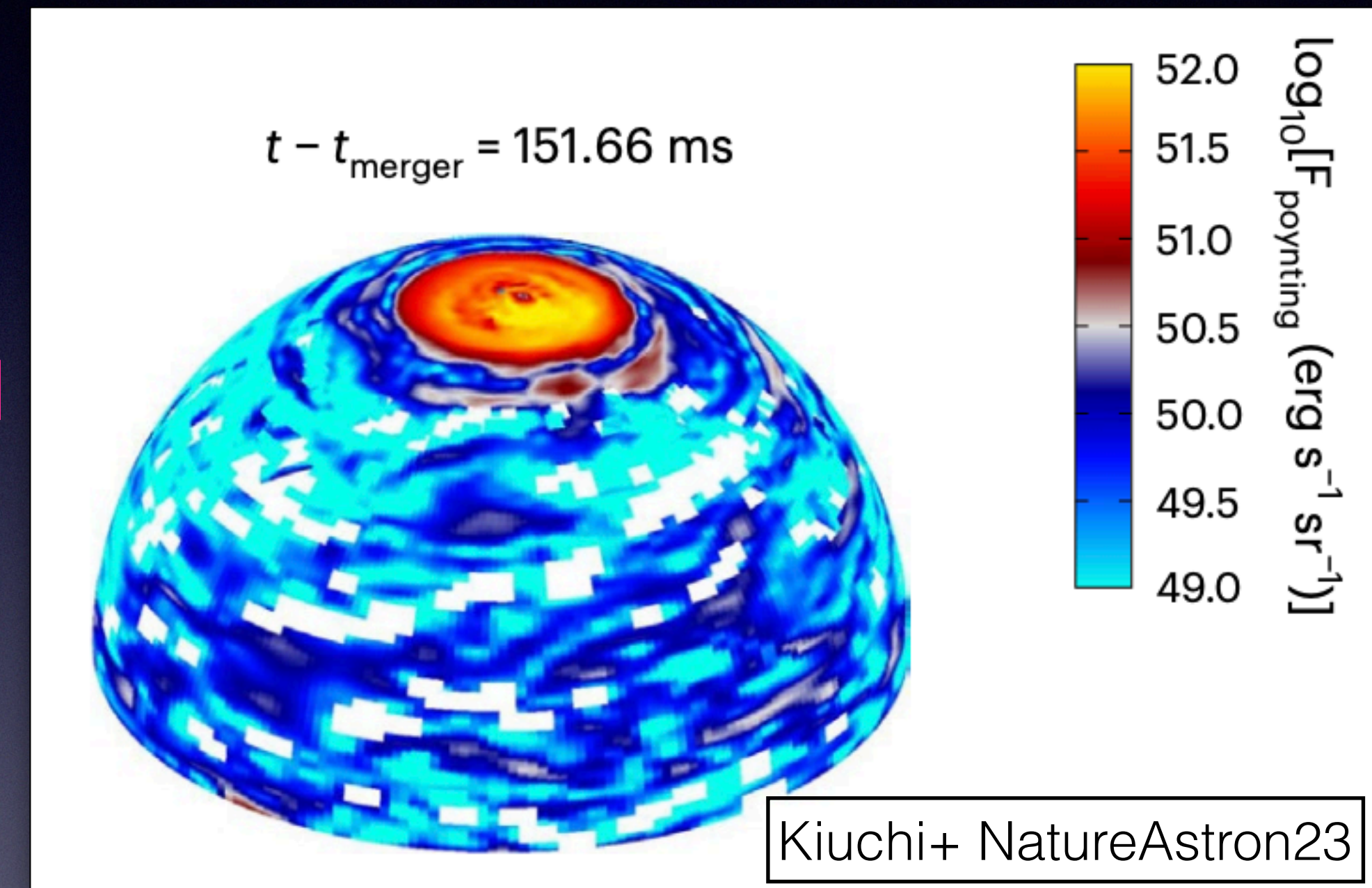
How to confirm it?

Binary Neutron Star Mergers

are only (currently known) source candidate satisfying all criteria

- Transient, but not long GRB, AGN, TDE ...
EhlertOikonomouUnger23
- BNS Mergers: Universal rigidity spectrum explained
 - Mass range of binary NS's is narrow
 - Magnetic field is generated by gravitational dynamo
Kiuchi+ NatureAstron23

➔ *Magnetic fields have nearly the same strength & structure in all BNSM's*



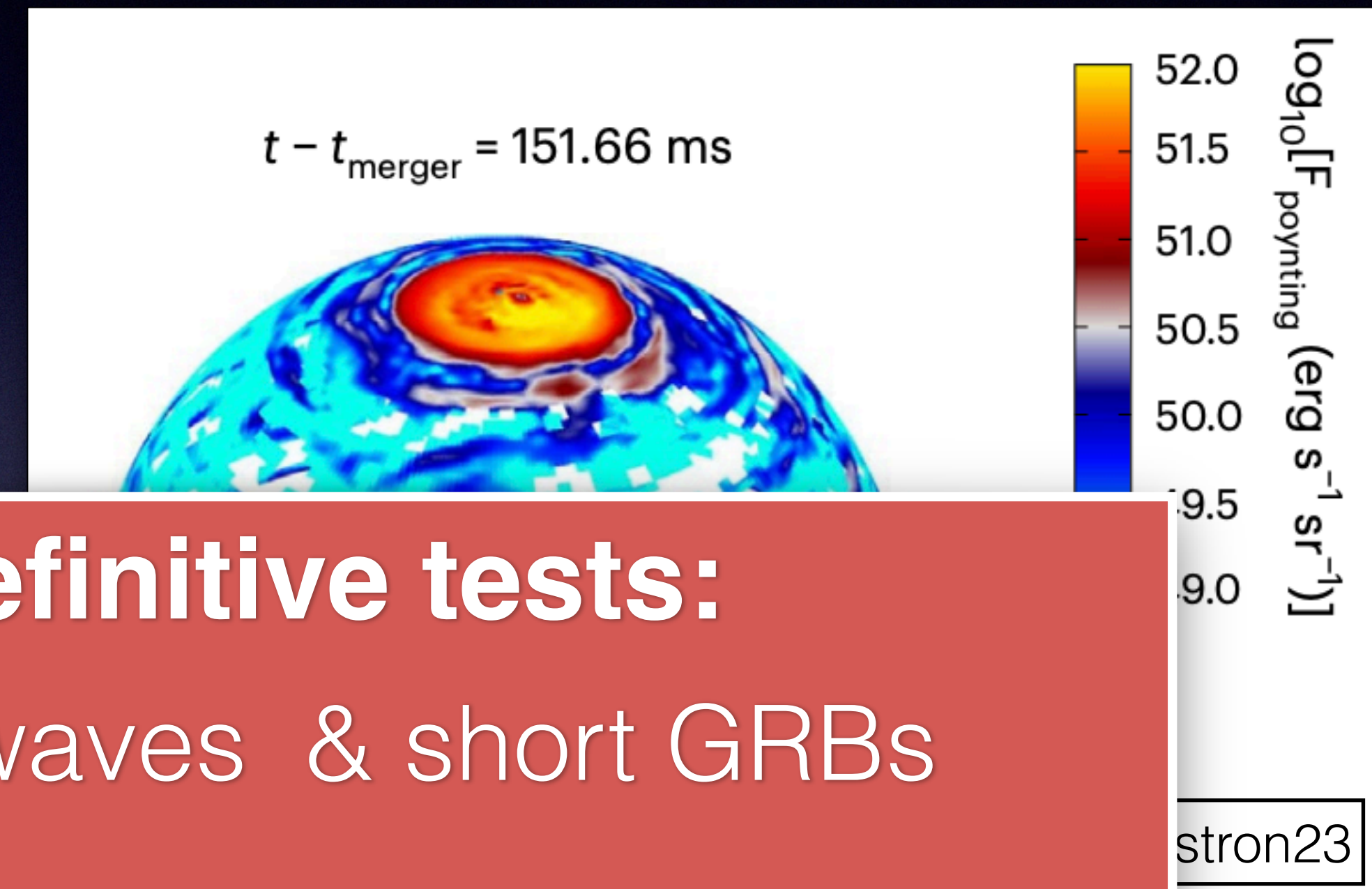
Binary Neutron Star Mergers

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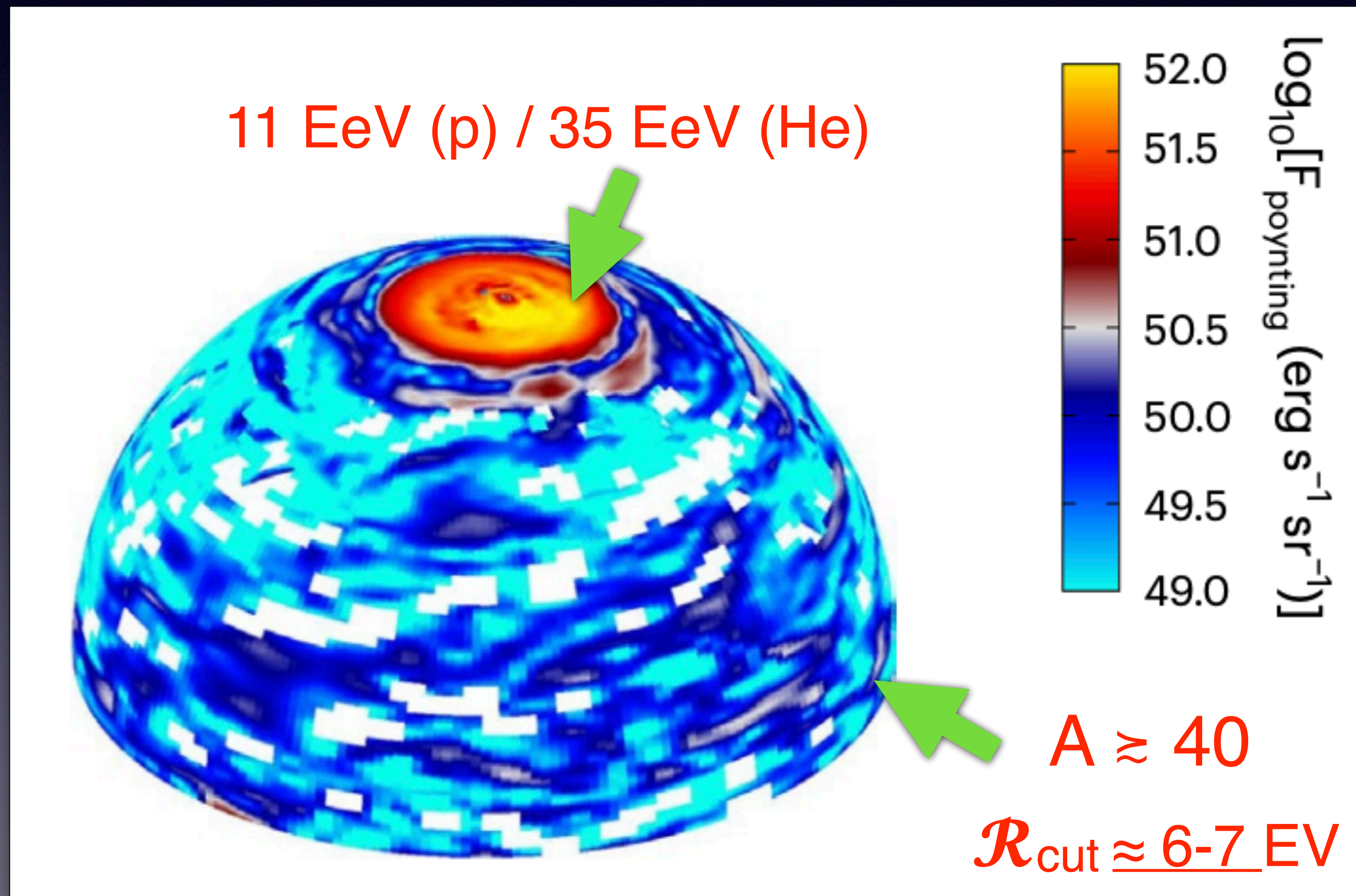
- BNSM: Universal rigidity spectrum explained:



Clean predictions enable definitive tests:

- EHE ν 's correlating with gravitational waves & short GRBs
- May have UHECRs with $Z > 26$
- ✓ BNS merger $\rightarrow$ initial B $\rightarrow$ (correctly) predicts spectrum & cutoff
- two populations of light CRs (p or He): jet and spallation
- UHE ν spectrum peaks at higher energy (bc sources at lower z)

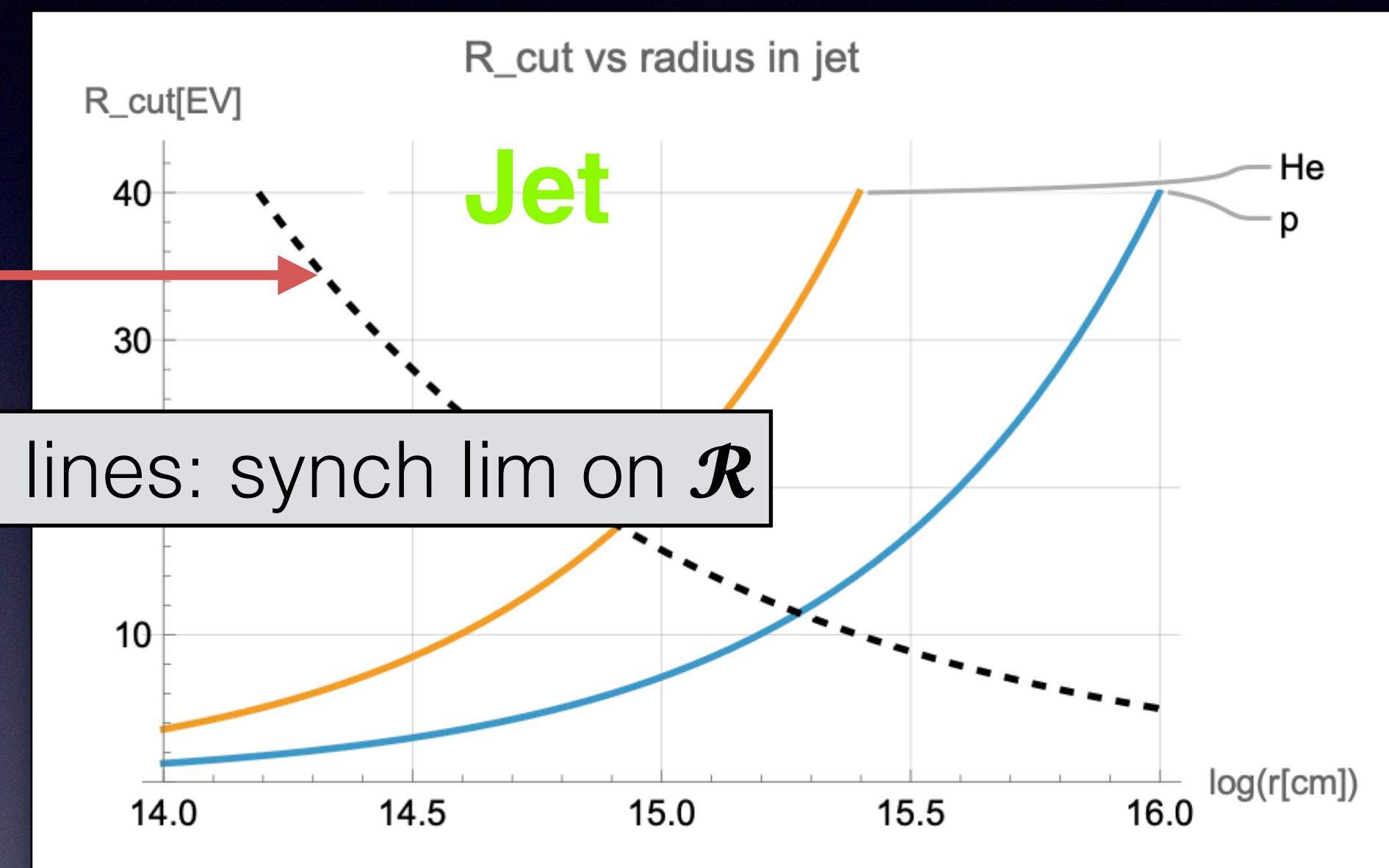
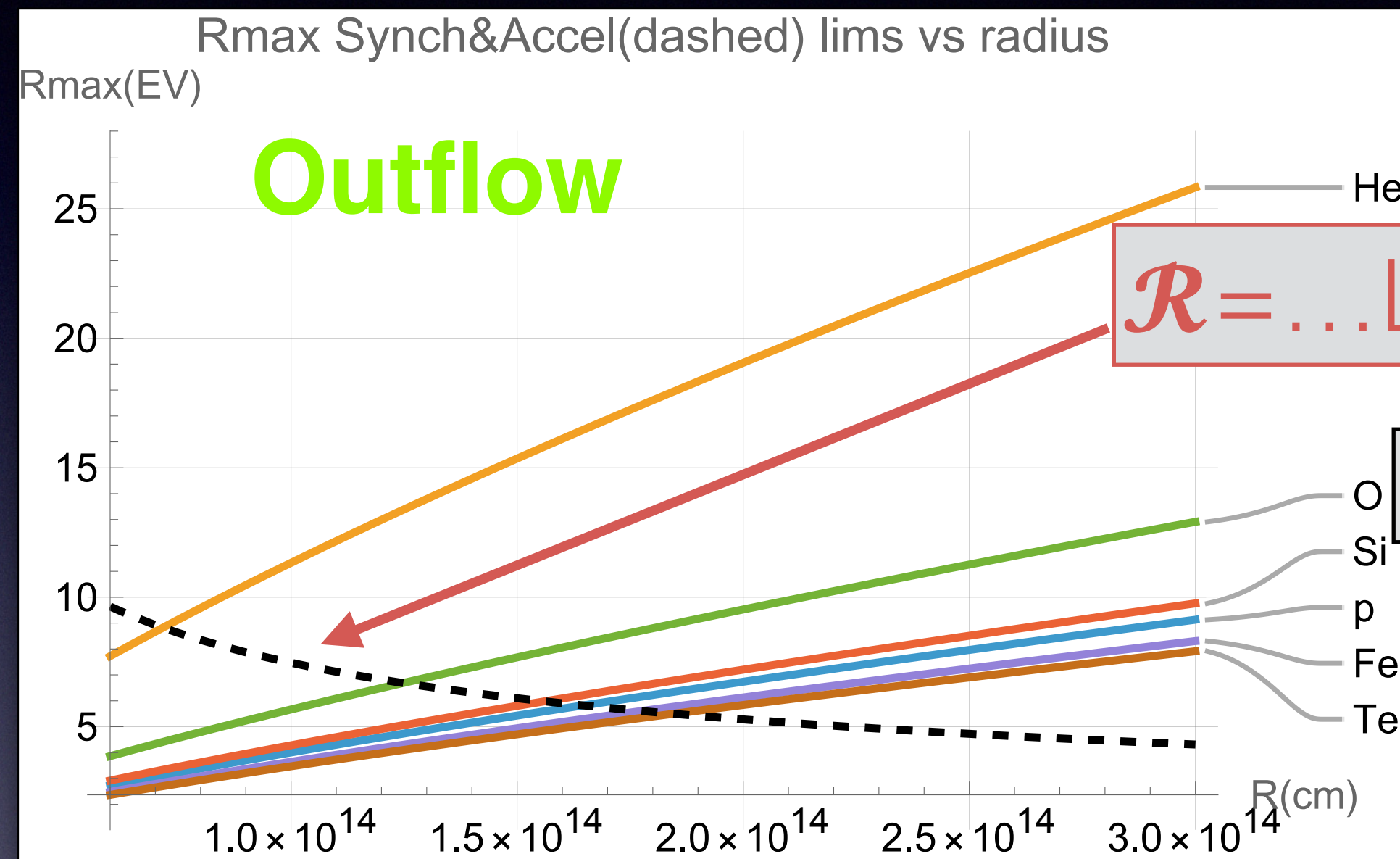
Two distinct populations of **UHECRs**: (1) **accelerated in the turbulent outflow**, (2) **accelerated in the jets**



- (e.g., Perego+22)
- **BNS nucleosynthesis:**
 - jets contain p or He
 - in outflow, $A \gtrsim 40$
- Kiuchi+ NatureAstron23
- Jets have 10x higher field strength → jet p or He reach higher E

No-free-parameter *prediction* of $\mathcal{R}_{\text{cut}}$

GRF ApJL25 & AAS YouTube



- **Turbulent outflow:** $\mathcal{R}_{\text{cut}} \{p, \text{He}, \text{O}, \text{Si}, \text{Fe}, \text{Te}\} \approx \{6.2, 9.4, \underline{7.1}, \underline{6.3}, \underline{6.0}, \underline{5.9}\} \text{ EV}$
- **Jet** (analyzed as if magnetized turbulence): $E_{\text{cut}} \approx 11 \text{ EeV}$ (proton), $E_{\text{cut}} \approx 35 \text{ EeV}$ (He)

Higher energy p or He component predicted from jet

Strong indirect evidence →

***UHECRs are produced in
Binary Neutron Star Mergers***

How to confirm it?

BNS merger scenario implies

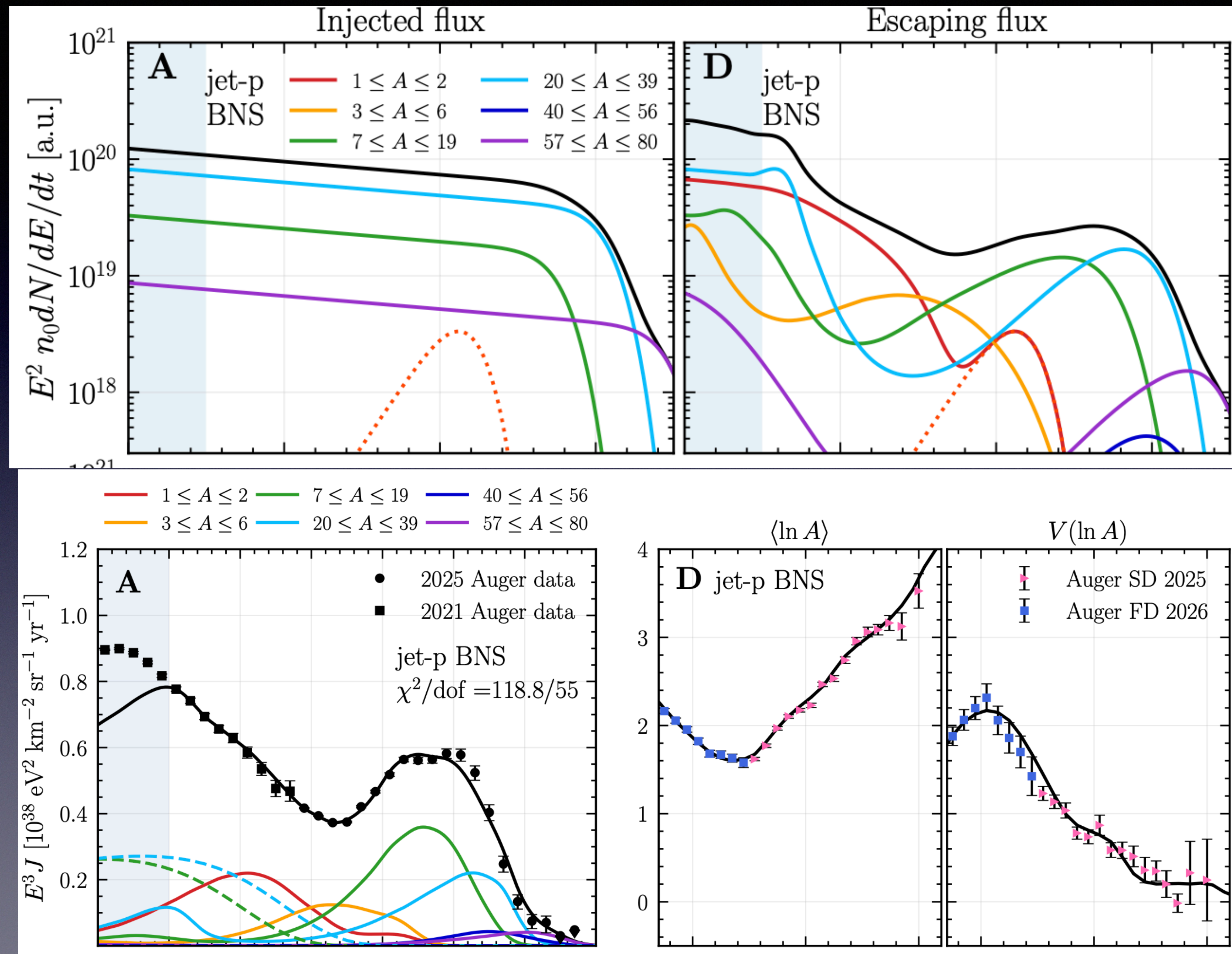
- ✓ Minimal source population variance, $\mathcal{R}_{\text{cut}} \approx \underline{6-7 \text{ EV}}$
- ✓ **Two populations of protons:** from jet, $E_{\text{cut}} \gtrsim 11 \text{ EeV}$;
from photo-disintegration of outflow, $E_{\text{cut}} \approx \mathcal{R}_{\text{cut}}/2 \approx \underline{6-7 \text{ EV}}$
- **Eroded r-process** ($A > 56$) among Ultrahigh Energy CRs?
- **Flux of UHE neutrinos** ($E_{\text{peak}} \approx 30 \text{ PeV}$)
- **GW- ν coincidences for UHE ν 's with time delay $\approx 1 \text{ day}$**

Today: new work with Anna Suliga



- Extend Unger's UFA code to include A up to 140
- Use Binary Neutron Star Merger (BNSM) source evolution
- "UFA" fit with mass groups $A=1, 14, 28, 56, 80$ (1st r-process peak)
- Fit with high energy (jet) proton or helium component

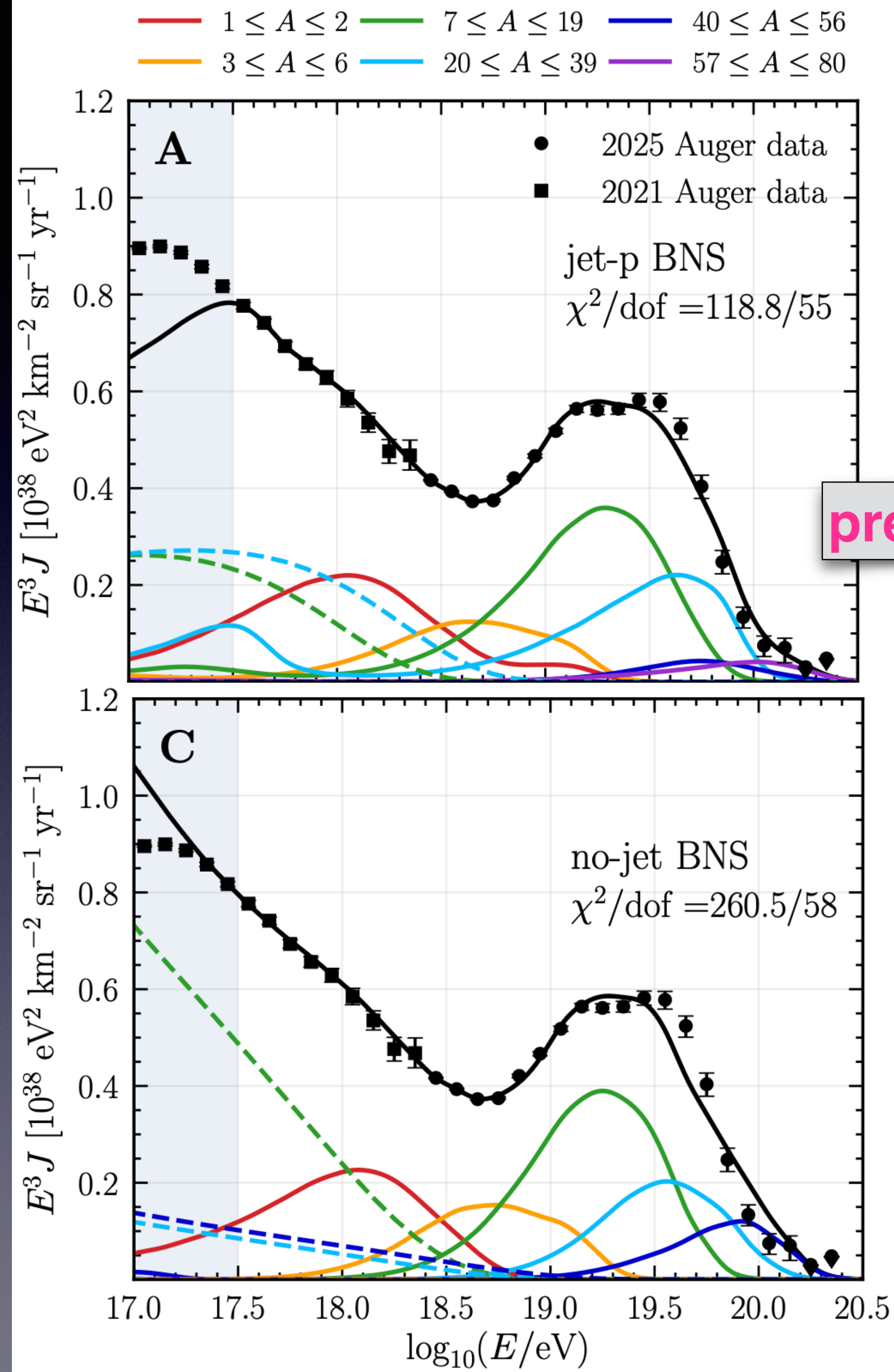
Interactions while
 escaping
 source environment
 are
 crucial to the UHECR
 spectrum
 & composition
 (“UFA”)



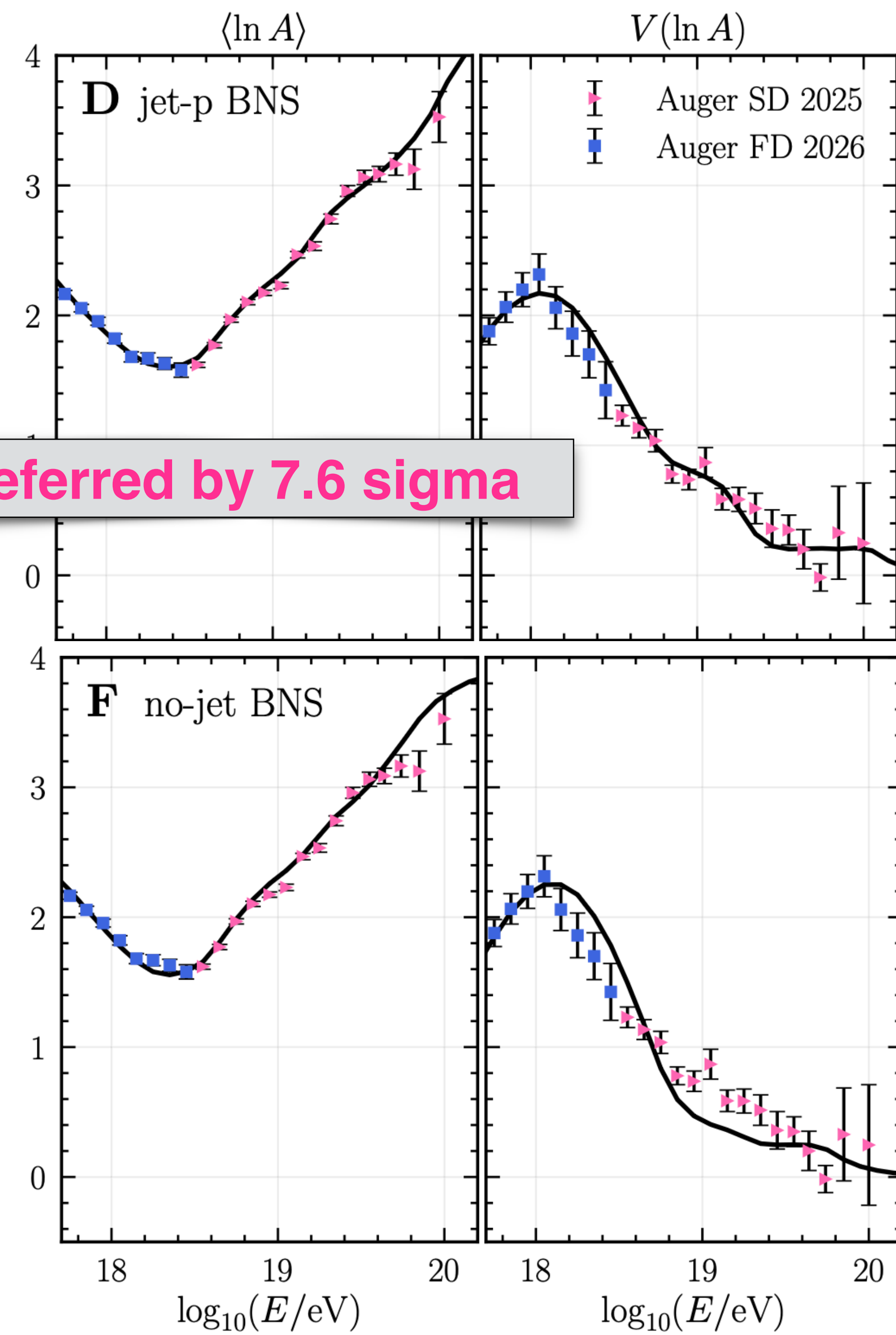
UHECR data vs best-fit models

jet & outflow

no jet



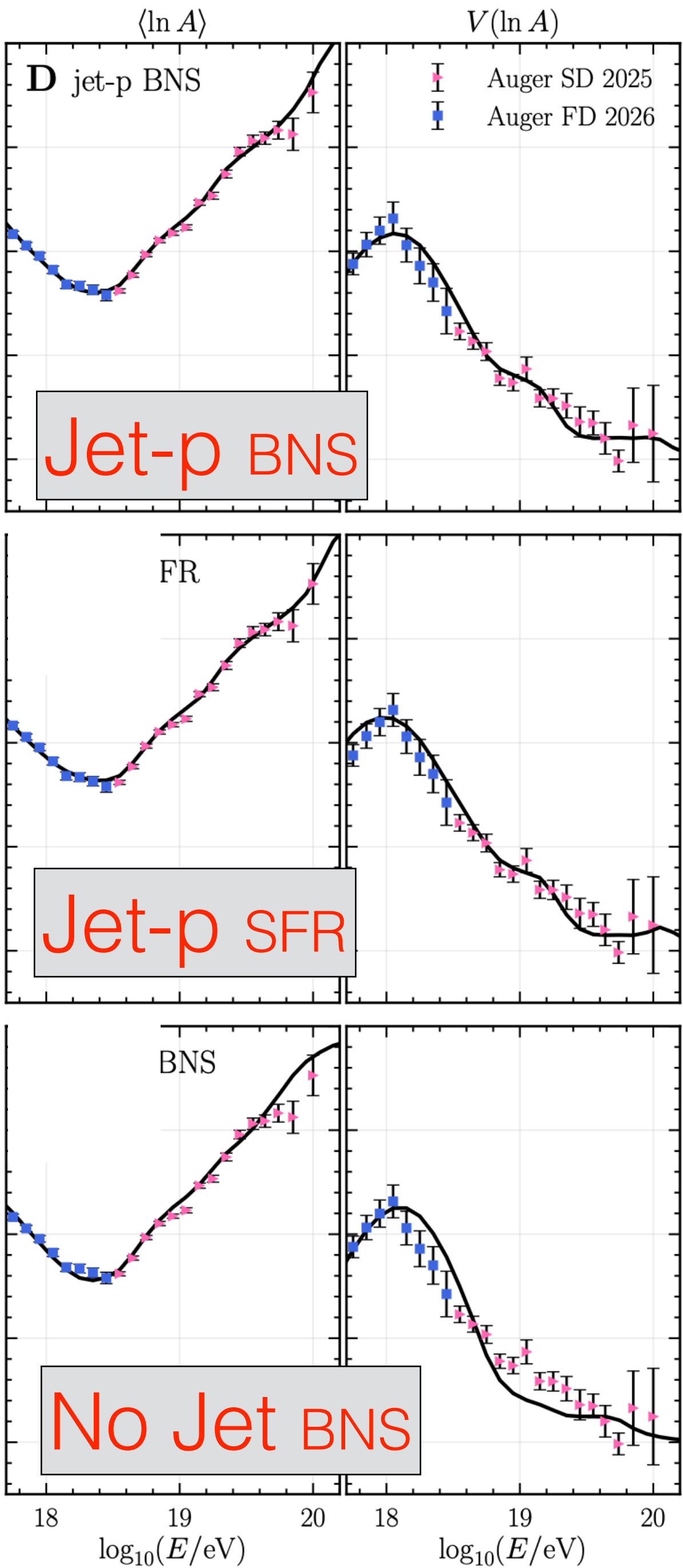
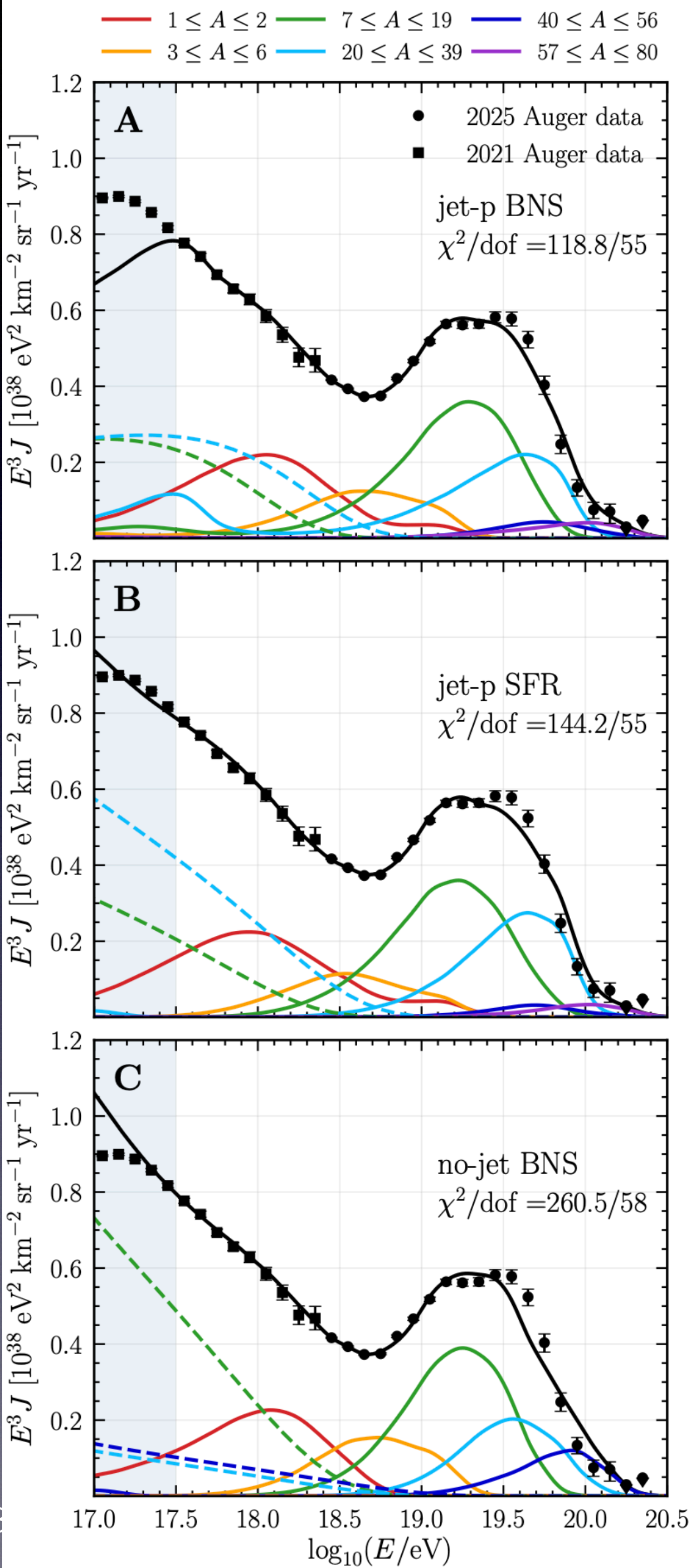
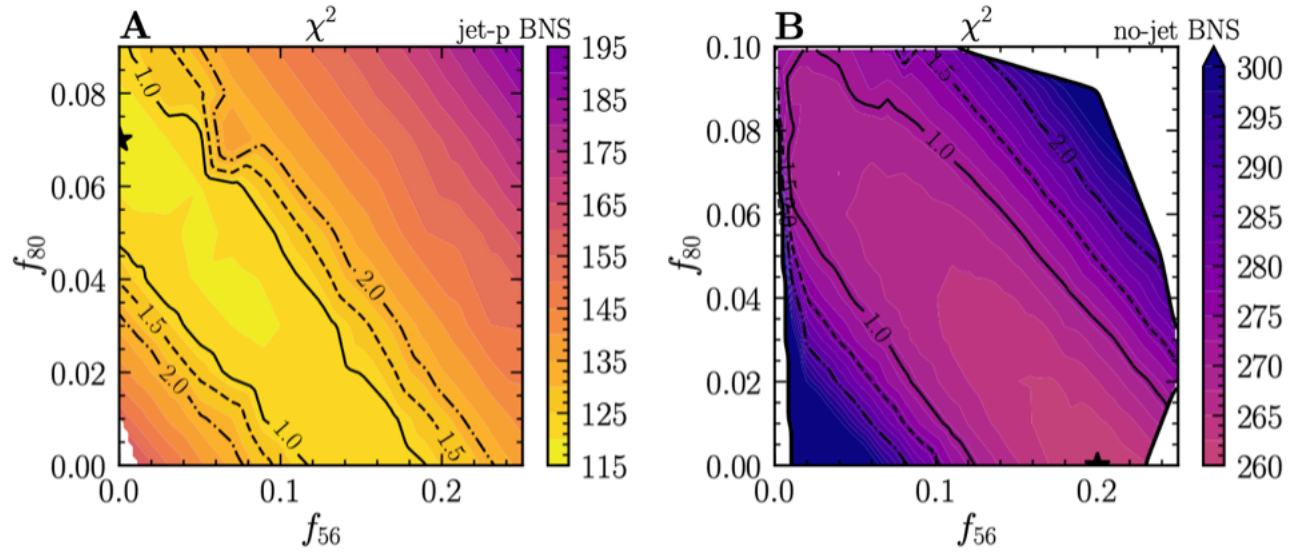
preferred by 7.6 sigma



Fit to Auger spectrum, $\langle \ln A \rangle$ & $V(\ln A)$

Key parameters of best-fit models:

	Jet-p BNS	Jet-p SFR	no jet BNS
$\chi^2_{\text{tot}}/\text{ndf}$	118.8/55 = 2.2	144.2/55 = 2.1	260.5/58 = 4.5
N_σ	favored by 7.6 sigma		
$R_{\text{cut,outflow}}$	7.2 EV	7.6 EV	7.1 EV
$E_{\text{cut,jet}}$	12 EeV	13 EeV	—
frac E_{jet}	0.05	0.07	—
Frac _{heavy}	0.07	0.04	—



Comparing models

Suliga-GF paper coming soon

5-10% r-process component favored

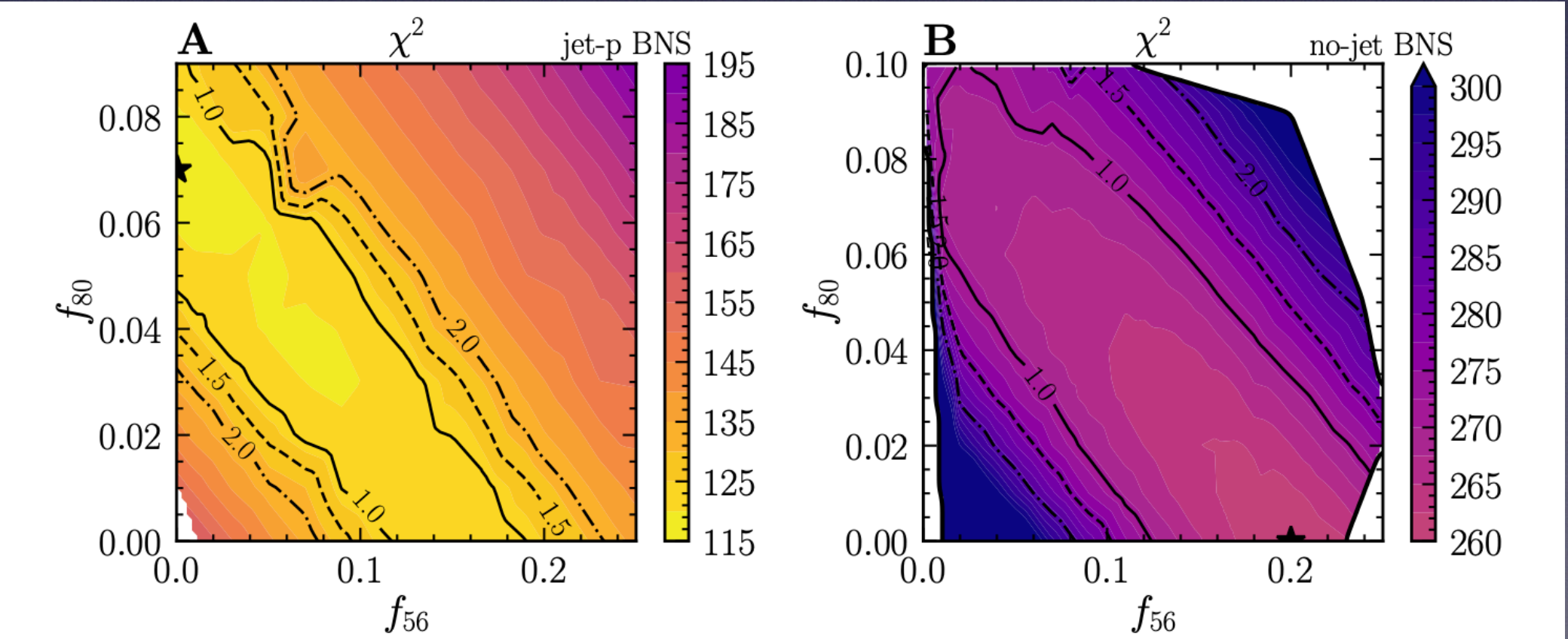


Figure 2: Fit quality (χ^2) as a function of the heavy-fractions. Best-fit model “jet-p BNS” (panel A) and “no-jet BNS” model (panel B).

Parameter	jet-p BNS sech	jet-p BNS exp	jet-p BNS shift	jet-p SFR	no-jet BNS	no-jet SFR
χ^2/ndf	118.8/55 =	124.3/55 =	99.9/55 =	144.2/55 =	260.5/58 =	320.2/58 =
	2.16	2.18	1.82	2.62	4.49	5.52
N_σ	7.6	7.2	8.9	6.1	–	–3.7
$\lg\langle N_{\text{int}}\rangle$	2.55	2.58	2.53	2.99	3.14	2.59
γ_{inj}	–2.11	–2.12	–2.13	–1.90	–2.14	–1.25
$\lg(R_{\text{max}}/V)$	18.86	18.85	18.92	18.88	18.85	18.81
$\lg(R_{\text{diff}}/V)$	18.01	17.93	18.04	15.58	15.89	16.63
r_{size}	7.0	6.7	7.4	$\gtrsim 100$	$\gtrsim 100$	$\gtrsim 100$
T [K]	563	568	578	756	1235	6044
$\lg(E^{\text{jet}}/\text{eV})$	19.08	18.72	19.34	19.12	–	–
γ^{jet}	≈ 0	≈ 0	–1.81	≈ 0	–	–
$\lg(f^{\text{jet}})$	–1.31	–1.29	–1.15	–1.19	–	–
f_1	≈ 0	≈ 0	≈ 0	≈ 0	0.02	0.33
f_{14}	0.27	0.27	0.07	0.21	0.65	0.52
f_{28}	0.66	0.62	0.82	0.75	0.13	0.13
f_{56}	≈ 0	0.07	4×10^{-3}	≈ 0	0.20	≈ 0
f_{80}	0.07	0.04	0.10	0.04	≈ 0	0.01

Highest energy UHECRs, above 130 EeV, are naturally explained!

GRF arXiv: 2405.112004 & PRL 2025

Events above $E_{\text{cut,Fe}} \approx 7 \text{ EV} \times 26 = 180 \text{ EeV}$ have had no good explanation. Now, r-process $\rightarrow$ natural!

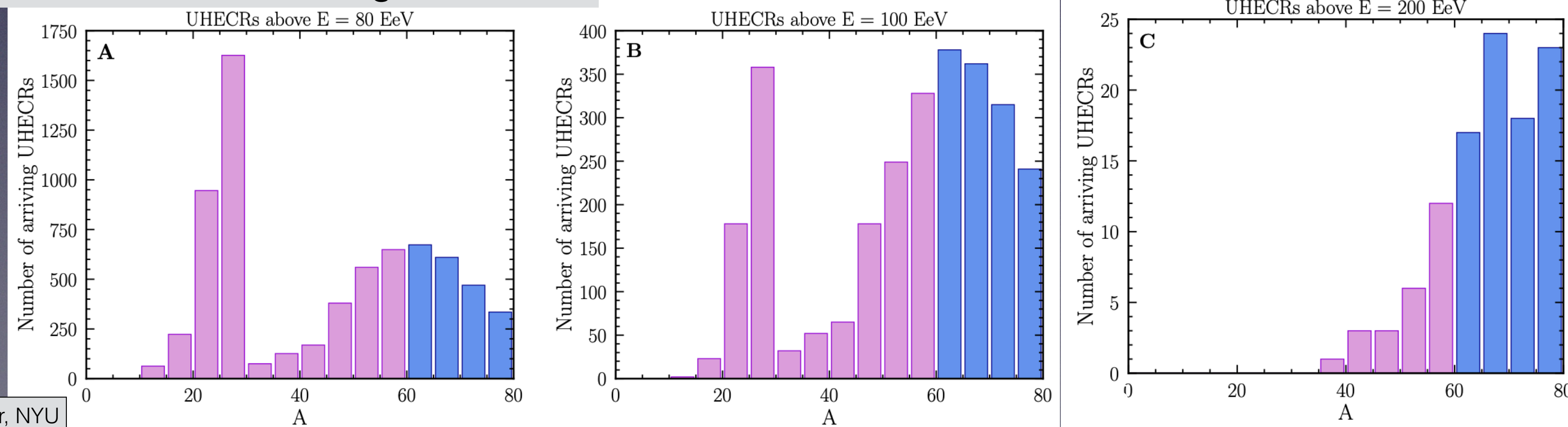
$$E_{\text{cut,80}} = \mathcal{R}_{\text{cut}} Z_{\text{Se}} \approx 7 \text{ EV} \times 34 = 240 \text{ EeV}$$

★ Auger has ≈ 10 events with $E > 130 \text{ EeV} + 1\sigma$!



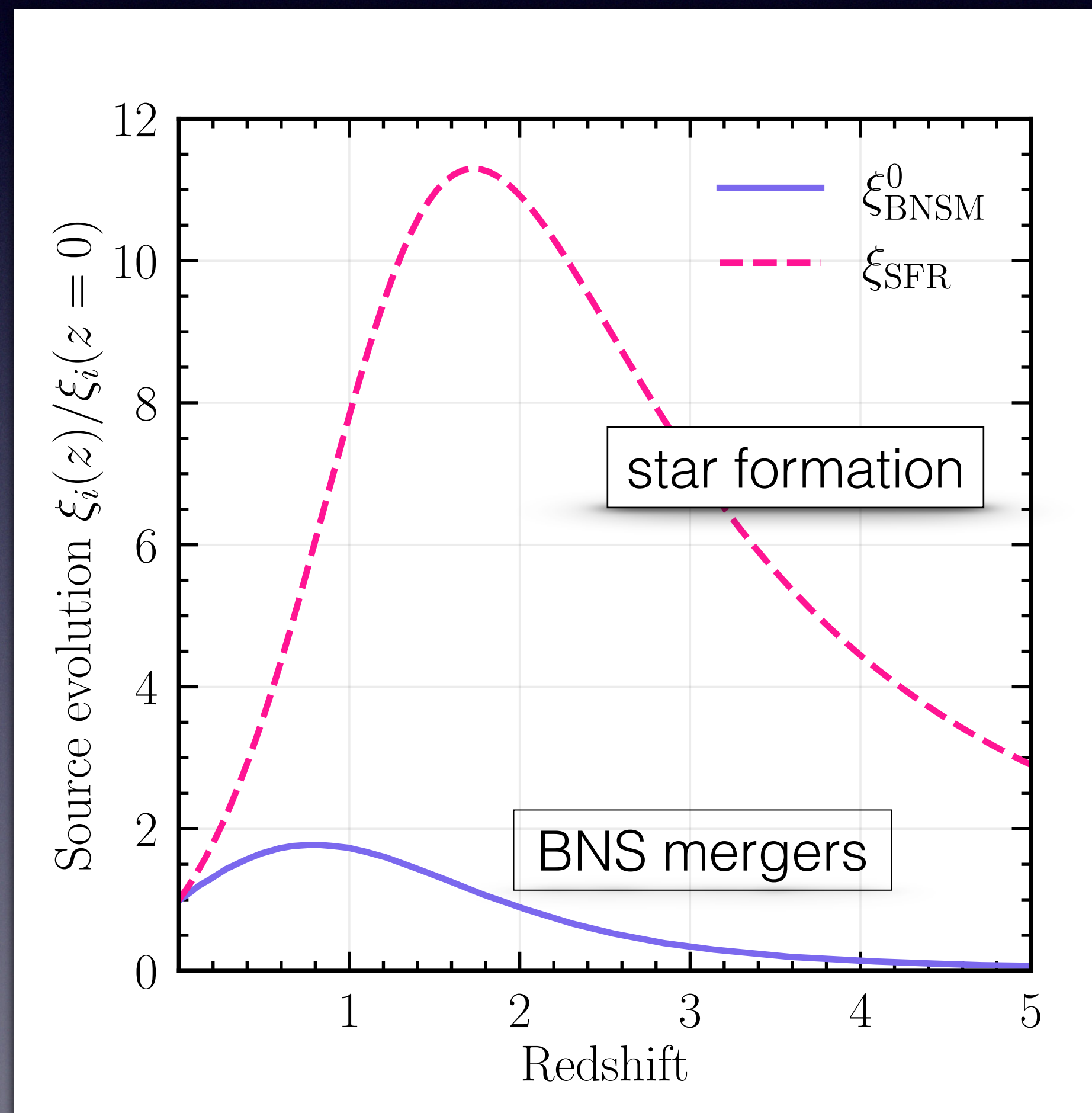
AS+GF: current Auger dataset contains 21 evts with $A > 60$ and $E > 80 \text{ EeV}$, 13 evts $> 100 \text{ EeV}$

perfect detector, 100x Auger dataset:



The Neutrino Spectrum

depends on source evolution with redshift



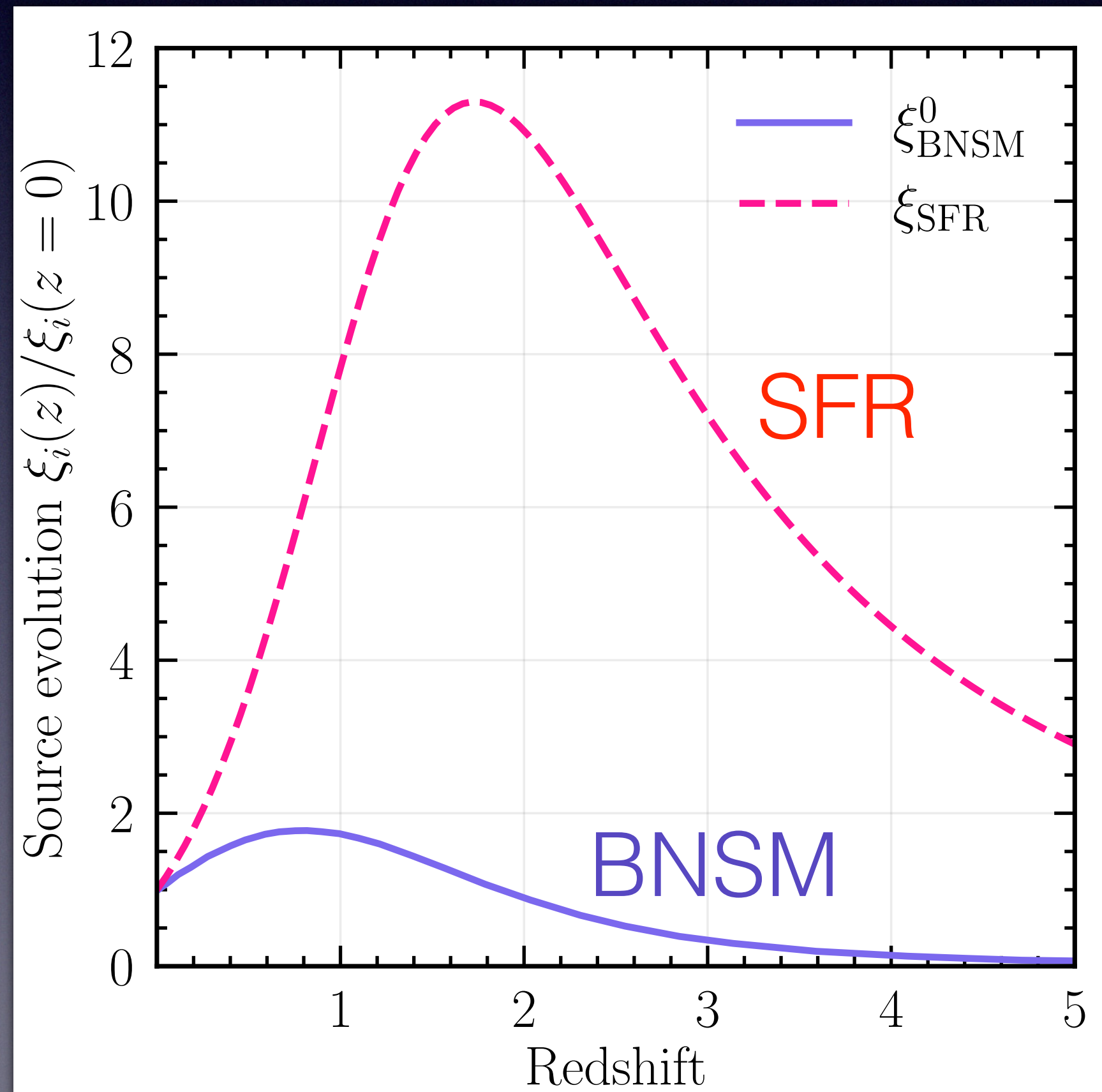
Star Formation

**$\therefore$ neutrino spectrum
discriminates between
BNS mergers & other
source types**

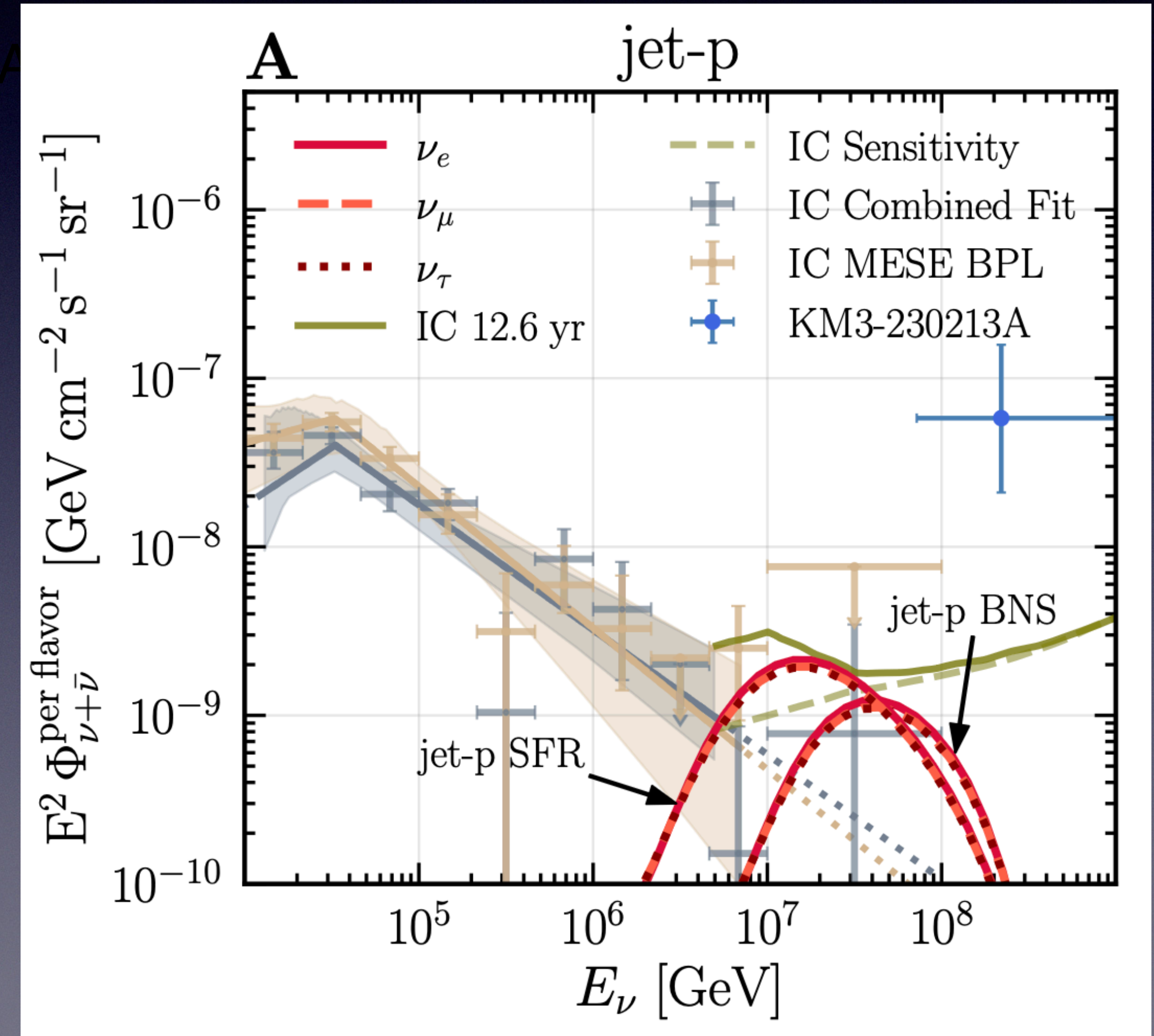
Neutrino spectrum harder with BNS

BNS merger rate peaks at $z \approx 1$, while SFR peaks at $z \approx 2$
→ fewer, but higher energy neutrinos

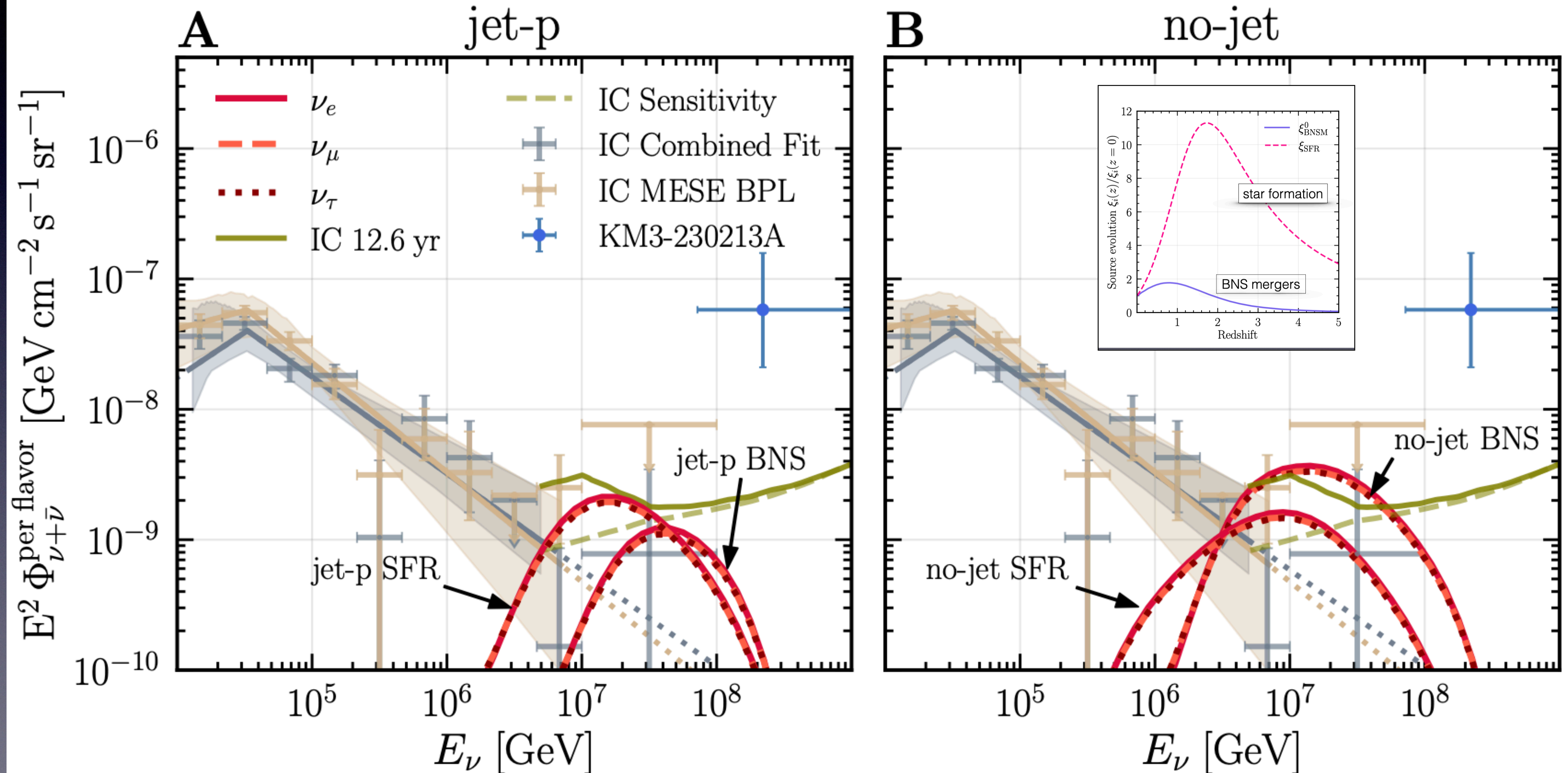
Comoving source density



Feasible for A

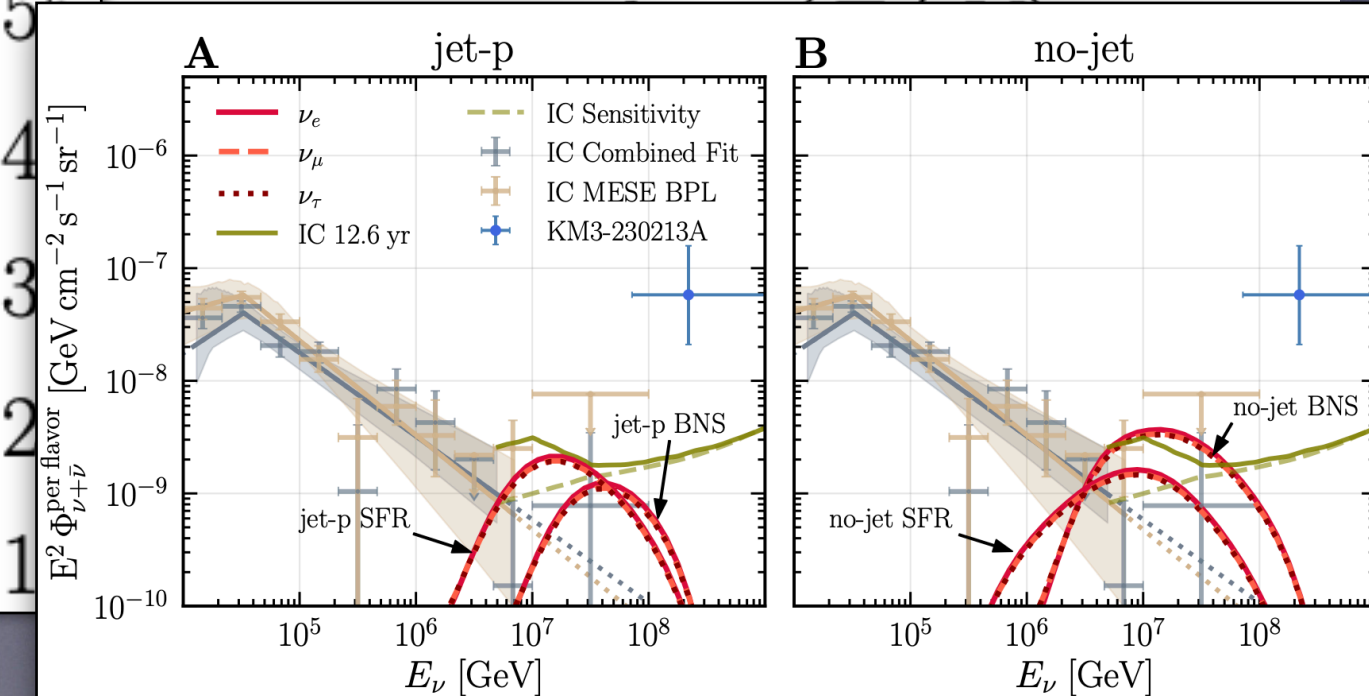
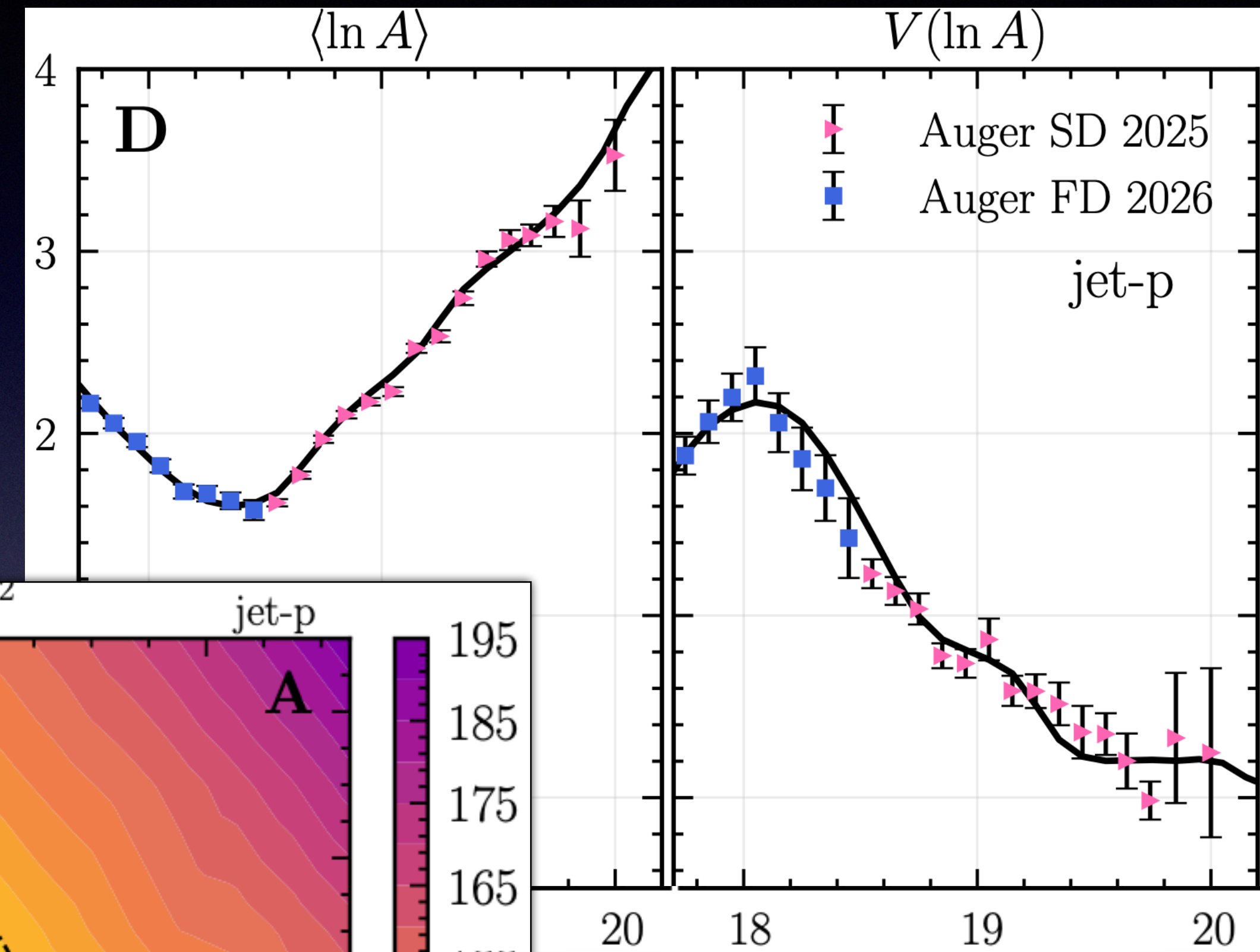
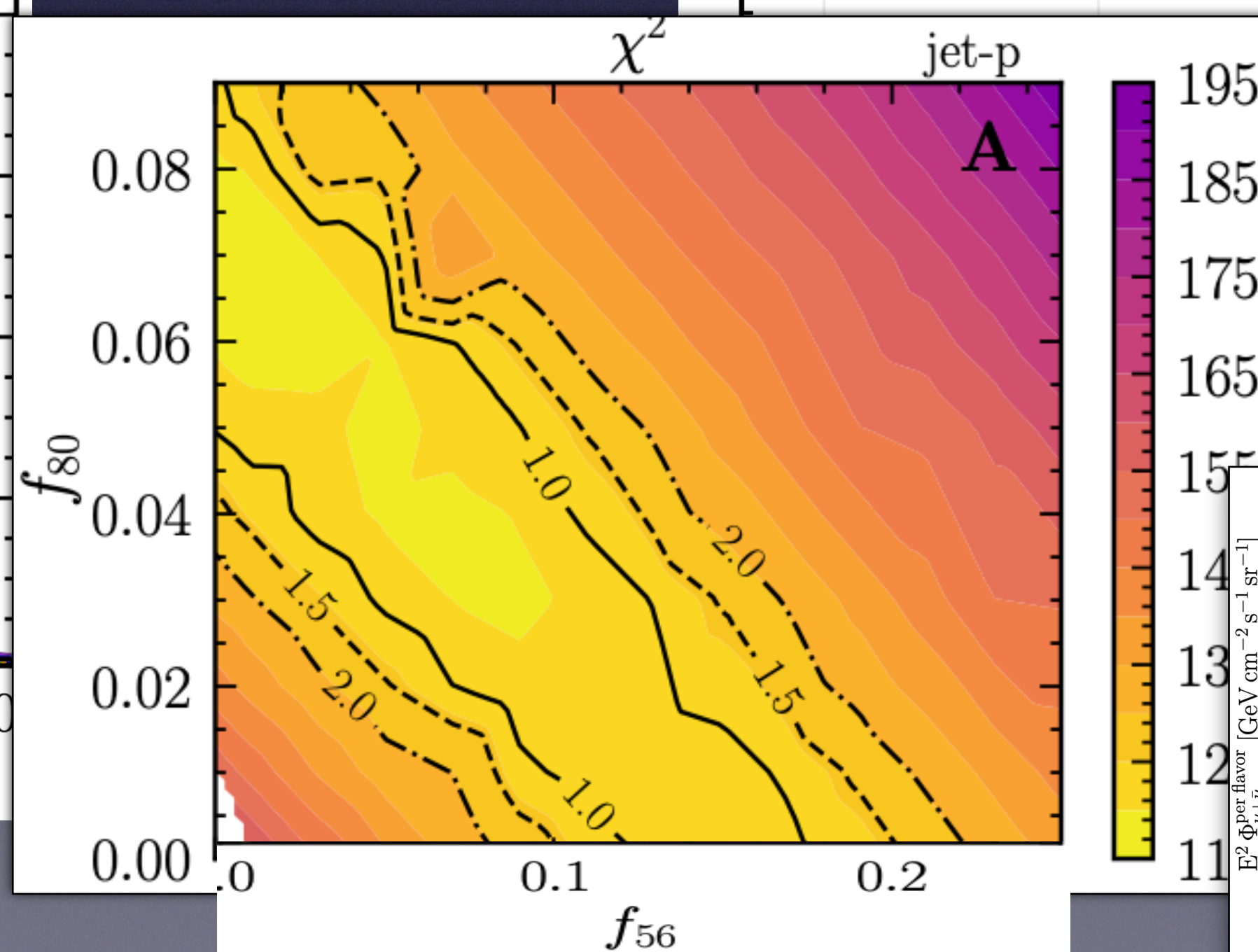
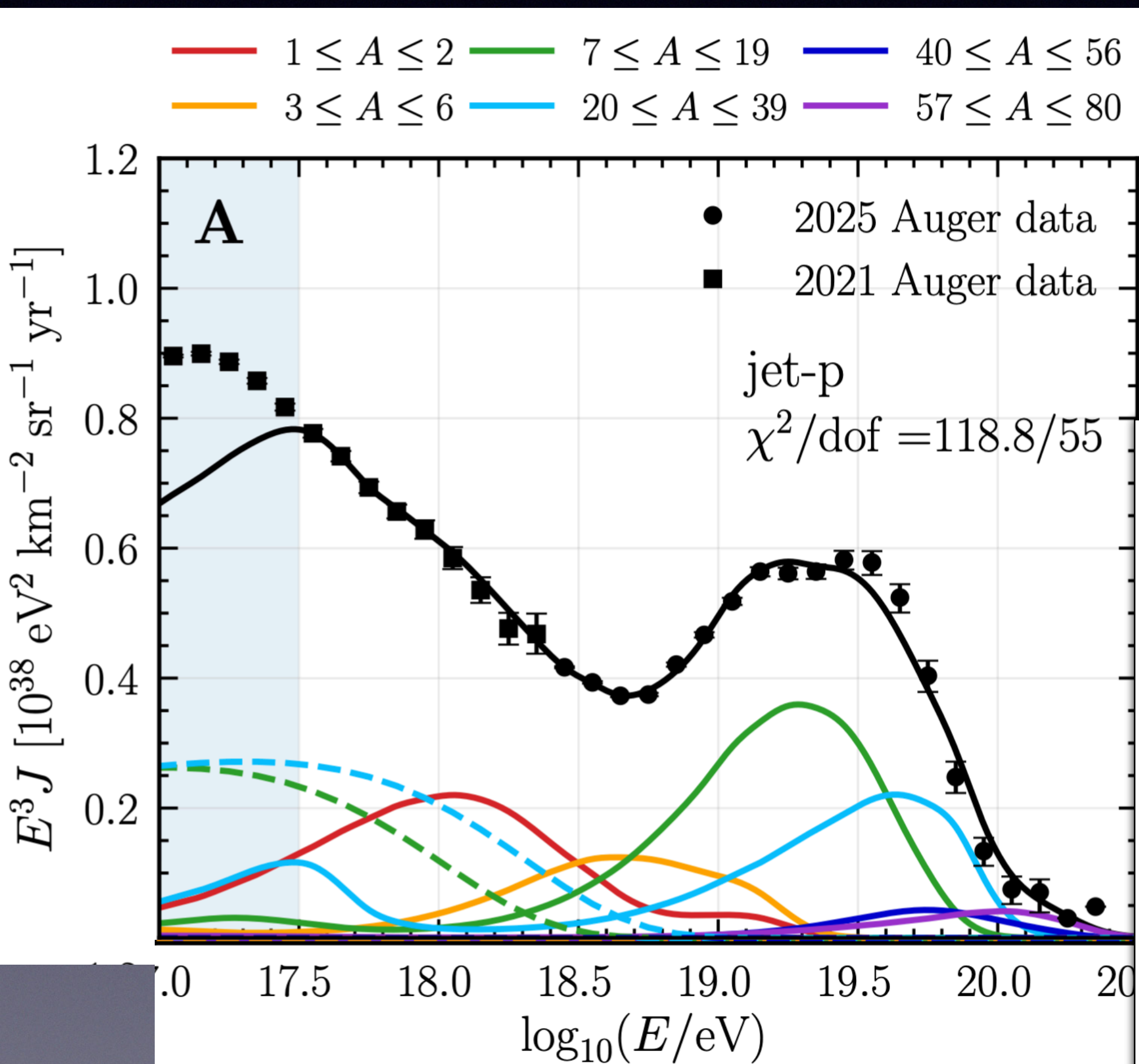


Diffuse Neutrino spectrum also probes jet component of UHECRs



Summary

- predicted jet and outflow confirmed at > 7.2 sigma
- mild preference for presence of $A > 56$
- neutrino spectrum can confirm jet/outflow & evolution



Fundamental Physics from BNSM UHECRs & ν 's

- QCD in strongly interacting regime: **Neutron Star Equation of State** He/p in jet?
- Particle acceleration:
 - ✓ spectral cutoff of bulk outflow — **confirms magnetized turbulence**
 - jet cutoff — **cutoff for DSA same as for magnetized turbulence?**
- **Extragalactic magnetic fields** — **spreading of nearby UHECR source jet $> B L_{\text{coh}}^{1/2}$**
- **Astrophysics of BNS mergers & r-process nucleosynthesis**

BACKUP SLIDES

Source candidates vs key constraints

	$n_s \gtrsim 10^{-3.5}$ Mpc $^{-3}$	energy injection	ordinary galaxy	Universal $R_{\max}$	Highest energy evts	High energy p or He
Powerful AGN	[X]	✓	X	X	X	X
Long GRBs	[X]	X	X	X	X	X
Tidal Disruption Events	?	?	✓	X	X	X
Accretion Shocks	?	?	[X]	X	X	X
BNS mergers	✓	[✓]	✓	✓	✓	✓

(All can satisfy Hillas size > Larmor radius)

Test 2: Every EHE Neutrino is accompanied by a Gravitational Wave

- Neutrinos come from UHECRs
 - spallation neutrons beta decay: $E_\nu \approx 10^{-3} (E_n \approx R/2) \sim \mathbf{2\ PeV}$
 - photo-pion production: $E_\nu \approx (E/A)/20 \sim R/40 \sim \mathbf{100\ PeV}$ (KM3NeT)
- Time delay for ν : $\gtrsim$ time for ejecta to expand to 10^{14} cm (where UHECRs form)
 - $\langle V_{ej} \rangle = 0.1\ c \rightarrow \mathbf{delay \approx O(day)}$

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

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

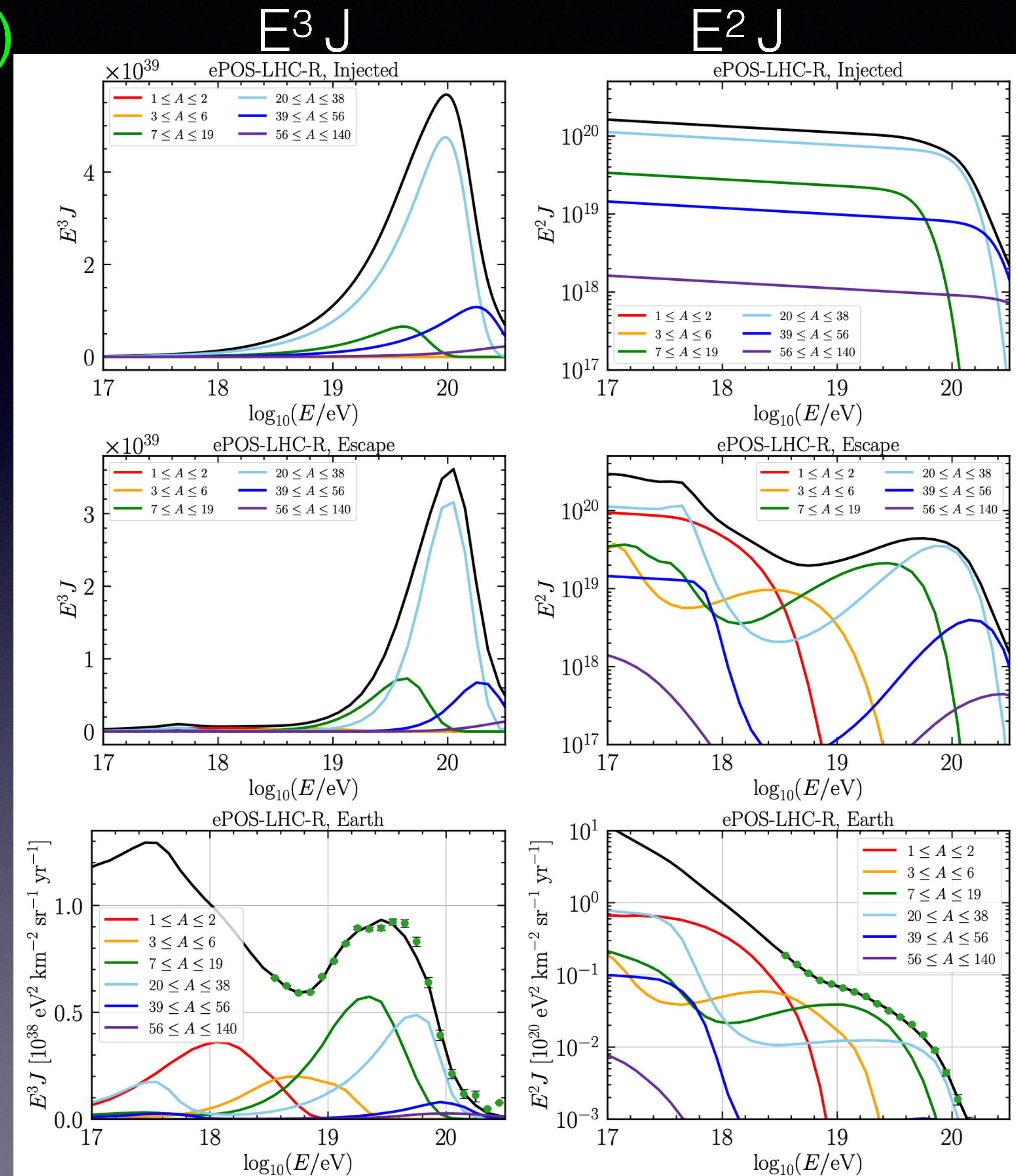
Impact of interactions (generalized UFA*)

*Unger,GF, Anchordoqui 2015

Spectrum injected

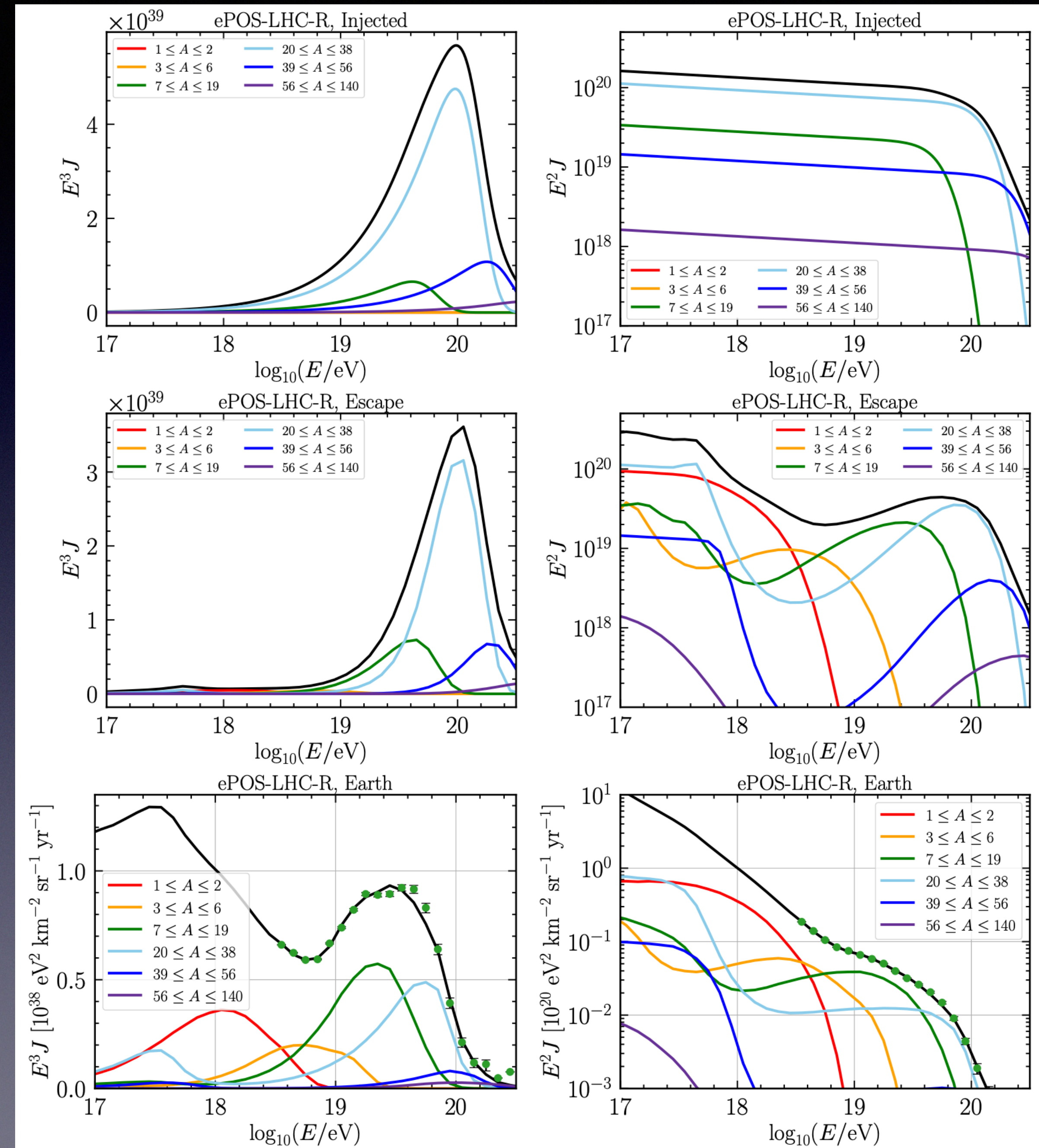
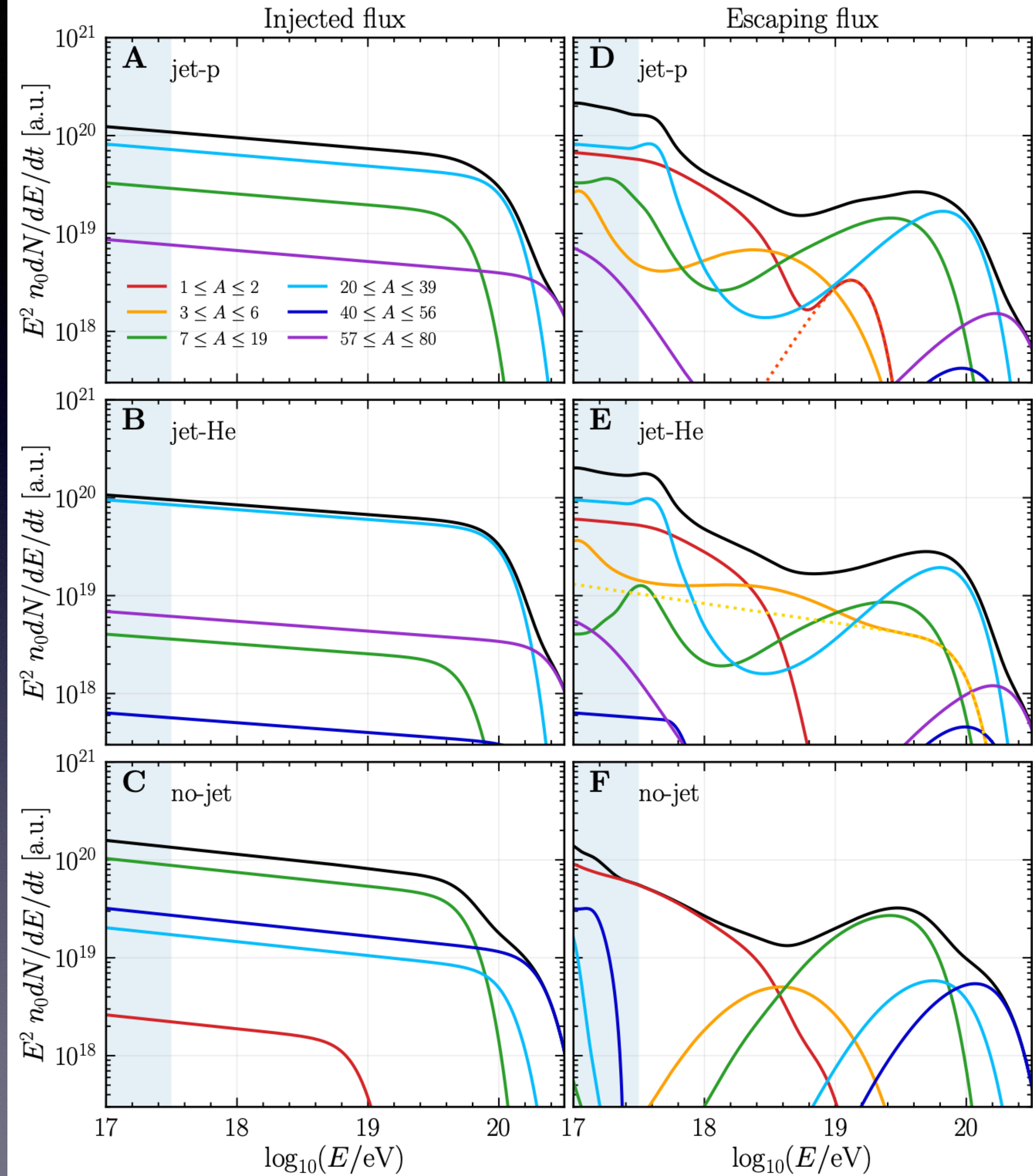
Spectrum after interactions with photons in source
(500°K blackbody)

Spectrum as observed



Theory to-do list

- *Normalized neutrino spectrum from individual BNSM (likelihood of sGRB or GW coincidence)*
- Constrain T in jet and outflow acceleration region from astro/sims
- Impact of expansion on acceleration and UFA analysis
- Impact of escape on observed spectral shape
- Calculate “injection” composition (complex but tractable nuclear physics problem)
- Calculate absolute flux (depends on uptake fraction, escape & BNSM rate)

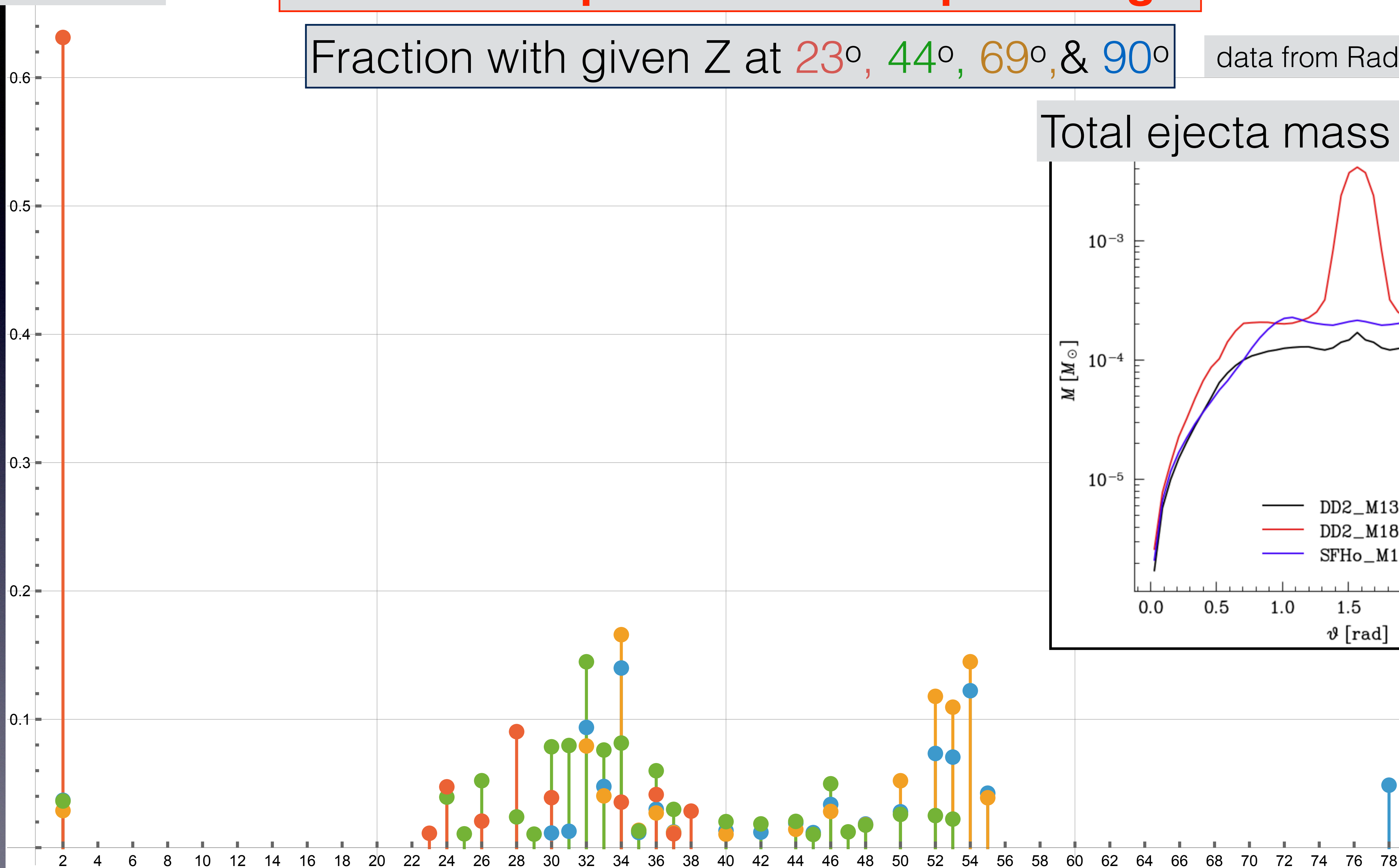


Fraction

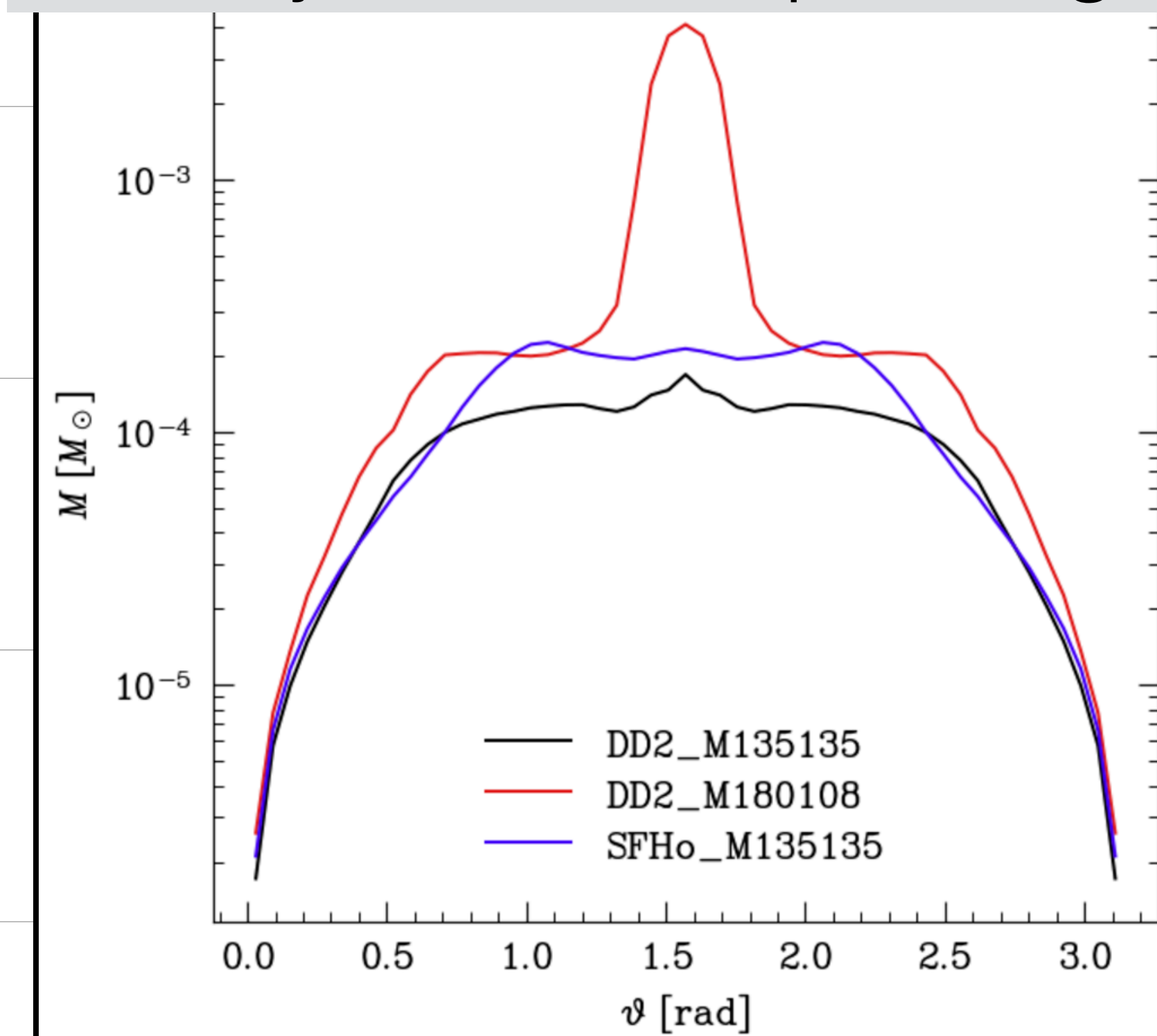
Nuclear Composition Mix vs polar angle

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

data from Radice&Gutierrez

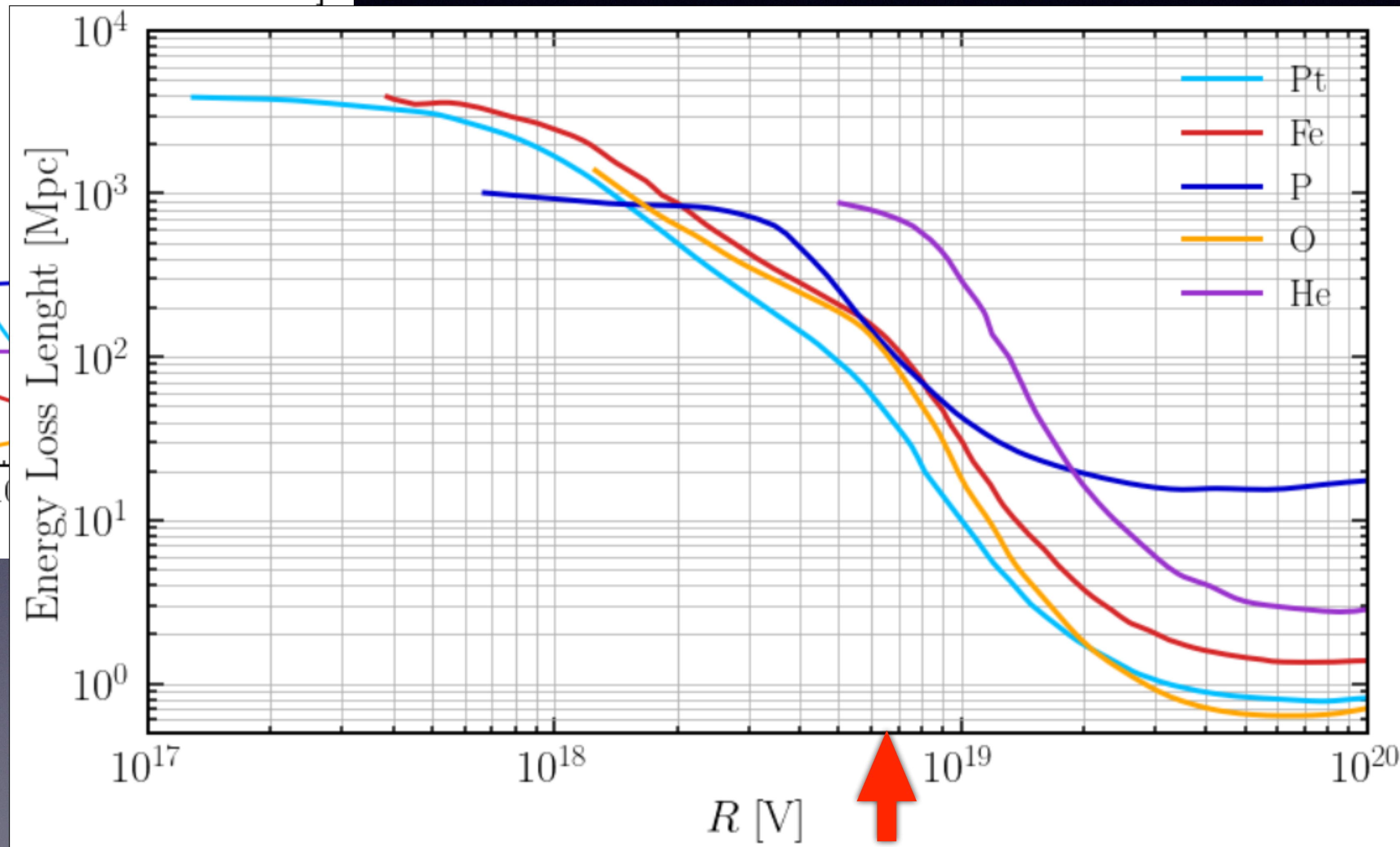
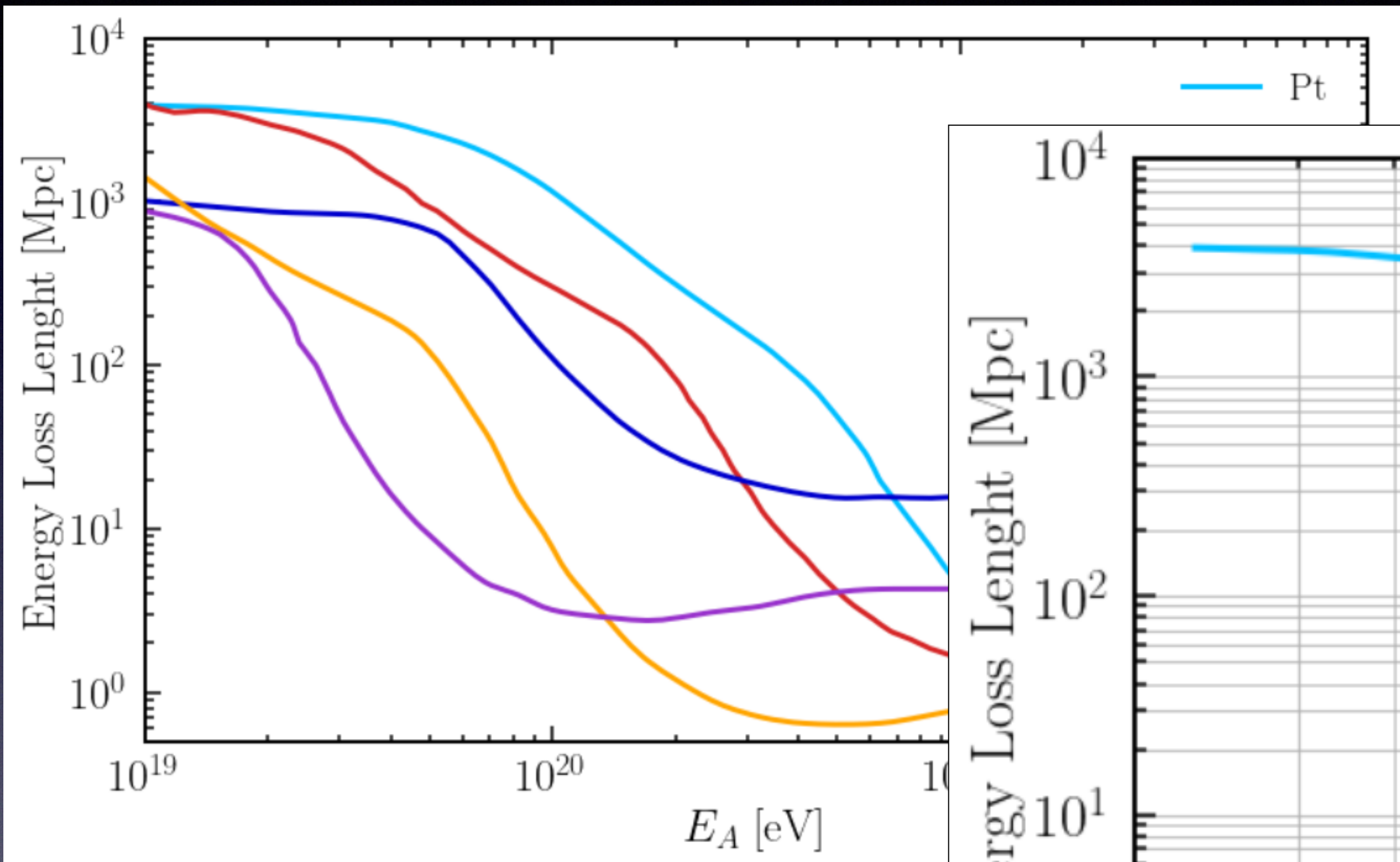


Total ejecta mass per angle



charge Z

Propagation energy loss length, from SimProp, enters into
extragalactic and surrounding source



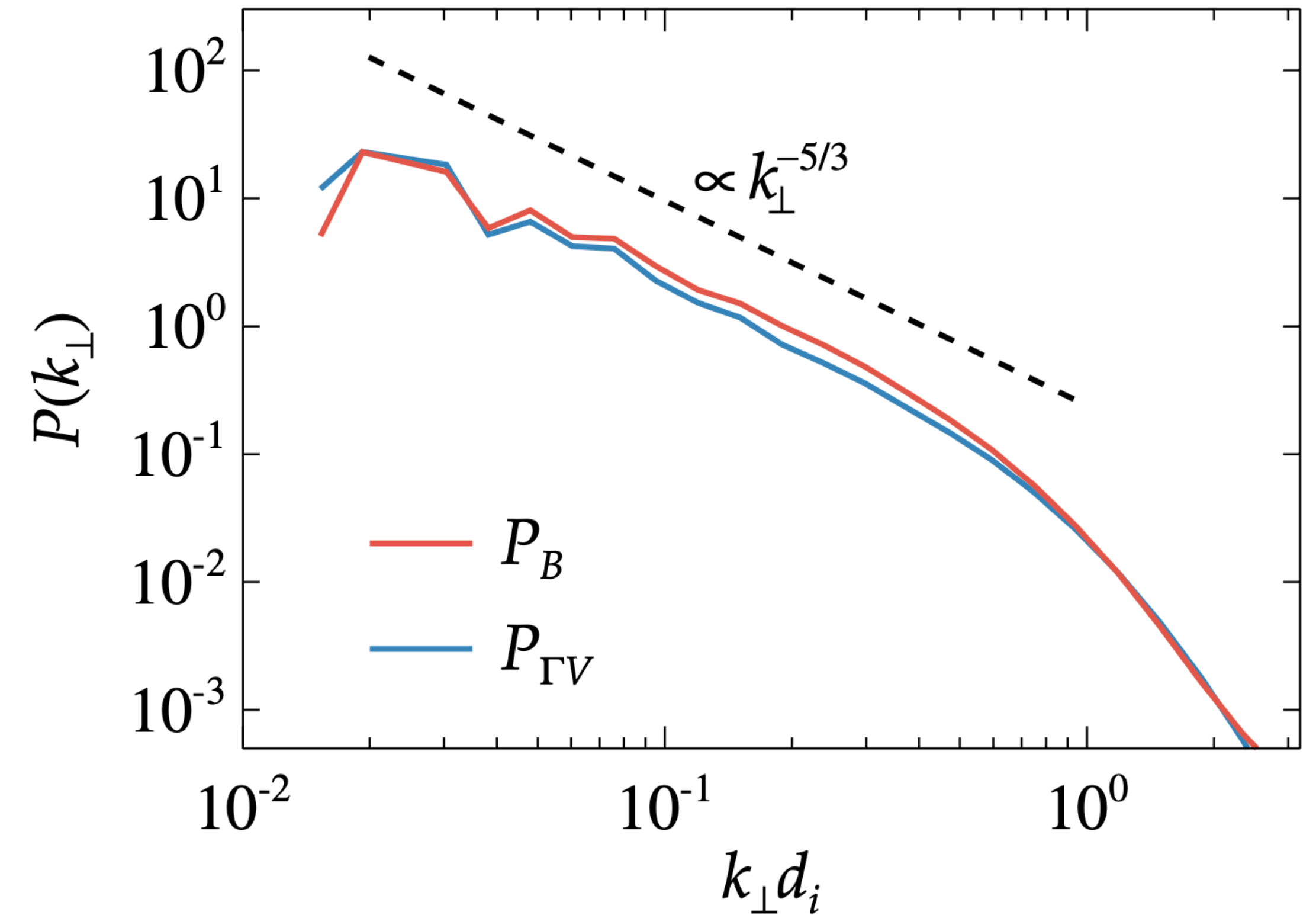
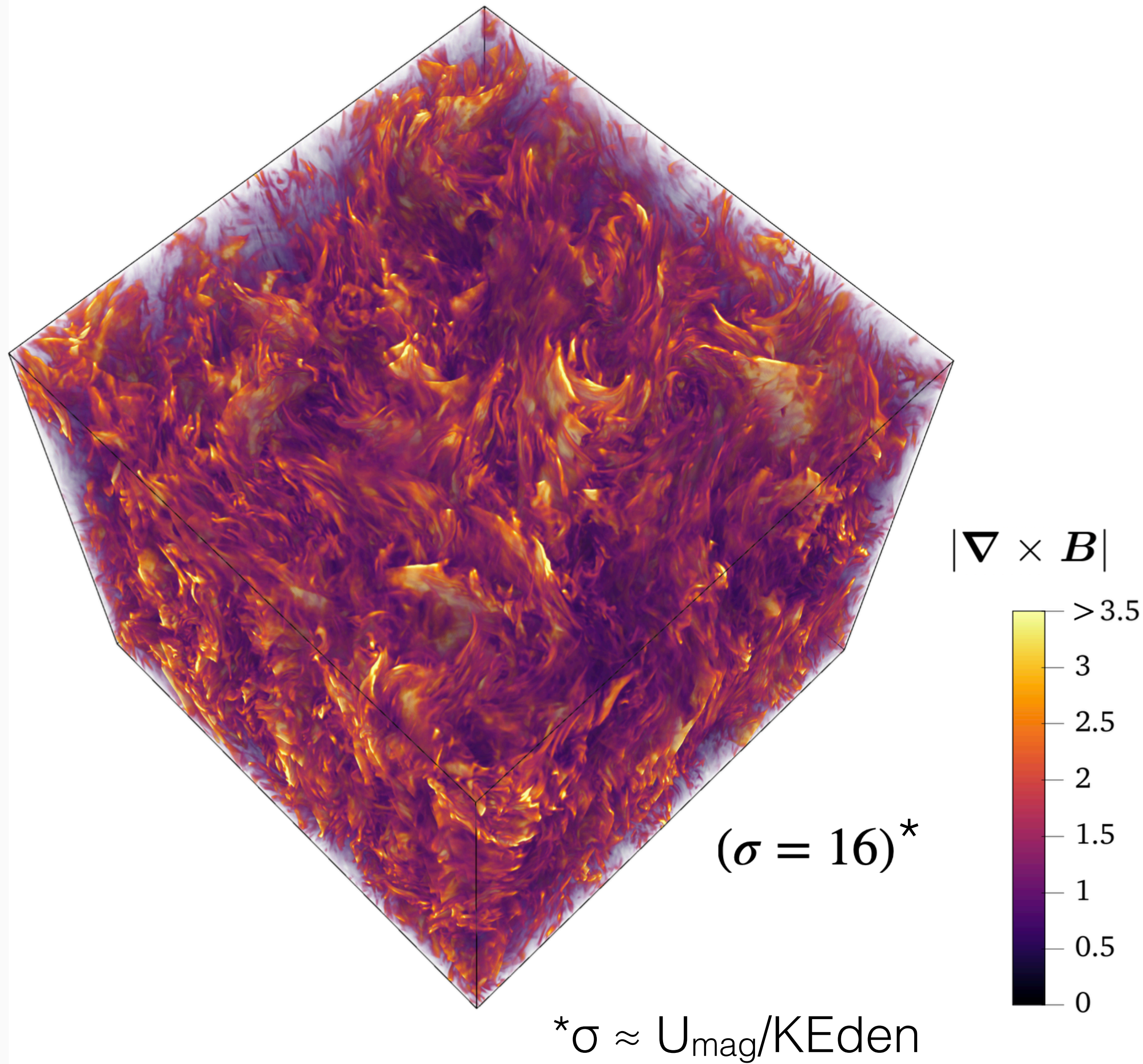
For $\mathcal{R} = 5$ EV:

$Z, A = \{36, 80\} \rightarrow \langle E_n \rangle = 2.25$

$Z, A = \{14, 28\} \rightarrow \langle E_n \rangle = 2.50$

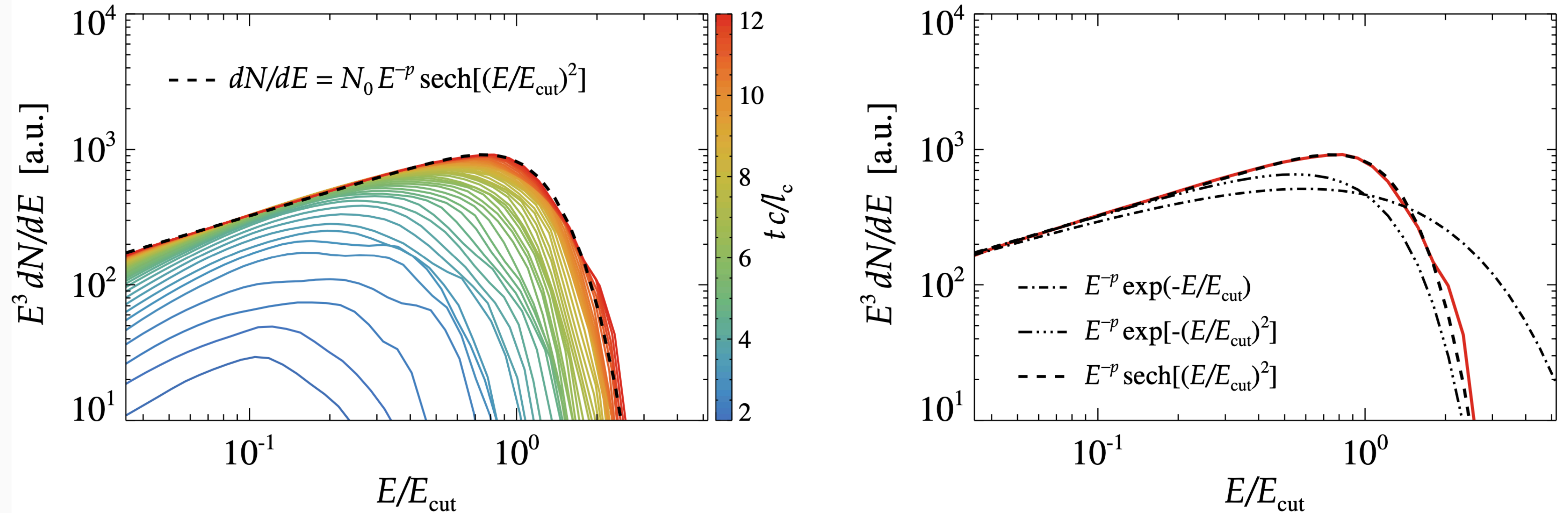
$Z, A = \{1, 1\} \rightarrow \langle E_p \rangle = 5.00$

Magnetically dominated turbulence from first-principles PIC simulations



- 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:

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

Future test of BNS-merger origin: EHE neutrino $\approx$ coincident with GW from BNS merger

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

