Testing the Binary Neutron Star Merger Scenario

Glennys Farrar and Anna Suliga, NYU
Trieste, September 9, 2026

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

Binary Neutron Star Mergers

only (currently known) source candidate satisfying all criteria

- Universal rigidity spectrum explained:

EhlertOikonomouUnger23

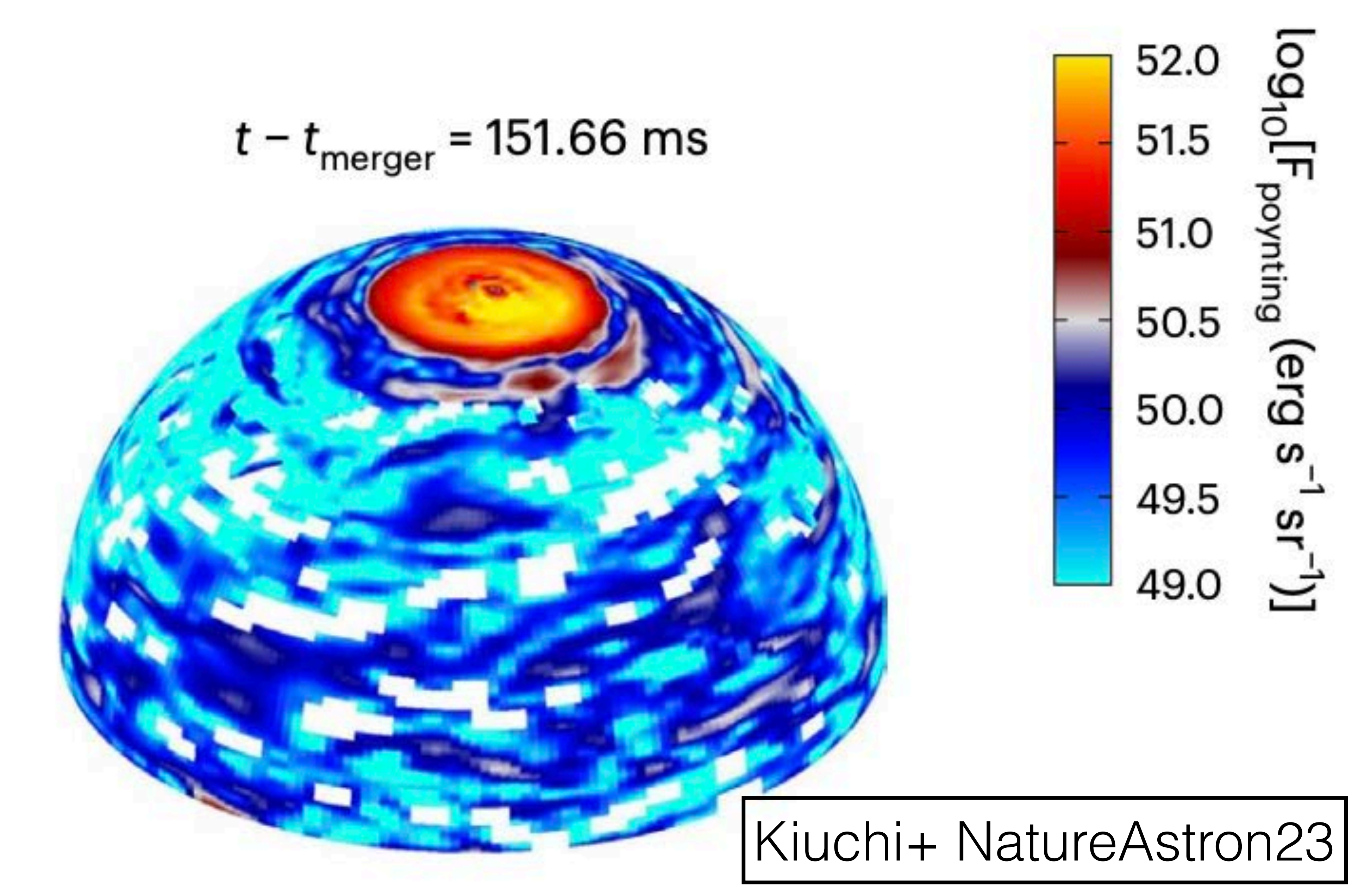
1. Magnetic field is generated by gravitational dynamo 💕

   Kiuchi+ NatureAstron23

2. Mass range of binary NS's is narrow 💕

   Known BNS's: M= 2.64±0.14 (5%) $M_\odot$

2.6-3.4 $M_\odot$ → <20% (negligible) spread in $\mathcal{R}_{max}$



Kiuchi+ NatureAstron23

Binary Neutron Star Mergers

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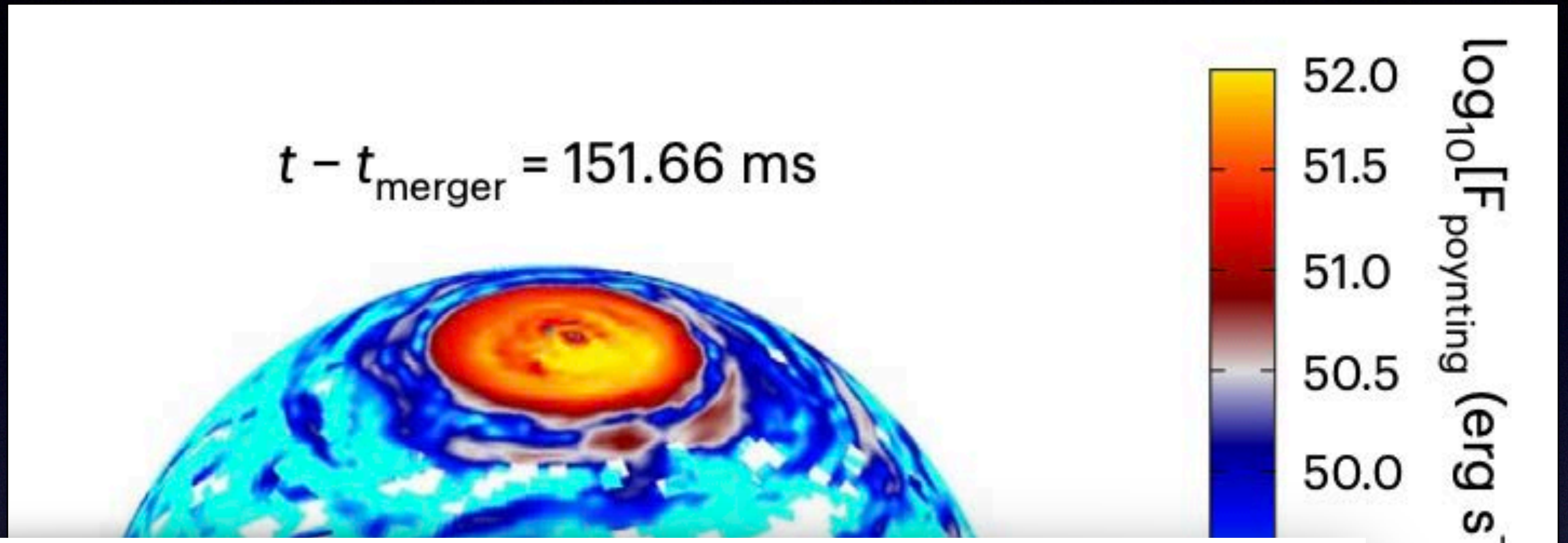

tron23

Clean predictions enable definitive tests:

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

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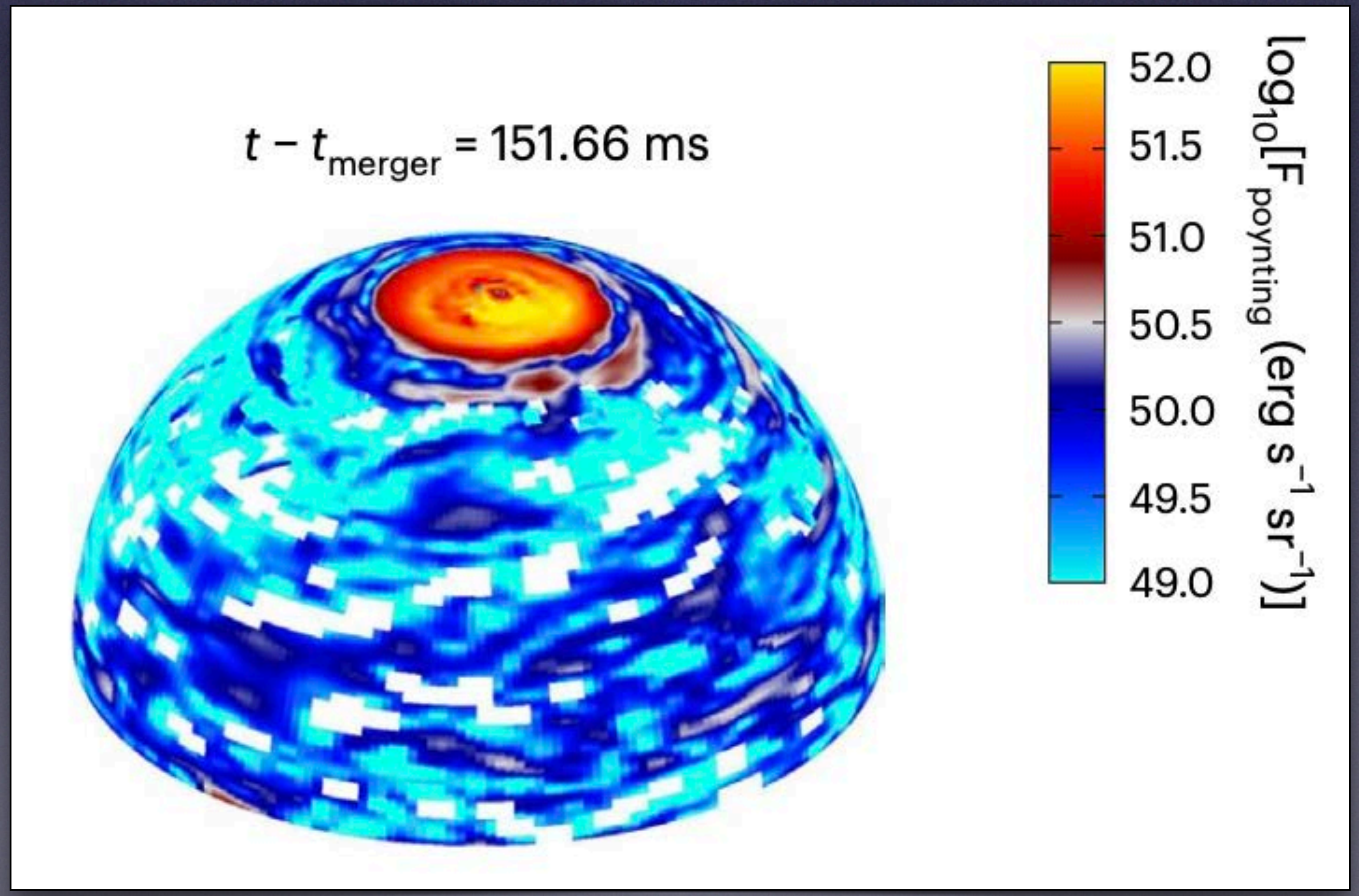
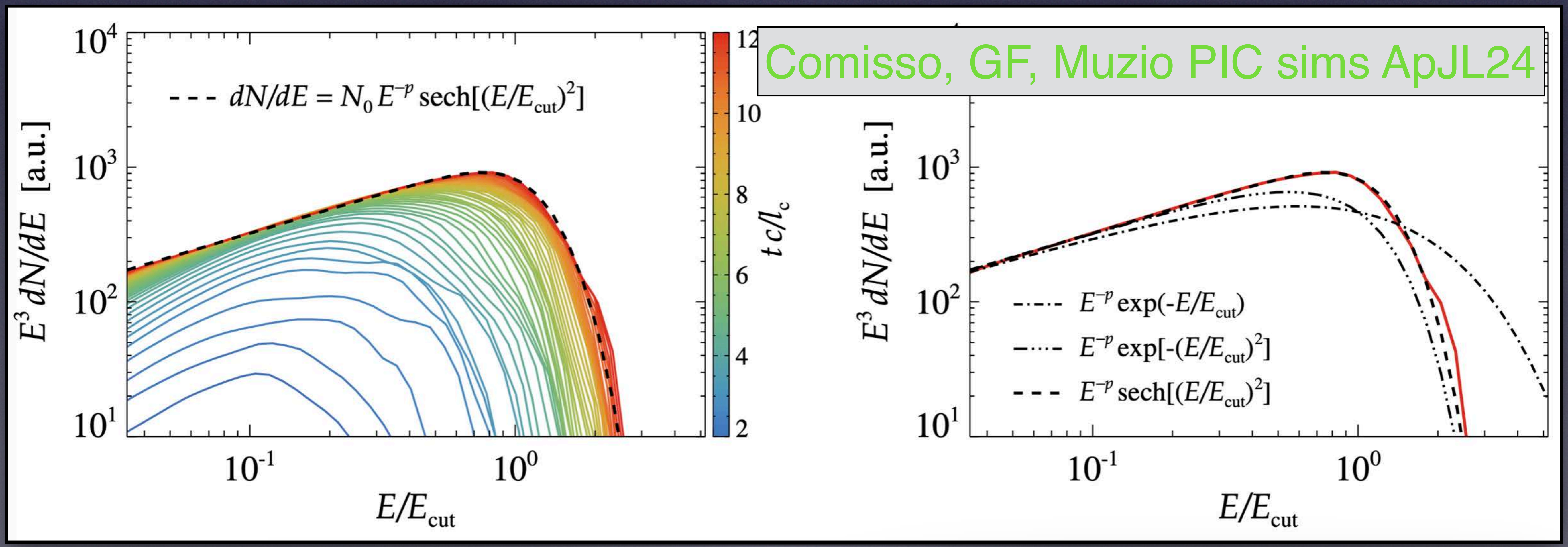
Most **UHECRs are produced in the turbulent outflow, not the jets**

1. UHECRs have masses up to (at least) Fe, but jets only have p or He (e.g., Perego+22)
2. **Jets have 10x higher field strength ➜ possible higher rigidity light component.**





UHECR data strongly favor $\mathrm{sech}[(E/E_{cut})^2]$ cutoff & gives expected $E^{-2.\varepsilon}$ power law

Big Picture

time → Expands at v~ 0.1 c

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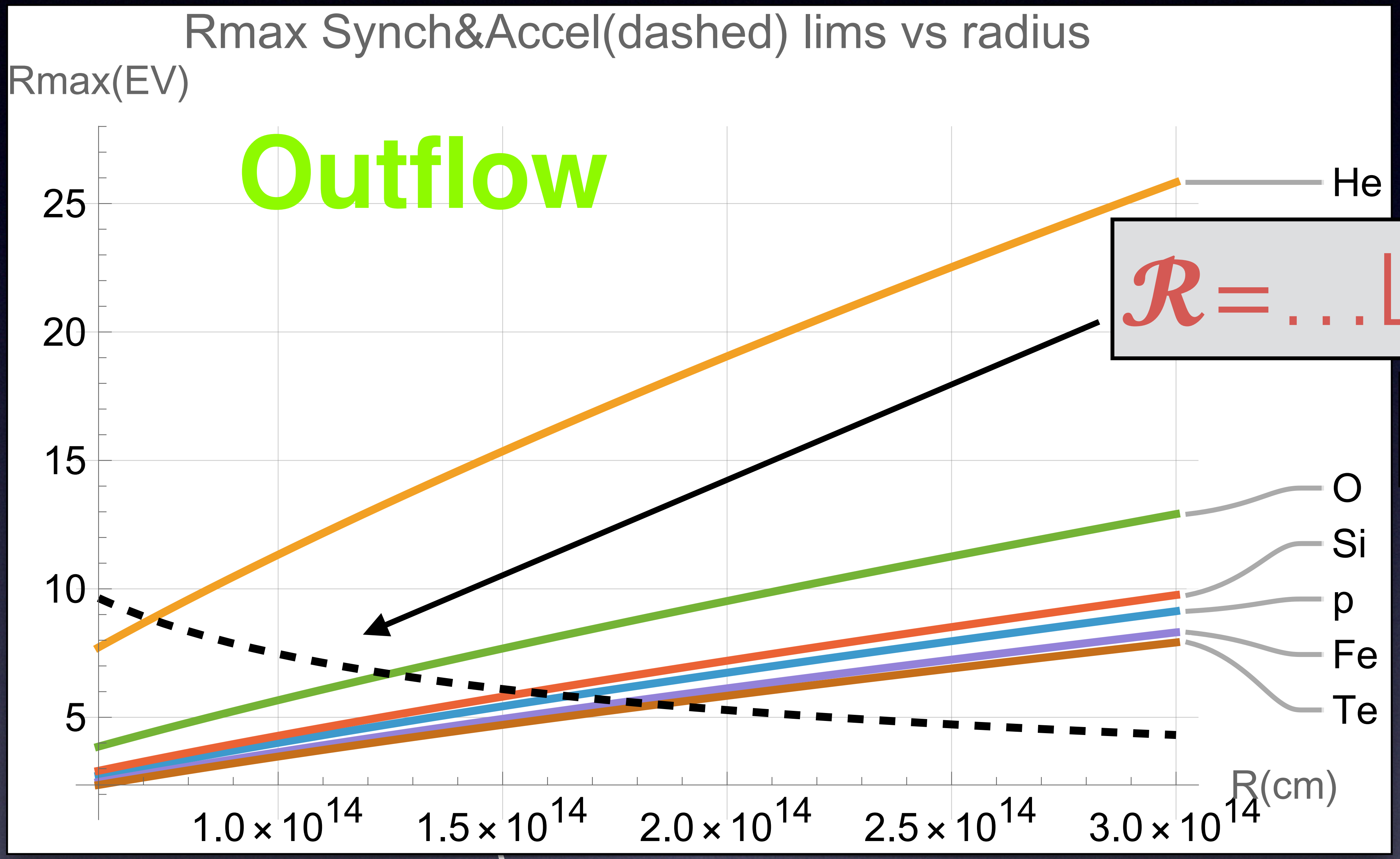
BNS merger scenario implies

- ✓ Narrow rigidity distribution
- ✓ Maximum energy of each nuclear type
- ➡ Eroded r-process nuclei (A>56) among Ultrahigh Energy CRs?
- Total magnitude of UHECR production (~ 1 ppb of escaping nuclei)
- Flux of EHE neutrinos ($E_{peak} \approx 50$ PeV)
- GW-ν coincidences for EHE ν's with time delay ≈1 day

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

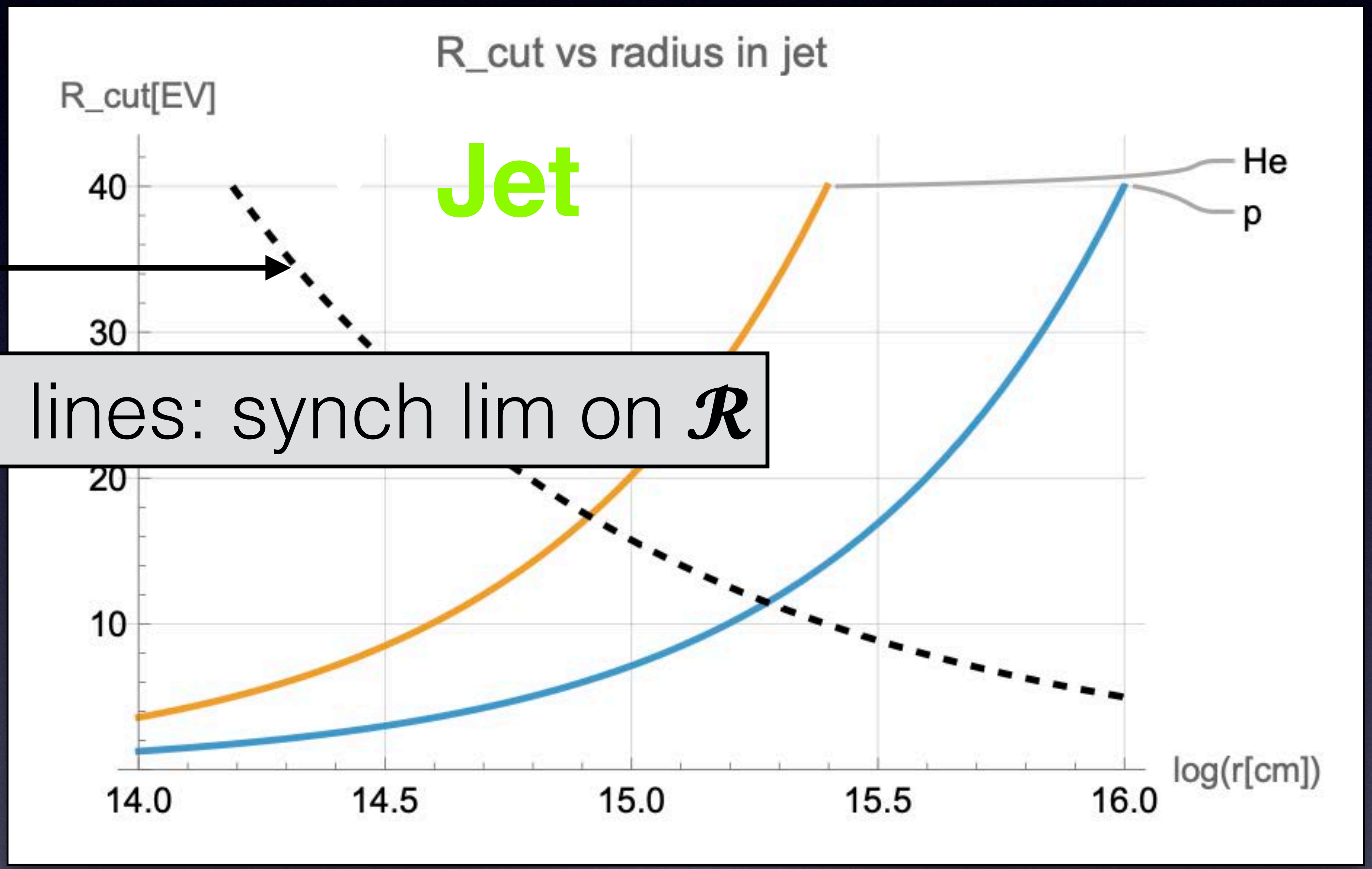
0th Approximation Analysis

GRF ApJL25



$\mathcal{R}=\ldots L_{coh}\ B$

colored lines: synch lim on $\mathcal{R}$



- **Turbulent outflow:** $\mathcal{R}_{\text{cut}}$ {p,He,O,Si,Fe,Te} ≈ {6.2, 9.4, 7.1, 6.3, 6.0, 5.9} EV

  Auger Peters cycle fit: $\mathcal{R}_{\text{cut}} = 6.8$ EV (+systematics ⇒ factor-2 uncertainty)

Higher energy p or He component possible from jet

- **Jet** *(analyzed as if magnetized turbulence)*: $E_{\text{cut}} \approx 11$ EeV (proton), $E_{\text{cut}} \approx 35$ EeV (He)

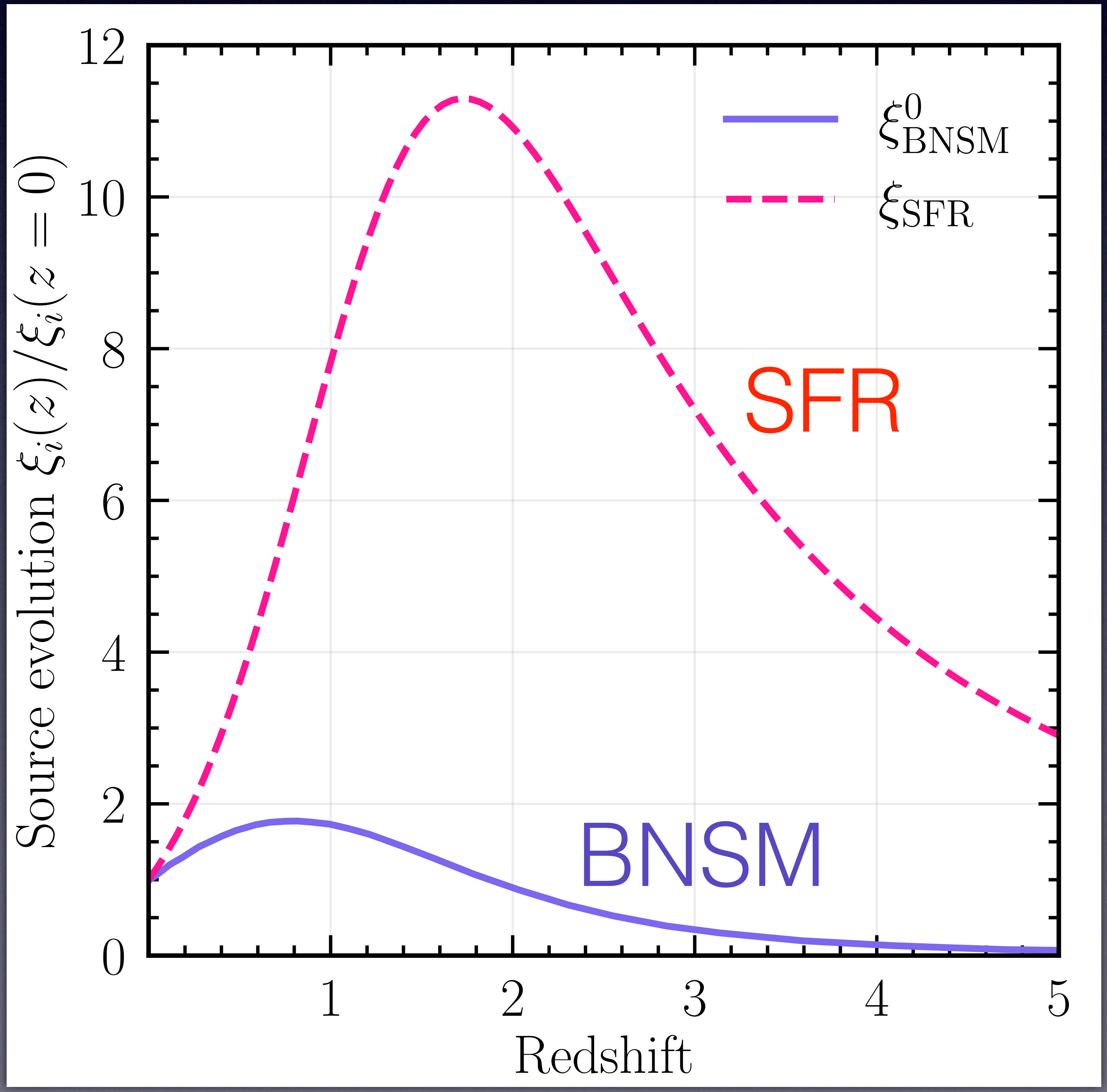
Neutrino spectrum harder with BNS

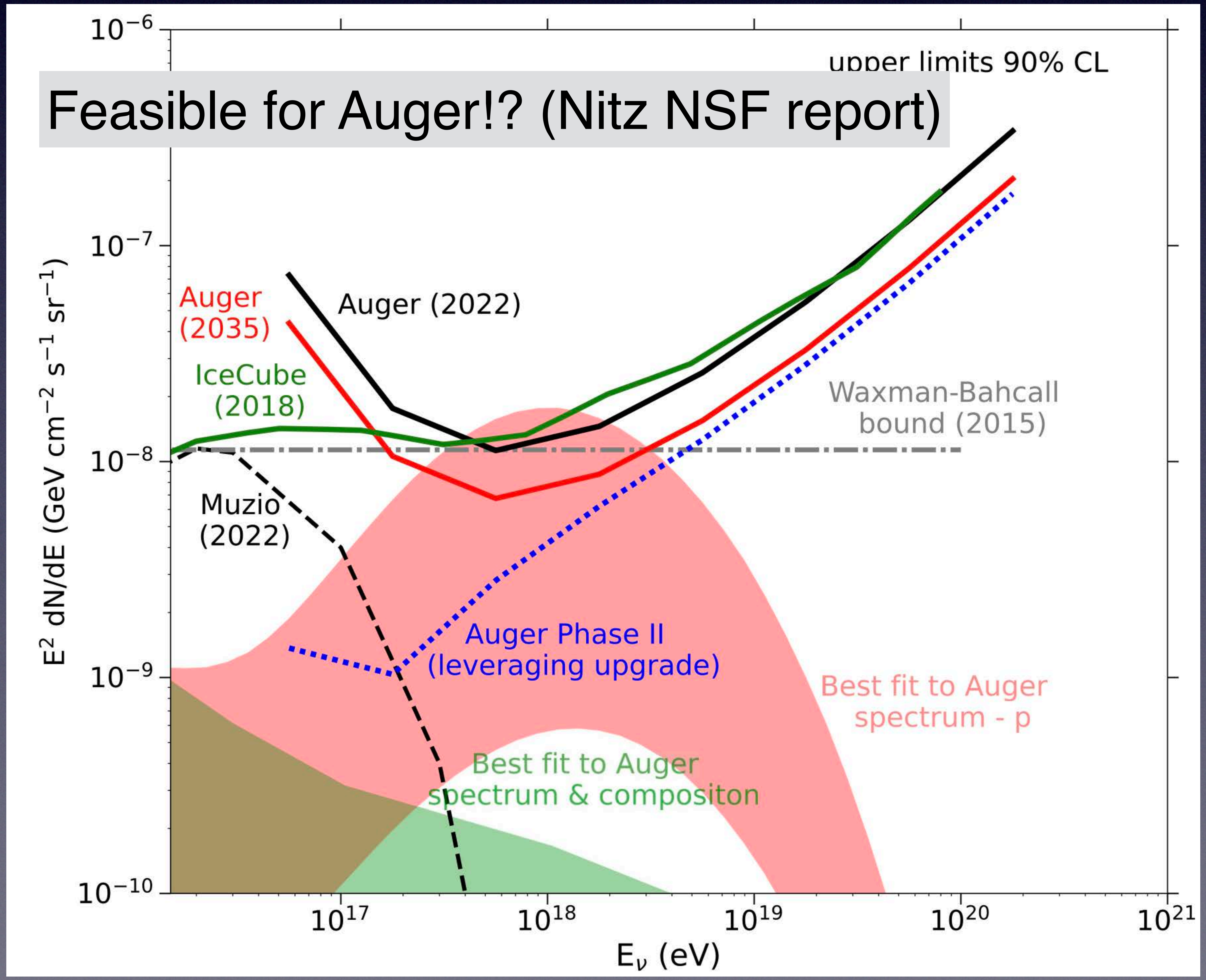
because BNS merger rate peaks at z≈1, SFR at z≈2
➜ fewer, but higher energy neutrinos

Comoving source density

Feasible for Auger! (Nitz NSF report)

Star Formation





Test 1: E>150 EeV cosmic rays coming from r-process primaries

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

$$E_{cut,Kr} = \mathcal{R}_{cut}\, Z_{Kr} \approx 7 \text{ EV} \times 36 = 240 \text{ EeV}$$

★ Auger has ≈10 events with E > 130 EeV + 1σ !

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

Verify by measuring their masses

G. Farrar, NYU

Test 2: 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

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

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

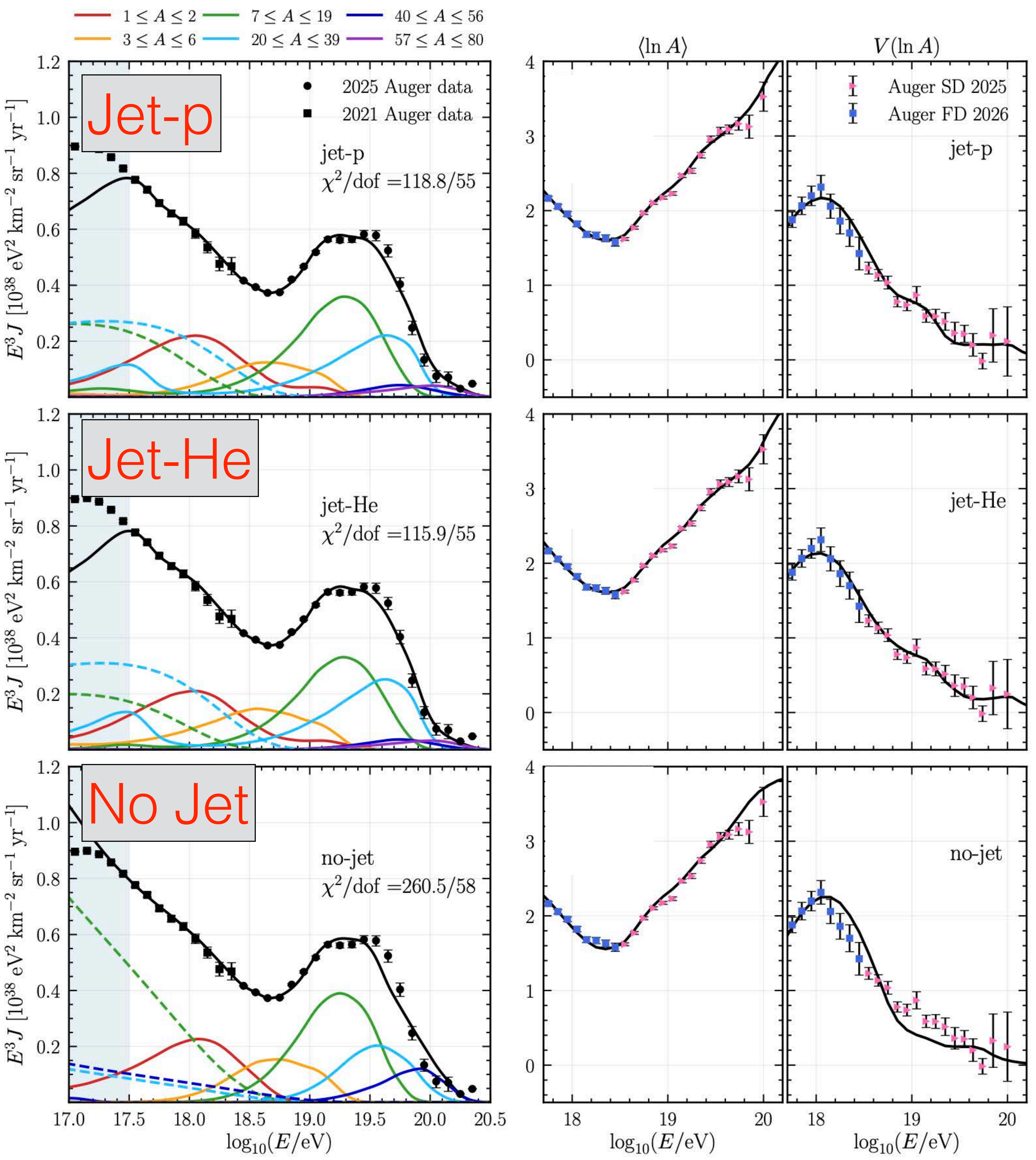
Best fit to latest Auger spectrum & composition

including jet proton & possible A=80 at source

Fit to Auger spectrum, <lnA> & V(ln A)

Key parameters of best-fit models:

	Jet-p	Jet-He	no jet
$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	118.8/55 = 2.2	115.9/55 = 2.1	260.5/58 = 4.5
R_{cut} outflow	7.2 EV	6.9 EV	7.1 EV
E_{cut} jet	12 EeV	81 EeV	
$fracE_{jet}$ >10 EeV	0.05	0.12	



caution: He fit does not include Jet He interactions

Impact of interactions in (generalized) UFA

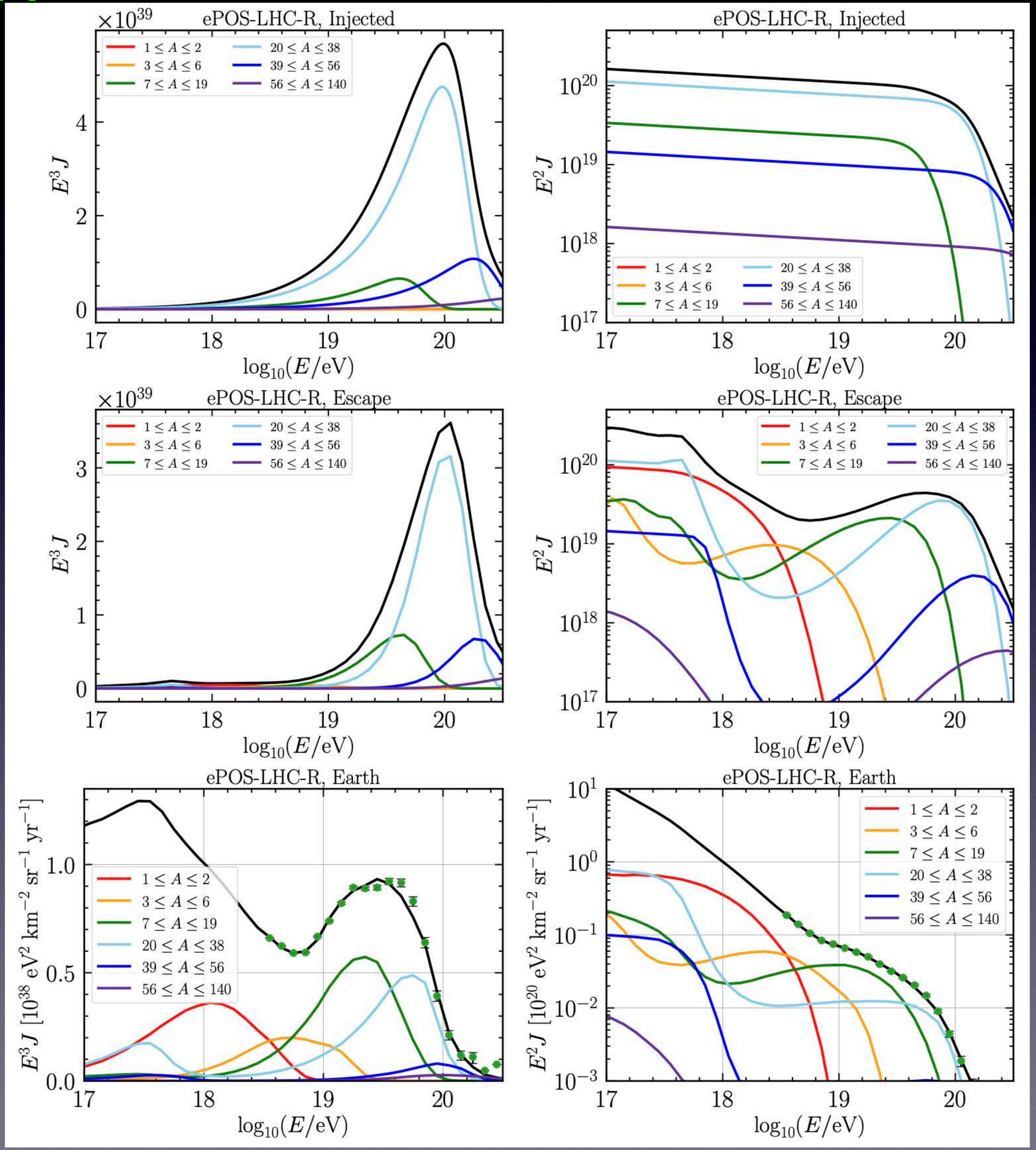
(Unger,GF, Anchordoqui 2015)

Spectrum injected

Spectrum after interactions with photons in source
(500ºK blackbody)

Spectrum as observed

$E^3\,J$ $E^2\,J$

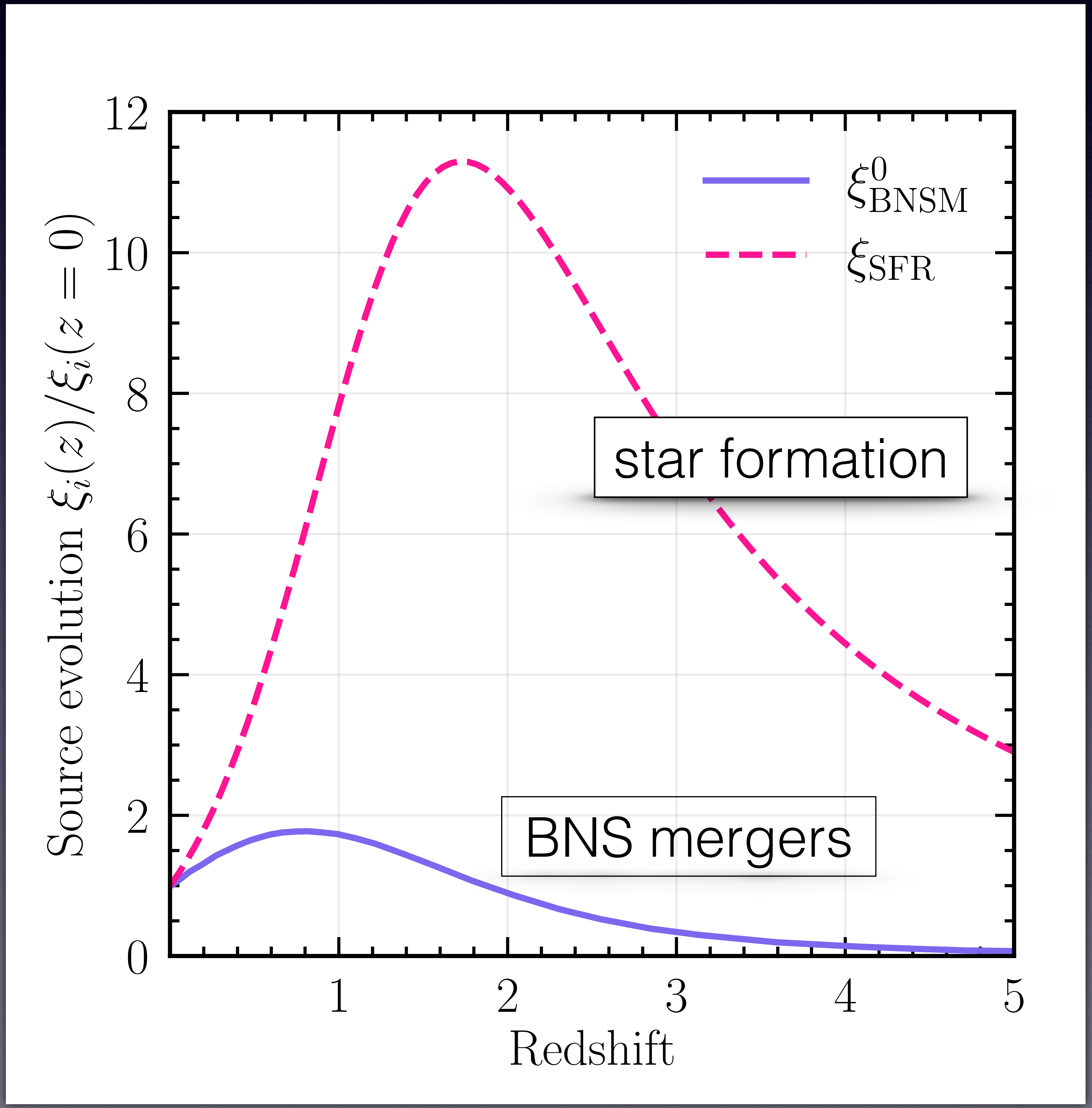


Predicted # events vs A, for 100x Auger exposure

(no systematics, best fit jet-p params)

The Neutrino Spectrum

depends on source evolution with redshift

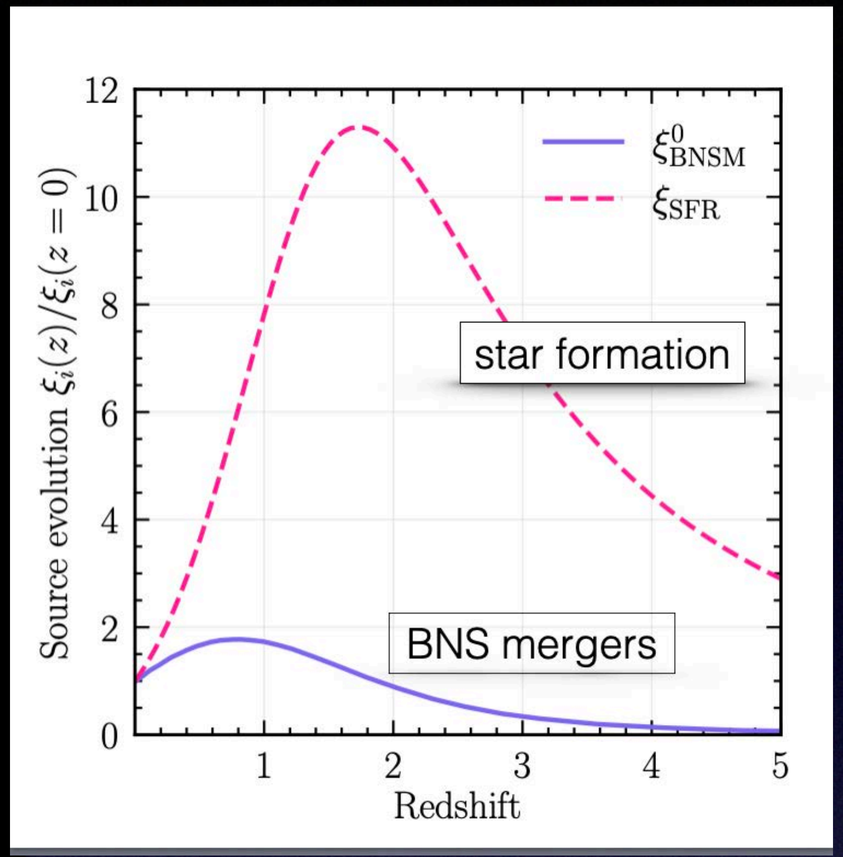


Star Formation

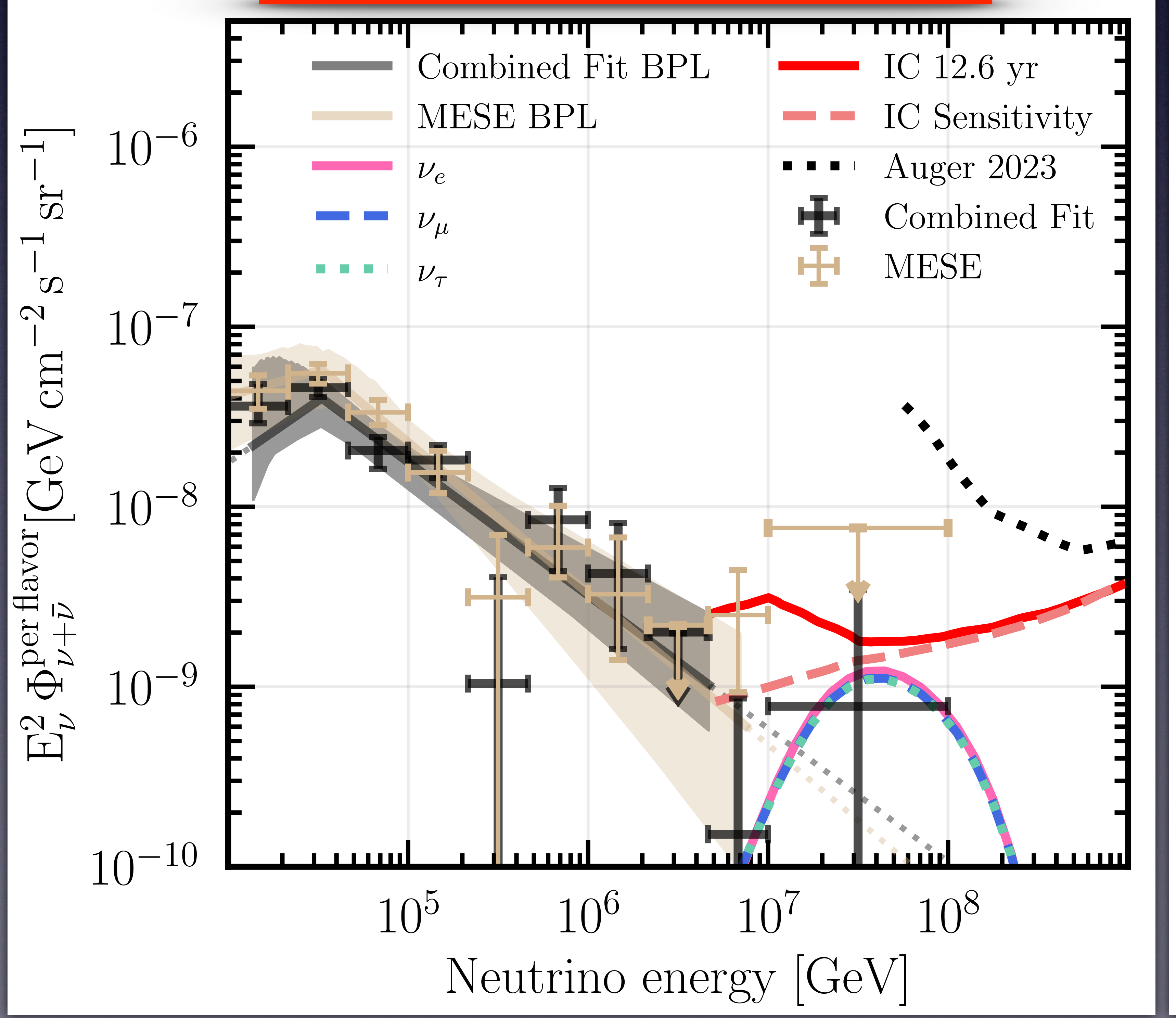
∴ neutrino spectrum

discriminates between BNS mergers & other source types

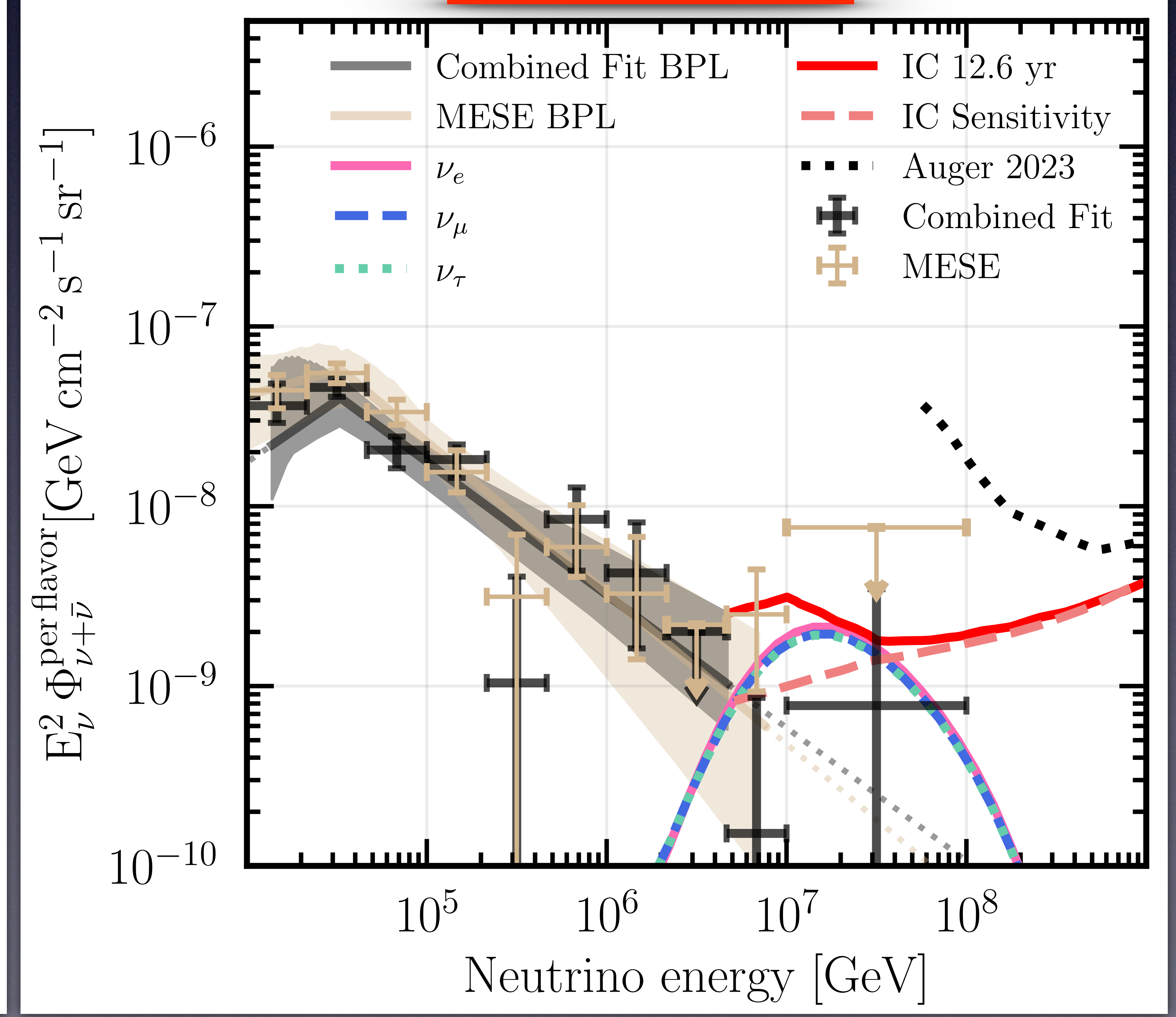
Neutrino Predictions probe source evolution



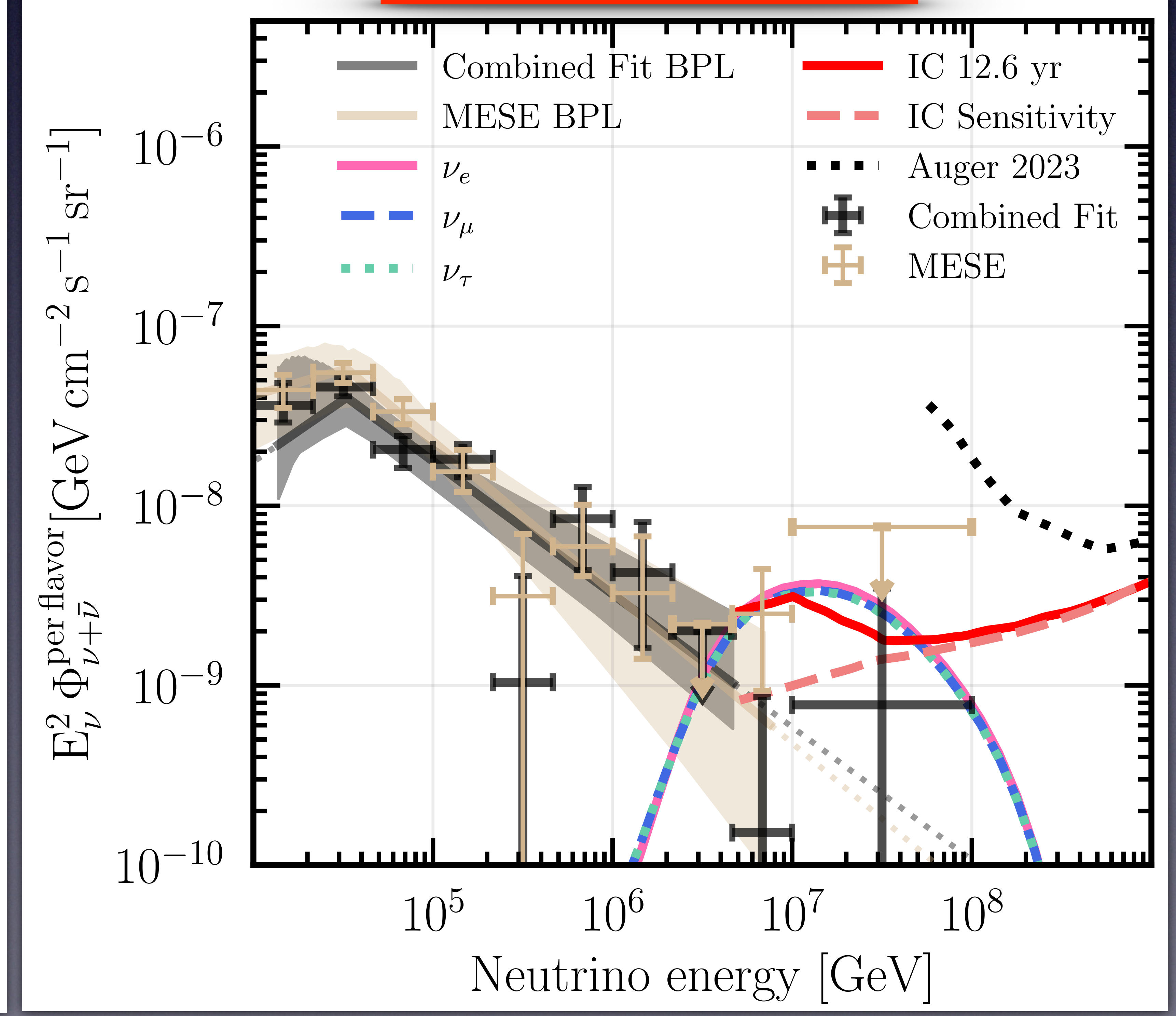
p or He jet, BNSM



p jet, SFR



no jet, BNSM



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	[✘]	✔	✘	✘	✘	✘
Long GRBs	[✘]	✘	✘	✘	✘	✘
TidalDistruption Events	?	?	✔	✘	✘	✘
Accretion Shocks	?	?	[✘]	✘	✘	✘
BNS mergers	✔	[✔]	✔	✔	✔	✔

(All can satisfy Hillas size > Larmor radius)

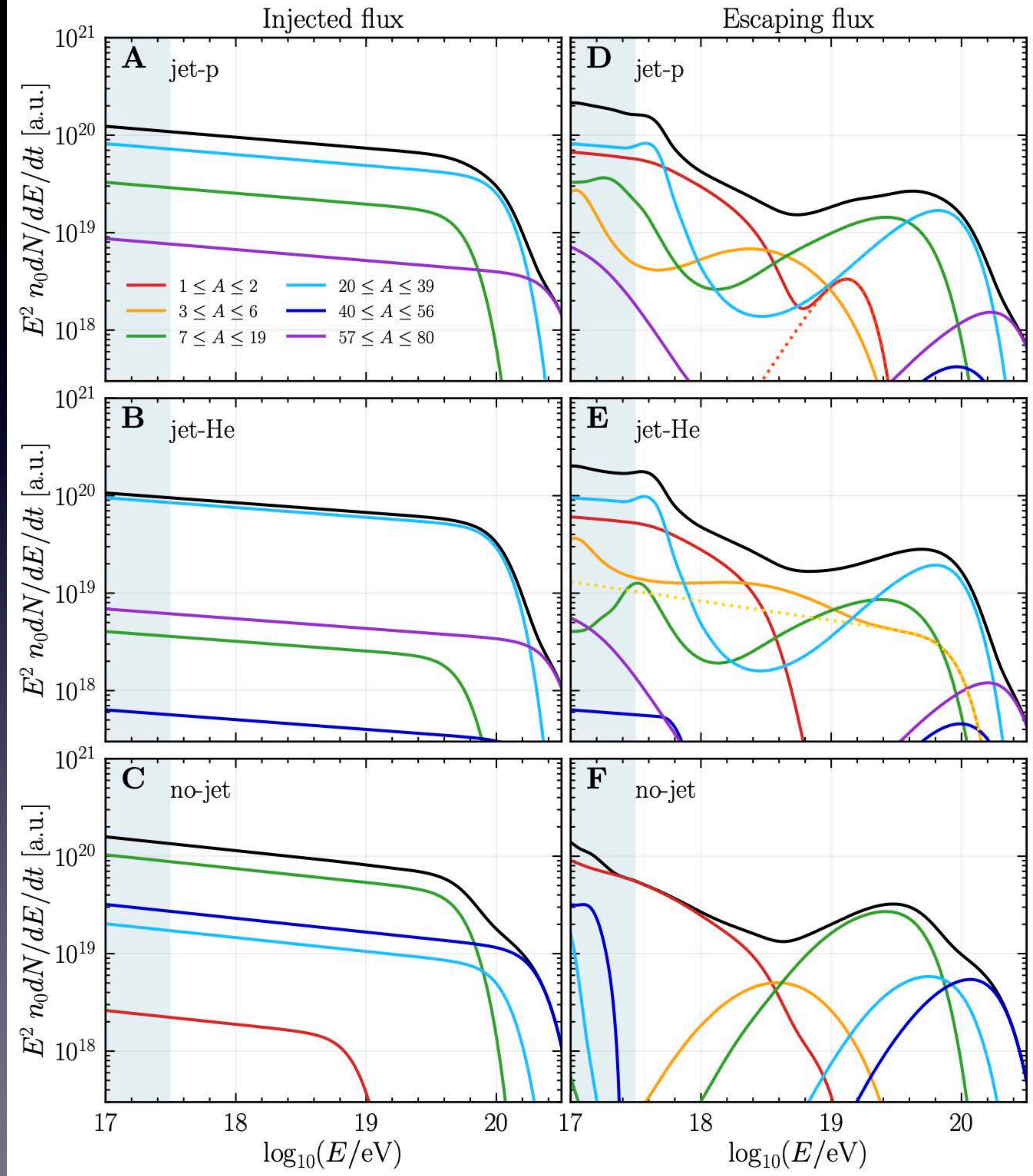
Theory to-do list

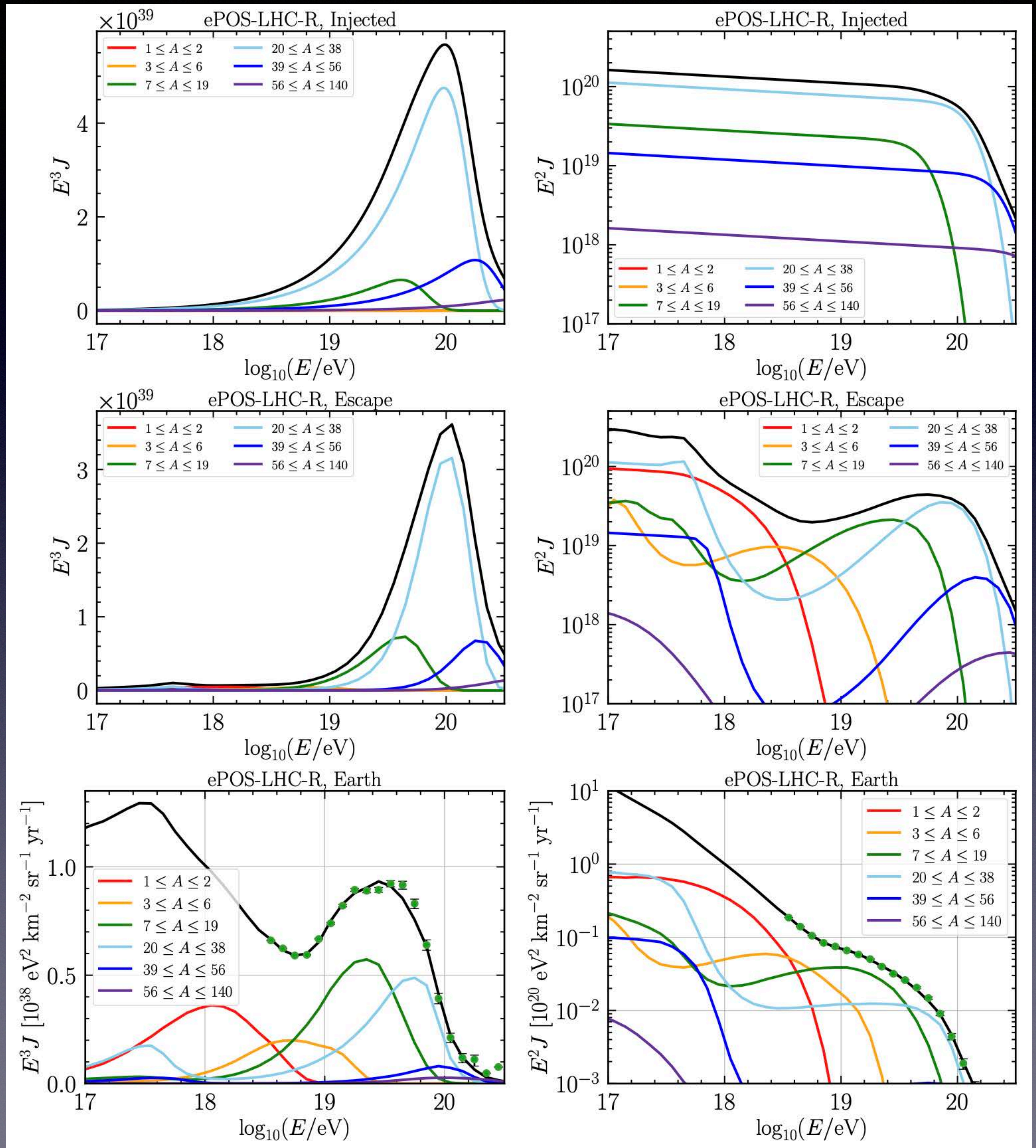
- *Include interactions in jet*
- *Normalized neutrino spectrum from individual BNSM (likelihood of sGRB or GW coincidence)*
- Constrain T in jet and outflow acceleration region from astro/sims
- Impact of expansion on acceleration and UFA analysis
- Impact of escape on observed spectrum
- Calculate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

Fundamental Physics from BNSM UHECRs

- QCD in strongly interacting regime: Neutron Star Equation of State (He/p in jet)
- Particle acceleration:
  - p/He from jets in BNS mergers — DSA vs magnetized turbulence
  - Outflow in BNS mergers — magnetized turbulence
- Jet in optical vs UHECRs -> extragalactic magnetic fields $B\ L_c^{1/2}$
- Astrophysics of BNS mergers & r-process nucleosynthesis

BACKUP SLIDES


Injected flux
Escaping flux
A jet-p
B jet-He
C no-jet
D jet-p
E jet-He
F no-jet
$E^2\, n_0 dN/dE/dt$ [a.u.]
$\log_{10}(E/\mathrm{eV})$
$1 \leq A \leq 2$
$3 \leq A \leq 6$
$7 \leq A \leq 19$
$20 \leq A \leq 39$
$40 \leq A \leq 56$
$57 \leq A \leq 80$


ePOS-LHC-R, Injected
ePOS-LHC-R, Escape
ePOS-LHC-R, Earth
$\times 10^{39}$
$E^3 J$
$E^2 J$
$E^3 J$ [10^{38} eV^2 km^{-2} sr^{-1} yr^{-1}]
$E^2 J$ [10^{20} eV^2 km^{-2} sr^{-1} yr^{-1}]
$\log_{10}(E/\mathrm{eV})$
$1 \leq A \leq 2$
$3 \leq A \leq 6$
$7 \leq A \leq 19$
$20 \leq A \leq 38$
$39 \leq A \leq 56$
$56 \leq A \leq 140$

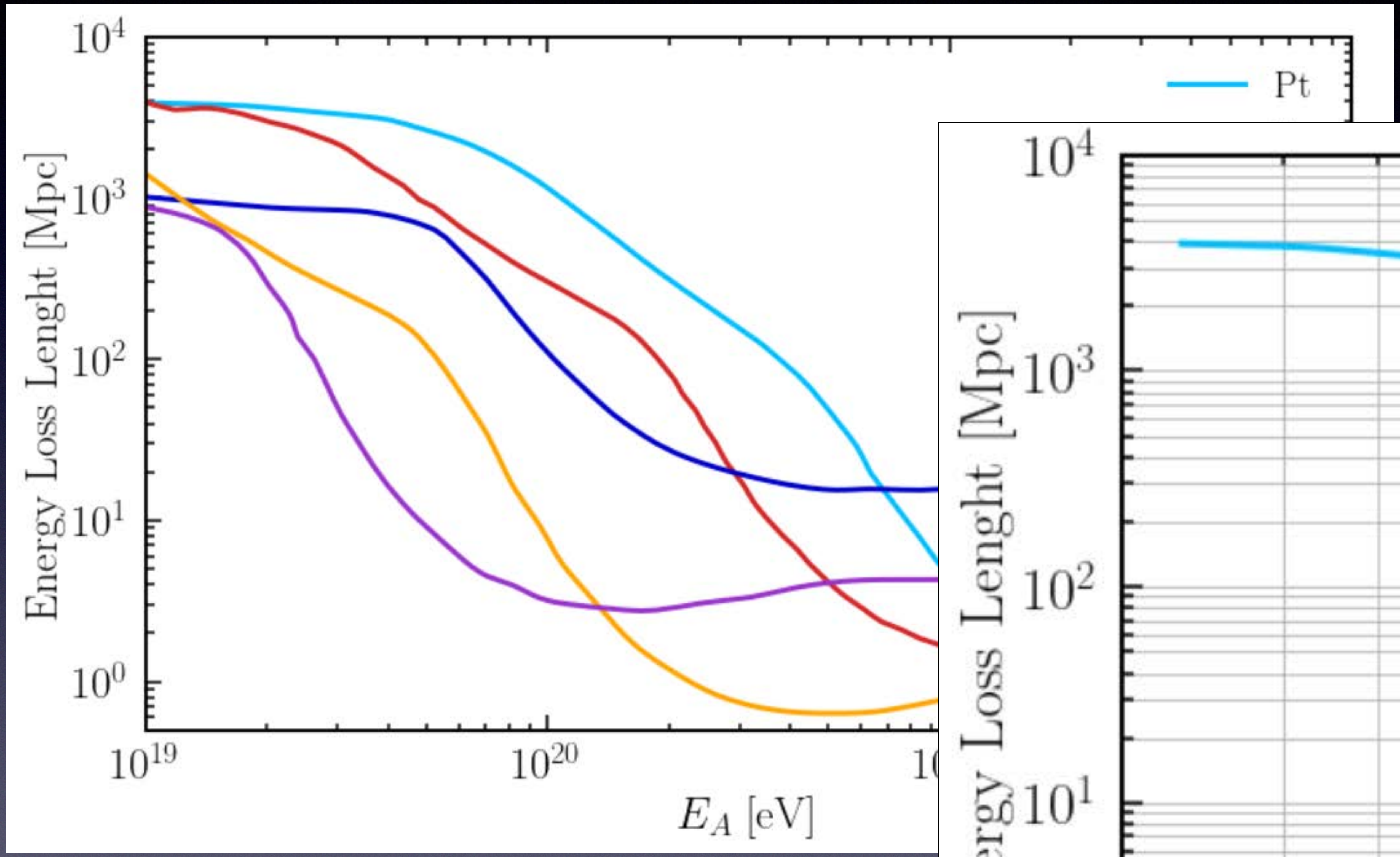
Parameters for best-fitting models

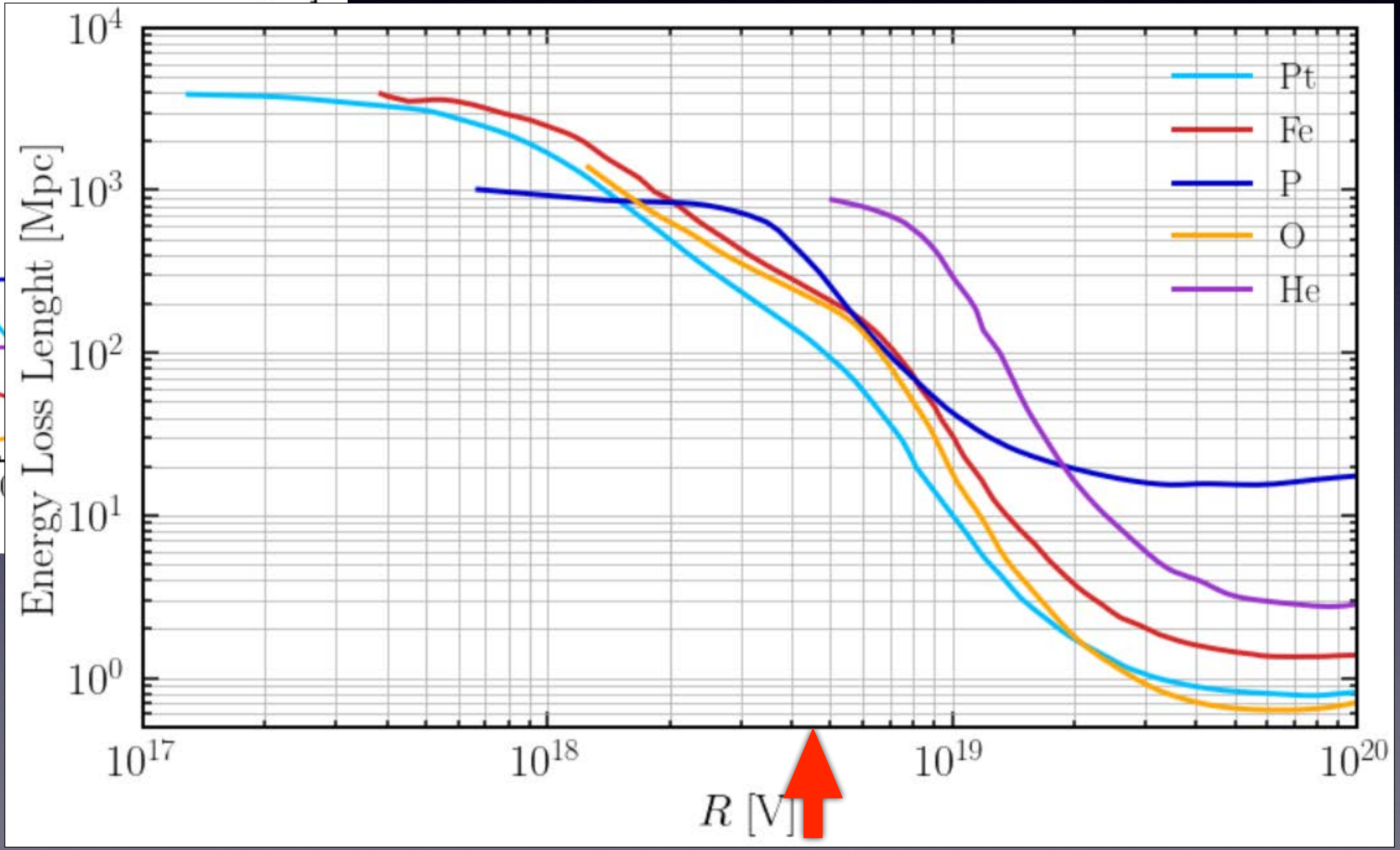
Suliga-GF

Parameter	sech jet-p	sech jet-He	exp jet-p	exp jet-He	no-jet
$\chi^2_{\text{tot}}/\text{ndf}$	118.8/55	115.9/55	124.2/55	120.7/55	260.5/58
	= 2.2	= 2.1	= 2.3	= 2.2	= 4.5
$\log_{10} r_{\text{esc}}$	2.55	2.57	2.59	2.61	3.14
γ_{inj}	−2.11	−2.10	−2.13	−2.11	−2.14
$\log_{10}(\mathfrak{R}_{\text{max}}/\text{V})$	18.86	18.84	18.85	18.84	18.85
$\log_{10}(R_{\text{diff}}/\text{V})$	18.01	18.00	17.92	17.94	15.89
$\tanh(\log_{10} r_{\text{size}})$	0.69	0.65	0.68	0.64	1.00
T [K]	563	567	572	566	1235
$\log_{10}(E^{\text{jet}}_{\text{max},i}/\text{eV})$	19.08	19.91	18.72	19.68	–
γ^{jet}_i	≈ 0	−2.20	≈ 0	−1.86	–
$\log_{10}(f^{\text{jet}}_i)$	−1.31	−0.92	−1.28	−0.69	–
f_1	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	0.02
f_{14}	0.27	0.04	0.28	0.04	0.65
f_{28}	0.66	0.89	0.59	0.85	0.13
f_{56}	$\lesssim 10^{-3}$	$\lesssim 10^{-2}$	0.10	0.06	0.20
f_{80}	0.07	0.06	0.03	0.05	$\lesssim 10^{-3}$
f_{gal}	0.63	0.60	0.63	0.60	0.83
γ_{gal}	−2.88	−2.88	−2.86	−2.83	−3.23
$\log_{10}(E^{\text{gal}}_{\text{max}}/\text{eV})$	18.49	18.45	18.51	18.46	18.75
f^{gal}_{14}	0.51	0.41	0.54	0.48	0.75
f^{gal}_{28}	0.49	0.59	0.46	0.52	0.12
f^{gal}_{56}	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	0.13

Nuclear Composition Mix vs polar angle
Fraction with given Z at 23o, 44o, 69o,& 90o
data from Radice&Guttierez
Fraction
charge Z
Total ejecta mass per angle
$M\ [M_\odot]$
ϑ [rad]
DD2_M135135
DD2_M180108
SFHo_M135135

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





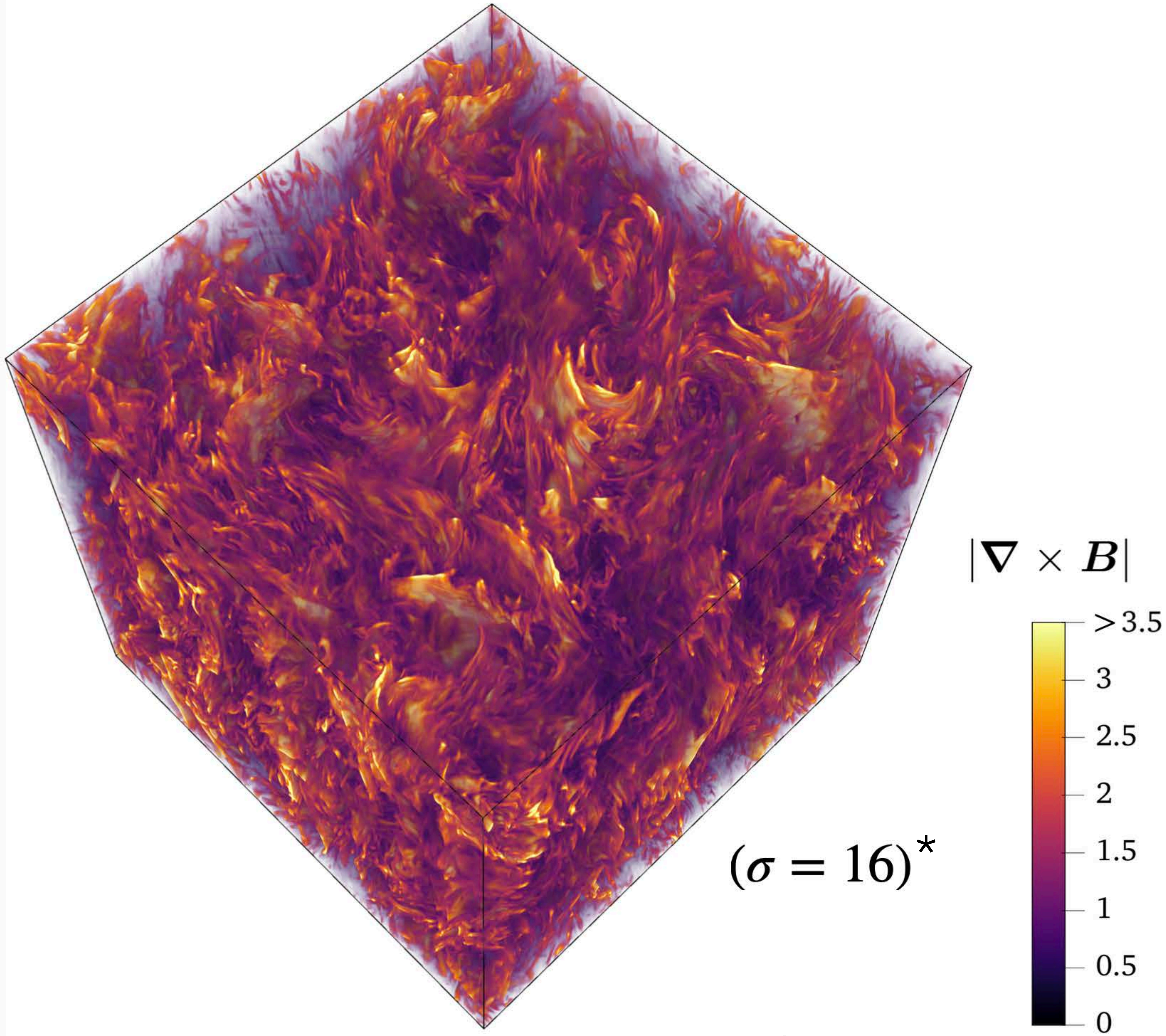
For $\mathcal{R}$ = 5 EV:

Z,A={36,80} ➜ <E_n>= 2.25

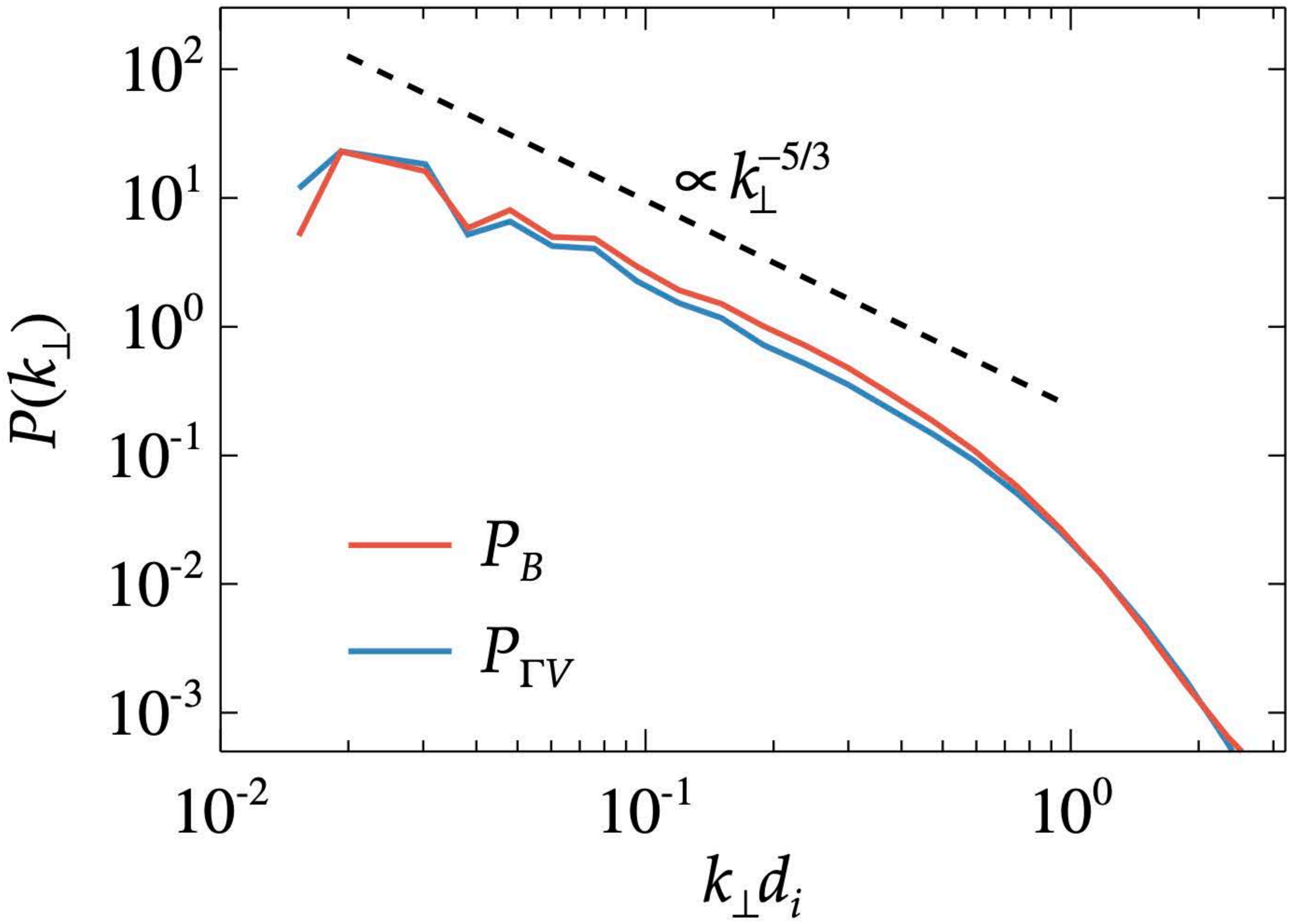
Z,A={14,28} ➜ <E_n>= 2.50

Z,A={1,1} ➜ <E_p>= 5.00

Magnetically dominated turbulence from first-principles PIC simulations



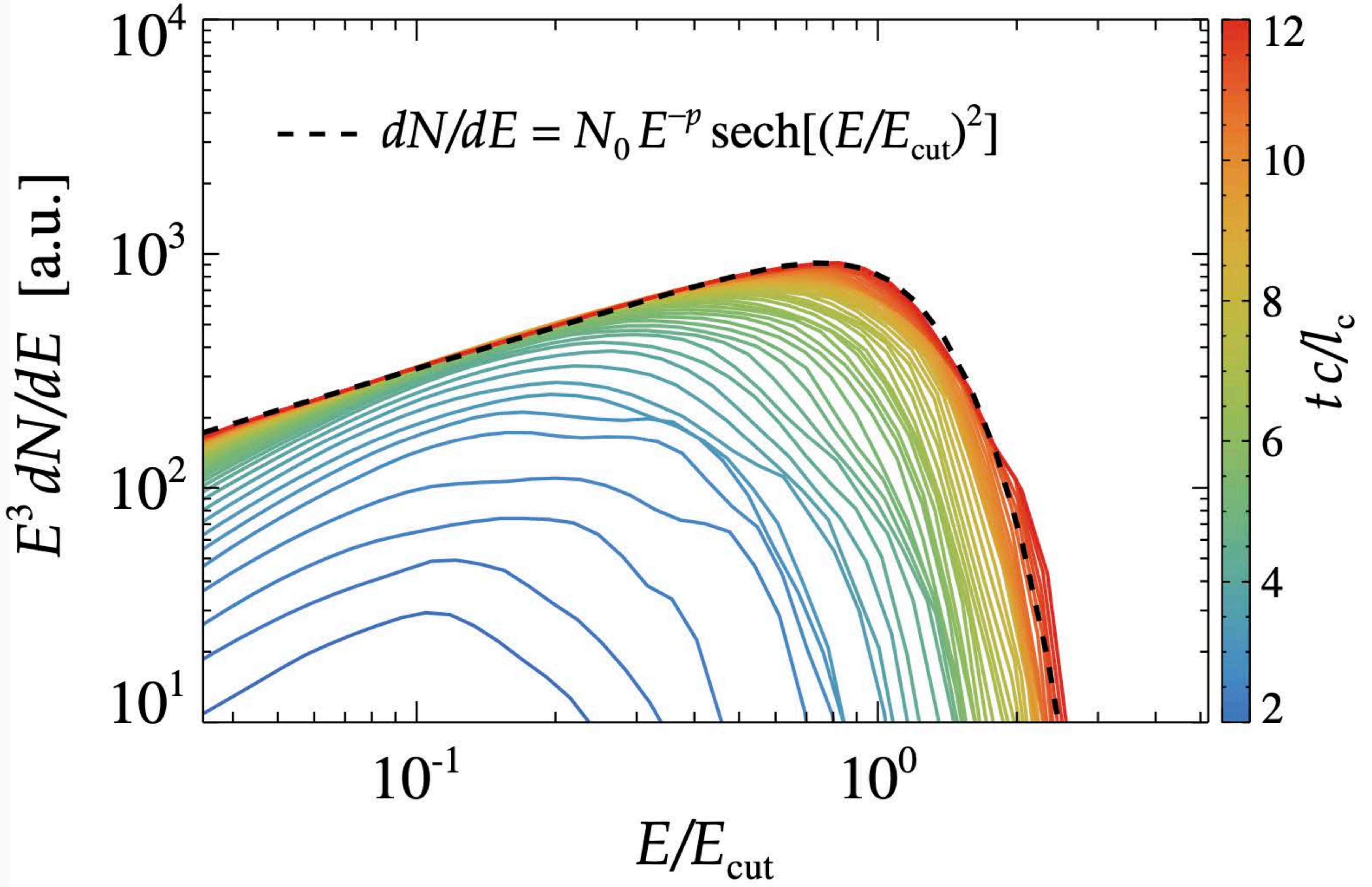
$^*\sigma \approx U_{mag}/KEden$

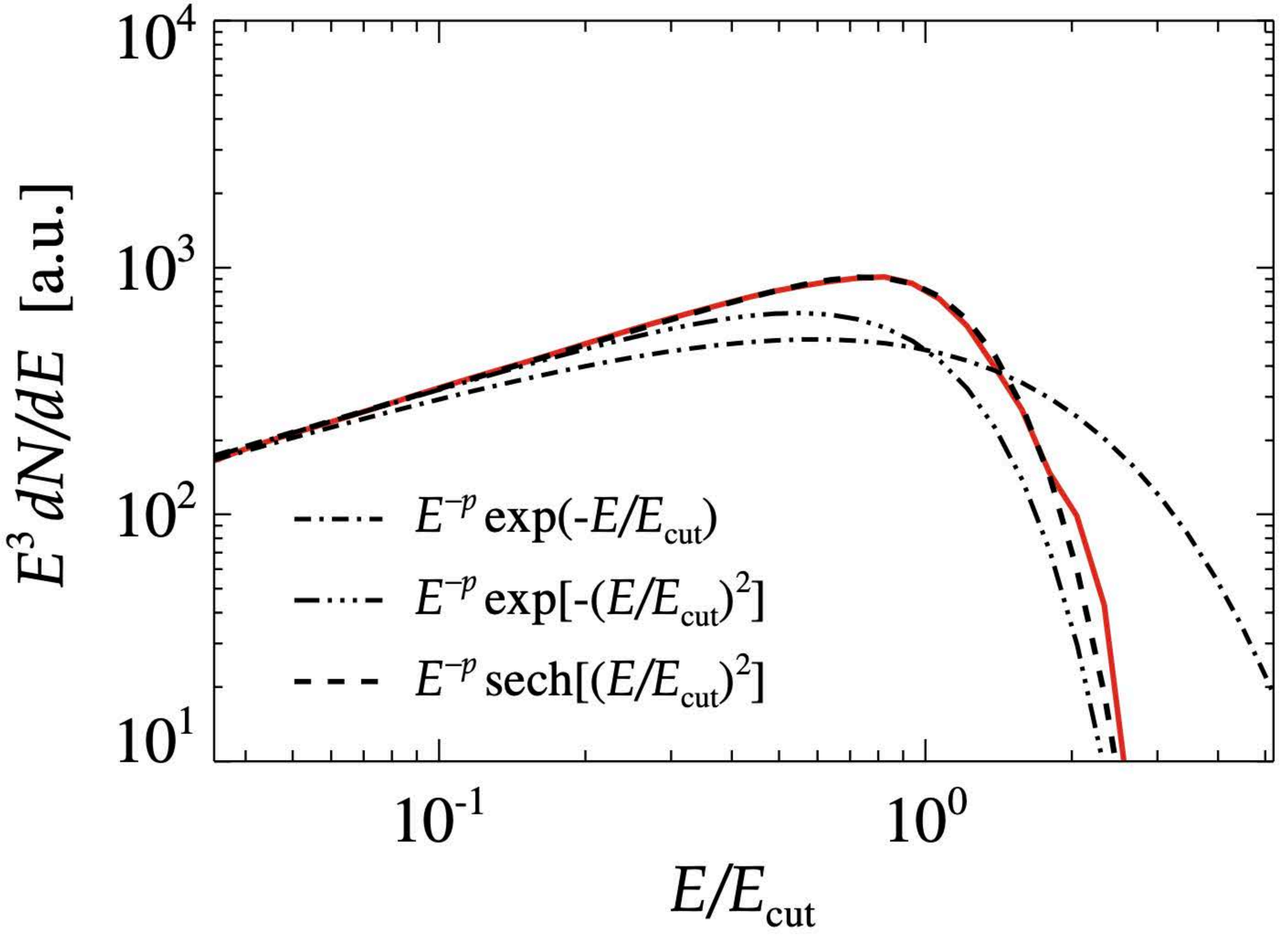


- The large computational domain allow us to capture both the MHD cascade at large scales and the kinetic cascade at small scales

L. Comisso, GRF, M. Muzio, ApJL2024

Particle acceleration via magnetized turbulence: nonthermal particle spectrum





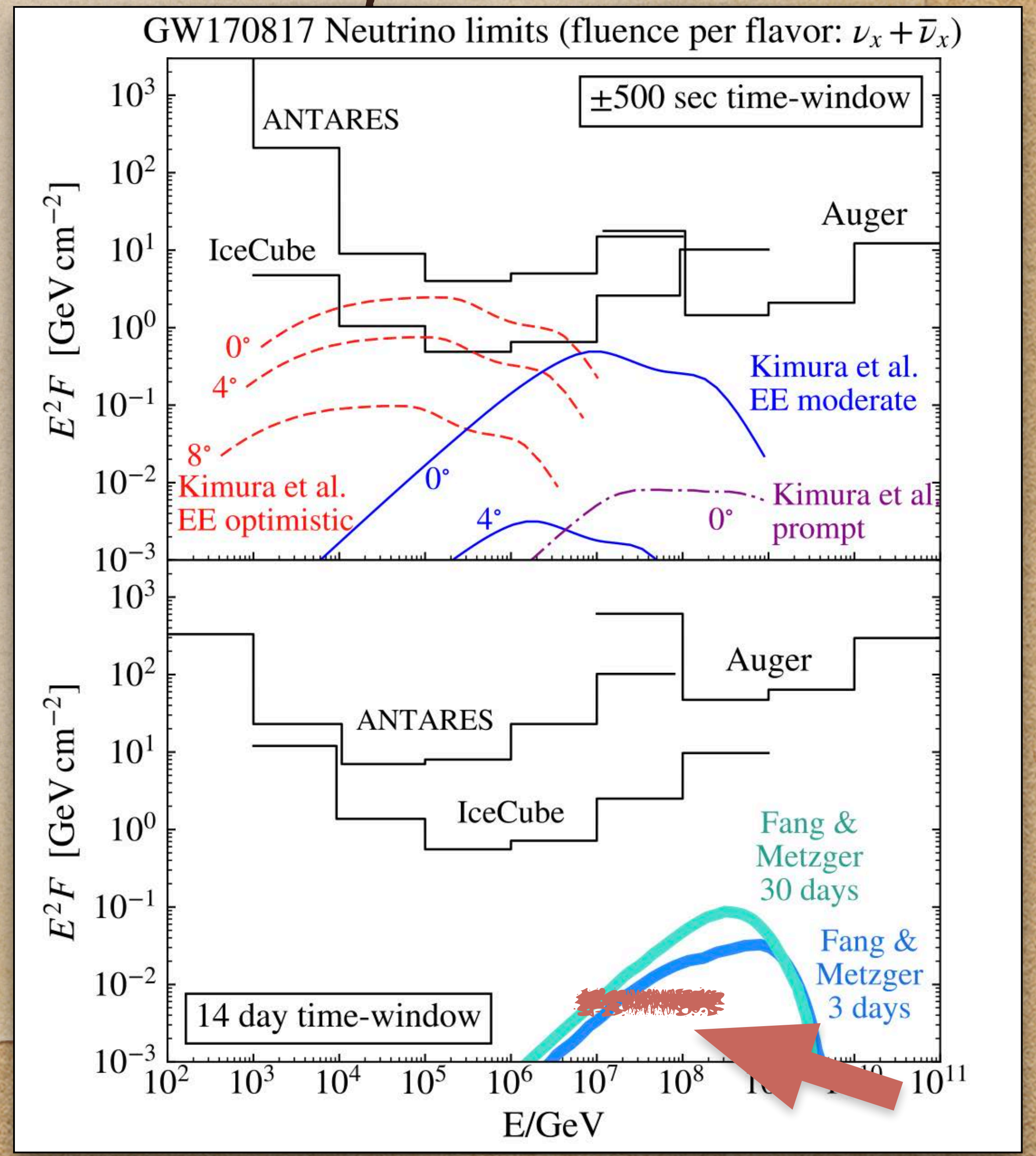
- magnetized turbulence accelerates particles into a spectrum of the form:

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

L. Comisso, GRF, M. Muzio, ApJL2024

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.
<u>Sensitivity not adequate by orders of magnitude</u>



Antares, IceCube, Auger, LVK '17