Binary Neutron Star Mergers as Cosmic Ray Sources

Anna M. Suliga

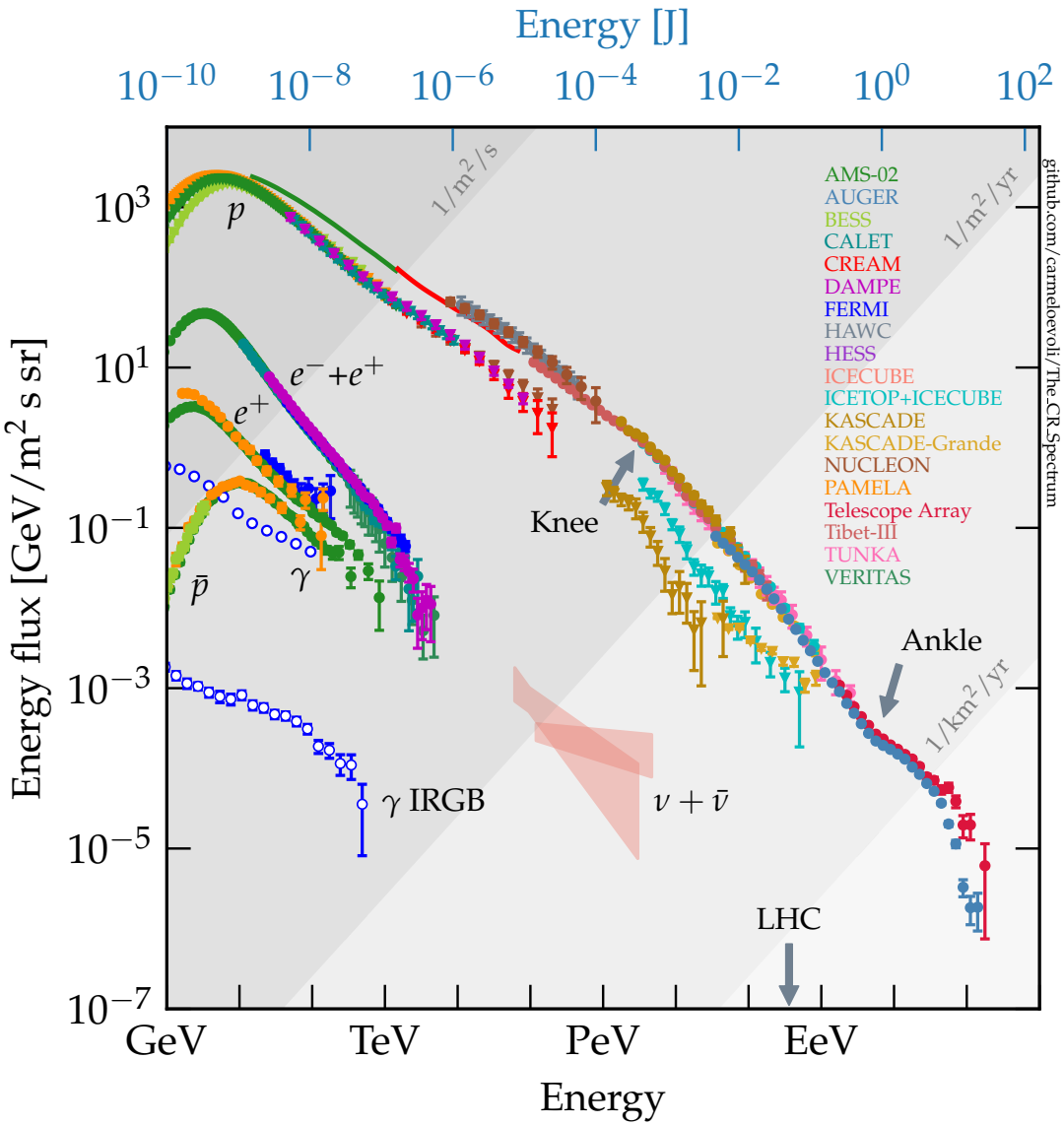
with Glennys Farrar
Neutrino Theory Network Fellow
New York University



University of Delaware, September 18, 2026

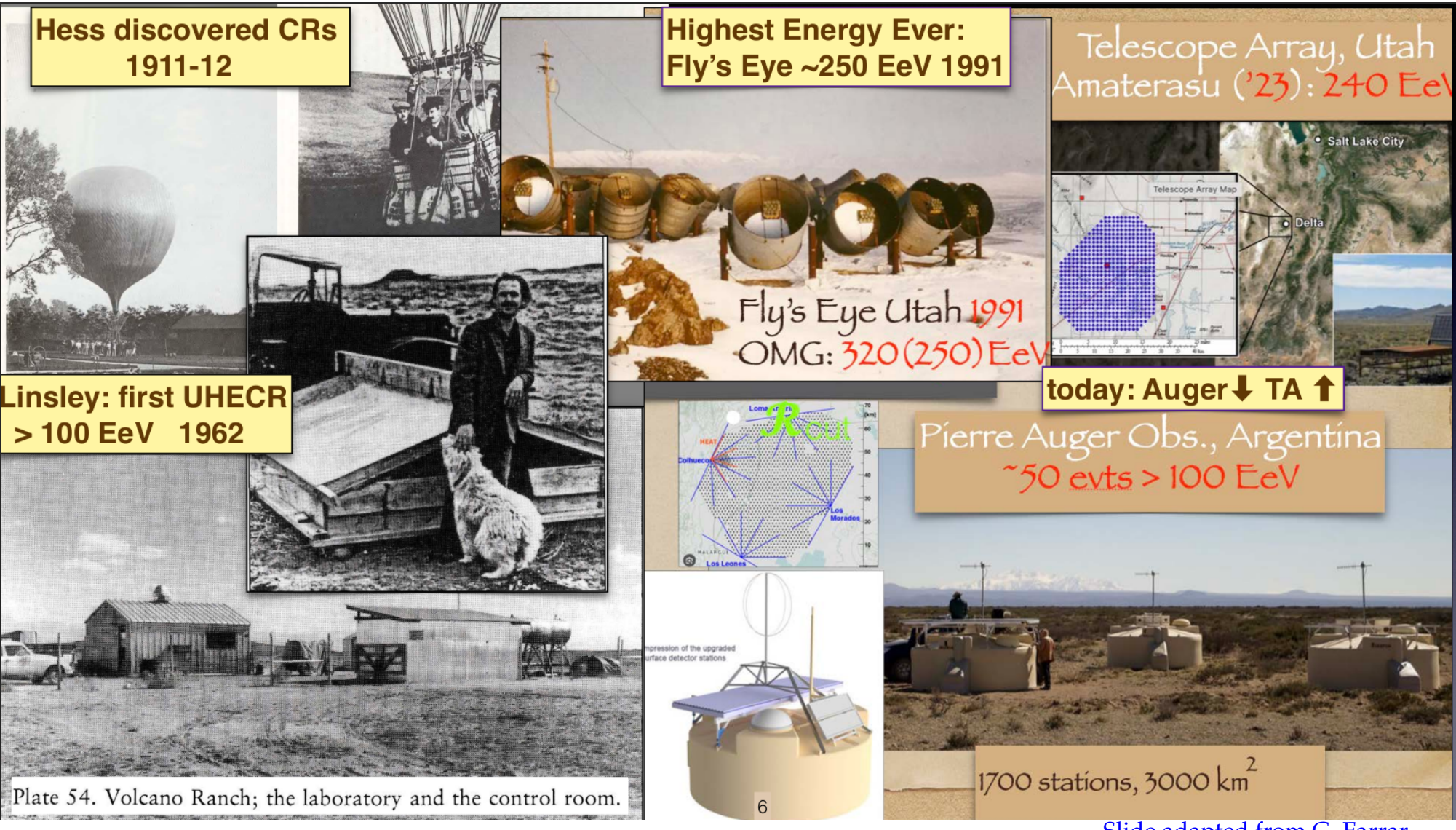
NYU

The cosmic ray spectrum



We are surrounded by particles from cosmos!

History of discoveries



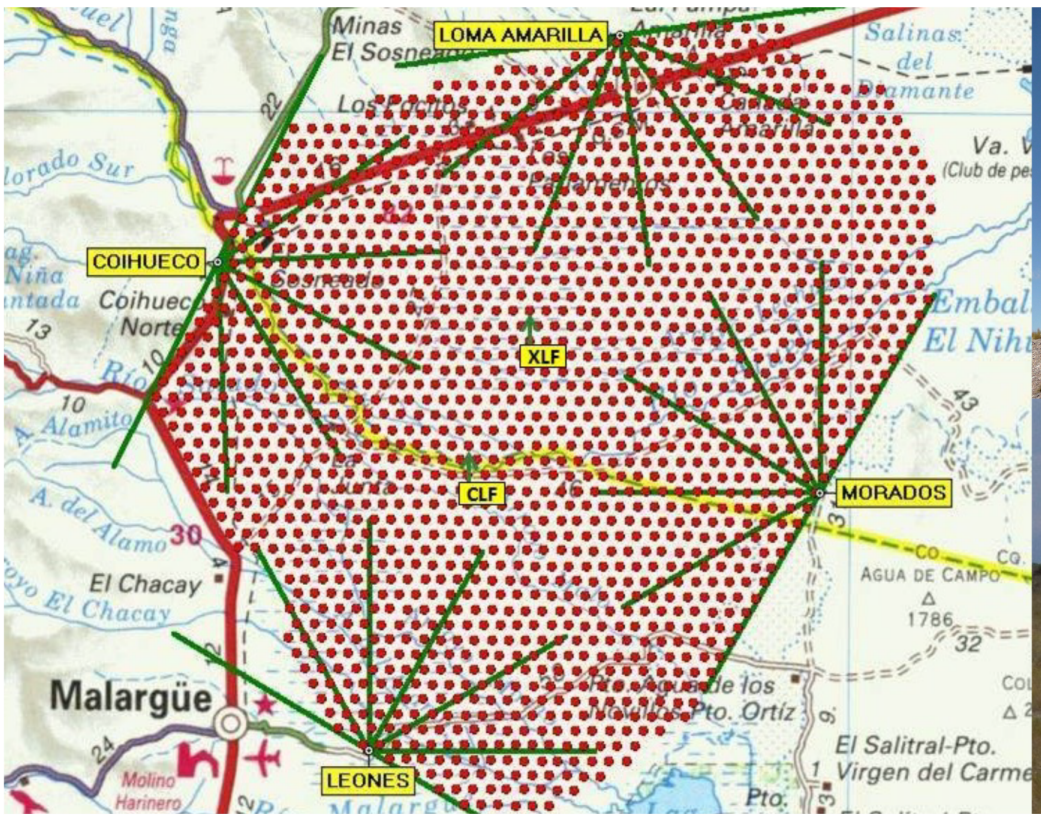
Slide adapted from G. Farrar

Ultra High Energy Cosmic Rays (UHECR) are

- **Very rare** less than 1 per km^2 per 100 yr arriving at Earth
- **Very energetic** 10^{18}-10^{20} eV; LHC 1.4×10^{13} eV
- **Composed of nuclei**
- **Can be produced in Binary Neutron Star Mergers?**

Pierre Auger Observatory in Argentina

- 1700 station
- 3,000 km^2 surface detector array
- 1,600 Cherenkov detectors - surface detectors (SD)
- 4 air-Cherenkov fluorescence telescopes - FD





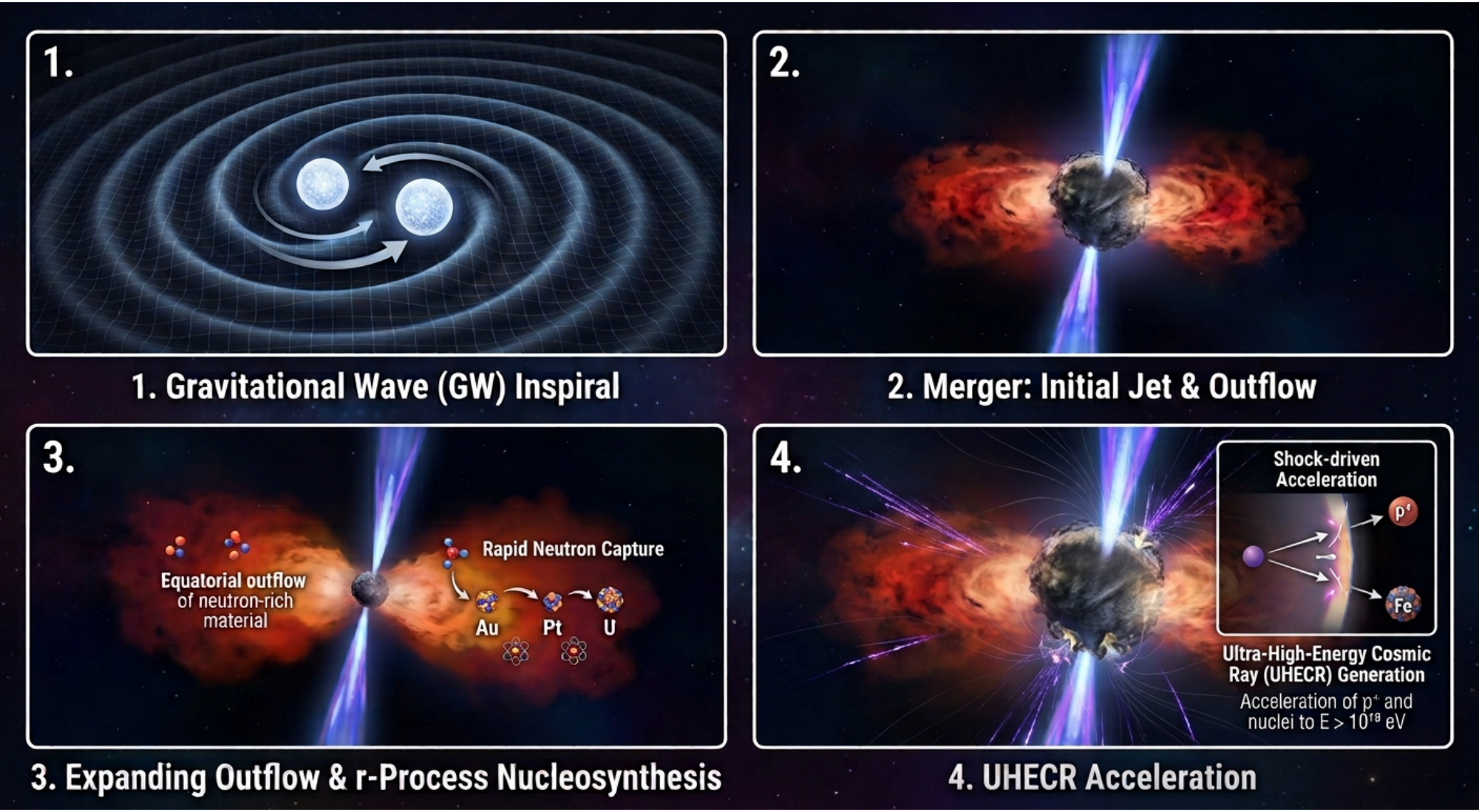
Properties of the sources from the data

Observed Spectrum and Composition of the UHECR by Pierre Auger Observatory indicates

- composition is mixed
- A mass increases with energy
- A mass range is narrow at a given energy; $\langle R \equiv \frac{E}{Z} \rangle \approx 4$ EV
- R spectrum is narrow $\rightarrow$ common R_{max}
- exponential cut-off returns unphysical power index

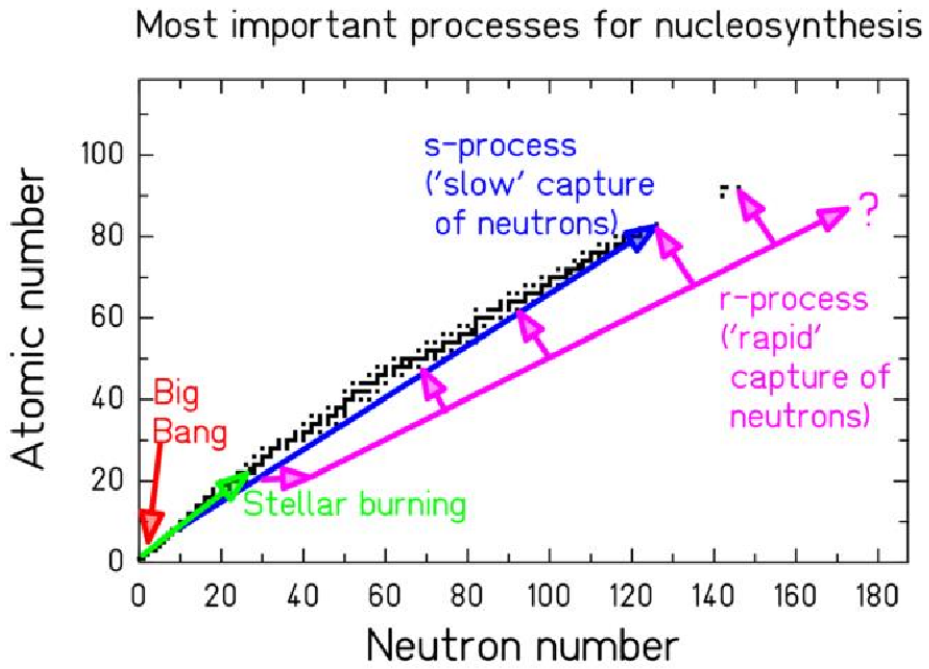
Pierre Auger Collaboration (2023), Ehlert, Oikonomou, Unger (2023), Pierre Auger Collaboration (2025), Pierre Auger Collaboration (2026) ....

Binary Neutron Star Mergers (BNSM) as UHECR Sources



Gemini generated image

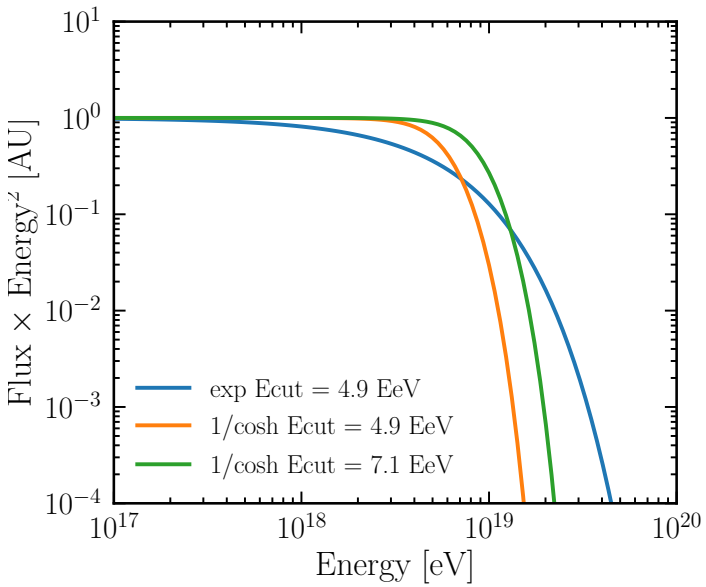
r-process nucleosynthesis in BNSM



- neutron lifetime capture $<<$ β decay
- very neutron rich enviroment

Binary Neutron Star Mergers (BNSM) as UHECR Sources

- large magnetic fields
- mass range of BNSM systems is narrow
- heavy nuclei present
- possible second HE light component from the jet
- magnetic dyamo can give sharper physical cut-off

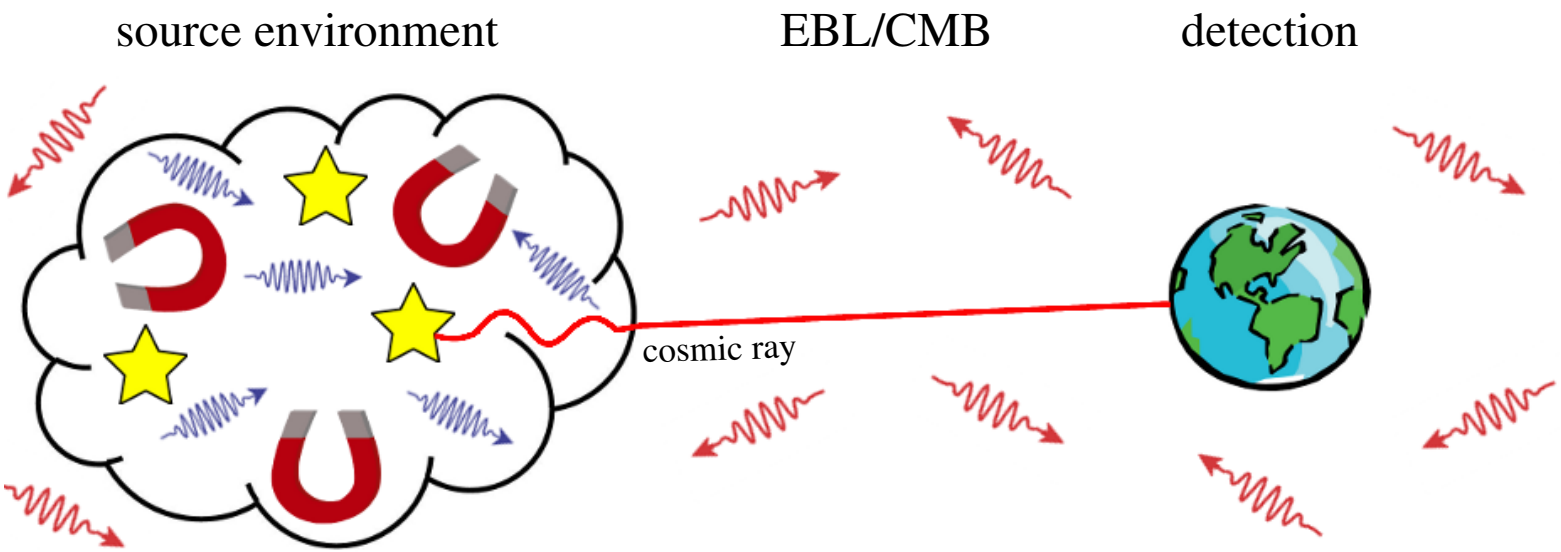


$$\Phi(E) \propto E^{-p}\,\mathrm{sech}\left((E/E_{\mathrm{cut}})^2\right)$$

$$\Phi(E) \propto E^{-p}\exp\left(-E/E_{\mathrm{cut}}\right)$$

Perego et al. (2021) Comisso, Farrar, Muzio (2024), Farrar (2045), Farrar (2025), ...

Ilustration of the model calculations

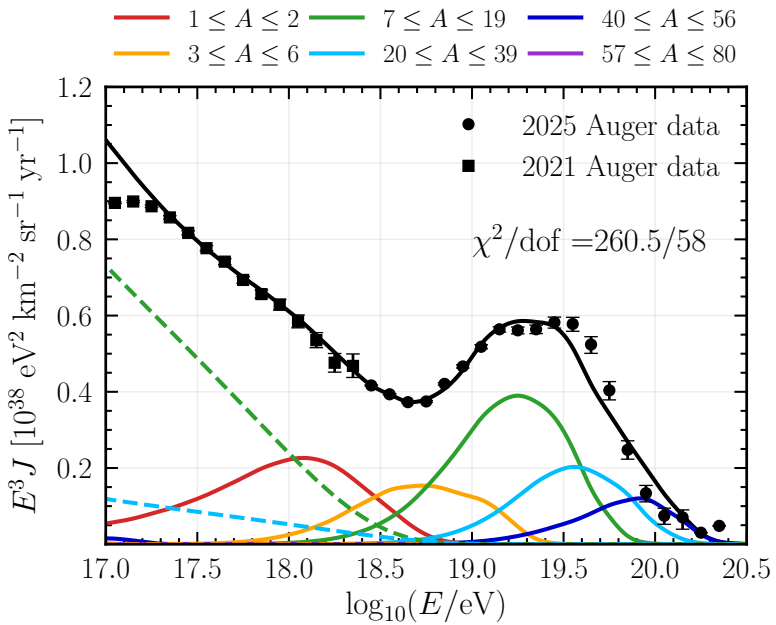


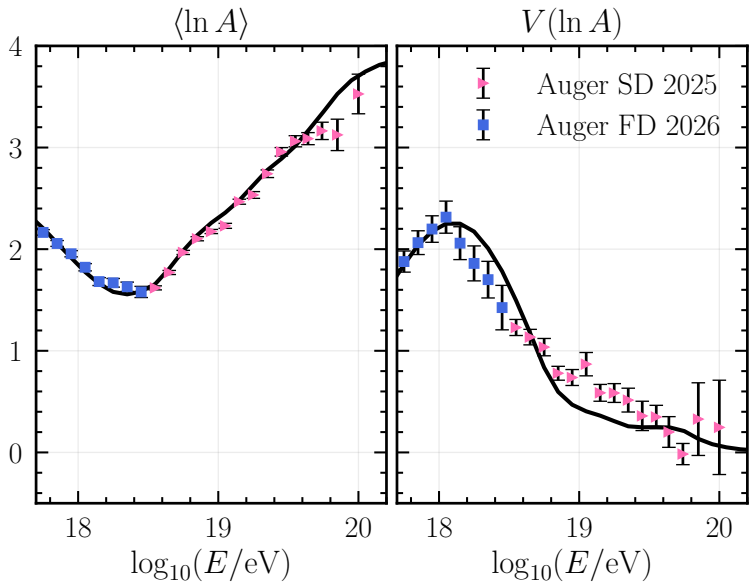
Unger, Farrar, Anchordoqui (2015)

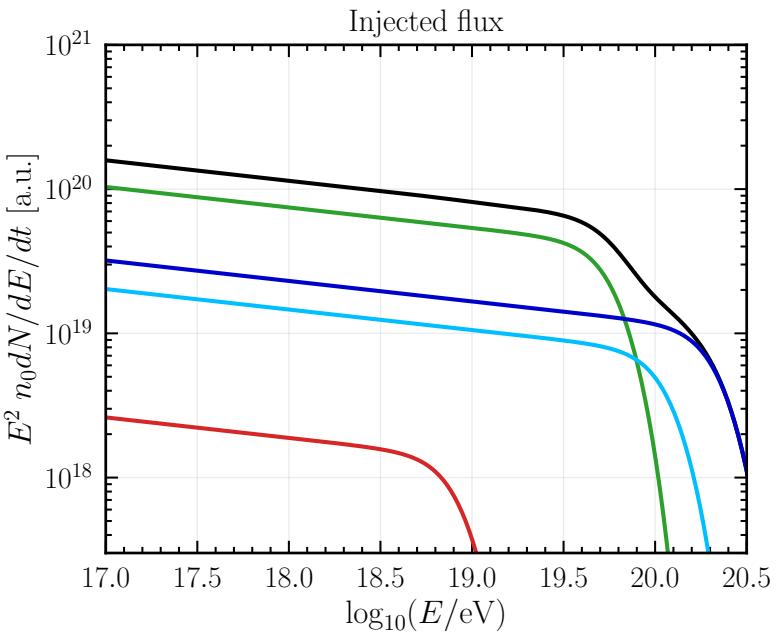
Ingredients in the calculation of the diffuse flux

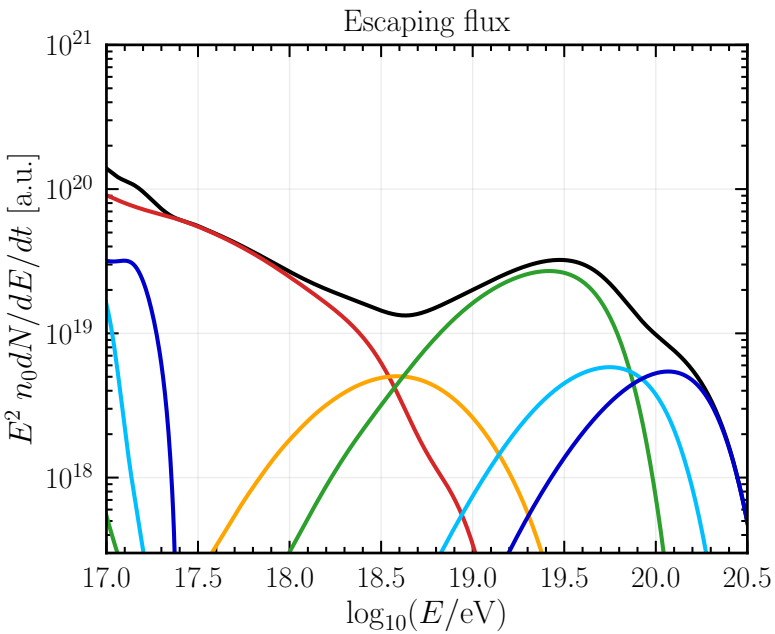
- single injected power index for all nuclei
- single cut-off rigidity for all nuclei (Peters cycle)
- sech cut-off
- photodisintegration and photomeson production erosion
- single temperature of the photon field
- BNSM redshift evolution
- propagation effects include interactions with CMB and EBL
- Galactic component with three nuclei composition fitted

Best fit does not need any heavies

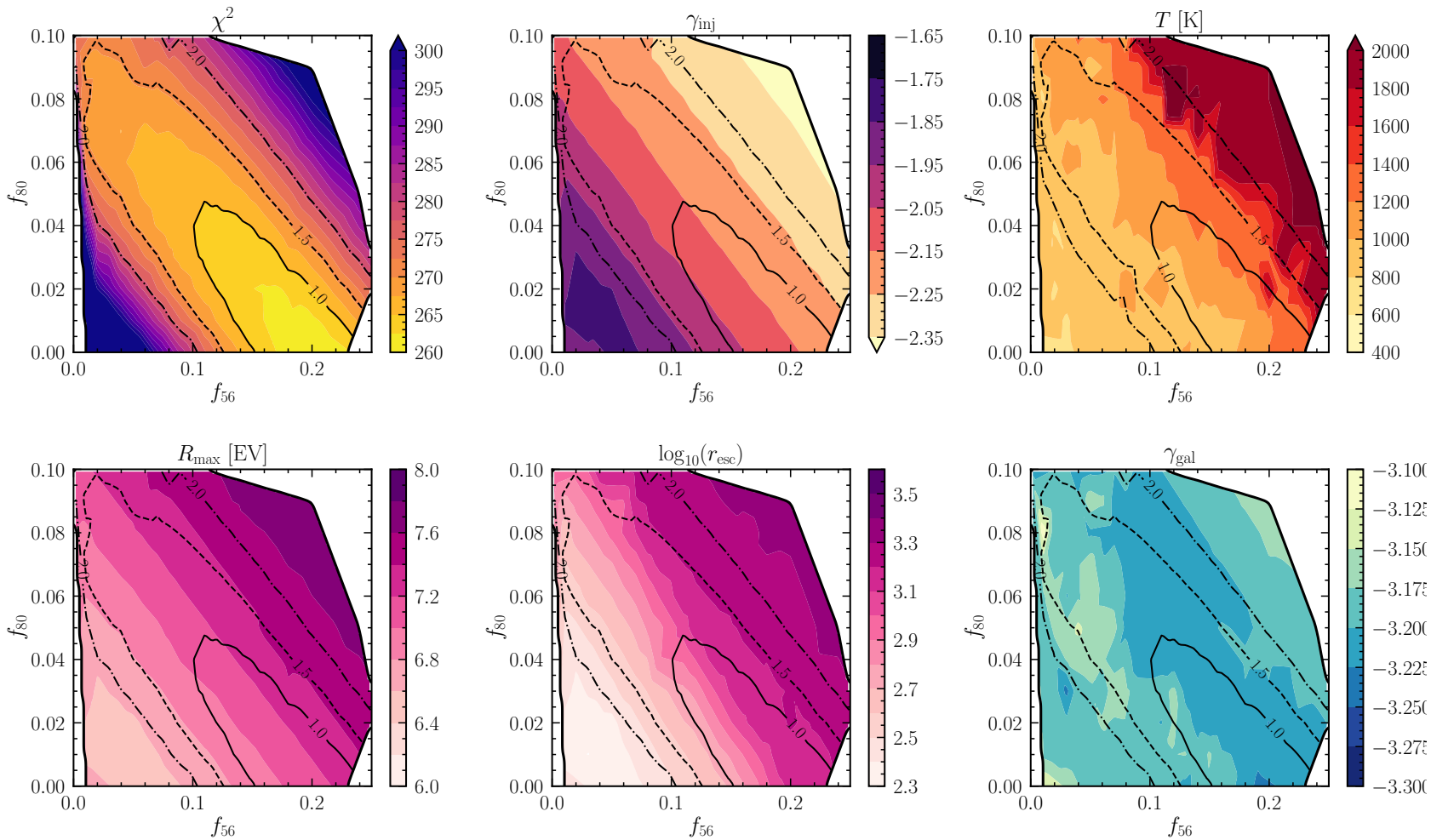




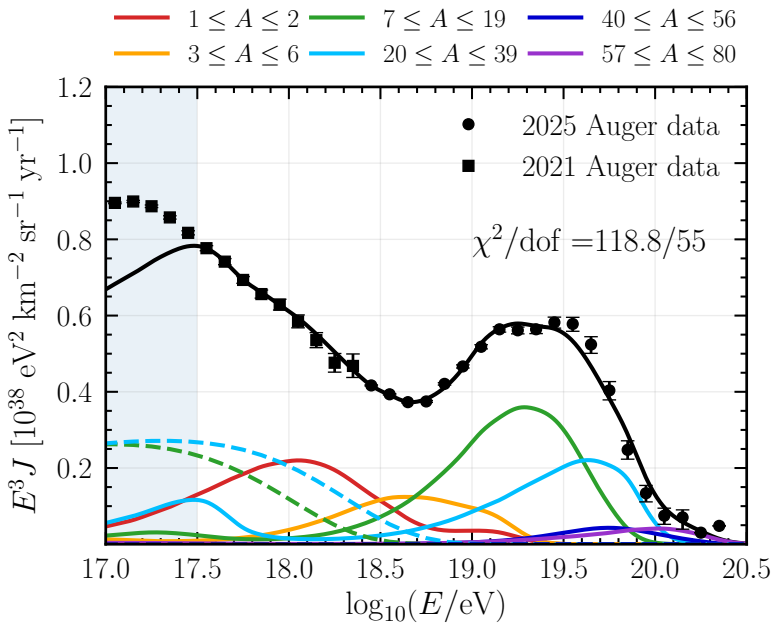


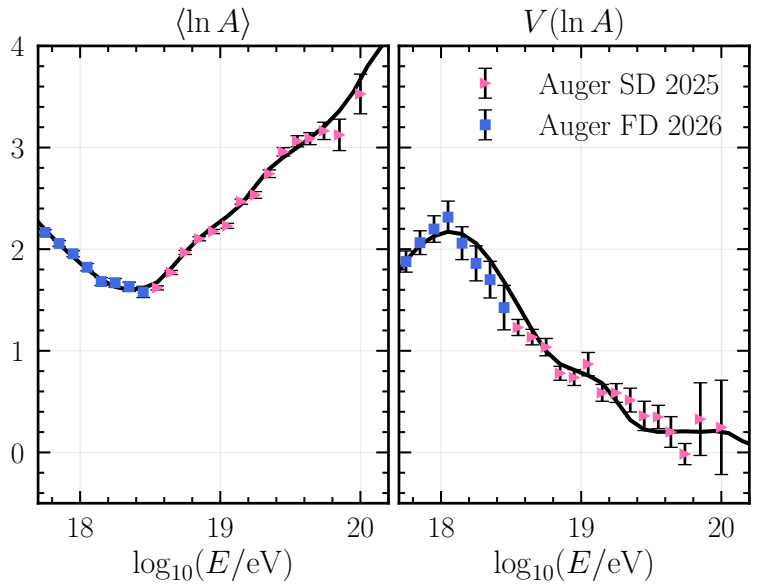


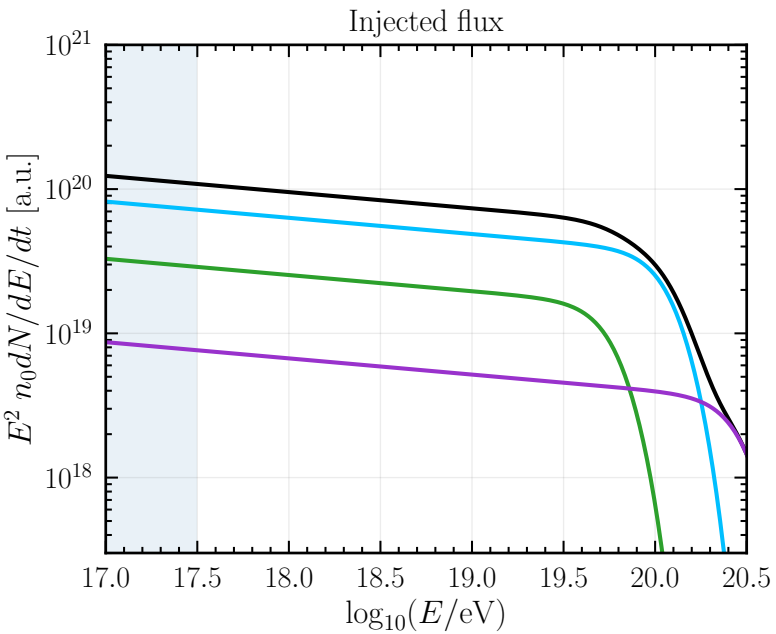
Allowed regions for different parameters

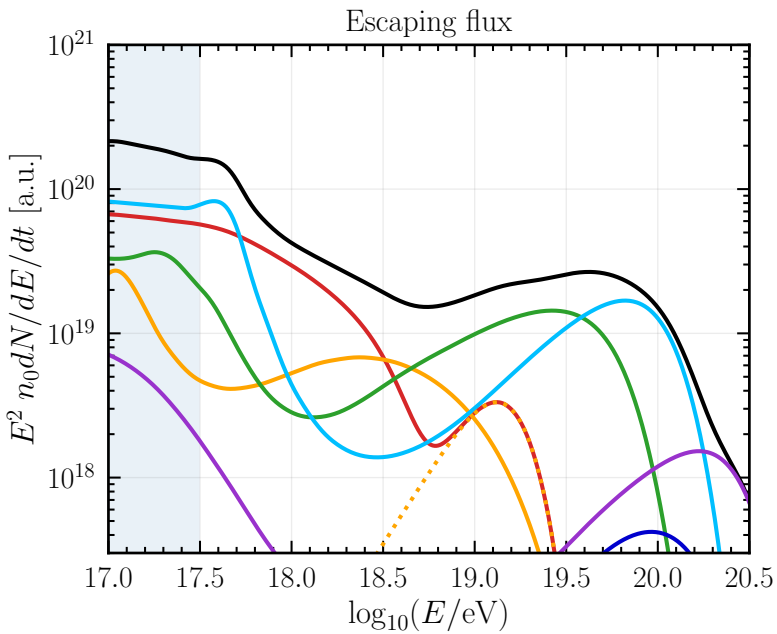


Best fit with extra high energy proton component

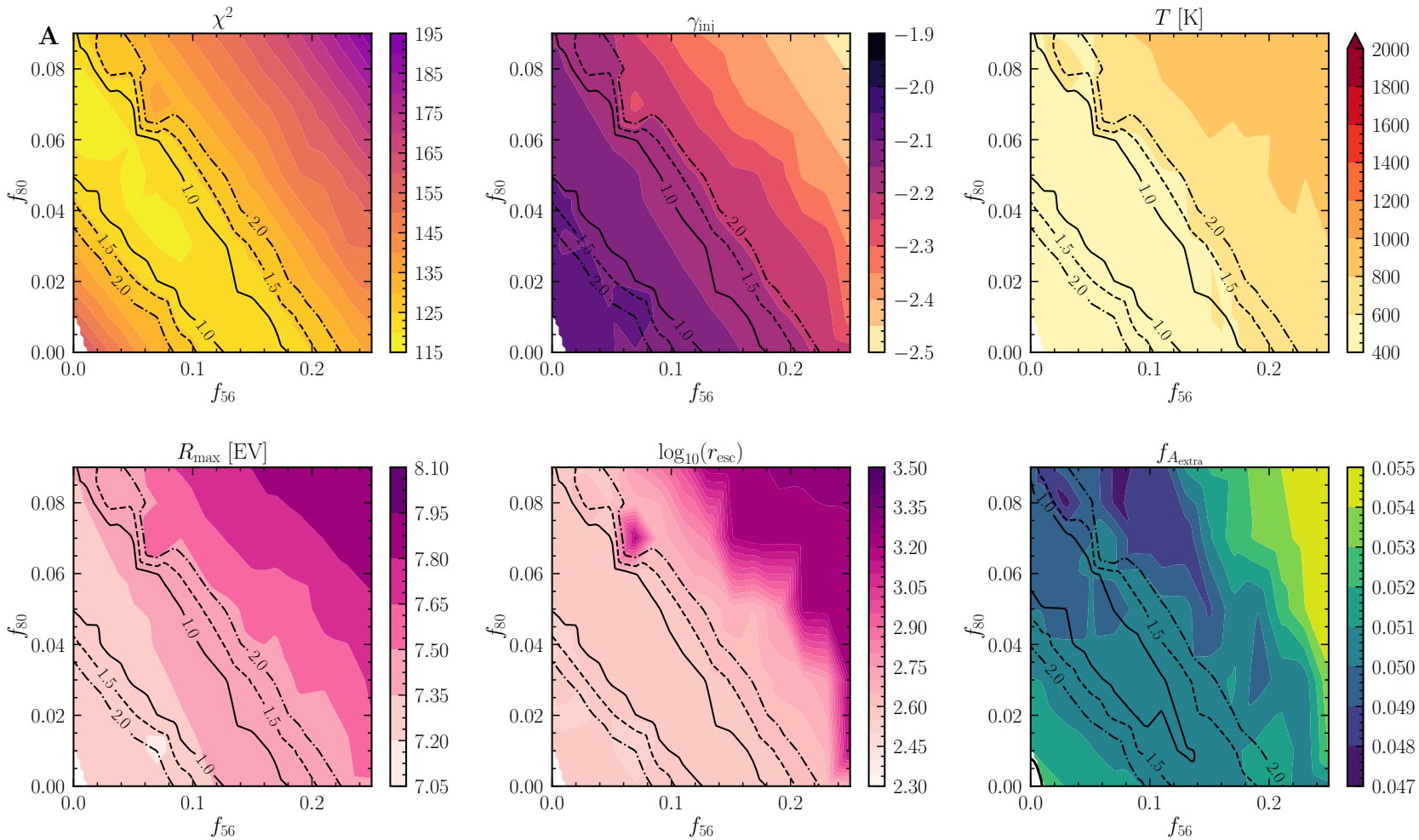




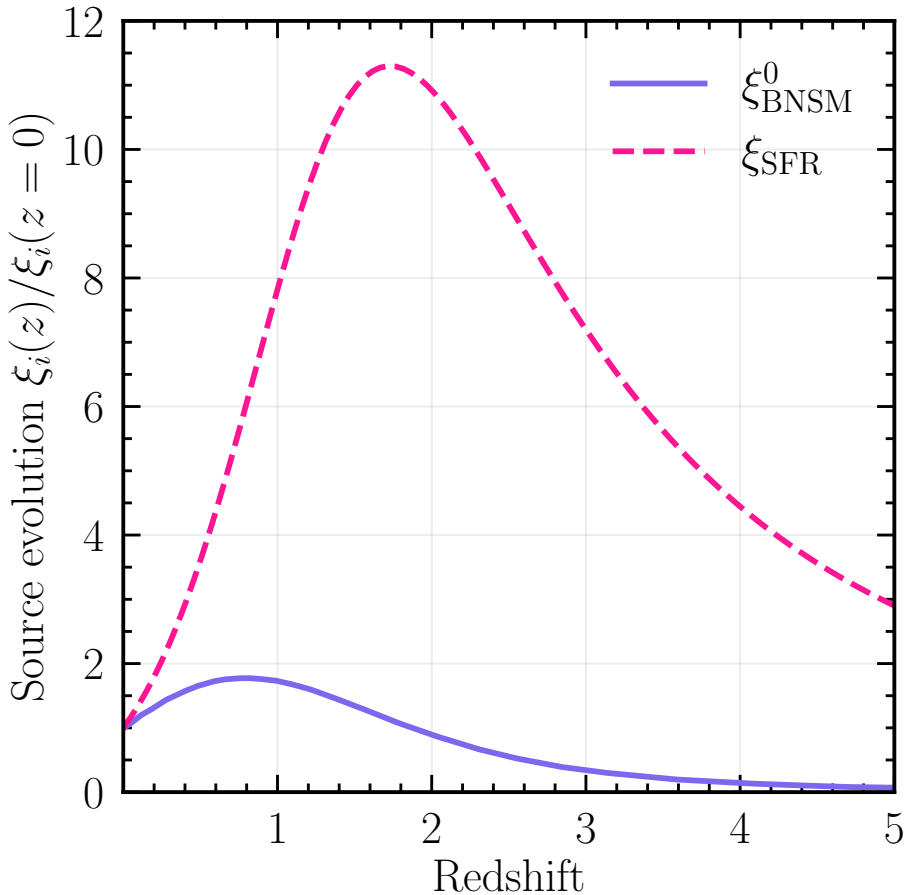




Allowed regions for different parameters



Redshift evolution of the sources



$$\xi_{\rm SFR} \propto \frac{1+z^a}{1+[(1+z/b)]^c}$$

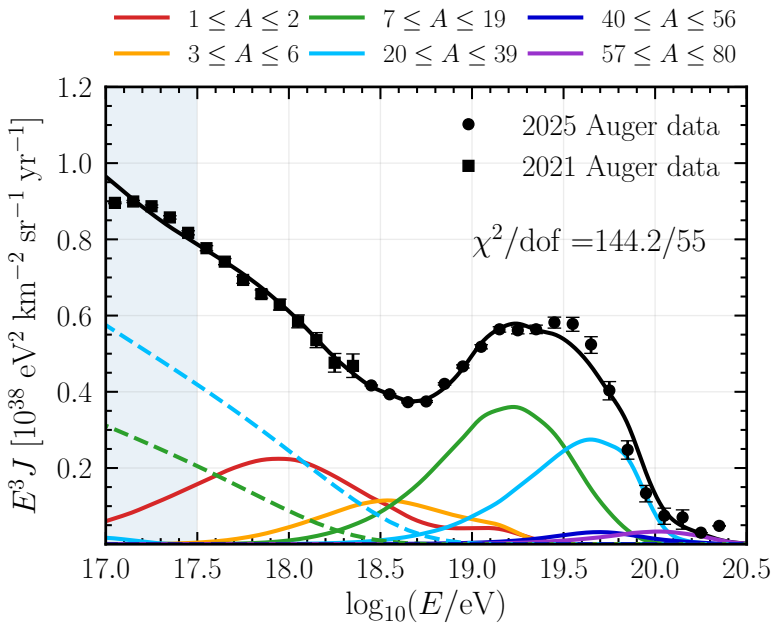
where $a = 3.26$, $b = 2.59$, and $c = 5.68$ from Robertson et al. 2015

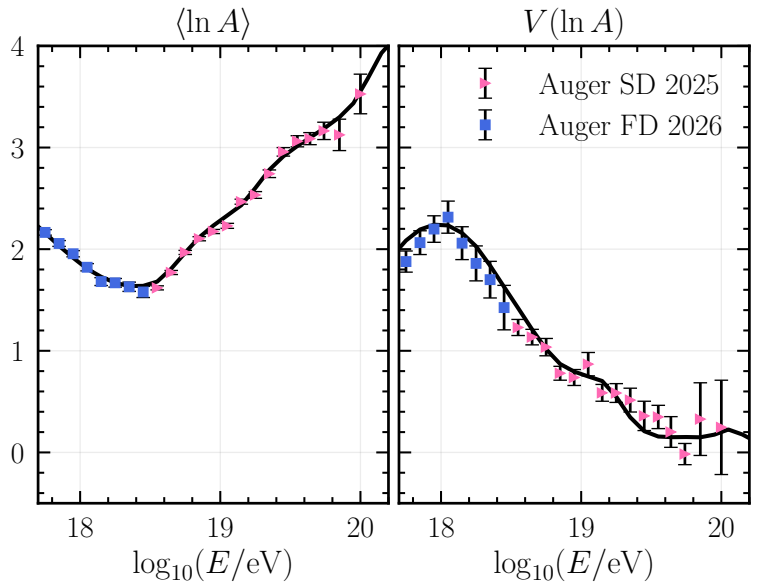
$$\xi^0_{\rm BNSM} \propto \begin{cases} \exp\left(-\frac{(z-\mu)^2}{(2\sigma)^2}\right) & \text{for} \quad z \leq 1.5 \\ \exp\left(-\iota z\right) & \text{for} \quad z > 1.5\,, \end{cases}$$

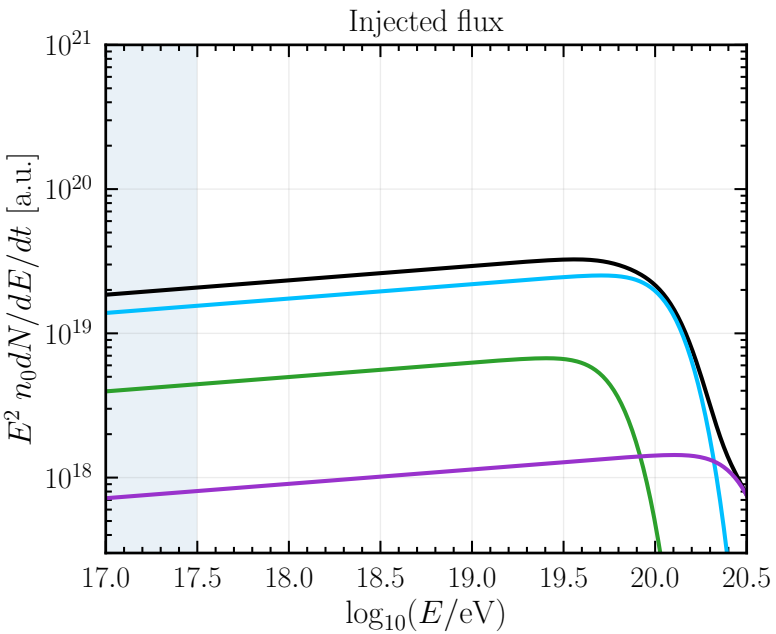
BNS evolution peaks at smaller redshift than SFR

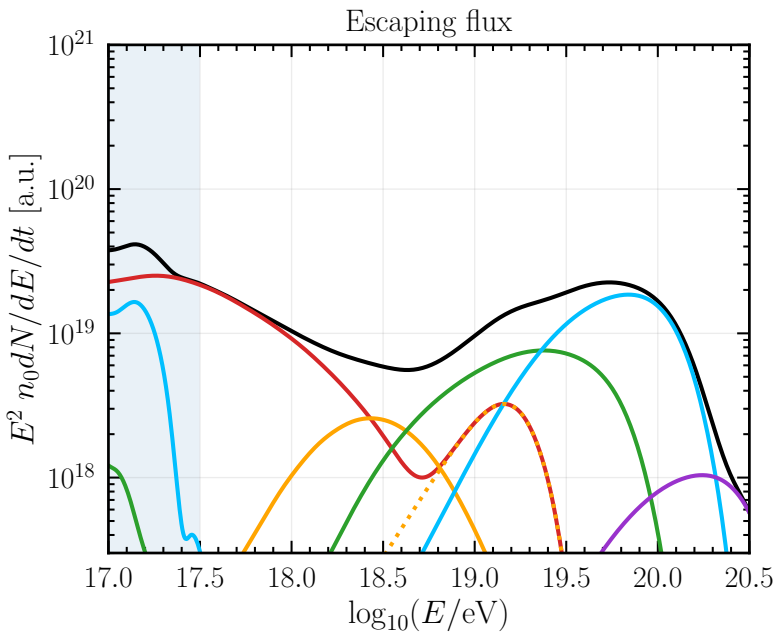
where $\mu = 0.87$, $\sigma = 0.60$, $\iota = 0.88$, and $\tau = 5$ Gyr from Du et al. 2025

Best fit with extra high energy proton component SFR





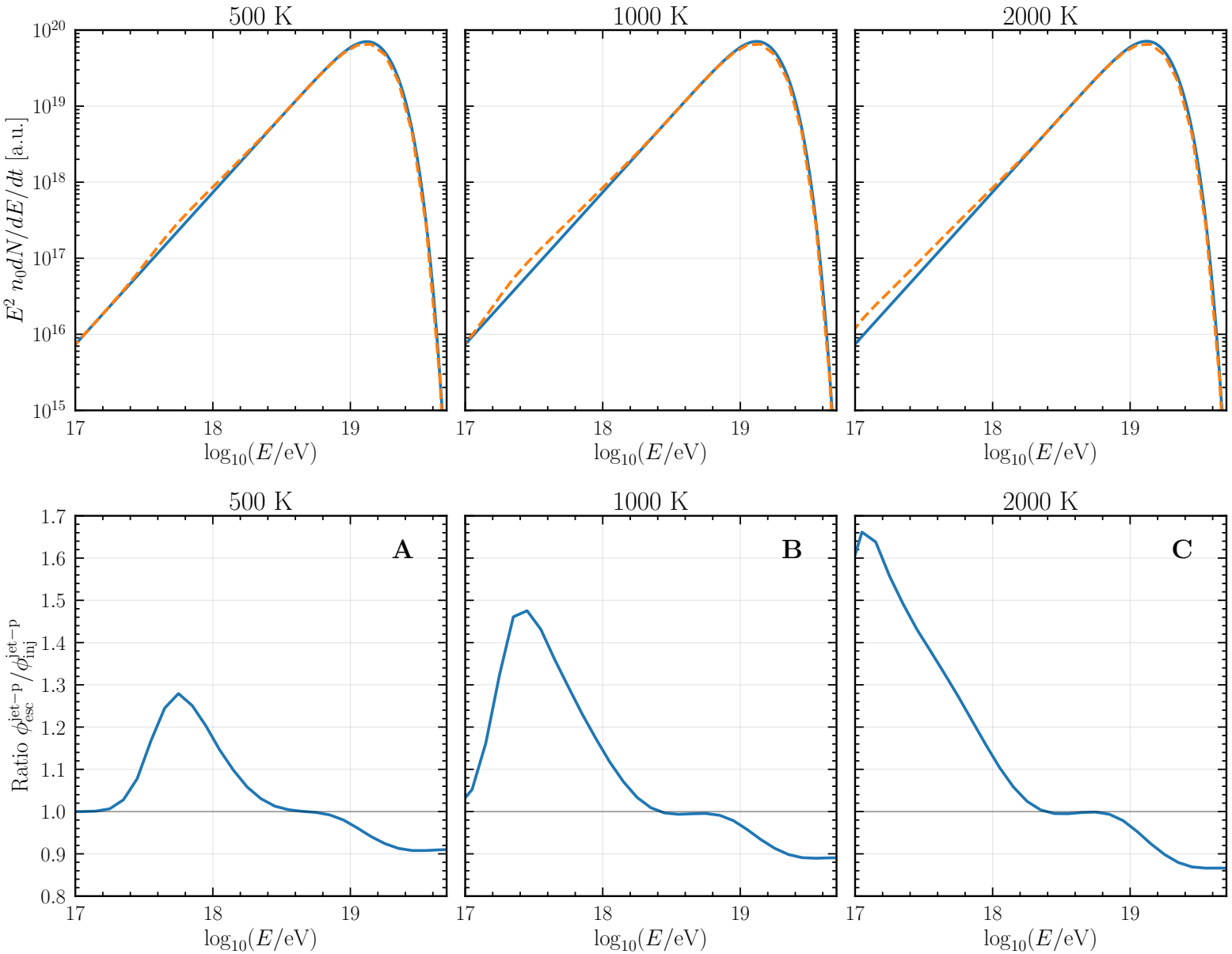




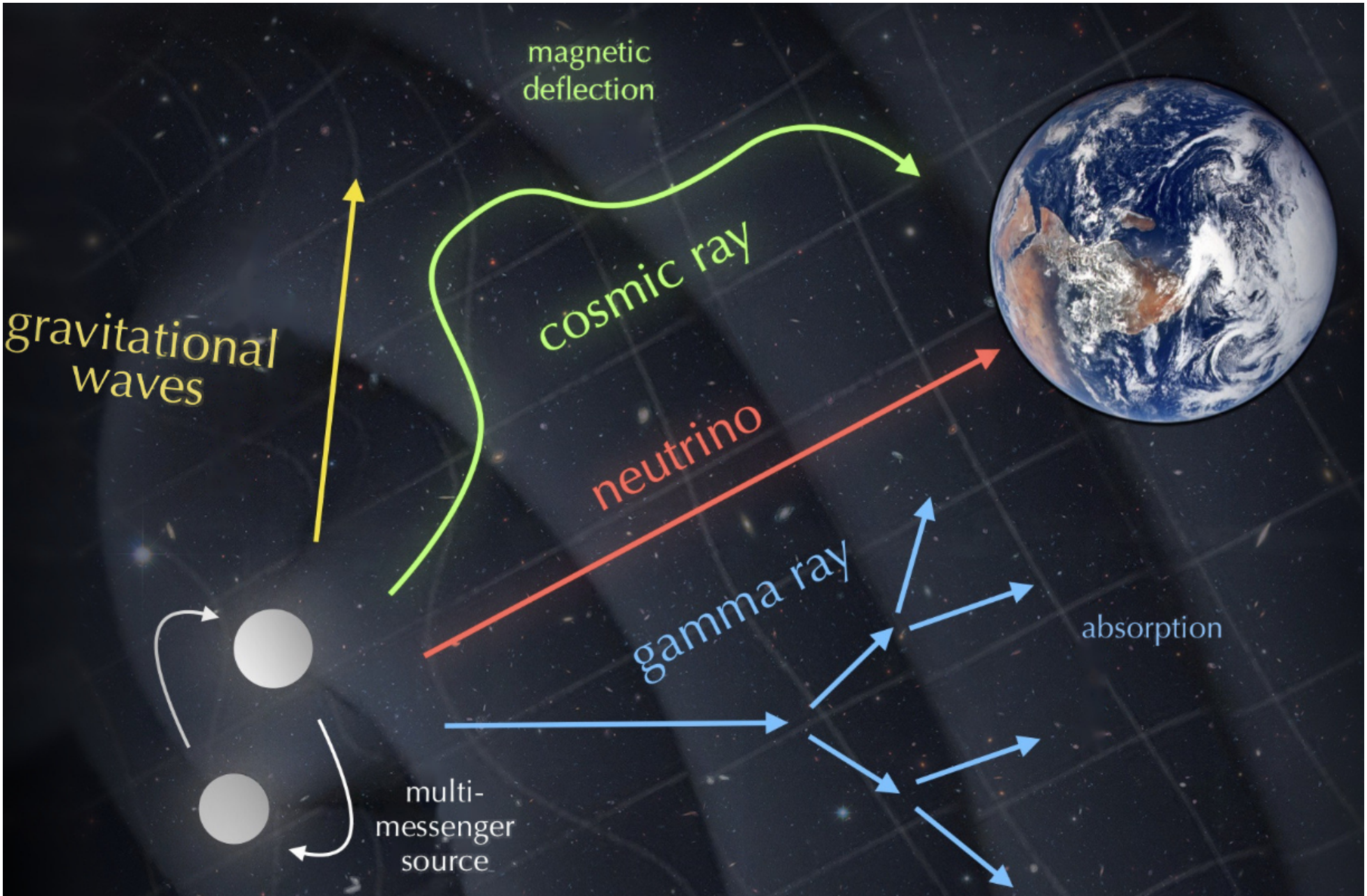
Best fits comparison

Parameter	sech jet-p BNS	exp jet-p BNS	no-jet BNS	sech jet-p SFR
$\chi^2_{\rm tot}/{\rm ndf}$	118.8/55 = 2.16	124.2/55 = 2.3	260.5/58 = 4.49	144.2/55 = 2.62
$\log_{10}\langle N_{\rm int}\rangle$	2.55	2.59	3.14	2.99
$\gamma_{\rm inj}$	−2.11	−2.13	−2.14	−1.90
$\log_{10}(R_{\rm max}/{\rm V})$	18.86	18.85	18.85	18.88
$\log_{10}(R_{\rm diff}/{\rm V})$	18.01	17.92	15.89	15.58
$\tanh(\log_{10} r_{\rm size})$	0.69	0.68	1.00	1.00
T [K]	563	572	1235	756
$\log_{10}(E_{\rm jet}/{\rm eV})$	19.08	18.72	-	19.12
$\gamma_{\rm jet}$	≈ 0	≈ 0	-	≈ 0
$\log_{10}(f^{\rm jet})$	−1.31	−1.28	-	−1.19
f_1	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	0.02	$\lesssim 10^{-7}$
f_{14}	0.27	0.28	0.65	0.21
f_{28}	0.66	0.59	0.13	0.75
f_{56}	$\lesssim 10^{-3}$	0.10	0.20	5.11×10^{-6}
f_{80}	0.07	0.03	2.76×10^{-7}	0.04
$f_{\rm Gal}$	0.63	0.63	0.83	0.77
$\gamma_{\rm Gal}$	−2.88	−2.86	−3.23	−3.19
$\log_{10}(E^{\rm gal,Fe}_{\rm max}/{\rm eV})$	18.49	18.51	18.75	18.60
$f^{\rm gal}_{14}$	0.51	0.54	0.75	0.36
$f^{\rm gal}_{28}$	0.49	0.46	0.12	0.64
$f^{\rm gal}_{56}$	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$	0.13	$\lesssim 10^{-7}$

Effects of the interactions in the jet on the proton spectrum

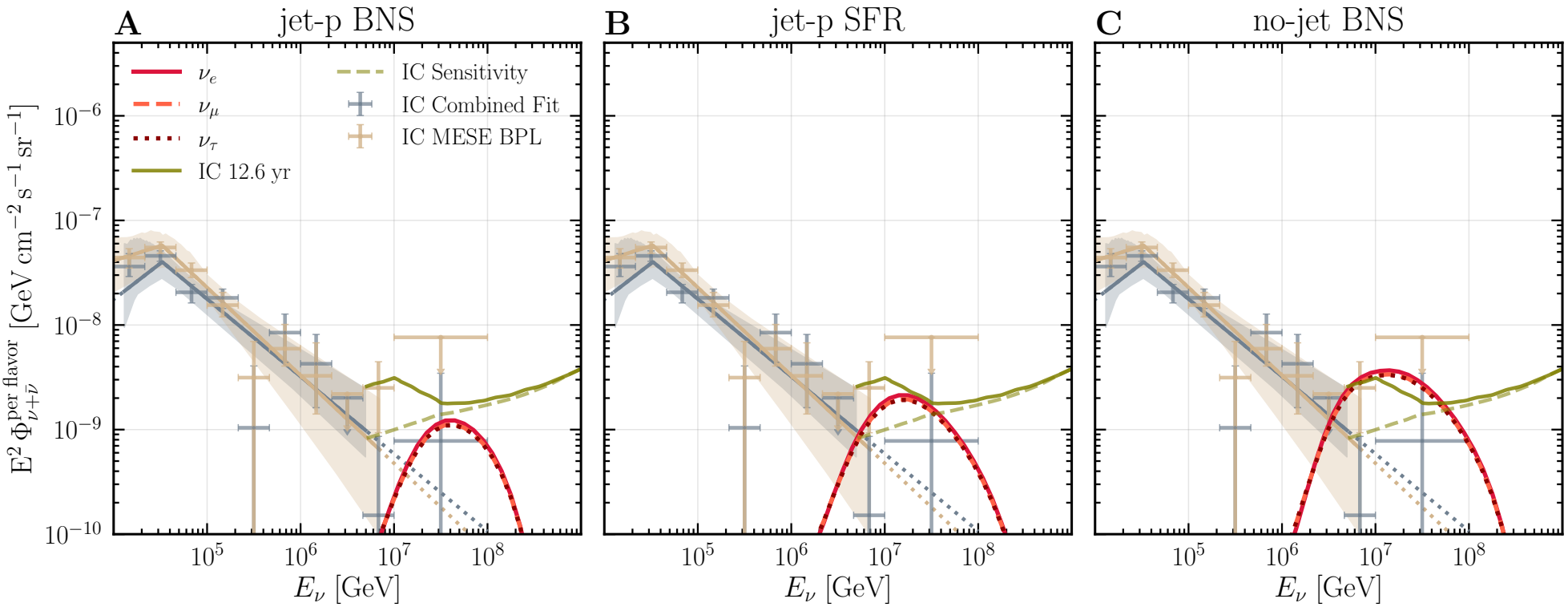


Ultra High Energy Neutrinos



Adapted from M. Unger slides

Diffuse Neutrino Flux



- jet-p BNS vs SFR
  - spectrum peaks at higher energies for BNS
  - less redshifting for BNS
  - lower source temperature for BNS → lower amplitude
- jet-p vs no-jet BNS:
  - higher temperature for no-jet → higher amplitude
  - higher number of ineractions → broader peak

Conclusions

- Binary Neutron Star Mergers can be UHECR sources
- Auger data is compatible with up to 6-10% of $A > 56$
- Extra high-energy component preferred by over 7.5σ
- Future: Potential to distinguish equation of state?
- Neutrinos can help narrow down some regions

Conclusions

- Binary Neutron Star Mergers can be UHECR sources
- Auger data is compatible with up to 6-10% of $A > 56$
- Extra high-energy component preferred by over 7.5σ
- Future: Potential to distinguish equation of state?
- Neutrinos can help narrow down some regions

Thank you for the attention!