The Origin and Acceleration of Very- and Ultra-High-Energy Cosmic Rays

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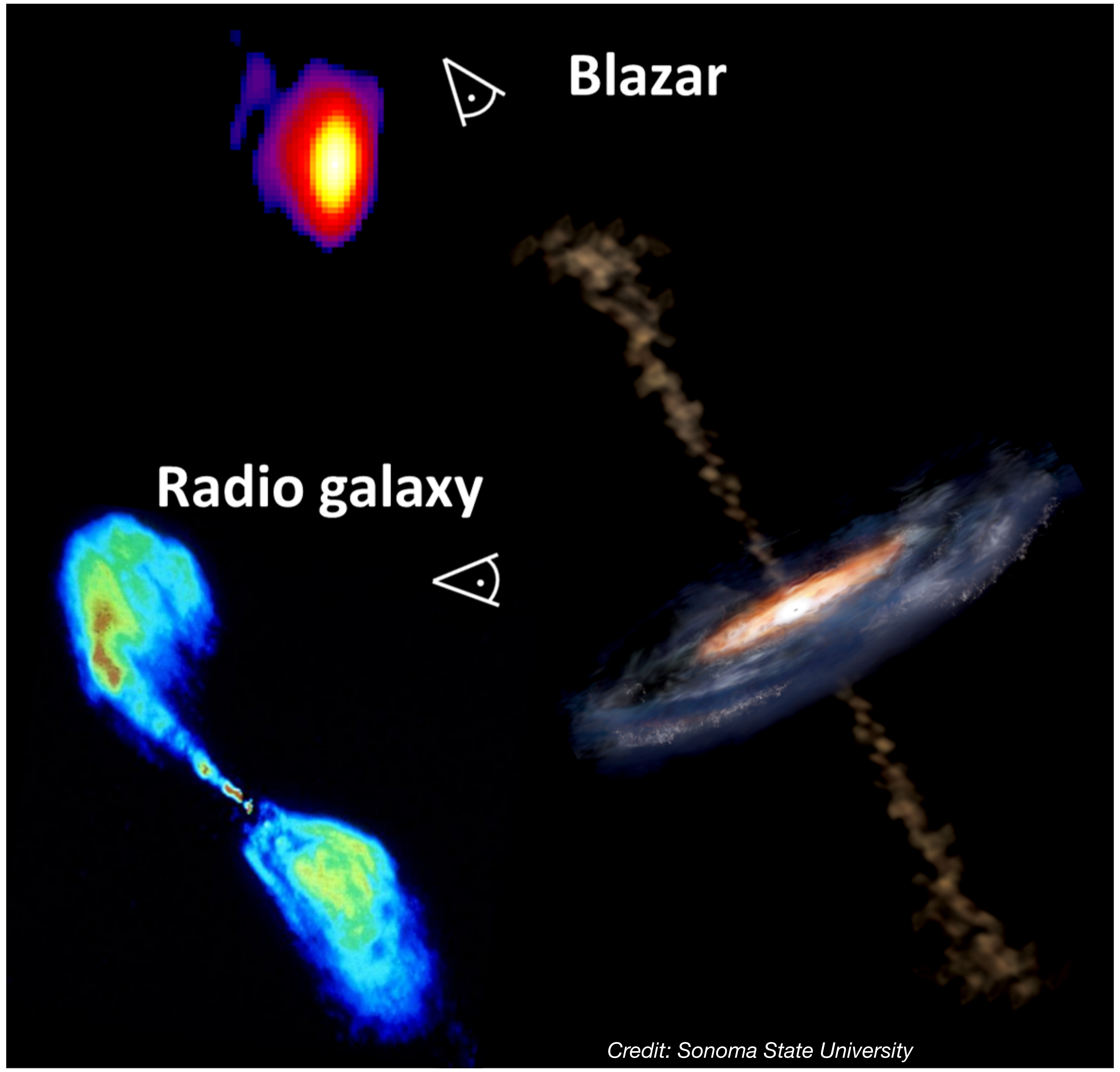
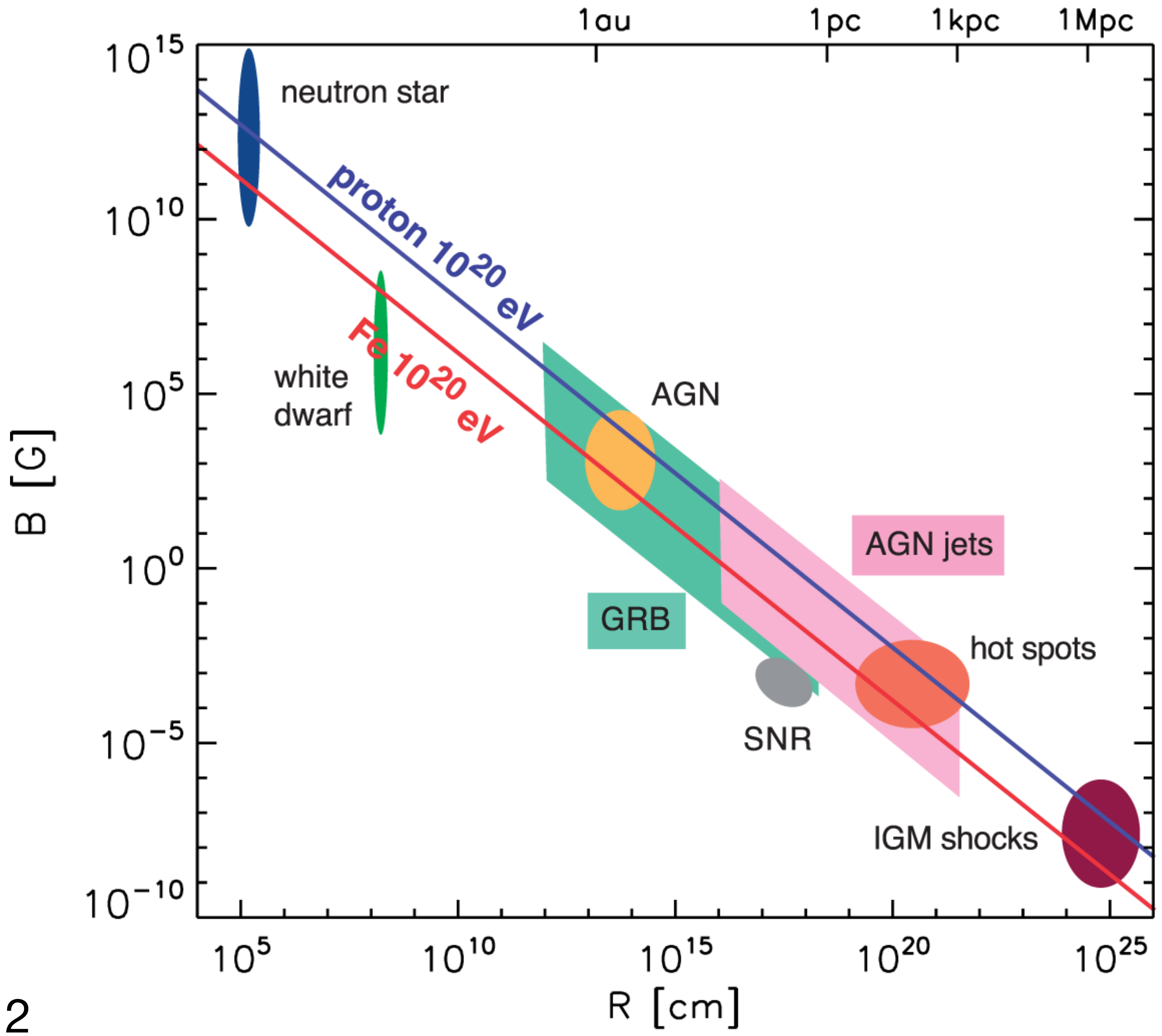
Centaurus A, credit: NASA/CXC

AGN as UHECR candidates

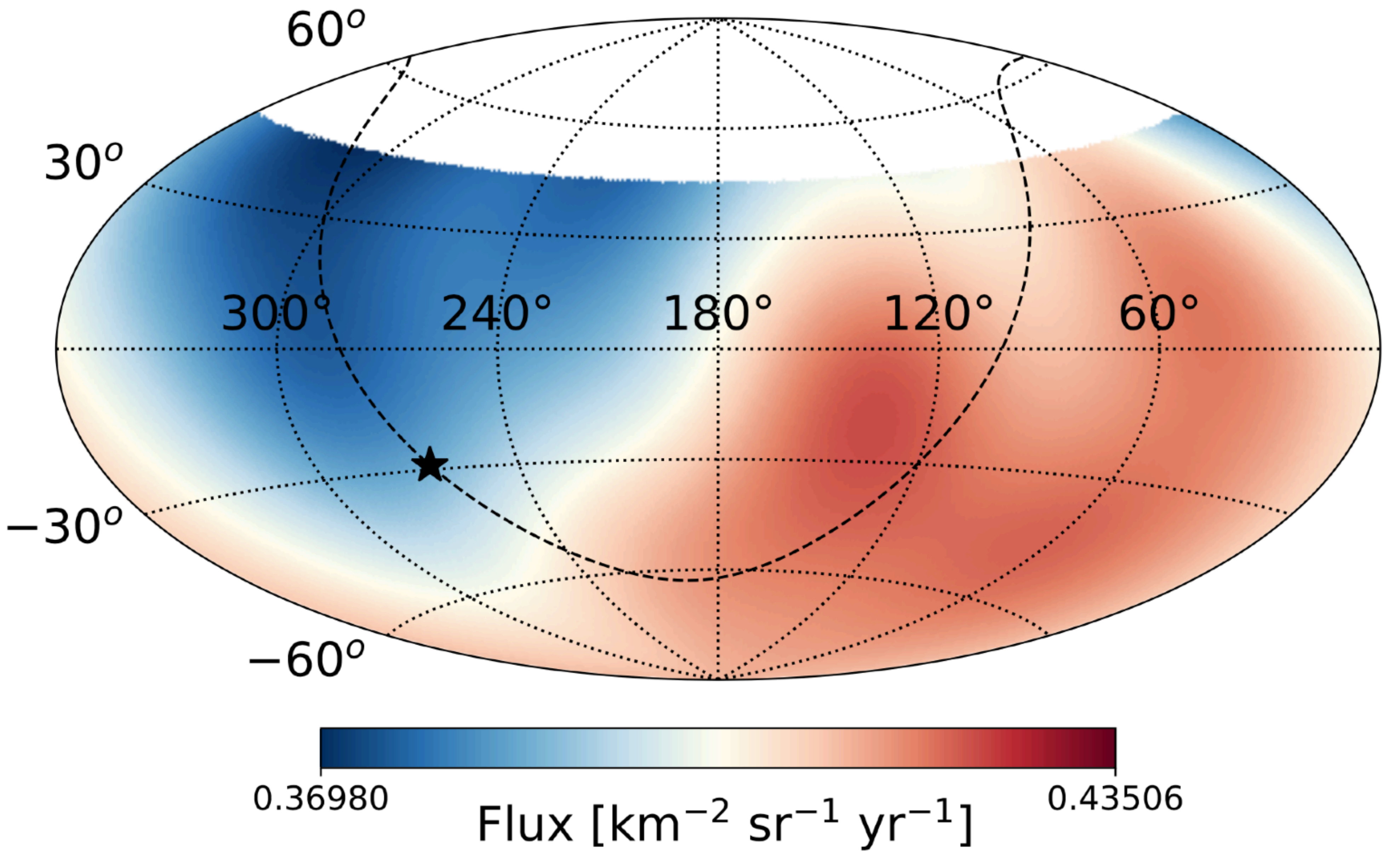
- Active galactic nuclei (AGN) are known for accelerating particles
  - 90 AGNs (84 blazars, 4 radio galaxies) in TeV catalog
  - Candidate of ultra-high-energy cosmic rays (UHECRs)

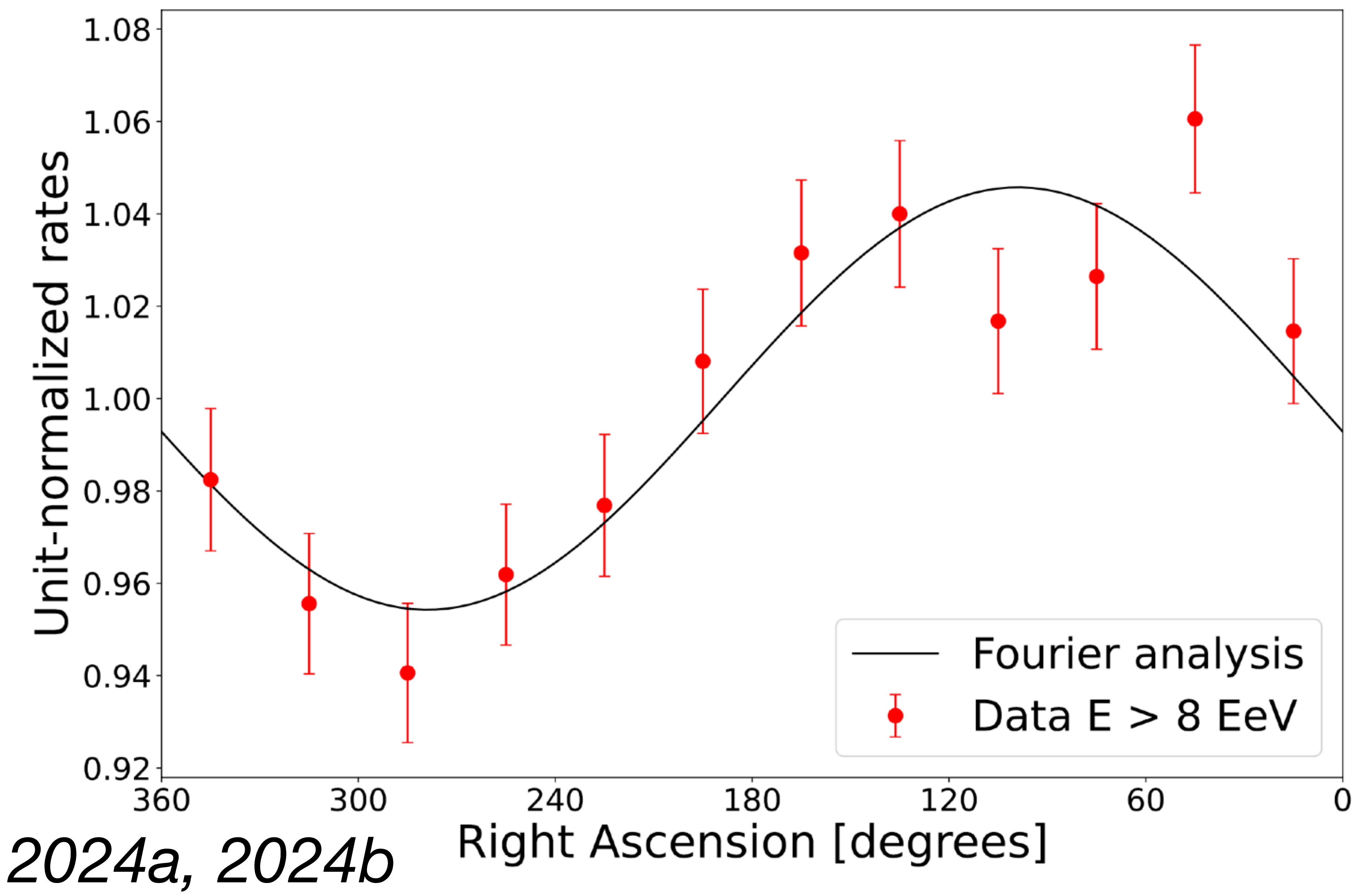




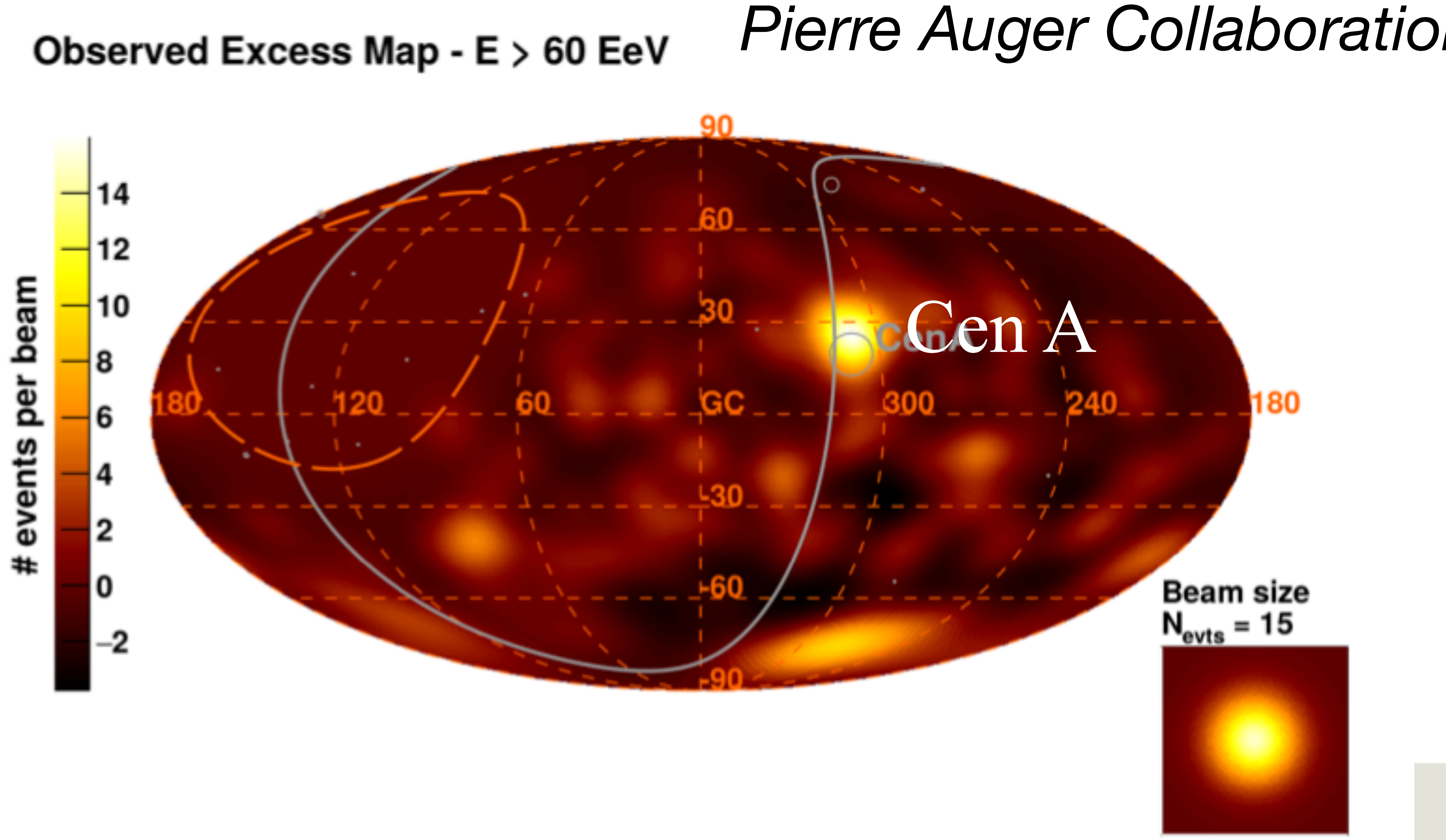
Kotera & Olinto, 2011, ARAA

Ultra-high-energy cosmic ray (UHECR)





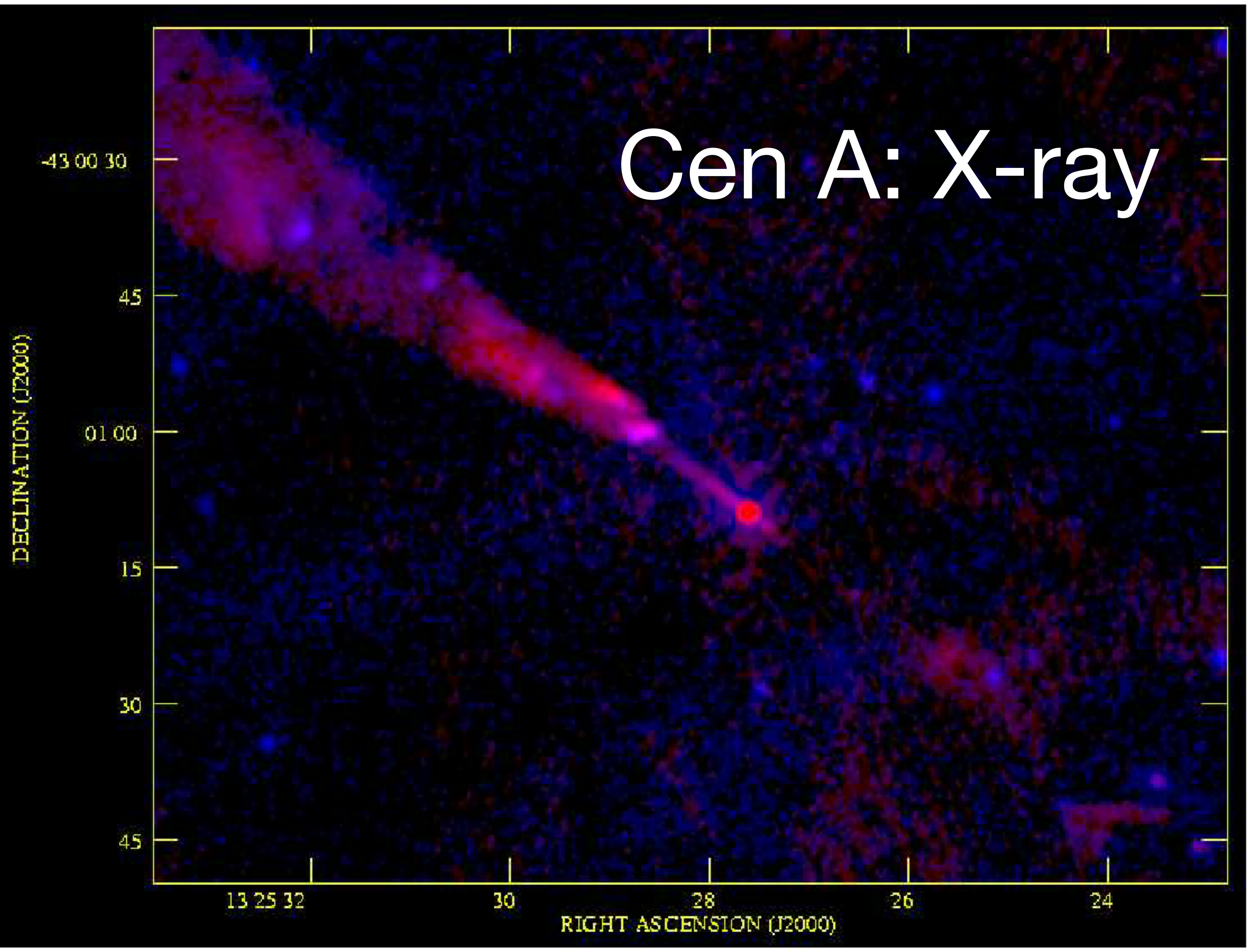
Pierre Auger Collaboration, 2018,2023,2024a, 2024b



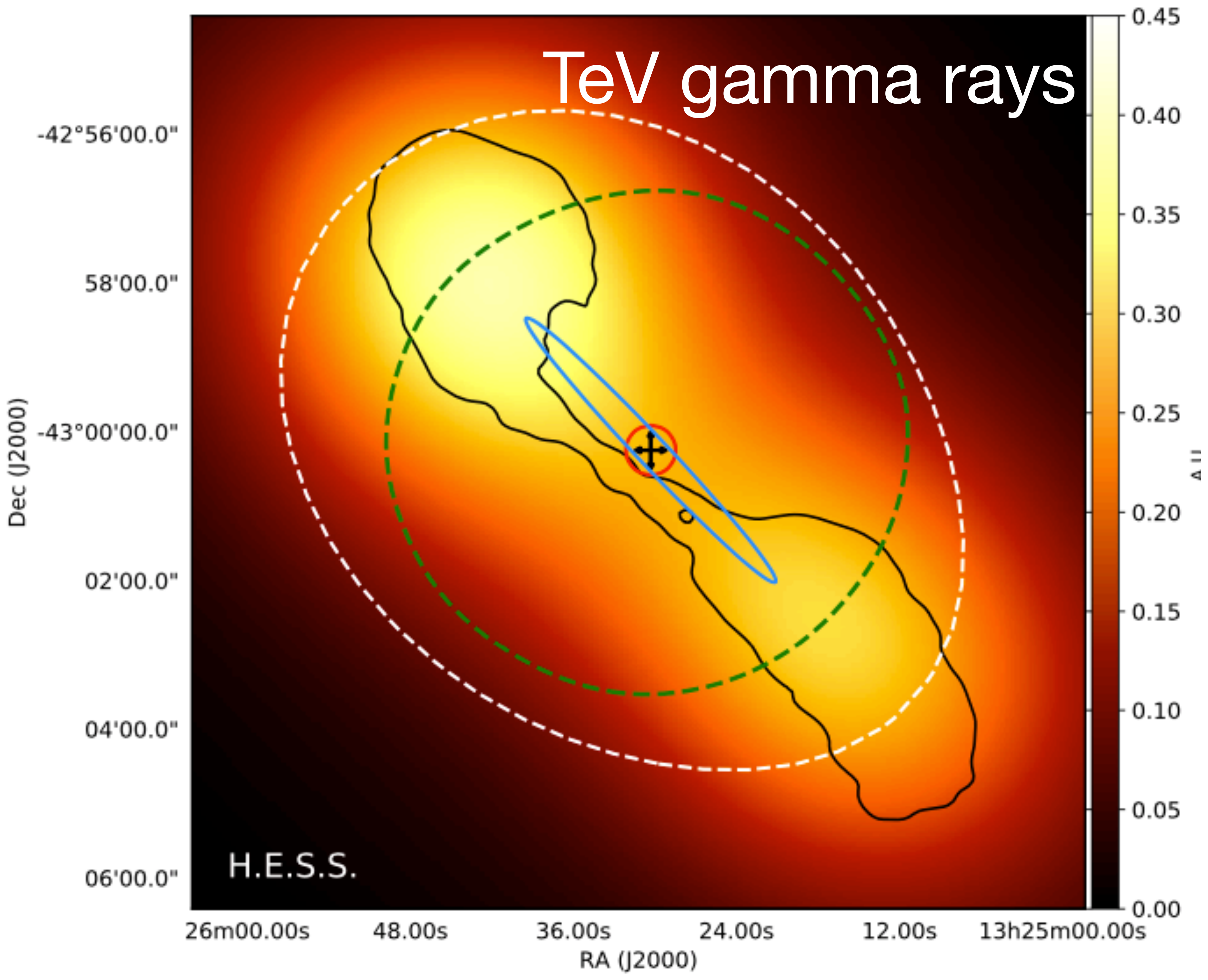
- Significant dipole anisotropy >8 EeV (1e18eV) (significance >5σ), Cen A as candidate source for dominant contribution
- Hotspot at >60EeV points to radio galaxies (significance ~4σ), especially Cen A region

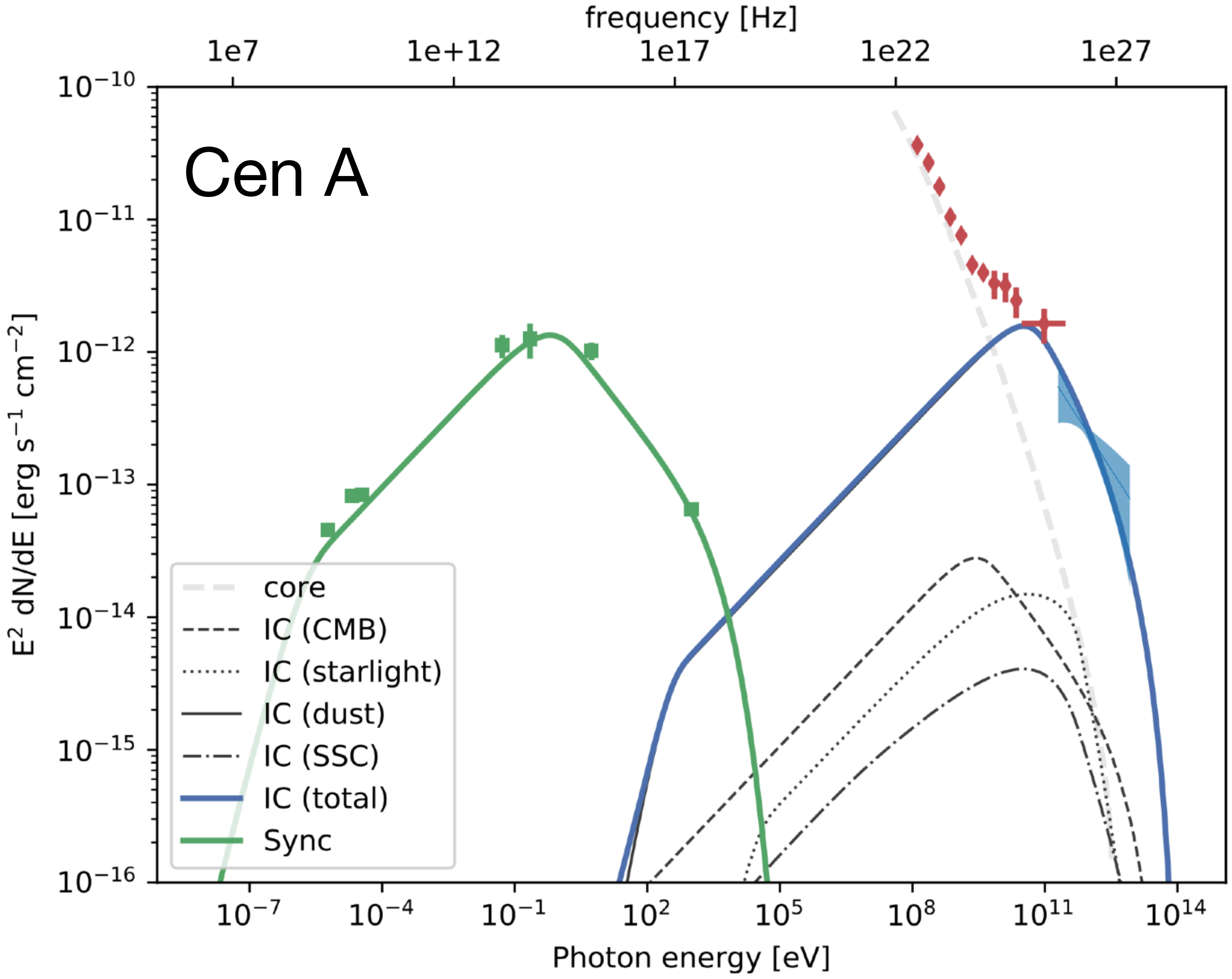
Centaurus A

- The unique UHECR source candidate: most nearby radio galaxy at D ~ 4Mpc (1′ = 1 kpc) and most powerful source in the nearby Universe
- Radio galaxies: diffuse emission along the jet



Hardcastle+, 2003, ApJ

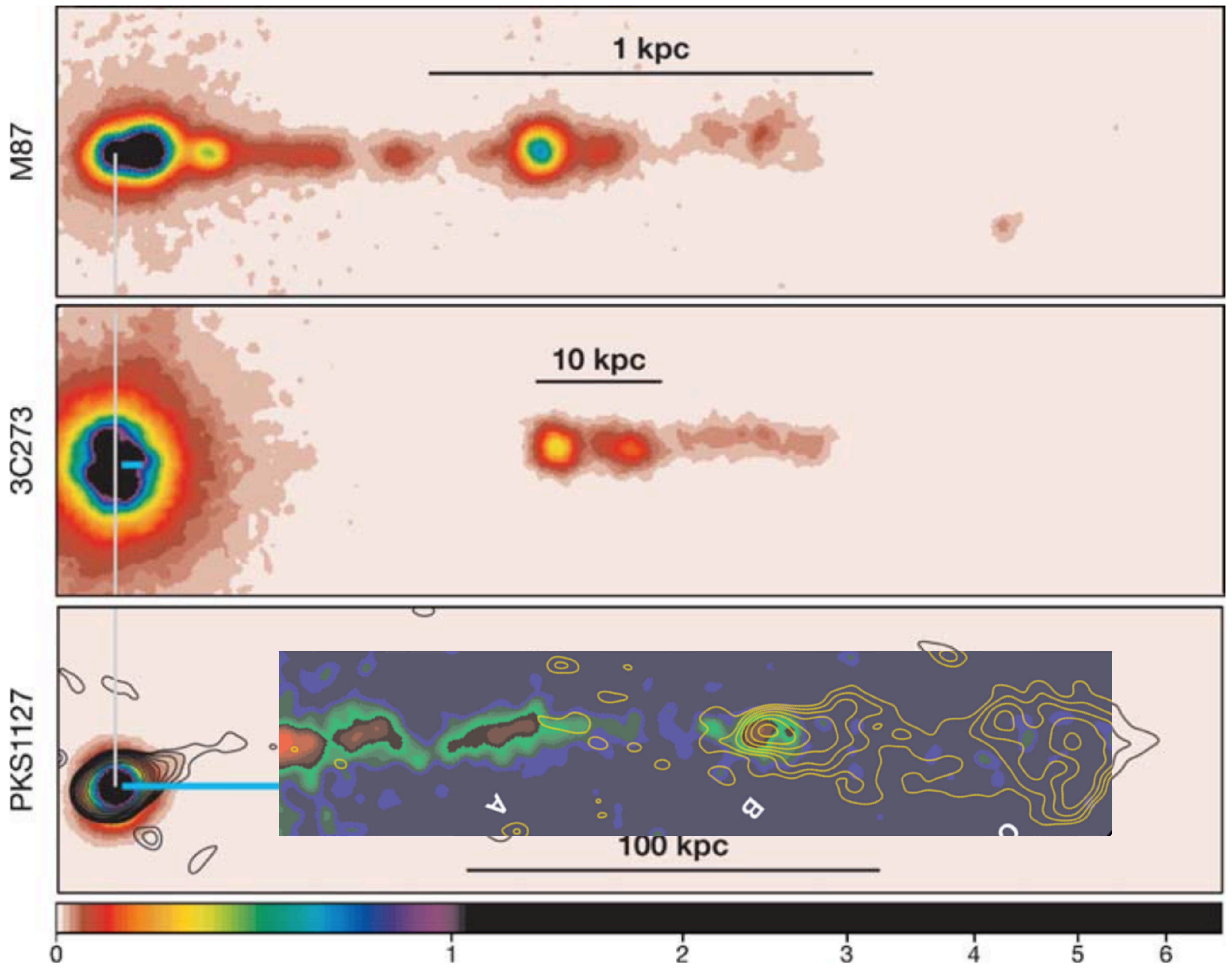




H. E. S. S. Collaboration, 2020, Nature

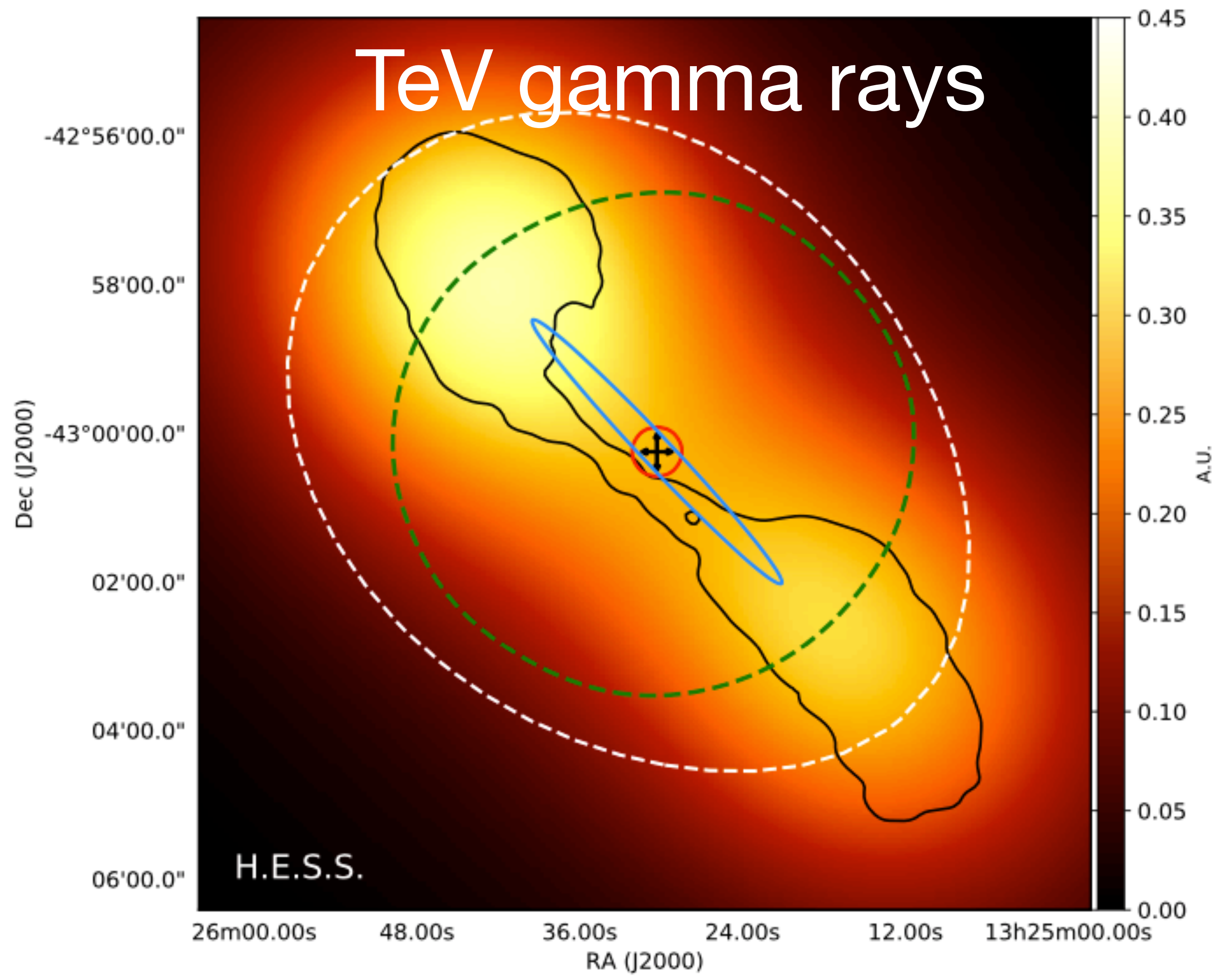
X-ray: Synchrotron origin

- Synchrotron X-rays requires efficient electron acceleration
- Efficient acceleration for electrons to sub-PeV ($\mathrm{PeV} = 10^{15}\mathrm{eV}$):
  $E_{\mathrm{syn}} = 2(E_e/0.1\mathrm{PeV})^2(B/10\mu\mathrm{G})\ \mathrm{keV}$
- Cooling time of sub-PeV electrons:
  $\tau_{\mathrm{c}} = 10^3(B/10\mu\mathrm{G})^{-2}(E_e/0.1\mathrm{PeV})^{-1}\ \mathrm{yrs}$
  → maximum $c\tau_{\mathrm{c}} = 0.37\ \mathrm{kpc}$
- For X-ray jet length $> \mathrm{kpc}$, particles are efficiently and continuously accelerated along jet

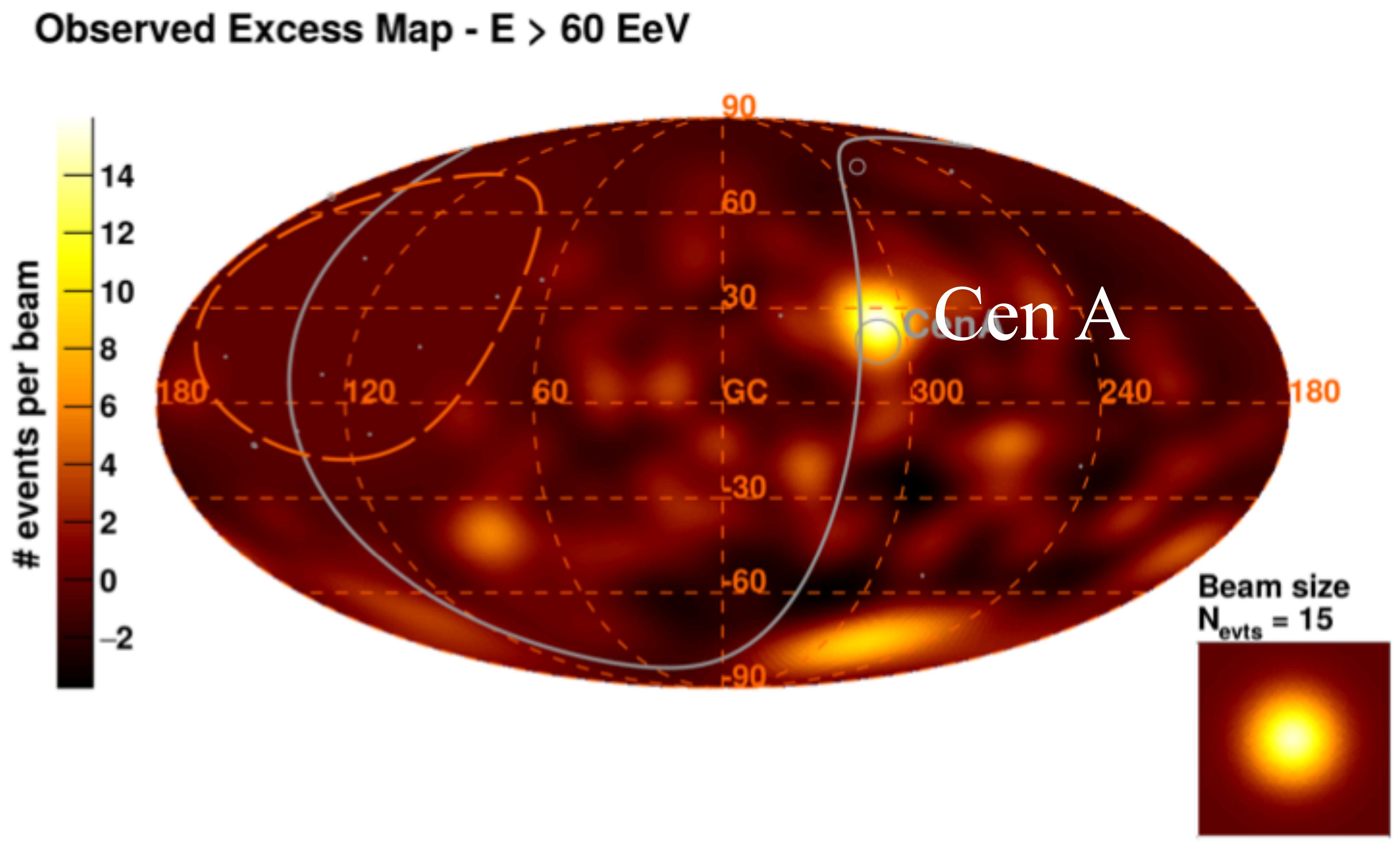


Multi messengers and kpc-scale jets

Is there ***a framework*** which can explain both the MWL and UHECR observations?

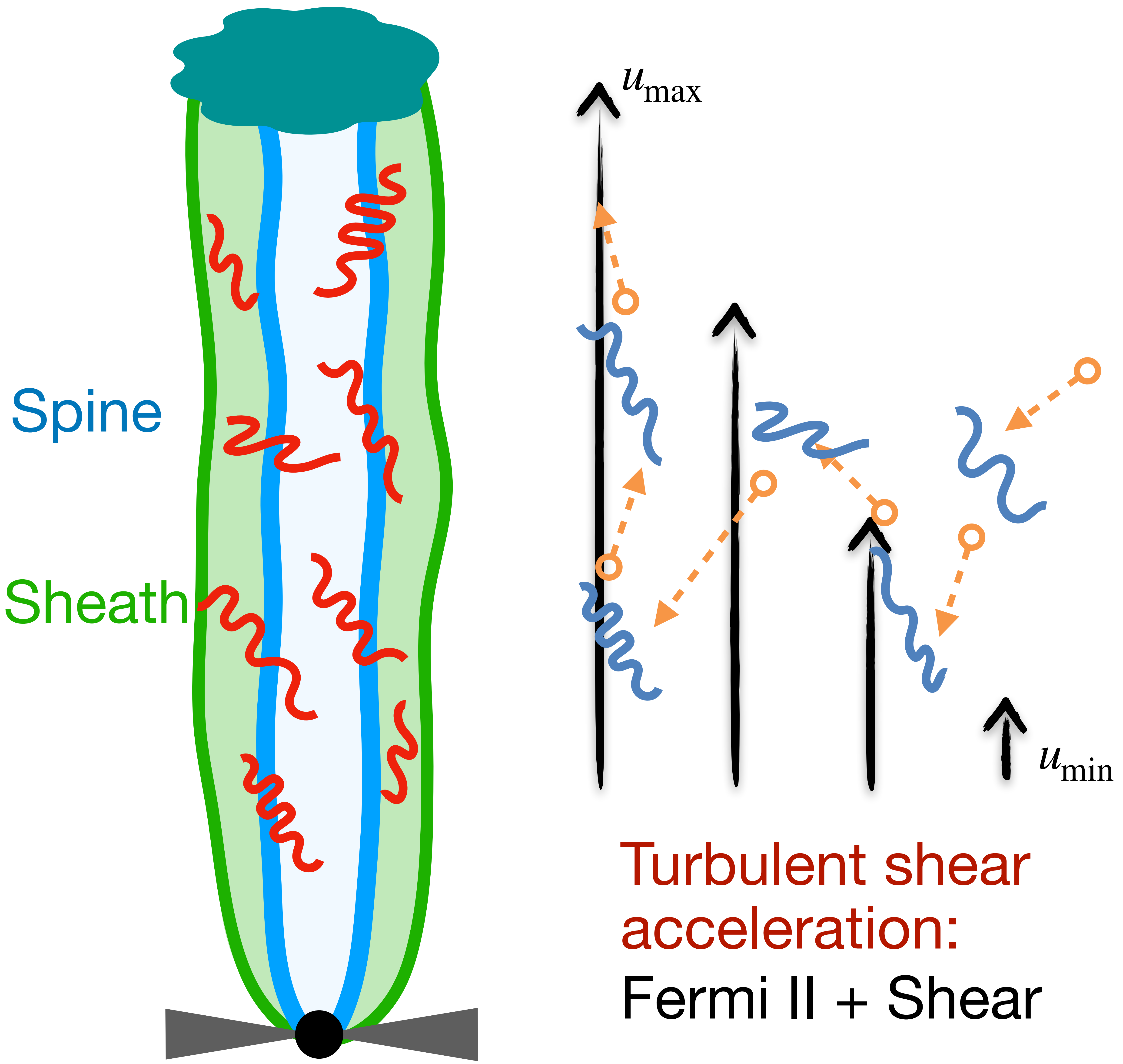


H. E. S. S. Collaboration, 2020, Nature



Continuous particle acceleration

- Continuous particle acceleration offers a natural explanation to diffuse emission
- In turbulent jet flows, continuous acceleration by Fermi II mechanism and shear acceleration
- Shock and magnetic reconnection can produce more localized features (e.g. knots, hotspots) and add to the turbulence development and particle injection



Turbulent shear acceleration:
Fermi II + Shear

Explanation for MWL spectra

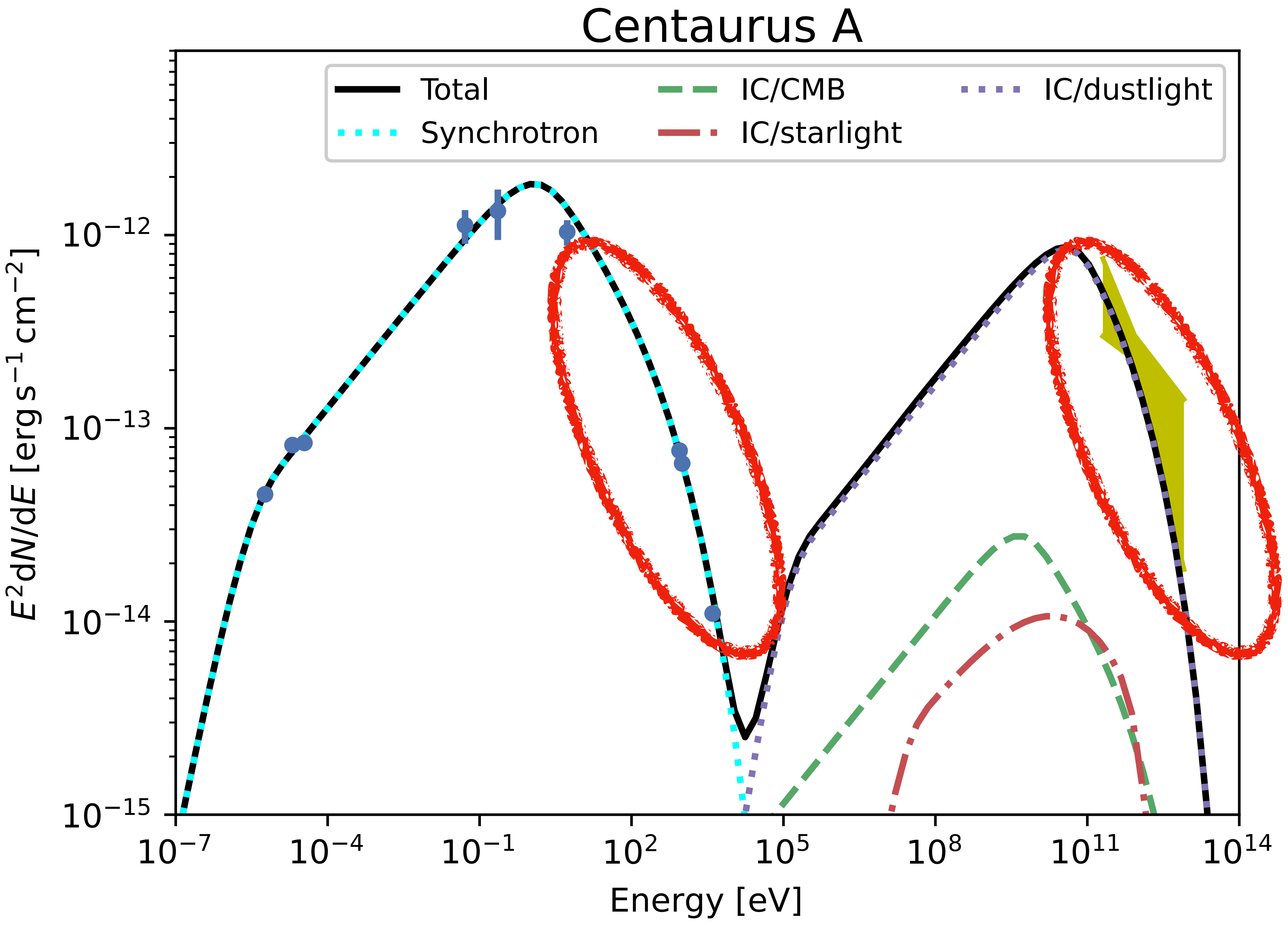
- Solving the Fokker–Planck equation to obtain the particle spectrum: dependence on radial velocity profile

$$n(\gamma) \propto \gamma^{s_-} F_-(\gamma, q) + C\gamma^{s_+} F_+(\gamma, q)$$

$$s_\pm = \frac{q-1}{2} \pm \sqrt{\frac{(5-q)^2}{4} + w}$$

$$w = \frac{10c^2}{\Gamma^4(r)R^2}\left(\frac{\partial u(r)}{\partial r}\right)^{-2}$$

- Analytical modeling to obtain B and u



$$E = \gamma mc^2$$

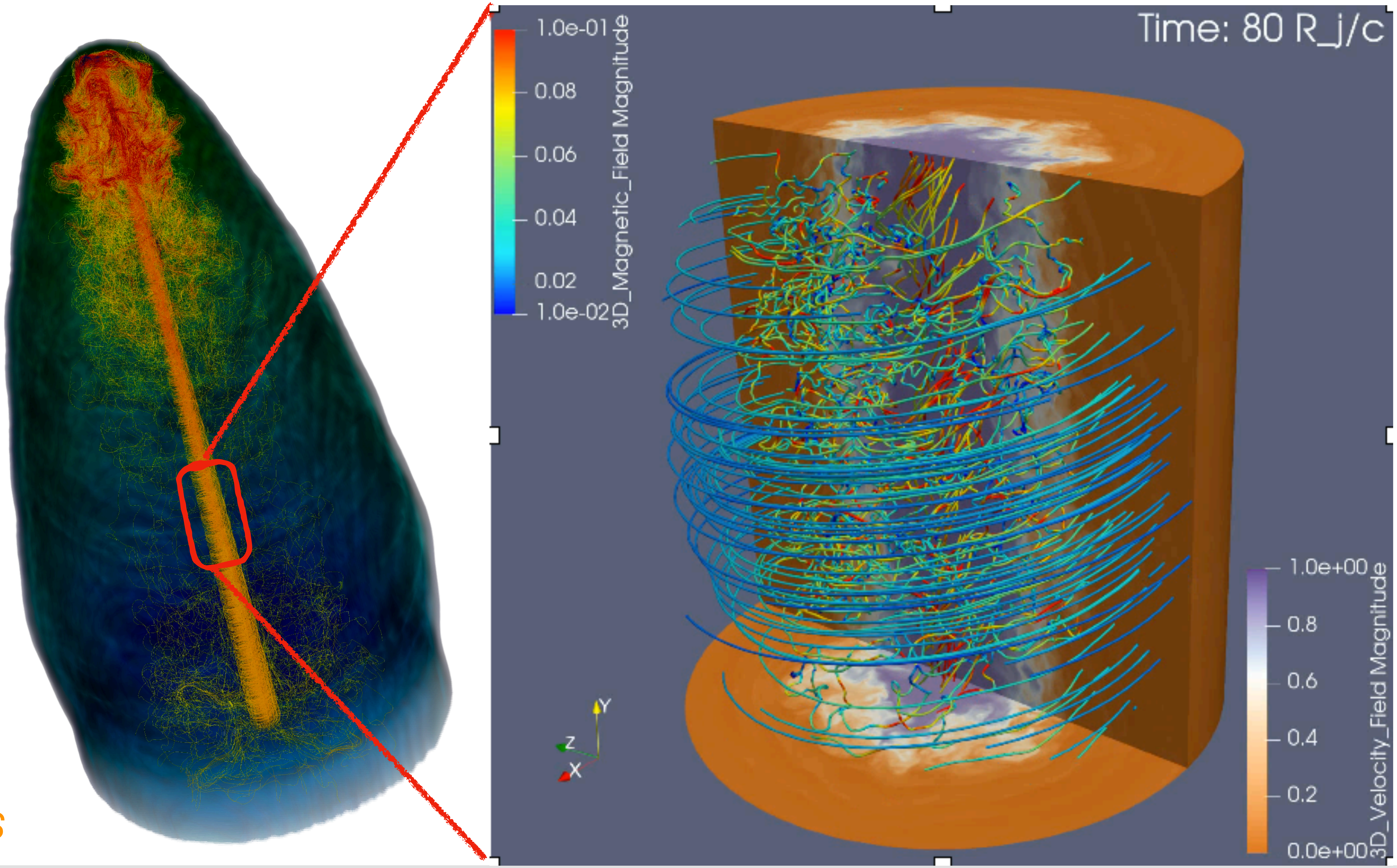
$$\frac{\partial n(\gamma,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial\gamma}\left[\left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle\frac{\partial n(\gamma,t)}{\partial\gamma}\right] - \frac{\partial}{\partial\gamma}\left[\left(\left\langle\frac{\Delta\gamma}{\Delta t}\right\rangle - \frac{1}{2}\frac{\partial}{\partial\gamma}\left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle + \langle\dot{\gamma}_c\rangle\right)\times n(\gamma,t)\right] - \frac{n}{t_{esc}} + Q(\gamma,t)$$

Wang+, 2021, MNRAS, arXiv:2105.08600

Numerical simulations of acceleration of UHECRs

RMHD Simulations

- Stochastic-shear acceleration depends on turbulence and velocity profile
- Periodic box simulations to study the jet instabilities (e.g. Kelvin-Helmholtz)
- Parameters derived from analytical MWL modeling



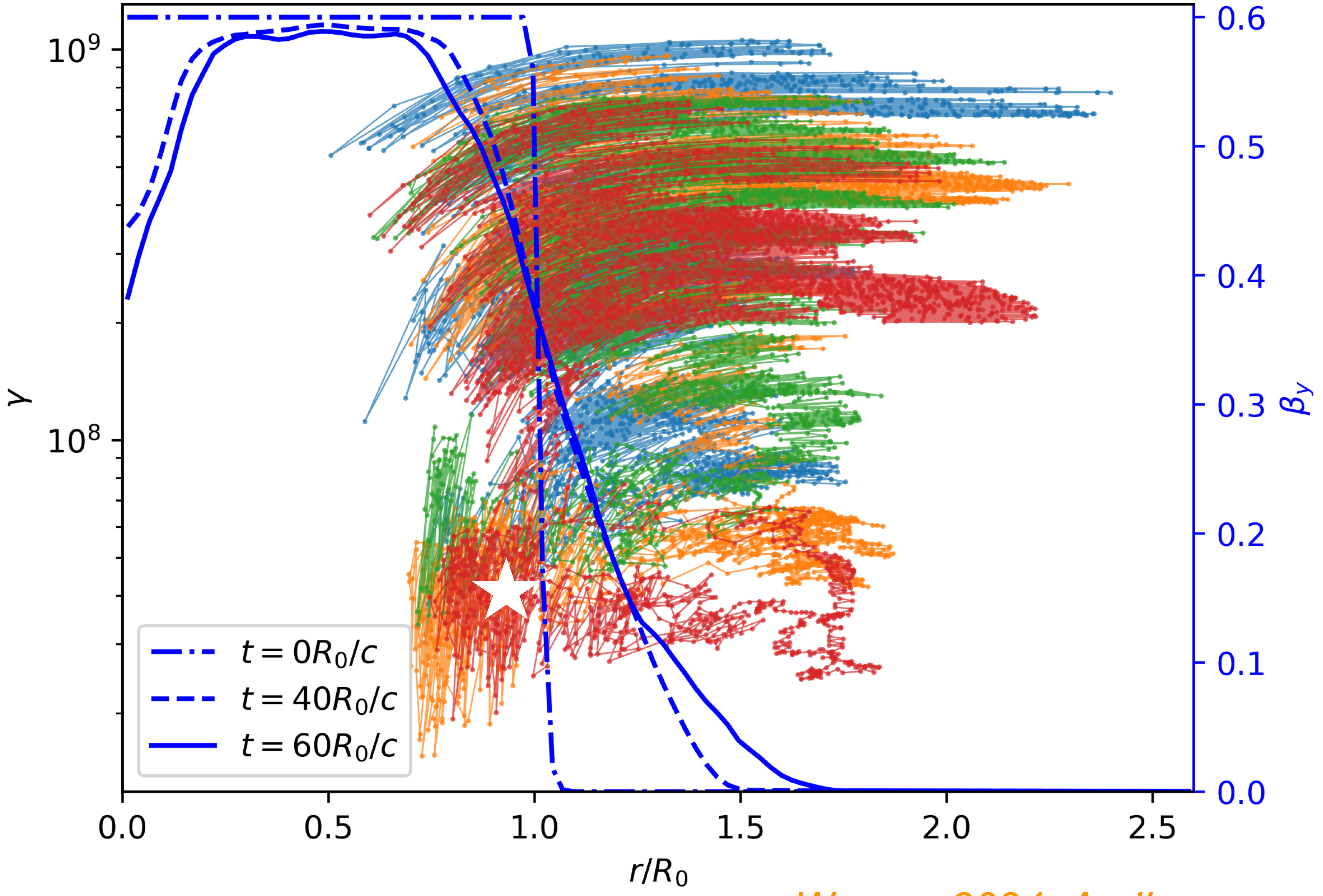
Wang+, 2023, MNRAS

Radial profiles and turbulence

- Velocity shearing profile self-generated through Kelvin-Helmholtz instability
- Turbulence (HD/MHD) is close to Kolmogorov

Wang+ 2023, MNRAS; 2024, ApJL

Particle trajectories and shear acceleration

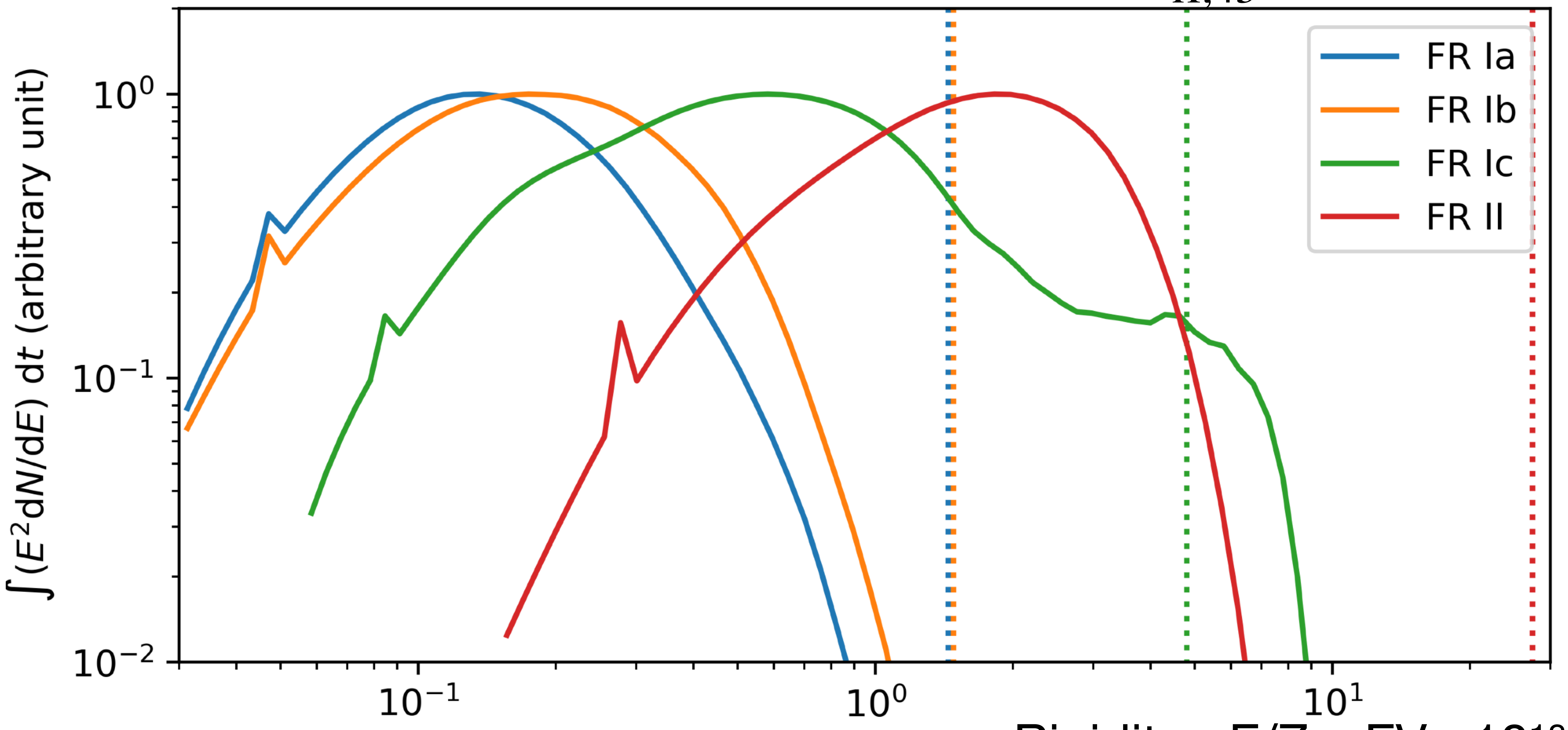


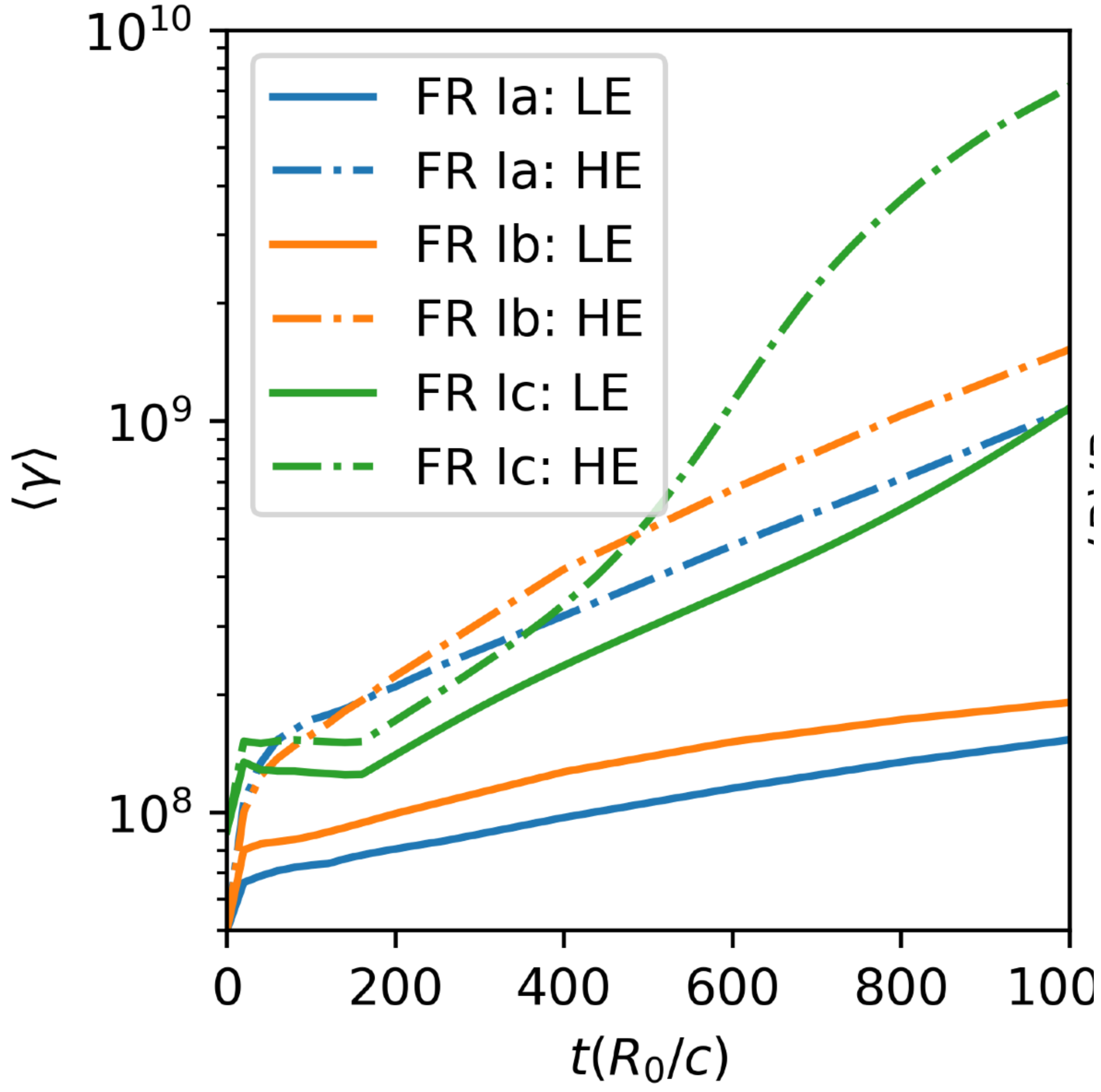
Wang+, 2024, ApJL

Particle spectra

- Particles efficiently accelerated close to the maximum theoretical limit: $E_{\rm peak} \gtrsim 0.1\ E_{\rm max}$ for different types of jets with different velocity and B

$$E_{\rm max} = Ze\beta BR = 10\ Z\beta^{1/2}\sigma^{1/2}L_{K,43}^{1/2}\ \text{EeV}$$

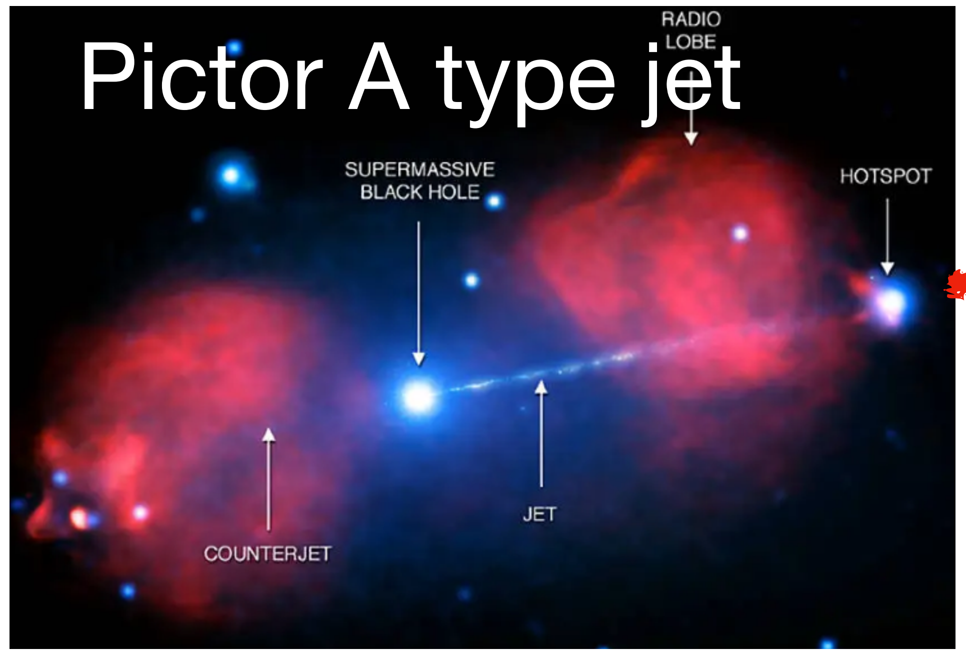


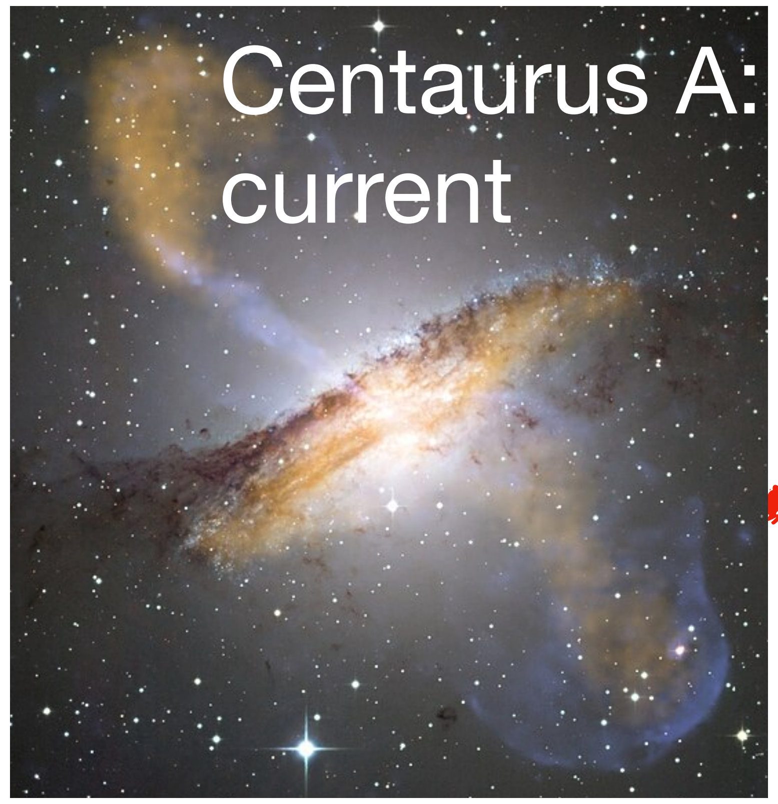


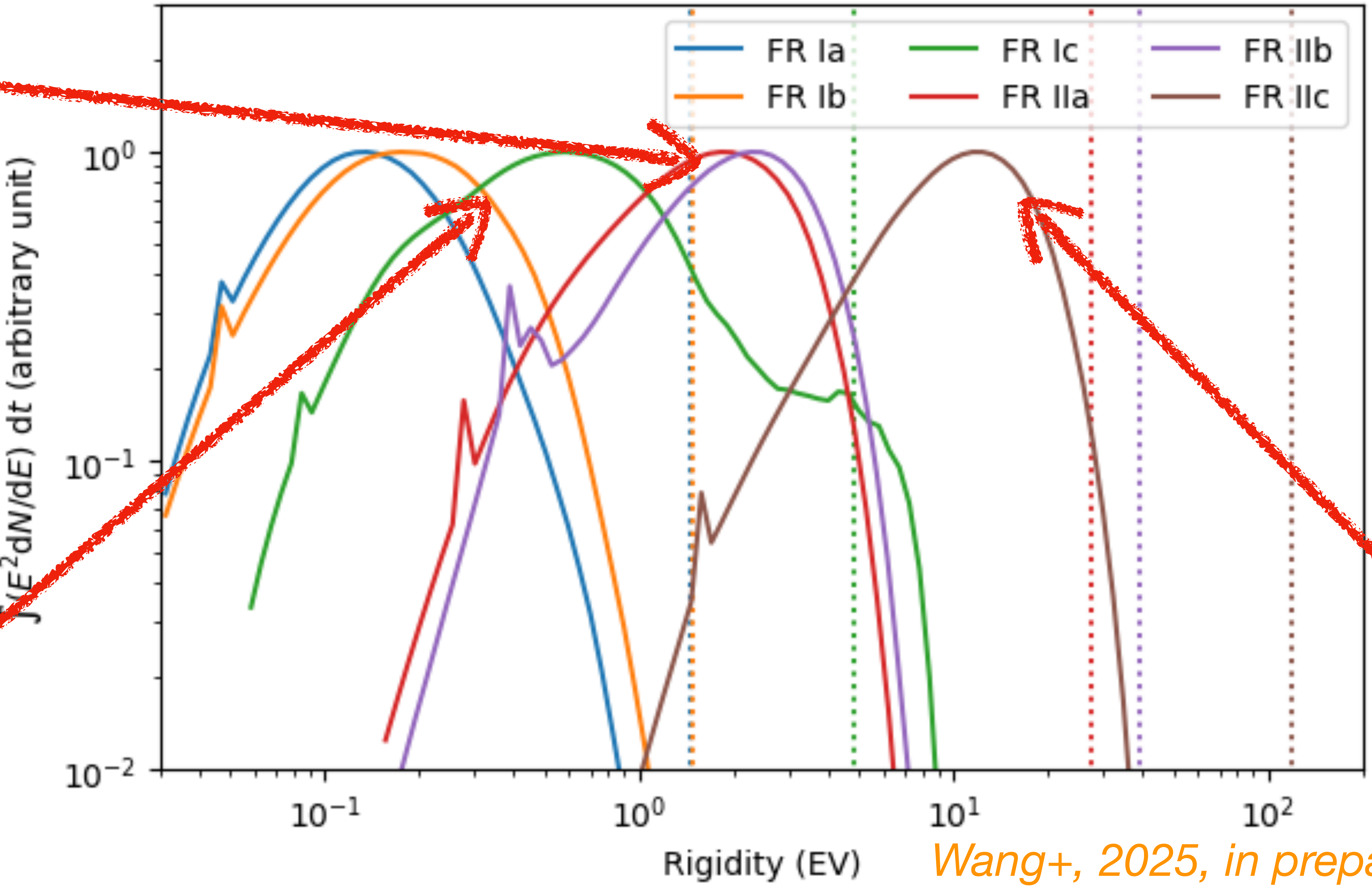
Wang+, 2024, ApJL

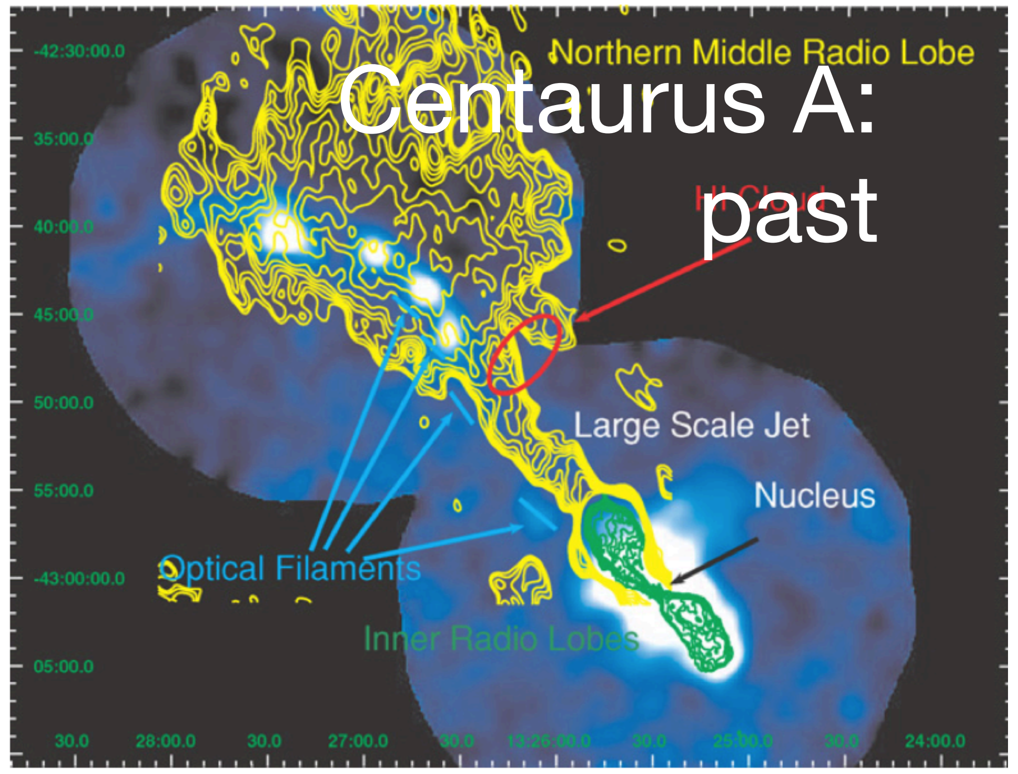
Rigidity= E/Ze, EV= 10^{18} eV

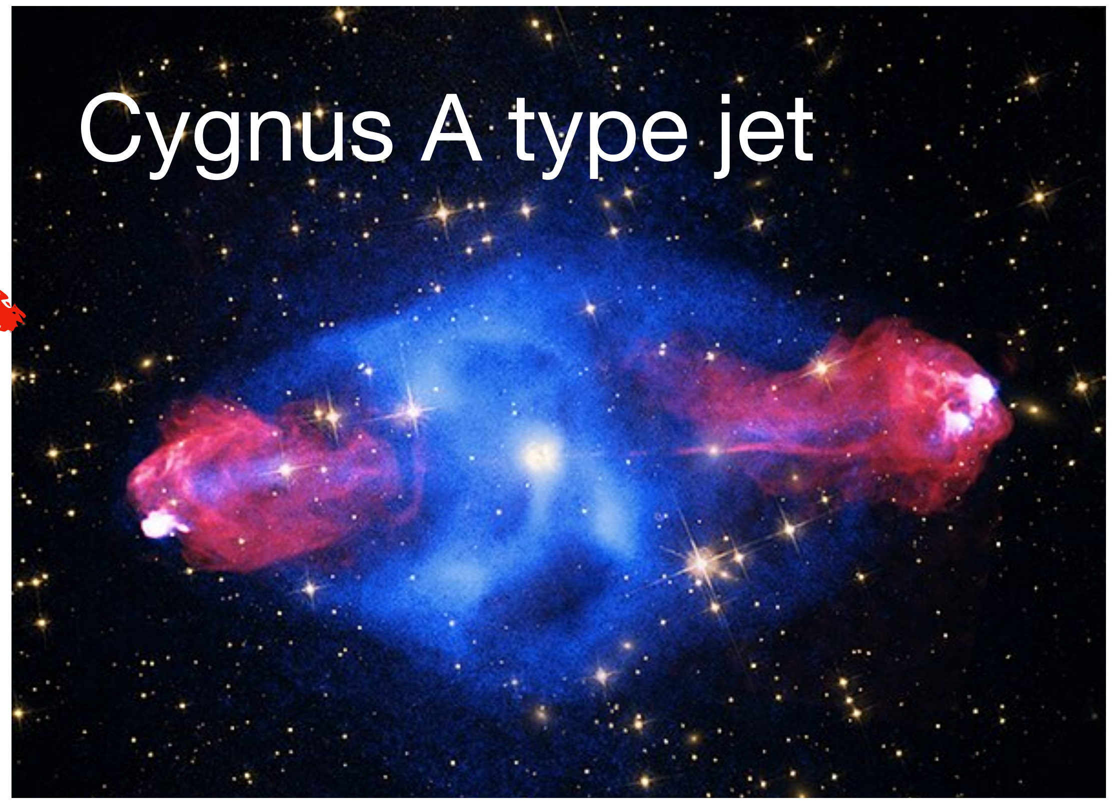
“A” jet origin of UHECR







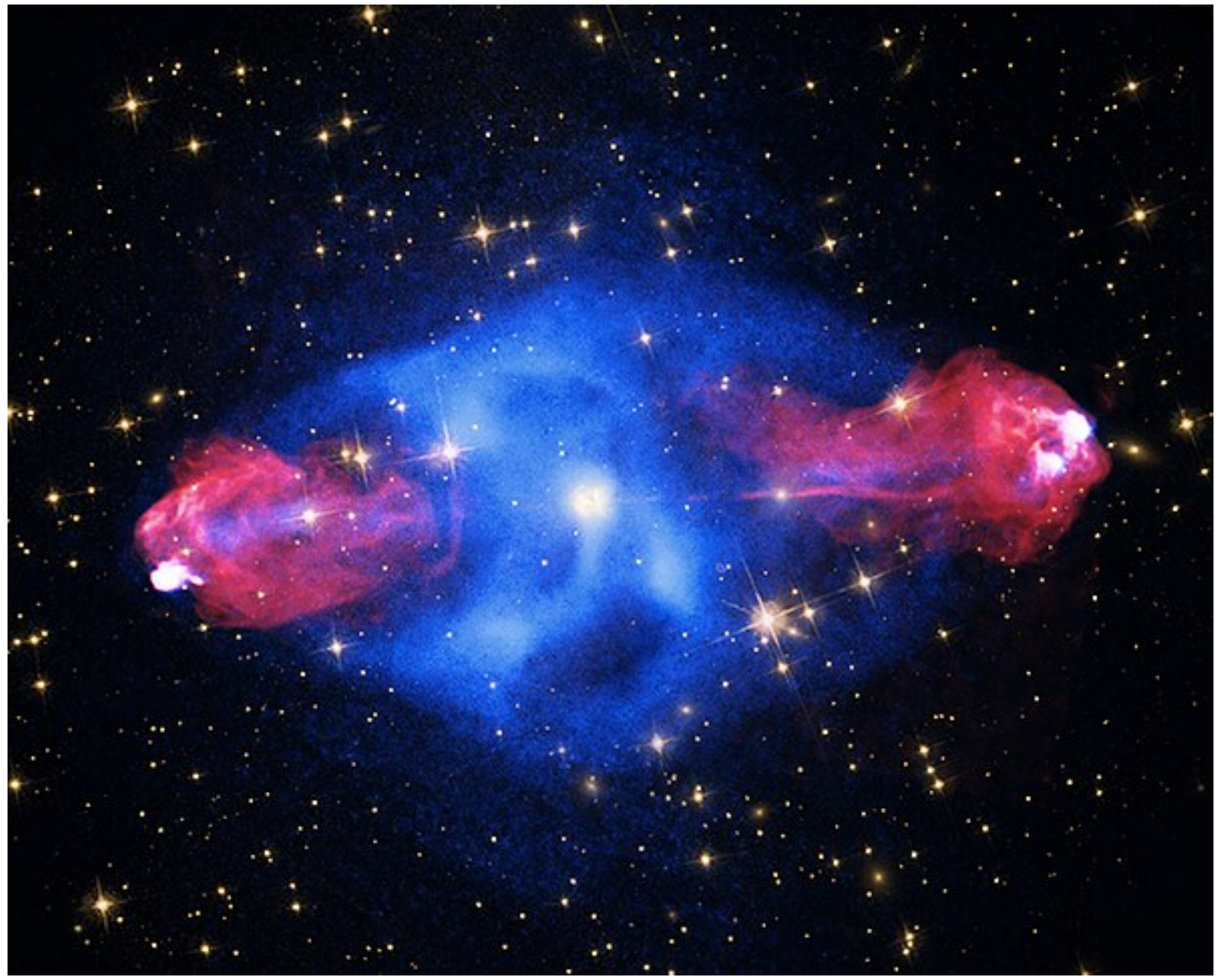




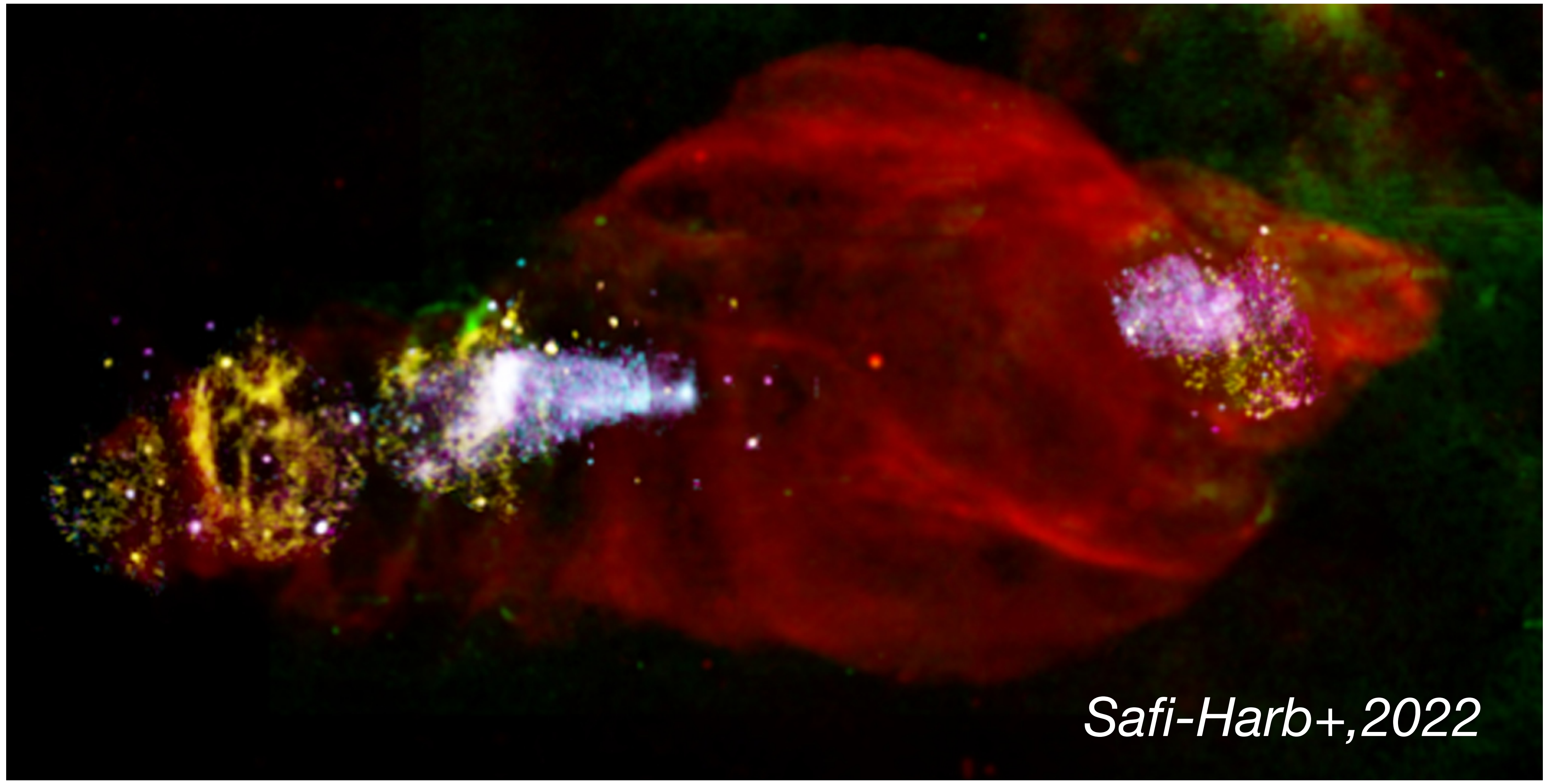
Wang+, 2025, in preparation

Jets of AGN and microquasars

Cygnus A: powerful AGN jet

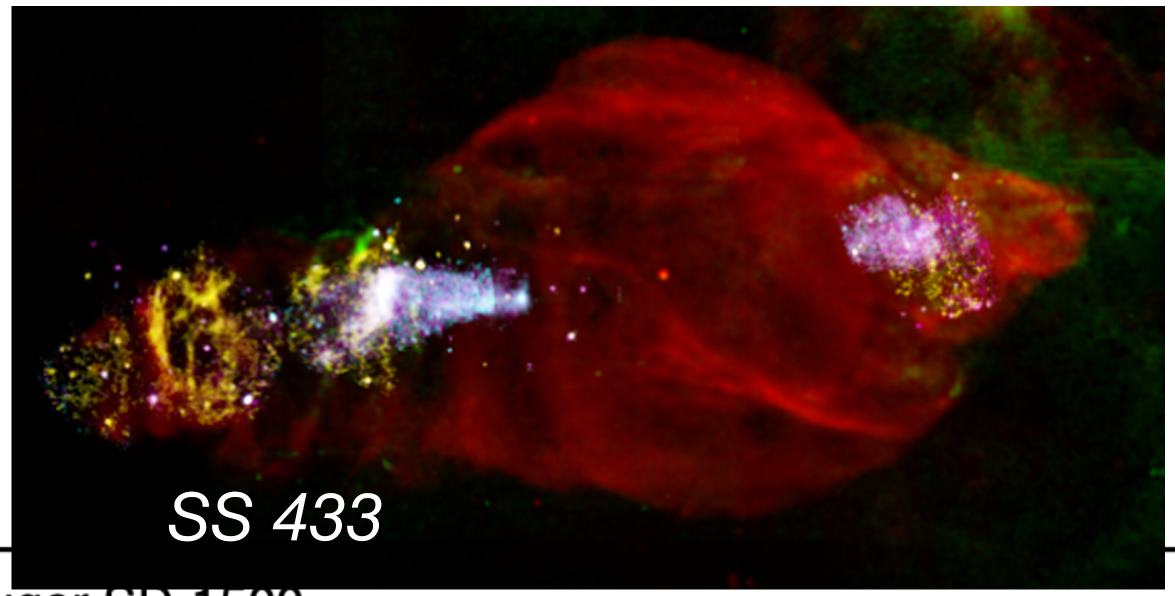


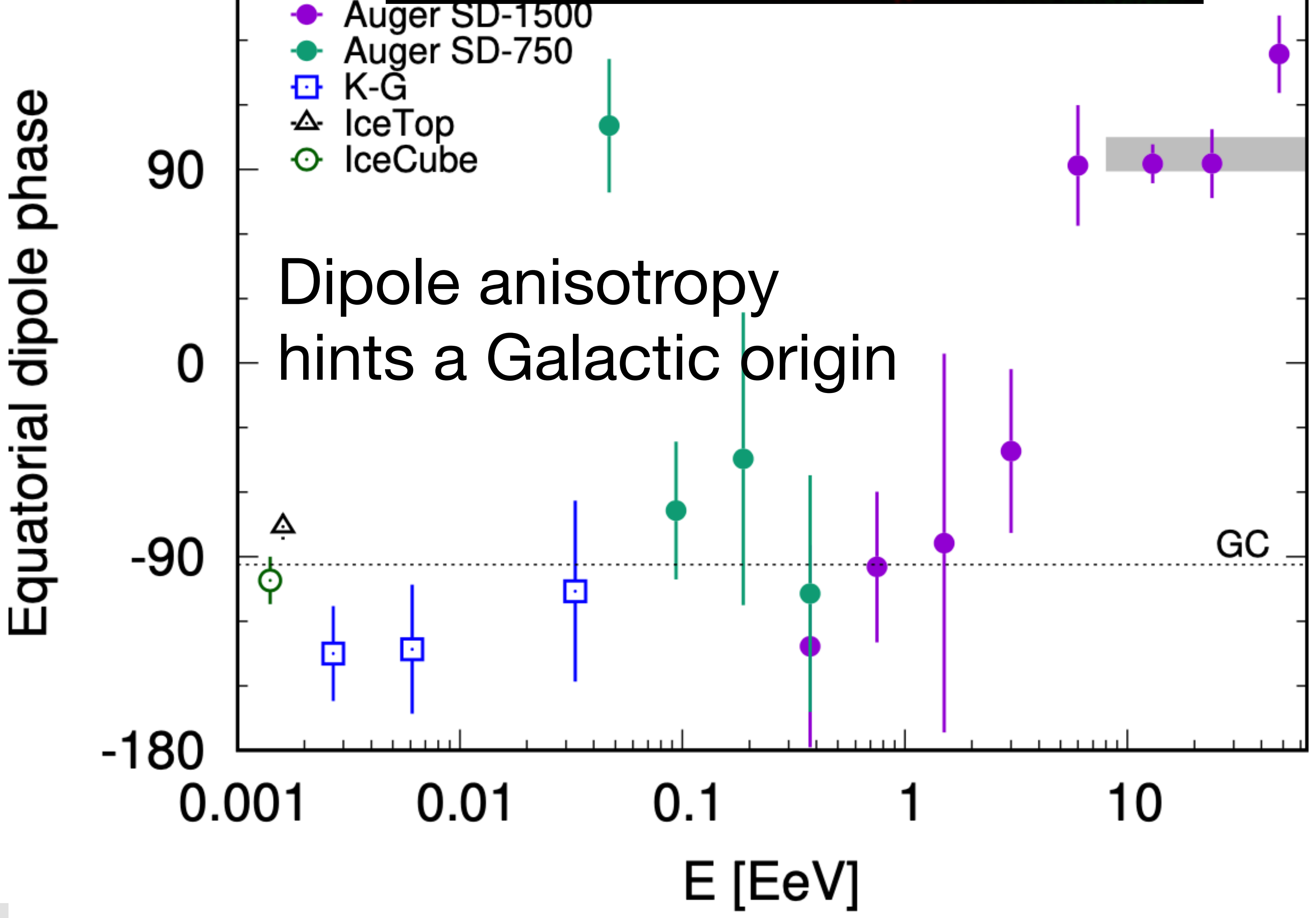
SS 433: microquasar jet

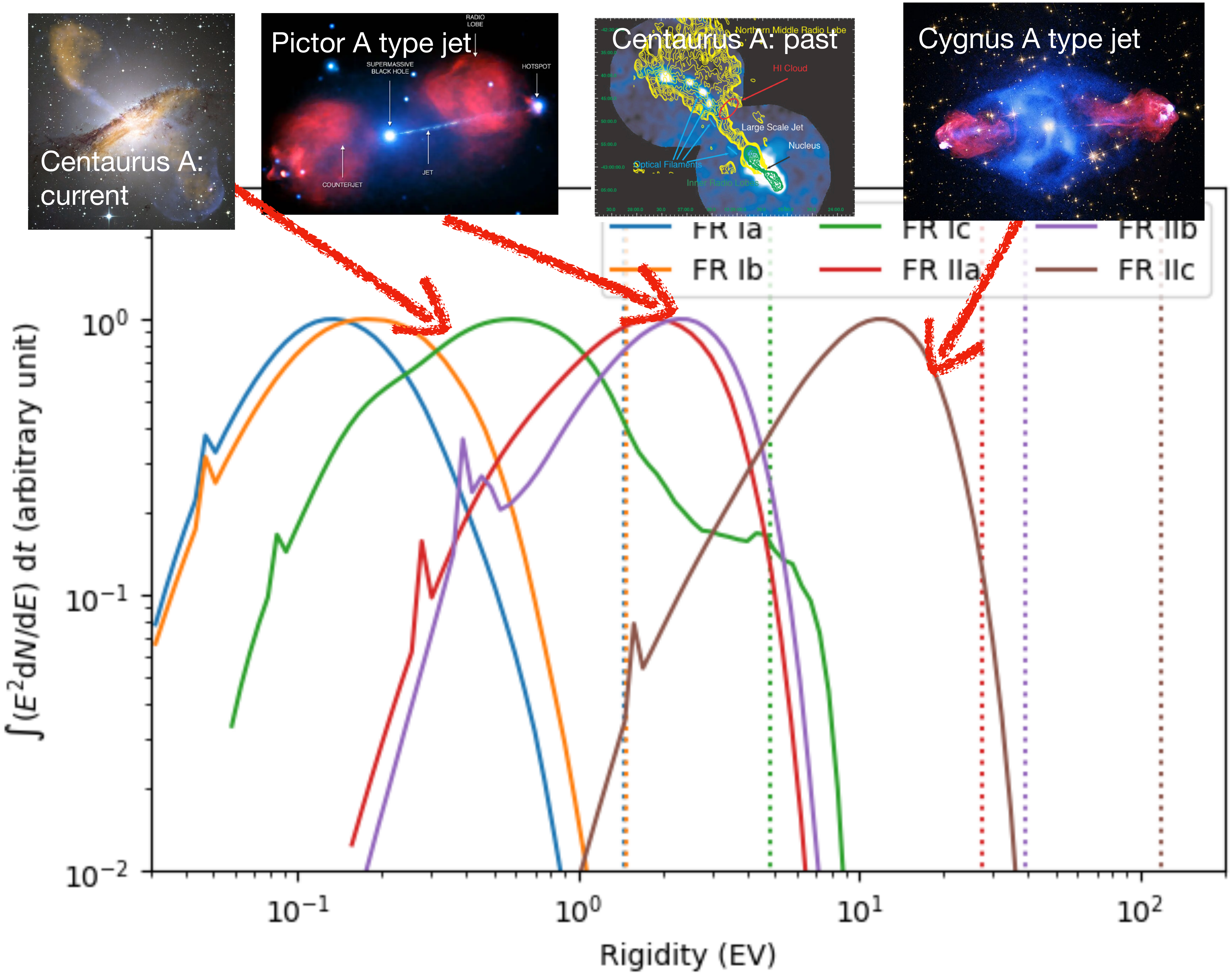


Super Accretor: Super Accelerator

Microquasar jet as PeV-EeV Galactic CR sources?

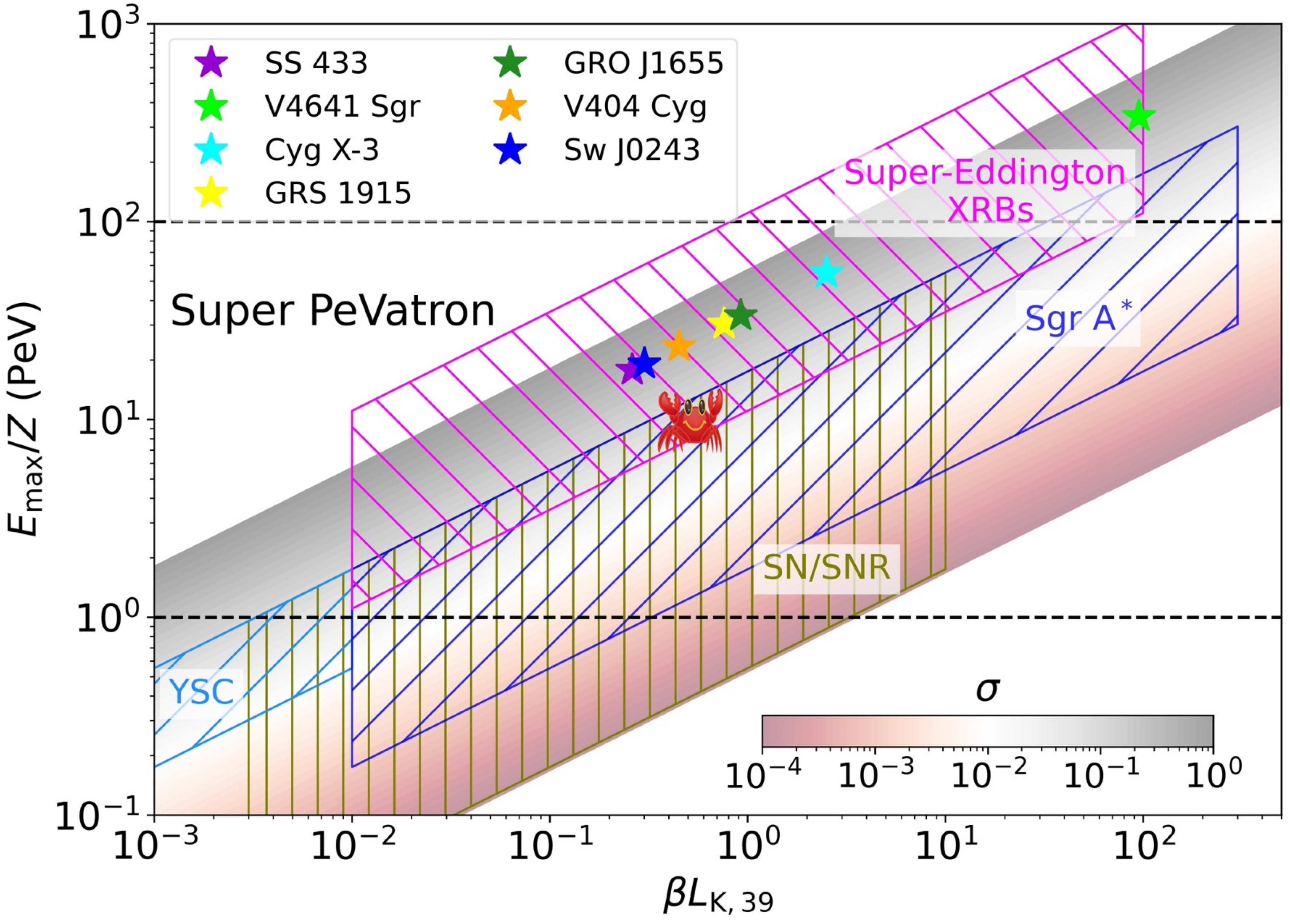




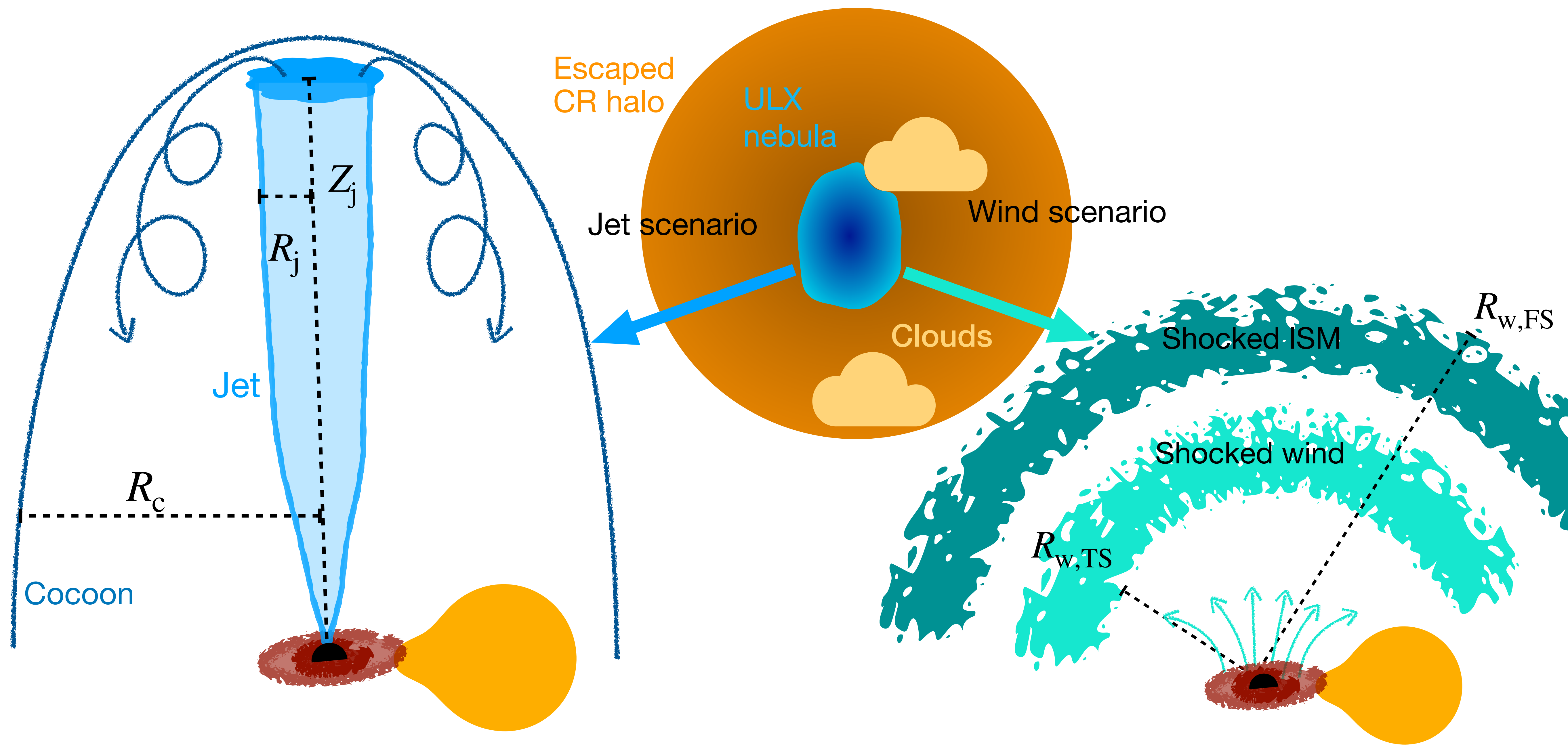


Sources of Highest-Energy Galactic CR?

XRB with super-Eddington flares: $E_{max} = Ze\beta BR = 1\ Z\beta^{1/2}\sigma^{1/2}L_{K,41}^{1/2}$ EeV



Jet/wind nebula+CR halo

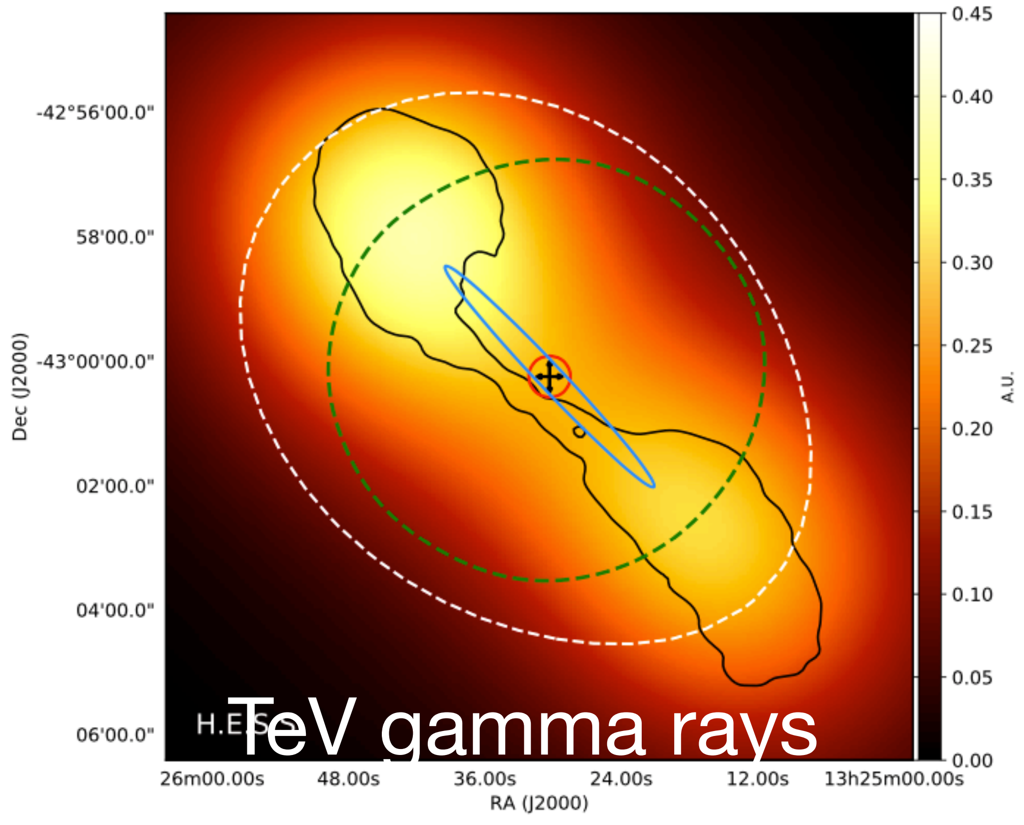


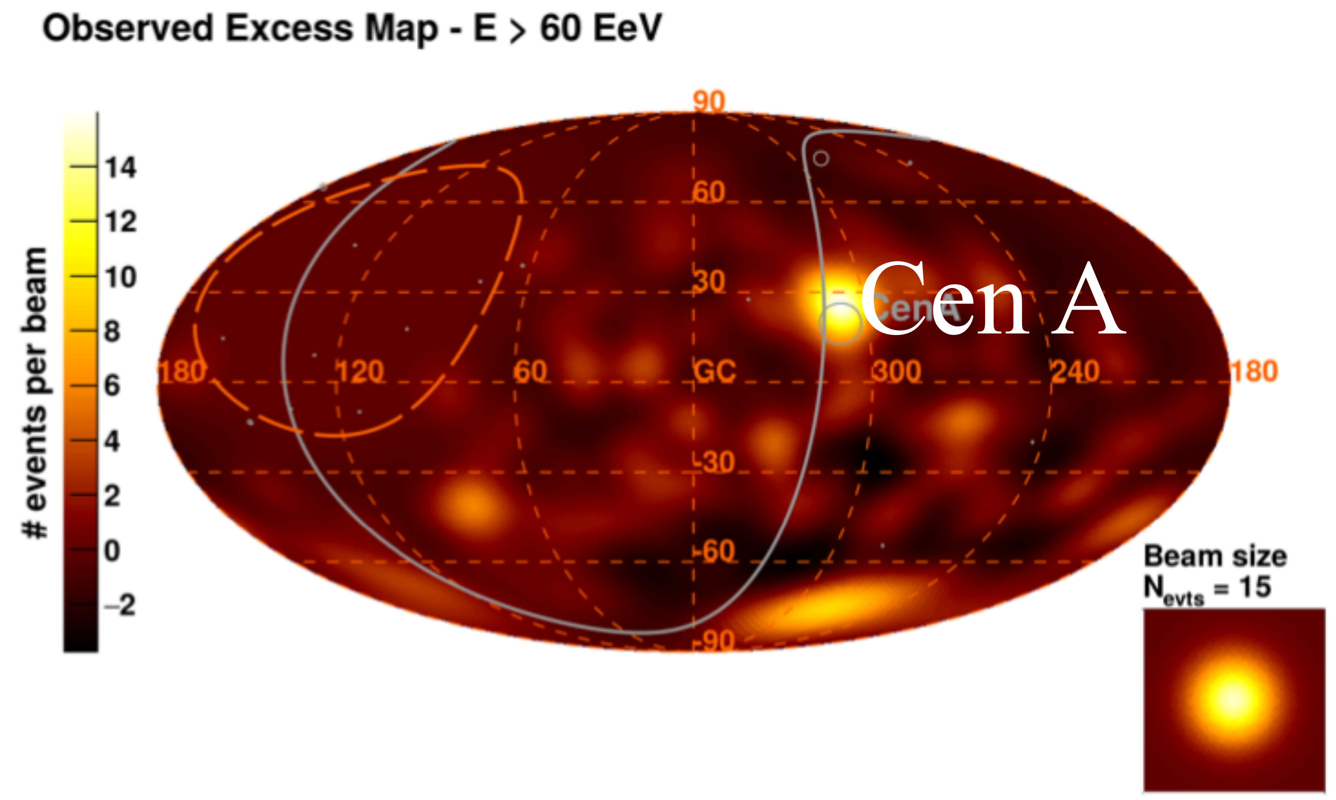
Wang, Reville, Aharonian, 2025, submitted

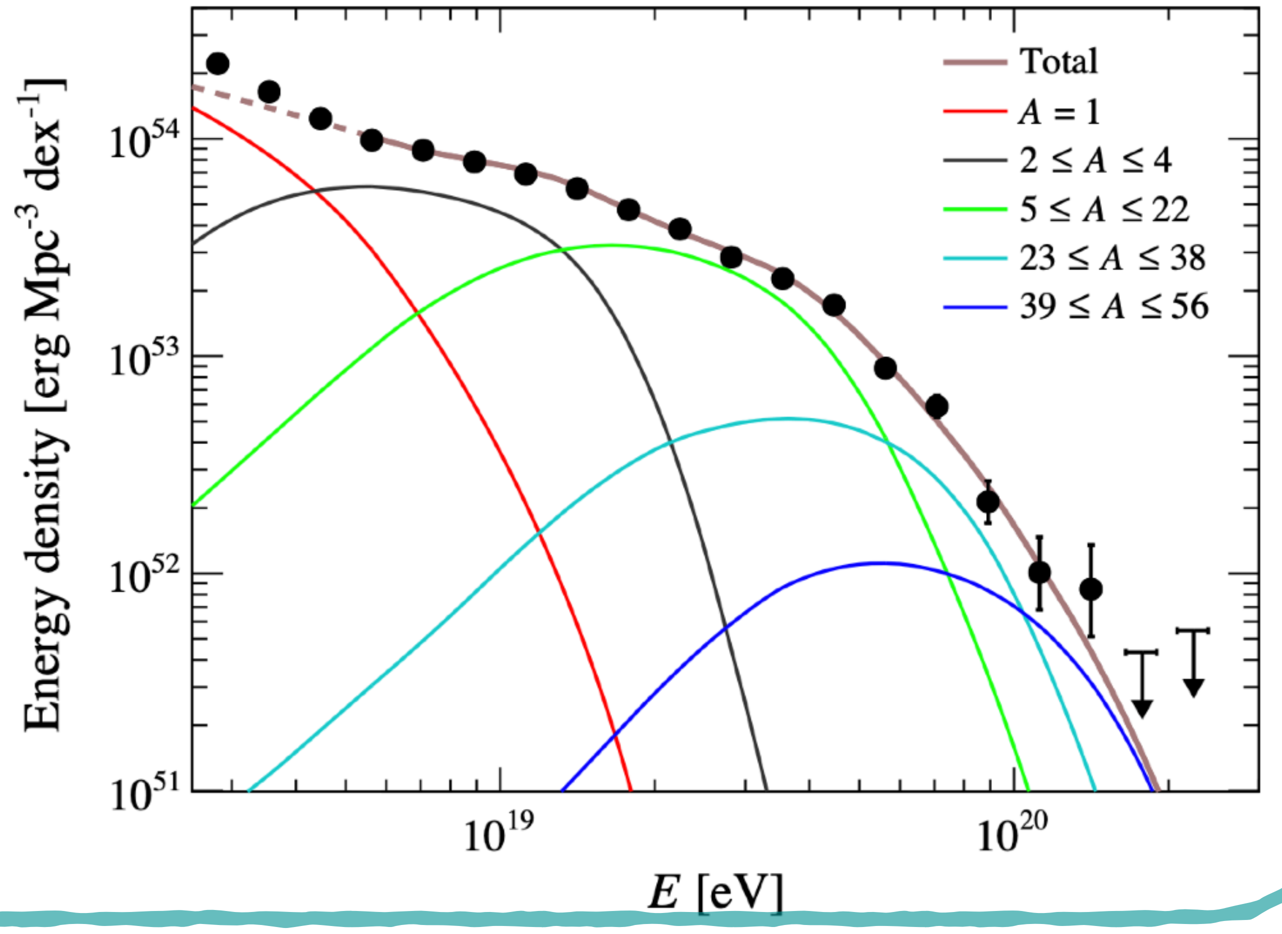
Summary

- In the framework of stochastic-shear acceleration, both MWL observation and UHECR acceleration (e.g. Cen A) can be explained
  - Turbulent-shear acceleration is an unavoidable (KH instability) and efficient mechanism in relativistic jets
- Jets as CR sources: Galactic jets ➔ VHECRs, Extra-galactic jets ➔ UHECRs?

A framework based on turbulent shear acceleration



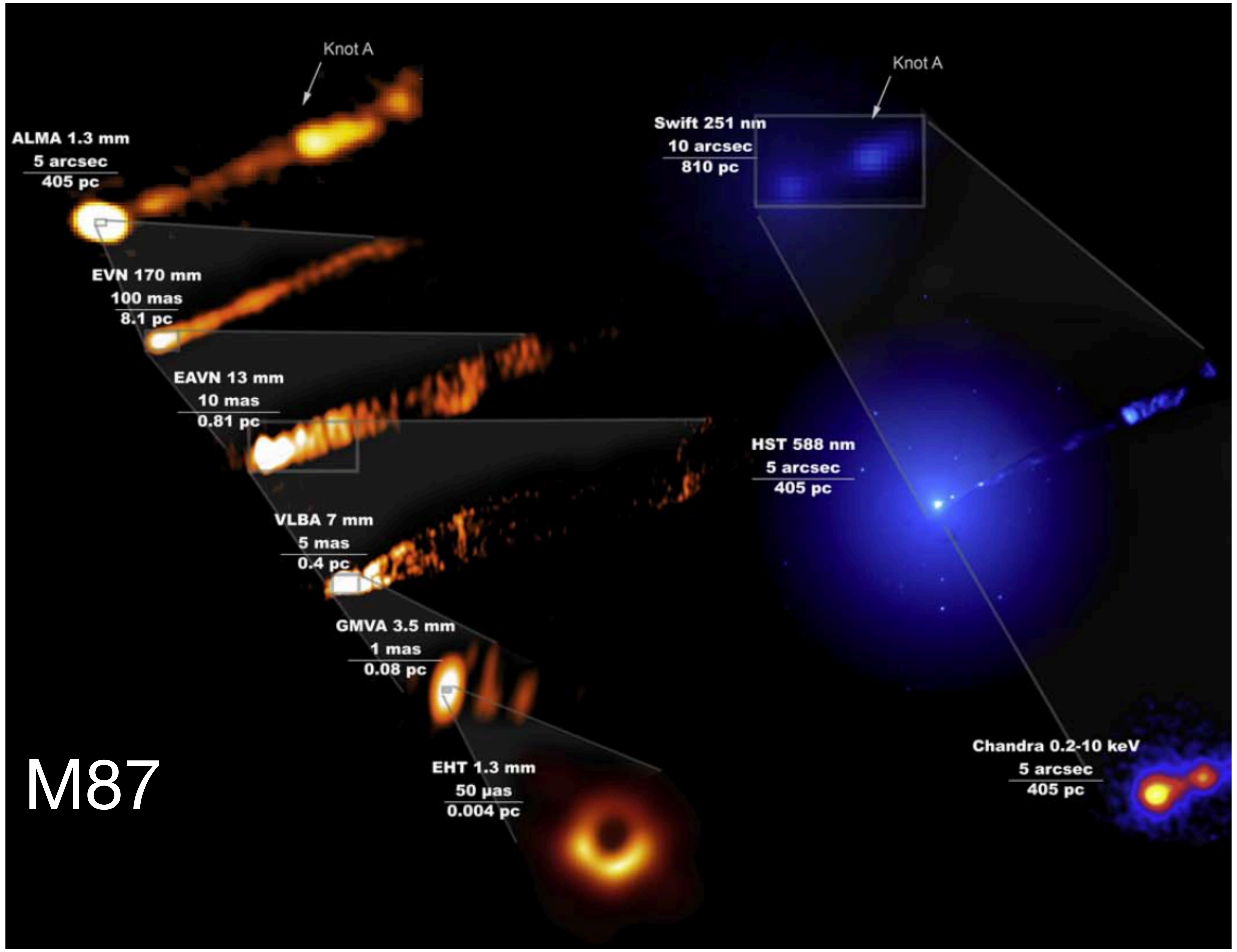




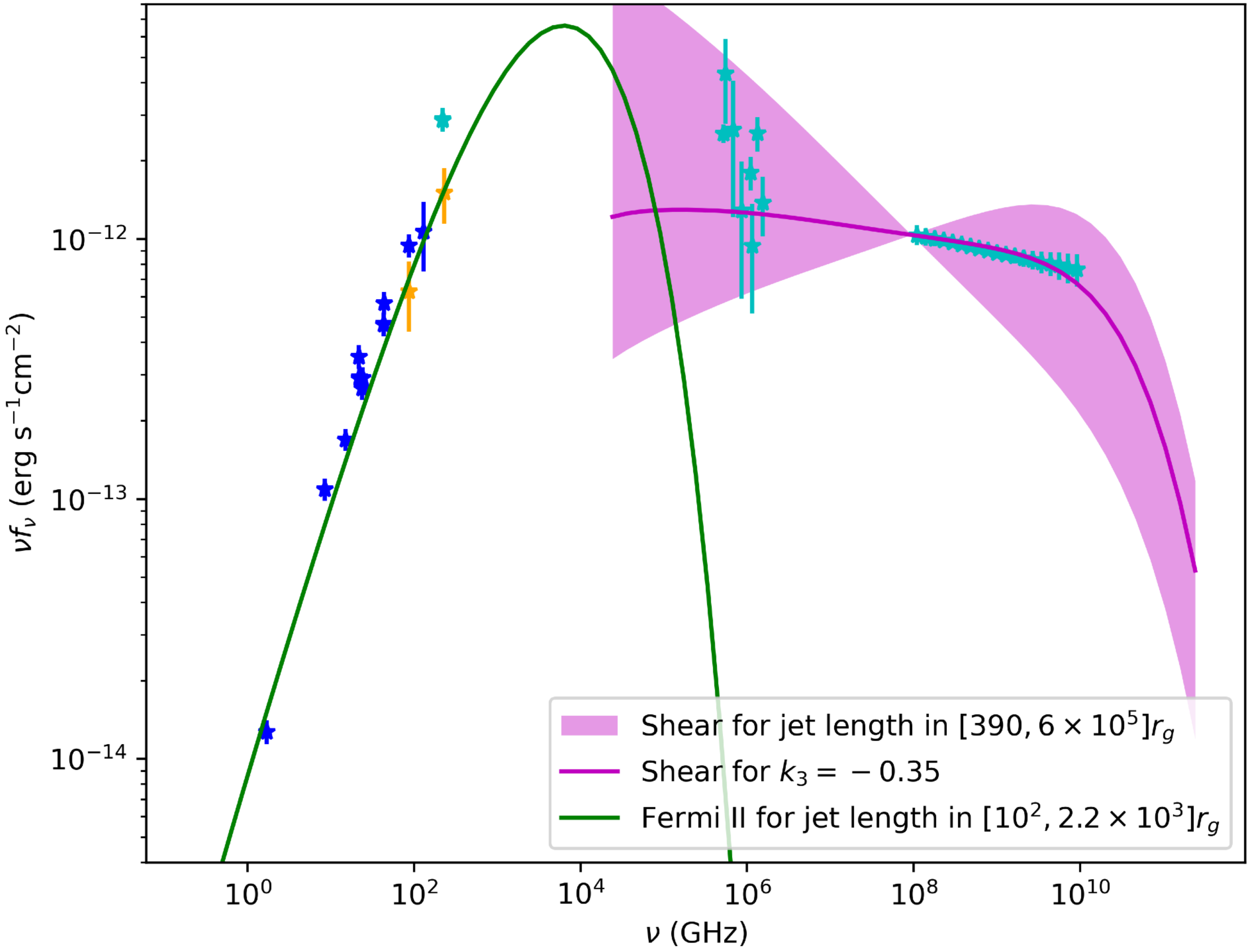
Matter: super solar abundance by AGN activity

Backup

M87 application



EHT MWL, 2021, ApJL



J.S.Wang+, 2024, ApJ