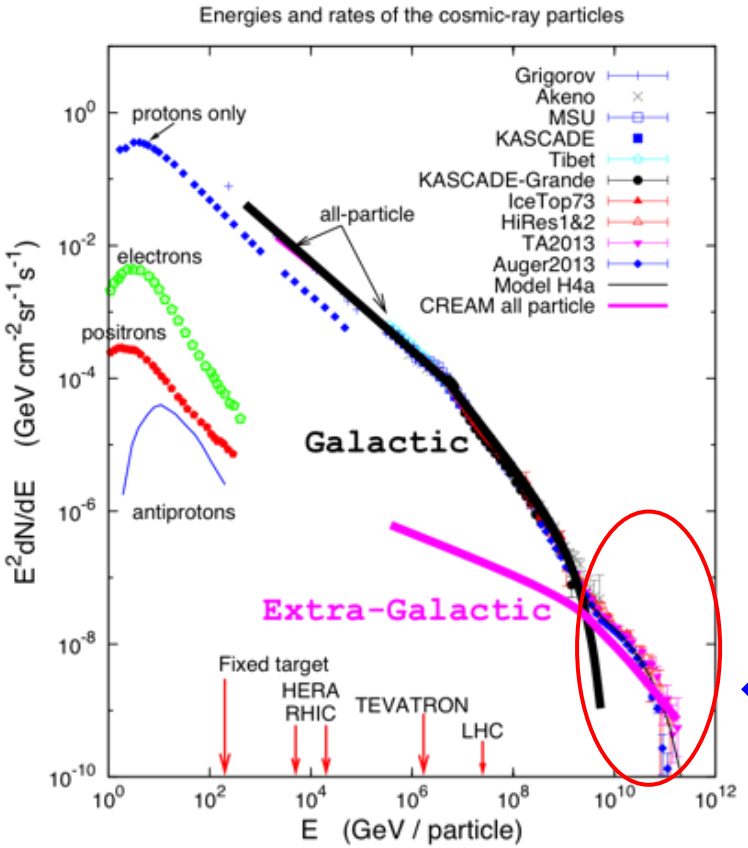
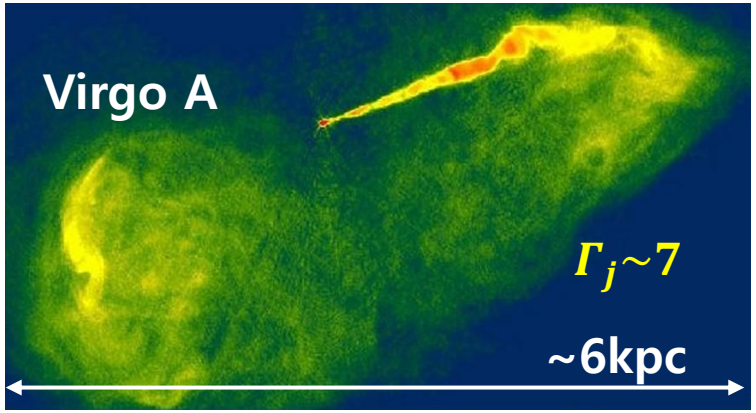
Ultra-High Energy Cosmic Rays Accelerated in FR Radio Galaxy Jets

Dongsu Ryu (UNIST, Ulsan, Korea)
Hyesung Kang (Pusan National University, Korea) and Jeongbhin Seo (LANL, USA)





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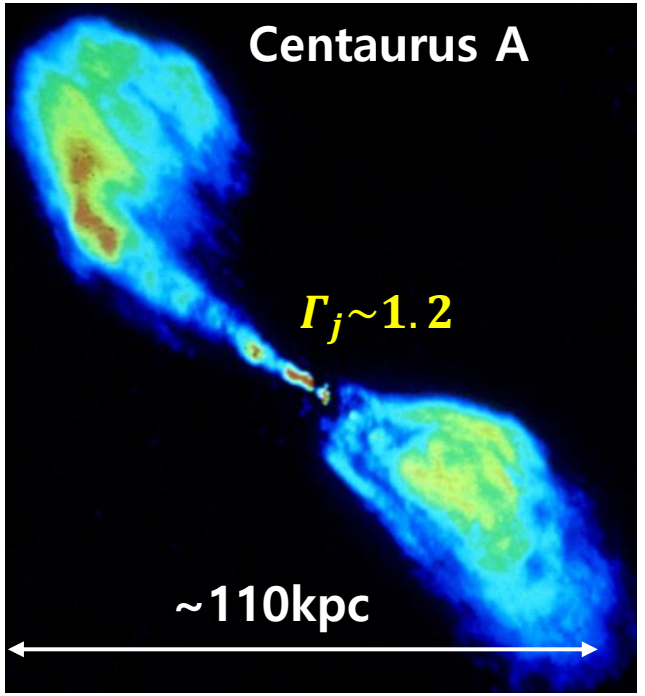
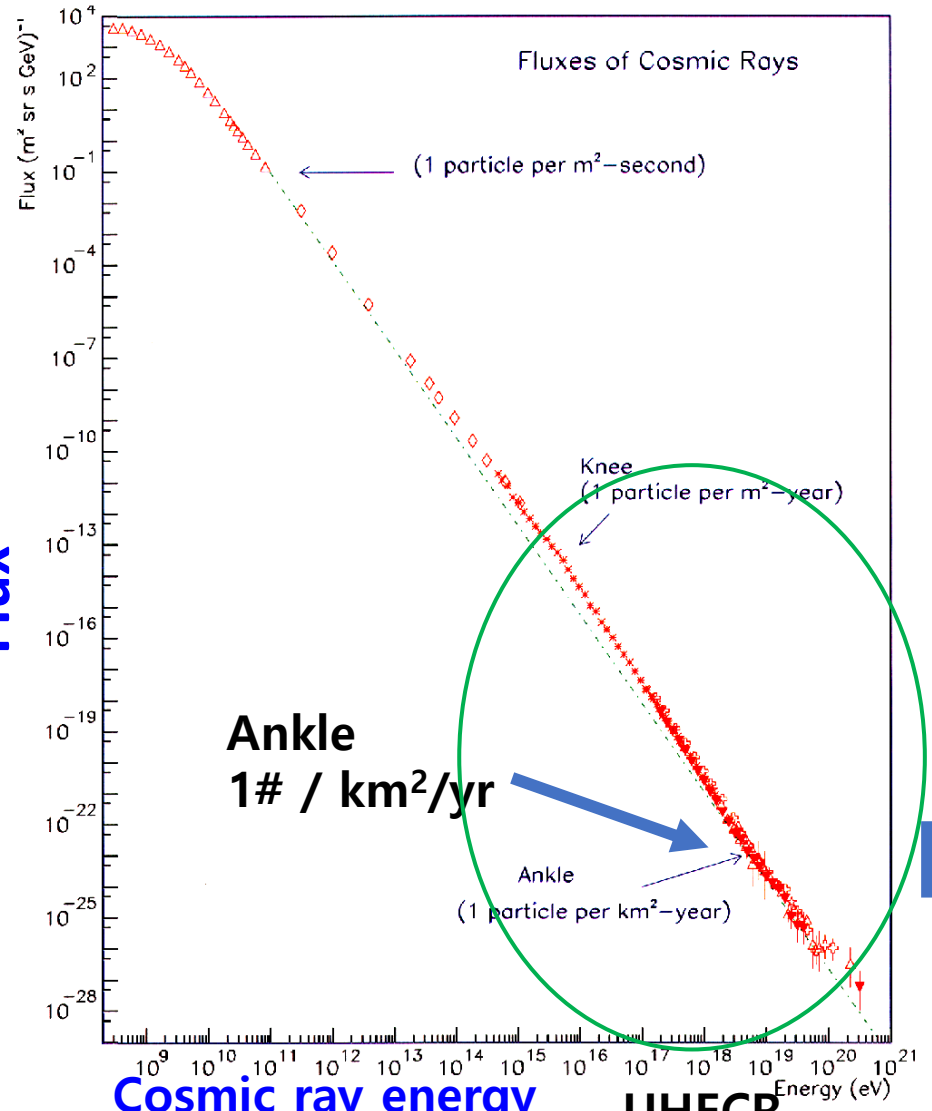


Observation of ultra-high energy cosmic rays (UHECRs)

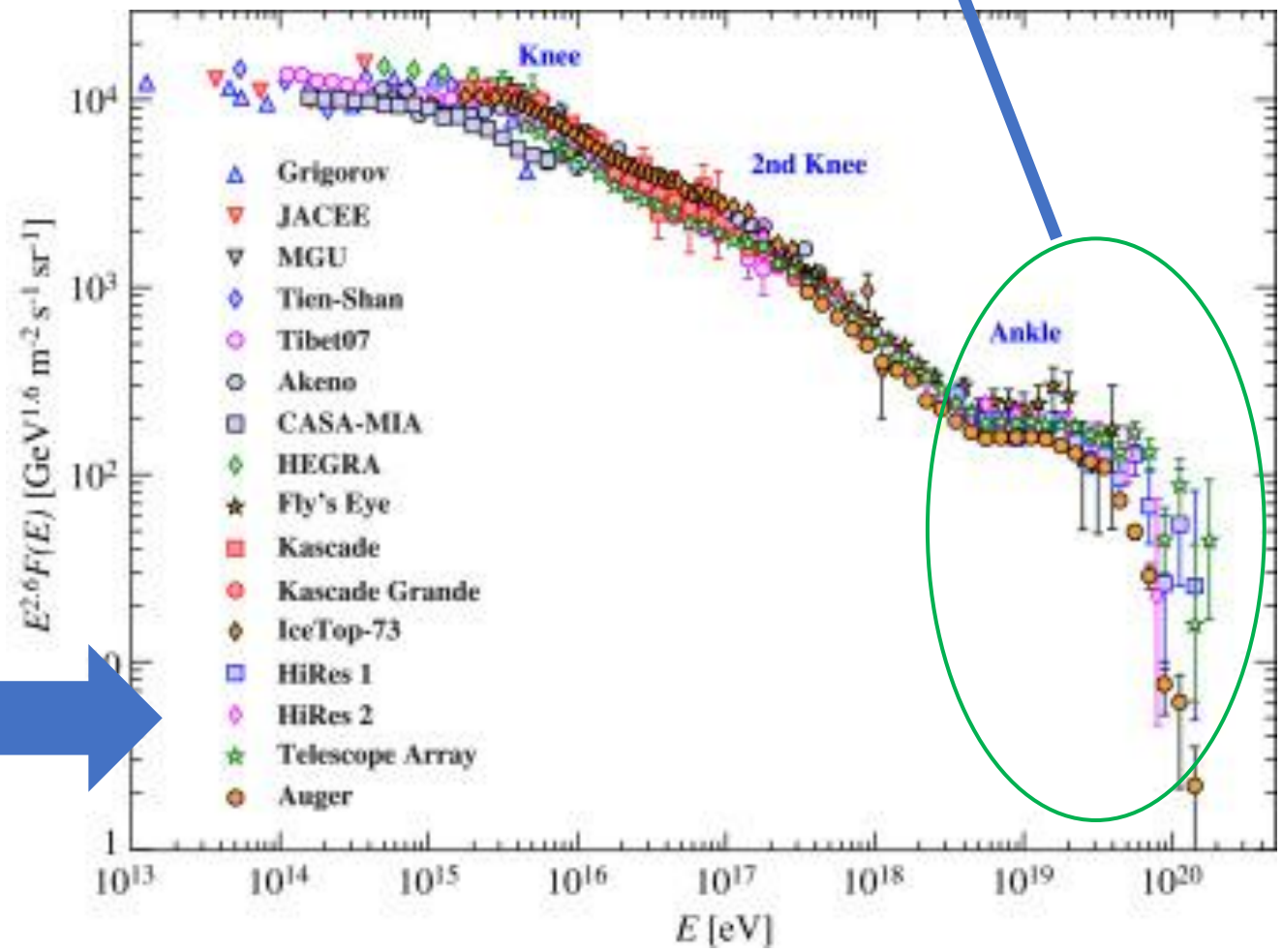


Flux

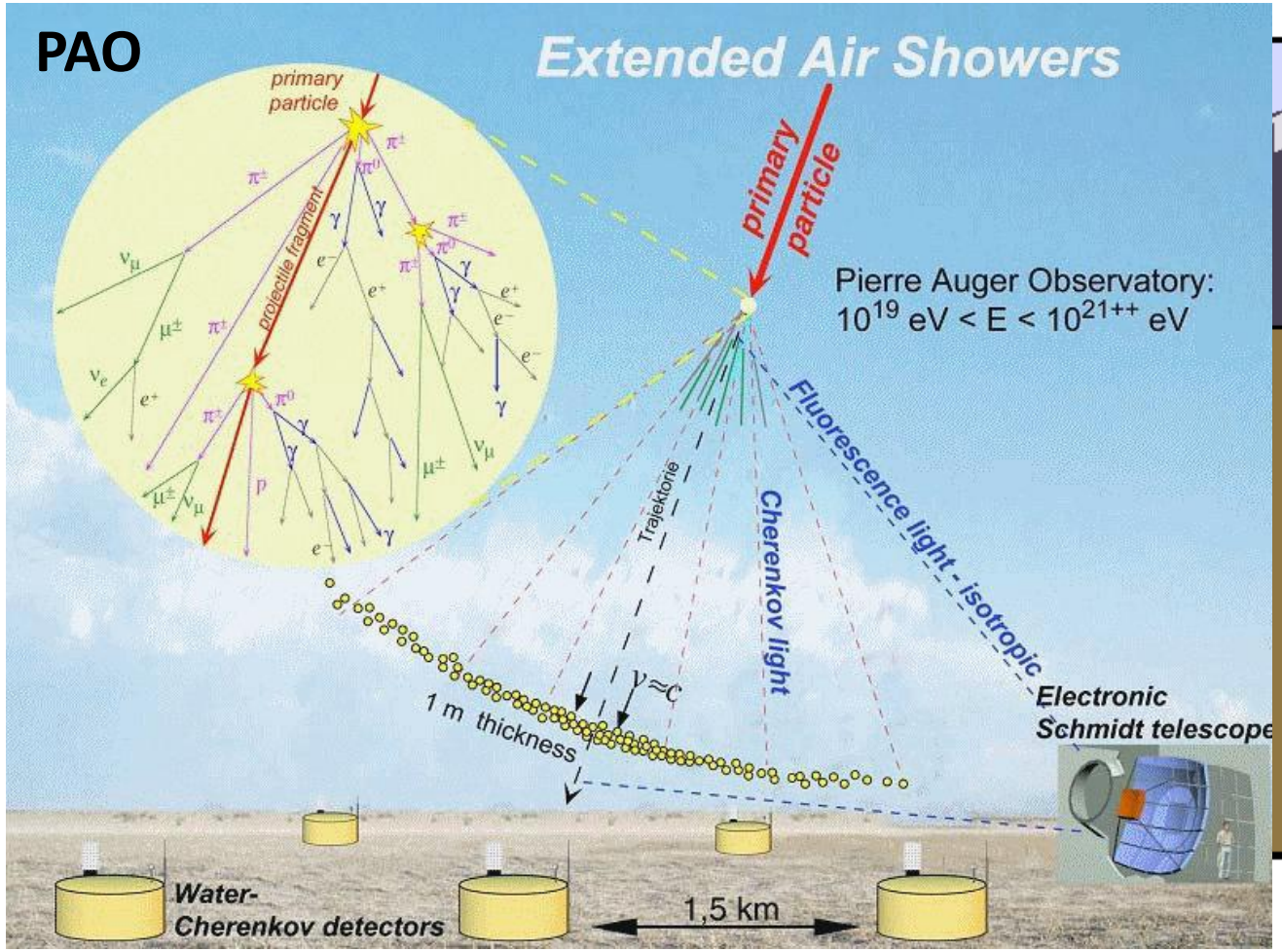
Ankle
1# / km²/yr

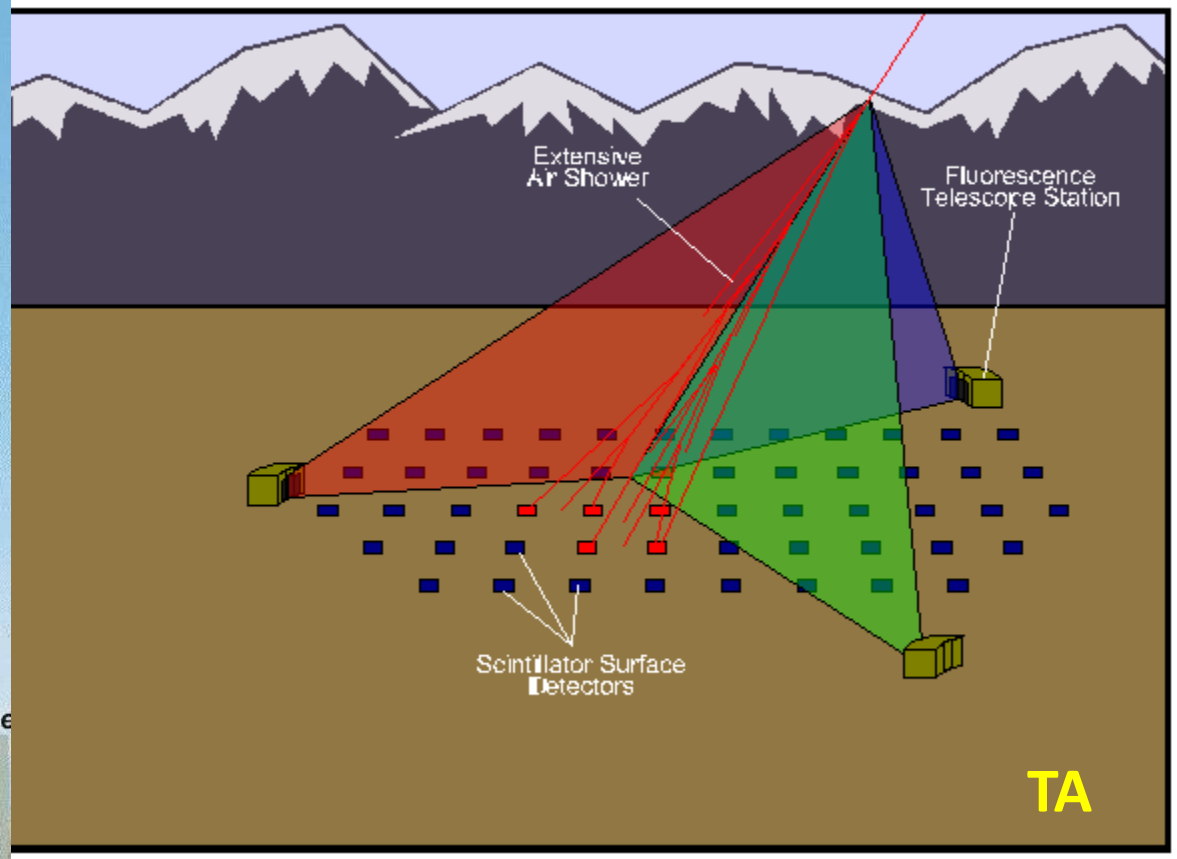
Cosmic ray energy spectrum

UHECR
≥ 10^{18}eV(EeV)



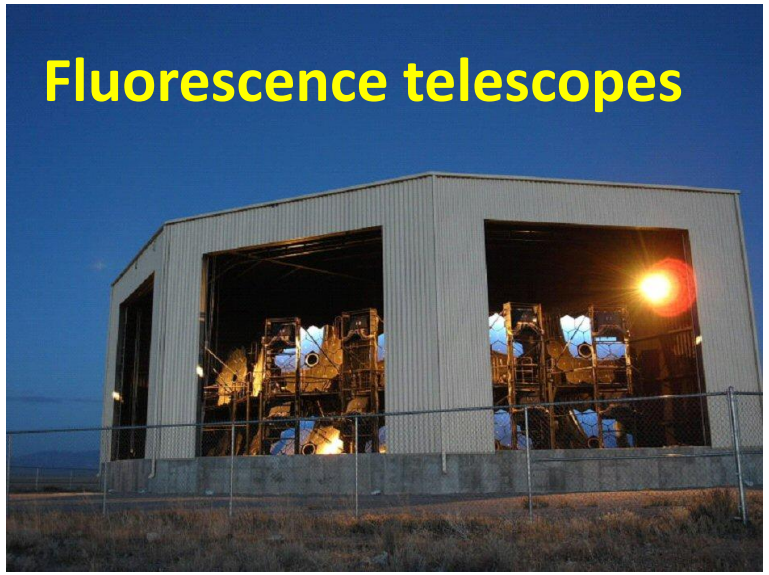
Observation of UHECRs: Extensive Air Shower (EAS)

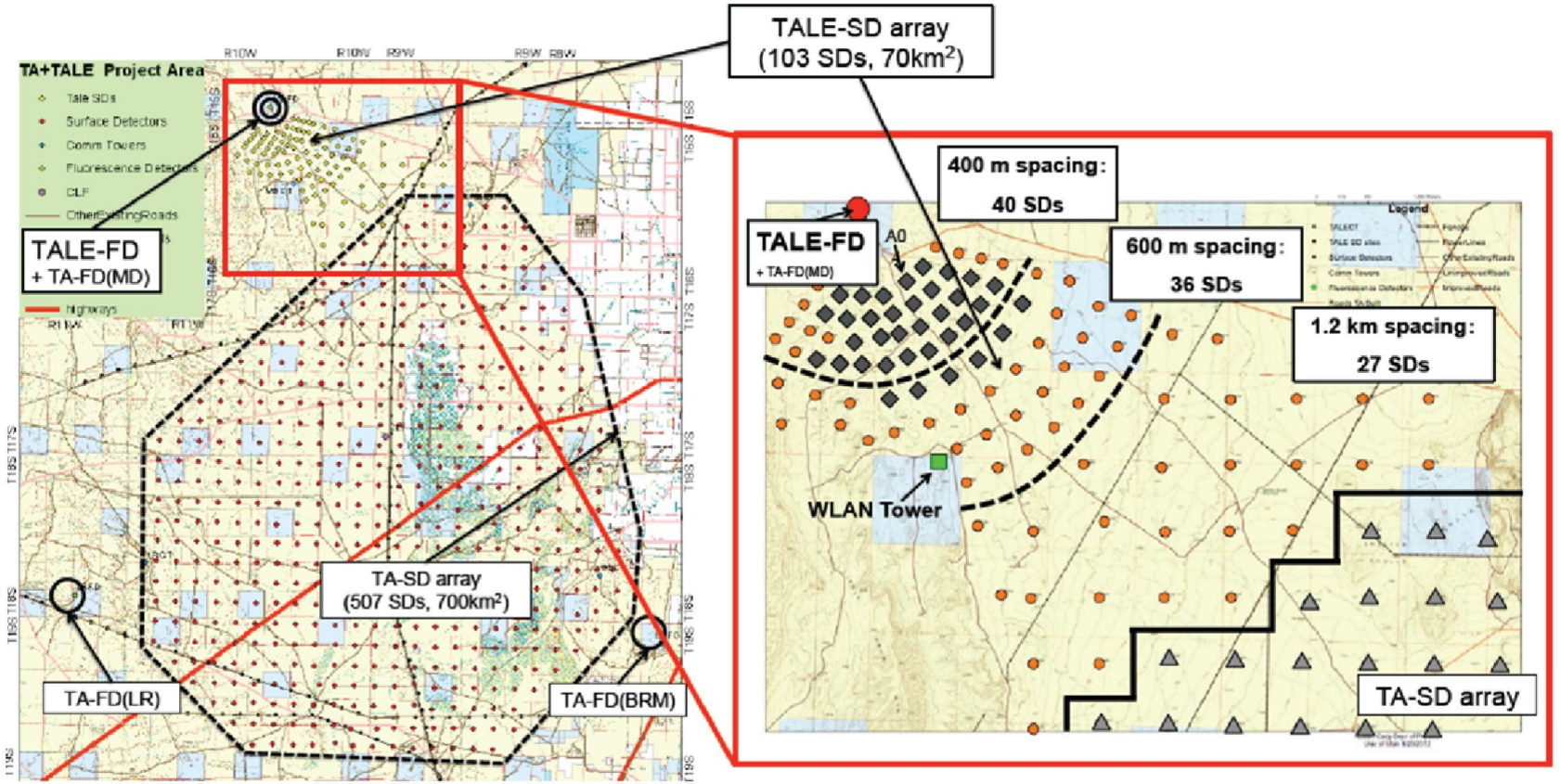




Two leading experiments for observation of UHECRs

Telescope Array (TA) experiment in Delta, Utah, USA → Northern hemisphere



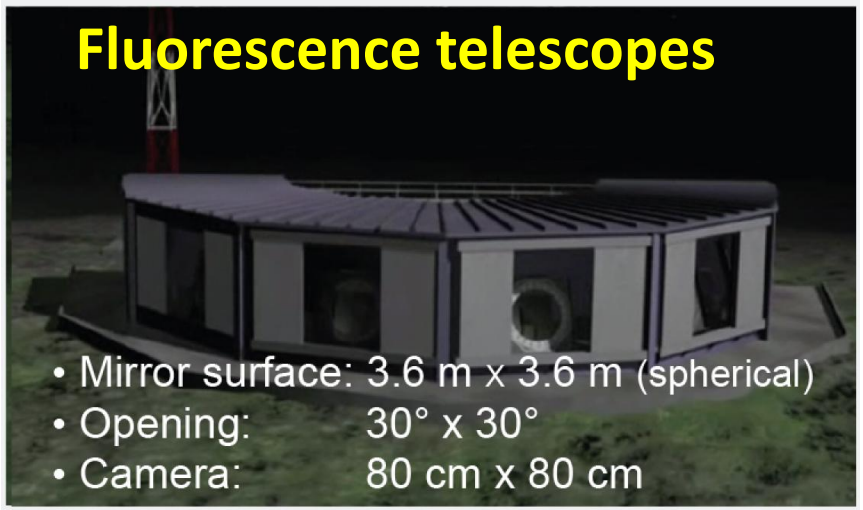


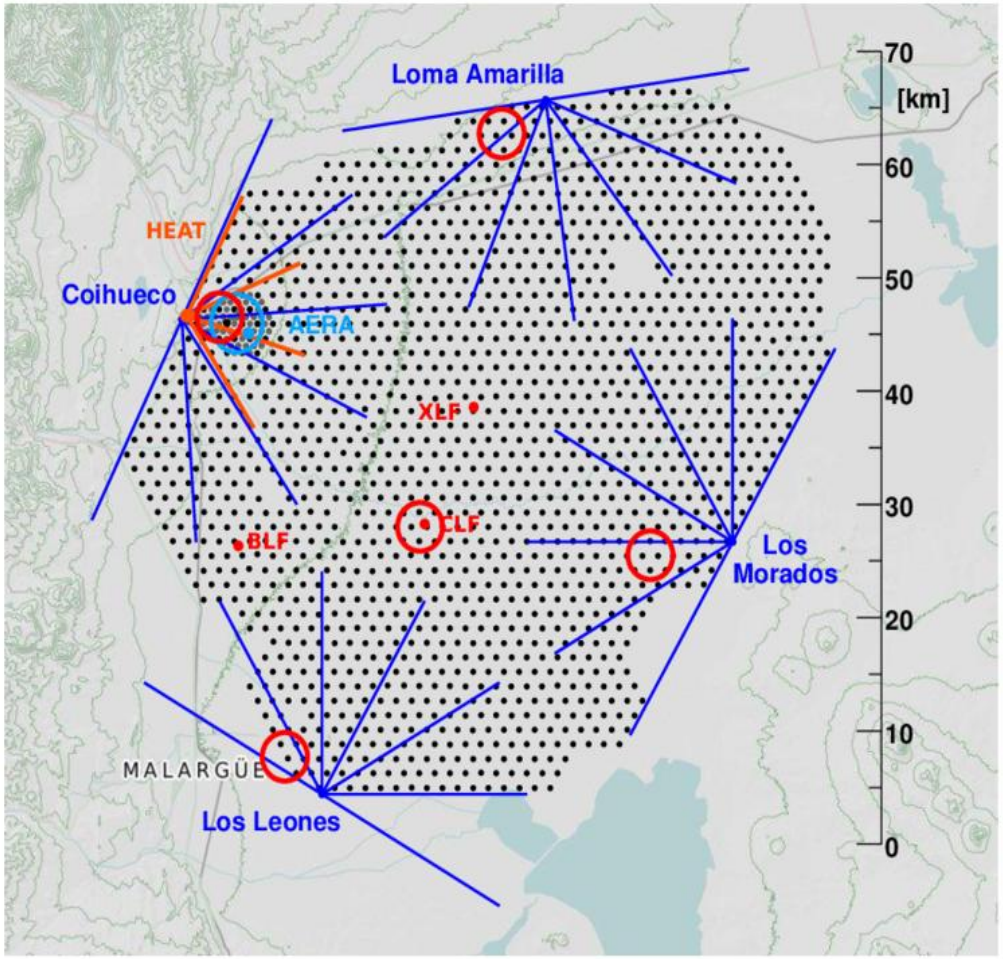
Japan, USA, Korea, & Russia

Two leading experiments for observation of UHECRs

Pierre Auger Observatory (PAO) in Argentina → Southern hemisphere

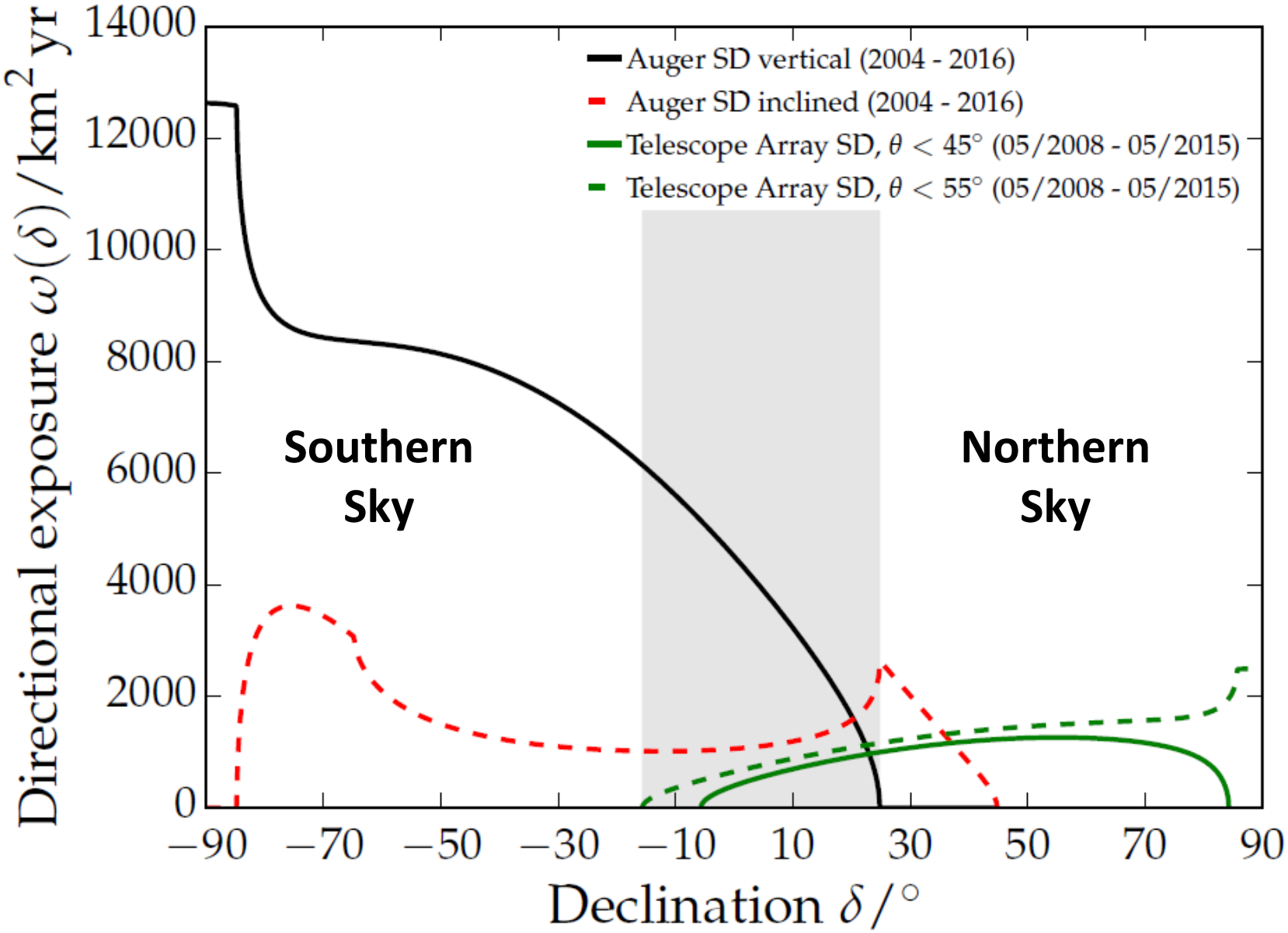
Location of Pierre Auger Observatory





Mostly European countries + Argentina

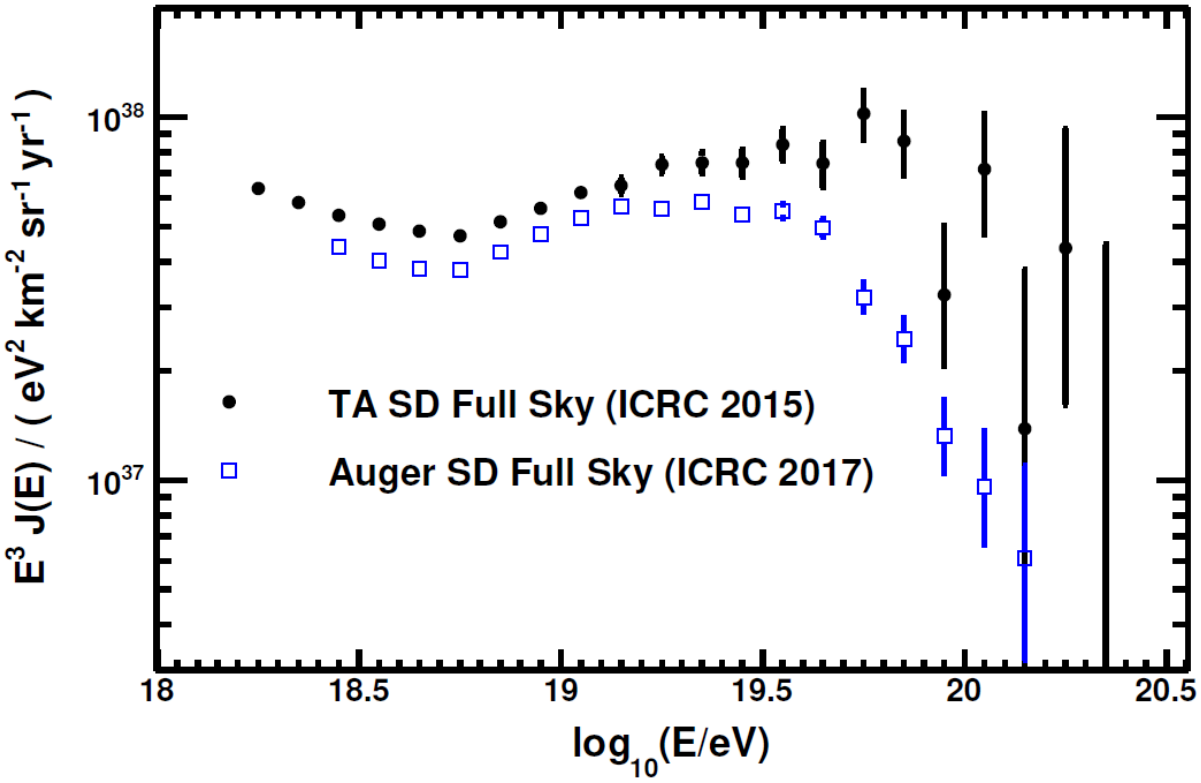
Sky coverage of two experiments

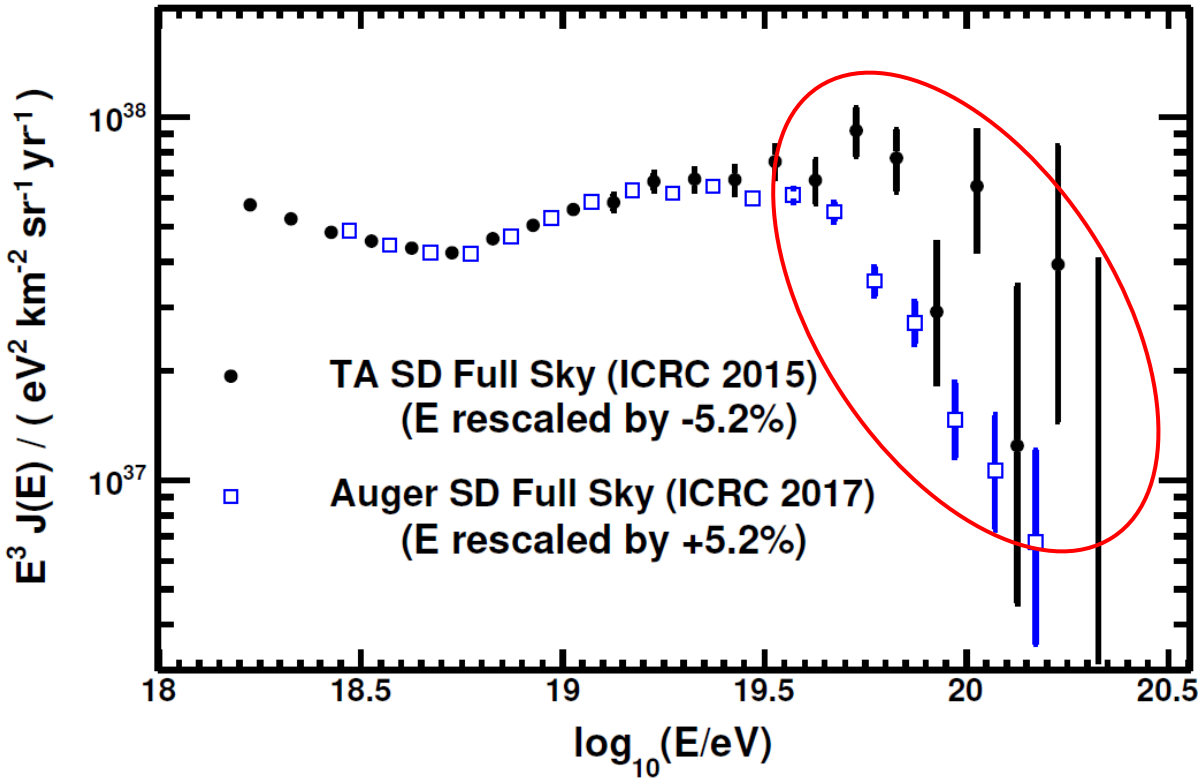


- PAO sees UHECRs coming through the southern sky
- TA sees UHECRs coming through the northern sky

Differences in UHECRs observed by two experiments

Energy spectrum of UHECRs



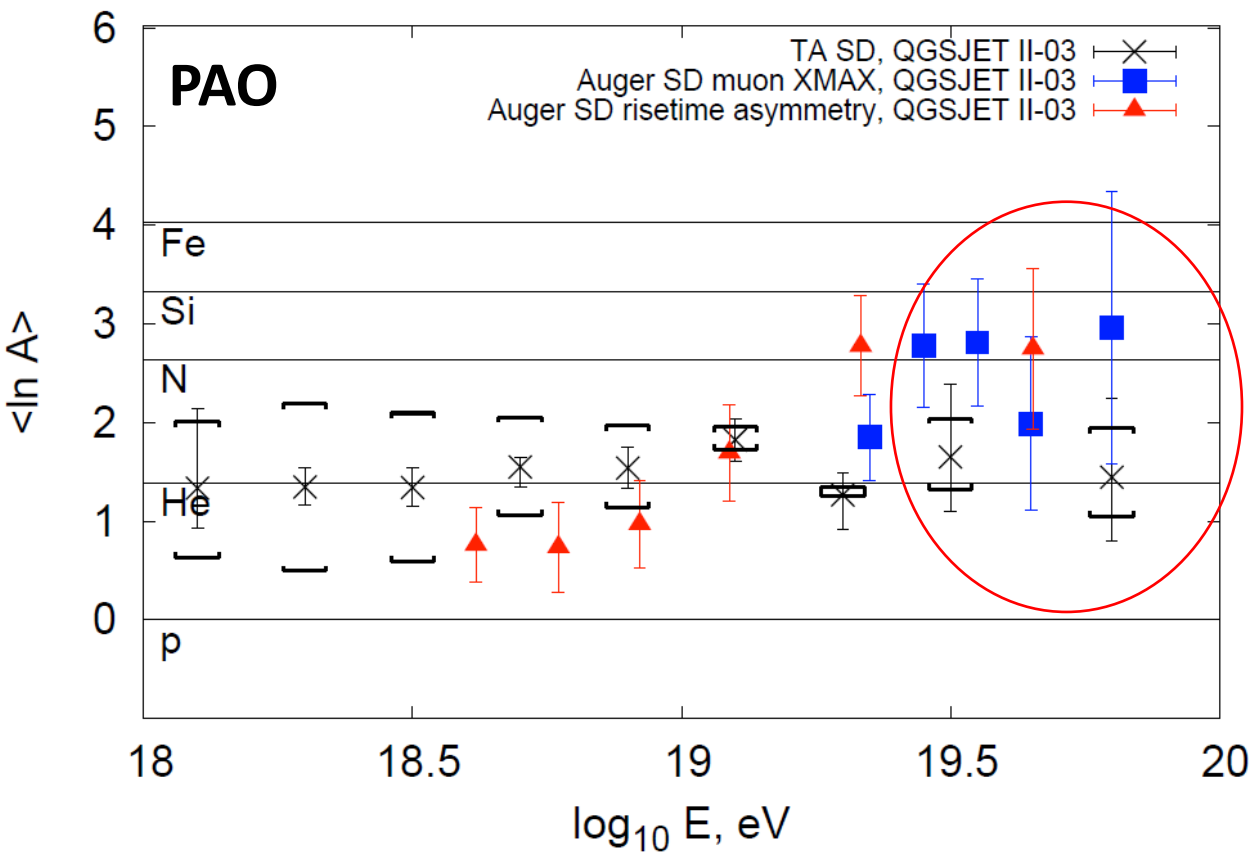


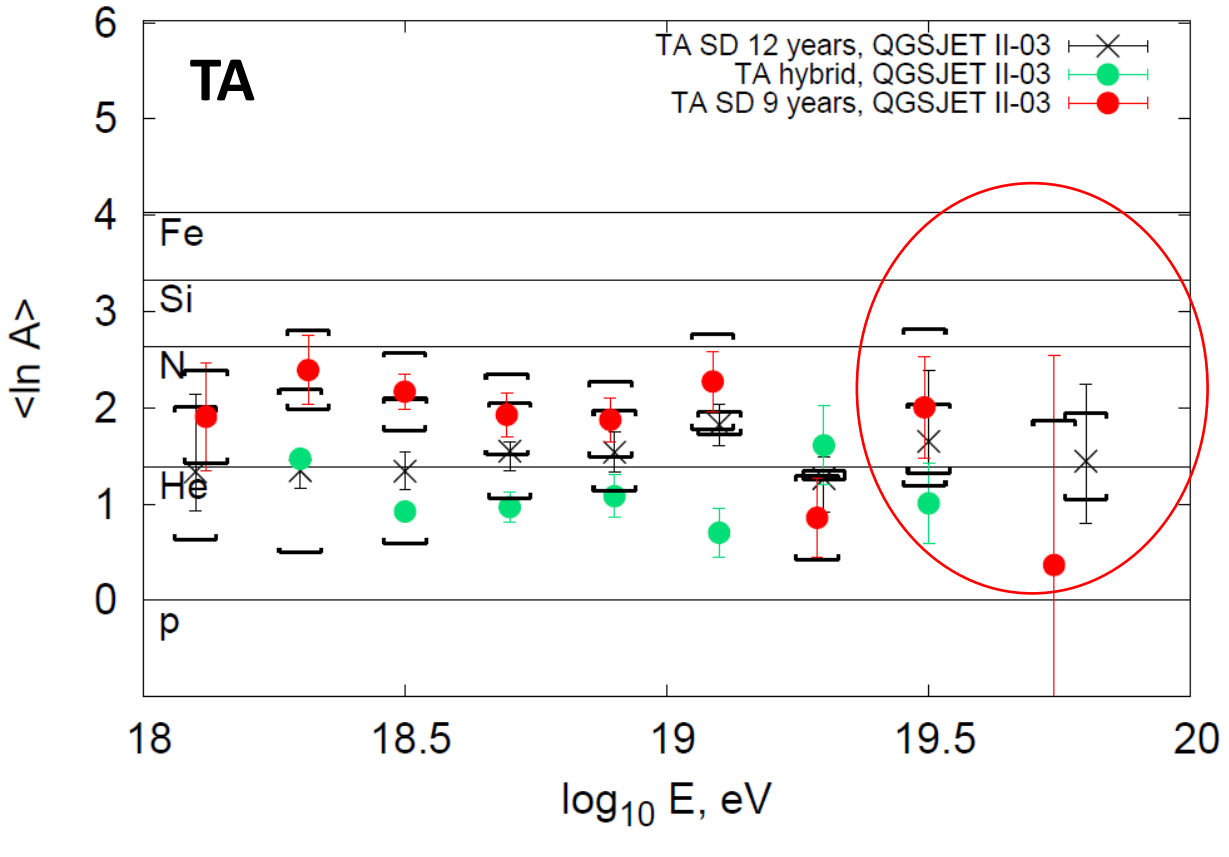
Flux of UHECRS with E > ~3×10^{19} eV is higher in the northern sky!

Differences in UHECRs observed by two experiments

Mass composition of UHECRs

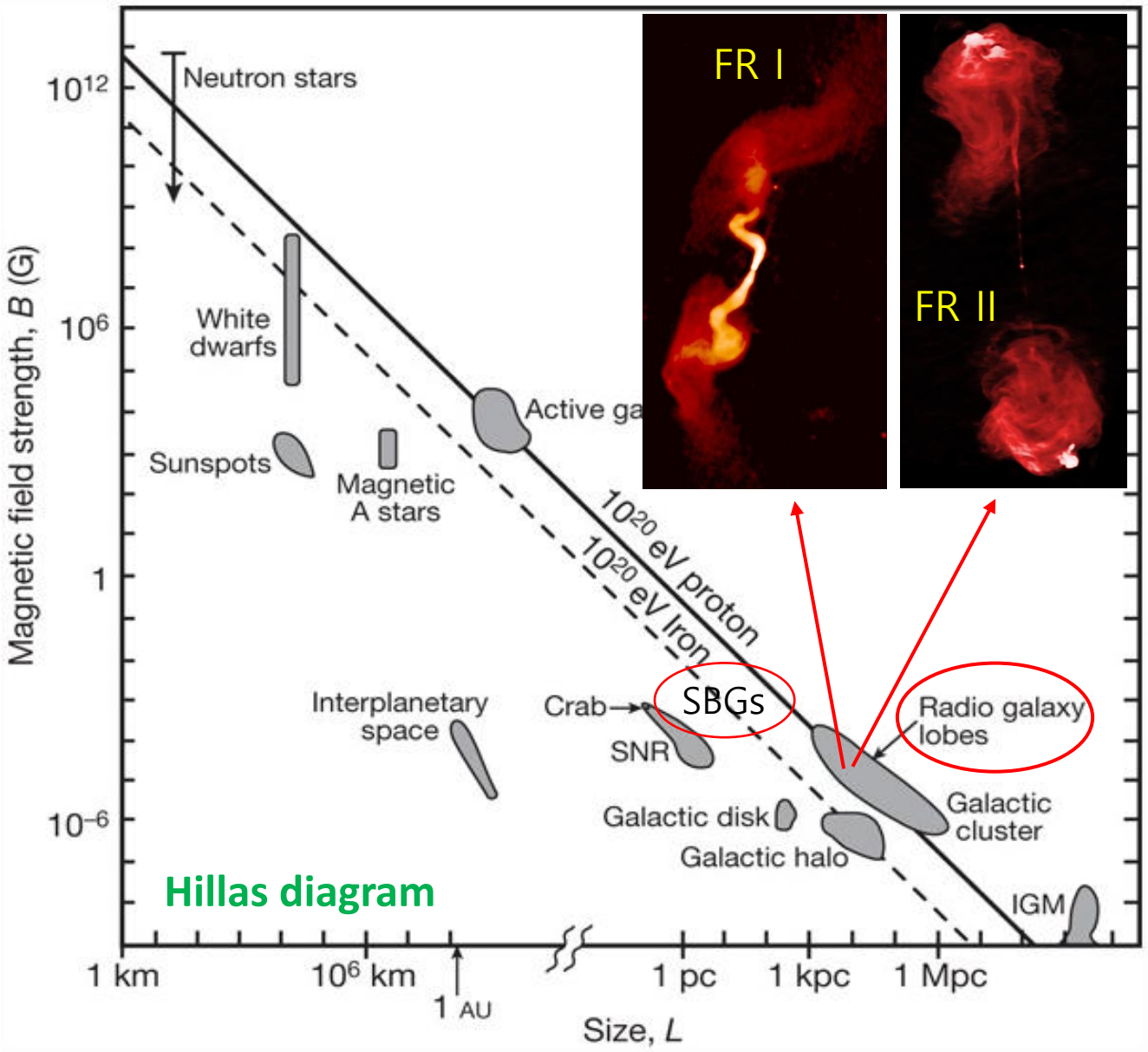
A: atomic mass





Mass of UHECRS with E > ~3x10^{19} eV is heavier in the northern sky!

Radio galaxies: possible astrophysical sources of UHECRs



Confinement condition ← Hillas criteria

Particles should be confined within accelerator in order to be accelerated. $r_g \leq L$

$$E_{Hillas}(EeV) \leq \beta_a \cdot B_{\mu G} L_{kpc}$$ **for proton**

$$E_{Z_i,Hillas} = Z_i E_{Hillas}$$

Z_i charge $\quad \beta_a = V_a/c \quad B_{\mu G} = \frac{B}{1\mu G} \quad L_{kpc} = \frac{L}{1kpc}$

Radio Galaxies (RGs):

FR-I : mildly relativistic jet, two-sided, plume-like

FR-II : highly relativistic jet, brighter lobed (hot spot), often one-sided (relativistic beaming)

Most promising candidate for UHECR sources ?

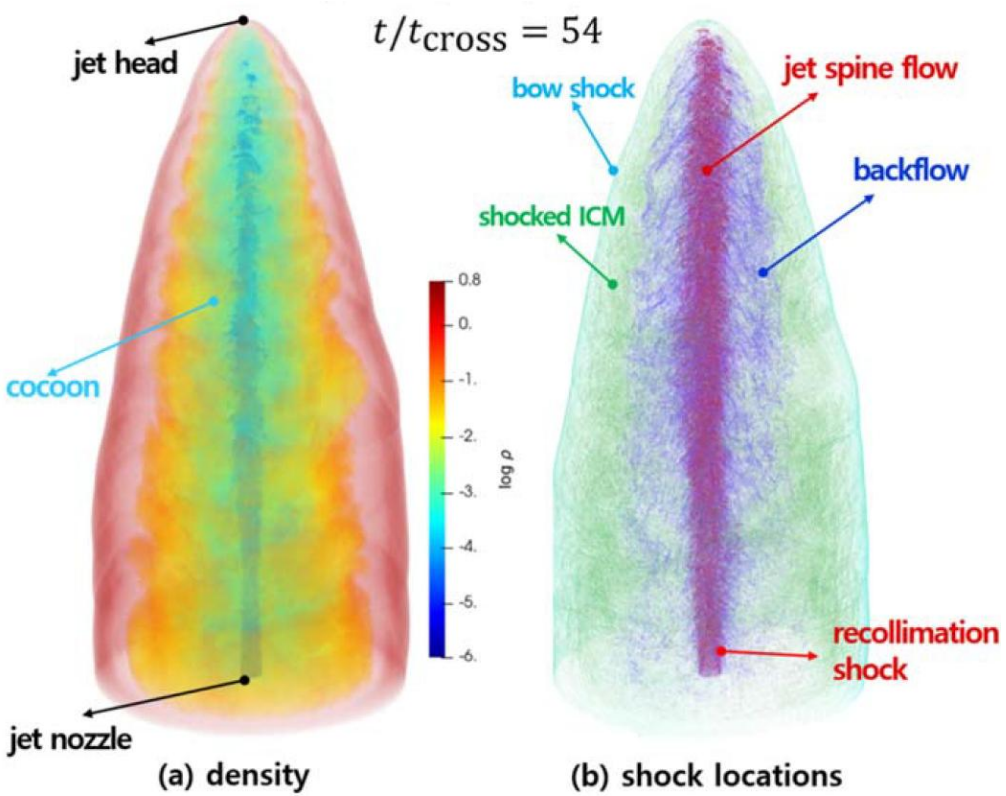
(Blandford et al. 2019; Rieger 2019; Hardcastle & Croston 2020; Matthews et al. 2020, + many previous studies)

Quantitative numerical estimation of UHECR spectrum from RG jets

3D Relativistic hydrodynamic (RHD) simulations for relativistic jets with $\Gamma_j \sim 1-100$ Seo et al. 2021b

adopt models for
- B field amp
- $\lambda_{\rm mfp} \propto p^{\delta}$

Monte Carlo simulations of the CR transport in the simulated jet-induced flows.



Jet Parameters: $Q_j, r_j, \eta = \rho_j/\rho_b$, while $p_j = p_b$

Jet power: $Q_j = \pi r_j^2 v_j (\Gamma_j^2 \rho_j h_j - \Gamma_j \rho_j c^2)$

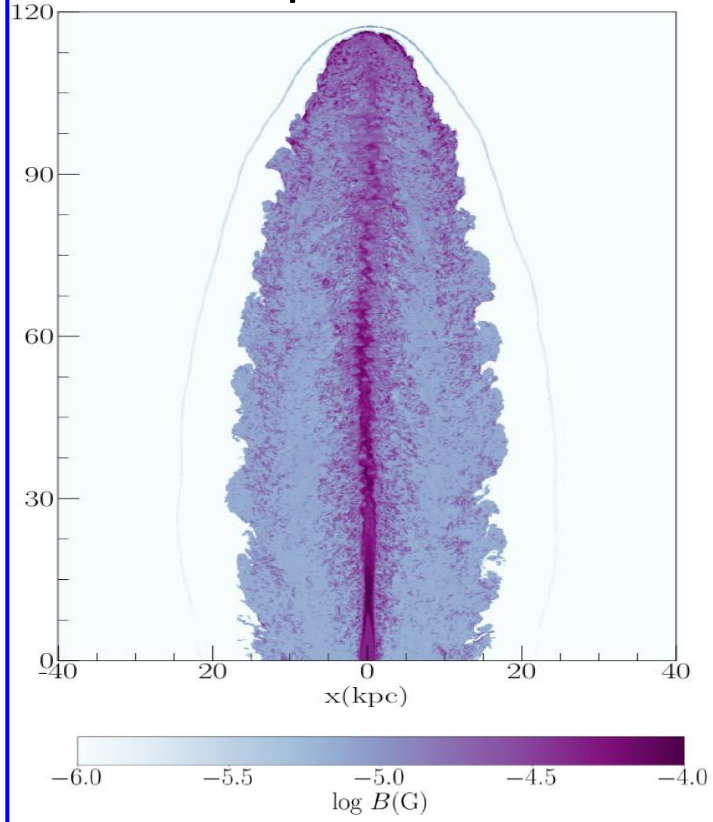
$r_j = 10\text{pc} - 1\text{kpc}, \ \Gamma_j \sim 1-100, \ \ Q_j \sim 10^{42} - 10^{47}\text{erg/s}$

jet bulk **Lorentz factor** $\Gamma_j = \dfrac{1}{\sqrt{1-\left(\frac{v_j}{c}\right)^2}} \propto \left(\dfrac{Q_j}{\rho_j \pi r^2}\right)^{1/2}$

Higher-power jets are more relativistic.

Monte Carlo simulations for CR transport

- Prescription for B fields



Jet spine: B ~ $100\mu G$
Backflow: B ~$10\mu G$
ICM: B ~$1\mu G$

- **MHD turbulence,** $\frac{\delta B}{B}$, on subgrid scales

$$\lambda_{\mathrm{mfp}} \propto E^{\delta}$$

$\delta = 1$ for Bohm

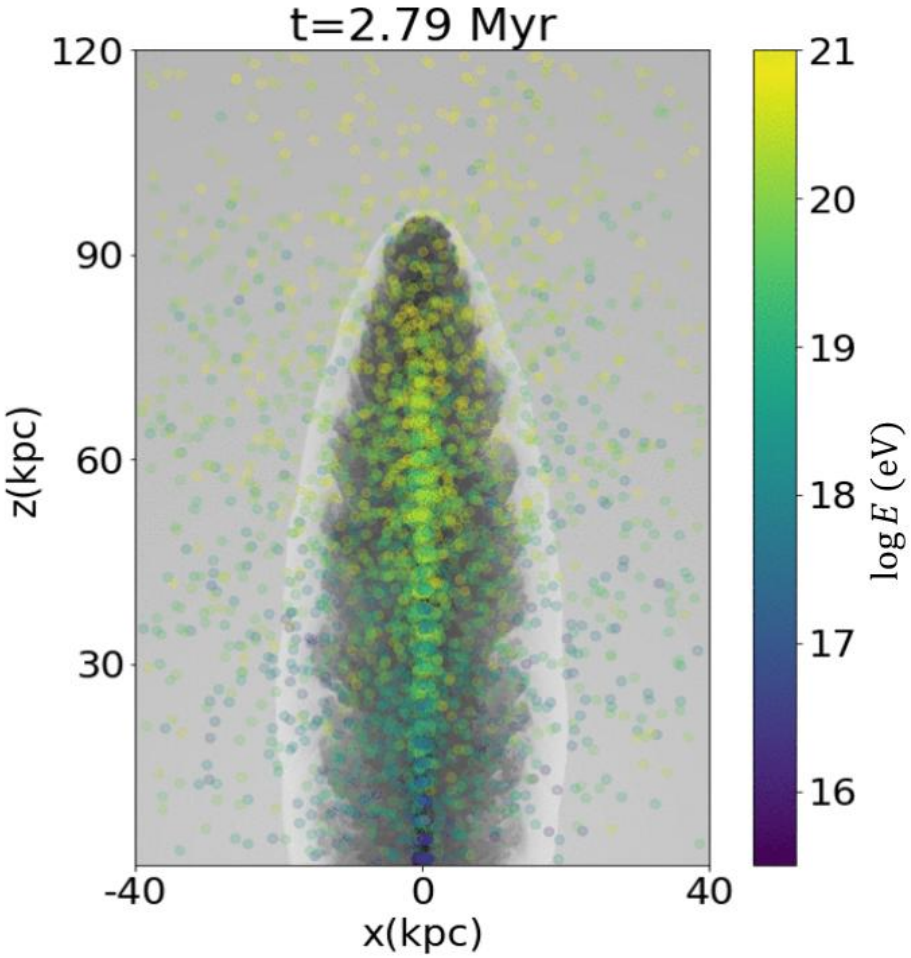
$\delta = 1/3$ for Kolmogorov

- **Galactic CR seeds**

$$dN/dE \propto E^{-2.7}$$

with $E = 10^{13} - 10^{15}$ eV

injected from the host galaxy through the jet nozzle

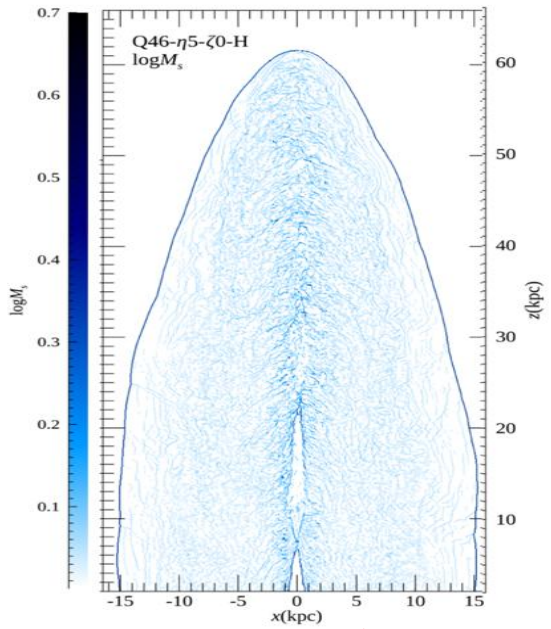


Particles are advected & energized by shocks, shear, and turbulence in the time-evolving jet flows.

Three Main Particle Acceleration Mechanisms

Diffusive Shock Acceleration

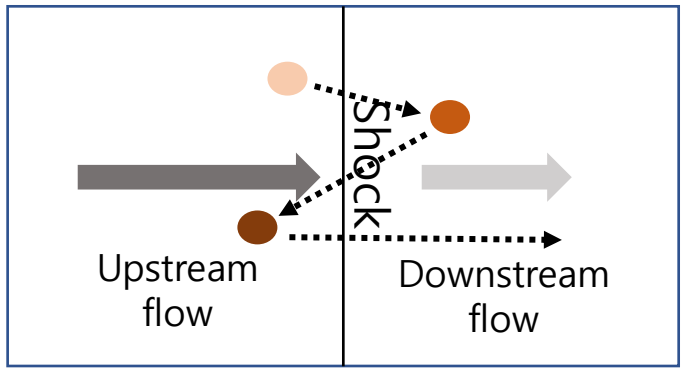
Shock Mach no.



steep spectrum

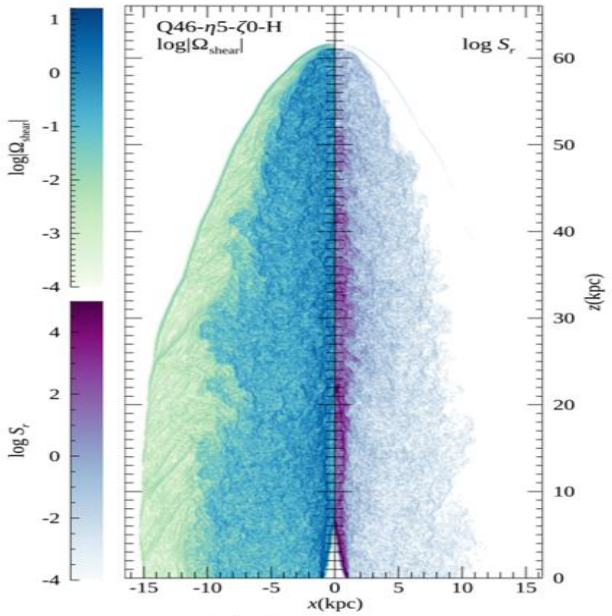
$dN/dE \propto E^{-\sigma} \quad \sigma = (\chi+2)/(\chi-1)$

$\chi = \rho_2/\rho_1$ compression ratio of the shock



Shear Acceleration

Relativistic shear coefficient

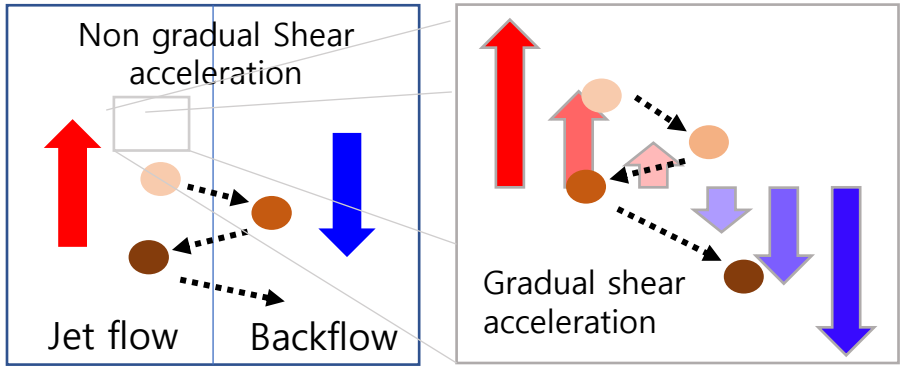


$\mathcal{S}_r = \frac{\Gamma_v^4}{15}(\frac{\partial v_z}{\partial r})^2,$

flat spectrum

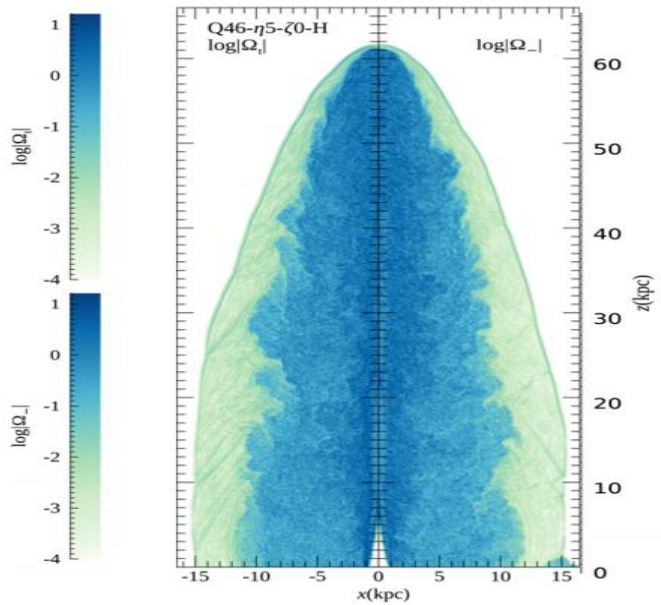
$dN/dE = 4\pi p^2 f(p) \propto E^{-1+\delta}. \ \tau(p) \propto p^{\delta}$

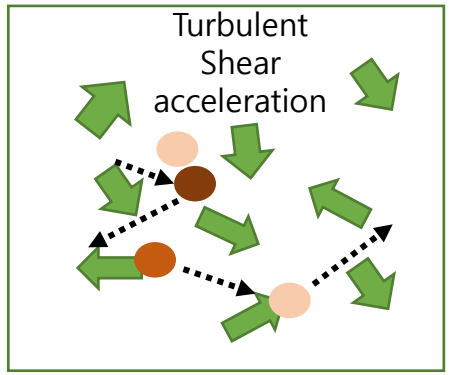
$dN/dE \propto E^0$ for the Bohm diffusion



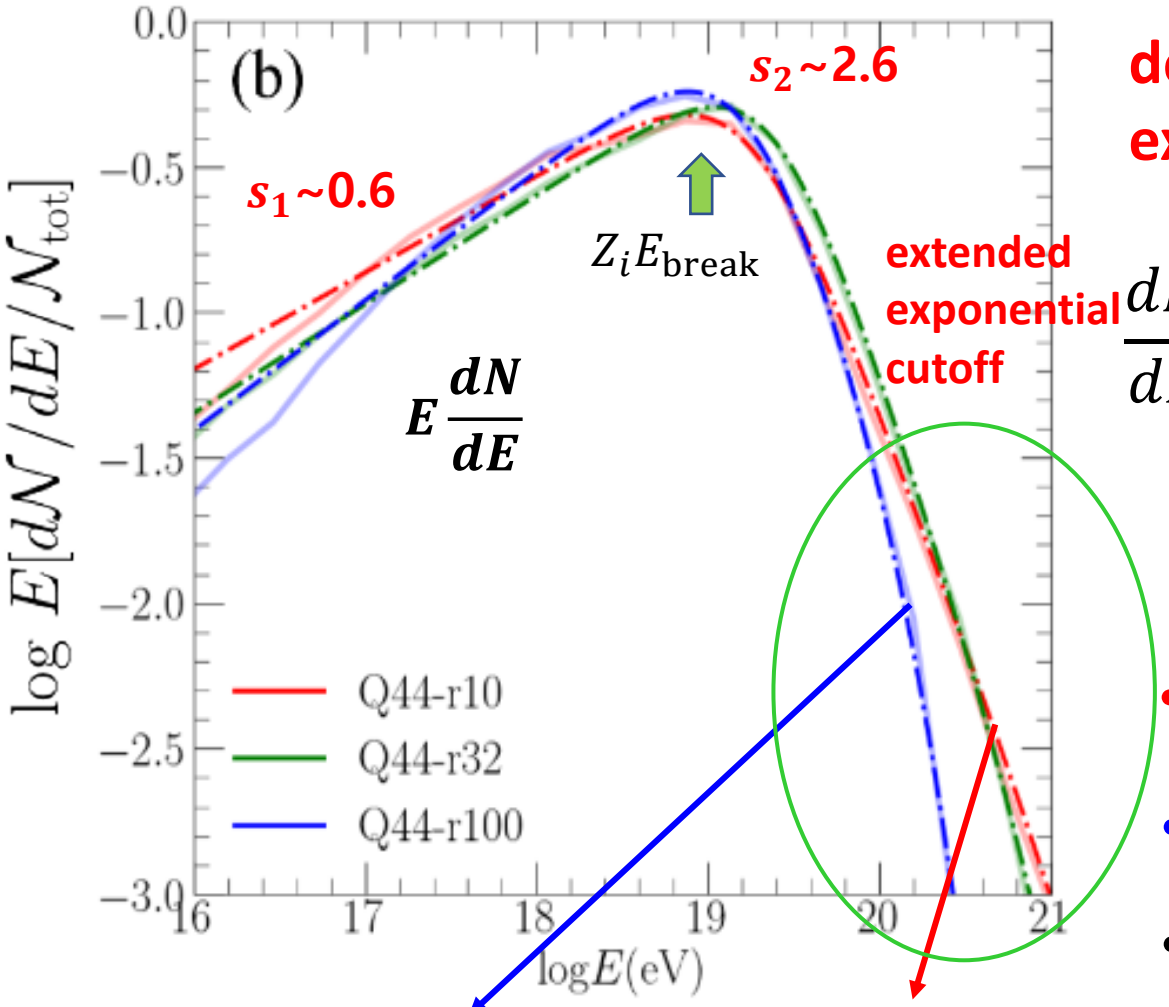
Turbulent Acceleration

Vorticity = turbulence





Energy spectrum of CR particles escaping from the jets



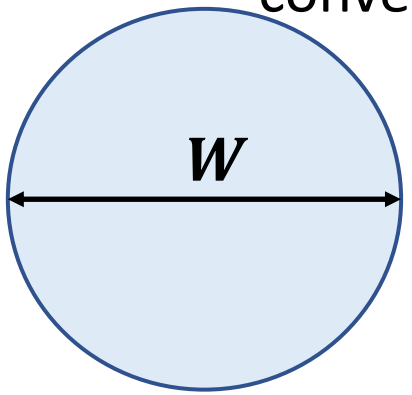
double power law with an extended exponential cutoff Seo et al 2024

$$\frac{dN}{dE} \propto \left(\left(\frac{E}{Z_i E_{\rm break}} \right)^{-s_1} + \left(\frac{E}{Z_i E_{\rm break}} \right)^{-s_2} \right)^{-1} \times \exp\left(- \frac{E}{Z_i E_{\rm break} \langle\Gamma\rangle_{\rm spine}^2} \right)$$

- s_1~0.6 & s_2~2.6
- $Z_iE_{\rm break}$: depends mainly on $\left(\frac{Q_j}{\pi r^2}\right)$
- exponential cutoff at $Z_iE_{\rm break}\langle\Gamma\rangle_{\rm spine}^2$
- $\langle\Gamma\rangle_{\rm spine}$: mean Lorentz factor of jet-spine flow

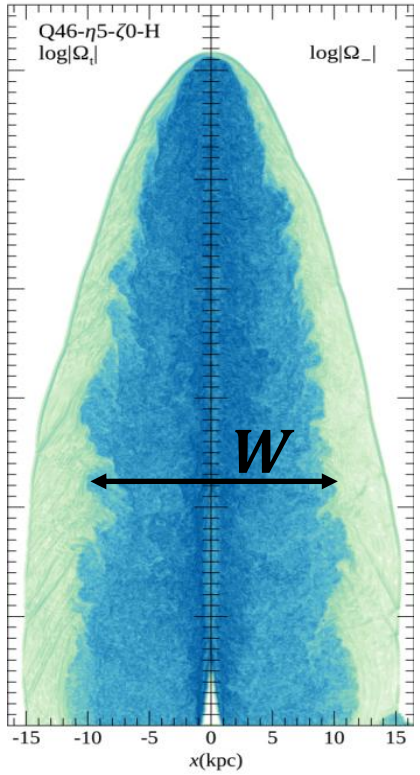
Why double power law with an extended exponential cutoff

conventional single power law with a cutoff



$$\frac{dN}{dE} \propto E^{-2}$$ DSA power law

$$E_{\rm break} \sim E_H \approx 0.9\ EeV \left(\frac{\langle B\rangle}{1\mu G}\right)\left(\frac{0.5W}{1kpc}\right)$$



- $E < Z_i E_{\rm break}$: $dN/dE \propto E^{-0.6}$

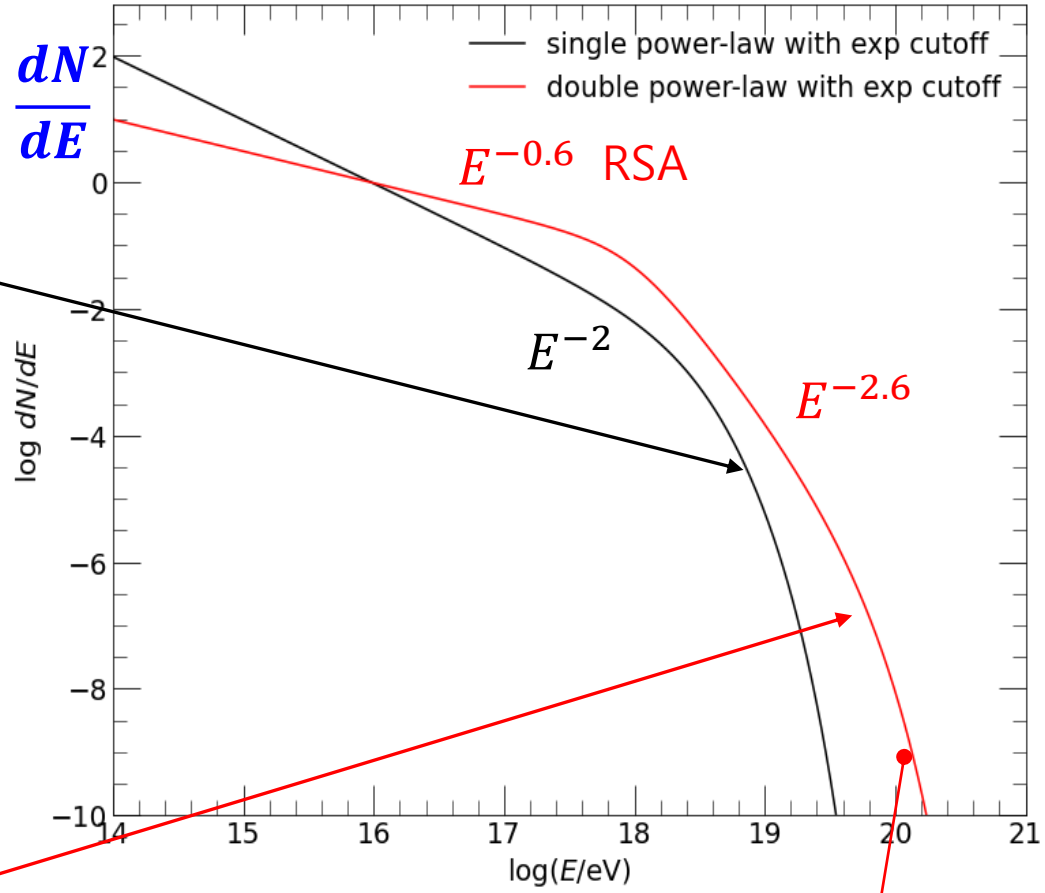
due to relativistic shear acceleration

cf. Ostrowski 1998
Kimura et al 2018

Elongated cylinder (cocoon)
double power-law with a cutoff

- $E > Z_i E_{\rm break}$: $dN/dE \propto E^{-2.6}$

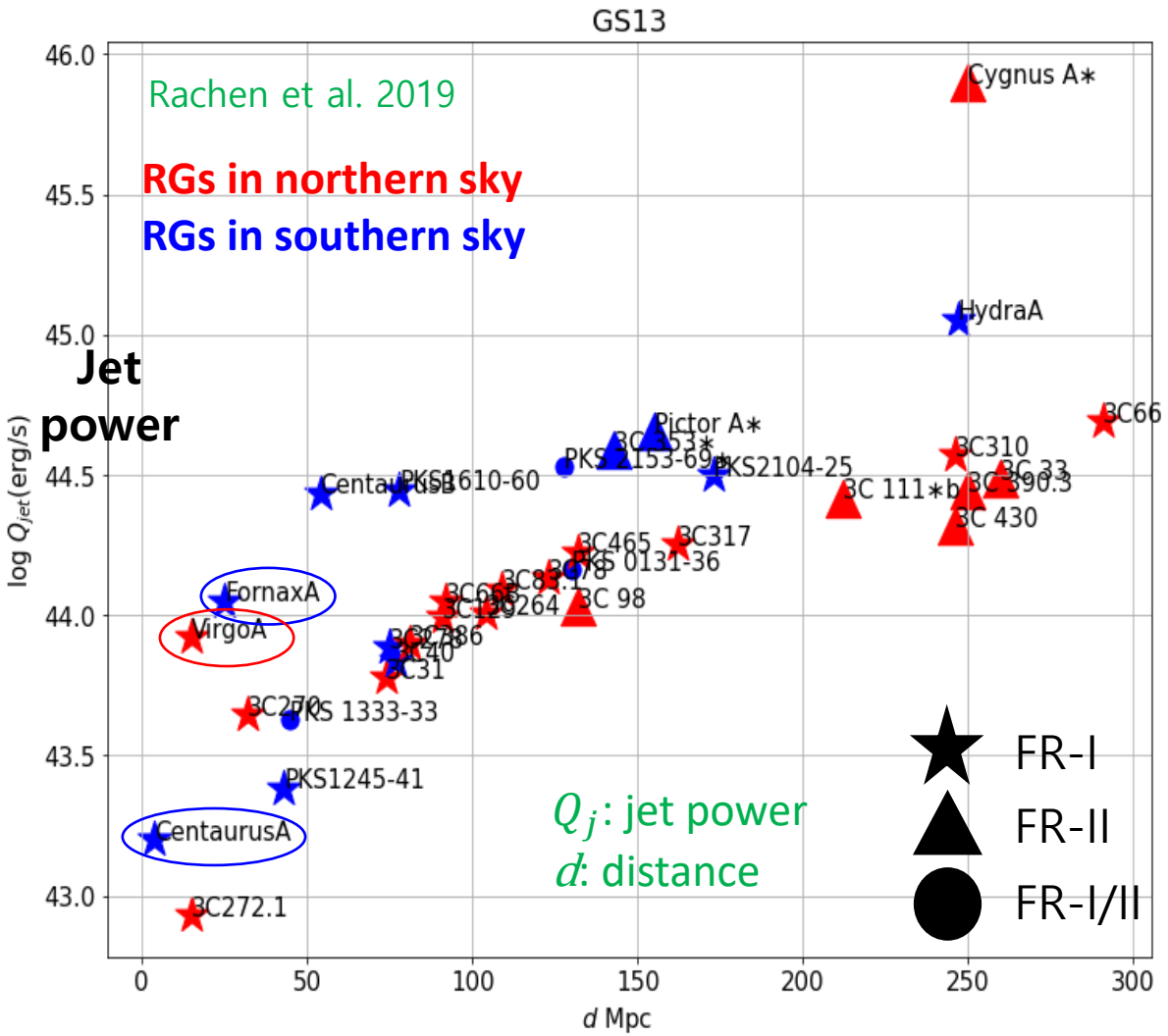
controlled by the confinement within an elongated cocoon



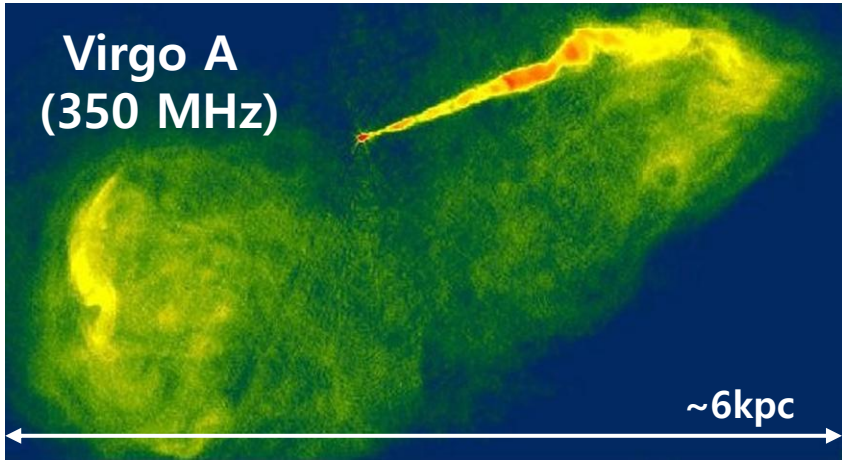
Non-gradual shear acceleration

$$E_{\rm cutoff} \sim Z_i E_{\rm break} \langle\Gamma\rangle^2_{\rm spine}$$

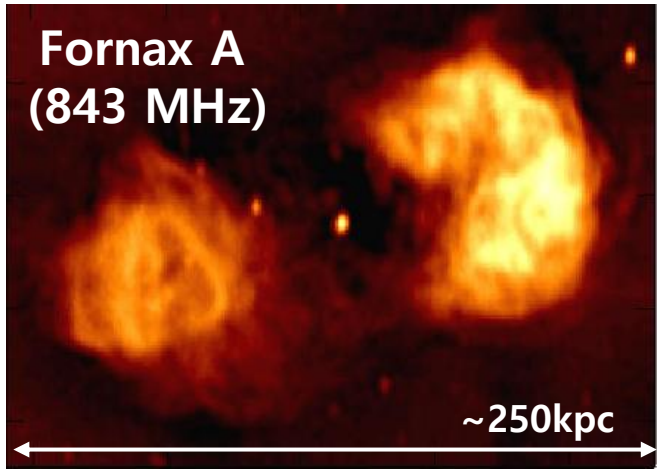
Can the observations of Auger and TA be explained with our UHECR source model?

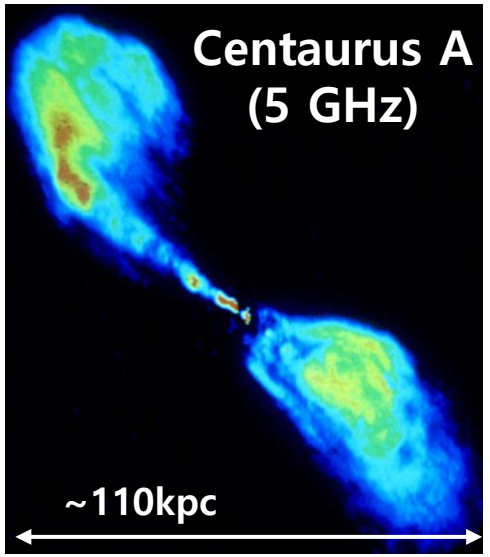


Radio galaxies in local universe



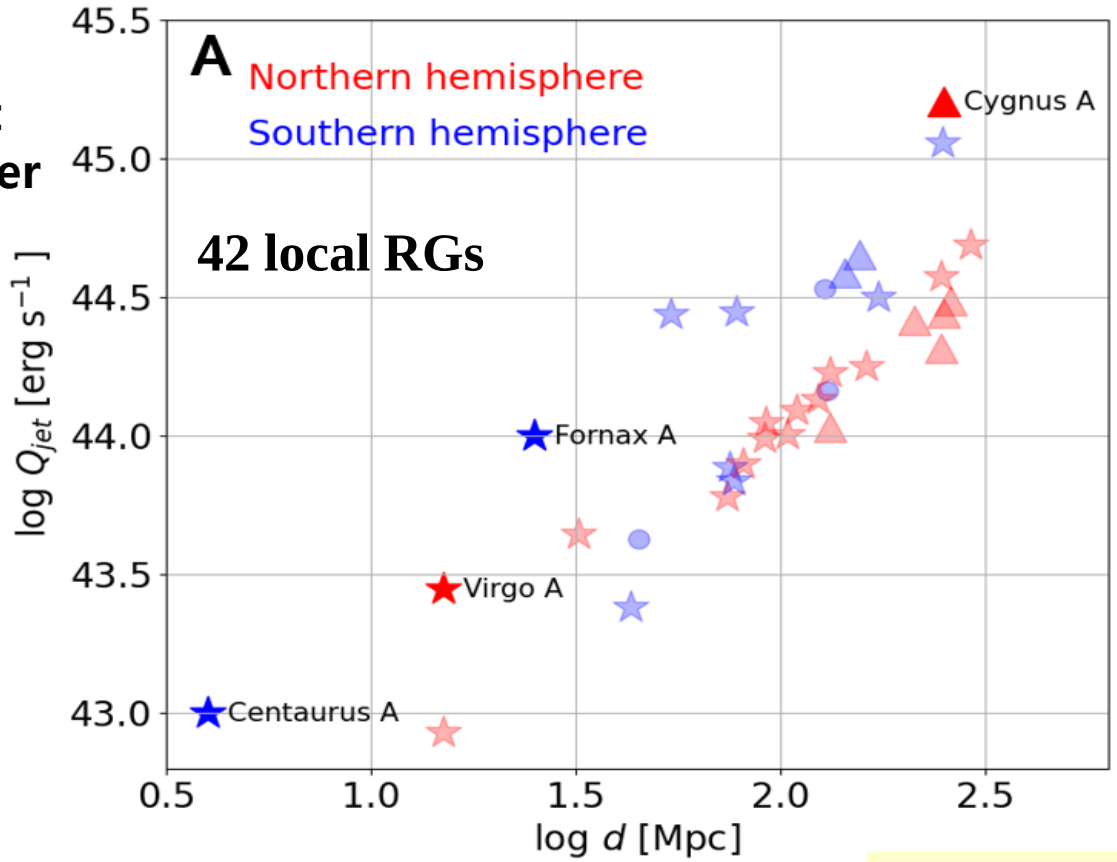
TA: dominant source of northern sky
→ Virgo A

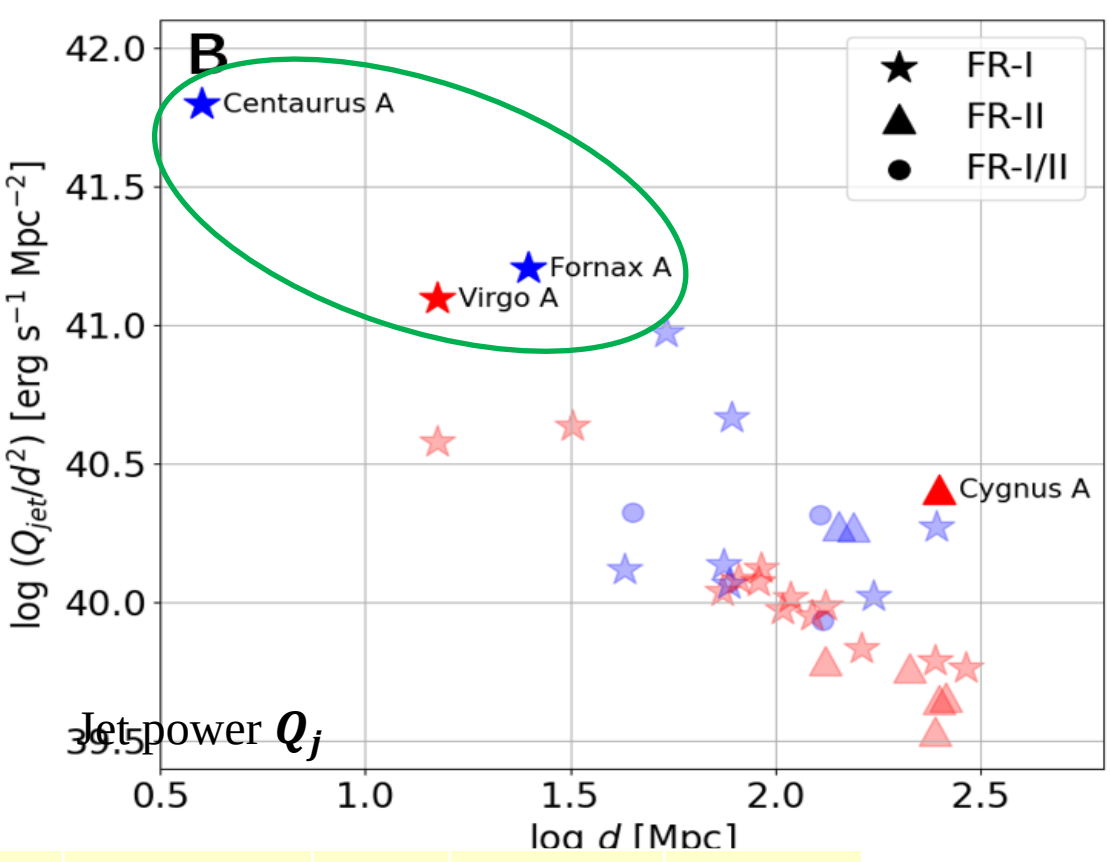




Auger: important sources of southern sky
→ Centaurus A & Fornax A

Jet power





Jet power / D^2

TA: dominant source of northern sky
→ Virgo A

Auger: important sources of southern sky
→ Centaurus A & Fornax A

Name	Q_j(erg/s)	Γ_j	E_b(Eev)	d(Mpc)
Virgo A	2.5E43	7.0	10.5	16
Cygnus A	1.5E45	10.0	51.2	250
Centaurus A	1.0E43	1.2	2.8	4
Fornax A	1.0E44	1.5	6.6	25

UHECRs keep loosing energy & disintegrated during propagation !

Application of our model spectrum to reproduce observations of UHECRs

- **Model Source Spectrum at RGs** Seo et al. 2025

$$\frac{dN}{dEdt} \propto \left(\left(\frac{E}{ZE_b} \right)^{-s_1} + \left(\frac{E}{ZE_b} \right)^{-s_2} \right)^{-1} \exp\left(-\frac{E}{\langle \Gamma_j \rangle^2 ZE_b} \right)$$

E & Z: energy & charge of the particle

$s_1 \approx 0.6$ & $s_2 \approx 2.6$ $\langle \Gamma_j \rangle$: Lorentz factor of the jet

Model for Break energy: $E_b(Q_j) = \xi\varphi \cdot E_H \cdot (Q_j/Q_n)^{\alpha}$

based on our RHD & MC simulation results

$Q_n \approx 3.5 \times 10^{44}$ erg/s, $E_H \approx 4.5 \times 10^{19}$ eV,

$\alpha \approx 1/4$ for FR-I & $\alpha \approx 1/3$ for FR-II,

$\xi\varphi \sim 0.15 - 0.7$ (depending on $\langle \Gamma_j \rangle$)

different $\langle \Gamma_j \rangle$ for different RGs, based on observations

- **Chemical abundance**: 3 x Galactic abundance for hosting elliptical galaxies

Propagation of UHECRs from RGs to Earth

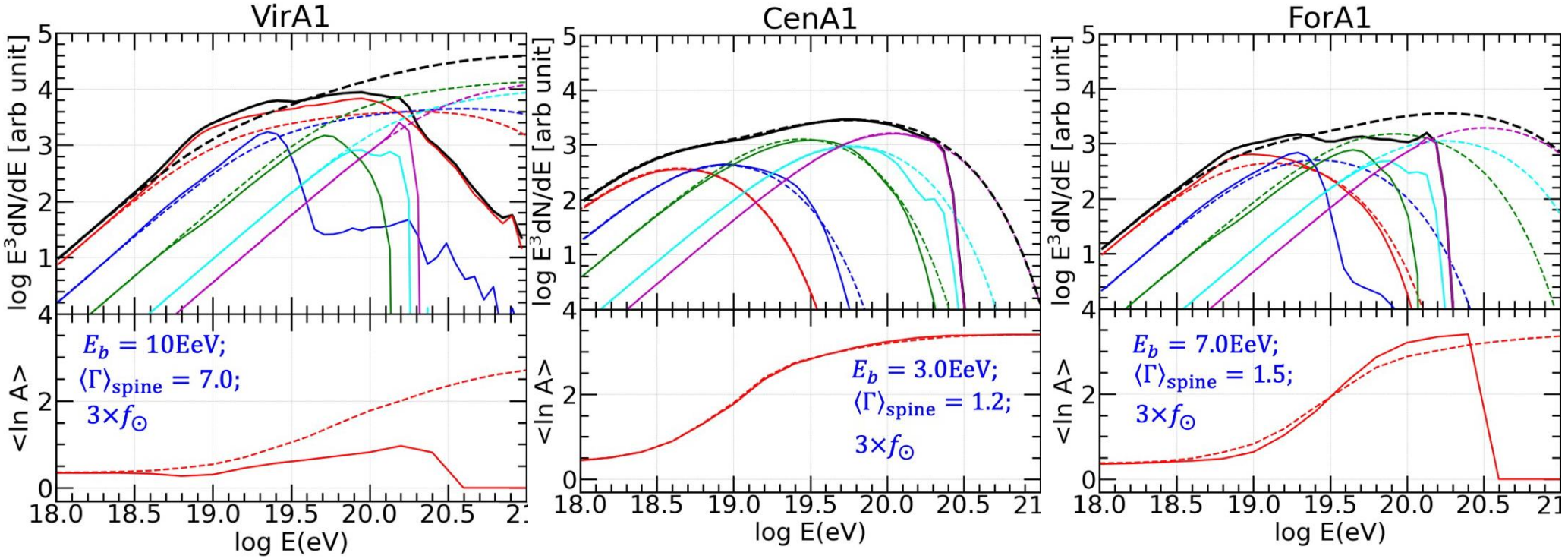
https://crpropa.desy.de/

R. Alves Batista, et al. 2022

In **CRPropa3** simulations, we include the following modules:

- photo-pion Production
- photodisintegration
- electron pair production by CMB and extragalactic background light (Gilmore et al. 2012)
- redshift evolution (adiabatic energy loss)

$$d_{\mathrm{prop}} \sim 1 - 1.5\, d_{RG}$$



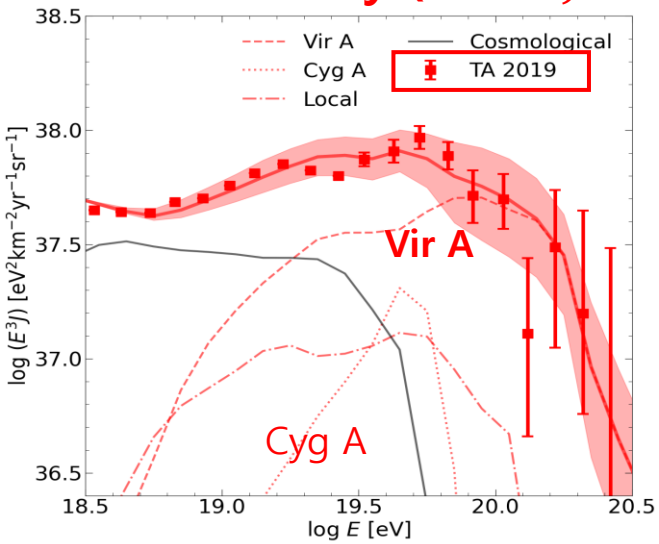
colors: CRs of different mass A

dashed lines: spectrum & composition at source

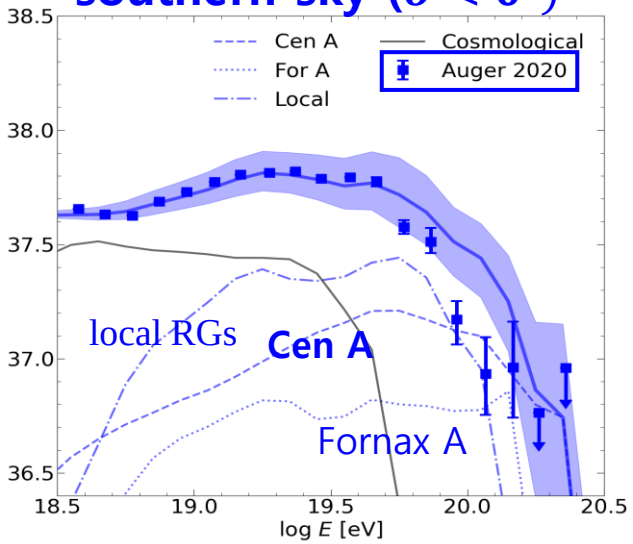
solid lines: spectrum & composition at Earth

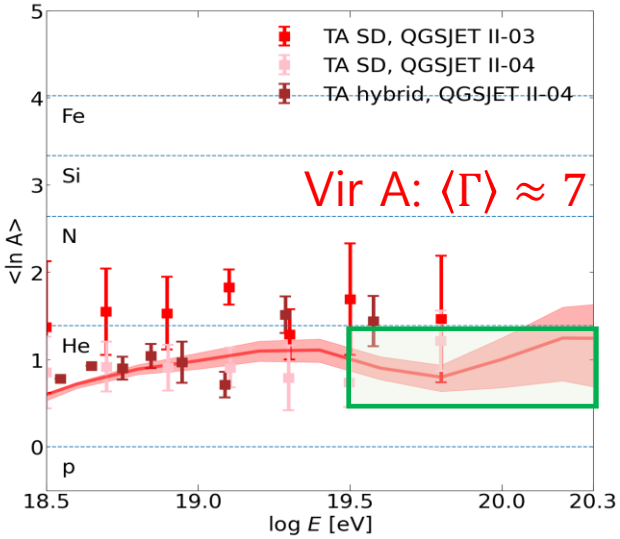
Energy spectrum & mass composition of UHECRs from radio galaxy jets

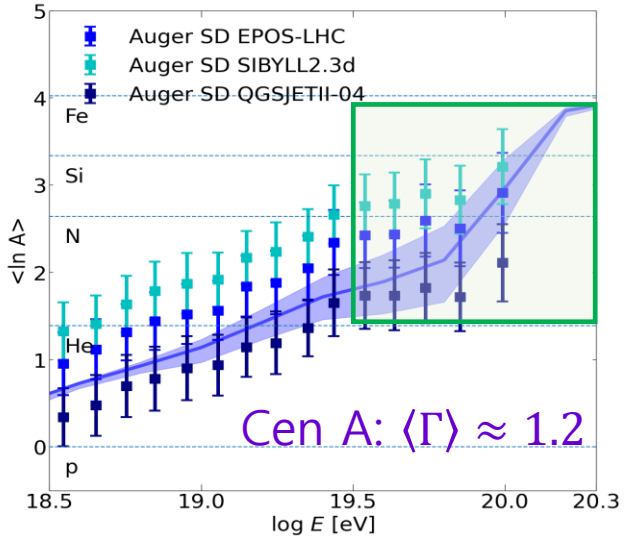
northern sky ($\delta > 0°$)



southern sky ($\delta < 0°$)







Shading represents ±20 % variations of model parameters.

- **Virgo A with $\langle \Gamma \rangle \sim 7$** is the dominant source in the northern hemisphere.
- **Cen A with $\langle \Gamma \rangle \sim 1.2$** and other **local RGs** are dominant sources in the southern hemisphere.
- RGs with larger $\langle \Gamma \rangle$ result in lighter mass composition, i.e., smaller $\langle \ln A \rangle$, of UHECRs with $E > 10^{19}$eV.

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Summary

1. The energy spectrum of UHECRs produced at radio galaxies (RGs) can be modeled as a double power law with an extended exponential cutoff.
2. Our source spectrum model suggests an observed UHECR spectrum that may extend to higher energies and exhibits a lighter mass composition, $\langle \ln A \rangle$, at the highest energies.
3. RGs in the local universe, including Virgo A, Cen A, and Fornax A, could be the primary sources of UHECRs. Virgo A, with its more relativistic jet, can generate a higher flux & a lighter composition at the highest end of the energy spectrum in the northern hemisphere, compared to those in the southern hemisphere.
4. Our model could explain the observed differences in the energy spectrum and mass composition of UHECRs between the northern and southern hemispheres. e.g., TA versus PAO.
5. Anisotropy in the observed directions of UHECRs is another important properties. To explain it, we need the distribution of magnetic fields in the local universe as well as in our galaxy.