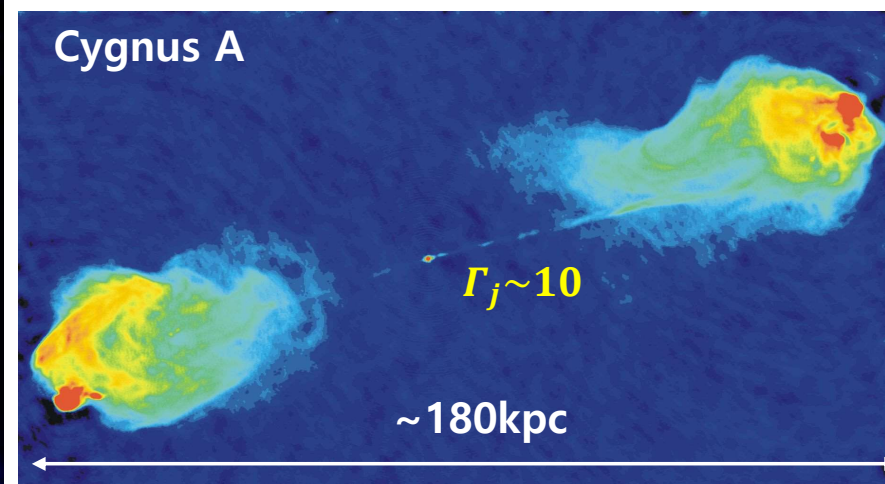
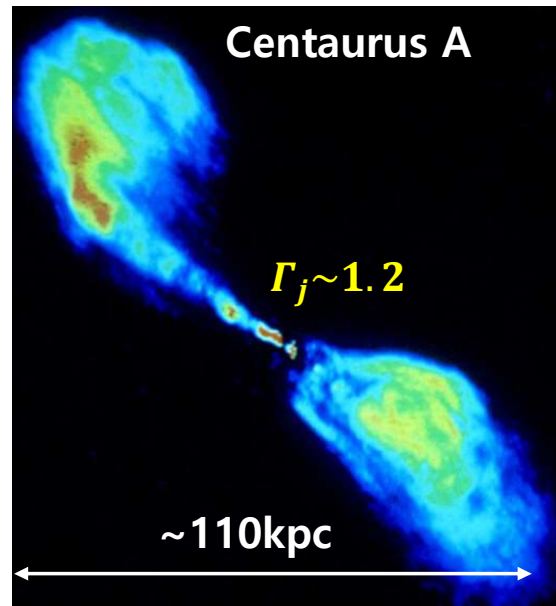
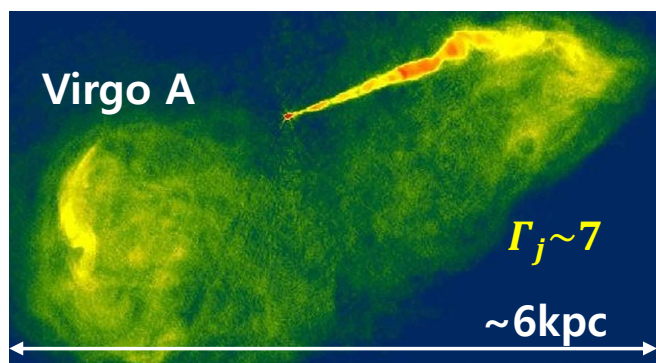


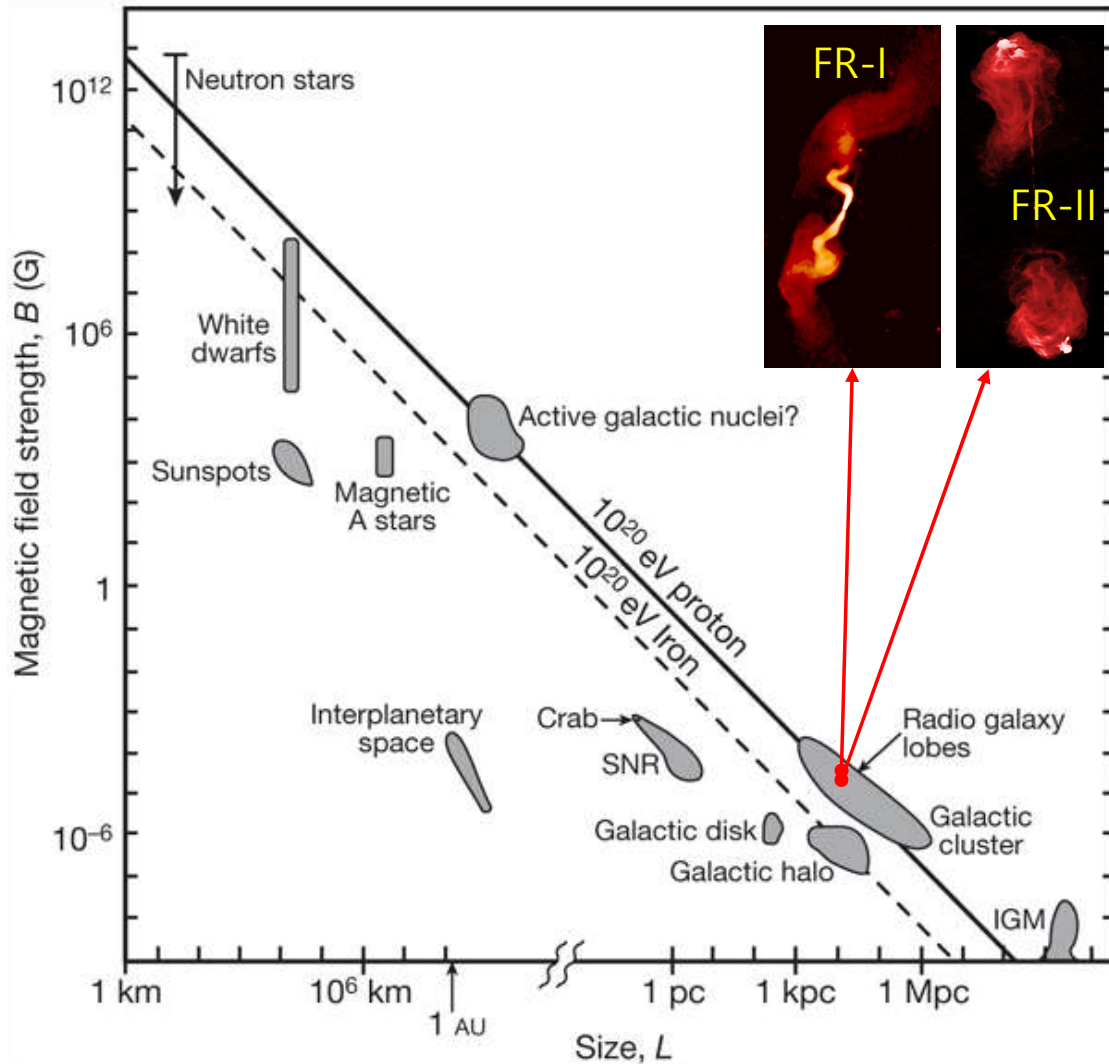
Ultra-High-Energy Cosmic Rays Accelerated in Relativistic Jets from Radio Galaxies

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Dongsu Ryu (UNIST, Ulsan, Rep. of Korea), and Jeongbhin Seo (LANL, USA)



Jets & Lobes of Giant Radio galaxies: potential acceleration sites of UHECRs



Hillas criteria: confinement condition

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

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

$$E_{Z_i, \text{Hillas}} = Z_i E_{\text{Hillas}} \quad \text{for heavy ions}$$

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

Relativistic jets on 10-100 kpc scales:

$$\text{FR-I: } \Gamma_j \sim 1 - 10, \quad Q_j \leq 10^{45} \text{ erg/s}$$

$$\text{FR-II: } \Gamma_j \geq 10, \quad Q_j \geq 10^{45} \text{ erg/s}$$

Most promising candidate for UHECR sources

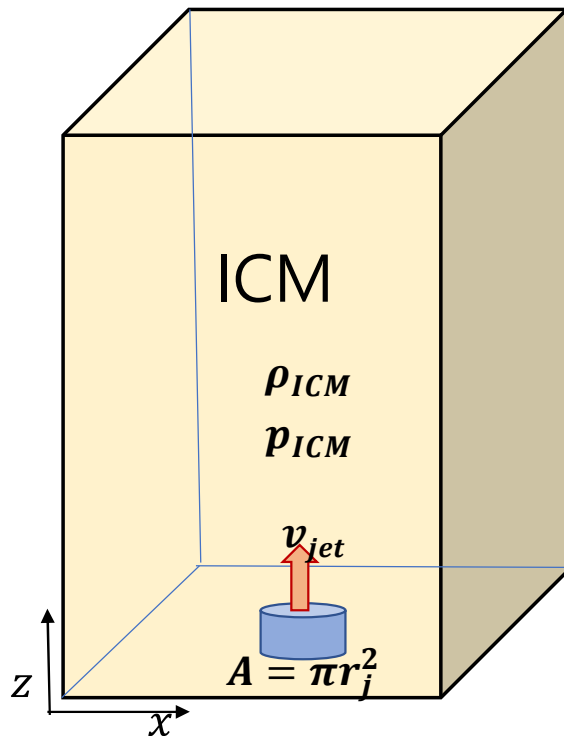
(Ostrowski 1998, Caprioli 2015, Kimura et al. 2018; Rieger 2019; Matthews et al. 2019; Rachen et al 2019, Hardcastle & Croston 2020; + many previous studies)

Quantitative numerical estimation of UHECR spectrum from RG jets

3D Relativistic hydrodynamic (RHD) simulations for relativistic jets with $\Gamma_j \sim 1 - 70$ Seo et al. 2021

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

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

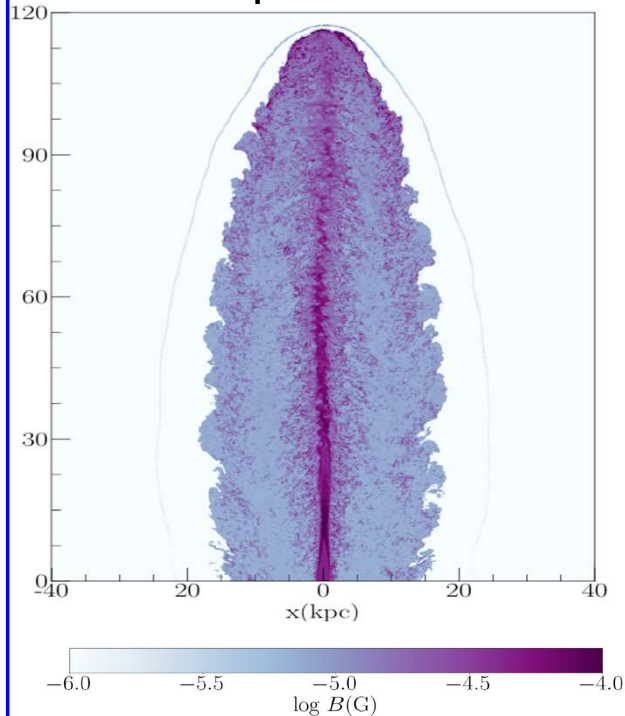
$$r_j = 10 \text{ pc} - 1 \text{ kpc}, \quad \Gamma_j \sim 1 - 70, \quad Q_j \sim 10^{42} - 10^{47} \text{ erg/s}$$

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

Higher-power jets are more relativistic.

Monte Carlo simulations for CR transport

- Prescription for B fields



Jet spine: $B \sim 100\mu G$

Backflow: $B \sim 10\mu G$

ICM: $B \sim 1\mu G$

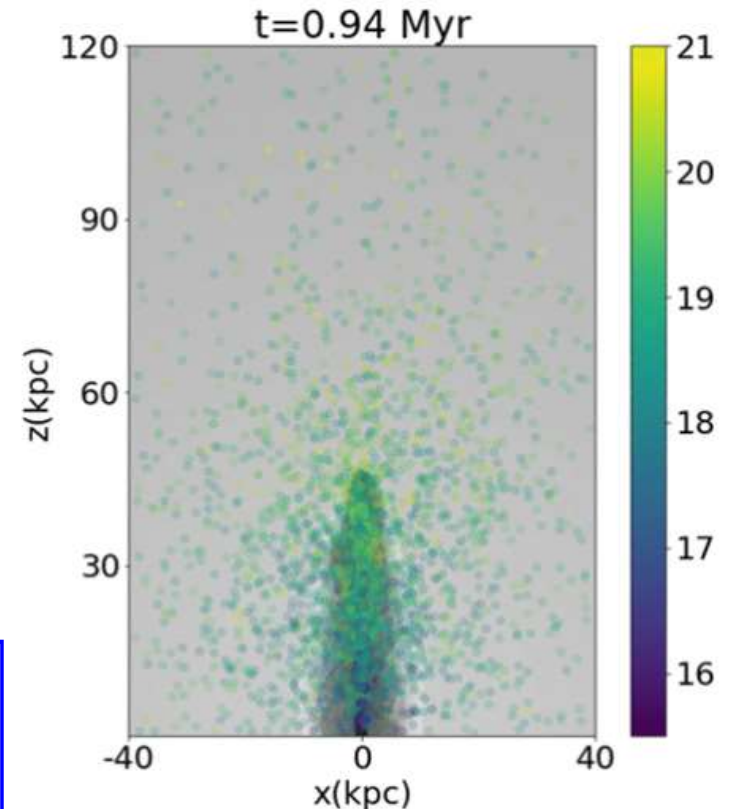
- **MHD turbulence**, $\frac{\delta B}{B}$,
on subgrid scales
 $\lambda_{\text{mfp}} \propto E^\delta$
 $\delta = 1$ for Bohm
 $\delta = 1/3$ for Kolmogorov

- **Galactic CR seeds**

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

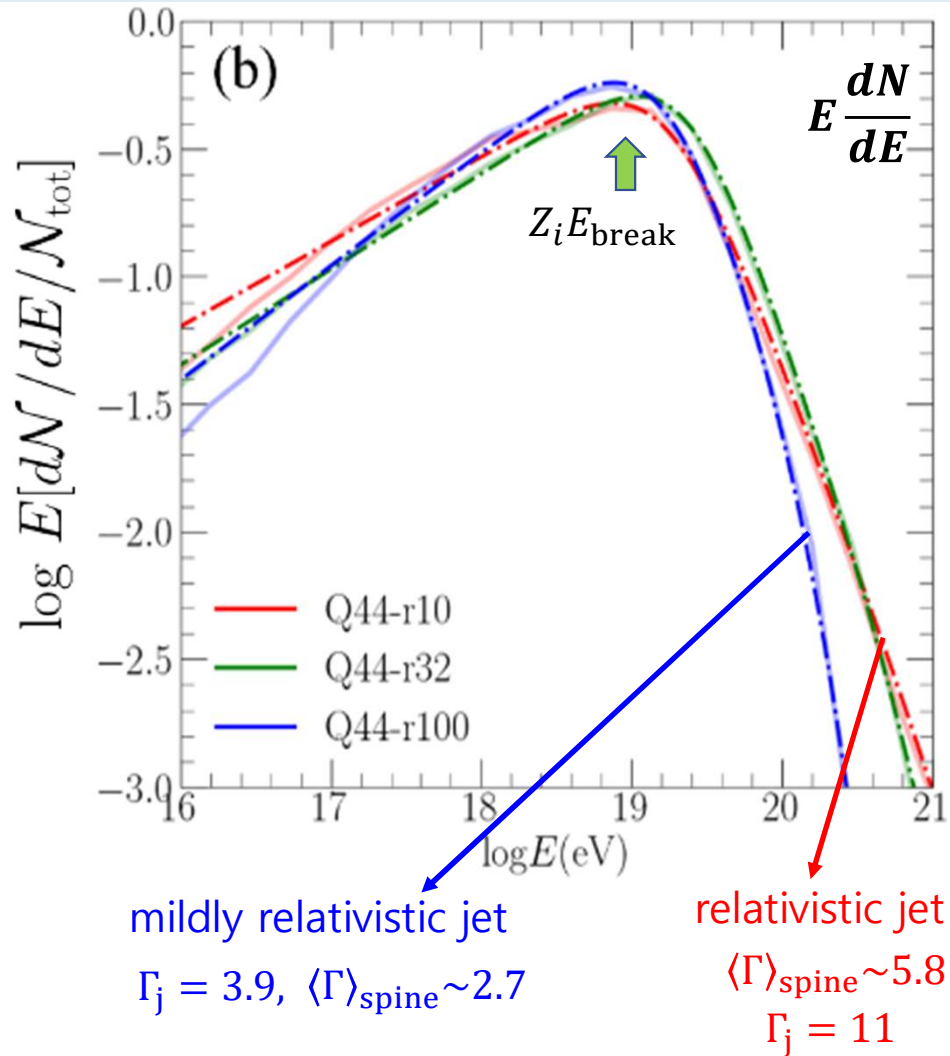
with $E = 10^{13} - 10^{15}$ eV

injected from the host galaxy
through the jet nozzle



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

Energy spectrum of CR particles escaping from the jets

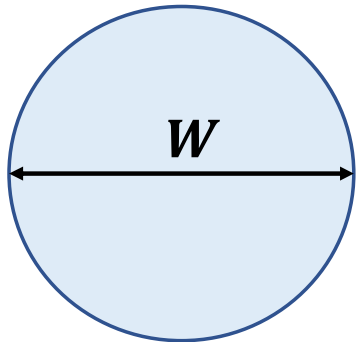


double power law with an extended exponential cutoff

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

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

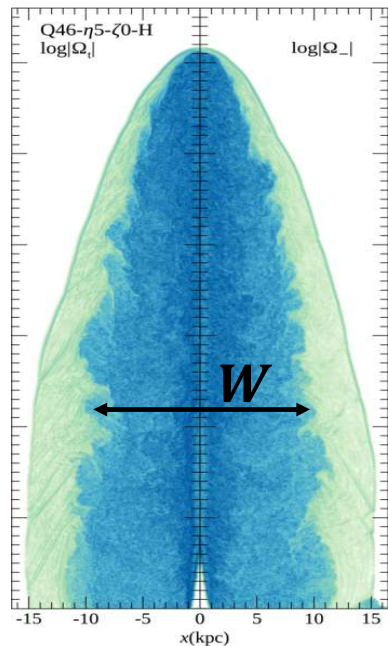
Why double power law?



conventional single power law
with a cutoff at E_H

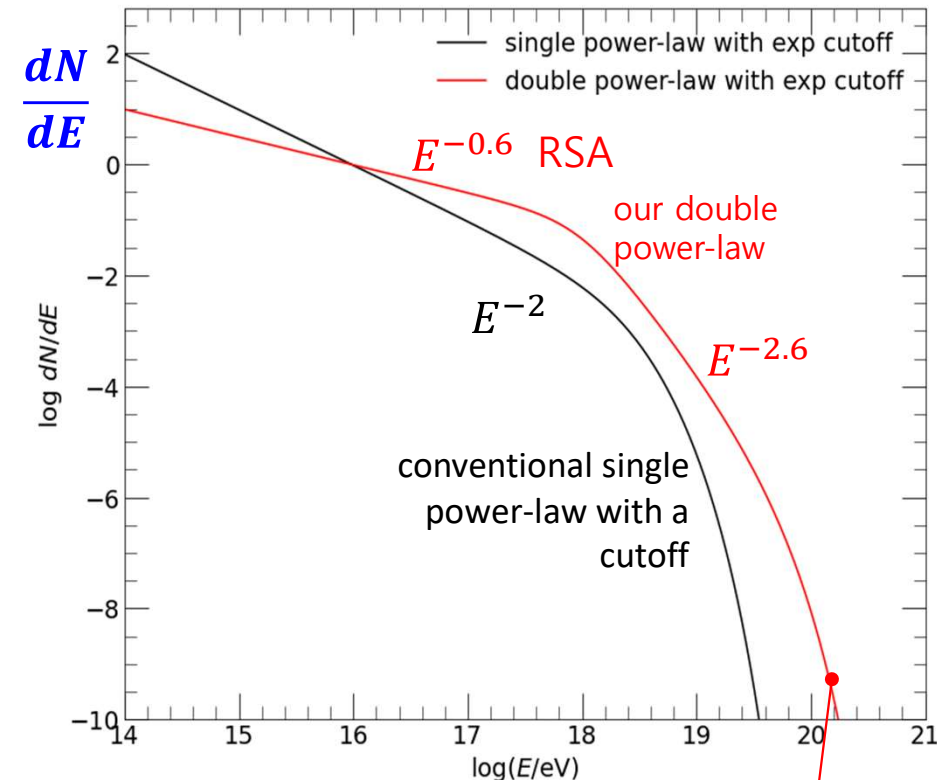
$$\frac{dN}{dE} \propto E^{-2} \quad \text{DSA power law}$$

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



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

- $E < Z_i E_{\text{break}} : dN/dE \propto E^{-0.6}$
due to **relativistic shear acceleration**
cf. Ostrowski 1998
Kimura et al 2018



- $E > Z_i E_{\text{break}} : dN/dE \propto E^{-2.6}$
**controlled by the confinement
within an elongated cocoon**

$$E_{\text{cutoff}} \sim Z_i E_{\text{break}} \langle \Gamma \rangle_{\text{spine}}^2$$

Application of our model spectrum to reproduce observations of UHECRs

- **Model Source Spectrum at RGs**

Seo et al. in prep

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

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

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

$$\alpha \approx 1/4 \text{ for FR-I} \quad \& \quad \alpha \approx 1/3 \text{ for FR-II},$$

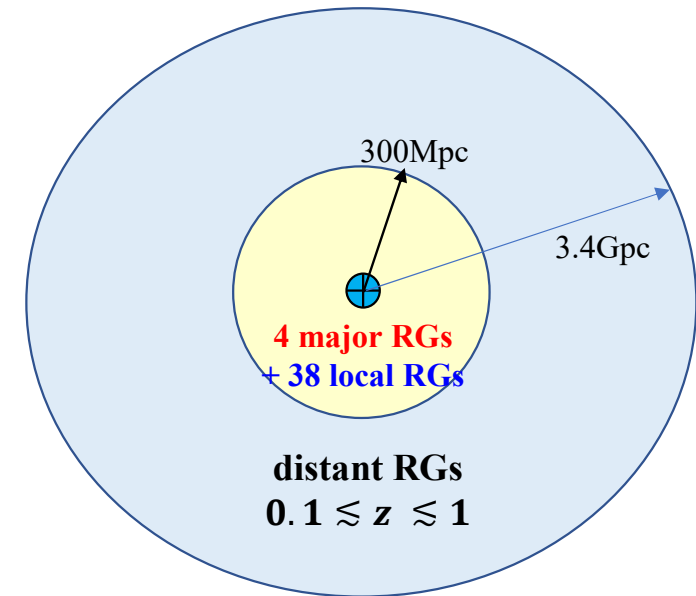
$$\xi\varphi \sim 0.15 - 0.7 \text{ (depending on } \langle \Gamma_j \rangle \text{)}$$

$$\langle \Gamma_j \rangle \approx 2 \text{ for FR-I} \quad \& \quad \langle \Gamma_j \rangle \approx 10 \text{ for FR-II},$$

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

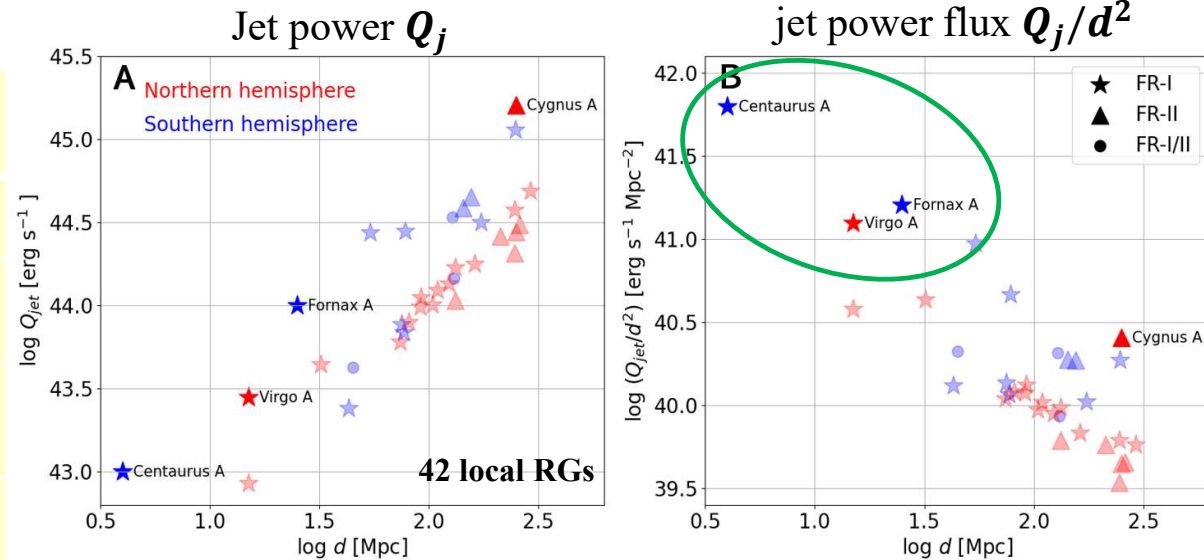
Source Modeling: 3 components

- 4 major RGs:** to be included individually
northern sky source: **Virgo A & Cygnus A**
southern sky source: **Centaurus A & Fornax A**
- 38 Local RGs** ($d < 300$ Mpc) in **Rachen & Eichmann 2019**
- cosmological sources:** $0.1 \lesssim z \lesssim 1$ from LoTSS survey
(Mingo et al. 2018, Hardcastel et al. 2019)



Jet Parameters for major RGs

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



Rachen & Eichmann 2019

- **Modeling the contribution from radio galaxies (RGs)**

The total energy of escaped CR particles is proportional to the jet power, which in turn scales with the radio luminosity of RGs.

$$L_{\text{CR}} \propto Q_j \propto L_{151}^\alpha$$

$$Q_{\text{FRI}} = 5 \times 10^{44} \left(\frac{L_{151}}{10^{25} \text{W Hz}^{-1} \text{sr}^{-1}} \right)^{0.64}$$

$$Q_{\text{FRII}} = 1.5 \times 10^{44} \left(\frac{L_{151}}{10^{25} \text{W Hz}^{-1} \text{sr}^{-1}} \right)^{0.67}$$

(Godfrey & Shabala, 2013)

- **Modeling for the Lorentz factor** for cosmological RG sources ($0.1 \lesssim z \lesssim 1$)

$$\Gamma_c(Q_j, q) = \Gamma_{\text{min}}(Q_j/Q_{\text{min}})^q \quad Q_{\text{min}} = 10^{42} \text{ erg/s} \quad q_1 = 1/5 \text{ for FR-I; } q_2 = 1/3 \text{ for FR-II}$$

Propagation of UHECRs from RGs to Earth

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

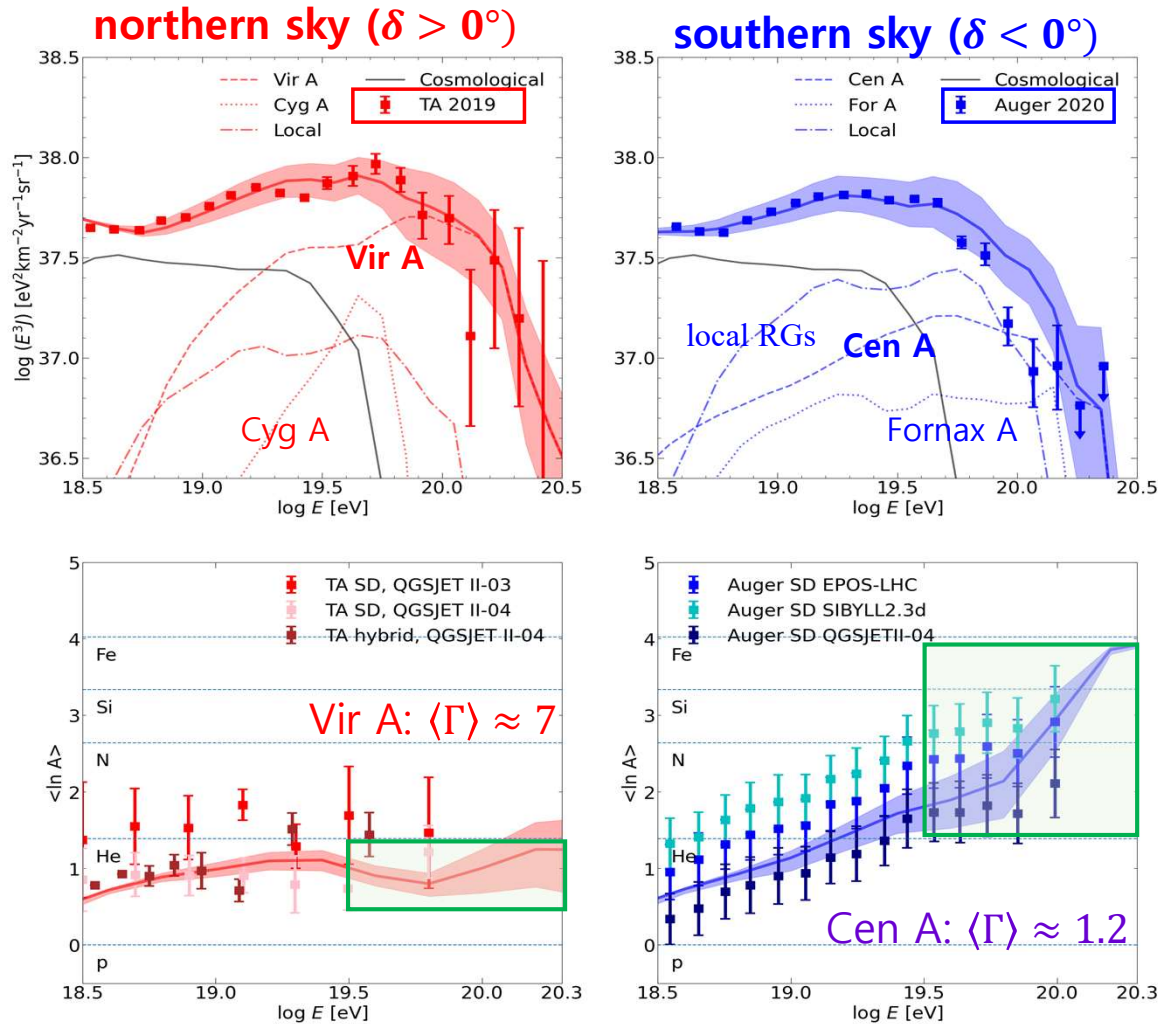
- photo-pion Production
- photodisintegration
- electron pair production by CMB and extragalactic background light (Gilmore et al. 2012)
- redshift evolution (adiabatic energy loss)



$$d_{\text{prop}} \sim 1 - 1.5 d_{\text{RG}}$$

R. Alves Batista, et al. JCAP (2022) no. 09, 035

Energy spectrum & mass composition of UHECRs from radio galaxy jets



- **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.

Source Modeling: 3 components

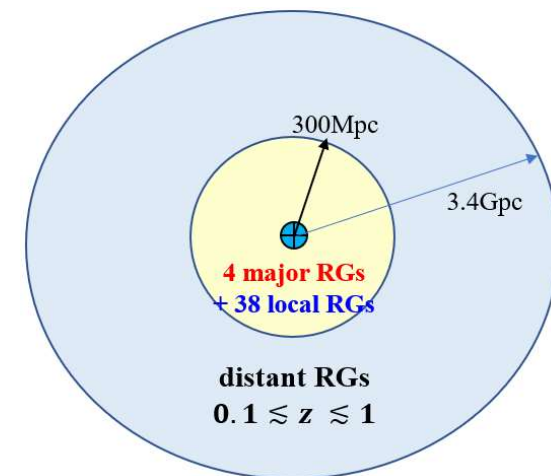
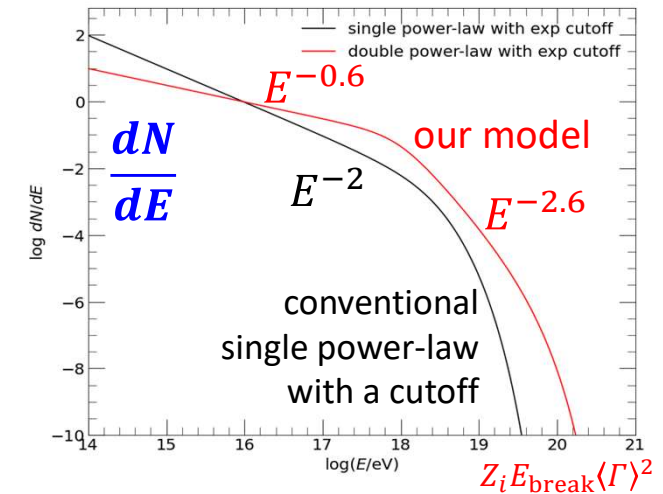
1. **4 major RGs:**
Vir A & Cyg A ($\delta > 0^\circ$)
Cen A & Fornax A ($\delta < 0^\circ$)
2. **38 Local RGs** ($d < 300$ Mpc):
3. **cosmological sources:** $0.1 \lesssim z \lesssim 1$

Shading represents ± 20 % variations of model parameters.

Seo et al. in prep

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 between the northern and southern hemispheres. **e.g., TA versus PAO**



Catalog of Radio Galaxies as UHECR Sources

Jörg P. Rachen

Radio name	RA	DEC	P_1/Jy	d/Mpc	type	Radio name	RA	DEC	P_1/Jy	d/Mpc	type
3C 31	16.85	32.41	7	74	FR-I	3C 33	17.22	13.34	16	260	FR-II
3C 40	21.50	-1.34	8	77	FR-I	PKS 0131-36	23.49	-36.49	9	130	FR-I/II
3C 66B	35.79	42.99	12	92	FR-I	3C 66	35.61	43.01	12	291	FR-I
PKS 0238-084	40.27	-8.26	0.5	21	BLU	3C 78	47.11	4.11	9	123	FR-I
3C 83.1	49.57	41.85	10	109	FR-I	Perseus A ^{*b}	49.95	41.51	7	76	BLU
Fornax A [*]	50.67	-37.21	163	25	FR-I	3C 98	59.73	10.43	13	132	FR-II
3C 111 ^{*b}	64.59	38.03	19	212	FR-II/SSRQ	3C 120 ^{*b}	68.30	5.35	3	143	BLU
3C 129	72.29	45.01	10	91	FR-I	3C 134	76.18	38.10	13	— [†]	FR-II
Pictor A [*]	79.96	-45.78	80	155	FR-II	PKS 0521-36 ^{*b}	80.74	-36.46	21	249	SSRQ
Hydra A [*]	139.52	-12.10	62	247	FR-I	3C 264	176.27	19.61	8	104	FR-I
3C 270 [*]	184.85	5.82	23	32	FR-I	3C 272.1	186.27	12.89	8	15	FR-I
Virgo A [*]	187.71	12.39	283	15	FR-I	PKS 1245-41	192.21	-41.31	5	43	FR-I
3C 278	193.65	-12.56	10	75	FR-I	Centaurus A [*]	201.37	-43.02	300	4	FR-I
PKS 1333-33	204.16	-33.97	11	45	FR-I/II	Centaurus B [*]	206.70	-60.41	140	54	FR-I
3C 310	226.24	26.02	11	246	FR-I	3C 317	229.19	7.02	8	162	FR-I
PKS 1610-60 [*]	243.77	-60.91	70	78	FR-I	4C +39.49	253.47	39.76	0.5	155	BLO
3C 353 [*]	260.11	-0.97	75	143	FR-II	3C 371	271.71	69.82	1	228	BLU
PKS 1814-63 ^{*b}	274.90	-63.76	18	290	BLU	3C 386	279.61	17.20	9	81	FR-I
3C 390.3	280.54	79.77	15	250	FR-II	Cygnus A [*]	299.87	40.73	2225	250	FR-II
PKS 2104-25	316.86	-25.42	17	173	FR-I	3C 430	319.58	60.80	10	246	FR-II
PKS 2153-69 [*]	329.27	-69.69	35	128	FR-I/II	3C 465	354.62	27.03	11	132	FR-I