Ultrahigh-Energy Cosmic-Ray Nuclei from Radio Galaxies:

Recycling Galactic Cosmic Rays through Shear Acceleration

ref) SSK, K. Murase, B.T. Zhang (arXiv:1705.05027)

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Collaborators

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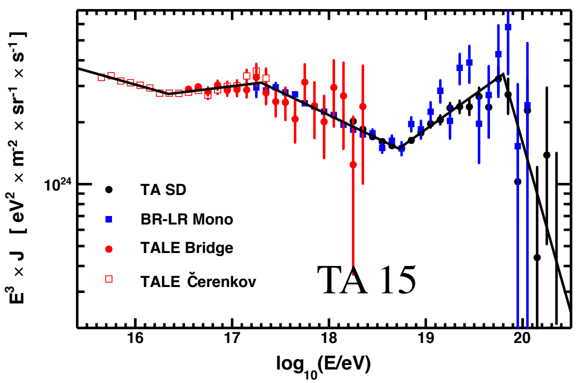
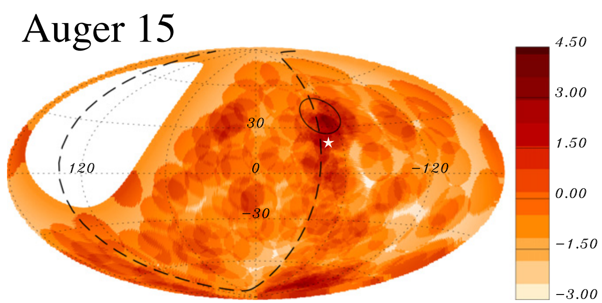
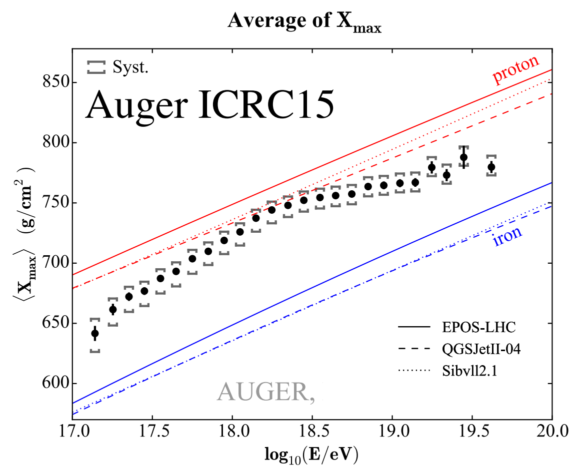
Experimental Results

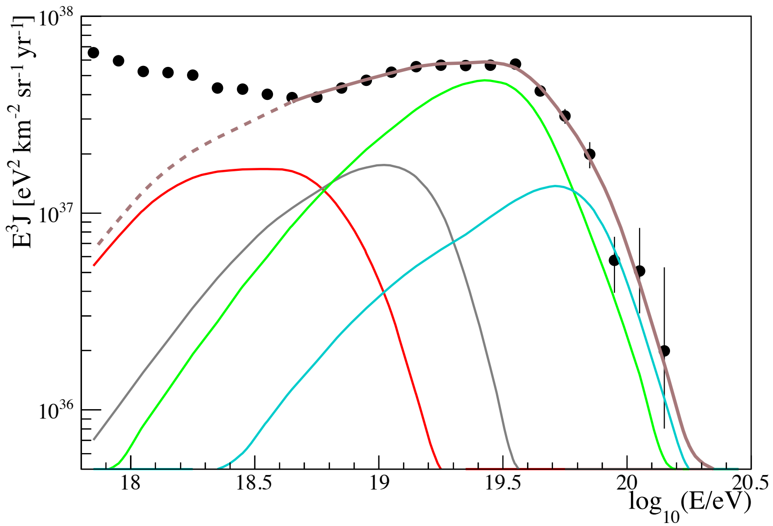
- Energy Flux —> Luminosity density ~ 10^{44} erg Mpc^{-3} yr^{-1}
- Spectral shape —> Cutoff energy E_{max} ~ 50 EeV
- Isotropy —> **source density $N_s \gtrsim 10^{-6}$ Mpc^{-3} for Fe**
  $N_s \gtrsim 10^{-4}$ Mpc^{-3} for p
- Shower depth —> **Composition is heavy for higher energy**
  (TA data is compatible with Auger data) Auger & TA UHECR 2014



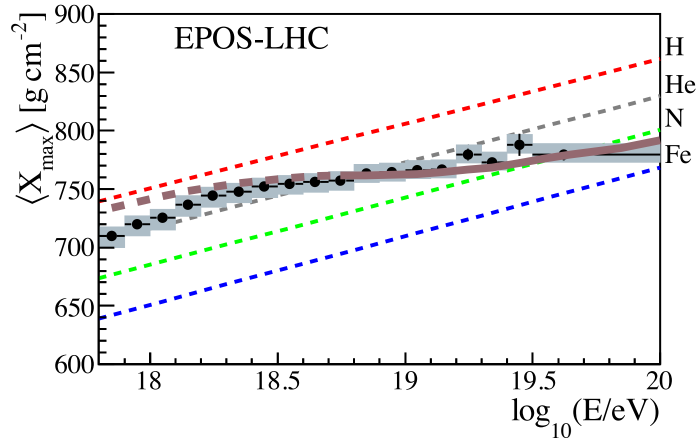


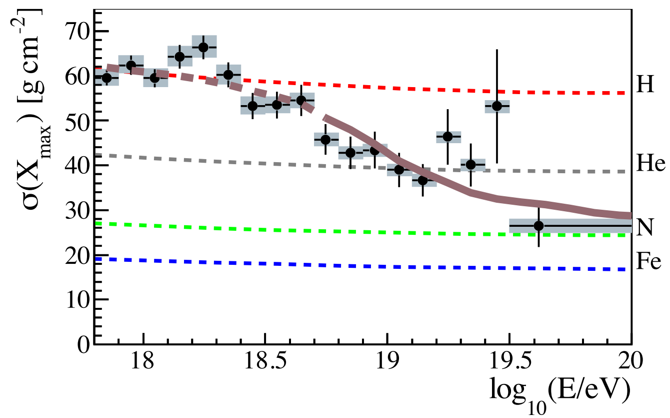


Fitting Requirements



Aloisio+14, Taylor+15, Auger 17





Assuming $E_{max,i} = Z_i \, E_{max,p}$

- **$E_{max,p} \sim$ 1-10 EeV**
- **heavier composition than the solar abundance**
- **Hard source spectrum: $s \lesssim 1$**

Source Candidates

- AGN jets

  Takahara 90; Murase+12, Caprioli 15; Araudo+16

- TDEs

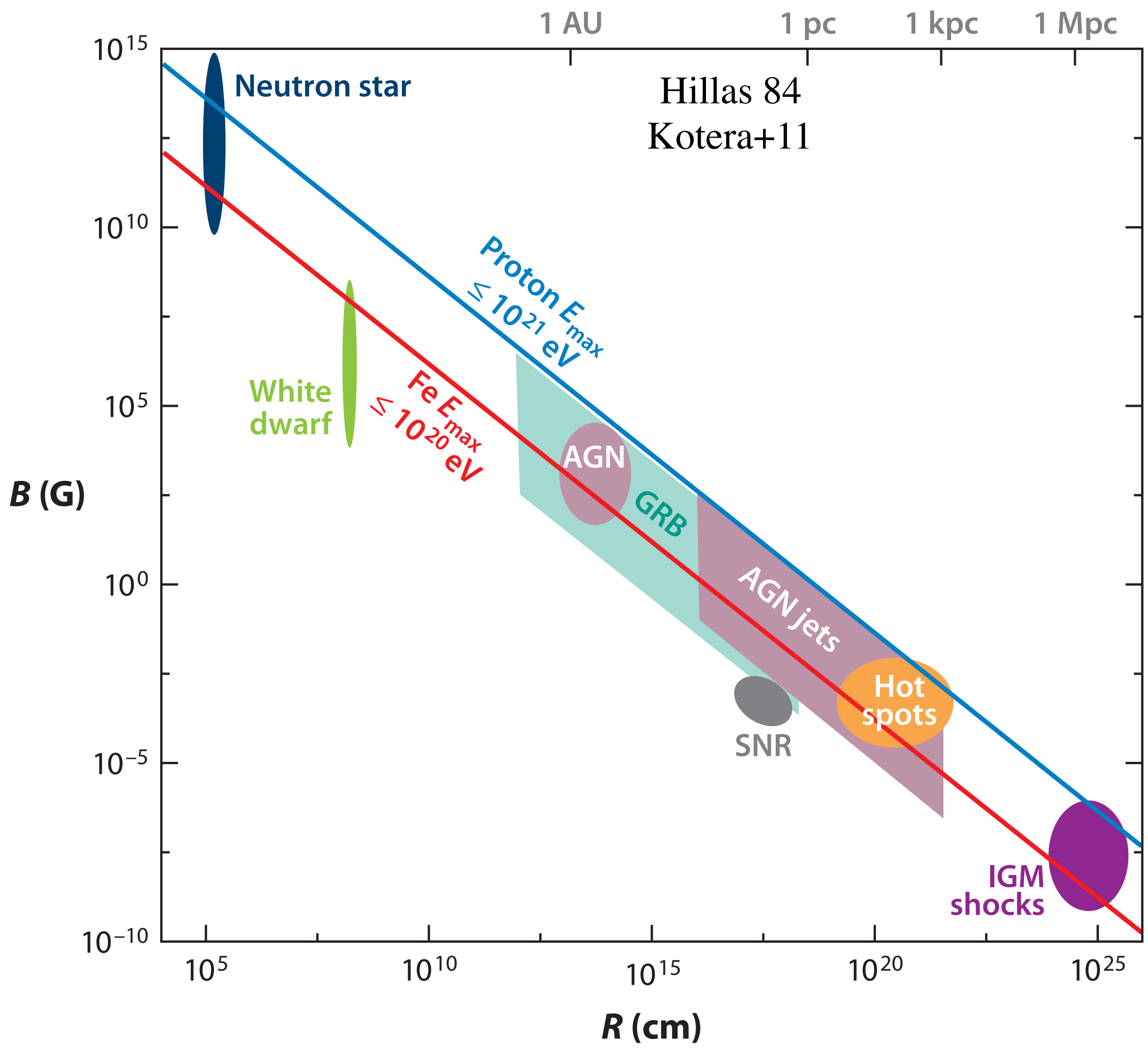
  Zhang+17

- GRBs

  Waxman 95; Murase+08 Wang+08; Globus+15

- newborn Pulsars

  Blasi + 00; Fang+12



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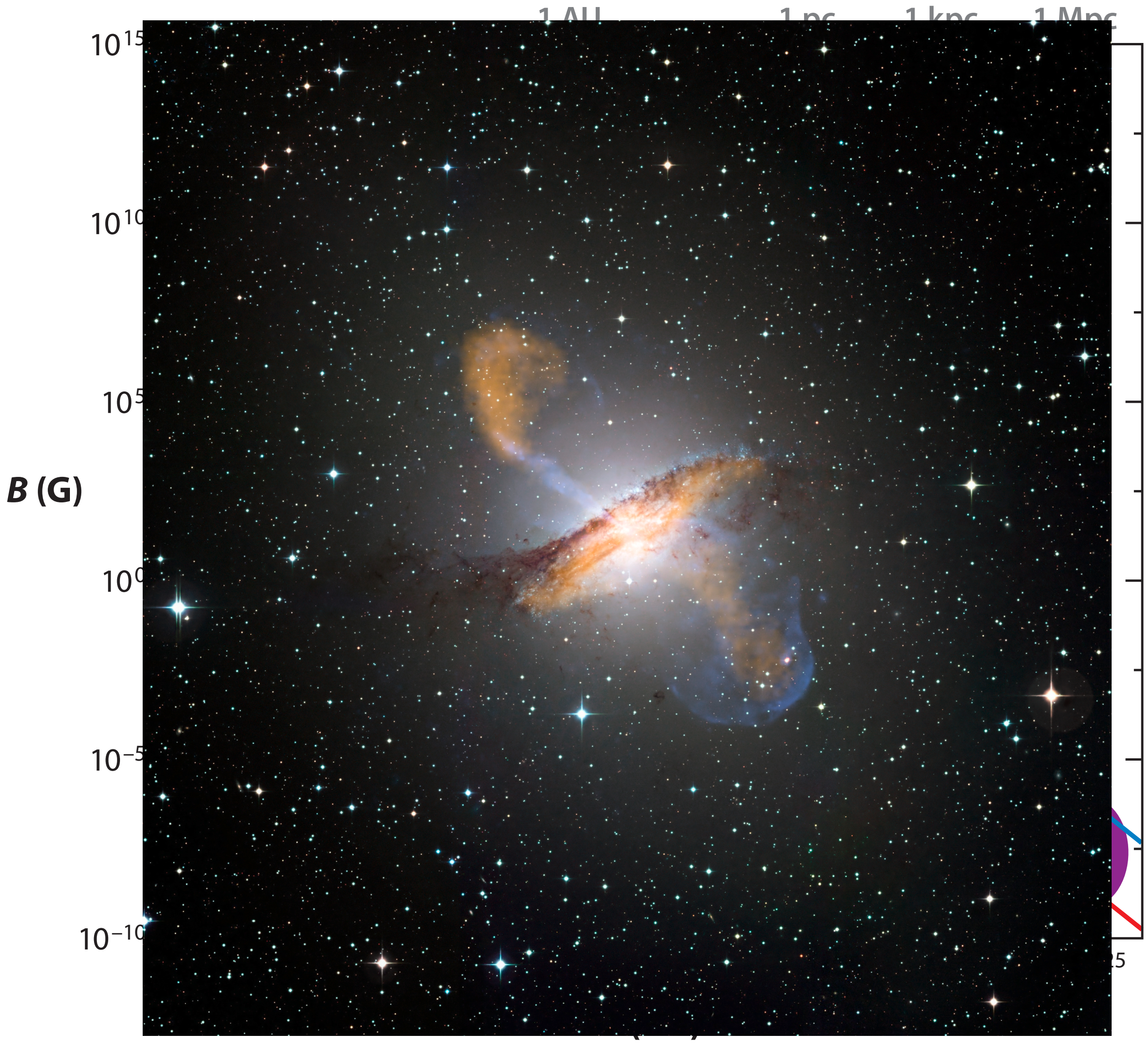

Requirements

- High source density Takami 12, Fang 16
- Harder spectrum than canonical shock accel. Aloisio+14, Taylor+15, Auger 16
- Heavy nuclei enhancement Aloisio+14, Taylor+15, Auger 16

Requirements & Ideas

- **High source density** Takami 12, Fang 16
  —> **FR-I radio galaxies with Fe** Padovani+11
- Harder spectrum than canonical shock accel.
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AGN model

- AGN jets

Takahara 90; Murase+12, Caprioli 15; Araudo+16

- Hillas condition for jets, $L_B > 3\text{x}10^{45}$ erg/s Γ^2 Z^{-2} $E_{20}{}^2$

Lumoine+ 09

AGN type	FR I	FR II
L_{jet} [erg/s]	10^{43}	10^{46}
E_{max} for p	×	○
E_{max} for Fe	○	○
N_s [Mpc^{-3}]	10^{-4}	10^{-7}
Anisotropy	○	×

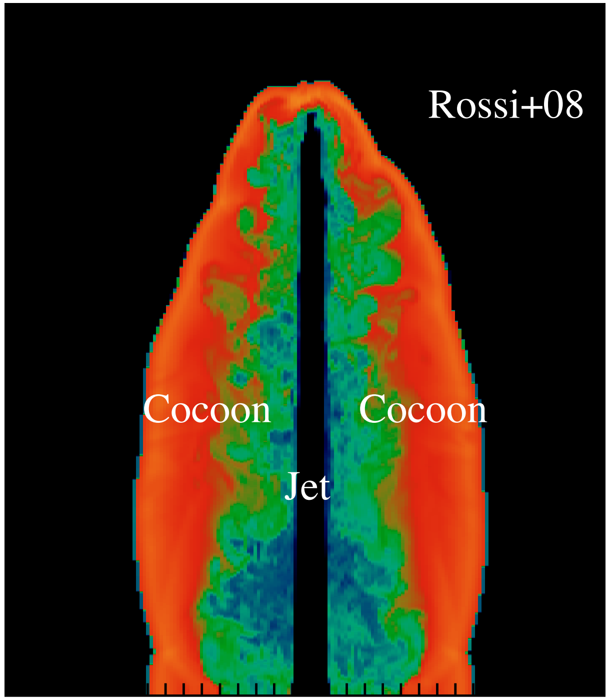
- **FR I with Fe is favorable.**

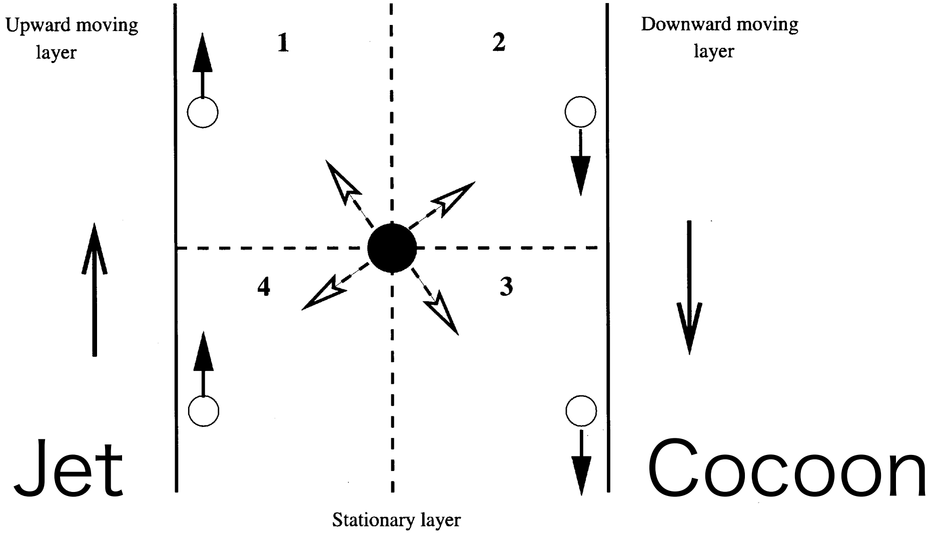
Fang+ 16

Requirements & Ideas

- High source density Takami 12, Fang 16
  —> **FR-I radio galaxies with Fe** Padovani+11
- **Harder spectrum than canonical shock accel.** Aloisio+14, Taylor+15, Auger 16
  —> **Shear Acceleration** cf.) Ostrowski 98, Rieger+ 06
- Heavy nuclei enhancement Aloisio+14, Taylor+15, Auger 16

Shear Acceleration





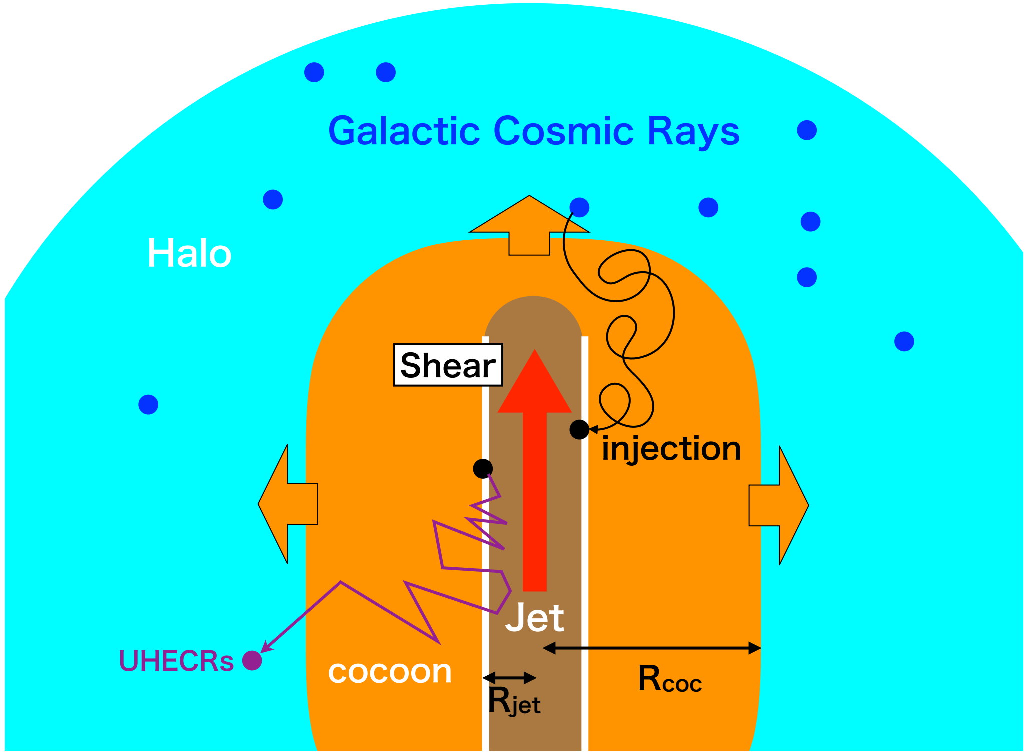
Earl 88, Subramanian 99, Rieger+ 06, SSK+ 16

region 1 & 3: tail-on collision —> E ↘

region 2 & 4: head-on collision —> E ↗

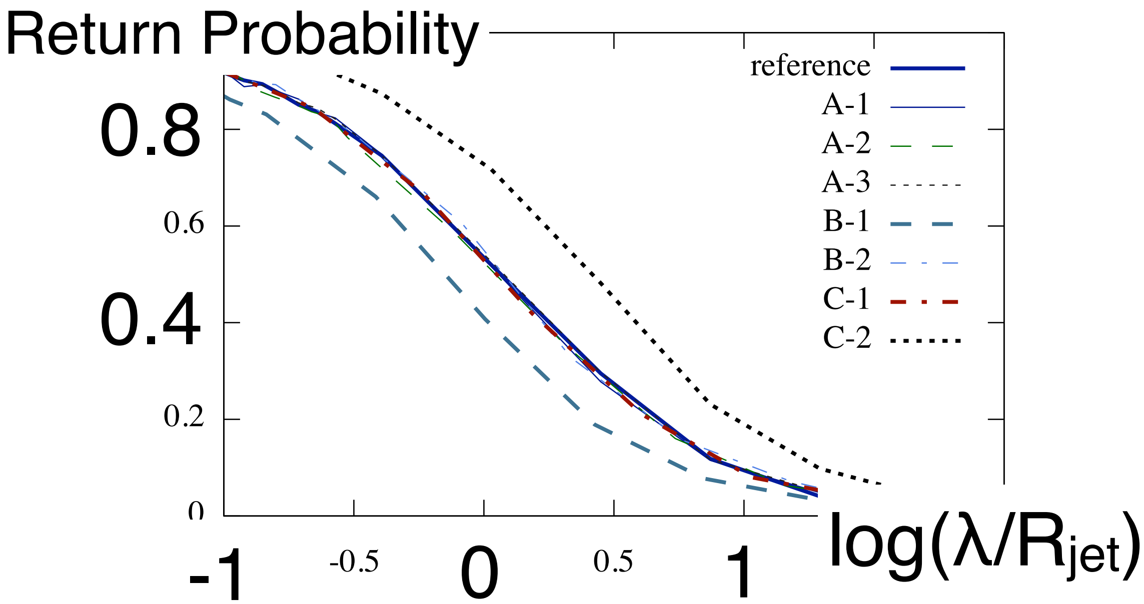
- Low energy CRs —> mean free path (λ) < size of shear layer (R_{sl}) —> Continuous shear —> Similar to 2nd-order Fermi acceleration
  Fermi 49, Stawartz+ 08
- **High energy CRs —> λ > R_{sl} —> Discrete shear —> numerical approach is required**

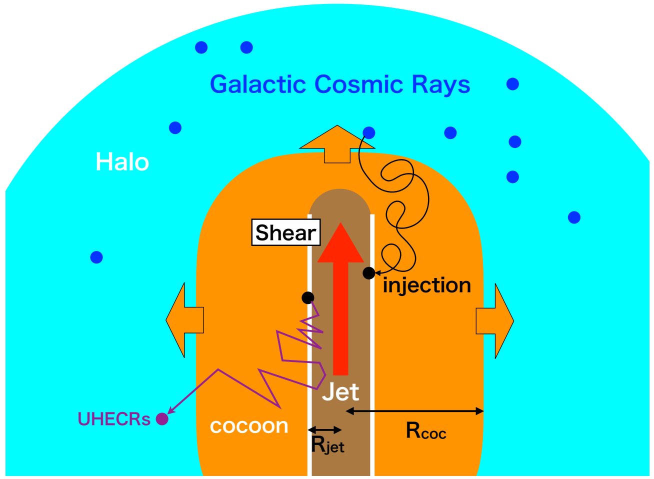
Schematic Picture



- We perform Monte Carlo Simulations for shear acceleration
- mean free path:
  Jet: $\lambda = r_L$ (Bohm limit)
  Cocoon: $\lambda = l_{coh}(E/E_{coh})^{\delta}$ (δ=1/3 for $E<E_{coh}$, δ = 2 for $E>E_{coh}$)
- CRs are scattered isotropically in a fluid-rest frame

Timescale

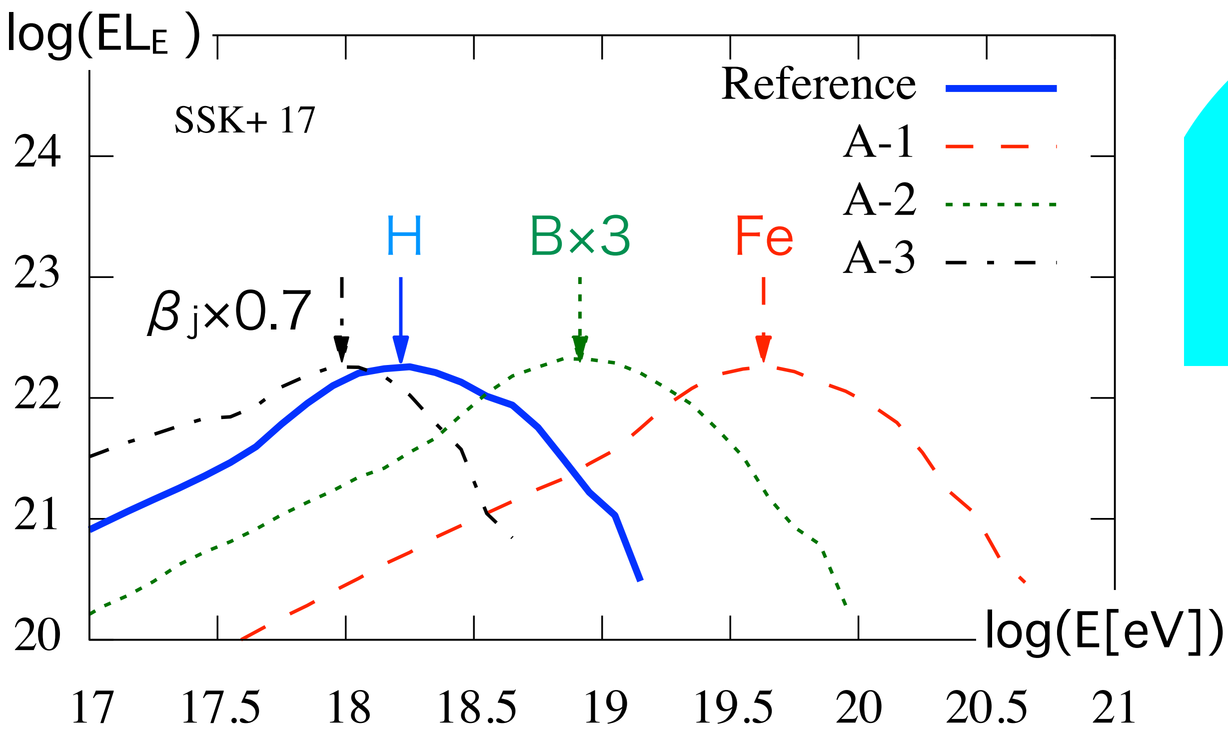


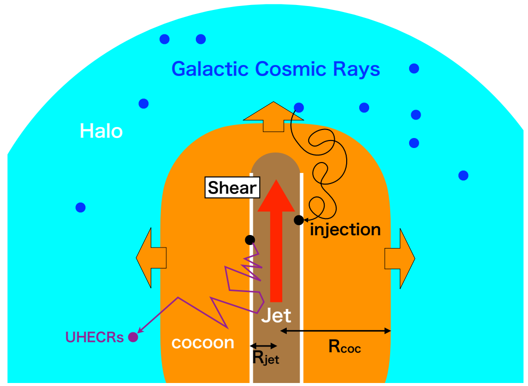


- For $\lambda < R_{jet}$, most CRs go back to jet in a few random steps —>Acceleration time: $t_{acc} \sim \zeta_a (\Gamma_{jet}\beta_{jet})^{-2}(\lambda/c)$
- Majority of CRs escape from system for $\lambda > R_{jet}$ —> confinement time : $t_{conf} \sim \zeta_c R_{jet}/c$
- $t_{acc} \sim t_{conf}$ →

$$E_{i,\max} \approx \zeta e Z_i B_{\rm coc} l_{\rm coc}^{1/2} R_{\rm jet}^{1/2} \Gamma_{\rm jet} \beta_{\rm jet},$$

Escape spectrum





R_{jet}=500 pc
ξ_{esc}=10
$L_{jet}=R_{coc}=H_h$=5kpc
l_{coh}=500pc
β_{jet}=0.7
B_{jet}=300μG
B_{coc} =3μG

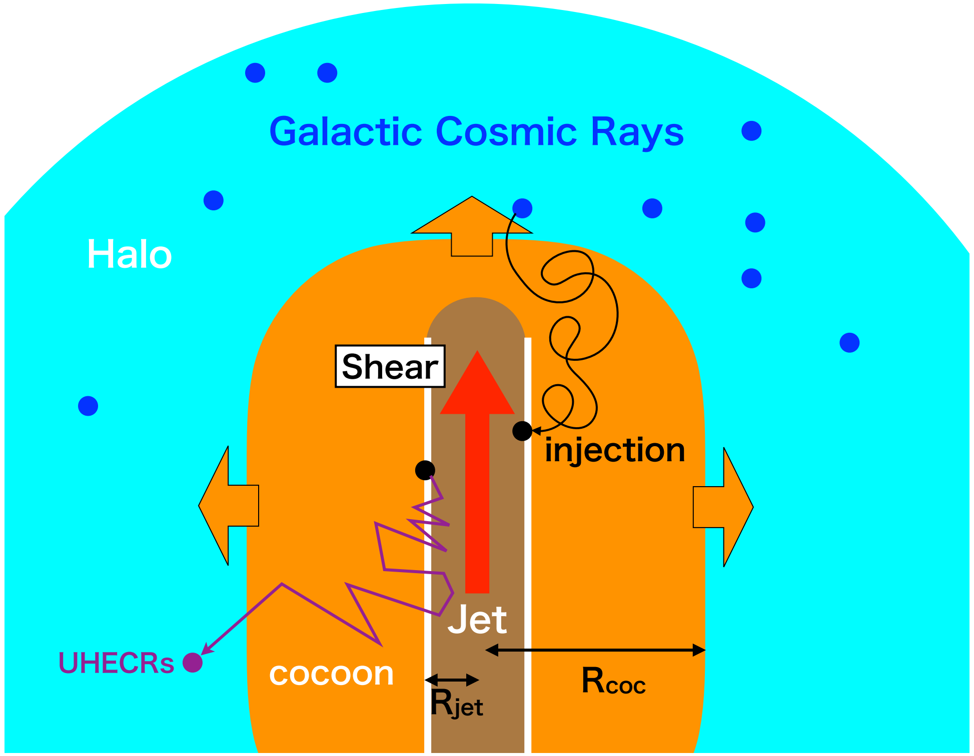
- $E_{i,max}$ ~ a few Z_i EeV
- CRs are well confined at $E<E_{i,max}$
  —>**Achieve hard spectrum**
  $dL_E/dE \sim E^{-1} — E^0$ cf. Ostrowski 98

Requirements & Ideas

- High source density Takami 12, Fang 16
  —> FR-I radio galaxies with Fe Padovani+11
- Harder spectrum than canonical shock accel. Aloisio+14, Taylor+15, Auger 16
  —> Shear Acceleration cf.) Ostrowski 98, Rieger+ 06
- **Heavy nuclei enhancement** Aloisio+14, Taylor+15, Auger 16
  —> Recycling Galactic Cosmic Rays Caprioli 15

Recycling GCRs

- Galactic cosmic rays (GCRs) are diffusing in halo



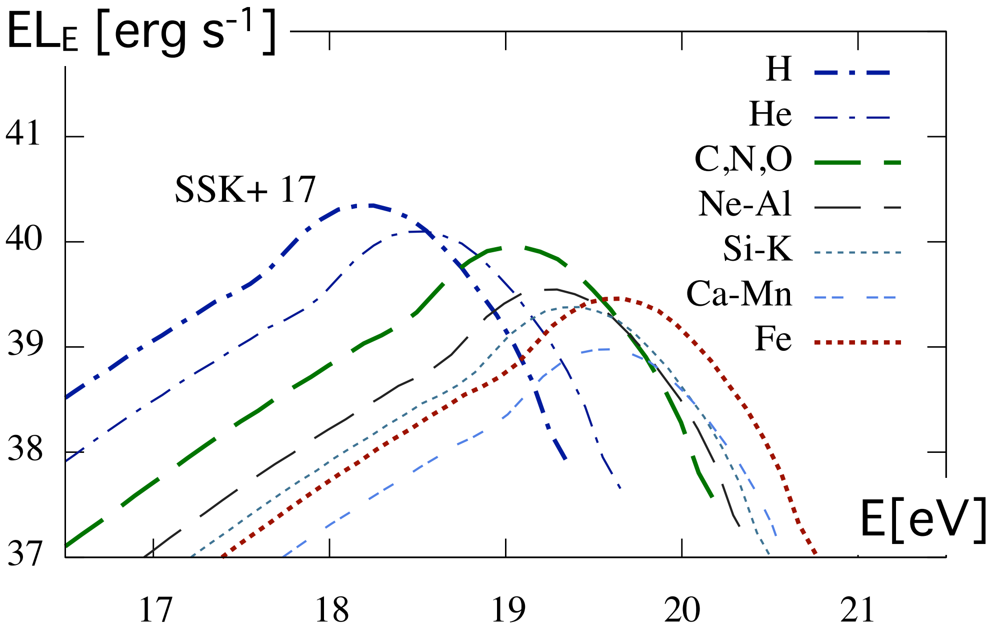
element	solar	TeV CR
H	1	1
He	9.7×10^{-2}	0.65
O	5.2×10^{-4}	0.18
Fe	3.0×10^{-5}	0.23

- $\lambda < R_{sl}$ —> cannot enter jet
- $\lambda > R_{sl}$ —> injection to acceleration
- $E_{inj} \sim$ 15 Z_i TeV

Shear acceleration lasts until adiabatic loss is effective

$$\dot{N}_{i,\rm inj} \approx \frac{N_{i,\rm inj}}{t_{\rm ad}} \approx \frac{2\pi R_{\rm jet}^2 H_h n_{i,d}}{t_{\rm ad}}$$

Recycling GCRs



- Most of radio galaxies are elliptical galaxies —> enhance metal abundance by factor 3

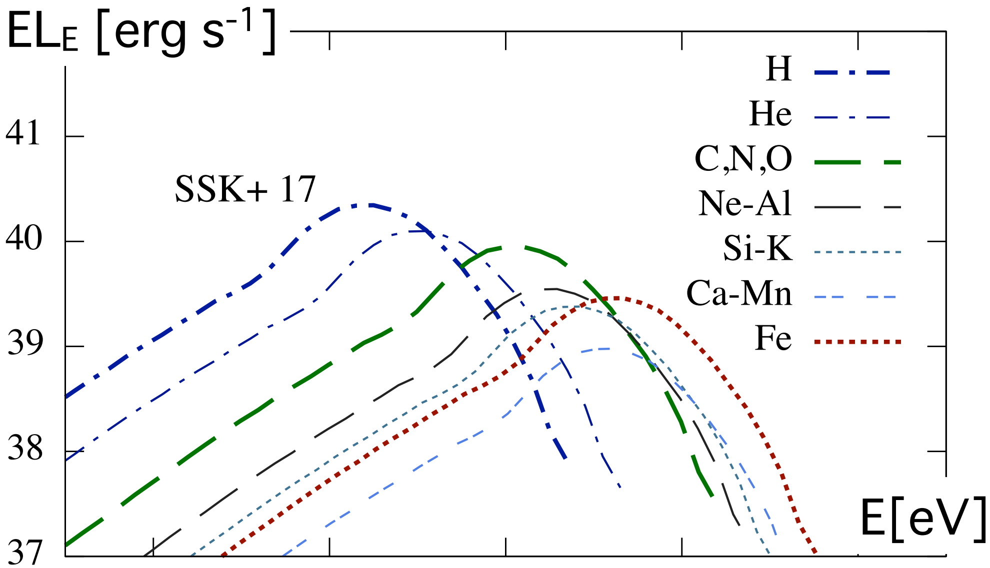
Henry+ 99

element	solar	UHECR
H	1	**1**
He	9.7×10^{-2}	**0.29**
O	5.2×10^{-4}	**5.8×10^{-2}**
Fe	3.0×10^{-5}	**5.1×10^{-3}**

Our model achieves
i) Heavier composition
ii) Hard spectral index
iii) required luminosity density
($L \sim 2 \times 10^{40}$ erg/s/Mpc^3 for radio galaxies)

e.g.)Takami+ 16

Recycling GCRs



- Most of radio galaxies are elliptical galaxies —> enhance metal abundance by factor 3

Henry+ 99

Composition and **spectral index** are **NOT free parameters**

O	5.2x10^{-4}	**5.8x10^{-2}**
Fe	3.0x10^{-5}	**5.1x10^{-3}**

for radio galaxies)

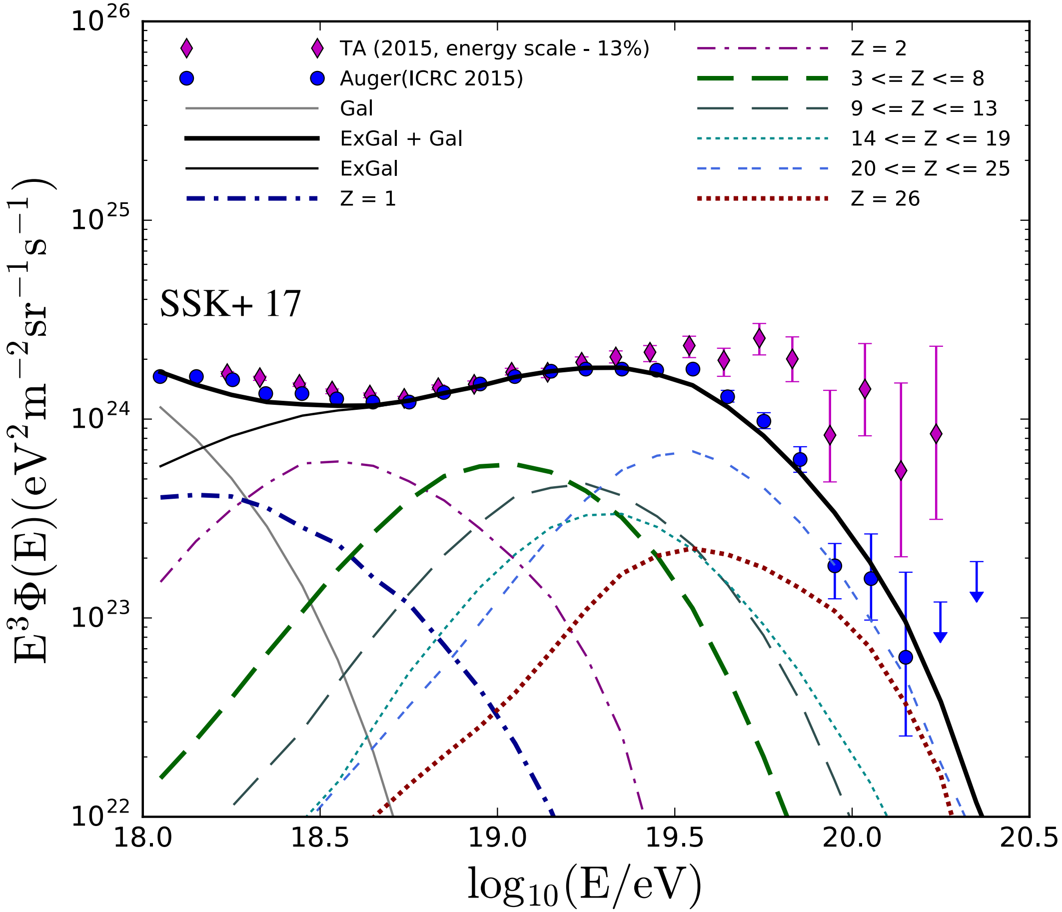
e.g.)Takami+ 16

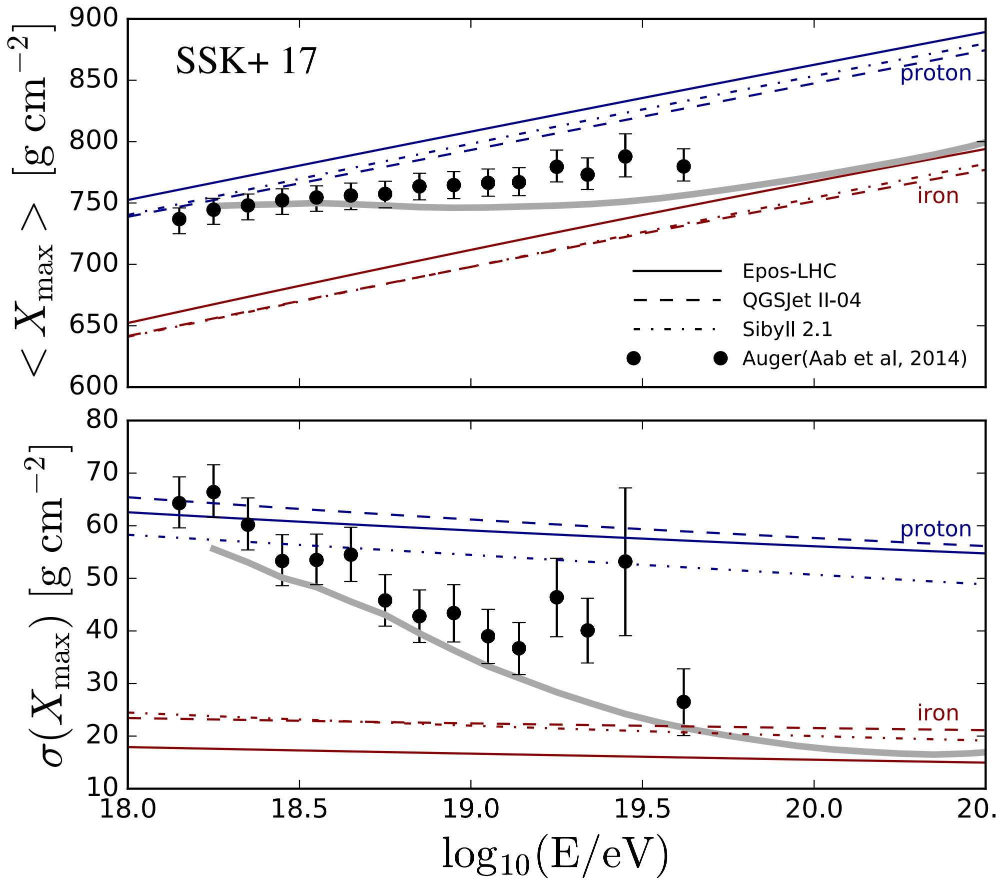
Propagation in IGM

Kampert+12, Batista + 16

- Using CRpropa code that includes
  a) decay of nuclei
  b) **photomeson production**: p+γ —> p + π
  c) **photodisintegration** : N^{A}+γ —> N^{A-1} + p
  d) photo-pair production: p+γ —> p + e^{+} + e^{-}
  (the code includes other channels)
- Radiation fields:
  CMB (radio), EBL (infrared) Fink+10

Spectrum & Composition





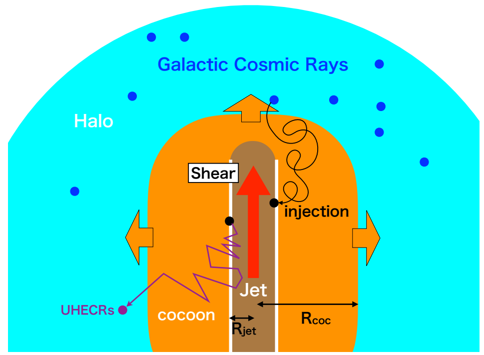
Padovani+11

- Luminosity function for FR-I can be no redshift evolution

Good agreement with experiments features

Summary

- To fit the experimental data, the source of UHECR has
  a) Luminosity density ~ 10^{44} erg Mpc^{-3} yr^{-1}
  b) Cutoff energy ~ 50 EeV
  c) Heavier composition for higher energy
  d) Large number density: $n > 10^{-6}$ Mpc^{-3}
  e) Harder spectrum: s ~ 0—1



- **Recycling GCRs by shear re-acceleration in radio galaxies are consistent with all the requirements.**

SSK, Murase, Zhang (arXiv:1705.05027)