Recycling Galactic Cosmic-Ray Nuclei by Shear Acceleration: A Radio Galaxy Model for Ultrahigh-Energy Cosmic Rays

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ref) SSK, T.B. Zhang, K. Murase in prep.

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Outline

- Introduction
- Shear Acceleration in FR-I radio galaxies
- UHECRs as Reaccelerated Galactic Cosmic Rays
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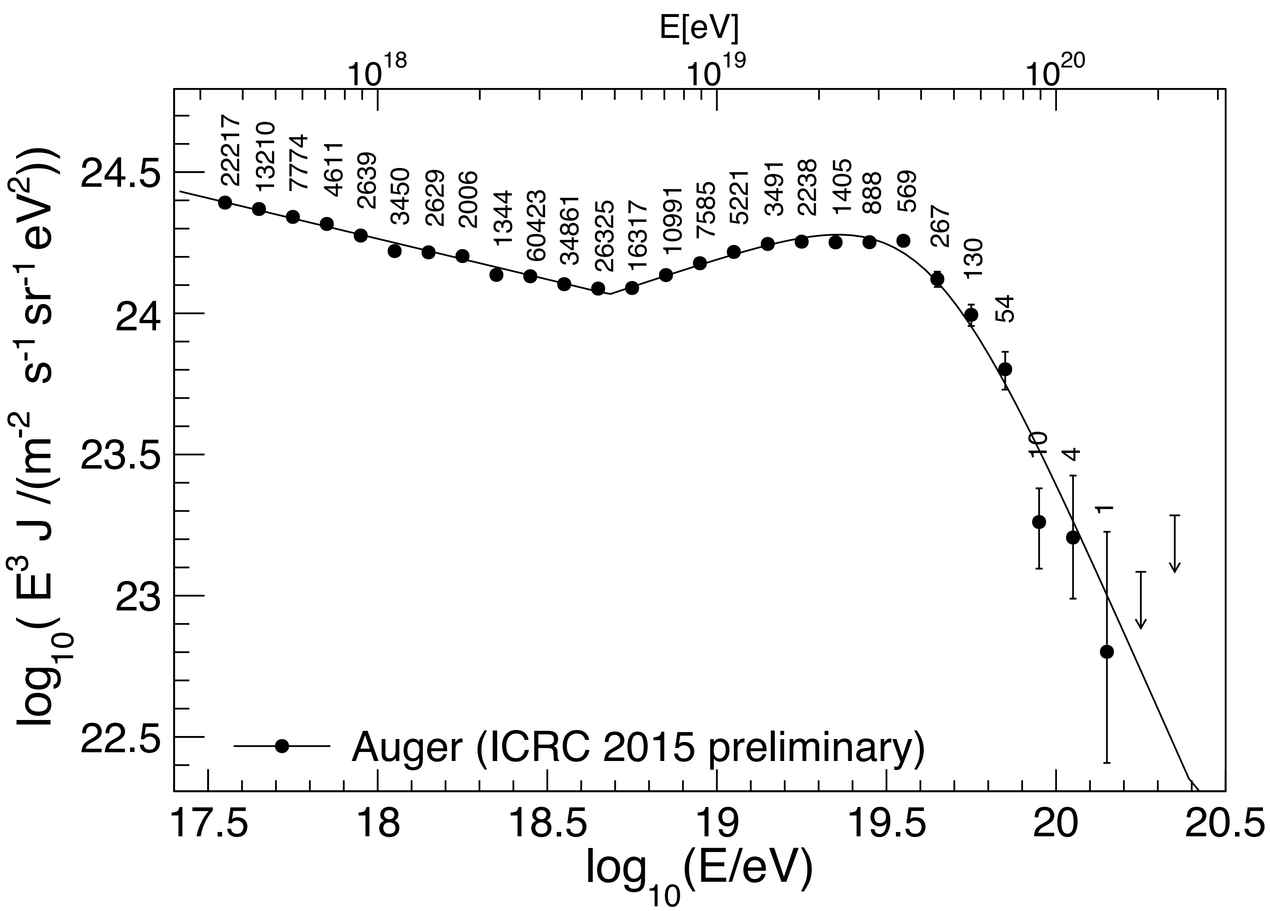
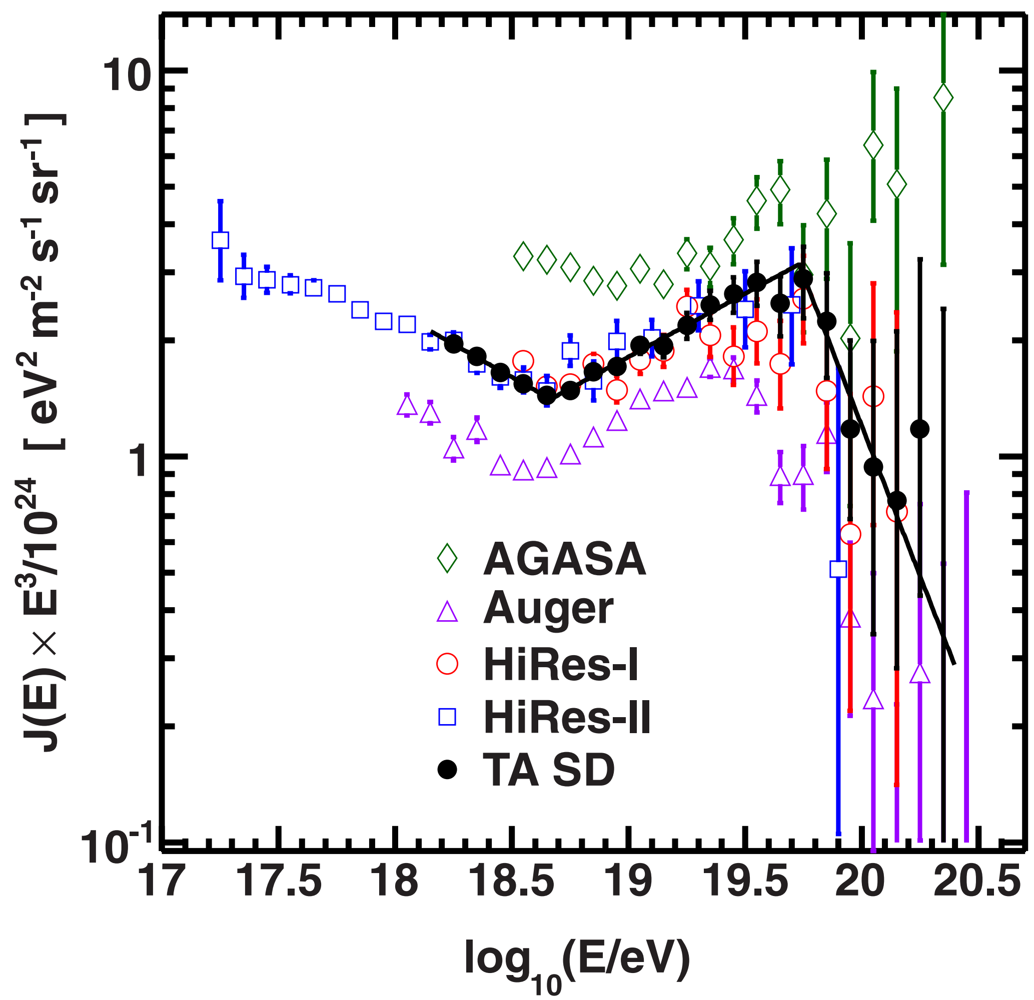
Ultra-High Energy Cosmic Rays



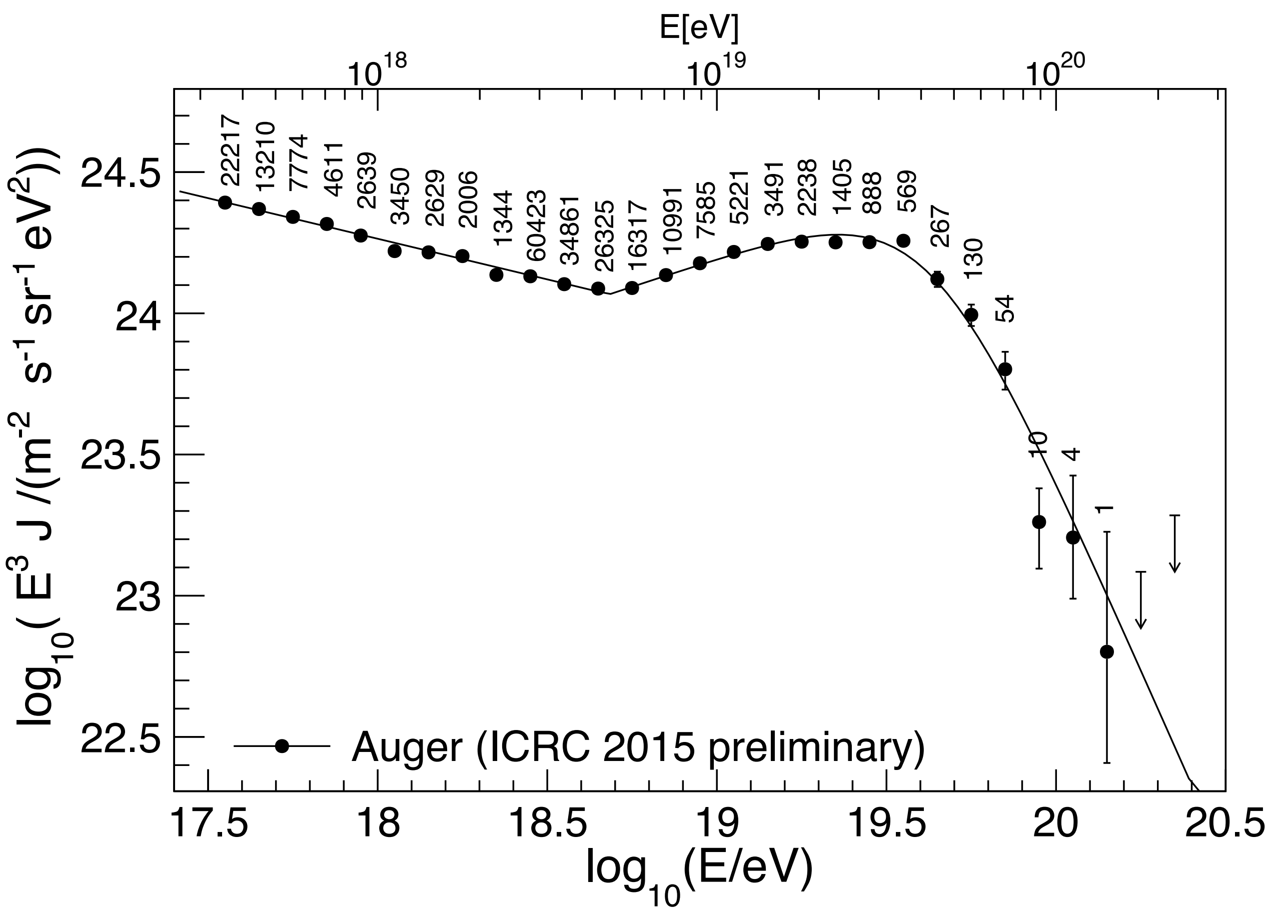
Auger (ICRC 15)

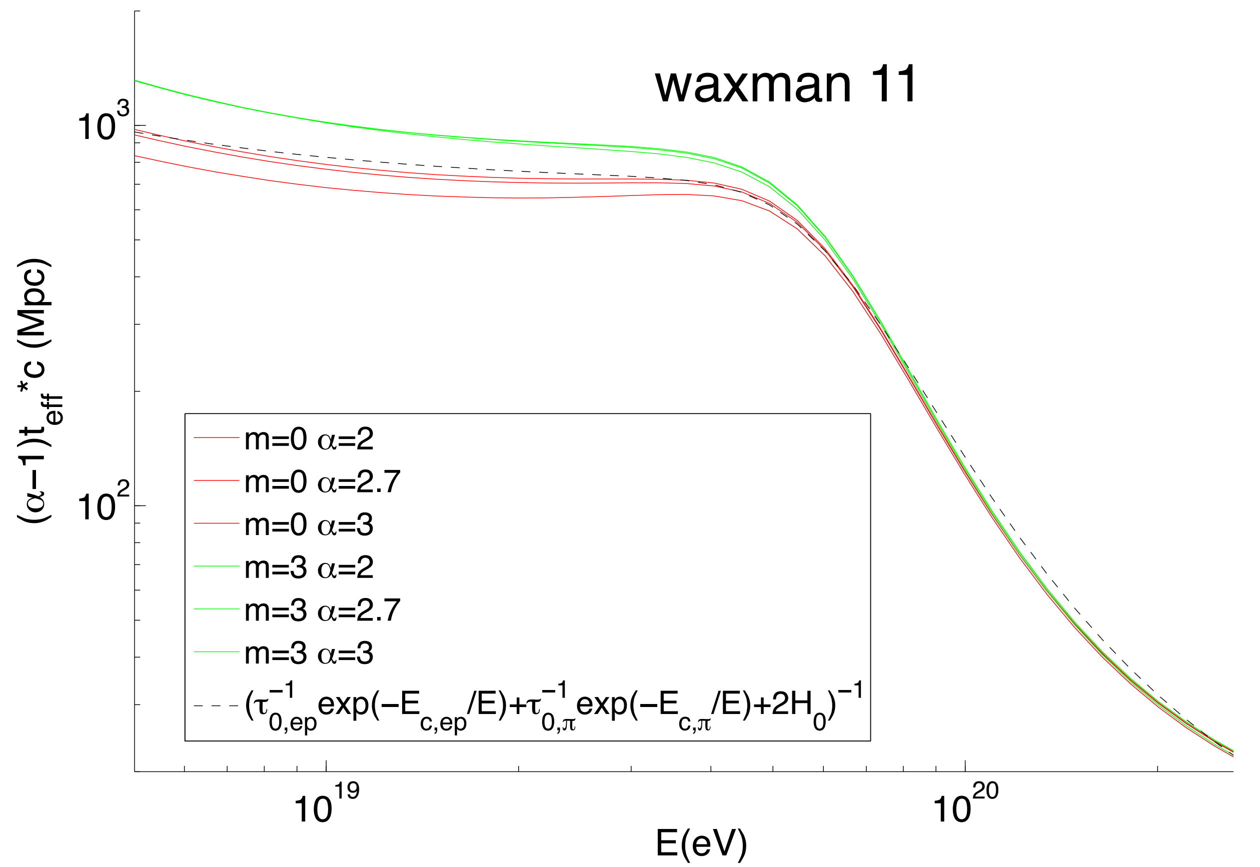


Abu-zayyat+13

- Air shower experiments reveal the existence of extremely efficient accelerators in the Universe.
- E_{cut} ~ 40—50 EeV ~ GZK cutoff energy

Luminosity density

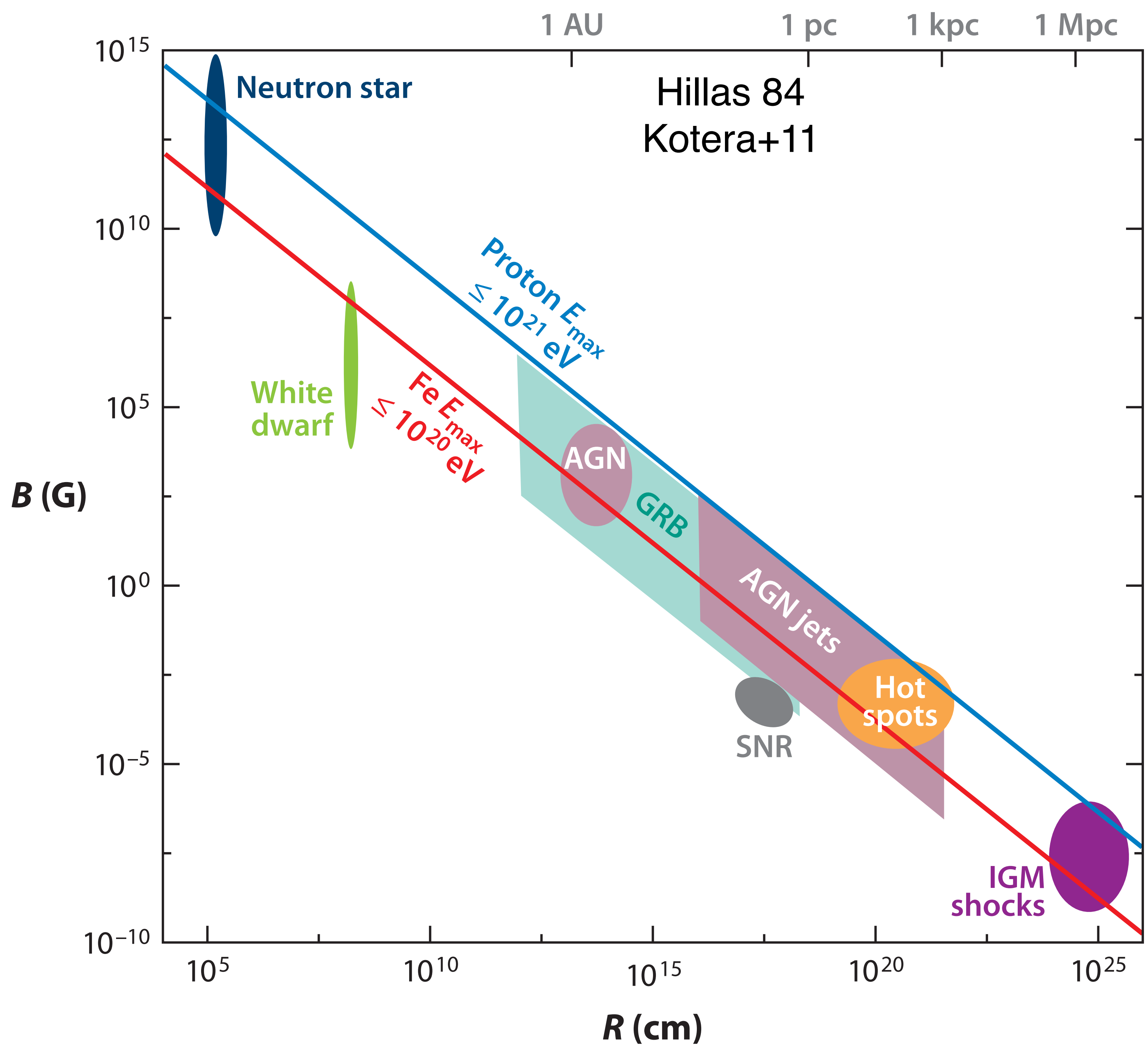




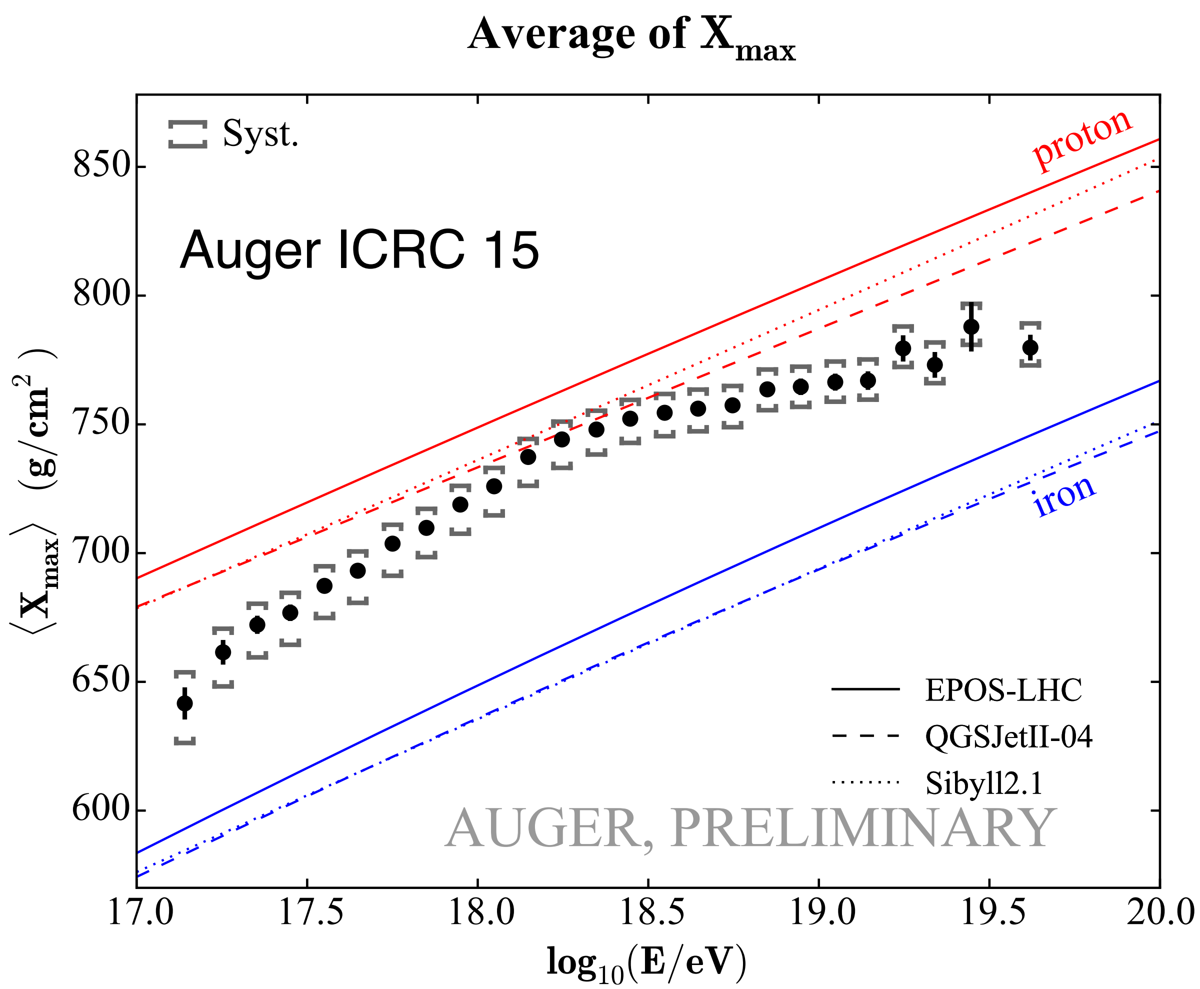
- UHECR flux: ~ 0.1 particle $km^{-2}\ yr^{-1}$ @100 EeV
- Mean-free path of UHECRs: 100 Mpc
- Luminosity density: 3×10^{43} erg $Mpc^{-3}\ yr^{-1}$

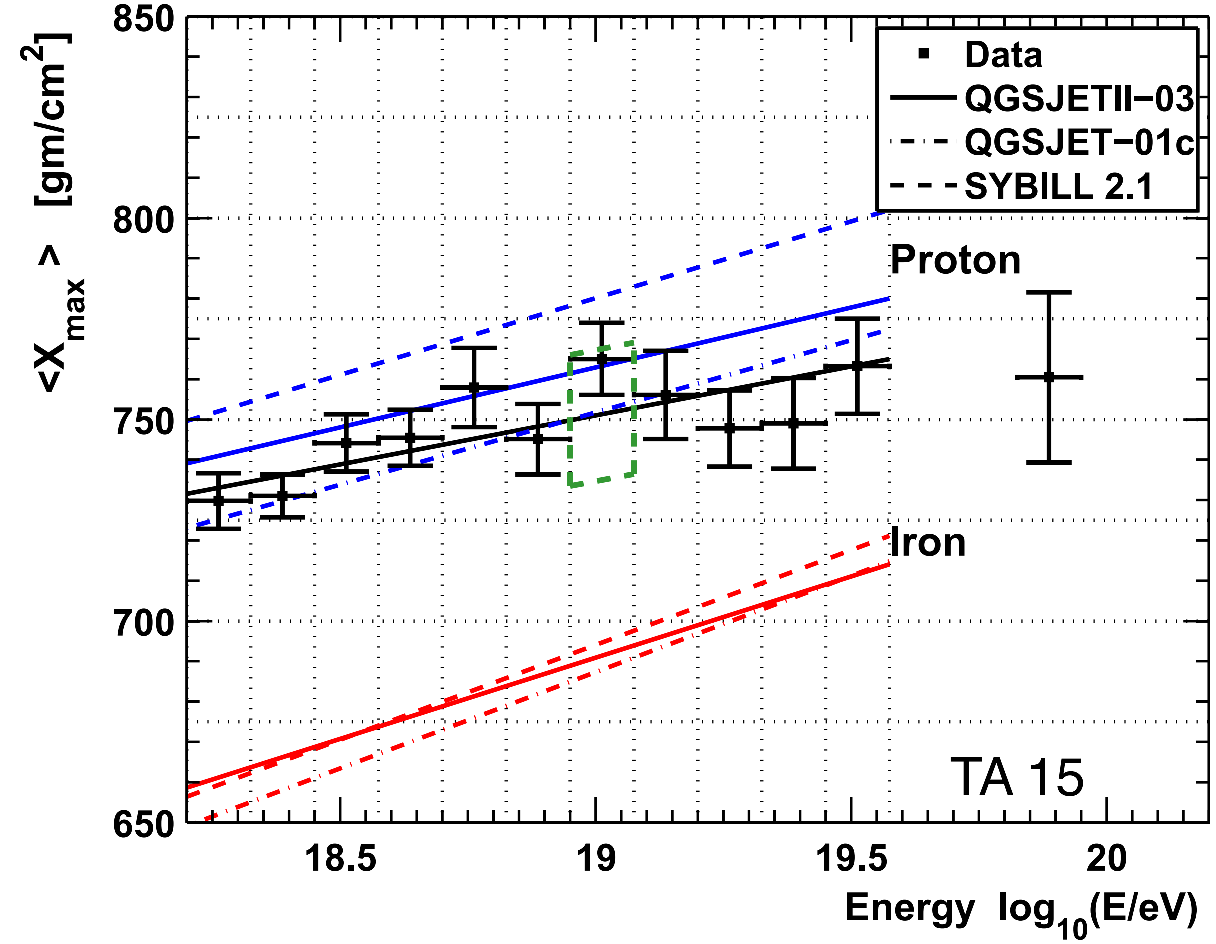
Source Candidates

- AGN jets
  - Takahara 90
  - Murase+12
  - Araudo+16
- GRBs
  - Waxman 95
  - Globus+15
  - Asano+16
- Pulsars
  - Blasi + 00,
  - Fang+12



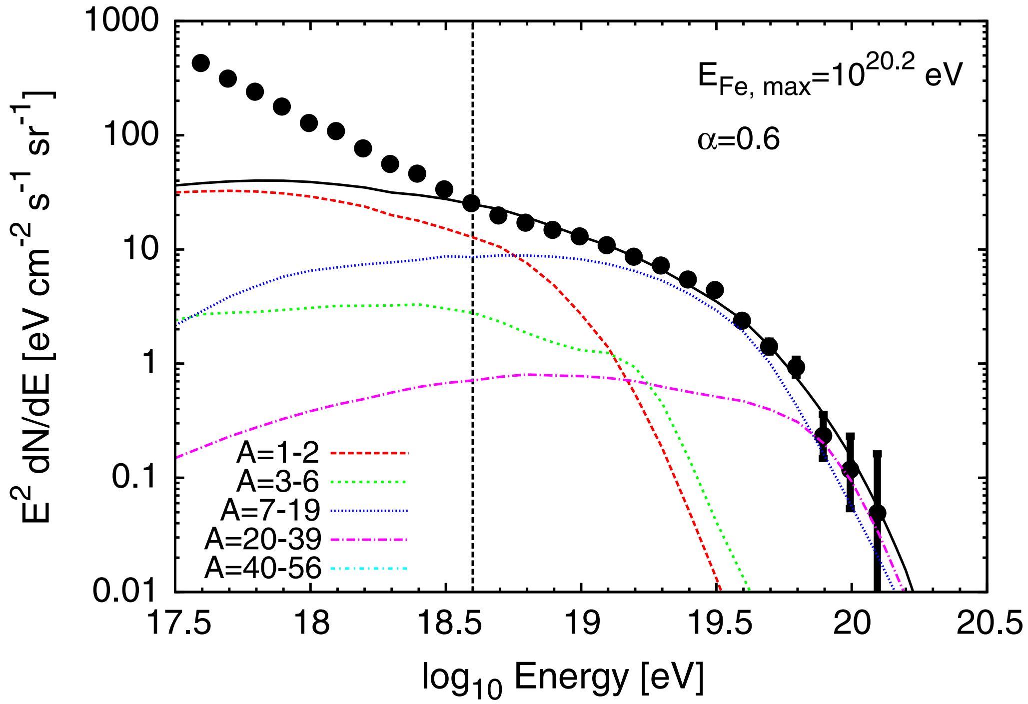
Composition

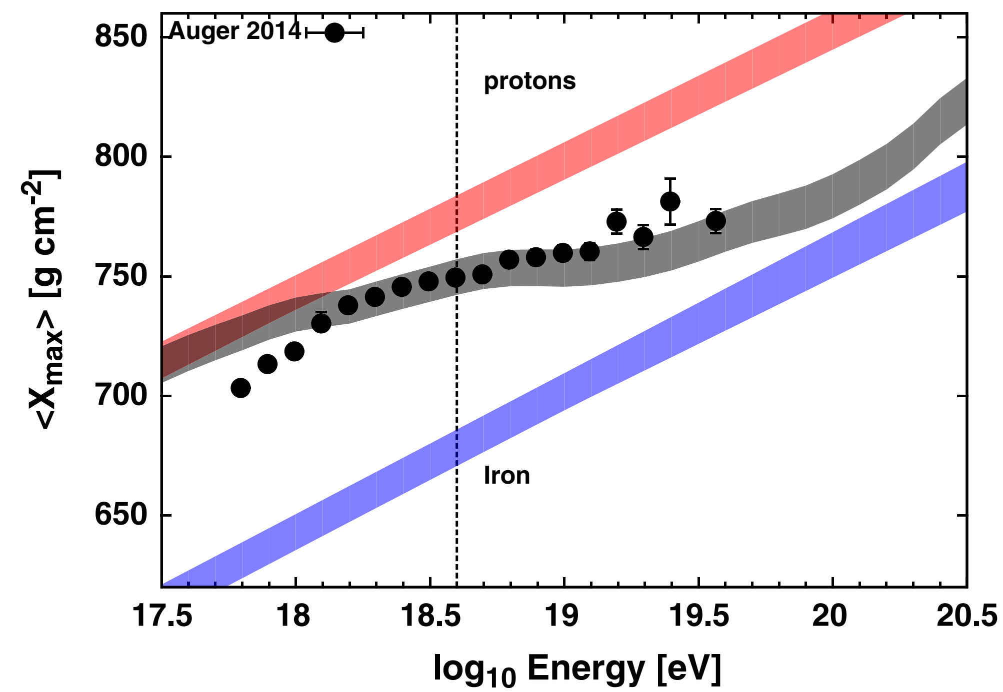




- Proton @ E~ EeV,
- gradually becomes heavier for higher energy
- Data is consistent for two experiments,
  but interpretation can be changed by analysis

Fitting requirement

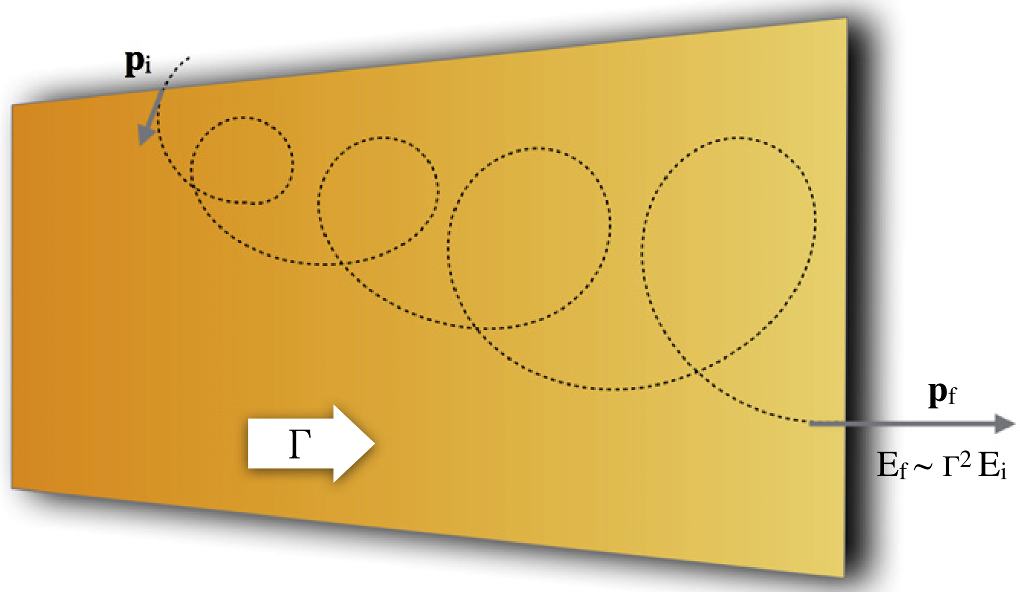




Aloisio+14, Taylor+15

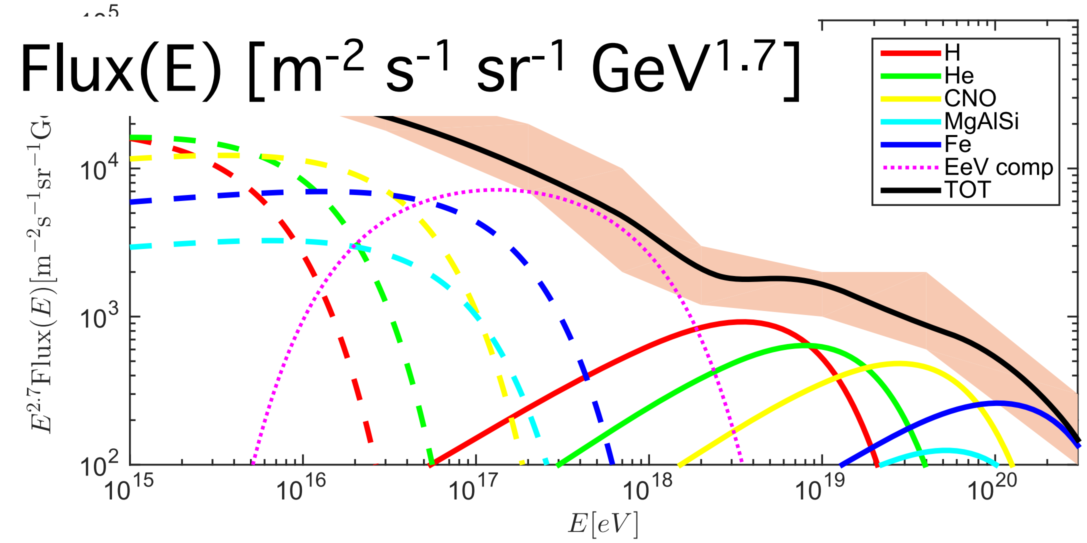
- $E_{max,p} \sim 6$ EeV
- Hard source spectrum: $s \lesssim 1$
- Abundance for Auger data:
  much heavier than the Galactic composition ratio
- Need another EeV component

Espresso Acceleration

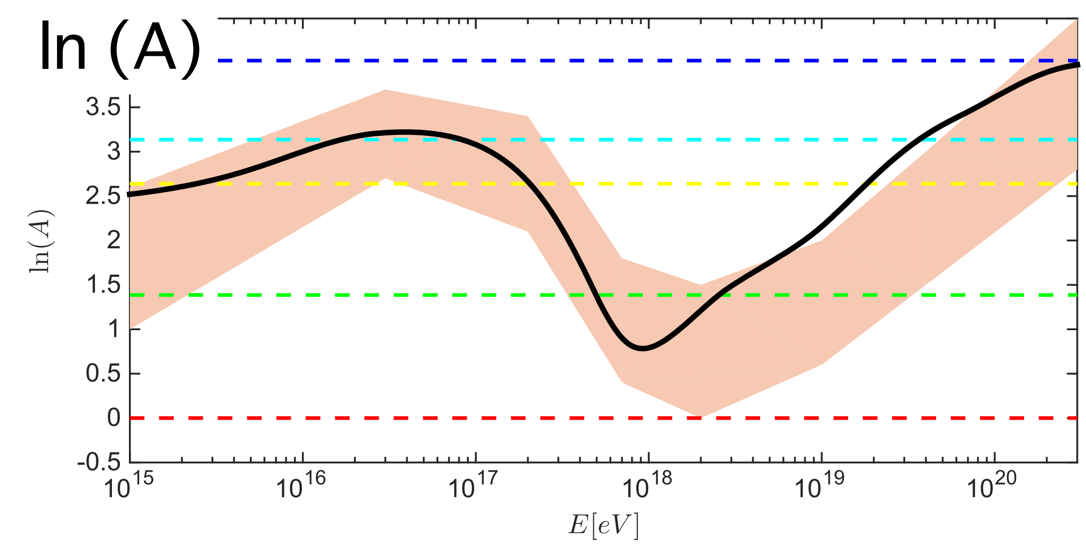


Caprioli 15

E$^{2.7}$ Flux(E) [m^{-2} s^{-1} sr^{-1} GeV$^{1.7}$]



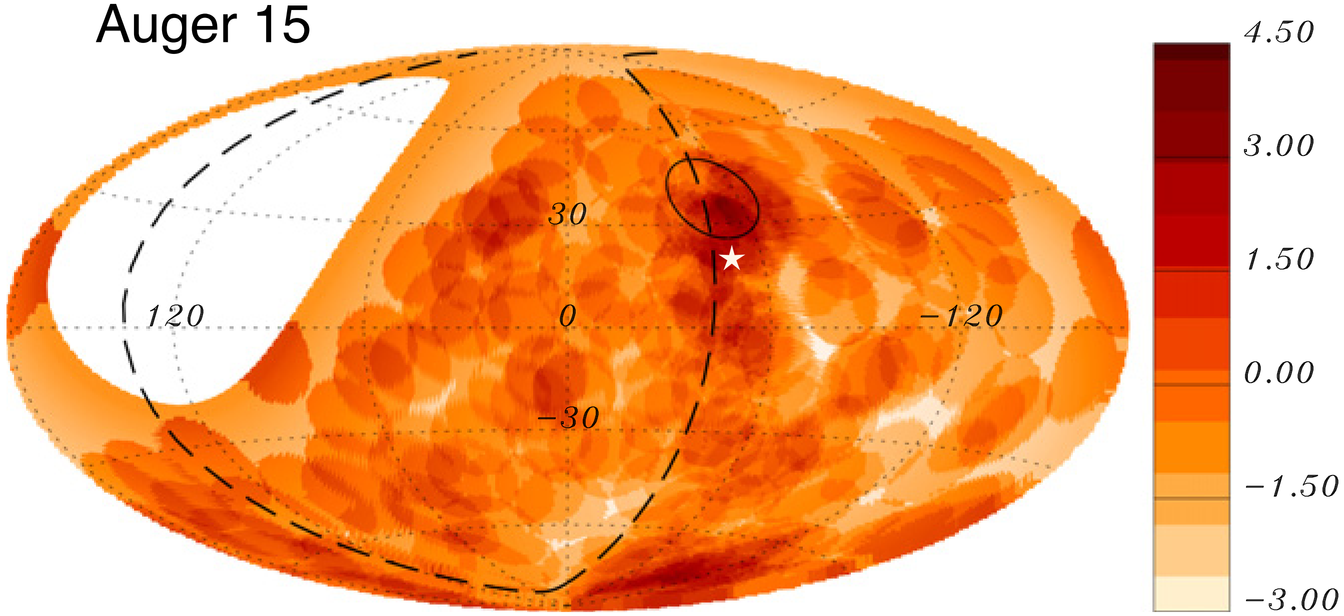
ln (A)



- Re-acceleration of galactic CRs by AGN jets
  —> composition & spectrum is well fitted
- However, this model require extremely strong jets
  —> No source inside the UHECR horizon

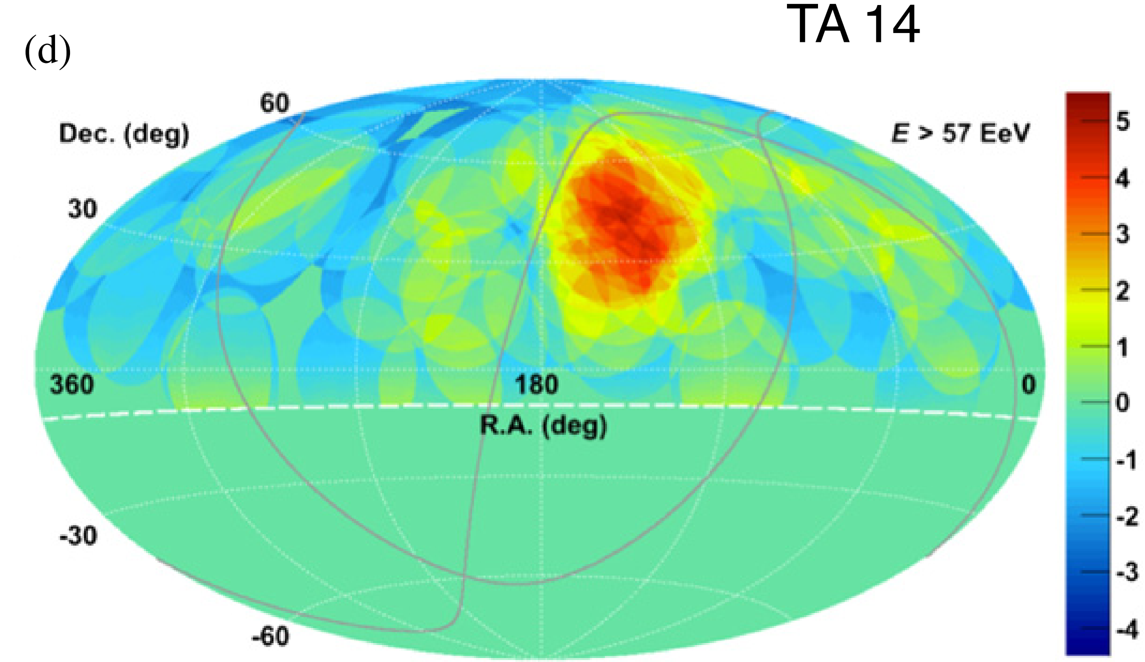
Anisotropy

Auger 15



Auger: Galactic coordinate

TA 14



TA: equatorial coordinate

- weakly clustering, but not statistically significant
- the result of cross correlation analysis is consistent with isotropic arrival —> $N_{source} \gtrsim 10^{-6}\ \mathrm{Mpc}^{-3}$ Takami+ 12 Auger 15
- Luminous sources are disfavored Fang+16

Purpose

- Re-cycling galactic CRs works for the composition
  —> consider AGN Jets
- Harder spectrum is required
  —> Shear acceleration
- High source density is favorable from anisotropy constraints
  —> FR-I galaxies

Consider recycling galactic cosmic rays by shear acceleration in the FR-I radio galaxies

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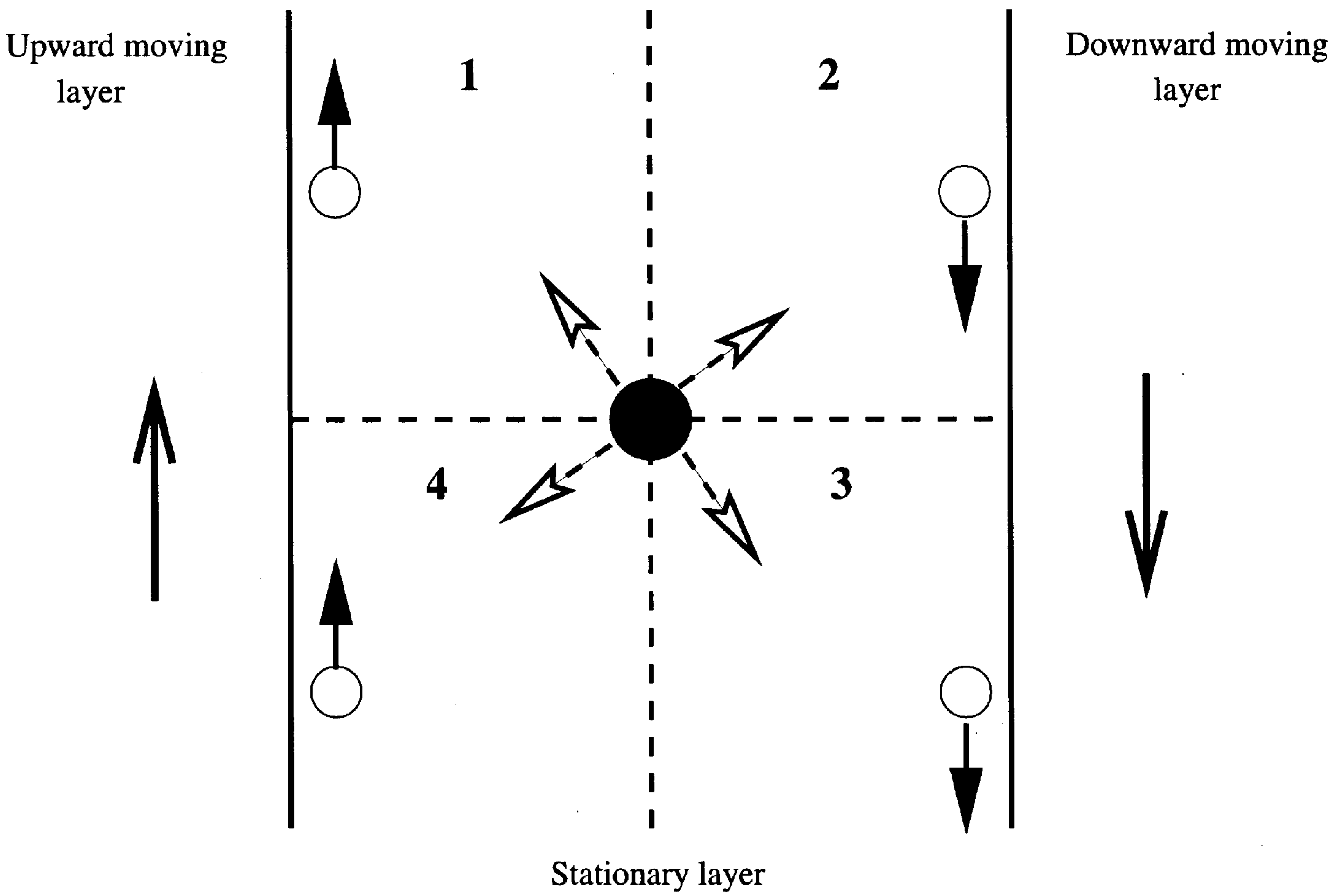
Shear Acceleration



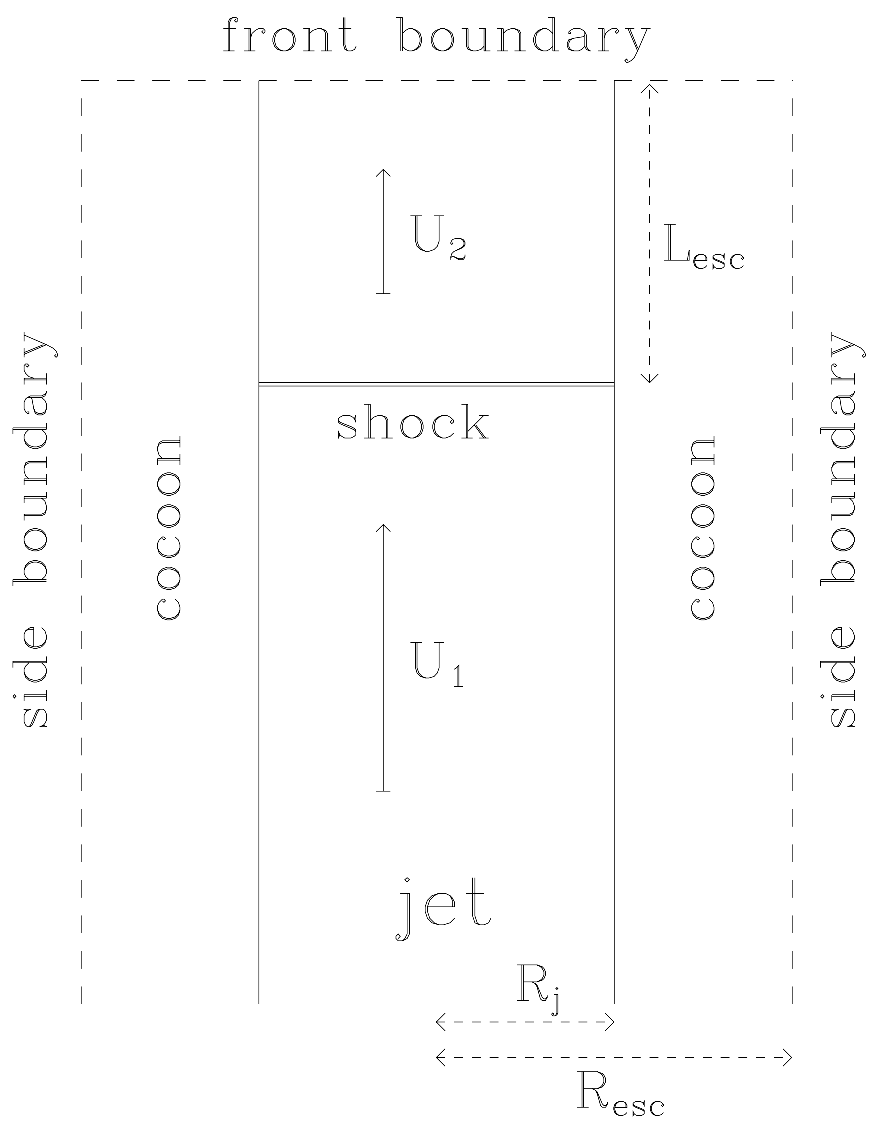
Earl 88, Subramanian 99, Rieger+ 06

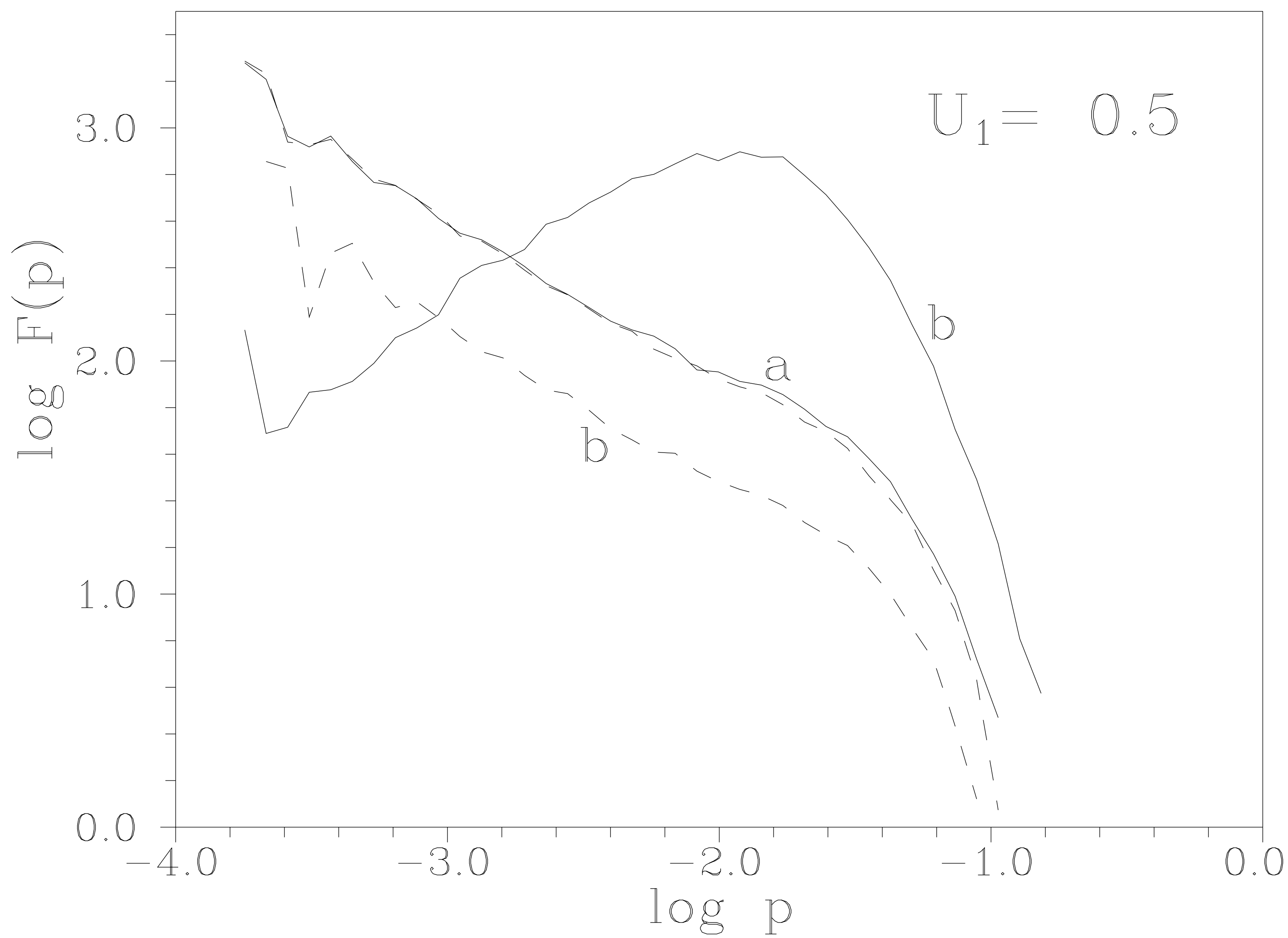
- region 1 & 3: tail-on collision —> E ⤵
- region 2 & 4: head-on collision —> E ⤴

For continuous shear layer, distribution function diffuses in p space

$$\frac{\partial f\,(p)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f\,(p)}{\partial p}\right)$$

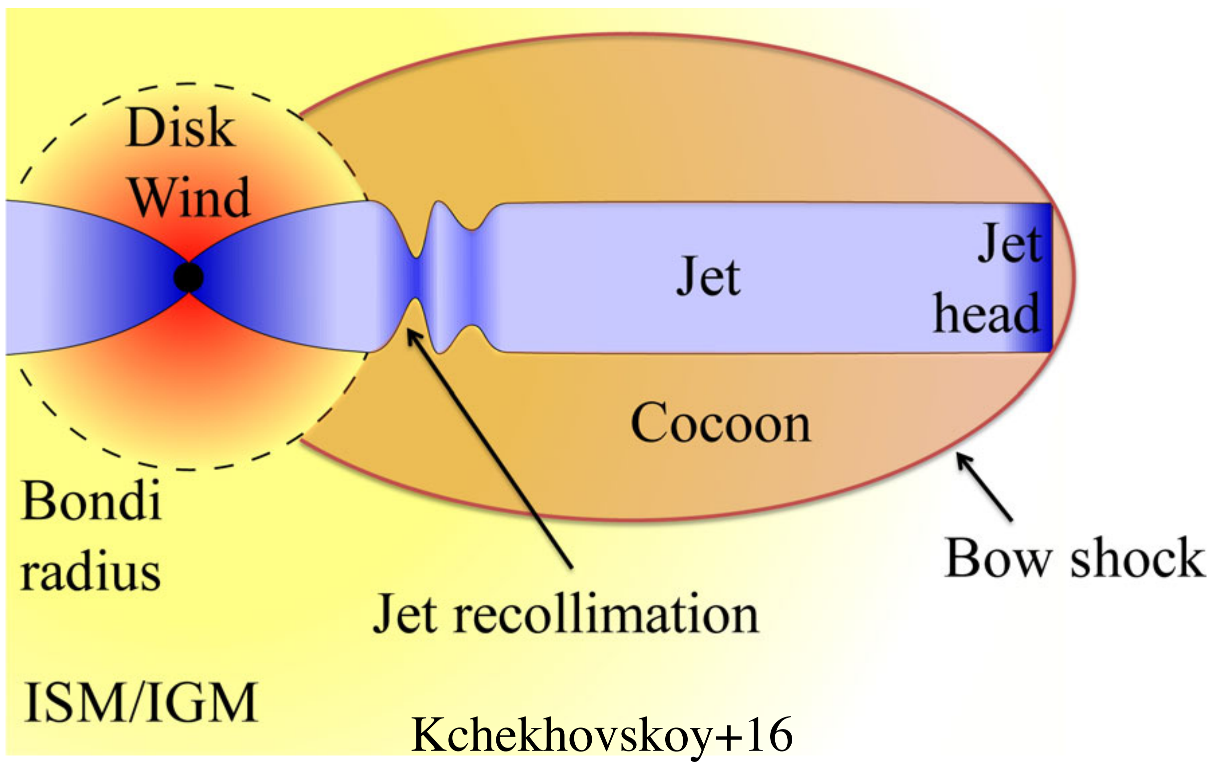
Shear Acceleration

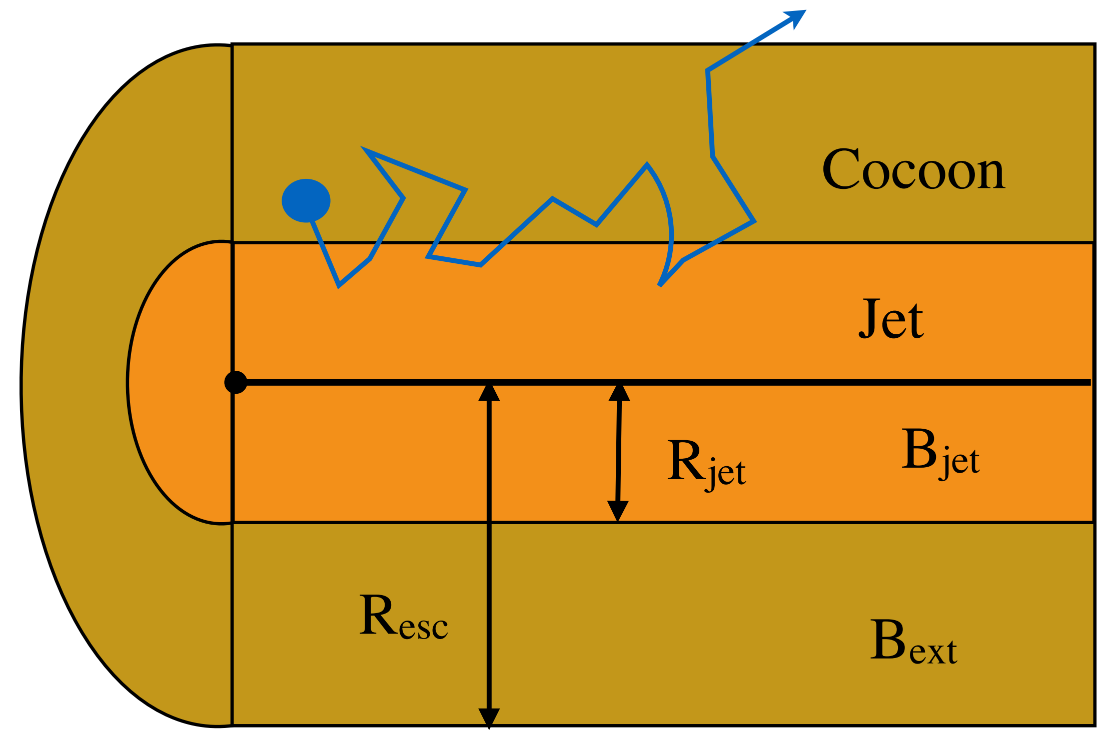




- gyro radius > size of shear layer → discrete shear
- Discrete shear: no analytic formulation
  From MC simu., dN/dE ~ E^0

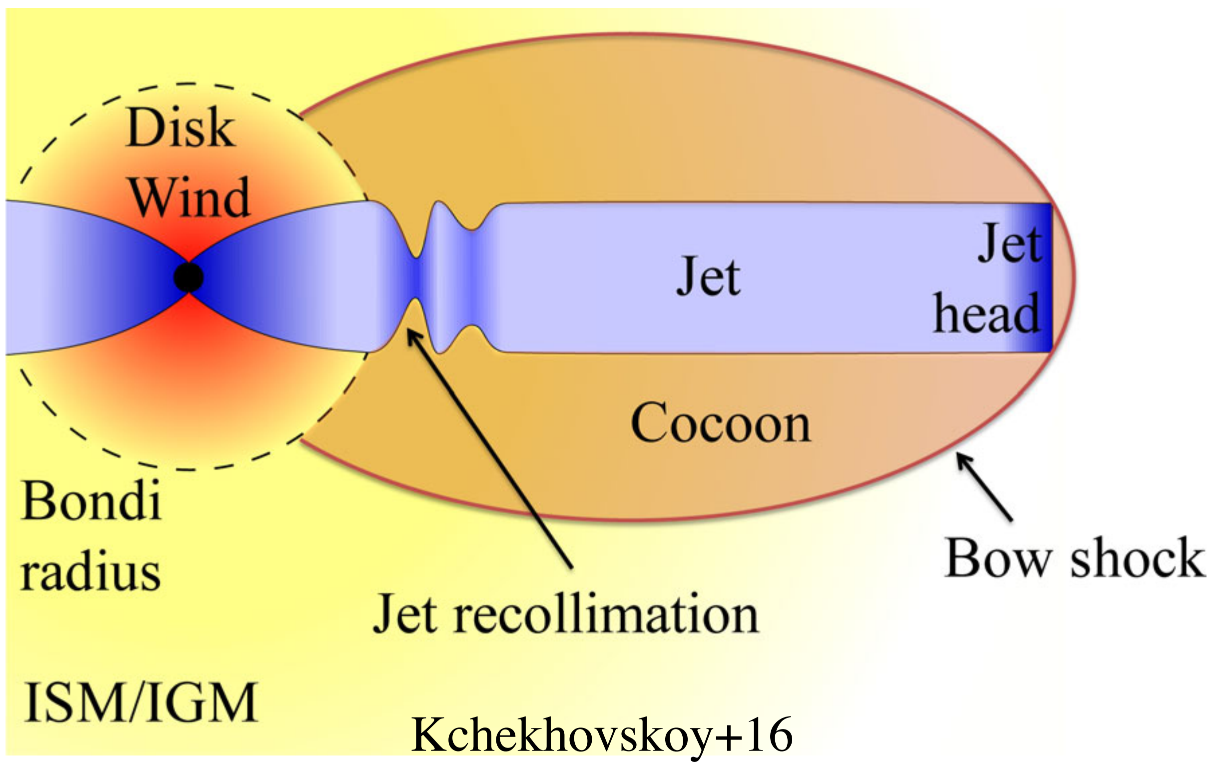
Model Setup

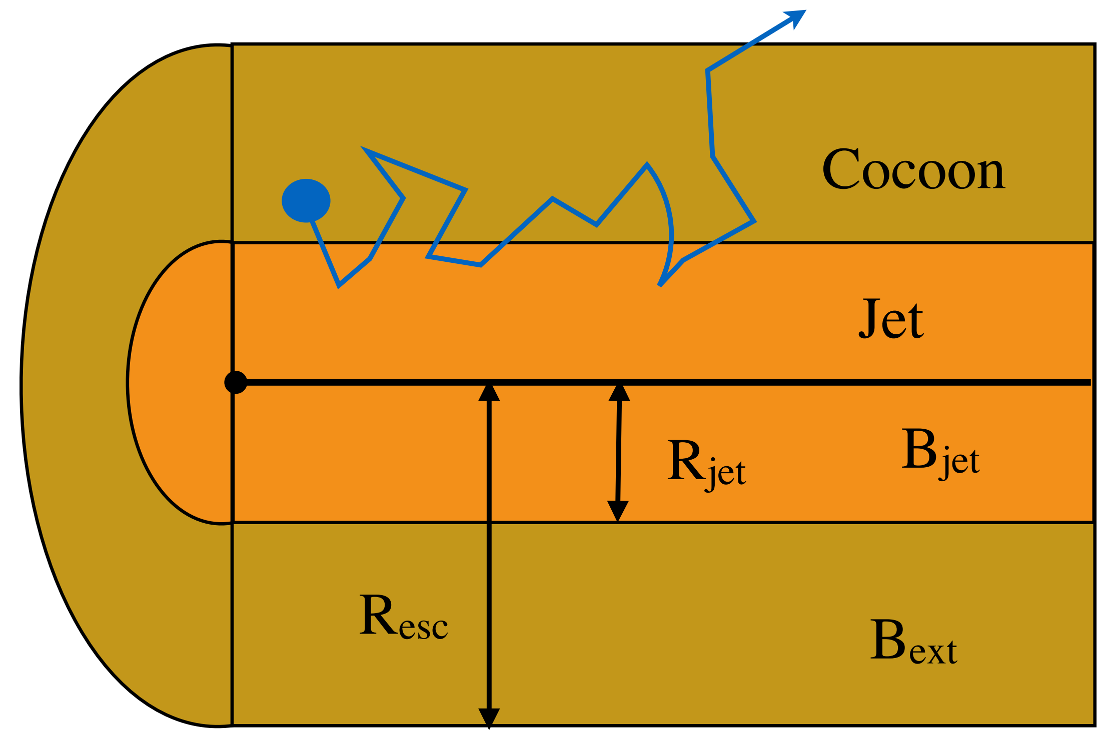




- Consider kpc away from the core
- Jet becomes cylindrical around kpc scale
- Mildly relativistic jet $\beta_j \sim 0.6$
- Jet is long, $L_{jet} \sim 20$ kpc >> $R_{jet} \sim 300$ pc

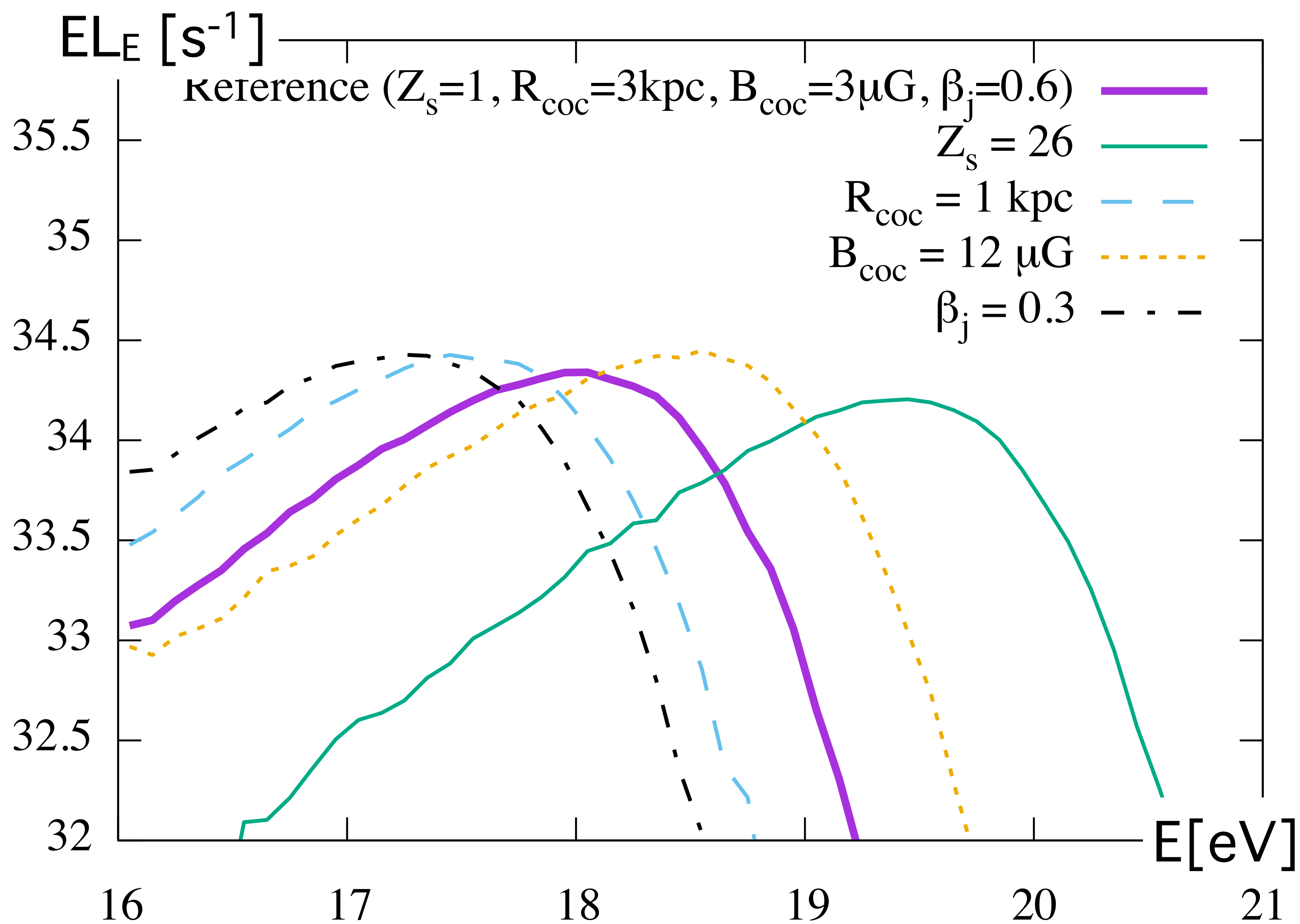
Model Setup





- We perform Monte Carlo simulation
- Bohm diffusion, $\lambda \sim r_g c/3$
- isotropic scattering at the fluid rest frame
- $R_{esc} \sim 10\ R_{jet}$

Simulation results



- Hard spectrum owing to shear acceleration
- $dN/dE \sim E^0$ for $E<E_{peak}$
  Consistent with previous works

Analytic Estimate

- Acceleration Time: $t_{\rm acc} = \langle \Delta t \rangle_p / \langle \Delta E/E \rangle_p$

from simulation results $\langle \Delta t \rangle_p \sim 2R_{\rm coc}/(c)$ $\langle \Delta E/E \rangle_p \simeq 4\Gamma_j^2 \beta_j^2/3$

$$t_{\rm acc} \simeq 3R_{\rm coc}/(2\beta_j^2 c)$$

- Escape time: $t_{\rm esc} \sim R_{\rm coc}^2/(6D_{\rm Bohm})$

$$t_{\rm acc} \simeq t_{\rm esc}$$

$$E_{\rm peak} \simeq \frac{eZ_s}{3}\Gamma_j^2 \beta_j^2 B_{\rm coc} R_{\rm coc} \sim 2.1 Z_s B_4 R_3 \beta_6^2 \ {\rm EeV}$$

Consistent with the MC simulations
Achieve a few EeV for protons

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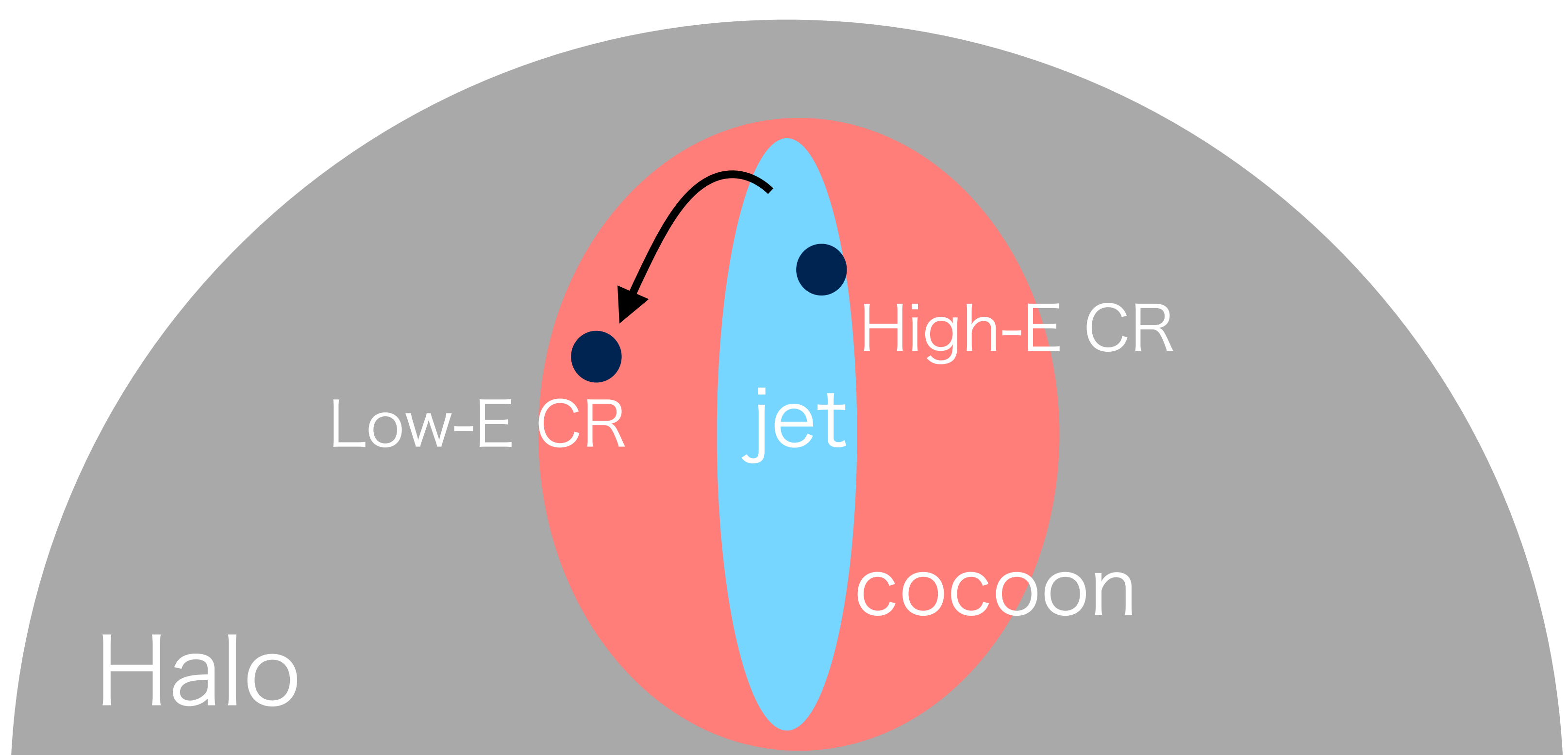
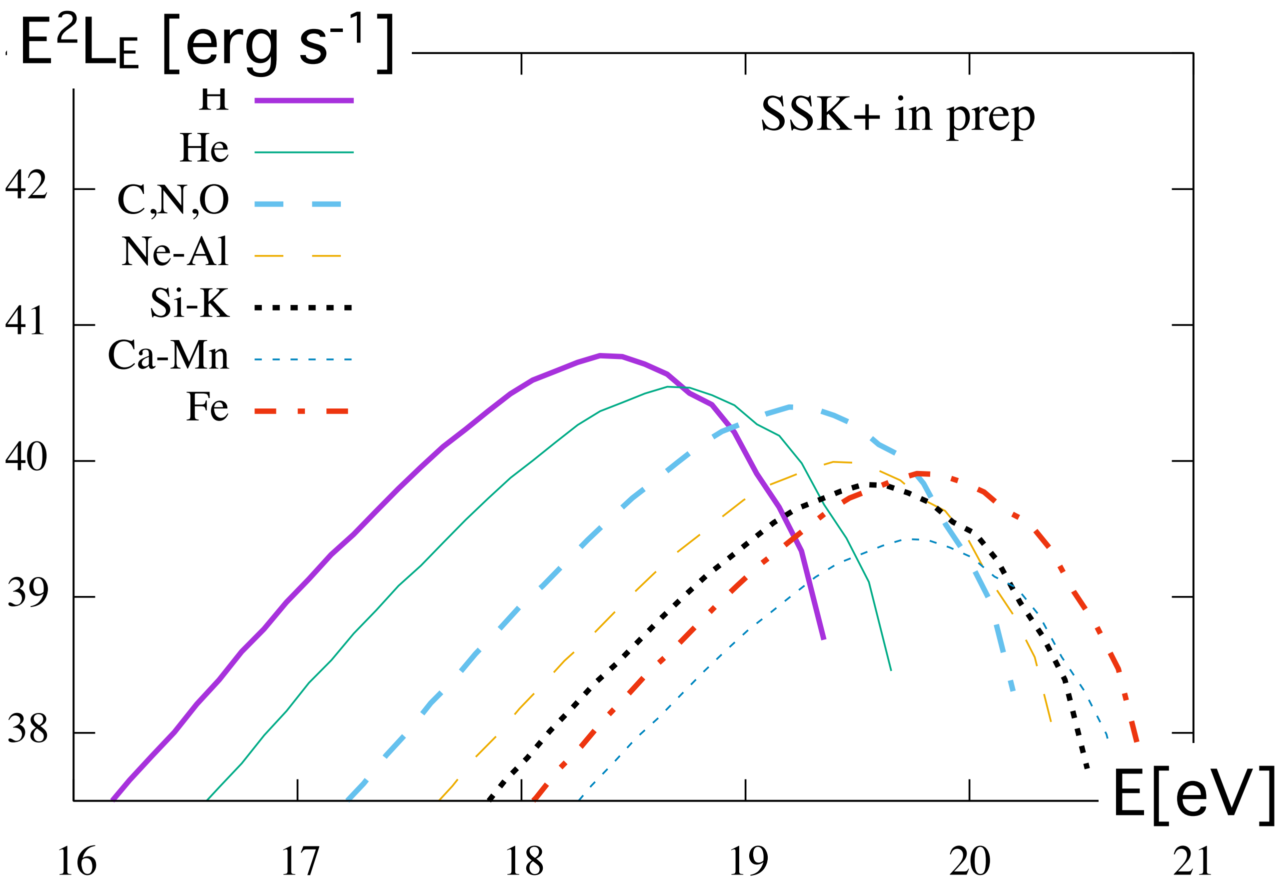
Re-acceleration of galactic cosmic rays

- Galactic cosmic rays (GCRs) are diffusing in halo
- Jet penetrates halo:
  Low-E GCRs ($< E_{inj}$) are advected & cools down,
  High-E GCRs ($> E_{inj}$) are injected to the shear accel.



Re-acceleration of galactic cosmic rays



- Since FR-I radio galaxies are elliptical, we enhance metal abundance for injected CRs.
- p, He : the Galactic CR
  others : the Galactic CR x3

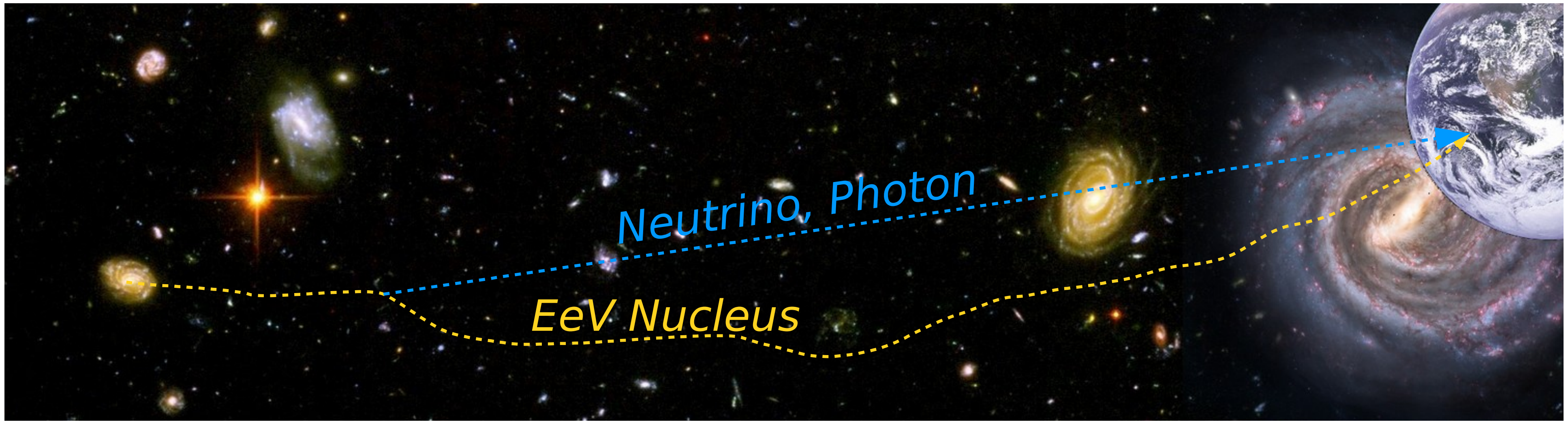
- We can obtain hard spectrum & heavier composition
- (f_H, f_{He}, $f_{C\text{-}O}$, $f_{Ne\text{-}Al}$, $f_{Si\text{-}K}$, $f_{Ca\text{-}Mn}$, f_{Fe}) =(72, 21, 4.3, 1.1, 0.54, 0.14, 0.38)
- Luminosity ~ 10^{41} erg/s, number density ~ 10^{-5} Mpc^{-3}
  —> consistent with the expected luminosity density & anisotropy

Propagation of IGM

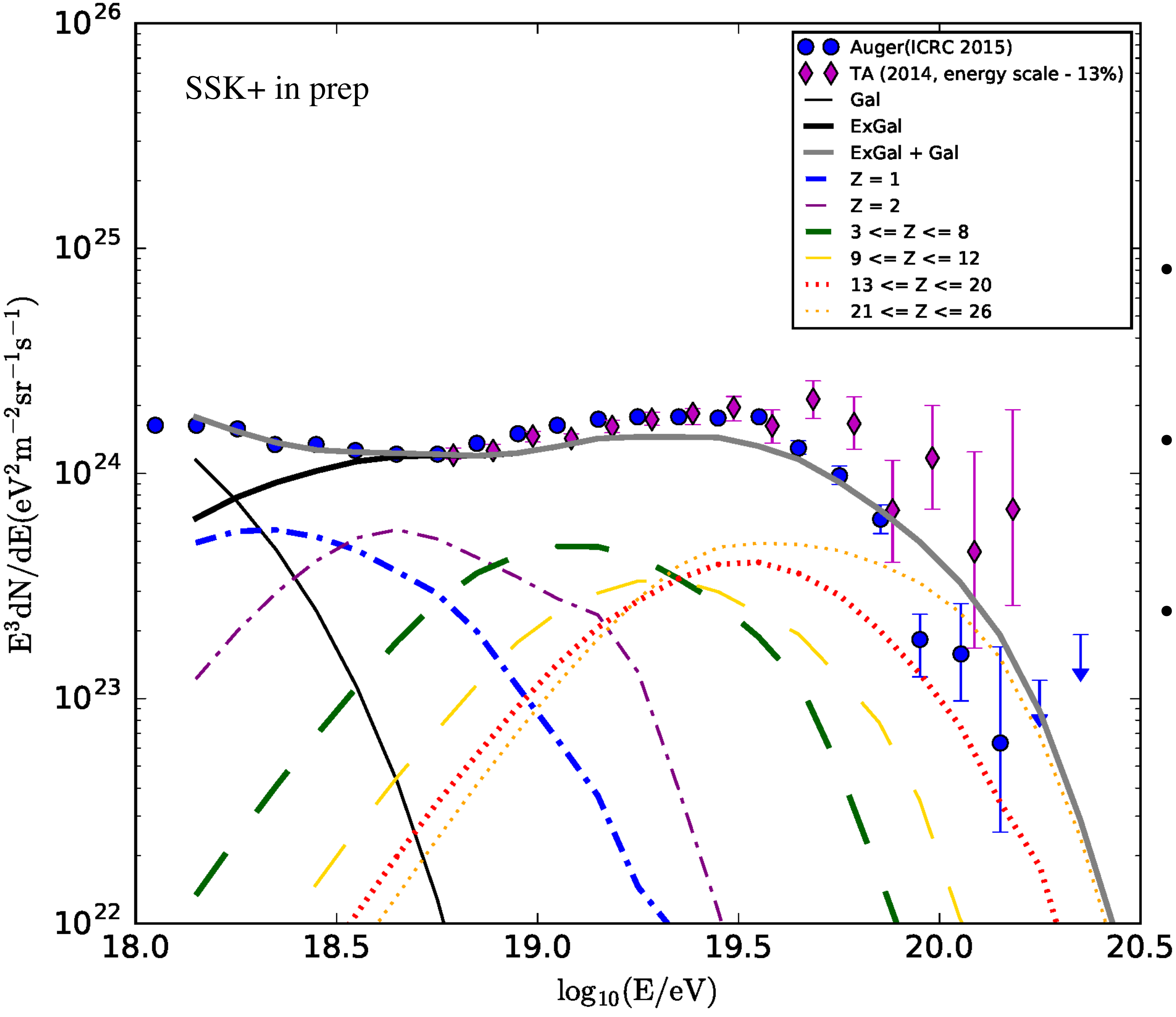
Batista + 16

- Using CRpropa code that includes
  a) decay of nuclei
  b) photomeson production: $p+\gamma \longrightarrow p + \pi$
  c) photodisintegration : $N^A+\gamma \longrightarrow N^{A-1} + p$
  d) photo-pair production: $p+\gamma \longrightarrow p + e^+ + e^-$
  (the code includes other channels)
- Radiation fields:
  EBL (infrared), CMB (radio)

G. Müller+ ICRC 13



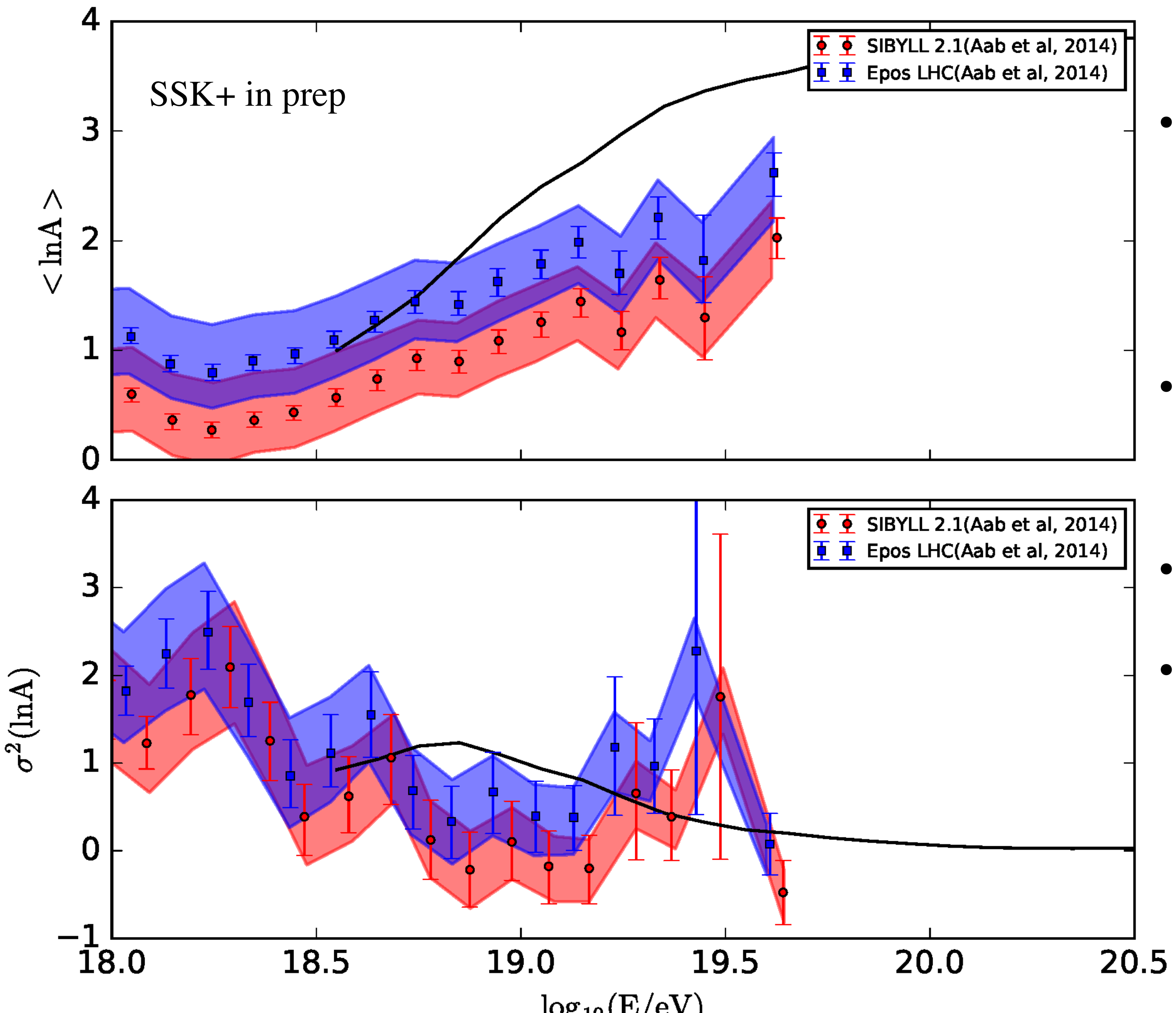
Spectrum at the Earth



- Compatible with the Auger result.
- A bit lower flux around E ~ 30 EeV
- We need another EeV component

cf.) Aloisio+14

Composition at the Earth



- Consistent with the Auger feature: heavier for higher E
- < ln A> is heavier for E > 10 EeV
- σ^2(ln A) is comparable
- For higher E_{peak} model, <ln A> is better, but the spectrum is worse

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Summary

- Experiments for UHECRs show
  a) Cutoff energy: 40-50 EeV
  b) Luminosity density: 3×10^{43} erg Mpc^{-3} yr^{-1}
  c) Heavier composition for higher energy
  d) Large number density: $n > 10^{-6}$ Mpc^{-3}
- The model of re-acceleration of galactic CRs by shear in FR-I radio galaxies are consistent with all the requirement above.