Ultra high energy cosmic rays from the Galactic center

V.N.Zirakashvili, S.I.Rogovaya

IZMIRAN

Particle acceleration in relativistic jets produced via accretion on supermassive black holes (SMBHs) in galactic centers

$$E_{\max} = 1.7 \cdot 10^{19}\text{eV}\ Z\beta^{1/2}\left(\frac{L_{\text{mag}}}{10^{44}\text{erg s}^{-1}}\right)^{1/2}$$

доускорение частиц, попадающих в джет сбоку

Caprioli 2015

- объясняет обогащение тяжелыми ядрами

тороидальное магнитное поле

сдвиговое течение

Фрикционное ускорение Бережко 1981

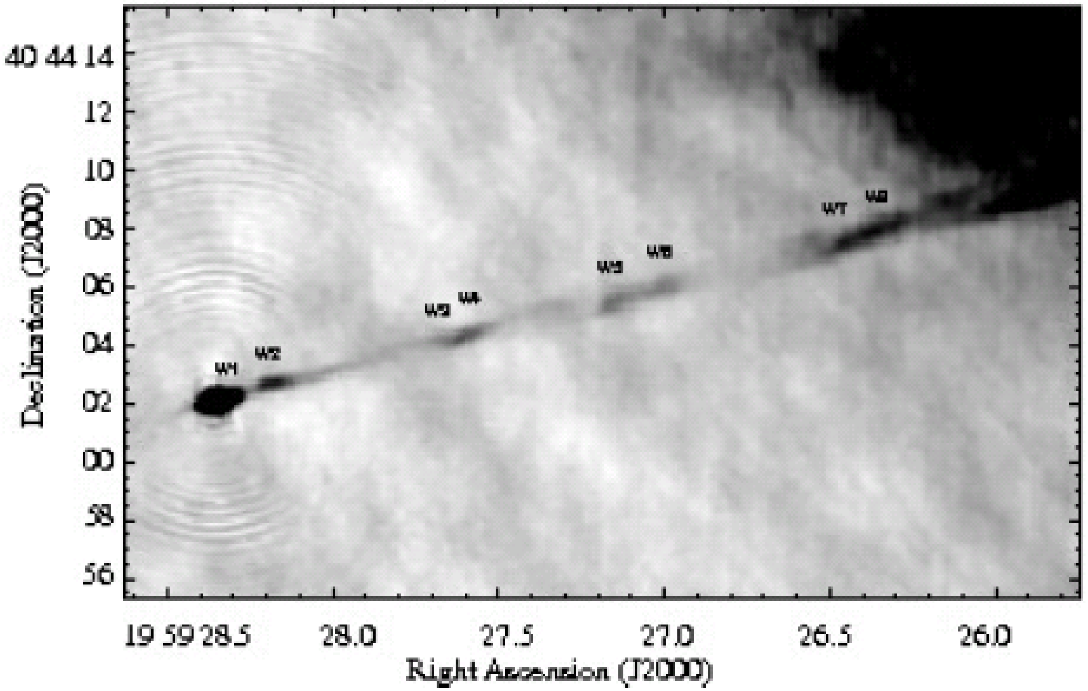
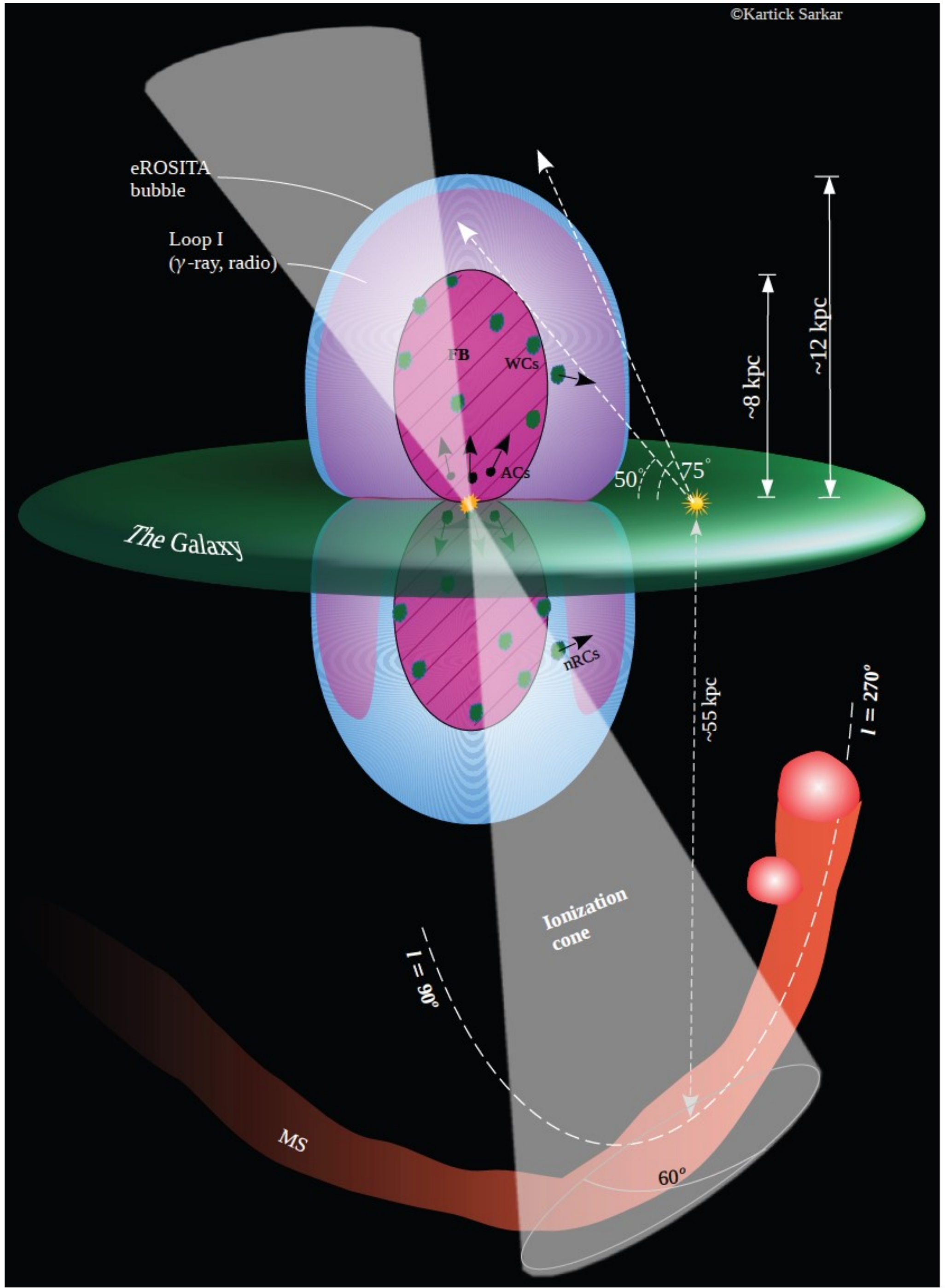


Figure 2. The inner jet of Cygnus A observed at 5 GHz. Note the weak emission between W1 and W2 which extends about half way to W3. Thereafter, there there are only hints of smooth emission between the jet knots, which become brighter from W7 onwards. The jet seems straight, but note the possible bend between W3 and W4. W7 and W8 are the first jet knots in what we call the 'outer jet'.



Galactic center energetics (Sarkar 2024)

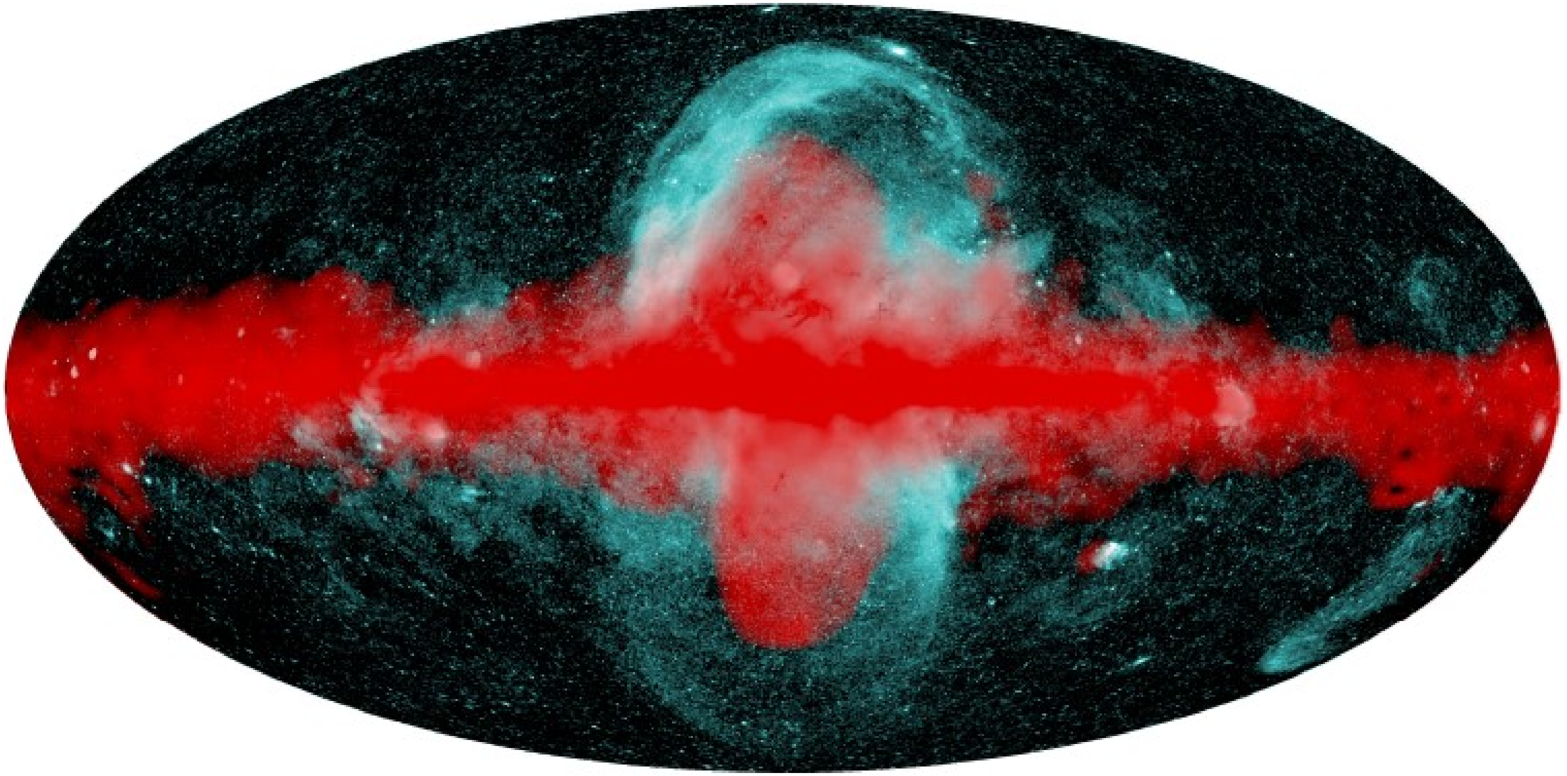
Activity	Scale	Rates	Power [erg s^{-1}]
Star formation	~ 100 pc	0.07, 0.2 – 0.8 $M_{\odot}$ yr^{-1}	$10^{40.3}$, $10^{40.9-41.5}$
AGN (Current)	~ 10^{-6} pc	10^{-8} $M_{\odot}$ yr^{-1}	$10^{38-38.7}$
AGN (~ 100 yr ago)	~ 10^{-6} pc	~ $10^{-5 \text{ to } -4}$ $M_{\odot}$ yr^{-1}	10^{41-42}
AGN (~ 1-3 Myr ago)	~ 10^{-6} pc	-	$10^{43.7-44.7}$

For super-massive black hole in the Galactic center
L_{Edd} = $5 \cdot 10^{44}$ erg/sec - enough for acceleration of UHECRs

Fermi and eRosita bubbles (Predehl et al. 2020)

Probably produced by SMBH activity several million years ago

W ~ 10^{56} erg,
L ~ 10^{41} - 10^{42} erg /sec

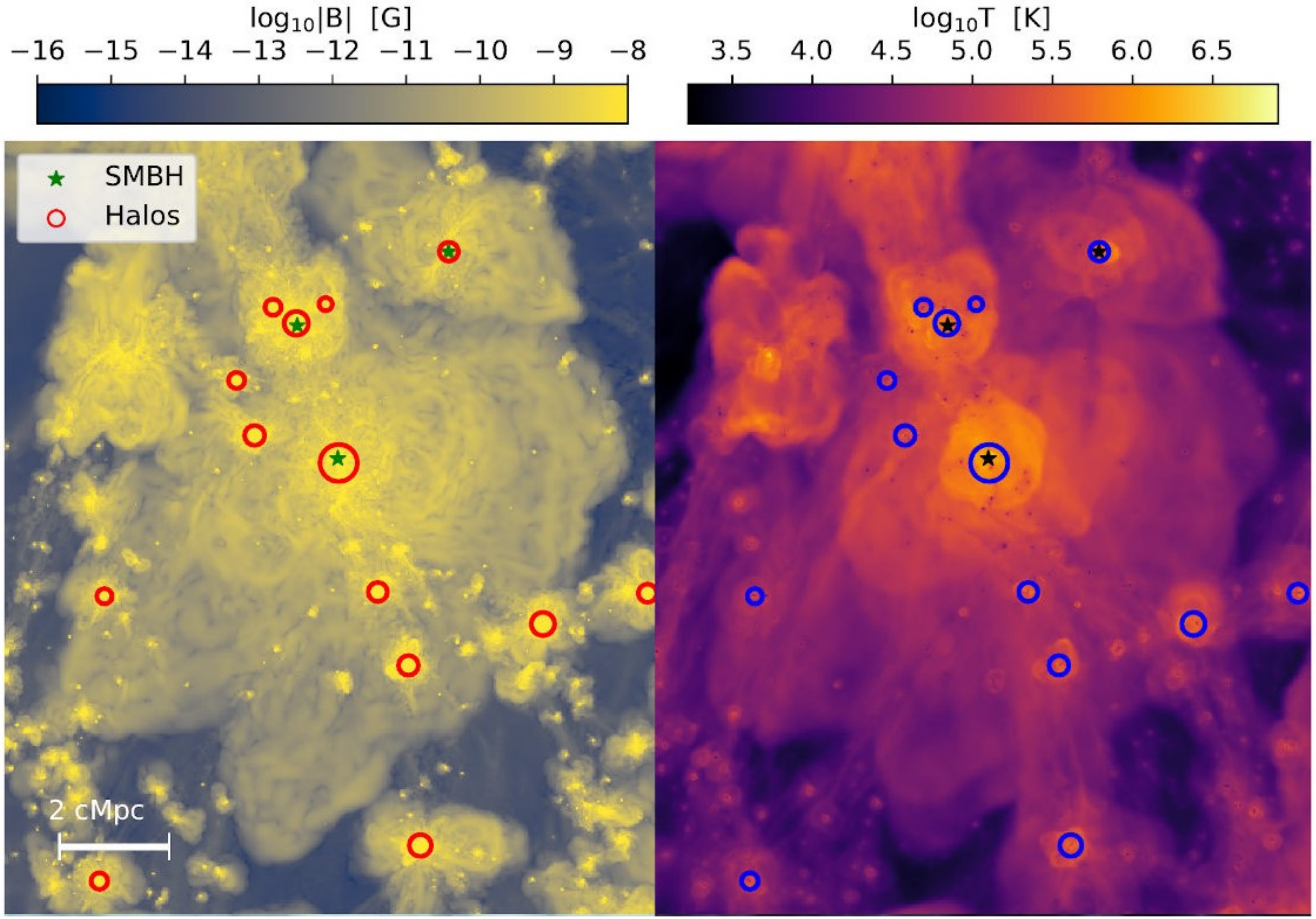


CR acceleration in GC

Fan 1951
Kulikov, Fomin, Khristiansen 1969 - UHECRs
Wayland 1972
Ptuskin & Khazan 1981
Giler 1983
Istomin 2014
Fujita et al. 2017

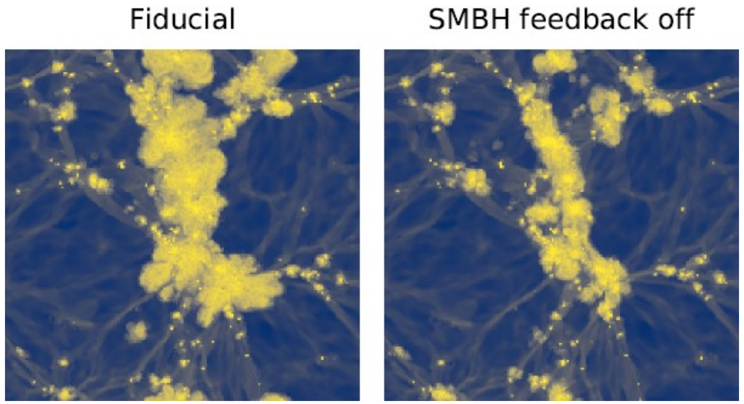
Confinement of UHECRs strongly depends on the magnetic fields in the circumgalactic medium.

Extended halos with hot gas and magnetic fields in cosmological simulations (Arámburo-García et al. 2021)



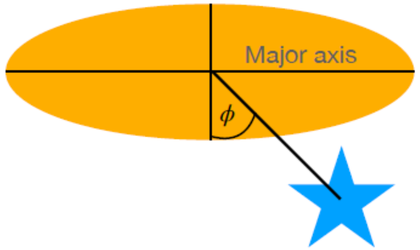
Mpc scale bubbles are produced by supernovae and growing SMBHs activity just after galactic formation.

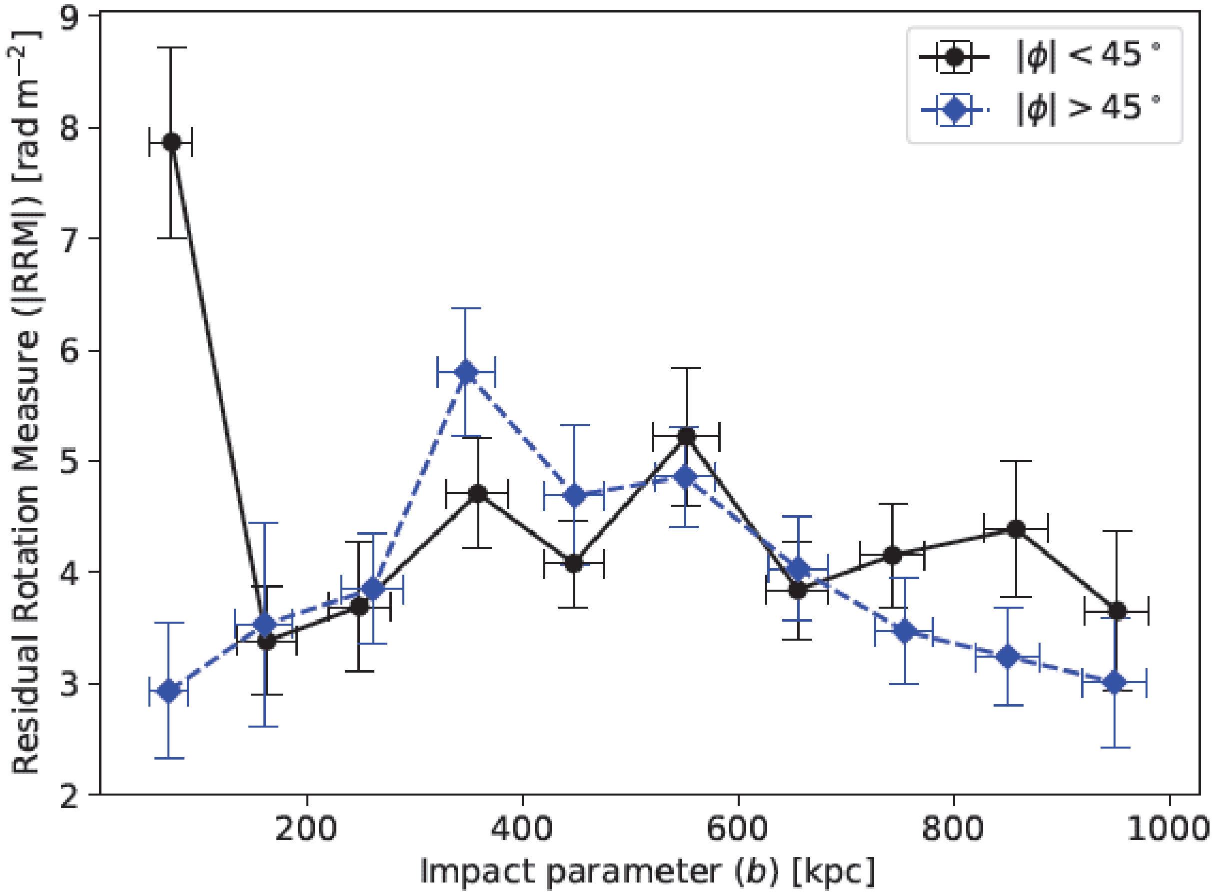
Input of SMBHs



25 Mpc

Magnetic field strength from Faraday rotation measurements in extended halos (Heesen et al. 2023, Böckmann et al. 2023)





$$\mathrm{RM} = 0.81 \int_{\mathrm{LoS}} \left(\frac{n_e}{\mathrm{cm}^{-3}}\right)\left(\frac{B_{\parallel}}{\mu\mathrm{G}}\right)\left(\frac{\mathrm{d}r}{\mathrm{pc}}\right) \mathrm{rad\,m}^{-2}$$

$B_{\parallel}$ ~ 0.5 μG, $n_e = 10^{-4}$ cm^{-3}

3 components of accelerated particles

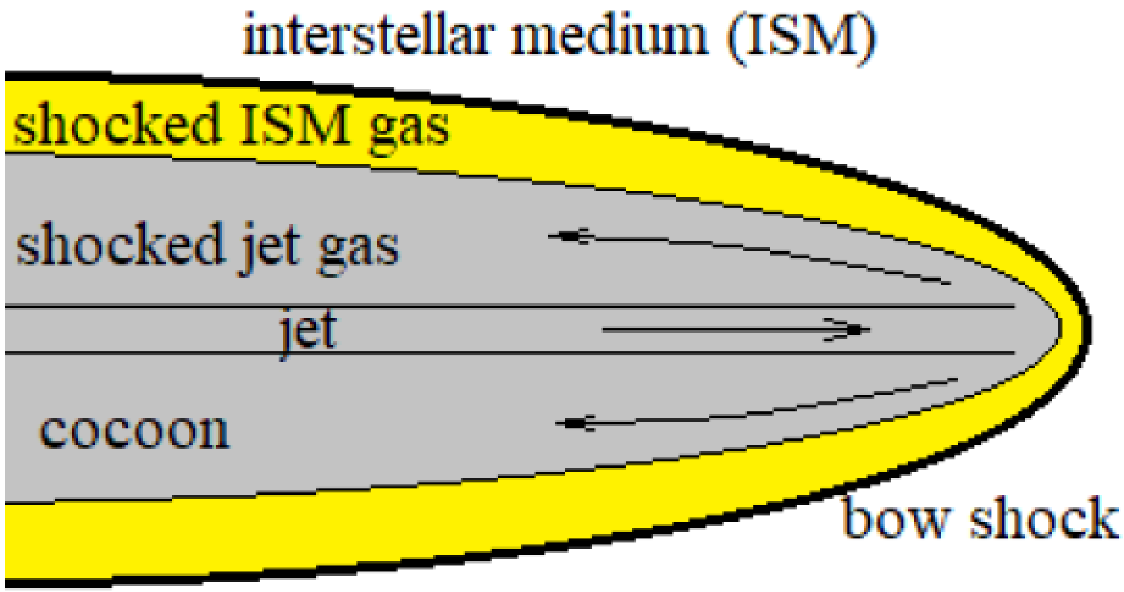
$$q(\epsilon, A) \propto \frac{k(A)}{\epsilon^2}\left(\frac{A\epsilon}{Z}\right)^{-\gamma+2}\exp\left(-\frac{A\epsilon}{Z\epsilon_{\max}}\right)$$

Source parameters (heavy jet composition, 20 times enrichment)

component	γ	$\epsilon_{\max}$	$E_{\rm cr}(E>1\ {\rm GeV})$	$k(A)/k_{\odot}(A)$
jet	0.0	3×10^{18} eV	2.9×10^{53}erg	$1, A=1,\ 2,\ A=4,\ 2\times20,\ A>4$
bow shock	2.0	4×10^{15} eV	1.9×10^{55}erg	$1, A=1,\ 2, A=4,\ A/4, A>16,$ $2A/Z,\ 4<A\leq16$
inner jet	2.0	3×10^{18} eV	3.5×10^{54}erg	$1,\ A=1,\ 0,\ A>1$

$$\epsilon^{j}_{\max} = e\sqrt{\beta_{\rm j}L_{\rm mag}c^{-1}}$$

$$= 1.73\times10^{19}{\rm eV}\ \beta_{\rm j}^{1/2}\left(\frac{L_{\rm mag}}{10^{44}{\rm erg\ s^{-1}}}\right)^{1/2}$$



Maximum energy at the bow shock (3-4 order lower)

$$\epsilon^{b}_{\max} = \frac{\eta_{\rm esc}}{2\ln(B/B_b)}e\sqrt{\beta_{\rm head}L_{\rm j}c^{-1}}$$

$$= 1.73\times10^{19}{\rm eV}\ \frac{\eta_{\rm esc}}{2\ln(B/B_b)}\beta_{\rm head}^{1/2}\left(\frac{L_{\rm j}}{10^{44}{\rm erg\ s^{-1}}}\right)^{1/2}$$

Diffusion from the nearby source

$$D = \frac{c l_c}{3}\left(4\frac{E^2}{E_c^2} + 0.9\frac{E}{E_c} + 0.23\frac{E^{1/3}}{E_c^{1/3}}\right), \quad E_c = ZeBl_c$$ (Harari et al. 2013)

$$\int_{-\infty}^{\infty} \mathrm{d}l \langle \vec{B}(0) \cdot \vec{B}(\vec{x}(l)) \rangle \equiv B^2 l_c$$

Nearby SMBHs:
Galactic center 8 kpc
$4 \cdot 10^6$ solar masses
Andromeda galaxy (M31) 800 kpc
$2 \cdot 10^8$ solar masses – both are not active

Kulikov, Fomin, Khristiansen (1969)
Mollerach & Roulet (2019) for nuclei and instantaneous source

Wdowczyk & Wolfendale (1979)
Berezinsky et al. (1988) for proton source

Equations for protons and nuclei

$$-H(z)(z+1)\frac{\partial N}{\partial z} = \frac{1}{r^2}\frac{\partial}{\partial r}r^2 D(\epsilon,r,z)(z+1)^2\frac{\partial N}{\partial r} + H(z)\epsilon\frac{\partial N}{\partial \epsilon} + \frac{\partial}{\partial \epsilon}b(\epsilon)N$$

$$+4\nu_{ph}(4)N_i(4) + \sum_{A=5}^{56}\nu_{ph}(A)N_i(A) + q(r,\epsilon,z)$$

$$-H(z)(z+1)\frac{\partial N_i(A)}{\partial z} = \frac{1}{r^2}\frac{\partial}{\partial r}r^2 D_i(\epsilon,r,z)(z+1)^2\frac{\partial N_i(A)}{\partial r} + H(z)\epsilon\frac{\partial N_i(A)}{\partial \epsilon} + \frac{\partial}{\partial \epsilon}b(\epsilon)N_i(A)$$

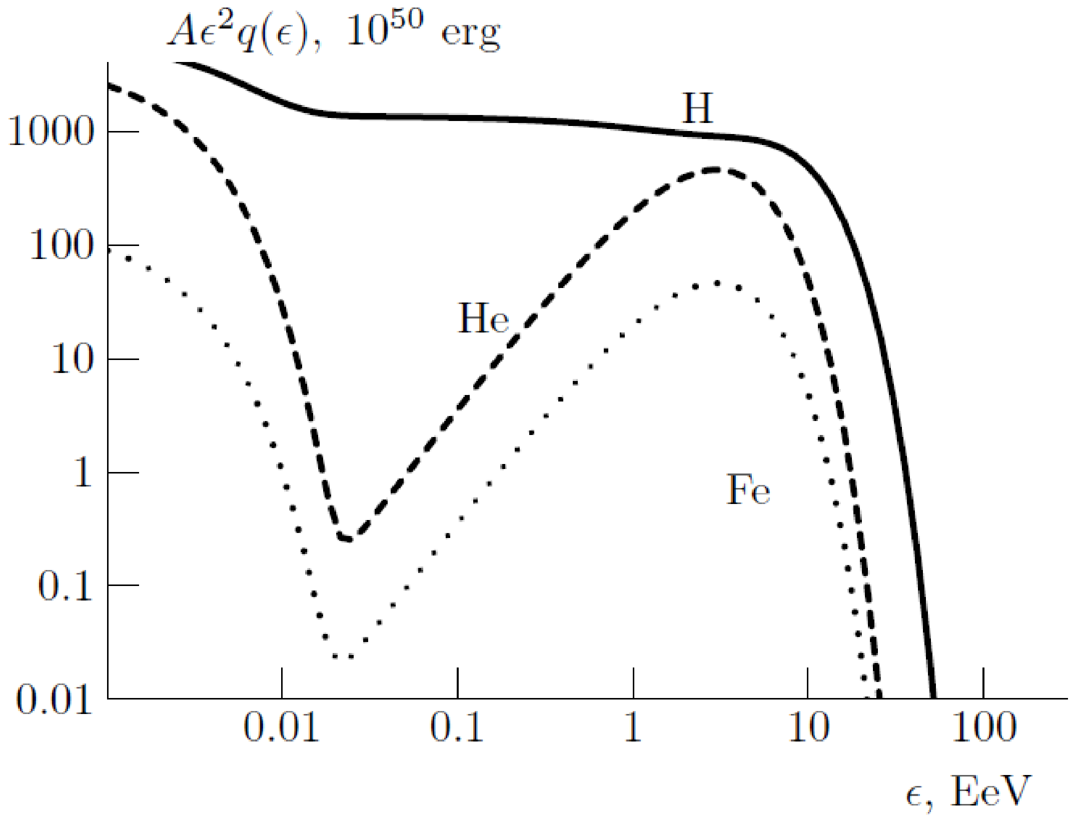
$$-\nu_{ph}(A)N_i(A) + \nu_{ph}(A+1)N_i(A+1) + q_i(r,\epsilon,z)$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3+\Lambda},\ \epsilon = E/A$$

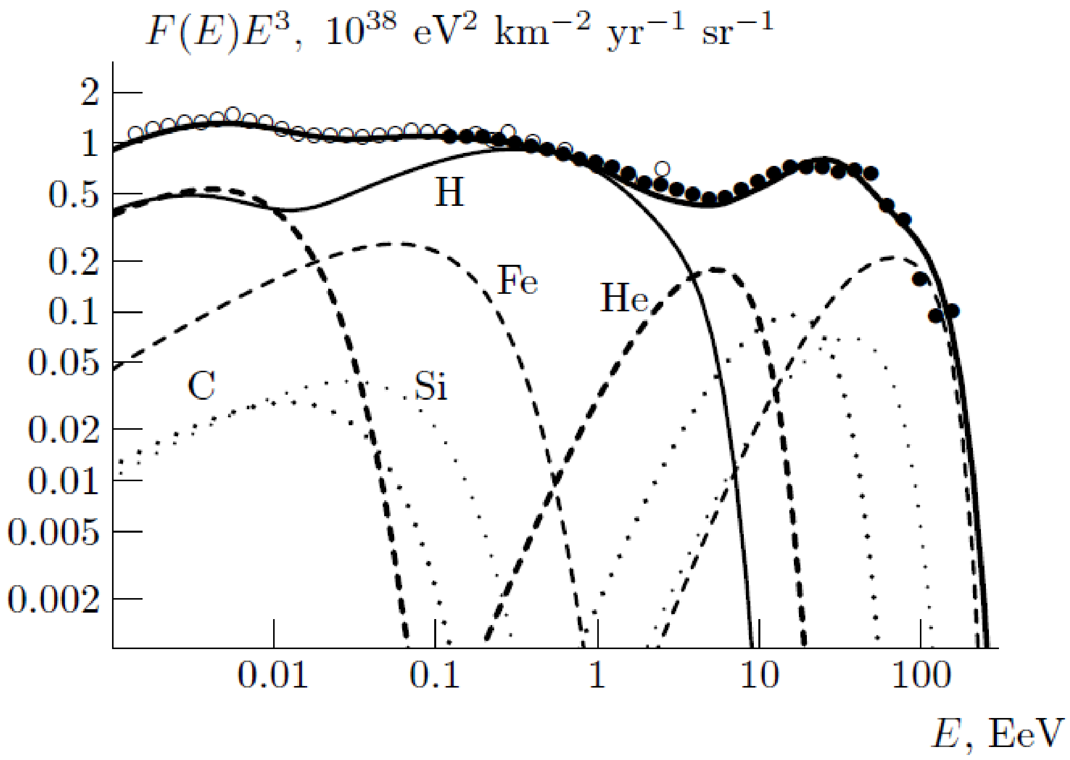
Spectra

R=400 kpc - radius of extended halo,
$l_c = 40$ kpc, $B = 0.2 \cdot 10^{-6}$ Гс,
SMBH activity 6 million years ago,
CR energy - $2.3 \cdot 10^{55}$ erg

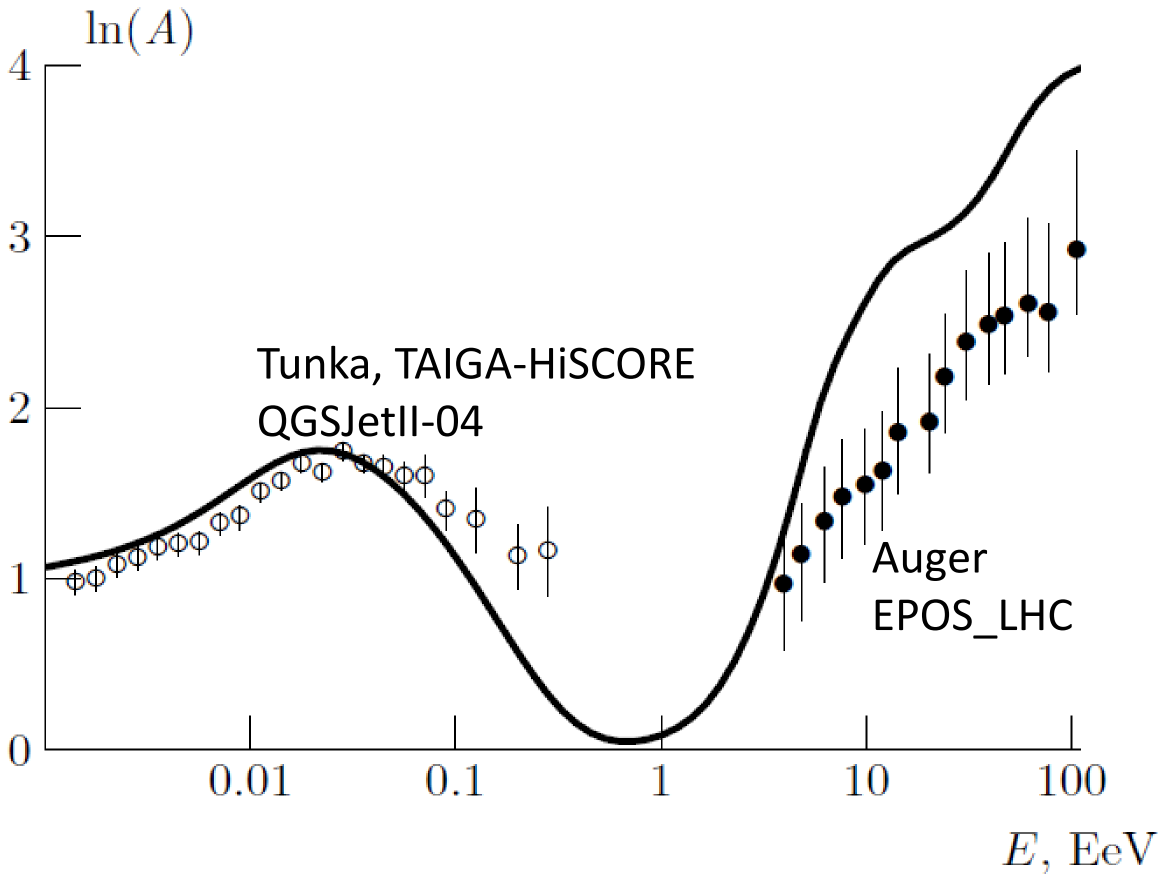
Source spectrum

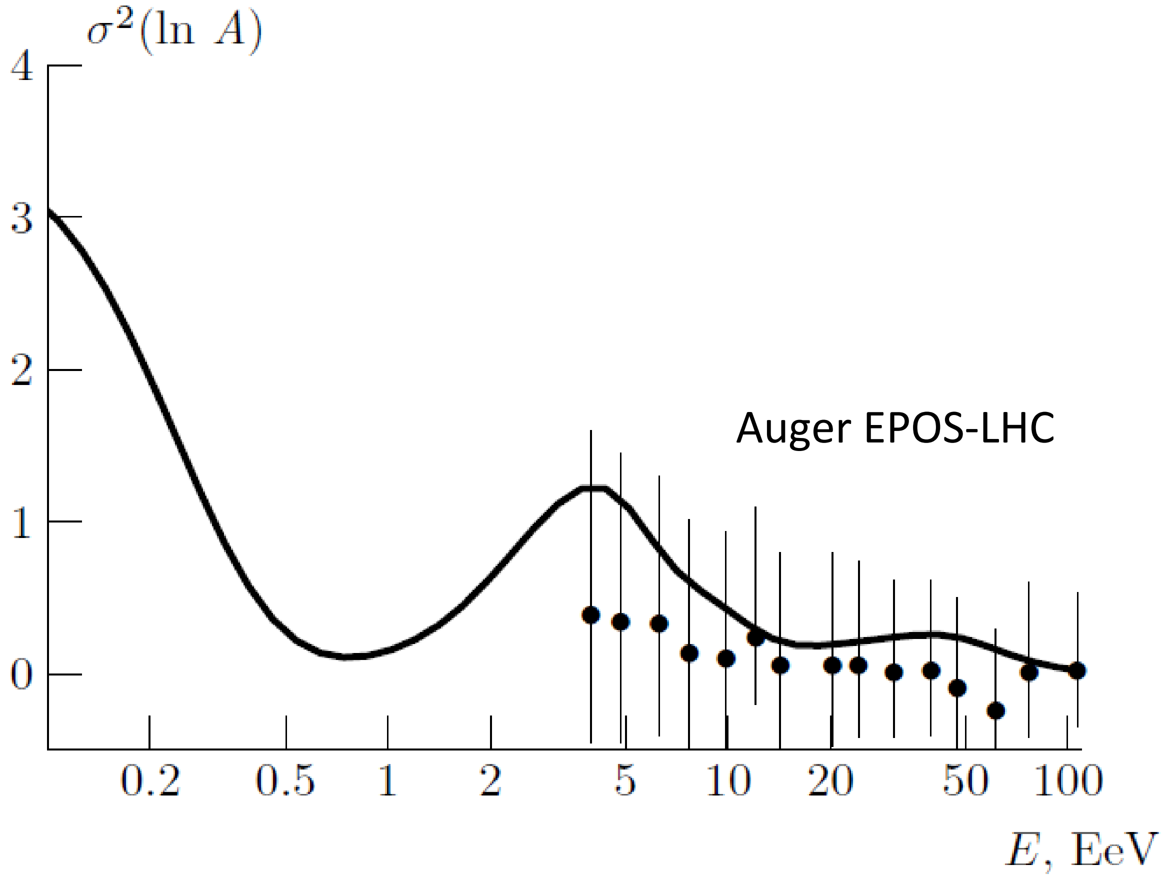


Spectra at the Earth

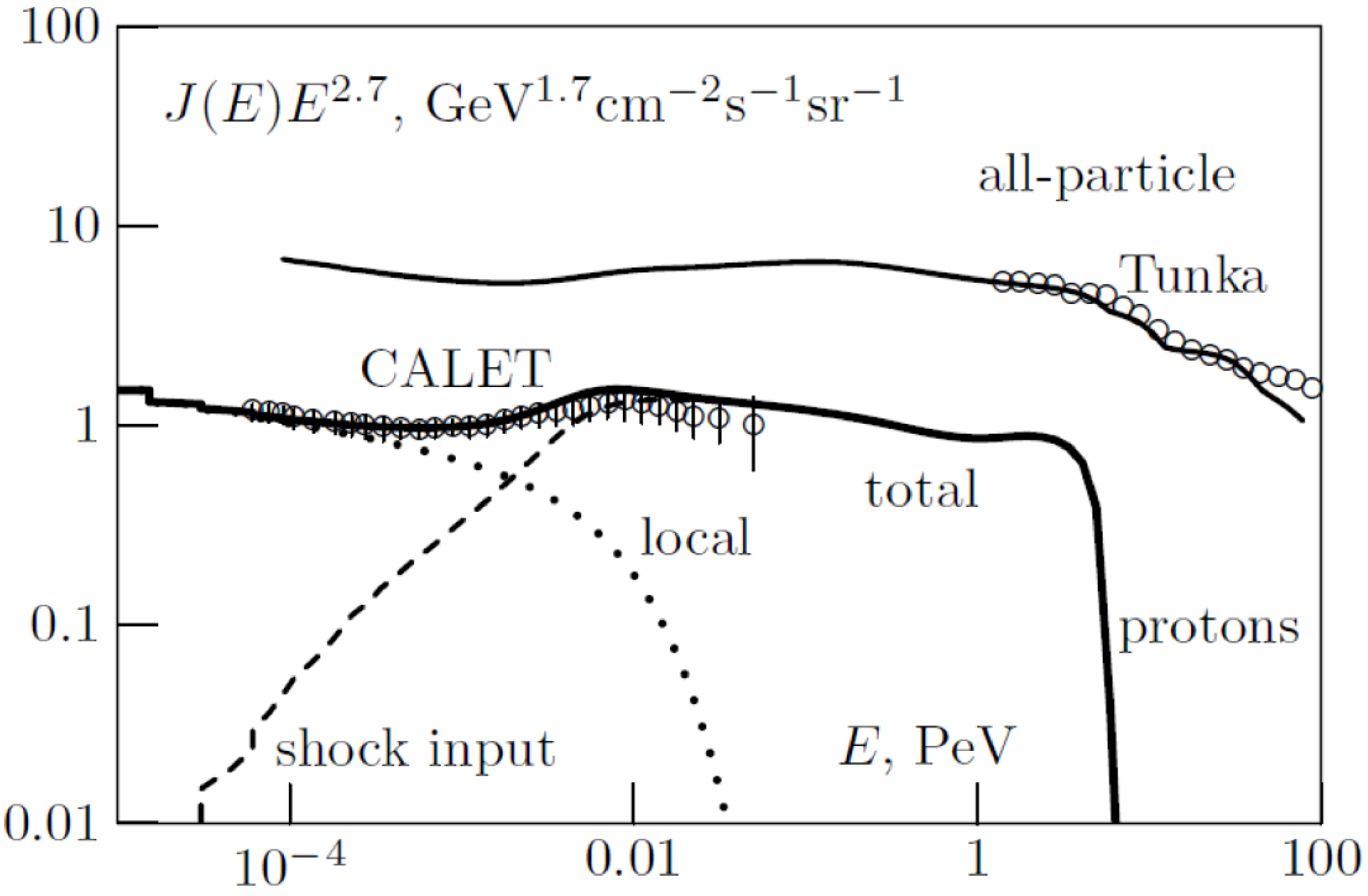


Chemical composition





Transition to lower energies? (Zirakashvili et al. 2025)



Conclusion

1. Cosmic ray spectra at energies above 1 PeV could be explained in the model of powerful energy release several million years ago in the Galactic center.
2. PeV cosmic rays are accelerated at the bow shock produced by the relativistic jet.
3. Highest energy CRs are accelerated in the jet.
4. The jet power required 10^{45} erg/sec is comparable with the Eddington luminosity of SMBH in the Galactic center.
5. UHECR particle are confined in extended (several hundreds kpc in size) Galactic halo. It is shown that the magnetic field strength $0.2 \cdot 10^{-6}$ G is enough for the effective confinement.