Relativistic jets are sources of cosmic rays in galaxies

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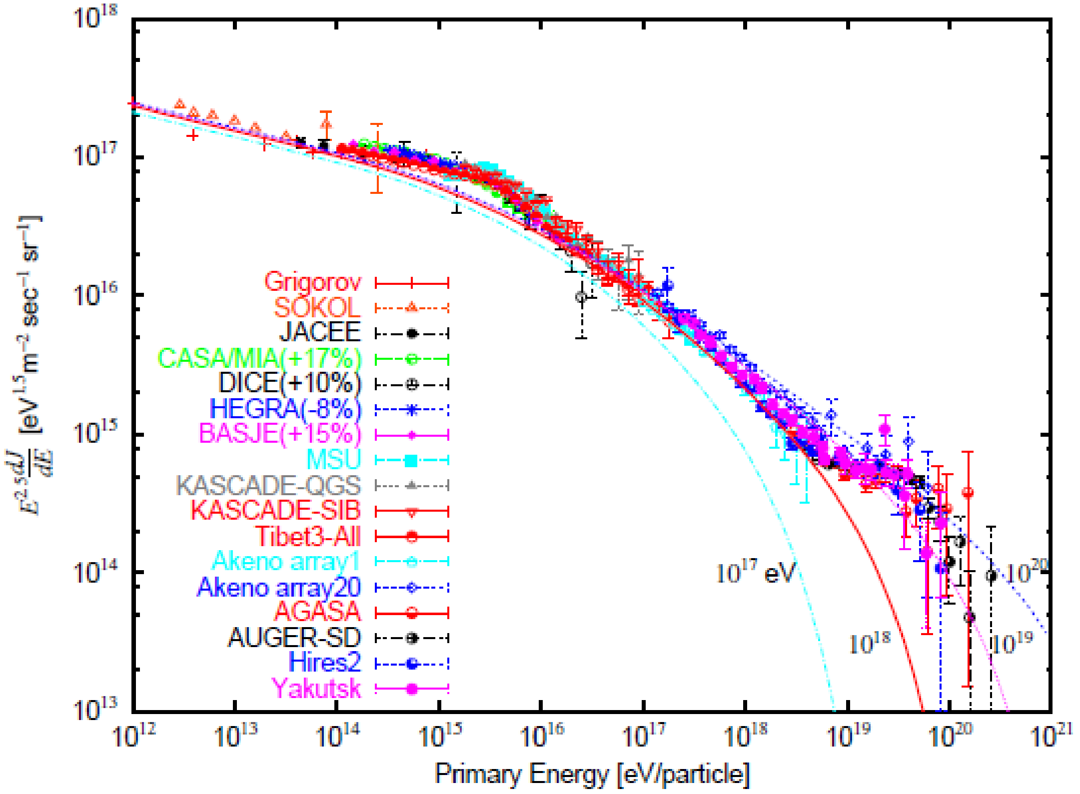
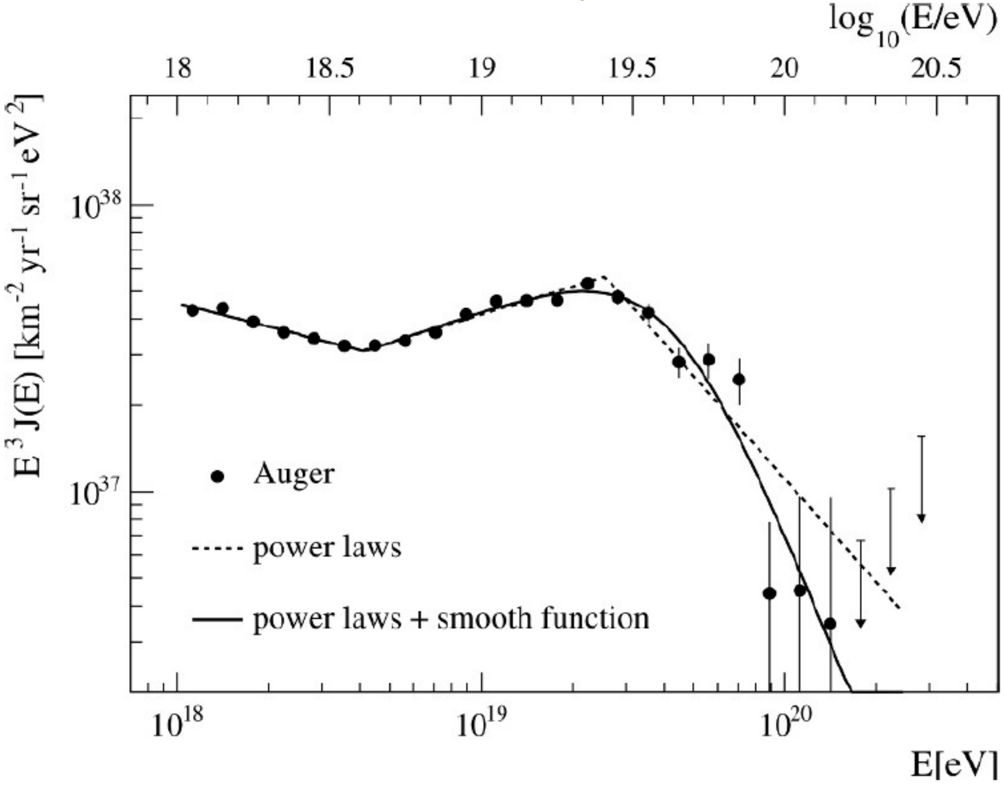
Cosmic rays spectrum

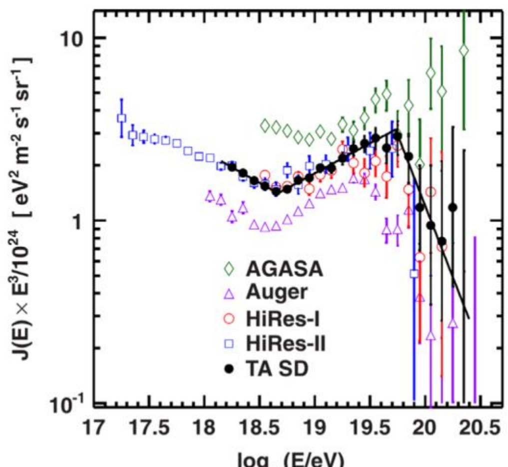


Extragalactic rays

Ankle: E>3e18 Ev – точно внегалактика

GZK-cutoff: E~1e20 Ev, R<100 Мпк





J(E) × E^3/10^24 [eV^2 m^-2 s^-1 sr^-1]
10
1
10^-1
17
17.5
18
18.5
19
19.5
20
20.5
log10(E/eV)
AGASA
Auger
HiRes-I
HiRes-II
TA SD

- Particle motion in the intergalactic media

$$r_L = \frac{E}{ZeB} = 11Z^{-1}\left(\frac{E}{10^{19}eV}\right)\left(\frac{B}{1nG}\right)^{-1} Mpc.$$

$$\Delta\theta = \left(\frac{l_c r}{r_L^2}\right)^{1/2} = 0.09Z\left(\frac{E}{10^{19}eV}\right)^{-1}\left(\frac{B}{1nG}\right)\left(\frac{l_c}{1Mpc}\right)^{1/2}\left(\frac{r}{1Mpc}\right)^{1/2}.$$

- Kinetic equation for relativistic particles

$$-c\frac{\partial N}{\partial r}+\frac{\partial}{\partial E}\left(\frac{dE}{dt}N\right)=\sum_i \frac{Q_i(E)}{4\pi r_i^2}\delta(r-r_i).$$

$p+\gamma \rightarrow N+\pi$

$$E_1=\mu c^2(1+\mu/m_p)m_p c^2/2T \simeq 4\cdot 10^{20} eV \quad m_p$$

$$\frac{d\epsilon}{dt'}=-(1+\epsilon)\exp(-\epsilon^{-1}).$$

$$\epsilon = E/4\cdot 10^{20} eV \quad t' = ct/L \quad L = 13.7 Mpc$$

p + γ = p + e+ + e−

$$E_2 = m_e c^2 m_p c^2 / T \simeq 2.1 \cdot 10^{18} eV$$

$$\left(\frac{d\epsilon}{dt'}\right)_e = -a\epsilon(\epsilon_e^{-2} + b\epsilon_e^{0.6})^{-1}\exp(-\epsilon_e^{-1}),\ \epsilon_e = E/E_2 = 190\epsilon.$$

$$a = 4.5 \cdot 10^{-4},\ b = 8.4 \cdot 10^{-3}$$

$$dE/dt = -HE \qquad H = 72\, km/s/Mpc$$

$$\left(\frac{d\epsilon}{dt'}\right)_a = -\alpha\epsilon,\ \alpha = 3.3 \cdot 10^{-3}.$$

$$\tau = \int_{\epsilon}^{\epsilon'} \frac{dx}{\mid d\epsilon/dt \mid_{\epsilon=x}}.$$

$$\frac{\partial}{\partial r}\left(\mid \frac{d\epsilon}{dt} \mid N\right) - \frac{\partial}{\partial \tau}\left(\mid \frac{d\epsilon}{dt} \mid N\right) = -\sum_i \frac{Q_i(\epsilon)\left|\frac{d\epsilon}{dt}\right|}{4\pi r_i^2}\delta(r - r_i).$$

$$N(r=0,\epsilon) = \frac{1}{|d\epsilon/dt|}\sum_i \frac{Q_i(\epsilon_i) \mid \frac{d\epsilon}{dt} \mid_{\epsilon=\epsilon_i}}{4\pi r_i^2} + \frac{\mid d\epsilon/dt \mid_{\epsilon=\epsilon_m}}{\mid d\epsilon/dt \mid} N(\epsilon_m, r_m).$$

$$r_i = \int_{\epsilon}^{\epsilon_i} \frac{dx}{\mid d\epsilon/dt \mid_{\epsilon=x}}.$$

$$\frac{1}{|d\epsilon/dt|} \sum_i \frac{Q_i(\epsilon_i) \mid \frac{d\epsilon}{dt} \mid_{\epsilon=\epsilon_i}}{4\pi r_i^2} = \frac{\int_{\epsilon}^{\epsilon_m} \bar{q}(\epsilon')d\epsilon'}{|d\epsilon/dt|}.$$

$$N(r=0,\epsilon) = \frac{\int_{\epsilon}^{\epsilon_0} \bar{q}(\epsilon')d\epsilon'}{|d\epsilon/dt|}.$$

Diffusion

$$\frac{\partial}{\partial E}\left(\frac{dE}{dt}N\right) - \frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial N}{\partial r}\right) = \sum_i \frac{Q_i(E)}{4\pi r_i^2}\delta(r - r_i).$$

$$D = D_0 E^\kappa \qquad \tau_D = \int_\epsilon^{\epsilon'} \frac{x^\kappa dx}{\mid d\epsilon/dt \mid_{\epsilon=x}}.$$

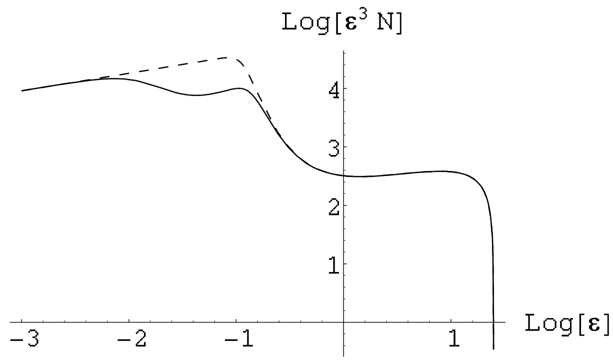
$$\frac{\partial}{\partial \tau_D}\left(\mid \frac{d\epsilon}{dt} \mid N\right) - \frac{D_0}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\left(\mid \frac{d\epsilon}{dt} \mid N\right)\right) = \epsilon^{-\kappa} \mid \frac{d\epsilon}{dt} \mid \sum_i \frac{Q_i(\epsilon)}{4\pi r_i^2}\delta(r - r_i).$$

$$N(r_m, \epsilon) = \frac{1}{|d\epsilon/dt|}\int_\epsilon^{\epsilon_0} \bar{q}(\epsilon')\Phi\left[\left(\frac{r_m^2}{4D_0\tau_D}\right)^{1/2}\right] d\epsilon'.$$

$$N(r=0,\epsilon) = \frac{\int_{\epsilon}^{\epsilon_0} \bar{q}(\epsilon')d\epsilon'}{|d\epsilon/dt|}.$$

$$\bar{q}(\epsilon) = q_0 \epsilon^{-\beta}$$

$$N(r = 0, \epsilon) = \frac{\int_{\epsilon}^{\epsilon_0} \bar{q}(\epsilon') d\epsilon'}{|d\epsilon/dt|}.$$


Log[ε³ N]
4
3
2
1
Log[ε]
−3
−2
−1
1

$$\bar{q}(E) = 8.4 \cdot 10^8 \left(\frac{E}{4 \cdot 10^{19} eV} \right)^{-2.7} eV^{-1} s^{-1} Mpc^{-3}.$$

$$\mathcal{E} = \int_{E_{min}}^{E_0} \bar{q}(E) E dE$$

$$\mathcal{E} = 1.8 \cdot 10^{43} \left(\frac{E_{min}}{5GeV} \right)^{-0.7} erg\, s^{-1} Mpc^{-3}.$$

- Jets

$$(10^{45} - 10^{46}) erg\, s^{-1}$$

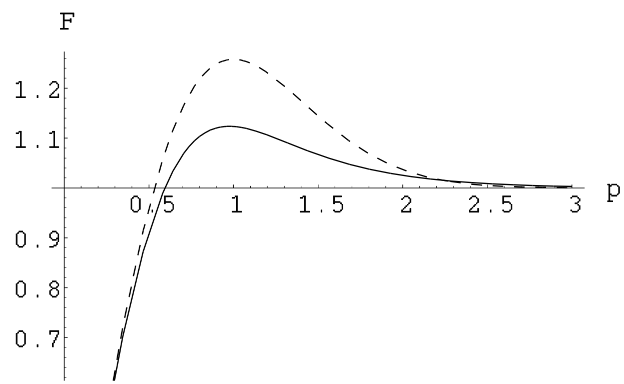
$$N_g \simeq (10^{-2} - 10^{-3}) Mpc^{-3}.$$

- Our Galaxy $E < 3 \cdot 10^{15} eV \quad \beta = 2.7$

$$N = Q\tau \quad \tau = R^2/D \qquad D \propto E^{0.7}$$

$$N(E) \propto E^{-2-0.7}$$

$$N(r,E,t) = N_0(E)F(p,r) \quad p(E,t) = [R^2/4D_g(E)t]^{1/2}$$


F
1.2
1.1
0.9
0.8
0.7
0.5
1
1.5
2
2.5
3
p

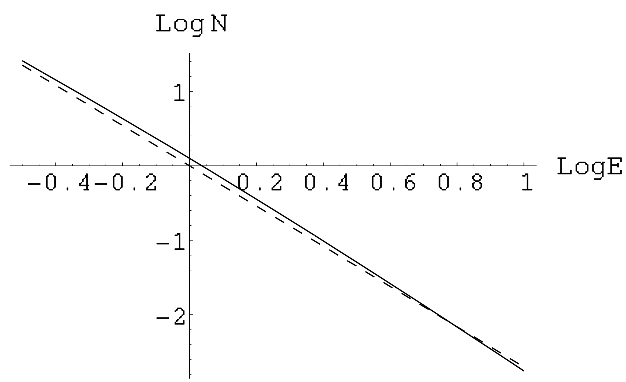
- P<1

$$F = 4p/\pi^{1/2}$$

$$N \propto E^{-2.7-0.7/2} = E^{-3.05}$$

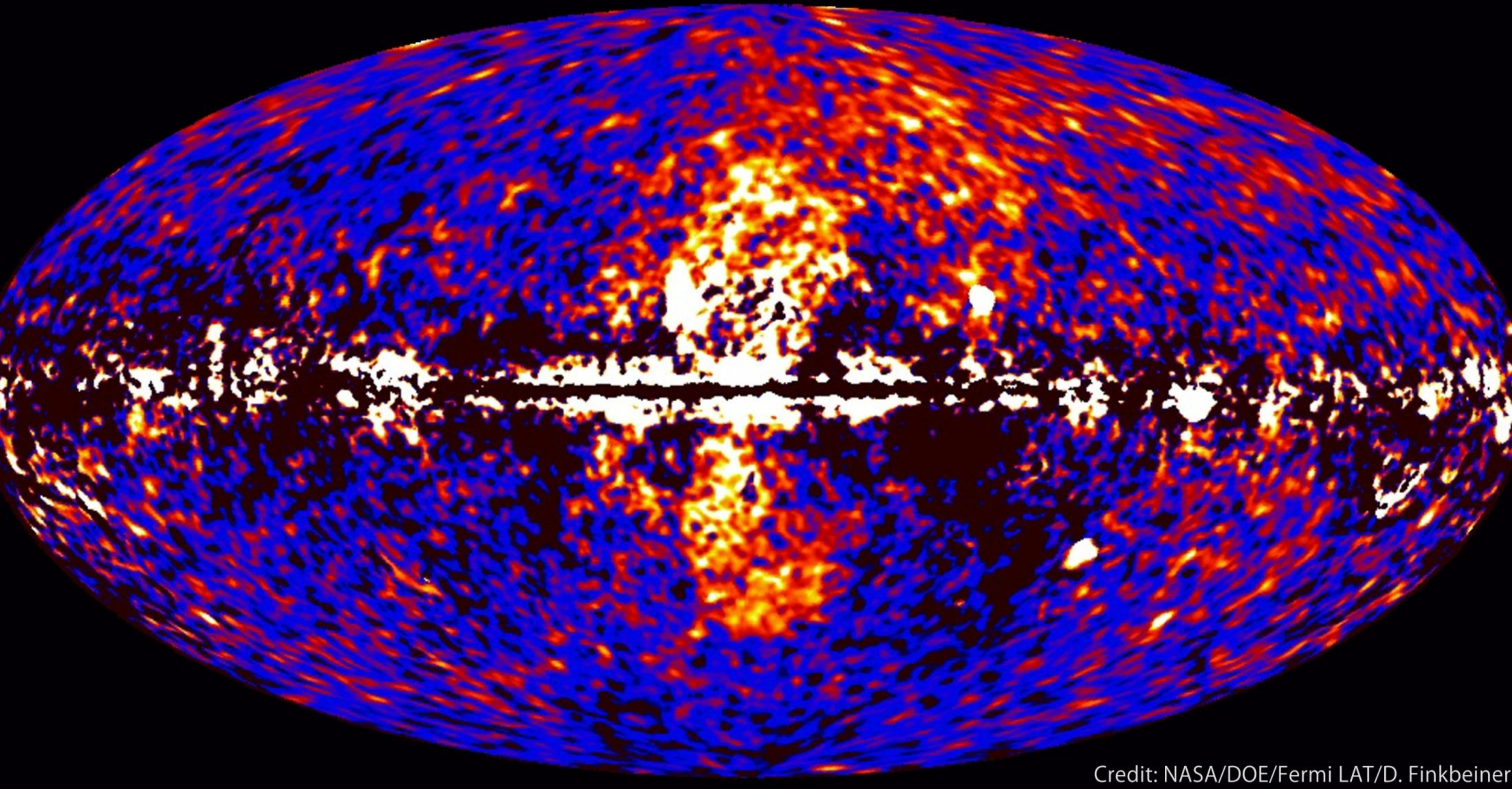
$$t_0 = \frac{R^2}{4D_g(E_k)} = 4.2 \cdot 10^4 \left(\frac{R}{5 \cdot 10^{22} cm}\right)^2 \left(\frac{D_g(1GeV)}{2.2 \cdot 10^{28} cm^2 s^{-1}}\right)^{-1} \left(\frac{E_k}{3 \cdot 10^{15} eV}\right)^{-0.7} year.$$

$$dE_k/dt = -1.43 E_k/t_0 = -10^{11} eV/year.$$

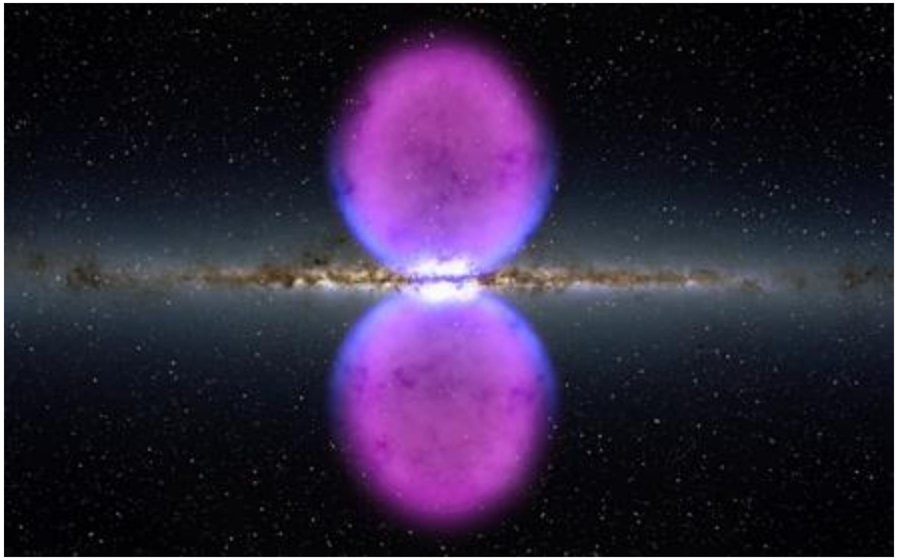

Log N
1
LogE
−0.4
−0.2
0.2
0.4
0.6
0.8
1
−1
−2

- Fermi Gamma-ray Space Telescope found bubbles of relativistic gas radiated in gamma range 0.1 − 1000 GeV
- Energy stored in bubbles is 10^54 − 10^55 erg
- F(E)=const E^(-2), size – 8kpc X 6kpc

Fermi data reveal giant gamma-ray bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner



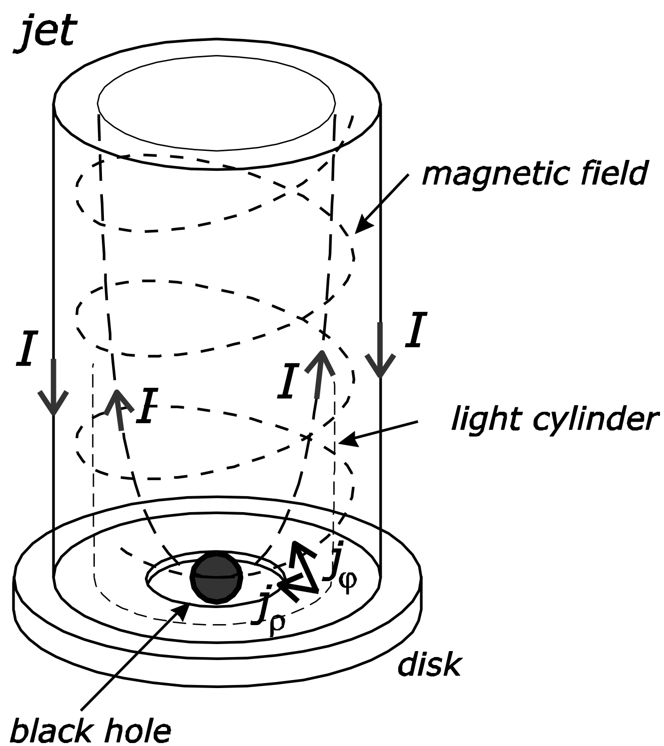
- Relativistic jets from active galaxies.

  Sgr A* - black hole

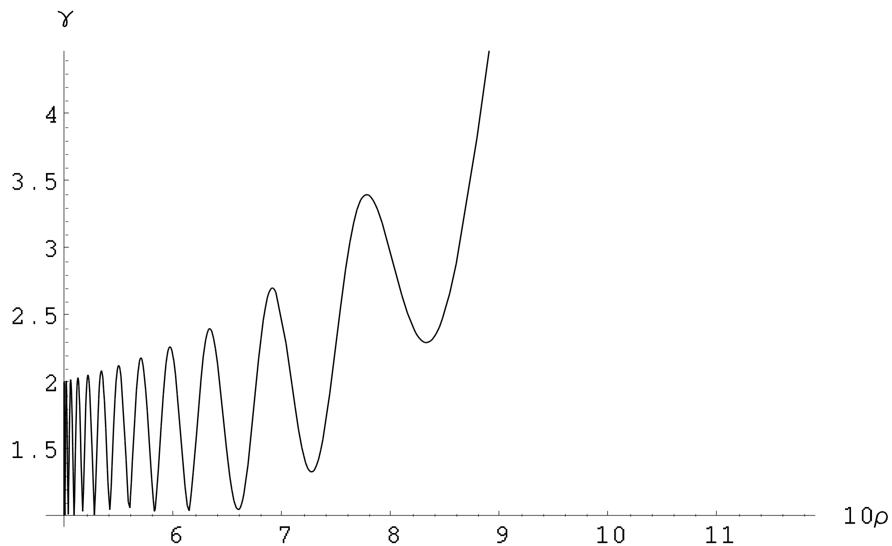
- $M \simeq 4 \cdot 10^6 M_\odot$ $L \simeq 10^{36}$ erg/s,

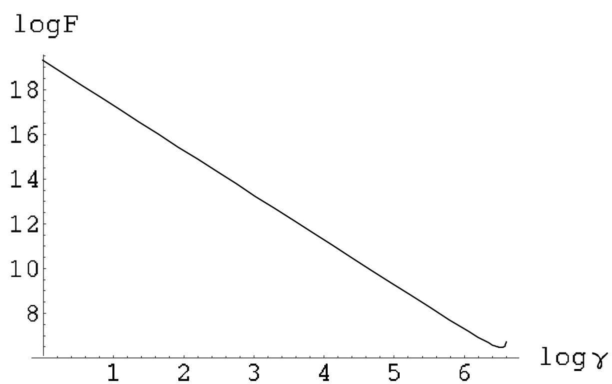
  $L_{Edd} = 5.2 \cdot 10^{44}$ erg/s

- Blandford-Znajek mechanism (1977)
- $E=10^{60} a^2$ erg, $a=cJ/M^2G$, $a<1$.
- Unipolar inductor: $U=\Omega f/2\pi c$,
- $\Omega=ac/2r$, $f=\pi Br^2$, $I=U/(R1+R)$, $R1=4\pi/c=$
- 377ohm. $R=R1$, $L=a^2B^2r^2c/256\pi$.
- $B>7\ 10^4\ a^{-8}$ Gauss.
- $L=2.5\ 10^{41} a^{-14}$ erg/s


jet
magnetic field
I
I
I
I
light cylinder
j_φ
j_ρ
disk
black hole

- Particle aceleration on the light surface, $l=c/\Omega=2r/a$. $\Gamma=(\Gamma1\ \ \Gamma)$^(1/2)
- $\Gamma1=\omega/\Omega>>1$, ω-cyclotron frequency on the light surface. $\Gamma1 >> 10$^(13)


γ
4
3.5
3
2.5
2
1.5
6
7
8
9
10
11
10ρ

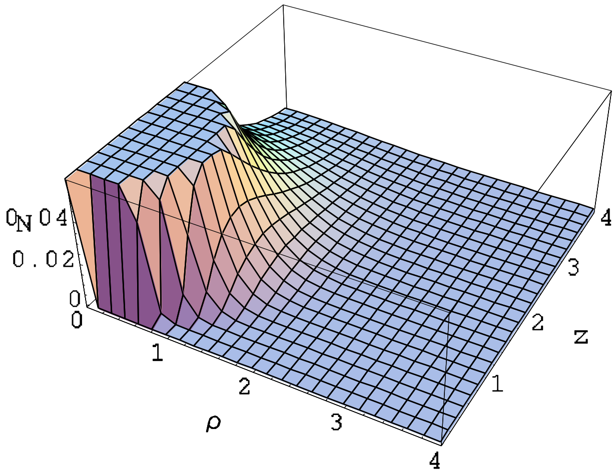

logF
18
16
14
12
10
8
log γ
1
2
3
4
5
6

- $F(\Gamma)=const\ \Gamma^{(-2)}$

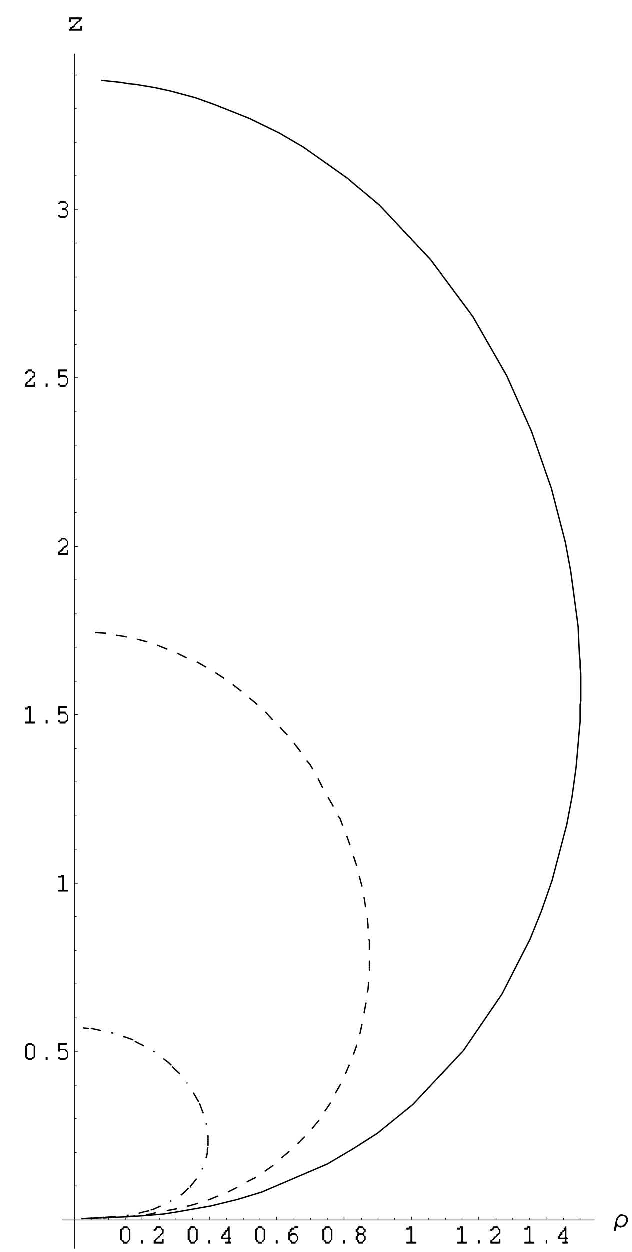
- Jet's remnants

$$\frac{\partial N}{\partial t} + \mathbf{u}\nabla N - \nabla \hat{D} \nabla N = Q(t)\delta(\mathbf{r}).$$

- $B = const\ e^{(-z/z_0)}$, $z_0 = 2$kpc
- $D = D_0\ e^{(z/z_0)}$
- $u_0 = D_0/z_0 = 10^2$ km/s
- $t_0 = z_0^2/D_0 = 2.4\ 10^7$ yr



N
0.04
0.02
0
0
1
2
3
4
ρ
1
2
3
4
z



z
3
2.5
2
1.5
1
0.5
0.2 0.4 0.6 0.8 1 1.2 1.4
ρ

- 1. Galactic cosmic rays can be produced by relativistic jet. Jet began to work 2.4 10^7 years ago and terminated 4.2 10^4 years ago.

  2. Remnants of the jet are bubbles of energetic particles.

- Discovery of the source of PeV particles in the center of Galaxy of the power of 10^37-10^38 erg/sec (Nature, HESS group, 2016)
- Sgr A* - black hole $M \simeq 4 \cdot 10^6 M_\odot$

$$L \simeq 10^{36}\ \mathrm{erg/s},$$
$$L_{Edd} = 5.2 \cdot 10^{44}\ \mathrm{erg/s}$$

Conclusions

1. Mechanisms of generation of extragalactic and Galactic cosmic rays are the same.
2. Sources of cosmic rays are jets from AGN, but not shock waves.
3. Our Galaxy was active in past and radiated jet.