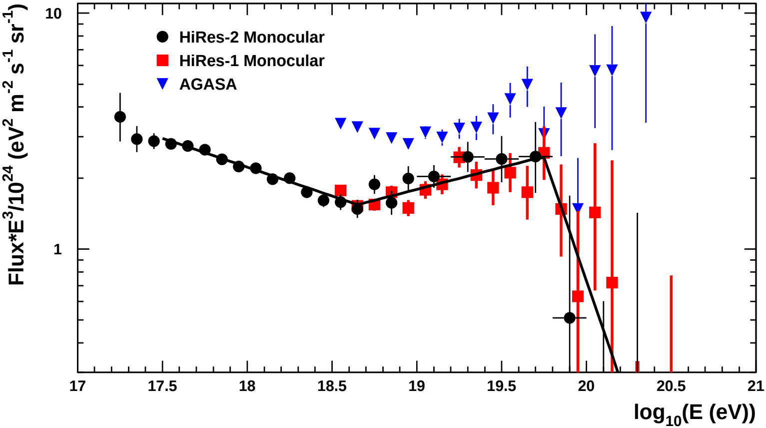
Ultra-High Energy Cosmic Ray production in the polar cap regions of black hole magnetospheres

A. Neronov, D. Semikoz, and I. Tkachev

see also A. Neronov, P. Tinyakov , & I. T. (2005)

Moscow, 20 May 2008

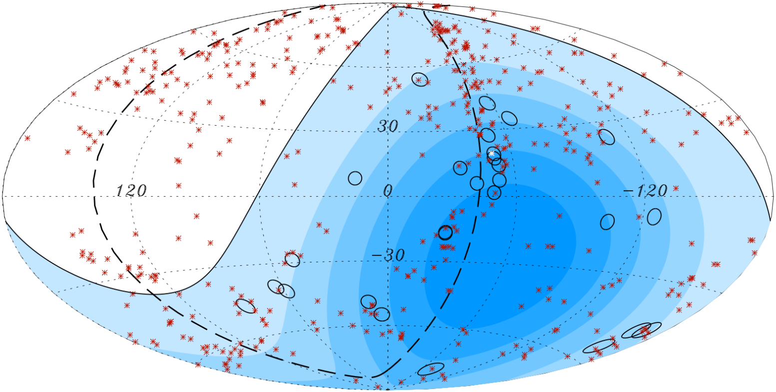
GZK cut-off



HiRes collaboration (2007)

Observation of the Greisen-Zatsepin-Kuzmin cut-off by the HiRes collaboration implyes extragalactic, but “local”, UHECR origin

Auger events and AGN



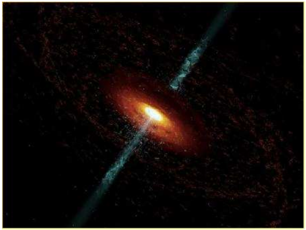
Pierre Auger collaboration has claimed association of the arrival directions of the highest energy primaries with AGNs. Tight angular scale of correlations imply protons.

Pierre Auger collaboration (2007)

Auger events and AGN

Question: is it possible to accelerate particles up to 10^{20} eV in the local AGNs ?

Shock acceleration (e.g. in jets and hot spots of radiogalaxies)

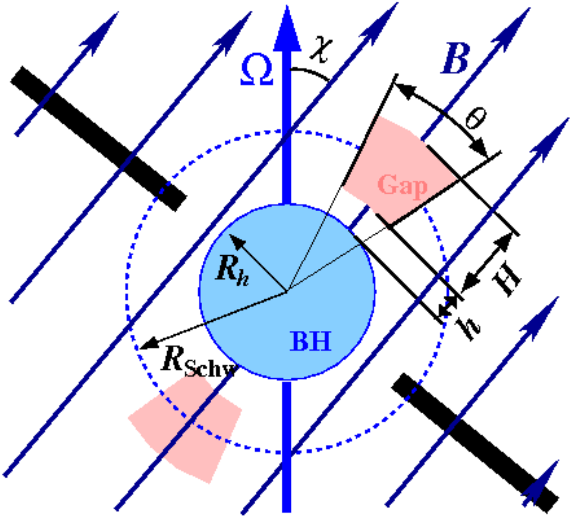


Direct acceleration (e.g. near pulsars and black holes)

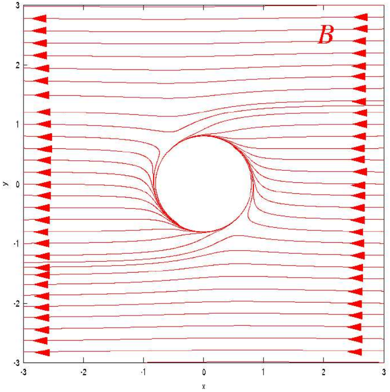
Note:

- majority of local AGNs are not radiogalaxies.
- BH of local AGNs have rather low masses

The model



The model



Kerr space-time:

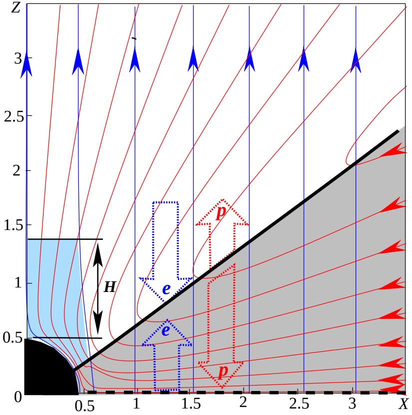
$$ds^2 = -\alpha^2 dt^2 + g_{ik}\left(dx^i + \beta^i dt\right)\left(dx^k + \beta^k dt\right)$$

$$\alpha = \frac{\rho\sqrt{\Delta}}{\Sigma}; \quad g_{rr} = \frac{\rho^2}{\Delta}; \quad g_{\theta\theta} = \rho^2; \quad g_{\phi\phi} = \frac{\Sigma^2 \sin^2\theta}{\rho^2};$$

$$\beta_\phi = -\frac{2aMr}{\Sigma^2}; \quad \Delta = r^2 + a^2 - 2Mr;$$

$$\Sigma^2 = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta; \quad \rho^2 = r^2 + a^2\cos^2\theta$$

The model



Solution of Maxwell equations:

$$
\begin{aligned}
F_{tr} = {} & \frac{aMB_0}{\rho^4\Delta}\Big[\cos\chi\Delta(r^2 - a^2\cos^2\theta)(1+\cos^2\theta) + \\
& \sin\chi r\sin\theta\cos\theta\Big\{(r^3 - 2Mr^2 + ra^2(1+\sin^2\theta) + 2Ma^2\cos^2\theta)\cos\psi - \\
& a(r^2 - 4Mr + a^2(1+\sin^2\theta))\sin\psi\Big\}\Big] \\
F_{t\theta} = {} & \frac{aMB_0}{\rho^4}\Big[2\cos\chi r\sin\theta\cos\theta(r^2 - a^2) + \\
& \sin\chi(r^2\cos 2\theta + a^2\cos^2\theta)(a\sin\psi - r\cos\psi)\Big] \\
F_{t\phi} = {} & \frac{B_0\sin\chi aM}{\rho^2}\sin\theta\cos\theta(a\cos\psi + r\sin\psi) \\
F_{r\theta} = {} & -B_0\sin\chi(a\cos\psi + r\sin\psi) - \\
& \frac{B_0\sin\chi a}{\Delta}\Big[(Mr - a^2\sin^2\theta)\cos\psi - a(r\sin^2\theta + M\cos^2\theta)\sin\psi\Big] \\
F_{r\phi} = {} & B_0\cos\chi r\sin^2\theta + a\sin^2\theta F_{tr} - \\
& B_0\sin\chi\sin\theta\cos\theta\Big[\Big(r - a^2M/\Delta\Big)\cos\psi - a\,(1 + rM/\Delta)\sin\psi\Big] \\
F_{\theta\phi} = {} & B_0\cos\chi\Delta\sin\theta\cos\theta + \\
& \frac{(r^2+a^2)}{a}F_{t\theta} + B_0\sin\chi\Big[(r^2\sin^2\theta + Mr\cos 2\theta)\cos\psi - \\
& a(r\sin^2\theta + M\cos^2\theta)\sin\psi\Big]
\end{aligned} \qquad (5)
$$

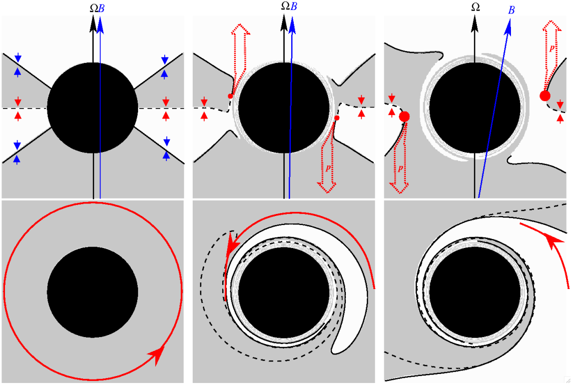
where

$$
\psi = \phi + \frac{a}{2\sqrt{M^2 - a^2}}\ln\left[\frac{r - M + \sqrt{M^2 - a^2}}{r - M - \sqrt{M^2 - a^2}}\right]. \qquad (6)
$$

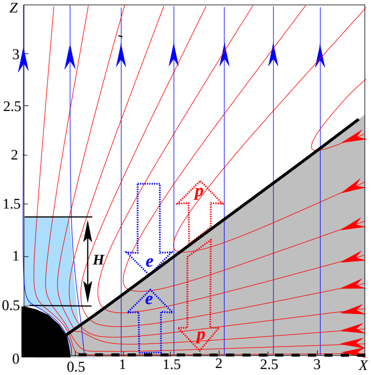
Wald (1974)

Bicak & Dvorak (1985)

The model



The model



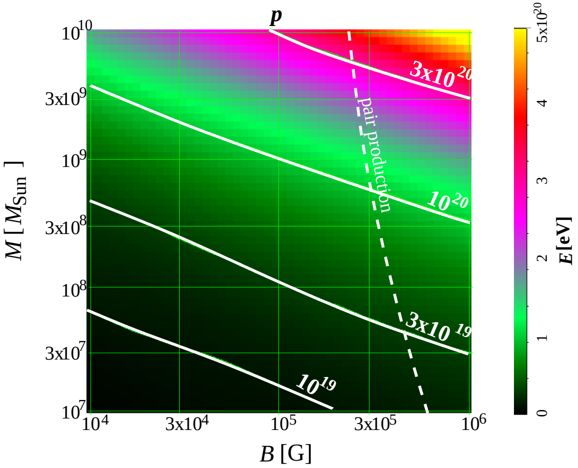
Particle acceleration:

$$\frac{d\vec{p}}{d\hat{t}} = e(\vec{E} + \vec{v} \times \vec{B}) + m\gamma\vec{g} + \hat{H}\vec{p} + \vec{f}_{rad}$$

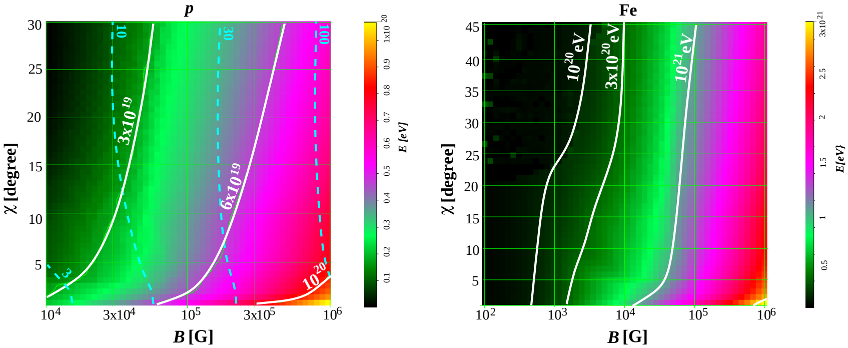
where

$$\vec{f}_{rad} = \frac{2e^4\gamma^2}{3m^2}\left((\vec{E} + \vec{v} \times \vec{B})^2 - (\vec{v} \cdot (\vec{E} + \vec{v} \times \vec{B}))^2\right)\frac{\vec{v}}{|v|}$$

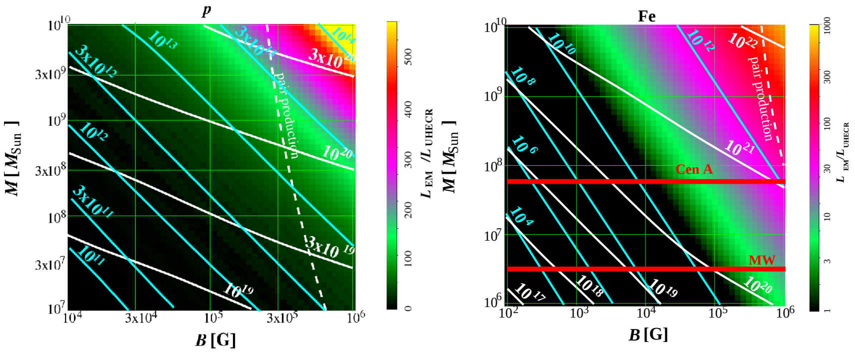
Maximum energy as a function of magnetic field B
and black hole mass M at fixed $\chi = 5^\circ$



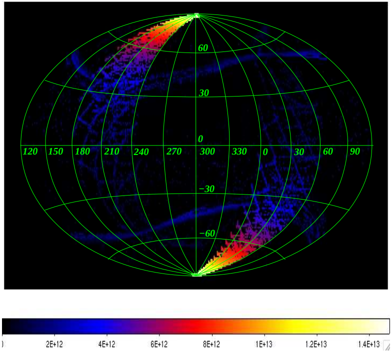
Maximum energy as a function of magnetic field B and the angle χ between B and black hole spin vector at fixed $M = 3 \times 10^8\ M_\odot$

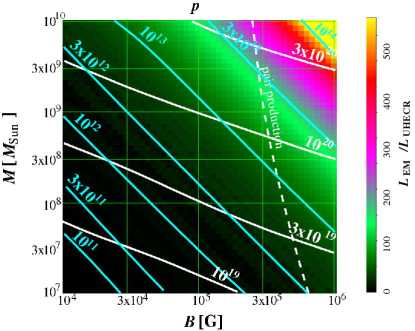


Maximum energy as a function of magnetic field B and black hole mass M at fixed $\chi = 5°$



Astrophysical accelerators are blasar-like objects





Conclusions

- It is difficult to accelerate protons to highest energies in "weak" local AGNs. But not impossible.
- It is easy to accelerate heavier nuclei.
- Astrophysical accelerators have characteristic γ signature.