Ultra-High-Energy Cosmic Rays from Supermassive Black Holes

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CREDO Visegrad Workshop 2019

Based on papers: **Universe,** 5, 125 (2019), arXiv:1905.05321
MNRAS Letters, 478, L89, (2018), arXiv:1804.09679
Astrophysical Journal, 861:2, (2018), arXiv:1803.09682
Phys. Rev. D, 93 (8), 084012, (2016), arXiv:1603.07264

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CREDO THE QUEST FOR THE UNEXPECTED

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Institute of Physics ~ 60 people

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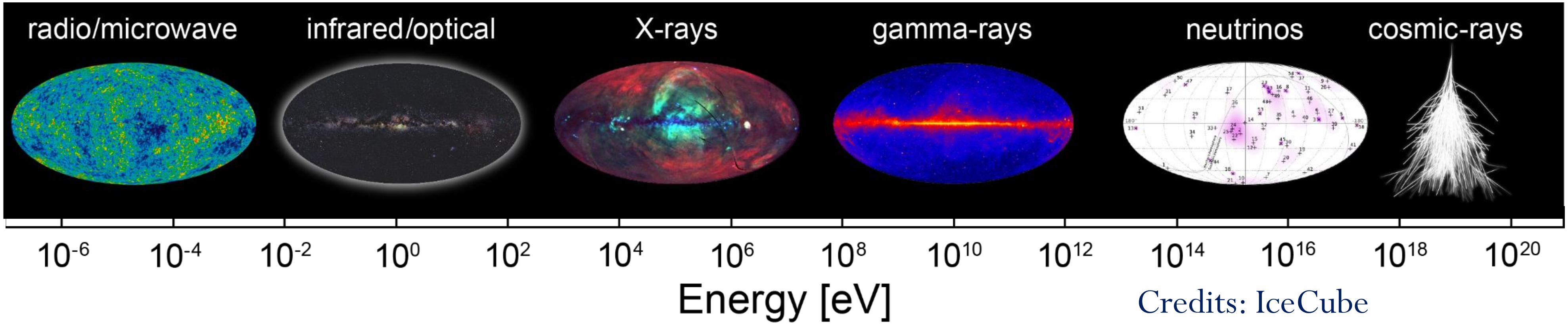
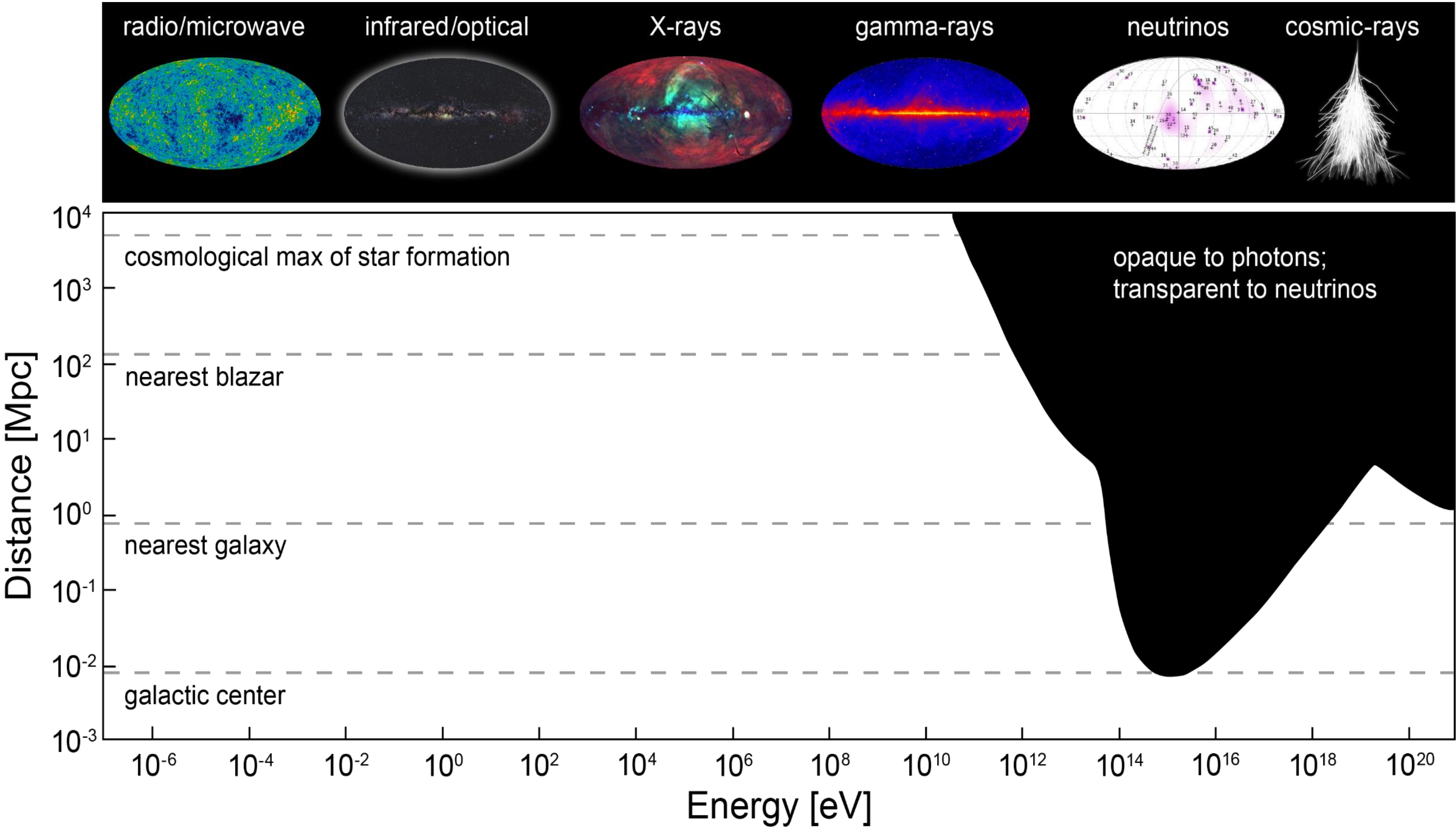
Recent discoveries related to BHs & CRs

- First image of a black hole (M87) by EHT (Apr 2019) – submillimeter
- Detection of close orbital motion around SgrA* by GRAVITY (Oct 2018) – near infrared (K-band) & multiwavelength
- First test of GR near SMBH by ESO's VLT (Jul 2018) – infrared/near infrared
- Extragalactic HE neutrino pointing to Blazar by IceCube (Jul 2018) – Neutrino astronomy
- *UHECRs* above 10^18 eV are extragalactic! – PAO (Sept 2017) & TA (2018) – Cosmic ray astronomy
- First detection of *gravitational waves* by LIGO/Virgo (Feb 2016) – GW astronomy



Credits: IceCube

Edge of the photon astronomy

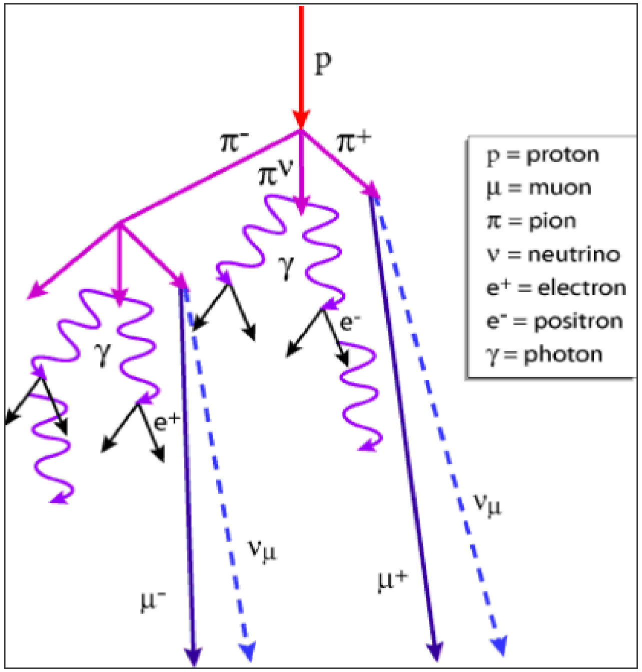


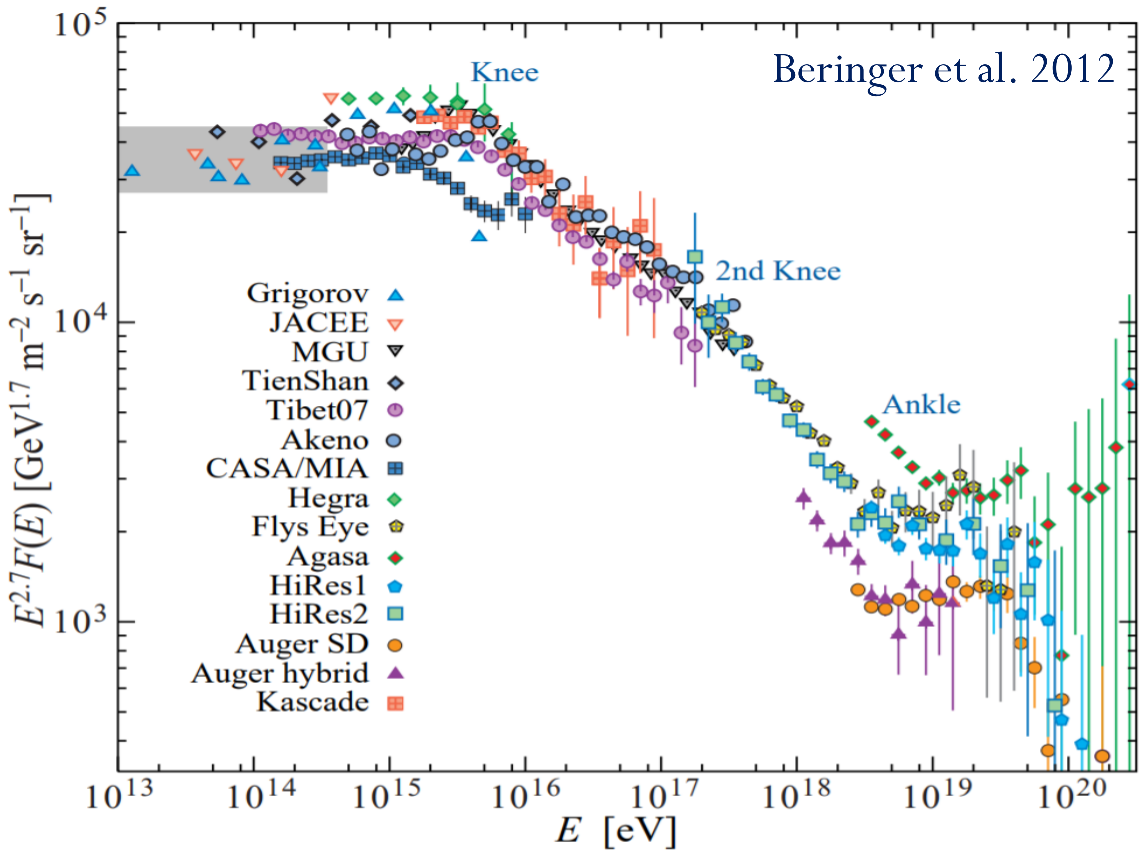
Almost 20% of the Universe cannot be studied using photon based telescopes

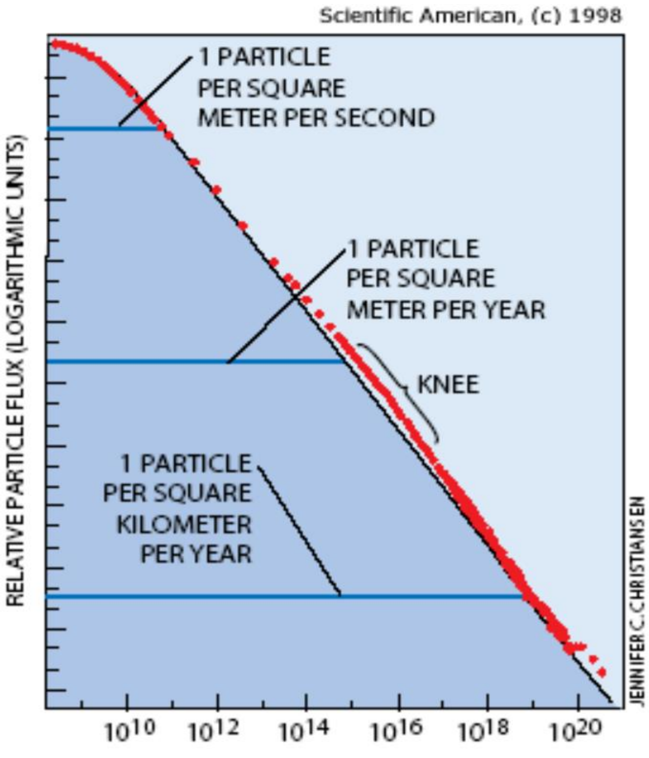
Credits: IceCube

UHECRs observations

- Phenomena which occur at energies E > 10^18 eV.
- Few things we know are
  - UHECR are charged particles
  - Spectrum has knees, ankle and steep suppression
  - Extremely rare
  - Probably proton dominated flux or iron nuclei
  - Extra-Galactic origin
- Mechanism is unknown – most energetic accelerator in the universe!







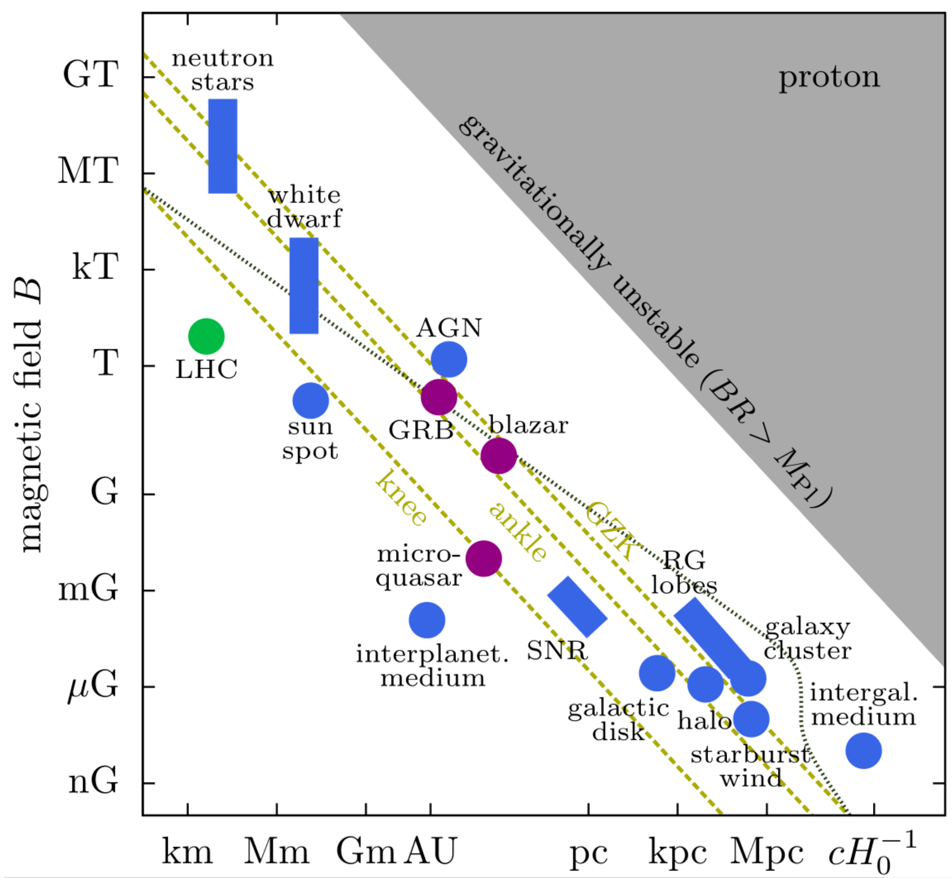
How to create them?

Exotics scenarios:

- extra dimensions scenarios;
- Lorentz invariance violation;
- existence of new particles;
- topological defects, strings, SUSY
- and others

The conditions for the accelerator are:

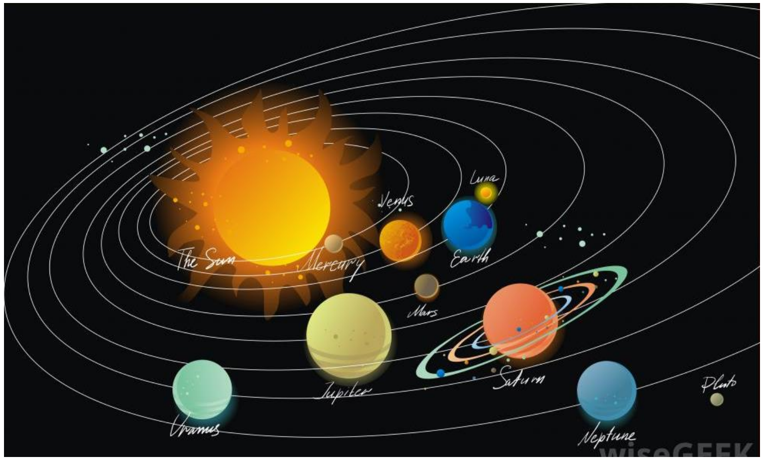
- powerful source with enough available energy;
- radiation losses suppressed or negligible;
- interaction losses (with other particles)
- accompanying photon and neutrino flux?



Hillas plot for various CR source candidates

In realistic conditions the accelerators have:

- small acceleration efficiency
- synchrotron loses;
- interactions in source region;
- GZK cutoff

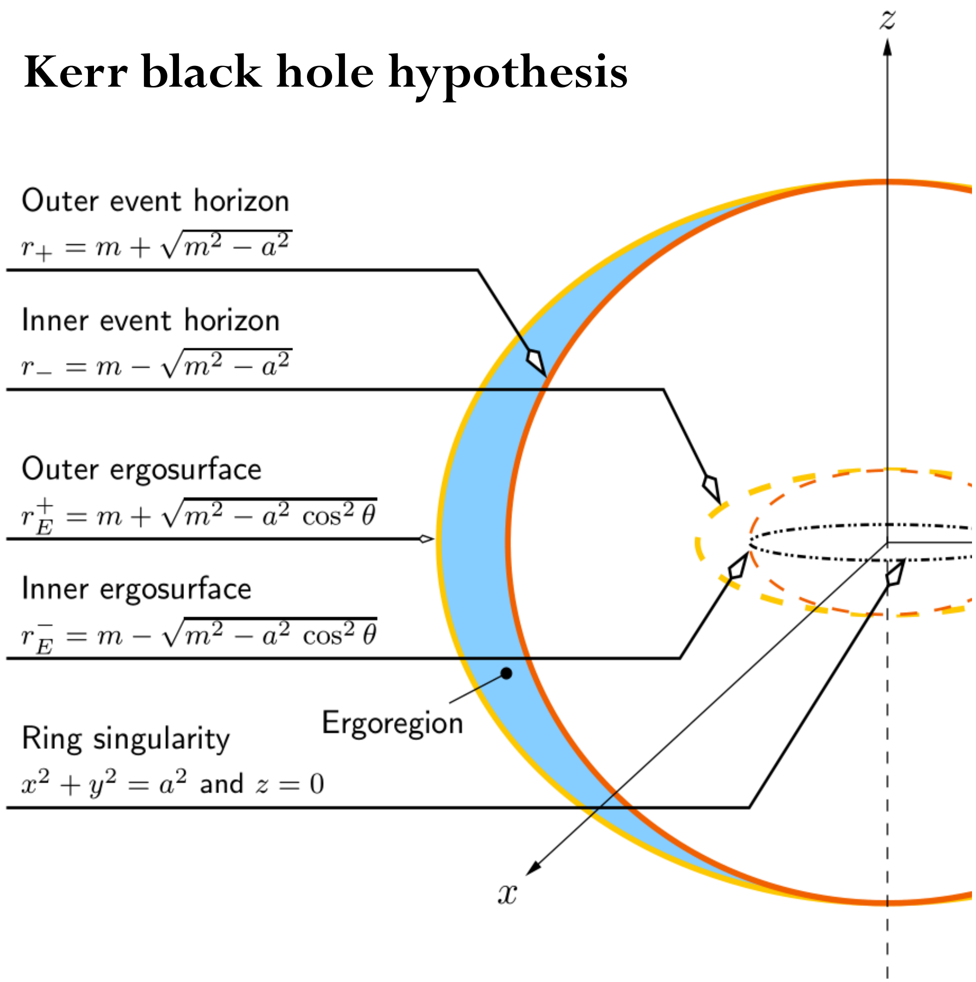


- or just build accellerator of ~400 mln km size with LHC techtology

What if UHECRs extract the energy from black holes?

Black hole mechanics and Thermodynamics have uncanny correspondence!
Black hole area non-decrease states that 29% of BH's energy is available for extraction.
For extremely rotating SMBH of 10^9 solar mass the available energy is 10^{74} eV

Kerr black hole hypothesis

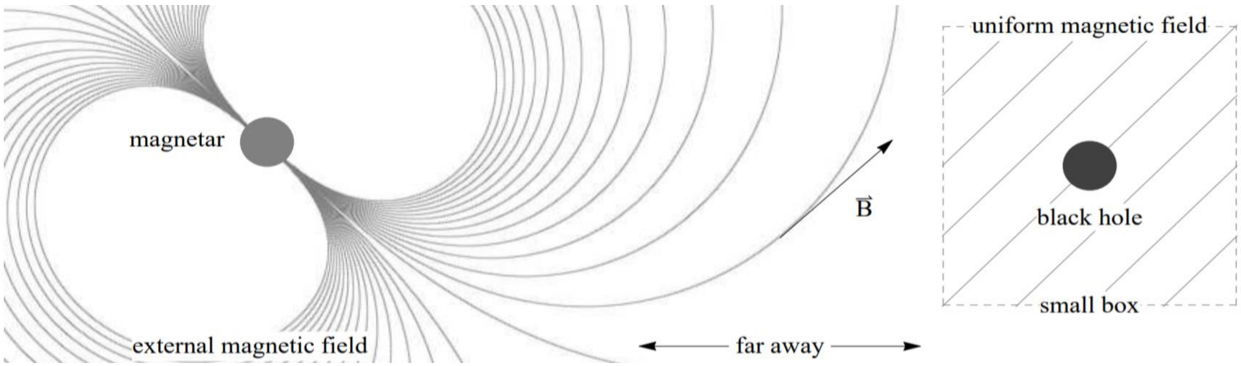


- Penrose (1969) – the energy can be extracted with the efficiency limited to 20.7%
- Bardeen et al. (1972) – Penrose process is not reliable in astrophysical conditions.
- Ruffini & Wilson (1975) – Electromagnetic energy extraction by charge separation in accreting magnetized plasma
- Blandford & Znajek (1977) & later MHD simulations – efficiency up to few 100%
- Wagh et al. (1985) – Electromagnetic version of Penrose process – efficiency can exceed 100%
- Many other versions of above mentioned processes with different efficiencies of few 100%
- Tursunov & colleagues (2019) – efficiency $> 10^{10}\%$ for protons from SMBHs

50 years of energy extraction from black holes:

Black holes are weakly magnetized

- Dynamics of surrounding plasma or accretion disk of BH
- Magnetic field of the companion or collapsed progenitor star



e.g. Magnetar with 10^{14}G has been found at 0.3 light years from Galactic Center by Effelsberg observatory

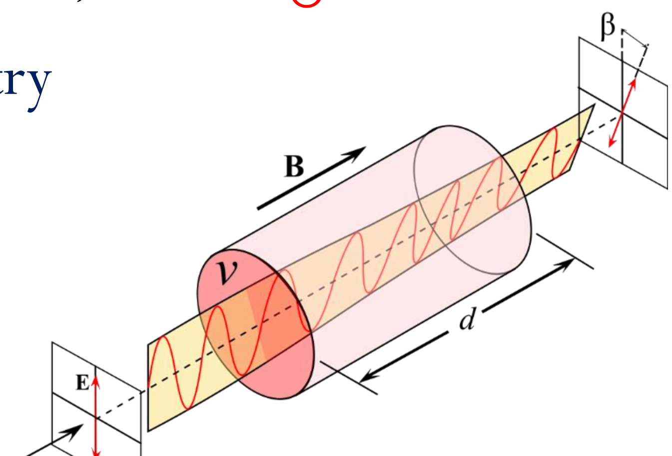
- MF of **SgrA* ~ 10G**. Characteristic MF for $10^9 M_\odot$ is 10^4G; for $10 M_\odot$ can exceed 10^8G.
- MF is weak – it does not modify the spacetime geometry

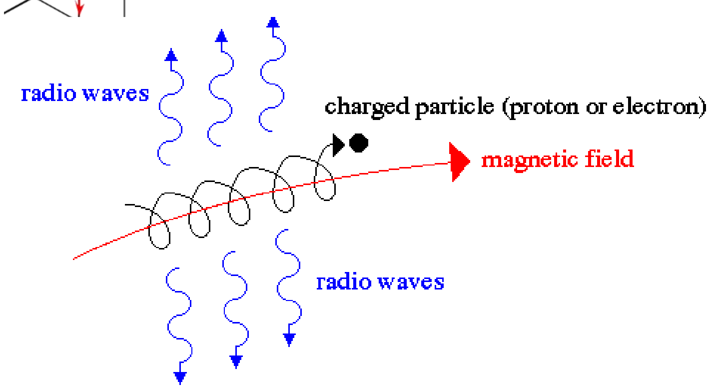
$$B \ll \frac{c^4}{G^{3/2} M_\odot}\left(\frac{M_\odot}{M}\right) \sim 10^{19}\frac{M_\odot}{M}\,\mathrm{G}$$

- Cannot neglect **MF effects** on the charged matter

$$\frac{F_{\mathrm{lorentz}}}{F_{\mathrm{grav.}}} = \frac{eBGM}{m_p c^4} \approx 10^{11}\left(\frac{B}{10^4\mathrm{G}}\right)\left(\frac{M}{10^9 M_\odot}\right)$$

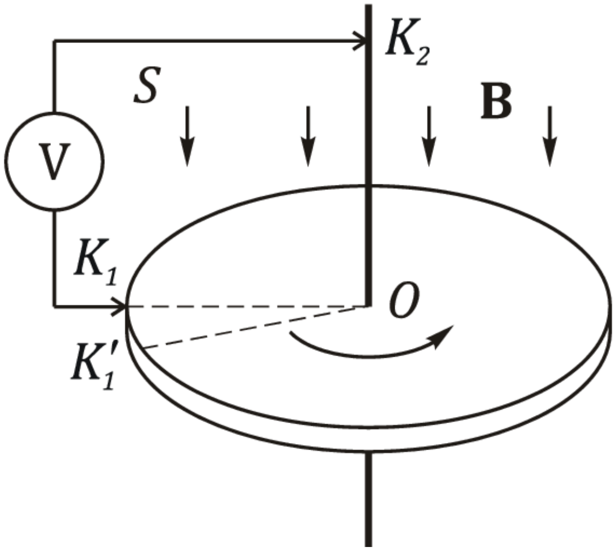
- This ratio for **SgrA* ~ 10^6**
- Measurements: Faraday rotation, synchrotron radiation, etc.





Charge separation in a magnetized plasma

- **Is a plasma surrounding BH always neutral?**
  - In ordinary plasma YES!
  - In relativistic and magnetized – NOT!



$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- **What supports the charge separation?**
  - Relativistic motion of a plasma induces electric field

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B},$$

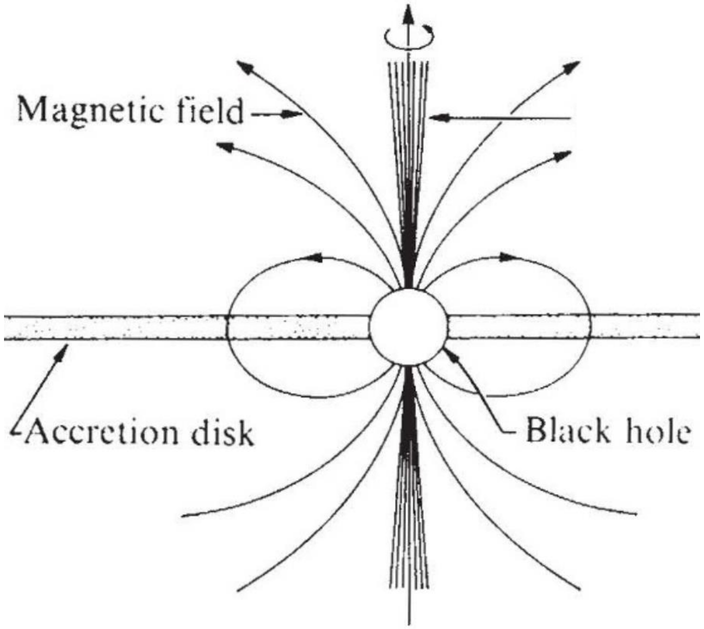
  - For the motion around BH with $\mathbf{v} = \mathbf{\Omega} \times \mathbf{R}.$ this leads to the net charge density

$$\rho_q = \frac{1}{4\pi c} \frac{\Omega B_\perp}{|e|},$$

- **Where is the extra charge?**
  - In a similar way, rotation of BH in MF induces EF and BH with the magnetosphere acts as dynamo!

$$A_t = \frac{B}{2}(g_{t\phi} + 2ag_{tt}), \qquad A_\phi = \frac{B}{2}(g_{\phi\phi} + 2ag_{t\phi}).$$

$$\Delta\varphi = \varphi_{\rm H} - \varphi_\infty = \frac{Q - 2aMB}{2M}.$$



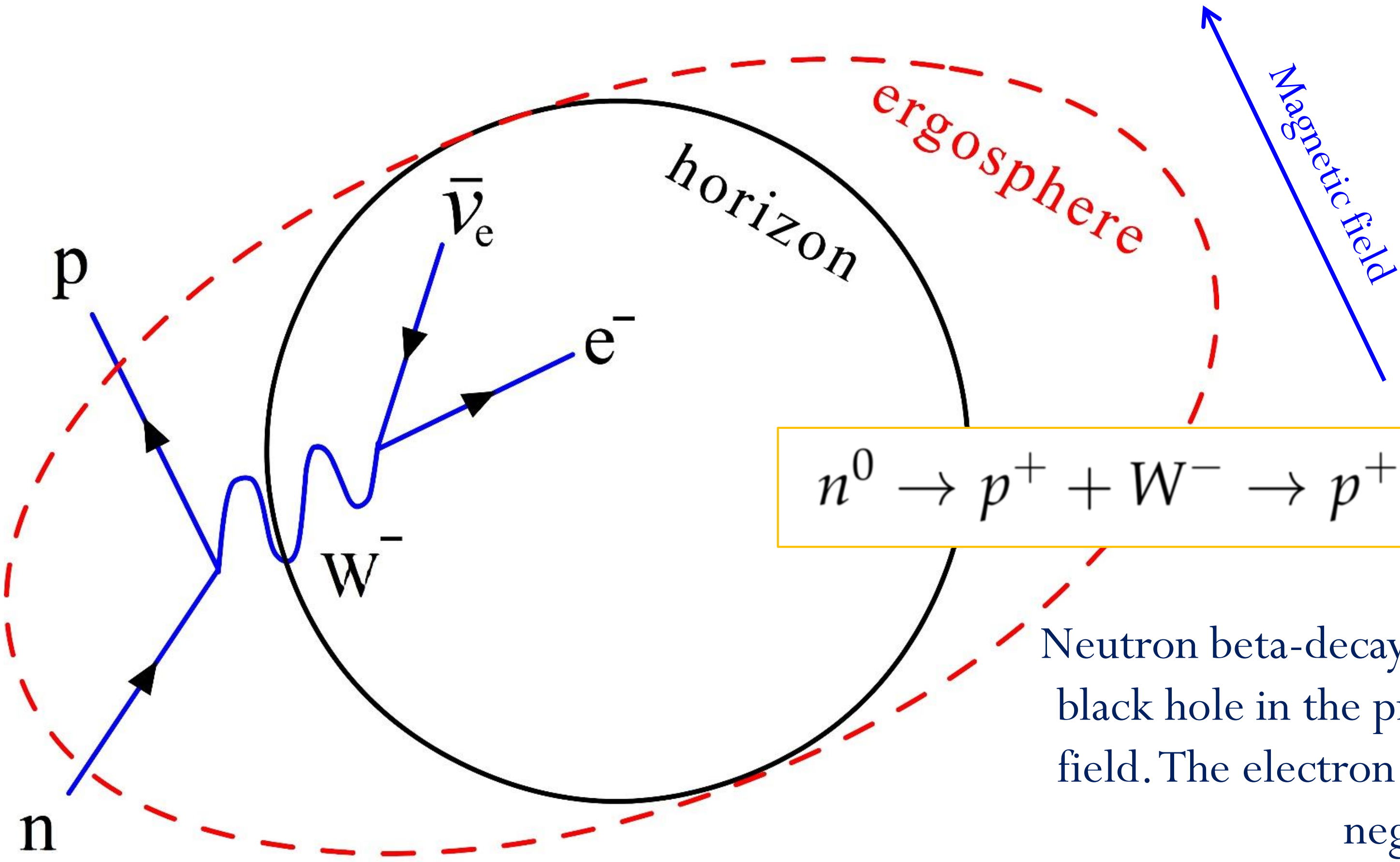
As a result, both black hole and the disk get net electric charge!

Neglected charge - electrically polarized Universe!

- Arthur Eddington (1926) – stars are positively charge to prevent e & p from further separation in stellar atmosphere. For Sun the charge is 77 C.
- Goldreich & Julian (1969) – NS induce electric field while rotating in magnetic field.
- Wald (1974) – BH immersed into MF induce electric charge – vacuum solution.
- Ruffini & Wilson (1975) – charge separation in a plasma – both BH and magnetosphere are charged.
- Bally & Harrison (1978) – any macroscopic body is positively charged with **~100C** per Solar mass.
- Zajacek, Tursunov, et al. (2018, 2019) – electric charge of Galactic centre SgrA* is $10^8 - 10^{15}$C . Charge of black holes are more likely positive.

Process	Limit	Notes
Mass difference between p and e	$Q_{\rm eq} = 3.1 \times 10^8 \left(\frac{M_\bullet}{4\times10^6 M_\odot}\right) {\rm C}$	stable charge
Accretion of protons	$Q^+_{\rm max} = 6.16 \times 10^8 \left(\frac{M_\bullet}{4\times10^6 M_\odot}\right) {\rm C}$	unstable charge
Accretion of electrons	$Q^-_{\rm max} = 3.36 \times 10^5 \left(\frac{M_\bullet}{4\times10^6 M_\odot}\right) {\rm C}$	unstable charge
Magnetic field & SMBH rotation	$Q^{\rm max}_{\bullet{\rm ind}} \lesssim 10^{15} \left(\frac{M_\bullet}{4\times10^6 M_\odot}\right)^2 \left(\frac{B_{\rm ext}}{10{\rm G}}\right) {\rm C}$	stable charge
Extremal SMBH	$Q_{\rm max} = 6.86 \times 10^{26} \left(\frac{M_\bullet}{4\times10^6 M_\odot}\right) \sqrt{1-\tilde{a}_\bullet^2}\,{\rm C}$	uppermost limit

Beta-decay in ergosphere



$$n^0 \to p^+ + W^- \to p^+ + e^- + \bar{\nu}_e,$$

Neutron beta-decay in the ergosphere of rotating black hole in the presence of external magnetic field. The electron falls into black hole with the negative energy.

In the hot and dense torus, with temperature of $\sim 10^{11}$ K and density $>10^{10}$ g·cm^{-3}, neutrinos are efficiently produced. The main reactions that lead to their emission are the electron/positron capture on nucleons, as well as the neutron decay. Their nuclear equilibrium is described by the following reactions:

$$p + e^- \to n + \nu_e$$

$$p + \bar{\nu}_e \to n + e^+$$

$$p + e^- + \bar{\nu}_e \to n$$

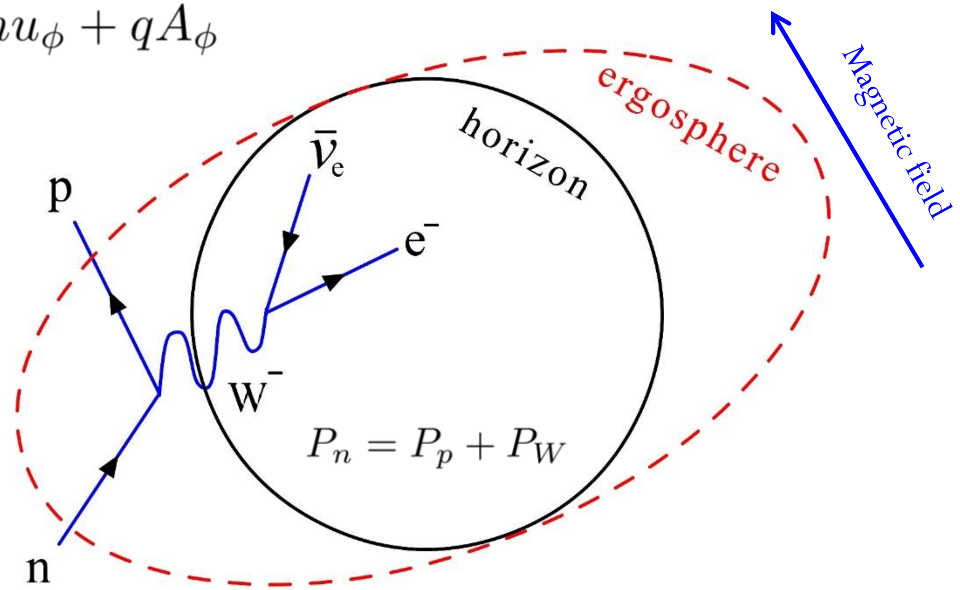
A. Janiuk et al, Galaxies 5, 15 (2017)

Efficiency of energy extraction by beta-decay

Integrals of motion $-E = mu_t + qA_t \quad L = mu_\phi + qA_\phi$

At the point of split the conservations laws read

$$
\begin{aligned}
E_1 &= E_2 + E_3, \\
L_1 &= L_2 + L_3, \\
q_1 &= q_2 + q_3, \\
m_1 \dot{r}_1 &= m_2 \dot{r}_2 + m_3 \dot{r}_3, \\
0 &= m_2 \dot{\theta}_2 + m_3 \dot{\theta}_3, \\
m_1 &\geq m_2 + m_3,
\end{aligned}
$$

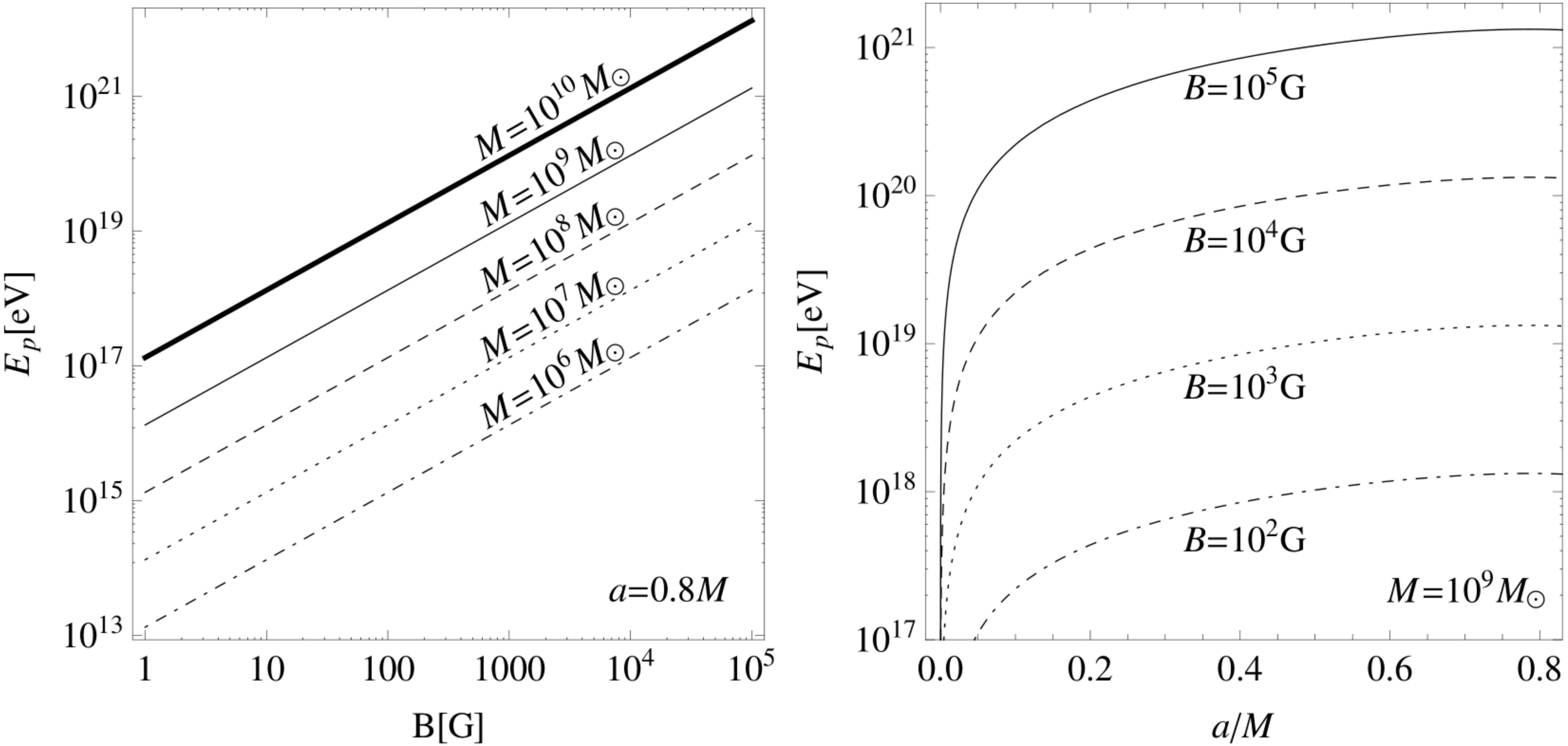


Efficiency is defined as the ratio between gain and input energy $\quad \eta_\beta = \frac{E_p - E_n}{E_n}$

Final result depends on the field configuration. In the absence of MF, the efficiency corresponds to Penrose process with maximum $\quad \eta_{\mathrm{Kerr}}^{\max} = \frac{\sqrt{2}-1}{2} \approx 20.7\%$

For uniform magnetic field $\quad \eta_\beta = \frac{1}{2}\left(\sqrt{\frac{2M}{r_H}} - 1\right) + a\mathcal{B}\left(1 - \frac{M}{r_H}\right), \quad \mathcal{B} = \frac{|e| G B M_{\mathrm{SMBH}}}{m_p c^4}.$

Energy of proton driven away from BH

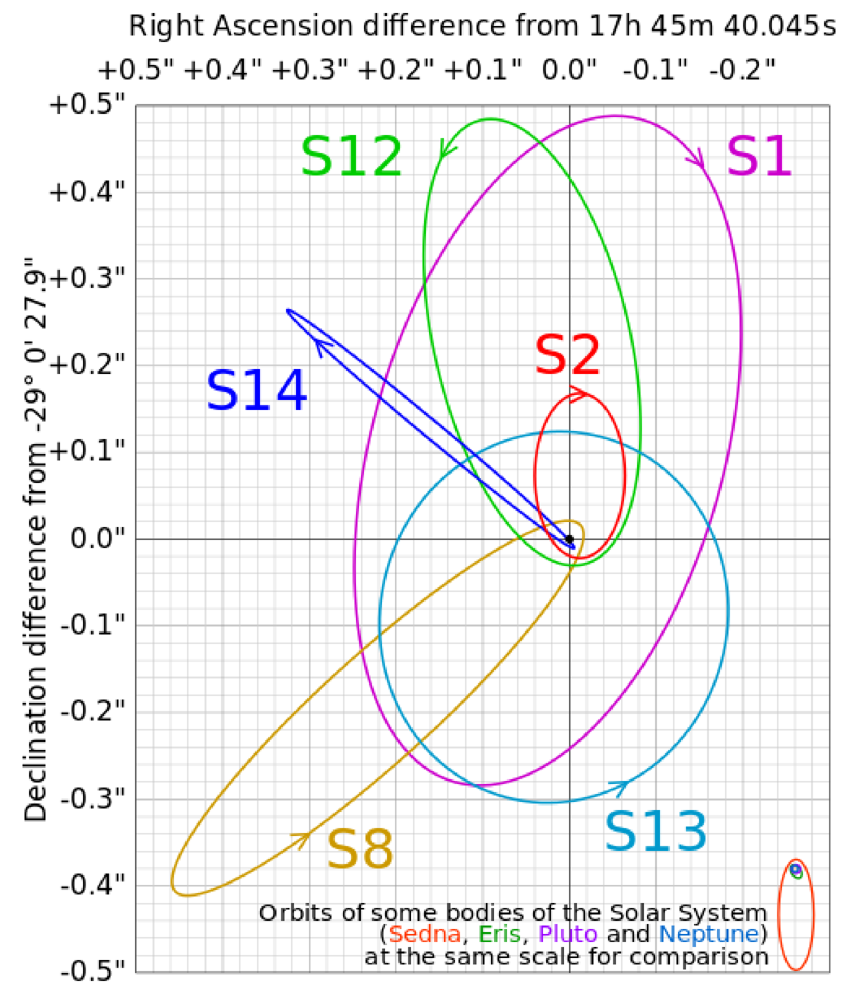


The energy of free neutron is ~ 0.94×10^9eV

$$E_{p^+} = 1.33{\times}10^{20}\mathrm{eV}\left(\frac{q}{e}\right)\left(\frac{m}{m_{p^+}}\right)^{-1}\left(\frac{B}{10^4\mathrm{G}}\right)\left(\frac{M}{10^9 M_\odot}\right).$$

The Milky Way's SgrA* as SMBH

- **Best known candidate for SMBH at 8 kpc**
- **Mass is ~ $4 \times 10^6 M_\odot$** based on different methods:
  - the orbits of S stars (Parsa et al. 2017)
  - modelling of the NSC (Do et al. 2013)
  - fits to double peaked X-ray flares (Karssen et al. 2017)
- **Spin is loosely constrained**
  - has no Newtonian effect
  - regime of strong gravity is needed
  - spin can be determined based on the modelling of e.g. the light curves of a hot spot or a jet base.
- **Magnetic field ~ 10 Gauss (10^{-3}Tesla)**
  - Modeling, e.g. SSC model (Eckart et al. 2012, 2017)
  - Faraday rotation (Eathough et al. 2013)
  - MF is ordered even at ISCO scales (GRAVITY 2018, Johnson et al. 2015)
  - MF is weak – satisfies to no-hear theorem: $B \ll 10^{12}$Gauss
  - However, even weak magnetic field can completely change the dynamics of elementary particles



$$\frac{F_{\rm Lorentz}}{F_{\rm grav}} = \frac{eGM_{\rm bh}B\,v}{m_p\,c^5} \sim 10^6 \left(\frac{B}{10{\rm G}}\right)\left(\frac{M}{4\times10^6 M_\odot}\right).$$

SgrA* as PeVatron

- **Rotating black hole**

– SgrA* is spinning ~0.5M

- **External magnetic field**

– around SgrA* ~10G

- **Negative energy inflow**

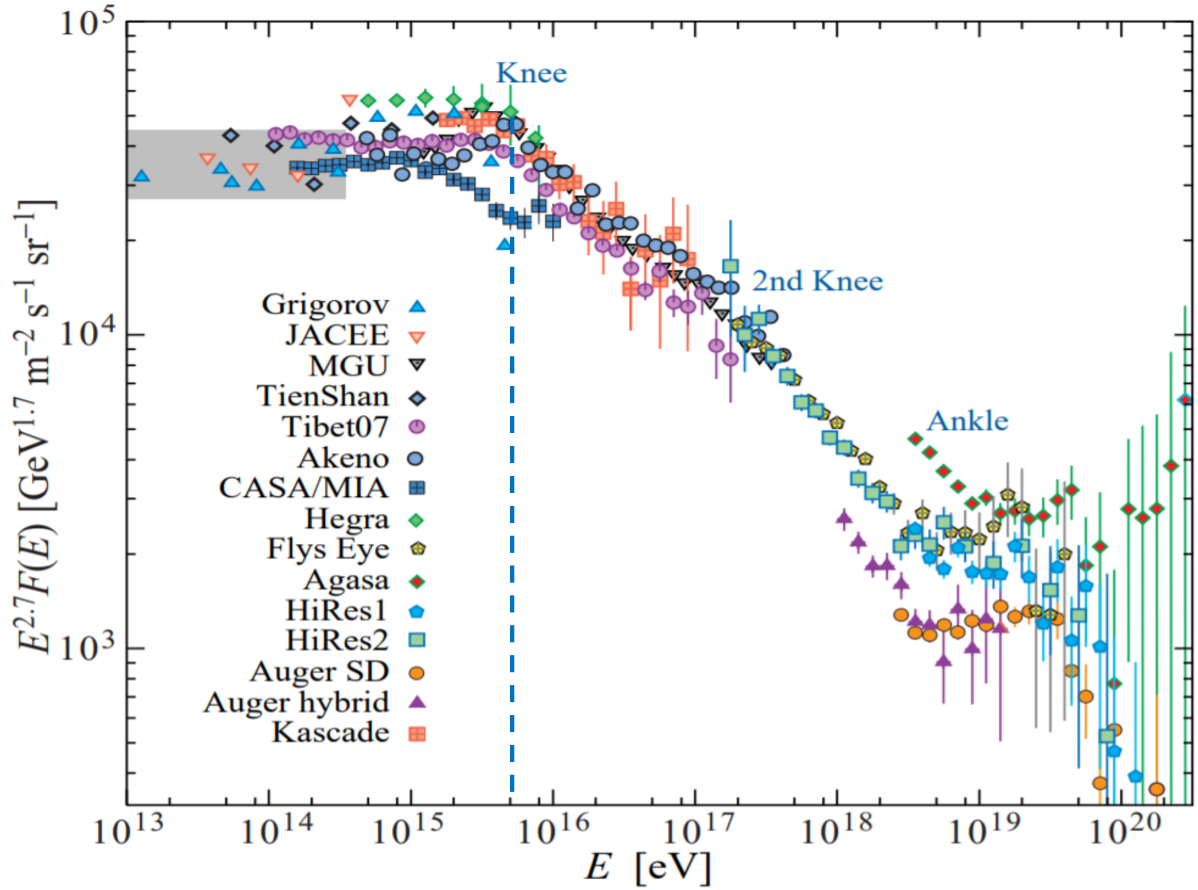
– gain Coloumb contribution

- **Discharge of electric field**

– charge of SgrA*

- **Infalling matter**

– neutral particle decay



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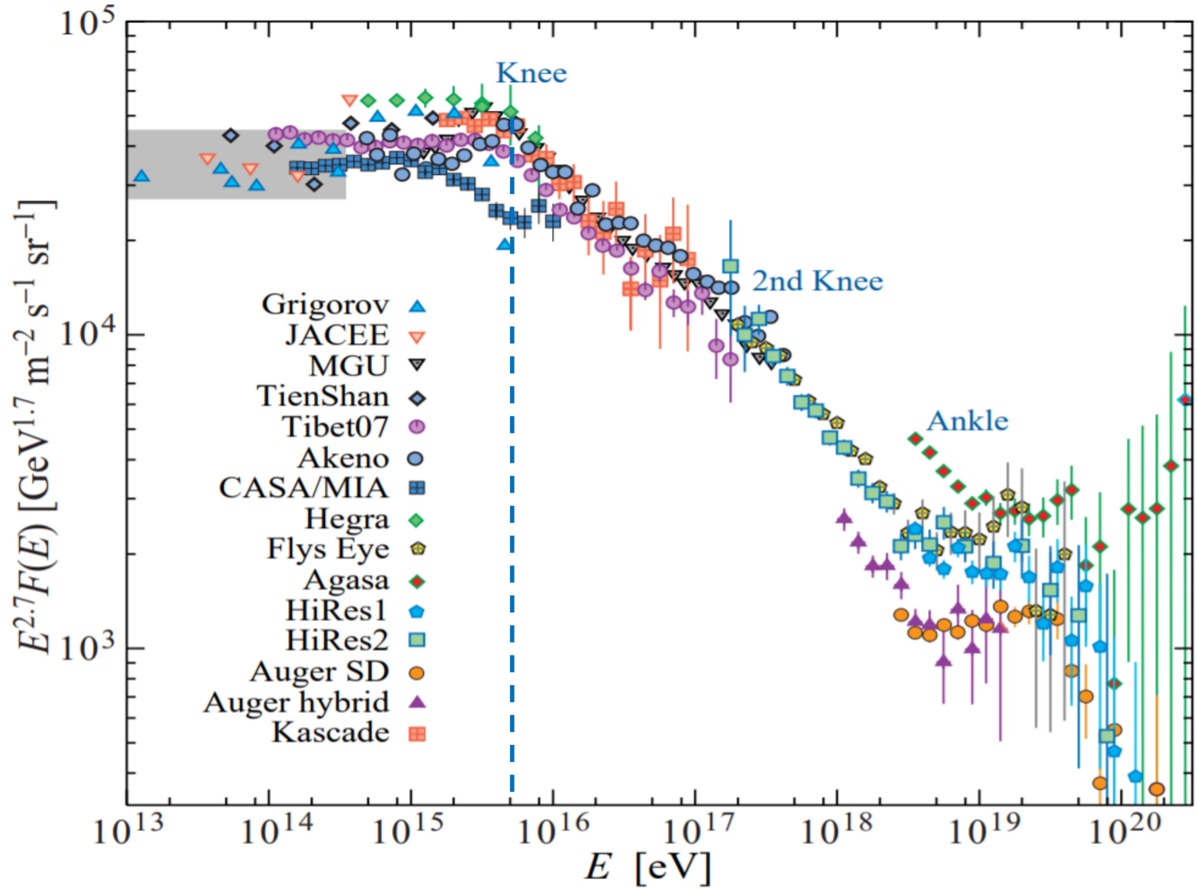


Applying ultra-MPP

$$n^0 \to p^+ + W^-$$

$$E_n = E_p + E_W,$$
$$L_n = L_p + L_W,$$
$$m_n \dot{r}_n = m_p \dot{r}_p + m_W \dot{r}_W,$$
$$q_W + q_p = 0.$$

Proton energy corresponds to the Knee

$$E_{\mathrm{p}^+} \approx 5 \times 10^{15}\mathrm{eV} \left(\frac{q}{e}\right) \left(\frac{m}{m_{p^+}}\right)^{-1} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{M}{M_{\mathrm{SgrA}^*}}\right)$$

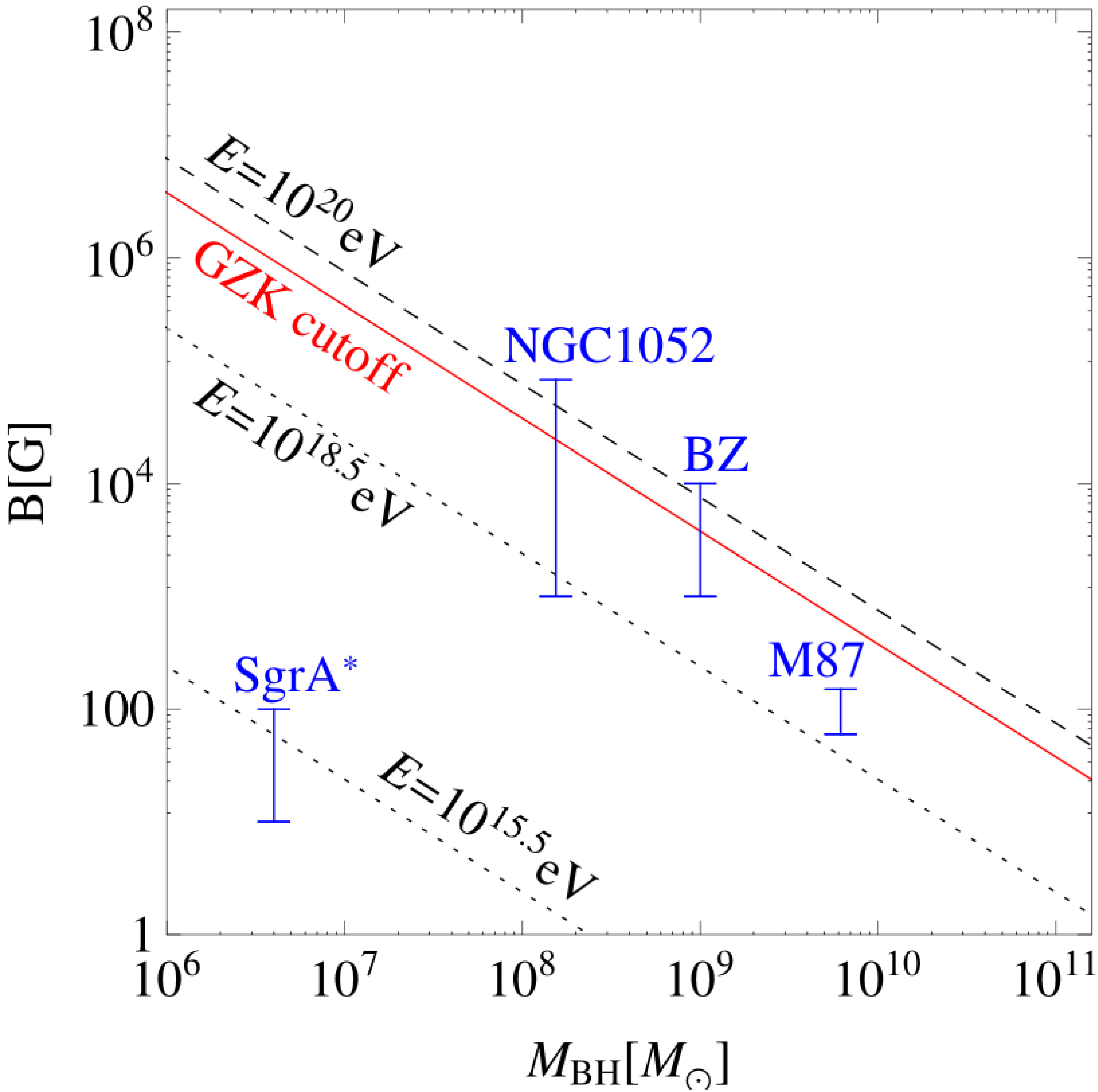
Tursunov & Dadhich, Universe, 5, 125 (2019)

Energy extraction in various radioactive decay modes

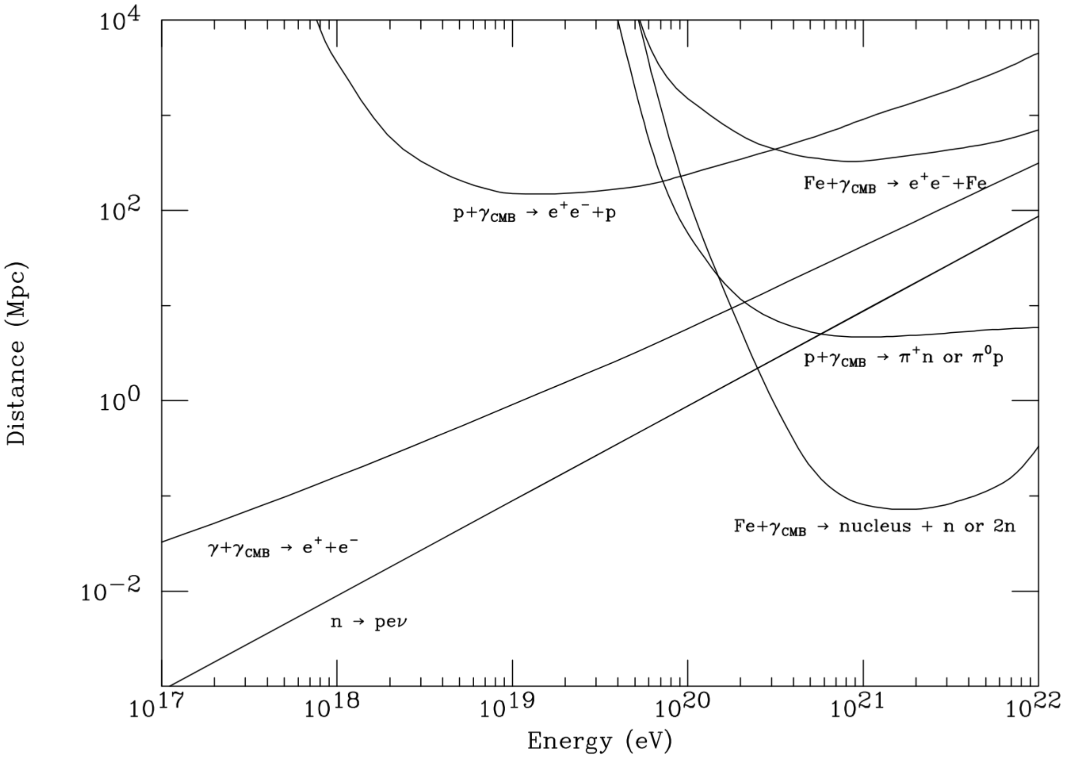
Decay Mode	Generic Equation	Esc. p.	Efficiency $\eta_{\max}$	Regime of MPP
α decay	${}^{A}_{Z}X^{0} \to {}^{A-4}_{Z-2}Y^{2-} + {}^{4}_{2}\alpha^{2+}$	Y	<0	-
		α	$1.2 \times 10^{6}/A$	ultra
	${}^{A}_{Z}X^{+} \to {}^{A-4}_{Z-2}Y^{-} + {}^{4}_{2}\alpha^{2+}$	Y	<0	–
		α	~ 1	moderate
	${}^{A}_{Z}X^{-} \to {}^{A-4}_{Z-2}Y^{3-} + {}^{4}_{2}\alpha^{2+}$	Y	~ 2	moderate
		α	< 0	-
β^{-} decay	${}^{A}_{Z}X^{0} \to {}_{Z+1}{}^{A}Y^{+} + e^{-} + \bar{\nu}$	Y	$6.1 \times 10^{5}/A$	ultra
		e^{-}	<0	–
		$\bar{\nu}$	0.06	low
β^{+} decay	${}^{A}_{Z}X^{+} \to {}_{Z-1}{}^{A}Y^{0} + e^{+} + \nu$	Y	<0	–
		e^{+}	~ 0	low/–
		ν	<0	–
γ emission	${}^{A}_{Z}X^{0} \to {}^{A}_{Z}X'^{0} + {}^{0}_{0}\gamma^{0}$	X′	0.06	low
		γ	0.06	low
Pair production	$\gamma^{0} \to e^{-} + e^{+}$	e^{-}	<0	–
		e^{+}	$5.5 \times 10^{8}/(2m_e c^2)$	ultra

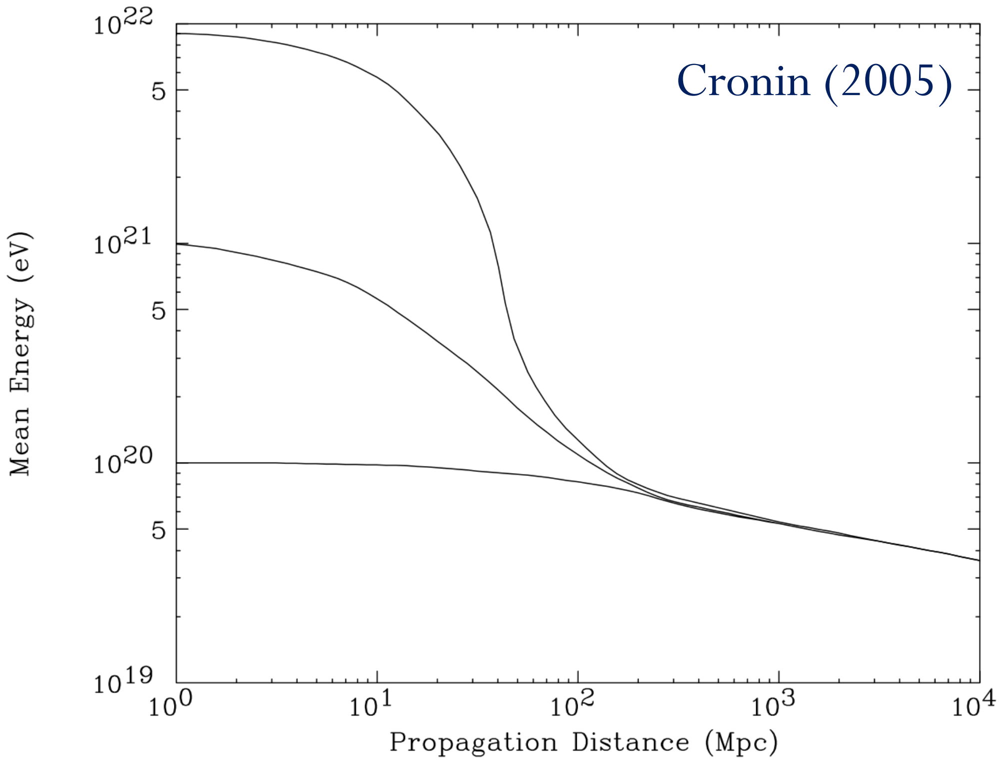
Efficiency of energy extraction from stellar mass black hole for various typical radioactive decay modes. Initial energy of decaying particle is taken to be equal to its rest mass.

Constraints on parameters



Energy loss: GZK cutoff





left: Panorama of the interactions of possible cosmic primaries with the CMB; right: and mean energy of protons as a function of propagation distance through the CMB, based on GZK cutoff.

$$p + \gamma_{\rm CMB} \rightarrow p + \pi^0,$$

$$p + \gamma_{\rm CMB} \rightarrow n + \pi^+.$$

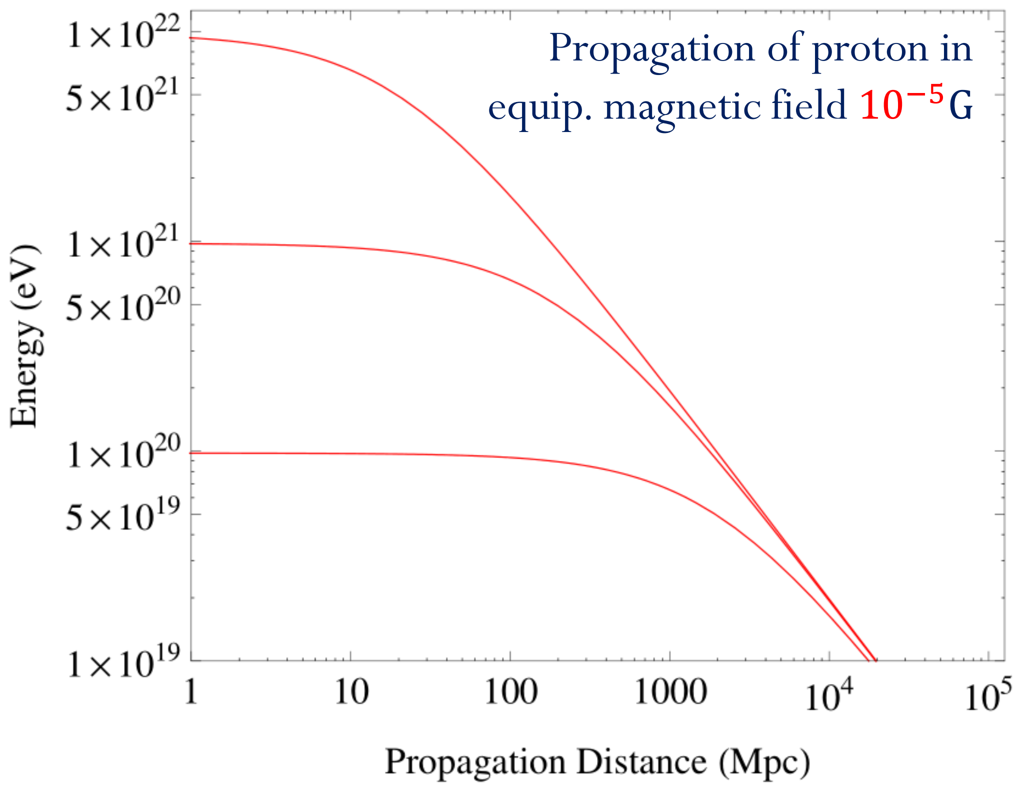
Collision of UHERCR proton with CMB produces 200 MeV in center-of-mass, which is the peak for photo-pion production

Energy loss: synchrotron radiation

$$\frac{Du^\mu}{d\tau} = \frac{q}{m}F^\mu{}_\nu u^\nu + \frac{2q^2}{3m}\left(\frac{D^2u^\mu}{d\tau} + u^\mu u_\nu \frac{D^2u^\nu}{d\tau}\right)$$
$$+\frac{q^2}{3m}\left(R^\mu{}_\lambda u^\lambda + R^\nu{}_\lambda u_\nu u^\lambda u^\mu\right)$$
$$+\frac{q^2}{m}u_\nu \int_{-\infty}^{\tau} D^{[\mu}G^{\nu]}_{+\lambda'}(\tau,\tau')u^{\lambda'}(\tau')\,d\tau'.$$

- **Neutral geodesics**
- **Charged particles**
- **Backreaction SR**
- **Backreaction GR**

(DeWitt and Brehme 1960)

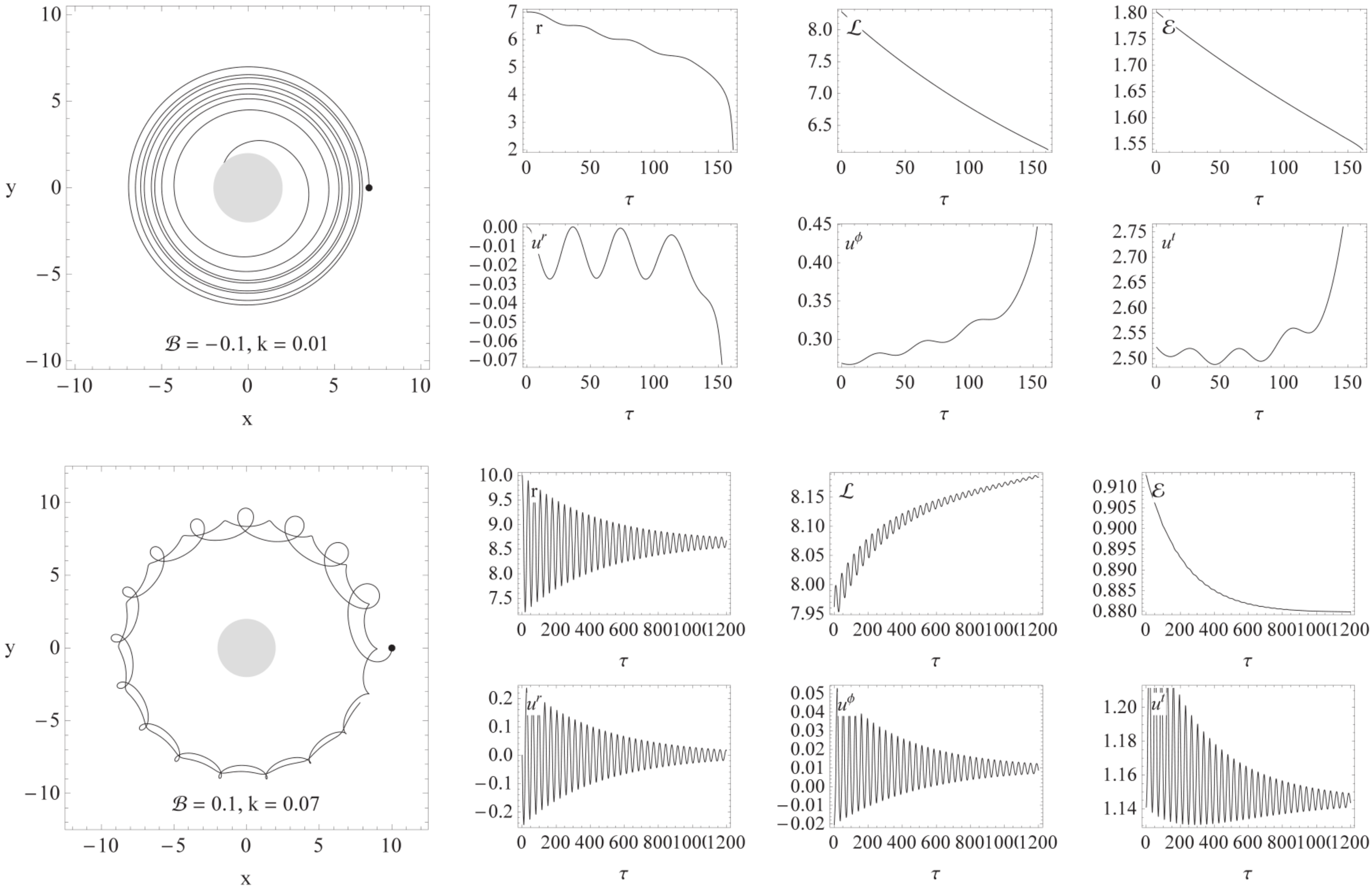


B (Gauss)	τ_p (s)	R (r_S)
10^{12}	10^{-6}	10^{-10}
10^8	10^2	10^{-2}
10^4	10^{10}	10^6
1	10^{18}	10^{14}
10^{-4}	10^{26}	10^{22}
10^{-6}	10^{30}	10^{26}

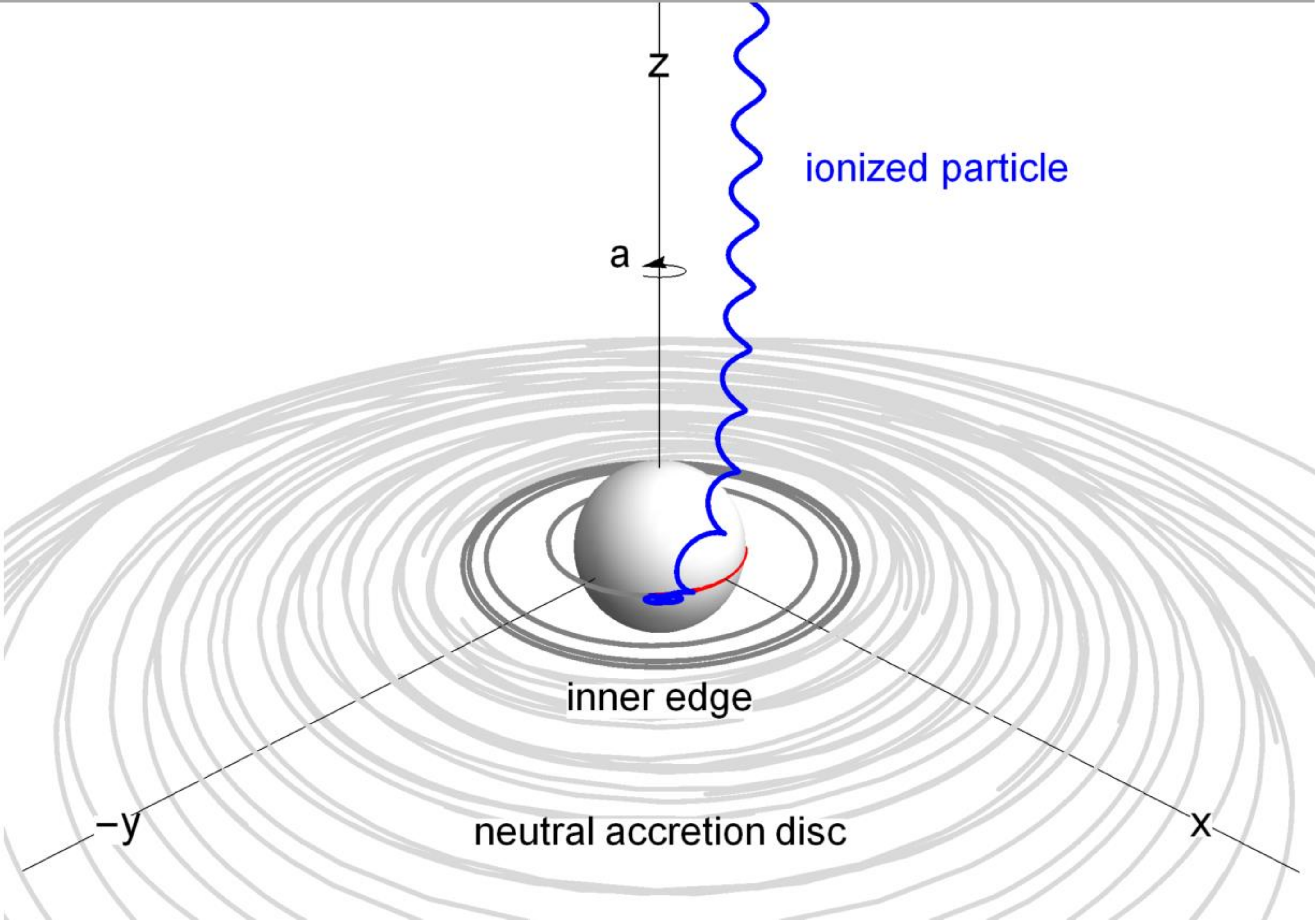
B (Gauss)	τ_e (s)	τ_p (s)	τ_{Fe} (s)
10^{12}	10^{-16}	10^{-6}	10^{-5}
10^8	10^{-8}	10^2	10^3
10^4	1	10^{10}	10^{11}
1	10^8	10^{18}	10^{19}
10^{-4}	10^{16}	10^{26}	10^{27}

Near neutron stars synchrotron loses of CRs are dominant unless the particles move along MF lines

Trajectories of radiating particle



Numerical modelling



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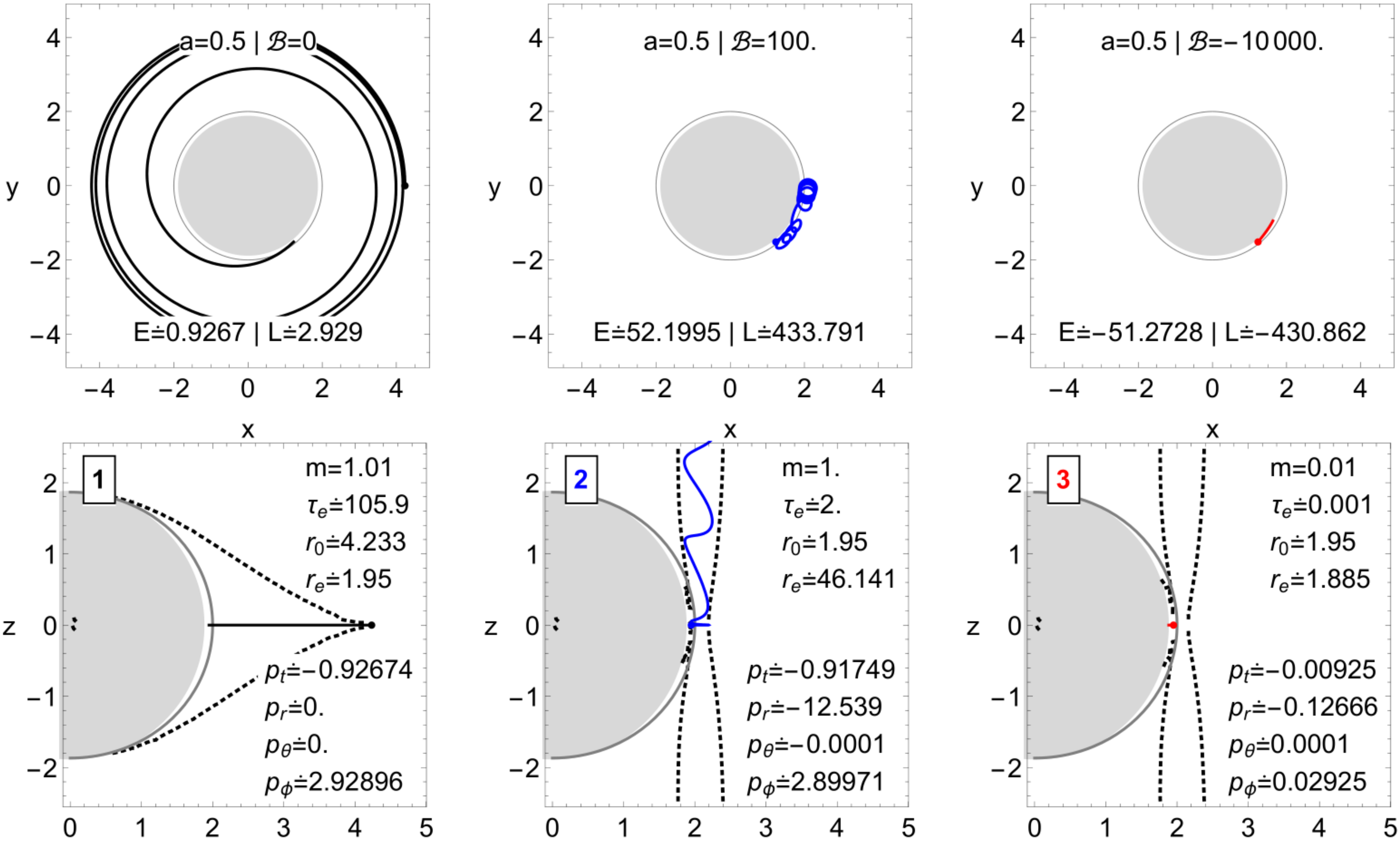

Summary

- We show that SMBHs can produce the highest-energy cosmic rays
- Model requires SMBH with moderate spin and typical magnetic field strength in its vicinity.
- Model does not require extreme or rapid BH rotation, nor extended acceleration zone.
- Applied to the Galactic center SMBH, proton energy coincides with the knee of the CR spectra.
- We provide verifiable constraints on the mass and magnetic field of the SMBH candidate sources

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