

# Supermassive Black Holes as Power Engines of Ultra-High-Energy Cosmic Rays

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Based on:

2020: Tursunov, et al. **Astrophysical Journal** 895:1, 14, [arXiv:2004.07907](#)

2019: Tursunov & Dadhich, **Universe**, 5, 125, [arXiv:1905.05321](#)

2018: Tursunov, et al. **Astrophysical Journal**, 861:2, [arXiv:1803.09682](#)

and some unpublished results



Division of Elementary Particle Physics

Institute of Physics

Czech Academy of Sciences

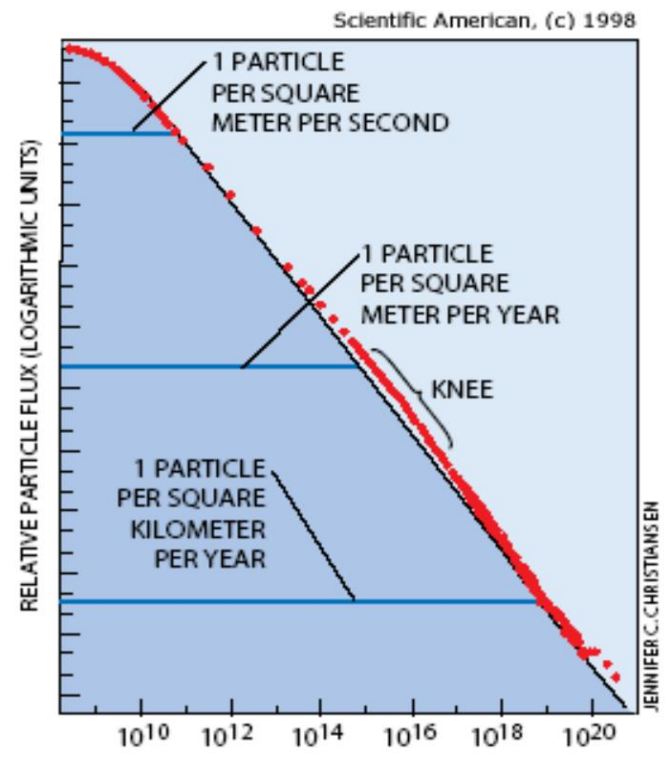
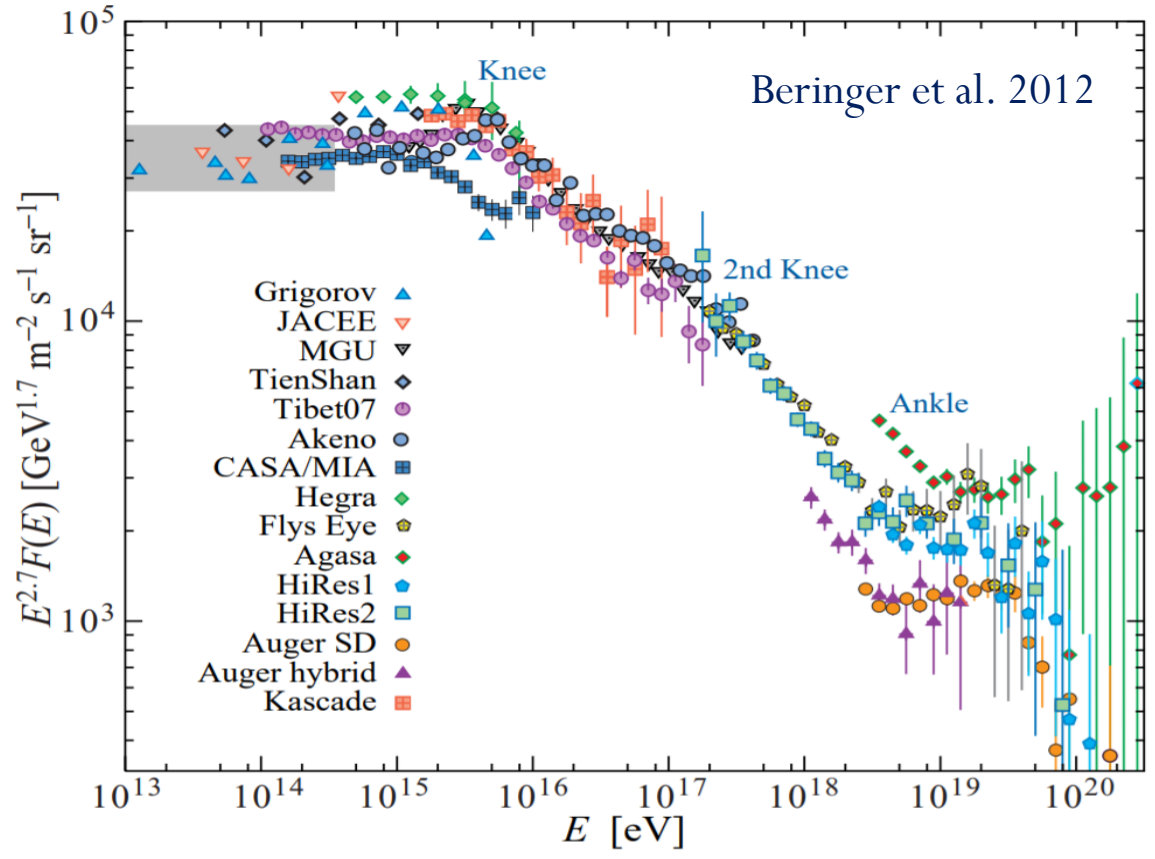
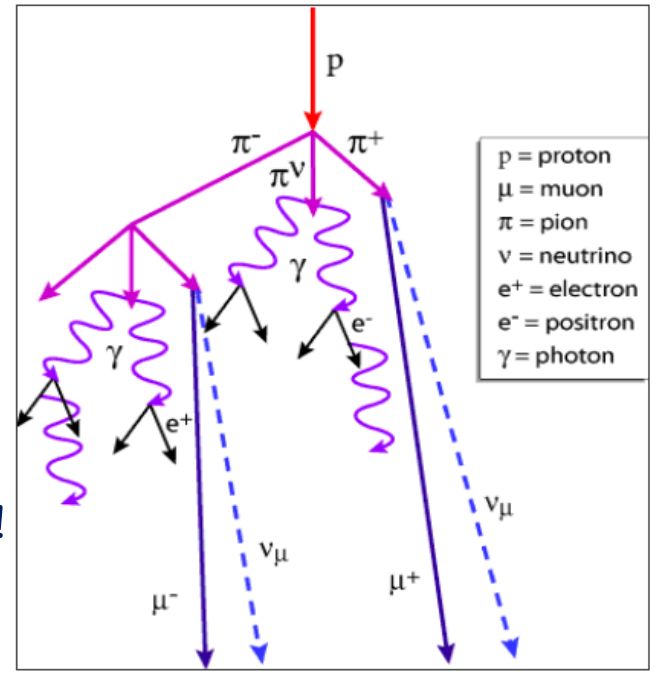
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**ZOOM / Prague / Opava**



# UHECRs observations

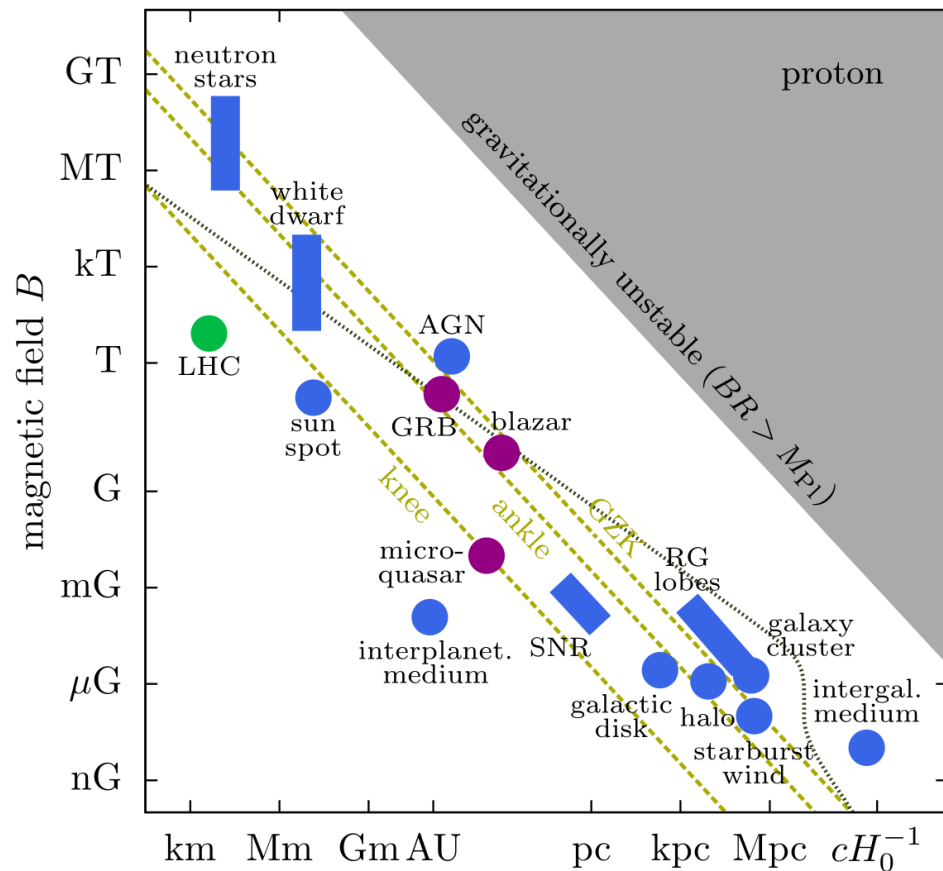
- Few things we know about UHECRs:
  - Unreachable energy by Earth based experiments
  - These are charged particles
  - Spectrum has knees and ankle
  - Extremely rare at ultra-high energies
  - Extra-Galactic origin
  - Detected mainly on Earth – composition at high energy is ?
- Mechanism is unknown – 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



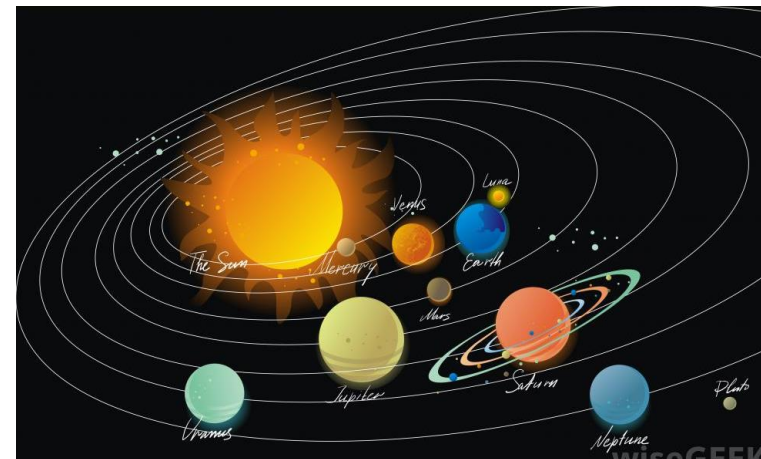
Hillas plot for various CR source candidates

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?

In realistic conditions the accelerators have:

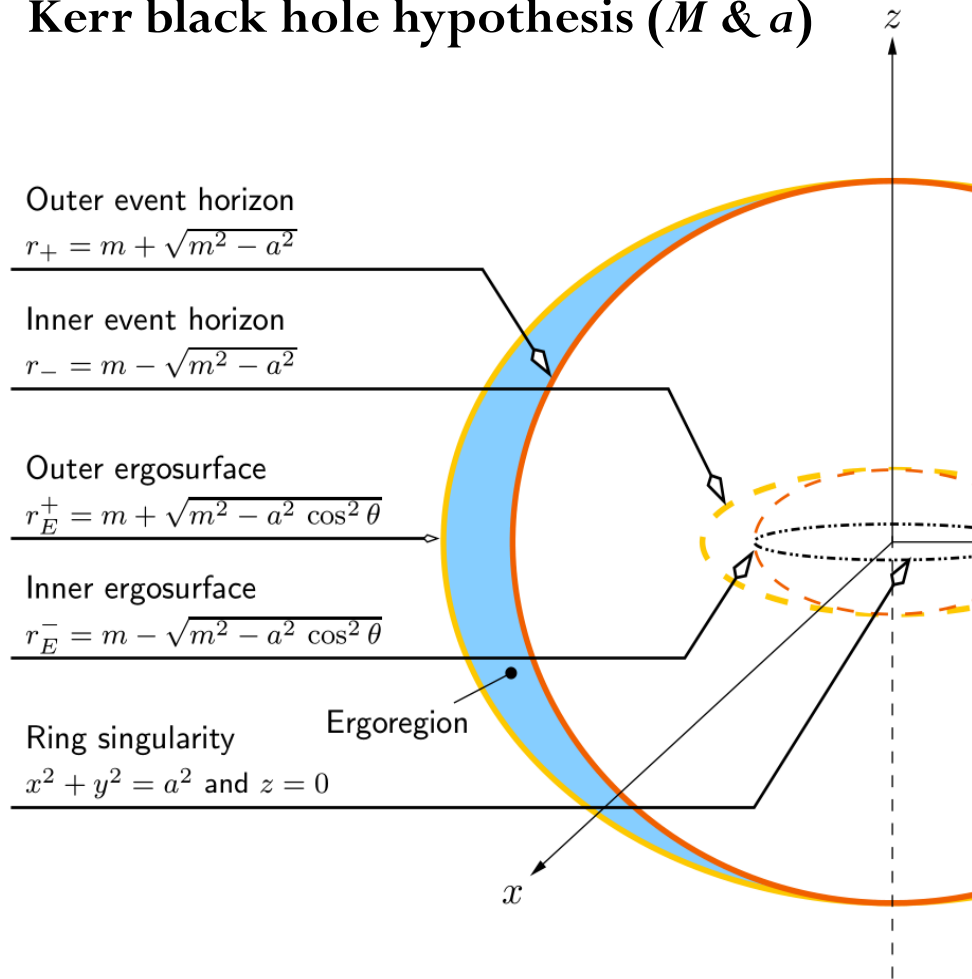
- small acceleration efficiency
- synchrotron losses;
- interactions in source region;
- GZK cutoff



- or just build accelerator of  $\sim 400$  mln km size with LHC technology

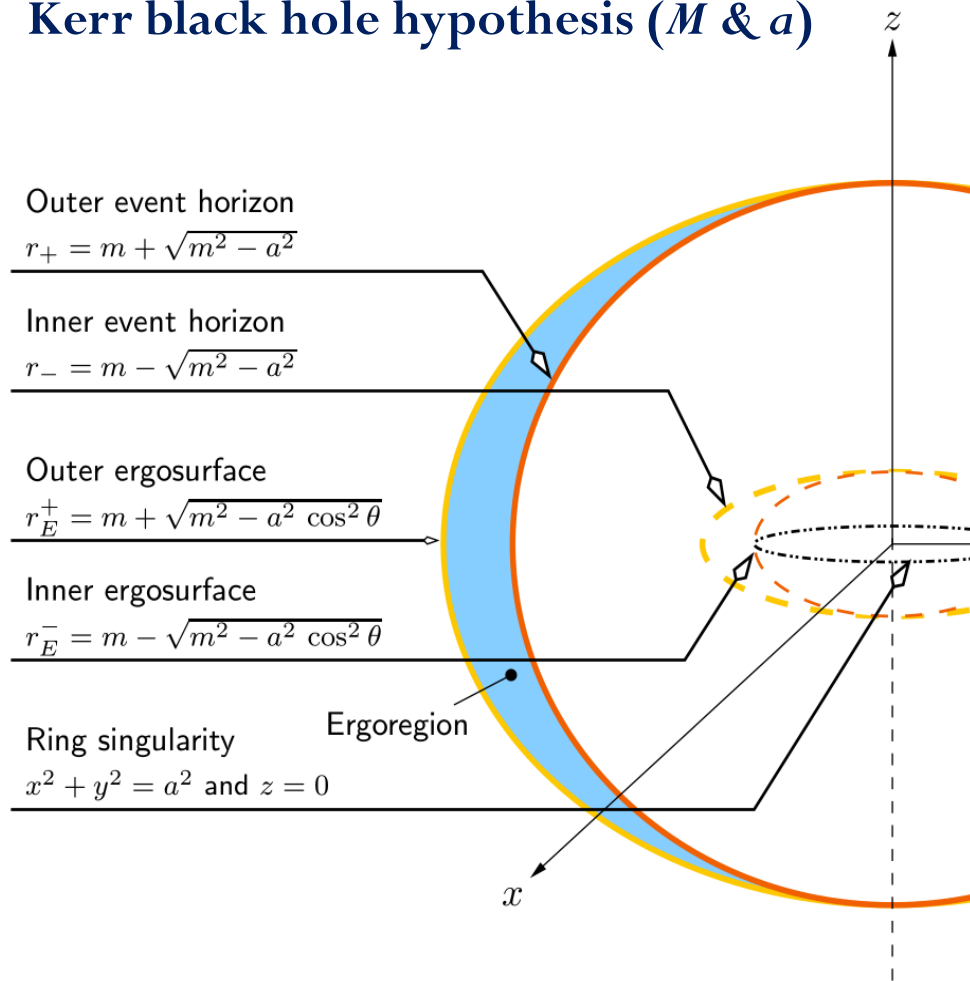
# Can UHECRs be accelerated by black holes?

## Kerr black hole hypothesis ( $M$ & $a$ )



# Can UHECRs be accelerated by black holes?

## Kerr black hole hypothesis ( $M$ & $a$ )



Entropy of black hole  $\sim$  to the event horizon area:

$$S_{\text{BH}} = \frac{c^3}{4G\hbar} A_H$$

$$A_H = \int_0^{2\pi} d\phi \int_0^\pi \sqrt{\det g} d\theta = \frac{8\pi G}{c^2} M r_H$$

$$E_{\text{irr}} = \sqrt{\frac{A_H}{16\pi G^2}} c^4 = \frac{Mc^2}{\sqrt{2}} \left[ 1 + \sqrt{1 - \left(\frac{a}{M}\right)^2} \right]^{\frac{1}{2}}$$

Energy extraction requires negative energy inflow

$$g_{tt} = \frac{2mr}{r^2 + a^2 \cos^2 \theta} - 1 \quad \text{Ergosphere: } g_{tt} = 0$$

Inside the ergosphere  $g_{tt}$  changes its sign

$$E = -p_t = -m u_t = -m g_{tt} u^t - m g_{t\phi} u^\phi$$

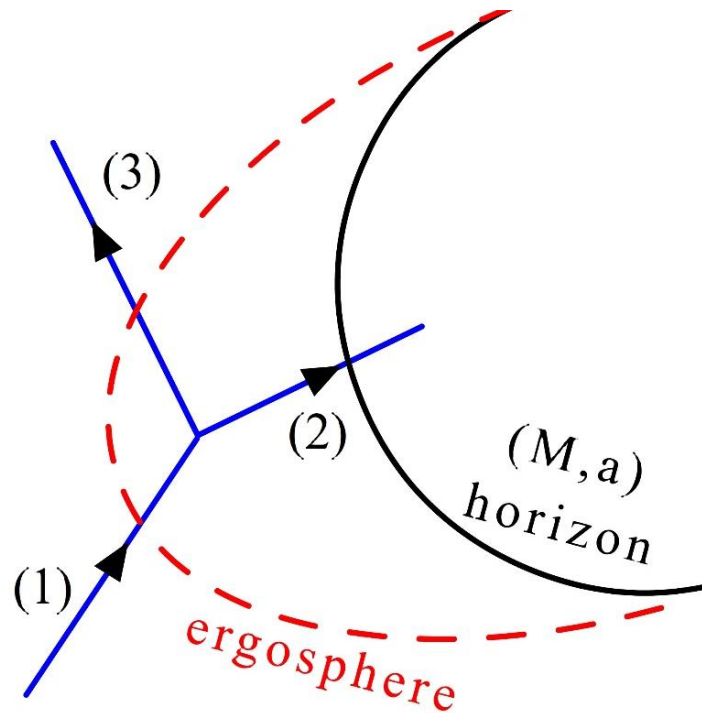
Black hole mechanics and Thermodynamics have uncanny correspondence!

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

# Penrose process (1969)

Schematic plot of Penrose process



Conservation laws:

$$E_1 = E_2 + E_3,$$

$$L_1 = L_2 + L_3,$$

$$m_1 \dot{r}_1 = m_2 \dot{r}_2 + m_3 \dot{r}_3,$$

$$0 = m_2 \dot{\theta}_2 + m_3 \dot{\theta}_3,$$

$$m_1 \geq m_2 + m_3,$$

$$m_1 u_1^\phi = m_2 u_2^\phi + m_3 u_3^\phi.$$

Efficiency of Penrose process:

$$\eta = \frac{E_3 - E_1}{E_1} = \frac{-E_2}{E_1}.$$

After several algebraic manipulations and setting

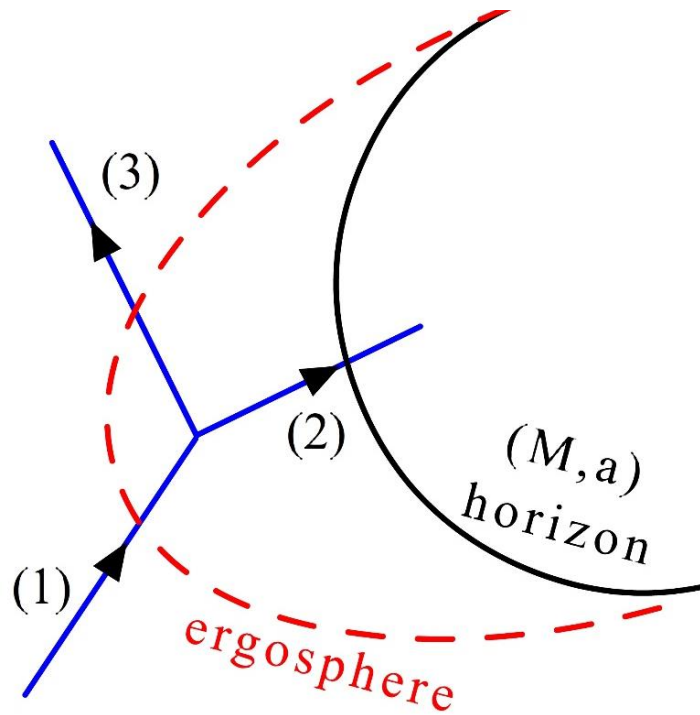
$$\Omega_1 = \Omega, \quad \Omega_2 = \Omega_-, \quad \Omega_3 = \Omega_+$$

$$\eta = \frac{1}{2} \left( \sqrt{1 + g_{tt}} - 1 \right)$$

Maximum efficiency of Penrose process is **21%**

# Historical development of the idea

Original Penrose process



Efficiency is defined as:

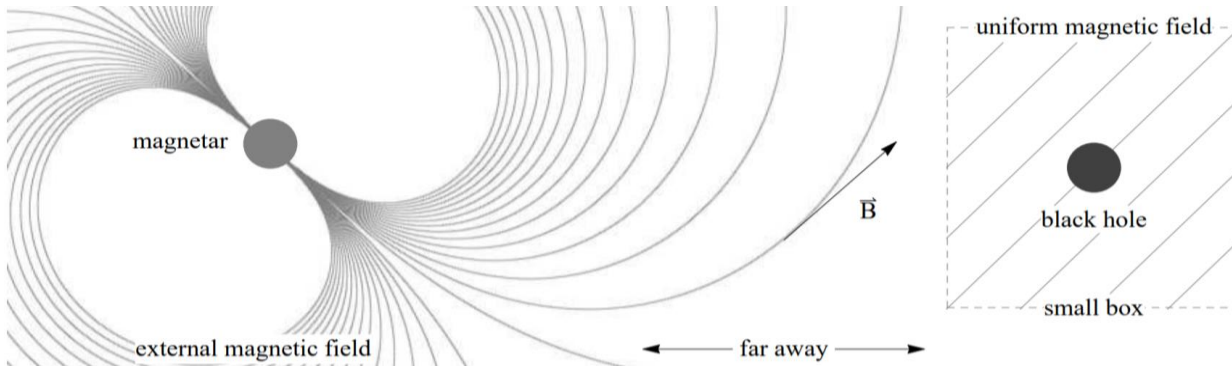
$$\eta = \frac{E_3 - E_1}{E_1} = \frac{-E_2}{E_1}.$$

- **Penrose** (1969) – the energy can be extracted with the **efficiency** limited to **20.7%**
- **Bardeen et al. & Wald** (1972, 1974) – Penrose process is **unrealizable** in astrophysical conditions.
- **Piran et al.** (1975/77) – Collisional Penrose process
- **Ruffini & Wilson** (1975) – Electromagnetic energy extraction by charge separation in **accreting magnetized plasma**
- **Blandford & Znajek** (1977) & later numerous **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 **up to few 100%**
- **Tursunov et al.** (2019, 2020) – efficiency **> 10<sup>10</sup>%** for protons in case of SMBHs



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

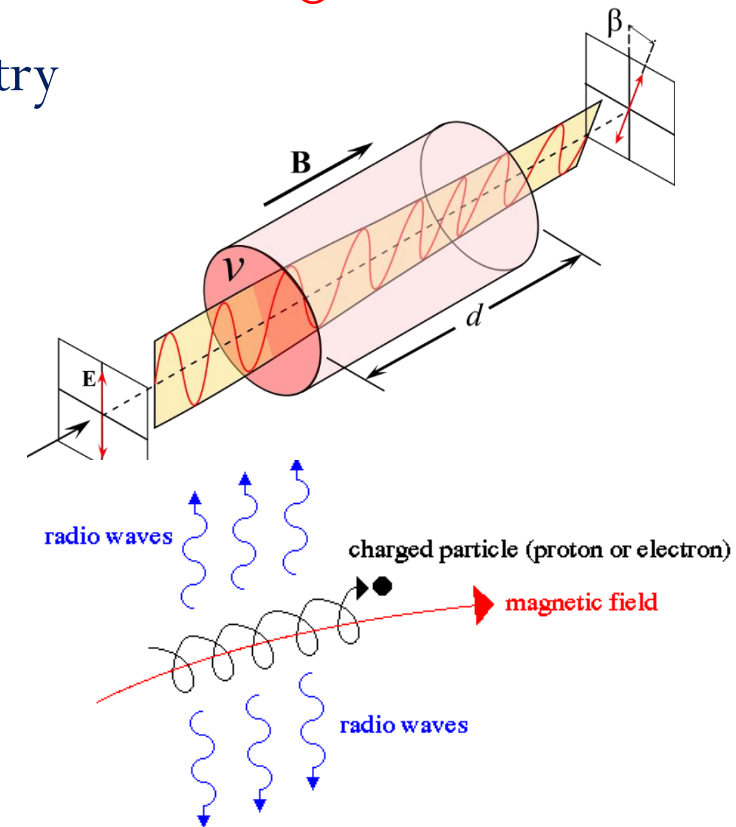
$$B \ll \frac{c^4}{G^{3/2} M_\odot} \left( \frac{M_\odot}{M} \right) \sim 10^{19} \frac{M_\odot}{M} \text{ G}$$

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

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

- This ratio for **SgrA\***  $\sim 10^6$

- Measurements: Faraday rotation, synchrotron radiation, etc.





# Black holes are weakly charged

- Assume that MF shares spacetime symmetries
  - $A^\phi \neq 0$  implies that  $A_\phi = g_{\phi\phi}A^\phi$  and  $A_t = g_{t\phi}A^\phi$ , i.e. **electric field is induced**
  - This will cause a **selective accretion** into BH and consequent **NET-charging of BH**.

- **Wald solution of Maxwell eqs. for uniform MF**

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

- $$\Delta\phi = \phi_H - \phi_\infty = \frac{Q - 2aMB}{2M}. \quad (\text{Wald, 1974})$$

- Potential difference is neutralized by accretion until **BH accretes positive net charge**  $2aMB$

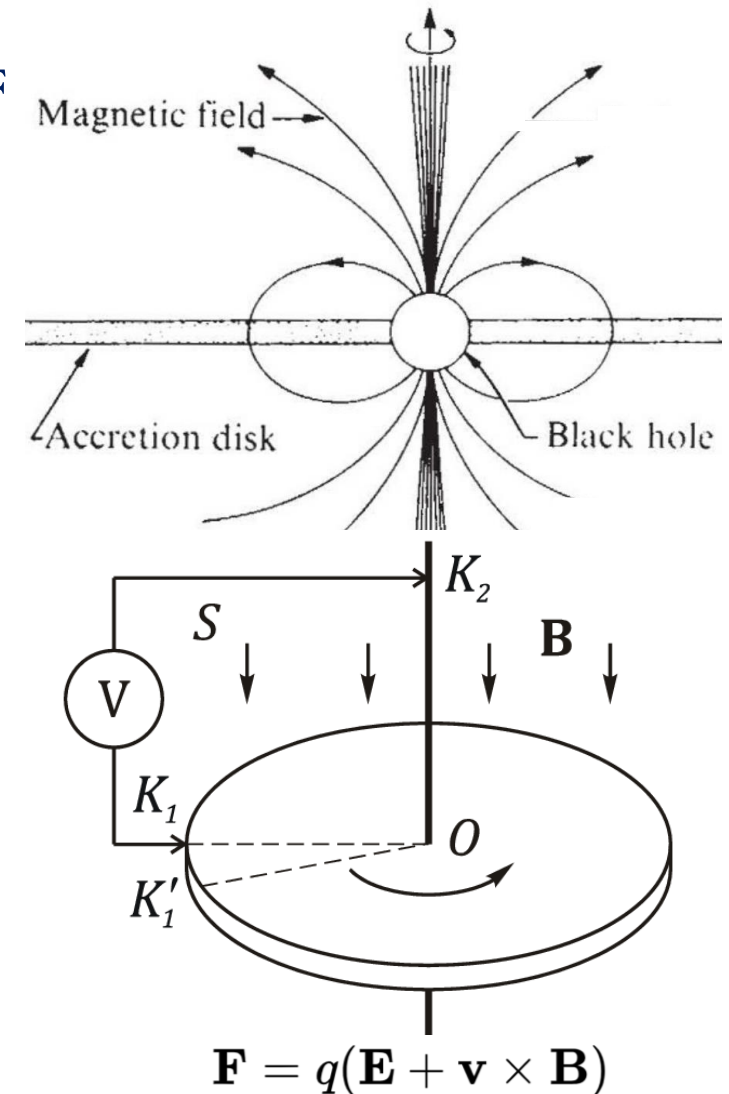
- Therefore, there are two Wald solutions:

- 1) **BH with zero charge** (formal mathematical solution)
- 2) **BH with net electric charge** (physical solution)

- **Magnetosphere is charged as well**

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

- $$Q_{\text{mag}} = -Q_{\text{BH}}.$$



# 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** (2018,2019,2020) – electric charge of Galactic centre SMBH is  **$10^8 - 10^{15}C$**

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

# Efficiency of energy extraction from rotating black hole

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

- Conservation laws:  $E_1 = E_2 + E_3$ ,  $L_1 = L_2 + L_3$ ,

$$q_1 = q_2 + q_3, \quad m_1 \geq m_2 + m_3,$$

$$m_1 \dot{r}_1 = m_2 \dot{r}_2 + m_3 \dot{r}_3, \quad 0 = m_2 \dot{\theta}_2 + m_3 \dot{\theta}_3$$

- Efficiency definition:  $\eta = \frac{E_3 - E_1}{E_1} = \frac{-E_2}{E_1}$ .

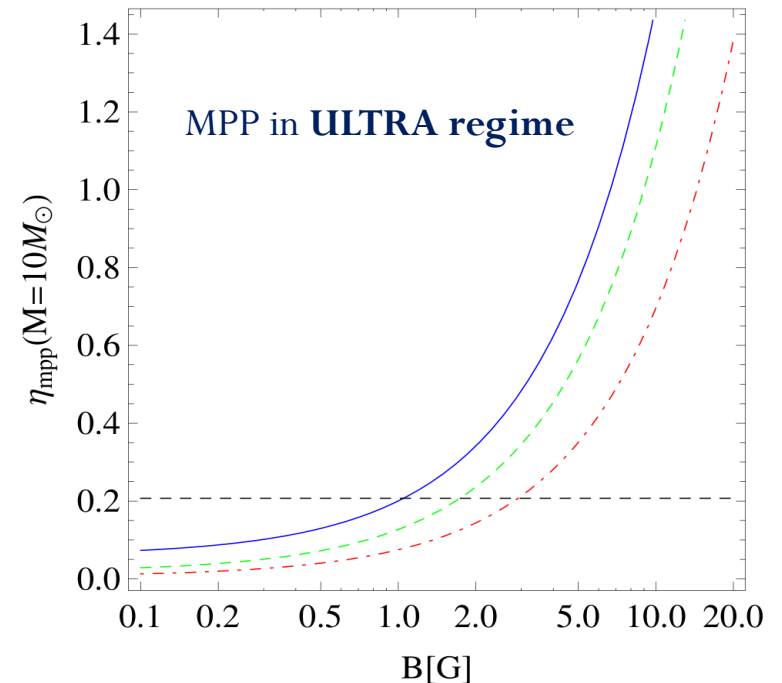
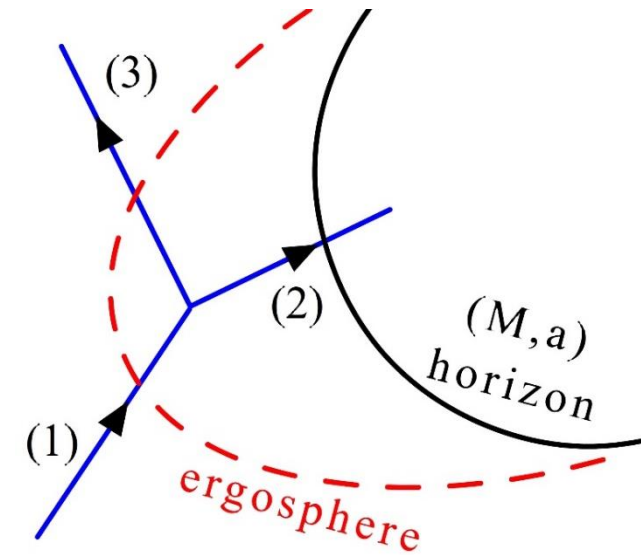
- Result:  $\eta_{\text{MPP}} = \chi - 1 + \frac{\chi q_1 A_t - q_3 A_t}{E_1}$ ,  $1 \leq \chi \leq 1.21$ , for spin  $0 \leq a \leq 1$ .

- There exist 3 regimes of BH energy extraction: **Low, Moderate and Ultra**

- Low: Penrose limit  $< 0.21$  **(neutral matter)**  $\eta_{\text{PP}} = \frac{1}{2} \left( \sqrt{\frac{2M}{r}} - 1 \right)$ .

- Moderate: same as BZ  $< 10$  **(charged matter)**  $\eta_{\text{MPP}}^{\text{mod.}} \approx \frac{q_3}{q_1} - 1$ .

- Ultra: novel regime  $> 10^9$  **(ionization of neutral matter)**  $\eta_{\text{MPP}}^{\text{ultra}} \approx \frac{q_3}{m_1} A_t$ .



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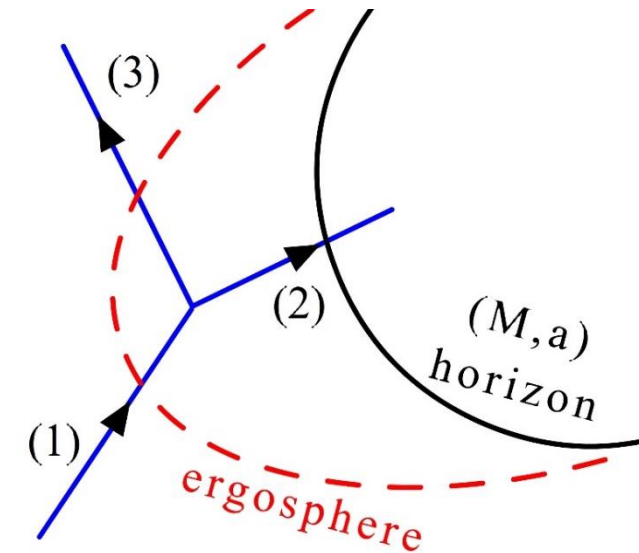
$$q_1 = q_2 + q_3, \quad m_1 \geq m_2 + m_3,$$

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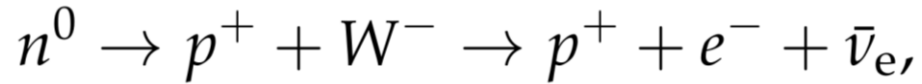
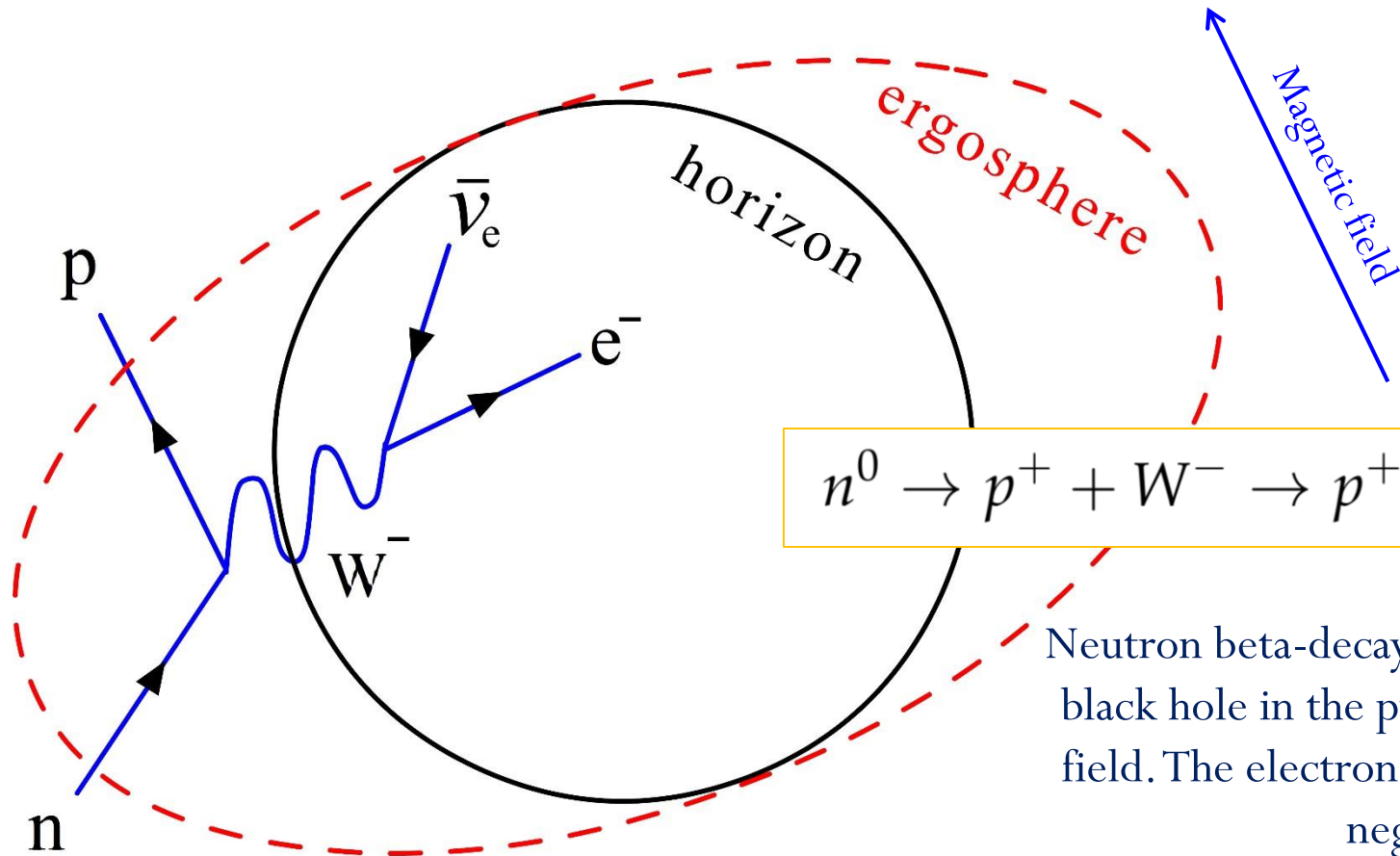
- Ultra: novel regime **> 10<sup>9</sup>**  $\eta_{\text{MPP}}^{\text{ultra}} \approx \frac{q_3}{m_1} A_t$ .  
(ionization of neutral matter)

Let us consider the two ionization processes around Kerr BH of  $10M_\odot$  mass and  $10^4 \text{G}$  MF:

$$\text{He}^+ \rightarrow \alpha(\text{He}^{++}) + e^-, \quad \eta_{\text{He}^+}^{\text{mod}} = 0.99.$$

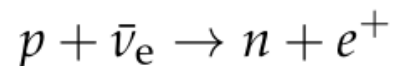
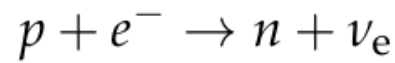
$$\text{He} \rightarrow \alpha(\text{He}^{++}) + 2e^-, \quad \eta_{\text{He}}^{\text{ultra}} = 2.4 \times 10^3$$

# Beta-decay in ergosphere



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  $> 10^{10}$   $\text{g}\cdot\text{cm}^{-3}$ , 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:

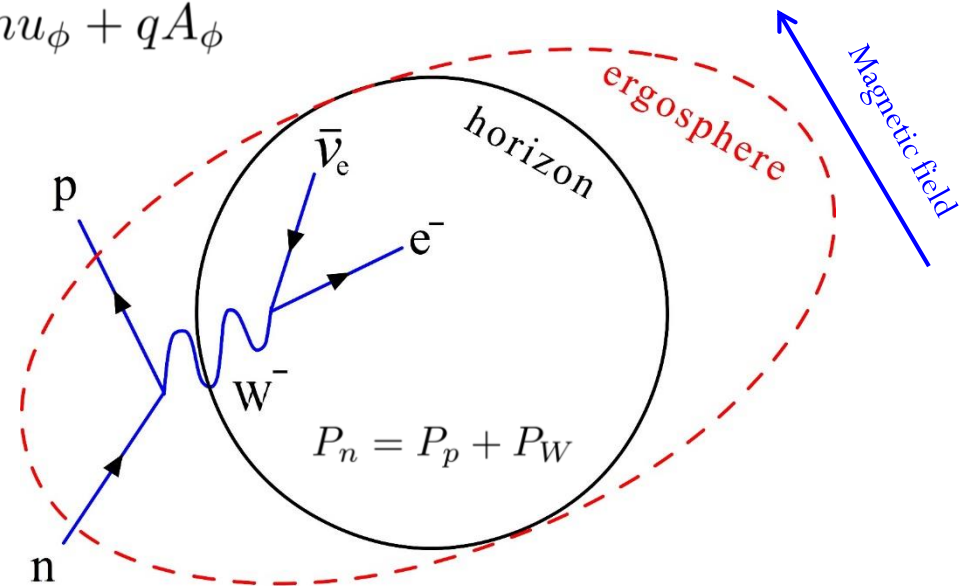


# Efficiency of energy extraction by beta-decay

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

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

$$\eta_\beta = \frac{E_p - E_n}{E_n}$$

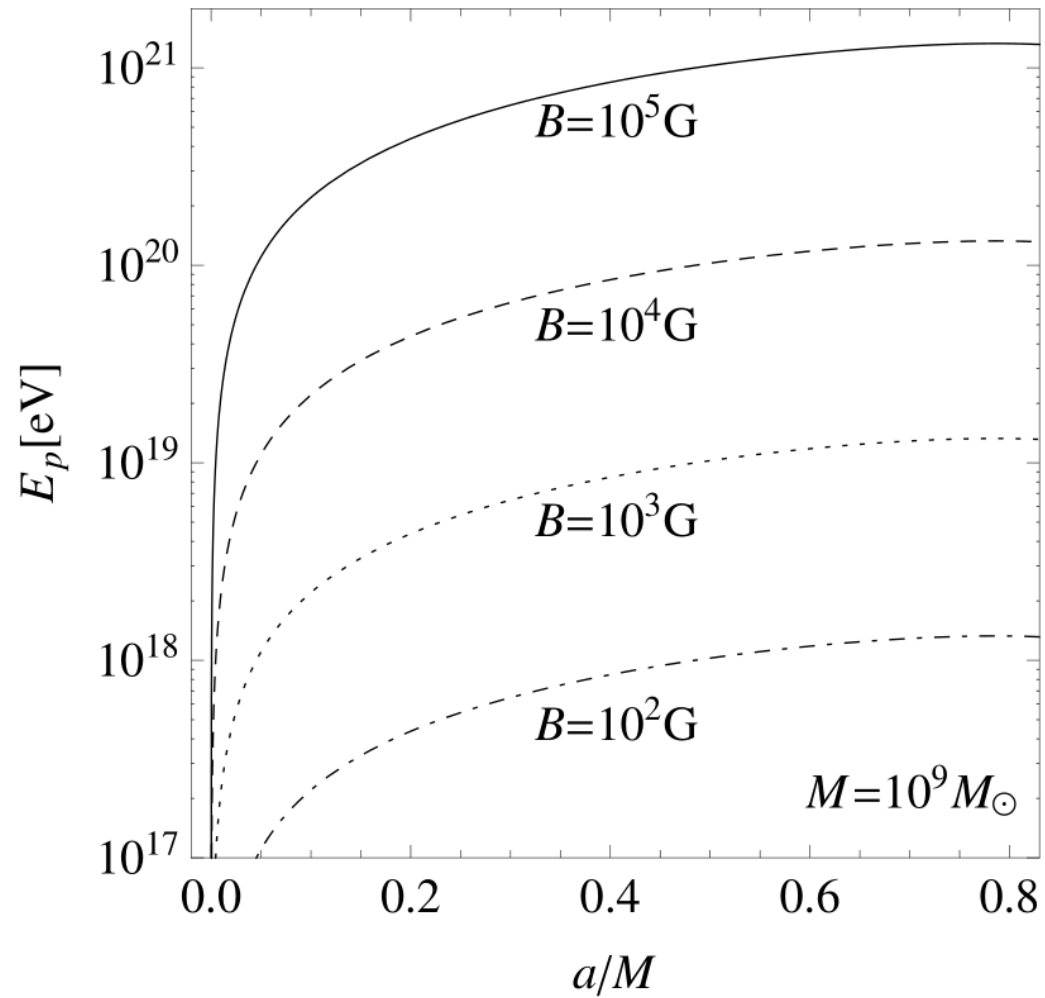
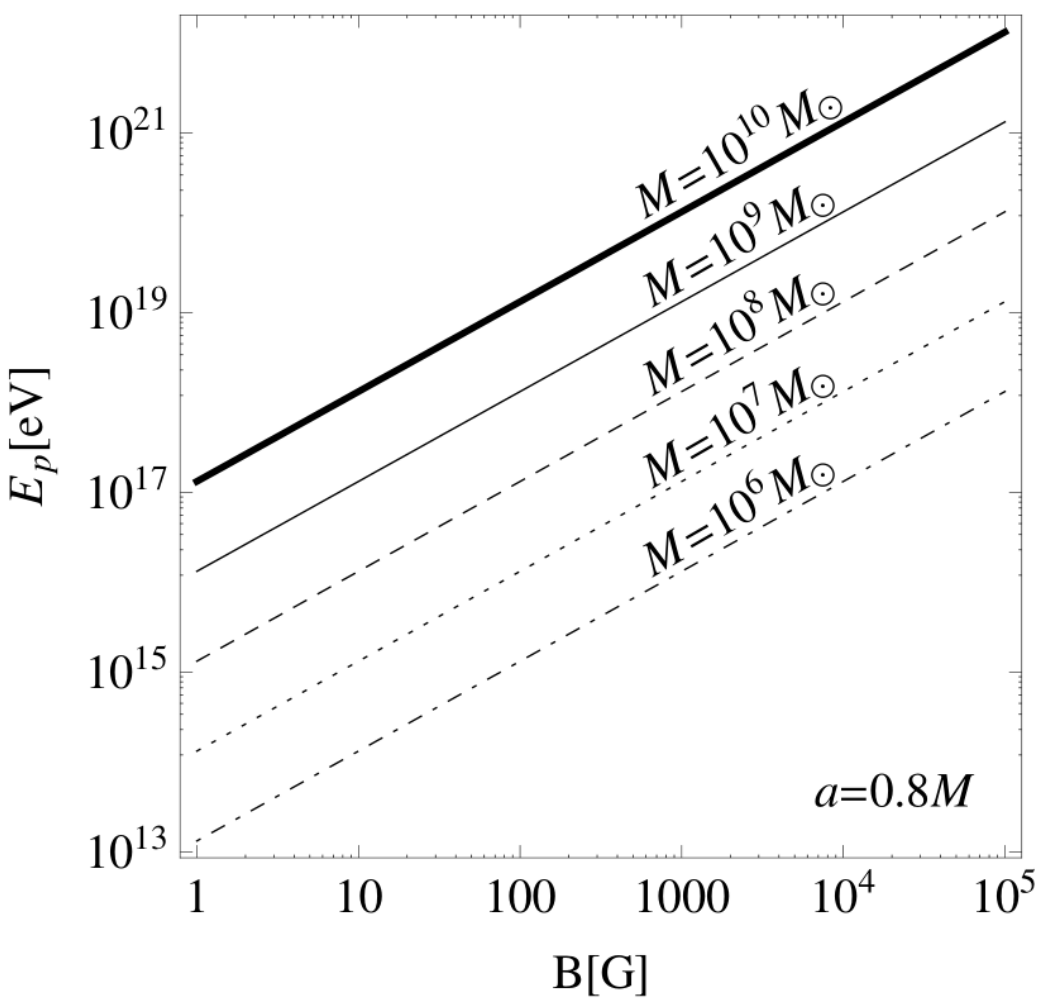
Final result depends on the field configuration. In the absence of MF, the efficiency corresponds to Penrose process with maximum

$$\eta_{\text{Kerr}}^{\text{max}} = \frac{\sqrt{2} - 1}{2} \approx 20.7\%$$

For uniform magnetic field

$$\eta_\beta = \frac{1}{2} \left( \sqrt{\frac{2M}{r_H}} - 1 \right) + a\mathcal{B} \left( 1 - \frac{M}{r_H} \right), \quad \mathcal{B} = \frac{|e|GBM_{\text{SMBH}}}{m_p c^4}.$$

# Energy of proton driven away from BH



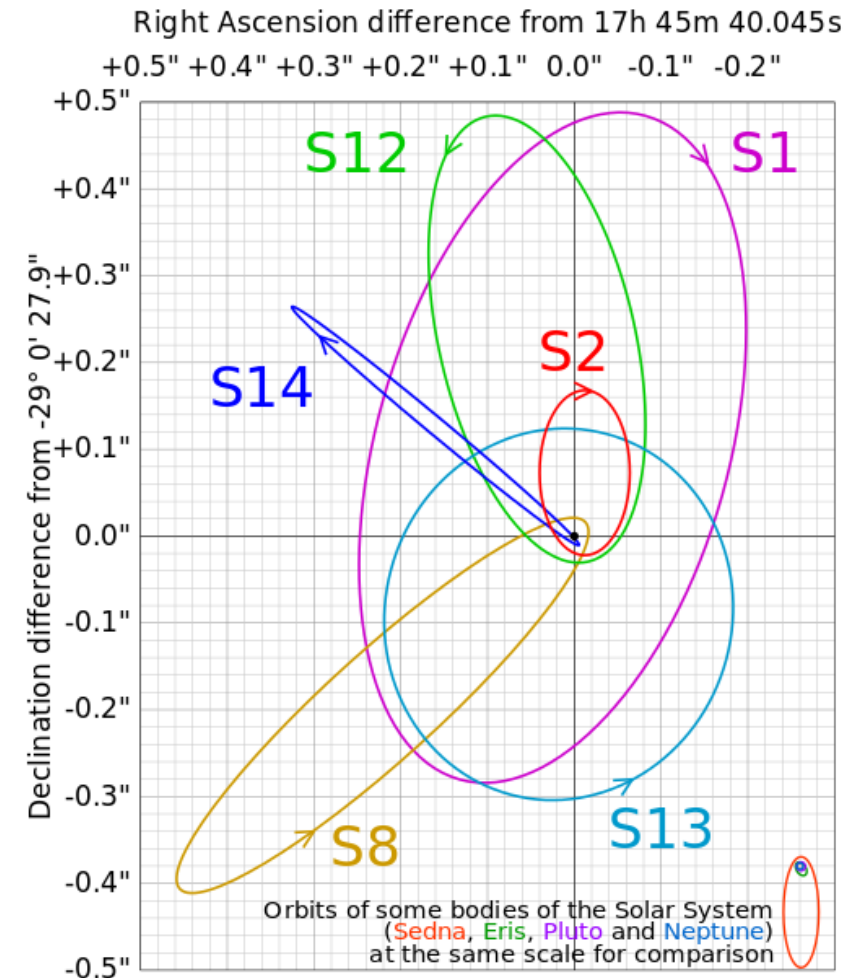
The energy of free neutron is  $\sim 0.94 \times 10^9$  eV

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



# The Milky Way's SgrA\* as SMBH

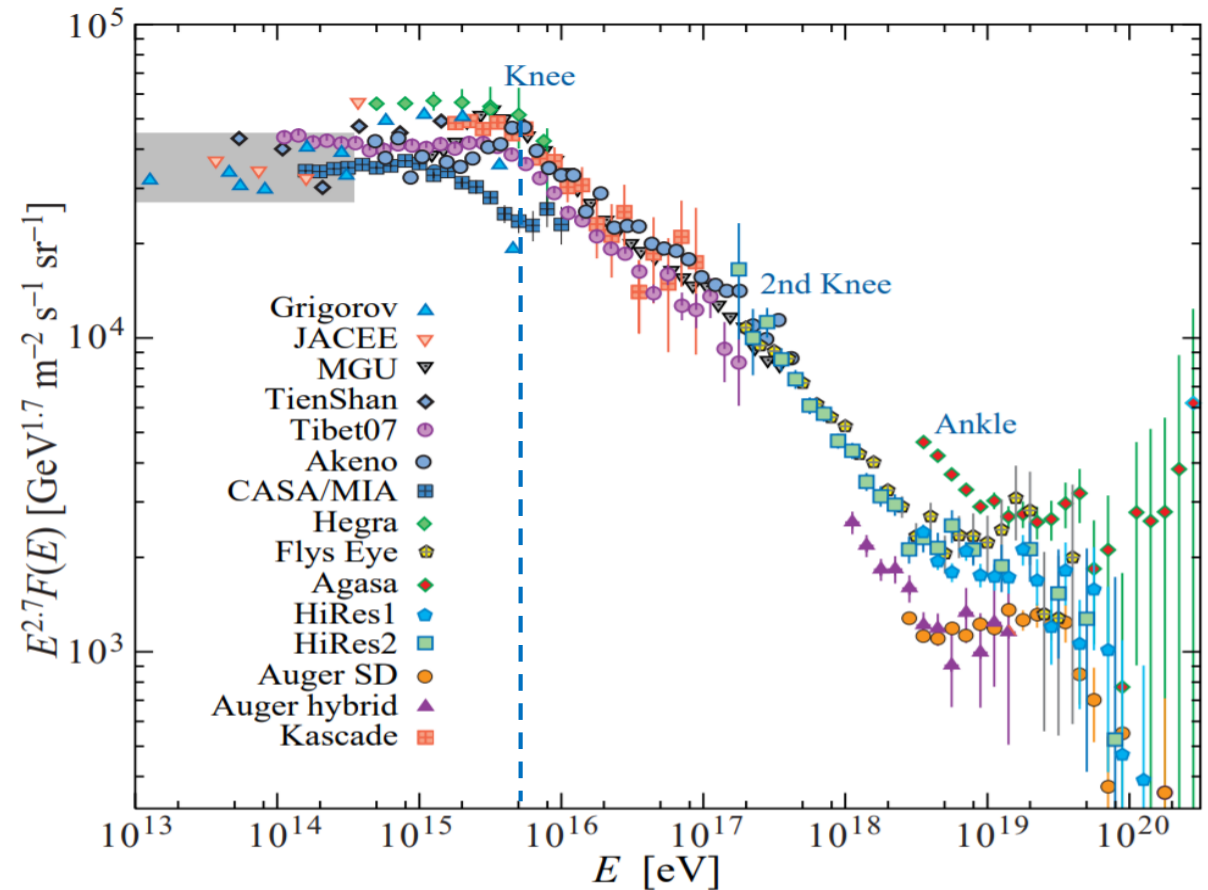
- **Best known candidate for SMBH at 8 kpc**
- **Mass is  $\sim 4 \times 10^6 M_{\odot}$**  based on different methods:
  - the orbits of **S stars** (Parsa et al. 2017)
  - modelling of the **NSC** (Do et al. 2013)
  - fits to double peaked **X-ray flares** (Karssen et al. 2017)
- **Spin is loosely 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  $\sim 10$  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-hair theorem:  **$B \ll 10^{12}$  Gauss**
  - However, even weak magnetic field can completely change the dynamics of elementary particles



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

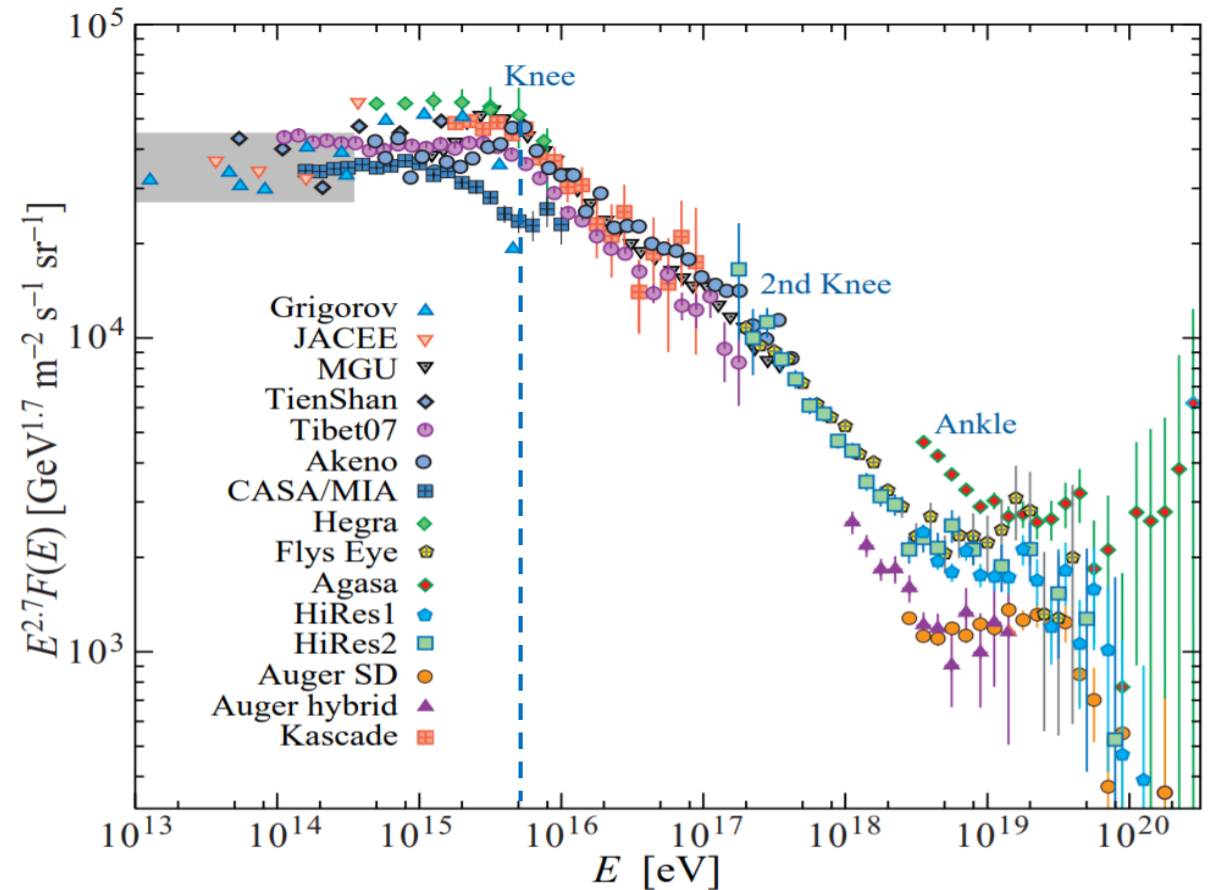
# The Milky Way's SgrA\* as PeVatron

- **Rotating black hole**
  - SgrA\* is spinning  $\sim 0.5M$
- **External magnetic field**
  - around SgrA\*  $\sim 10G$
- **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

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

$$E_n = E_p + E_W,$$

$$L_n = L_p + L_W,$$

$$m_n \dot{r}_n = m_p \dot{r}_p + m_W \dot{r}_W,$$

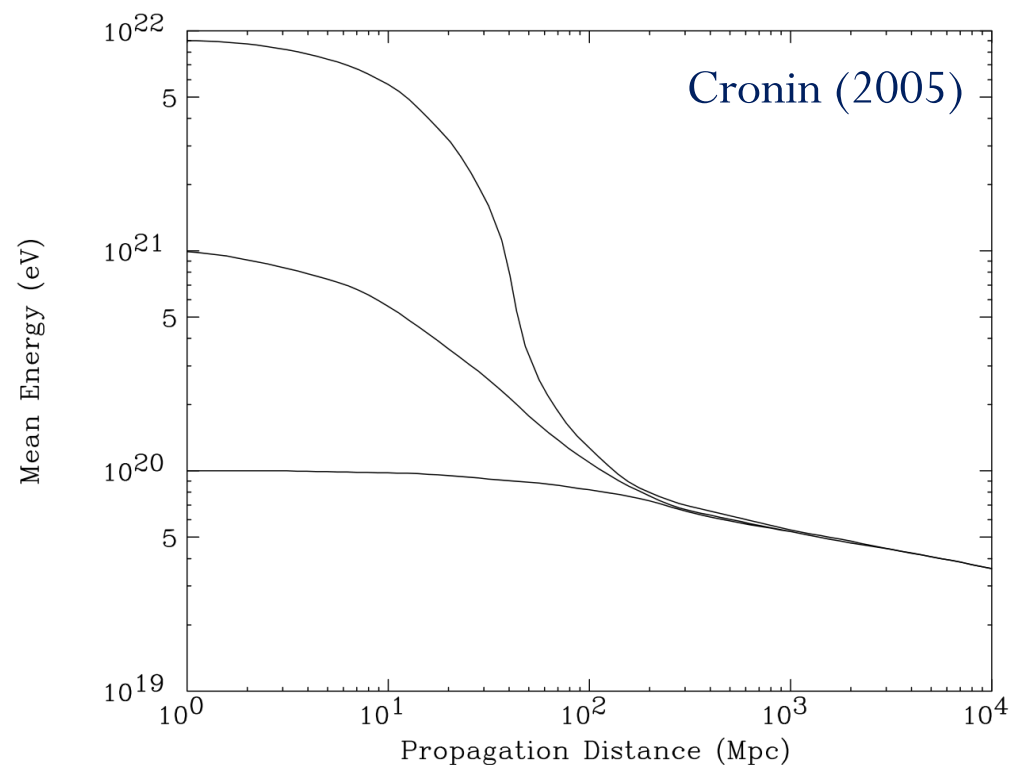
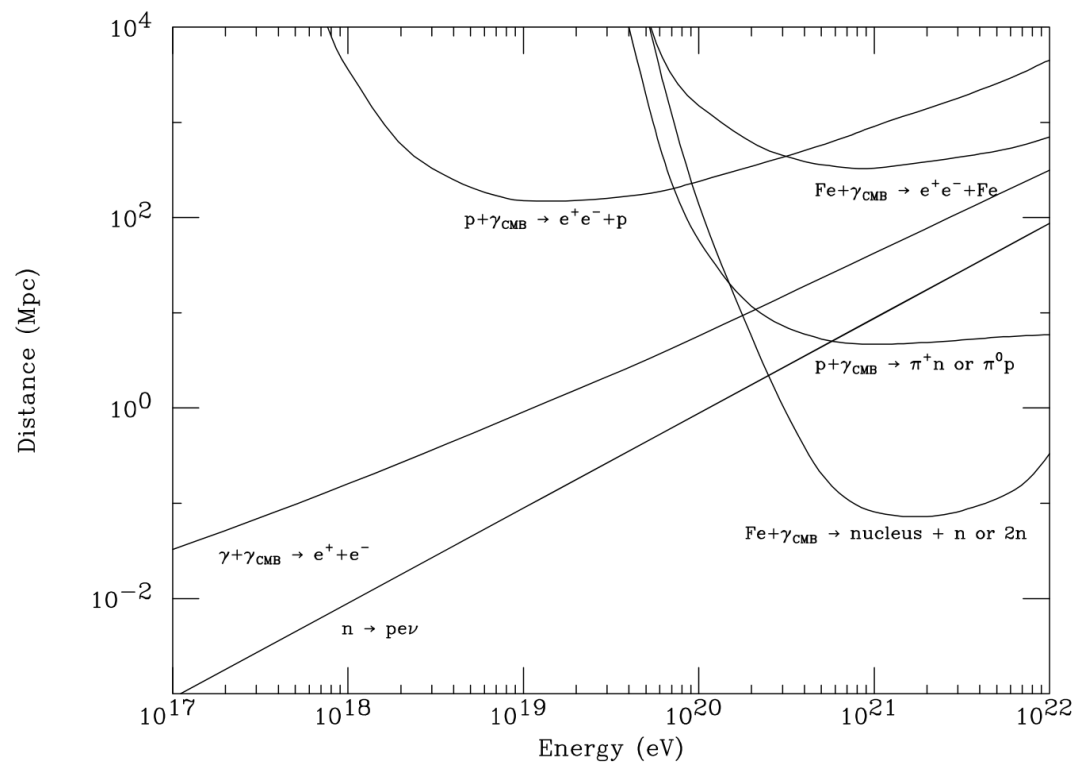
$$q_W + q_p = 0.$$

## Proton energy corresponds to the Knee

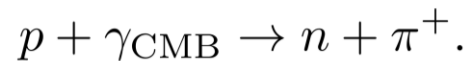
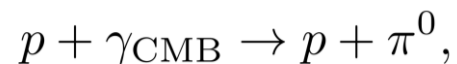
$$E_{p^+} \approx 5 \times 10^{15} \text{ eV} \left( \frac{q}{e} \right) \left( \frac{m}{m_{p^+}} \right)^{-1} \left( \frac{B}{10G} \right) \left( \frac{M}{M_{\text{SgrA}^*}} \right)$$

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

# GZK cutoff

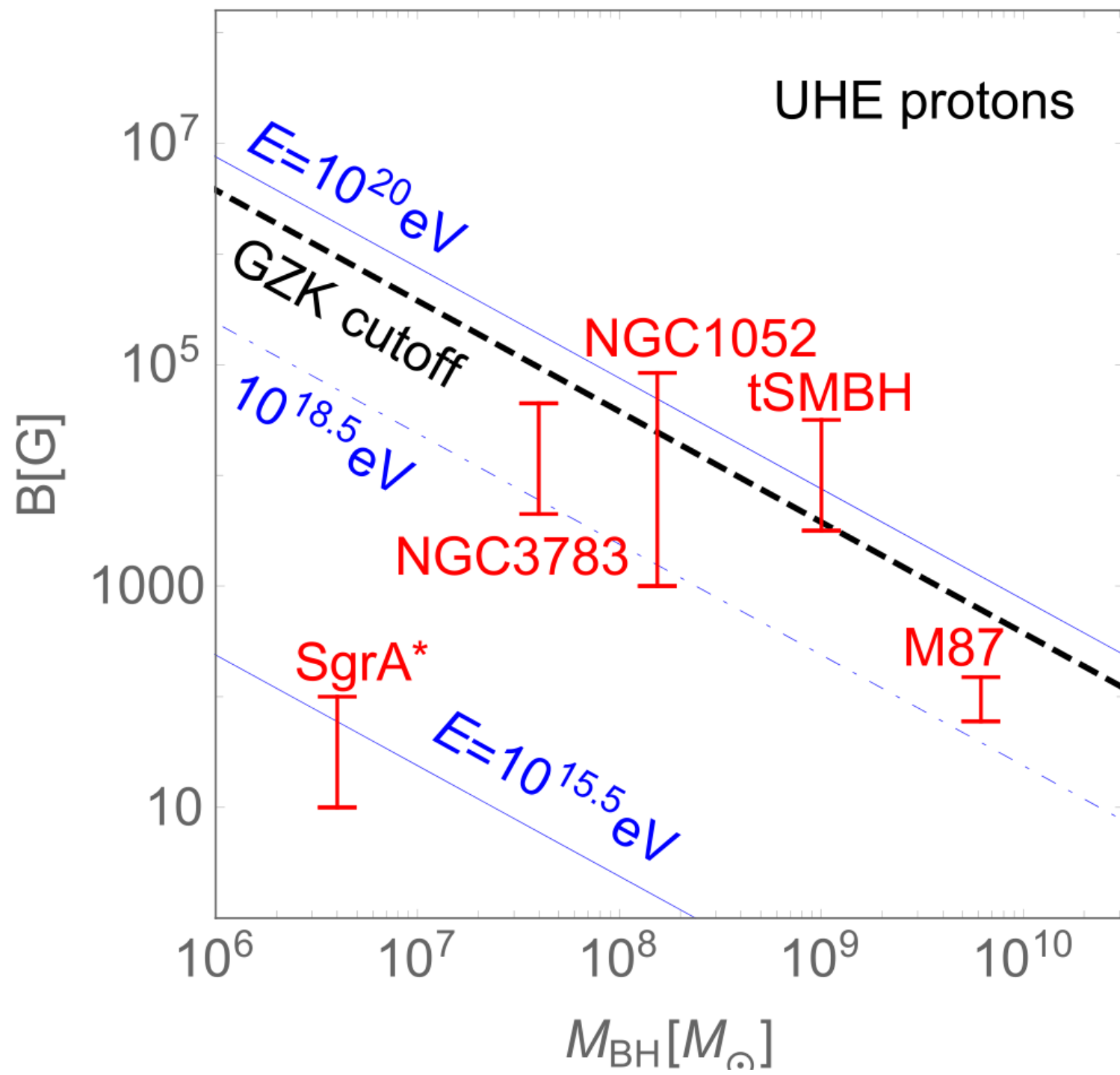


left: Panorama of the interactions of possible cosmic primaries with the CMB; right: and mean energy of protons as a function of propagation distance through the CMB, based on GZK cutoff.



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

# Constraints on parameters and source candidates



# Selected nearby SMBH candidates

SMBH	Log( $M/M_{\odot}$ )	Spin $a$	d (Mpc)	Log( $B/1\text{G}$ )	Log( $E_{p+}^{\text{mean}}/1\text{eV}$ )
Sgr A*	6.63	0.5	0.008	2	15.64
NGC 1052	8.19	$\lesssim 1$	19	4.8	20.11
NGC 1068 / M77	6.9	$\lesssim 1$	15	4.54	18.56
NGC 1365	6.3	$\lesssim 1$	17.2	4.70	18.12
NGC 2273	6.9	0.97	29	4.58	18.41
NGC 2787	7.6	$\lesssim 1$	8	3.73	18.45
NGC 3079	6.4	$\lesssim 1$	22	4.06	17.58
NGC 3516	7.4	0.64	42	4.88	19.37
NGC 3783	7.5	0.98	41	4.15	18.77
NGC 3998	8.9	0.54	15	3.58	19.52
NGC 4151	7.8	0.84	14	4.6	19.53
NGC 4258 / M106	7.6	0.38	8	4.14	18.65
NGC 4261	8.7	$\lesssim 1$	32	3.51	19.33
NGC 4374 / M84	9	0.98	20	3	19.12
NGC 4388	6.9	0.51	18	5.19	19.11
NGC 4486 / M87	9.7	$\lesssim 1$	17	2.84	19.66
NGC 4579	8	0.82	18	4.11	19.23
NGC 4594	8.8	0.6	11	3.18	19.05
NGC 5033	7.2	0.68	20	4.47	18.77
NGC 5194 / M51	6.0	0.57	8	4.51	17.57
MCG-6-30-15	7.3	0.98	33	4.74	19.16
NGC 5548	7.8	0.58	75	4.48	19.34
NGC 6251	8.8	$\lesssim 1$	102	3.70	19.62
NGC 6500	8.6	$\lesssim 1$	43	3.60	19.32
IC1459	9.4	$\lesssim 1$	31	3.20	19.72

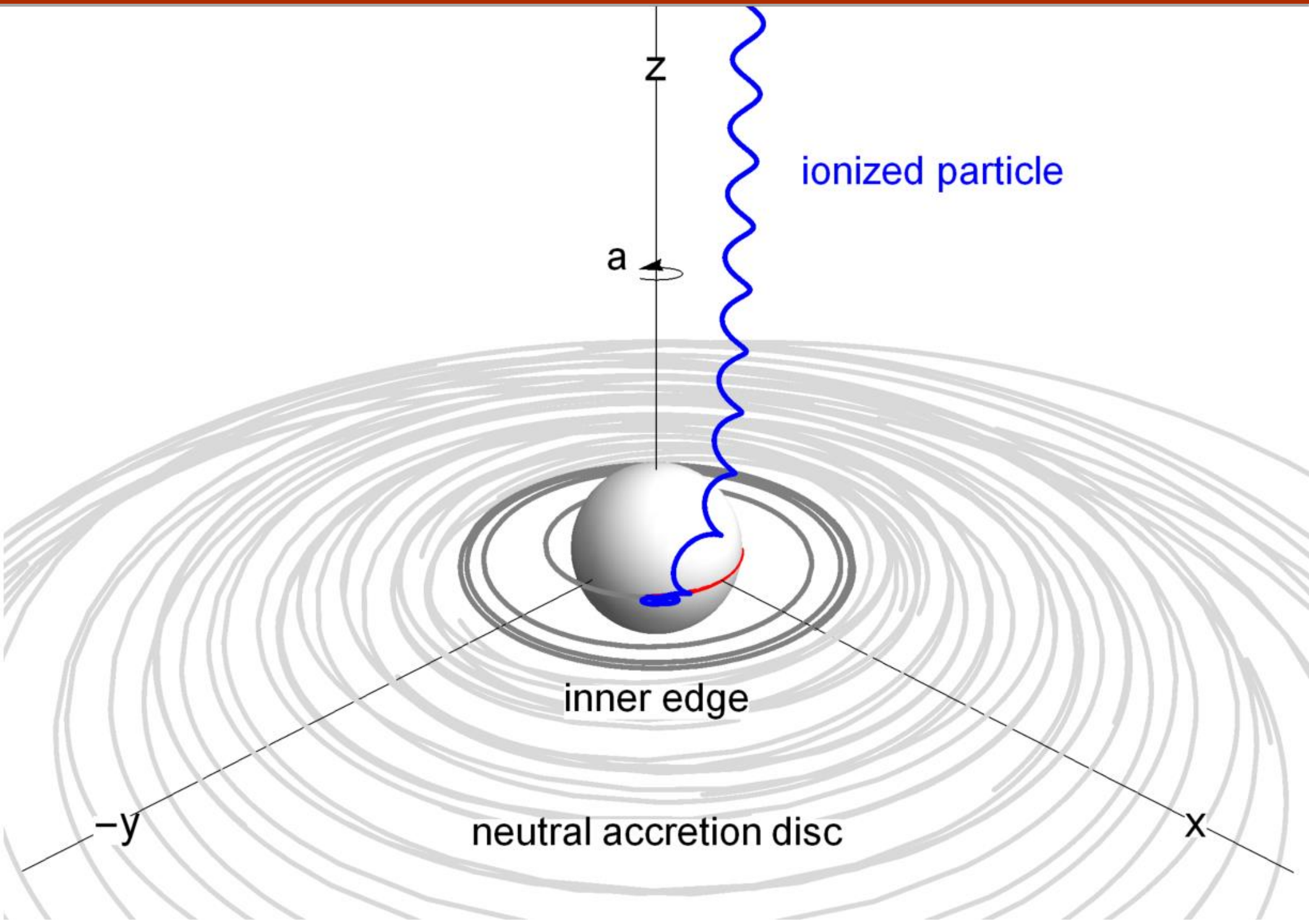
# Energy extraction in various radioactive decay modes

Decay Mode	Generic Equation	Esc. p.	Efficiency $\eta_{\max}$	Regime of MPP
$\alpha$ decay	${}^A_Z X^0 \rightarrow {}^{A-4}_{Z-2} Y^{2-} + \frac{4}{2} \alpha^{2+}$	Y $\alpha$	$<0$ $1.2 \times 10^6 / A$	- ultra
	${}^A_Z X^+ \rightarrow {}^{A-4}_{Z-2} Y^- + \frac{4}{2} \alpha^{2+}$	Y $\alpha$	$<0$ $\sim 1$	- moderate
	${}^A_Z X^- \rightarrow {}^{A-4}_{Z-2} Y^{3-} + \frac{4}{2} \alpha^{2+}$	Y $\alpha$	$\sim 2$ $<0$	moderate -
$\beta^-$ decay	${}^A_Z X^0 \rightarrow {}^A_{Z+1} Y^+ + e^- + \bar{\nu}$	Y	$6.1 \times 10^5 / A$	ultra
		$e^-$	$<0$	-
		$\bar{\nu}$	0.06	low
$\beta^+$ decay	${}^A_Z X^+ \rightarrow {}^A_{Z-1} Y^0 + e^+ + \nu$	Y	$<0$	-
		$e^+$	$\sim 0$	low/-
		$\nu$	$<0$	-
$\gamma$ emission	${}^A_Z X^0 \rightarrow {}^A_Z X'^0 + {}^0_0 \gamma^0$	$X'$	0.06	low
		$\gamma$	0.06	low
Pair production	$\gamma^0 \rightarrow e^- + e^+$	$e^-$	$<0$	-
		$e^+$	$5.5 \times 10^8 / (2m_e c^2)$	ultra

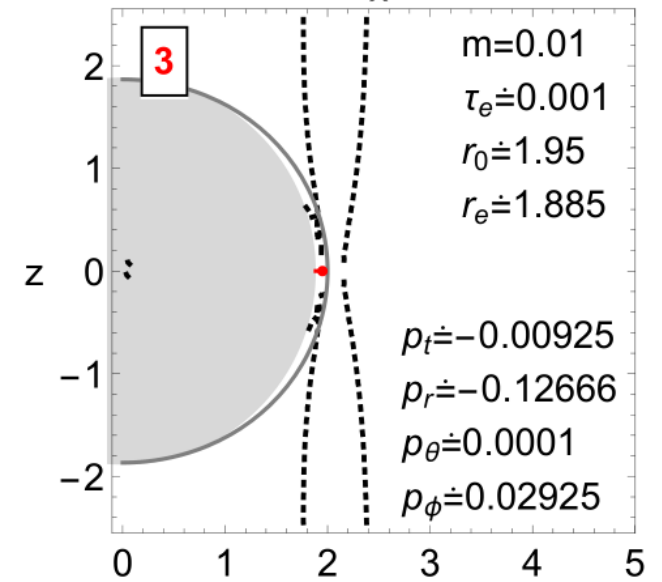
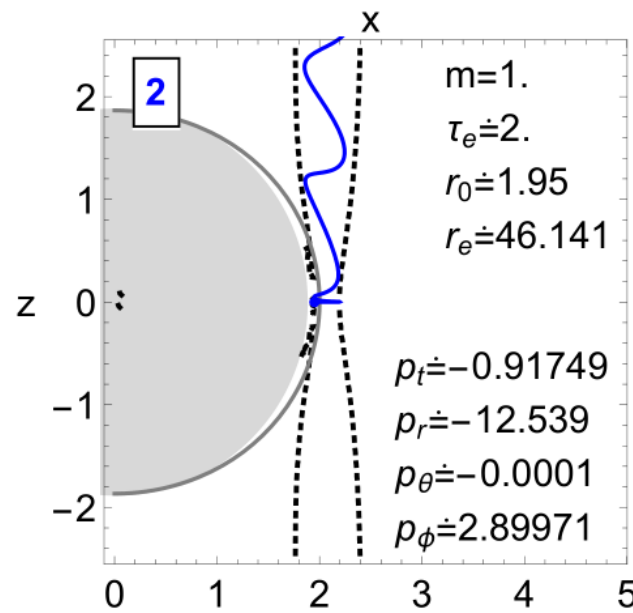
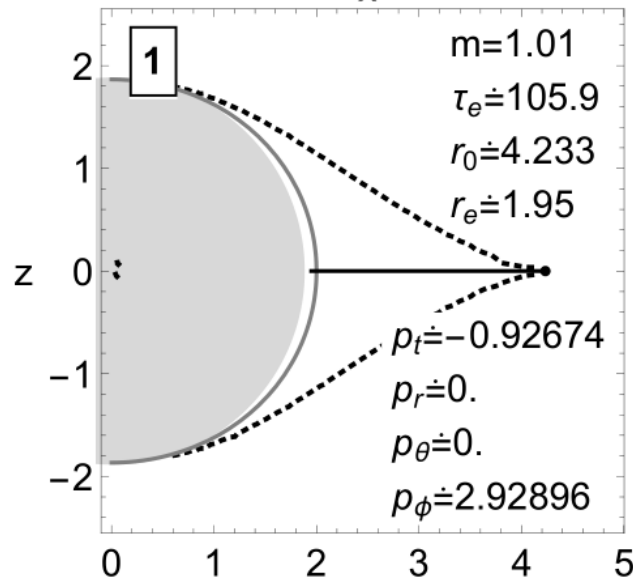
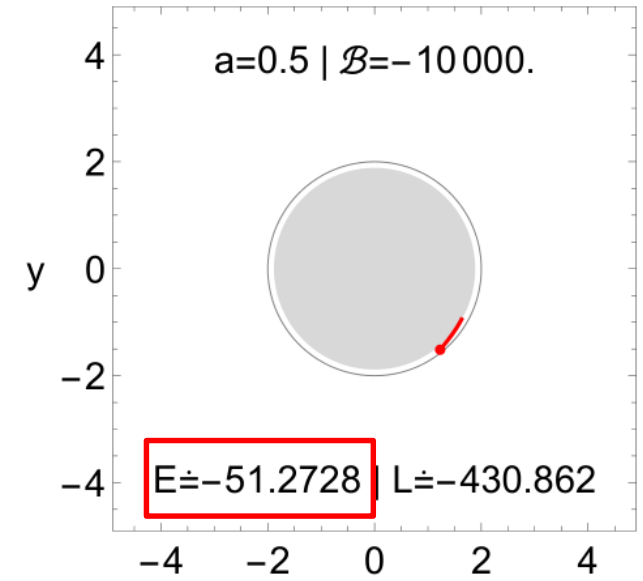
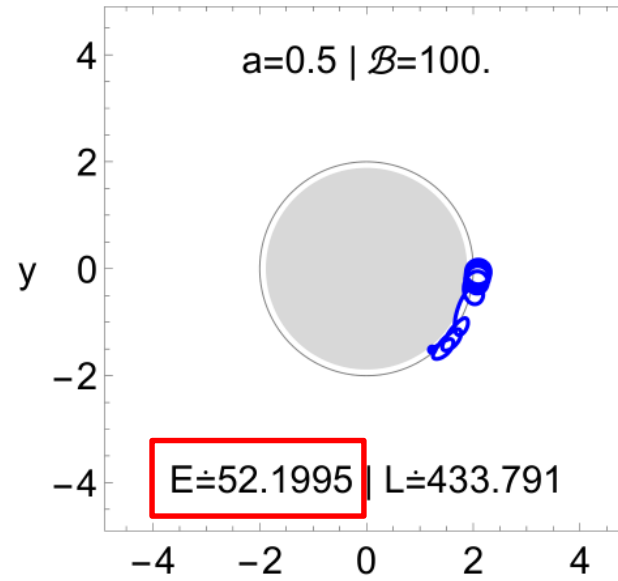
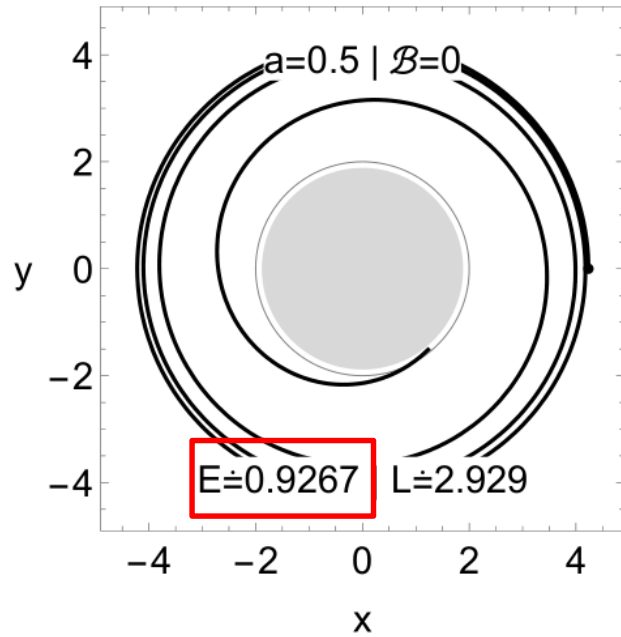
Efficiency of energy extraction from stellar mass black hole for various typical radioactive decay modes. Initial energy of decaying particle is taken to be equal to its rest mass.



# Numerical modelling



# Numerical modelling



$$\mathcal{B} = \frac{|e| B G M_{\text{BH}}}{m_p c^4} \approx 10^6 \frac{B}{10 \text{G}} \frac{M_{\text{SgrA}^*}}{10^{6.6} M_\odot}.$$

# Role of BH charge!

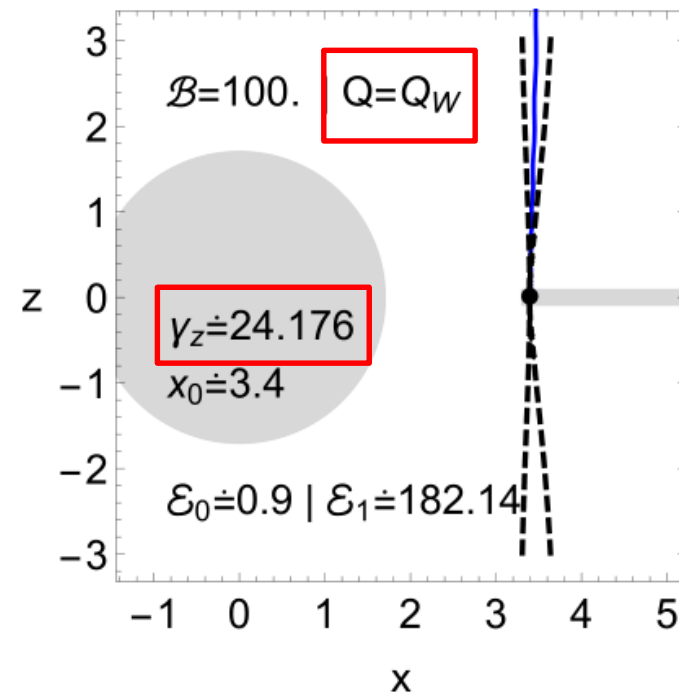
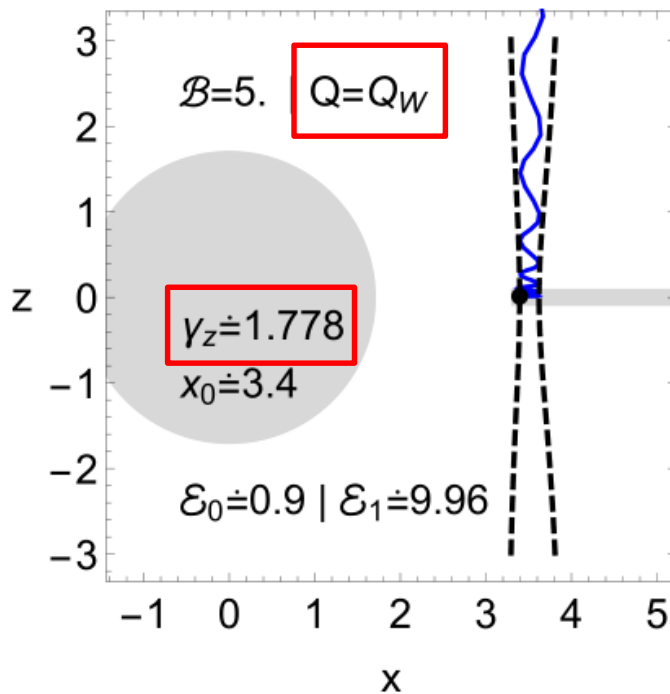
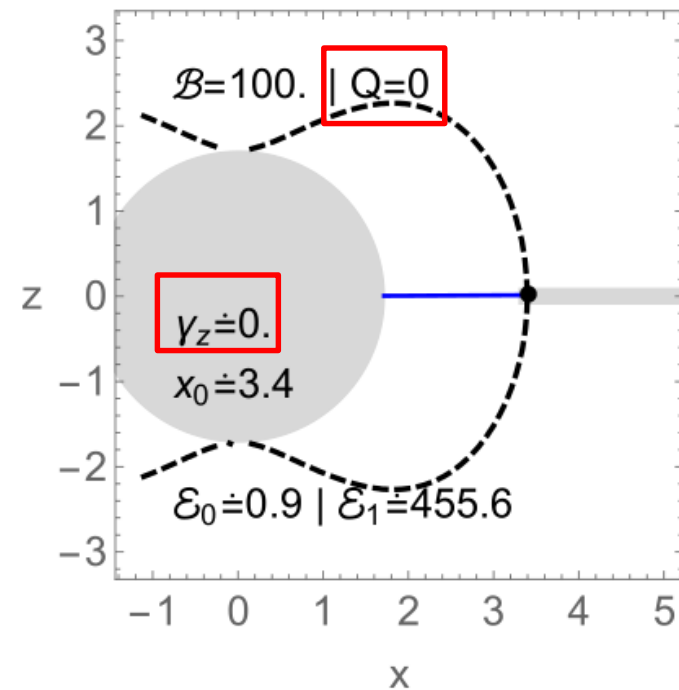
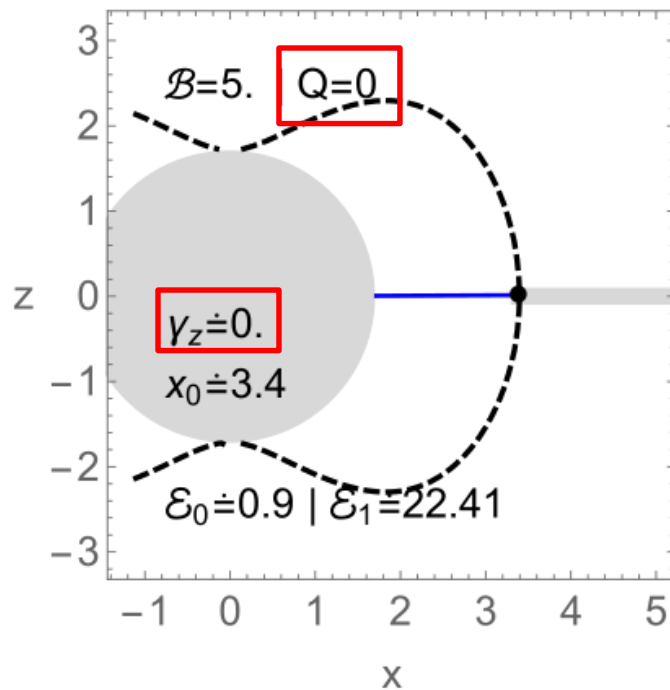
$$\mathcal{E} = \frac{E}{m}, \quad E_0 = E_1 + E_2$$

$\gamma_z$  – factor of esc. par.

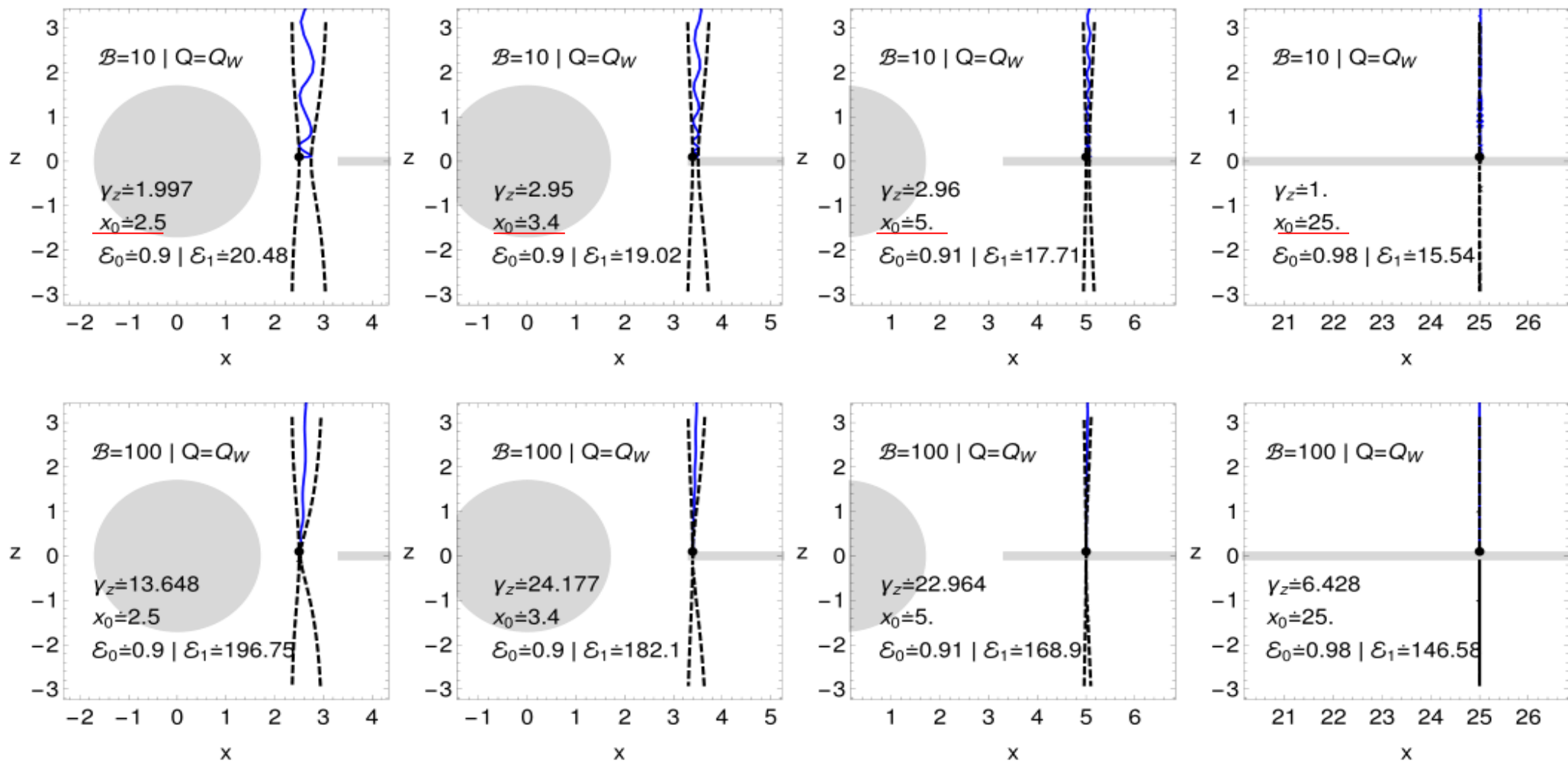
$$\mathcal{B} = \frac{|e|BGM_{\text{BH}}}{m_p c^4}$$

$$\approx 10^6 \frac{B}{10\text{G}} \frac{M_{\text{SgrA}^*}}{10^{6.6} M_{\odot}}.$$

Ionized particle  
**escapes** from BH  
 only in the presence  
 of **induced net charge**



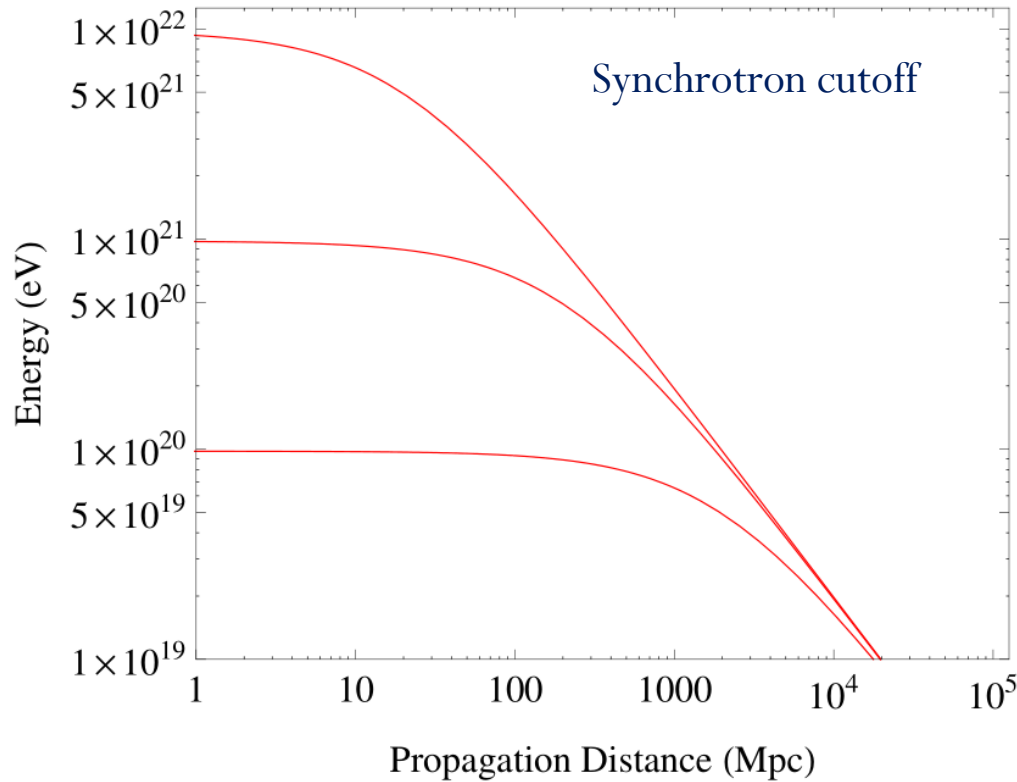
# Our process does not require existence of ergosphere!



Ionization may occur far away from the horizon, although the energy of ionized particle decreases with increasing the distance of ionization point from the BH. In contrast to competing mechanisms of energy extraction, the process does not require the existence of ergosphere.

# Energy loss due to synchrotron radiation

Propagation of proton in equipartition  
magnetic field of order  $10^{-5} \text{G}$



$$\frac{d\mathcal{E}}{d\tau} = -2k\mathcal{B} \left[ 2\mathcal{B}\mathcal{E}^3 - \mathcal{E} \left( 2\mathcal{B}f + \frac{u^\phi}{r} \right) \right].$$

$$\tau_{\max} \approx \frac{1}{k\mathcal{B}^2 f(r)}, \quad \mathcal{B} \gg 1$$

$$\mathcal{B}_{\text{SgrA}^*} = \frac{|e|BGM}{2m_e c^4} \approx 1.86 \times 10^{10},$$

$$k_{\text{SgrA}^*} = \frac{2}{3} \frac{|e|^2}{m_e GM} \approx 10^{-25}.$$

$$\frac{\tau_{\max}}{\tau_c}(\text{SgrA}^*) \approx 10^{-9}$$

B (Gauss)	$\tau_e$ (s)	$\tau_p$ (s)	$\tau_{\text{Fe}}$ (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	$10^8$	$10^{18}$	$10^{19}$
$10^{-4}$	$10^{16}$	$10^{26}$	$10^{27}$

Timescale of collisions of particles in plasma: ( $T = 10^8 \text{K}$ ,  $n = 10^{14} \text{cm}^{-3}$ )

$$\tau_{ee} \approx 6.4 \times 10^{-4} \text{s}, \quad \tau_{ei} \approx 4.5 \times 10^{-4} \text{s}, \quad \tau_{ii} \approx 4 \times 10^{-2} \text{s}.$$

**Neutron stars are also ruled out** due to large synchrotron losses of protons in strong MF of NSs.

# Synchrotron radiation-reaction near black hole

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

- Neutral geodesics
  - Charged particles
  - Backreaction SR
  - Backreaction GR
- (DeWitt and Brehme 1960)

- Ricci terms are irrelevant in vacuum metrics

- Tail term can be estimated, e.g. around Schwarzschild BH as  $F_{\text{tail}} \sim \frac{GMq^2}{r^3 c^2}$ .

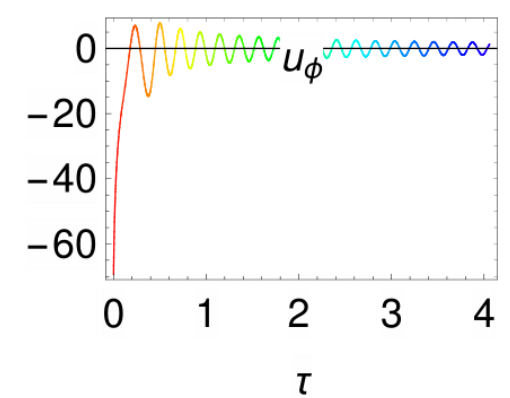
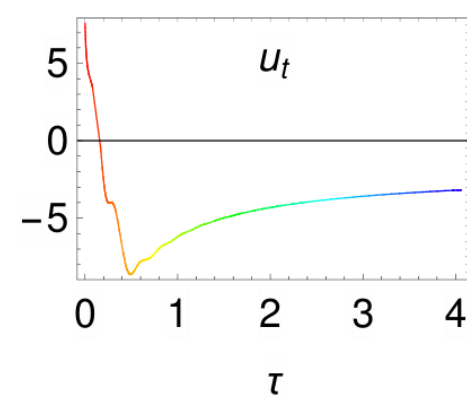
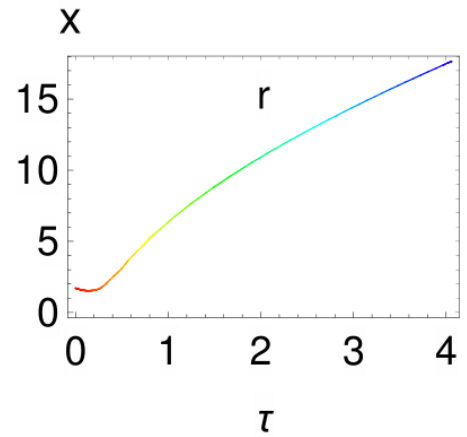
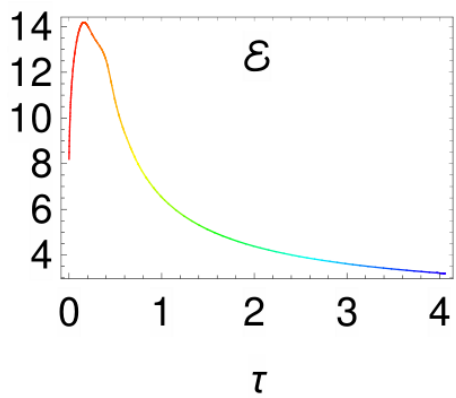
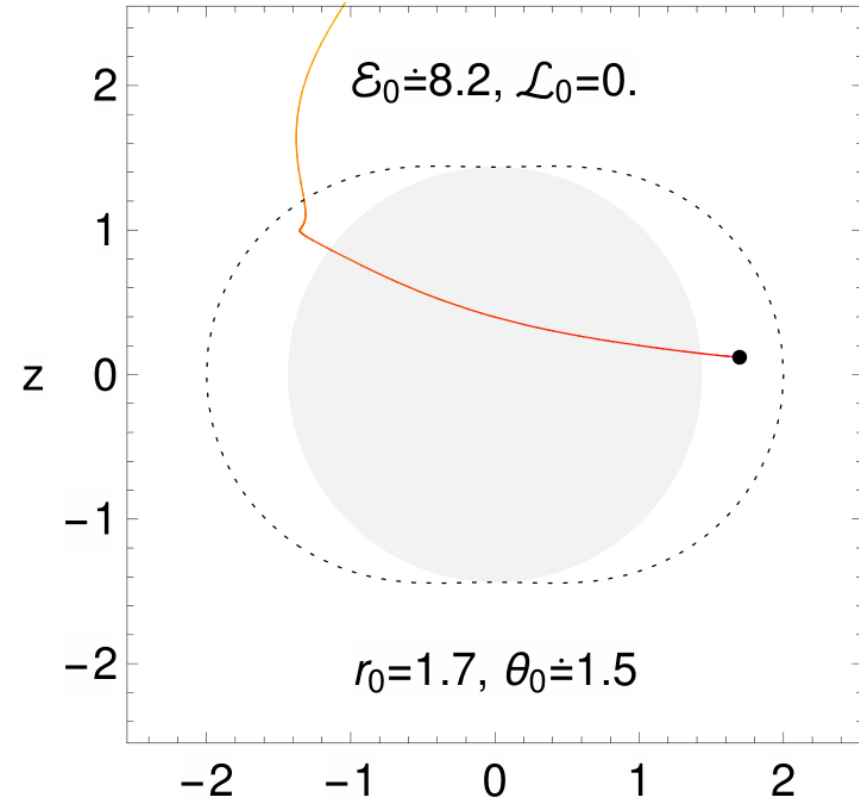
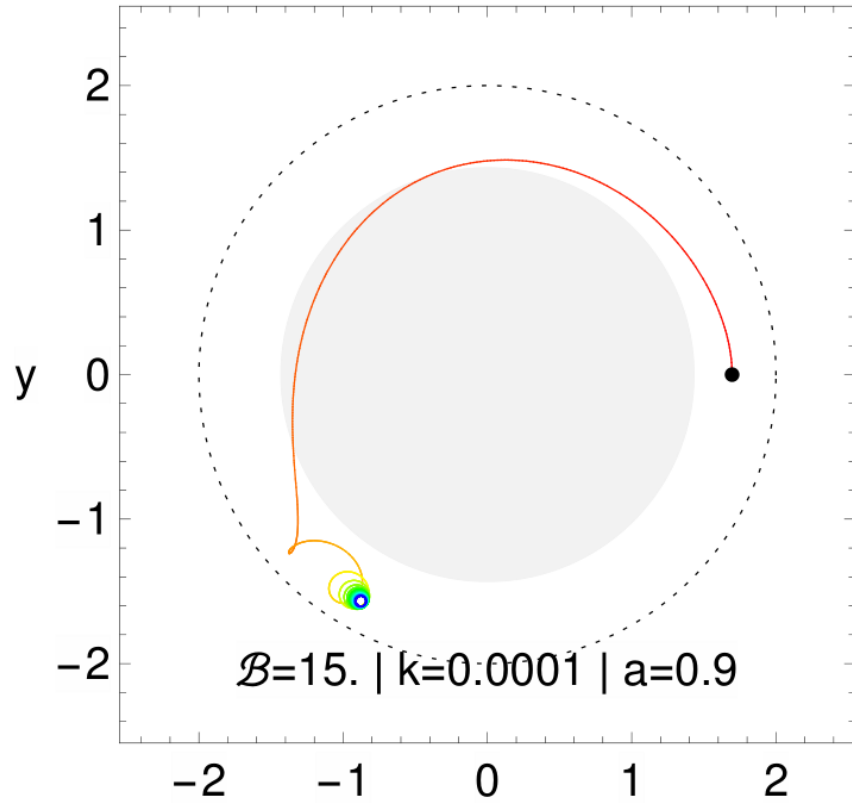
$$\frac{F_{\text{tail}}}{F_N} \sim \frac{q^2}{mMG} \sim 10^{-19} \left(\frac{q}{e}\right)^2 \left(\frac{m_e}{m}\right) \left(\frac{10M_\odot}{M}\right)$$

e.g. Dewitt & Dewitt (1964), Smith & Will (1980), Gal'tsov (1982), ...

- Radiation-reaction term can be estimated as  $F_{\text{RR}} \sim q^4 B^2 / (m^2 c^4)$

$$\frac{F_{\text{RR}}}{F_N} \sim \frac{q^4 B^2 MG}{m^3 c^8} \sim 10^3 \left(\frac{q}{e}\right)^4 \left(\frac{m_e}{m}\right)^3 \left(\frac{B}{10^8 \text{G}}\right)^2 \left(\frac{M}{10M_\odot}\right)$$

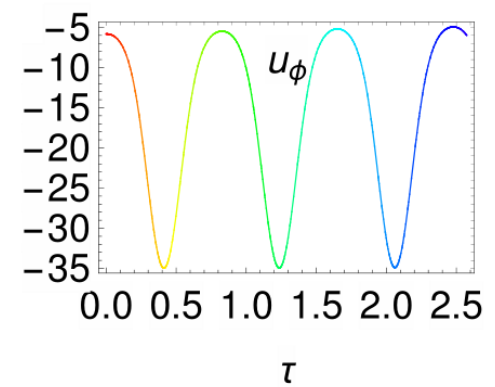
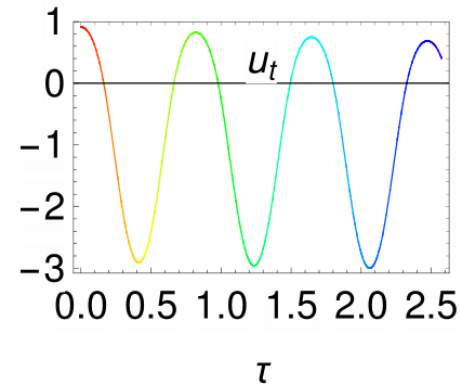
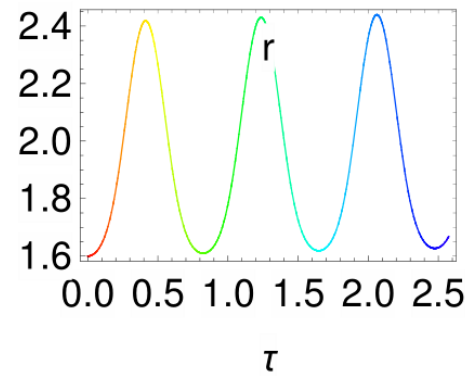
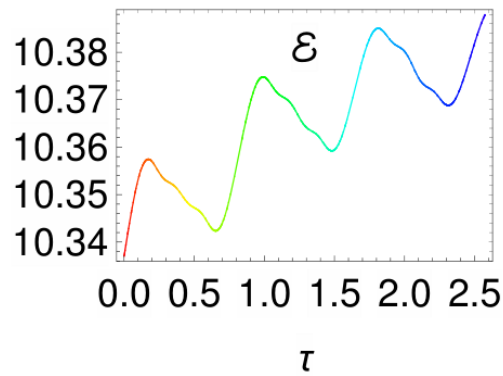
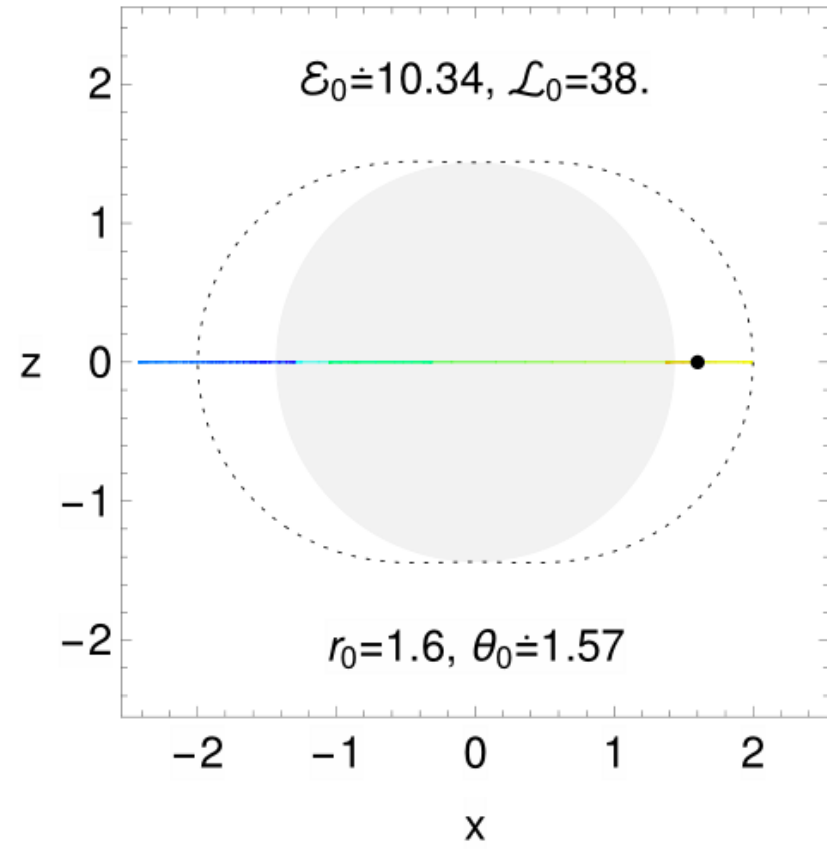
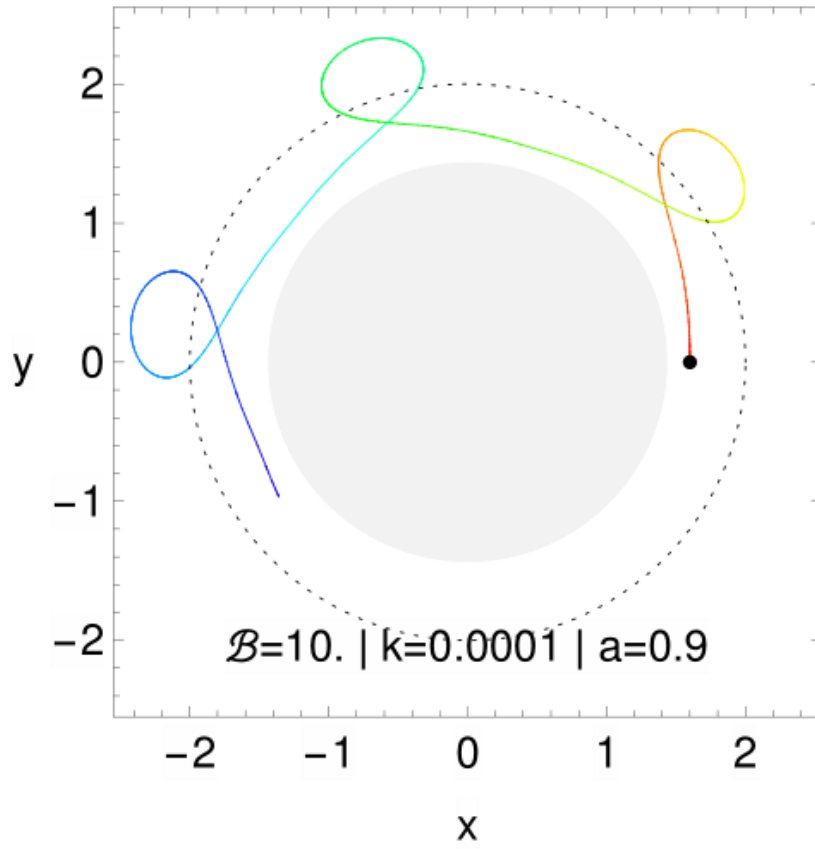
# Energy extraction by a single particle: Radiative Penrose Process



$$u_t > 0, \quad u_\phi < 0,$$



# Energy extraction by a single particle: Radiative Penrose Process



Higher energy emission from the edge of the ergosphere

## Required ingredients for the black hole energy extraction:

- Rotating BH & magnetic field
- Negative energy inflow into BH:
  - either due to electromagnetic interaction of charged particle with BH
  - or geometric effect in the ergosphere
- **Required ingredients for escape to infinity:**
- Sharing symmetries of BH and magnetic field lines
- Induced BH charge (Wald mechanism)

## Main advantages & predictions of the model:

- The model predicts SMBHs as the source of highest-energy cosmic rays
- Provides verifiable constraints on Mass and B-field of the SMBH candidate to produce UHECRs
- Operates in viable astrophysical conditions for SMBH with moderate spin and MF strength
- Does not require extended acceleration zone (jet models), nor the fine-tuning of parameters
- Energy extracting action can take place relatively far from the event horizon without high redshifts
- Galactic center can act as a PeVatron of cosmic rays and contributes to the knee of the CR spectra
- Radiative mechanism predicts higher I of non-thermal radiation from the edge of the Ergosphere

# Summary

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*Děkuji za pozornost!*

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Detector is in your pocket!

**CREDO**  
THE QUEST FOR THE UNEXPECTED



**CREDO**  
THE QUEST FOR THE UNEXPECTED

**Cosmic-Ray Extremely Distributed Observatory**

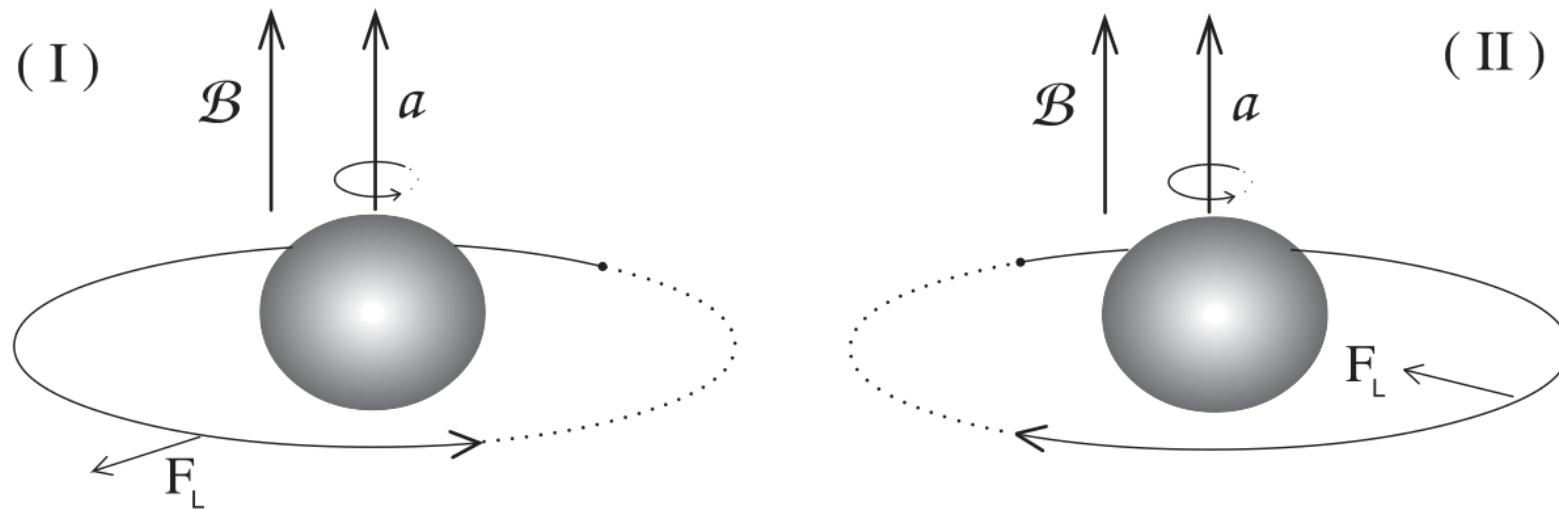
25 institutions (incl. SLU)

12 countries on 5 continents.



# Types of orbit around magnetized black hole

In the presence of magnetic field the Lorentz force acting on a charged particle can be both attractive and repulsive, depending on the orientation of magnetic field lines and direction of the motion



- Tursunov, Stuchlík, Kološ, Phys. Rev. D **93**, 084012 (2016)



# Trajectories of radiating particle

