Acceleration of UHECR by local supermassive black holes

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Based on: 2020: Tursunov, et al. **Astrophysical Journal** 895:1, 14, arXiv:2004.07907
2020: CREDO Collaboration (Homola et al.), **Symmetry**, 12 (11), 1835, arXiv:2010.08351

Also, follow the contribution by **Piotr Homola "Invitation to the CREDO"**, ID 1448

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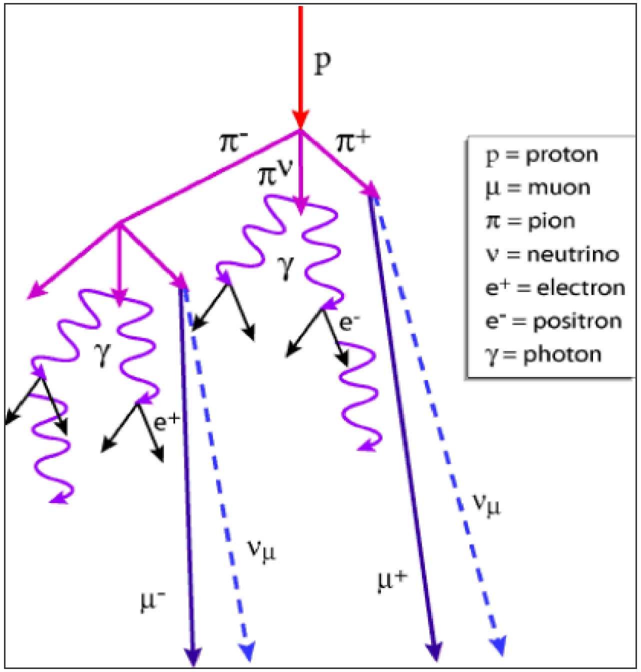
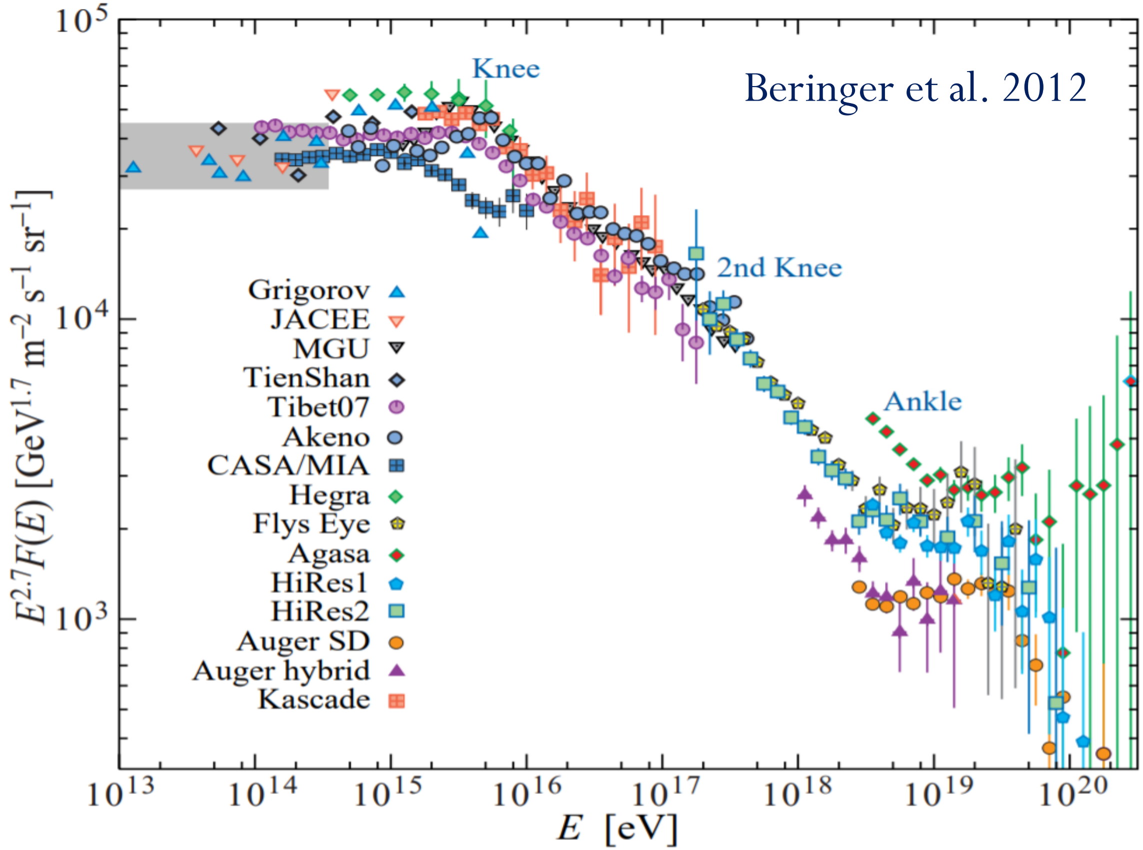
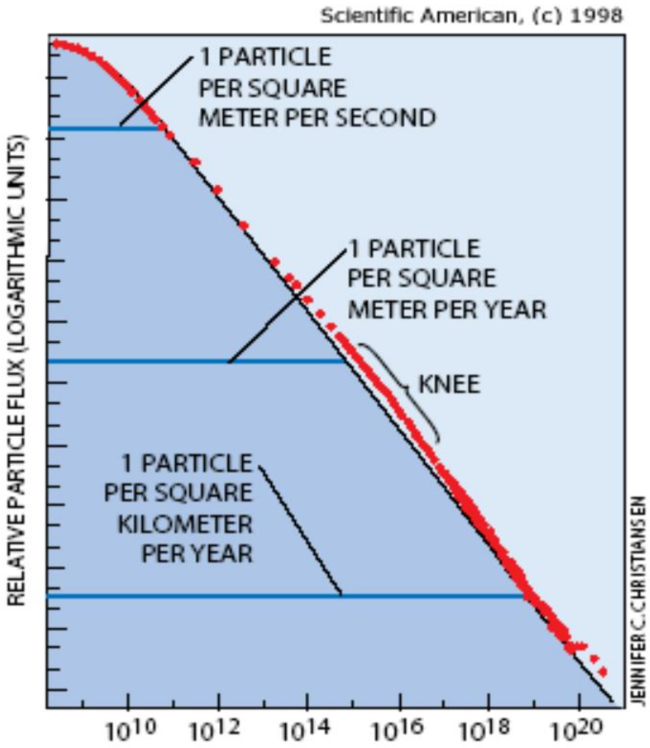
UHECRs observations

- 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
- Mechanism is unknown – most energetic accelerator in the universe!

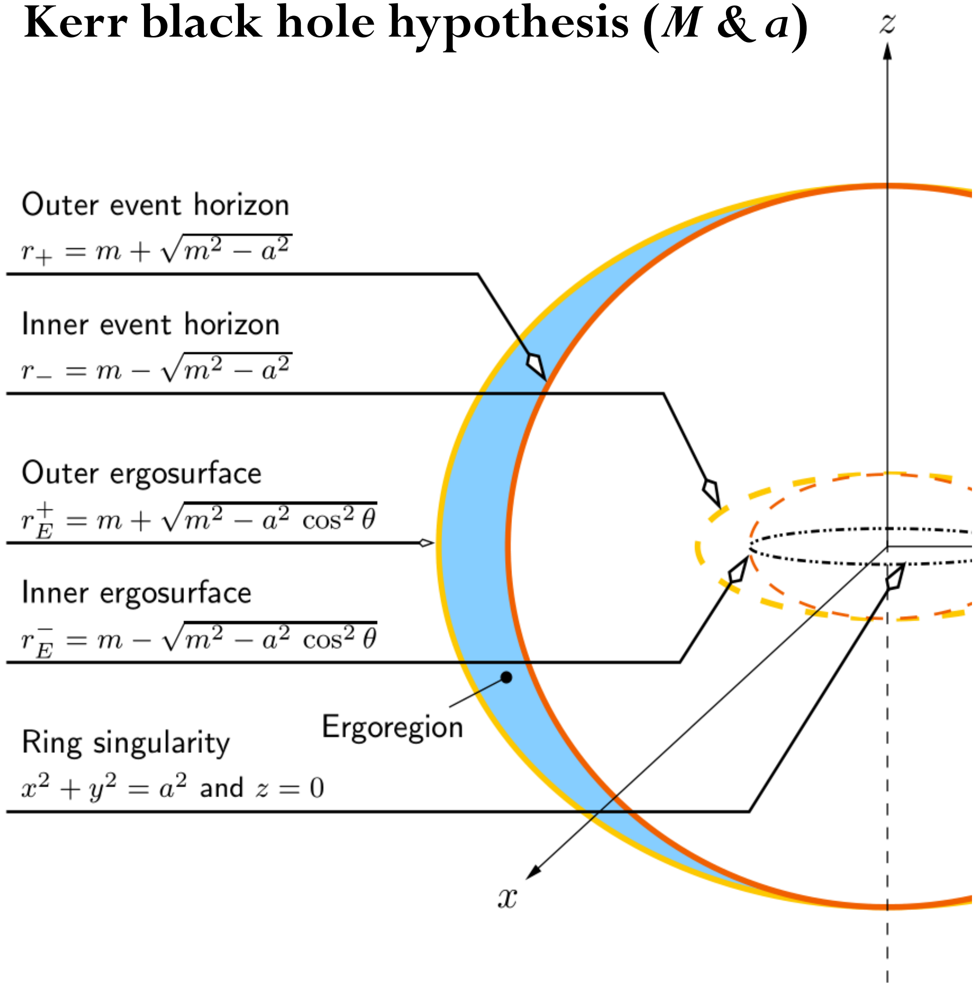






Can UHECRs be accelerated by black holes?

Kerr black hole hypothesis (M & a)



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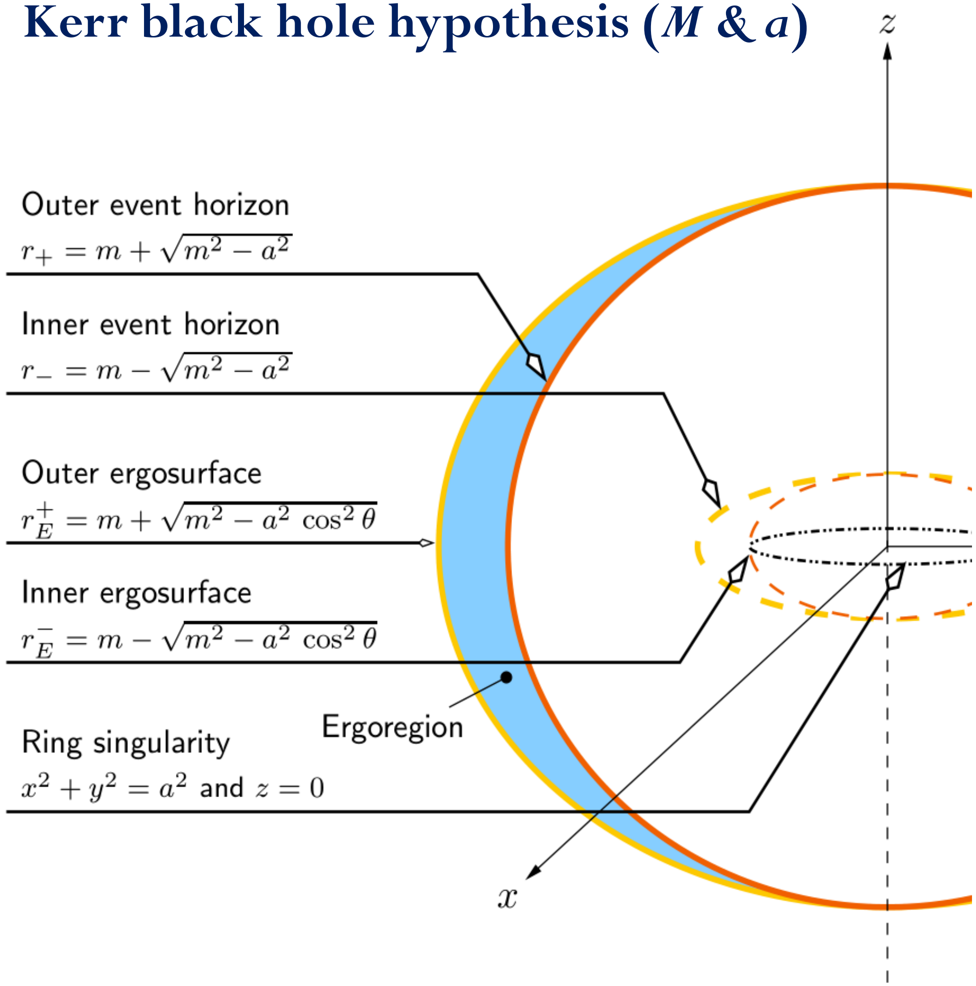


Entropy of black hole ~ to the event horizon area:

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

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

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

Energy extraction requires negative energy inflow

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

Inside the ergosphere g_{tt} changes its sign

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

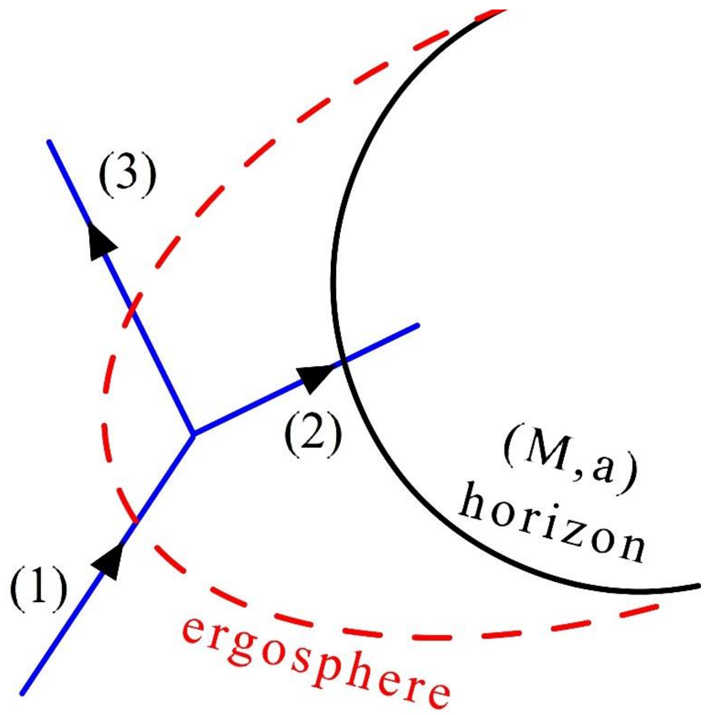
Black hole mechanics and Thermodynamics have uncanny correspondence!

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

Historical development of the idea

Original Penrose process



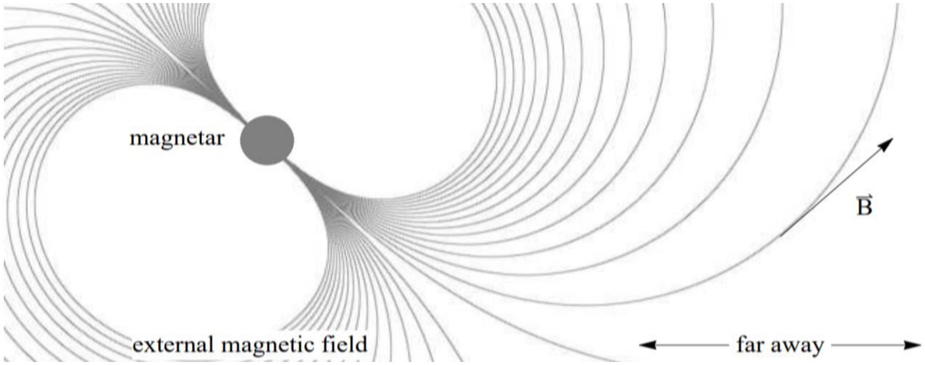
Efficiency is defined as:

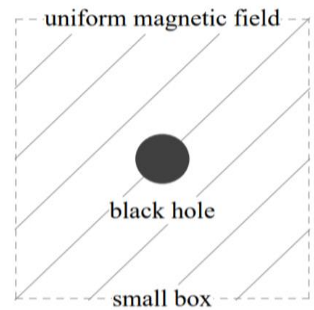
$$\eta = \frac{E_3 - E_1}{E_1} = \frac{-E_2}{E_1}.$$

- 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 $> 10^{10}\%$ 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

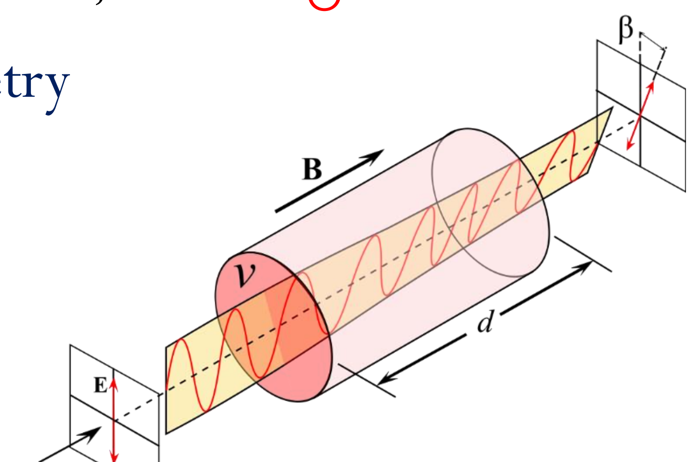




e.g. Magnetar with 10^{14}G has been found at 0.3 light years from Galactic Center by Effelsberg observatory

- MF of **SgrA* ~ 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

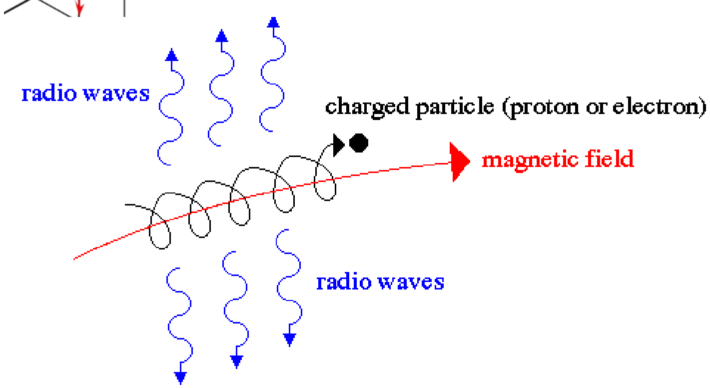
$$B \ll \frac{c^4}{G^{3/2} M_\odot}\left(\frac{M_\odot}{M}\right) \sim 10^{19} \frac{M_\odot}{M}\ \mathrm{G}$$



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

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

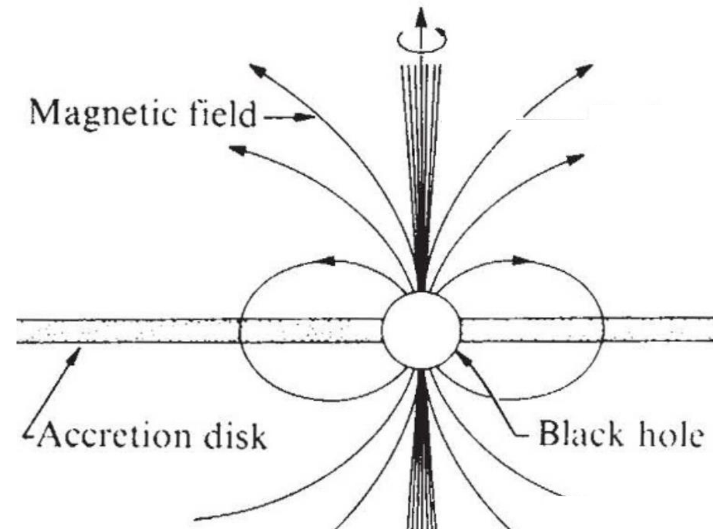
- This ratio for **SgrA* ~ 10^6**
- Measurements: Faraday rotation, synchrotron radiation, etc.

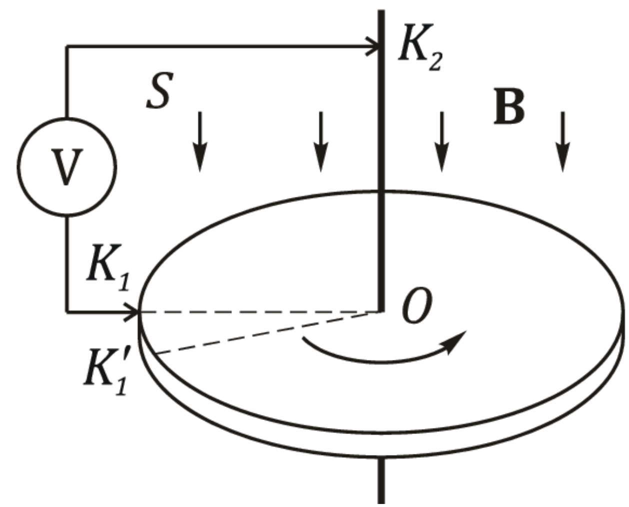


Black holes are weakly charged

- **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**
  - $A_t = \frac{B}{2}(g_{t\phi} + 2a g_{tt}), \qquad A_\phi = \frac{B}{2}(g_{\phi\phi} + 2a g_{t\phi}).$
  - $\Delta\varphi = \varphi_{\mathrm{H}} - \varphi_\infty = \frac{Q - 2aMB}{2M}.$ (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)

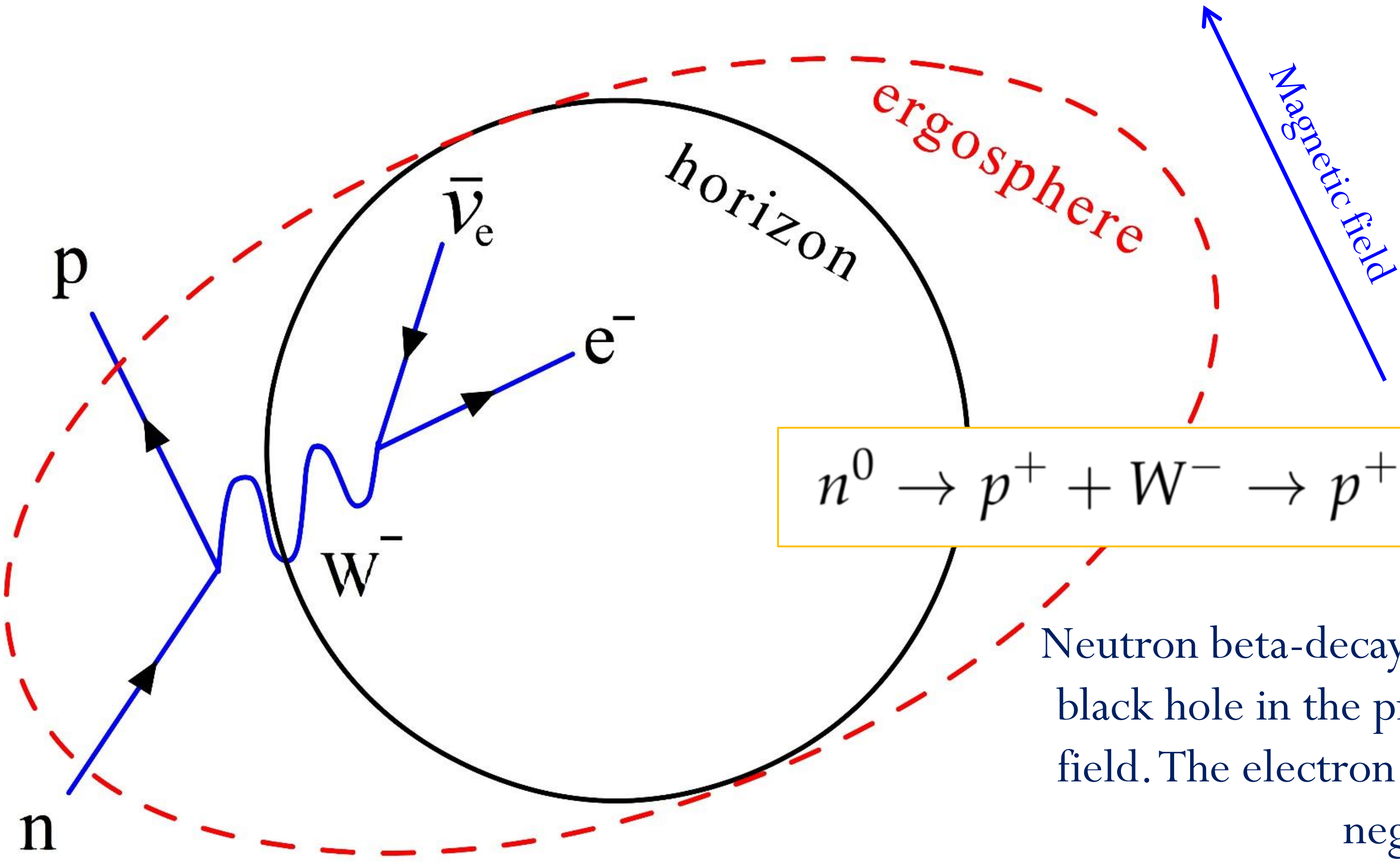




$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

- **Magnetosphere is charged as well**
  - In a similar way, rotation of BH in MF induces EF and BH with the **magnetosphere acts as dynamo**!
  - $Q_{\mathrm{mag}} = -Q_{\mathrm{BH}}.$

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:

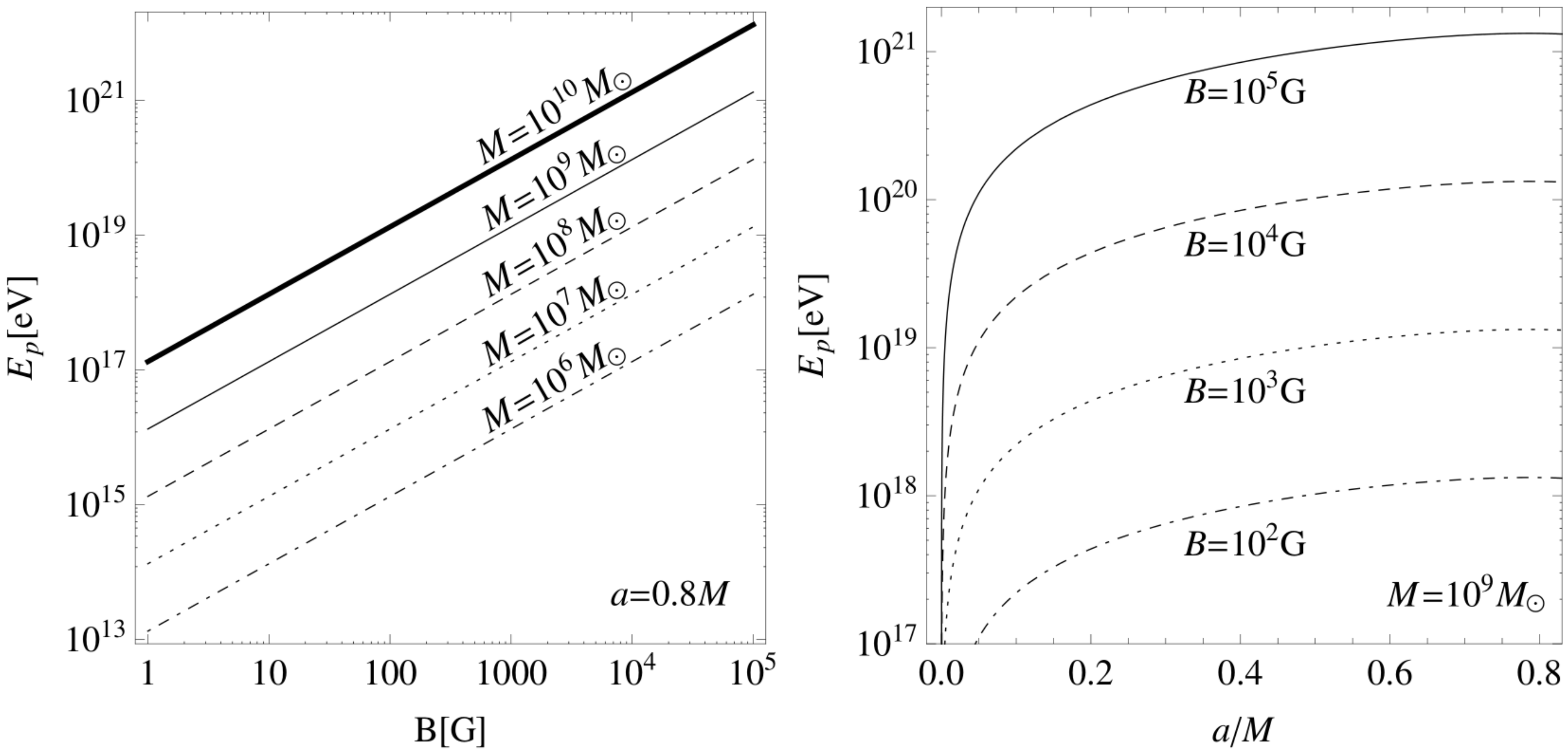
$$p + e^- \to n + \nu_e$$

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

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

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

Energy of proton driven away from BH

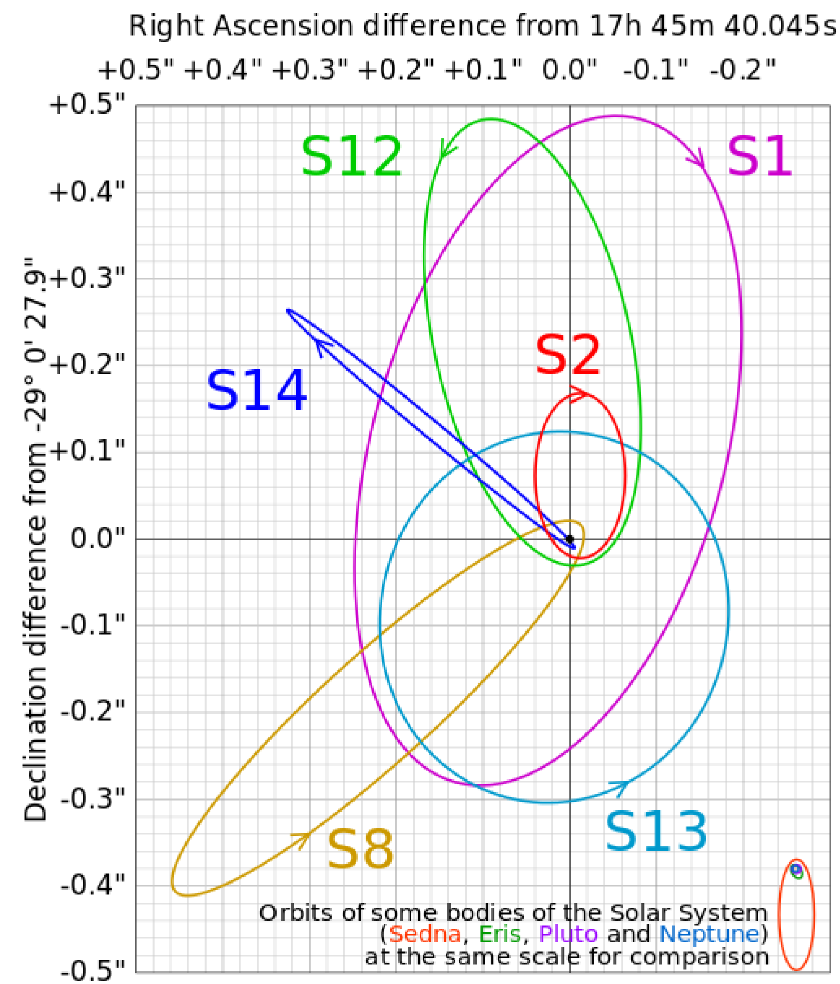


The energy of free neutron is ~ 0.94×10^9eV

$$E_{p^+} = 1.33\times10^{20}\mathrm{eV}\left(\frac{q}{e}\right)\left(\frac{m}{m_{p^+}}\right)^{-1}\left(\frac{B}{10^4\mathrm{G}}\right)\left(\frac{M}{10^9 M_\odot}\right).$$

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

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

The Milky Way's SgrA* as PeVatron

- **Rotating black hole**

– SgrA* is spinning ~0.5M

- **External magnetic field**

– around SgrA* ~10G

- **Negative energy inflow**

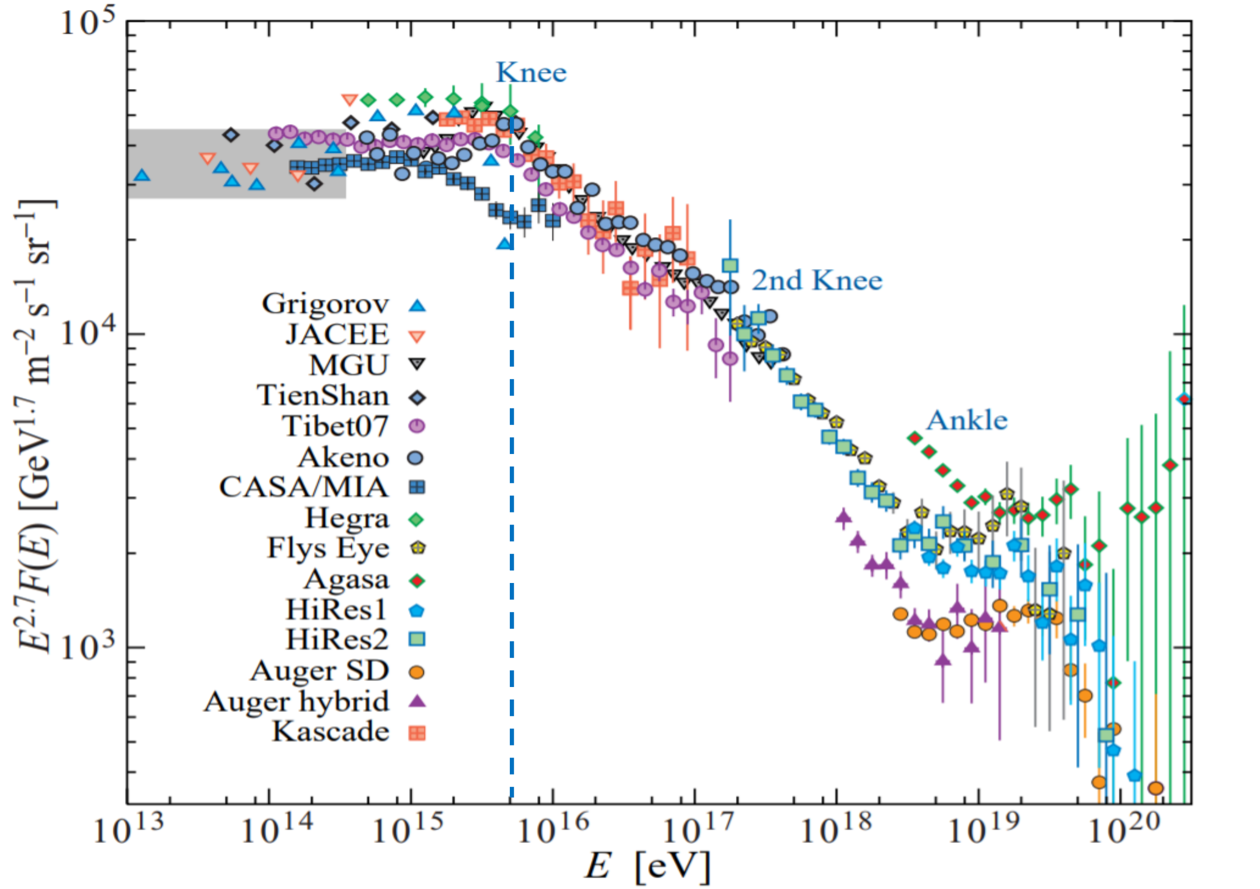
– gain Coloumb contribution

- **Discharge of electric field**

– charge of SgrA*

- **Infalling matter**

– neutral particle decay



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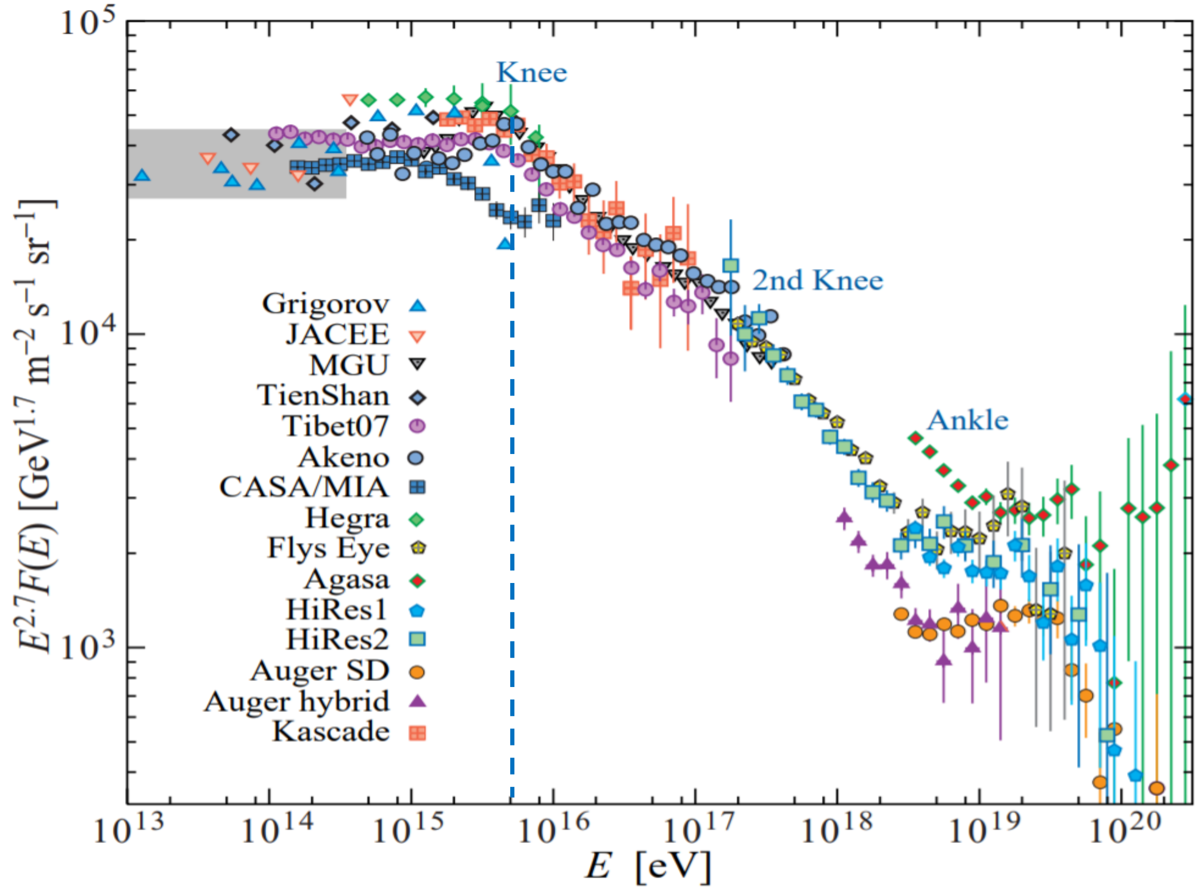


Applying ultra-MPP

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

$$E_n = E_p + E_W,$$

$$L_n = L_p + L_W,$$

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

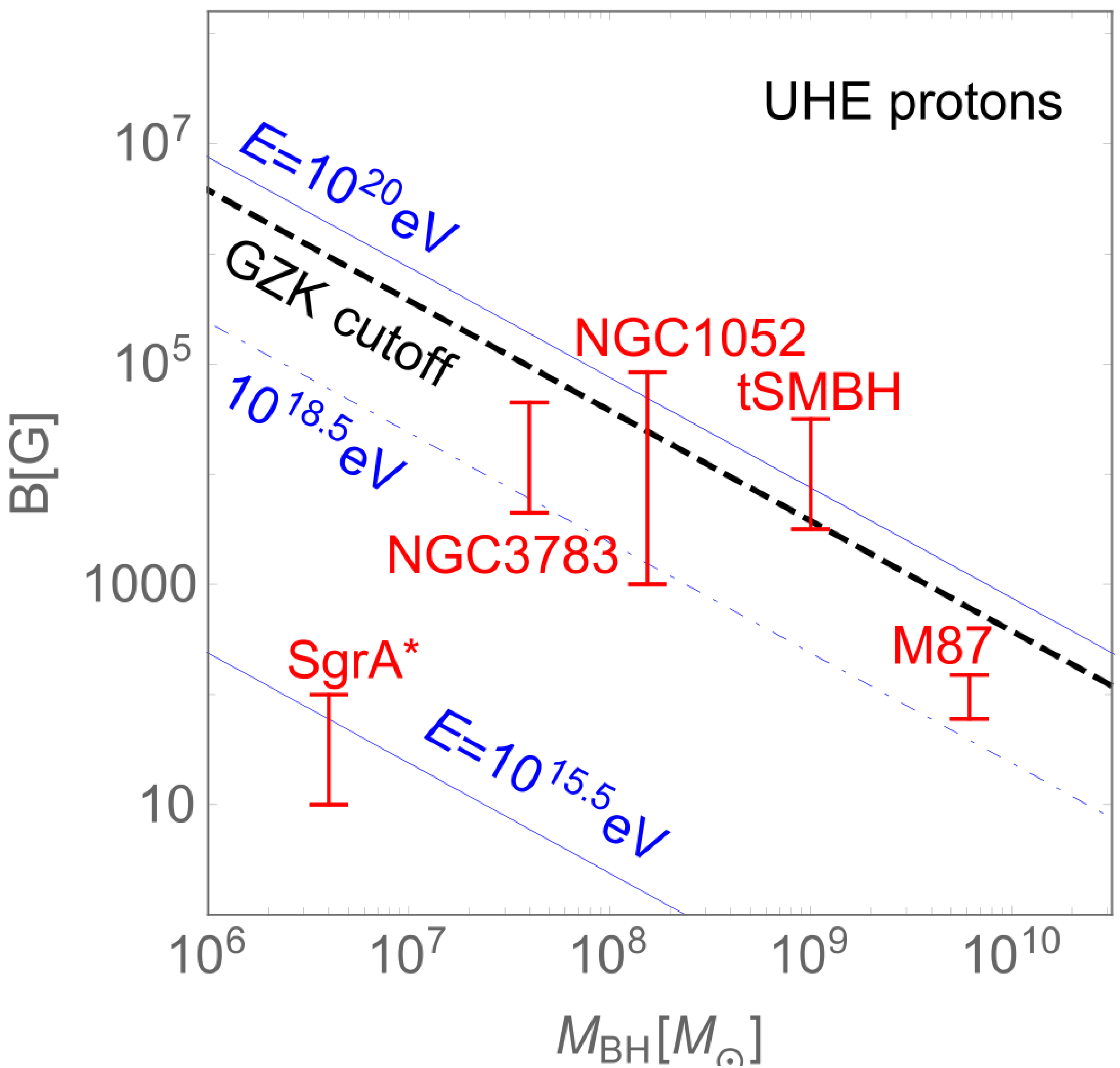
$$q_W + q_p = 0.$$

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)

Constraints on parameters and source candidates



Selected nearby SMBH candidates

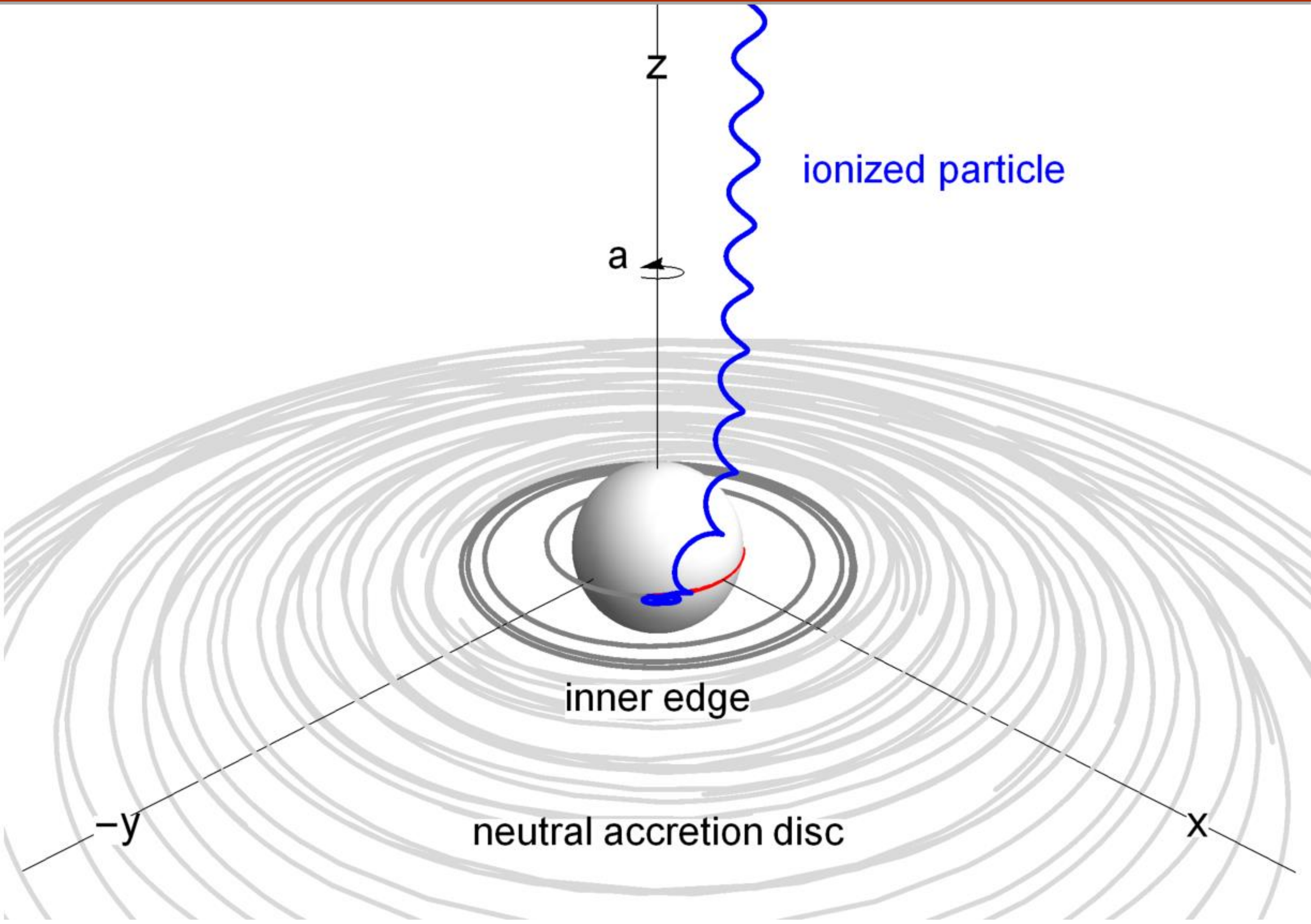
SMBH	$\text{Log}(M/M_\odot)$	Spin a	d (Mpc)	$\text{Log}(B/1\text{G})$	$\text{Log}\left(E_{p+}^{\text{mean}}/1\text{eV}\right)$
Sgr A*	6.63	0.5	0.008	2	15.64
NGC 1052	8.19	$\lesssim 1$	19	4.8	20.11
NGC 1068 / M77	6.9	$\lesssim 1$	15	4.54	18.56
NGC 1365	6.3	$\lesssim 1$	17.2	4.70	18.12
NGC 2273	6.9	0.97	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
IC 1459	9.4	$\lesssim 1$	31	3.20	19.72

Energy extraction in various radioactive decay modes

Decay Mode	Generic Equation	Esc. p.	Efficiency η_{max}	Regime of MPP
α decay	${}^{A}_{Z}X^{0} \rightarrow {}^{A-4}_{Z-2}Y^{2-} + {}^{4}_{2}\alpha^{2+}$	Y	<0	-
		α	$1.2 \times 10^{6}/A$	ultra
	${}^{A}_{Z}X^{+} \rightarrow {}^{A-4}_{Z-2}Y^{-} + {}^{4}_{2}\alpha^{2+}$	Y	<0	–
		α	$\sim$1	moderate
	${}^{A}_{Z}X^{-} \rightarrow {}^{A-4}_{Z-2}Y^{3-} + {}^{4}_{2}\alpha^{2+}$	Y	$\sim$2	moderate
		α	< 0	-
β^{-} decay	${}^{A}_{Z}X^{0} \rightarrow {}_{Z+1}^{A}Y^{+} + e^{-} + \bar{\nu}$	Y	$6.1 \times 10^{5}/A$	ultra
		e^{-}	<0	–
		$\bar{\nu}$	0.06	low
β^{+} decay	${}^{A}_{Z}X^{+} \rightarrow {}_{Z-1}^{A}Y^{0} + e^{+} + \nu$	Y	<0	–
		e^{+}	$\sim$0	low/–
		ν	<0	–
γ emission	${}^{A}_{Z}X^{0} \rightarrow {}^{A}_{Z}X'^{0} + {}^{0}_{0}\gamma^{0}$	X′	0.06	low
		γ	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



Synchrotron radiation-reaction near black hole

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

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

(DeWitt and Brehme 1960)

- Ricci terms are irrelevant in vacuum metrics
- Tail term can be estimated, e.g. around Schwarzschild BH as $F_{\rm tail} \sim \frac{GMq^2}{r^3c^2}$.

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

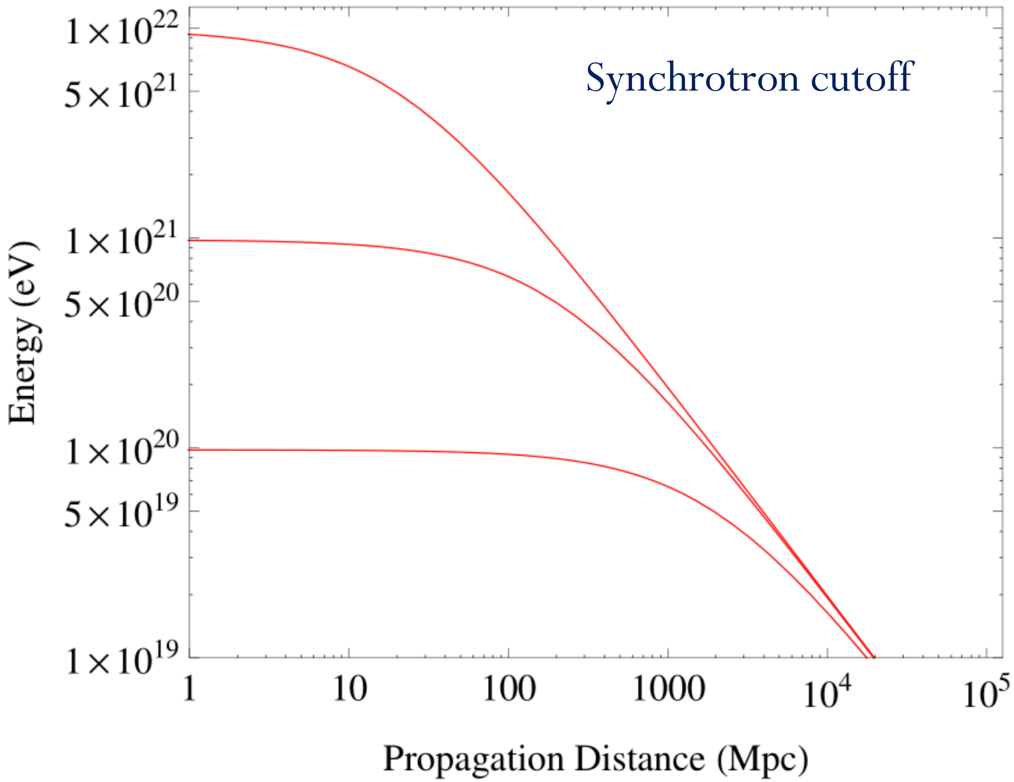
e.g. Dewitt & Dewitt (1964), Smith & Will (1980), Gal'tsov (1982), …

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

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

Energy loss due to synchrotron radiation

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



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

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

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

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

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

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}

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

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

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

Summary

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 rom 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

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- **42 institutions; 19 countries; 5 continents; > 10 mln detections**