UNTERSTÜTZT VON / SUPPORTED BY

Alexander von HUMBOLDT STIFTUNG

Supermassive Black Holes from PeV to ZeVatrons

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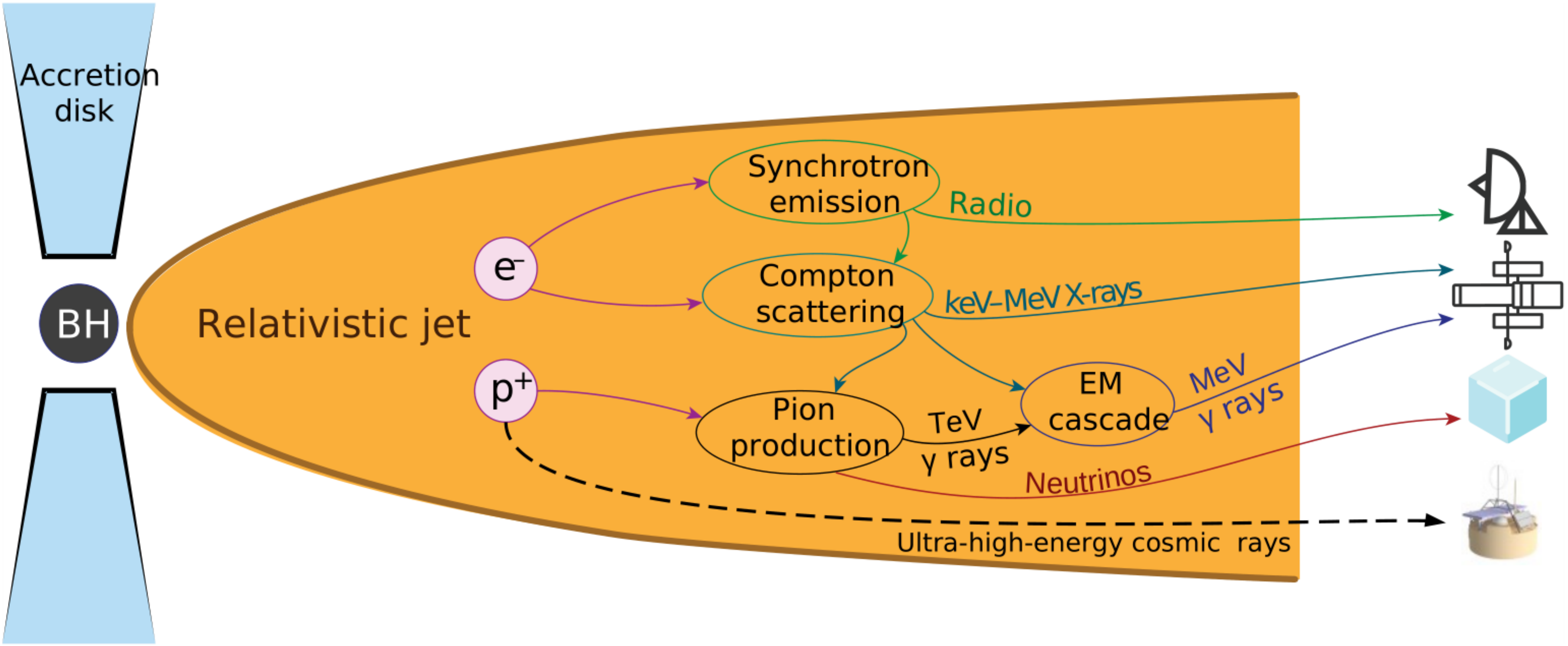
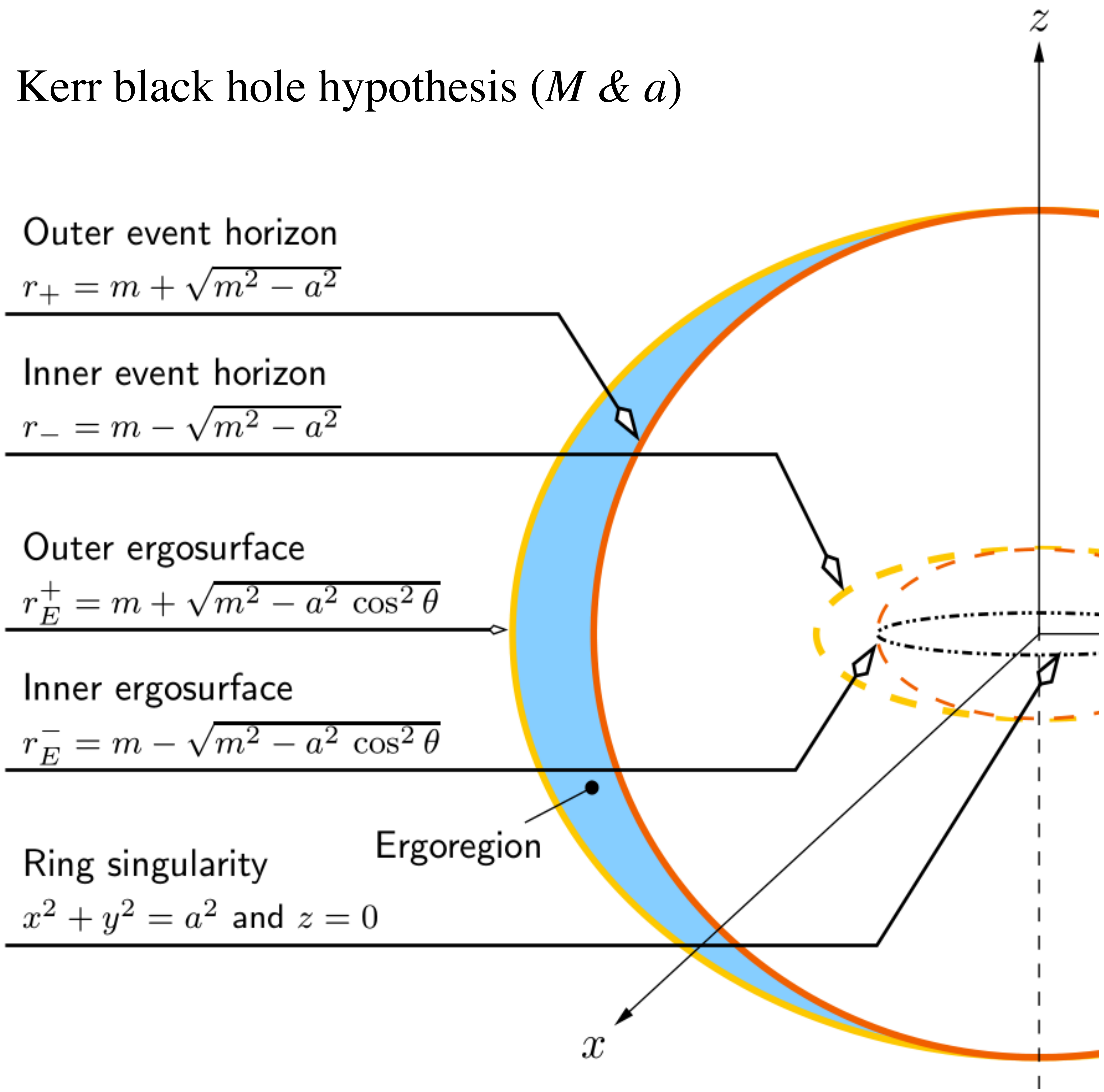
Black hole as a multimessenger & multiwavelegths source



credit: A.V.Plavin, Y.Y.Kovalev, Yu.A.Kovalev, S.V.Troitsky, Directional Association of TeV to PeV Astrophysical Neutrinos with Radio Blazars, The Astrophysical Journal, Volume 908, Issue 2, id.157 (2021) + my small update

Black holes are largest energy reservoirs in Universe

Kerr black hole hypothesis (M & a)



Entropy of black hole ~ to the event horizon area:

$$S_{\rm BH} = \frac{c^3}{4G\hbar} A_H \qquad A_H = \int_0^{2\pi} d\phi \int_0^{\pi} \sqrt{\det g}\, d\theta = \frac{8\pi G}{c^2} M r_H$$

$$E_{\rm irr} = \sqrt{\frac{S_H \hbar c^5}{4\pi G k_{\rm B}}} \equiv \sqrt{\frac{A_H}{16\pi G^2}} c^4 = \frac{Mc^2}{\sqrt{2}} \left[1 + \sqrt{1 - \left(\frac{a}{M}\right)^2}\right]^{\frac{1}{2}}$$

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

Inside the ergosphere g_{tt} changes its sign

$$E = -p_t = -mu_t = -mg_{tt}u^t - mg_{t\phi}u^\phi$$

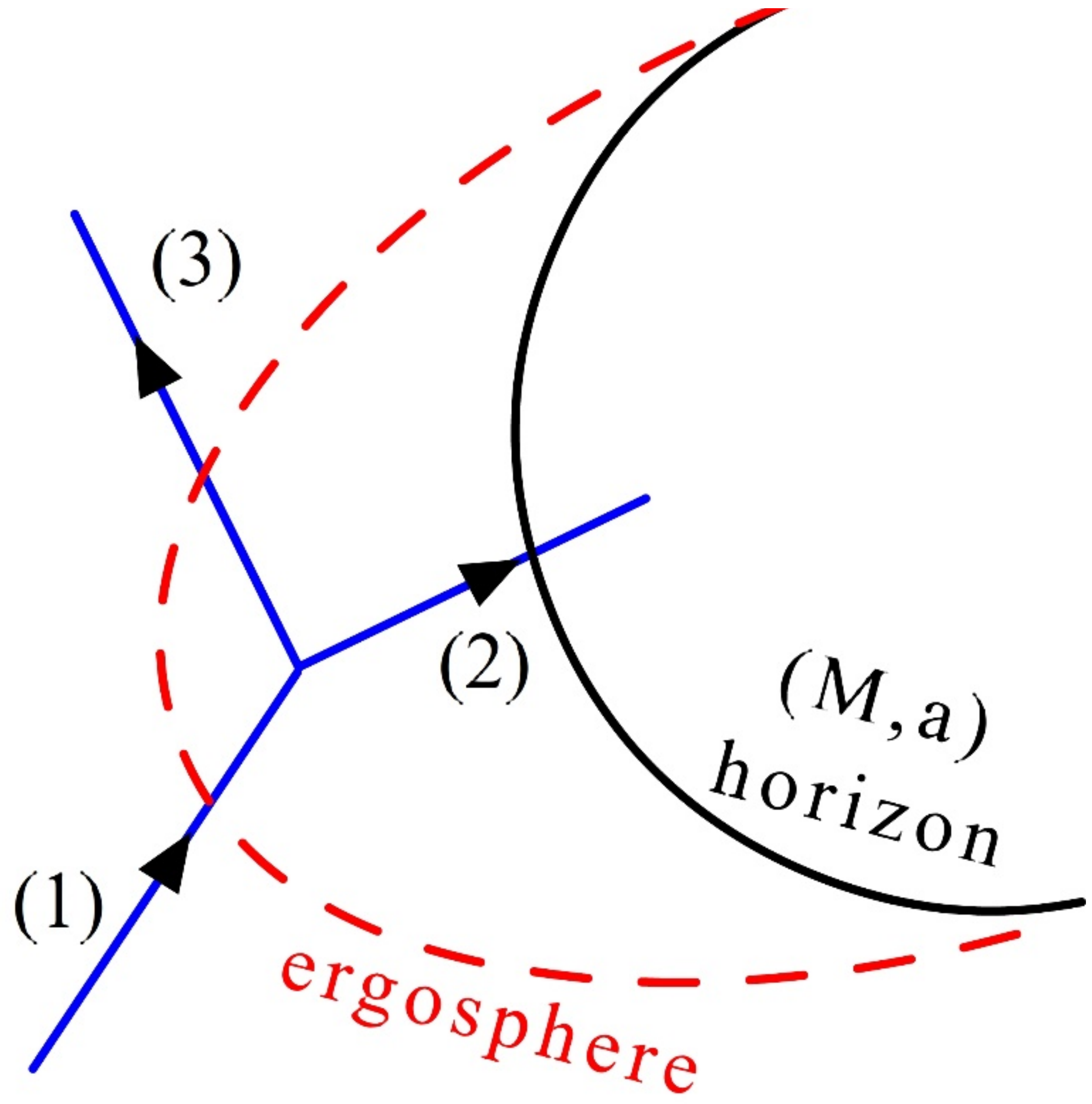
$$L = p_\phi = mu_\phi = mg_{\phi\phi}u^\phi + mg_{\phi t}u^t$$

Black hole area non-decrease states that up to 29% of BH's energy is rotational and available for extraction.

For typical rotating SMBH of 10^9 solar mass the available energy is ~10^{74} eV ~ 10^{55} Joules

55 years of energy extraction from black holes

Original Penrose process

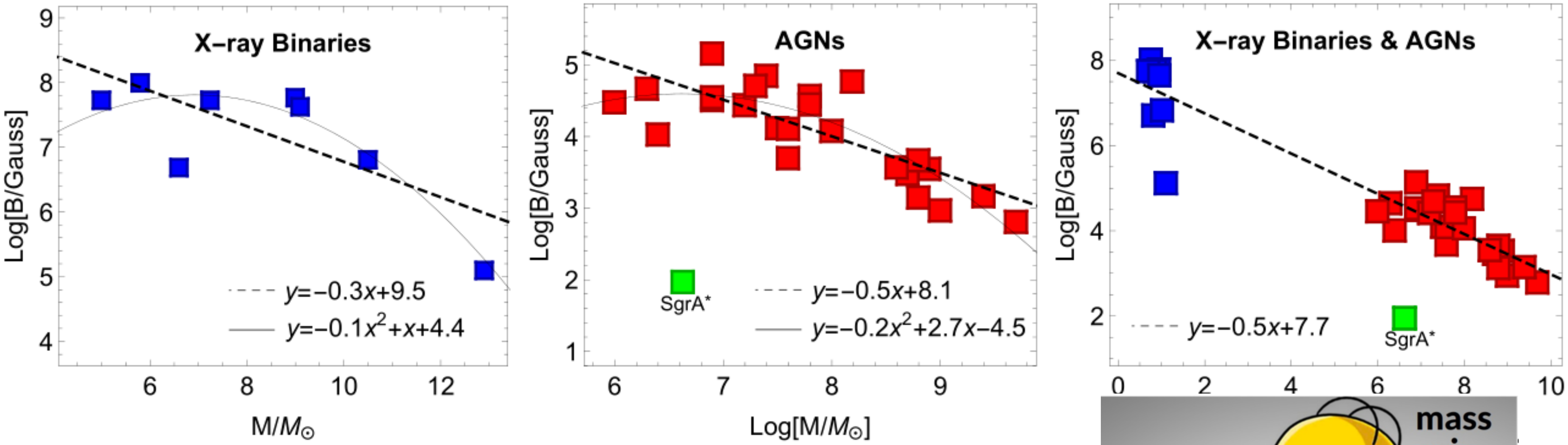


$$\text{Efficiency} = \frac{\text{energy extracted}}{\text{energy infalling}}$$

- Penrose (1969), Bardeen etal. & Wald (1972, 1974): **Efficiency** < 0.21
- Piran et al. (1975/77) – Collisional Penrose process.
- Ruffini & Wilson (1975) – charge separation in **accreting plasma**
- Blandford & Znajek (1977) & MHD simulations – **Efficiency** a few
- Wagh et al. (1985) – Magnetic Penrose process MPP – for the first time **efficiency can exceed** 2
- Many other versions of the above processes with **efficiencies** of a few
- Ultra-efficient MPP (Tursunov et al. ApJ 2020) – efficiency $> 10^{10}$ for protons in case of SMBHs
- Radiative Penrose process (Kolos, Tursunov, Stuchlik PRD, 21) – first mechanism utilising radiating particles
- Electric Penrose process (Tursunov et al PRD 2022) – efficiency is limited to $< 10^{6}$

Black holes are weakly magnetized

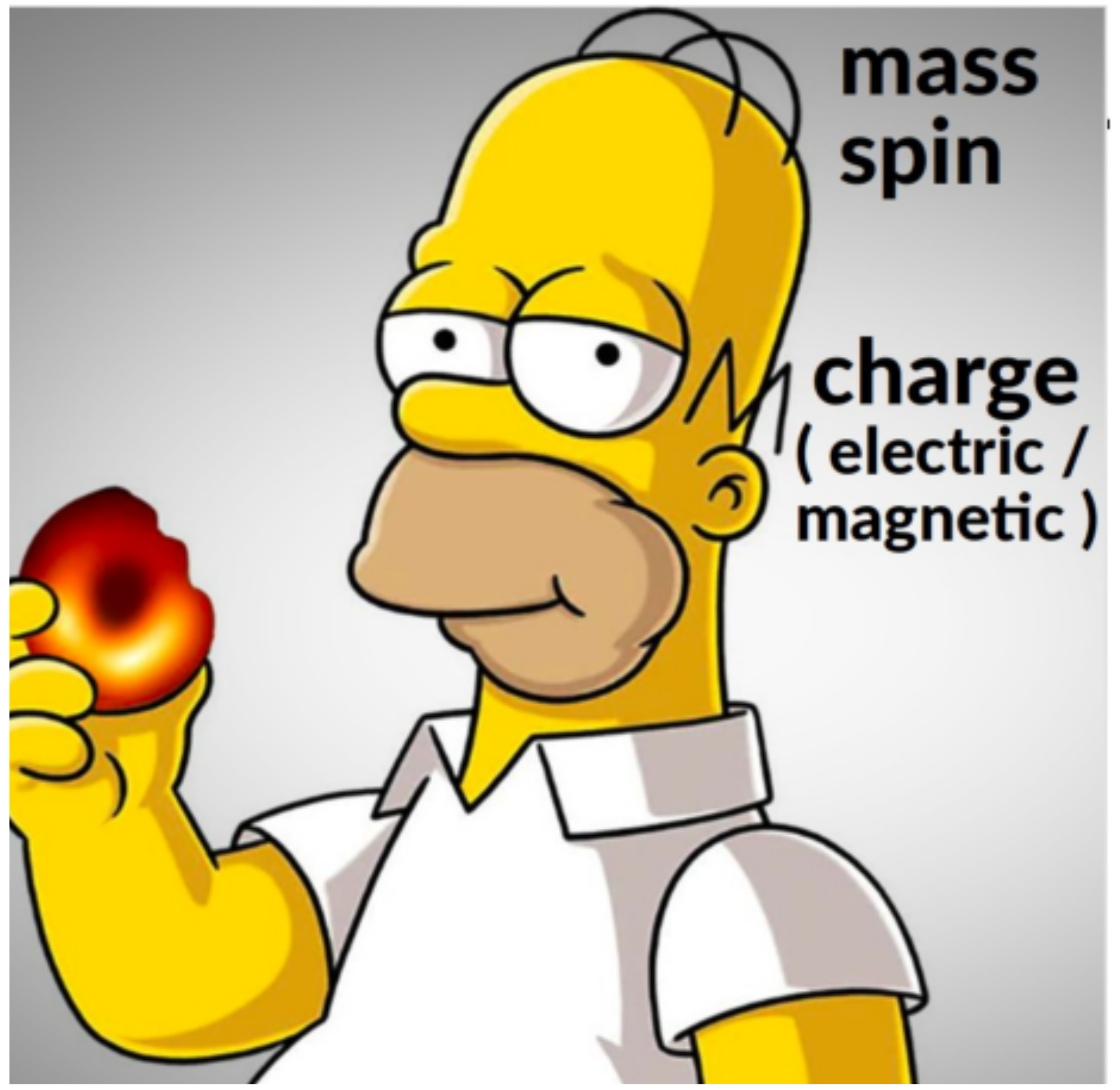
- Magnetic fields are indeed present around BHs e.g. due to dynamics of plasma disk or companion star
- MF of **SgrA* ~** 10G. Characteristic MF for $10^9 M_\odot$ is 10^4G; for $10 M_\odot$ can exceed 10^8G.



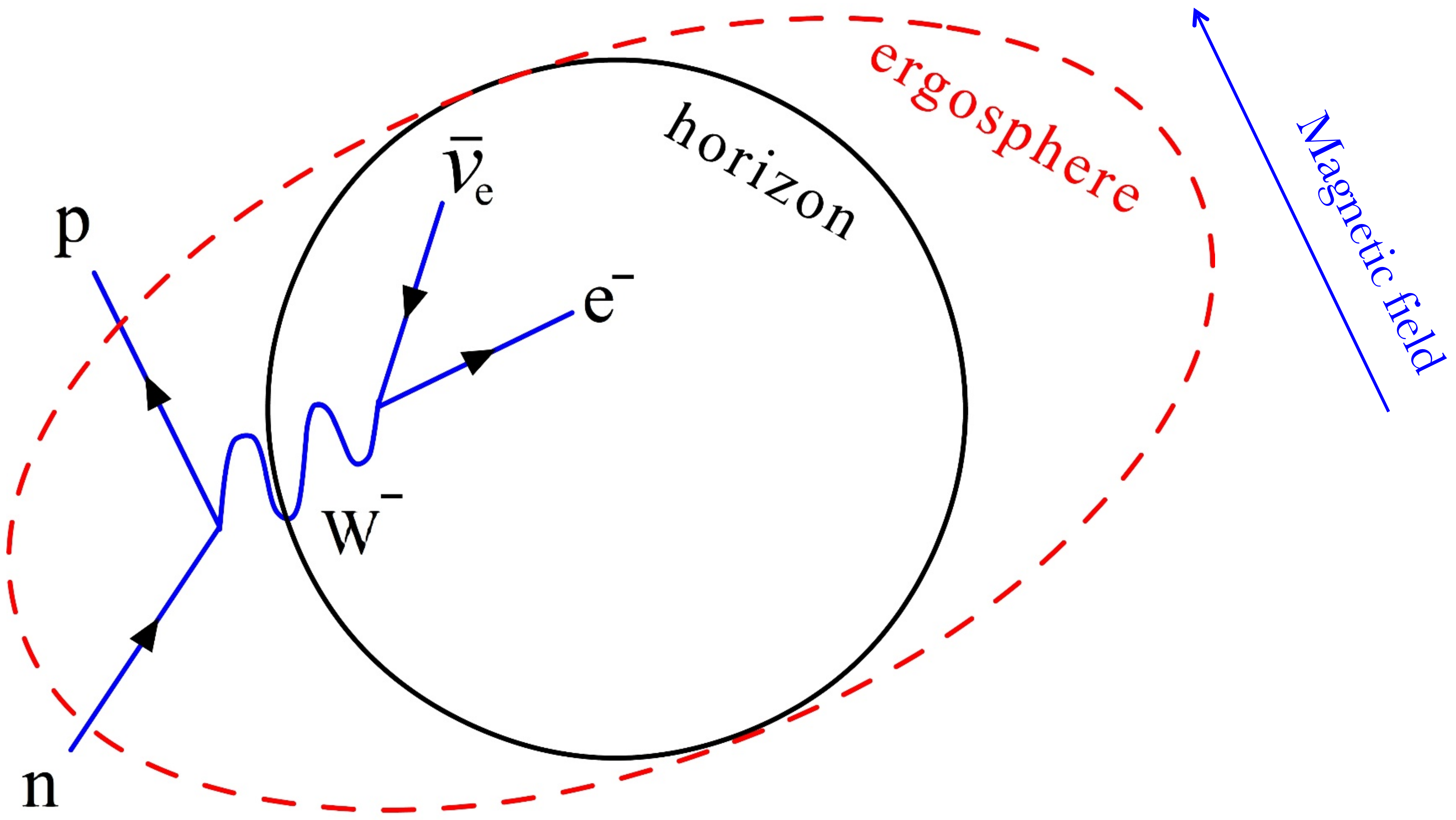
- MF is weak – it does not modify the spacetime geometry, $B \ll 10^{18}$G
- Cannot neglect **MF effects** on the charged matter

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

- This ratio for **our Galactic center BH ~** 10^6



Ionization near black hole: beta decay



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

Neutron beta-decay in ergosphere in the presence of magnetic field. Electron falls into black hole with the negative energy, protons escape.

In the hot and dense torus, with temperature of $\sim 10^{11}$ K and density $>10^{10}$ g$\cdot$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:

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

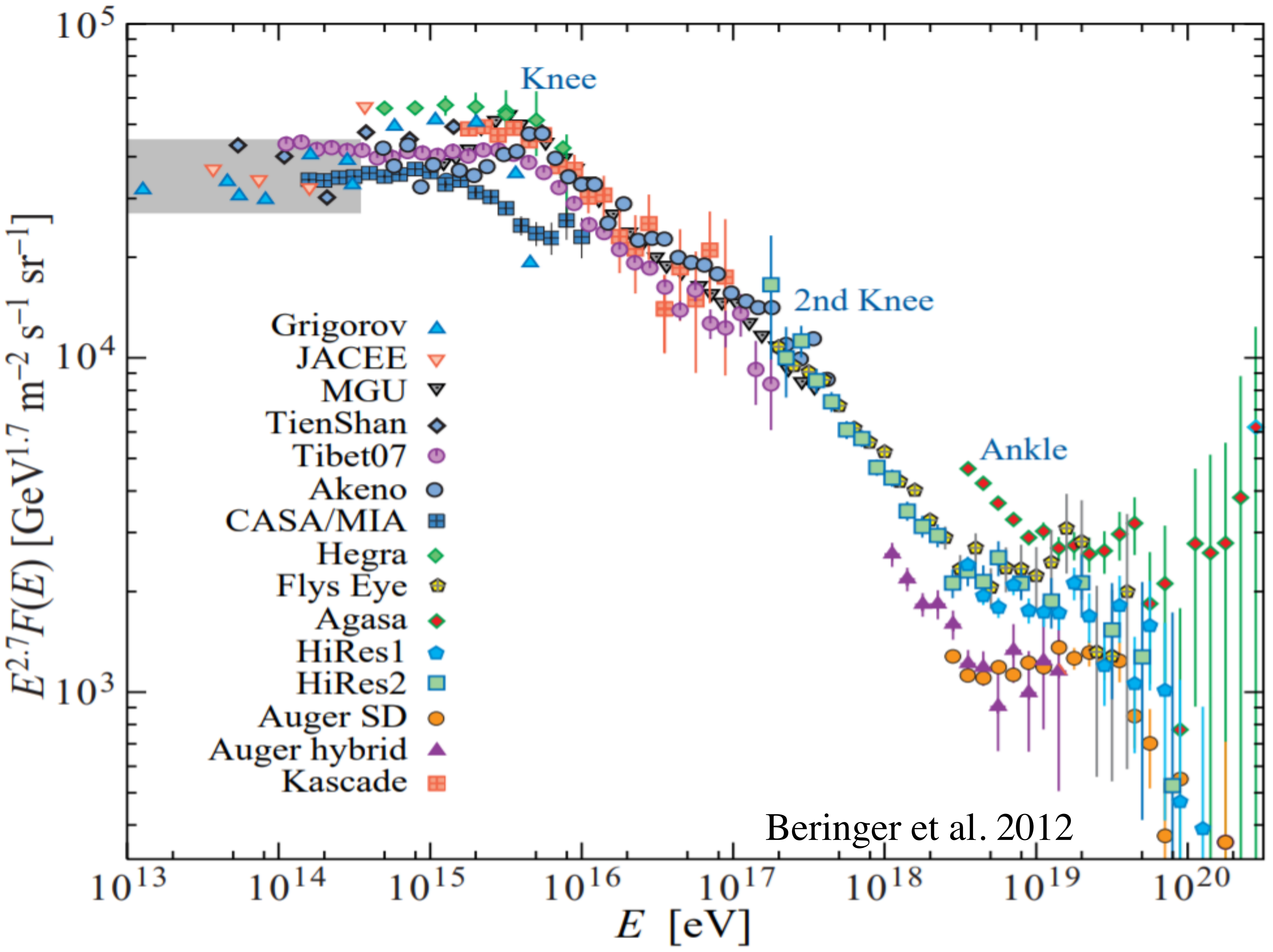
$$p + \bar{\nu}_e \to n + e^+$$

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

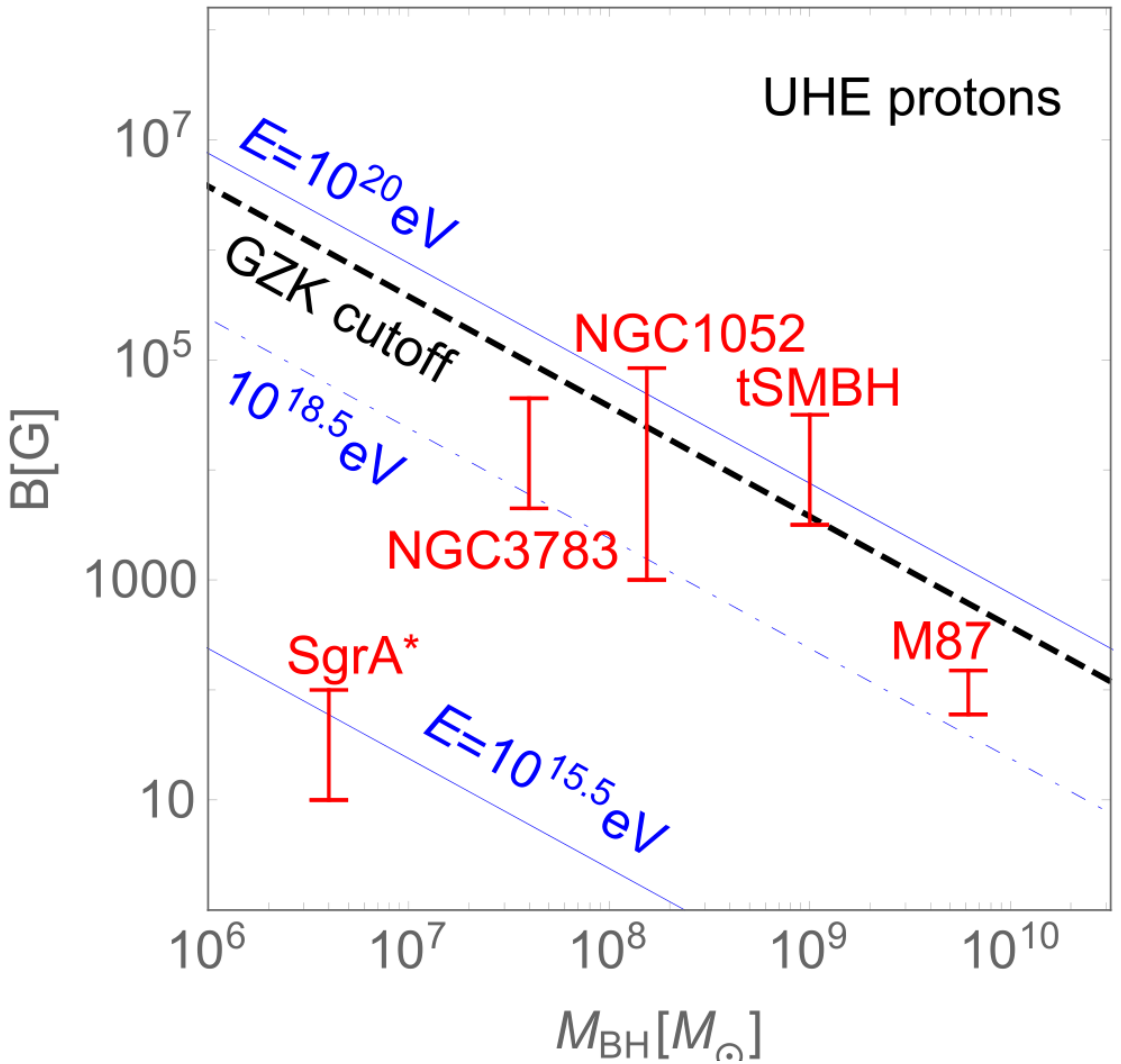
A. Janiuk et al, Galaxies 5, 15 (2017)

Energy of protons: acceleration of cosmic rays

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



Tursunov, et al, ApJ 2020



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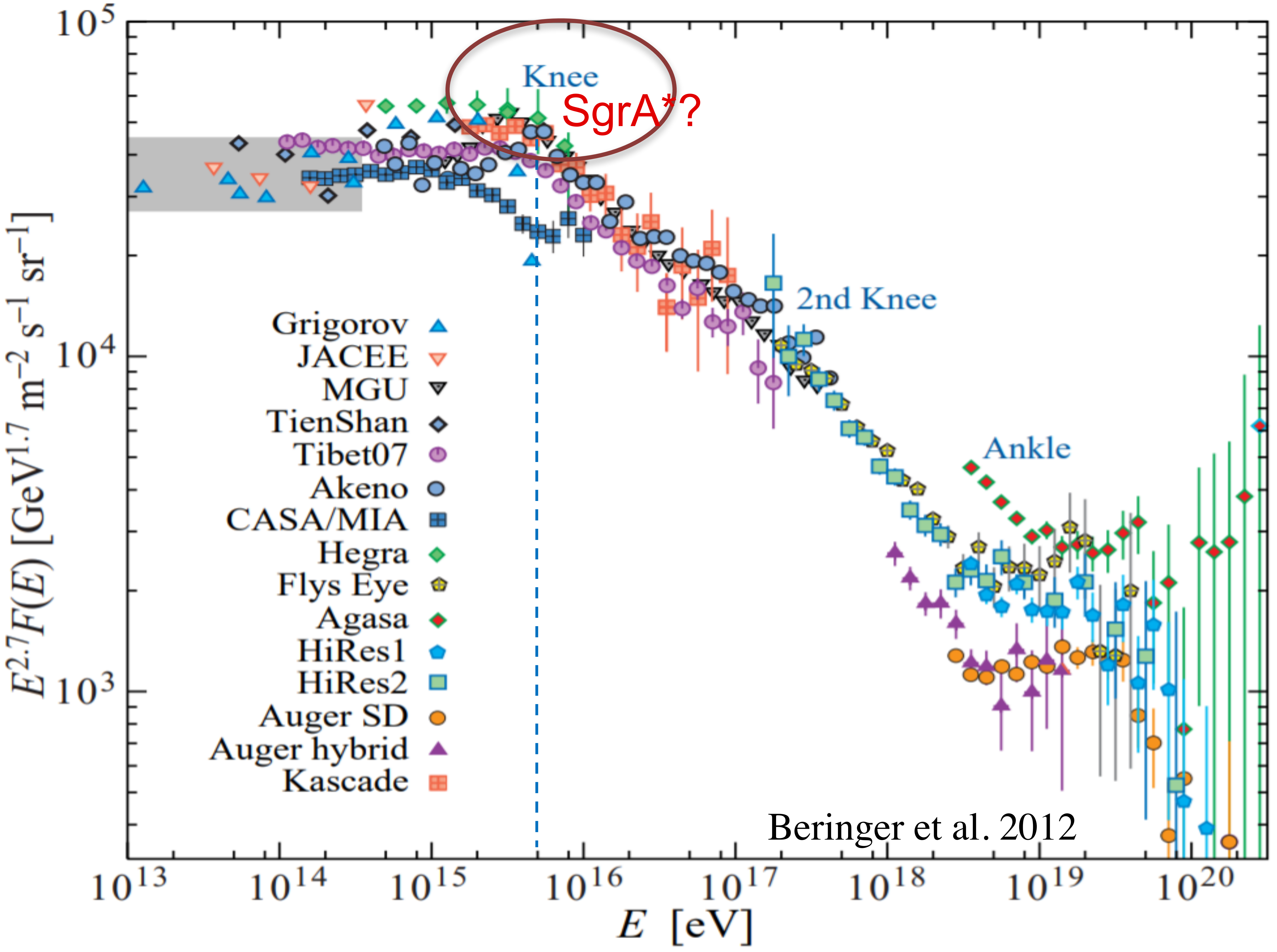

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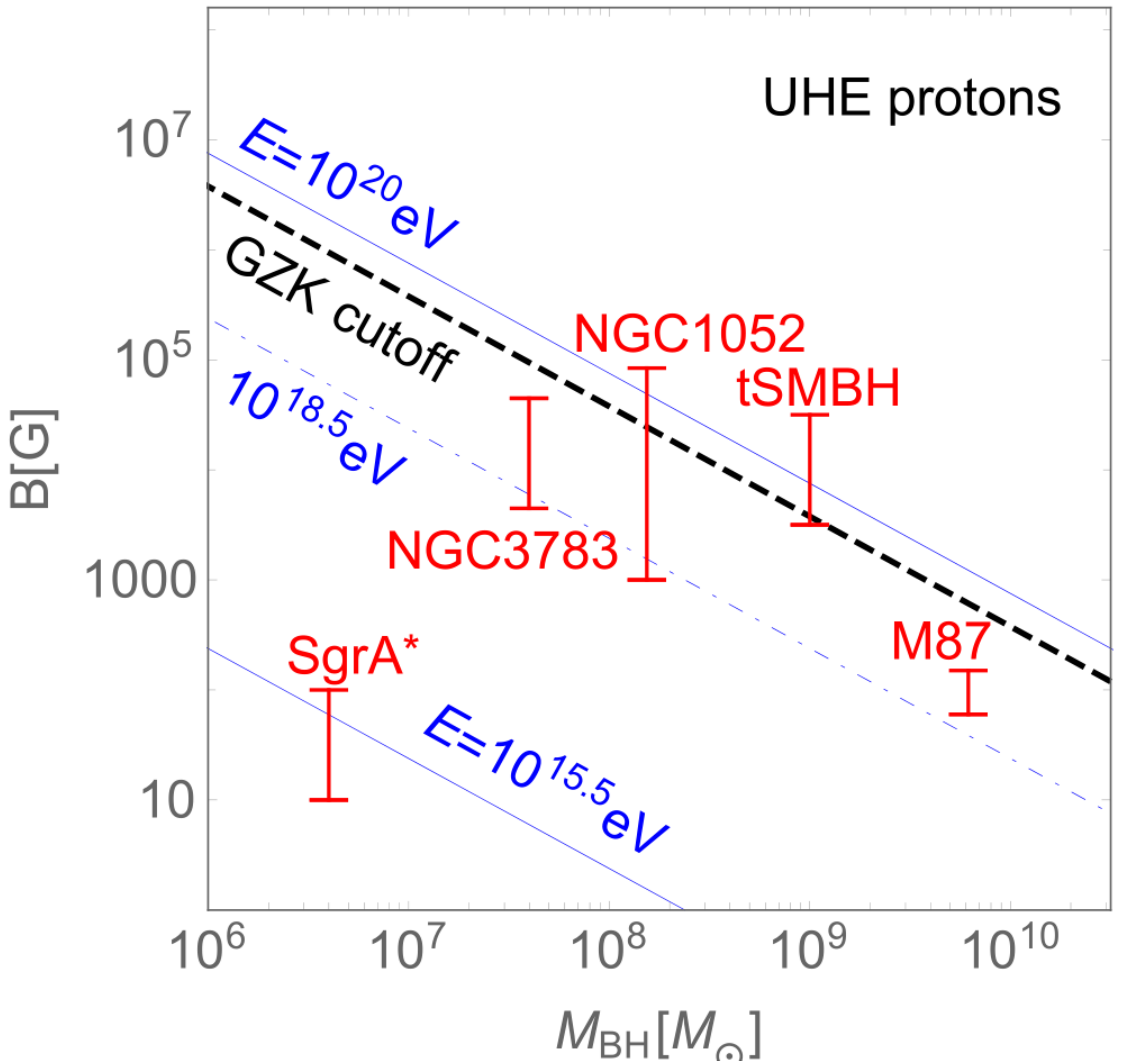
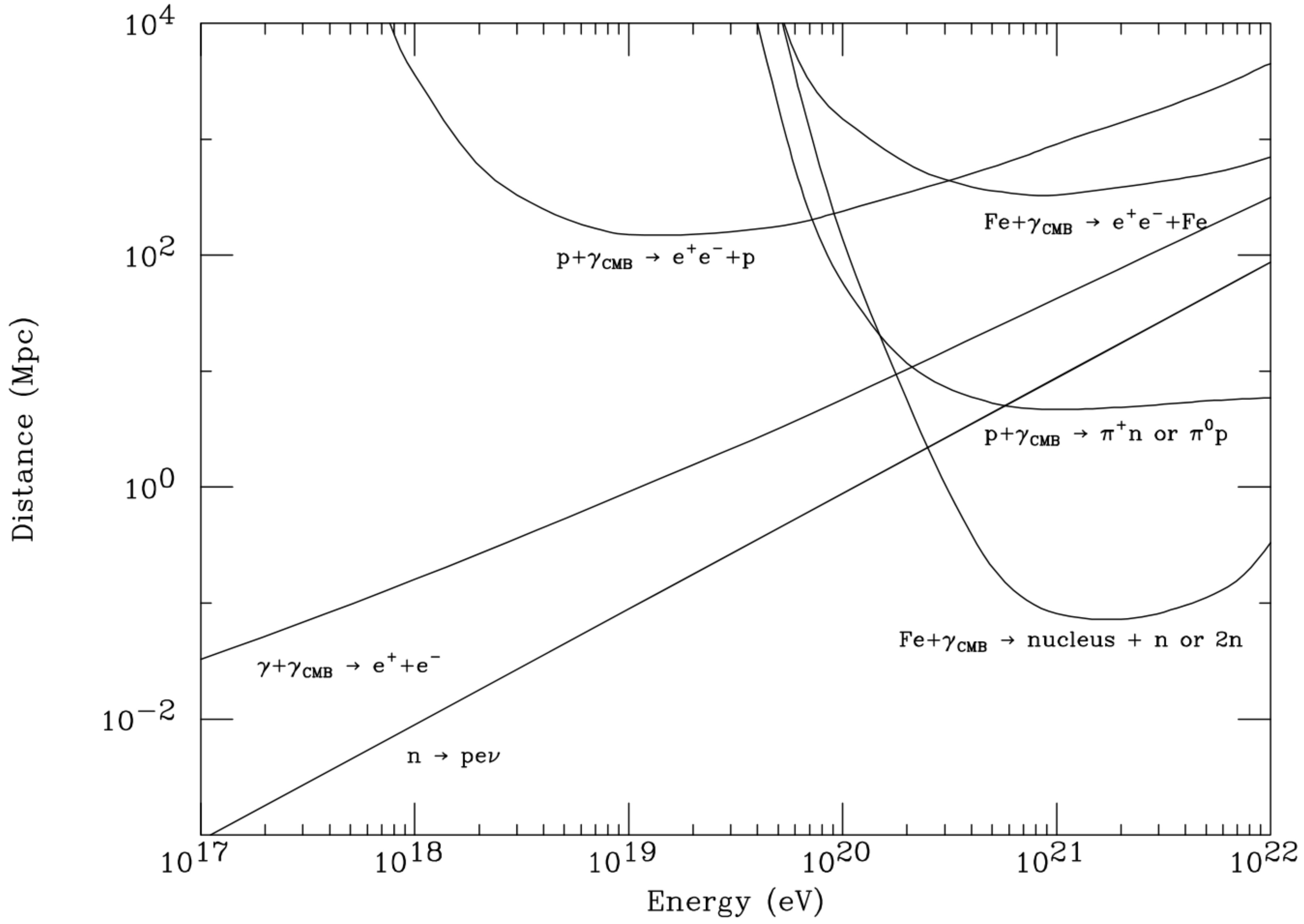
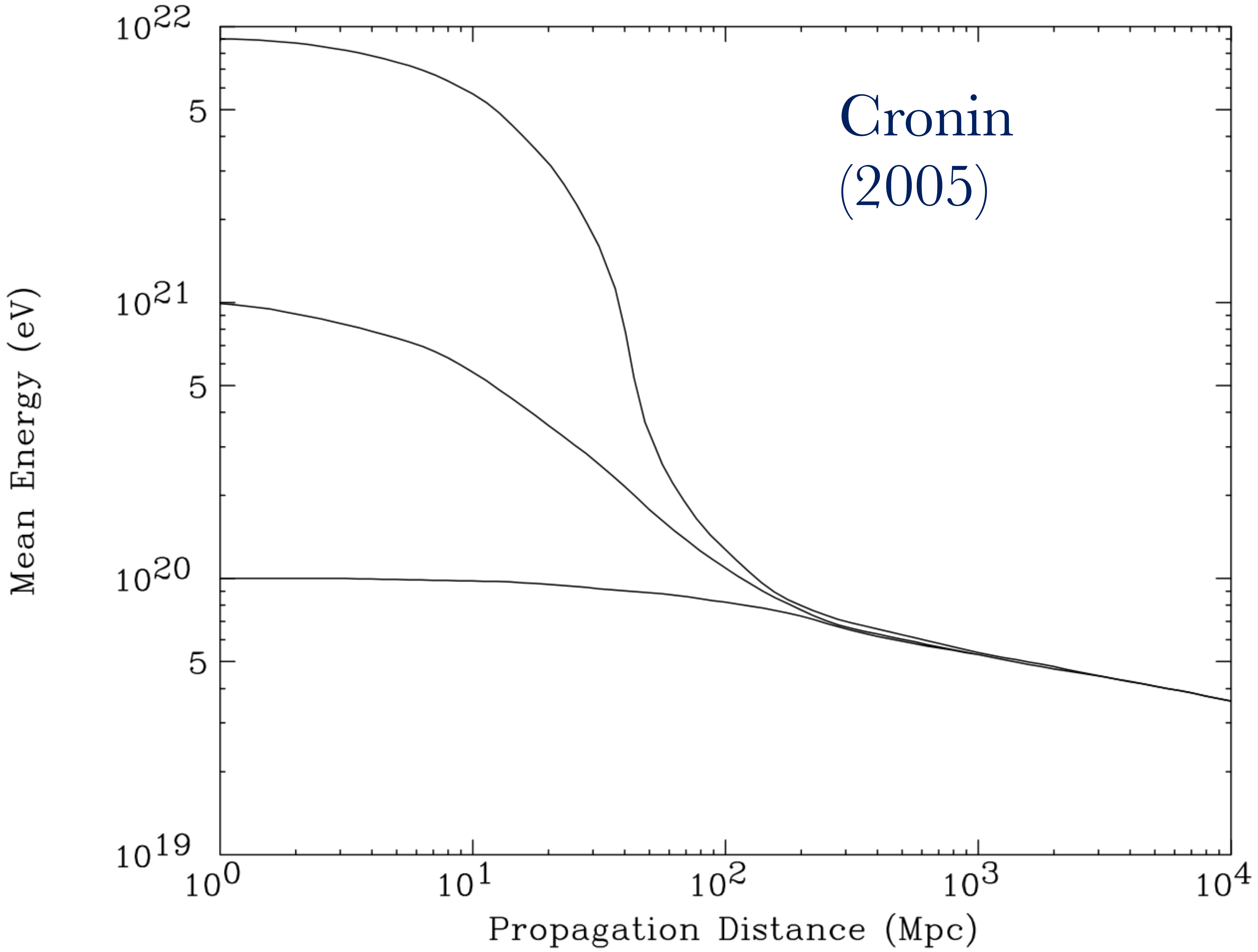


GZK cutoff





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.

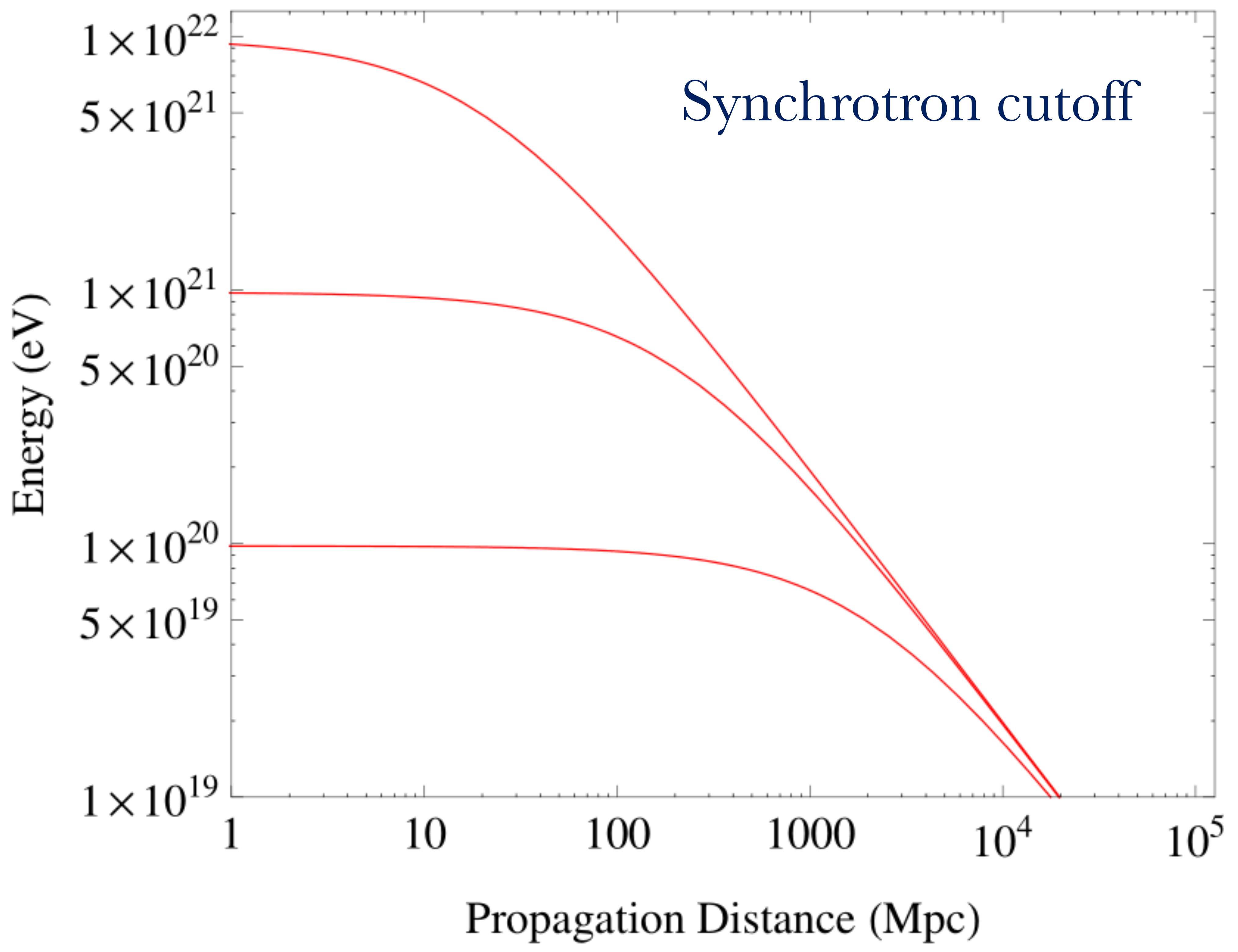
$$p + \gamma_{\rm CMB} \rightarrow p + \pi^0,$$

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

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

Energy loss due to synchrotron radiation

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



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:

$$\left(T = 10^8\mathrm{K}, \quad n = 10^{14}\mathrm{cm}^{-3}\right)$$

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

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

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

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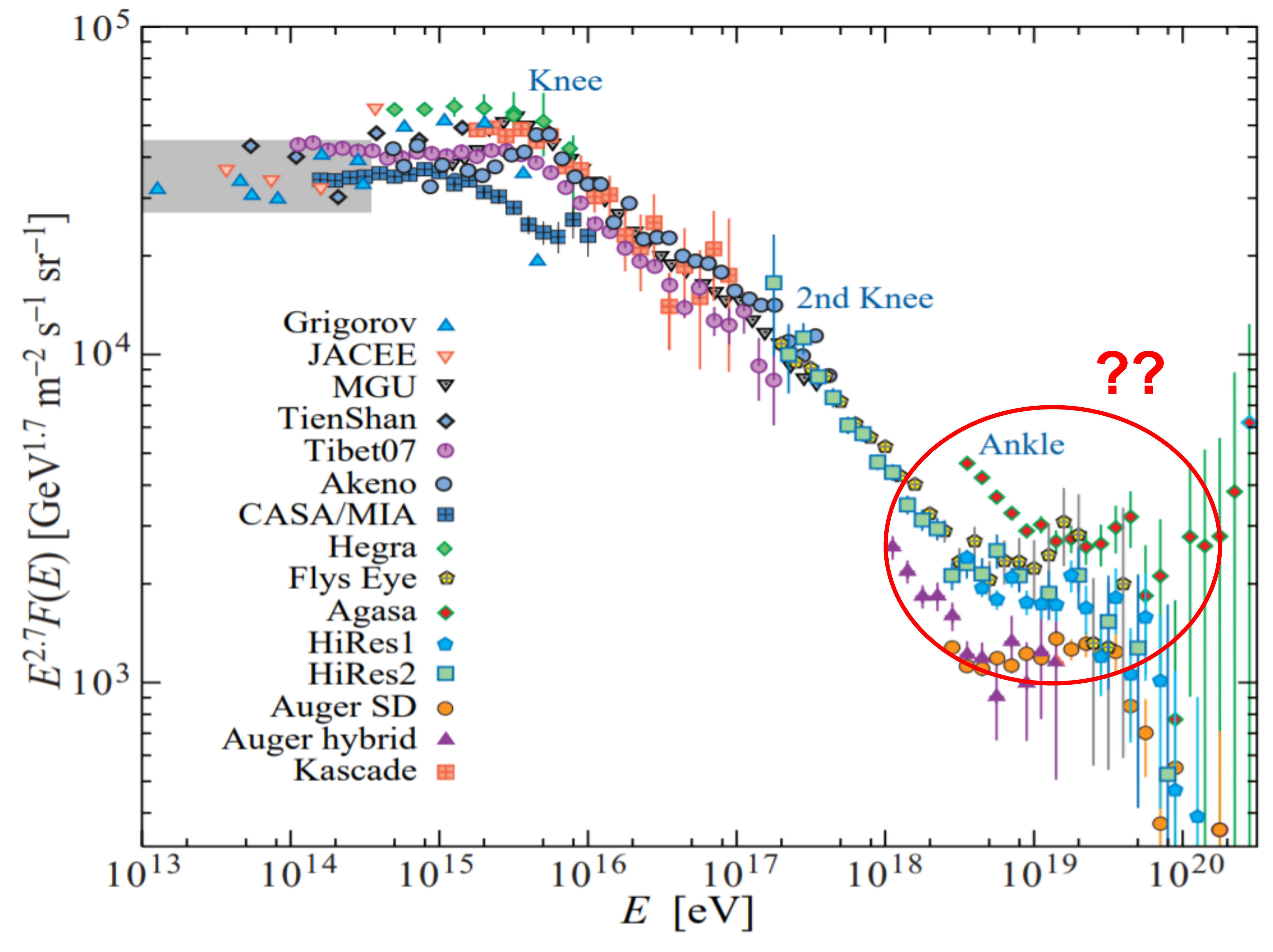


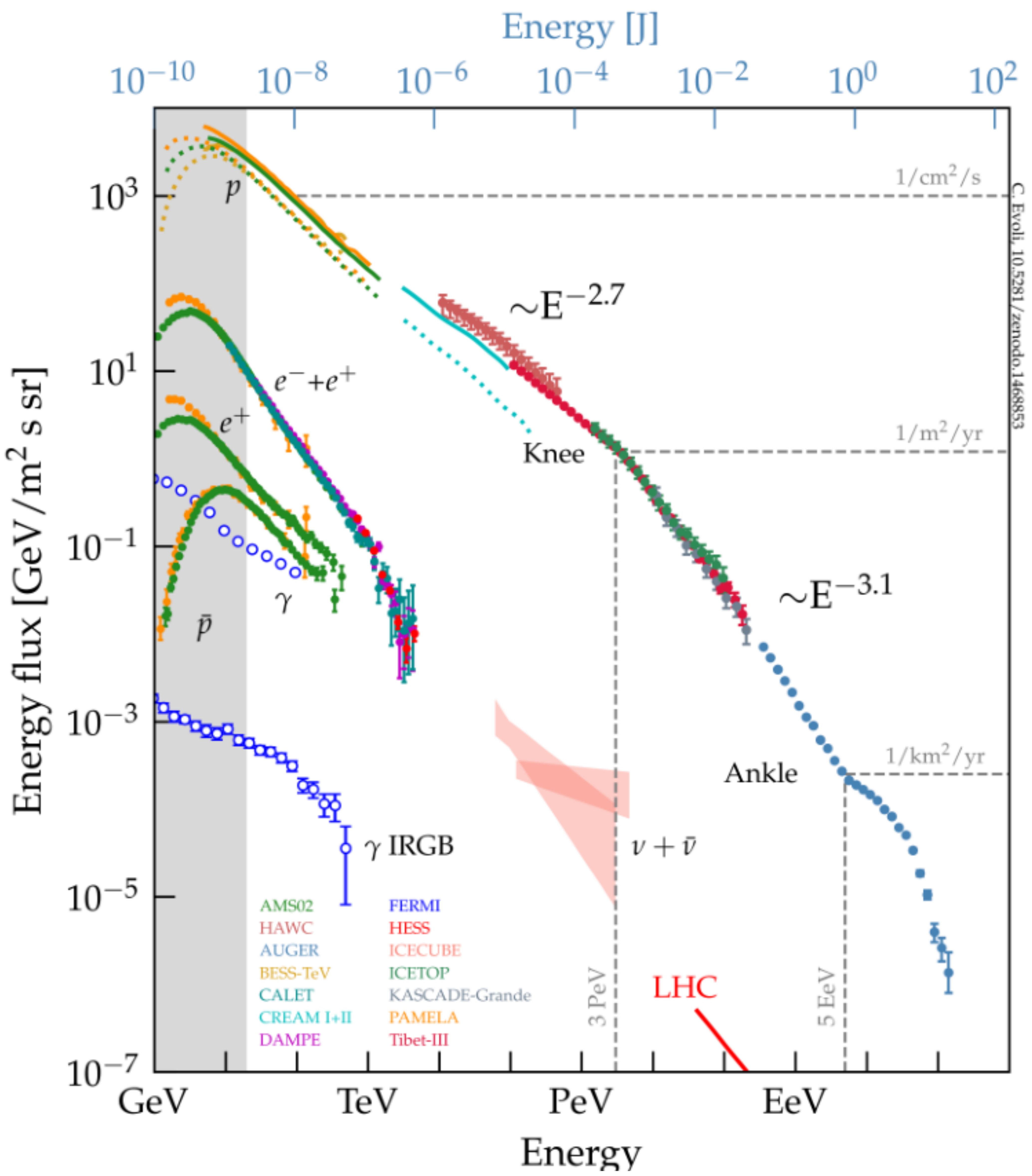
Particle acceleration in various radioactive decay modes

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	~ 1	moderate
	${}^{A}_{Z}X^{-} \rightarrow {}^{A-4}_{Z-2}Y^{3-} + {}^{4}_{2}\alpha^{2+}$	Y	~ 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^{+}	~ 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

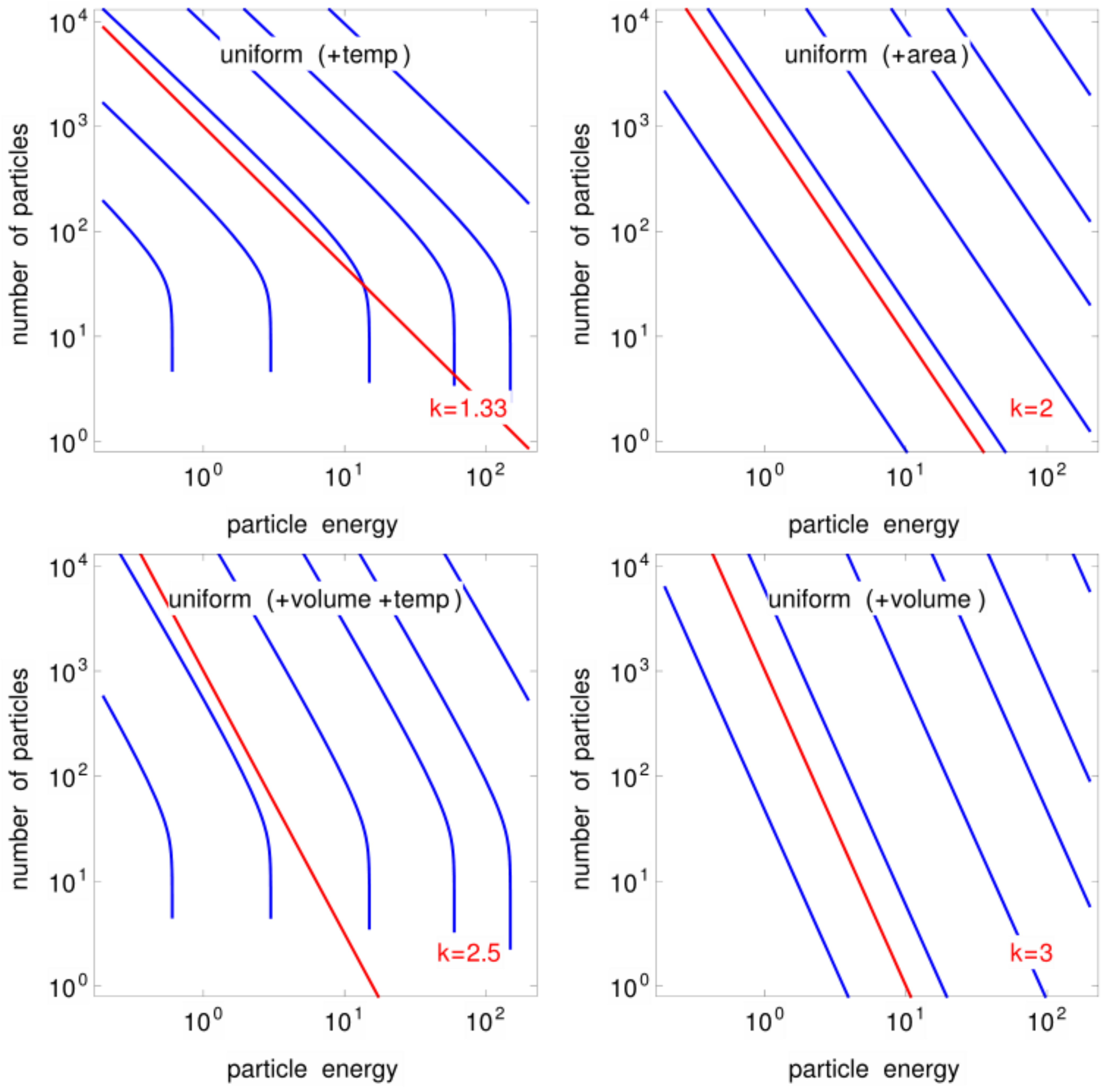
Tursunov, Dadhich, 2019

Spectrum of UHECR acceleration model

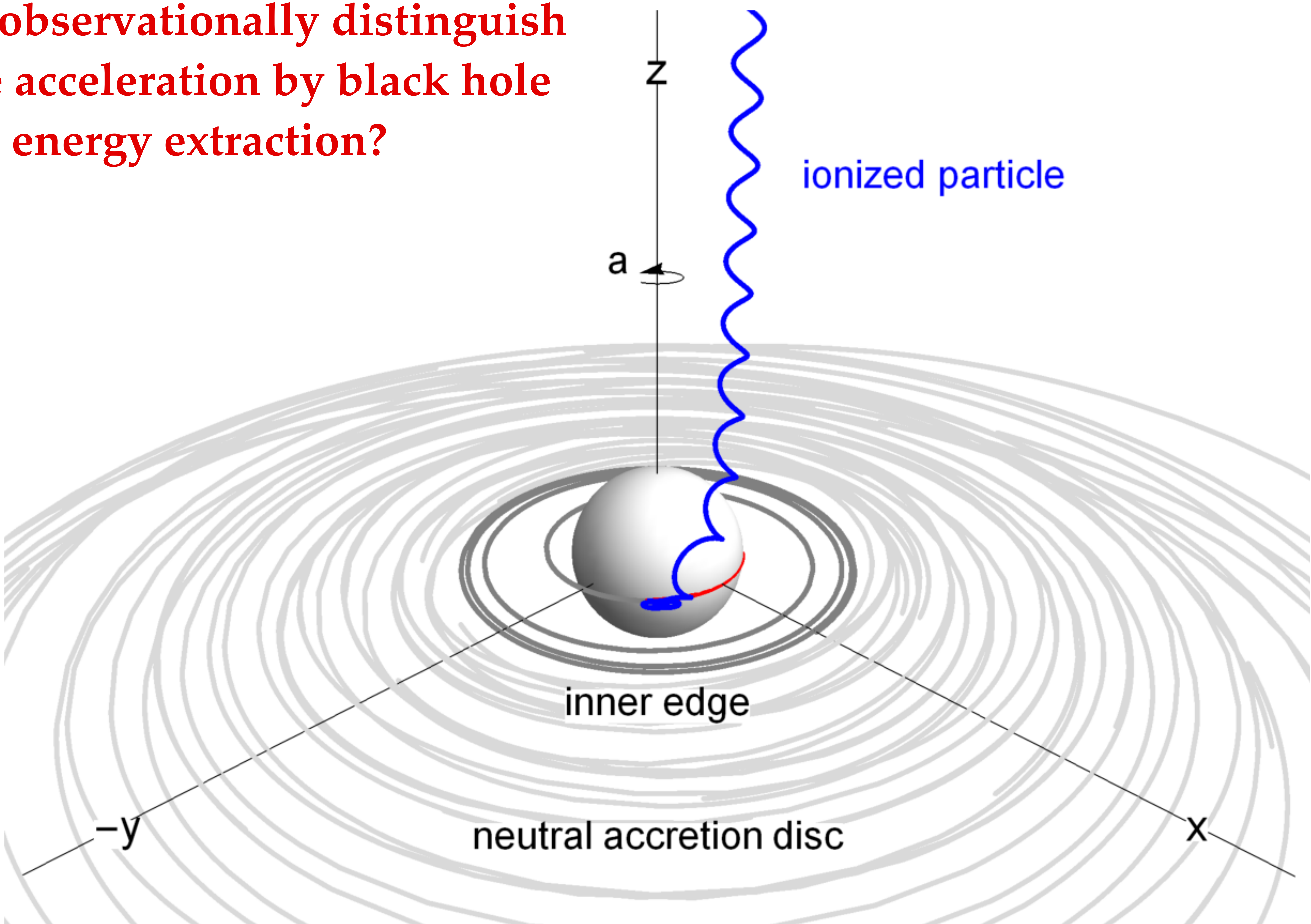
model: available energy ✓ acceleration mechanism ✓ energy spectrum × . . .



preliminary theoretical models:



Can we observationally distinguish particle acceleration by black hole energy extraction?



Motion of radiating charged particles

Gravity + Lorentz force + EM radiation reaction

radiation emitted by a charged particle leads to appearance of **back-reaction force**

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^{\mu}_{\alpha\beta} u^\alpha u^\beta = \frac{q}{m} F^{\mu}{}_{\nu} u^\nu + \frac{q}{m} \mathcal{F}^{\mu}{}_{\nu} u^\nu ,$$

Kolos, Tursunov, Stuchlik, PRD 2021 & Tursunov, et al. ApJ 2018.

Radiation inside the ergosphere: energy extraction

Gravity + Lorentz force + EM radiation reaction

radiation emitted by a charged particle leads to appearance of **back-reaction force**

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^{\mu}_{\alpha\beta} u^\alpha u^\beta = \frac{q}{m} F^{\mu}{}_{\nu} u^\nu + \frac{q}{m} \mathcal{F}^{\mu}{}_{\nu} u^\nu ,$$

Kolos, Tursunov, Stuchlik, PRD 2021 & Tursunov, et al. ApJ 2018.

Can we detect black hole energy extraction?

Event Horizon Telescope Image of M87

Can we detect black hole energy extraction?

Future ngEHT may resolve internal ring structures