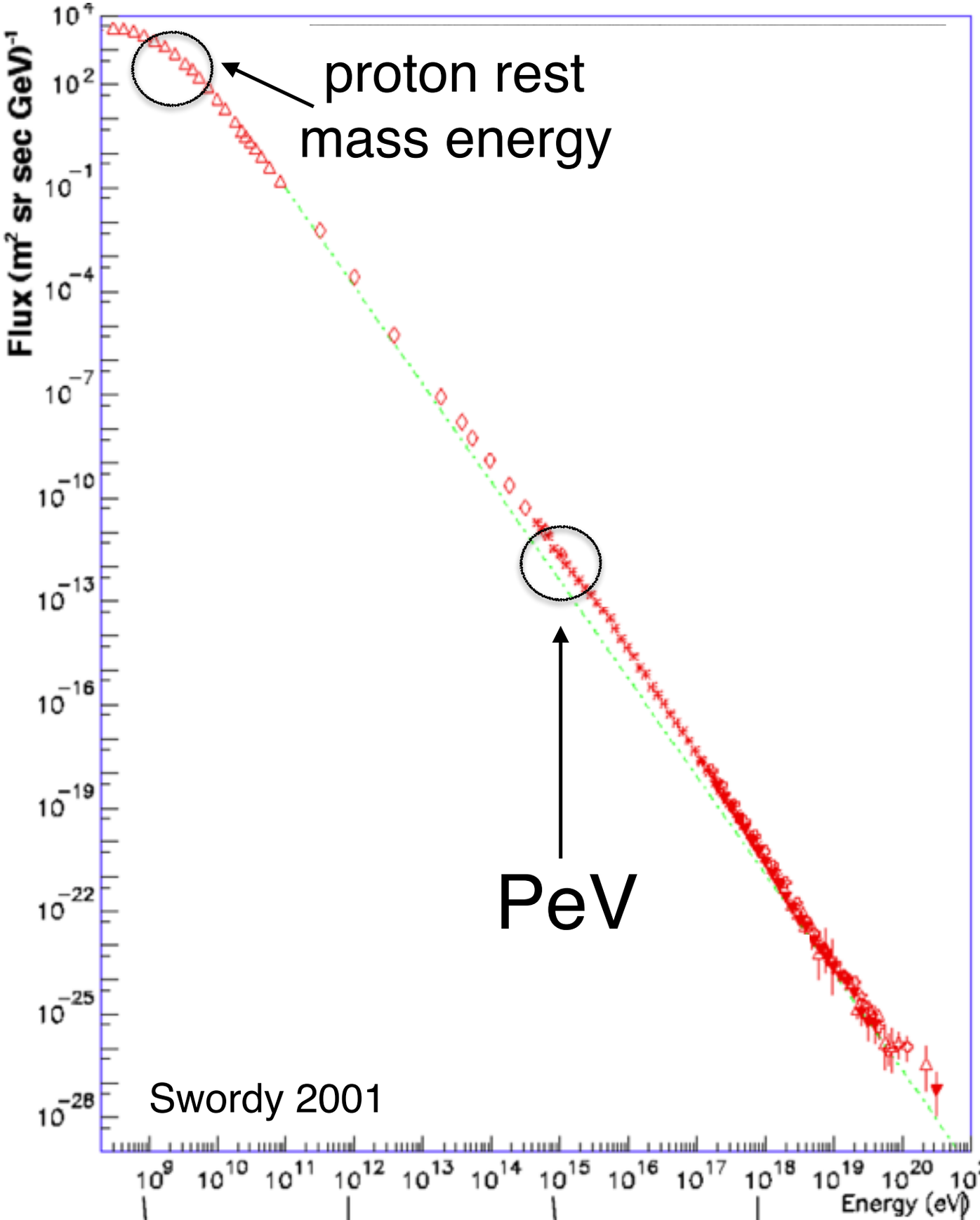
Accreting Black Holes as PeVatrons

Yuto Teraki
Kyoto university (Japan)

collaborators: Kunito Ioka, Tatsuya Matsumoto

ref. YT, Matsumoto & Ioka (in prep.)

Observed cosmic-ray spectrum



Discovery : AD1912
by Victor Hess

$$\frac{dN}{dE} \propto E^{-\alpha}, \ (\alpha \sim 3)$$

Hadron (p, He….)

$$E_{\rm min} \lesssim 10^9 {\rm eV}$$

PeV $= 10^{15}$eV

$$E_{\rm max} \gtrsim 10^{20} {\rm eV}$$

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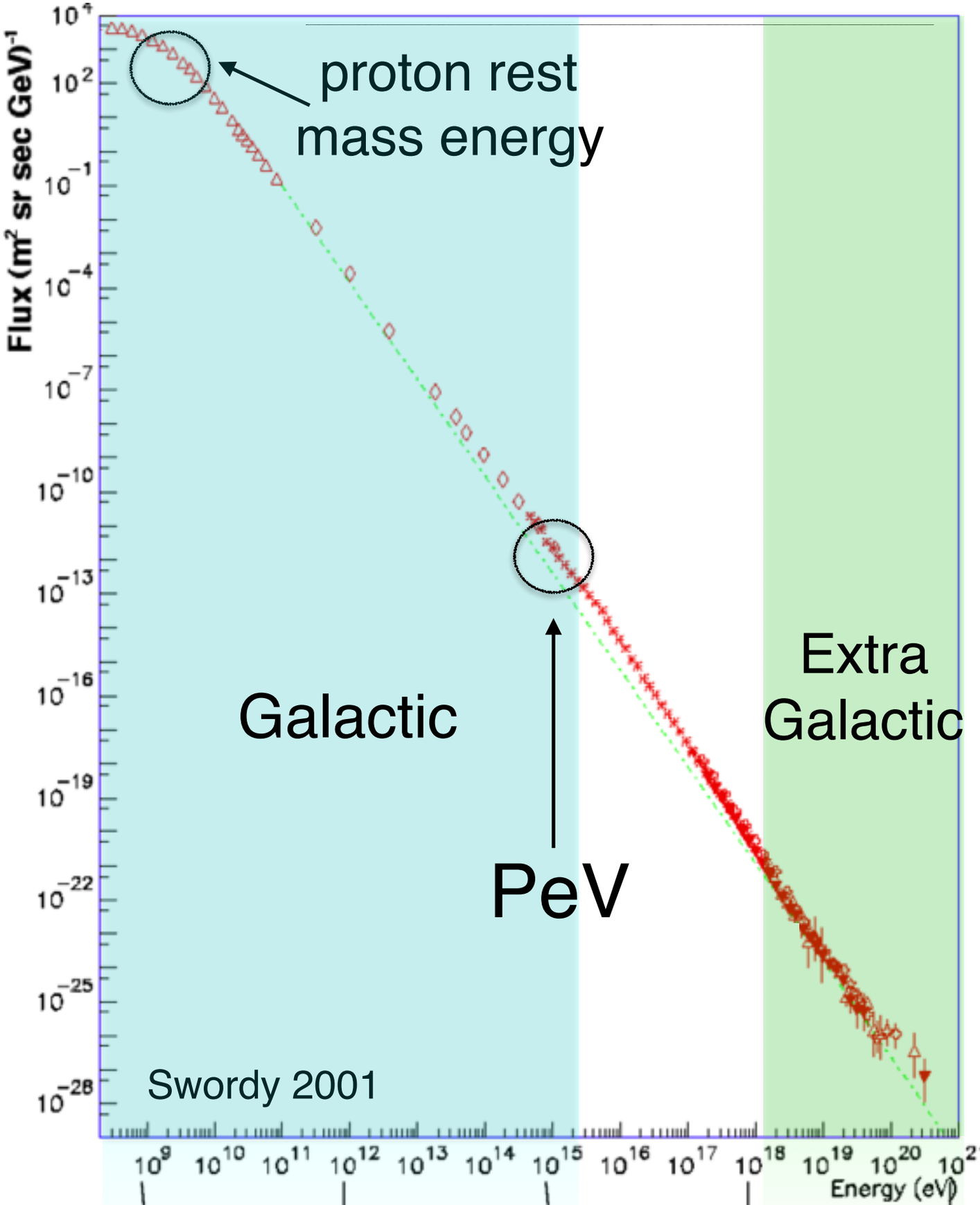

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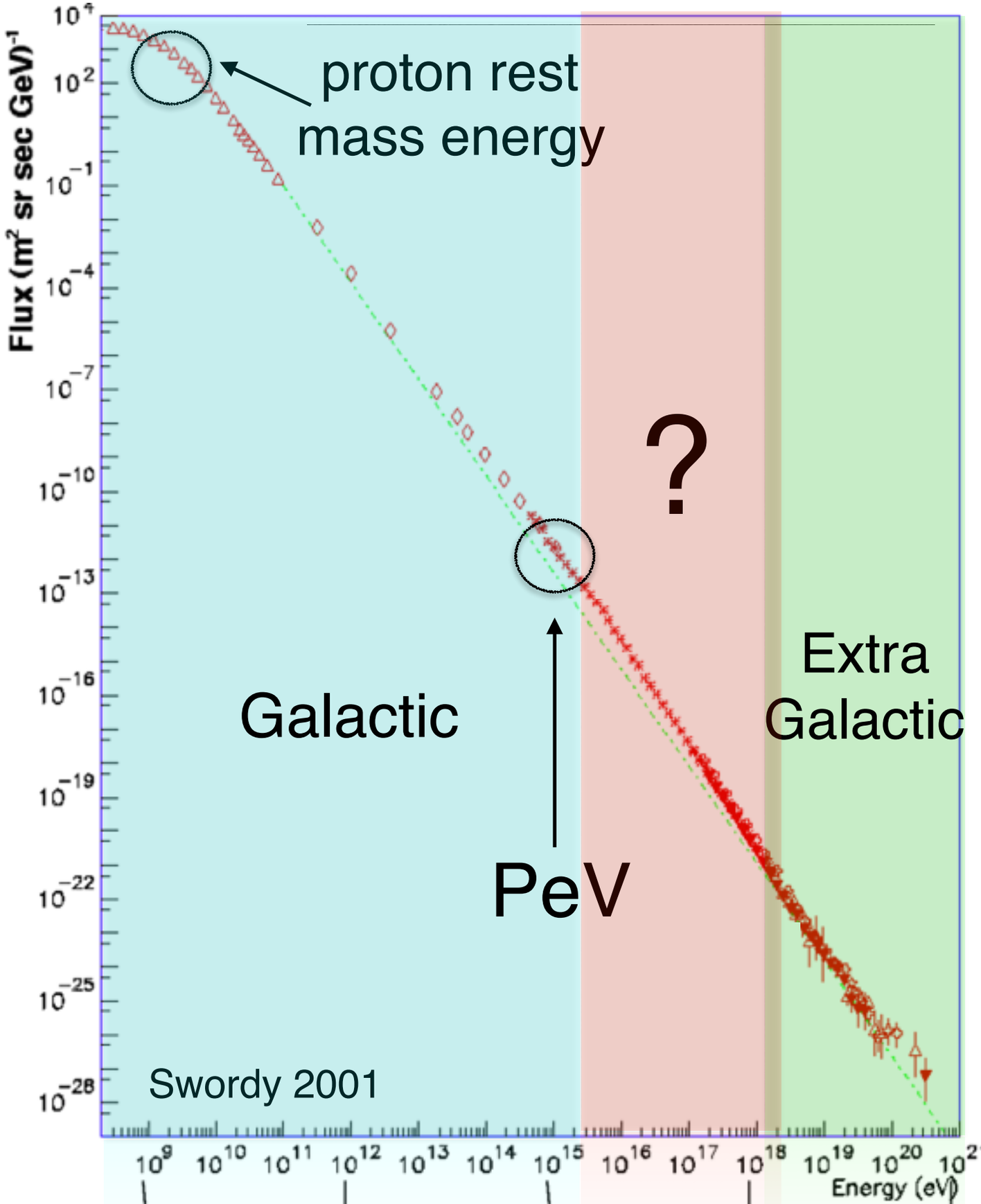

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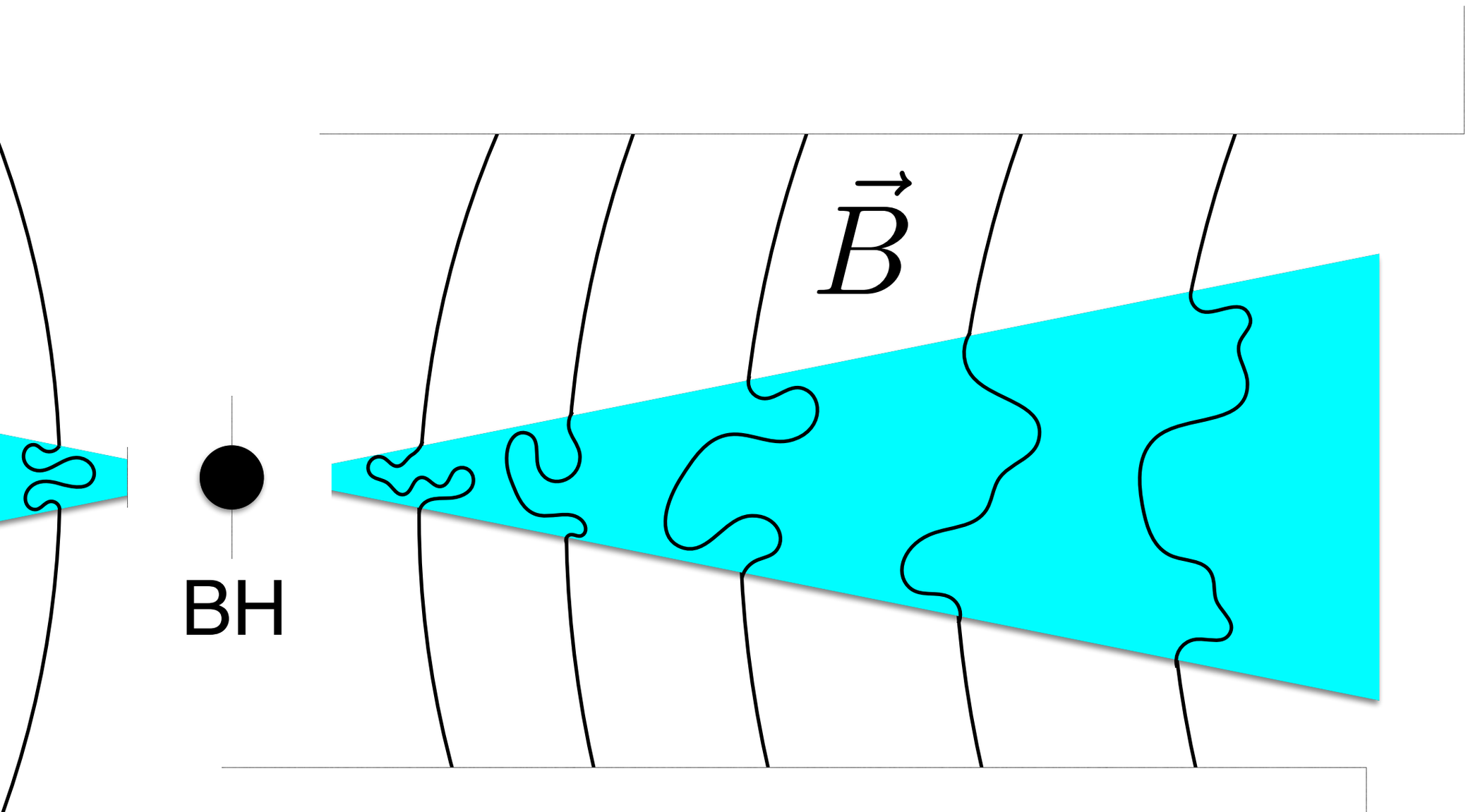
We propose a new hypothesis that

“Galactic”
BH accretion disks

supply the PeV cosmic-rays

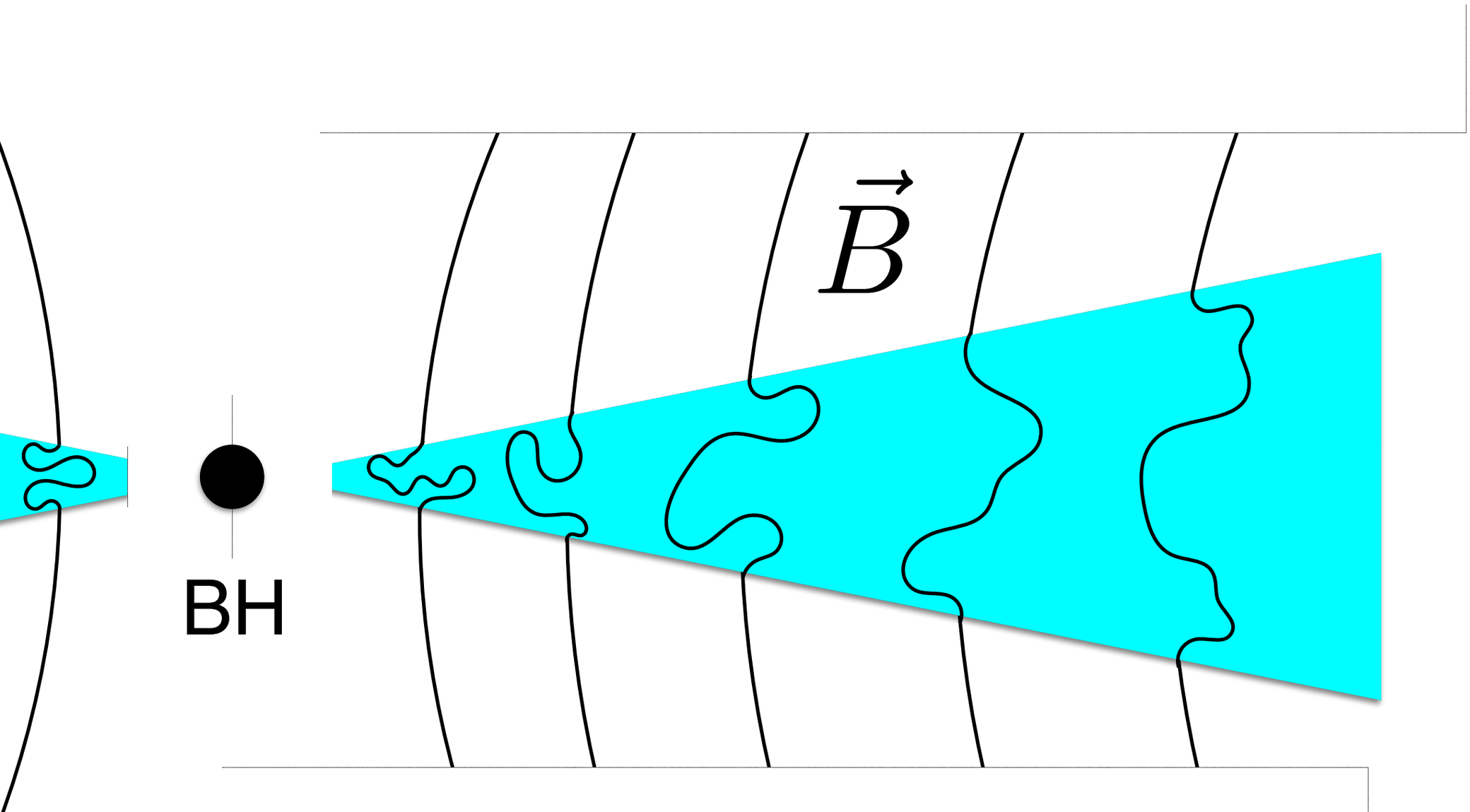
Yuto Teraki (Kyoto unv.)

Particle acceleration in accretion disks



Particle acceleration in accretion disks

1. collisional relaxation time $\ll$ accretion time in ADAF



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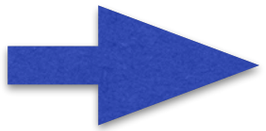
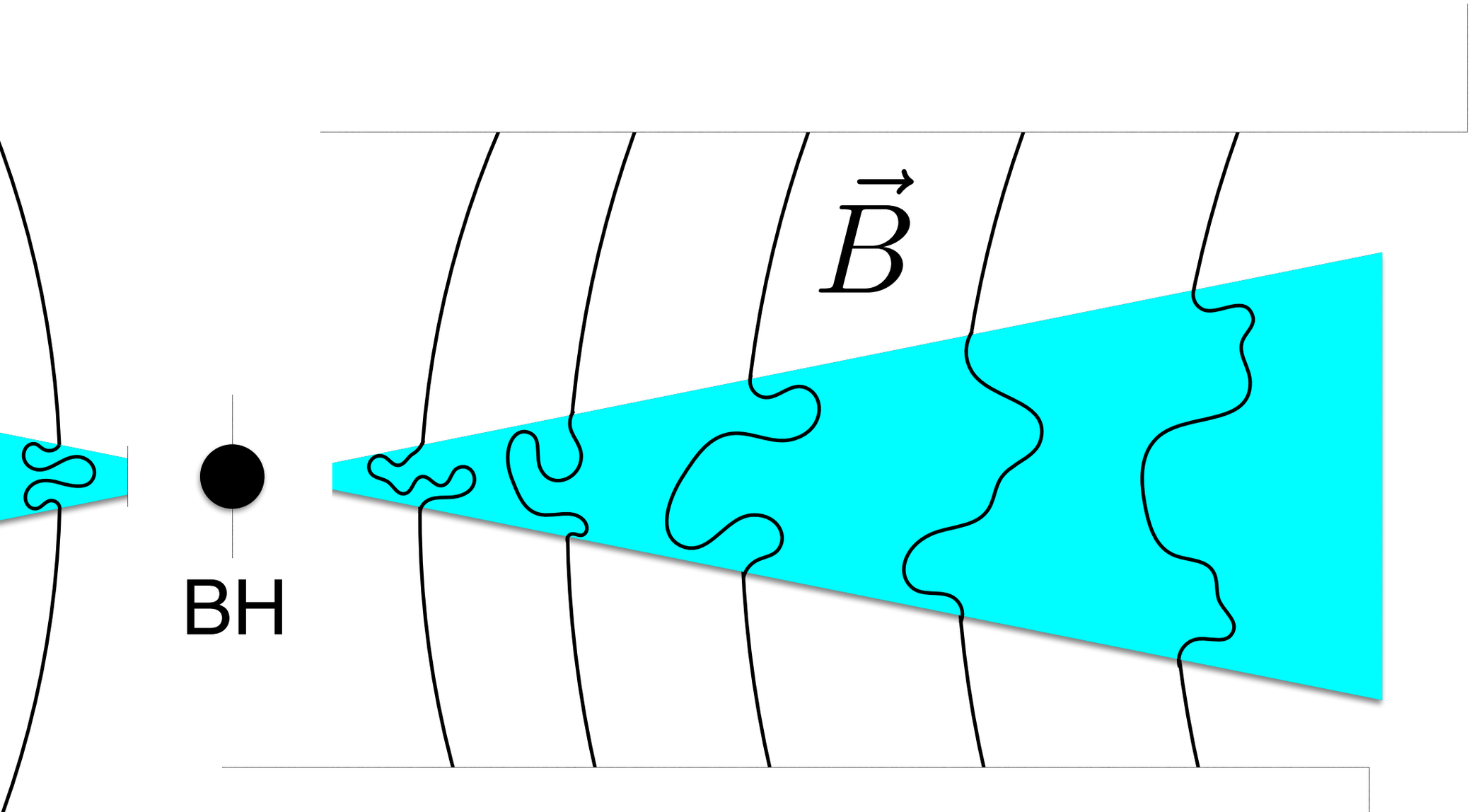


non-thermal distribution is allowed



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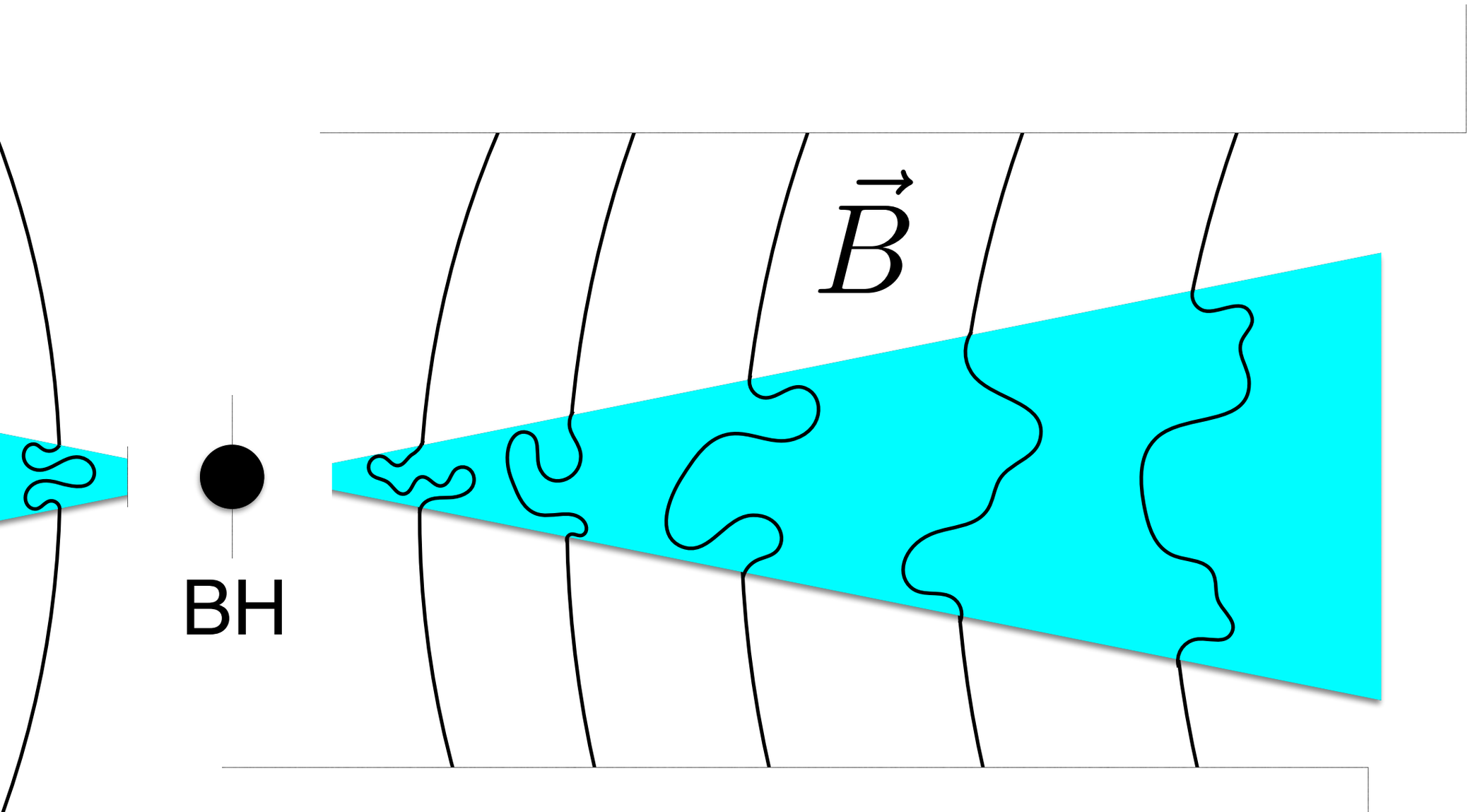
2. MHD turbulence



Particle acceleration in accretion disks

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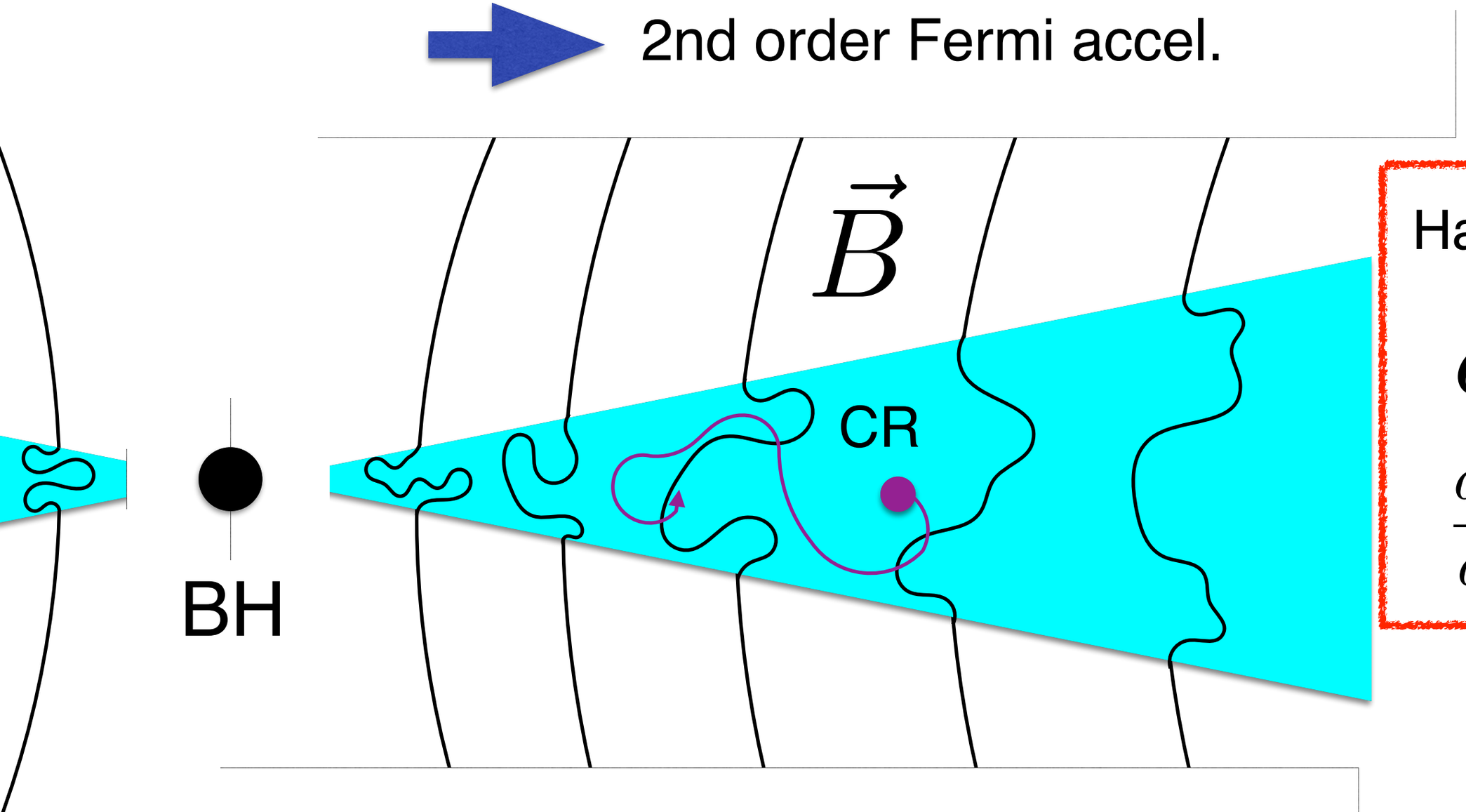
→ non-thermal distribution is allowed

2. MHD turbulence

→ 2nd order Fermi accel.



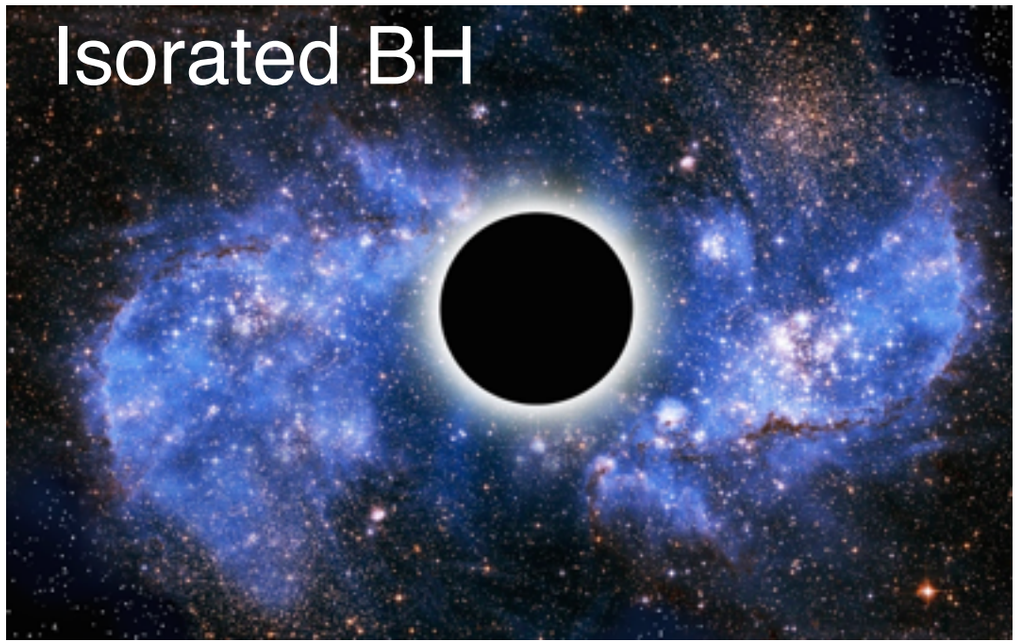
Hard spectrum

$$\alpha < 2$$

$$\frac{dN}{dE} \propto E^{-\alpha}$$

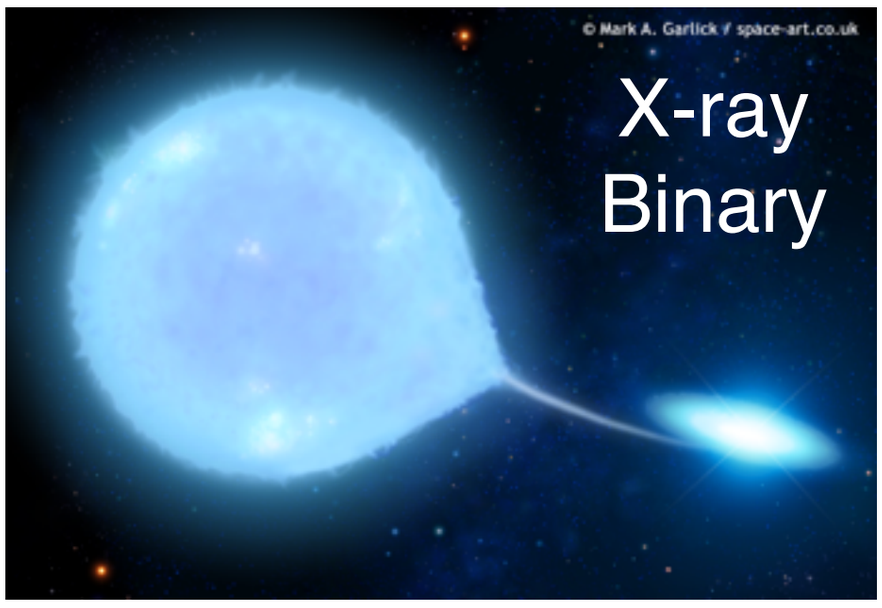
e.g. Stawarz & Petrosian (2008)

Galactic Black Holes



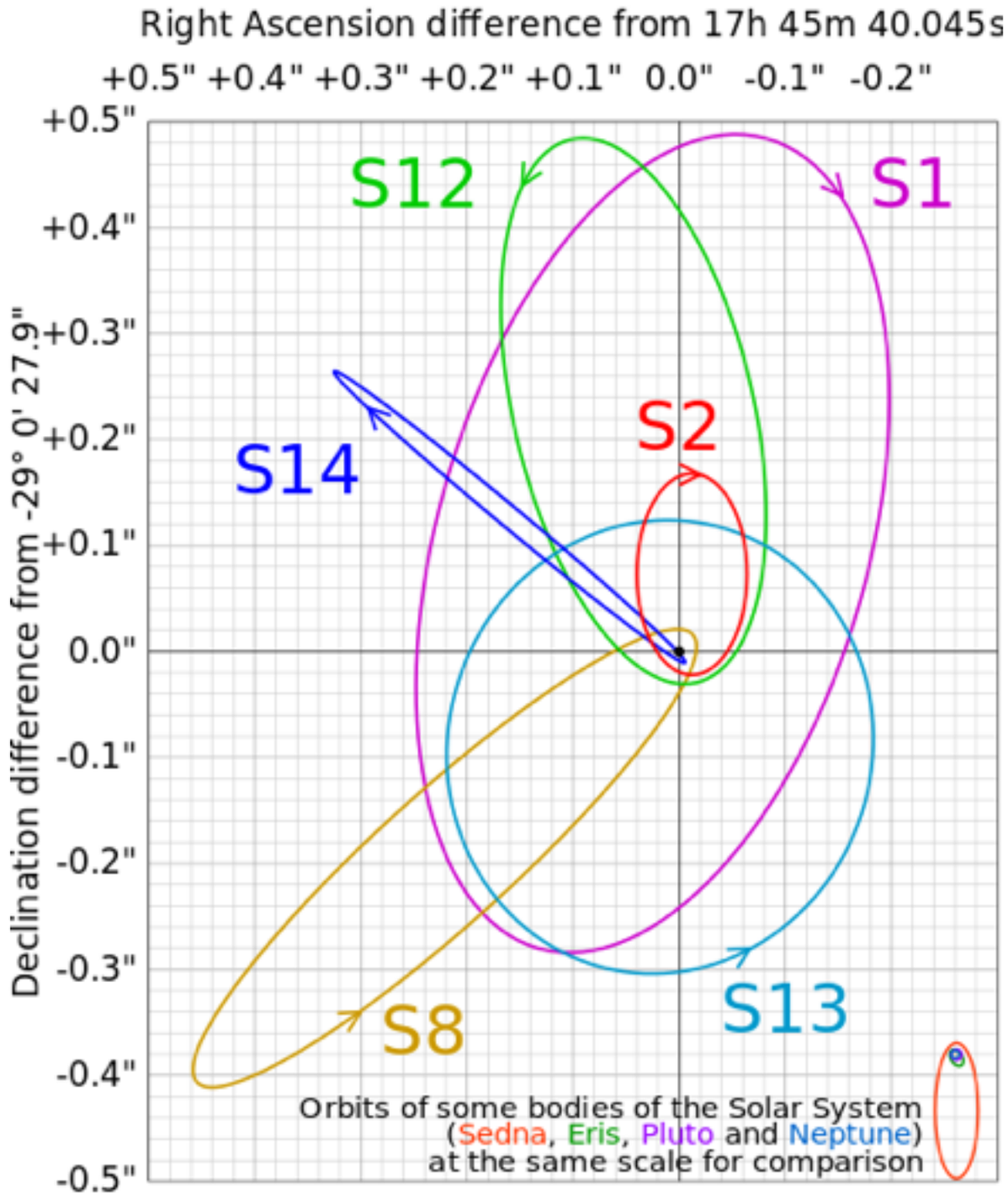
Victor de Schwanberg/Science Photo Library

$$N_{\mathrm{IBH}} = 10^8 - 10^9$$



Mark A. Garlick

$$N_{\mathrm{XRB}} = 10^3 - 10^4$$

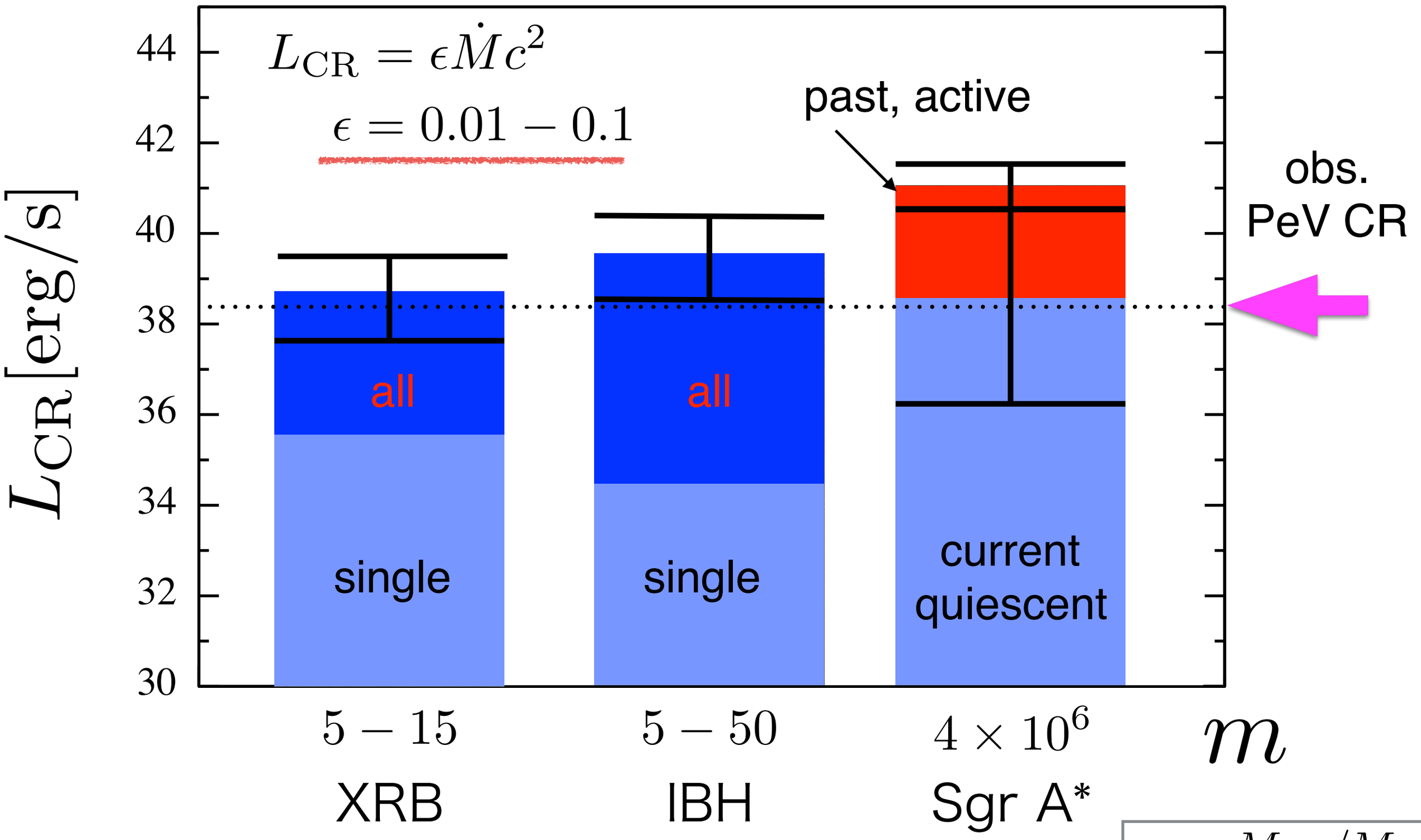


Eisenhauer, F.; et al. (July 20, 2005)

Sgr A*

Yuto Teraki (Kyoto unv.)

Expected cosmic ray luminosity



$m \equiv M_{\rm BH}/M_\odot$

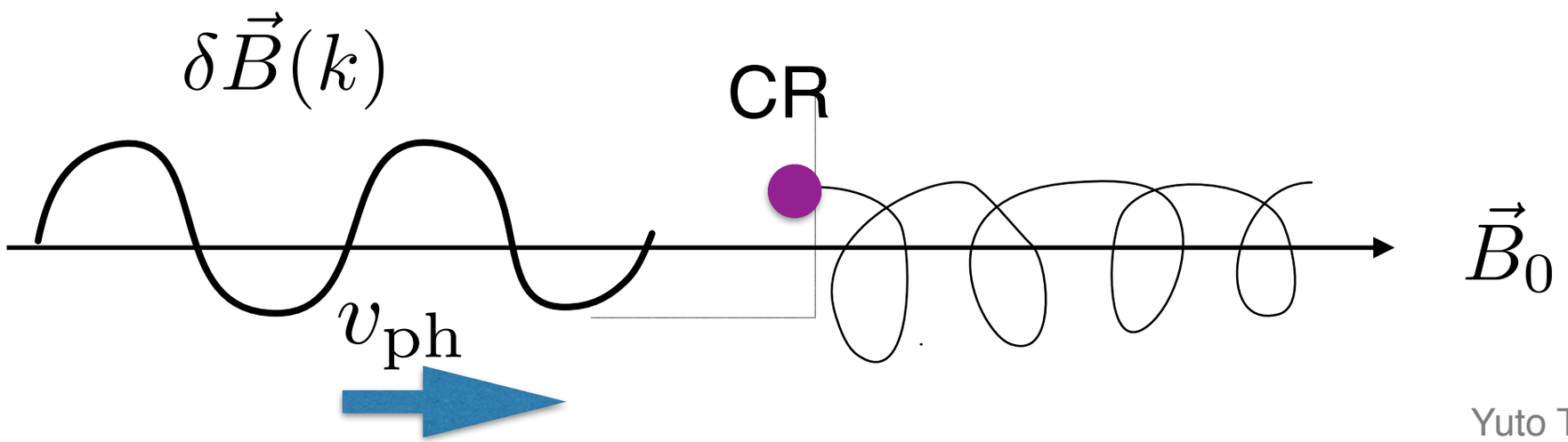
Models

Disk
- ADAF (original Advection Dominated Accretion Flow) Narayan & Yi 1994
- MAD (Magnetically Arrested Disk) Narayan, Igumenshchev & Abramowicz 2003

$$P_B(k) \propto k^{-q}$$

Turbulence
- K41 (Kolomogorov 1941) $q = 5/3$
- IK (Iroshnikov 1964, Kraichnan 1965) $q = 2/3$
- GS95 (Goldreich &Sridhar 1995) anisotropic

Stochastic Acceleration
- Gyro resonance
- Transit time damping



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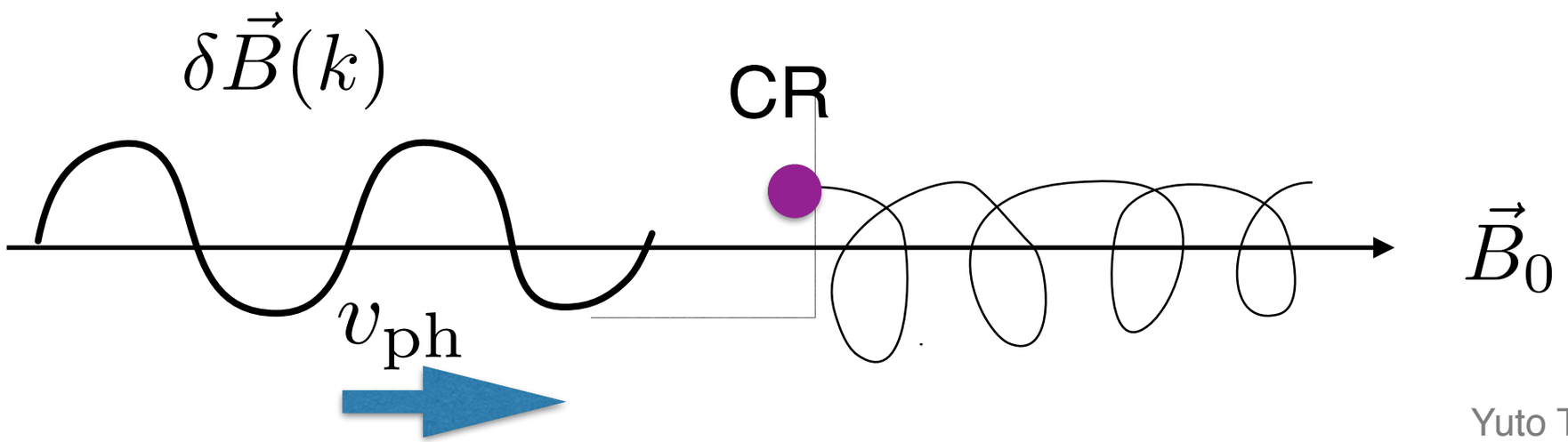

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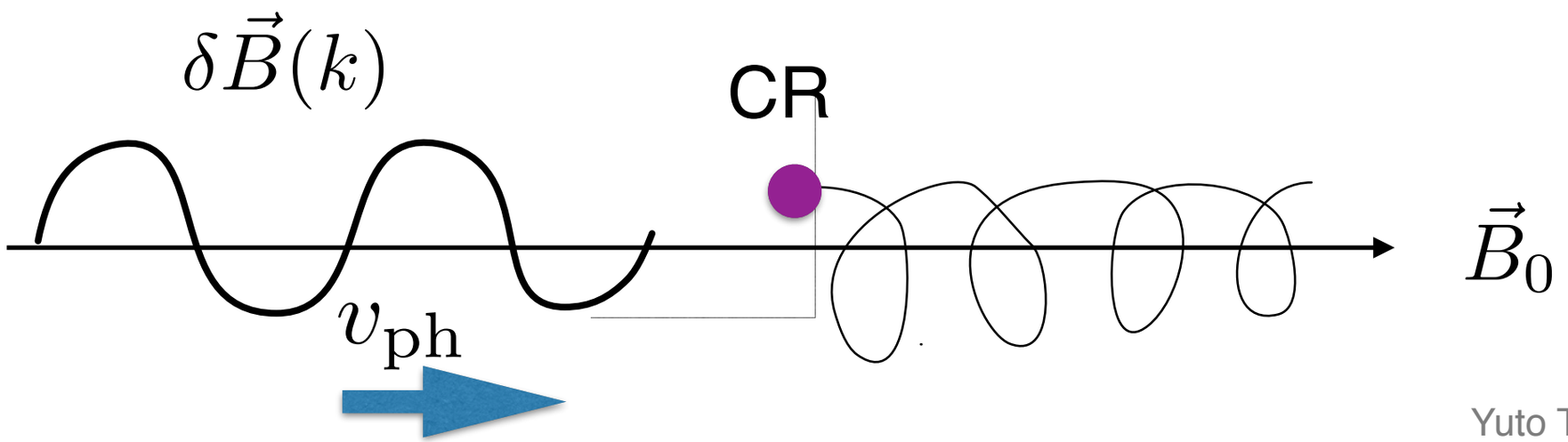


Related timescales

QLT

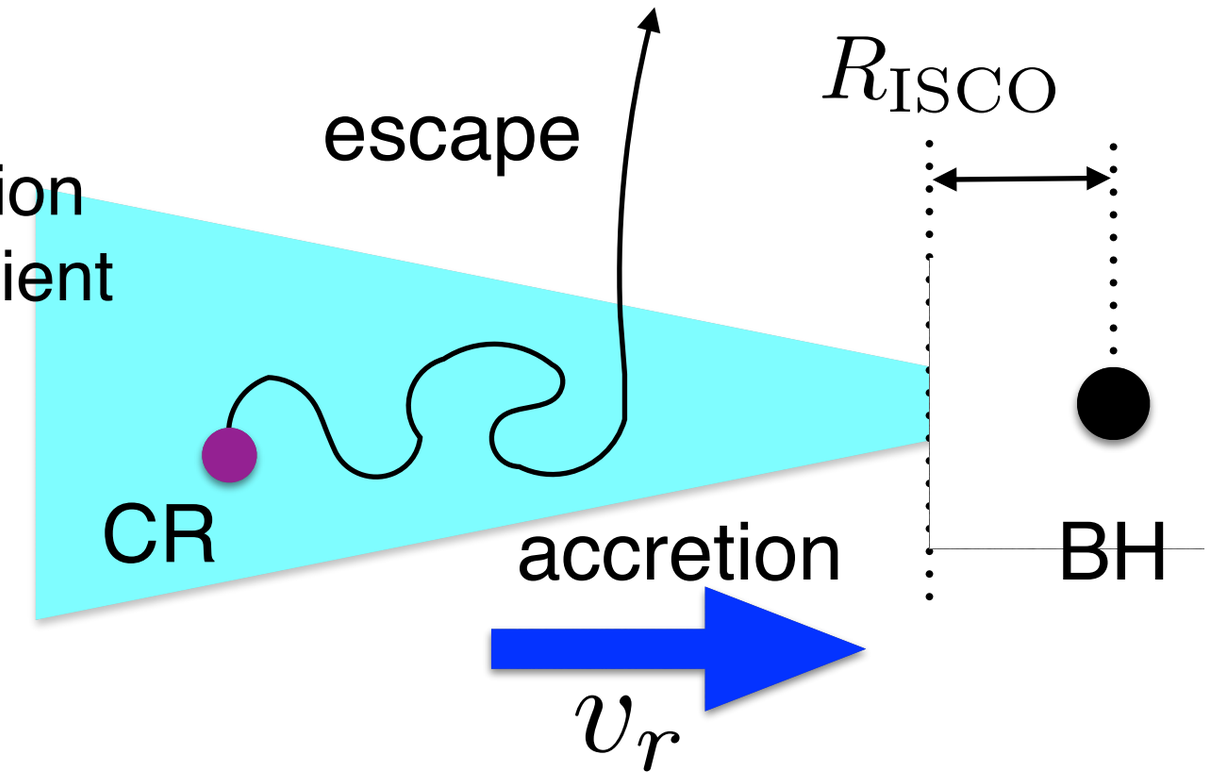
$$t_{\rm acc} = p^2/D_{pp}$$

$$t_{\rm esc} = R^2/D_{xx}$$

diffusion coefficient

Fluid

$$t_{\rm r} = R/v_r$$



coolings

$$t_{\rm synch} = \frac{\gamma m_p c^2}{P_{\rm synch}}$$

$$t_{pp} = (n_p \sigma_{pp} c K_{pp})^{-1}$$

$$t_{p\gamma} = \{n_{\rm ph}(\epsilon_{\rm res})\sigma_{p\gamma} c K_{p\gamma}\}^{-1}$$

How high the maximum energy is ?

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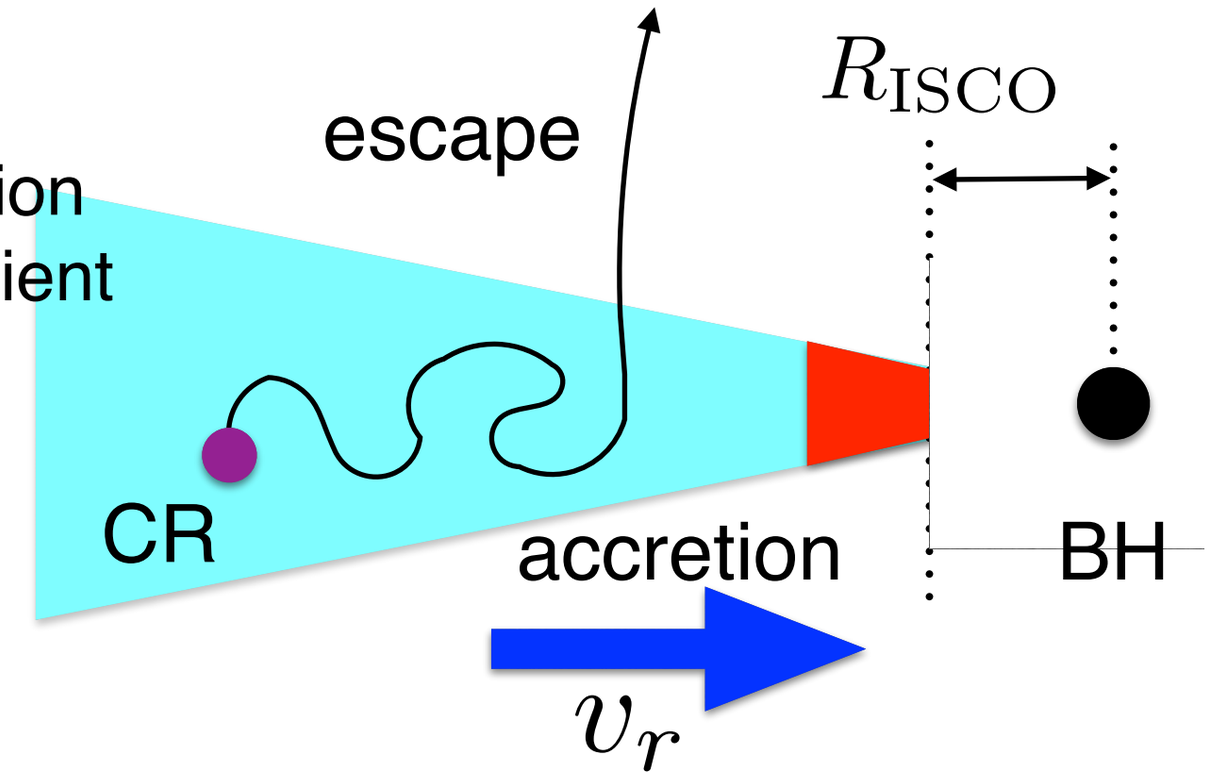

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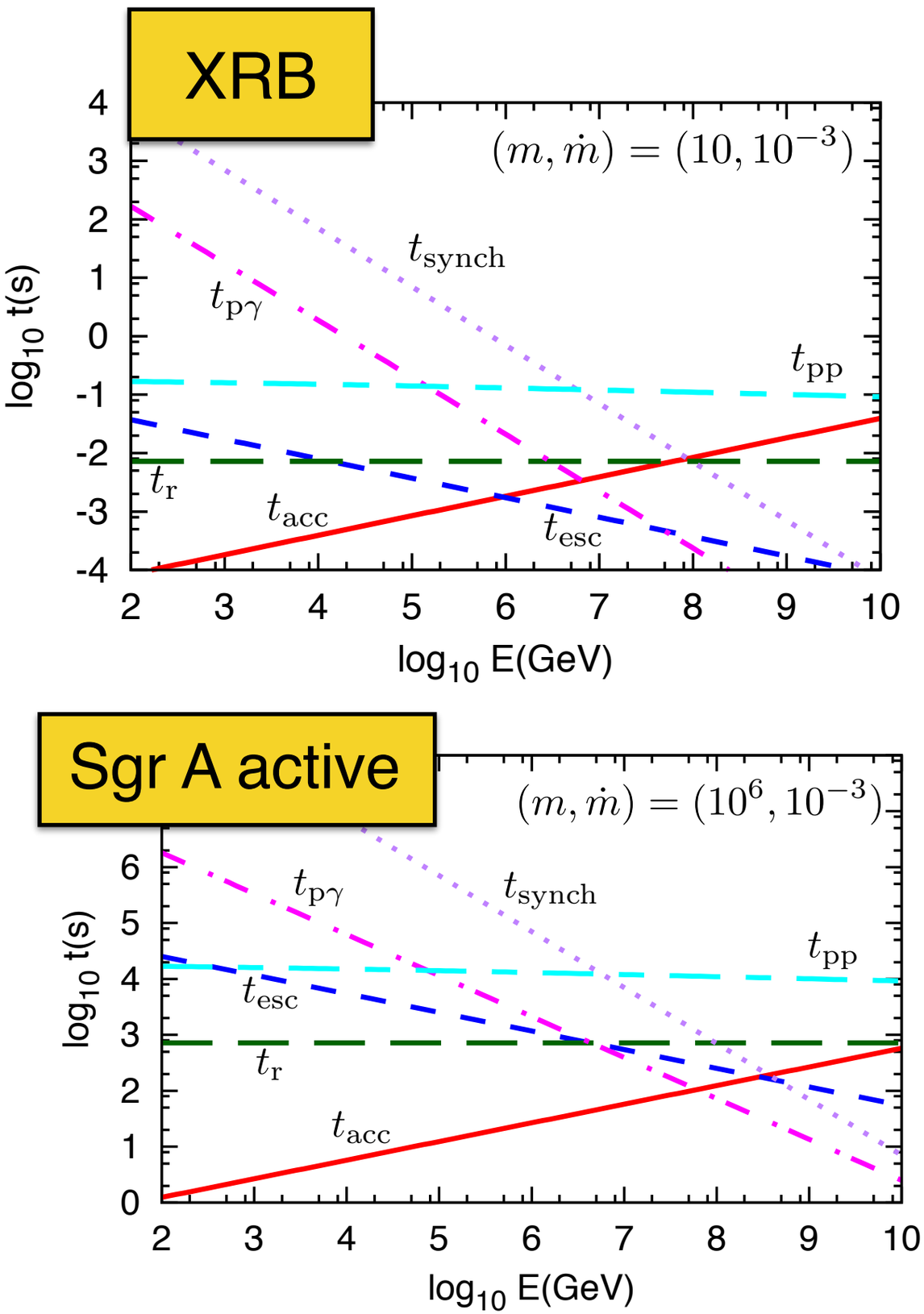
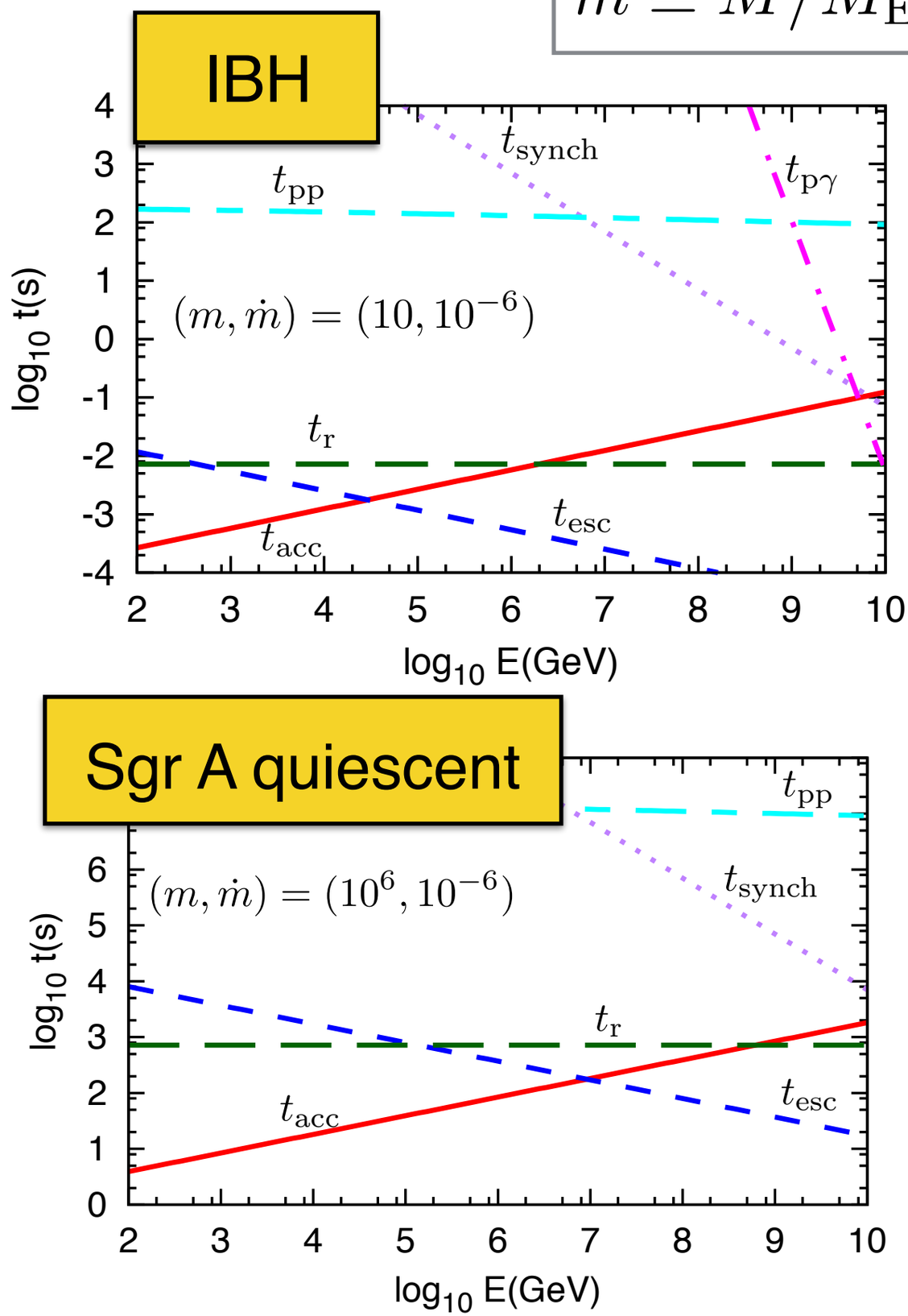
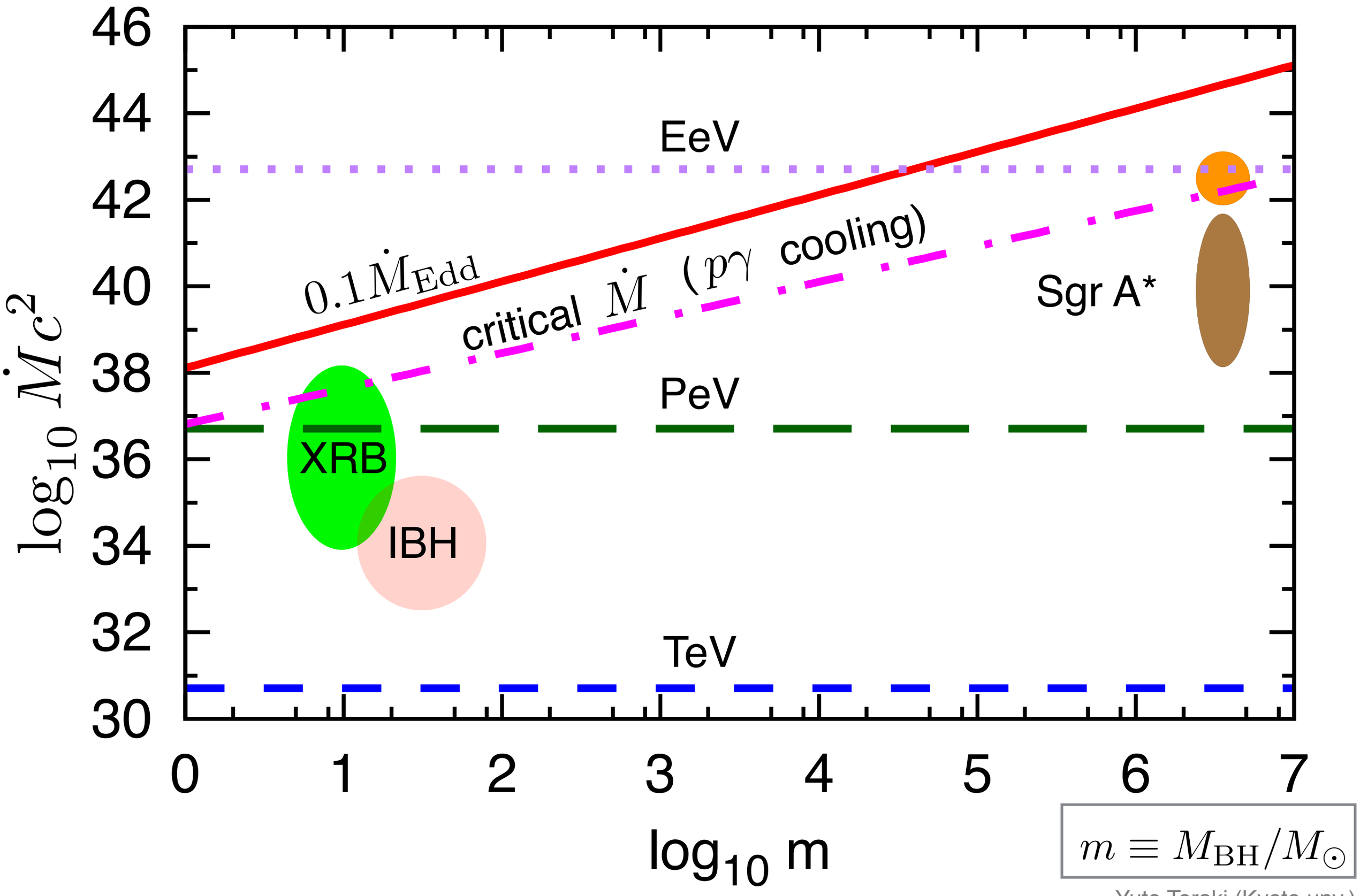
Examples of Time scales ADAF K41

$$m \equiv M_{\rm BH}/M_\odot$$
$$\dot{m} \equiv \dot{M}/\dot{M}_{\rm Edd}$$



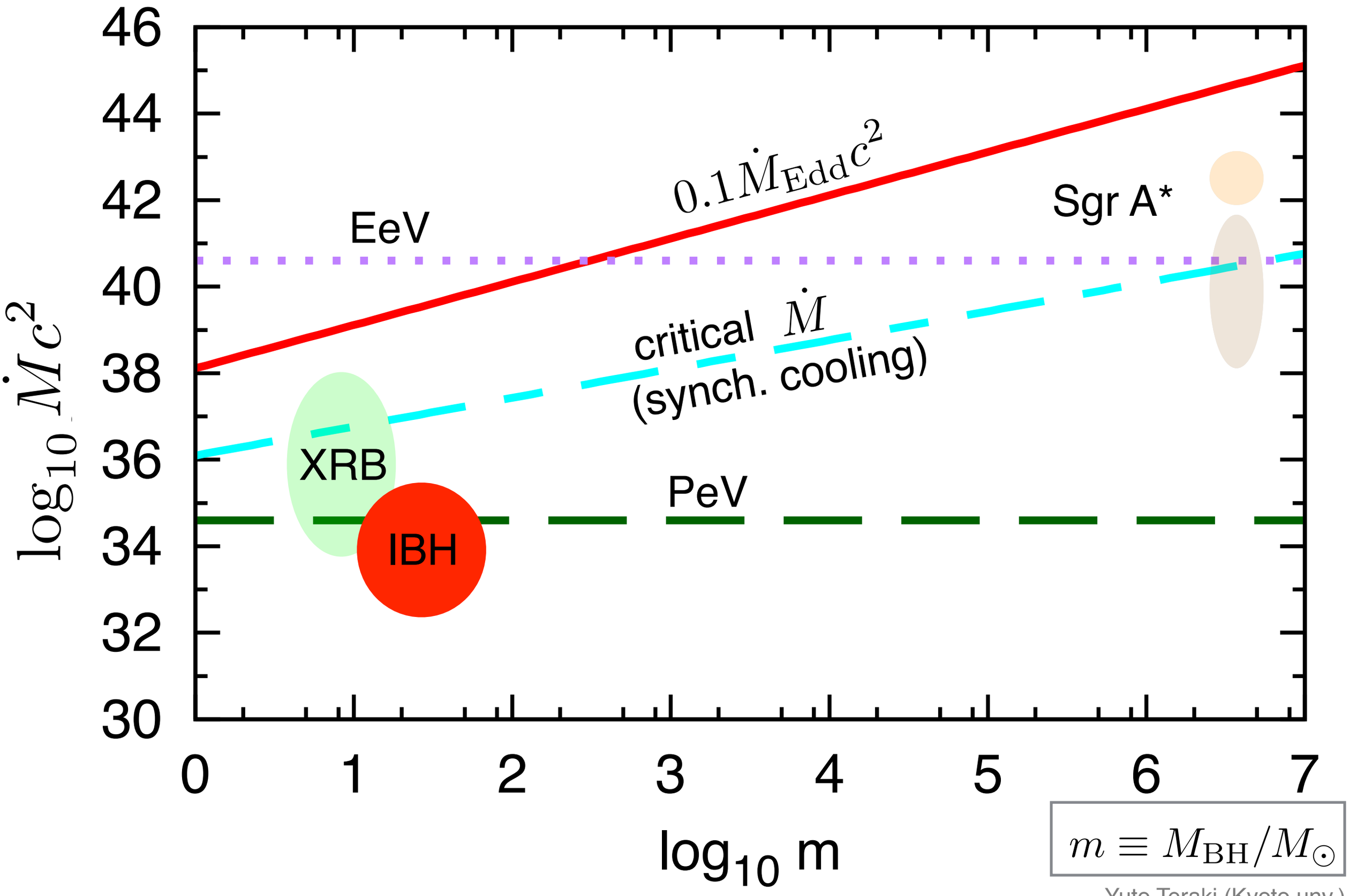


Maximum energy diagram for ADAF & K41 $P_B(k) \propto k^{-5/3}$



Maximum energy diagram for MAD & IK

$P_B(k) \propto k^{-3/2}$



Summary

Galactic BH accretion disks can supply the PeV cosmic rays

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Necessary conditions

$m \equiv M_{\rm BH}/M_\odot$
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IBHs : MAD for $E_{\rm CR} > {\rm PeV}$

XRBs : Fine tuned to $\dot{m} \sim 10^{-3}$ for $E_{\rm CR} > {\rm PeV}$

Sgr A* : $\dot{M}c^2 > 10^{39}{\rm erg/s}$ to fulfill the energetics

for more detail, see YT, Matsumoto & Ioka (in prep.)

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Thank you!

back up

Maximum energy

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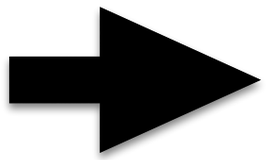
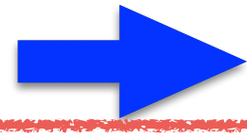
- Low accretion rate : $\dot{m} \lesssim 10^{-3}$



escape limit

$$\gamma_{\rm max,esc} \propto (m\dot{m})^{1/2} \propto \dot{M}^{1/2}$$

$\dot{M}$ ↗  $\gamma_{\rm max}$ ↗

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$\dot{M}$ ↗ ➡ $\gamma_{\rm max}$ ↗

- High accretion rate : $\dot{m} \gtrsim 10^{-3}$

➡ cooling limit

$$\gamma_{\rm max,cool} \propto \begin{cases} m^{\frac{1+\mu}{2+\mu-q}} \dot{M}^{\frac{2+6\mu+5q}{10(q-2-\mu)}} \\ m^{\frac{1}{3-q}} \dot{M}^{\frac{-q}{2(3-q)}} \end{cases}$$

$\dot{M}$ ↗ ➡ $\gamma_{\rm max}$ ↘

$p\gamma$ cooling ADAF

* μ : power law index of background photon spectrum

synch. cooling MAD

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→ escape limit

$\dot{M}$ ↗ → $\gamma_{\rm max}$ ↗

$$\gamma_{\rm max,esc} \propto (m\dot{m})^{1/2} \propto \dot{M}^{1/2}$$

↕

Critical mass accretion rate : $\dot{m} \sim 10^{-3}$

- High accretion rate : $\dot{m} \gtrsim 10^{-3}$

→ cooling limit

$\dot{M}$ ↗ → $\gamma_{\rm max}$ ↘

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$p\gamma$ cooling ADAF

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PeV gamma-rays from XRBs

$E_{\rm CR} > {\rm PeV}$

$\Updownarrow$

$\dot{m} \sim 10^{-3}$

&

conversion rate

$\epsilon_\gamma = 0.01$

$L_\gamma = \epsilon_\gamma \dot{M} c^2$

$L_\gamma \sim 10^{35} {\rm erg/s}$

$\Downarrow$

$5 \times 10^{33} {\rm erg/s}$

@ 10kpc

CTA design sensitivity

$3 \times 10^{-13} [{\rm TeV/cm^2/s}]$

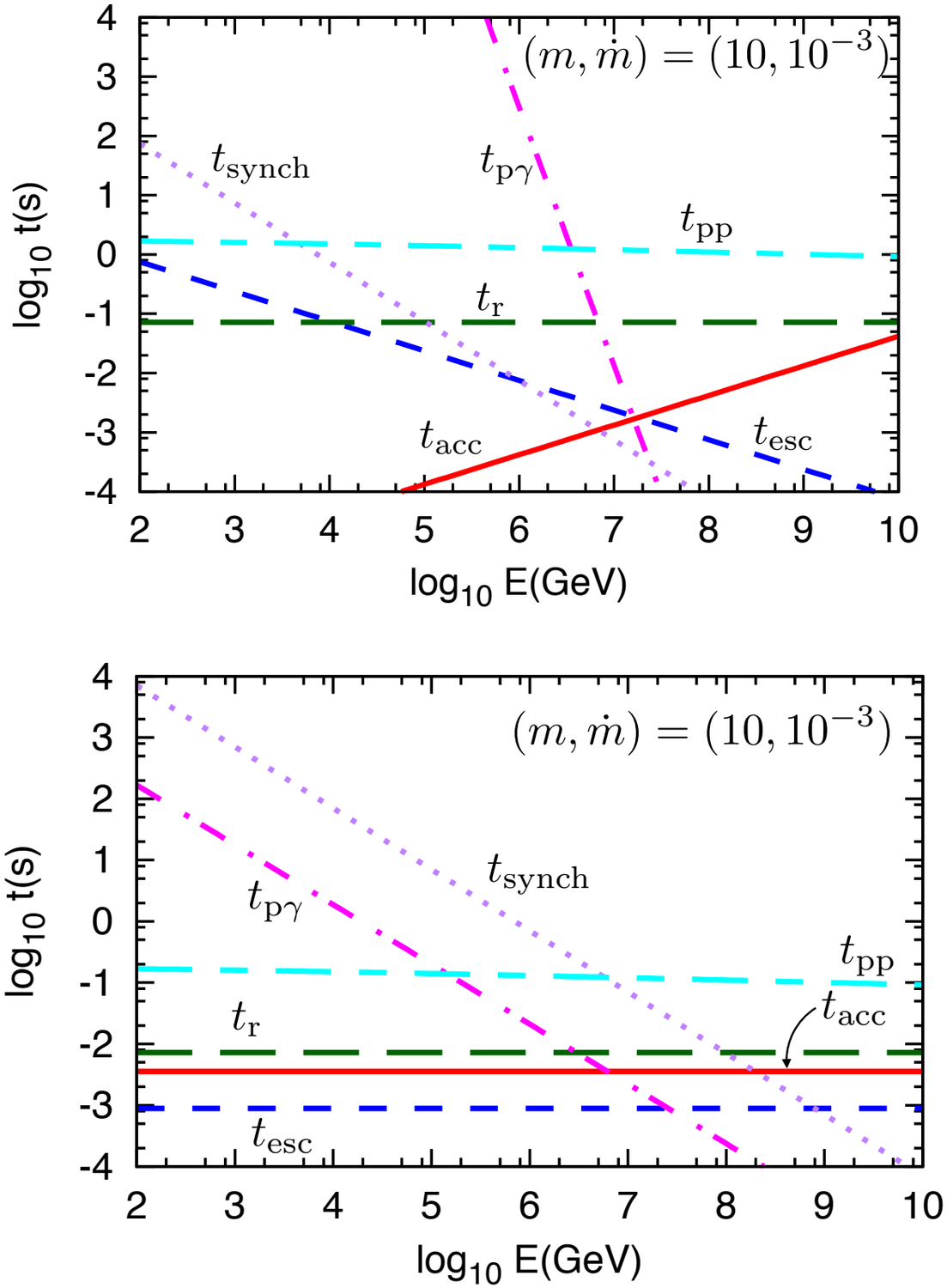
Detectable!

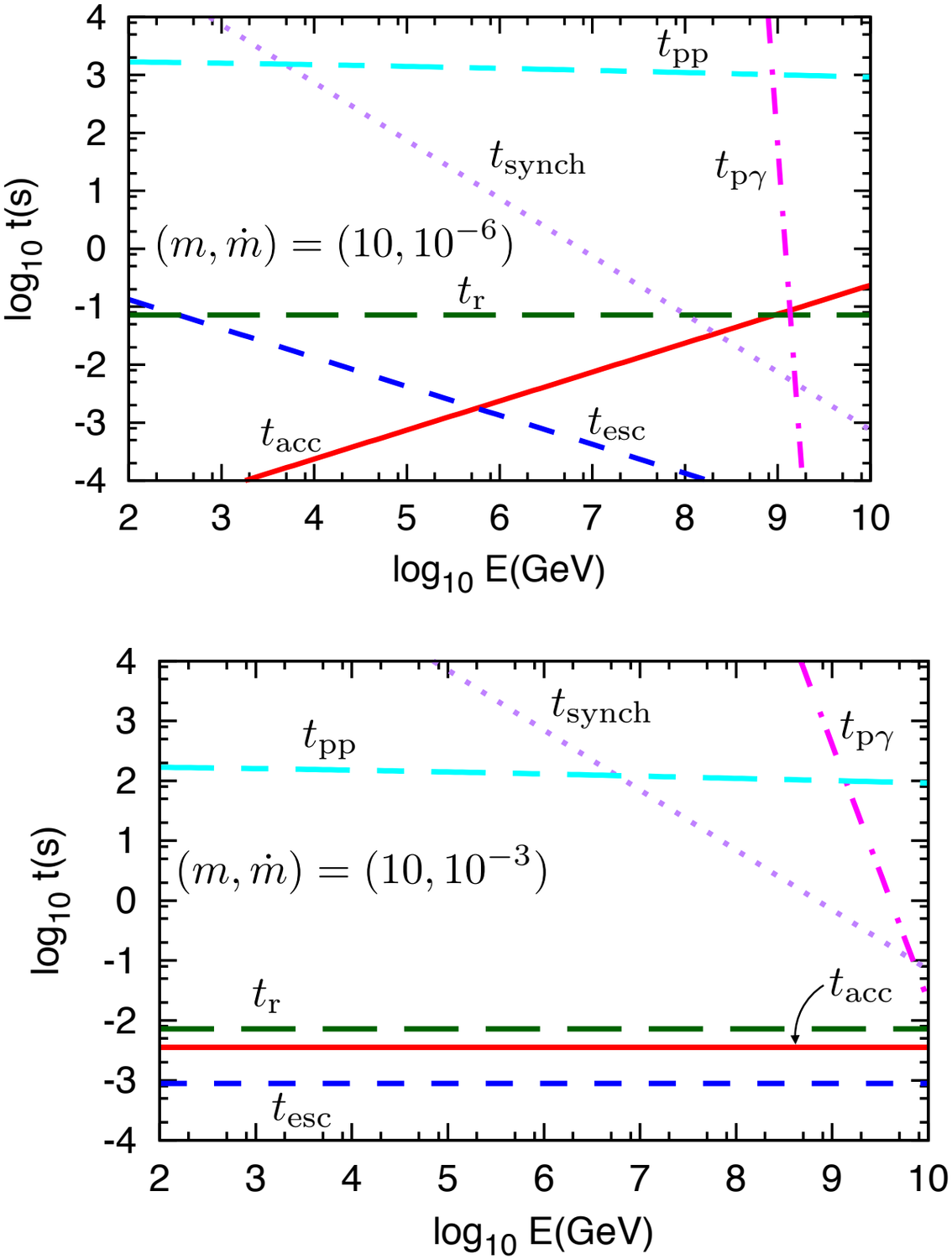
$\dot{m} \sim 10^{-3}$

If we see them in “weak” outburst state

Time scales

MAD IK (upper) HS (lower)



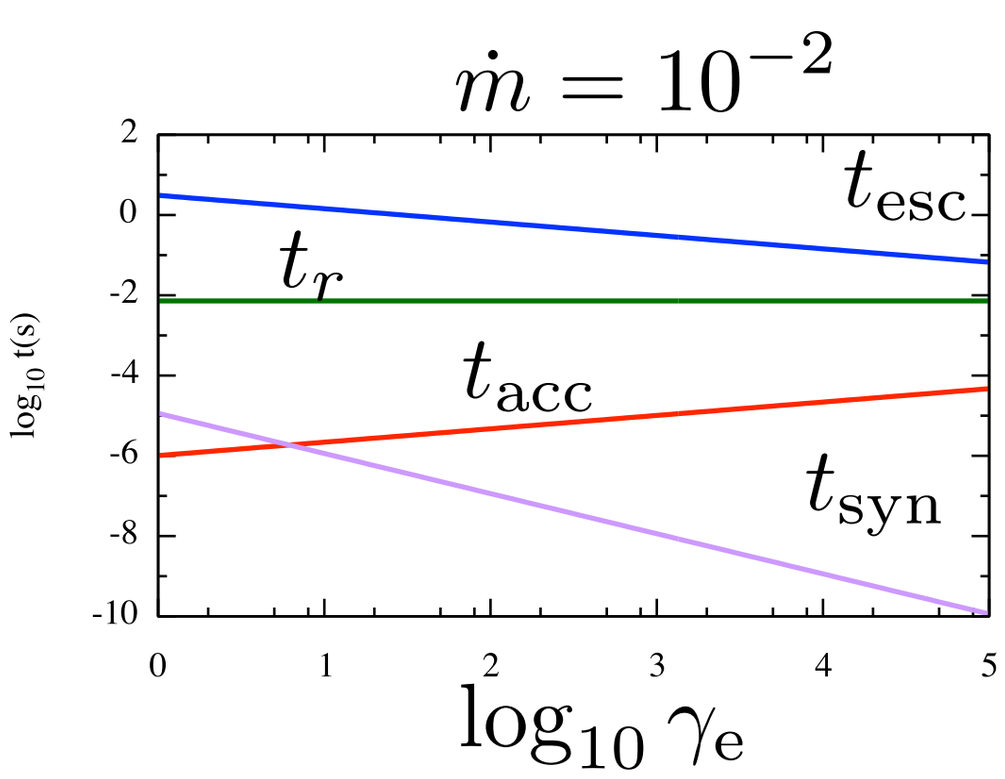


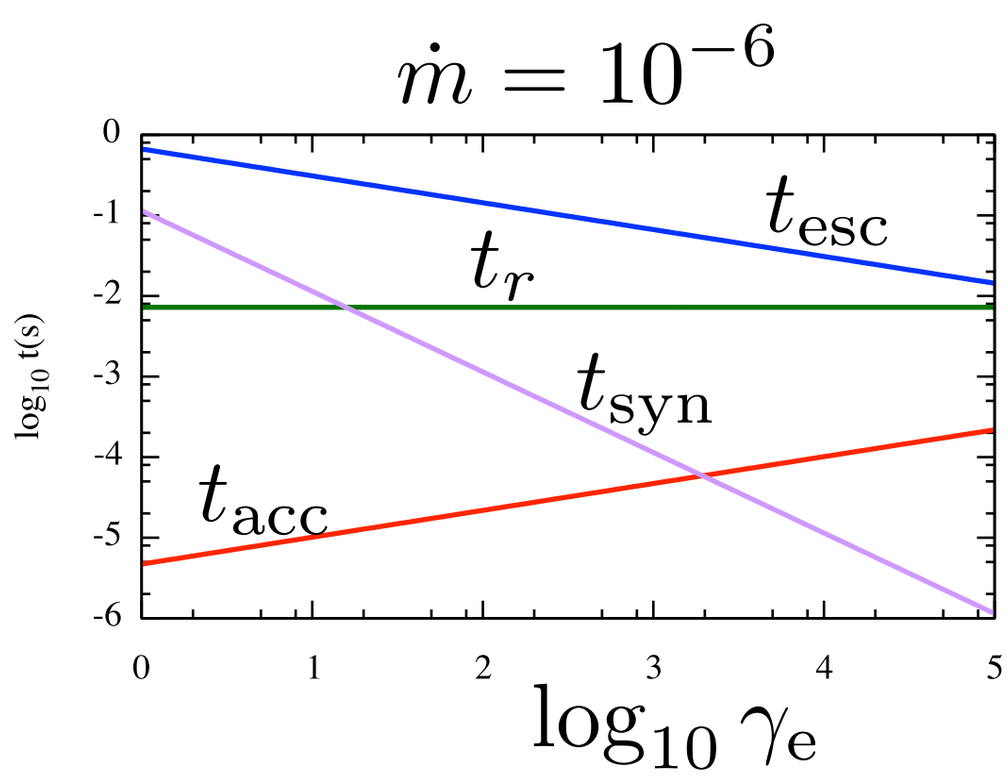
Electron acceleration

$$t_{\rm acc,iso} = p^2/D_{\rm pp} = \left(\frac{R}{c}\right)\left(\frac{v_{\rm ph}}{c}\right)^{-2}\xi\left(\frac{R_{\rm Ln}}{R}\right)^{2-q}\gamma^{2-q}\ [{\rm s}]$$

$$t_{\rm syn,e} = \frac{\gamma m_e c^2}{P_{\rm syn,e}} \qquad t_{\rm syn,e} = t_{\rm acc,iso}$$

for ADAF, K41 $m = 10$





Timescales

$$t_{\rm acc,iso} = p^2/D_{\rm pp} = \left(\frac{R}{c}\right)\left(\frac{v_{\rm ph}}{c}\right)^{-2}\xi\left(\frac{R_{\rm Ln}}{R}\right)^{2-q}\gamma^{2-q}\ [\rm s]$$

$$t_{\rm esc} = \frac{9R}{c}\xi^{-1}\left(\frac{R_{\rm Ln}}{R}\right)^{q-2}\gamma^{q-2}[\rm s]$$

Parameters

$$\frac{B_0^2}{\delta B} = 3$$

$$\frac{v_{\rm ph}}{c} = 1/2$$

@ISCO

Back ground photon spectrum

Mahadevan 1997

IC range $L_\nu \propto \nu^{-\kappa}$

$$\kappa \equiv \frac{-\ln \tau_{\rm es}}{\ln A}.$$

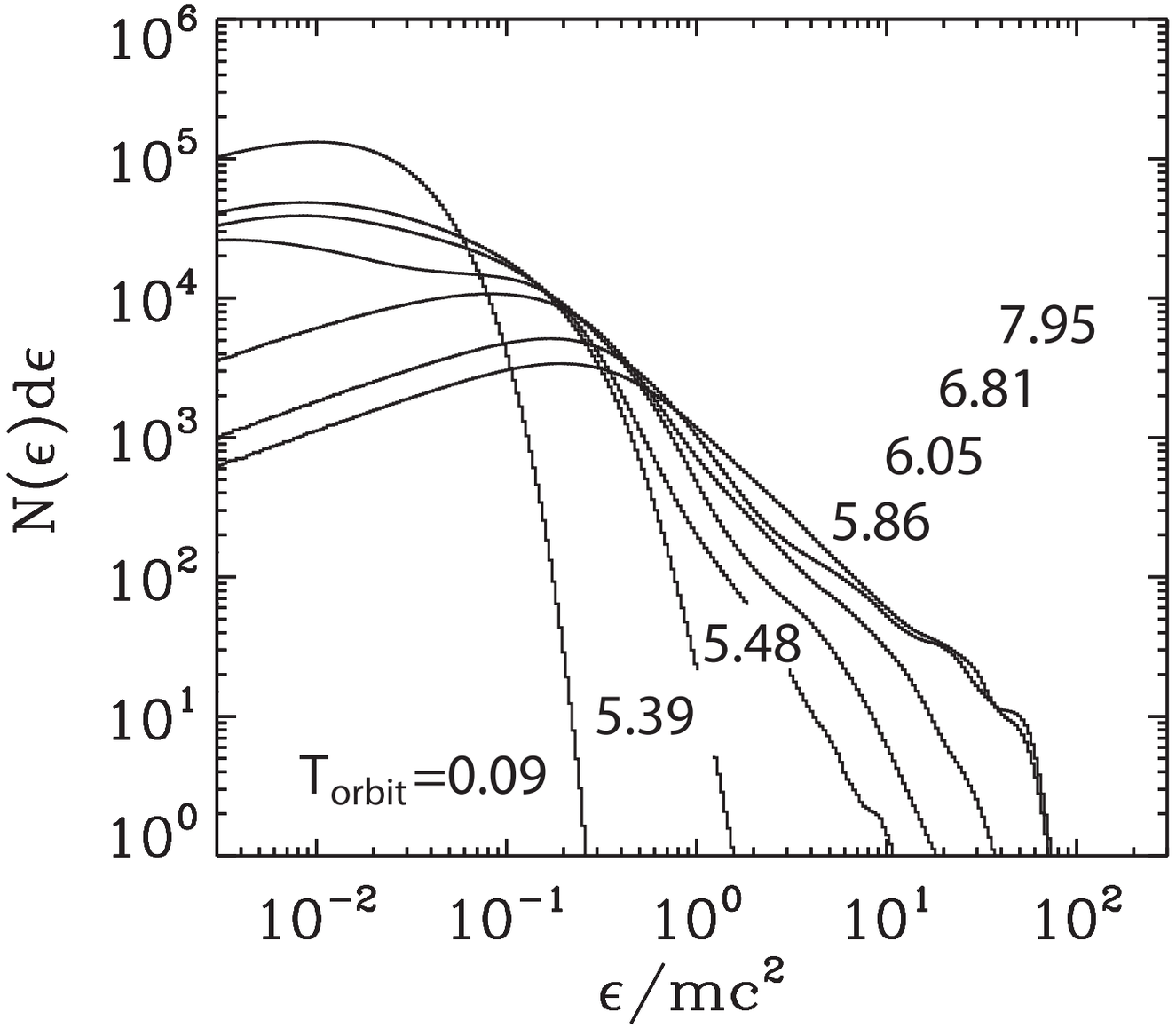
$$A = 1 + 4\theta_e + 16\theta_e^2$$

$$\theta_{\rm e} = kT_e/m_e c^2$$

$\tau_{\rm es}$: optical depth to electron scattering

Injection to acceleration cycle

Main process: magnetic reconnection



Hoshino 2012

$$\frac{dN}{dE} \propto E^{-1}$$

In the reconnection region, highest energy particles have large part of the energy

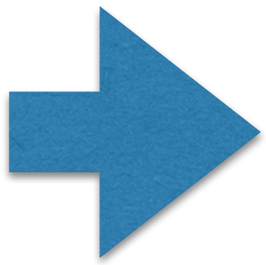
Wind feedback

Accreting matter can be blown away !

$$\epsilon_{\rm w} \dot{M}_{\rm BH} c^2 > \dot{M}_{\rm out} V^2$$

$\epsilon_{\rm w} \gtrsim 10^{-3}$: energy conversion rate to wind

e.g. Yuan et al. 2015



Duty cycle?