High-energy gamma-rays from isolated stellar-mass black hole magnetosphere

(see also Kin et al. accepted in ApJ, arXiv:2310.12532)

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CTA conference

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TOHOKU UNIVERSITY

Theoretical Astrophysics
Tohoku University

◎Take home massage:

Galactic isolated stellar-mass BHs can be GeV-TeV target!

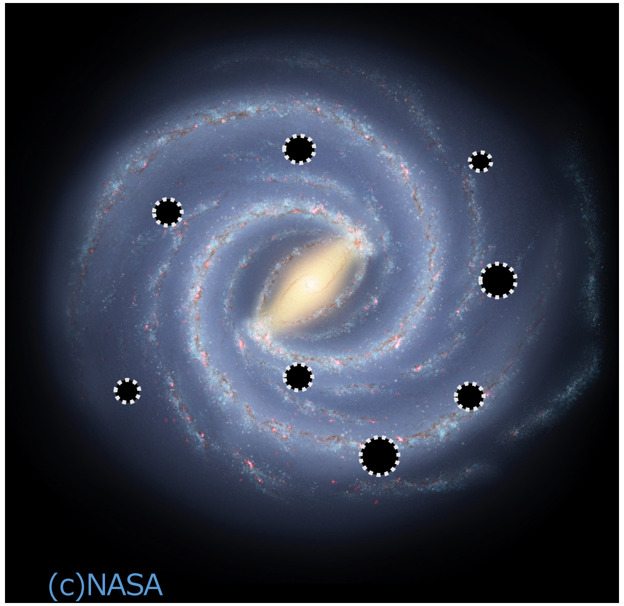
Introduction:
Isolated stellar-mass Black Holes in our Galaxy

◎ $\sim 10^{7-8}$ undetected IBHs in our Galaxy
(e.g. Sartore & Treves 10; Caputo et al. 17; Abrams & Takada 20)

→ possible interactions w/ Galactic gas clouds

implication:

- massive star evolution
- upper limit on primordial BHs formation rate
- Galactic PeVatron? (c.f. Ioka et al.17)



Question:

Can we detect signals from gas-accreting IBH?

・accretion disk (Agol & Kamionkowski 02; Tsuna et al. 18; Kimura et al. 21)

・jet/disk outflow (Ioka et al. 17; Tsuna & Kawanaka 19)

・**magnetosphere ← this research**

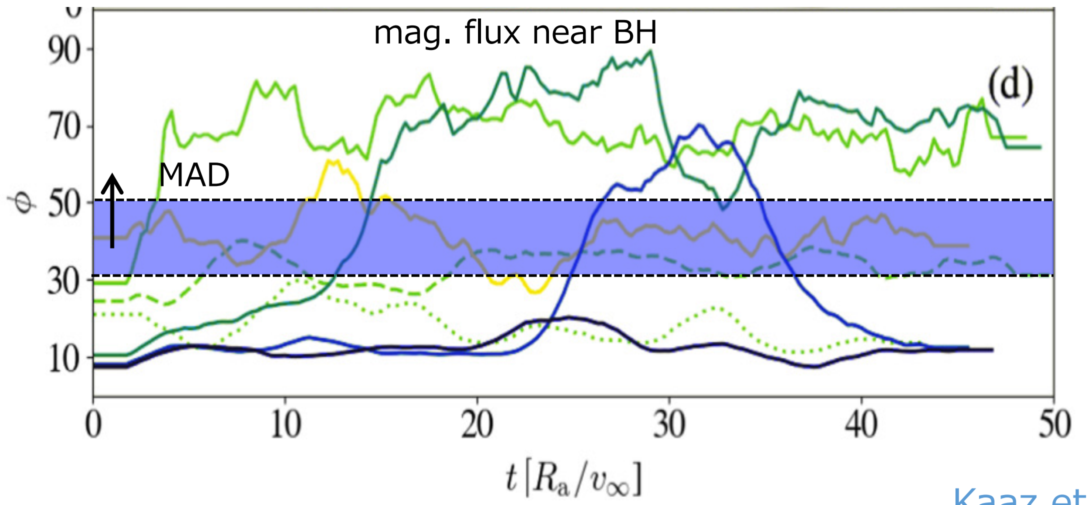
Introduction: IBH magnetosphere?

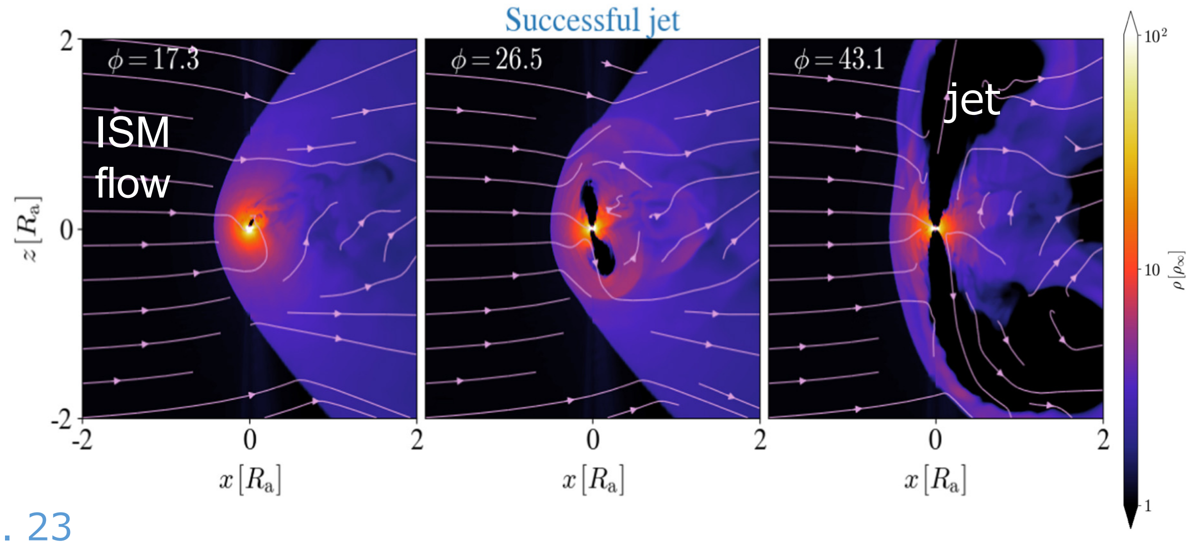
◎Highly-magnetized disk (MAD) around IBH (Ioka et al.17; Kimura et al. 21; Kaaz et al. 23)

magnetic flux accumulate during gas accretion

→ B-field strong enough to become MAD state

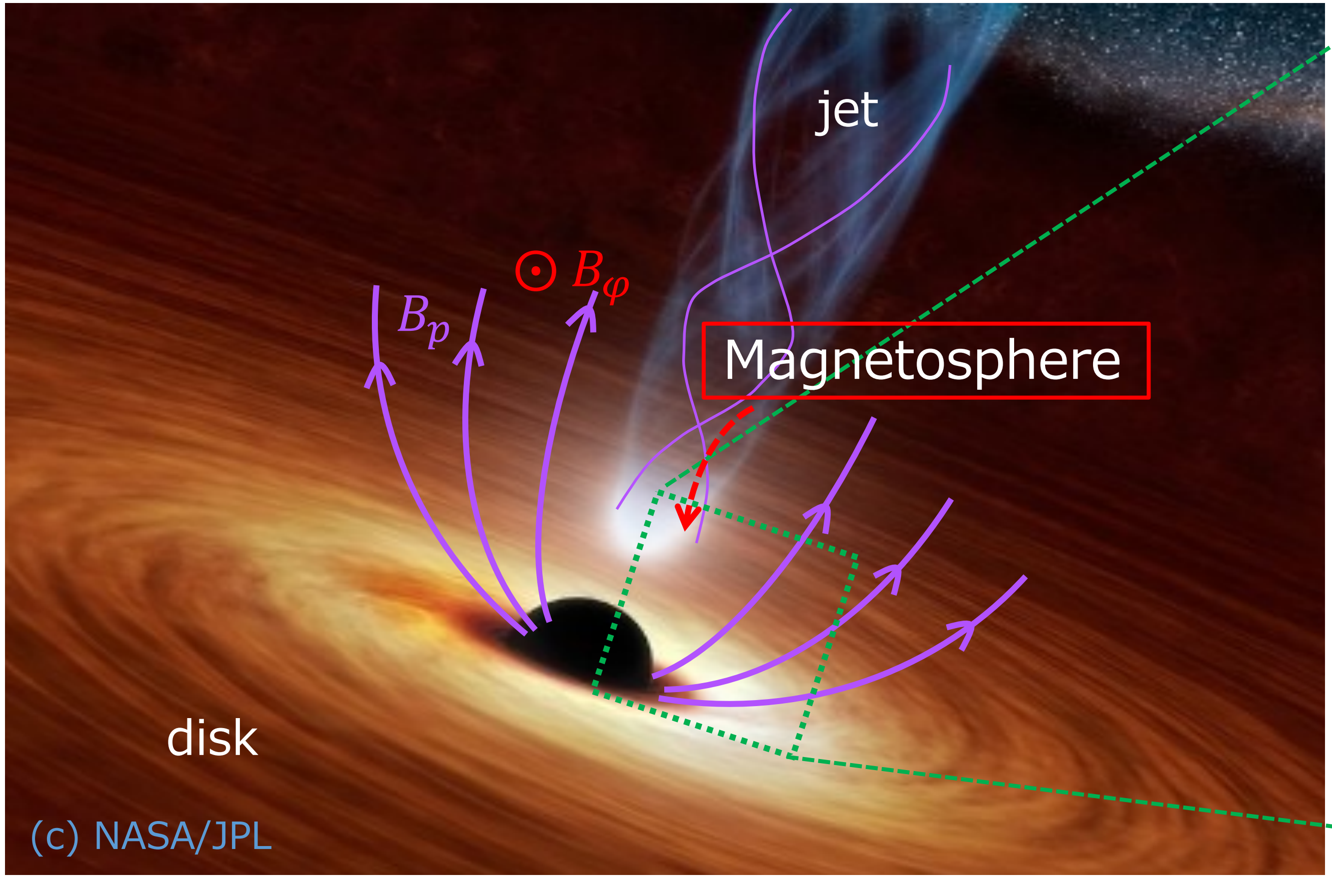
magnetospheres expected to be formed inside / launch jet

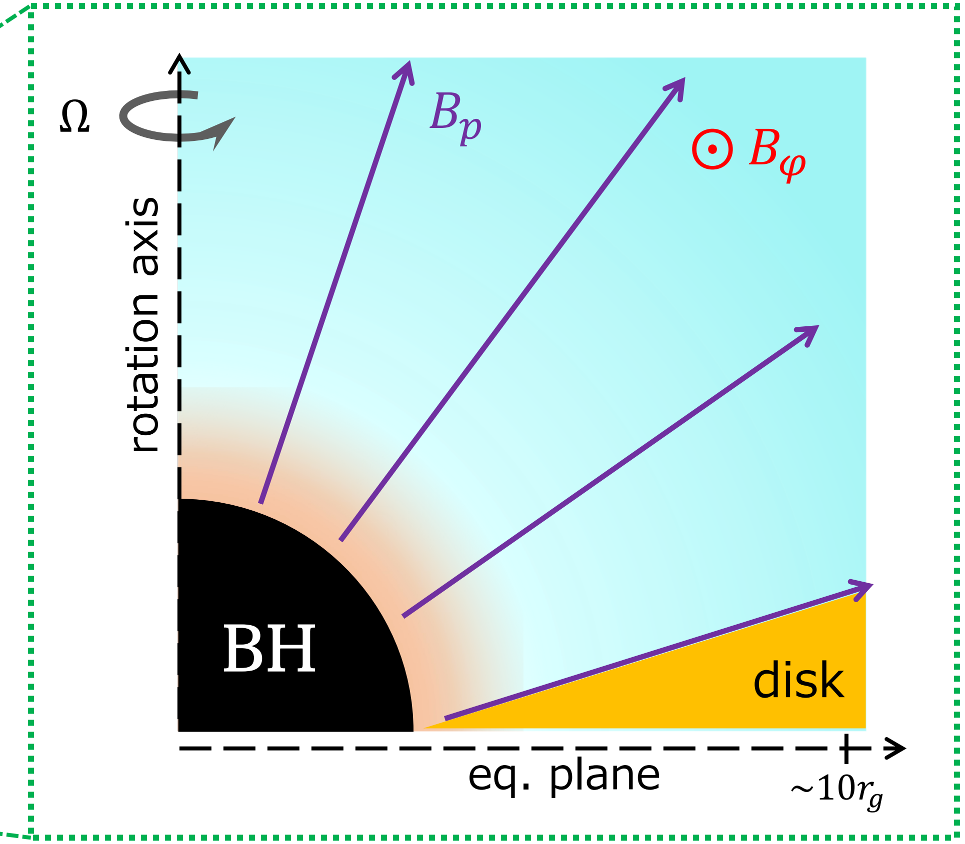




Kaaz et al. 23

Introduction: Particle acceleration in BH magnetosphere



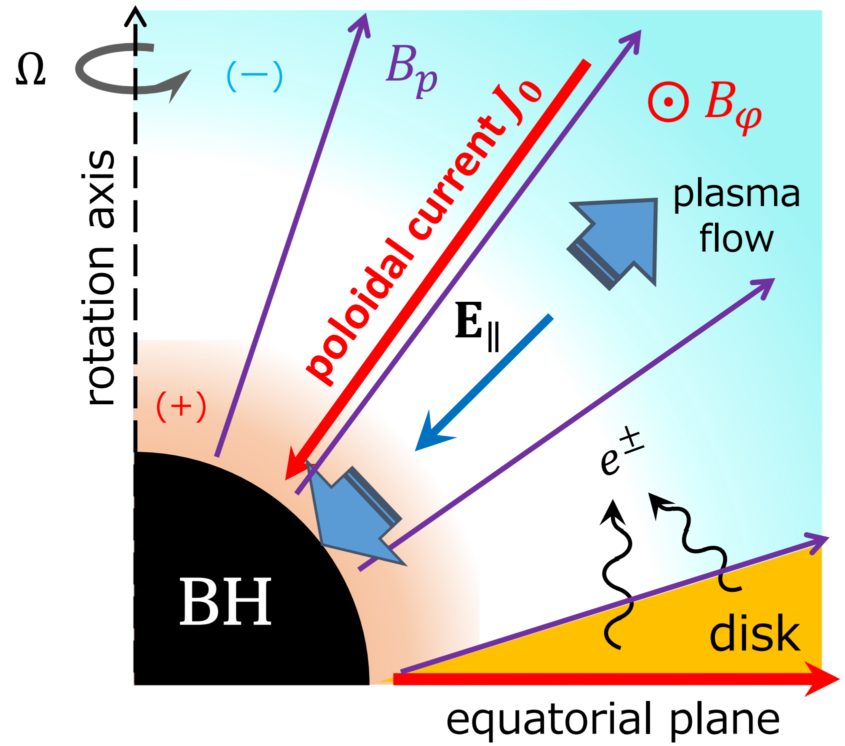


Introduction: Particle acceleration in BH magnetosphere

◎(expected) plasma source:
annihilation of two disk photons $\gamma + \gamma \rightarrow e^+ + e^-$

◎ ρ_e too low to maintain J_0 & screen $\boldsymbol{E}_\parallel$ for low $\dot{M}$
(Levinson & Rieger 11)

→ time-dependent particle acceleration
GeV-TeV gamma-rays?
(e.g.; Chen et al. 20; Kisaka et al. 20, 22; Crinquand et al. 20, 21)



Motivation:
Can we detect IBH magnetospheric gamma-rays?
→ numerical approach for acceleration dynamics & radiation feature

Methods: Numerical simulation of stellar-mass BH magnetosphere

Numerical simulation of stellar-mass BH magnetosphere

◎**1D general-relativistic PIC** code (based on **Zeltron**, Levinson & Cerutti18; Kisaka et al.20;22)

Particle-in-Cell

- background Kerr metric, monopole B-field

$$\frac{du_\pm}{dt} = -\sqrt{g_{rr}}\gamma_\pm \partial_r(\alpha) + \alpha\left(\frac{q_\pm}{m_e}E_r - \frac{P}{m_e v_\pm}\right)$$: $e^\pm$ EoM along B-field

gravity (inertia term) — acceleration — back reaction of gamma-ray radiation

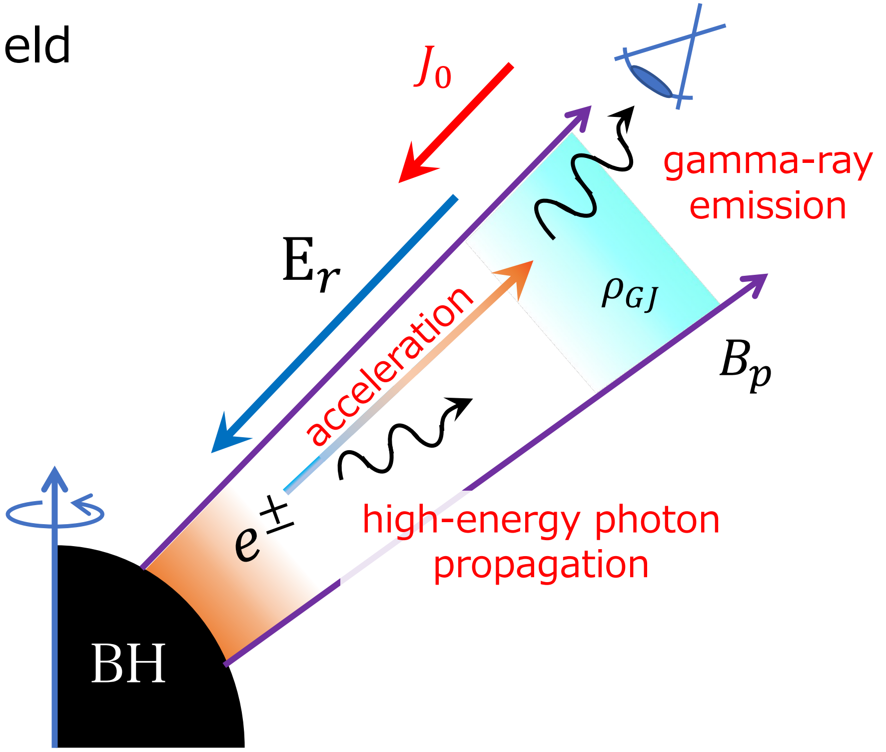
$$\frac{dp^r}{dt} = -\sqrt{g^{rr}}p^t\partial_r(\alpha)$$: high-energy photon propagation

↓current density

$$\partial_t(\sqrt{A}E_r) = -4\pi(\Sigma j^r - J_0)$$: Ampere's law

$$\partial_r(\sqrt{A}E_r) = 4\pi\Sigma(j^t - \rho_{GJ})$$: Gauss' law

↑charge density



Numerical simulation of stellar-mass BH magnetosphere

◎**1D general-relativistic PIC** code (based on **Zeltron**, Levinson & Cerutti18; Kisaka et al.20;22)

- reaction: IC, pair creation ($\gamma + \gamma \rightarrow e^+ + e^-$)
  Monte-Carlo approach to calculate each reactions

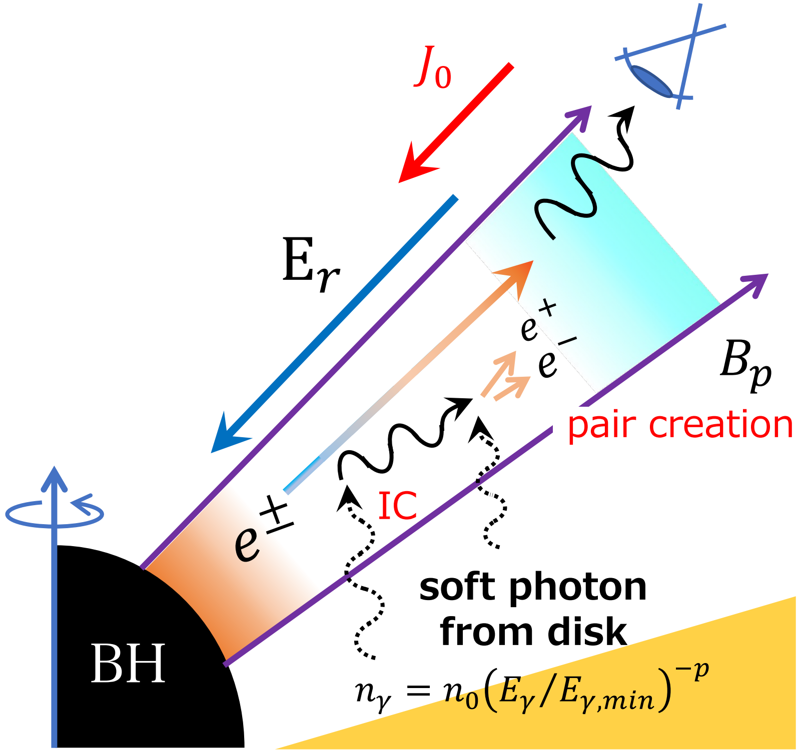
- parameters:

$M = 10M_\odot$, $a_* = 0.9$, $B_H = 2\pi\times10^7\mathrm{G}$, $\theta = 30°$

$\boldsymbol{\tau_0 = n_{\gamma,disk}\sigma_T r_g = \{30, 55, 100, 175, 300\}}$

$\boldsymbol{|j_0| \equiv |J_0/J_{0,BZ}| = \{1/2\, , 1/2\pi\}}$

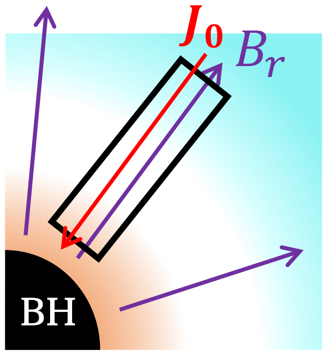
lower than steady state (BZ) solution
(c.f. Blandford & Znajek 77; Komissarov 04)

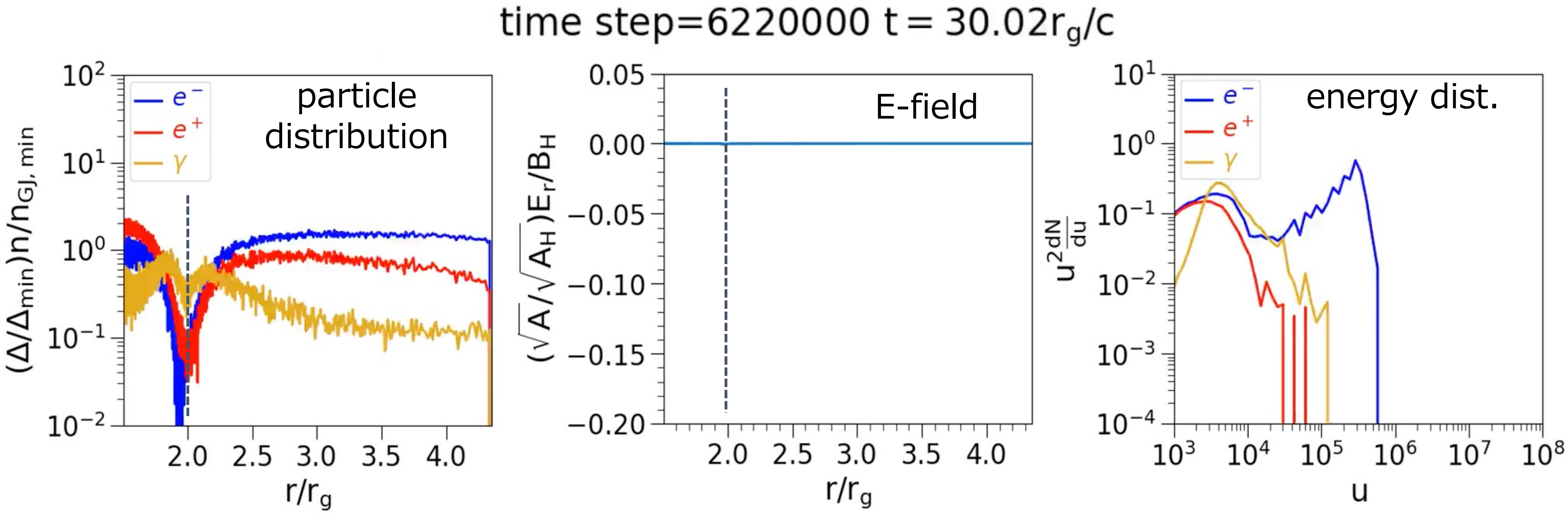


Numerical simulation of stellar-mass BH magnetosphere

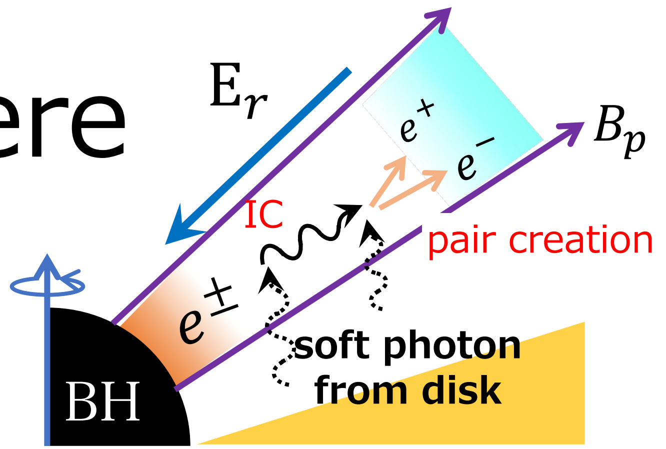
◎Results:

- quasi-periodic/steady E_r (period: $\lesssim 10\, r_g/c \sim 10^{-4} M_1\ s$)
- $\gamma_{e^-,pk} \sim 10^7 \rightarrow$ GeV-TeV gamma-rays (via curvature process, IC)





Numerical simulation of stellar-mass BH magnetosphere

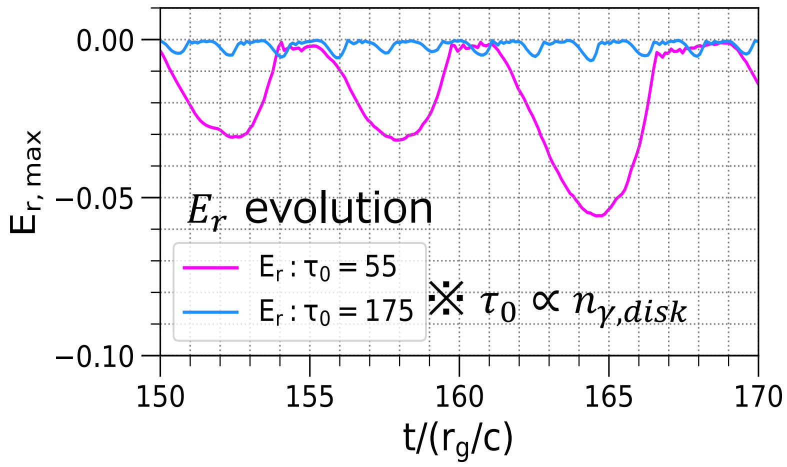


◎Results:

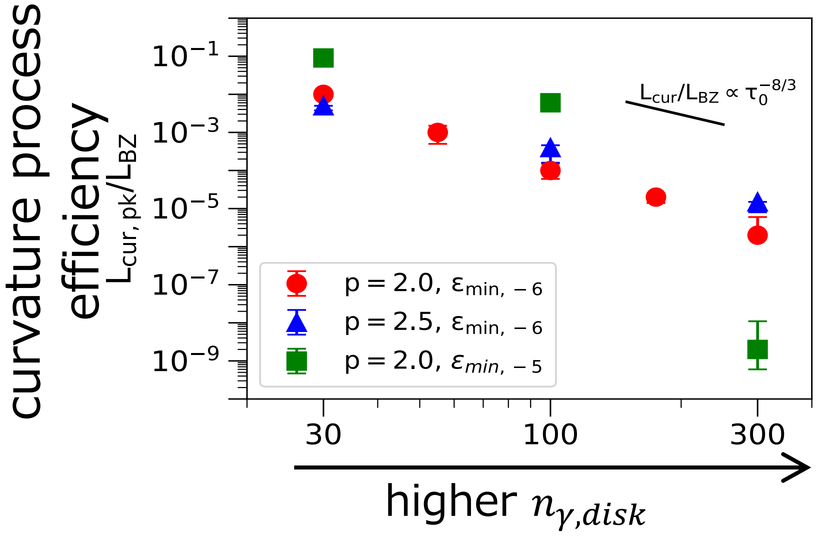
- higher $n_{\gamma,disk}$ ↔ weaker E_r

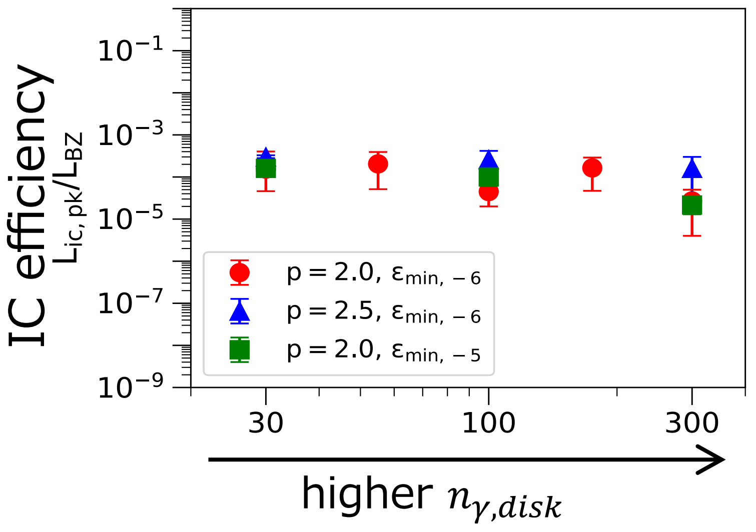
→ $L_{cur}/L_{BZ} \propto {\gamma_e}^4 n_{plasma}$ lower : $L_{cur,pk}/L_{BZ} \sim 10^{-2}(\tau_0/30)^{-\alpha}$ ($\alpha \sim 8/3$ for $p = 2.0, E_{\gamma,min} = 10^{-6} m_e c^2$)

$L_{IC}/L_{BZ} \propto n_{plasma}$ almost const.



※ $\tau_0 \propto n_{\gamma,disk}$





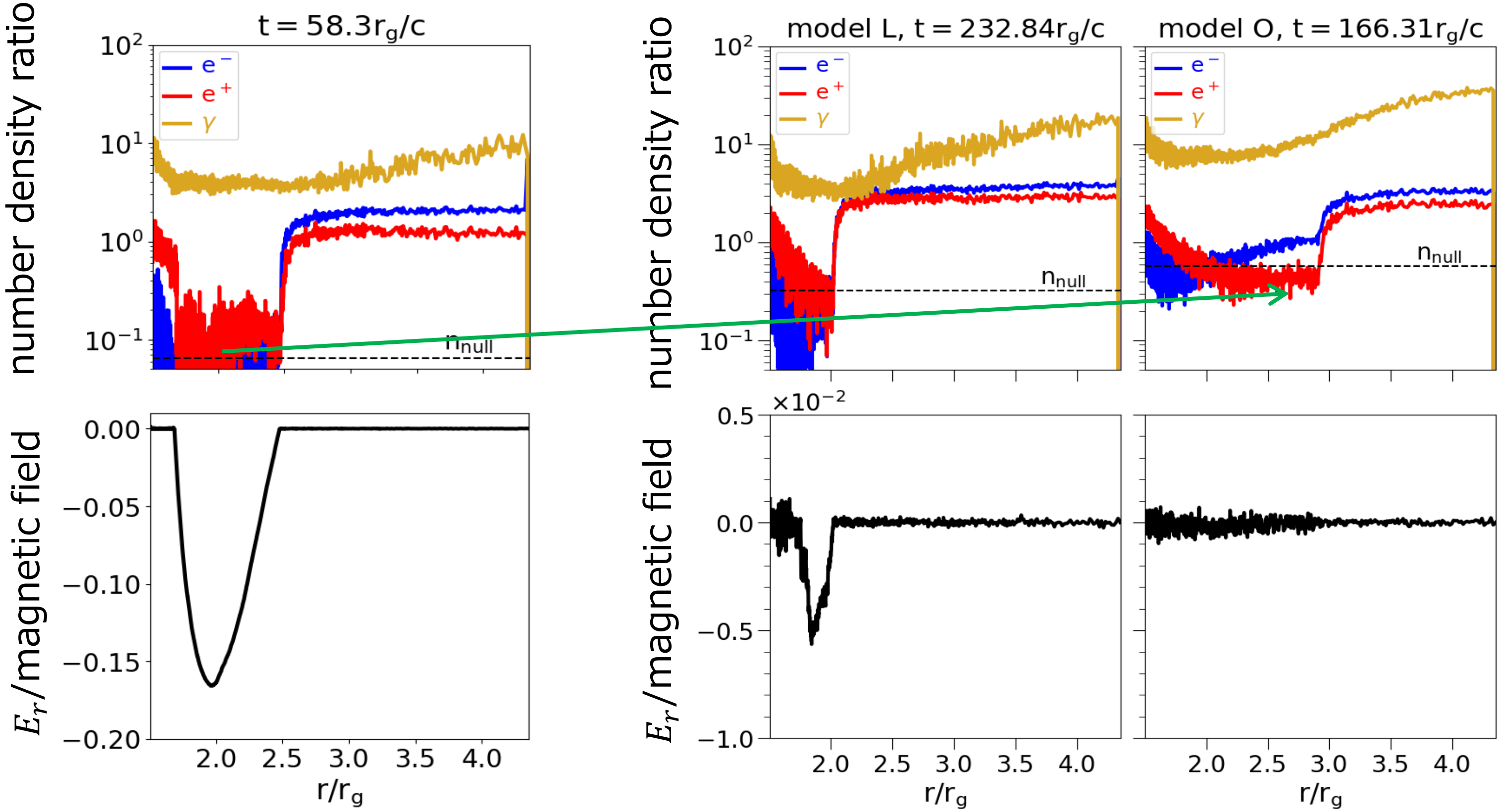
Numerical simulation of stellar-mass BH magnetosphere

◎Results:

- higher J_0 ↔ higher amount of plasma, weaker E_r

$$\partial_t\left(\sqrt{A}E_r\right) = -4\pi(\Sigma j^r - \boldsymbol{J_0})$$
$$\partial_r\left(\sqrt{A}E_r\right) = 4\pi\Sigma(j^t - \rho_{GJ})$$

※$|\boldsymbol{j_0}| = |\boldsymbol{J_0}/\boldsymbol{J_{0,BZ}}|$

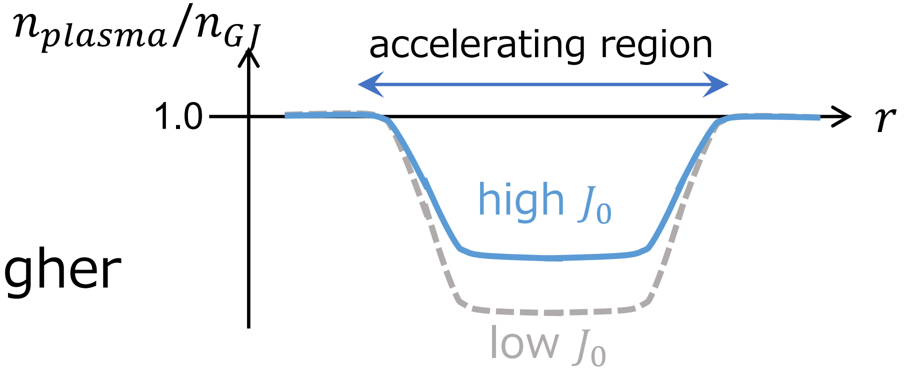


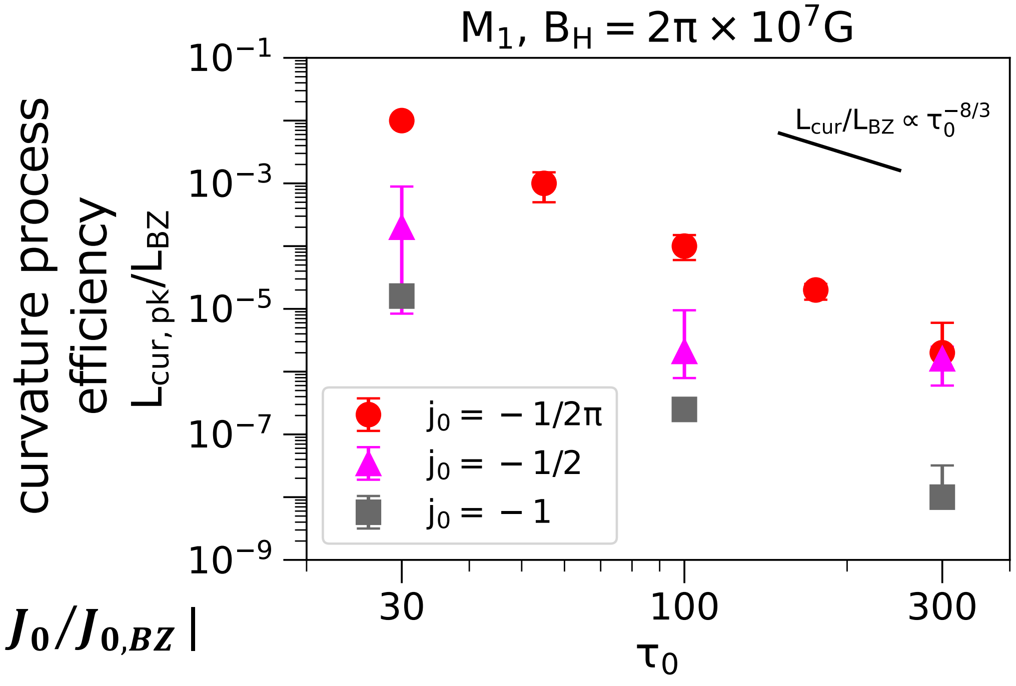
$|j_0| = 1/2\pi$ $|j_0| = 1/2$ $|j_0| = 1$

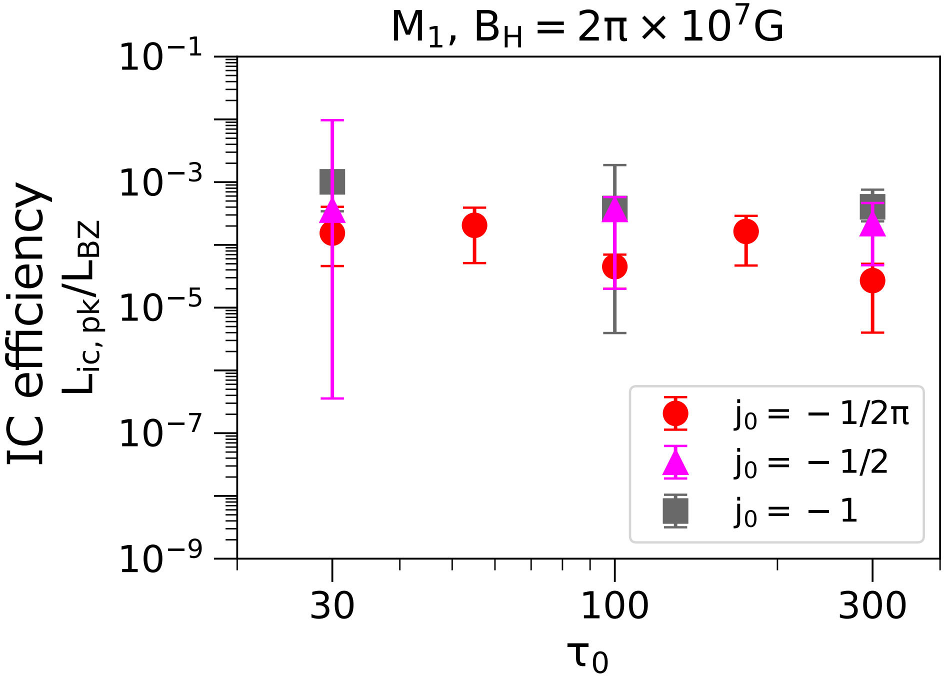
Numerical simulation of stellar-mass BH magnetosphere

◎Results:

- higher J_0 ↔ higher amount of plasma, weaker E_r
  → $L_{cur}/L_{BZ} \propto {\gamma_e}^4 n_{plasma}$ lower, but $L_{IC}/L_{BZ} \propto n_{plasma}$ higher







※$|\boldsymbol{j_0}| = |\boldsymbol{J_0/J_{0,BZ}}|$

Discussions on detectability

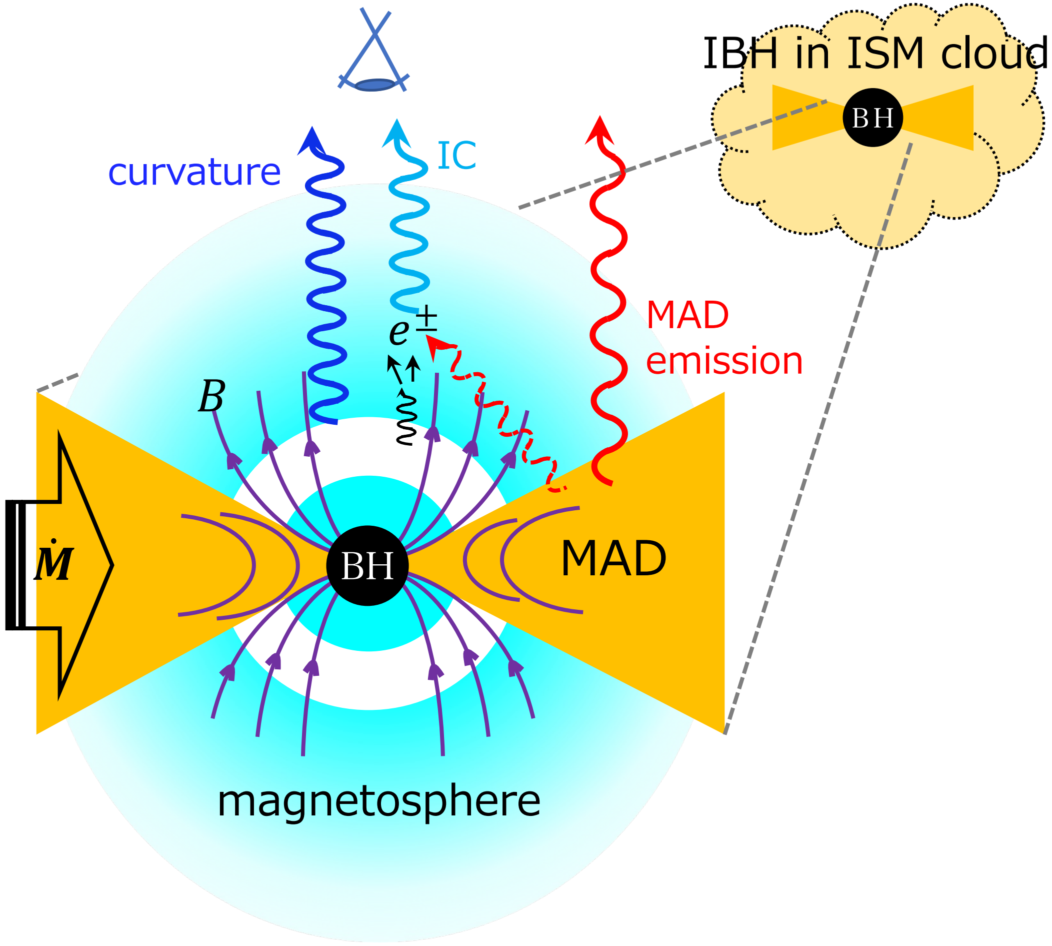
Expected emitting region

◎ two zones of emitting region:

- **Magnetospheric gamma-rays**:
  - curvature emission from accelerated plasma
  - IC emission from 2nd gen. of pairs

➡ **semi-analytic model based on simulations**

- MAD broadband emission (c.f. Kimura et al. 21):
  - synchrotron from thermal e^- (IR~UV)
  - 〃 from non-thermal e^- (X-ray~MeV)



Magnetospheric gamma-ray semi-analytic model

◎predicting gamma-ray emissivity **for wider range of BH mass , ISM density**

$\dot{M}(M_{BH}, n_{ISM})$ mass accretion rate → one-zone MAD model (Kimura et al. 21) → [semi-analytic model: input parameters: $n_{\gamma,disk}$ $E_{\gamma,min}$ B_H → solve EoM, reaction photon transfer → E_r amplitude $\gamma_{e,max}$ $L_{cur,pk}$ $L_{ic,pk}$]

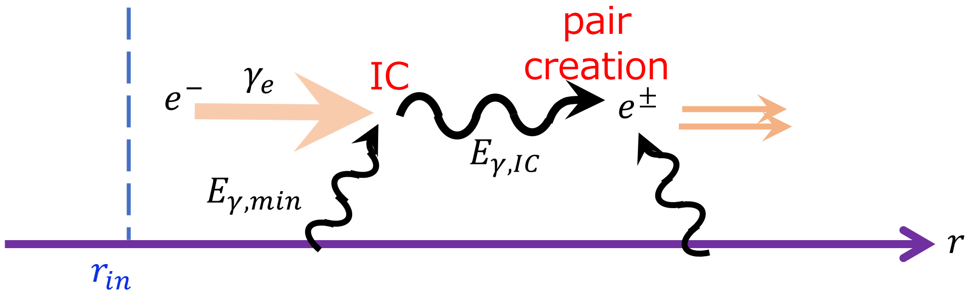
↑ disk photon peak energy (for $E_{\gamma,min}$)

<basic eqs.>

electron EoM from inner boundary r_{in}:

$$E_r = E_r(B_H, r),\ E_r(r_{in}) = 0$$

$$\frac{d\gamma_e}{dr} \sim \frac{1}{m_e c^2}\left(-eE_r - \frac{P_{cur}}{c} - \frac{P_{IC}}{c}\right)\ (\because cdt \sim dr)$$



IC, pair annihilation mean free path・energy:

$$l_{IC} \sim \frac{1}{n_{\gamma,disk}\sigma_{IC}} \sim \frac{r_g}{\tau_0} \times \begin{cases} 1 \\ \left(\frac{\gamma_e E_{\gamma,min}}{m_e c^2}\right) \end{cases},\quad E_{\gamma,IC} \sim \begin{cases} \gamma_e^2 E_{\gamma,min} & \text{Thomson} \\ \gamma_e m_e c^2 & \text{KN} \end{cases}$$

$$l_{\gamma\gamma} \sim \frac{1}{n_{\gamma,disk}\sigma_{\gamma\gamma}} \sim 10\frac{r_g}{\tau_0} \times \left(\frac{E_{\gamma,IC}E_{\gamma,min}}{(m_e c^2)^2}\right)$$

Magnetospheric gamma-ray semi-analytic model

◎predicting gamma-ray emissivity **for wider range of BH mass , ISM density**

$\dot{M}(M_{BH}, n_{ISM})$
mass accretion rate

➡

one-zone MAD model
(Kimura et al. 21)

➡

semi-analytic model:

input parameters:
$n_{\gamma,disk}$ $E_{\gamma,min}$ B_H
↑ disk photon peak energy

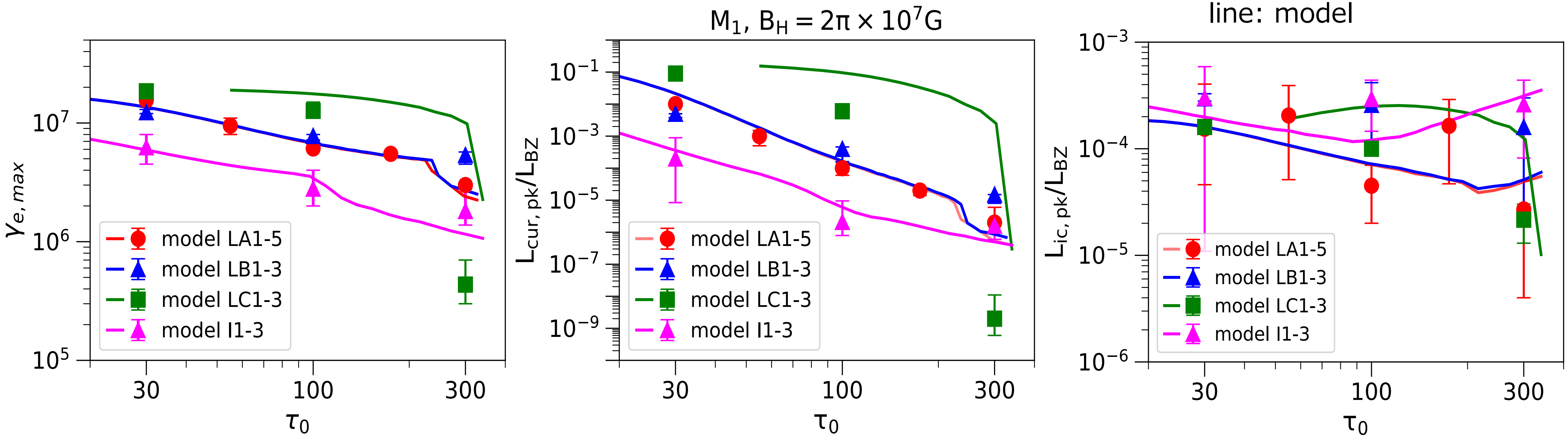
➡

solve EoM, reaction photon transfer

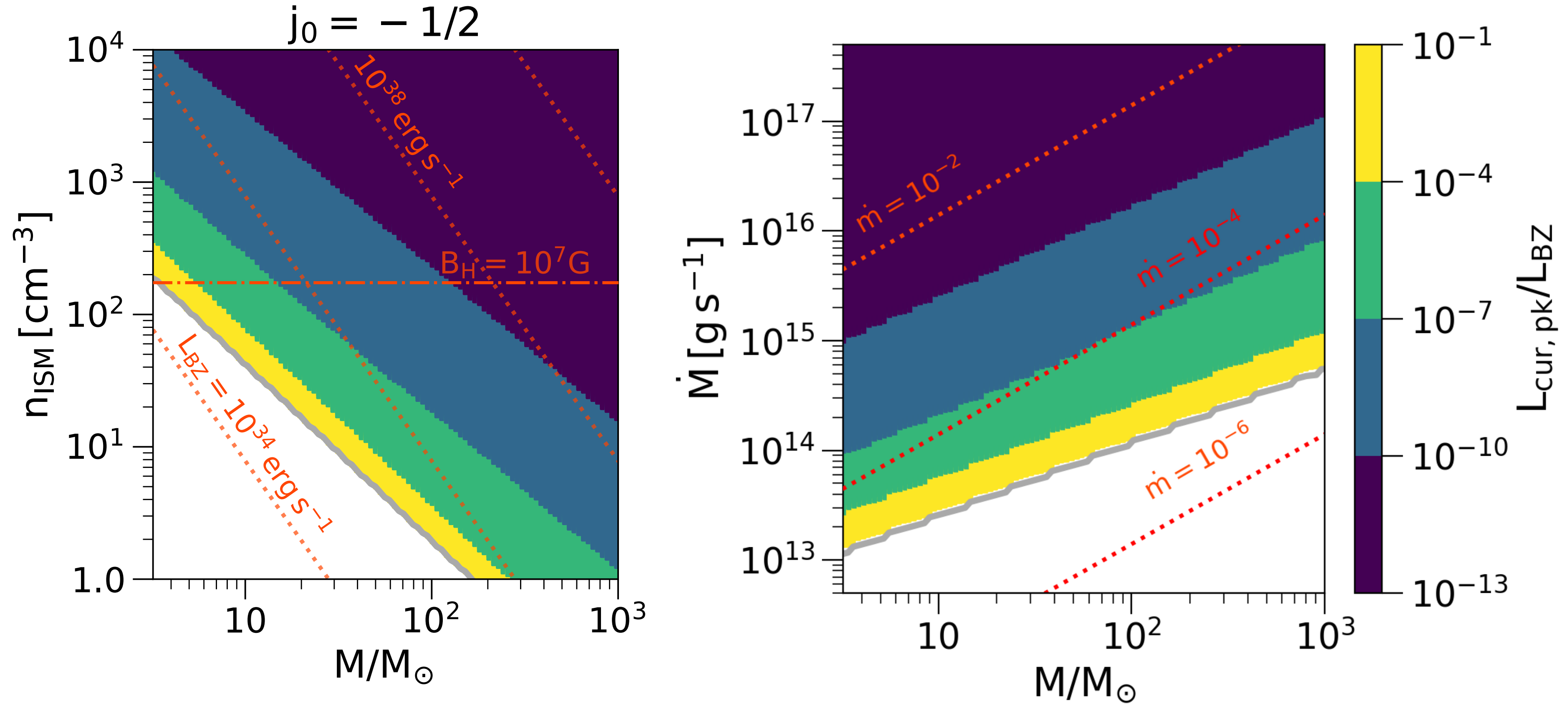
➡

E_r amplitude
$\gamma_{e,max}$ $L_{cur,pk}$ $L_{ic,pk}$

dot: simulation result
line: model



Application of Semi-analytic Model

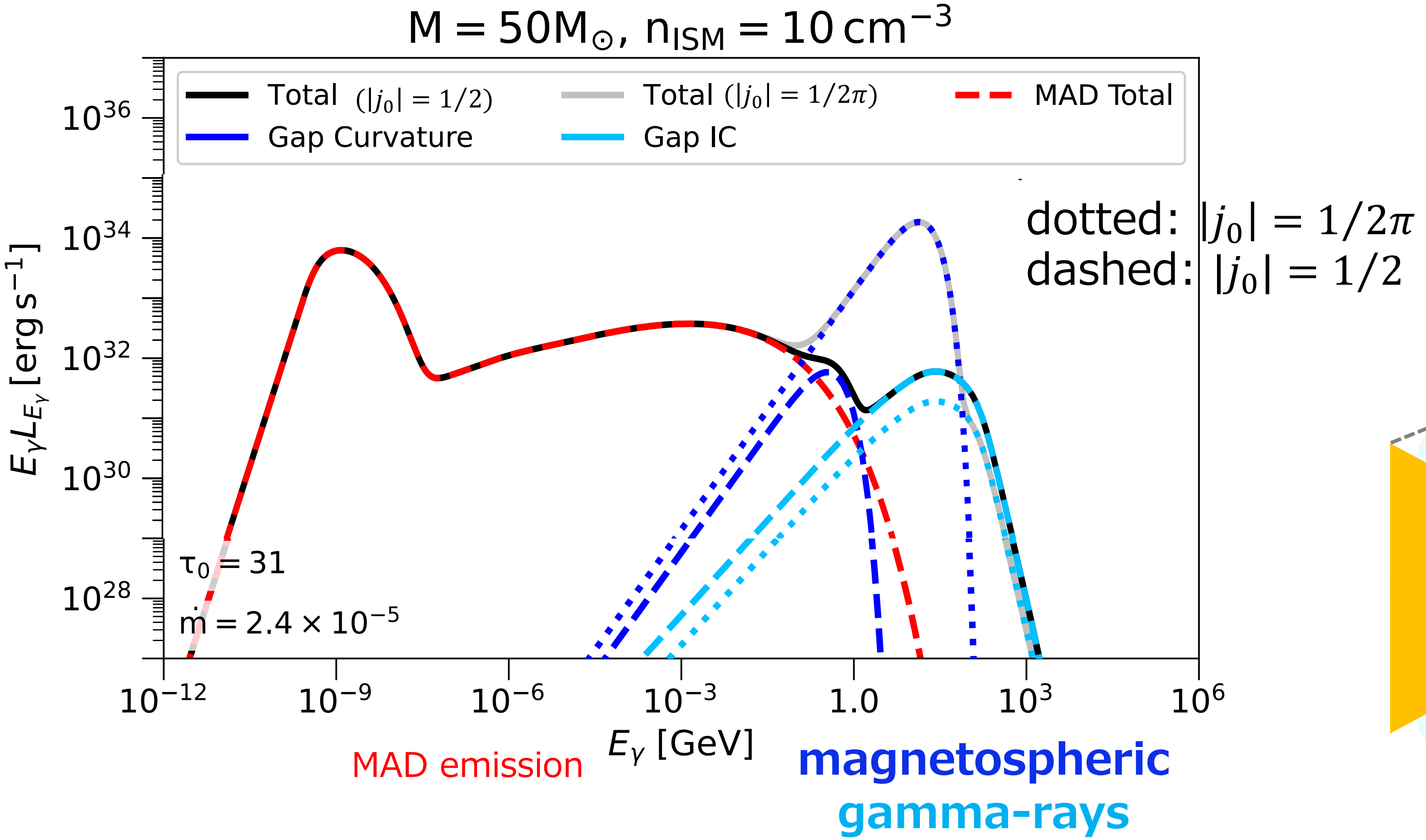


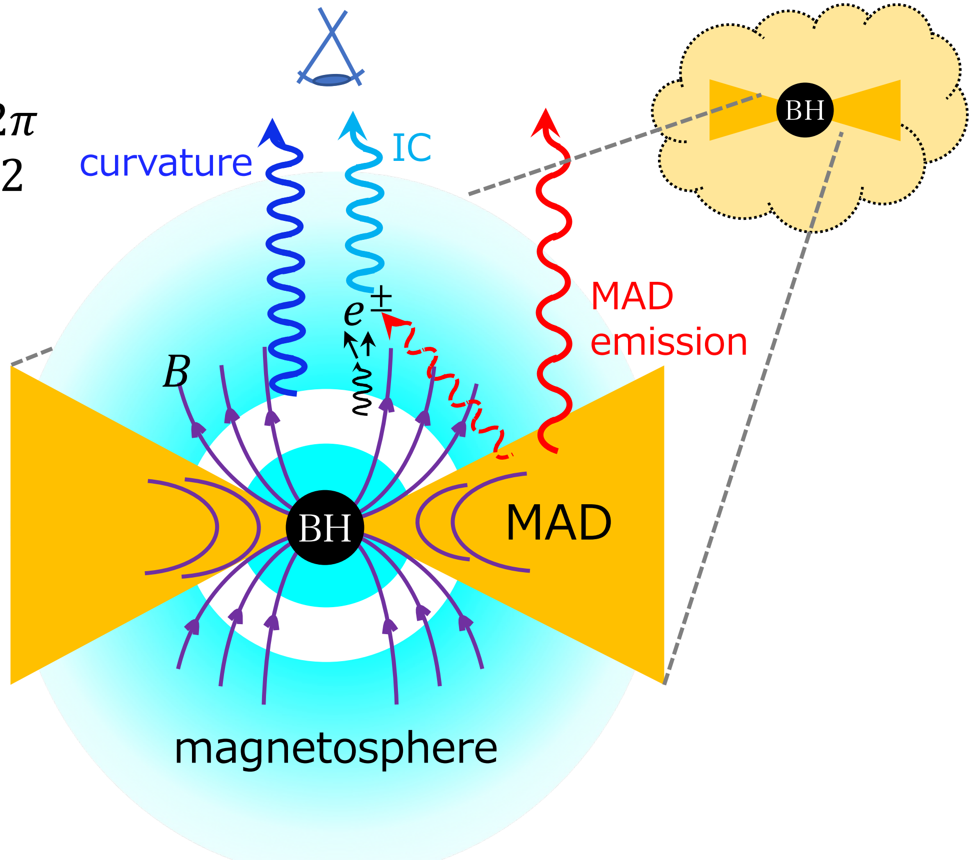
◎ IBHs in dense gas clouds = bright in GeV-TeV

◎ sweet spot: $\dot{m} = \dot{M}/\dot{M}_{Edd} \sim 10^{-5} - 10^{-4}$ $(\sim 10^{14} M_1\,\mathrm{g\,s^{-1}})$

Spectra

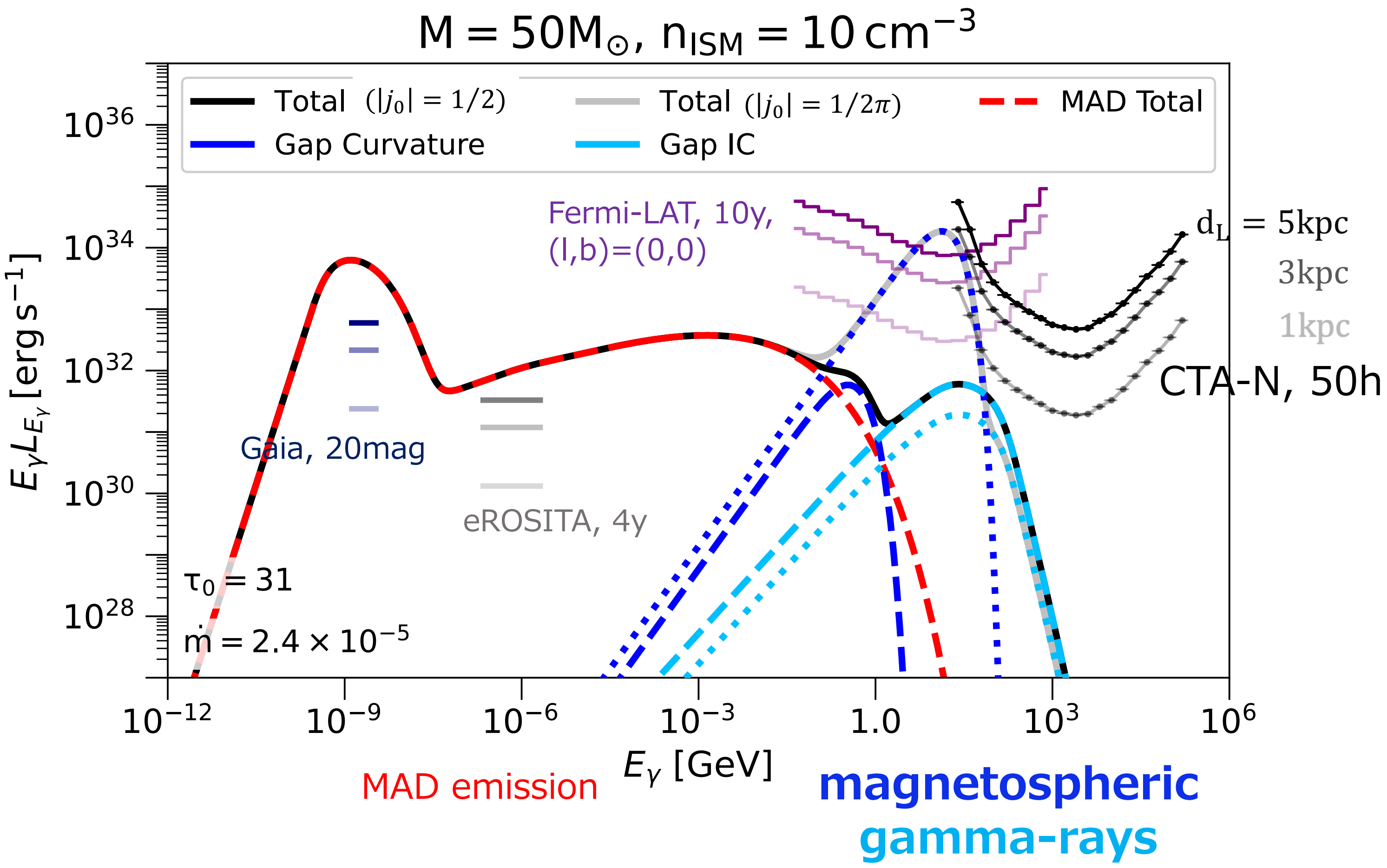
◎ GeV-TeV gamma-rays: $L_{GeV-TeV} \gtrsim 10^{-4} L_{BZ} \sim 10^{32} M_1^2 \left(\frac{a}{0.9}\right)^2 B_{H,7}\ \mathrm{erg\ s^{-1}}$

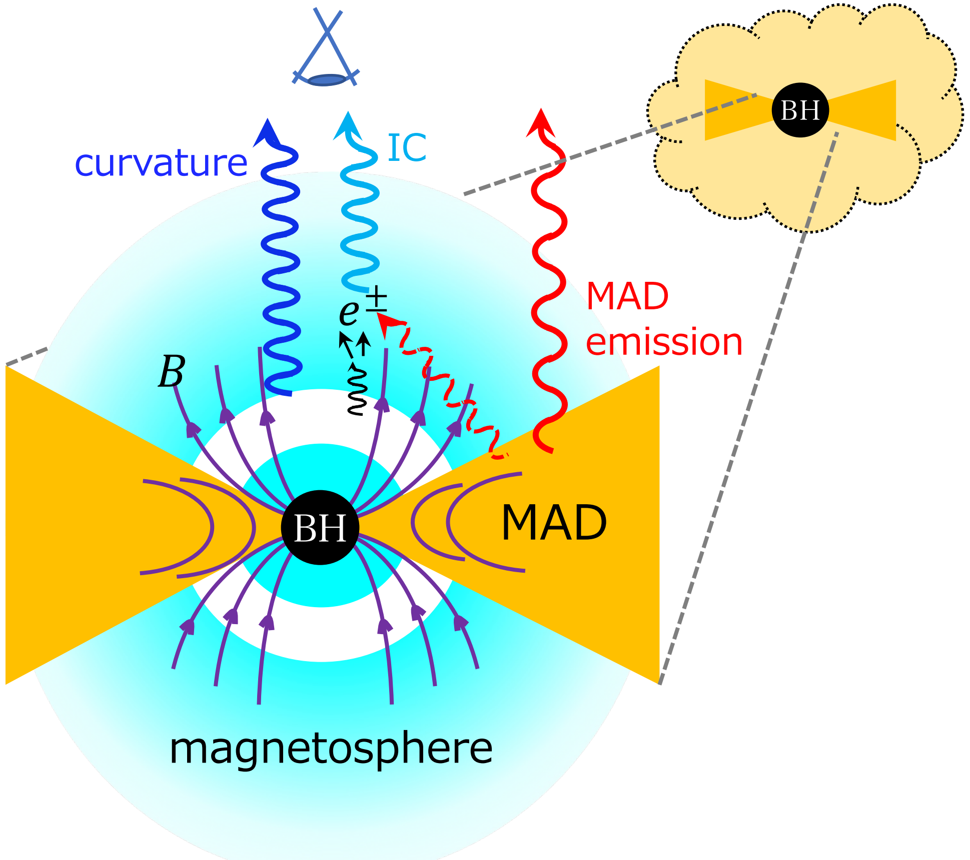




Spectra

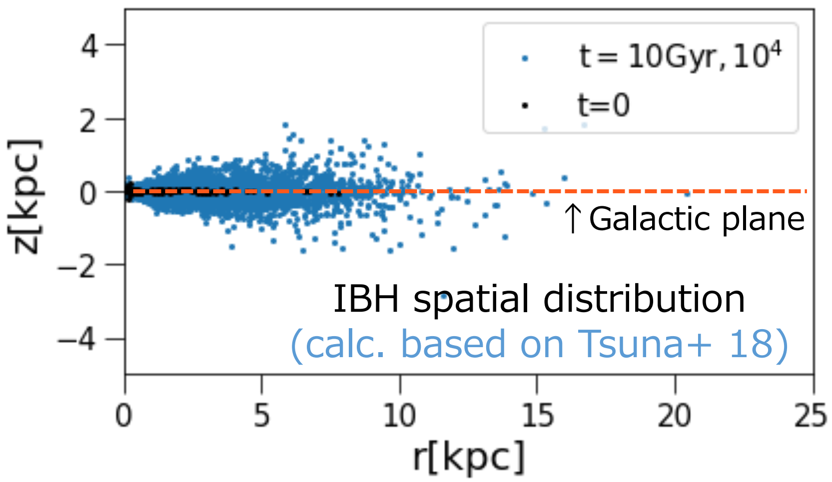
◎ GeV-TeV gamma-rays detectable from ~kpc, by Fermi-LAT, CTA

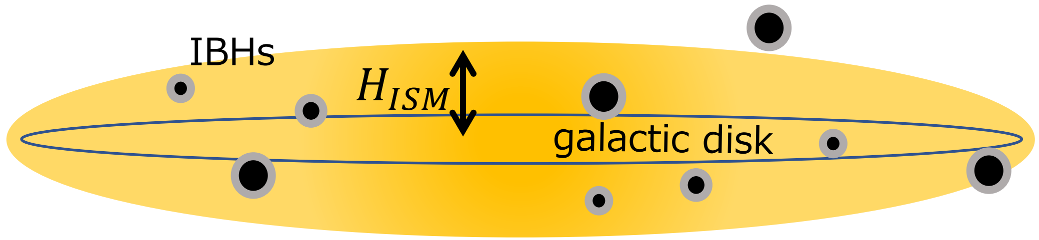




Preliminary: Expected number of detection

$v_{ini,avg} = 50 \text{ km s}^{-1}$

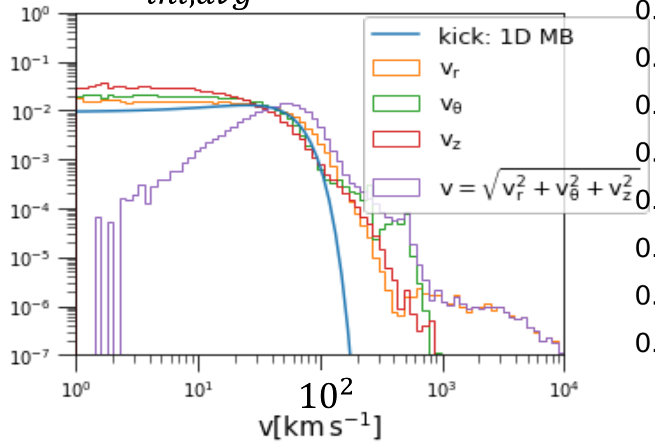




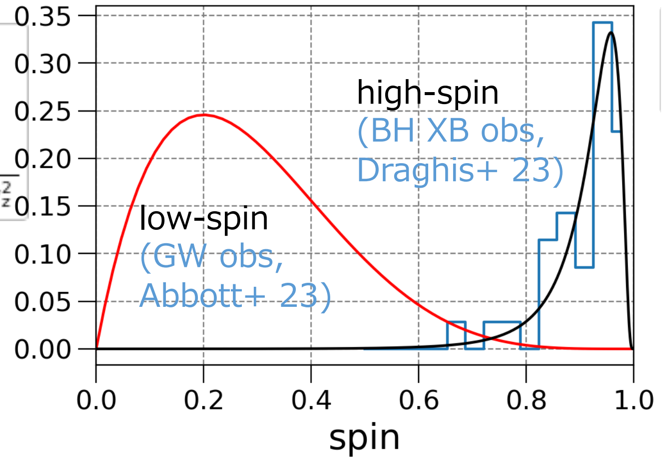
ISM distribution

◎ How many IBHs in Galactic ISM?

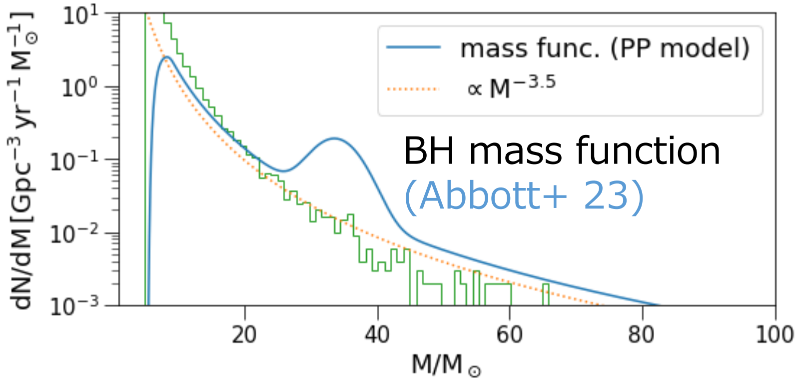
$v_{ini,avg} = 50 \text{ km s}^{-1}$



velocity histogram
(calc. based on Tsuna+ 18)



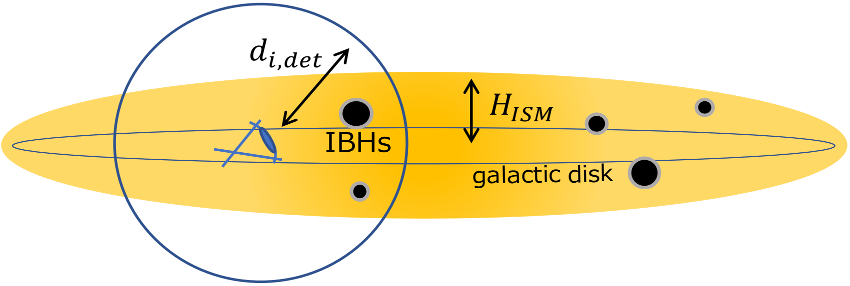
spin probability dist.

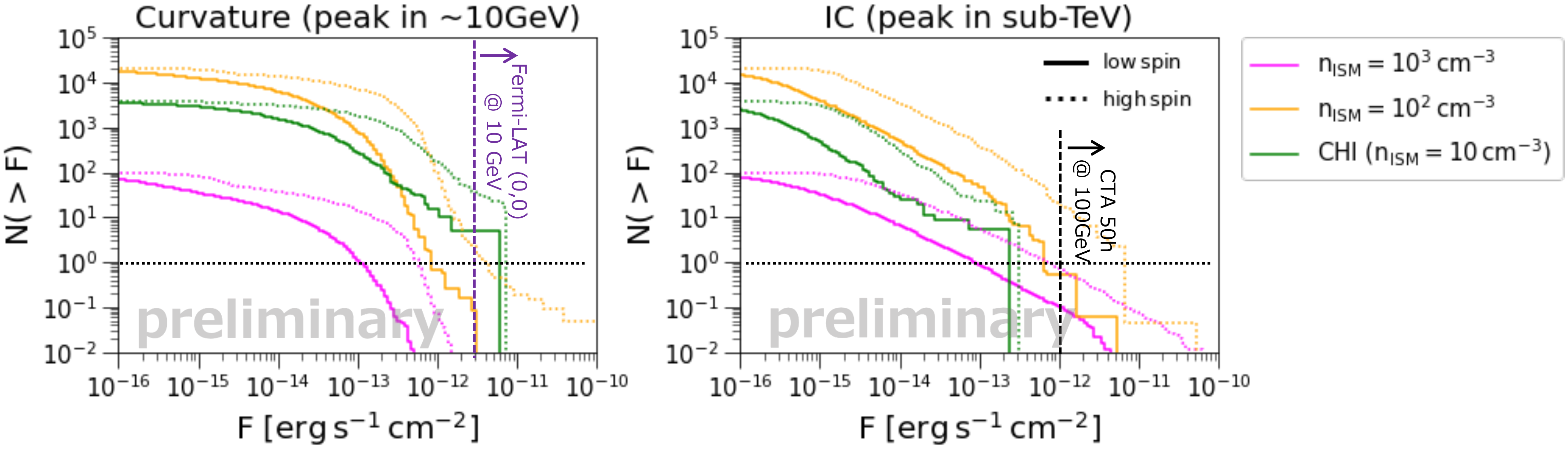


◎ How many of them are detectable in GeV-TeV?

Preliminary: Expected number of detection

◎ 10-100 IBH detectable, sensitive to BH spin





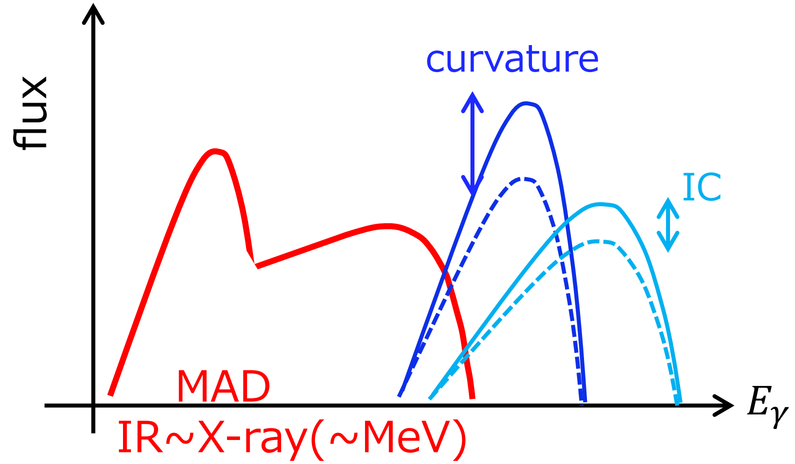
Detection strategy

◎**Optical~X-ray:** MAD signals

Gaia ↔ X-ray survey (eROSITA, Chandra⋯)

◎**Fermi-LAT:** ~3000 unIDs

criteria :
- hard index (flux $\propto E_\gamma^{4/3}$)
- spectral break
- association w/ Galactic MC



◎**CTA**: flux time variation via short-term observation

gamma-ray efficiency sensitive to $n_{\gamma,disk}$ i.e. $\dot{M}$

→ ISM turbulence creates $\times 10^{\pm 2}$ flux variation

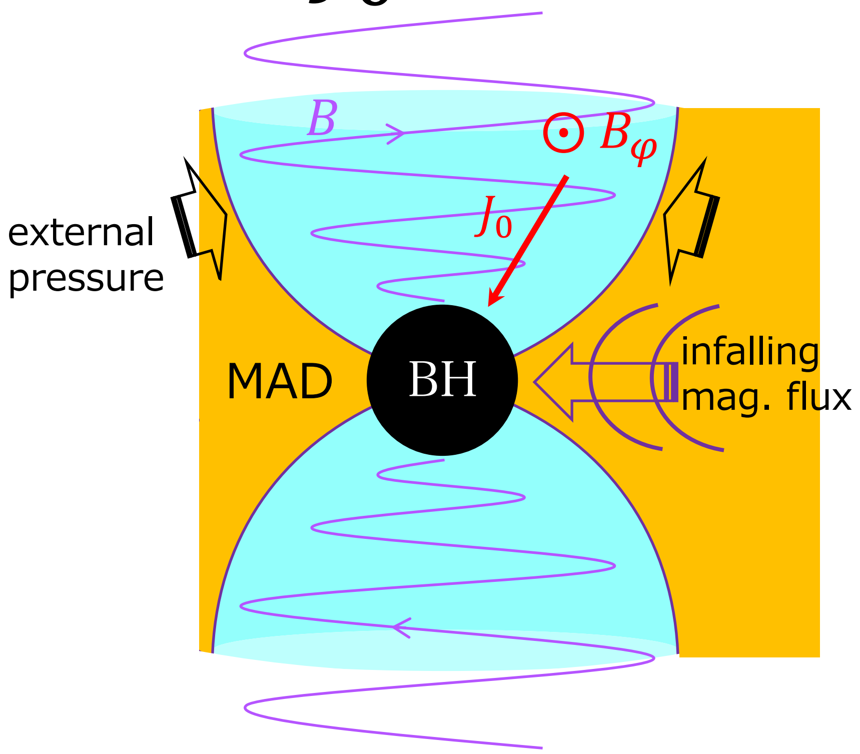
$$\Delta t \sim \frac{GM}{v^3} \sim 10^7 M_1 \left(\frac{v}{40\mathrm{km\,s^{-1}}}\right)^{-3} \mathrm{s}$$

Caveat: magnetospheric current J_0

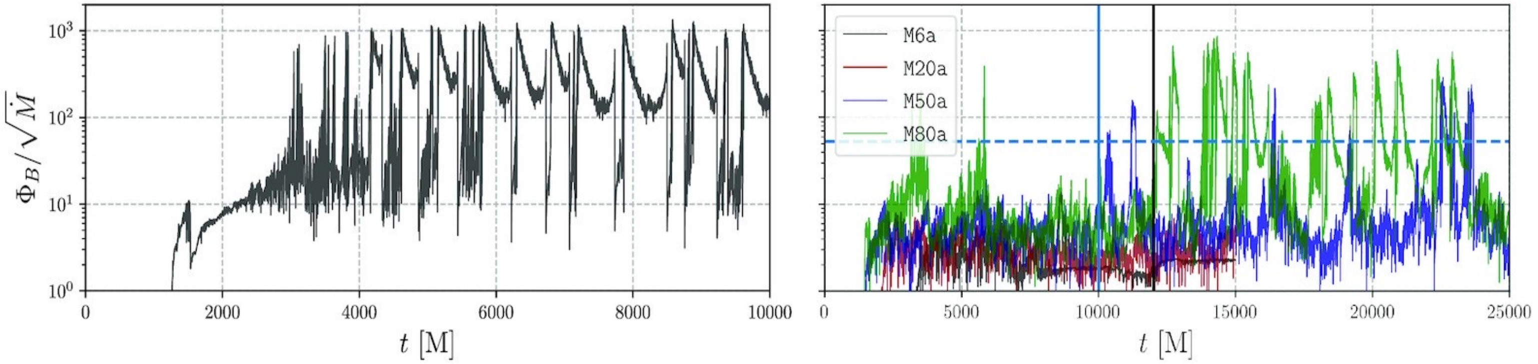
◎ assumption: $|J_0/J_{0,BZ}| < 1$

$$J_0 \propto \nabla \times B_\varphi$$

→ accretion flow pressure / mag. flux perturbation determine J_0 fluctuation timescale



Jiang et al. 23: infalling mag. flux at the horizon



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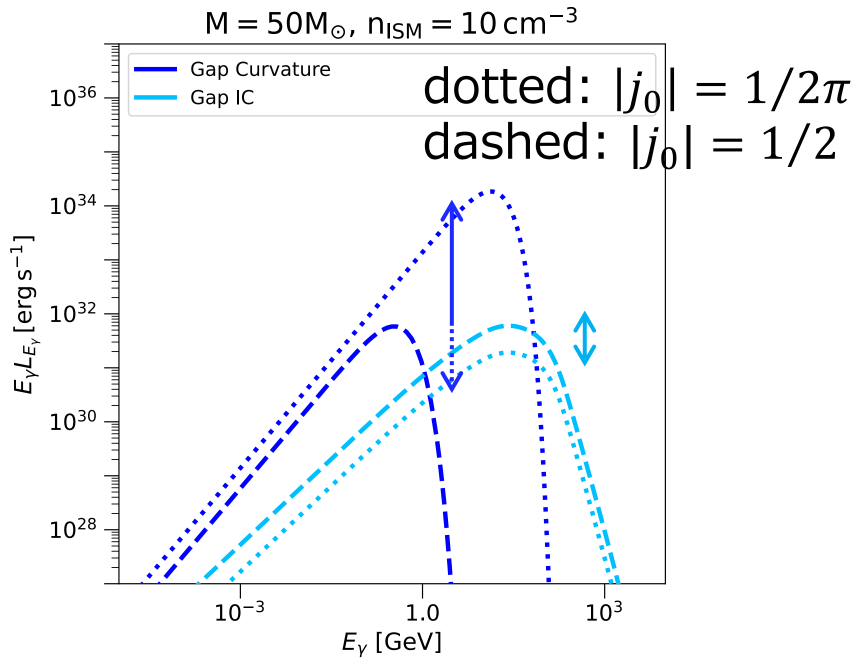
◎ assumption: $|J_0/J_{0,BZ}| < 1$

$$J_0 \propto \nabla\times B_\varphi$$

→ accretion flow pressure / mag. flux perturbation determine J_0 fluctuation timescale
curvature: luminosity duty cycle ~1-10%?
IC: almost persistent



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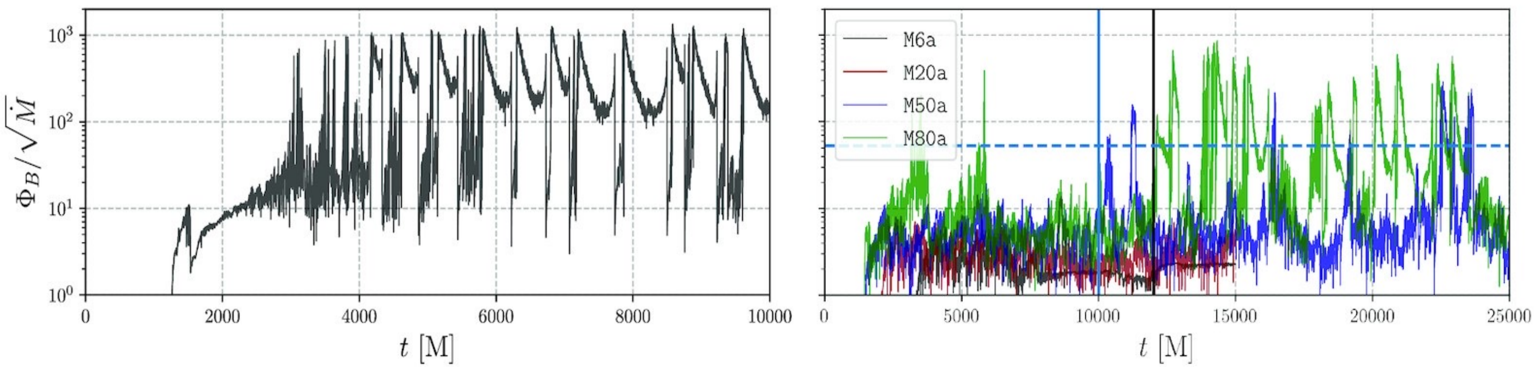


Summary & future works

◎Motivation: finding undetected isolated BHs through **gamma-ray from magnetosphere**

◎Method: **1D GRPIC simulation + semi-analytic modeling**

→ **GeV-TeV gamma rays detectable from ~kpc**

(see also Kin et al. accepted in ApJ, arXiv:2310.12532)

optimistic estimate on the detection number: 10-100 in Fermi-LAT・CTA

◎Model uncertainty:

- J_0 evolution timescale
- additional plasma injection
- B_φ structure affecting on plasma flow dynamics, radiation feature, plasma injection

◎Future work:

- simulation including **additional plasma injection, multi-dimensional effect**
- candidate search from catalog data

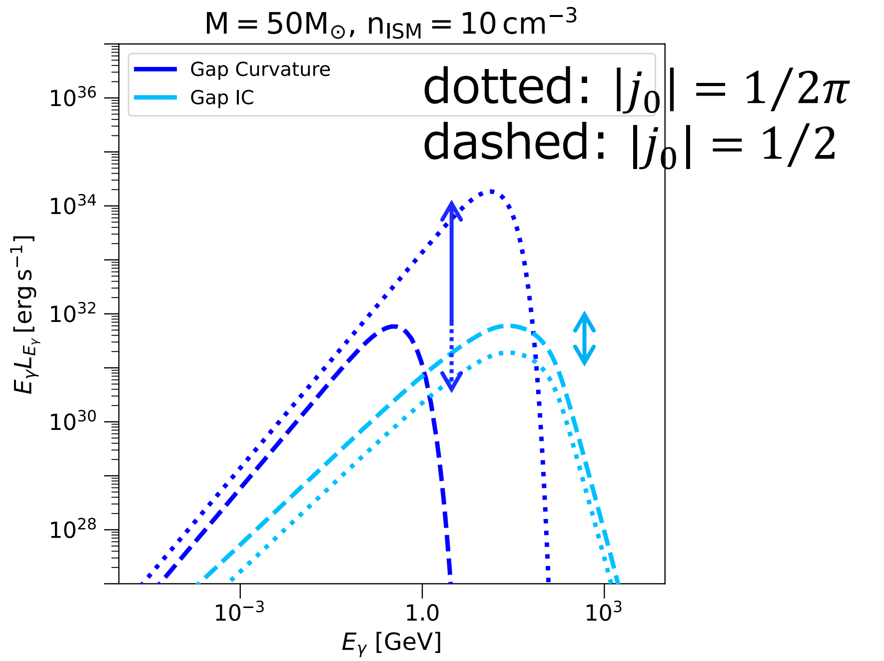
Back up

Caveat: magnetospheric current J_0

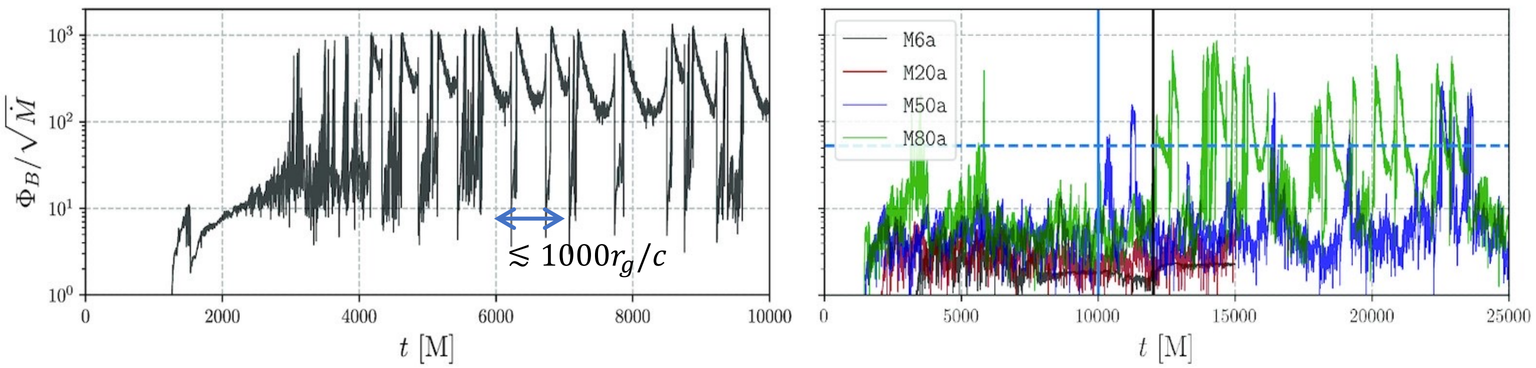
◎ assumption: $|j_0| < 1$

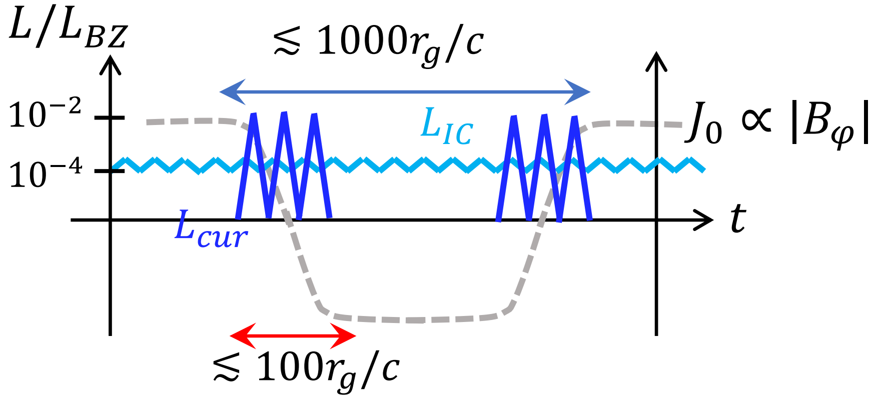
$J_0 \propto \nabla \times B_\varphi$

→ accretion flow pressure determine
J_0 fluctuation timescale
curvature: luminosity duty cycle ~1-10%?
IC: almost persistent



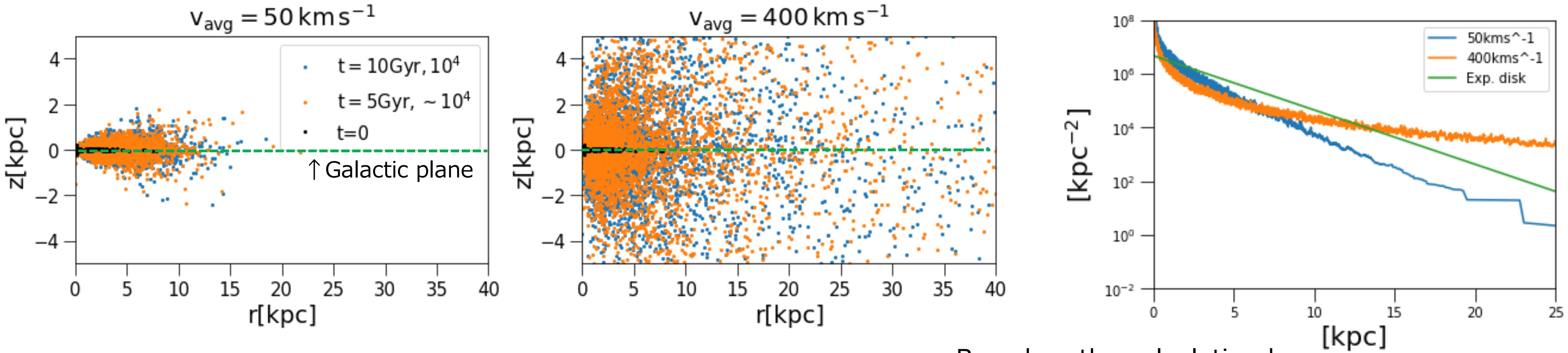
Jiang et al. 23: infalling mag. flux at the horizon





IBH dist. in Galaxy

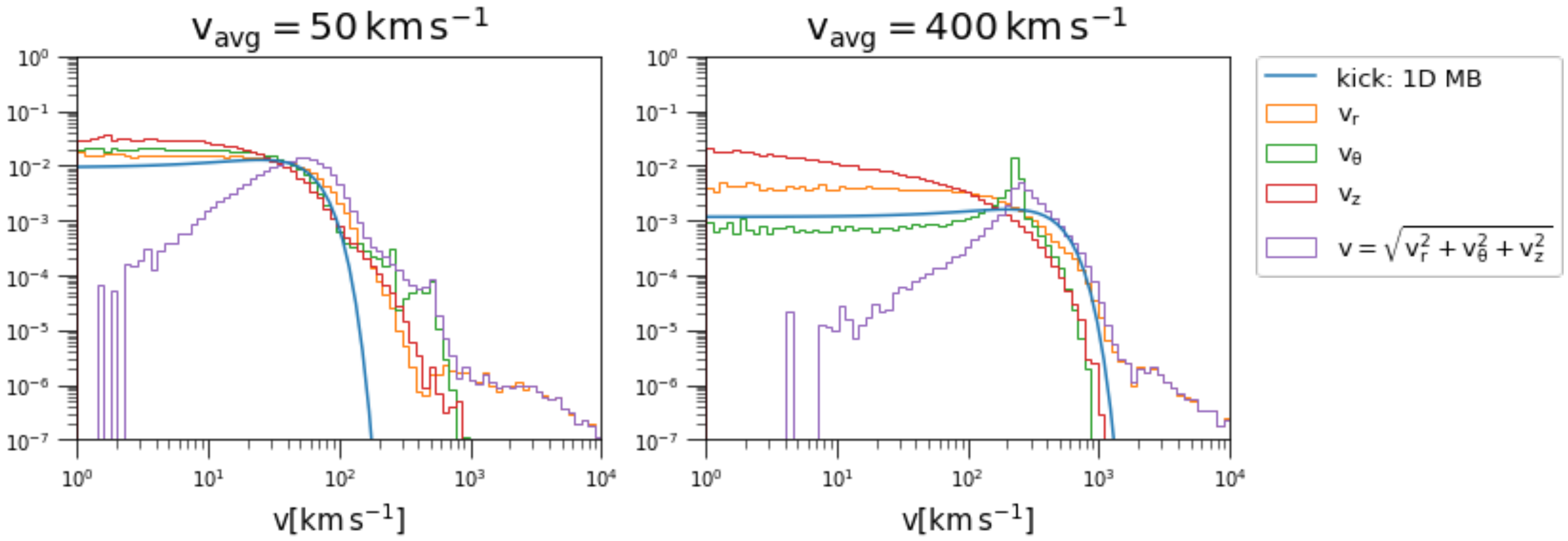
◎sensitive to "initial" velocity of BHs: $\boldsymbol{v_{init}} = \begin{pmatrix} v_{prog,disk} \\ v_{prog,bulge} \end{pmatrix} + \boldsymbol{v_{kick}}$



Based on the calculation by
Tsuna et al. 18

IBH velocity in Galaxy

◎typically $10 \sim 10^2\ \mathrm{km\ s^{-1}}$

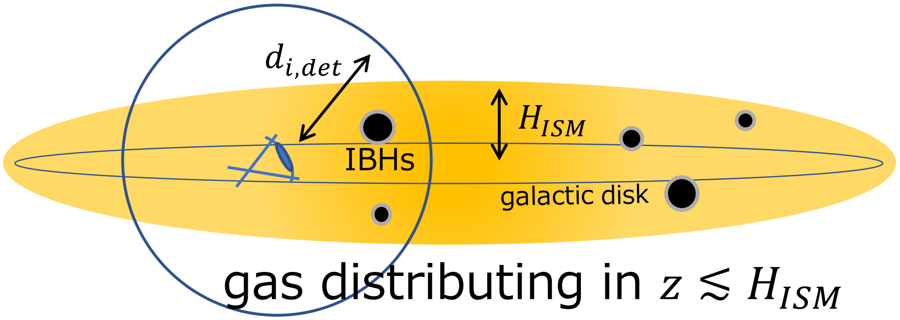


Based on the calculation by
Tsuna et al. 18

Discussion: expected number of detection in certain gas phase $\mathcal{N}_{det}$

◎$\mathcal{N}_{det}$=number of IBHs in gas & sensitivity limit

sensitivity limit $d_{i,det}$: luminosity vs sensitivity



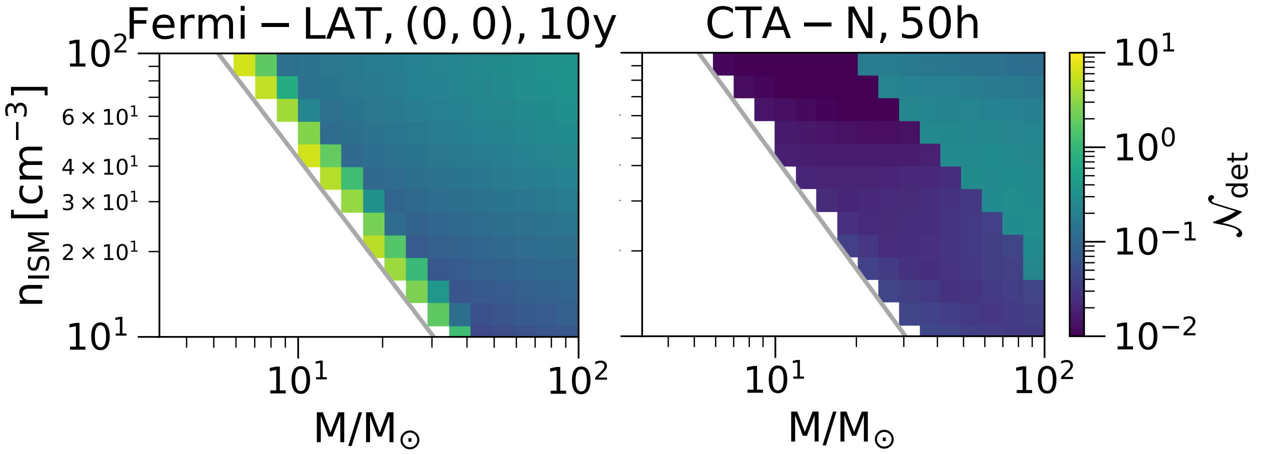
$$d_{i,det} = \sqrt{\frac{L_{obs}}{4\pi F_{sen}}} \sim 5\, L_{obs,33}^{1/2} F_{sen,-12}^{-1/2}\ \mathrm{kpc}$$

$$\therefore\ \mathcal{N}_{det} \sim n_0 \xi_0 M \frac{dN}{dM} 2\pi H_{ISM} d_{i,det}^2 \simeq 3.7 \left(\frac{d_{i,det}}{5\mathrm{kpc}}\right)^2 \left(\frac{M}{50M_\odot}\right)^{1-\gamma}$$

($\frac{dN}{dM} \propto M^{-\gamma}$ (γ~2.6 Abbott et al.21)

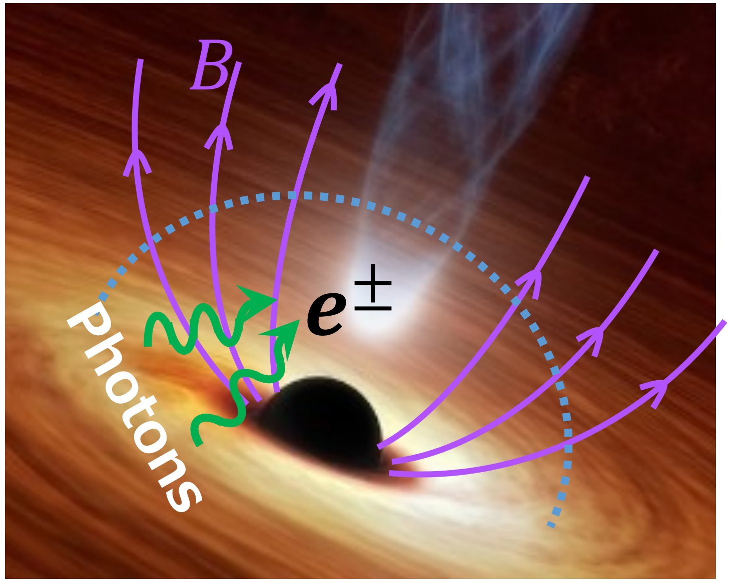
ξ_0 : Volume filling factor

$n_0 \sim \mathcal{R}_{GW} n_{gal}^{-1} H_0^{-1} \sim 2\times10^2 \mathrm{kpc}^{-3}$: merged BH density)



Preliminary: Introducing MeV Photon Injection

◎evaluate how injection via **MeV photon annihilation** affects gap dynamics, radiation feature



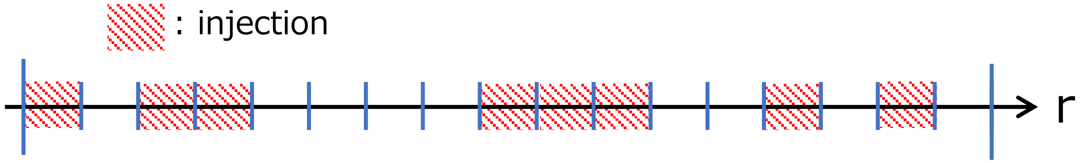
expectation for gap formation threshold :

$$n_{inj}(\dot{M}) \gtrsim n_{GJ}$$

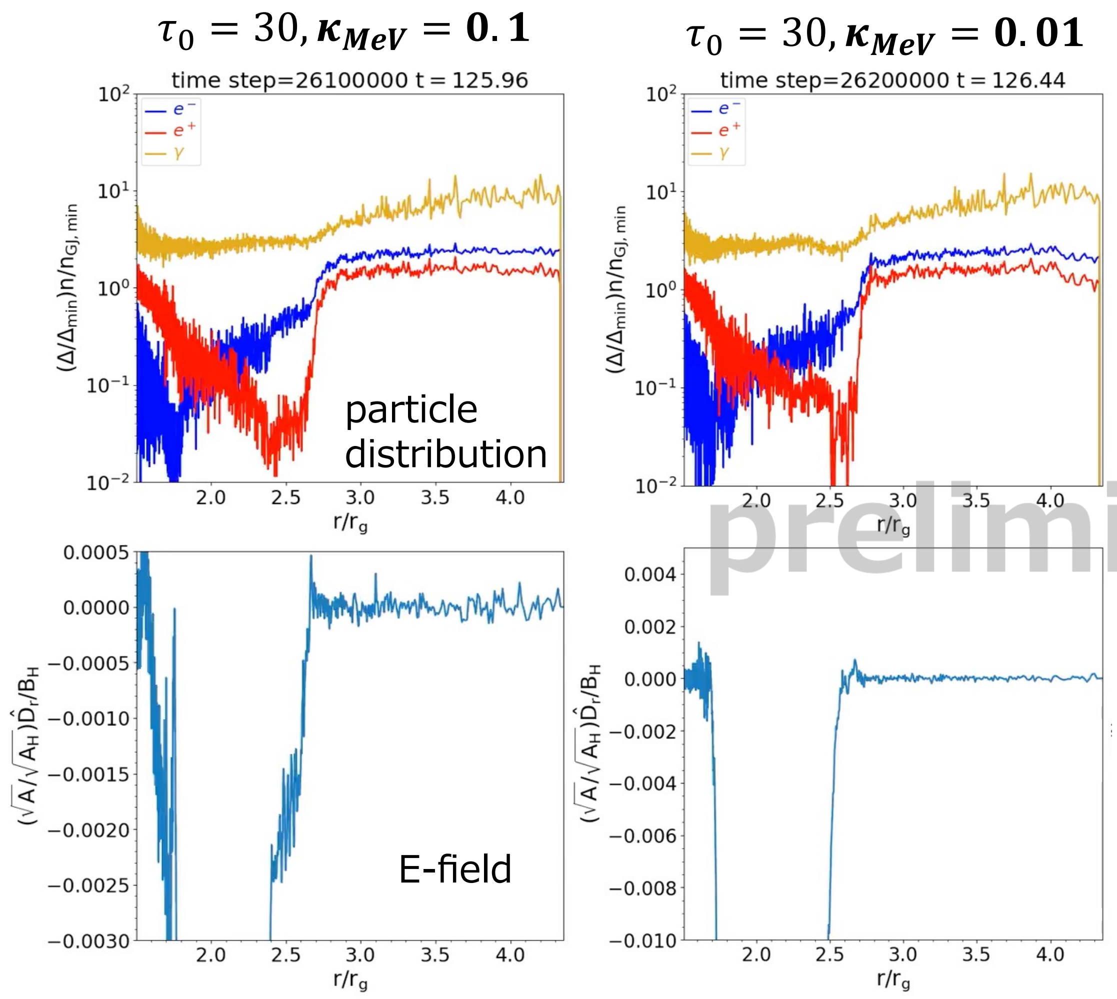
(Levinson & Rieger 11; Kimura & Toma 20)

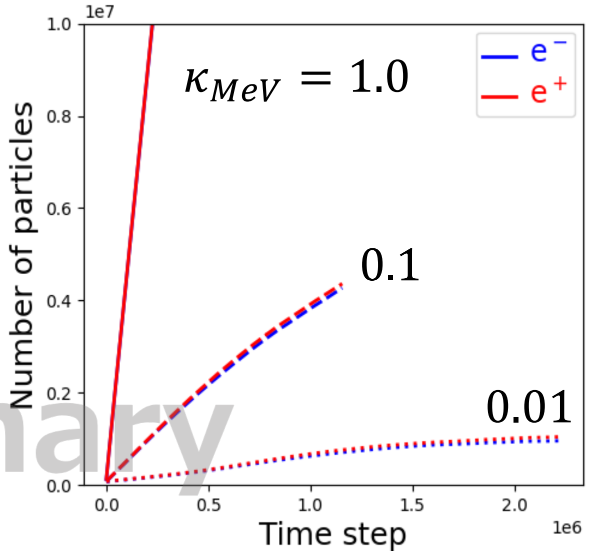
◎Methodology:

random injections in each step, $\dot{n}_{inj} dt \sim \kappa_{MeV} n_{GJ}$ in total



Preliminary: Introducing MeV Photon Injection

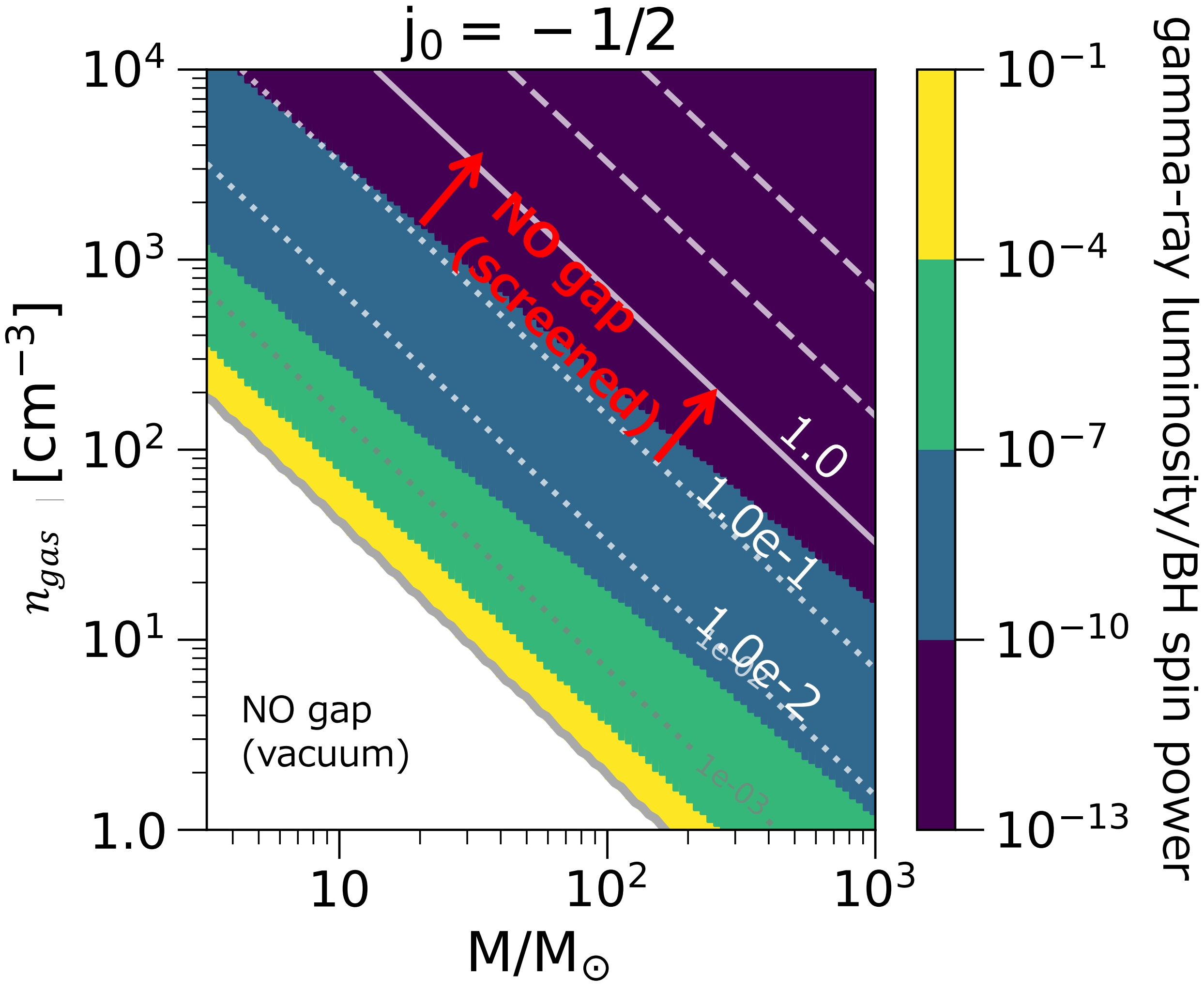




j_0	κ_{MeV}	gap?
$-1/2$	1.0	×
〃	10^{-1}	×
〃	10^{-2}	○
$-1/2\pi$	10^{-1}	×

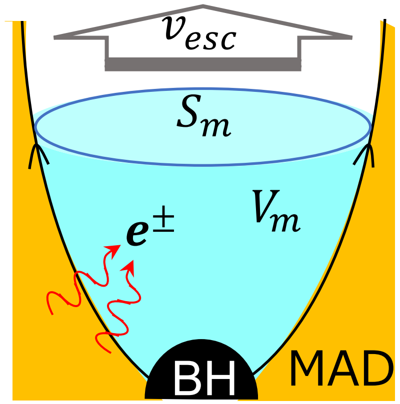
◎ E-field screened for $\boldsymbol{n_{inj} \gtrsim 0.1 n_{GJ}}$???
→ setting upper limit on gamma-ray bright parameter range?

Preliminary discussion: Upper Limit on Gap Formation in $M - n_{gas}$ Plane



contour : $\kappa_{MeV} \sim n_{inj}/n_{GJ}$

$$\kappa_{MeV} = \frac{n_{inj}}{n_{GJ}} \sim \frac{\sigma_{\gamma\gamma}\left(\frac{L_{MeV}}{4\pi R^2 c E_{MeV}}\right)^2 \frac{V_m c}{S_m v_{esc}}}{\frac{\Omega_H B}{4\pi e c}}$$



◎ insignificant for gamma-ray bright range?

◎ future work: dynamical difference, gap formation lower limit

Very preliminary: intermediate BHs in TeV?

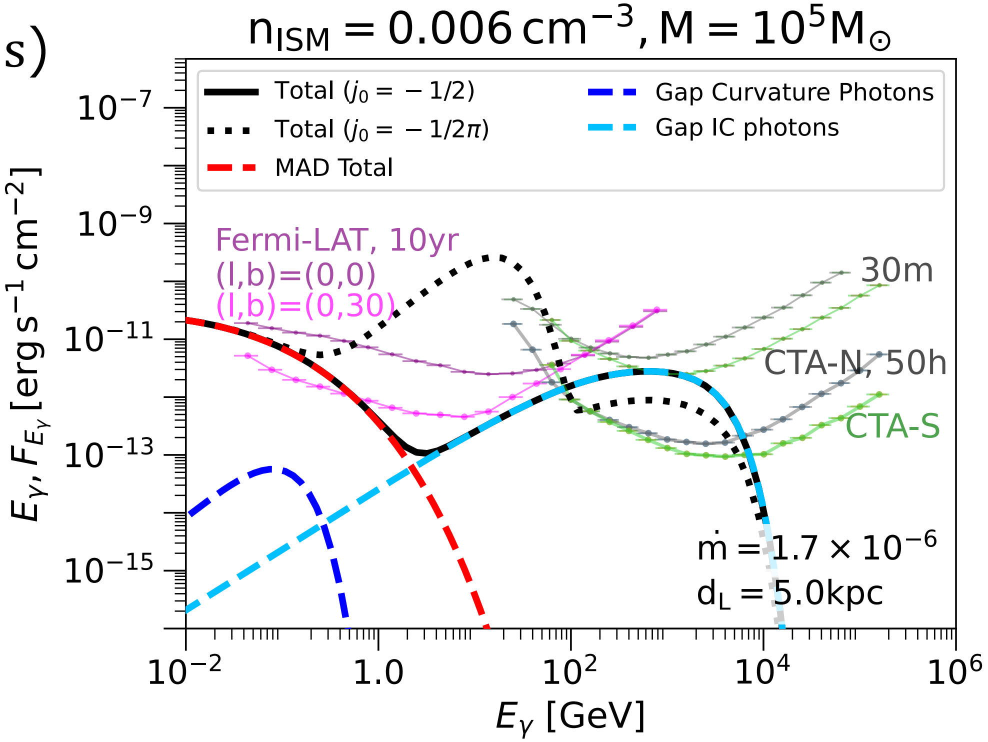
◎ GeV-TeV bright in $\dot{M}/\dot{M}_{Edd} \sim 10^{-5} - 10^{-4}$ ⬌ $n_{ISM} \sim 10^{-3} - 10^{-1}\mathrm{cm}^{-3}$ for $10^3 - 10^5 M_\odot$ BHs

→ 10~1000 intermediate BH in Galaxy (e.g., Rashkov & Madau 14)

some of them found in TeV?

MAD dynamical timescale ($\sim 10^3\, r_g/c \sim 10^4 M_5\ s$)

distinguishable?



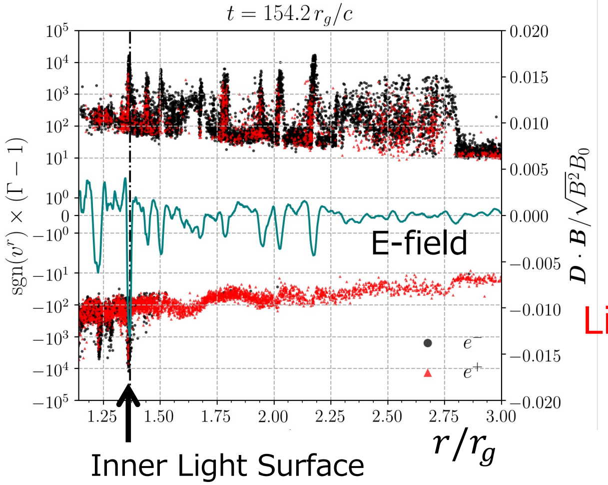
Light surfaces

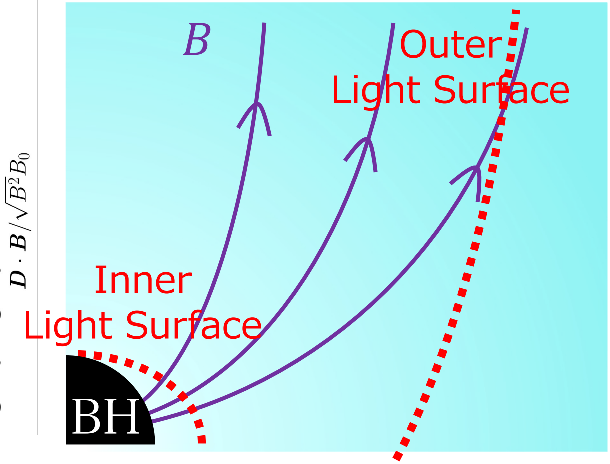
◎E×B drift velocity $\hat{v}^{\varphi} = 1$ under $B_{\varphi} = 0$ assumption (monopole-like)

$\hat{v}^{\varphi} = (\Omega - \omega)\sqrt{\gamma_{\varphi\varphi}}/\alpha = \pm 1$ (c.f. Toma & Takahara 14) $\rightarrow r_{ILS} \sim 1.5 r_g$、$r_{OLS} \sim 12 r_g$ for a=0.9

B_{φ} dominant inside/outside LS

E-field develops around LS (Crinquand et al. 20)

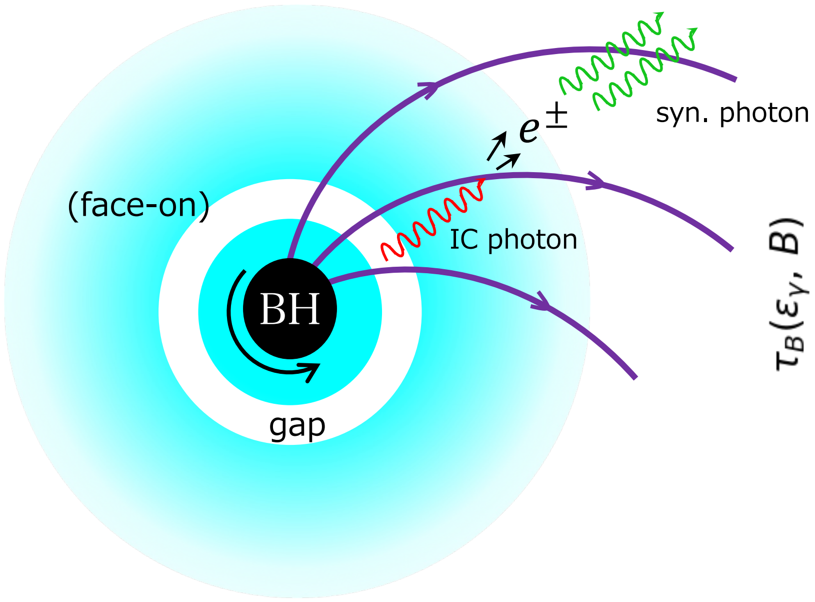


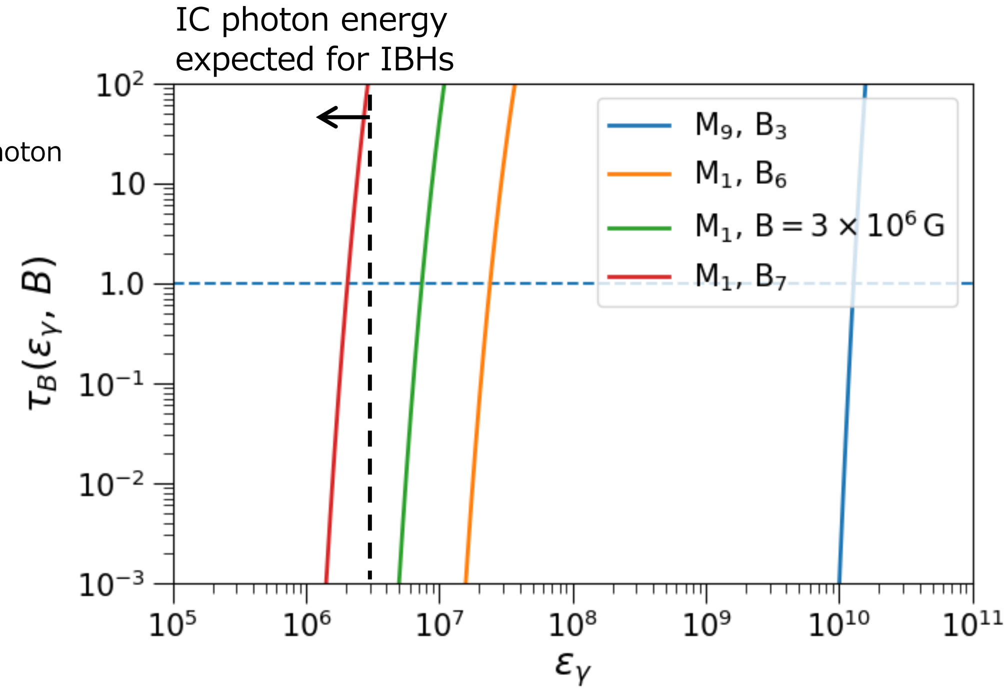


B_φ effect on radiation/plasma injection

◎synchrotron emission from 2nd pairs propagating in curved B-field?

◎magnetic pair production: $\gamma + B \rightarrow e^+ + e^-$ in 〃 ?

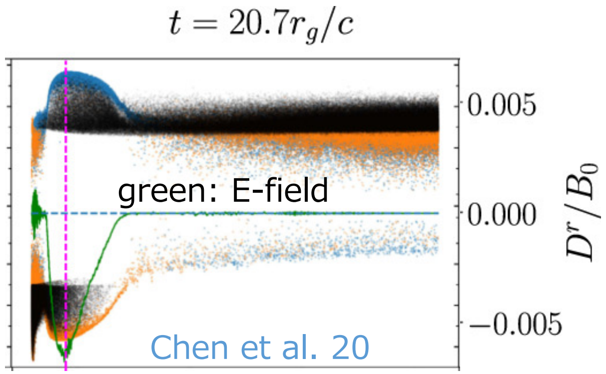




BH magnetosphere PIC: so far

- 1D local model
  (Levinson & Cerutti 18; Chen et al. 20; Kisaka et al. 20, 22)
  fixed global B-field structure
  solving E-field & plasma evolutions

- 2D global model
  (Parfrey et al. 19; Crinquand et al. 20,21; Hirotani et al. 22,23; Niv et al. 23)
  time-dependent B-field



◎local E-field particle acceleration (Kisaka et al. 20;22, Chen et al. 20; Crinquand et al.20)

→ gamma-ray luminosity ≲ 1% of BZ luminosity

◎magnetic reconnection at equatorial plane/in ergosphere

→ flare-like Poynting flux release? (Hirotani et al.23)

◎injection site affect dynamics (Niv et al.23)