High-Energy Gamma-Ray Emission from Isolated Stellar-Mass Black Hole Magnetospheres

(Kin et al. submitted)

Presenter: **Koki Kin** (Tohoku U. D1)

with Shota Kisaka (Hiroshima U.), Shigeo S. Kimura (FRIS, Tohoku U.),
Kenji Toma (FRIS, Tohoku U.), and Amir Levinson (Tel Aviv U.)

HEPRO 2023

2023.10.26 @ Institut d'Astrophysique de Paris

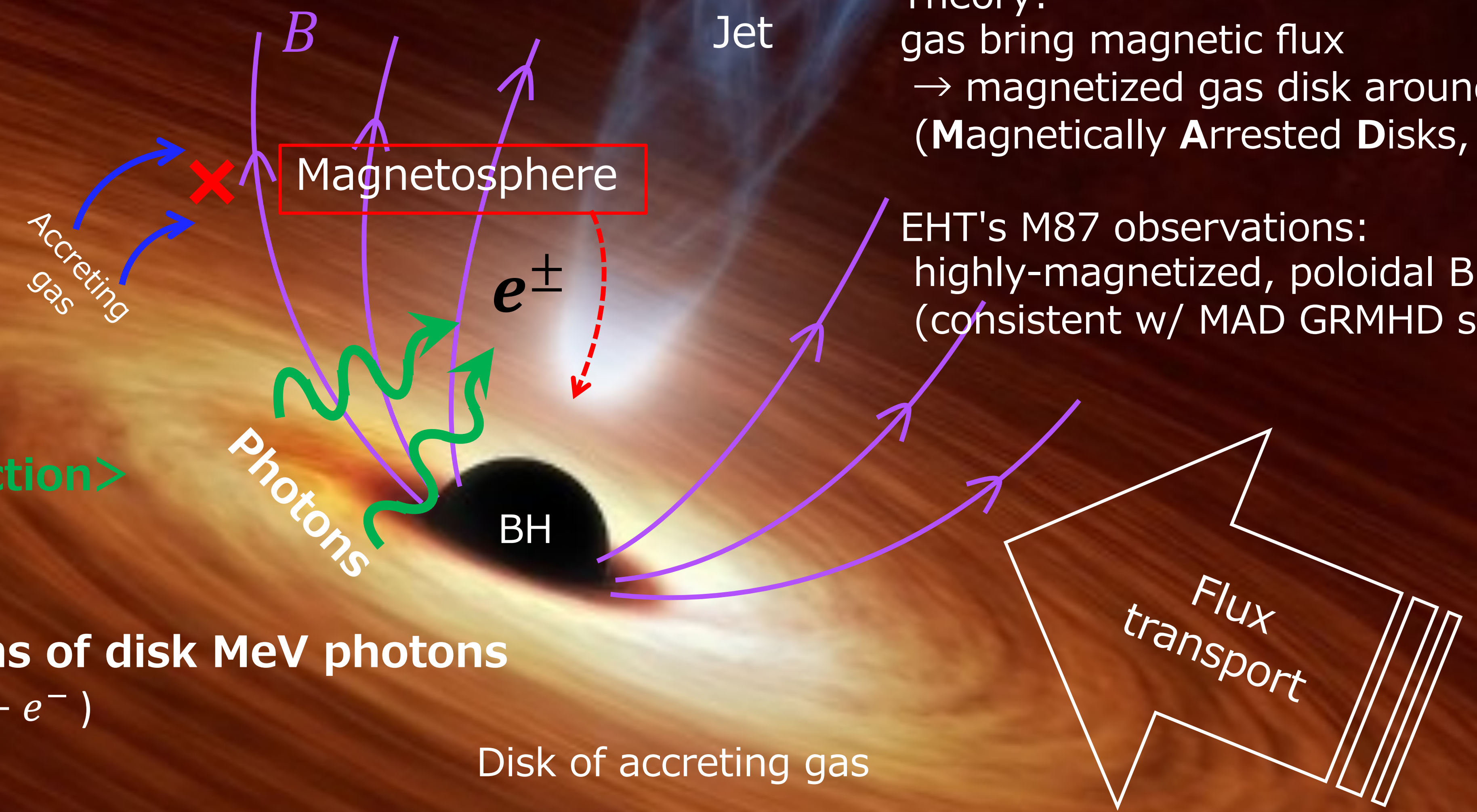
TOHOKU UNIVERSITY

Theoretical Astrophysics
Tohoku University

Contents

Formation of BH Magnetospheres

(c)NASA/JPL



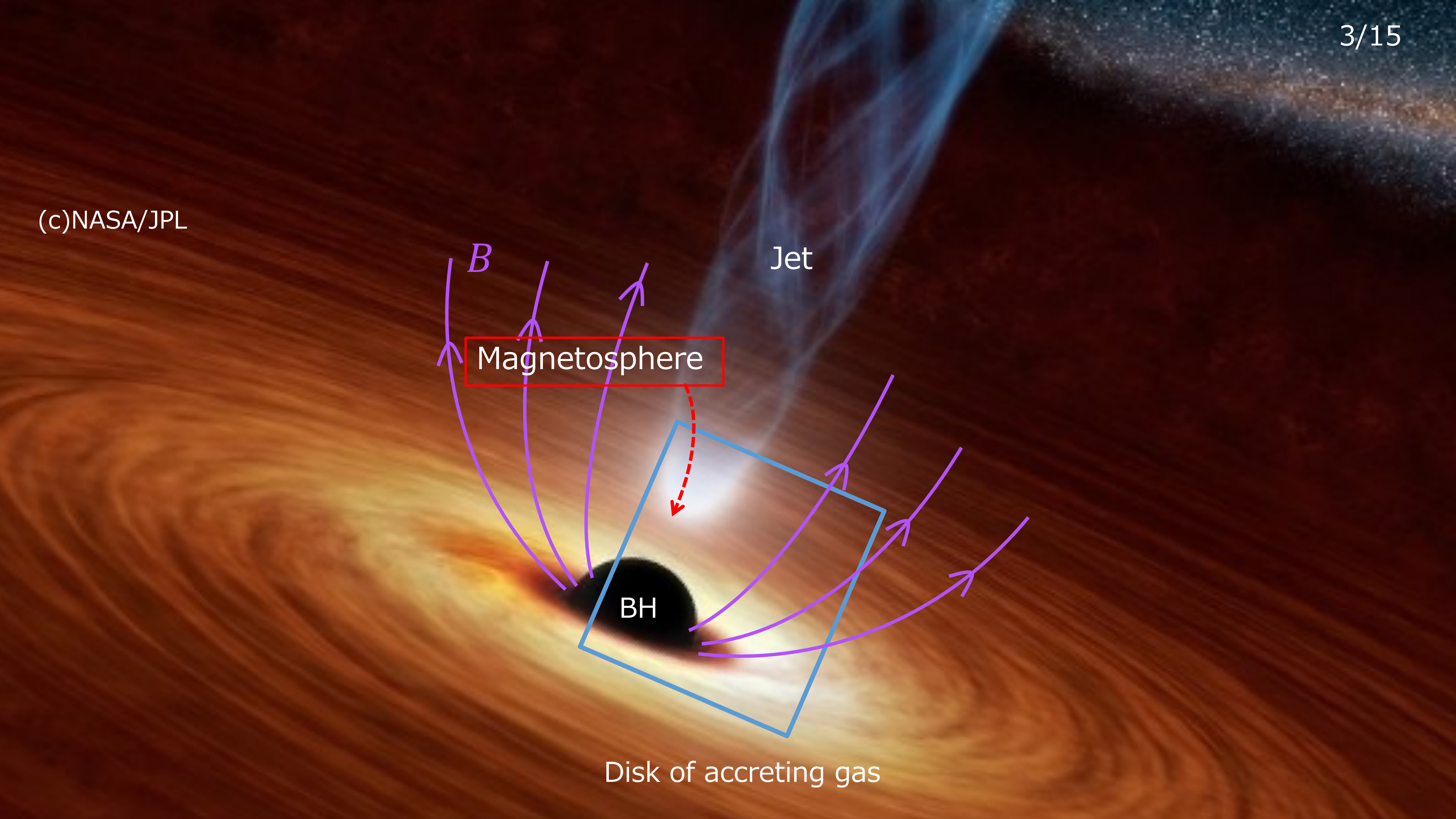
<B-fields transportation>

Theory:
gas bring magnetic flux
→ magnetized gas disk around BHs
(**M**agnetically **A**rrested **D**isks, **MADs**)

EHT's M87 observations:
highly-magnetized, poloidal B
(consistent w/ MAD GRMHD simus)

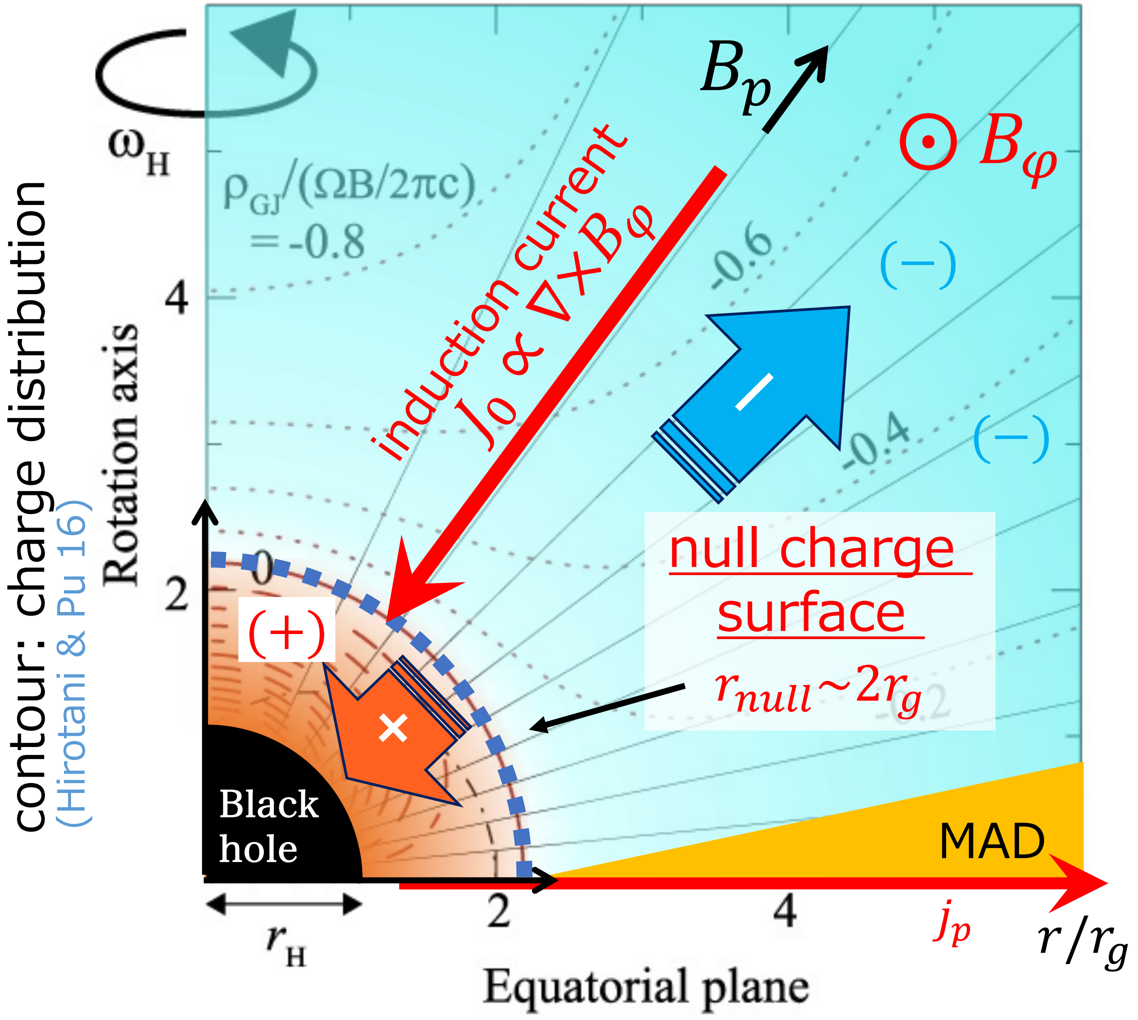
<Plasma injection>

Theory:
primary source
= **annihilations of disk MeV photons**
$(\gamma + \gamma \rightarrow e^{+} + e^{-})$


(c)NASA/JPL
B
Jet
Magnetosphere
BH
Disk of accreting gas

Current Structure・Charge Distribution in BH Magnetosphere

◎**sufficient plasma** → steady EM structure, $\boldsymbol{E} \cdot \boldsymbol{B} = 0$ (e.g. Blandford & Znajek 77)



extraction of BH rotation energy
→ $v \sim c$ **plasma flow**
maintain poloidal current

(Blandford-Znajek process)

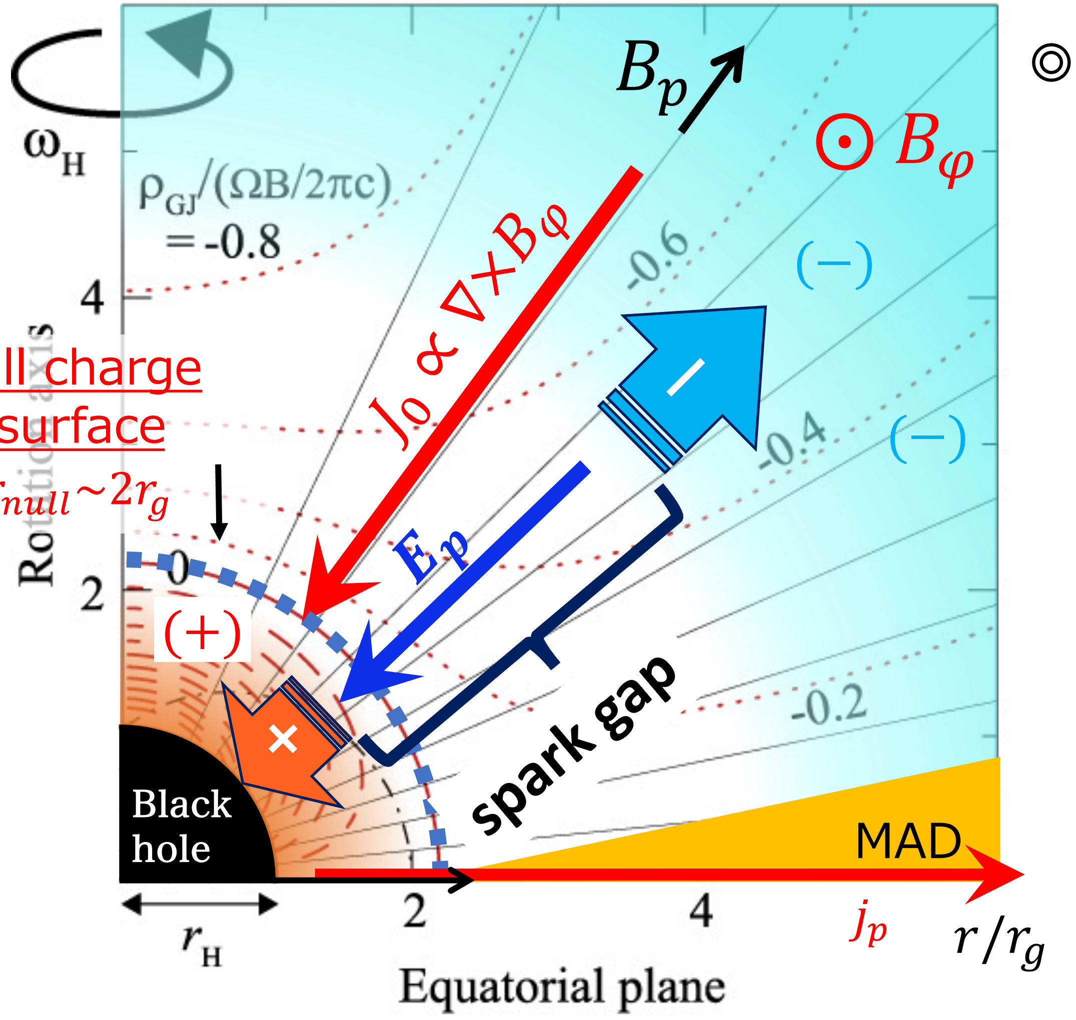
◎ **far zone:** (−) outflow (connected to the jet)

◎ **near horizon:** (+) inflow
(due to gravity, rapid rotation)

charge & flow separation at $r_{null} \sim 2r_g$

Formation of Spark Gap in Charge-Starved Magnetosphere

◎**charge-starved** → time-dependent E-field



◎ charge-starved due to low MeV photon injection
(Levinson & Rieger 11; Levinson & Segev 17; Hirotani & Pu 16 etc...)

→ local charge deficiency in magnetosphere

$$n < n_{GJ}(= |\rho_{GJ}|/e)$$

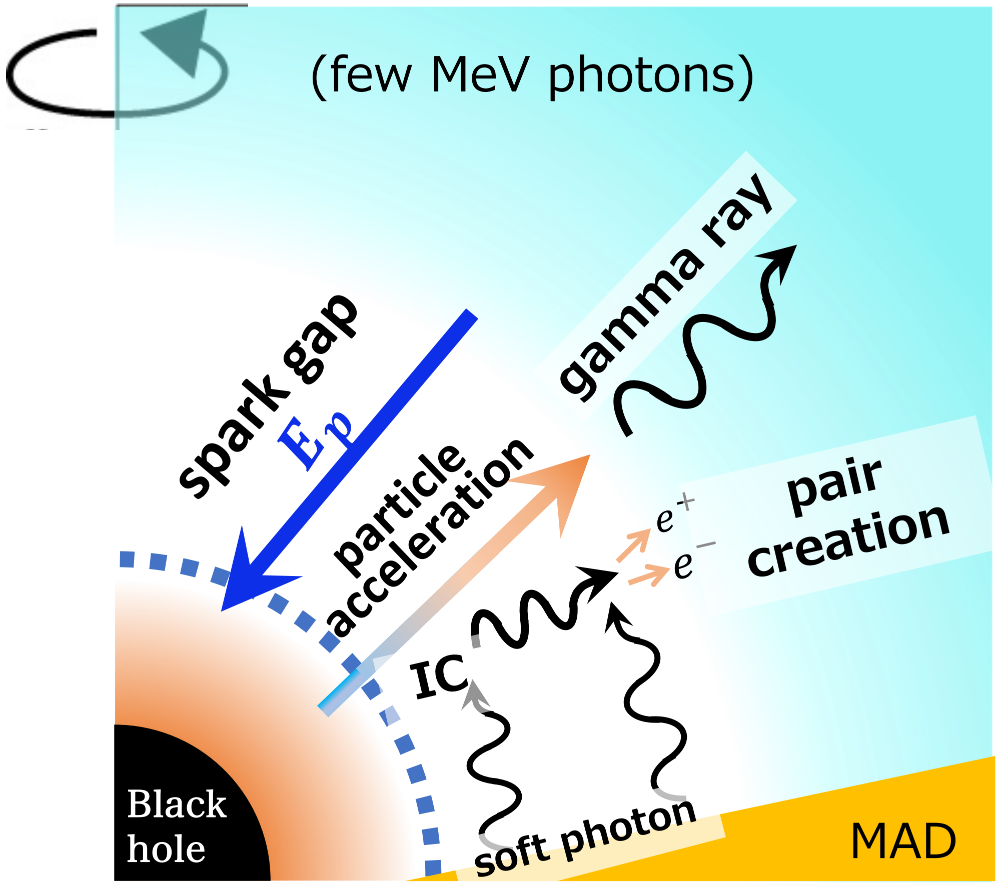
→ displacement current develops

$$\partial_t(E_p) \approx -4\pi(j^r - J_0/r^2)$$

local intermittent E-field region (**spark gap**)

Formation of Spark Gap in Charge-Starved Magnetosphere

◎**charge-starved** → time-dependent E-field



◎ charge-starved due to low MeV photon injection
(Levinson & Rieger 11; Levinson & Segev 17; Hirotani & Pu 16 etc...)

→ local charge deficiency in magnetosphere

$$n < n_{GJ}(= |\rho_{GJ}|/e)$$

→ displacement current develops

$$\partial_t(E_p) \approx -4\pi(j^r - J_0/r^2)$$

local intermittent E-field region (**spark gap**)

efficient acceleration, gamma-ray emission
secondary pair creation

Motivation: Detecting Isolated stellar-mass Black Holes via Gamma-Rays?

◎ $\sim 10^{7-8}$ **undetected IBHs in our Galaxy**

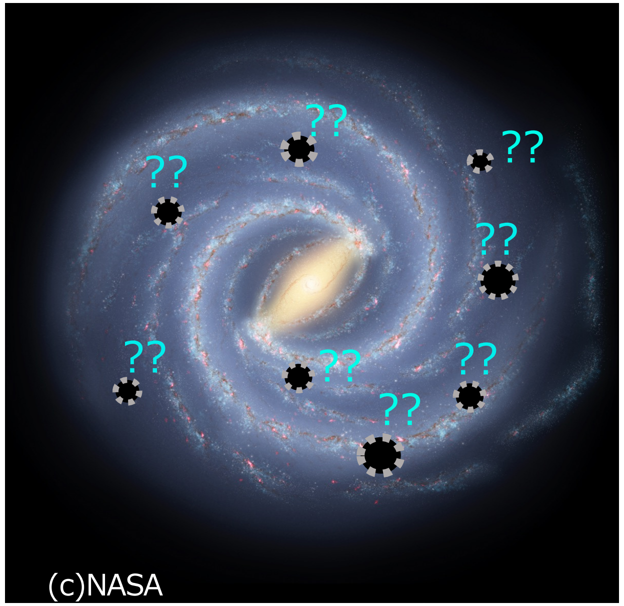
$SFR \times V_{gal} \times t_{galaxy}$ (e.g. Sartore & Treves 10; Caputo et al. 17; Abrams & Takada 20)

$\sim 10^{-14}\mathrm{pc}^{-3}\mathrm{yr}^{-1}$ for $10 M_\odot$ $\sim 10^{11}\mathrm{pc}^3$ $\sim 10\mathrm{Gyr}$

→ possible interactions w/ Galactic gas clouds

→ **MAD around IBHs** even for weakly-magnetized gas accretion

(e.g. Ioka et al.17; Kimura et al. 21)



Can we detect gamma rays from IBH "spark gap"?

- implications to **massive star evolution** theory
- Galactic **cosmic ray** origin? (c.f. Ioka et al.17)
- BH spin, B-field strength → confirming **BH jet theory**

Motivation: Detecting **I**solated stellar-mass **B**lack **H**oles via Gamma-Rays?

◎ **$\sim 10^{7-8}$ undetected IBHs in the Galaxy**

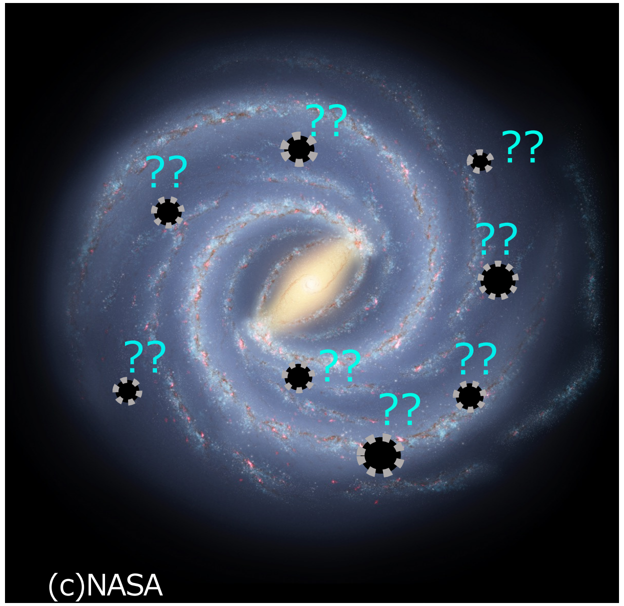
$SFR \times V_{gal} \times t_{galaxy}$ (e.g. Sartore & Treves 10; Caputo et al. 17; Abrams & Takada 20)

$\sim 10^{-14}\mathrm{pc^{-3}yr^{-1}}$ for $10 M_{\odot}$ $\sim 10^{11}\mathrm{pc^3}$ $\sim 10\mathrm{Gyr}$

→ possible interactions w/ Galactic gas clouds

→ **MAD around IBHs** even for weakly-magnetized gas accretion

(e.g. Ioka et al.17; Kimura et al. 21)



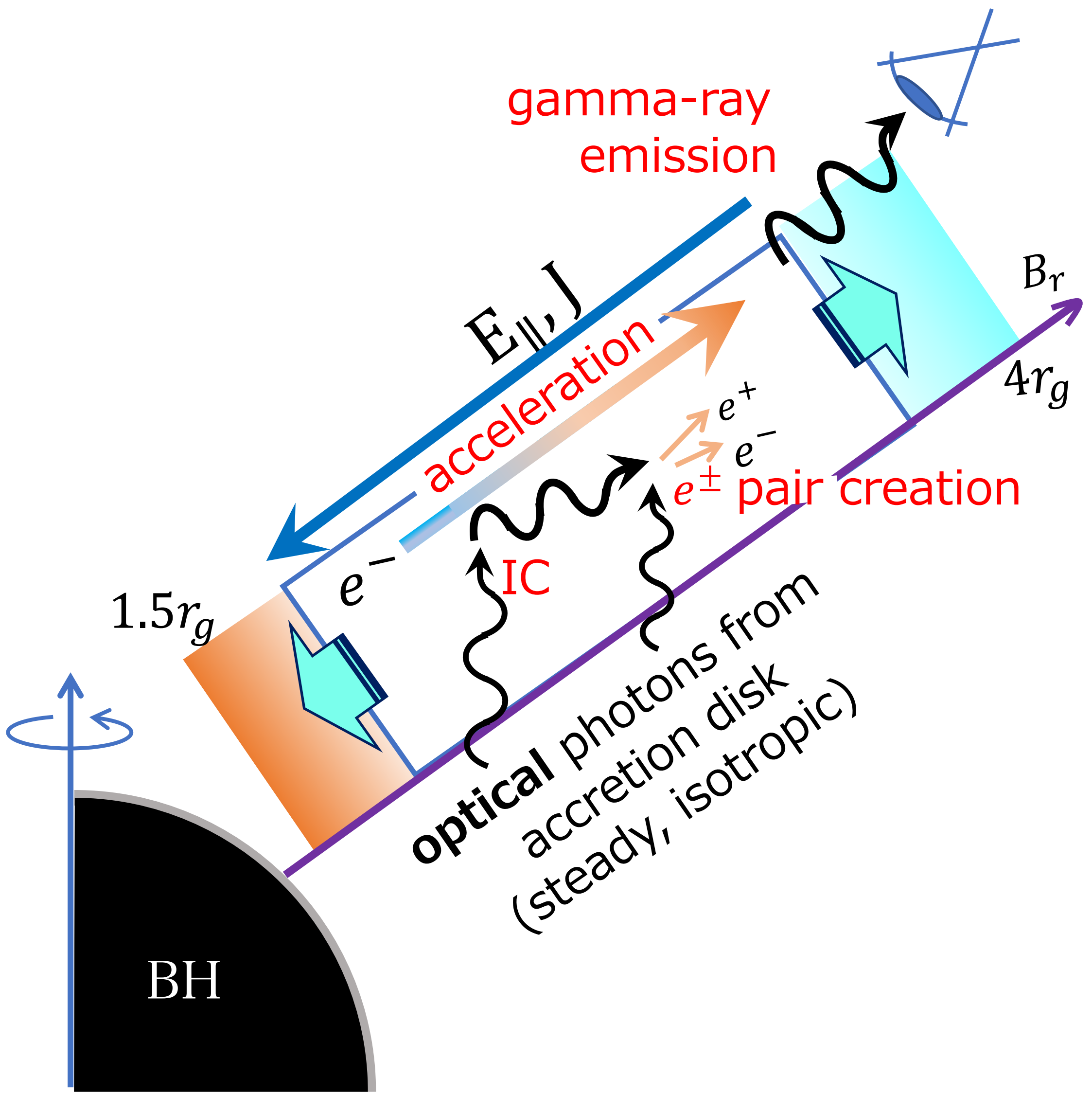
Can we detect gamma rays from IBH "spark gap"?

YES for nearby IBHs

- BH spin, B-field strength → confirming **BH jet theory**

Contents

Simulation Setting



Particle-In-Cell

◎ 1D・GRPIC simulation code

(Levinson & Cerutti18; Kisaka et al.20;22)

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

gravity (inertia term) — acceleration — back reaction of radiation

$$\frac{dp^r}{dt} = -\sqrt{g^{rr}}p^t\partial_r(\alpha) : \text{IC photon trajectory}$$

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

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

◎ IC・secondary pair creation by Monte-Carlo

(NOT 'primary' injection via MeV photon annihilation)

◎ Kerr spacetime

◎ steady, split-monopole B-field

Parameters

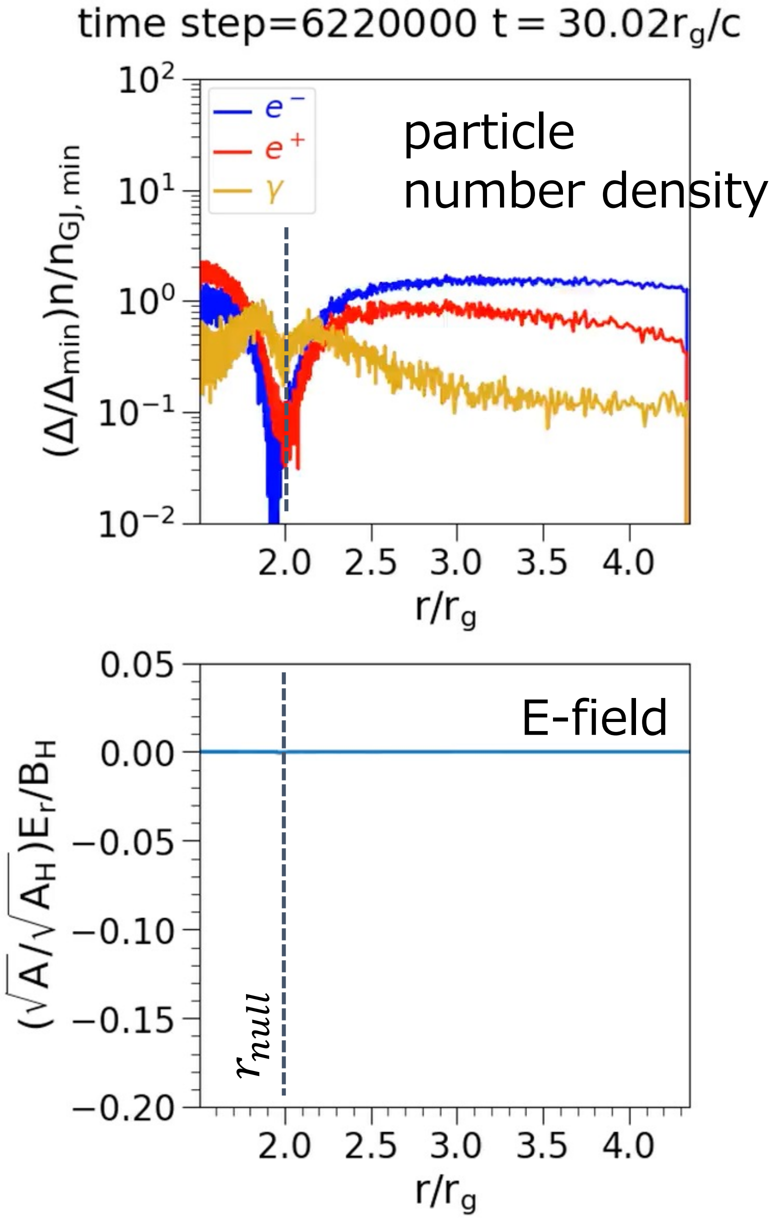
$M = 10M_\odot$, $a_* = 0.9$, $B_H = 2\pi\times10^7$G

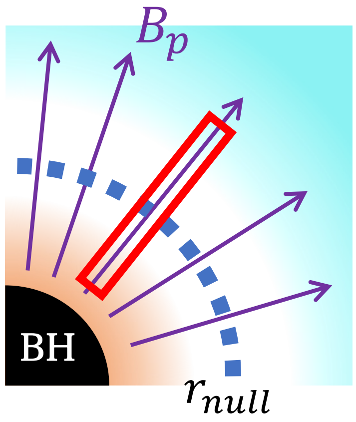
$\theta = 30°$, $1.5r_g \lesssim r \lesssim 4.3r_g$

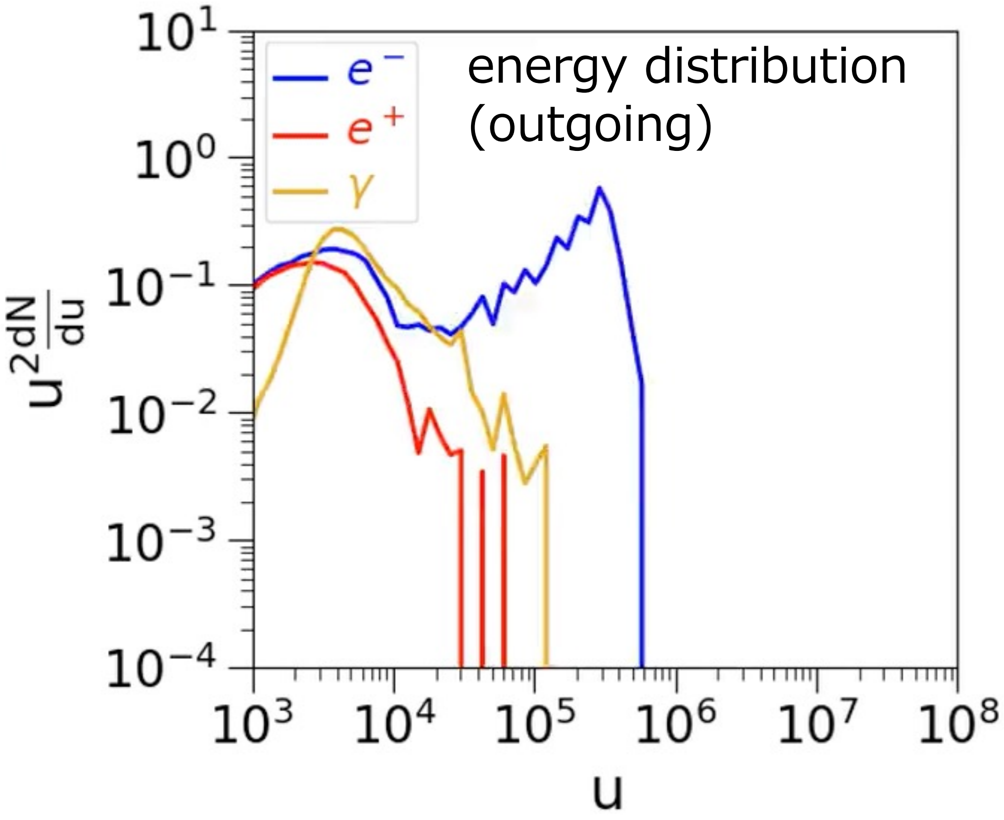
$(r_g = \frac{GM}{c^2} \sim 1.5\times10^6 M_1 \text{cm})$

Simulation Result: Overall Evolution

($\tau_0 = 30$)







(4-velocity, $\sim\gamma$ for relativistic limit)

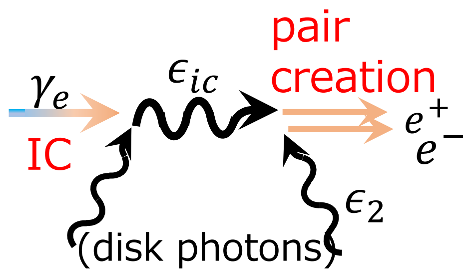
◎**quasi-periodic gap** **(similar to Kisaka 20;22)**

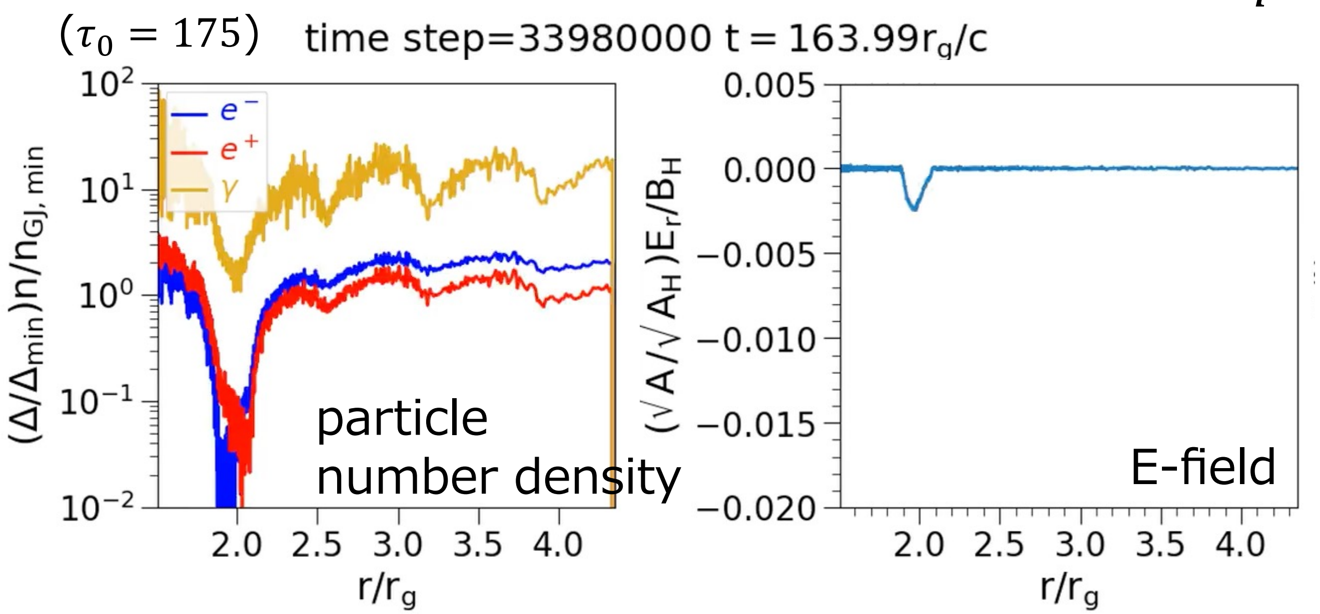
◎$\boldsymbol{\gamma_{e^-,pk} \sim 10^7}$

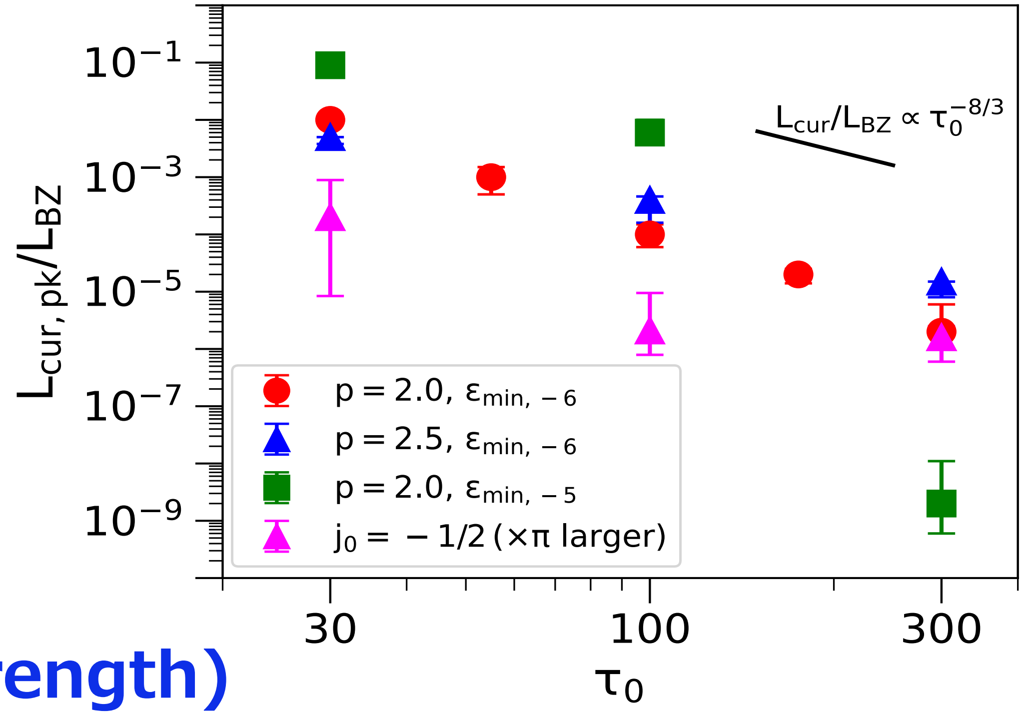
→ **GeV-TeV gamma-rays**

Simulation Result: Disk Photon Intensity Dependence

$\boldsymbol{\tau_0 \approx n_\gamma \sigma_T r_g}$ ∝ **disk photon intensity** : Thomson depth for r_g controlling secondary pair multiplicity ($\tau_{pair} \sim 0.1\tau_0 \times (\epsilon_{ic}\epsilon_2)^{-1}$)







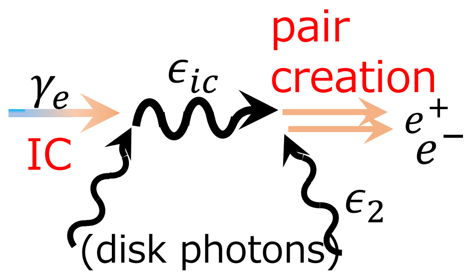
◎ secondary pair multiplicity affects gap dynamics (period, gap size, E strength)

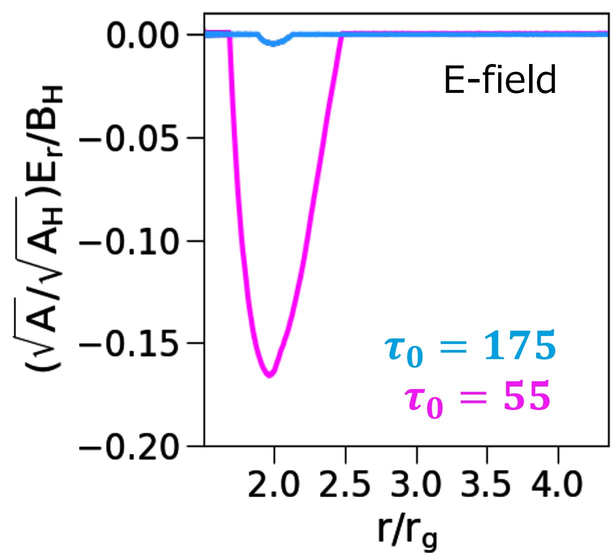
◎ $L_{cur,pk}/L_{BZ} \sim 10^{-1}(\tau_0/30)^{-\alpha}$ ($\alpha \sim 8/3$ for $p = 2.0, \epsilon_{min} = 10^{-6}$)

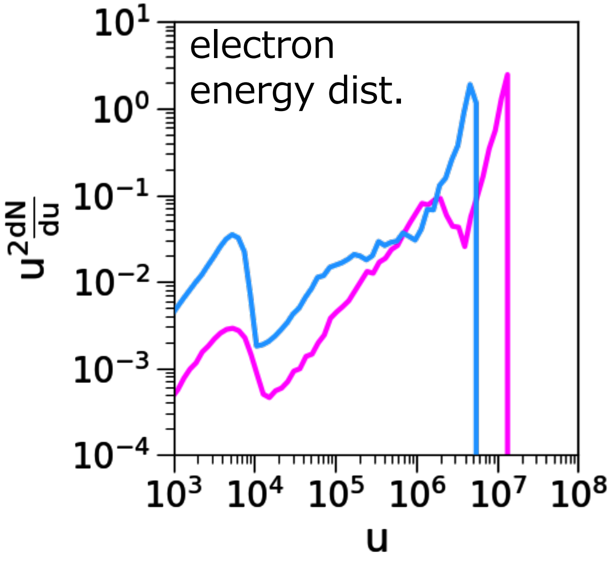
L_{BZ}:BZ luminosity

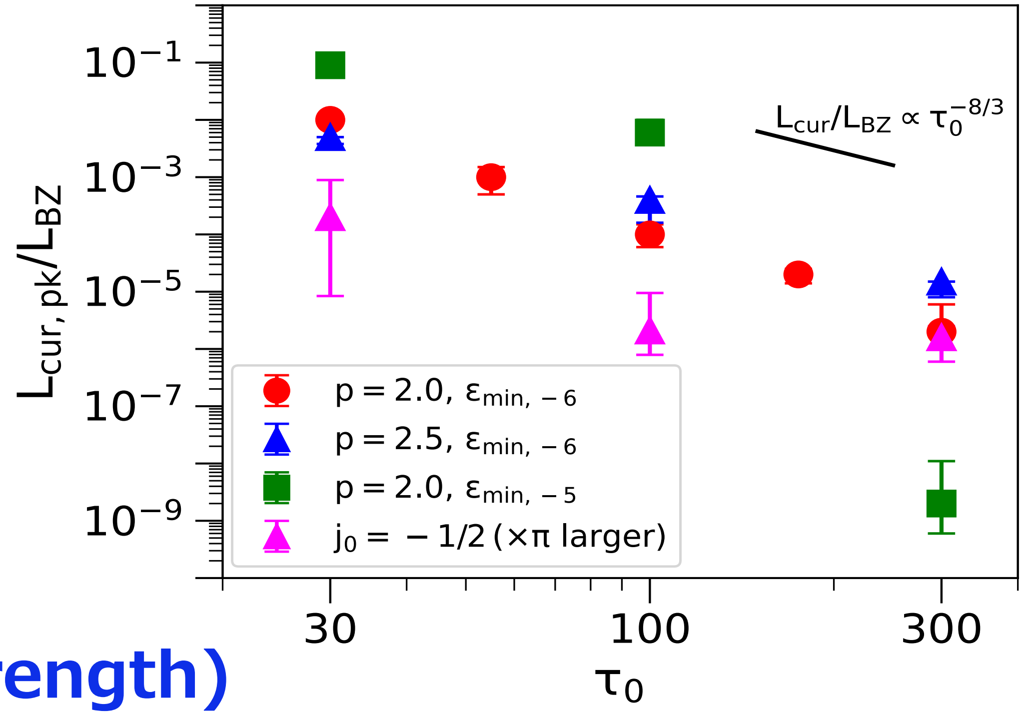
Simulation Result: Disk Photon Intensity Dependence

$\boldsymbol{\tau_0 \approx n_\gamma \sigma_T r_g} \propto$ **disk photon intensity** : Thomson depth for r_g controlling secondary pair multiplicity ($\tau_{pair} \sim 0.1\tau_0 \times (\epsilon_{ic}\epsilon_2)^{-1}$)









◎ secondary pair multiplicity affects gap dynamics (period, gap size, E strength)

◎ $L_{cur,pk}/L_{BZ} \sim 10^{-1}(\tau_0/30)^{-\alpha}$ ($\alpha \sim 8/3$ for $p = 2.0, \epsilon_{min} = 10^{-6}$)

L_{BZ}:BZ luminosity

Contents

Semi-Analytic Model of Averaged Gamma-Ray Emission from Gap

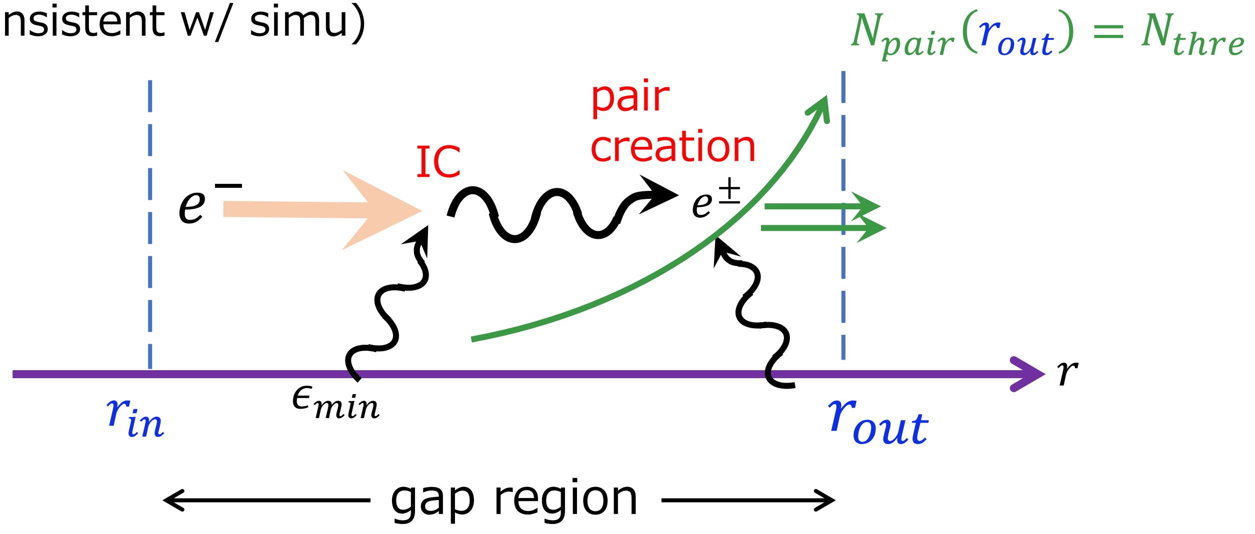
◎predicting gamma-ray emissivity **for wide range of BH mass , gas density**

$\dot{M}(M_{BH}, n_{ISM})$ → one-zone IBH MAD model (Kimura et al.21) → τ_0、 ϵ_{min}、 B_H

assuming Bondi accretion

disk photon peak energy

solve EoM, IC photon transfer, pair creations
→ gap boundaries: enough pairs created (consistent w/ simu)
maximum Lorentz factor γ_{pk}
gamma-ray peak luminosity $L_{cur,pk}$



Semi-Analytic Model of Averaged Gamma-Ray Emission from Gap

◎predicting gamma-ray emissivity **for wide range of BH mass , gas density**

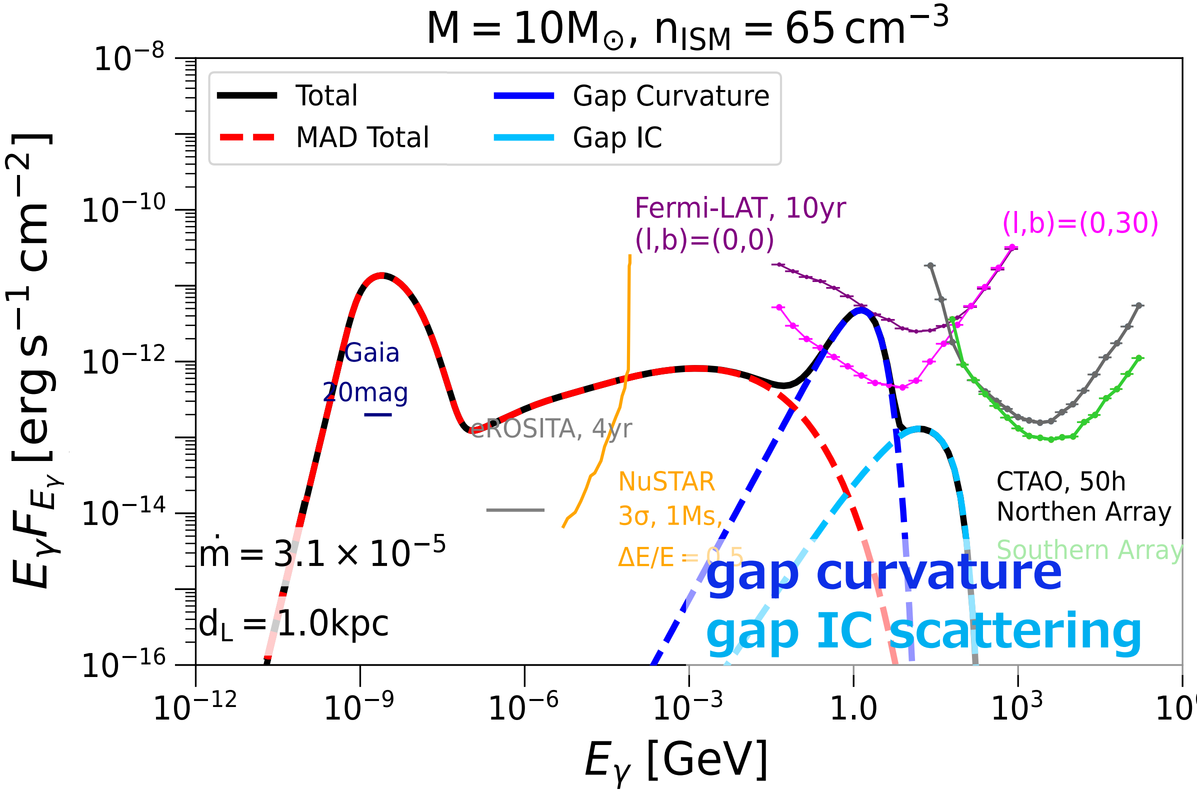
$\dot{M}(M_{BH}, n_{ISM})$ → one-zone IBH MAD model (Kimura et al.21) → τ_0、 ϵ_{min}、 B_H

assuming Bondi accretion

disk photon peak energy

solve EoM, IC photon transfer, pair creations
→ gap boundaries: enough pairs created
maximum Lorentz factor γ_{pk}
gamma-ray peak luminosity $L_{cur,pk}$

calculate **persistent gamma-ray spectra** →



Semi-Analytic Model of Averaged Gamma-Ray Emission from Gap

◎predicting gamma-ray emissivity **for wide range of BH mass , gas density**

$\dot{M}(M_{BH}, n_{ISM})$ ➡ one-zone IBH MAD model (Kimura et al.21) ➡ τ_0、 ϵ_{min}、 B_H

disk photon peak energy

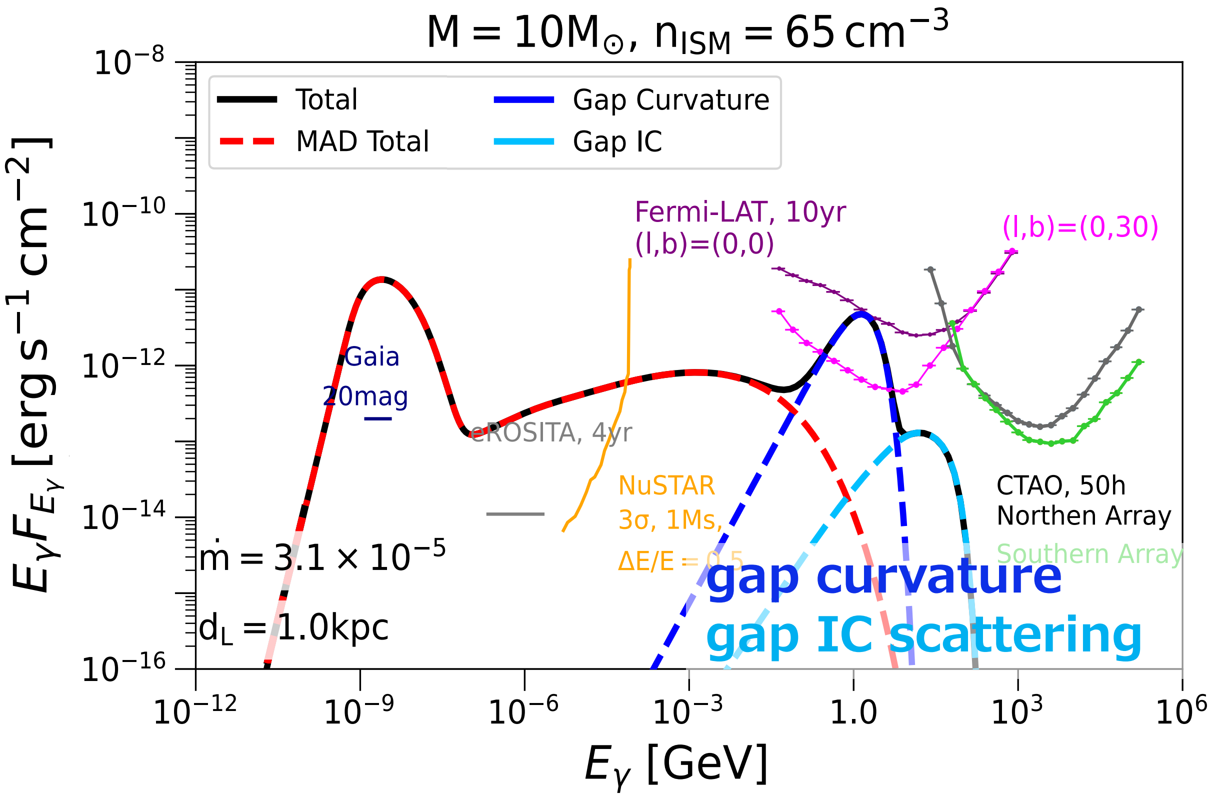
[Submitted on 19 Oct 2023]

1D GRPIC Simulations of Stellar-Mass Black Hole Magnetospheres: Semi-Analytic Model of Gamma-Rays from Gaps

Koki Kin, Shota Kisaka, Kenji Toma, Shigeo S. Kimura, Amir Levinson

(Kin et al. submitted; arXiv:2310.12532)

GeV-TeV gamma-ray emission detectable from ~kpc

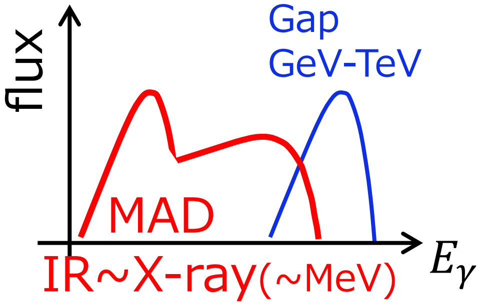


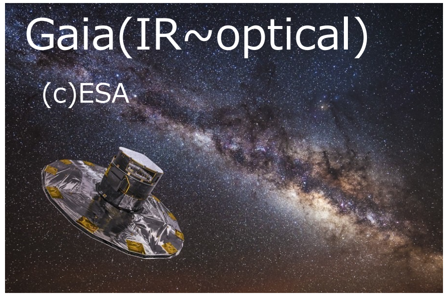
Discussion: strategy

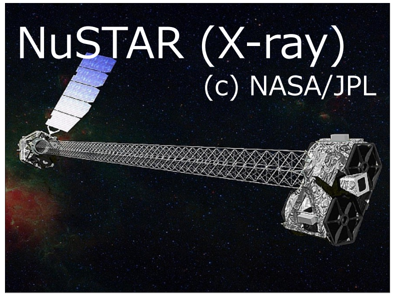
◎peak in GeV-TeV → **Fermi-LAT unIDs**

criteria :
- hard spectral index ($dN/dE_\gamma \propto E_\gamma^{-\Gamma}$, $\Gamma \sim 2/3$)
- spectral break
- point source, association w/ gas clouds

◎cross-correlation w/ **MAD signals in IR~X-ray**

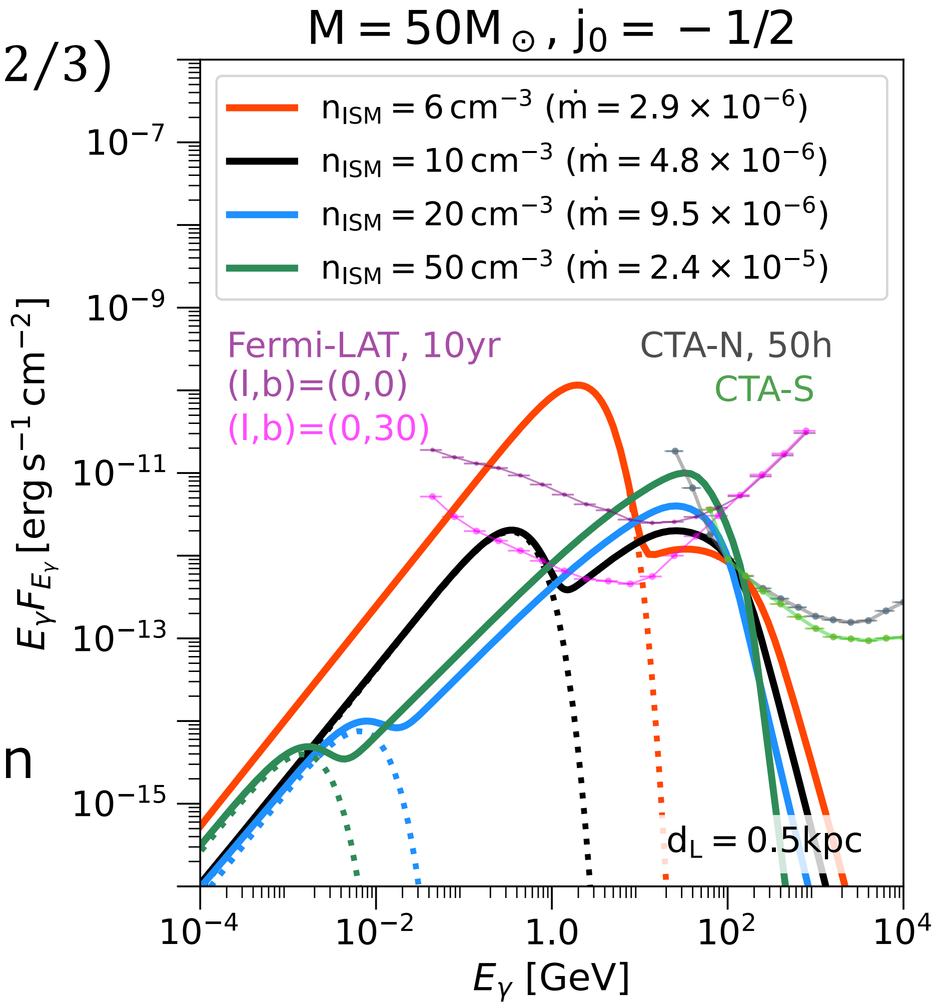






◎$L_{GeV} \propto \dot{M}^{-3} \propto n_{ISM}^{-3}$ → detecting $\sim 10^{\pm 2}$ luminosity variation

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



Summary

◎Research Motivation: finding undetected isolated BHs through **gamma-ray** observation

gas infall → formation of **BH magnetosphere**, particle acceleration in **spark gap**?

◎Method: analyze plasma dynamics & gamma-ray characteristics using

1D GRPIC simulation + semi-analytic modeling

GeV-TeV gamma rays from BH gap detectable from ~kpc

~a few in Fermi-LAT unID objects, cross-correlation w/ opt~X-ray

luminosity variation w/ ~yr timescale?

◎Model uncertainty: J_0 fluctuation timescale, lensed photons affect luminosity/lightcurve

$\dot{M}$ calculation

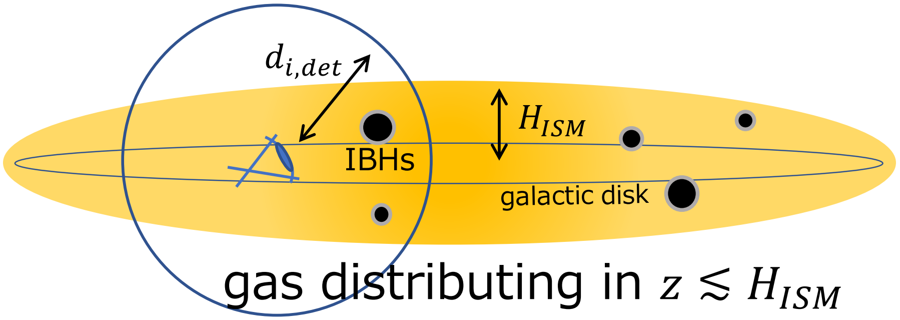
◎Future work: candidate search, multi-D simulation

Back up

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

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

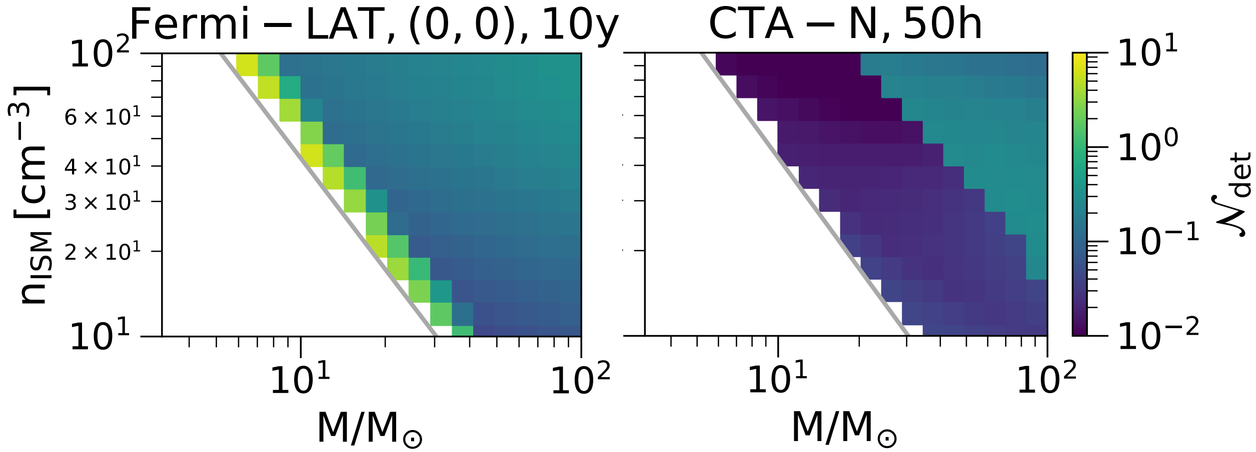
sensitivity limit $d_{i,det}$: luminosity vs sensitivity



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

$$\therefore \mathcal{N}_{det} \sim n_0 \xi_0 \frac{1-\gamma}{M_2^{1-\gamma} - M_1^{1-\gamma}} M^{1-\gamma} 2\pi H_{ISM} d_{i,det}^2 \simeq 3.7 \left(\frac{d_{i,det}}{5\mathrm{kpc}}\right)^2 \left(\frac{M}{50 M_\odot}\right)^{1-\gamma}$$

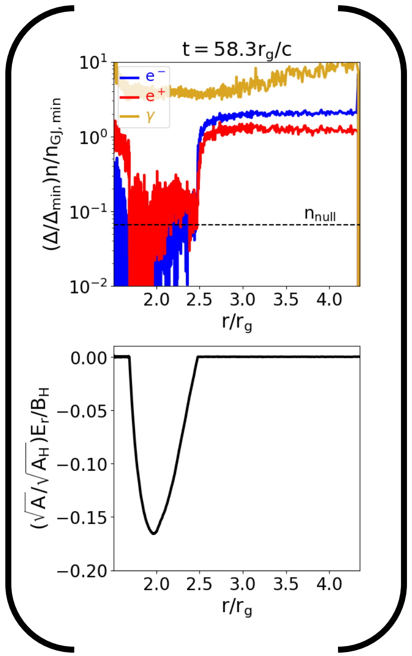
(
$\frac{dN}{dM} \propto M^{-\gamma}$ ($\gamma \sim 2.6$ Abbott et al.21)
ξ_0 : Volume filling factor
$n_0 \sim \mathcal{R}_{GW} n_{gal}^{-1} H_0^{-1} \sim 2\times 10^2 \mathrm{kpc}^{-3}$: merged BH density
)

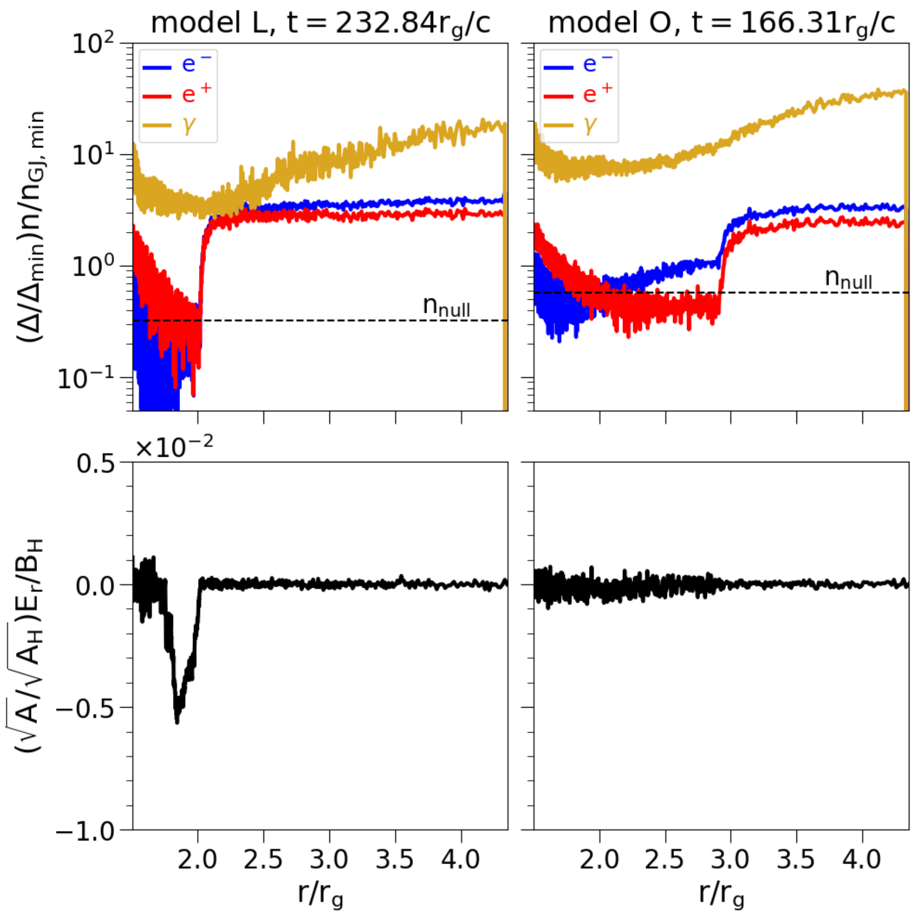


Simulation Results : higher J_0

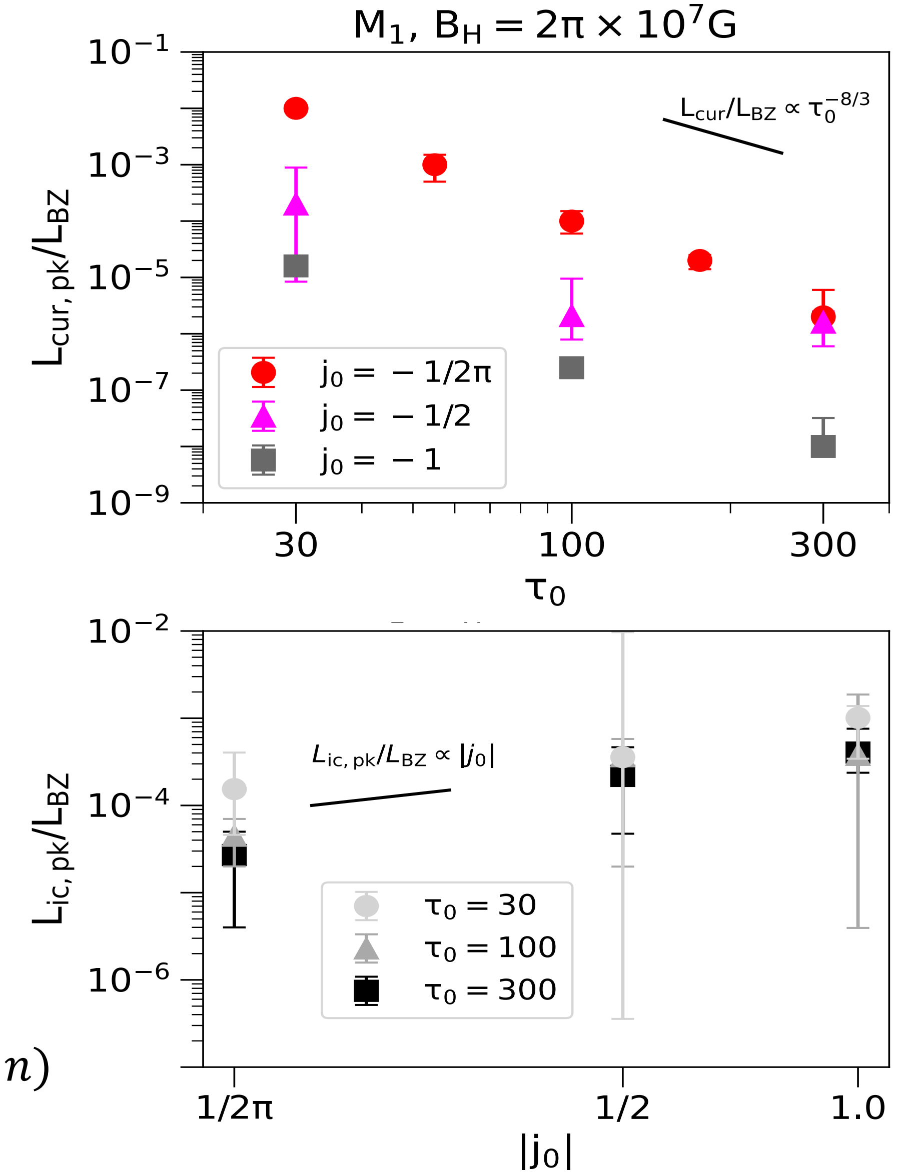
$(j_0 \equiv J_0/|J_{BZ}|)$

$j_0 = -1/2\pi$





$j_0 = -1/2$ $j_0 = -1$



higher n in gap → E_r ↘ ($\gg 10^{-2}B_H$) → L_{cur} ↘, but $L_{ic} \propto |j_0|(\propto n)$