Magnetospheric GeV-TeV emission from Galactic isolated stellar-mass black holes

(KK et al. 2024 ApJ; KK et al. 2025 accepted, **arXiv 2502.09181**)

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2025.4.8 @Ecole de physique des Houches

TOHOKU UNIVERSITY

Theoretical Astrophysics Tohoku University

@ St.Louis in June last year

Detection of Galactic stellar-mass BHs

$\sim 10^8 - 10^9$ expected from star-formation history
(cf. e.g., Timmes et al. 96; Caputo et al. 17; Olejak et al. 20)

◎ as X-ray binaries ⋯ ~70 so far、~20 specified as BHs

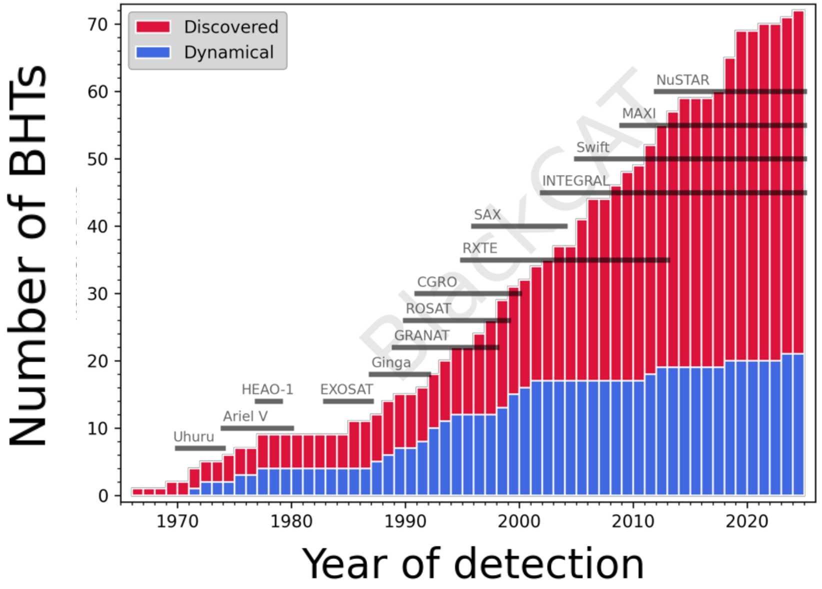
◎ Gaia BH 1, 2, and 3

(El-Badry et al. 23a,b; Tanikawa et al. 23; Balbinot et al. 24)

→ both binaries

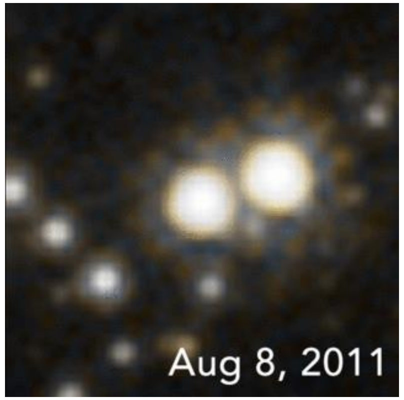
◎ <u>isolated</u> BHs ⋯ only 1 microlensing event
(MOA-2011-BLG-191/OGLE-2011-BLG-0462 ; Sahu et al. 22)

(https://www.astro.puc.cl/BlackCAT/index.php)



Detectability: EM radiation during ISM accretion

- accretion disk/out flow (Fujita et al. 1998; Tsuna et al. 18; Tsuna & Kawanaka 19; Kimura et al. 21)
- relativistic jets (Fender et al. 2013; Ioka et al. 17)
- PeV CRs production, inelastic collision in ambient gas (Kimura, incl. KK et al. 25)



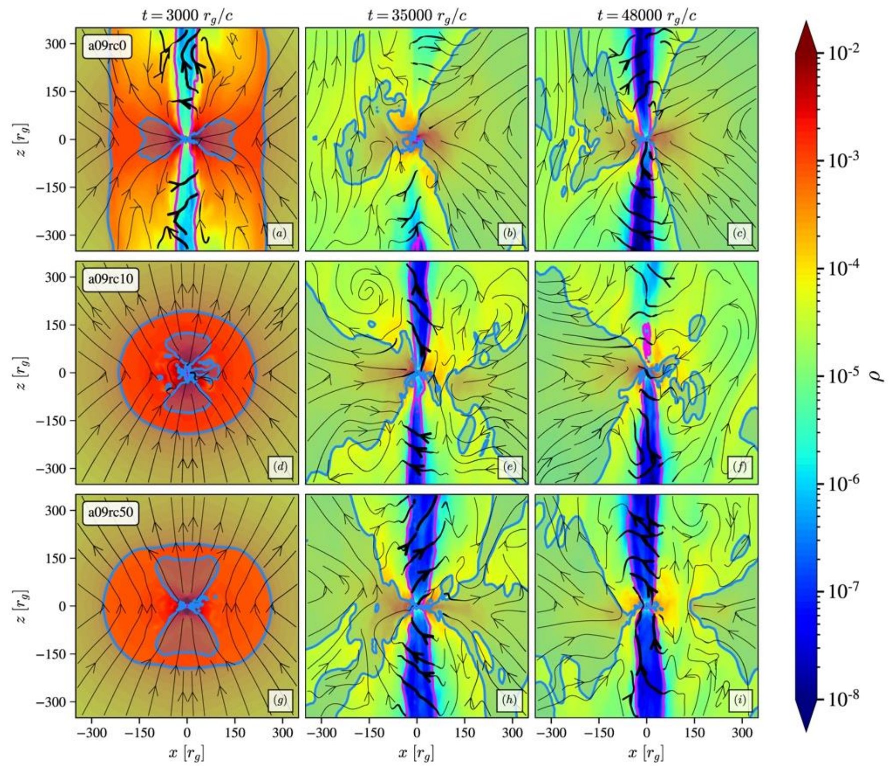
IBH-MADs/magnetosphere formation?

$$r_{BHL} = \frac{GM}{c_{s,ISM}^2 + v_{BH}^2} \sim 0.1 \text{ AU}$$

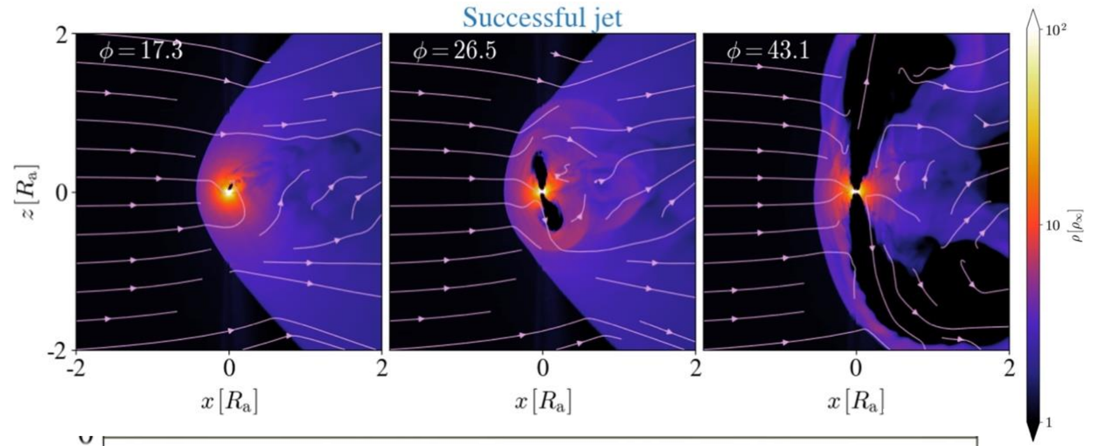
◎ heuristic: $2\pi r_{BHL}^2 B_\infty \sim 2\pi (10 r_g)^2 B \quad \therefore B \sim 10^7 (B_\infty/\mu\text{G})(v_{BH}/50 \text{ km s}^{-1})^{-4} \text{ G}$, strong enough to be MAD

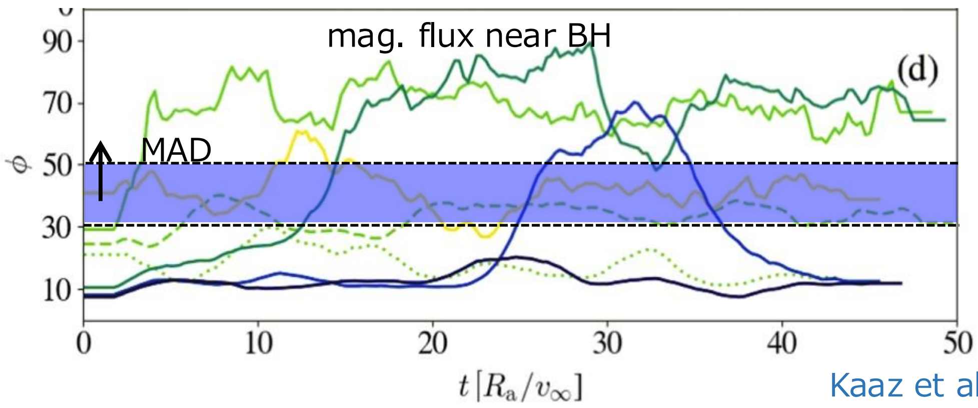
◎ 3D GRMHD: MAD formed nearby of IBH during BHL accretion

→ **magnetosphere (& jet) formation?**



Kwan et al.23





Kaaz et al. 23

IBH magnetospheric spark gap?

◎ steady plasma injection required to maintain current & screen $E_{||}$

◎ main injection channel: disk photon annihilation inside the magnetosphere

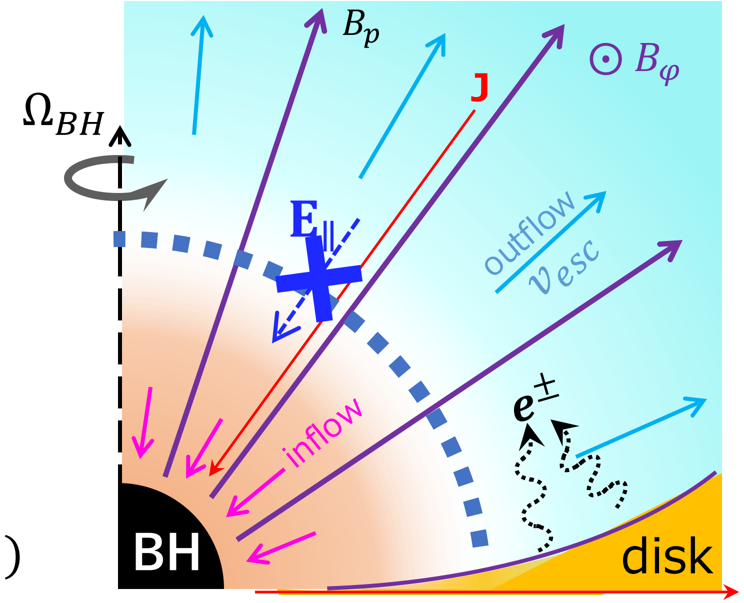
→ $n_{\pm}(\dot{M}) \lesssim n_{GJ}$ for sub-Eddington accration rate

(Levinson & Rieger 11; Levinson & Segev 17; Hirotani & Pu 16, but see also Wong et al. 21)

$\dot{M} = \lambda_w 4\pi (GM)^2 m_p n_{ISM} / (c_s^2 + v_{BH})^{3/2}$ (Bondi-Hoyle-Littleton rate)

$\simeq 10^{14} \lambda_{w,0} M_{10M_\odot}^2 n_{ISM,10\,\mathrm{cm}^{-3}} v_{BH,10\mathrm{km\,s}^{-1}}^{-3}\ \mathrm{g\,s^{-1}} \ll \dot{M}_{Edd} (\simeq 10^{18} M_1\ \mathrm{g\,s^{-1}})$

cf. Blandford & Znajek 1977



spark gap formation expected during ISM accretion onto IBHs
→ **efficient acceleration, gamma-ray emitted?**

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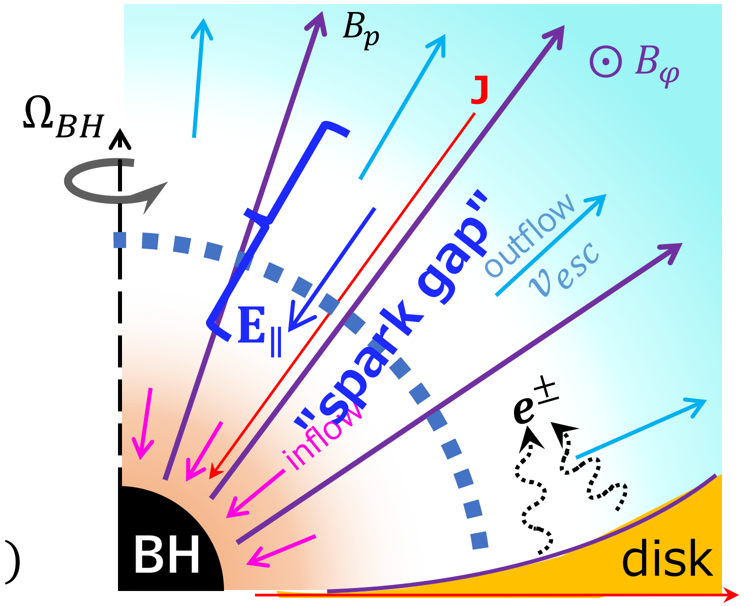

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1DGRPIC: stellar-mass BH model

(see KK et al. 24 ApJ; KK et al. 25 accepted for details)

◎ **1D GRPIC** code (grzeltron; Levinson & Cerutti18)

parameters: $M = 10M_{\odot}, B_0 = 2\pi \times 10^7\text{G},$

$\theta = 30°,\ \epsilon_{s,min} = 10^{-6} m_e c^2,\ \boldsymbol{a} = \{\mathbf{0.1, 0.5, 0.9}\}$

solve IC, pair production

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

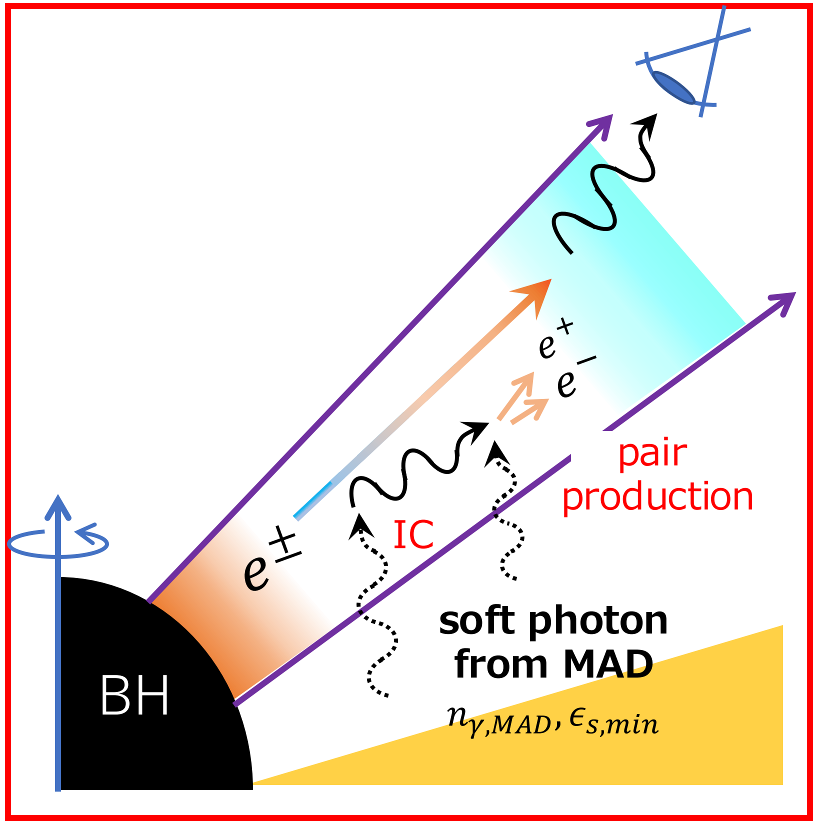
Basic eqs.:

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

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

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

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



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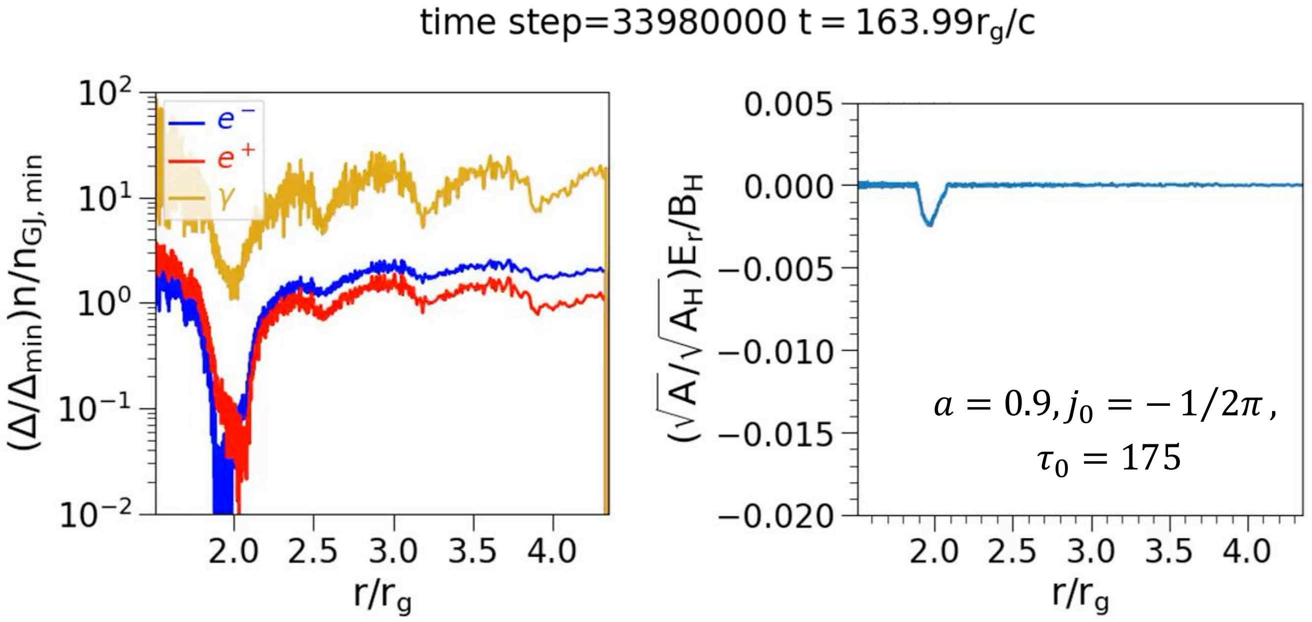

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solve IC, pair production

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

results:

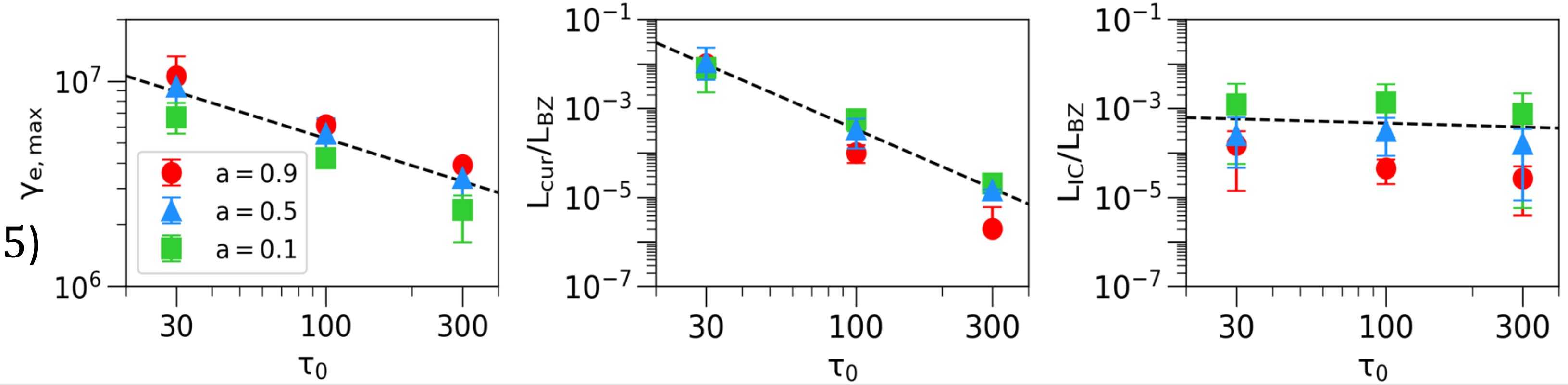
- oscillating gap around ~2r_g (~null surface) for $\tau_0 \gtrsim 30$
- gamma-ray luminosity

  depends on τ_0

$\gamma_{e,max} \sim 10^7(\tau_0/30)^{-\alpha}(\alpha \sim 6/5)$

$L_{cur,pk}/L_{BZ} \sim 10^{-2}(\tau_0/30)^{-\beta}$ (β~ 14/5)

$L_{IC,pk}/L_{BZ} \sim 10^{-4}(\tau_0/30)^{-\gamma}$ (γ~ 1/5)



IBH-MAD/spark gap multi-wavelength radiation model

(KK et al. 2025, accepted)

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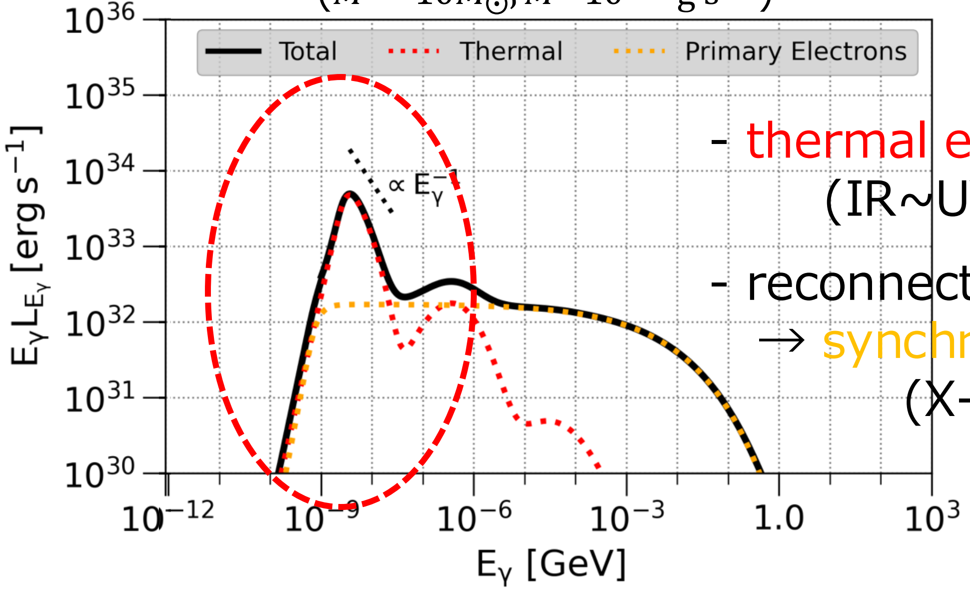
$B_H = \phi\sqrt{\dot{M}c}/2\pi r_g^2 \simeq 10^7 \phi_{50} M_{10M_\odot}^{-1} n_{ISM,10\mathrm{cm}^{-3}}^{1/2}\ \mathrm{G}$ (cf. e.g., Tchekhovskoy et al. 2011)

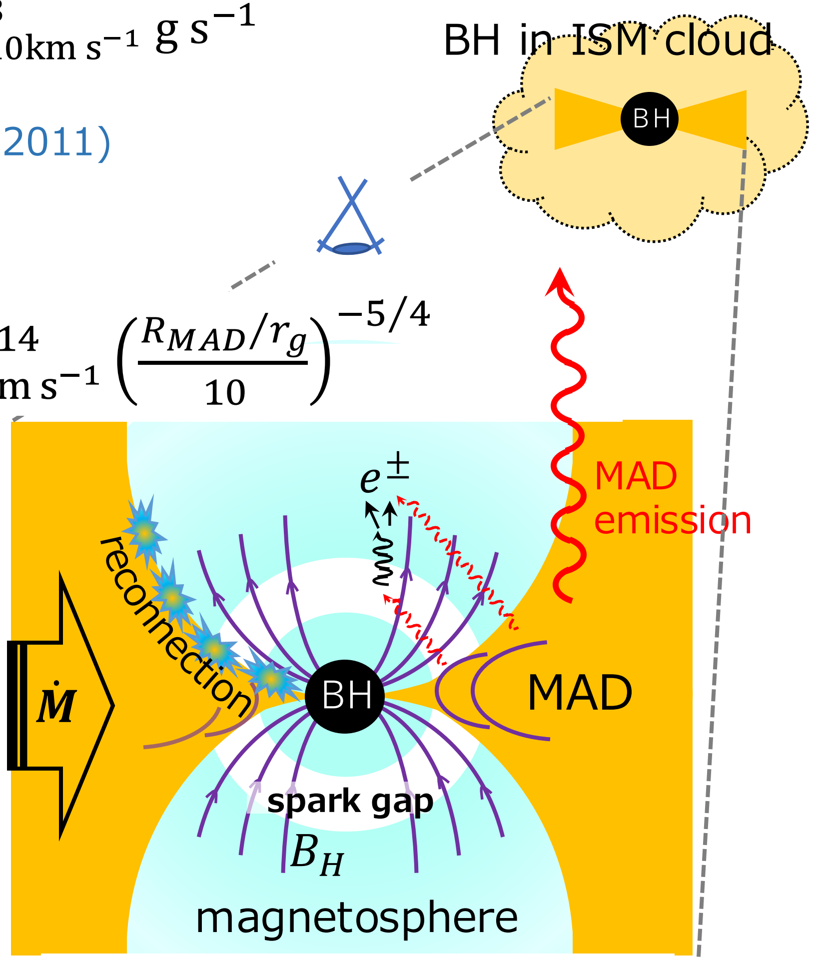
◎ MAD radiation: one-zone model (Kimura et al. 21)

$\rightarrow \tau_0 \sim L_{syn,pk}/\pi R_{MAD}^2 E_{\gamma,syn,pk}\, c\, \sigma_T r_g \simeq 50 M_{10M_\odot} n_{ISM,10\mathrm{cm}^{-3}}^{9/14} v_{BH,10\mathrm{km\,s}^{-1}}^{-27/14} \left(\frac{R_{MAD}/r_g}{10}\right)^{-5/4}$

$(M = 10M_\odot, \dot{M} \sim 10^{-14}\mathrm{g\,s}^{-1})$



- thermal electron synchrotron・IC (IR~UV)
- reconnection (or turbulent) acceleration → synchrotron from NT electrons (X-ray~MeV)



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

$\tau_0, E_{\gamma,syn}, L_{syn}$

◎ **spark gap gamma-rays**:

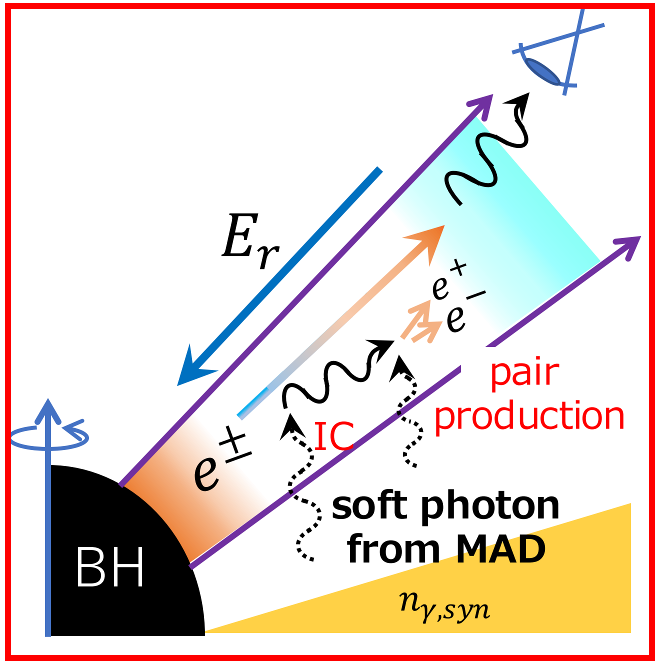
- Curvature emission from gap-accelerated particles
- IC from secondary-pairs

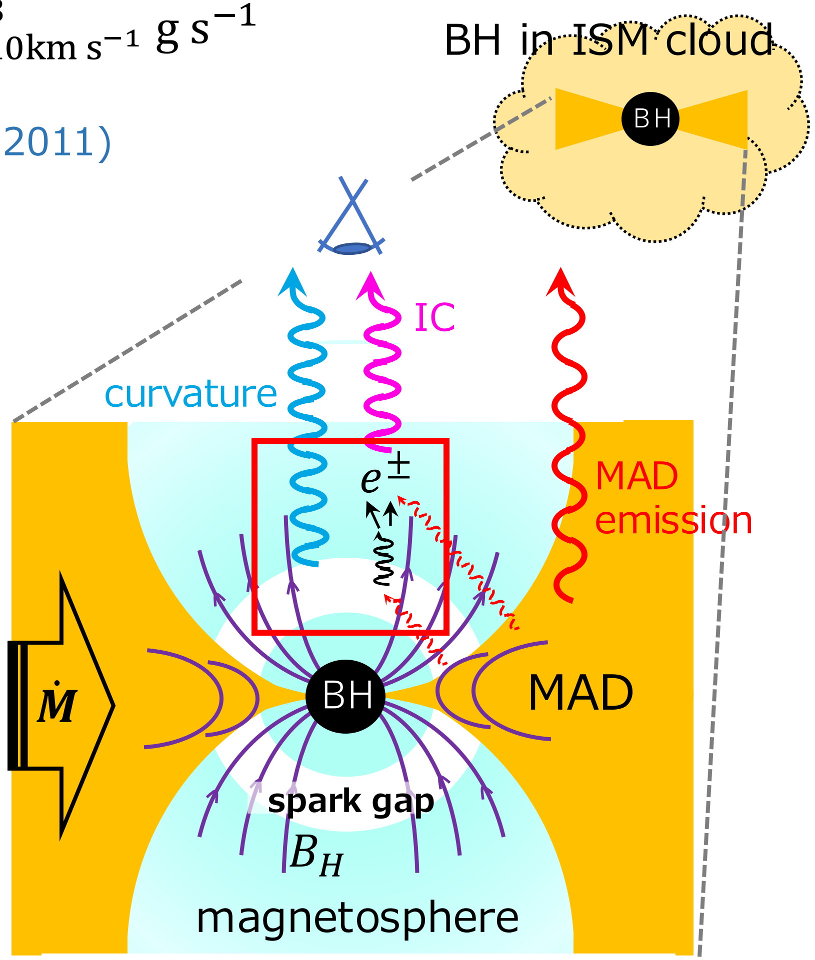
empirical relation from simu.:

$\gamma_e \sim 10^7 (\tau_0/30)^{-\alpha} (\alpha \sim 6/5)$

$L_{cur,pk}/L_{BZ} \sim 10^{-2} (\tau_0/30)^{-\beta}$ (β~ 14/5)

$L_{IC,pk}/L_{BZ} \sim 10^{-4} (\tau_0/30)^{-\gamma}$ (γ~ 1/5)





IBH-MAD/spark gap multi-wavelength radiation model

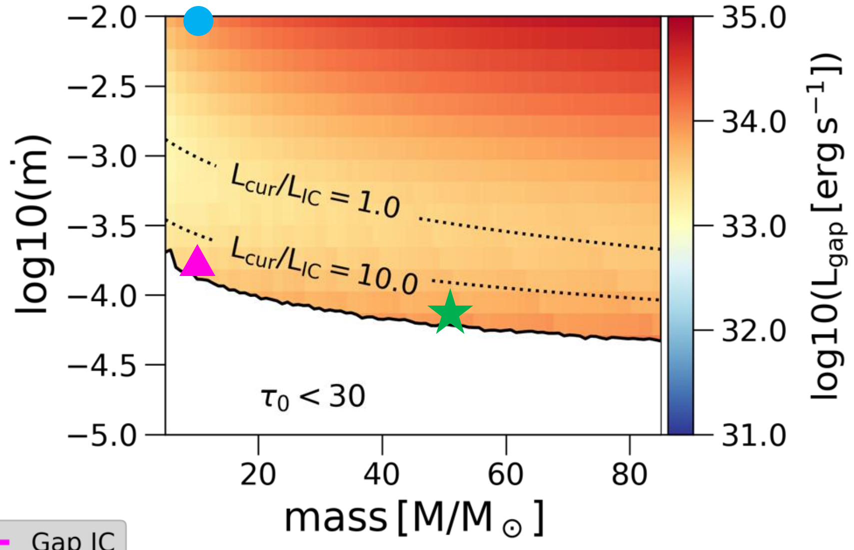
(KK et al. 2025, accepted)

◎ bright in optical-X-(MeV)-100GeV

◎ spark gap active for $10^{-5} \lesssim \dot{m} = \dot{M}/\dot{M}_{Edd}$ ($\lesssim 10^{-2}$)

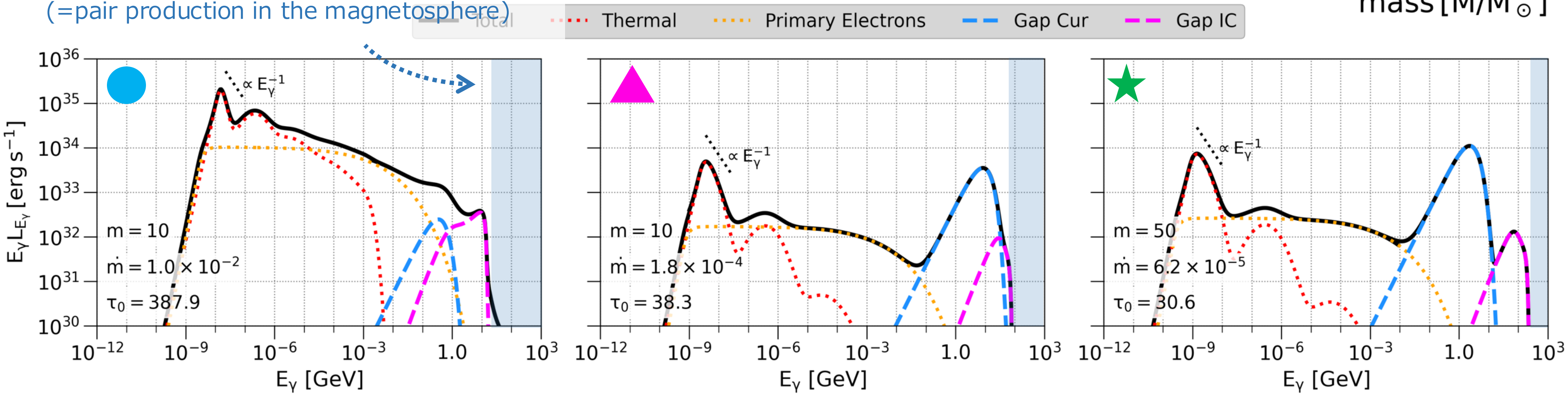
◎ $L_{gap} = L_{cur} + L_{IC} \sim 10^{-2} - 10^{-4} L_{BZ}$ ($\sim \dot{M}c^2$)

$\rightarrow F_{gap} \sim 10^{-10}\, M_{10M_\odot}^{2}\, n_{ISM,10\,\mathrm{cm}^{-3}}\, v_{BH,10\mathrm{km\,s}^{-1}}^{-3}\, \mathbf{d_{1kpc}^{2}}\, \mathrm{erg\,s^{-1}\,cm^{-2}}$



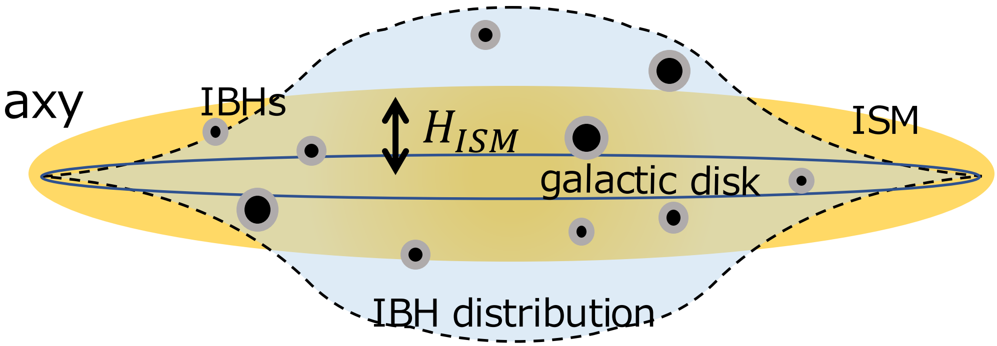
$a = 0.9$

annihilation
(=pair production in the magnetosphere)



Detection number calculation

(KK et al. 2025, accepted)

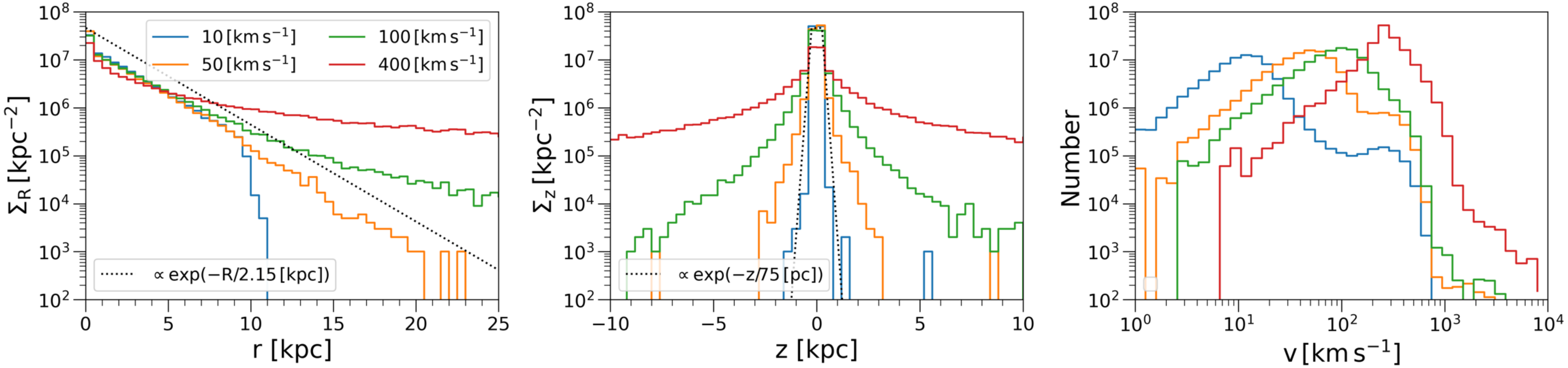


1. dynamical calculation to obtain IBH positions/v_{BH} in Galaxy
   (cf. Tsuna et al. 18)
   - initial kick: 3D MB dist. , $v_{avg} = \{10, 50, 100, 400\}\ \mathrm{km\,s^{-1}}$

→ How many IBHs are in specific phase of ISM?

$\dot{M}(M, n_{ISM}, v_{BH})$

ISM Phase	⋯	$H_{\rm ISM}$ [kpc]
Molecular Clouds		0.075
Cold HI		0.15
Warm HI		0.5
⋯		

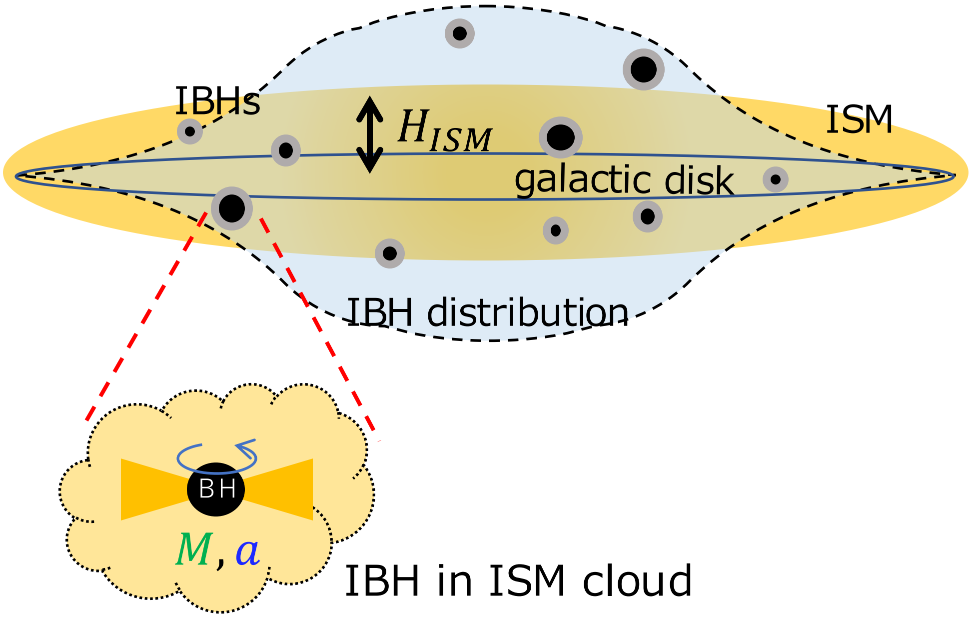


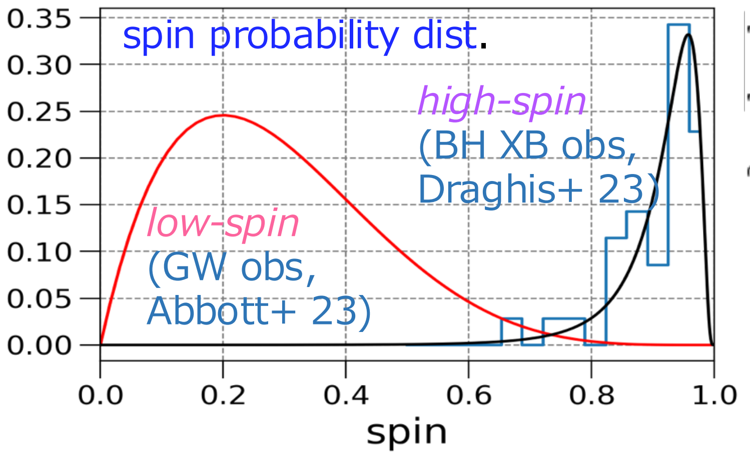
Detection number calculation

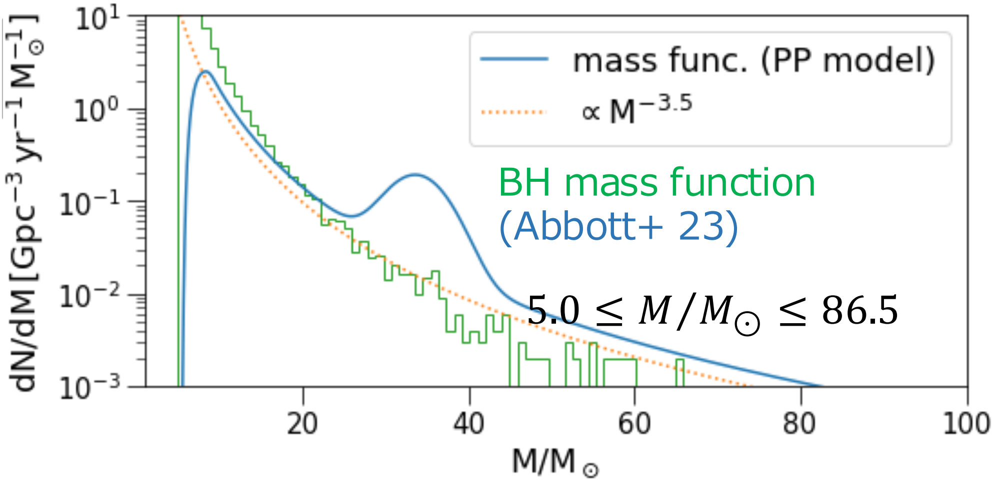
(KK et al. 2025, accepted)

2. give each IBH mass and spin, derive gamma-ray flux for given n_{ISM}:

$$F_{GeV-TeV} = L_{GeV-TeV}\left[\tau_0\left(\dot{M}(M, n_{ISM}, v_{BH})\right), L_{BZ}(a)\right]/4\pi d_{BH}^2$$







ISM Phase	n_{ISM} [cm^{-3}]
Molecular Clouds	$10^2, 10^3$
Cold HI	10
Warm HI	0.3

Detection number calculation

(KK et al. 2025, accepted)

◎ result :

- maximum number achieved for $v_{avg} < 10^2 \mathrm{km\,s^{-1}}$ & *high-spin*

  Fermi-LAT @~10GeV: ~500 (≲10% of current un-IDs) , H.E.S.S. @~100GeV: ~10 (〃) ,

  CTA @~100GeV : ~50

- sensitive dependence

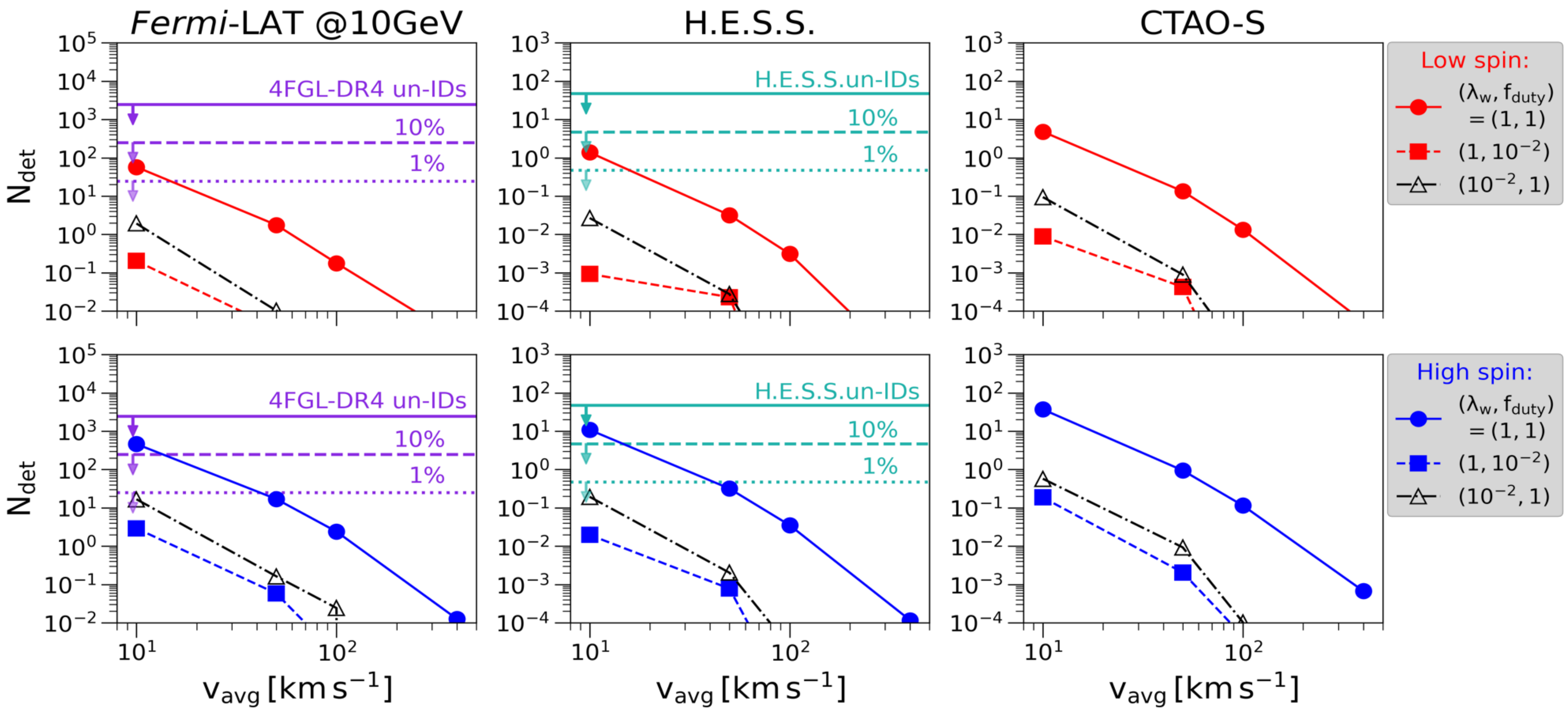
  on v_{avg} , spin dist.

  → N_{det} may put a constraint

  both on v_{avg} & spin

- considerable contribution

  to GeV diffuse emission



Summary

◎Motivation: **IBHs can possess MADs/magnetospheres during ISM accretion**

◎**1D GRPIC stellar-mass model** (KK et al. 24; see also Levinson & Crutti 18; Kisaka et al. 20;22)

- spark gap formation (consistent w/ previous works; cf. e.g., Chen et al. 20)
- efficient GeV-TeV emission ($L_{GeV-TeV} \sim 10^{-2} L_{BZ}$ at maximum)

◎IBH-MAD/spark gap radiation analytic model・detection number estimate (KK et al. 25 accepted, **arXiv 2502.09181**)

- at maximum $\sim \boldsymbol{a\ few\ 10^2}$ **as 10-100GeV un-IDs (~10%)**
- can be third-party of GeV diffuse emission, may put constraint on kick velo、BH spin dist.

(related topic: IBHs as PeVatrons, LHAASO "dark" sources? (Kimura, incl. KK et al. 2025, ApJL))

◎future work:

- time-dependency, co-evolution analysis using 2D GRPIC code (in progress)

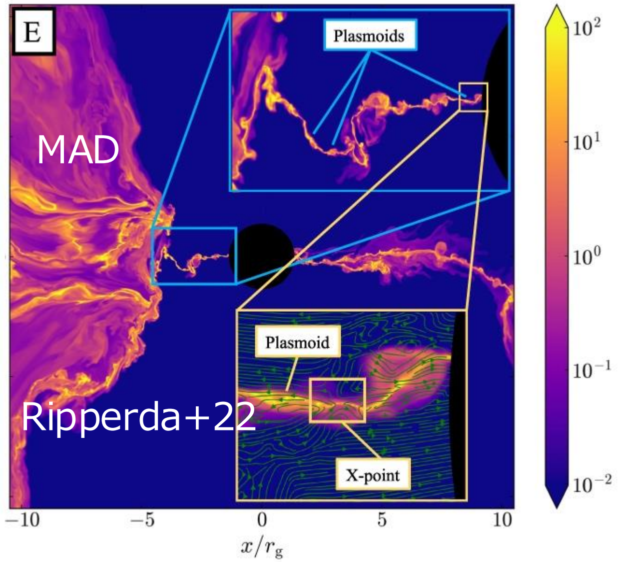
On-going : investigating gap time dependency & co-evolution

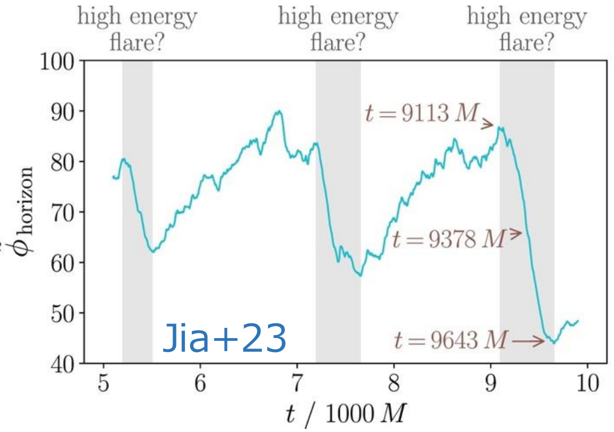
◎ reconnection @ equatorial plane w/ $\sim 10^3\, r_g/c$ duty cycle (e.g. Ripperda et al. 2022)

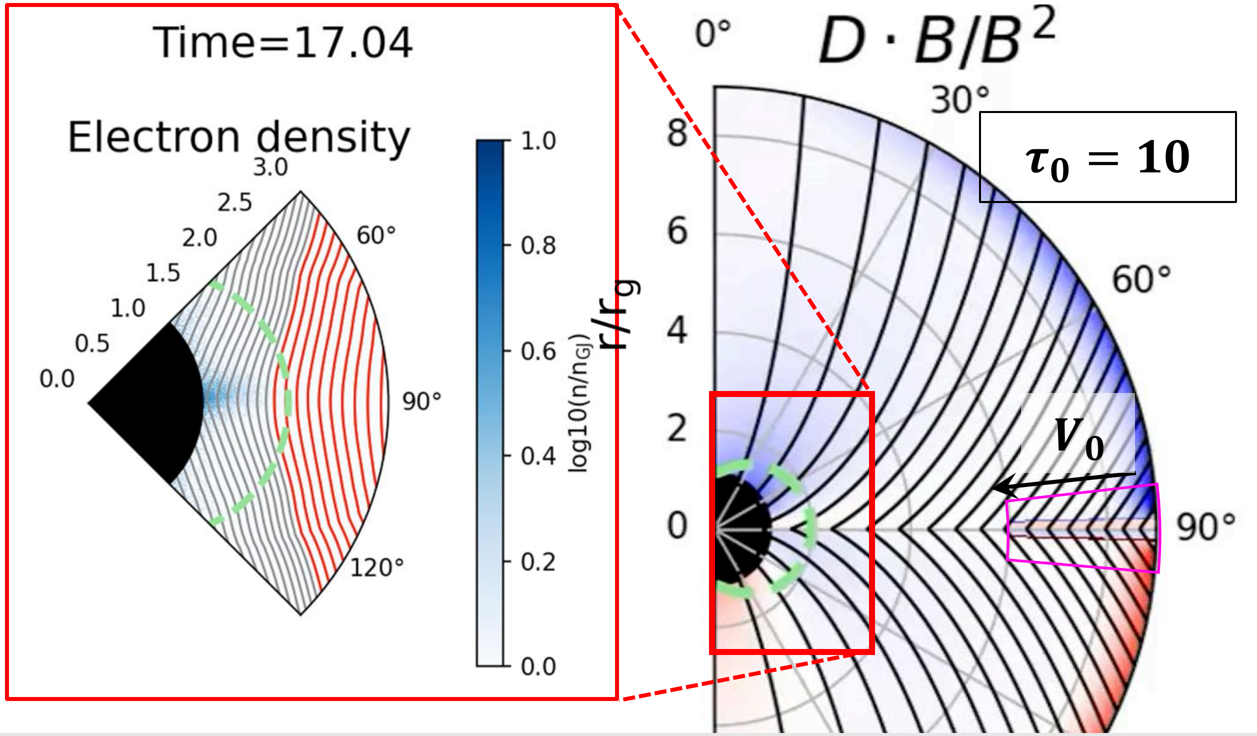
spark gap can be affected? :

- change electric current、cyclic particle acceleration b/w gap & current sheet ? (Vos et al. 2025)

→ **analysis focussing on gap & reconnection co-evolution required to discuss spark gap gamma-ray feature**





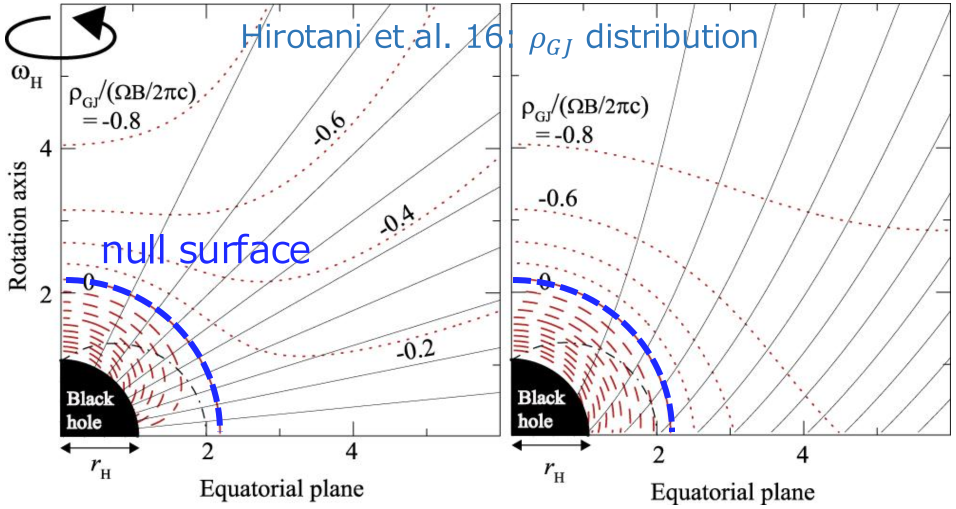


Back up

IBH-MAD/spark gap multi-wavelength radiation model

◎ few notes:

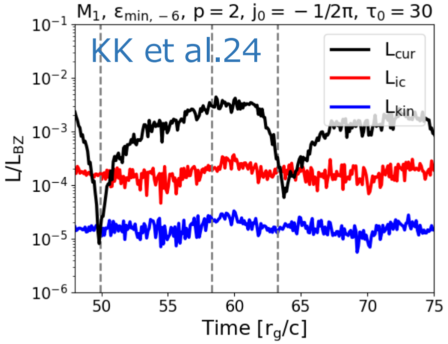
- assuming isotropy for both MAD & gap emission
  - spherical null surface (at least for monopole-like B-field)
  - very weak scattering/absorption via MAD plasma, ambeint cloud

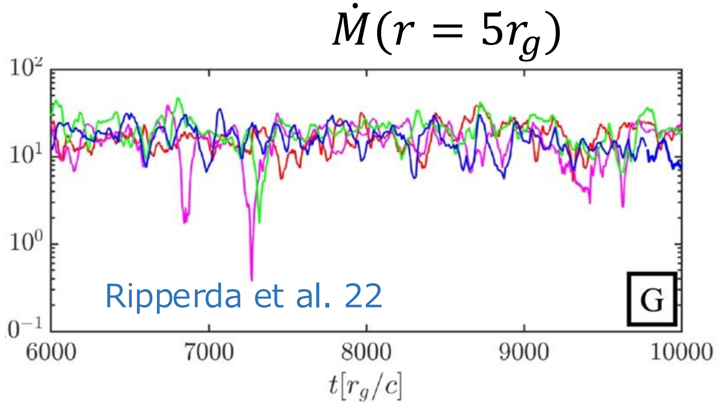


- indecomposible spark gap fluctuation
  - $t_{gap} \sim \tau_{\gamma\gamma}^{-1}\, r_g/c \sim 1-10\, r_g/c \sim 1-10\, M_1$ ms
  - $t_{disk} \sim t_{vis} \sim \frac{2\pi}{\alpha\Omega_K}\left(\frac{R}{H}\right) \sim 0.1-1\alpha_{-0.5}^{-1}\mathcal{R}_1^{7/2}\left(\frac{H}{0.5R}\right)^{-2} M_1$ s

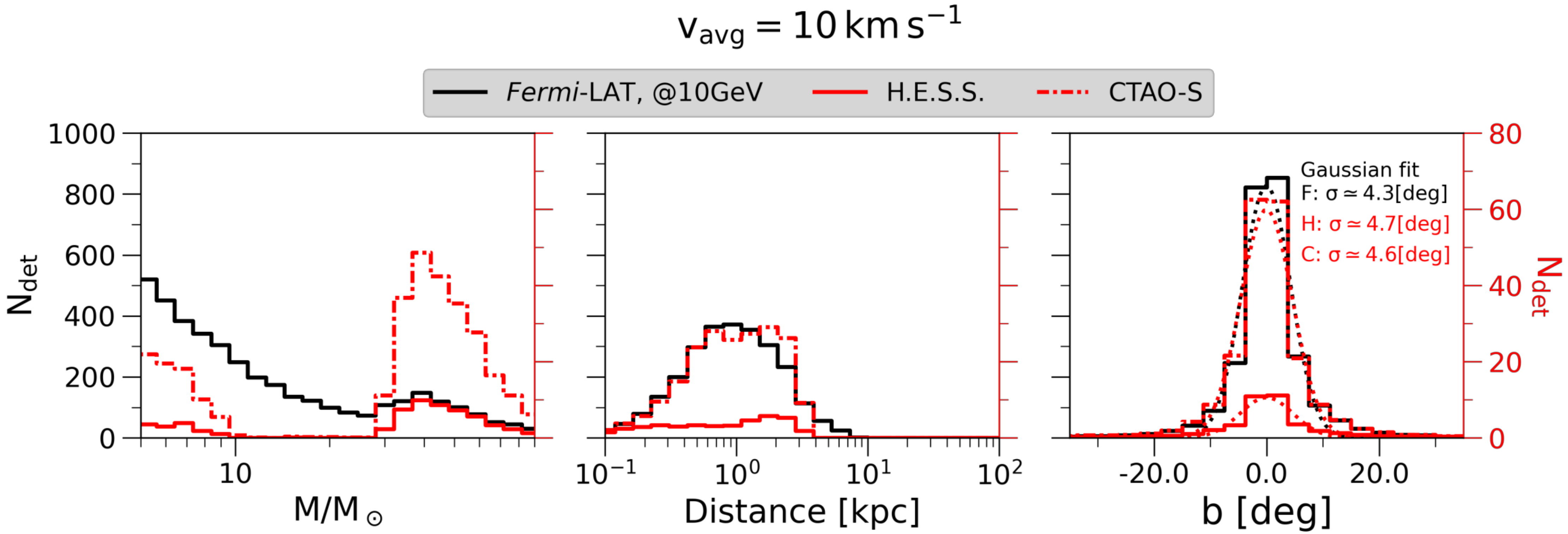
→ active↔inactive duty cycle will be smeared out by time integration:

$$L_{obs} = f_{duty} L_{int}\ (f_{duty} \sim 1-10^{-2})$$





Mass, position of detectable IBHs

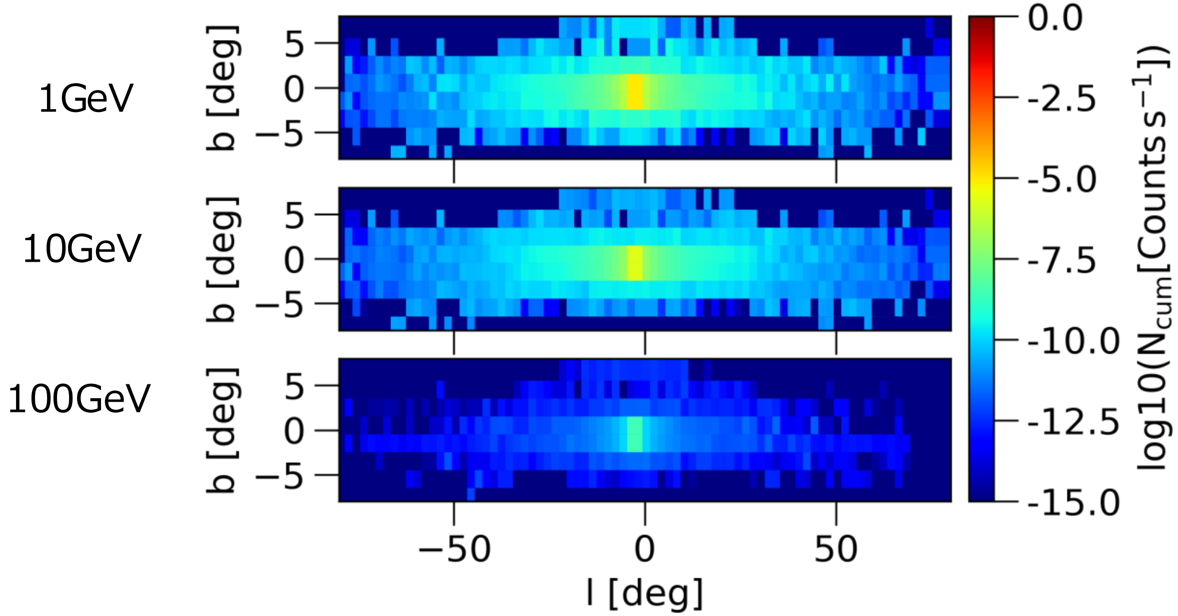


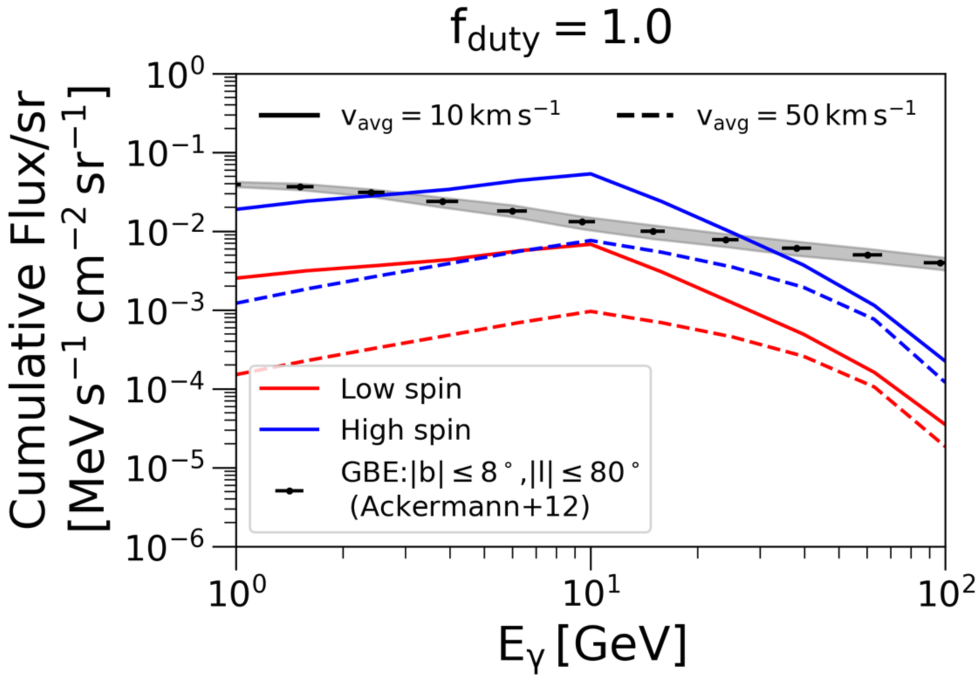
Contribution to Galactic GeV diffuse flux

◎ significant contribution, even overshoot observation for $v_{avg} \sim 10\ \mathrm{km\,s^{-1}}$, *high-spin*

→ $\boldsymbol{v_{avg} \sim a\ few\ \mathrm{km\,s^{-1}}}$ **and *low-spin* prefered**

(cf. $v_{avg} \sim 51\ \mathrm{km\,s^{-1}}$ based on microlensing event; Sahu et al.25)





Detection/classification strategy

- Catalog matching in multi-band :

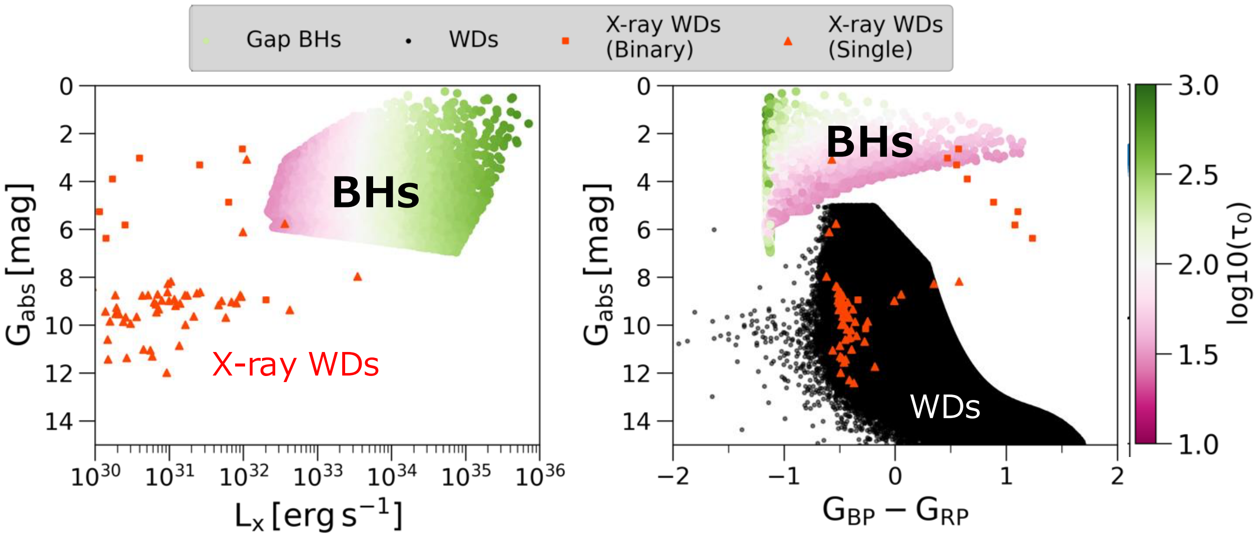
(LHAASO; Kimura incl. KK et al. 2025)

Optical (Gaia) -X (eROSITA, Chandra) -10-100 GeV (Fermi-LAT) +~10-100TeV?

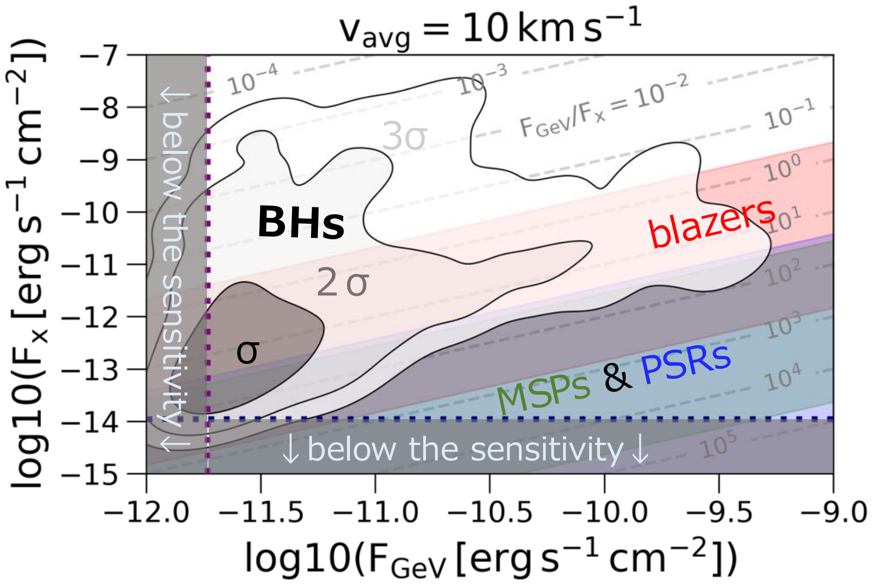
detailed spectral analysis will be the key to distinguish IBH candidates

- luminosity variation… t_{vis} in MAD$\sim\frac{R}{\alpha c}$~sub sec 、 Bondi timescale $t_B\sim\frac{R_{acc}}{V_{acc}}\sim\frac{GM/v_{BH}^2}{V_{acc}}$~yr

(detectable mainly in X) (longer, detectable in gama-ray band)



Opt-X flux ratio/HR diagram comparisons to WDs



GeV-X flux ratio comparison to PSRs, Blazers

Related: IBHs as Pevatrons & LHAASO "dark" sources

(Kimura, incl. KK et al. 2025)

Isolated Black Holes as Potential PeVatrons and Ultrahigh-energy Gamma-ray Sources

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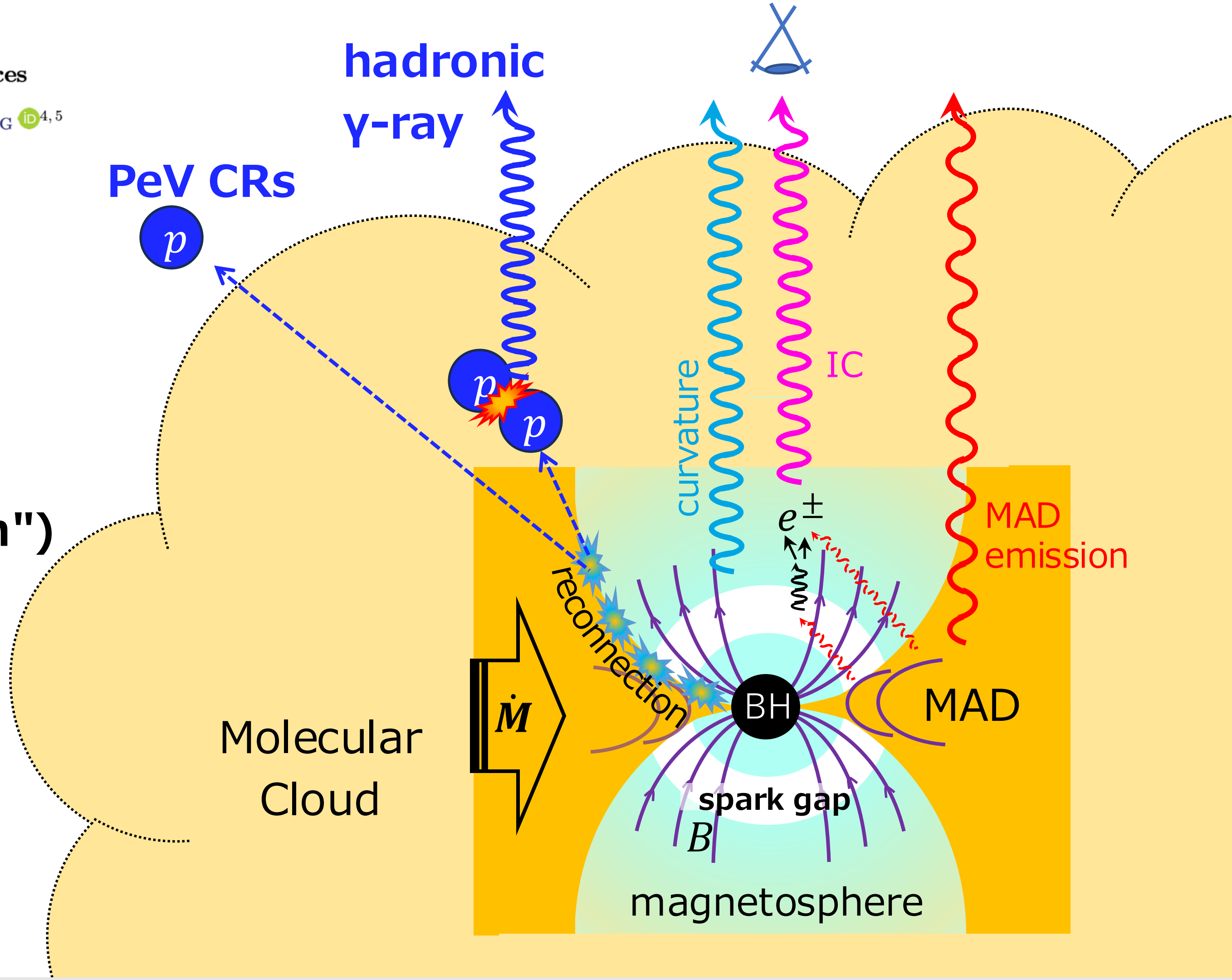
◎ IBH-MADs in dense ($n > 10^3 \mathrm{cm}^{-3}$) MC:

reconnection accelerate proton up to ~PeV

→ fraction escape from MC **(IBH-"PeVatron")**

rest interact w/ ambient gas to produce

~10-100TeV gamma-rays



Related: IBHs as Pevatrons & LHAASO "dark" sources

(Kimura, incl. KK et al. 2025)

◎ $\dot{m} \gtrsim 5 \times 10^{-4}$ to be efficient PeVatron

→ $L_{gap} \lesssim 10^{-4} L_{BZ}$ $(\sim 10^{-4} \dot{M} c^2)$

<u>GeV-TeV dark, 10-100TeV bright</u>

can explain some of LHAASO "dark" sources

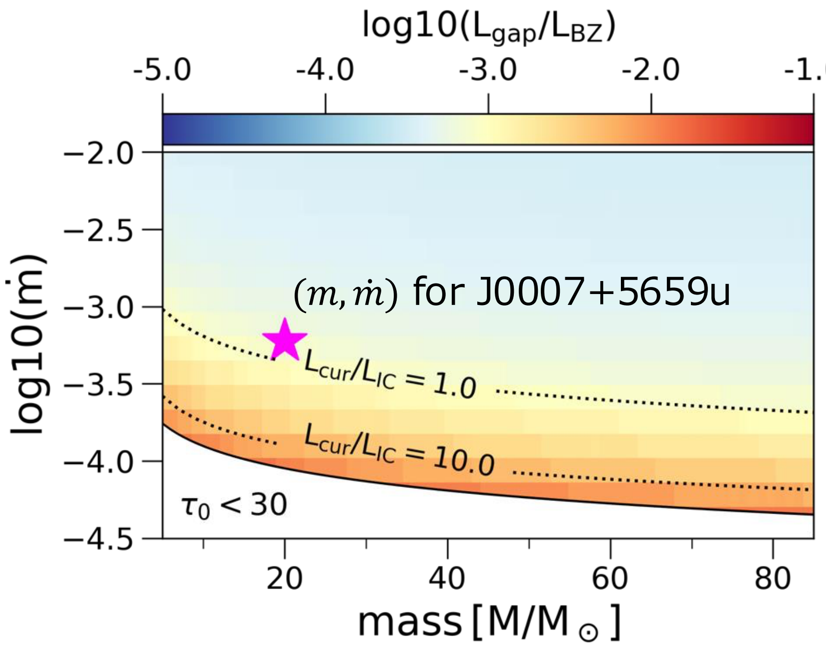
ex) J007+5659u

Shared parameters

$\mathcal{R}$	α	β	λ_w	f_{CR}	η_{rec}	η_{diff}	s_{inj}
10	0.3	0.1	0.1	0.035	10	10	2.0

Model parameters

Model	$M_\bullet$ $[M_\odot]$	n_{MC} $[cm^{-3}]$	V_k $[km\ s^{-1}]$	R_{MC} [pc]	B_{MC} $[\mu G]$	d [kpc]
Typical	10	100	20	20	10	0.50
J0007	20	1000	20	5.0	30	2.0



demonstration for J0007+5659u