# Multi-wavelength Emission from Accretion Flows around Isolated Black Holes


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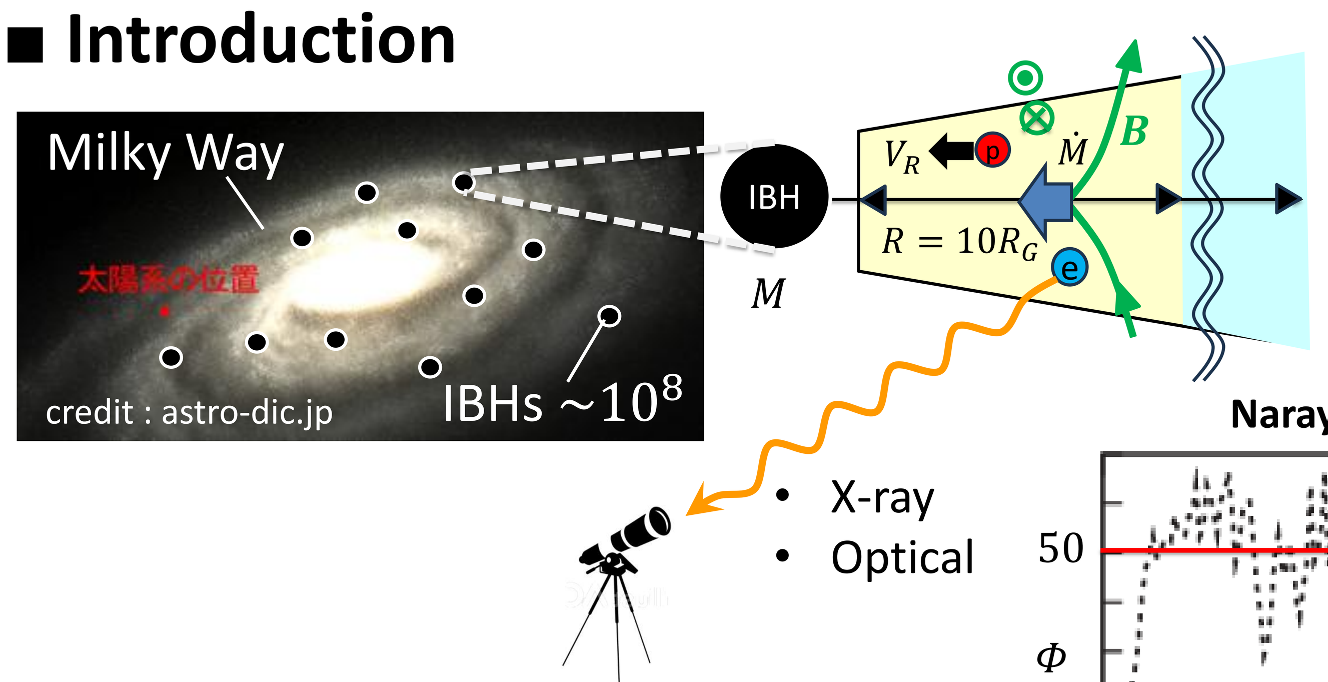
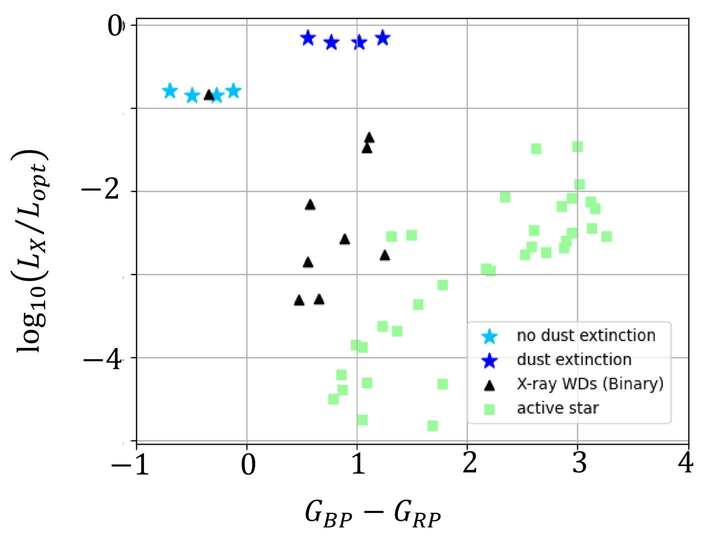
**Abstract** :

- ✓ It is estimated that **there are ~$10^8$ Isolated Black Holes (IBHs) in the Milky Way**
- ✓ Recent studies (Kimura et al. 2021) suggest the possibility of **detecting IBHs in optical light and X-rays, but this is challenging due to dust and gas extinction**
- ✓ We extended previous research to a **1D radiation model and estimated infrared radiation, which is less affected by dust extinction**
- ✓ X-rays are dominated by synchrotron radiation from non-thermal particles in the Magnetically Arrested Disk (MAD).But, previous studies made optimistic estimates assuming magnetic flux conservation. **This study reevaluates the conditions for MAD formation by incorporating magnetic flux transport**.


## ■ Introduction

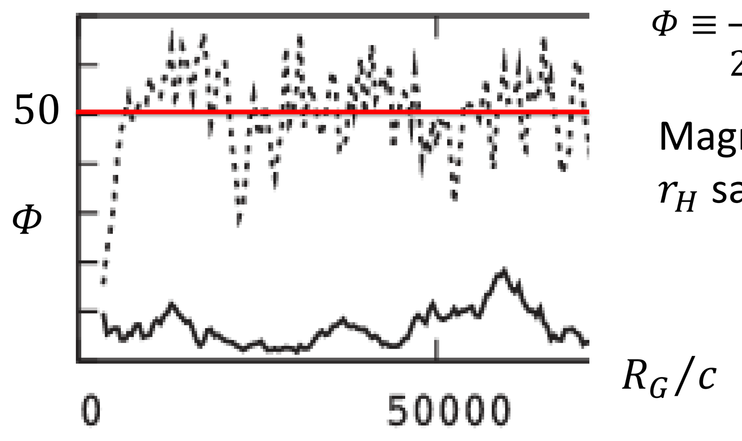



- Recent studies (Kimura et al. 2021**) indicate the potential to detect IBHs in optical and X-ray emission from an accretion disk.**
  - -> The synchrotron self-absorption peak lies in the optical band.
  - **-> X-rays are dominated by synchrotron radiation from non-thermal electrons**




- IBHs exhibit **higher X-ray-to-optical luminosity than typical contaminants -> It may be possible to identify the IBHs**

**Narayan et al. (2012)**




$$\Phi \equiv \frac{1}{2\sqrt{\dot{M}c}} \int\int |B^r(r_H, t)| \sqrt{-g}\, d\theta d\varphi$$

Magnetic flux $\Phi$ at the event horizon $r_H$ saturates, leading to the MAD state

- **Achieving $\sigma = B^2/4\pi n_e m_e c >$ a few in the MAD state and producing non-thermal electrons** via relativistic magnetic reconnection (Zhang et al. 2023).

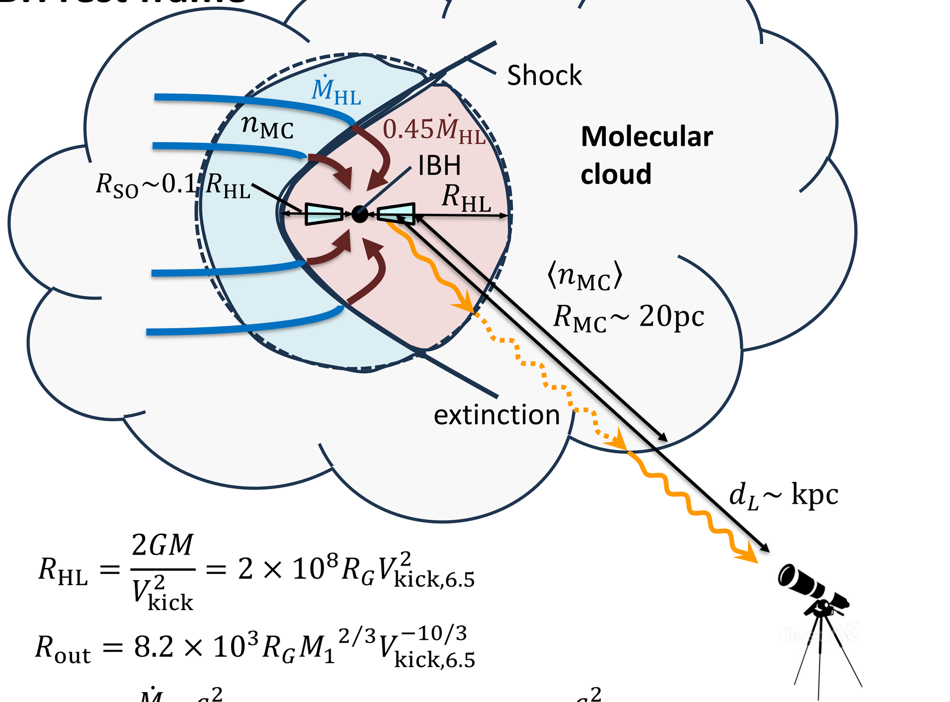
- **Isolated Black Hole (IBH)** : a stellar-mass BH wandering in the ISM without a companion
  - **-> IBHs are essential for testing the evolution of solitary stars and accretion-flow physics.**
- The only observational candidate is Sahu et al. (2022), and **no radiation from an accretion disk has been detected.**

**Limitations & Improvements**

- ✓ Previous studies assumed magnetic-flux conservation.
- -> We reevaluate the MAD formation conditions by including magnetic-flux transport.
- ✓ Previous work also adopted a 1-zone model and ignored dust/gas extinction.
- -> We extend this to a 1D model and compute radiation fluxes including infrared emission, which is less affected by dust.

## ■ Methods

**IBH rest frame**




$$R_{HL} = \frac{2GM}{V_{kick}^2} = 2 \times 10^8 R_G V_{kick,6.5}^2$$

$$R_{out} = 8.2 \times 10^3 R_G M_1^{2/3} V_{kick,6.5}^{-10/3}$$

$$\dot{m}_{HL} \equiv \frac{\dot{M}_{HL}c^2}{L_{Edd}} = \pi R_{HL}^2 \mu_{MC} n_{MC} m_p V_{kick} \frac{c^2}{L_{Edd}} = 2.2 \times 10^{-3} V_{kick,6.5}^{-3} n_{MC,3} M_1^2$$

**Induction equation**

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [(\boldsymbol{v} \times \boldsymbol{B}) - \eta \nabla \times \boldsymbol{B}] \quad R_m = \frac{|\boldsymbol{v} \times \boldsymbol{B}|}{|\eta \nabla \times \boldsymbol{B}|} \sim \frac{vB}{\eta}$$

advection diffusion

We solve the induction equation in two stages (Region 1 and Region 2) to evaluate magnetic-flux transport.

**Region 1** : From the accretion radius $R_{HL}$ to the outer edge of the accretion disk $R_{out}$

**Region 2** : From the outer edge of the disk $R_{out}$ to the black hole's event horizon $R_H$

### Region 1 ($R_{HL} \geq R \geq R_{out}$)

**Upstream** ($R_{HL} \geq R \geq R_{SO}$)

- Ionization degree $x_e = 10^{-5} n_{MC,0}^{-0.5}$
- Ambipolar diffusion dominated

$$R_m \sim \frac{V_{kick}R}{\eta_A} < 1, \eta_A = \frac{(1-x_e)^2 B^2}{4\pi x_e \rho v_{in}}$$

(Magnetic diffusion coefficient $\eta \approx \eta_A$)

- Using $V_{kick}, \rho = \mu_{MC} n_{MC} m_p$ as the average value, **1-zone model approximation**

$$R_m \sim \frac{V_{kick}R}{\eta_A} \sim 1$$

$$\to B = B_u \sim 6.0\, n_{MC,3}^{0.75} M_1^{0.5} V_{kick}^{-0.5}\ [\mu G]$$

**Downstream** ($R_{SO} \geq R \geq R_{out}$)

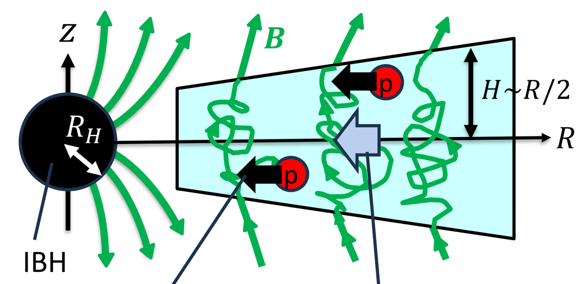
- Ionization degree $x_e \sim 1$
- Advection dominated

$$R_m \sim \frac{V_{ff}R}{\eta} > 1, V_{ff} = \sqrt{\frac{2GM}{R}}$$

- Magnetic flux is conserved

$$B = B_u \left(\frac{R_{SO}}{R}\right)^2$$

### Region 2 ($R_{out} \geq R \geq R_H$)




$$V_R = \frac{\alpha}{2}\sqrt{\frac{GM}{R}} \quad \dot{M} = 0.45\dot{M}_{HL}\left(\frac{R}{R_{out}}\right)^{0.5}$$

kinematic viscosity $\nu = \alpha C_s H$

sound velocity $C_s = \frac{1}{2}\sqrt{\frac{GM}{R}} \quad \alpha = 0.1$

- Assuming axisymmetry, a magnetic flux function $\psi$ is introduced

$$\boldsymbol{B} \equiv \nabla \times \left(\frac{\psi}{R}\boldsymbol{e}_\varphi\right) \quad B_r = -\frac{1}{R}\frac{\partial \psi}{\partial z} \quad B_z = \frac{1}{R}\frac{\partial \psi}{\partial R}$$

Averaging of z

$$\frac{\partial \psi(R,t)}{\partial t} = -V_R(R)\frac{\partial \psi(R,t)}{\partial R} - \frac{2\pi R\eta(R,t)}{cH} K_\varphi(R,t) \cdots (1)$$

$$\psi(R,t) = \frac{4}{c}\int_{R_{in}}^{R_{out}} R_> \left[K\left(\frac{R_<}{R_>}\right) - E\left(\frac{R_<}{R_>}\right)\right] K_\varphi(R')dR' \cdots (2)$$

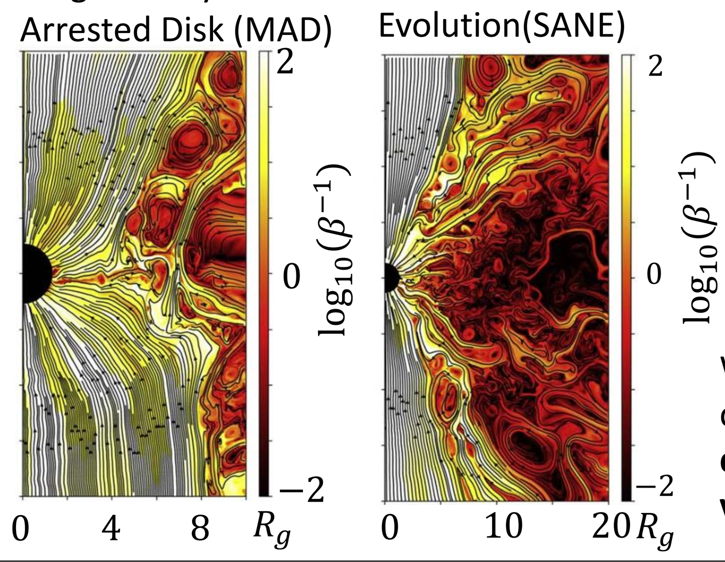
$R_> \equiv \max(R, R'), R_< \equiv \min(R, R')$

$K, E$ : the complete elliptic integrals

- We adopt an α-viscosity accretion disk (Shakura and Sunyaev 1973 ). **Using the magnetic Prandtl number $P_m \equiv \eta/\nu$ as a parameter**, we solve Equations (1) and (2) simultaneously to obtain the magnetic flux function $\psi$.

### MAD Criterion

**Ripperda et al. (2020)**




$$\Phi_{MAD} \approx 50 R_G \sqrt{\dot{M}(R = R_H)c}$$

$$\Phi_H = 2\pi B(R = R_H)R_H^2$$

$$R_H = R_G\left(1 + \sqrt{1-a^2}\right)$$

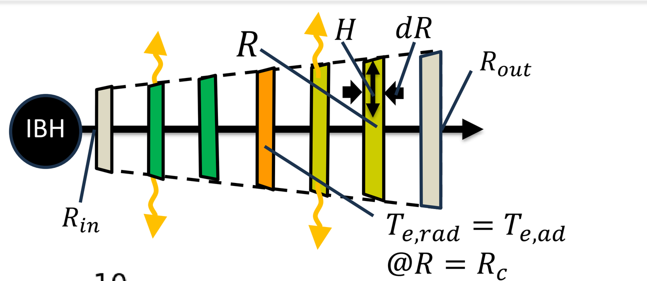
$$a = 0.9375$$

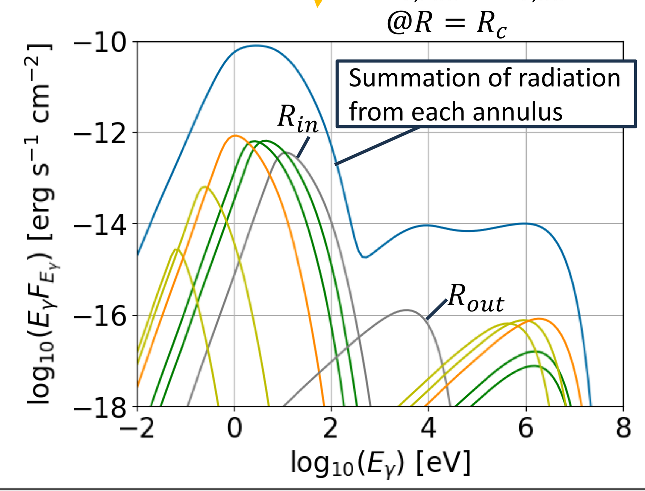
$\Phi_H \geq \Phi_{MAD} \to$ MAD

$\Phi_H < \Phi_{MAD} \to$ SANE

We evaluate the MAD and SANE conditions using **molecular-cloud density $n_{MC}$ and IBH kick velocity $V_{kick}$ as parameters**

### Radiation Flux calculation




- **Luminosity due to viscous heating**

$$L_{e,th}(R) = (1 - \epsilon_{NT})\delta_e \epsilon_{diss} n_e \mu_{MC} m_p 2\pi R dR c^2 V_R/R$$

$\delta_e$ : ratio of energy of electrons to protons

$\epsilon_{diss}$ : ratio of dissipated energy

- **Radiative luminosity**

$$L_{e,rad}(T_e, R) = L_{e,syn} + L_{e,br}$$

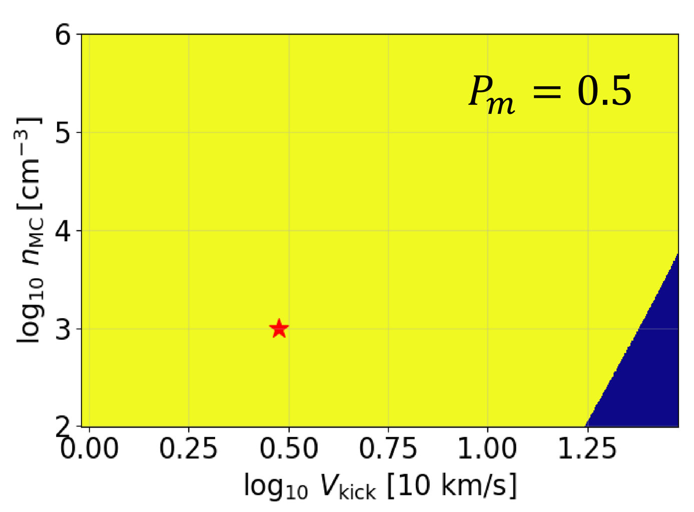
- Solve $L_{e,th}(R) = L_{e,rad}(T_e, R)$ for each annulus to determine $T_e$

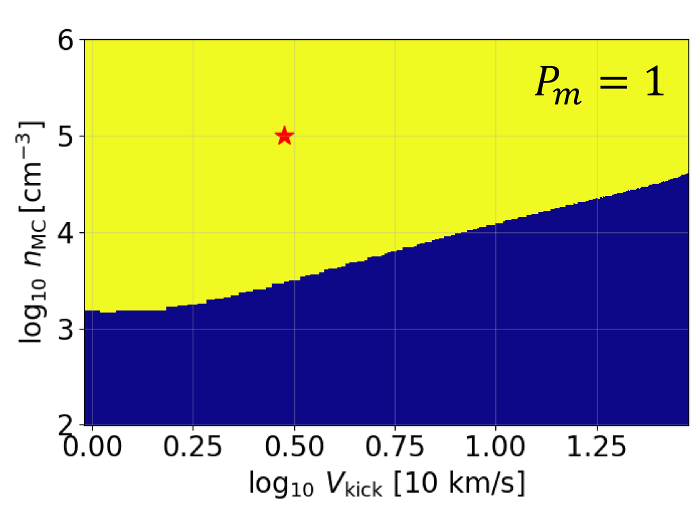
Note : $T_e \leq T_{e,ad} = \delta_e T_p$

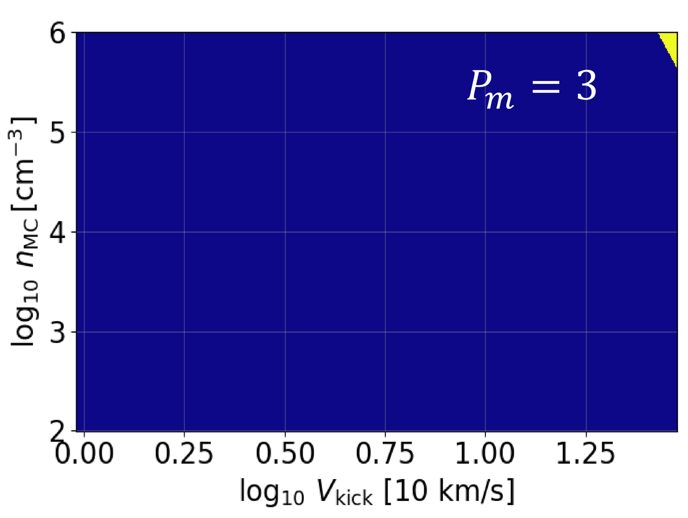
## ■ Results & Discussion

**MAD Criterion**

★ : Parameter in the right-hand side radiation flux calculation



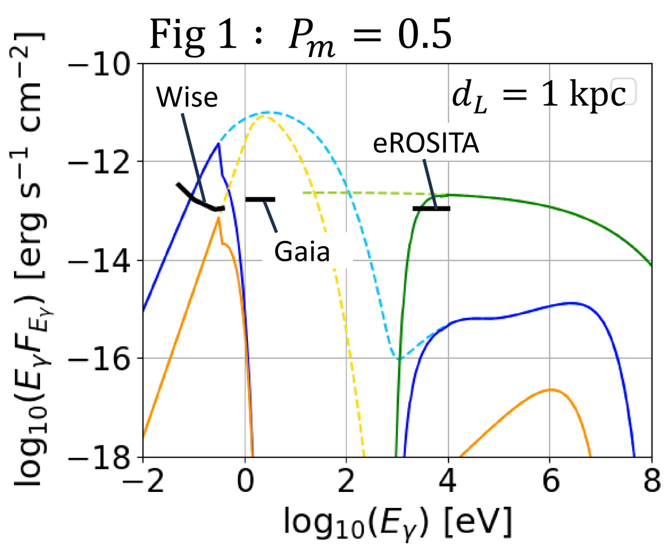



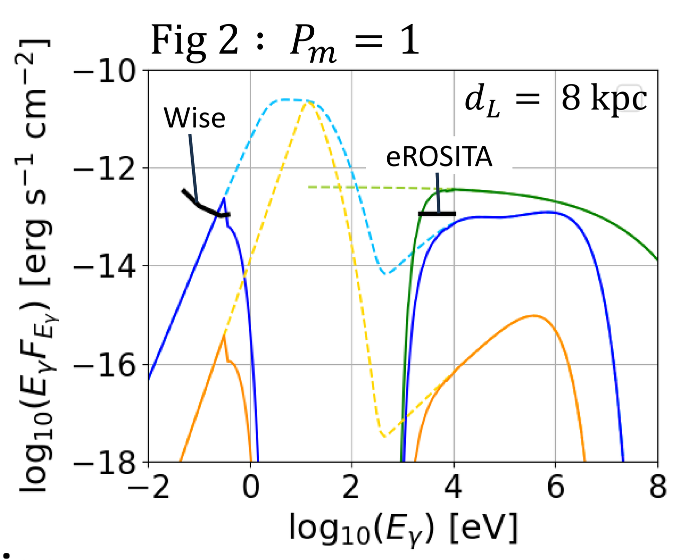




- At Pm=0.5, **MAD is possible in most cases**
- At Pm=3, **MAD is unrealistic, becoming SANE**
- At Pm=1, both MAD and SANE coexist.However, **forming MAD is difficult unless the molecular cloud is relatively dense.**
- **$P_m$ significantly influences the formation conditions of MAD as a factor**.

**Radiation Flux calculation**

1-zone model (Kimura et al.2021)
1D model (This study)
Non-thermal synchrotron




- Fig. 1 assumes a typical molecular cloud
- Fig. 2 adopts a dense molecular-cloud core/filament in the Galactic center for Pm = 1, since MAD formation requires relatively high densities.

**Note**: Although cores/filaments are locally dense, dust/gas extinction was computed using the average molecular-cloud value $\langle n_{MC} \rangle = 10^3 \mathrm{cm}^{-3}$.

- **X-rays become observable if non-thermal electrons in a MAD** produce the emission.
- Optical observations are quite challenging, whereas **the infrared band offers better observability in the 1D models.**

## ■ Conclusion

- We discussed the **observability of isolated black holes (IBHs) based on radiation from accretion disks**
- This study estimates **magnetic flux transport and radiation from the entire accretion disk, which were not addressed in previous work**.
- **In the Magnetically Arrested Disk (MAD) , non-thermal electrons are generated**. We evaluate the conditions for MAD formation based on the molecular-cloud density $n_{MC}$ and the IBH kick velocity $V_{kick}$.
- Considering magnetic flux transport, **conditions where MAD does not occur** also exist.
- **The model of this study (1D radiation model) enables infrared estimates that are less affected by dust and gas extinction.**
- **The results of this study are influenced by a factor in the magnetic Prandtl number $P_m$ given as a parameter.** Fluid simulations must be performed to determine this accurately.