1D GRPIC Simulations of High-Energy Gamma Rays from BH Magnetospheres

一般相対論的プラズマ粒子シミュレーションによるブラックホール磁気圏強電場領域由来ガンマ線放射の研究

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Theoretical Astrophysics
Tohoku University

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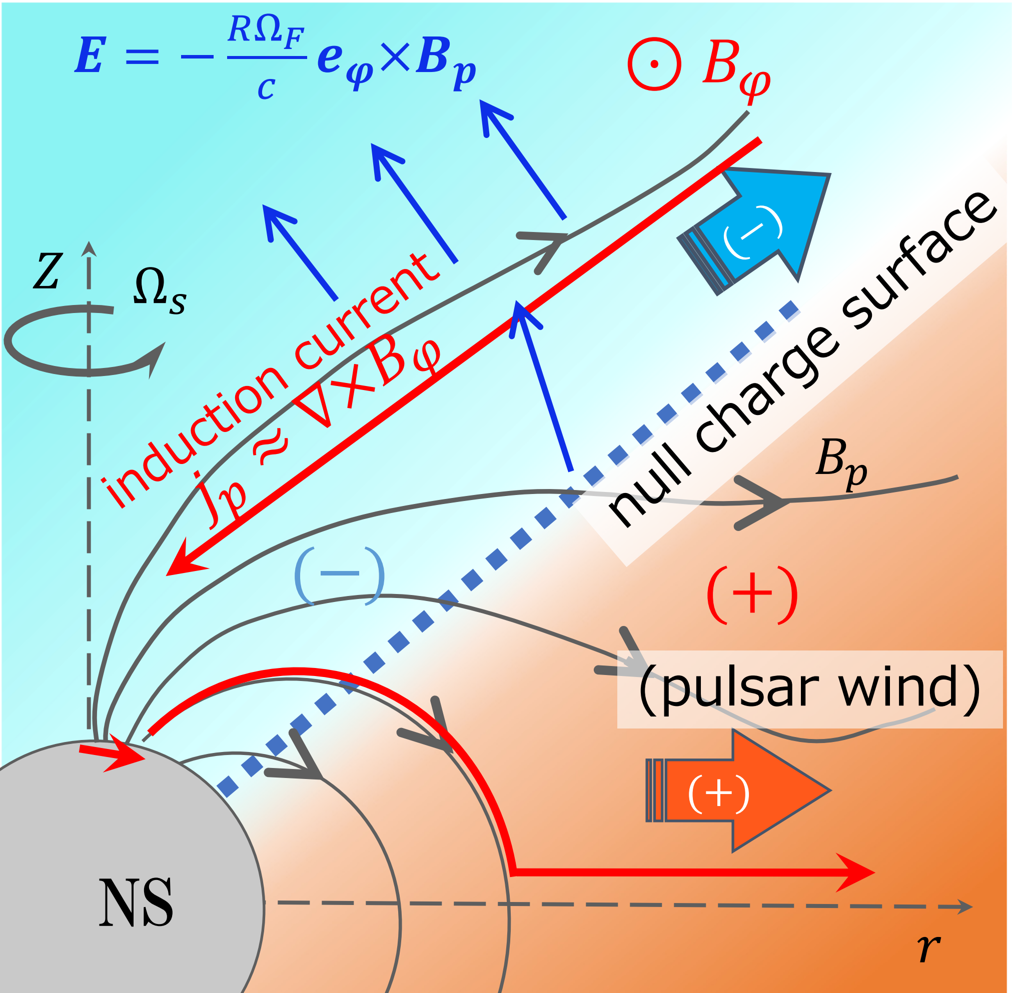
Current Structure・Charge Distribution of Pulsar Magnetospheres

Goldreich & Julian 1969



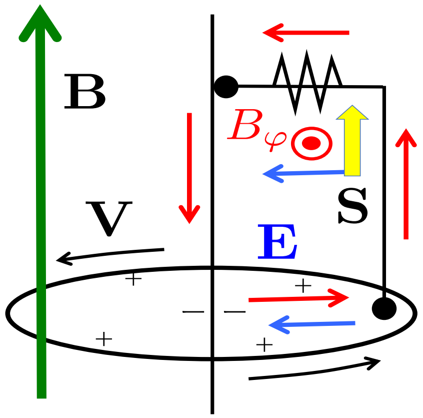
- **plasma injection** from NS / via γB・$\gamma\gamma$ interactions
- **co-rotation** of NS, axisymmetrical B-field, plasma

  ($\boldsymbol{\Omega_s} = \boldsymbol{\Omega_F}$)

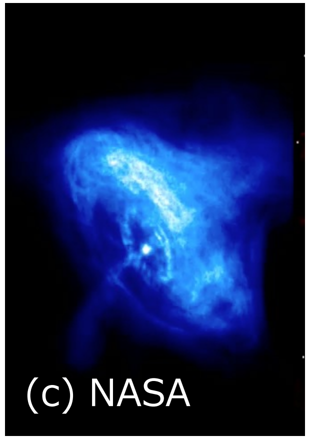
NS rotation energy → **steady plasma flow**

maintaining j_p

$$S_p = \frac{1}{4\pi} \boldsymbol{E} \times \boldsymbol{B_\varphi} = -\frac{1}{4\pi} R \Omega_F B_\varphi \boldsymbol{B}_\mathbf{p}$$ "pulsar wind"

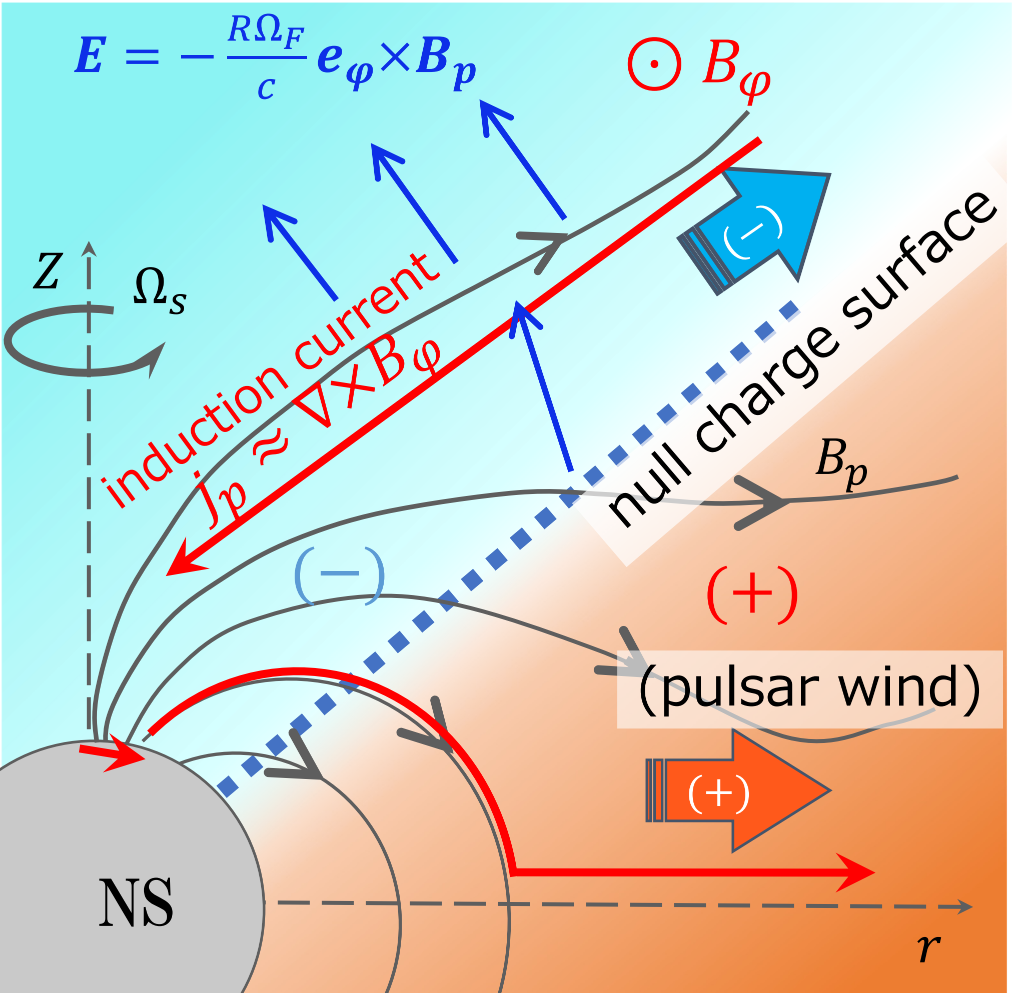


"unipolar induction"



Current Structure・Charge Distribution of Pulsar Magnetospheres

Goldreich & Julian 1969



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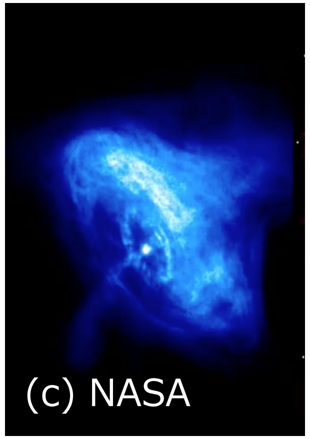
- Goldreich-Julian charge distribution

$$\rho_e = \frac{1}{4\pi}\boldsymbol{\nabla}\cdot\boldsymbol{E} \approx -\frac{1}{2\pi c}\boldsymbol{\Omega_s}\cdot\boldsymbol{B}$$

→ cone-like null charge surface

(where $\boldsymbol{\Omega_s}\cdot\boldsymbol{B}$ vanishes)

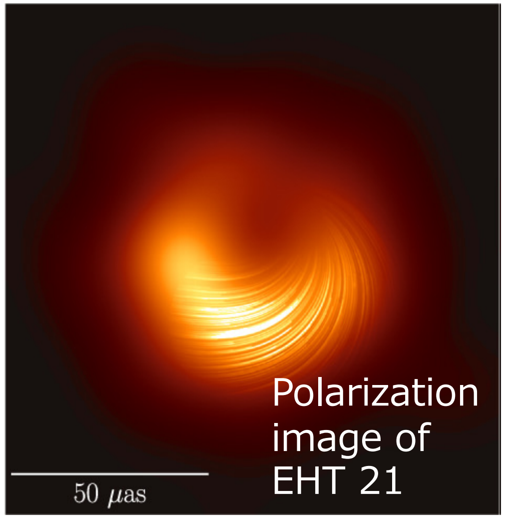


Formation of BH magnetospheres

<B-fields transportation>

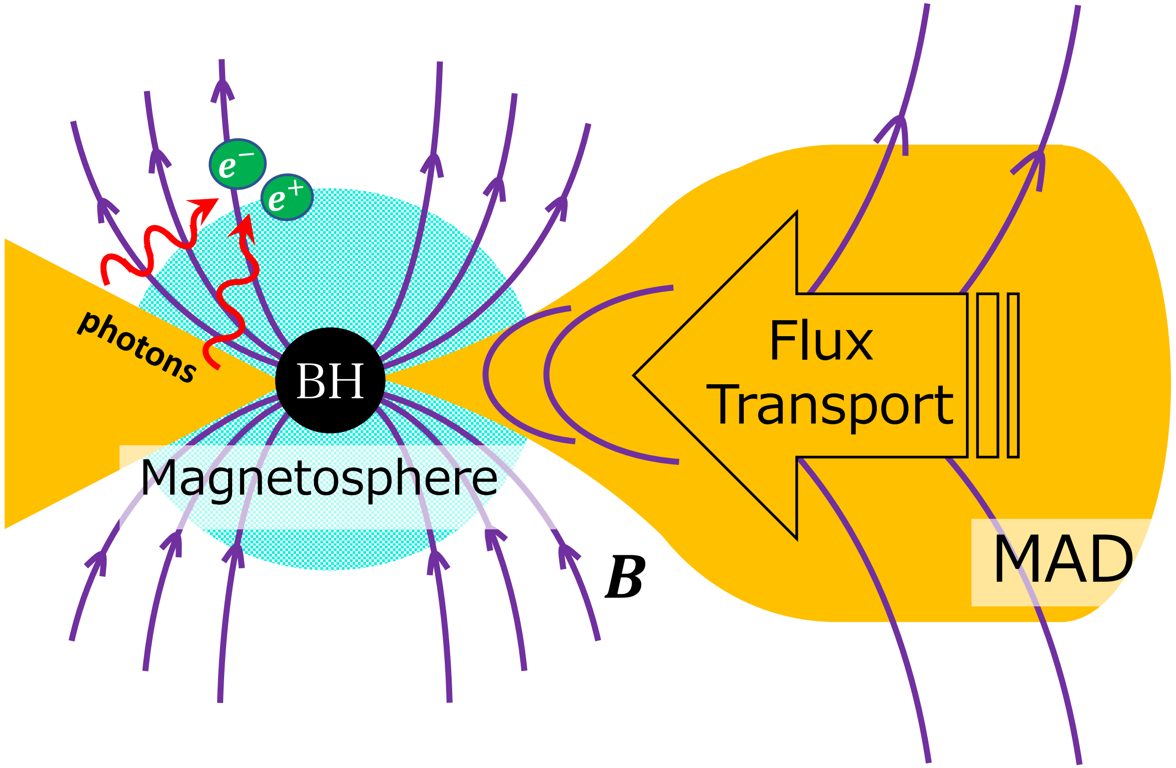
Theory:
infalling gas bring magnetic flux
→ highly-magnetized gas disk around BHs
(**Magnetically Arrested Disks, MADs**)

EHT observations:
highly-magnetized, poloidal B structure
are expected at M87 vicinity



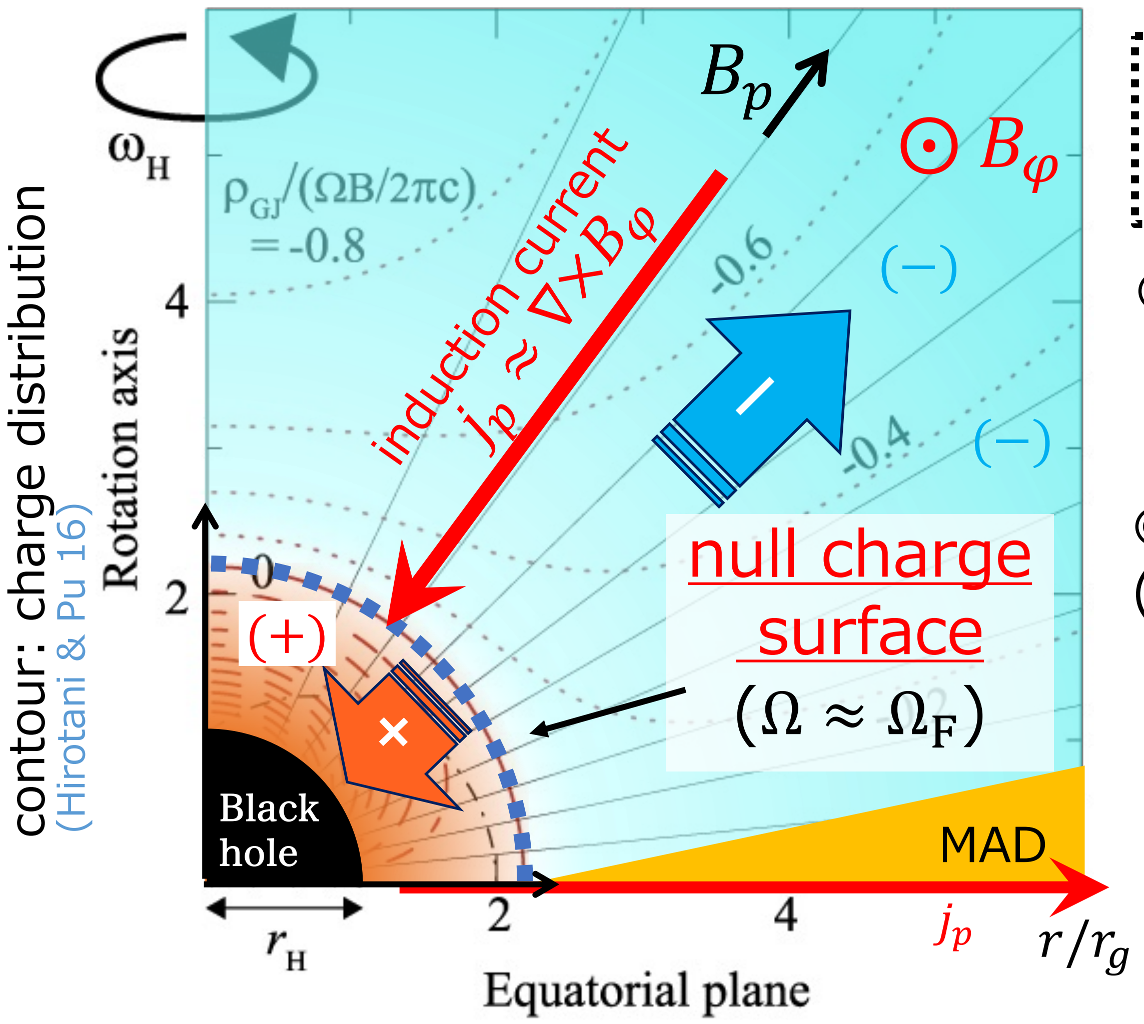
<Plasma injection>

Theory:
main source = $\gamma\gamma$ **interactions of disk photons**



Current Structure・Charge Distribution of BH Magnetosphere

◎**sufficient plasma** → steady EM structure **(BZ process)** (e.g. Blandford & Znajek 77)



Difference

OPEN B-field structure

$\boldsymbol{\Omega(r,\theta) > \Omega_F}$ **in nearby,** $\boldsymbol{\Omega < \Omega_F}$ **at far**

◎ **far zone:** negatively charged outflow maintains the stational current (connected to the jet)

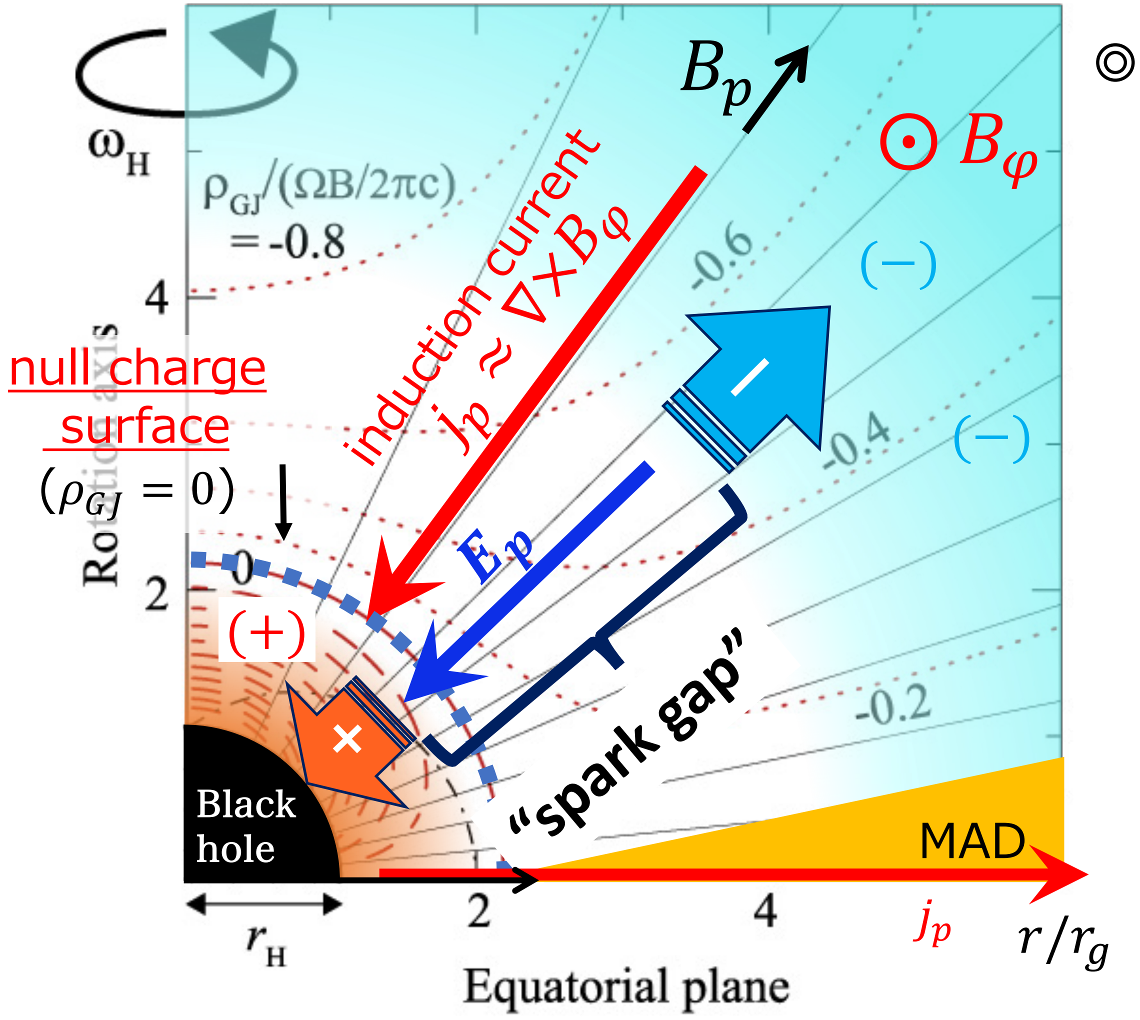
◎ **near horizon:** positively charged inflow (consistent w/ infall due to the gravity, rapid rotation)

↓

almost spherical null charge surface ($r_{null} \sim 2r_g$)

Formation of "Spark Gap" in Charge-Starved BH Magnetospheres

◎**charge starved** → time-dependent E-field (analogical to pulsar polar cap/outer gap)



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

→ local charge deficiency around null surface

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

→ displacement current develops, maintaining electric current

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

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

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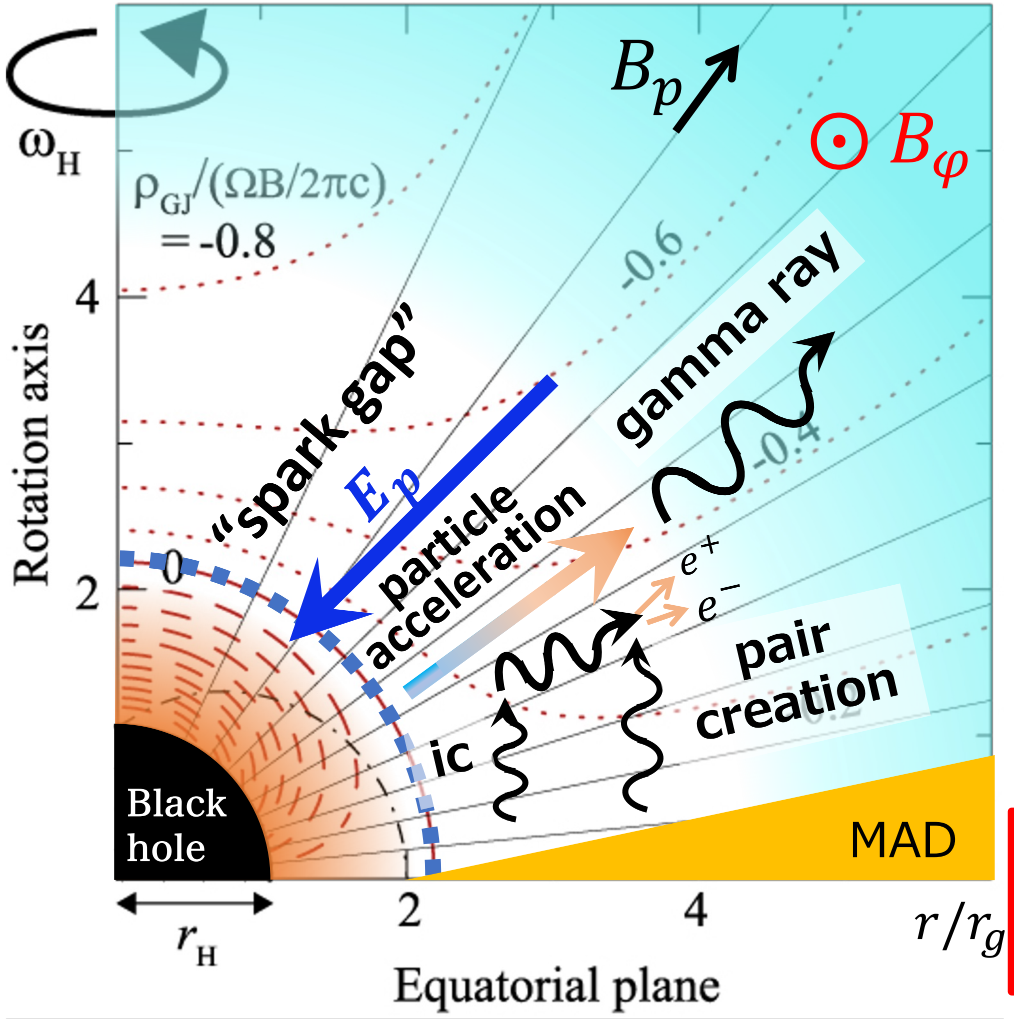

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local, intermittent E-field region ("**spark gap**")

efficient acceleration, gamma-ray emission
secondary pair creation

Examining BH Spark Gap Natures…

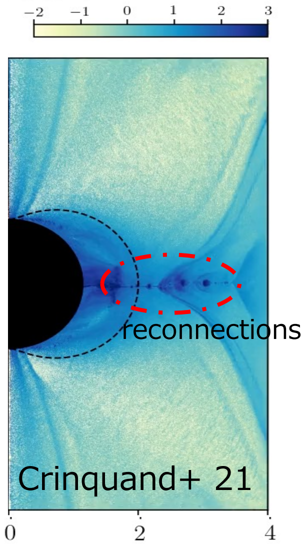
◎ … **by semi-analytic modeling** (Beskin et al. 92; Hirotani & Pu 16; Levinson & Segev 17 etc...)

steady gap approximations (likewise pulsar outer gap model Cheng et al.1986a,b)

◎ … **by Particle-In-Cell simulations (mainly for SMBHs)**

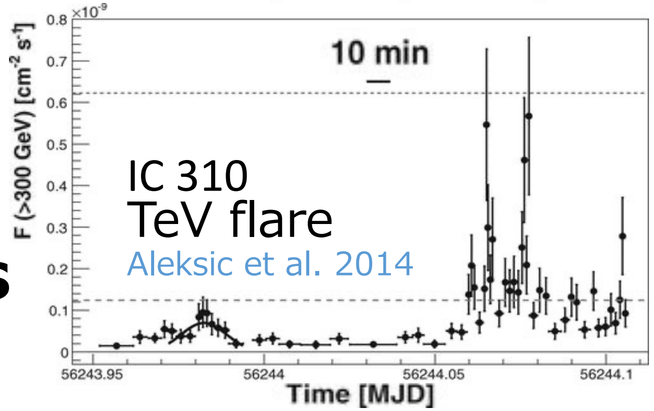
introducing time-dependence

- 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)
  considering time-dependent B-field



escapicng gamma rays for SMBH magnetospheres = detectable!

possible connection w/ TeV flares from known AGNs



My Current Research:

High-energy Gamma Rays from Stellar-Mass BH Magnetospheres in 1D GRPIC Simulations

(Kin et al. 23 in prep.)

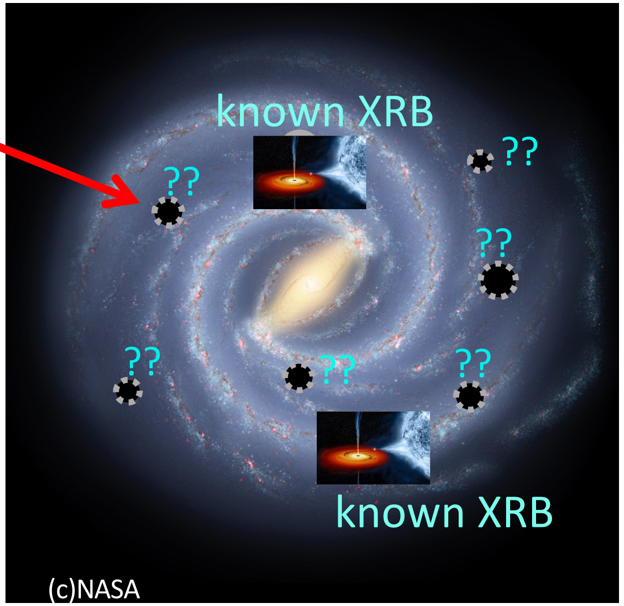
Motivation: Detecting Isolated stellar-mass Black Holes via Gamma-Rays?

◎ $\sim 10^8$ **undetected IBHs in the Galaxy**

$$SFR \times V_{gal} \times t_{galaxy}$$

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

→ possible interactions w/ ISM clouds



◎ **MAD formation around IBHs** (e.g. Ioka et al.17; Kimura et al. 21)

efficient magnetic flux transportation

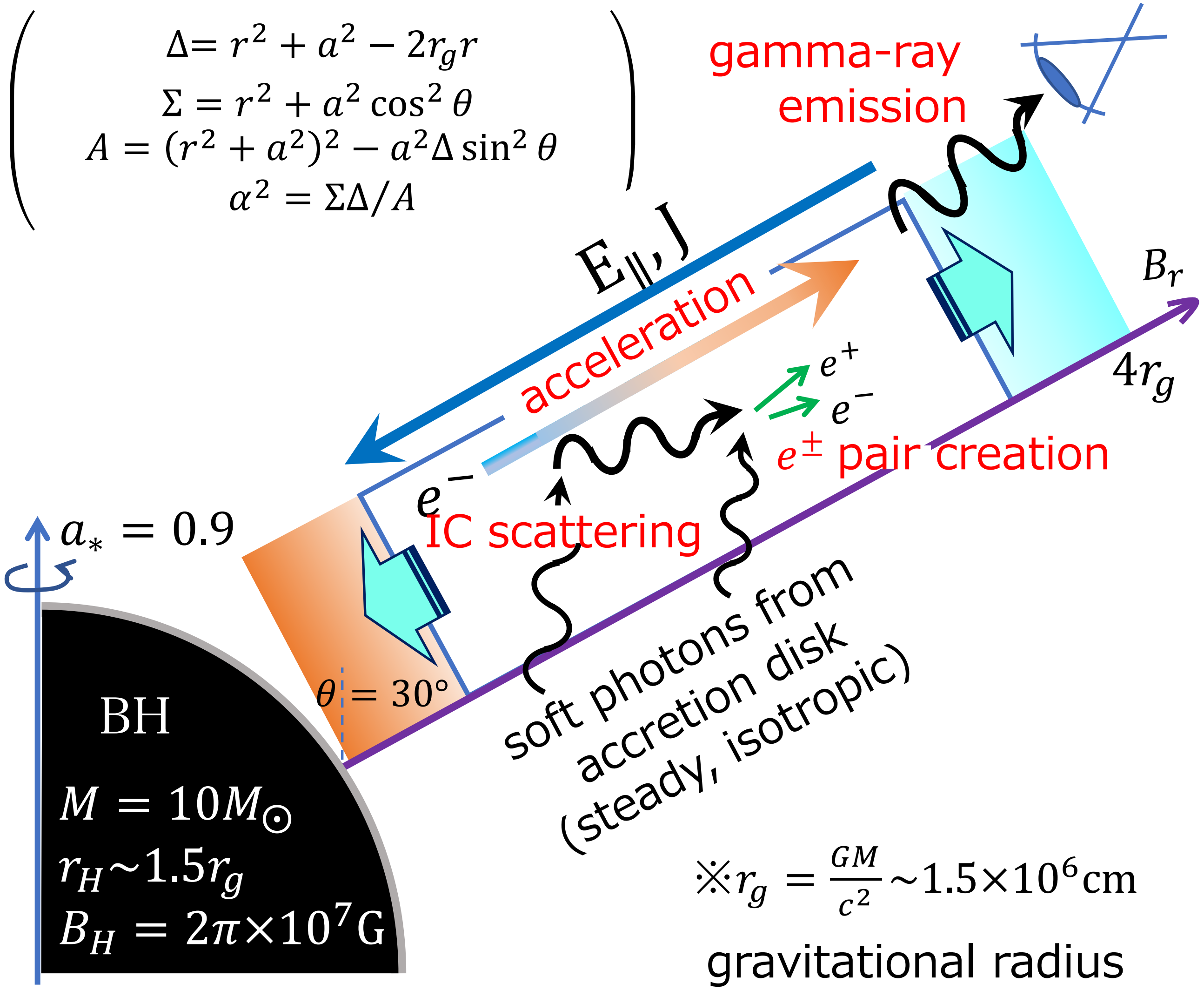
→ become MAD for low-β ISM accretion

Gamma rays from IBH magnetospheric "spark gap" can be detected?

Simulation Setting

Metric term

$$\Delta = r^2 + a^2 - 2r_g r$$
$$\Sigma = r^2 + a^2\cos^2\theta$$
$$A = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta$$
$$\alpha^2 = \Sigma\Delta/A$$



※$r_g = \frac{GM}{c^2} \sim 1.5\times10^6$cm
gravitational radius

Particle-In-Cell

◎ 1D・GRPIC simulation code

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

- considering General Relativistic effect
- solve particle motion **w/ real mass**

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

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

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

→ evaluate the charge/current distribution, solve the Maxwell's eq. at each grid

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

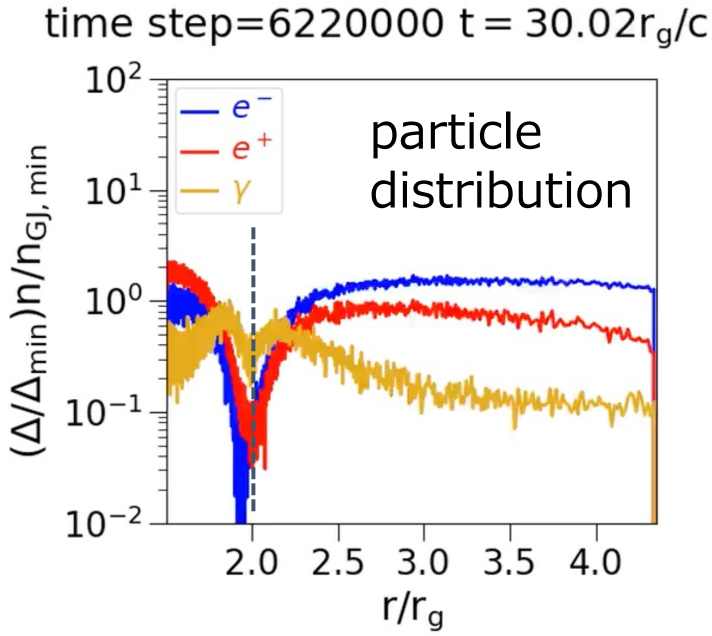
$$\partial_r(\sqrt{A}E_r) = 4\pi\Sigma(j^t - \rho_{GJ}) : \text{Gauss' law}$$

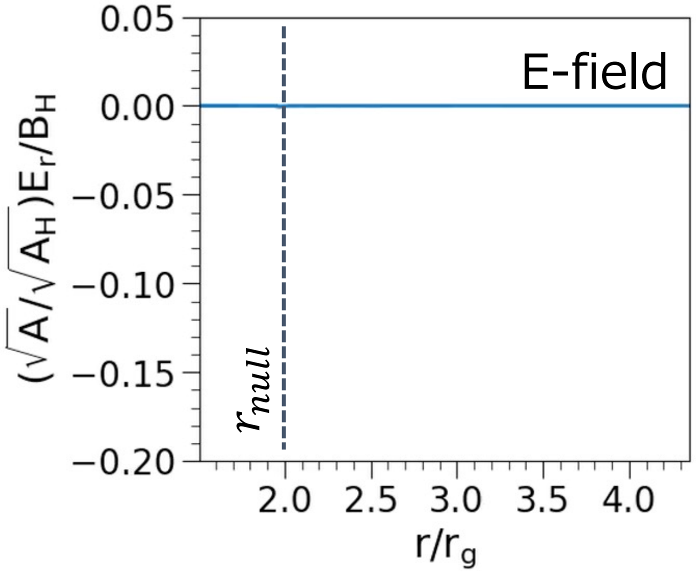
- include IC・pair creation interactions

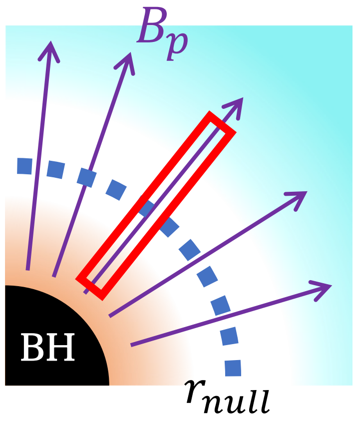
◎ Kerr spacetime

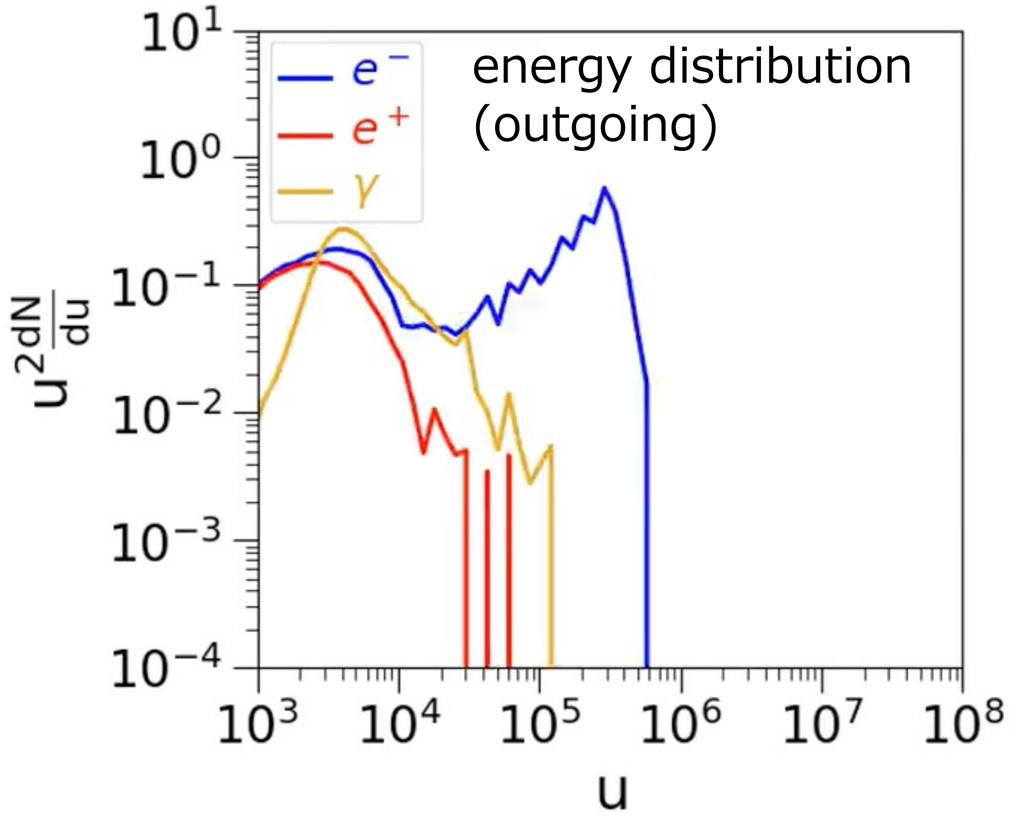
◎ steady, axisymmetric B-field (split-monopole)

Simulation Result: Overall Evolution









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

◎quasi-periodic gap

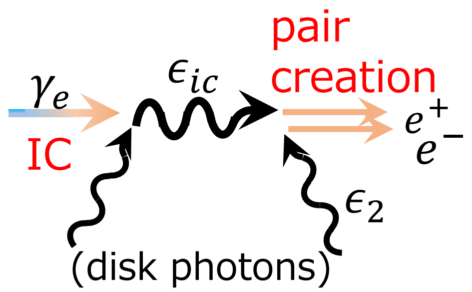
◎$\gamma_{e^-,pk}\sim 10^7$

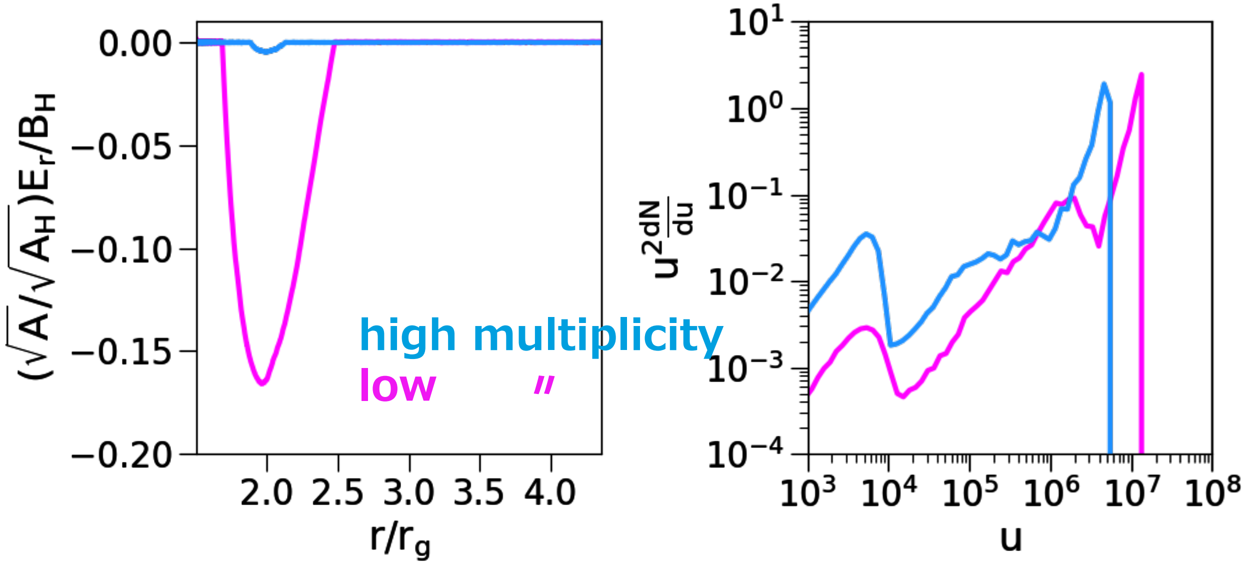
→ GeV-TeV gamma-rays

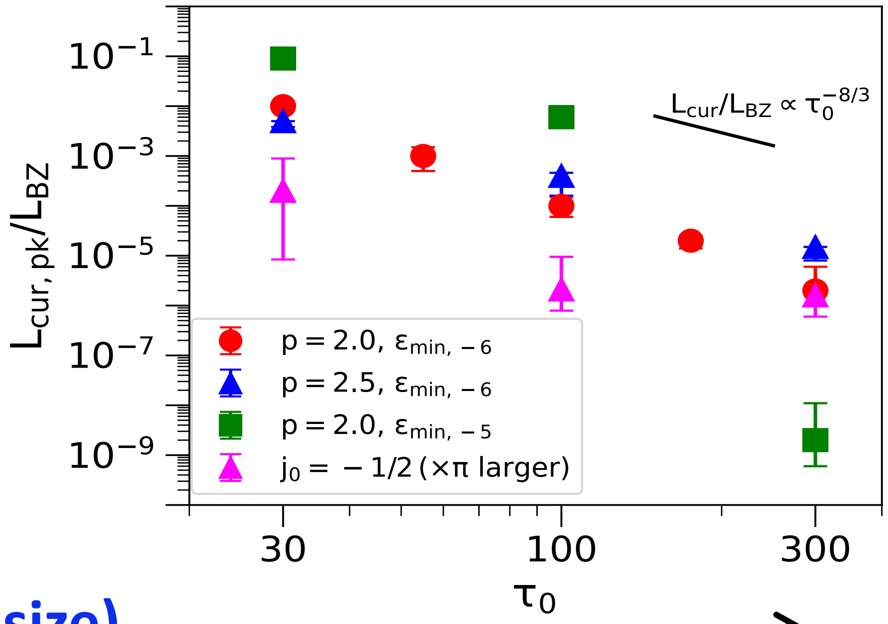
Simulation Result: Disk Photon Intensity Dependence

$\tau_0 \approx n_\gamma \sigma_T r_g \propto$ disk photon intensity : Thomson depth for r_g

controlling $e^{\pm}$ pair multiplicity ($\tau_{pair} \sim 0.1 \tau_0 \times (\epsilon_{ic}\epsilon_2)^{-1}$)







higher intensity = higher multiplicity

◎ **multiplicity affects gap dynamics (period, gap size)**

◎ $L_{cur,pk}/L_{BZ} \sim 10^{-2}(\tau_0/30)^{-\alpha}$

($\alpha \sim 8/3$ **for** $p = 2.0, \epsilon_{min} = 10^{-6}$)

L_{BZ}:BZ luminosity

Semi-Analytic Model of Gamma-Ray Emission from Gap

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

ISM density、BH mass → one-zone IBH MAD model (Kimura et al.21) → τ_0、ϵ_{min}、B_H

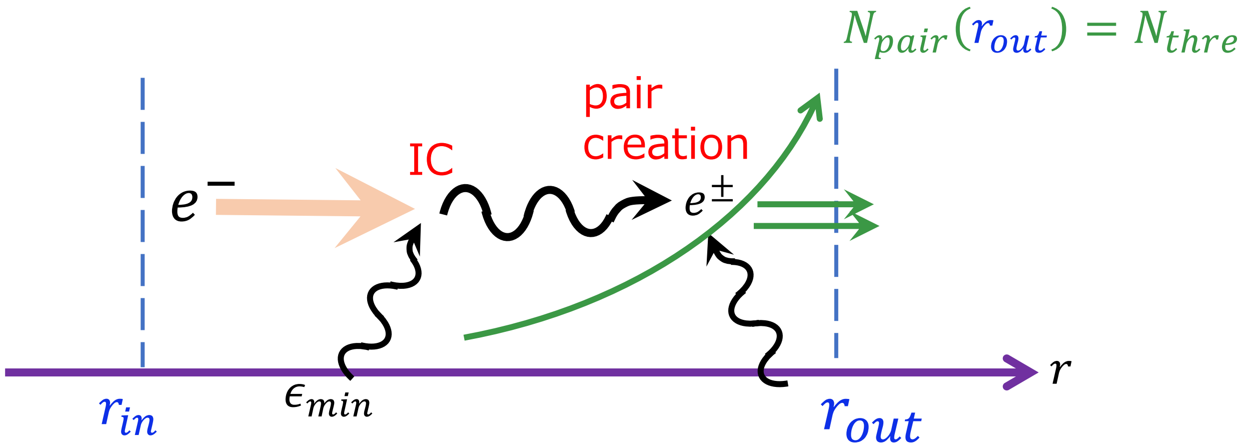
(the gap opacity; disk photon peak energy; B-field strength at the horizon)

solve simplified EoM, photon transfer, pair creations

→ gap boundaries: enough pairs created

maximum Lorentz factor γ_{pk}

gamma-ray peak luminosity $L_{cur,pk}$



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ISM density、BH mass ➡ one-zone IBH MAD model (Kimura et al.21) ➡ τ_0、ϵ_{min}、B_H

(the gap opacity / disk photon peak energy / B-field strength at the horizon)

$n_{ISM} = 65\,cm^{-3}, M = 10M_\odot$

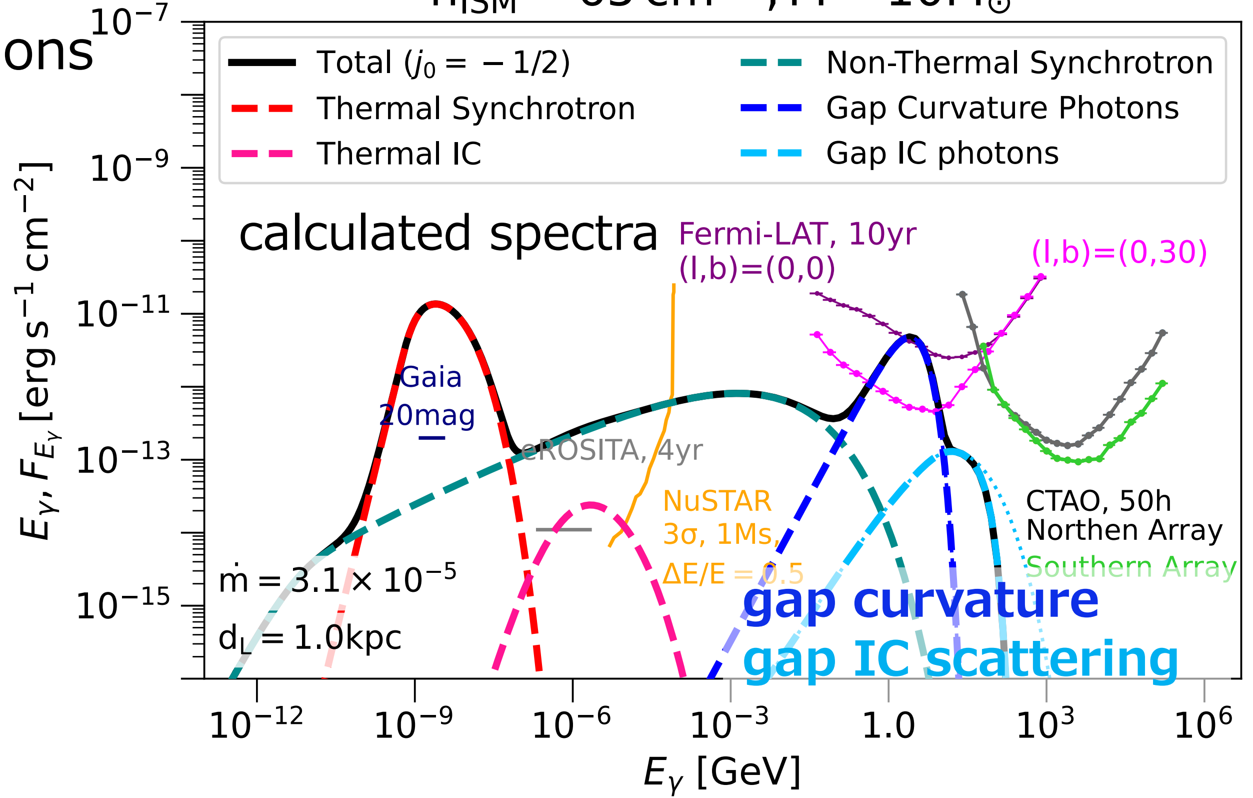
solve simplified EoM, photon transfer, pair creations

→ gap boundaries: enough pairs created

maximum Lorentz factor γ_{pk}

gamma-ray peak luminosity $L_{cur,pk}$

GeV-TeV gamma-ray emission detectable from ~kpc



Summary

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

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

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

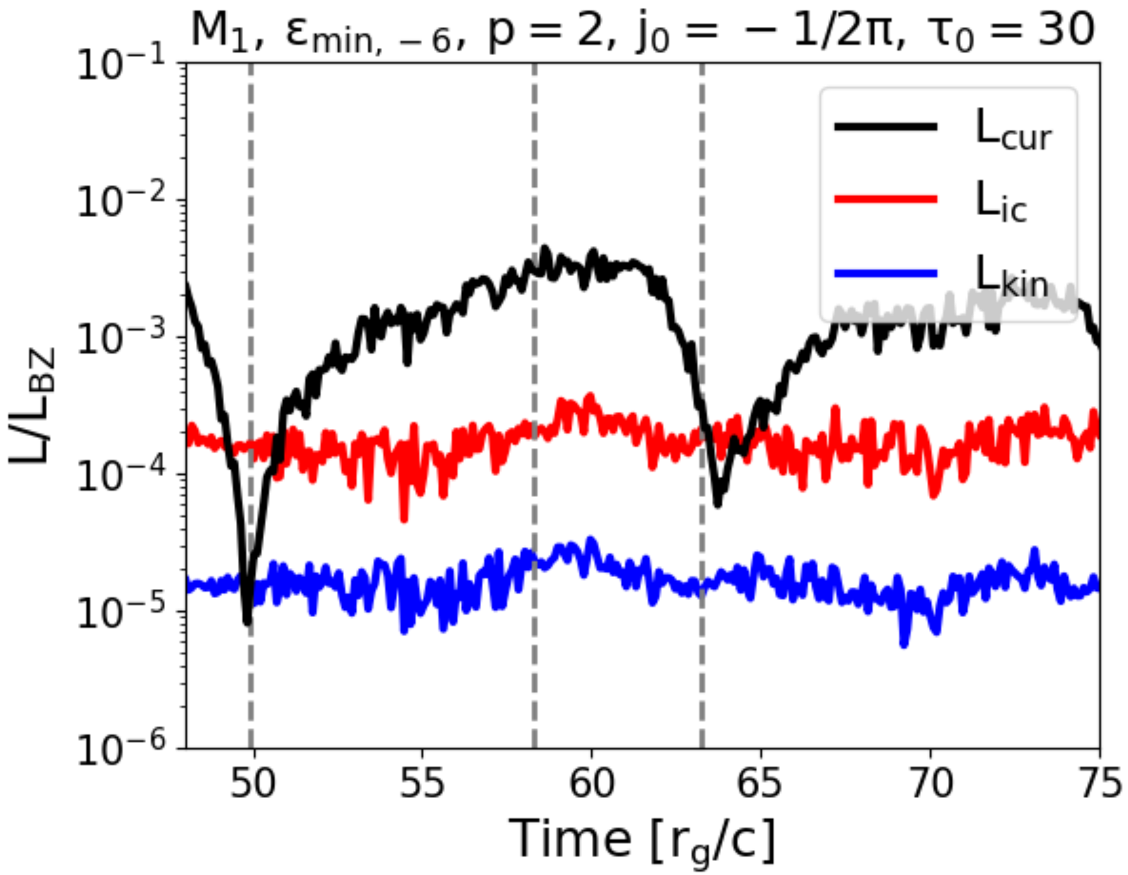
1D · GRPIC simulation + semi-analytic modeling

⇒GeV-TeV gamma rays detectable from ~kpc, unID candidates

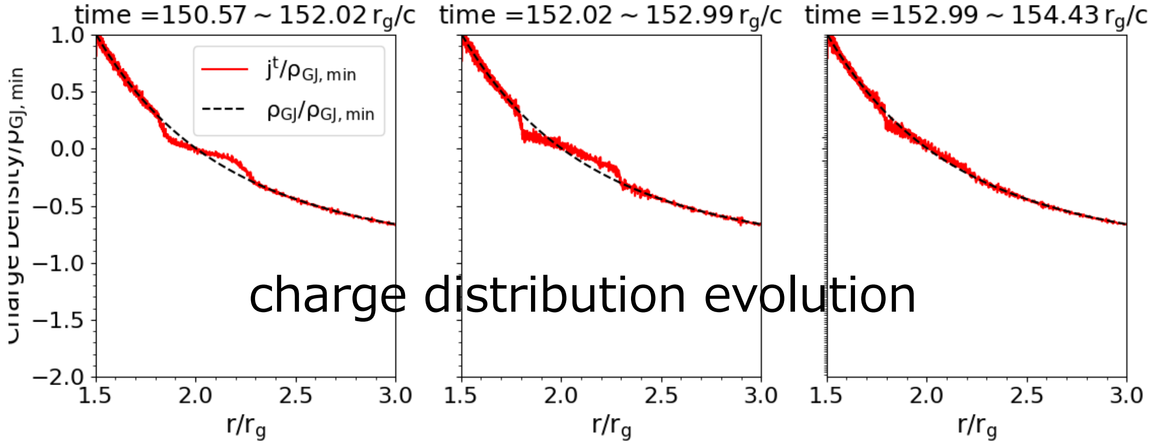
Back up

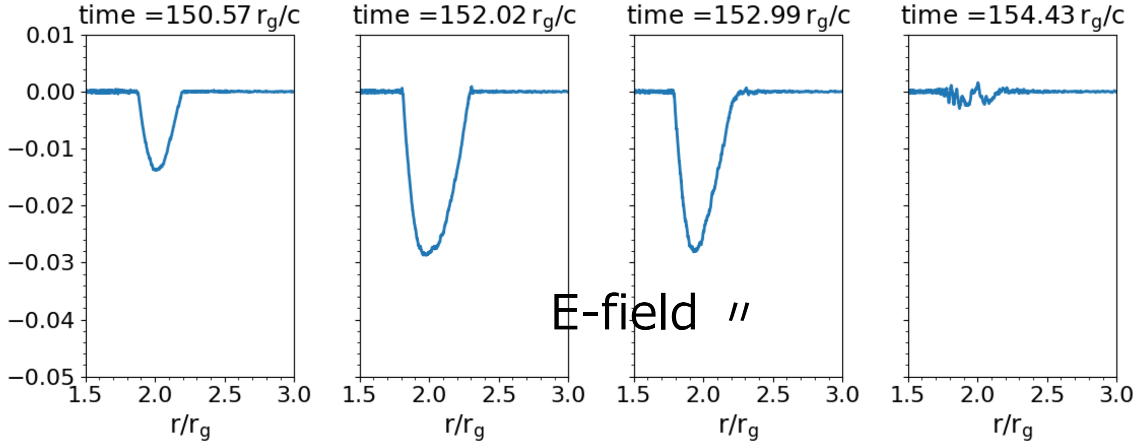
$j_0 = -1/2\pi$

~~$\alpha = -1$~~, $p = 2.0$, $\varepsilon_{min} = 10^{-6}$, $\tau_0 = 55$



typical light curve at the outer boundary





Discussion: strategy

※ pc (persec)~3×10^{18}cm

◎spectrum peak: 10-100GeV → main target: **Fermi-LAT unIDs**

- hard spectral index for low energy side
- has a peak in Fermi-LAT sensitivity range
- association w/ gas clouds, point source

...will be the selection criteria

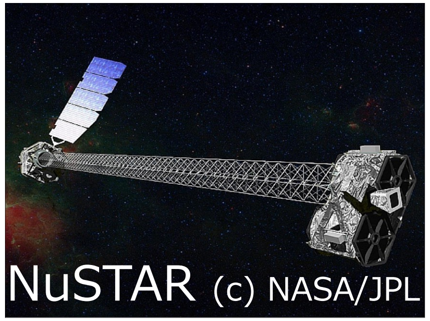
◎determining the position: cross-match w/ optical~X-ray

spatial resolution of gamma-ray detector: ~1°

→ if ~kpc distant, size of error circle: ~pc!

cross-matching w/ data from other observation;

- Gaia(IR~optical)
- NuSTAR etc... (X-ray)



...will be crucial to narrow down & determine the location

Discussion: time variability

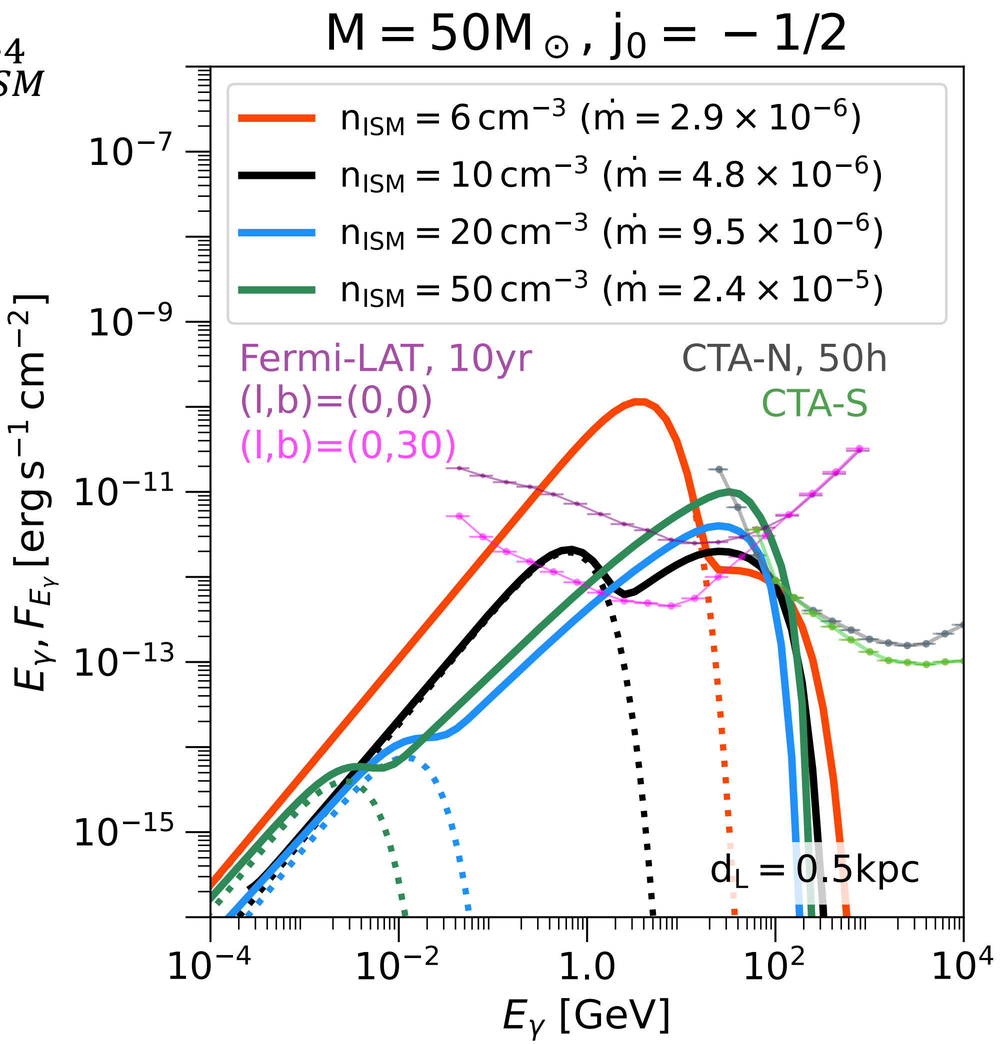
◎L_{cur} sensitive to gas density: $L_{cur}/L_{BZ} \propto \tau_0^{-3.8} \propto n_{ISM}^{-4}$

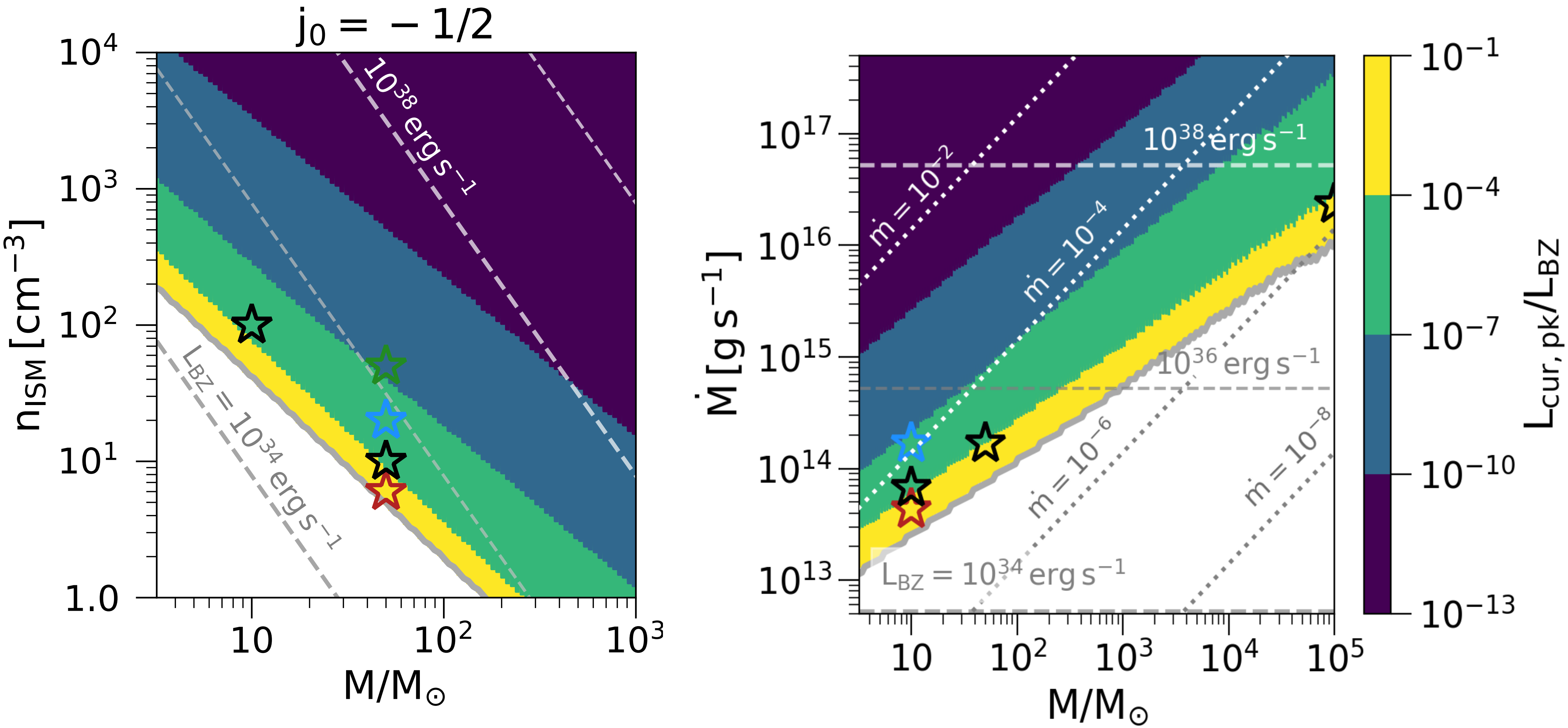
→ variable due to the gas turbulence

the timescale :

$$\tau \sim \frac{R_a\text{(length scale of gas turbulence)}}{V_R\text{(infalling gas velocity)}}$$

$$\simeq \frac{8.3\times10^{13}\,\mathrm{cm}}{10^6\,\mathrm{cm\,s^{-1}}} \simeq 10^8\,\mathrm{s}$$





$j_0 = -1/2$
$n_{ISM}\,[\mathrm{cm}^{-3}]$
$M/M_\odot$
$10^{38}\,\mathrm{erg\,s^{-1}}$
$L_{BZ} = 10^{34}\,\mathrm{erg\,s^{-1}}$
$\dot{M}\,[\mathrm{g\,s^{-1}}]$
$10^{38}\,\mathrm{erg\,s^{-1}}$
$10^{36}\,\mathrm{erg\,s^{-1}}$
$L_{BZ} = 10^{34}\,\mathrm{erg\,s^{-1}}$
$\dot{m} = 10^{-2}$
$\dot{m} = 10^{-4}$
$\dot{m} = 10^{-6}$
$\dot{m} = 10^{-8}$
$L_{cur,pk}/L_{BZ}$

Semi-Analytic Model of Gamma-Ray Emission from The “Gap”

◎ imitate the acceleration of e^-, gamma-ray emissivity during the oscillation

Kimura et al.21 one-zone IBH disk model

gas density、BH mass → mass infall rate in the disk → radiation from the disk ⇒ τ_0、 ϵ_{min}

disk photon peak energy

B_H (gas transports magnetic flux)

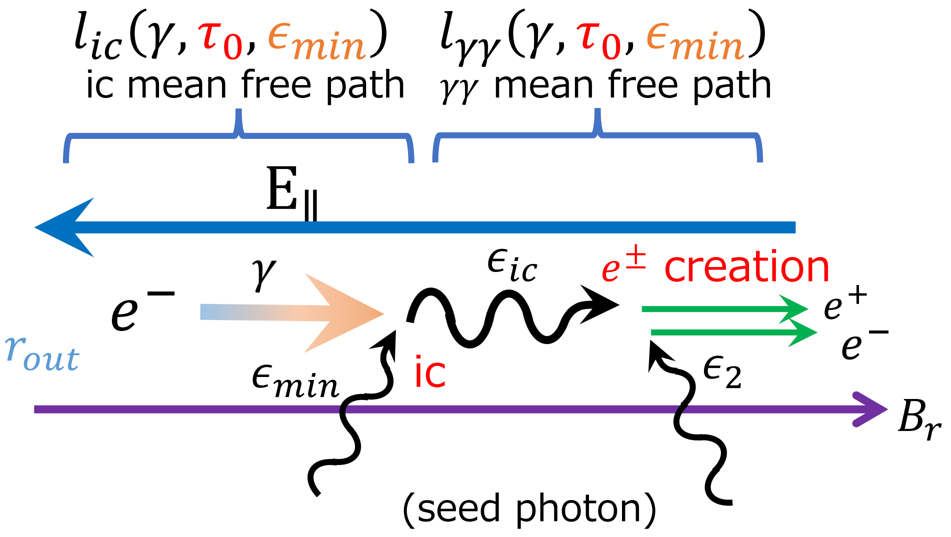
1) solve the simplified EoM of one e^- from inner boundary r_{in}

$$\frac{d(\gamma m_e c)}{dt} = eE_r(B_H, r_{in}) - \frac{P_{cur}(\gamma)}{c} - \frac{P_{ic}(\gamma)}{c}$$

2) consider the pair creation

→ the position where enough pair created = outer boundary r_{out}

3) iteration, find r_{in} , r_{out} that satisfy $\frac{r_{in}+r_{out}}{2} \sim 2.0 r_g$



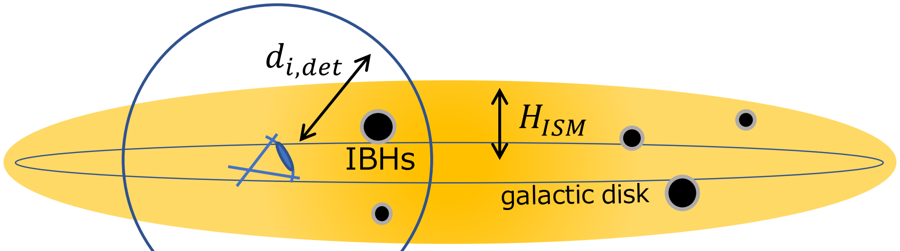
define the evolution of the e^- energy from $r_{in} \rightarrow r_{out}$

⇒ gamma-ray luminosity of the e^- also found unanimously

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

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

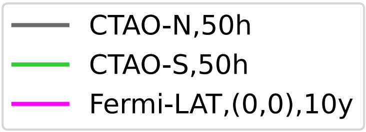
sensitivity limit $d_{i,det}$: luminosity vs sensitivity



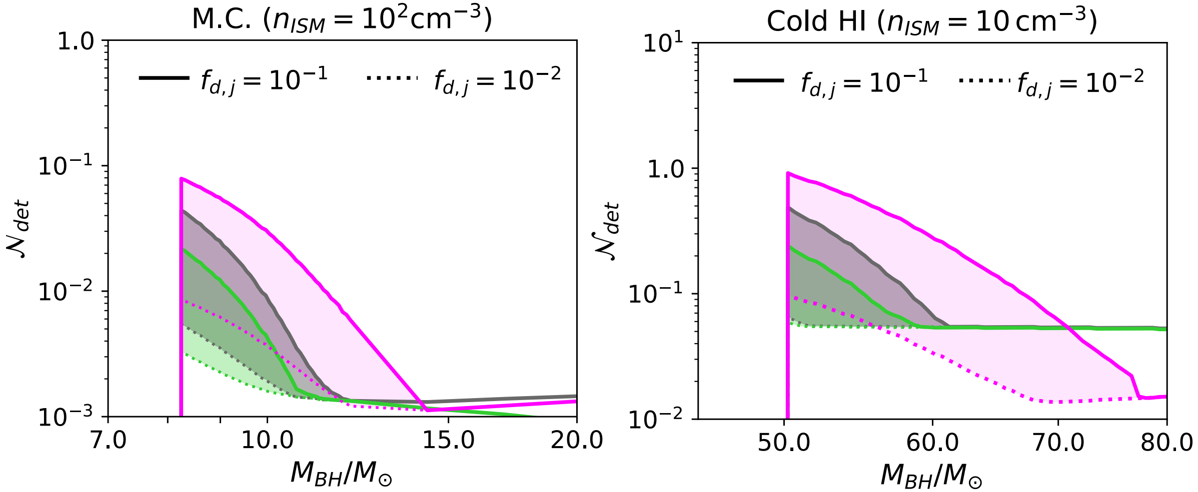
gas distributing in $z \lesssim H_{ISM}$

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

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



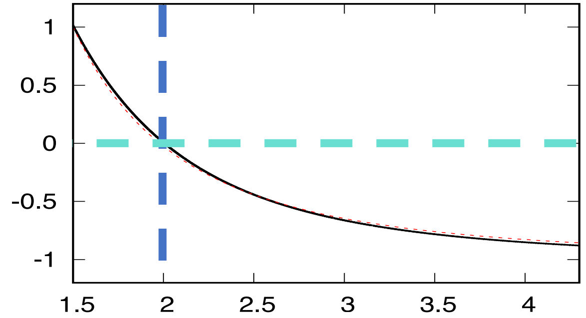
$$\left(\begin{array}{c} \frac{dN}{dM} \propto M^{-\gamma}\ (\gamma \sim 2.6\ \text{Abbott et al.21}) \\ \xi_0\ \text{: Volume filling factor} \\ n_0 \sim \mathcal{R}_{GW} n_{gal}^{-1} H_0^{-1} \sim 2\times 10^2 \mathrm{kpc}^{-3}\ \text{: merged BH density} \end{array} \right)$$



if n_0 is high, could be larger

ブラックホール磁気圏

GJ電荷密度分布 $\rho_{GJ}/\rho_{GJ}(r_H)$



◎パルサーとの大きな違い：磁場をアンカーする “表面”がない

→ブラックホール周りの時空の角速度 $\Omega(\equiv \frac{d\varphi}{dt})$ と“磁力線の角速度” Ω_F が一致しない

スプリットモノポール型の磁場を仮定すると

赤道面以外はモノポール

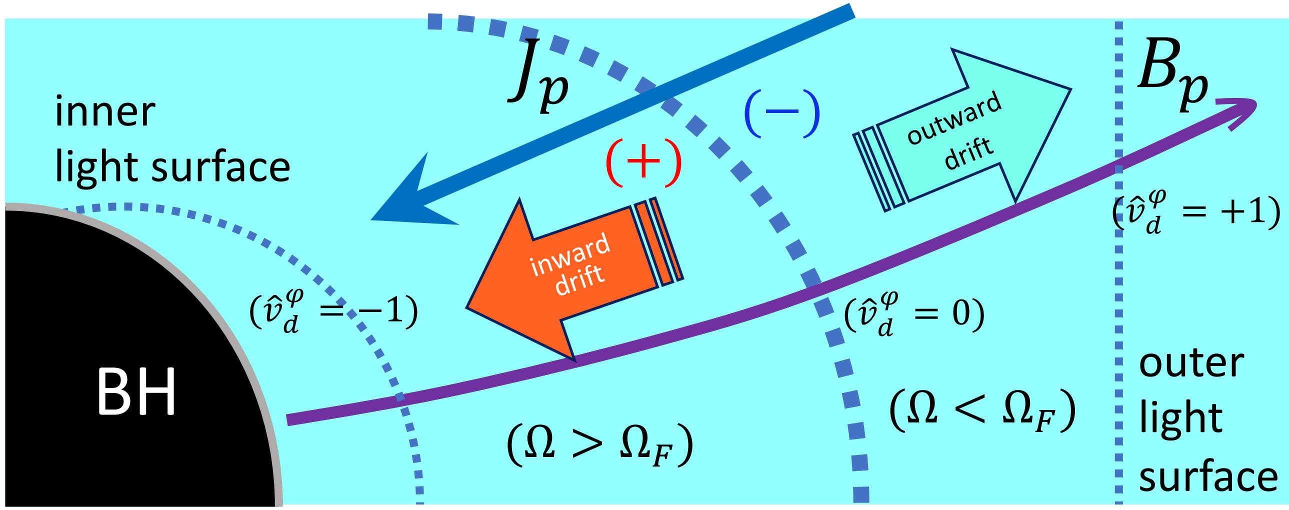
$$\Omega_F = \boxed{\frac{\Omega_H}{2}} + O(a^3)$$

(Ω_H:ホライズンでの Ω)

$$\boldsymbol{D}_p = -\frac{1}{\alpha}(\Omega_F - \Omega)\boldsymbol{e}_\varphi \times \boldsymbol{B}_p \quad v\times B\text{電場}$$

$$\rho_{\rm GJ} = \frac{1}{4\pi}\nabla\cdot\boldsymbol{D}_p = \cdots = \frac{B_H\sqrt{A_H}}{4\pi\sqrt{-g}}\times\partial_\theta\left[\frac{\sin^2\theta}{\alpha^2}\underline{(\Omega-\Omega_F)}\right]\cdots \approx \boxed{-\frac{\Omega_F B_H}{2\pi c}}$$

$\rho_e \approx 0$ at $\Omega \approx \Omega_F$



null charge
surface

(B_H, : ホライズンでの磁場)