Chapter 7

Gap Emission from BHs Moving in Molecular Clouds

§1 VHE observations of molecular clouds

§2 Gap emission from stellar-mass BHs

§3 HE detectability of gap emission from XRBs

§1 VHE observations of molecular clouds

§ 1 VHE observations of molecular clouds

In VHE (10GeV-100TeV), 76 sources have been found on the Galactic Plane with IACTs.

Fig.) Imaging Atmospheric Cherenkev Telescopes (IACTs
Left: VERITAS (USA); Right: MAGIC (Germany-Spain)

§1 VHE observations of molecular clouds

In VHE, 76 sources have been found on the Galactic Plane with IACTs, 36 of which are still remained unidentified.

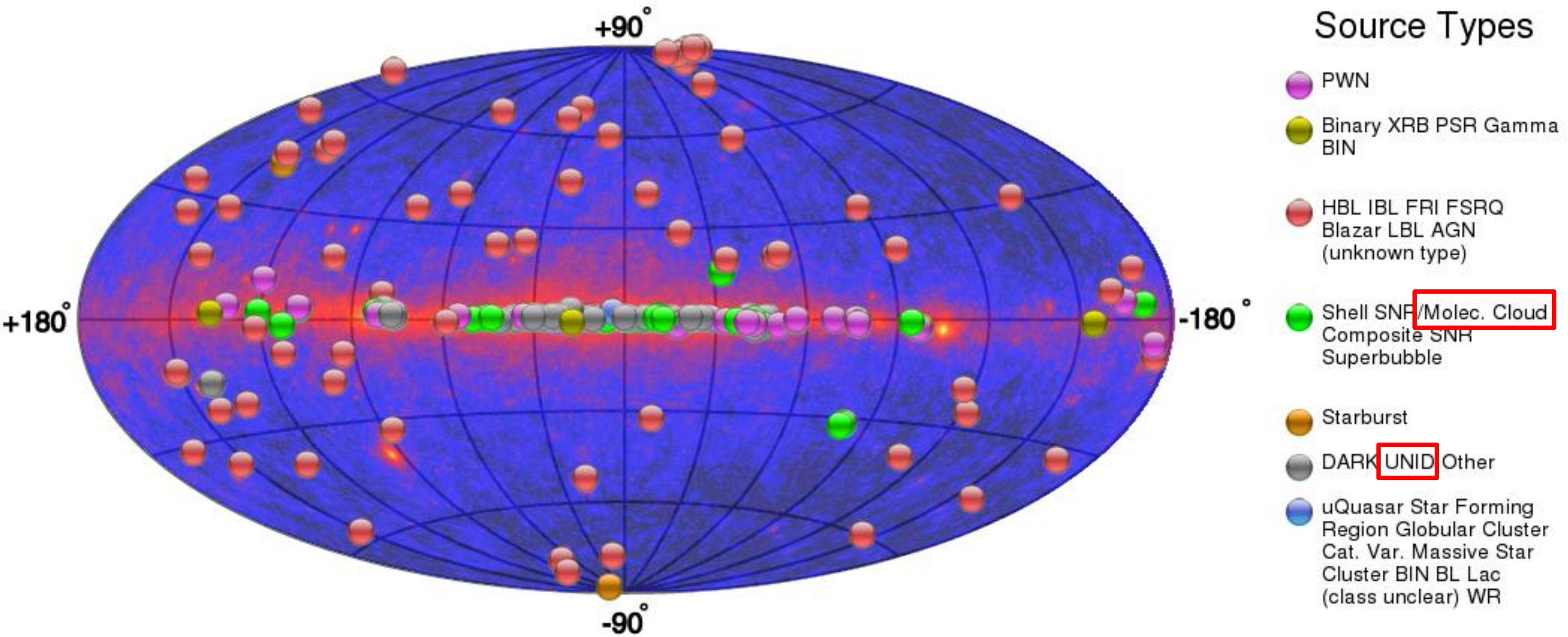

Fig.) Very High Energy (VHE) sky (0.01 TeV<$h\nu$< 100 TeV)
TeV CAT (http://tevcat.uchicago.edu/)

§1 VHE observations of molecular clouds

In VHE, 76 sources have been found on the Galactic Plane with IACTs, 36 of which are still remained unidentified.

HESS found that 38 of 49 TeV sources are positionally associated with dense molecular clouds and 12 of 18 unidentified TeV sources are associated with dense MC (10^5 cm^{-3} > n_{H2} > 10^3 cm^{-3}). De Wilt + ('17) MN 468, 2093

Fig.) High Energy Stereoscopic System (HESS)

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Among the 12 unID sources, 9 sources are Gaussian-fitted and 5 of them are compact or point-like.

I will show that such a point-like VHE image is expected if a rapidly rotating BH encounters a dense molecular cloud.

KH+ (2017) ApJ 845, 77

§ 1 VHE observations of molecular clouds

On the other hand, extended sources may be due to cosmic-ray (accelerated in SNR) vs. molecular cloud interactions.

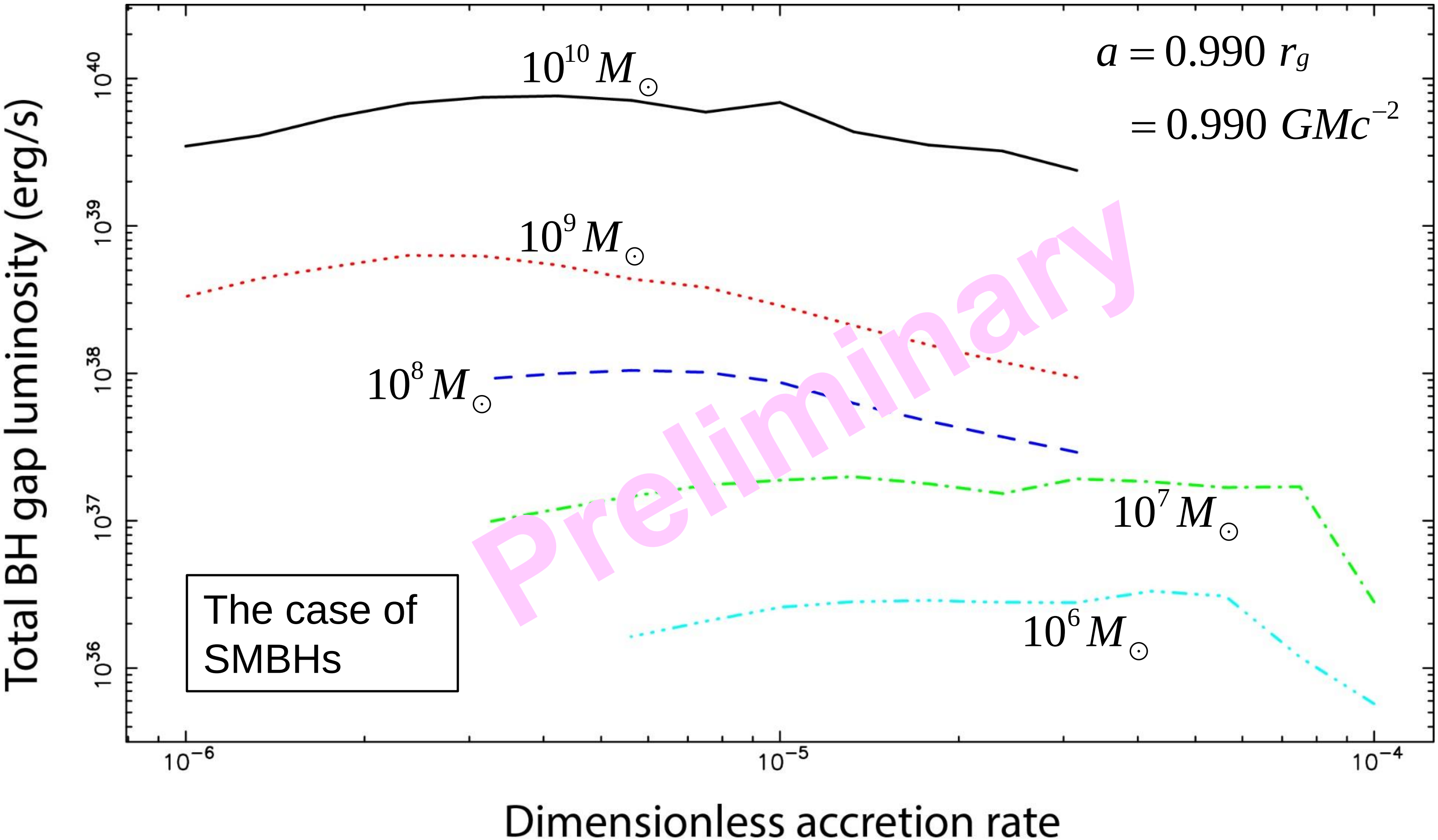
Ginzburg, Syrovatskii, *The Origin of Cosmic Rays (New York; Maccmillan)*, (1964)
Blandford, Eichler, *Phys. Rep.*, **154**, 1 (1987)
Aharonian +, *Mon. Not. R. Astron. Soc.* **291**, 162 (1997)
van der Swaluw +, *Astron. Astroph.* **380**, 309 (2001)
Hillas +, *Astroph. J.* **503**, 744 (1998)

→ To be compared with the BH gap scenario later.

Today, we will focus on the BH gap scenario, which predicts a point-like morphology when a rotating BH accretes in a molecular cloud.

§ 3 Results: BH lepton accelerator

The luminosity of a BH lepton accelerator (or a BH gap) is controlled by M, a, and $\dot{m}$.



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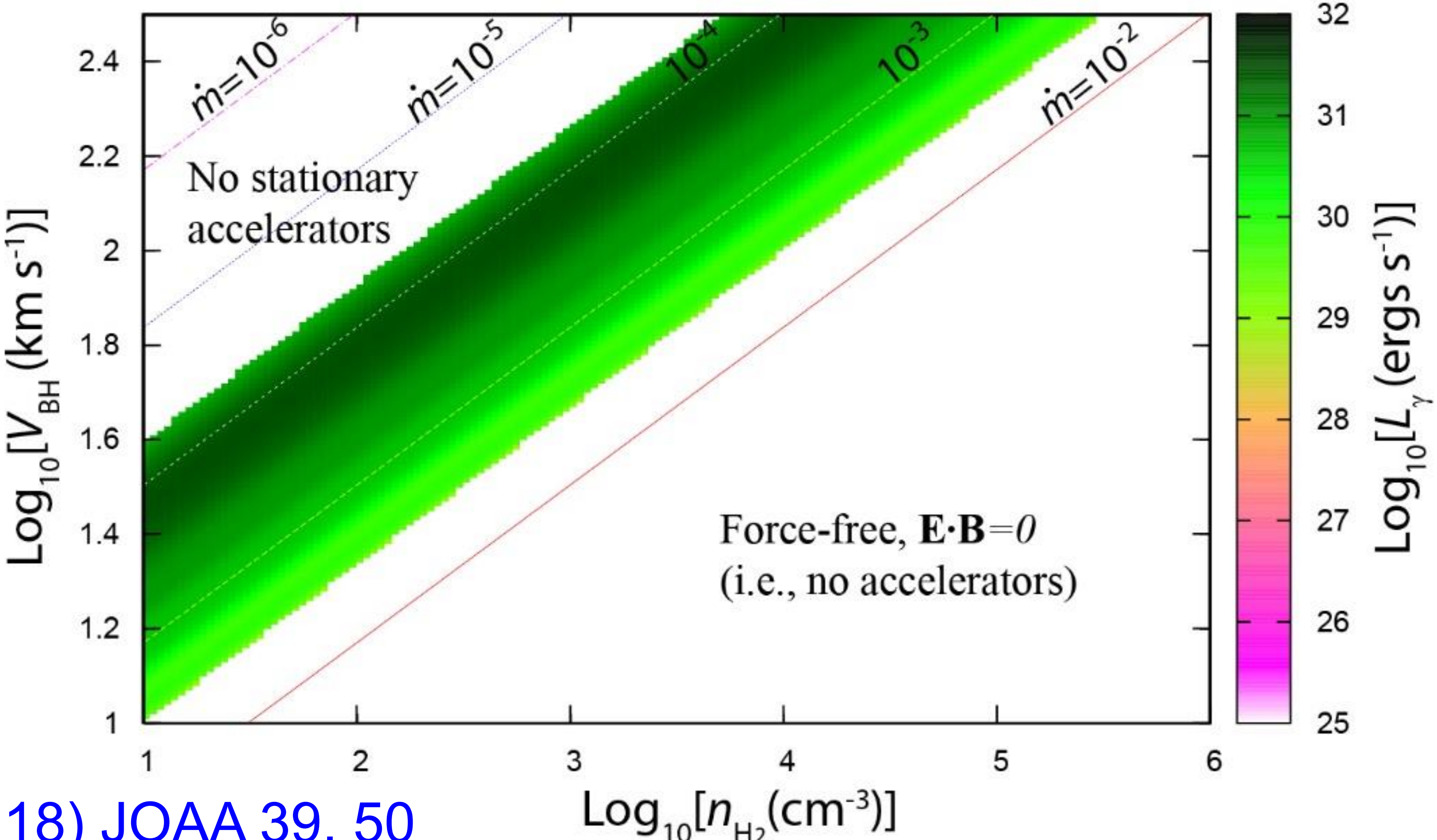
When a BH enters a gaseous cloud with velocity V_{BH}, its accretion rate can be estimated by the Bondi accretion rate (Bondi H., Hoyle F. 1944, MNRAS, 104, 273),

$$\dot{m}_{\mathrm{B}} = 4.3\times 10^{-5} \frac{n_{H_2}}{10^3\,\mathrm{cm}^{-3}} \left(\frac{V_{\mathrm{BH}}}{50\ \mathrm{km\ s}^{-1}} \right)^{-3}.$$

For fixed M and a, we can plot $\dot{m}$, and hence the gap bolometric luminosity, L_{gap} , on (n_{H2},V_{BH}) plane.

Lepton accelerator: total luminosity

BH gap luminosity maximizes when $6\times10^{-5} < \dot{m} < 2\times10^{-4}$, which is realized in a narrow range in the (n,V) plane.



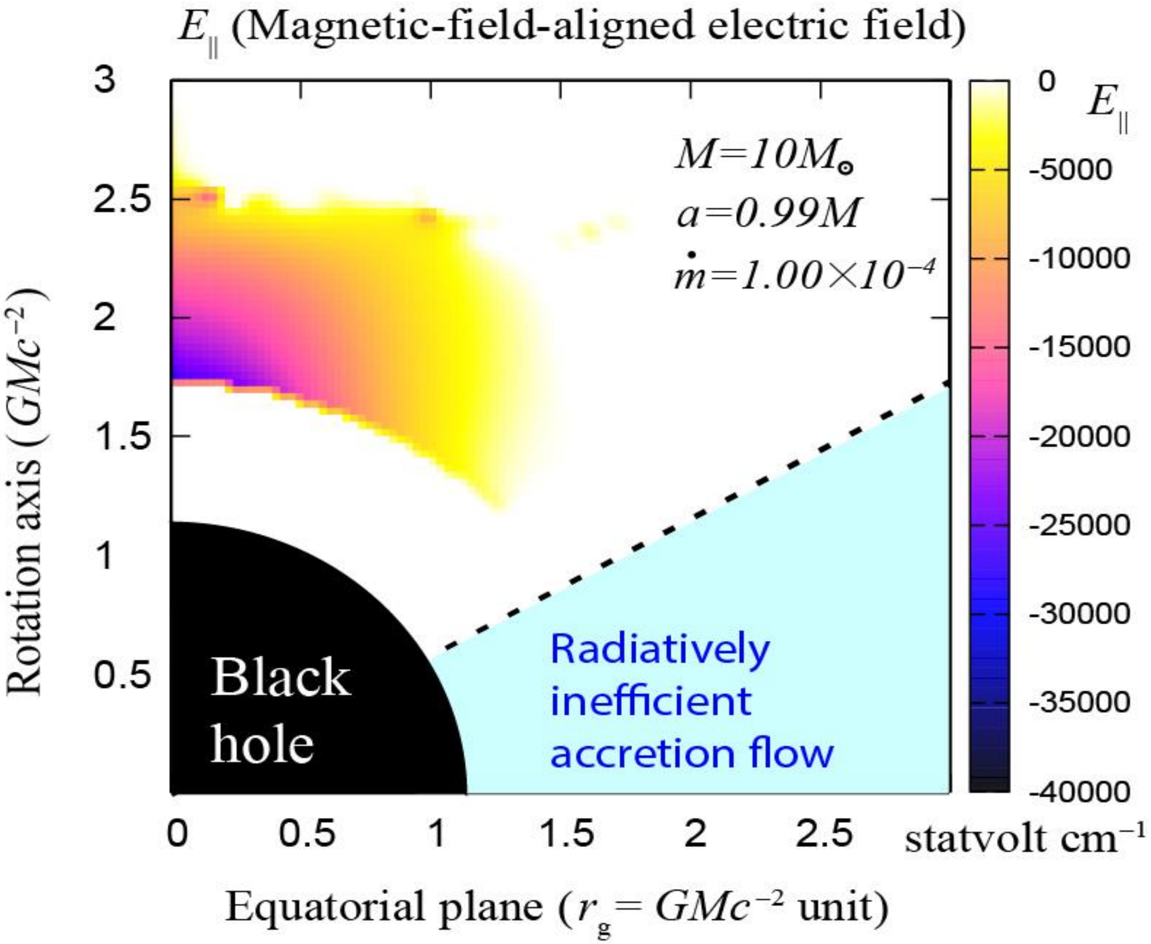
KH + ('18) JOAA 39, 50

Acceleration electric field

Magnetic-field-aligned electric field, $E_{\|}$, is solved from the set of Maxwell-Boltzmann eqs.

Fig. Acceleration electric field on the poloidal plane (in Boyer-Lindquist coord.)

$E_{\|}$ maximizes along rotation axis, θ=0.



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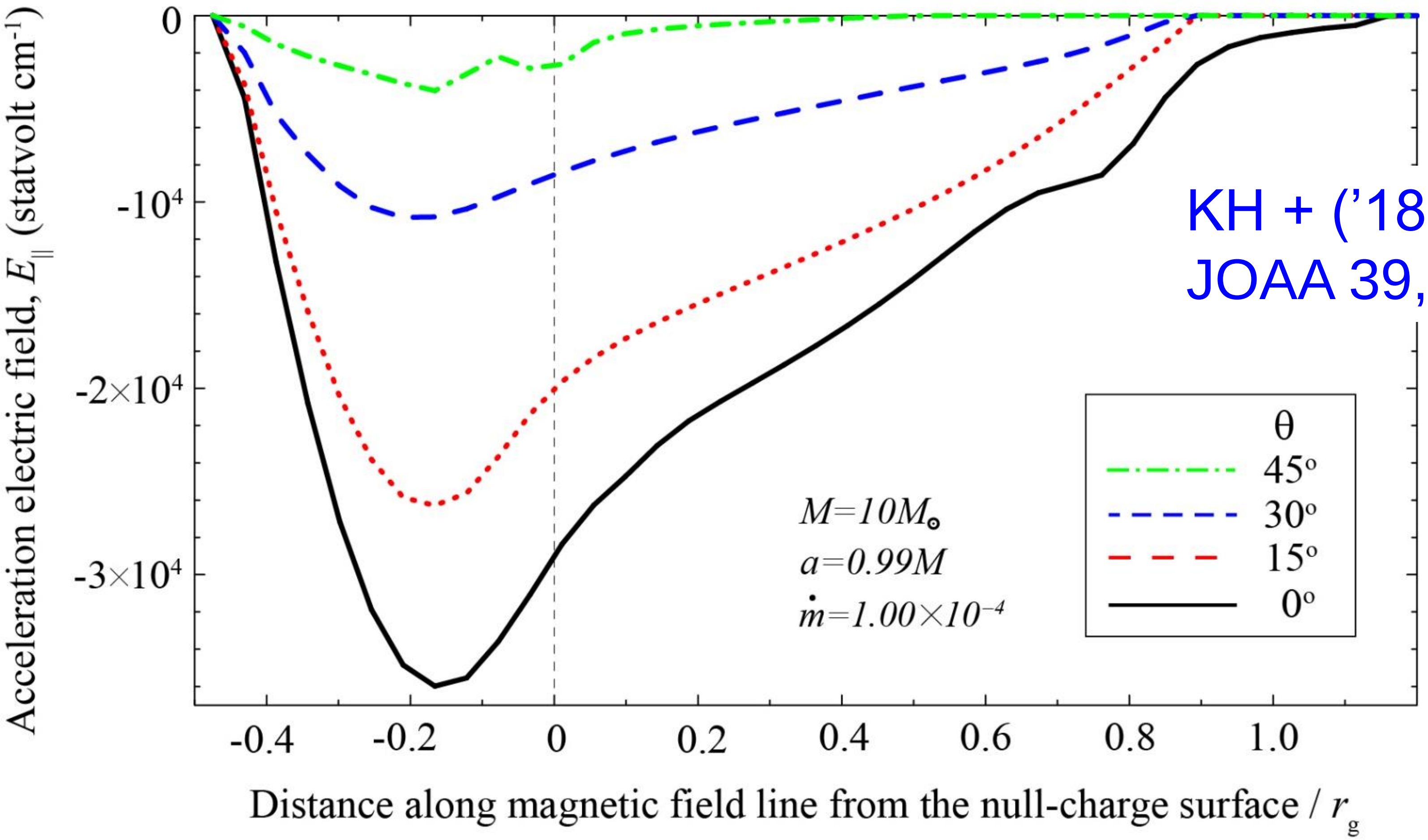
§ 3 Results: Acceleration electric field

Consider a rapidly rotating ($a=0.99M$) stellar-mass BH.

$E_{\|}$ maximizes slightly inside the null surface, where $\rho_{GJ}=0$.



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JOAA 39, 50

Fig. Acceleration electric field, $E_{\|}(r,\theta)$.

§ 3 Results: Acceleration electric field

$E_{\parallel}$ maximizes if $6\times10^{-5} < \dot{m} < 10^{-4}$.

KH + ('18)
submitted to ApJ

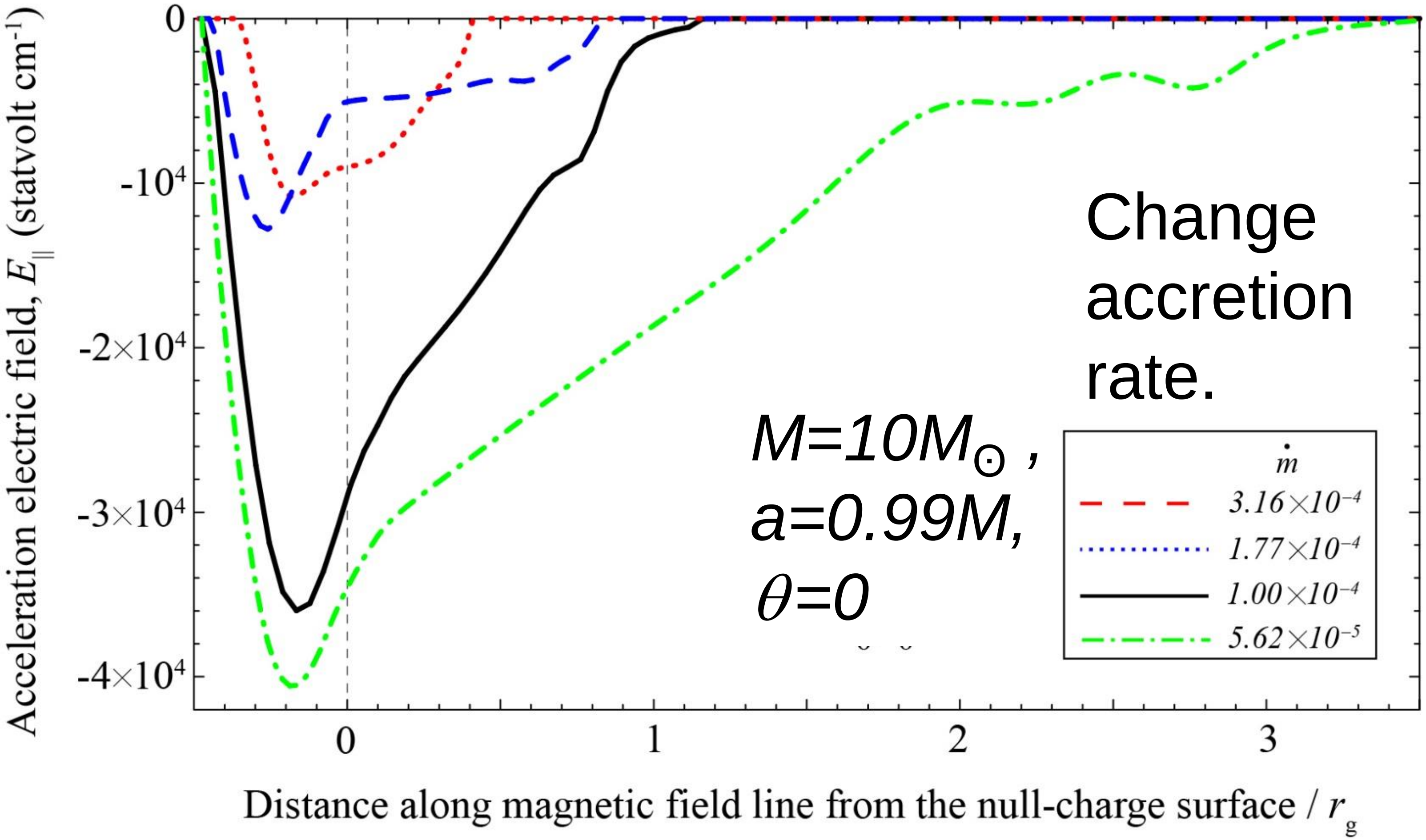

Fig. Acceleration electric field, $E_{\parallel}(r,\theta=0)$.

§ 3 Results: Ultra-relativistic electrons

$e^{\pm}$'s are created via γ-γ collisions and accelerated into opposite directions by $E_{\parallel}$, saturating in $10^6 < \gamma < 3 \times 10^6$ by curvature drag and in $5 \times 10^4 < \gamma < 10^6$ by IC drag.

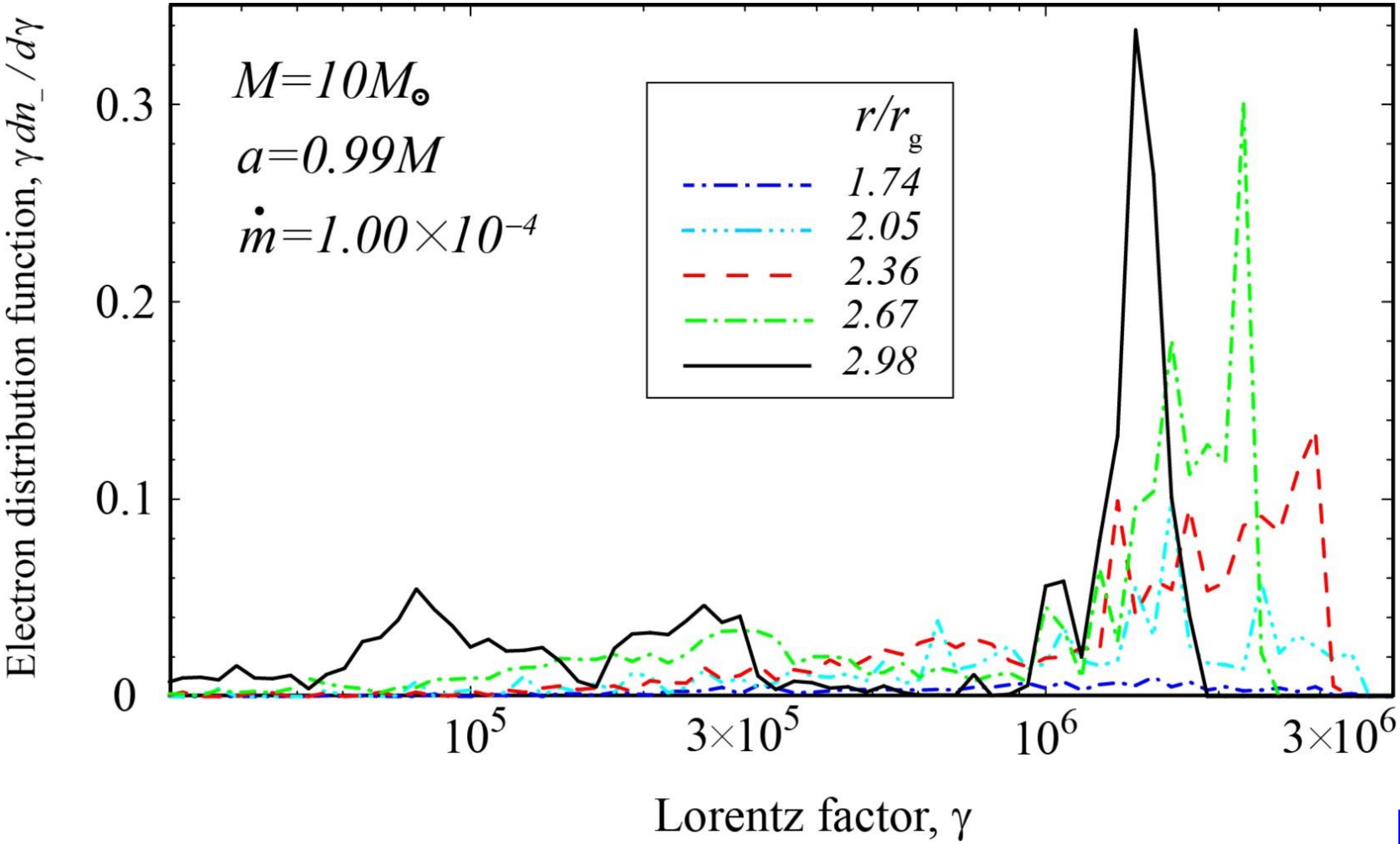

Fig. Distribution function of e⁻'s at five discrete positions.

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§ 3 Results: SED of BH gap

BH gap emission becomes detectable if $d<1$ kpc and $6\times10^{-5} < \dot{m} < 2\times10^{-4}$.

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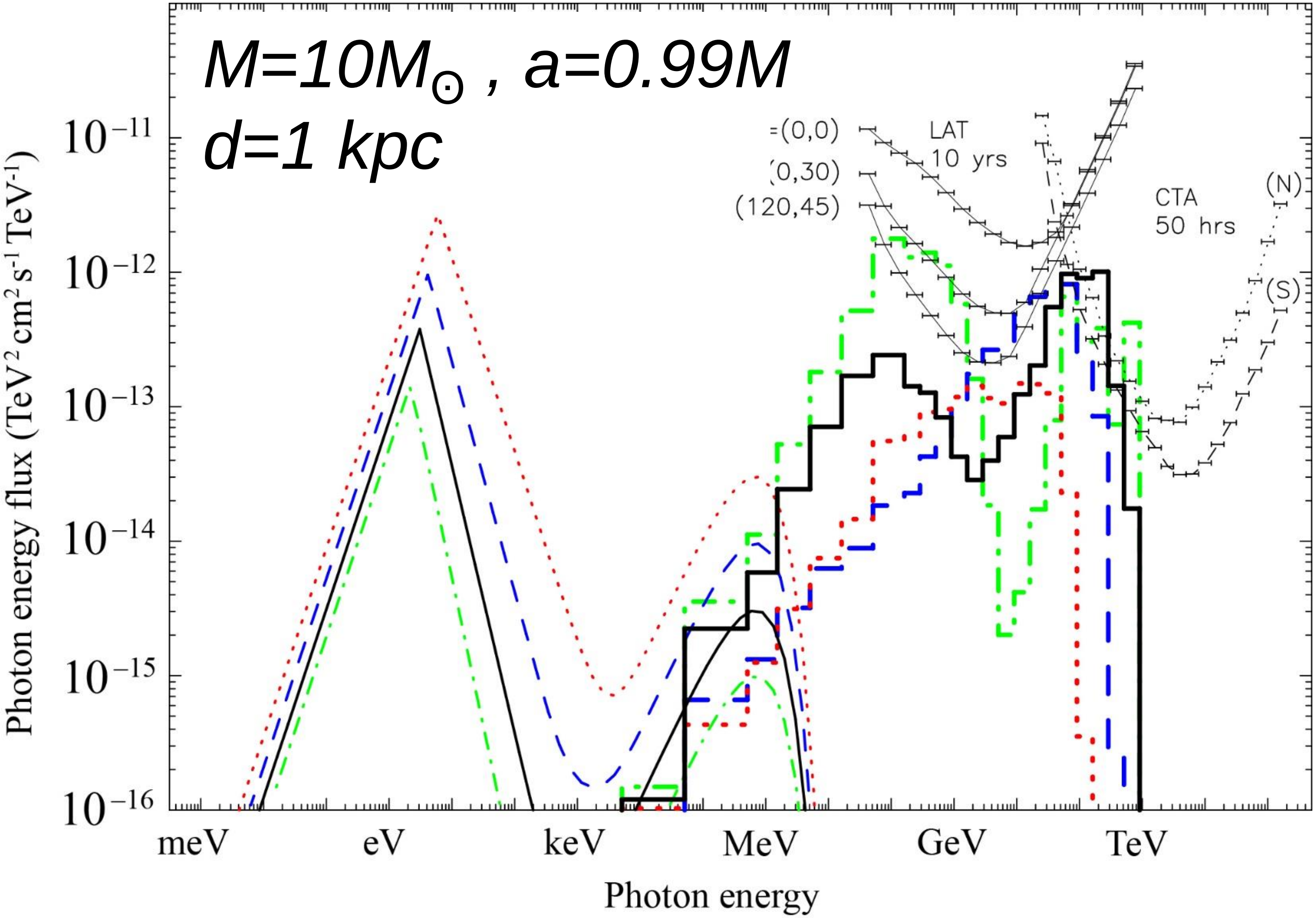

Fig.) SED of gap emission at

$\dot{m} = 3.2\times10^{-3}$,

1.8×10^{-4},

1.0×10^{-4},

5.6×10^{-5}

Curvature vs. IC emission in BH gap

Curvature emission appears in MeV-3GeV,
while IC one appears in 0.01-1 TeV.

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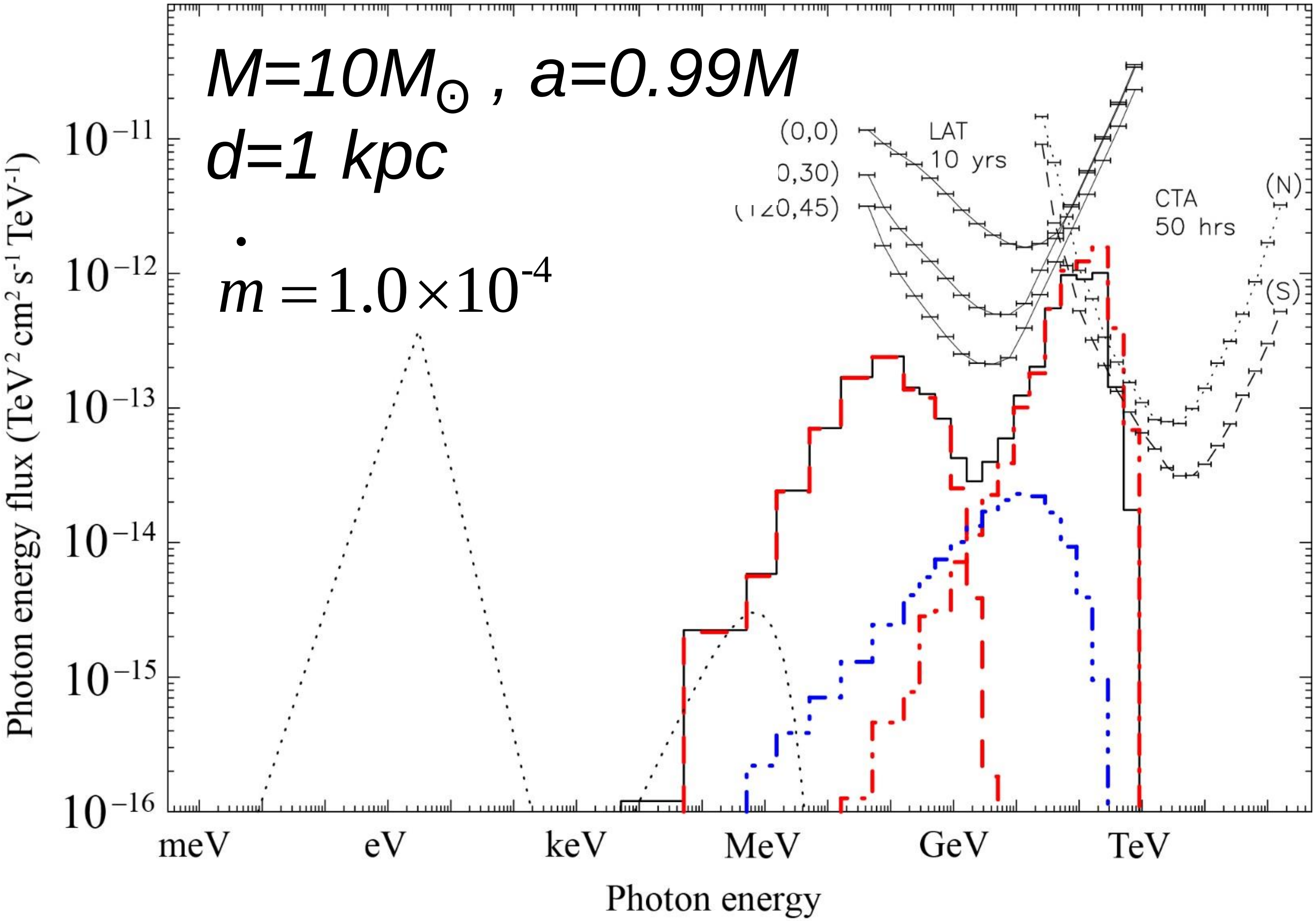

Fig.) Emission components

§ 4 Scenarios of TeV emission from MC

If a TeV image is extended with a power-law spectrum in GeV–100 TeV, it strongly suggests hadronic CR scenario.

If a TeV image is point-like with a broad peak spectrum in 0.01-1 TeV, it strongly suggests the BH gap scenario.

Model	Emission processes (spectral shape; energy range)	Size
Protostellar jets	e^- synchrotron (power-law; 10^{-6}eV-10^{2}eV); e^- Bremsstrahlung (power-law; 0.1MeV-TeV); pp collisions, π^0 decays(power-law; GeV-TeV)	10^{16}-10^{17} cm
Cosmic ray hadrons	pp collisions, π^0 decays (power-law; GeV-100 TeV)	10^{18}-10^{19} cm
Cosmic ray leptons	e^- synchrotron (power-law; 10^{-6}eV-10^{2}eV); e^- IC scatterings (broad peak; GeV-10 TeV)	10^{18}-10^{20} cm
Black hole lepton accelerator	e^- curvature process (broad peak; 0.1 GeV-10 GeV); e^- IC scatterings (sharp peak; 10GeV-1TeV)	10^{7} cm

Summary on BH gap model

- When the mass accretion rate is highly sub-Eddington, the polar funnel becomes charge-starved. Gaps appear within a few GM/c^2 above the event horizon.
- The gap emission concentrates toward the rotation axis as $a \to M$. (Song +, 2017, MNRAS 471, L135)
- If a rapidly rotating, stellar-mass BH enters a molecular cloud, its magnetospheric sub-TeV emission will be detectable with CTA as a point source if $d<1$ kpc and $6 \times 10^{-6} < \dot{M} / \dot{M}_{\rm Edd} < 10^{-5}$. (KH+, 2018, JOAA 39, 50)
- BH gap luminosity exhibits an anti-correlation with the accretion rate, and hence the ADAF IR luminosity.

(KH+, 2016, ApJ 818, 50)