Galactic Black Holes as PeVatrons and sub-PeV gamma-ray sources

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References
SSK, Sudoh, Kashiyama, Kawanaka, 2021, ApJ, 915, 31
SSK, Kashiyama, Hotokezaka, 2021, ApJL, 922, L15
SSK et al. in preparation
SSK & Sahu in preparation

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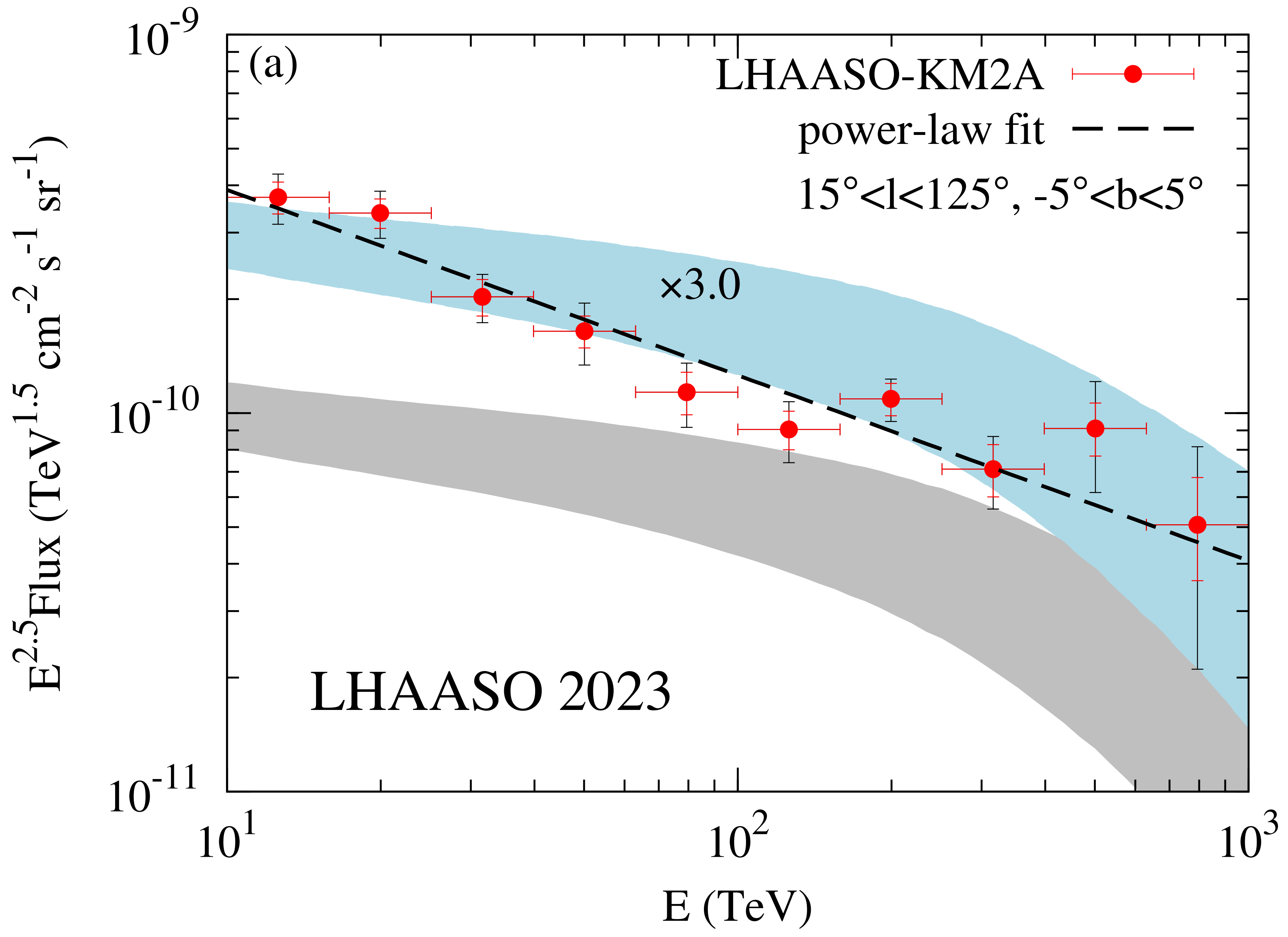
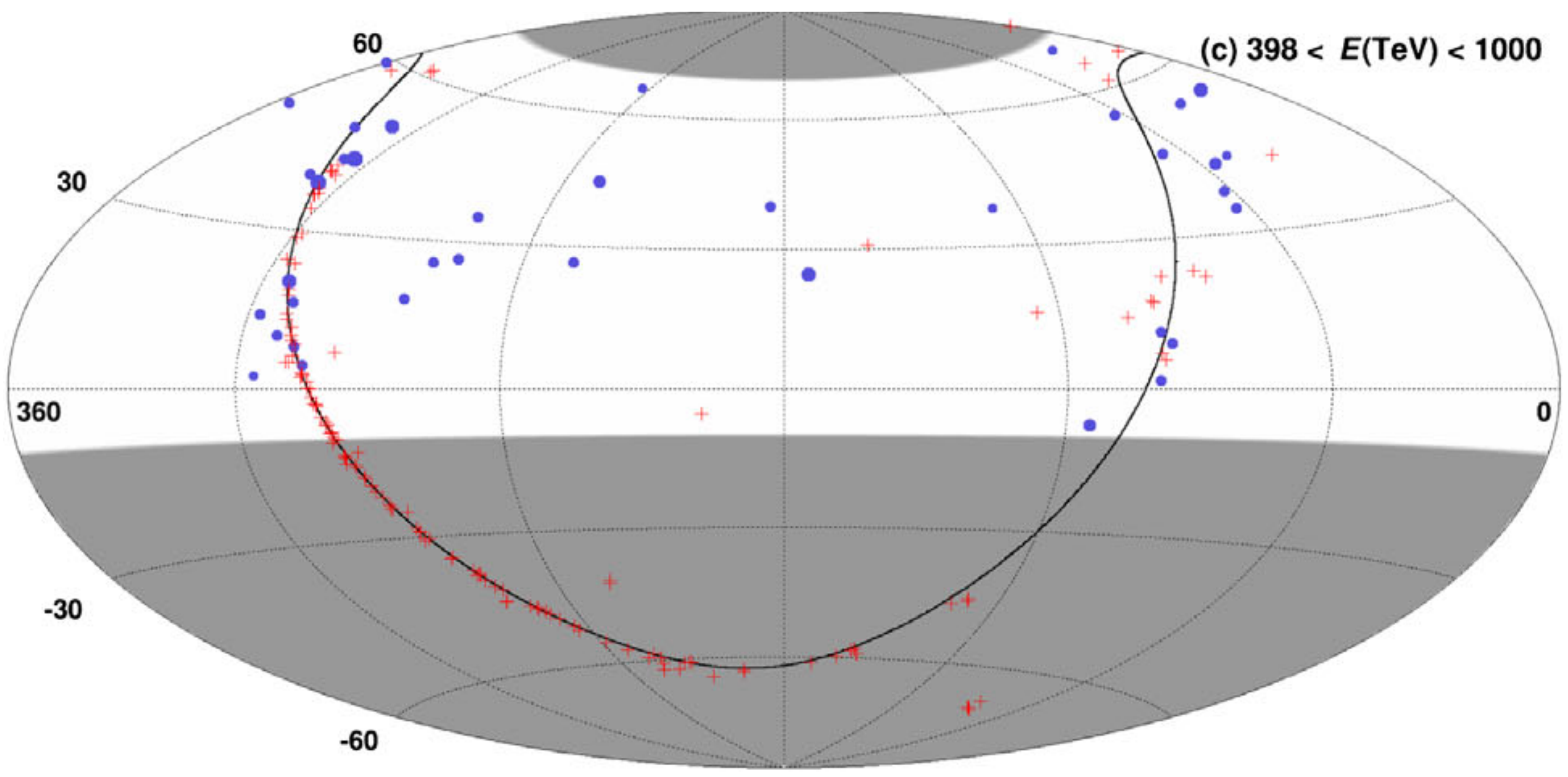
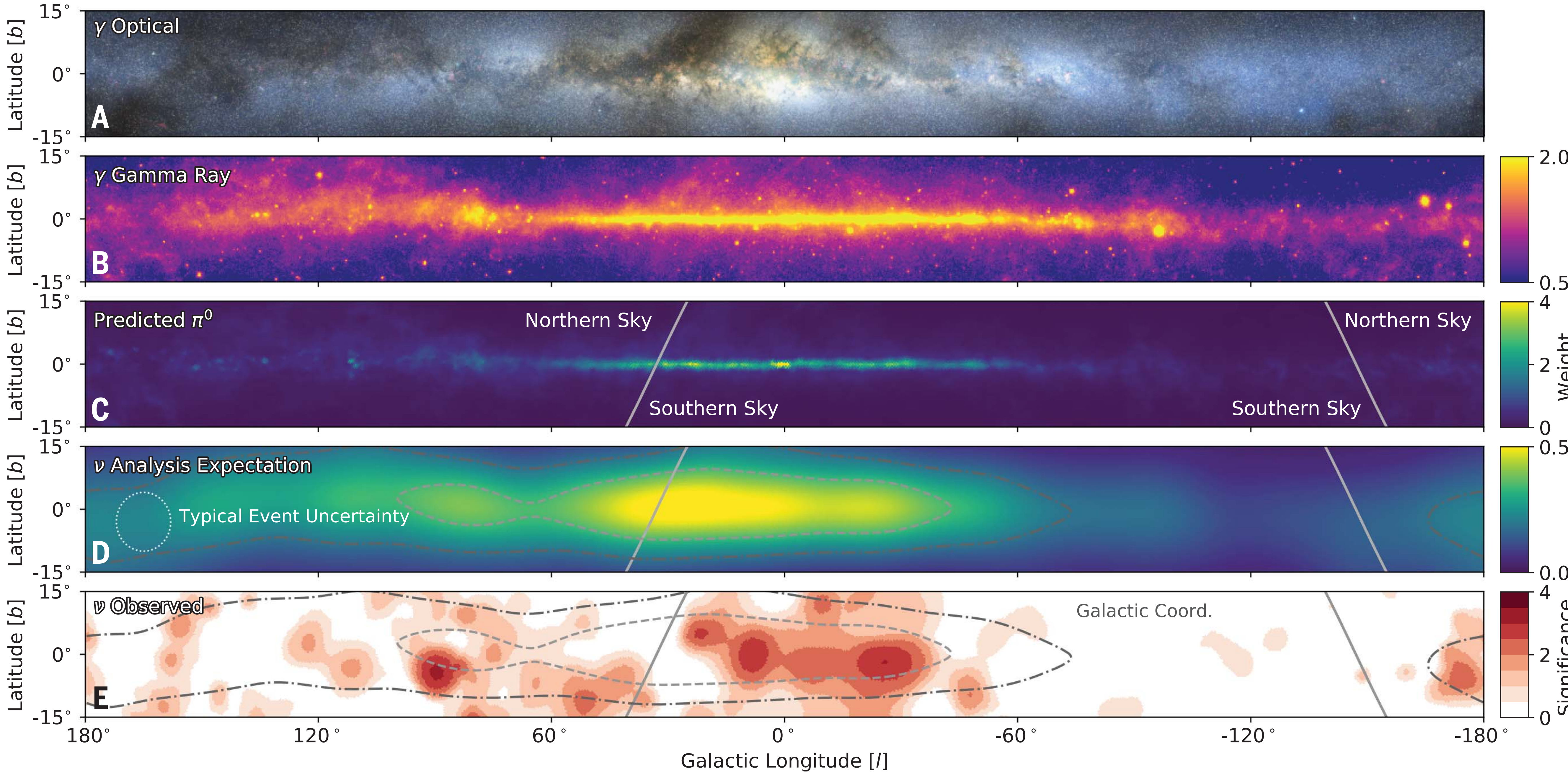
Galactic PeVatrons

- Origins of PeV CRs are unknown
- Tibet ASγ detected 0.1 - 1 PeV γ rays from Milky-way
- LHAASO detected diffuse γ-rays in 0.01 - 1 PeV
- IceCube detected diffuse Galactic neutrinos
- **Strong evidence of Galactic PeVatron**



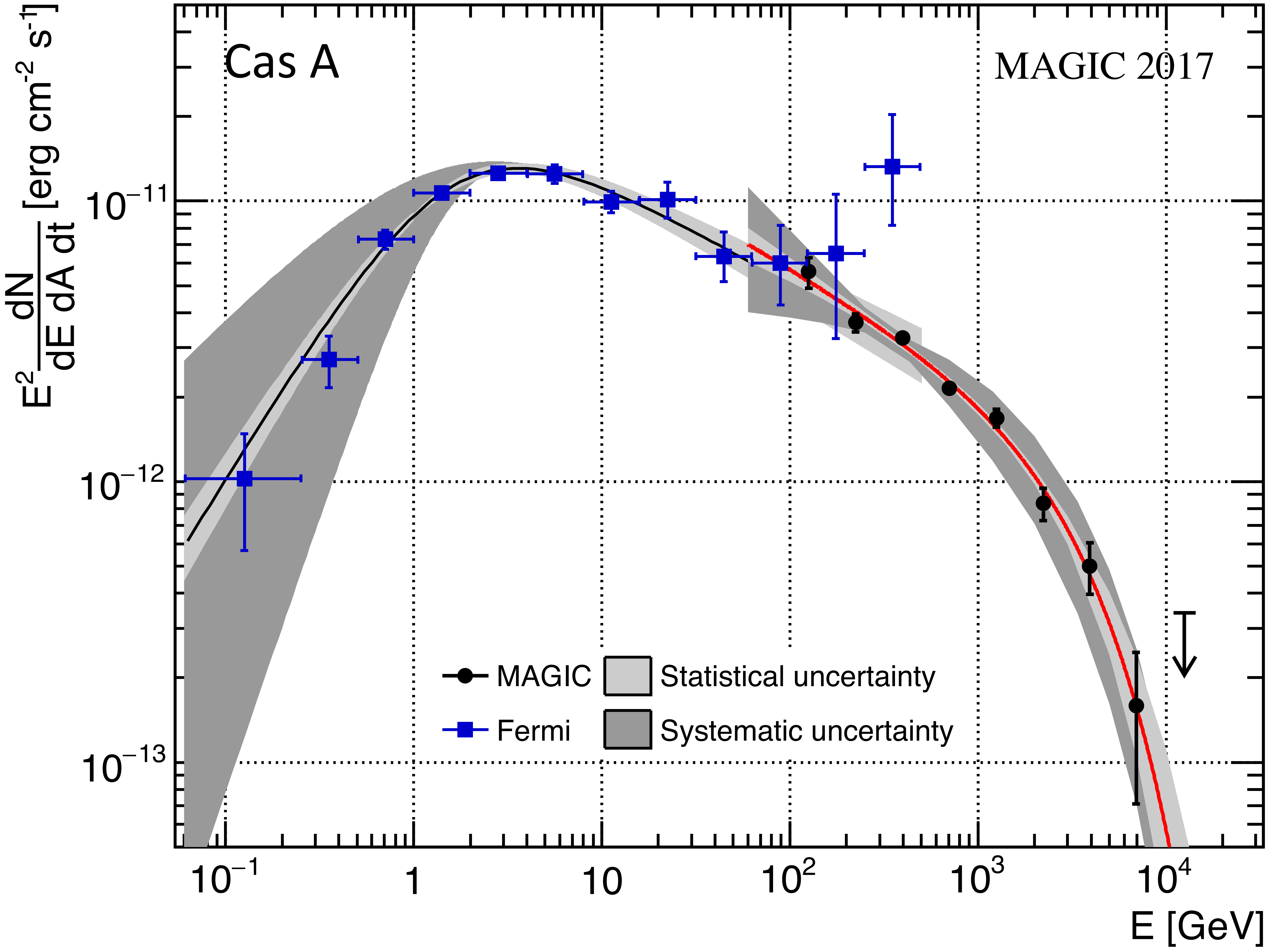
Tibet ASγ 2021





SNR as origin of PeV cosmic rays?

- γ-rays from majority of SNRs have break or cutoff around 1 - 10 TeV
- Some SNRs are identified as PeVatrons, but many have soft spectra at $E_\gamma \gtrsim$ 1 TeV
- It is unclear whether SNR can provide sufficient PeV CRs observed at Earth
- **Are there other PeVatrons in our Galaxy?**

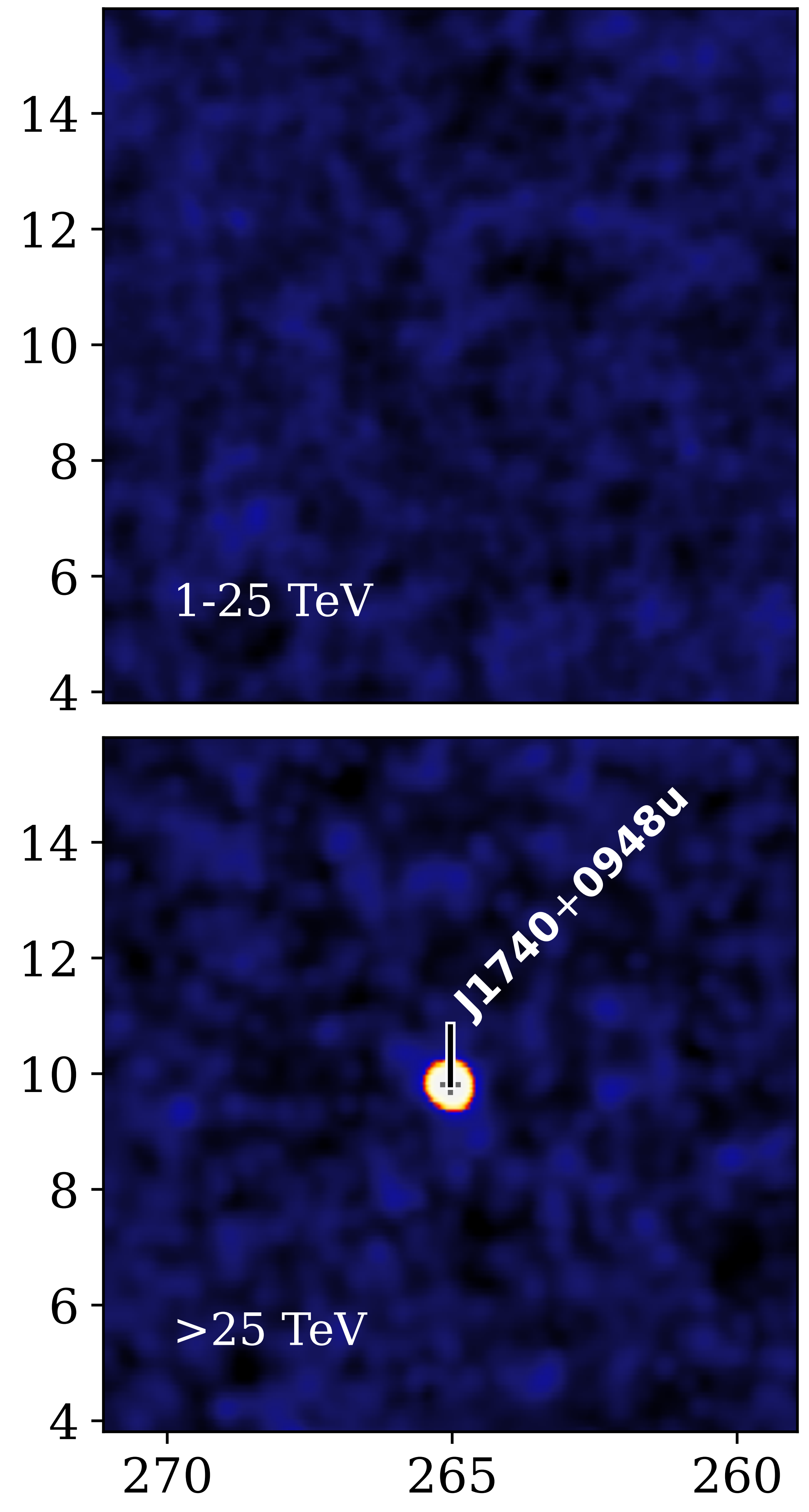


New class of UHE γ-ray sources?

- LHAASO discovered sources in E_γ > 100 TeV without detecting photons in 1 TeV < E_γ < 25 TeV
- **What is the origins of the new class of UHE photon sources?**

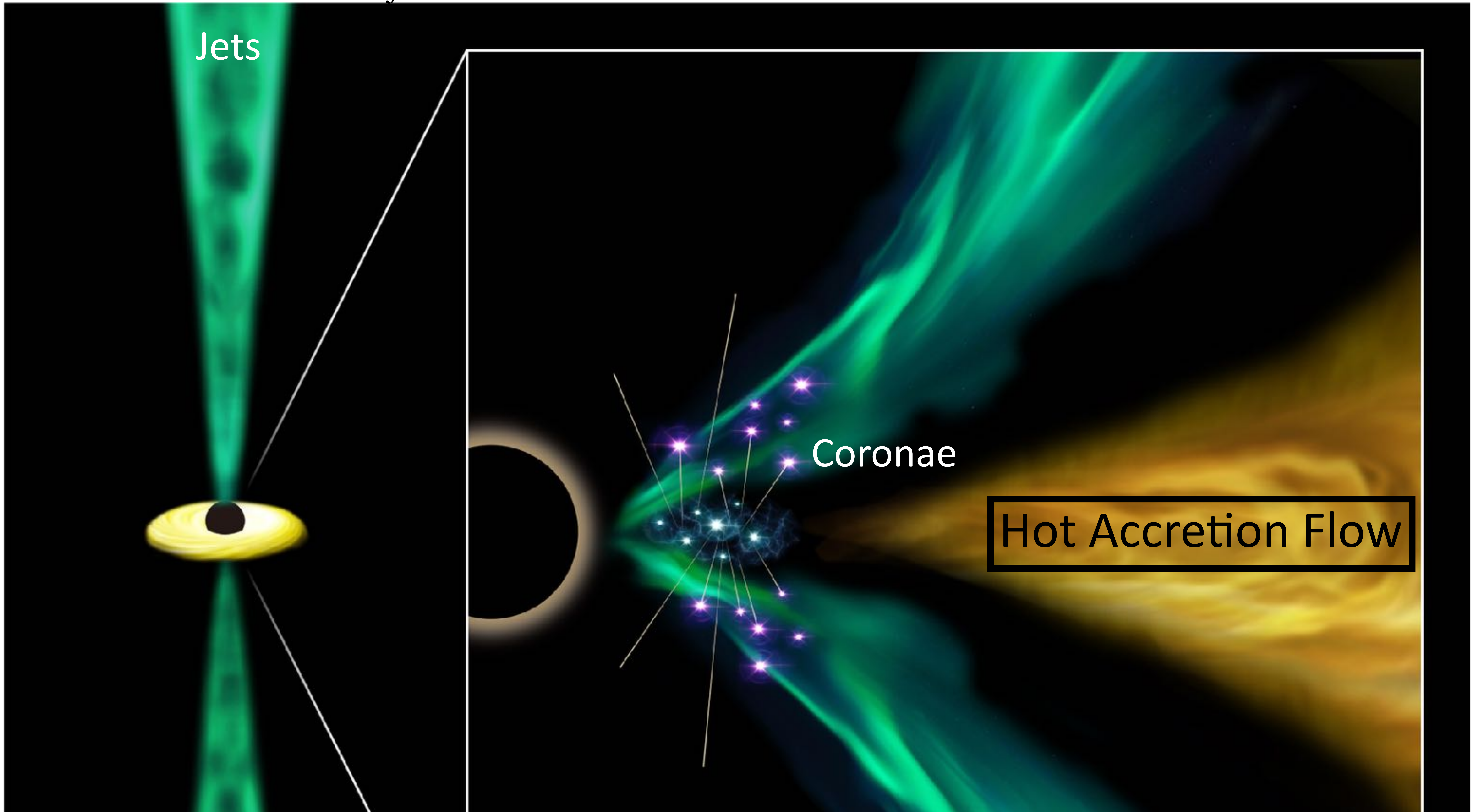
LHAASO 1st catalog

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}
1LHAASO J0007+5659u	KM2A	1.86	57.00	0.12	<0.18	86.5	0.33±0.05	3.10±0.20	43.6
	WCDA						<0.27		
1LHAASO J0206+4302u	KM2A	31.70	43.05	0.13	<0.27	96.0	0.24±0.03	2.62±0.16	82.8
	WCDA						<0.09		
1LHAASO J0212+4254u	KM2A	33.01	42.91	0.20	<0.31	38.4	0.12±0.03	2.45±0.23	30.2
	WCDA						<0.07		
1LHAASO J0216+4237u	KM2A	34.10	42.63	0.10	<0.13	102.0	0.18±0.03	2.58±0.17	65.6
	WCDA						<0.20		



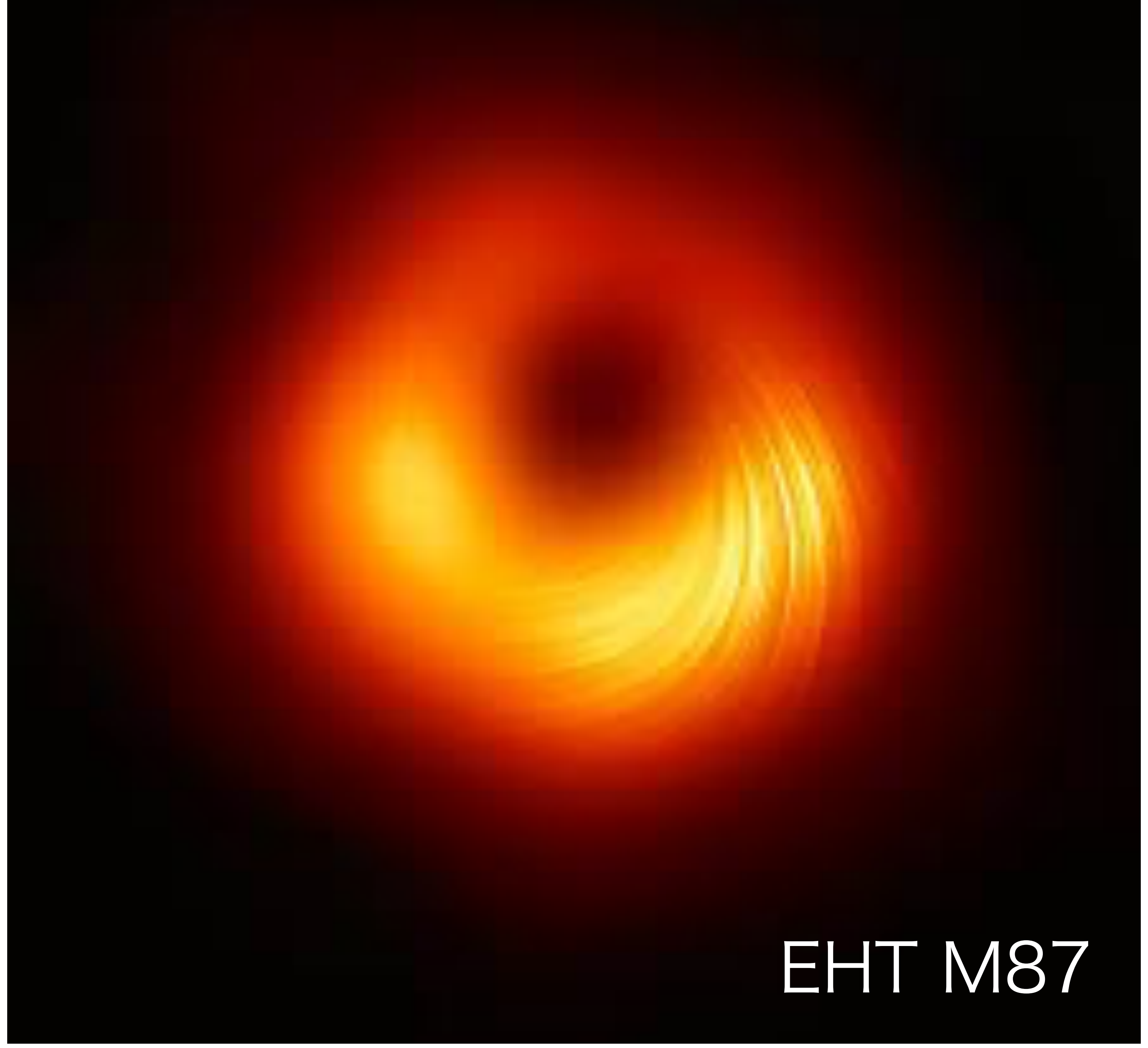
Isolated Black Holes as Particle Accelerators

See Ioka et al. 2017 for jet scenario

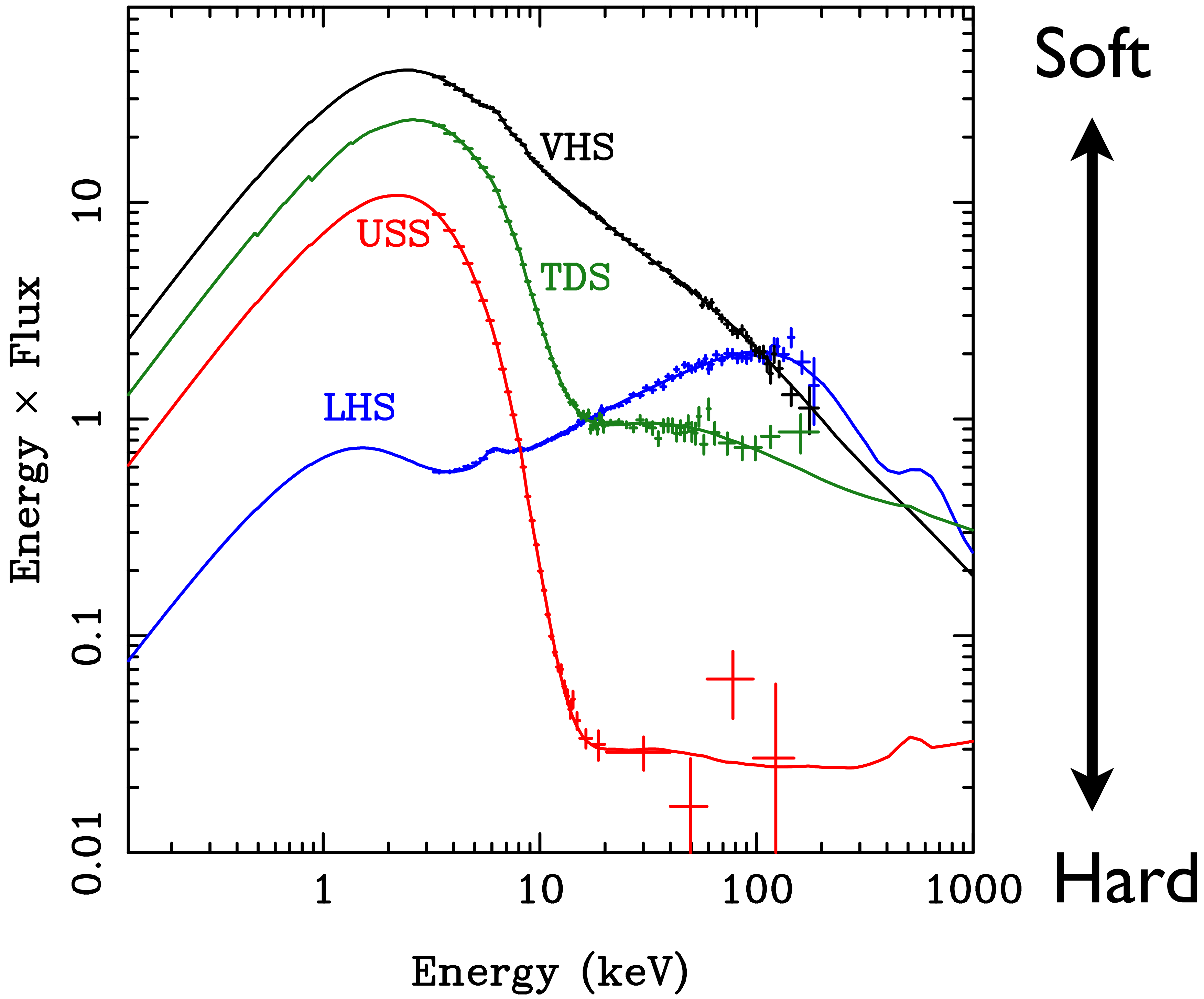


RIAFs around Black Holes

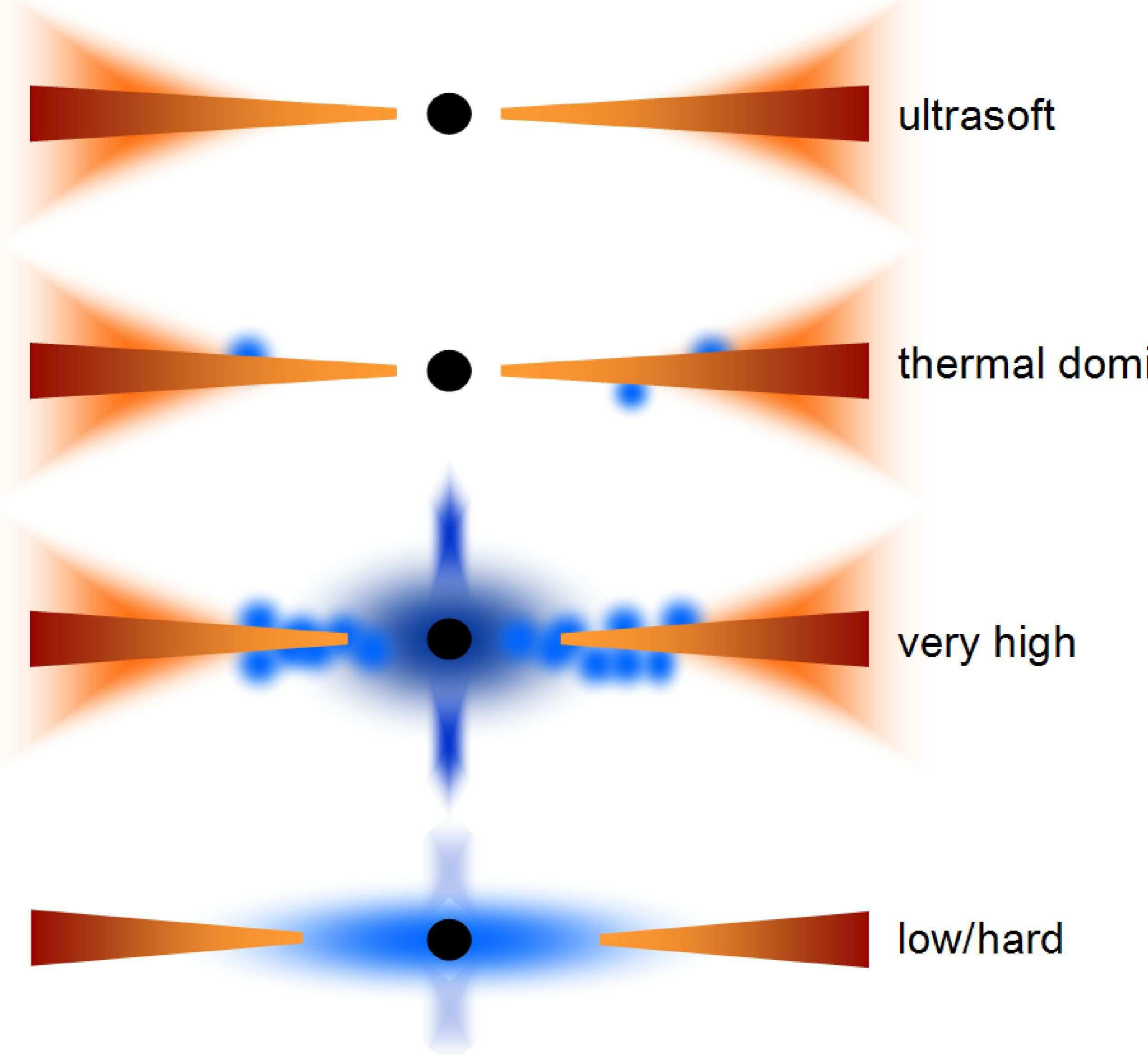
- Low-luminosity AGN



- X-ray binaries

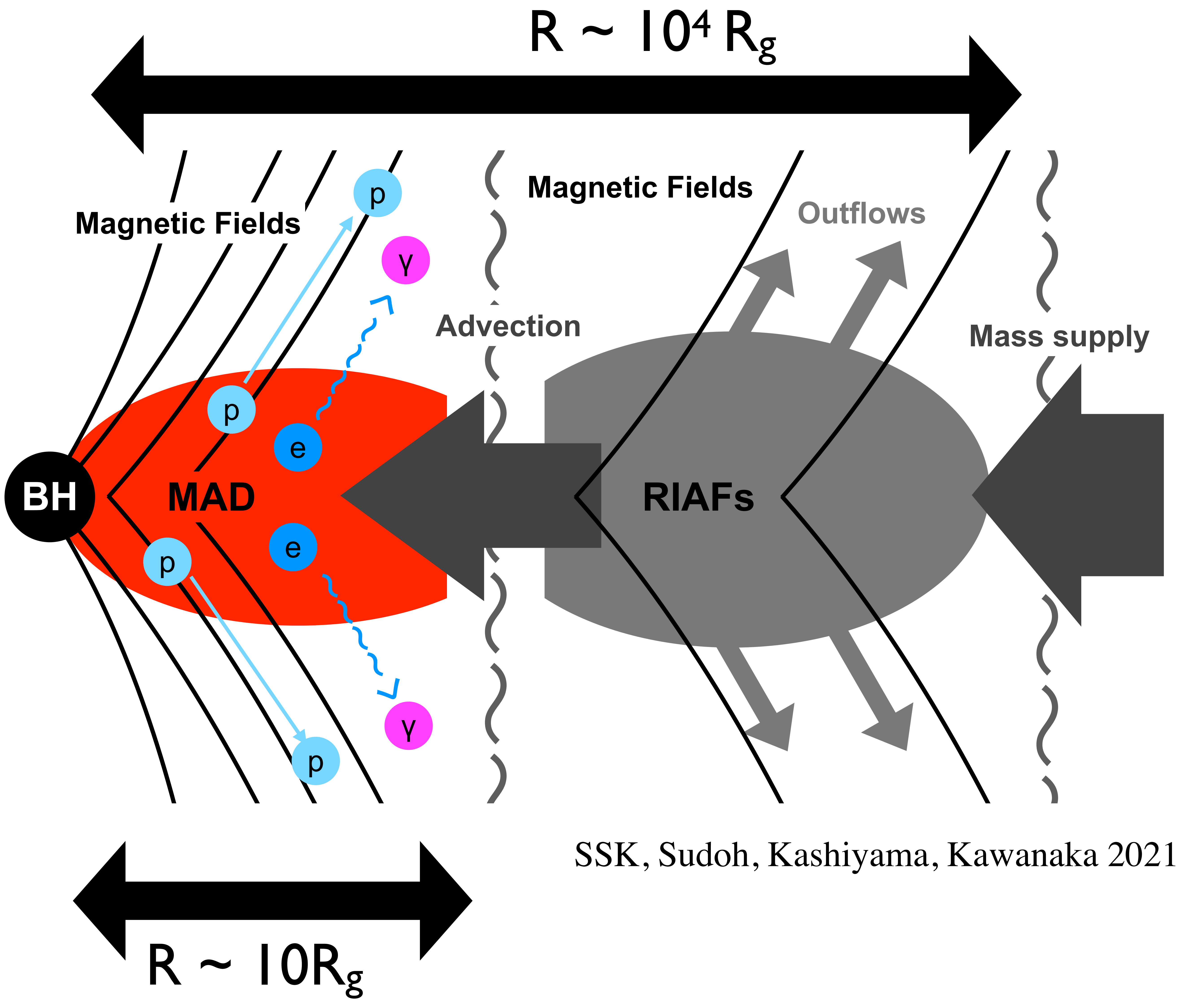


Done et al. 2007



- Accretion rate is high ($\dot{M}c^2 \gtrsim 0.01 L_{\rm Edd}$) —> optically thick accretion disk + corona
- Accretion rate is low ($\dot{M}c^2 \lesssim 0.01 L_{\rm Edd}$) —> only hot plasma surrounding the BH
- **Coulomb timescale >> infall timescale —> non-thermal particle production?**

MAD formation in low-accreting objects

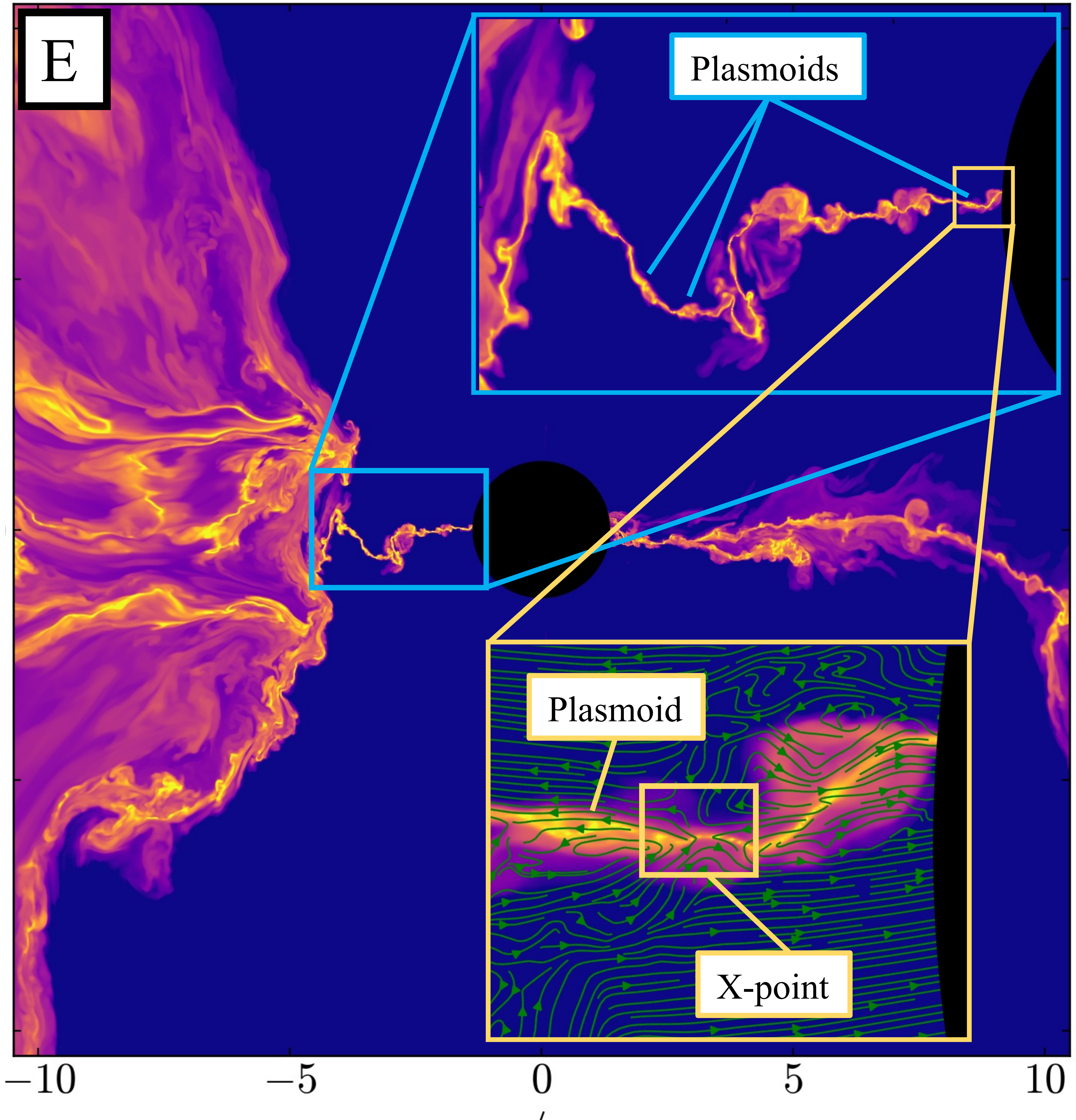


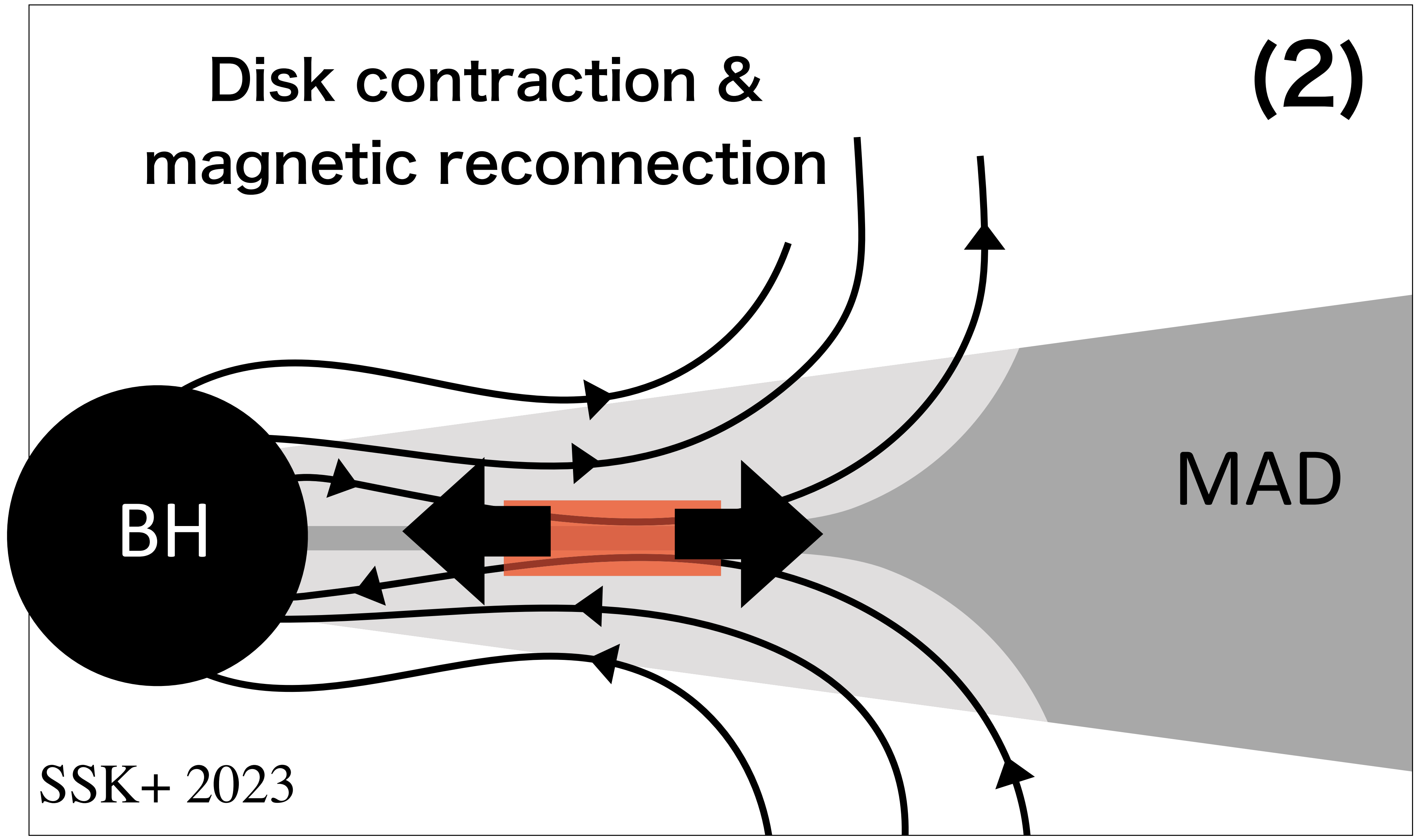
SSK, Sudoh, Kashiyama, Kawanaka 2021

- Low accretion rate e.g. Esin et al. 1997
  → Radiatively inefficient accretion flow (RIAF)
- Comparison of infall and cooling timescales
  → truncation radius $R_{trn} \sim 10^4\ R_g$
- Disk winds from RIAF e.g. Ohsuga et al. 2011
  → Large scale B-field with $\beta_p \sim 10^3 - 10^4$
  e.g., SSK+ 2019 MNRAS
- Rapid advection in RIAF e.g. Cao 2011
  → carry global B-field to inner region
  Blandford+ 1999
- Flux freezing + ADIOS: $\beta_p \propto R^{-1.5} - R^{-2}$
  $\rightarrow \beta < 1 @ R \lesssim 10 R_g$
  → **Formation of Magnetically Arrested Disk (MAD)**

Magnetic Reconnection in BH Magnetosphere

Ripperda+ 2022

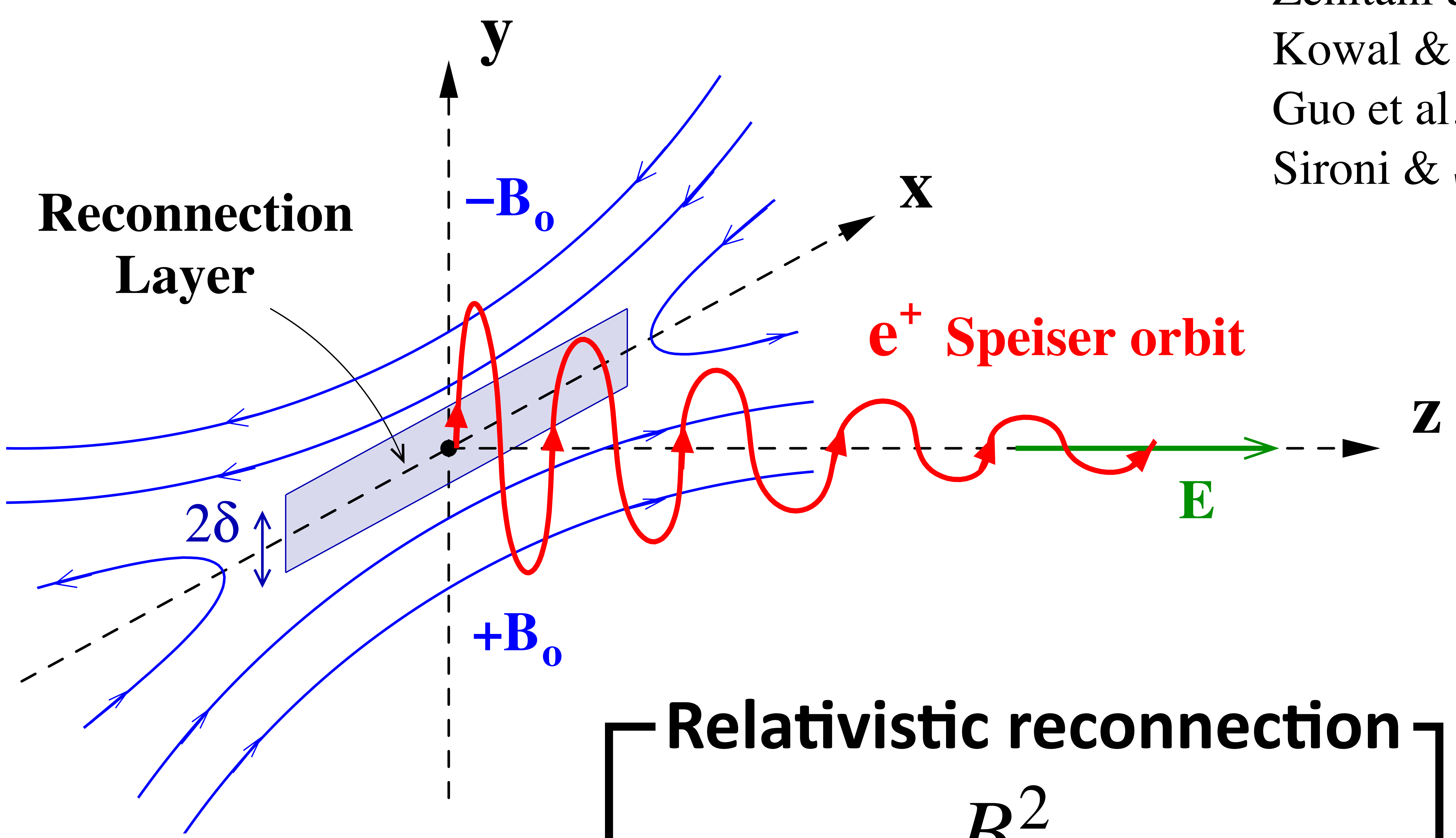




- GRMHD simulations revealed that MADs release its magnetic energy by magnetic reconnection
- Accretion process naturally induces magnetic reconnection at the mid plane
- Reconnection occur in other places as well

Particle Acceleration by Reconnection

Zenitani & Hoshino 2001
Kowal & Lazarian 2011
Guo et al. 2014
Sironi & Spitkovsky 2014



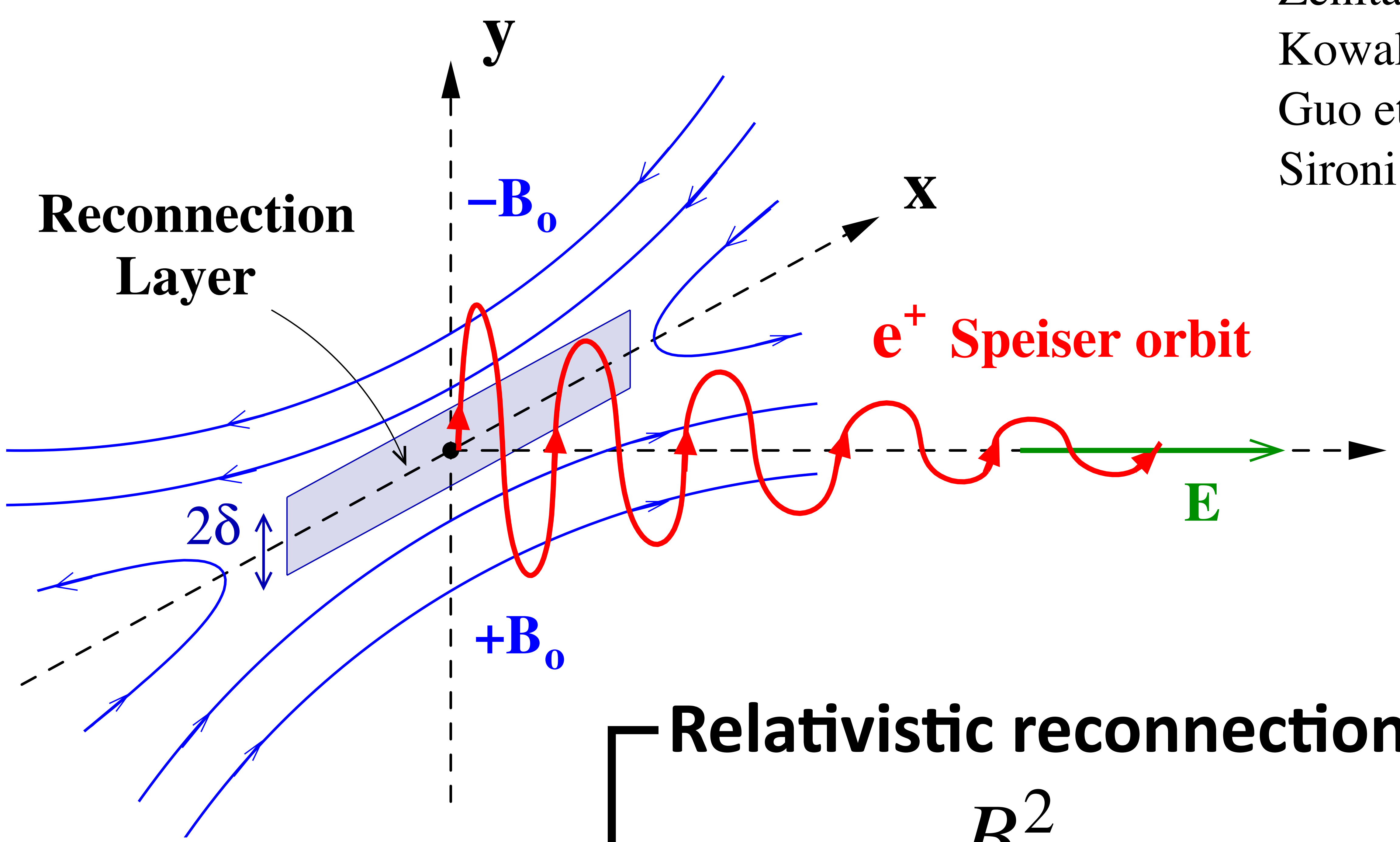
Cerutti+ 2013

Relativistic reconnection

$$\sigma = \frac{B^2}{4\pi n_\pm m_e c^2} > 1$$

- Relativistic reconnection
  → strong E-field development
  → Efficient non-thermal particle production

Particle Acceleration by Reconnection



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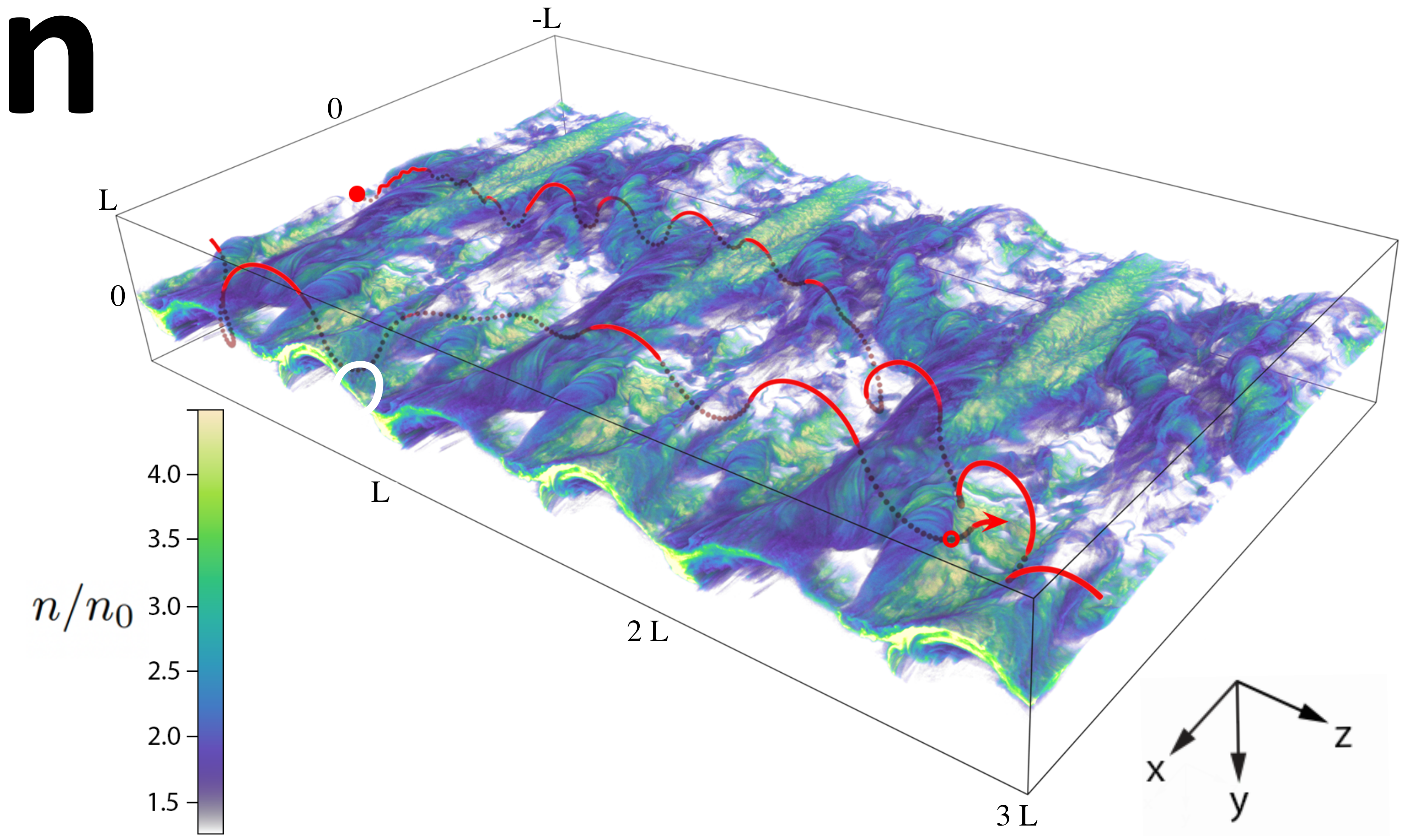
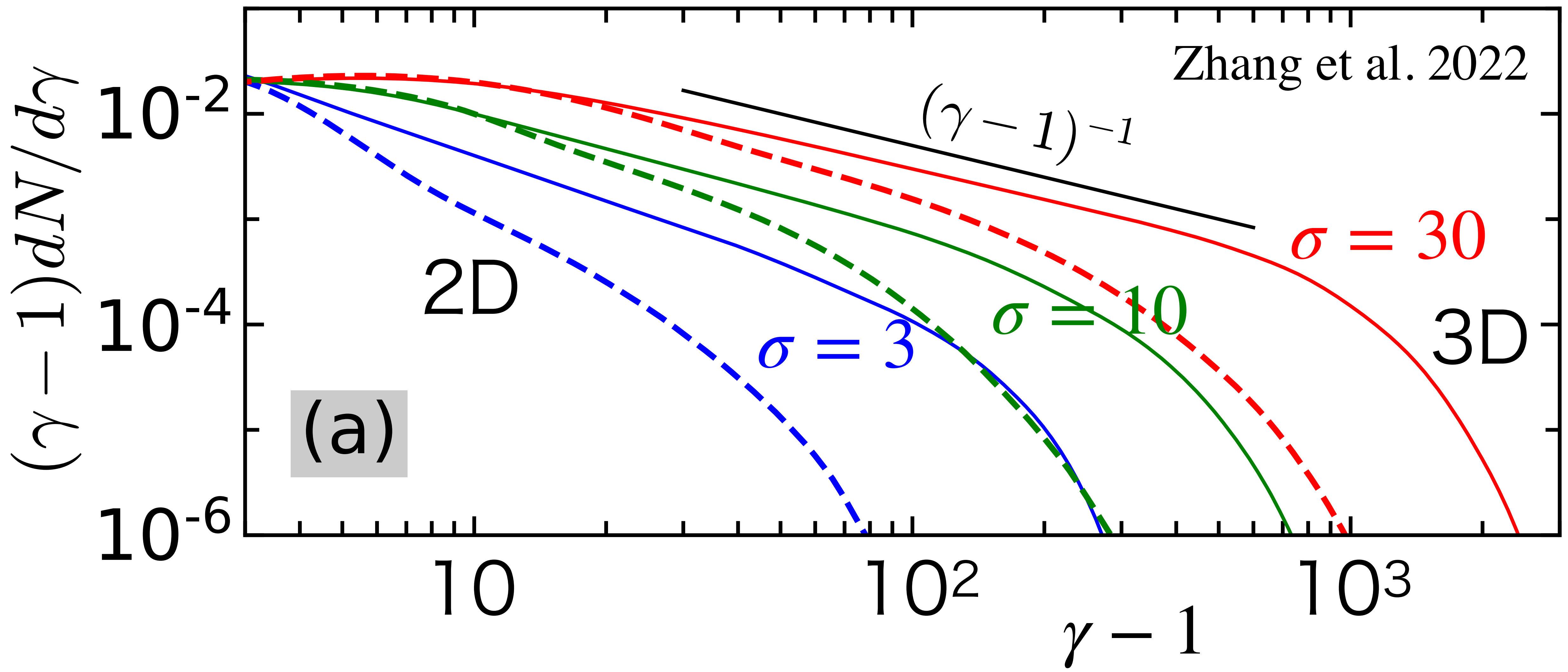




Relativistic reconnection

$$\sigma = \frac{B^2}{4\pi n_\pm m_e c^2} > 1$$

- Relativistic reconnection
  → strong E-field development
  → Efficient non-thermal particle production

- Non-thermal tail with hard spectrum: $dN/dE \propto E^{-2}$ for $\gamma_e > 3\sigma$
- Acceleration timescale: $t_{\rm acc} \sim \eta_{\rm rec} r_g/c$

MAD model

SSK & Toma 2020; Kuze, SSK+ 2022
SSK, Sudoh, Kashiyama, Kawanaka 2021
SSK, Kashiyama, Hotokezaka 2021

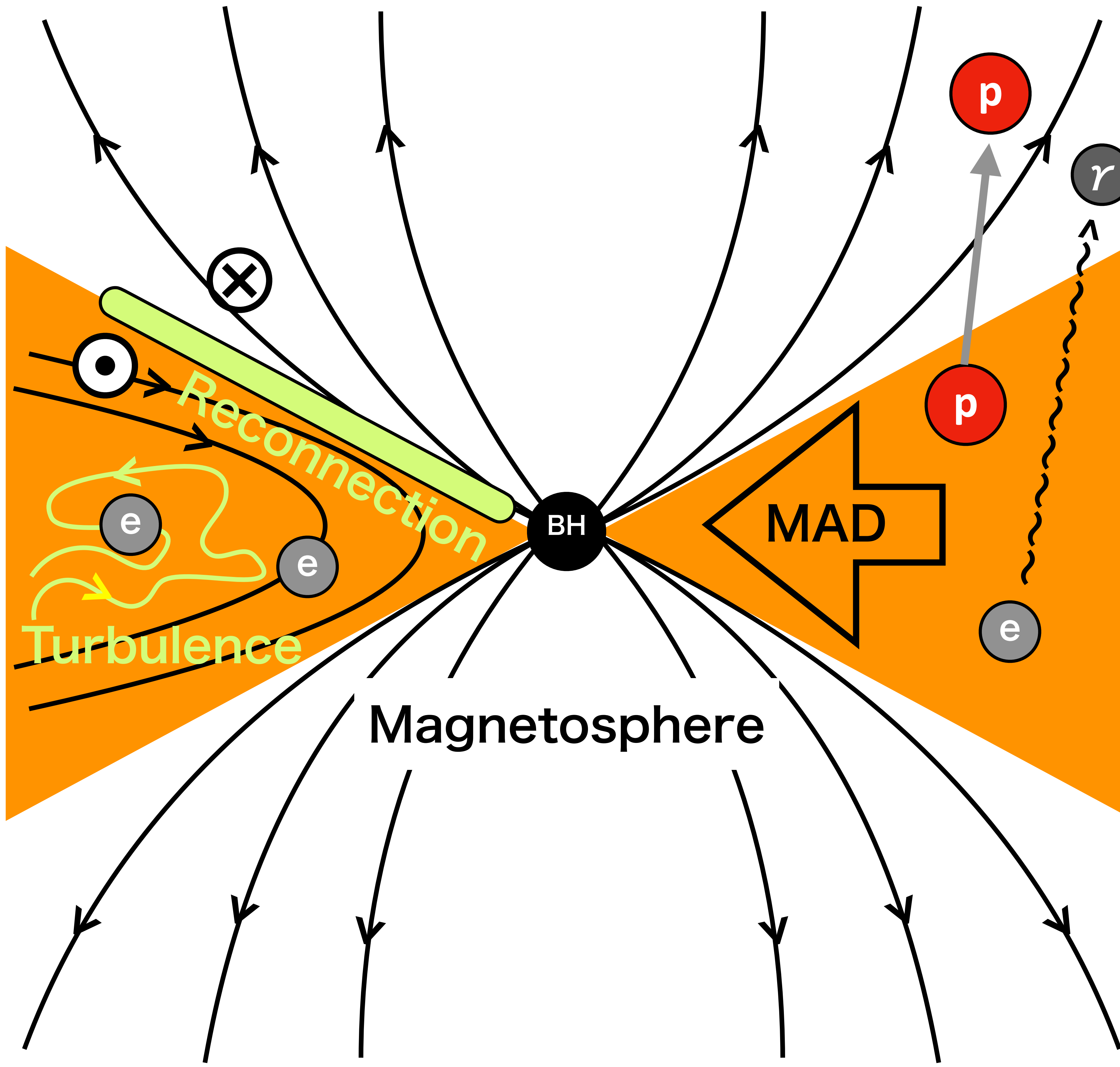
- Steady-state & one-zone approximation

Dissipation $\epsilon_{\rm dis}\dot{M}c^2$

→ Electron $f_e\epsilon_{\rm dis}\dot{M}c^2$
  - → Non-thermal electron $\epsilon_{\rm NT}f_e\epsilon_{\rm dis}\dot{M}c^2$
  - → Thermal electron $(1-\epsilon_{\rm NT})f_e\epsilon_{\rm dis}\dot{M}c^2$

→ Proton $(1-f_e)\epsilon_{\rm dis}\dot{M}c^2$
  - → Non-thermal Proton $\epsilon_{\rm NT}(1-f_e)\epsilon_{\rm dis}\dot{M}c^2$
  - → Thermal Proton $(1-\epsilon_{\rm NT})(1-f_e)\epsilon_{\rm dis}\dot{M}c^2$

PIC results for Trans-relativistic reconnection
Rowan+2017; Chael+ 2018

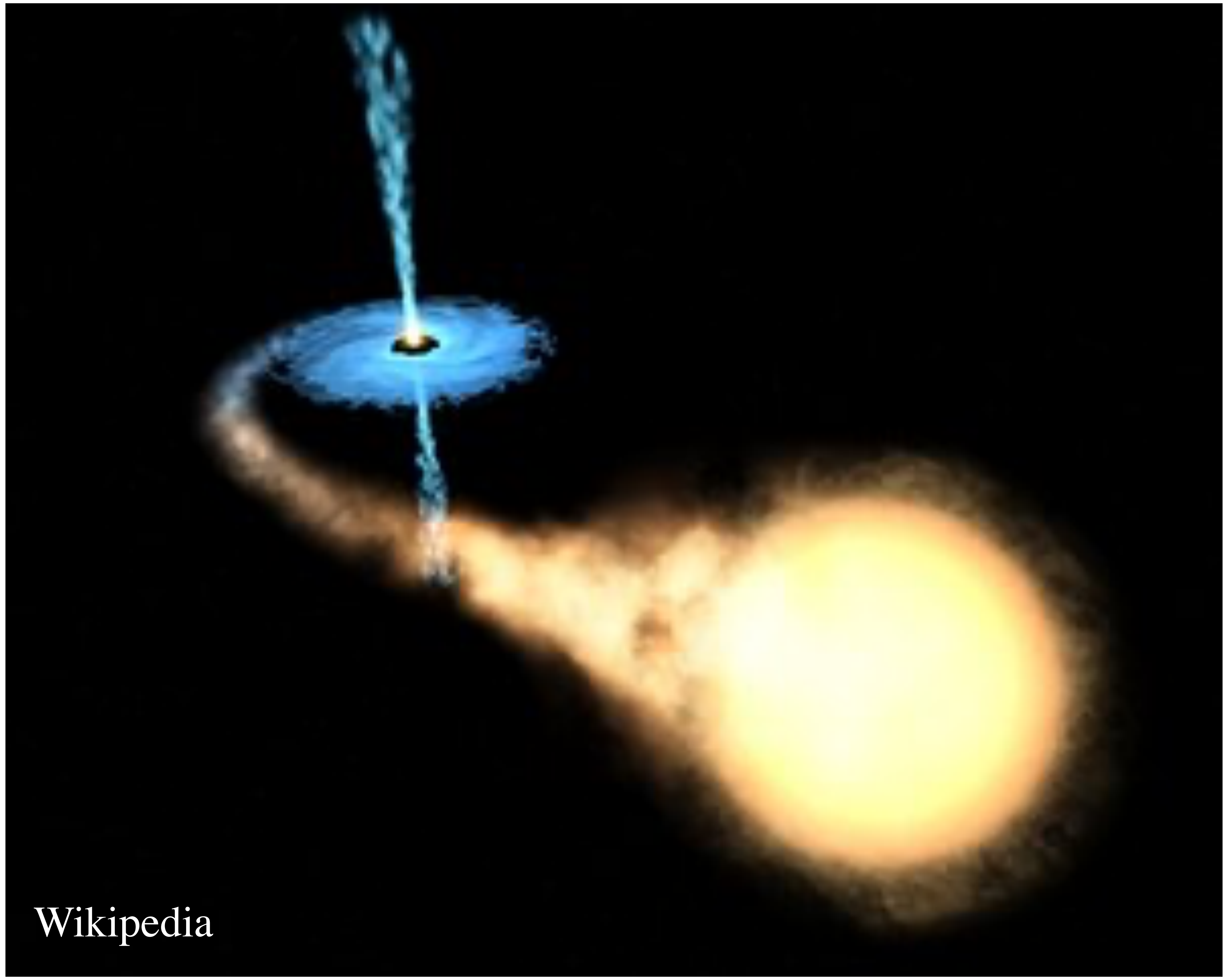


- Unknown parameters:
  - plasma beta β —> f_e
  - Non-thermal fraction: $\epsilon_{\rm NT}$
- Parameter calibration is needed

- Non-thermal: transport equation with power-law injection
- Thermal: $Q_{\rm heat} = Q_{\rm cool} + Q_{\rm adv}$
- Synchrotron dominates over the other cooling processes

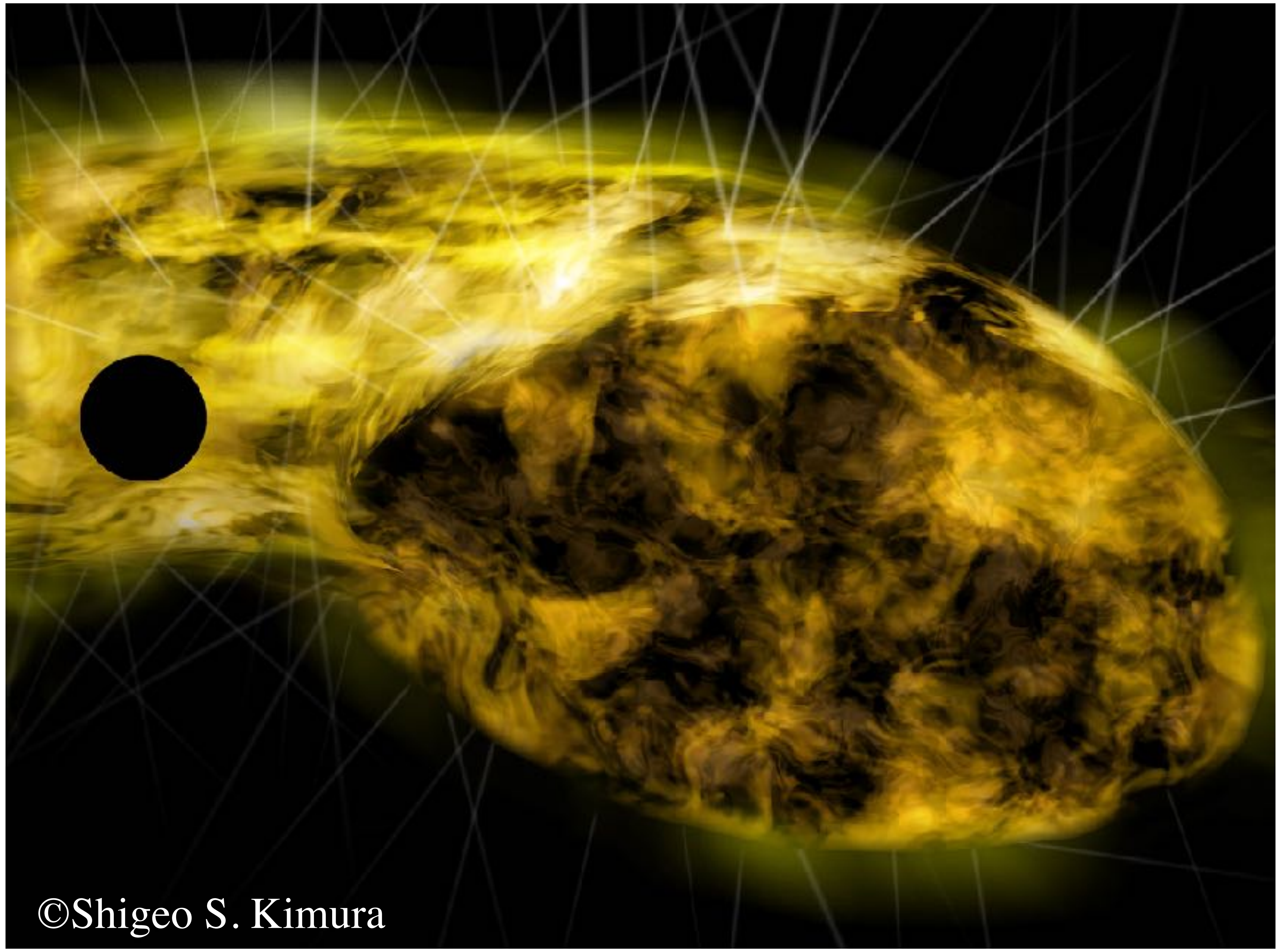
MADs in Various Environments

- X-ray binaries



SSK, Sudoh, Kashiyama, Kawanaka 2021

- Isolated Black Holes



SSK, Kashiyama, Hotokezaka 2021
SSK et al. in prep.
SSK, Murchikova, Sahu in prep.

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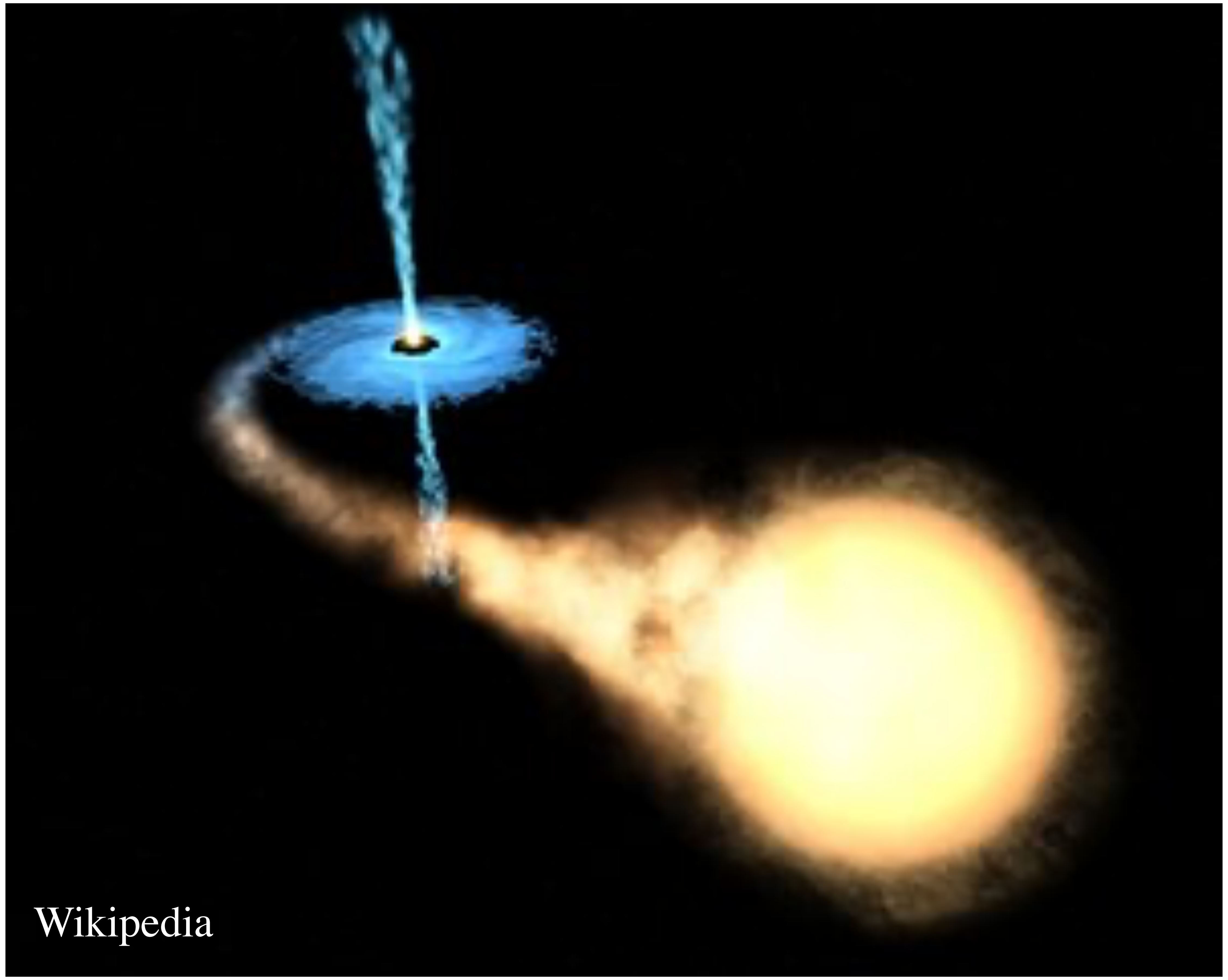

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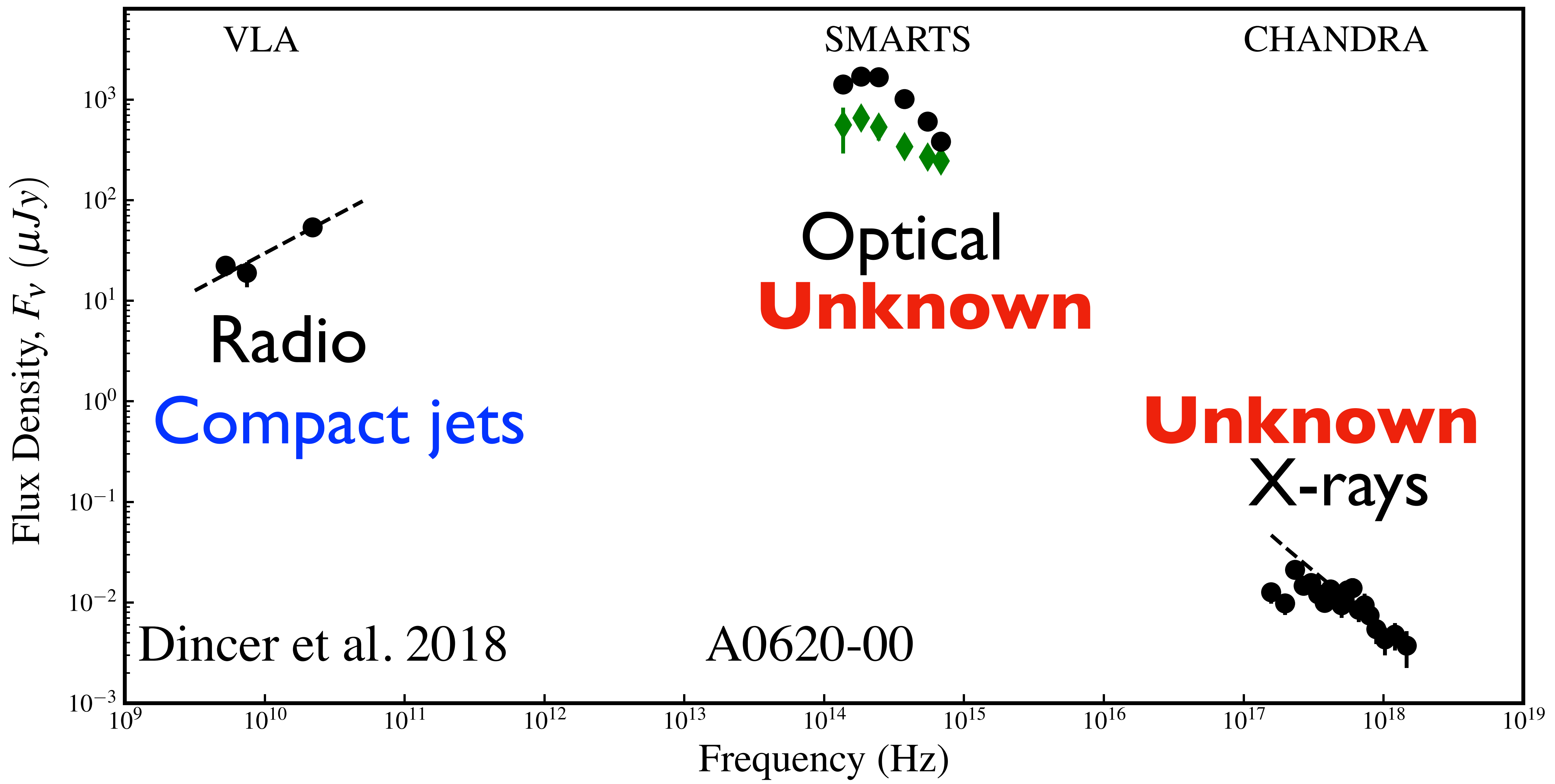
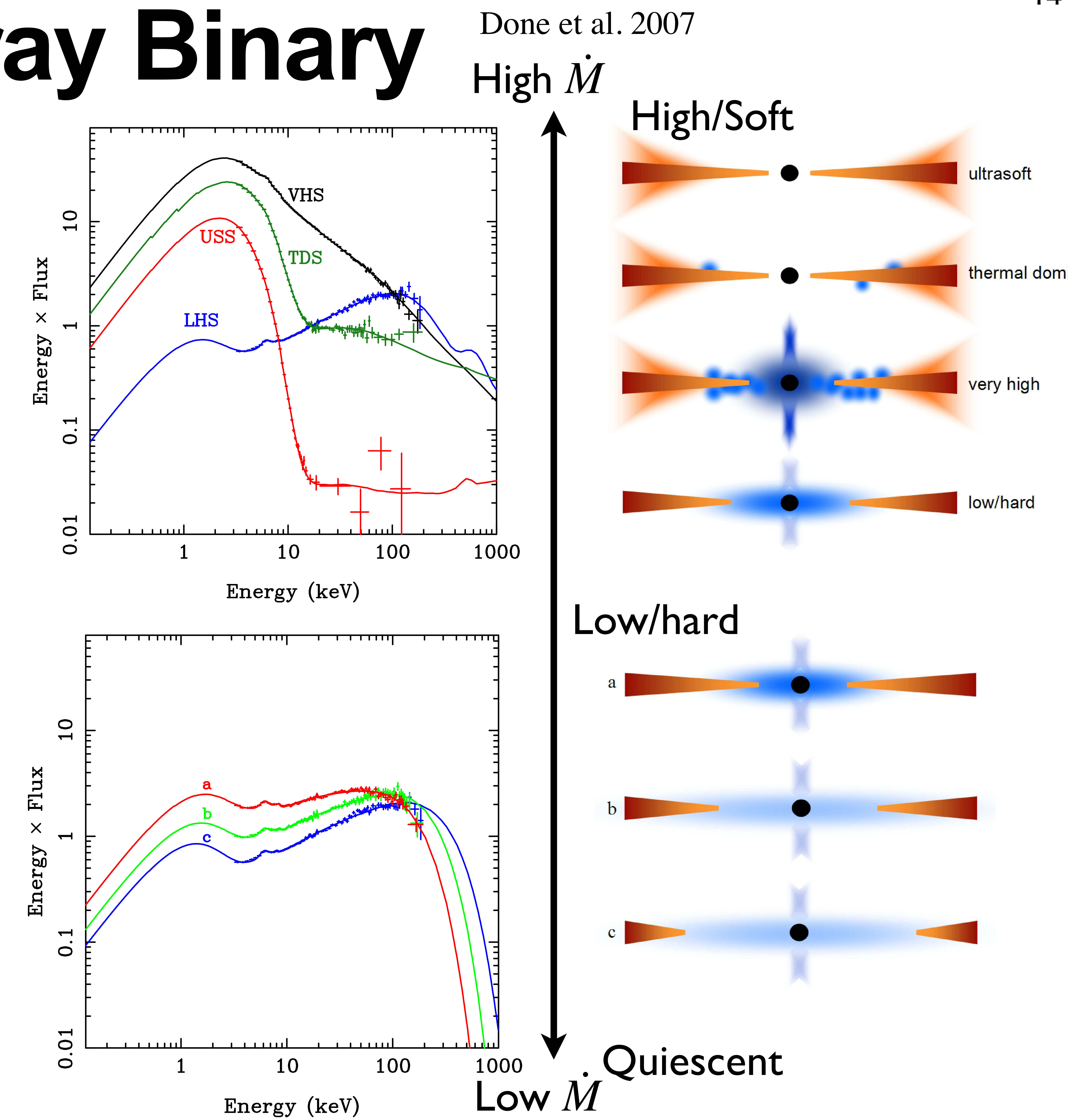
Quiescent State in X-ray Binary

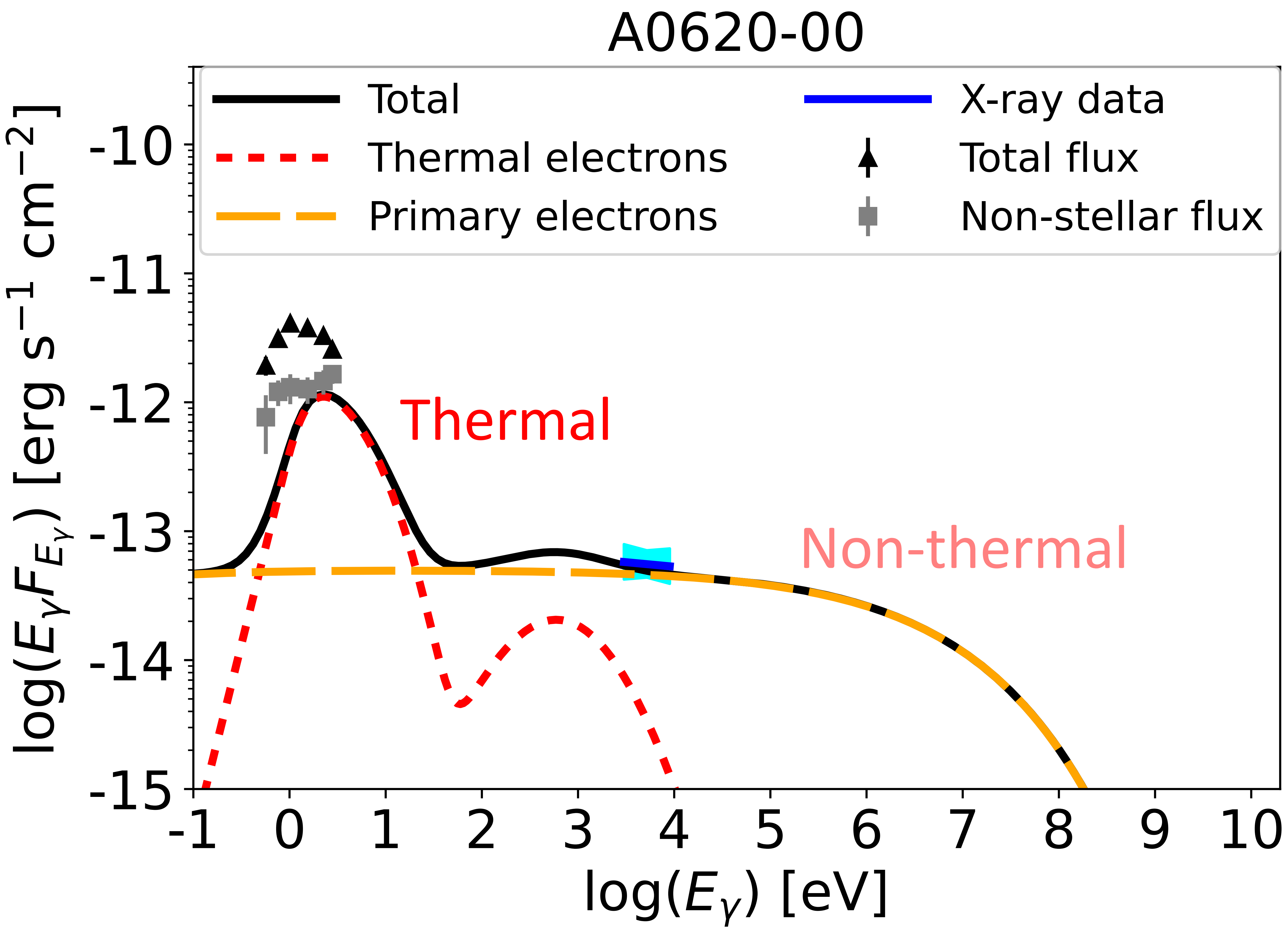


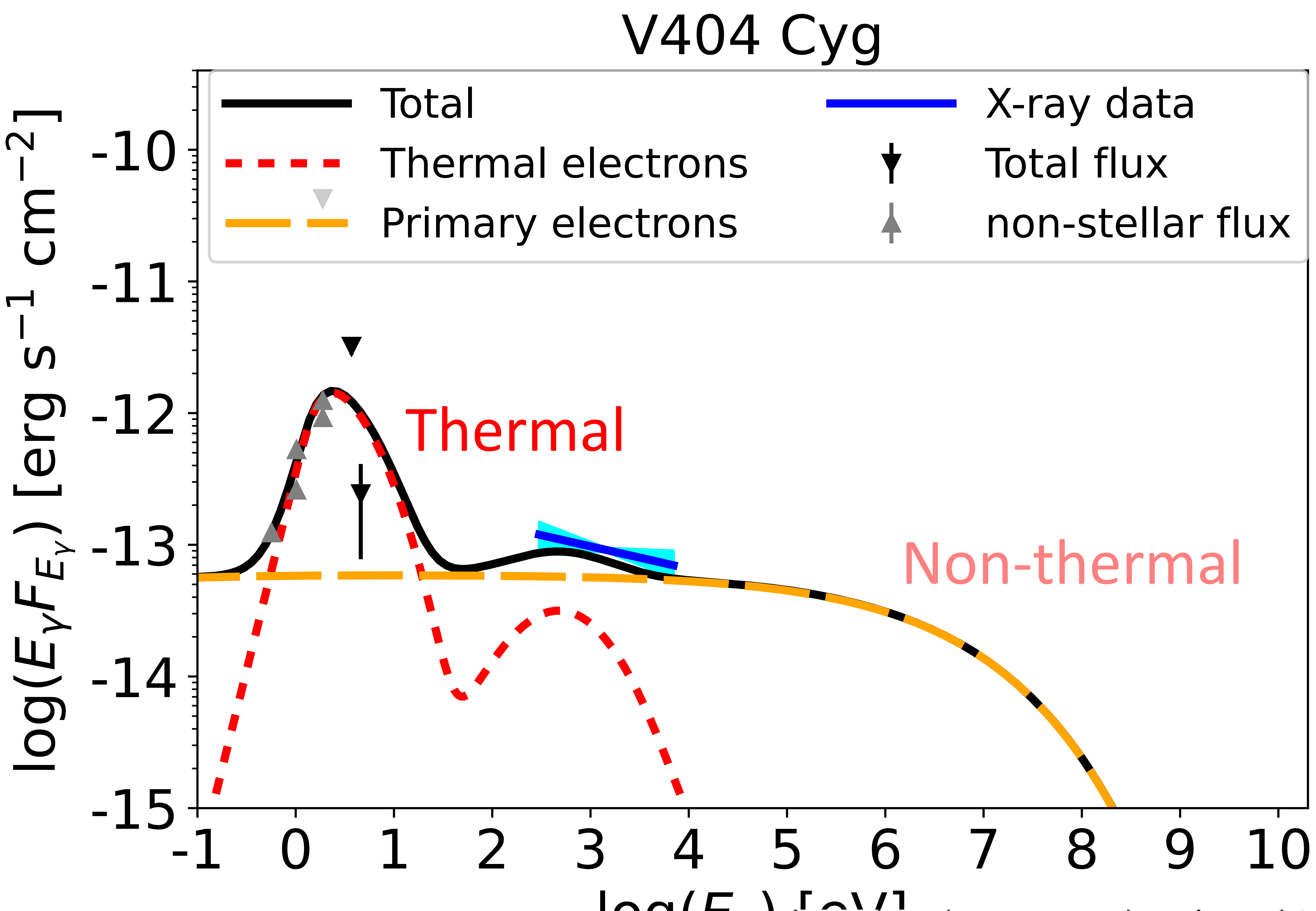


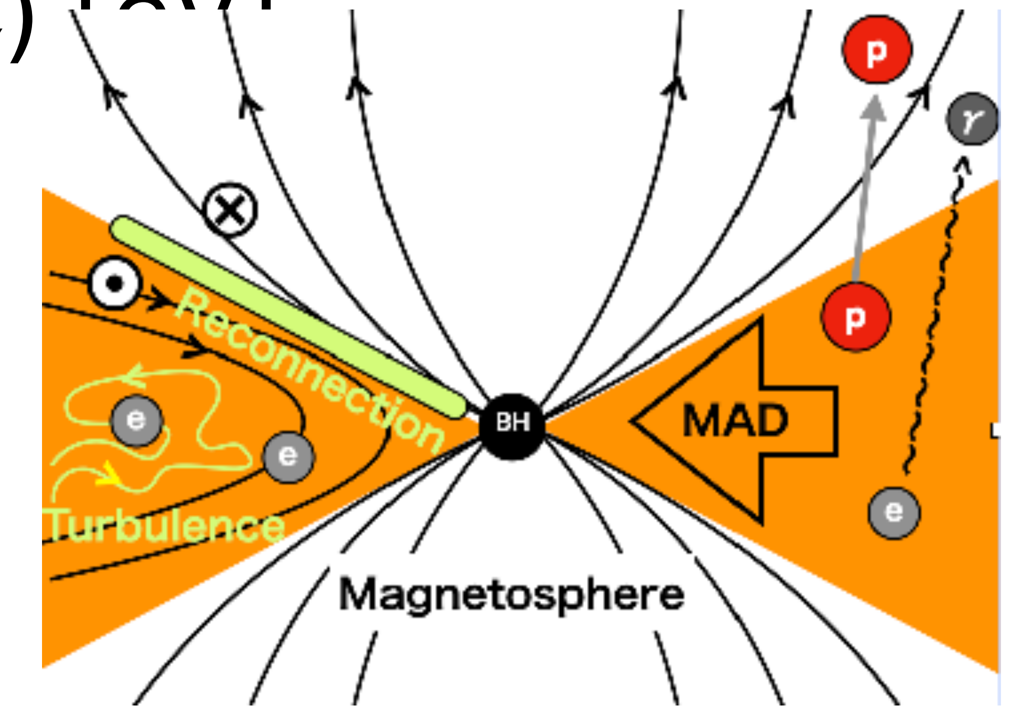
- X-ray binaries show various spectral state
- Quiescent state: faintest state in X-ray binaries
- $L_X \sim 10^{30} - 10^{33}$ erg/s
  —> $\dot{M}c^2 \lesssim 10^{-3} - 10^{-5} L_{\rm Edd}$
- Radio, optical, and X-ray signals are observed
  —> calibrate parameters by opt & X data

Photon spectra from MADs in X-ray Binaries

SSK, Sudoh, Kashiyama, Kawanaka 2021







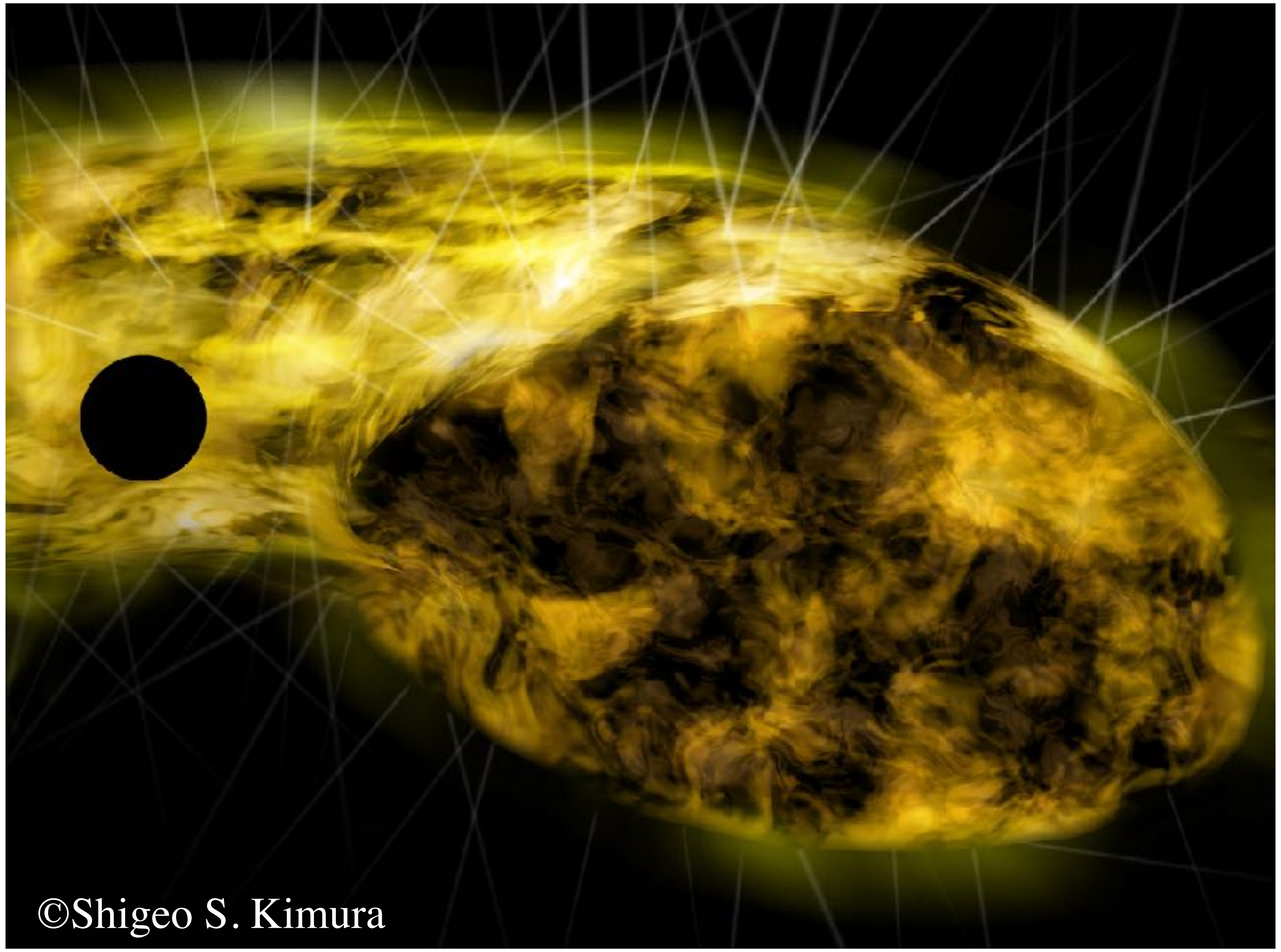
- Optical: Thermal synchrotron
- X-rays: Synchrotron by non-thermal electrons
- $\beta = 0.1, \quad \epsilon_{\rm NT} = 0.33$

MADs in Various Environments

- X-ray binaries

SSK, Sudoh, Kashiyama, Kawanaka 2021

- Isolated Black Holes



SSK, Kashiyama, Hotokezaka 2021
SSK et al. in prep.
SSK, Murchikova, Sahu in prep.

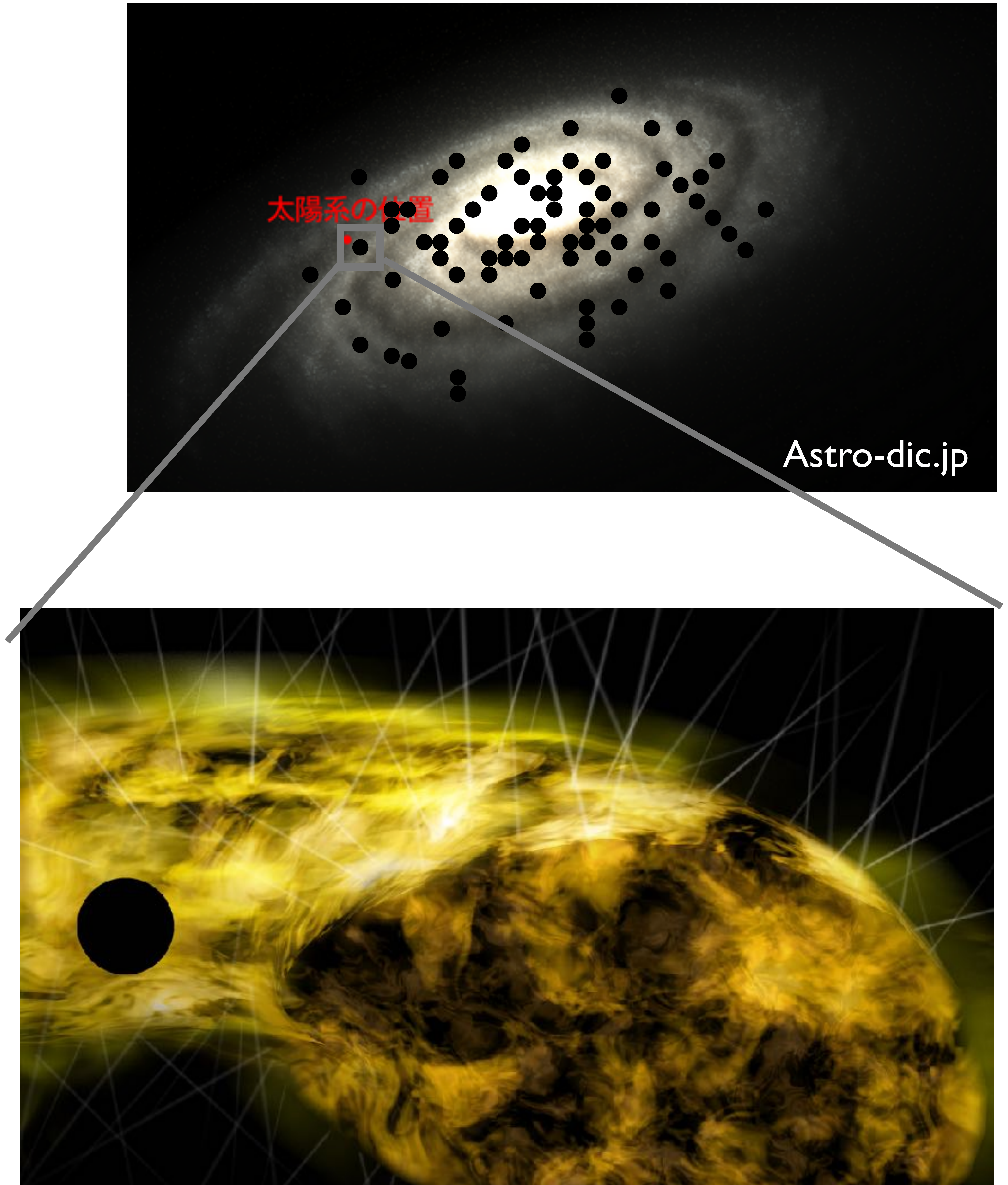
Isolated Black Holes (IBHs)

- 0.1% of stars form BHs: $N_{\rm BH} \sim f_{\rm BH} N_{\rm star} \sim 3 \times 10^8$
  —> many IBHs wandering interstellar medium
- IBHs accretes ISM gas by Bondi-Hoyle-Littleton rate

$$\dot{M}_\bullet \approx \lambda_w \frac{4\pi G^2 M^2 \mu_{\rm ISM} m_p n_{\rm ISM}}{(C_s^2 + v_k^2)^{3/2}}$$

- Accretion onto IBHs depends on ISM phase
- warm medium: $\dot{M}c^2 \sim 10^{32}$ erg/s $n_{ISM,-1} v_{k,40{\rm km/s}}^{-3}$
- **molecular clouds**
  $\dot{M}c^2 \sim 10^{35}$ erg/s $n_{ISM,2} v_{k,40{\rm km/s}}^{-3}$
- Parameters are similar to quiescent X-ray binaries
  —> **IBHs as PeVatrons?**

(Fujita+ 1998; Ioka+2017; Matsumoto+2018; Tsuna+ 2018,2019 etc)



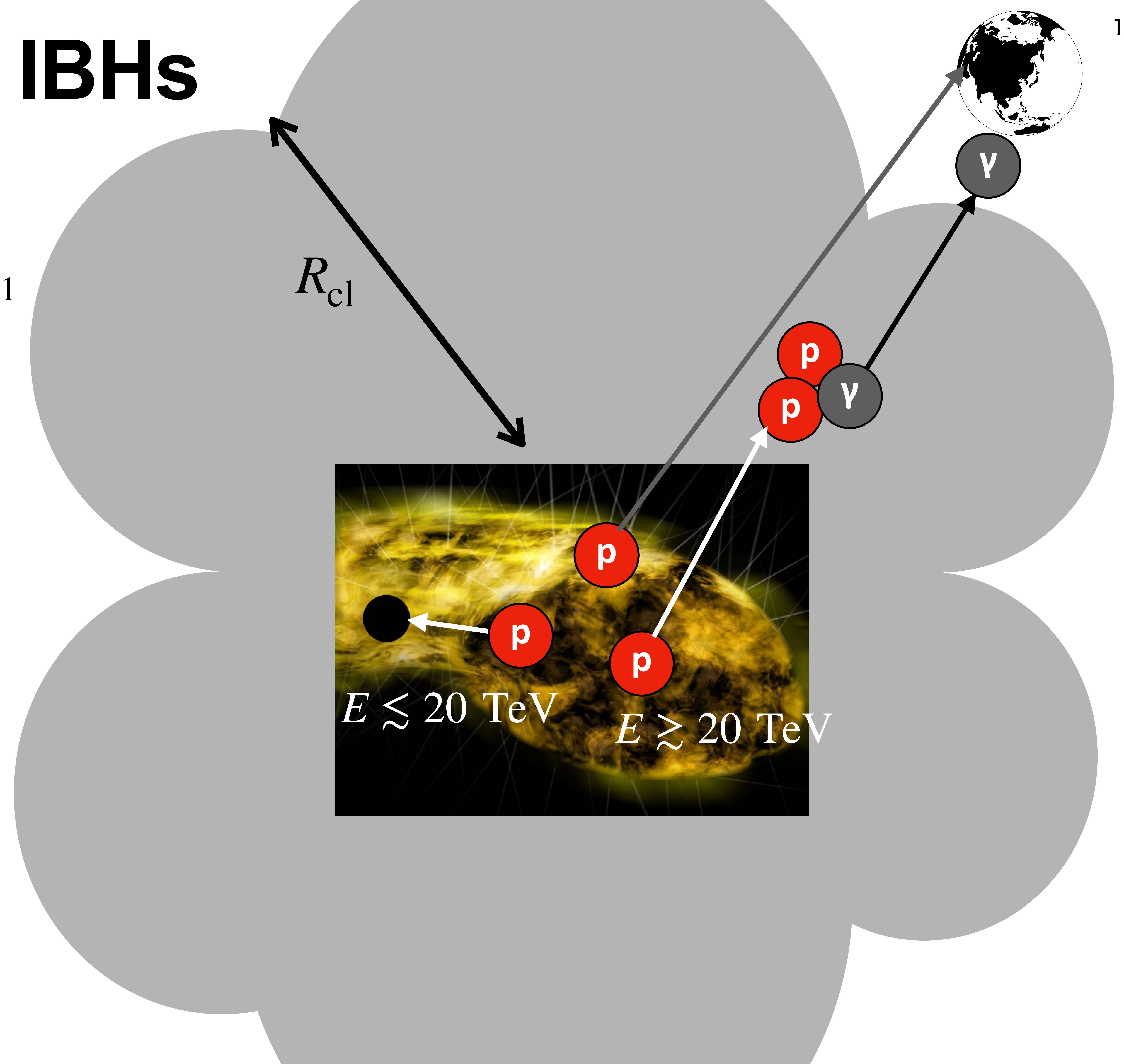
CR production by IBHs

- IBH produce CR protons
- Equating $t_{diff,MAD}$ and $t_{fall,MAD}$
  —> $E_{p,esc} \sim 20 \text{ TeV } B_{5.5} V_{R,9} R_7 \eta_1^{-1}$
- Balancing $t_{accel,MAD}$ and $t_{diff,MAD}$
  —> $E_{p,cut} \sim 200 \text{ TeV } B_{5.5} R_7 \eta_1^{-1}$
- Kolmogorov turbulence in clouds:

$$D_{cl} \approx \frac{c l_{coh}}{3} \left(\frac{E}{e B_{cl} l_{coh}} \right)^{1/3}$$

- Diffusive escape from clouds:
  - $t_{diff,cl} \approx R_{cl}^2 / D$
  - $t_{pp,cl} \approx (n_{cl} \sigma_{pp} \kappa_{pp} c)^{-1}$

  —> $f_{pp} < 1$ for E_p>TeV

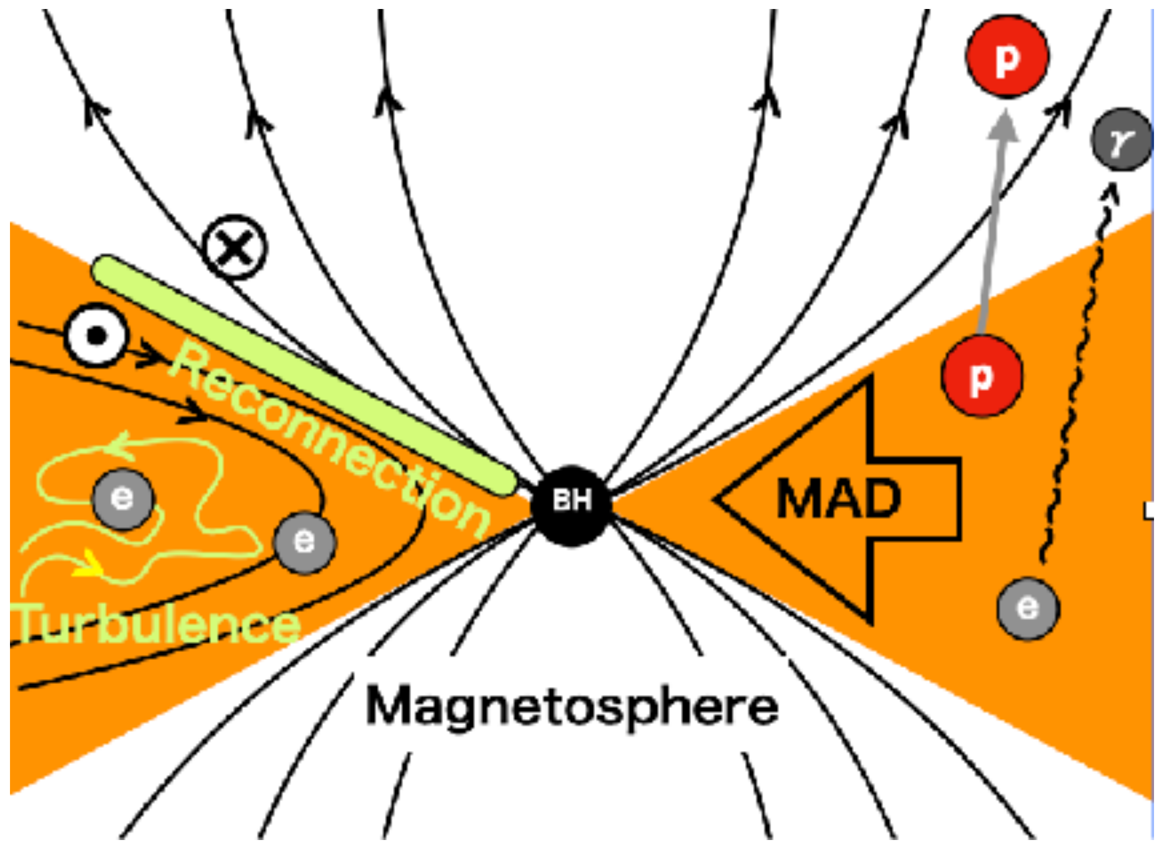


IBHs in Molecular Clouds as PeVatrons

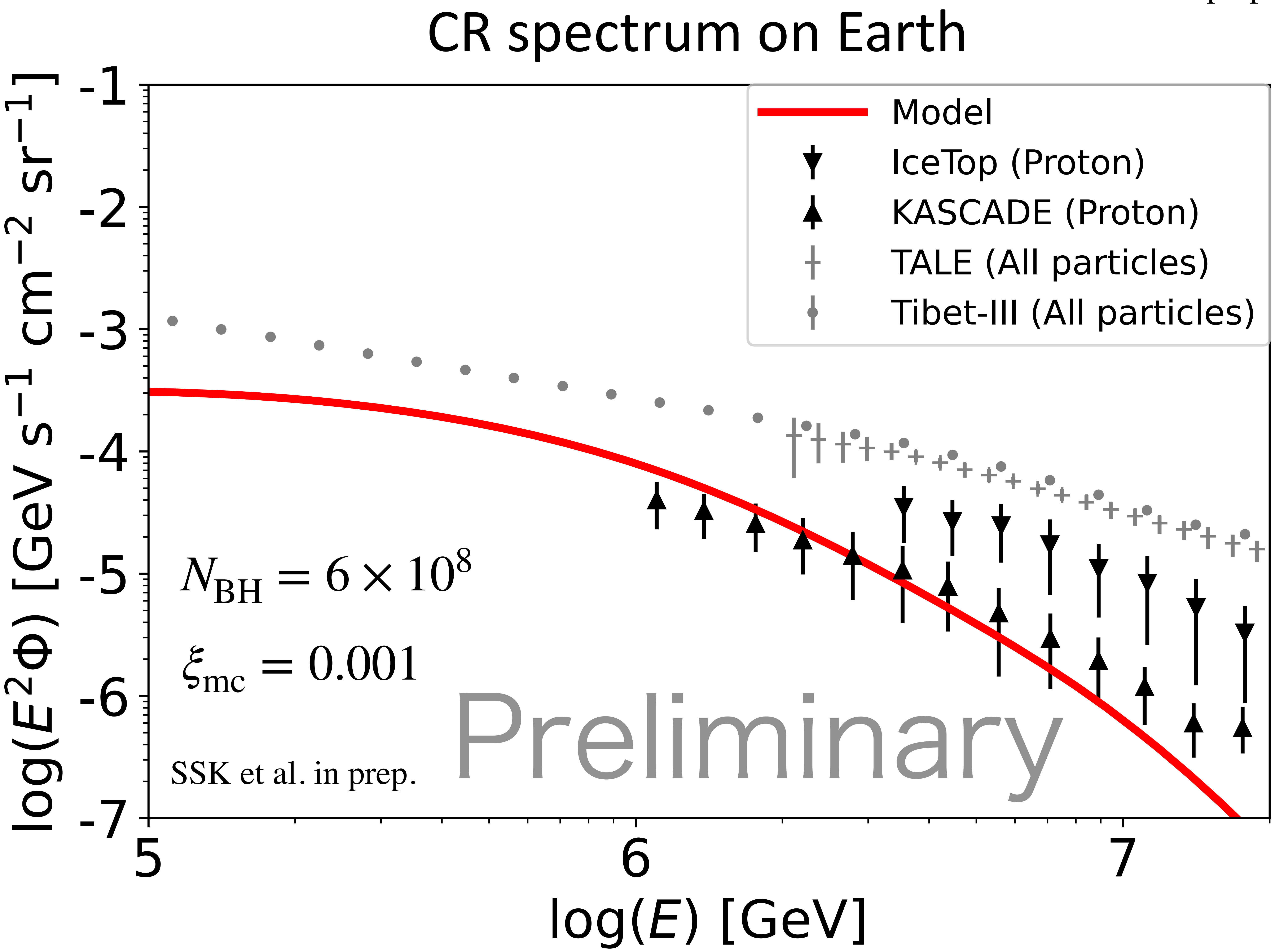
- $\sim 10^8 - 10^9$ IBHs in our galaxy
- $\sim 10^5 - 10^6$ IBHs in MCs
- Leaky box approximation:

$$E_p^2 \Phi_p \approx \frac{E_p Q_{E_p} X_{\rm esc}}{4\pi M_{\rm gas}}.$$

- **They can be source of PeV CRs**



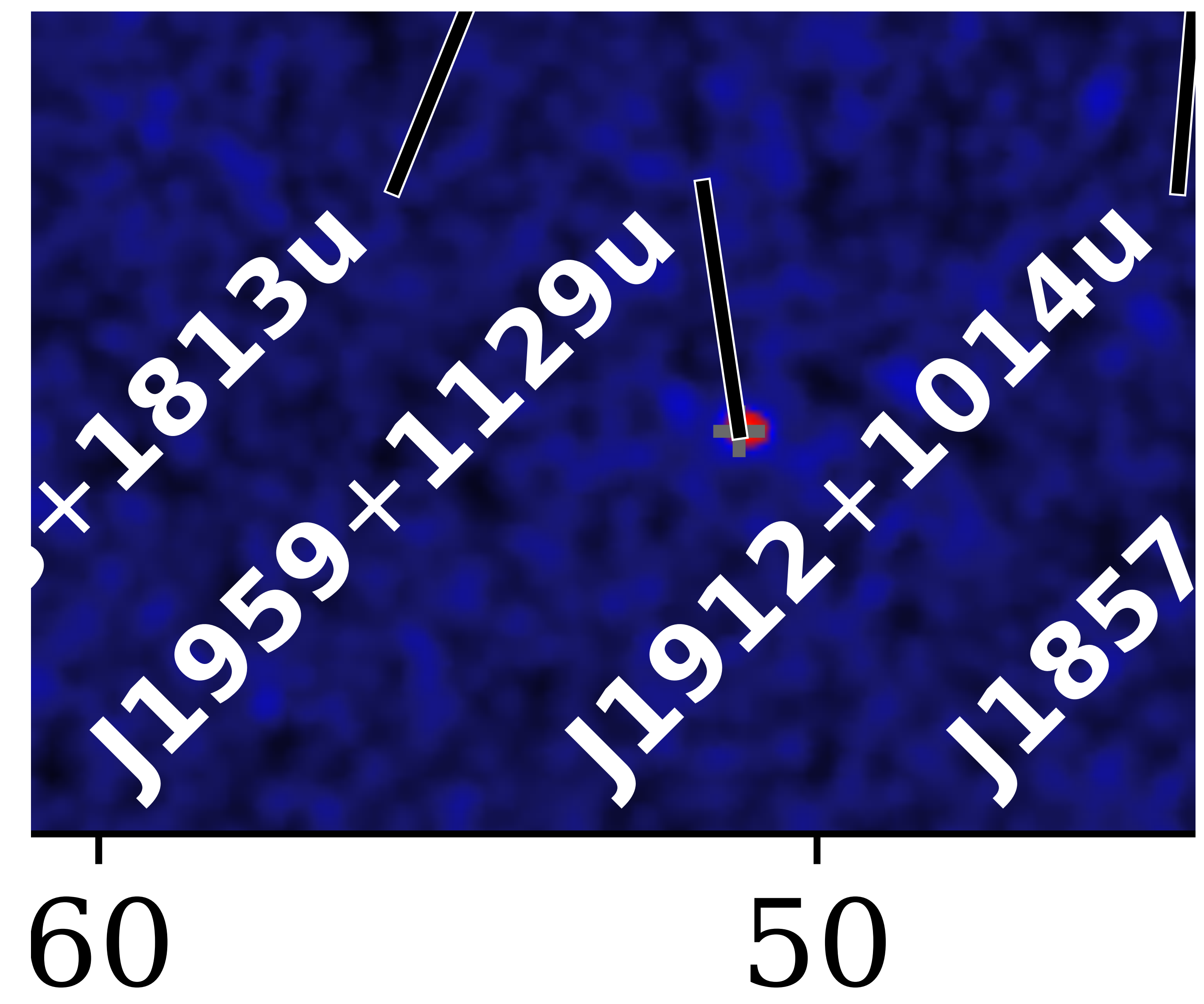
SSK et al. in prep.

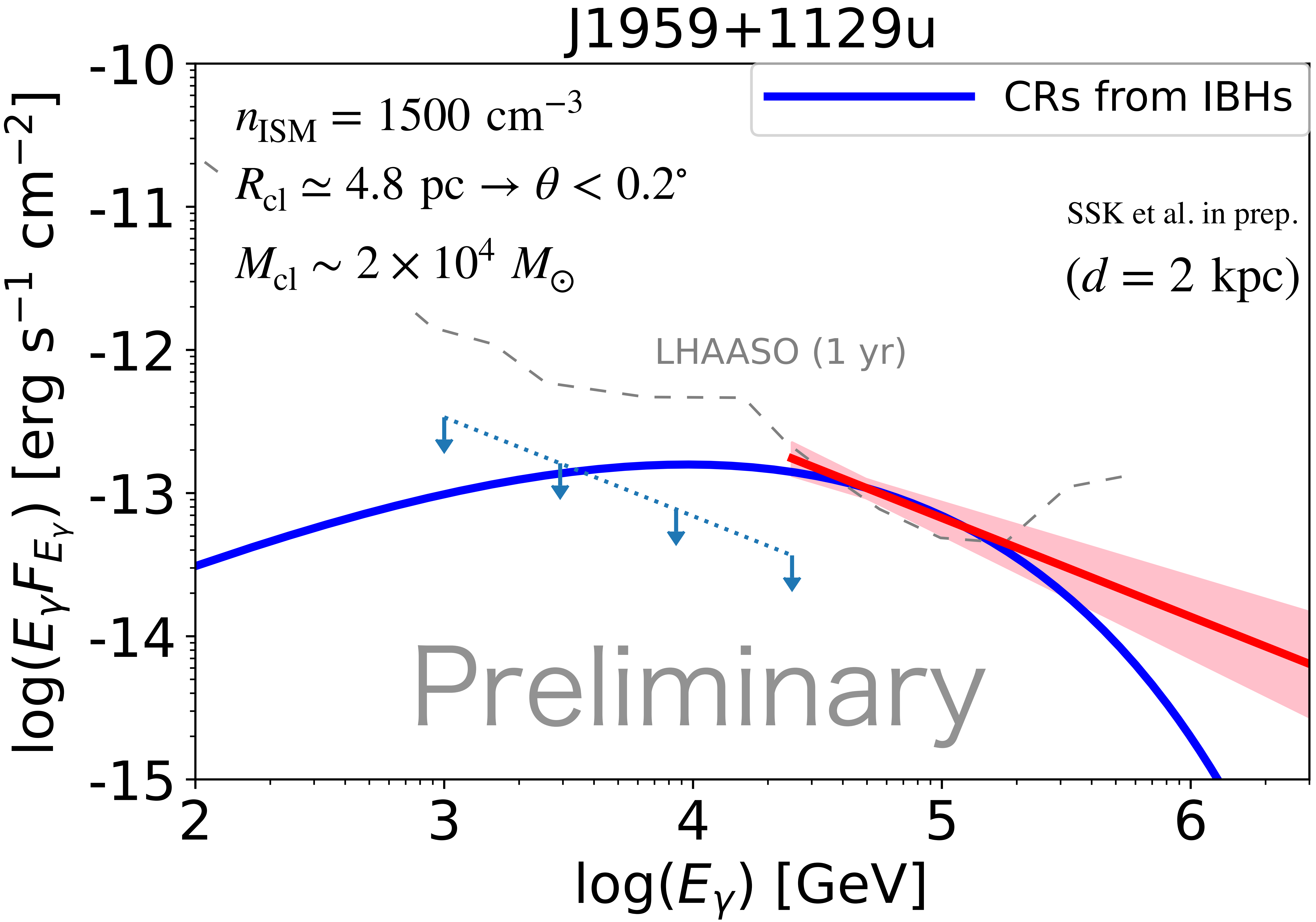


UHE gamma-rays from IBHs in molecular clouds

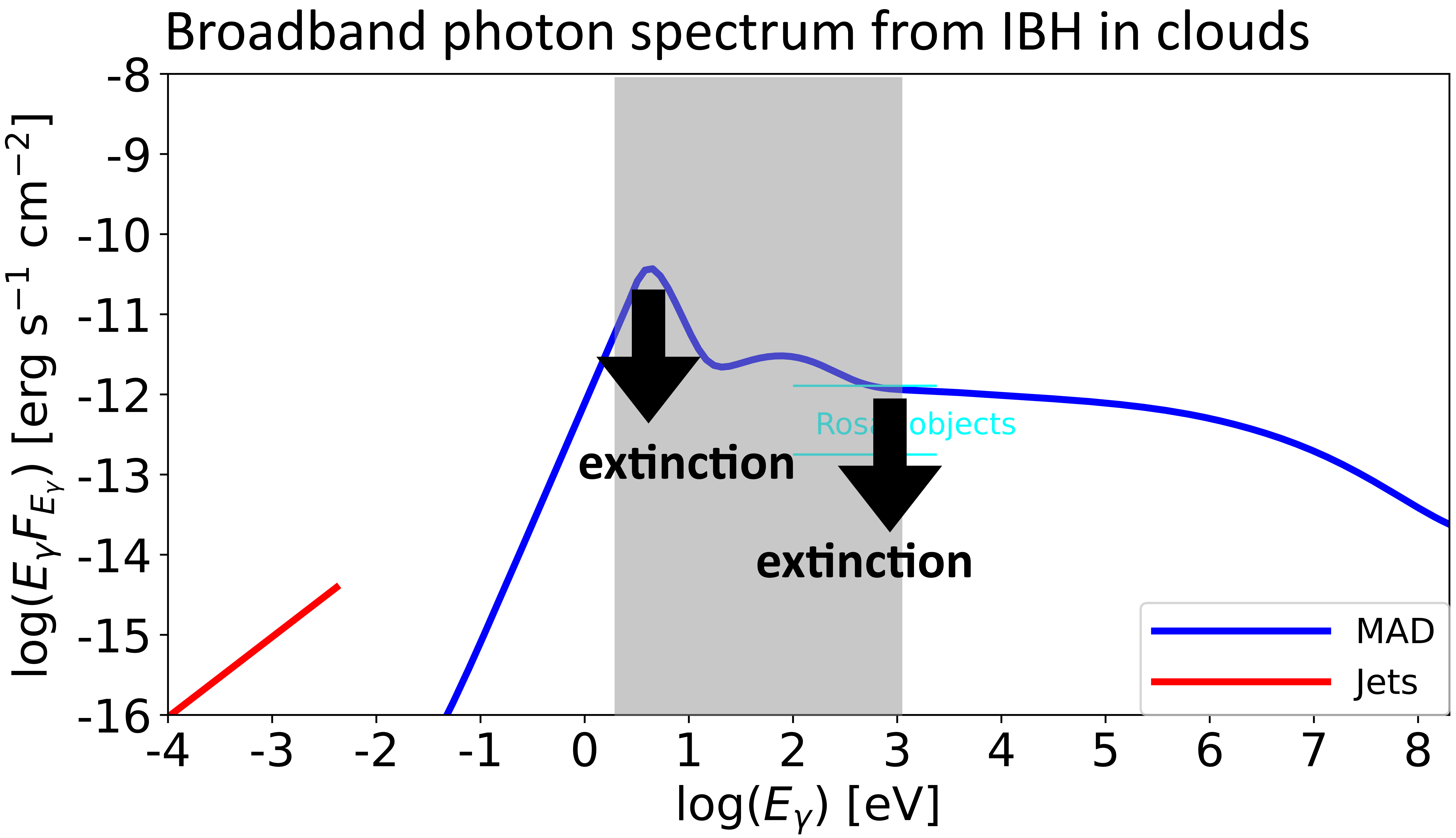
SSK et al. in prep.

- IBH in molecular clouds can emit UHE γ-rays
- **Our scenario can be the origin of new source class only observed by KM2A.**



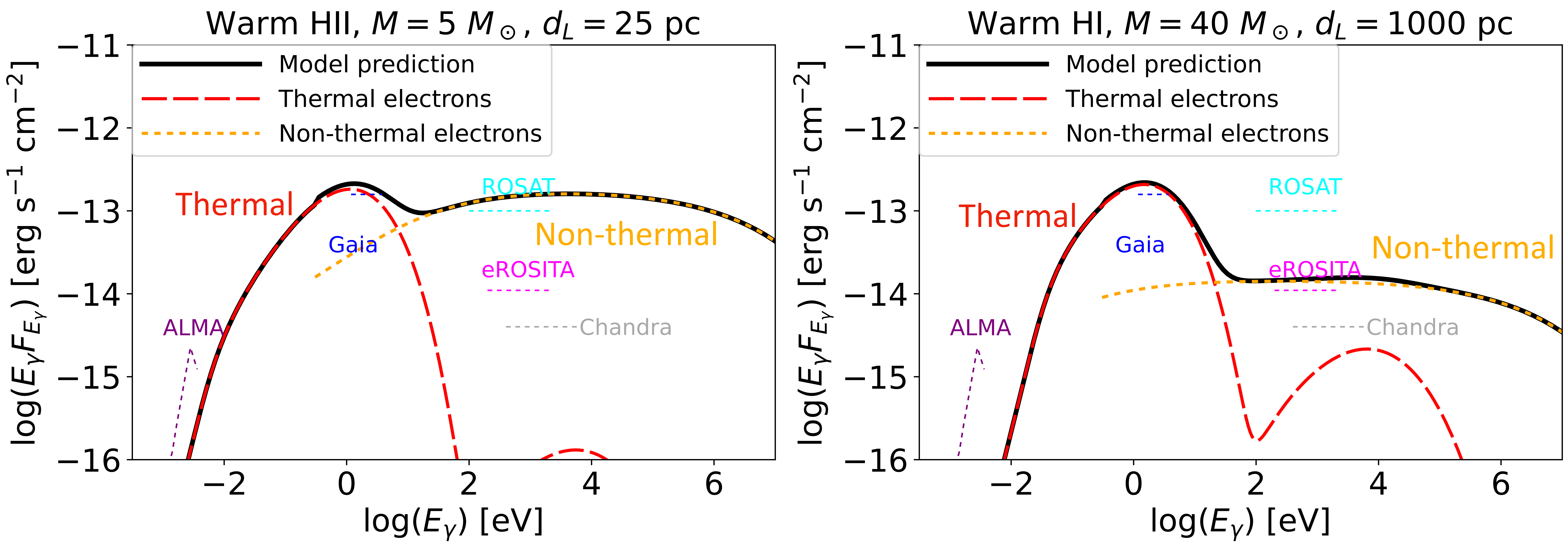


Photon emission from IBH in dense clouds



- Naive test for our scenario: **observe direct emission from MADs around IBH**
- Column density for molecular cloud: $N_H \simeq 2 \times 10^{22}\ \mathrm{cm}^{-2}$
  —> Strong extinction [$A_V \simeq 10$, $\exp(-\tau_{1\ \mathrm{keV}}) \simeq 0.02$] —> Hard X-ray (> 10 keV) is necessary
- Contamination by protostars (similar L_{opt} & L_X) —> **challenging to identify IBHs**

Photon spectra from MADs around IBHs

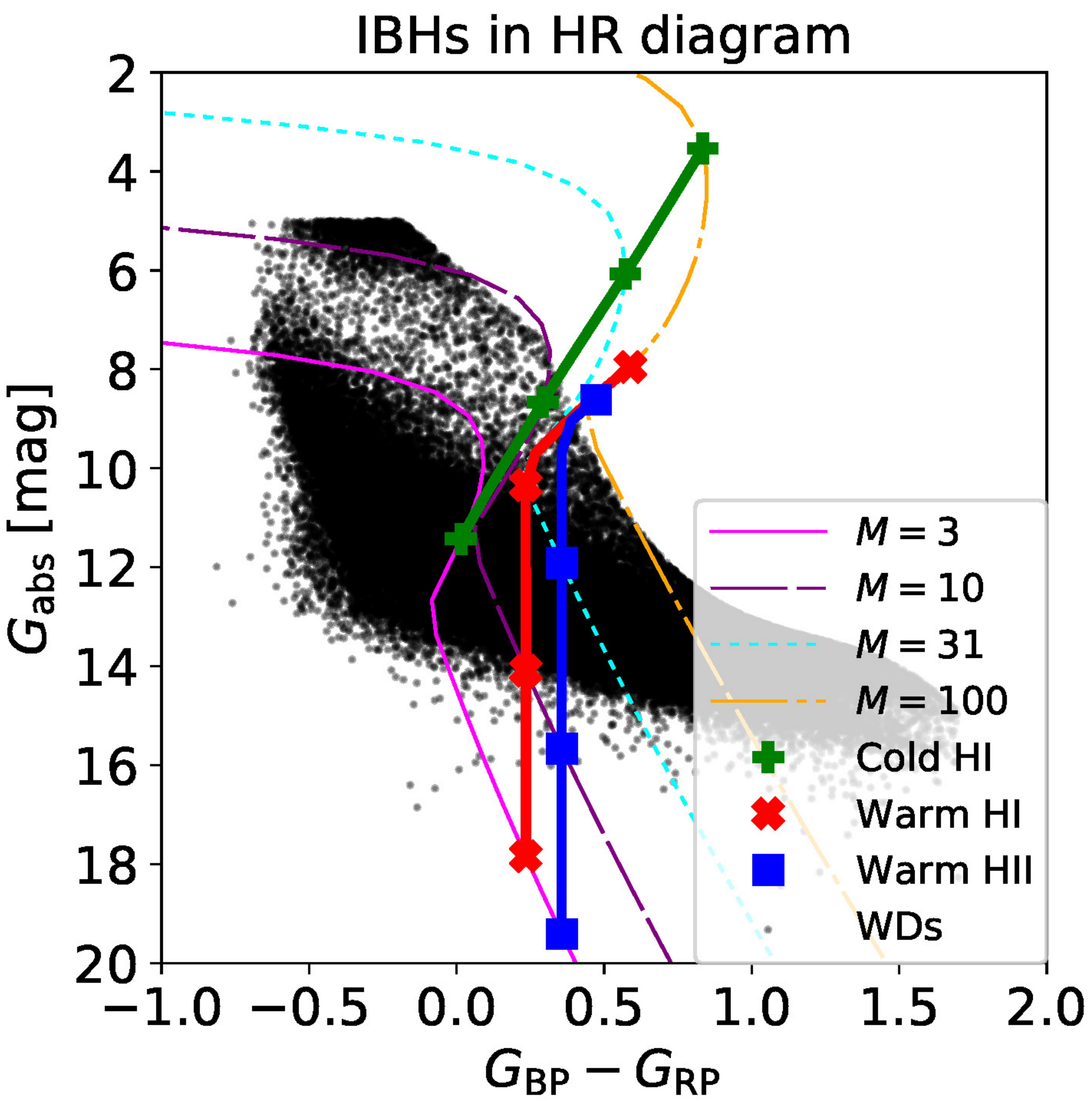


Modified from SSK, Kashiyama, Hotokezaka 2021

- To avoid contamination, other phase are better
- Hot medium: too low accretion rate —> **warm & cold media are best**
- Gaia & eROSITA will detect nearby IBHs
  —> **provide a good test for IBH–PeVatron scenario**

IBH Identification strategy

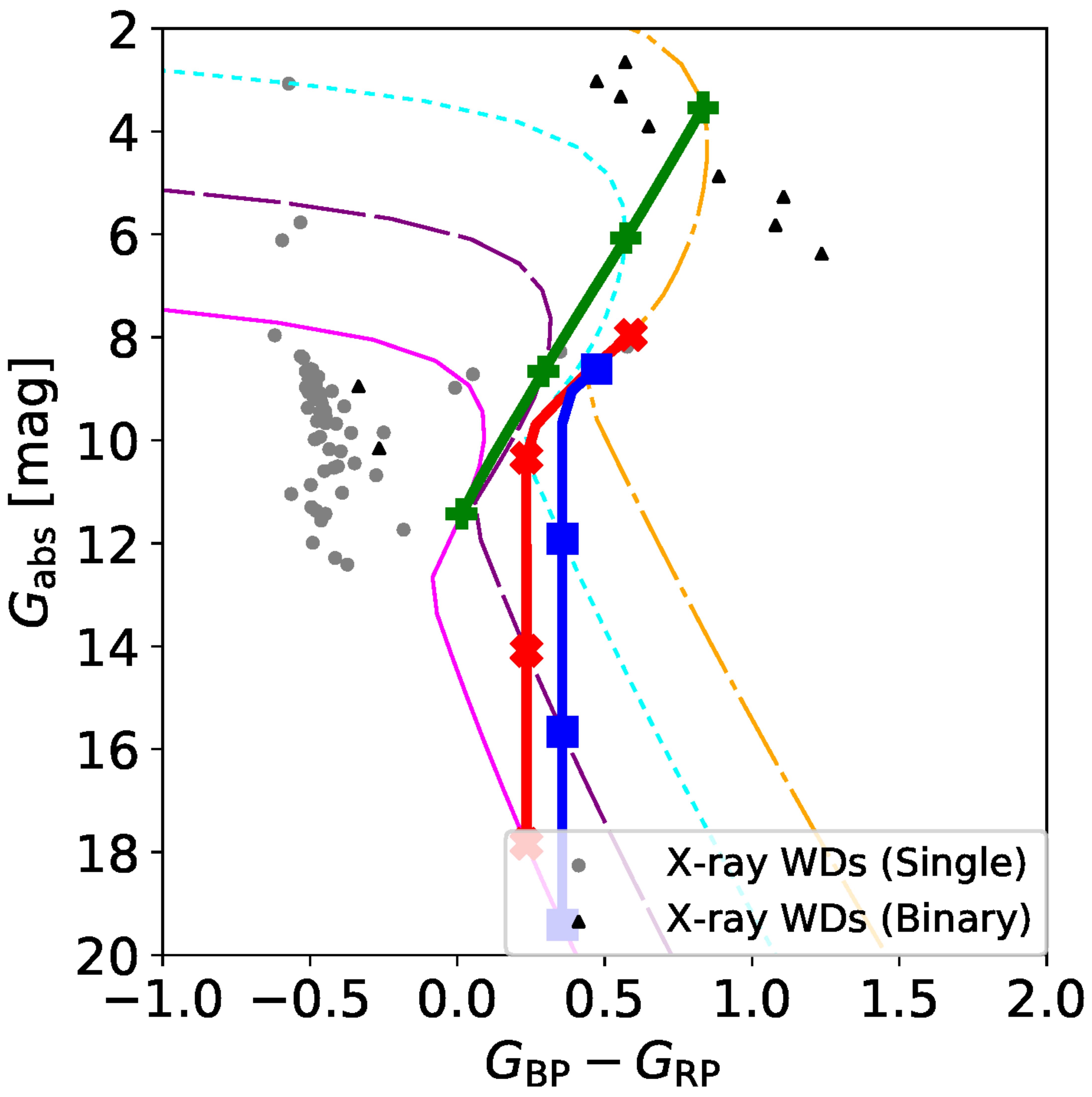
SSK, Kashiyama, Hotokezaka 2021



- Main contamination: distant QSO
  —> using parallax & proper motion by Gaia
- **HR-diagram is useful to distinguish IBHs**
- IBHs located around cooling sequence of WDs
- How to dig out IBHs from millions of WDs?

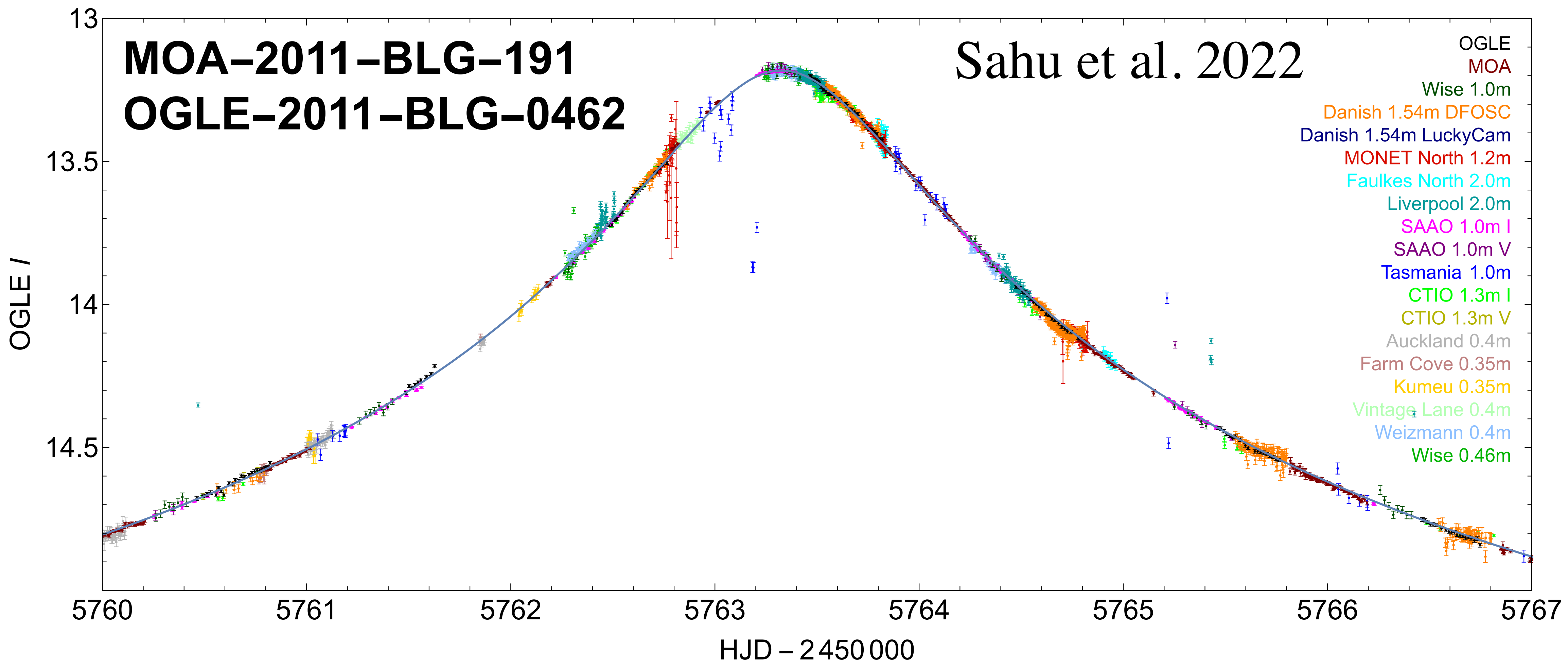
IBH Identification strategy

SSK, Kashiyama, Hotokezaka 2021

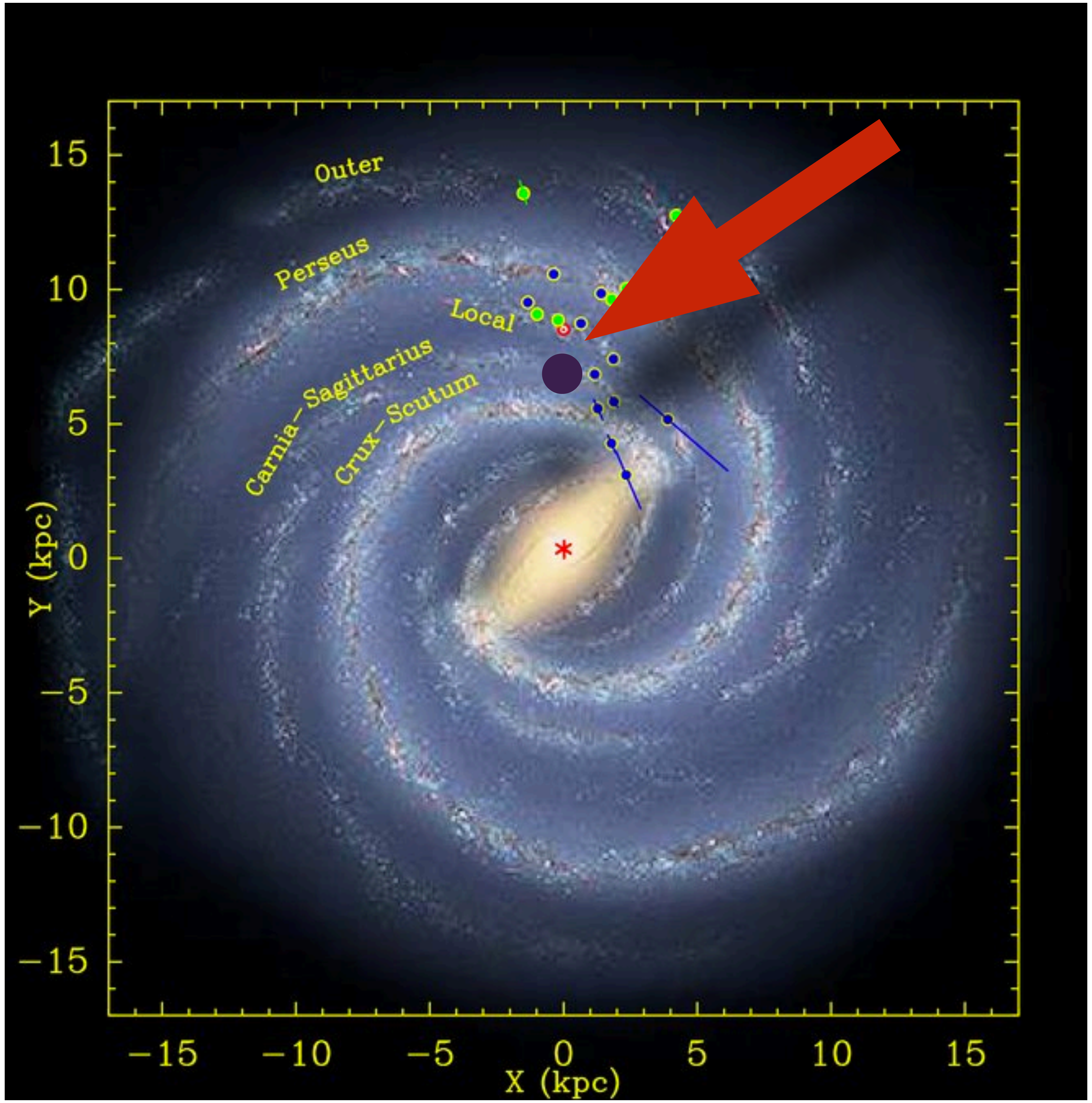


- Main contamination: distant QSO
  —> using parallax & proper motion by Gaia
- **HR-diagram is useful to distinguish IBHs**
- IBHs located around cooling sequence of WDs
- How to dig out IBHs from millions of WDs?
- X-ray bright WDs are blue or luminous
  → **Red/faint sources with X-rays can be IBHs**
- X-ray spectrum is useful
  (WDs: $\Gamma_X > 3$、IBH: $\Gamma_X \lesssim 2$)
- Variability is useful
  (WDs: almost no variability、IBH: $t_{\rm var} < 1$ sec)

OGLE2011-BLG-0462

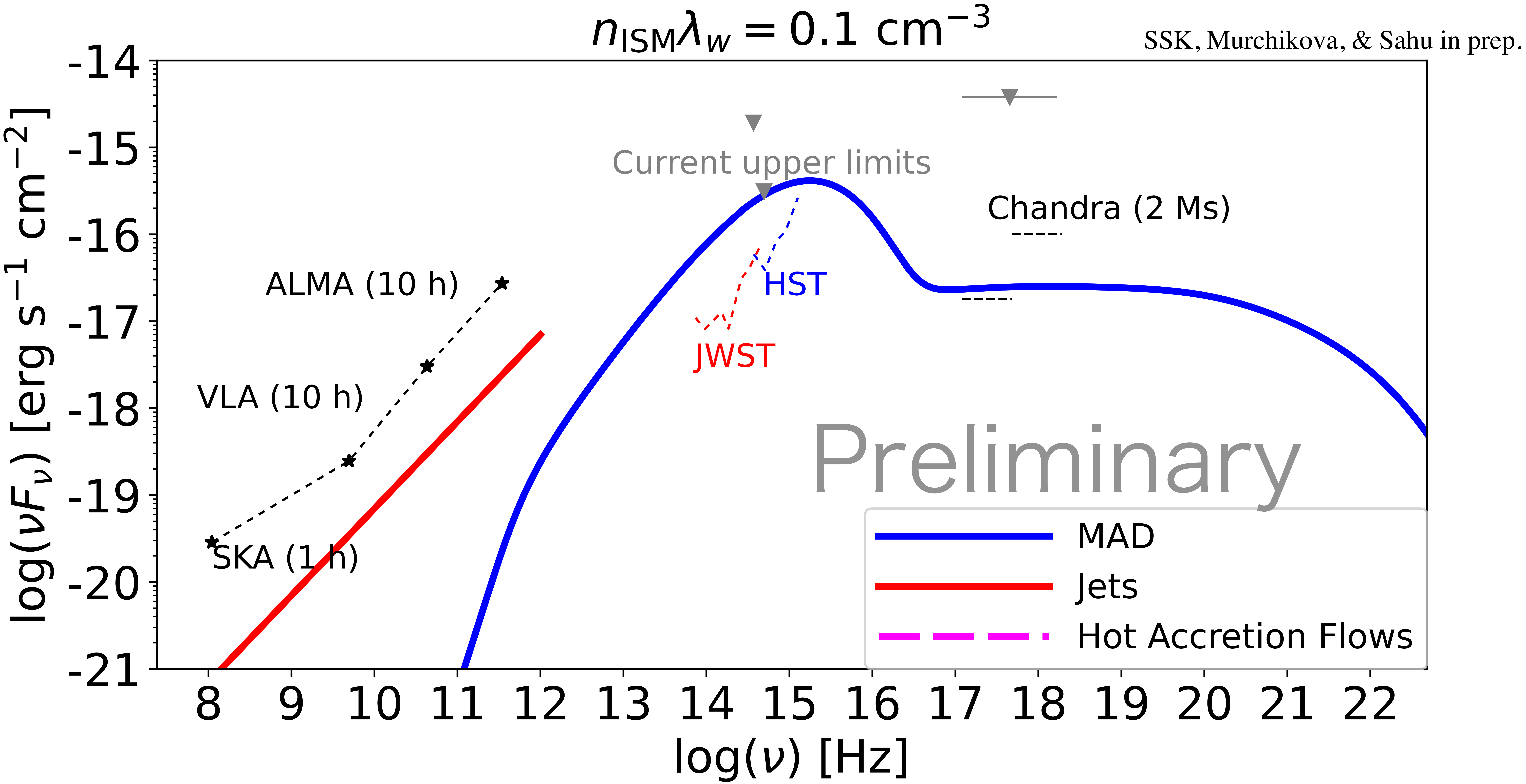


- Lens objects must be isolated BH
- First identification of isolated BHs
- M=7.1 Msun, d=1.58 kpc, v = 45 km/s
- We can estimate the signals from MADs



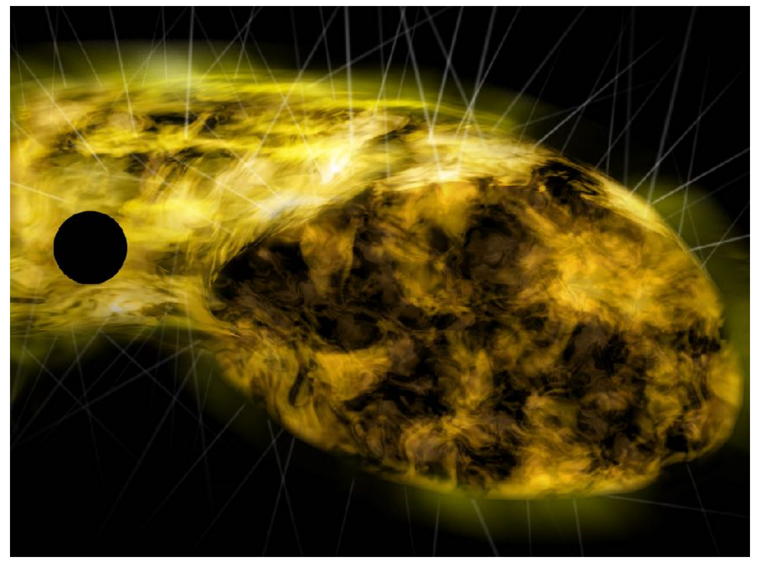
K. Sahu©

Prospects for detecting OGLE-11-0462

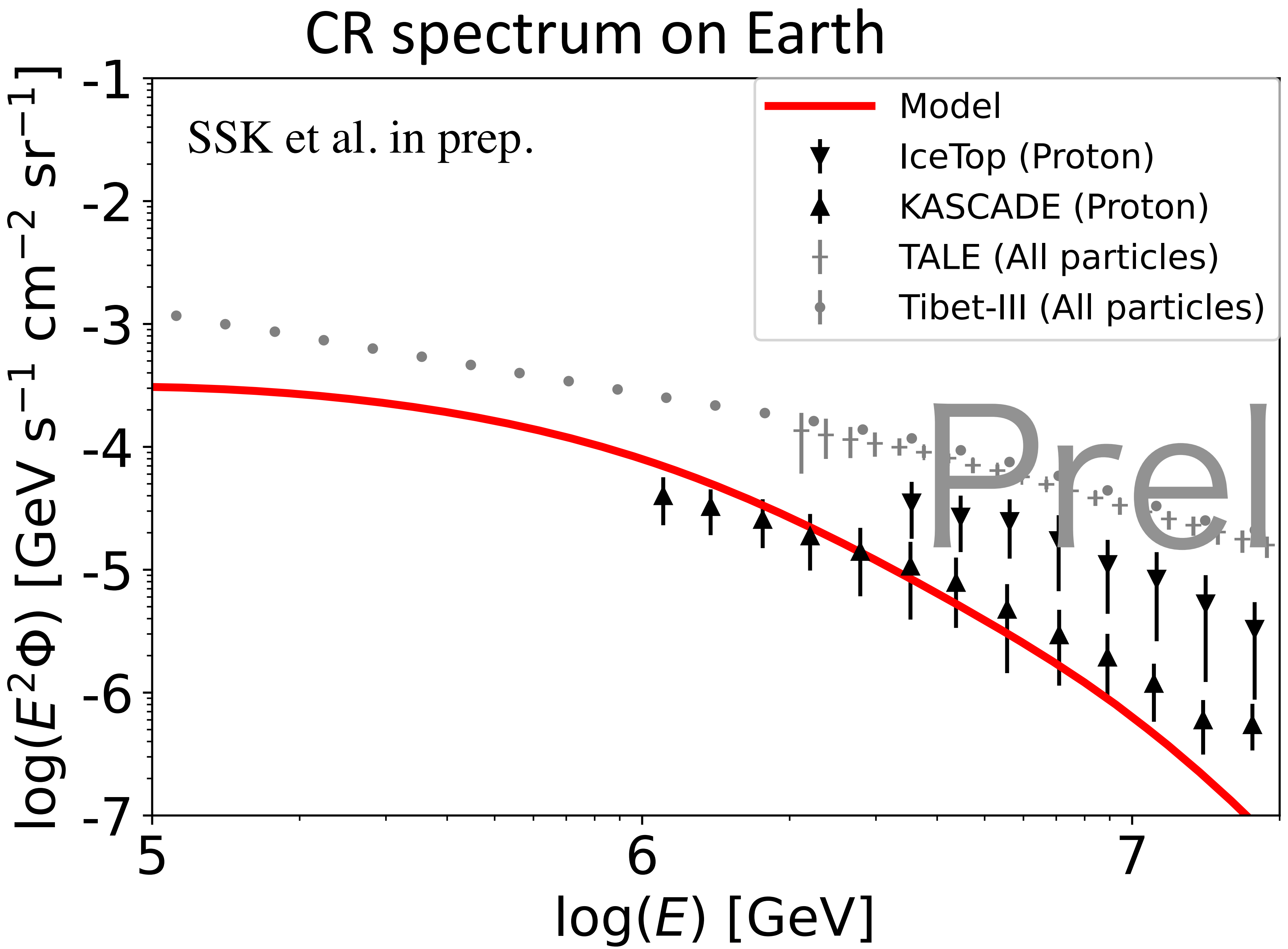


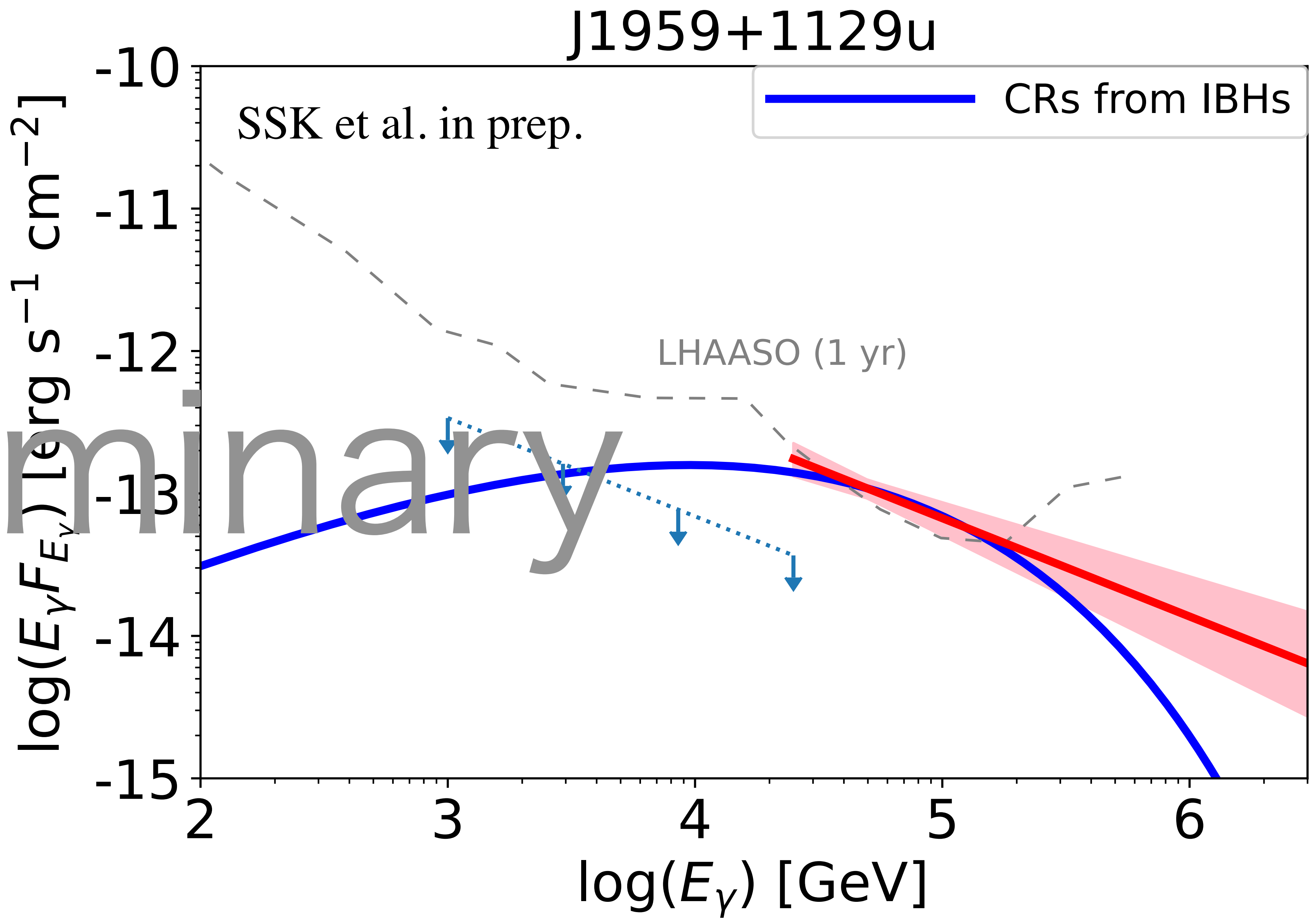
- Detection will be useful to calibrate emission model & number of IBHs found by Gaia

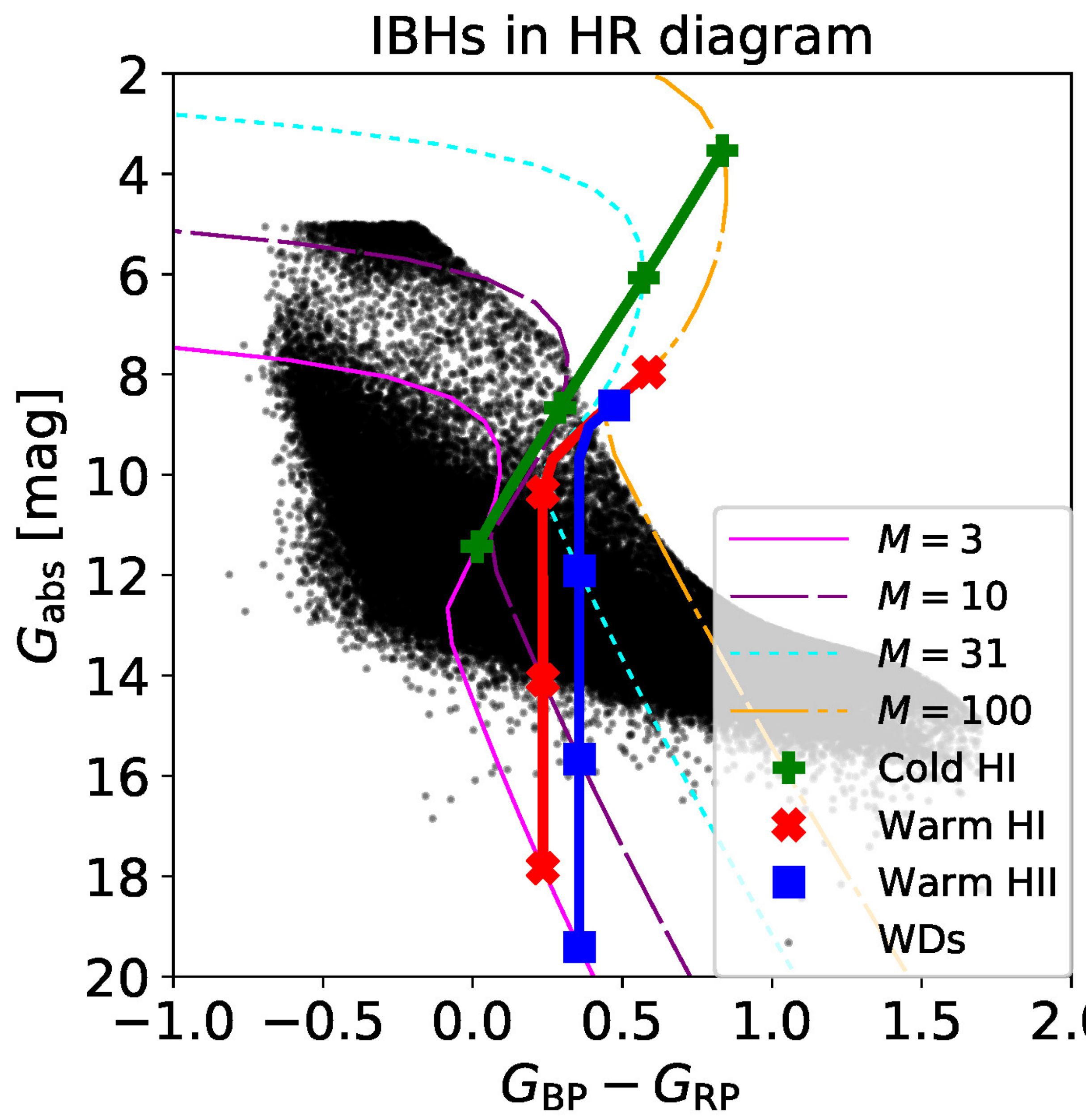
Summary



- Magnetic reconnection in MADs can efficiently accelerate non-thermal particles
- Calibrating parameters using optical/X-ray data from quiescent BH X-ray binaries, we find that i**isolated black holes embedded in molecular clouds can be PeVatrons**
- γ-rays from molecular clouds might be potential origin of LHAASO sources only seen in > 25 TeV
- We might be able to identify IBHs by Gaia & eROSITA, which will provide a test on our scenario







Thank you
for
your attention