

TeV-PeV gamma-ray emissions from Galactic Stellar-mass Black Holes

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TI-FRIS

References

SSK, Tomida, Kobayashi, Kin, Zhang, 2025, ApJL, 981, L36

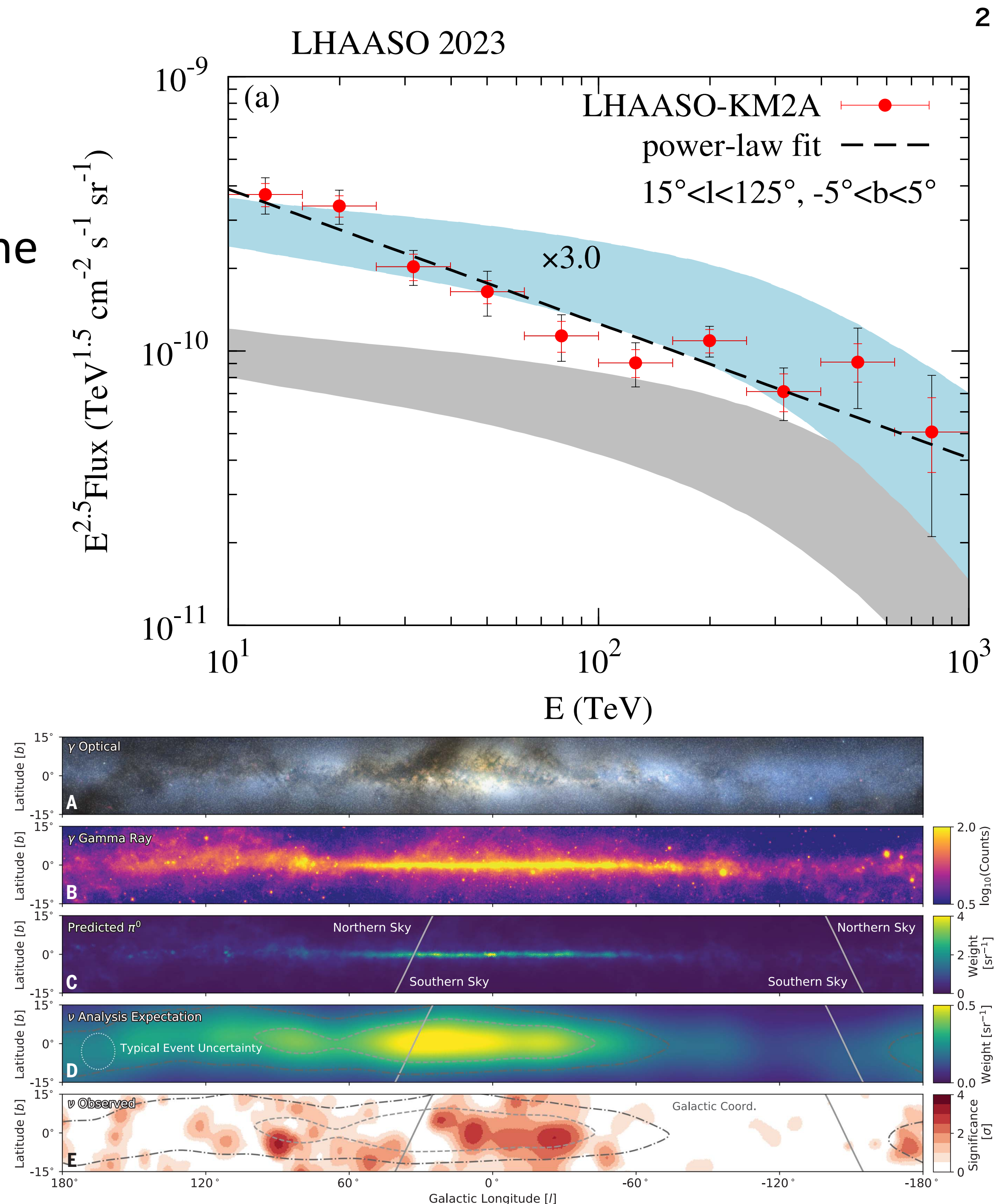
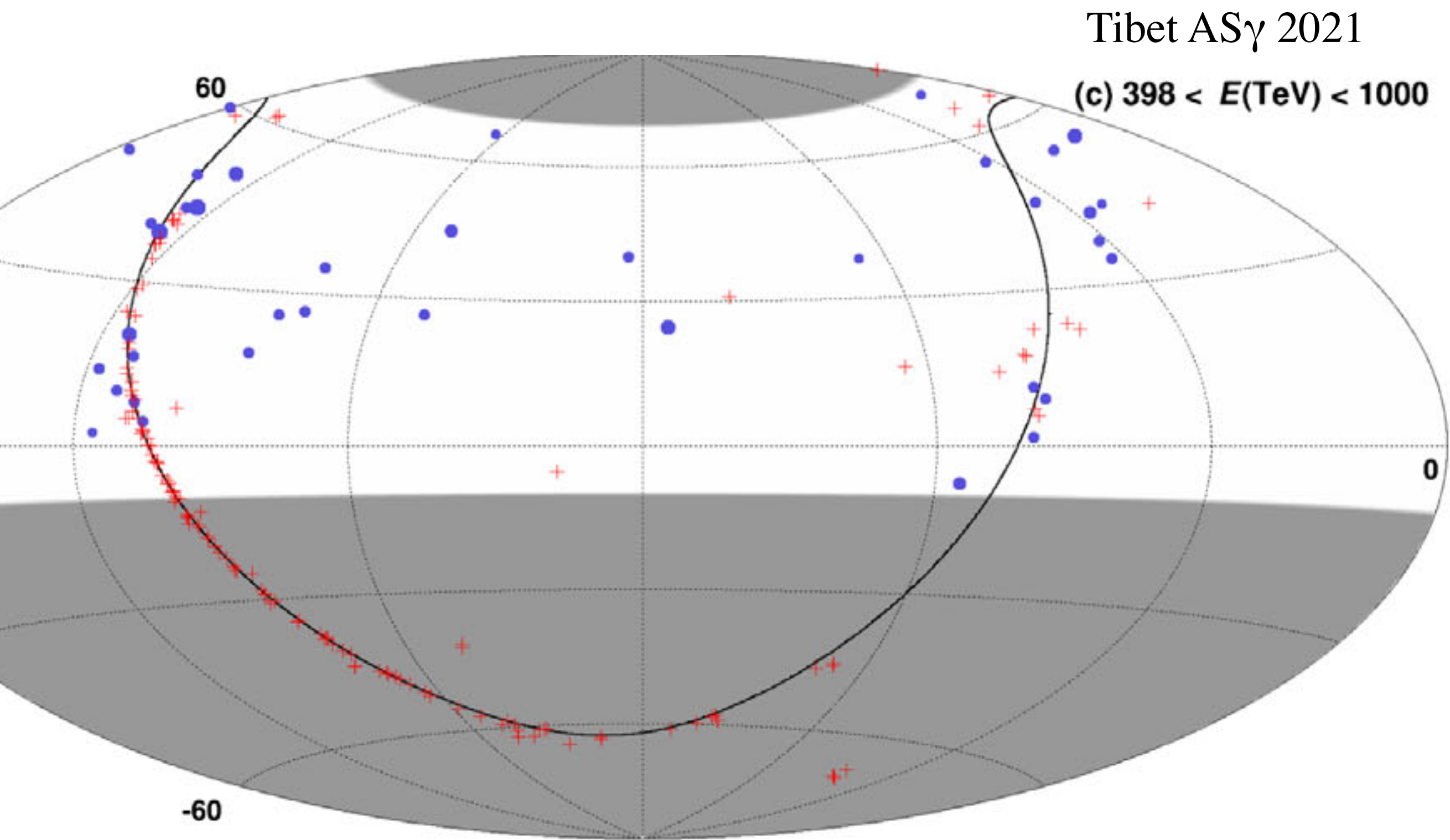
Koshimizu & SSK, 2025 ApJ accepted (arXiv:2606:31477)



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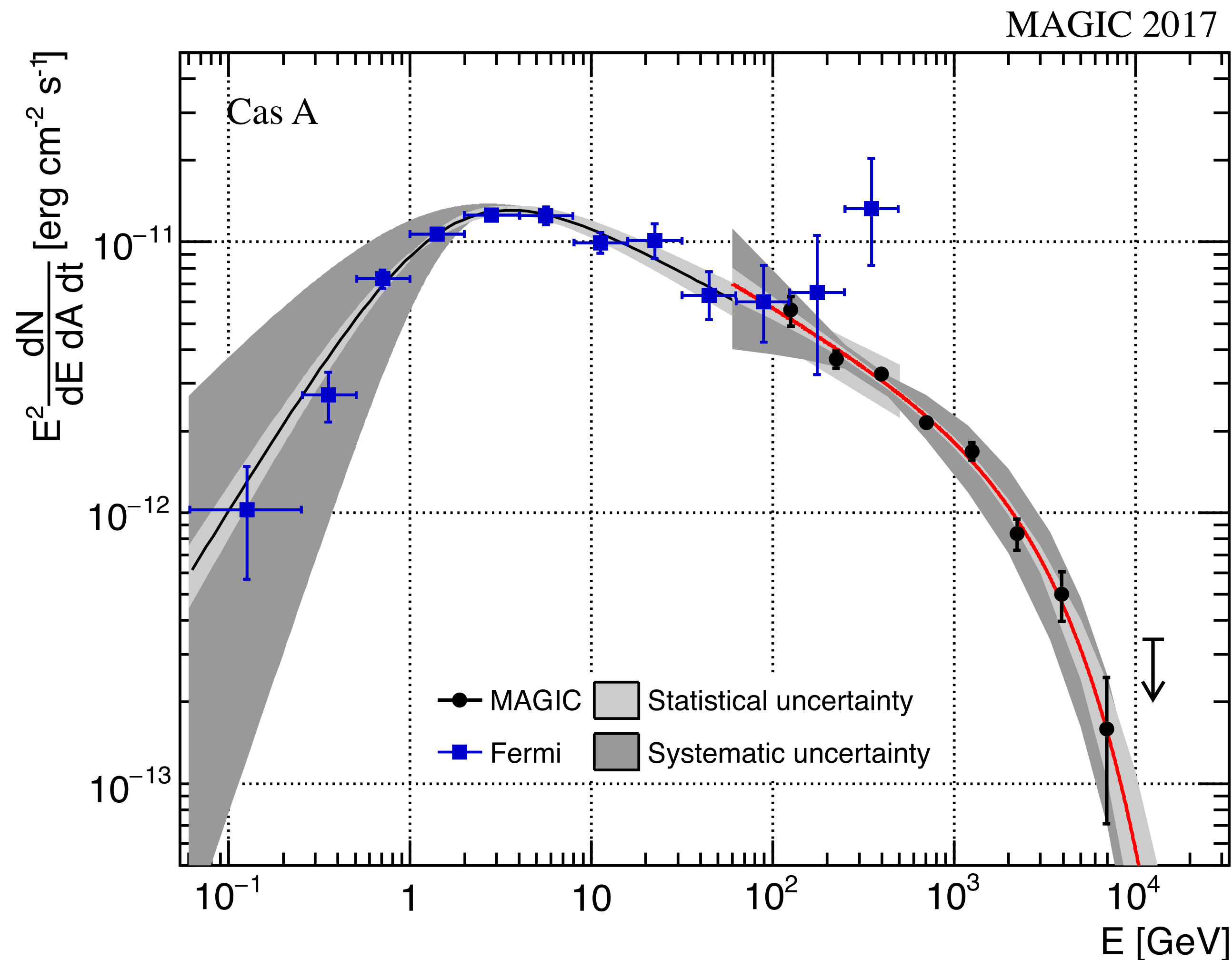
Galactic PeVatrons

- Origins of PeV CRs are unknown
- Tibet AS γ detected sub-PeV γ rays from Galactic plane
- LHAASO detected diffuse γ -rays in 0.01 - 1 PeV
- IceCube detected neutrinos from Galactic plane
- **Strong evidence of Galactic PeVatron**



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 $E_\gamma \sim 100$ TeV
- It is unclear whether SNR can provide sufficient PeV CRs observed at Earth
- **Are there other PeVatrons in our Galaxy?**



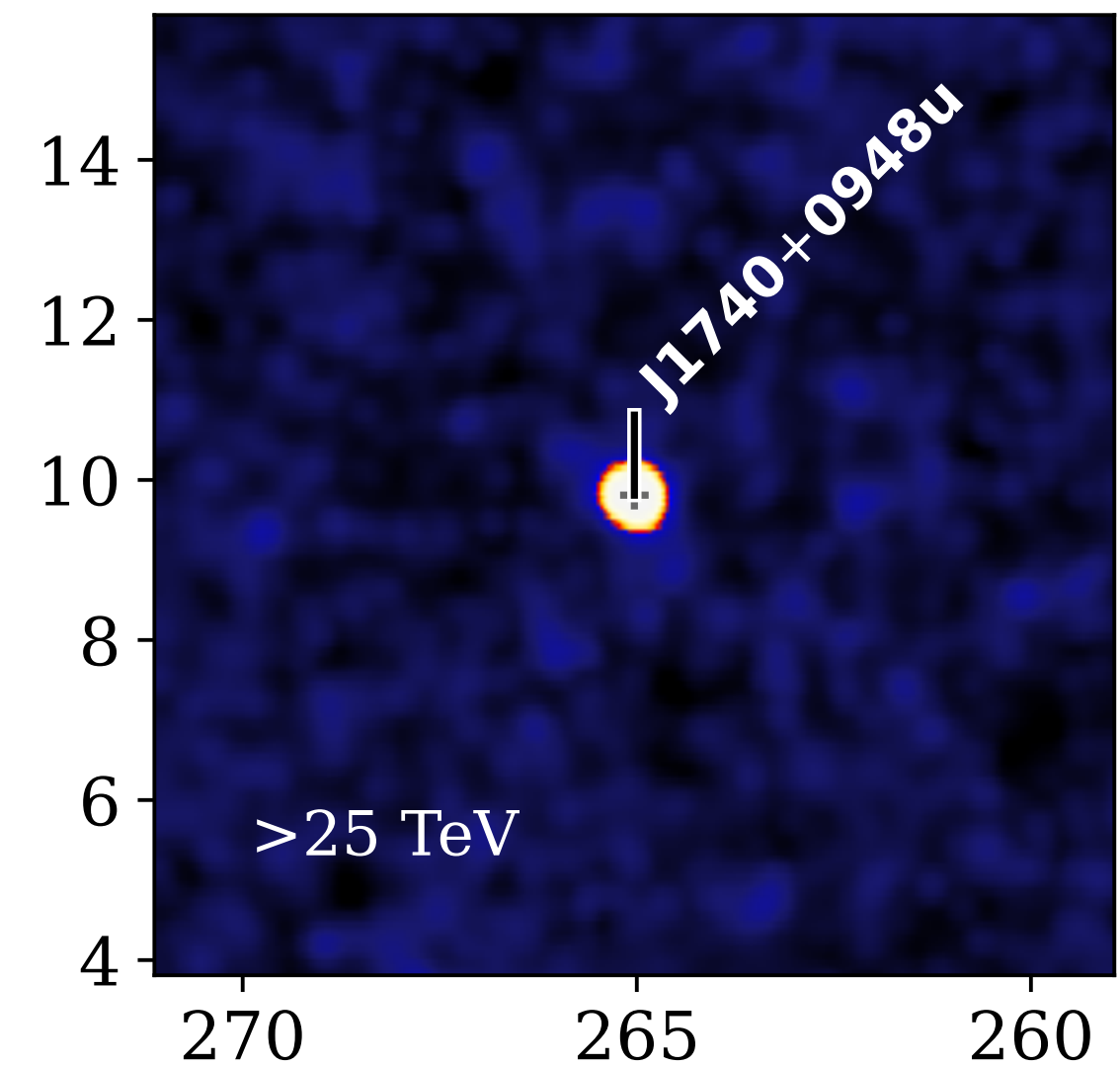
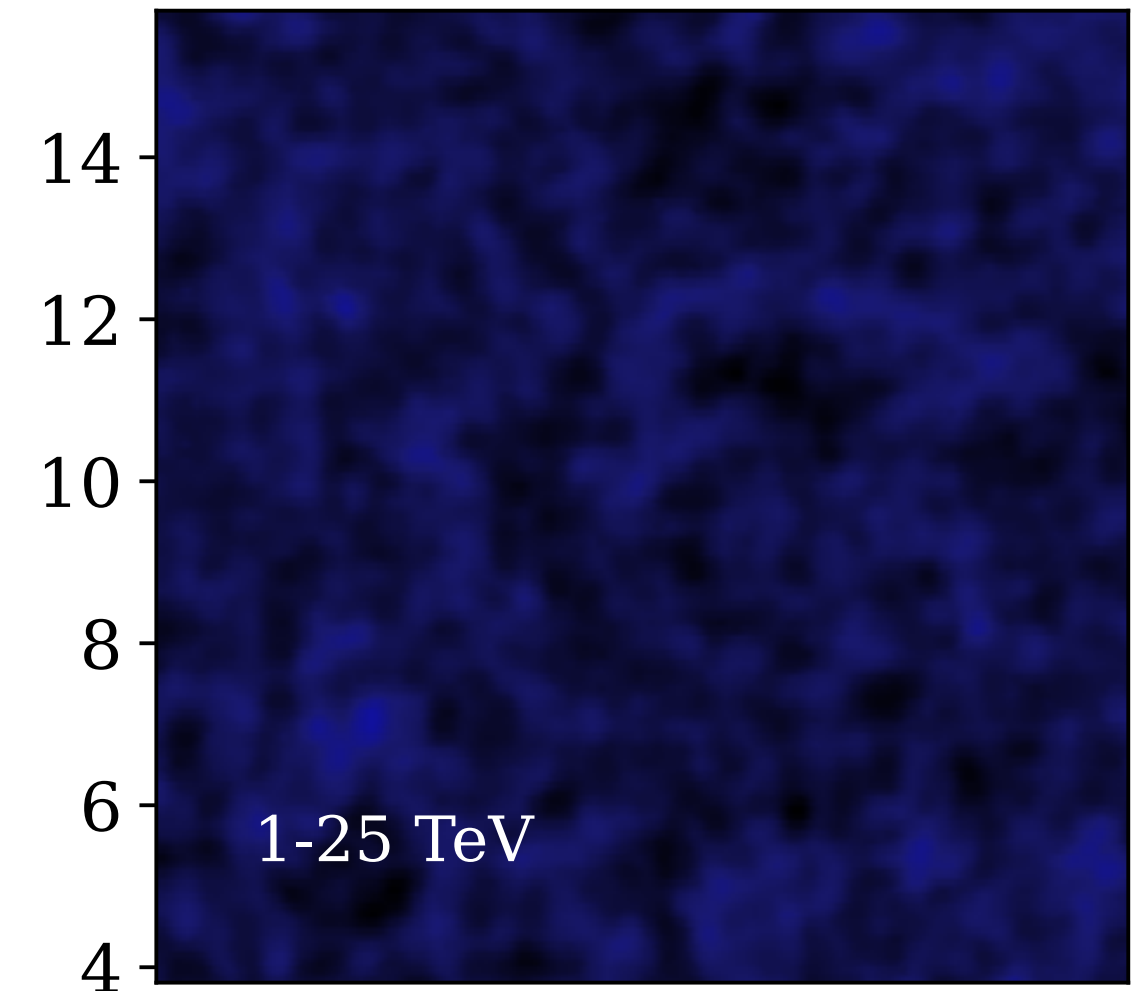
New class of UHE γ -ray sources?

- LHAASO discovered sources in $E_\gamma > 100$ TeV without detecting γ -rays for $E_\gamma < 25$ TeV
- These objects are named “dark” sources
- **What is the origins of the “dark” sources detected by LHAASO?**

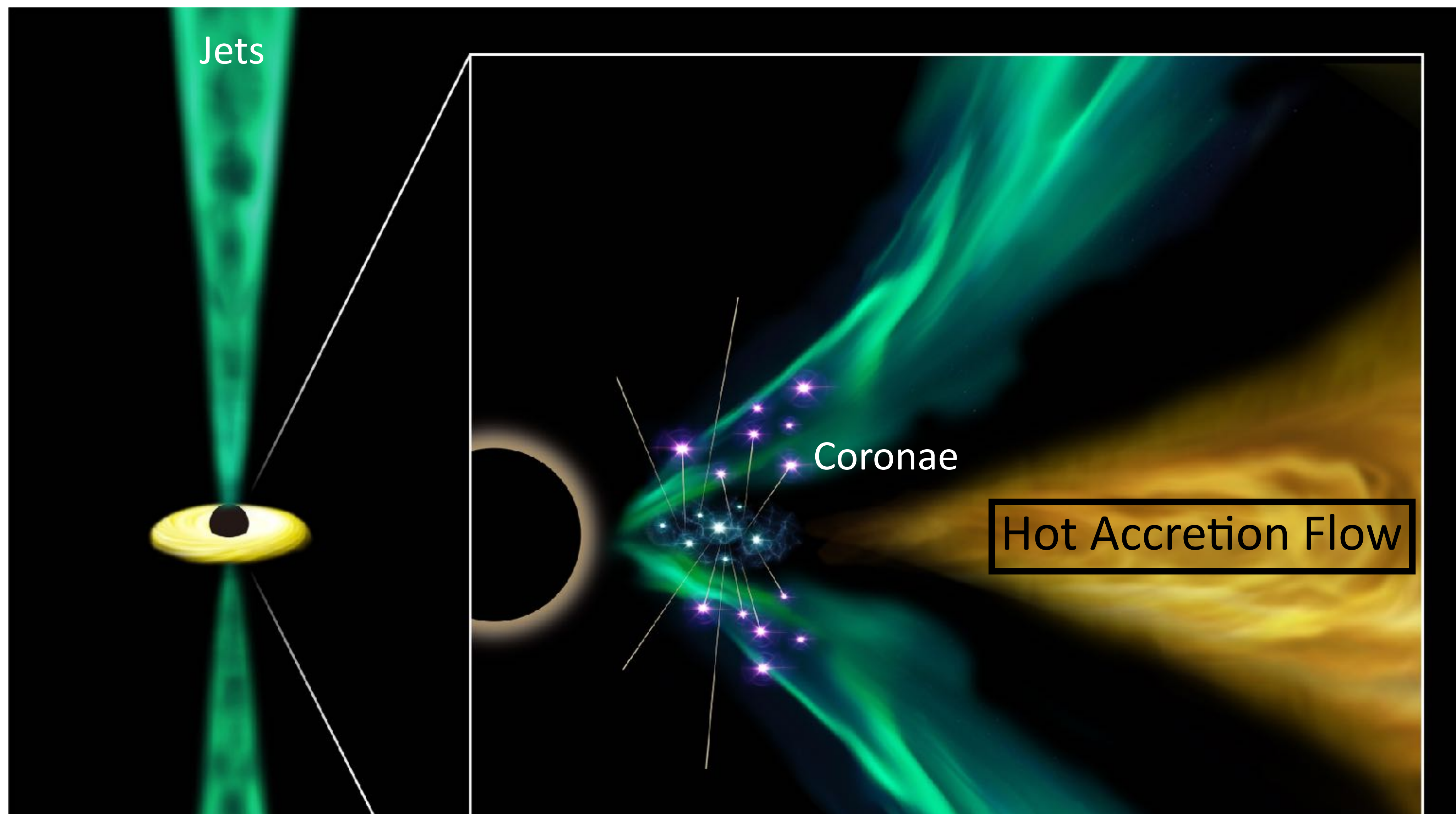
LHAASO 1st catalog 2024

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		

LHAASO 1st catalog paper 2024



Stellar-mass Black Holes as PeVatrons



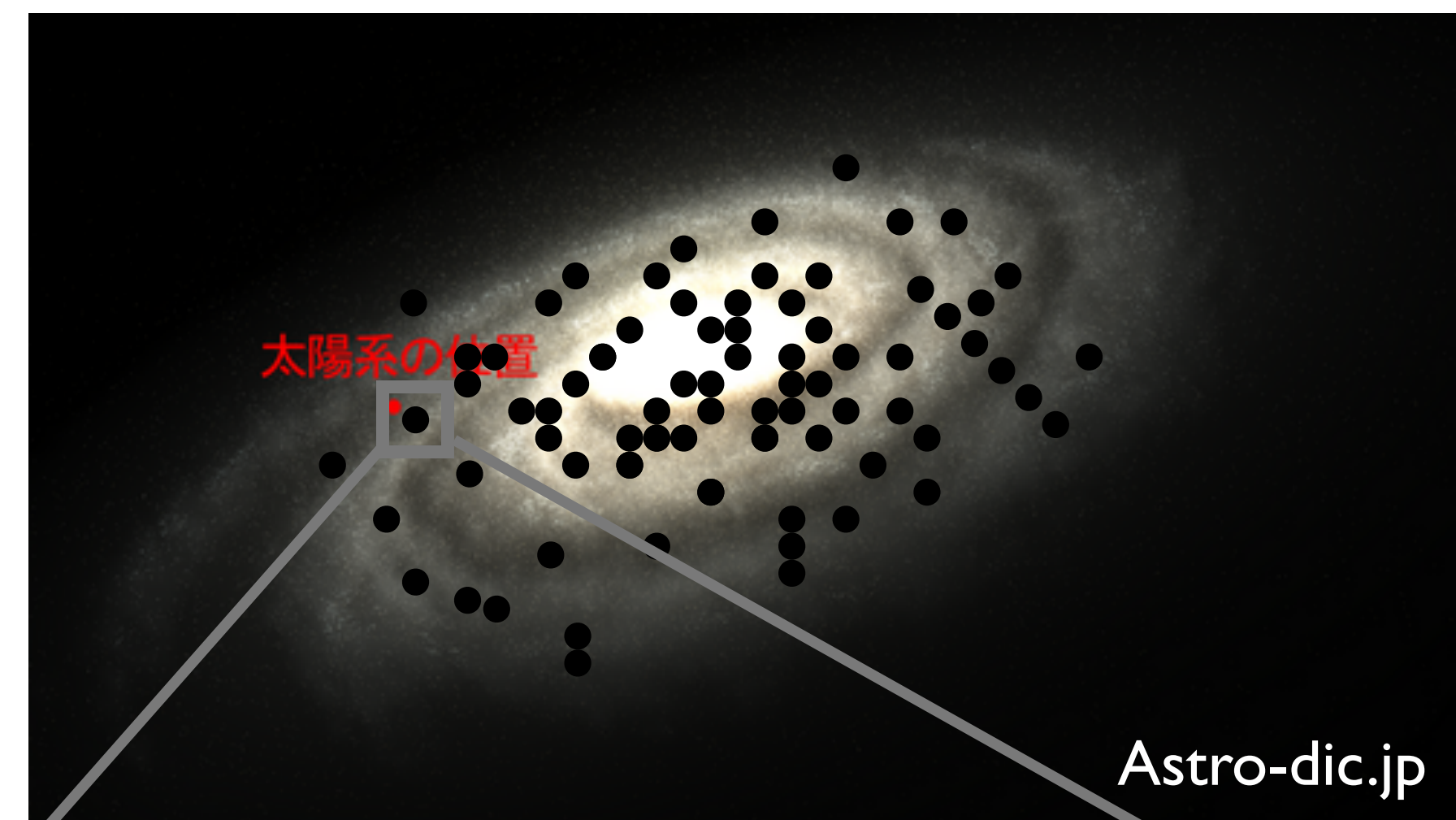
Isolated Black Holes (IBHs)

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

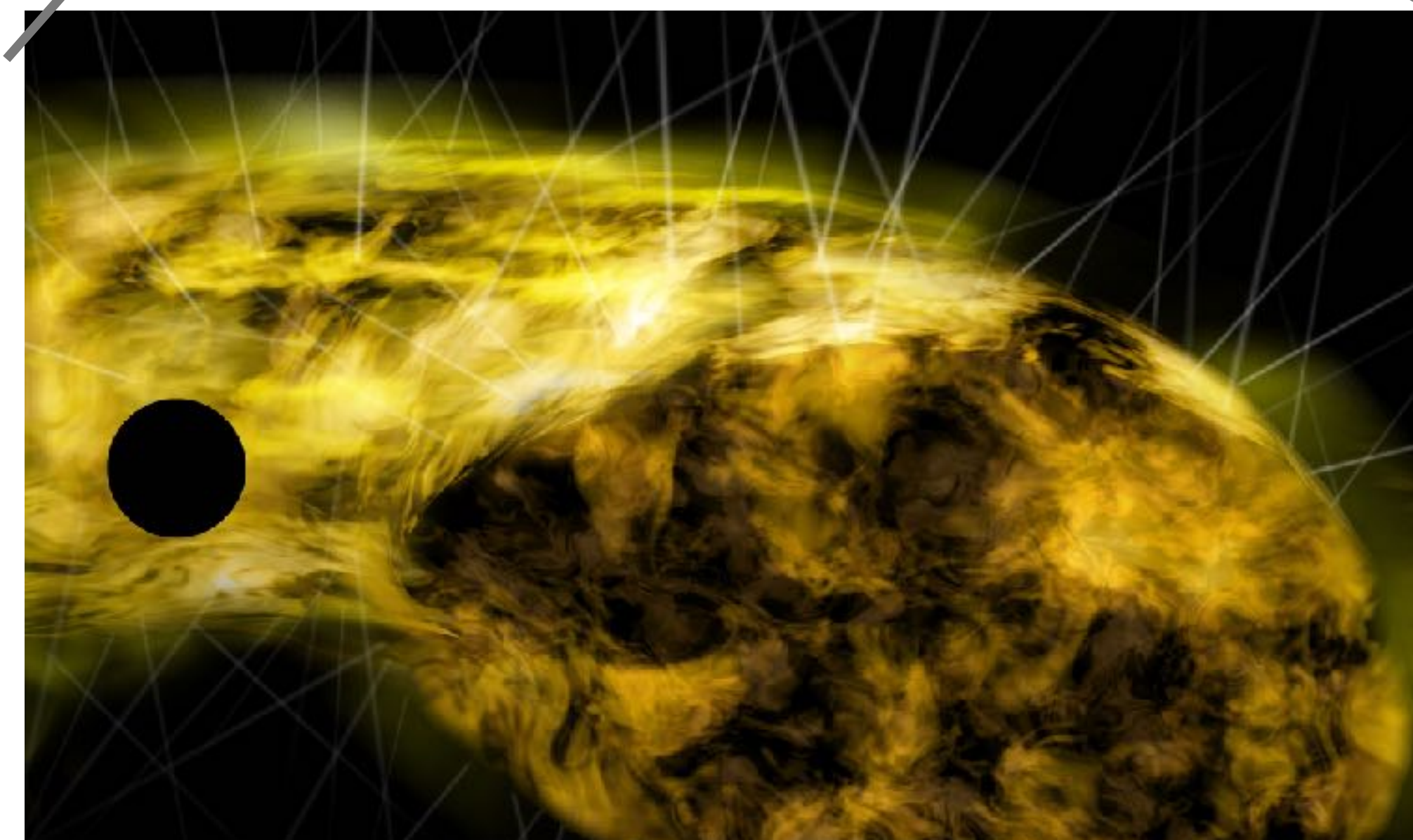
$$\dot{M} \approx \lambda_w \frac{4\pi G^2 M^2 \mu_{\text{ISM}} m_p n_{\text{ISM}}}{(C_s^2 + v_k^2)^{3/2}}$$

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

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

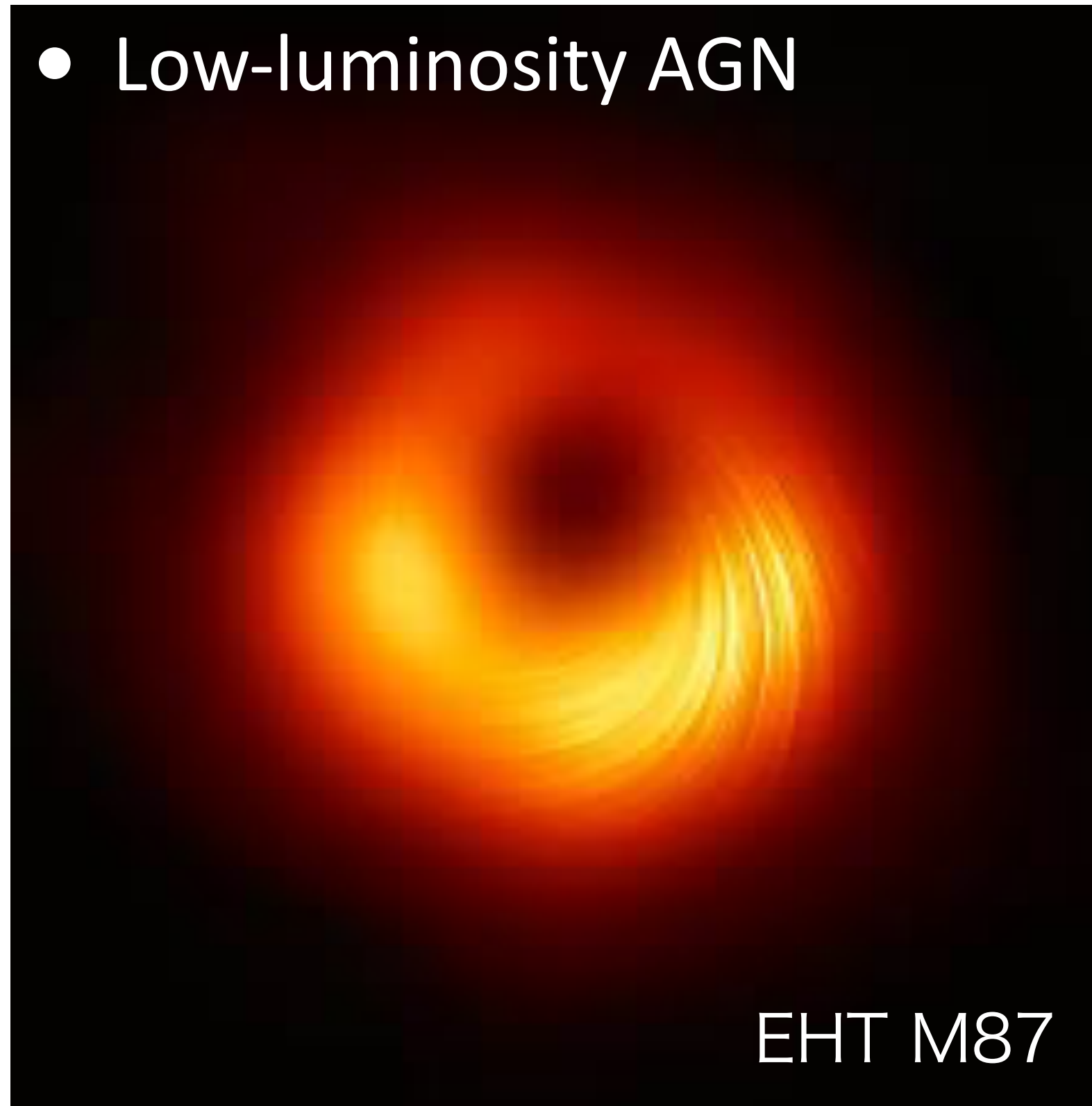


Astro-dic.jp

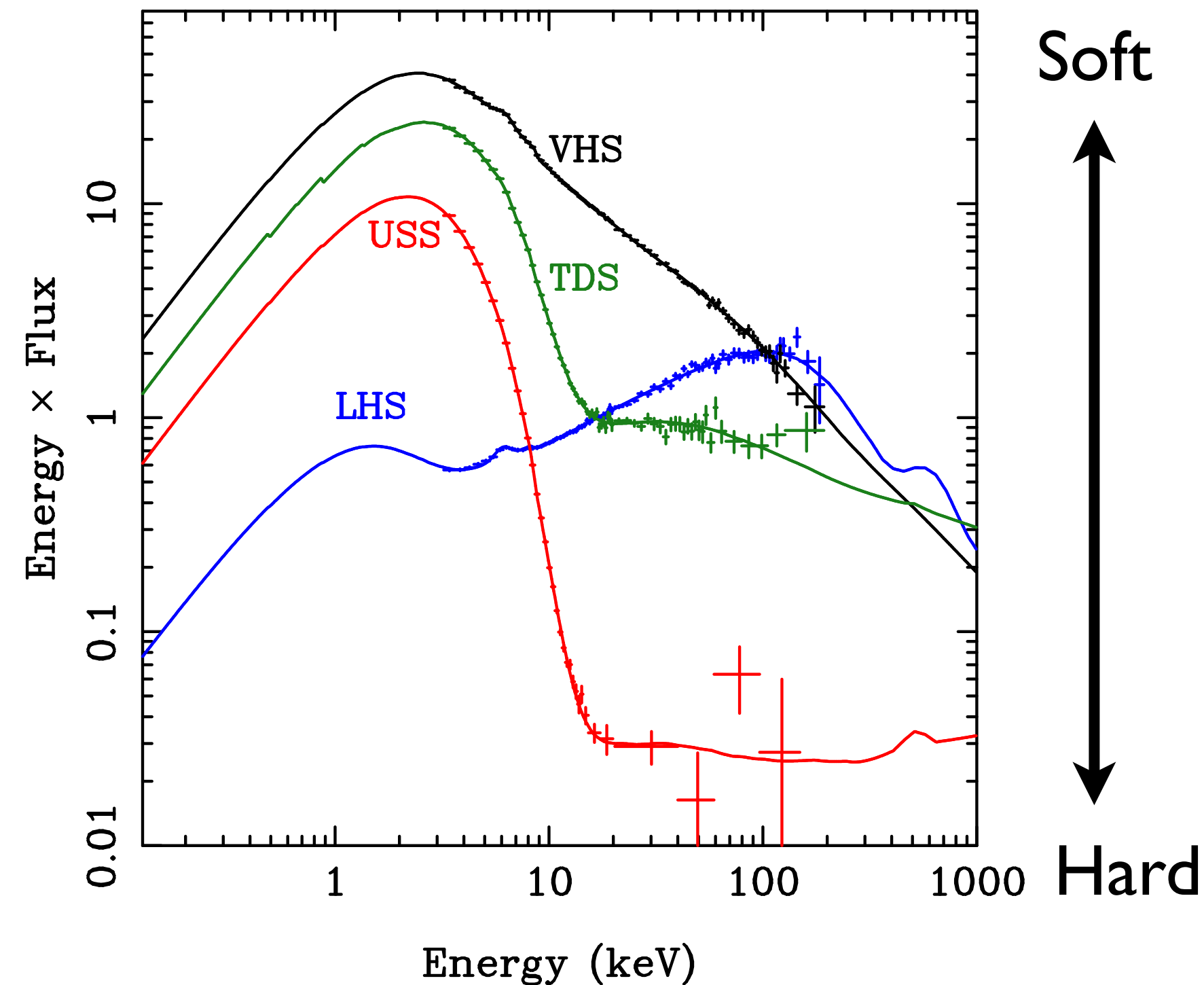


RIAFs around Black Holes

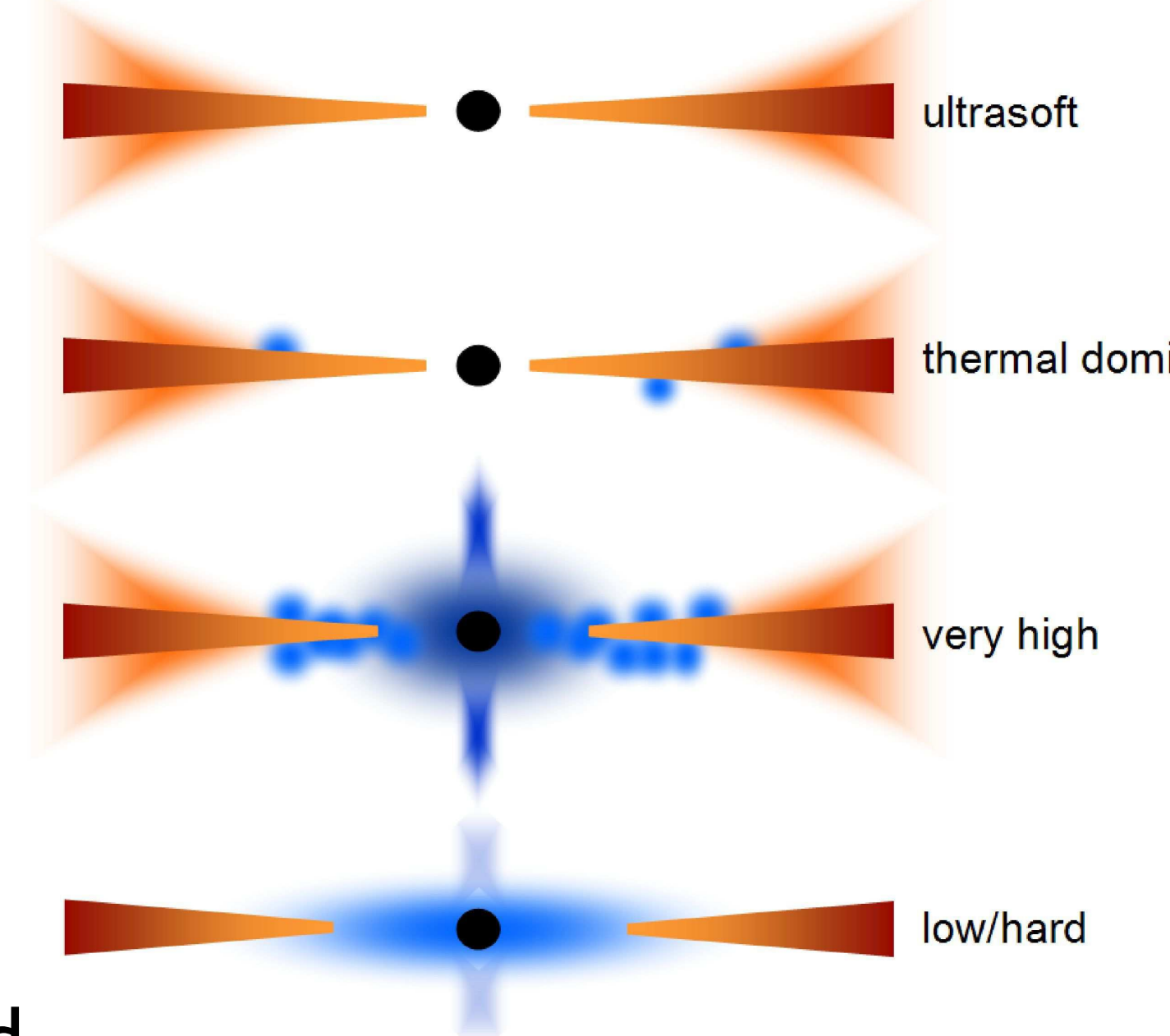
- Low-luminosity AGN



- X-ray binaries



Done et al. 2007



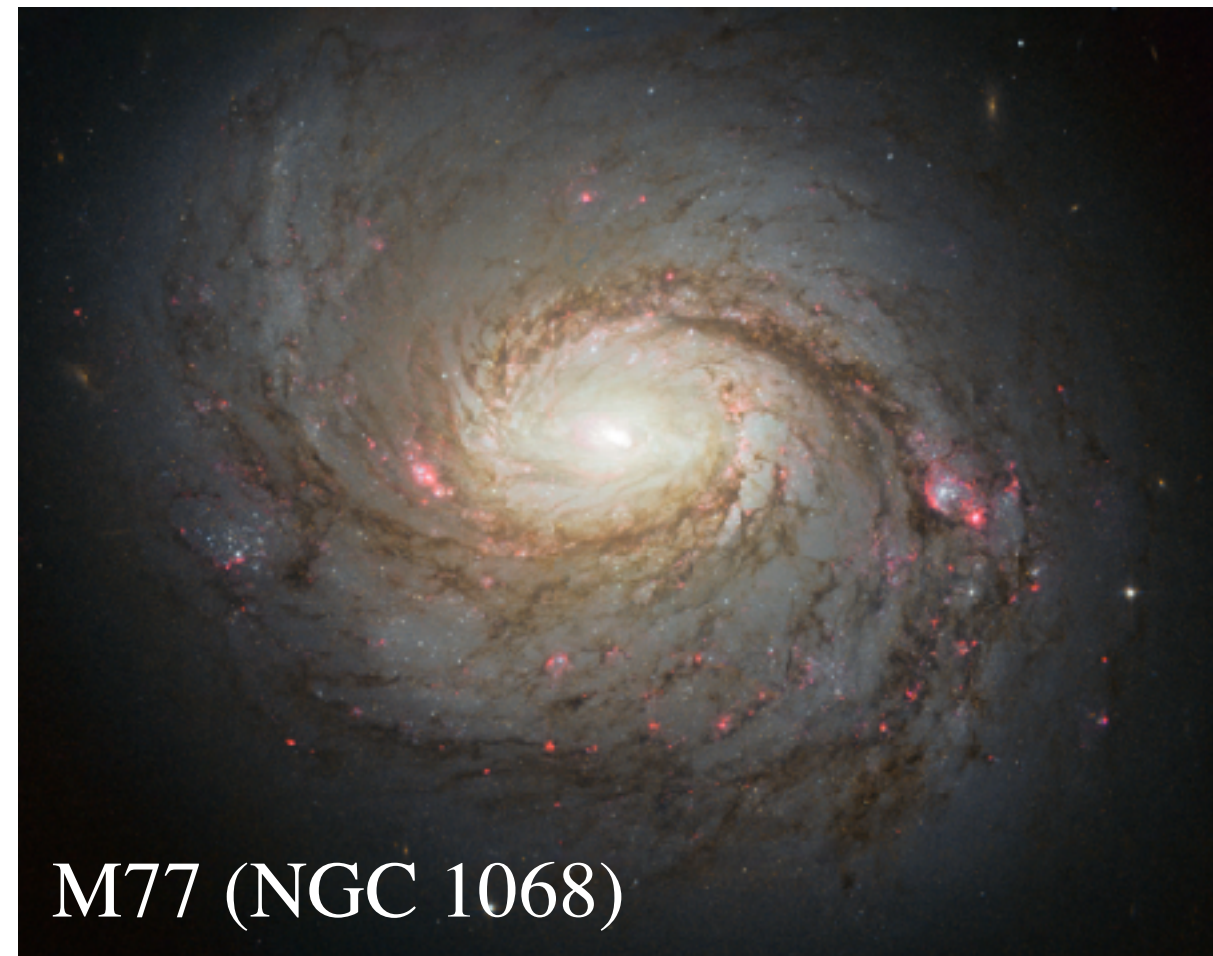
- Accretion rate is high ($\dot{M}c^2 \gtrsim 0.01L_{\text{Edd}}$) $\rightarrow$ optically thick accretion disk + corona
- Accretion rate is low ($\dot{M}c^2 \lesssim 0.01L_{\text{Edd}}$) $\rightarrow$ only hot plasma surrounding the BH
- Coulomb timescale $\gg$ infall timescale $\rightarrow$ non-thermal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

SANE & MAD

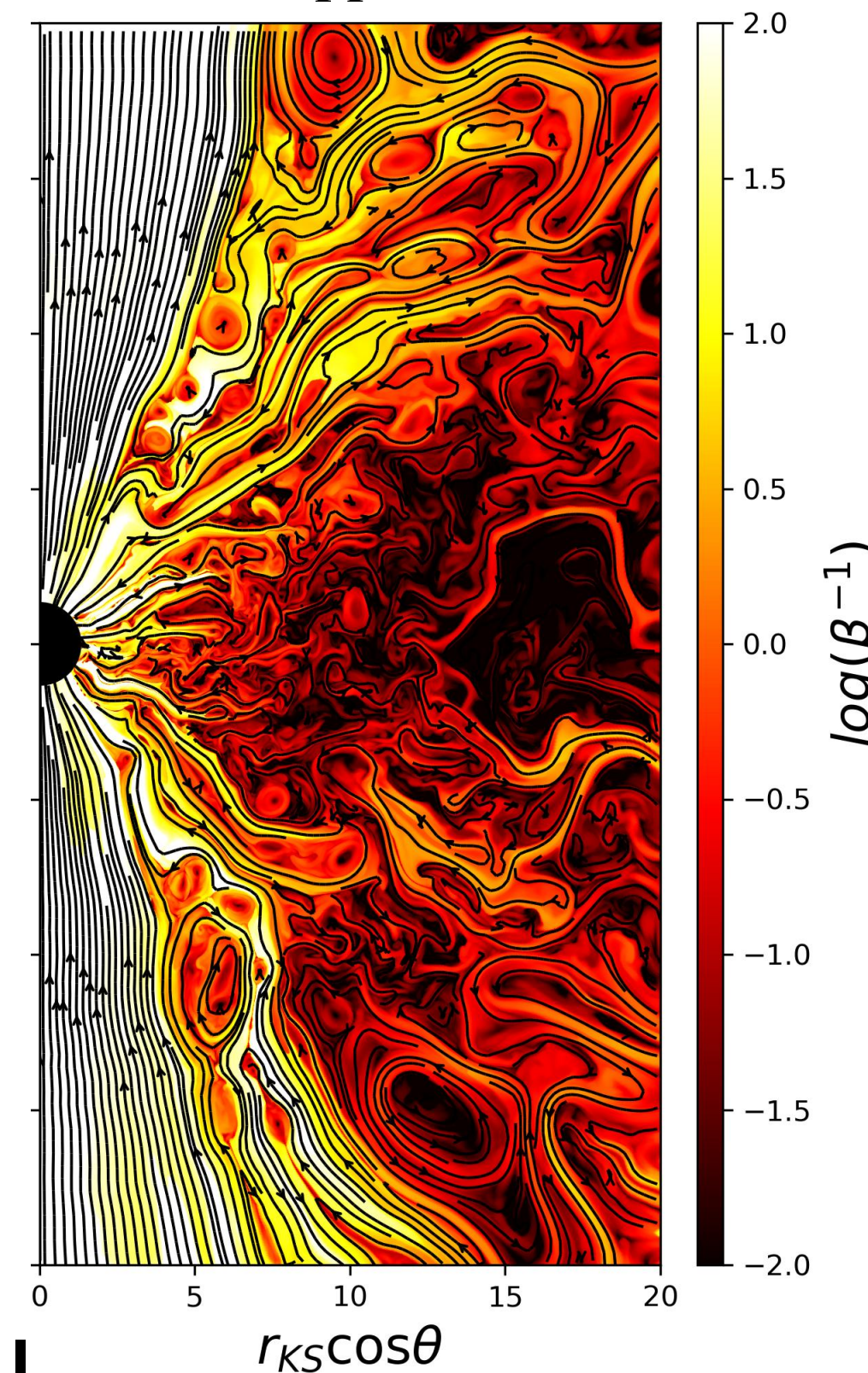
Narayan et al. 2012

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- Standard and Normal Evolution (SANE)



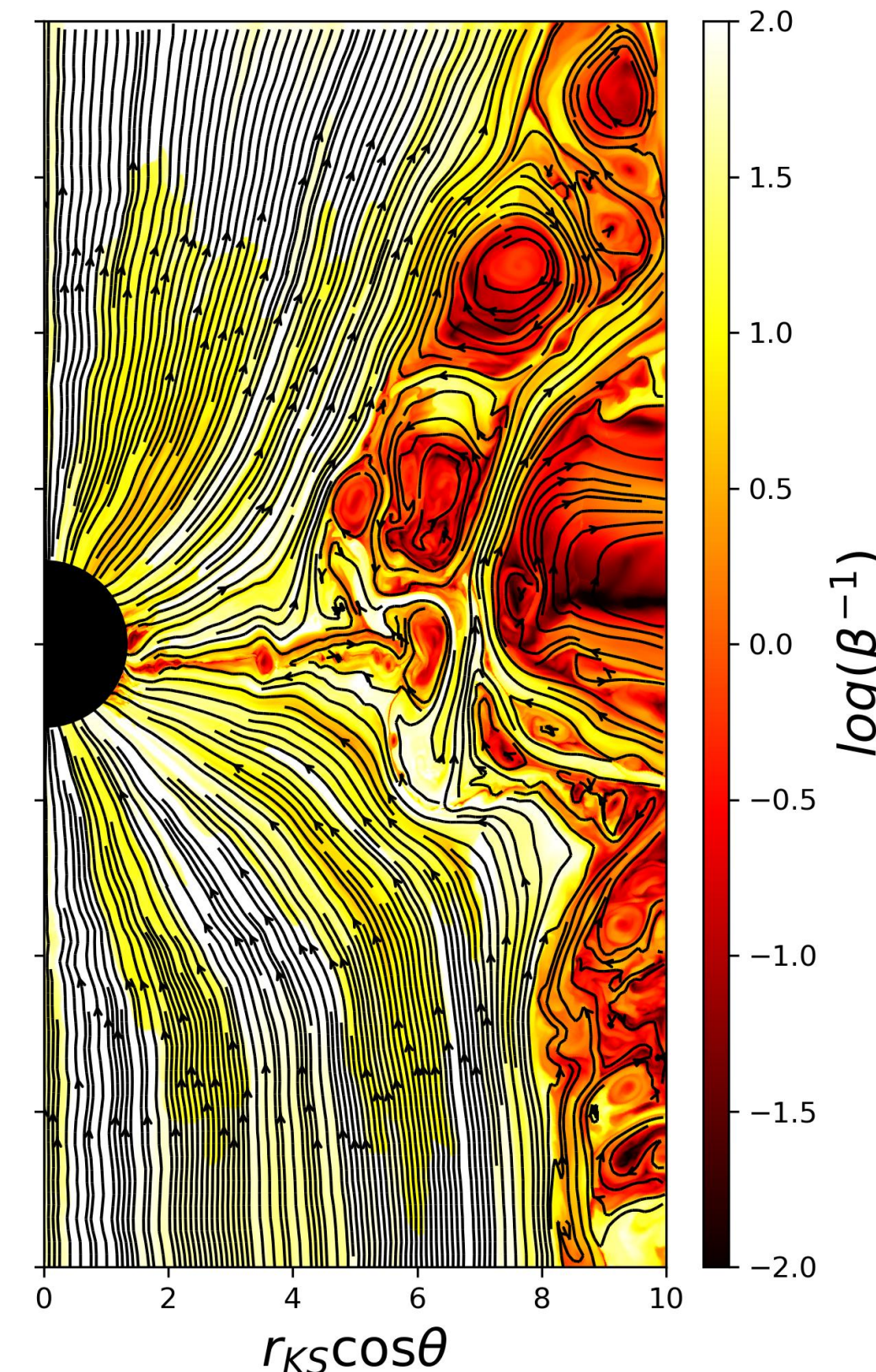
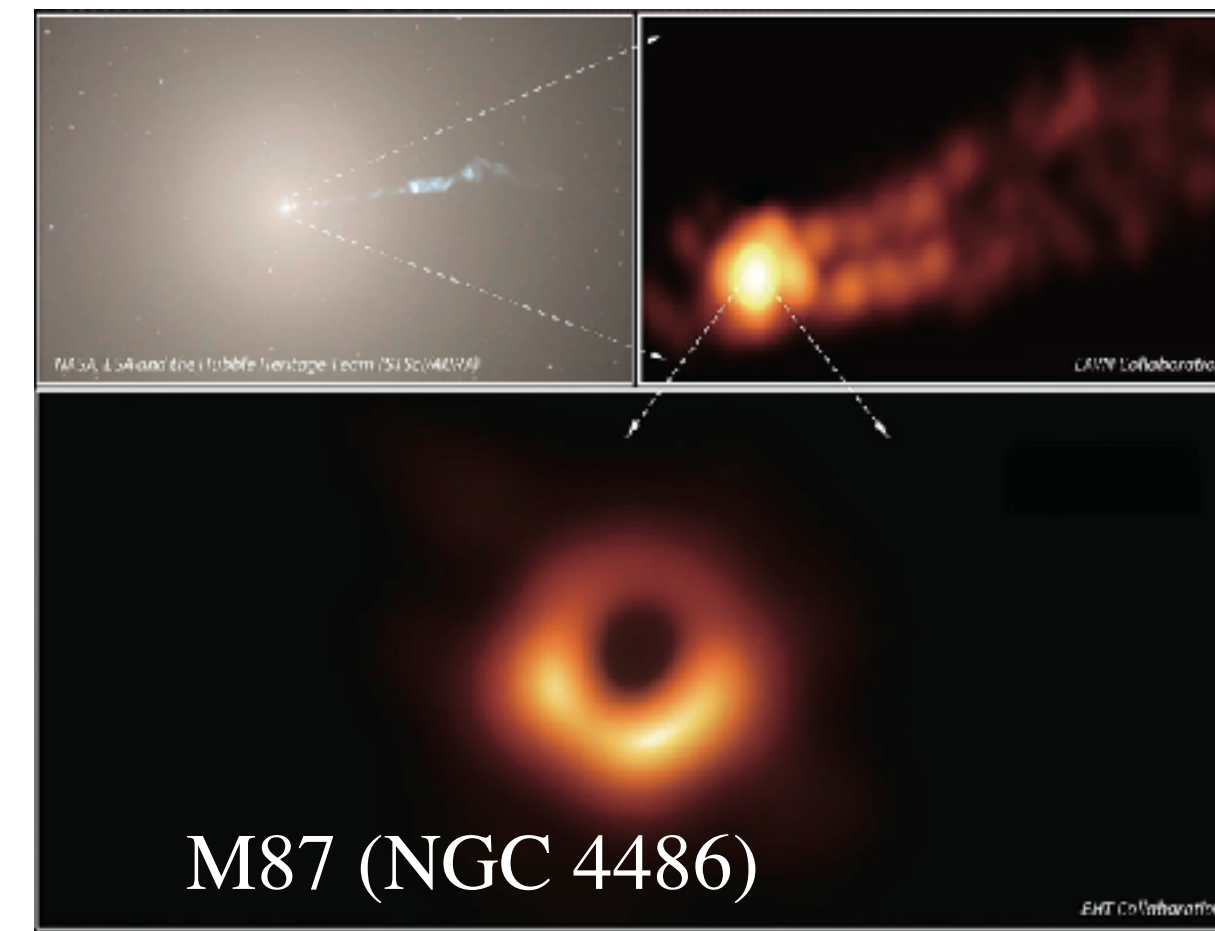
Ripperda et al. 2020



- Turbulence driven by MRI
- Weaker jets are launched
→ related to **radio-faint states**

- Magnetically Arrested Disk (MAD)

Ripperda et al. 2020



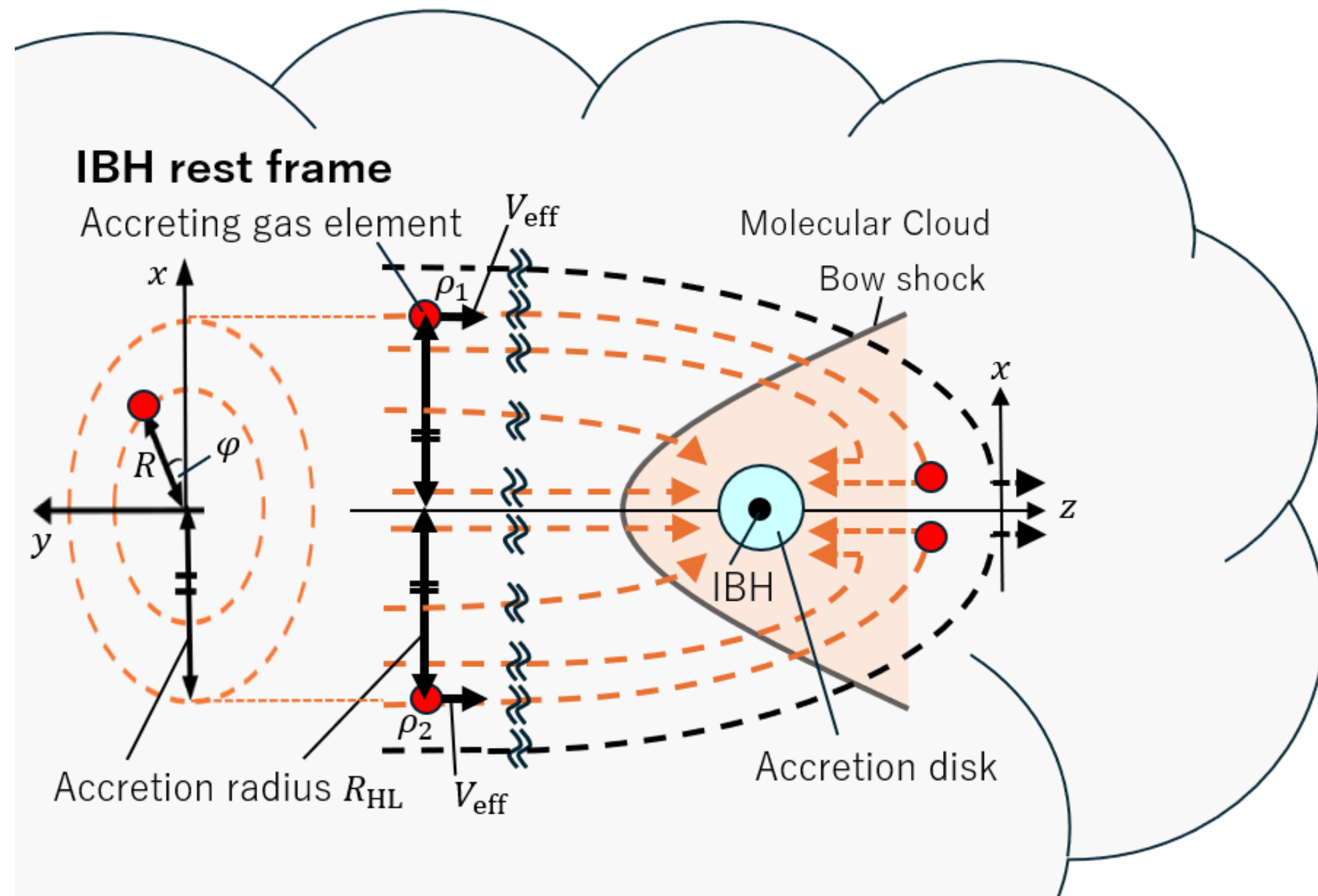
- Strong and ordered magnetic fields
- Powerful jet can be launched
→ related to **radio-loud States**

Magnetic transport to IBH

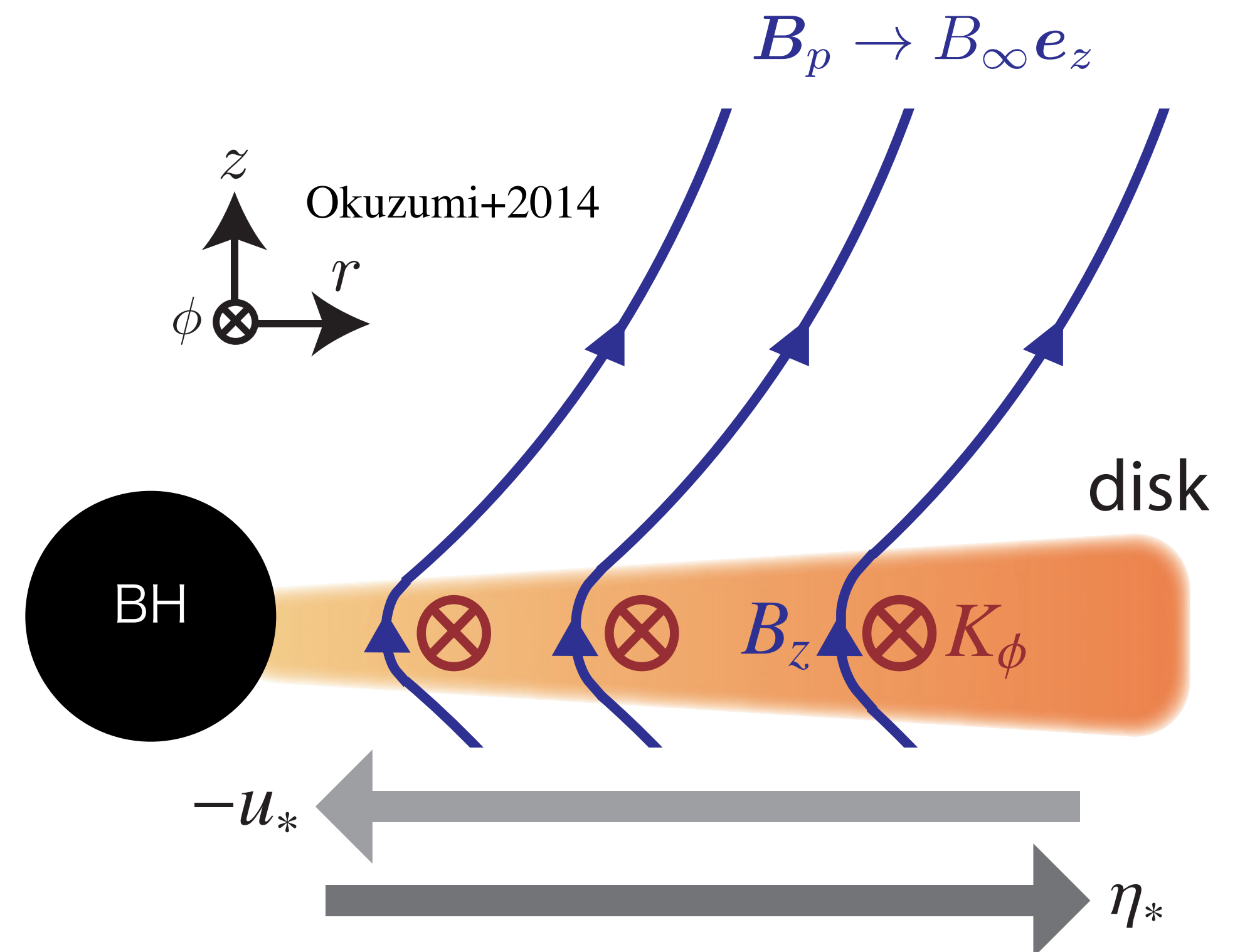
Koshimizu & SSK 2026



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- Density fluctuations in molecular clouds
=> net angular momentum => formation of disk
- Molecular cloud => accretion disk
 - magnetic flux freezing
- Accretion disk => turbulence transport
- **Important parameter: Prandtl number** $P_m = u_*/(R\eta_*)$

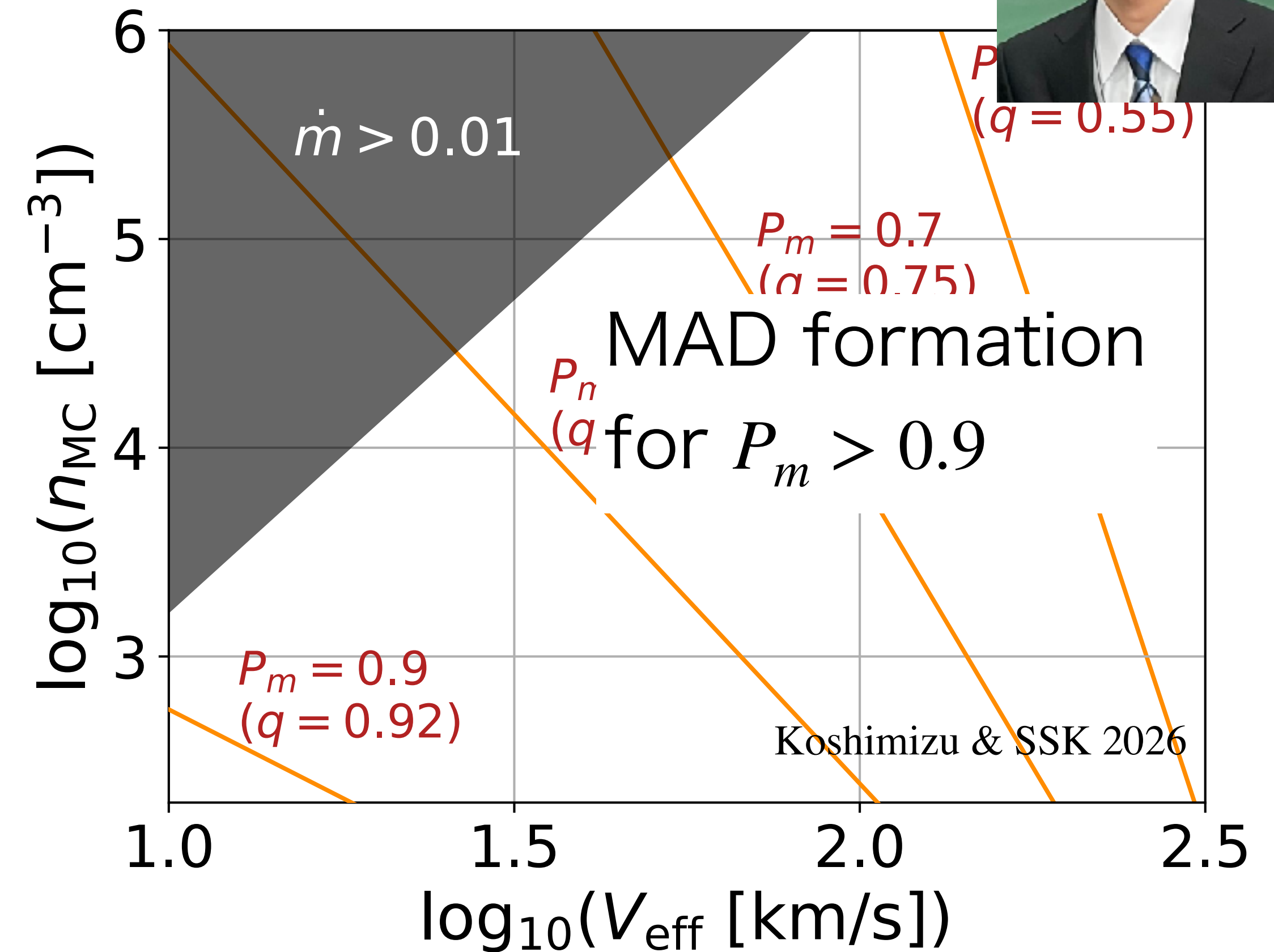
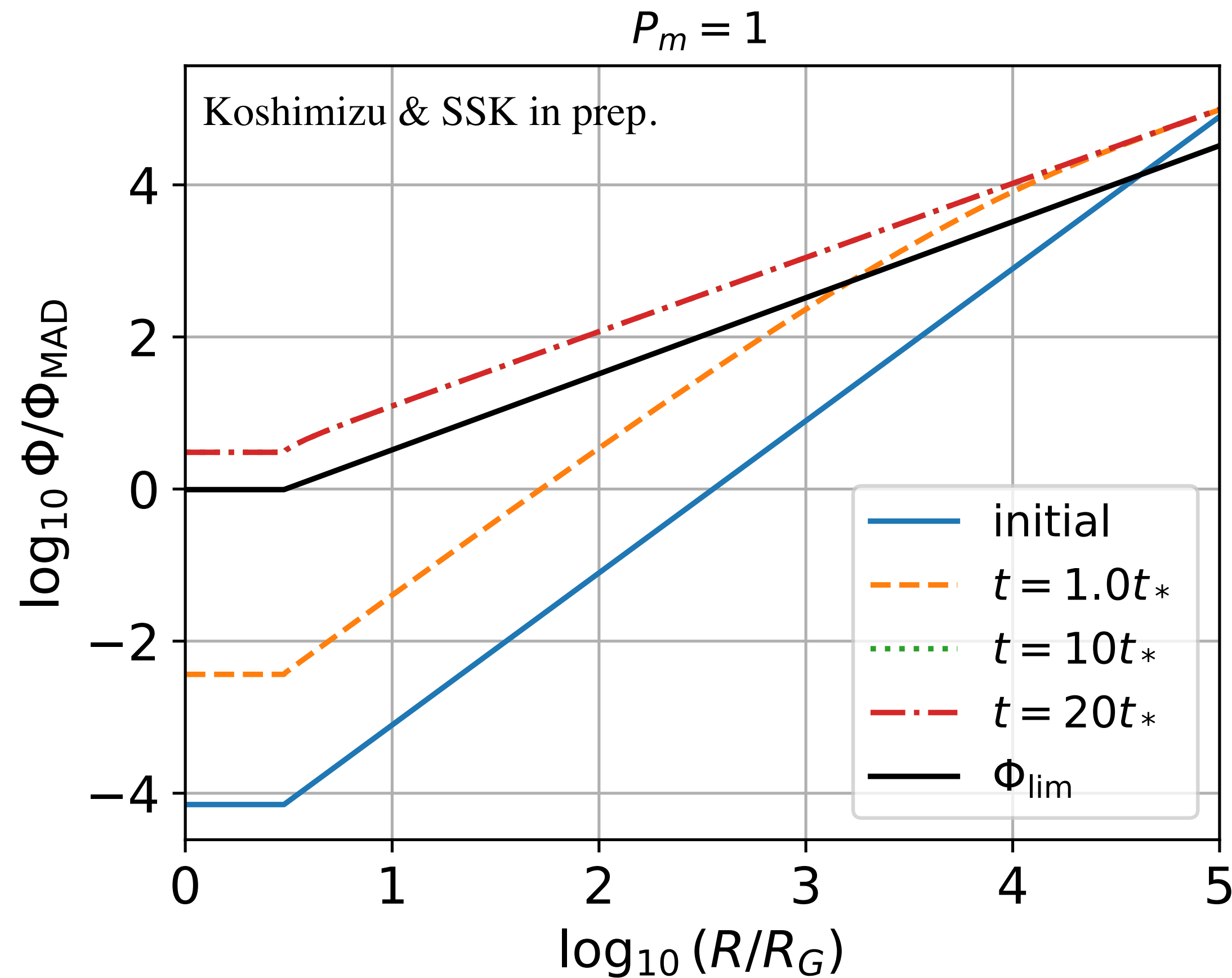


$$\frac{\partial \psi}{\partial t} = -u_* \frac{\partial \psi}{\partial R} - \frac{2\pi R \eta_*}{cH} K_\varphi,$$

MAD Formation Condition



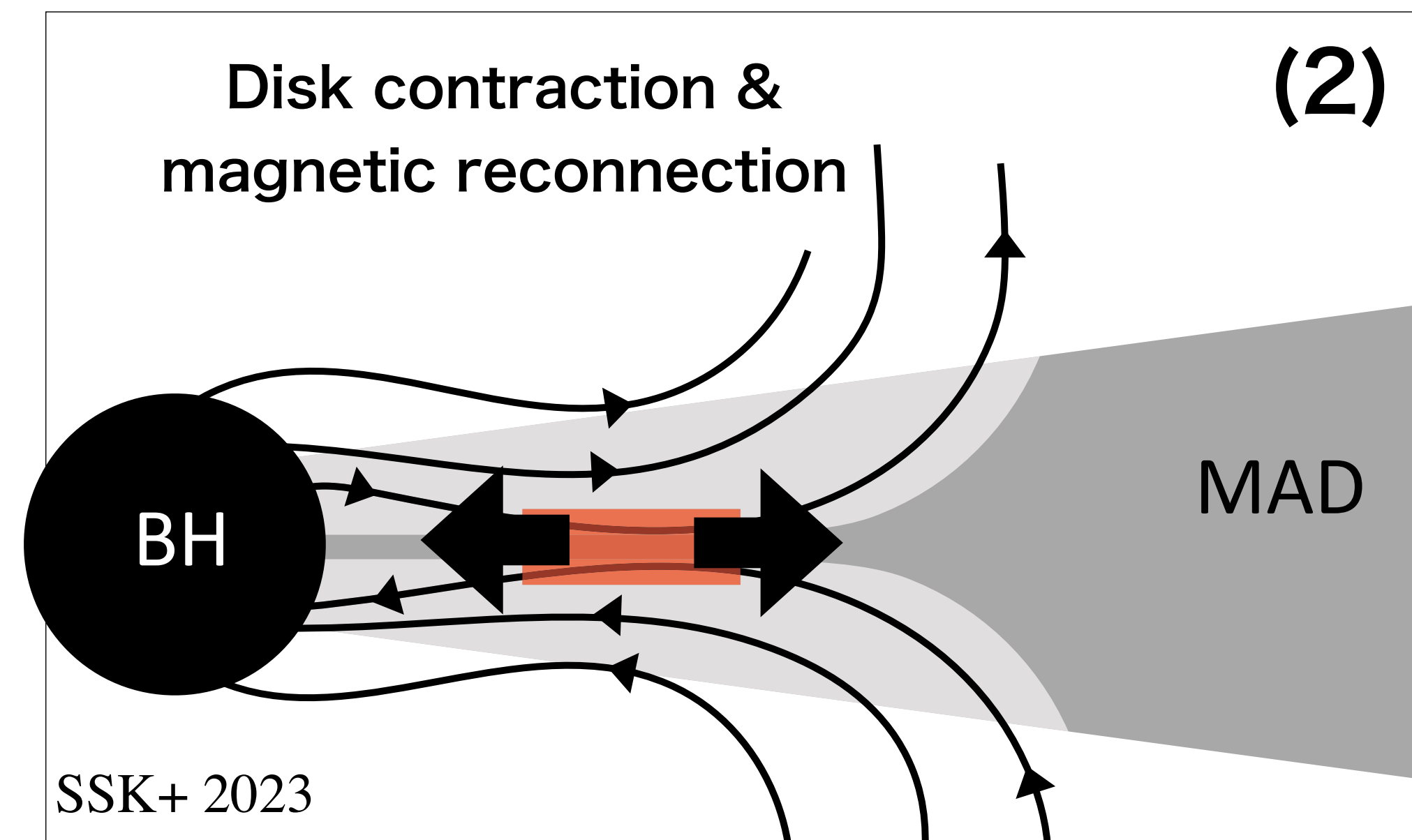
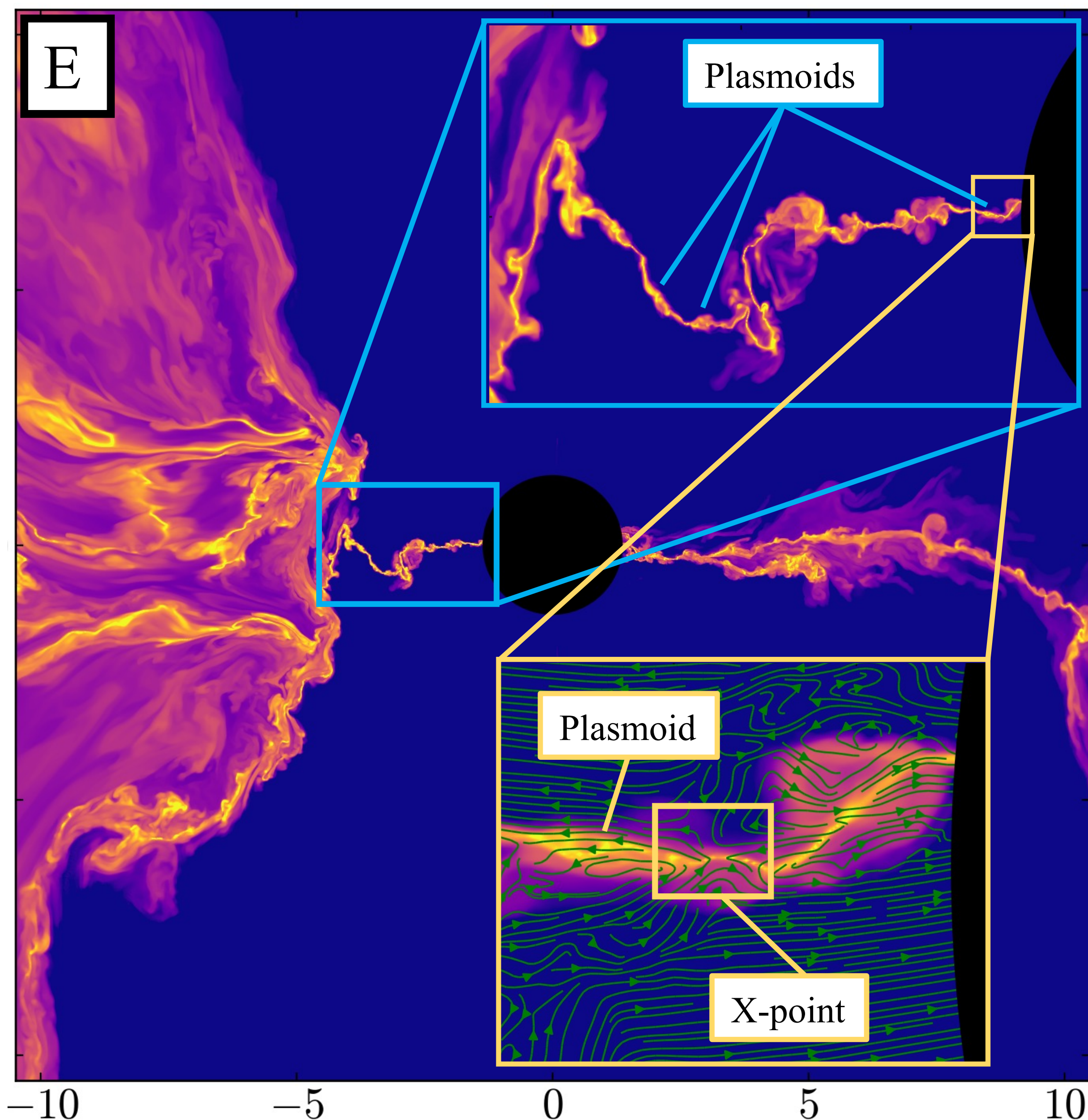
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- Magnetic flux profiles in disk: Power-law
- MAD formation conditions: $\psi_H > \psi_{\text{MAD}}$
- MHD simulations: $P_m \simeq 1 - 5 \Rightarrow$ IBH in molecular clouds likely host MADs!

Magnetic Reconnection in BH Magnetosphere

Ripperda+ 2022



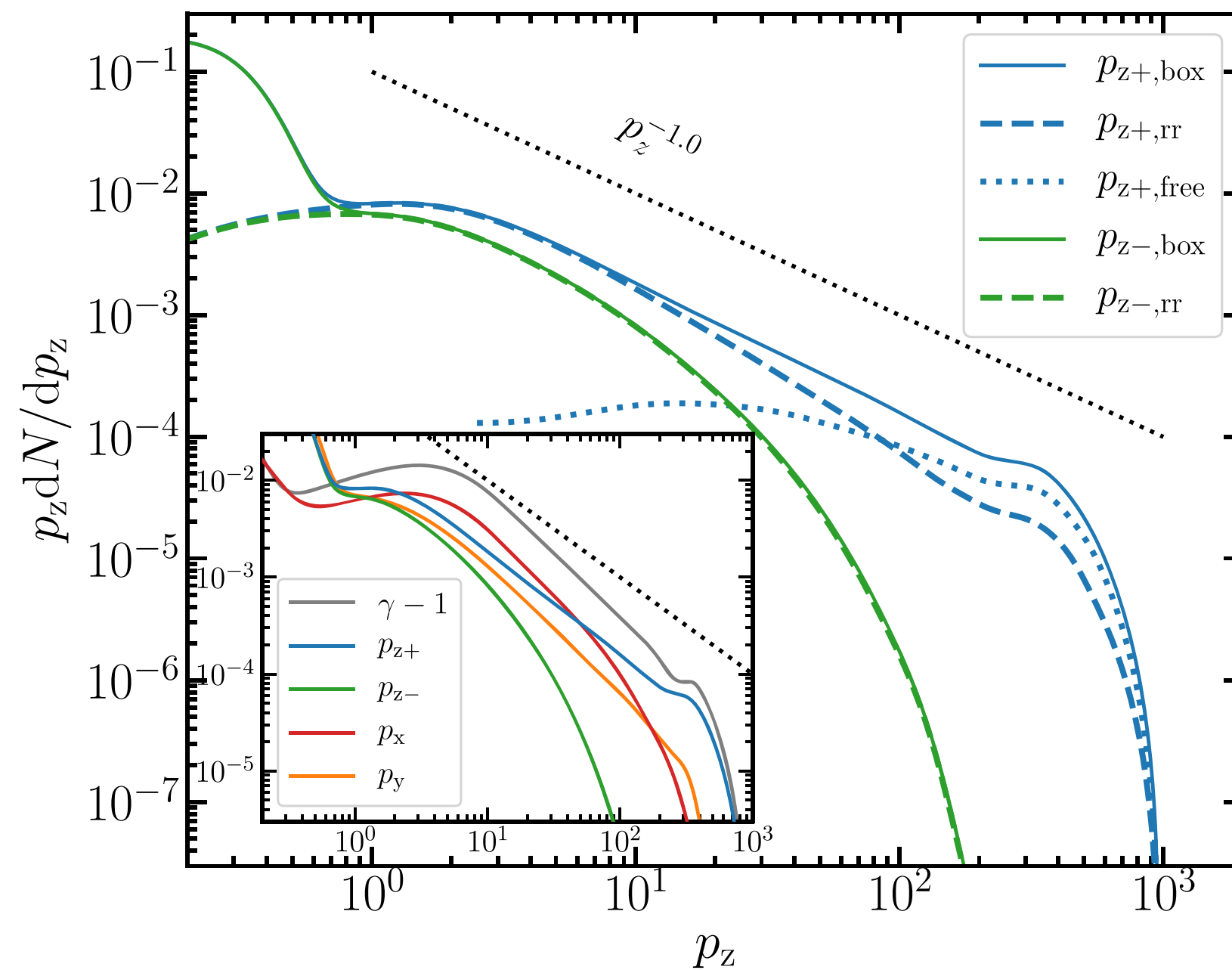
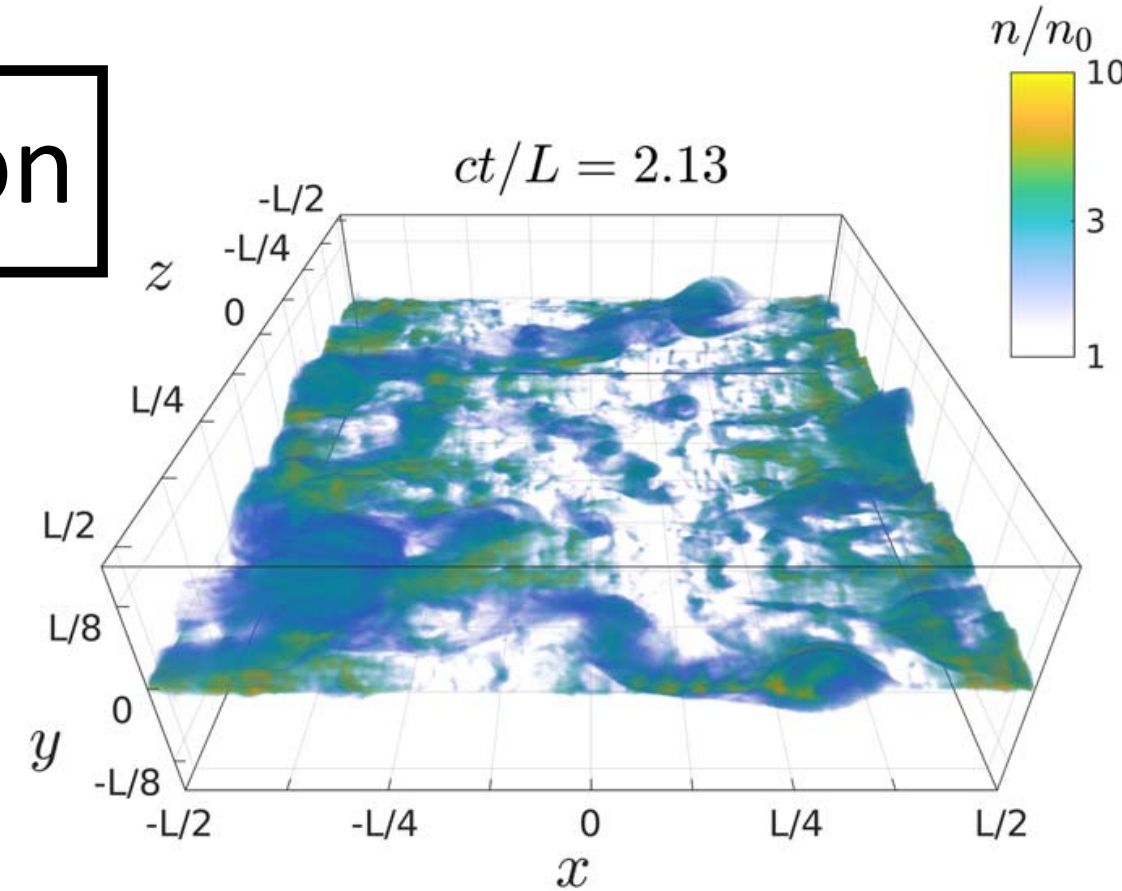
- GRMHD simulations revealed that MADs release its magnetic energy by magnetic reconnection
- Accretion process naturally induces magnetic reconnection at the mid plane
- Reconnection induces turbulence
- MHD instabilities also drive turbulence

Particle Acceleration by Reconnection & Turbulence

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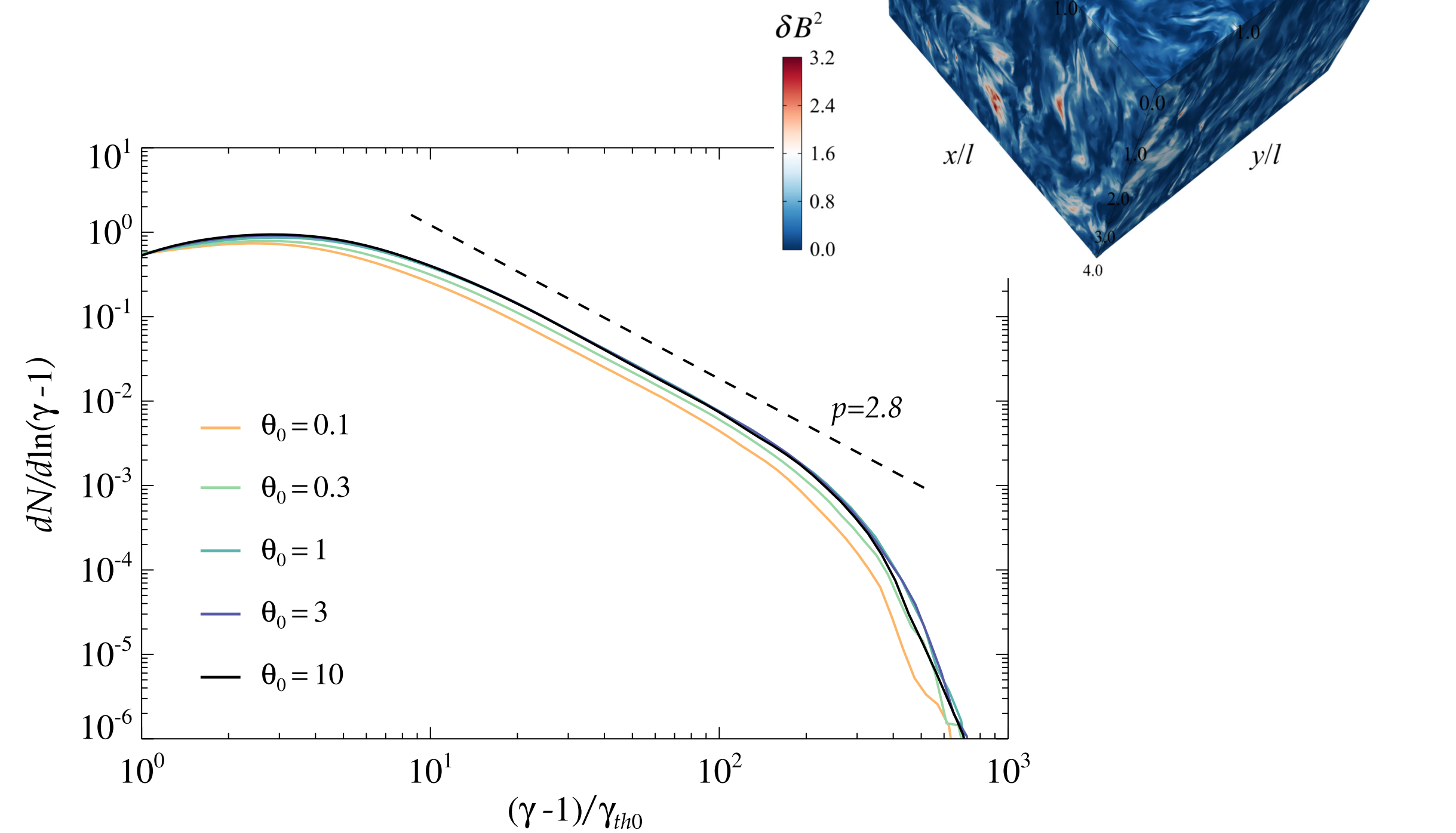
• PIC for reconnection

Zenitani & Hoshino 2001
Sironi & Spitkovsky 2014
Zhang et al. 2021, 2023



• PIC with turbulence

Zhdankin et al. 2018
Comisso & Sironi 2019



See also SSK+ 2019; Sun & Bai 2021 for MHD + test particle simulations

• Reconnection & Turbulence in magnetized plasma lead to power-law distribution

MAD model

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

- Steady-state & one-zone approximation
- Proton-electron plasma
- Thermal & non-thermal components
- Transport equation for non-thermal components:

$$-\frac{d}{dE_i} \left(\frac{E_i N_{E_i}}{t_{\text{cool}}} \right) = \dot{N}_{E_i, \text{inj}} - \frac{N_{E_i}}{t_{\text{esc}}},$$

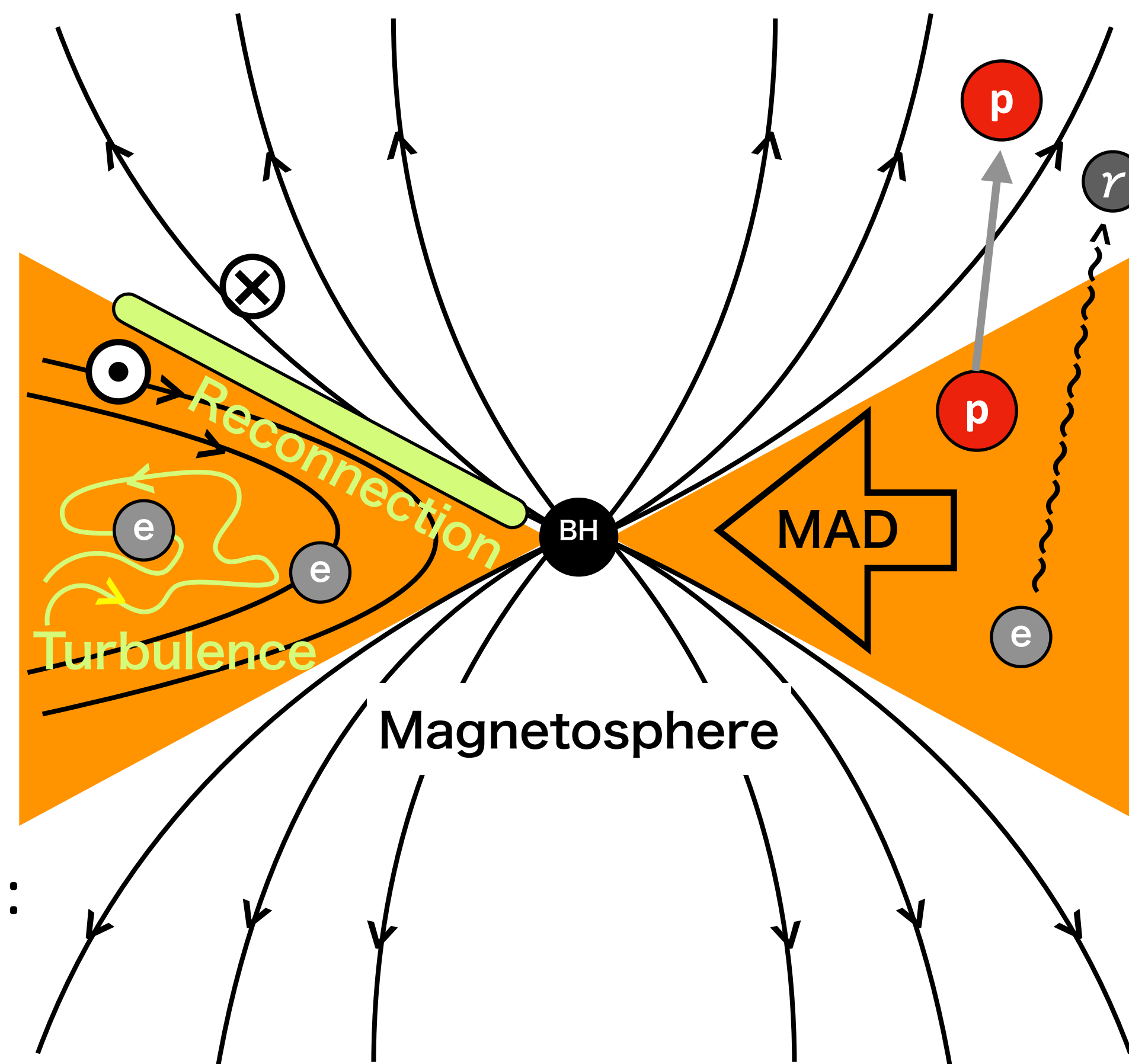
- Reconnection/turbulence produce power-law distribution:

$$\dot{N}_{E_i, \text{inj}} \approx \dot{N}_0 (E_i / E_{i, \text{cut}})^{-s_{\text{inj}}} \exp(-E_i / E_{i, \text{cut}})$$

- Normalization for non-thermal electrons

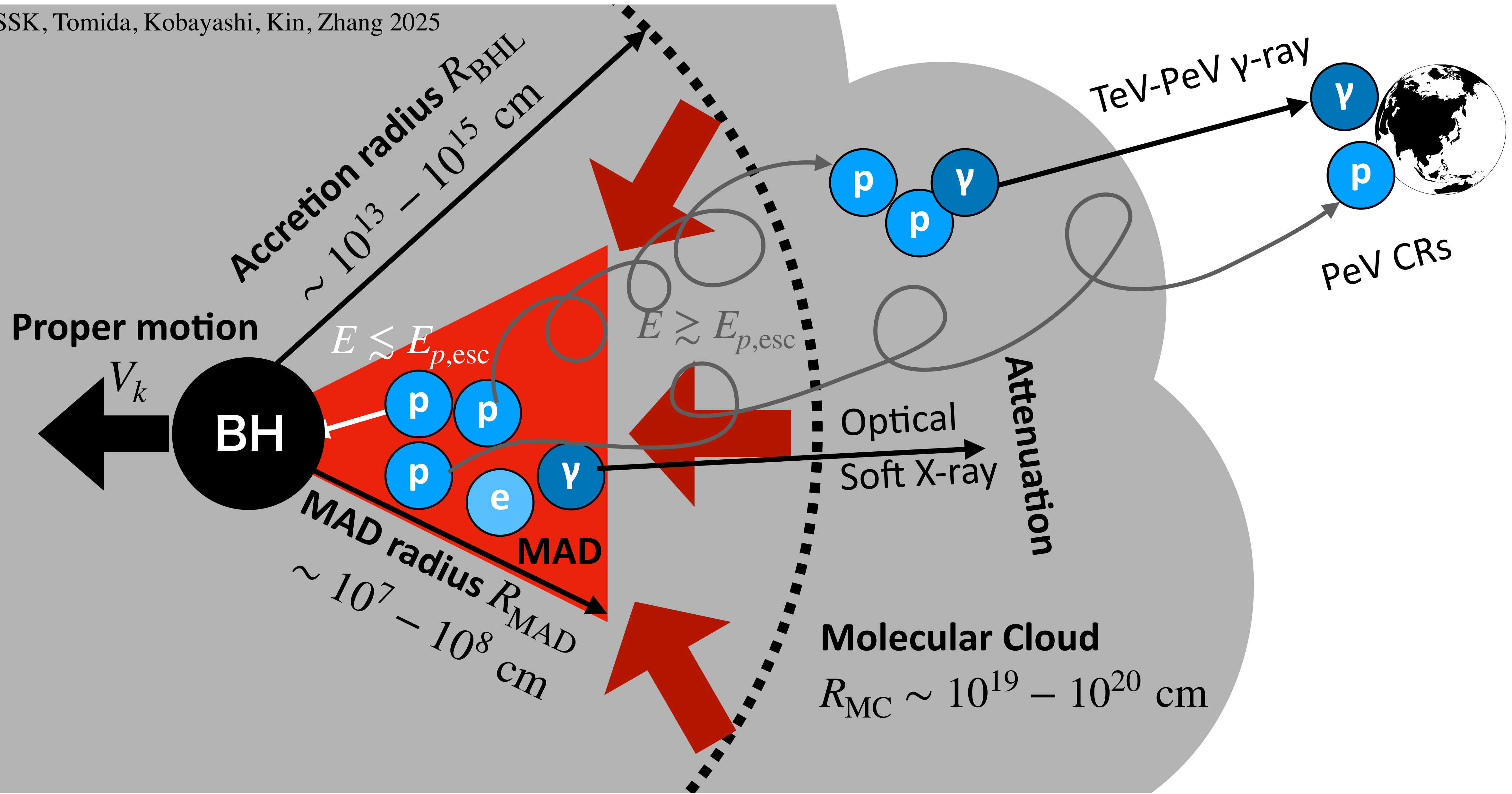
$$\int E_i \dot{N}_{E_i, \text{inj}} dE_i = f_i \epsilon_{\text{NT}} \dot{M} c^2$$

- Synchrotron dominates over the other cooling processes



Schematic picture of our scenario

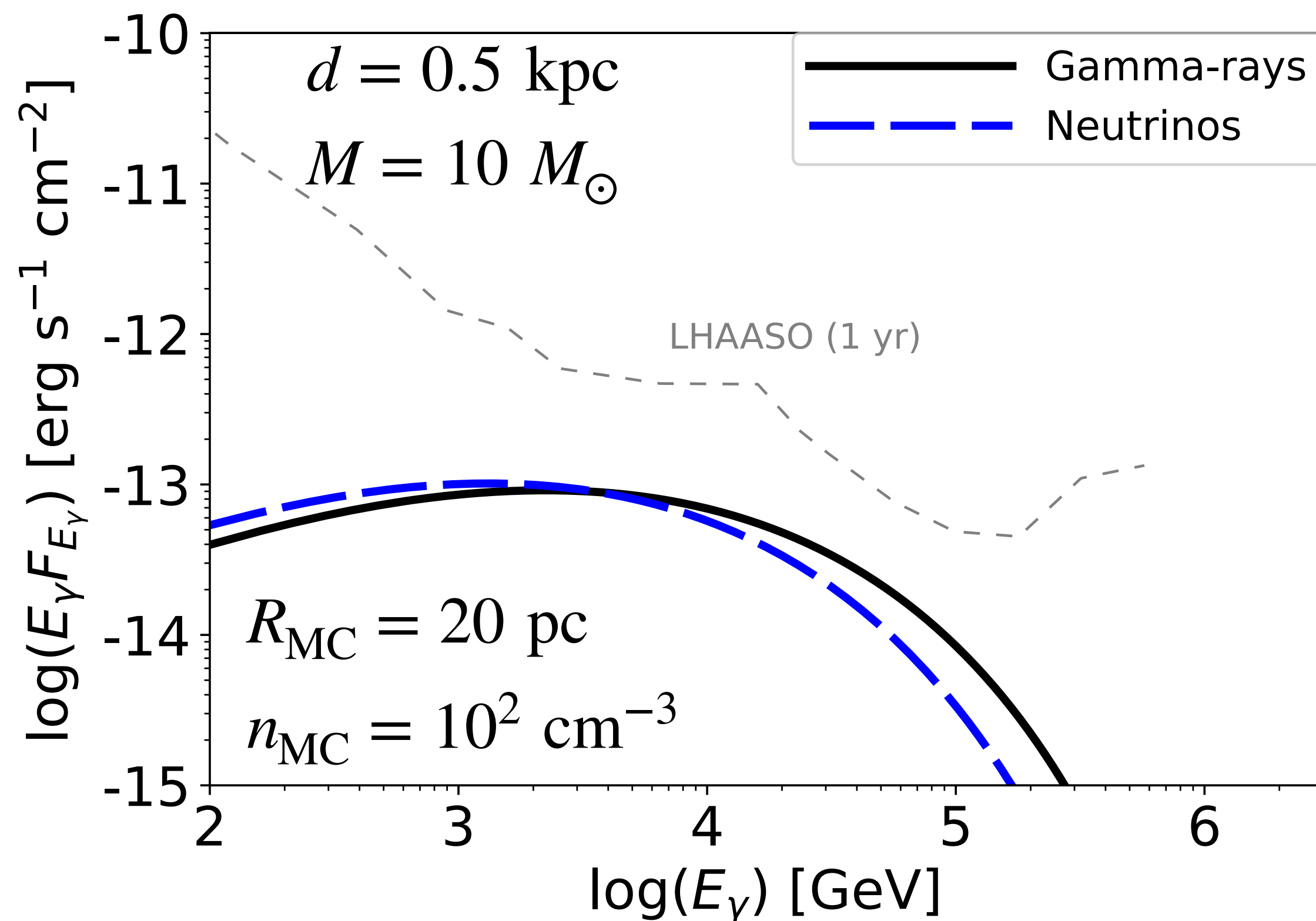
SSK, Tomida, Kobayashi, Kin, Zhang 2025



γ -rays from molecular clouds

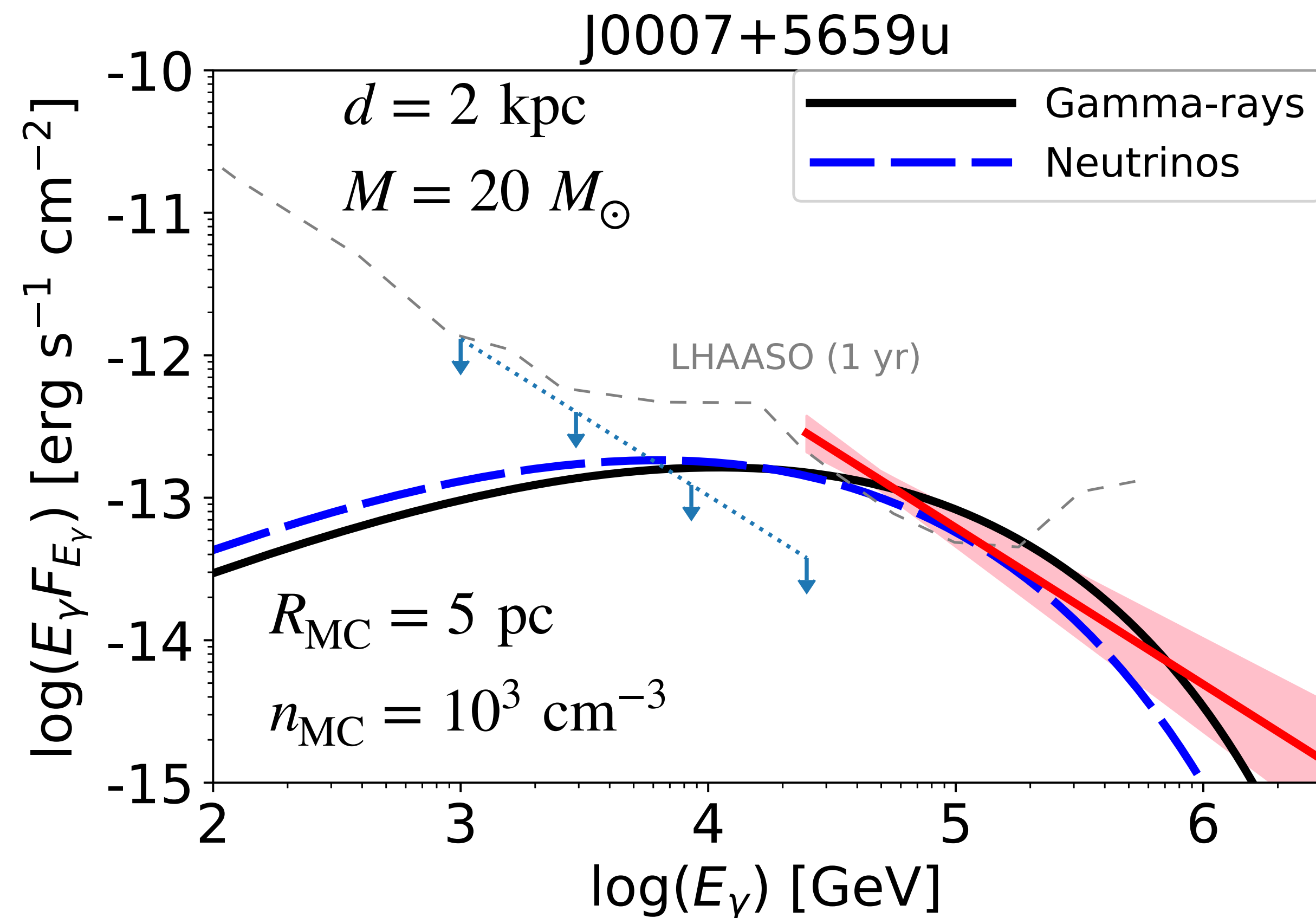
SSK, Tomida, Kobayashi, Kin, Zhang 2025

• Typical environment



- We cannot detect γ -rays with LHAASO
- We cannot expect neutrino detection even with future detectors

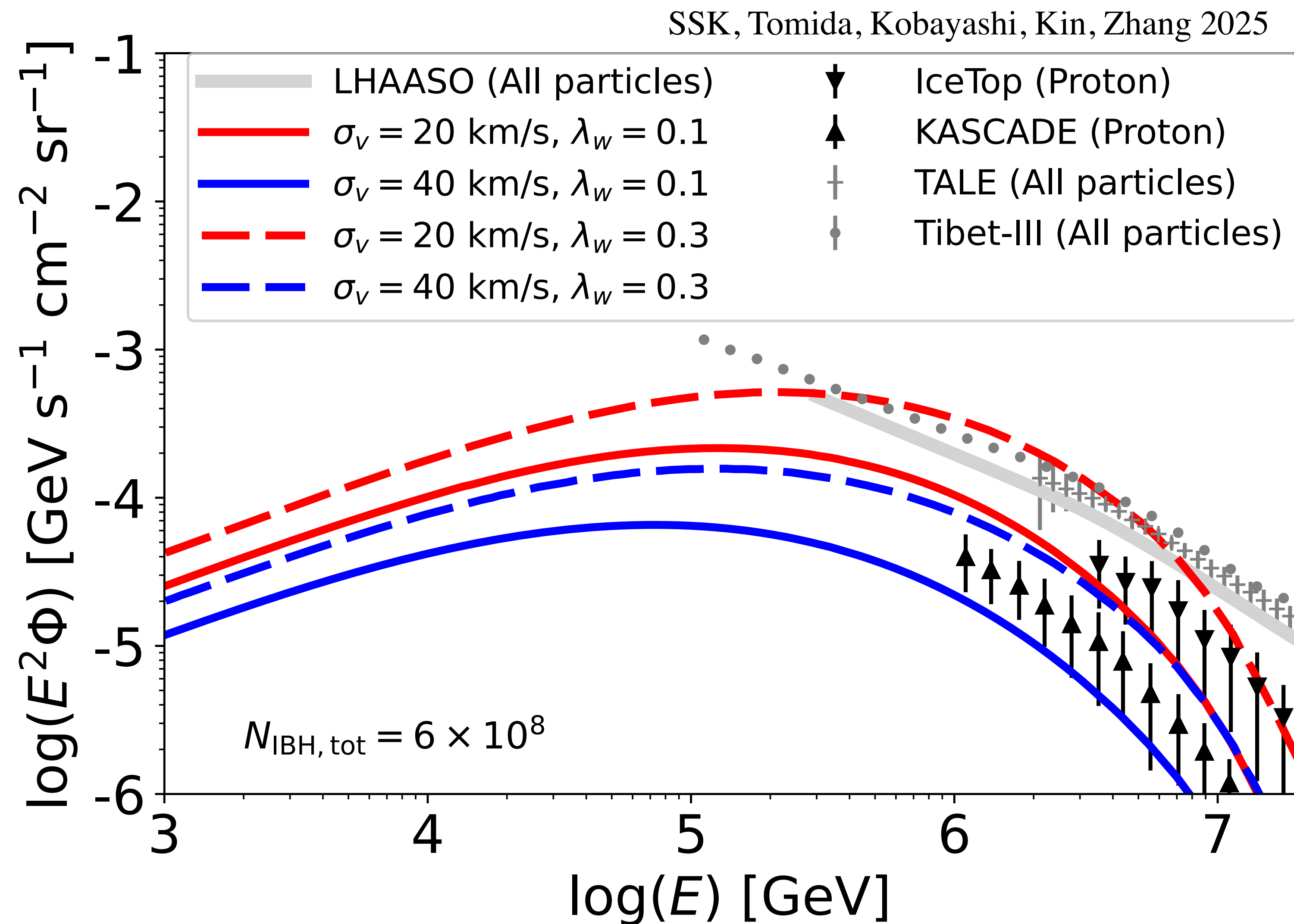
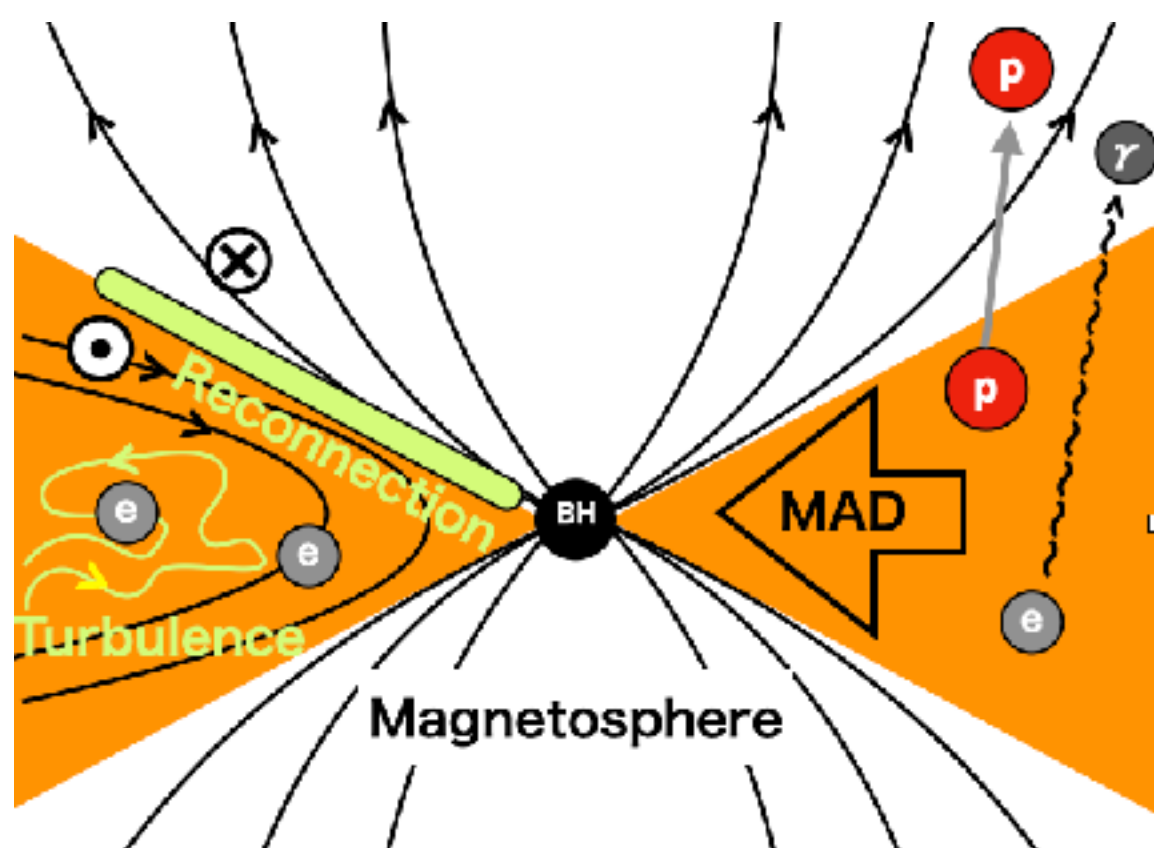
• Optimistic environment



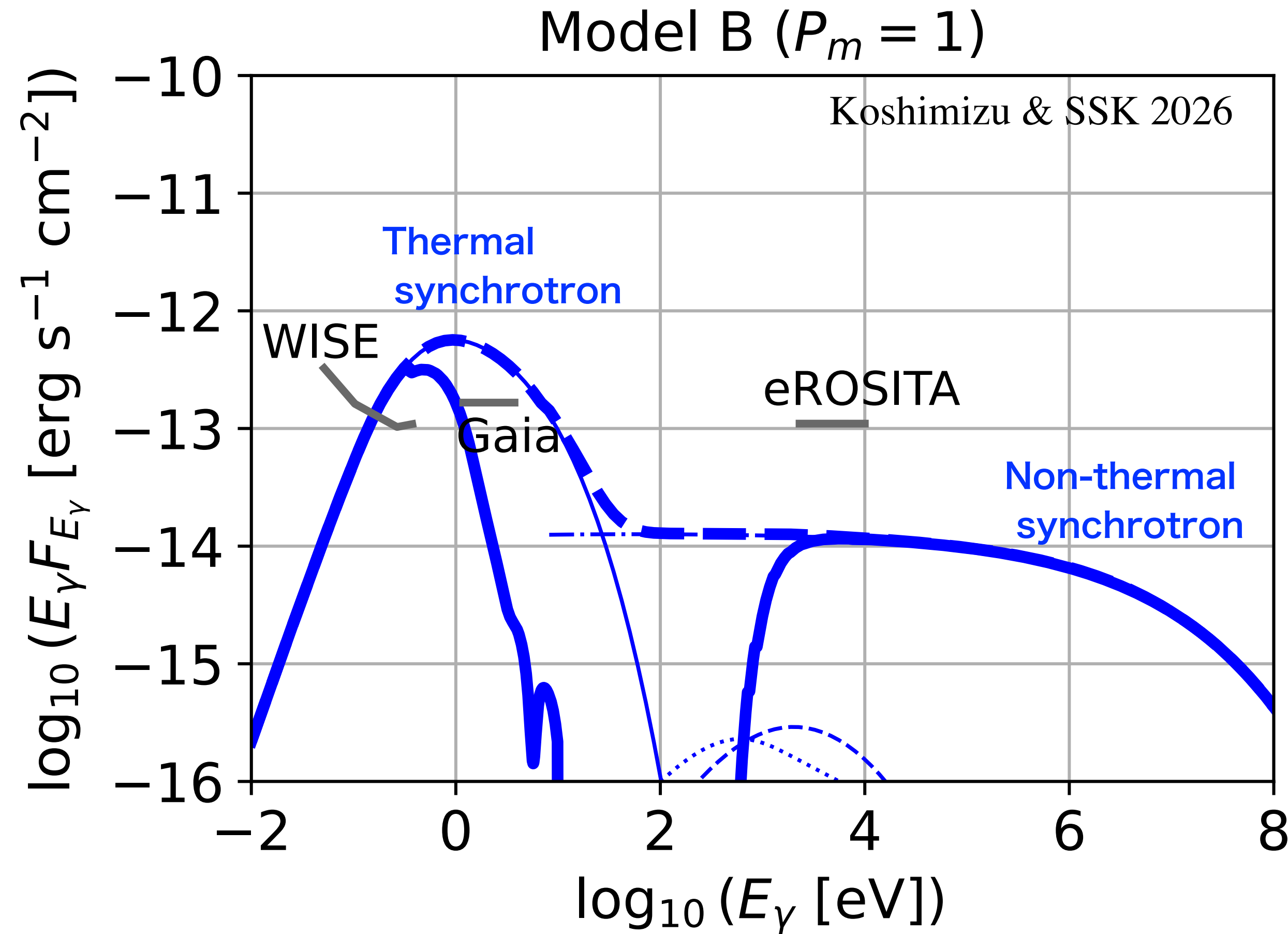
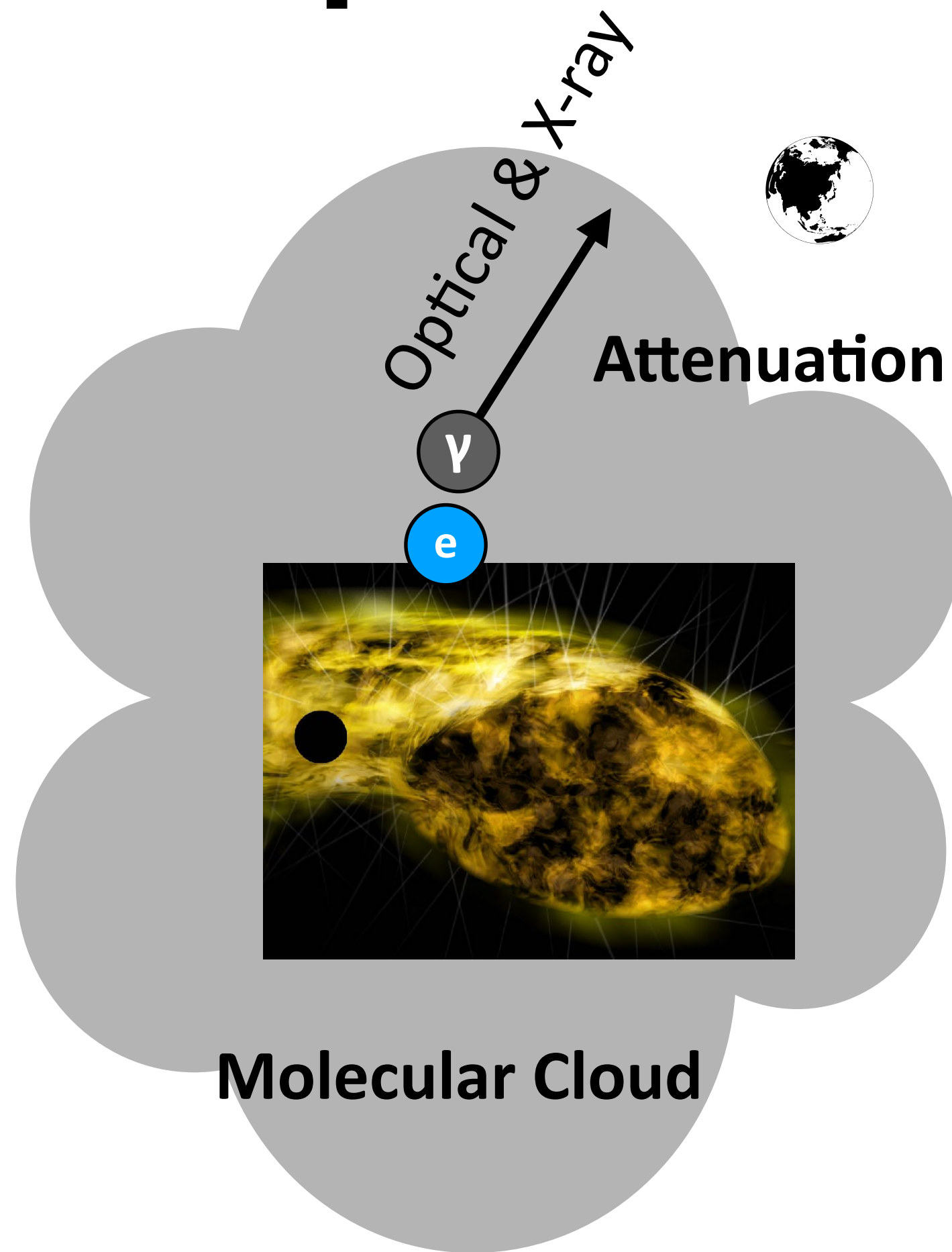
- Our scenario can explain LHAASO data
- Future detectors may be able to detect neutrinos from “dark” sources

IBHs in Molecular Clouds as PeVatrons

- $\sim 10^8$ IBHs in our galaxy
- $\sim 10^5$ IBHs in molecular clouds
- IBHs in molecular clouds can accelerate CRs up to PeV
- Protons accelerated in MADs will escape to ISM
- **They can be source of PeV CRs**



Simple Test: identify IBH using IR & X-rays



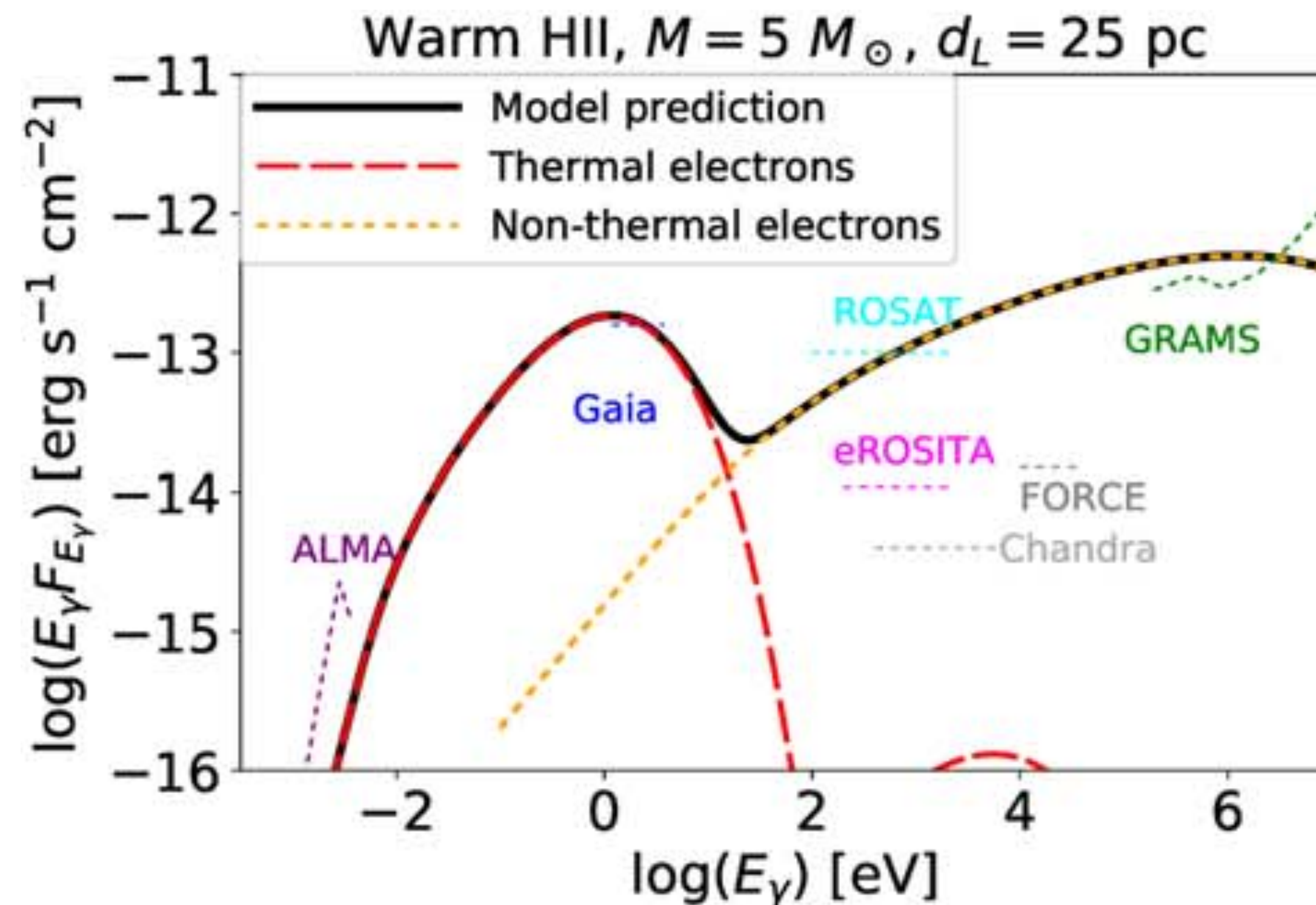
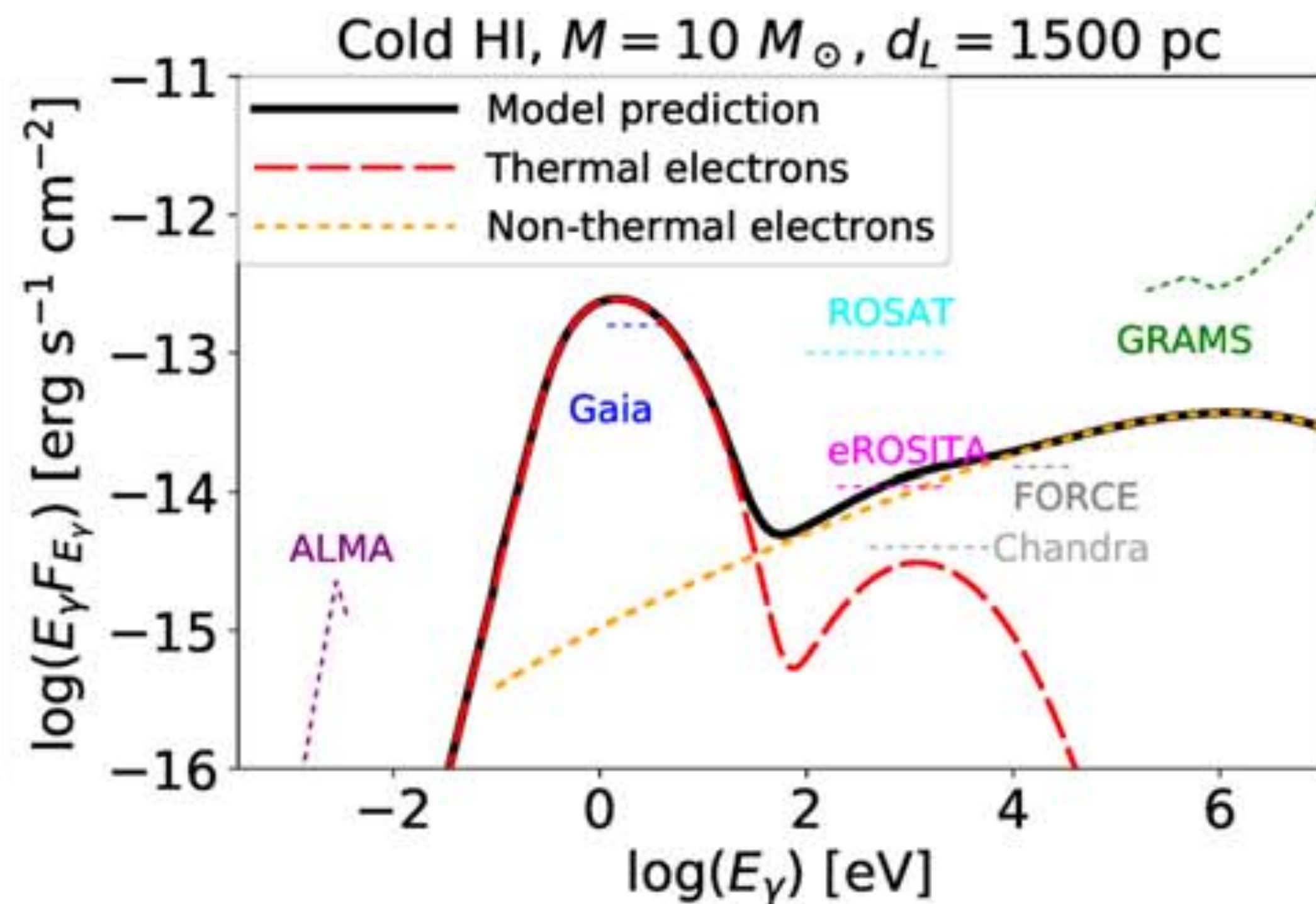
$$N_H \simeq 9 \times 10^{21} \text{ cm}^{-2}$$

$$d = 1 \text{ kpc}$$

- Simple test for our scenario: **observe direct emission from MADs around IBH**
- Extinction [$A_V \simeq 10$, $\exp(-\tau_{1 \text{ keV}}) \simeq 0.02$] $\rightarrow$ **Hard X-ray ($> \text{keV}$) is necessary**
- Contamination by protostars & background AGN $\rightarrow$ **challenging to identify IBHs in MC**

Future test of our scenario: identification of IBH

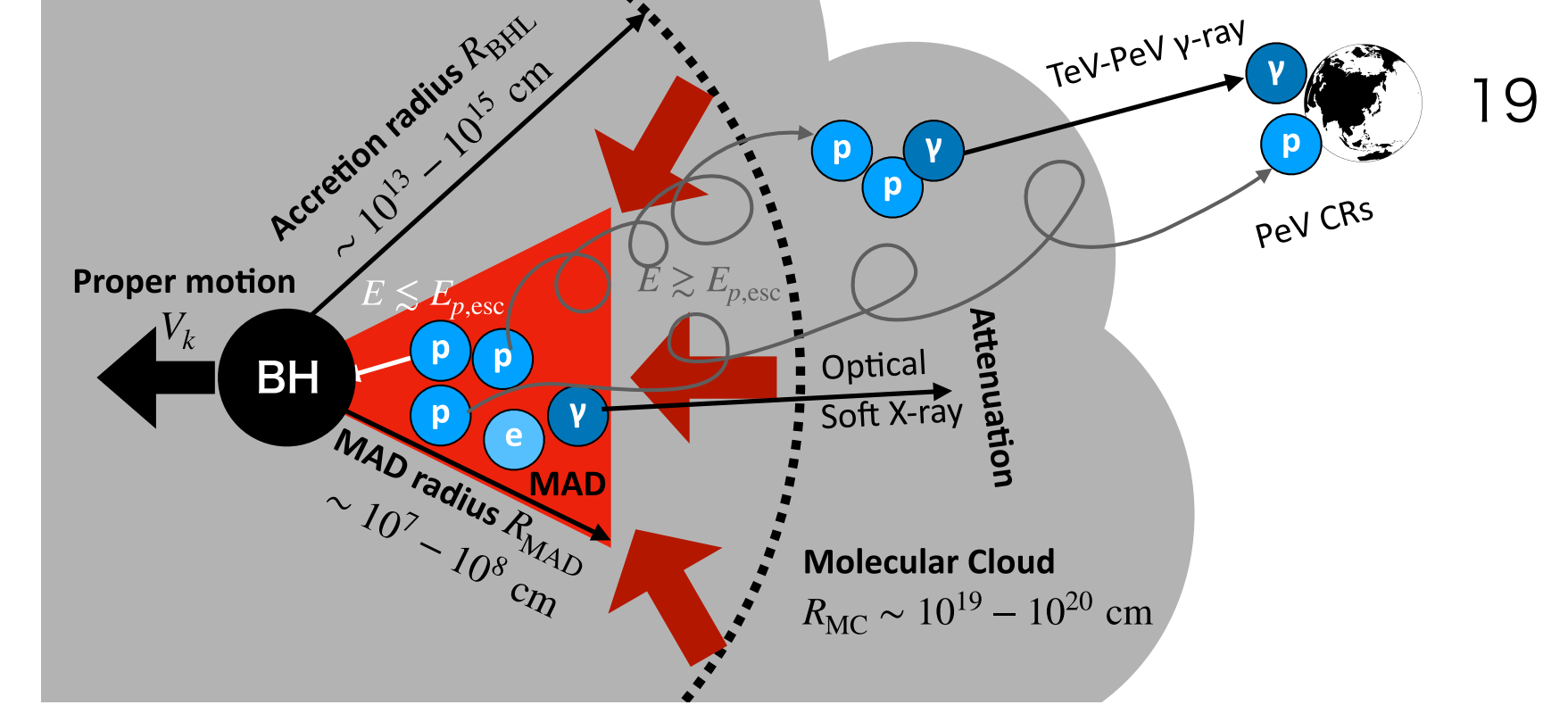
SSK, Kashiya, Hotokezaka 2021



- Photon spectra from IBHs: bright in optical & X-rays
- X-ray by eROSITA & Optical by Gaia satellites
=> possibly able to identify IBHs using the data
- Our proposals for IBH search are accepted by Seimei telescope
Please stay tuned

Summary

- Origins of PeV cosmic rays (PeVatrons) are still under debate.
- Magnetic reconnection & turbulence in MADs can efficiently accelerate non-thermal particles
- **Isolated black holes embedded in molecular clouds can be PeVatrons**
 - **γ -rays from molecular clouds might be potential origin of “dark” LHAASO sources**
 - Isolated black holes can power PeV cosmic rays observed on Earth
- Multi-wavelength follow-up to LHAASO sources provides robust test to our model



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