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

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References

SSK, Sudoh, Kashiyama, Kawanaka, 2021, ApJ, 915, 31
SSK, Kashiyama, Hotokezaka, 2021, ApJL, 922, L15
Kuze, SSK, Fang, 2025, ApJ submitted (arXiv:2501.17467)
SSK, Tomida, Kobayashi, Kin, Zhang, 2025, ApJL, 981, L36

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2nd LHAASO Symposium 2025/03/20 — 2025/03/25

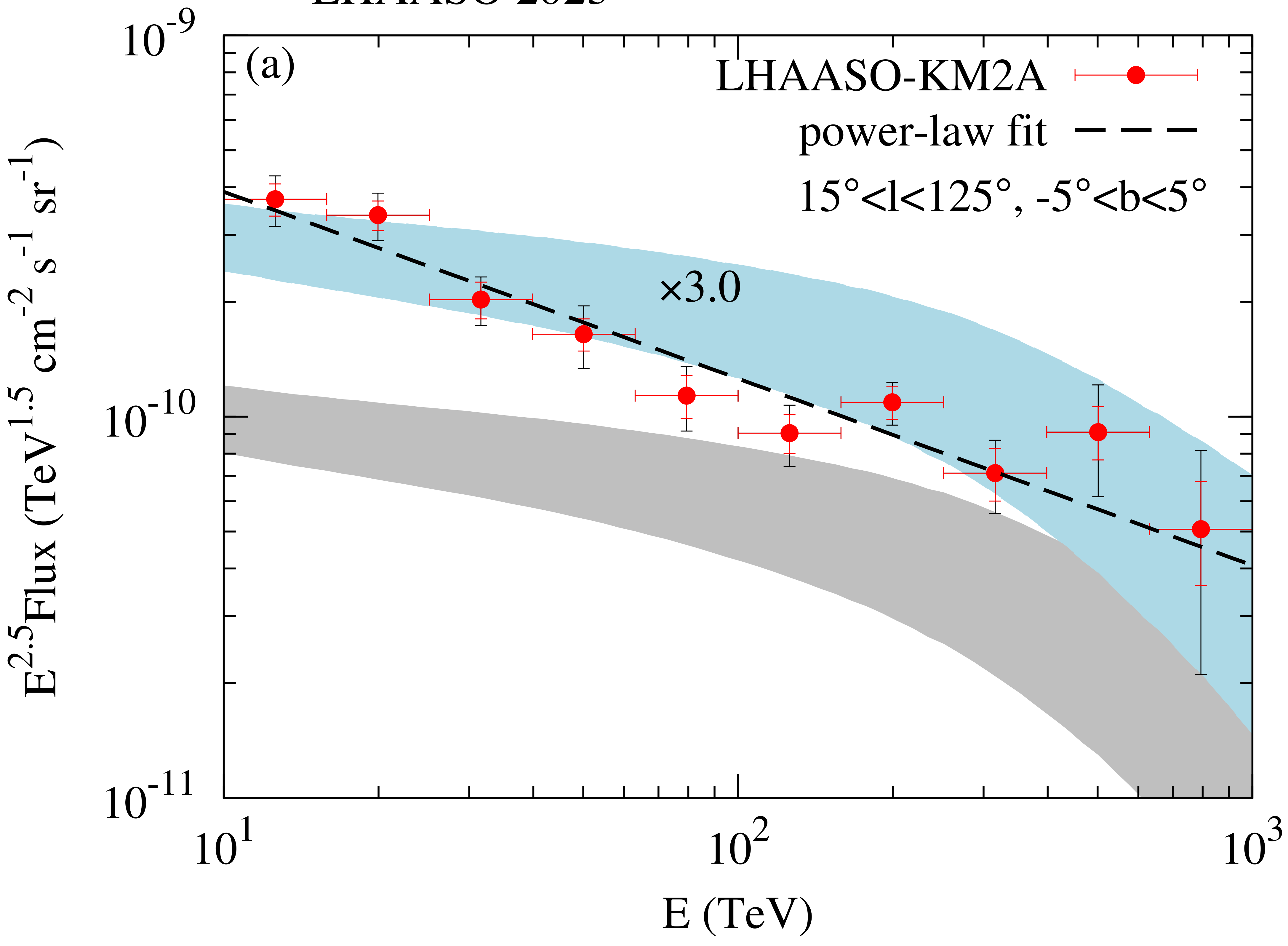
Index

- Galactic PeVatrons & black hole accretion flows
- Galactic black holes as PeVatron candidates
  - X-ray binaries
  - Isolated black holes
- Summary

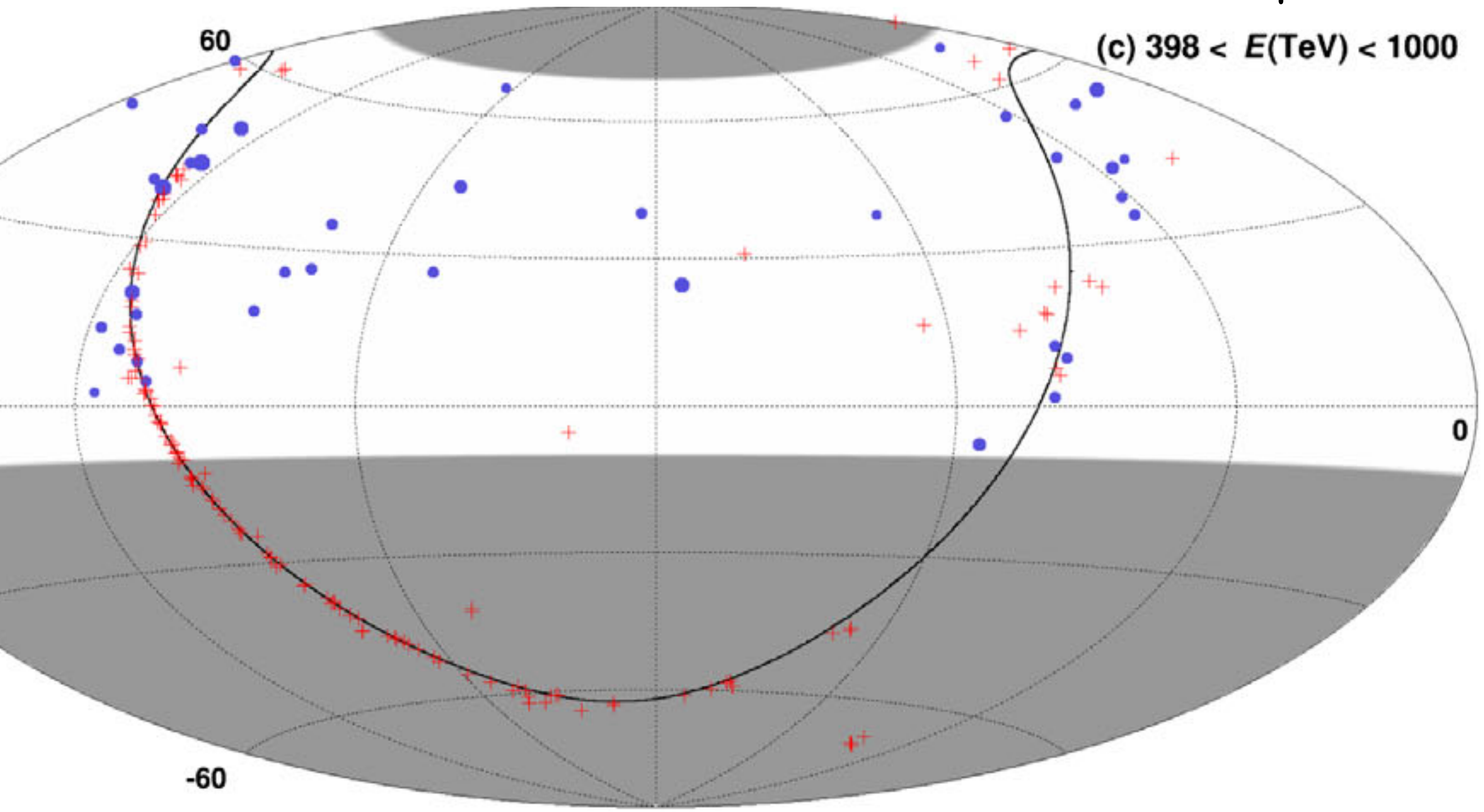
Galactic PeVatrons

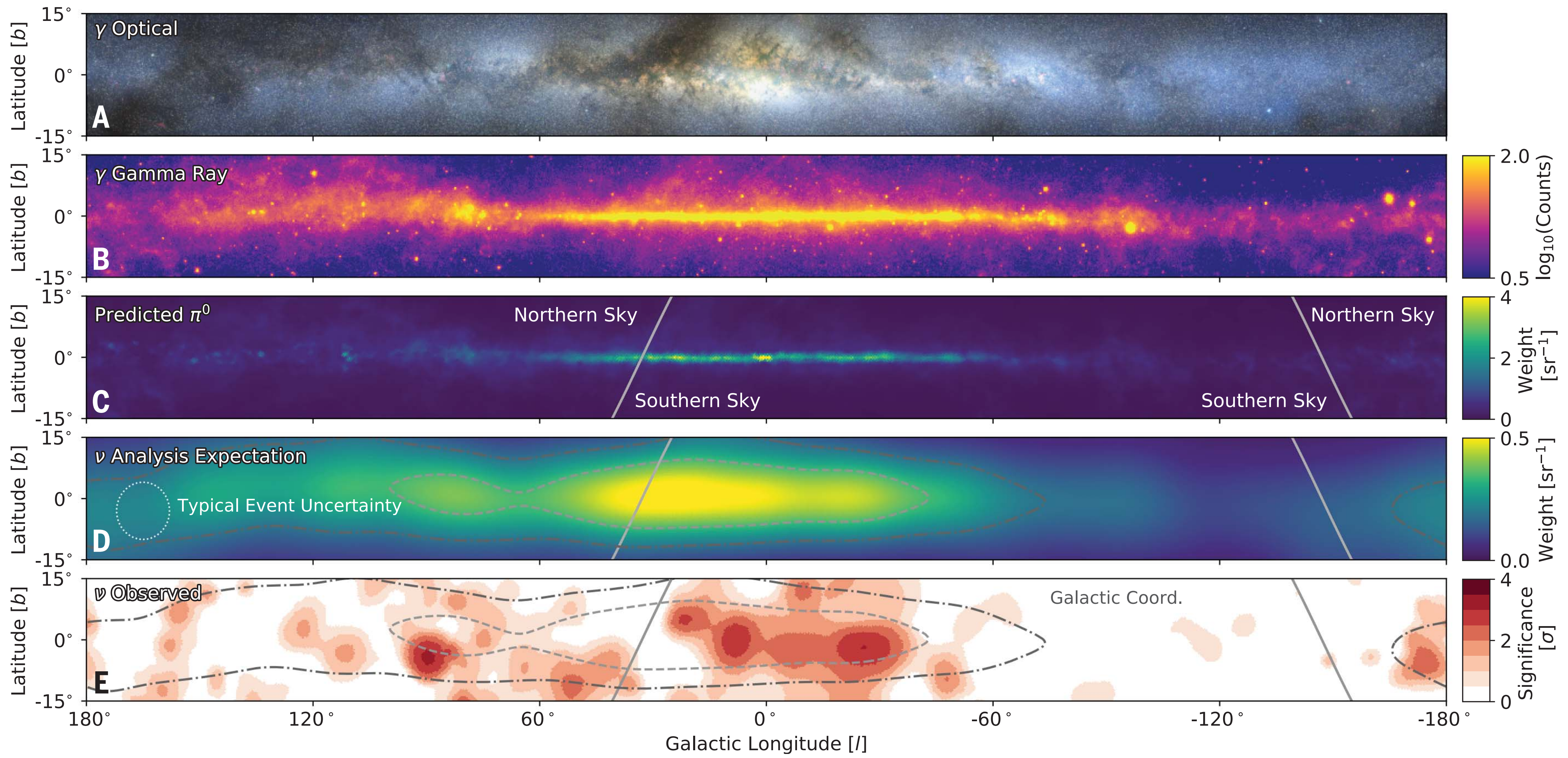
- Origins of PeV CRs are unknown
- Tibet ASγ detected sub-PeV γ rays from Galactic plane
- LHAASO detected diffuse γ-rays in 0.01 - 1 PeV
- IceCube detected neutrinos from Galactic plane
- **Strong evidence of Galactic PeVatron**

LHAASO 2023



Tibet ASγ 2021

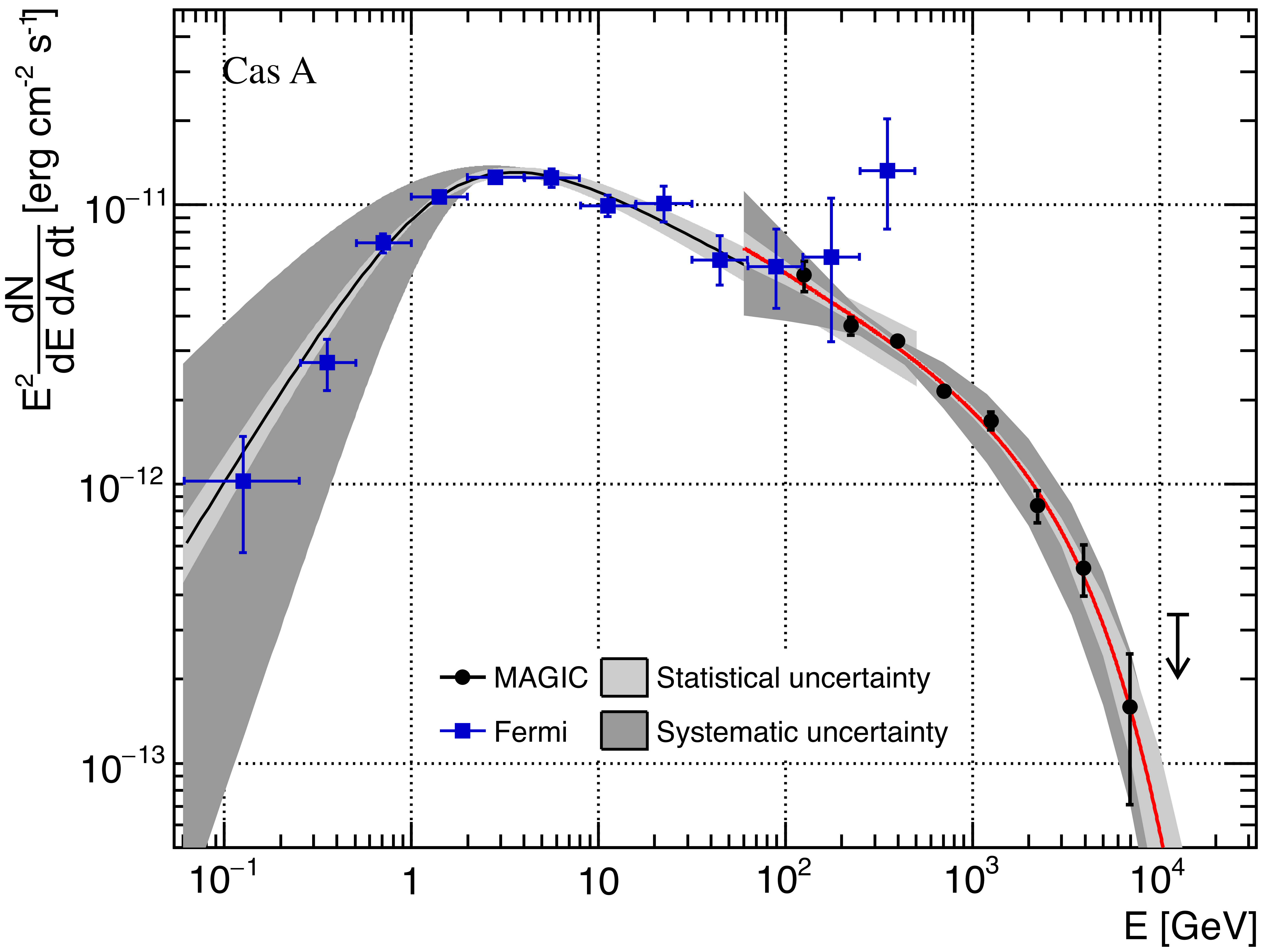




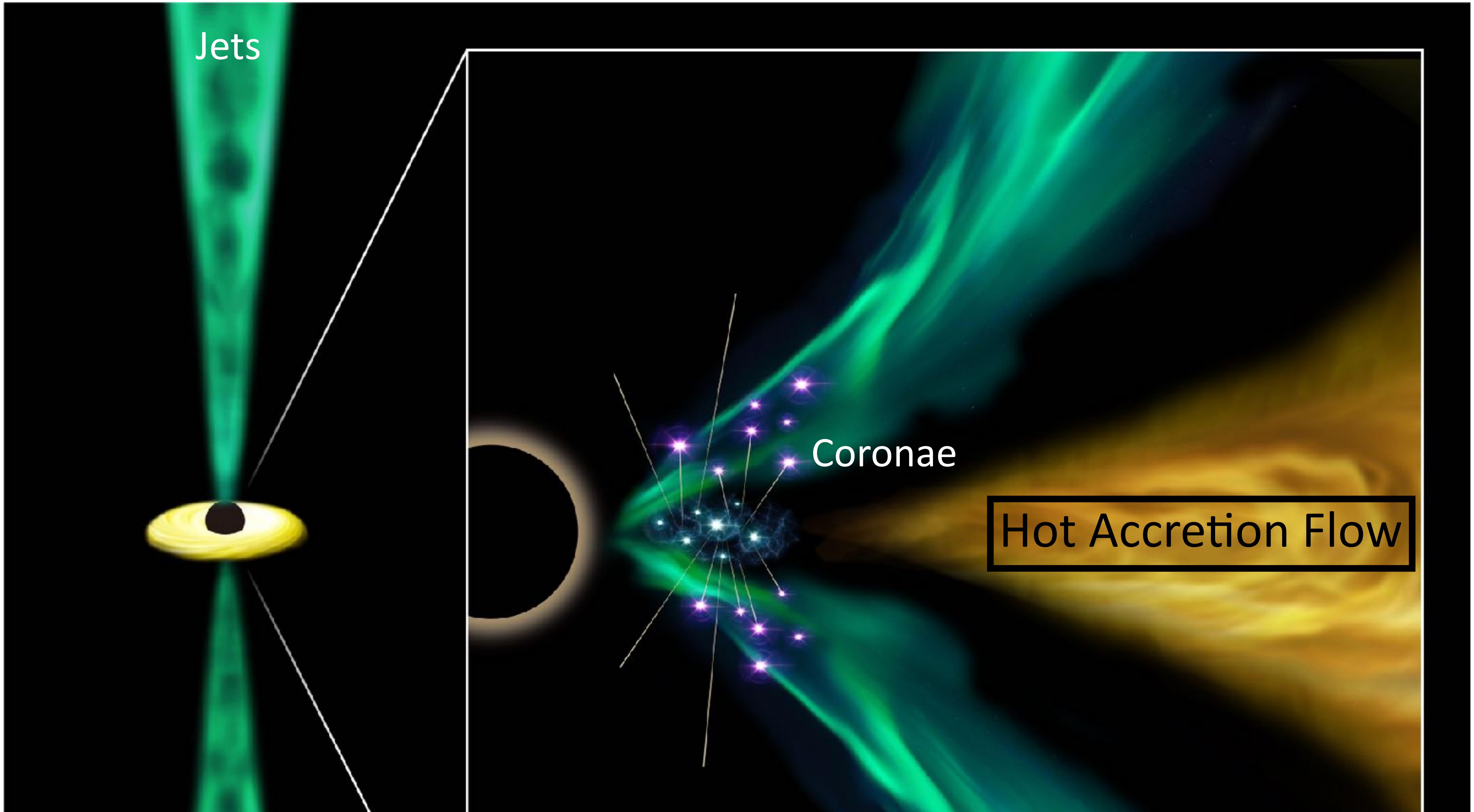
SNR as origin of PeV cosmic rays?

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

MAGIC 2017

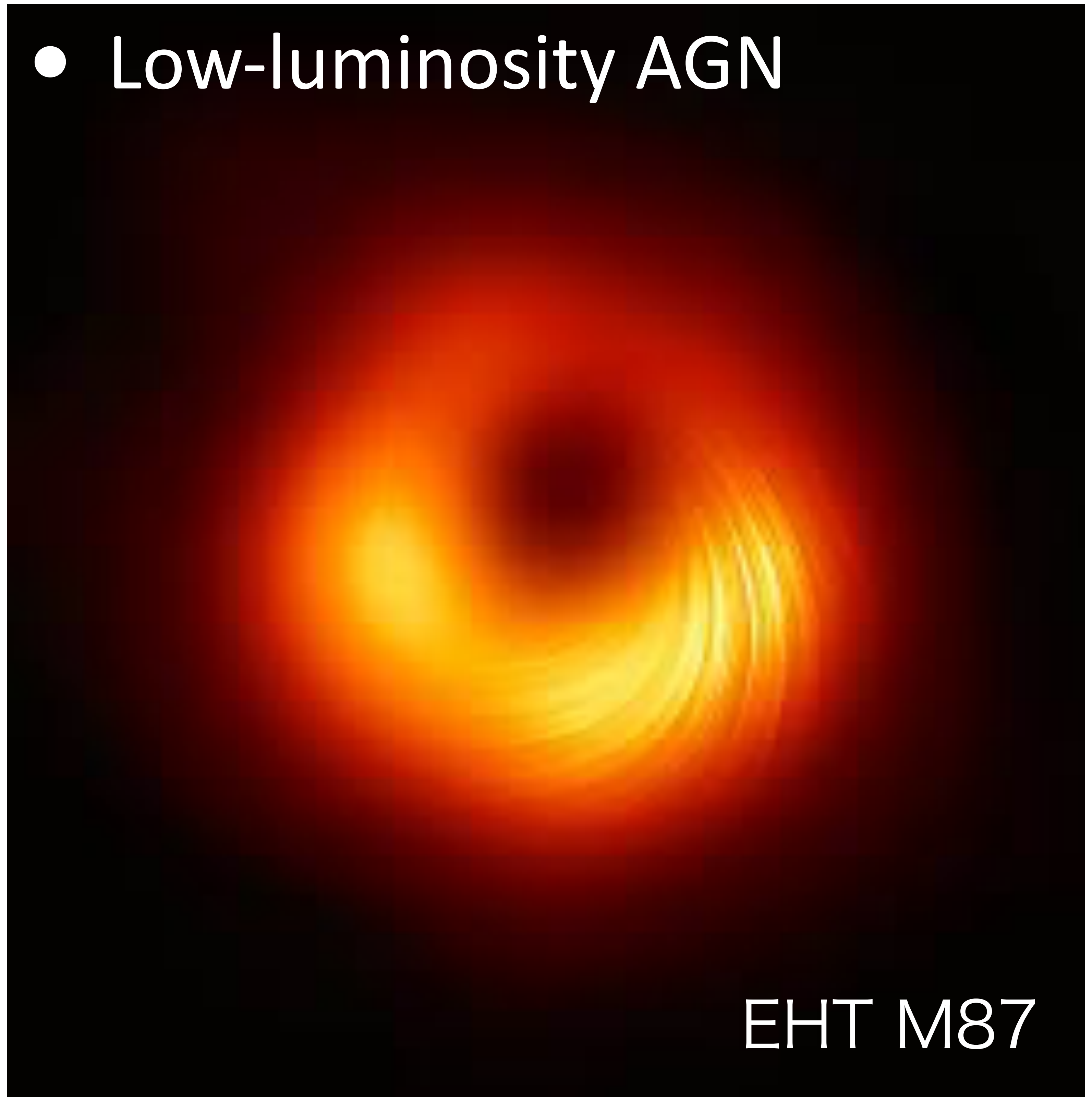


Stellar-mass Black Holes as PeVatrons

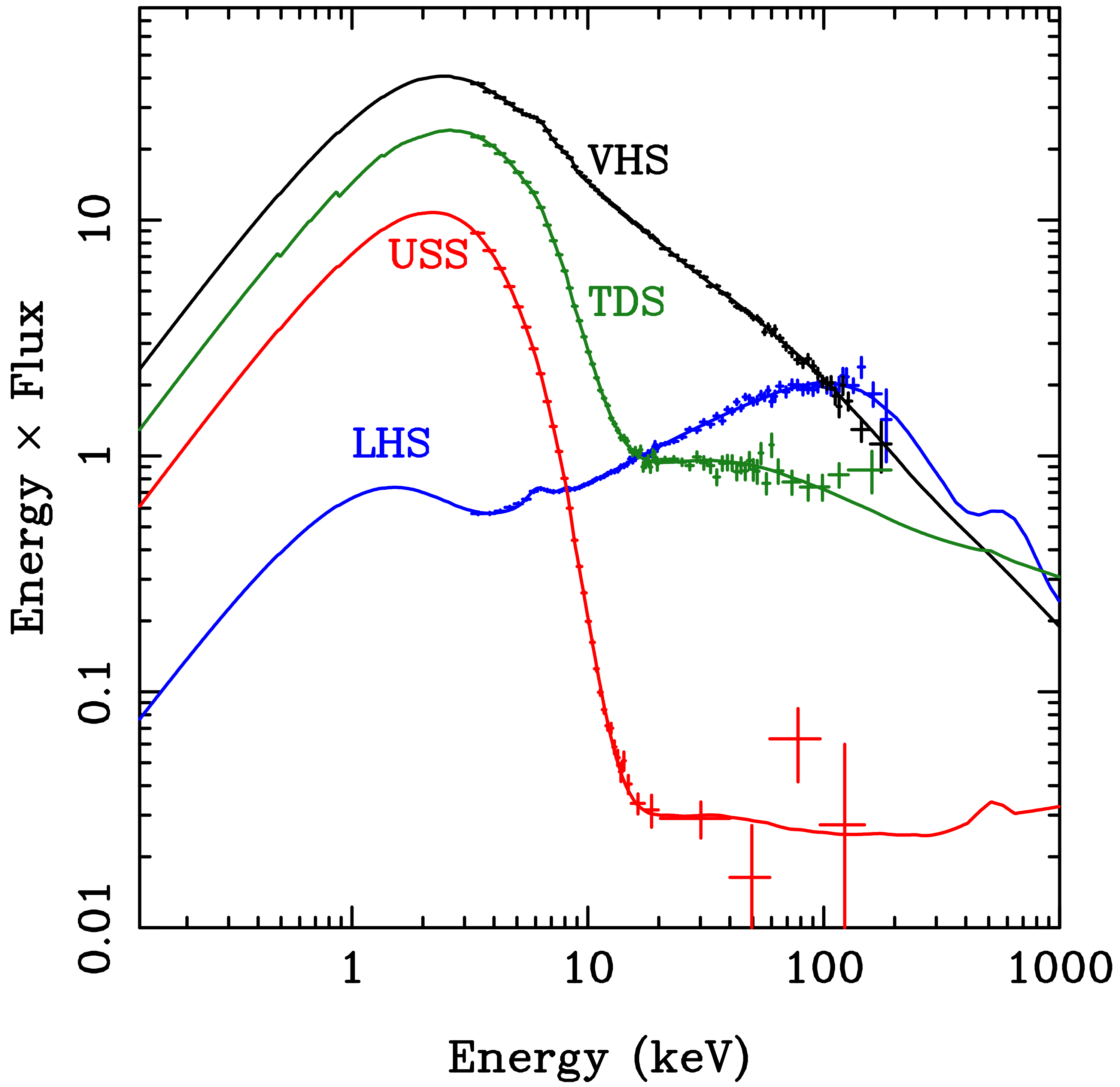


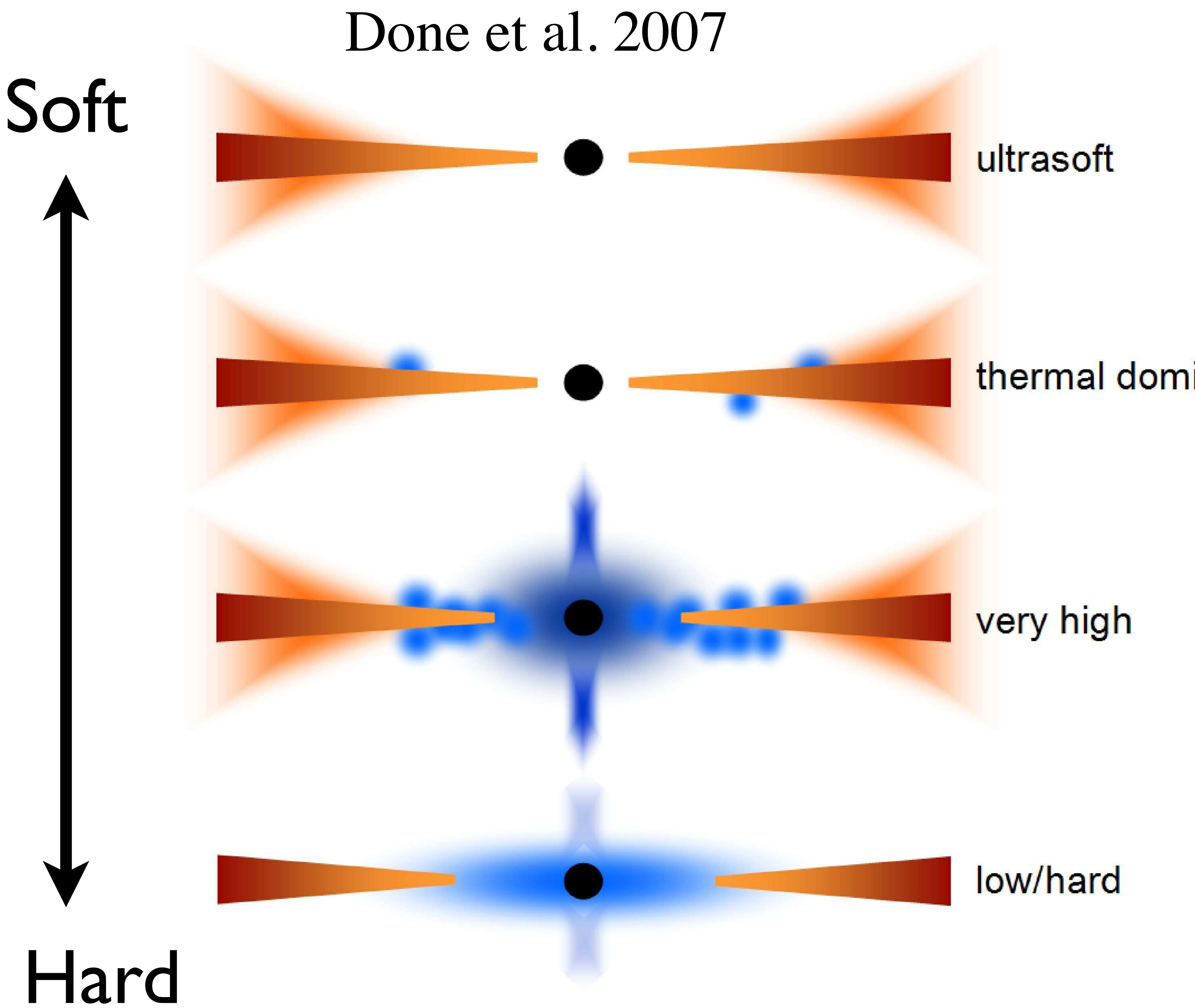
RIAFs around Black Holes

- Low-luminosity AGN



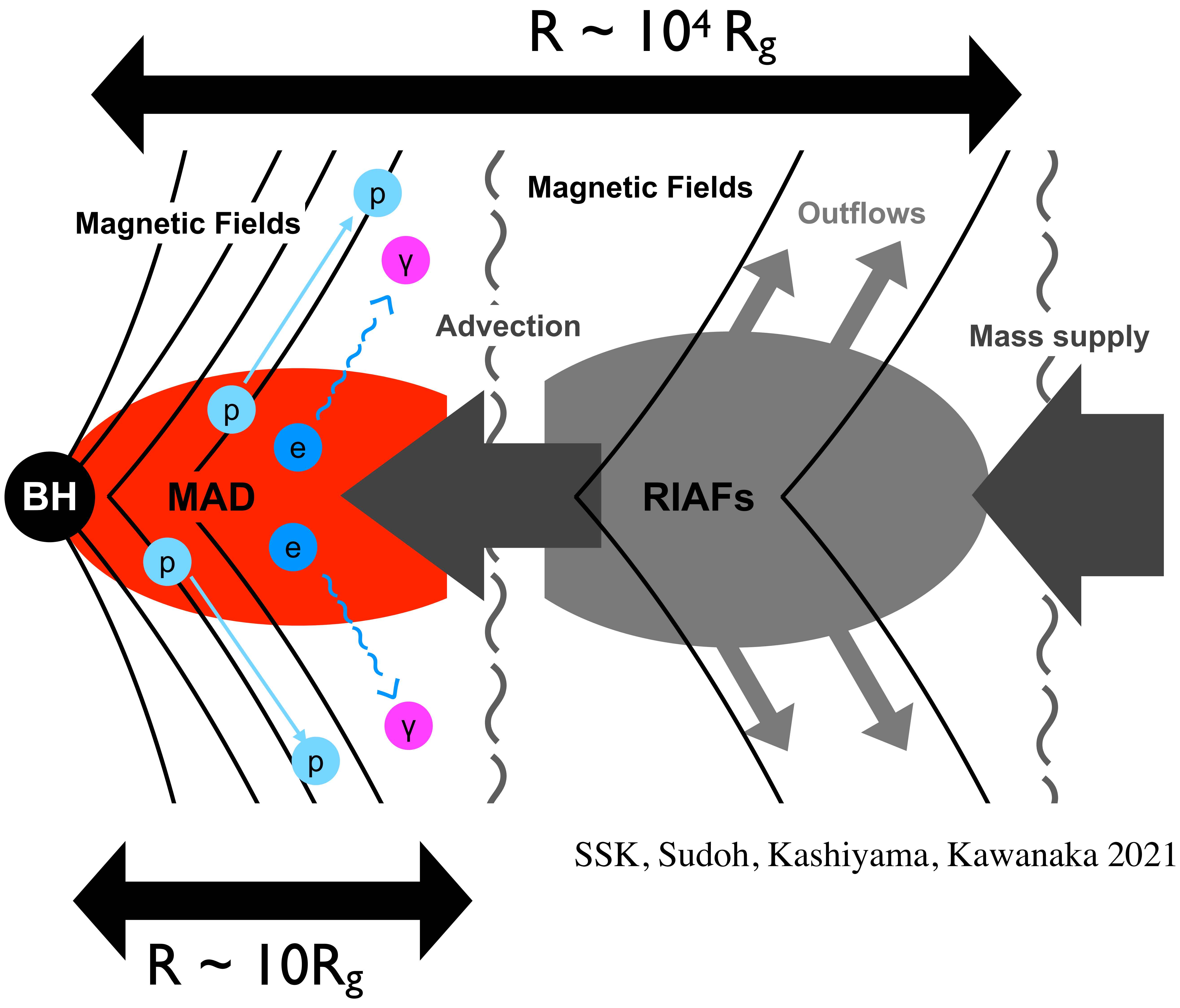
- X-ray binaries





- 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

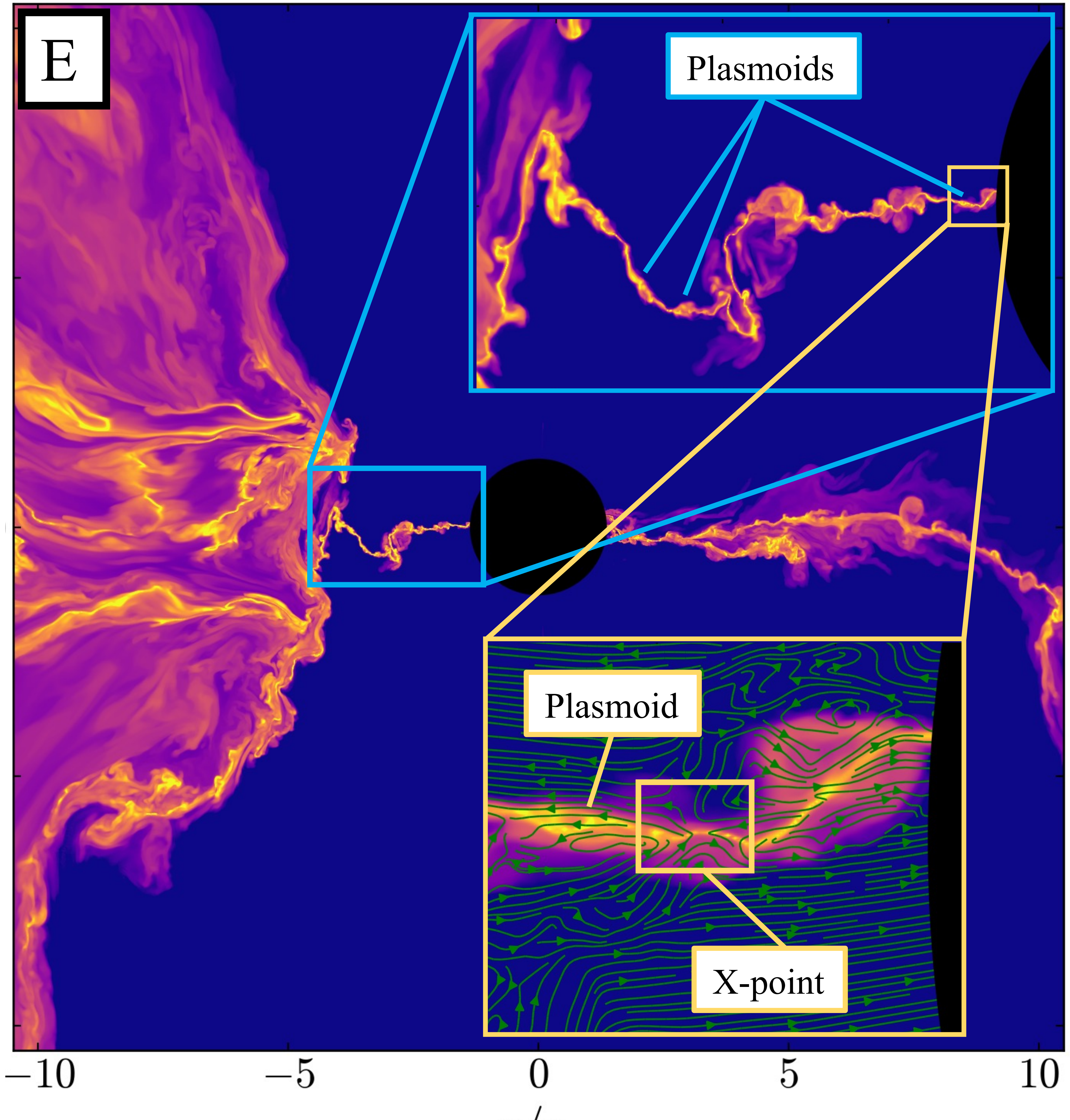


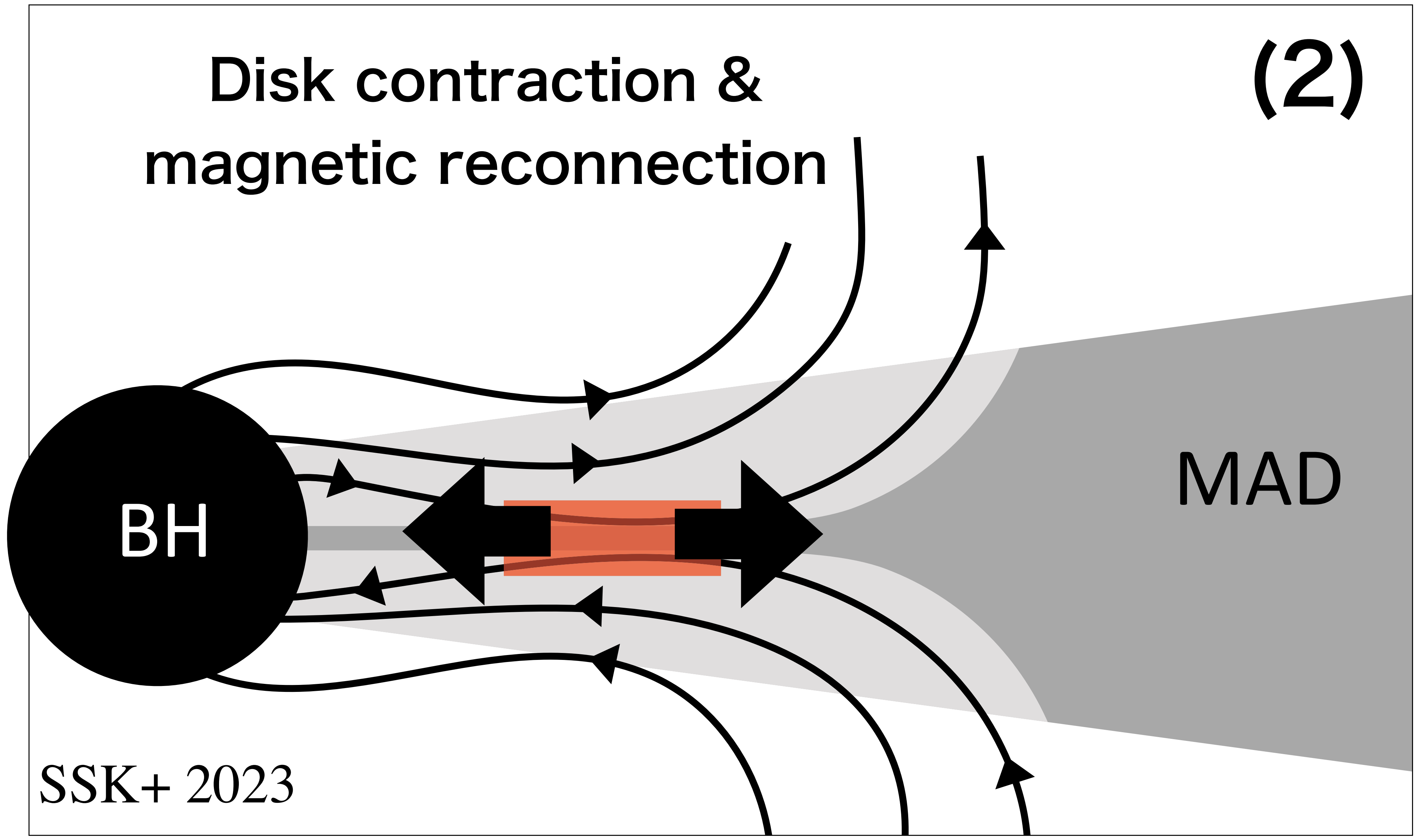
SSK, Sudoh, Kashiyama, Kawanaka 2021

- Low accretion rate e.g. Esin et al. 1997
  → Radiatively inefficient accretion flow (RIAF)
- Comparison of infall and cooling timescales
  → truncation radius R_{trn} ~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: $\beta_p \propto R^{-1.5} - R^{-2}$
  →$\beta < 1 @ R \lesssim 10R_g$
  → **Formation of Magnetically Arrested Disk (MAD)**

Magnetic Reconnection in BH Magnetosphere

Ripperda+ 2022



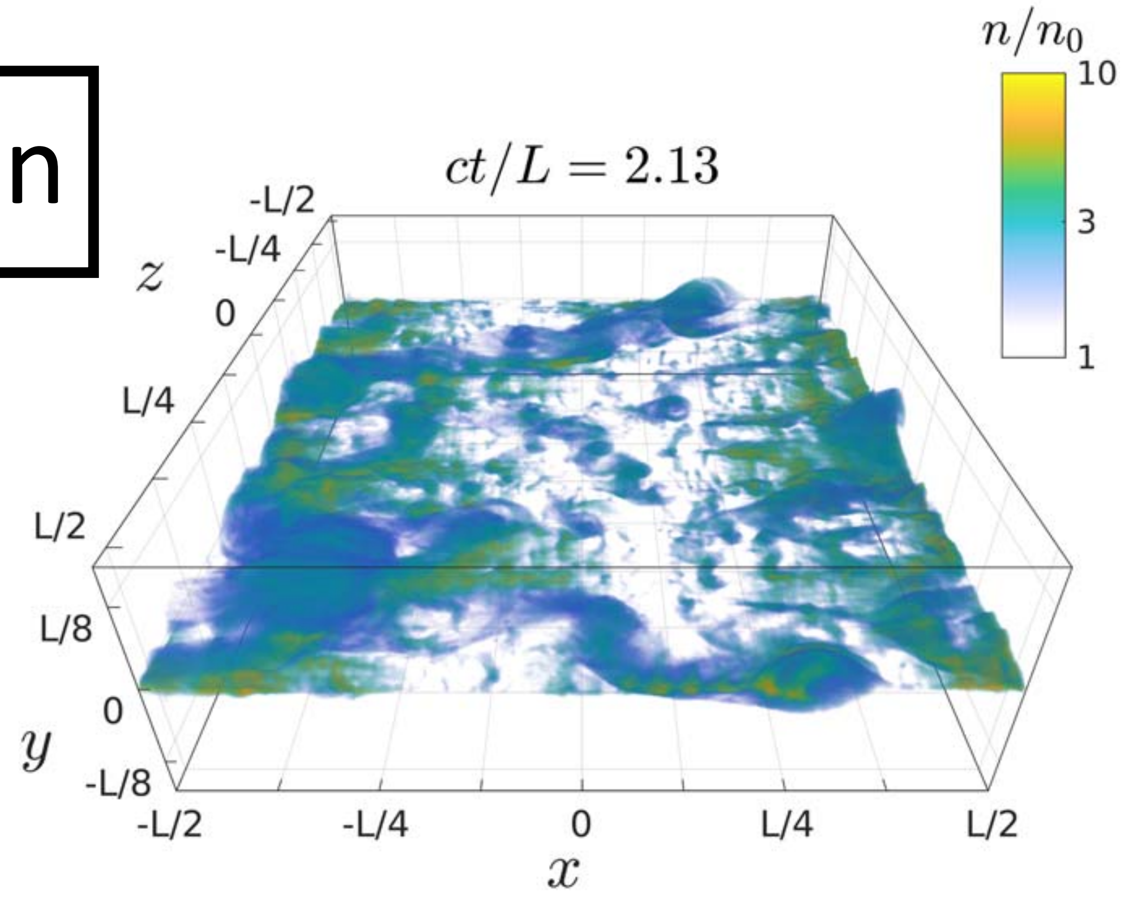


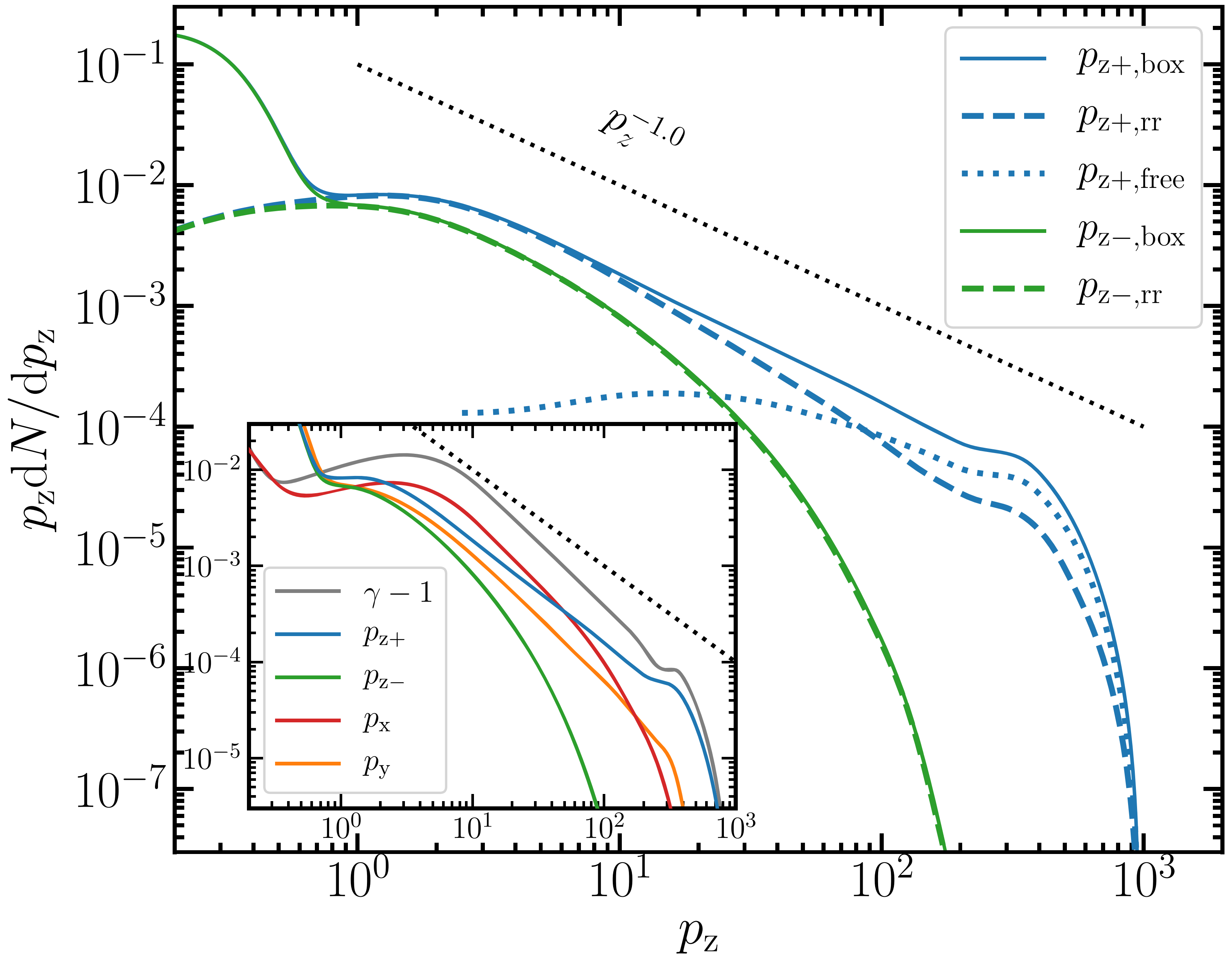
- GRMHD simulations revealed that MADs release its magnetic energy by magnetic reconnection
- Accretion process naturally induces magnetic reconnection at the mid plane
- Reconnection induces turbulence
- MHD instabilities also drive turbulence

Particle Acceleration by Reconnection & Turbulence

- PIC for reconnection

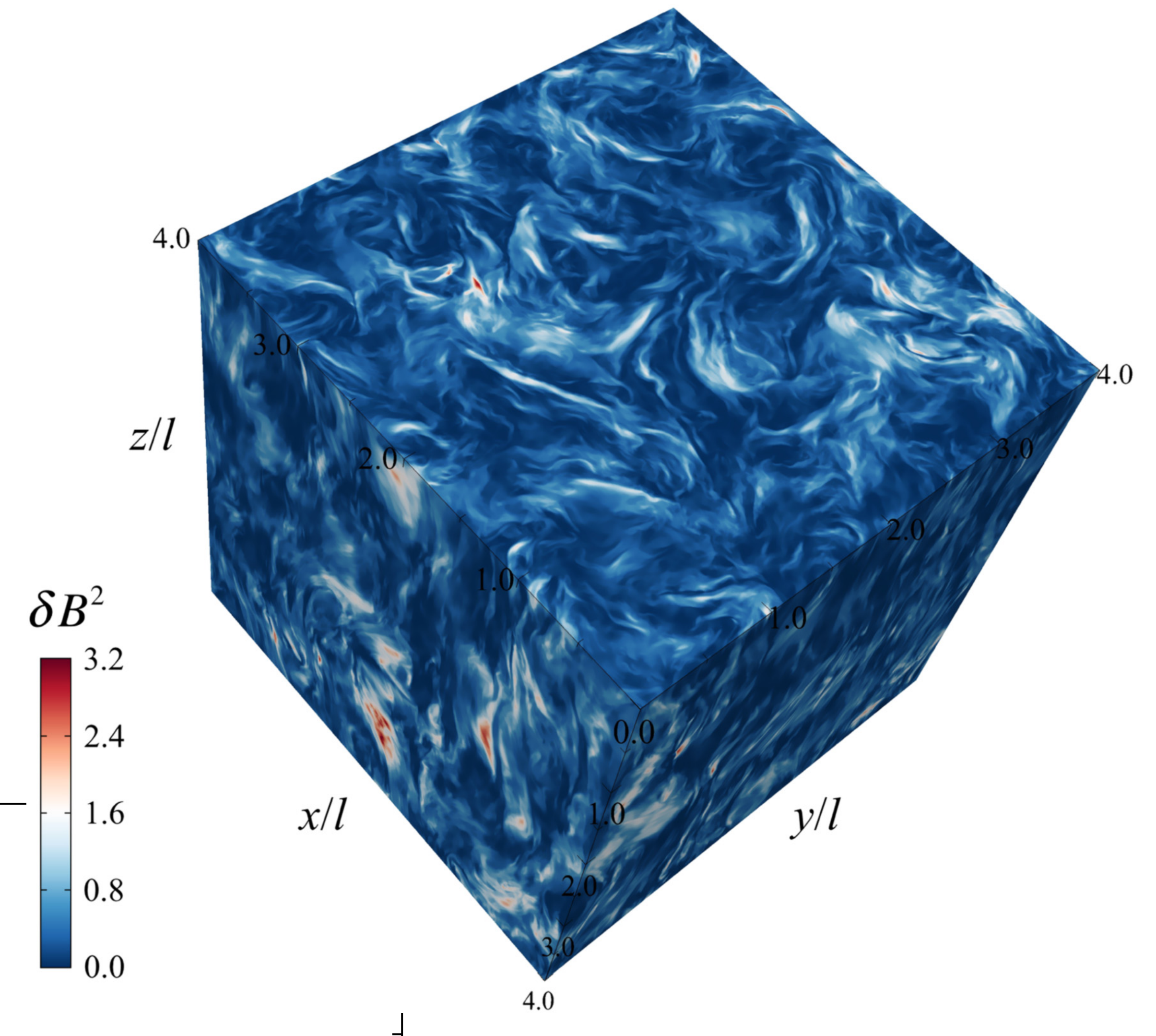
Zenitani & Hoshino 2001
Sironi & Spitkovsky 2014
Zhang et al. 2021, 2023

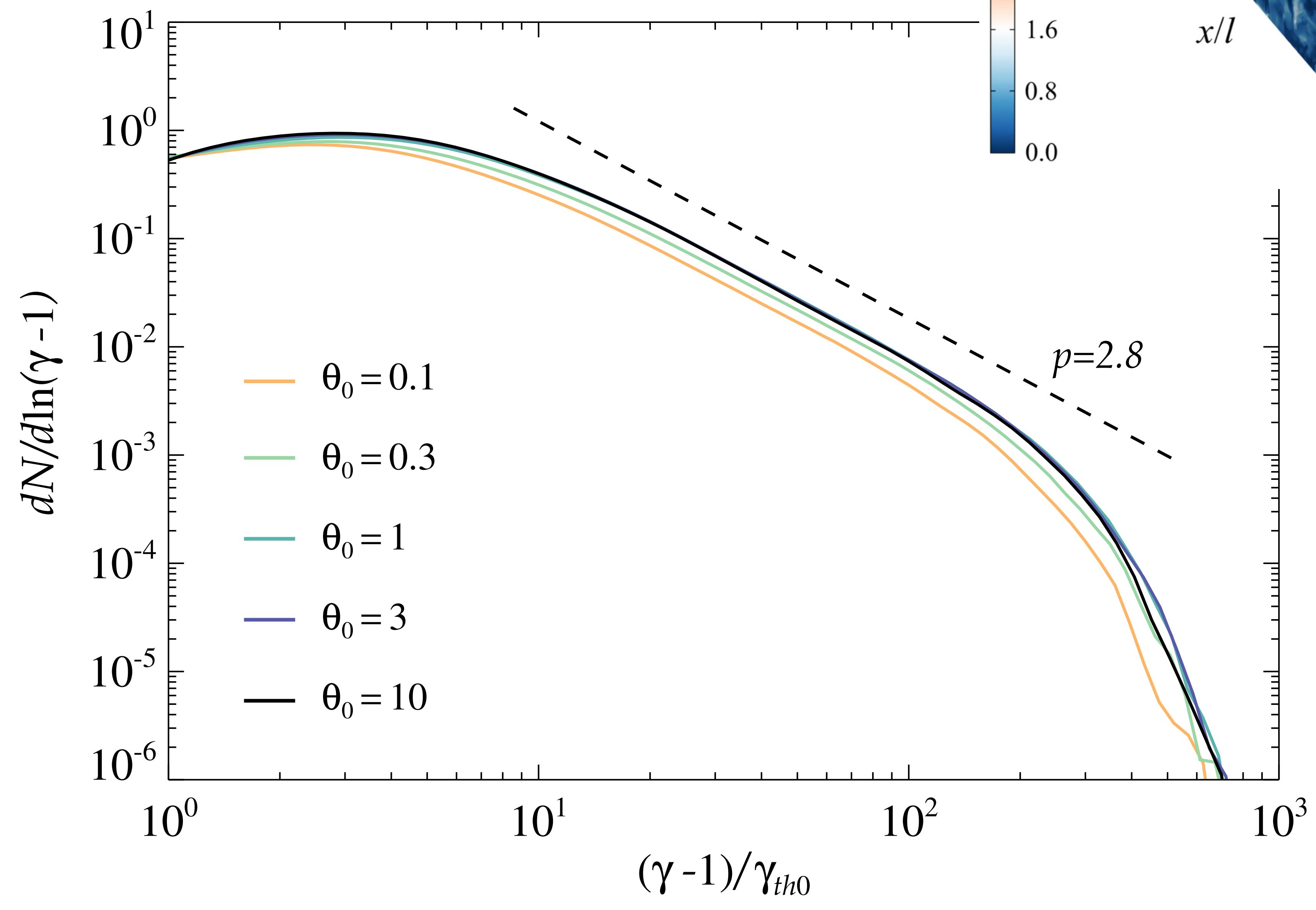




- PIC with turbulence

Zhdankin et al. 2018
Comisso & Sironi 2019



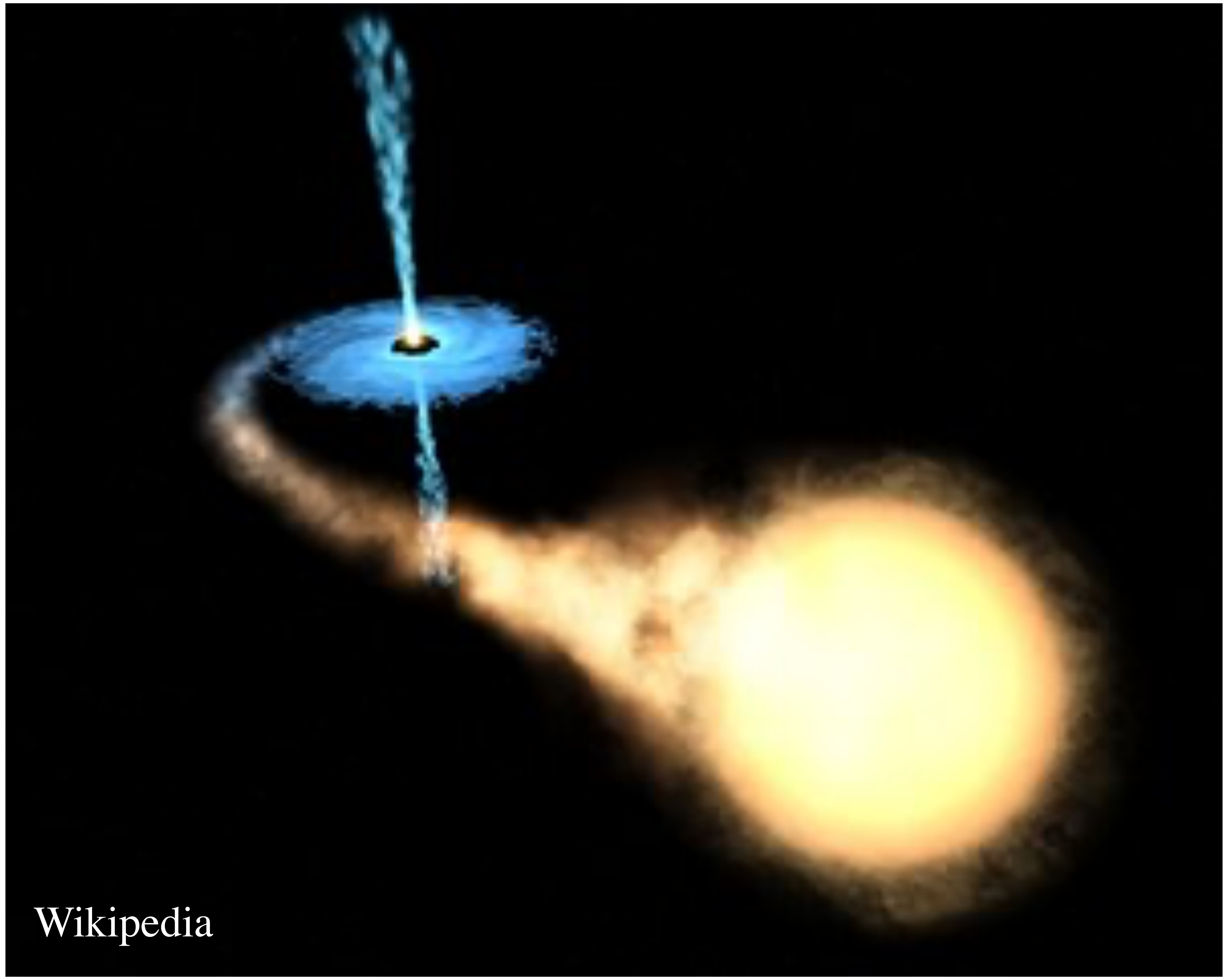


See also SSK+ 2019; Sun & Bai 2021 for MHD + test particle simulations

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

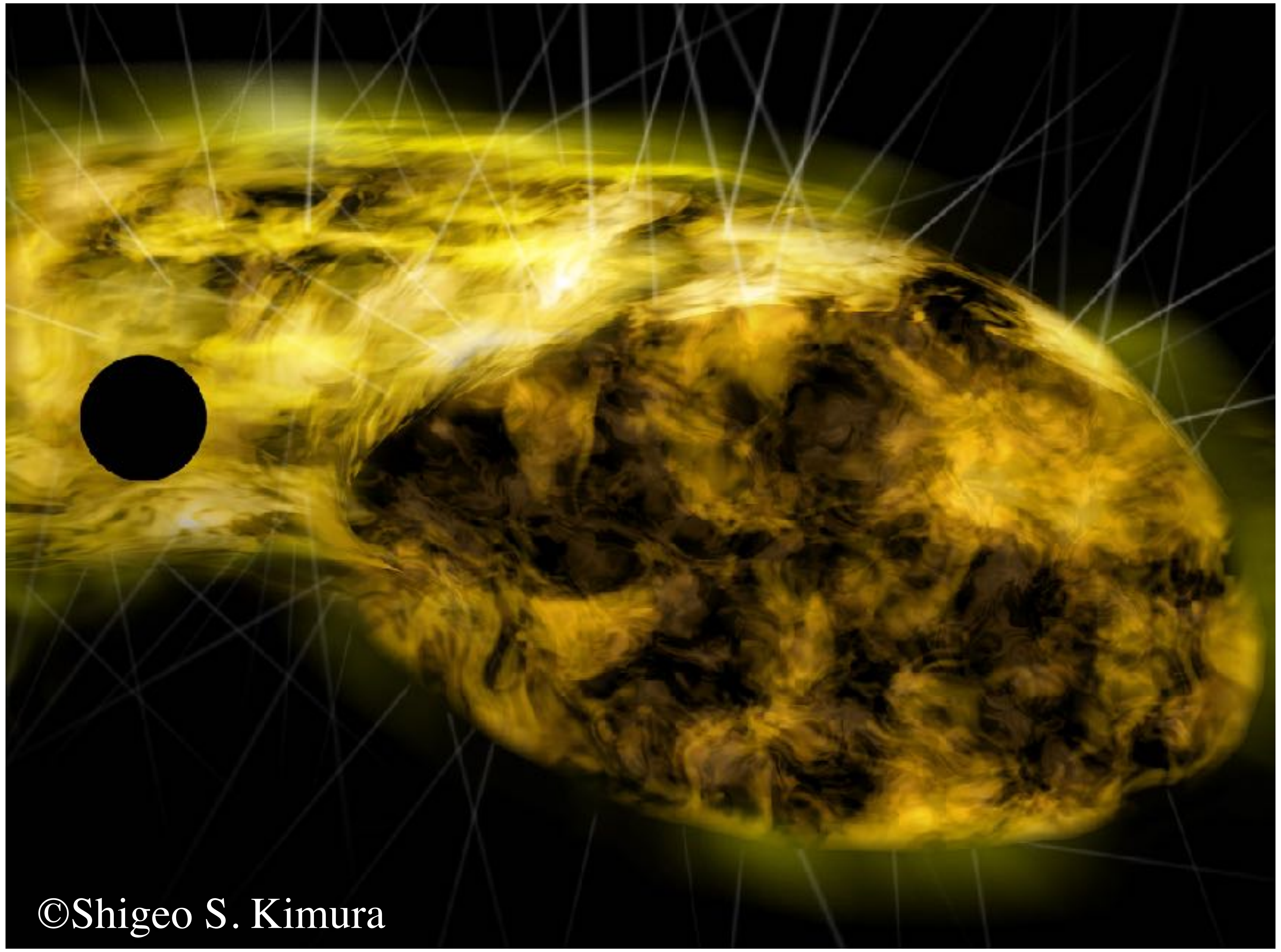
MADs in Various Environments

- X-ray binaries



SSK, Sudoh, Kashiyama, Kawanaka 2021
Kuze, SSK, Fang 2025 (ApJ submitted)

- Isolated Black Holes



SSK, Tomida, Kobayashi, Kin, Zhang 2025
SSK, Kashiyama, Hotokezaka 2021

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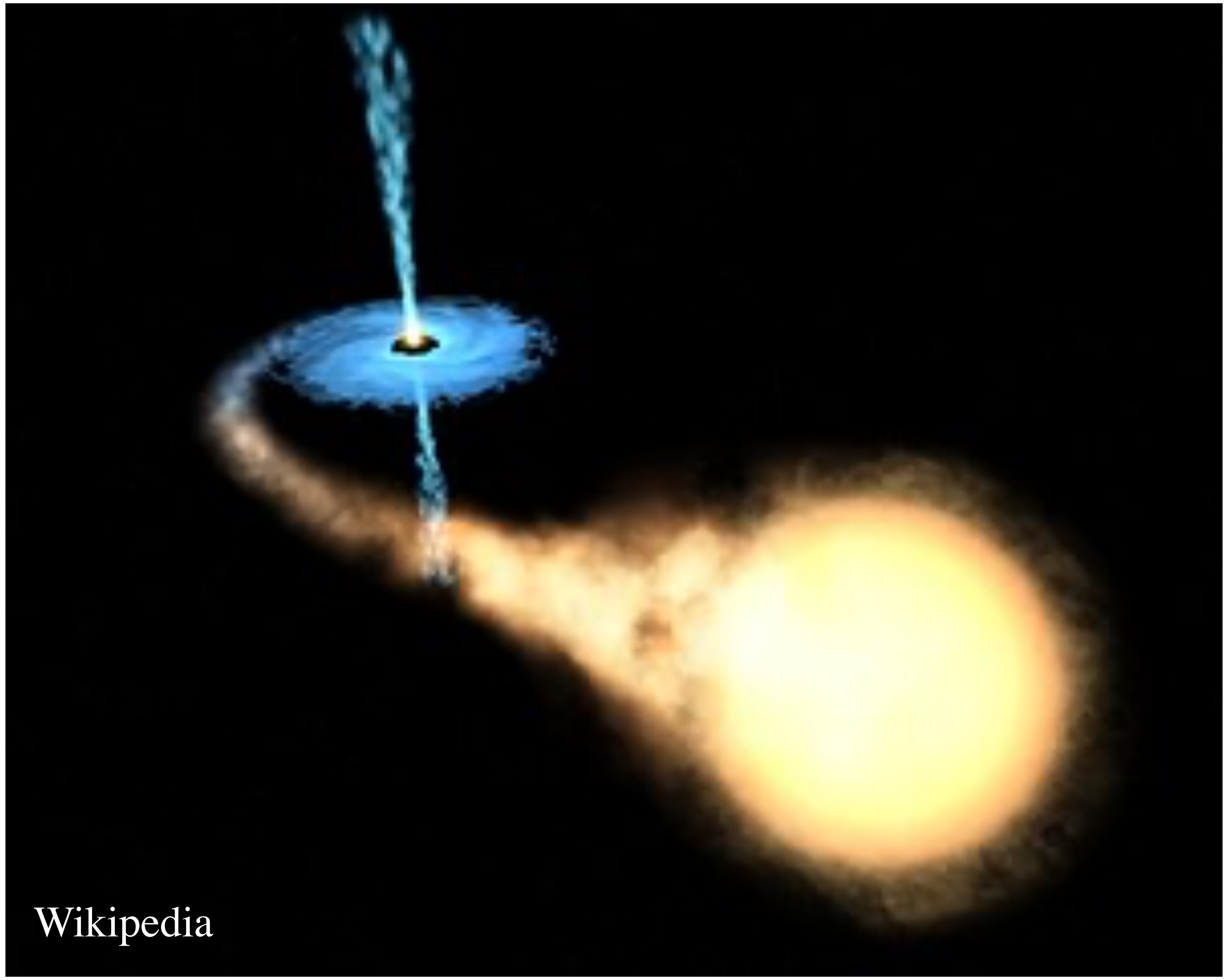

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- Isolated Black Holes

SSK, Tomida, Kobayashi, Kin, Zhang 2025
SSK, Kashiyama, Hotokezaka 2021

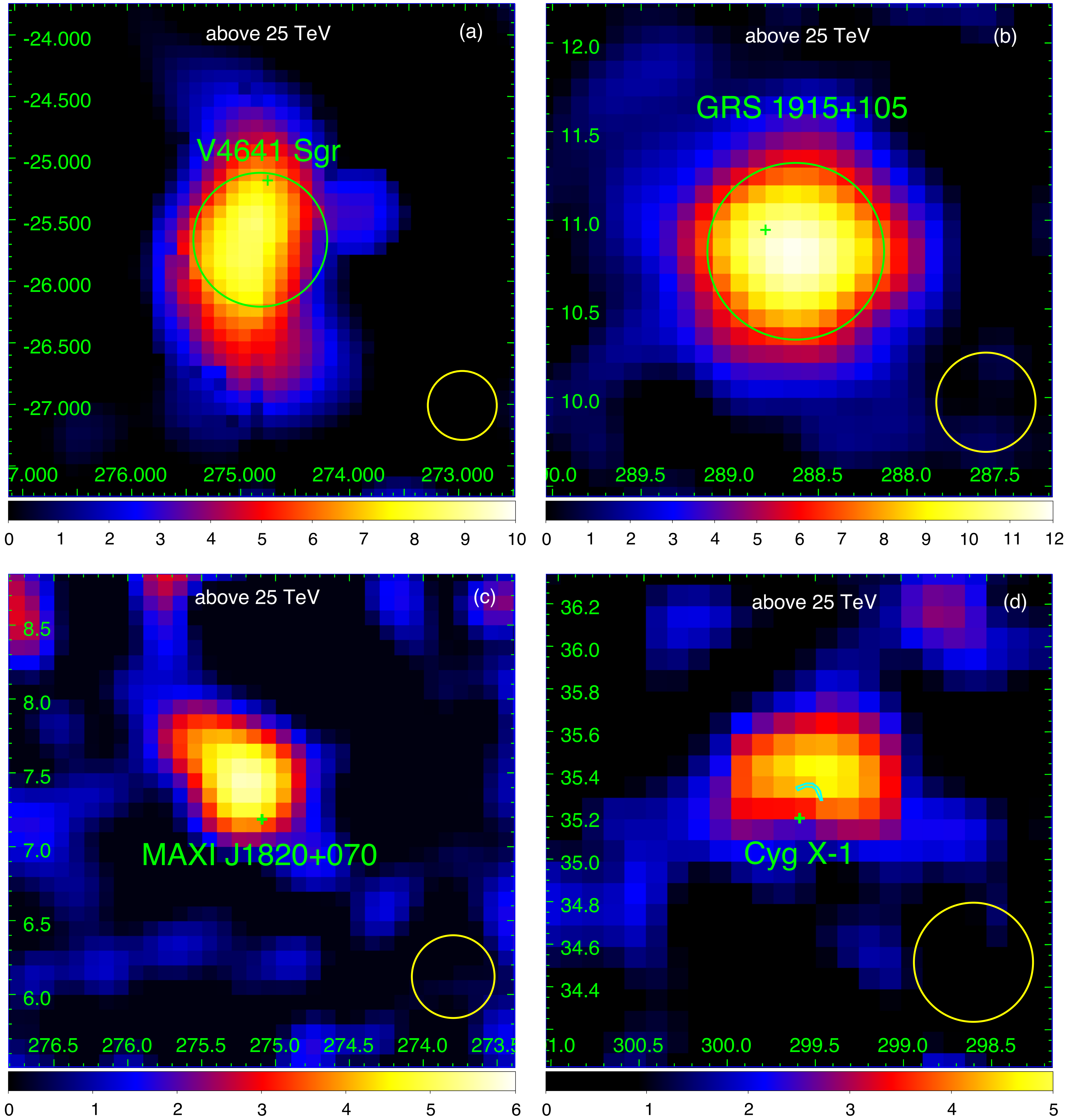
UHE γ-rays from X-ray binaries

- 5 X-ray binaries:
  SS433, V4641 Sgr, G1915+105,
  Cyg X-1, MAXI J1820+070

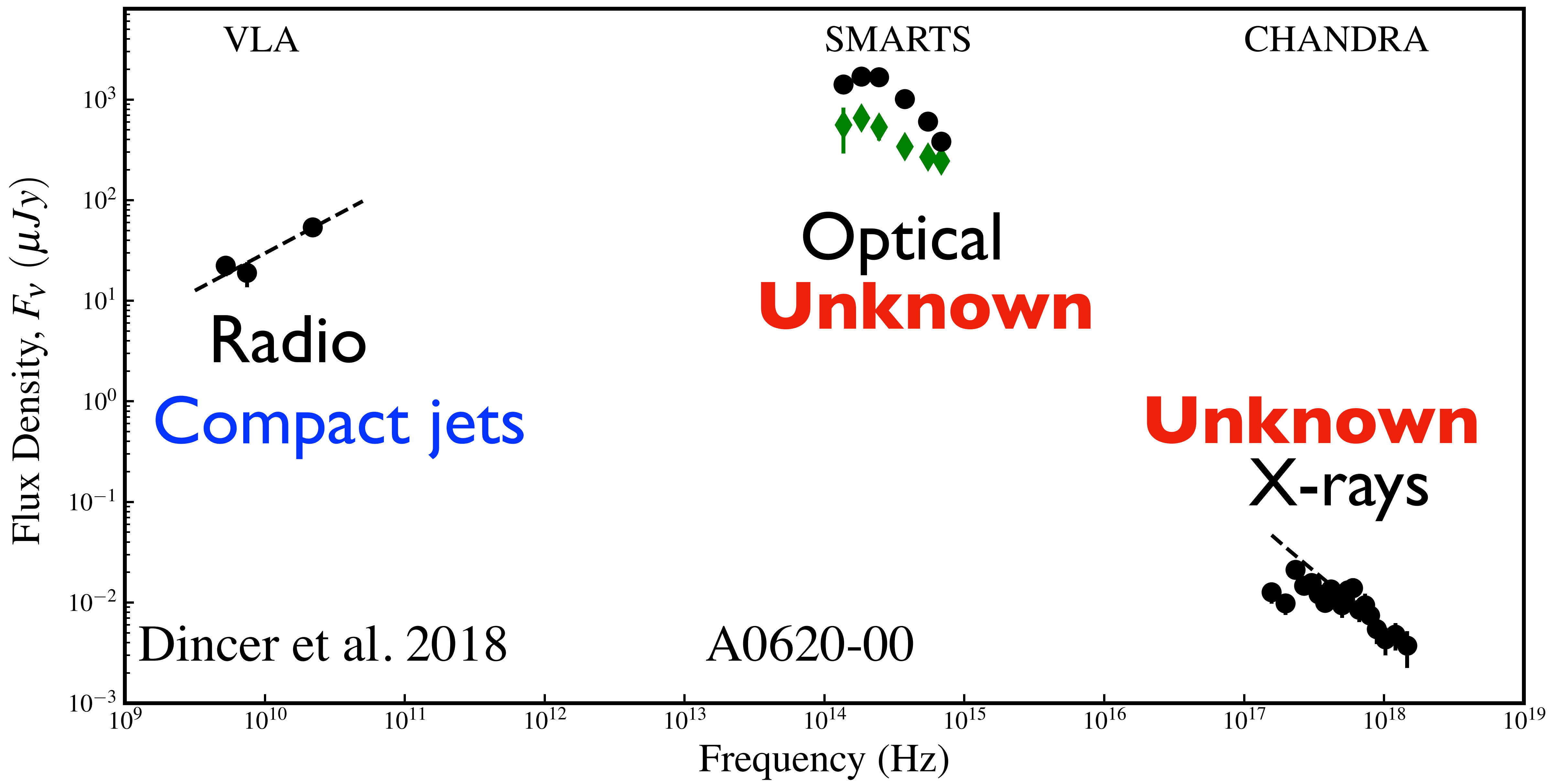
- SS433, V4641 Sgr, G1915+105:
  – extended morphology
  => Extended jets?
  CRs escaping from the center?

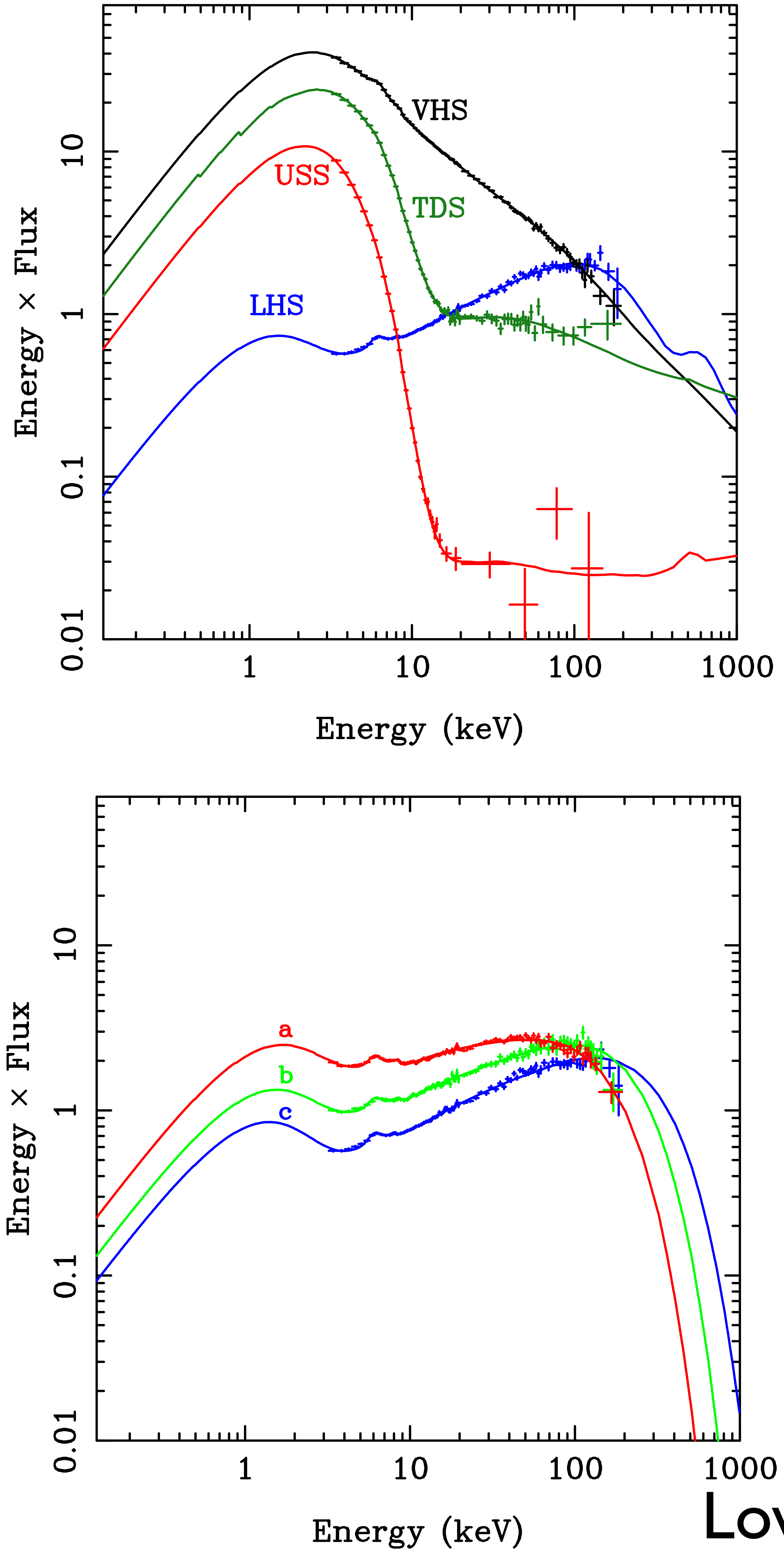
- **Cyg X-1 & MAXI J1820+070:**
  – point source-like morphology
  => Compact jets?
  Accretion flows?

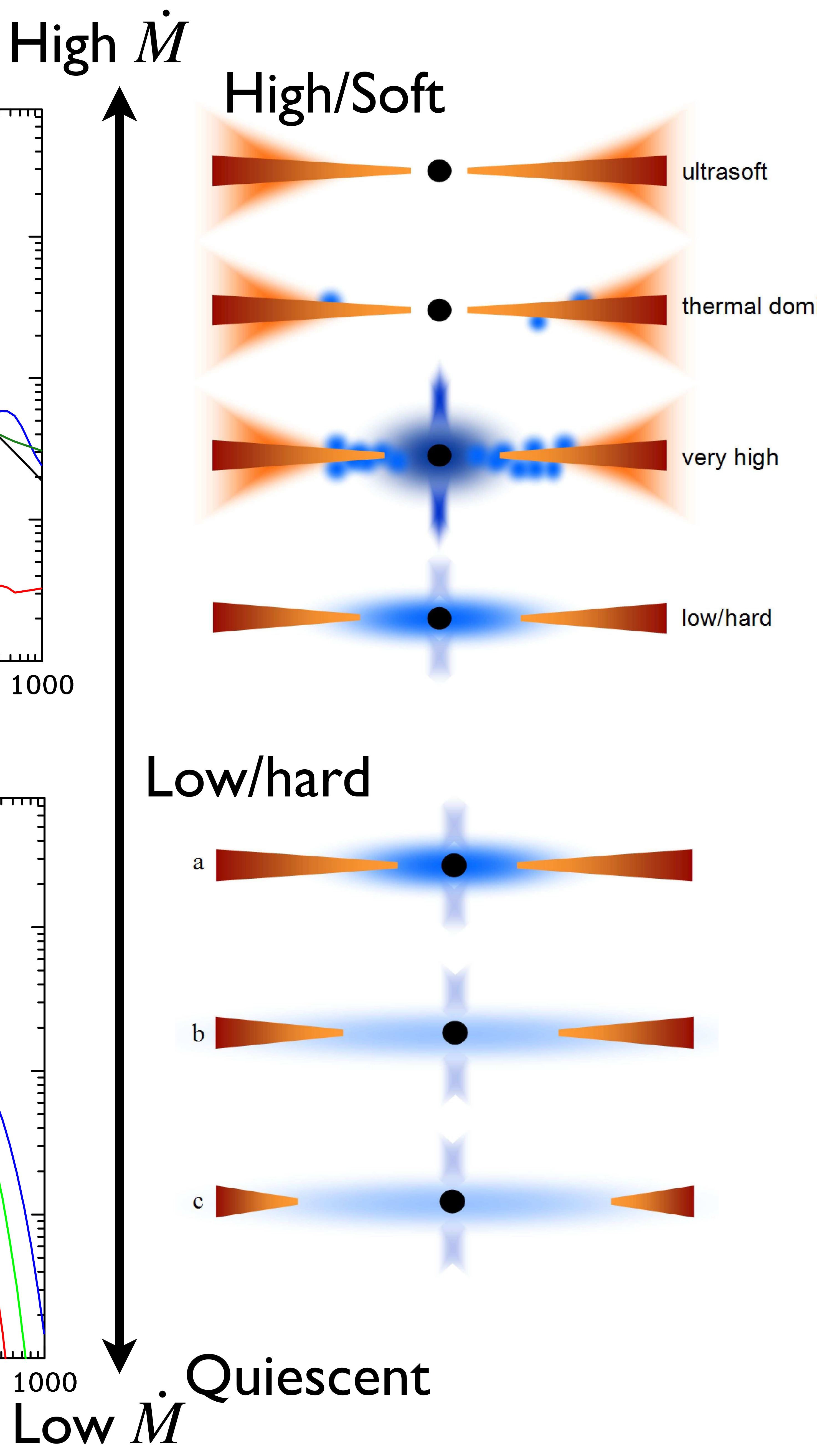
LHAASO 2024



Quiescent State in X-ray Binary



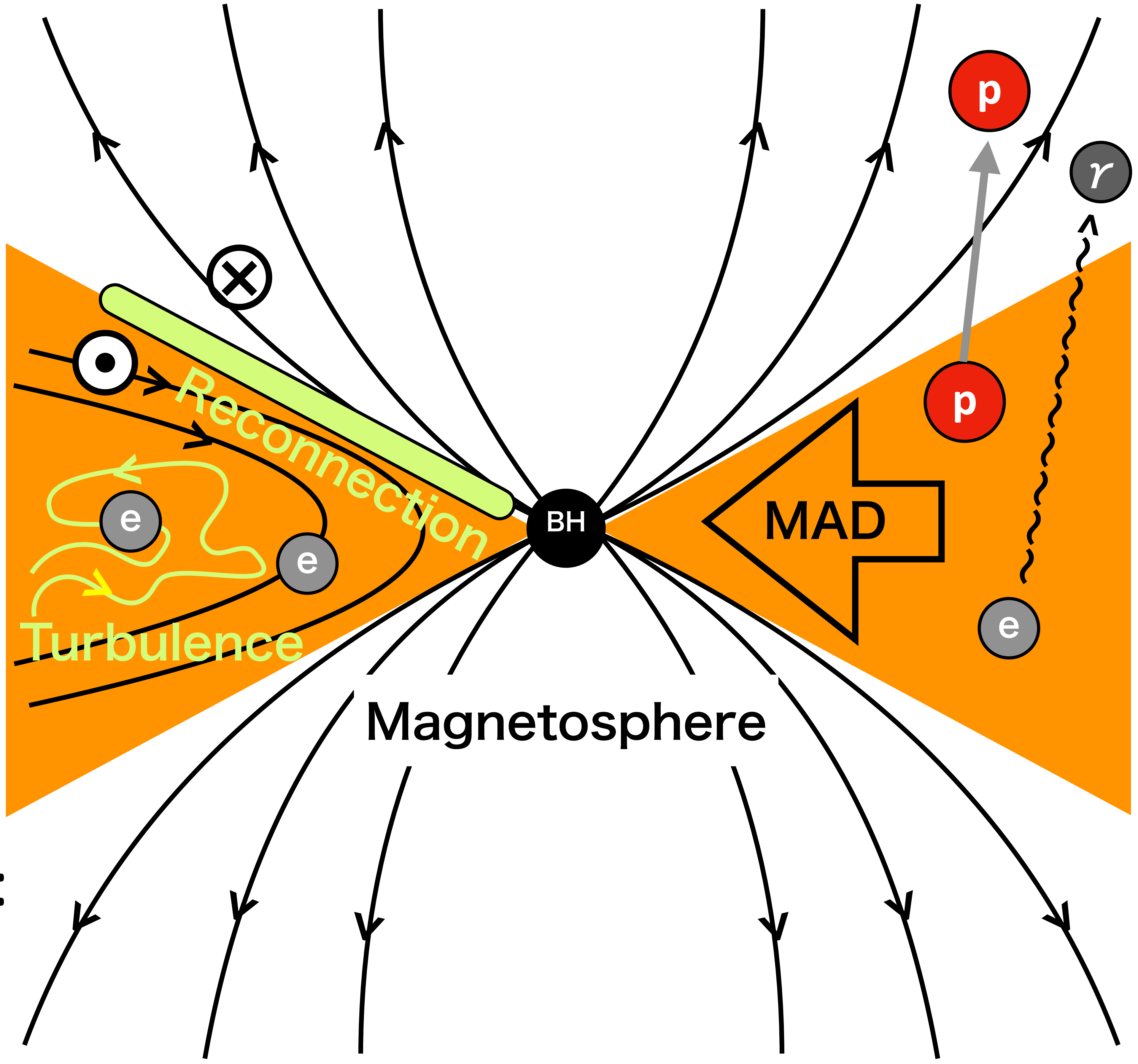




- X-ray binaries show various spectral state
- Quiescent state: faintest state in X-ray binaries
- $L_X \sim 10^{30} - 10^{33}$ erg/s
  —> $\dot{M}c^2 \lesssim 10^{-3} - 10^{-5} L_{\rm Edd}$
- Radio, optical, and X-ray signals are observed
  —> calibrate parameters by opt & X data

MAD model

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



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

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

- Reconnection/turbulence produce power-law distribution:

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

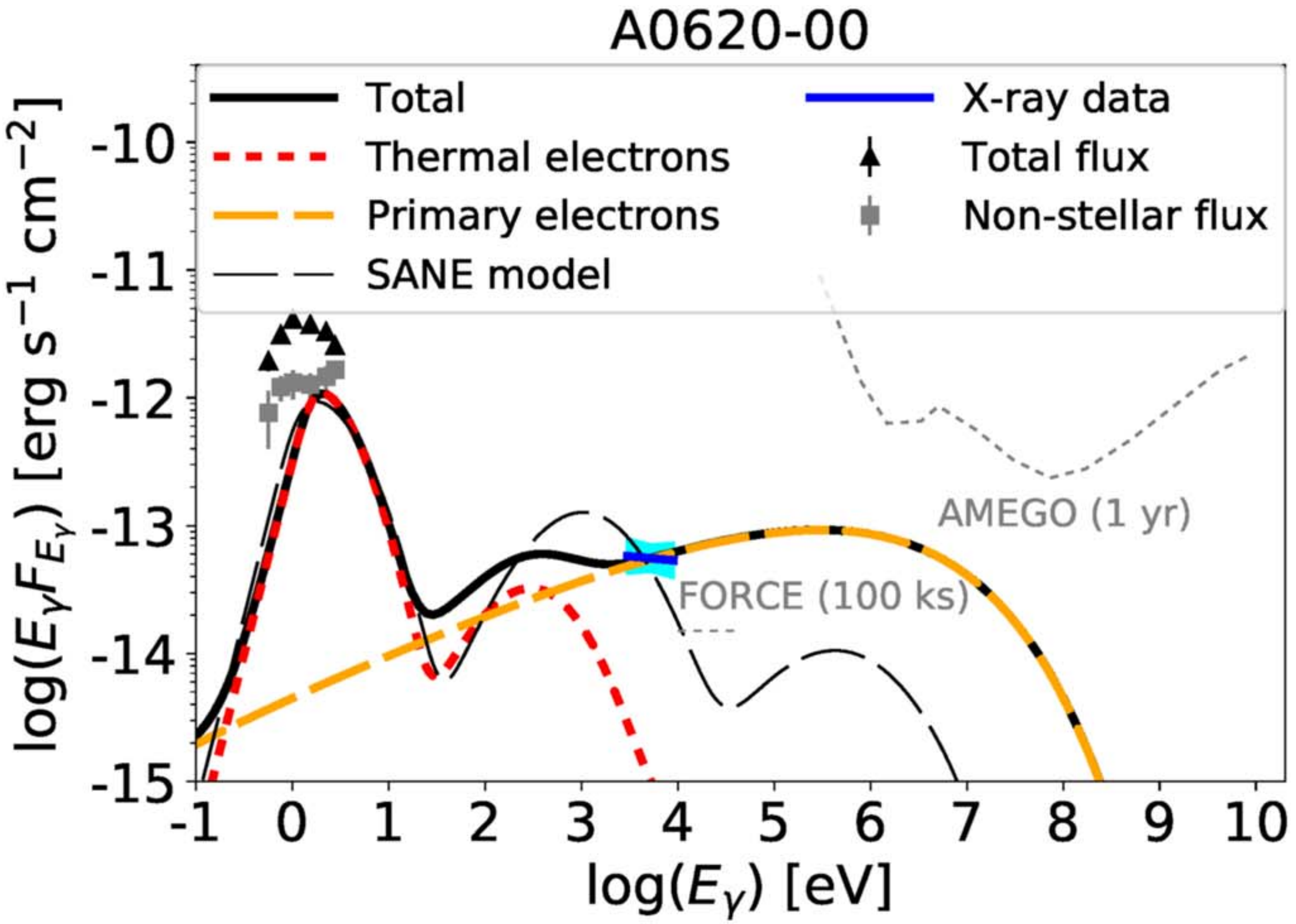
- Normalization for non-thermal electrons

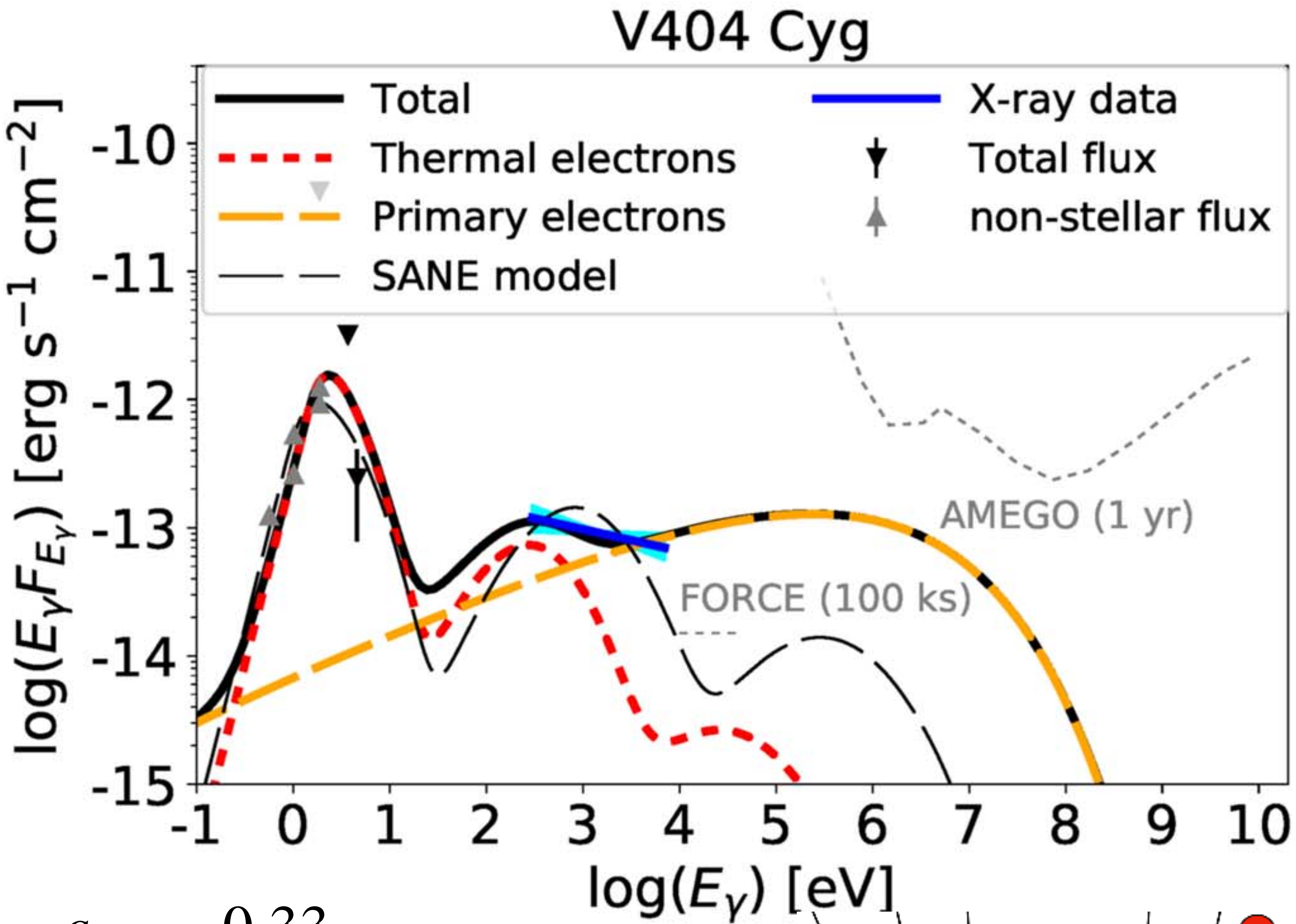
$$\int E_i \dot{N}_{E_i,\rm inj} dE_i = f_i \epsilon_{\rm NT} \dot{M} c^2$$

- Synchrotron dominates over the other cooling processes

Photon spectra from MADs in X-ray Binaries

SSK, Sudoh, Kashiyama, Kawanaka 2021

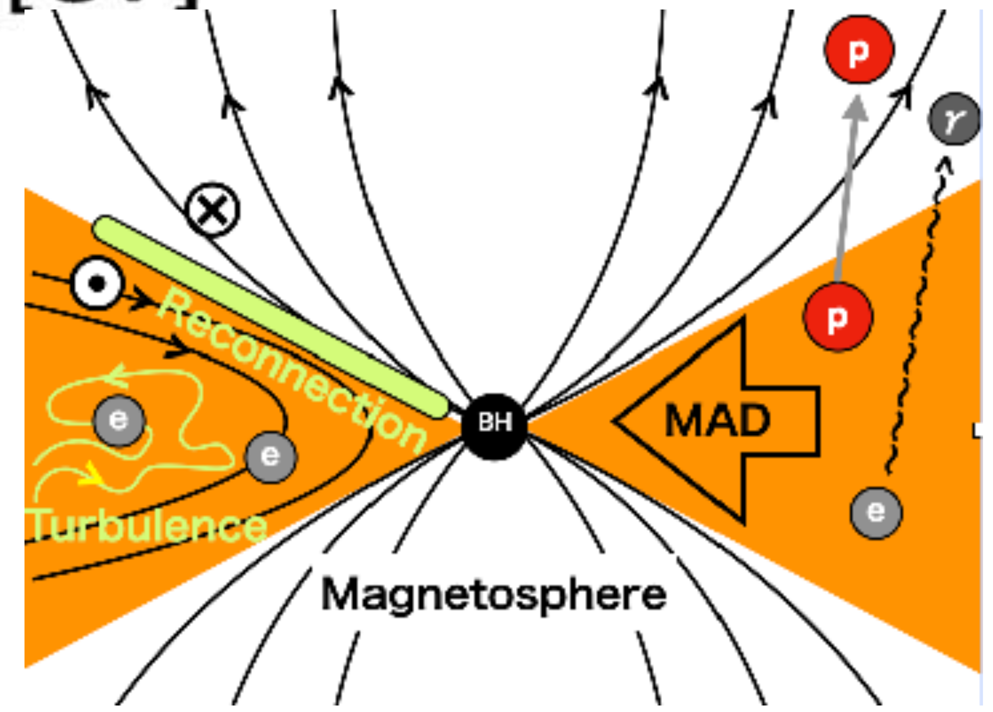




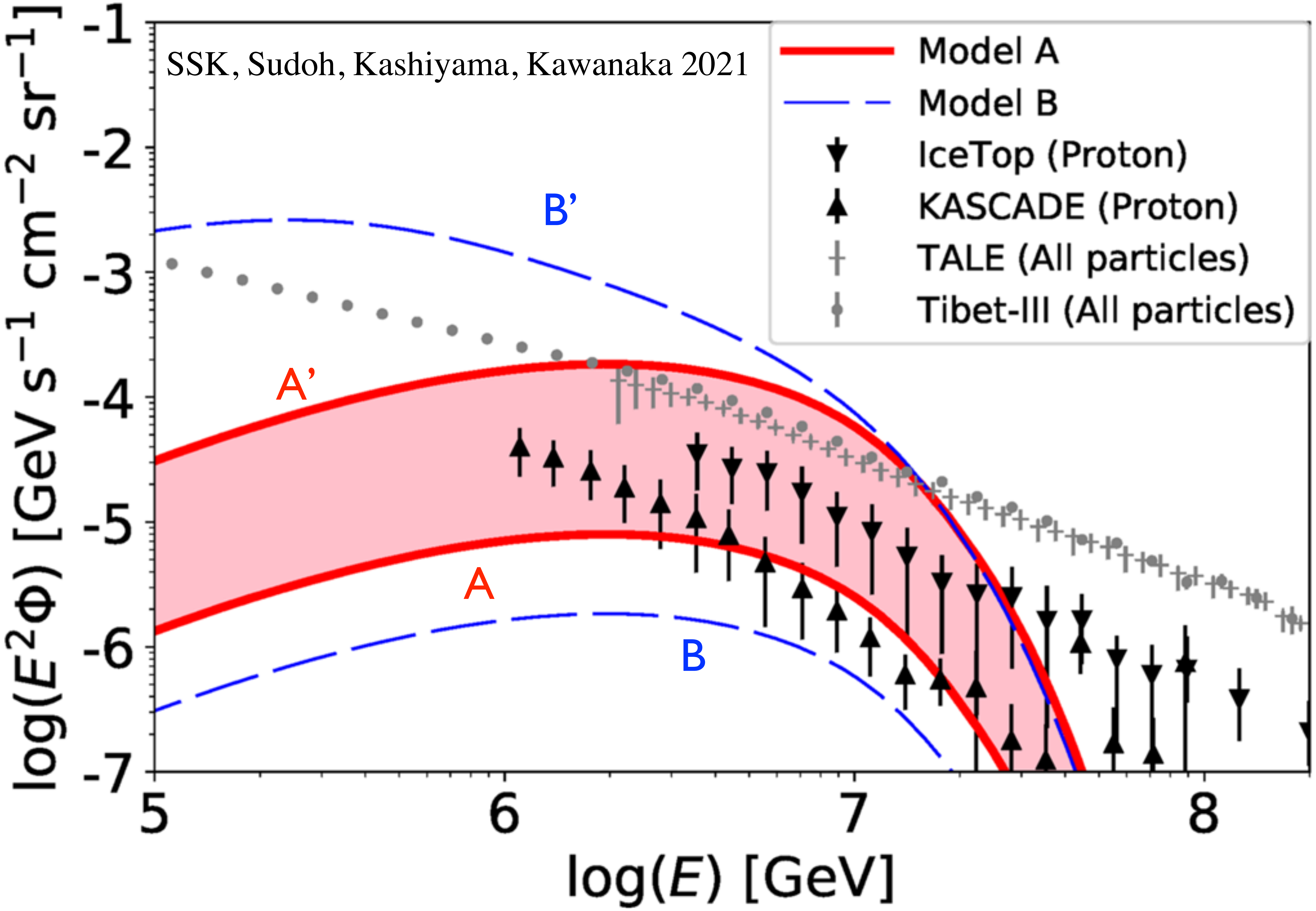
$\epsilon_{NT} = 0.33$

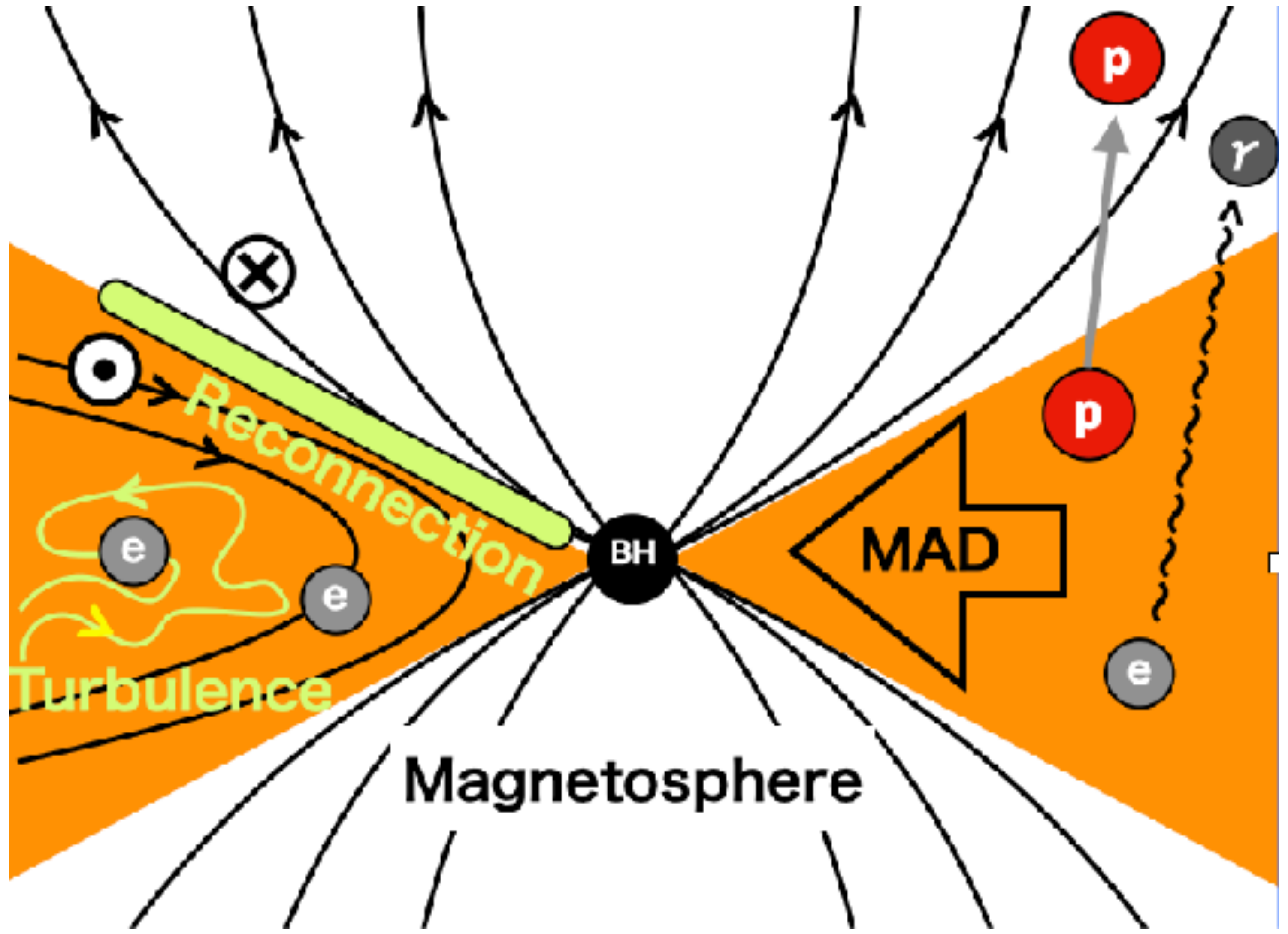
$f_e = 0.3$

- Optical: Thermal synchrotron
- X-rays: Synchrotron by non-thermal electrons
- **Consistent with opt/X-ray data for nearby objects**



Cosmic-Rays from MADs



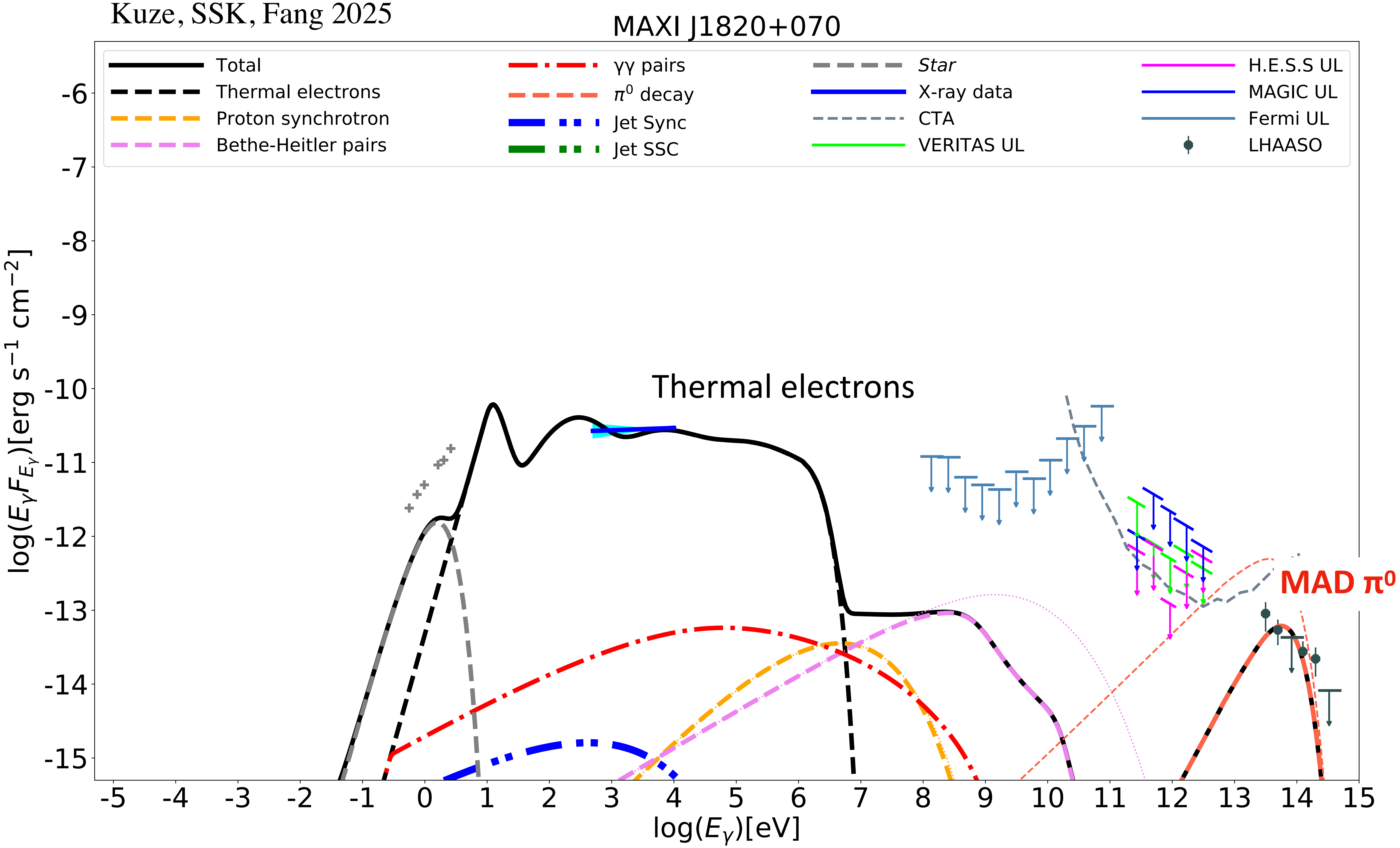


- Maximum energy: E ~ 1 PeV (balance of escape & acceleration)
- **Model prediction consistent with data within their uncertainties**
- Model uncertainty mainly from number of X-ray binaries
- Future X-ray surveys will reduce model uncertainty

Application to MAXI J1820+070

- Our model can reproduce X-ray & γ-ray data

Kuze, SSK, Fang 2025



$$\dot{m} = \dot{M}c^2/L_{\rm Edd} = 5\times10^{-3}$$
$$s_{\rm inj,MAD} = 1.24$$

$$B_{\rm mad} = 3.3\times10^6\ {\rm G}$$
$$E_{p,\rm max} = 2.7\times10^5\ {\rm GeV}$$

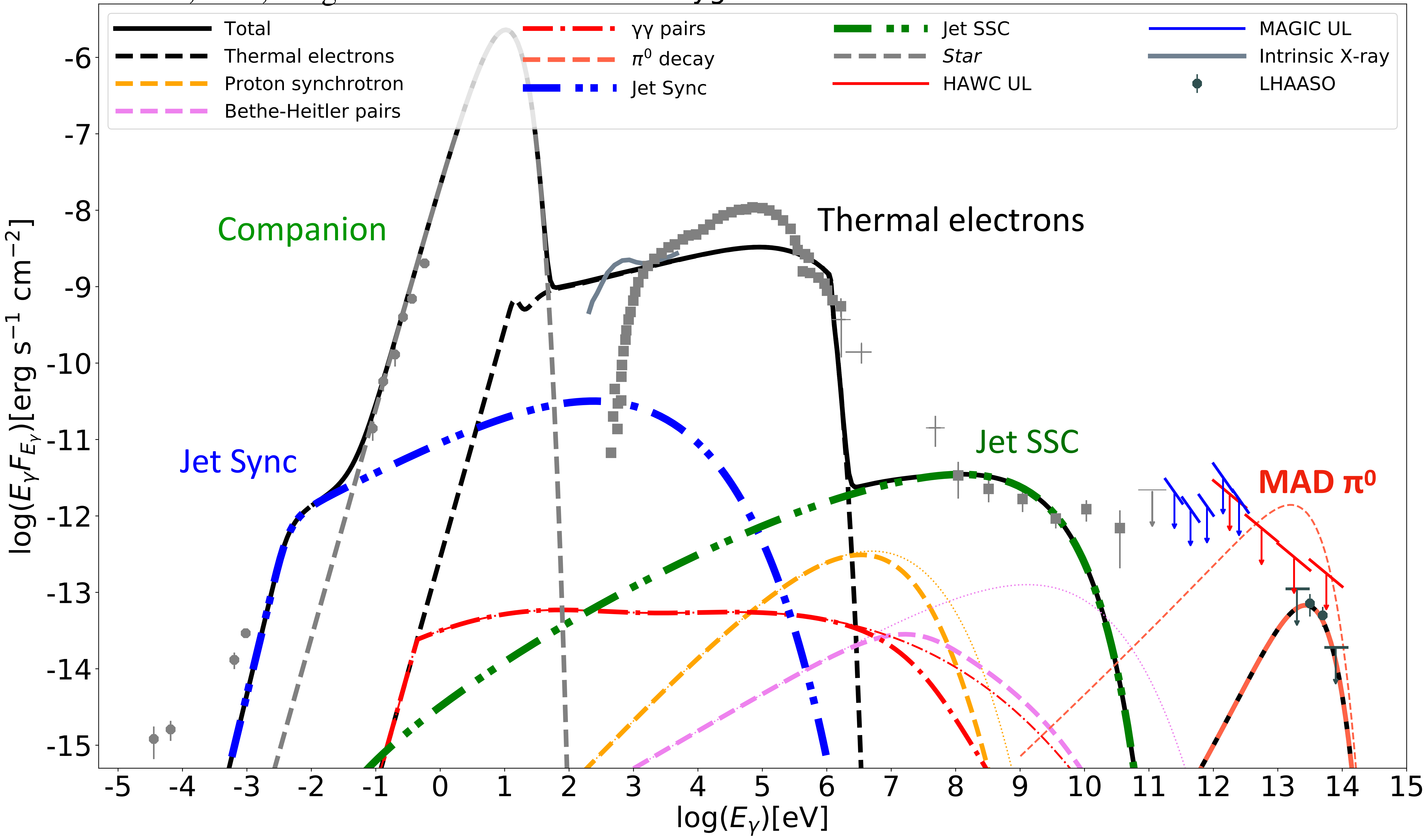
$$\epsilon_{\rm NT} = 0.33$$

$$f_e = 0.3$$

Application to Cyg X-1

- Our model can reproduce broadband features

Kuze, SSK, Fang 2025



$\dot{m} = \dot{M}c^2/L_{\rm Edd} = 10^{-1}$

$s_{\rm inj,MAD} = 1.21$

$B_{\rm mad} = 1.2 \times 10^7$ G

$E_{p,\rm max} = 1.6 \times 10^5$ GeV

$\epsilon_{\rm NT} = 0.003$

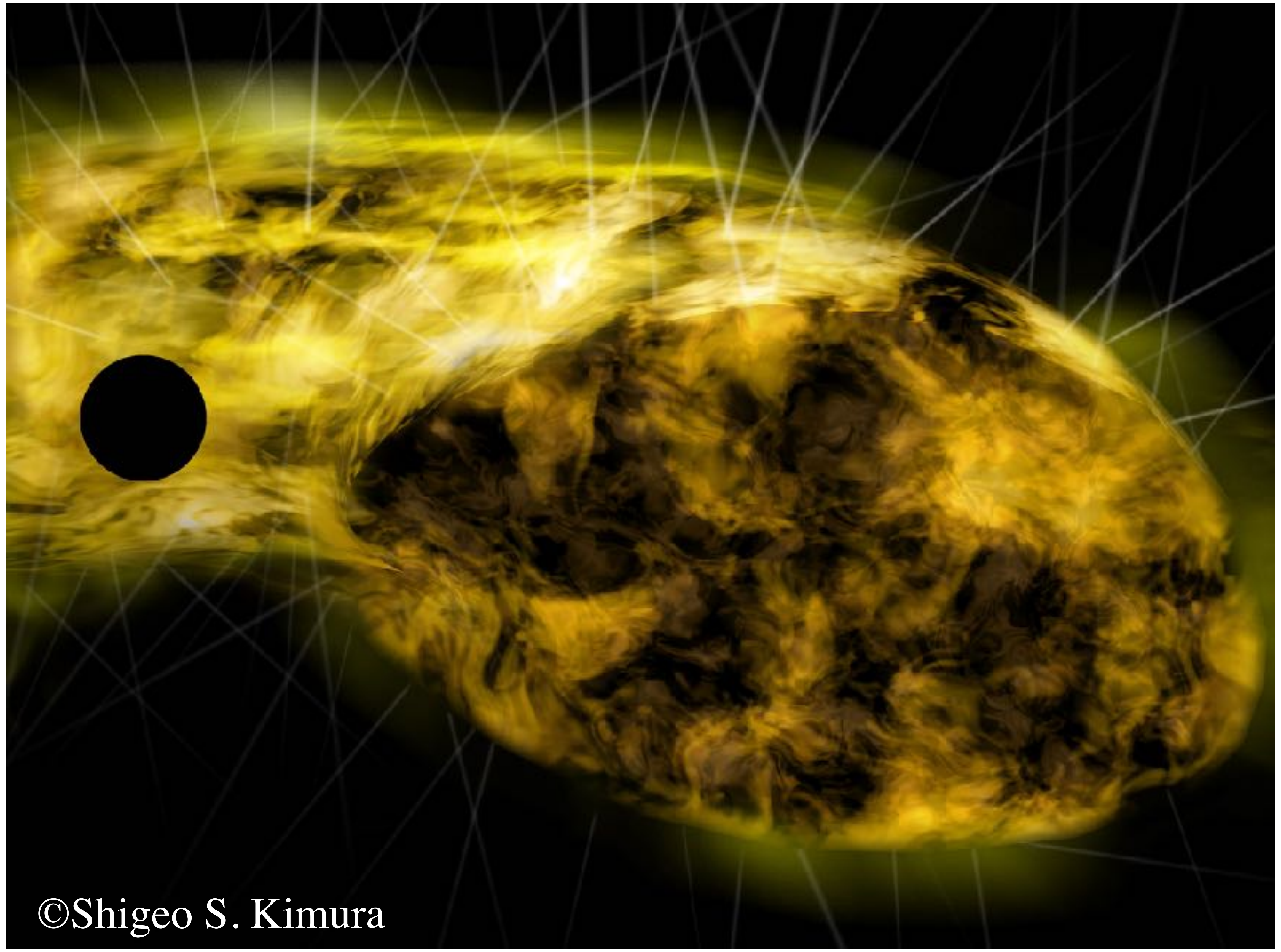
$f_e = 0.3$

MADs in Various Environments

- X-ray binaries

SSK, Sudoh, Kashiyama, Kawanaka 2021
Kuze, SSK, Fang 2025 (ApJ submitted)

- Isolated Black Holes



SSK, Tomida, Kobayashi, Kin, Zhang 2025
SSK, Kashiyama, Hotokezaka 2021

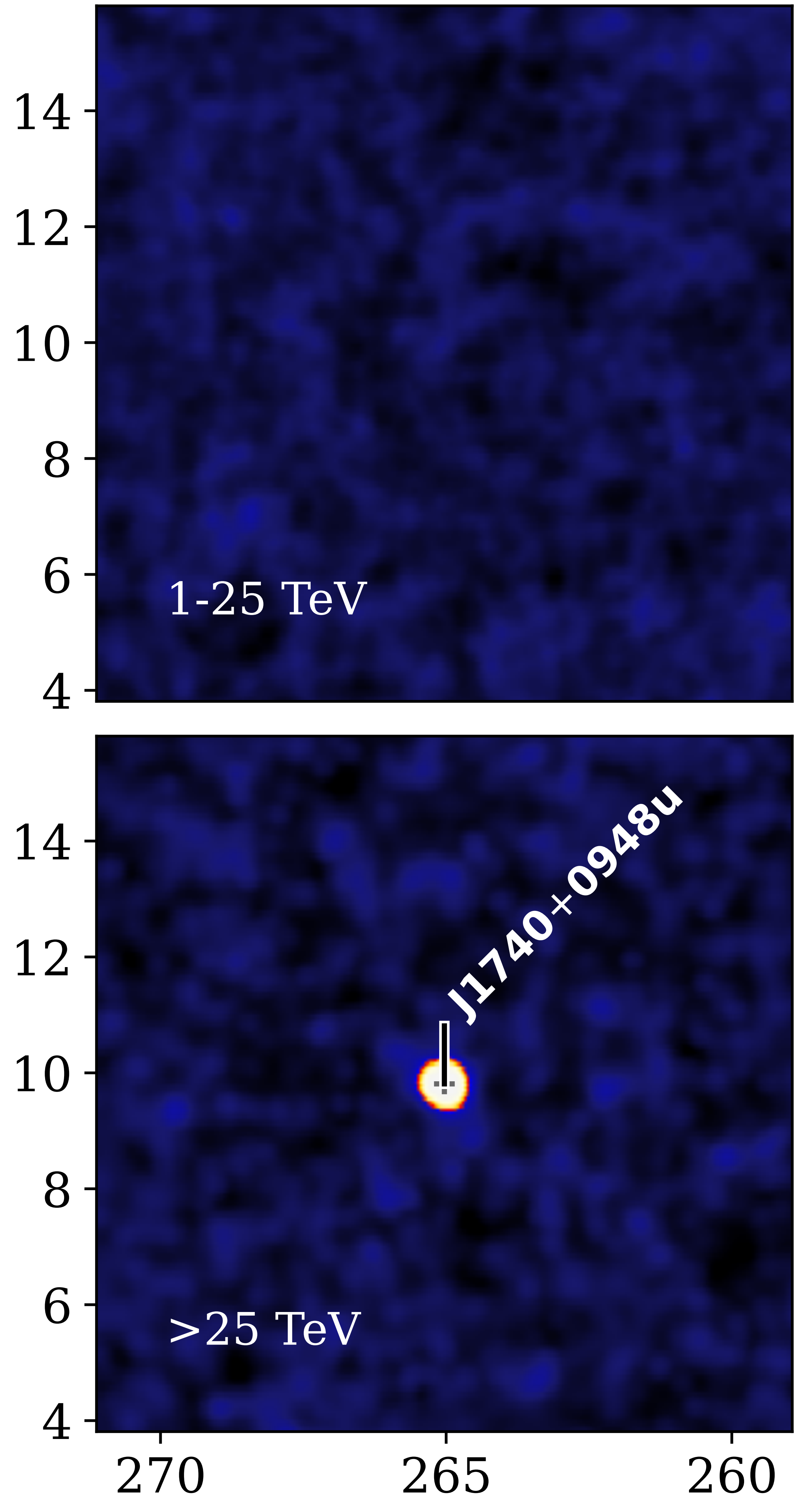
New class of UHE γ-ray sources?

- 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



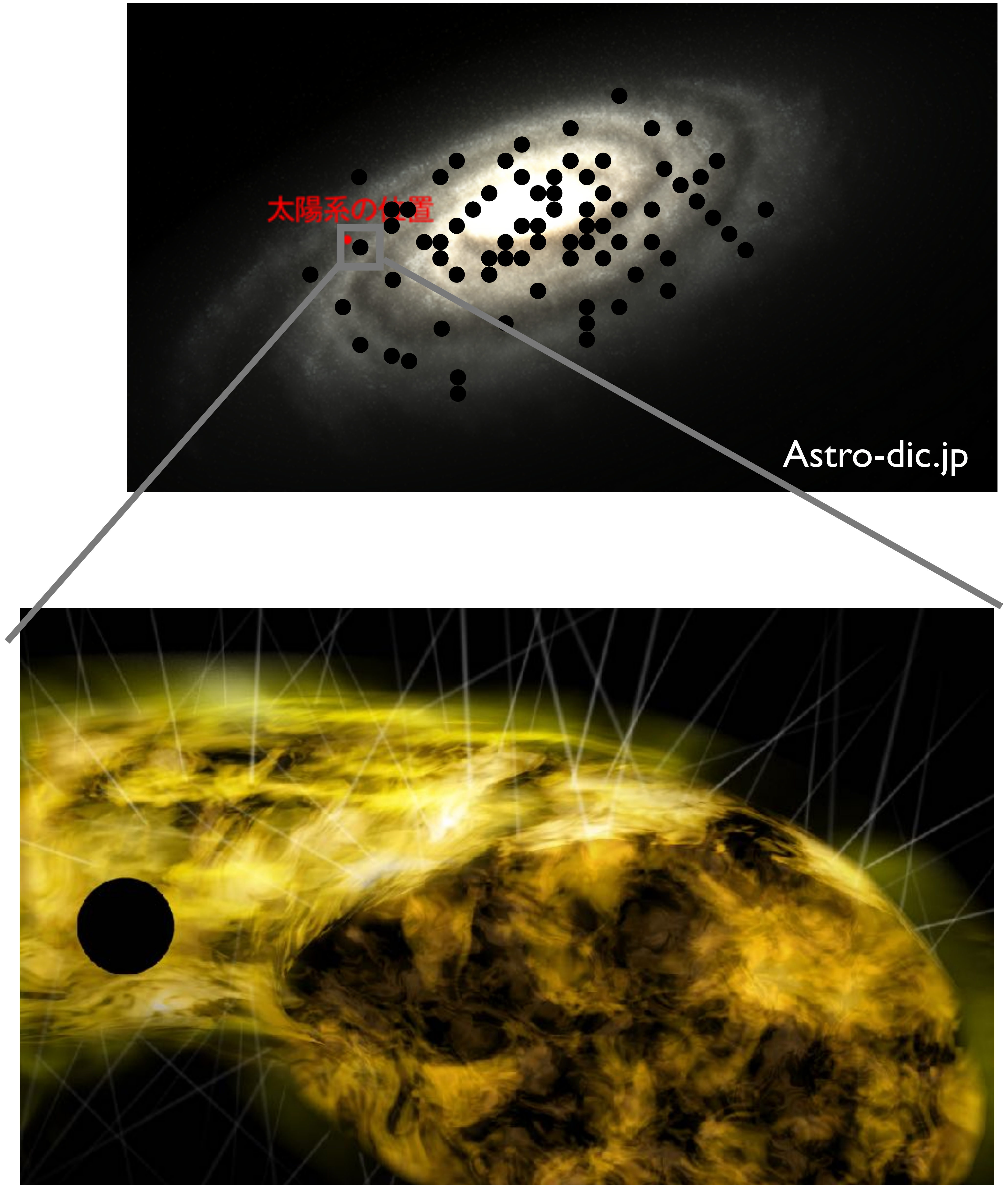
Isolated Black Holes (IBHs)

- 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

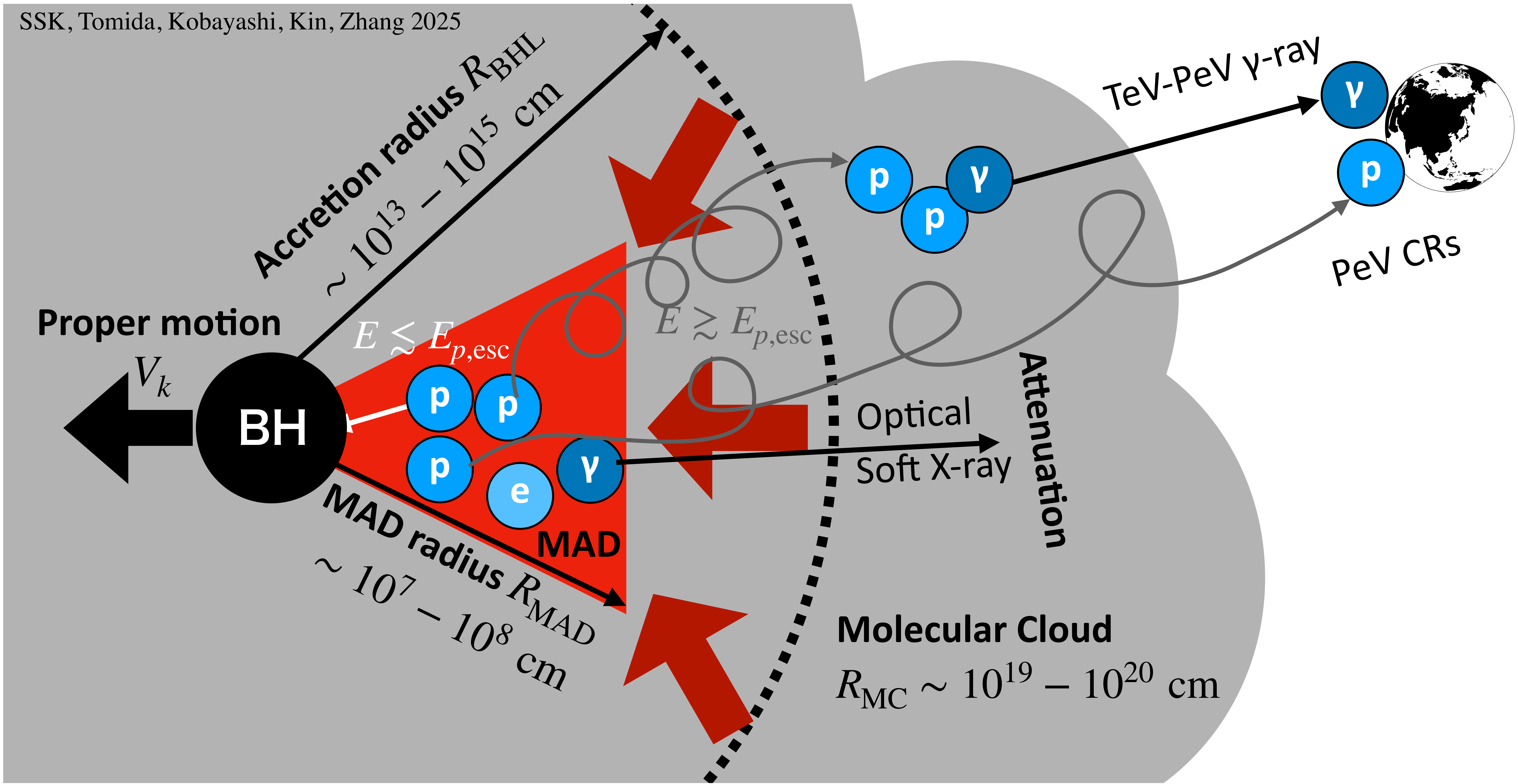
$$\dot{M}_\bullet \approx \lambda_w \frac{4\pi G^2 M^2 \mu_{\rm ISM} m_p n_{\rm ISM}}{(C_s^2 + v_k^2)^{3/2}}$$

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

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



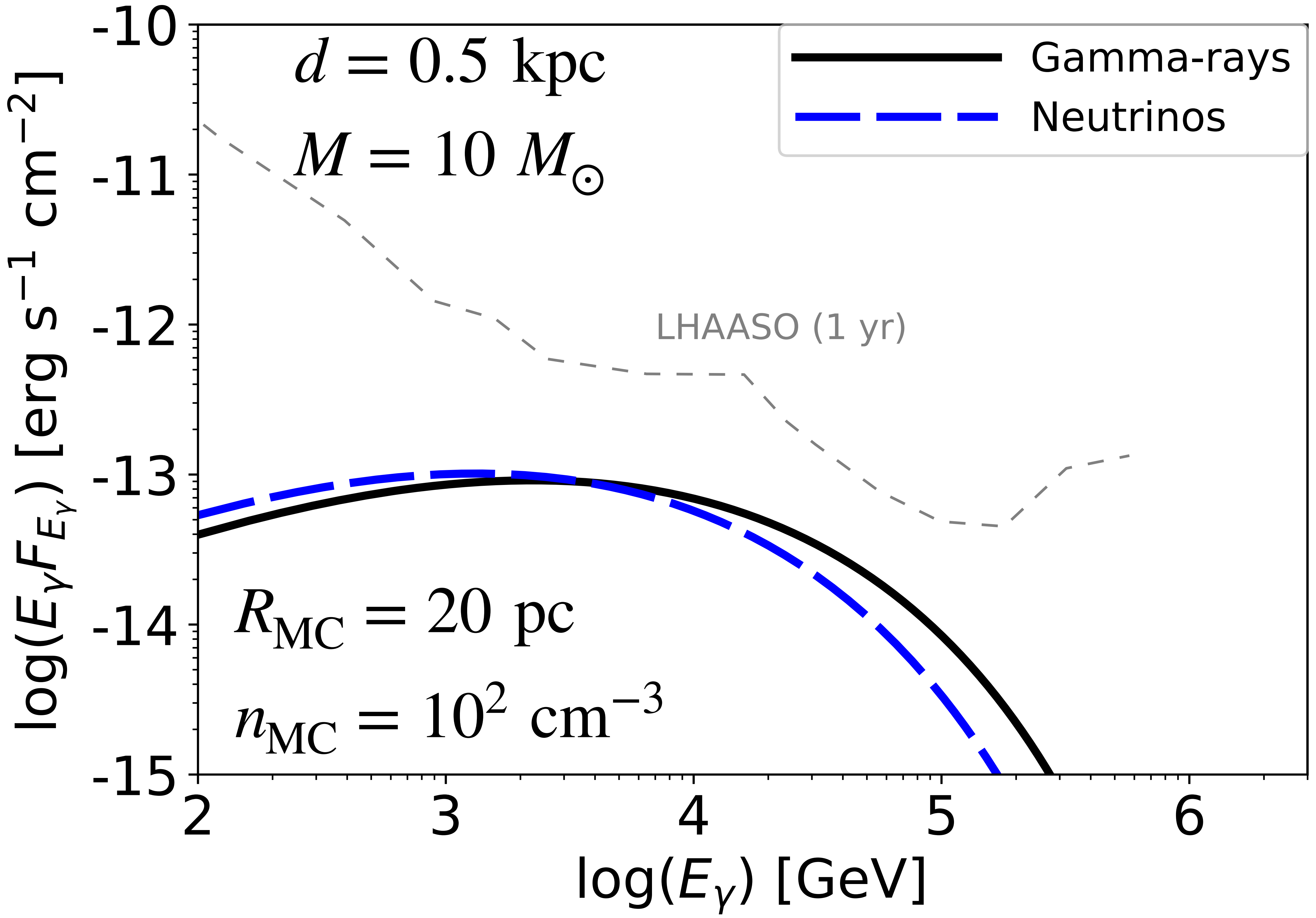
Schematic picture of our scenario



γ-rays from molecular clouds

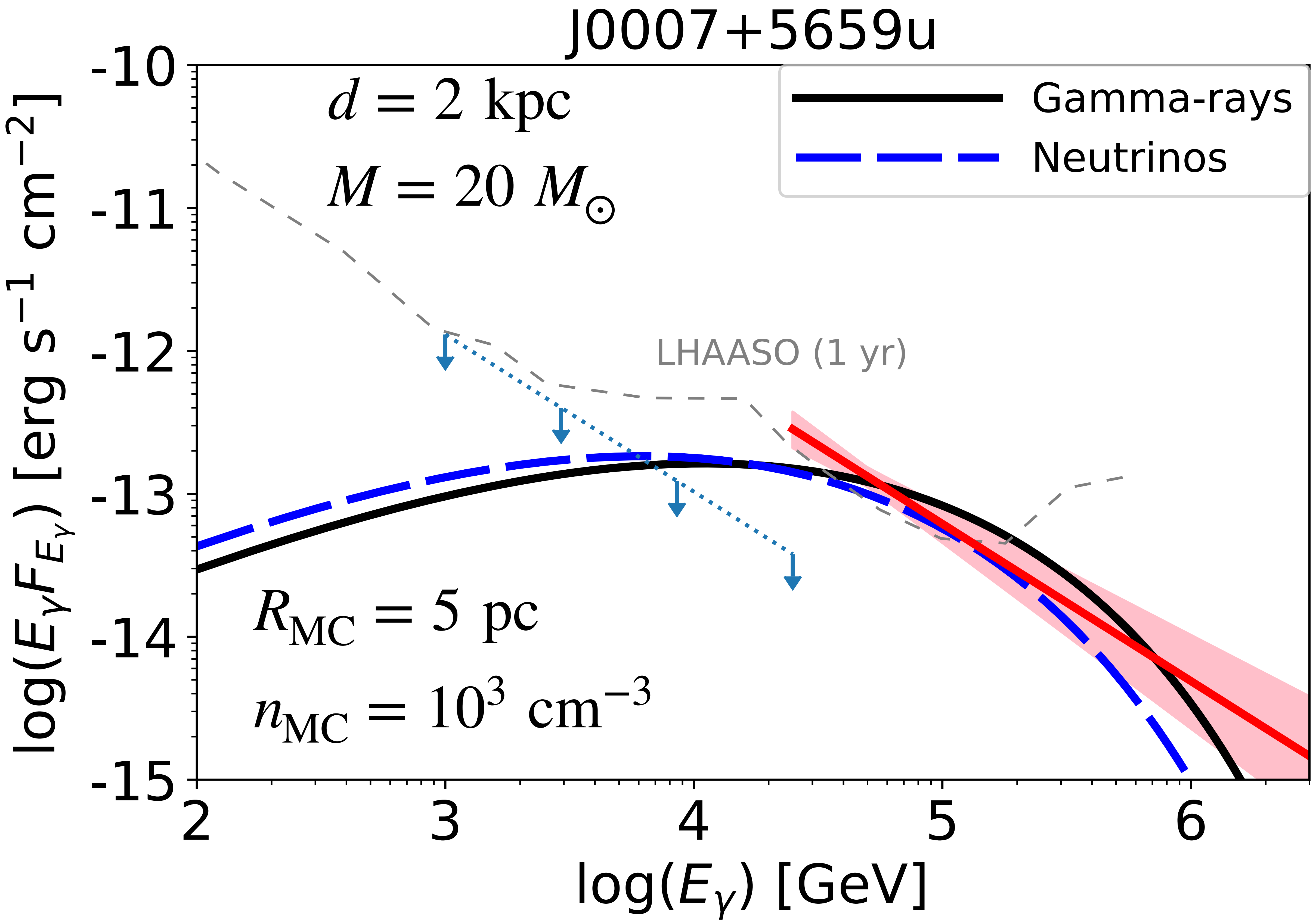
SSK, Tomida, Kobayashi, Kin, Zhang 2025

- Typical environment



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

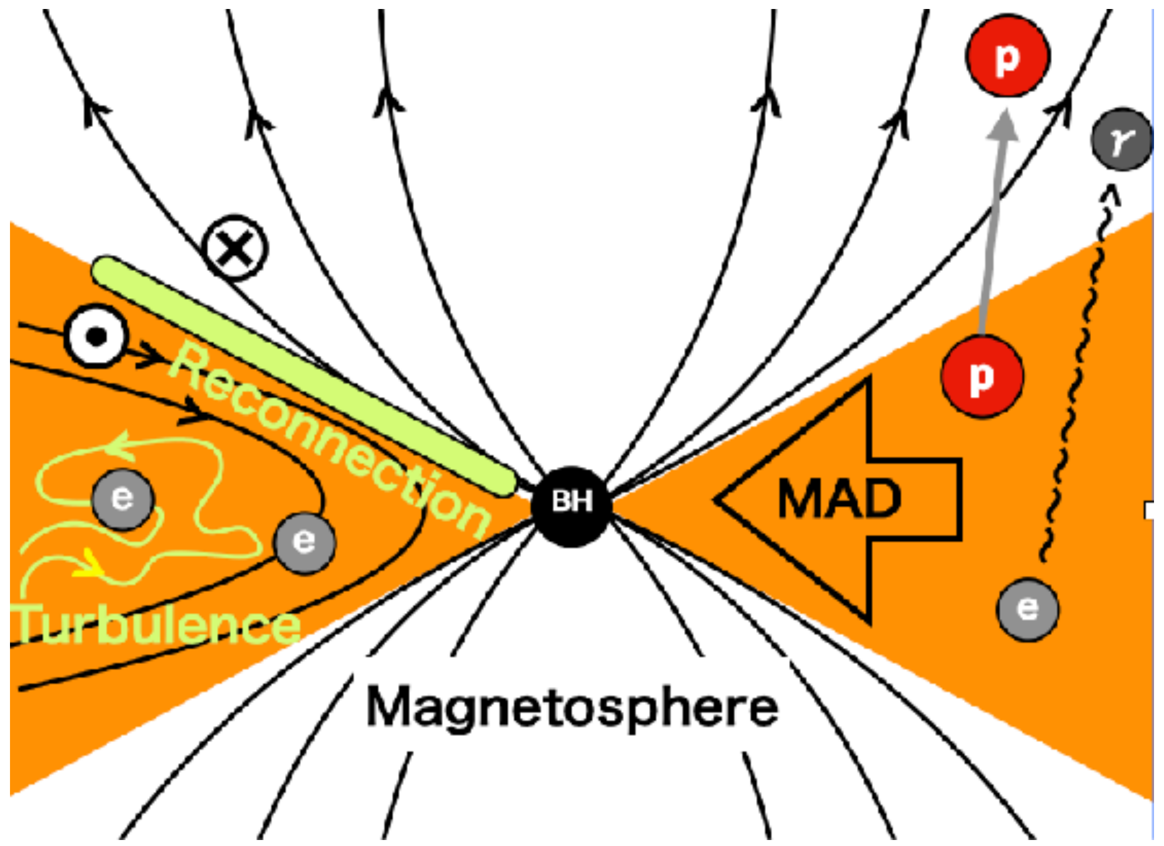
- Optimistic environment



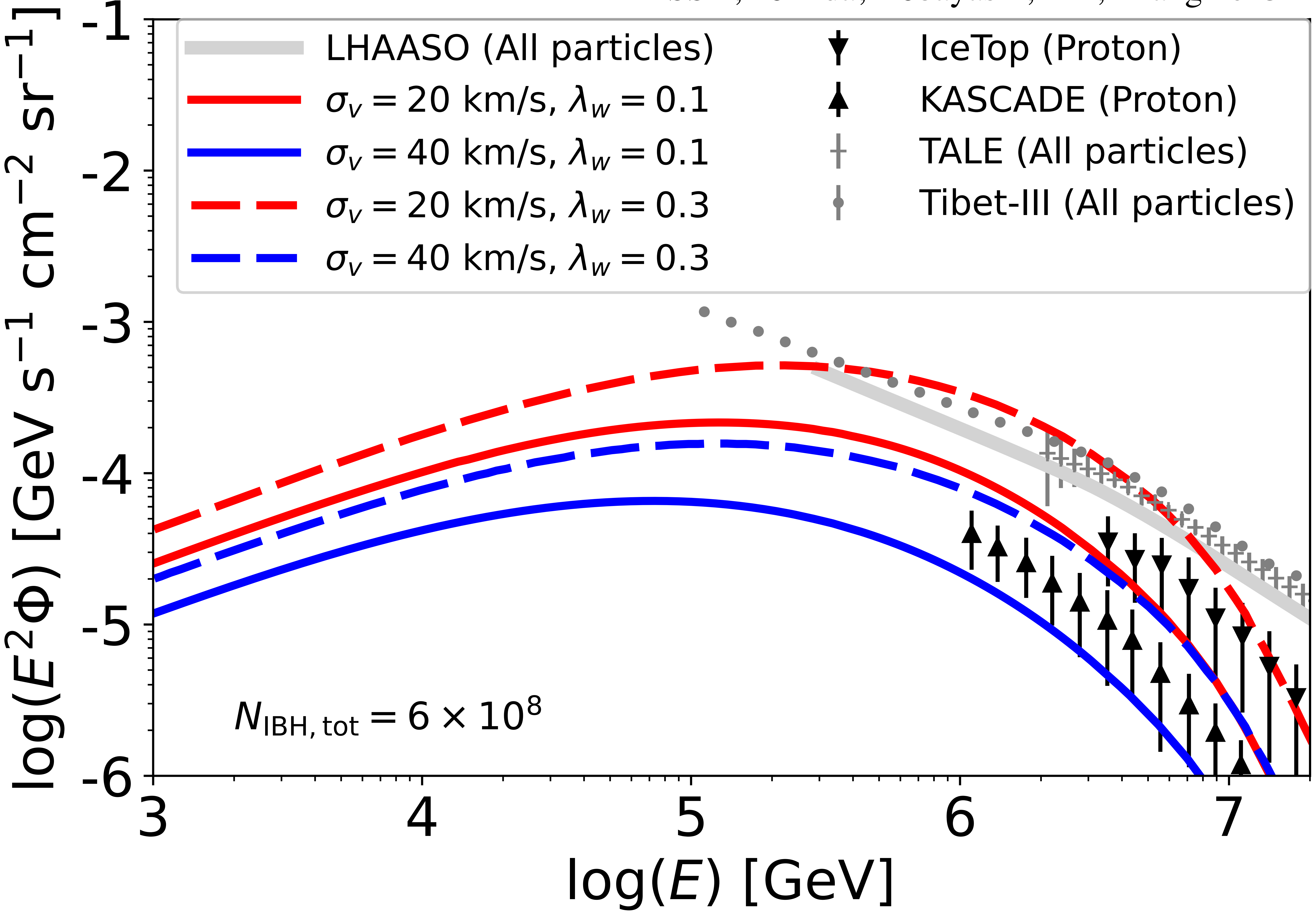
- Our scenario can explain LHAASO data
- Future detectors may be able to detect neutrinos from "dark" sources

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**

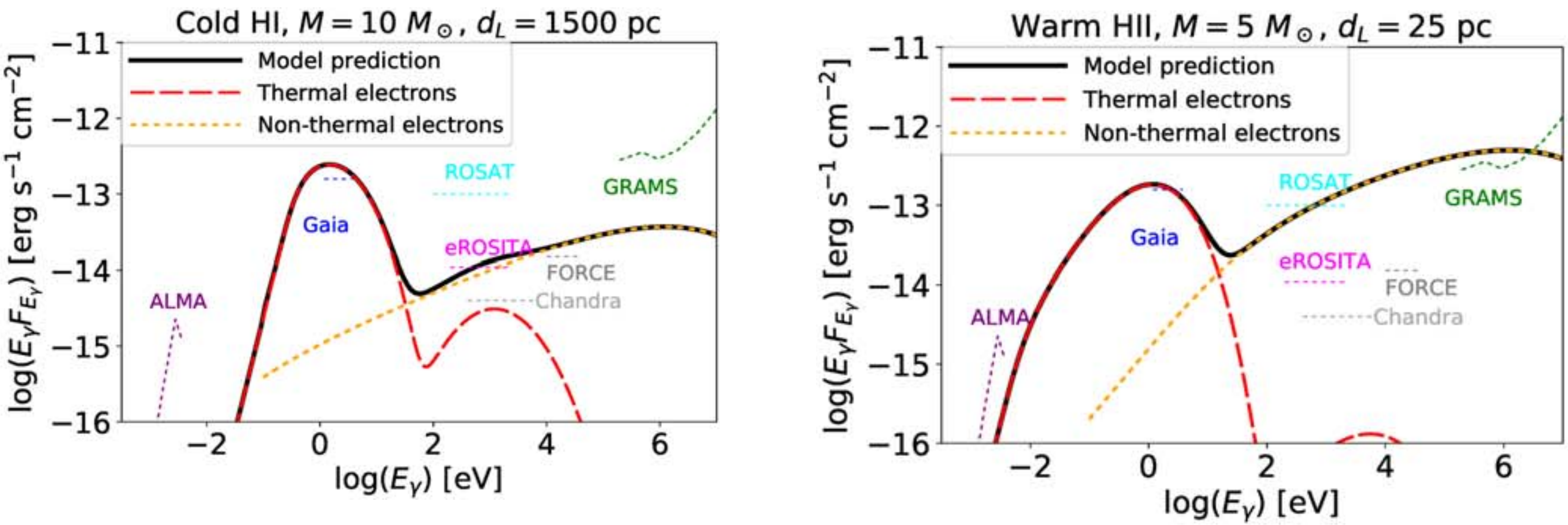


SSK, Tomida, Kobayashi, Kin, Zhang 2025



Future test of our scenario: identification of IBH

SSK, Kashiyama, Hotokezaka 2021

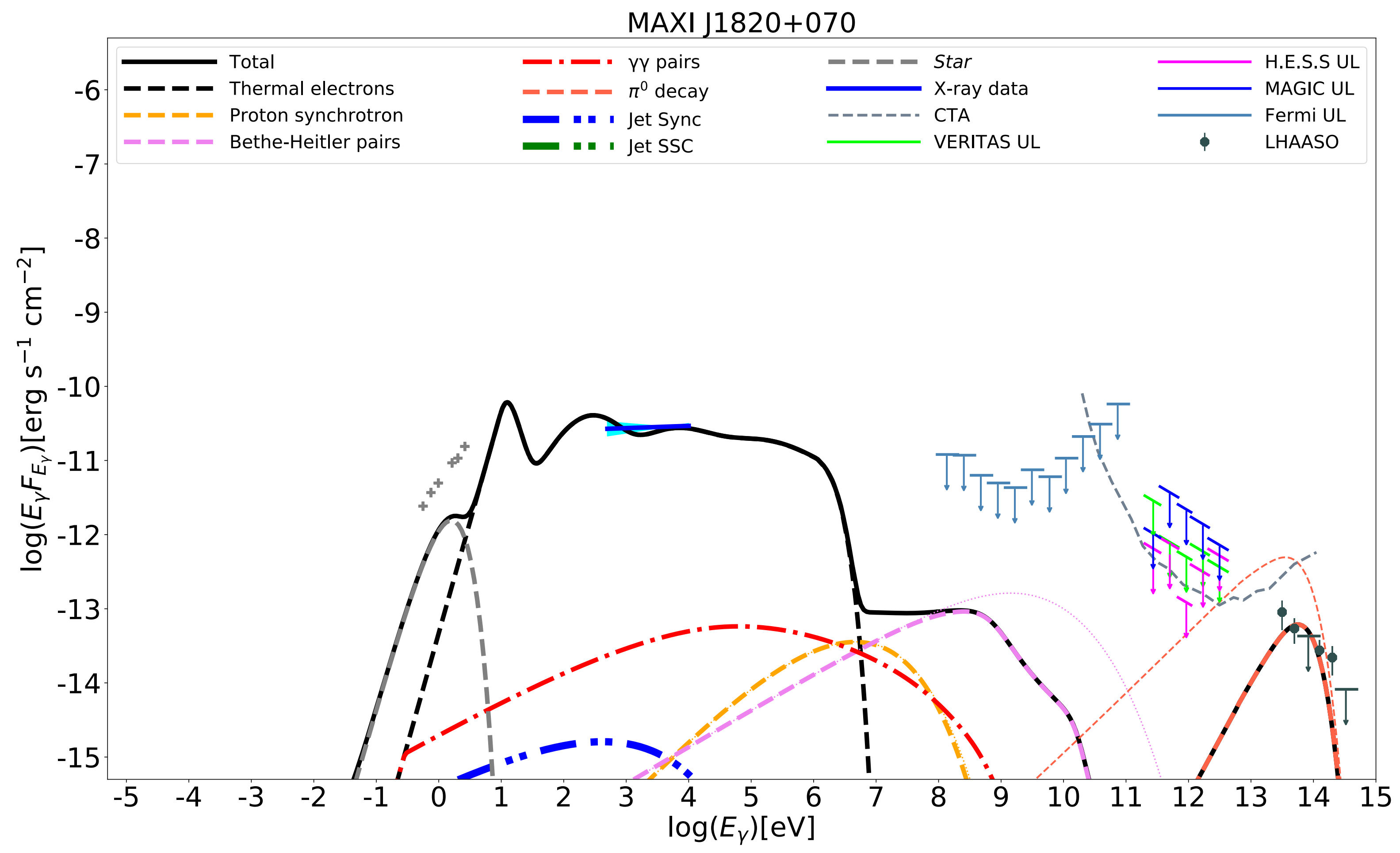


- Photon spectra from IBHs: bright in optical & X-rays
- X-ray by eROSITA & Optical by Gaia satellites
  => possibly able to identify IBHs using the data
- Our proposals for IBH search are accepted by Seimei telescope
  Please stay tuned

Summary

- Magnetic reconnection & turbulence in MADs can efficiently accelerate non-thermal particles
- Calibrating parameters using optical/X-ray data from quiescent BH X-ray binaries,
  MADs in X-ray binaries can explain UHE gamma-rays from Cyg X-1 & MAXI J1820+070
- Isolated black holes embedded in molecular clouds can be PeVatrons
  - **γ-rays from molecular clouds might be potential origin of "dark" LHAASO sources**
  - Optical & X-ray observations will provide good tests on our scenario

Kuze, SSK, Fang 2025



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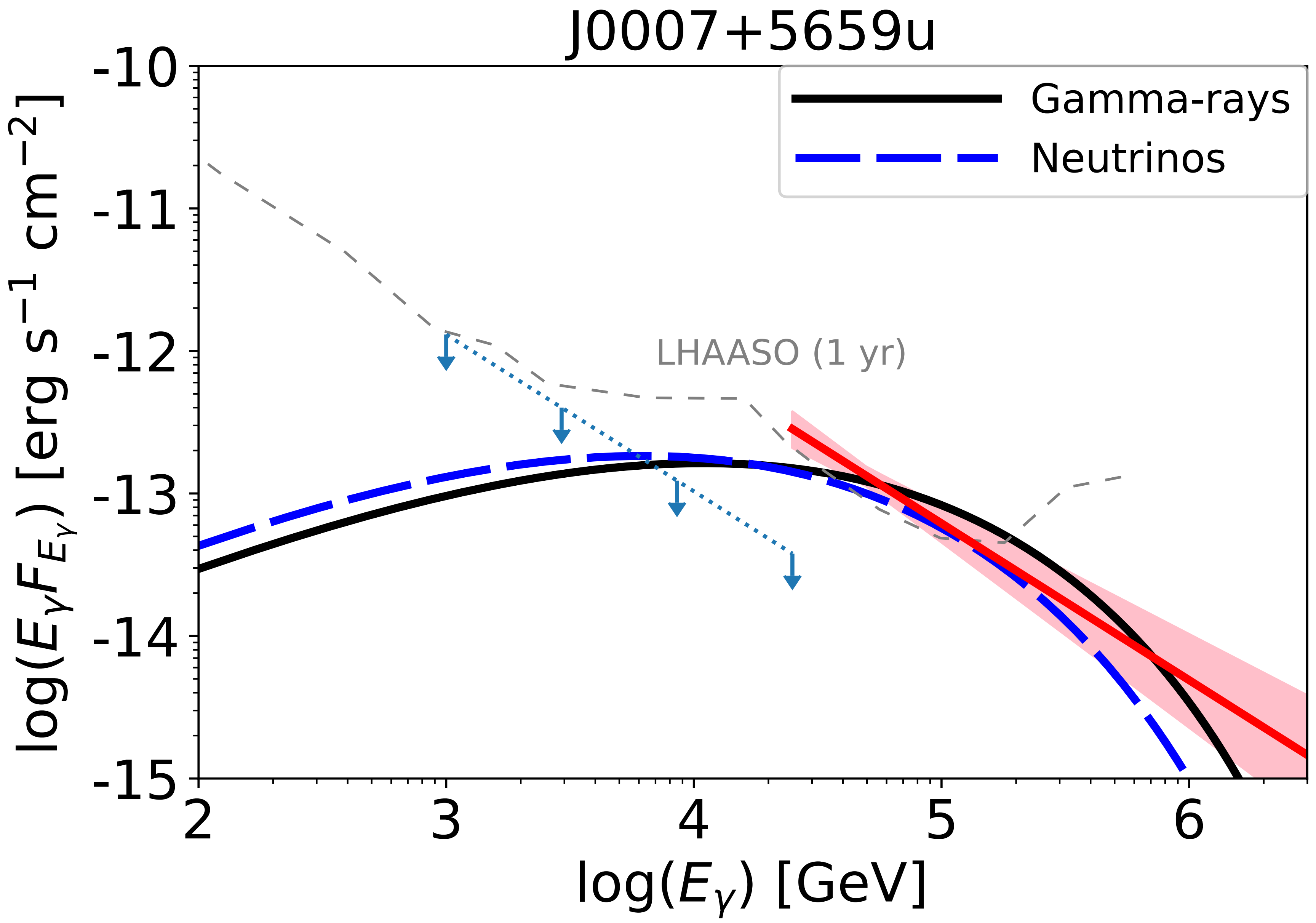

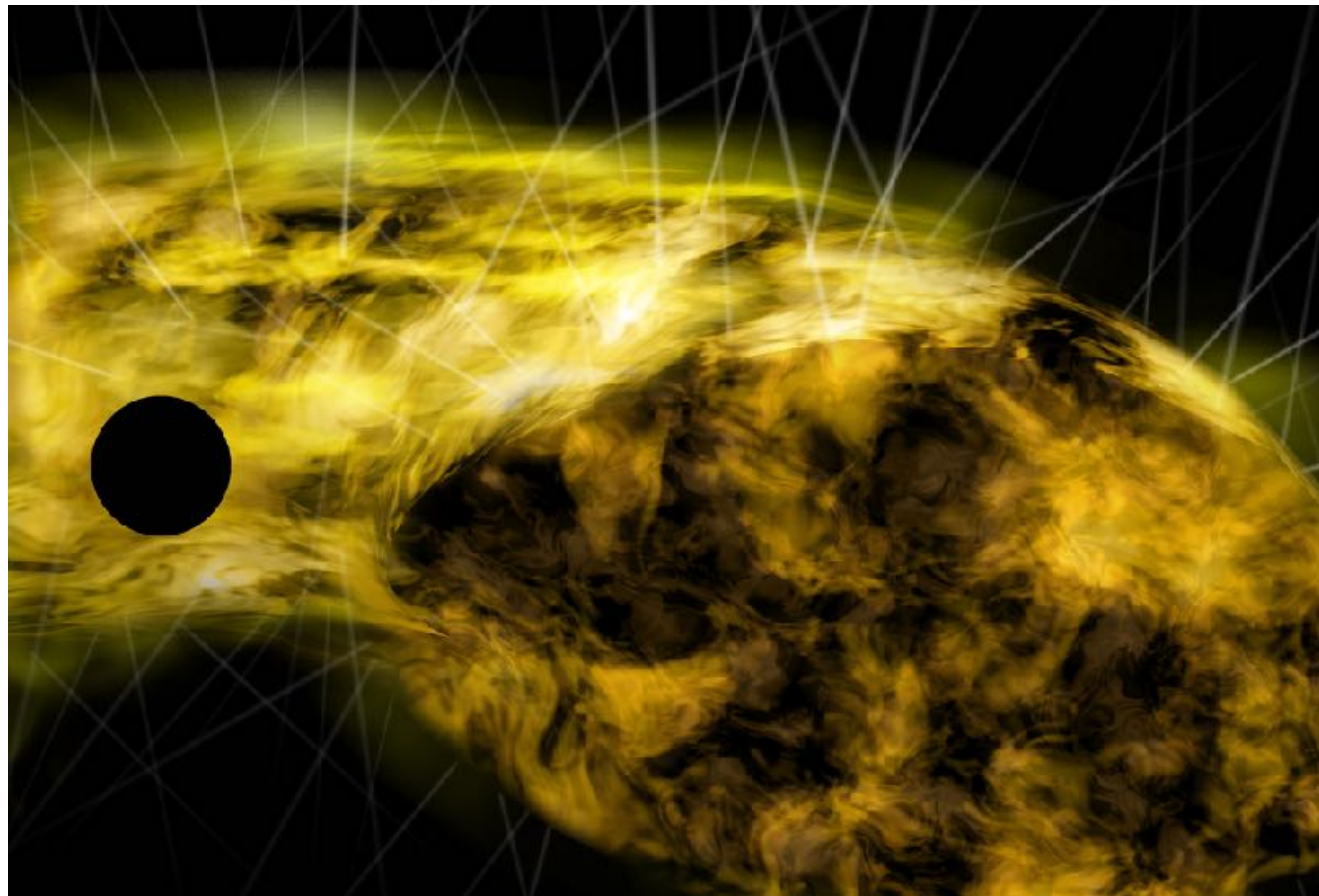

Thank you
for
your attention