Galactic Stellar-mass Black Holes as Potential PeVatrons

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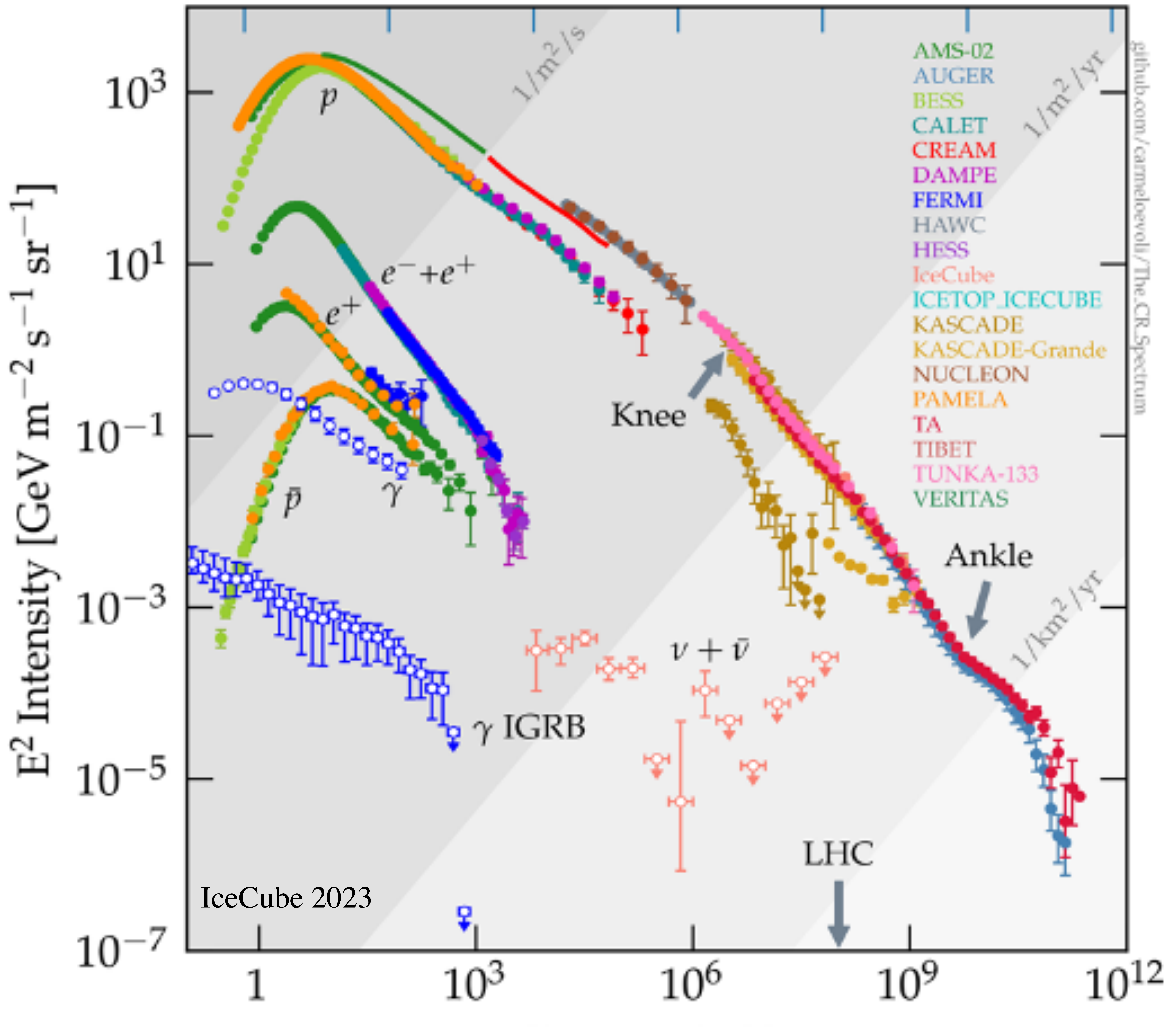
References
B.T. Zhang, SSK, Murase et al. 2025, PRD
Kuze, SSK, K. Fang 2025 ApJ
SSK, Tomida Kobayashi et al. 2025 ApJL

MeV–PeV Frontiers: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration
2025/12/16 — 2025/12/18

Index

Cosmic ray spectrum

- Power-law spectrum from 1 GeV — 100 EeV
- GeV-TeV: supernova remnants
- **PeV-EeV: unknown** (probably Galactic)
- EeV - : Extragalactic

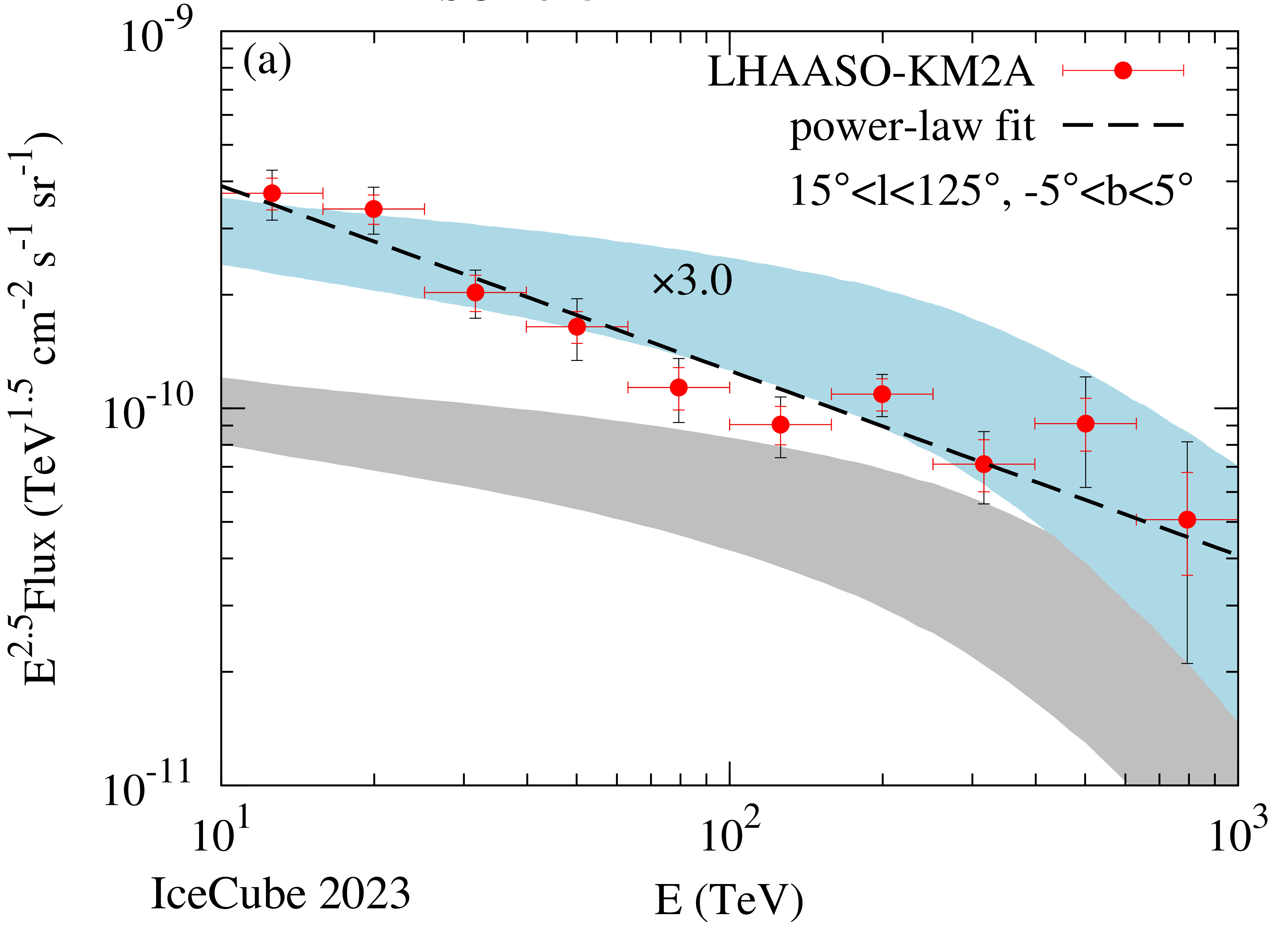


Credit: C. Evoli

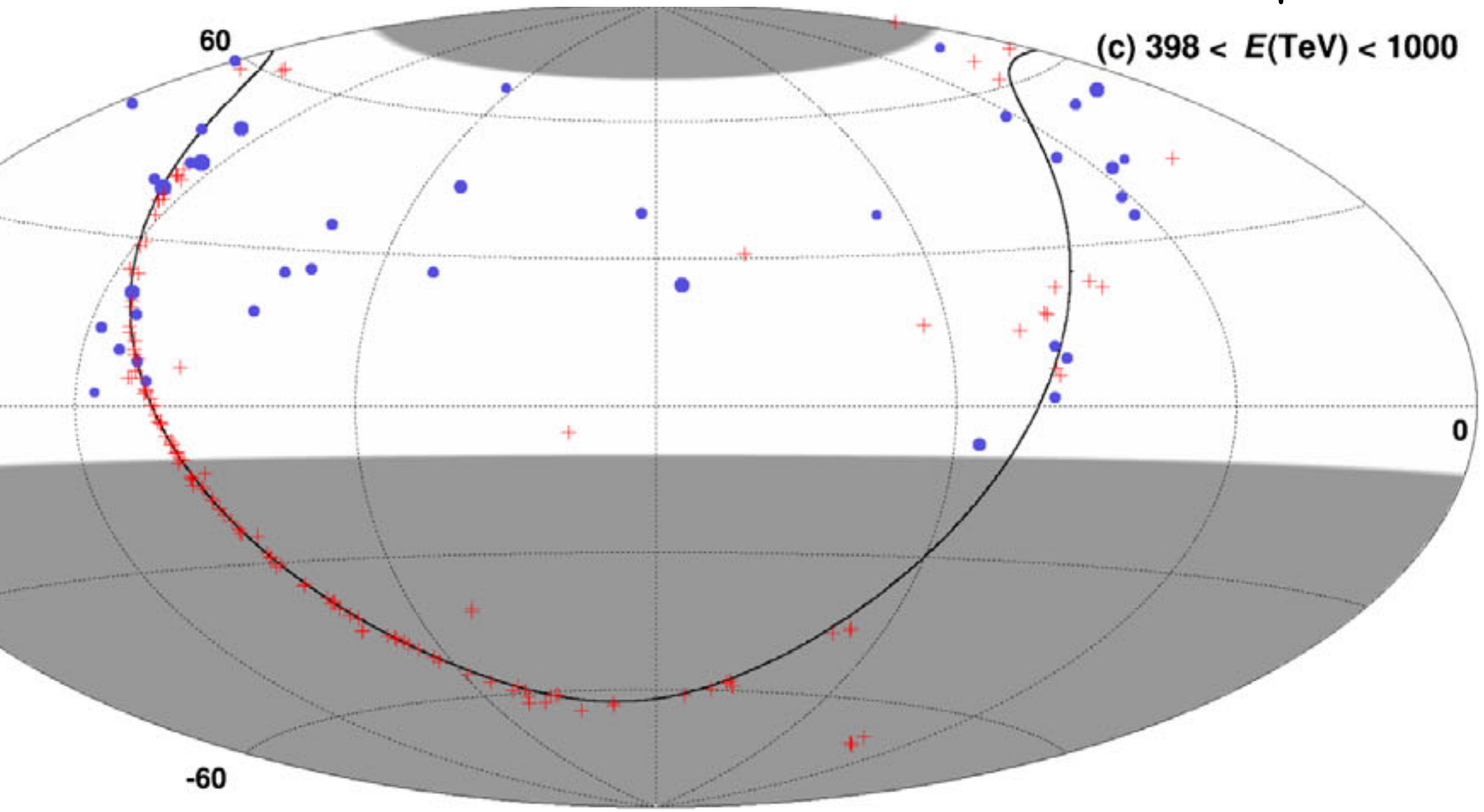
Galactic PeVatrons

- 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**

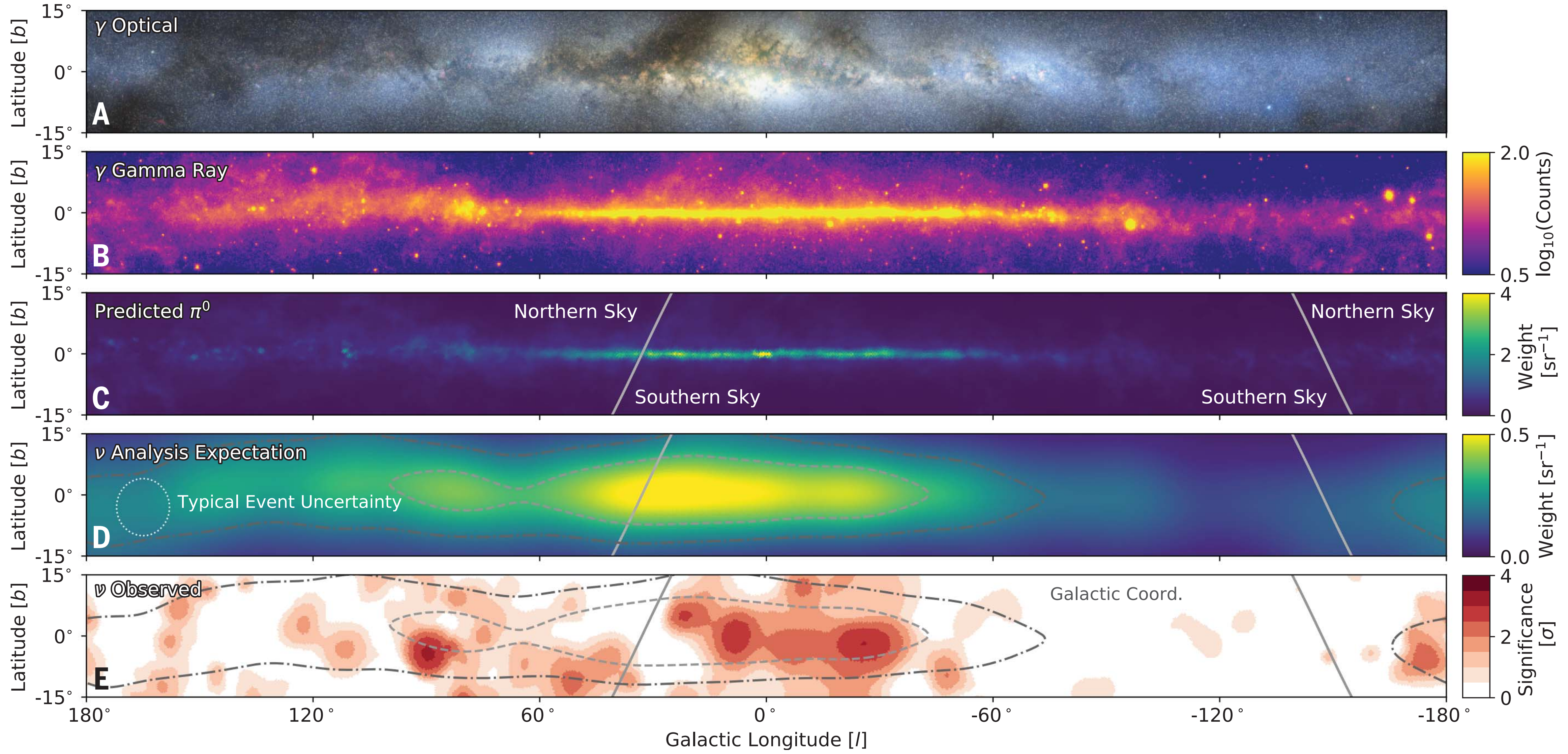
LHAASO 2023



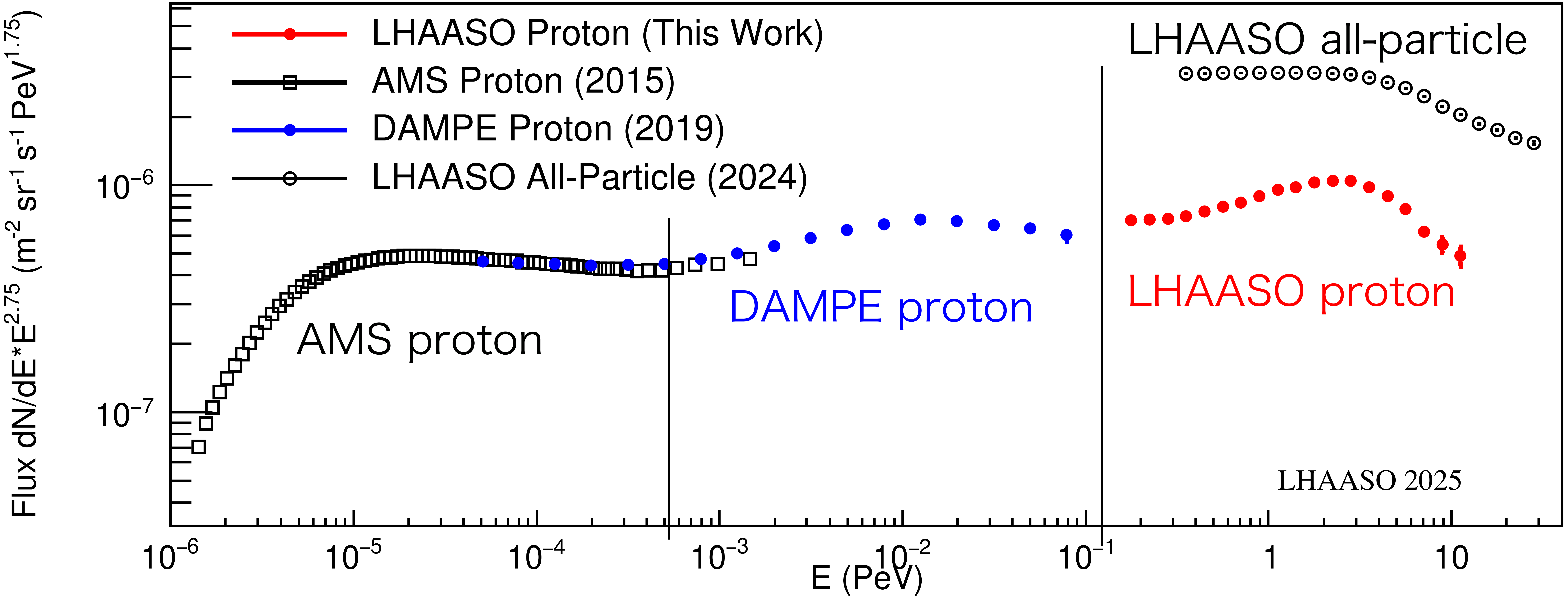
Tibet ASγ 2021



IceCube 2023

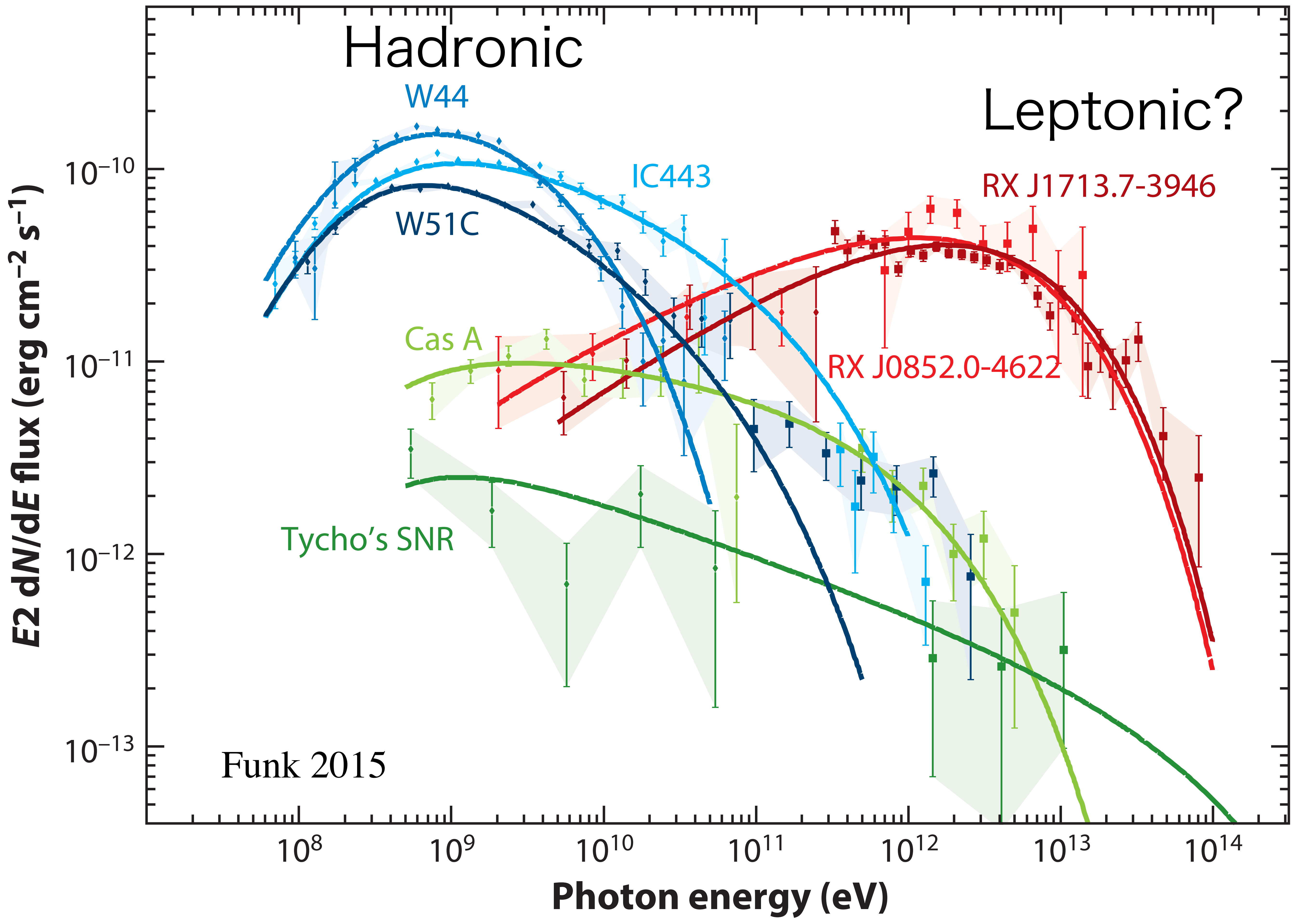


LHAASO & DAMPE CR spectrum

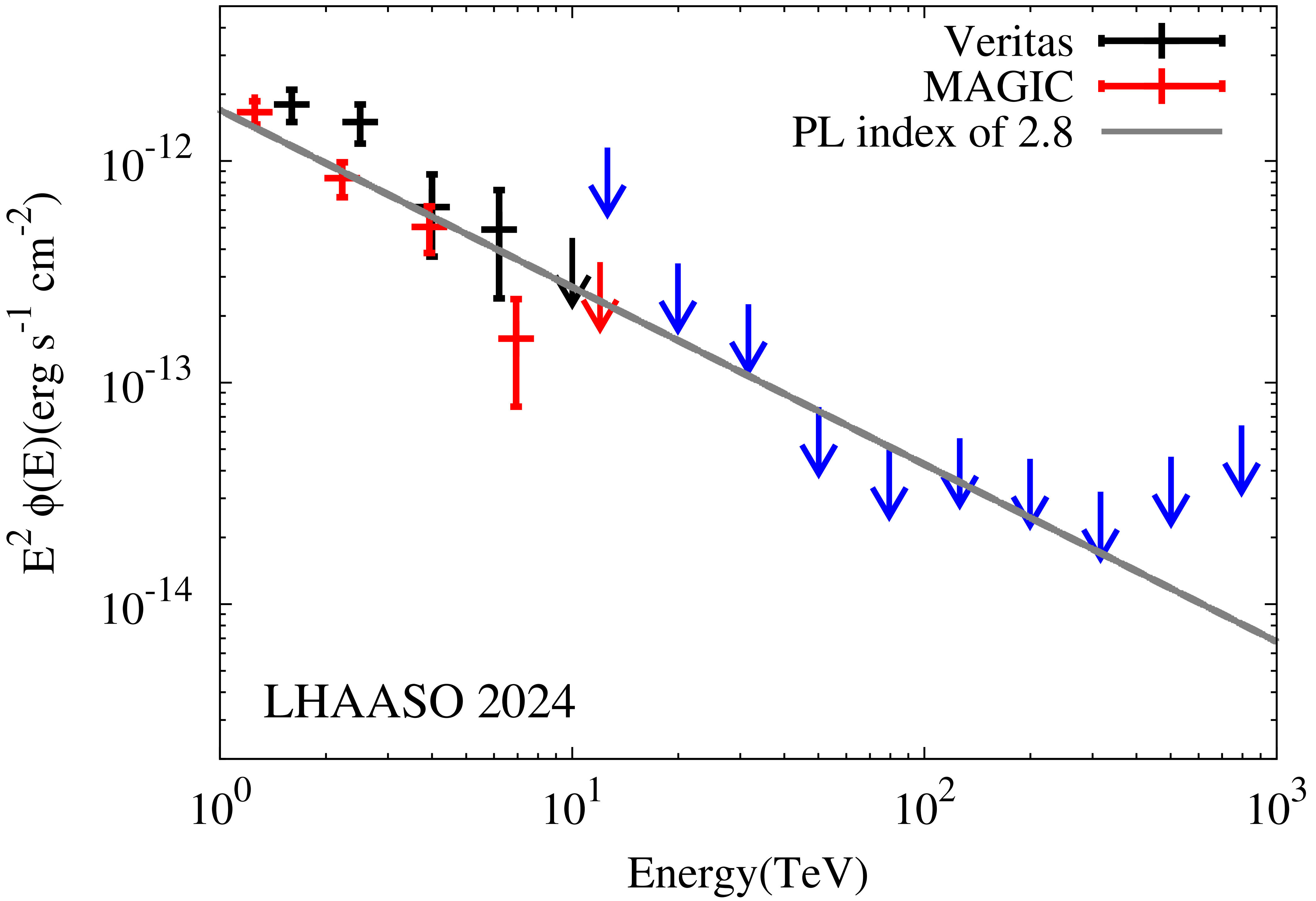


- Hardening around 100 TeV
  => New sources at E > 100 TeV?
- The break energy in proton spectrum is consistent with that in all-particle one

Gamma-ray spectrum from SNR



Gamma-ray spectrum of Cas A



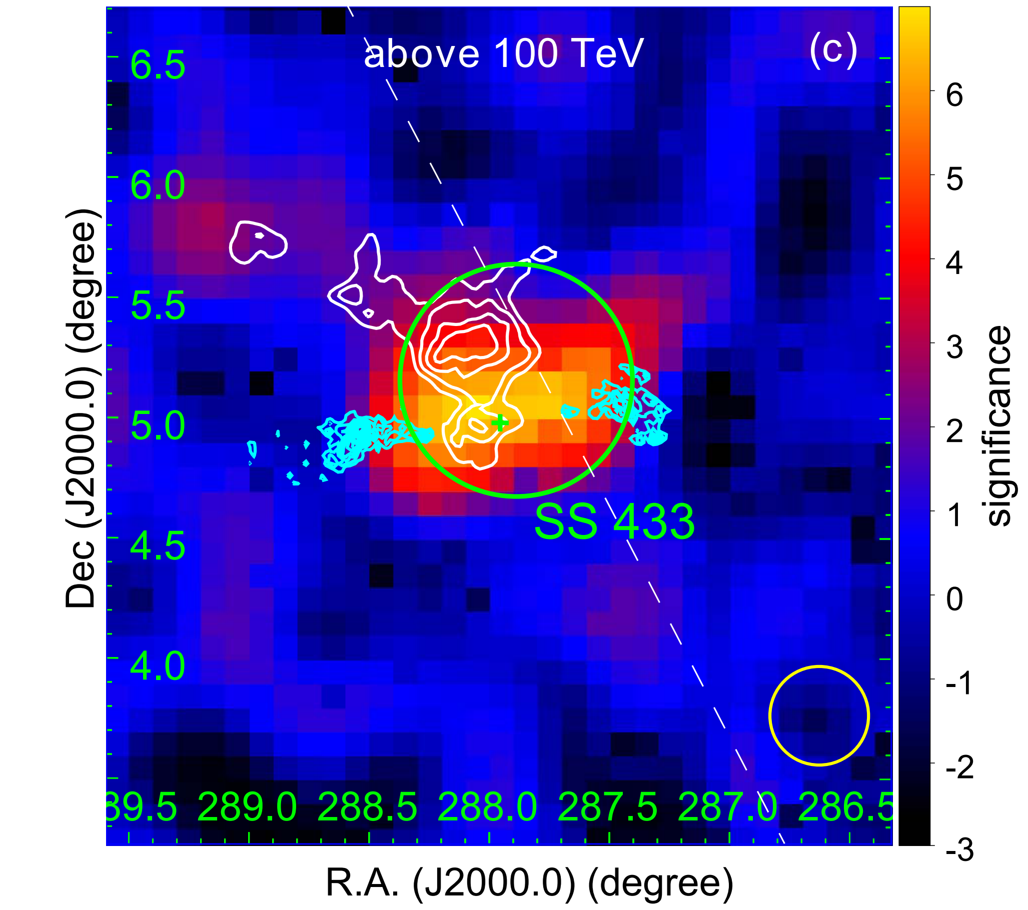
- Some SNRs are identified as PeVatrons, but many have soft spectra at $E_\gamma \sim 10$ TeV
- The youngest SNR (Cas A) does not accelerate CRs up to 100 TeV?
- We need another class of PeVatrons

UHE γ-rays from X-ray binaries

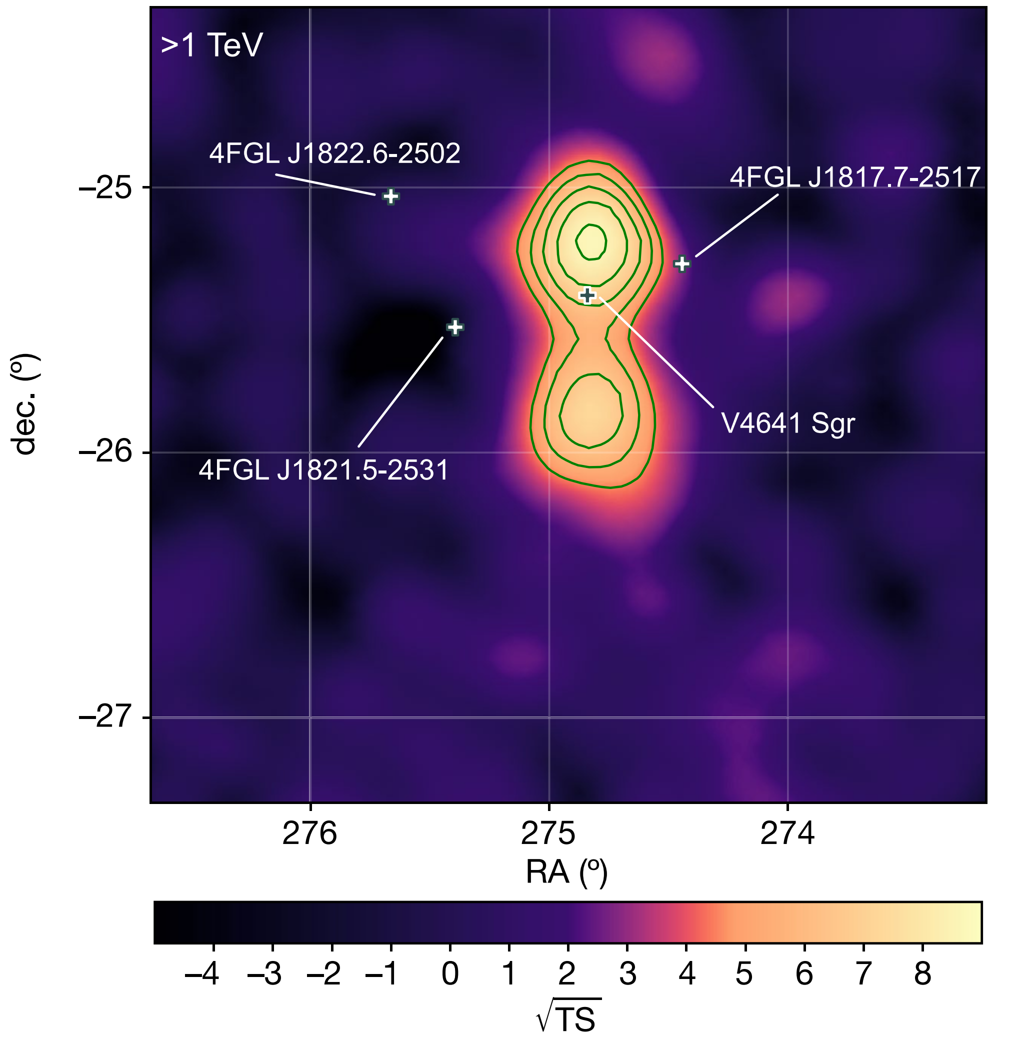
- HAWC detection of 2 microquasars SS433, V4641 Sgr
  - Extended morphology => extended jets?
- LHAASO detection of 5 X-ray binaries SS433, V4641 Sgr, G1915+105, Cyg X-1, MAXI J1820+070
  - E > 100 TeV without softening => Hadronic origin?

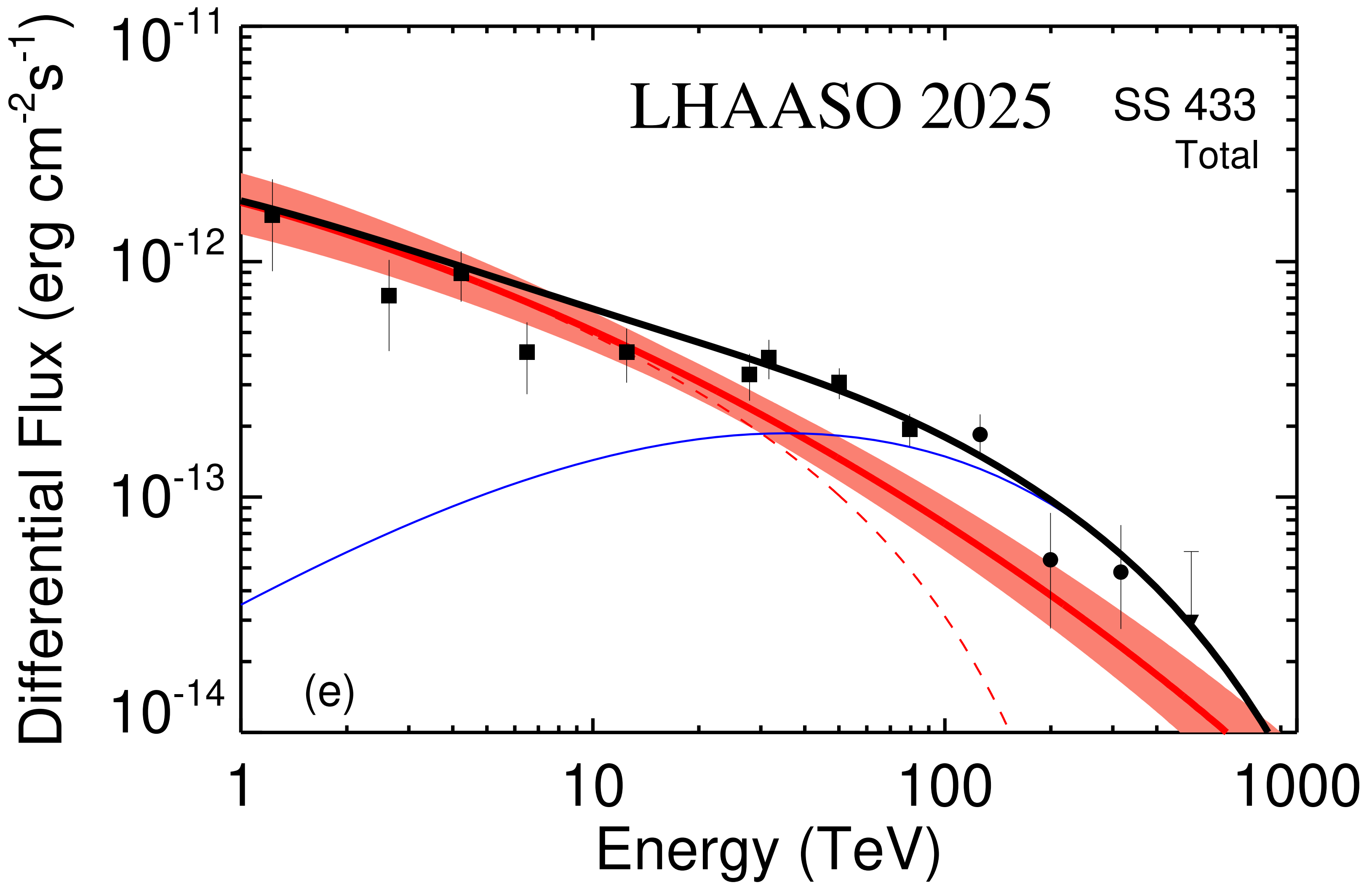
e.g., Ohira 2025
See Wan et al. 2025 for leptonic interpretation of V4641 Sgr

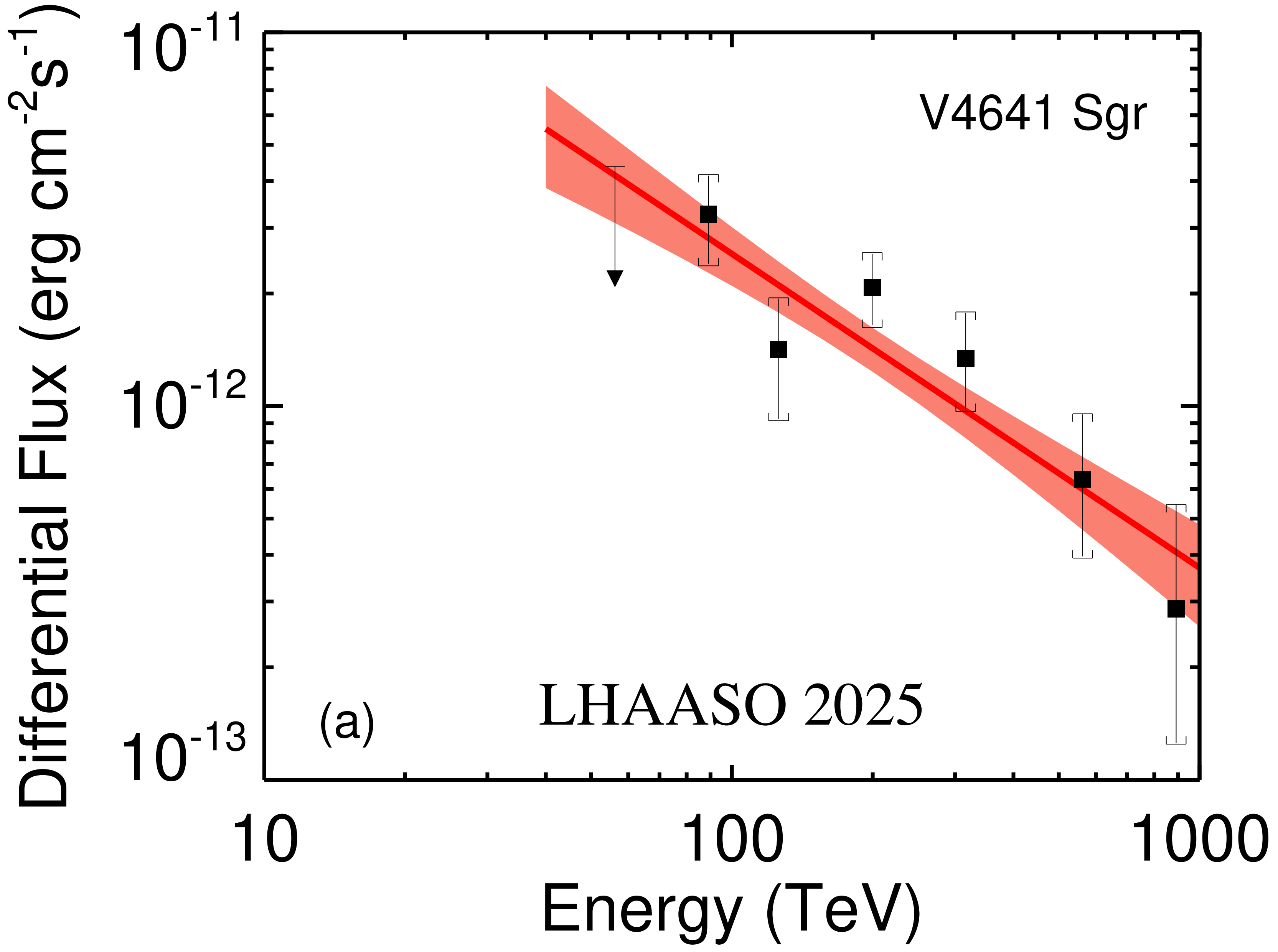
LHAASO 2025



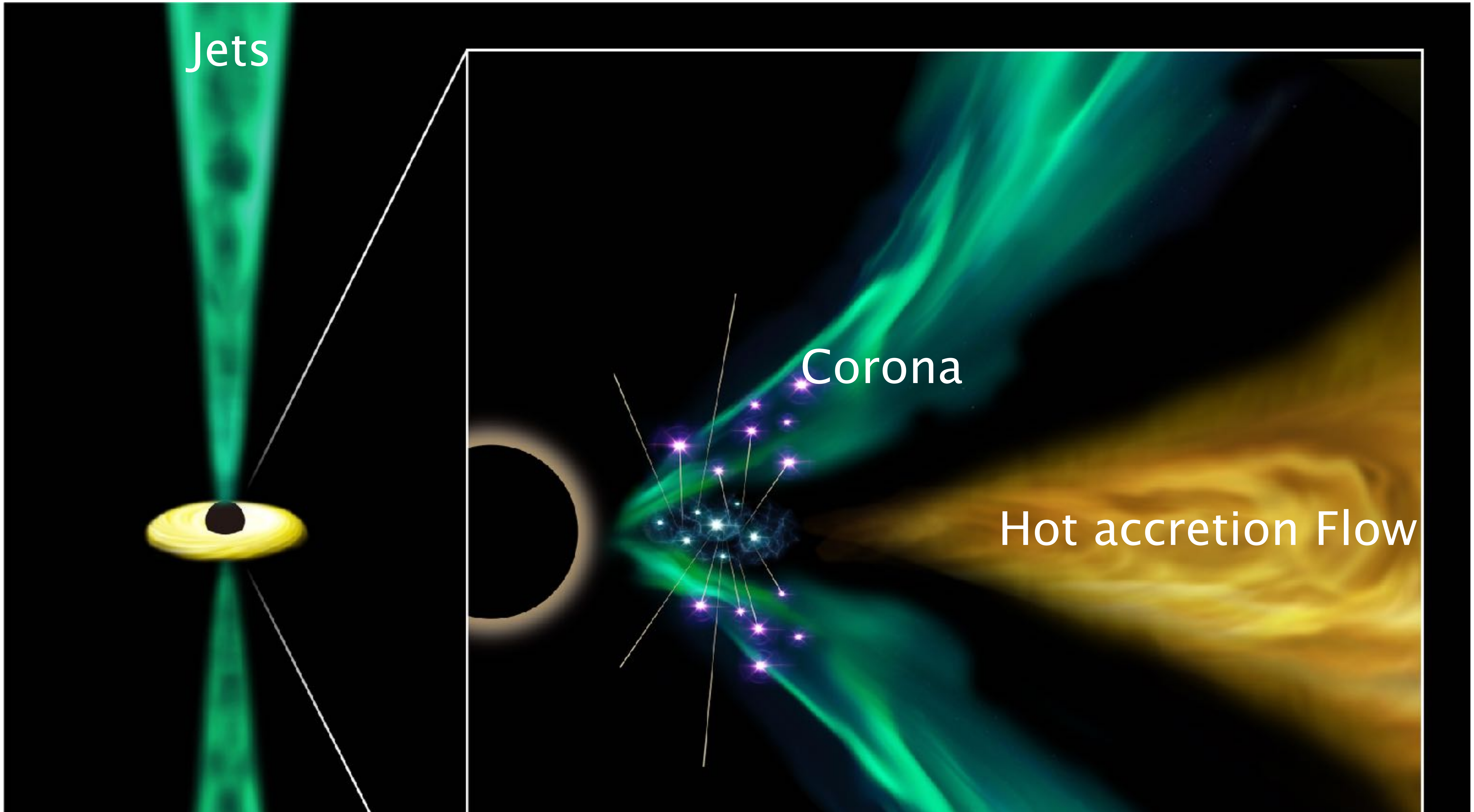
HAWC 2024







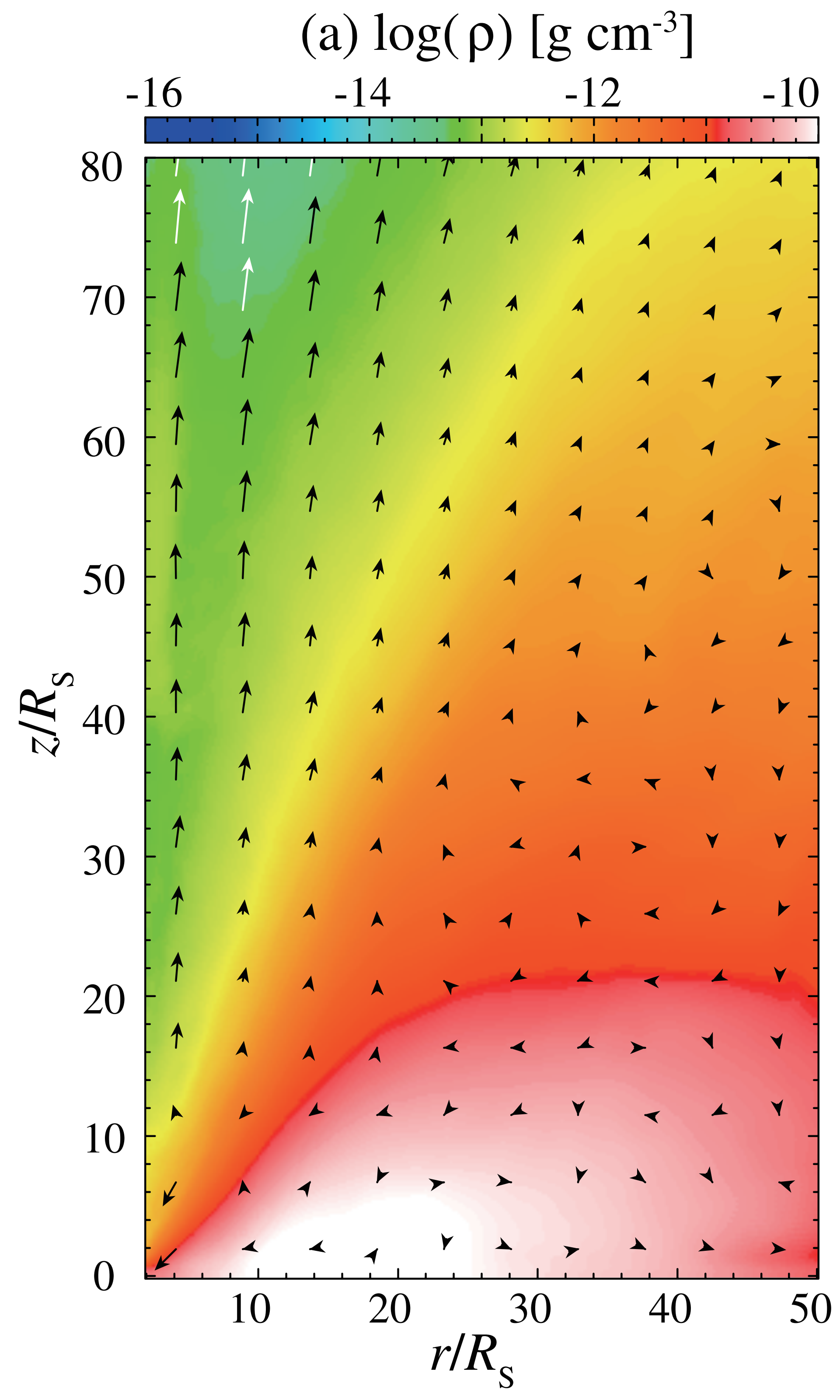
Stellar-mass Black Holes as PeVatrons



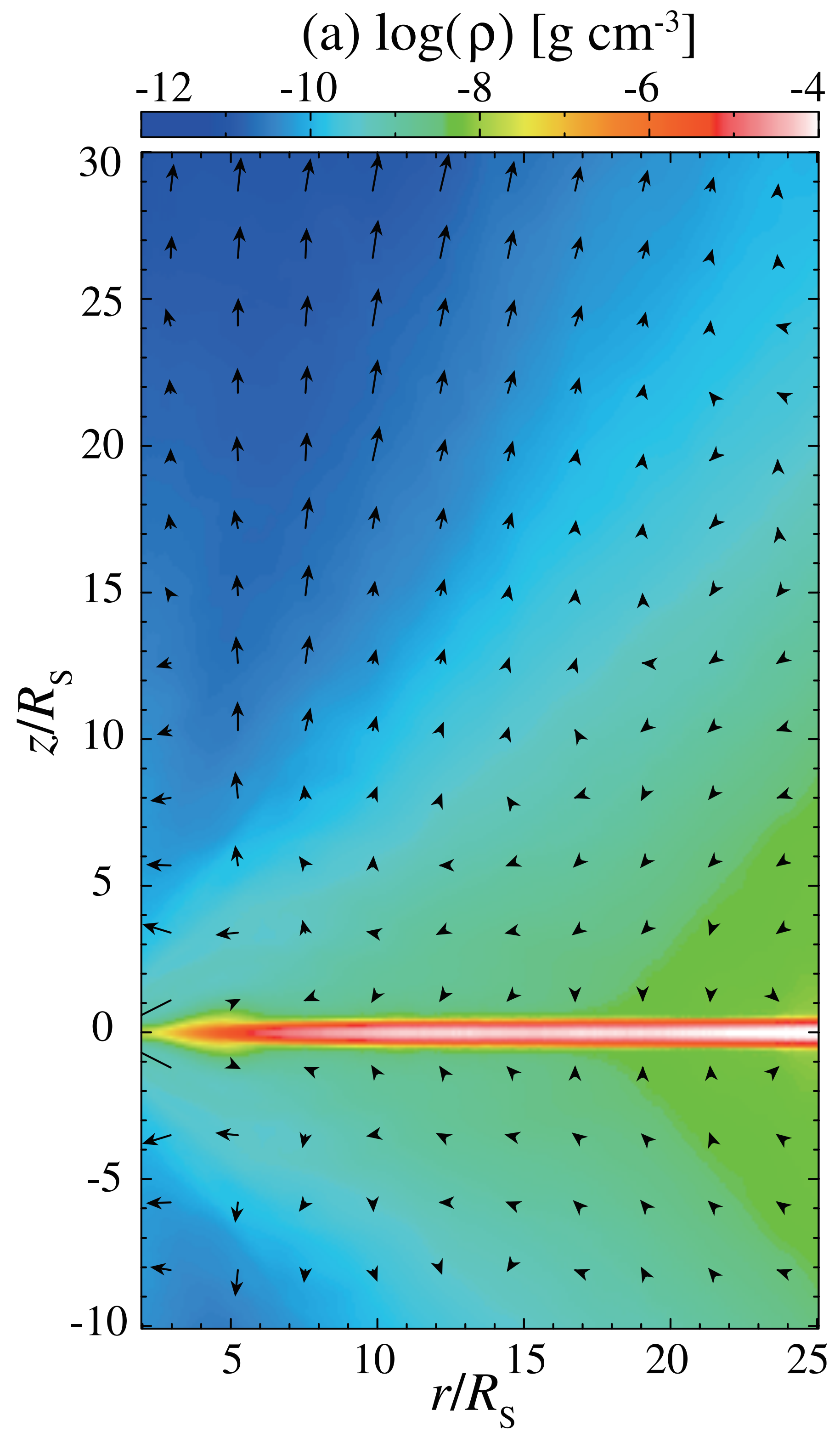
3 states of black hole accretion

Ohsuga & Mineshige 2011

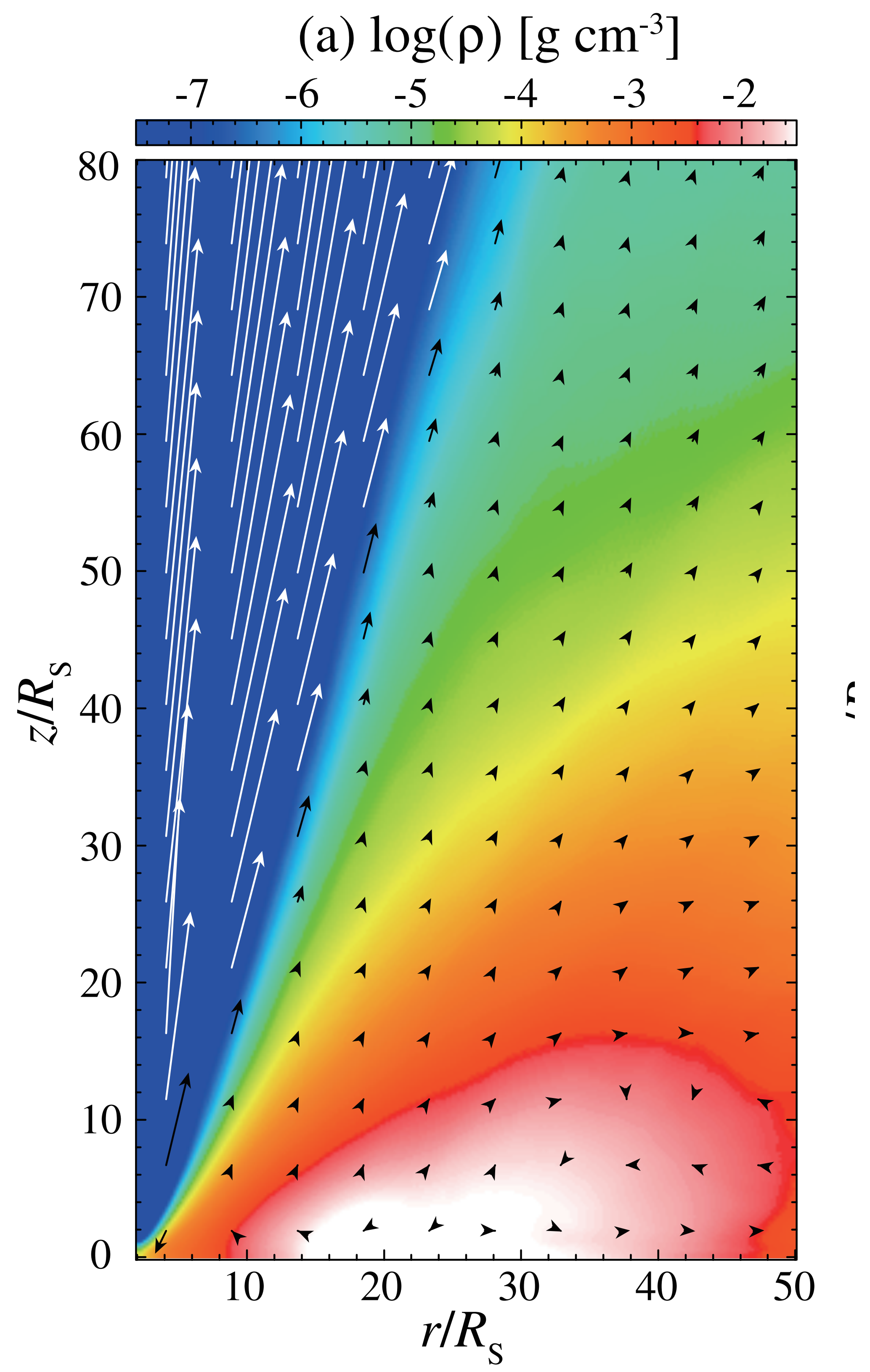
Hot Accretion Flow (RIAF)



Standard accretion disk



Slim disk + Jets



$L \sim 0.01 L_{\mathrm{Edd}}$

$L \sim L_{\mathrm{Edd}}$

$L = \eta \dot{M} c^2$

3 states of black hole accretion

Ohsuga & Mineshige 2011

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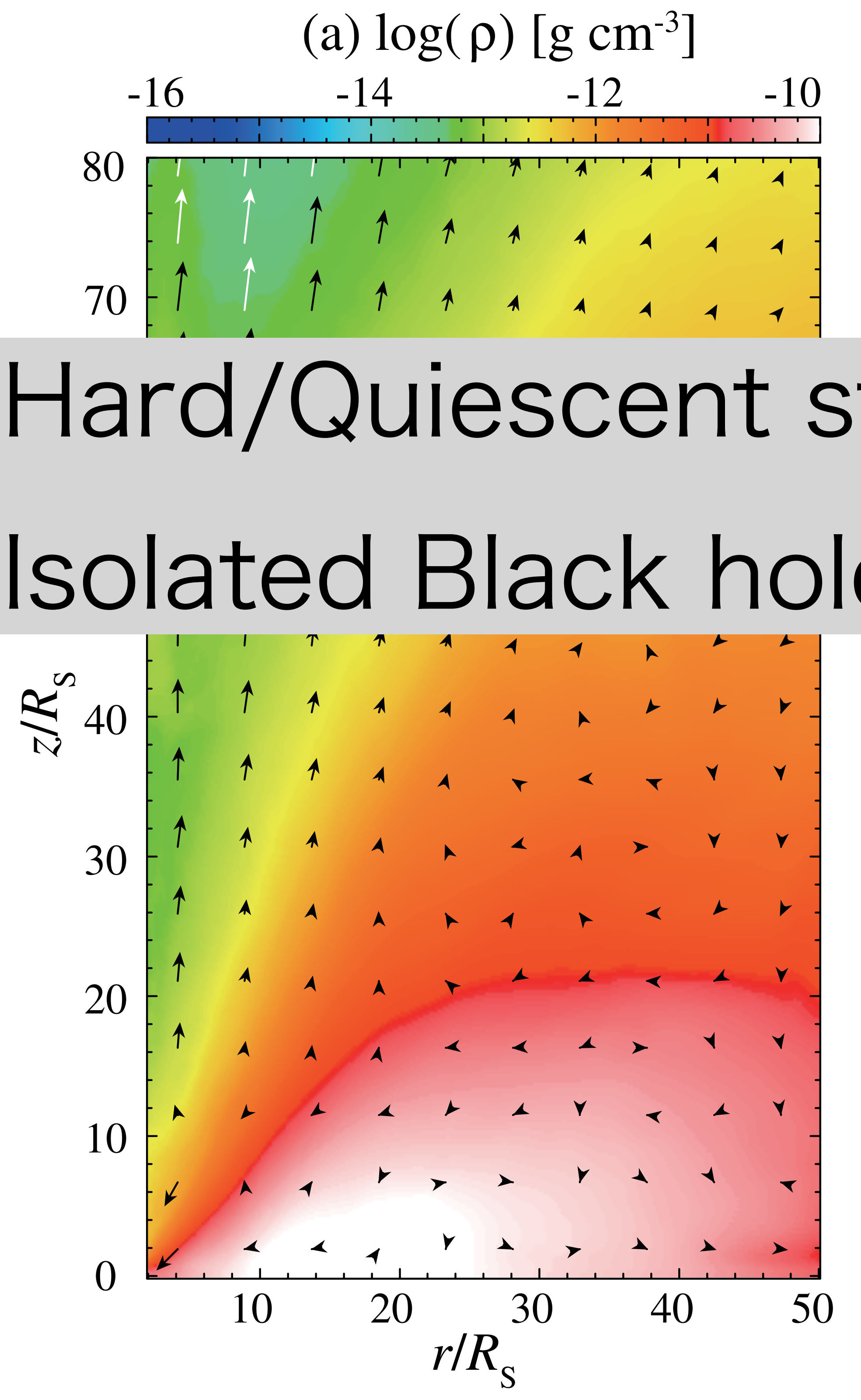
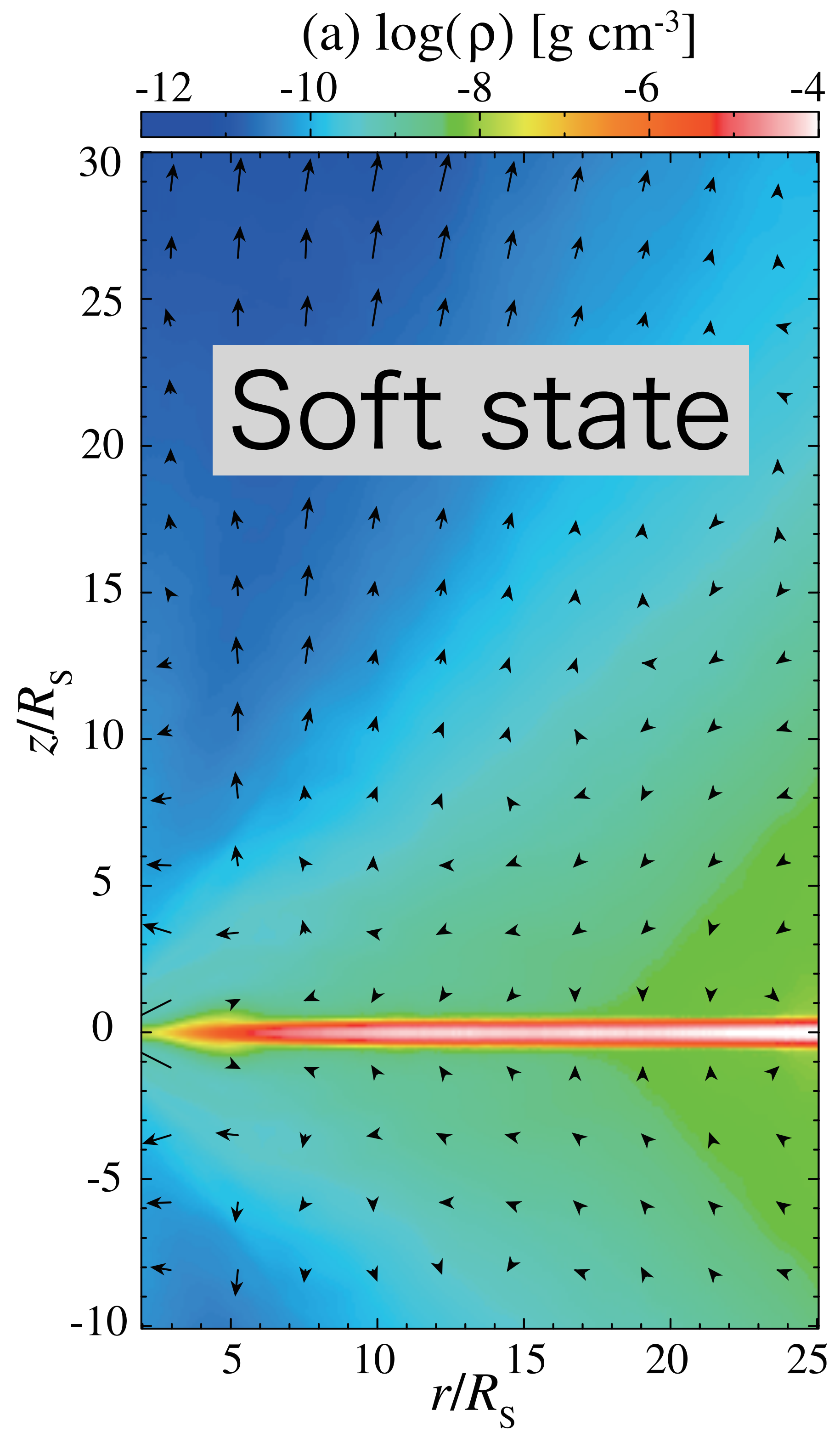


Hard/Quiescent state

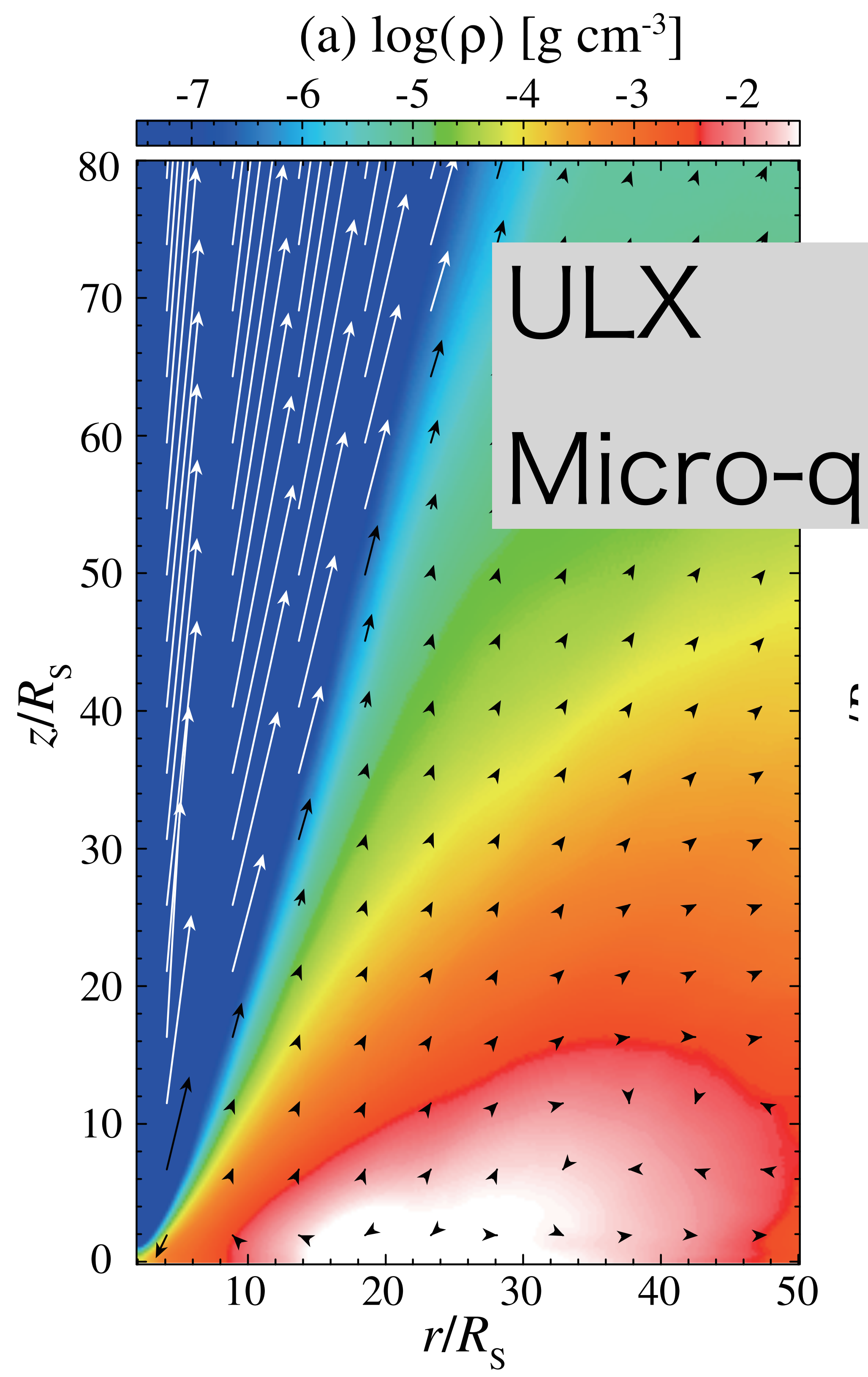
Isolated Black holes

Standard accretion disk



Soft state

Slim disk + Jets



ULX

Micro-quasars

$L \sim 0.01 L_{Edd}$ $L \sim L_{Edd}$ $L = \eta \dot{M} c^2$

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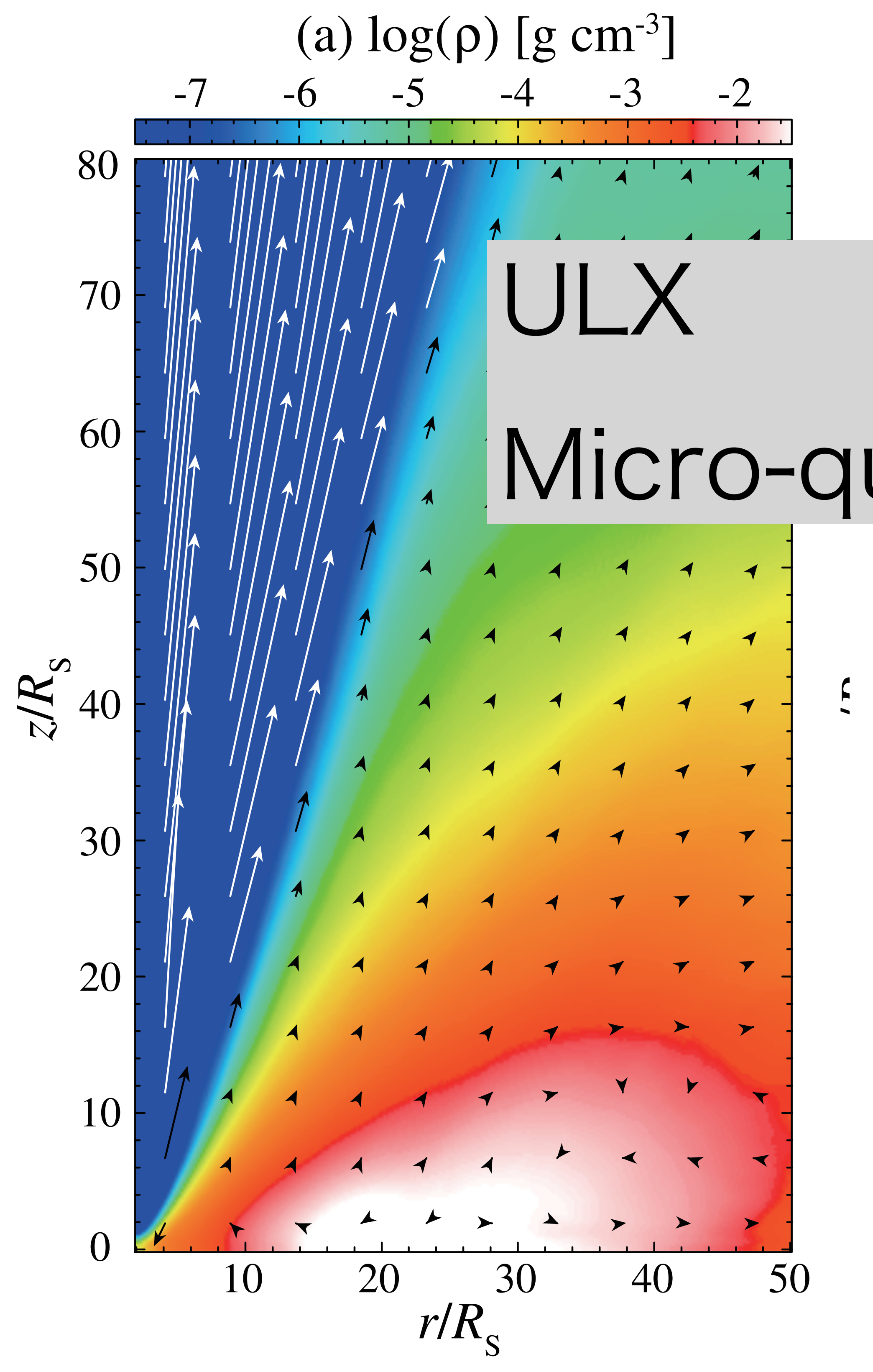

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$L = \eta \dot{M} c^2$

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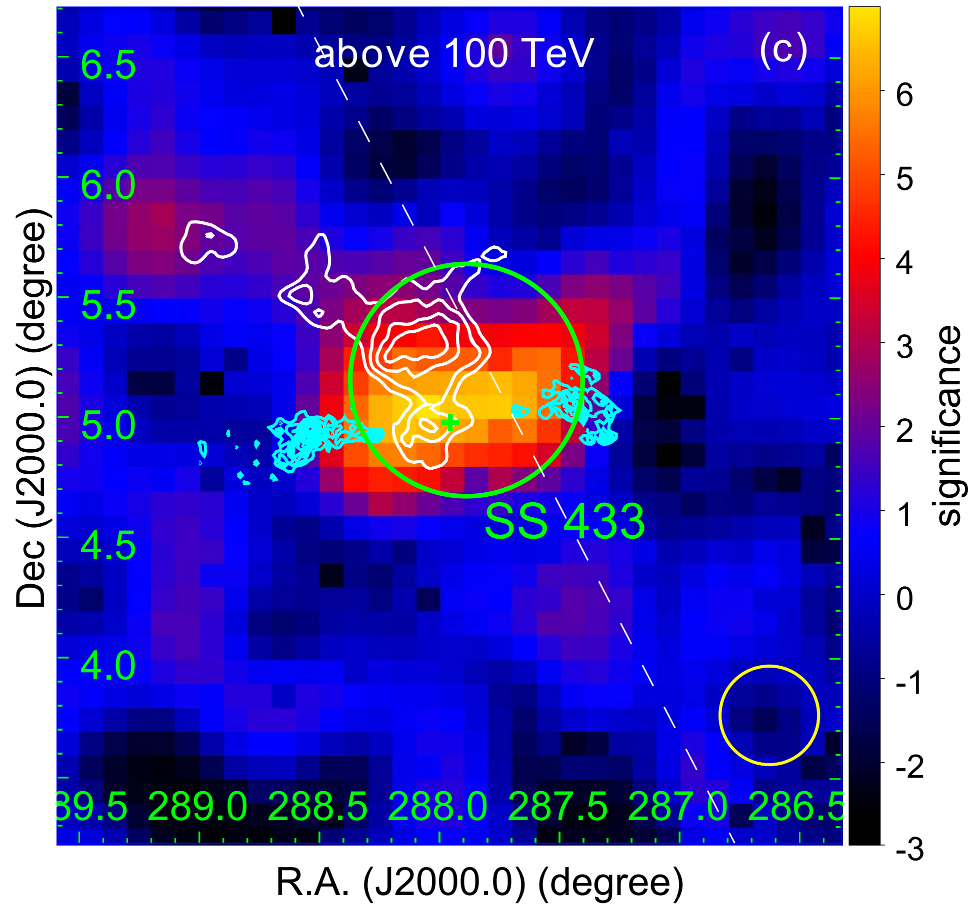
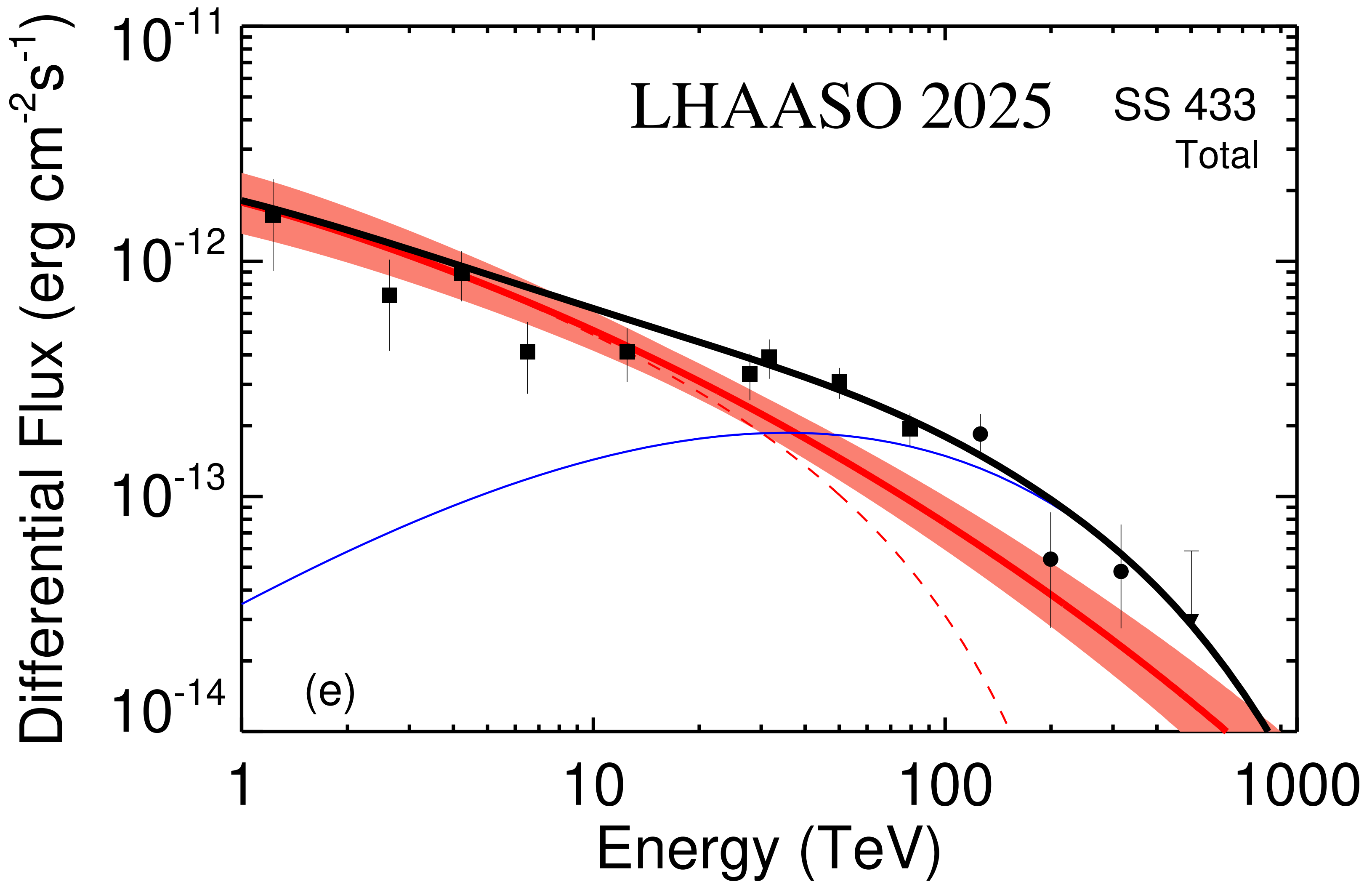
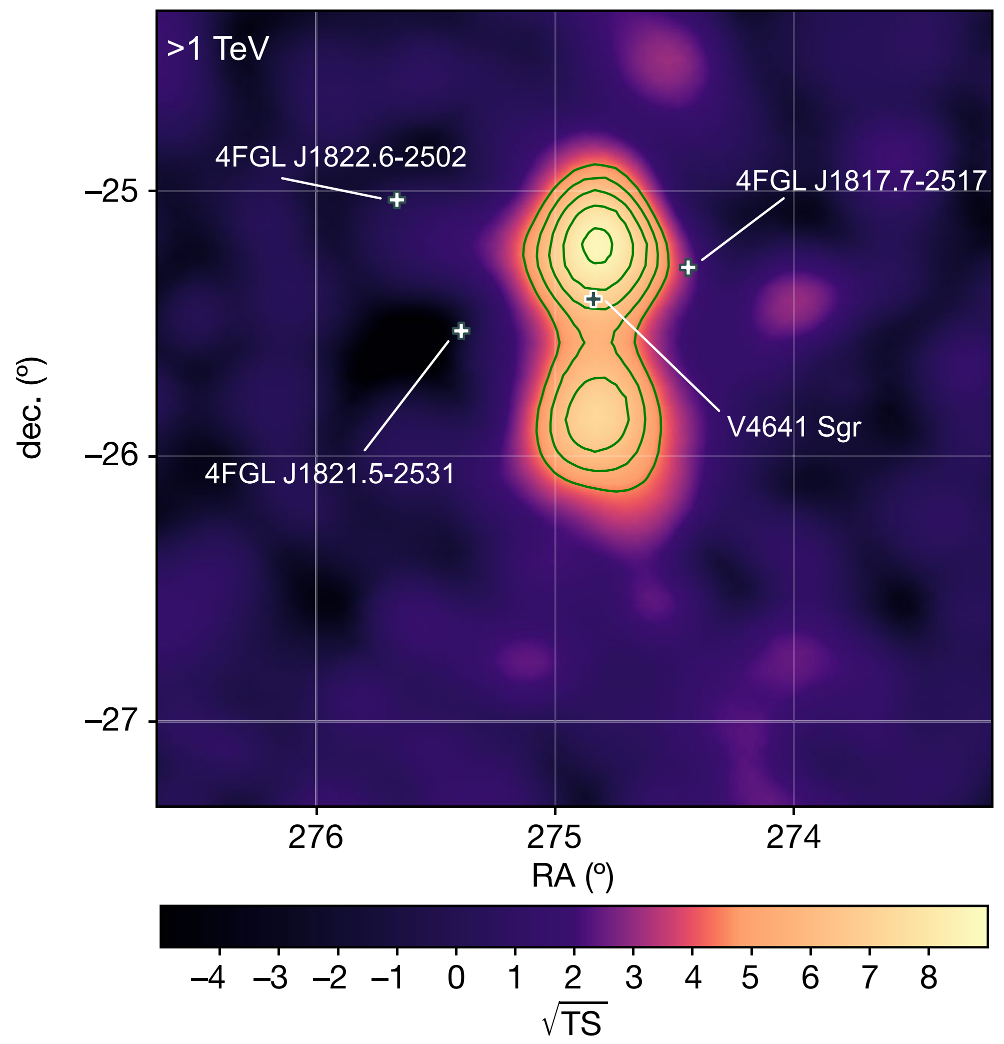
- LHAASO detection of 5 X-ray binaries SS433, V4641 Sgr, G1915+105, Cyg X-1, MAXI J1820+070
  - SS433, V4641 Sgr, G1915+105: – extended morphology
  - MAXI J1820+070, Cyg X-1: – Point-source like morphology

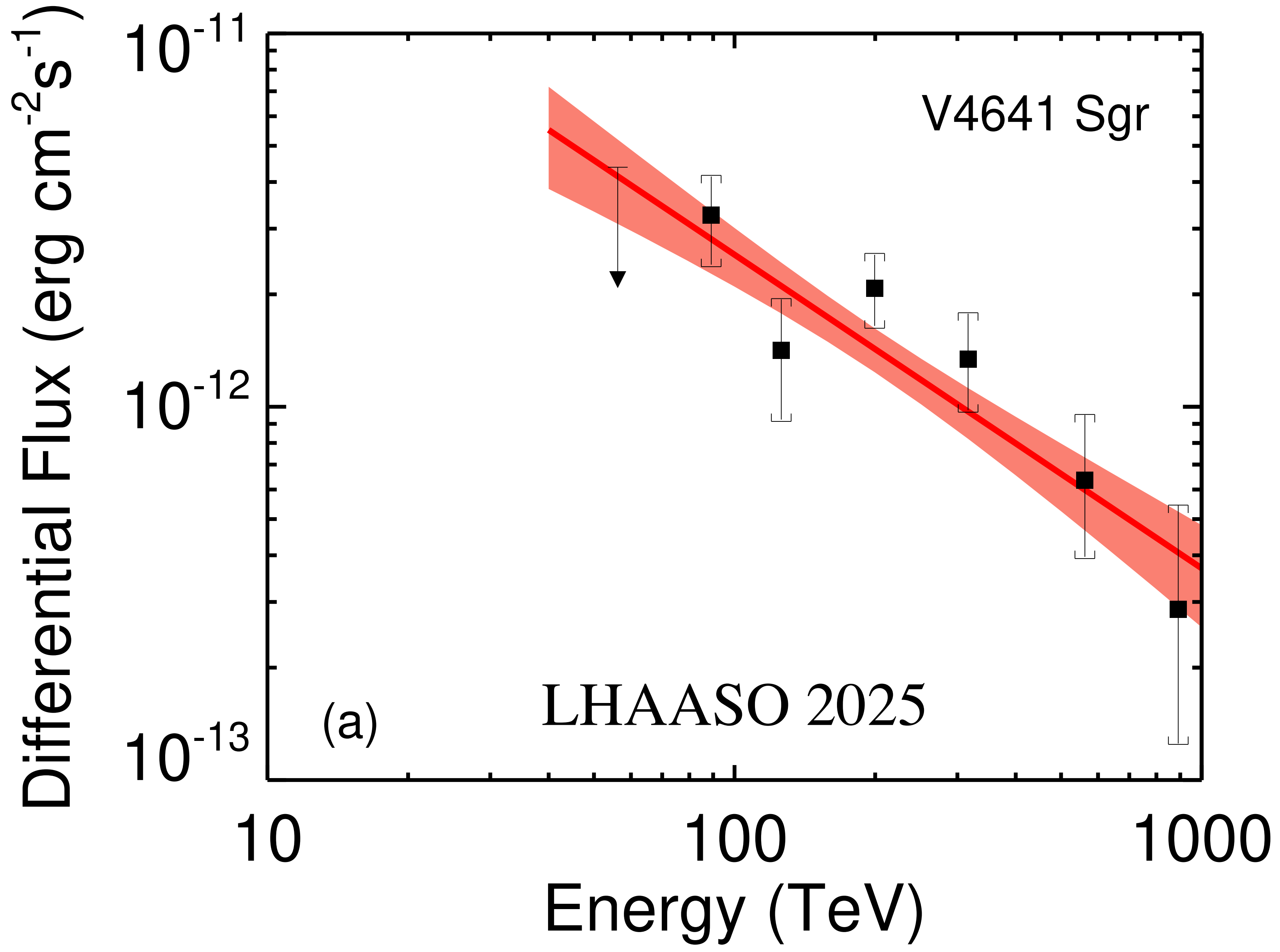
LHAASO 2025





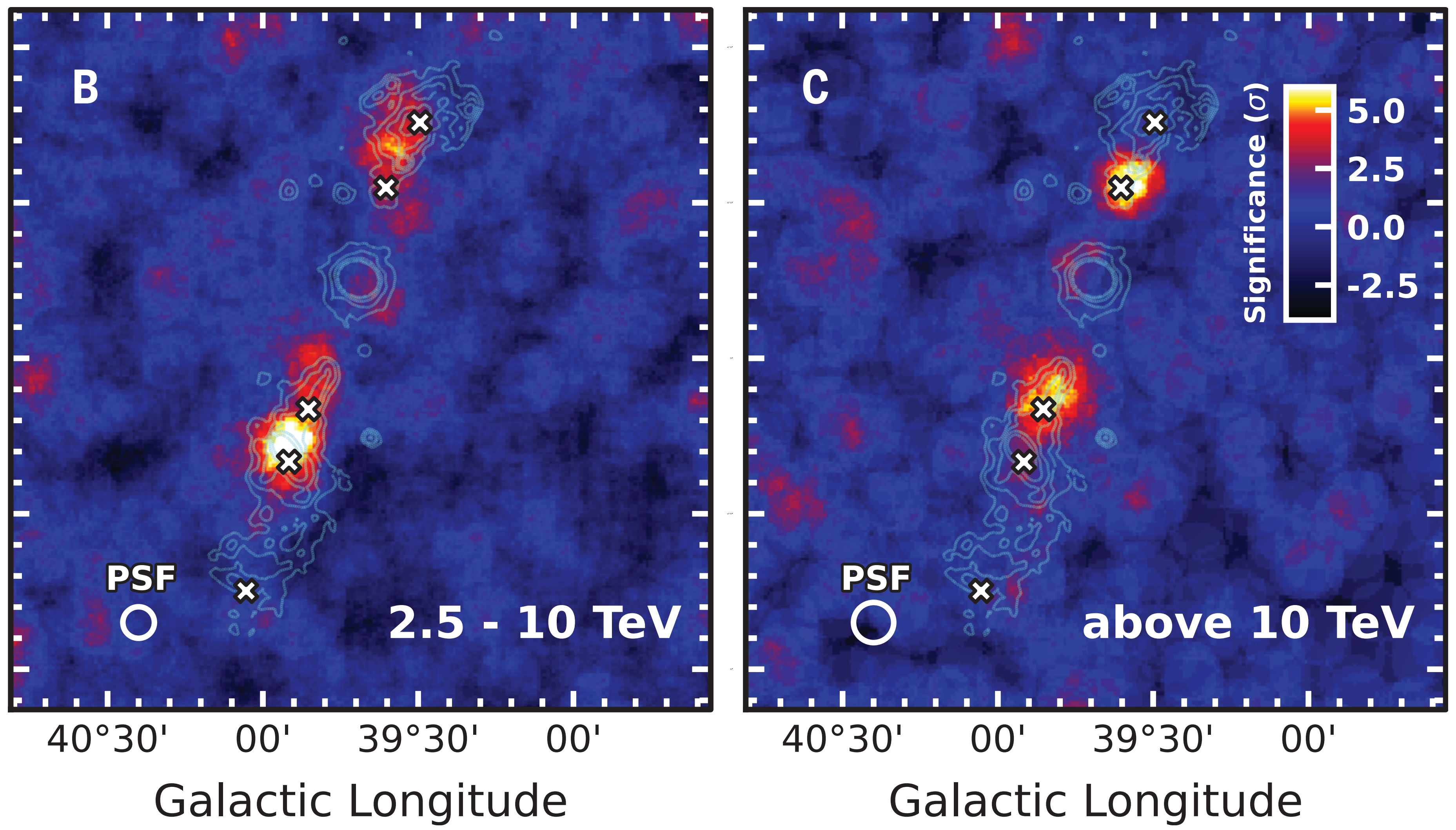
HAWC 2024

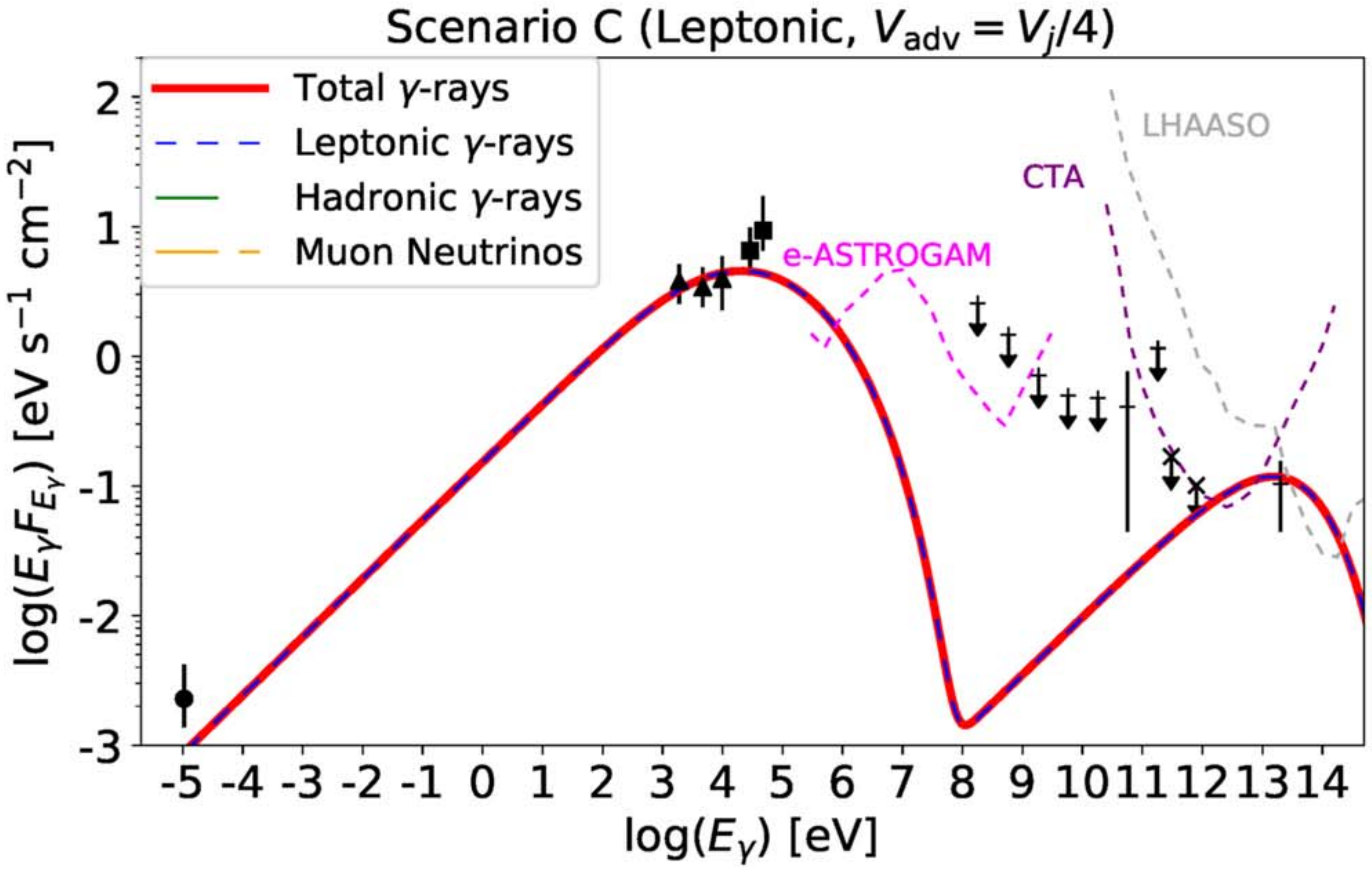




HESS observation of SS433

- Morphological change
  - 1–5 TeV : Extended to e2
  - 10–20 TeV: Concentrated on e0
- Strongly supporting leptonic origin
- Velocity: ~ 0.05 – 0.1 c
- Our prediction in 2020 is consistent with HESS analysis results in 2022
- B-field: 10 – 20 G to reconcile X-ray data





Super-Eddington micro-quasars

- Hillas Energy for SS433 jets:

  $E_{\rm max} \approx eBR\beta \sim 10 B_{-5} R_{5\rm pc}$ PeV

  => Micro-quasars can be super-PeVatron

- Luminosity of super-Eddington XRBs:

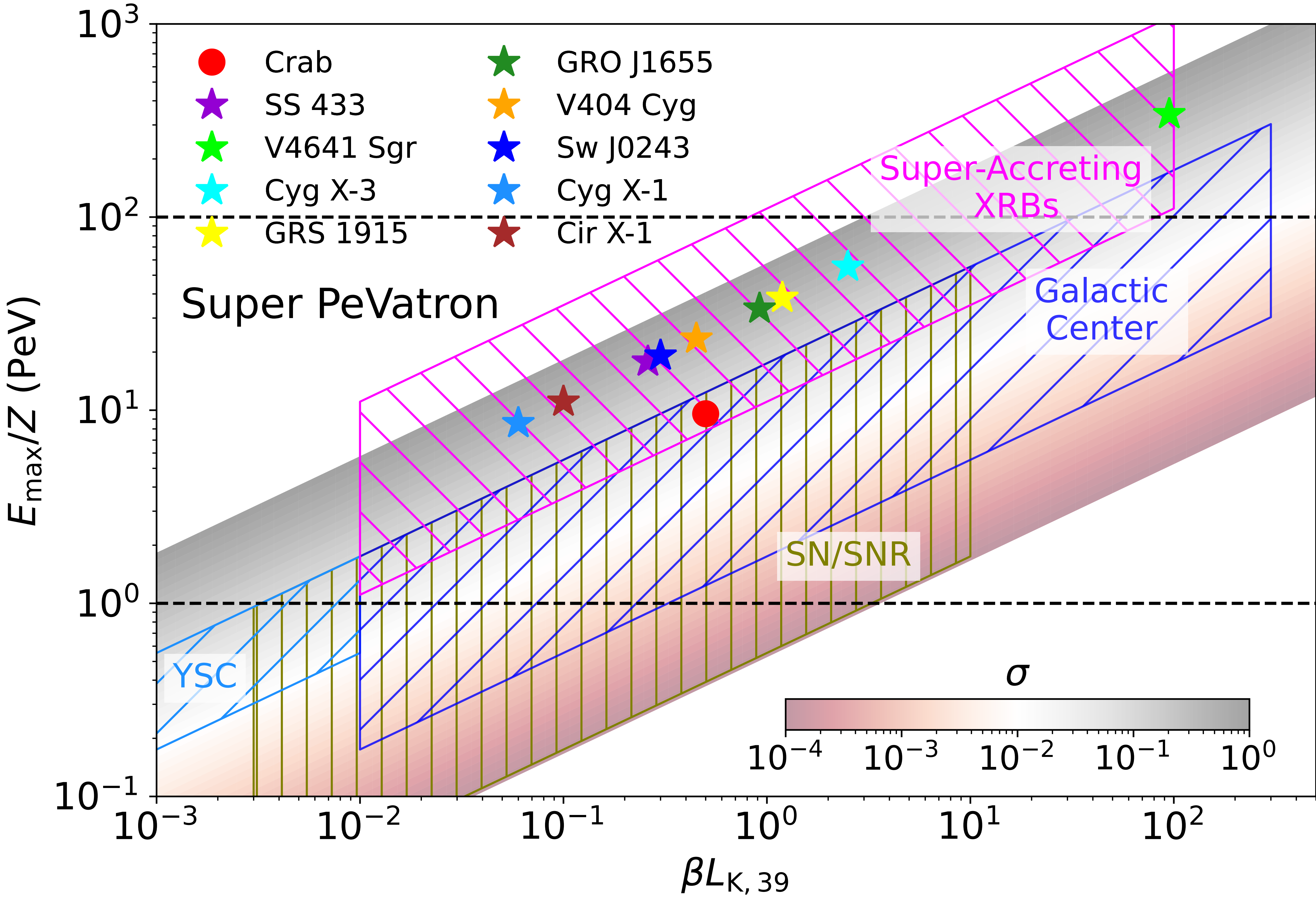
  $L_j \sim 10^{39}$ erg/s

  => $L_{CR,\rm xrb} \sim 3\times10^{37}\epsilon_{p,-1.5}$ erg/s

- CR power necessary to explain PeV CRs:

$$L_{\rm cr,tot} = Q_{\rm CR,tot} V_G \simeq 1.5\times10^{38}\ {\rm erg\ s^{-1}},$$

B.T. Zhang, SSK, Murase 2025

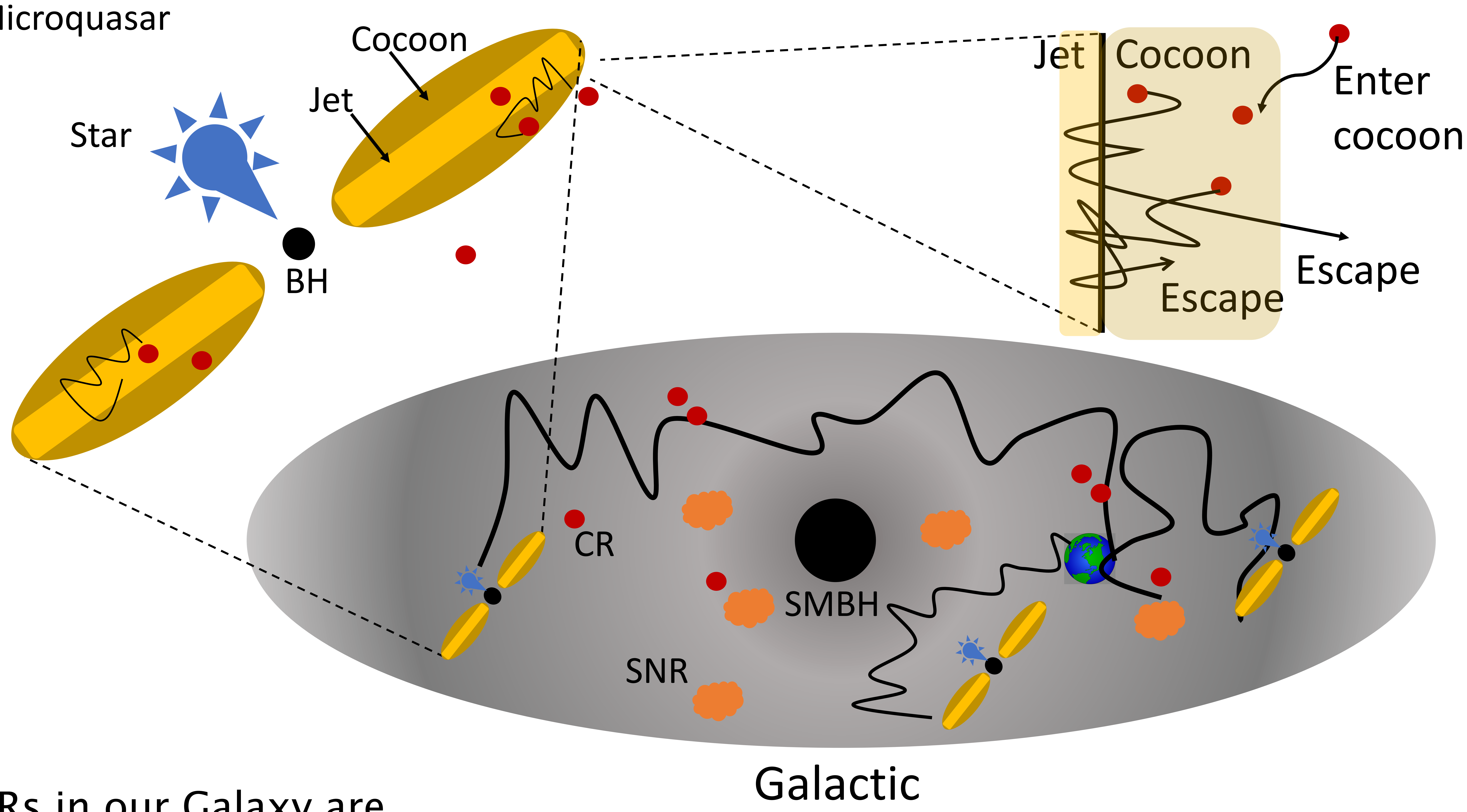


Wang et al. 2025

- **A few to 10 super-Eddington objects suffices to explain PeV CRs**

Shear Acceleration Scenario

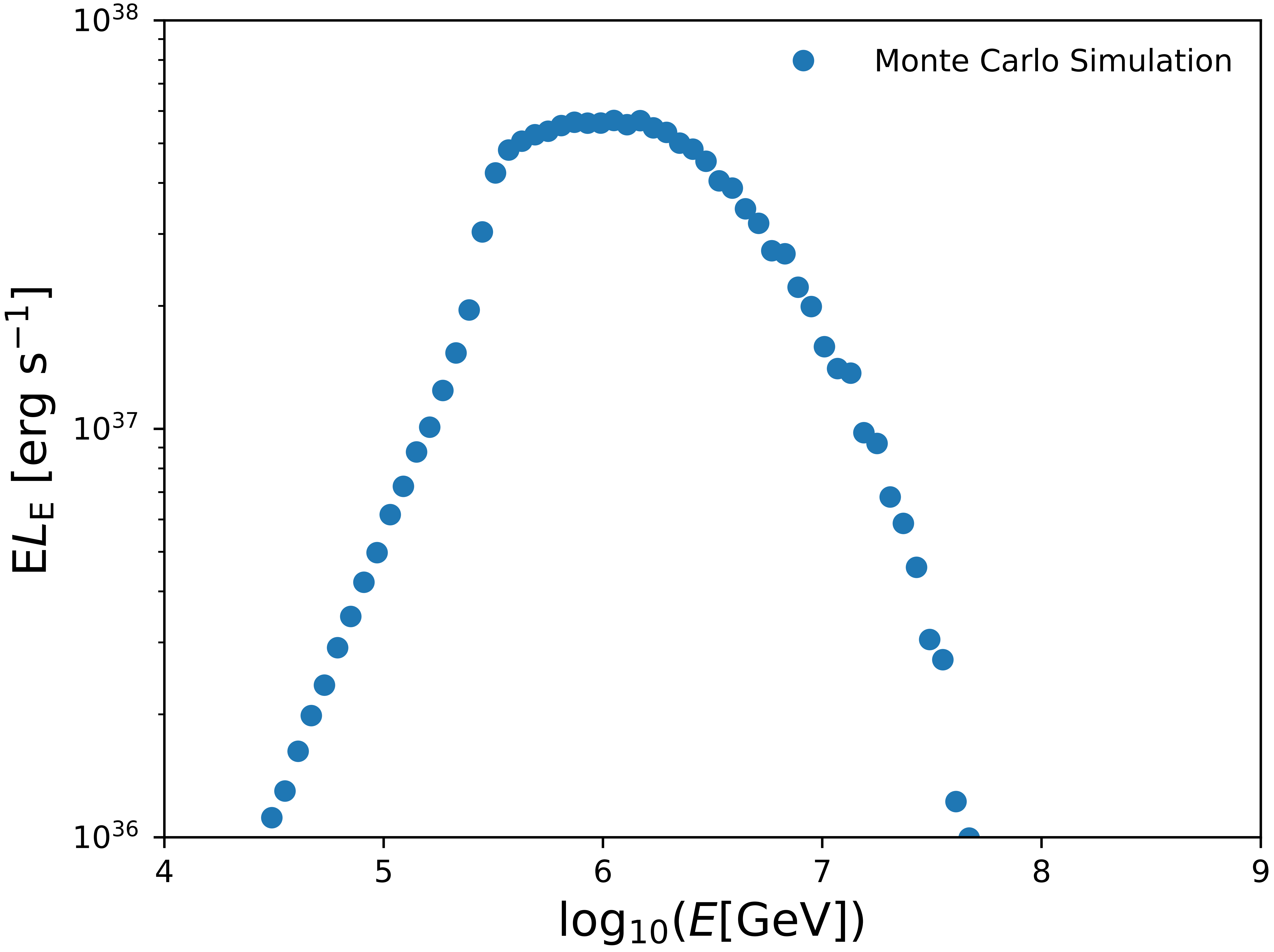
B.T. Zhang, SSK, Murase 2025



- TeV CRs in our Galaxy are re-accelerated by micro-quasar jets by shear acceleration

PeV CR spectrum by shear acceleration

- Monte-Carlo simulation for discrete shear acceleration
  $r_L > l_{\mathrm{shear}}$ => TeV CRs are injected
- Typical micro-quasars can achieve $E_{\mathrm{pk}} \sim 1-3$ PeV
- $E^2 \frac{dN}{dEdt} \propto E$ for $E < E_{\mathrm{pk}}$
- Gradual cutoff for $E > E_{\mathrm{pk}}$
- Entrainment of Galactic CRs of TeV energies leads to $L_{\mathrm{CR}} \sim 5 \times 10^{37}$ erg/s



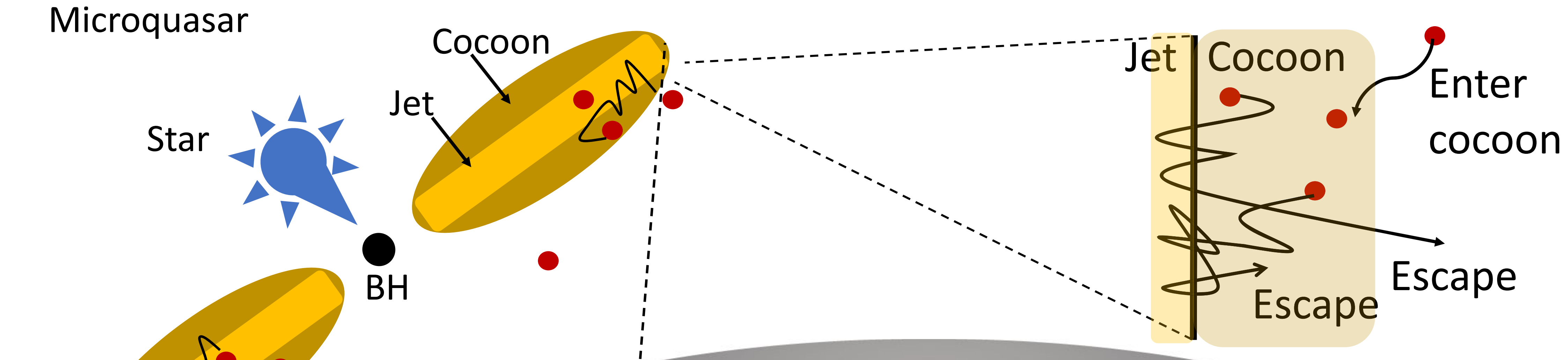
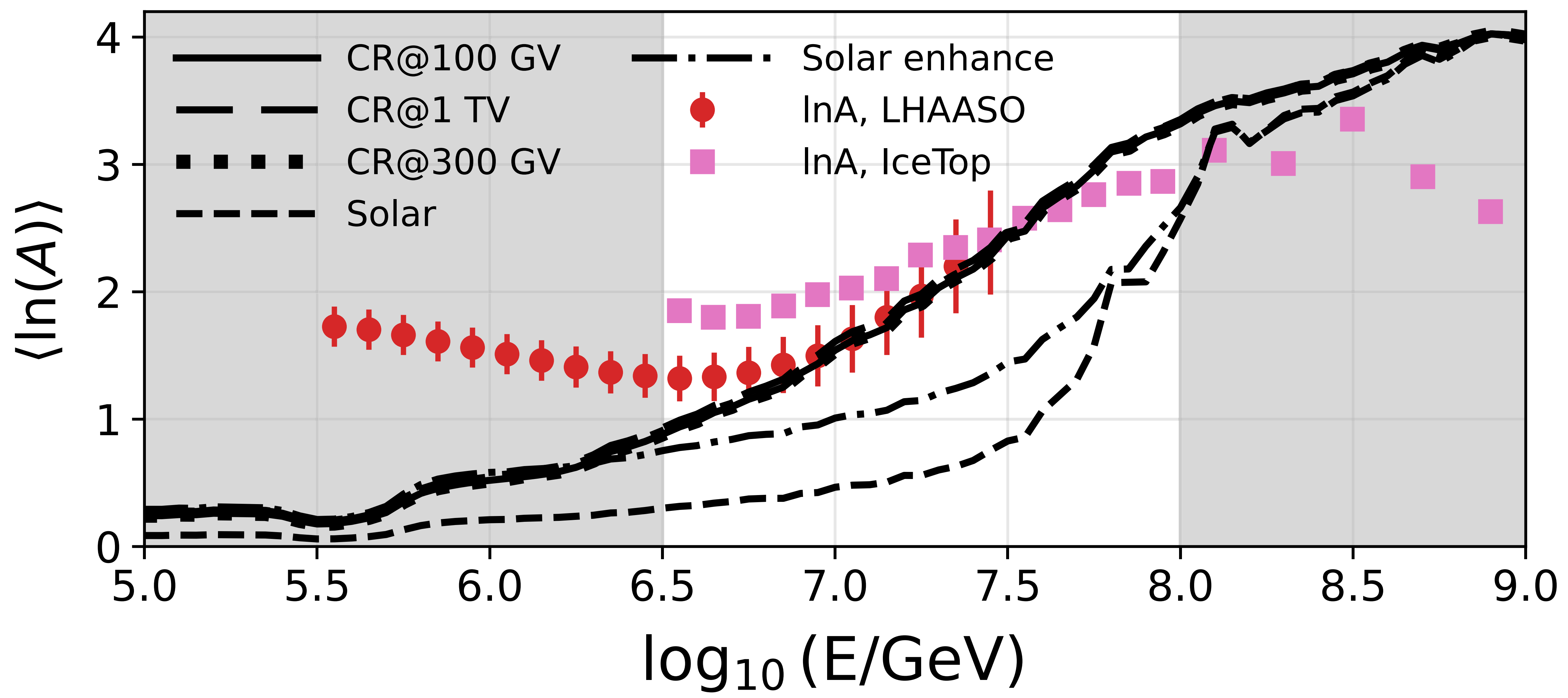


TABLE I. Model parameters used in Monte Carlo simulations.

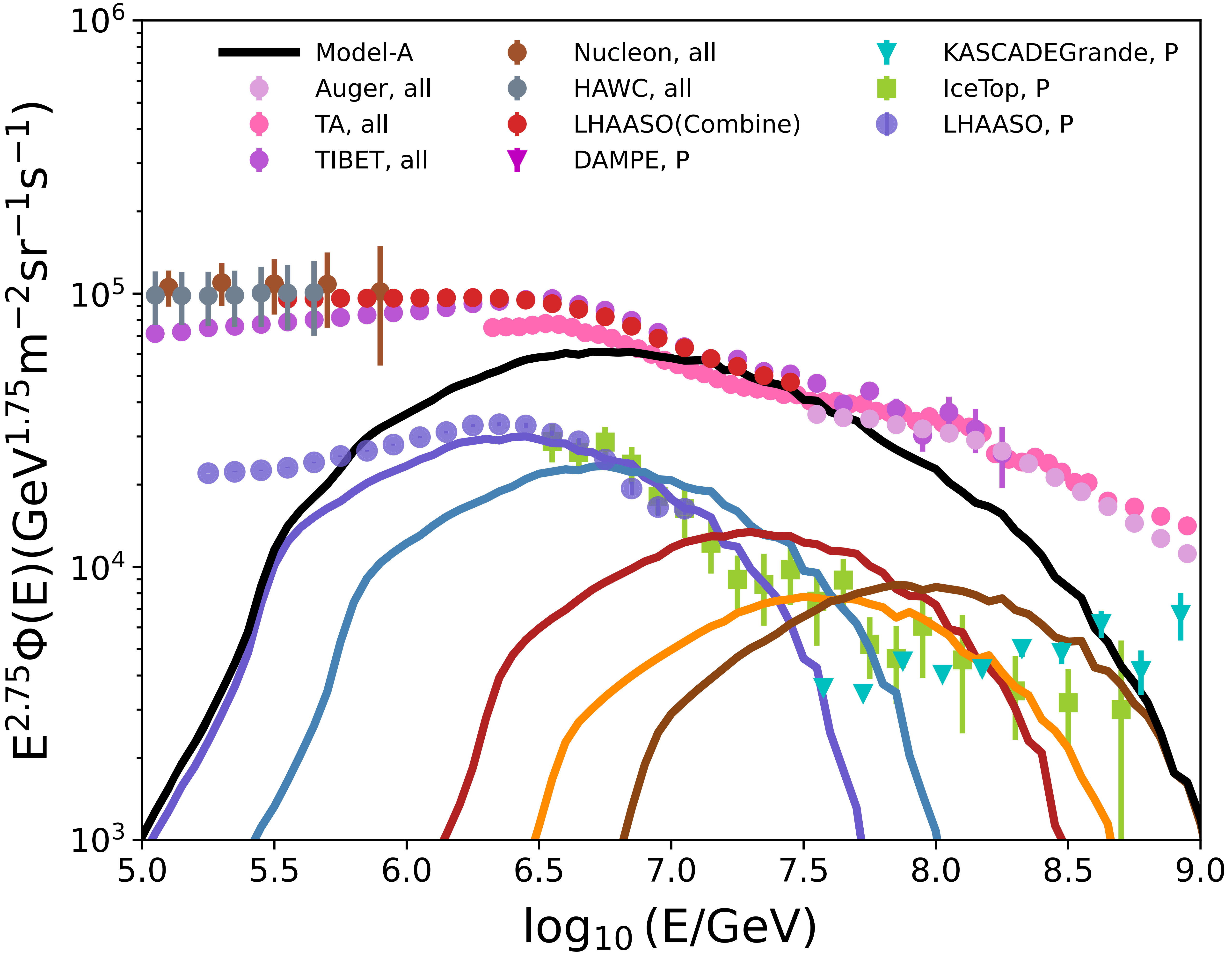
Parameters	r_{jet} (pc)	B_{jet} (μG)	β_{jet}	r_{coc} (pc)	B_{coc} (μG)	l_{coh} (pc)	l_{jet} (pc)
Value	3	50	0.3	60	10	1.8	100

PeV - EeV CR spectrum & Composition

- Re-acceleration of Galactic TeV CRs by shear acceleration
- Our model prediction matches both spectrum & composition
- Composition ratio by TeV CRs => **He & Fe spectra will give a robust test**

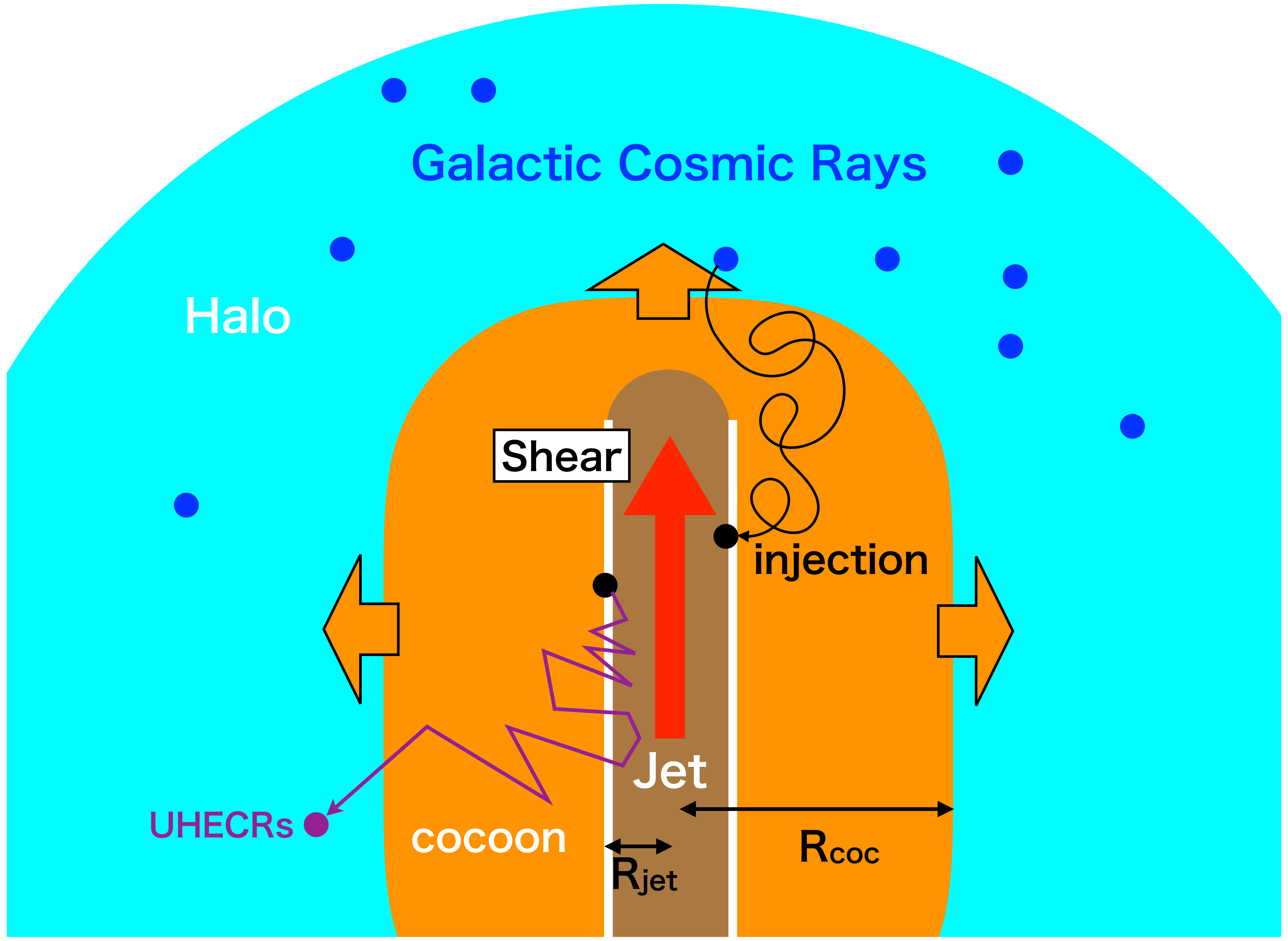


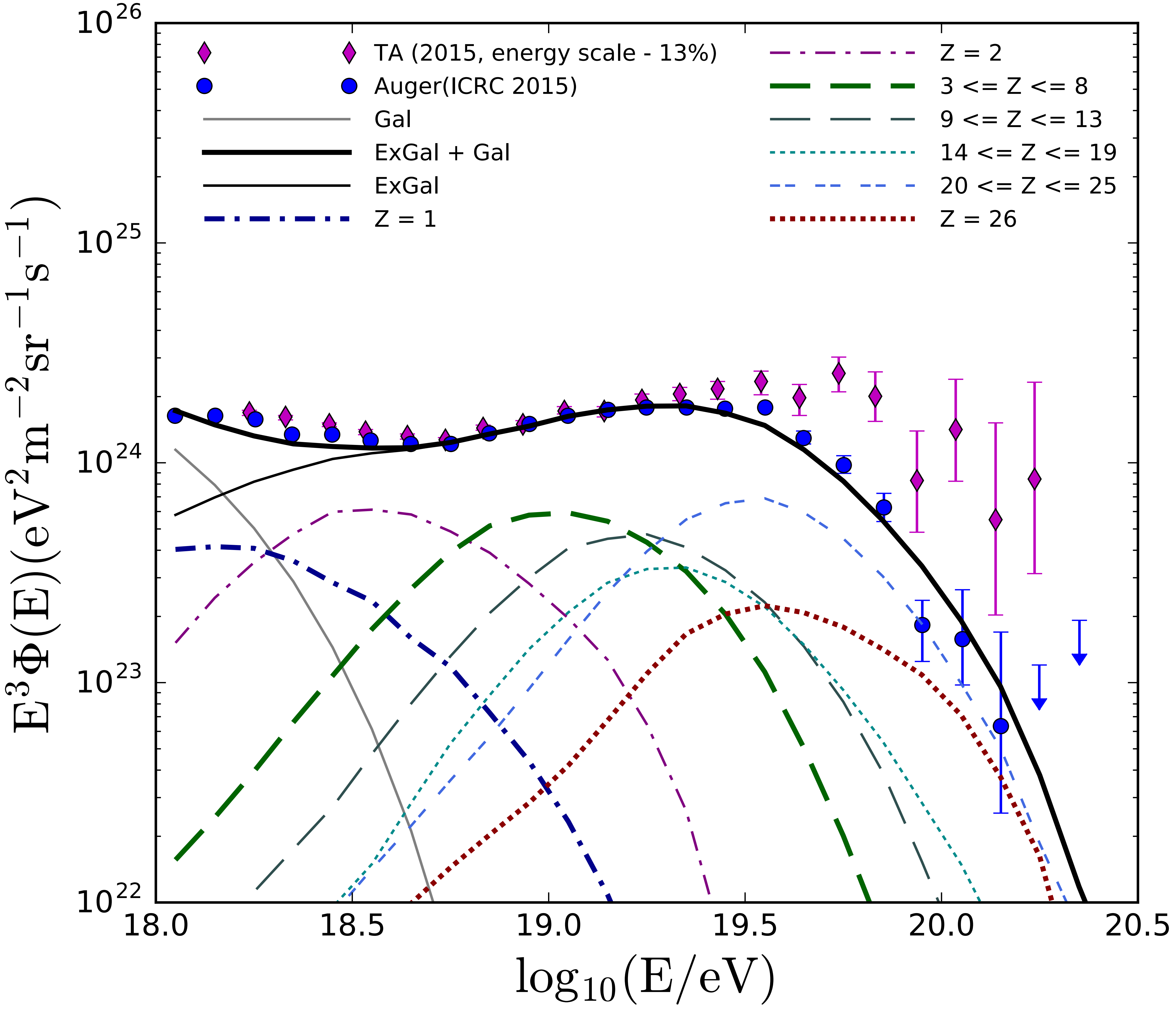
B.T. Zhang, SSK, Murase 2025



Shear acceleration in radio galaxies

SSK, Murase, B.T. Zhang 2018



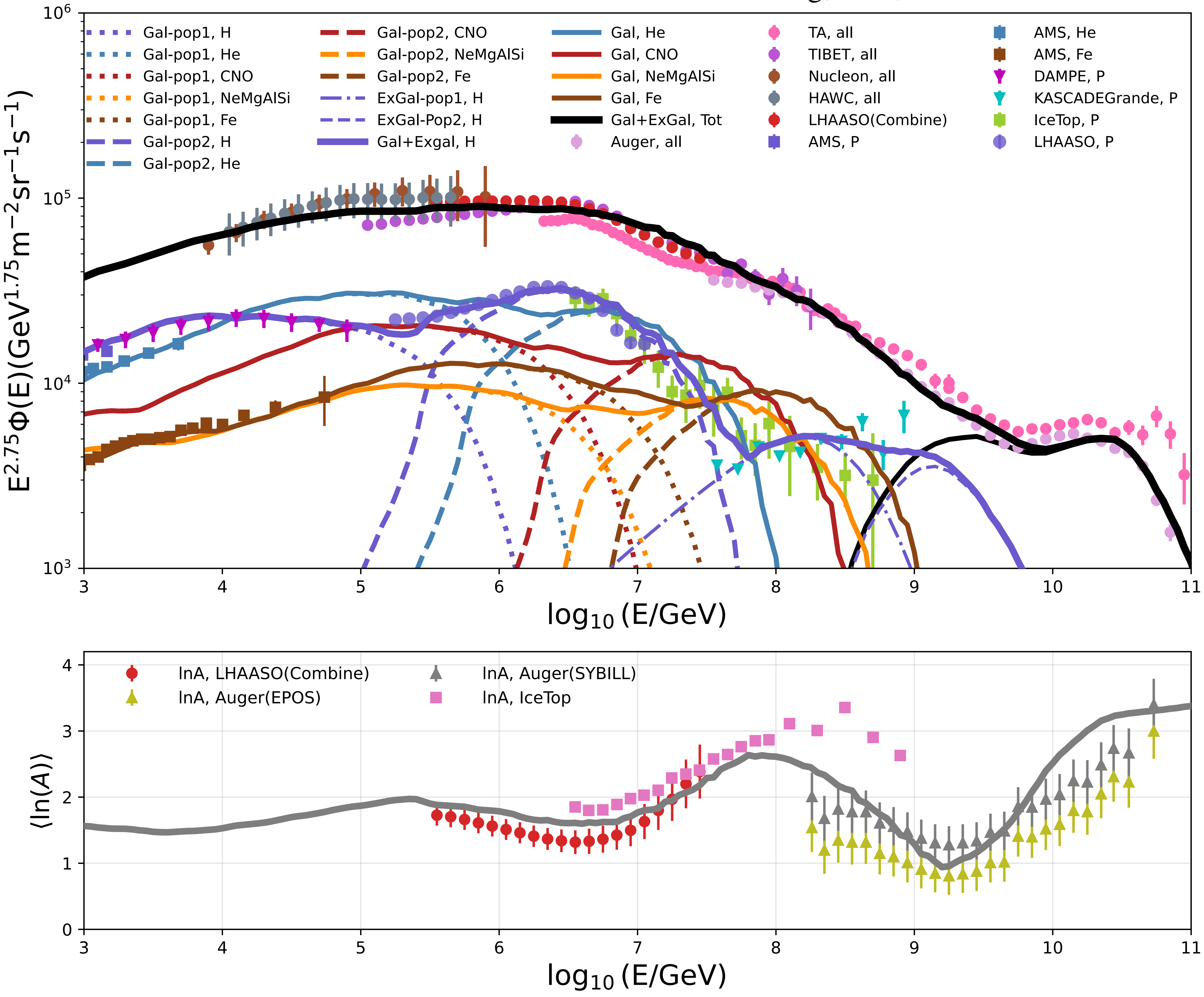


- Same scenario applied to radio galaxy => We can explain UHECRs

B.T. Zhang, SSK, Murase 2025

Global fit result

- E < 1 PeV:
  Supernova remnants
- **1 PeV < E < 0.3 EeV:**
  Micro-quasars
- 0.3 EeV < E < 2 EeV:
  Extragalactic component 1
  (e.g., Galaxy clusters)
- 2 EeV < E:
  Radio galaxies



3 states of black hole accretion

Ohsuga & Mineshige 2011

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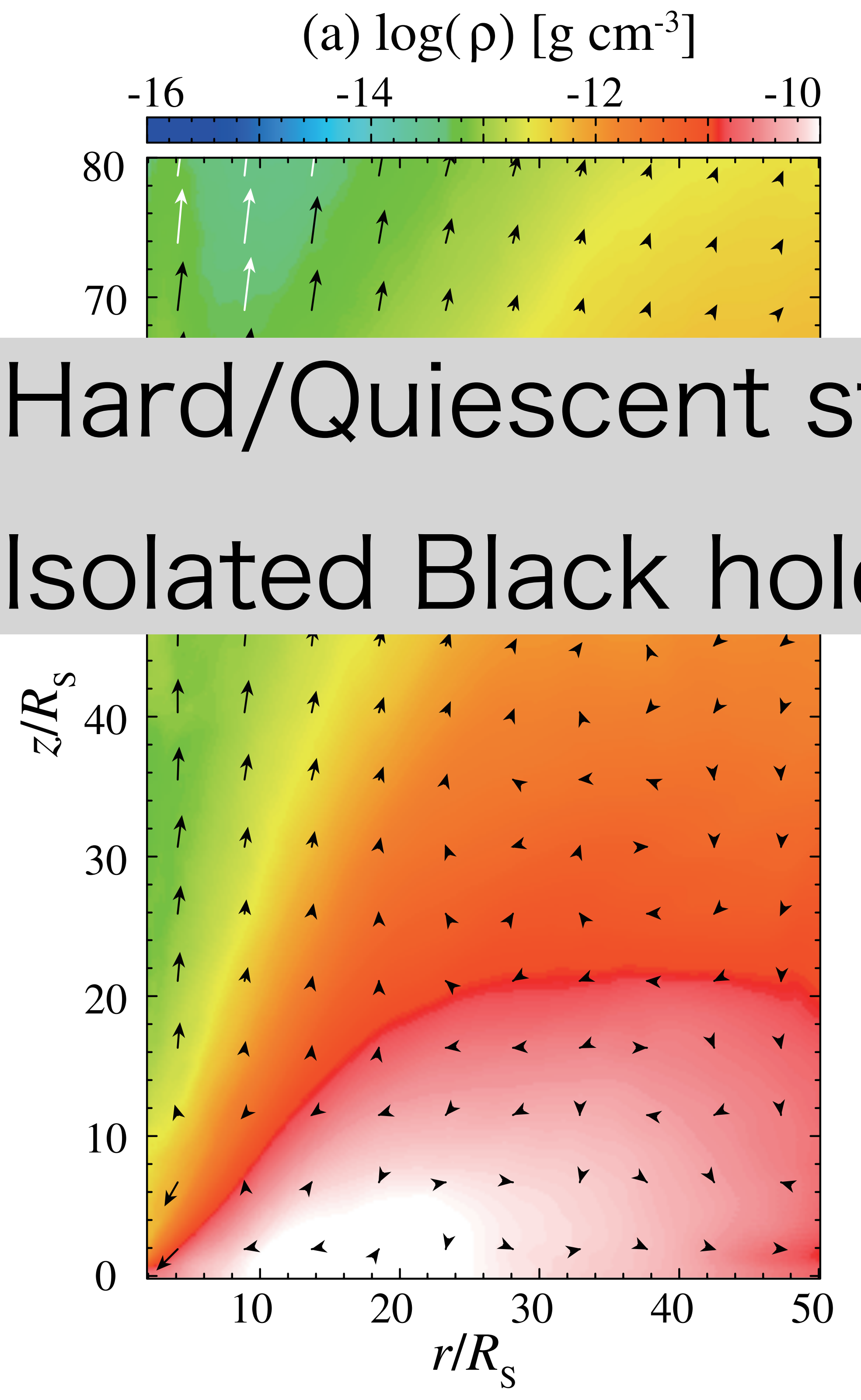


Hard/Quiescent state

Isolated Black holes

Standard accretion disk

Soft state

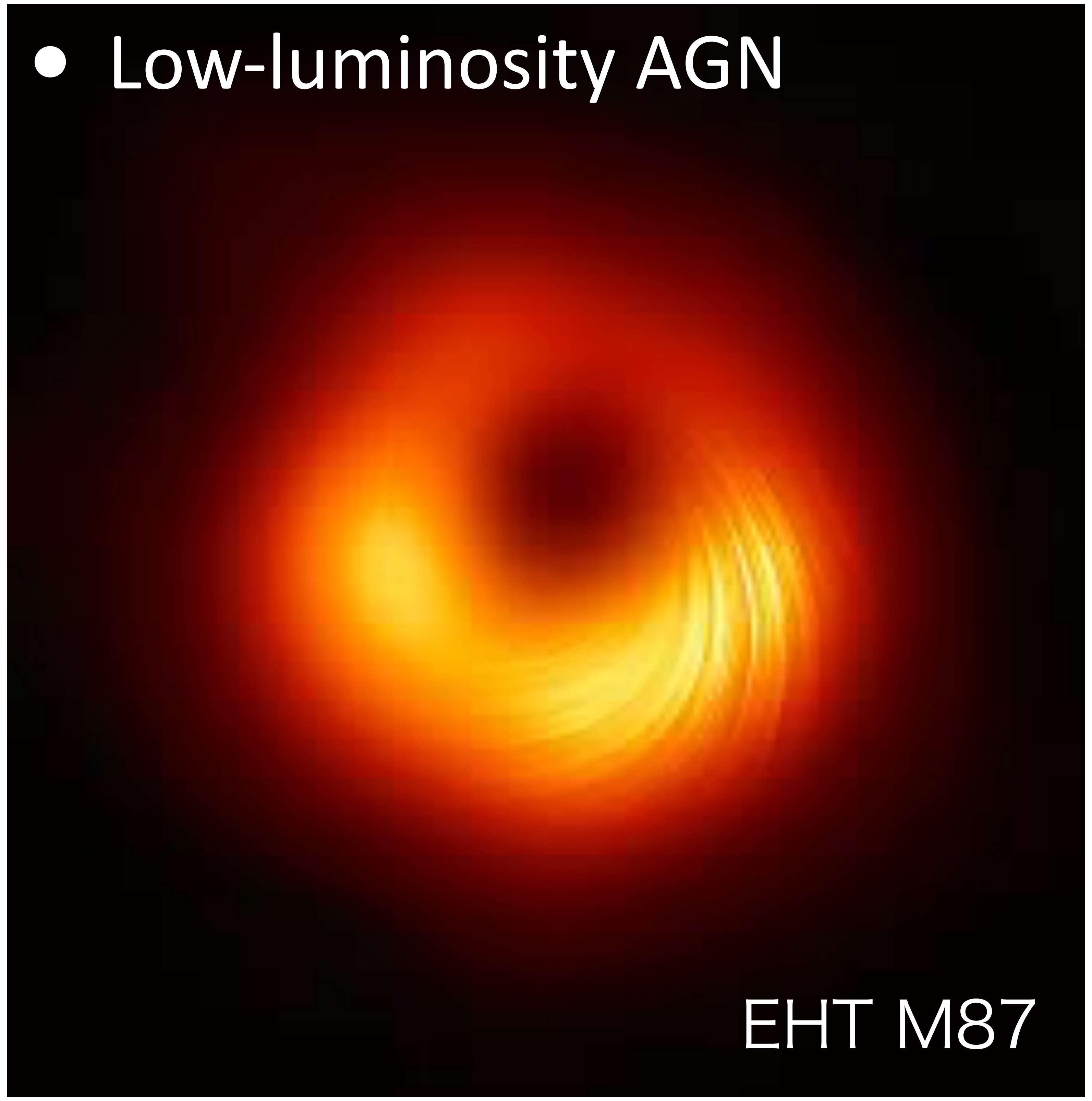
Slim disk + Jets

ULX

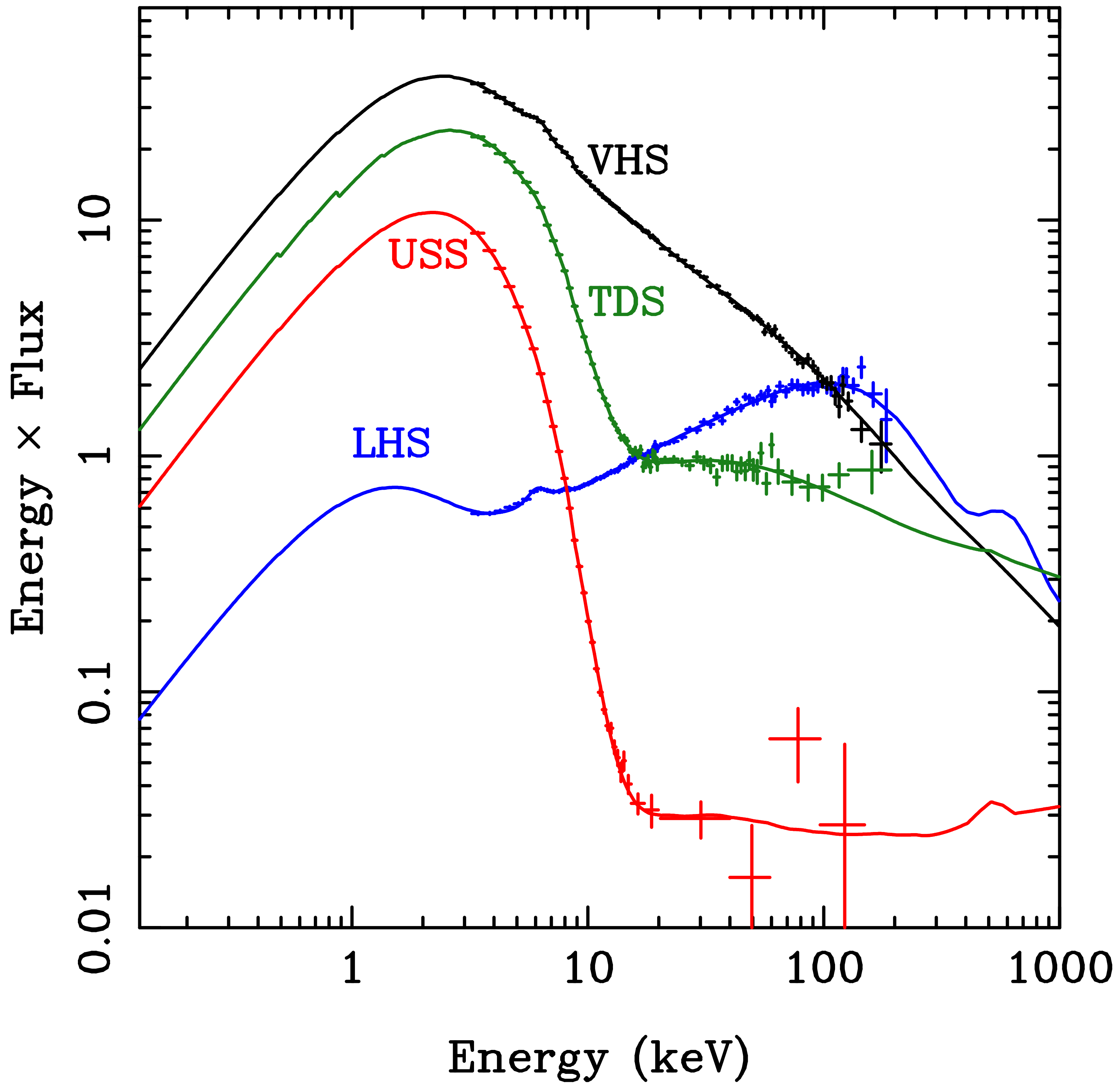
Micro-quasars

$L \sim 0.01 L_{\mathrm{Edd}}$ $L \sim L_{\mathrm{Edd}}$ $L = \eta \dot{M} c^2$

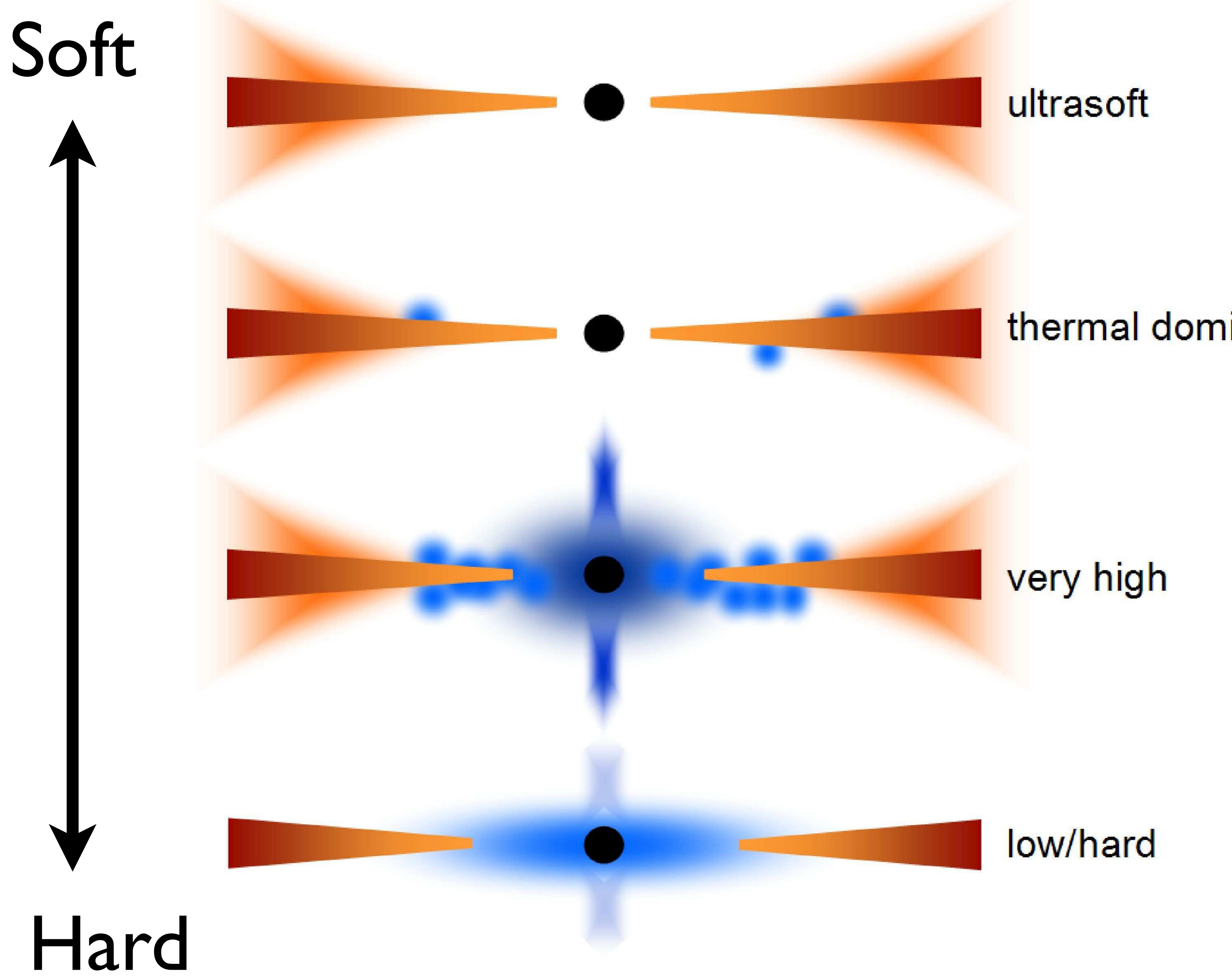
RIAFs around Black Holes



• X-ray binaries



Done et al. 2007



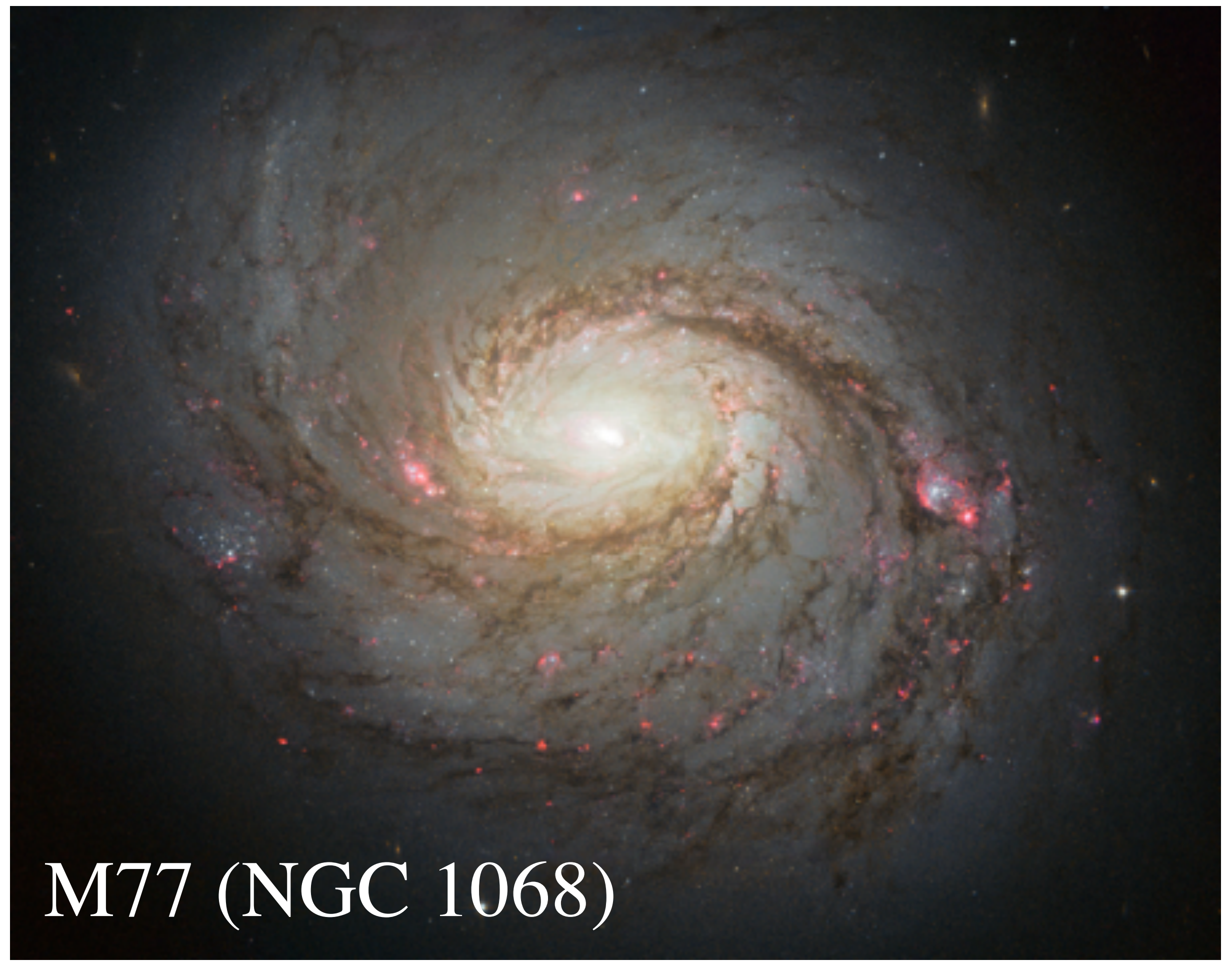
- Accretion rate is high ($\dot{M}c^2 \gtrsim 0.01 L_{\rm Edd}$) —> optically thick accretion disk + corona
- Accretion rate is low ($\dot{M}c^2 \lesssim 0.01 L_{\rm Edd}$) —> only hot plasma surrounding the BH
- **Coulomb timescale >> infall timescale —> non-thermal particle production?**

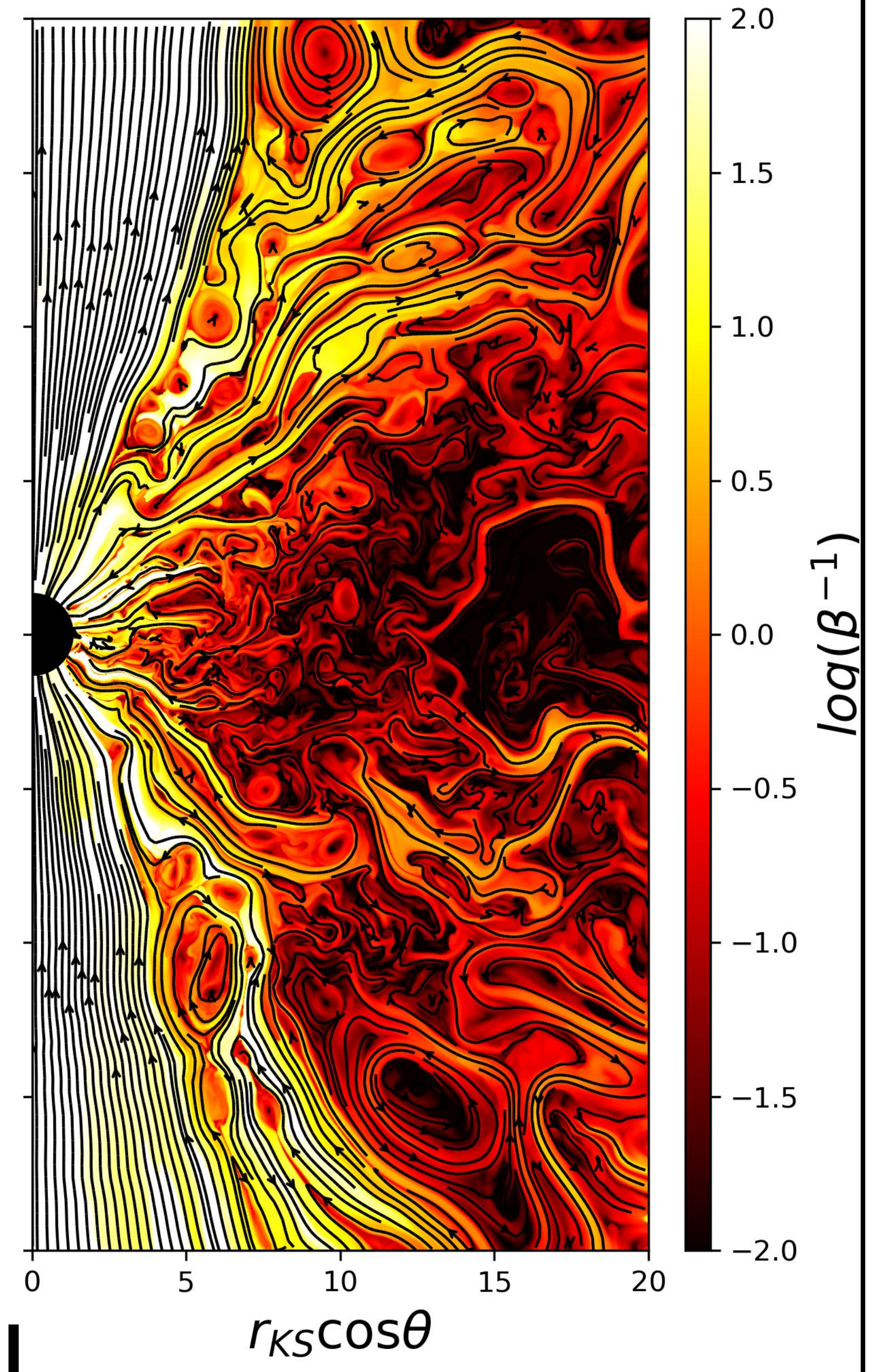
SANE & MAD

Narayan et al. 2012

- Standard and Normal Evolution (SANE)

Ripperda et al. 2020

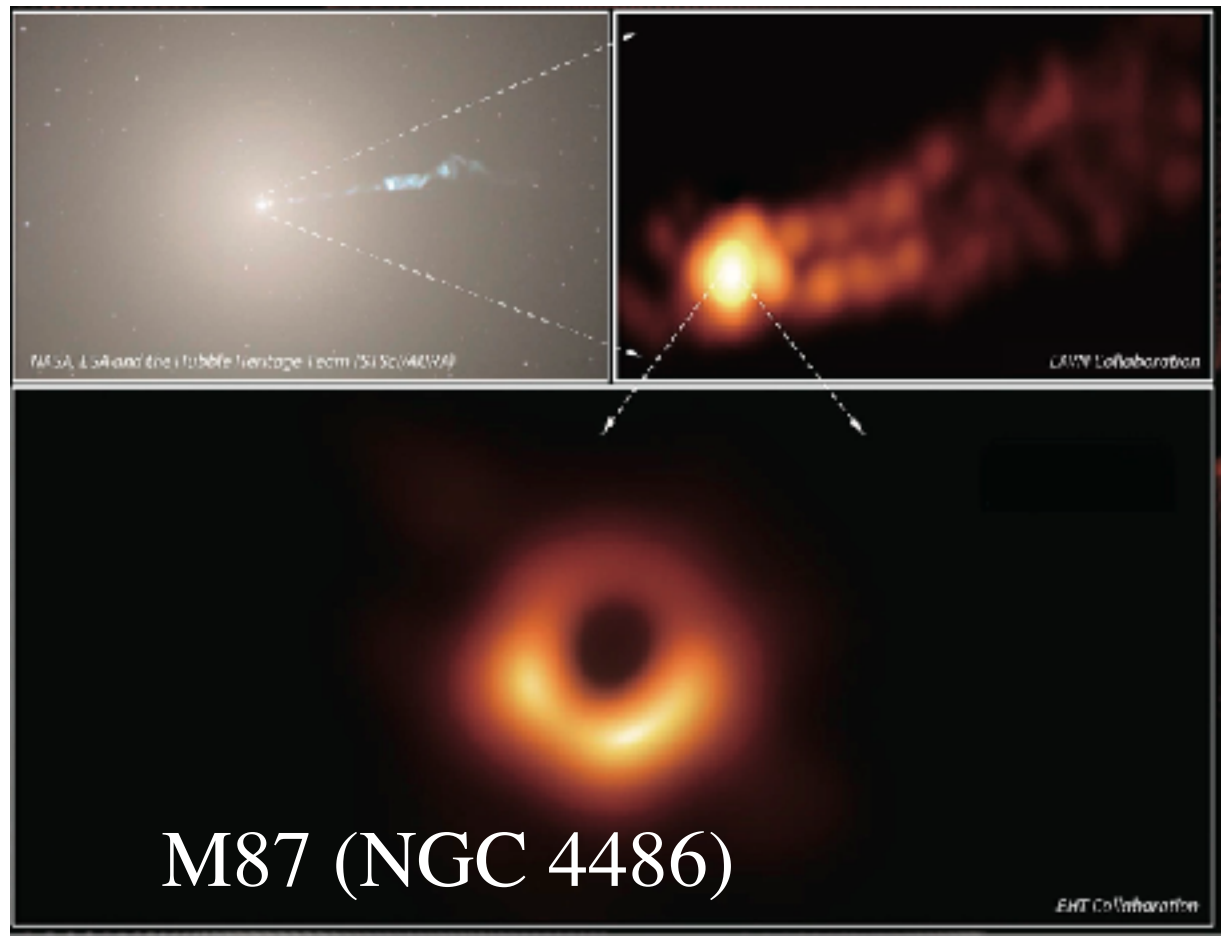


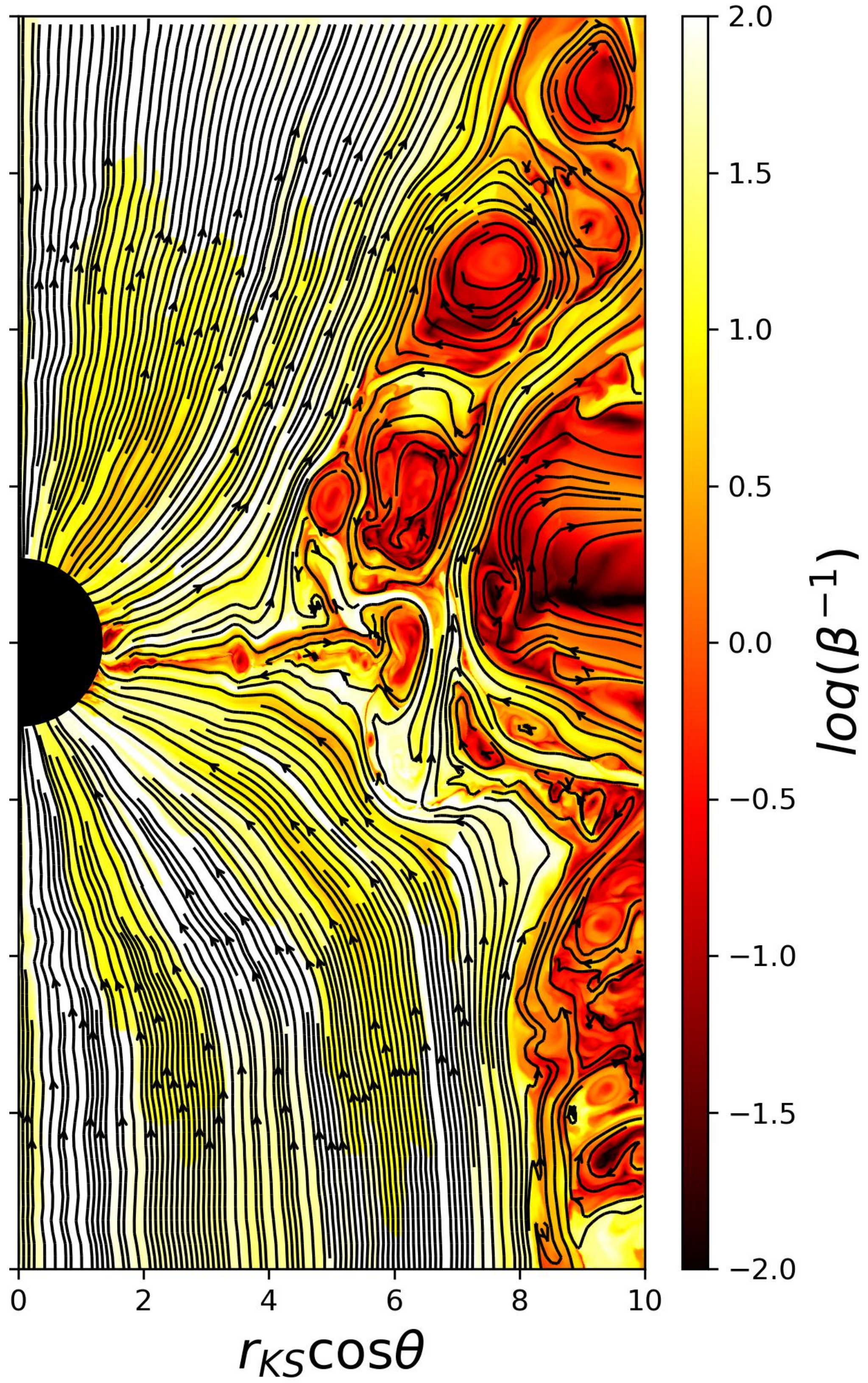


- Turbulence driven by MRI
- Weaker jets are launched
  → related to **radio-faint states**

- Magnetically Arrested Disk (MAD)

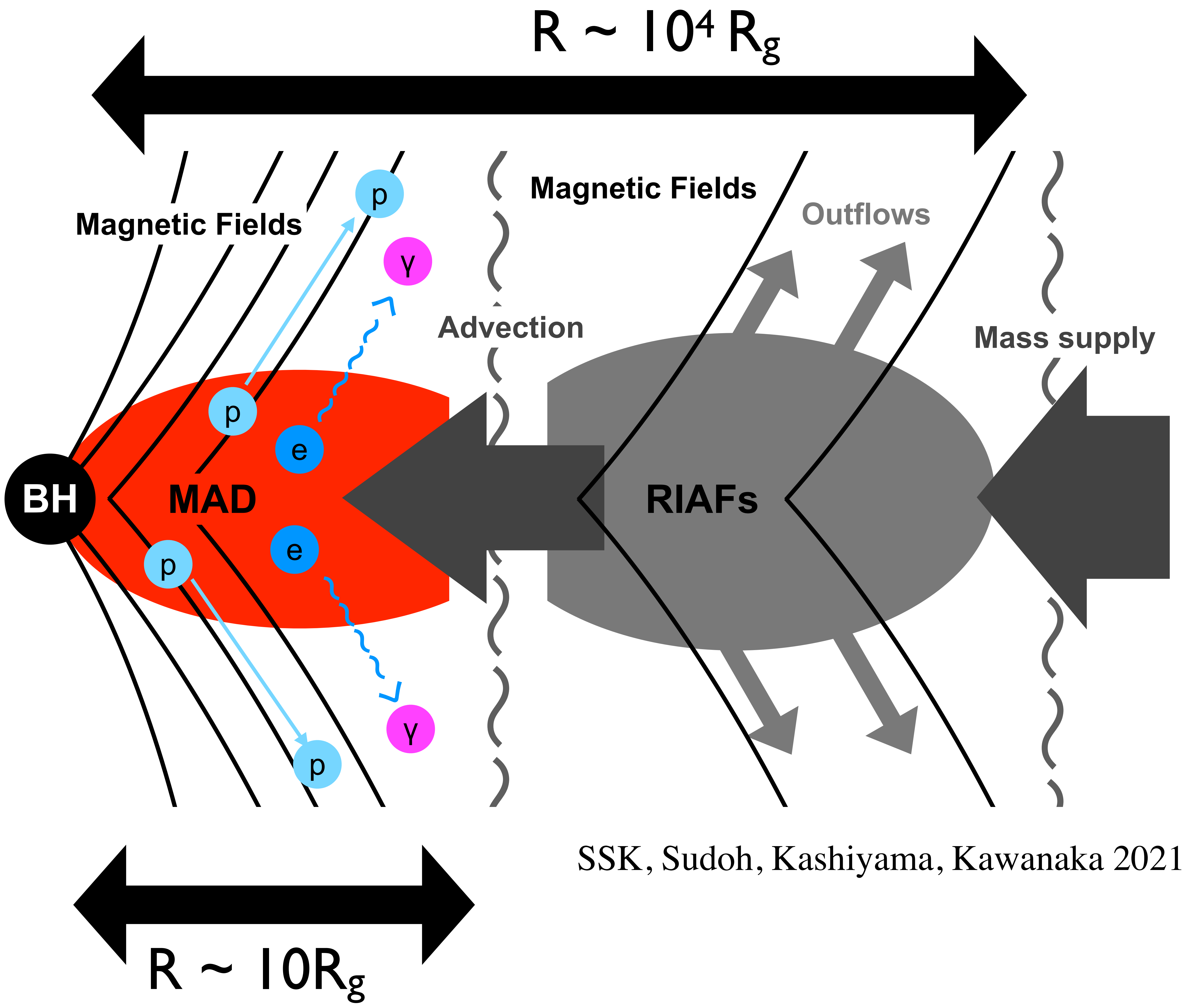
Ripperda et al. 2020





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

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

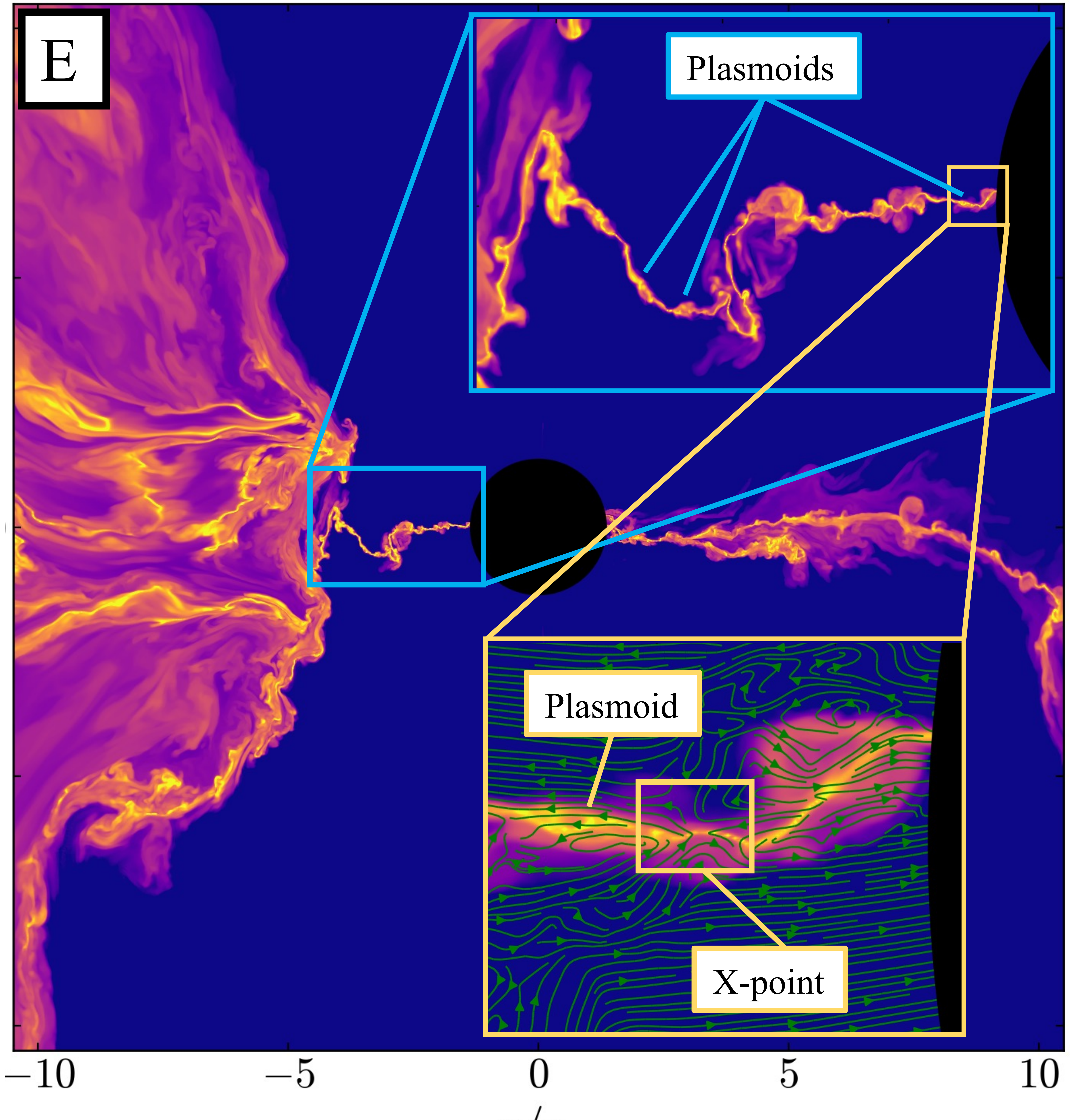
- Flux freezing + ADIOS: $\beta_p \propto R^{-1.5} - R^{-2}$

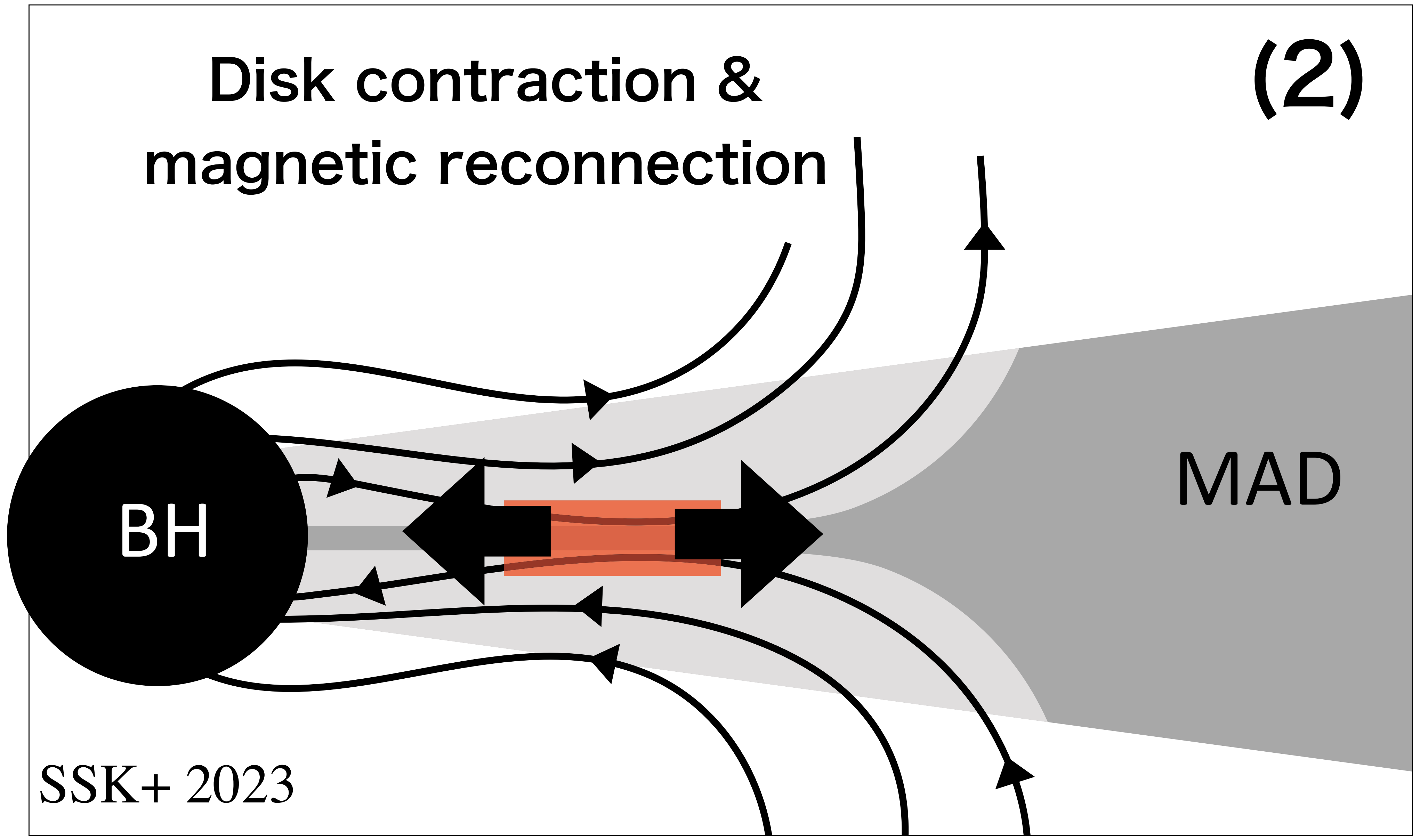
  →$\beta < 1 @ R \lesssim 10 R_g$

  → **Formation of Magnetically Arrested Disk (MAD)**

Magnetic Reconnection & Turbulence

Ripperda+ 2022



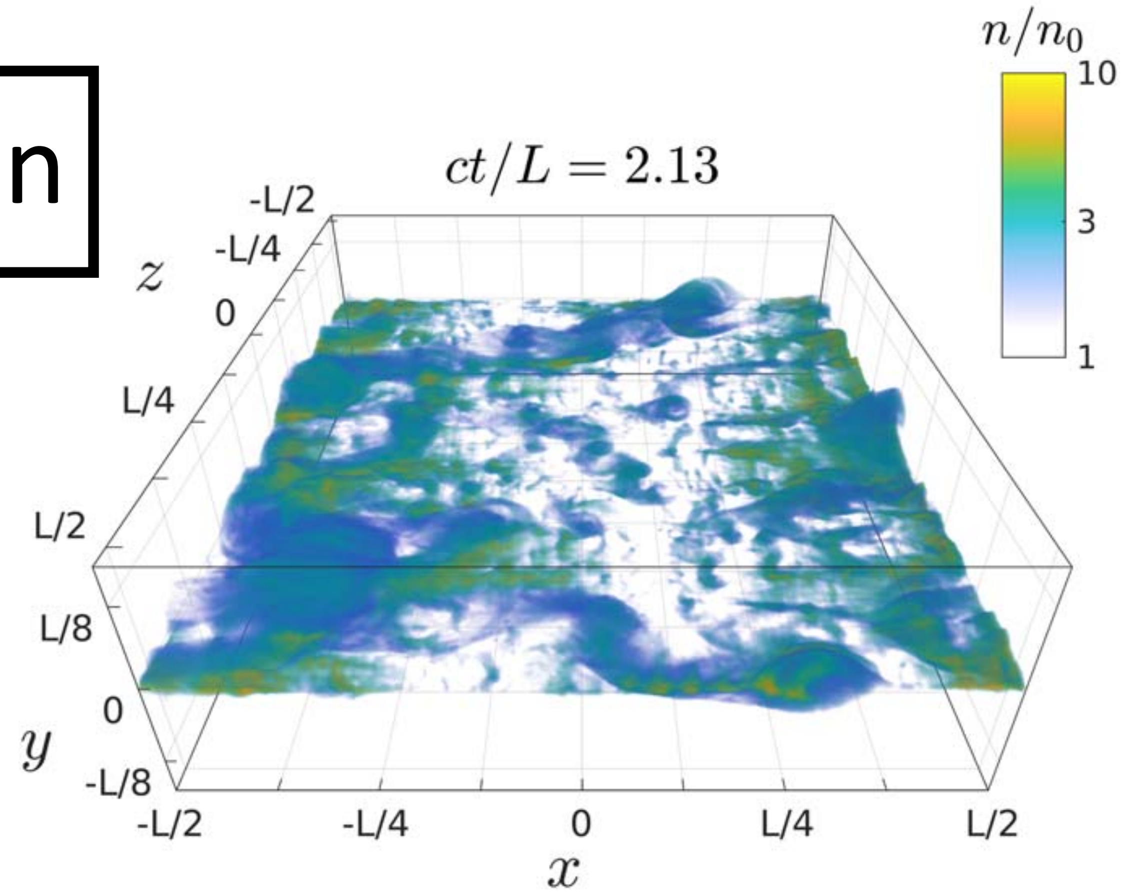


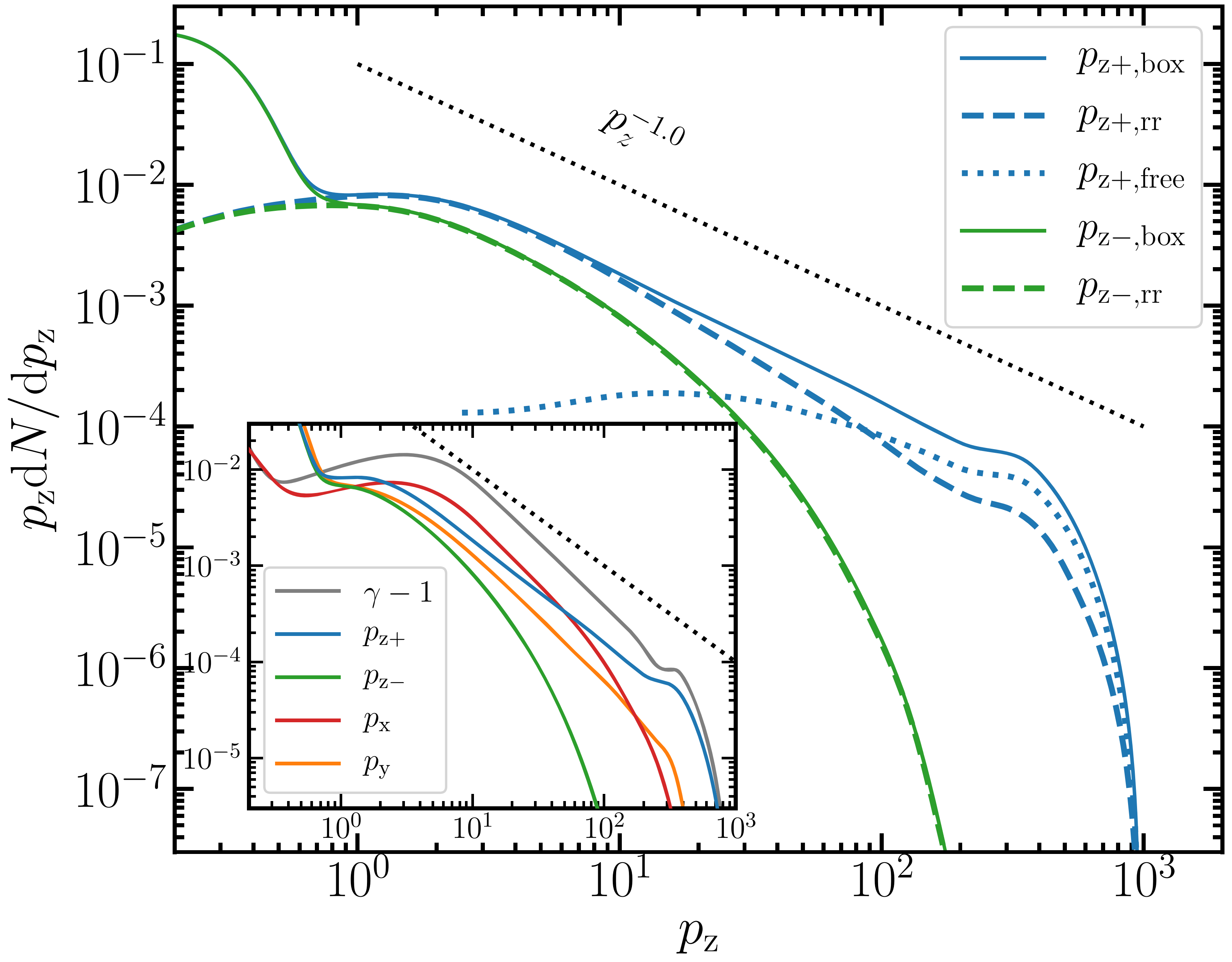
- GRMHD simulations revealed that MADs release its magnetic energy by magnetic reconnection
- Accretion process naturally induces magnetic reconnection at the mid plane
- Reconnection induces turbulence
- MHD instabilities also drive turbulence

Particle Acceleration by Reconnection & Turbulence

- PIC for reconnection

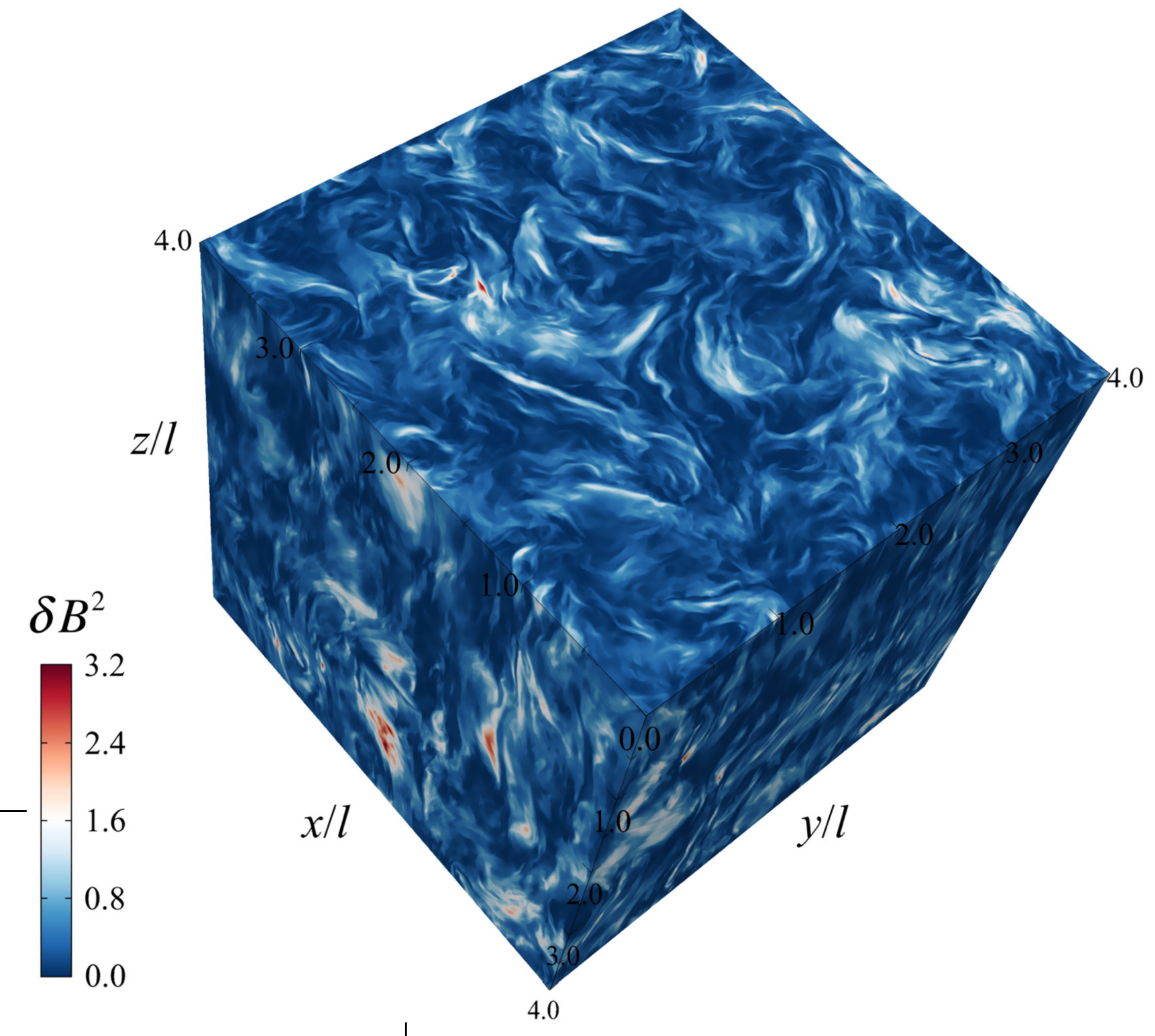
Zenitani & Hoshino 2001
Sironi & Spitkovsky 2014
Zhang et al. 2021, 2023

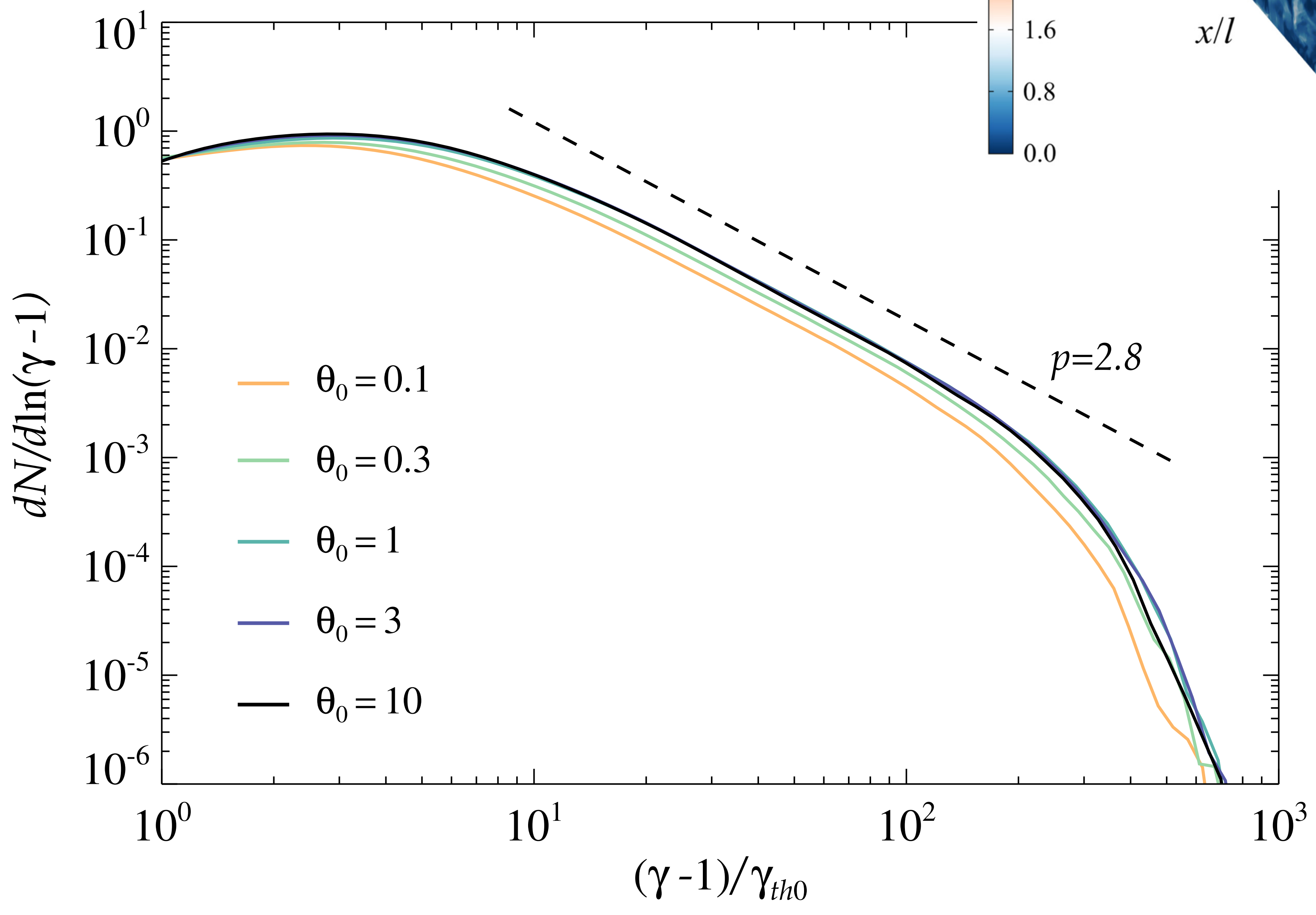




- PIC with turbulence

Zhdankin et al. 2018
Comisso & Sironi 2019



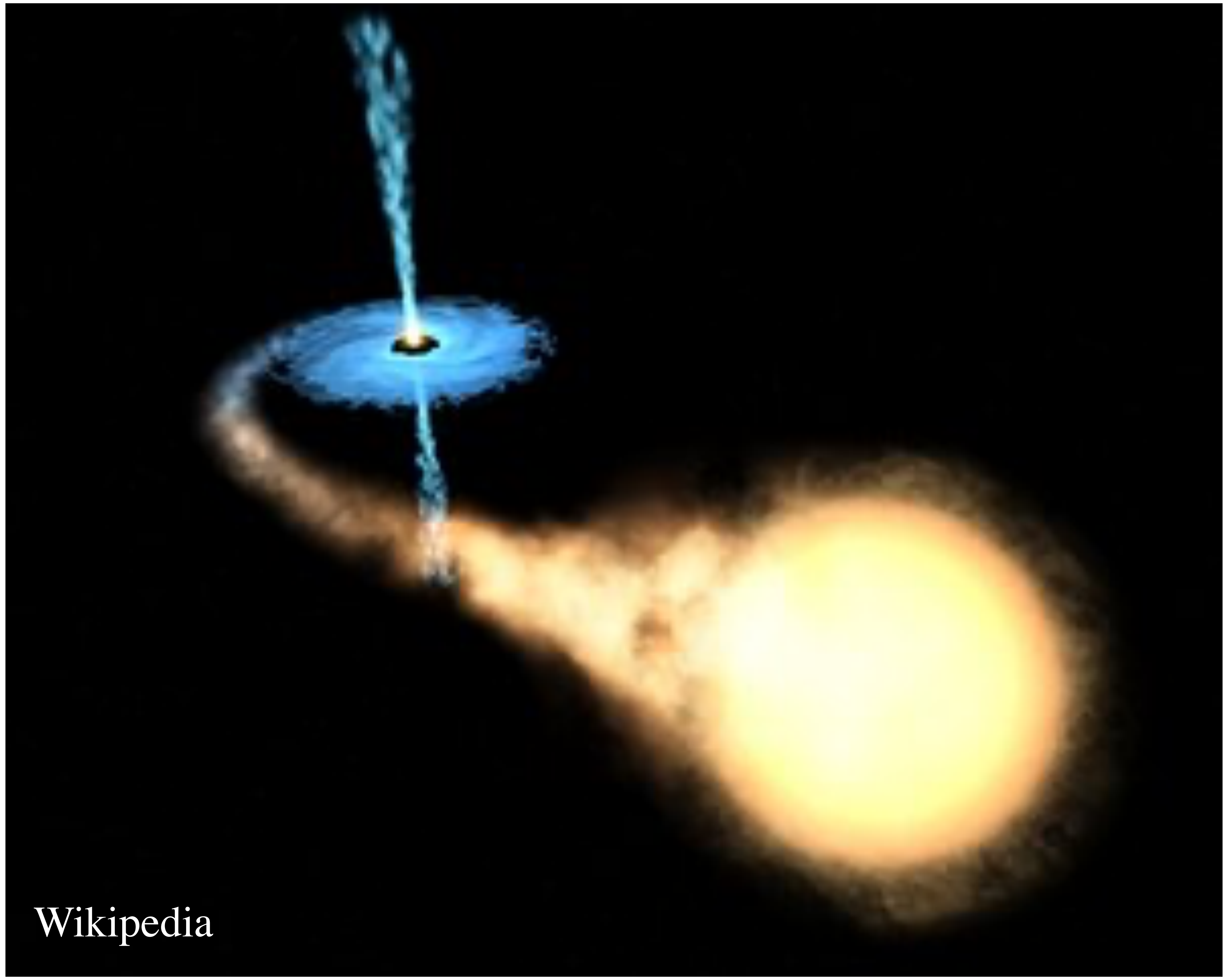


See also SSK+ 2019; Sun & Bai 2021 for MHD + test particle simulations

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

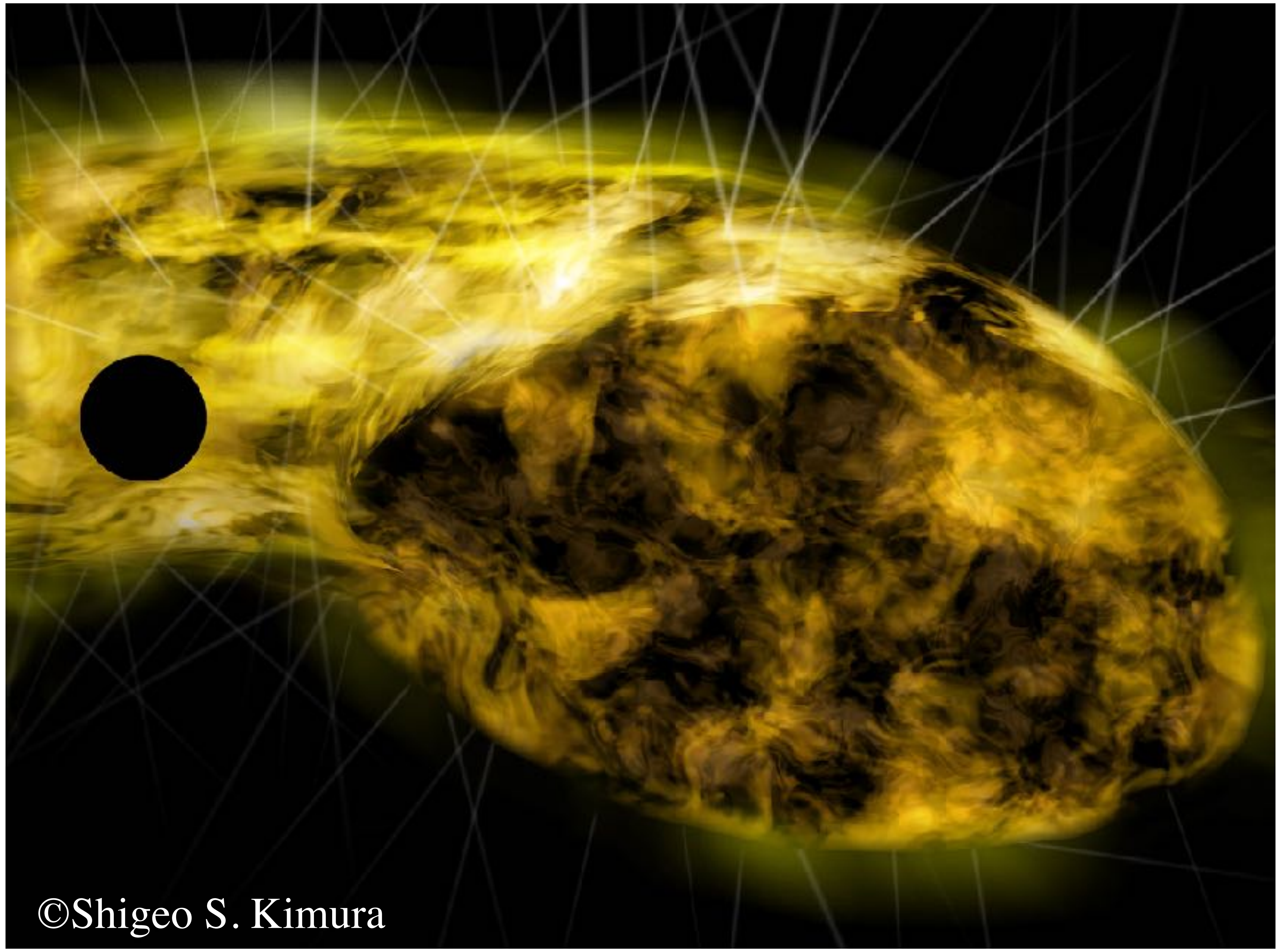
MADs in Various Environments

- 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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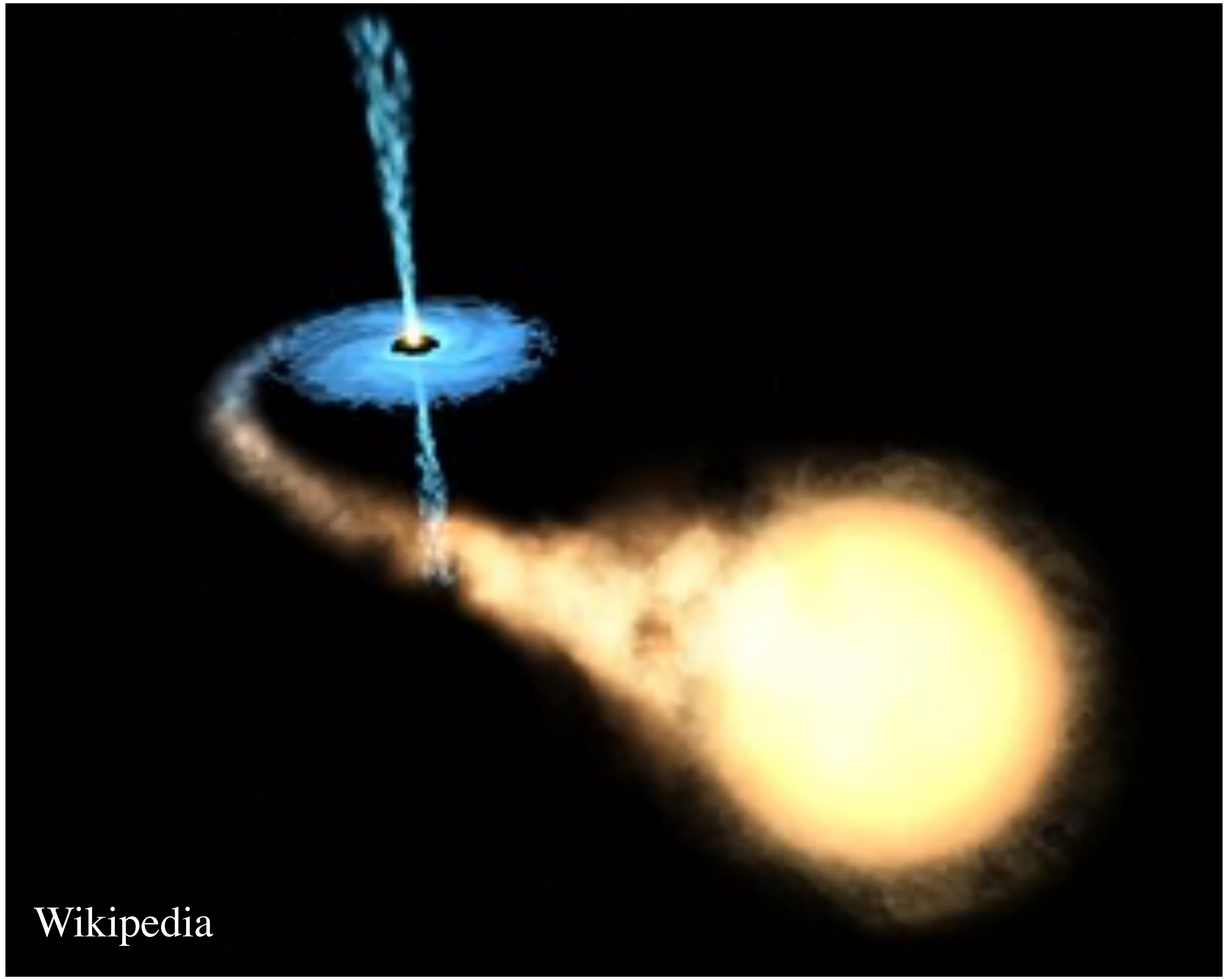

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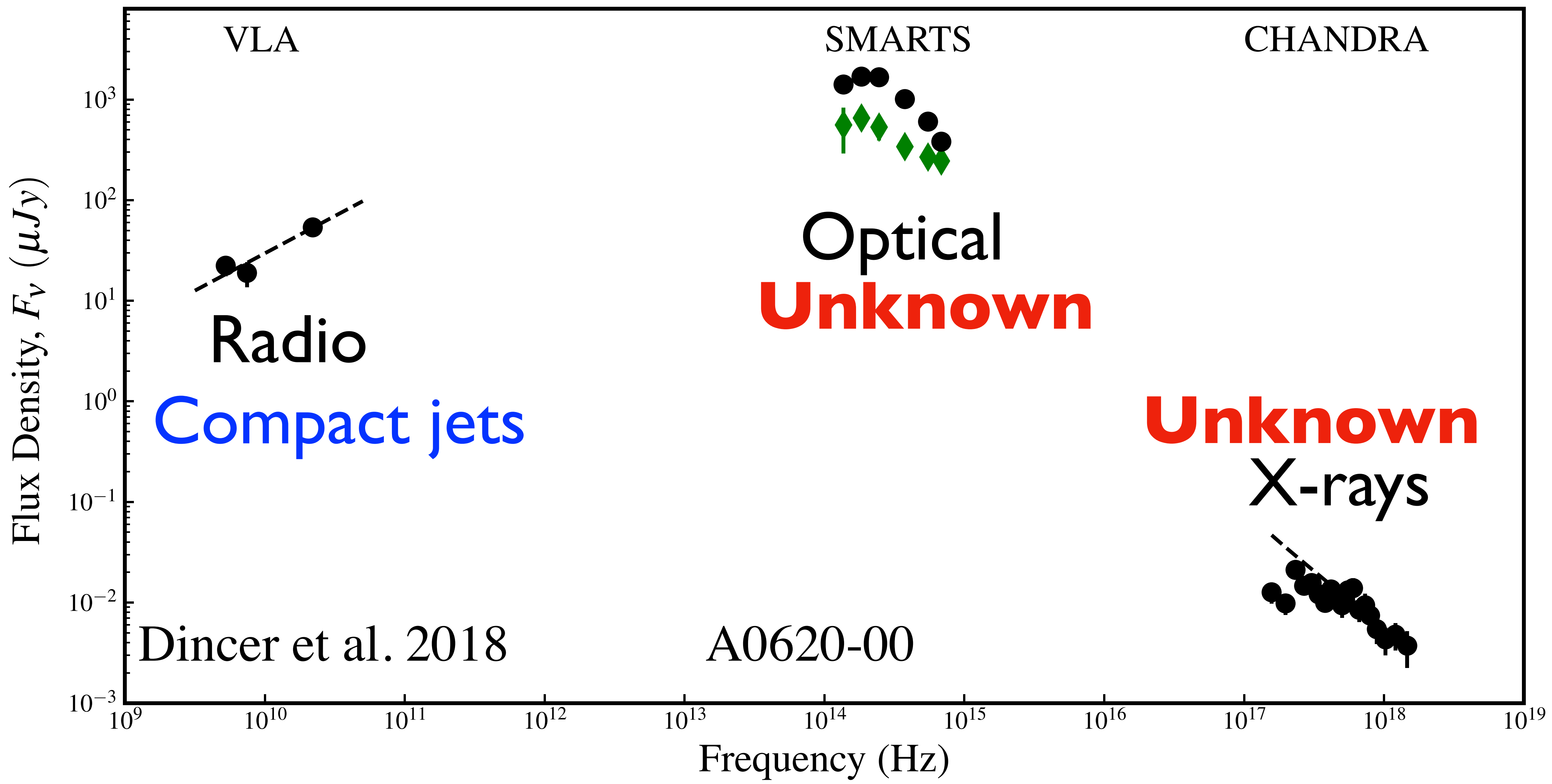
Kuze, SSK, Fang 2025

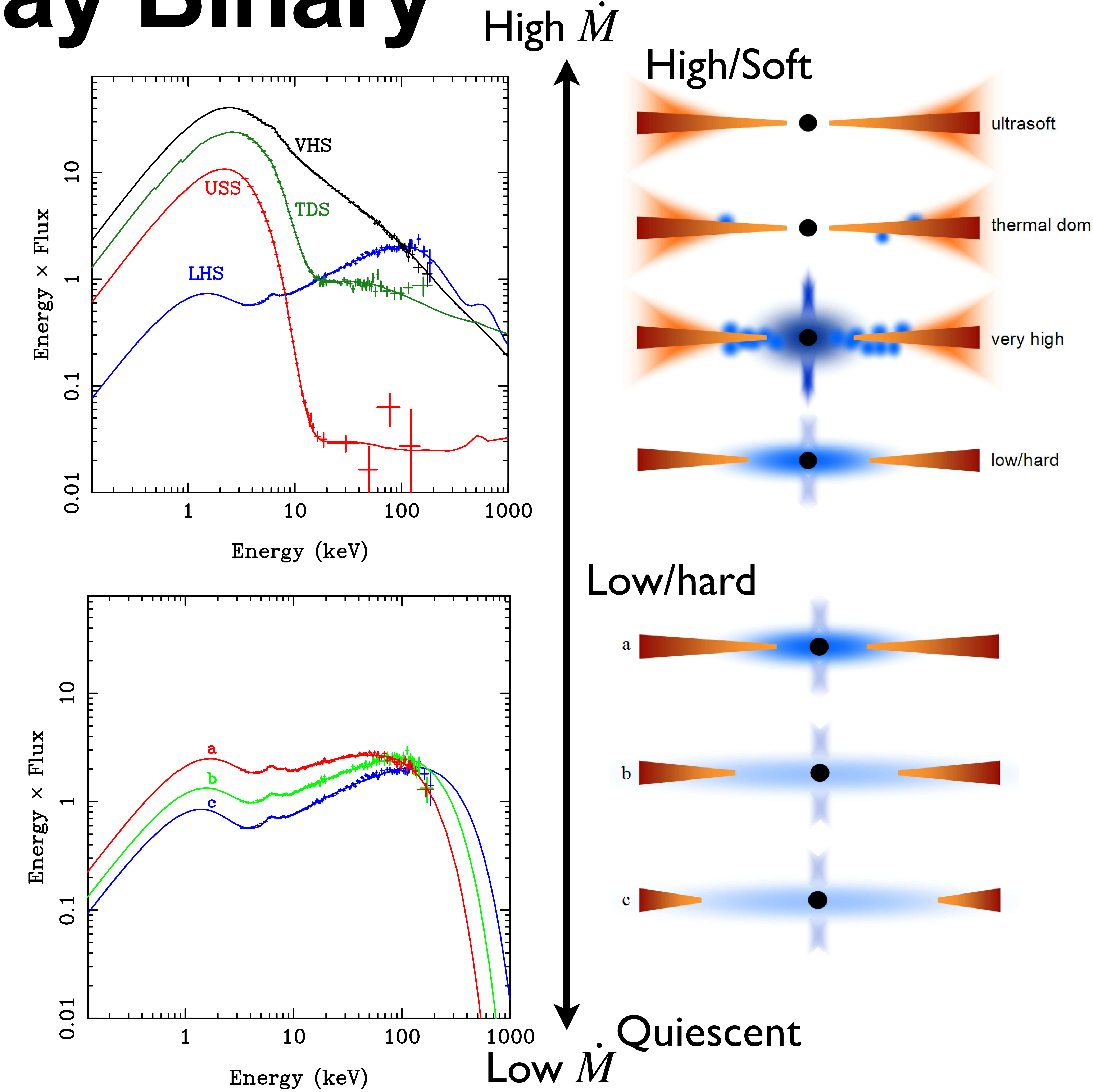
- Isolated Black Holes

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

Quiescent State in X-ray Binary

Done et al. 2007

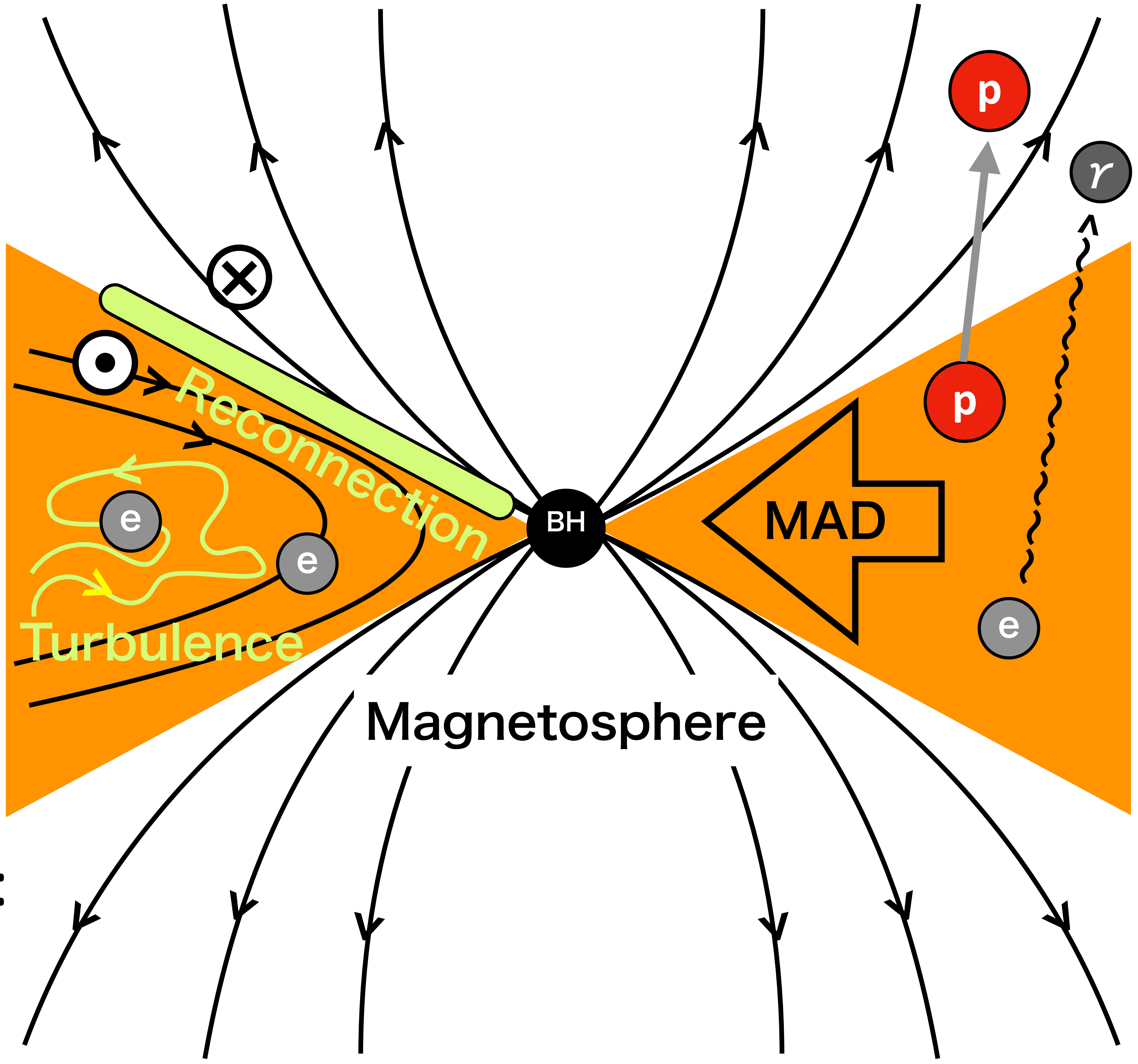




- X-ray binaries show various spectral state
- Quiescent state: faintest state in X-ray binaries
- $L_X \sim 10^{30} - 10^{33}$ erg/s
  —> $\dot{M}c^2 \lesssim 10^{-3} - 10^{-5} L_{\rm Edd}$
- Radio, optical, and X-ray signals are observed
  —> calibrate parameters by opt & X data

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:

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

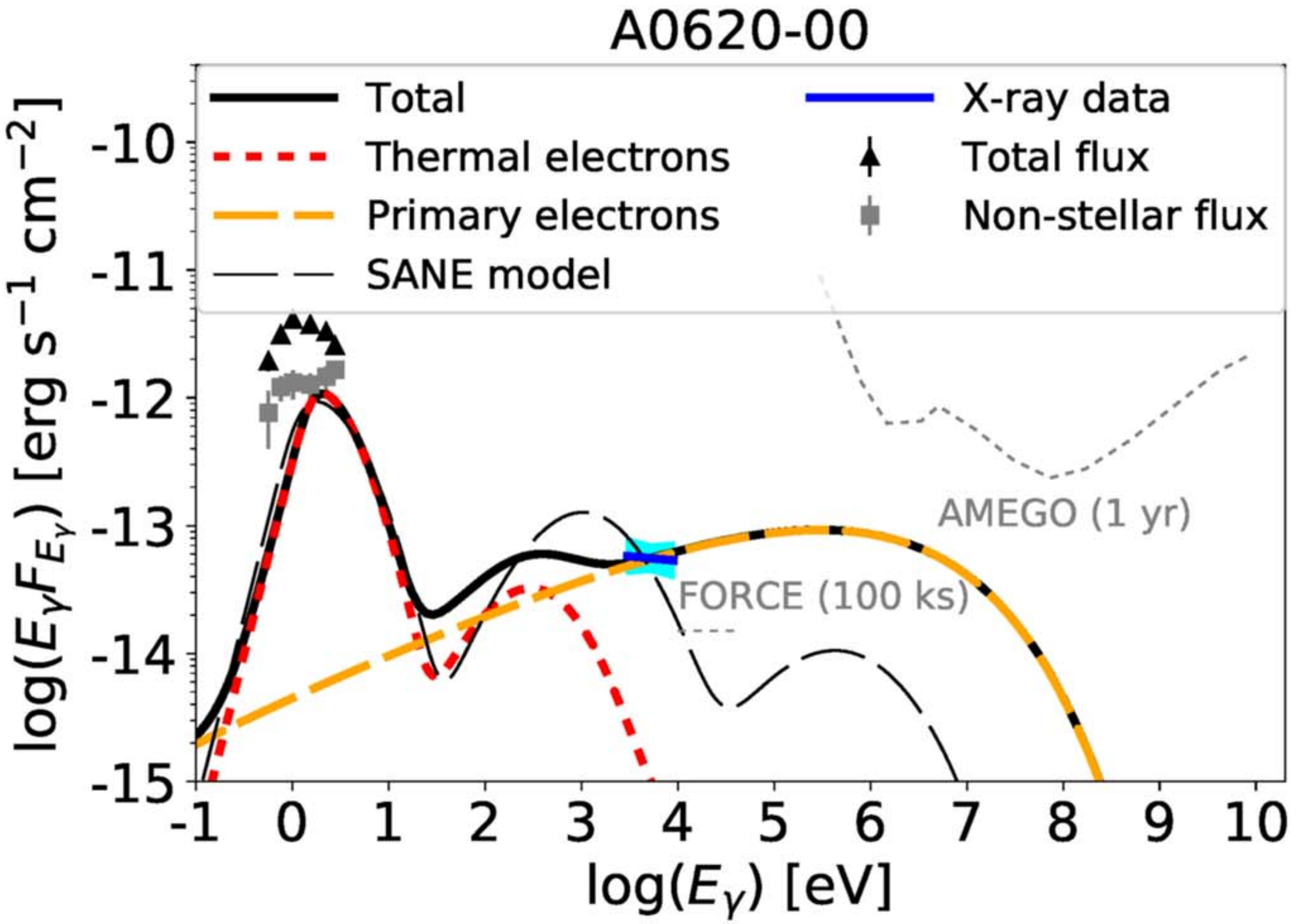
- Normalization for non-thermal electrons

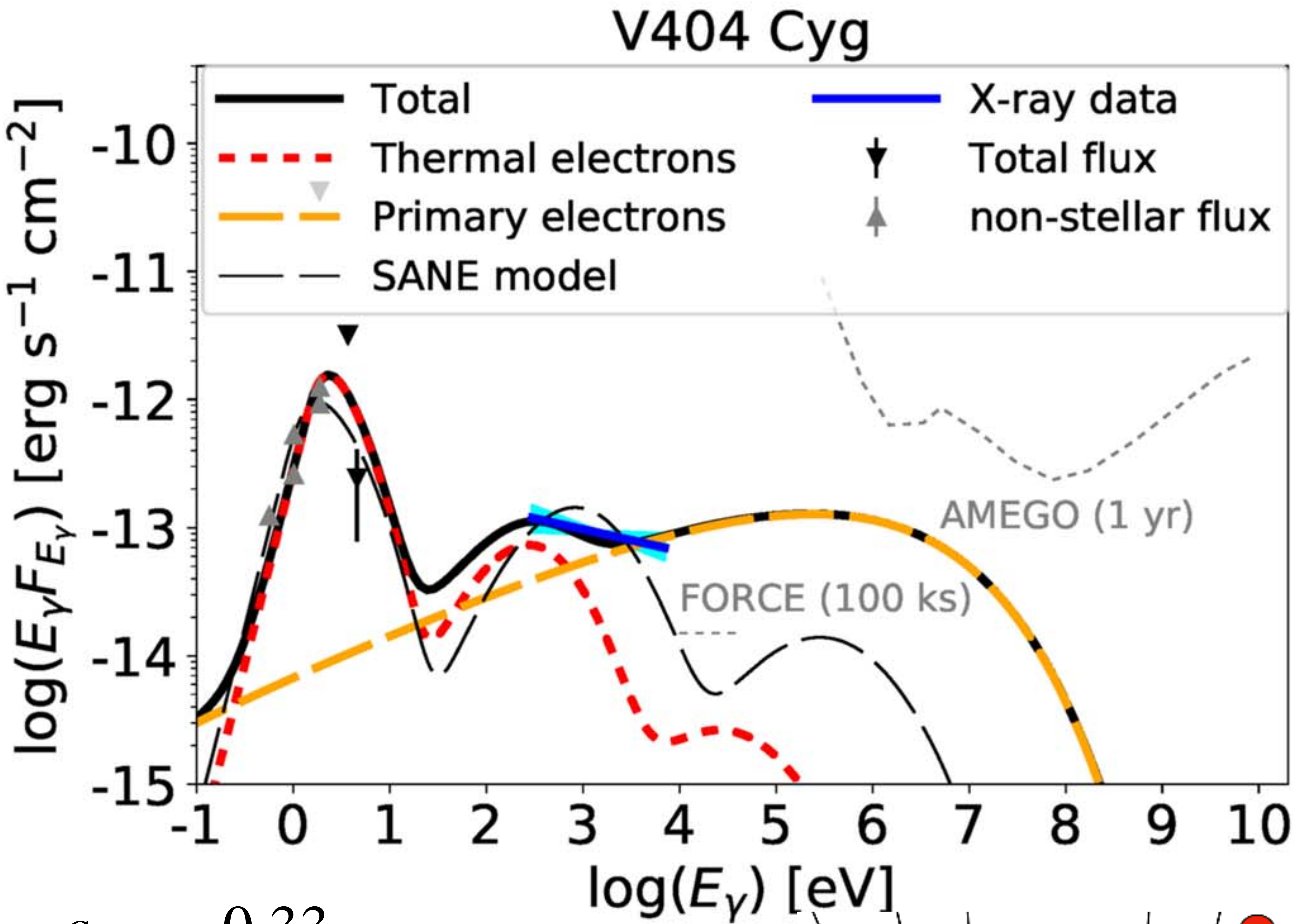
$$\int E_i \dot{N}_{E_i,{\rm inj}} dE_i = f_i \epsilon_{\rm NT} \dot{M} c^2$$

- Synchrotron dominates over the other cooling processes

Photon spectra from MADs in X-ray Binaries

SSK, Sudoh, Kashiyama, Kawanaka 2021

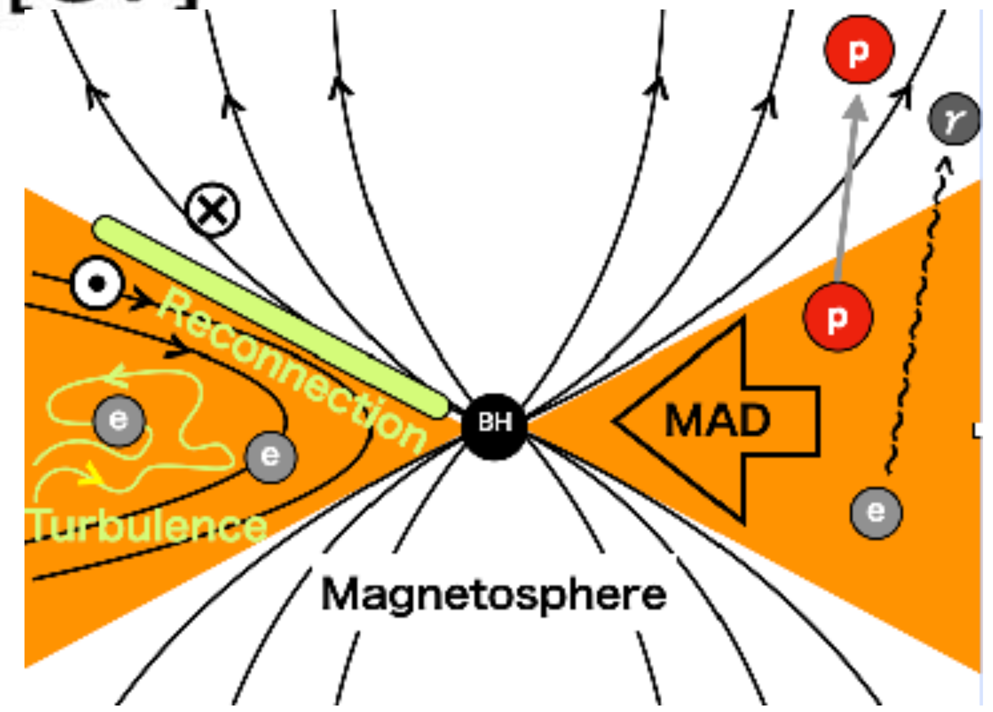




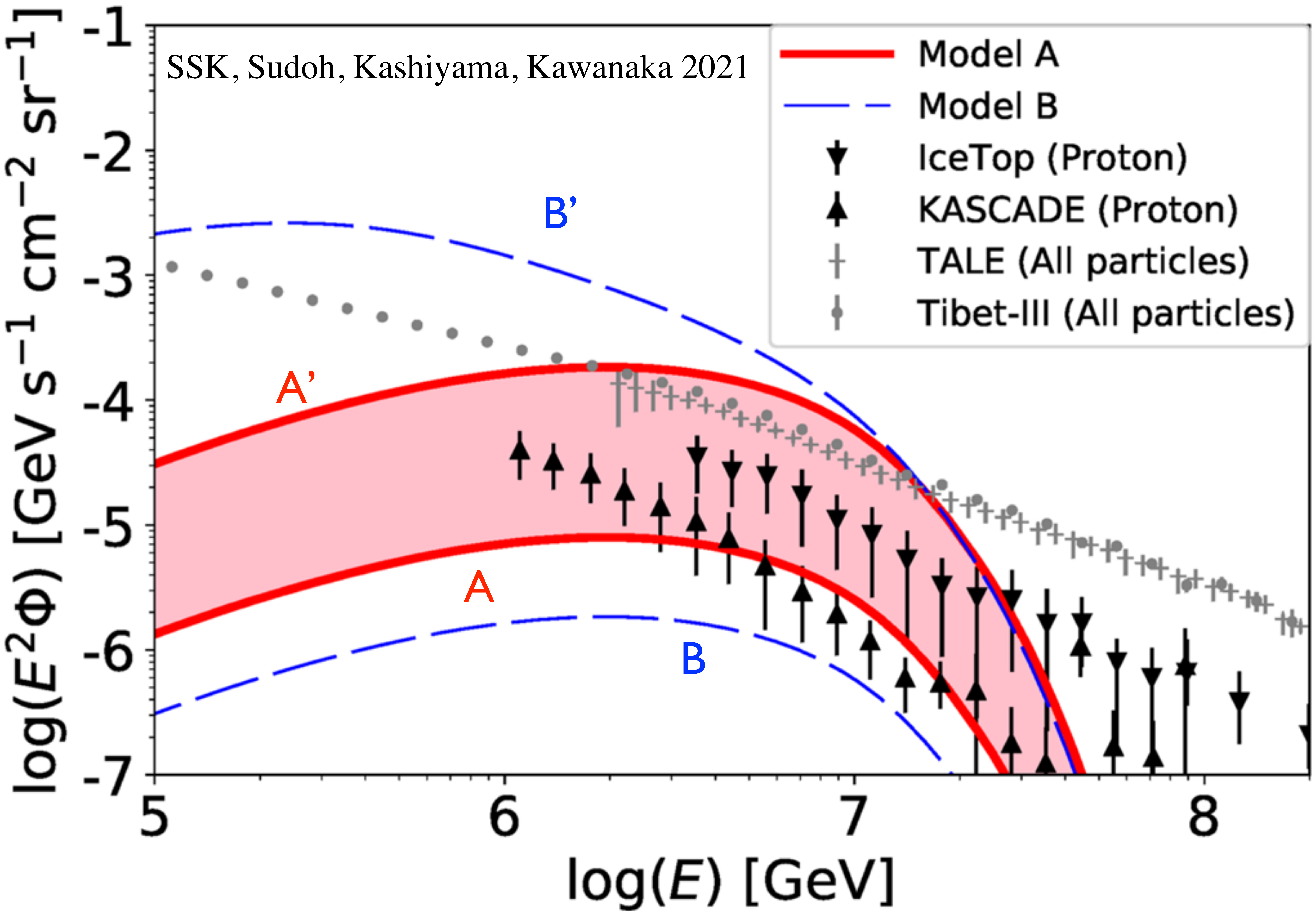
$\epsilon_{\rm NT} = 0.33$

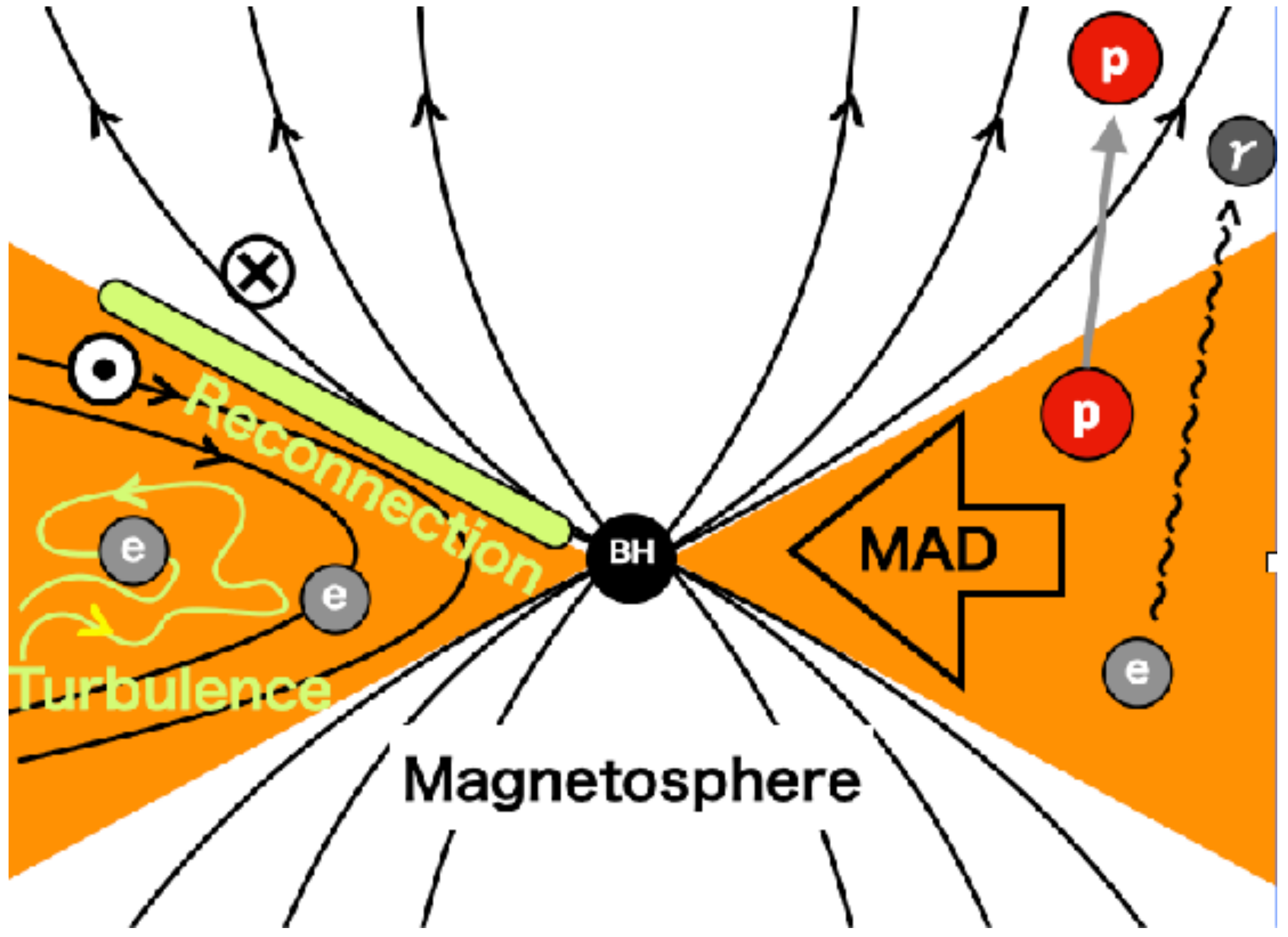
$f_e = 0.3$

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



Cosmic-Rays from MADs



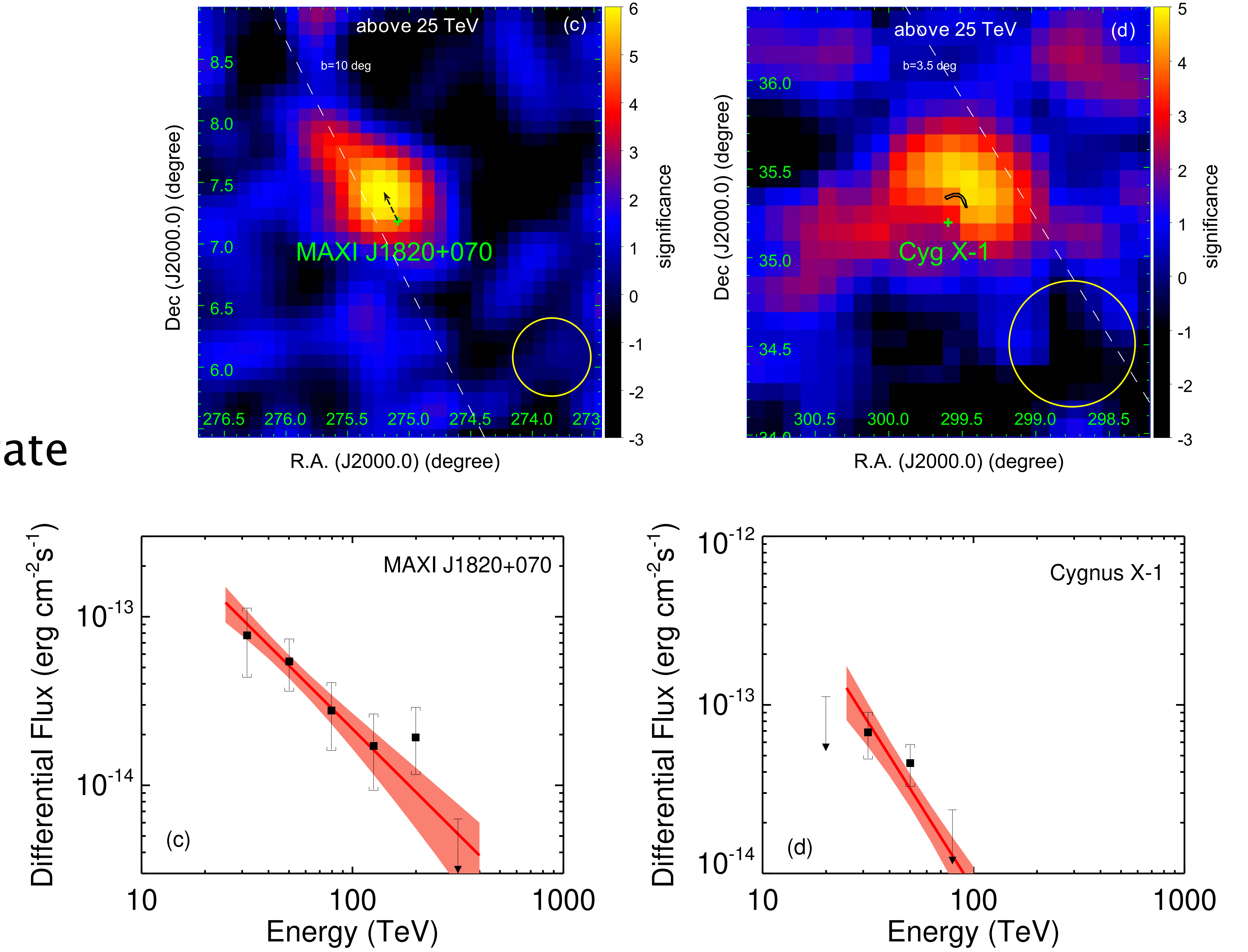


- Maximum energy: E ~ 1 PeV (balance of escape & acceleration)
- **Model prediction consistent with data within their uncertainties**
- Model uncertainty mainly from number of X-ray binaries
- Future X-ray surveys will reduce model uncertainty

UHE γ-rays from Microquasars

LHAASO 2025

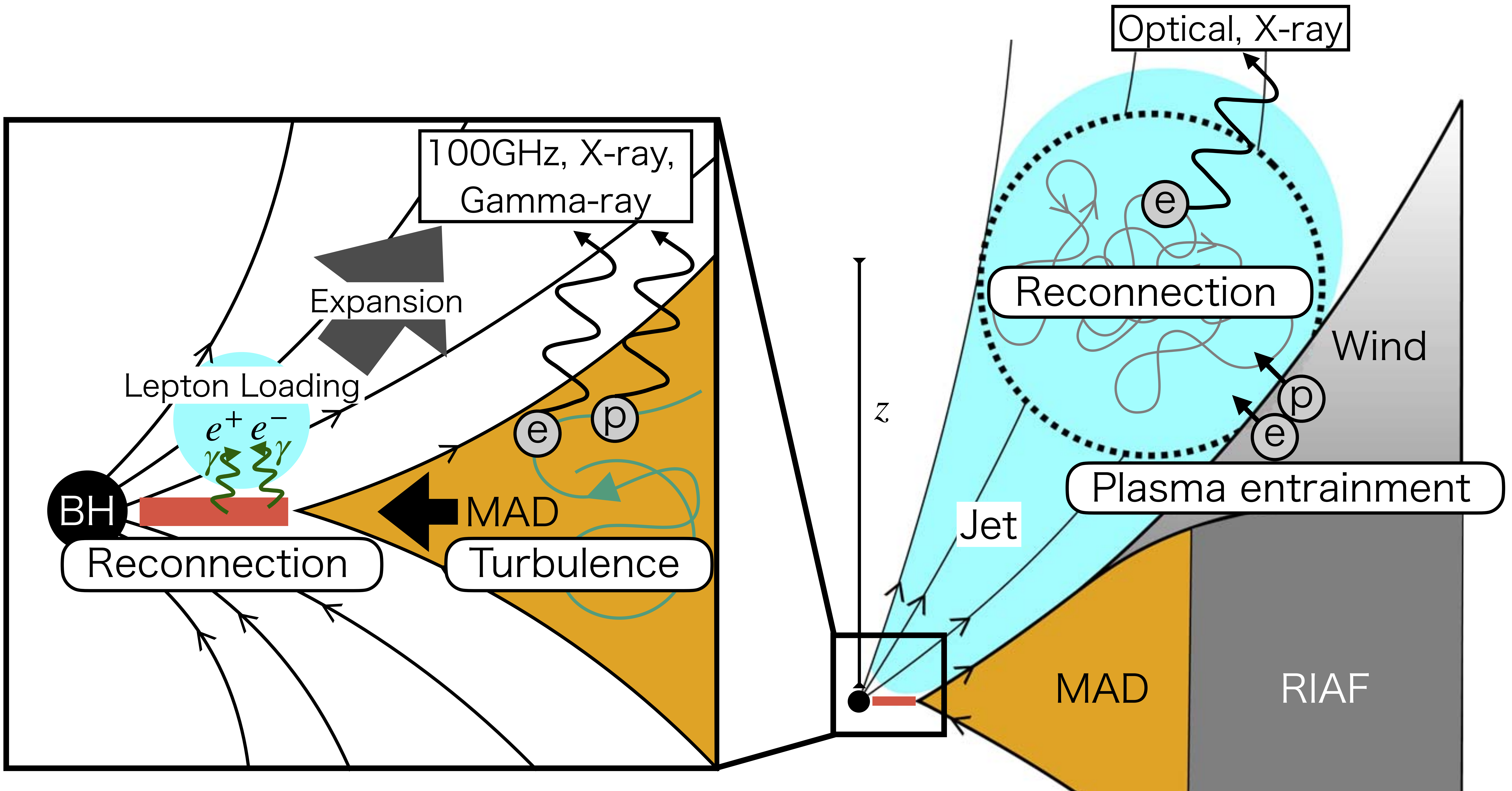
- LHAASO detection of Cyg X−1 & MAXI J1820+070
  - Both sources are consistent with point sources
  - Cyg X−1 in hard state (Position offset ~ 1.6σ)
  - MAXI J1820+070 in quiescent state (Position offset ~ 3.5σ)
- Cyg X−1 detected in GeV γ => jet component?
- **Can we explain these with our hot accretion flow model?**



Jet-MAD model

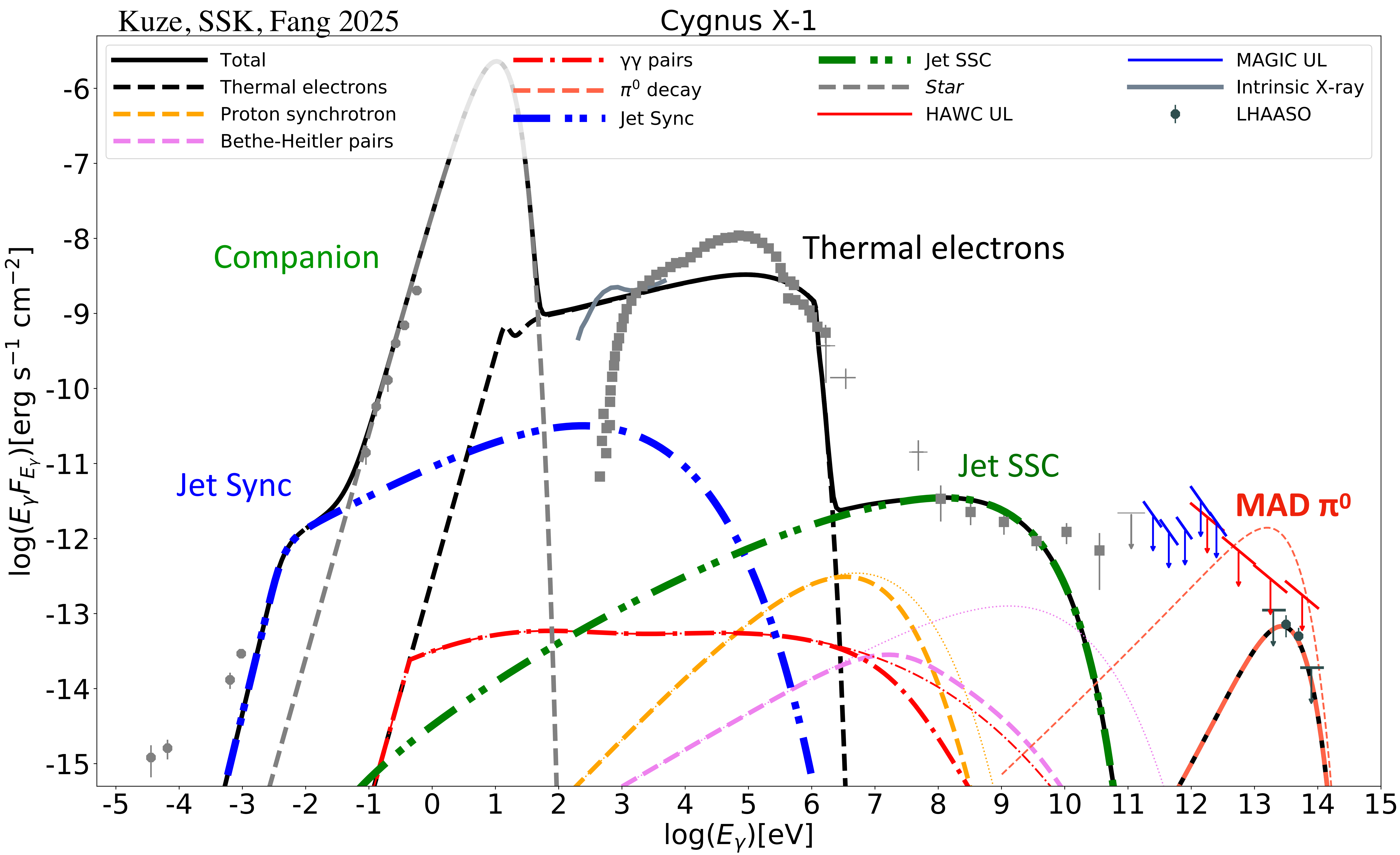
Kuze, SSK, Toma 2024

Kuze, SSK, Fang 2025



Application to Cyg X-1

- Our model can reproduce broadband features

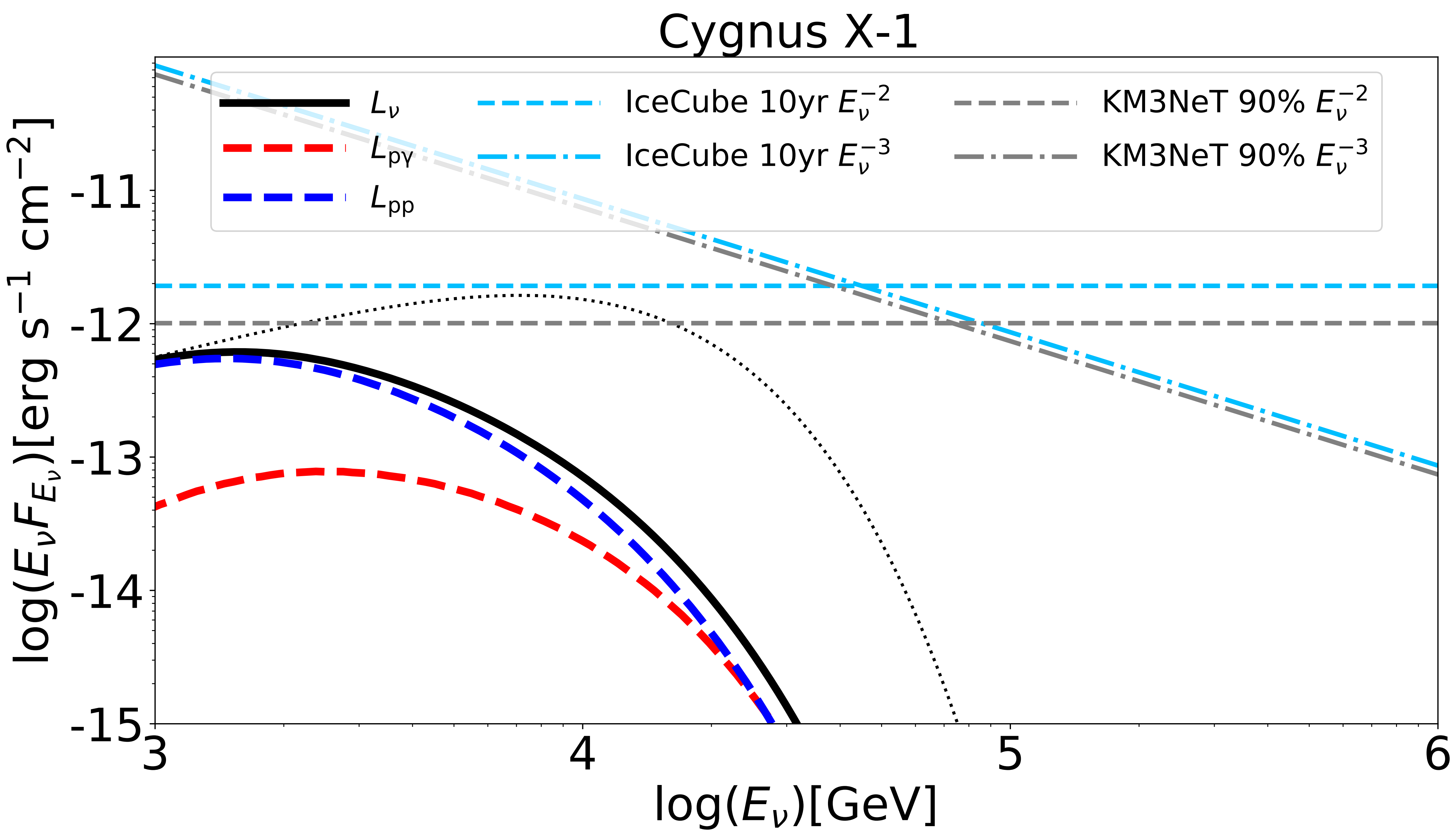


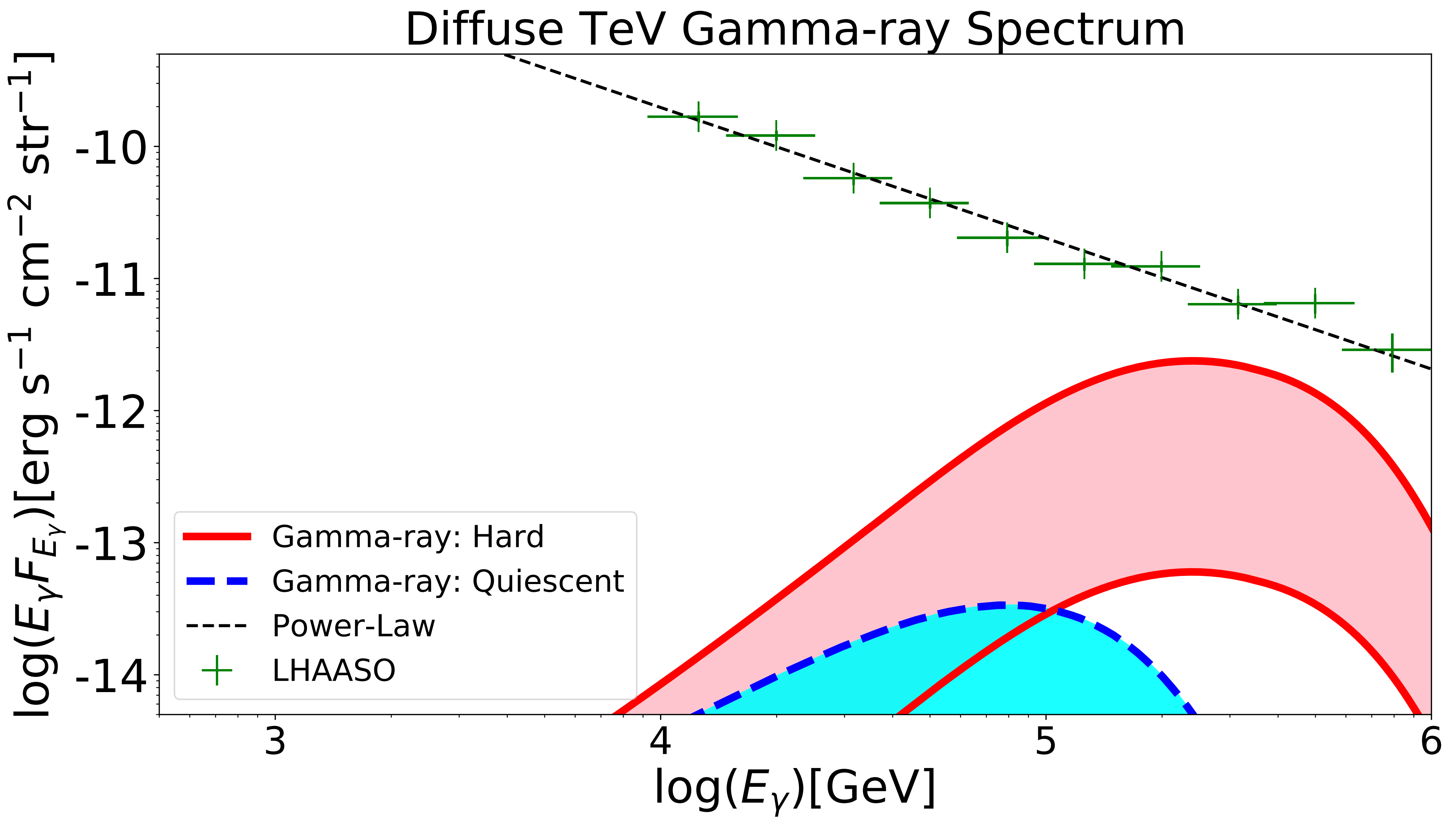
$$\dot{m} = \dot{M}c^2/L_{\rm Edd} = 10^{-1}$$
$$s_{\rm inj,MAD} = 1.21$$

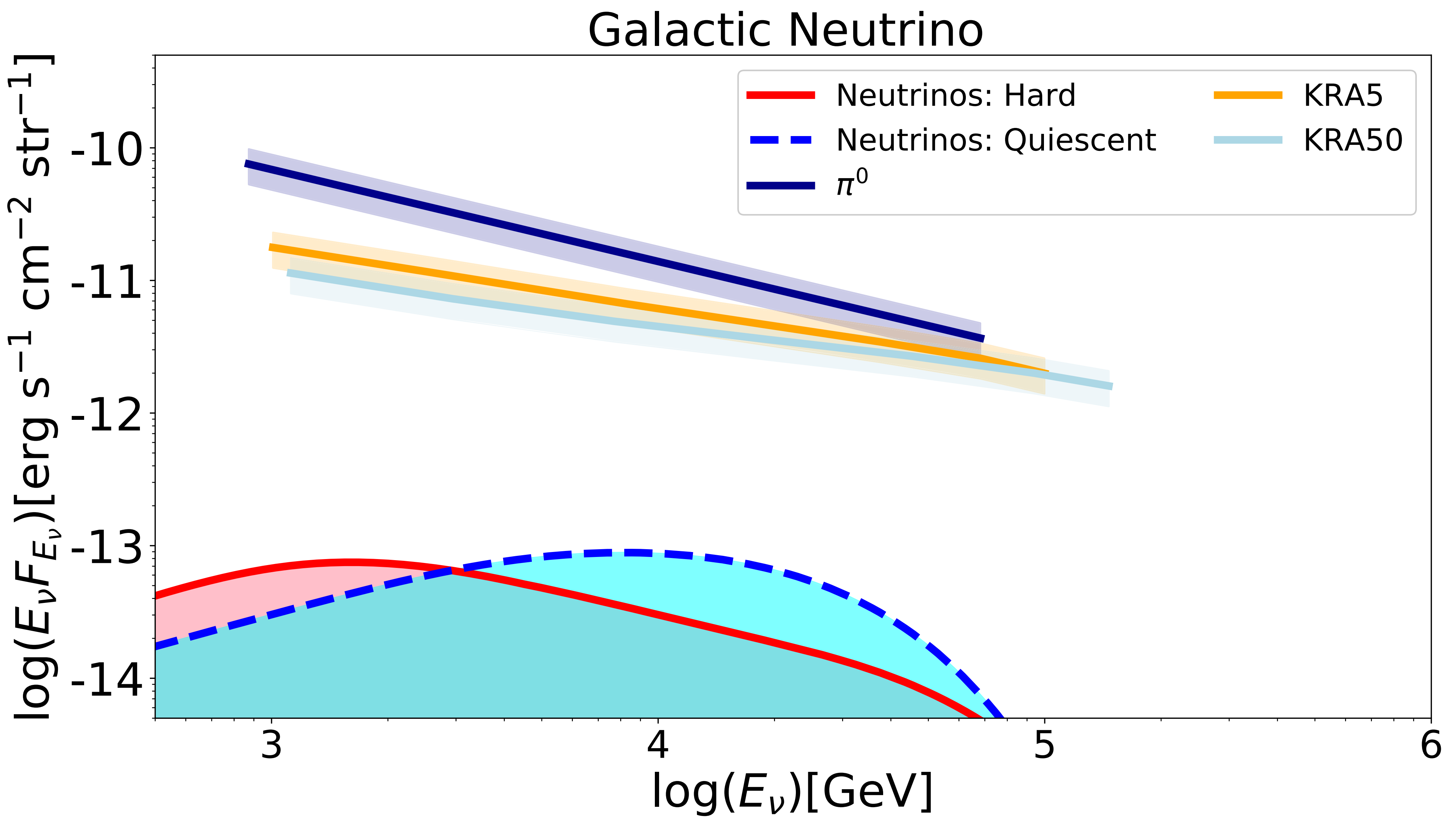
$$B_{\rm mad} = 1.2 \times 10^7 \ {\rm G}$$
$$E_{p,\rm max} = 1.6 \times 10^5 \ {\rm GeV}$$

$$\epsilon_{\rm NT} = 0.003$$
$$f_e = 0.3$$

Neutrinos & Gamma-rays from X-ray Bianries







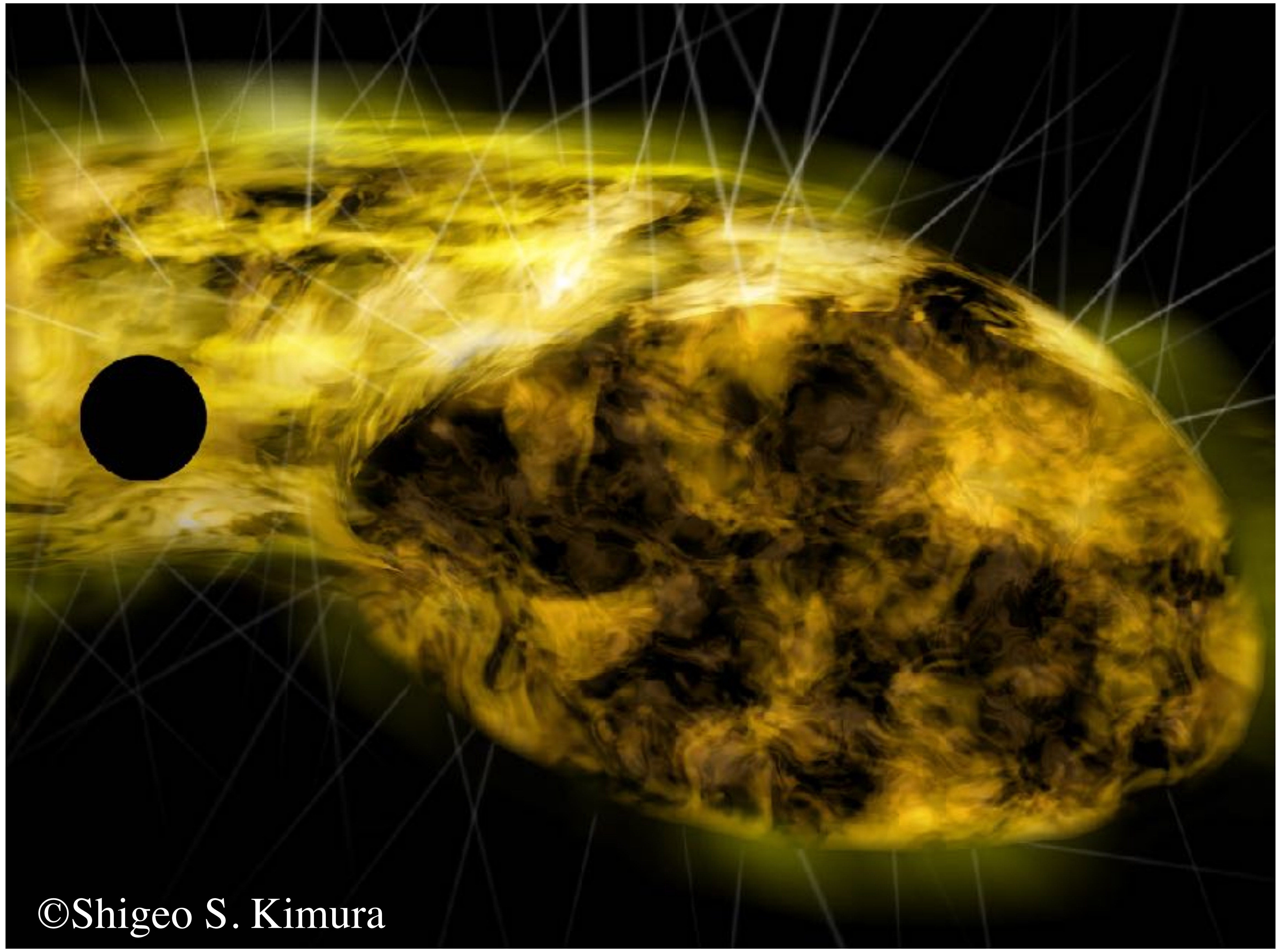
- Strong B-field => pion synchrotron cooling
  => neutrino production suppressed at ~ TeV
  => Unable to detect by near-future detectors
- Cumulative contribution to Galactic diffuse ν/γ
  =>Possible significant contribution to γ,
  negligible contribution to ν

MADs in Various Environments

- X-ray binaries

SSK, Sudoh, Kashiyama, Kawanaka 2021
Kuze, SSK, Fang 2025

- Isolated Black Holes

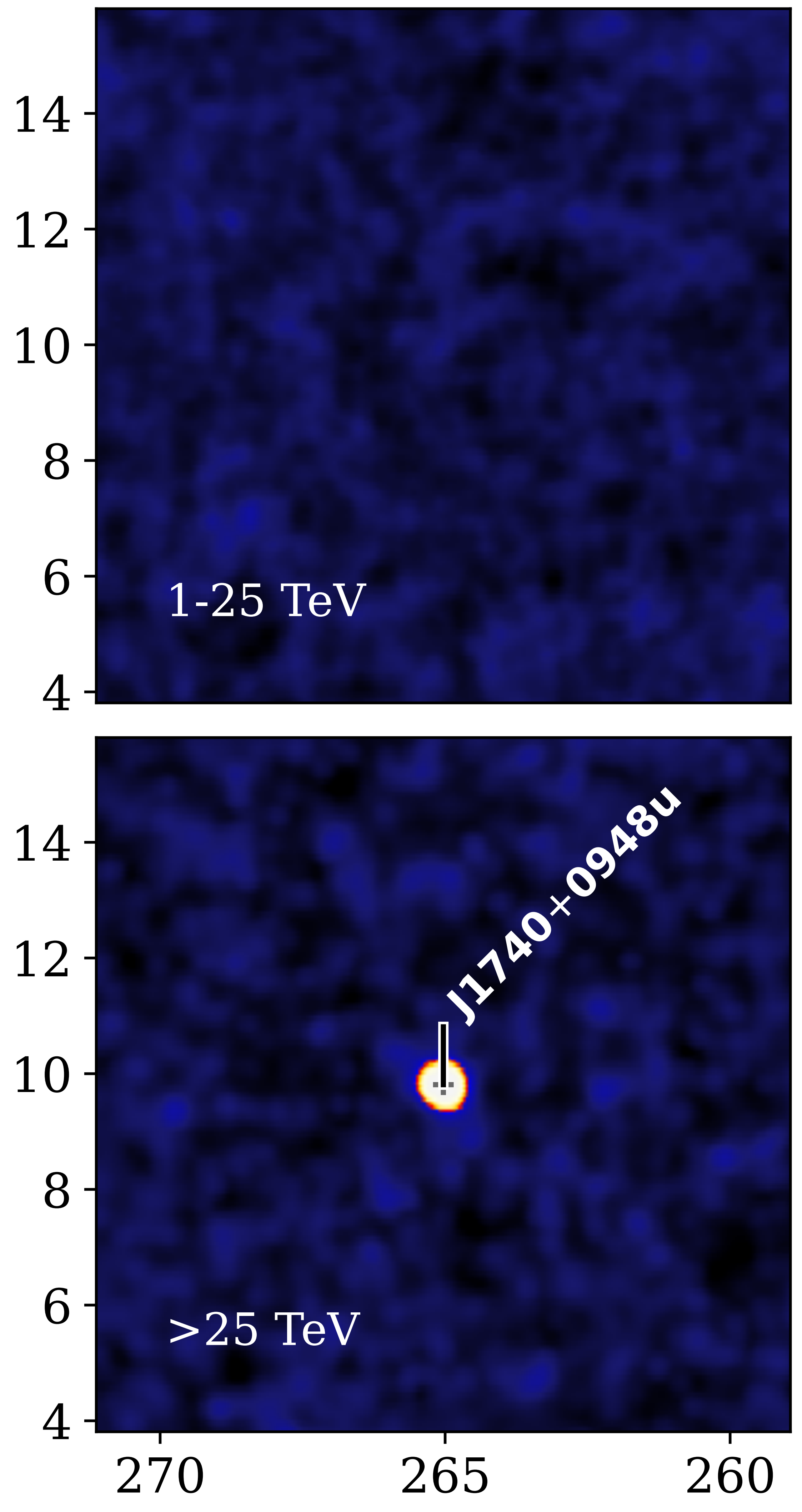


SSK, Tomida, Kobayashi, Kin, Zhang 2025
SSK, Kashiyama, Hotokezaka 2021
SSK, Murchikova, Sahu 2025

New class of UHE γ-ray sources?

- LHAASO discovered sources in E_γ > 100 TeV without detecting γ-rays for E_γ < 25 TeV
- These objects are named "dark" sources
- **What is the origins of the "dark" sources detected by LHAASO?**

LHAASO 1st catalog paper 2024



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		

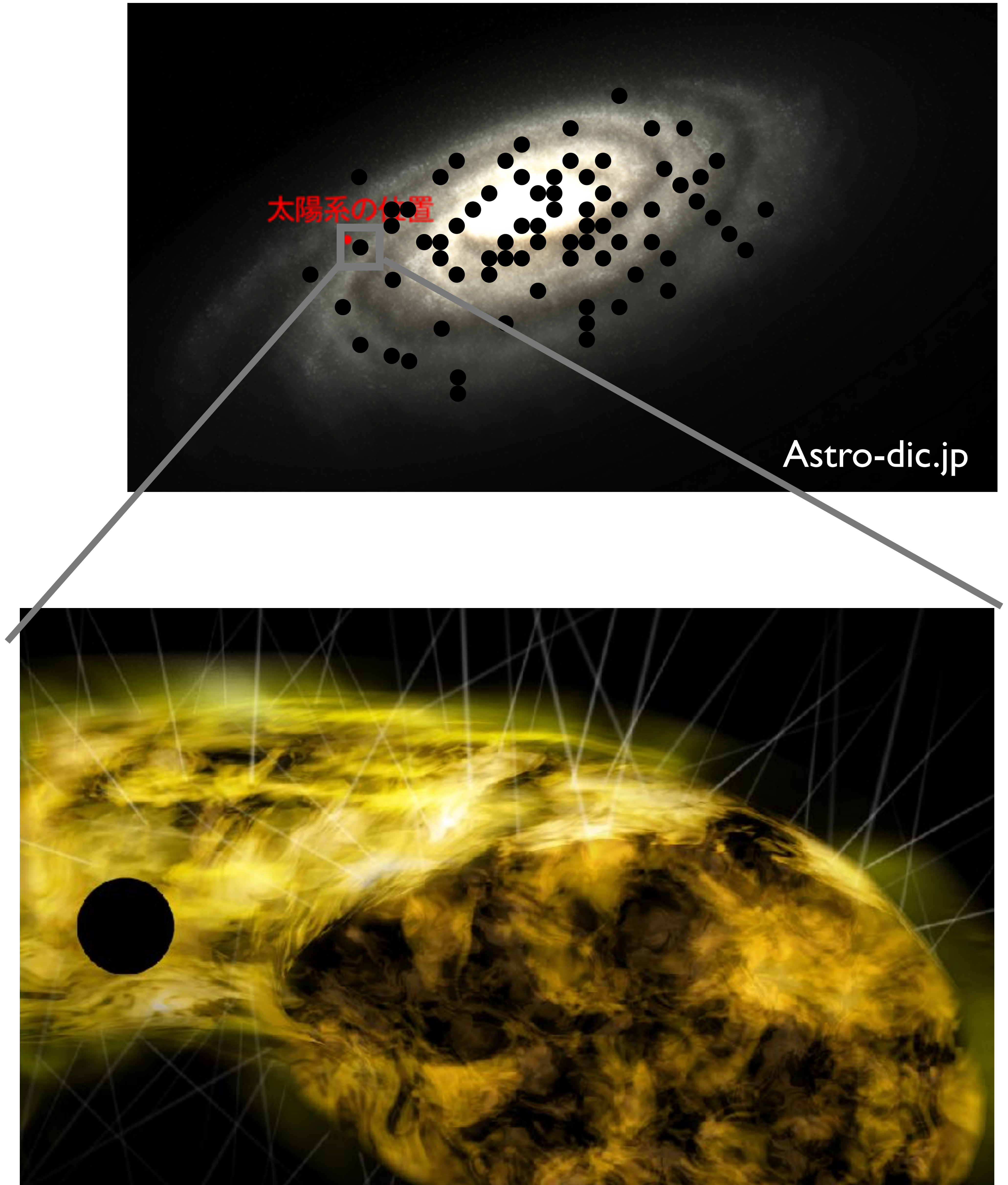
Isolated Black Holes (IBHs)

- 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

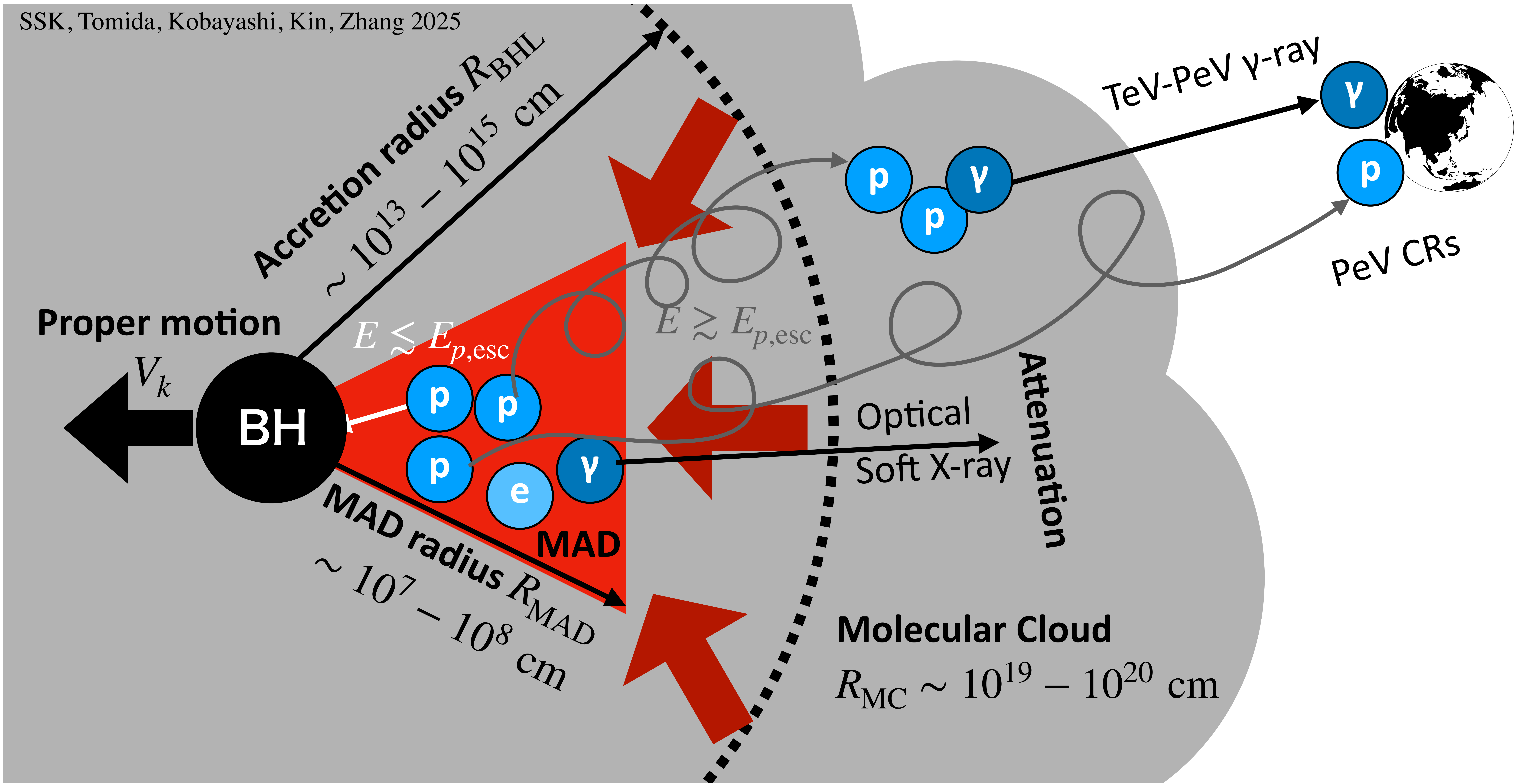
$$\dot{M}_{\bullet} \approx \lambda_w \frac{4\pi G^2 M^2 \mu_{\rm ISM} m_p n_{\rm ISM}}{(C_s^2 + v_k^2)^{3/2}}$$

- 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 $n_{ISM,2} v_{k,40{\rm km/s}}$
- Hillas energy for isolated BH
  => $E_{\rm max} \approx eBR \sim 0.8 L_{35}^{1/2} \epsilon_B^{1/2}$ PeV
  IBHs as PeVatrons?

(Barkov et al. 2012; Ioka et al. 2017)



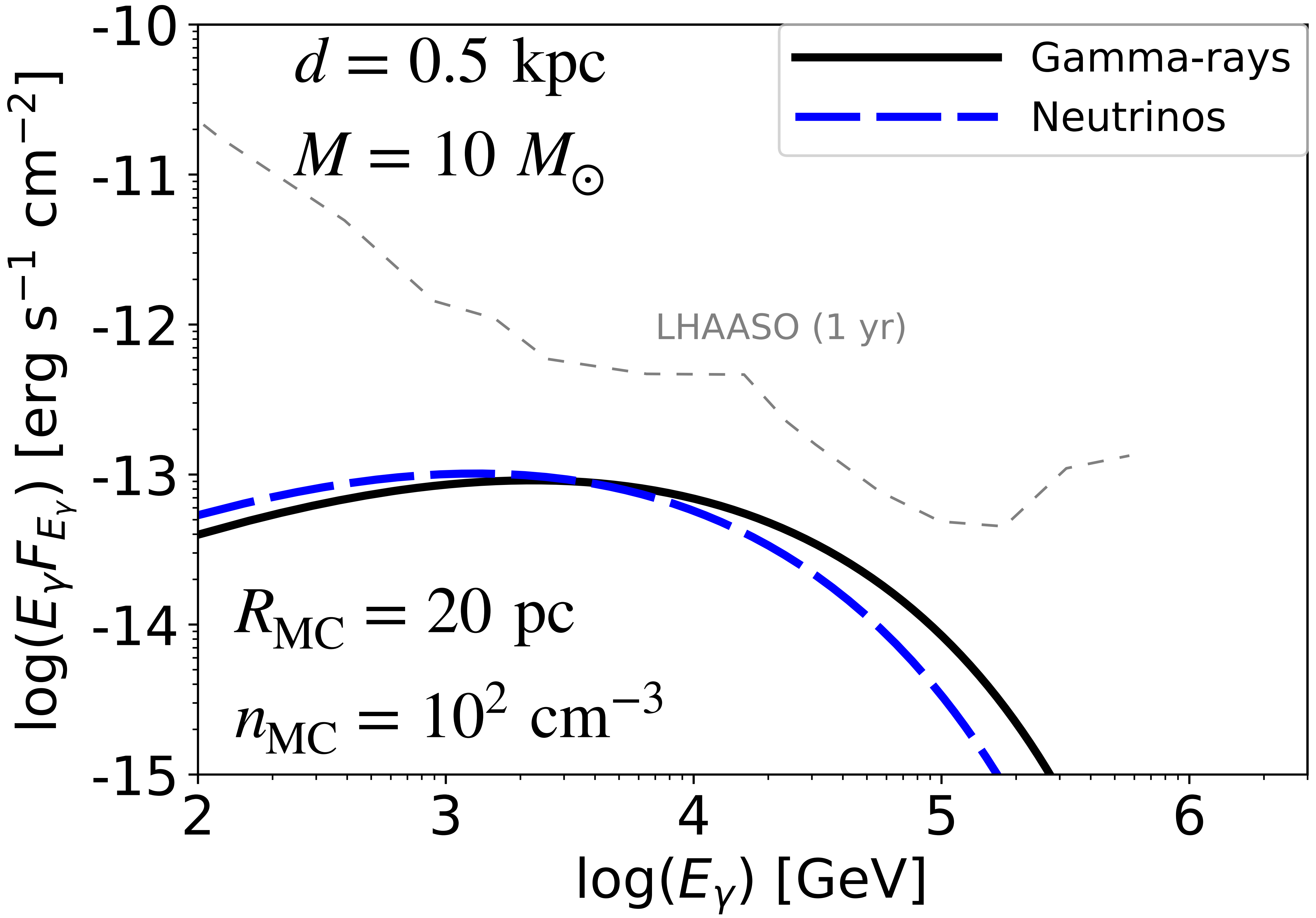
Schematic picture of our scenario



γ-rays from molecular clouds

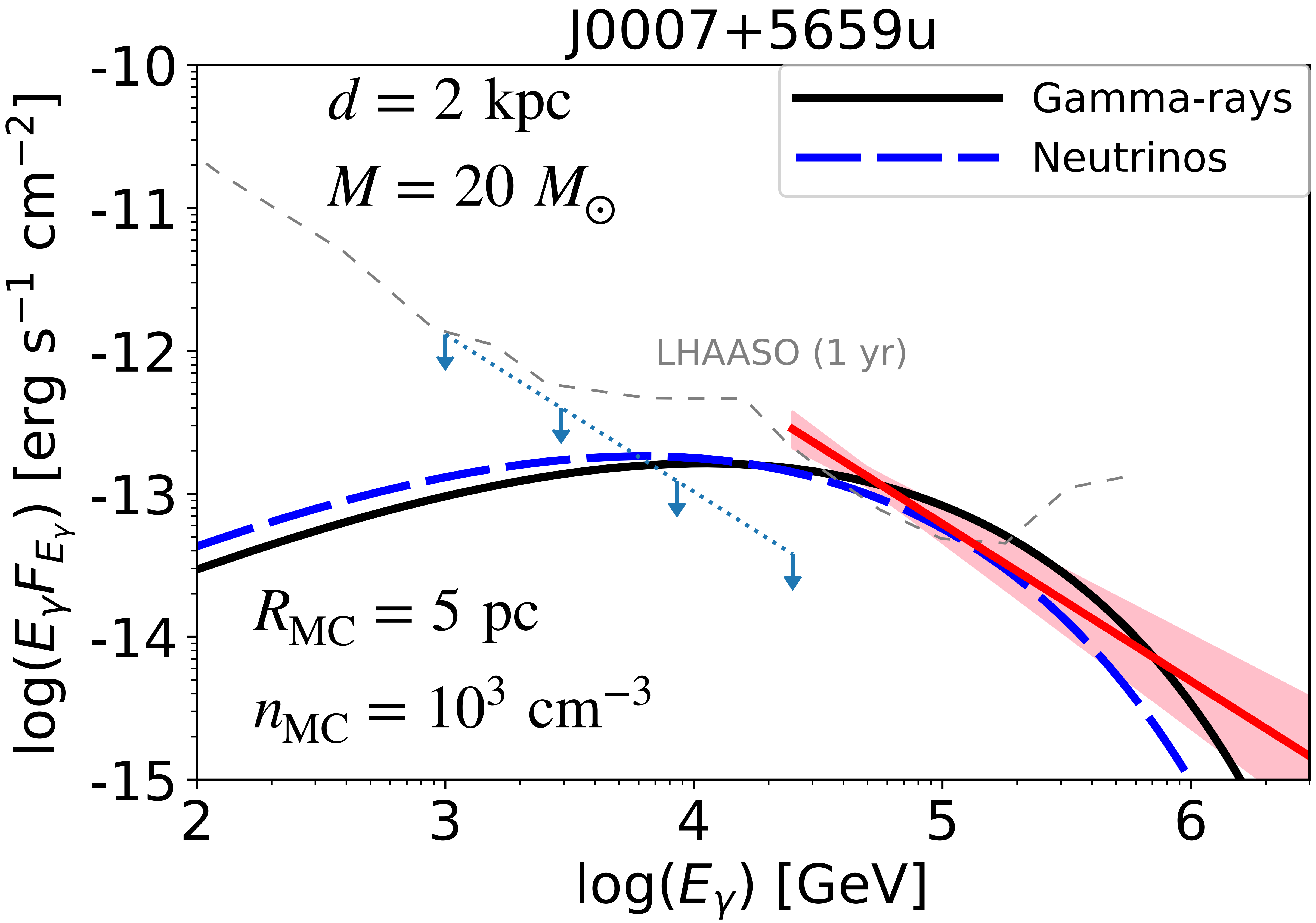
SSK, Tomida, Kobayashi, Kin, Zhang 2025

- Typical environment



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

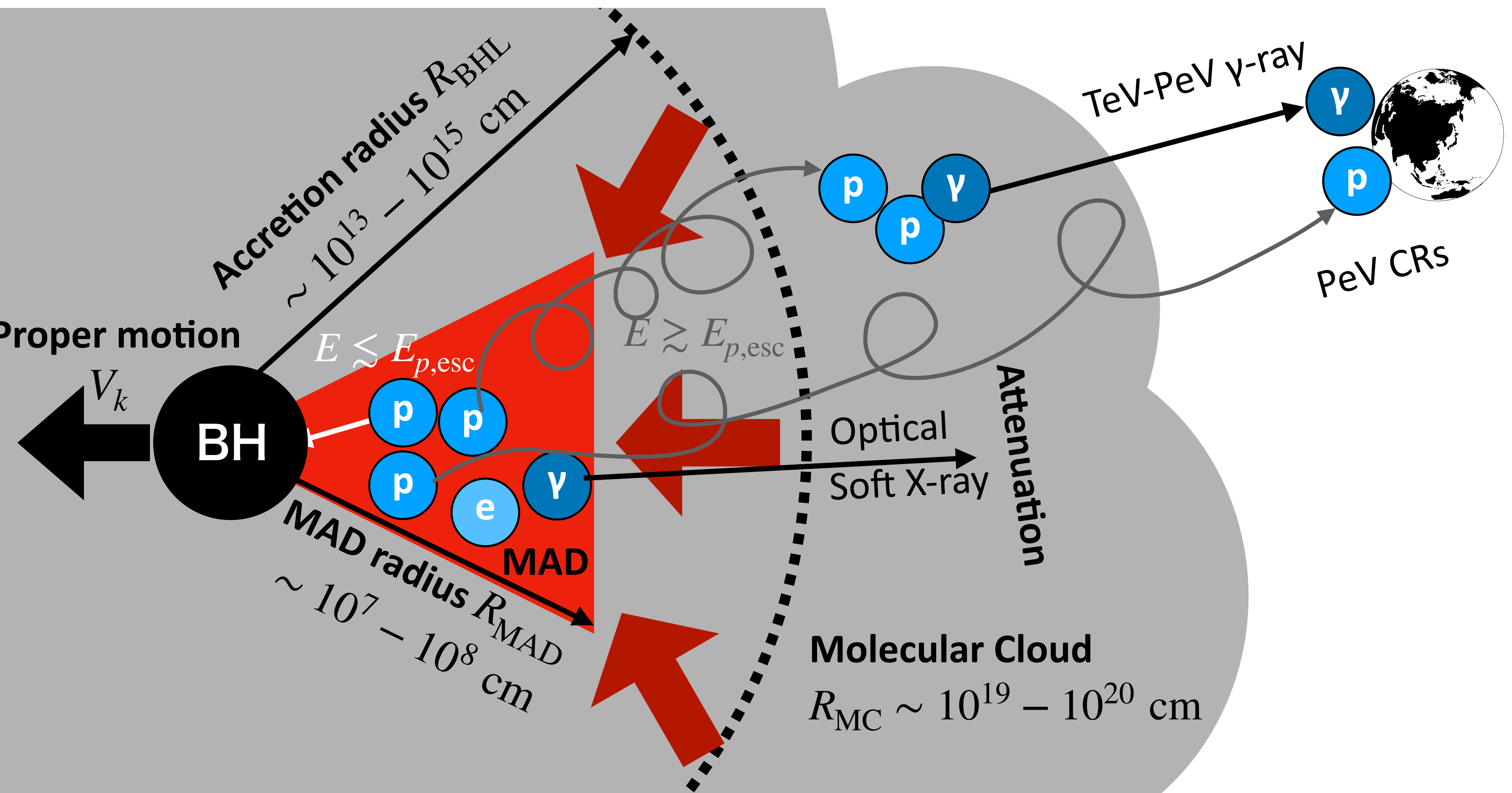
- Optimistic environment

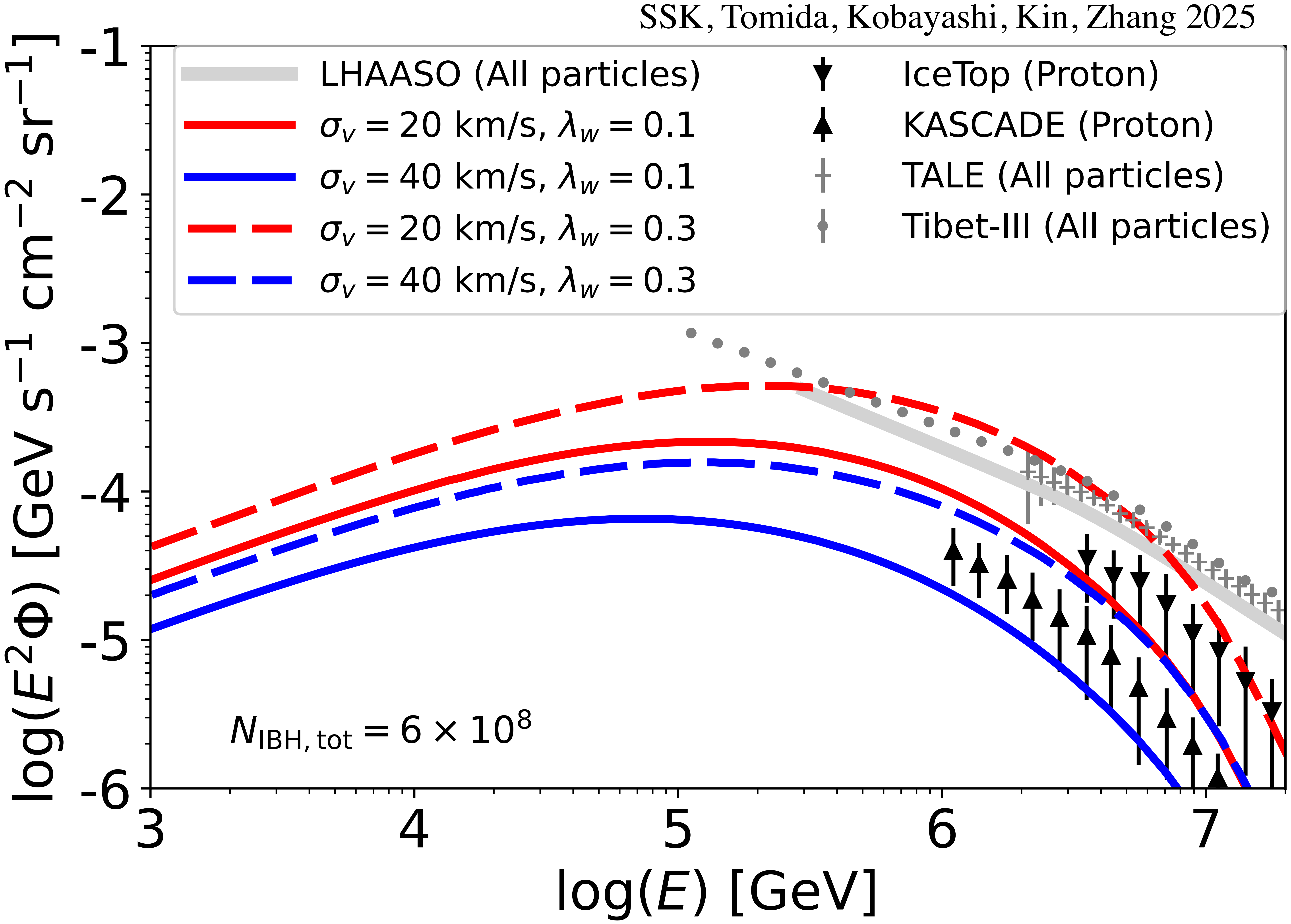


- Our scenario can explain LHAASO data
- Future detectors may be able to detect neutrinos from "dark" sources

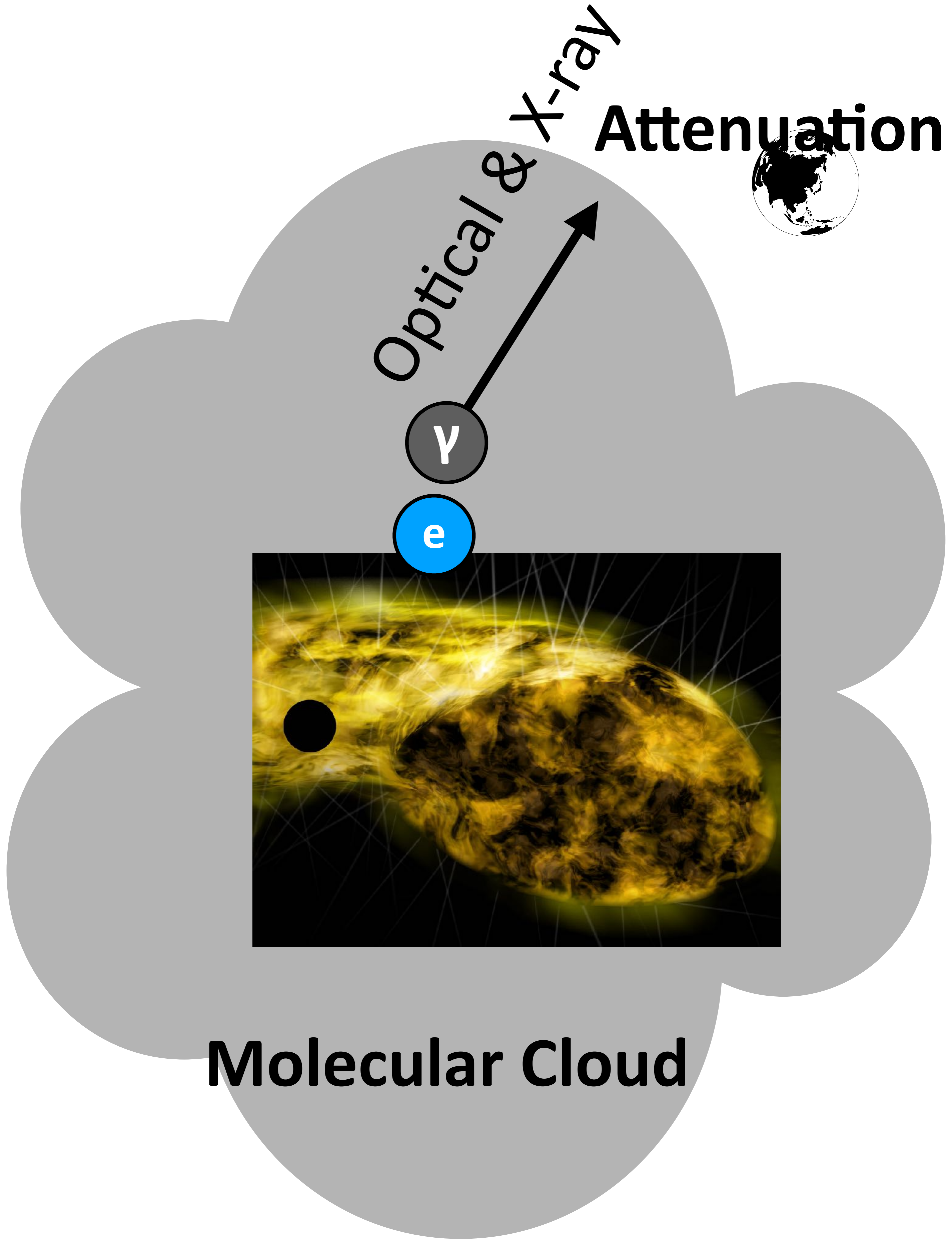
IBHs in Molecular Clouds as PeVatrons

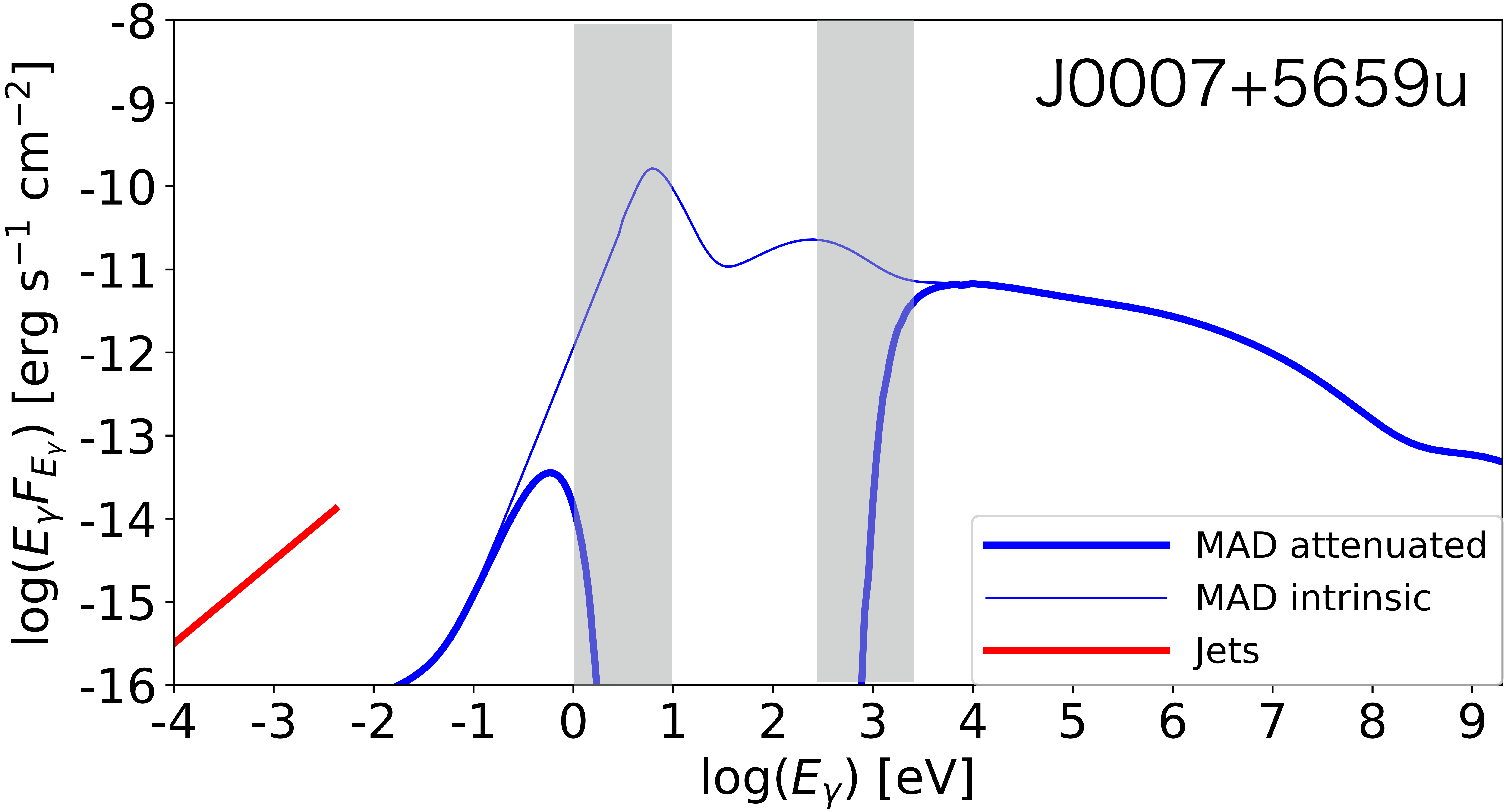
- IBHs in molecular clouds:
  $N_{\mathrm{BH,MC}} \sim 10^5 N_{\mathrm{IBH},8}\xi_{\mathrm{MC},-3}$
- $L_{\mathrm{CR}} \sim 10^{33}\epsilon_{p,-2}(\dot{M}c^2)_{35}$ erg/s
- $L_{\mathrm{CR,IBH}} \approx N_{\mathrm{BH,MC}} L_{\mathrm{CR}} \sim 10^{38}$ erg/s
  $\gtrsim L_{\mathrm{CR,PeV}} \simeq 1.5 \times 10^{38}$ erg/s
- **They can be source of PeV CRs**





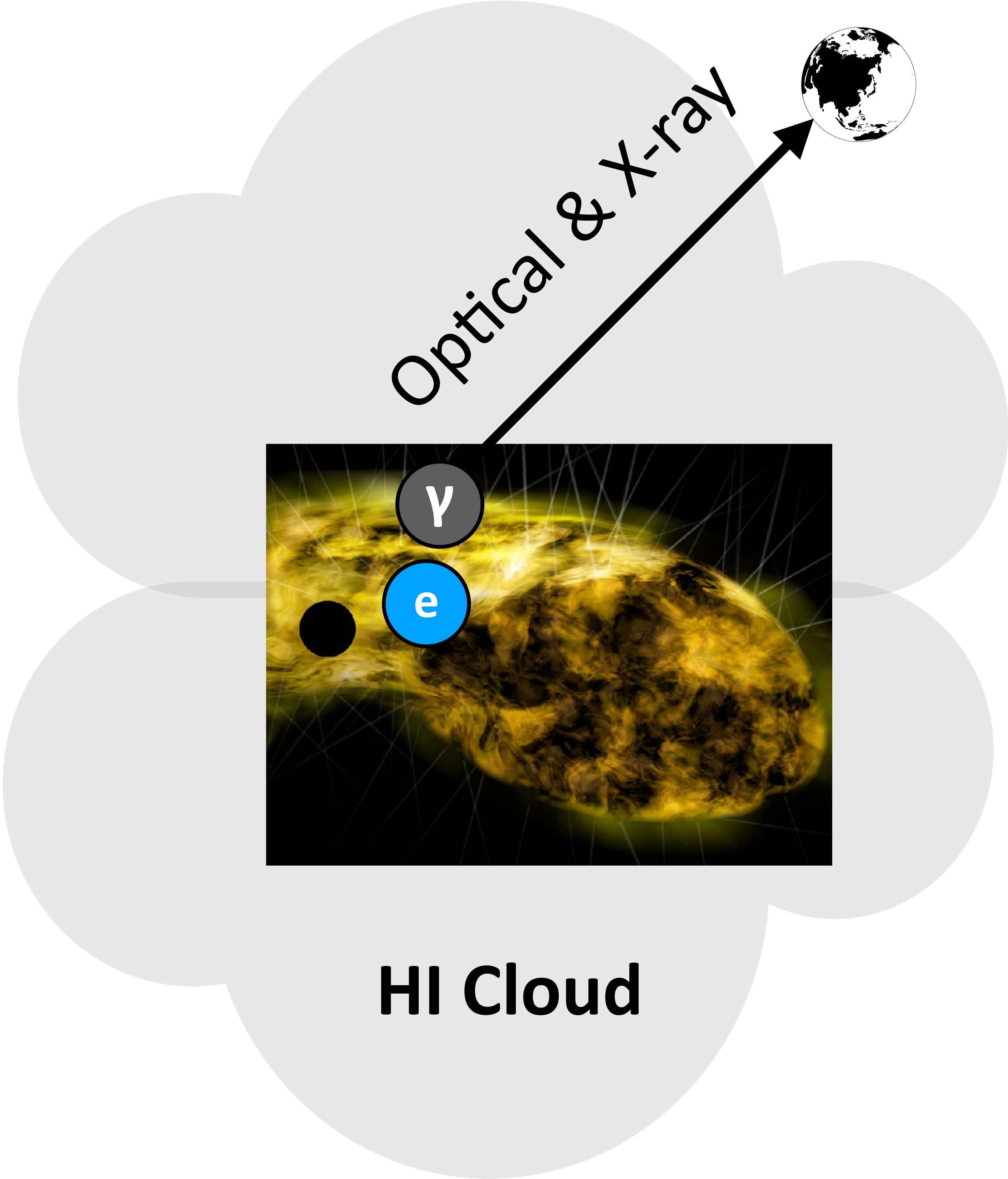
Photon emission from IBH in dense clouds

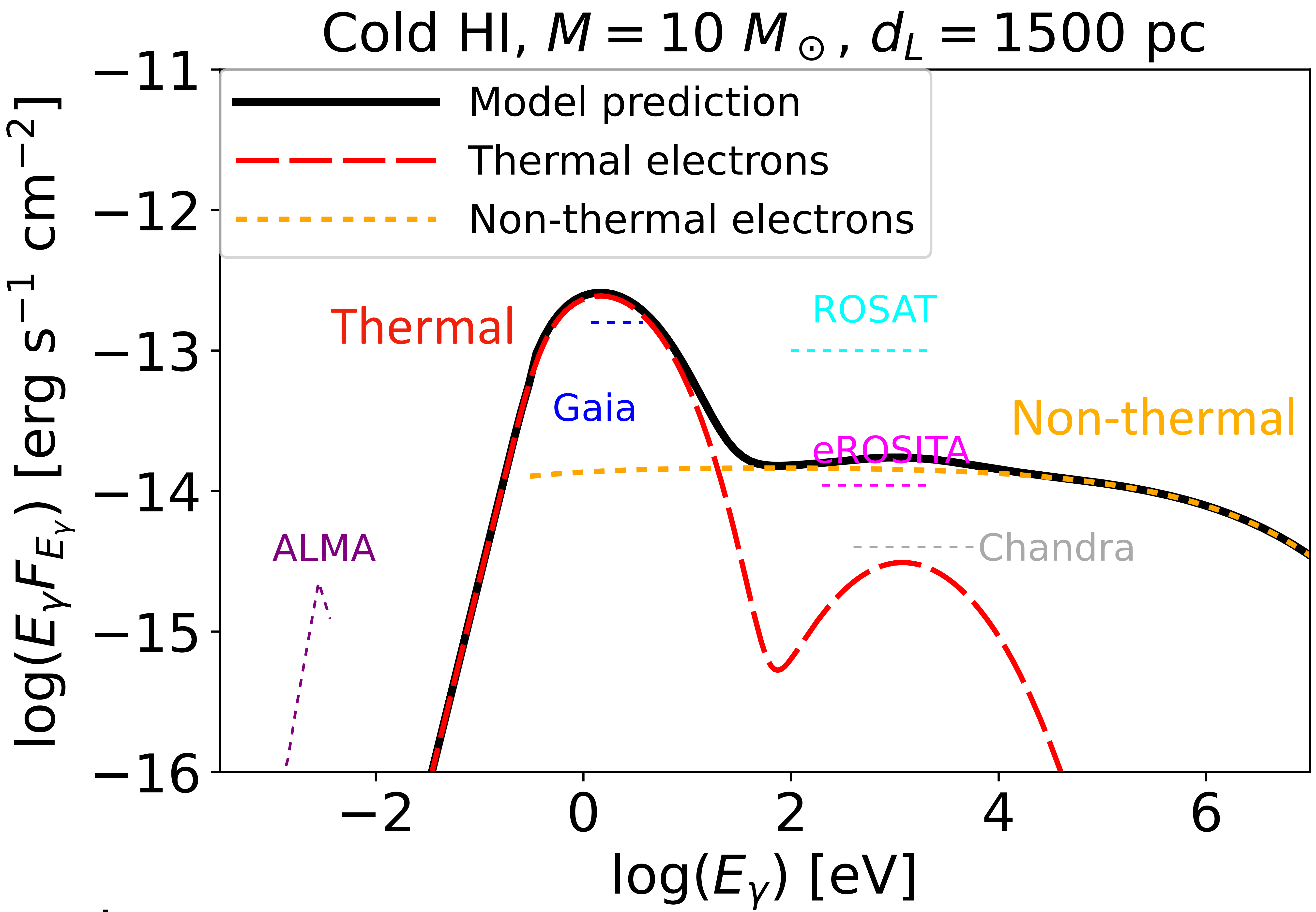




- Simple test for our scenario: **observe direct emission from MADs around IBH**
- Column density for molecular cloud: $N_H \simeq 2 \times 10^{22}\ \mathrm{cm}^{-2}$
  —> Extinction [$A_V \simeq 10$, $\exp(-\tau_{1\ \mathrm{keV}}) \simeq 0.02$] —> Hard X-ray (> a few keV) is necessary
- Contamination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

Photon spectra from MADs around IBHs

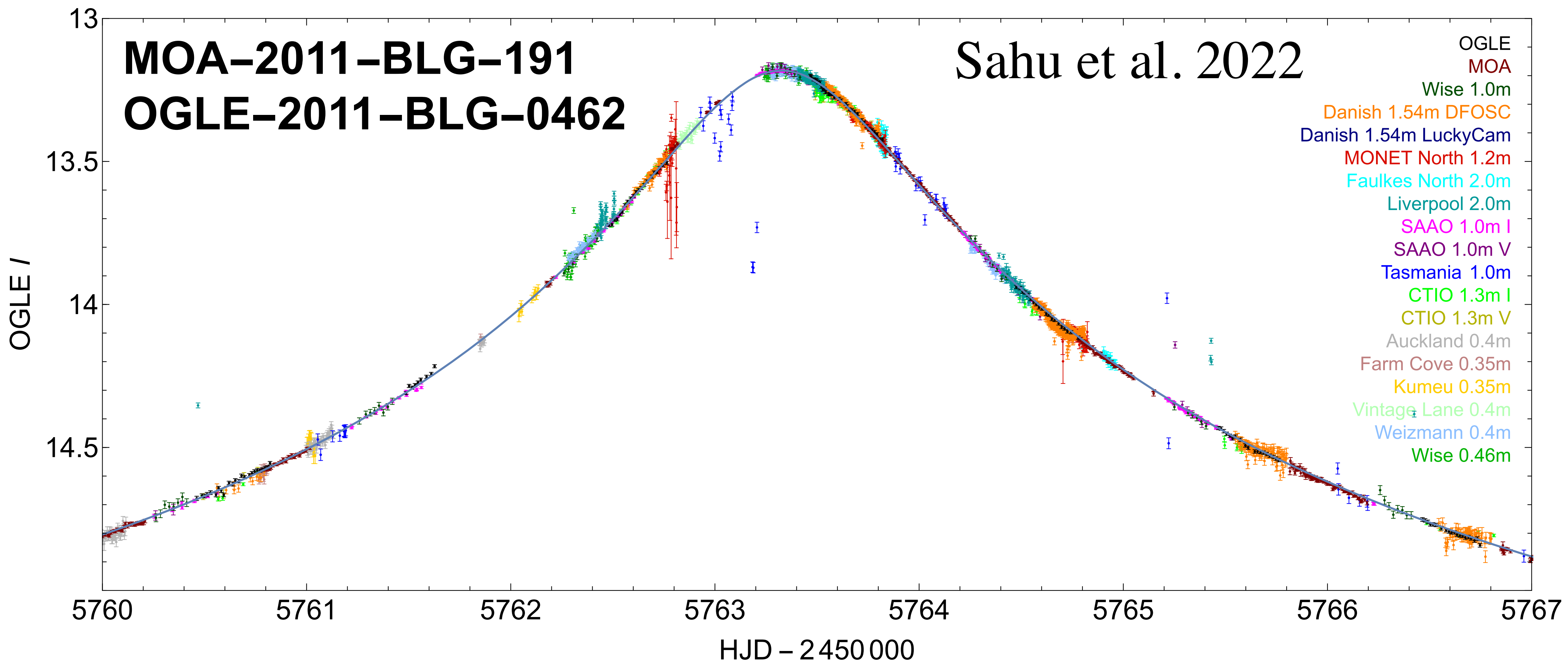




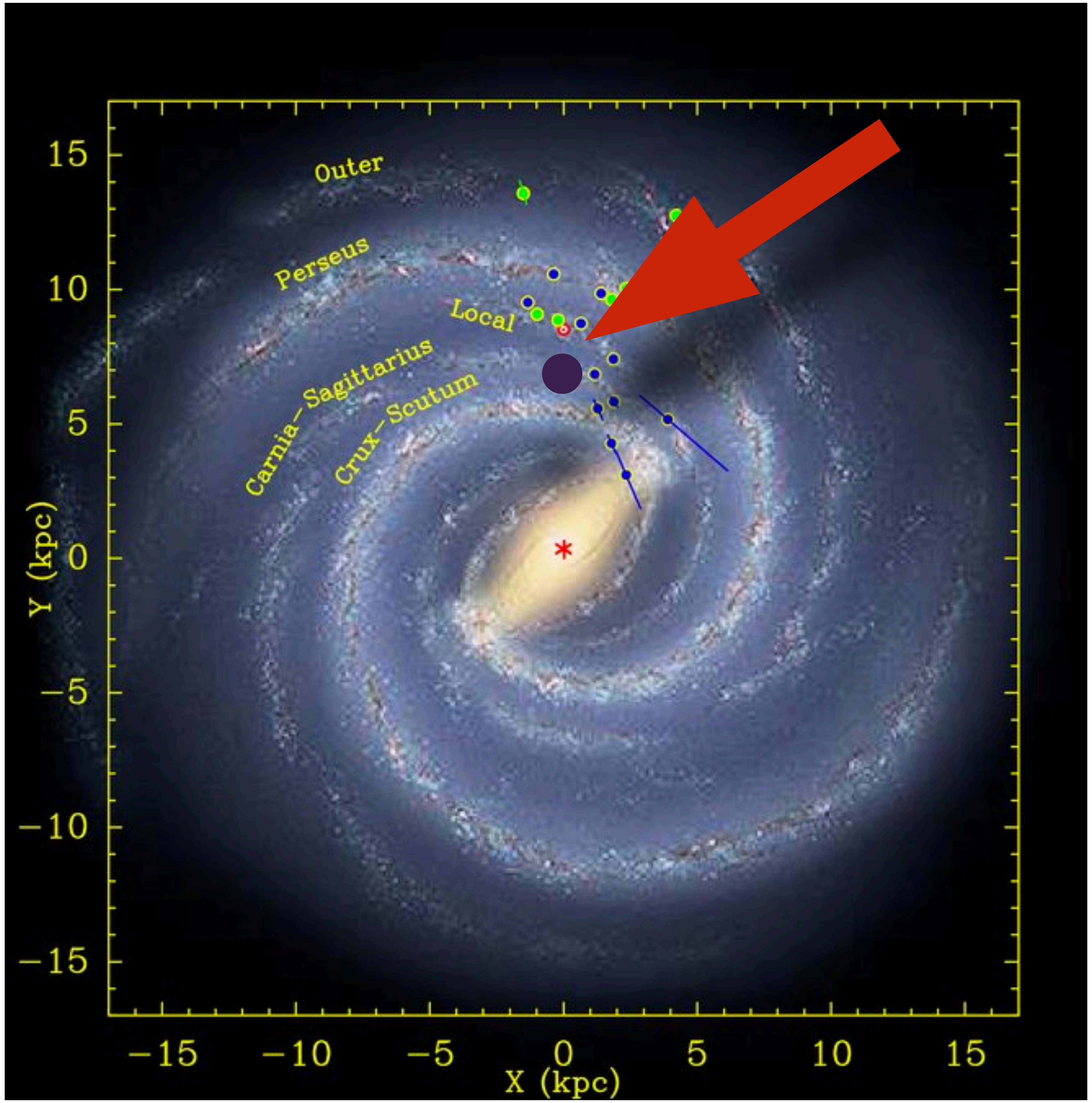
Modified from SSK, Kashiyama, Hotokezaka 2021

- To avoid complication, other ISM phases 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**
- We are searching for IBH using optical–X-ray crossmatch catalog. Please stay tuned.

OGLE2011-BLG-0462

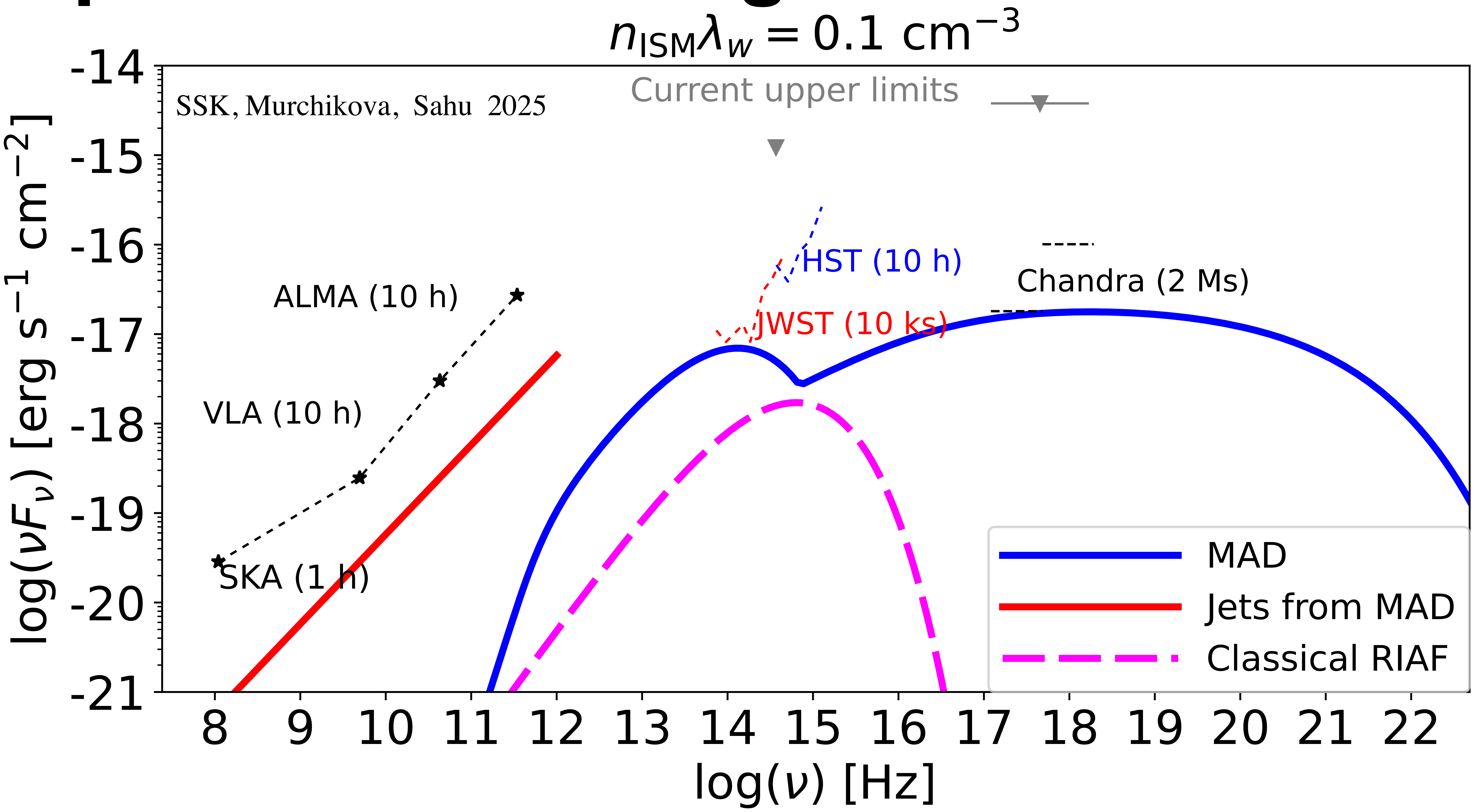


- Lens objects must be isolated BH
- First identification of isolated BHs
- M=7.1 Msun, d=1.58 kpc, v = 45 km/s
- We can estimate the signals from MADs



K. Sahu©

Prospects for detecting OGLE-11-0462



- Detection will be useful to calibrate emission model & number of IBHs found by Gaia
- We submitted proposal for JWST observation of OGLE-11-0462.

Summary

- Identification of Galactic PeVatrons is a hot topic owing to UHE gamma-ray observations
- Canonical SNRs cannot be sources of PeV CRs
- Micro-quasars became the leading candidate of PeVatrons
  => Shear acceleration scenario can explain super-Knee CR data
- Hot accretion flows can accelerate CRs by magnetic reconnection or turbulence
  => XRBs in hard/quiescent states could be potential PeVatrons & LHAASO sub-TeV γ
- Isolated black holes embedded in molecular clouds are similar to XRBs in quiescent state
  => potential PeVatrons and LHAASO unID sources
  & testable by searching IBHs using Gaia & eROSITA

Thank you
for
your attention