降着流での高エネルギー現象 (High-energy phenomena in Accretion flows)

〜強磁場降着流からの多波長放射〜 (Multi-wavelength emission from MADs)

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天文学専攻

東北大学

FRIS

相対論的現象で探る宇宙の進化II@佐渡島　2022/05/27

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- Lepton injection to Radio Jets

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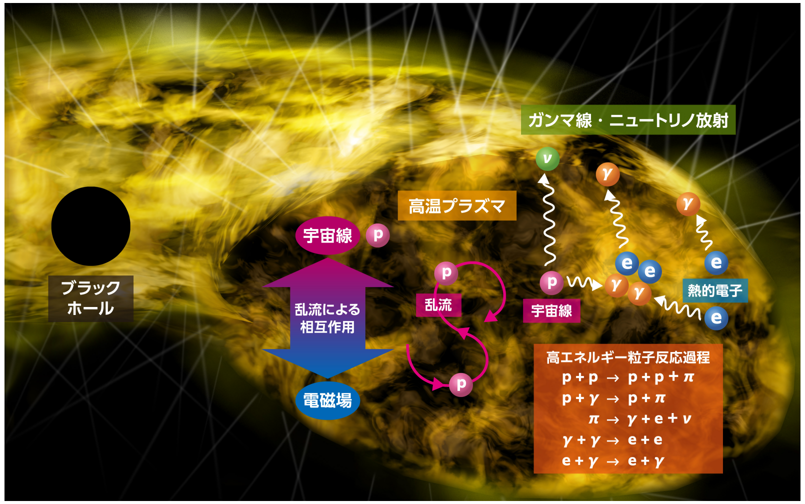
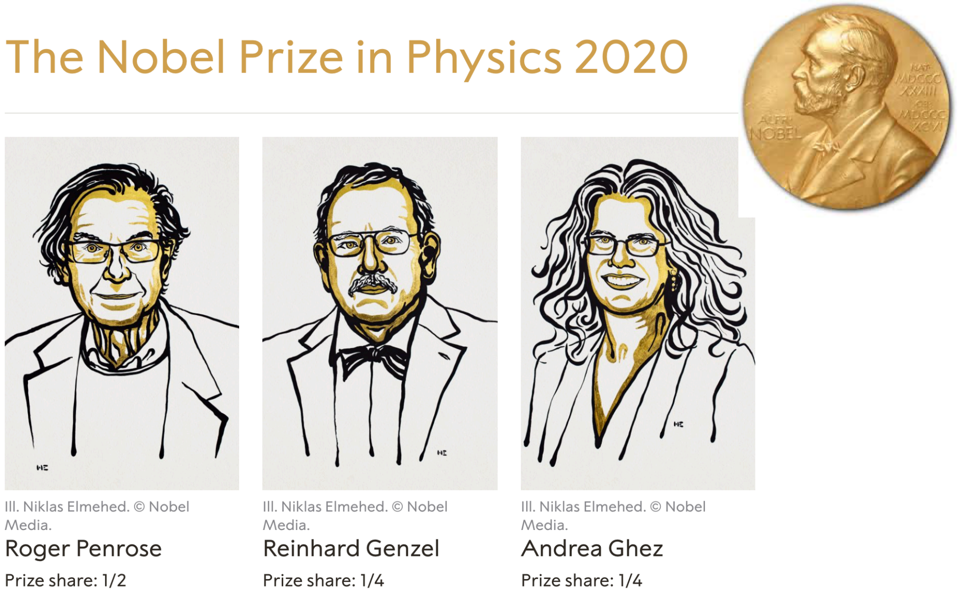
Black Hole Accretion

- Plasma flow falls onto black holes
- Gravitational energy → thermal, radiation
- The best power plant in the Universe
  $E_g \approx GMm_p/(2R) \sim 0.1 m_p c^2 @ R = 5R_G$
- Discovery of Black holes = Novel Prize 2020





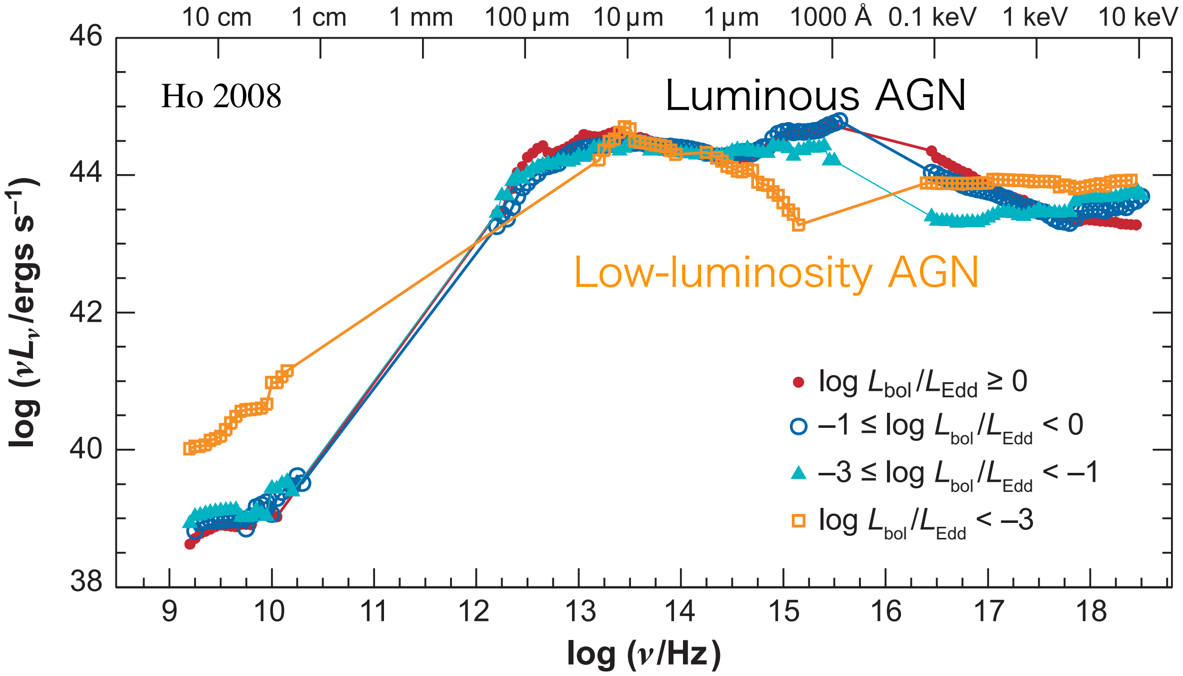
The Nobel Prize in Physics 2020

Ill. Niklas Elmehed. © Nobel Media.
Roger Penrose
Prize share: 1/2

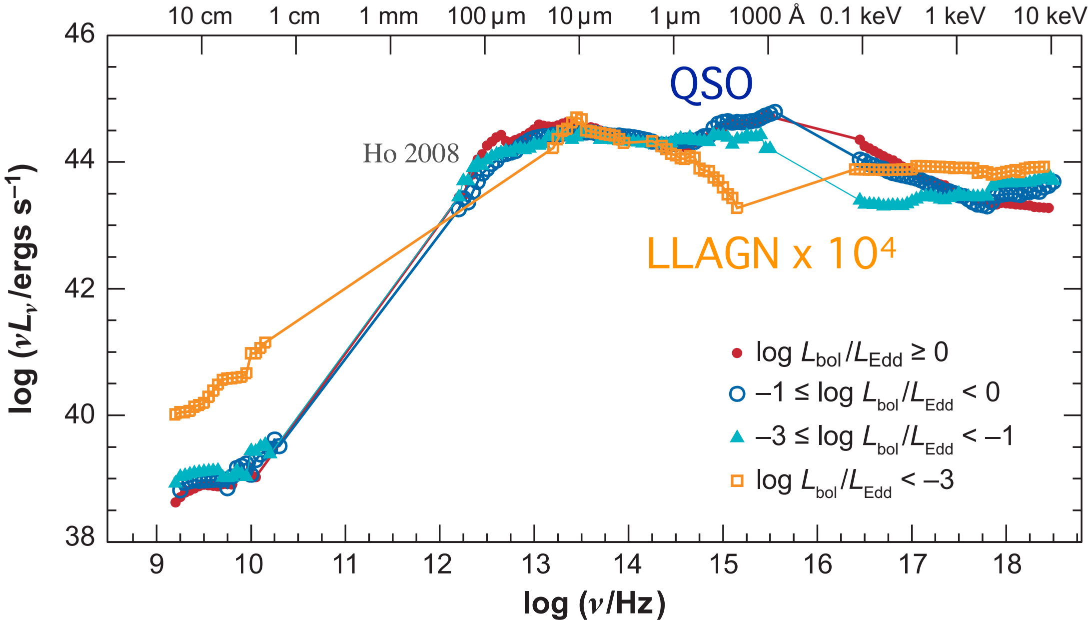
Ill. Niklas Elmehed. © Nobel Media.
Reinhard Genzel
Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.
Andrea Ghez
Prize share: 1/4

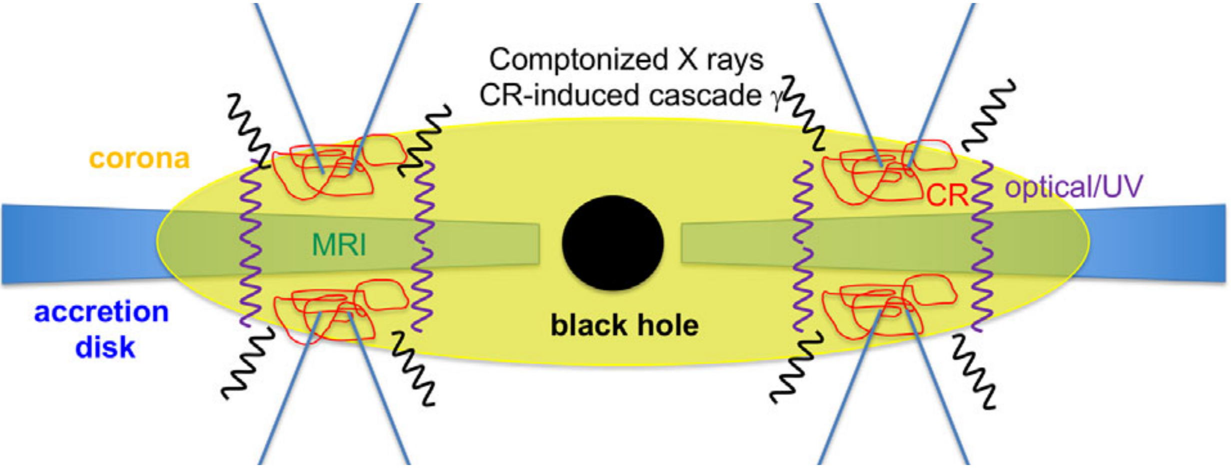
- **Active Galactic Nuclei (M_{BH} ~ $10^8 M_{sun}$)**

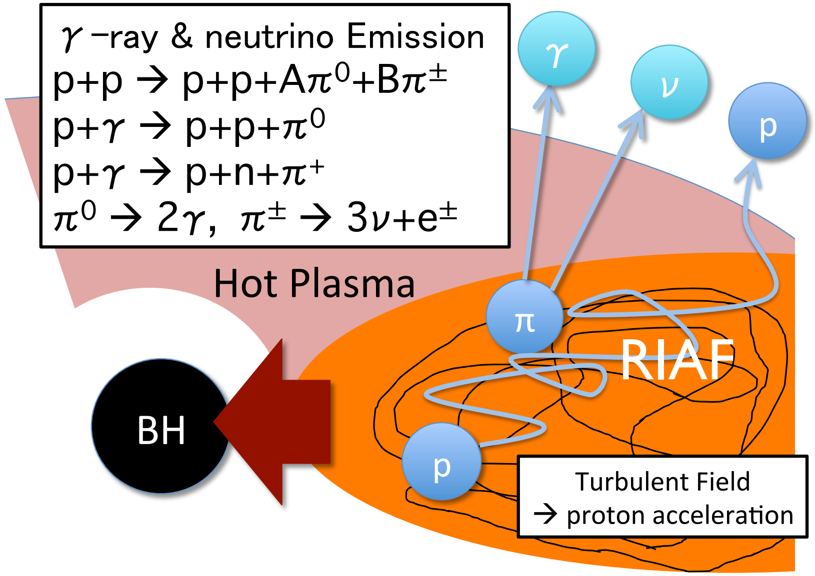


Classification of Accretion Flow I



- Quasar : Blue bump & strong X-ray
  →standard disk ＋ corona
- Lou-luminosity AGN: no blue bump & X-ray
  → Radiatively Inefficient Accretion Flow (RIAF)




γ −ray & neutrino Emission
p+p → p+p+Aπ^0+B$\pi^\pm$
p+γ → p+p+π^0
p+γ → p+n+π^+
π^0 → 2γ, $\pi^\pm$ → 3ν+e$^\pm$

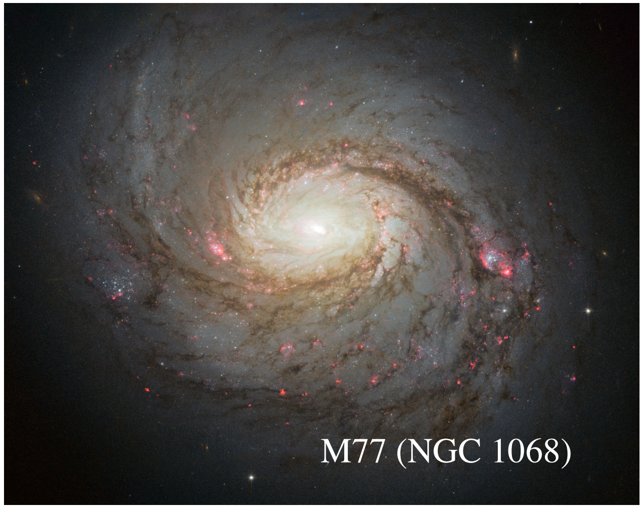
Turbulent Field
→ proton acceleration

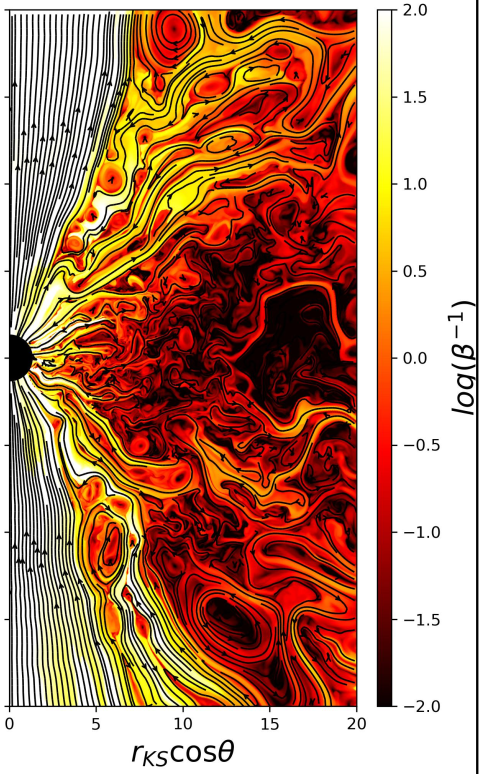
Classification of RIAFs

Narayan et al. 2012

- Standard and Normal Evolution (SANE)

Ripperda et al. 2020

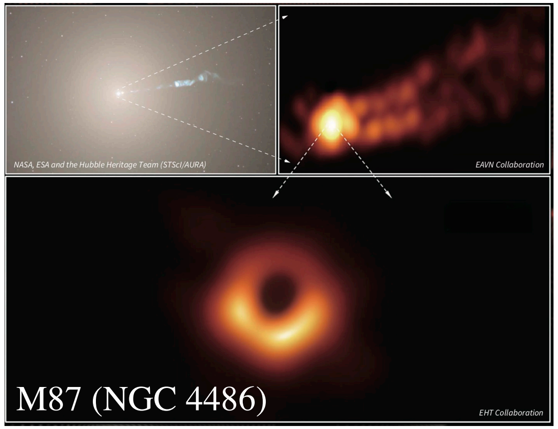


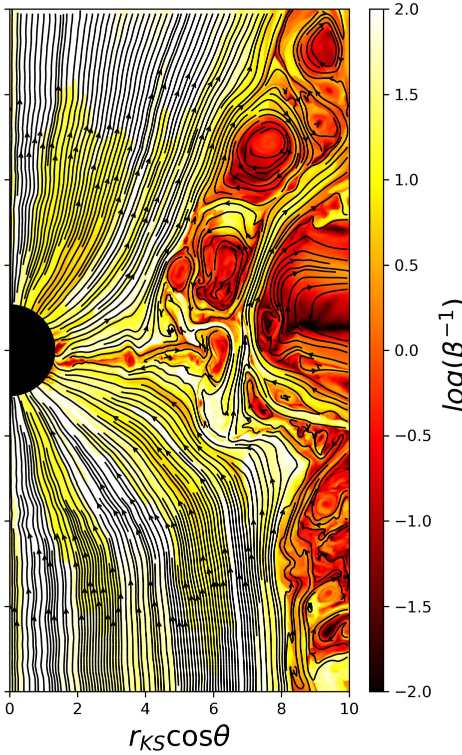


- Turbulence driven by MRI
- Weaker jets → **radio-quiet AGNs**

- Magnetically Arrested Disk (MAD)

Ripperda et al. 2020



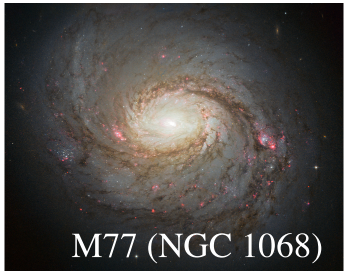


- Strong and ordered magnetic fields
- Powerful jets → **radio galaxies**

Classification of Accretion Flow

Radio Quiet AGNs (weak B)

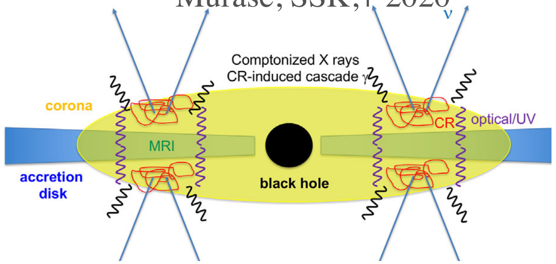
Standard & Normal Evolution (SANEs)



QSO

Disk + Corona

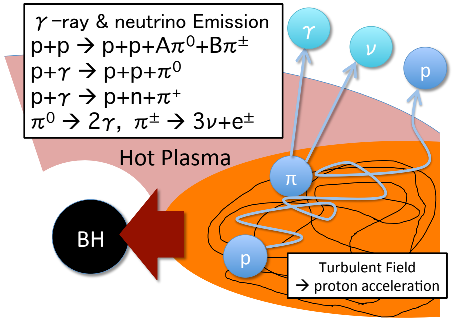
Murase, SSK,+ 2020



LL AGN

RIAFs

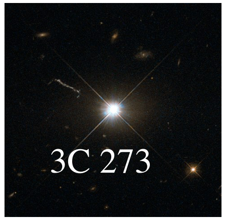
SSK et al. 2015, 2019, 2020



γ −ray & neutrino Emission
p+p → p+p+Aπ^0+B$\pi^\pm$
p+γ → p+p+π^0
p+γ → p+n+π^+
π^0 → 2γ, $\pi^\pm$ → 3ν+e$^\pm$

Radio Loud AGNs (strong B)

Magnetically Arrested Disk (MAD)

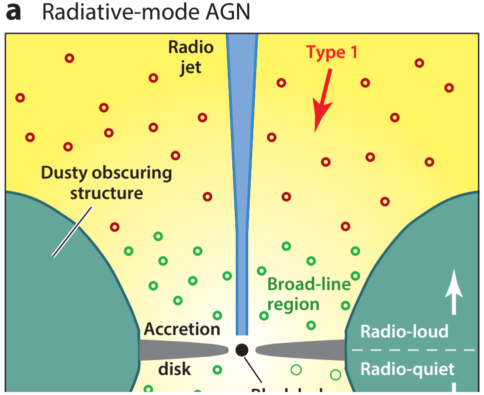


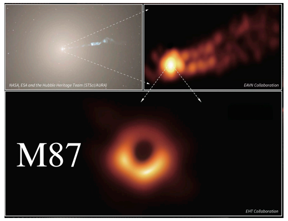
High-Excitation Radio Galaxy

HERG

Heckman & Beck 2014

Jet + Disk



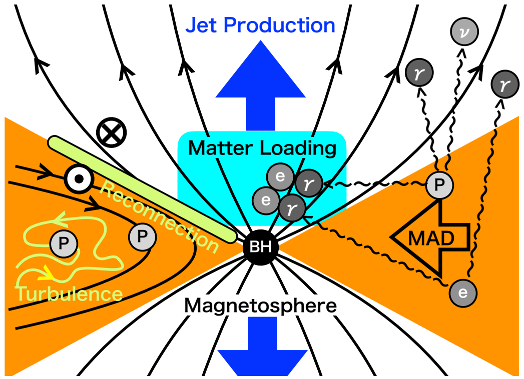


Low-Excitation Radio Galaxy

LERG

Jet + RIAFs

SSK & Toma 2020



Classification of Accretion Flow

Radio Quiet AGNs (weak B)

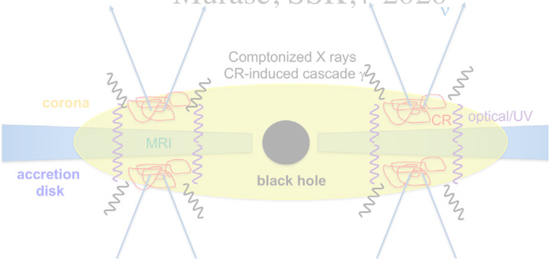
Standard & Normal Evolution (SANEs)

M77 (NGC 1068)

QSO

Disk + Corona

Murase, SSK,+ 2020



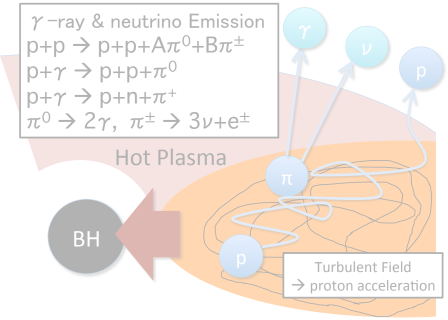
Needle Galaxy

(NGC 4565)

LL AGN

RIAFs

SSK et al. 2015, 2019, 2020



γ-ray & neutrino Emission

$p+p \rightarrow p+p+A\pi^0+B\pi^\pm$

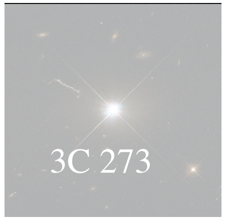
$p+\gamma \rightarrow p+p+\pi^0$

$p+\gamma \rightarrow p+n+\pi^+$

$\pi^0 \rightarrow 2\gamma,\ \pi^\pm \rightarrow 3\nu+e^\pm$

Radio Loud AGNs (strong B)

Magnetically Arrested Disk (MAD)



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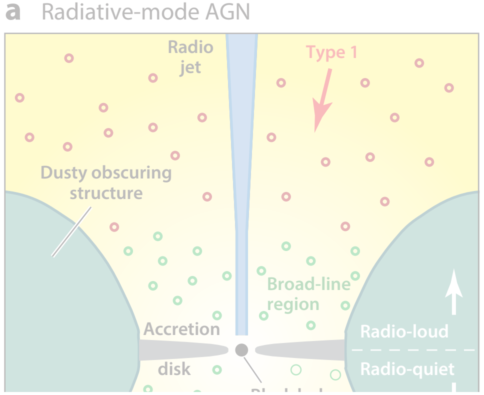
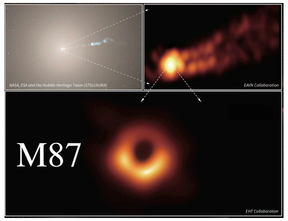
High-Excitation Radio Galaxy

HERG

Heckman & Beck 2014

Jet + Disk





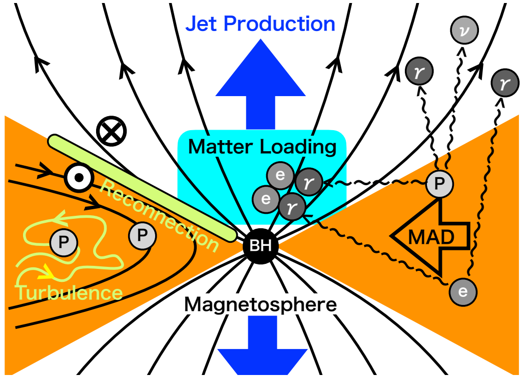
M87

Low-Excitation Radio Galaxy

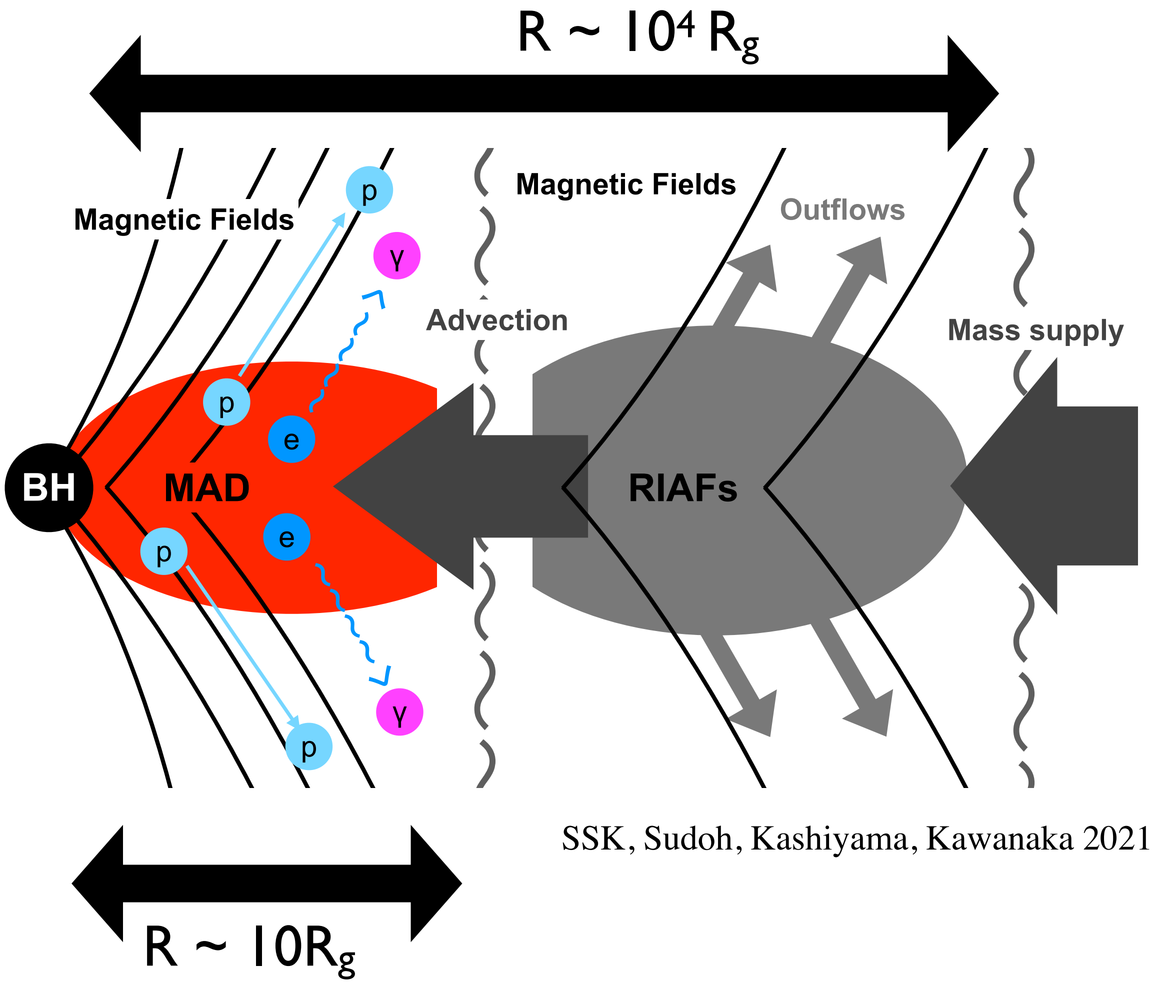
LERG

Jet + RIAFs

SSK & Toma 2020



Outflows & Global magnetic Fields



SSK, Sudoh, Kashiyama, Kawanaka 2021

- Low accretion rate
  → RIAF formation e.g. Esin et al. 1997
- 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: $\beta_p \propto R^{-1.5} - R^{-2}$
  $\rightarrow \beta < 1 @ R \lesssim 10R_g$
  → MAD formation

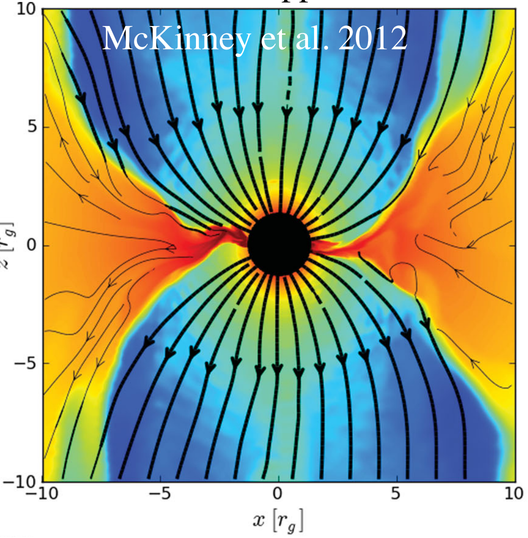
Magnetically Arrested Disks

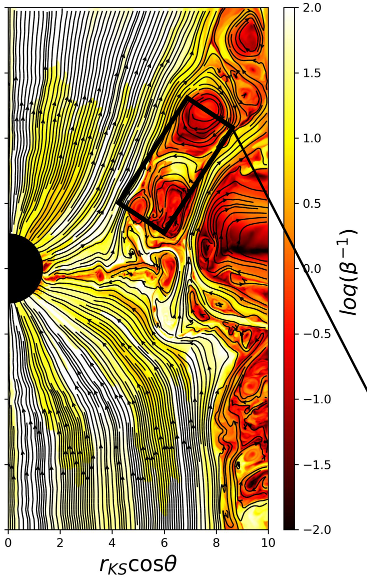
Narayan et al. 2003
White et al. 2019; Chael et al. 2019

Sironi & Spitkovsky 2014
Guo et al. 2016
Zhang et al. 2021

- Recent PIC simulations:
  Reconnection with σ >1
  → **Efficient cosmic-ray acceleration**

Ball et al. 2018;
Ripperda et al. 2020



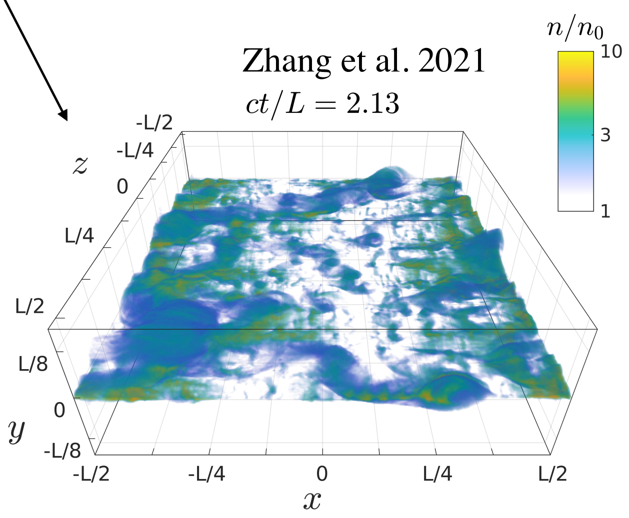


Ripperda et al. 2020

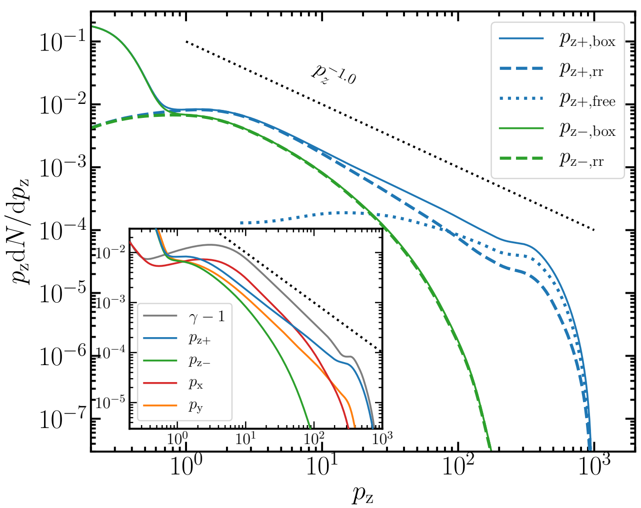
- Strongly magnetized plasma
  $(\sigma = B^2/(8\pi nmc^2) > 1)$
- Heating by magnetic reconnections
  → **Relativistic electron temperature**

Rowan+ 2017; Chael+ 2018; Hoshino 2018

Zhang et al. 2021



Zhang et al. 2021



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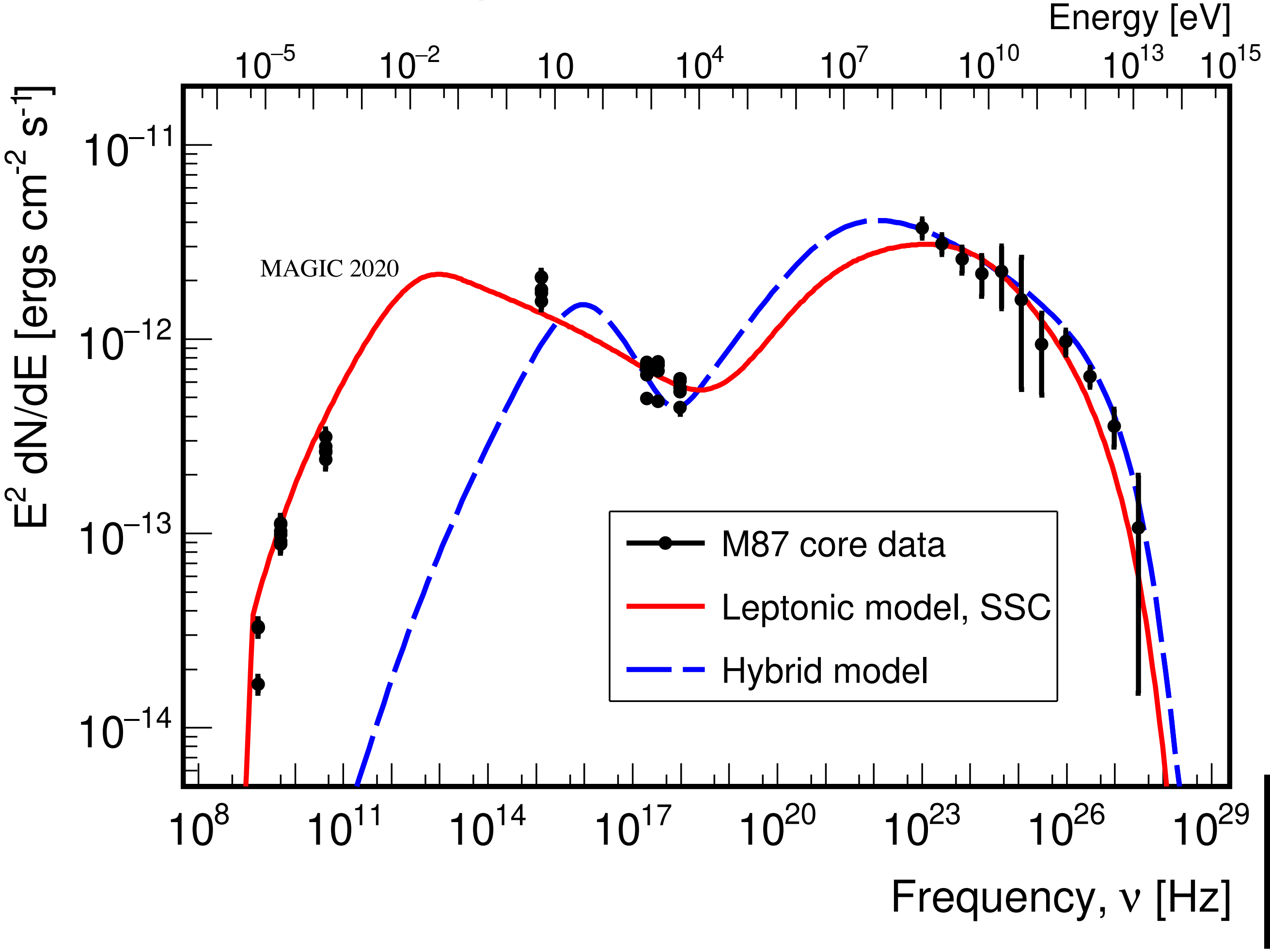
Gamma-rays from Radio Galaxy

M87 broad band spectrum



- Core-shift measurements
  → B ~ 1 G
  Kino et al. 2015
- X-ray & optical Jet observations
  → $L_j \lesssim 10^{44}$ erg s^{-1}
  Stawarz et al. 2006

⇕ 矛盾！！

- SSC broadband spectral fits
  → B ~ mG
  MAGIC 2020
- Hadronic jets model
  → $L_j > 10^{44}$ erg s^{-1}

Let’s discuss non-thermal process in MADs

MAD model

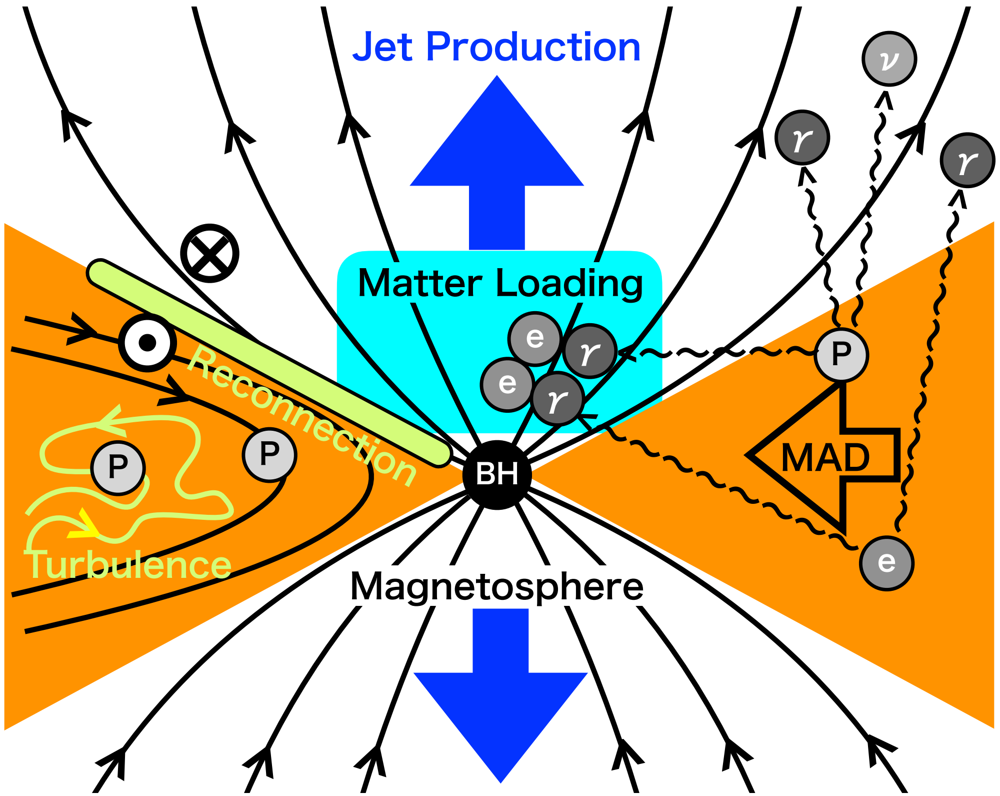
- Steady, one-zone approximation
- 5 emission component
  Thermal e$^-$, non-thermal p, primary e$^-$,
  Bethe-Heitler e$^+$e$^-$ $(p+\gamma \to p+e^+ + e^-)$
  Breit-Wheeler e$^+$e$^-$ $(\gamma+\gamma \to e^+ + e^-)$
- Electron heating: $Q_{e,\mathrm{thrml}} = f_e \epsilon_{\mathrm{dis}}(1-\epsilon_{\mathrm{NT}})\dot{M}c^2$
  → Typical electron temperature: ~ 1-2 MeV
- Transport equation for non-thermal particles:

$$-\frac{d}{dE_e}\left(\frac{E_e N_{E_e}}{t_{\mathrm{cool}}}\right) = \dot{N}_{E_e,\mathrm{inj}} - \frac{N_{E_e}}{t_{\mathrm{esc}}},$$

$$\dot{N}_{E_e,\mathrm{inj}} \approx \dot{N}_0 (E_e/E_{e,\mathrm{cut}})^{-s_{\mathrm{inj}}} \exp(-E_e/E_{e,\mathrm{cut}})$$

$$\int \dot{N}_{E_e,\mathrm{inj}} E_e dE_e = f_e \epsilon_{\mathrm{NT}} \epsilon_{\mathrm{dis}} \dot{M}_\bullet c^2$$

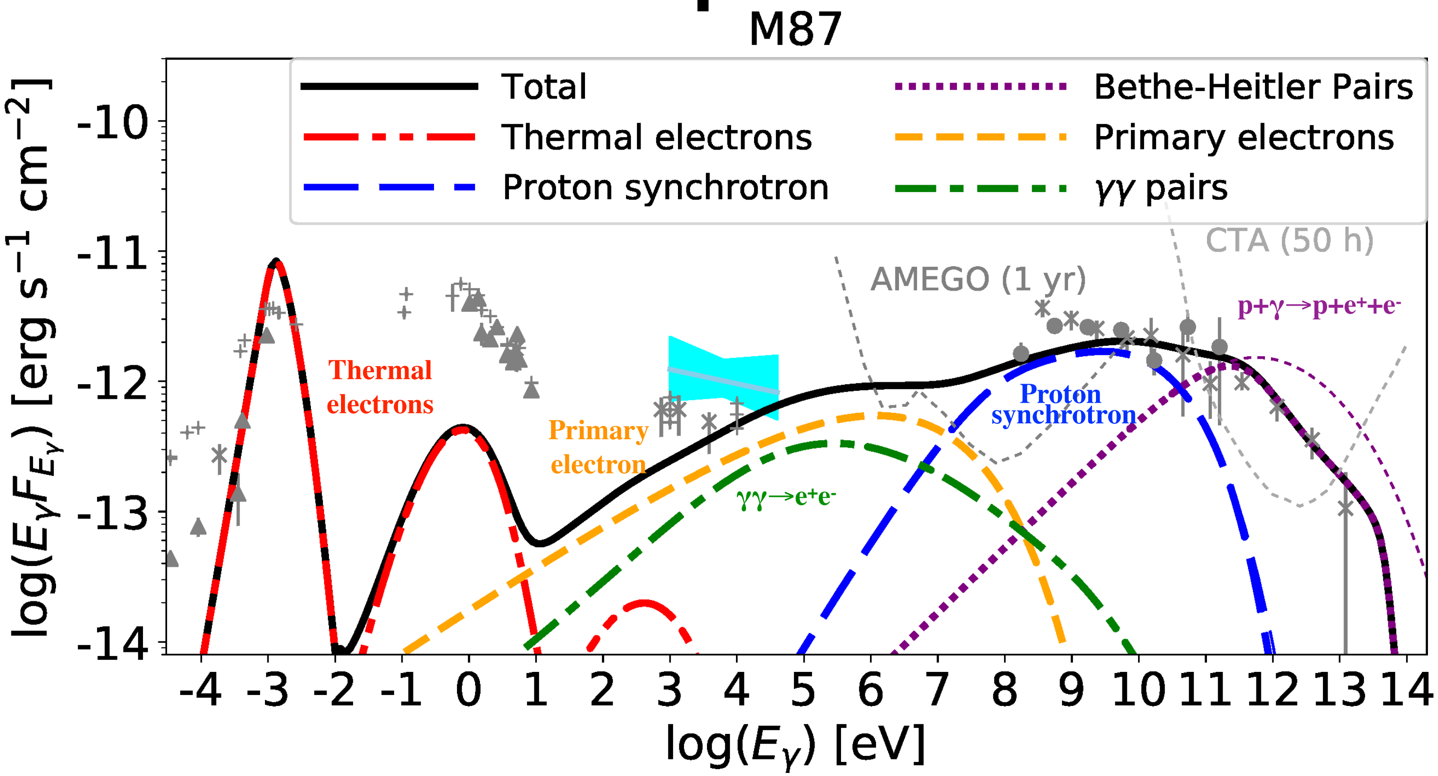
SSK & Toma 2020

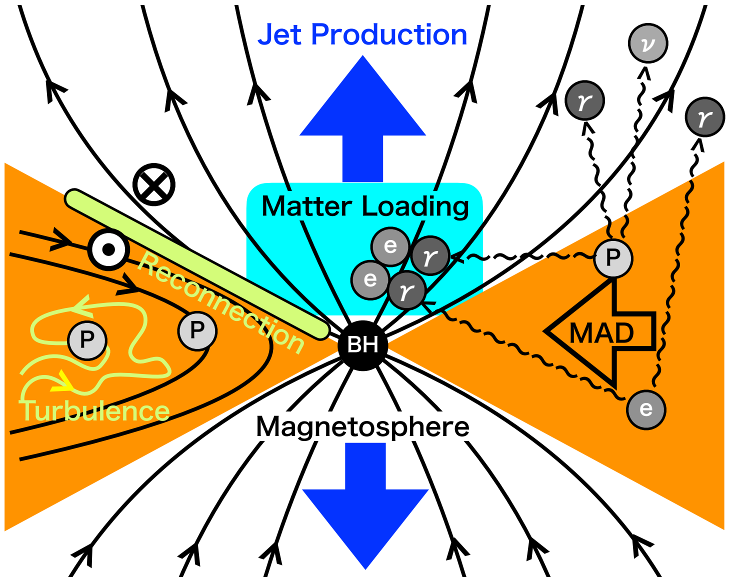


- Synchrotron dominant
  (Compton, escapes are inefficient)

Photon spectrum from MADs

SSK & Toma 2020





- 5 component synchrotron → broadband photon spectrum
- Thermal e- → sub mm , non-thermal p→GeV, primary e-→ MeV
  Bethe-Heitler e⁺e- $(p+\gamma \rightarrow p+e^+ + e^-)$ → TeV
  Breit-Wheeler e+e- $(\gamma+\gamma \rightarrow e^+ + e^-)$ → MeV

$M_{\rm BH} = 6.3 \times 10^9\ {\rm M}_\odot$

$\dot{M}c^2/L_{\rm Edd} = 5 \times 10^{-5}$

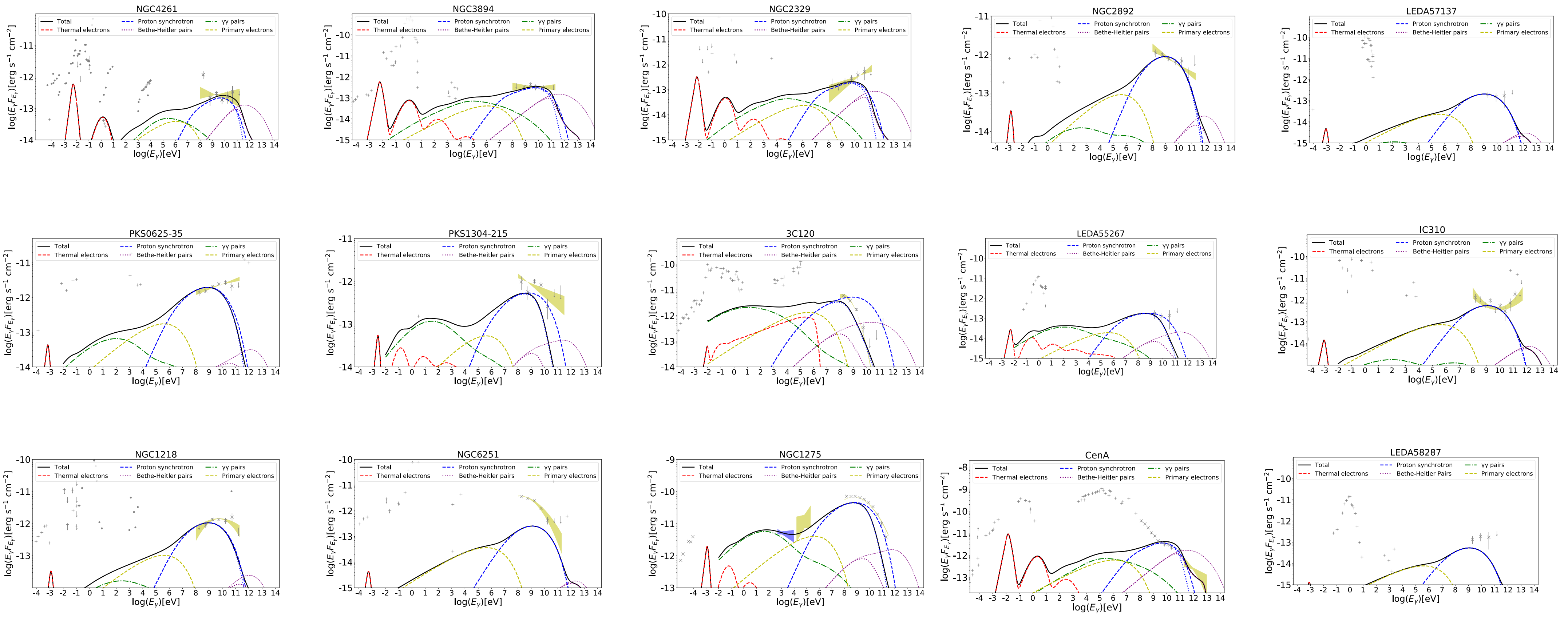
$L_p = 2.0 \times 10^{42}$ erg/s

$L_p/(\dot{M}c^2) = 0.05$

$E_{p,\rm max} = 8.1{\rm EeV}$

Application to many radio galaxies

Kuze, SSK, Toma 2022

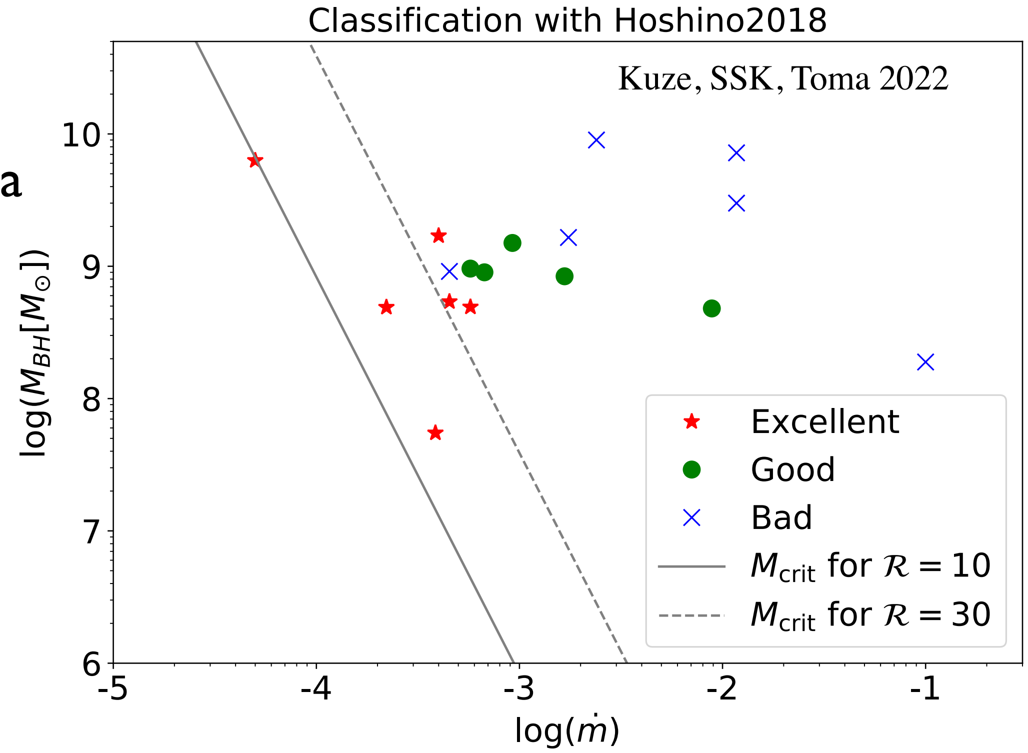


MADs are suitable for low $\dot{m}$?

- chi^2 fitting to GeV data
- Jet emission contributes to radio - X-ray data
- $$\chi^2 = \sum_i \left(\frac{F_{\mathrm{data},i} - F_{\mathrm{model},i}}{\sigma_i} \right)^2$$

MAD model can explain GeV data in cases $\dot{m} < 0.001$

- Large mass accretion rate
  → high low-energy photon density
  → absorption by $\gamma + \gamma \to e^+ + e^-$
  → photon spectra have cutoff below GeV



- * : reproduce GeV data
- ● : reproduce GeV data with larger M and r
- ×: cannot explain GeV data

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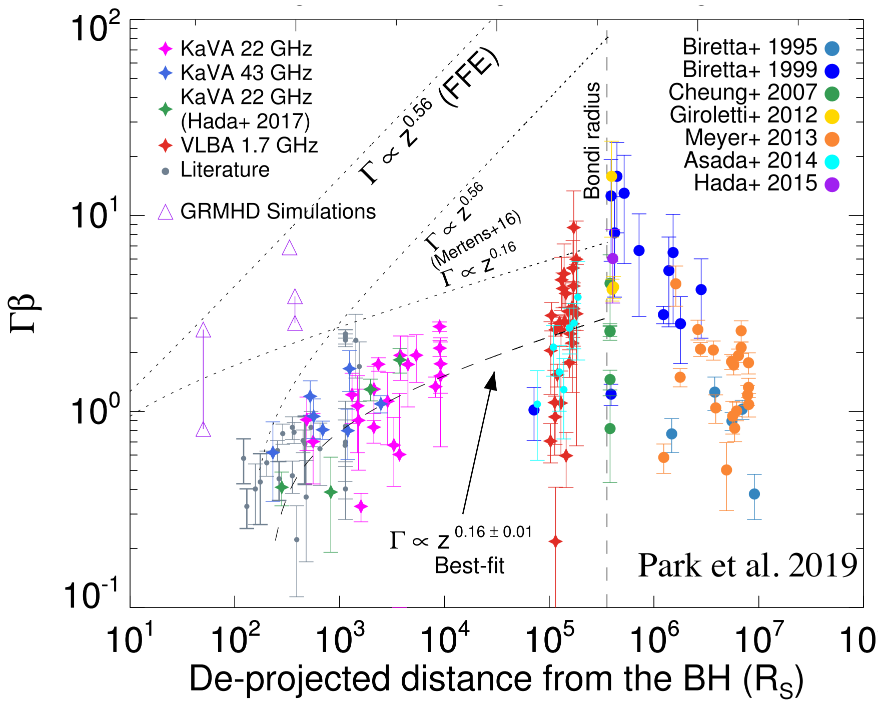
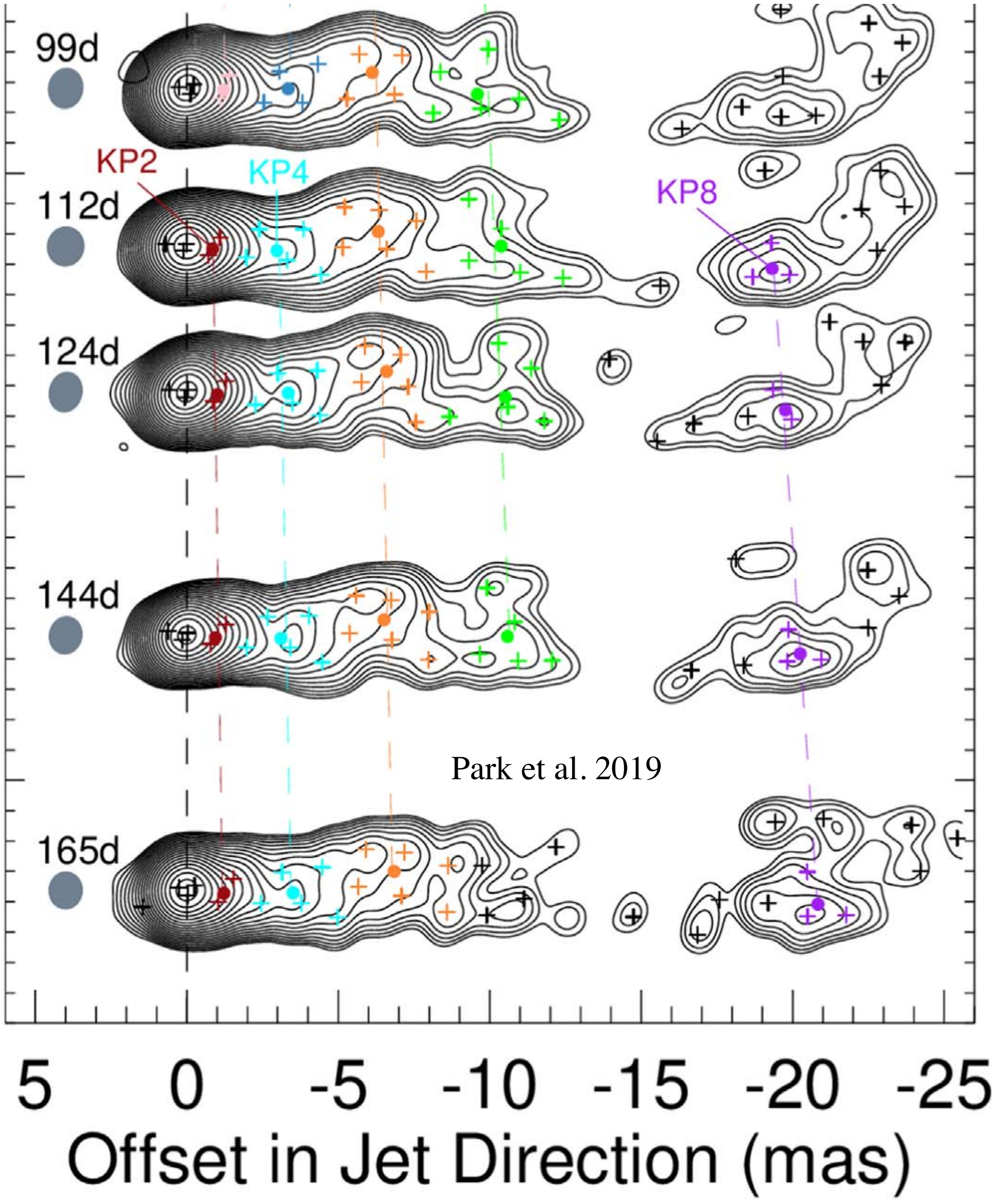
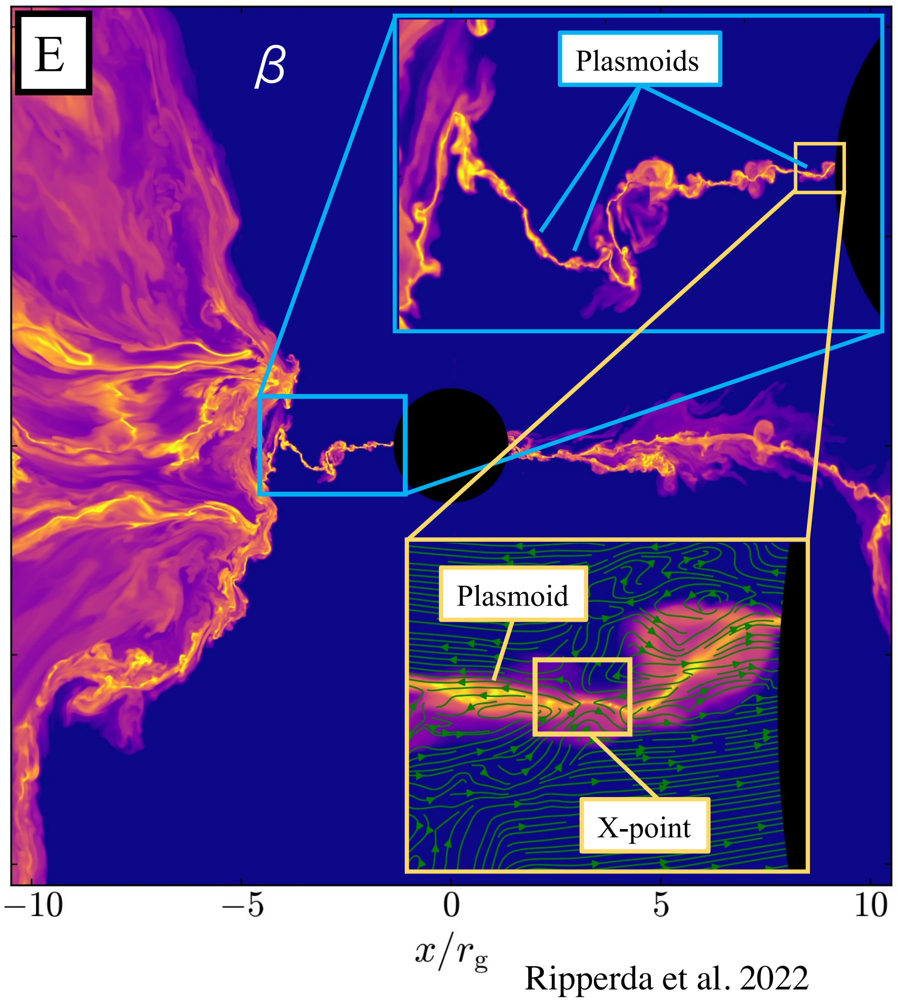
Superluminal radio blob

- Complex structure by VLBI observations
- Apparent velocity > c
  → Relativistically moving radio source
- Radio bright → relativistic electrons
- Origin of electrons are unknown

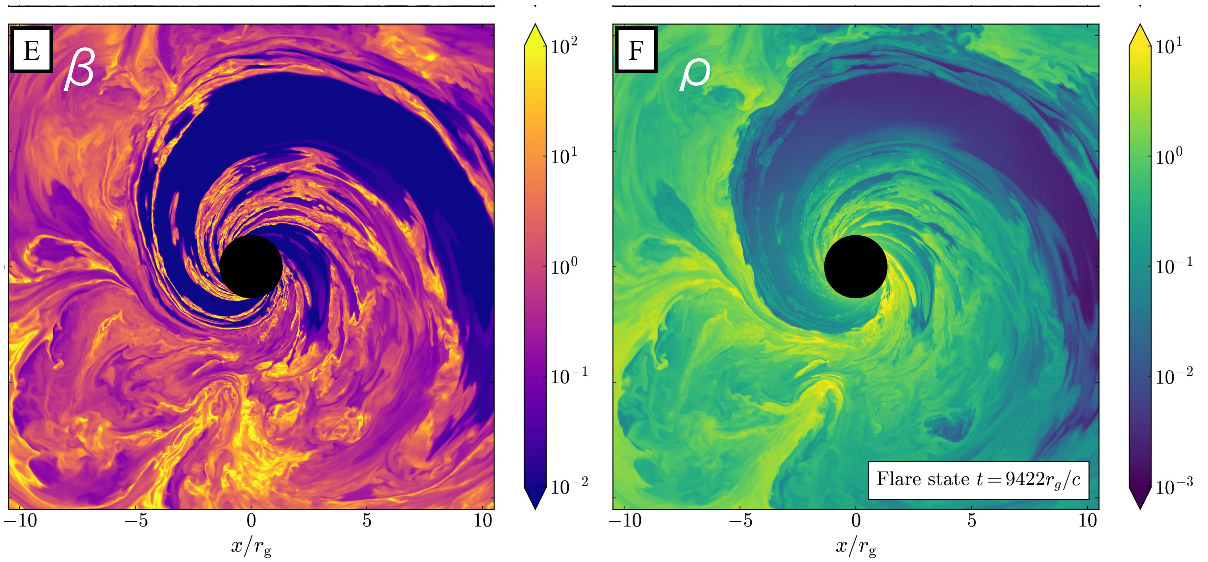




Magnetic Reconnection in BH Magnetosphere

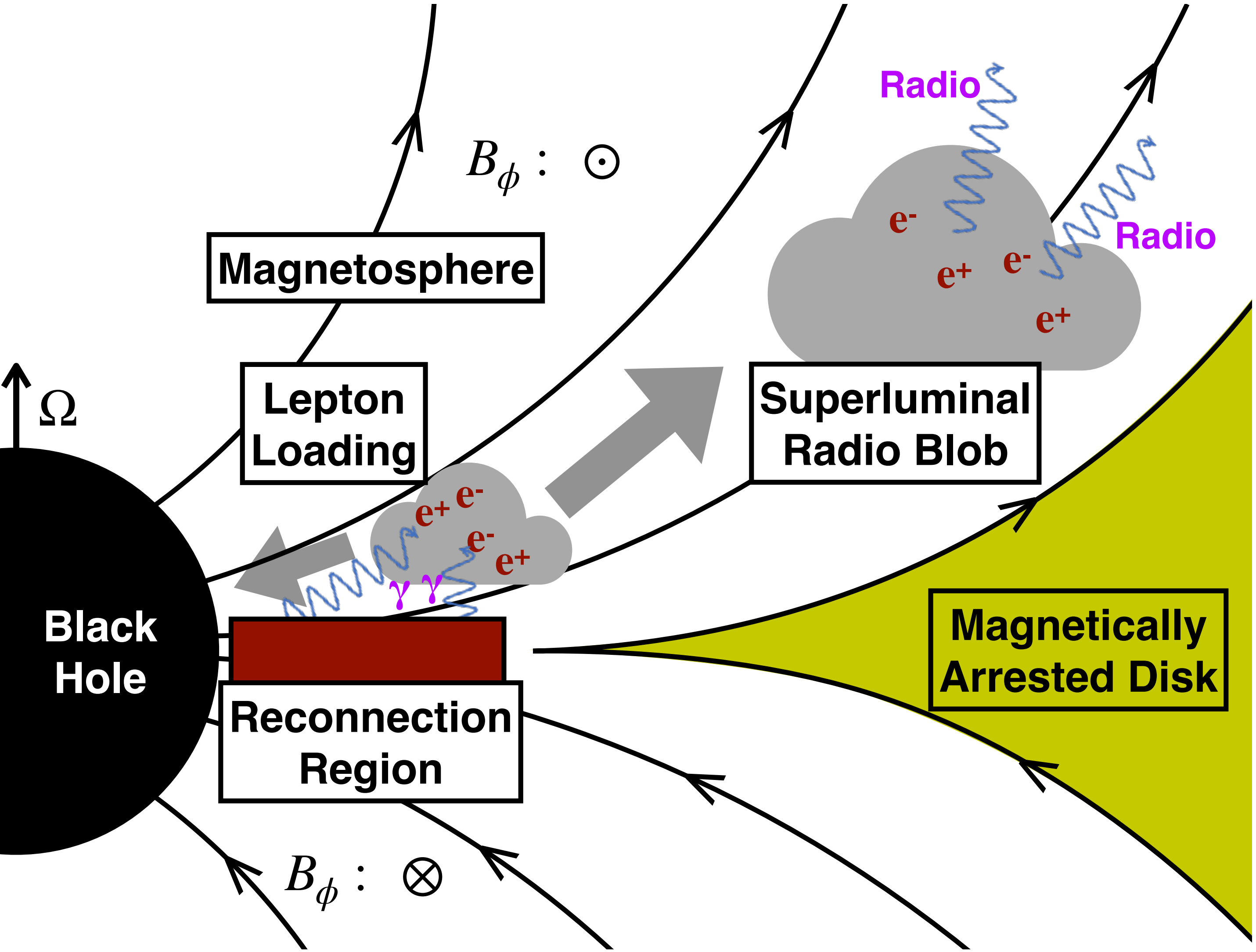


Ripperda et al. 2022



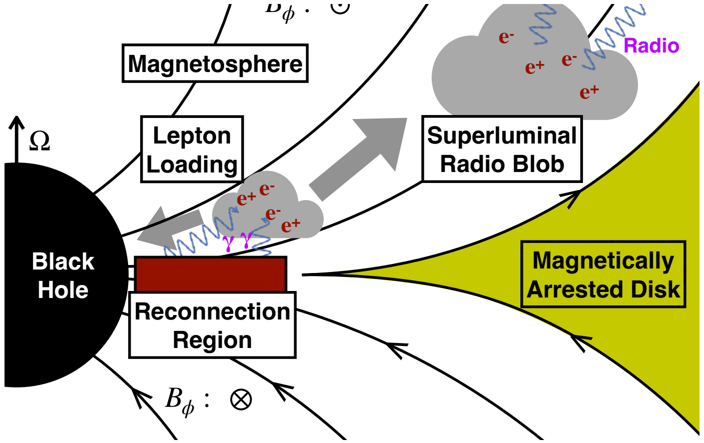
- Ultrahigh resolution GRMHD simulations ($\sim 4000^3$)
- BH magnetosphere & Rayleigh-Taylor spiral
- Reconnection in low-density region
  → transient magnetic energy release
  → Observable as flares?
- Lepton loading by $\gamma + \gamma \rightarrow e^{+} + e^{-}$?

Scenario for superluminal radio blob



- Reconnection in magnetosphere
  → non-thermal particles
  → gamma-ray emission
  → $\gamma + \gamma \to e^+ + e^-$
  → lepton loading
  → SSA Fireball
  → bulk kinetic energy
  → some dissipation
  → superluminal radio blob

磁気リコネクションとガンマ線放射



- MAD B field：

$$B_{\rm mad}=\sqrt{\frac{\dot{M}c\Phi_{\rm mad}^2}{4\pi^2R_G^2}}\simeq 1.1\times10^3 M_9^{-1/2}\dot{m}_{-4}^{1/2}\Phi_{\rm mad,1.7}\ {\rm G},$$

- Magnetization parameter：

$$\sigma_{B,\rm GJ}=\frac{B_{\rm mad}^2}{4\pi n_{\rm GJ}m_ec^2}\approx 1.9\times10^{14}M_9^{1/2}\dot{m}_{-4}^{1/2}\Phi_{\rm mad,1.7}.$$

- Released B-field —> radiation：

$$L_{\rm rec}\approx\frac{l_{\rm rec}^2B_{\rm mad}^2\beta_{\rm rec}c}{4\pi} \qquad (6)$$

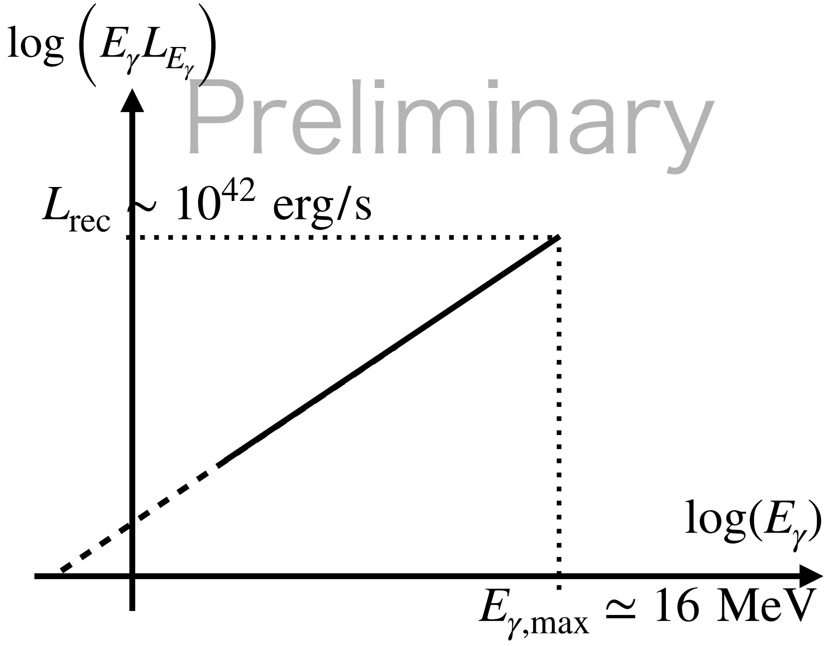
$$\simeq 6.3\times10^{41}M_9\dot{m}_{-4}f_{\rm rec,-0.5}^2\beta_{\rm rec,-1}\Phi_{\rm mad,1.7}\ {\rm erg\ s^{-1}},$$

- Maximum energy of lepton: $t_{\rm syn}=t_{\rm acc}$
  → Photon energy is the Burn-off limit

$$E_{\gamma,\rm max}=\frac{heB\gamma_{e,\rm max}^2}{2\pi m_ec}\simeq 16\beta_{\rm rec,-1}\ {\rm MeV},$$

- Reconnection accelerates all the particles
  & synchrotron cooling inside islands（fast cooling regime）

$$E_\gamma L_{E_\gamma}\approx L_{\rm rec}\left(\frac{E_\gamma}{E_{\gamma,\rm max}}\right)^{1/2}.$$



Lepton loading

- Lepton loading rate : $\dot{N}_{\gamma\gamma} = 2\int n_{\gamma_1} n_{\gamma_2} \sigma_{\gamma\gamma} c dV, \quad \dot{N}_{\gamma\gamma} \approx \frac{L_{\rm rec}\tau_{\gamma\gamma}}{E_{\gamma,\rm max}}.$
- Optical depth for pair production :

$$\begin{aligned}\tau_{\gamma\gamma} &\approx n_{\gamma_2}\sigma_{\gamma\gamma} l_{\rm rec}\\ &\simeq 2.9\times 10^{-3}\dot{m}_{-4} f_{{\rm rec},-0.5}\beta_{{\rm rec},-1}\Phi_{{\rm mad},1.7},\end{aligned}$$

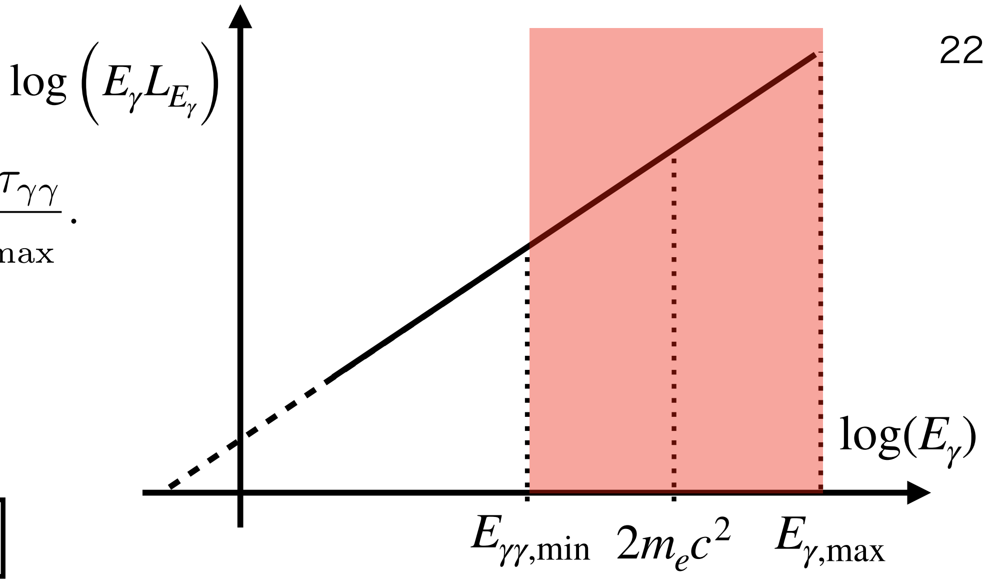
Significant fraction of γ converted to e⁺e⁻ !

- Multiplicity:

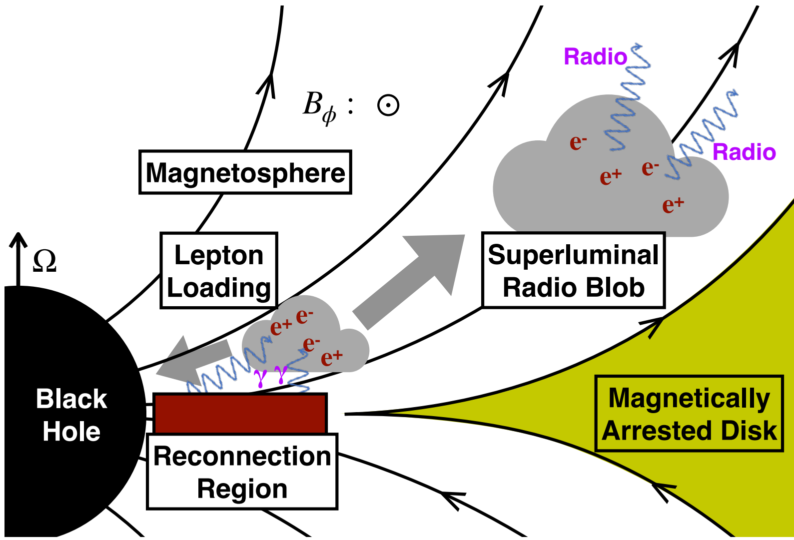
$$\begin{aligned}\kappa_\pm = \frac{n_\pm}{n_{\rm GJ}} &= \frac{16}{27}\frac{\beta_{\rm rec} f_{\rm rec} f_{\gamma\gamma}\alpha_F^4 R_G^2}{\sigma_T}\left(\frac{B_{\rm mad}}{B_{\rm cr}}\right)^3 \qquad (16)\\ &\simeq 5.5\times 10^9 M_9^{1/2}\dot{m}_{-4}^{3/2} f_{{\rm rec},-0.5}\Phi_{{\rm mad},1.7}^3\beta_{{\rm rec},-1}\ {\rm G},\end{aligned}$$

σ becomes low → weakens γ-rays
→ Pair production ceases → σ increases
→ strengthen γ-rays → Pair production
→ σ becomes low → …

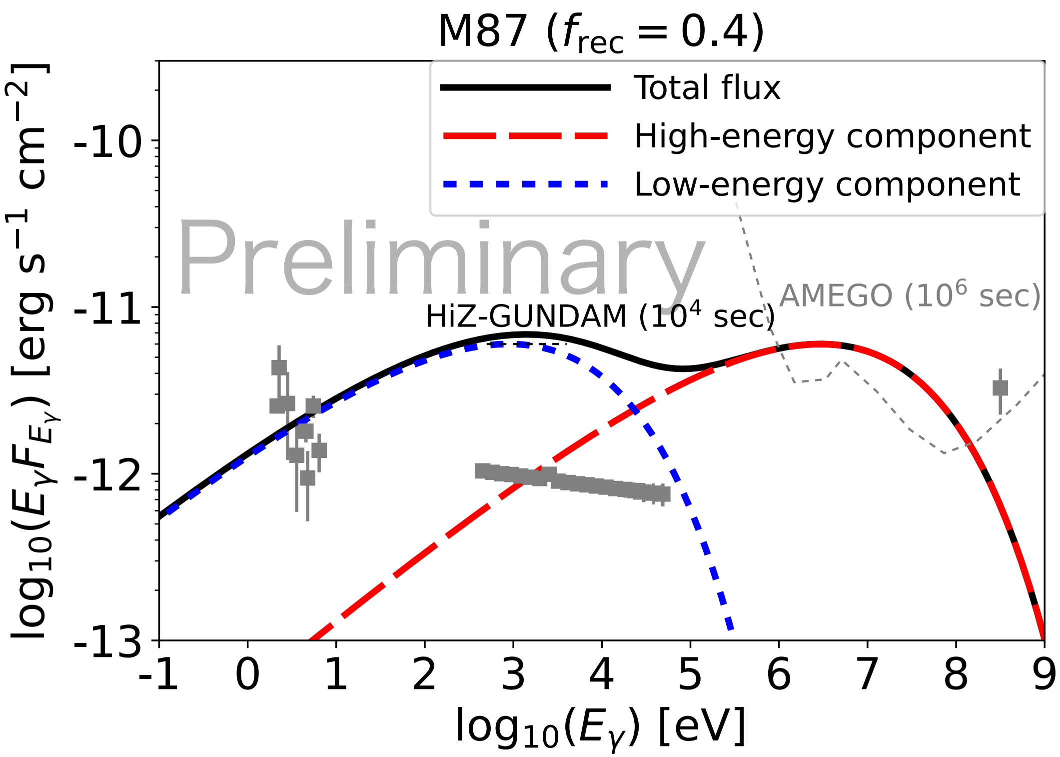
Synchrotron peak should be oscillated !

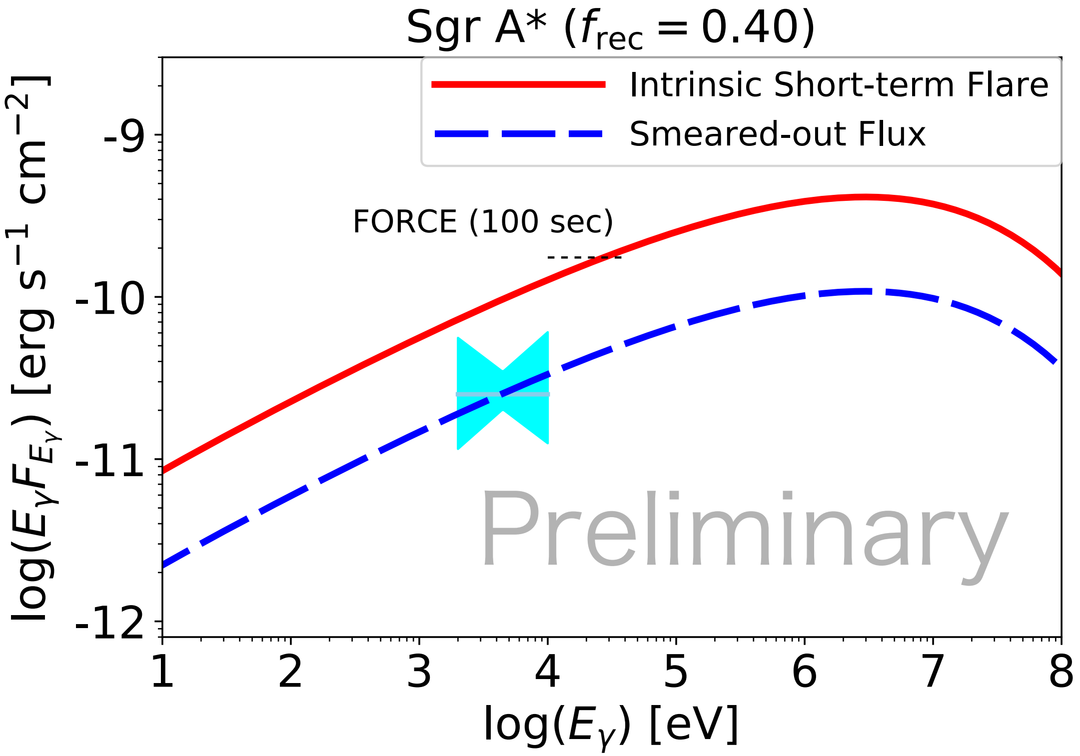


Preliminary



X-ray・γ-ray Flares





- Short-term X-ray flares when magnetic reconnection occurs
- Duration: ~ $f_{\rm rec}R_G/(\beta_{\rm rec}c)$ ~10^5 s (M87) or ~ 100 s (Sgr A*)
- HiZ-GUNDAM can detect M87 flare
- FORCE can detect Sgr A* flare

Lepton plasma energy

- Cooling & Heating in the plasma：
  synchrotron cooling VS synchrotron-self absorption heating

$$t_{\rm syn} = 6\pi m_e c/(\sigma_T B^2 \gamma_e) \quad > \quad t_{\rm ssa} = \frac{\gamma_e m_e c^2}{\int dE_\gamma E_\gamma n_{E_\gamma} \sigma_{\rm ssa} c} \approx \frac{4\pi l_{\rm rec}^2 \gamma_{e,} m_e c^2}{L_{\rm rec} \sigma_{\rm ssa}},$$

Thermalize by SSA proces → Fireball Formation !

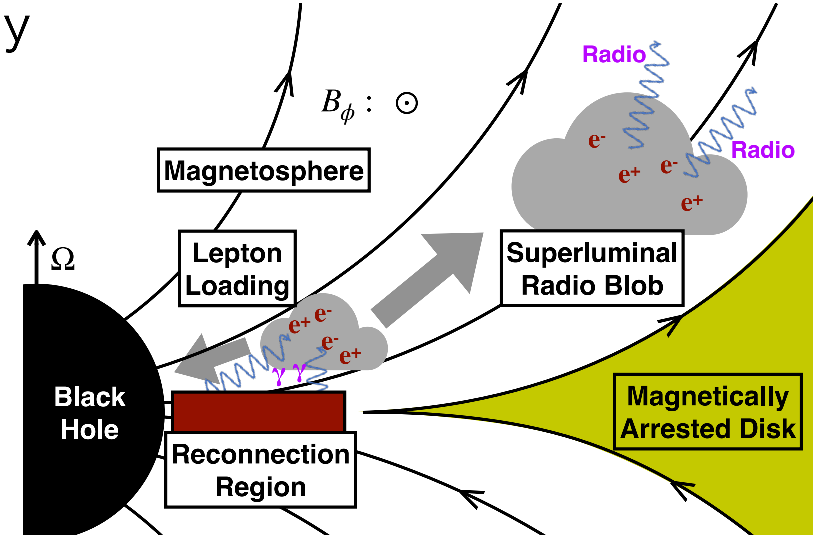
Preliminary

- Fireball is SSA thick even after expansion
  →All the thermal energy is converted to kinetic energy
- Kinetic energy of fireball：

$$E_{\rm fb} \approx \dot{N}_{\gamma\gamma} T_{\rm dur} E_{\pm,\rm max}/2 \simeq 2.9 \times 10^{43} \times M_9^2 \dot{m}_{-4}^2 f_{{\rm rec},-0.5}^3 f_{{\rm mag},-0.5} \beta_{{\rm rec},-1} \Phi_{{\rm mad},1.7}^2 \ {\rm erg}, \tag{22}$$

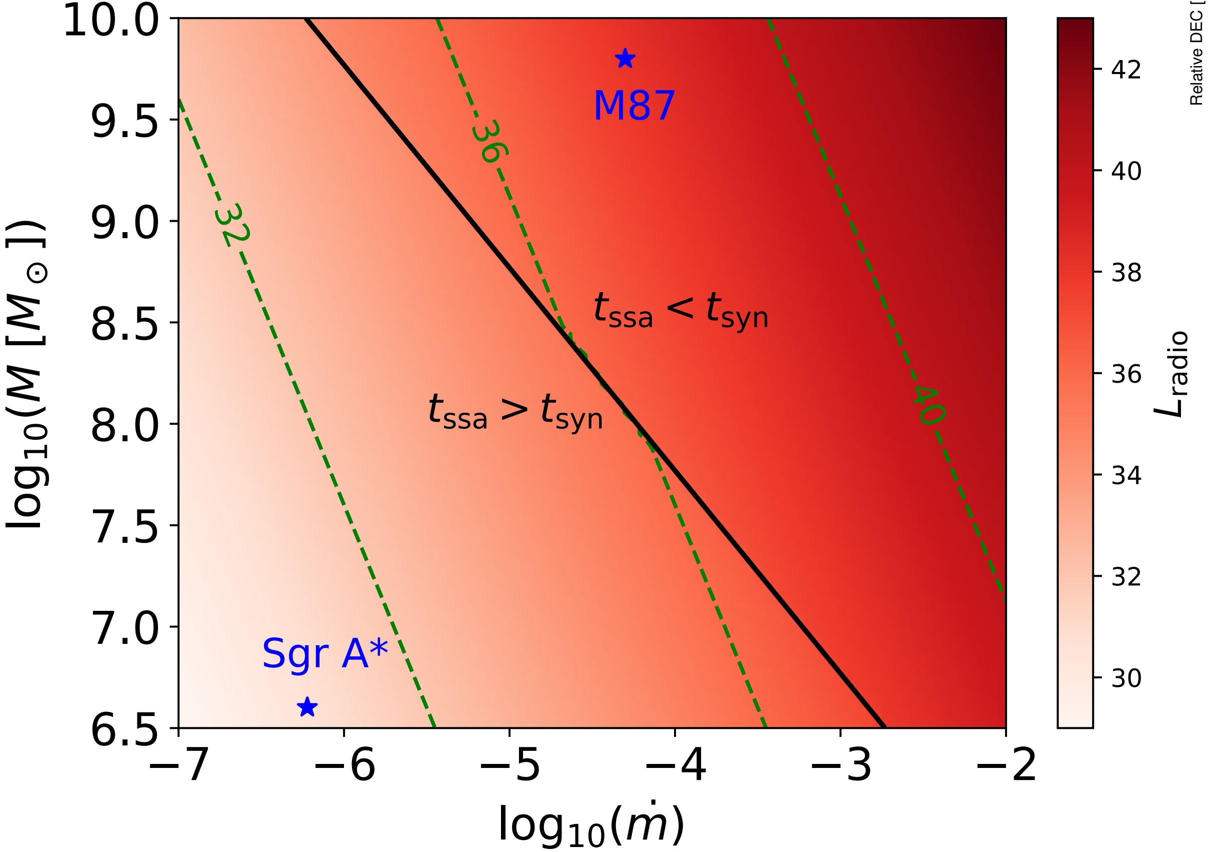
- Radio luminosity：

$$L_{\rm radio} \approx \frac{E_{\rm fb}}{R_{\rm dis}/c}$$

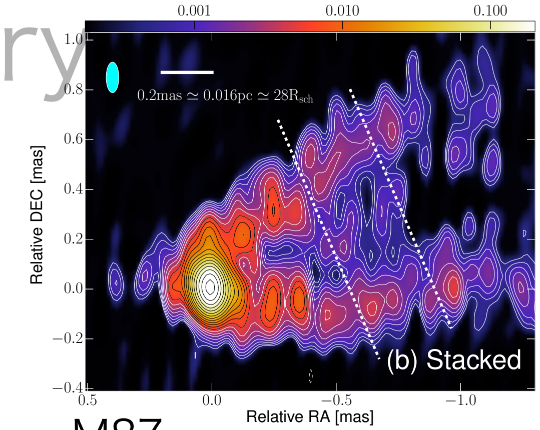


Radio luminosity in our scenario

Name	$\log(L_{\rm radio})$	$F_{\rm radio}$
	[erg s^{-1}]	[mJy]
M87	38.1	9.0
Sgr A*	30.6	1.1

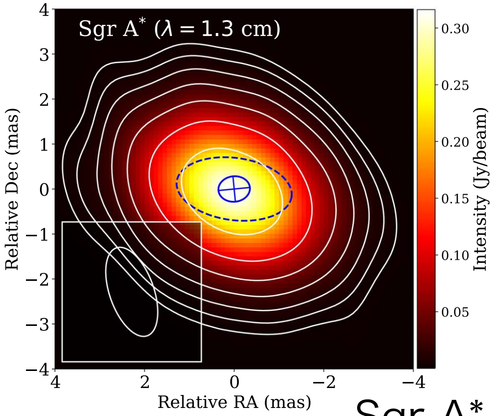


Kim et al. 2018



M87

Cho et al. 2022



Sgr A*

- Radio luminosity depends on $\dot{m}$ & M
- High lepton loading rate in M87
  → luminous radio blob
- Low lepton loading rate in Sgr A
  → no observable radio blob

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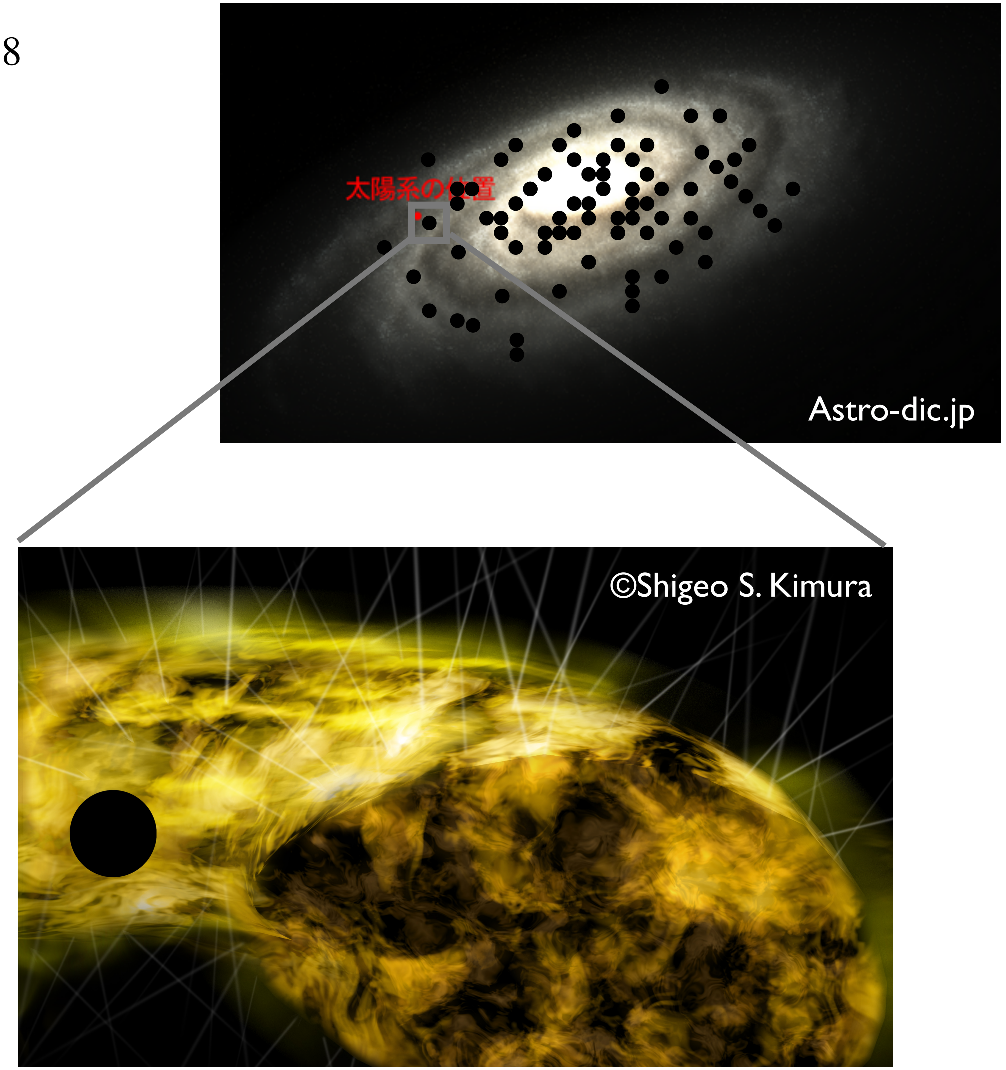
Isolated Black Holes (IBHs)

- 0.1% of stars form BHs: $N_{\rm BH} \sim f_{\rm BH} N_{\rm star} \sim 3 \times 10^8$
- Number of observed Galactic BH: ~20 <<< $N_{\rm BH}$
- Observed nearest BH: ~ 500 pc (V723 Mon)
- Estimated distance to nearest IBH:

$$\sim 20\ \mathrm{pc} \left(\frac{N_{\rm BH}}{10^8}\right)^{-1/3} \left(\frac{V_{\rm gal}}{10^3\ \mathrm{kpc}^3}\right)^{1/3}$$

- **Accretion onto IBHs**
  → Various electromagnetic emission
  (Fujita+ 1998; Ioka+2017; Matsumoto+2018; Tsuna+ 2018,2019 etc)
- **We would like to find the nearest BH**
  (Stellar physics; accretion physics)
- **Let's discuss detectability using Gaia & eROSITA**



Mass accretion onto IBH

- IBH is wandering in multi-phase ISM
  - Molecular cloud: attenuation & contamination
  - Hot HII : too low mass accretion rate

  → **Cold & Warm medium are the best**
- Mass accretion onto IBH in warm medium

$$\dot{M}_\bullet \approx \lambda_w \frac{4\pi G^2 M^2 \mu_{\rm ISM} m_p n_{\rm ISM}}{(C_s^2 + v_k^2)^{3/2}} \qquad (1)$$

$$\simeq 7.3 \times 10^{10} \lambda_{w,0} M_1^2 n_{{\rm ISM},-1} \left(\frac{\sqrt{C_s^2 + v_k^2}}{40 \ {\rm km\ s^{-1}}} \right)^{-3} \ {\rm g\ s^{-1}},$$

- Typical luminosity:

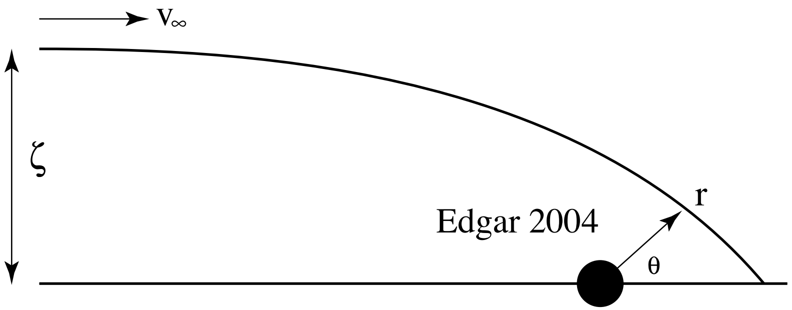
  $L \sim \eta_{\rm rad} \dot{M} c^2 \sim 10^{30}$ erg/s $\dot{M}_{\bullet,11} \eta_{\rm rad,-2} \ll L_{\rm Edd}$

  → **RIAF formation**

SSK, Kashiyama, Hotokezaka 2021

Bland-Hawthorn & Reynolds 2000

ISM phase	$n_{\rm ISM}$ [cm^{-3}]	$C_{s,{\rm ISM}}$ [km s^{-1}]	$H_{\rm ISM}$ [kpc]	ξ_0
Molecular clouds	10^2	10	0.075	0.001
Cold HI	10	10	0.15	0.04
Warm HI	0.3	10	0.50	0.35
Warm HII	0.15	10	1.0	0.2
Hot HII	0.002	150	3.0	0.43

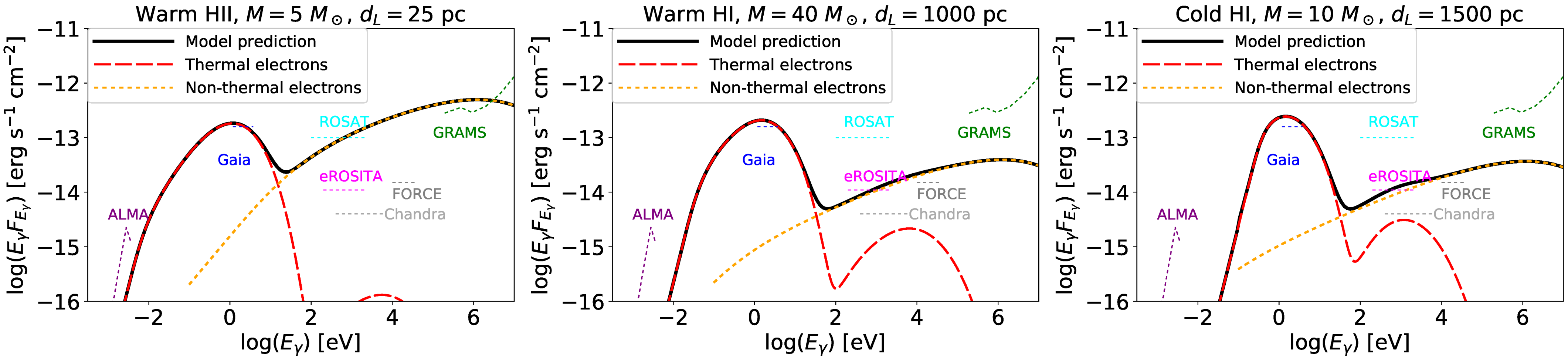


Edgar 2004

Fig. 1. Sketch of the Bondi–Hoyle–Lyttleton accretion geometry.

Photon spectra from MADs around IBHs

SSK, Kashiyama, Hotokezaka 2021



- Thermal synchrotron → optical signals
- Gaia can detect typical IBHs up to ~ 30 pc
- Gaia can detect IBHs of M~40 Msun or in Cold HI up to ~ 1 kpc
- Non-thermal synchrotron: X-ray and MeV γ-ray signals
- eROSITA can detect all the IBHs found by Gaia
- Hard X-ray spectrum: testable by Hard X-rays & MeV γ-rays

$$\nu_{\rm syn,pk} \approx \frac{75 e B \theta_e^2}{4\pi m_e c} \simeq 2.0\times10^{14} B_4 \mathcal{R}_1^{-2}\left(\frac{f_e}{0.3}\right)^2\ {\rm Hz},$$

$$\nu_{\rm syn,pk}L_{\nu_{\rm syn,pk}} \approx \frac{4}{3}(3\theta_e)^2\frac{\sigma_T c B^2}{8\pi}(\pi R^3 N_p) \qquad (10)$$

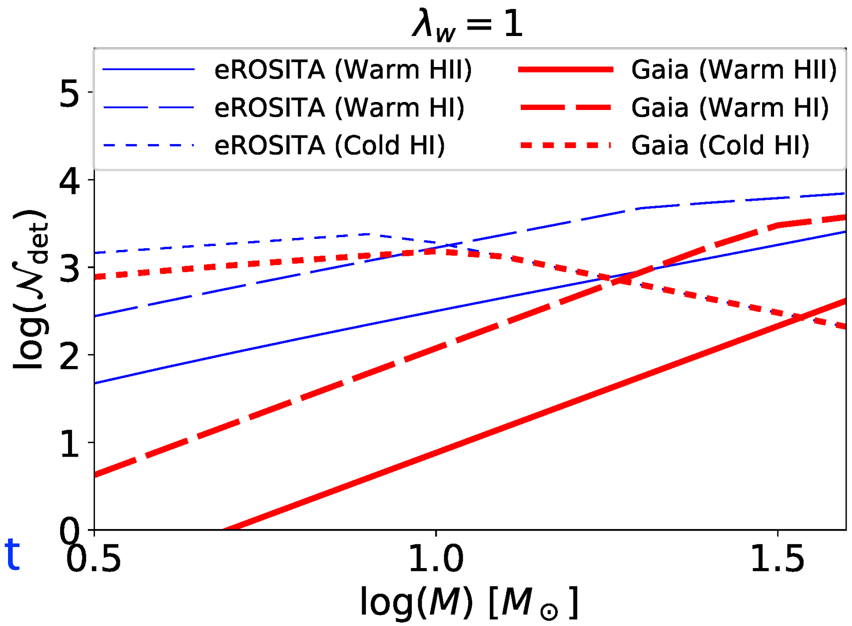
$$\simeq 9.3\times10^{28}\dot{M}_{\bullet,11}^2 M_1^{-1}\mathcal{R}_1^{-3}\alpha_{-0.5}^{-2}\beta_{-1}^{-1}\left(\frac{f_e}{0.3}\right)^2\ {\rm erg\ s^{-1}}.$$

$$E_X L_X \simeq 1.3\times10^{29}\dot{M}_{\bullet,11} f_{X,-1}\left(\frac{f_e\epsilon_{\rm NT}\epsilon_{\rm dis}}{0.3\cdot0.33\cdot0.15}\right)\ {\rm erg\ s^{-1}},$$

Expected detection number

$$\mathcal{N}_{\rm det}(M) \sim M \frac{dN_{\rm IBH}}{dM\,dV}\xi_0 \min\left(\frac{4\pi}{3}d_{i,{\rm det}}^3,\ 2\pi H_{\rm ISM} d_{i,{\rm det}}^2\right)$$

- Gaia can detect ~ 100 IBHs in warm HI
- IBH in cold HI: O(1000)
- eROSITA can detect more IBHs than Gaia
  →Follow-up for eROSITA un-ID sources are important



SSK, Kashiyama, Hotokezaka 2021

- Detection horizon: $d_{i,{\rm det}} = \min(\sqrt{L_{i,{\rm band}}/(4\pi f_{i,{\rm sen}})},\ d_{\rm max})$
  $f_{i,{\rm sen}}$: sensitivity of Gaia or eROSITA
- $dN_{\rm IBH}/dV = 10^5\ {\rm kpc}^{-3}$: number density of IBH in ISM
- $dN_{\rm IBH}/dM \propto M^{-2.6}$: mass function of IBH
- ζ_0: Volume filling factor

Bland-Hawthorn & Reynolds 2000

ISM phase	$n_{\rm ISM}$ $[{\rm cm}^{-3}]$	$C_{s,{\rm ISM}}$ $[{\rm km\ s}^{-1}]$	$H_{\rm ISM}$ [kpc]	ξ_0
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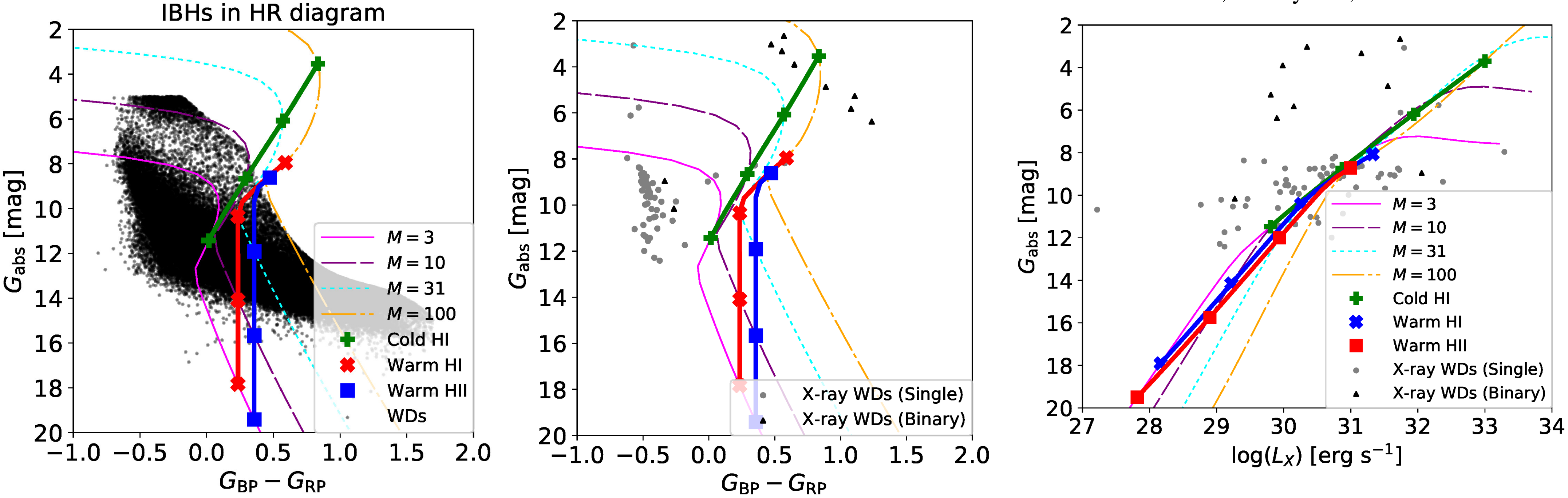
Isolated Black Holes in HR diagram

SSK, Kashiyama, Hotokezaka 2021



- IBHs are located around cooling sequence of WDs (left panel)
- X-ray bright WDs are blue or luminous (middle panel)
  → **Red or faint objects emitting X-rays are likely IBHs**
- $L_X/L_{\rm opt}$ is similar between WDs and IBHs (left panel)

IBH Identification strategy

SSK, Kashiyama, Hotokezaka 2021

- Contamination I: Isolated WDs

  – variability is useful

  (WDs: $t_{\rm var} \sim 1$ min、IBH: $t_{\rm var} < 1$ sec)

  – X-ray spectrum is useful

  (WDs: $\Gamma_X > 3$、IBH: $\Gamma_X \lesssim 2$)

- Contamination II: WD-Main sequence binaries

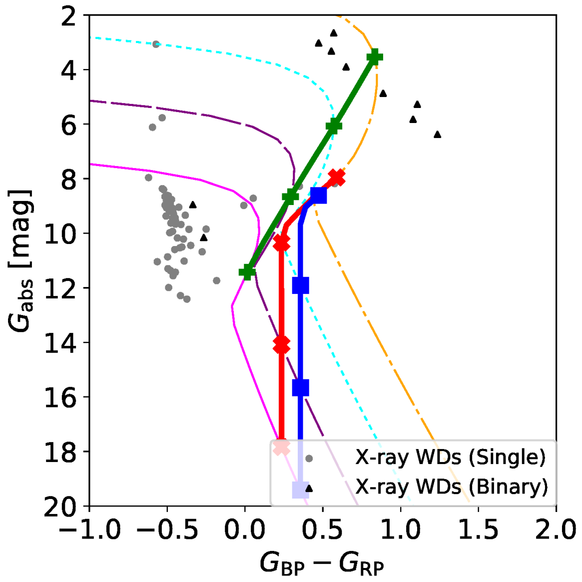
  – multi-color photometry is useful

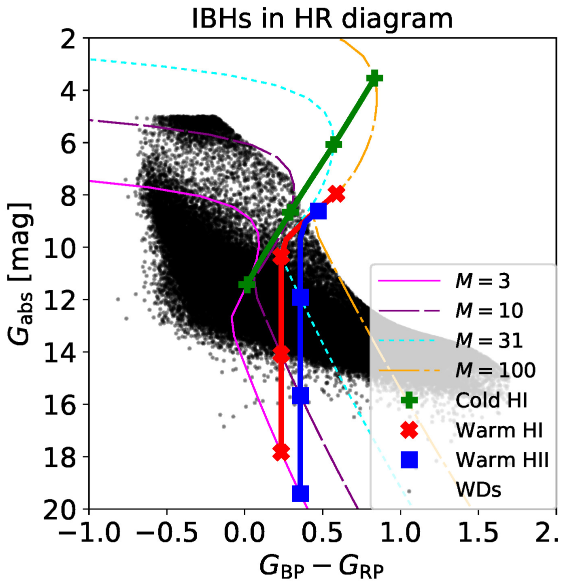
  (Binary = 2-temp. Black body; IBH = thermal synchrotron)

- Contamination III: isolated NSs

  – $L_X/L_{\rm opt}$ is useful

  (Isolated NS: $L_X/L_{\rm opt} \gg 1$、IBH: $L_X/L_{\rm opt} \lesssim 1$)





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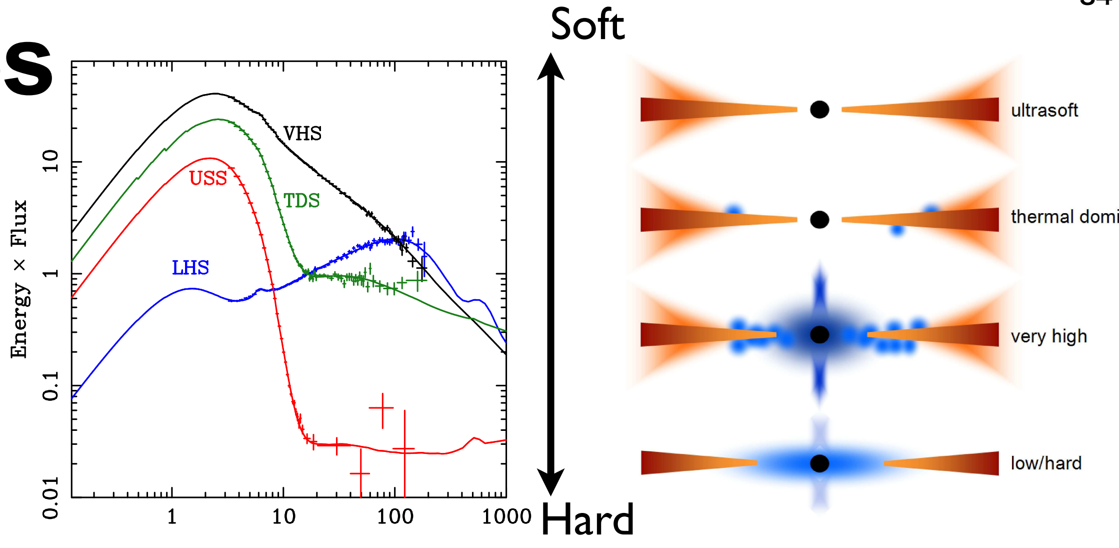
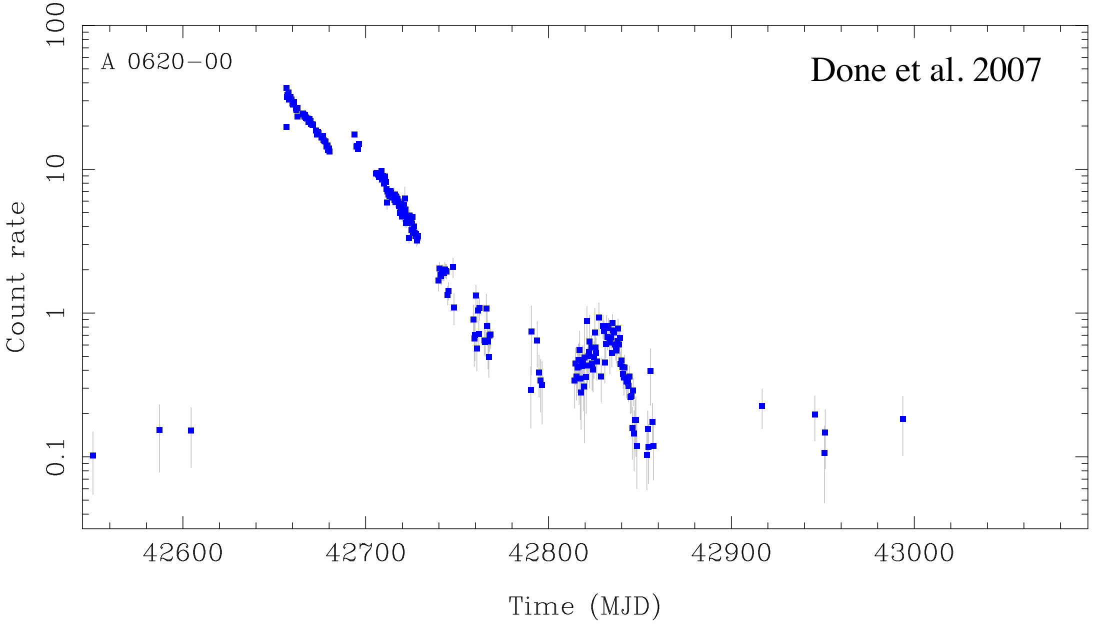
Black-hole X-ray Binaries

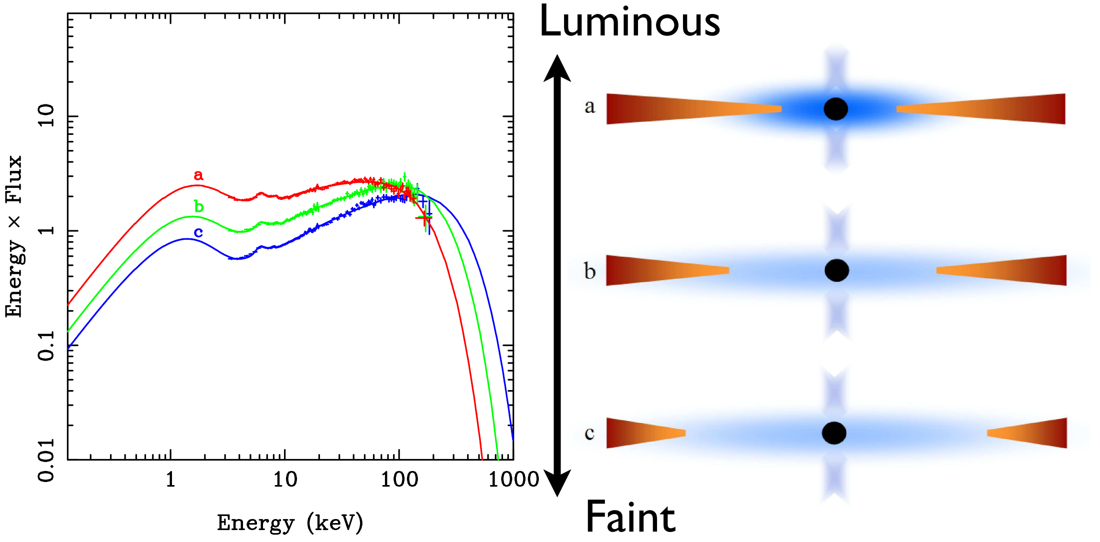
BlackCat 2016; WATCHDOG 2016

- Most black holes are detected as X-ray novae
- Different State = Different accretion regime
- **Quiescent State:**
  Inner hot plasma + Outer cold disk





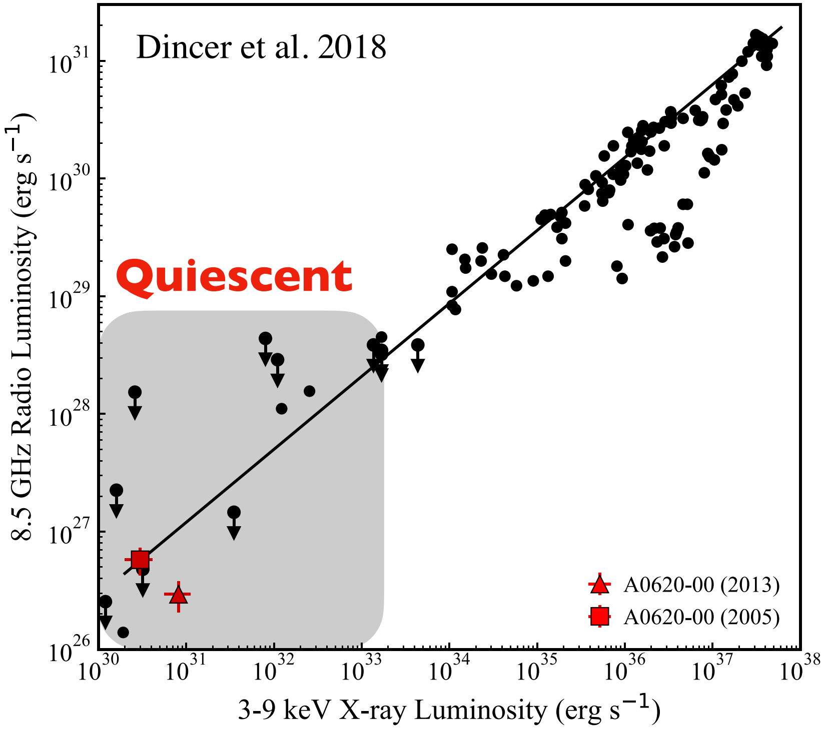
Done et al. 2007

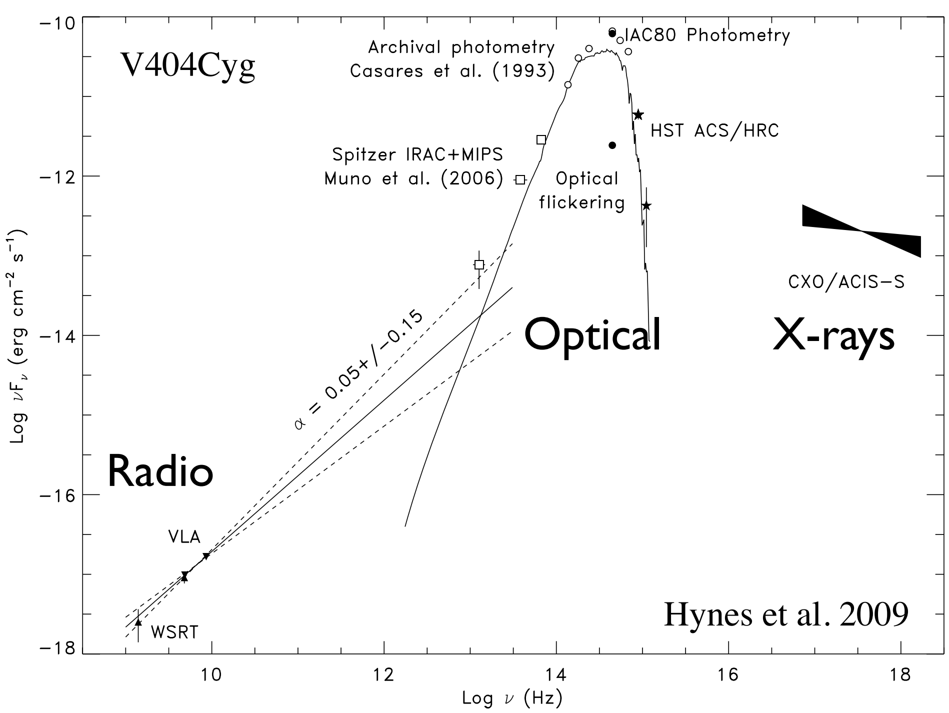


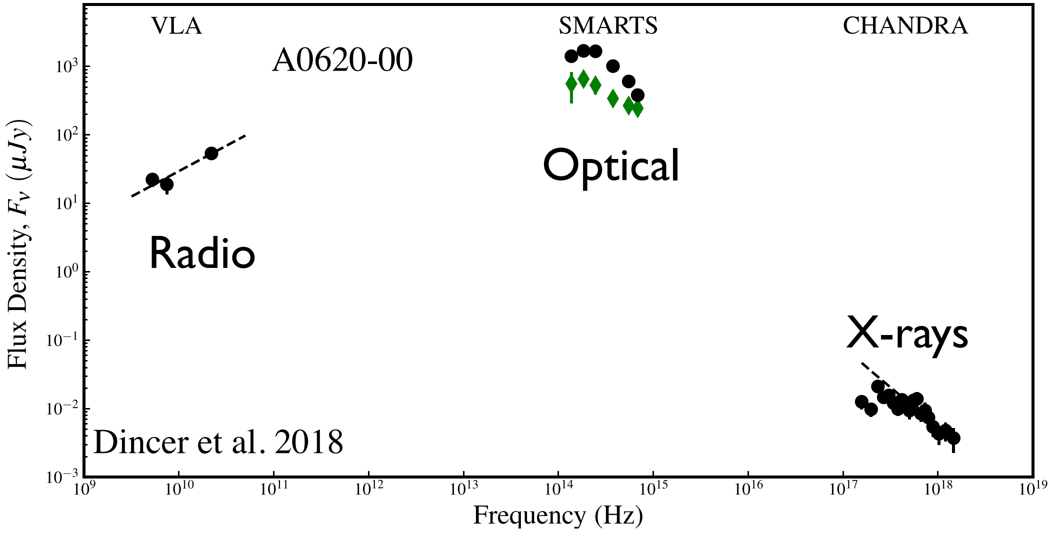
Done et al. 2007

Quiescent State

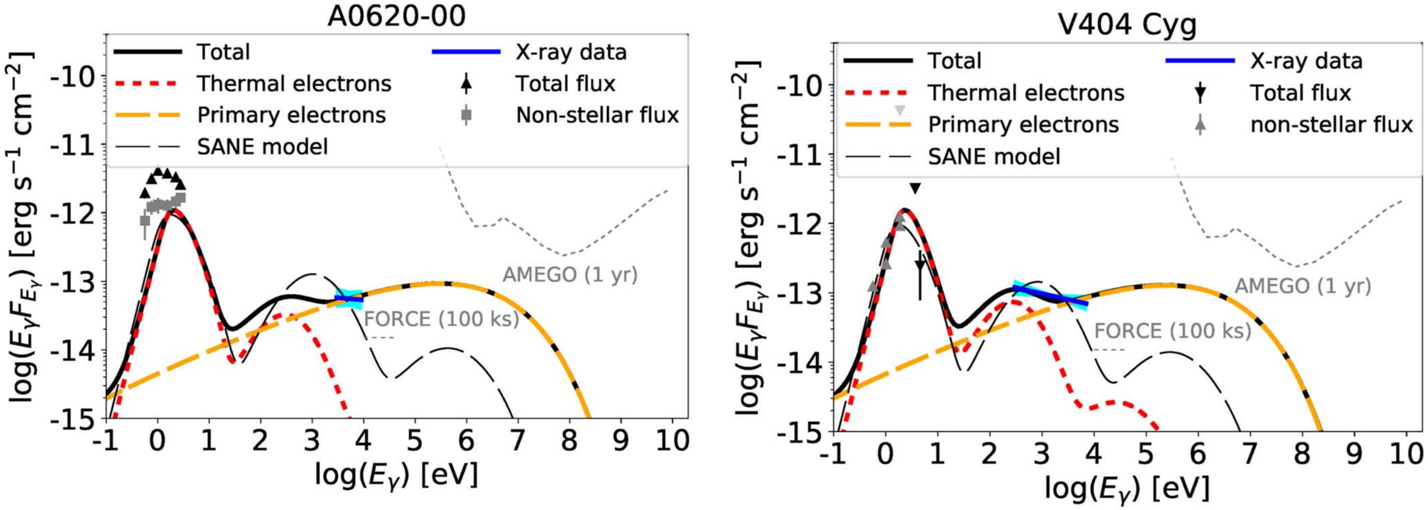
- Faintest state in X-ray binaries ($L_X < 10^{33}$ erg/s)
- Detected by radio, IR/opt/UV, and X-rays
- Radio emissions come from compact jets
- **Emission regions of Opt & X are unknown**
  → **We propose MAD as emission site**





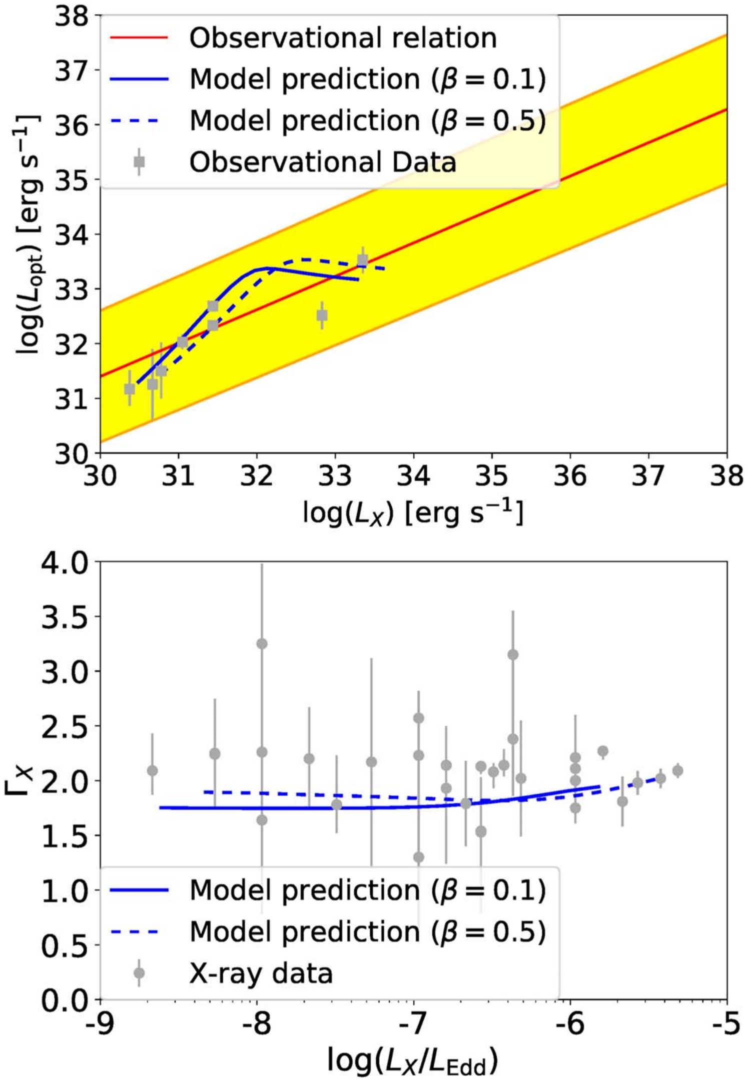


Photon spectra from MAD



SSK, Sudoh, Kashiyama, Kawanaka 2021

SSK et al. 2021

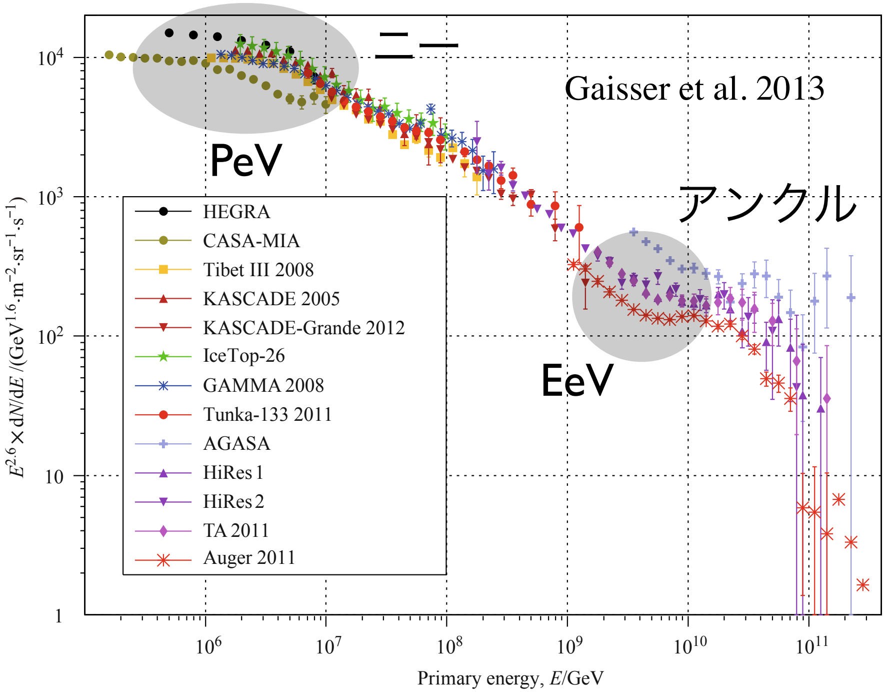


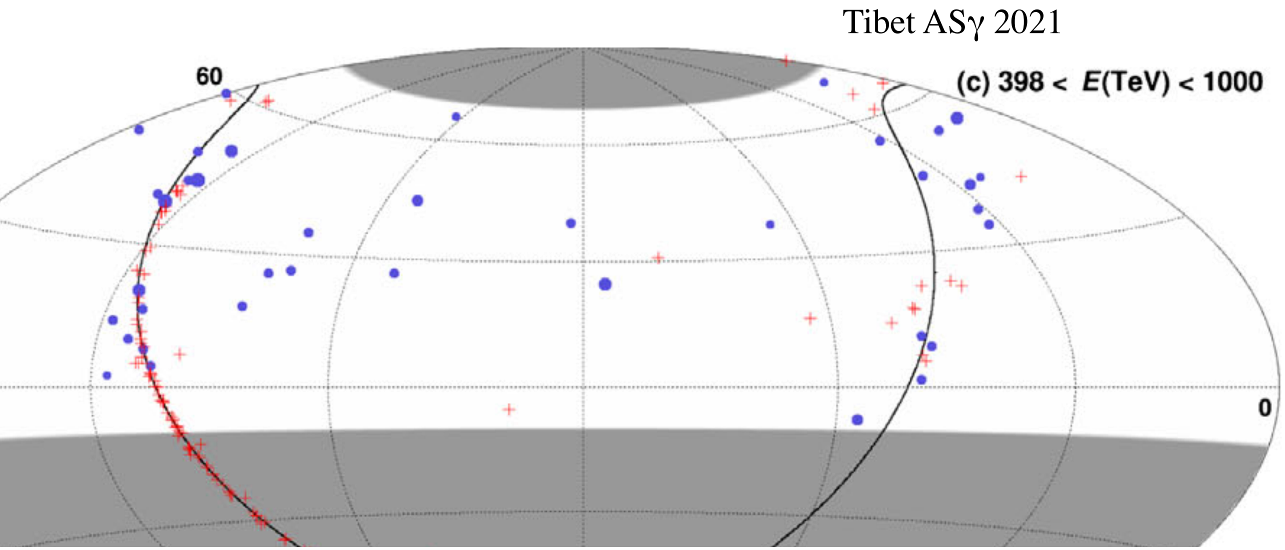
- Optical: Thermal synchrotron
- X-rays: Synchrotron by non-thermal electrons
- Consistent with opt/X-ray data for nearby objects
- Can reproduce empirical relation (L_X–$L_{\rm opt}$; L_X–Γ_X)

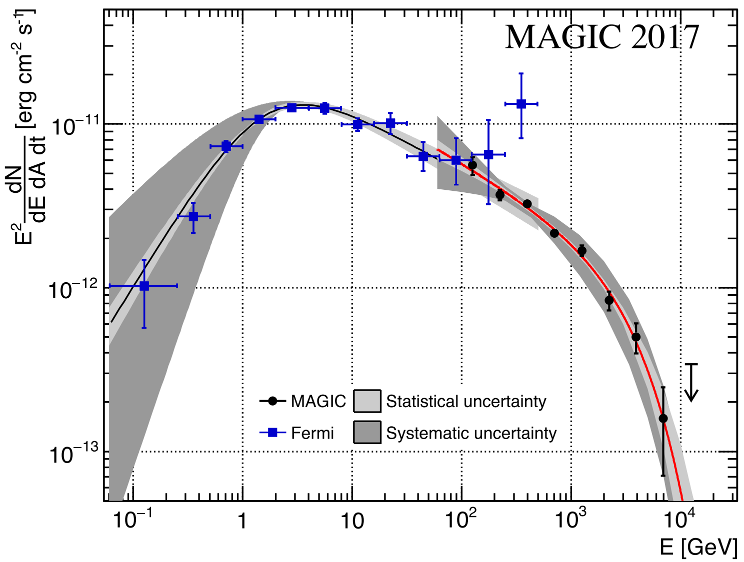
Russell+2006 Plotkin+2013

Galactic CRs & PeVatron

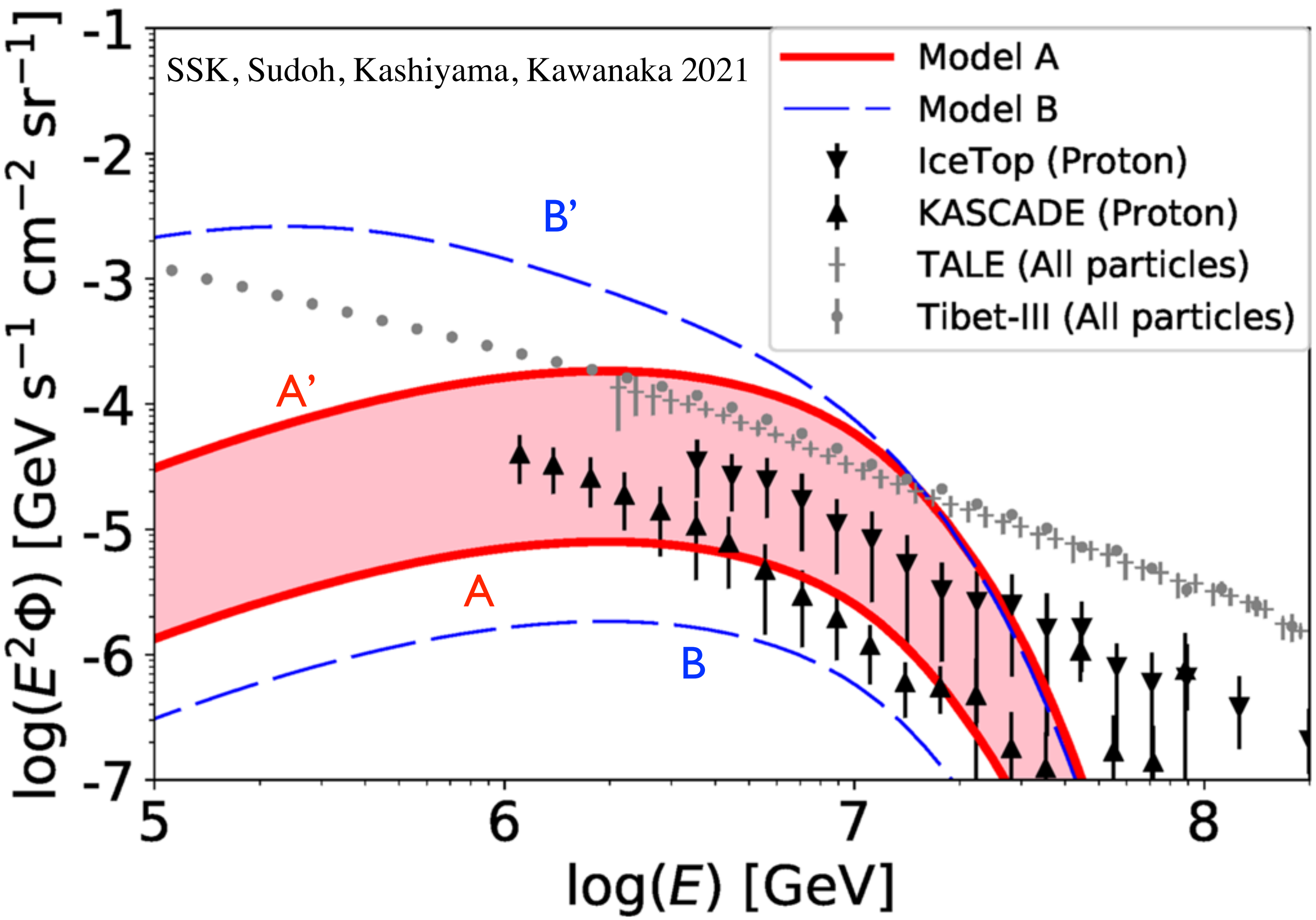
- Origin of PeV(=10^{15} eV) CRs are unknown
- Tibet ASγ detected gamma-ray of 10^{14}–10^{15} eV
  → **Oricin of 10^{15}–10^{16}eV CRs should be Galactic**
- Gamma-ray from SNR: cutoff around 10^{12}–10^{13}eV
  →Hadron energy in SNR is 10^{14} eV ?
  →**Other CR sources may be important !**

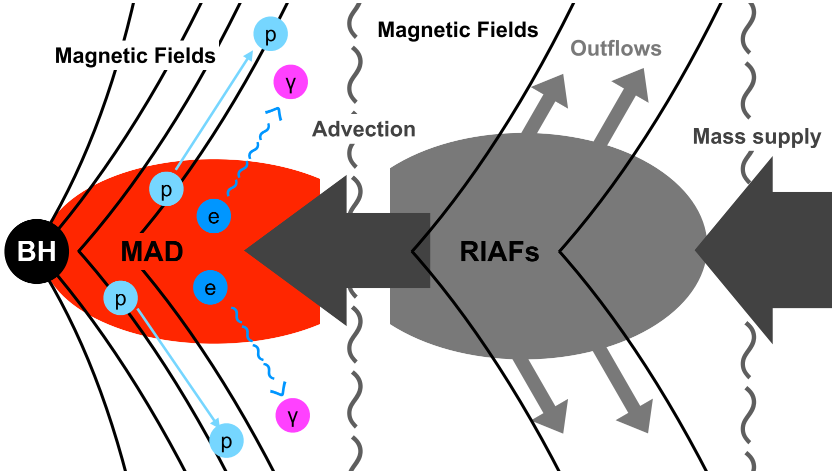

Gaisser et al. 2013


Tibet ASγ 2021


MAGIC 2017

Cosmic-Rays from MADs


SSK, Sudoh, Kashiyama, Kawanaka 2021



- Magnetic reconnections accelerate protons
- Maximum energy: E ~ 10^{15}eV (balance of escape & acceleration)
- Number of BH binaries:
  - X-ray nova observations (A) :10^3
  - Population Synthesis (A’) :3x10^4
  - Luminous X-ray binaries (B) : 300
  - number of unID source (B’) :10^5 – 10^6
- **Consistent with data within their uncertainties**

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Summary

- Magnetic reconnection in MAD can produce non thermal particles
  →Many possible interesting phenomena in various environments
- GeV γ-ray from radio galaxies?
  → MAD can produce gamma-ray if mass accretion rate is low
- Lepton loading into jets?
  → Future X-ray satellites can detect X-ray flares from M87 & Sgr A*
- MADs around Isolated BH?
  → We can search for Isolated BHs using X-ray and optical data
- Quiescent state in X-ray binary? → Possible PeVatron