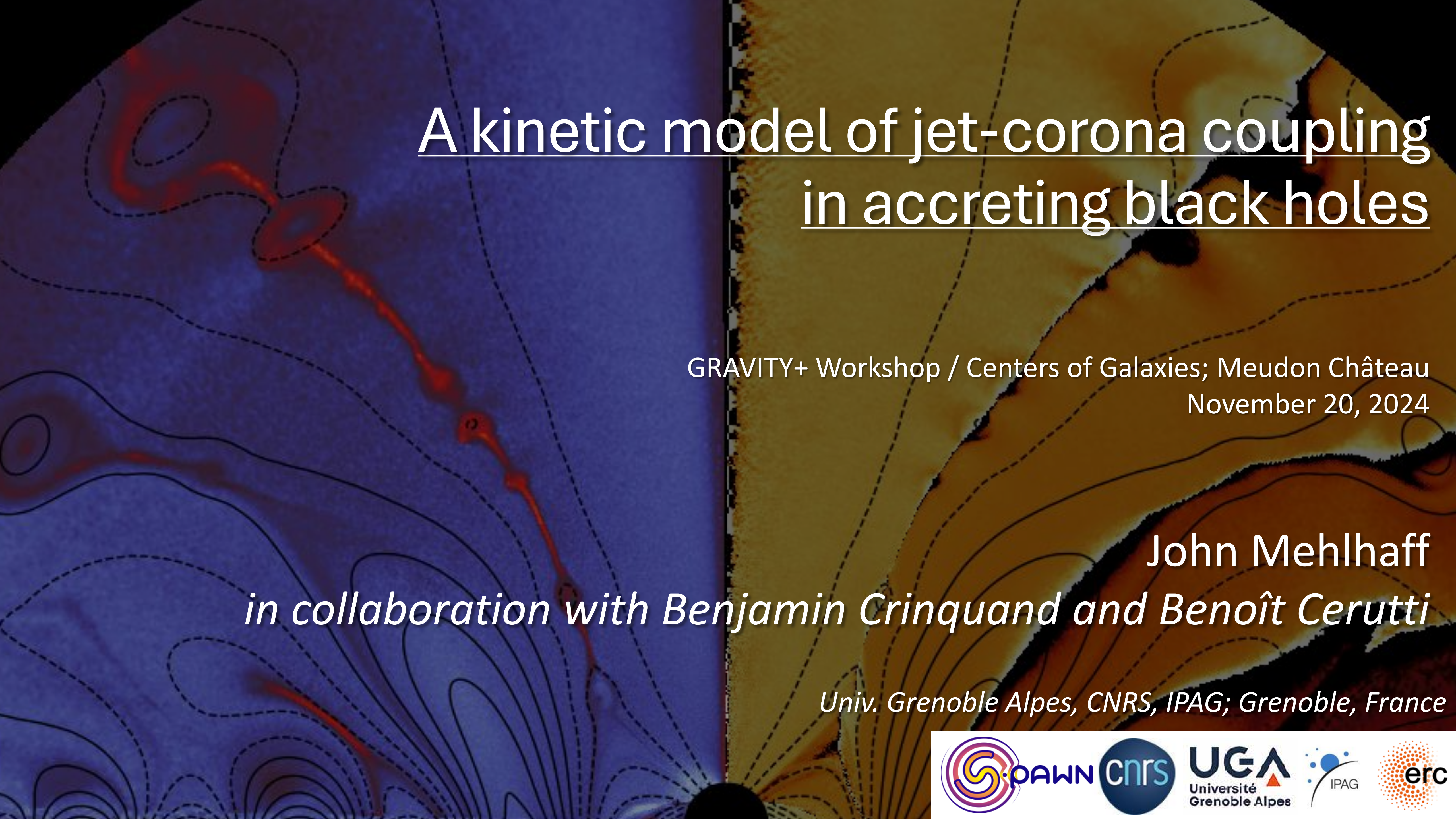


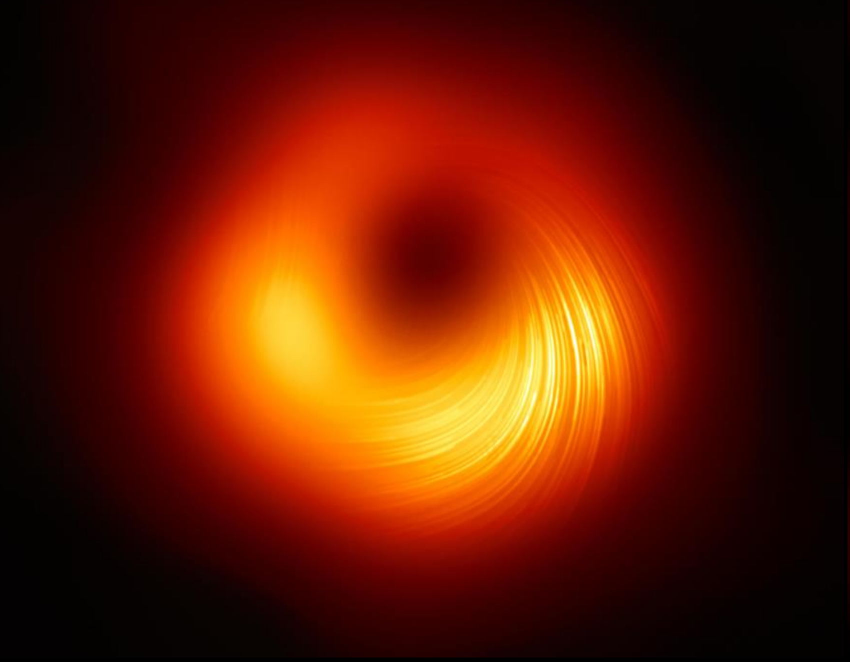
A kinetic model of jet-corona coupling in accreting black holes

GRAVITY+ Workshop / Centers of Galaxies; Meudon Château
November 20, 2024

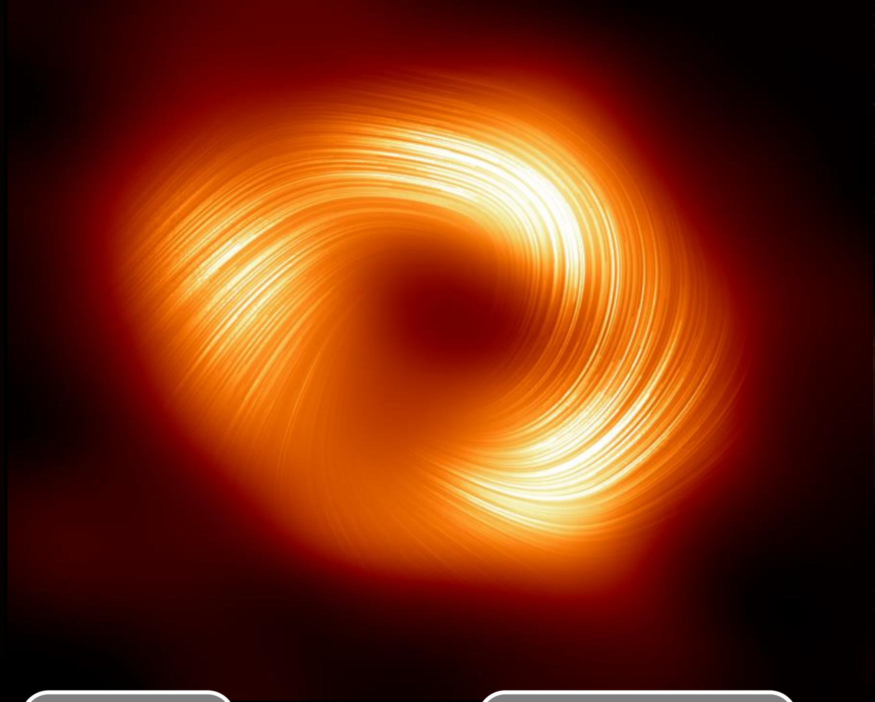
John Mehlhaff
in collaboration with Benjamin Crinquand and Benoît Cerutti

Univ. Grenoble Alpes, CNRS, IPAG; Grenoble, France

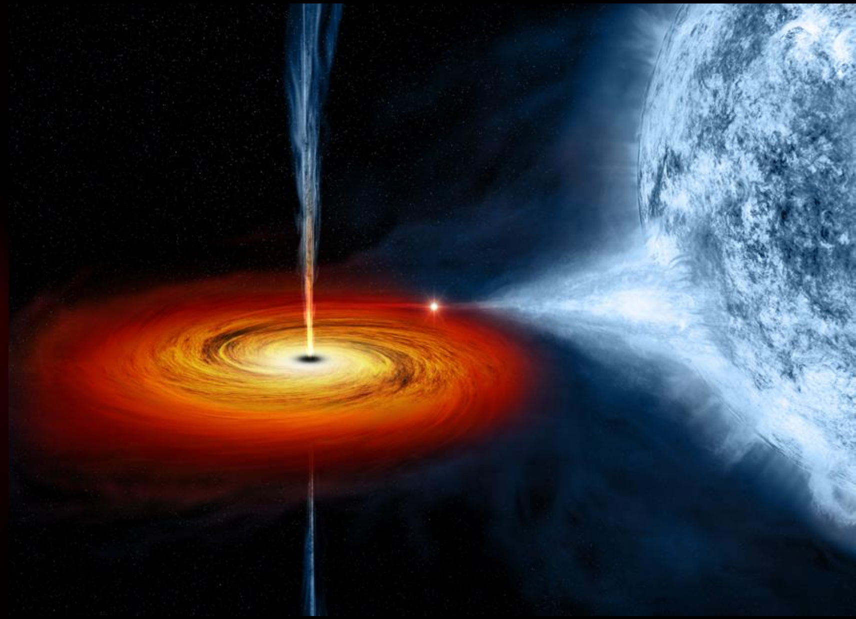
M87*
(EHT)



Sgr A*
(EHT)



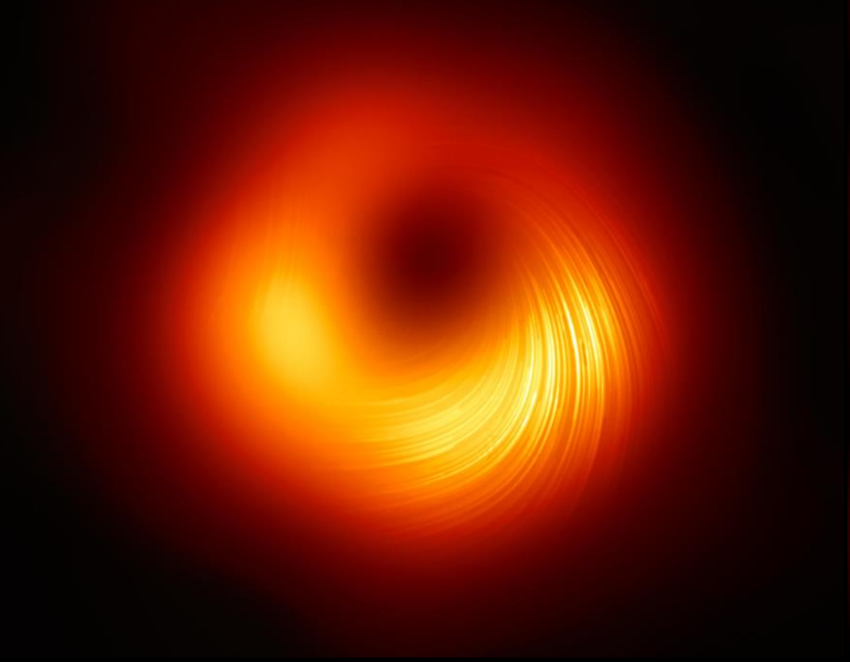
Cyg X-1
(artist's impression; NASA)



BH + Plasma → Particle Acceleration → (High-energy) Radiation

M87*

(EHT)



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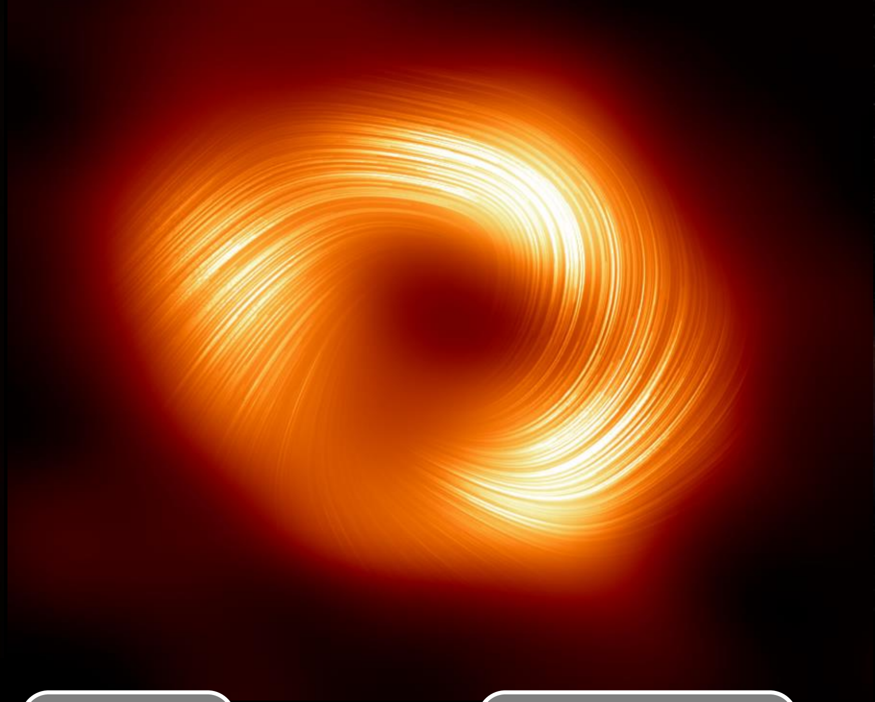

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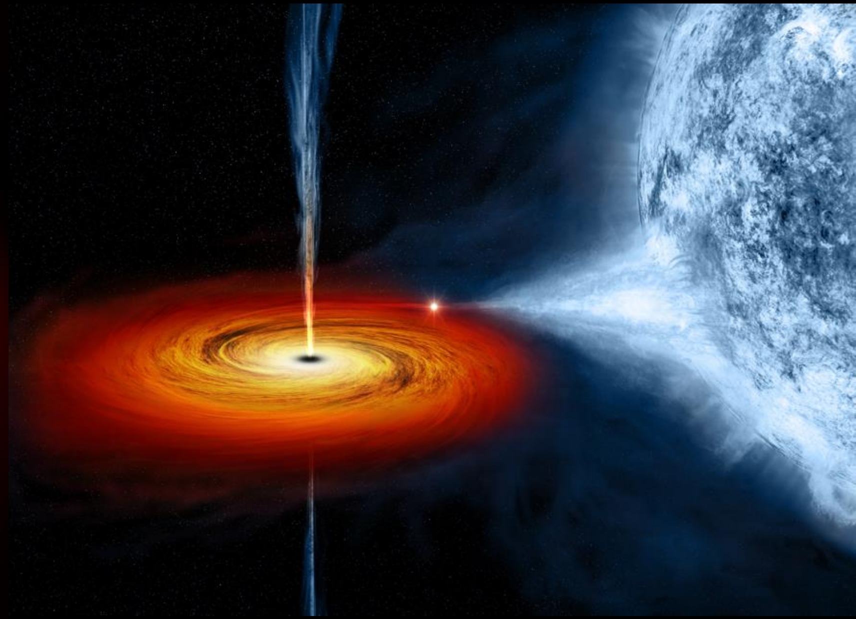


BH + Plasma → Particle Acceleration → (High-energy) Radiation

$M \sim 6 \times 10^9 M_\odot$

$r_g = \frac{GM}{c^2} \sim 60\ \text{AU}$

$\frac{r_g}{c} \sim 8\ \text{hr}$

$M \sim 4 \times 10^6 M_\odot$

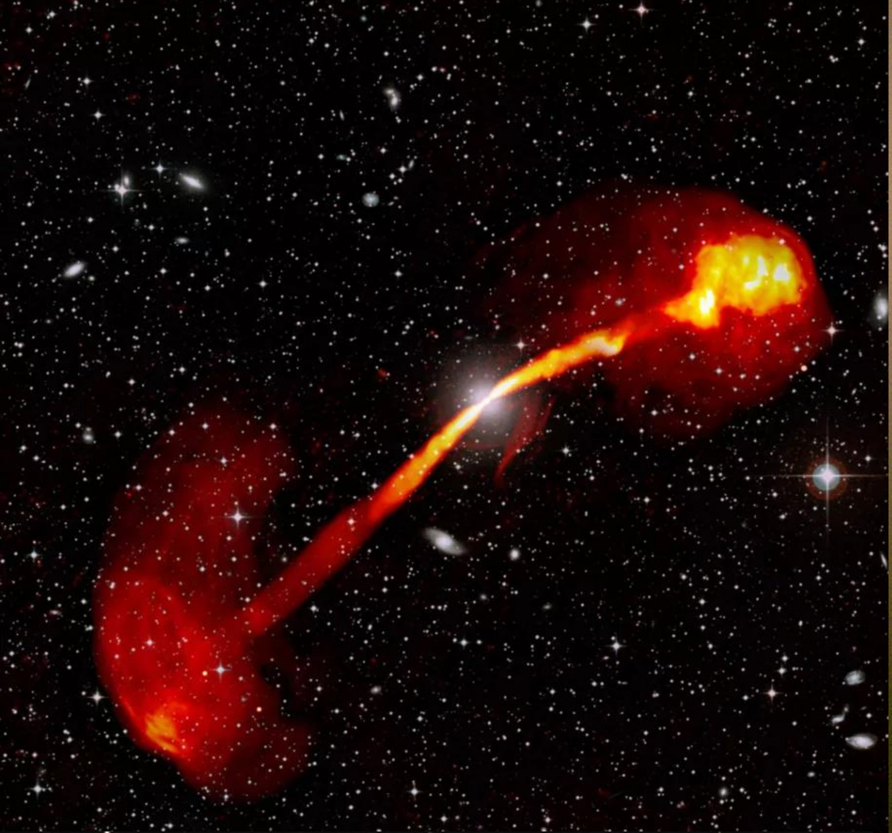
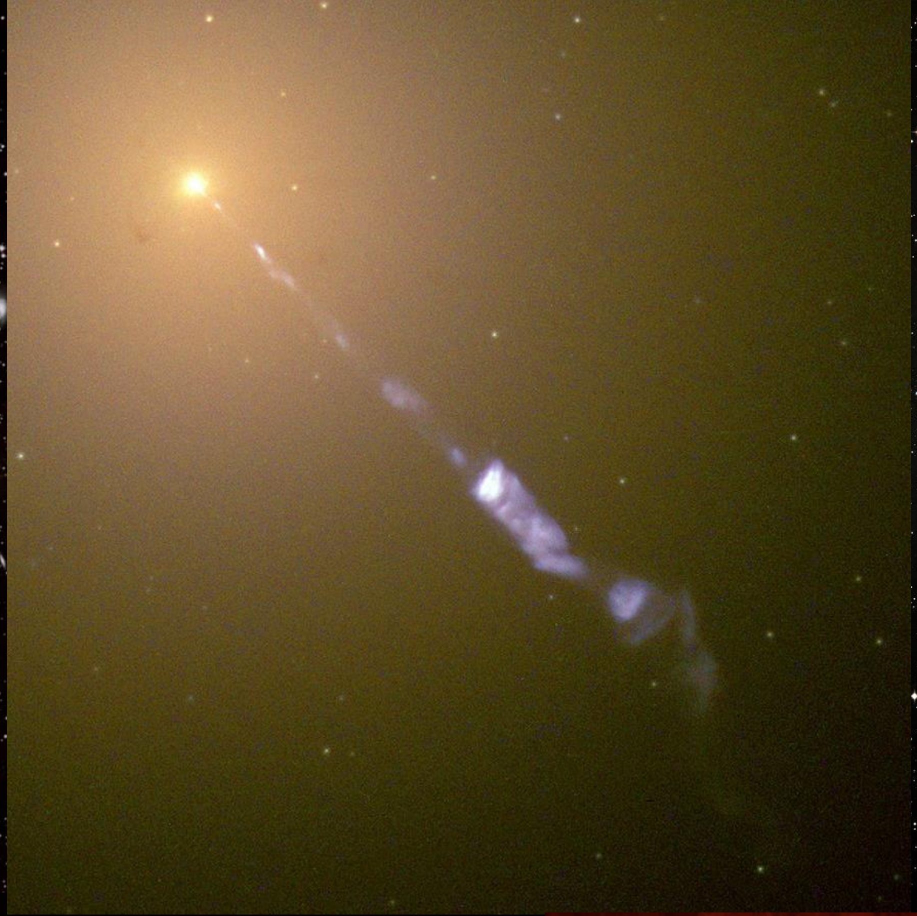
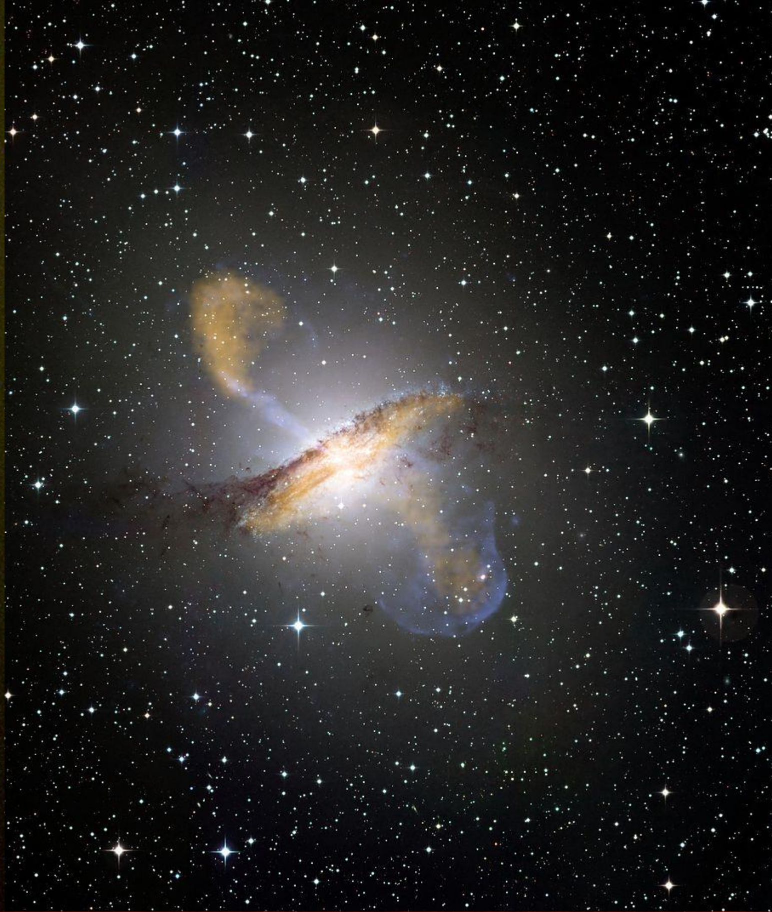
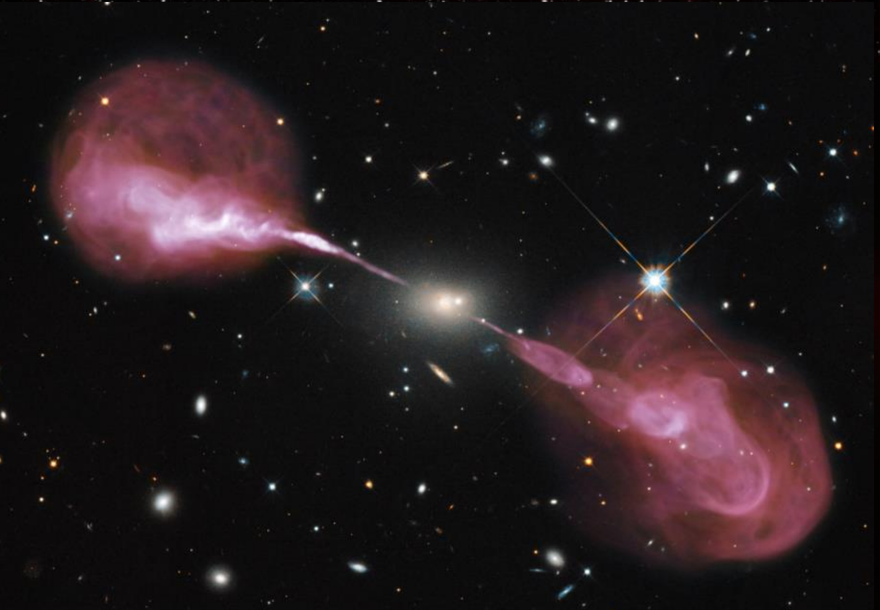
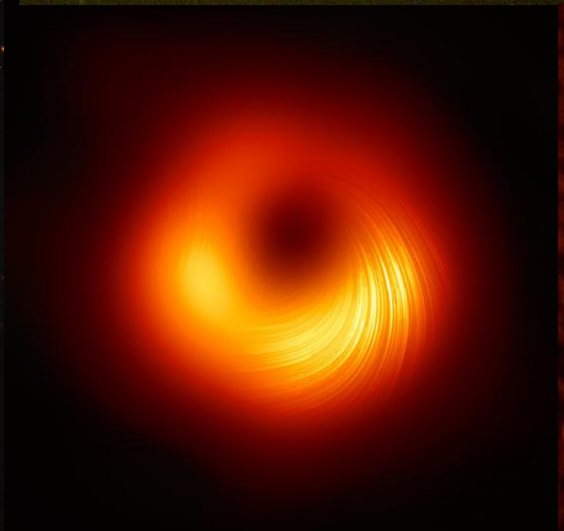
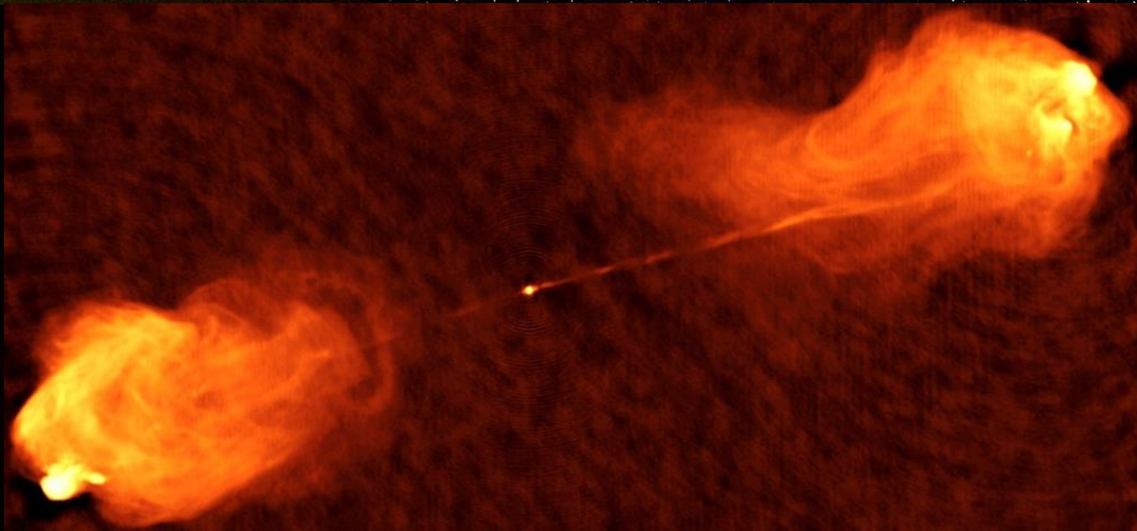
$r_g = \frac{GM}{c^2} \sim 8\text{R}_\odot$

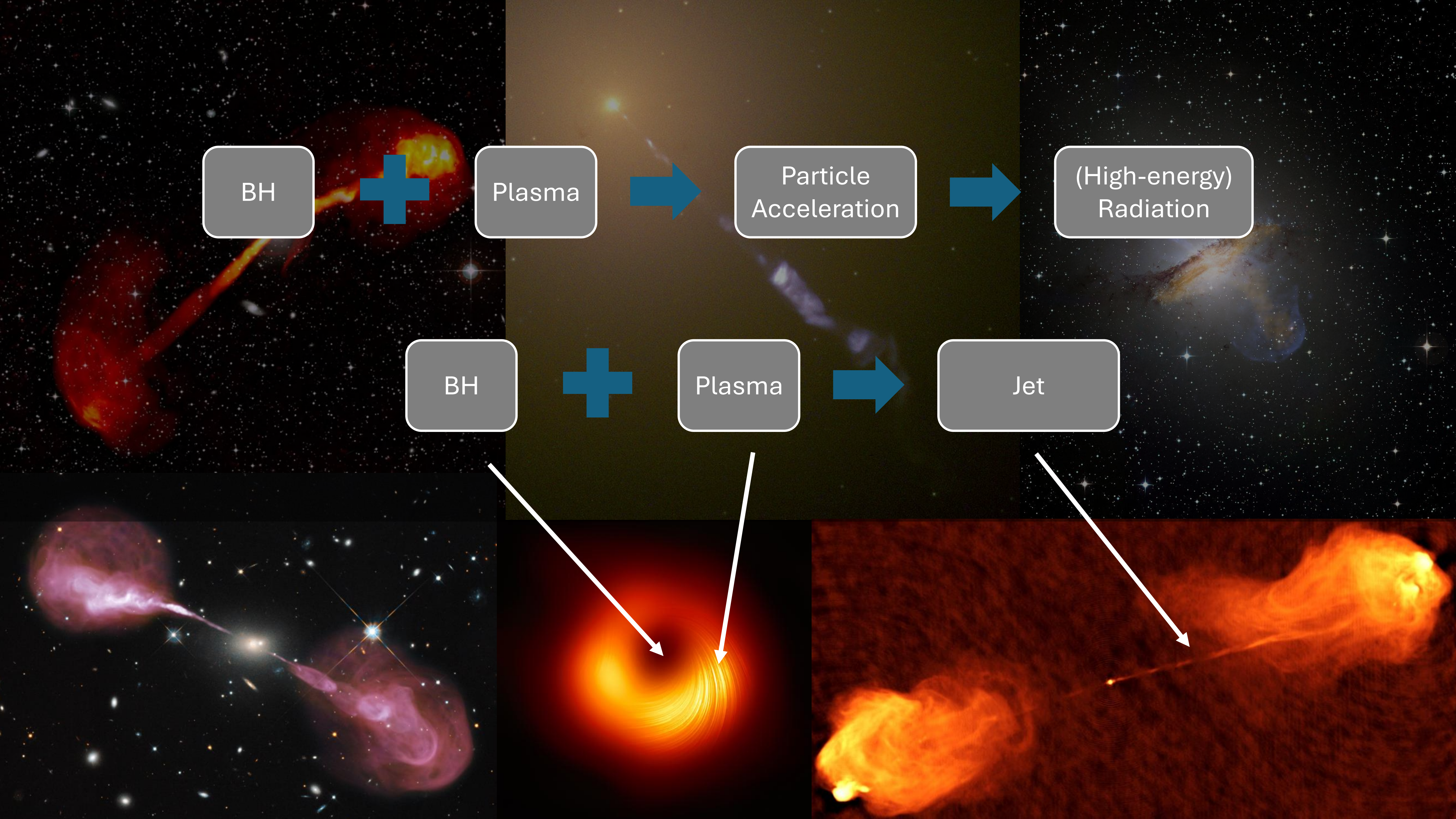
$\frac{r_g}{c} \sim 20\ \text{s}$

$M \sim 20 M_\odot$

$r_g = \frac{GM}{c^2} \sim 30\ \text{km}$

$\frac{r_g}{c} \sim 0.1\ \text{ms}$


BH
Plasma
Particle Acceleration
(High-energy) Radiation
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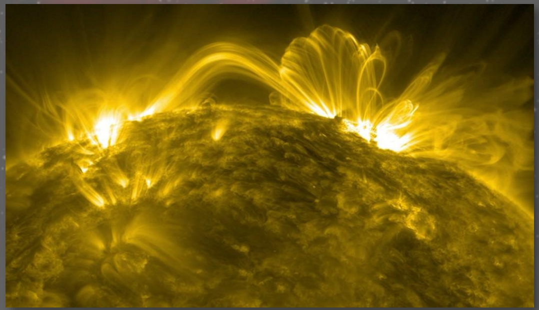
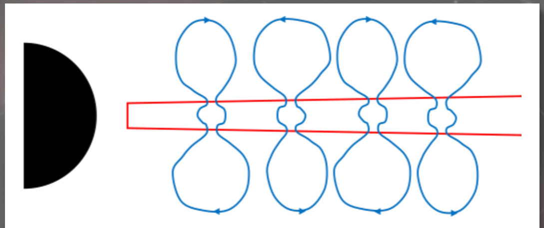
Plasma
Jet

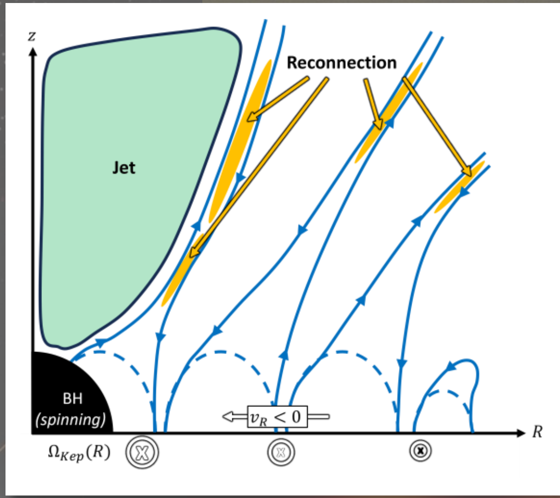
Outline

Black hole accretion disk coronae primer





A model for a BH coupled to its corona



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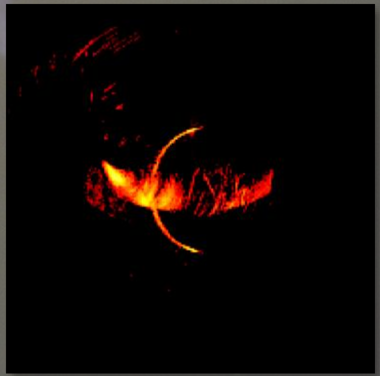
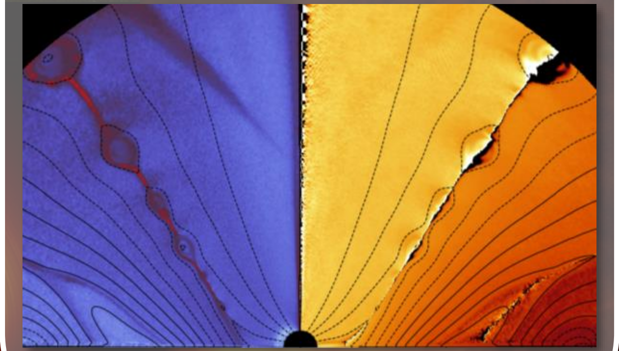
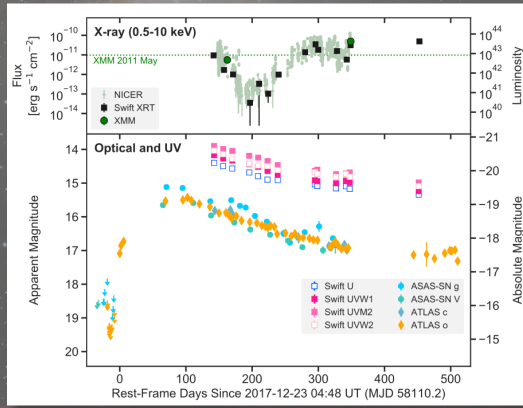
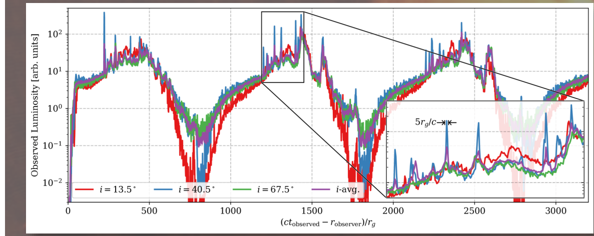




Links to changing-look AGN and X-ray binaries





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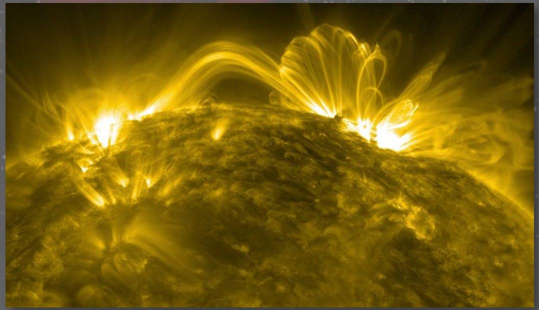

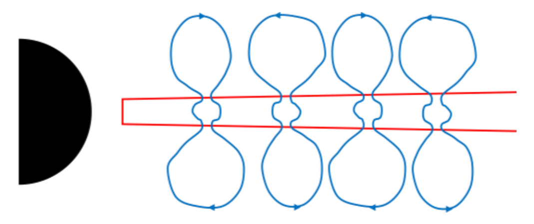

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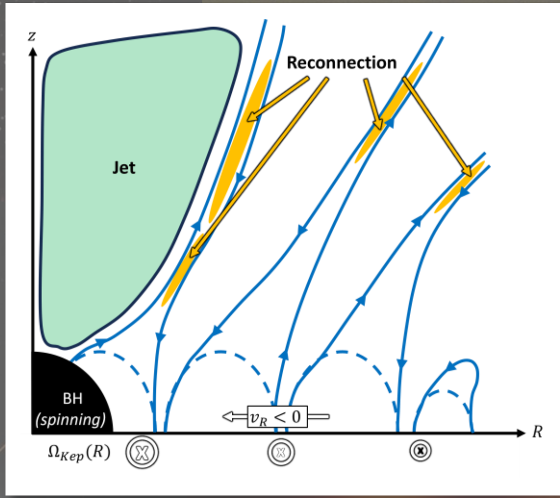

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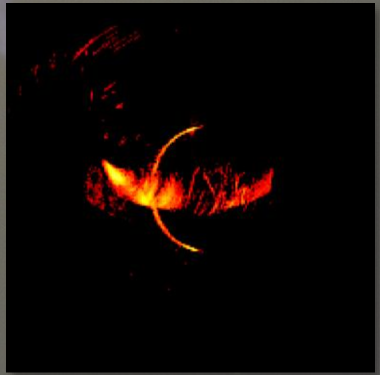

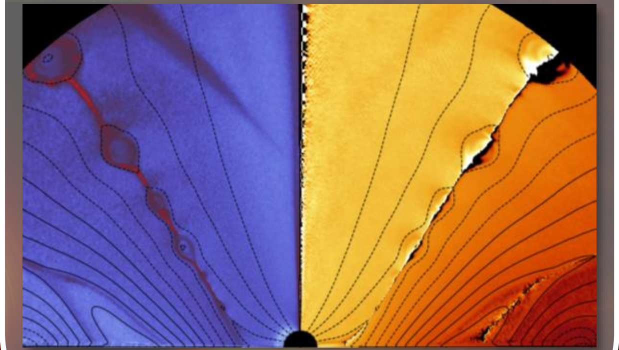

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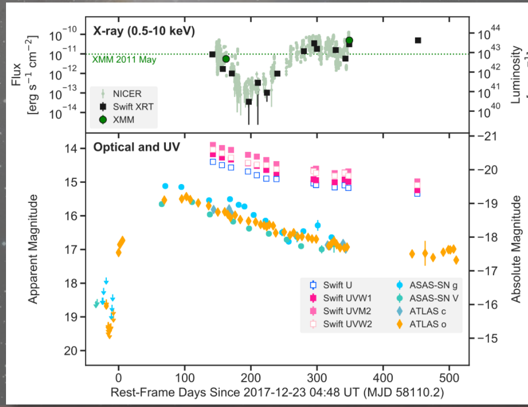
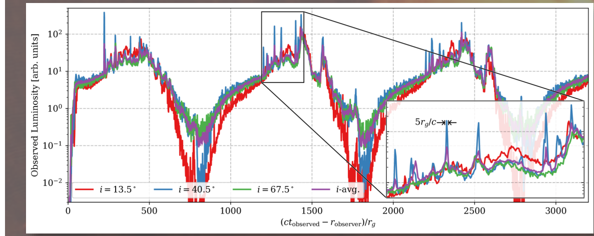
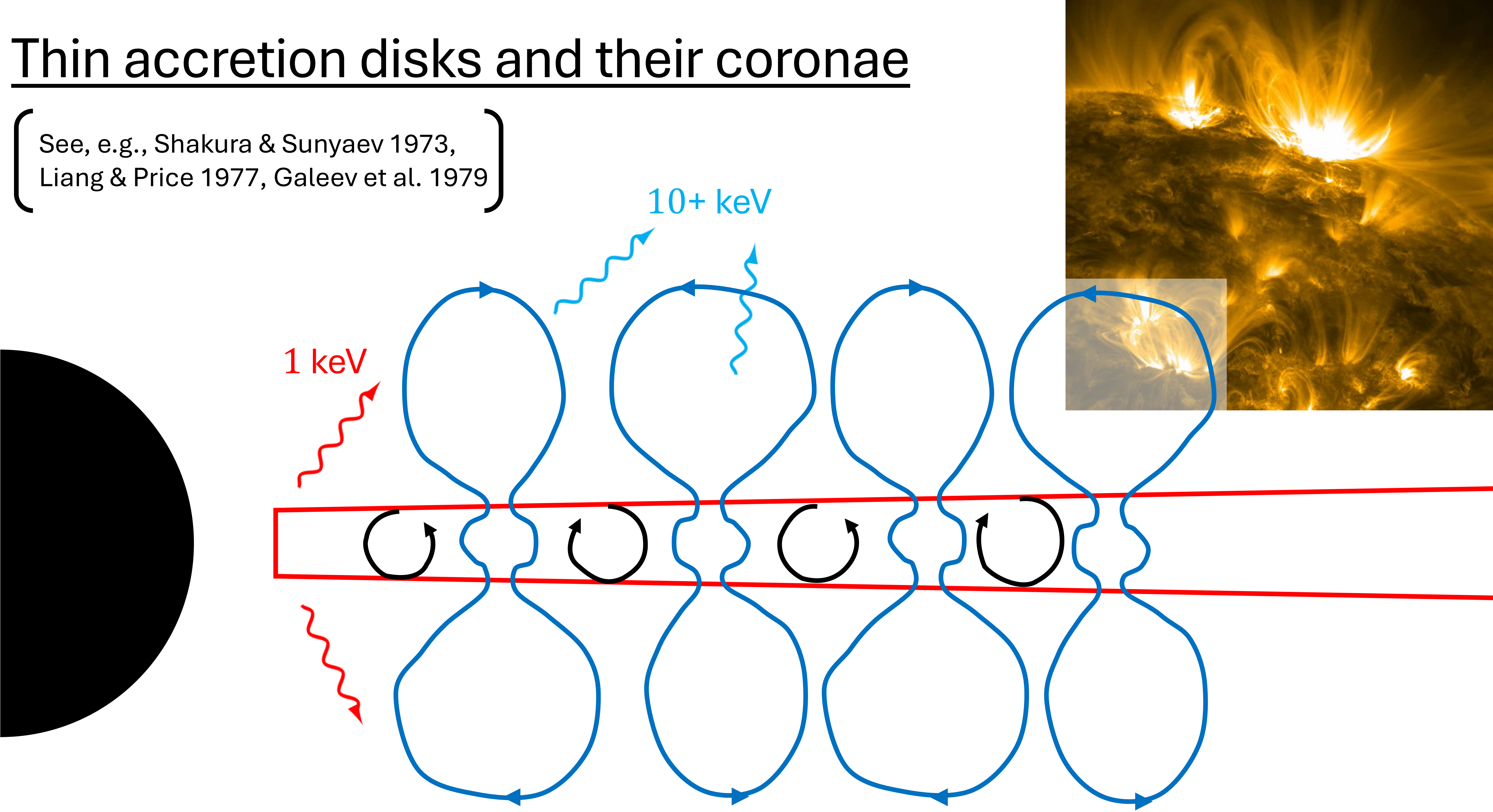




Thin accretion disks and their coronae

See, e.g., Shakura & Sunyaev 1973, Liang & Price 1977, Galeev et al. 1979



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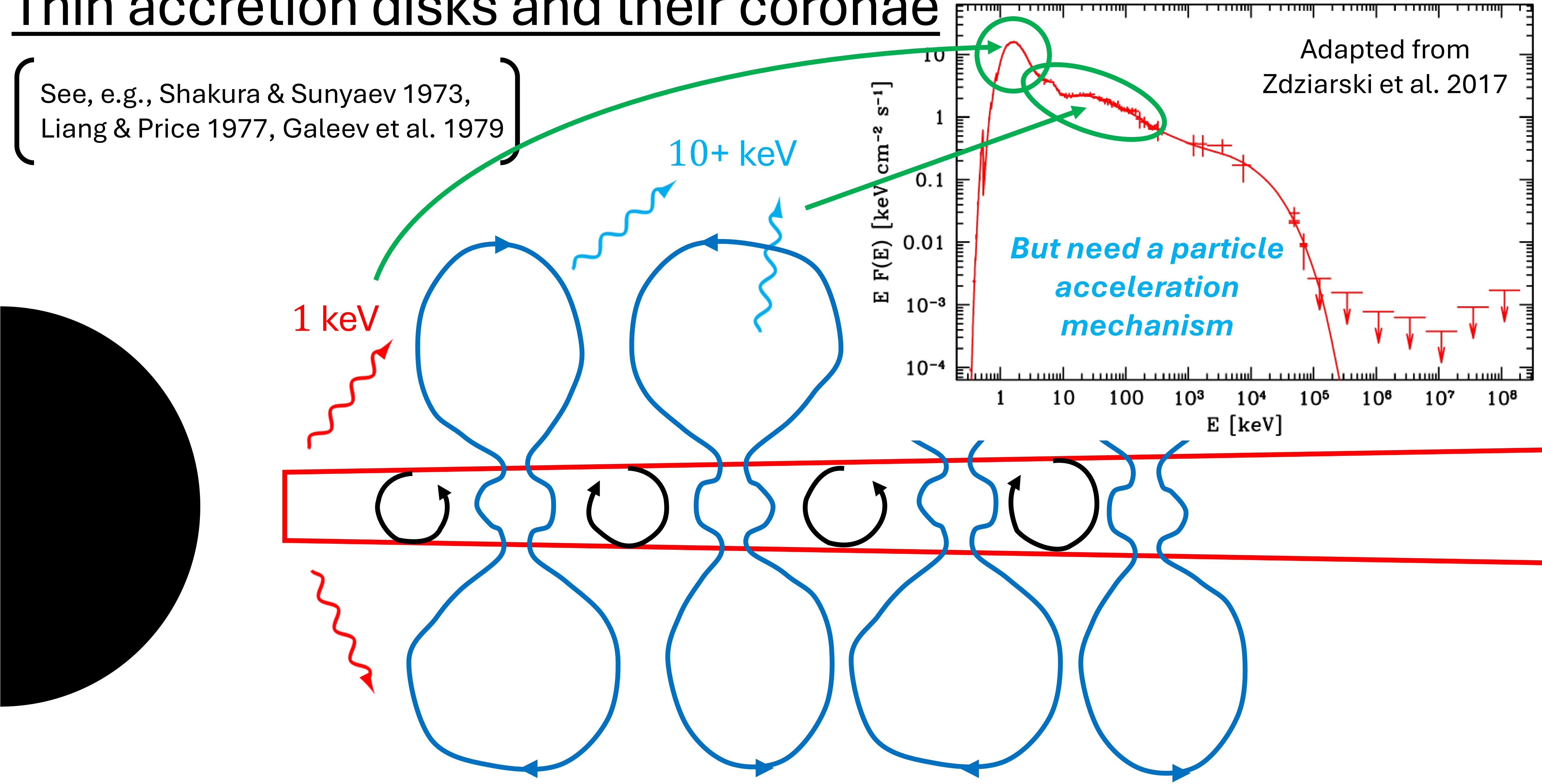
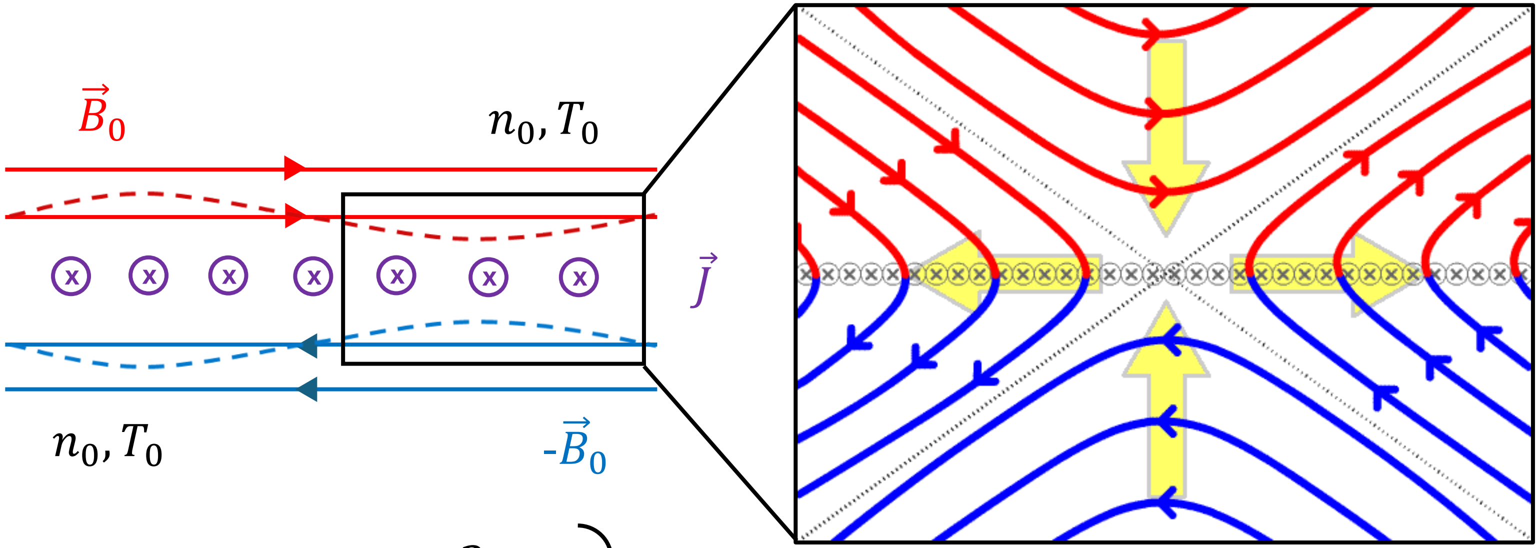
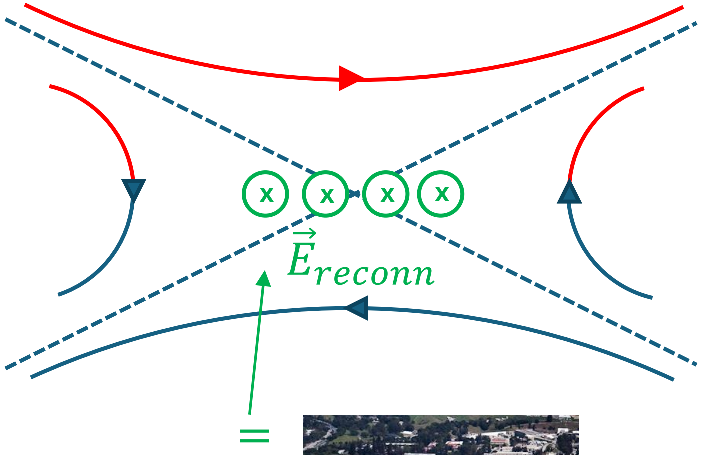


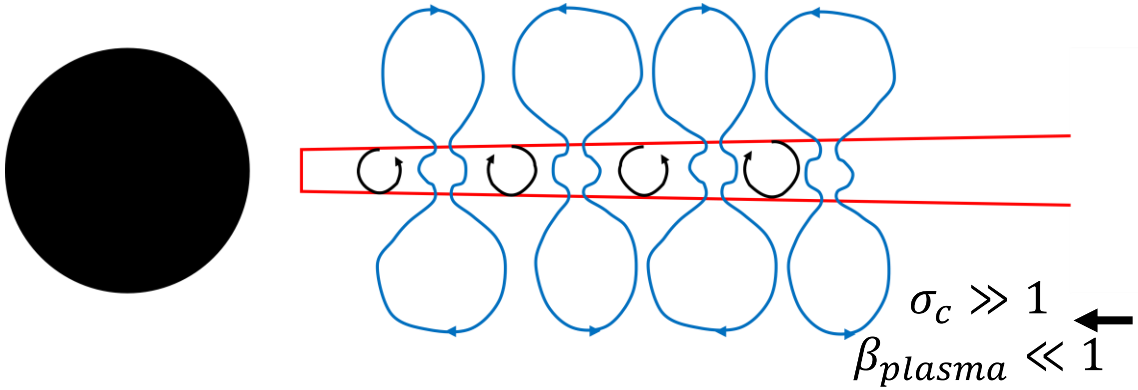

Solar Dynamics Observatory

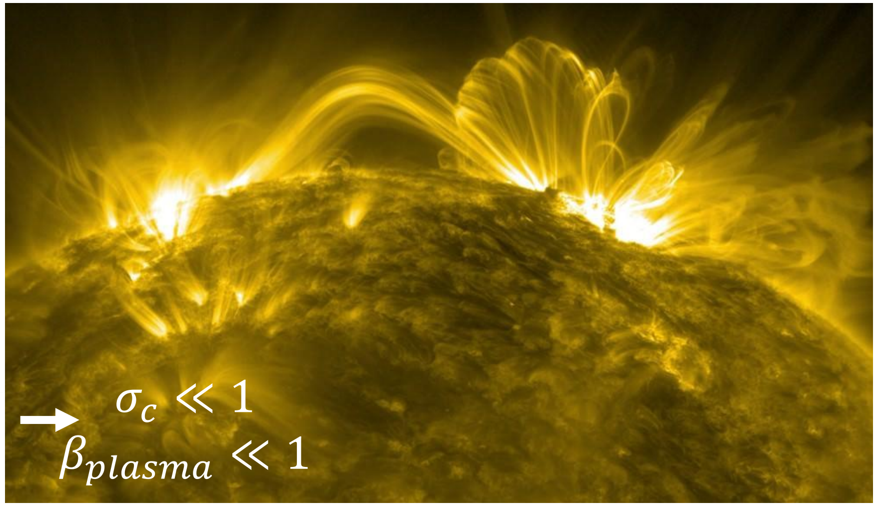
Reconnection as a relativistic particle accelerator

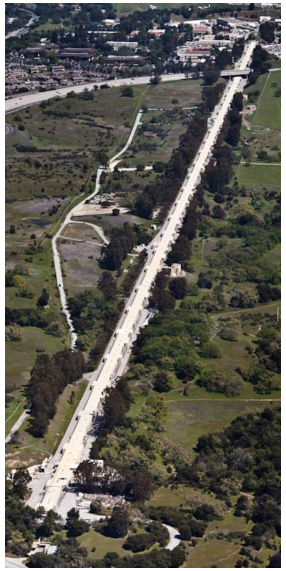




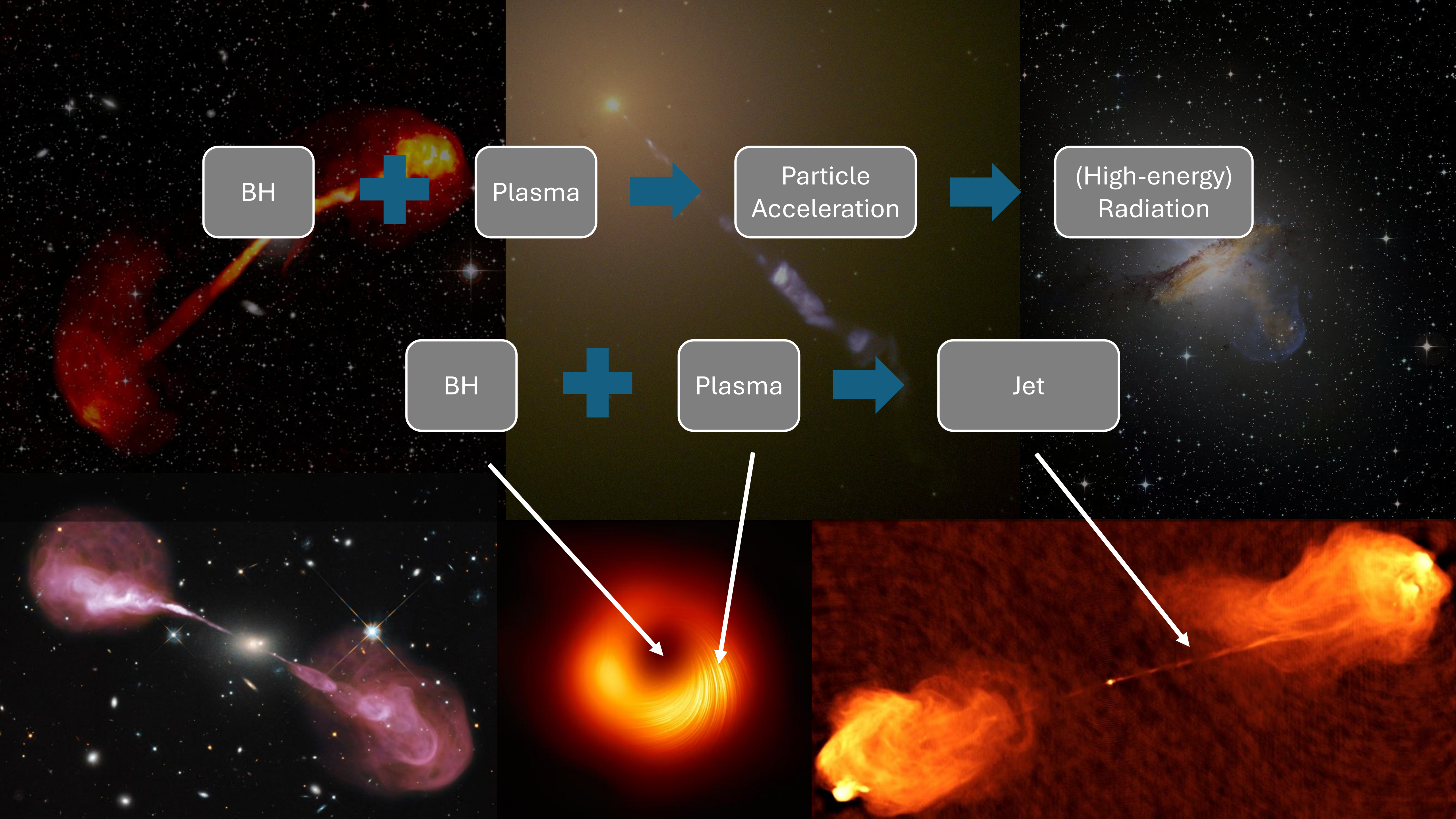
$$\beta_{plasma} = 8\pi n T_0 / B_0^2 \ll 1$$
$$\sigma_c = B_0^2 / 4\pi n_0 m_e c^2 \gg 1$$







SLAC (Wikipedia)


BH
Plasma
Particle Acceleration
(High-energy) Radiation
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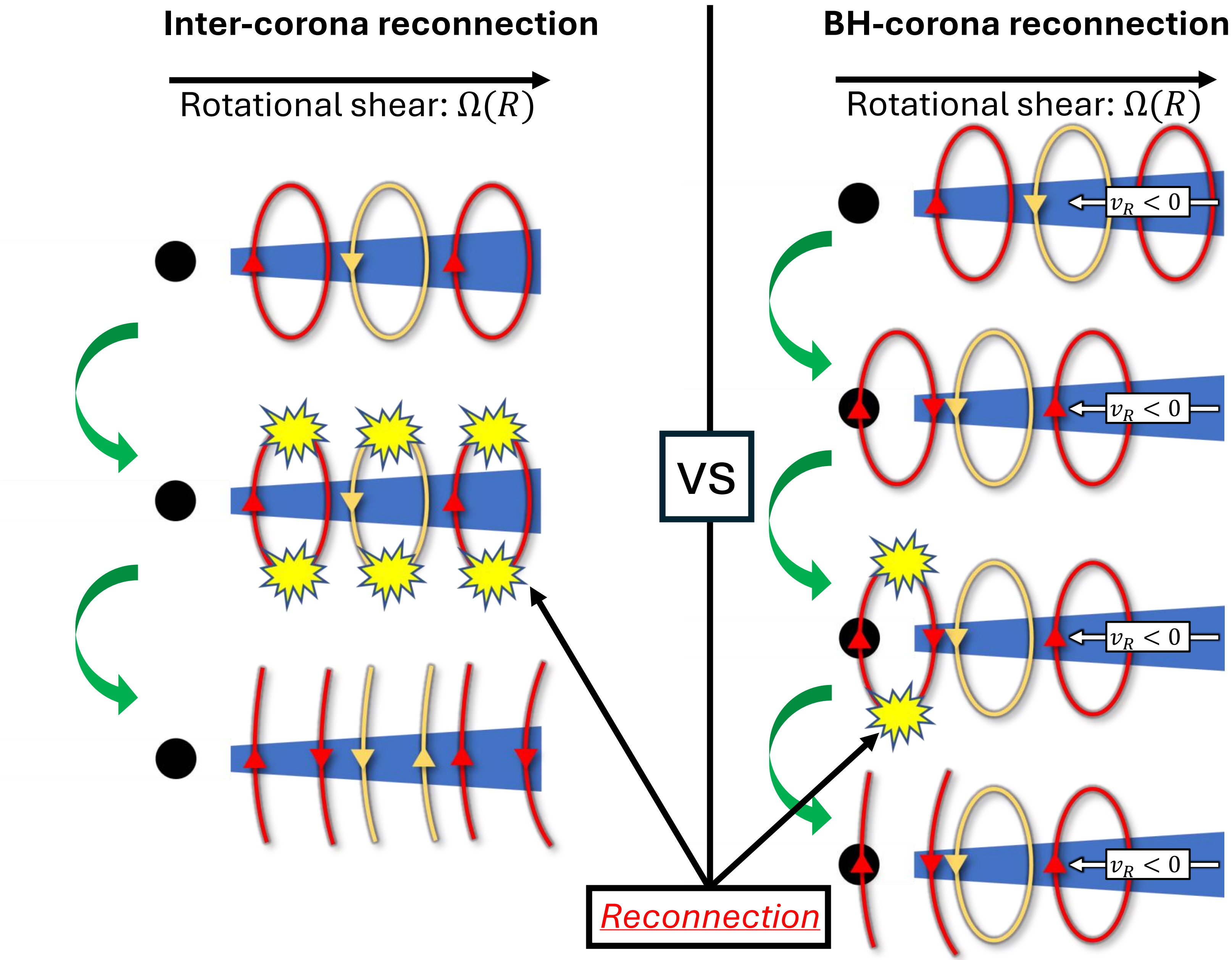
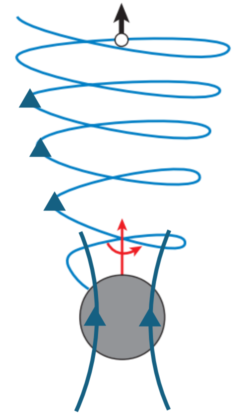
Jet

Coronal reconnection and jet launching



Key idea: horizon-penetrating magnetic field → jet (Blandford & Znajek 1977)



Adapted from Davis+ 2020

Driving questions:

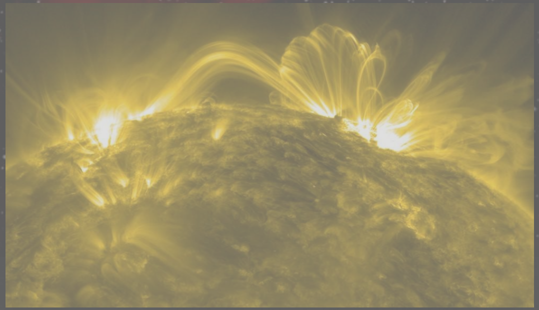
How much energy does magnetic reconnection dissipate? What region dominates?

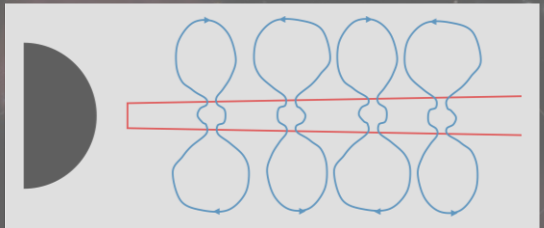
Can a strong jet be launched?

What are the observable signatures?

Outline

Black hole accretion disk coronae primer





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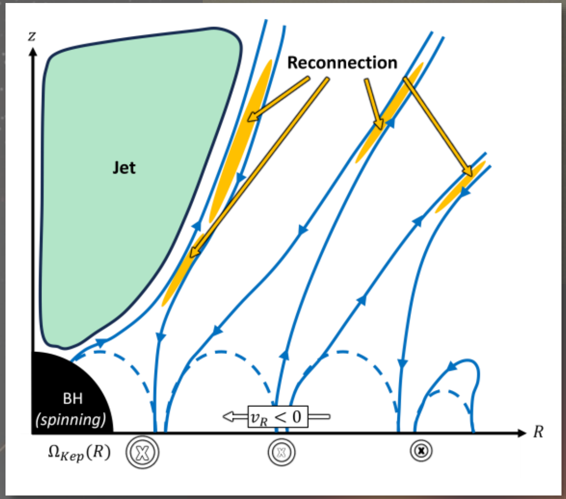

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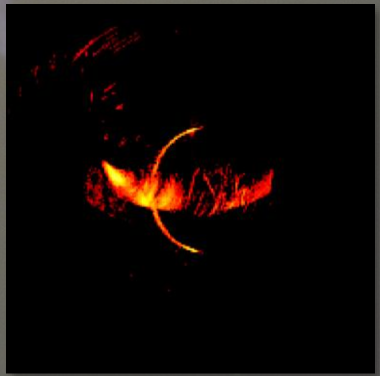

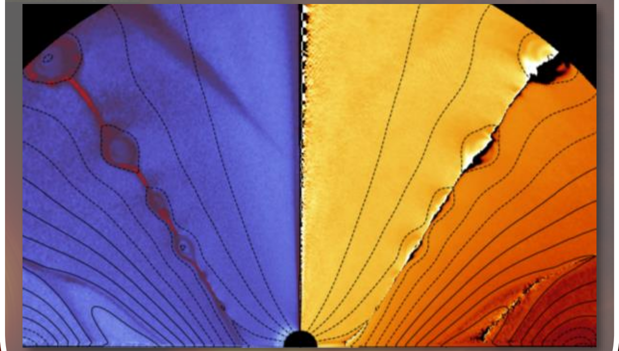

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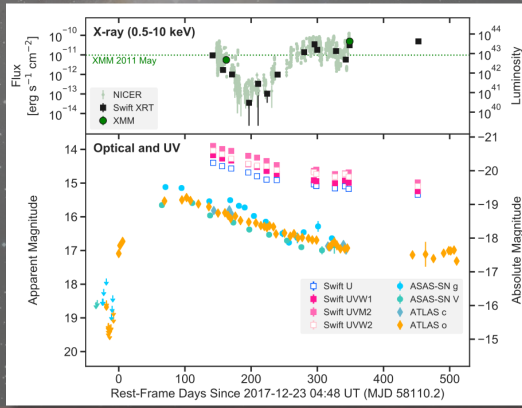
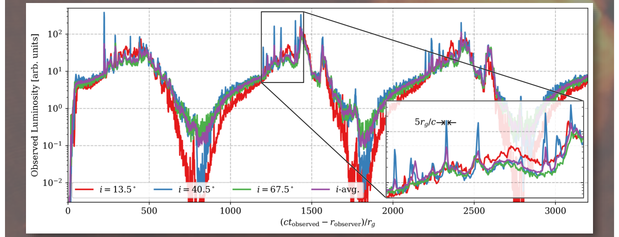
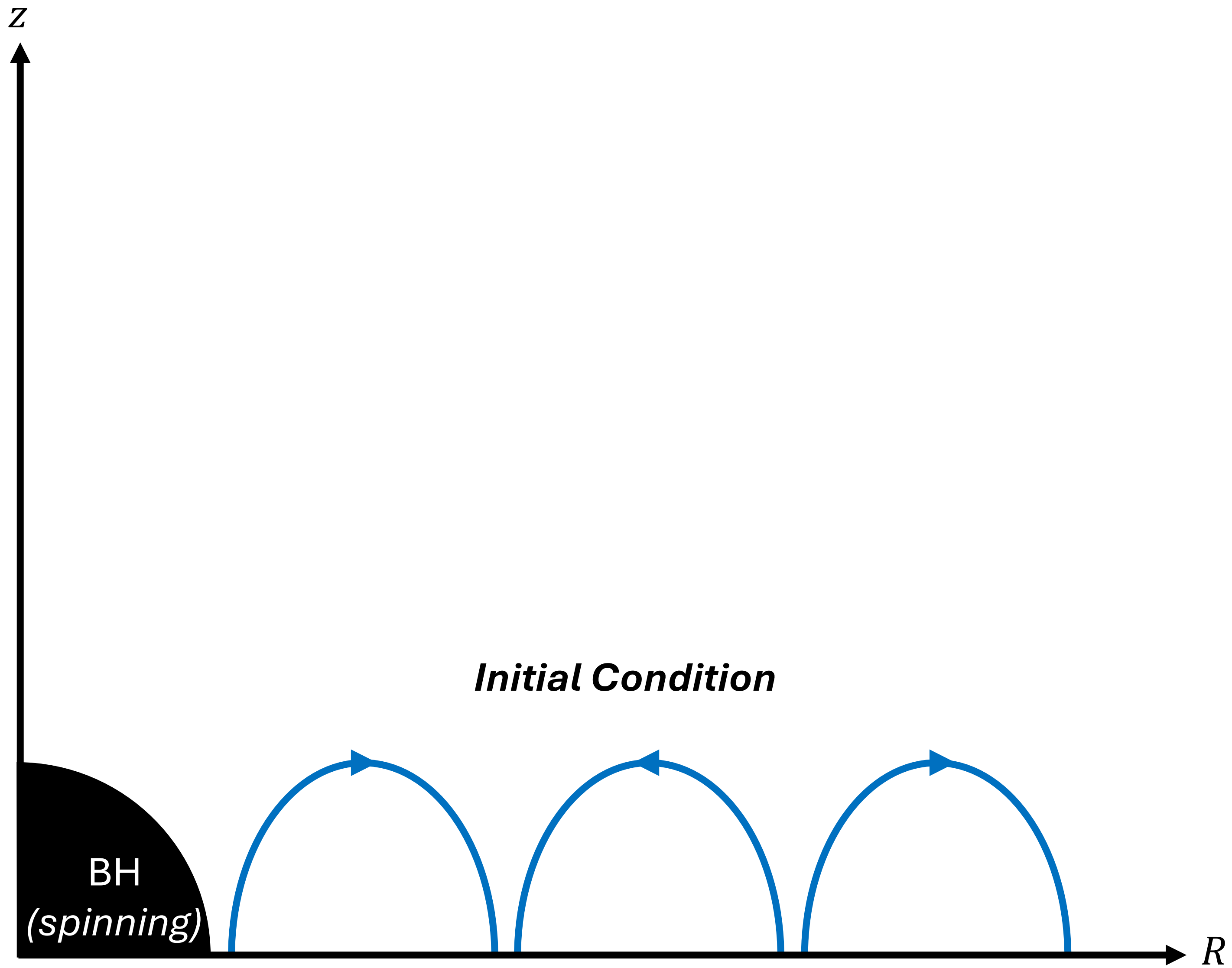




Constructing a minimal numerical model



Model needs:

- Rotational shear
- Accretion
- Magnetic coupling (disk-disk + disk-BH)
  - Potential jet formation
- Plasma description must capture:
  - General relativity
  - Particle acceleration
  - Radiation
  - Reconnection

Driving questions:

How much energy does magnetic reconnection dissipate? What region dominates?

Can a strong jet be launched?

What are the observable signatures?

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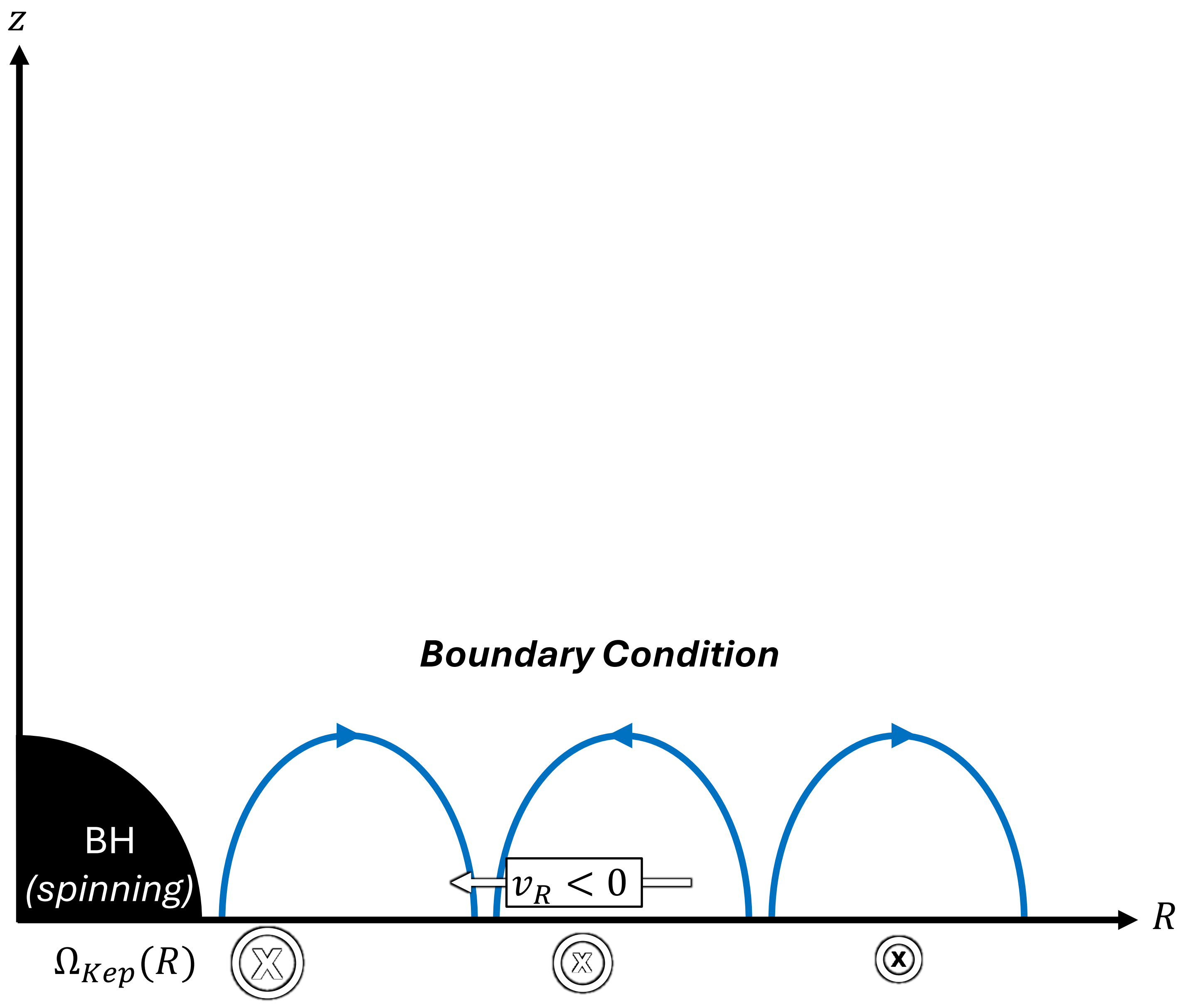

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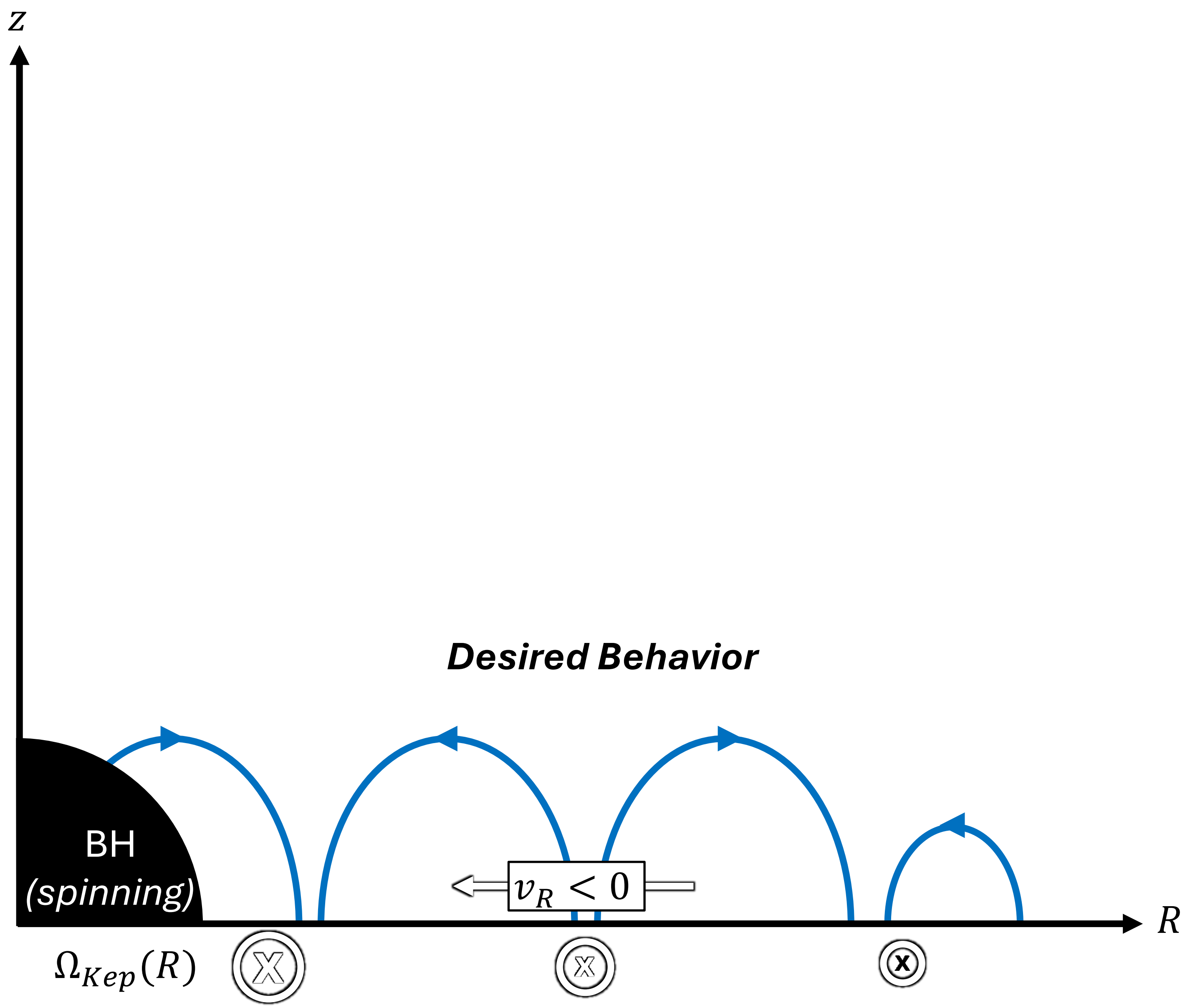

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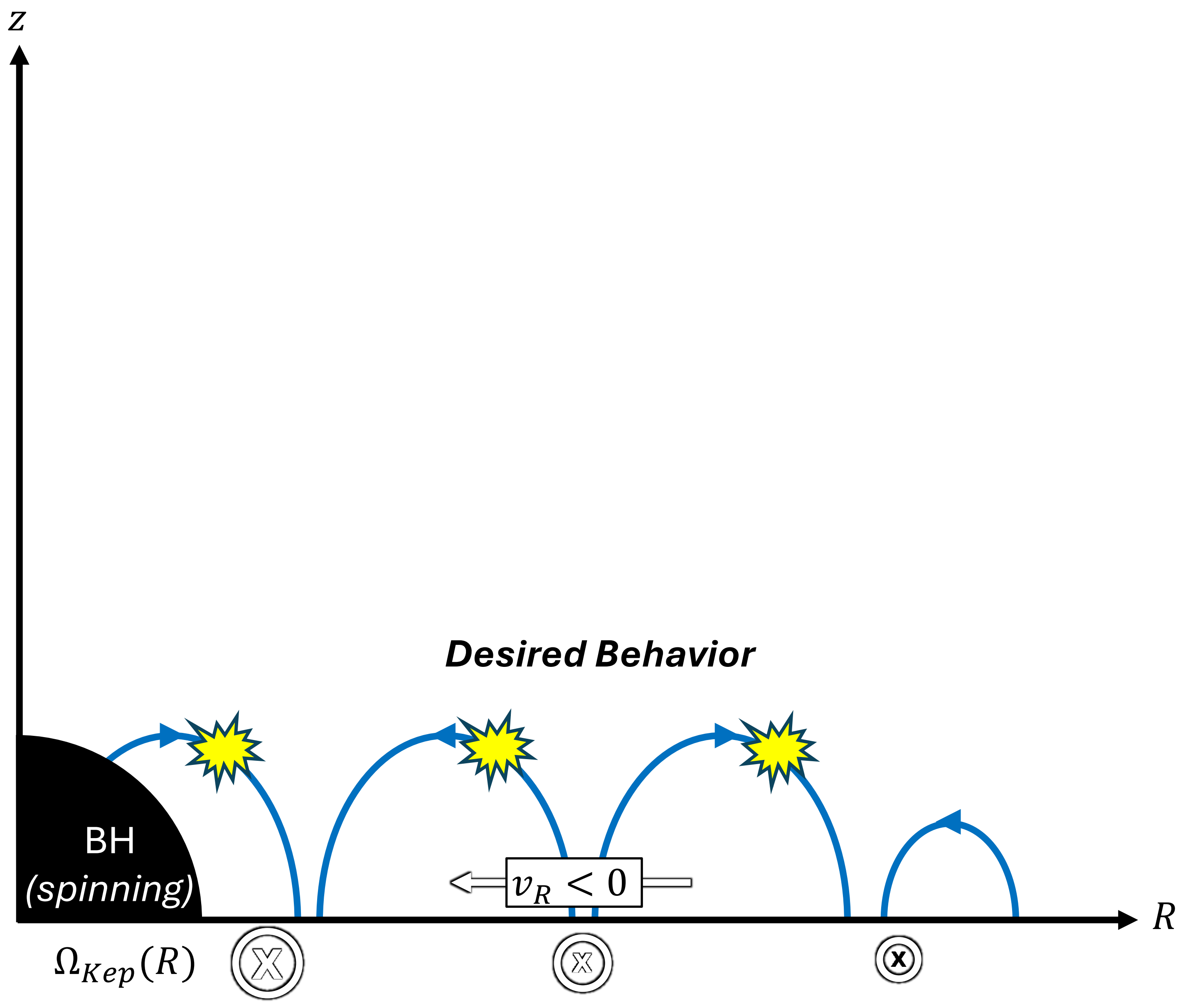

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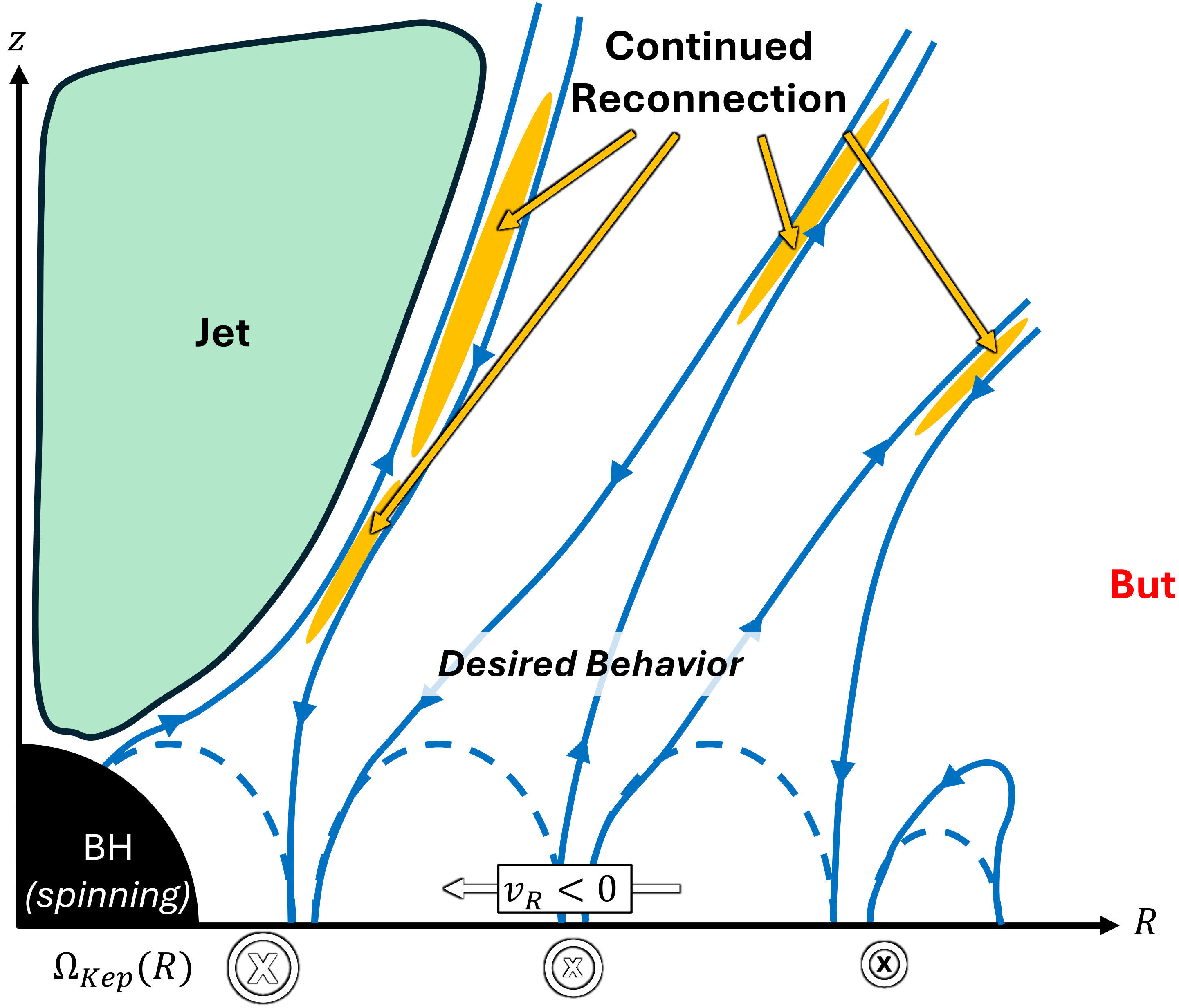

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But how??

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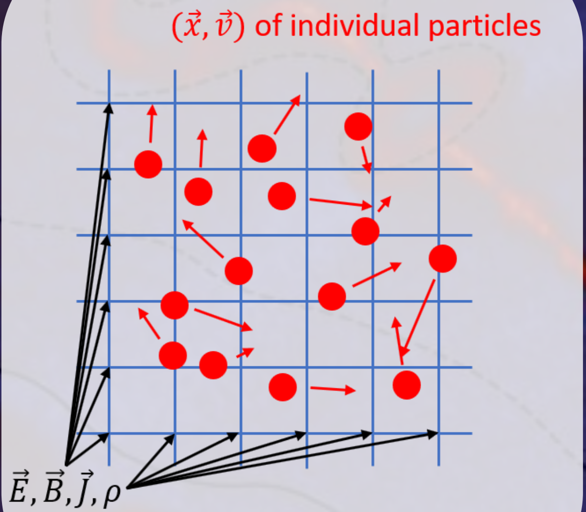
Zeltron: a general relativistic particle-in-cell code*



$$\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) + \text{gravity}$$

Update $(\vec{x}, \vec{p})$ of all particles from $\vec{E}, \vec{B}$

Δt

Compute ρ and $\vec{J}$ on grid from $(\vec{x}, \vec{v})$ of particles

$(\rho, \vec{J}) \rightarrow$ Maxwell's equations $\rightarrow (\vec{E}, \vec{B})$

$$\vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho$$
$$c\vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0$$
$$c\vec{\nabla} \times \vec{B} - \partial_t \vec{E} = 4\pi\vec{J}$$

- Plasma description must capture:
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✓

*Cerutti et al. 2013, Parfrey et al. 2019

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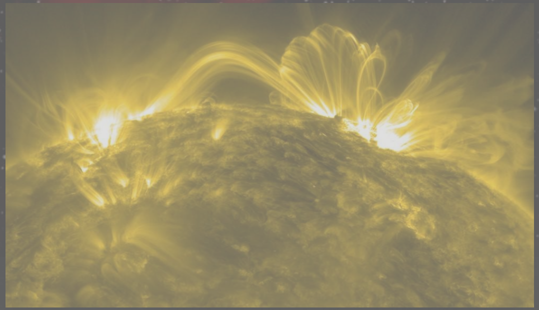

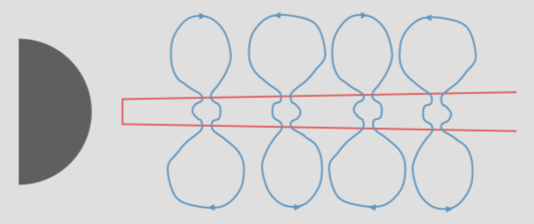

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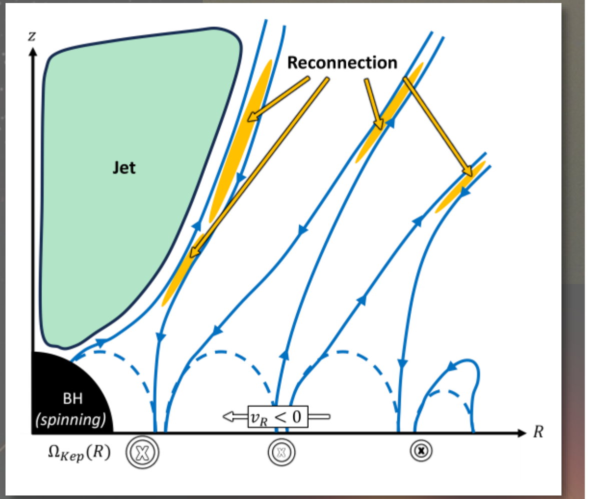

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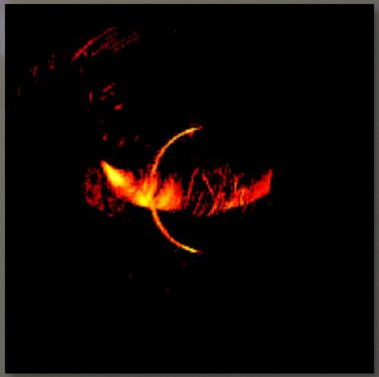

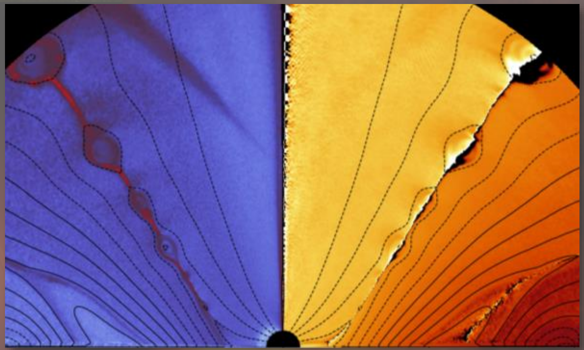

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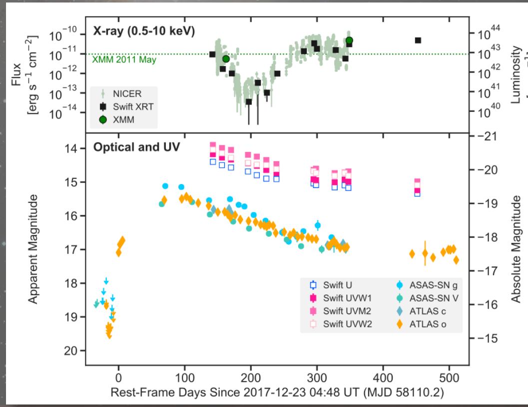
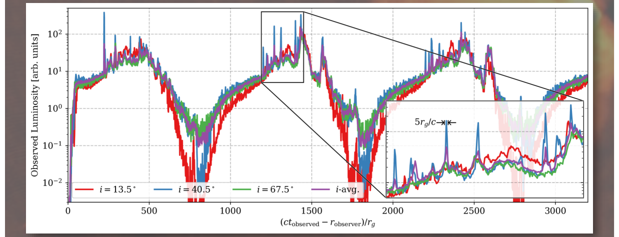
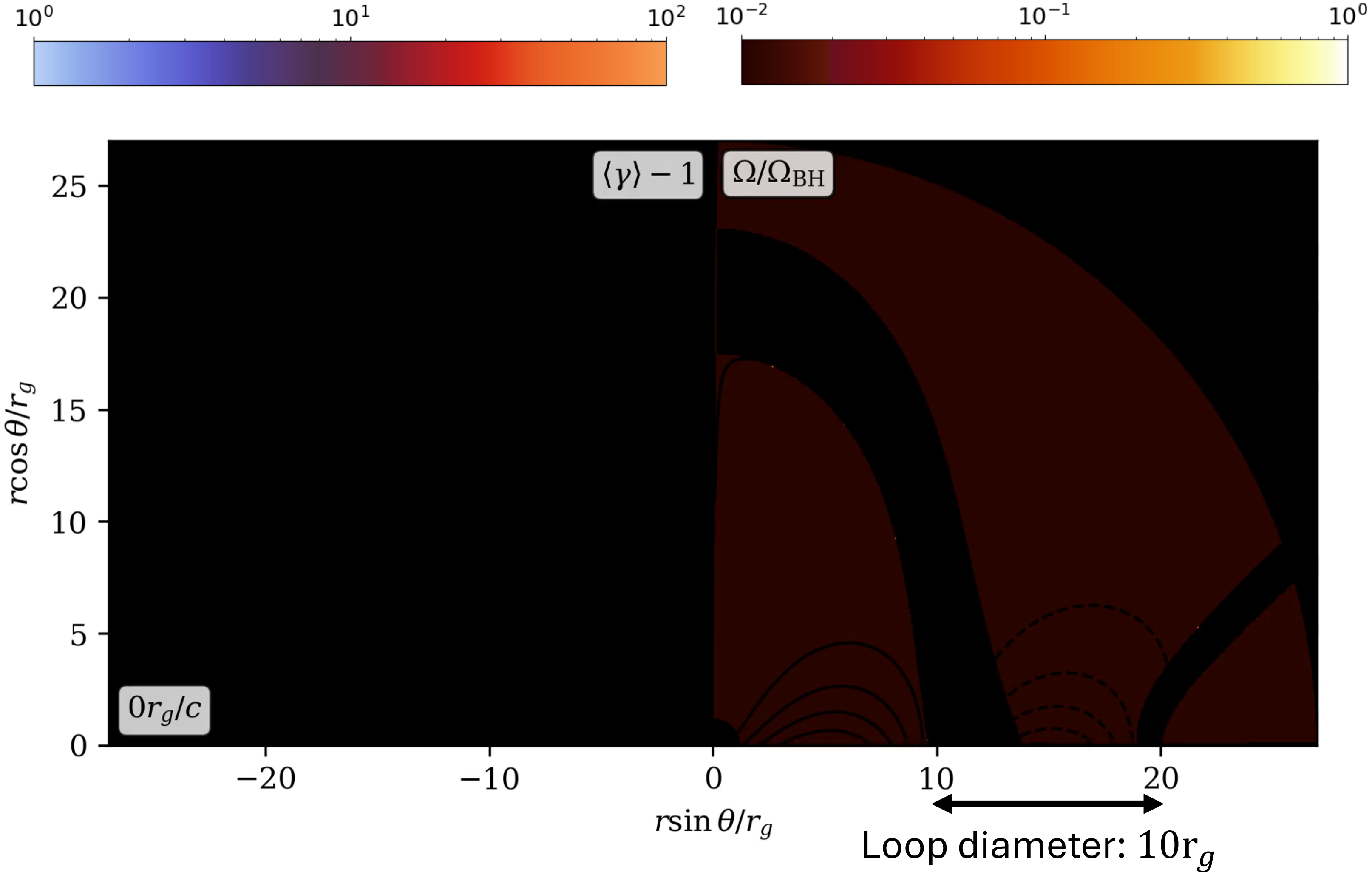




Simulating a minimal numerical model

GRPIC simulations:

- Pair plasma
- Loop size: $10 r_g$
- Ad-hoc injection enforces $n > n_0 (r_H/r)^2$
- 2D axisymmetry



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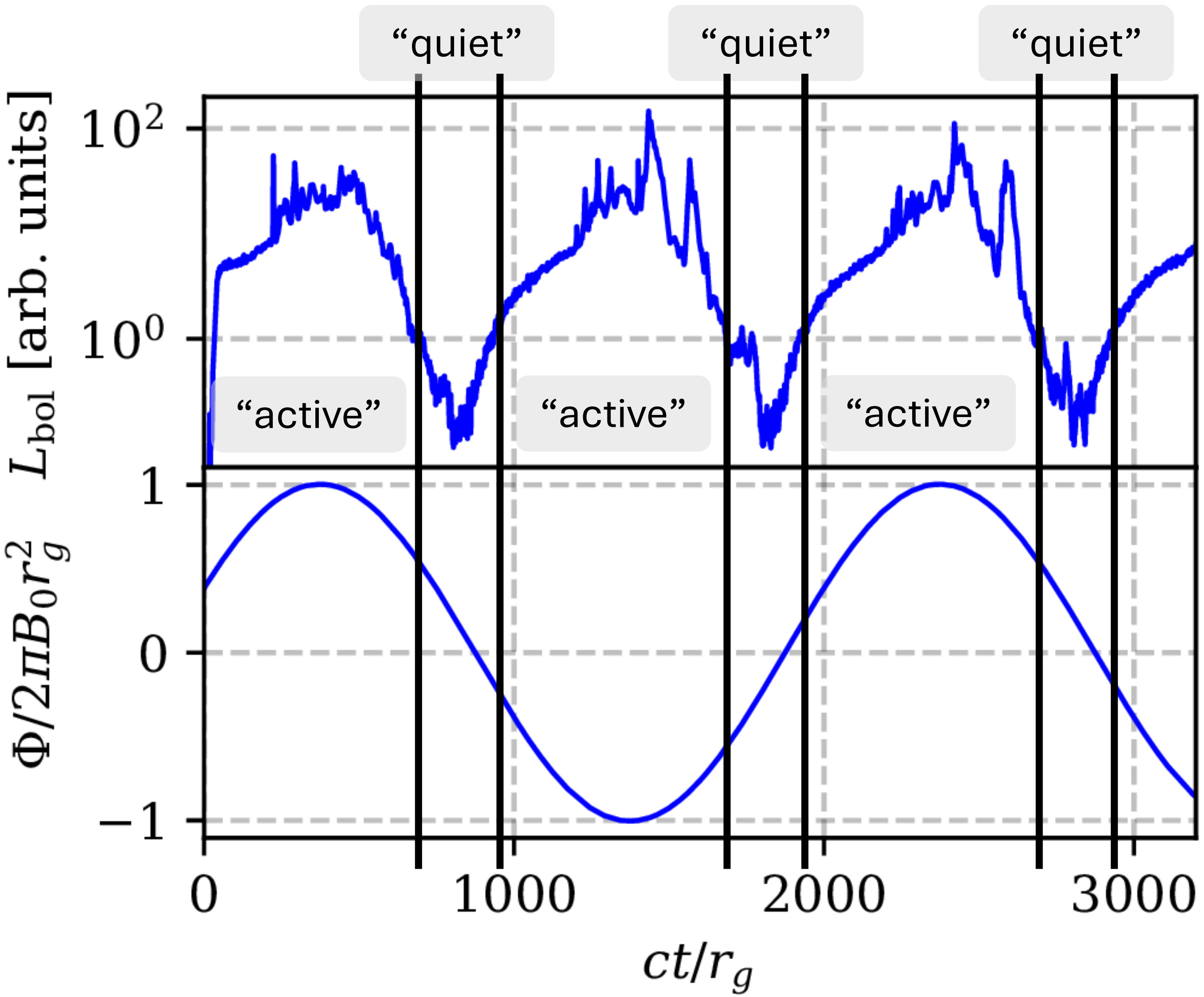
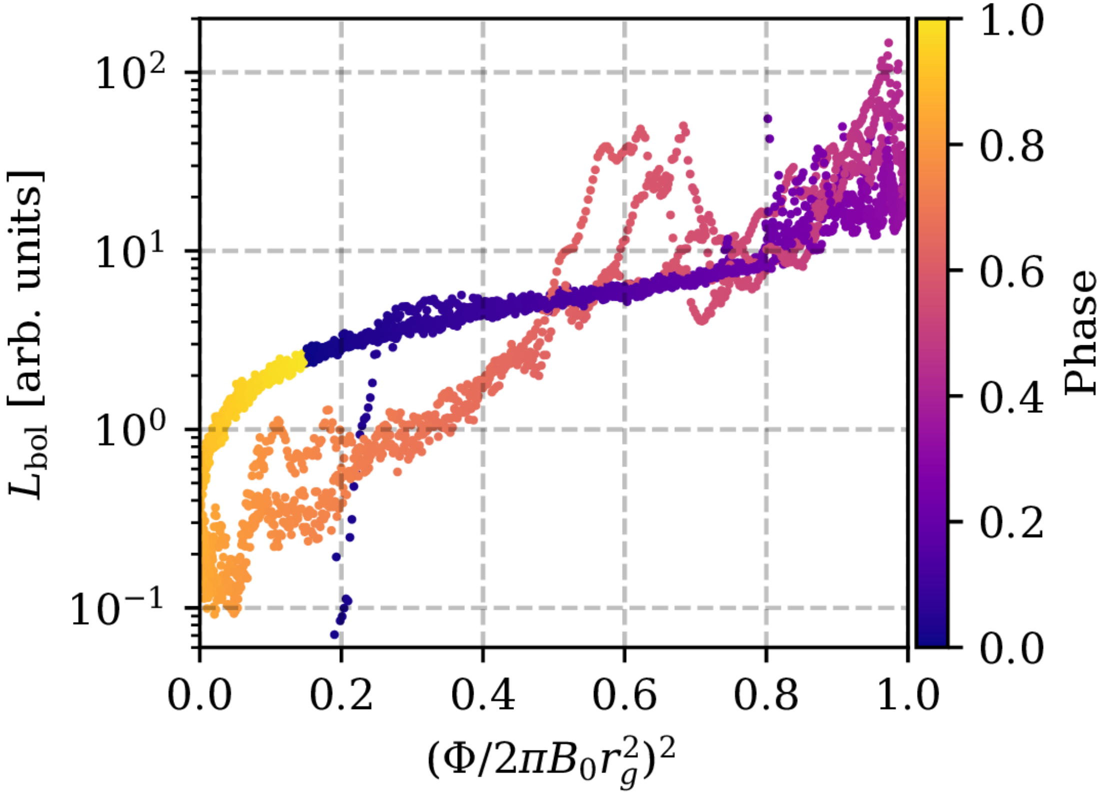
Bolometric luminosity is correlated with flux on BH

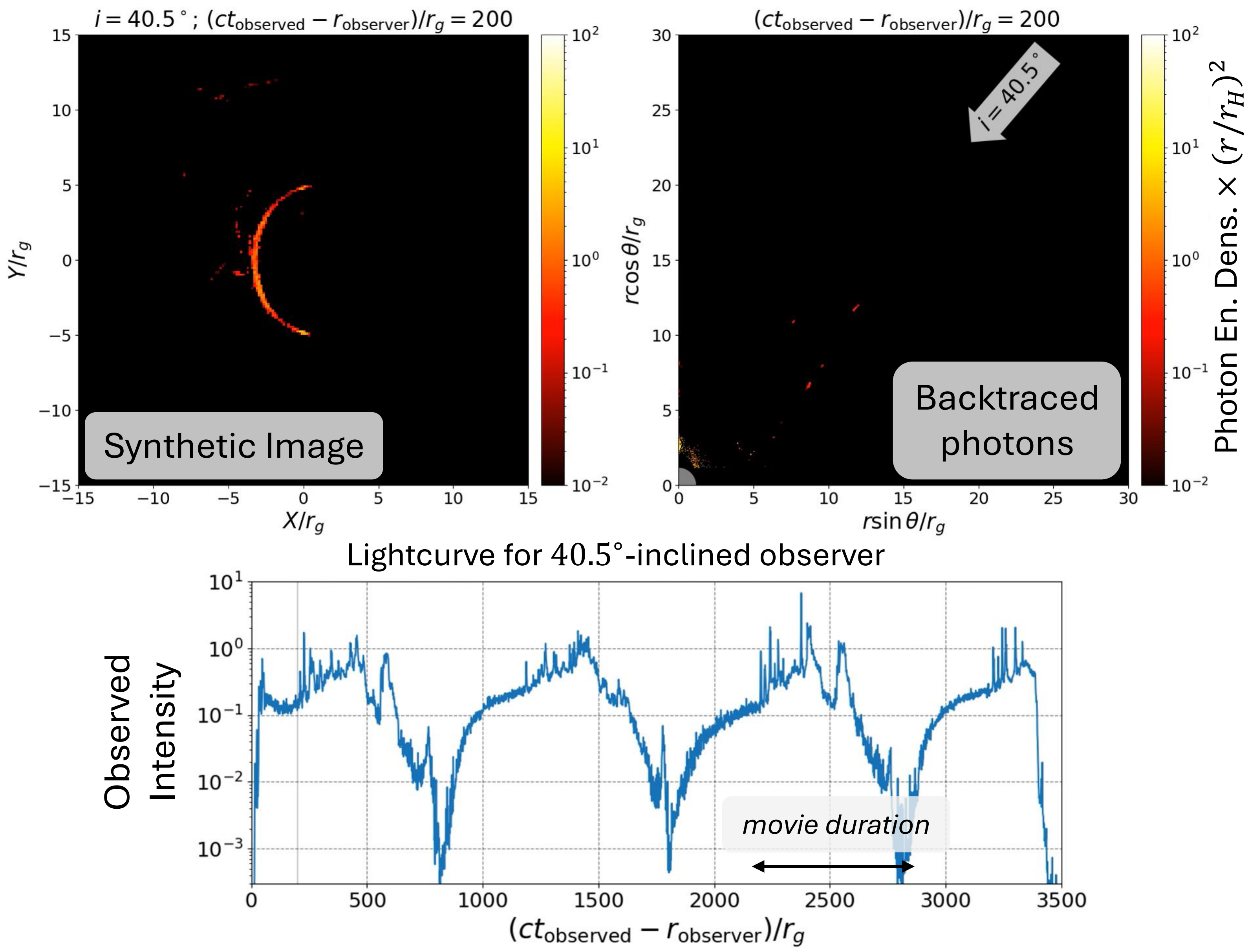
- Alternating loud/variable **active** and stable **quiet** periods
- Rapid variability during loud periods due to magnetic reconnection





Raytracing links observed variability in active periods to reconnection

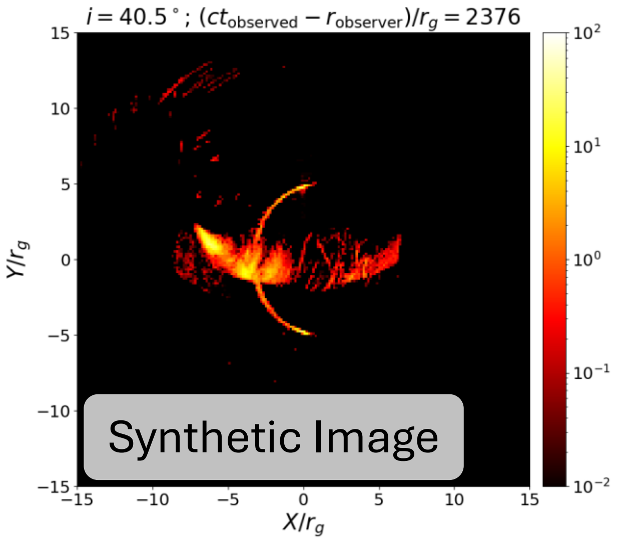
- High contrast (~10^3) in observed intensity between active and quiet periods
- Relativistic compression and amplification of variability

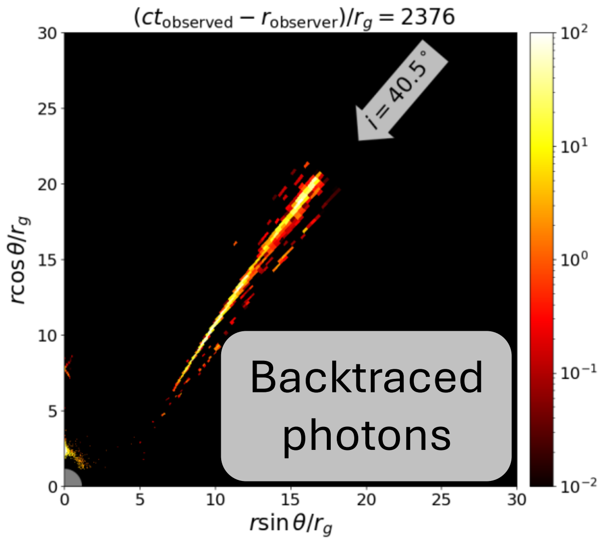


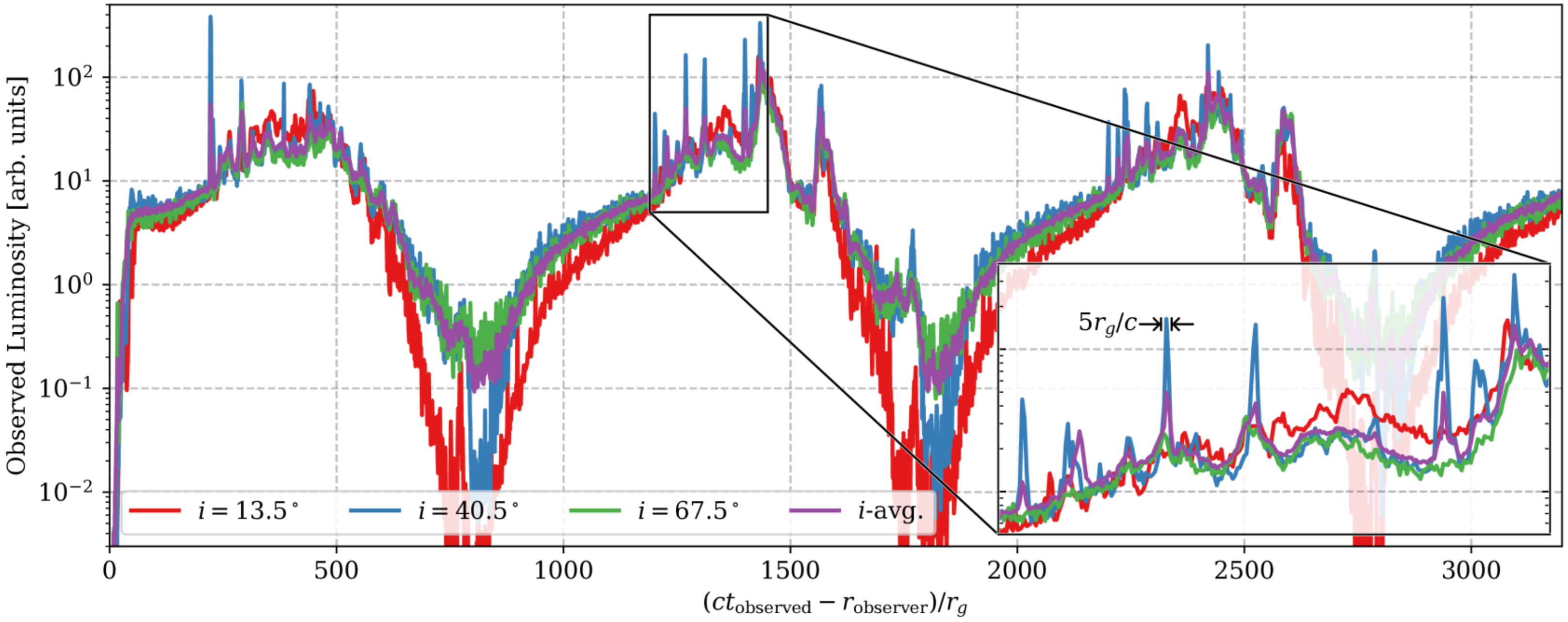
Observers looking along BH-disk current sheet witness most extreme variability

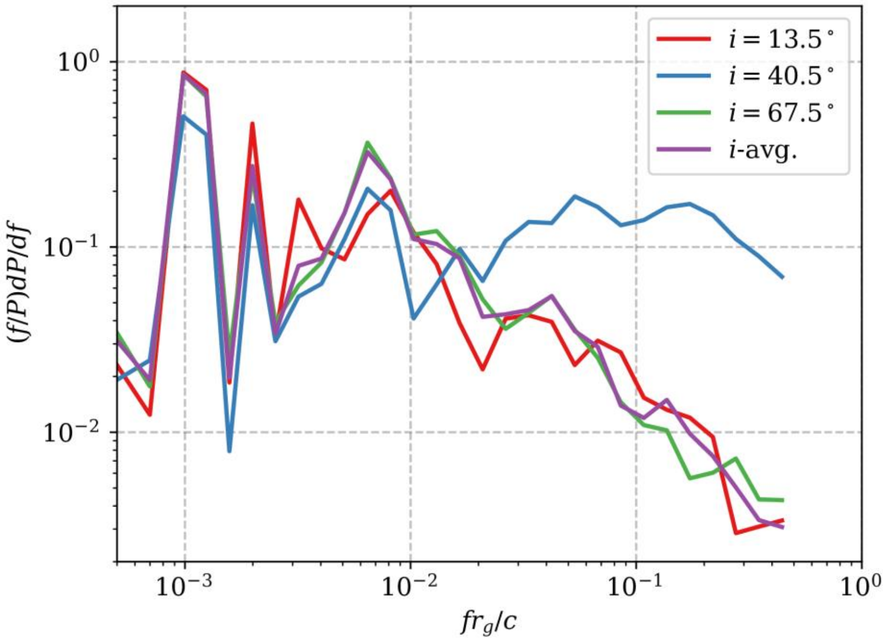
- A "blazar effect" – photons are beamed toward this observer

- Brightening by up to an order of magnitude
- Rise times as short as r_g/c







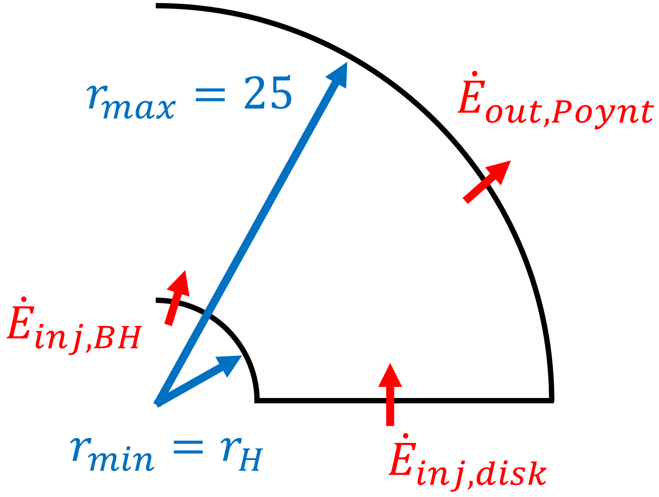


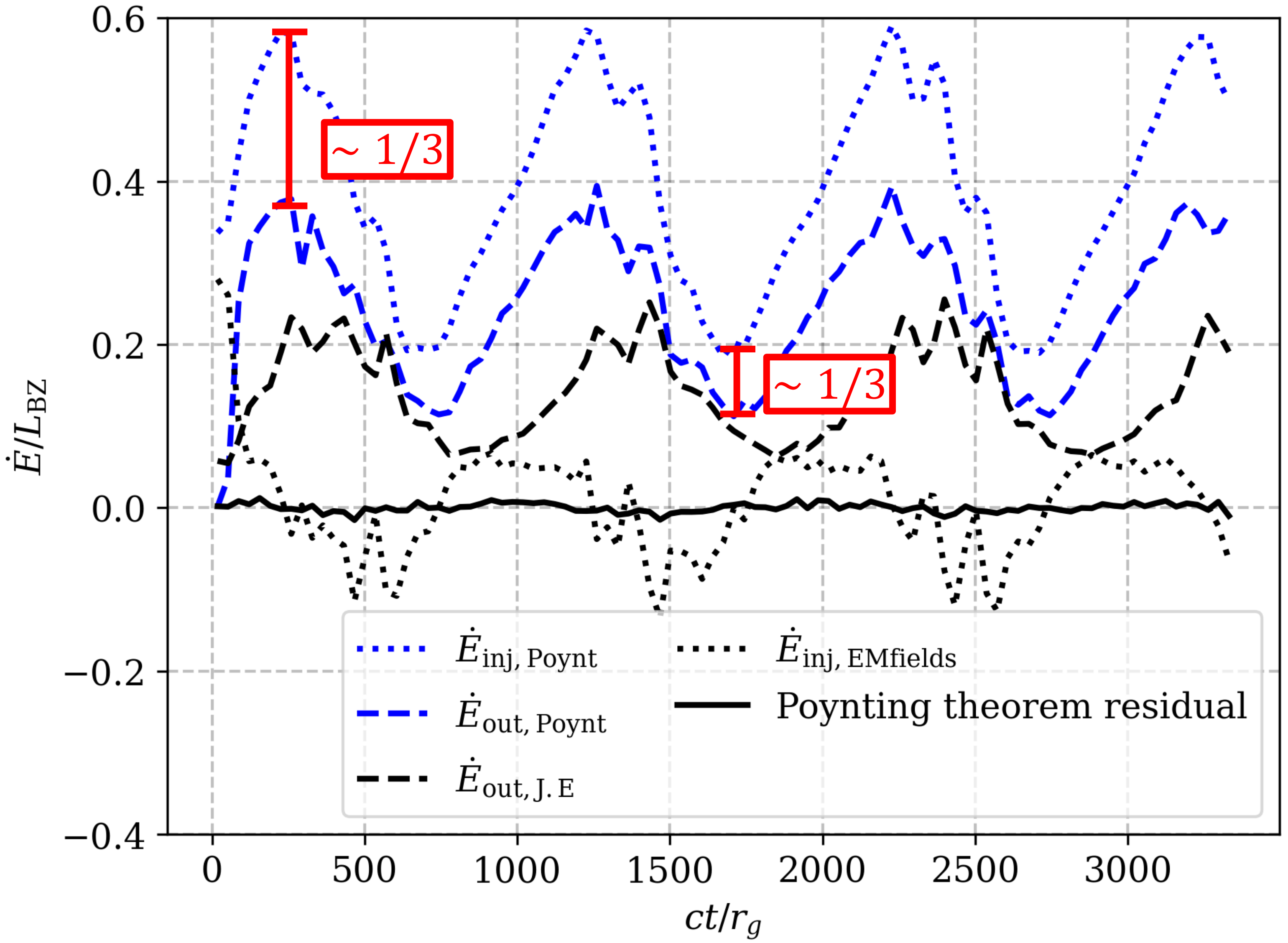
The magnetosphere dissipates ~1/3 of the injected Poynting flux

We evaluate the contributions to Poynting's Theorem (quoted in flat space),

$$\frac{1}{8\pi}\partial_t(E^2+B^2)+\vec{\nabla}\cdot\vec{S}=-\vec{J}\cdot\vec{E},$$

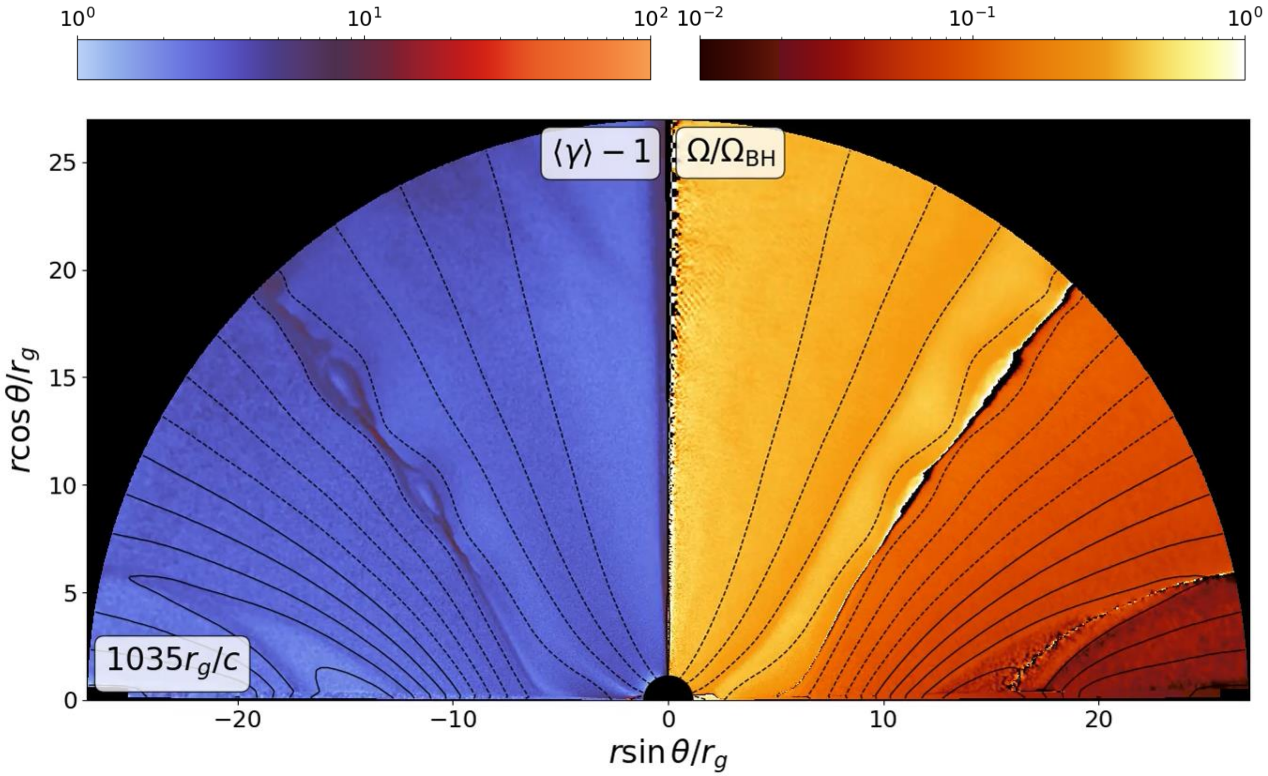
We use the integration surface:





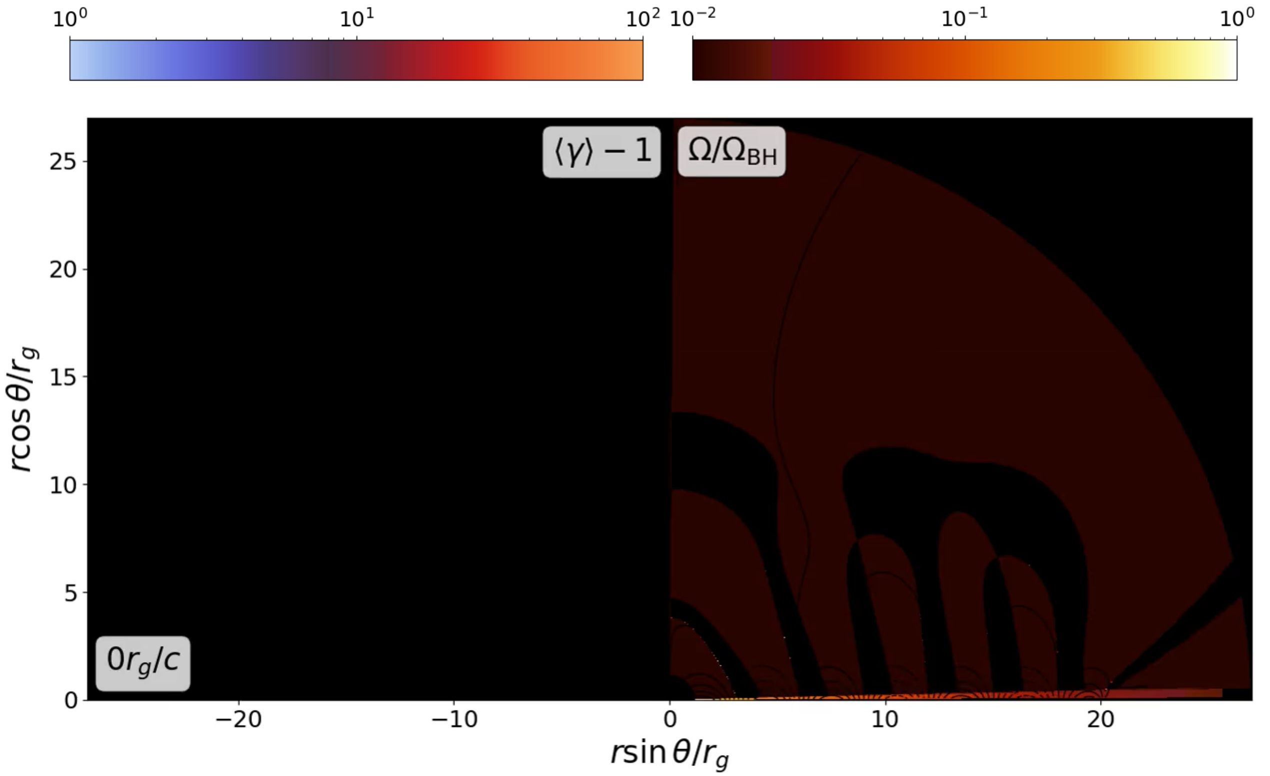
Decreasing loop size enhances coronal activity

Reminder for loop diameter $10r_g$ ($\gg r_H$):



- Strongest dissipation on disk-BH field lines
- Coronal loops open but particle acceleration is weak

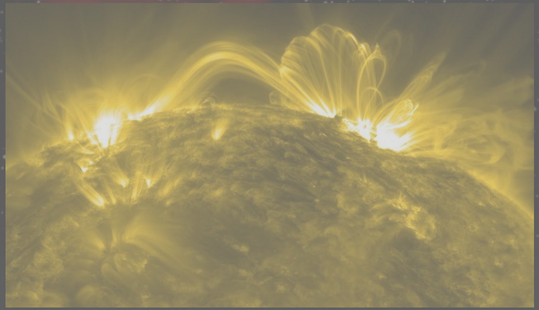
Here's a loop diameter of $3r_g$ (similar to BH size):

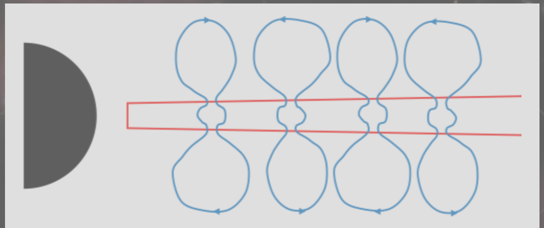


- Disk-BH field lines are active but short-lived
- Intense inter-loop reconnection and particle acceleration

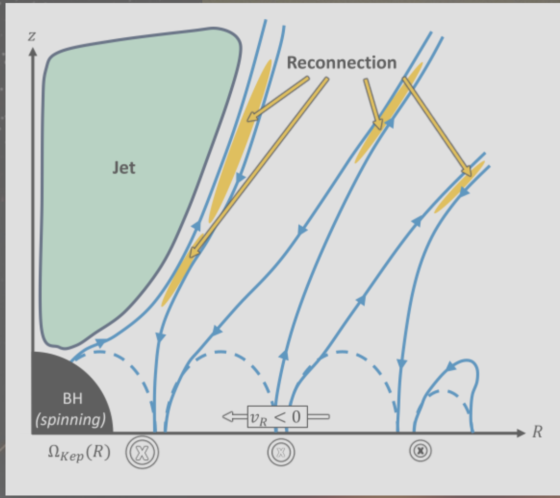
Outline

Black hole accretion disk coronae primer



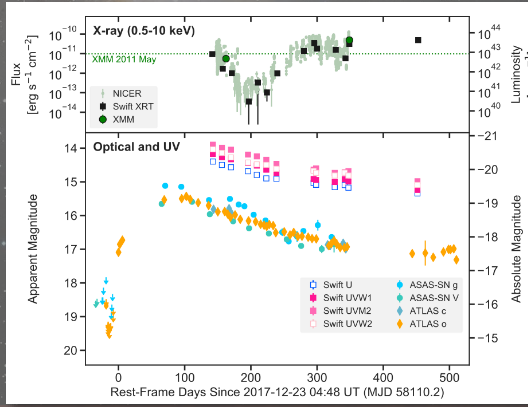


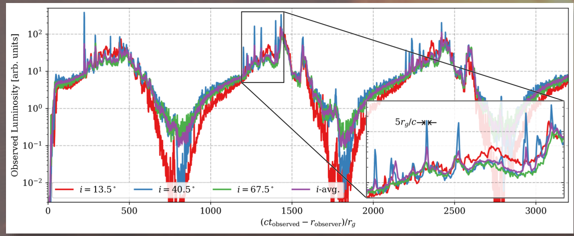
A model for a BH coupled to its corona



Insights from BH-corona simulations

Links to changing-look AGN and X-ray binaries





M87*

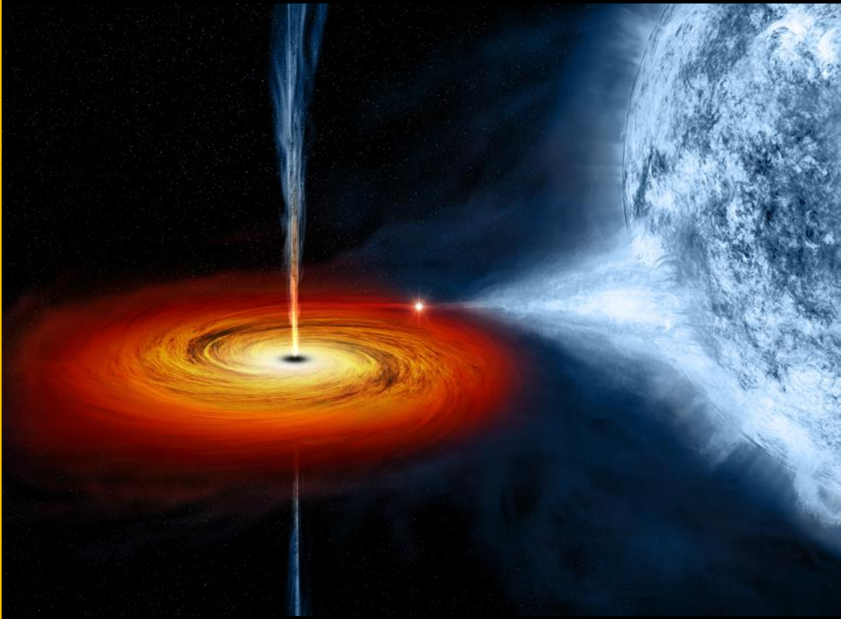
(EHT)

Sgr A*

(EHT)

Cyg X-1

(artist's impression; NASA)



BH + Plasma → Particle Acceleration → (High-energy) Radiation

$M \sim 6 \times 10^9 M_\odot$

$r_g = \frac{GM}{c^2} \sim 59$ AU

$\frac{r_g}{c} \sim 8$ hr

$M \sim 4 \times 10^6 M_\odot$

$r_g = \frac{GM}{c^2} \sim 8 R_\odot$

$\frac{r_g}{c} \sim 20$ s

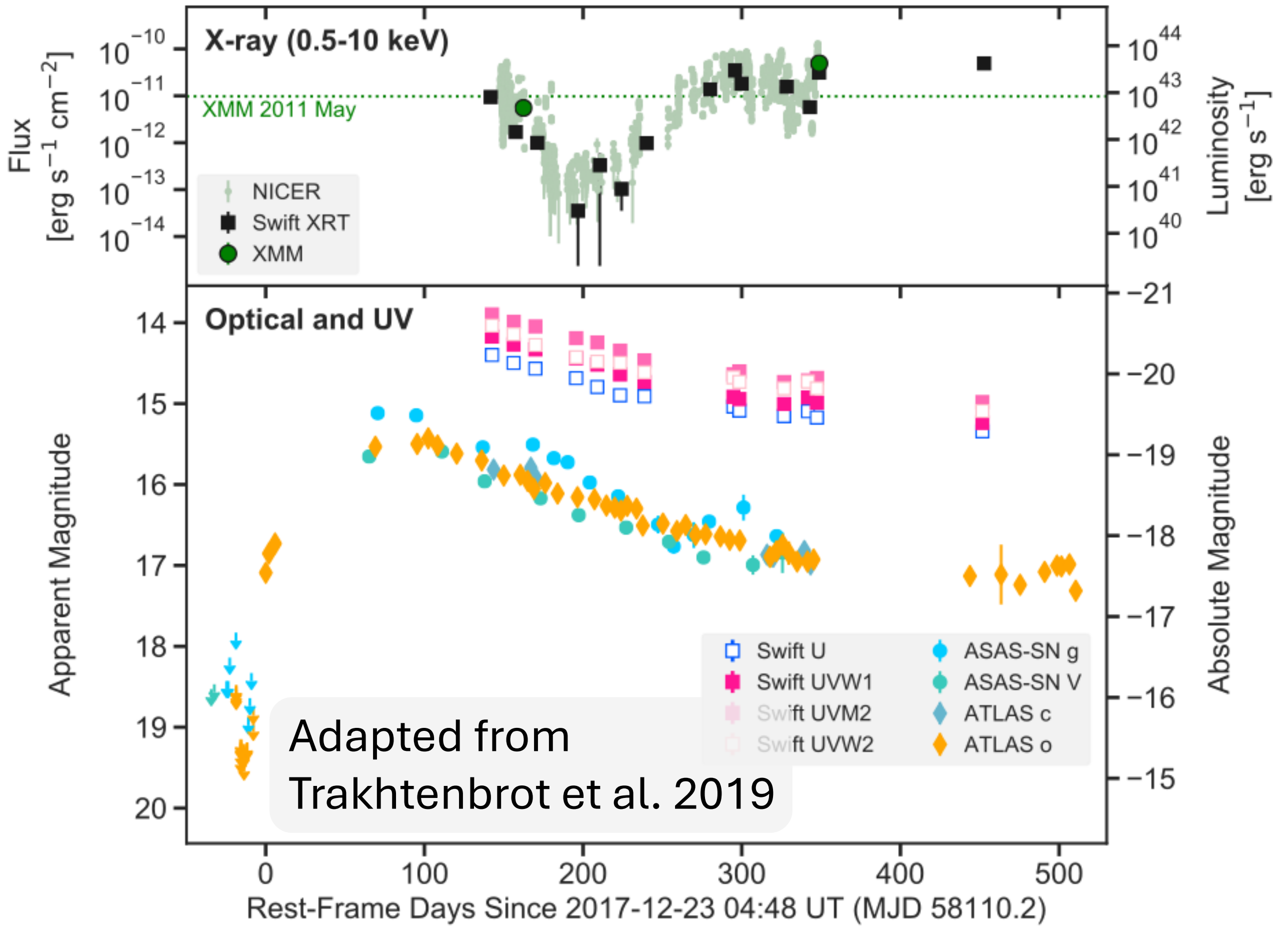
$M \sim 20 M_\odot$

$r_g = \frac{GM}{c^2} \sim 30$ km

$\frac{r_g}{c} \sim 0.1$ ms

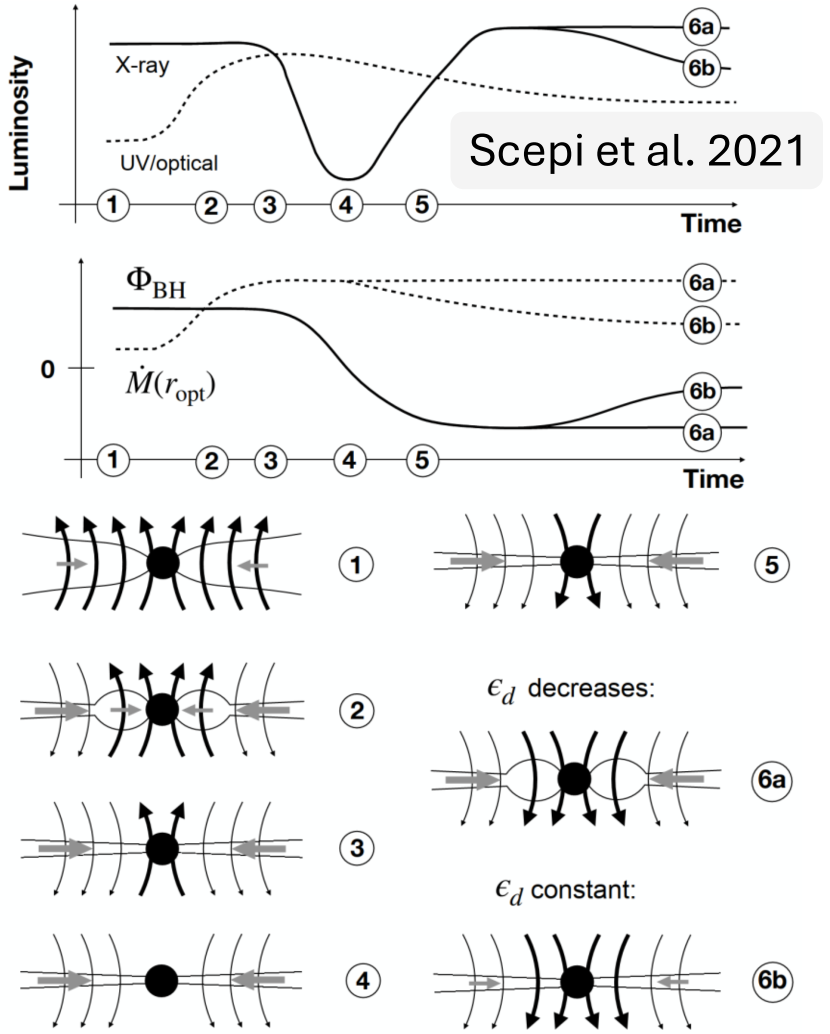
Application to changing-look event in 1ES1927+654

Optical/UV/X-ray observations



Adapted from Trakhtenbrot et al. 2019

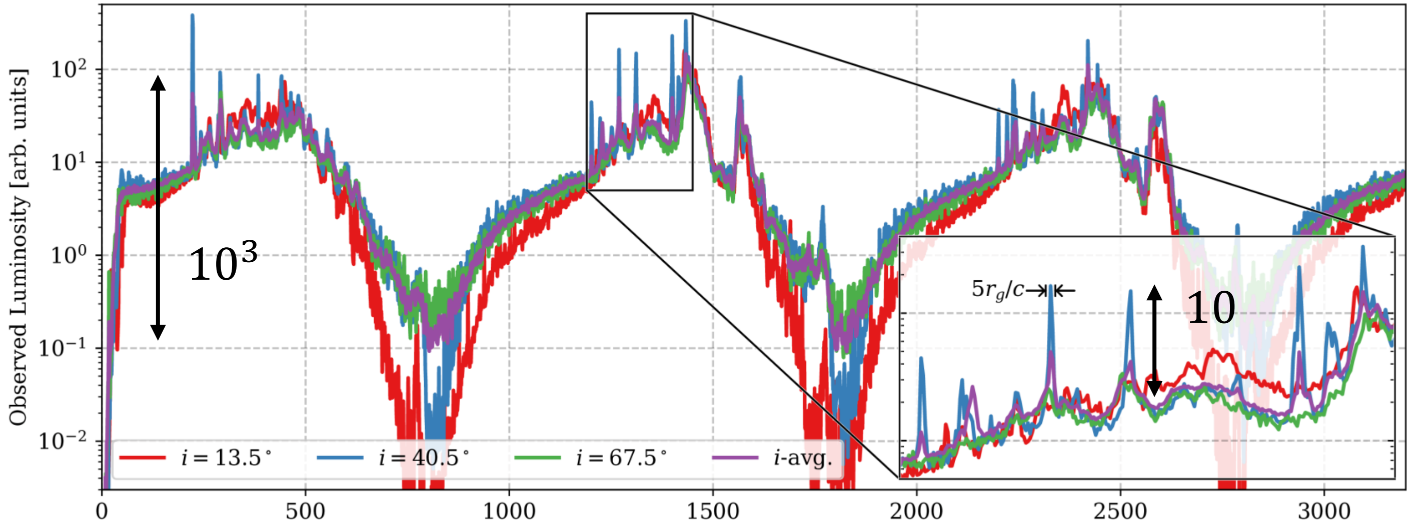
Theoretical scenario: magnetic flux inversion

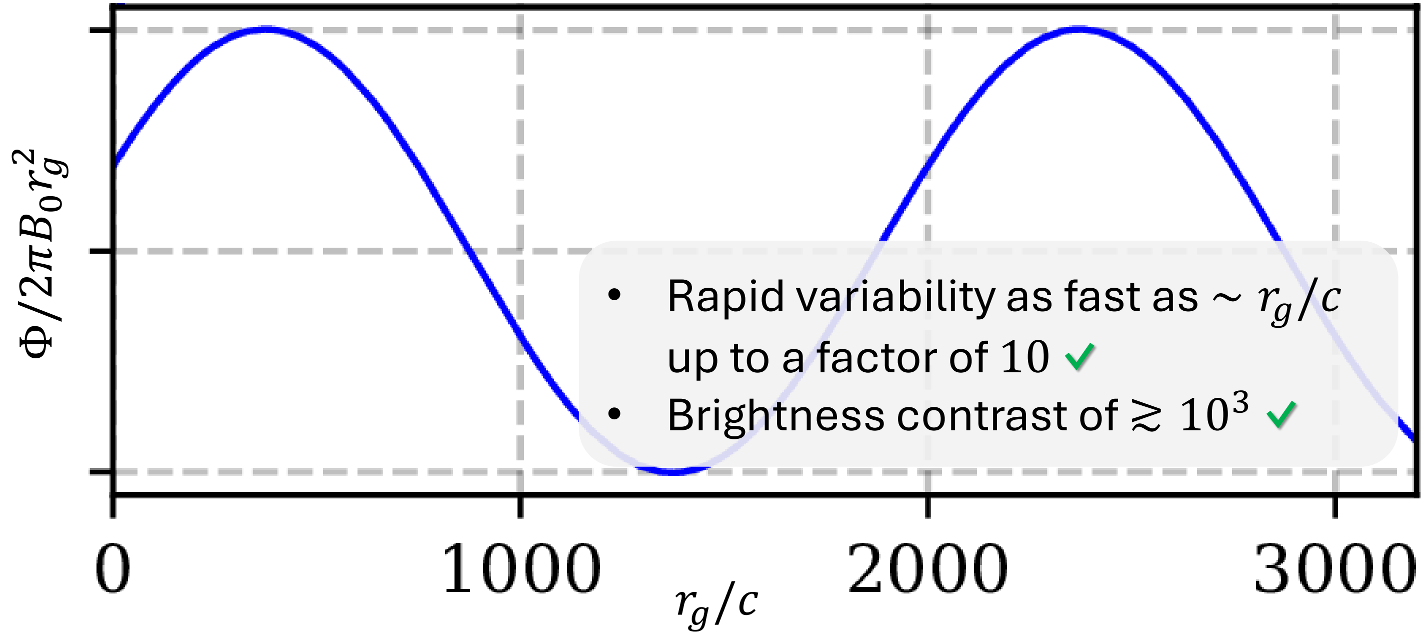


Scepi et al. 2021

Application to changing-look event in 1ES1927+654

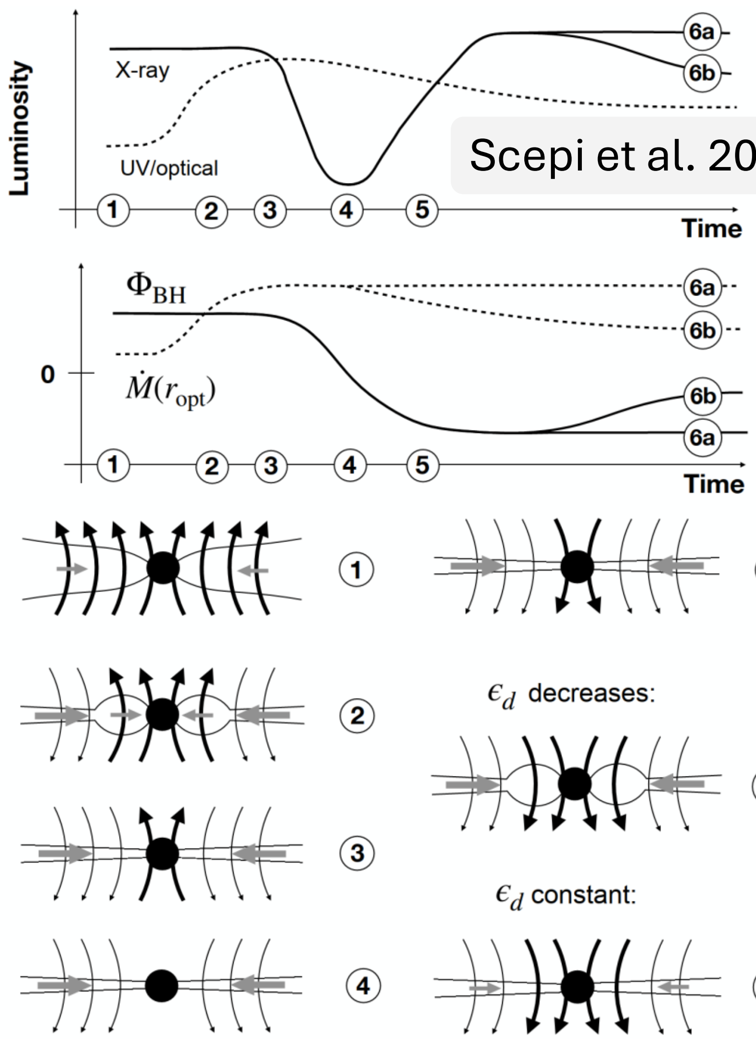
Simulations





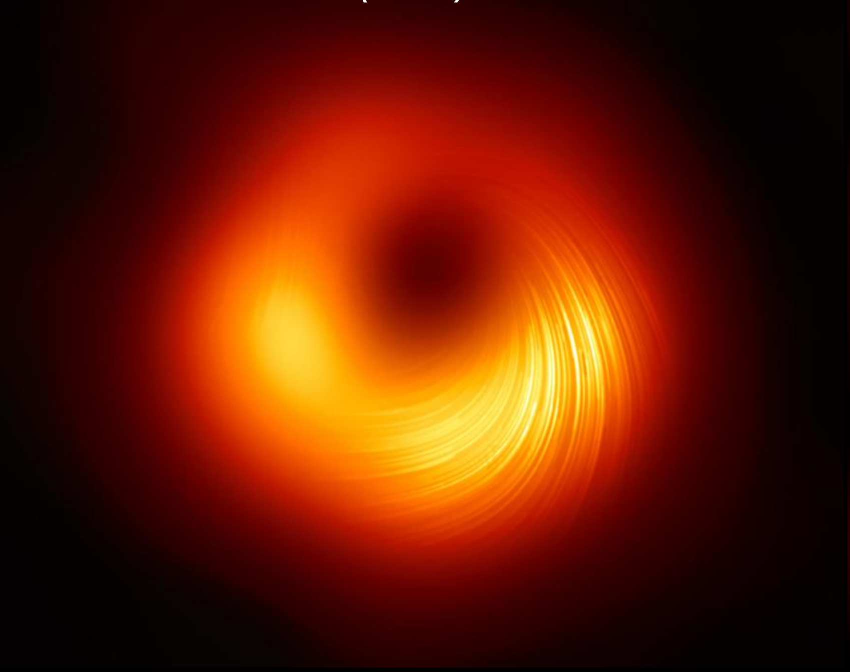
- Rapid variability as fast as $\sim r_g/c$ up to a factor of 10 ✓
- Brightness contrast of $\gtrsim 10^3$ ✓

Theoretical scenario: magnetic flux inversion

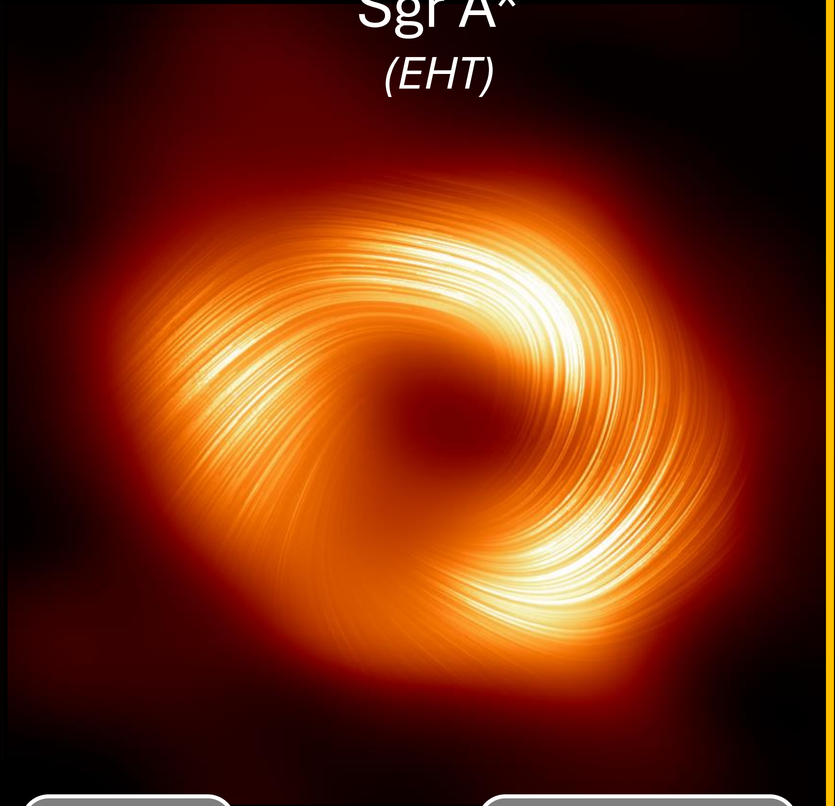


Scepi et al. 2021

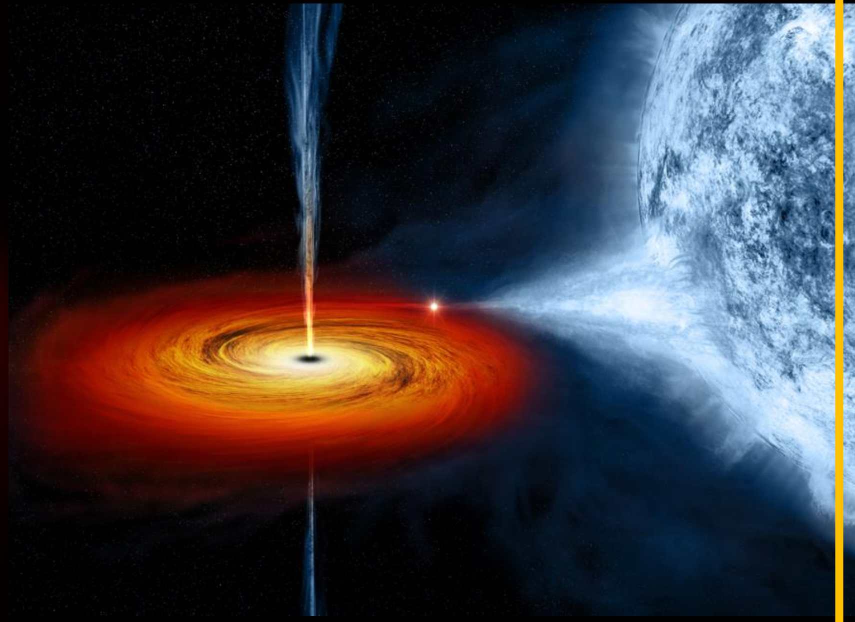
M87*
(EHT)



Sgr A*
(EHT)



Cyg X-1
(artist's impression; NASA)



BH + Plasma → Particle Acceleration → (High-energy) Radiation

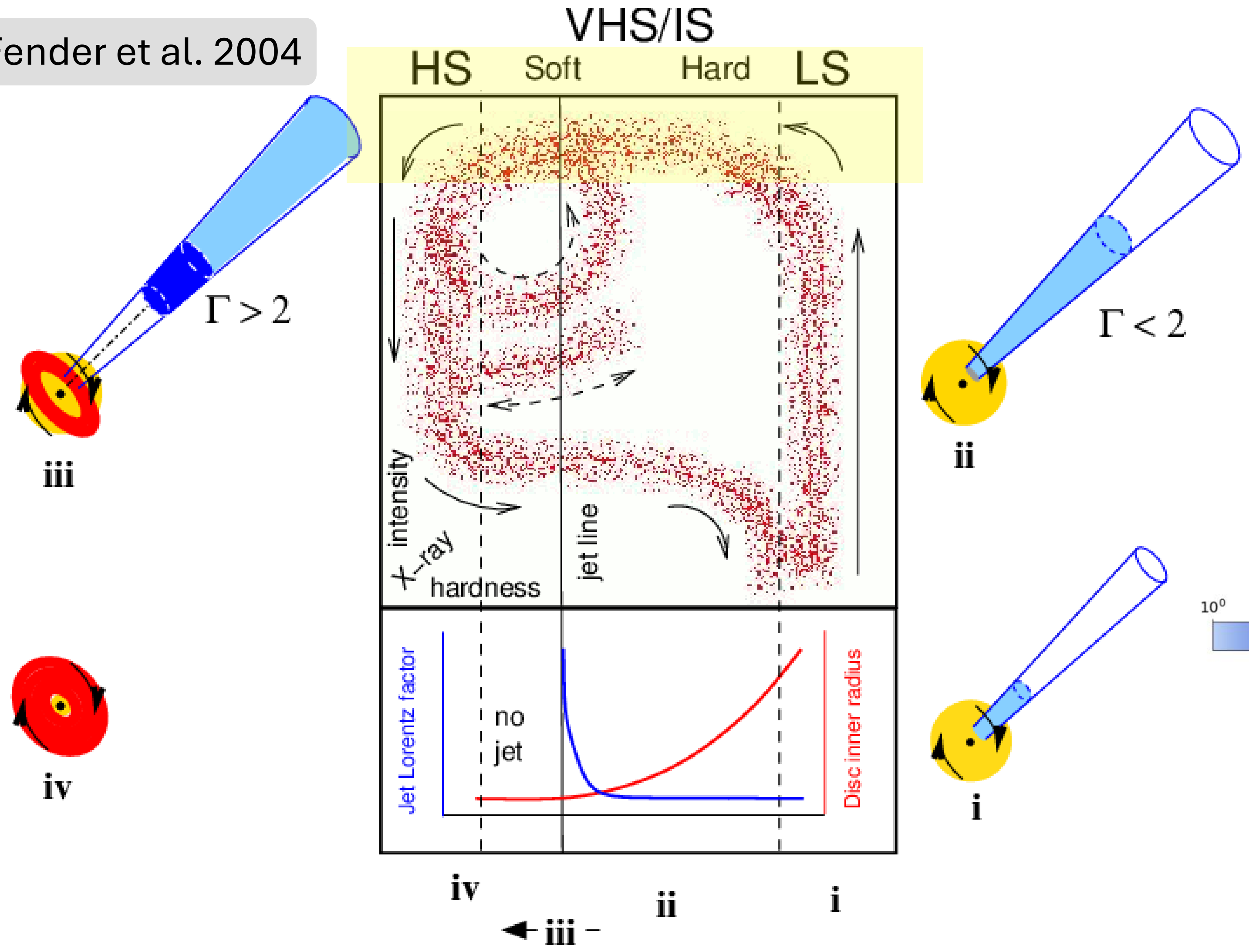
$$M \sim 6 \times 10^9 M_\odot$$
$$r_g = \frac{GM}{c^2} \sim 59\ \text{AU}$$
$$\frac{r_g}{c} \sim 8\ \text{hr}$$

$$M \sim 4 \times 10^6 M_\odot$$
$$r_g = \frac{GM}{c^2} \sim 8\text{R}_\odot$$
$$\frac{r_g}{c} \sim 20\ \text{s}$$

$$M \sim 20 M_\odot$$
$$r_g = \frac{GM}{c^2} \sim 30\ \text{km}$$
$$\frac{r_g}{c} \sim 0.1\ \text{ms}$$

Application to X-ray binary hard-to-soft state transitions

Fender et al. 2004

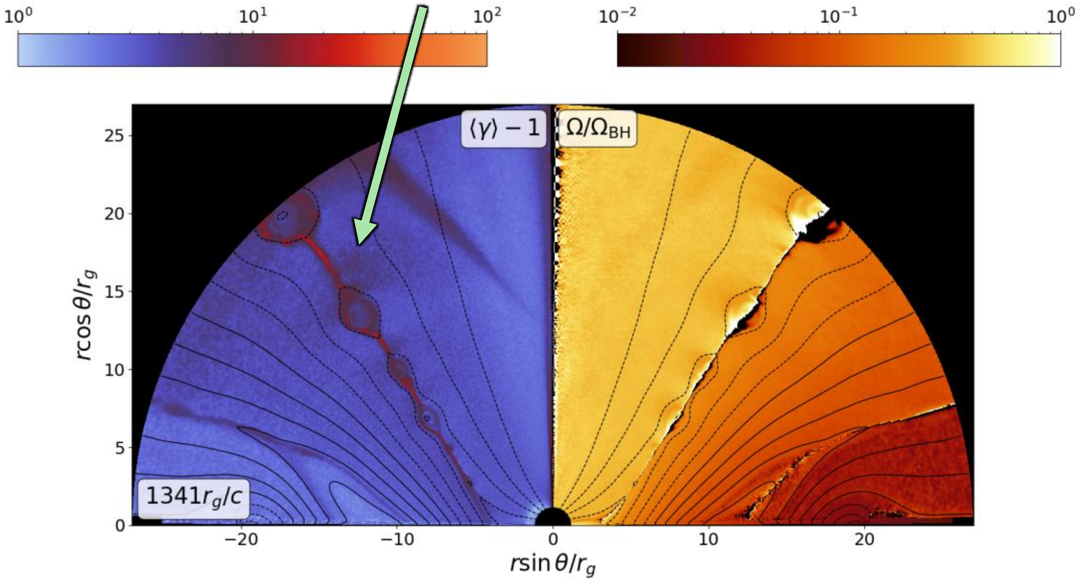


General features of hard-to-soft transition:

- Correlated X-ray and radio (jet) luminosity
  - Radio and X-ray peak coincide
- Hard state: steady/slow jet
- Soft state: no jet
- Transition: fast/episodic jet

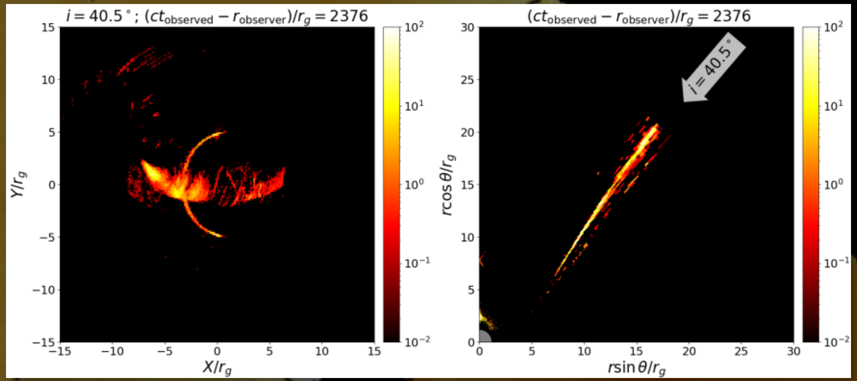
Connection to simulations:

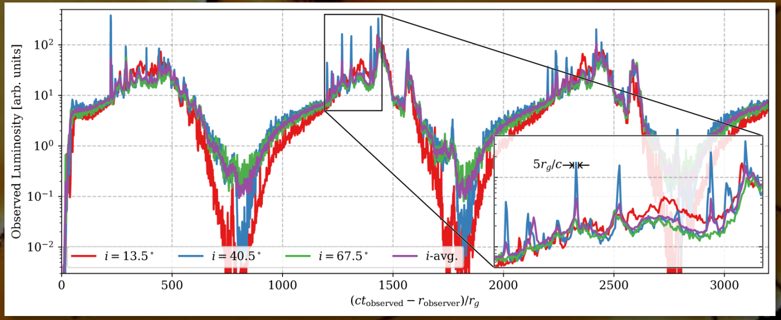
- Presence of jet during hard-to-soft transition suggests large loops
- Could a variable/episodic jet be the result of loop ejection?

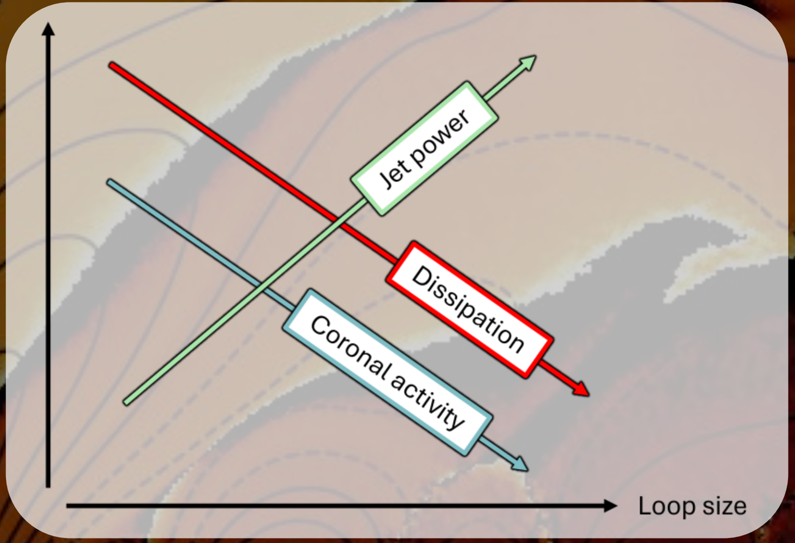


Conclusions

- GR particle-in-cell simulations can probe the energy budget and radiative signatures of a black hole feeding on its accretion disk corona
- Loop advection/ejection provides a secular variability timescale
  - $>10^3$ brightness contrast between loud and quiet periods
- Magnetic reconnection is the main dissipation mechanism
  - Leads to rapid variability
  - Relativistic compression and amplification
- Radiative signals match 1ES1927+654 changing-look event
- Loop size is correlated with jet power; anticorrelated with dissipation and coronal activity
- X-ray binary hard-to-soft state transitions reminiscent of a BH feeding on large coronal loops







Thank you!