MNRAS accepted

arxive: 2307.10576

With animations

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Efficient Magnetic Energy Dissipation by Internal Shocks

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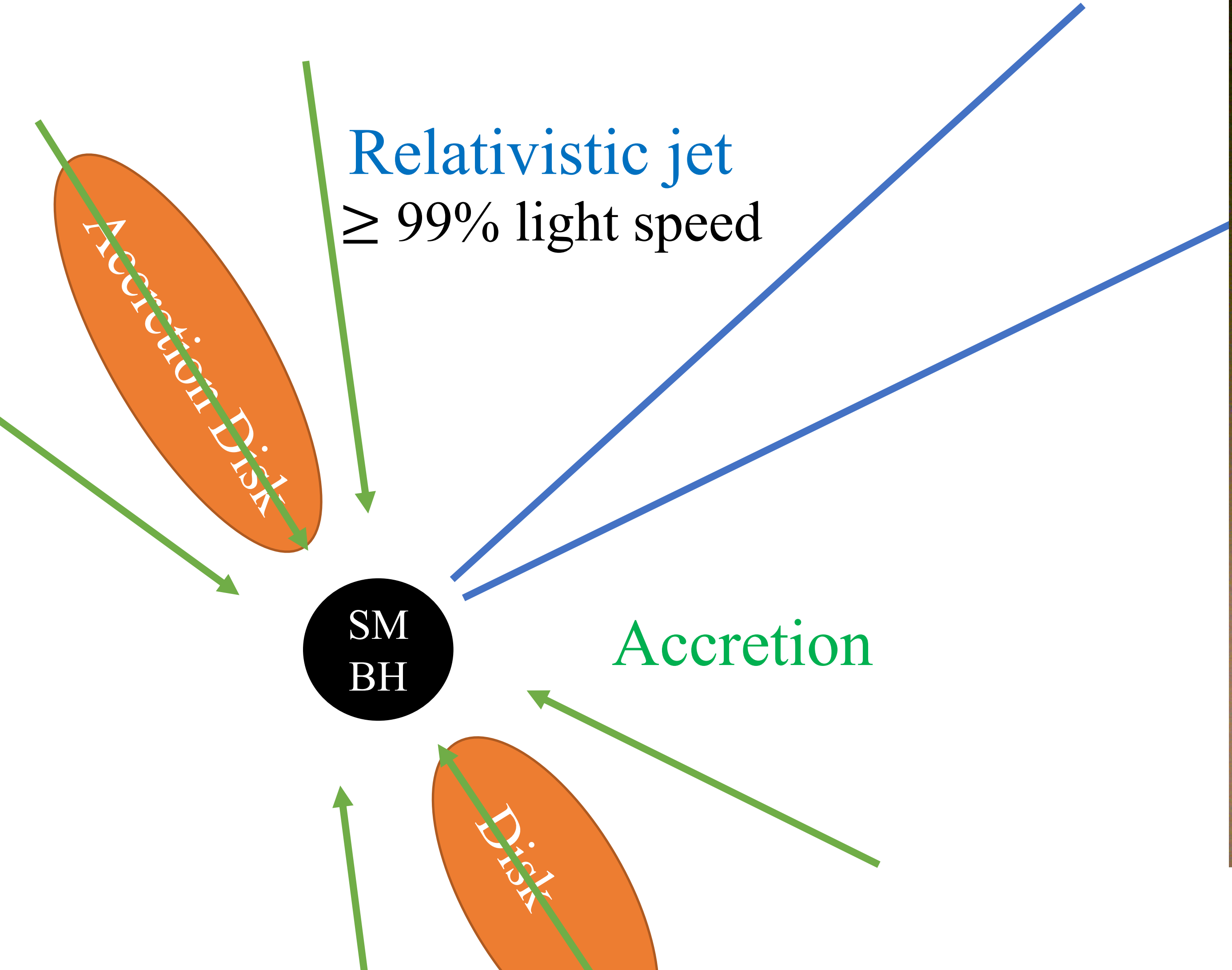
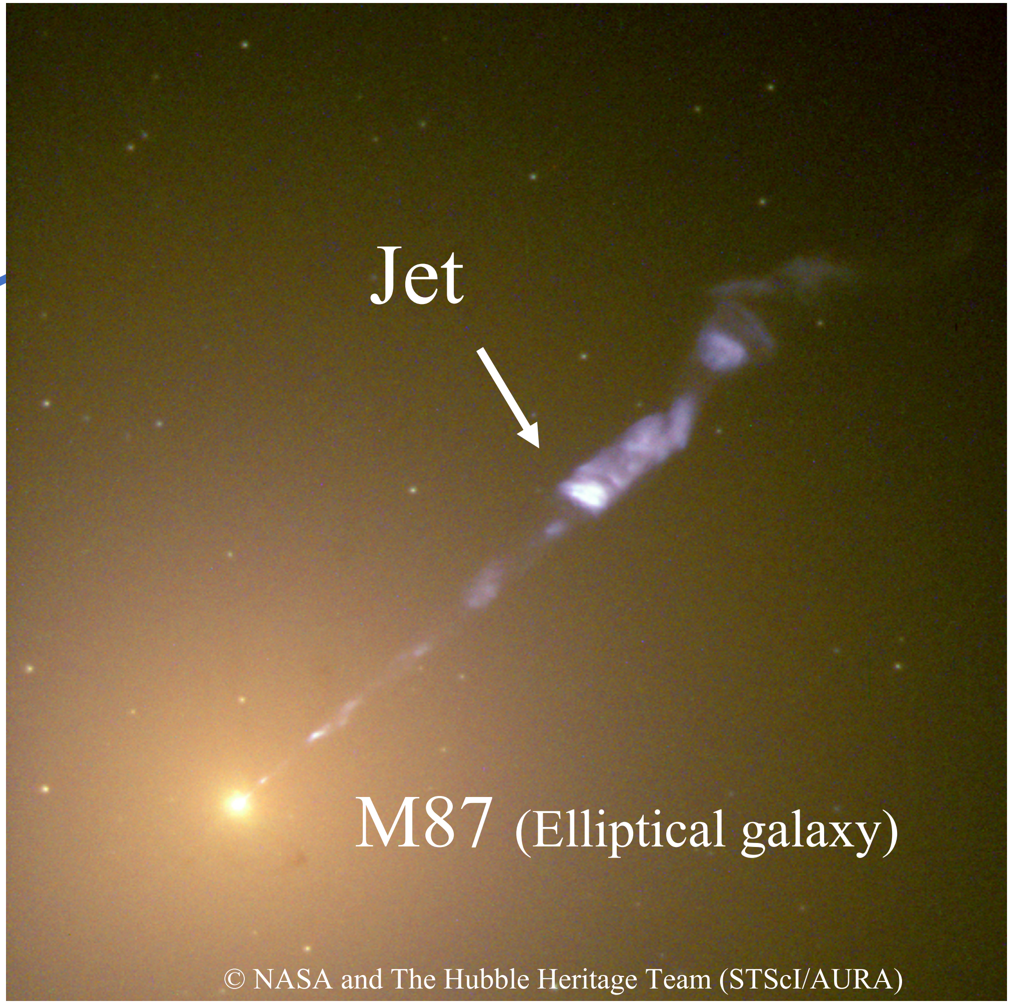
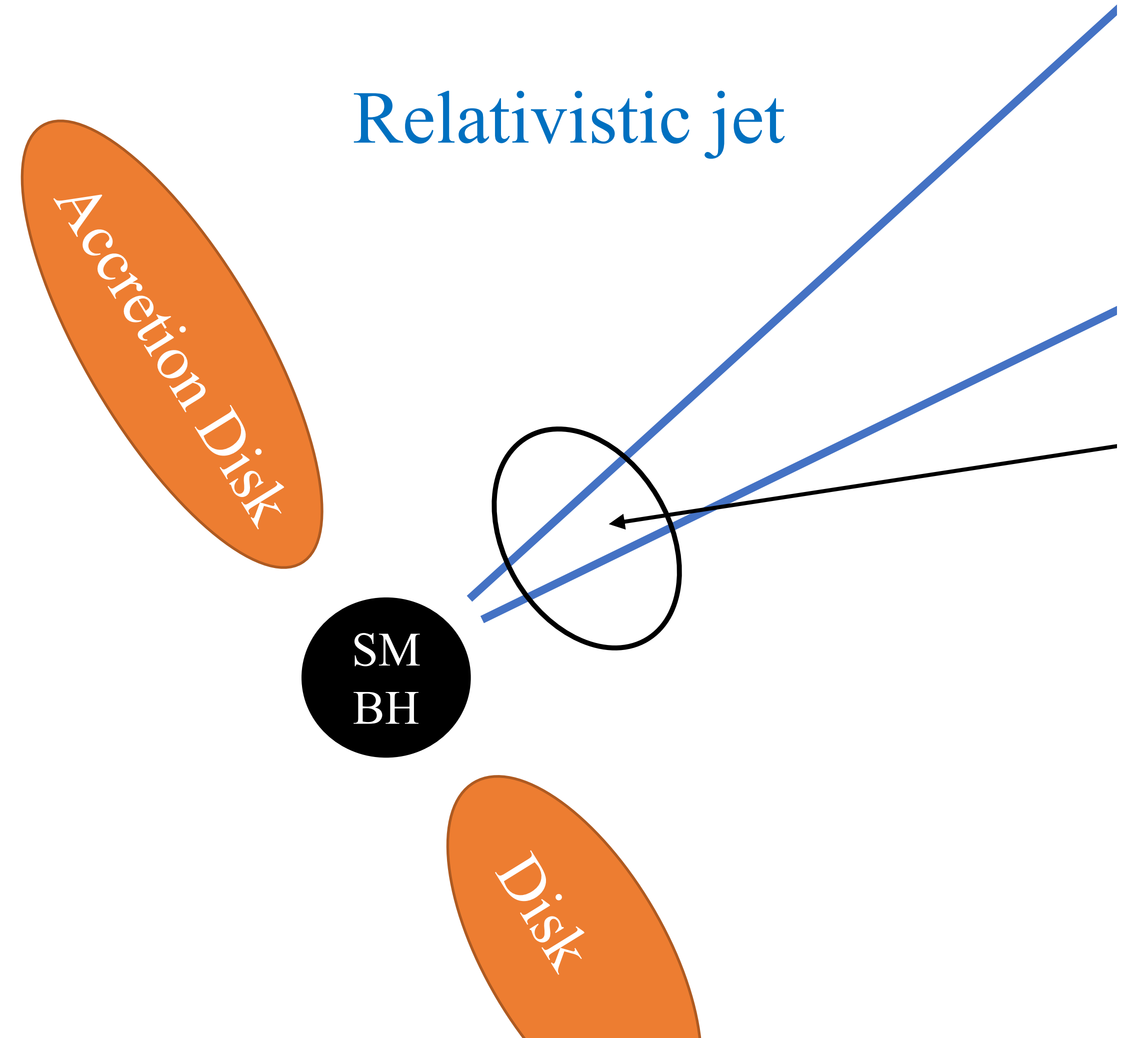
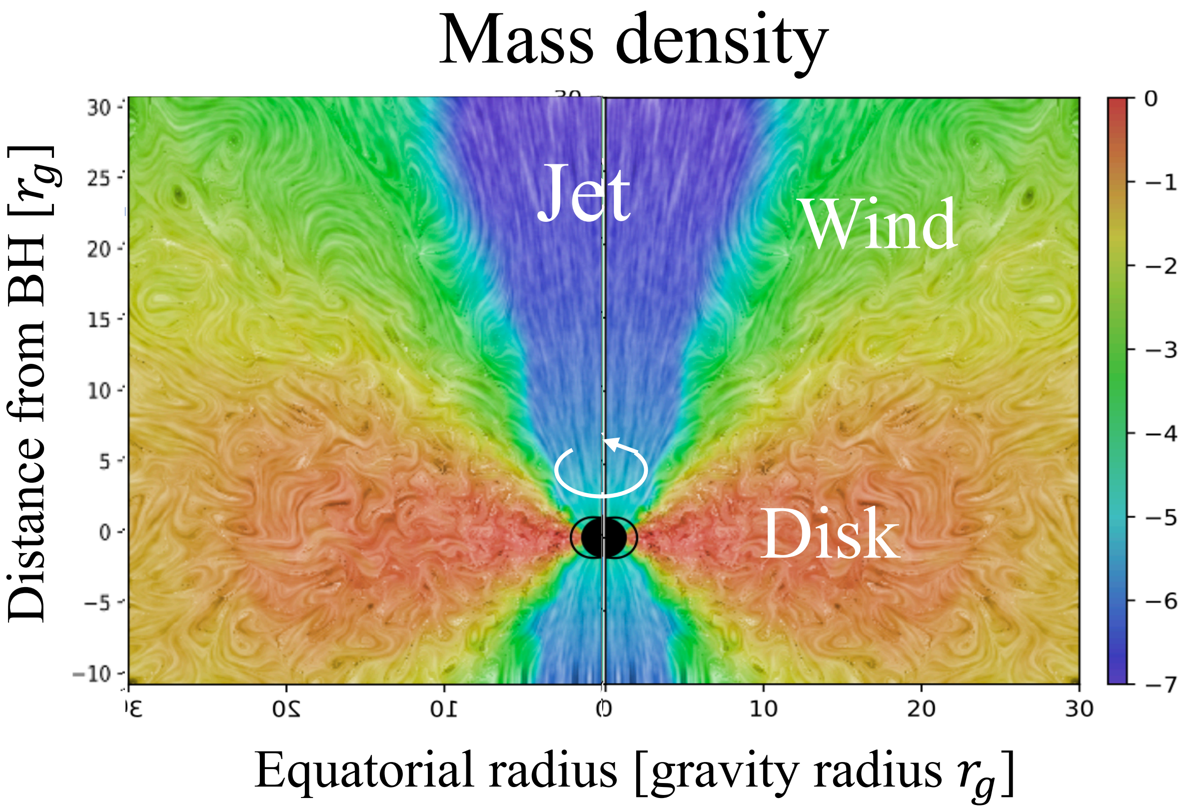
Relativistic Jets in the Center of Galaxies





Magnetic Energy of Jets (Theory)

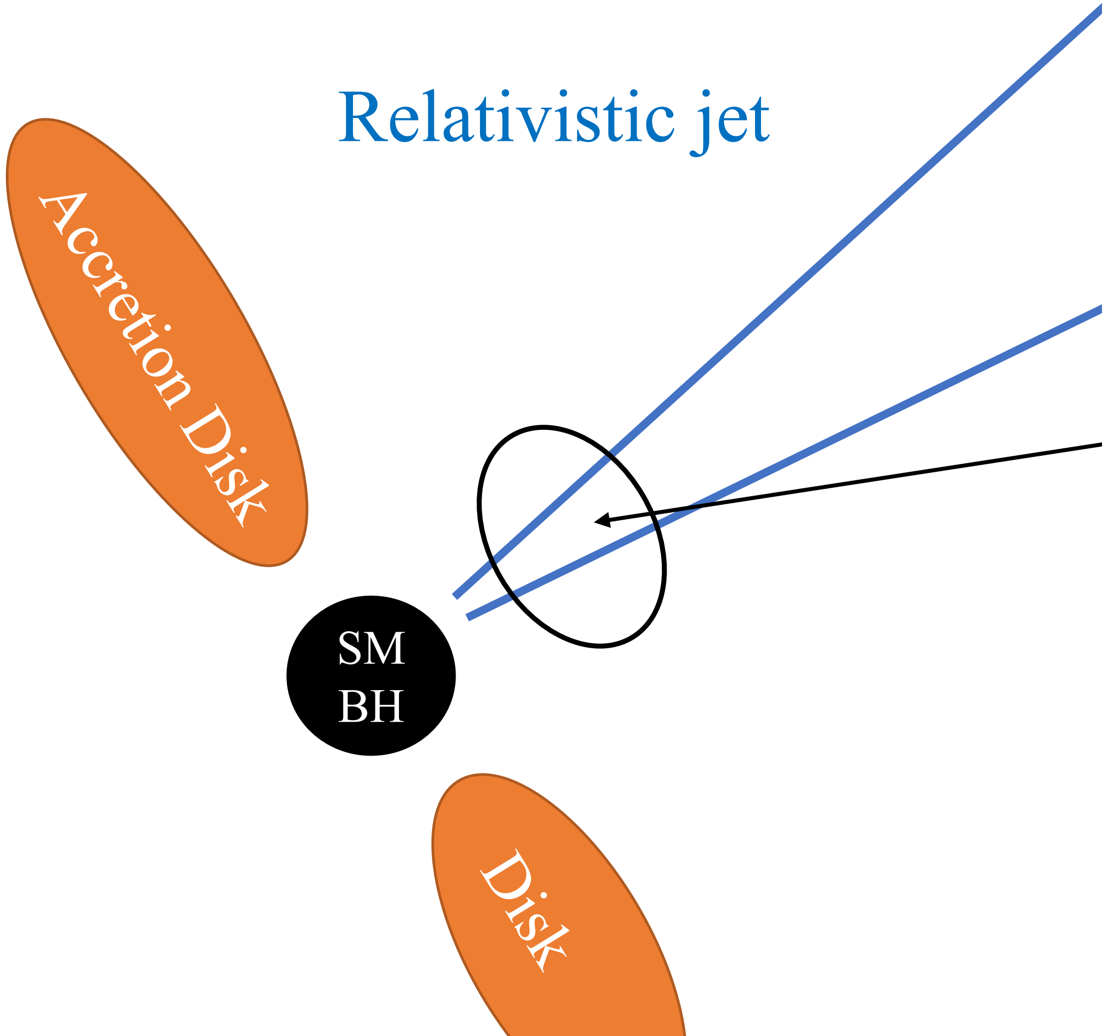


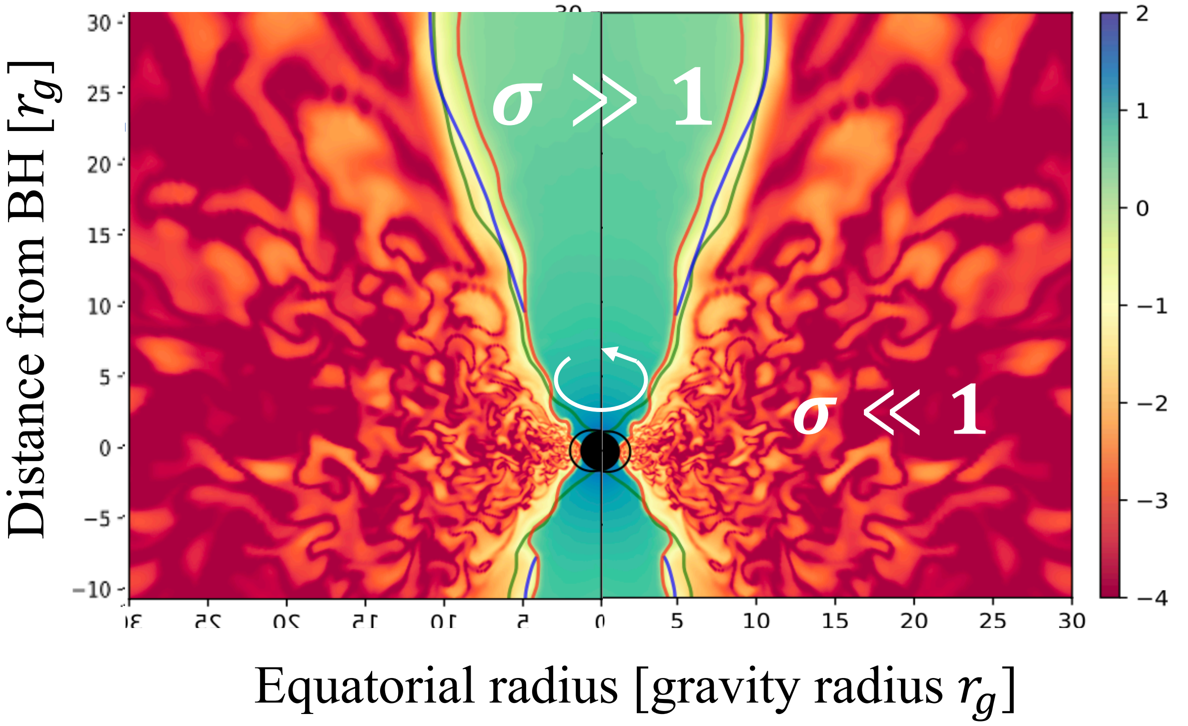


Porth et al., (2019)

Magnetic Energy of Jets (Theory)

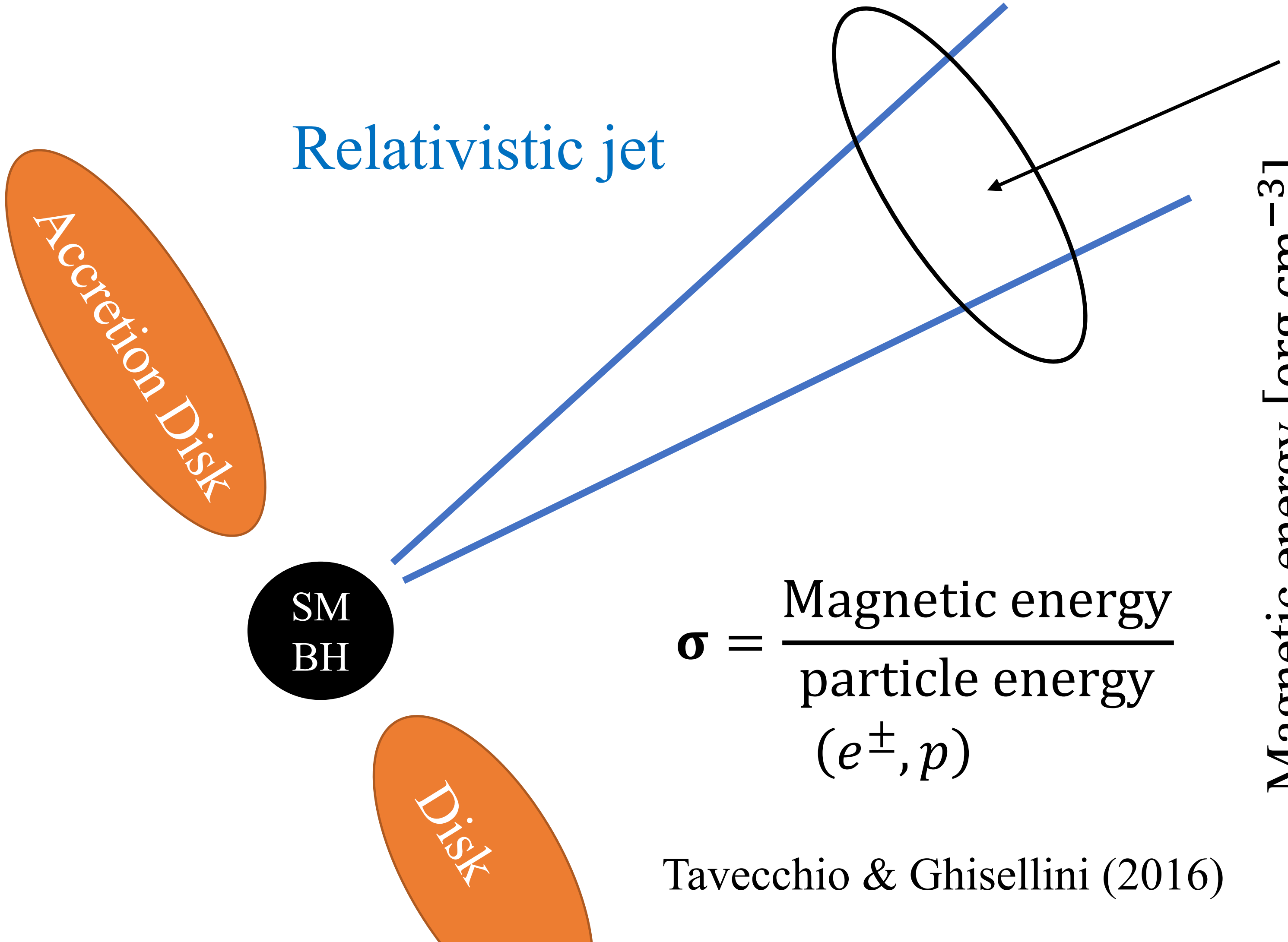
$$\boldsymbol{\sigma} = \frac{\text{Magnetic energy}}{\text{particle energy}}$$



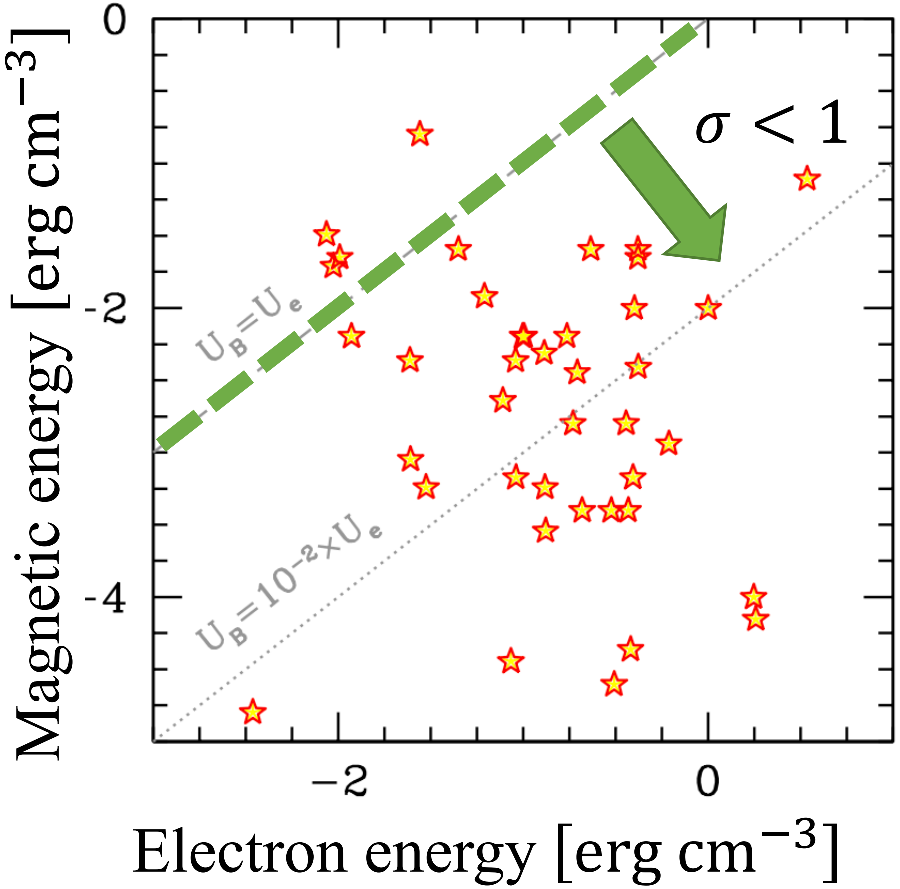


Jet launching site: $\boldsymbol{\sigma} \gg \mathbf{1}$

Magnetic Energy of Jets (Observation)



γ ray emission site: $\boldsymbol{\sigma \ll 1}$

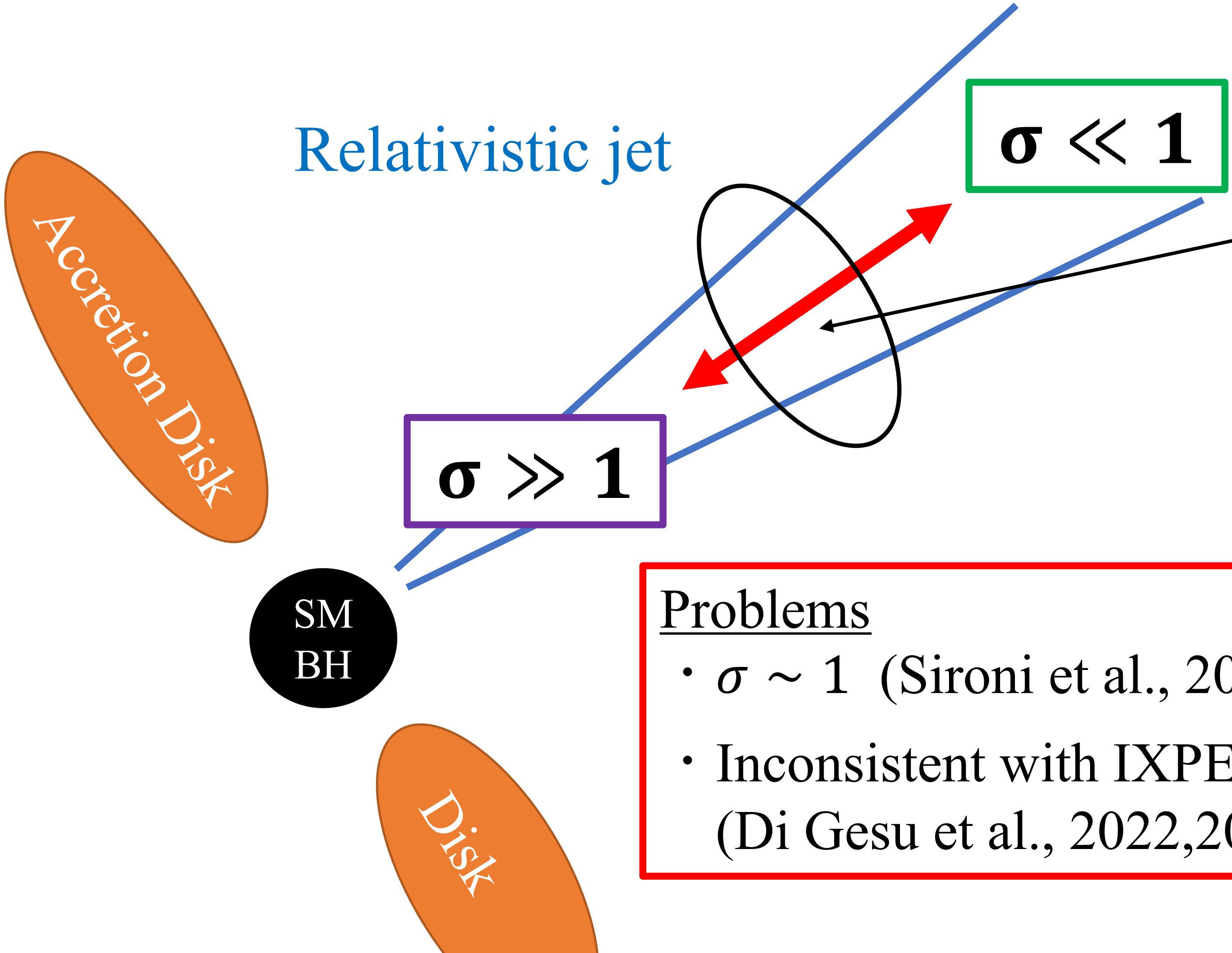


$$\boldsymbol{\sigma} = \frac{\text{Magnetic energy}}{\text{particle energy}}$$

$(e^{\pm}, p)$

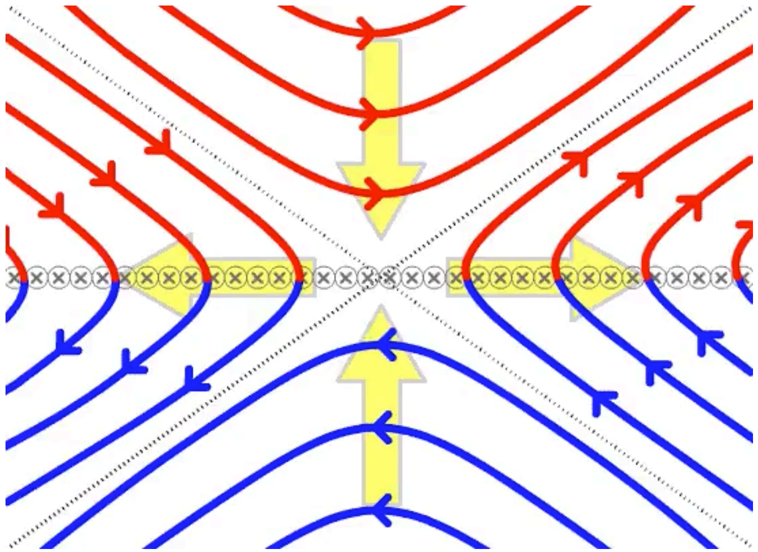
Tavecchio & Ghisellini (2016)

Magnetic Energy Dissipation in Jets



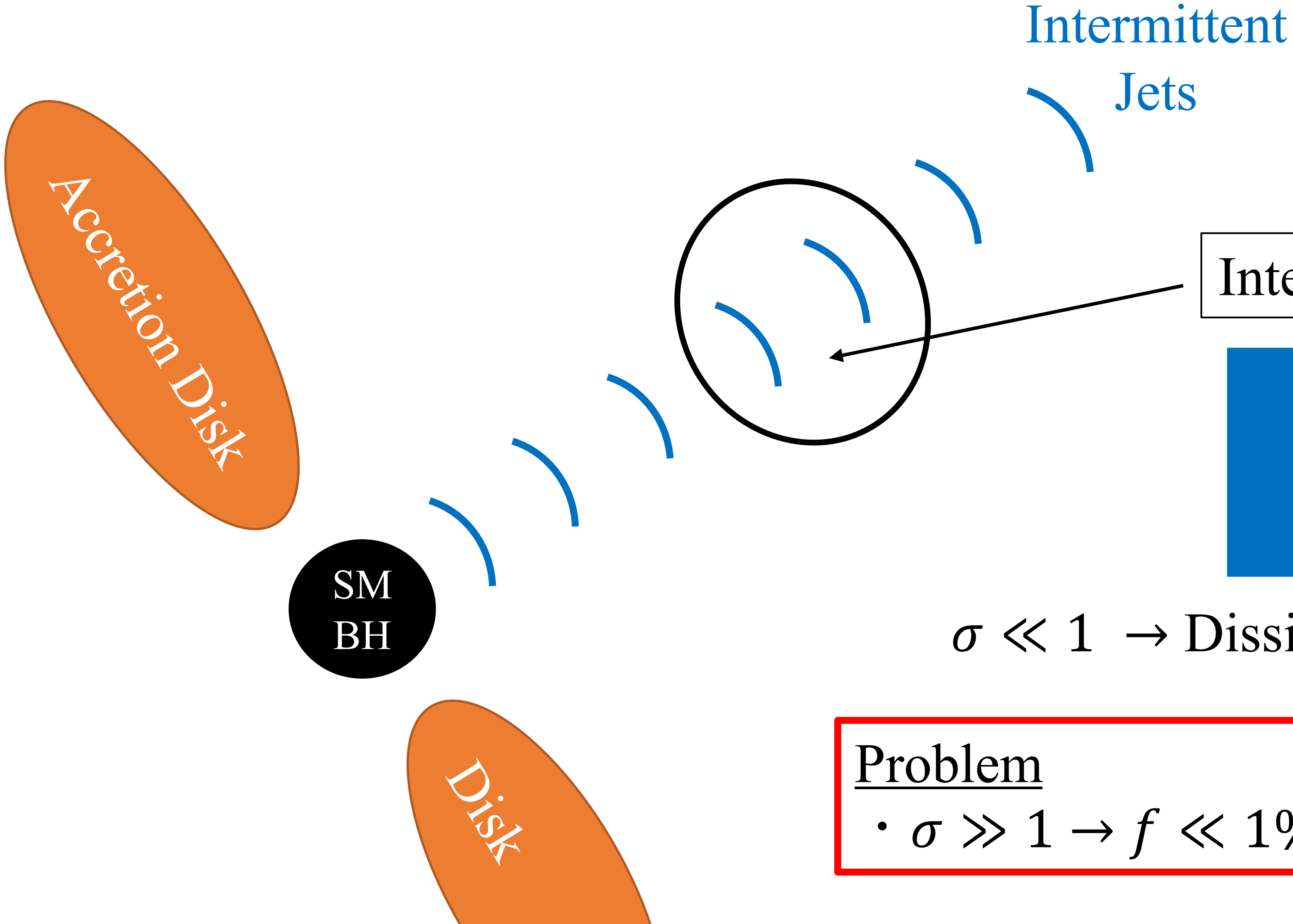
Problems
- $\sigma \sim 1$ (Sironi et al., 2015)
- Inconsistent with IXPE (Di Gesu et al., 2022,2023)

Magnetic reconnection



From Wikipedia

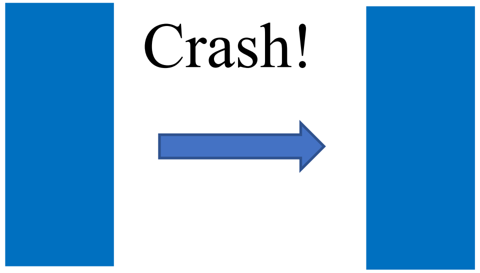
Shock Dissipation of Intermittent Jets



Intermittency

(Chaskina et al., 2021; Christie et al., 2019)

Internal shock model

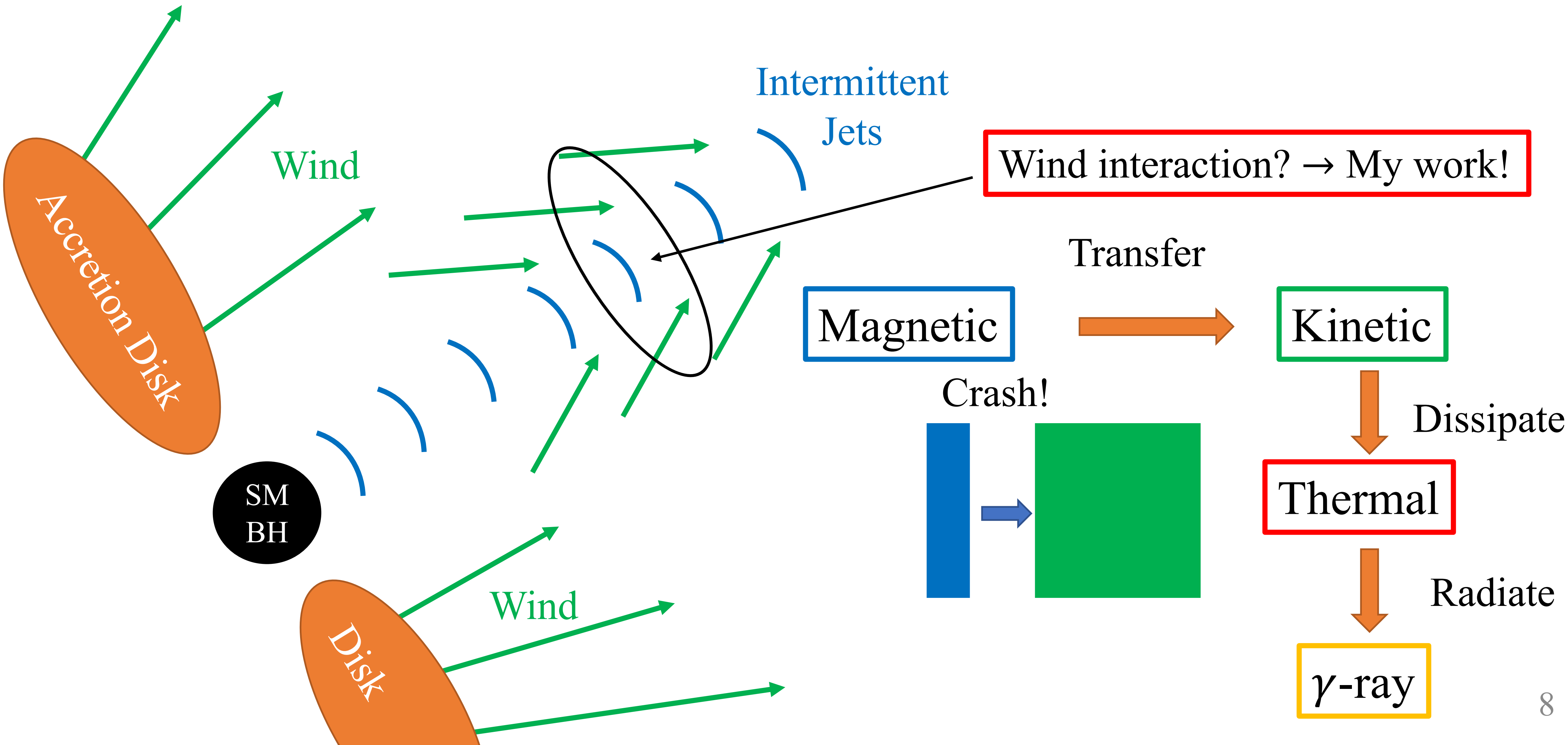


$\sigma \ll 1$ → Dissipation Efficiency $f \sim 10\%$

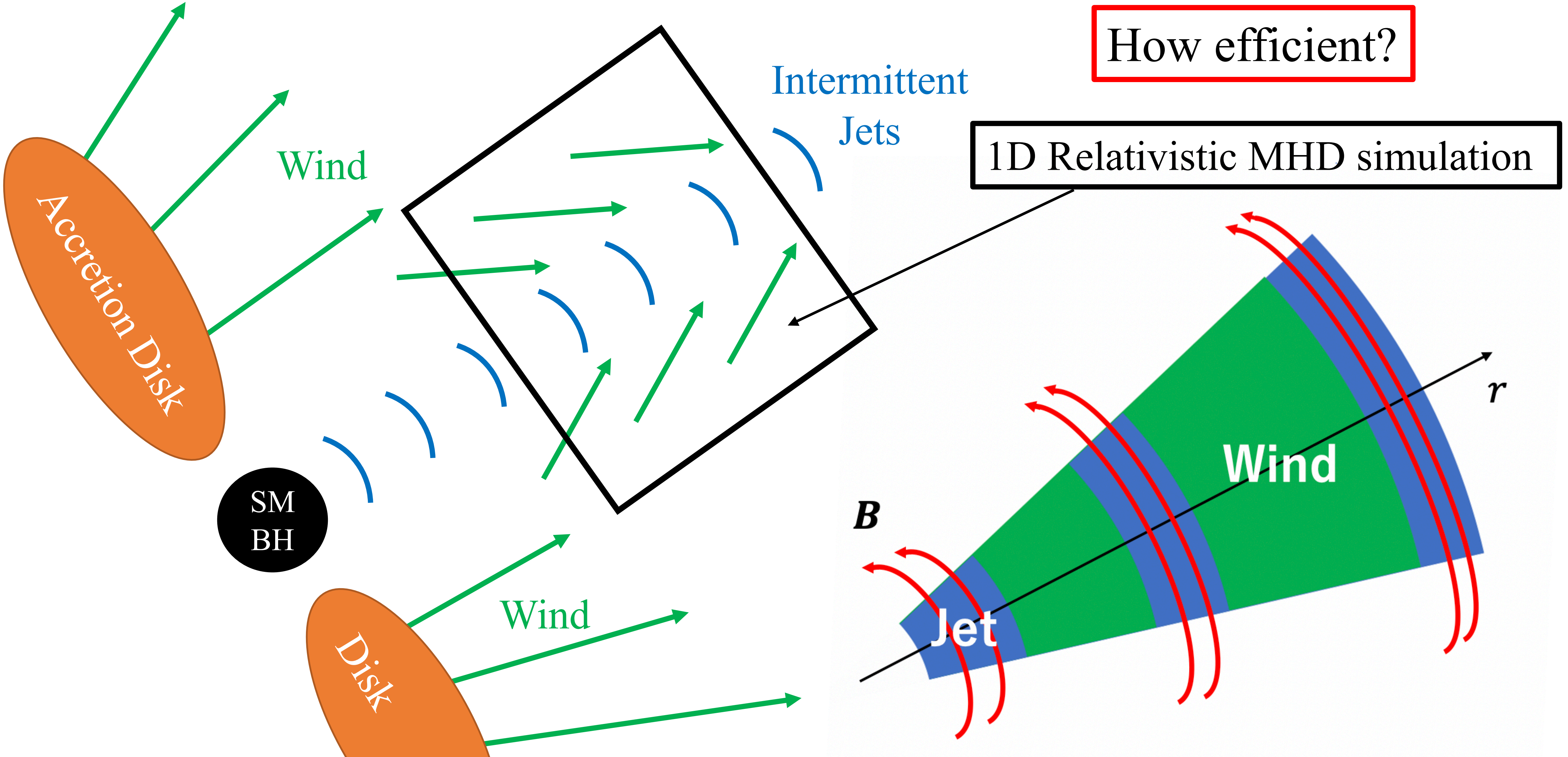
Problem

・$\sigma \gg 1 \rightarrow f \ll 1\%$ (Kennel & Coloniti, 1984)

Alternative Scenario – Intermittent Jets and Wind



Our Work – Demonstration of Our Scenario



Our Implemented Code – 1D AMR-SRMHD

1D Special Relativistic MHD system equations

- $\frac{\partial \rho\Gamma}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2(\rho\Gamma v_r) = 0$: Mass
- $\frac{\partial \tau}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2(w\Gamma^2 v_r - \rho\Gamma v_r) = 0$: Energy
- $\frac{\partial S}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2(w\Gamma^2 v_r^2 + p) = \frac{2p}{r}$: Momentum
- $\frac{\partial B_\theta}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r(B_\theta v_r) = 0$: Induction

$\tau = w\Gamma^2 - p - \rho\Gamma$: energy density
$S = w\Gamma^2 v_r$: momentum density
$w = \varepsilon + p_g + 2p_m$: enthalpy
$\rho, p_g, p_m, \varepsilon$: measured at the fluid rest frame

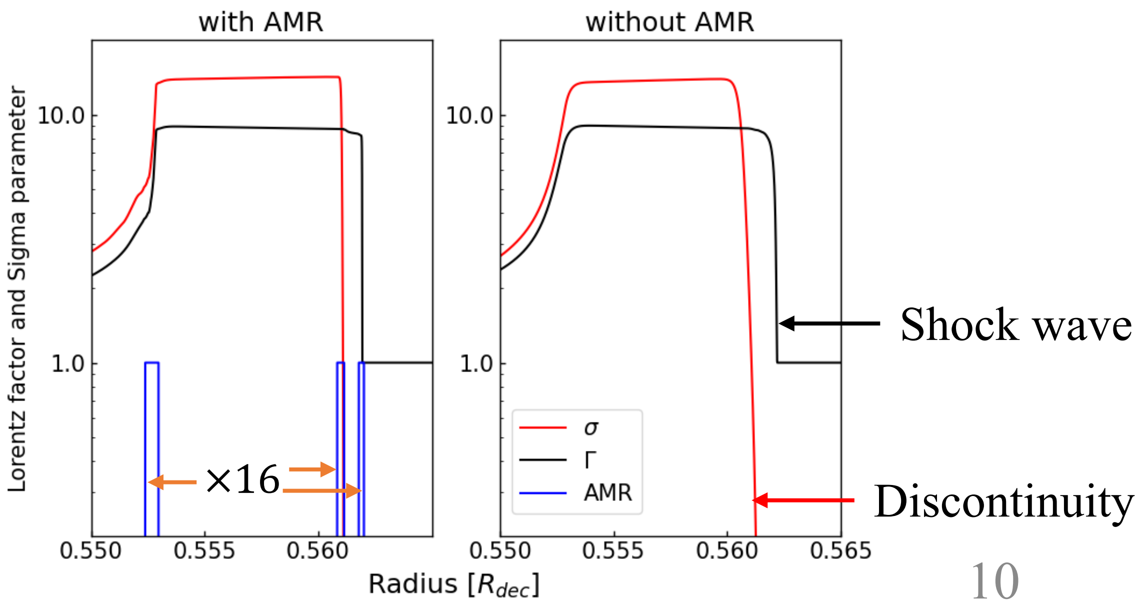
The heat ratio : $\hat{\gamma} = 1 + \frac{\epsilon + \rho}{3\epsilon}$

$\boldsymbol{v} = (v_r, 0, 0), \boldsymbol{B} = (0, B_\theta, 0)$: assumption

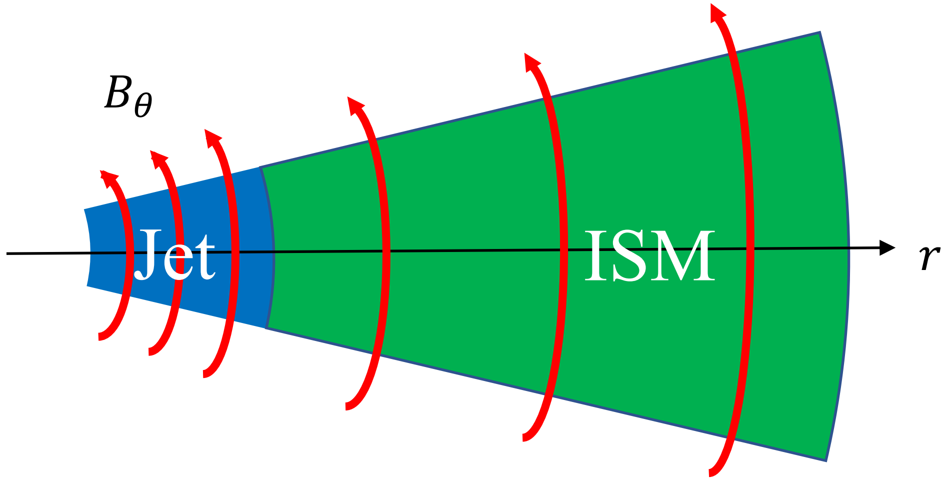
Magnetization : $\sigma = \frac{B_\theta^2}{4\pi(\varepsilon + p_g)\Gamma^2}$

Numerical scheme

- 2nd order MUSCL-TVD (van Leer 1979)
- 2nd order Runge-Kutta method
- Flux limiter function : minmod (Roe 1986)
- Riemann solver : CENTRAL (Rusanov 1962)
- AMR (Berger & Oliger 1984)



Single Jet Simulation

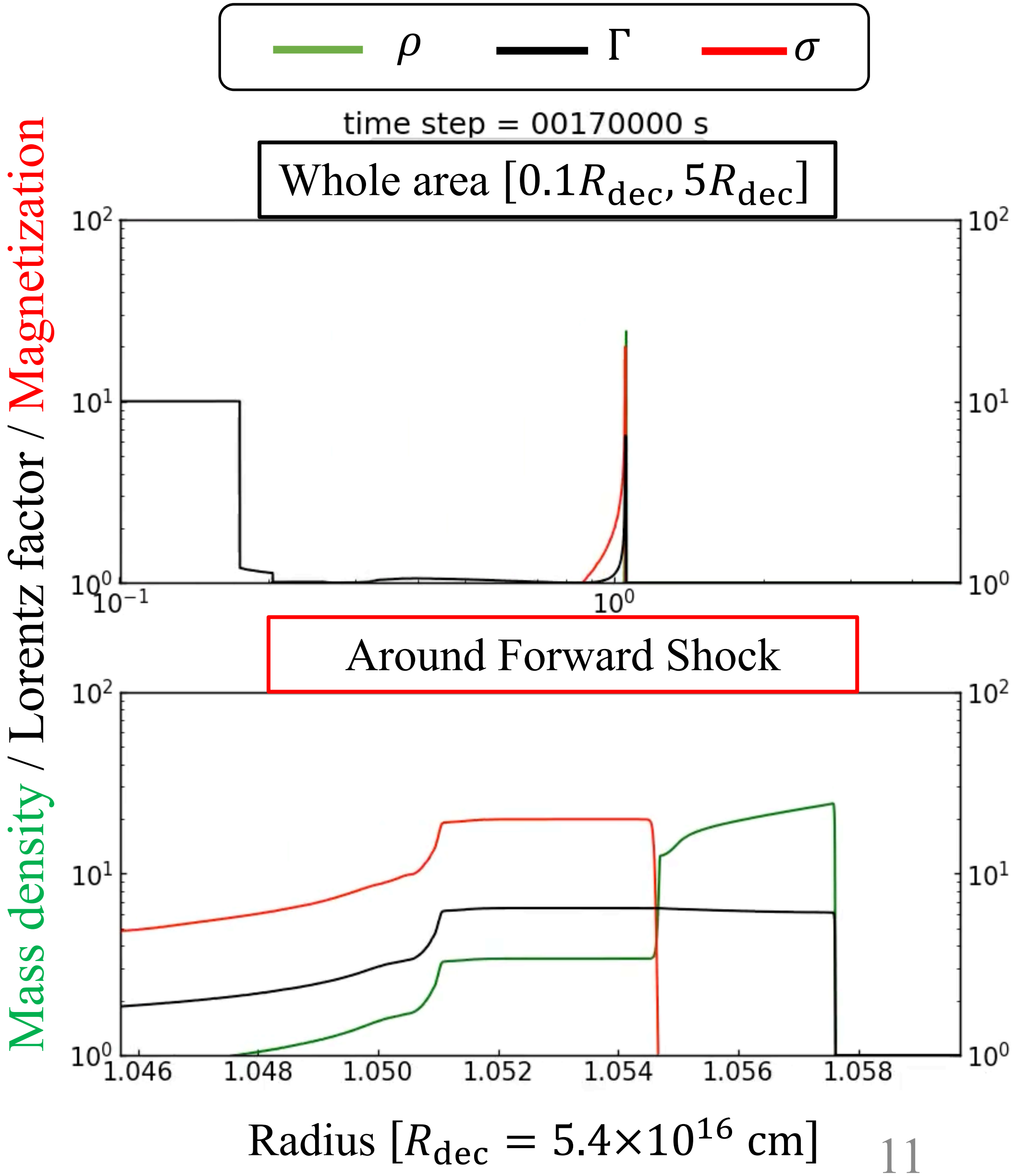


Jet

- $E_{\text{jet}} = 10^{50}$ erg
- $\Gamma = 10$
- $\rho \propto r^{-2}$
- $T = 100$ MeV
- $\sigma_0 = 10$

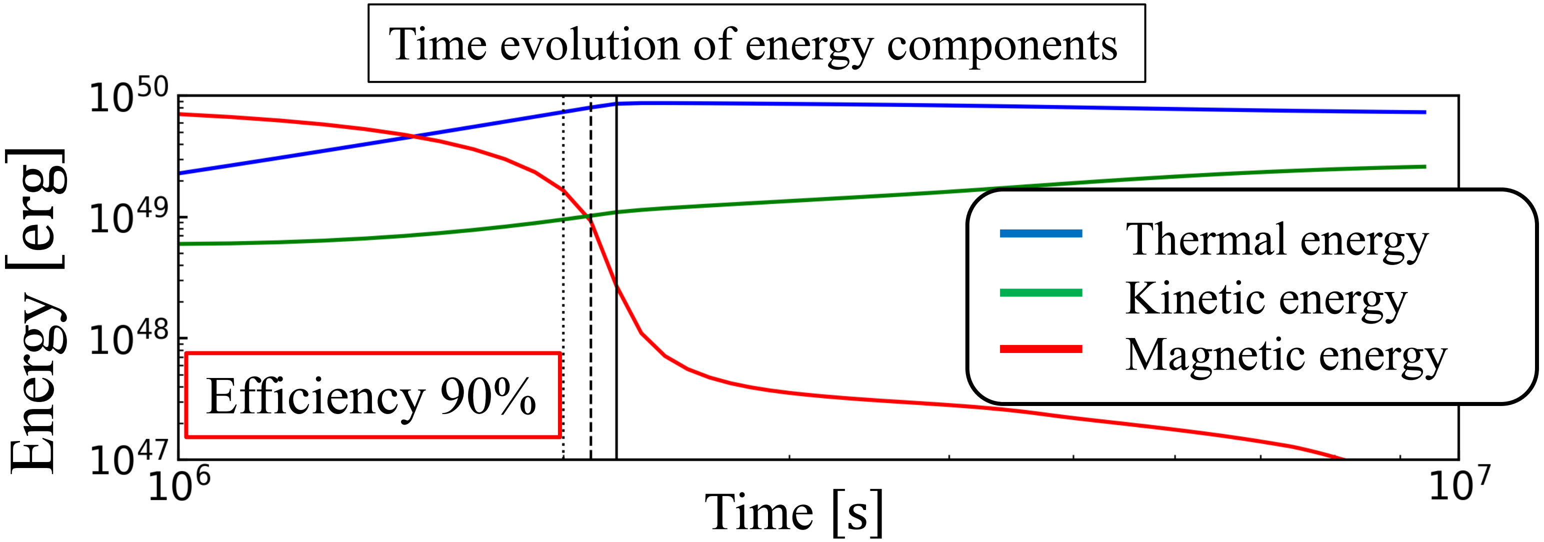
ISM

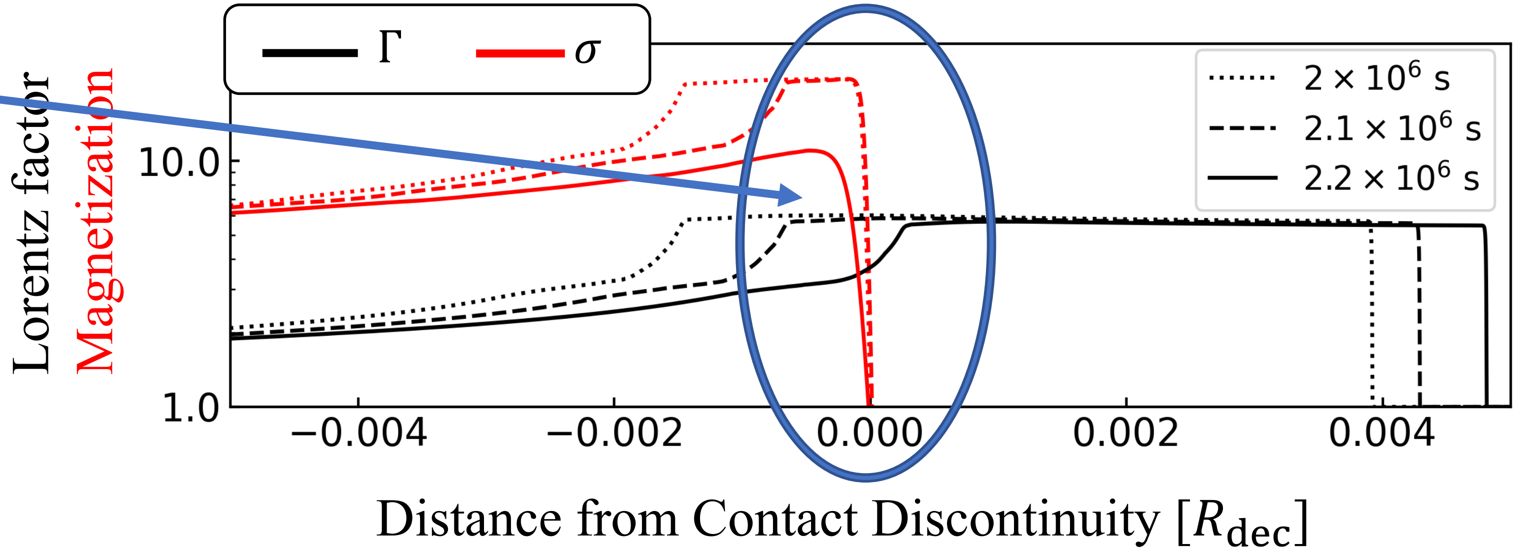
- $m_p = 938$ MeV
- $\Gamma = 1\ (v = 0)$
- $n_{\text{ISM}} = 1\ \text{cm}^{-3}$
- $T = 1$ MeV
- $B_{\text{ISM}} = 1\ \mu\text{G}$



Magnetic Energy Dissipation (Conversion)

Collision with ISM
↓
Decelerate FS
↓
Magnetic pressure
↓
Rarefaction wave
↓
Dissipation ends





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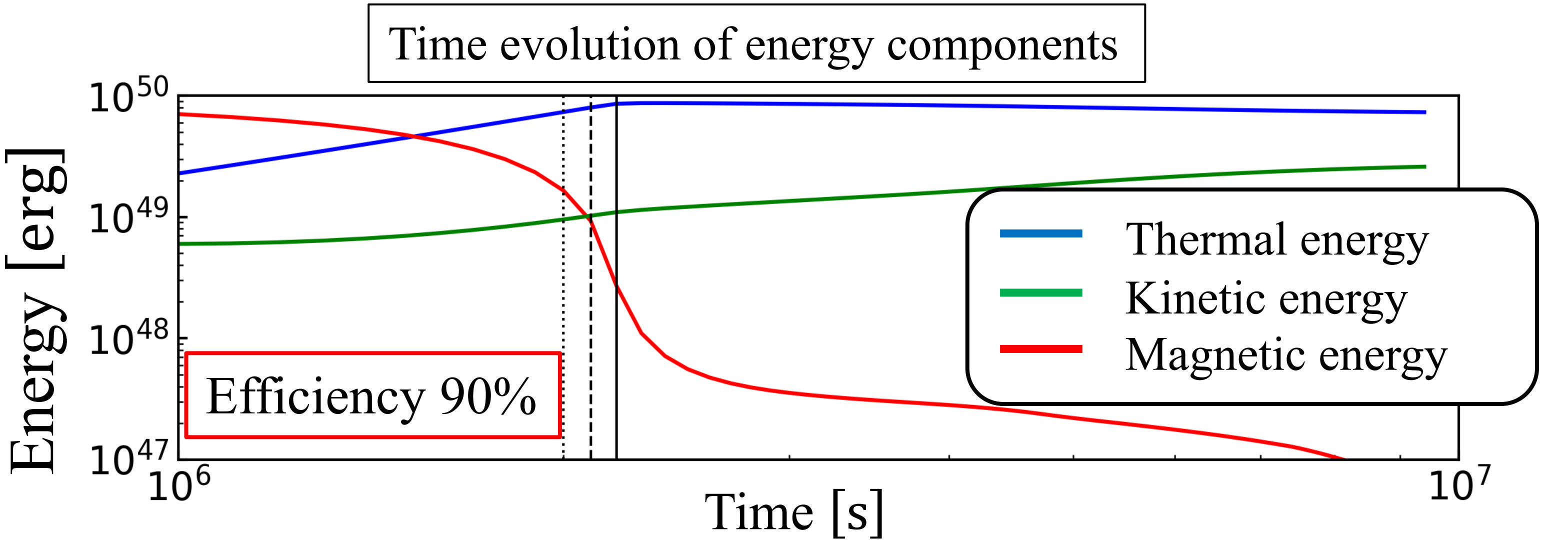
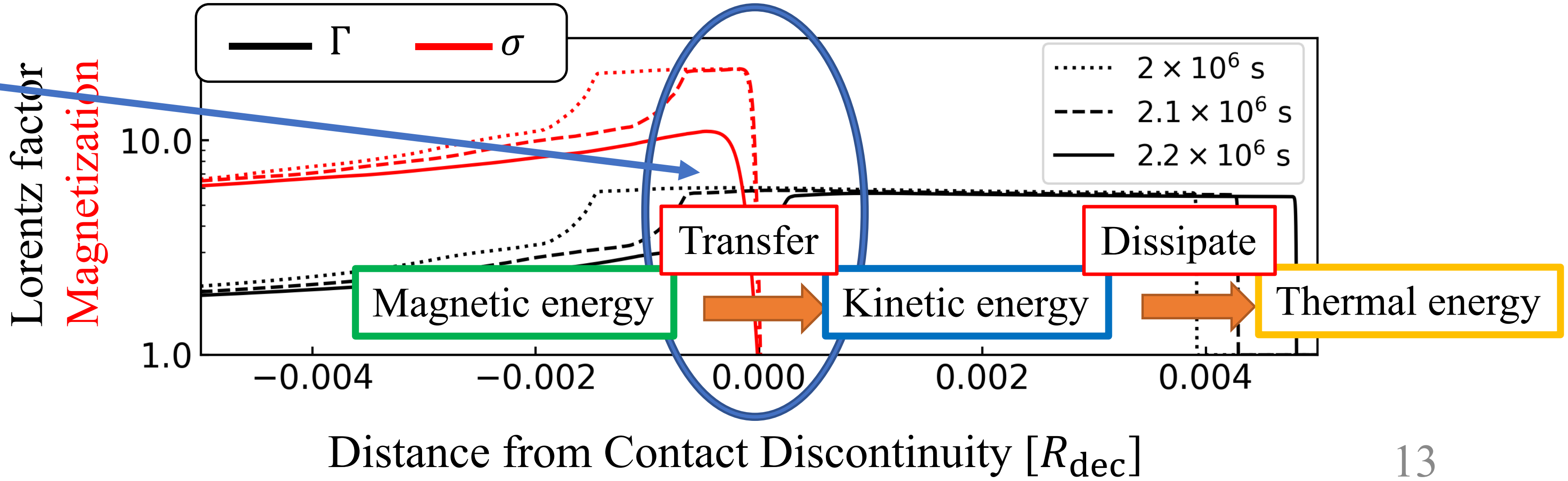
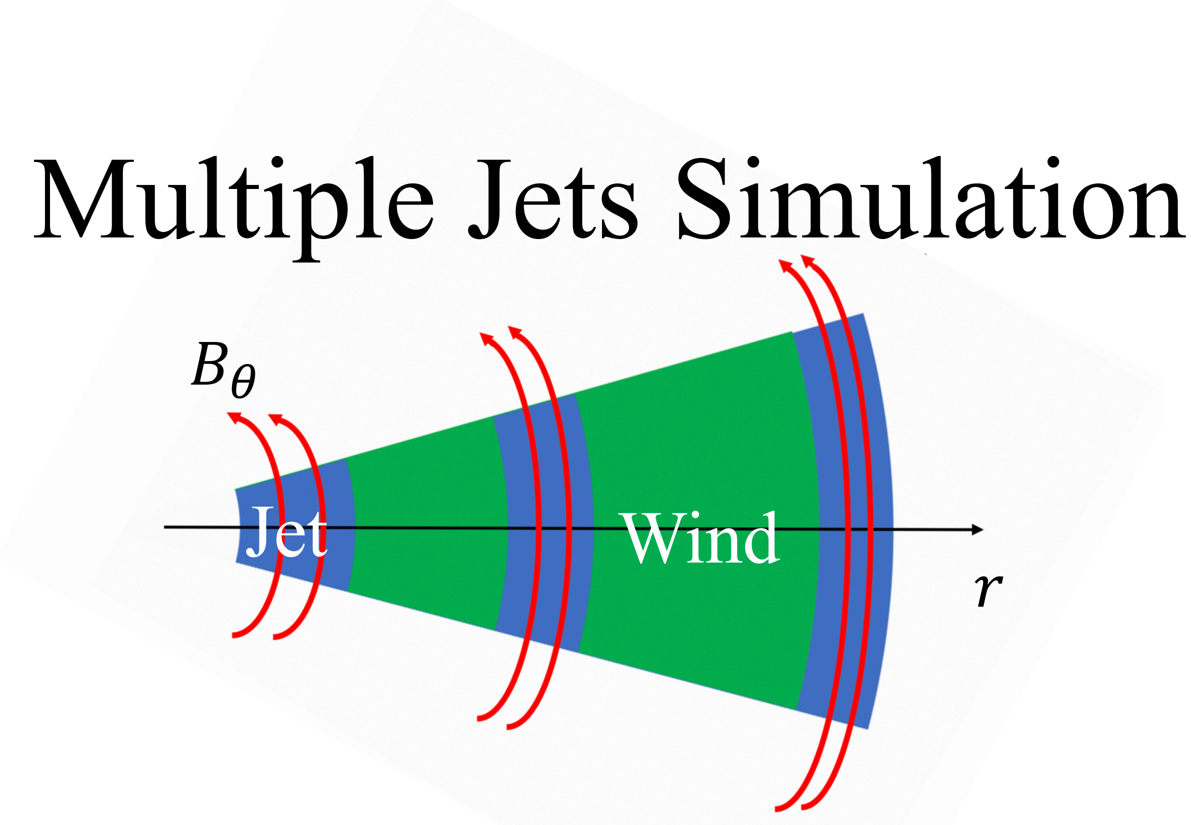




Multiple Jets Simulation

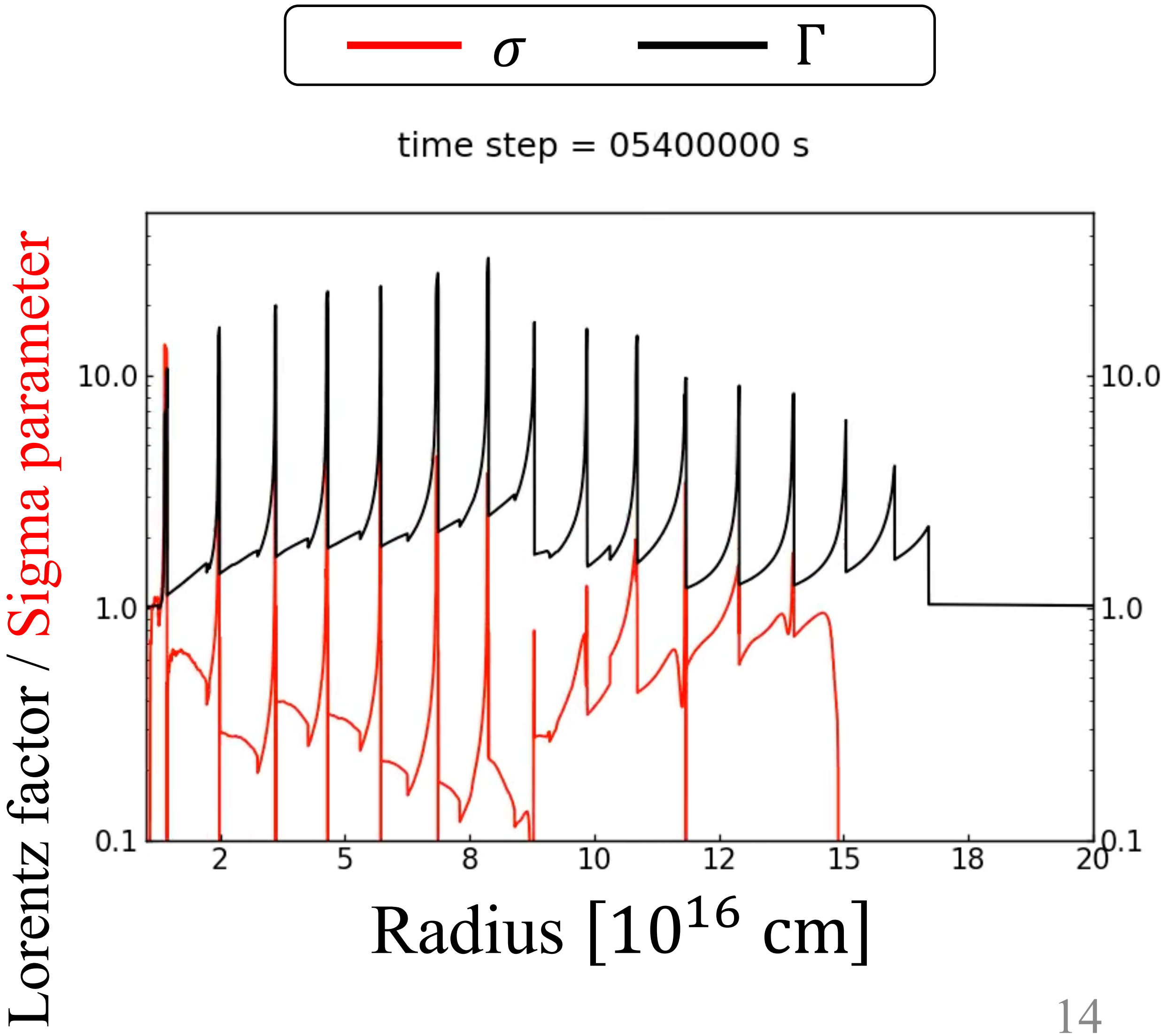


Intermittent jets

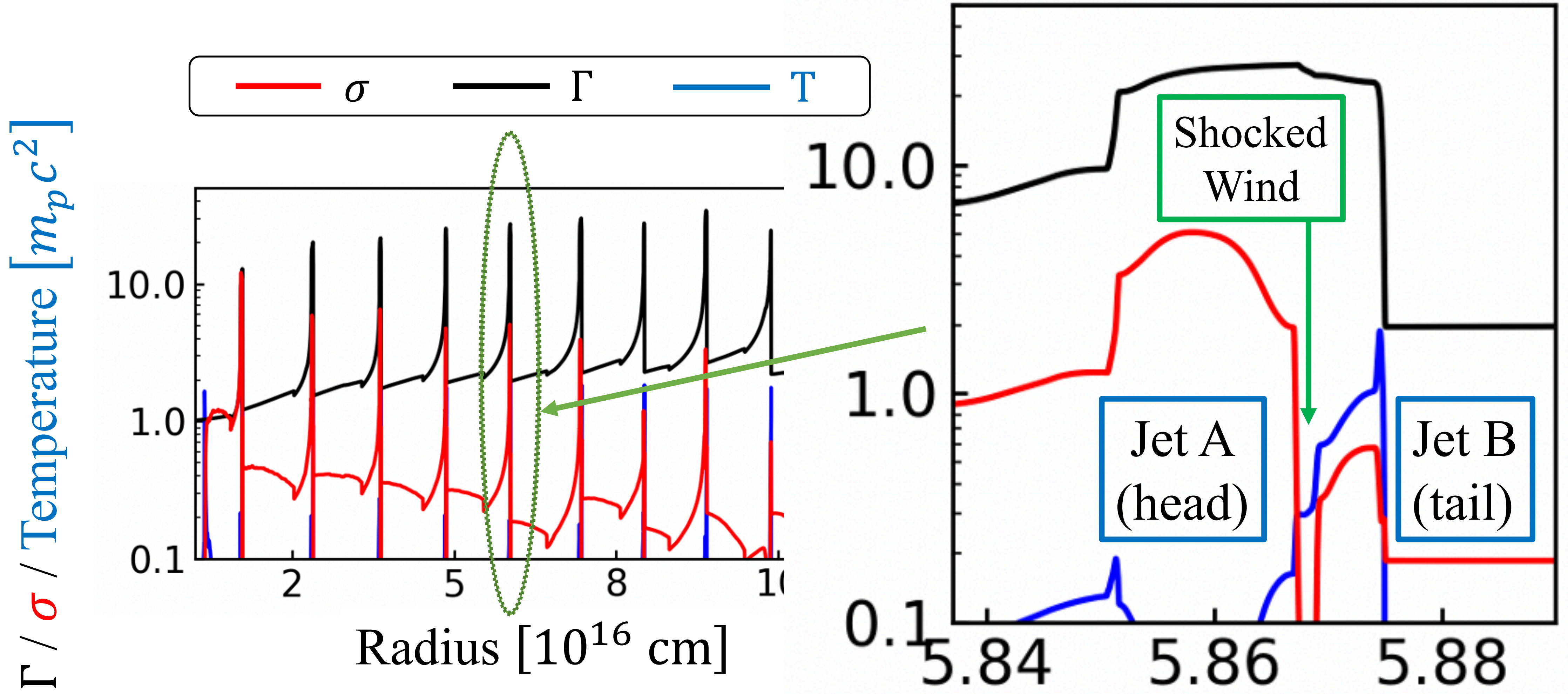
- $L_{jet} = 10^{45}$ erg/s
- $\sigma_{jet} = 10$
- $T_{jet} = 100$ MeV
- $\boldsymbol{\Gamma = 10 \pm 5}$
- $\boldsymbol{t_{jet} = (3 \pm 2)\frac{R_0}{\Gamma^2 c}}$

Winds

- $L_{wind} = 10^{-4} L_{jet}$
- $\sigma_{wind} = 10^{-10}$
- $T_{wind} = 100$ MeV
- $v_{wind} = 0.1c$ cm/s
- $\boldsymbol{t_{wind} = (1 \pm 0.1)\frac{R_0}{c}}$



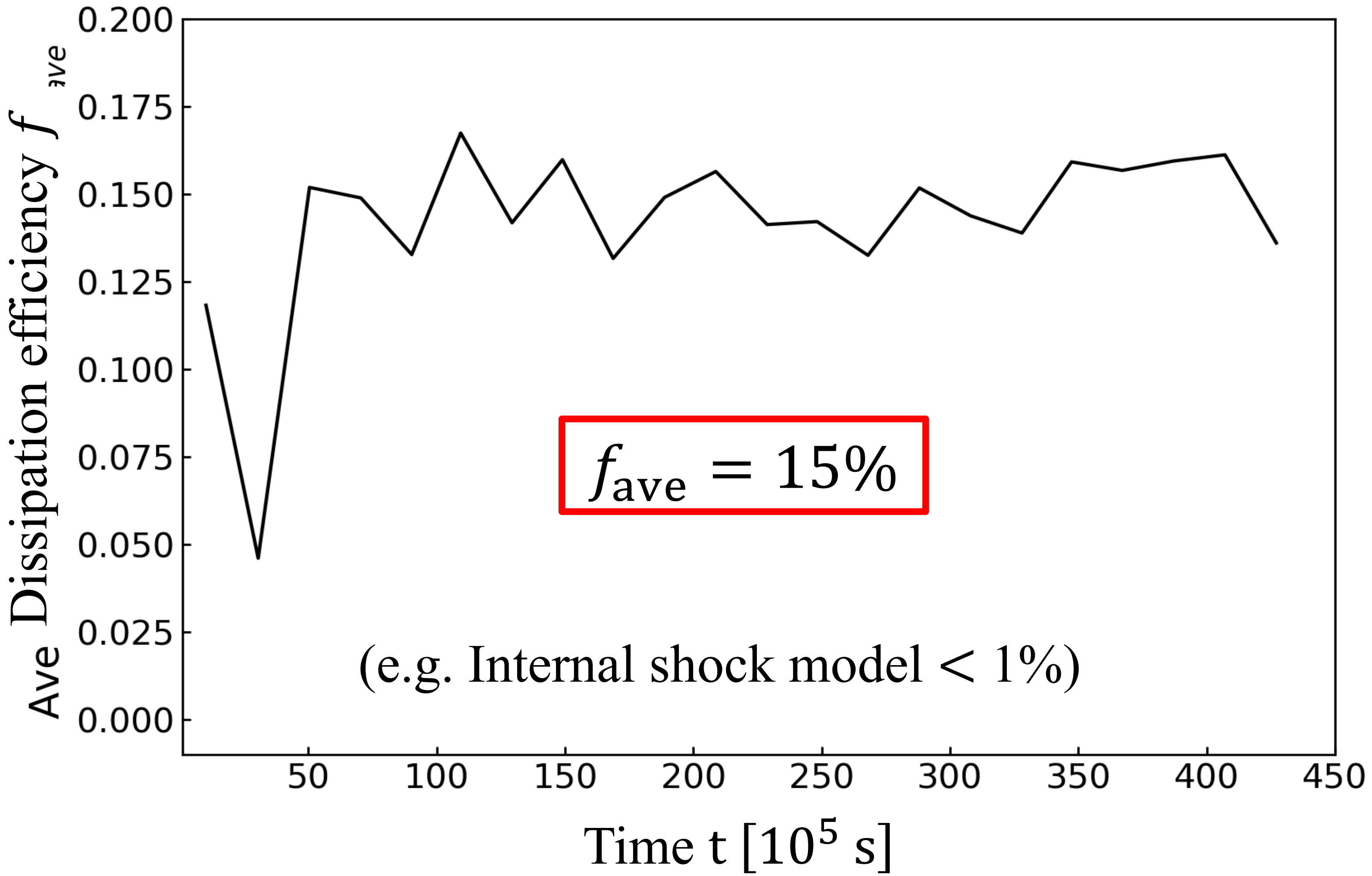
Low Sigma Relativistic Hot Outflow

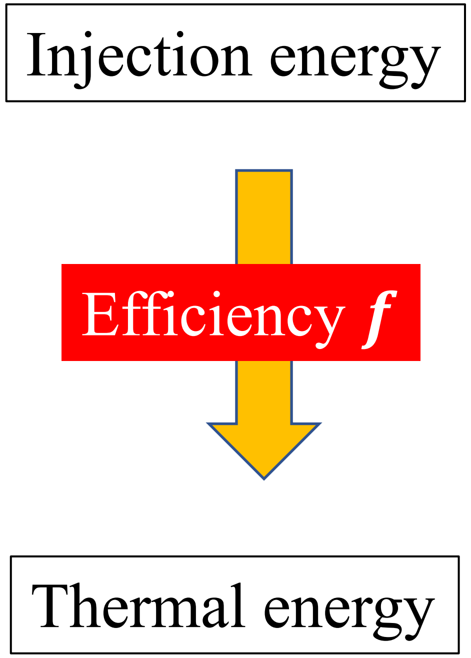


Our scenario can generate $\boldsymbol{\sigma} < \mathbf{1}, \boldsymbol{\Gamma} > \mathbf{1}, \boldsymbol{T} > \mathbf{1}$ **MeV**

Dissipation Efficiency

$$f = \left\langle \frac{\text{Thermal energy}}{\text{Injection energy}} \right\rangle_{\text{partial average}}$$



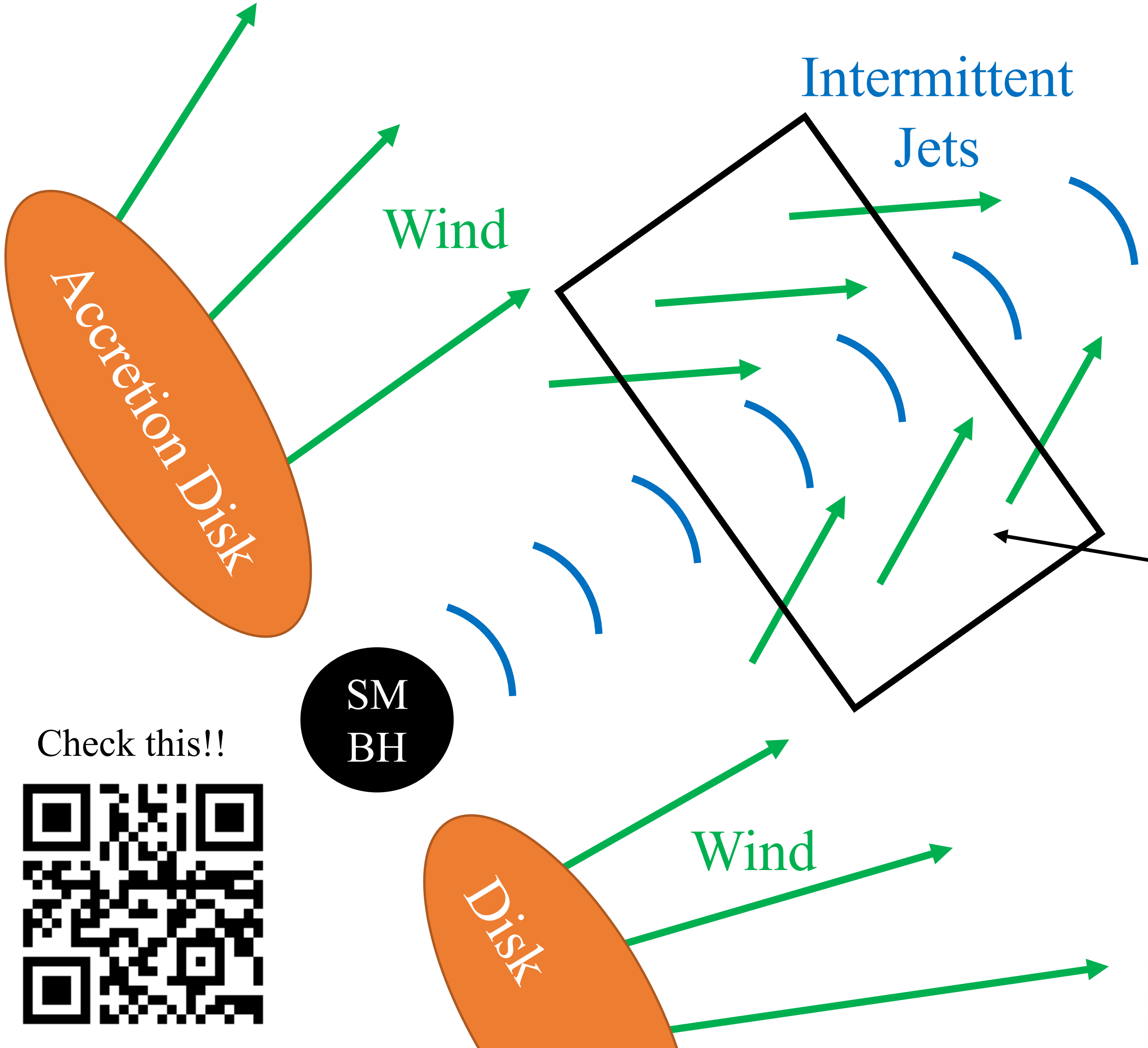


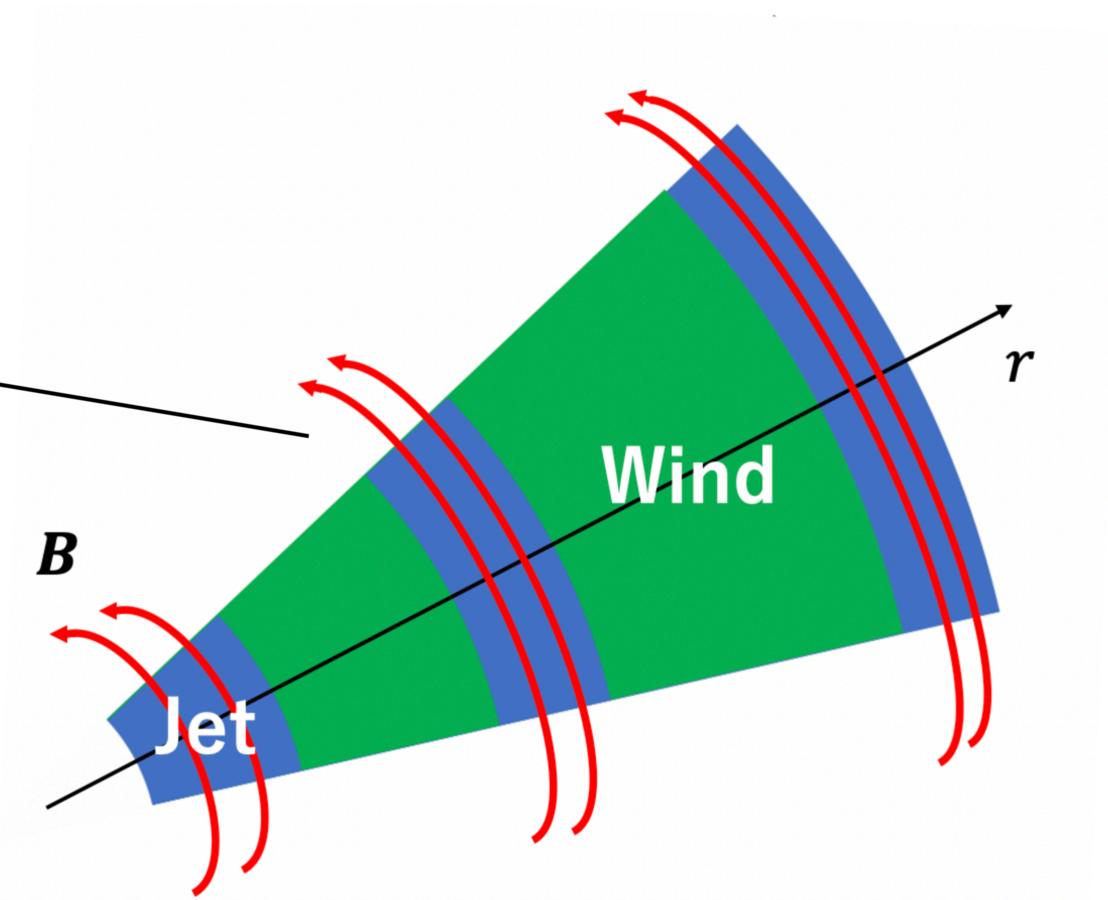
Summary

<u>Purpose</u>: Demonstrate new model

<u>Method</u>: Simulation by our code

<u>Result</u> : 15% efficient dissipation





Check this!!

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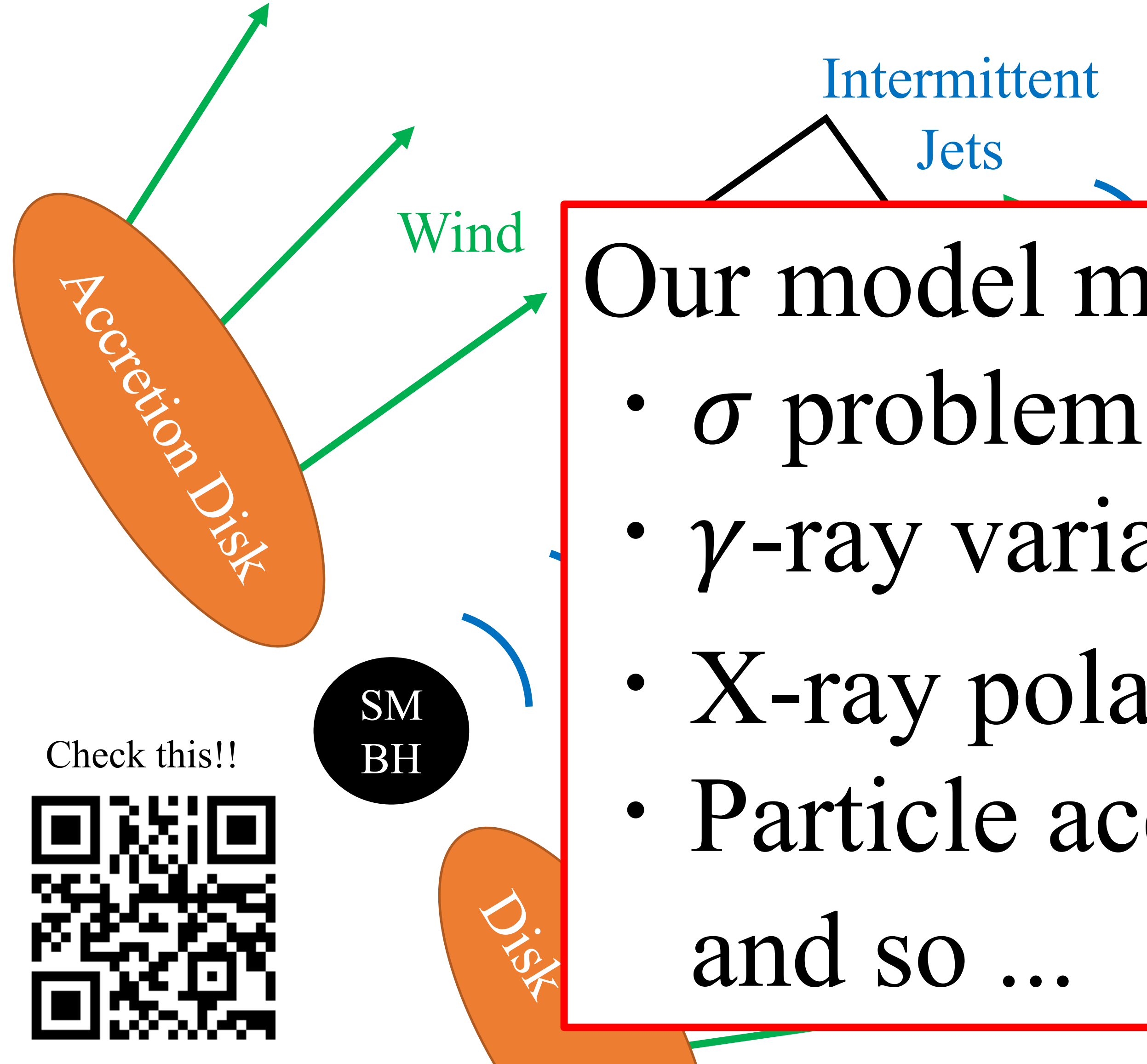
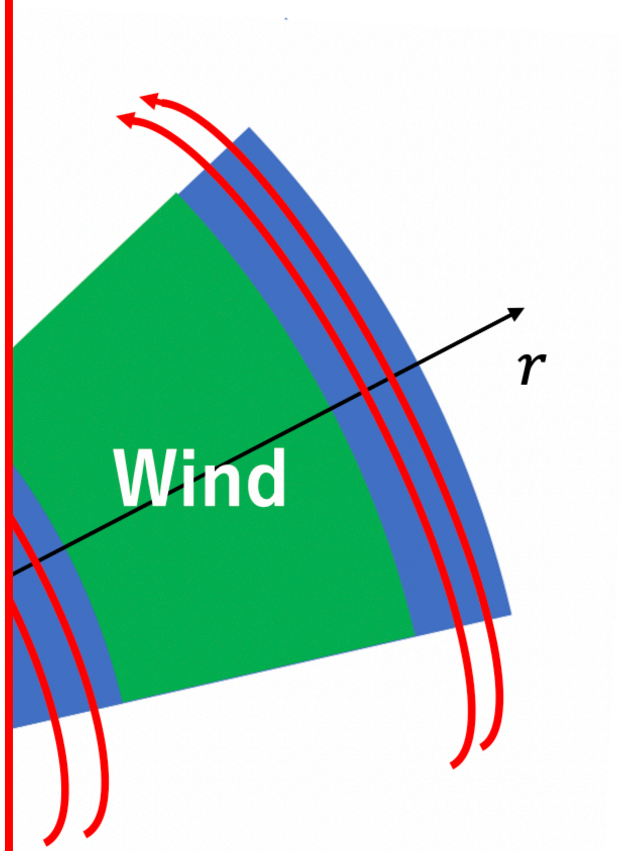


Our model may explain

- σ problem
- γ-ray variability
- X-ray polarization
- Particle acceleration

and so …



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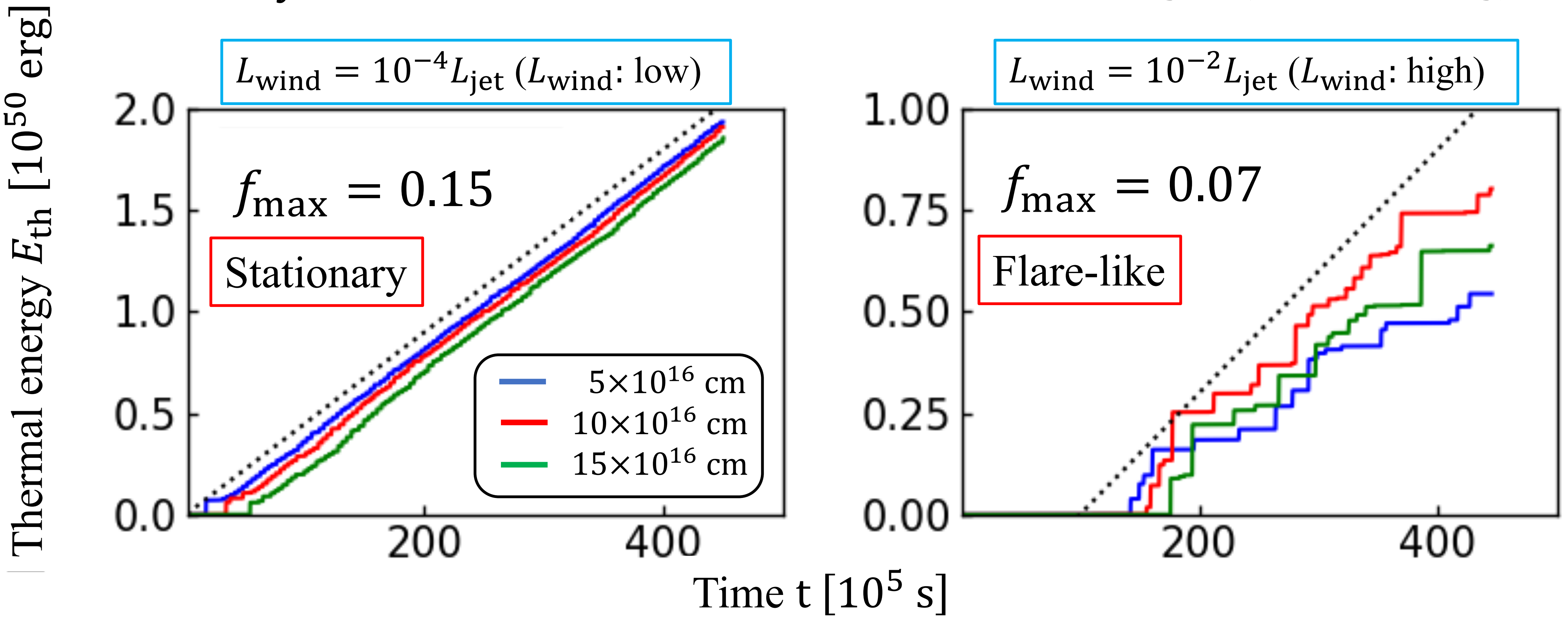
Backup

Dissipation Efficiency

BL lac：$\sigma \ll 1, \Gamma \sim 10$ (Ghisselini et al., 1993)

$$E_{th}(t) = \int^{t} L_{th}(t', R; \sigma < 1, \Gamma > 5) dt'$$

$$f = \frac{\text{Time averaeged } E_{th}}{\text{Average injection energy}}$$



Dissipation Efficiency

Model	η	$t_{\rm wind}$	$f_{\rm max}$	Behaviour
A	10^{-4}	$(1 \pm 0.1)t_w$	0.15	stationary
B	10^{-2}	$(1 \pm 0.1)t_w$	0.07	flare-like
C	10^{-3}	$(1 \pm 0.1)t_w$	0.12	both
D	10^{-3}	$(1 \pm 0.1)t_w/2$	0.075	stationary

$$\eta = \frac{L_{wind}}{L_{jet}}$$