Modeling M87 with Relativistic Radiation MHD and Electron Thermodynamics

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Part of NSF TCAN horizon collaboration
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OUTLINE

- Motivation: Heating and Cooling in M87
- Numerical Technique
- M87 Model

Heating and Cooling Estimates

For M87:

$$m \equiv \frac{M}{M_\odot} = 6.6 \times 10^9,\ \dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm Edd}} = 10^{-5},\ \beta = 20\ \left(\alpha = \frac{1}{2\beta}\right),\ \frac{T_p}{T_e} = 3\ \text{at}\ r \equiv \frac{Rc^2}{GM} = 10$$

Accretion timescale: $t_{\rm acc} \simeq 7 \times 10^{-6} \alpha^{-1} m r^{3/2}$ s

Heating

Coulomb collisions

$$t_{ep} \simeq 3 \times 10^{-5} \alpha \Theta_e^{3/2} m \dot{m} r^{3/2}\ \text{s}$$

Assuming plasma instabilities keep separate species near thermal

$$t_{ep}/t_{\rm acc} \sim 10^4$$

➡ Two-temp

Cooling

$$L_{\rm synch} = \int d\nu d\Omega j_\nu$$

$$L_{\rm Compt} = \left(\frac{\Delta E_\gamma}{E_\gamma} N_{\rm scatt}\right) L_{\rm synch}$$

$$t_{\rm cool} \simeq E/(-dE/dt)$$

$y \sim 10$ ➡ Compton important

$$t_{\rm cool}/t_{\rm acc} \sim 0.1$$

➡ Cooling important

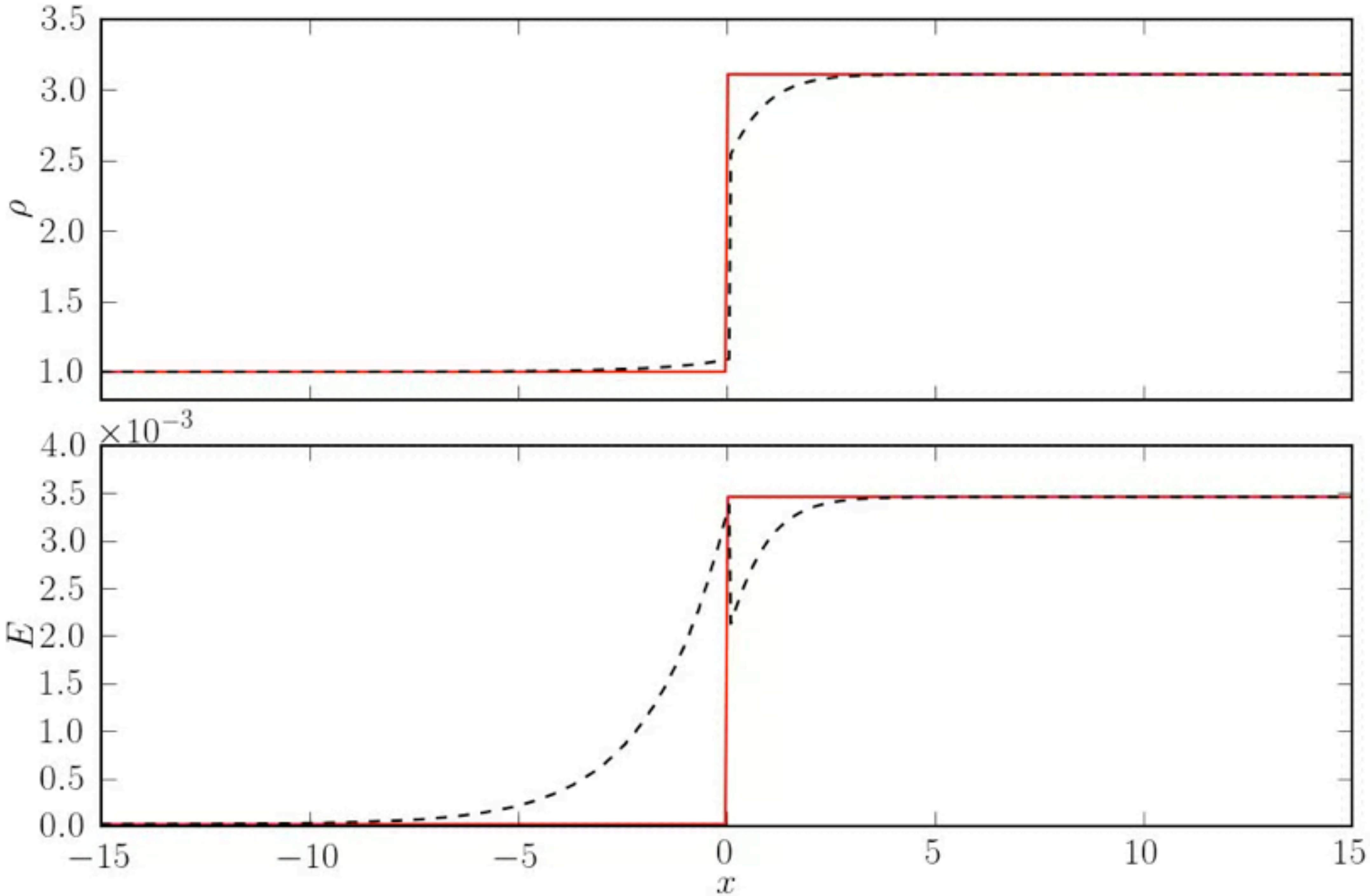
Narayan & Yi 1994, Mahadevan & Quataert 1997

bhlight with electrons

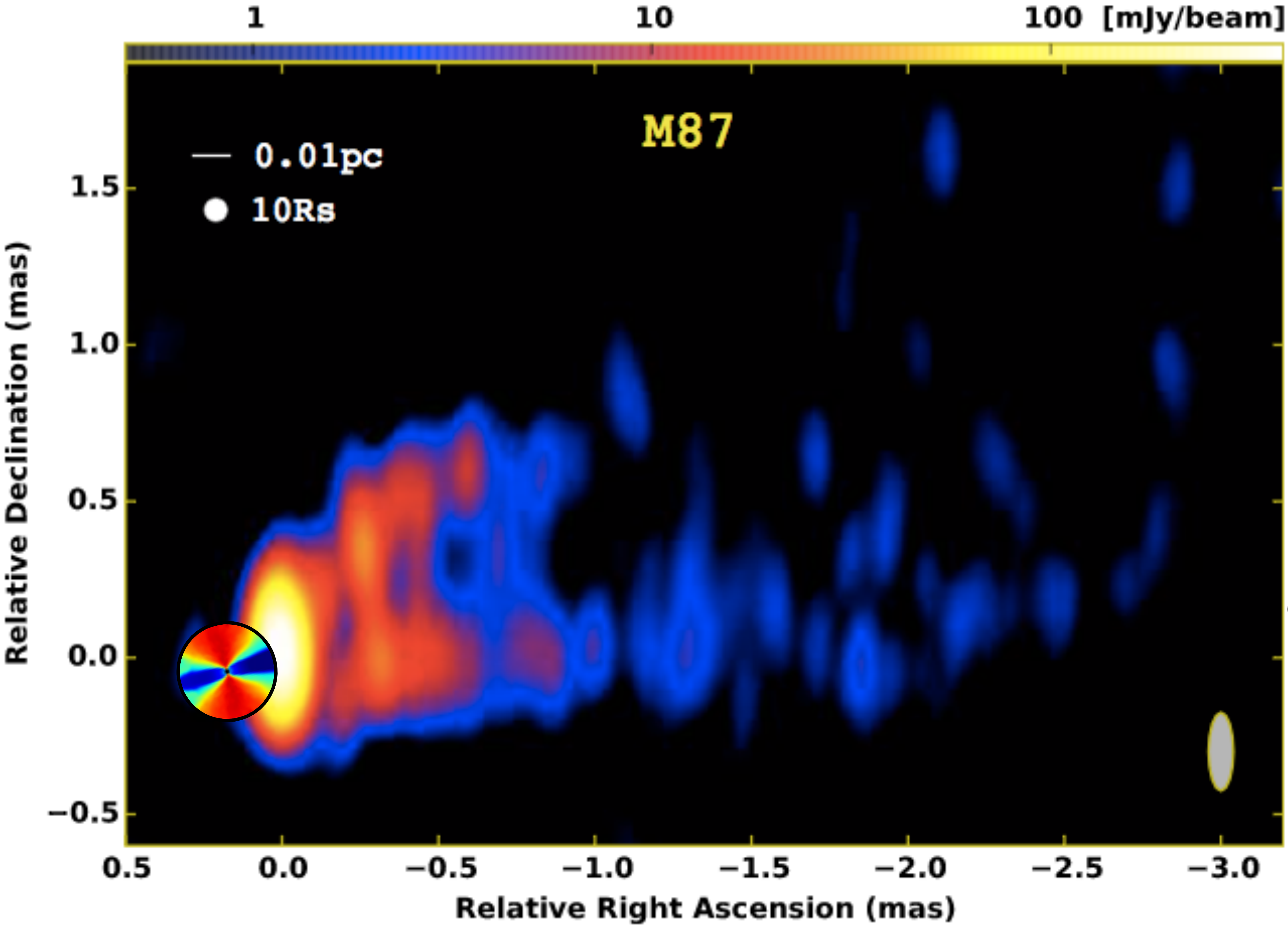
- Numerical approach
- bhlight (Ryan, Dolence & Gammie 2015) General relativistic radiation MHD in stationary spacetimes
  - GRMHD: harm (Gammie, McKinney & Toth 2003)
    - Flux conservative shock-capturing MHD, widely used for black hole accretion
  - Monte Carlo radiation: grmonty (Dolence+ 2009)
    - Full transport solution (emission, absorption, scattering) in curved spacetime
- Collisionless e- heating (Ressler+ 2015, see also Sadowski+ 2016)
  - Alfvenic cascade + linear gyroaveraged damping rates: beta-dependent heating fraction
  - Heating captured by following entropy

bhlight with electrons

Relativistic (Minkowski) radiation hydrodynamic shock (Farris+ 2008)
bhlight versus diffusion solution



Model



Hada, K., Kino, M., Doi, A., et al. 2016, ApJ,

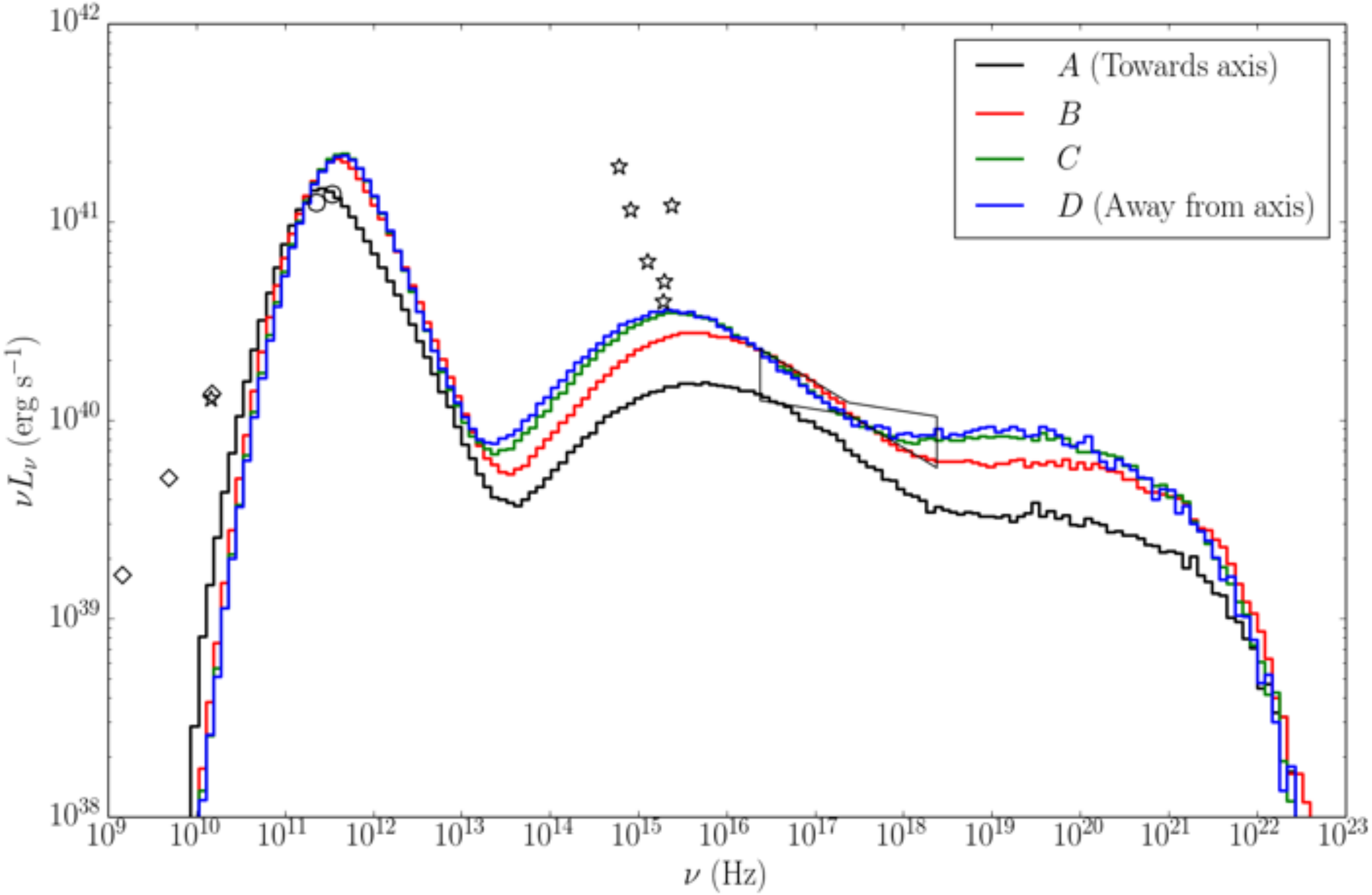
$$M = 6.6 \times 10^9 M_\odot$$

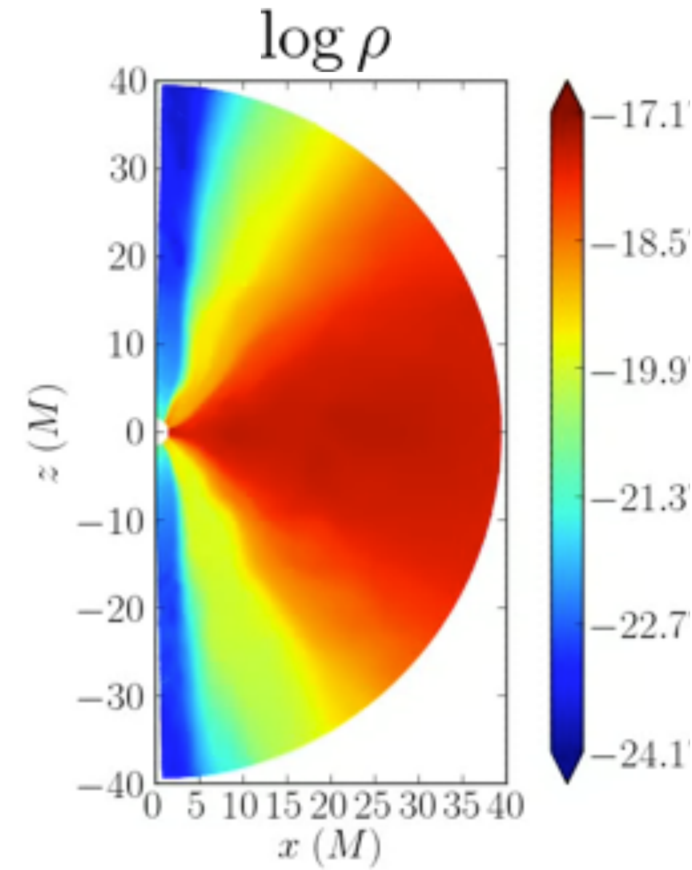
$$a = 0.5$$

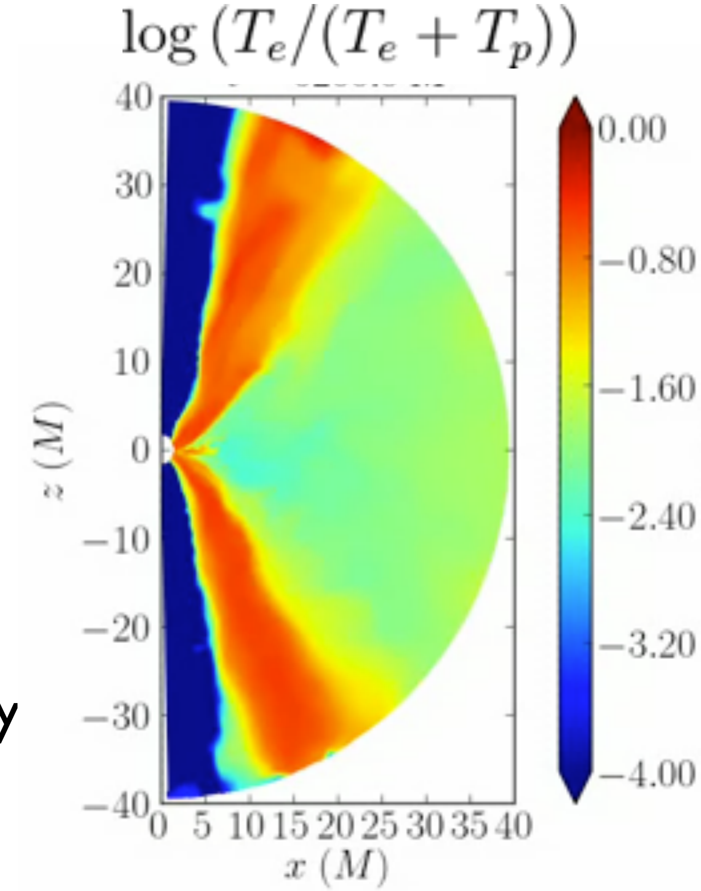
$$\dot{M} \approx 2.3 \times 10^{-5} \dot{M}_{\rm Edd}$$

$$r_{\rm out} = 40\ GM/c^2$$

Model





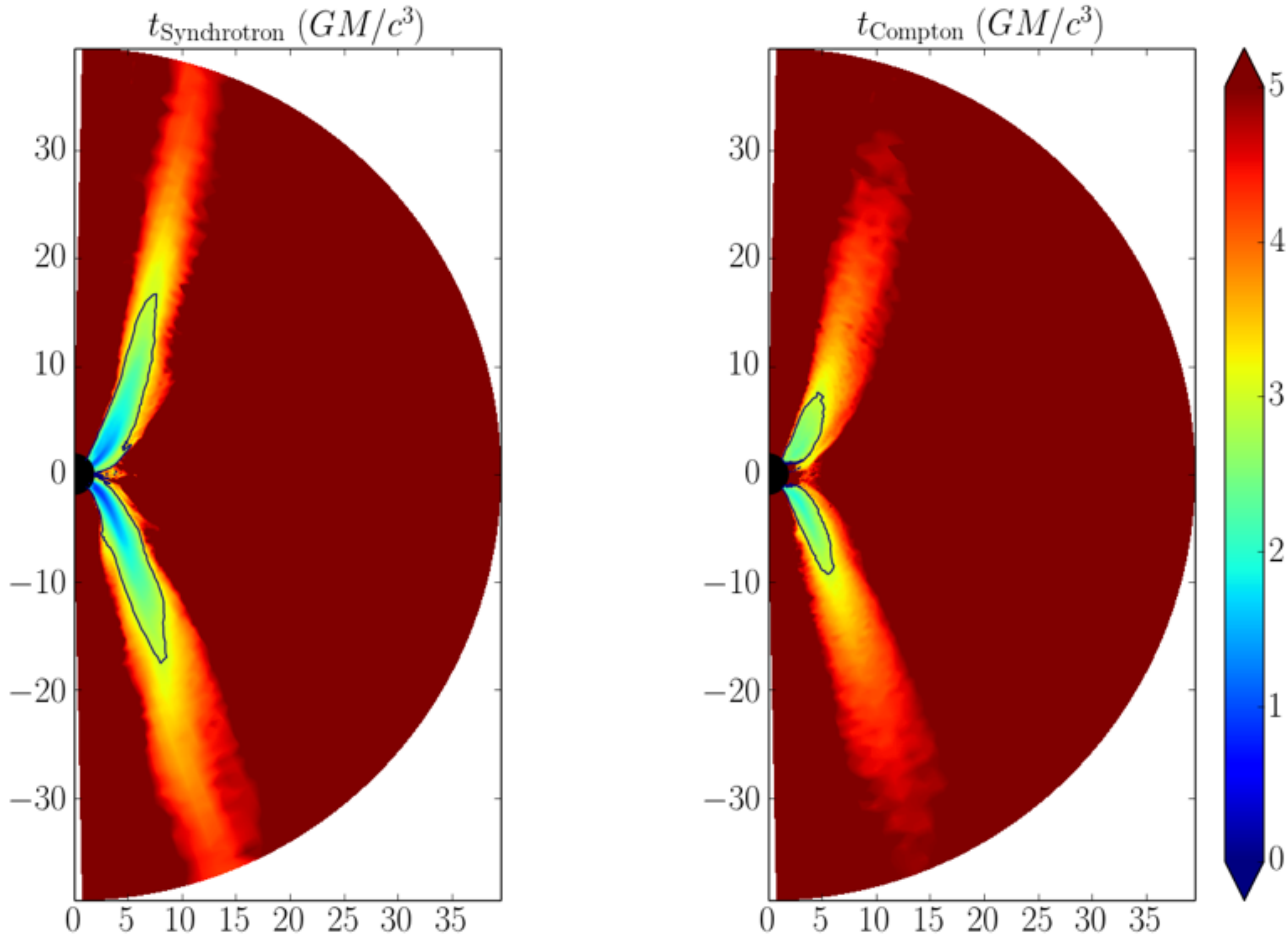


$$\dot{M} \approx 2.3 \times 10^{-5} \dot{M}_{\rm Edd}$$

$$\epsilon \approx 0.6\%$$

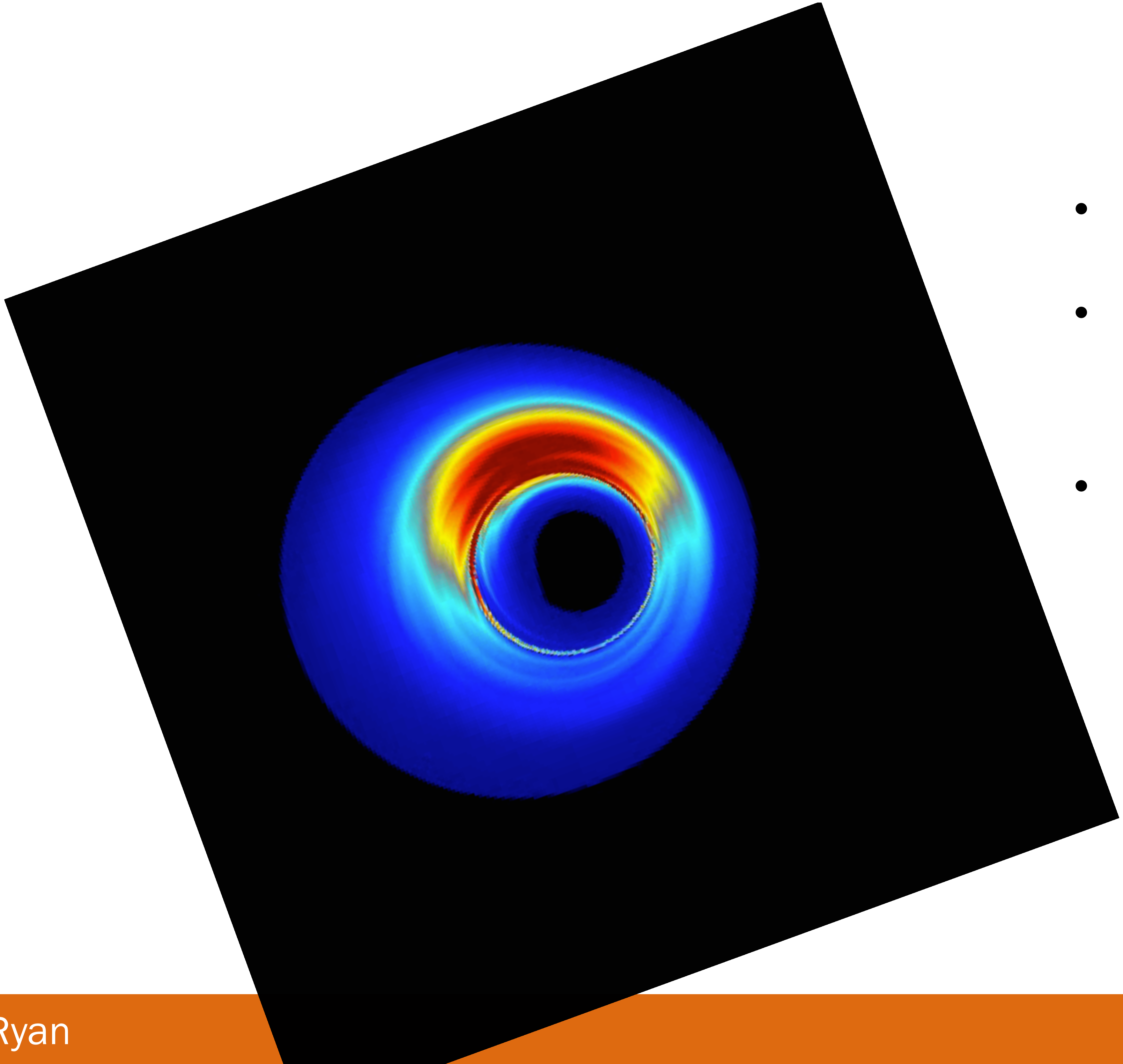
Low frequency: Jet heating? Pressure anisotropy IMPORTANT (Foucart+ 2016)

Optical: Nonthermal population?



Synchrotron dominates Compton 2 to 1

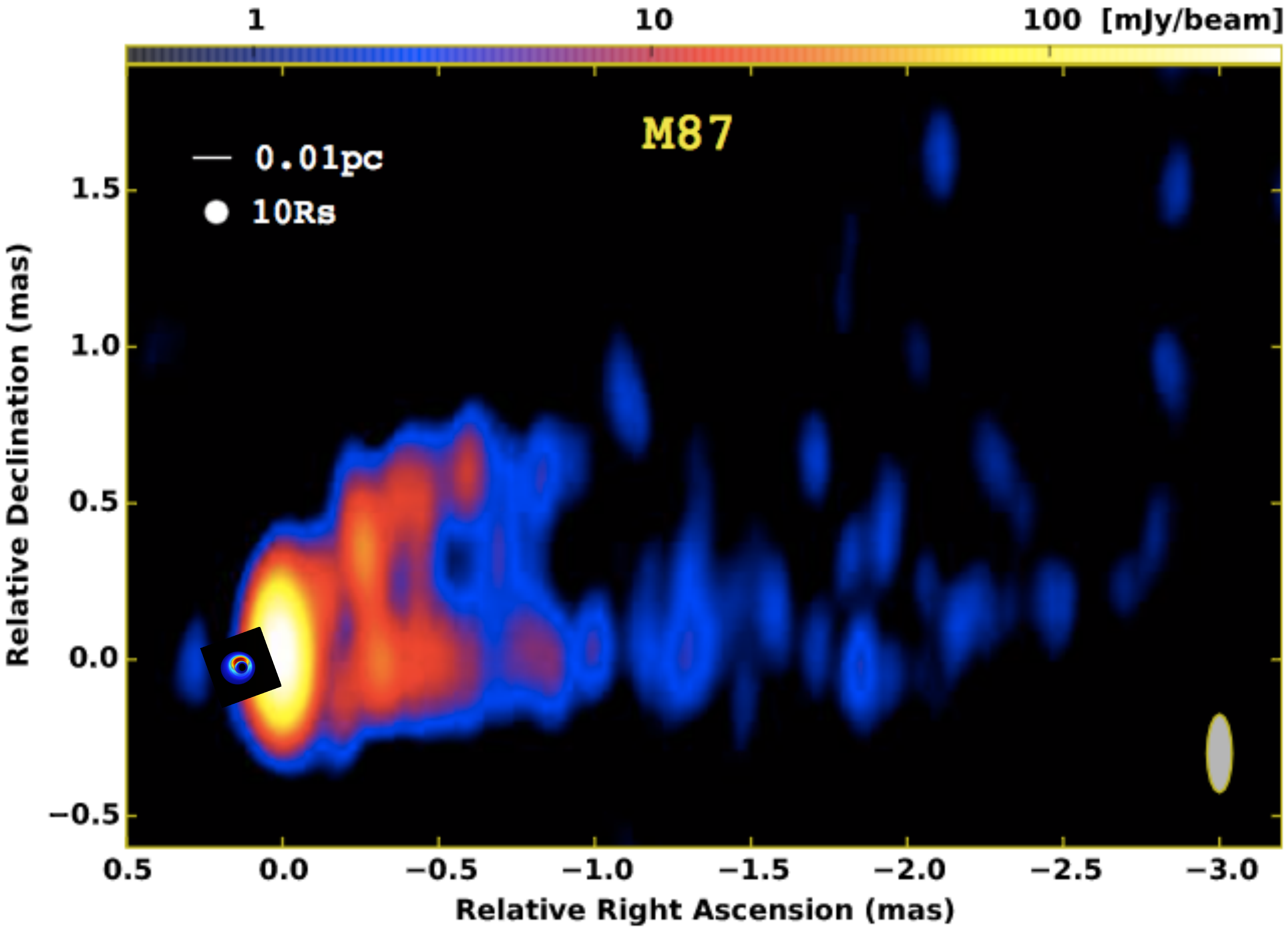
Model



- 230 GHz
- 50 gravitational radii on a side
- 20 degree observer angle

Conclusion

- Radiation and collisionless heating likely important in M87
- Radiative GRMHD model of M87 using frequency-dependent Monte Carlo transport and electron heating
- Need to go further: 3D, MADs, viscosity and conduction, larger domain



Hada, K., Kino, M., Doi, A., et al. 2016, ApJ, 817, 131

STOP

$$
\begin{aligned}
\partial_t \left(\sqrt{-g}\rho u^t\right) &= -\partial_i \left(\sqrt{-g}\rho u^i\right) \\
\partial_t \left(\sqrt{-g}T^t{}_\nu\right) &= -\partial_i \left(\sqrt{-g}T^i{}_\nu\right) + \sqrt{-g}T^\kappa{}_\lambda \Gamma^\lambda{}_{\nu\kappa} + \sqrt{-g}G_\nu \\
\partial_t \left(\sqrt{-g}B^i\right) &= \partial_j \left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right] \\
\partial_i \left(\sqrt{-g}B^i\right) &= 0 \\
P &= (\gamma - 1)\, u
\end{aligned}
$$

$$
\begin{aligned}
\frac{dx^\mu}{d\lambda} &= k^\mu \\
\frac{dk^\mu}{d\lambda} &= -\Gamma^\lambda{}_{\mu\nu} k^\mu k^\nu \\
\frac{D}{d\lambda}\left(\frac{I_\nu}{\nu^3}\right) &= \left(\frac{\eta_\nu}{\nu^2}\right) - (\nu\chi_\nu)\left(\frac{I_\nu}{\nu^3}\right)
\end{aligned}
$$

$$
G_\mu \equiv R^\nu_{\mu;\nu} = \frac{1}{h^3}\int \frac{d^3p}{\sqrt{-g}p^t} p_\mu \left[(\nu\chi_\nu)\left(\frac{I_\nu}{\nu^3}\right) - \left(\frac{\eta_\nu}{\nu^3}\right)\right]
$$

$$
\begin{aligned}
\partial_t \left(\sqrt{-g}\rho u^t \kappa_e\right) &= -\partial_t \left(\sqrt{-g}\rho u^i \kappa_e\right) + \frac{\sqrt{-g}(\gamma_e - 1)}{\rho^{\gamma-1}}\left(f_e Q_H + Q_R\right) \\
Q_H &= \frac{\rho^\gamma}{\gamma - 1} u^\mu \partial_\mu (P\rho^{-\gamma}) \\
Q_R &= u^\mu G_\mu
\end{aligned}
$$