Black hole jet reactivation through magnetic polarity reversal in GRMHD simulations

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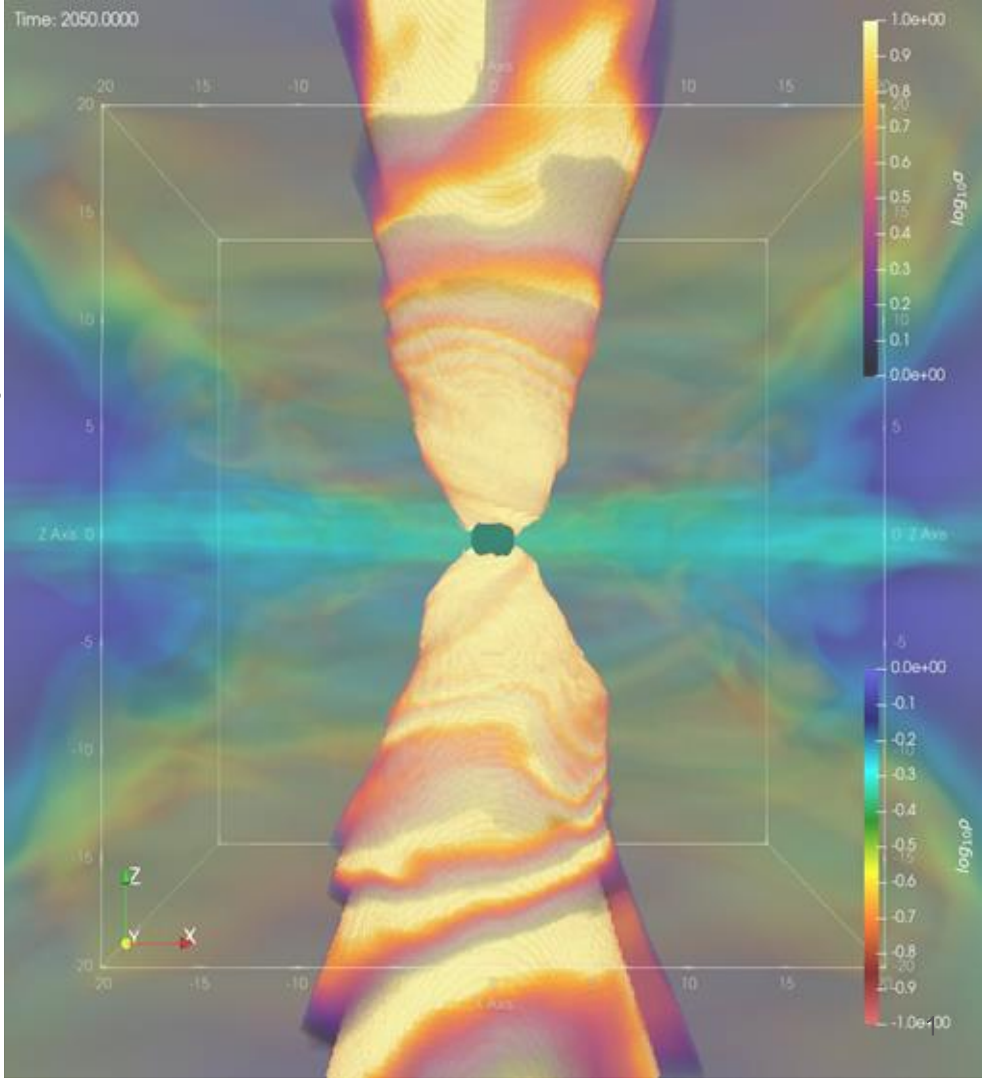
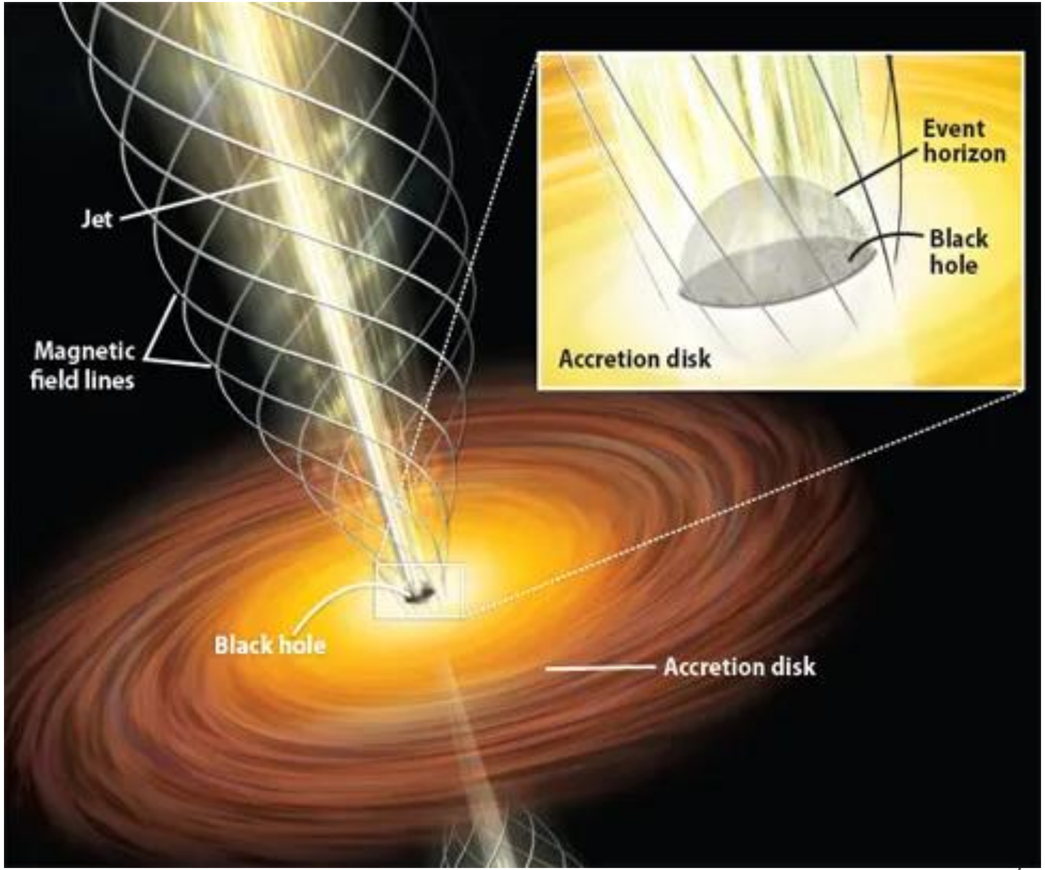
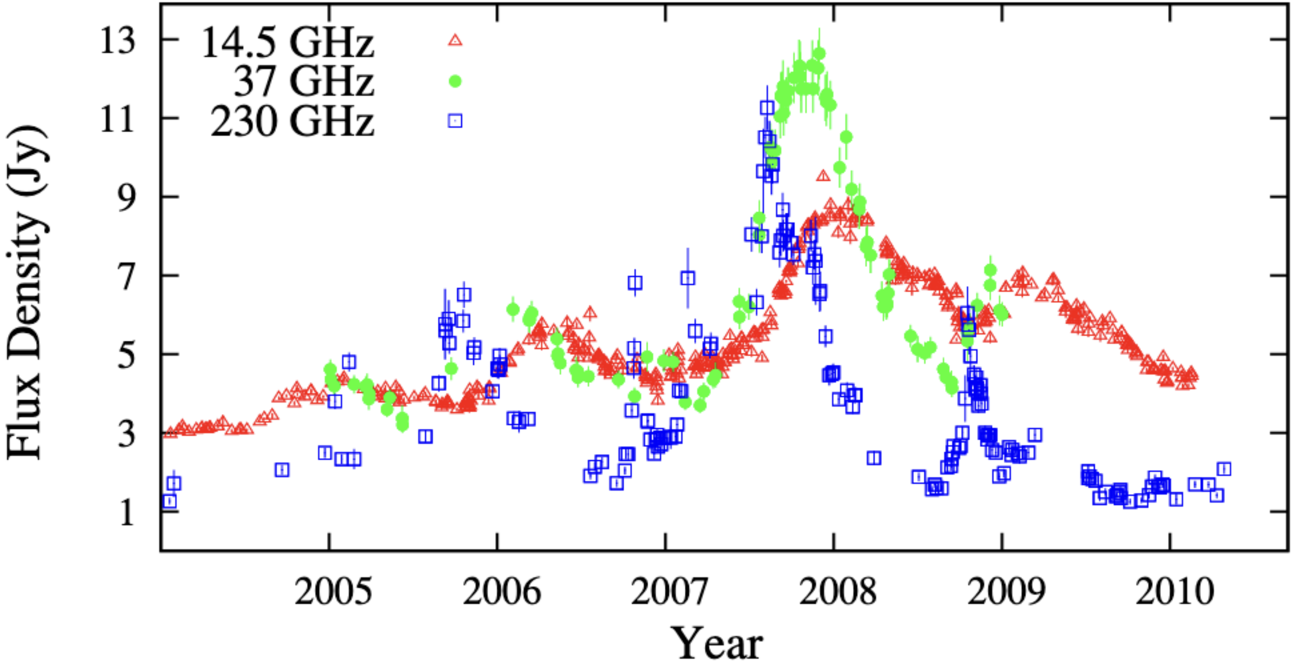


Jets from Black Holes

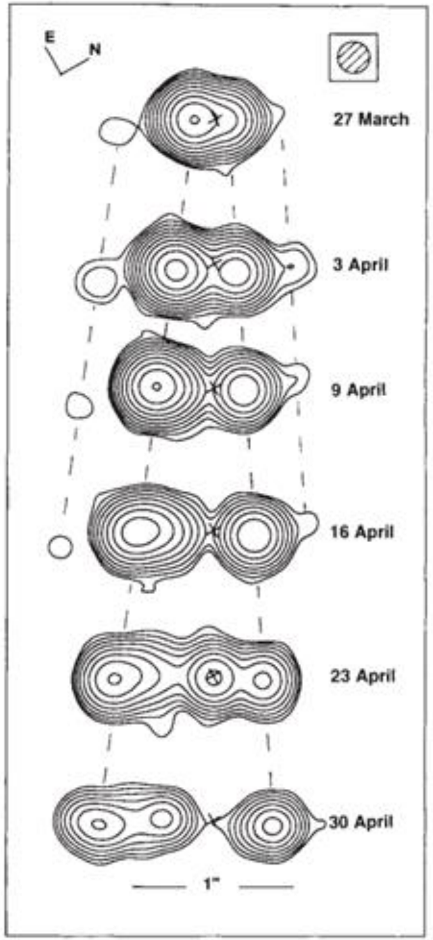
- Collimated outflows that carry energy to parsec scales
- Powered by black hole rotation and accreted net poloidal flux on the horizon – Blandford-Znajek mechanism



Motivation



3C 111[1]
(AGN)



GRS 1915+105[2]
(X-ray binary)

[1] Chatterjee R. et al., 2011, ApJ, 734, 43
[2] Rodriguez, L. F. and Mirabel, I. F., 1995, PNAS, 92, 25

Magnetic Polarity Reversals in GRMHD simulations

- Kaaz et.al 2025: GRMHD simulation starting with initial conditions from cosmological simulations

- Chan et.al 2026: Collapsar simulation with jets forming

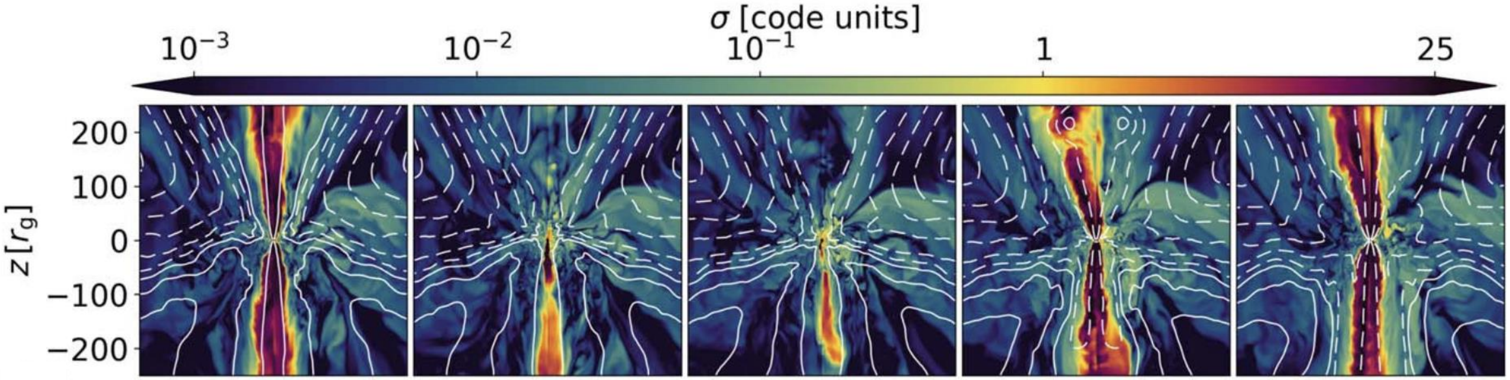


Figure from Kaaz et.al 2025

GRMHD simulation – Grid setup

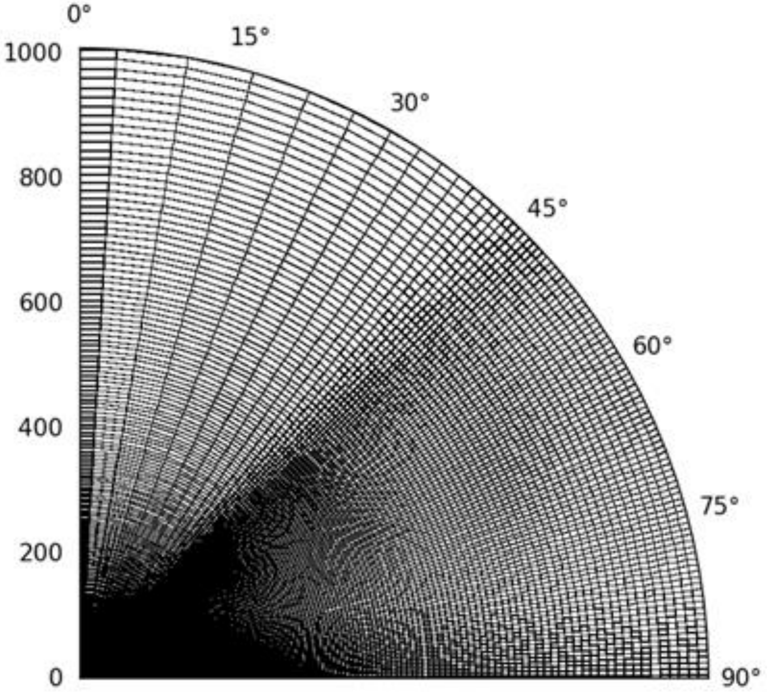
- Ideal Magnetohydrodynamics (MHD) in Kerr spacetime (a = 15/16)

- KHARMA →GPU accelerated GRMHD solver

- $\theta = \frac{\pi}{2}\left[1 + f_{lin}(2x^{\theta} - 1) + (1 - f_{lin}) \times \left\{\tanh\left(\frac{x^{\theta} - 1}{\lambda}\right) + 1\right\} - (1 - f_{lin})\left\{\tanh\left(-\frac{x^{\theta}}{\lambda}\right) + 1\right\}\right]$

- $N_r \times N_\theta \times N_\phi = 420 \times 192 \times 128$ (e.g R32)

- $N_r \times N_\theta \times N_\phi = 732 \times 256 \times 256$ (e.g R32H)

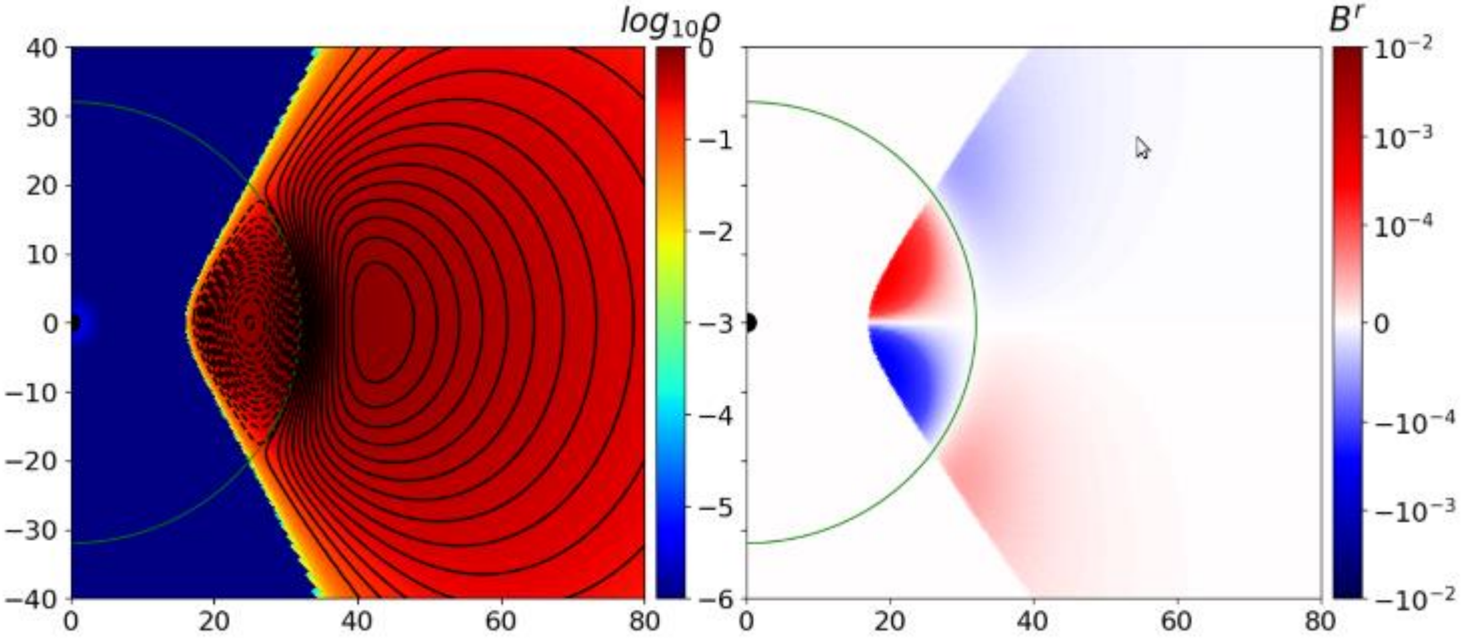


Grid example in 2D

GRMHD simulation – Initial Conditions (R32)

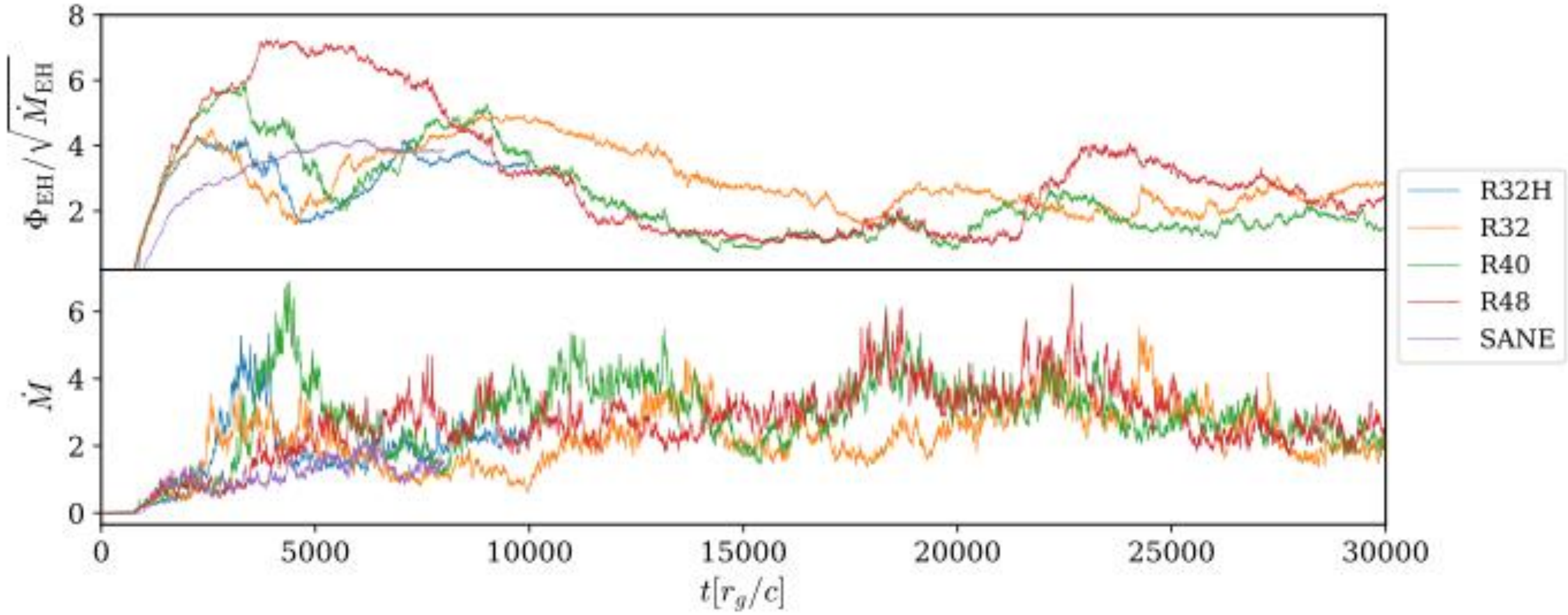
- Alternate initial magnetic polarity with $\beta_{min} = 100$

- Sign flip at : $r_{inv} = 32r_g, 40r_g, 48r_g$ (R32, R40, R48)



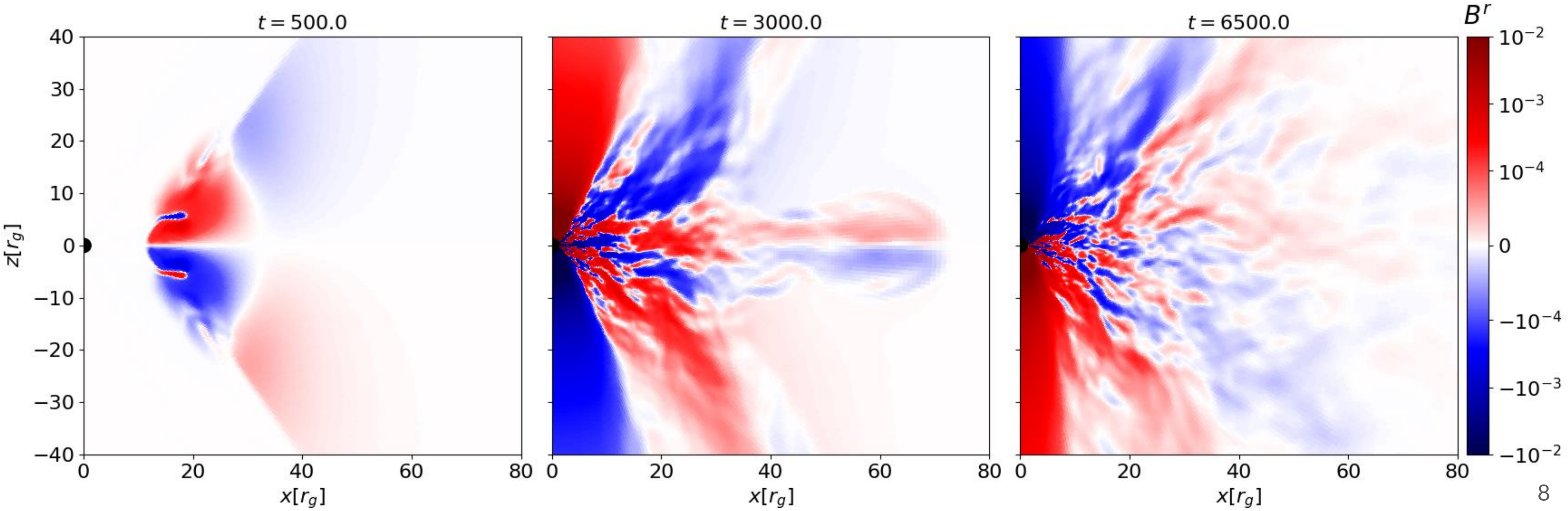
Results – Accretion History

- Standard-and-normal-evolution (SANE) for all cases
- Higher accretion rate in all cases compared to baseline SANE simulation

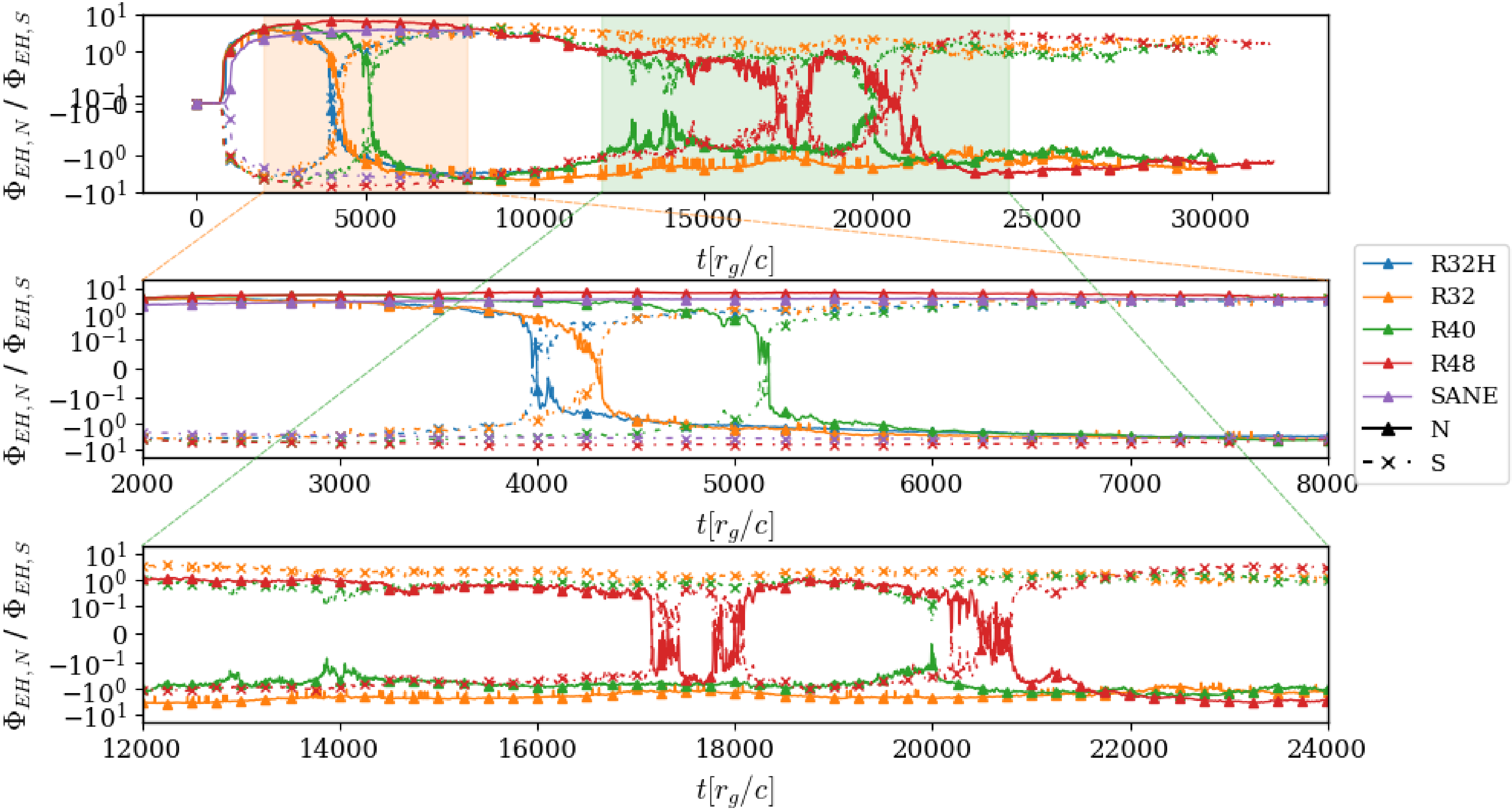


R32 – Phi-Averaged Maps of B^r (show R32H)

- Initial B^r evolution for R32
- Part of the inertial reservoir of magnetic flux are pushed out due to instabilities
- Inversion timing may differ due to the location of the reservoir



Accretion History – Zoom in

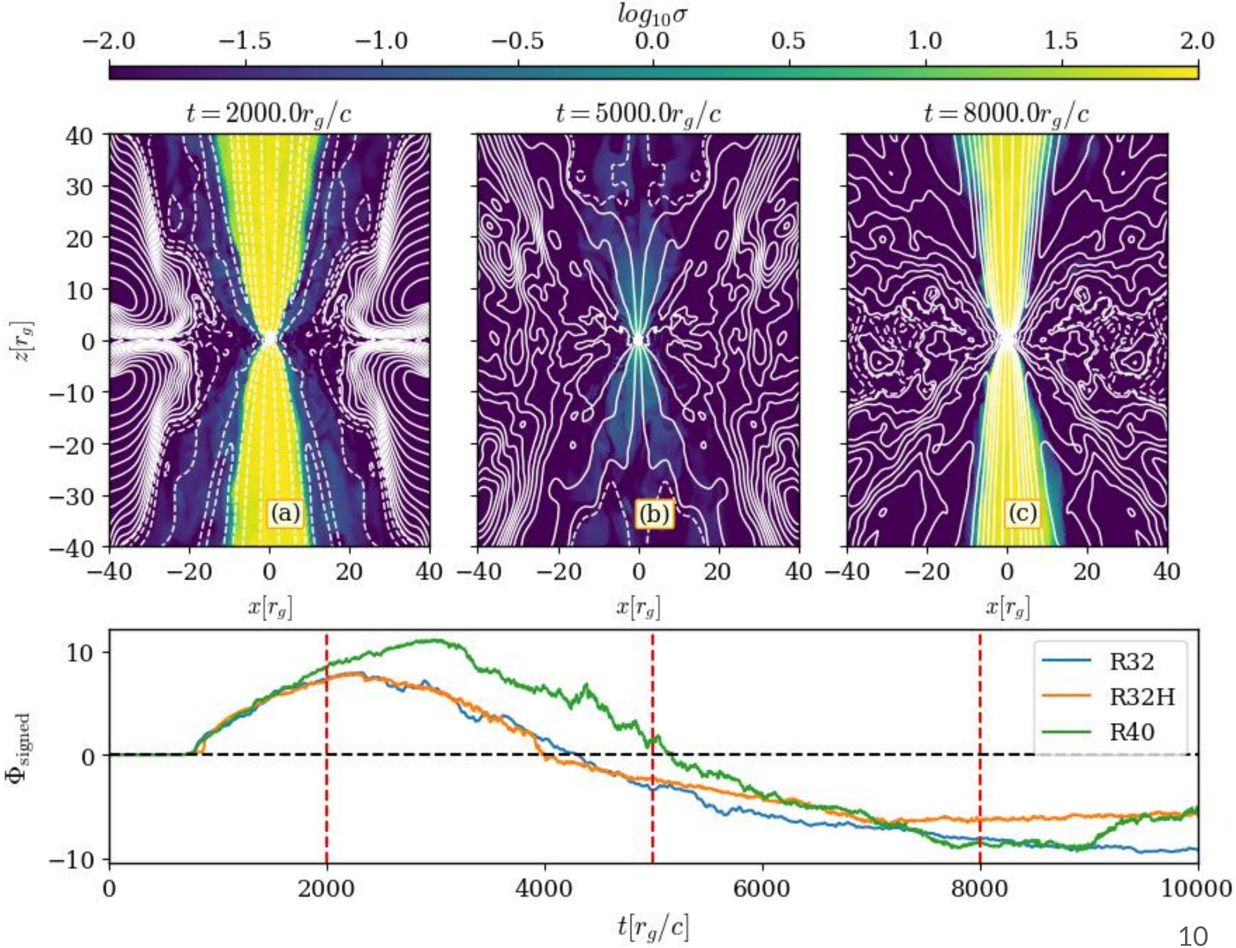


Polarity reversal – Side View of R32H

- Side view of magnetization $\sigma = b^2/\rho$ with magnetic field lines overplotted
- Signed magnetic flux:

  $$\Phi_{\text{signed}} = \Phi_{NH} - \Phi_{SH}$$

- Vertical red dotted line represents the time on the side view while black horizontal dotted line refers to $\Phi_{\text{signed}} = 0$



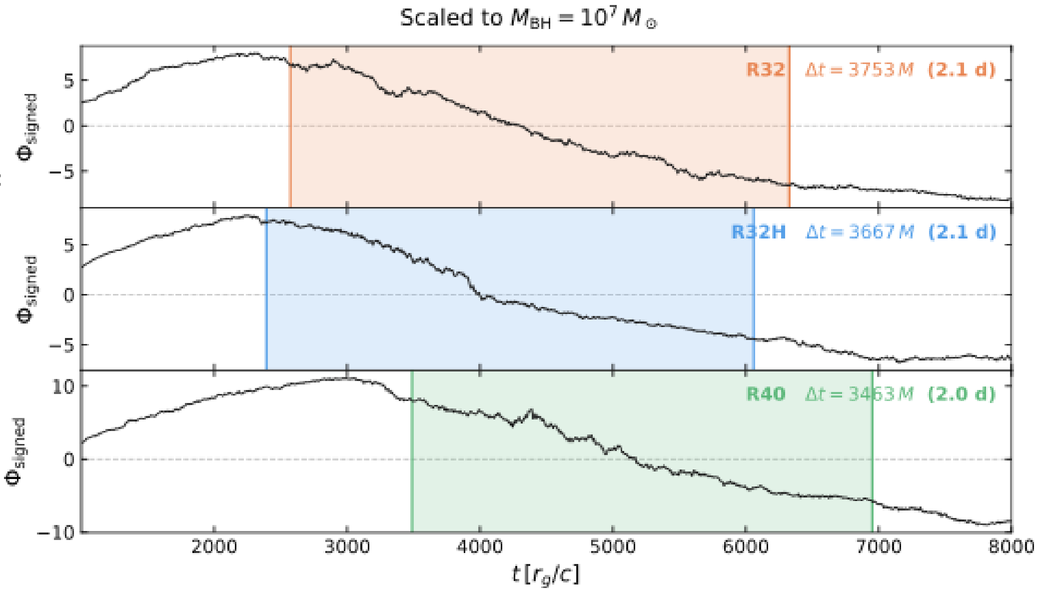
Reversal Timescale – R32 & R40

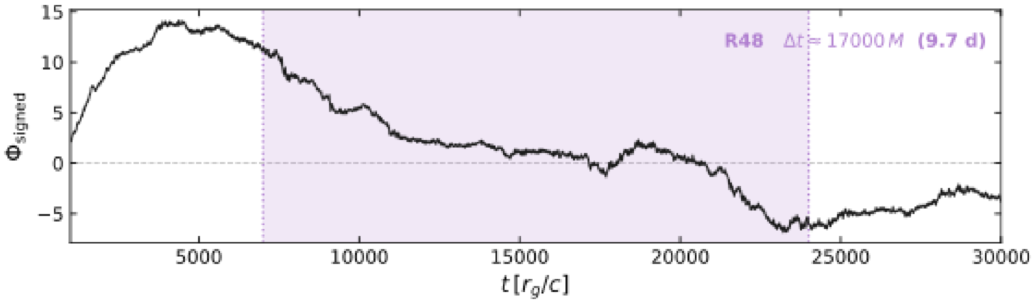
- Fit with the equation ($\Phi_{signed}(t_0) = 0$):

  $$\Phi_{signed} = A \tanh\left(\frac{t - t_0}{\Delta t/2}\right)$$

- When scaled to $M = 10^7 M_{\odot}$, R32, R40 and R32H all has similar inversion timing of ~ $\Delta t = 3600M(\sim 2days)$

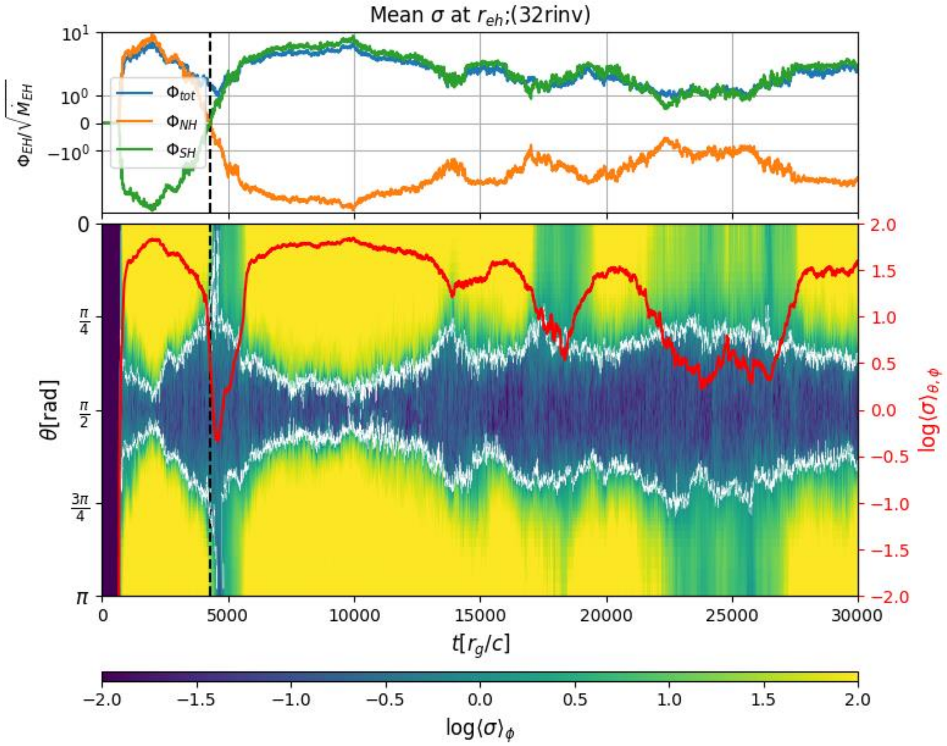
- Rough estimate for R48 inversion timing is $\Delta t \approx 17000M(\sim 10days)$

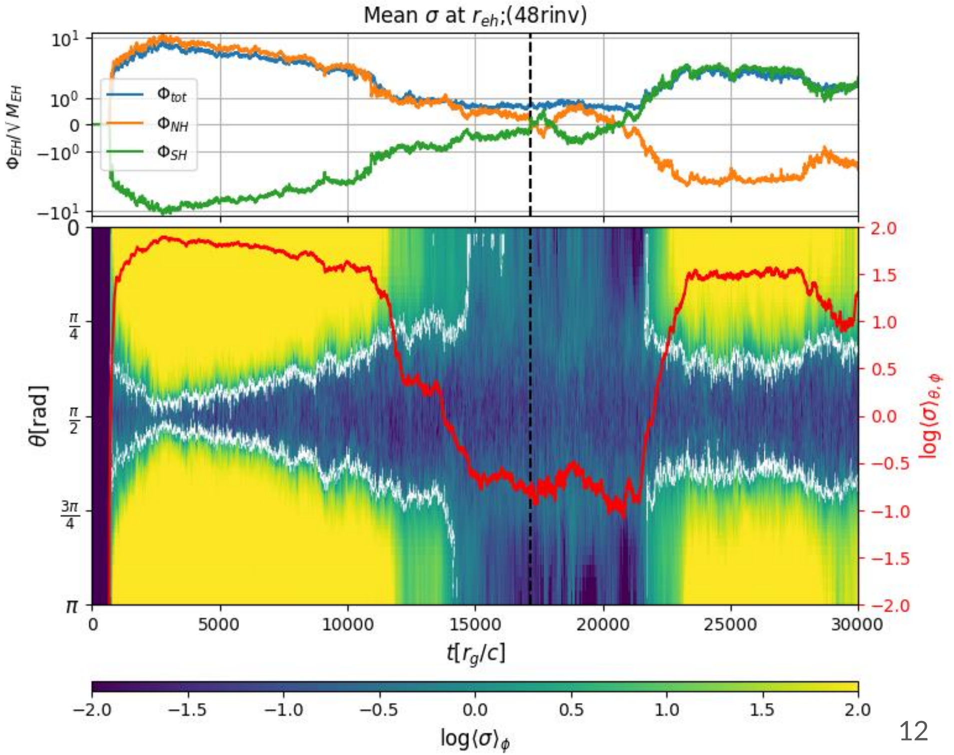




Magnetization $\sigma(t, \theta)$ at the Horizon

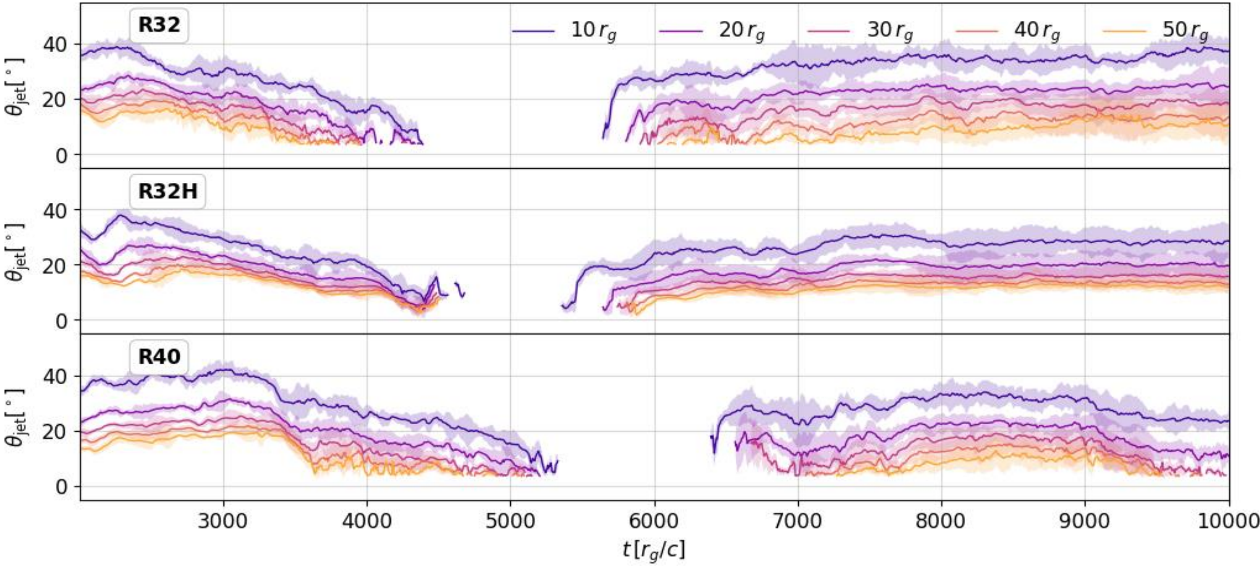
- Red line represents the averaged magnetization $\sigma(t)$
- Vertical dotted line represents the time where the $\Phi_{signed} = 0$
- Time asymmetry near the dotted line for the $\sigma(t)$ observed for R32, R32H and R40

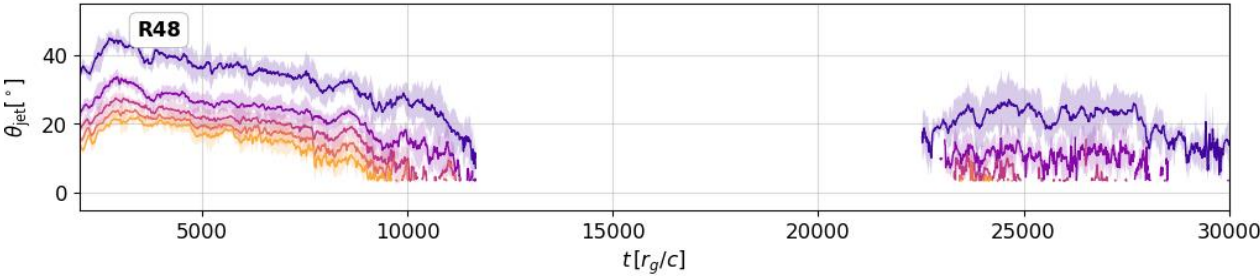




North Jet opening angle

- Jet opening angle obtained at 5 different radius
- Angle is determined by taking the mean of the $\sigma = 1$ contour along the ϕ direction
- Opening angles for lower resolution runs are generally larger and has bigger spread
- Relaunched-jet from R48 does not extend to larger radii
- Funnel geometry recovers faster than the magnetization





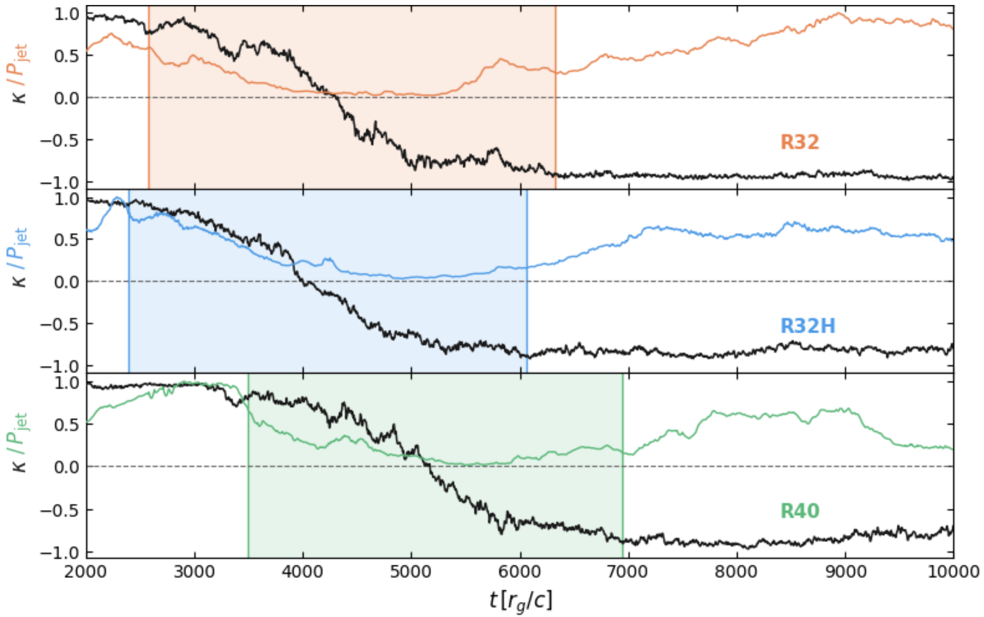
Jet Power vs Magnetic Flux Coherence

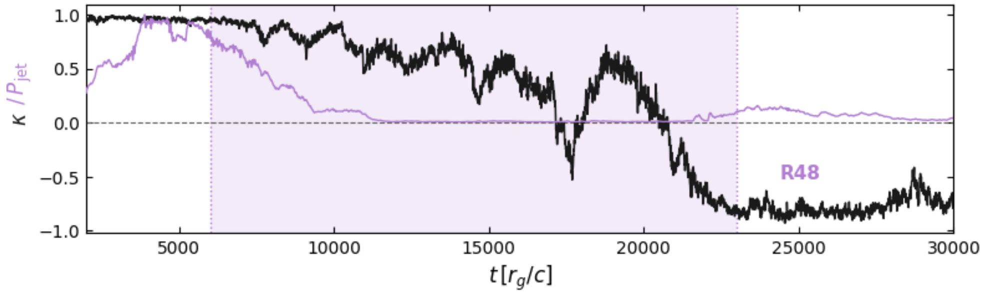
- Magnetic flux coherence (black line):
$$\kappa = \frac{\int_0^{NH} B^r \sqrt{-g}\, d\theta d\phi}{\int_0^{NH} |B^r| \sqrt{-g}\, d\theta d\phi}$$

- Normalized jet power measured at $r = 20 r_g$ and masked with $\theta \leq 30°$ (color lines)

- Jet appears when $\kappa >\approx 0.7$.

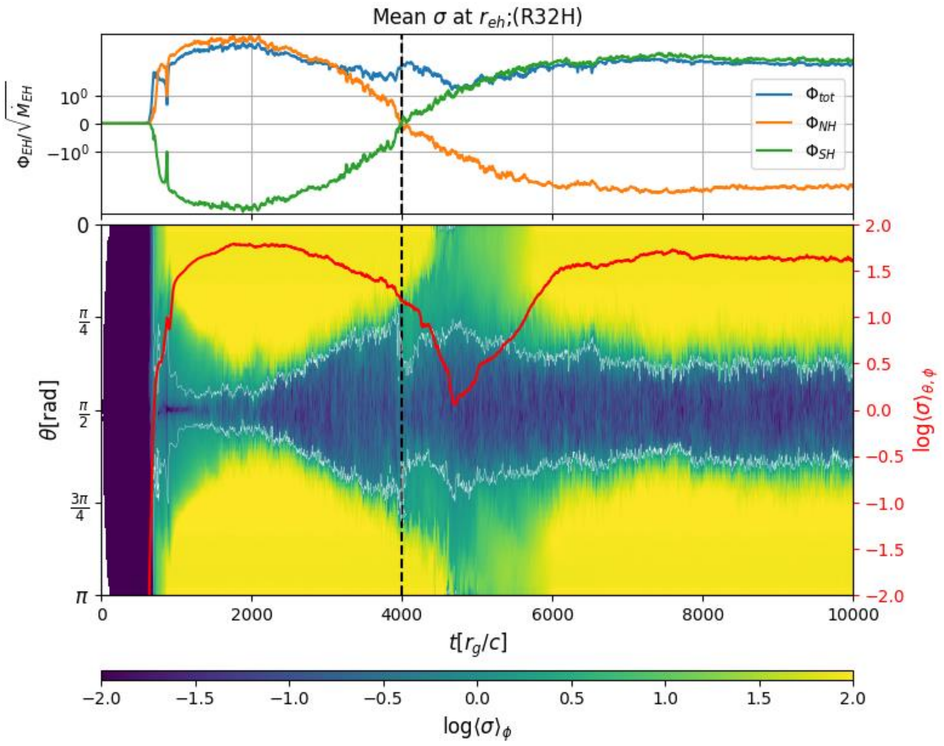
- R48 has a failed restart at $t \approx 19000$ and has a weak jet after reversal



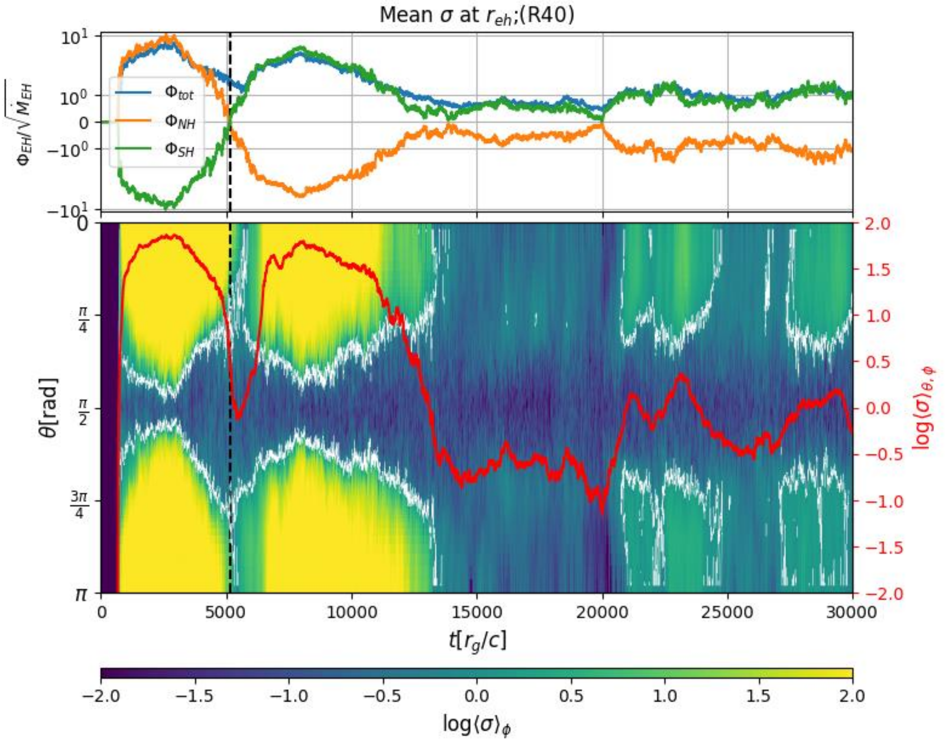


Summary

- We investigated the main drivers of jet reactivation using GRMHD simulations
- Multiple sets of initial conditions have been explored to study jet reactivation process.
- Jet reversal proceeds smoothly if the incoming poloidal flux remains coherent.
- Jet reversal process is time-asymmetric – flux is destroyed by reconnection, but must be rebuilt by advection.
- 2 version of reversal process observed, where one has a longer dormant jet-less period.



Mean σ at r_{eh};(R32H)
$\Phi_{EH}/\sqrt{\dot{M}_{EH}}$
Φ_{tot}
Φ_{NH}
Φ_{SH}
θ[rad]
$\log\langle\sigma\rangle_{\theta,\phi}$
$t[r_g/c]$
$\log\langle\sigma\rangle_{\phi}$



Mean σ at r_{eh};(R40)
$\Phi_{EH}/\sqrt{\dot{M}_{EH}}$
Φ_{tot}
Φ_{NH}
Φ_{SH}
θ[rad]
$\log\langle\sigma\rangle_{\theta,\phi}$
$t[r_g/c]$
$\log\langle\sigma\rangle_{\phi}$

South Jet opening angle