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Interactions of torus and unmagnetized stellar wind around a black hole

Two-dimensional GRMHD simulations with constant, periodic and decaying mass injection

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Black holes are often fed by winds, not disks

High-mass X-ray binaries

A compact object captures part of the line-driven wind of an OB companion; clumpy winds are linked to the flaring of supergiant fast X-ray transients.

Symbiotic binaries

A white dwarf captures the slow wind of an evolved red-giant companion, at lower accretion rates.

Sagittarius A*

Fed mainly by the winds of young massive stars, studied from semi-analytic models to horizon-scale GRMHD.

Tidal disruption events

The fallback supply declines with time, motivating declining injection profiles.

The captured gas need not share the angular momentum or the magnetization of the flow it joins.

Where this work fits

Low-angular-momentum flows

A simpler model of wind-fed accretion: shocks, outflows and jets (Dihingia & Mizuno 2024; Dihingia et al. 2025, 2026).

Perturbed transonic inflow

Olivares et al. 2023: velocity perturbations injected at 1000 M in hydrodynamics are amplified into a red-noise spectrum.

This work

Mass injection with a prescribed time dependence into a magnetized, MRI-turbulent torus.

AIM

Separate what is generic to external mass loading from what depends on its time dependence.

Numerical setup

CODE

HARM

Ideal GRMHD, constrained transport

GRID

800 × 400

2D axisymmetric, FMKS, h_slope = 0.3

INITIAL TORUS

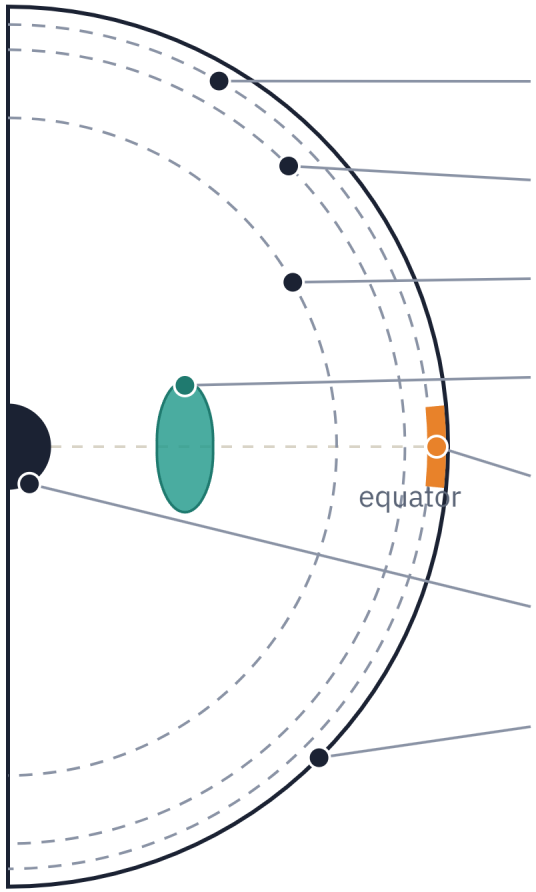
Fishbone–Moncrief

r_in = 12 M, r_max = 25 M, Γ = 5/3

MAGNETIC FIELD

Weak, poloidal

β = 100



900 M
diagnostic radius

600 M
diagnostic radius

200 M
diagnostic radius

Torus
r_in = 12 M, r_max = 25 M

Injection shell
r = 1000 ± 10 M, within 5° of the midplane

Black hole
r_H = 2 M; inner boundary 1.91 M

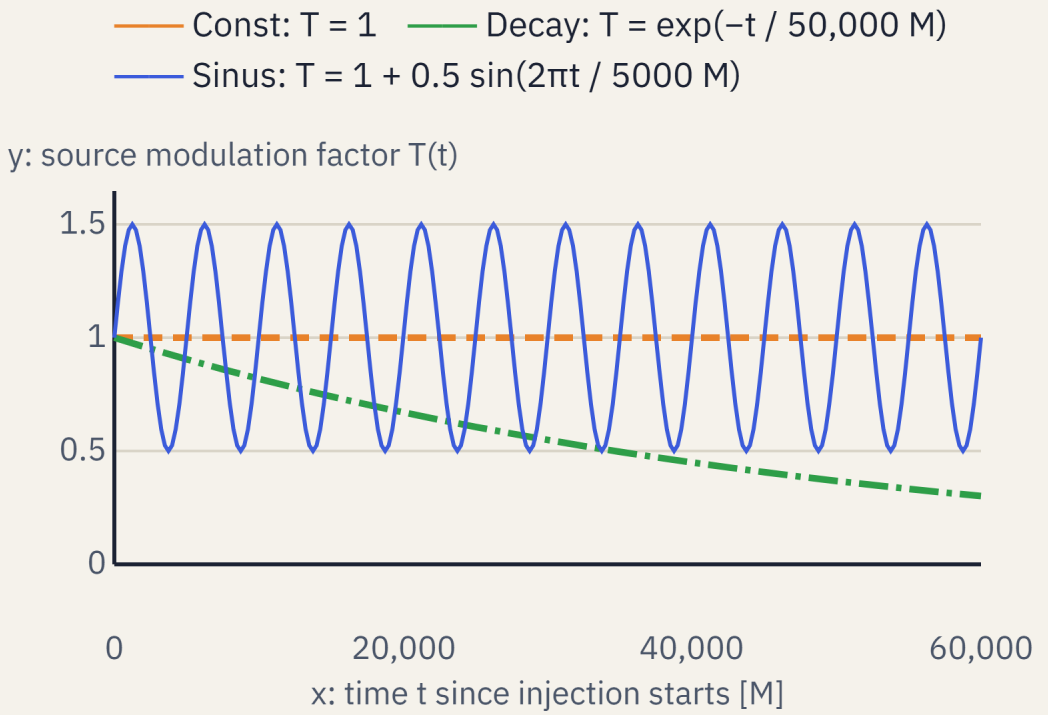
Outer boundary
r = 1200 M

Poloidal half-plane, radius on a log scale (illustrative)

Wind injection: unmagnetized mass at 1000 M

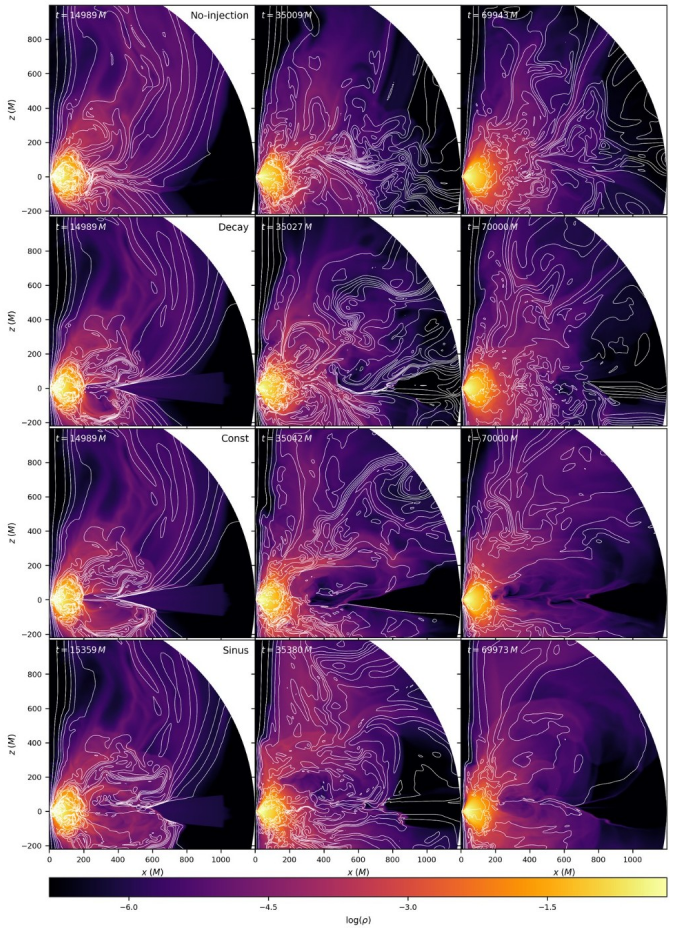
Source term in an equatorial shell

- Shell at r = 1000 ± 10 M, within ±5° of the midplane
- Density $\rho_w = 10^{-7} (r_{inj}/r)^2 T(t)$
- Inflow speed 10^{-3} c $(r_{inj}/r)^{1/2} T(t)$, with zero angular momentum
- Magnetic field untouched: the wind is magnetized only by flux freezing
- No-injection control: same restart, source off





Injected gas leaves the torus bulk undisturbed



Four models, three epochs

No-injection, Decay, Const, Sinus (top to bottom) at t ≈ 15,000, 35,000 and 70,000 M; white contours are field lines.

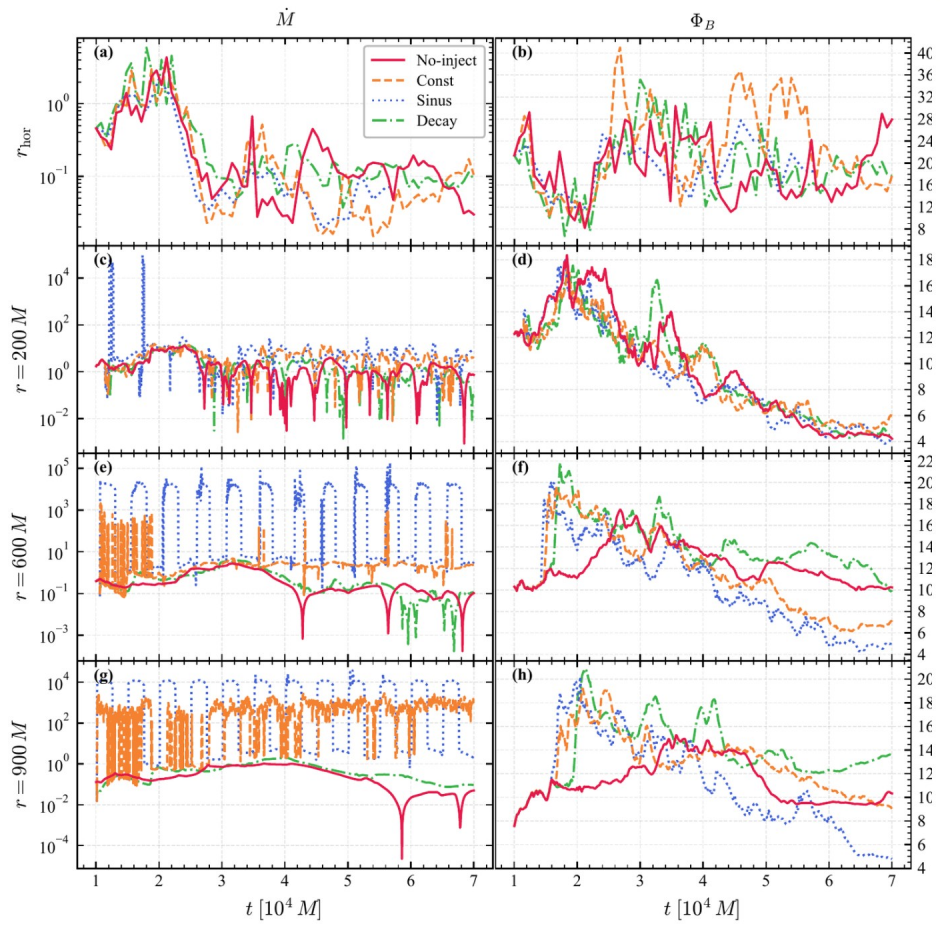
The torus bulk stays put

Dense gas remains near r_max = 25 M; the wind is much less dense than the torus and cannot disrupt it.

But the wind carries no field

The field visibly weakens where the wind arrives, a dynamically minor addition with magnetic consequences.

Large radii feel the modulation strongly



Spikes in Ṁ at 600 and 900 M

For Sinus they recur every 5076 ± 604 M (600 M) and 5051 ± 418 M (900 M): the 5000 M injection period.

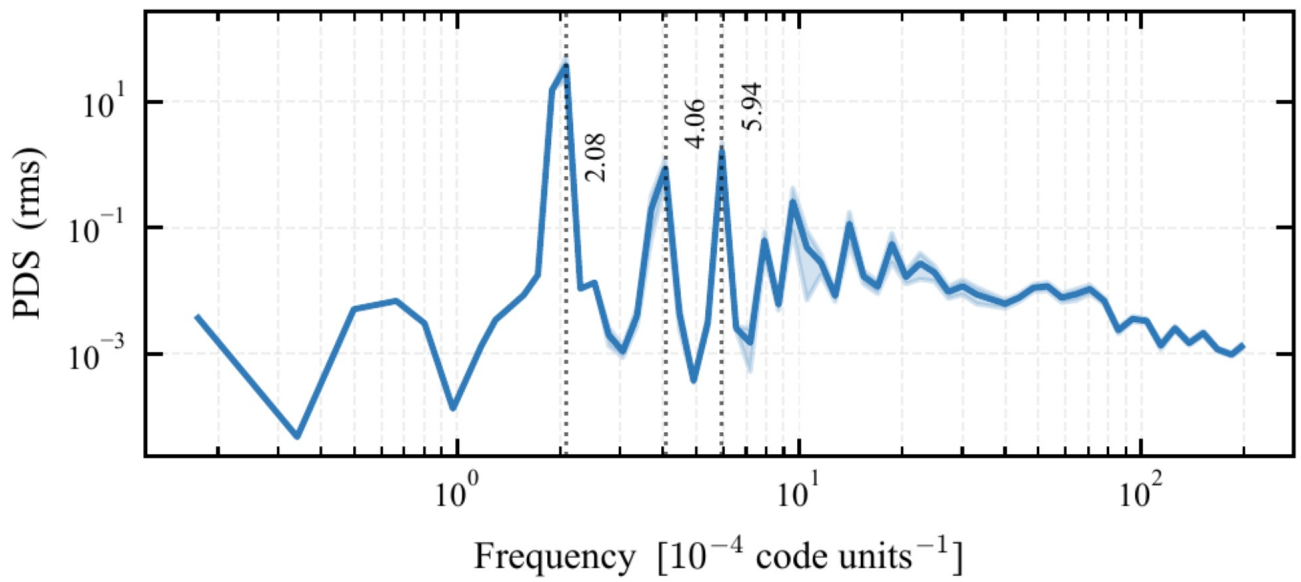
Energy flux at 200 M

Its scatter exceeds the control by ×4.2 (Sinus), ×3.3 (Const) and ×1.3 (Decay).

Magnetic flux Φ_B

At 600 and 900 M it is above the control early, then falls below it for Sinus and Const at late times; all models agree at 200 M.

Periodic injection becomes a harmonic series



Sinus model, $\dot{M}(t)$ at r = 900 M, t = 10,000–70,000 M. Dotted lines mark the three most prominent peaks.

A sinusoidal source is not transmitted as a pure tone: the flow reshapes it.

1.04 · 2.03 · 2.97

strongest peaks, in units of f_drive = 2.0 × 10^{-4} M^{-1} (P = 5000 M)

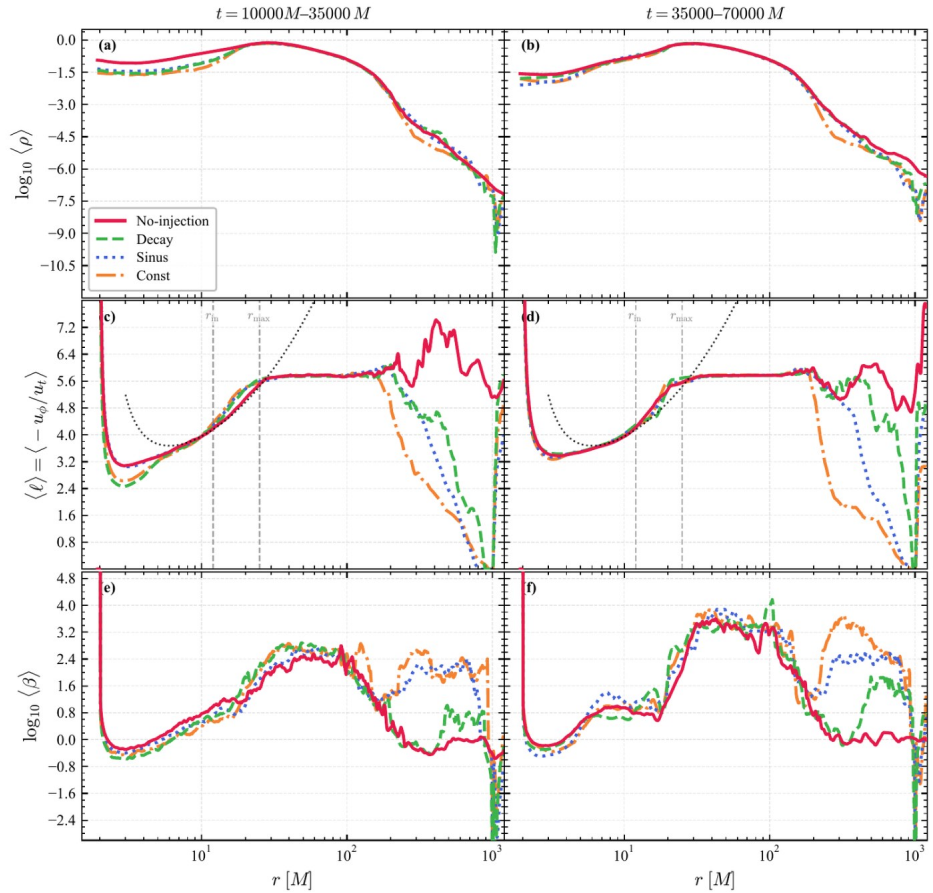
n ≈ 9

harmonic ladder at r = 900 M (n ≳ 5 tentative)

n = 2

at r = 600 M only the fundamental and second harmonic; fourth marginal

The wind lowers angular momentum and weakens the field



Density ⟨ρ⟩

Close to the control; slightly lower for r ≳ 200 M.

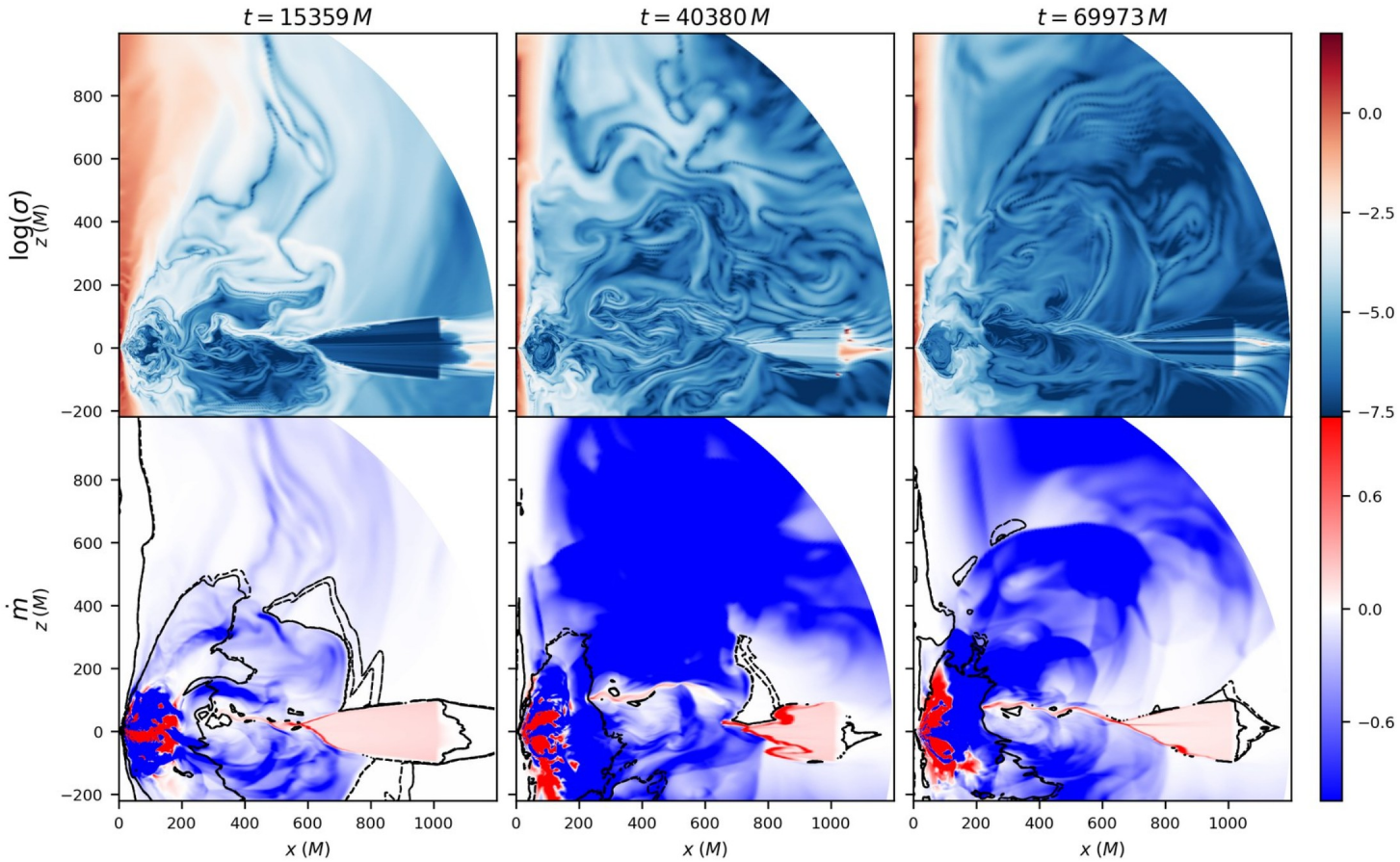
Angular momentum ⟨ℓ⟩

Zero-angular-momentum wind pulls ⟨ℓ⟩ below the control at r ≳ 200 M, most for Const.

Plasma β

Sustained injection raises equatorial ⟨β⟩ by orders of magnitude at r ≈ 300–900 M; all models agree inside r ≈ 100 M.

The outer flow is diluted and unbound



σ falls in the outer disk

Sinus, t = 15,359 → 69,973 M; the funnel stays magnetically dominated. b is the field strength in the fluid frame.

$$\sigma = b^2 / \rho$$

Large radii: outflow

Gas outside the Be = 1 contour is unbound and flows out; the bound torus has mixed inflow and outflow. ε is the gas internal energy, Γ = 5/3.

$$Be = -h\, u_t,\ h = 1 + \Gamma\, \varepsilon / \rho$$

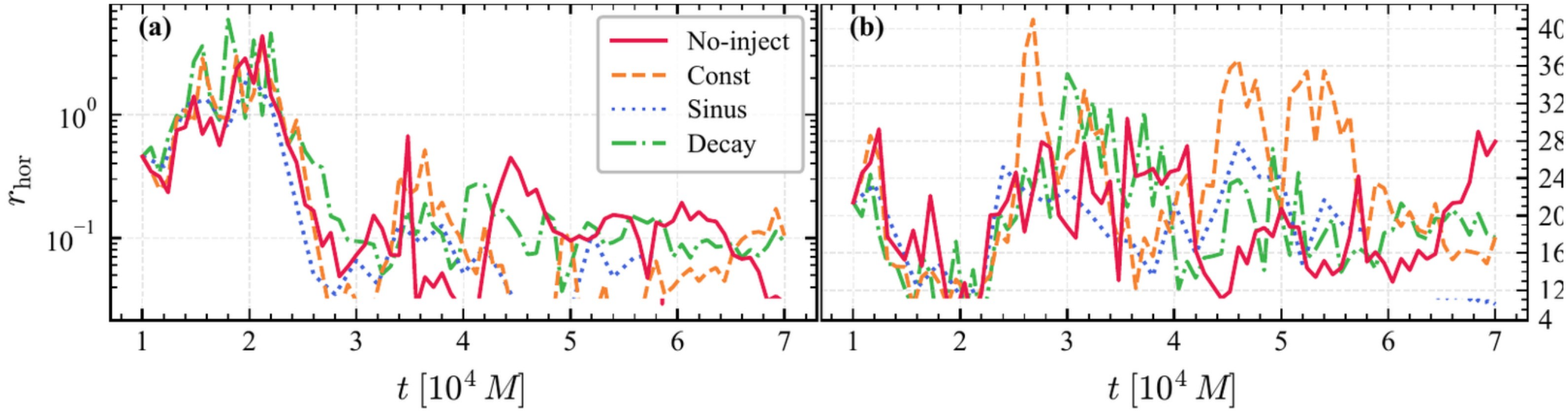
Mass flux

Red is inflow, blue is outflow. Accretion has $\dot{M} < 0$ when integrated.

$$\dot{m} = -\sqrt{-g}\, \rho\, u^r$$

$$\dot{M}(r) = 2\pi \int \rho\, u^r \sqrt{-g}\, d\theta$$

Horizon accretion rate is not enhanced



Left: horizon Ṁ; right: horizon Φ_B; all four models, t in units of 10⁴ M.

0.1–0.6 ×

horizon Ṁ of Sinus and Const vs. control, t ≳ 40,000 M

No trend

Decay: weak dilution, no sustained suppression

Φ_B higher

horizon magnetic flux with injection is above the no-injection case for most of the run, strongest for Const

Take-aways

1

Periodic supply gives harmonics

Sinusoidal injection becomes a harmonic series, strongest near the source (n up to ≈ 9 at 900 M, n = 2 at 600 M).

2

Unmagnetized mass dilutes the field

Sustained injection raises ⟨β⟩ by orders of magnitude at r ≈ 300–900 M and lowers ⟨ℓ⟩ at r ≳ 200 M.

3

More mass is not more accretion

Horizon $\dot{M}$ is not enhanced, and is 0.1–0.6 × the control for Sinus and Const at late times; transient Decay shows no such trend.

Relevant for wind-fed X-ray binaries, symbiotic binaries, Sgr A* and TDE fallback, where the supplied gas has its own magnetization.

Caveats and next steps

Caveats

- 2D axisymmetric: no dynamo, and MRI turbulence decays
- Non-spinning black hole
- The wind carries no magnetic field of its own
- 70,000 M of evolution, one realization per model
- Dilution and horizon suppression: correlation, not yet shown to be causal

Next steps

- Magnetized-wind injection
- Three-dimensional runs
- Spinning black holes
- Longer integrations and more random seeds
- Tracer and lag analysis to test the causal link

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Thank you

More mass is not more accretion when the added gas is unmagnetized.

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Questions welcome!

Backup: numerical details

Grid and boundaries

- $r_{in} = 1.91\ M$: five zones inside $r_H = 2\ M$
- $r_{out} = 1200\ M$, $r = e^{x_1}$, $\Delta r/r \approx 0.8\%$
- $h_{slope} = 0.3$, 800×400 zones

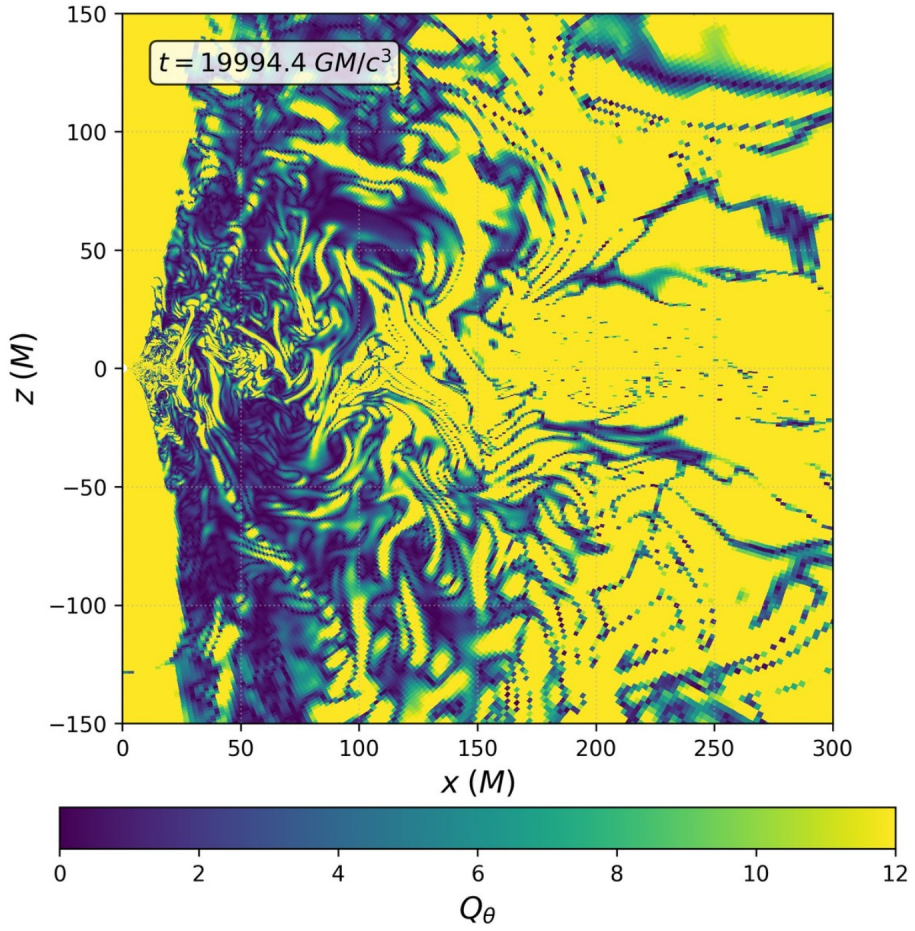
Floors

- $\rho_{floor} = 10^{-6}\, f(r)$, $u_{floor} = 10^{-8}\, f(r)^{\gamma}$
- $f(r) = r^{-2} / (1 + r/10\ M)$
- Hard floors 10^{-20}; $\sigma \le 100$ and $u/\rho \le 100$, enforced by raising ρ

Wind versus floors

- $\rho_{floor}(1000\ M) \approx 10^{-14}$ against $\rho_w = 10^{-7}$
- $v_{inj} = 10^{-3}\, c$, $c_s^2 = 10^{-9}\, c^2$
- Sinus: $P = 5000\ M$, $T = 1 \pm 0.5$; Decay: $\tau = 50{,}000\ M$

Backup: MRI resolution



Same in all four models

Median Q_θ from 13.0 (Sinus) to 18.3 (No-injection) at t ≈ 20,000–23,000 M.

Marginal resolution

Density-weighted disk body: 29–33% with Q_θ ≥ 10 and 54–57% with Q_θ ≤ 6, in every model.

Injection does not change it

The limitation is shared by all models, so it is not specific to any injection profile.

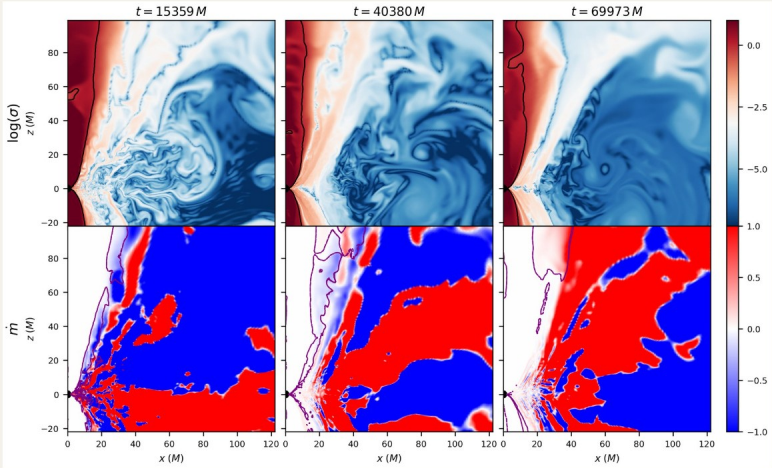
Backup: near-horizon region

Stable funnel

The σ = 1 boundary is a smooth parabola that barely changes across the three epochs.

Be = 1 is unrelated

Magnetic domination and boundedness follow different physics here.



Turbulent accretion

The mass flux near the horizon stays mixed in and out at all epochs.