

Searching for Scalar Ultralight Bosons through High-Frequency X-ray Variability



Zhiren Wang, Avery Broderick

University of Waterloo & Perimeter Institute for Theoretical Physics

August 24, 2026

2nd New Horizons for Psi Workshop



UNIVERSITY OF
WATERLOO

WATERLOO CENTRE FOR
ASTROPHYSICS



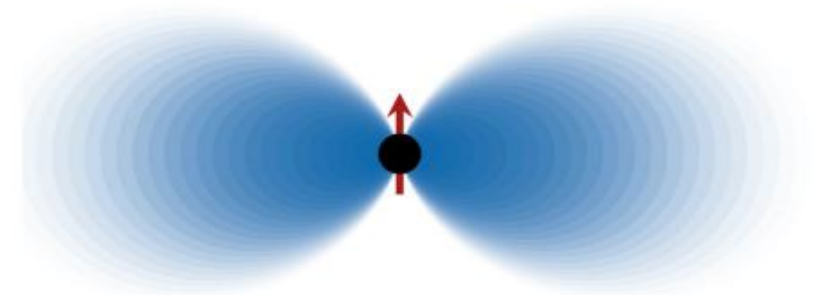
PERIMETER
INSTITUTE

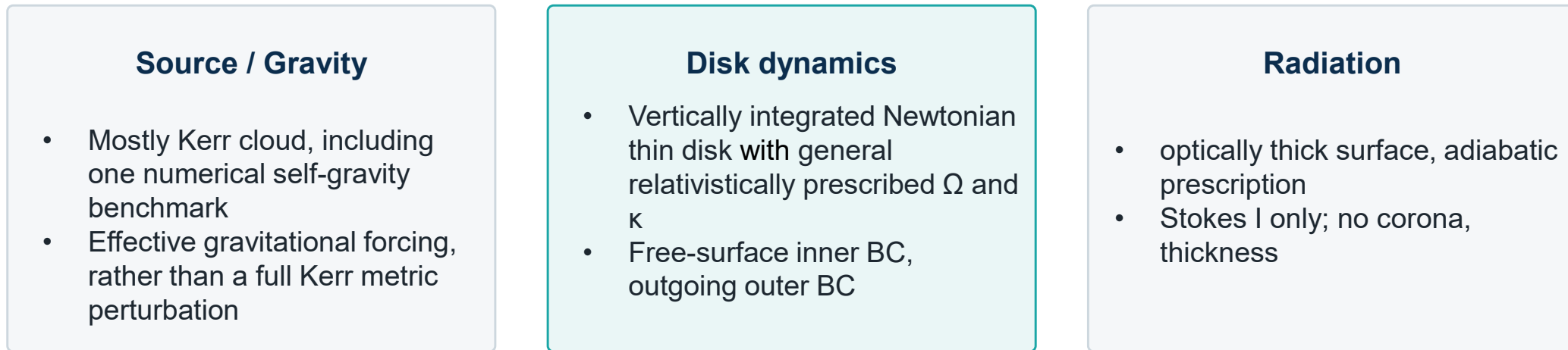
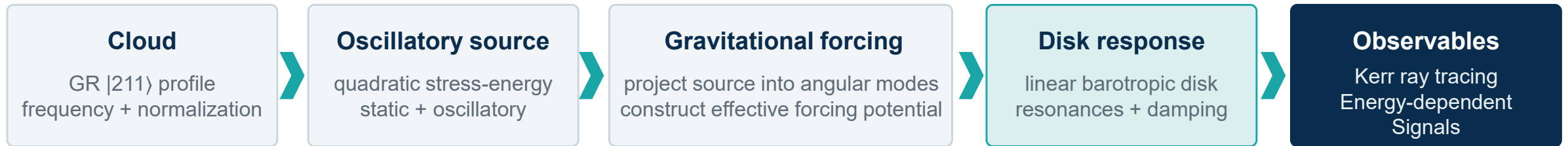
© 2018

- **ULBs** arise in many extensions of the Standard Model and can be viable dark-matter candidates.
- Around spinning black holes, superradiance can build long-lived, coherent boson clouds which **oscillate** at a characteristic frequency set by $\alpha = M\mu$.
- Most existing BH superradiance searches mainly rely on **gravitational signatures**: black-hole spin evolution, continuous gravitational waves.

Question

Can a luminous accretion disk transduce coherent ULB gravitational forcing into detectable high-frequency X-ray variability?





Interpretation

A proof-of-principle response and observability calculation, not a complete accretion disk model.

1 Kerr $|211\rangle$ mode

$$\hat{\phi} = \Psi_0 R(r) S(\theta) e^{-i\omega t + im\phi}$$

$$|211\rangle: \ell = m = 1$$

Eigenproblem fixes the unit profile; Ψ_0 remains free.

2 Coherent oscillatory source

$$\varphi = \Re \hat{\phi}$$

$$\varepsilon_\xi = \varepsilon_\xi^{\text{DC}} + \Re \left[\varepsilon_\xi^{(2)} e^{-2i\omega_R t + 2i\phi} \right]$$

Quadratic Killing-energy density
Static background + one coherent oscillatory harmonic.

3 Coherent $m = 2$ forcing

$$\omega_f = 2\omega_R$$

$$m_s = 2m = 2$$

quadrupolar harmonic at $2\omega_R$

Cloud normalization

$$E_{\text{cloud}} = q_{\text{cloud}} M \implies \Psi_0 \propto \sqrt{q_{\text{cloud}}}$$

This fixes Ψ_0 for snapshots and endpoints on the same energy convention.

GR to non-GR: Construct an effective gravitational potential

Preserve the GR source weighting when mapping to the simplified propagation model.

$$\rho_{\text{eff}}(r, \theta) r^2 \sin \theta \, dr d\theta d\phi = \varepsilon_\xi(r, \theta) \sqrt{\gamma} \, dr d\theta d\phi$$

$$\varepsilon_\xi^{(2)} \longrightarrow \rho_{\text{eff}}^{(2)} \longrightarrow s_{L2}(r) \longrightarrow \Phi_{L2}(r)$$

disk input: $\delta\Phi_{\text{mid}}(r), \delta\Phi'_{\text{mid}}(r)$ phase retained

Disk response: resonances and damping

- We use a vertically integrated, **barotropic**, **thin** disk with **axisymmetric** background profiles: $\Sigma_0(r)$, $c_s(r)$, $\Omega(r)$, $\kappa(r)$
- The local response is organized by the **Doppler-shifted frequency** $\tilde{\omega}(r; \omega) = \omega - m\Omega(r)$ $\Omega_p \equiv \frac{\omega}{m}$, $\tilde{\omega} = m(\Omega_p - \Omega)$
- Two types of **resonant radii**

Corotation ($\tilde{\omega} = 0$)

- forcing pattern locally corotates with the disk
- Angular momentum exchange can become important

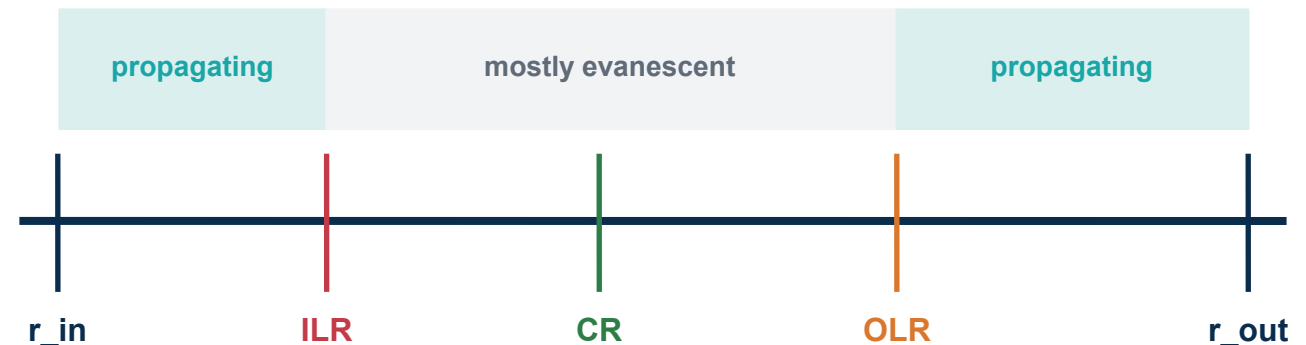
Lindblad radii ($\kappa^2 - \tilde{\omega}^2 = 0$)

- radial wave turning points
- separate propagating and evanescent regions

- Cloud sets the forcing frequency through α , varying α moves these radii through the disk.
- Global frequency **selectivity**: $\omega_f(\alpha)$ approaching the disk eigenfrequencies.
- We then solve for the forced response at the **externally imposed** $\omega_f(\alpha)$.
- Phenomenological linear velocity drag** $\beta(r)$ parameterized by Q_{drag} .
- $Q_{\text{drag}}=5, 10, 20 \Rightarrow$ e-folding over $\sim 1.6, 3.2, 6.4$ local periods

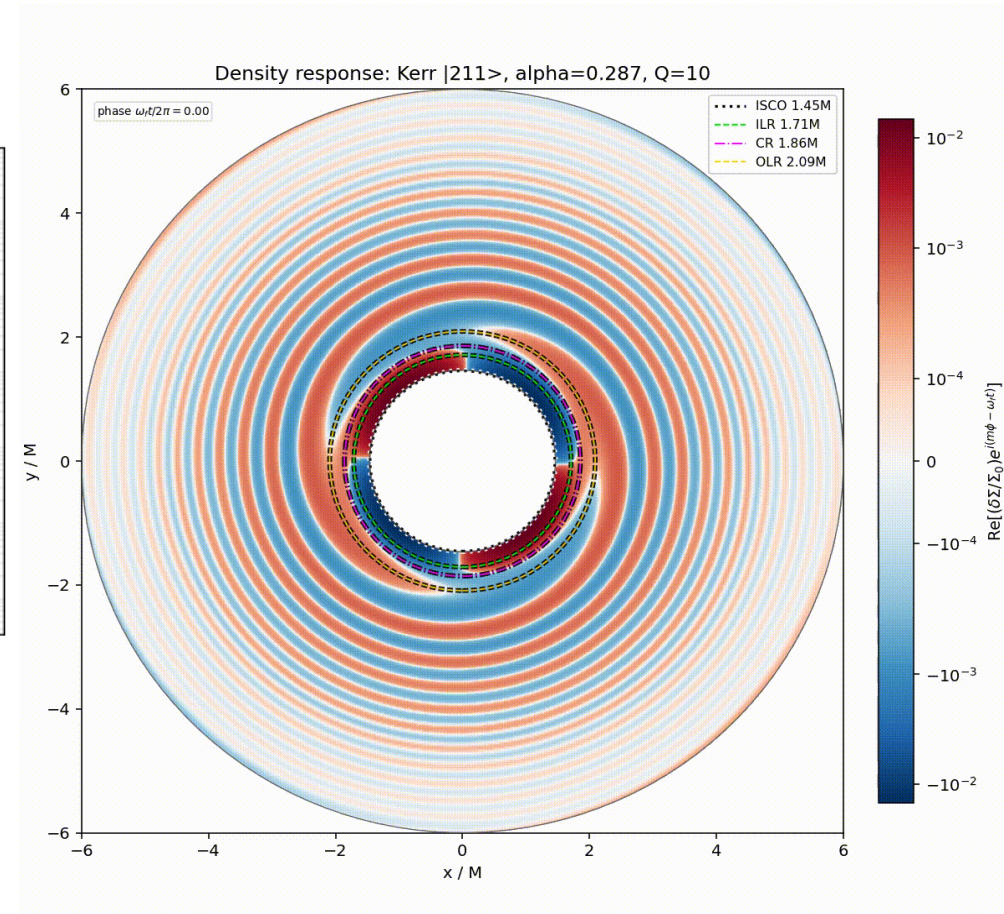
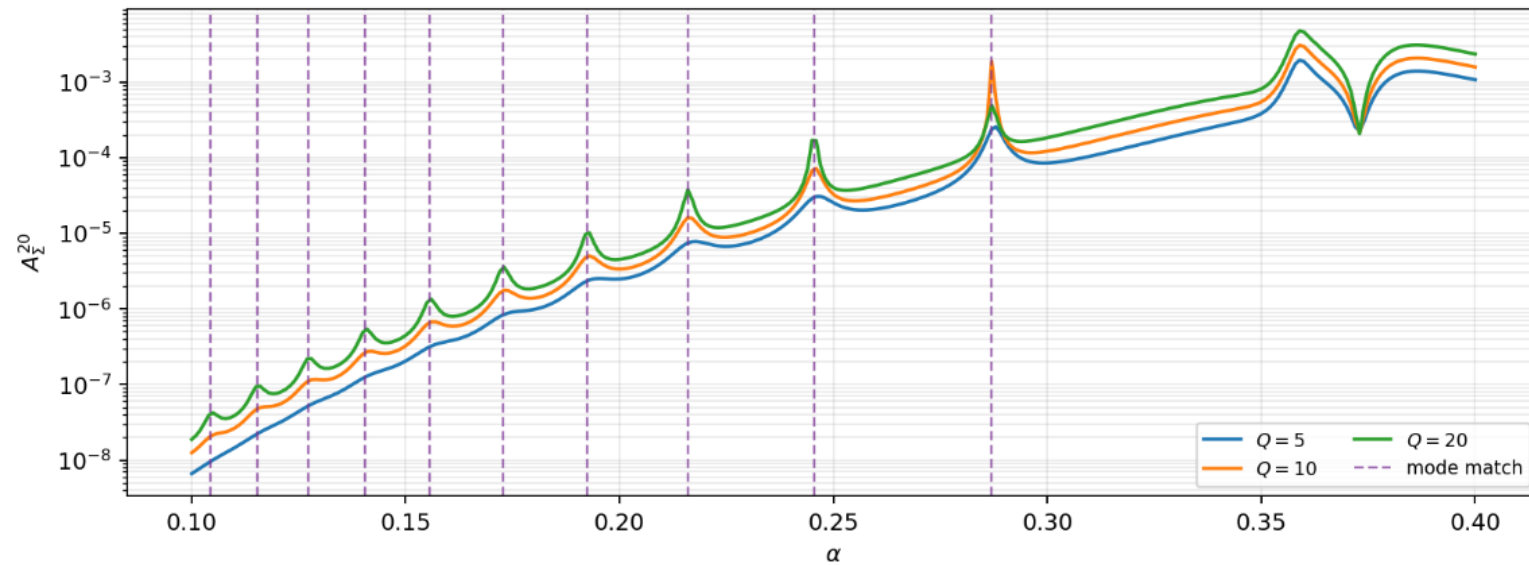
$$\mathbf{f}_{\text{damp}} = -\beta(r) \delta \mathbf{u}, \quad \delta \mathbf{u} = (\delta u_r, \delta u_\phi)$$

$$\beta_{\text{drag}}(r) = \frac{\omega_{\text{ref}}(r)}{2Q_{\text{drag}}}, \quad \omega_{\text{ref}}(r) = \sqrt{\kappa^2(r) + \tilde{\omega}^2(r)},$$



Frequency-selective disk response

Before imposing isolated superradiant evolutions: diagnostic α sweep (fixed $a=0.99$, disk model, and cloud mass=0.01 fixed; varying α changes the forcing frequency and source profile)



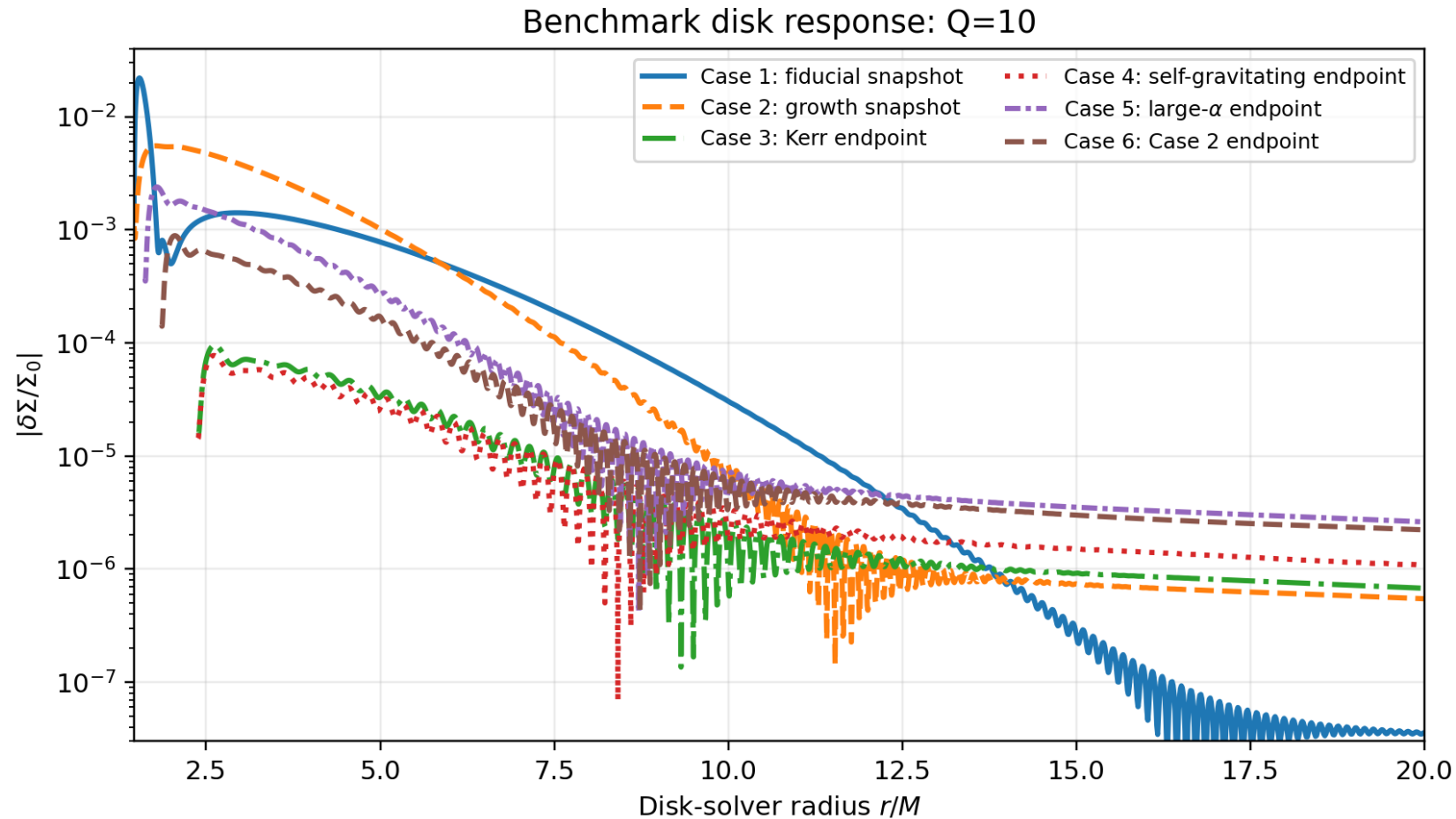
Benchmark suite: mechanism / snapshots / saturated endpoints

CASES

Case	Parameters	Physical status / use	Key limitation	GRRT
1	$\alpha=0.287$ $a=.990$ $q_{\text{cloud}}=1.0\%$	Near-resonant mechanism benchmark	Not on the isolated superradiant evolution track.	Yes
2	$\alpha=0.400$ $a=0.990$ $q_{\text{cloud}}=1.0\%$	Superradiantly allowed growth snapshot	The 1% cloud fraction is a chosen snapshot.	Yes
3-4	$\alpha=0.3106$, $a=0.891(\text{K})/0.898(\text{SG})$ $q_{\text{cloud}}=9.5\%$	One matched Kerr $\leftrightarrow$ SG endpoint pair	Parameters fixed by the available SG solution; not optimized for resonance. No SG ray tracing.	No
5	$\alpha=0.4199$ $a=0.980$ $q_{\text{cloud}}=3.0\%$	Formal large- α endpoint benchmark	Not generated from a specified progenitor trajectory.	Yes
6	$\alpha=0.3817$ $a=0.959$ $q_{\text{cloud}}=5.83\%$	Isolated endpoint evolved from Case 2	Track-consistent only under the assumed isolated free-scalar evolution.	Yes

Availability-limited self-gravity comparison

Cases 3–4 use one numerical SG solution provided by Taillte May (see [May et al. 2025](#)). It provides a clean Kerr-vs-self-gravity comparison because alpha and the cloud Killing energy can be matched, but it samples only that one endpoint and was not optimized for resonance.



Snapshots

Case 1: $A_{\max} \approx 2.2\%$
Case 2: $A_{\max} \approx 0.55\%$

Matched endpoints

Cases 3–4: $A_{\max} \approx 10^{-4}$

Largest cloud fraction

Case 3/4: $q_{\text{cloud}} = 9.5\%$, but $A_{\max} \approx 10^{-4}$

$A_{\max}$ is a local disk quantity. Ray-traced RMS is an emission-weighted integral and can reorder the cases.

A matched Kerr vs self-gravity comparison

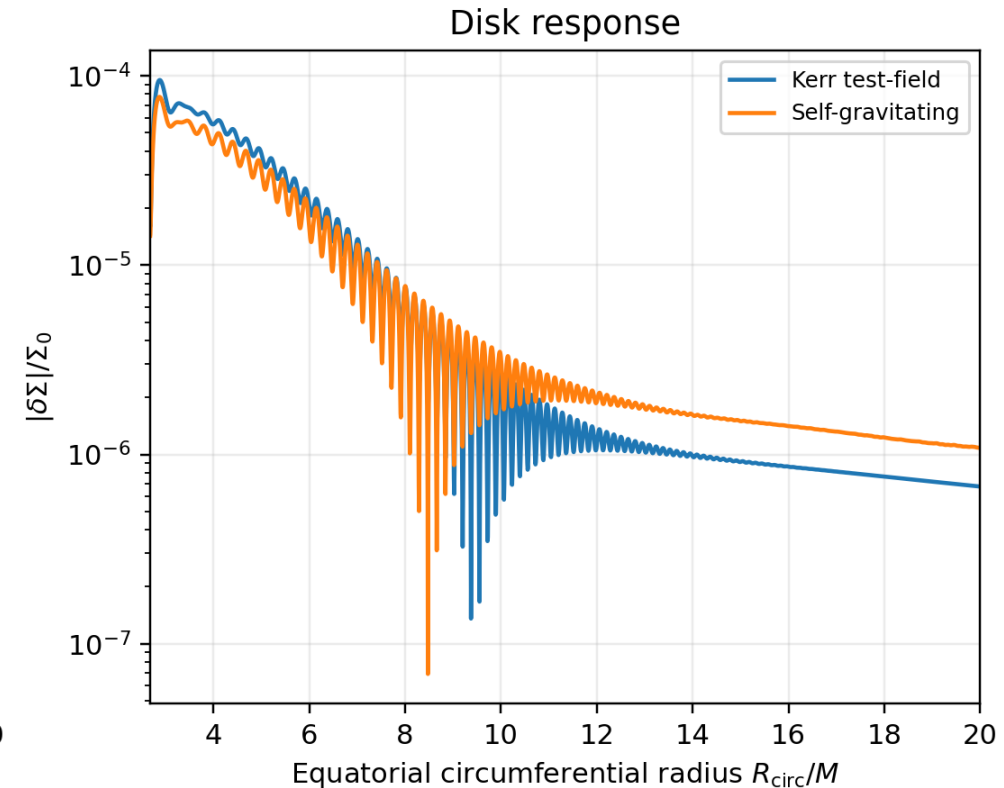
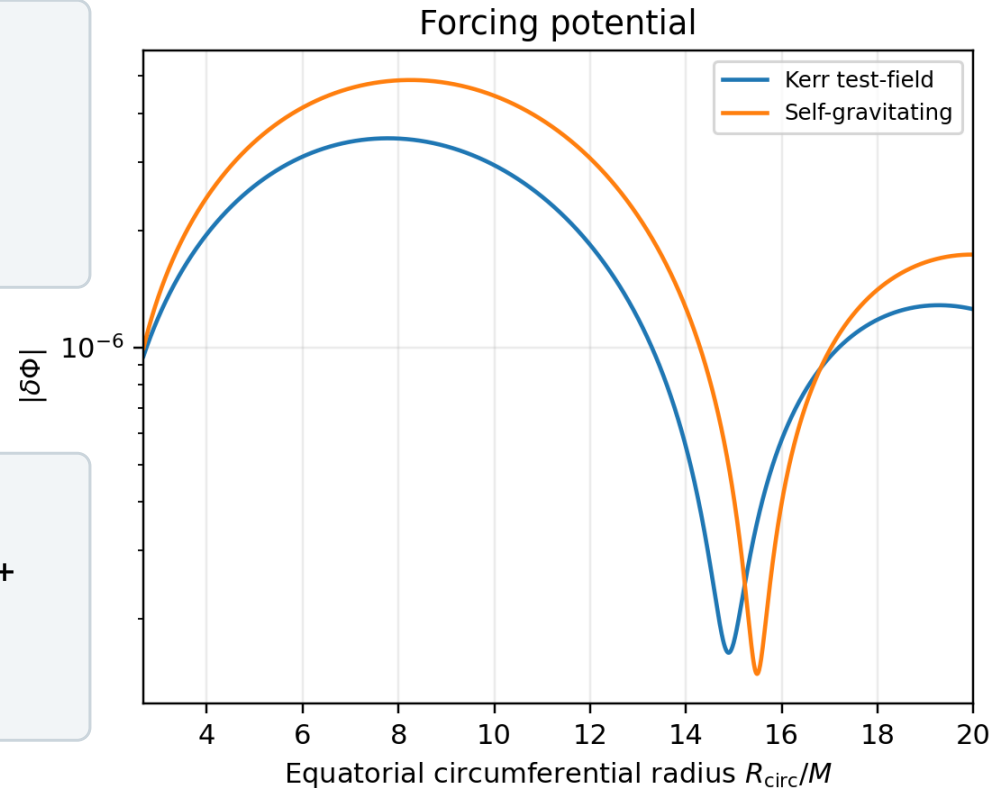
Matched saturated endpoint at $\alpha = 0.3106$, $q_{\text{cloud}} = 9.50\%$

Test-field Kerr

- Kerr cloud + forcing
- Kerr ISCO and orbital dynamics

Self-gravitating

- BH+cloud spacetime + forcing
- modified background orbital dynamics



Difference

At the same final α and q_{cloud} , the two treatments predict slightly different synchronized endpoints (Kerr $a^*=0.891$, SG $a^*=0.898$).

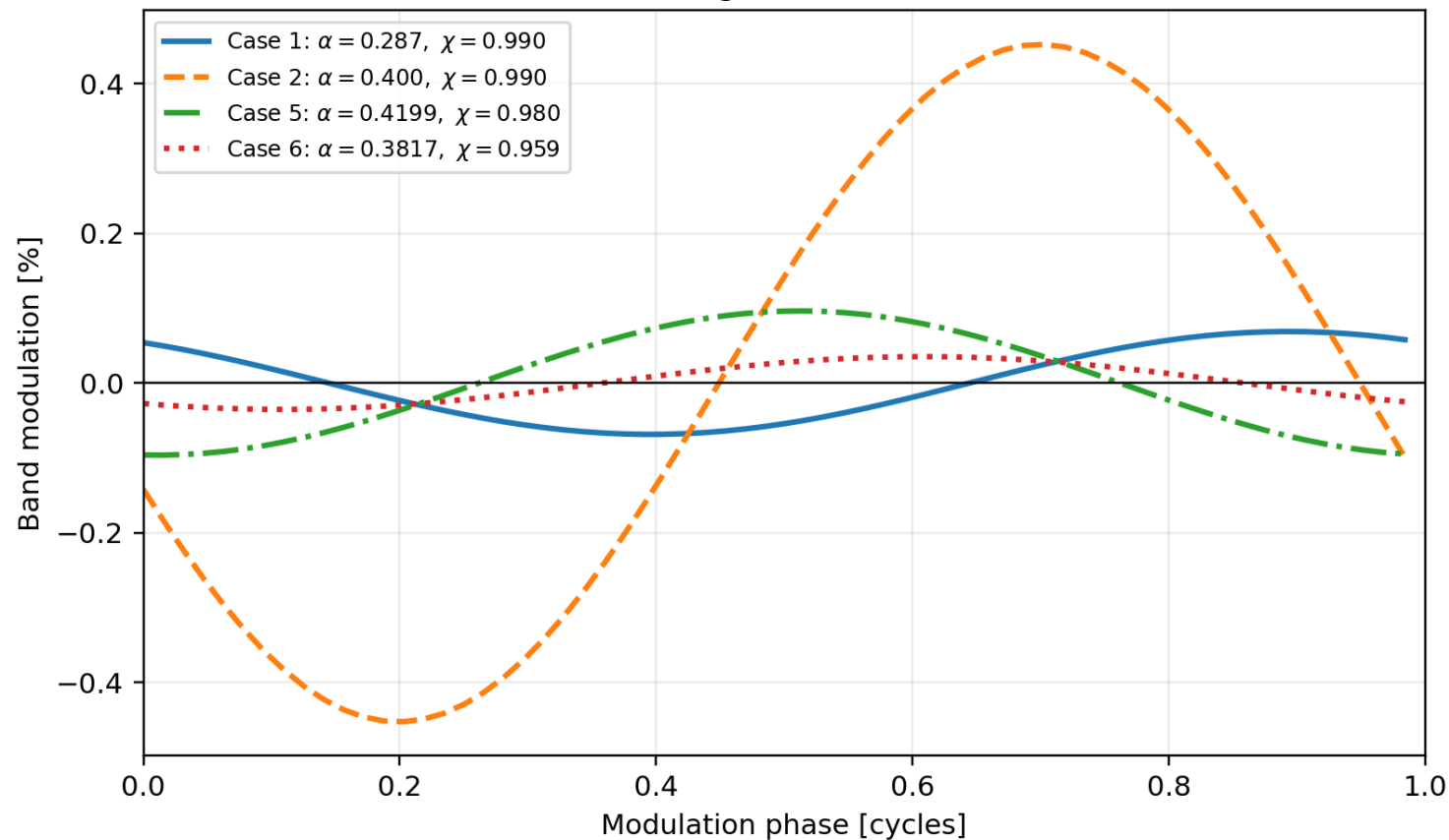
Interpretation

At this matched point, self-gravity changes the near field response amplitude by $\sim 20\%$, without a qualitative change in the response structure.

A minimal GRRT model: from disk perturbations to X-ray variability



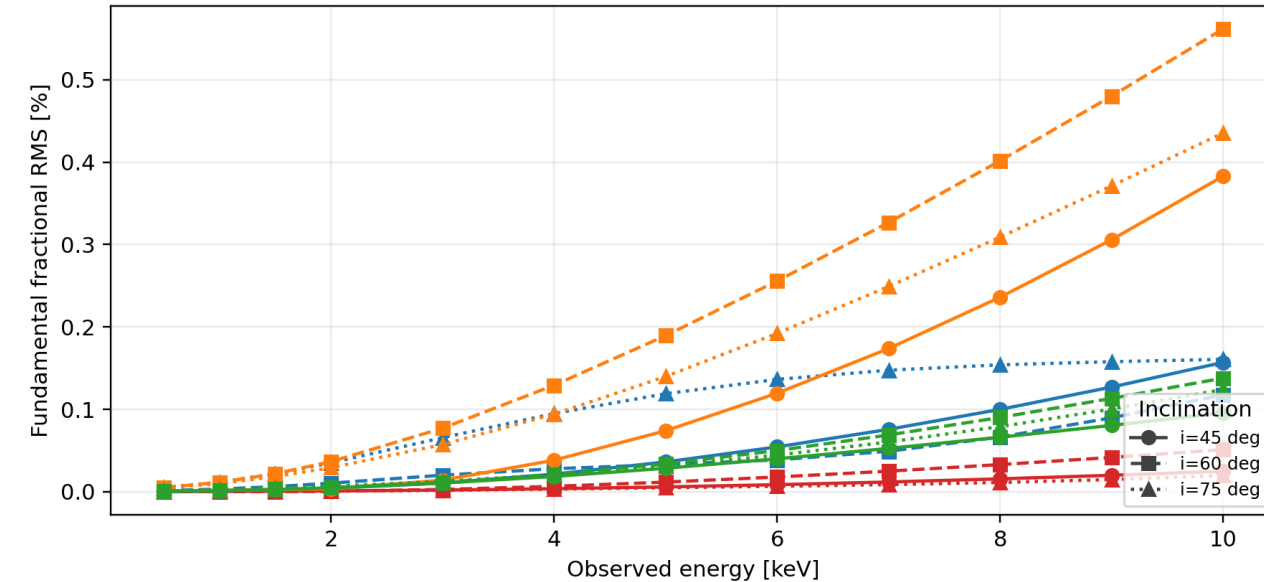
6-10 keV light curve ($i = 60^\circ$)



Ray-tracing choices

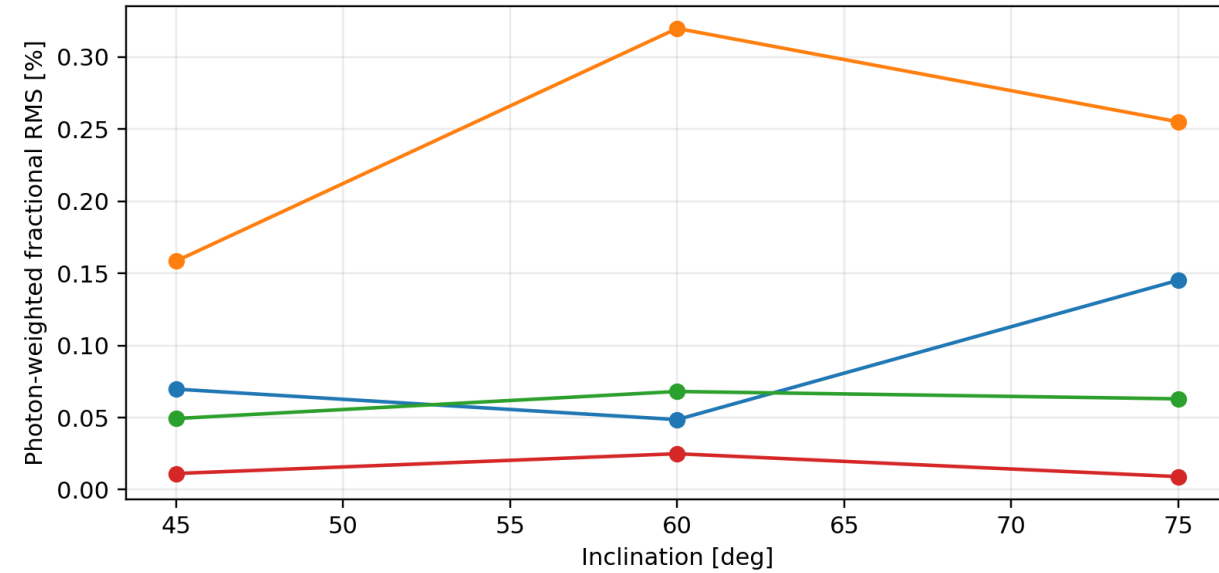
- Stokes I from a thin, optically thick surface
- Temperature peak = 1 keV
- $E_{\text{obs}} = 0.5\text{--}10$ keV
- $i_{\text{disk}} = 45^\circ, 60^\circ, 75^\circ$
- No corona, polarization, finite thickness, finite coherence time

Monochromatic photon fractional RMS vs energy



Models (parameters vary jointly; not an α scan)
 Case 1: $\alpha = 0.287$ Case 5: $\alpha = 0.4199$
 Case 2: $\alpha = 0.400$ Case 6: $\alpha = 0.3817$

Instrument-independent photon RMS vs inclination: 6-10 keV



Models (parameters vary jointly; not an α scan)
 Case 1: $\alpha = 0.287$ Case 5: $\alpha = 0.4199$
 Case 2: $\alpha = 0.400$ Case 6: $\alpha = 0.3817$

Monochromatic RMS

0.56% RMS at 10 keV
 (Case 2, $i = 60^\circ$)

Inclination

Non-monotonic: beaming,
 projected area, and radial
 cancellation compete

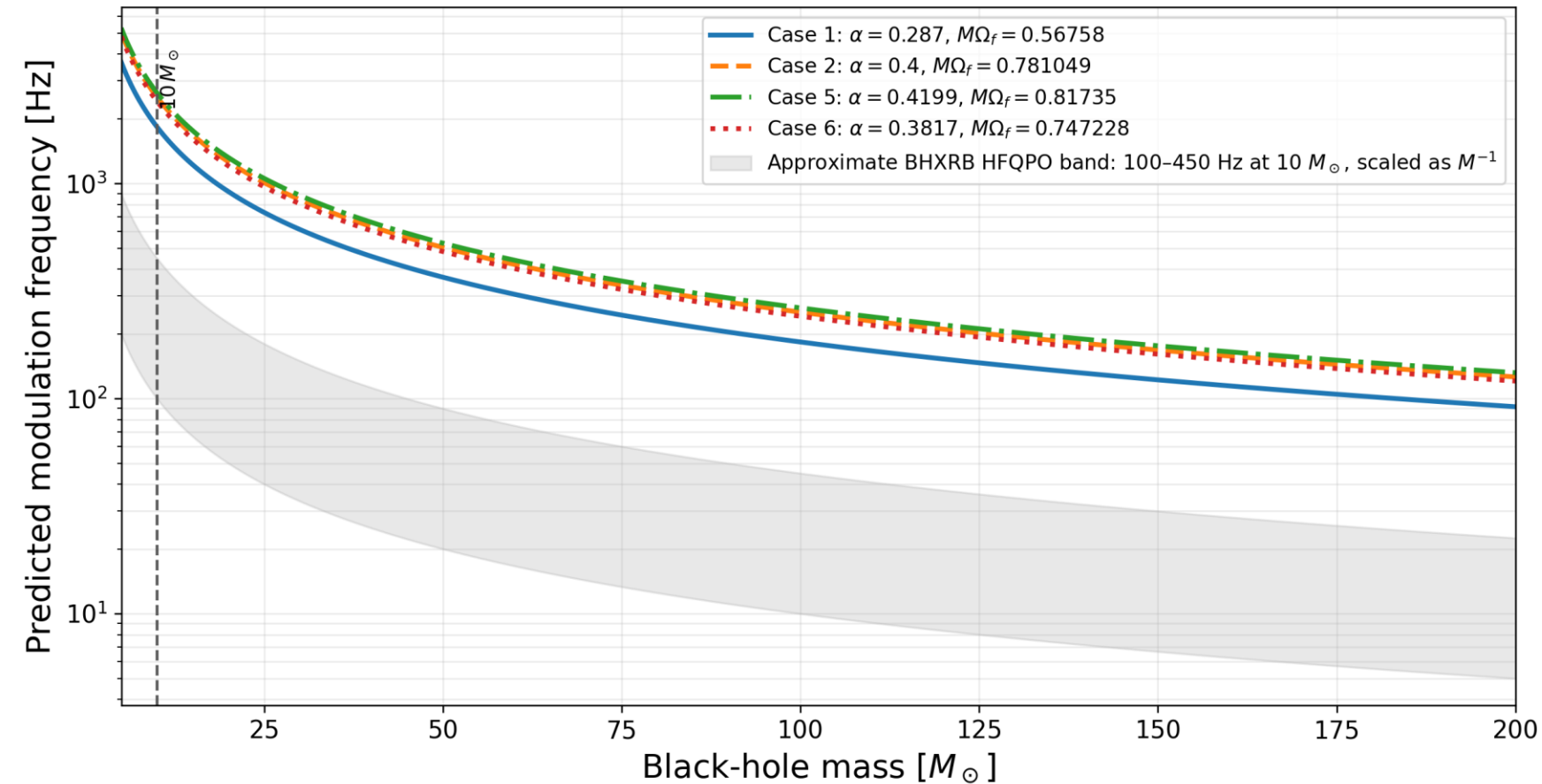
Hard band RMS

0.32% RMS in 6–10 keV
 (Case 2, $i = 60^\circ$), see Slide 10

Predicted Frequencies above known BHXRB HFQPOs

FREQUENCY

Frequency Mass Scaling



All curves and the reference band scale as M^{-1} ; vertical offsets are mass-independent.

At $10 M_\odot$

$f \sim 1.83\text{--}2.64$ kHz.

Observed BHXRB HFQPOs

Gray band: 100–450 Hz at $10 M_\odot$, shown with an illustrative M^{-1} scaling.

A distinct timing regime

The predicted signal lies well above the frequency range where BHXRB HFQPOs are usually reported.

Proof of principle: scalar-cloud forcing can produce selective, potentially observable kHz disk variability.

1

Coherent driver

A real cloud can generate a coherent **non-axisymmetric** gravitational forcing.

2

Selective disk response

Disk response is highly **selective**: frequency detuning, resonance structure, and radial phase/overlap matter more than cloud mass alone.

3

Impact of self-gravity

At the available matched benchmark, self-gravity changes the response **quantitatively** but not qualitatively, no universal correction can yet be inferred.

4

Potential X-ray signature

Favorable thermal-disk cases reach **a few $\times 10^{-3}$ fractional rms at kHz frequencies**, motivating targeted searches in disk-dominated BHXRBs.

Potential identifying features

- *One coherent driver $\rightarrow$ a common frequency across energy bands, with stable energy-dependent phase relations.*
- *Long-term frequency/phase stability may distinguish it from stochastic variability.*

Next Physics?

Physical damping and thermal lag · coronal emission · finite coherence and PSD/instrument forward modeling · self-consistent metric perturbation