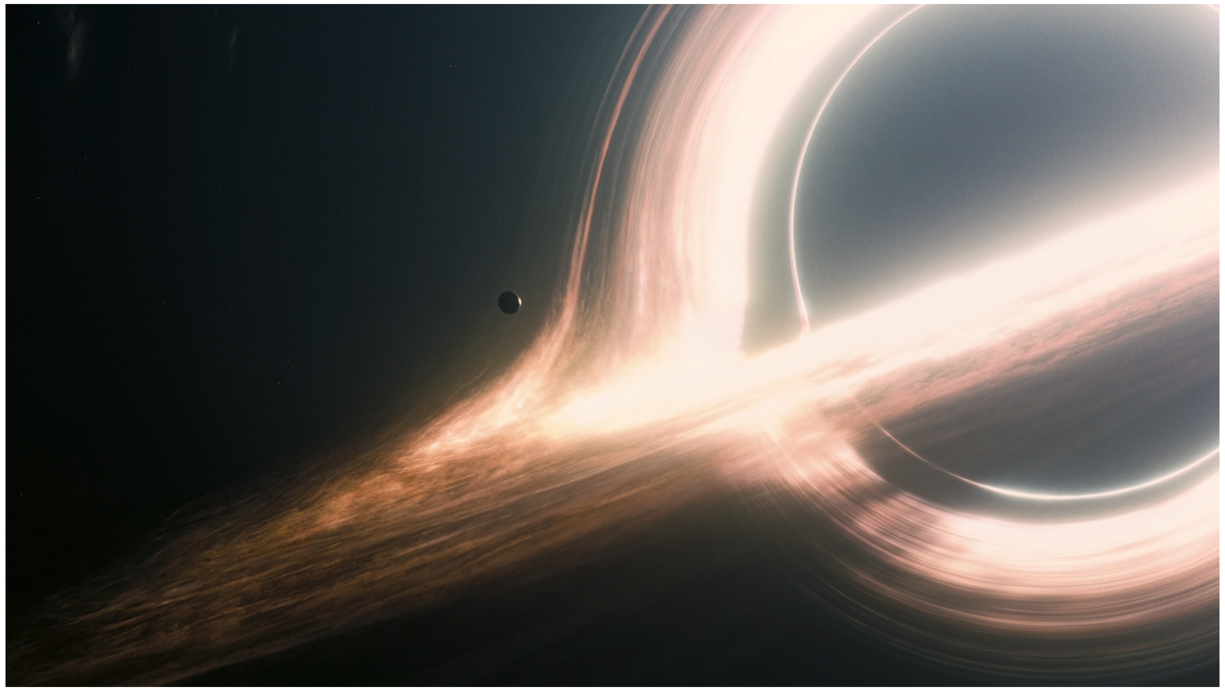
# Inspiral into Gargantua

Niels Warburton
Sam Gralla
Scott Hughes

Marc Casals
Chris Kavanagh
Adrian Ottewill
Barry Wardell

# Gargantua?



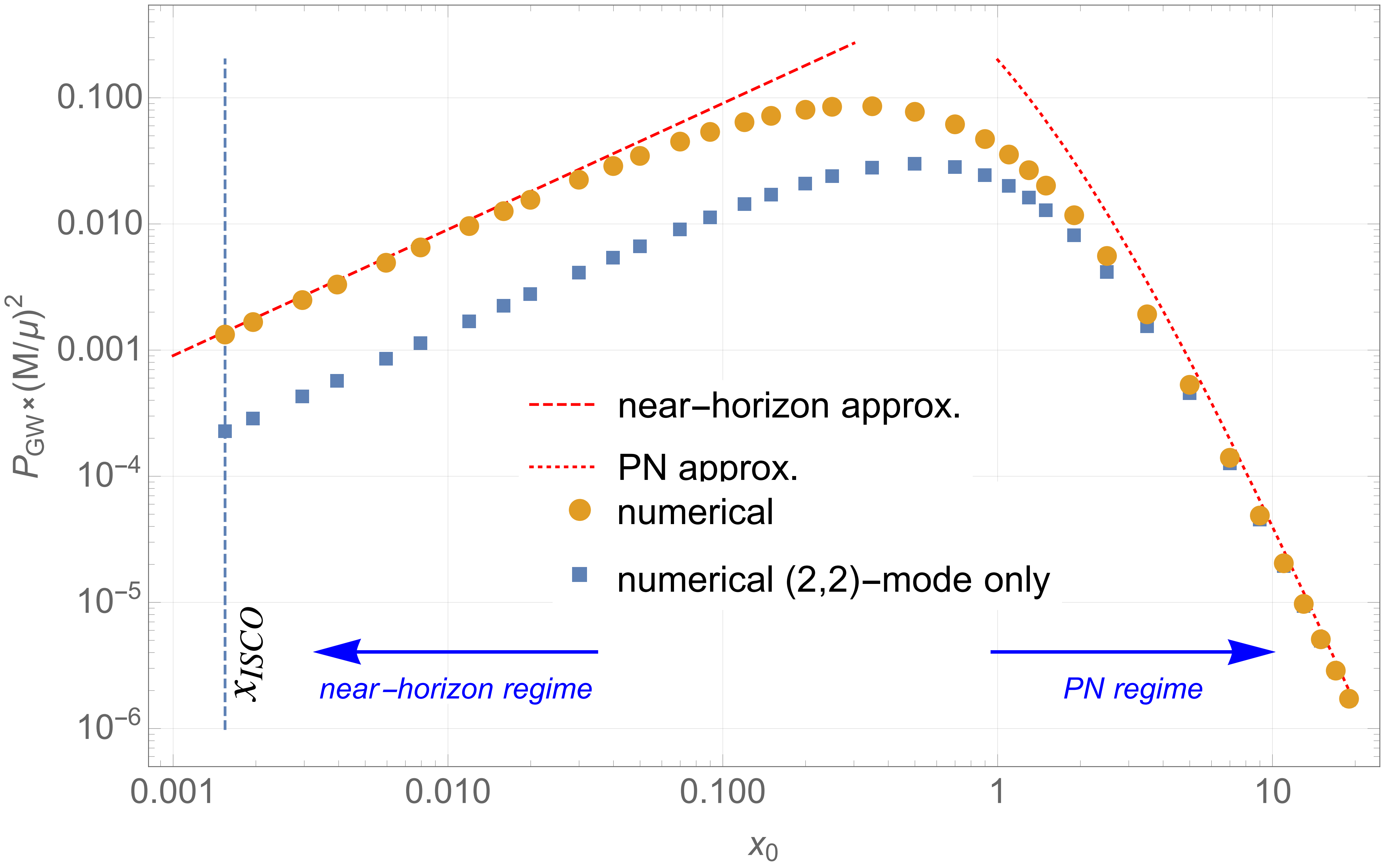
For 'Interstellar' Thorne estimates the black hole (Gargantua) must be spinning at

$$a/M \simeq 1 - 10^{-14}$$

This talk: Gravitational wave emission from an inspiral into a near-extremal Kerr (NEK) black hole. $\mathrm{NEK} \implies a/M \gtrsim 0.9999$

Useful notation: $x = \frac{r - r_+}{r_+}$ $\epsilon = \sqrt{1 - a^2/M^2}$

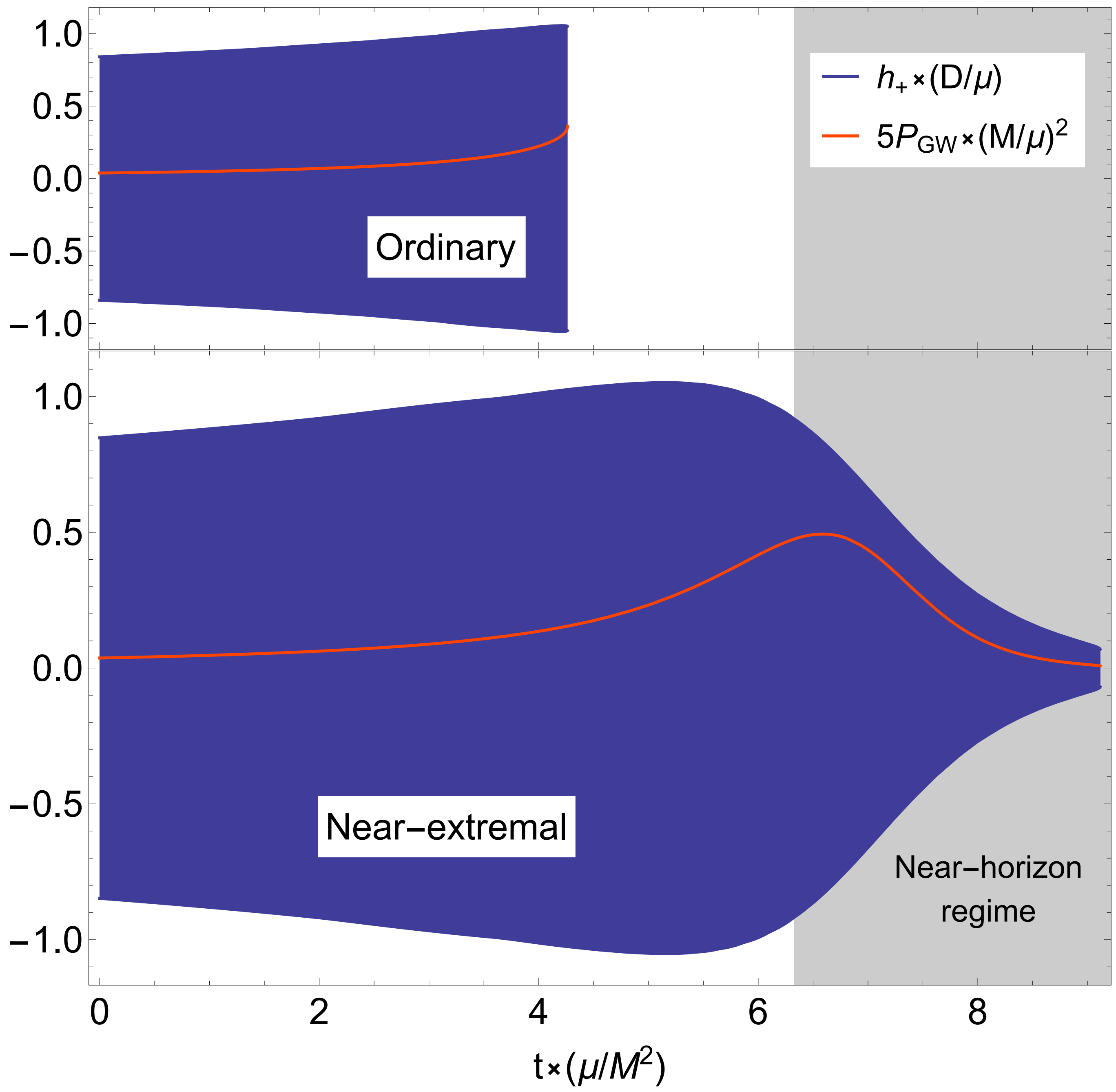
# Anatomy of a NEK inspiral




Flux decreases as horizon is approached

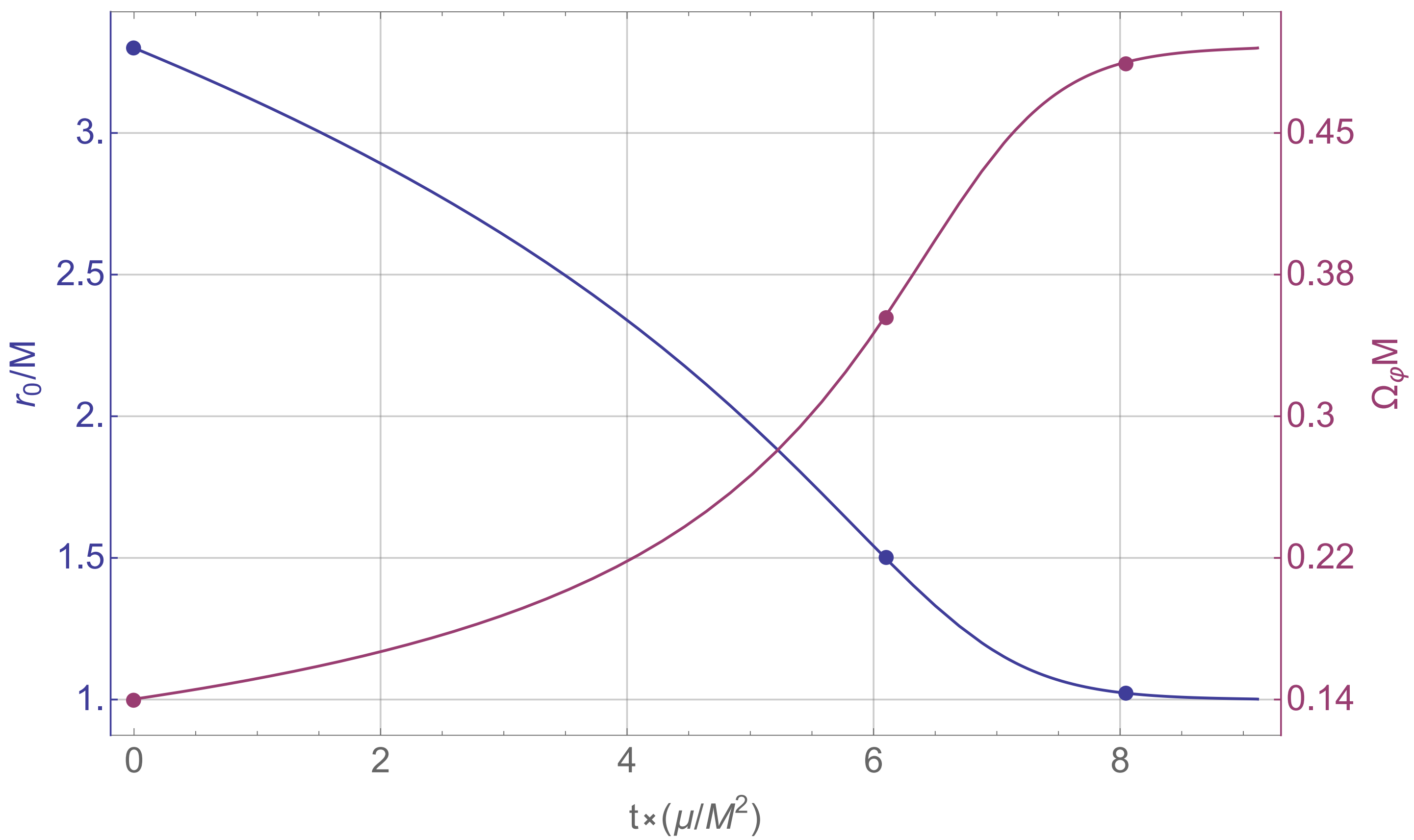
New analytic flux approximation

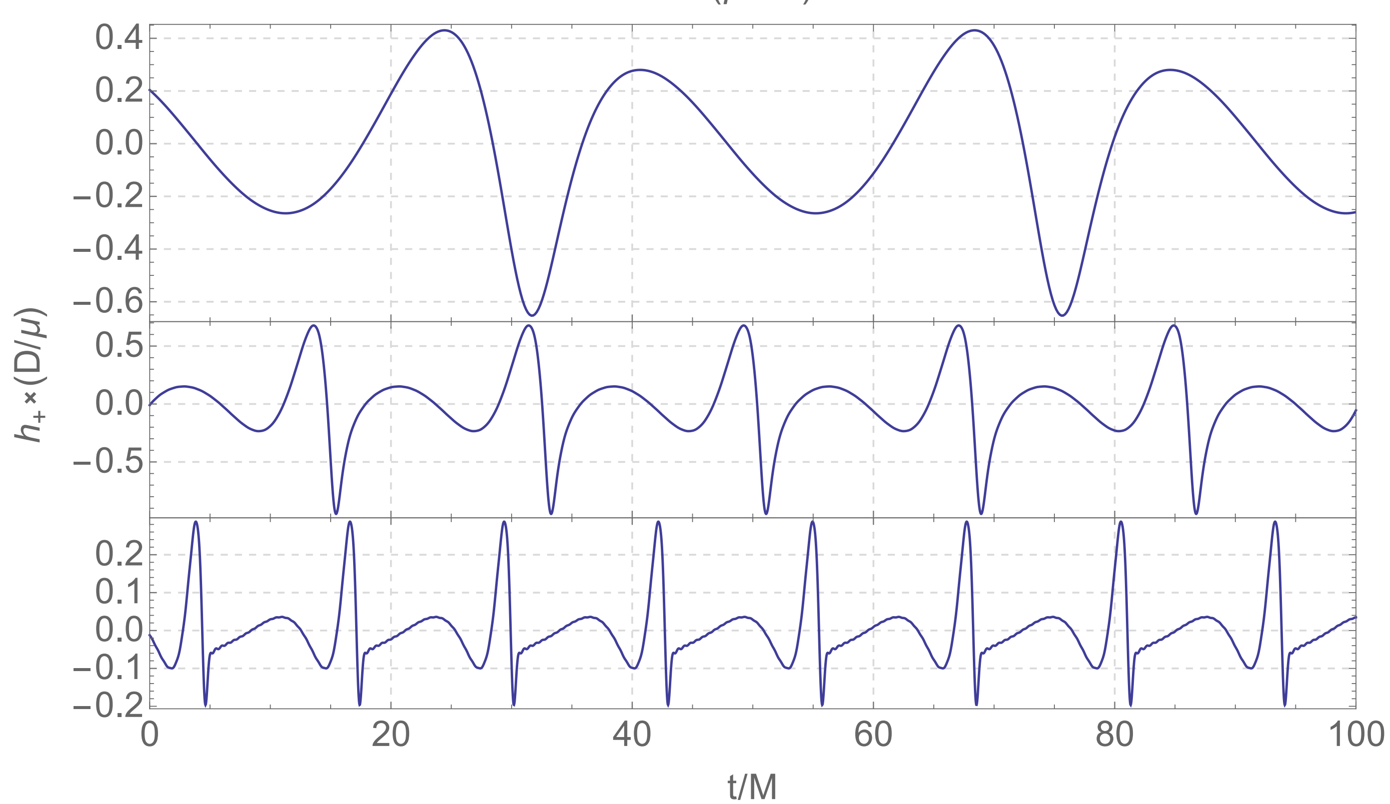
# Results: circular, equatorial




There is no chirp

# Results: circular, equatorial inspiral



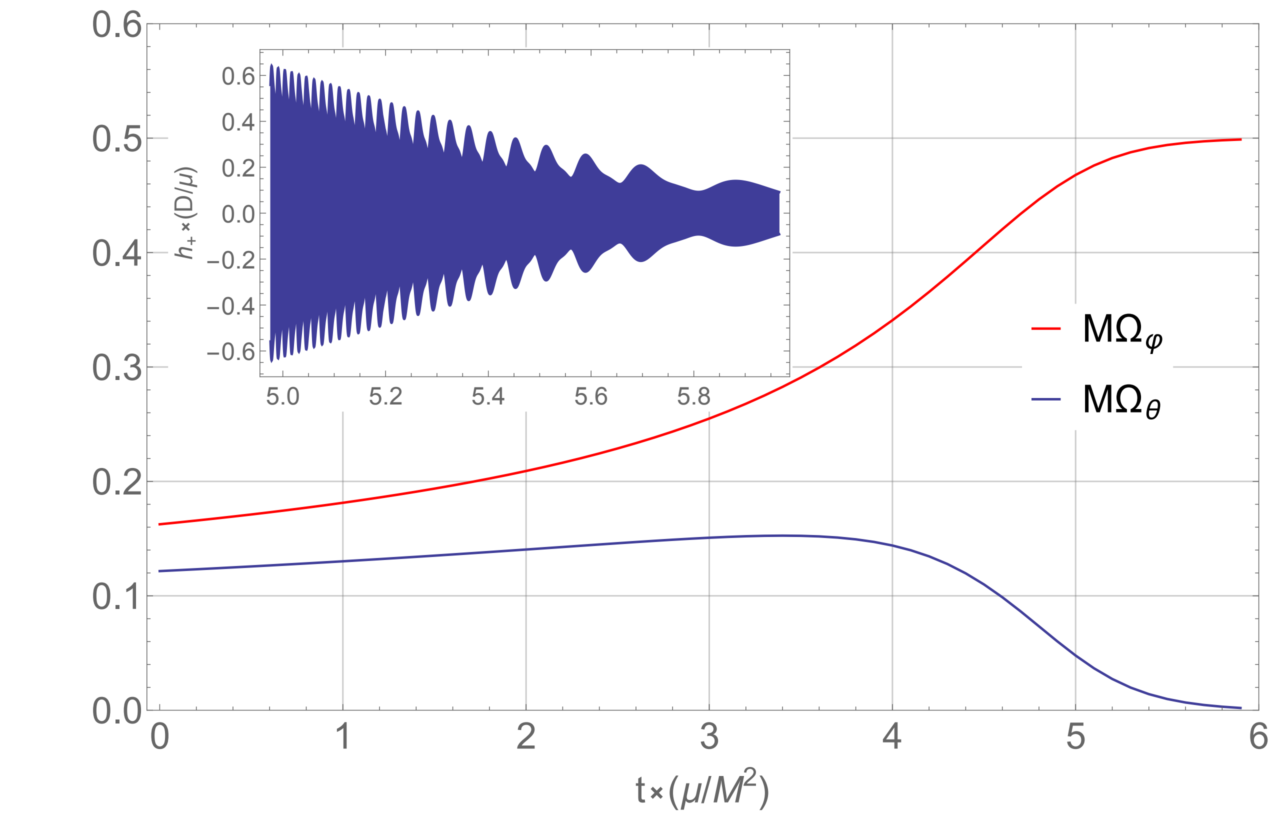




Orbital radius decays slowly near the horizon

Orbital frequency saturates at the horizon frequency

Strong relativistic beaming in the near-horizon regime

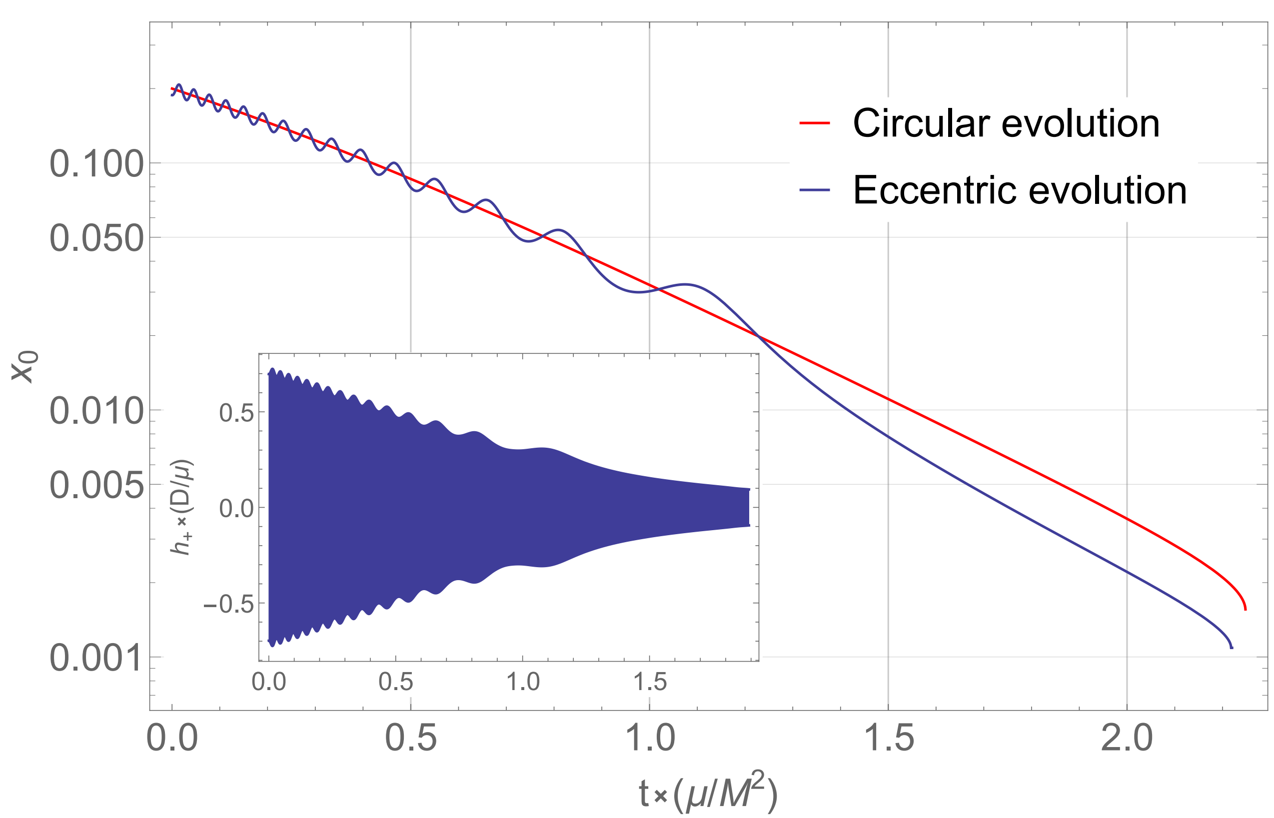
# Results: spherical and eccentric, equatorial inspirals




## Spherical

- Azimuthal frequency saturates at horizon frequency. Polar frequency tends to zero

- Waveform: exp. decay modulated with polar libration frequency




## Eccentric, equatorial

- Considered low eccentricity inspirals (e~0.01)

- Waveform: exp. decay modulated with radial libration frequency

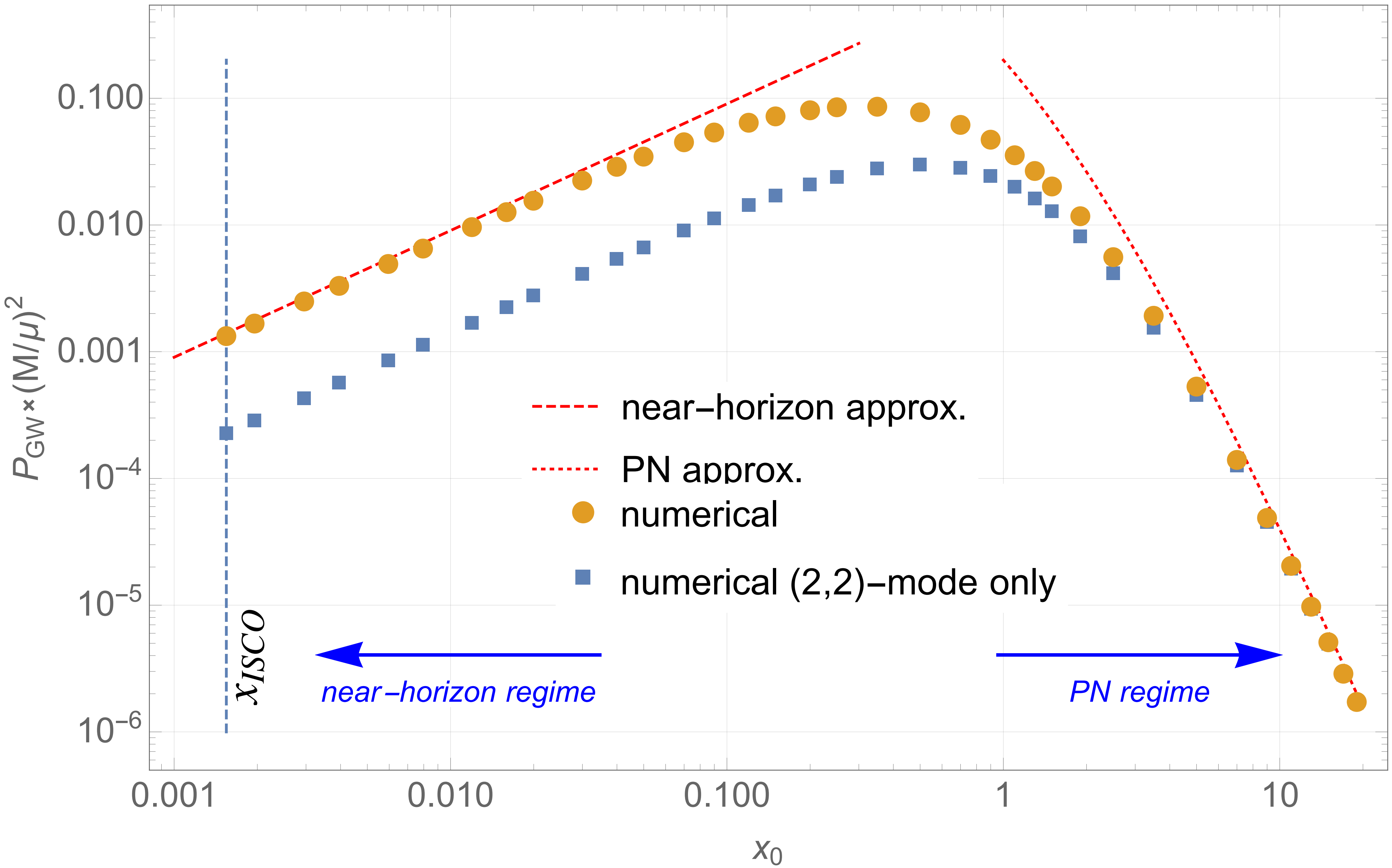
## Extra details in the paper

- detectability with eLISA and ground-base detectors
- enough room for extended body near the horizon?
- when is the evolution adiabatic?
- zoom-whirl orbits can have ‘inverted’ behaviour
- confusion with quasi-normal mode ringing?

## Extra details not in the paper

Shift in the ISCO location due to the smaller body…

# The ISCO gives access to the near-horizon region




Near horizon flux not sensitive to ε.
The location of the ISCO more important.

# ISCO shift in Kerr spacetime

Isoyama+, PRL 113, 161101 (2014)

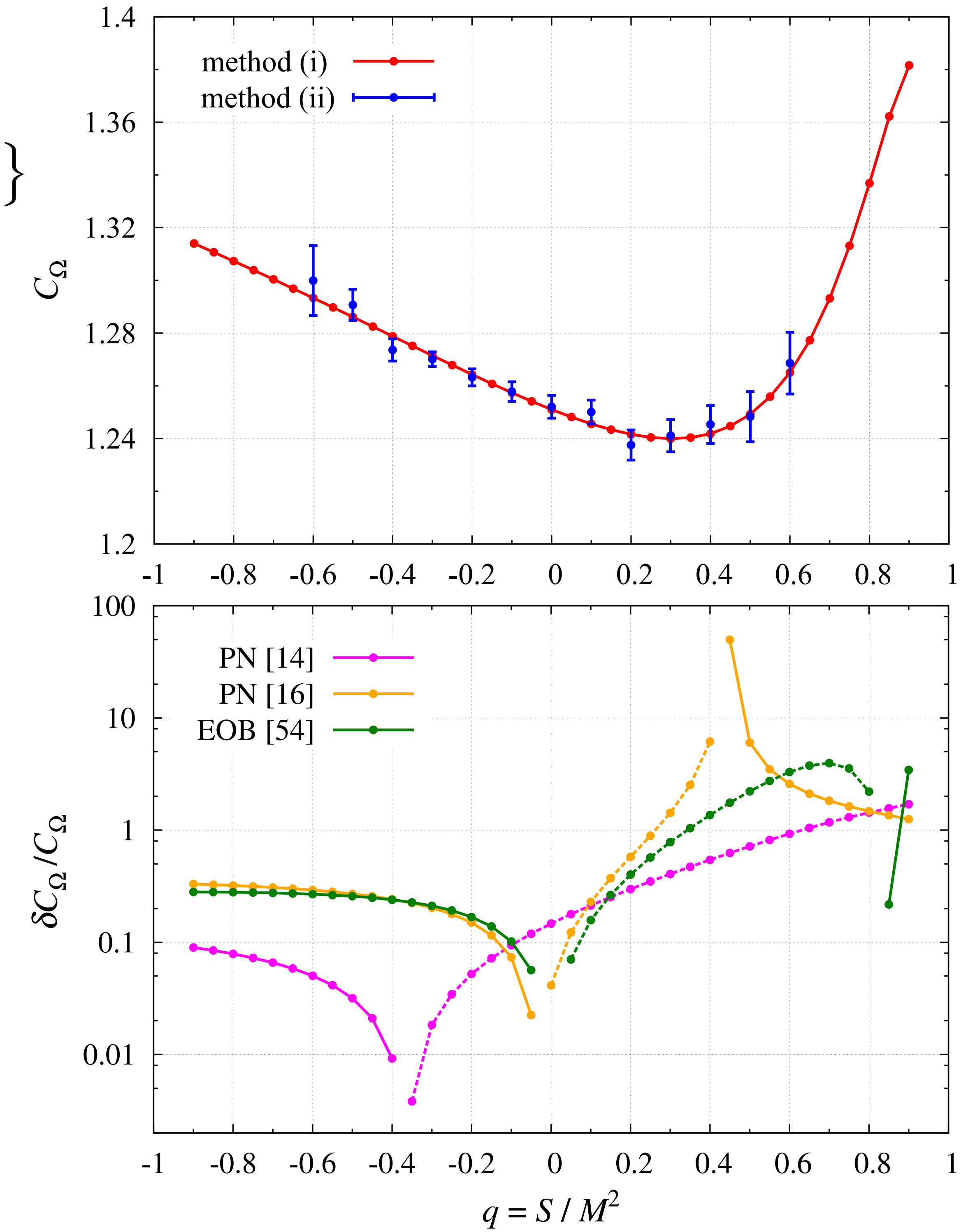
$$(M+\mu)\,\Omega_{\rm isco} = M\Omega^{(0)}_{\rm isco}(q)\,\{1+\eta\, C_\Omega(q) + \mathcal{O}(\eta^2)\}$$

$C_\Omega$ can be calculated from the redshift invariant computed for a sequence of circular orbits

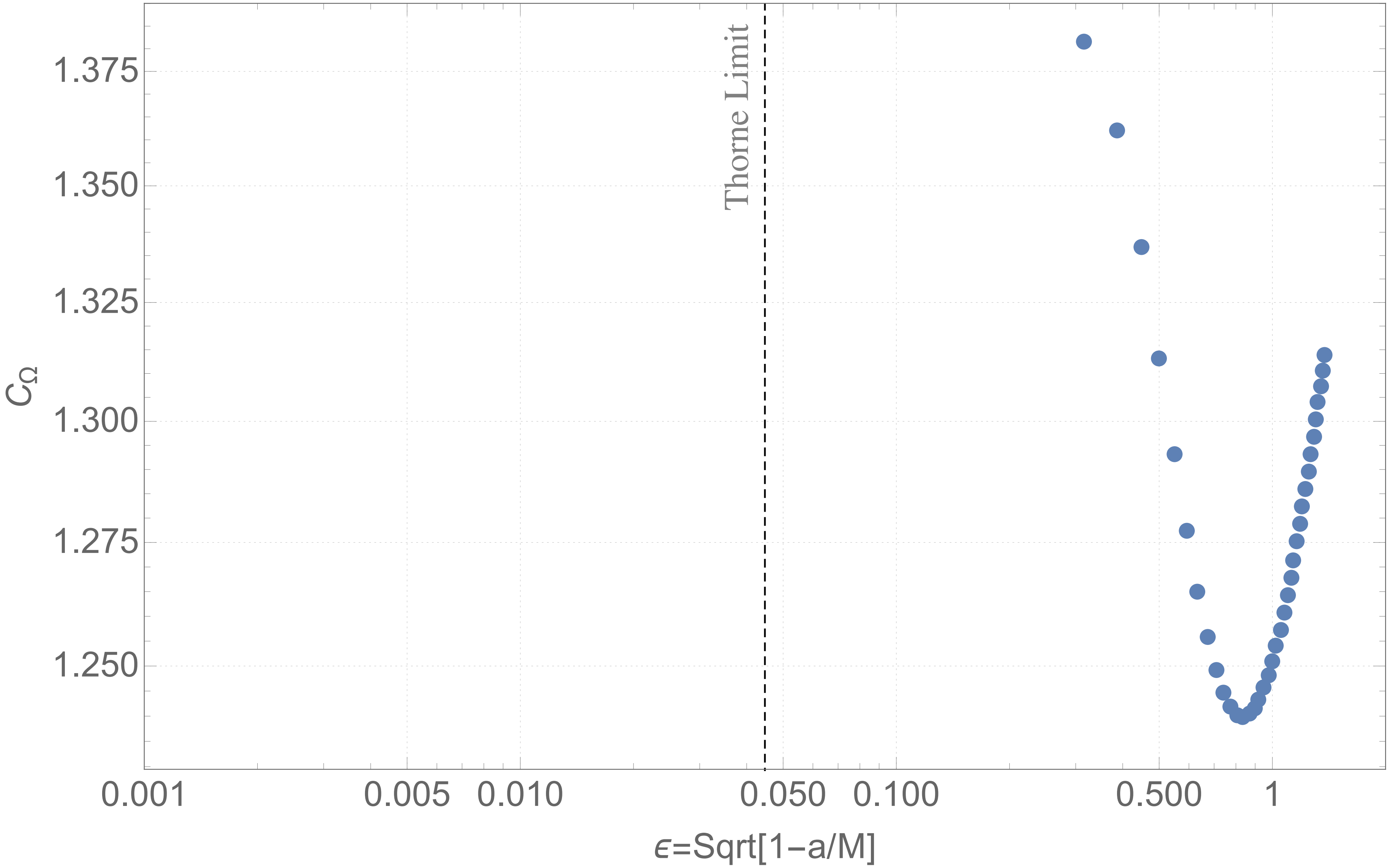
$$z \equiv 1/u^t$$
$$= z_{(0)} + \eta z_{(1)} + \mathcal{O}(\eta)^2$$

$$z_{(1)} = z_{(0)} H, \quad \text{where} \quad H = \frac{1}{2} h^R_{\alpha\beta} u^\alpha u^\beta$$

$$C_\Omega = 1 - \frac{1}{2}\,\frac{z''_{(1)}(\Omega^{(0)}_{\rm isco})}{\Omega^{(0)}_{\rm isco}\, z'''_{(0)}(\Omega^{(0)}_{\rm isco})}$$

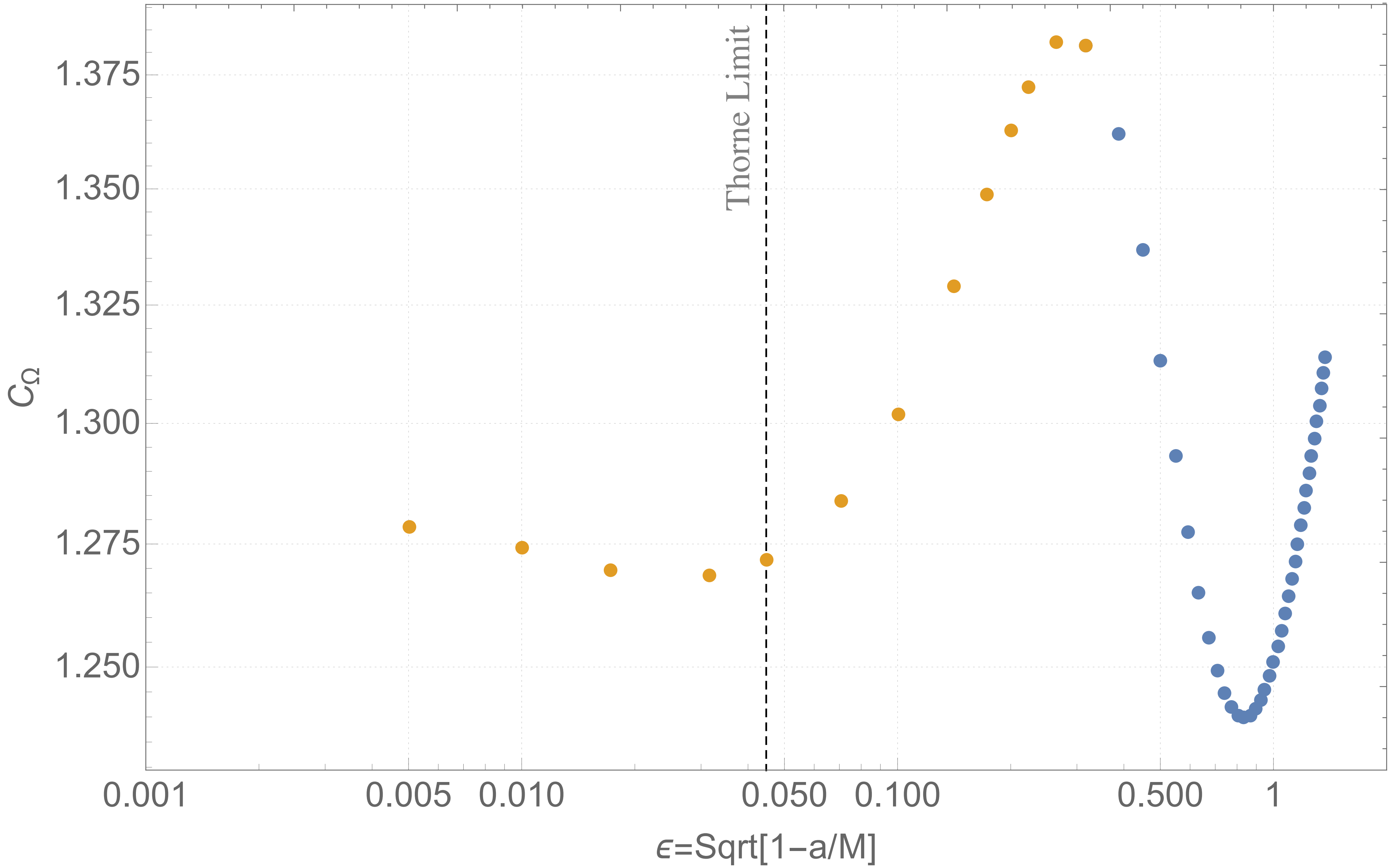


# Near-extremal Kerr ISCO shift

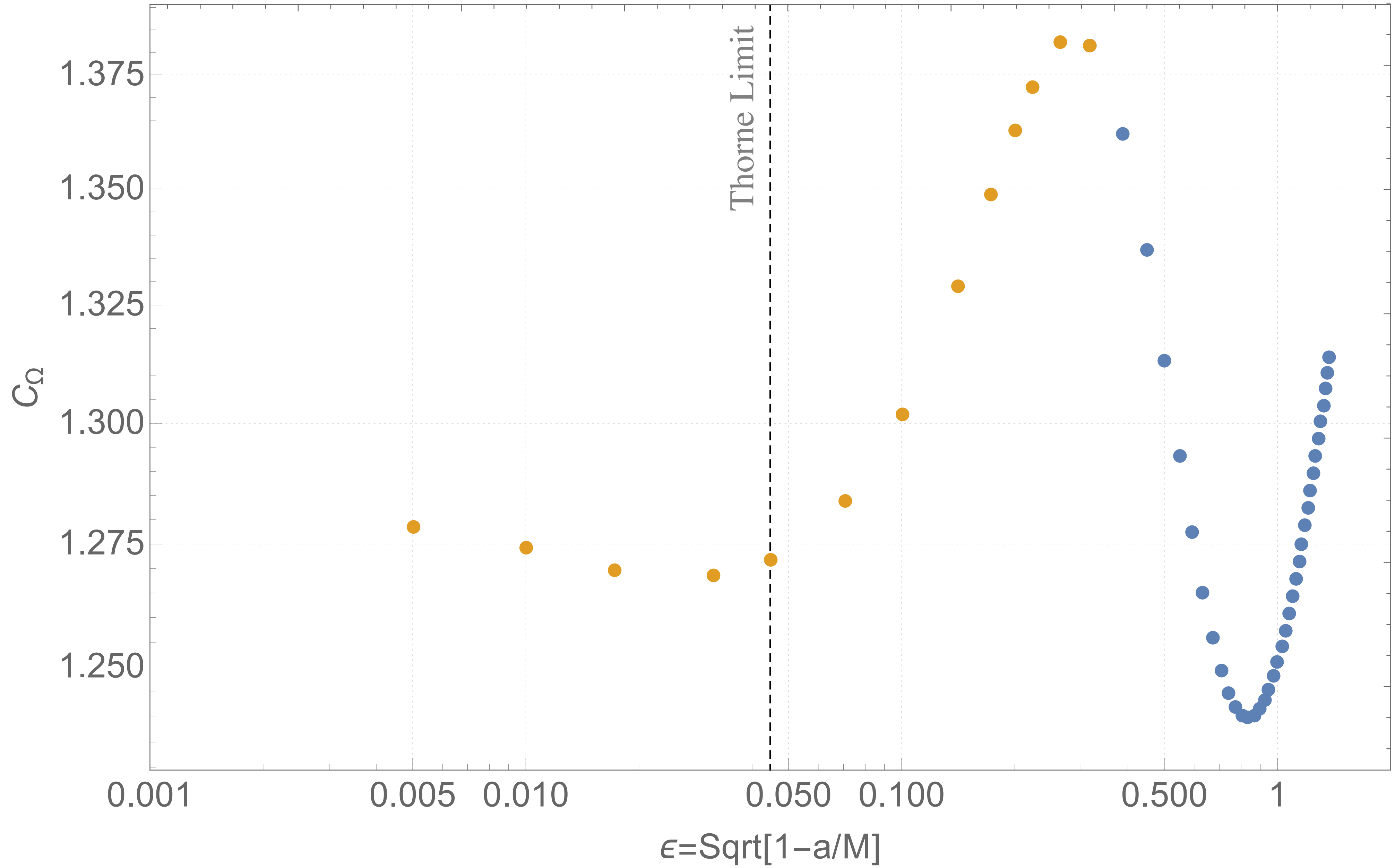



key new technology: regularize spheroidal-harmonic modes directly

# Near-extremal Kerr ISCO shift



# Near-extremal Kerr ISCO shift




Similar numerical results recently found by Maarten van de Meent

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# Can we say anything about the extremal limit?
# Maybe…

$$C_\Omega = 1 - \frac{1}{2}\frac{z''_{(1)}(\Omega^{(0)}_{\rm isco})}{\Omega^{(0)}_{\rm isco}\, z'''_{(0)}(\Omega^{(0)}_{\rm isco})}$$

$$z'''_{(0)}(\Omega^{(0)}_{\rm isco}) \sim \epsilon^{-2/3}$$

For $z''_{(1)}(\Omega^{(0)}_{\rm isco})$ take inspiration from Colleoni+ (arXiv:1508.04031)

and split result into completion piece $z''^{\rm compl}_{(1)}(\Omega^{(0)}_{\rm isco}) \sim \epsilon^{-2/3}$

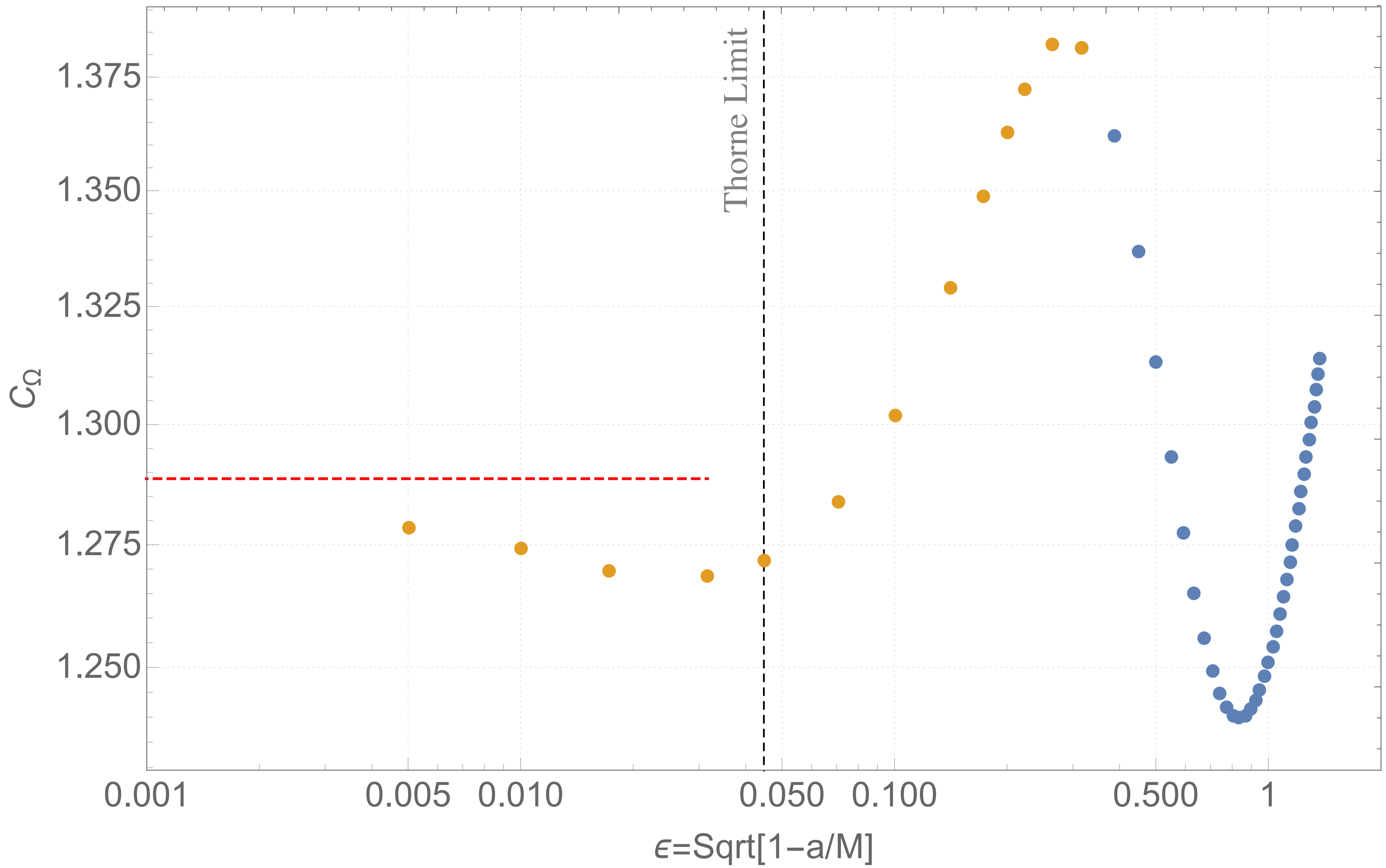
singular piece $z''^{S}_{(1)}(\Omega^{(0)}_{\rm isco}) \sim {\rm const}$

reconstruction piece

Preliminary numerical results suggest that $z''^{\rm recons}_{(1)}(\Omega^{(0)}_{\rm isco})$

is finite, or at least doesn't diverge as fast as $\varepsilon^{-2/3}$

# Near-extremal Kerr ISCO shift




$$C_\Omega(\epsilon = 0) = 1 + \frac{1}{2\sqrt{3}}$$

# Gravitational wave emission from an inspiral into a near-extremal Kerr black hole

## Recap

- Characteristic exponential decay in waveform amplitude and rapid rise in the frequency: there is no chirp
- Signal robust to perturbations of the inspiral away from circular, equatorial
- Inspiral into Gargantua details in CQG 33:155005, arXiv:1603.01221
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## Future directions

- Calculate next near-extremal term $P_{GW} = (C_\infty + C_H)x_0 + \mathcal{O}(x_0)^2$
- Analytically calculate ISCO shift
- Analytically add plunge (see Hadar's talk next) and ringdown