Stone Skipping Black Holes in Ultralight Dark Matter Solitons

arXiv 2602.11512

Alan Zhang
Yourong Wang
J. Luna Zagorac
Richard Easther

CosPA 2026,
University of Canterbury

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

NEW ZEALAND GRAVITY

Front Cover: *"Lake Mapourika, NZL"*

Ultralight Dark Matter

A Scalar DM Candidate

$m \sim 10^{-22}$ eV, behaves like CDM on large scales but self-smoothing at small scales.

λ_{dB} ~ kpc at Galactic Velocities

Wave mechanics of astrophysical proportions.

Ultralight Dark Matter

$$i\dot{\psi} = \left[-\frac{1}{2m}\nabla^2 + V \right]\psi$$

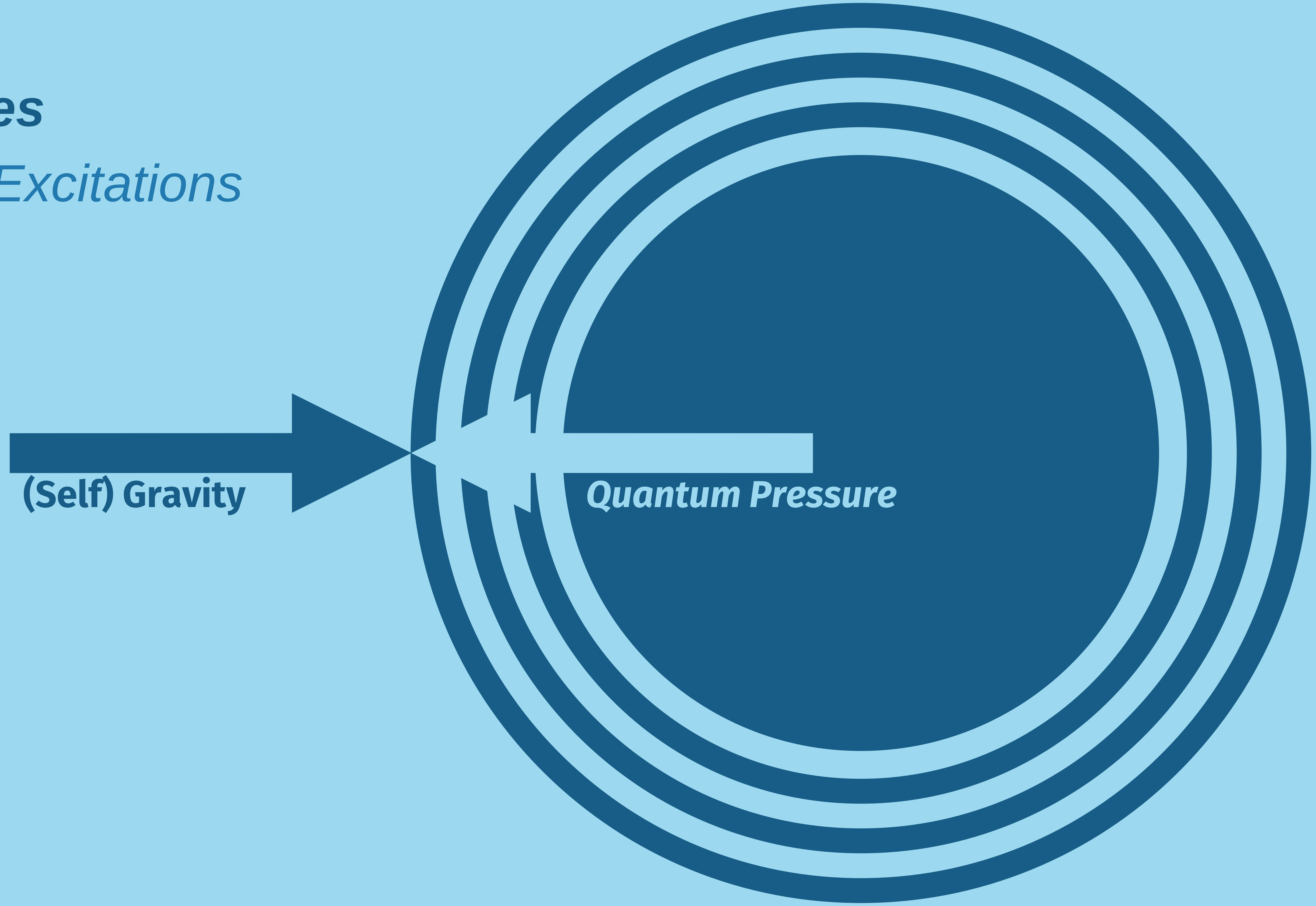
$$\nabla^2 \Phi_U = 4\pi m |\psi|^2$$

A nonlinear modification to Schrödinger Equation,
giving the wavefunction an associated mass density.

Ultralight Dark Matter

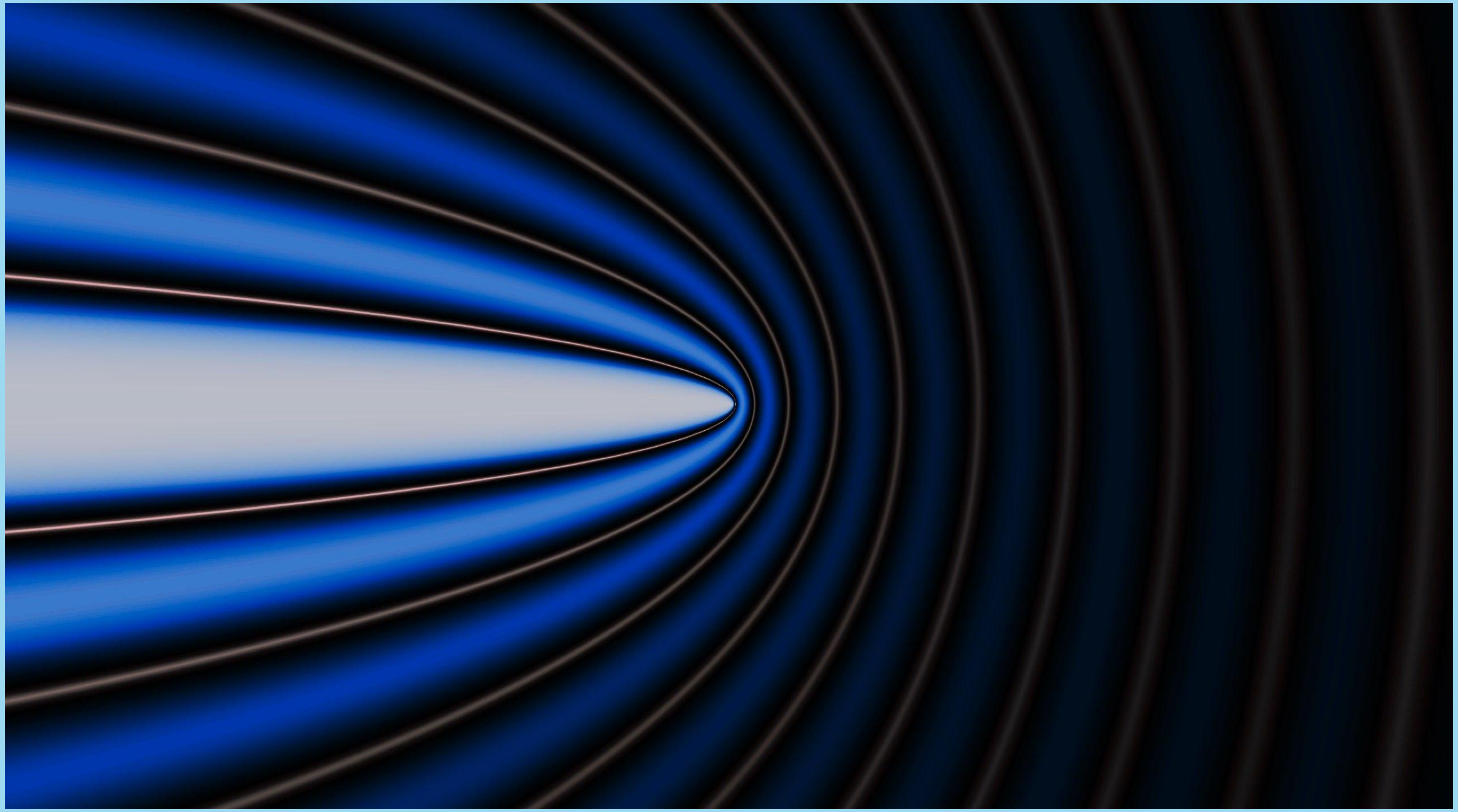
Solitons at Halo Centres

Coherent ground state. Excitations carry dynamics.

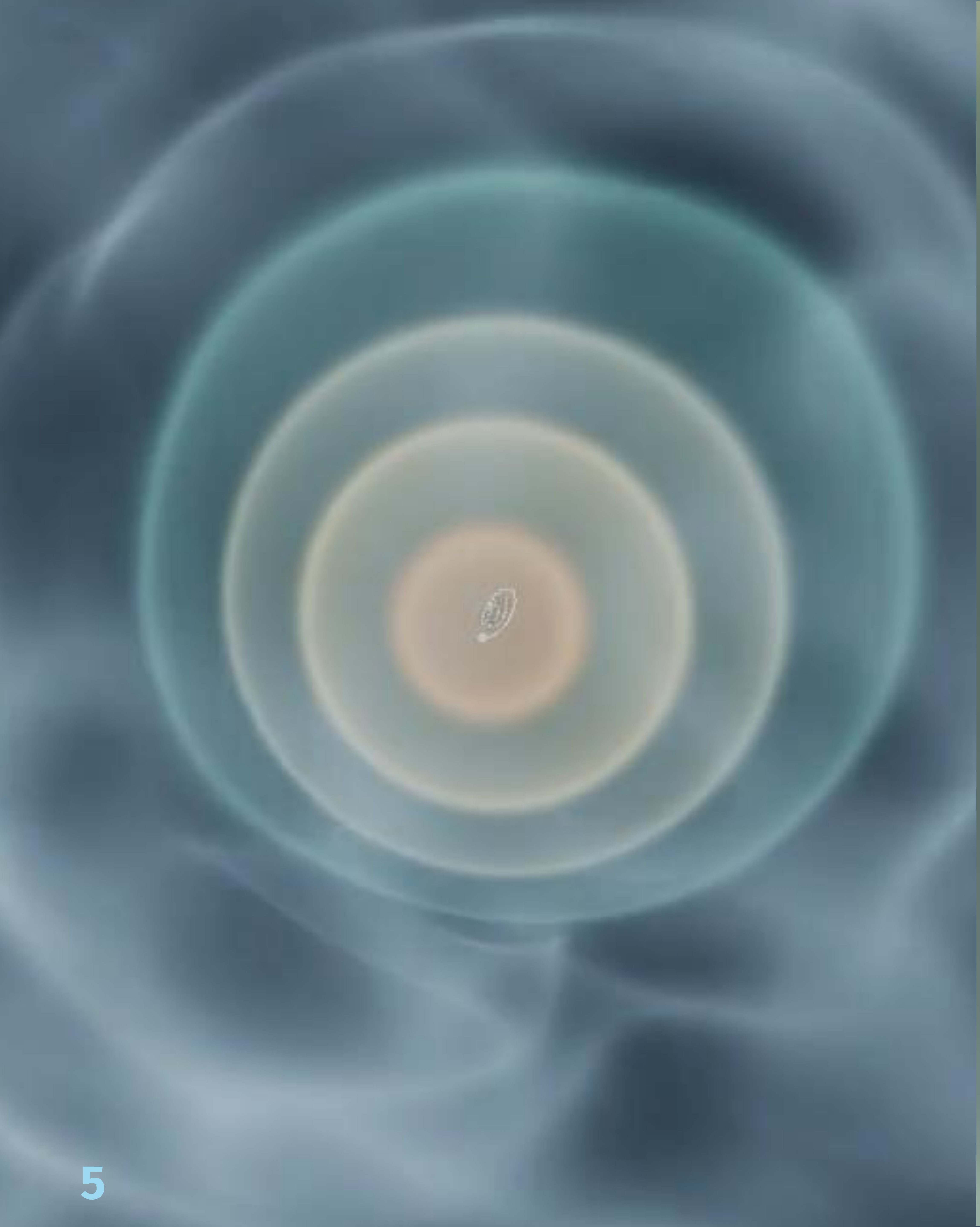


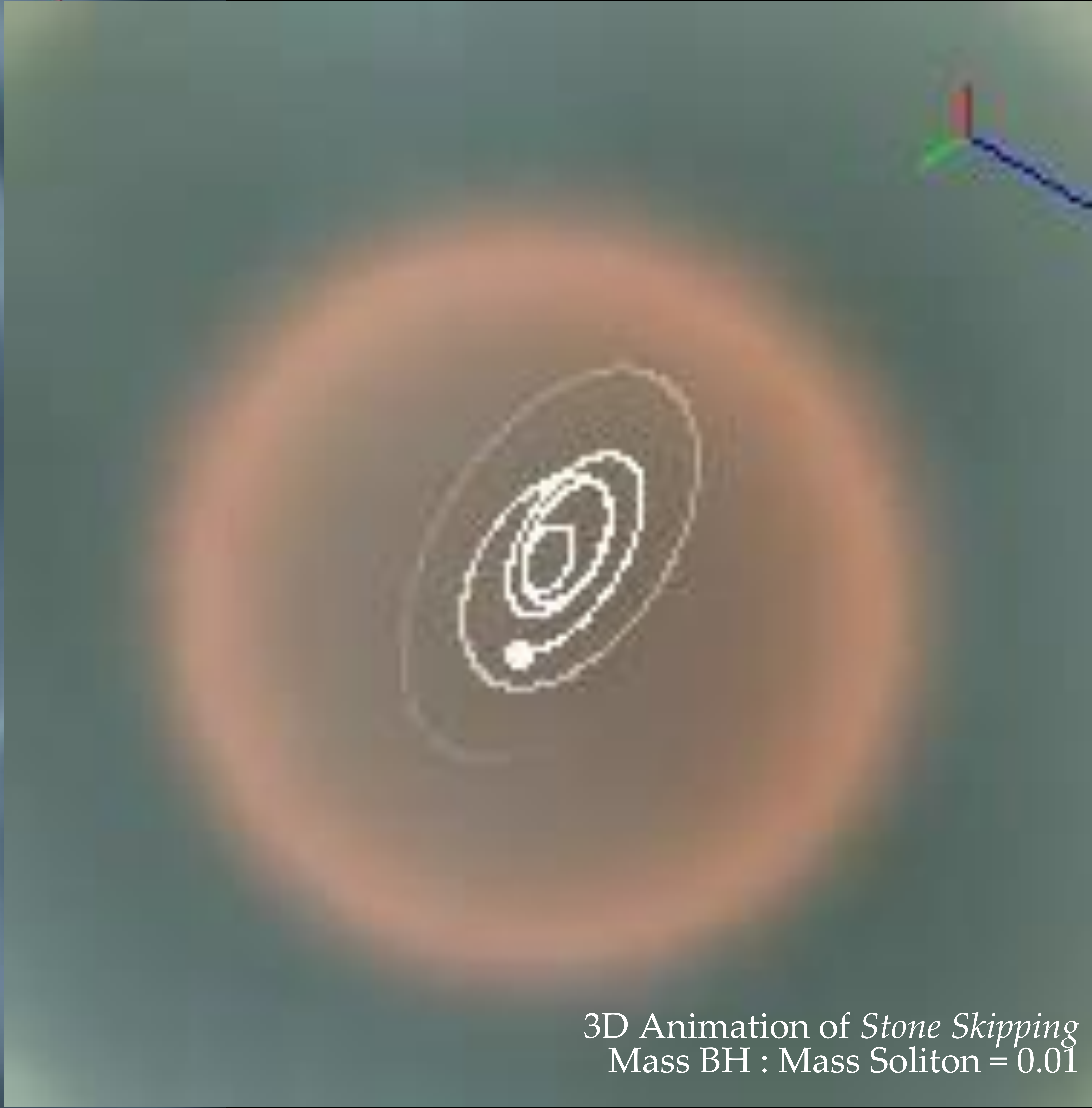
Dynamical Friction

Massive perturbers lose momentum to the wake in interstellar medium they create

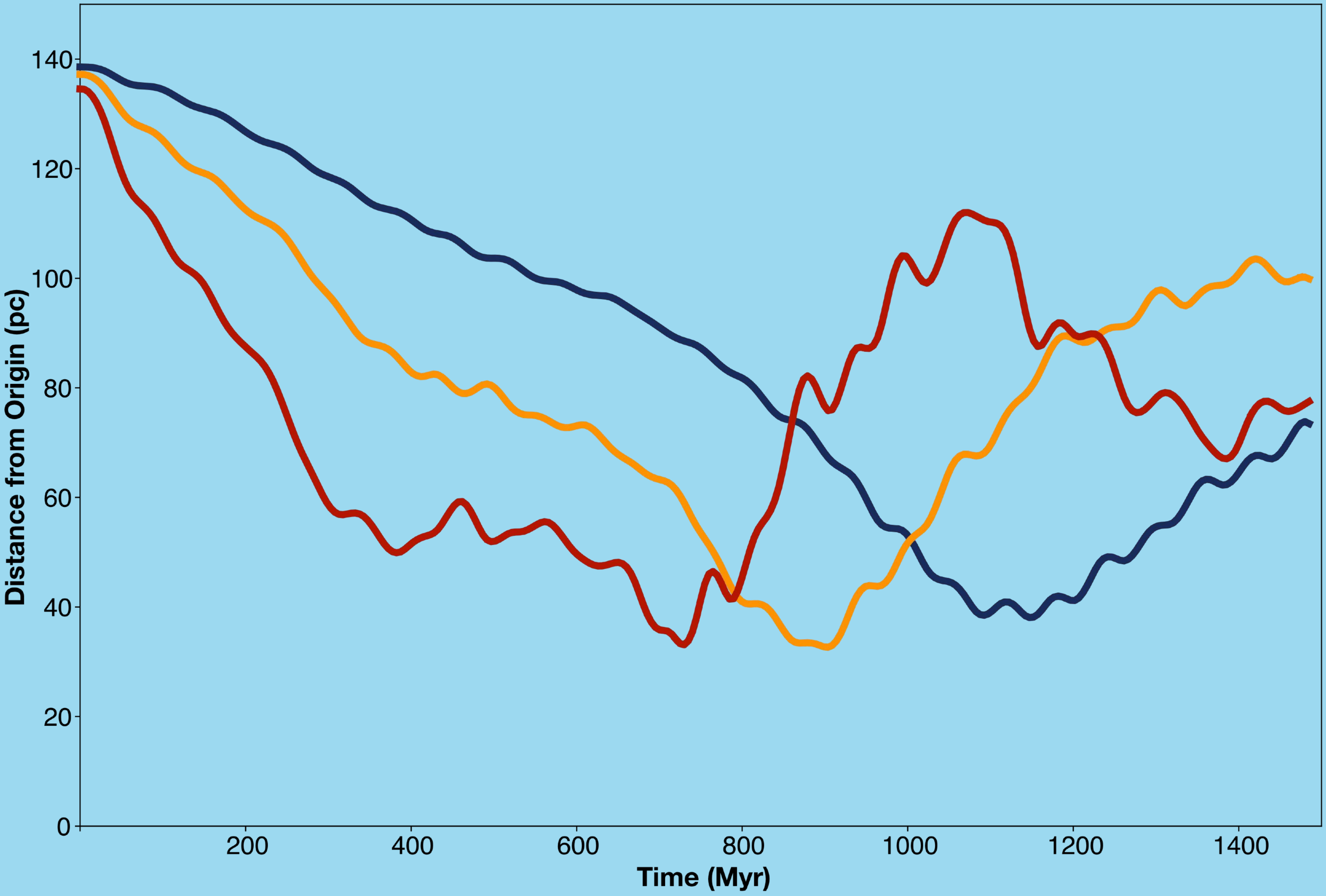


Dynamical Friction. I. Chandrasekhar, S. (1943)
Wang & Easther (2110.03428)





3D Animation of *Stone Skipping*
Mass BH : Mass Soliton = 0.01



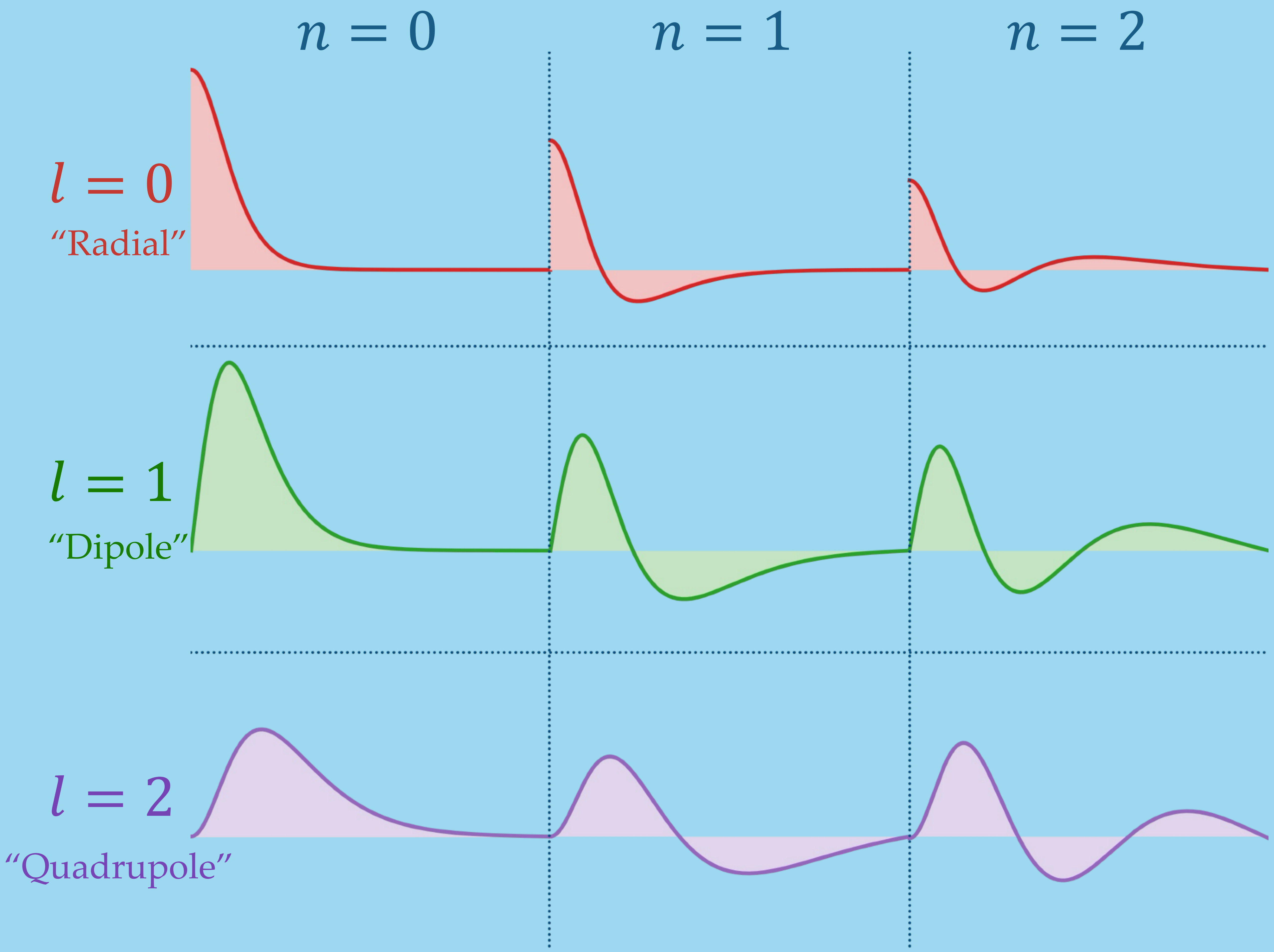
Time evolution of the orbital radius of black holes in initially circular orbits and masses **1**, **2**, and **5**% of the soliton mass

Modes of a Perturbed Soliton

Linearise ψ around the soliton ground state

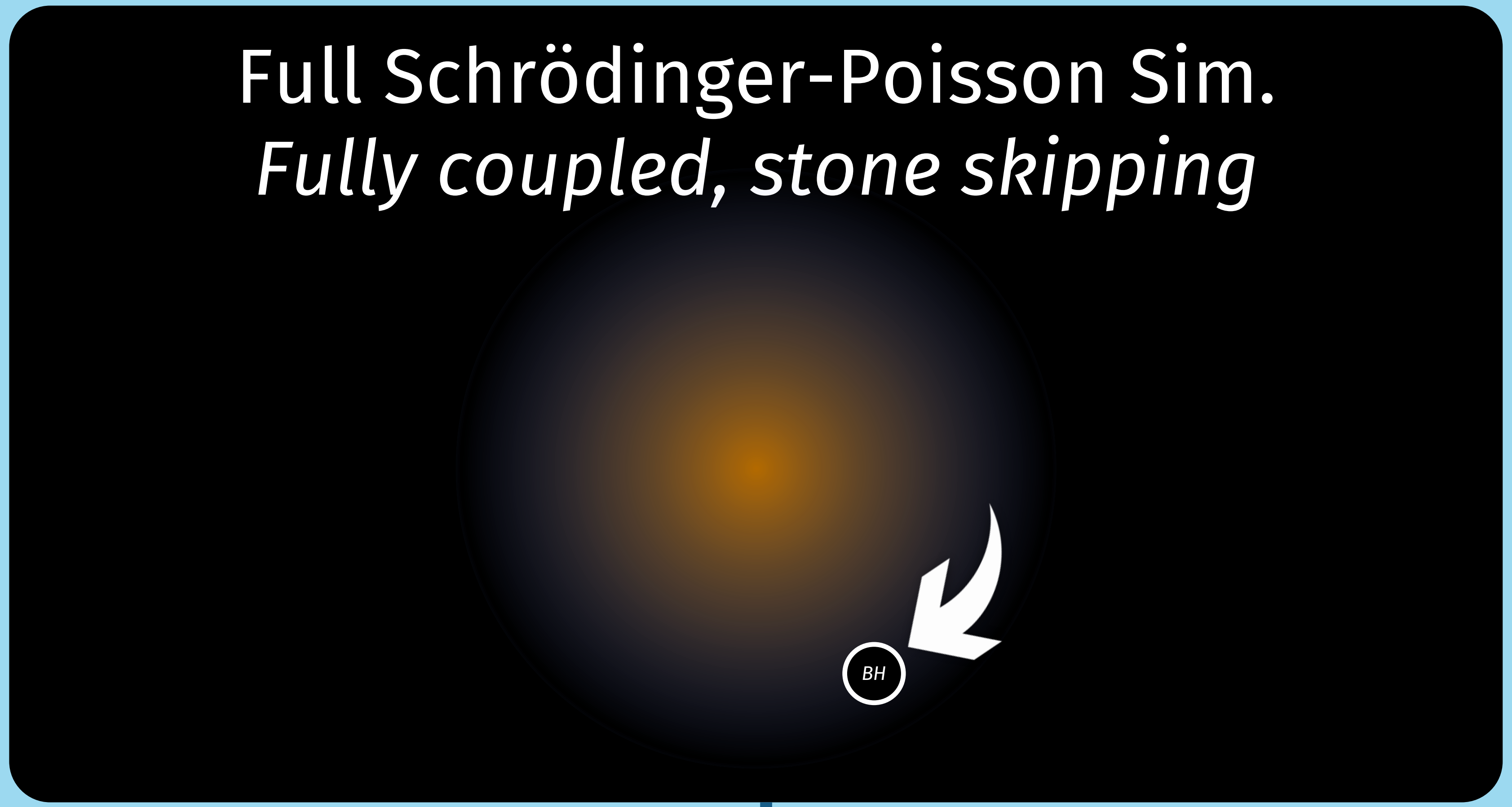
$$\psi(r,t) = \sum_{nlm} c_{nlm}(t)\psi_{nlm}(r)$$

Here, ψ_{nlm} solve the Schrödinger equation in the ground state potential.



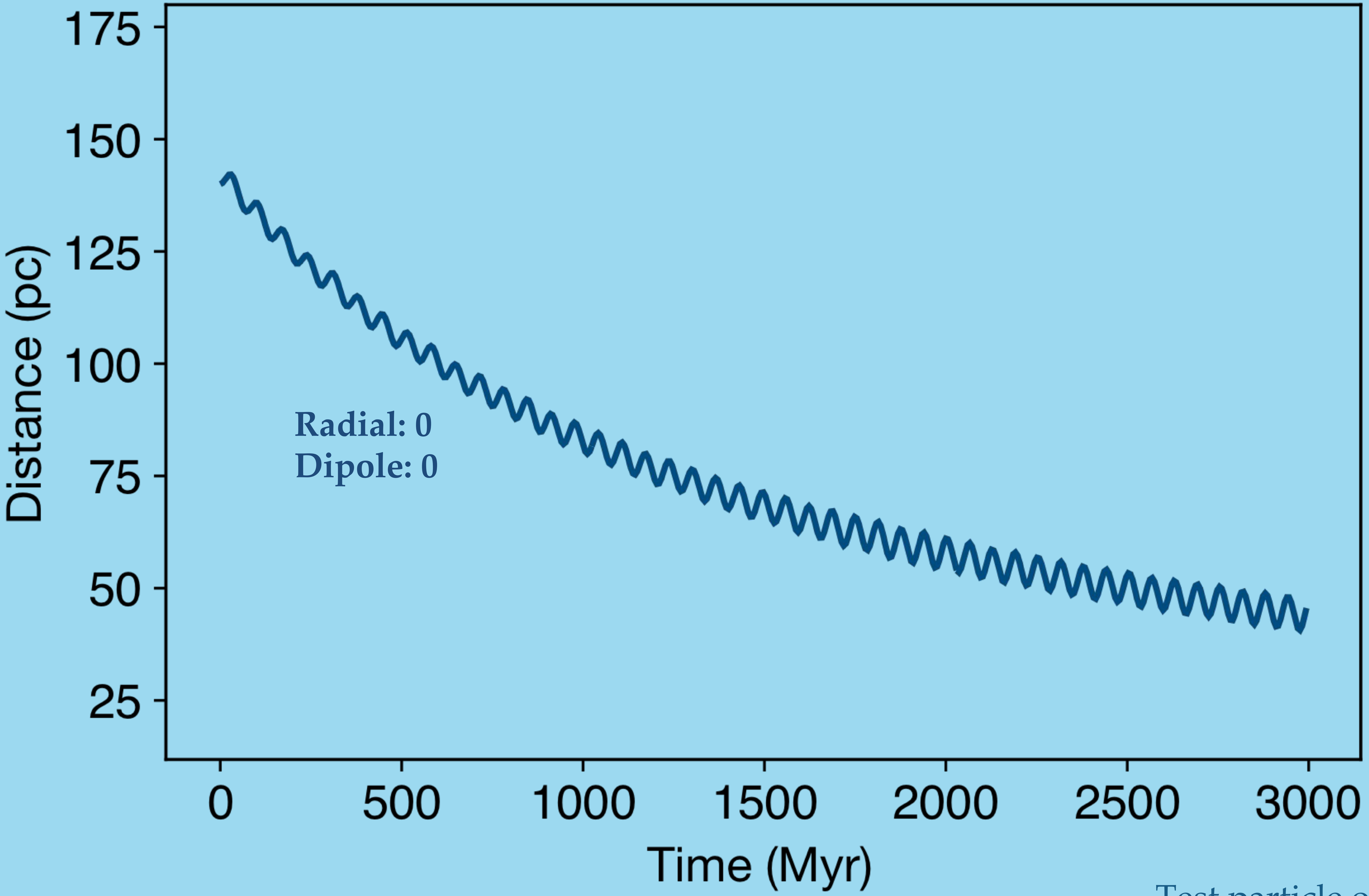
Radial profiles $f_{nl}(r)$ for $n = 0,1,2$ and $l = 0,1,2$

Modes of a Perturbed Soliton

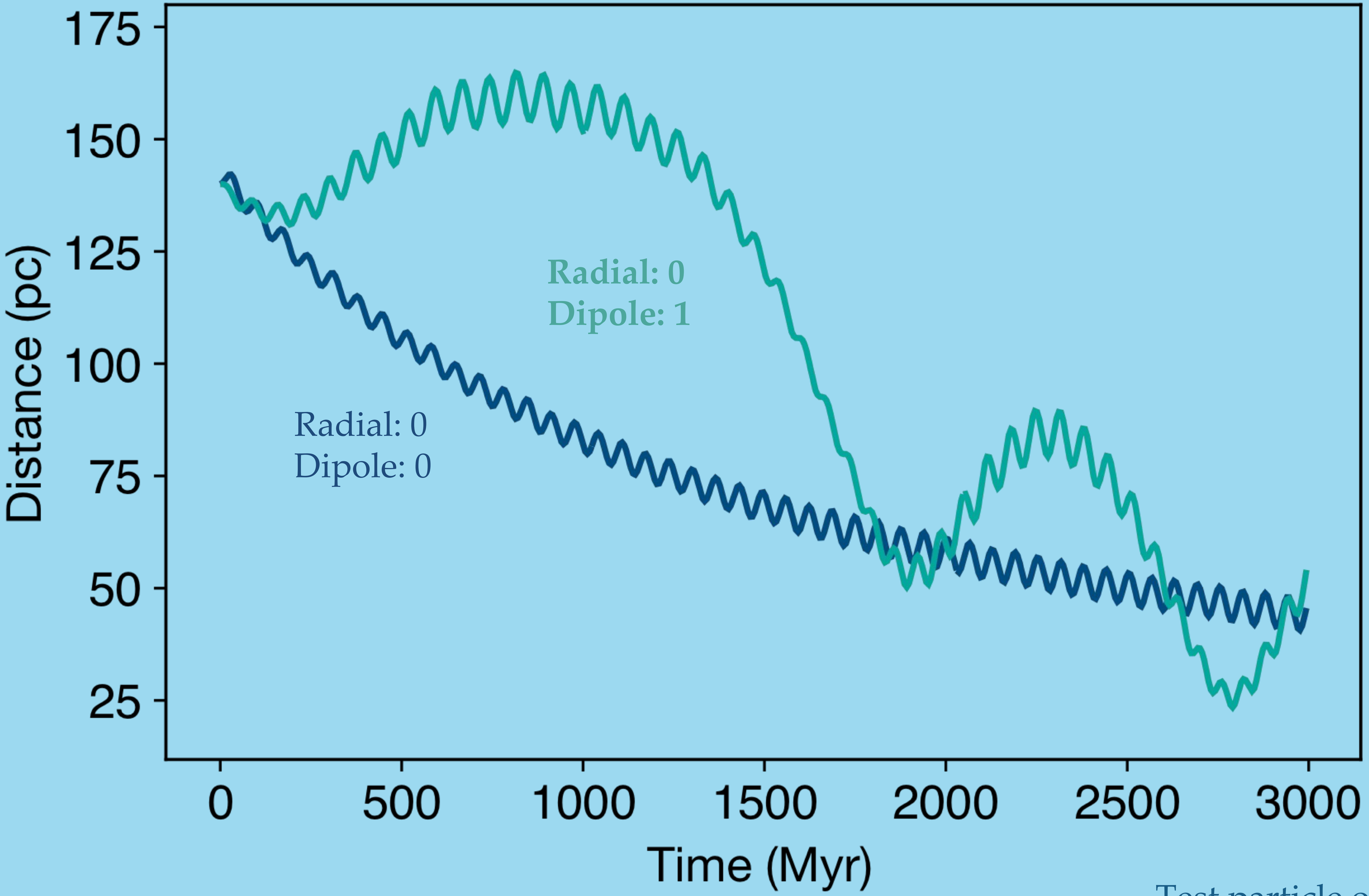


Compute Mode Decomposition
$\{c_{nlm}(t)\}$

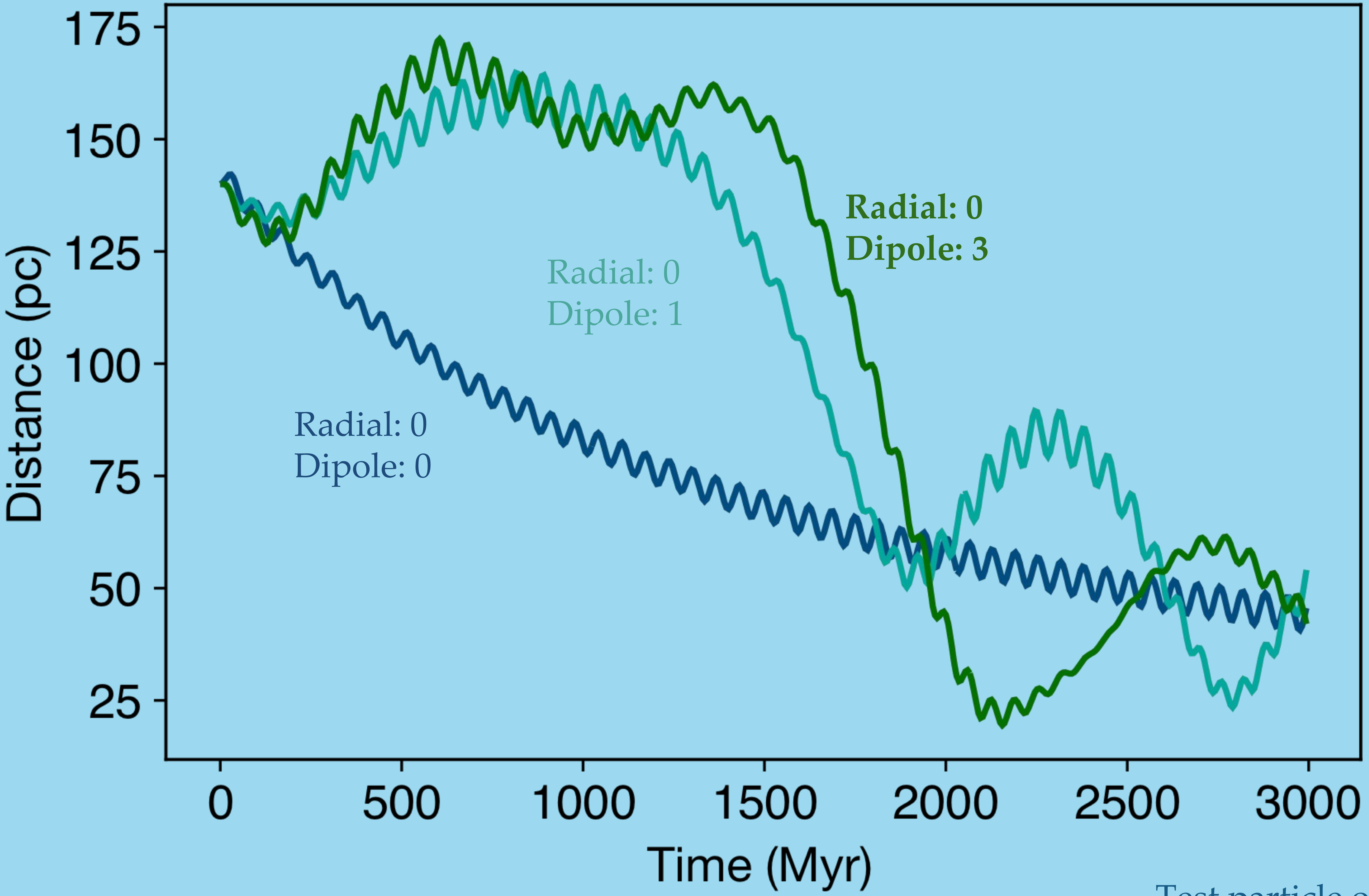
Reconstruct pre-excited $\psi(r, 0)$
with select modes
(e.g. Ground state + Dipole)



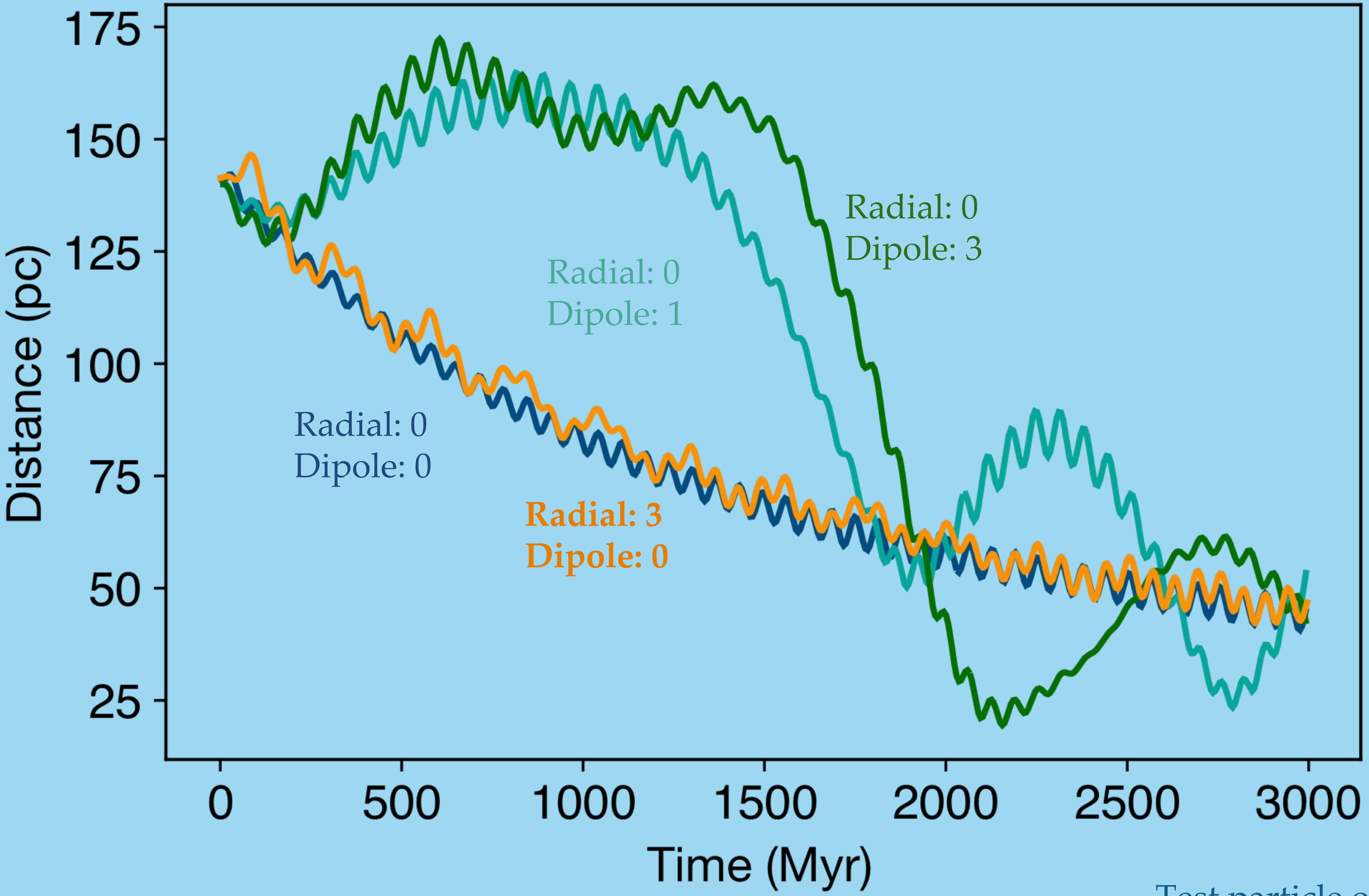
Test particle orbital radius vs. time
with different soliton perturbations



Test particle orbital radius vs. time
with different soliton perturbations



Test particle orbital radius vs. time
with different soliton perturbations



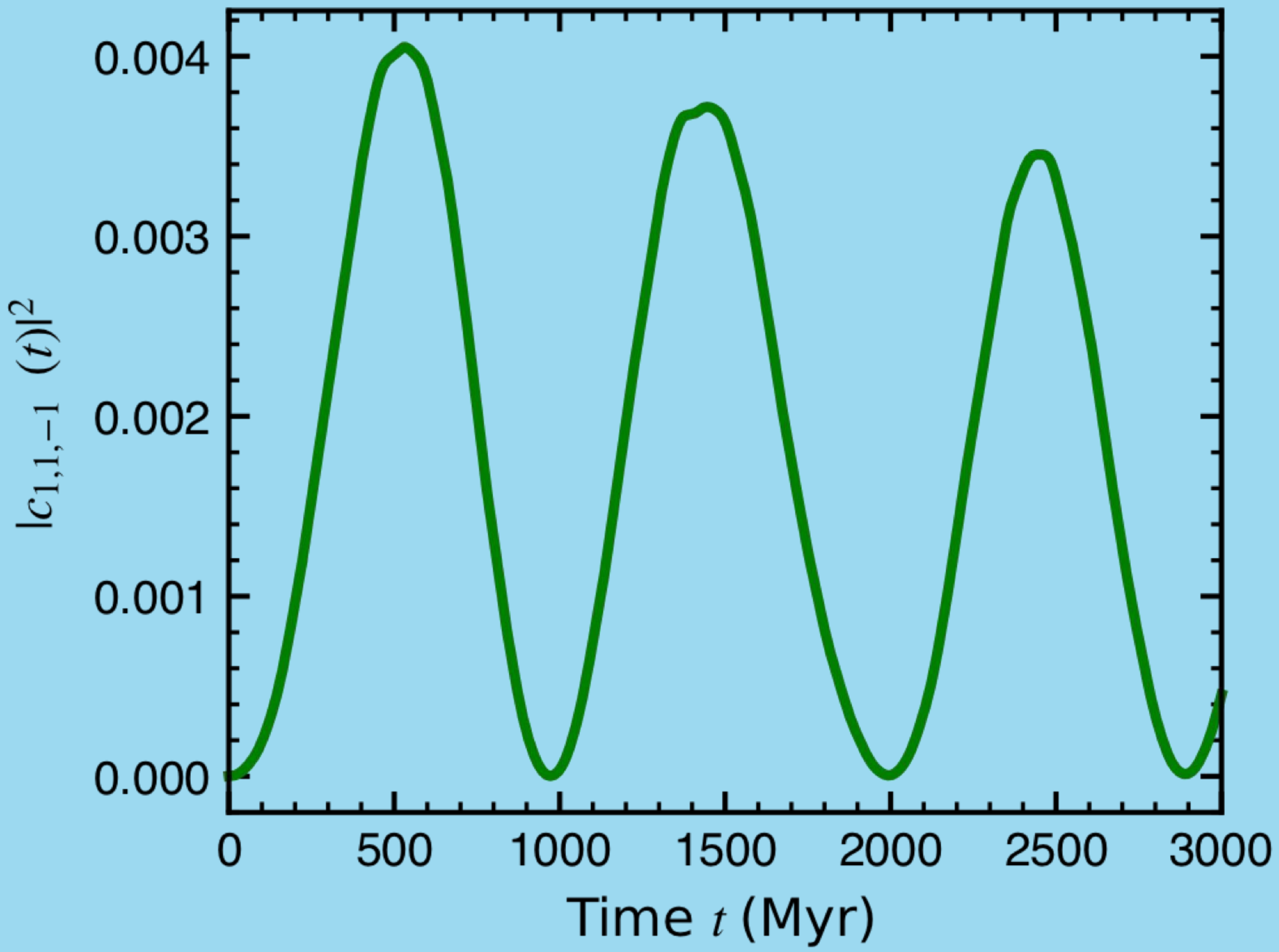
Test particle orbital radius vs. time
with different soliton perturbations

Soliton Stone Skipping is a **Dipole Resonance**

A forced–damped oscillator. BH gravity excites the Soliton's **dipole mode**, which in turn resonates with the orbit. **Two-way energy transfer.**

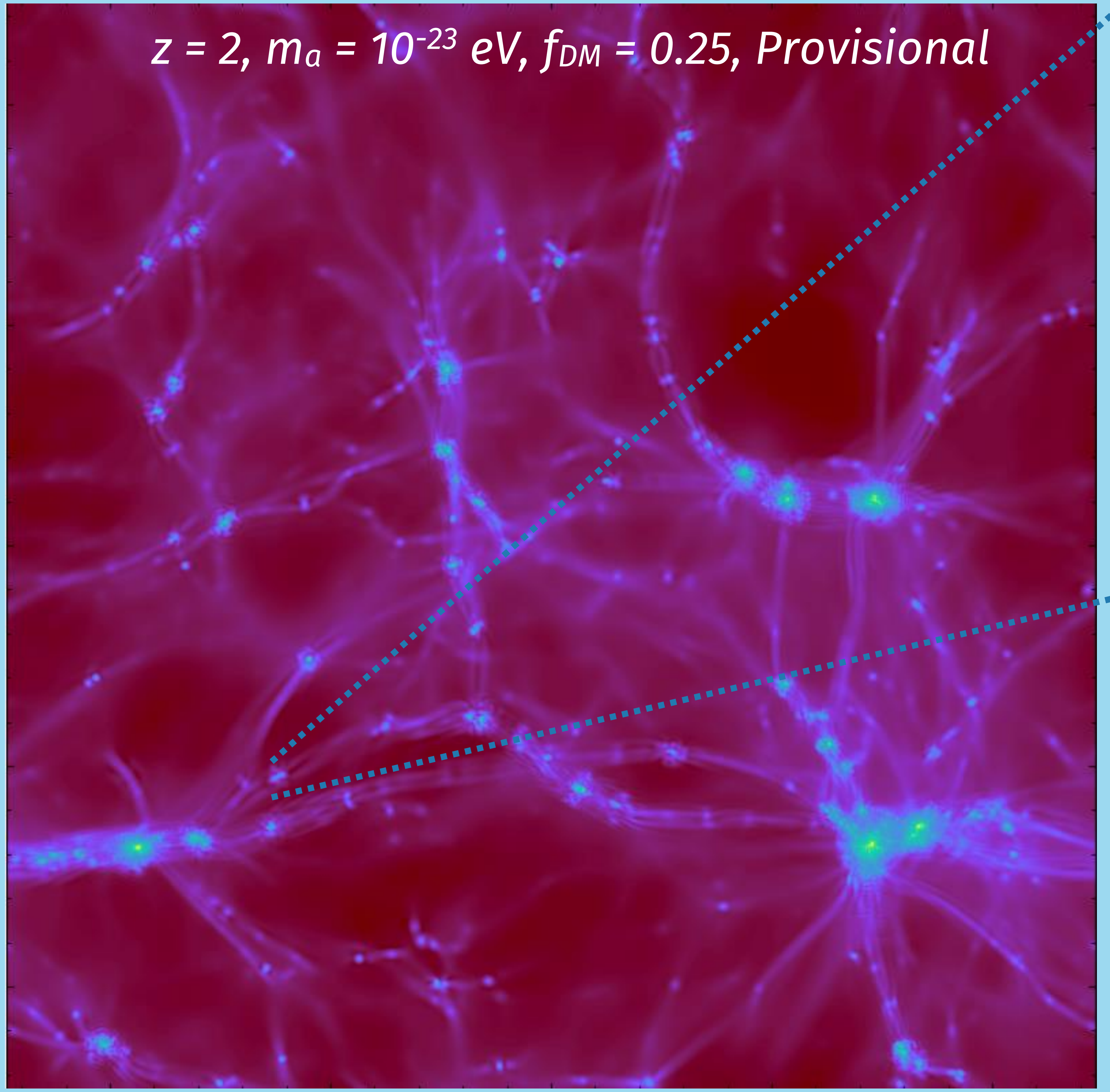
More significant for single BH: binaries scramble the dipole signal.

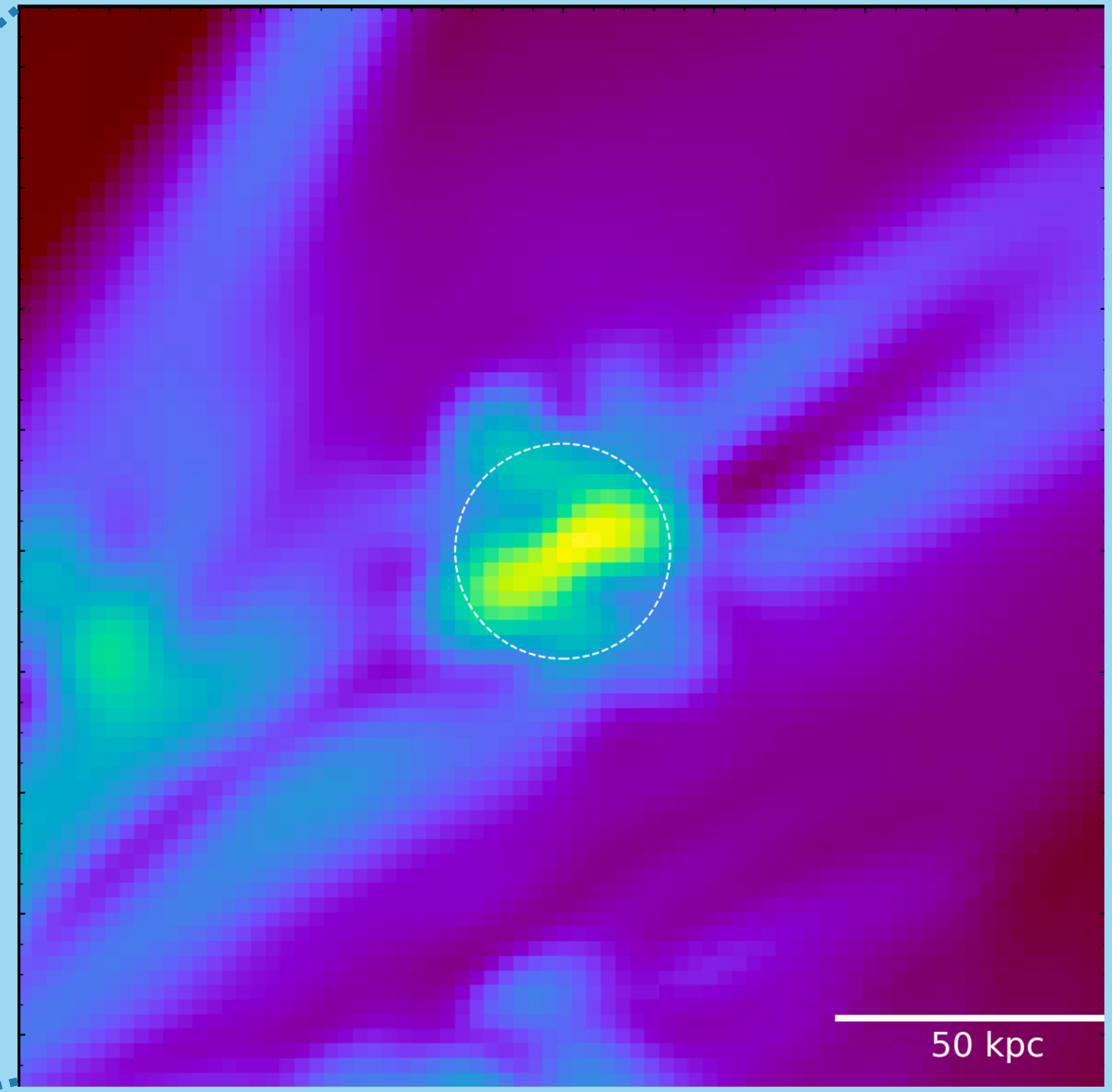
Implication: ULDM excitations modifies inspiraling behaviour and naive dynamical friction predictions.

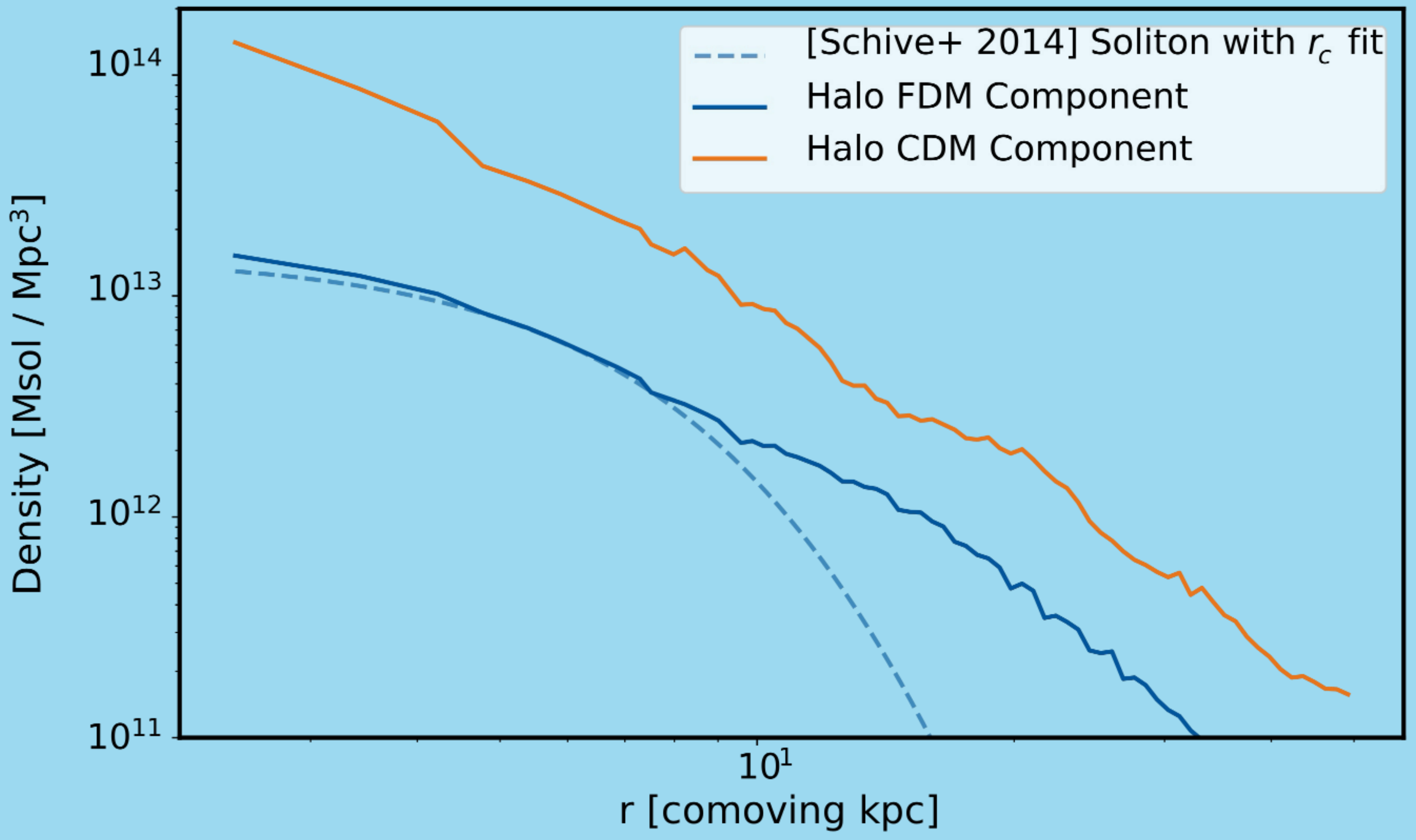


Amplitude of the dipole component $|c_{1,1,-1}(t)|^2$ for the stone skipping run with a single black hole

Cosmology Context / Ongoing







Mixed DM Structure Formation for LyA - Wang 2604.06038, Under revision at MNRAS
Try the Latest *AxioNyx 1.1*: FWPhys.com/AxioNyx

Summary

Stone skipping: dipole resonance, not Chandrasekhar drag

Single-perturber phenomenon: binaries phase-scramble

Modified inspiral when $M_{BH} \ll M_{soliton}$

What's Next?

Accretion of ULDM by BHs (development / testing)

Cosmological solitons + complex object inspiral (open)

Let's Chat!

yourong.wang@uni-goettingen.de

FWPhys.com/PyUL · FWPhys.com/axionyx

Rear Cover: *"Fimbabach, CHE"*