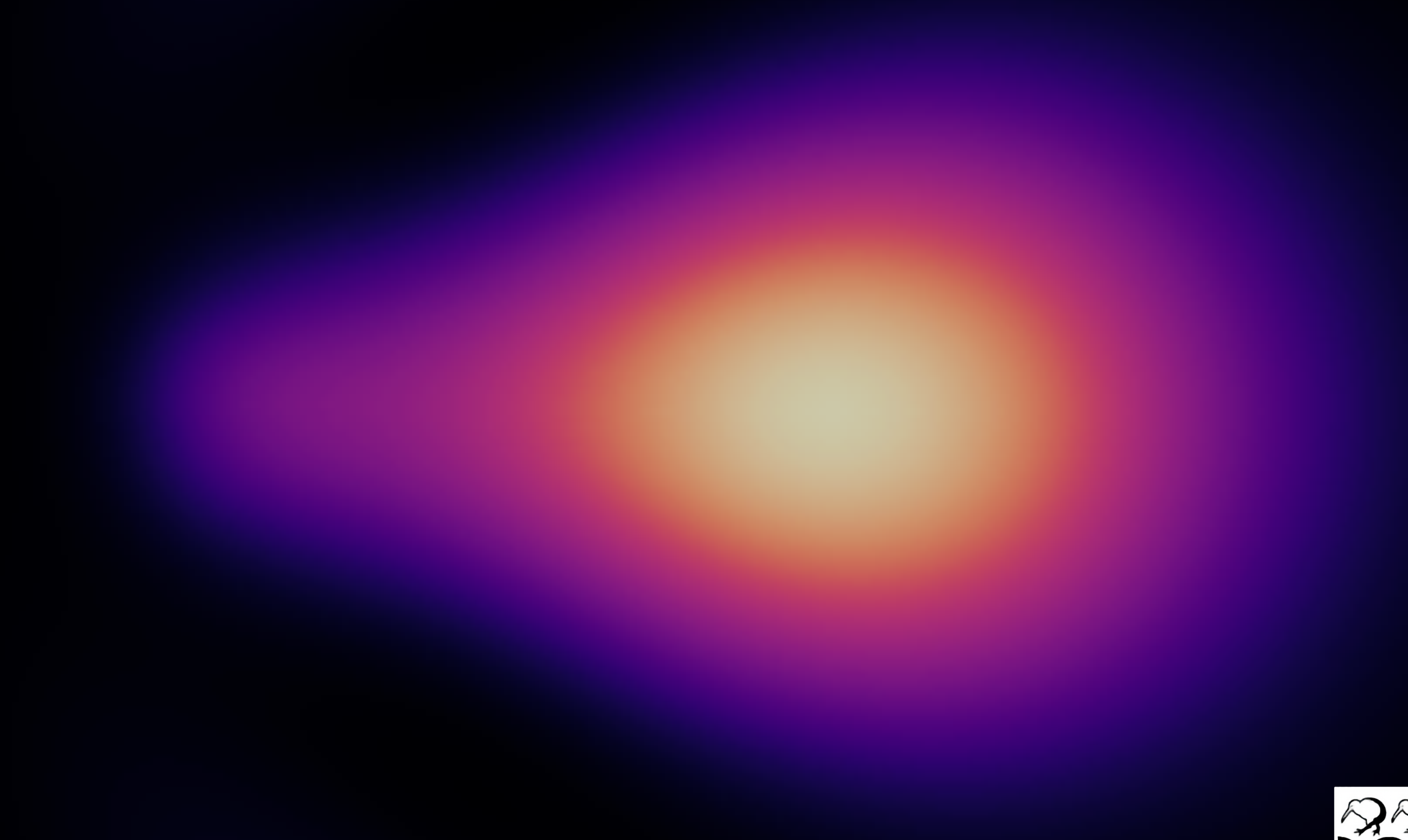
Simulations of Interactions Between **Ultra-Light Dark Matter** and **Massive Particles**



You-Rong Wang & Richard Easther

VLDM WORKSHOP, KAVLI IPMU, TOKYO

29 SEPTEMBER, 2021

arXiv: 2110.xxxxx

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Schrödinger-Poisson (SP) Equations

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

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

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

Schrödinger-Poisson

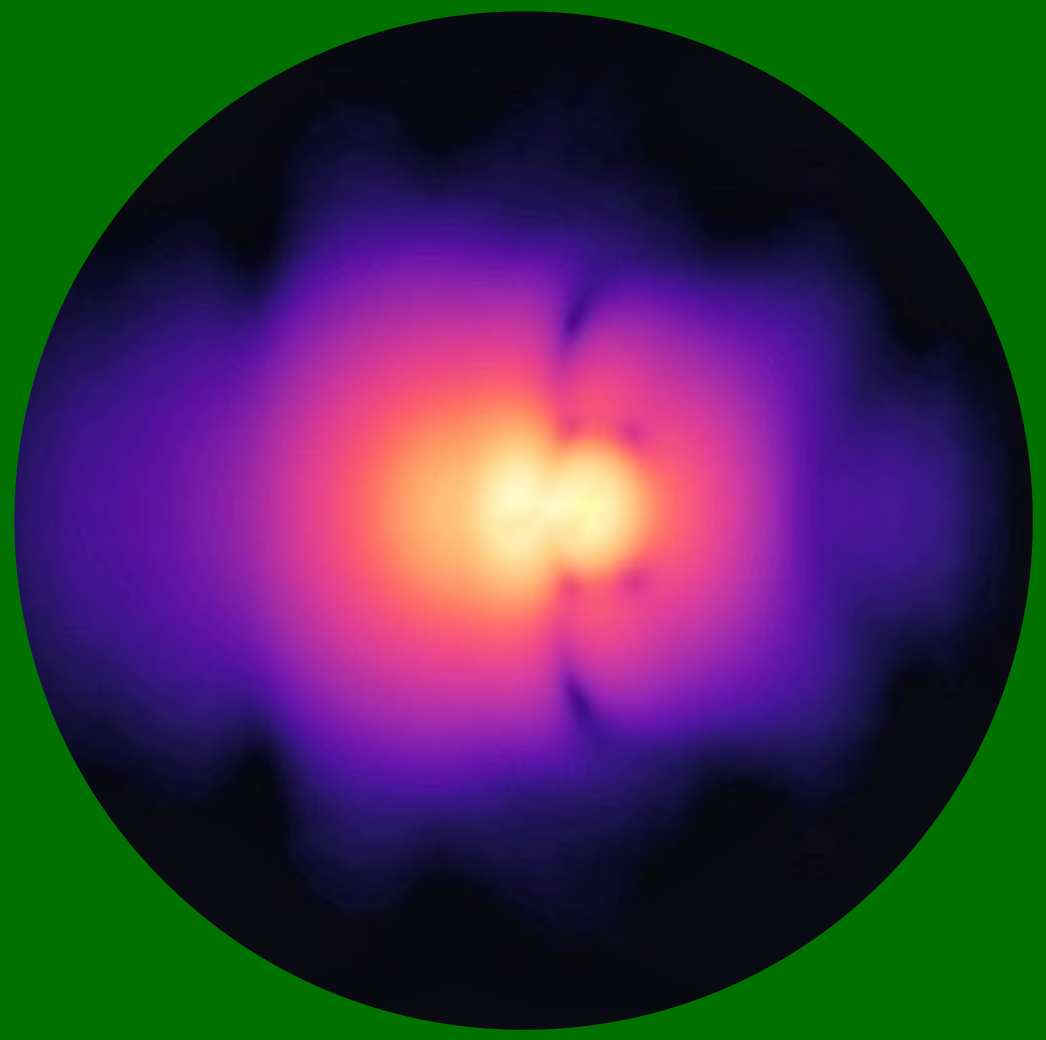
$$i\hbar\dot{\psi} = \left[-\frac{\hbar^2}{2m}\nabla^2 + \left(\Phi_U + \Phi_N\right)\right]\psi$$

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

Rigid N Body System Using Plummer Spheres

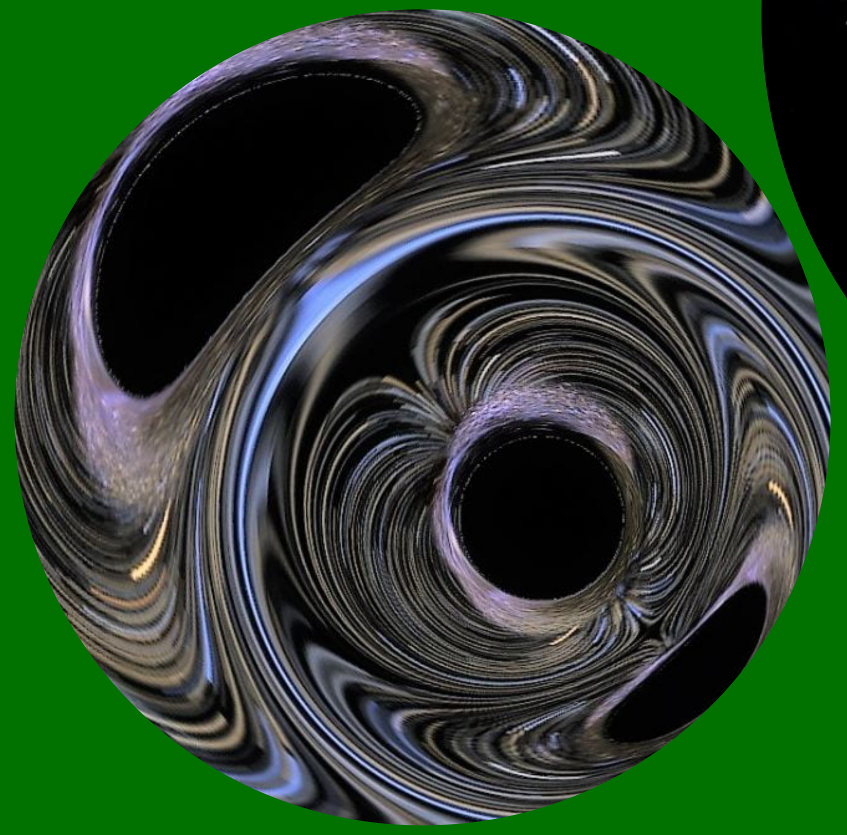
$$\Phi_N = \sum_{j}^{n} \phi_j$$

$$\ddot{\mathbf{x}}_j = -\sum_{k\neq j}^{n} \nabla\phi_k(\mathbf{x}) - \nabla\Phi_U(\mathbf{x}_j)$$



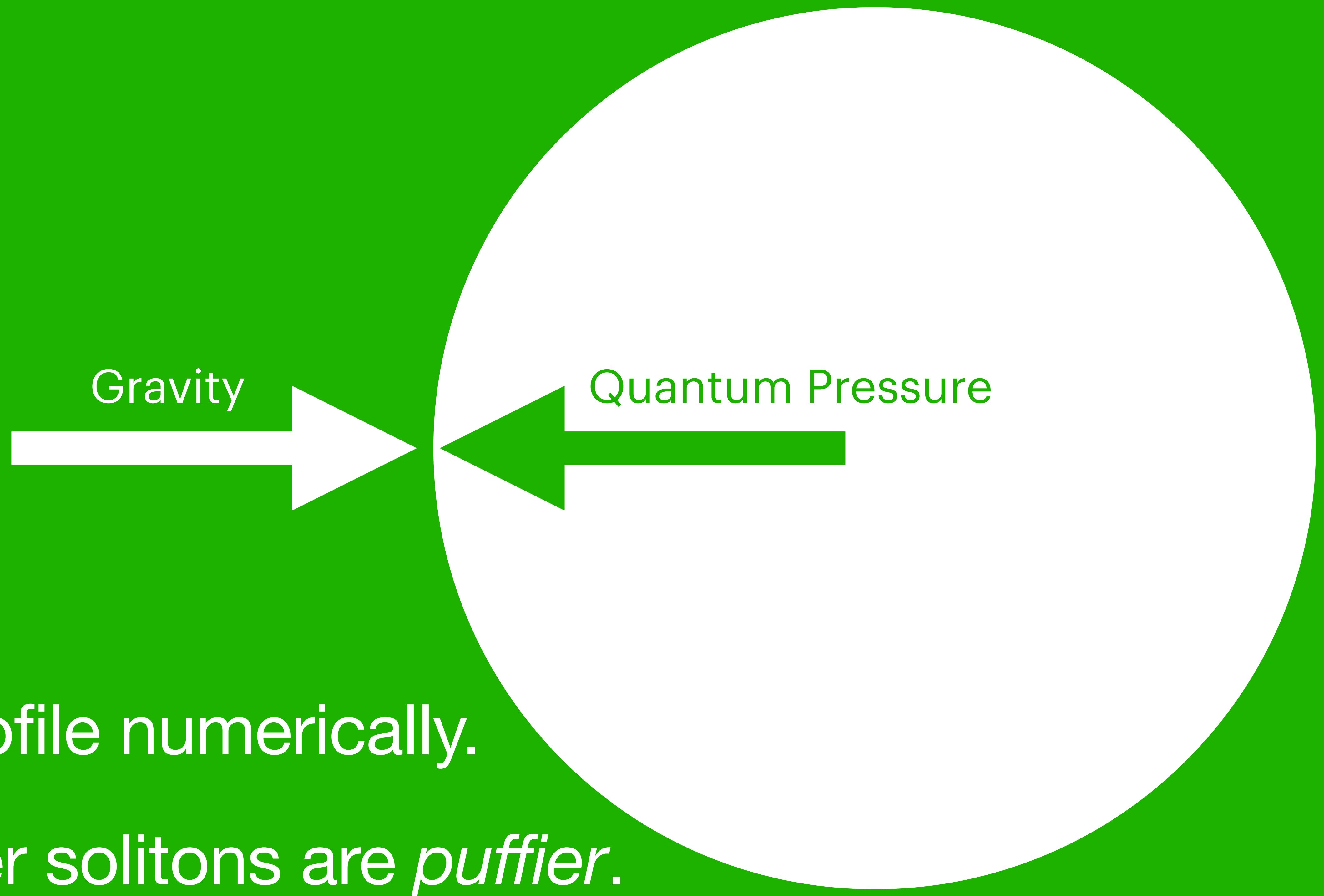
ULDM Halos

Globular Clusters



Black Holes

Schrödinger-Poisson Solitons



Can obtain the general radial profile numerically.

Know some scaling laws—lighter solitons are *puffier*.

1 Dynamical Friction in Uniform ULDM

Dynamical Friction

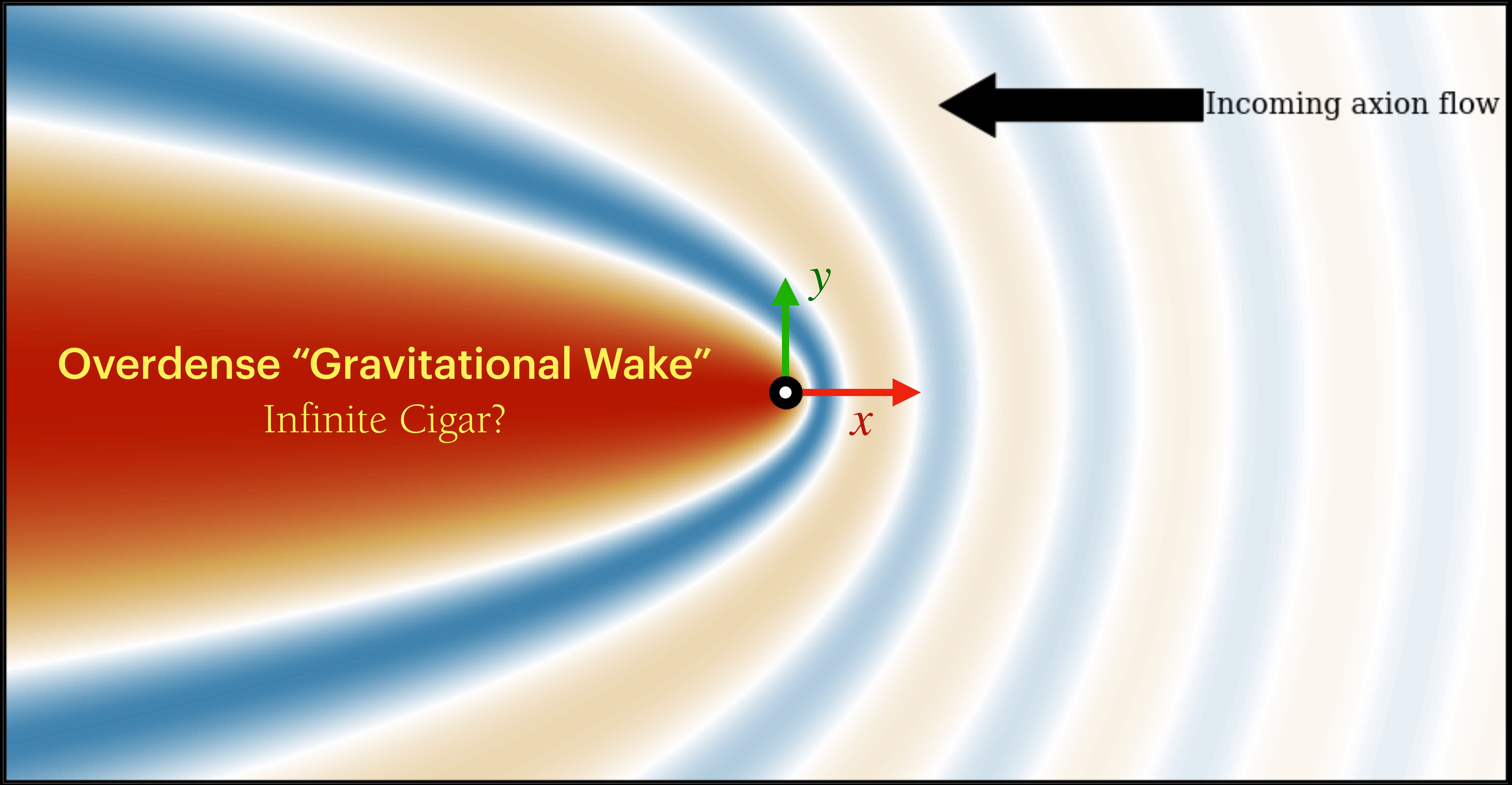
How **a heavy object** travelling through a distribution of **stars, gas, and dark matter** can lose **momentum and energy**.

The SAO Encyclopedia of Astronomy
https://astronomy.swin.edu.au/cosmos

Dynamical Friction. I. General Considerations: the Coefficient of Dynamical Friction
Chandrasekhar, S. (1943).

(Dramatisation)

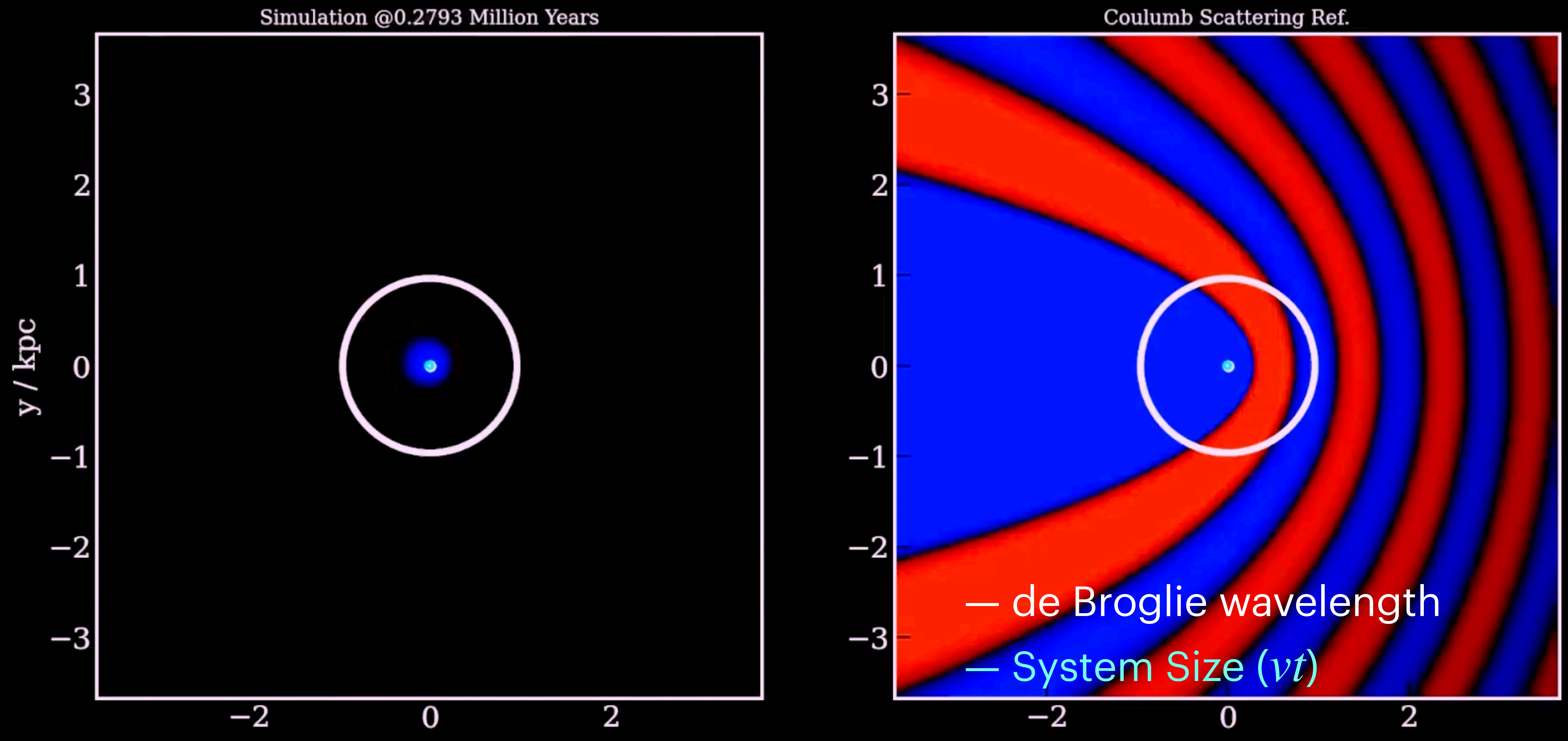
Steady-State ULDM Overdensity in the plane z = 0



$$\psi(\mathbf{x}) = \sqrt{\rho} e^{\pi\beta/2 + 2\pi i x/\lambda_{\mathrm{dB}}} |\Gamma(1 - i\beta)| \times M\left[i\beta, 1; i\frac{2\pi(r+x)}{\lambda_{\mathrm{dB}}}\right].$$

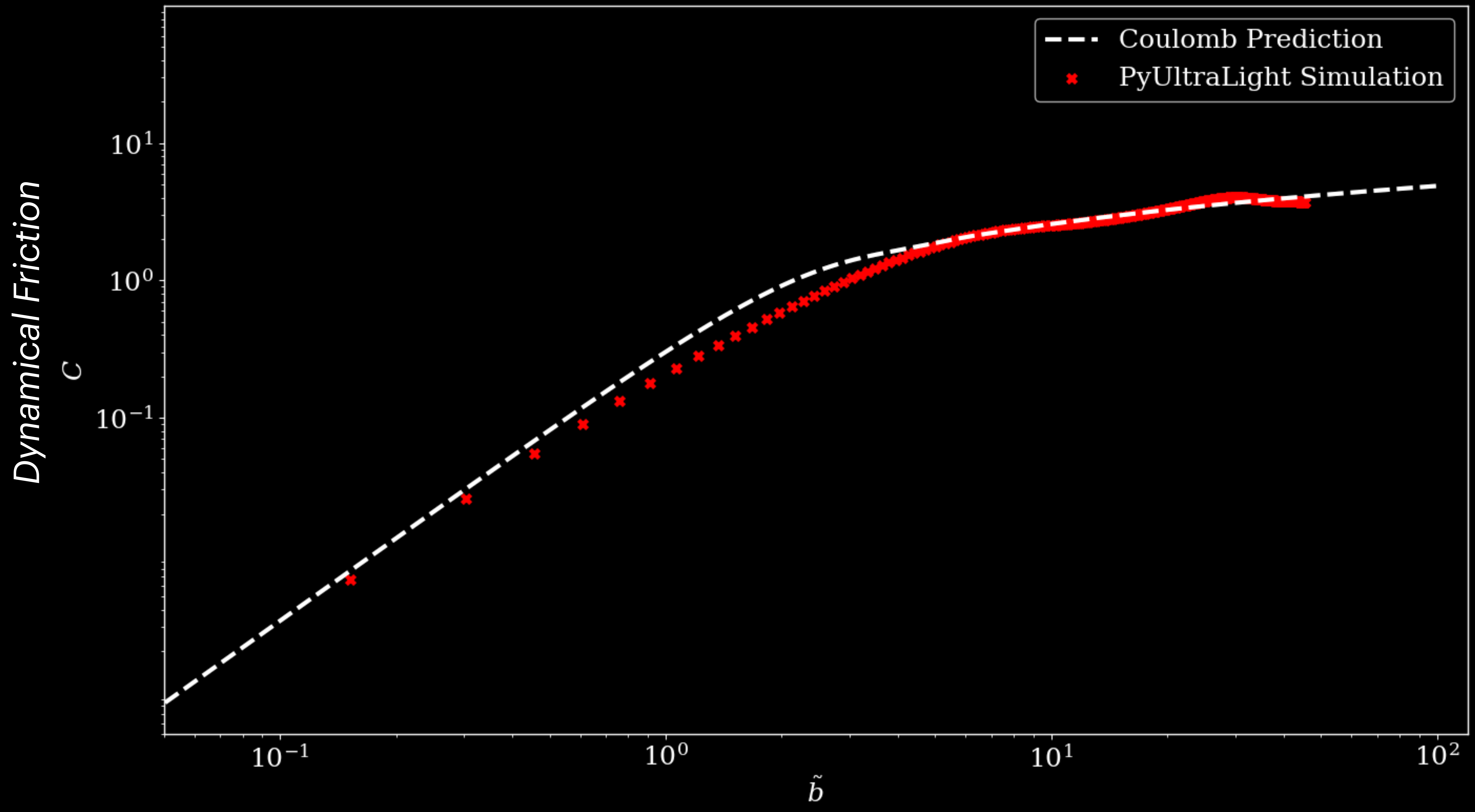
$$\beta = 2\pi \frac{GM}{v^2 \lambda_{\mathrm{dB}}} \qquad M(a, b; z) = \sum_{n=0}^{\infty} \frac{a^{(n)} z^n}{b^{(n)} n!} \qquad p^{(q)} \equiv \frac{\Gamma(p+q)}{\Gamma(p)}.$$

Simplified Simulation vs. Coulomb Scattering

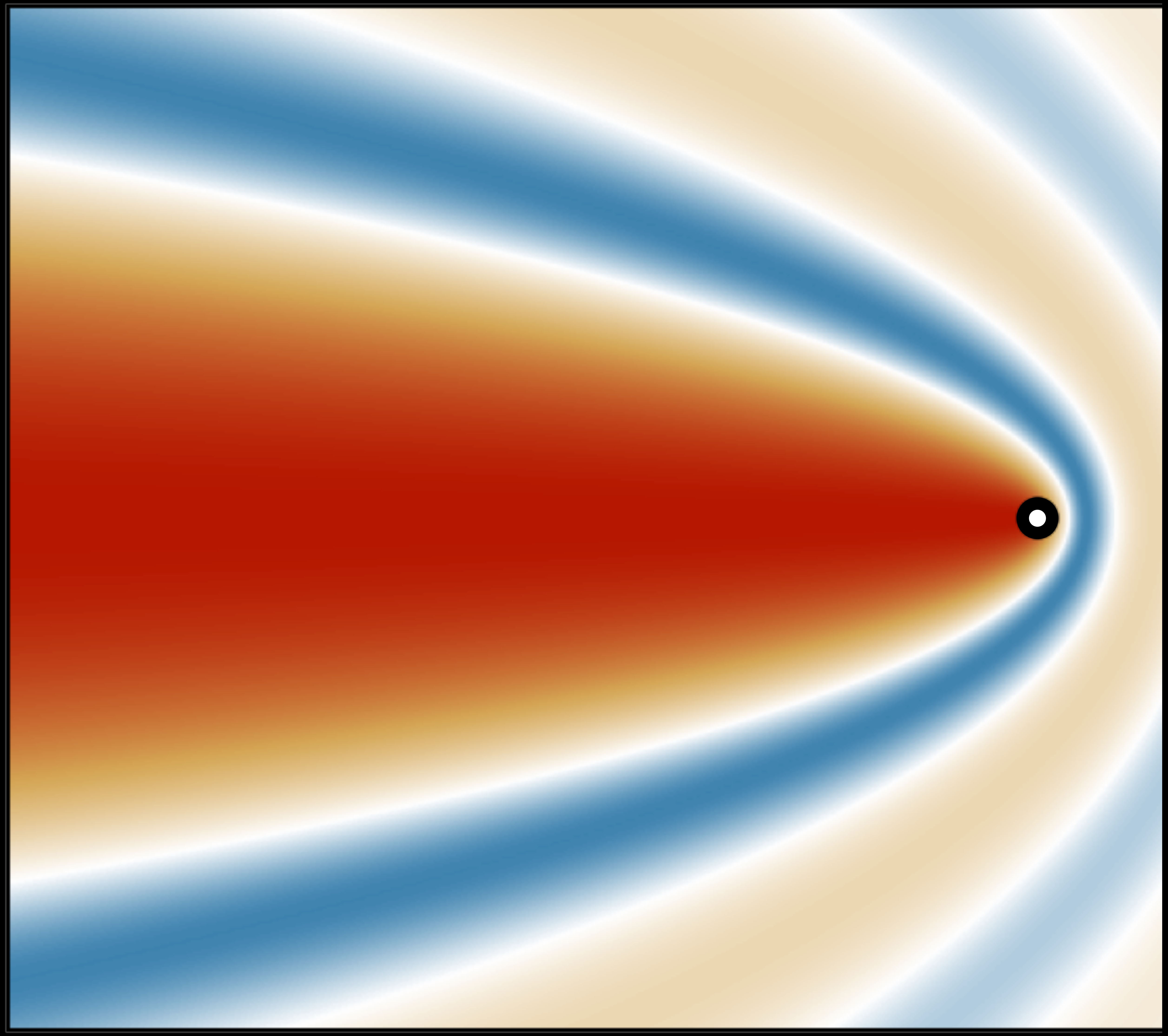


(Two plots share colour scales as left panel)

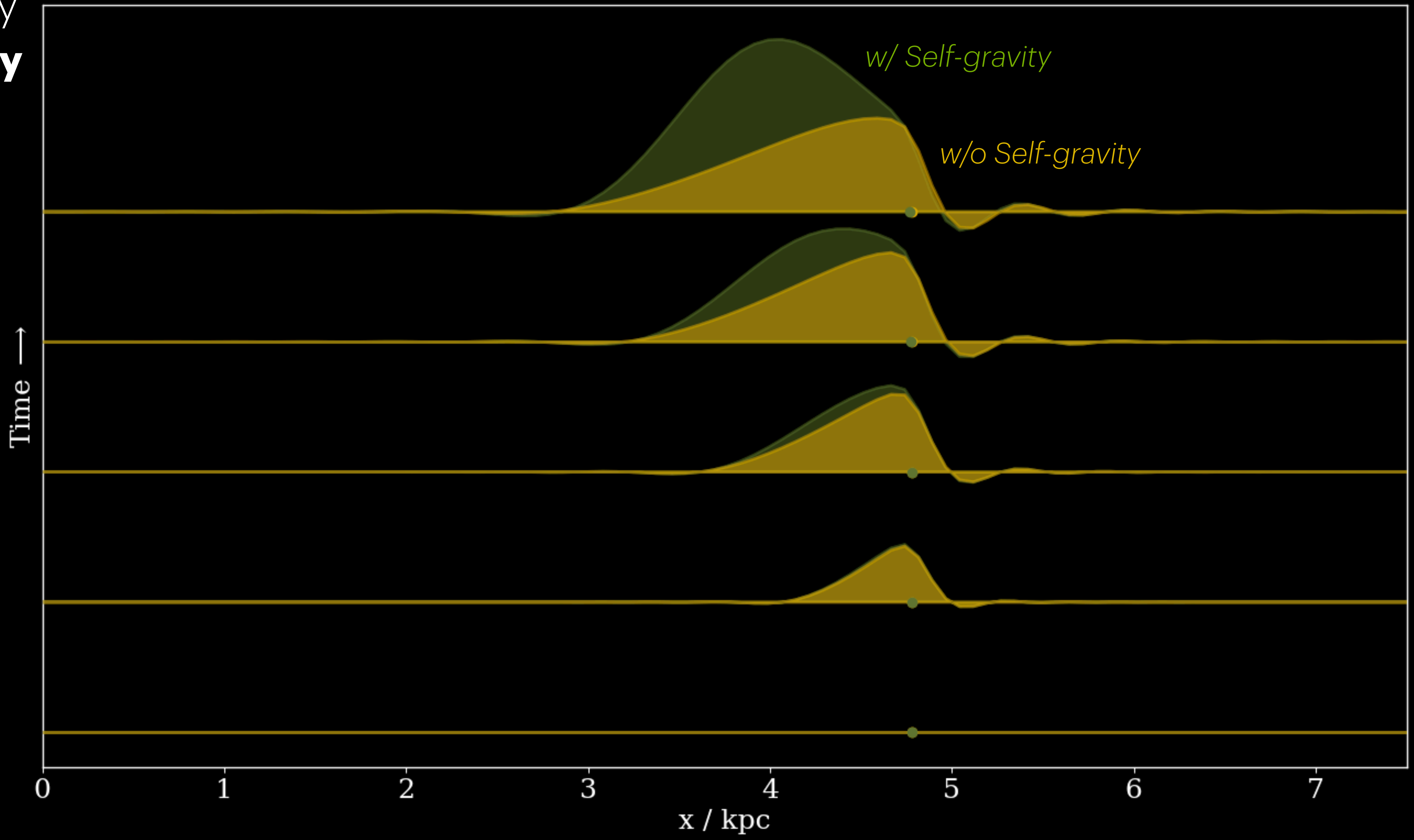
Simplified Simulation vs. Coulomb Scattering



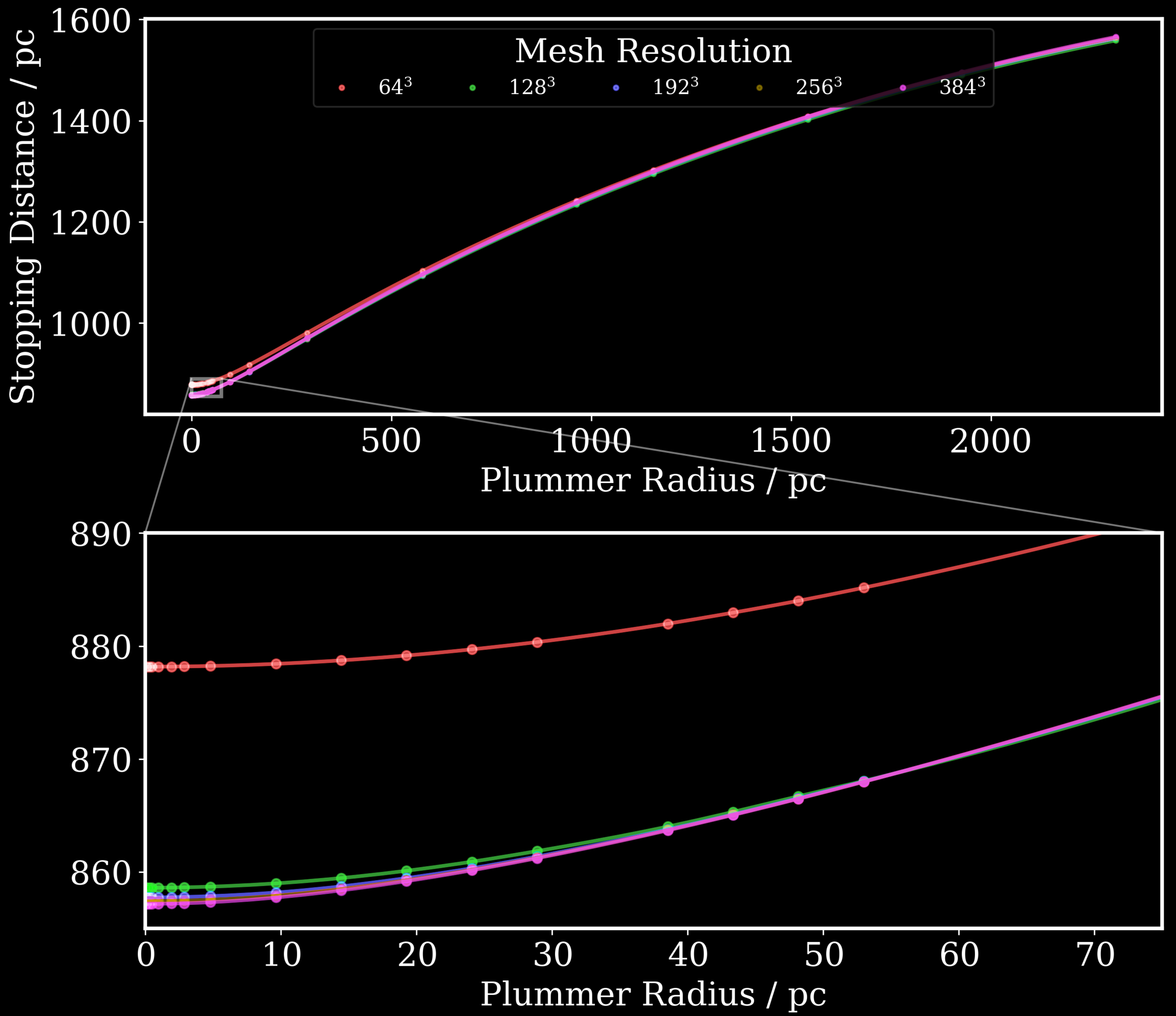
An Infinite Cigar **is not stable** under its own gravity



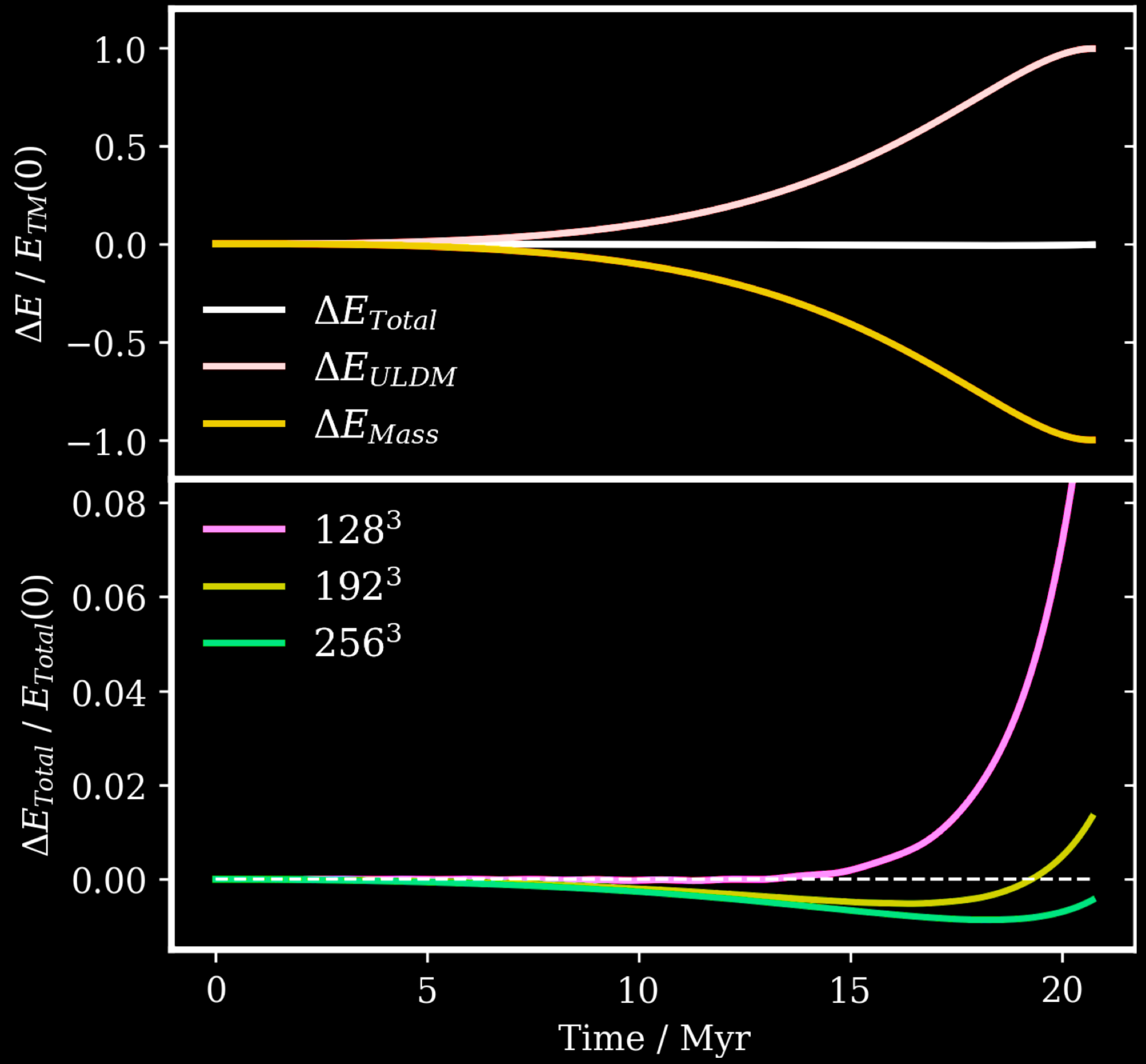
Simulated ULDM Density Profile **with Self-Gravity** (Along x-Axis)



Stopping Distances for BH is **robust** across **resolutions** and **Plummer radii**



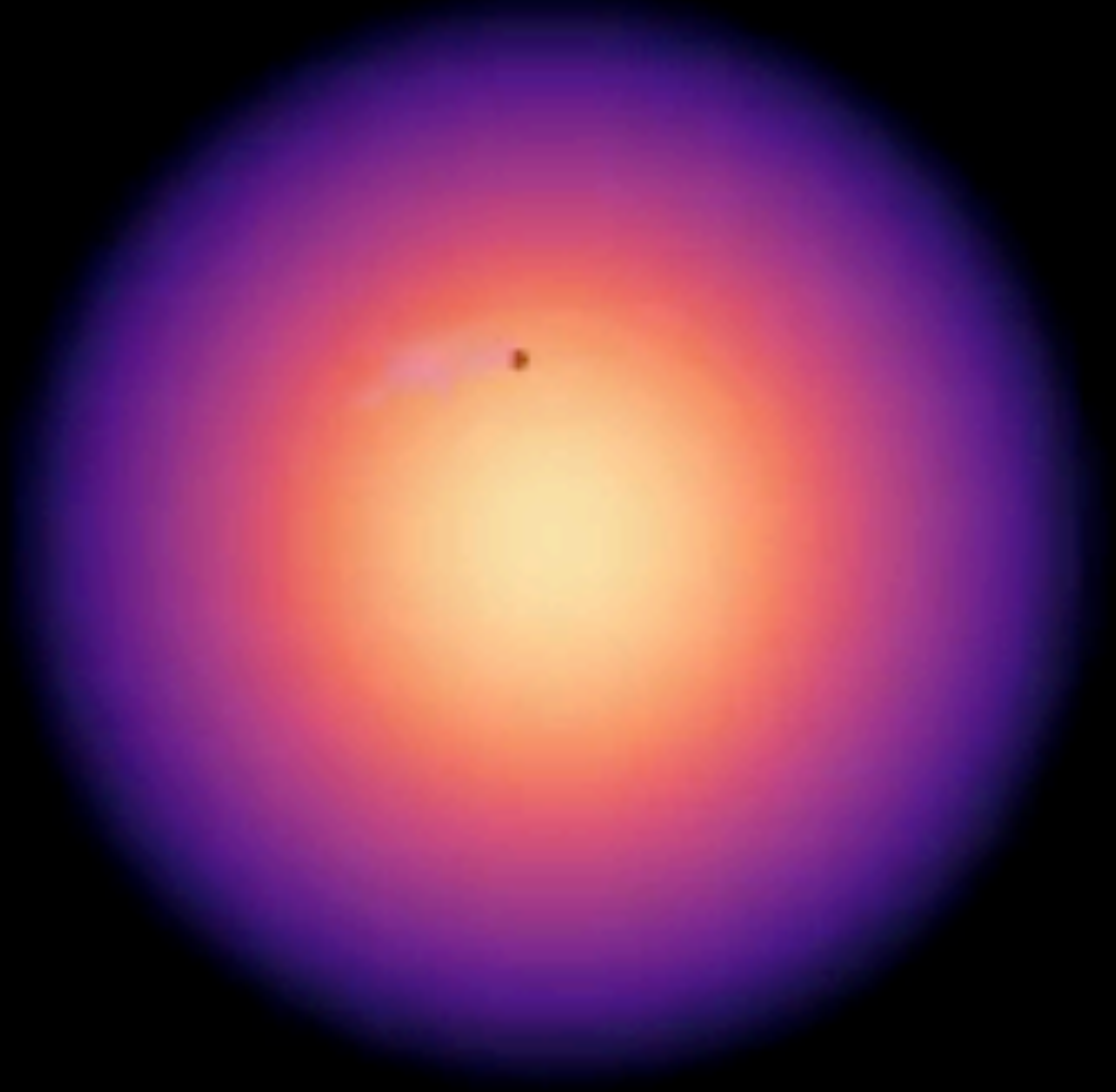
Energy Conservation



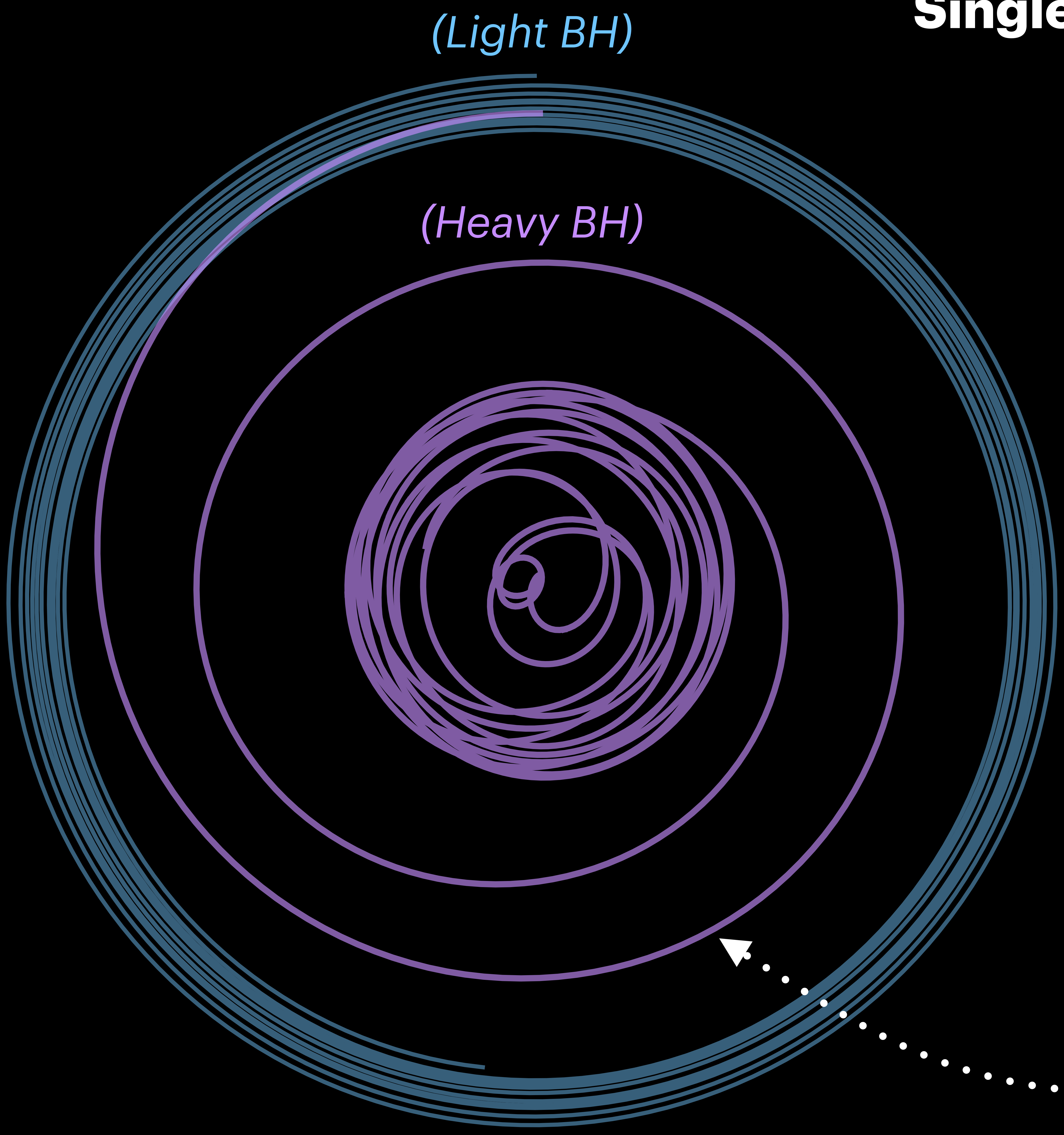
2

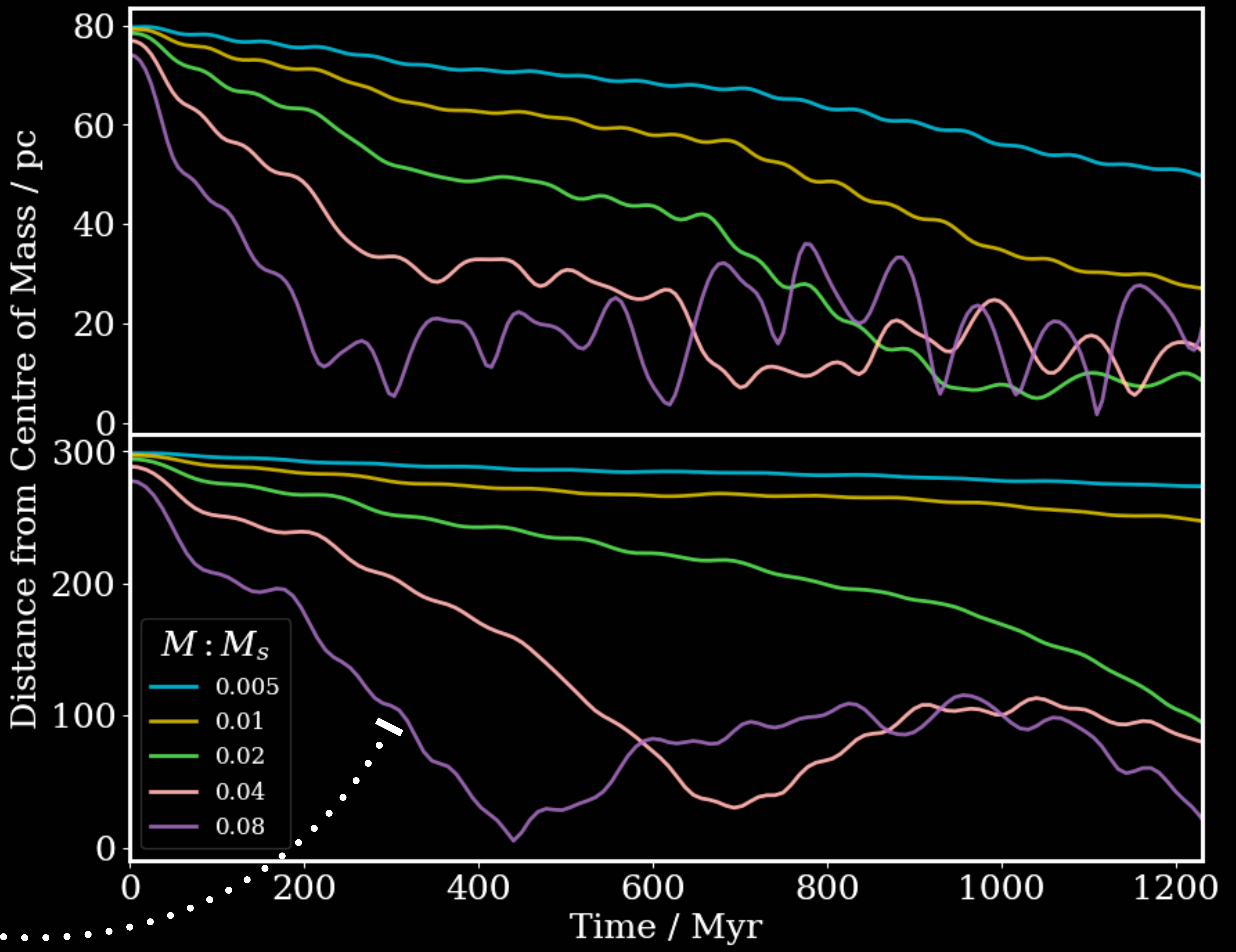
Black Hole Orbiting a Soliton

A Black Hole Orbiting a Soliton

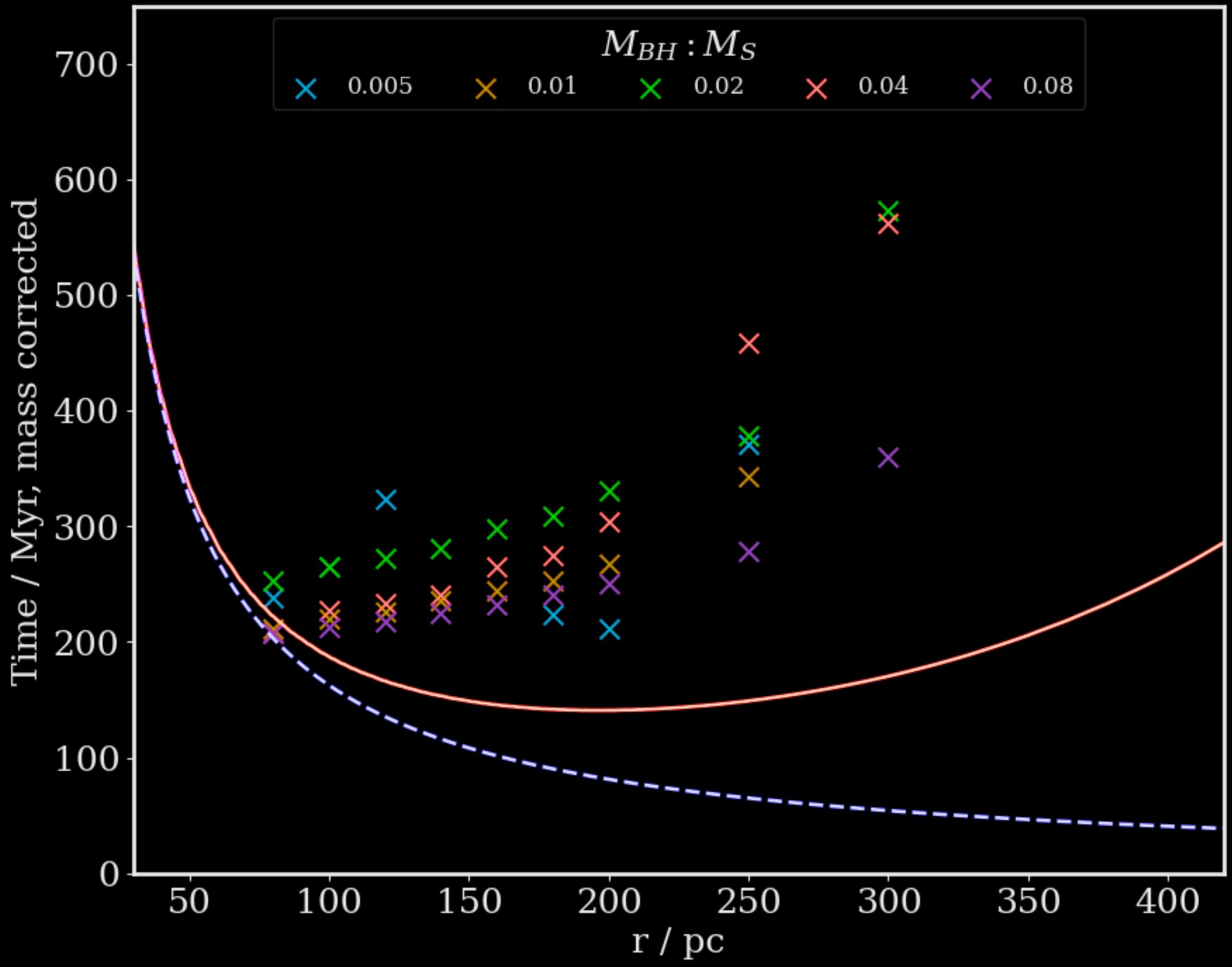


Single BH Orbit Decay





Single BH Orbit Decay



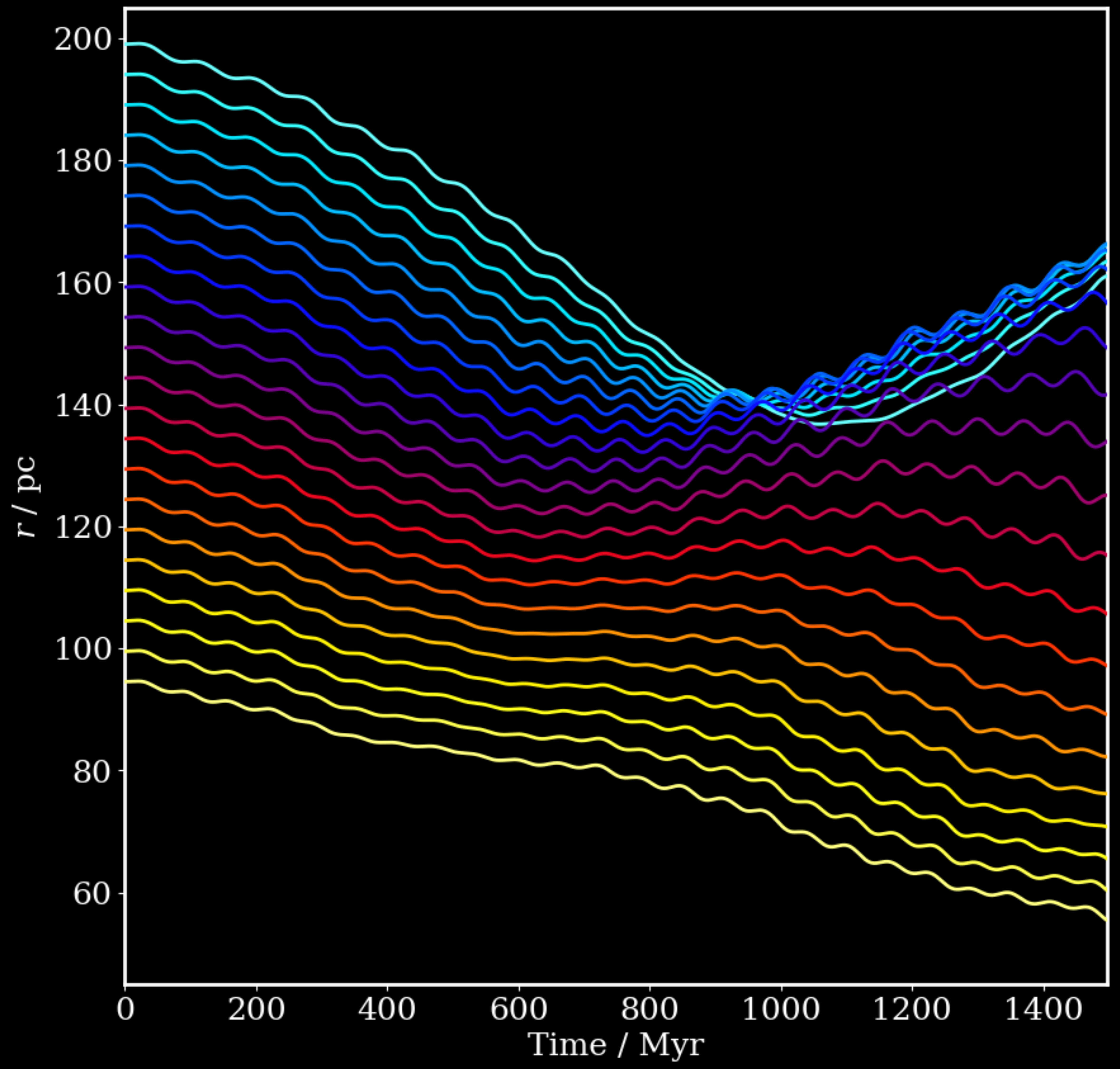
If deceleration is solely caused by the torque generated by Coulomb D.F

evaluated using (initial) local properties

evaluated using core properties

(Better time estimates are being performed)

Skipping Stones?



(These simulations use a light, 0.5% M_s mass)

Infalling BH's with orbital periods near **resonance** with the soliton's **intrinsic breathing modes** may experience either **facilitation** or **inhibition** of the orbital decay process.

(A stone skipping attempt by Y.W.)

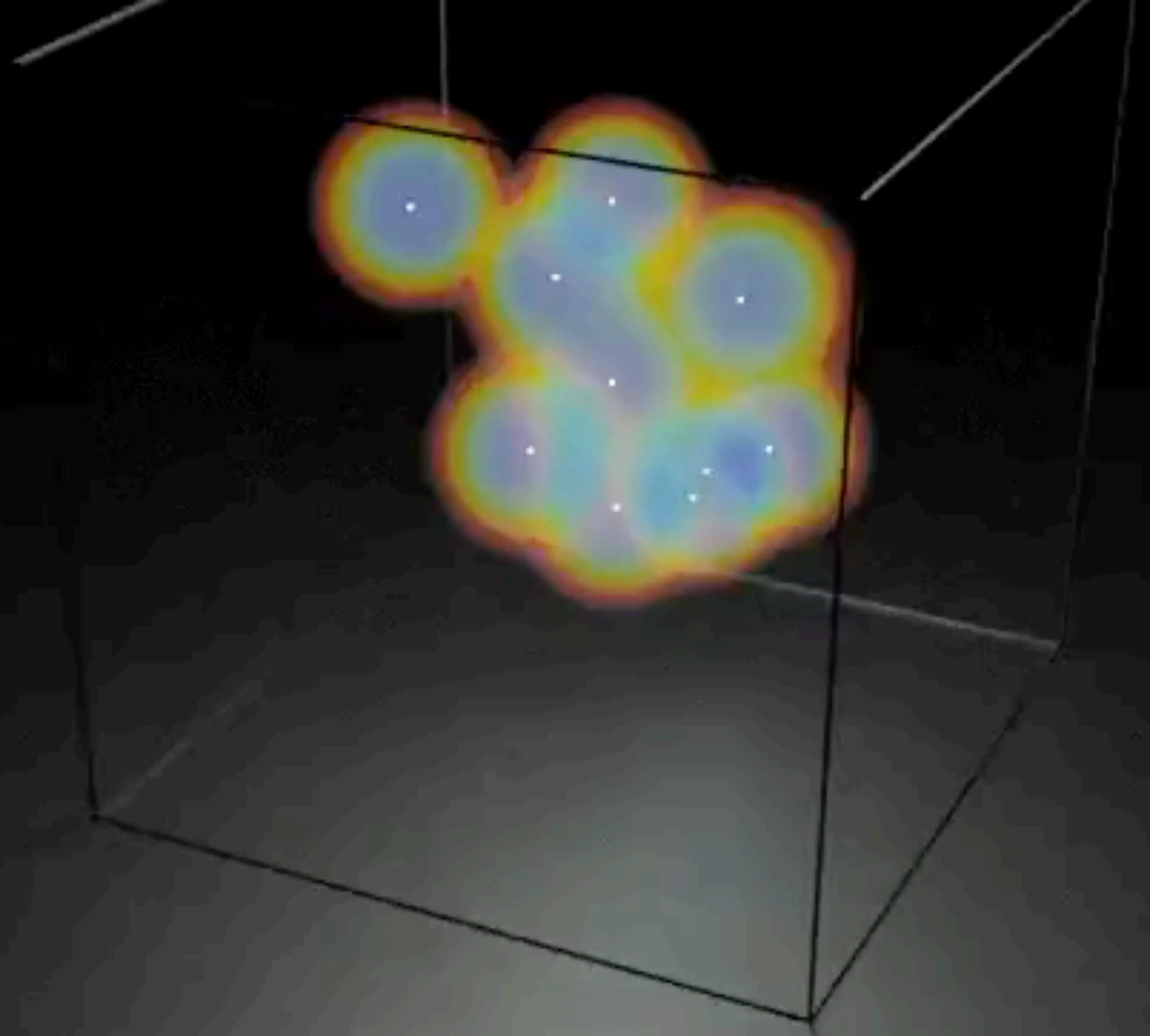
Summary

- N body systems coupled to a mesh-based ULDM simulation.
- Verified the dynamical friction results in literature.
- *Direct simulations* of nonlinear interactions between a ULDM soliton and a black hole.
- Novel dynamics and *complex behaviour* even with *a single black hole.*

PyUltraLight 2

github.com/Sifyrena/PyUL_NBody

Public Release Soon...



For HD Version of This Video:

FWPhys.com/BoxSol

Cosmology @ Auckland

MARSDEN FUND
TE PŪTEA RANGAHAU A MARSDEN

ROYAL SOCIETY TE APĀRANGI

NEW ZEALAND GRAVITY

ARDC

Backup Slides

Soliton Interference

Destructive
(π Global Phase Difference)

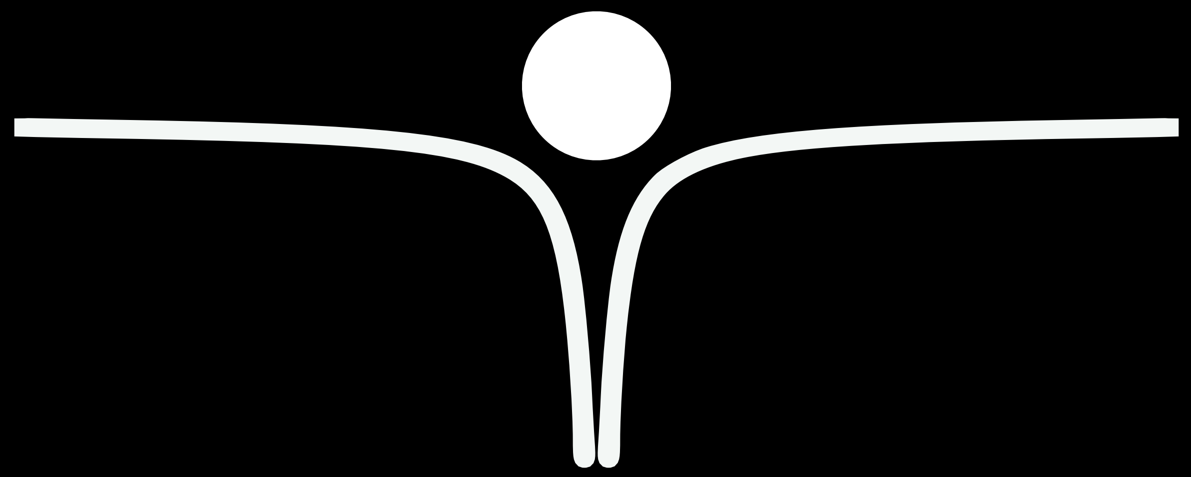
Constructive
(0 Global Phase Difference)

Naive ULDM Dynamical Friction **Without Self-Gravity**

Work in Particle's co-moving reference frame.

Particle sources a $1/r$ potential.

Assume the dynamical friction does not affect particle motion.

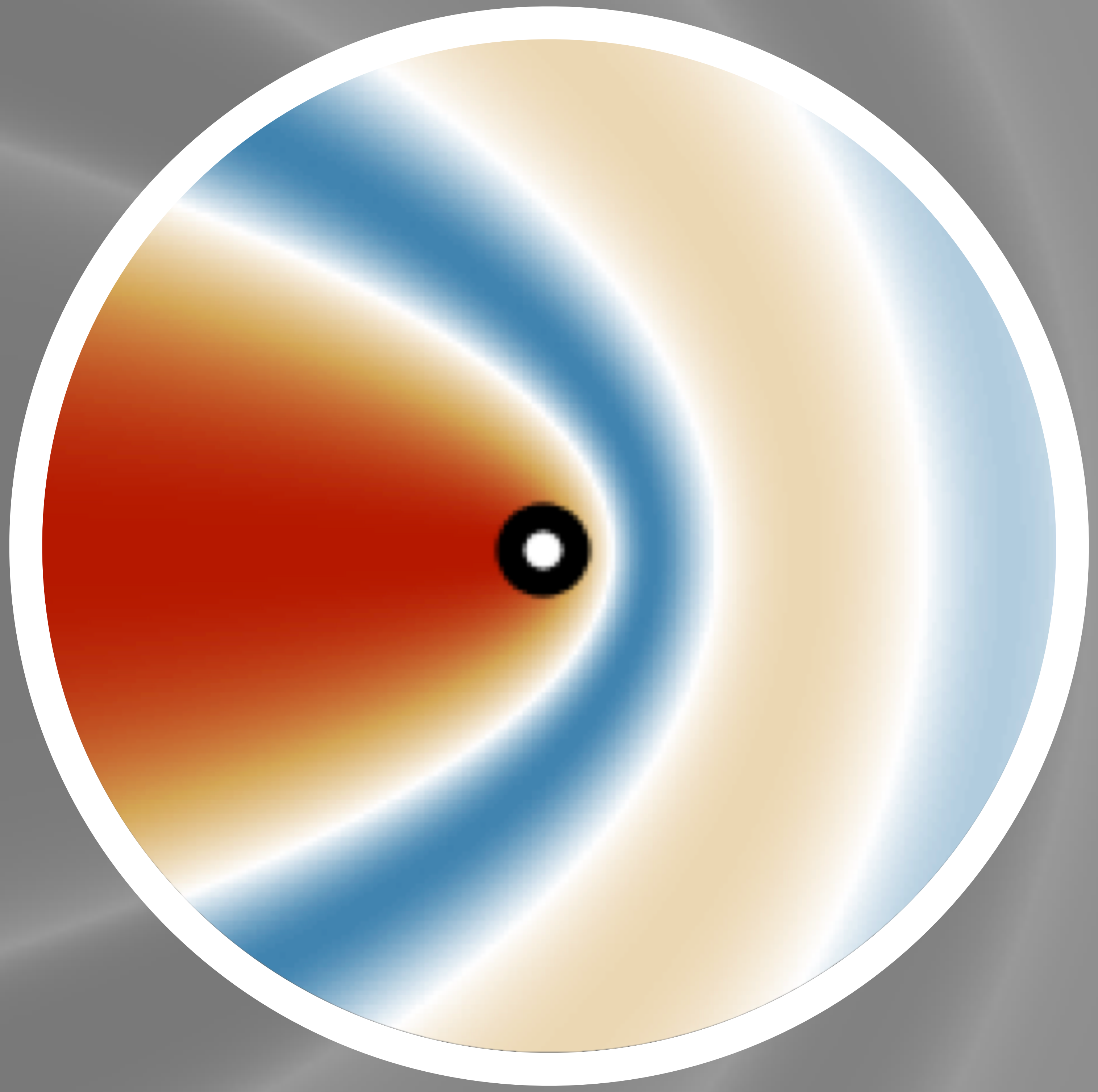


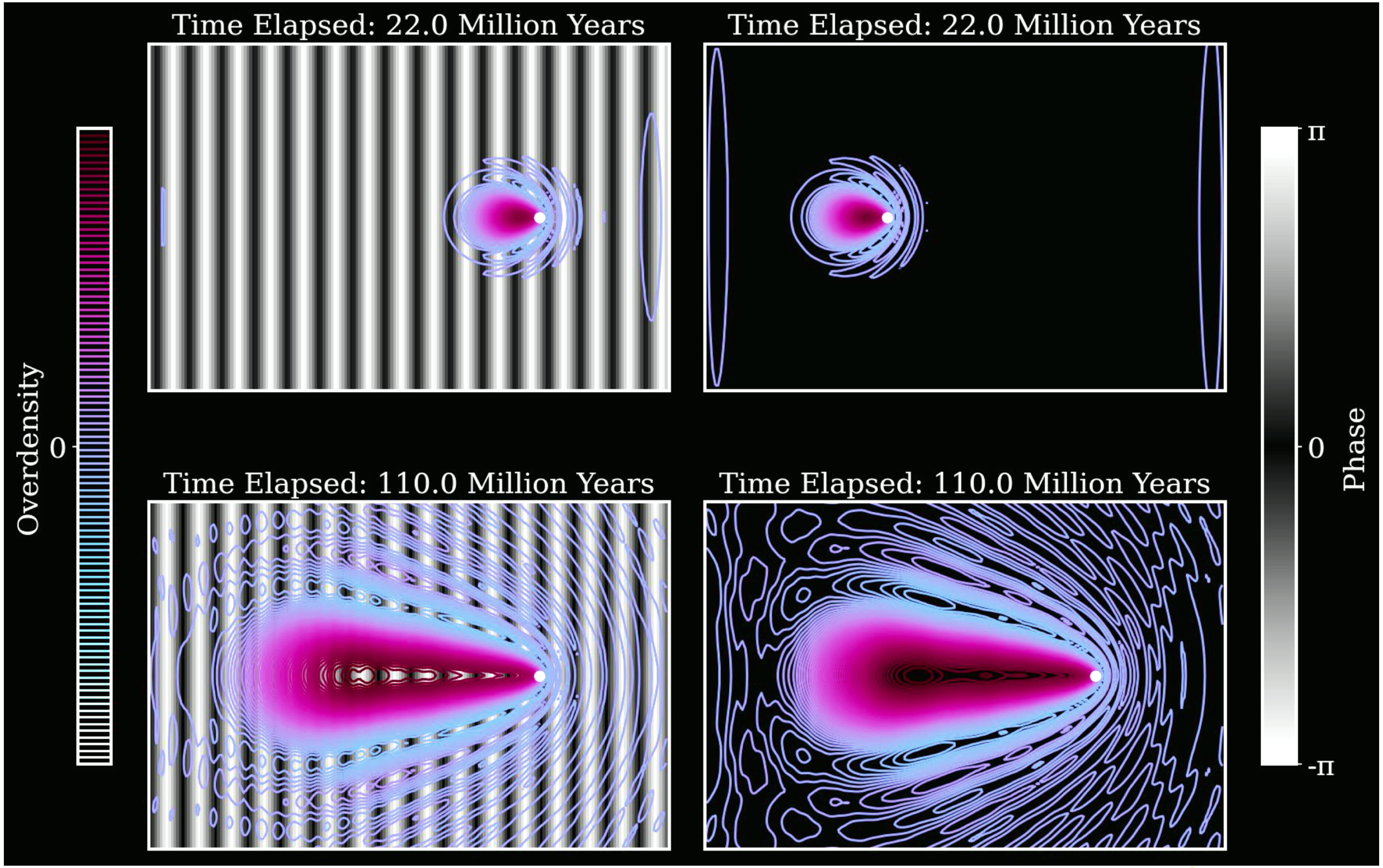
Axions arrive as a **plane wave** with uniform velocity and density far away.

Coulomb Scattering
Sakurai. Modern Quantum Mechanics. Sec. 7.13

Dynamical Friction in a Fuzzy Dark Matter Universe
Lancaster, L.et al. (2019).

- *Assume the interaction was “turned on” a finite time ago.*
- *Only consider the effects of the Coulomb Scattering model within* $b = vt$.





Moving BH, Stationary ULDM

“Quantum Wind”

Source of Interesting Dynamics
Local Causes Lead to Non-Local ULDM Behaviour

Bringing Together Black Holes
Interactions mediated by dark matter might give us a solution to the ***Final Parsec Problem***

How do two SMBHs find each other during a galaxy merger and coalesce?

The Final Parsec Problem
Milosavljević, M. & Merritt, D. (2003).

The LISA Collaboration
LISA Consortium, ESA