Dynamical Friction From **Ultra-Light Dark Matter**

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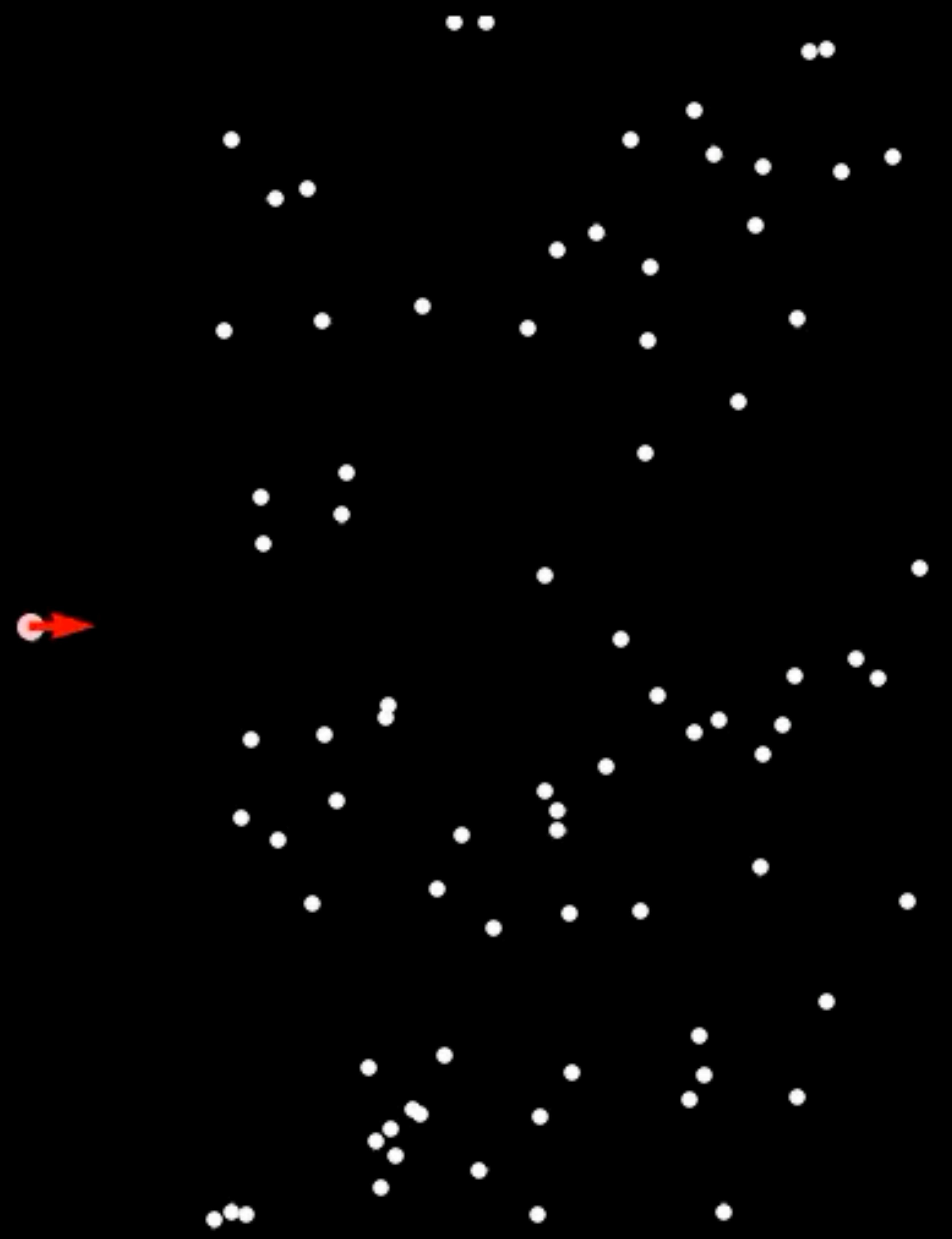
Dynamical Friction

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

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

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



(Dramatization)

stars

gas

dark matter

ULDM Basics

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left(g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - m^2\phi^2\right)$$

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

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

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

Schrödinger-Poisson

$$i\dot{\psi} = \left[-\frac{1}{2m}\nabla^2 + \left(\Phi_U + \Phi_{Ext}\right) \right] \psi$$

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

External Gravitational Potentials

Non-Gravitational Self-Interaction

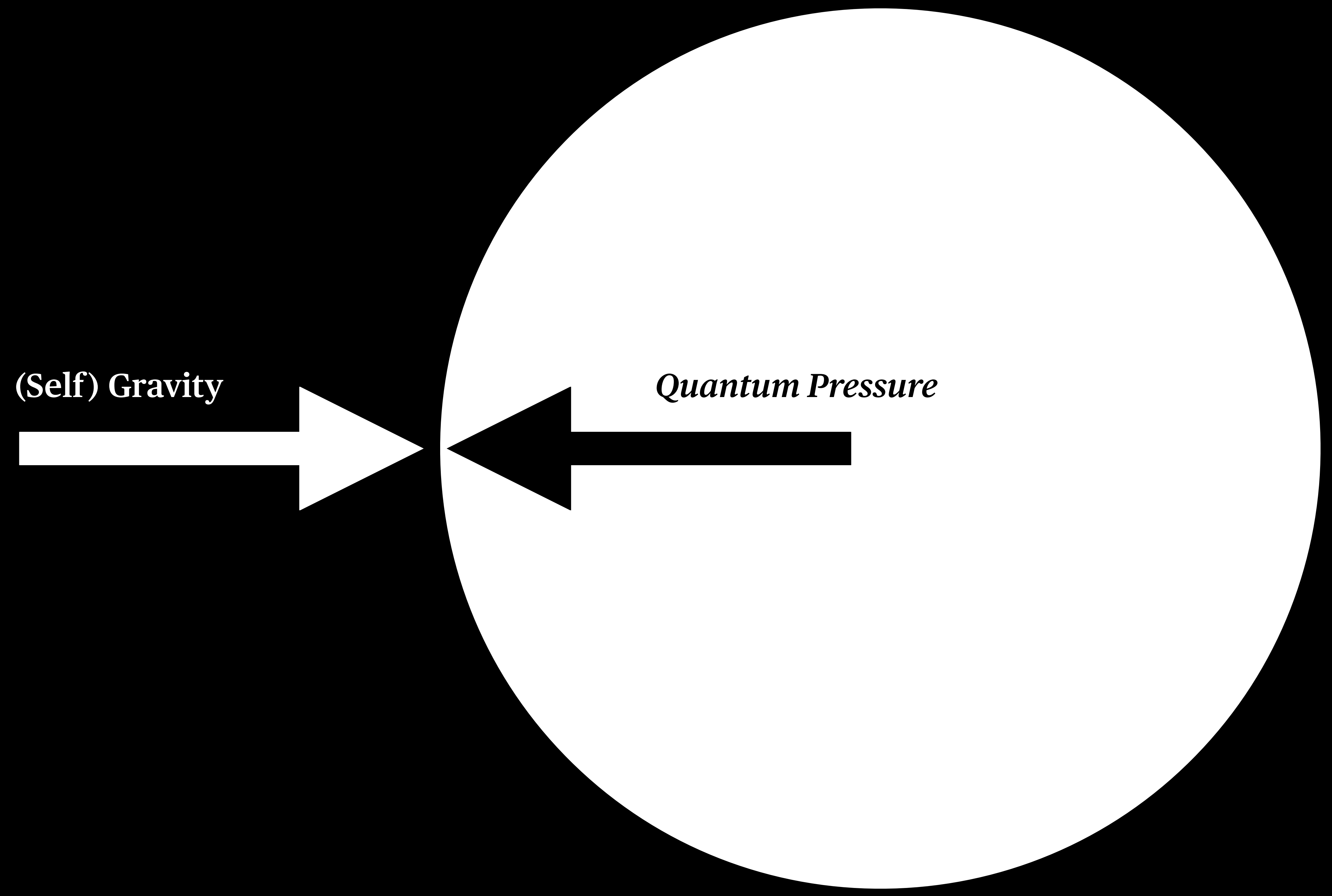
Expansion of Universe

...

Schrödinger-Poisson Solitons

Can obtain the general radial profile numerically*.

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



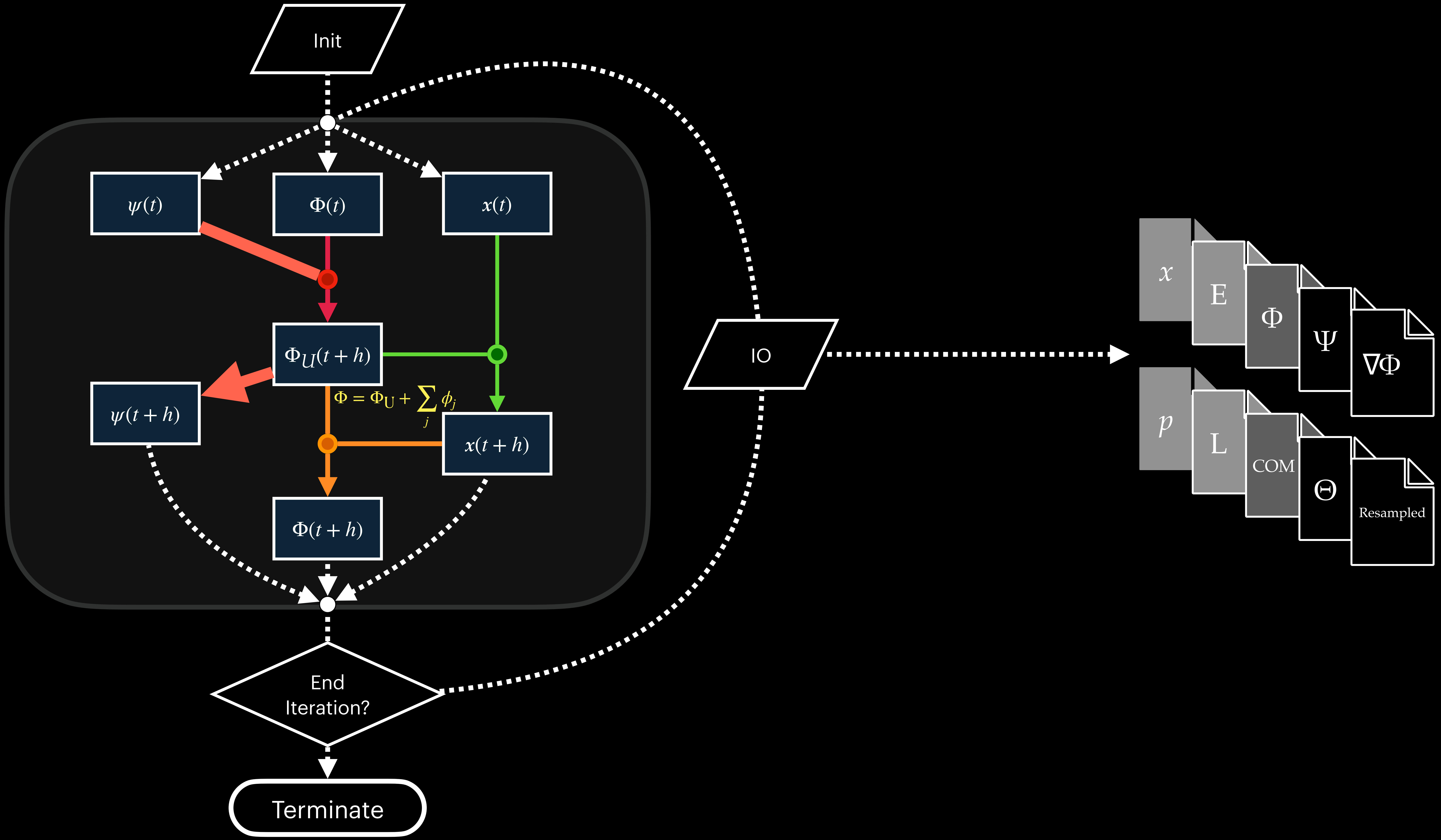
Madelung Picture

$$\psi(t) \equiv \sqrt{\rho(t)}e^{i\theta(t)}$$

$$\mathbf{v} = \nabla\theta$$

PyUltraLight 2

A Foundation for Efficient and Flexible ULDM Simulations


Init
$\psi(t)$
$\Phi(t)$
$x(t)$
$\Phi_U(t+h)$
$\psi(t+h)$
$\Phi = \Phi_U + \sum_j \phi_j$
$x(t+h)$
$\Phi(t+h)$
IO
End Iteration?
Terminate
x
E
Φ
Ψ
$\nabla\Phi$
p
L
COM
Θ
Resampled

ULDM System

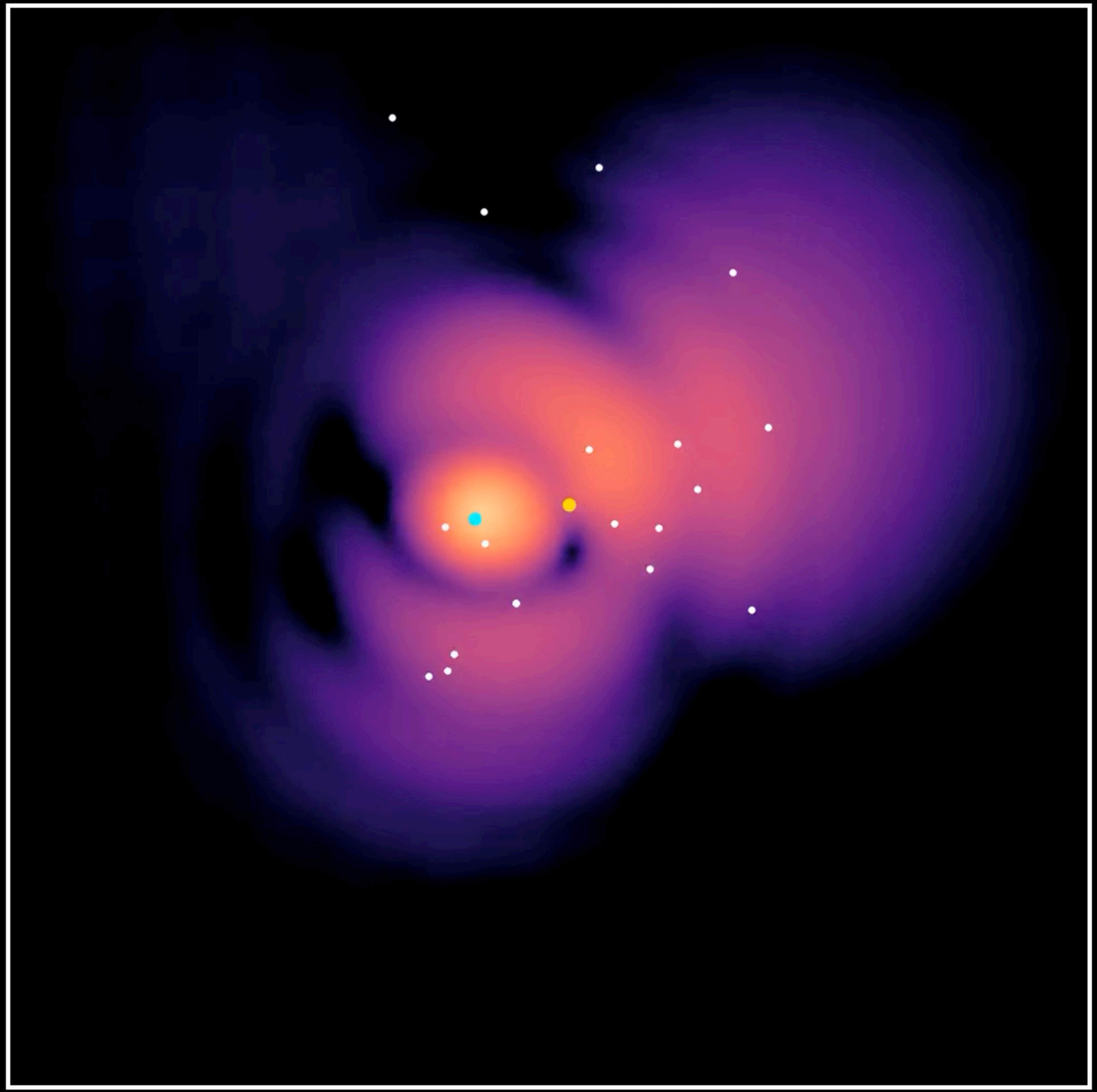
- Built-in soliton profile solver.
- Can impose a range of boundary conditions - periodic, dissipative sponge, or reflective sponge.
- Poisson equation solved either in frequency domain or using Green functions.
- (*Optional*) - Zero-padded density field when solving Poisson equation. This reduces boundary artifacts.

Numerical Consistency

- Integrator is fully modular – and each component have been individually tested against state-of-the art solvers for N body and Schrödinger systems.
- ULDM Mass Conservation.
- Good System Energy Conservation.
- Robust results across resolutions and scaling.
- Convert and shift simulations across a variety of reference frames.

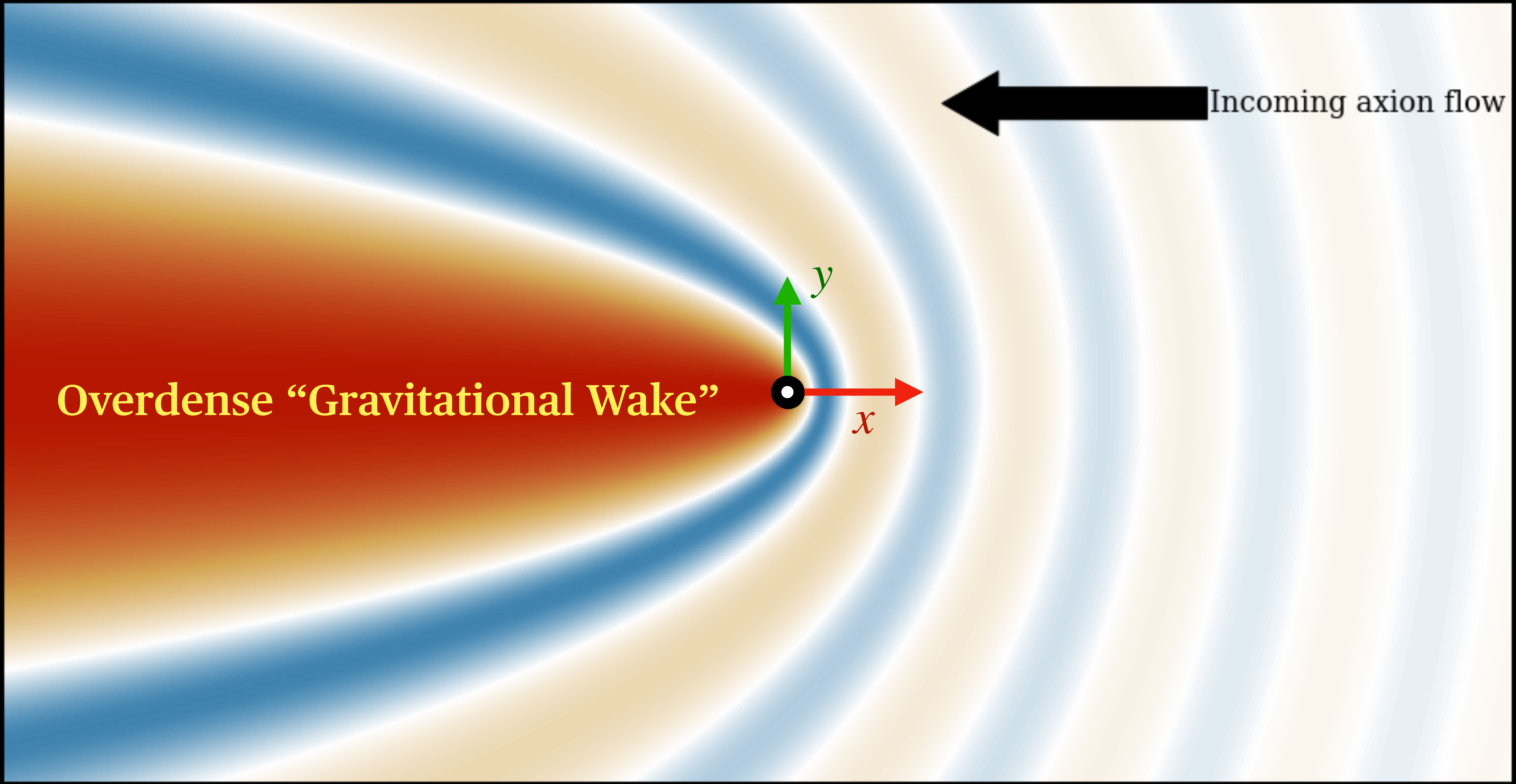
N-body System

- Particles are represented by **Plummer Spheres** and are allowed to move in $\mathbb{R}^3$ following an RK4 solver.
- They feel a locally interpolated version of Φ_U.
- Their gravitational field is resampled and fed into the S-P equation governing ULDM motion.
- Can have variable mass.



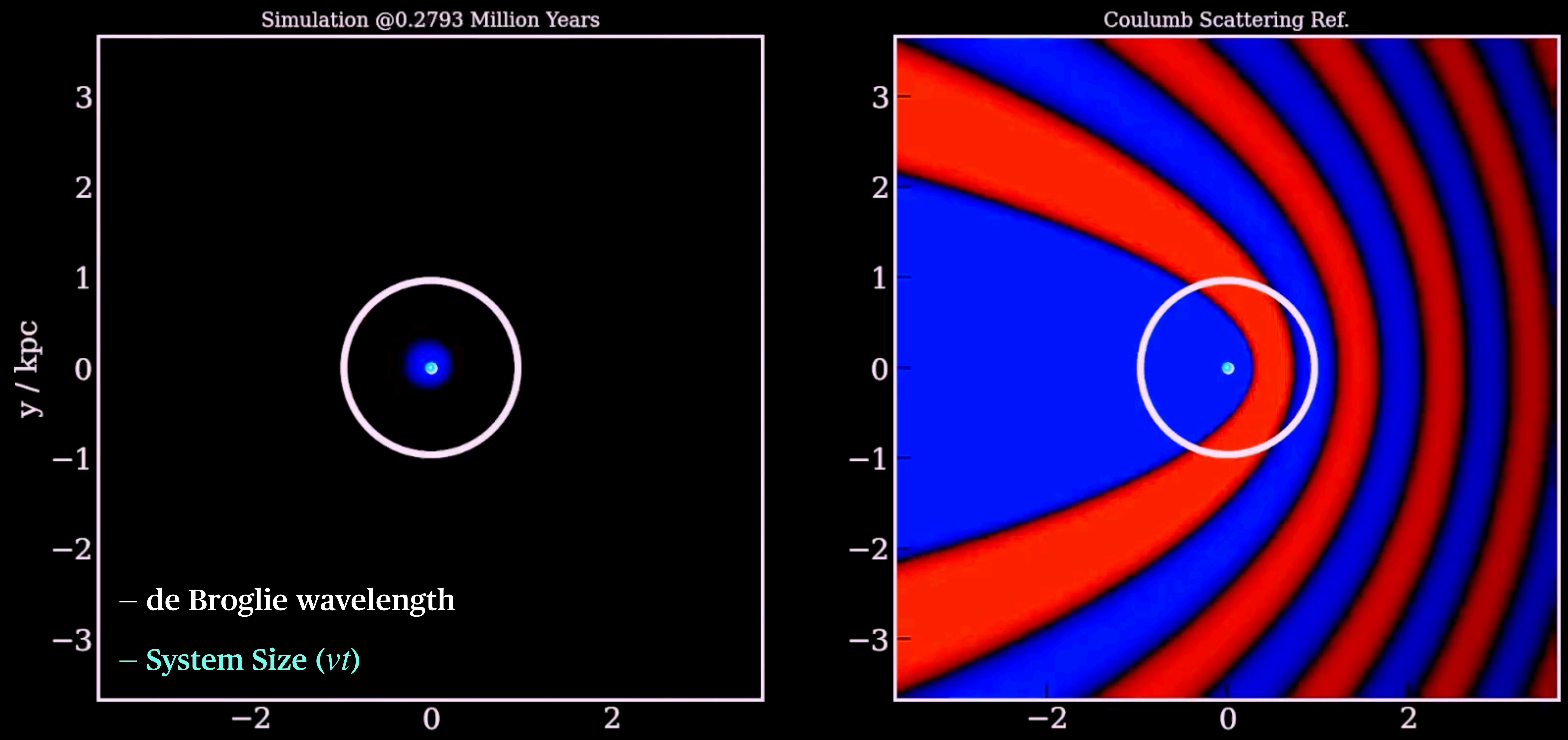
Linear Pass through Uniform ULDM

Dynamical Friction from Uniform ULDM



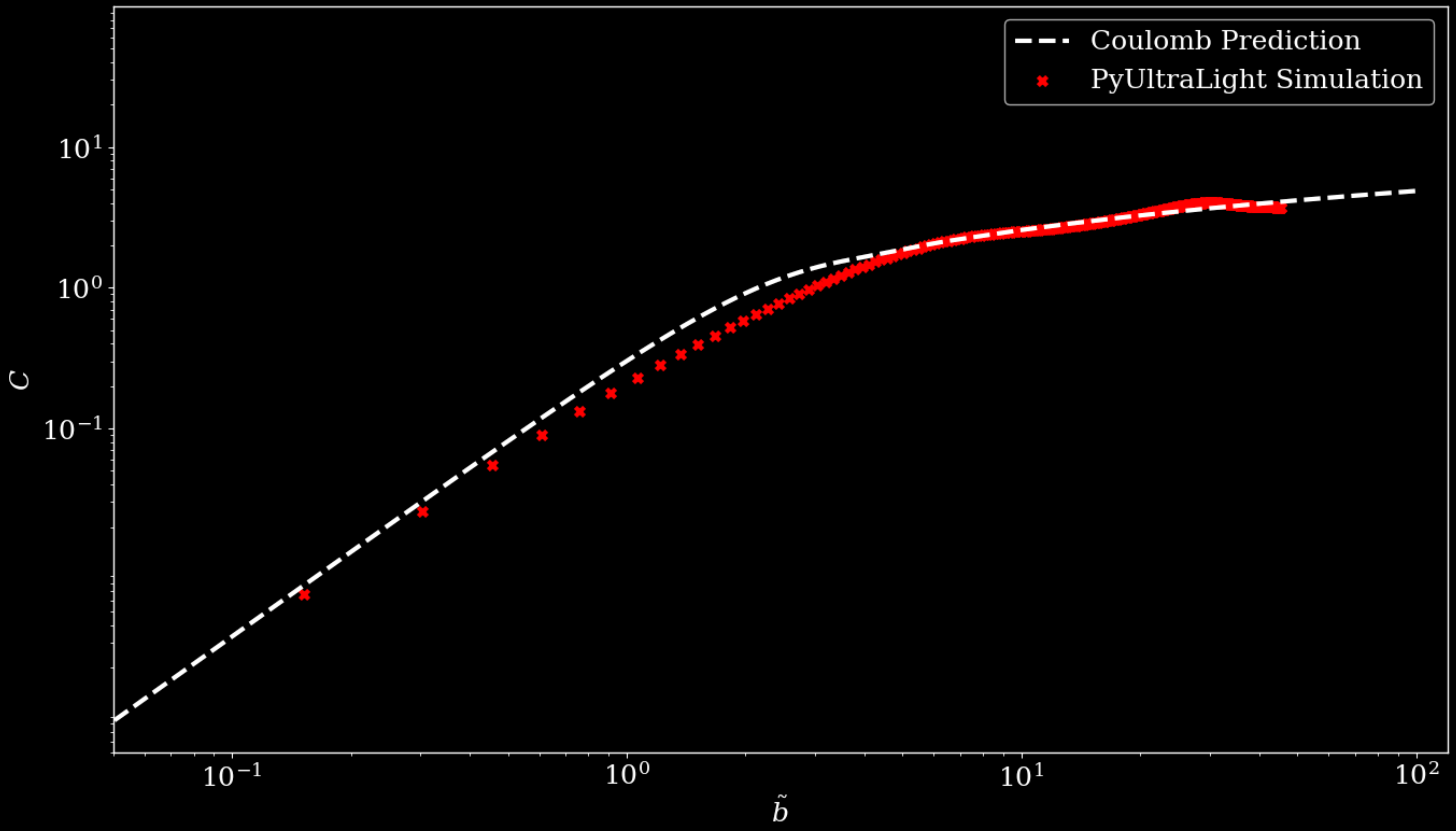
Dynamical friction in a Fuzzy Dark Matter universe
Lancaster et al. JCAP(2020).

Numerical Solution vs. Coulomb Scattering

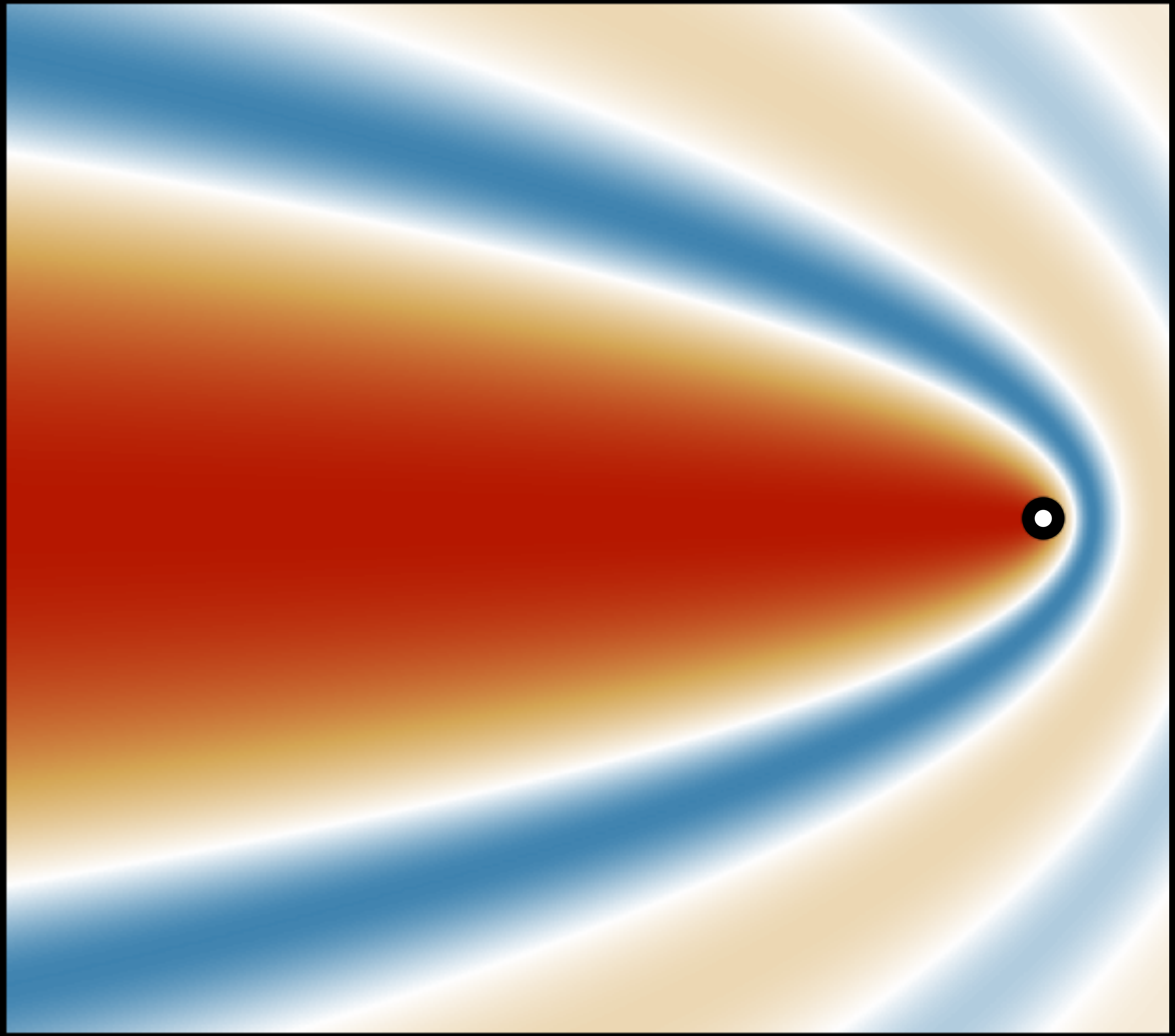


(Two plots always share color scales as left panel evolves in time)

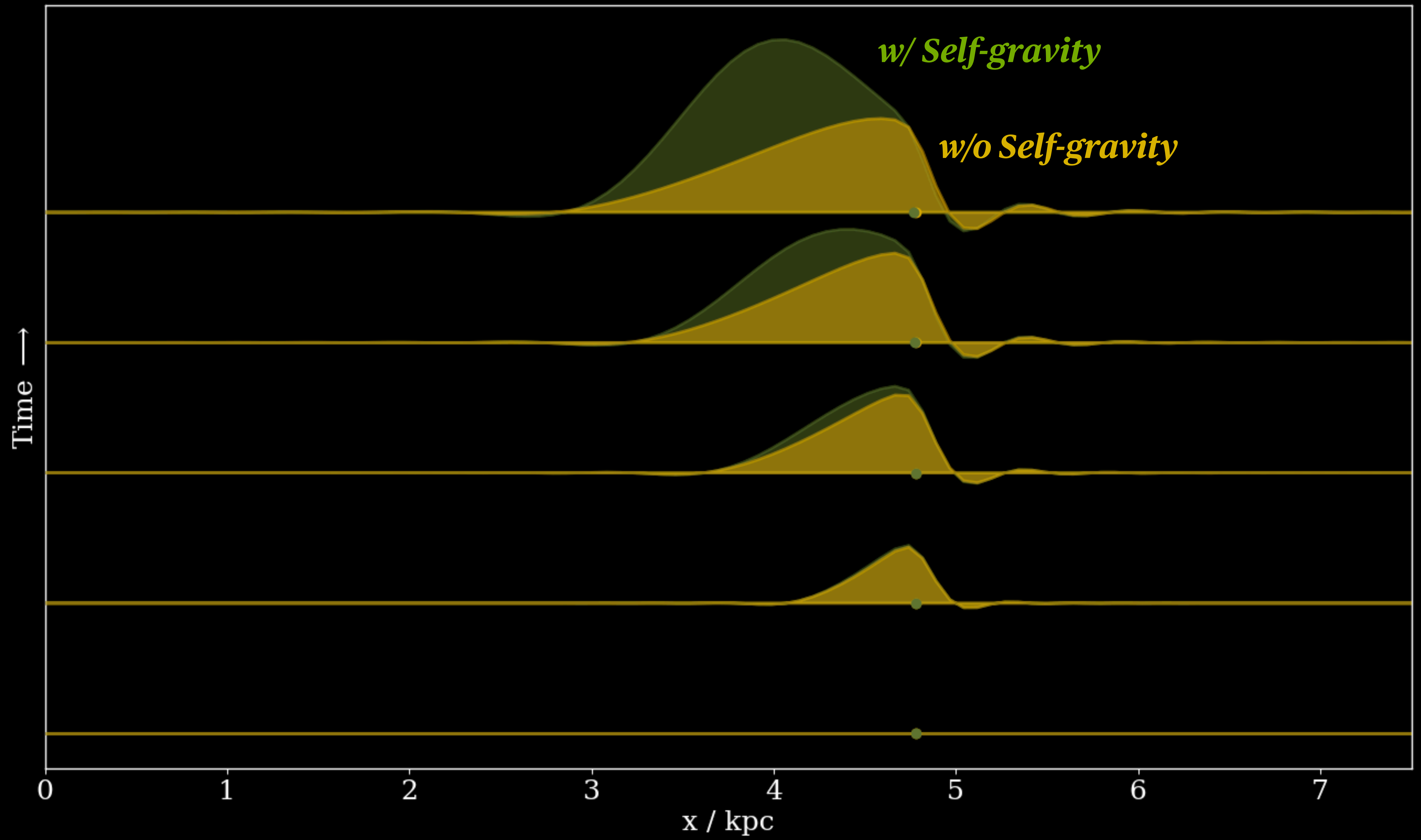
Numerical Solution vs. Coulomb Scattering



The tail is **not stable** under its own gravity

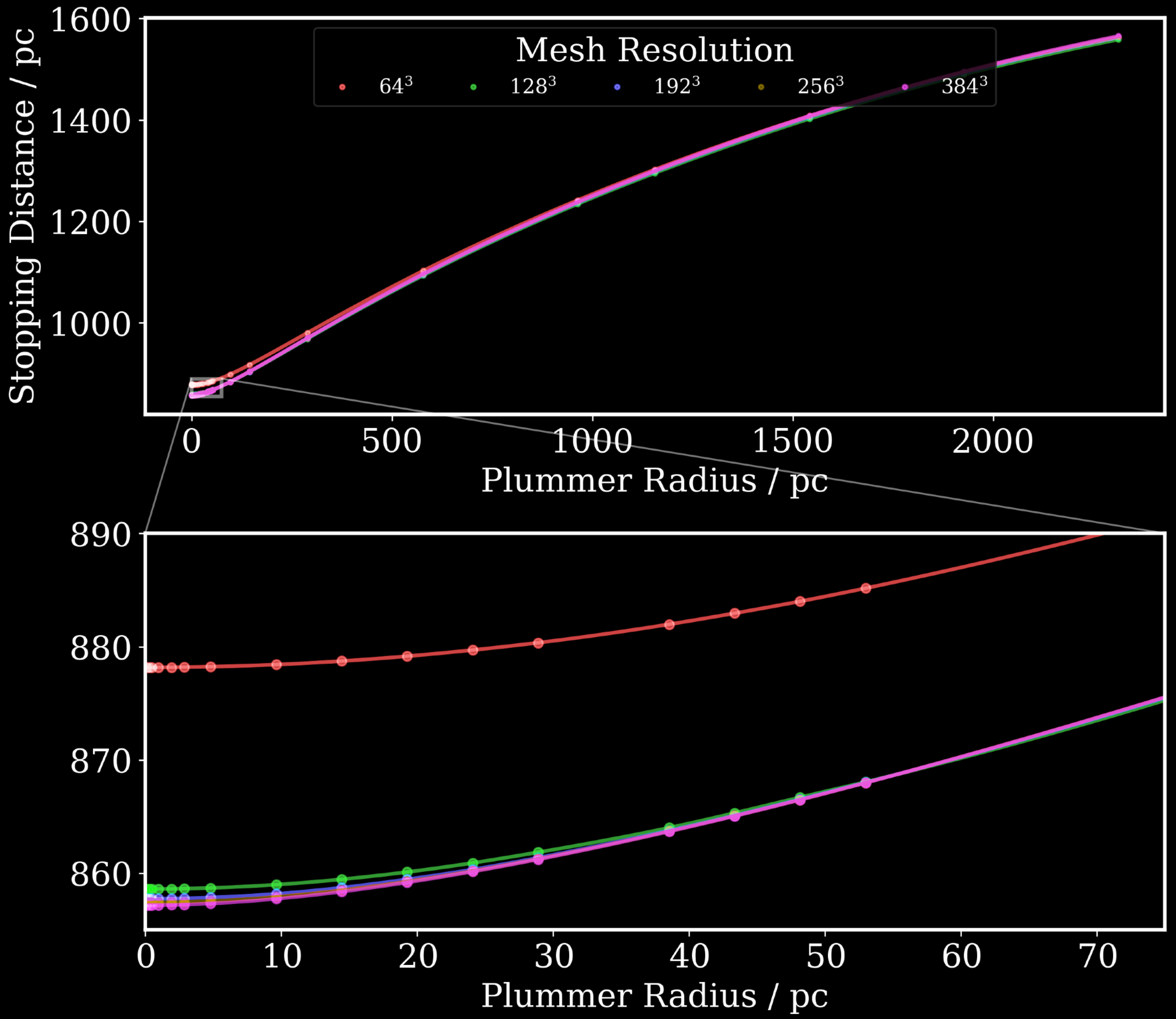


Full ULDM Density
Profile **with Self-Gravity**
(Along Axis of Symmetry)



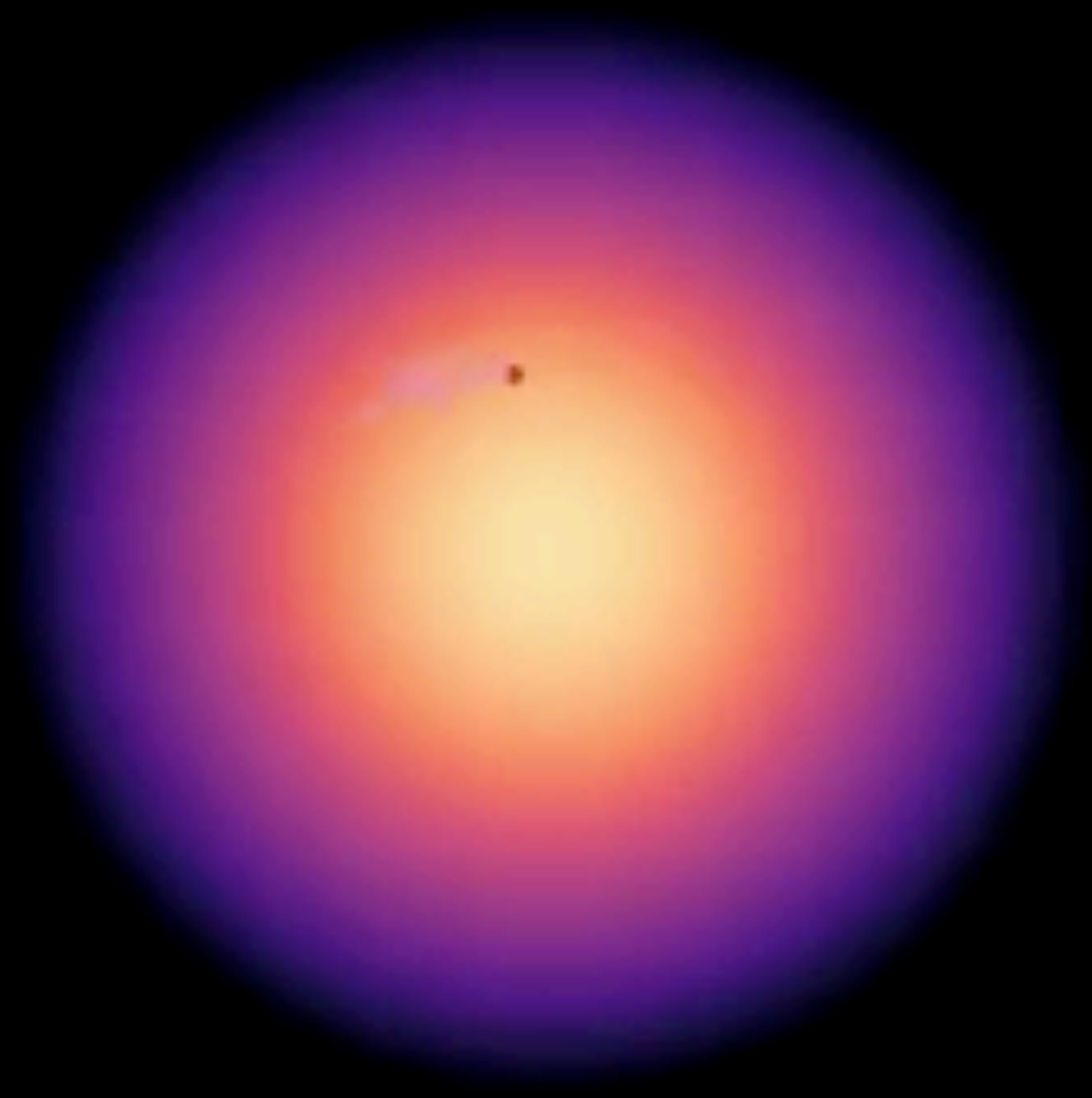
Dynamical friction from ultralight dark matter
Yourong Wang and Richard Easther. Phys. Rev. D 105, 063523

Stopping Distances for BH is **robust** across **resolutions** and **system size** (Plummer radii)

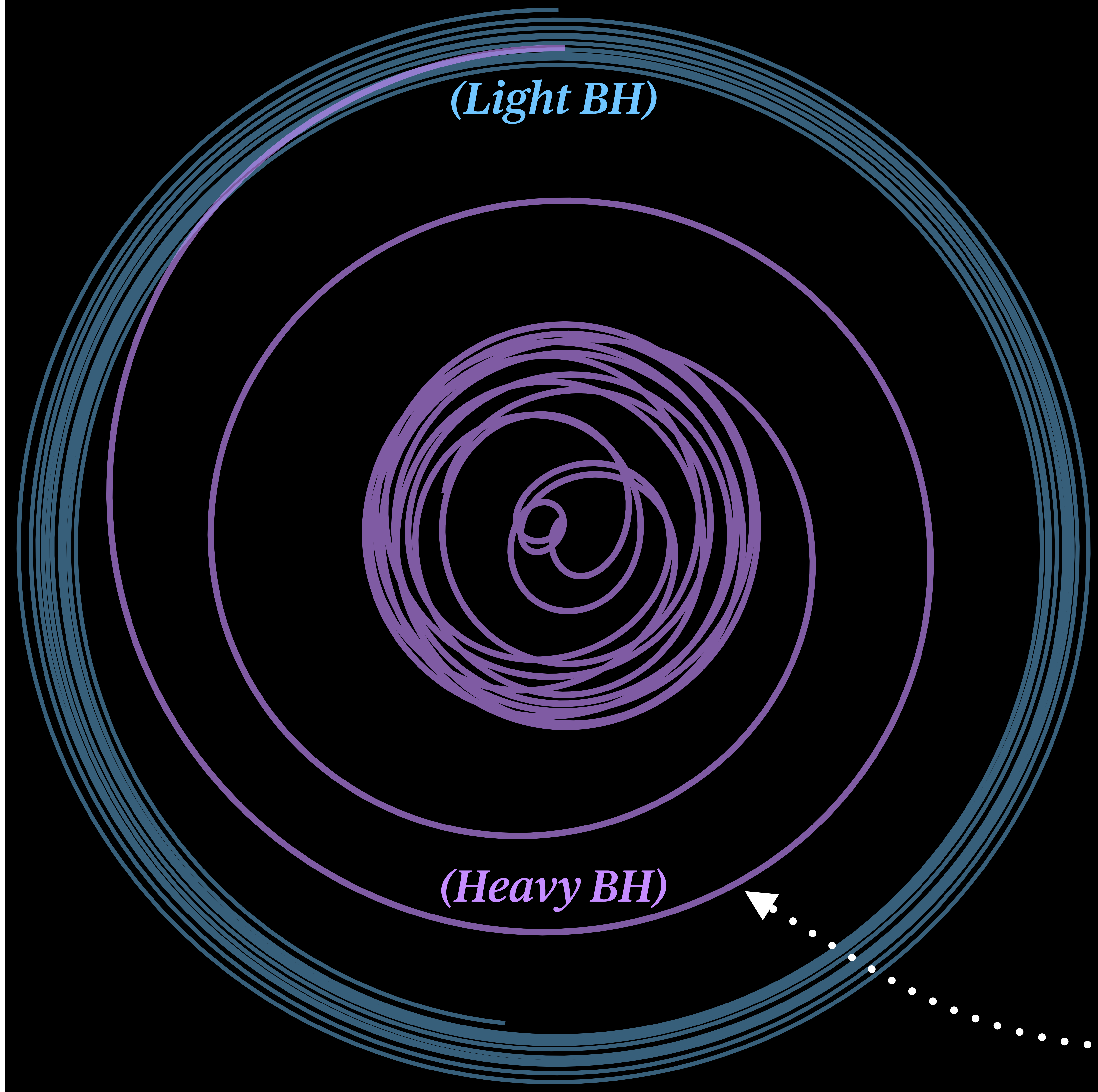


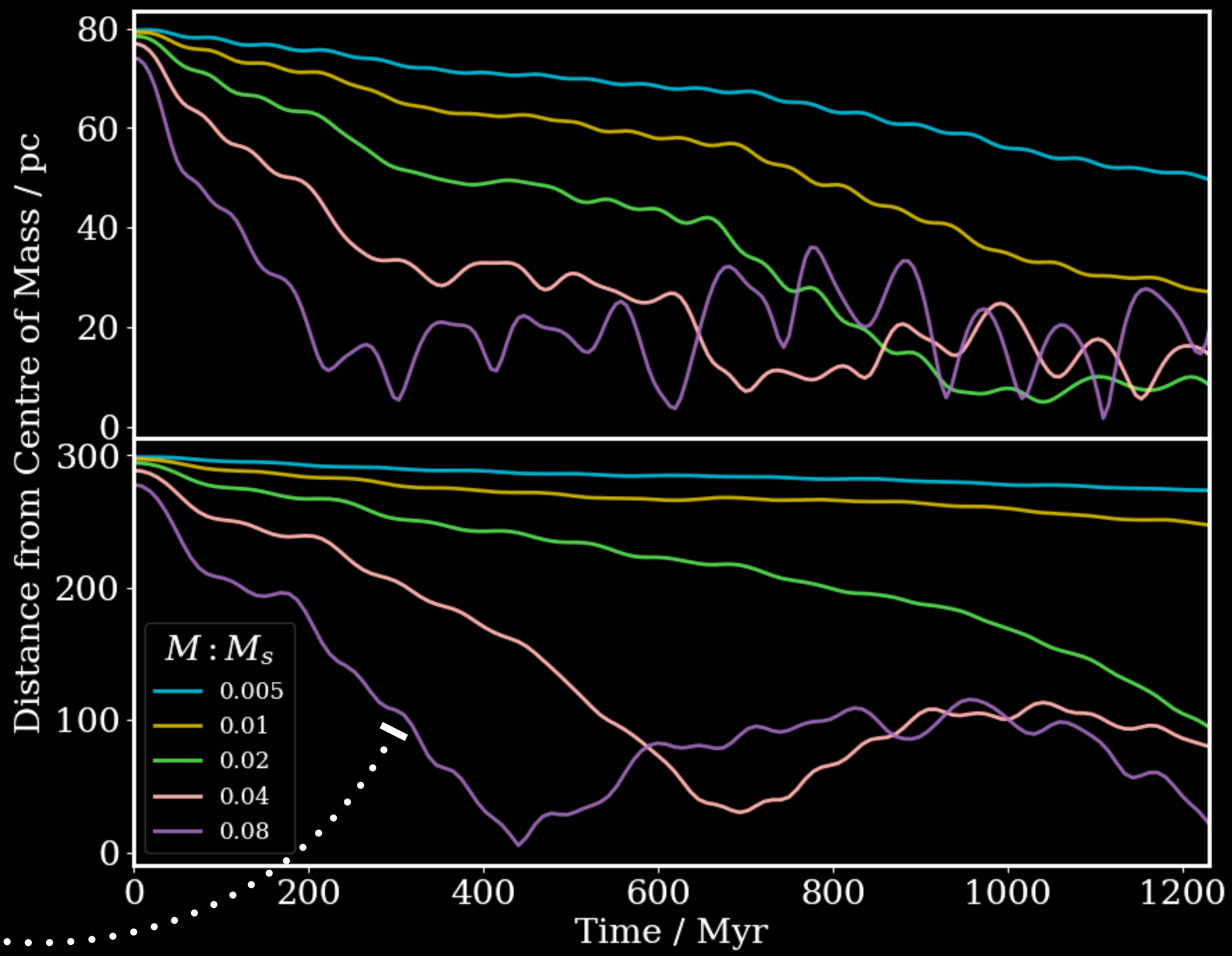
II

A Point Mass Orbiting a Soliton



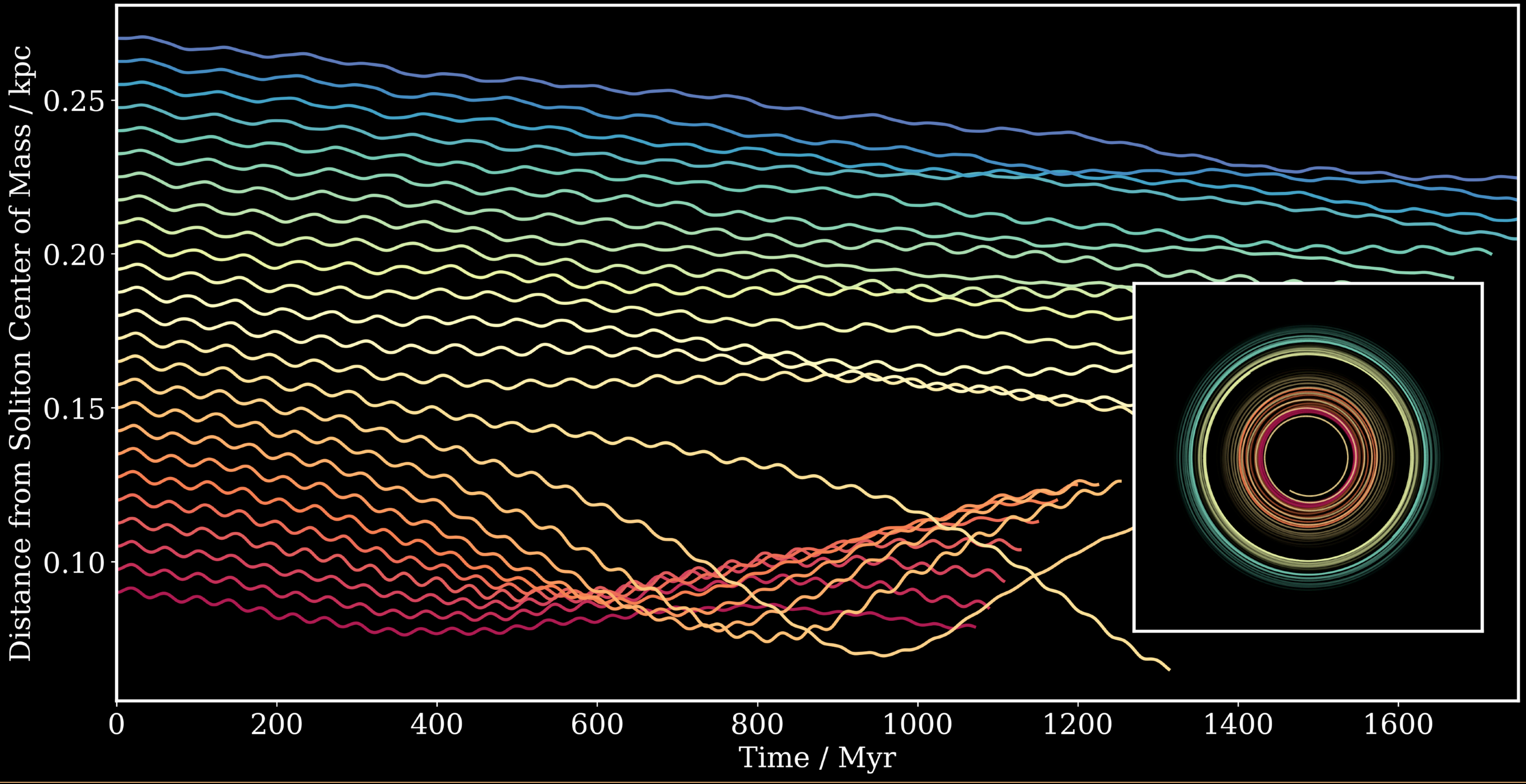
Single BH Orbit Decay vs. BH Mass





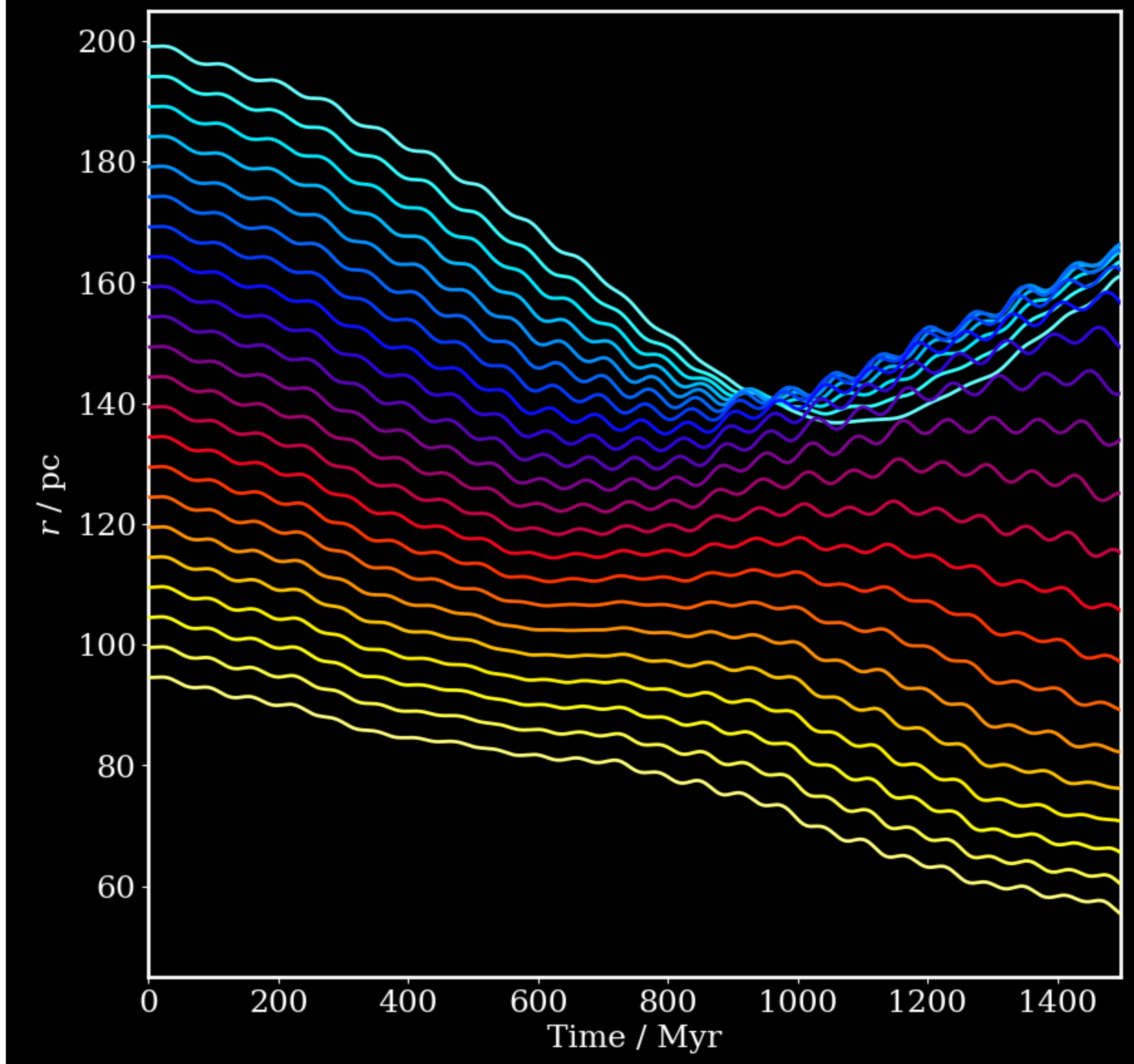
(Presented in system frame of reference)

Single BH Orbit Decay vs. Initial Radius



(25 independent runs, each carried out for 14 nominal orbital periods.)

Skipping Stones?

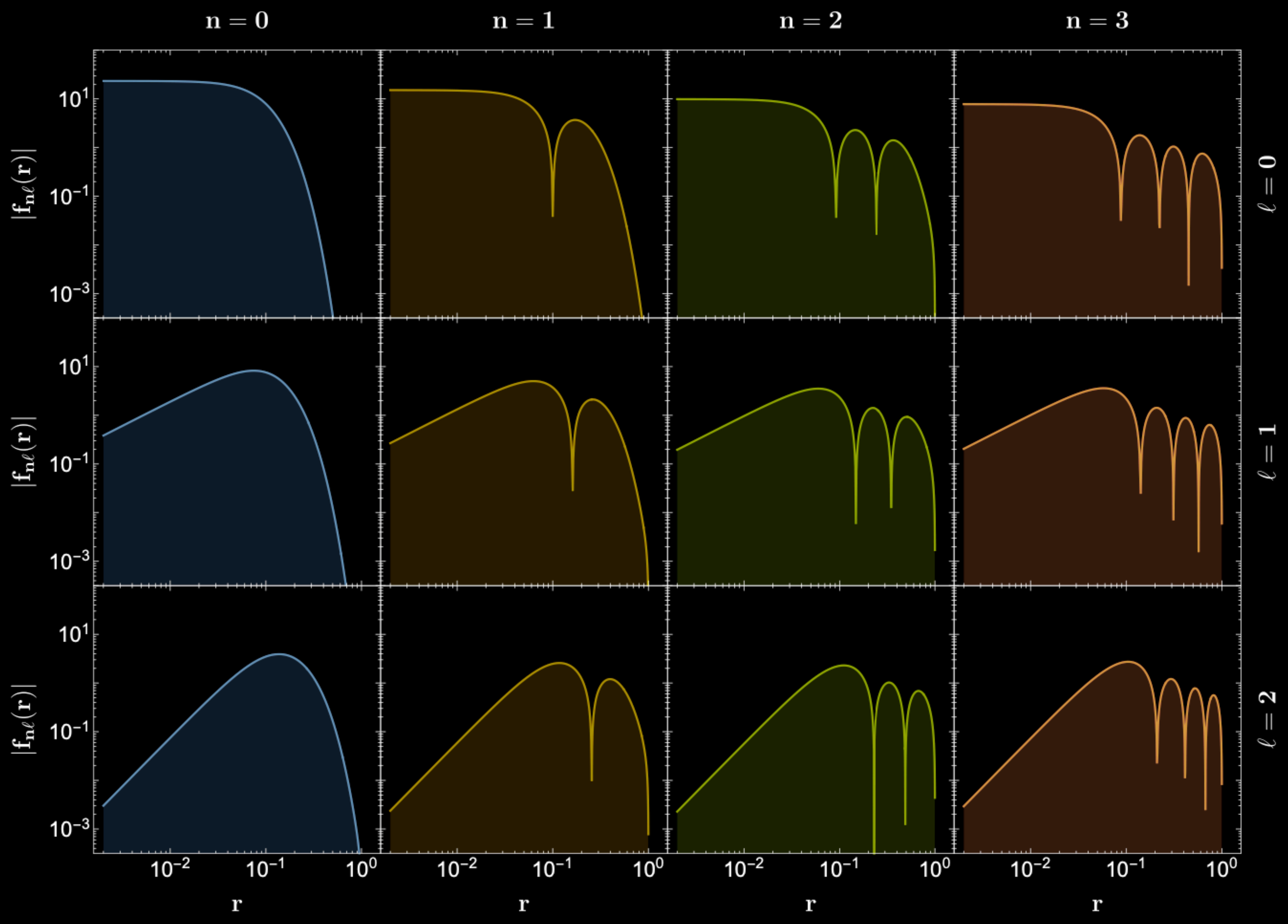


Infalling BH's with orbital periods near resonance with the soliton's intrinsic breathing modes may experience either facilitation or inhibition of the orbital decay process.

A stone skipping attempt by author

(This parameter scan is based on a different system than the previous slide)

Soliton Eigenmode Decomposition

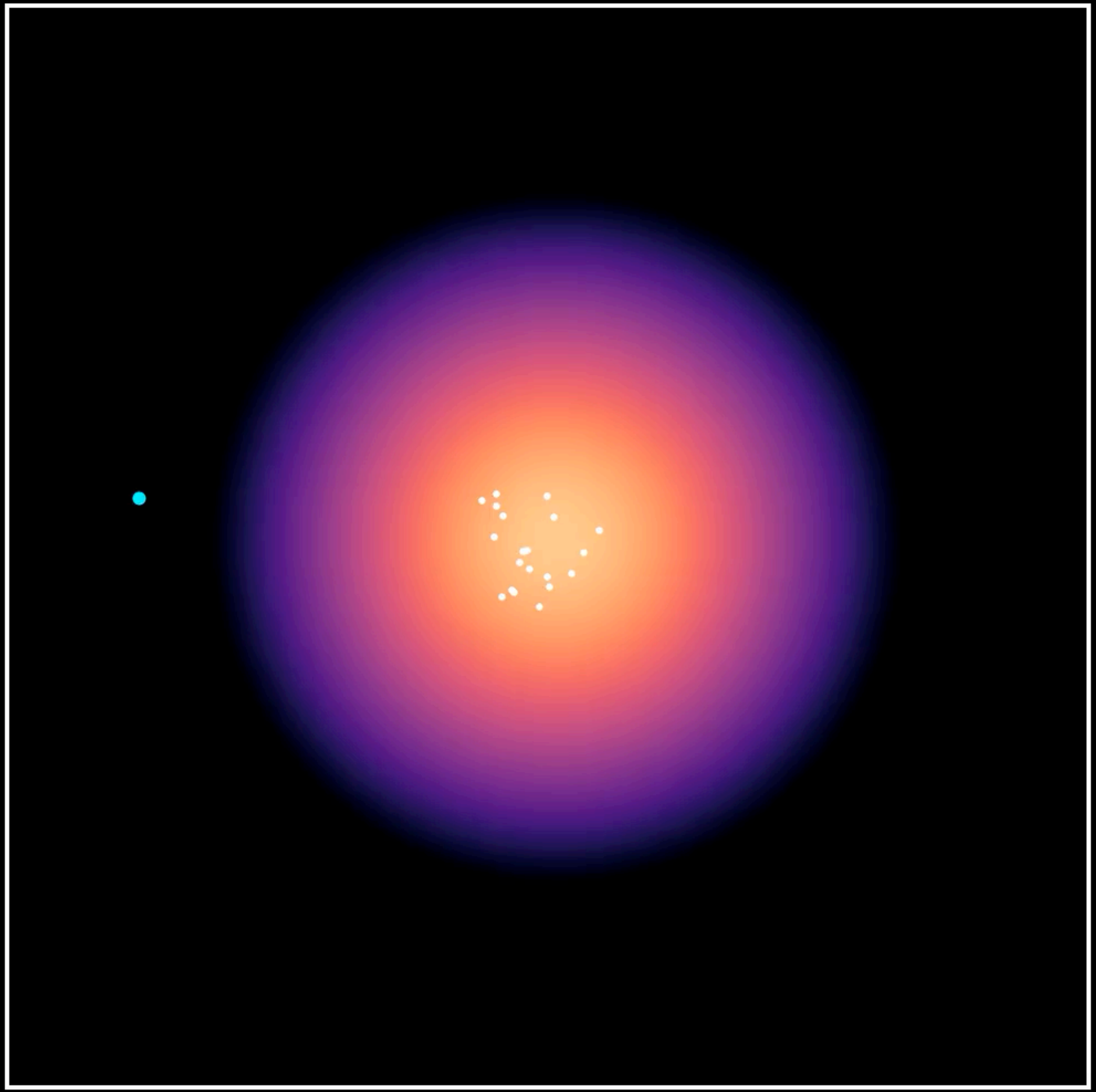


Ongoing investigation with Tim Koorey (Auckland) and Luna Zagorac (Perimeter)

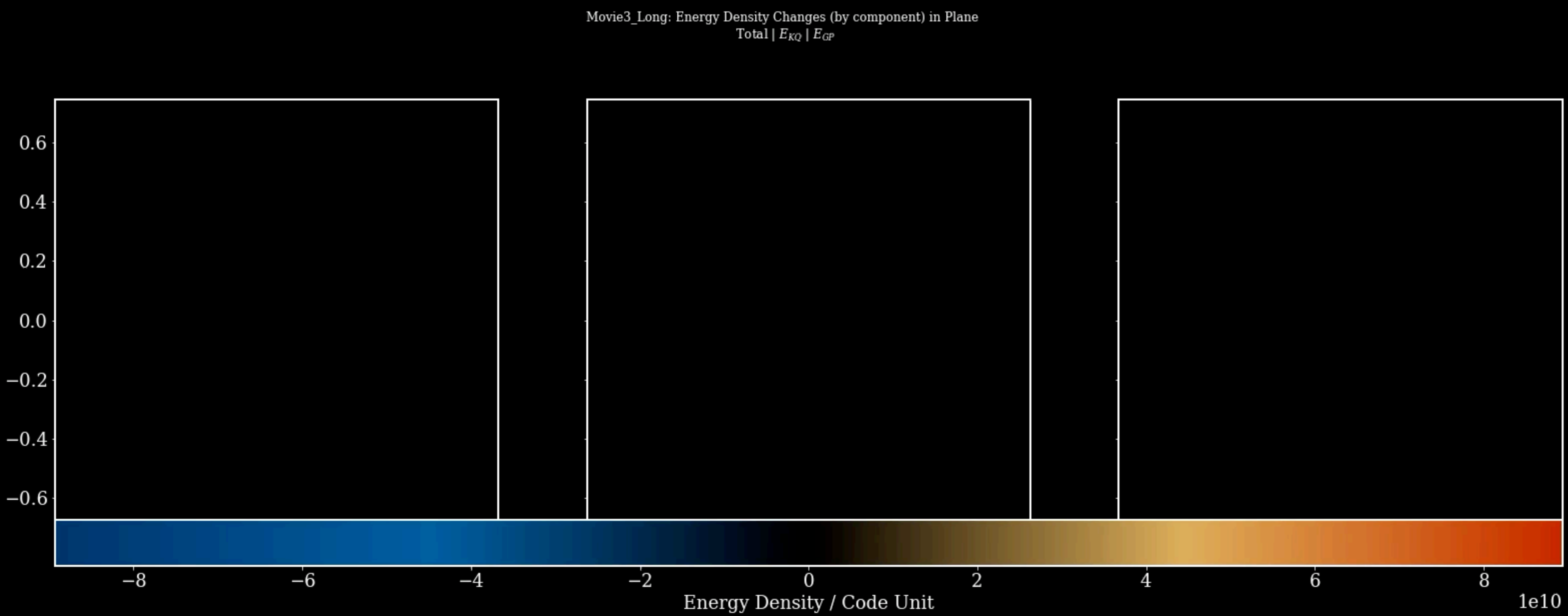
Schrödinger-Poisson solitons: Perturbation theory
Zagorac et al. PRD 105, 103506.

Caveats of This Toy Model

- Effectively, the initial soliton is instantly taken out of equilibrium at t=0, which is unrealistic.
- No astrophysical systems that we know of would consist of a fully relaxed “ground state” solitonic core.
- Nonlinearity might be dramatically disturbed by the presence of other massive objects and structures nearby.
- Local effects may be significant, like the BH’s accretion of axions.
- PyUL is a versatile and reliable tool for scratch work, but full-size simulations call for more sophisticated numerical routines such as **ChplUltra** (Yale Cosmology) and **AxioNyx** (Goettingen Cosmology).



 PYULTRALIGHT2 Another Example Simulation



Movie3_Long: Energy Density Changes (by component) in Plane
Total | E_{KQ} | E_{GP}
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−8 −6 −4 −2 0 2 4 6 8
Energy Density / Code Unit
1e10

Summary

- With PyUltraLight 2, we can now couple arbitrary N body systems to a mesh-based ULDM simulation.
- Comparable results with the simplified dynamical friction models in literature.
- *Direct simulations* of nonlinear interactions between a ULDM soliton and a black hole.
- Intricate dynamics and *complex behavior* even with *a single black hole*.

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

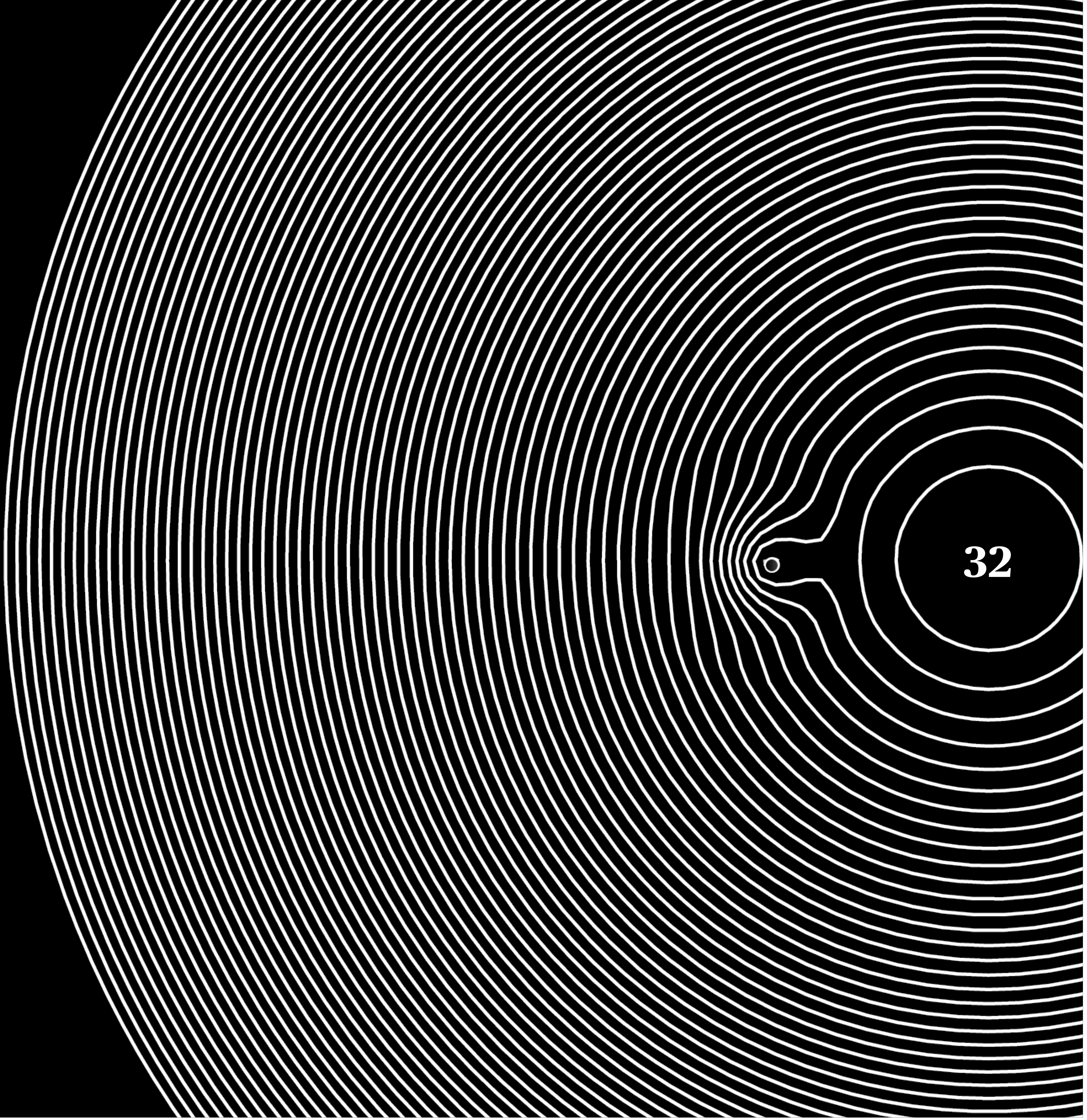
How do two SMBHs find each other during a galaxy merger and coalesce?

The Final Parsec Problem

Milosavljević, M. & Merritt, D. (2003).

The LISA Collaboration

LISA Consortium, ESA



Acknowledgements

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NEW ZEALAND GRAVITY

ARDC

A computer's impression of jets from a galaxy merger