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

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COSMOLOGY FROM HOME - PARALLEL TALK (PRE-RECORDED)

JUNE 2022

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

Dark Matter

Dark: Does not participate in EM or strong interactions.

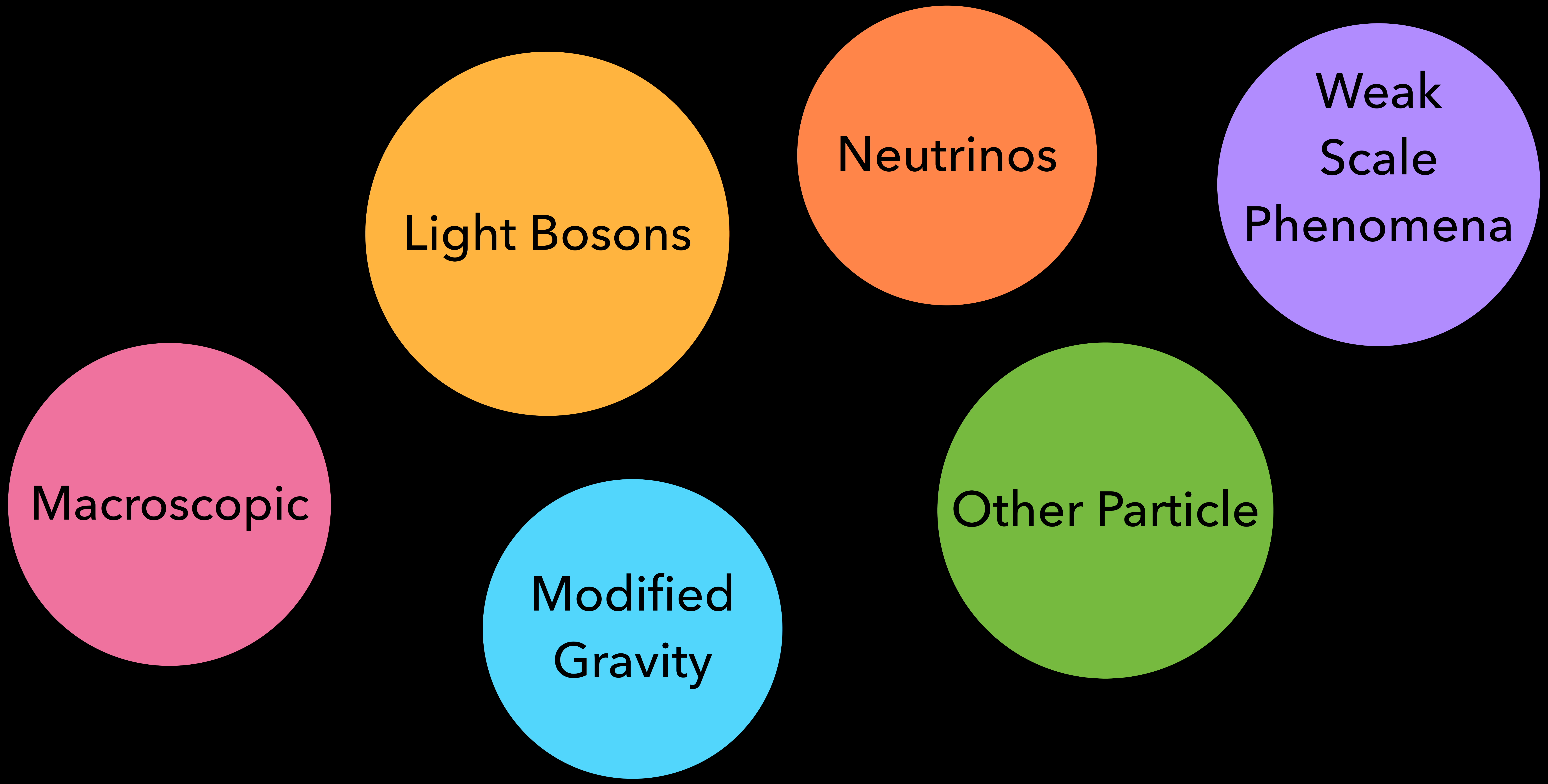
Stable: Persists in large quanties in the modern universe.

Cold: Motion, if any, only at non-relativistic speeds.

Exotic: Created by unknown physics in the early universe.

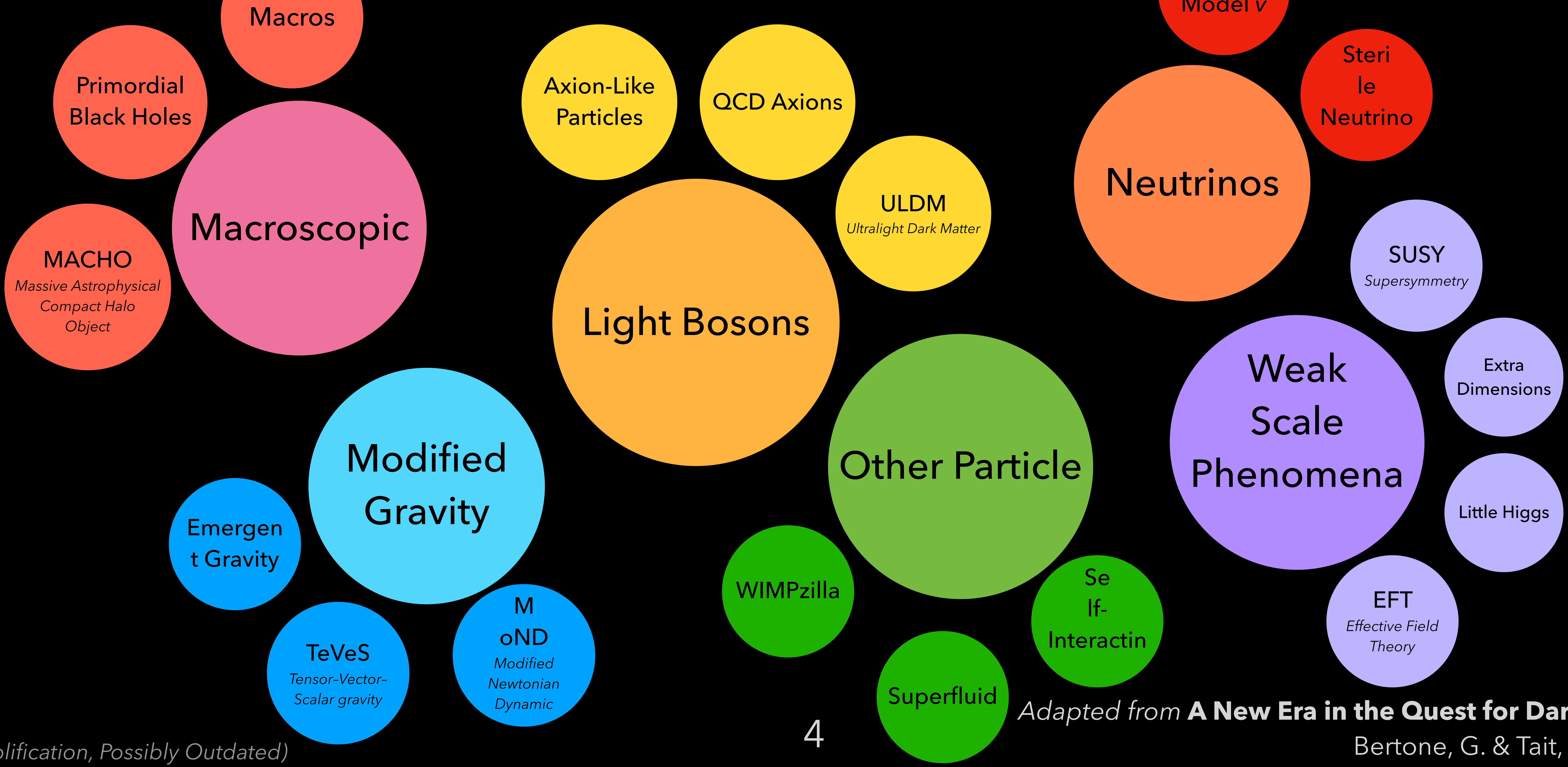
Dark Matter Candidates

From All Across Modern Physics



Dark Matter Candidates

From All Across Modern Physics



(Simplification, Possibly Outdated)

Adapted from **A New Era in the Quest for Dark Matter**
Bertone, G. & Tait, T. (2018).

ULDM

Ultralight Dark Matter

A bosonic scalar field **minimally coupled to gravity** with corresponding particle **mass** around **10^{-21} eV.**

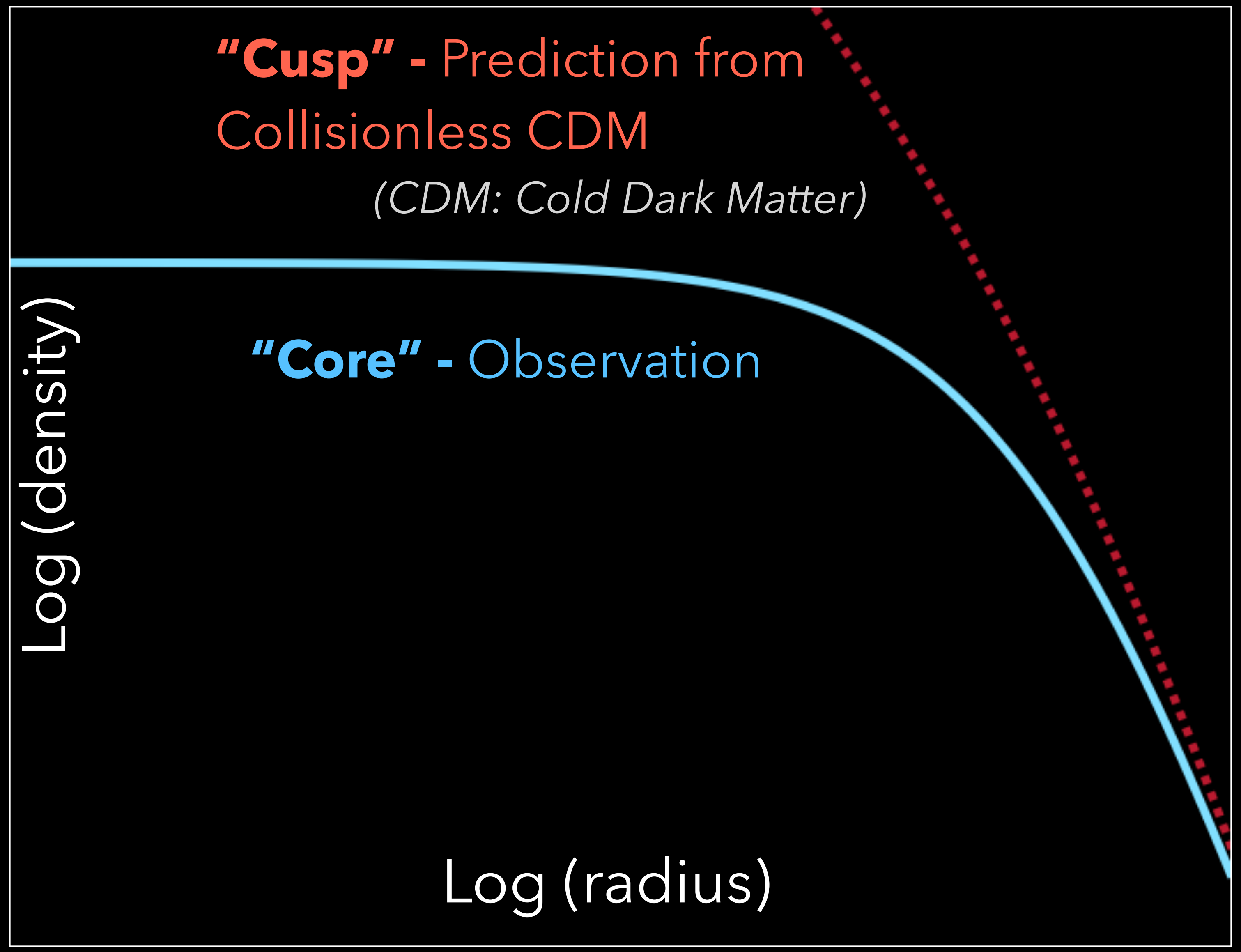
Capable of generating similar large-scale features of the cosmos as other DM models.

Behaves differently inside galaxies due to huge de Broglie wavelength.

Forms Bose-Einstein Condensates!

Core Cusp Problem

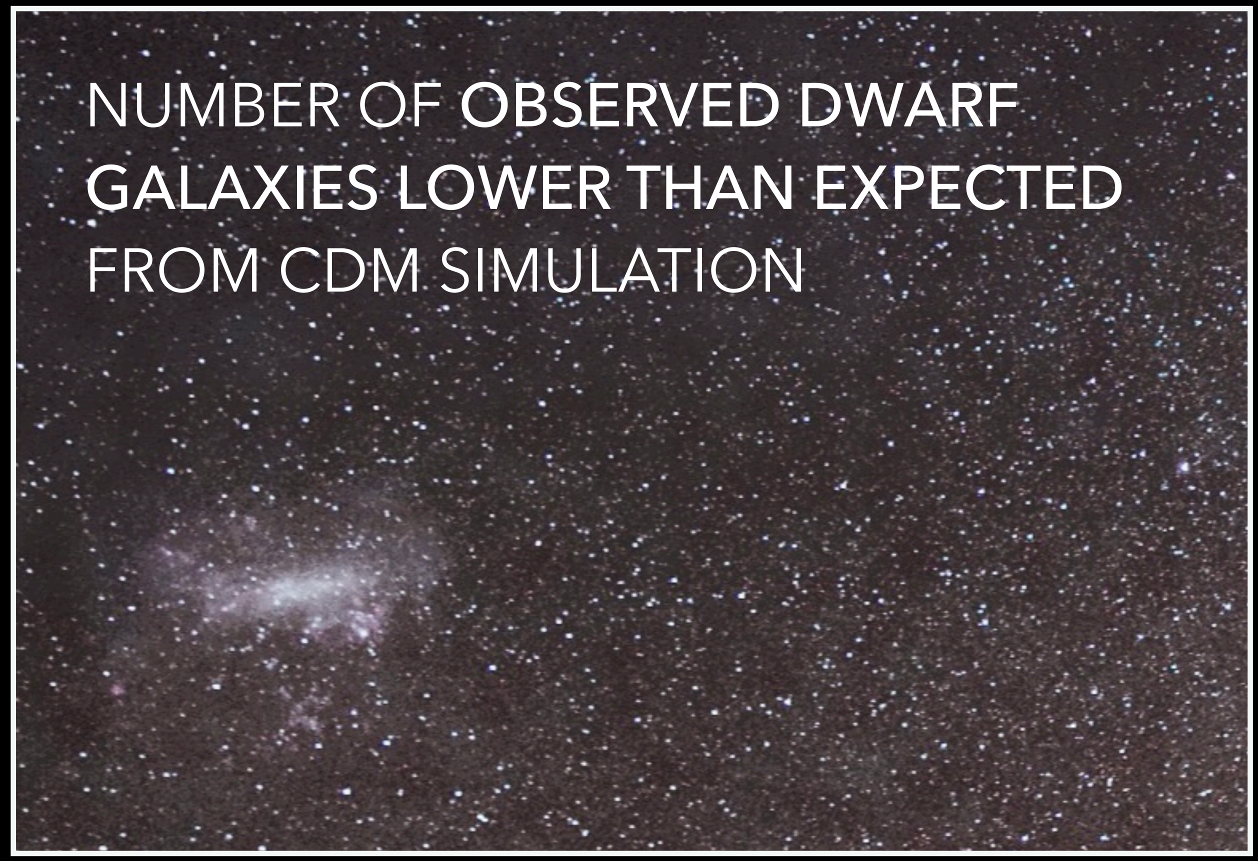
Smooth Density Profiles in Core Regions of Galaxies



Lack of Direct DM
Detection on Earth

"Missing Satellites"

Lack of Detected Dwarf Galaxies



ULDM

Ultralight Dark Matter

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

Mandelung Formalism of QM

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

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

Structure Formation with Scalar Field Dark Matter: The Fluid Approach
Suárez, A. &, Matos, T. (2011).

(Up to suitable unit scalings)

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

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

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

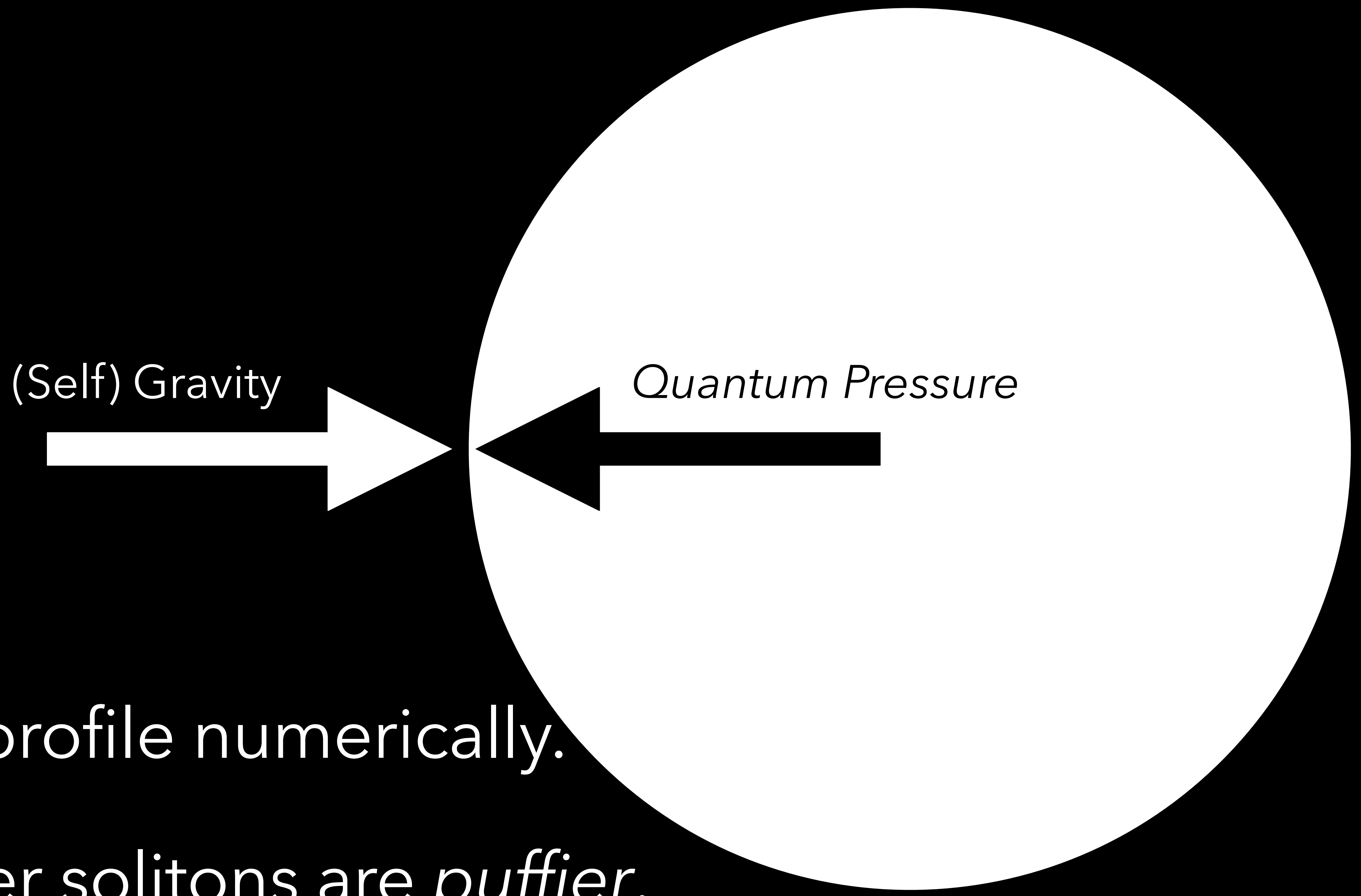
External Gravitational Potentials

Non-Gravitational Self-Interaction

Expansion of Universe

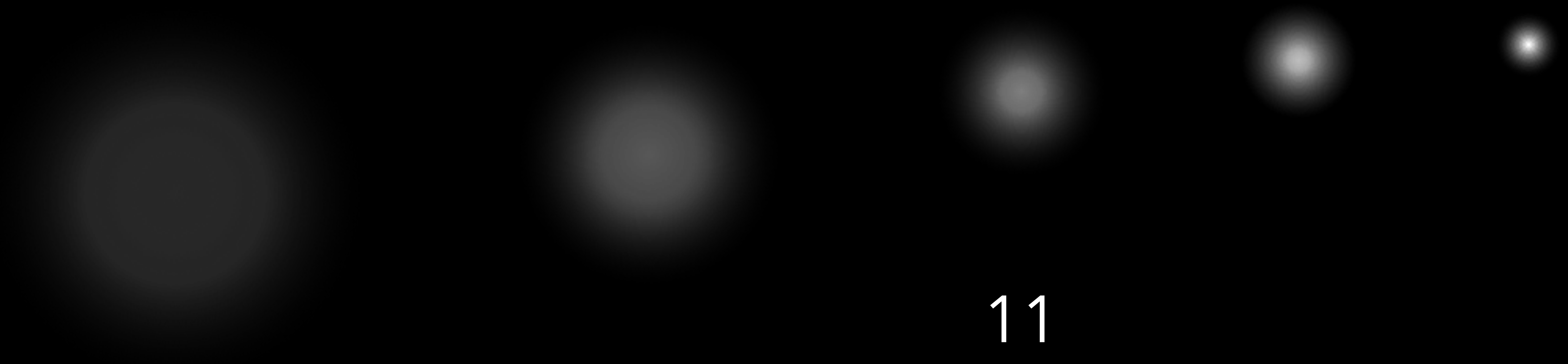
...

Schrödinger-Poisson Solitons



Can obtain the general radial profile numerically.

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



Destructive Interference
(π Global Phase Difference)

Constructive Interference
(0 Global Phase Difference)

II

Dynamical Friction

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

(Dramatisation)

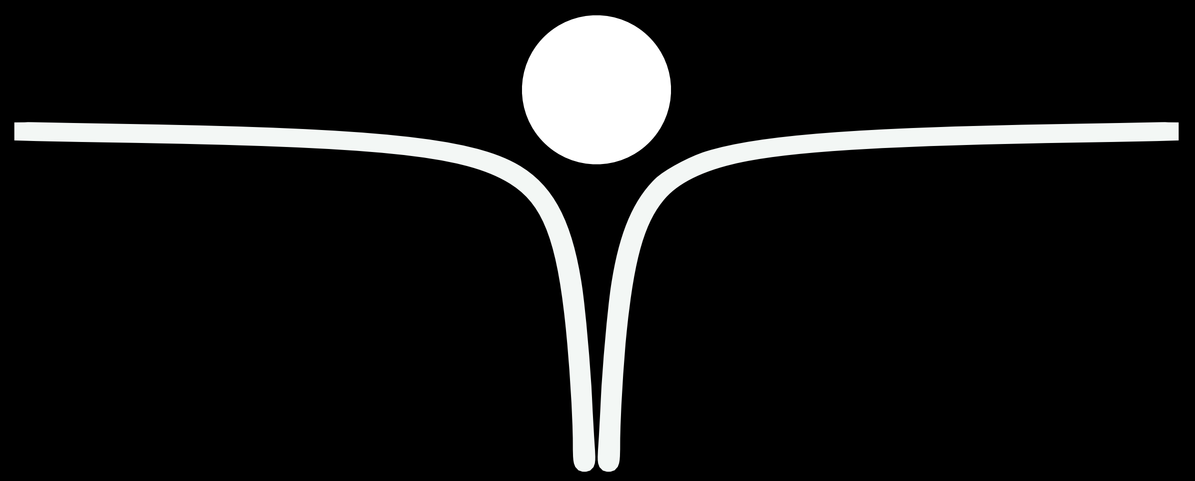
The SAO Encyclopedia of Astronomy
https://astronomy.swin.edu.au/cosmos

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

Naive ULDM Dynamical Friction Without Self-Gravity

Work in Particle's co-moving reference frame.
Assume the dynamical friction does not affect particle motion.

Particle sources a $1/r$ potential.

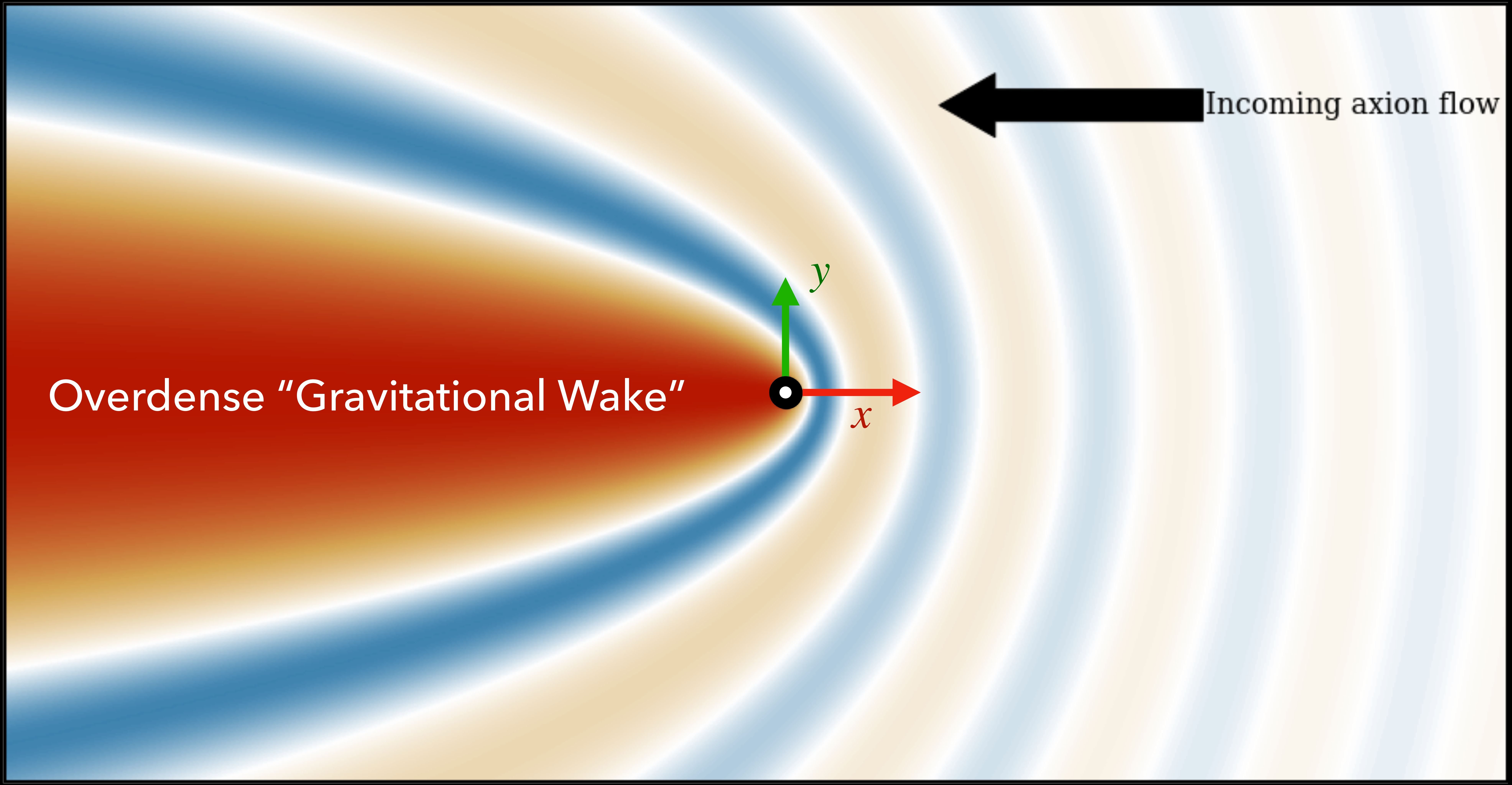


Axions arrive in a plane wave with uniform velocity and density far away.

Coulomb Scattering
Sakurai. Modern Quantum Mechanics. Sec. 7.13

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

Steady-State ULDM Overdensity in the plane z = 0



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

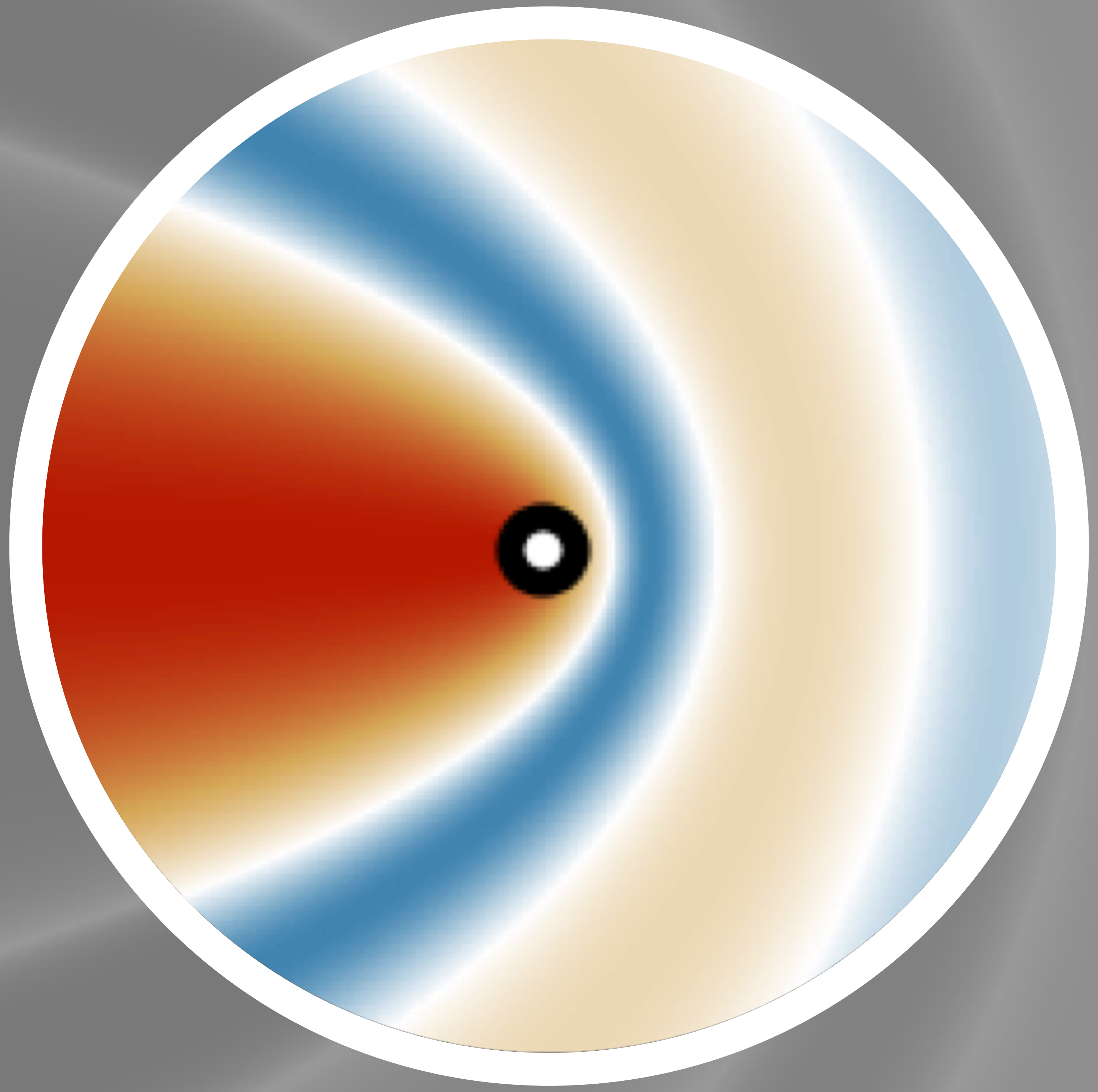
$$\beta = 2\pi \frac{GM}{v^2 \lambda_{\rm dB}} \qquad M(a, b; z) = \sum_{n=0}^{\infty} \frac{a^{(n)} z^n}{b^{(n)} n!} \qquad p^{(q)} \equiv \frac{\Gamma(p+q)}{\Gamma(p)}.$$

Problem*

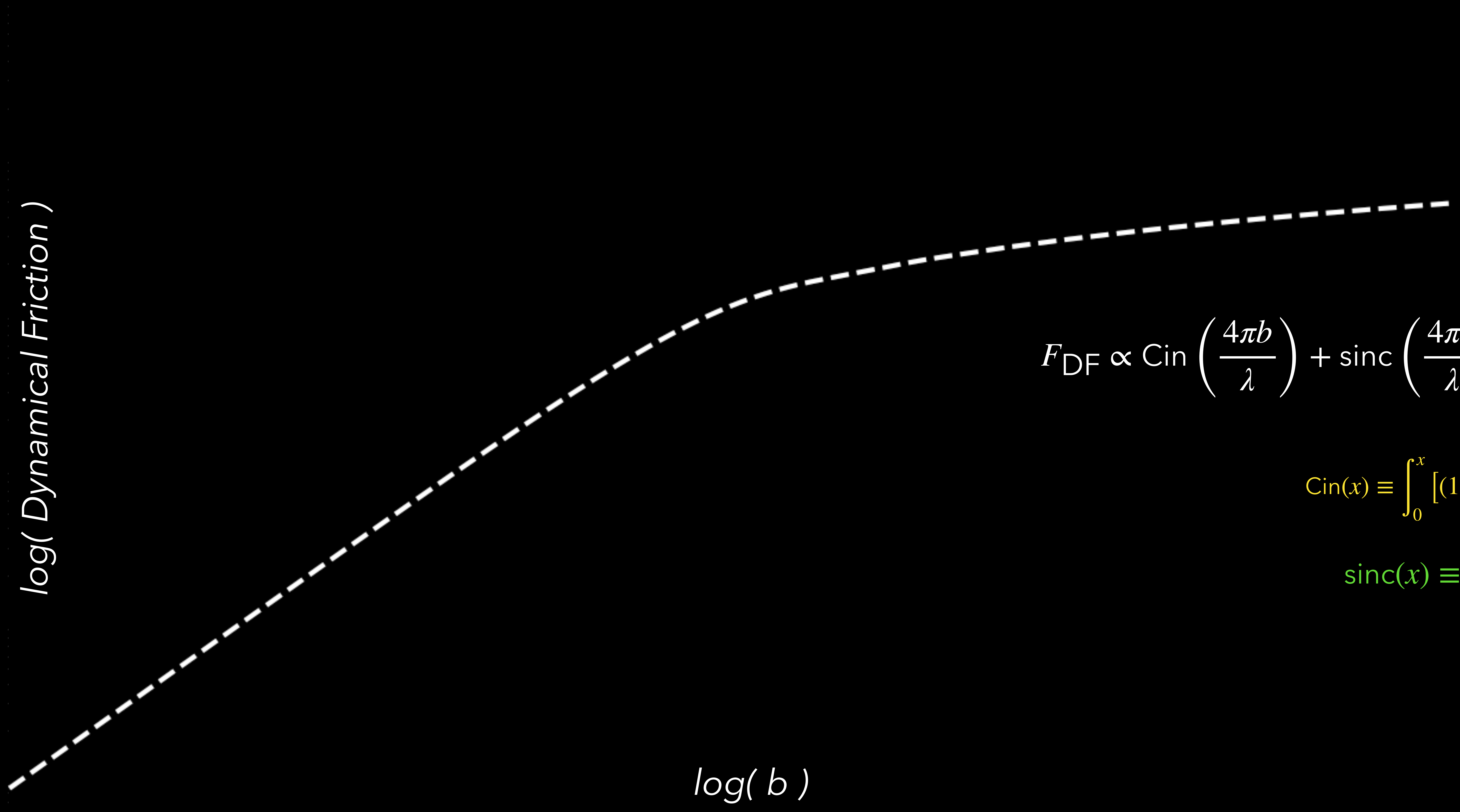
The overdensity tail never ends!

A Remedy ...?

- *Assume the interaction was "turned on" a finite time ago.*
- *The system only partially resembles the Coulomb scattering model.*
- *Only consider the effects of the Coulomb Scattering model within $b = vt$.*



Analytical Relationship



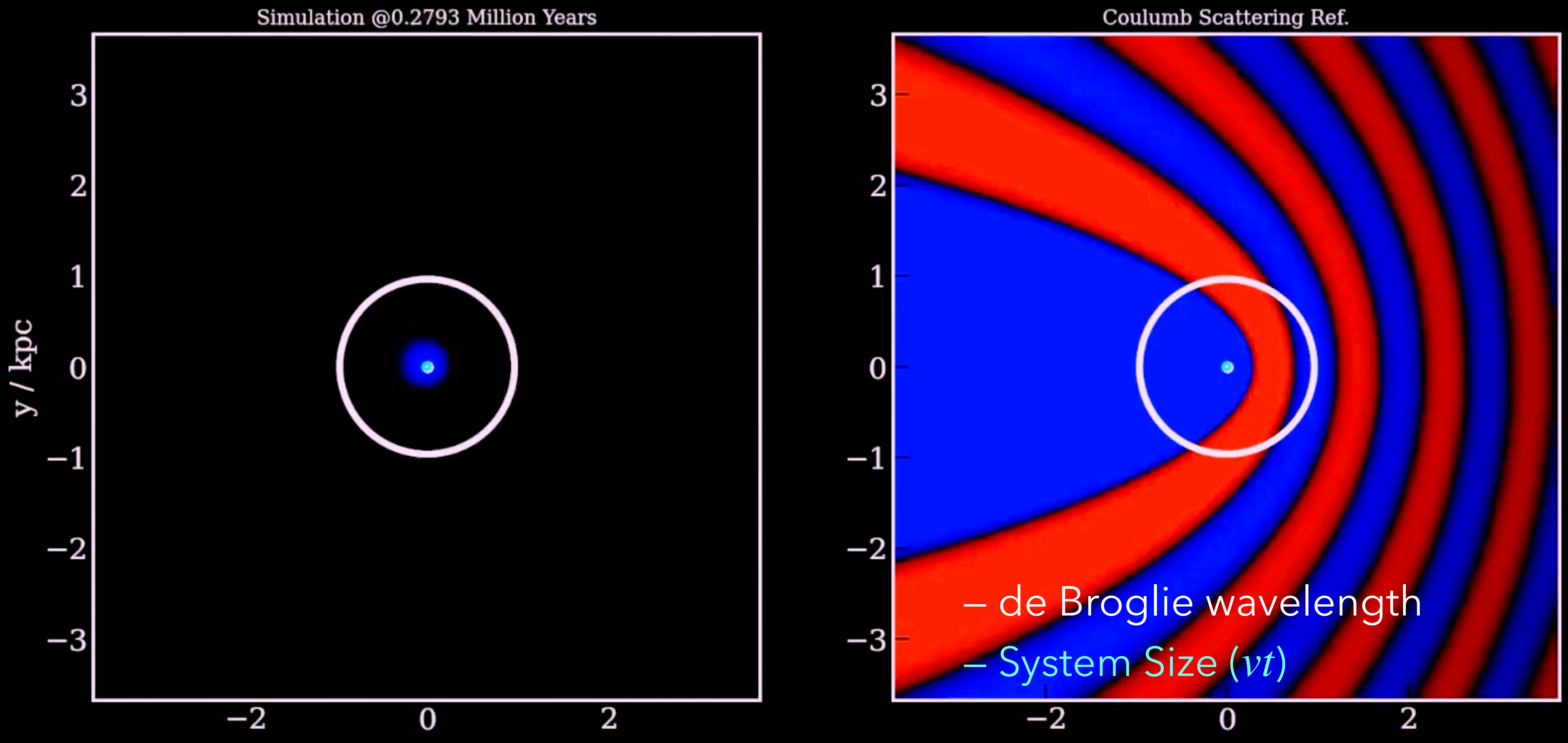
$$F_{\mathrm{DF}} \propto \mathrm{Cin}\left(\frac{4\pi b}{\lambda}\right) + \mathrm{sinc}\left(\frac{4\pi b}{\lambda}\right) - 1 + \mathcal{O}(\beta)$$

$$\mathrm{Cin}(x) \equiv \int_0^x \left[(1 - \cos(t))/t\right] dt$$

$$\mathrm{sinc}(x) \equiv \sin(x)/x$$

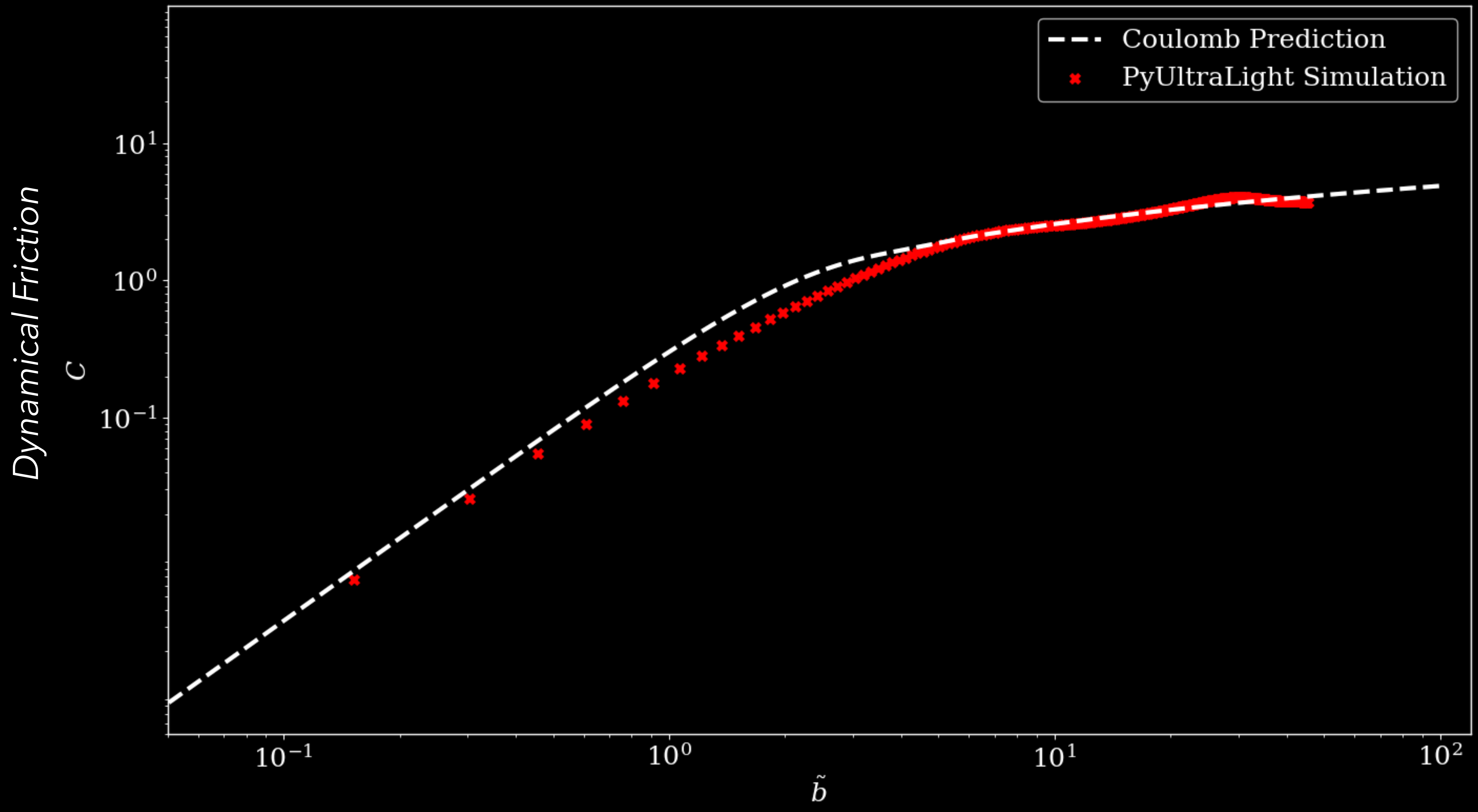
Ultralight scalars as cosmological dark matter
Hui, L.et al. (2017).

Our (Simplified) Simulation vs. Coulomb Scattering

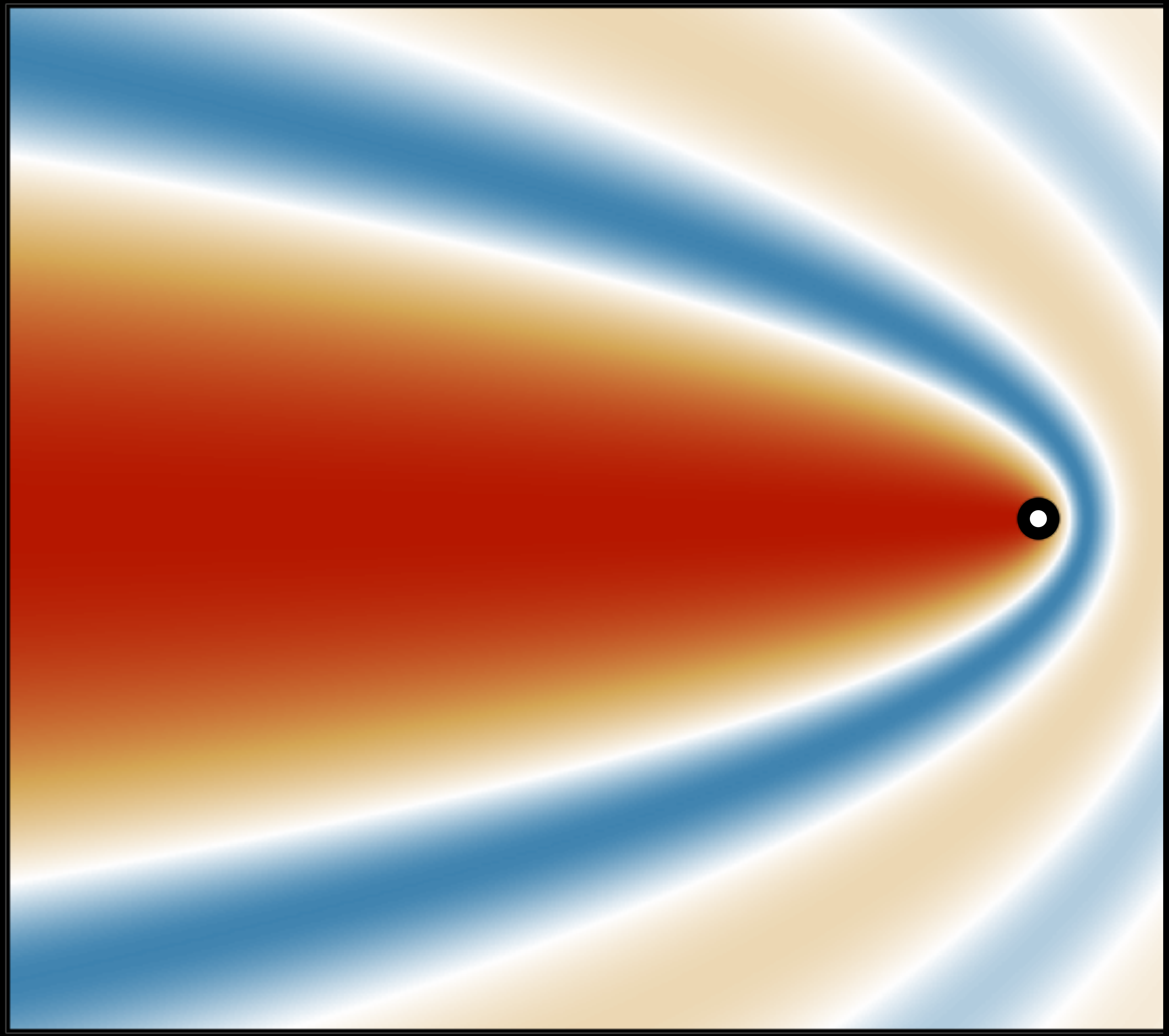


(Two plots share colour scales as left panel)

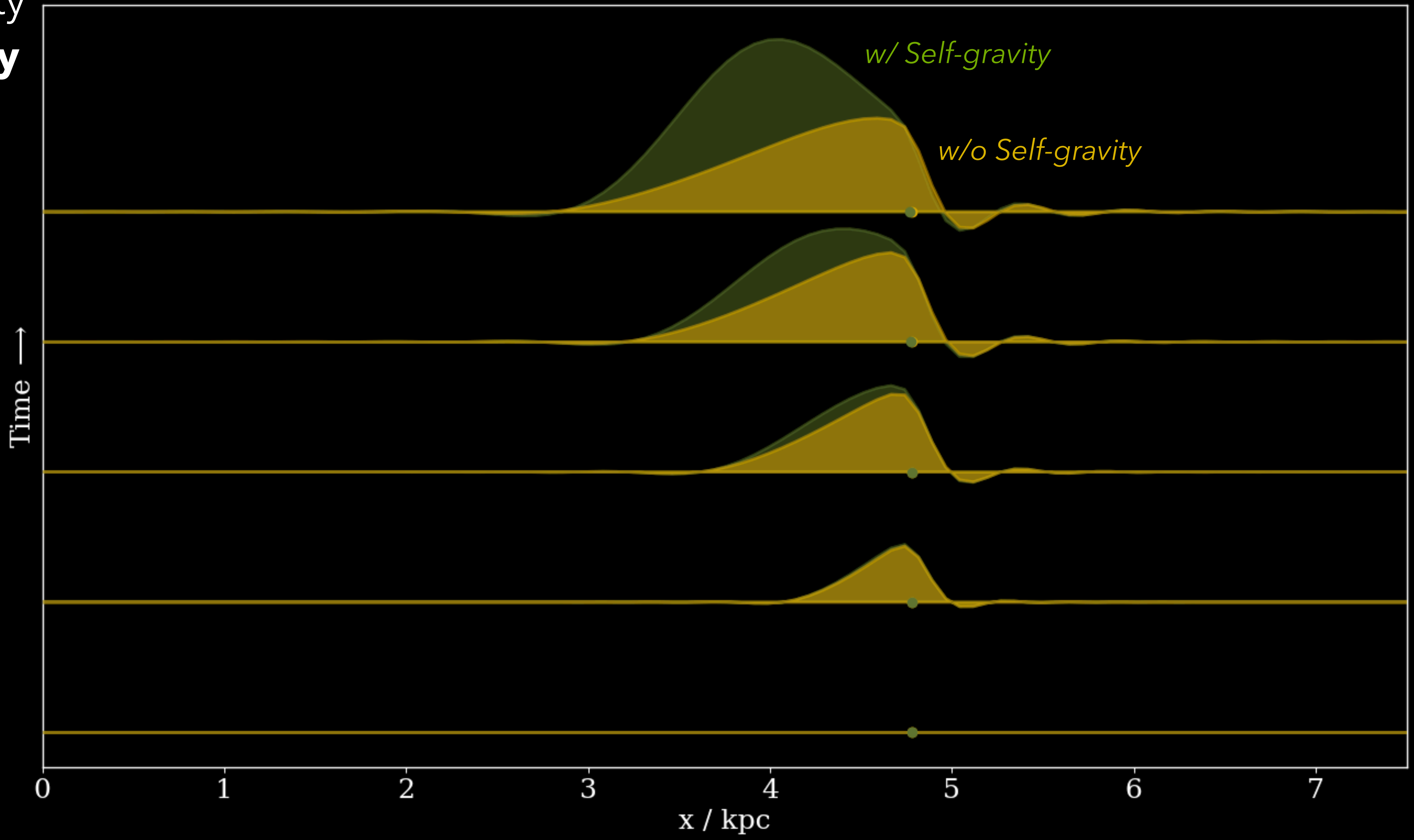
Our (Simplified) Simulation vs. Coulomb Scattering



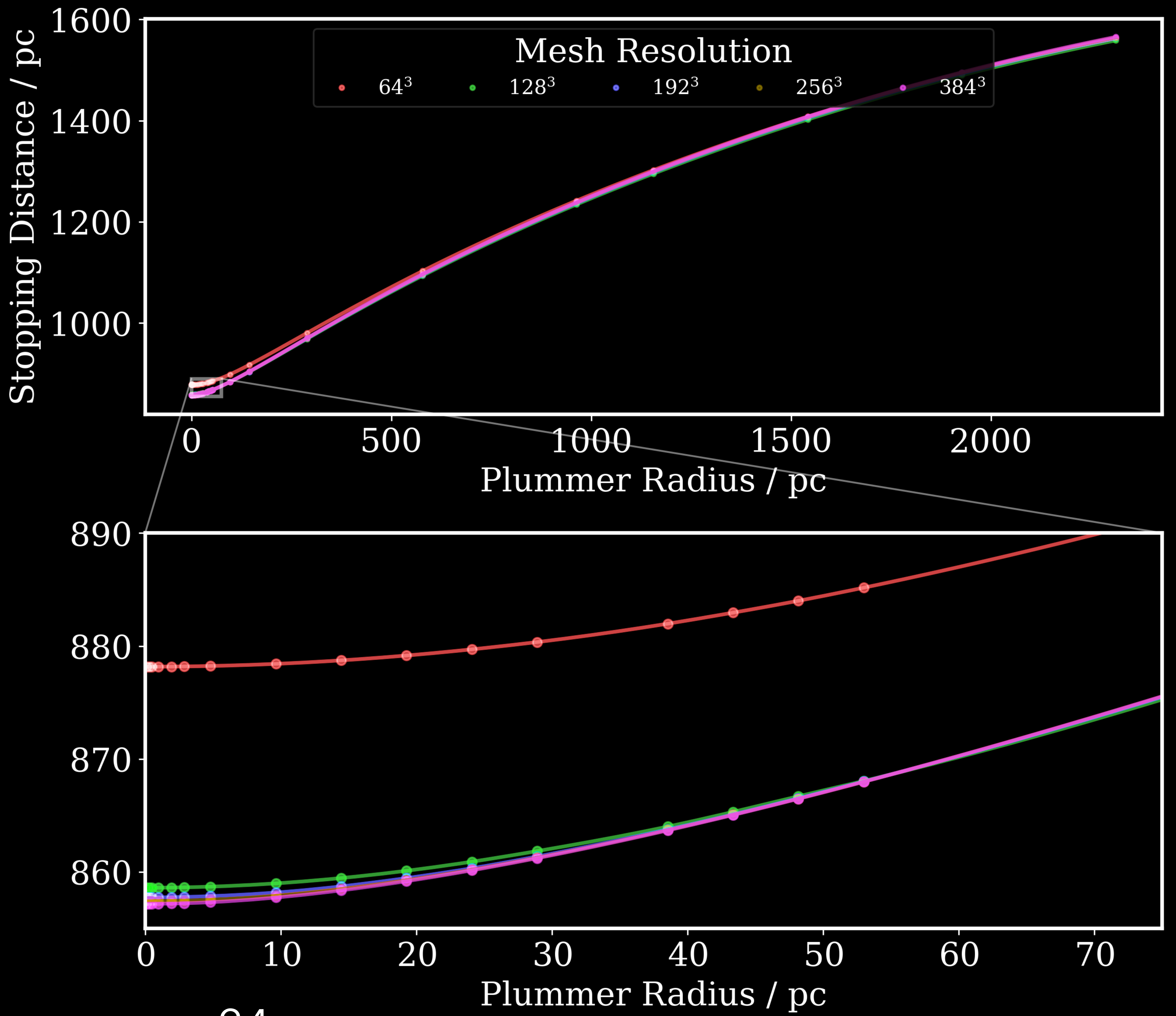
This solution is **not stable** under its own gravity



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



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



III² PyUltraLight

A Foundation for Efficient and Flexible ULDM Simulations

PyUltraLight2

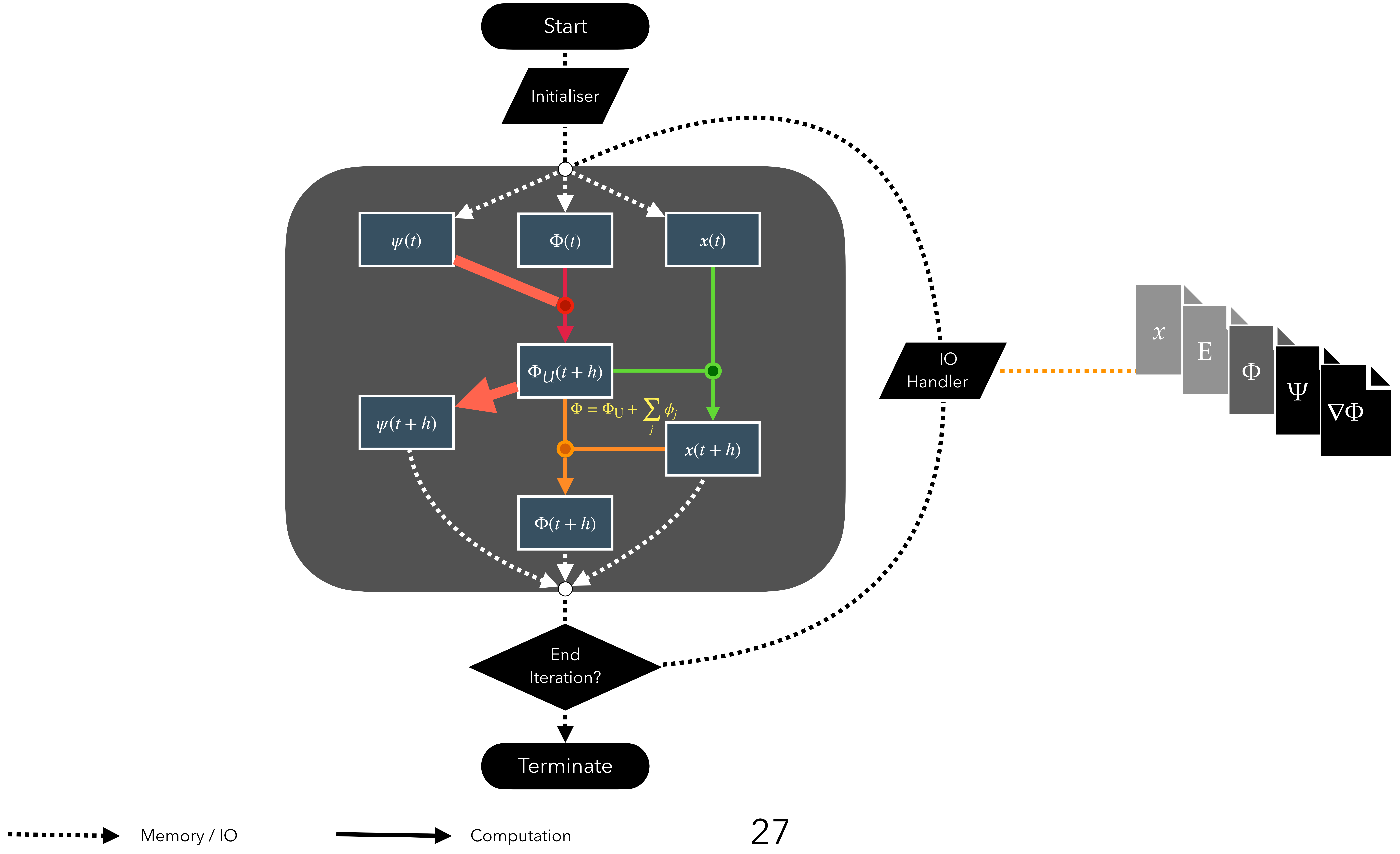
Ideas from

Nonlinear Optics

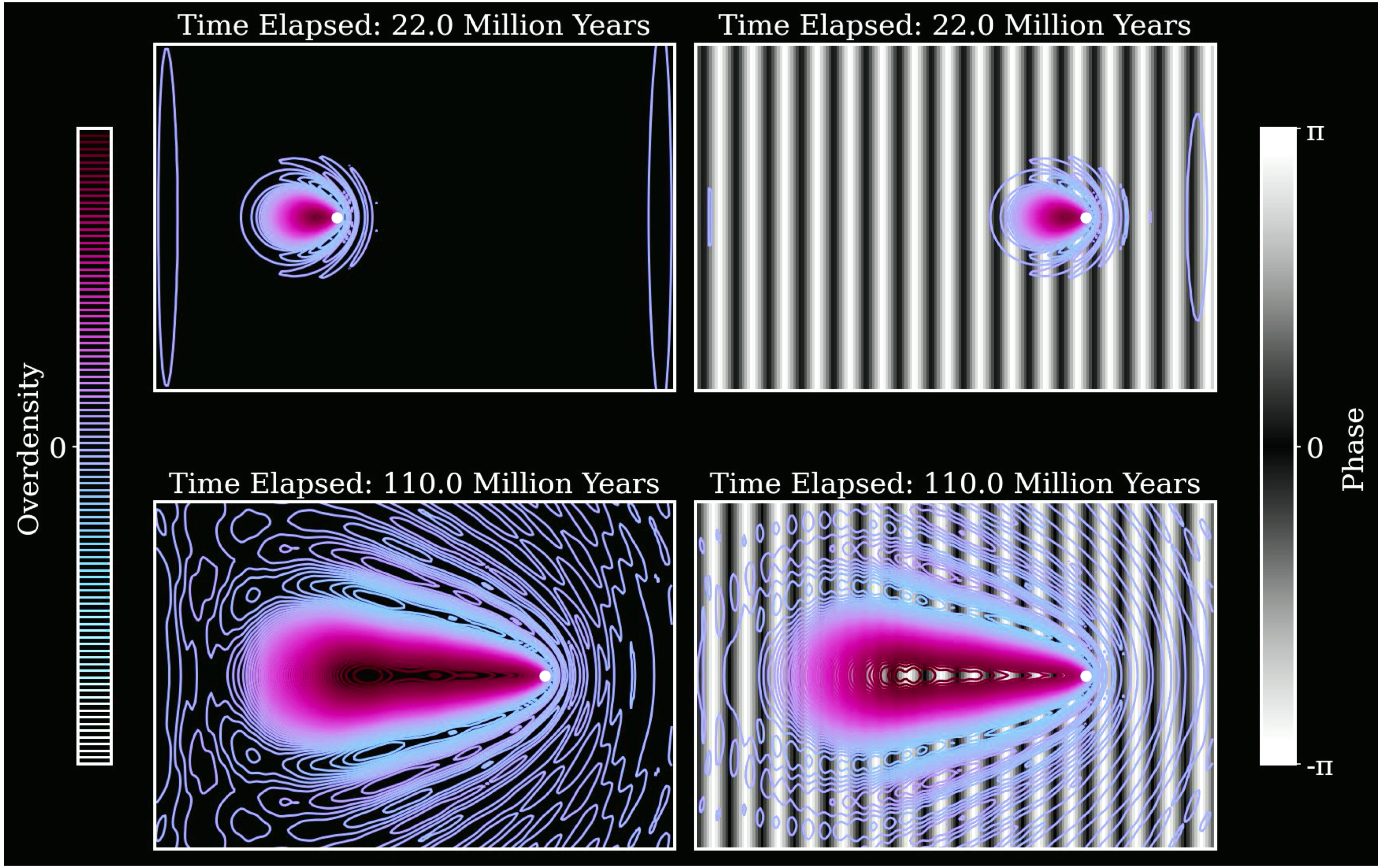
Fluid Mechanics

...

./Computational_Cosmology

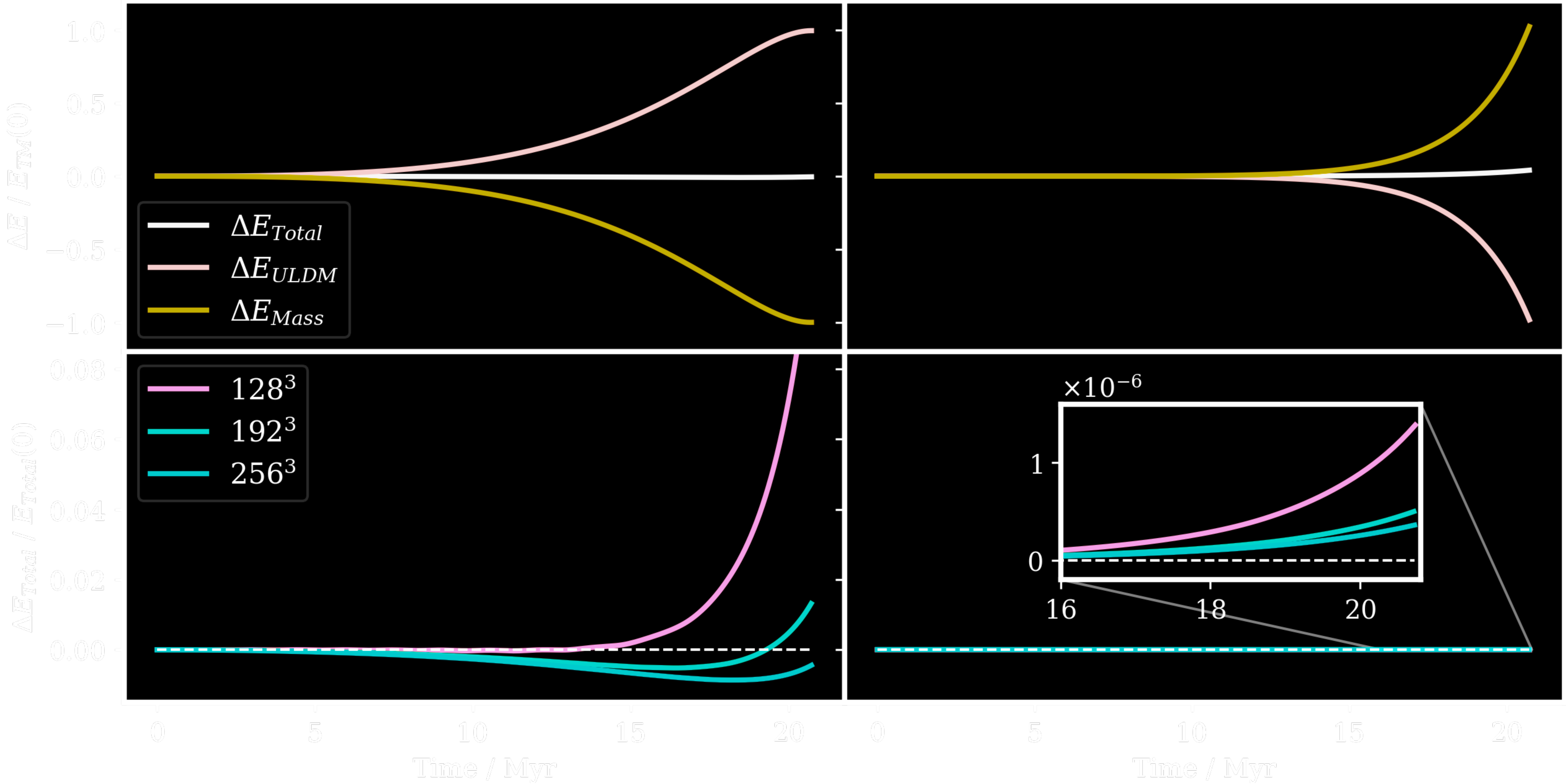


Start
Initialiser
$\psi(t)$
$\Phi(t)$
$x(t)$
$\Phi_U(t+h)$
$\psi(t+h)$
$\Phi = \Phi_U + \sum_j \phi_j$
$x(t+h)$
$\Phi(t+h)$
IO Handler
x
E
Φ
Ψ
$\nabla\Phi$
End Iteration?
Terminate
Memory / IO
Computation



Moving BH, Stationery ULDM

"Quantum Wind"

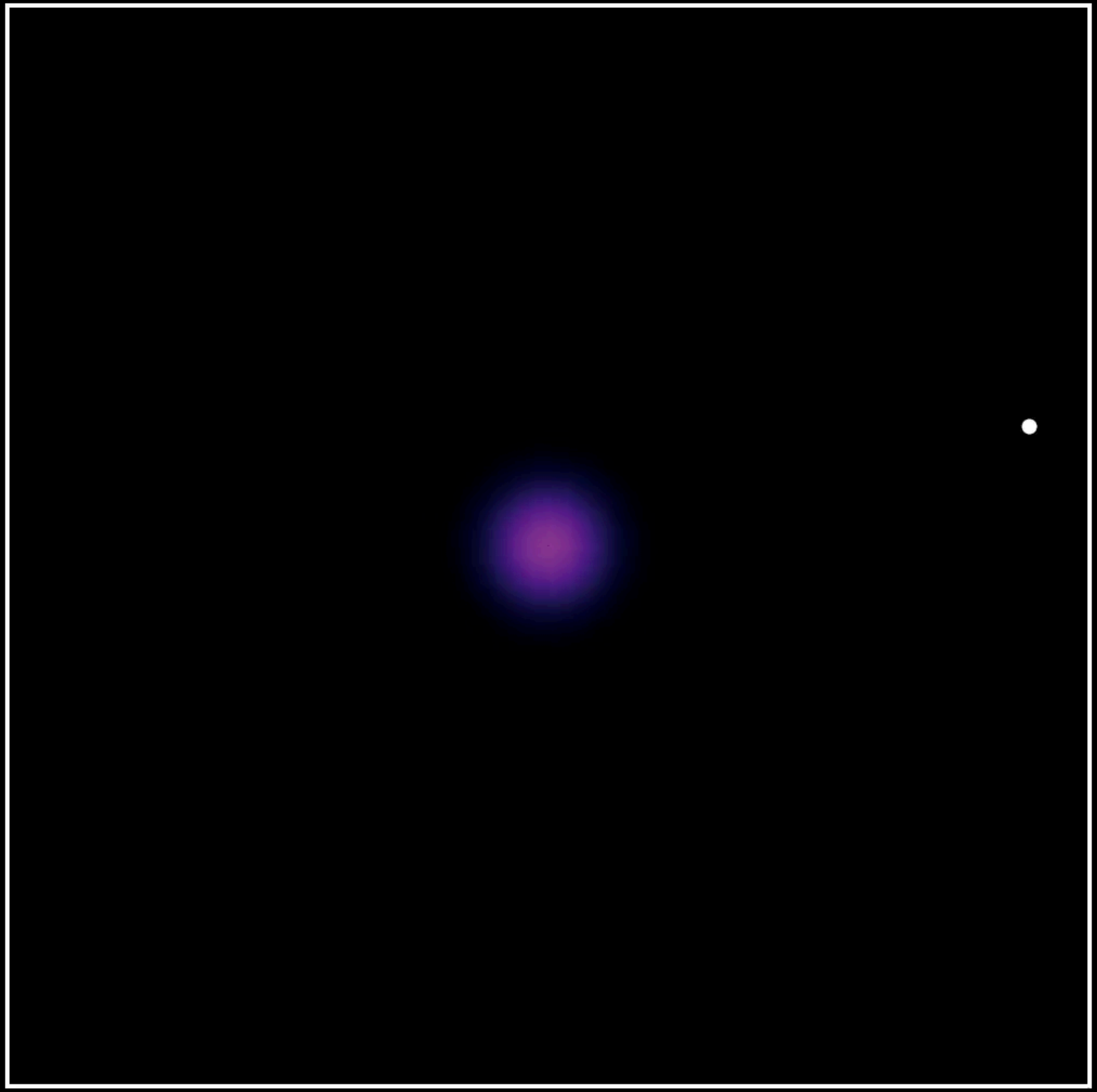


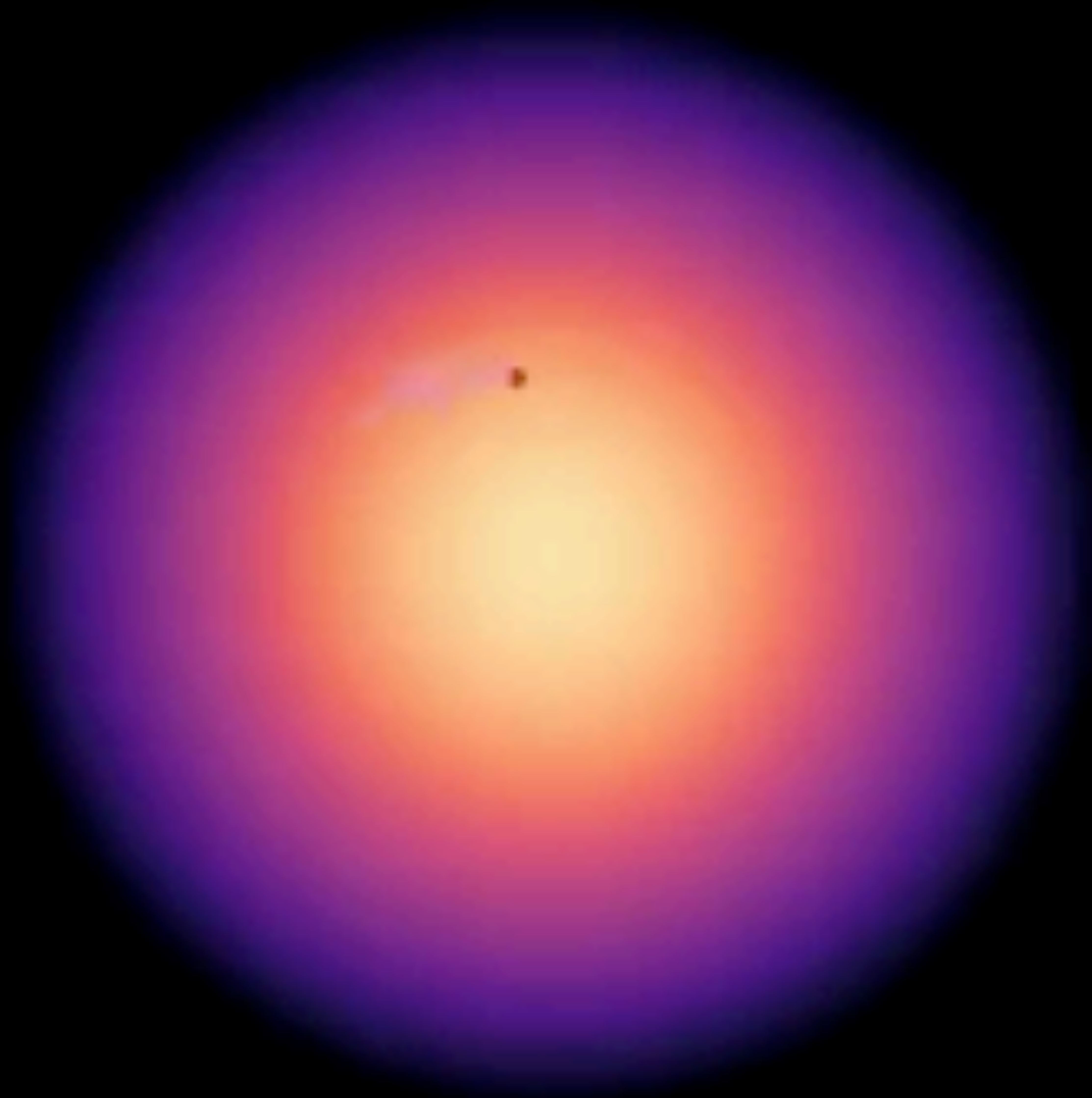
(Nice Energy Conservation)

IV

A Black Hole and a Soliton

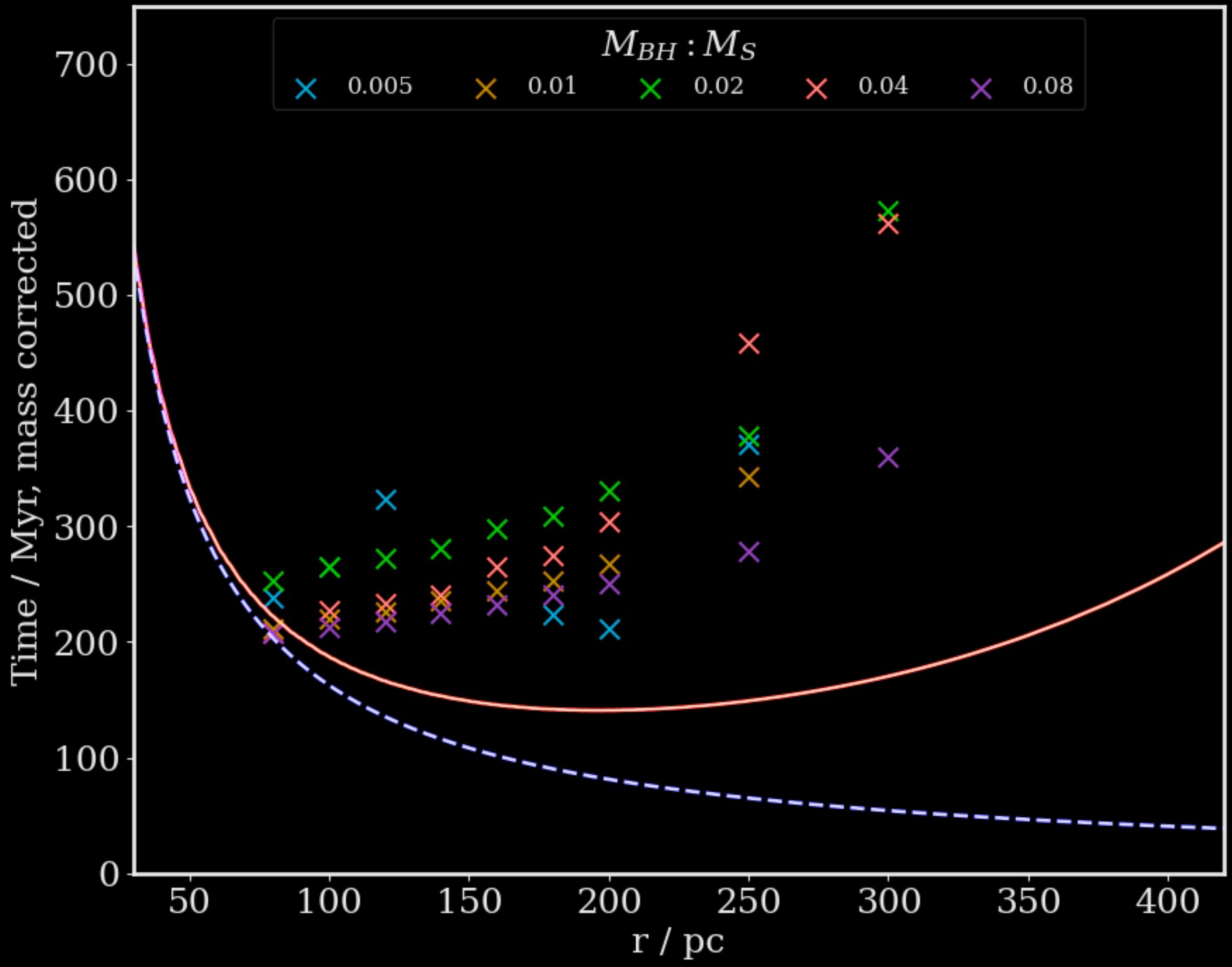

Live Demo





Single BH Orbit Decay

Single BH Orbit Decay

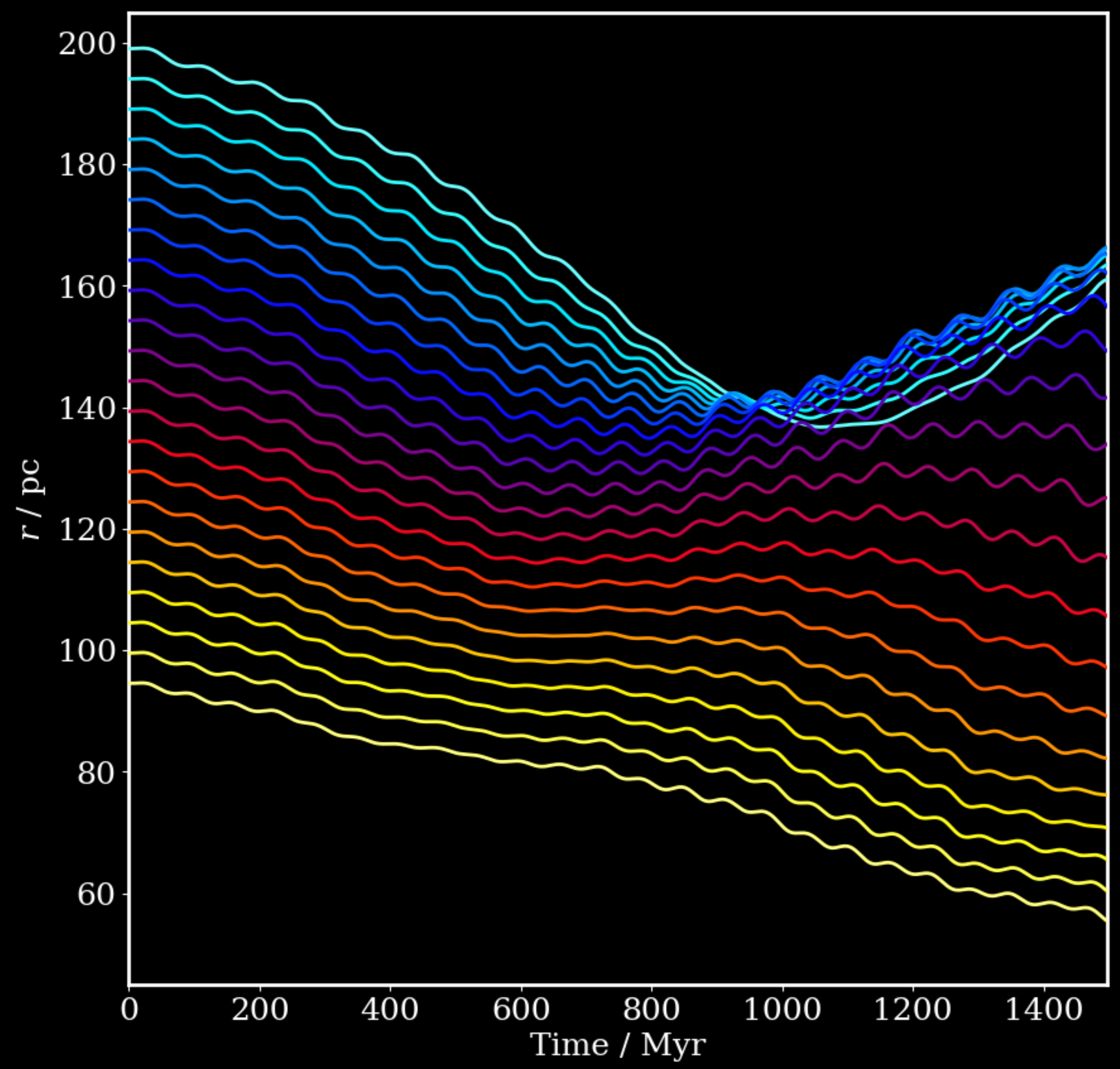


If deceleration is solely caused by the torque generated by Coulomb D.F.

evaluated using (initial) local properties

evaluated using core properties

Skipping Stones?

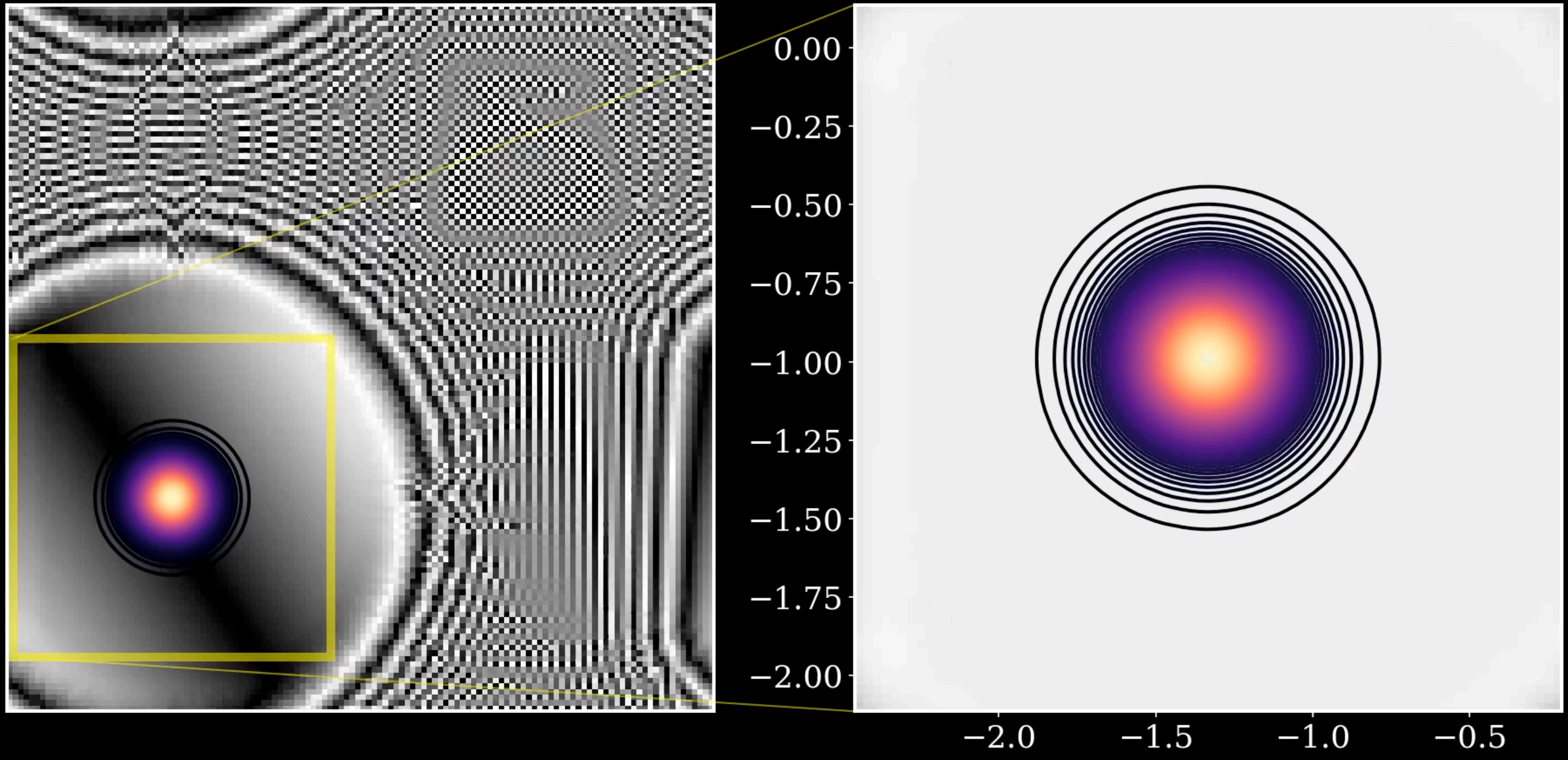


(These simulations use a light, 0.5% M_s mass)

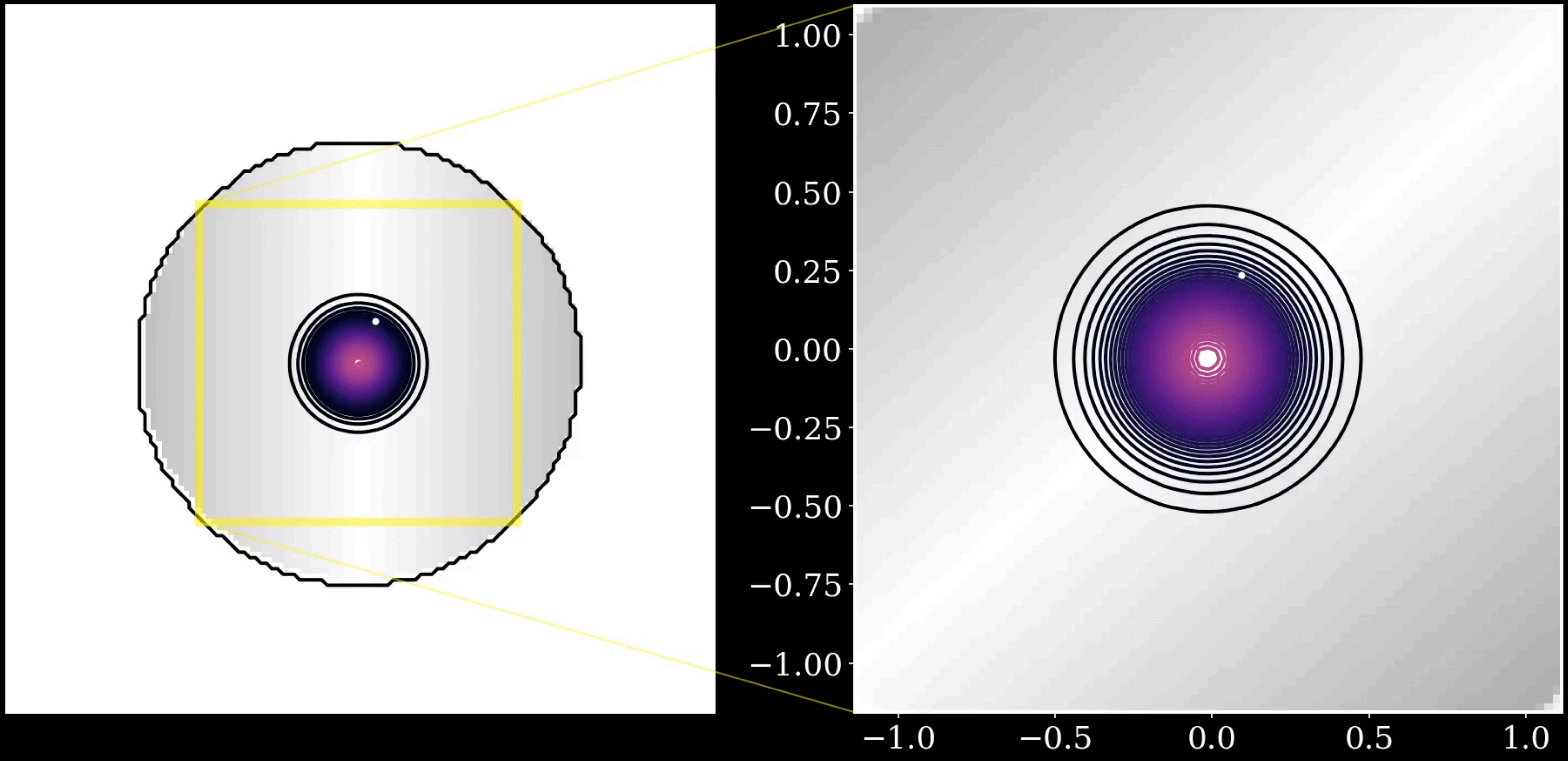
Infalling BH's with orbital periods near **resonance** with the soliton's **intrinsic breathing modes** may experience either **facilitation** or **inhibition** of the orbital decay process.

(A stone skipping attempt by author)

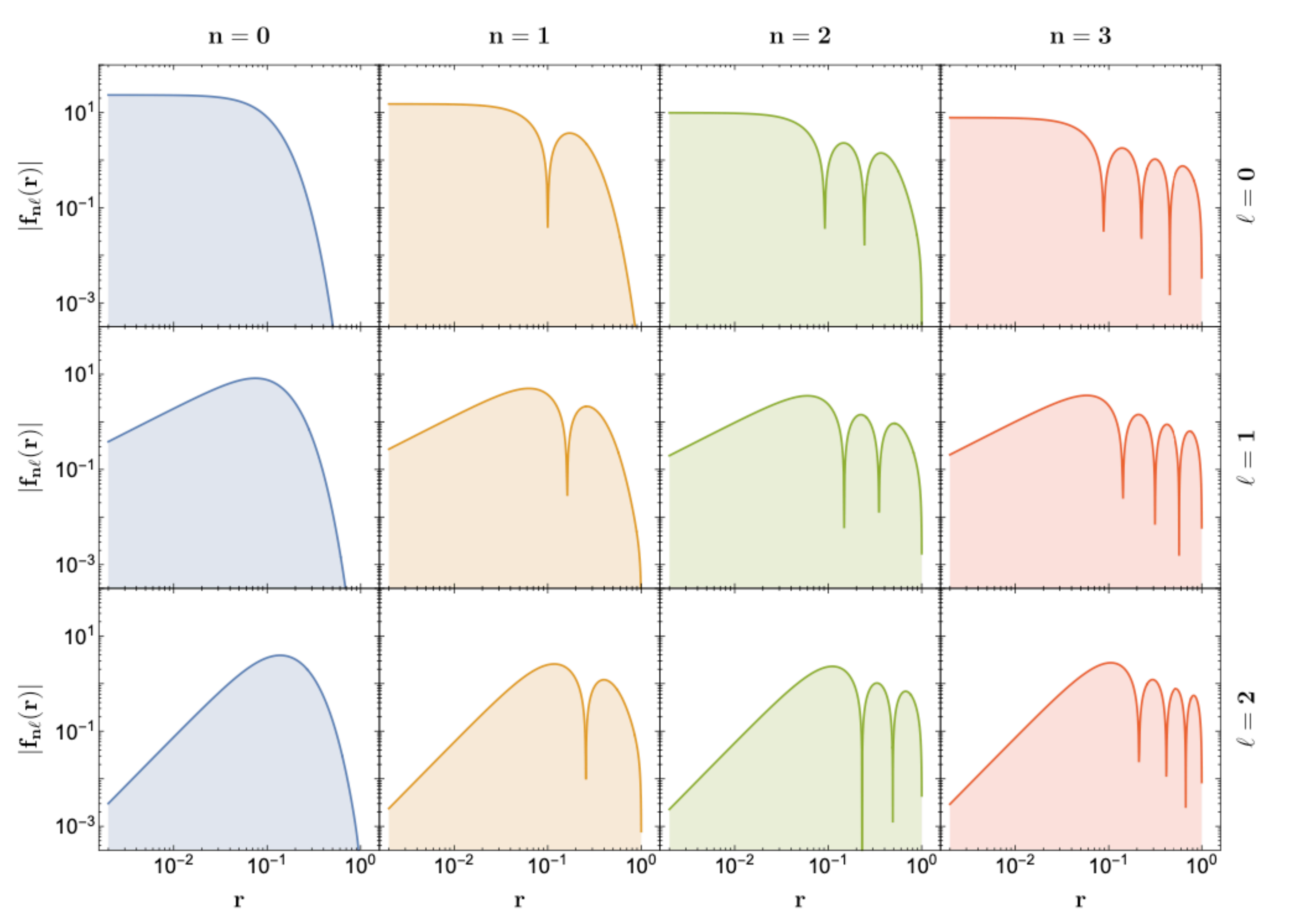
Flexible Reference Frame Shifts and COM Corrections



Flexible Reference Frame Shifts and COM Corrections

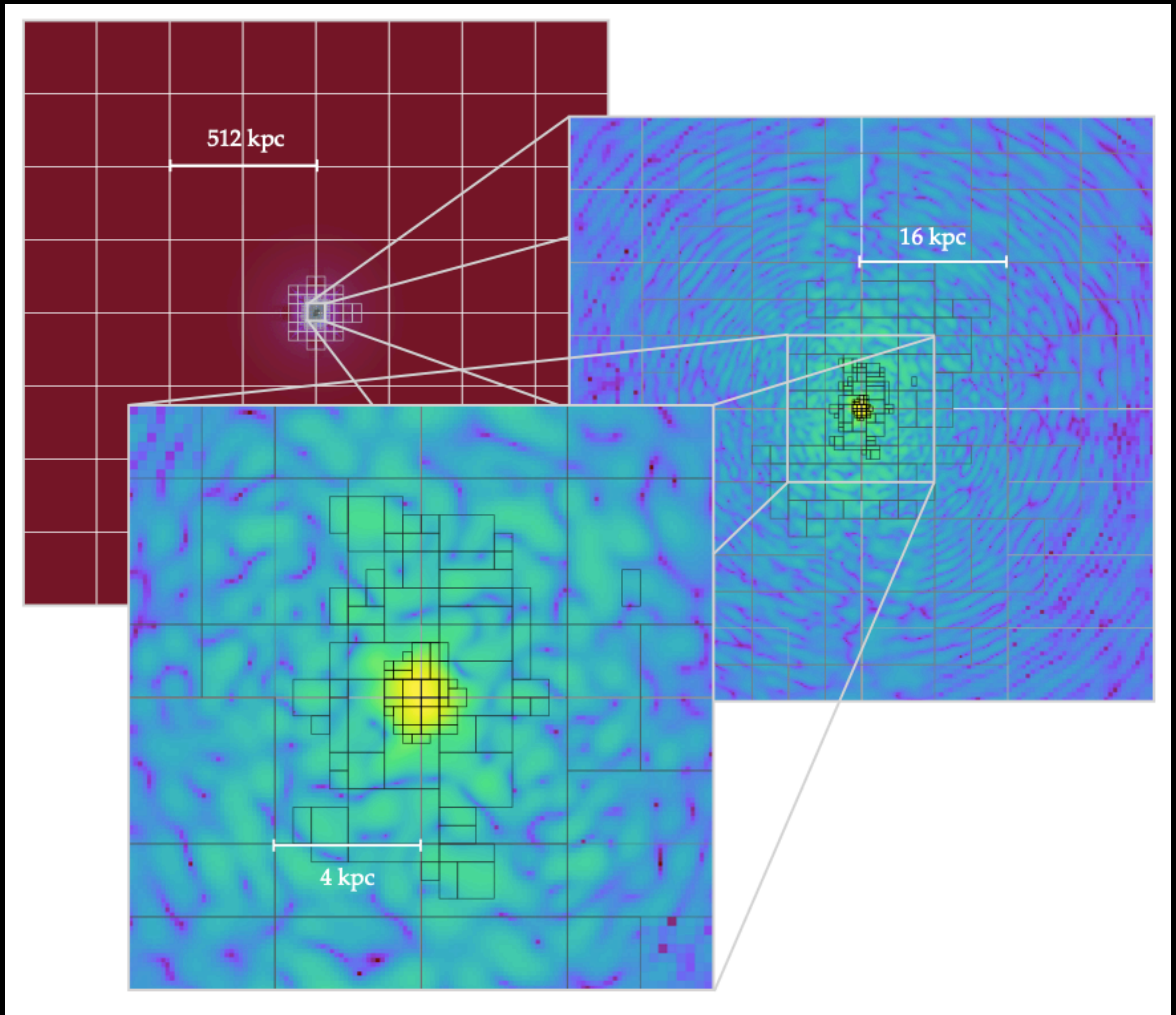


Quantitative Investigation of Soliton's Time Evolution



Schroedinger-Poisson Solitons: Perturbation Theory
Zagorac, J. L. et al. (2022).

Moving to More Sophisticated Tools



AxioNyx: Simulating Mixed Fuzzy and Cold Dark Matter.
Schwabe, B. et al. (2020).

Summary

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

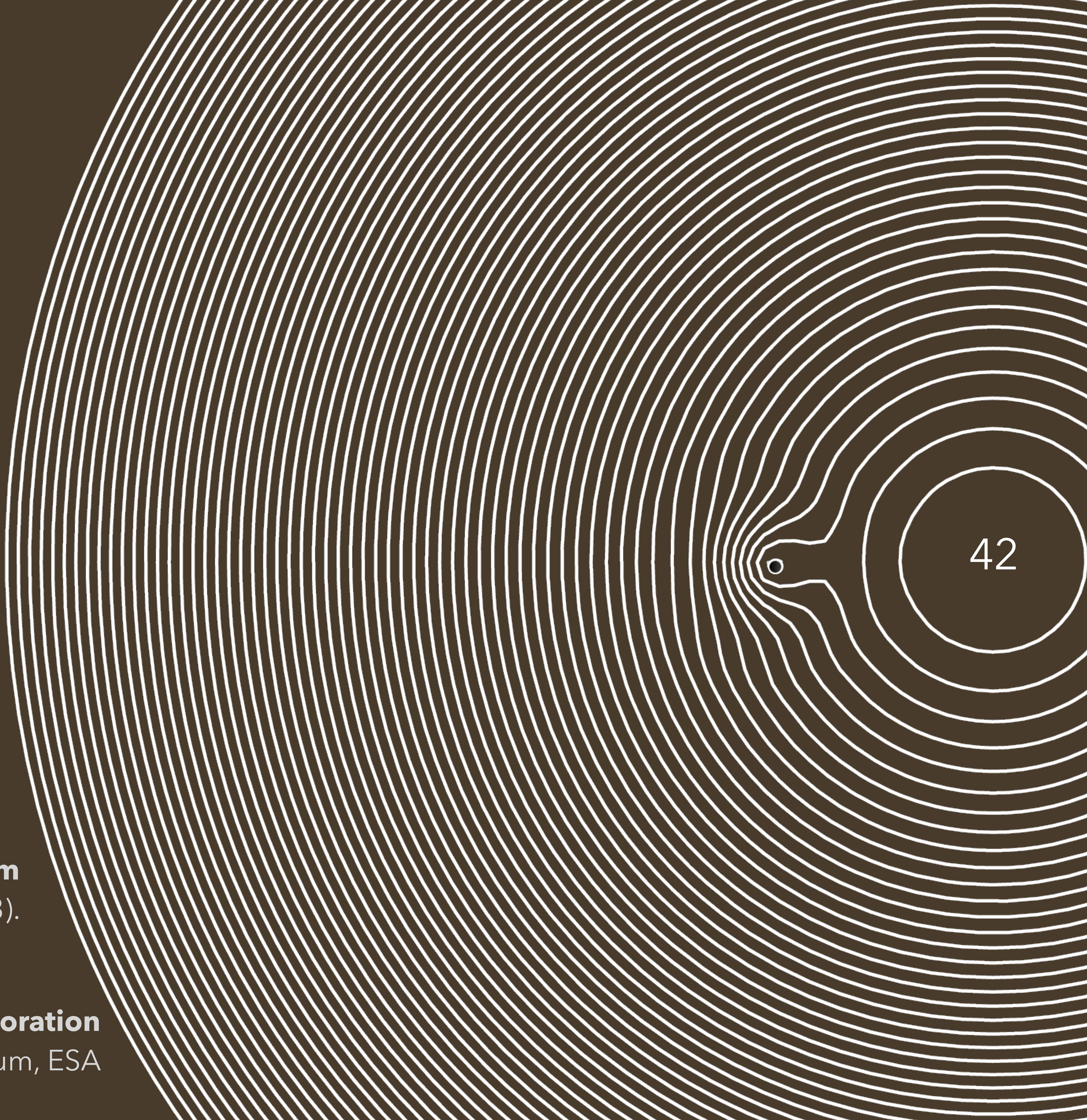
Source of Interesting Dynamics
Local Causes Lead to Non-Local ULDM Behaviour

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



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