Evolution of Mixed FDM-Baryon Systems

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Cosmology from Home (CfH23)
Online
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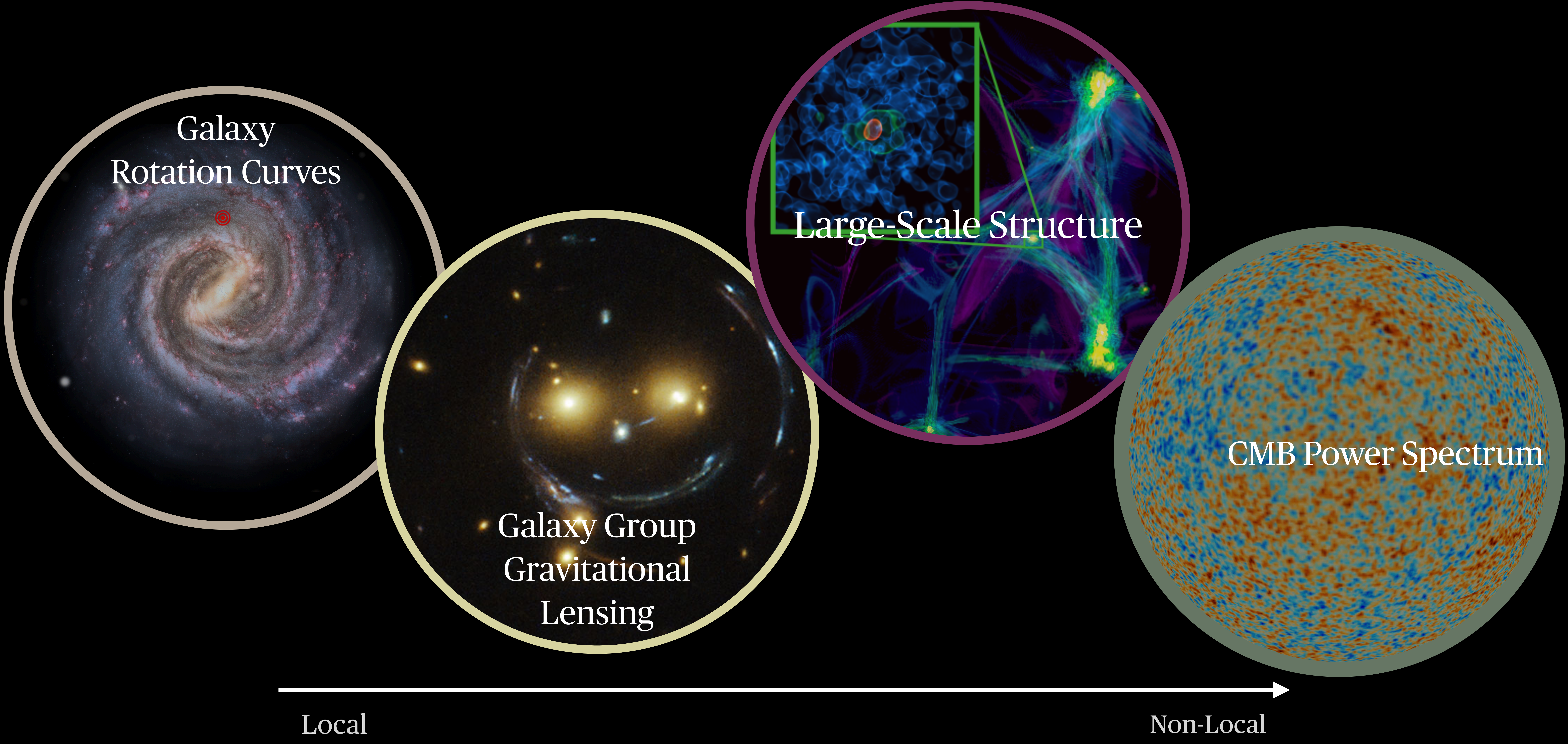
NEW ZEALAND GRAVITY

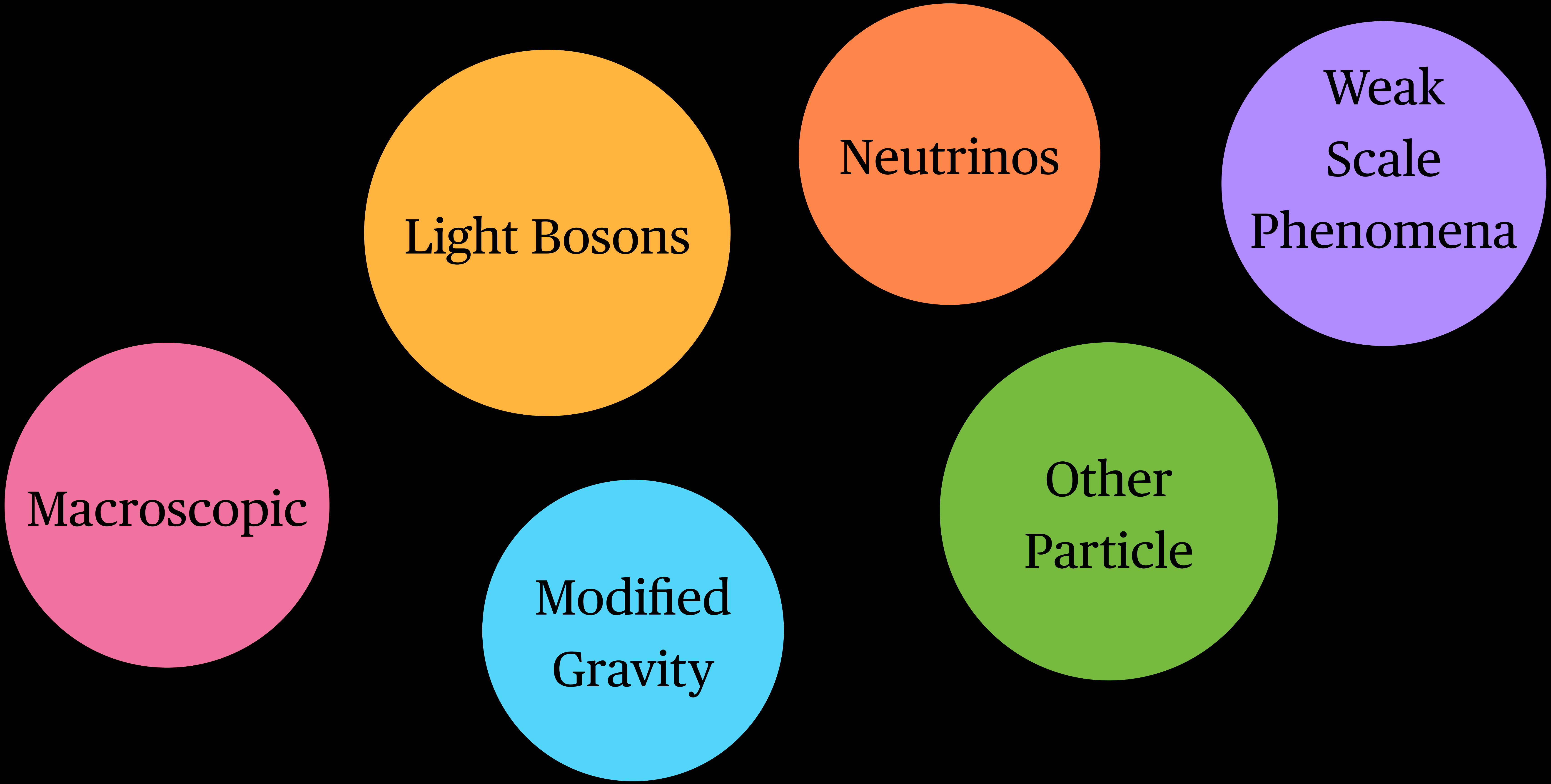
Evidence for and **Constraints** on Dark Matter



Structural Formulation Simulation by Göttingen Cosmology
CMB Anisotropy by WMAP

Dark Matter Candidates

From All Across Modern Physics



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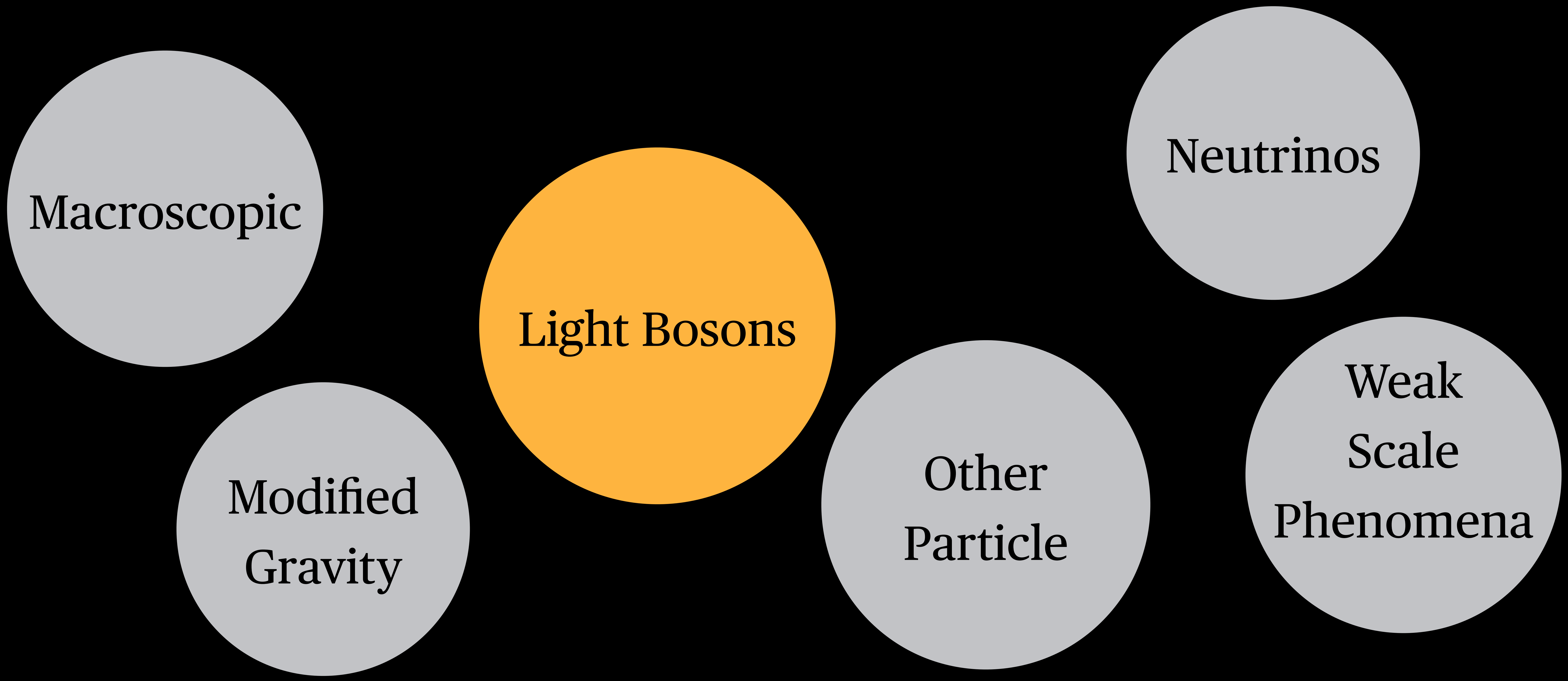

(Simplification)

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

Dark Matter Candidates

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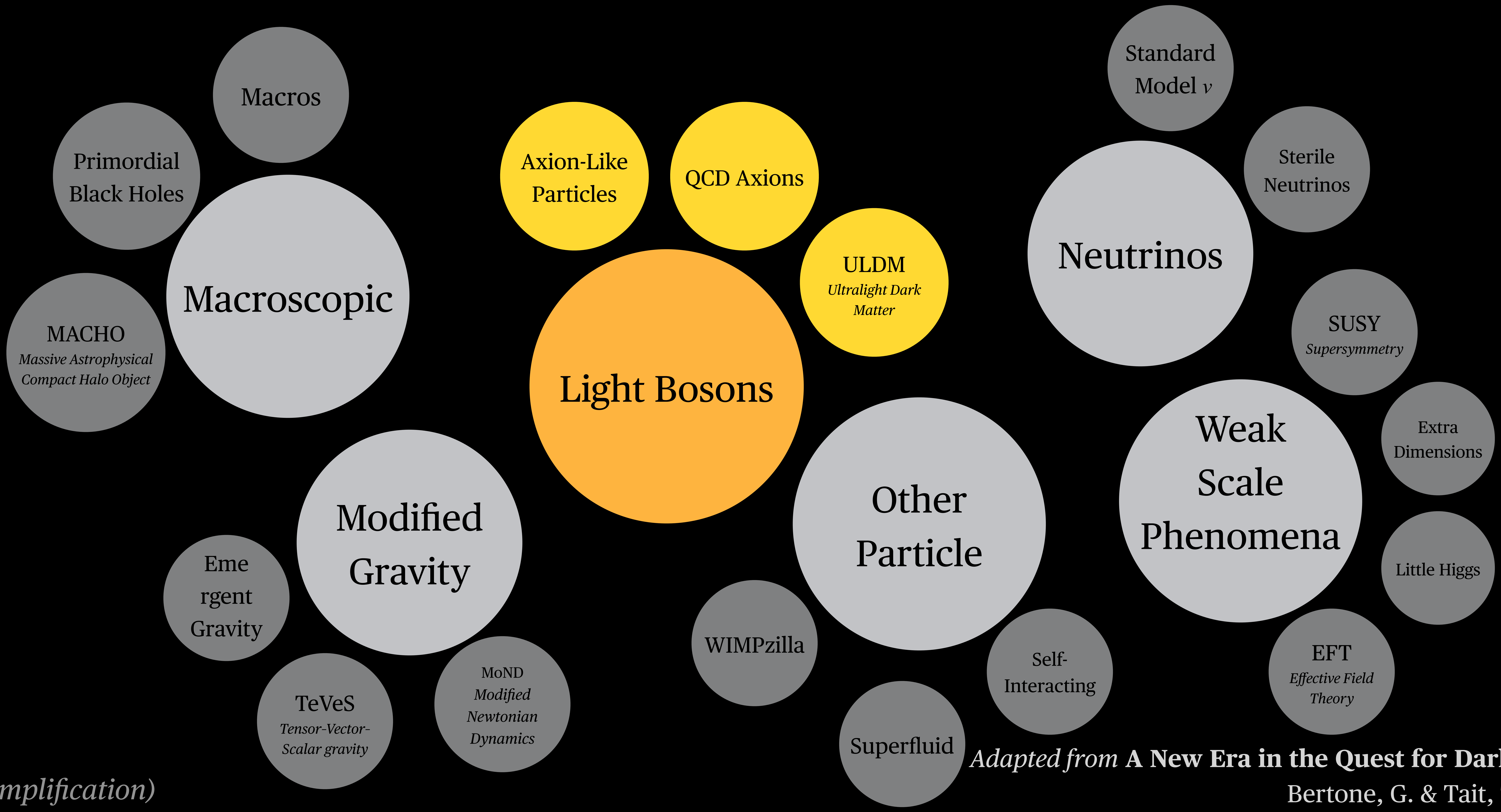

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ULDM

Ultralight Dark Matter

A bosonic scalar field **minimally coupled to gravity** with corresponding particle **mass** around **10^{-22}* eV.**

*Bounds contested between observational constraints.

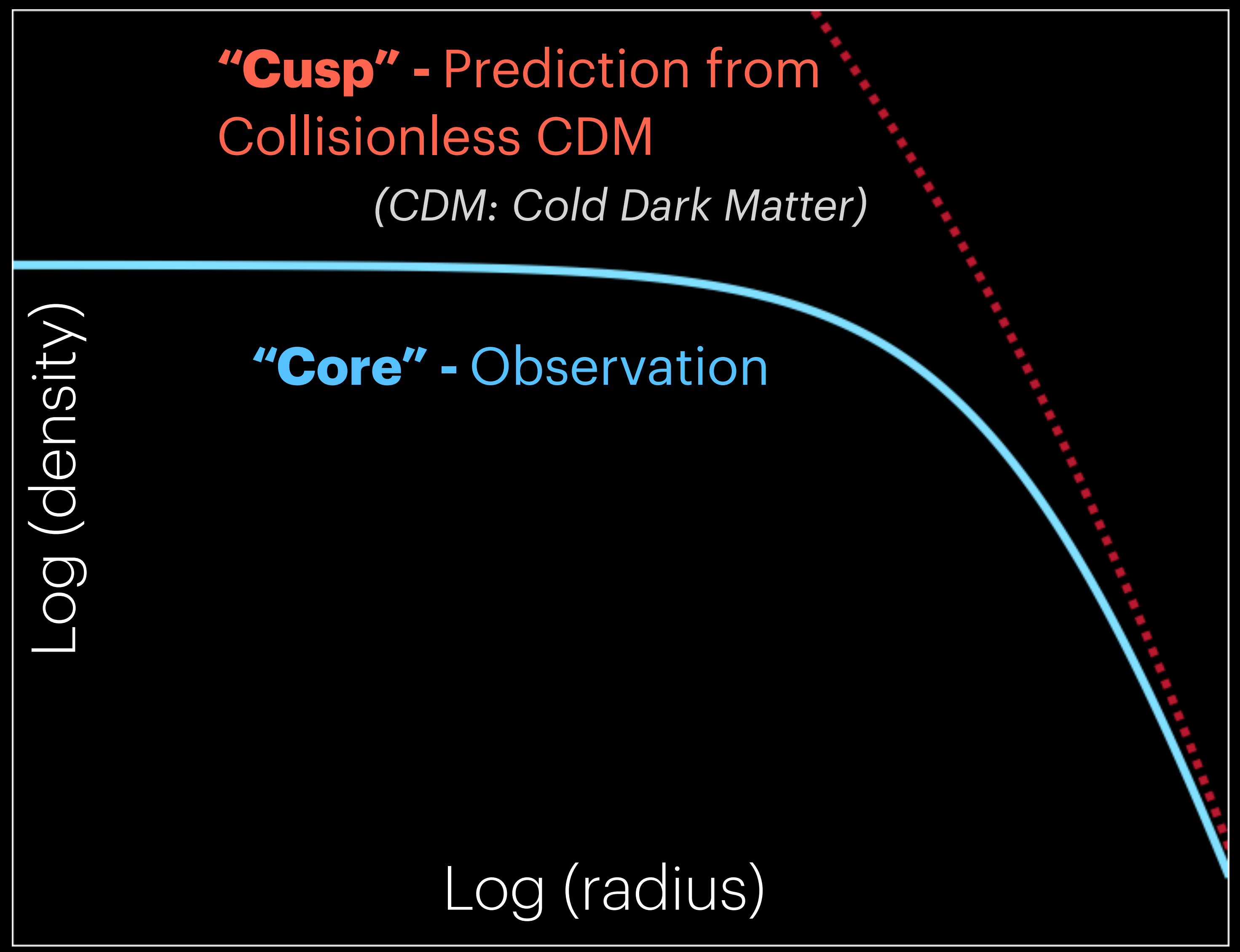
Very Long de Broglie Wavelengths

Behaviour at small scales modulated by quantum mechanics.

Lack of Direct DM Particle Detection on Earth.

Core Cusp Problem

Smooth Density Profiles in Core Regions of Galaxies



ULDM

Ultralight Dark Matter

7

NewScientist

Space

Weird dark matter waves seem to warp the light from distant galaxies

Ultralight dark matter particles that behave like waves, called axions, seem to be a better match for gravitational lensing measurements than more traditional explanations for dark matter

By Leah Crane

20 April 2023

Anomalies in Gravitational-Lensed Images Revealing Einstein Rings Modulated by Wavelike Dark Matter
arxiv 2304.09895

ULDM

Ultralight Dark Matter

8

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

9

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

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

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

10

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

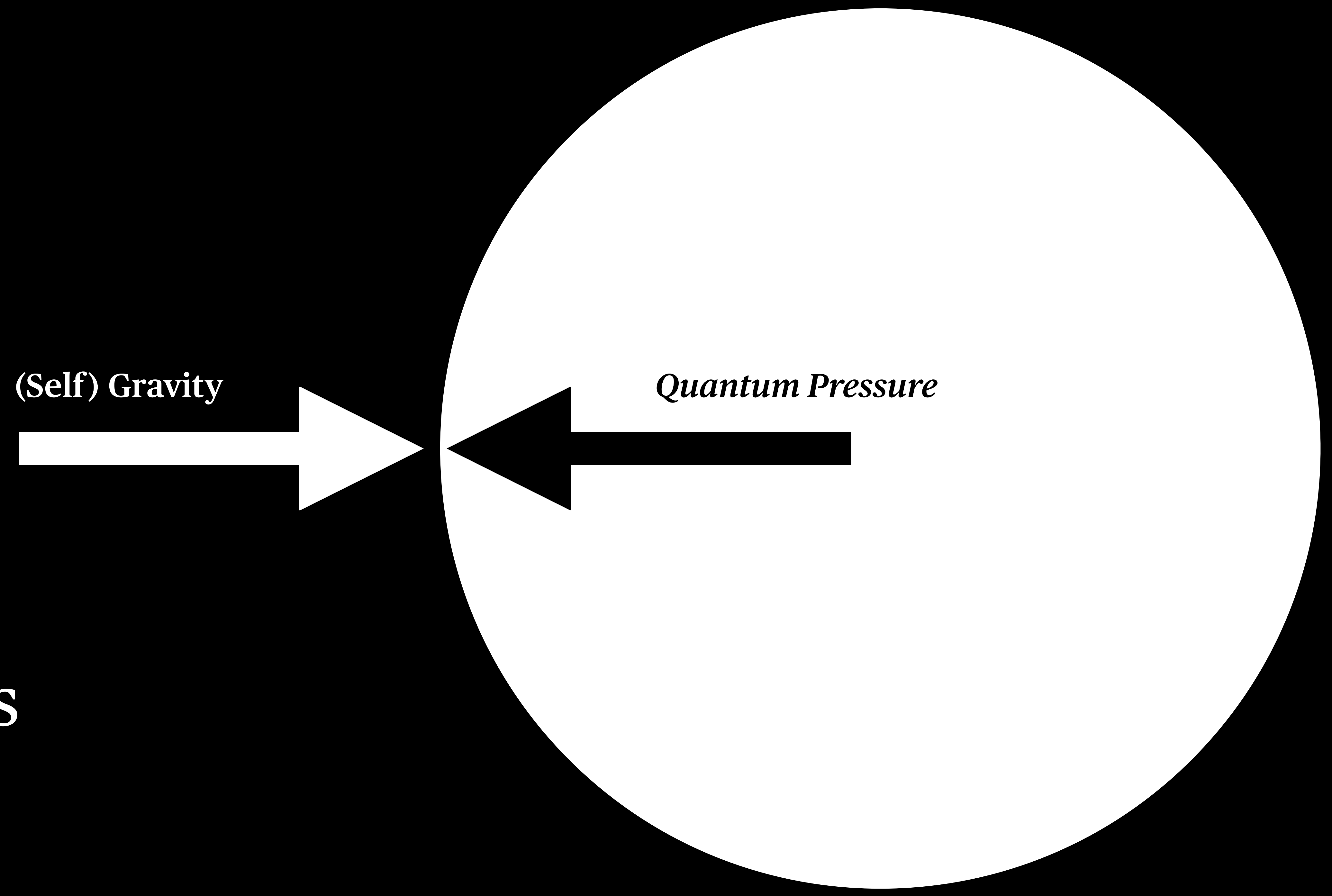
…

Schrödinger-Poisson **Solitons**

May form dynamically in ULDM haloes.

Can obtain the general radial profile numerically*.

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



Schrödinger-Poisson **Solitons**

Main object of interest in my ULDM work so far.

In isolation, we can perform quasi-normal mode decompositions on them.

Quantum pressure is rather weak, so external potentials might profoundly change the shape and dynamics of solitons.

Schrödinger-Poisson Solitons: Perturbation Theory
Zagorac et al, arXiv 2109.01920

Madelung Picture of Quantum Mechanics

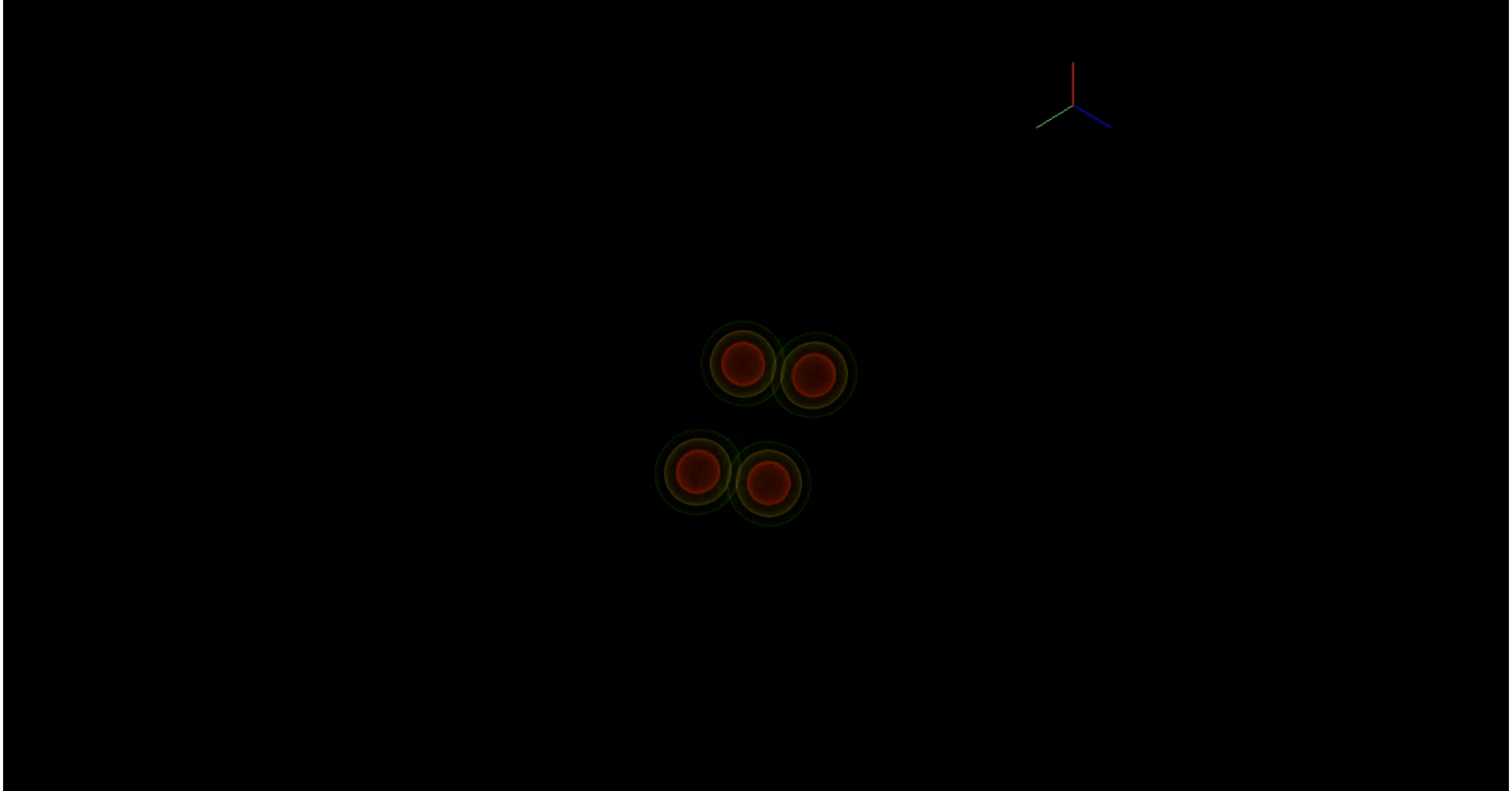
$$\psi(\mathbf{x}, t) \equiv \sqrt{\rho(\mathbf{x}, t)}\, e^{i\theta(\mathbf{x}, t)}$$

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

Power of Madelung Picture

- In some sense, we model a quantum wavefunction as a fluid.
- Can even be generalised to work in the opposite direction, i.e. to capture the dynamics of a fluid (for example, in multi-streaming CDM models) using an effective wavefunction.

Making (dark matter) waves: Untangling wave interference for multi-streaming dark matter
Gough, Uhlemann, arXiv 2206.11918



16 4 ULDM Solitons Orbiting Each Other

Caveats (?) of Madelung Picture

- Spatial resolution imposes a speed limit on all simulated FDM structures (aliasing)
- Phase (and hence momentum) information susceptible to numerical fluctuations when density is small.
- Such fields are spin-less by construction.
  - Does this mean our simulations lack some fundamental ways that ULDM can evolve or talk to their environment?

Scalar dark matter vortex stabilization with black holes
Glennon et al, arXiv 2301.13220

Schrödinger-Poisson

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

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

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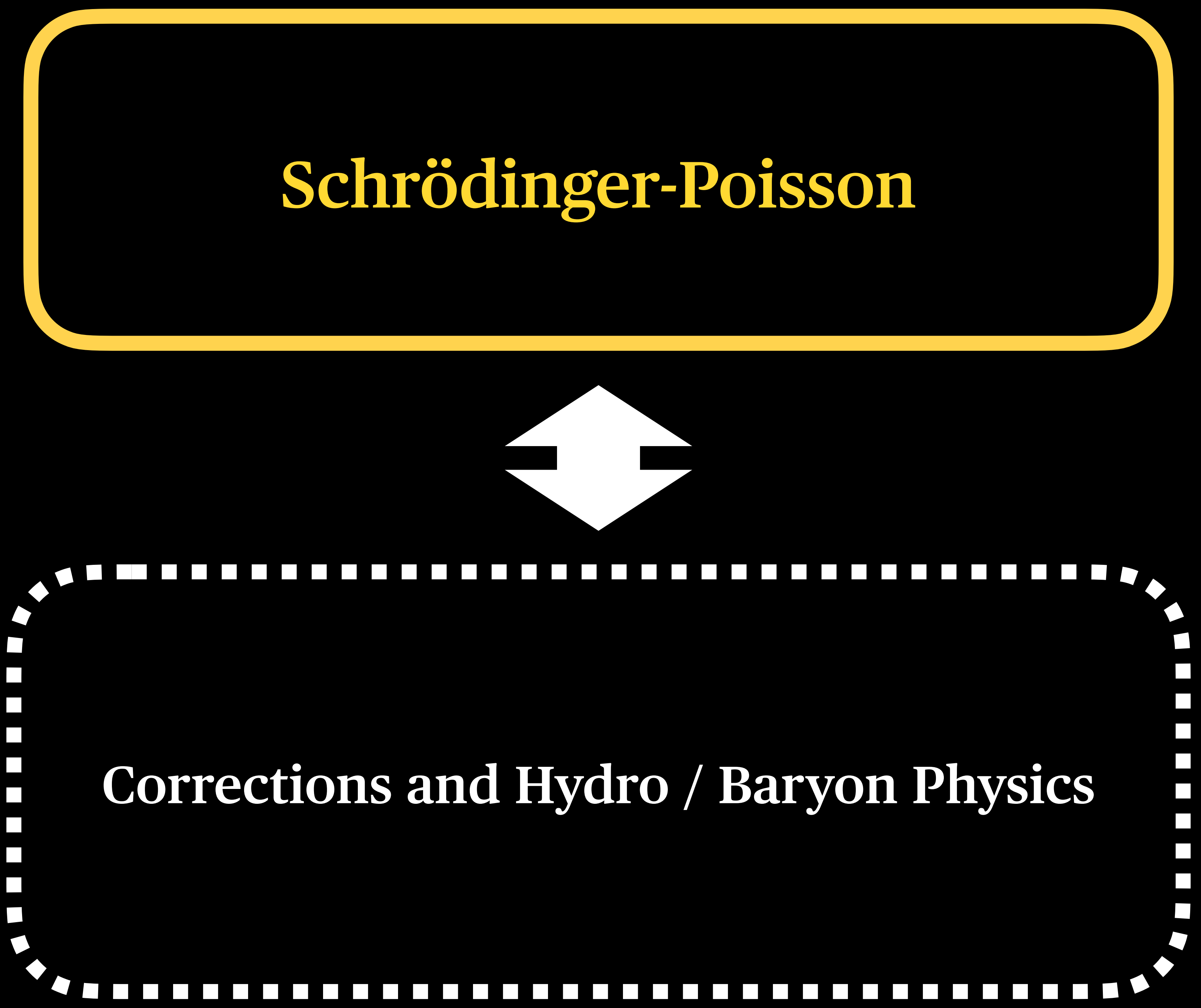
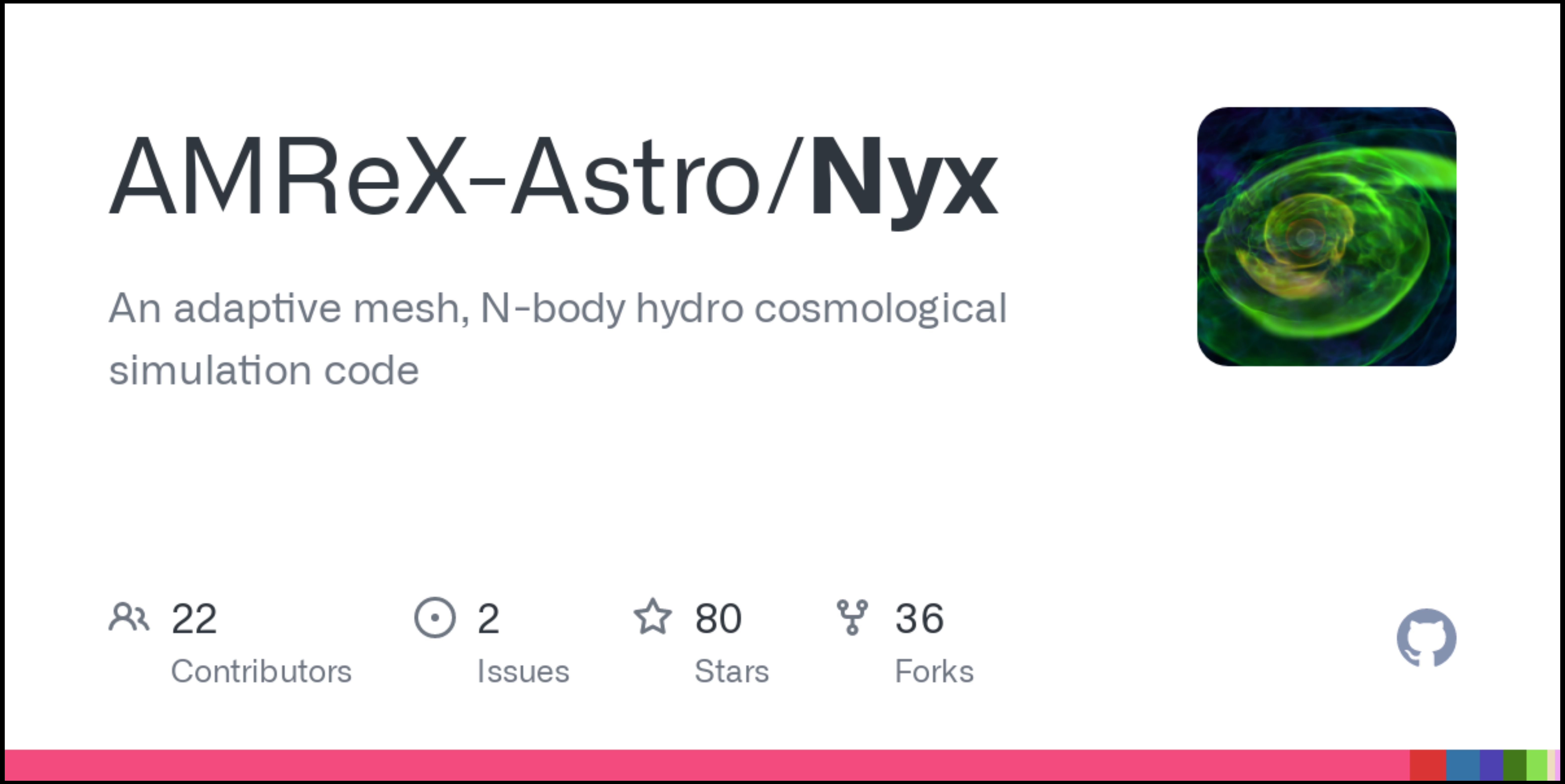


- **S-P equation** is solved on a mesh grid with either pseudo-spectral or finite difference methods.
  - Each method brings in a unique set of advantages and disadvantages (performance; features preserved or cut off).
  - Further, pseudo-spectral methods introduces periodic boundaries on the domain over which it is employed.

- Advancing spatial or temporal steps over empty space seems like a waste of compute resources.
  - Want to focus on regions of interest.

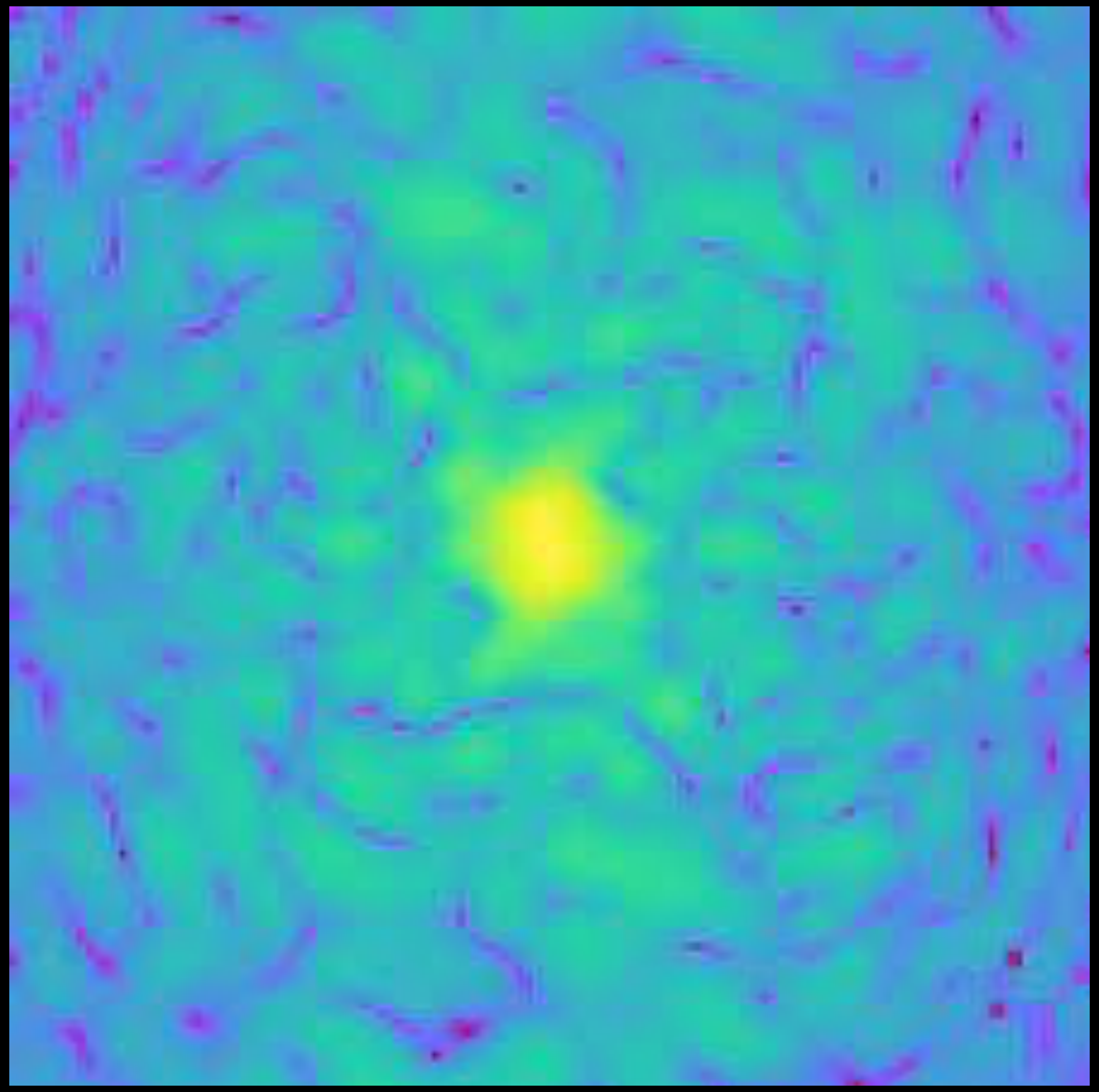
- **Overall strategy:**
  Use adaptive mesh refinement.
  FFT on the root grid, finite difference on refined grids.

Nyx



Nyx: A Massively Parallel AMR Code for Computational Cosmology
Almgren *et al.* *ApJ* 765, 39

AxioNyx



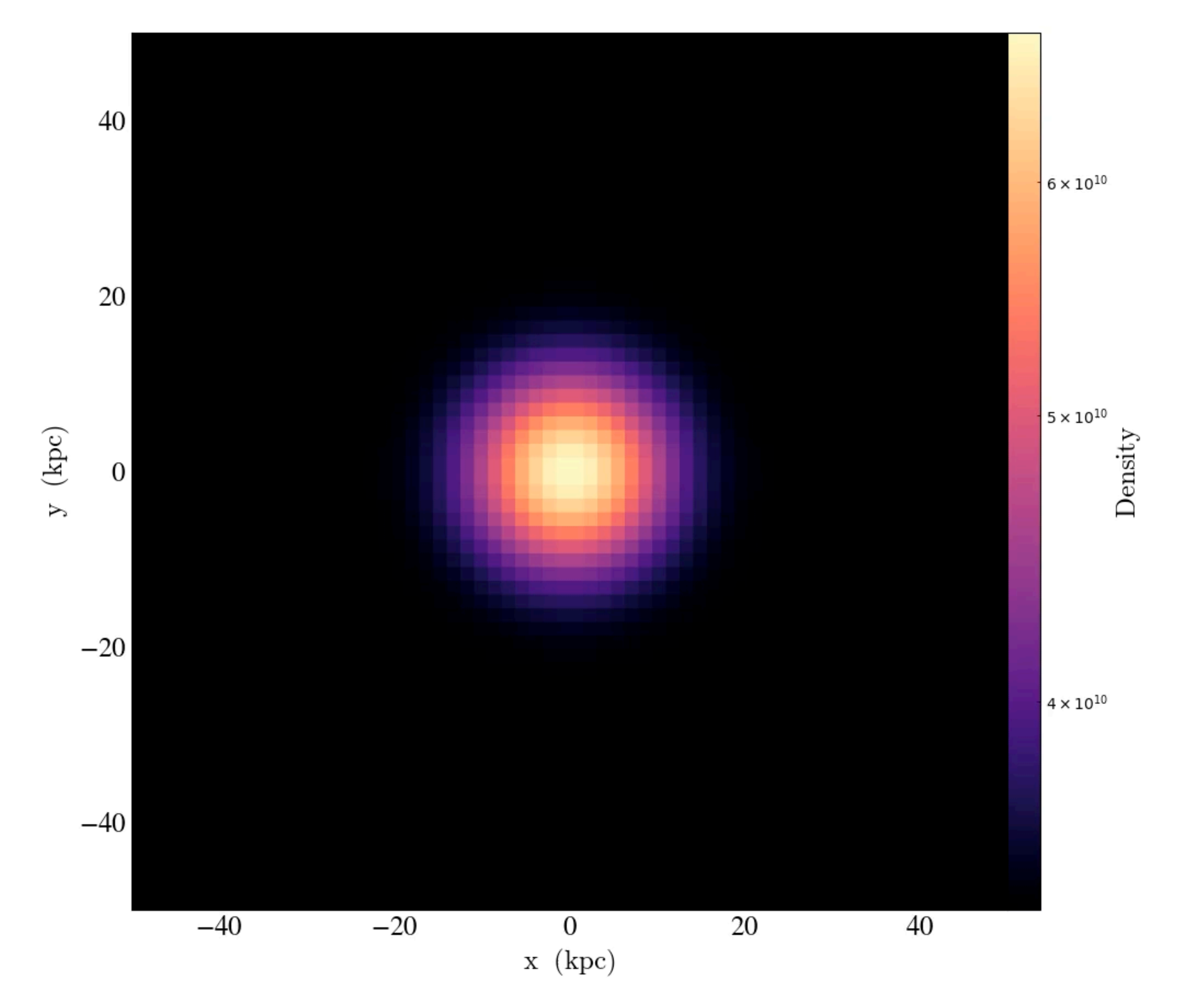
AxioNyx: Simulating Mixed Fuzzy and Cold Dark Matter
Schwabe *et al.* arXiv 2007.08256

Our Pipeline

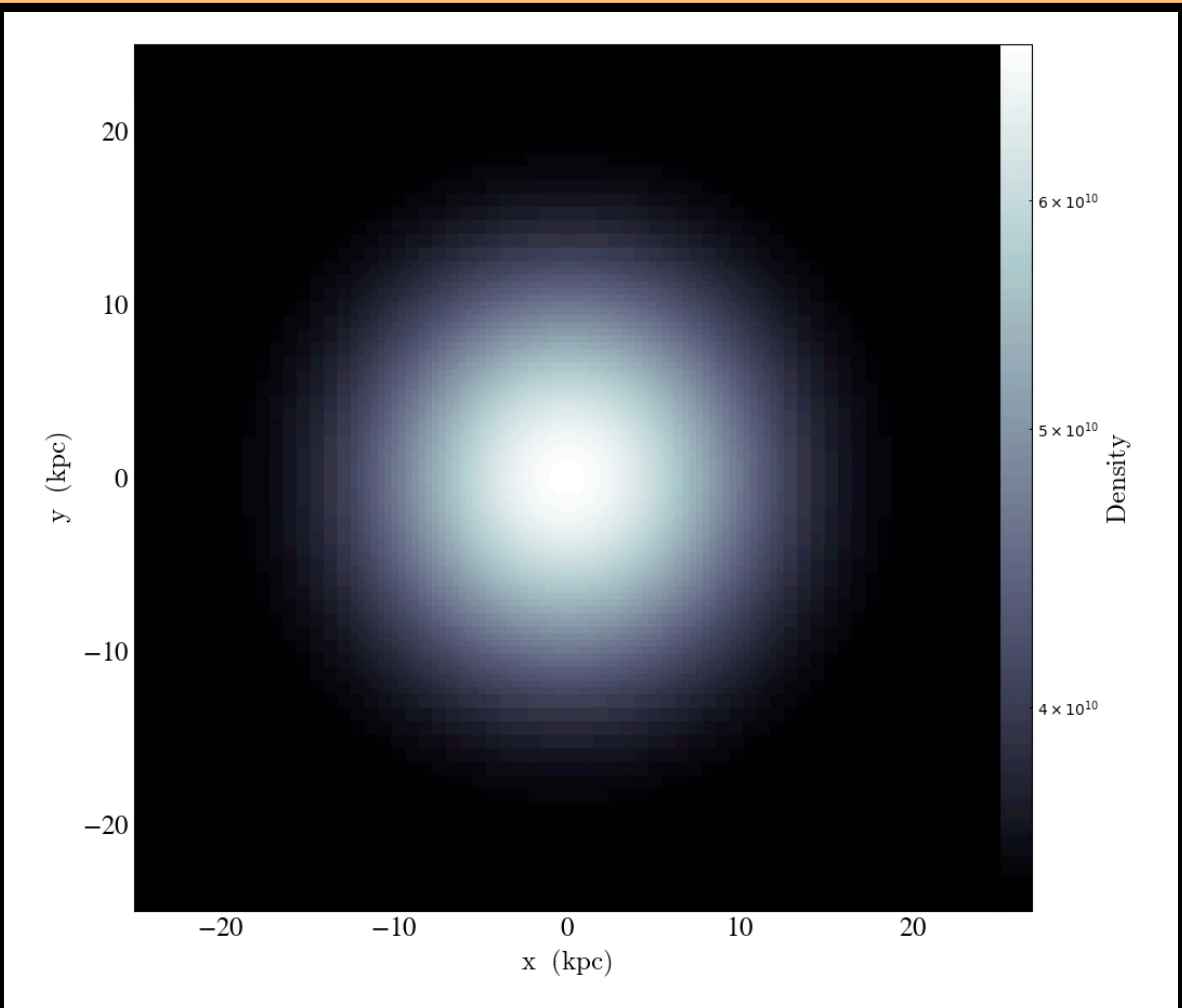
- Built upon the public version of AxioNyx 2
- Grid-based hydrodynamical code coupled to axions via gravity.
- For the moment, no radiative cooling or feedback mechanisms are implemented.
- Both systems can trigger grid refinement subject to certain criteria.
- Compatibility with other tool sets like Nyx and PyUltralight.

Spherical Collapse

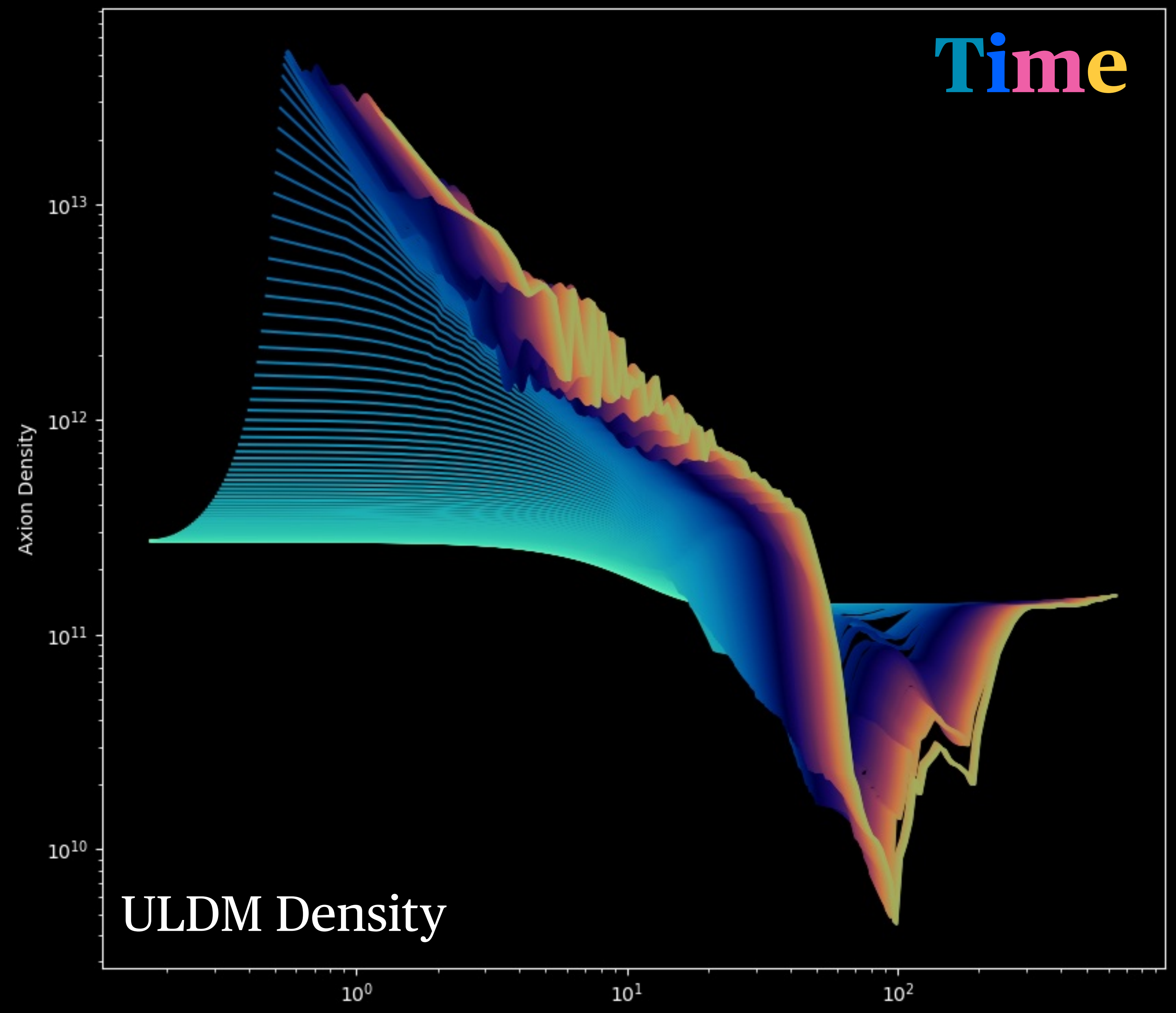
- A highly dynamical process, simulated within an expanding background.
- Take an spherically over-density of both ULDM and gas, and let the combined system evolve in time under own gravity.
- First high-resolution runs on NeSI are being conducted as we speak.

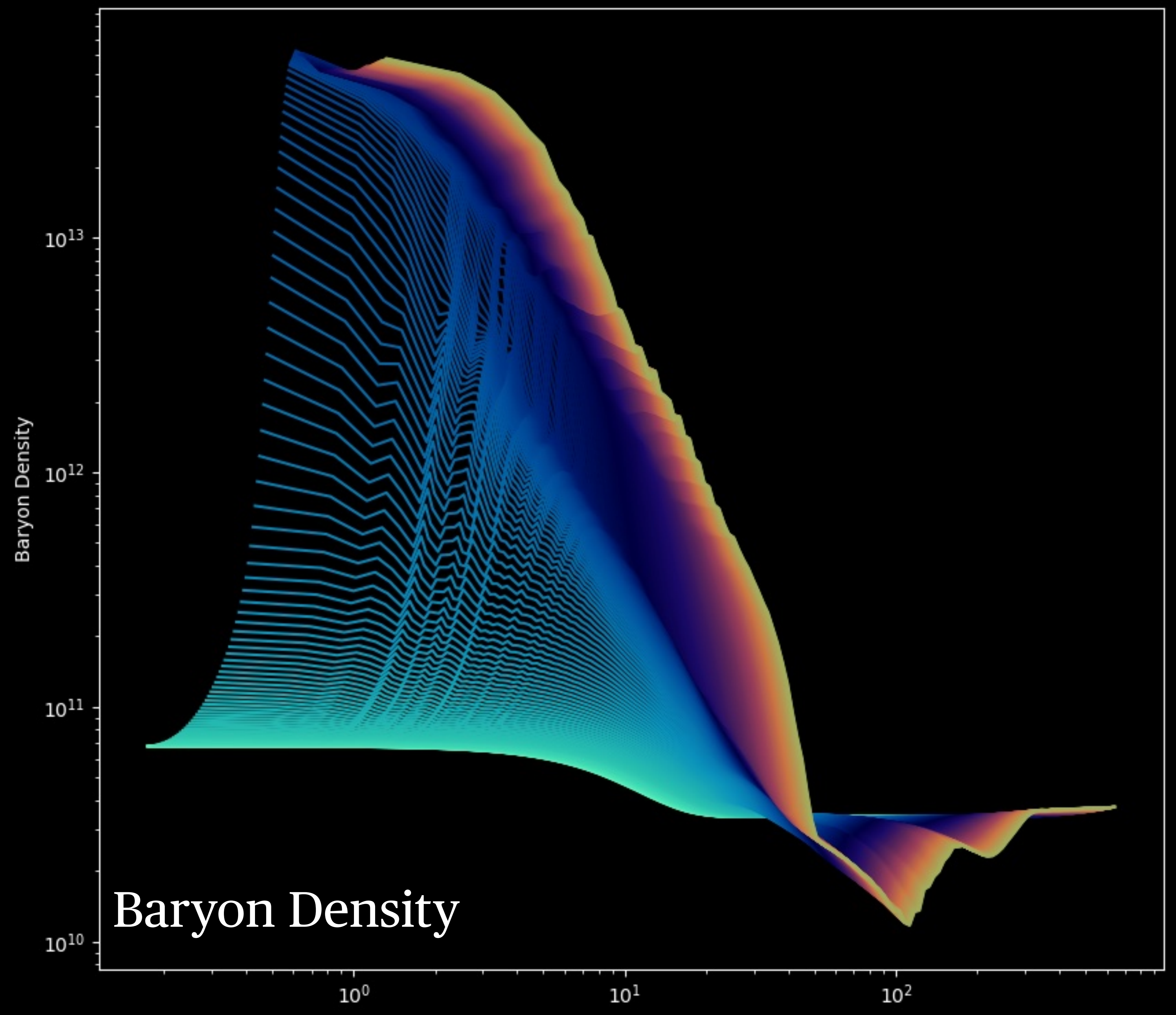


24 **Sph. Collapse: ULDM Overdensity**



25 Sph. Collapse: Gas Overdensity





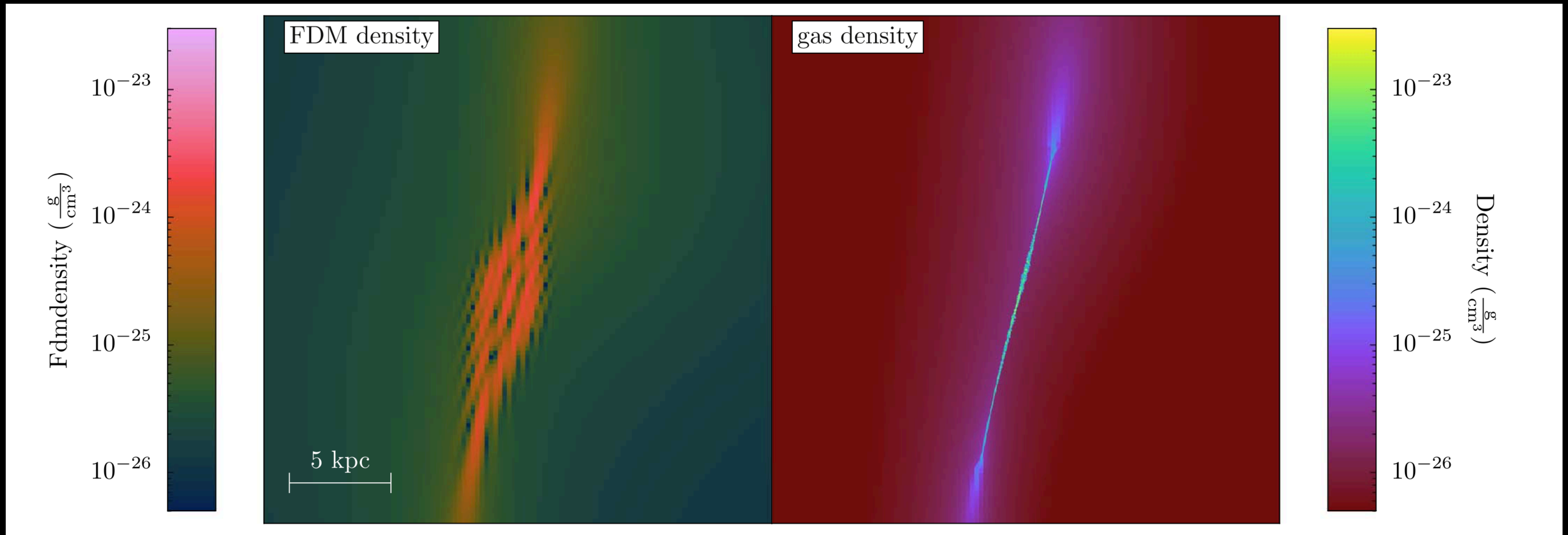
26 Sph. Collapse: Density Evolution in Time

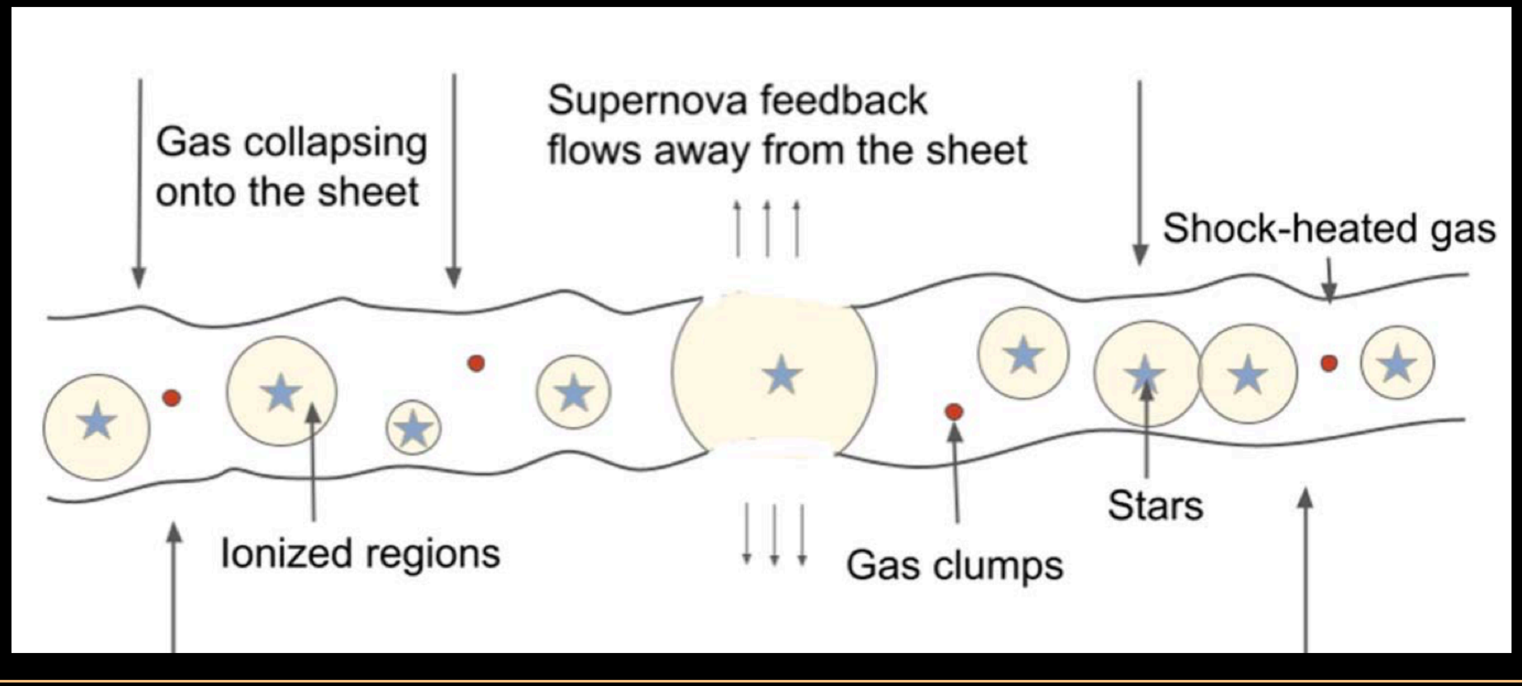
Just a Start …

- Higher resolution runs for the spherical collapse case.
- Bigger boxes with more realistic initial overdensity profiles.
- Systematically compare simulation results with ULDM-only runs
  - highlight how the system's evolution depends on baryon component.
- Implement rudimentary star formation and feedback considerations in the code.

Just a Start …

- Compare with and extend other works in this direction,e.g.





If dark matter is fuzzy, the first stars form in massive pancakes

Kulkani *et al. ApJL* 941 L18

Summary

- ULDM is an interesting dark matter candidate.
- Modelling its behaviour with a wavefunction in Madelung picture leads to a rich array of interesting dynamics.
- Coupling our ULDM simulator to hydrodynamical code is an important step in constructing testable models of ULDM properties, and bridging our predictions with astrophysics.

NeSI
New Zealand eScience Infrastructure

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