Ultralight dark matter haloes in galaxies

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Fundamentale Physik für Metrologie (FPM) PTB Braunschweig, TU Braunschweig

Durham 2026

"High Precision Experiments for Light Dark Matter"

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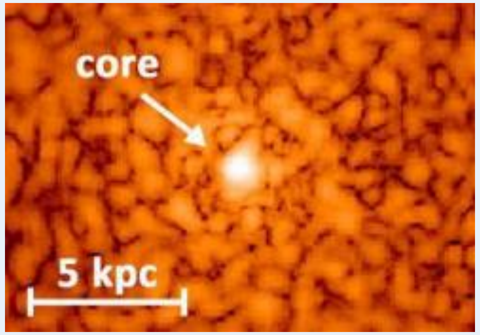
1.Ultralight dark matter (ULDM): introduction



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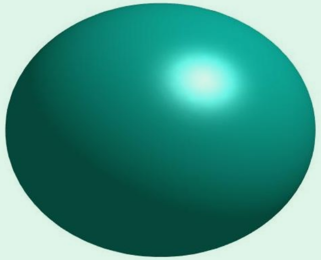

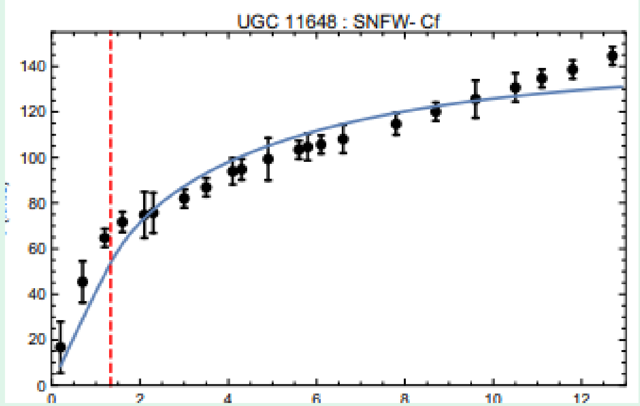

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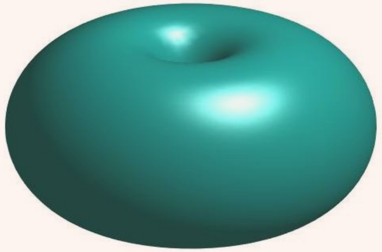

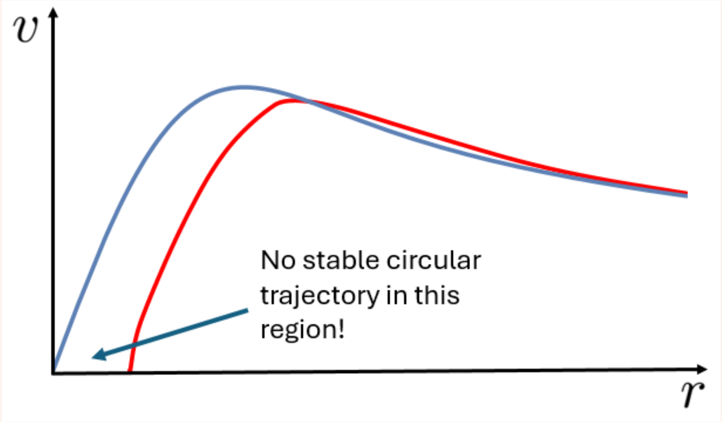

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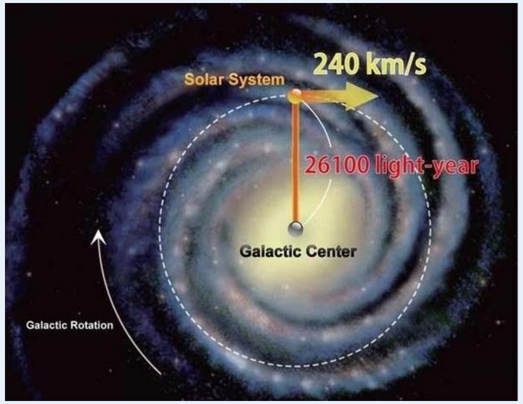

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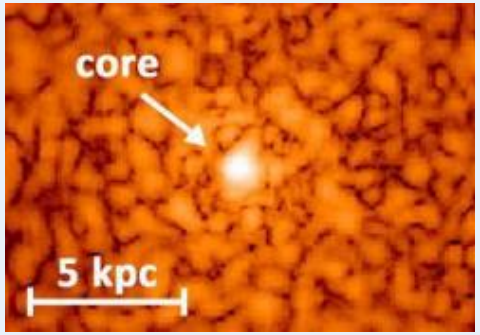

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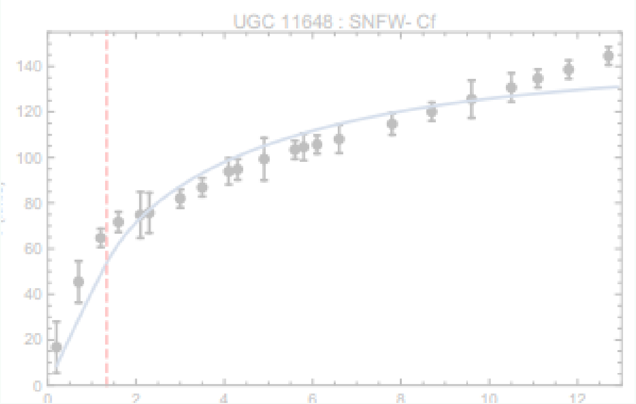

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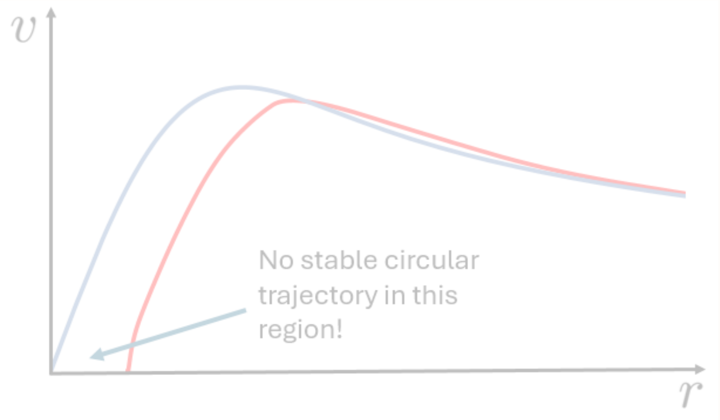

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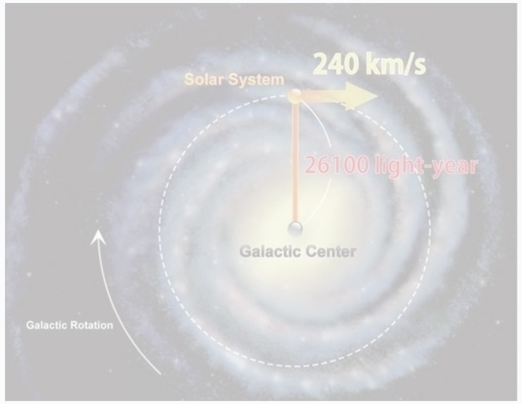
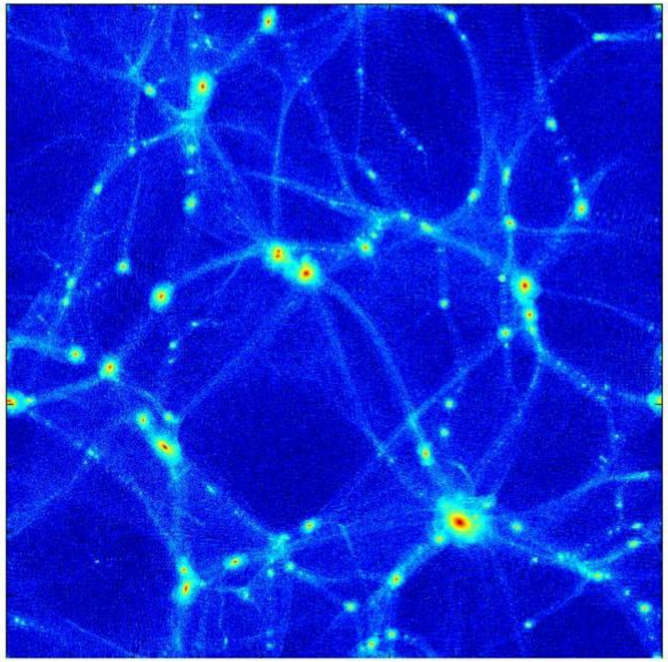


Cold dark matter (CDM)

On large scales dark matter is well-described by cold dark matter (CDM) model as a non-relativistic collisionless perfect fluid.

CDM



Hsi-Yu Schive, Tzihong Chiueh, Tom Broadhurst, NaturePhysics (2014)

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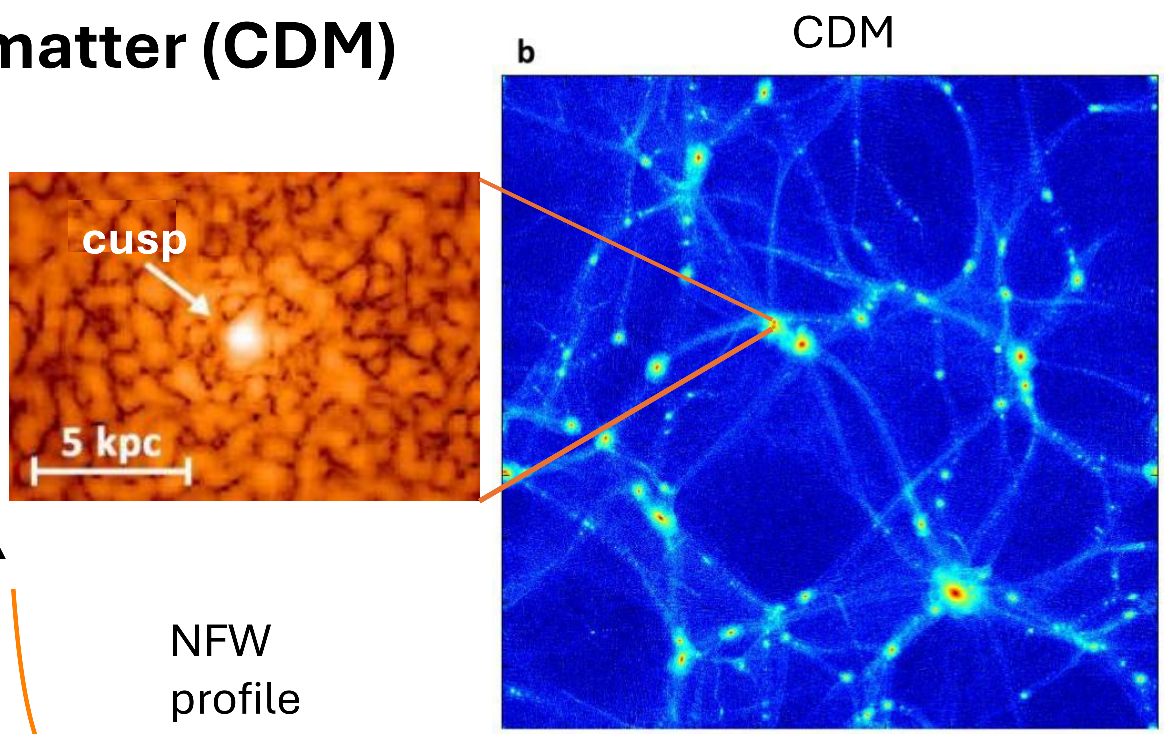

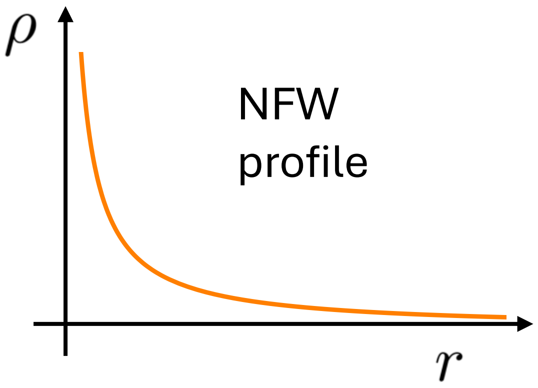

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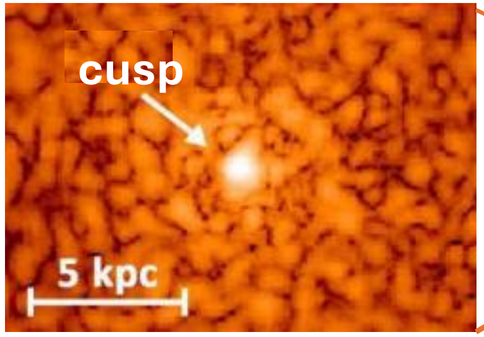

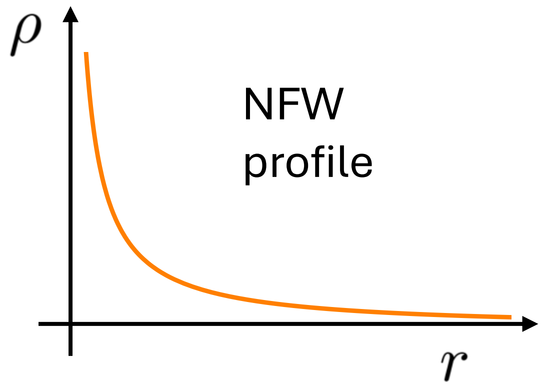

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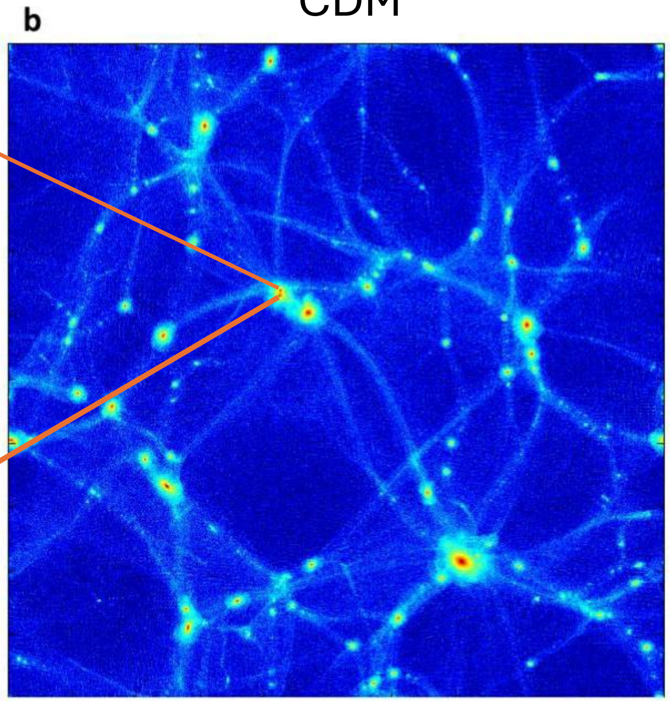

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However, within galaxies CDM description faces a few problems. These problems can be addressed with three approaches:

Include the impact of baryonic matter in galactic simulations

Introduce modified gravity, based on the scaling relations in galaxies

Account for microscopic properties of dark matter

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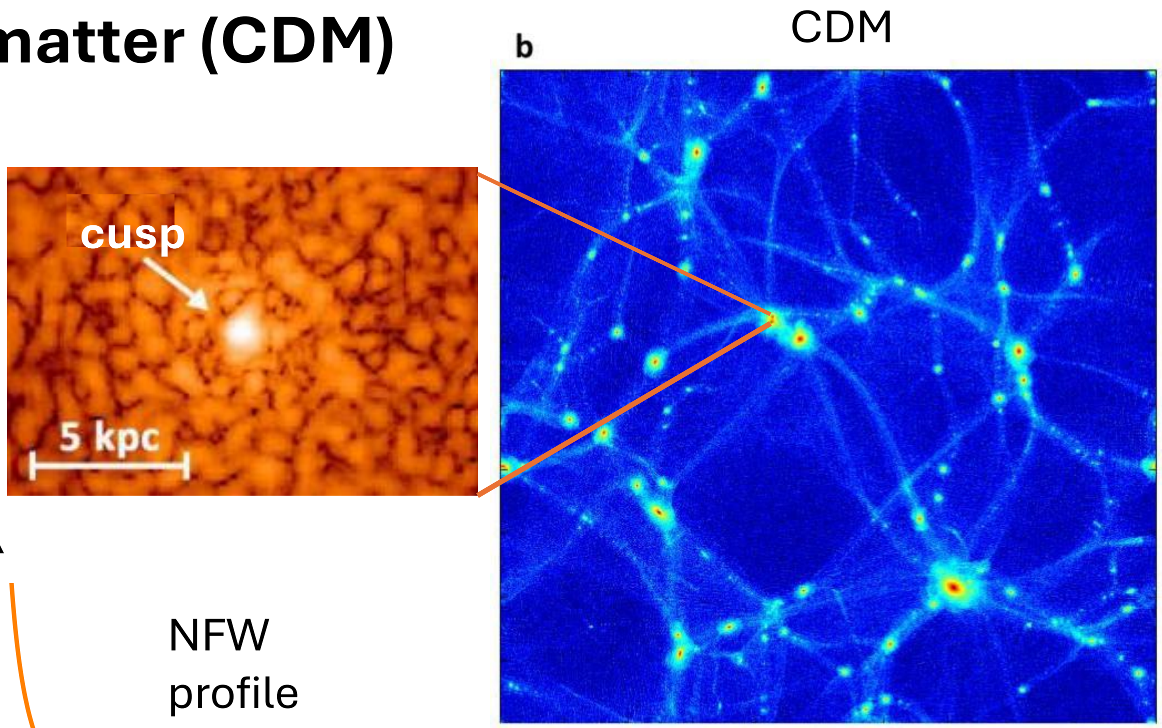

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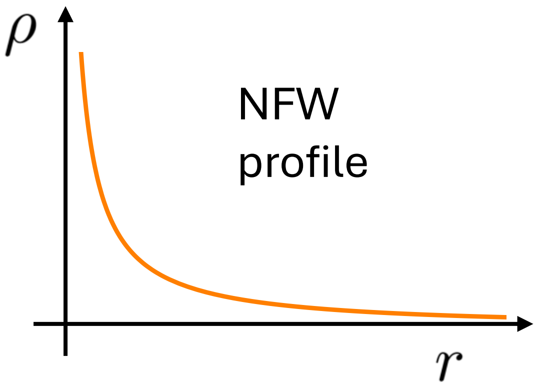

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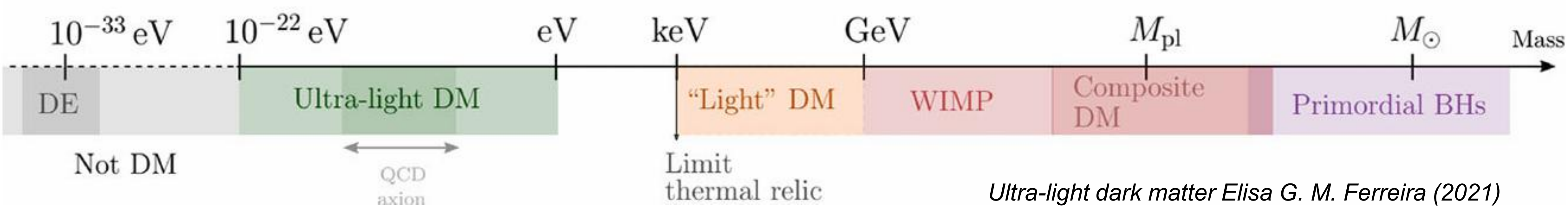
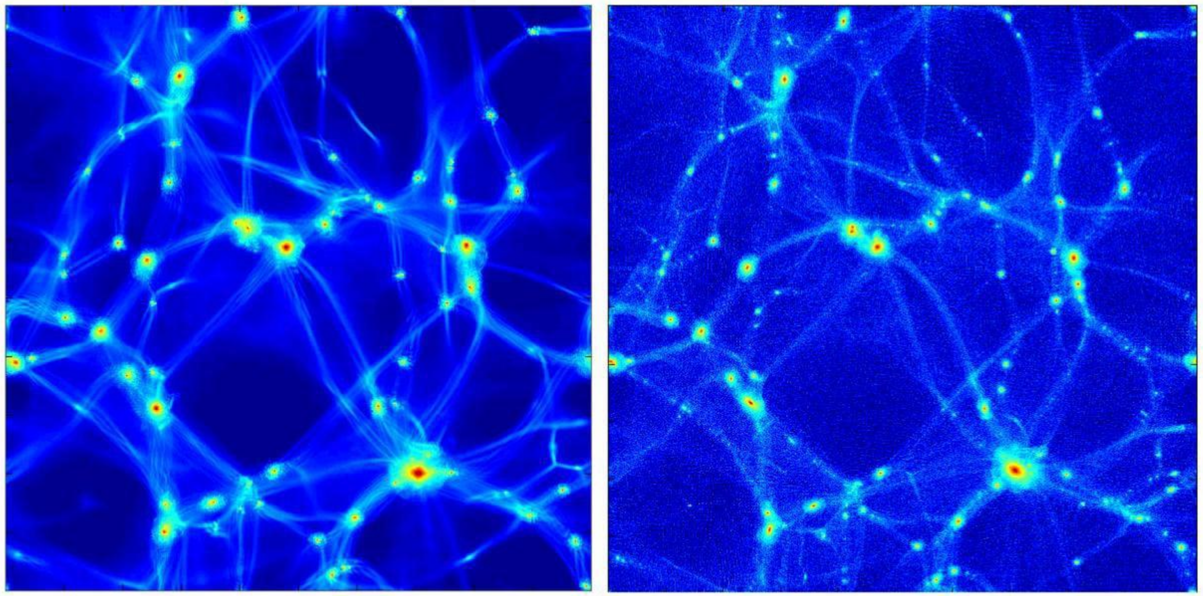


Ultra-light dark matter Elisa G. M. Ferreira (2021)

Ultralight dark matter

We assume that the DM consists of **ultralight bosons** from Standard Model extensions – axions or axionlike particles



Cosmic Structure as the Quantum Interference of a Coherent Dark Wave, Hsi-Yu Schive et al. (2014)

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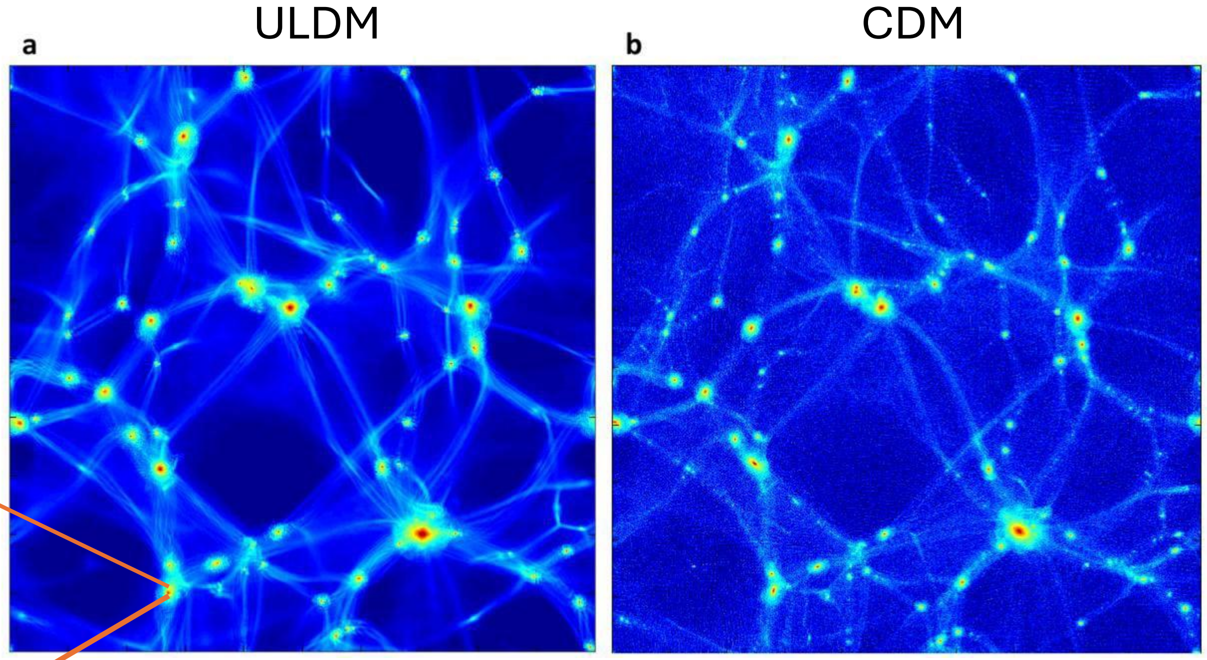

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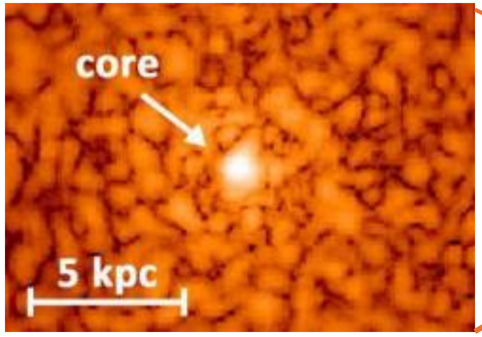

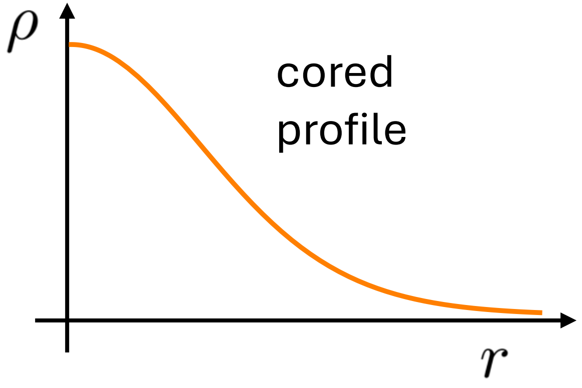

On the large scales (> galaxy) ULDM reproduces CDM, but it behaves differently on galactic scales!

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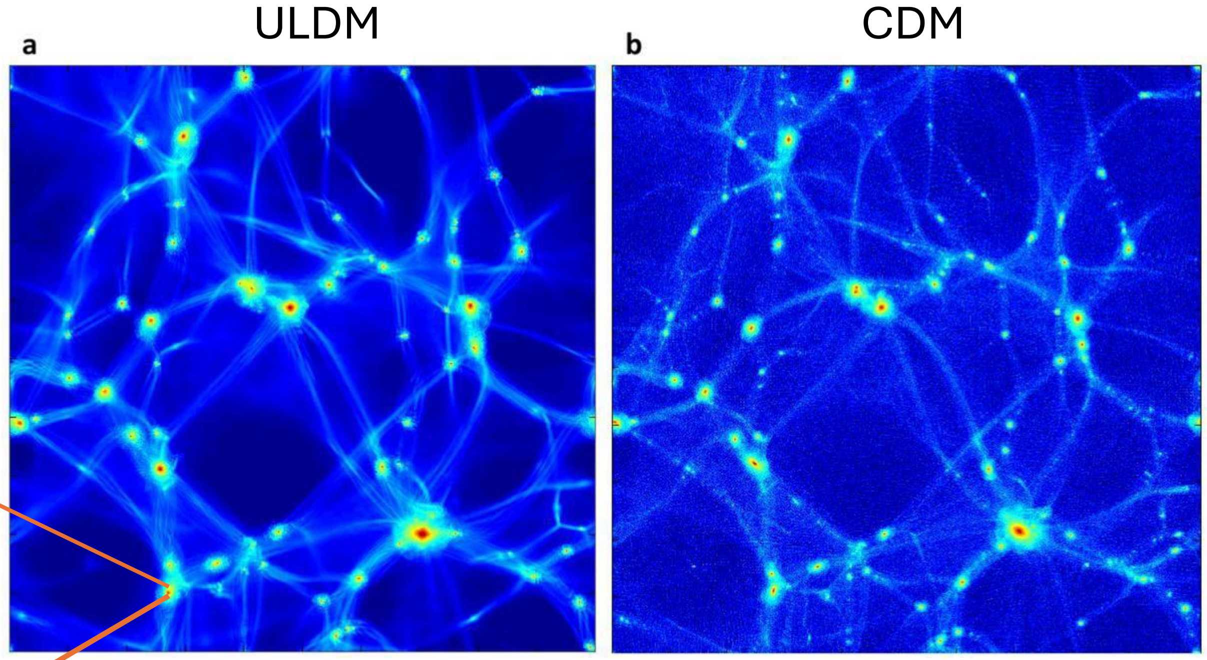

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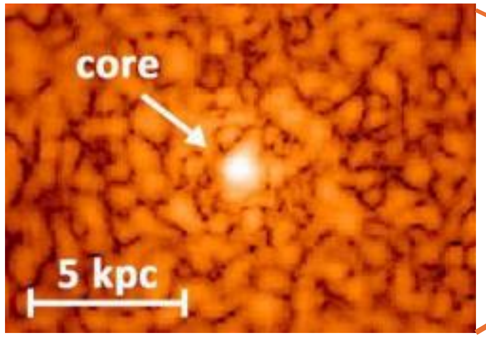

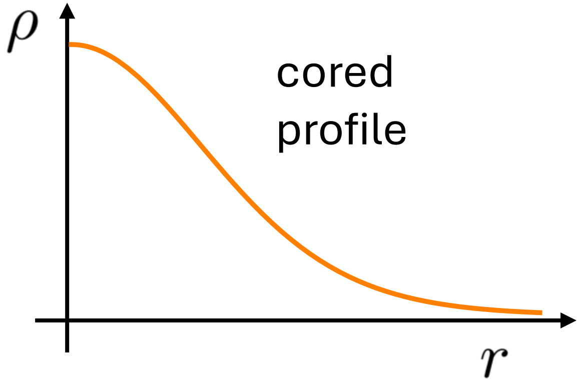

On the large scales (> galaxy) ULDM reproduces CDM, but it behaves differently on galactic scales!

Why?

GPP equations

Ultralight dark matter is described by the system of Gross-Pitaevskii-Poisson equations

$$\begin{cases} i\hbar\partial_t\psi(\mathbf{r},t) = \left(-\frac{\hbar^2}{2m}\Delta + m\Phi(\mathbf{r},t) + gN|\psi(\mathbf{r},t)|^2\right)\psi(\mathbf{r},t) \\ \Delta\Phi(\mathbf{r},t) = 4\pi G m N|\psi(\mathbf{r},t)|^2 \end{cases}$$

P.-H. Chavanis, Quantum Aspects of Black Holes, 151 (2015)

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Names in literature: BECDM, ψDM, ULDM, wave DM, fuzzy DM (FDM)

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Extremely small boson mass: $m \sim 10^{-22}\ \mathrm{eV}/c^2 \rightarrow \lambda \sim 1\ \mathrm{kpc}$

Huge occupation numbers: $\dfrac{10^8 M_\odot}{10^{-22}\ \mathrm{eV}/c^2} \sim 10^{96}$

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Let's transform GPP to equivalent hydrodynamic equations

$\psi = |\psi| e^{\frac{i}{\hbar}S(\mathbf{r},t)}$ $\quad\rho = mN|\psi|^2$ - density $\quad\mathbf{u} = \frac{1}{m}\nabla S$ - velocity

$$\partial_t\rho + \nabla(\rho\mathbf{u}) = 0$$

$$\partial_t\mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p - \nabla\Phi - \frac{1}{m}\nabla Q$$

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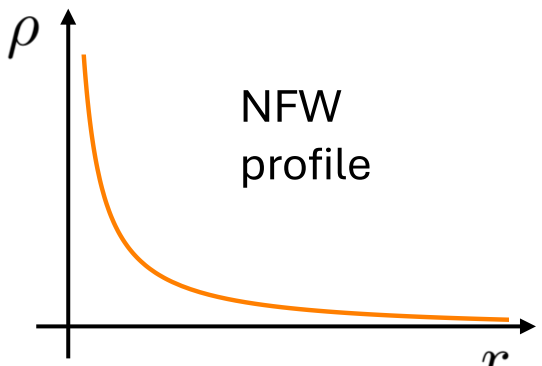
Absent in the case of CDM!

CDM is pressureless, but ULDM is not, since it has

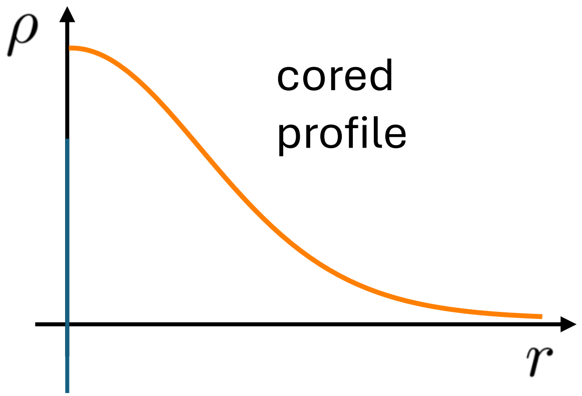
- quantum pressure $$Q = -\frac{\hbar^2}{2m}\frac{\Delta\sqrt{\rho}}{\sqrt{\rho}}$$
- pressure due to self-interaction $$p = \frac{g}{2m^2}\rho^2$$

Ultralight boson and halo structure

CDM: gravity attracts matter to the center



ULDM: quantum pressure and self-interaction (if present) counteract gravity



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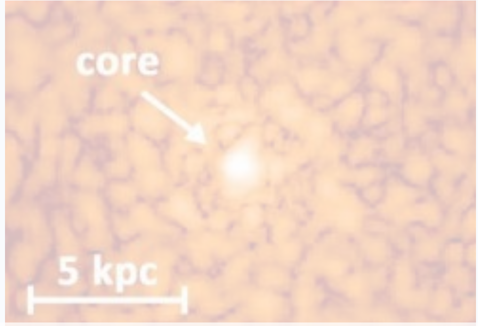

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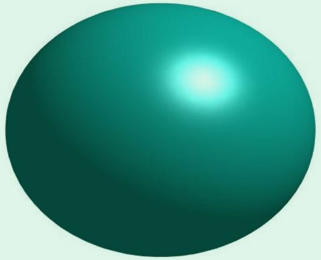

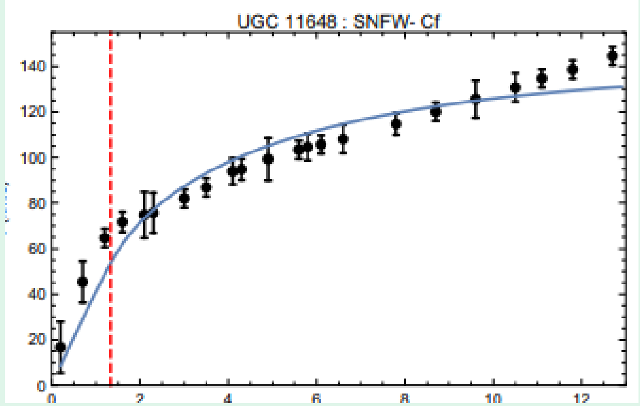

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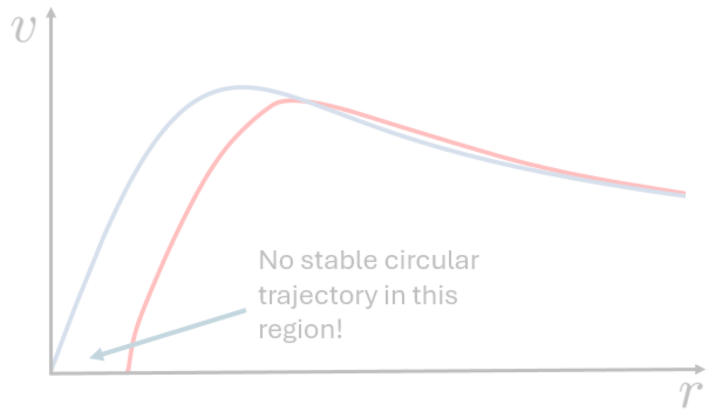

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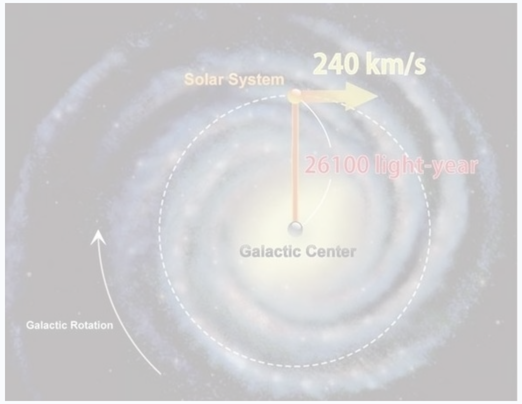

Simple model to describe a ULDM core

One can fit the numerical solution of the GPP equations

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„Understanding the Core-Halo Relation of Quantum Wave Dark Matter from 3D Simulations" H.-Y. Schive et al. 2014

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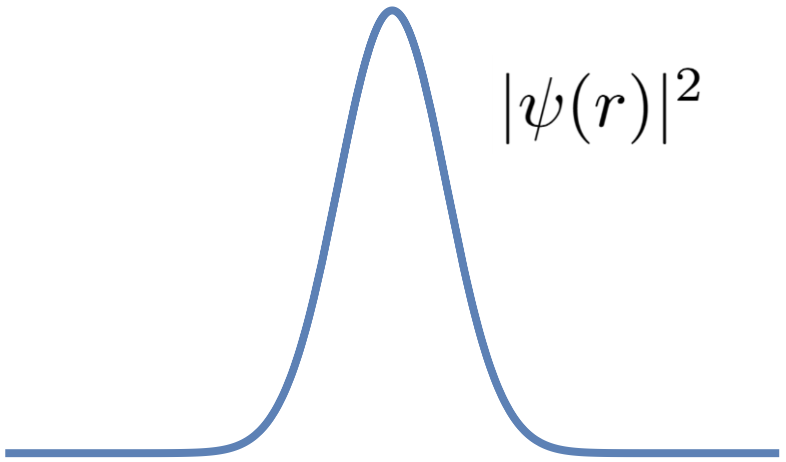
A complementary approach: variational ansatz

$$\boxed{\psi(\mathbf{r},t) = \frac{\sqrt{M}}{\pi^{3/4}R^{3/2}}e^{-r^2/(2R^2)+i\beta r^2}}$$

variational parameters

$$S_{\mathrm{GPP}} = \frac{1}{m}\int dt\int d\mathbf{r}\,\psi^*\left[i\hbar\frac{\partial}{\partial t} + \frac{\hbar^2}{2m}\nabla^2 - \frac{m}{2}\Phi\right]\psi$$



Chavanis P. Phys Rev D (2011)

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$$\begin{cases} \beta = \dfrac{m}{2\hbar}\dfrac{\dot{R}}{R} \\ \ddot{R} - \underbrace{\dfrac{\hbar^2}{m^2}\dfrac{1}{R^3}}_{\text{quantum pressure}} + \underbrace{\dfrac{\sqrt{2}}{3\sqrt{\pi}}\dfrac{GM}{R^2}}_{\text{gravity}} = 0 \end{cases}$$

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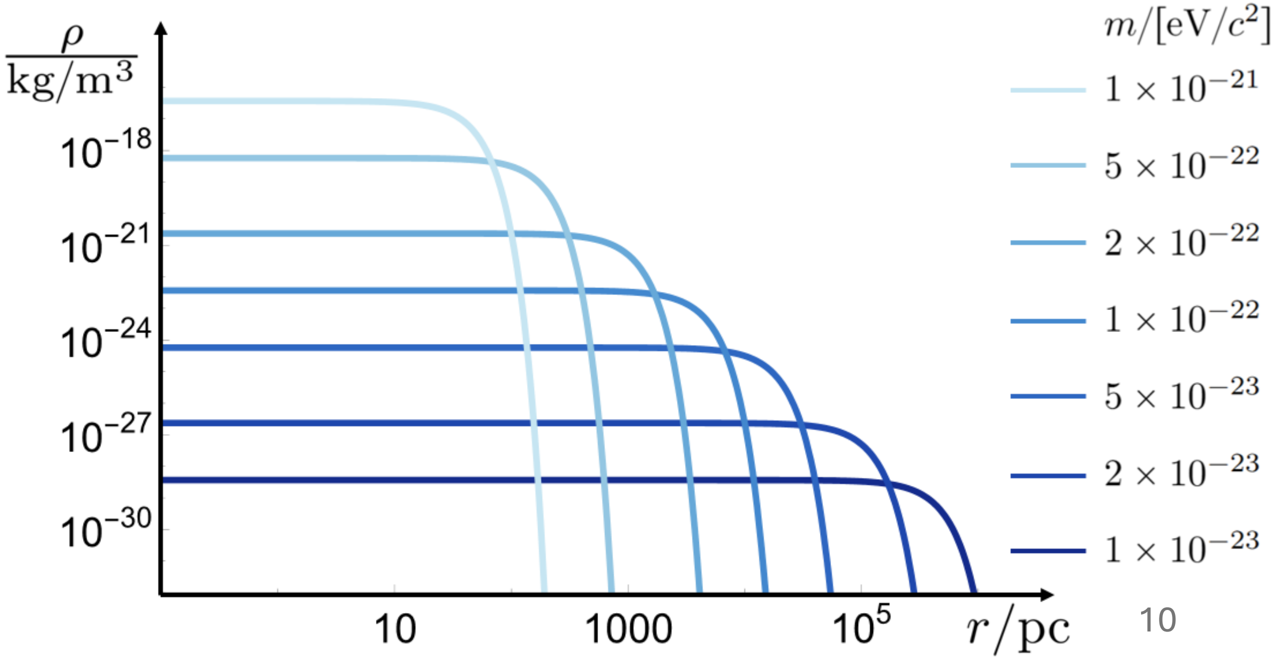
*CDM limit: nothing would counteract gravity and we would get $R \to 0$

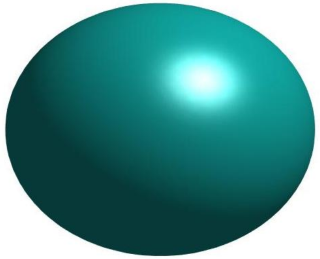
Equilibrium stationary solution: $\dot{R} = 0,\ \beta = 0$

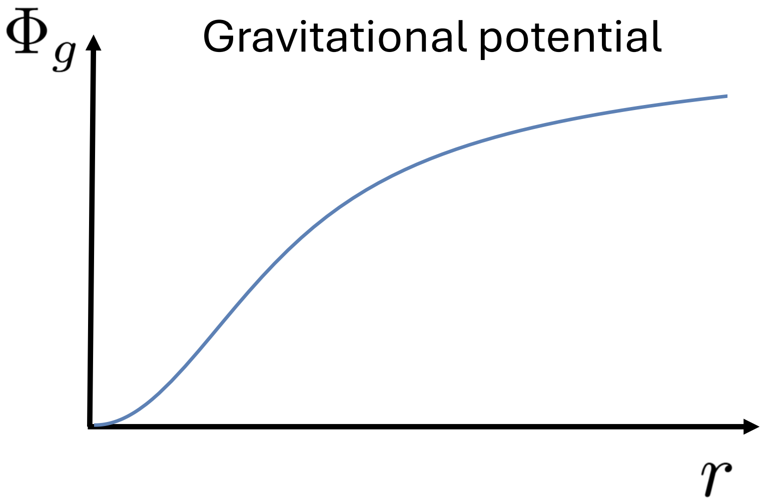
$$R = \frac{3\sqrt{\pi}}{\sqrt{2}}\frac{\hbar^2}{GMm^2}$$

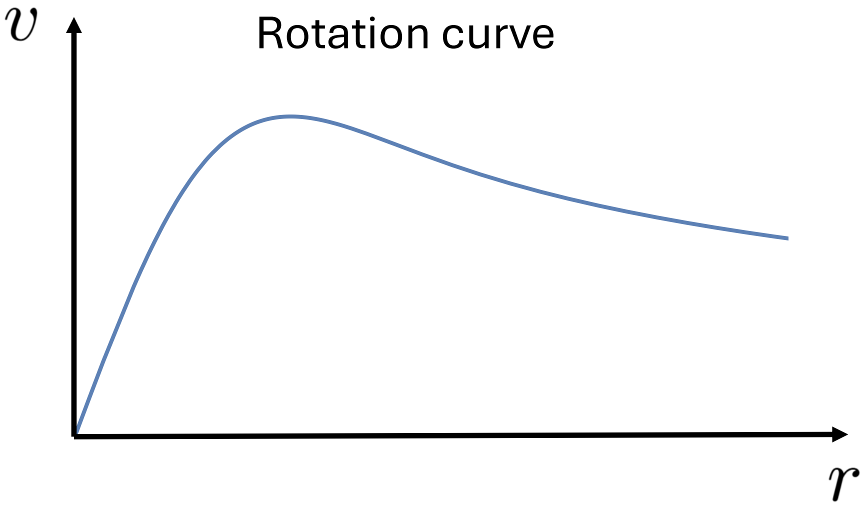


Rotation curves

ULDM soliton







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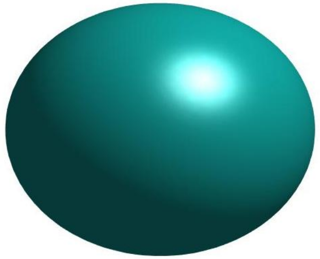
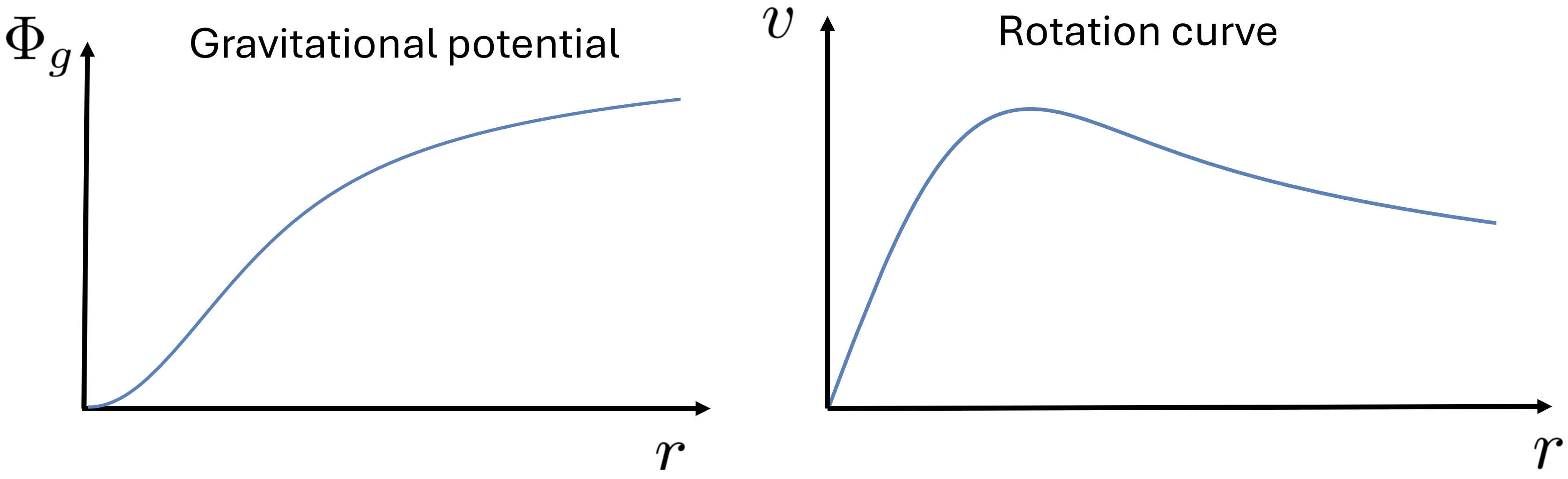
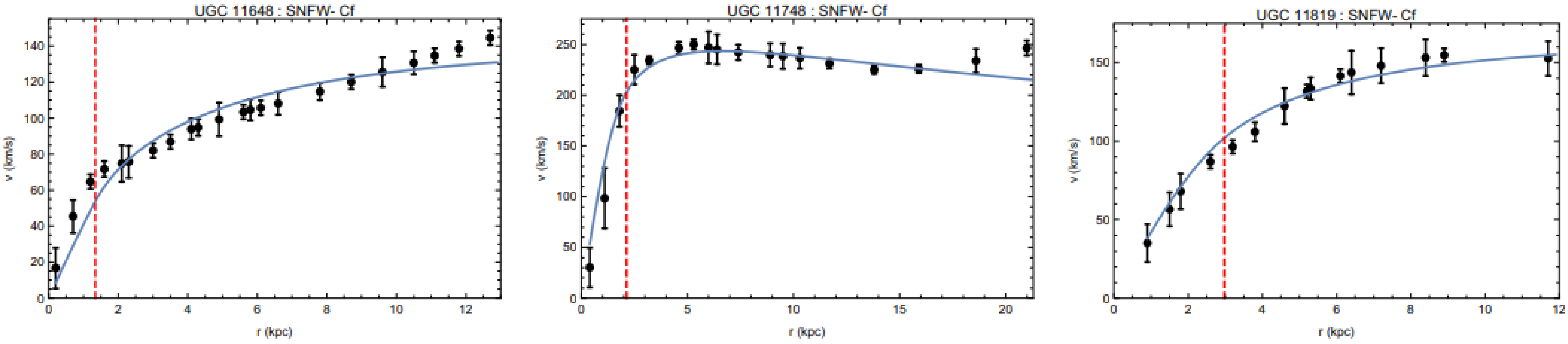




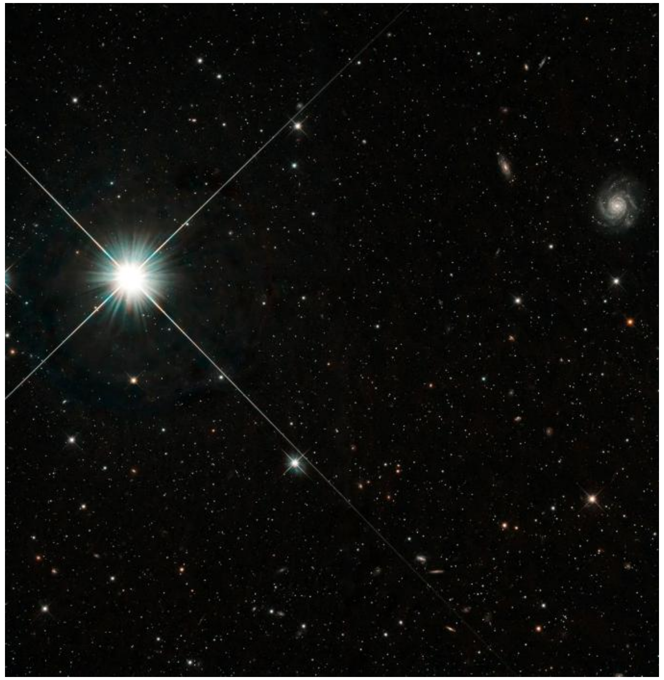


Fit of observed rotation curves for LSB galaxies.

T Bernal, L M Fernández-Hernández, T Matos, M A Rodríguez-Meza, Monthly Notices of Royal Astronomical Society (2017)

Velocity dispersion in dwarf galaxies

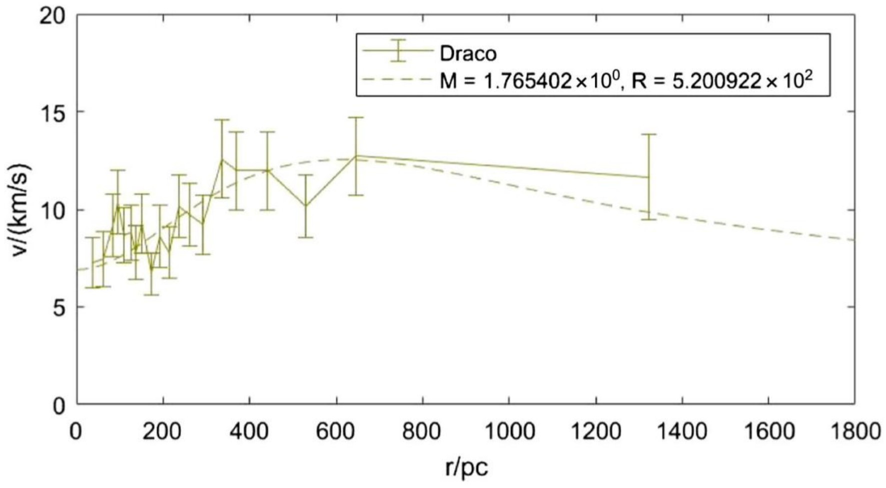
Idea: fit velocity dispersion data for seven Milky Way dwarf spheroidals with ULDM halo model

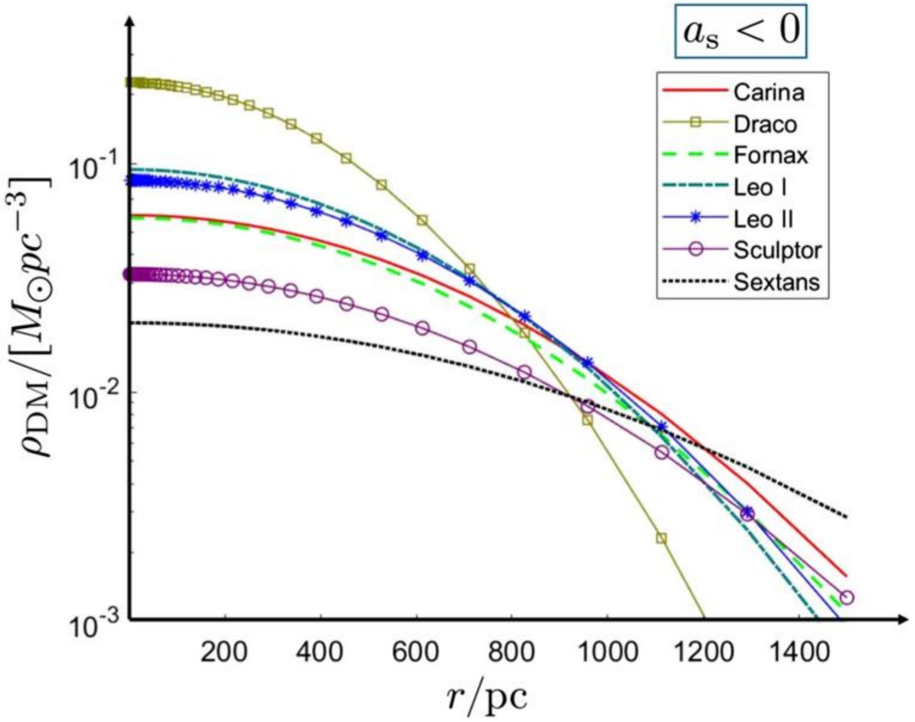


Hubble Space Telescope view showing part of the Draco Dwarf Galaxy. Credits: NASA, ESA, Eduardo Vitral, Roeland van der Marel, and Sangmo Tony Sohn (STScI), DSS; Image processing: Joseph DePasquale (STScI)

Velocity dispersion $$\overline{v_r^2} = \frac{1}{\rho_b(r)} \int_r^\infty dr' \rho_b(r') \frac{d\Phi}{dr'}$$

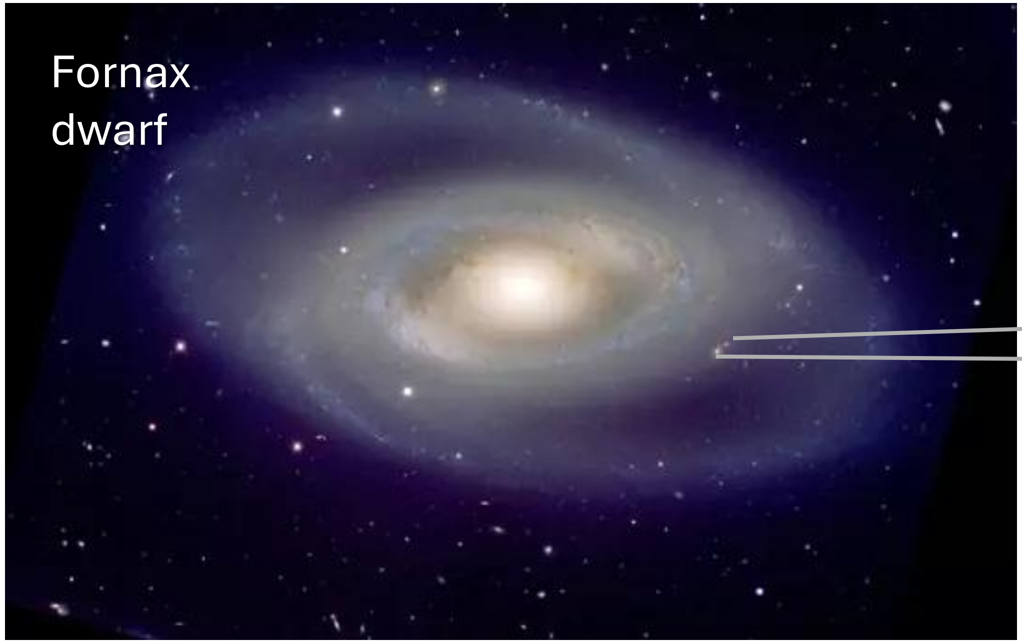
Gravitational potential, dominated by ULDM halo



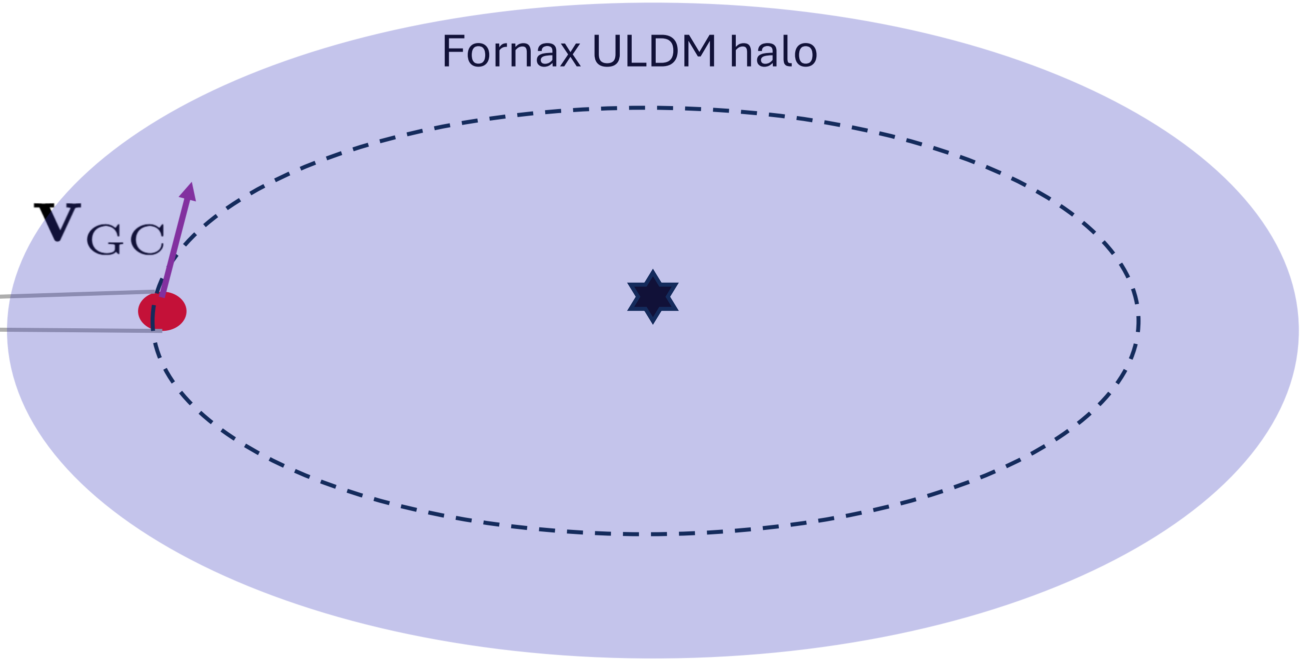


K Korshynska, EV Gorbar, YM Bidasyuk, AI Yakimenko, Y Revaz Phys Rev D (2026)

Trajectories of globular clusters: dynamical friction



https://www.constellation-guide.com/constellation-list/fornax-constellation/



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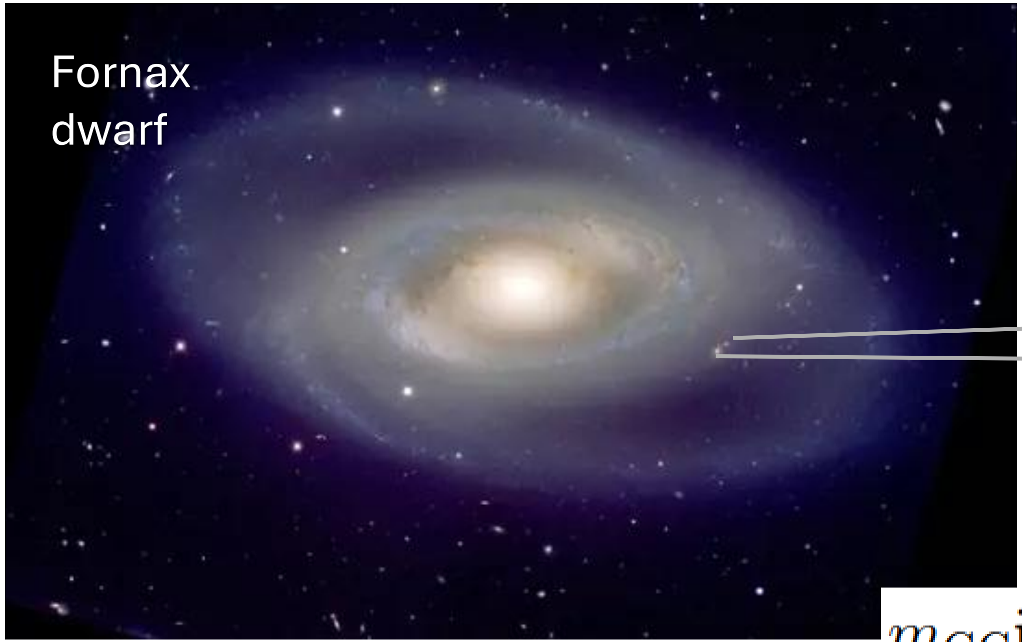

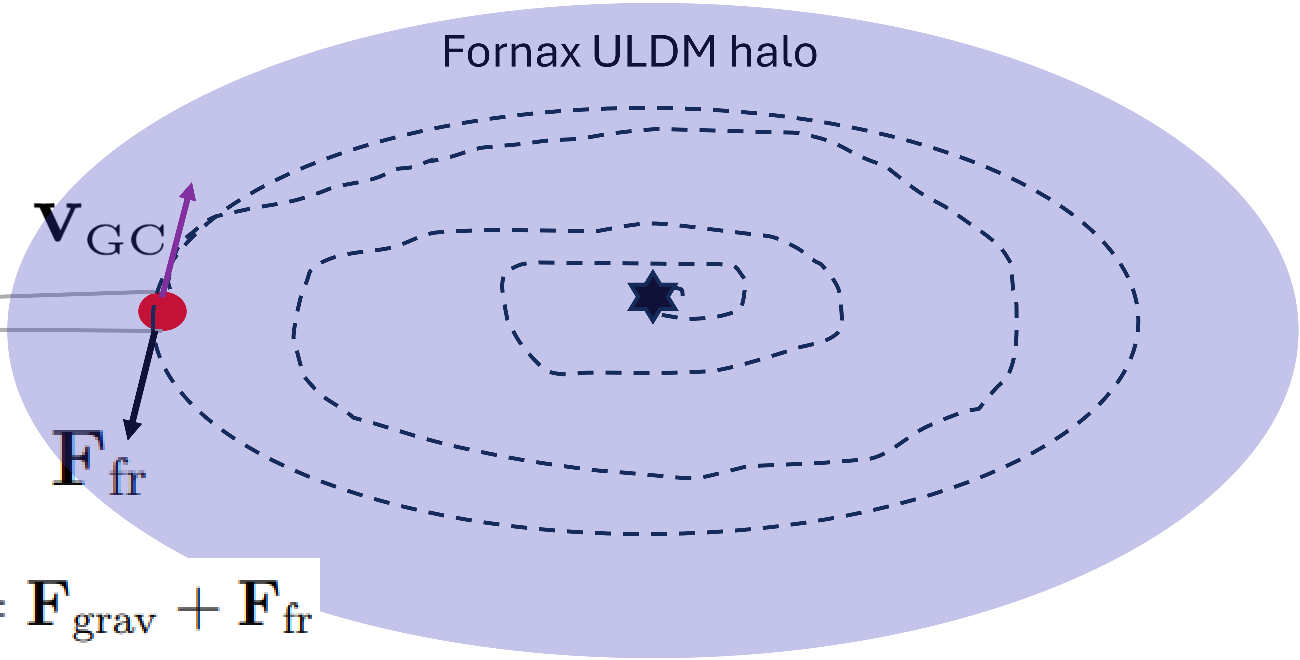

$$m_{\mathrm{GC}}\ddot{\mathbf{r}} = \mathbf{F}_{\mathrm{grav}} + \mathbf{F}_{\mathrm{fr}}$$

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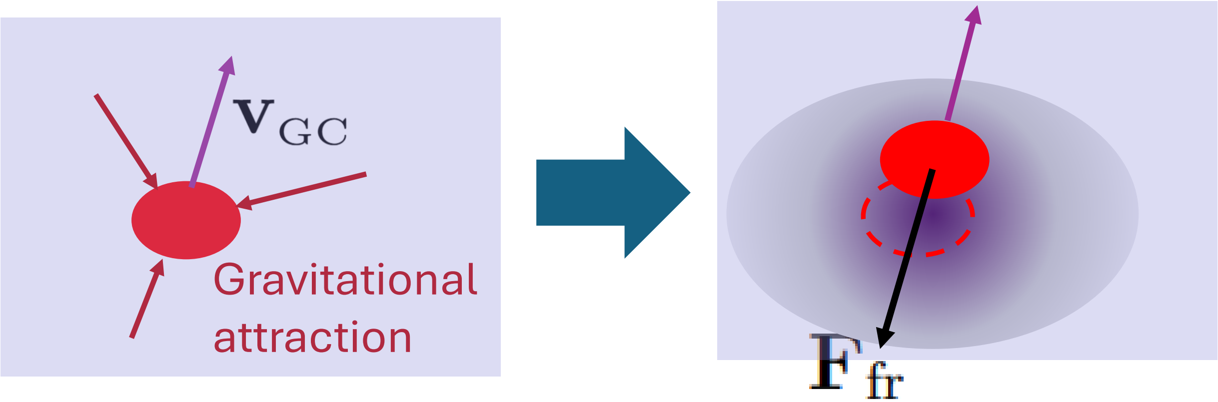
For the supersonic velocity of a globular cluster



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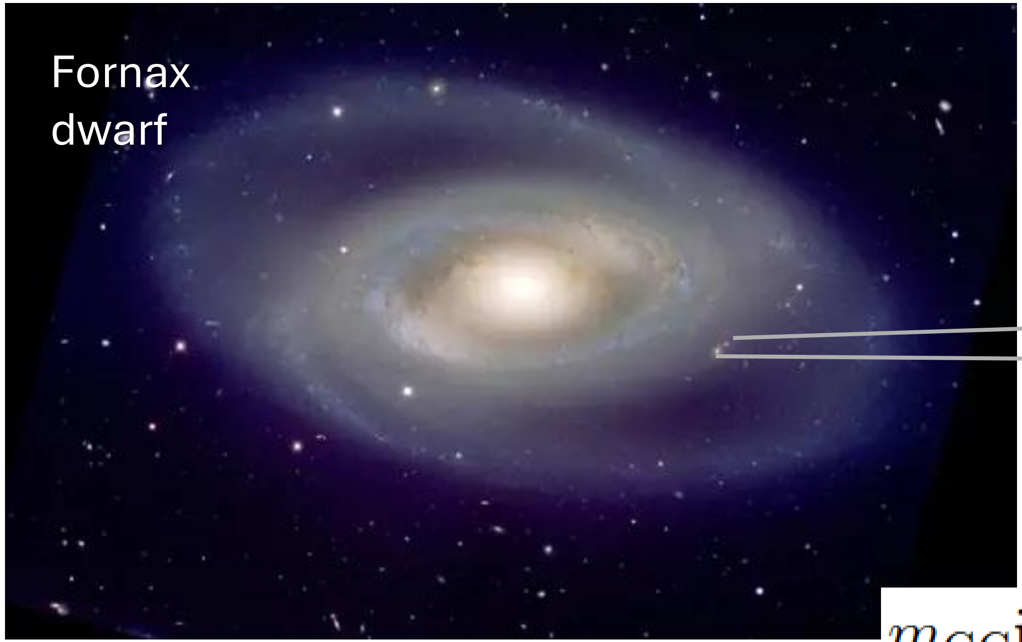

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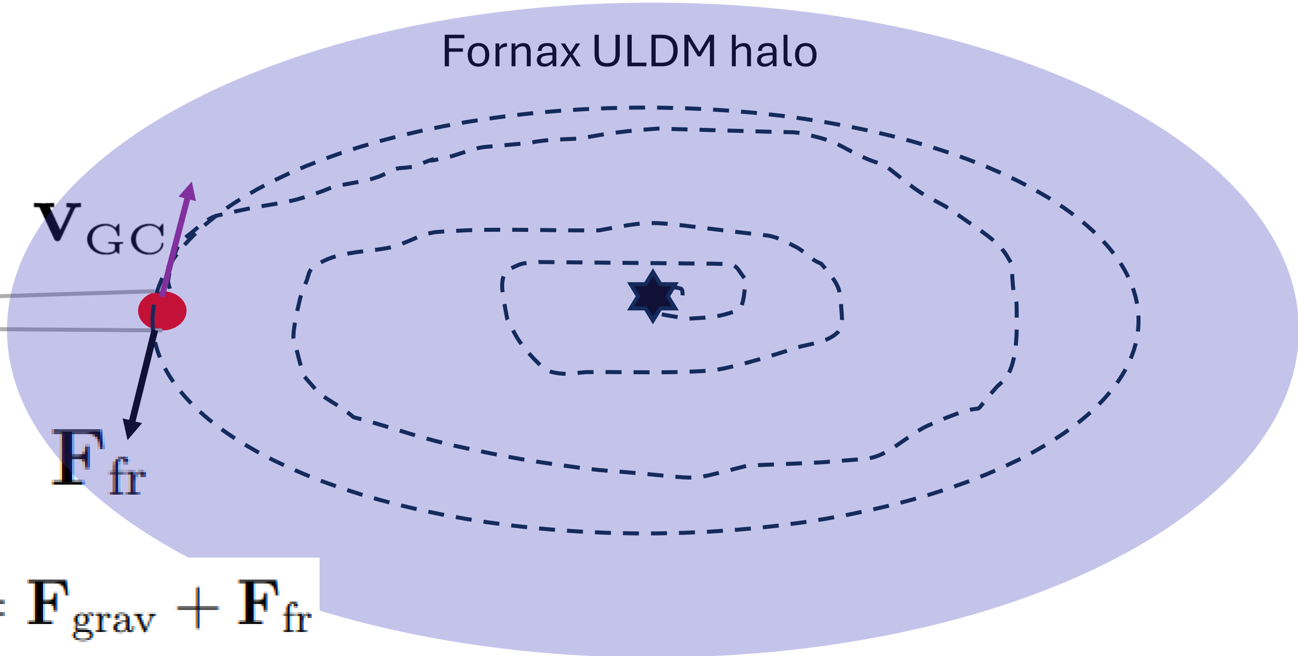

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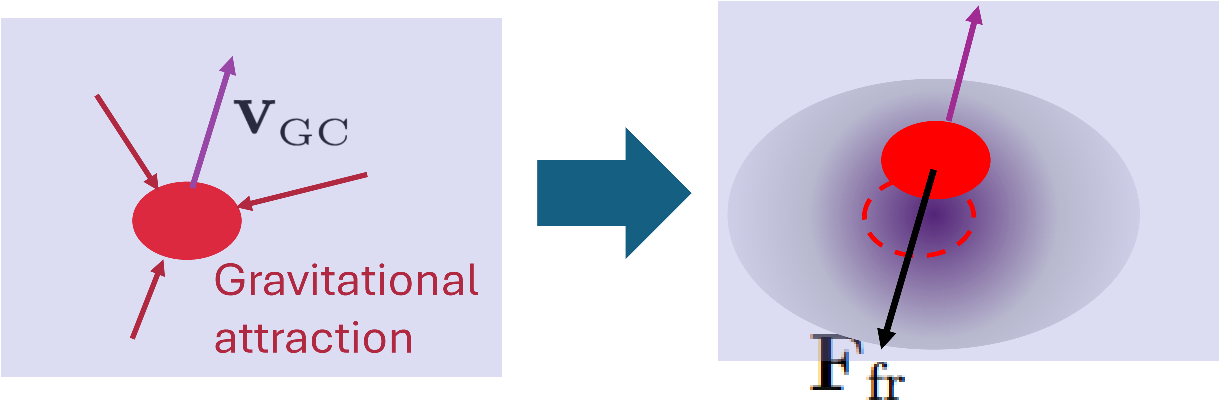

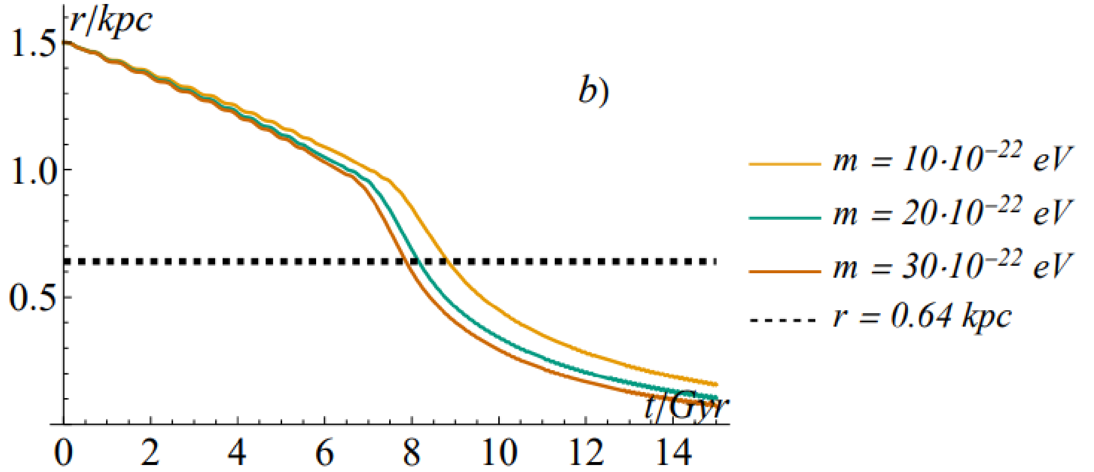

V.M. Gorkavenko, A.I. Yakimenko, A.O. Zaporozhchenko, E.V. Gorbar, Physica Scripta (2025)
E Gorbar, O Barabash, V Gorkavenko, K Korshynska, Andriy Momot, A Zaporozhchenko Classical and Quantum Gravity (2026)

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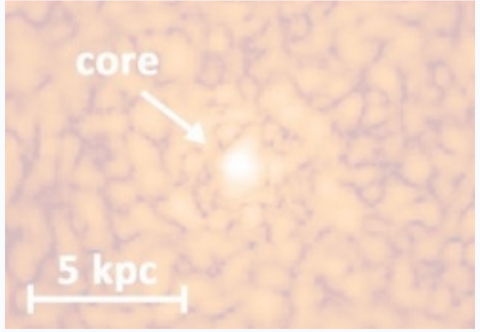

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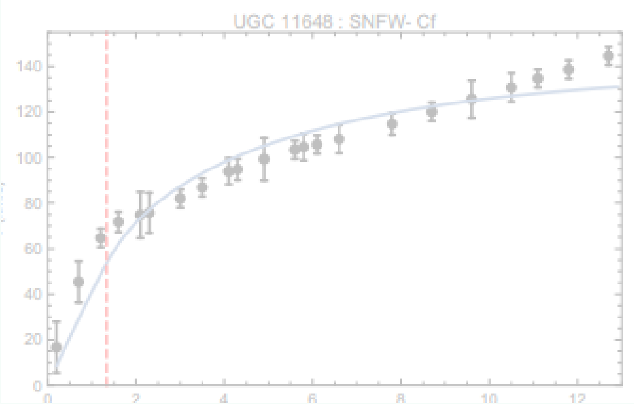

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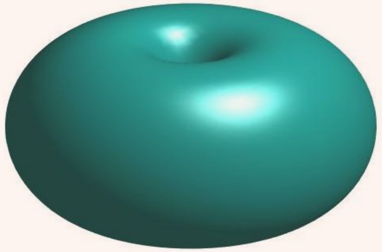

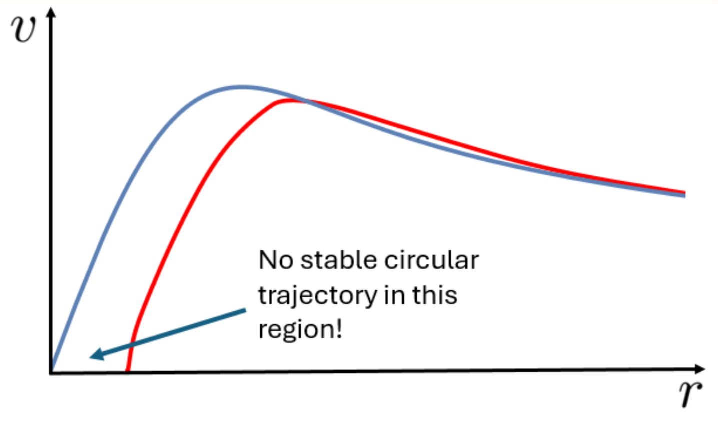

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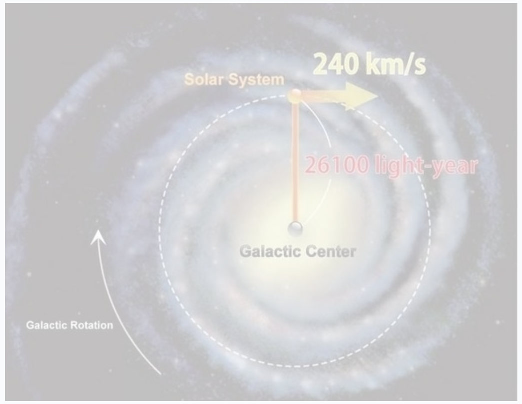


ULDM vortices

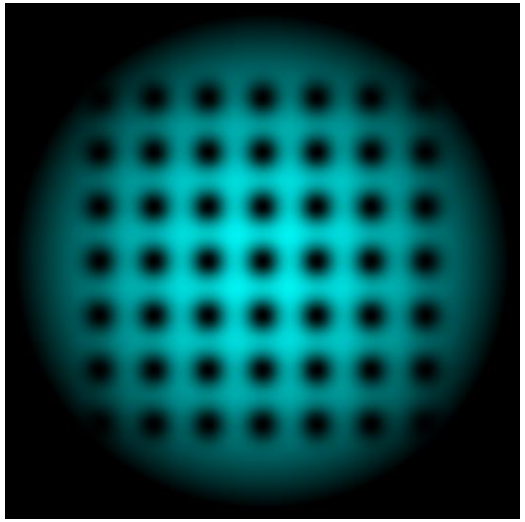
Could be formed due to

ULDM co-rotates with baryonic matter in spiral galaxies

$$\omega \quad >> \quad \omega_{cr}$$

Baryon rotational velocity

Critical velocity for vortex formation



M. P. Silverman and R. L. Mallett, General Relativity and Gravitation (2002)

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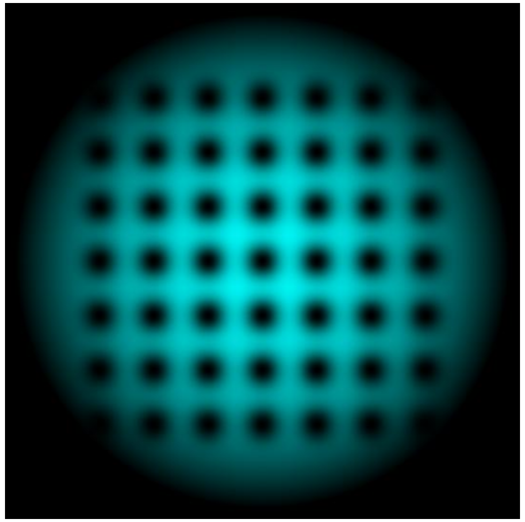

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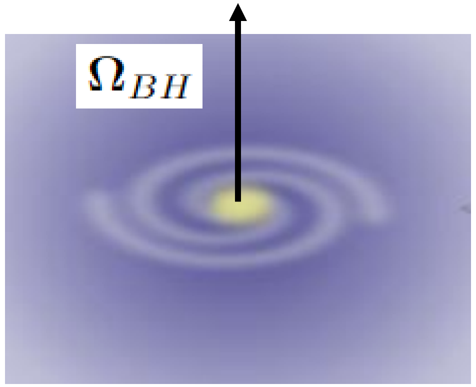

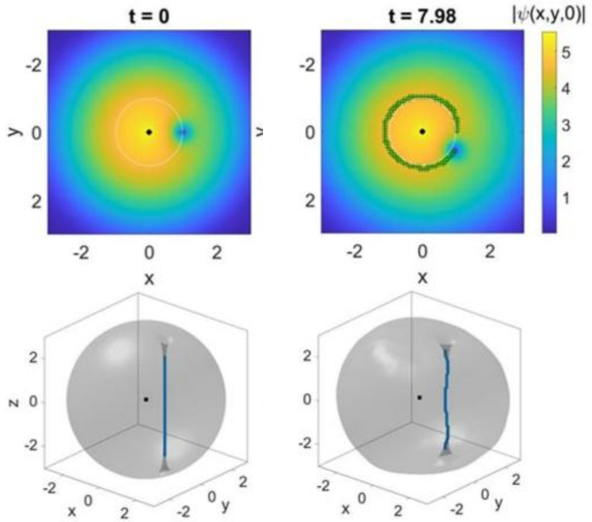

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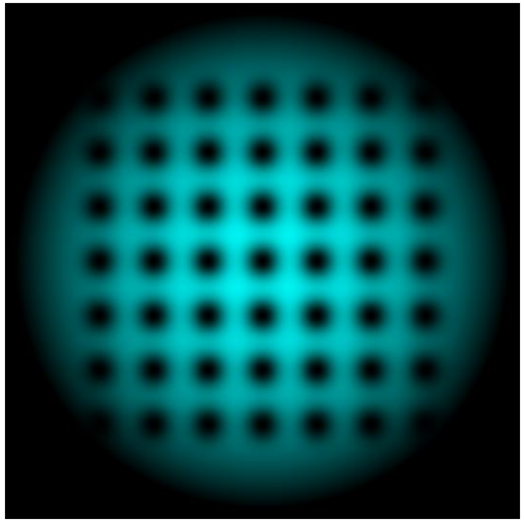

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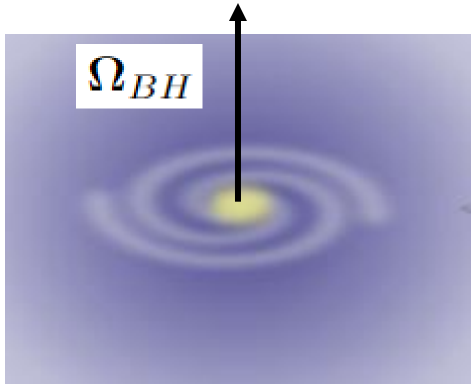

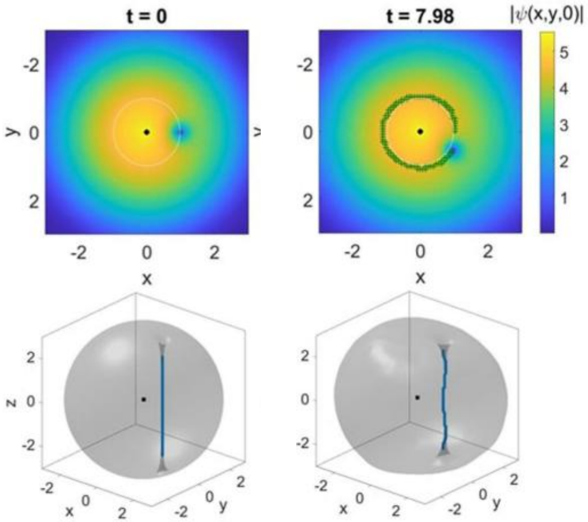

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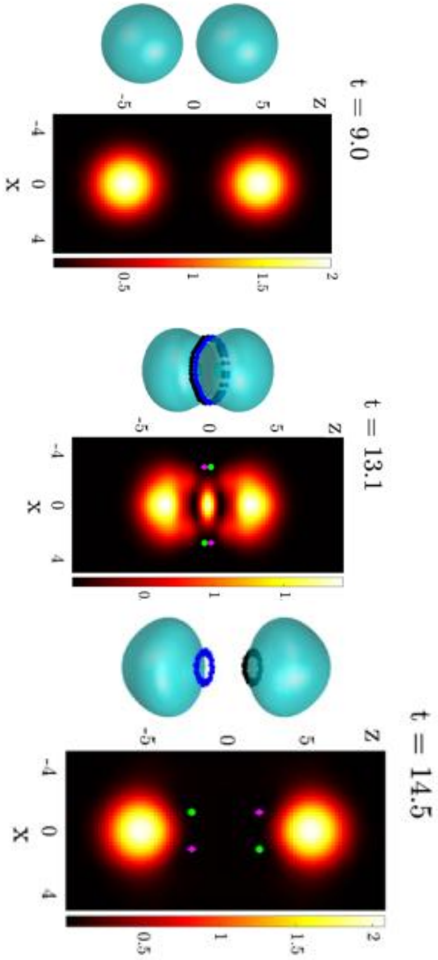
Collisions of halos



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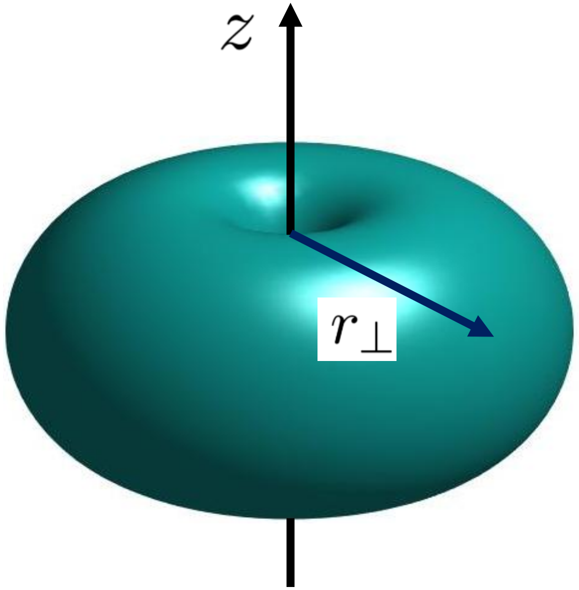
ULDM vortices

GPP equations

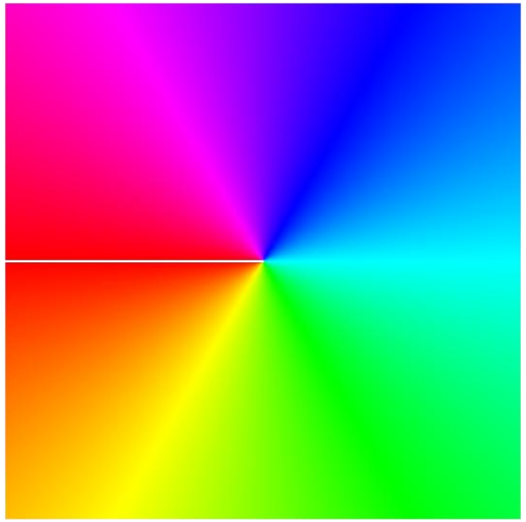
$$\begin{cases} i\hbar\partial_t\psi(\mathbf{r},t) = \left(-\frac{\hbar^2}{2m}\Delta + m\Phi(\mathbf{r},t) + gN|\psi(\mathbf{r},t)|^2\right)\psi(\mathbf{r},t) \\ \Delta\Phi(\mathbf{r},t) = 4\pi GmN|\psi(\mathbf{r},t)|^2 \end{cases}$$

... have another type of stationary solution – vortices!

$$\psi(r_\perp, \theta, z) = A\left(\frac{r_\perp}{R}\right)^s e^{-\frac{r_\perp^2}{2R^2} - \frac{z^2}{2(R\eta)^2} + is\theta}$$



density



phase (s=1)

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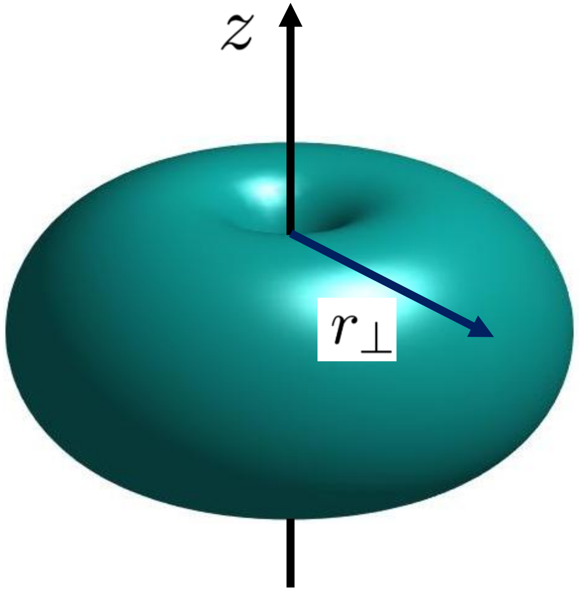

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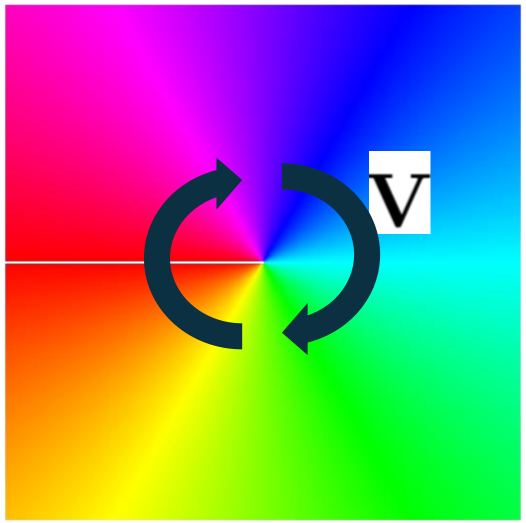

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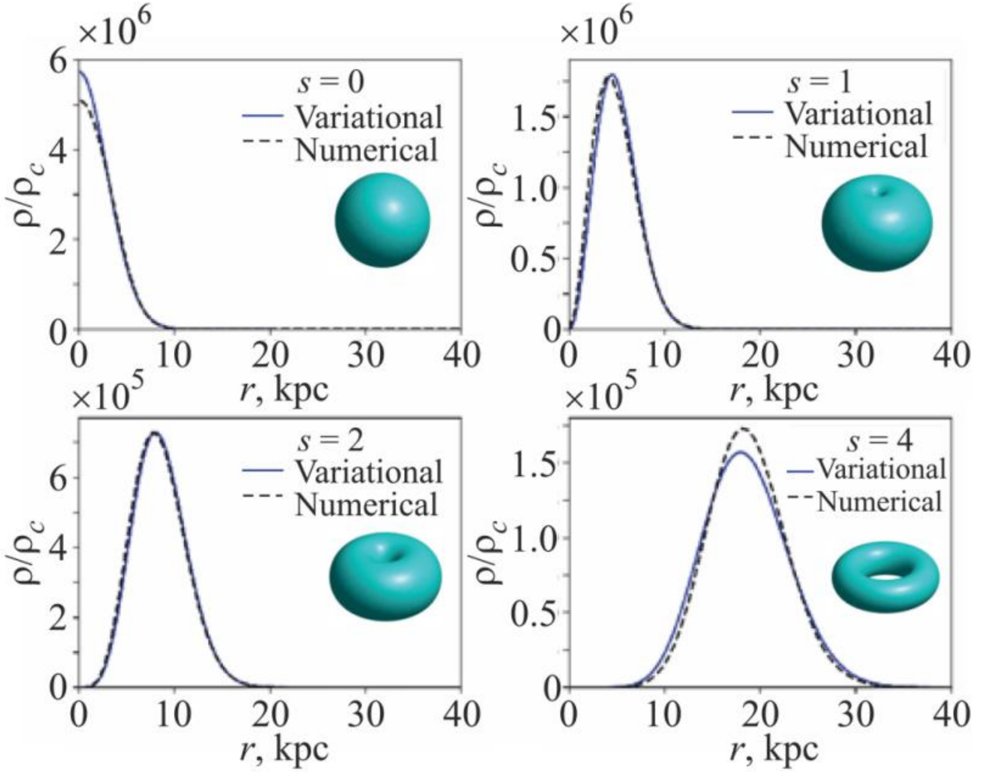


Y. O. Nikolaieva, A. O. Olashyn, Y. I. Kuriatnikov, S. I. Vilchynskii, A. I. Yakimenko et al. Low Temp Physics (2021)

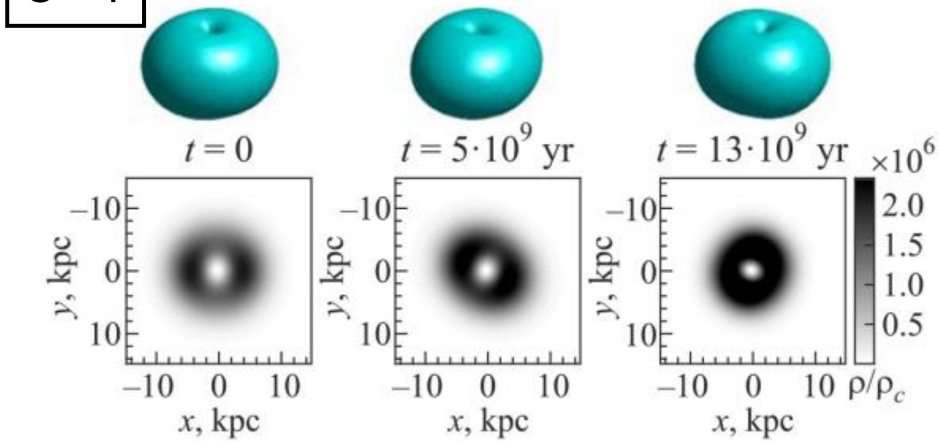
Vortices have a superfluid flow

$$\mathbf{V} = \frac{\mathbf{j}}{|\psi|^2} = -\frac{i\hbar}{2m}\frac{\psi^\star\nabla\psi - \psi\nabla\psi^\star}{|\psi|^2} = \frac{s\hbar}{m}\frac{\mathbf{e}_\phi}{r_\perp}$$

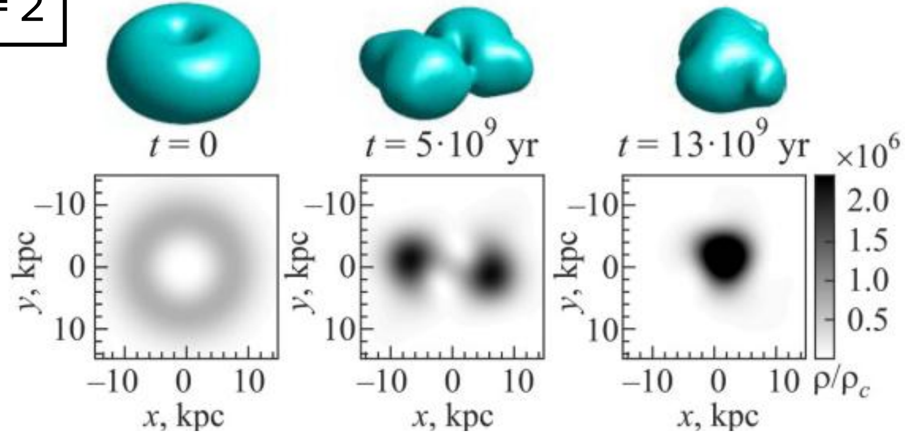
ULDM vortices

Are stable with respect to perturbations:

S = 1



S = 2



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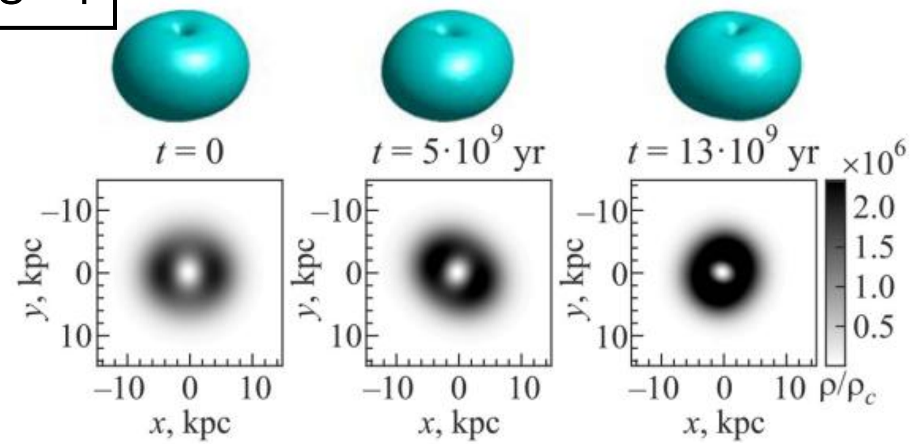

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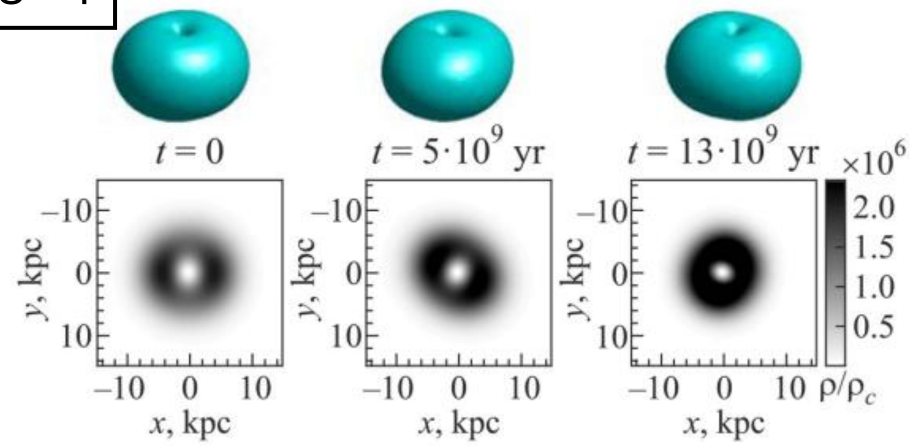

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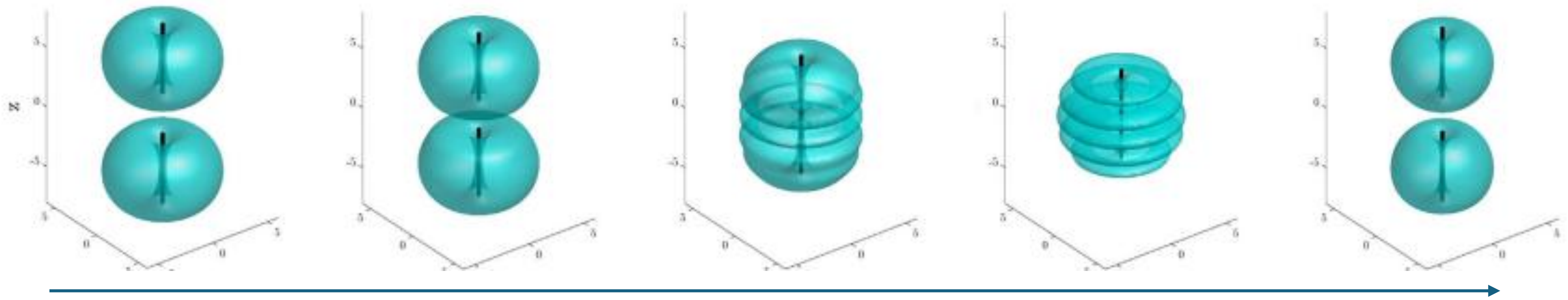
Are stable with respect to collisions:



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ULDM vortices: gravielectric potential

The presence of a vortex changes the spacetime metric:

$$dS^2 = g_{\mu\nu}dx^\mu dx^\nu = \left(1 - \frac{2\Phi_{\mathrm{g}}}{c^2}\right)(dx^0)^2 + \frac{4}{c^2}\left(\mathbf{A}_{\mathrm{g}}\mathbf{dx}\right)dx^0 + \left(-1 - \frac{2\Phi_{\mathrm{g}}}{c^2}\right)\delta_{ij}dx^i dx^j$$

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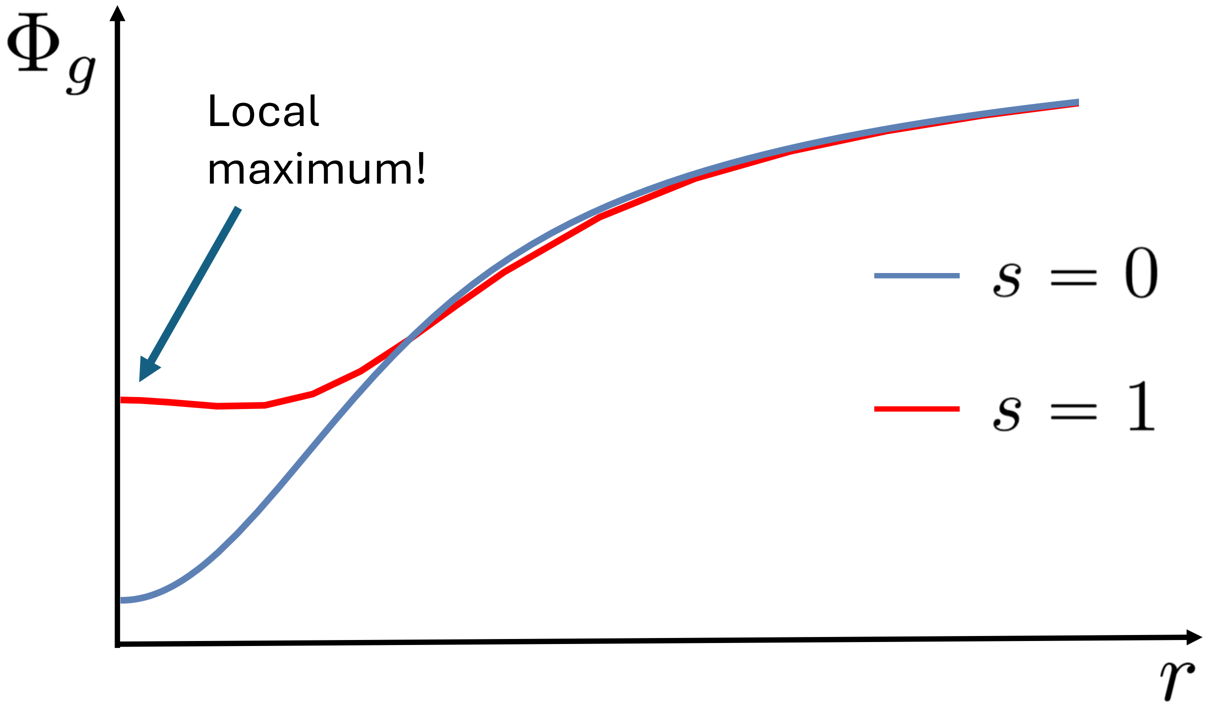
Gravielectric (Newtonian) potential and rotation curves



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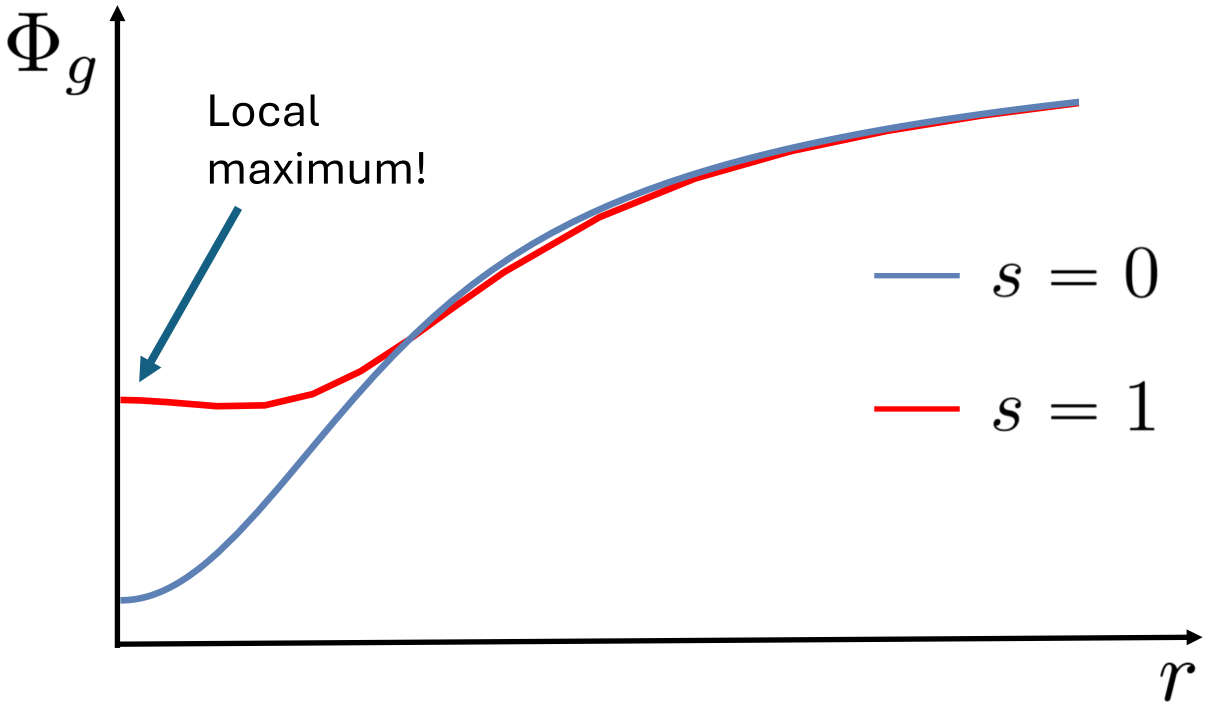

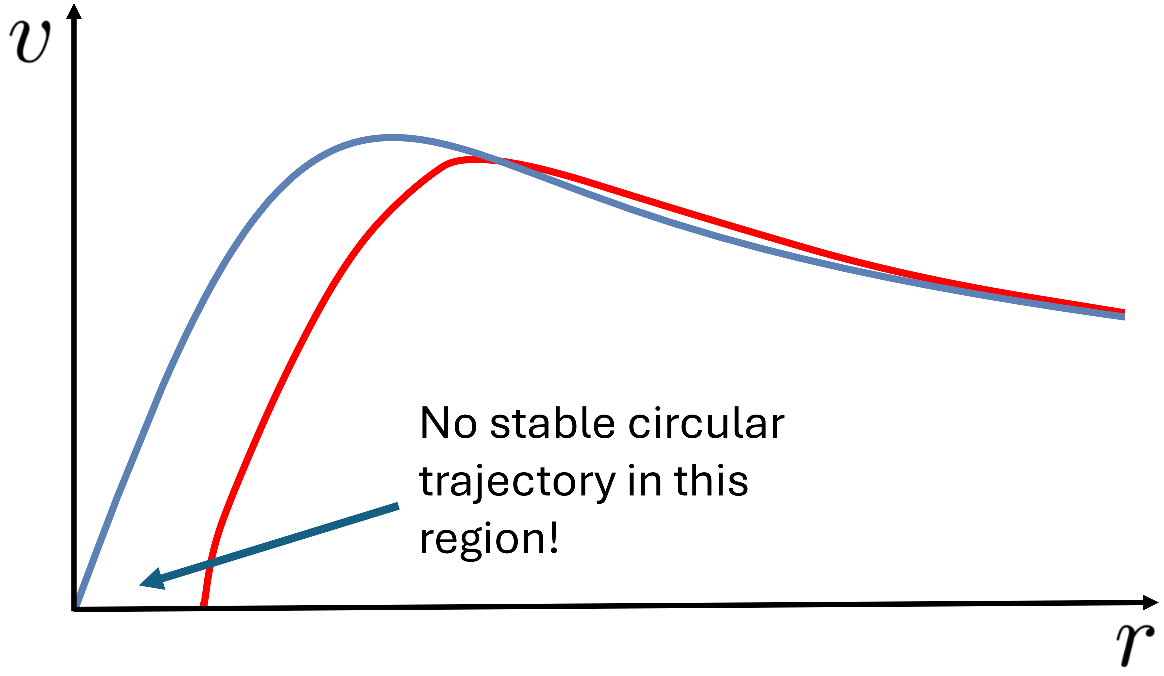

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The geodesic trajectory of a test particle is determined by a gravielectromagnetic force

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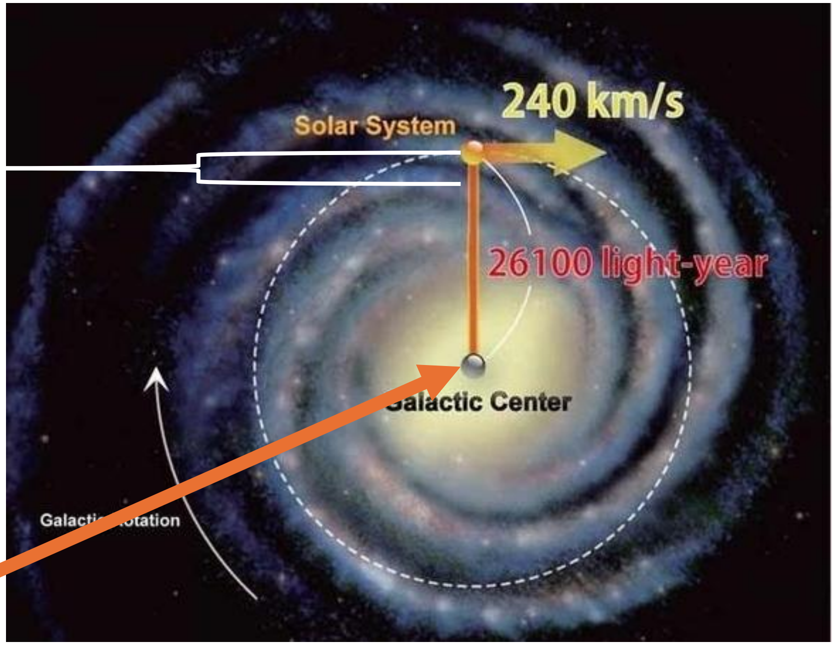
$$\boxed{\frac{|\mathbf{a}_B|}{|\mathbf{a}_E|} \sim 10^{-6}}$$

Gravimagnetic force: Lense-Thirring effect

For a distant star (8 kpc from the MW center): gravimagnetic force would displace the Sun trajectory by only 80 solar radii!

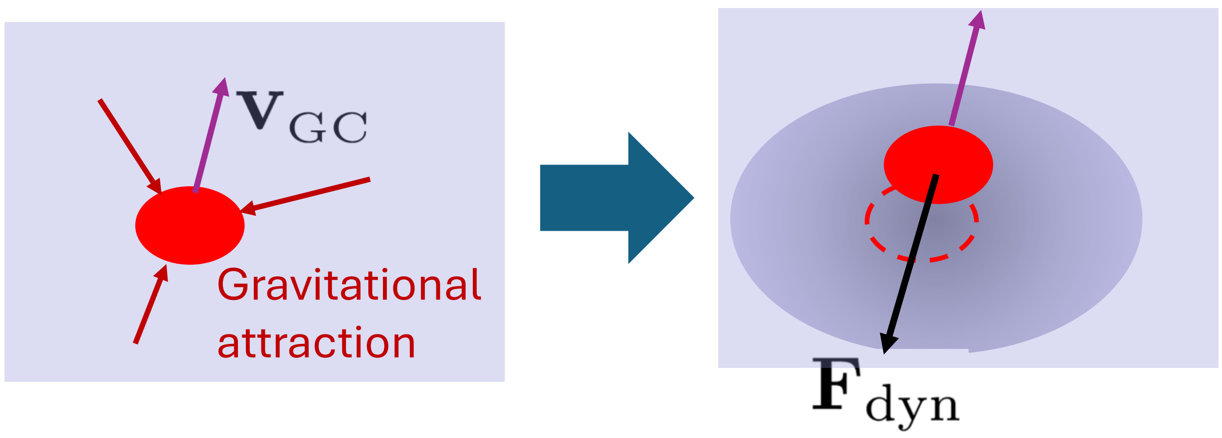


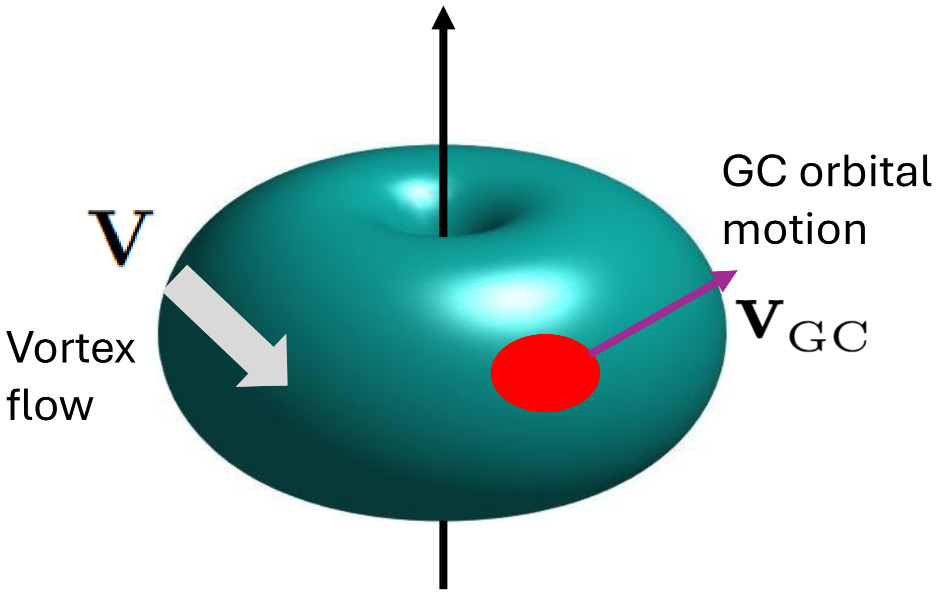
https://cosmosatyourdoorstep.com/2023/01/18/how-massive-is-the-milky-way/

Here the vortex model could be tested better!

K. Korshynska, Y.M. Bidasyuk, E.V. Gorbar, Junji Jia, A.I. Yakimenko EPJC (2023)

ULDM vortices: dynamical friction





V Gorkavenko, O Barabash, T Gorkavenko, K Korshynska, O Teslyk, A Zaporozhchenko, E Gorbar, Universe (2026)

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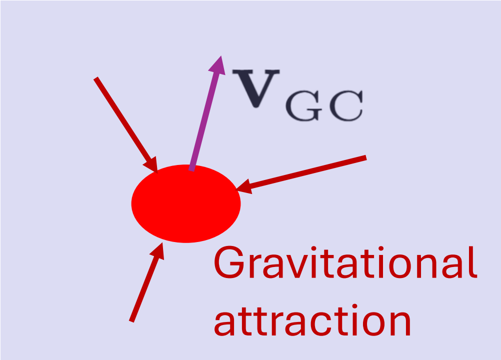

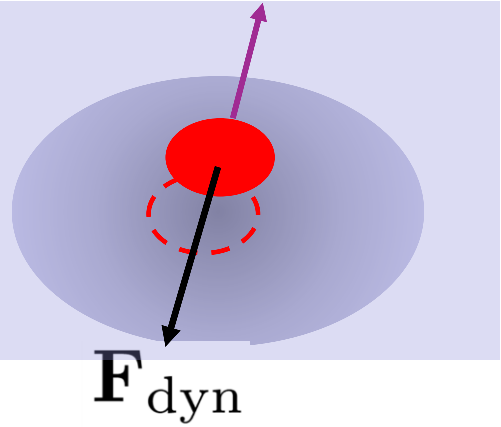

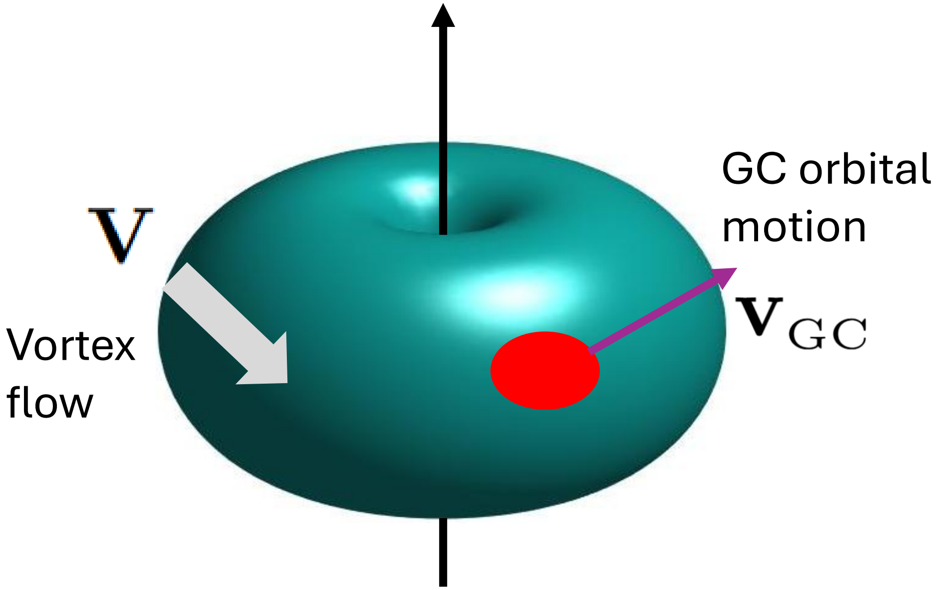

Now relative velocity between the Globular Cluster and the ULDM medium is:

$$\mathbf{v}_{\mathrm{GC}} - \mathbf{V}$$

co-directional rotation leads to a pronounced suppression of dynamical friction

V Gorkavenko, O Barabash, T Gorkavenko, K Korshynska, O Teslyk, A Zaporozhchenko, E Gorbar, Universe (2026)

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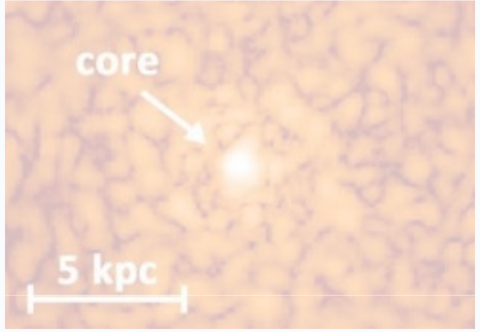

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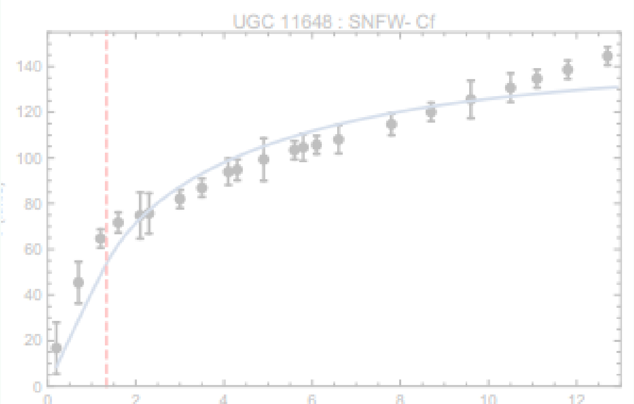

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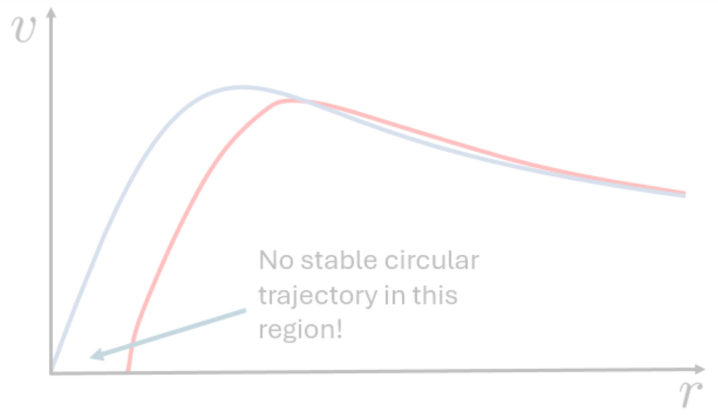

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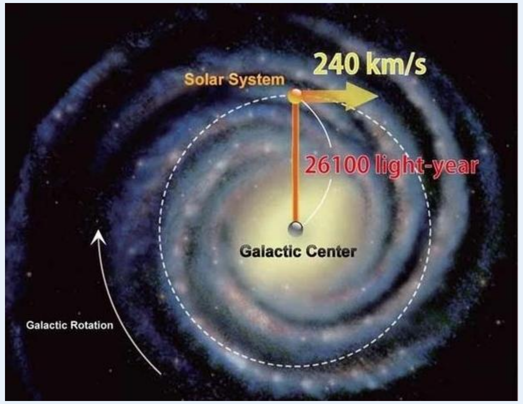
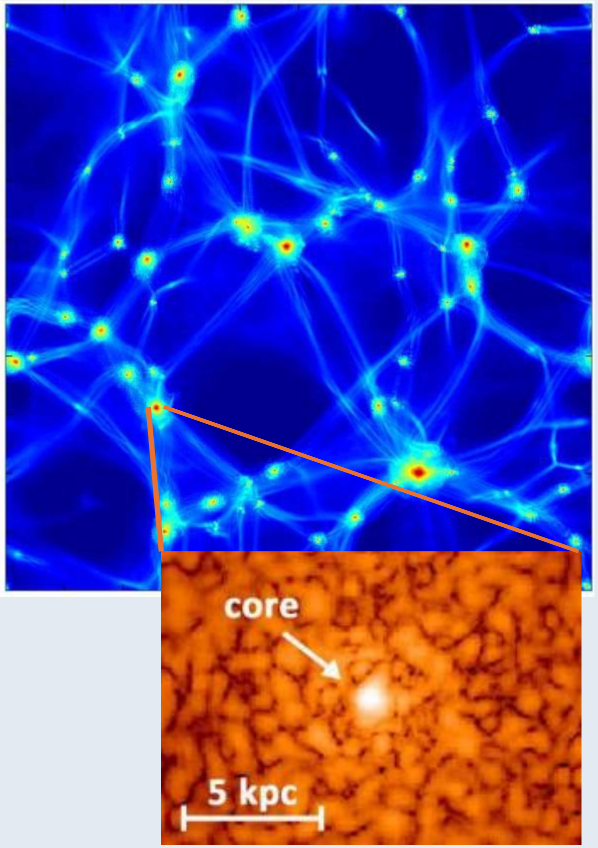


Conclusions

Ultralight dark matter model:

- axionlike bosons with small masses;
- cores in galactic centers



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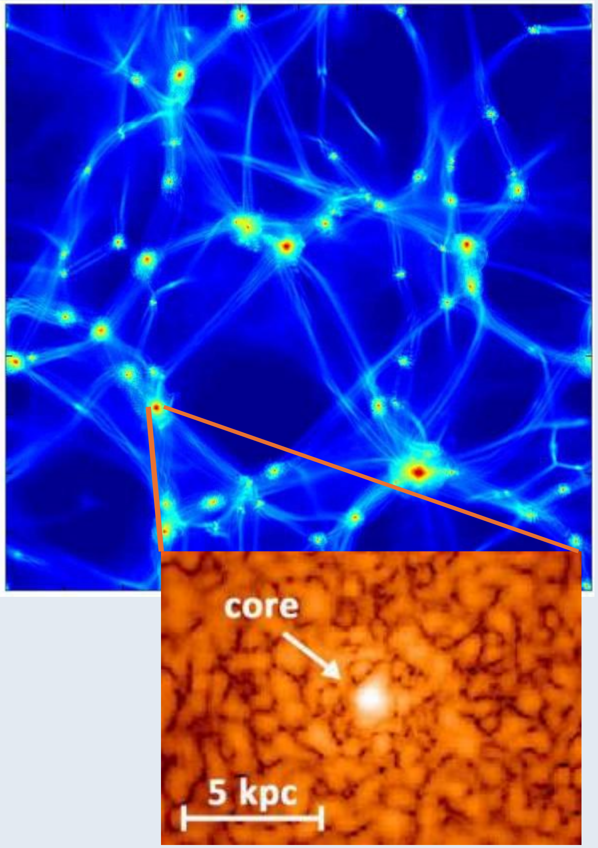

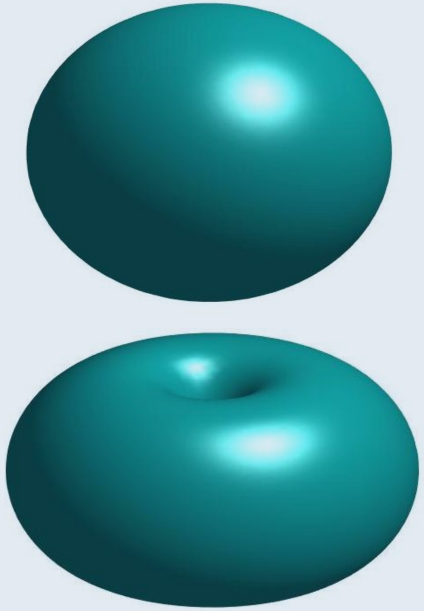

Balance between gravitational attraction and quantum pressure -> cores in ULDM

They can also form stable vortices

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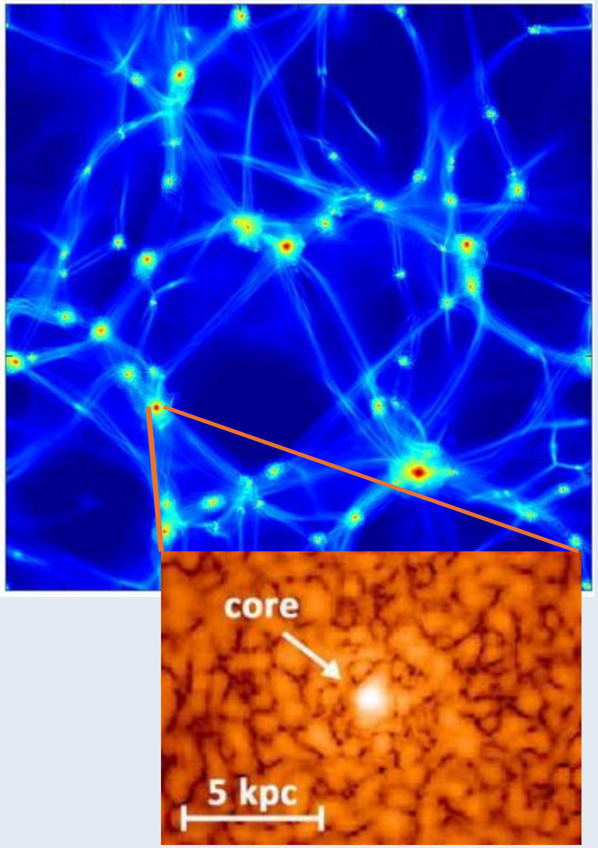
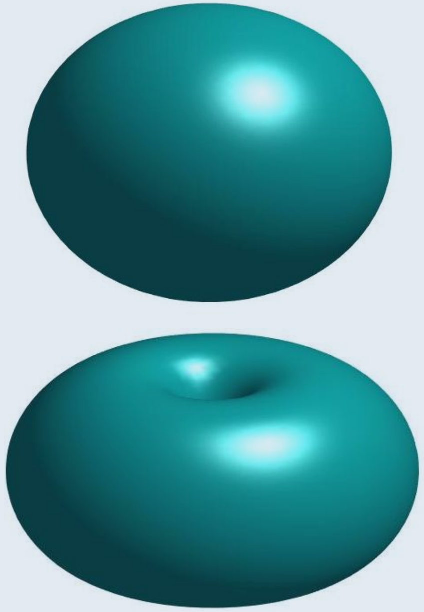
- cores in galactic centers

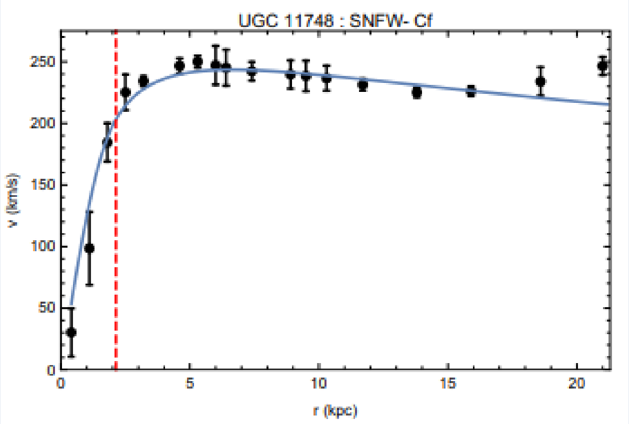


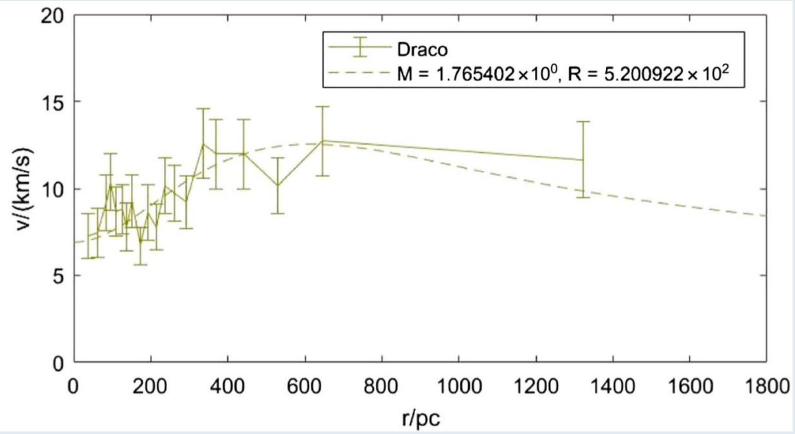


Balance between gravitational attraction and quantum pressure -> cores in ULDM

They can also form stable vortices

ULDM model test: comparison with astrophysical observations (rotation curves, velocity dispersion and globular clusters' trajectories)





I would like to acknowledge


Olexander Yakymenko


Eduard Gorbar


Yurii Bidasyuk


Volodymyr Gorkavenko


Oleh Barabash


Yves Revaz

...and many others for their collaboration.

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FPM

PTB

TARAS SHEVCHENKO NATIONAL UNIVERSITY OF KYIV

Utilitas, Honor et Gloria

1834

EPFL

And especially FPM institute at PTB=)

Literature

- **„Dynamical galactic effects induced by solitonic vortex structure in bosonic dark matter“**

K. Korshynska, Y.M. Bidasyuk, E.V. Gorbar, Junji Jia, A.I. Yakimenko EPJC (2023)

- **„Stable vortex structures in colliding self-gravitating Bose-Einstein condensates“**

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- **„Damping of dynamical friction force in self-interacting ultralight dark matter and Fornax timing problem“**

E Gorbar, O Barabash, V Gorkavenko, K Korshynska, Andriy Momot, A Zaporozhchenko Classical and Quantum Gravity (2026)

- **„The Vortex State of Ultralight Dark Matter and the Fornax Timing Problem“**

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- **„Cosmological structure formation in ultralight dark matter“**

K. Korshynska, A. I. Yakimenko, Y. Revaz and E. V. Gorbar [in preparation]

Literature

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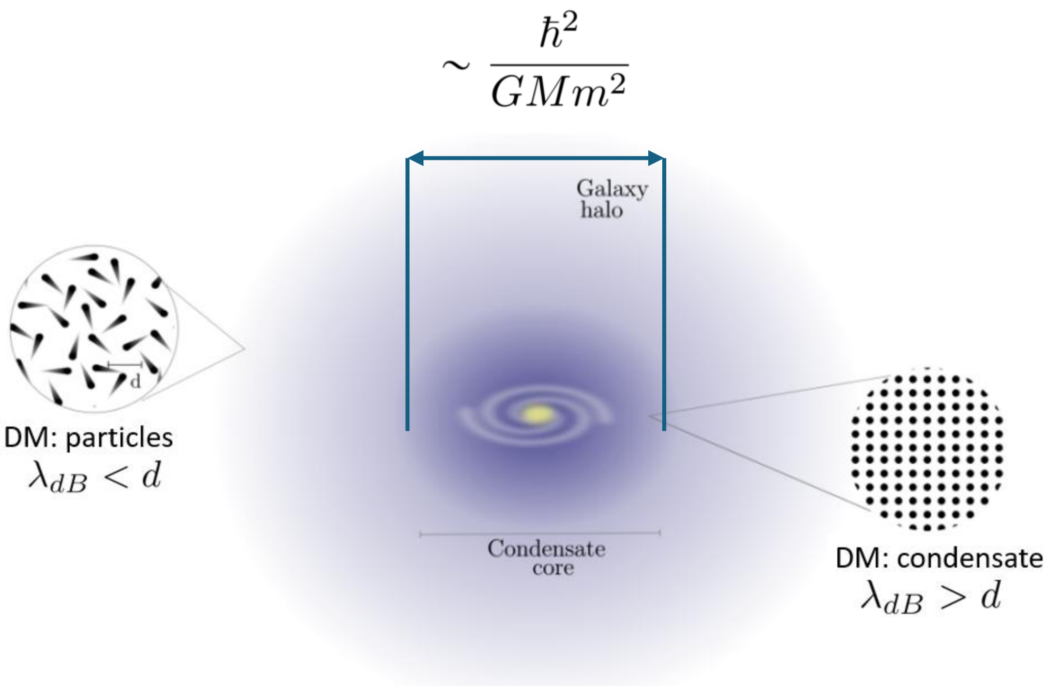
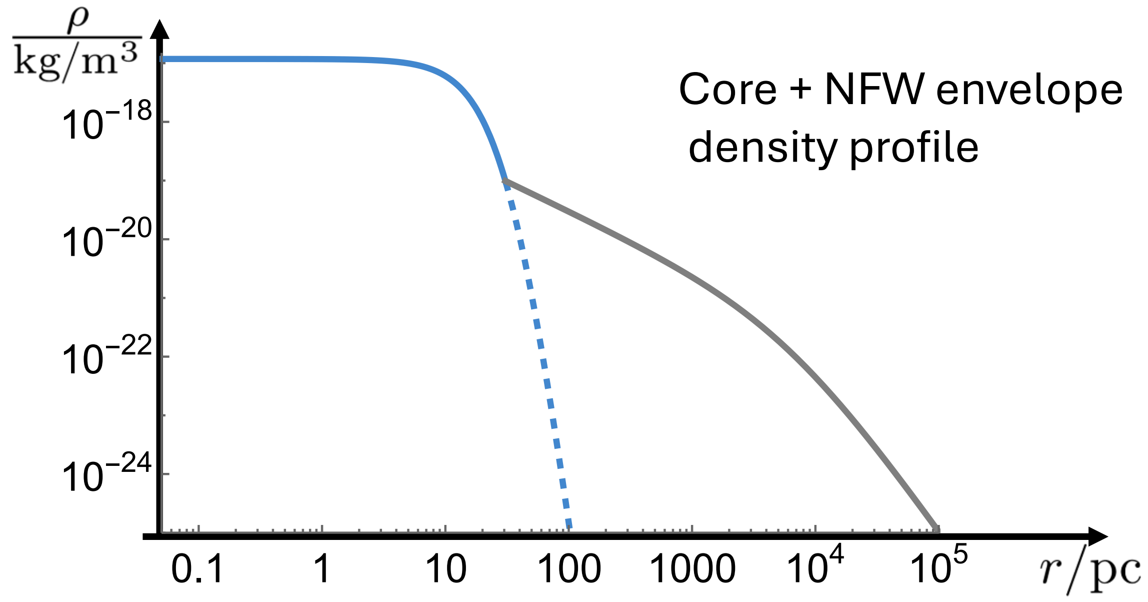
Thank you for your attention!

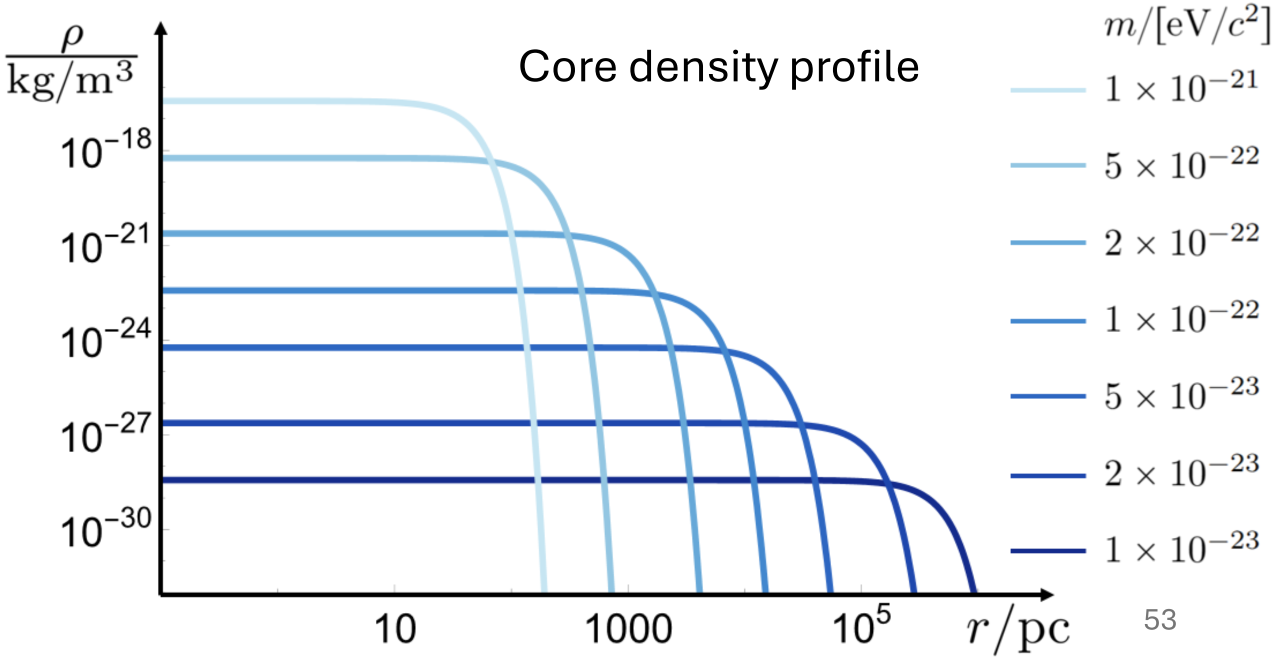
Backup slides

Ultralight boson and halo structure



Ultra-light dark matter Elisa G. M. Ferreira (2021)





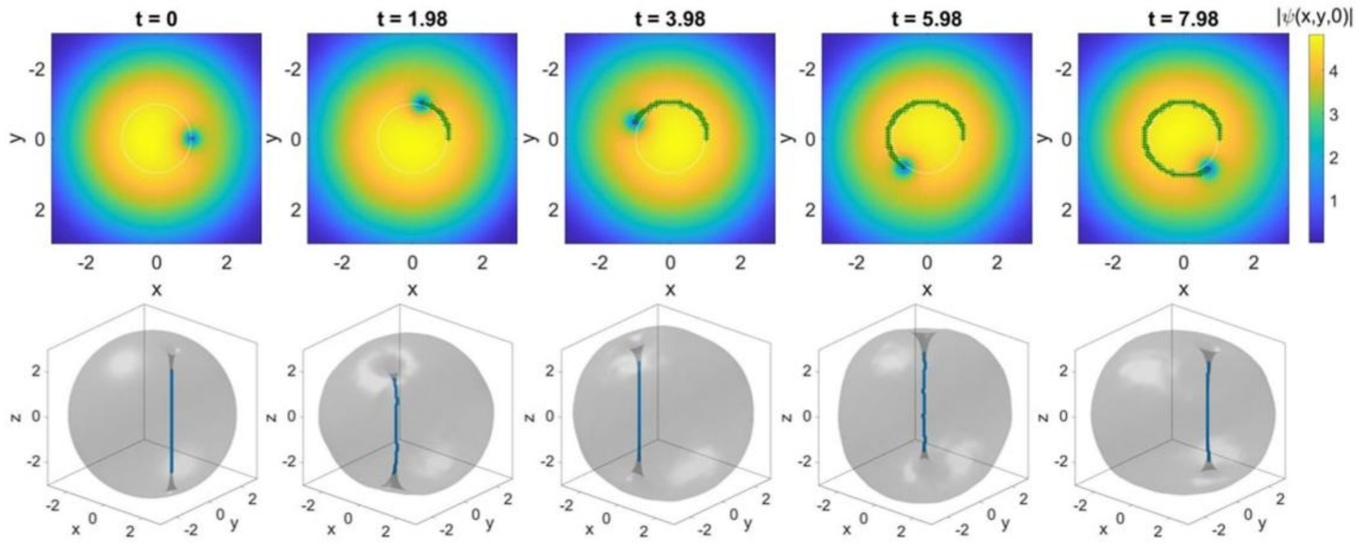
While for small galaxies (dwarf spheroidals or ultra-faint dwarfs) the core can be used to model the total halo, the bigger halos (spiral, like Milky Way) require core+envelope model

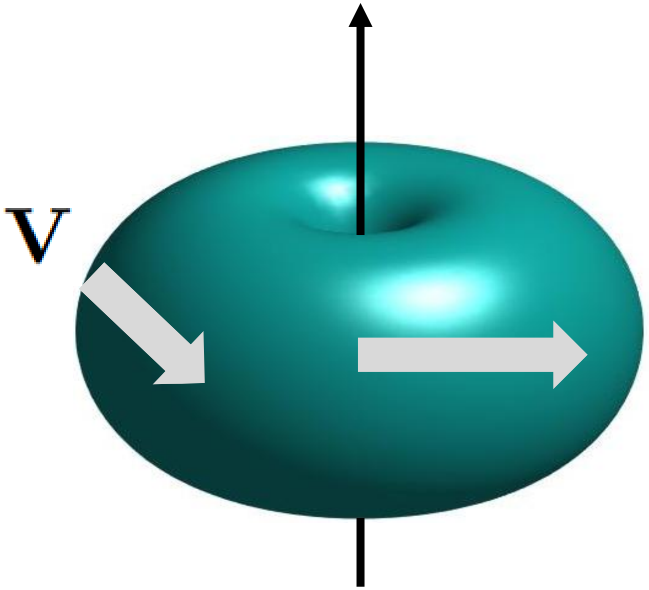
ULDM vortices

1) Have density hole and the superfluid flow

$$\mathbf{V} = \frac{\mathbf{j}}{|\psi|^2} = -\frac{i\hbar}{2m|\psi|^2}(\psi^*\nabla\psi - \psi\nabla\psi^*) = \frac{s\hbar}{m}\frac{1}{r}\mathbf{e}_\phi$$

2) Interesting dynamics

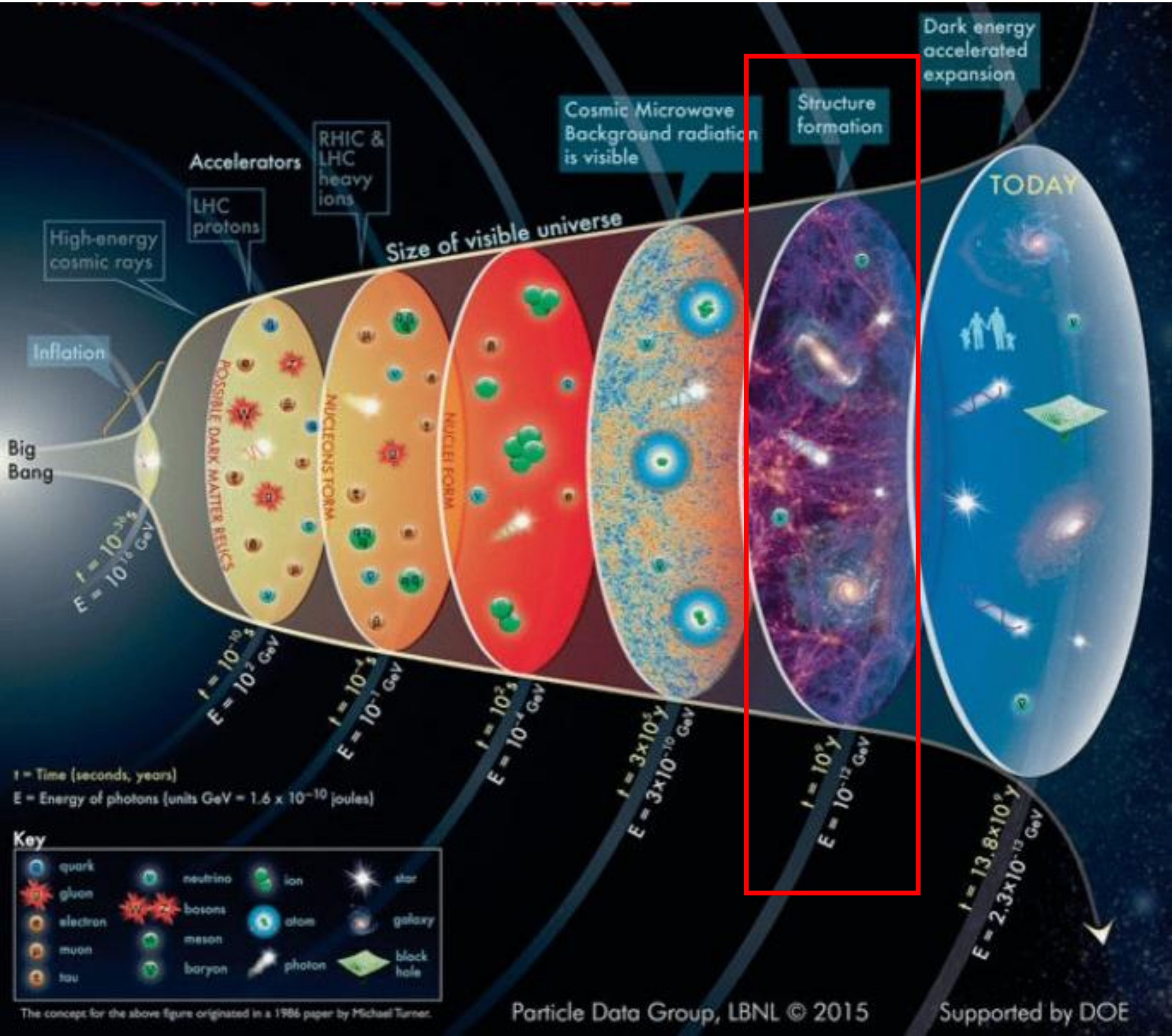




3) Have interesting implications on astrophysical observations...

K Korshynska, OO Prykhodko, EV Gorbar, Junji Jia, AI Yakimenko PhysRev D (2025)

Cosmological perspective: structure formation



"The emergence of stars, galaxies, groups and clusters of galaxies, and even larger inhomogeneities from the nearly homogeneous early universe is referred to as structure formation".

Galactic Dynamics J. Binney and S. Tremaine (2011)

ULDM structure formation

Investigated in ....

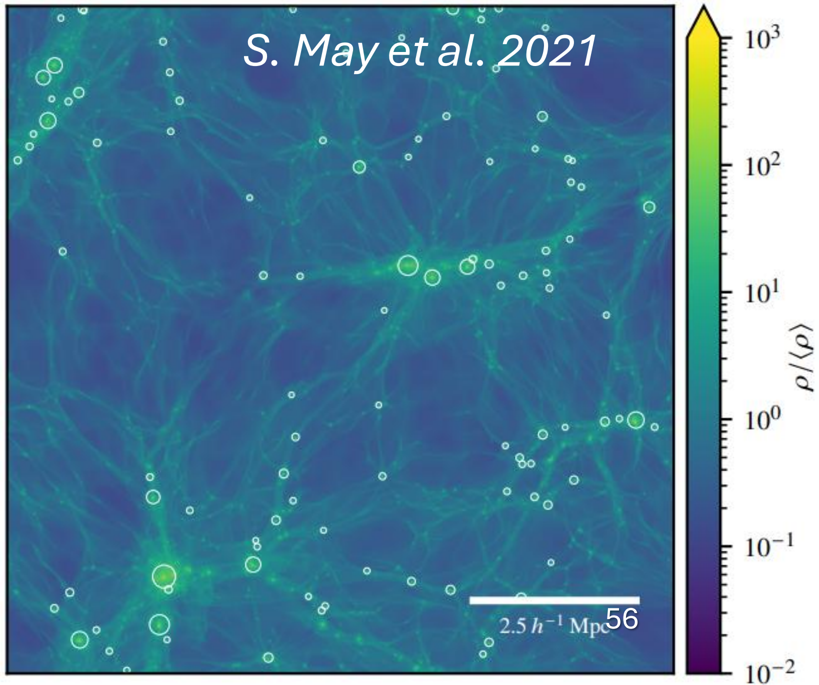
- „Fuzzy dark matter simulations“ Schive 2026
- „Cosmic structure as the quantum interference of a coherent dark wave “ Schive et al. 2014
- „Jeans-type instability of a complex self-interacting scalar field in general relativity “A. Suarez et al., Phys Rev D 2018
- “Structure formation in large-volume cosmological simulations of fuzzy dark matter: impact of the non-linear dynamics” S. May et al. 2021
- “Coherent and incoherent structures in fuzzy dark matter haloes” I.-K. Liu et al. 2023....
- and many more.

Usual approach:
GPP equations + Universe expansion

$$\begin{cases} i\hbar\left(\frac{\partial}{\partial t}+\frac{3}{2}\boxed{H}\right)\psi = -\frac{\hbar^2}{2m\boxed{a^2}}\nabla^2\psi + m\Phi\psi \\ \frac{1}{\boxed{a^2}}\Delta\Phi = 4\pi G\rho \end{cases}$$

... and then a large-scale numerical simulation

Can we try to understand this process with a simple model?



ULDM structure formation

Perturbed FLRW spacetime:

$$ds^2 = \left(1 + \frac{2\Phi}{c^2}\right) c^2 dt^2 + a^2(t) \left(-1 + \frac{2\Phi}{c^2}\right) \delta_{ij} dx^i dx^j$$

$$\Box\psi + \left(\frac{mc}{\hbar}\right)^2 \psi = 0 \xrightarrow{\text{nonrelativistic limit}} \boxed{i\hbar \left(\frac{\partial}{\partial t} + \frac{3}{2}H\right)\psi = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + m\Phi\psi}$$

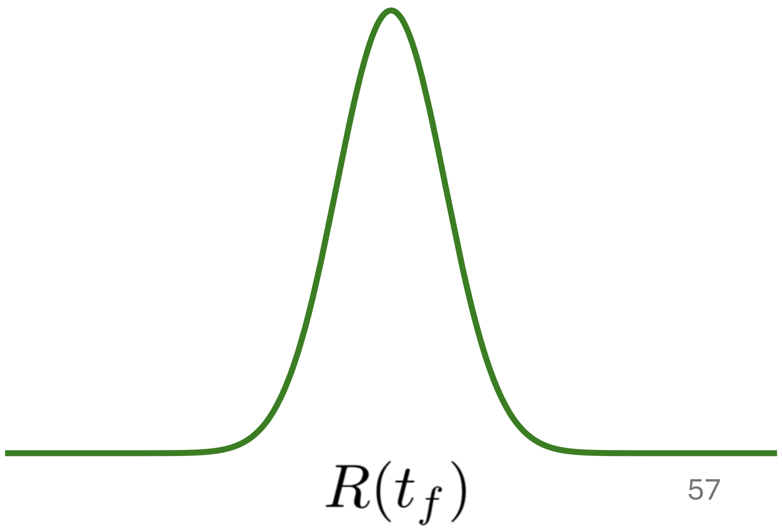
Variational approach: $\psi(\mathbf{r}, t) = \sqrt{\rho_0(t)} \left(e^{i\alpha(\mathbf{r})} + e^{i\theta(\mathbf{r},t)}\sqrt{\delta(\mathbf{r}, t)}\right)$

Inhomogeneity (halo) wavefunction

time-dependent uniform background density

random phase

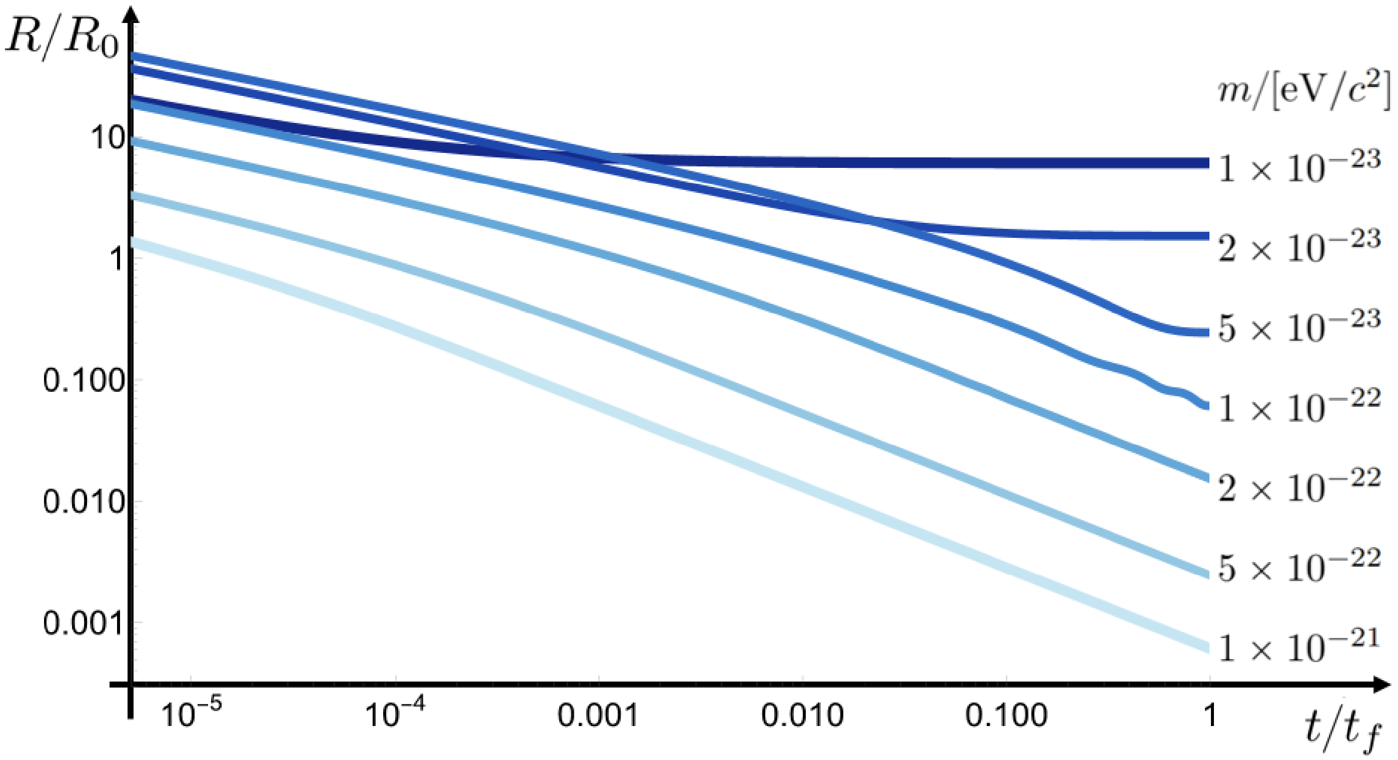
$$\boxed{\delta(r) = \frac{R_0^3}{R(t)^3} e^{-r^2/R(t)^2}}$$



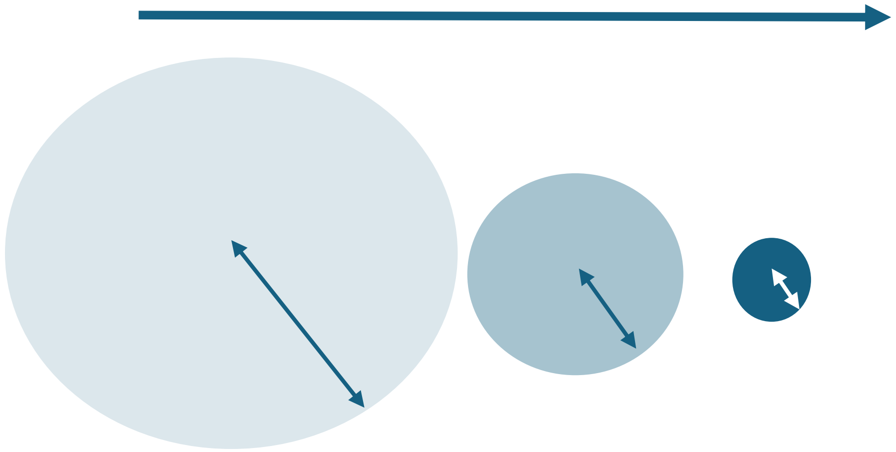
Evolution of the halo size

in expanding Universe

$$\ddot{R}+\frac{4}{3t}\dot{R}-\frac{\hbar^2 t_f^{8/3}}{m^2 t^{8/3}}\frac{1}{R^3}+\frac{2c^2R_0^3 t_f^{4/3}R}{3t^2}\int_{t_i}^{t}\frac{\tau^{-1/3}d\tau}{(R^2(t)+R^2(\tau)+4C(\tau,t))^{5/2}}=0$$



Collapse towards a halo



[In preparation]

ULDM gravitational potential

Einstein's equations in the perturbed FLRW spacetime:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\frac{1}{a^2}\Delta\Phi - \frac{3\dot{a}}{a}\frac{\dot{\Phi}}{c^2} - 8\pi G\rho_0\frac{\Phi}{c^2} = 4\pi G\rho_0\delta$$

$$\mathcal{L}(t) = \frac{1}{Gmt_f^2}\frac{\sqrt{\pi}}{4}\left[-\hbar R_0^3 R^2\dot{\beta} - \frac{\hbar^2 t_f^{4/3}}{mt^{4/3}}\frac{R_0^3(1+4R^4\beta^2)}{2R^2} + \frac{mc^2 R_0^6 t_f^{2/3}}{6t^{2/3}}\int_{t_i}^{t}\frac{\dot{a}(\tau)d\tau}{(R^2(t)+R^2(\tau)+4C(\tau,t))^{3/2}}\right]$$

$$\int_u^\eta dv\,\frac{a}{a'}$$

$$\Phi(\eta,\mathbf{x})$$