Astronomical observations and Fuzzy dark matter

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Based on: arXiv: 2312.09079, 2412.01307, 2412.08372, 2507.01686

Outline

- Brief introduction and fuzzy dark matter
- Dynamical heating of Nube by FDM
- Tidal suppression of the heating effect
- Summary

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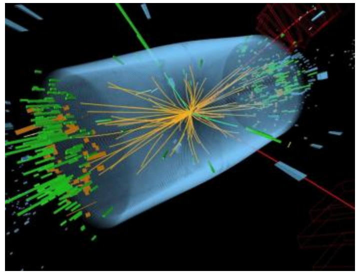
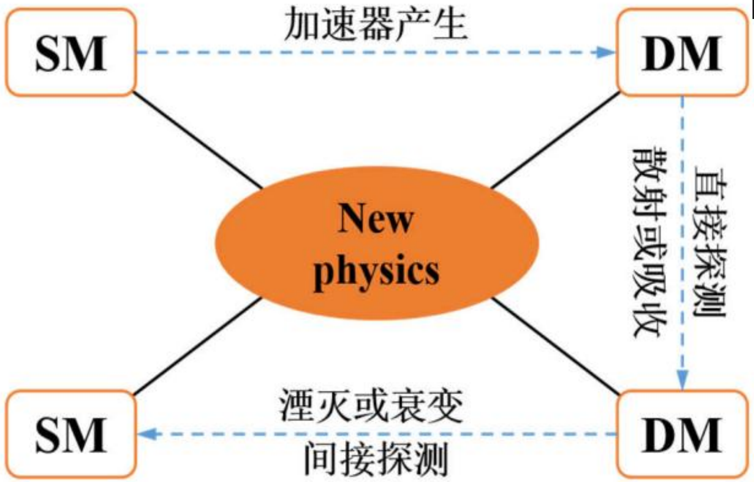
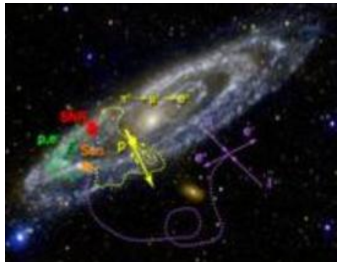
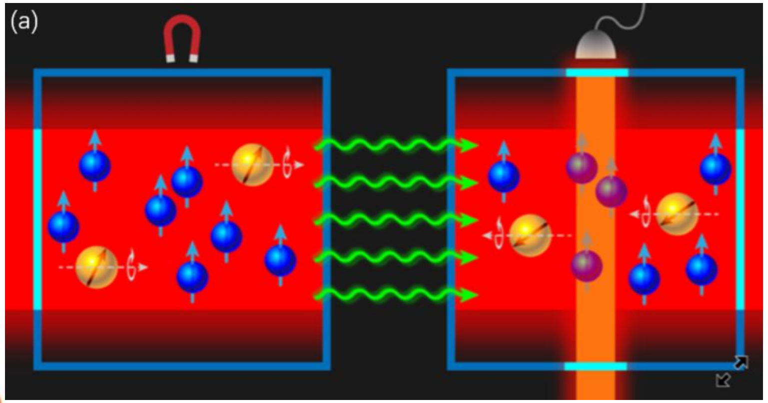
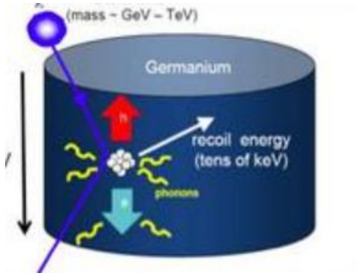
- **Methods to detect dark matter**

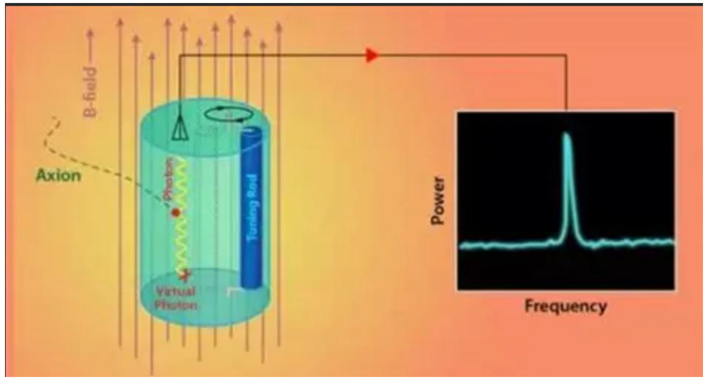


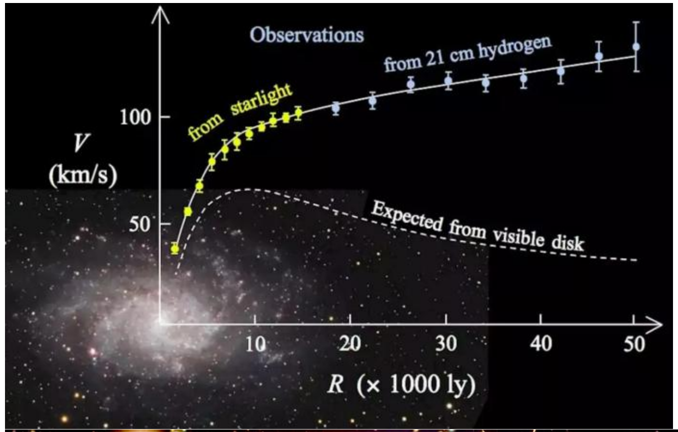










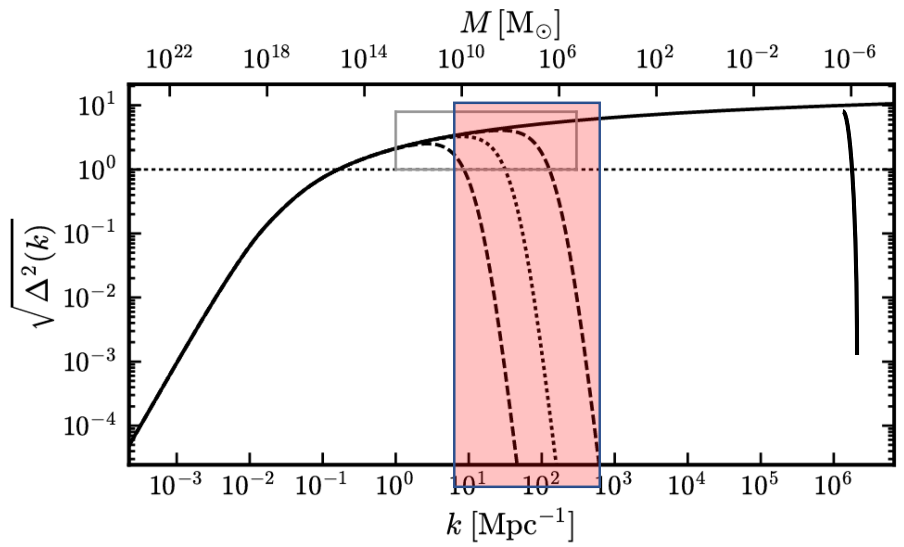


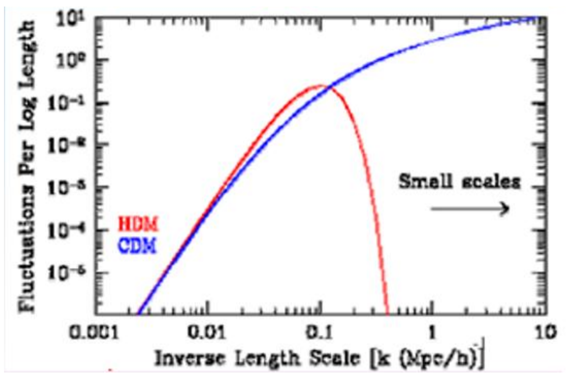
Model dependent searches

Model independent astronomical constraints

Probing properties of dark matter by astronomical observations

- In ΛCDM, dark matter particles are assumed to be generated with ***~0 momentum*** and ***collisionless,*** which means there is no interaction between DM besides gravity. DM seeds the structure formation by a nearly ***scale-invariant*** fluctuation spectrum.
- If DM is different from CDM, it may affect structure at the smallest scale and different from prediction of ΛCDM. Astronomical observations to smaller scales ($< 10^{10}$ M_{sun}) may set constraints on the properties of DM particles.
- It is very promising because there are very powerful astronomical instruments, DESI, JWST, LSST, CSST, WFIRST, EUCLID ⋯ M ~ 10^6 M_* at ~ 1 Mpc from the Milky Way and M31 are planed attractive targets.

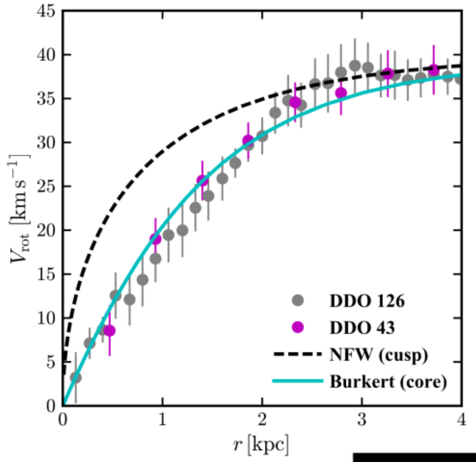


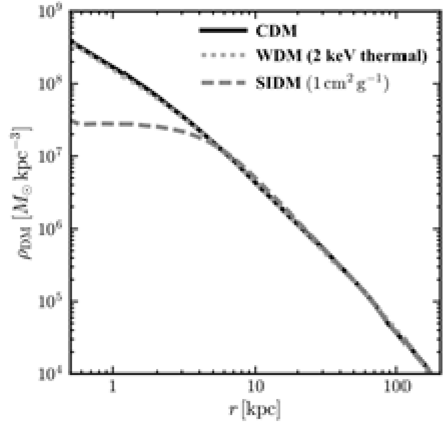


- **numerical simulation** is necessary;

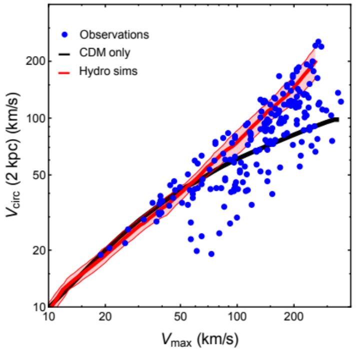
The small scale problems are possible implications on the nature of dark matter particles

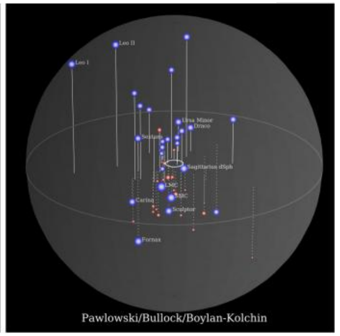
1, core-cusp: The dashed line shows the ΛCDM expectation for a typical rotation curve of a Vmax ≈ 40 km s^{-1} in dwarf galaxies. The data points show the measured rotation curves of two example galaxies of this size requiring a constant DM density core. (LITTLE THINGS survey, Oh et al. 2015)





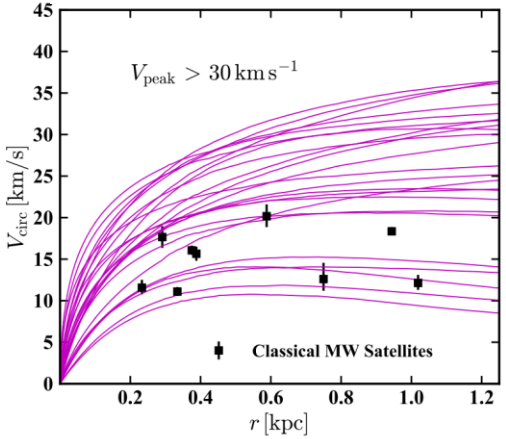
2, missing satellites. Figure show Simulated and observed dwarf galaxies. Deep survey '*seems*' solve the problems. (Garrison-Kimmel et al. 2017)

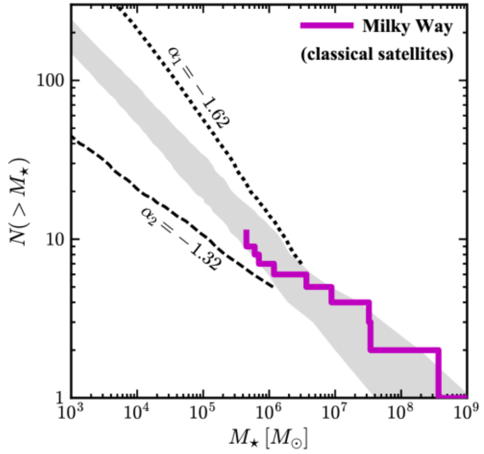




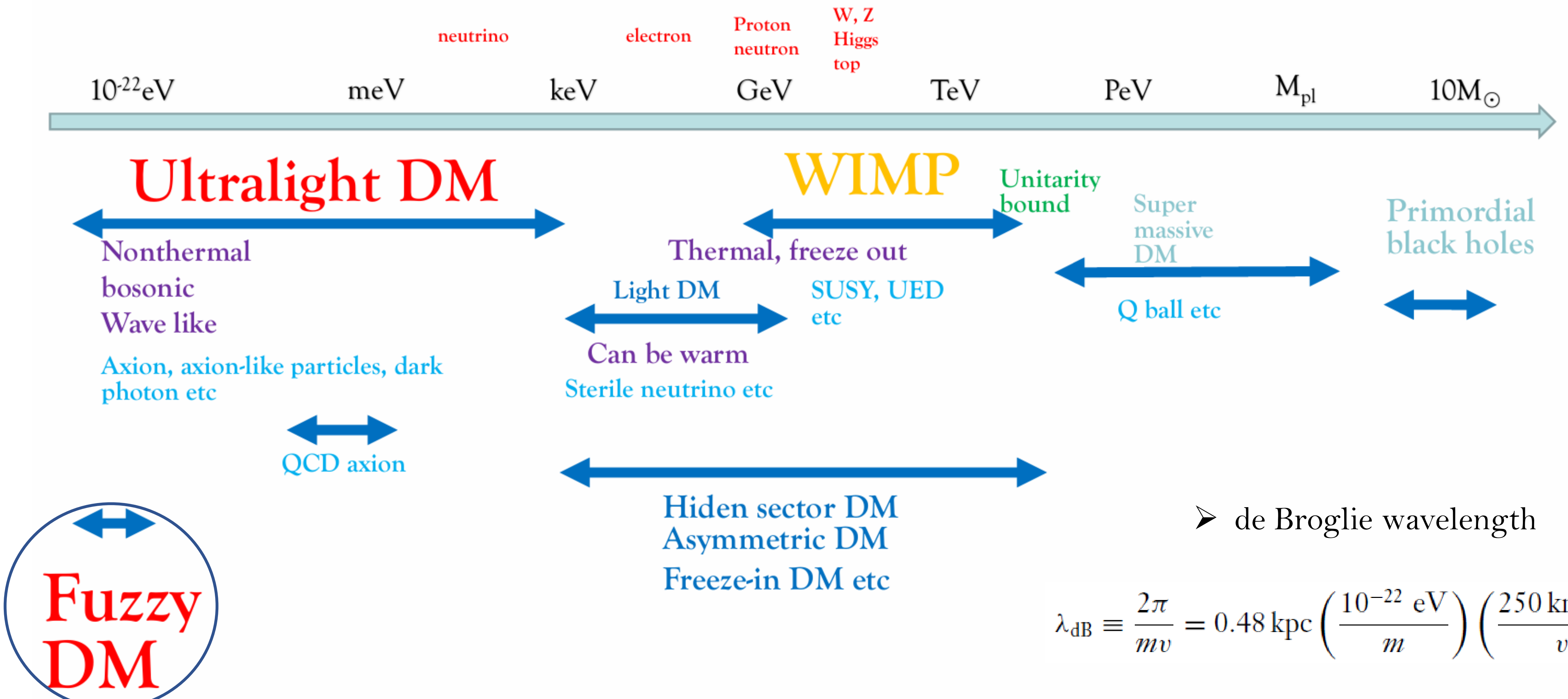
3, diversity problem. The observation of rotation curves shows that the rotation velocity vs maximal velocities have very large dispersion.

4, too-big-to-fail. Simulation gives rotation curves for biggest subhalos, while only smaller dwarf galaxies are observed. No dwarf corresponds to the biggest ones. this is an independent problem to the 1st one.





Dark matter and Ultra light DM



- de Broglie wavelength

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.48\,{\rm kpc}\left(\frac{10^{-22}\ {\rm eV}}{m}\right)\left(\frac{250\,{\rm km\,s^{-1}}}{v}\right)$$

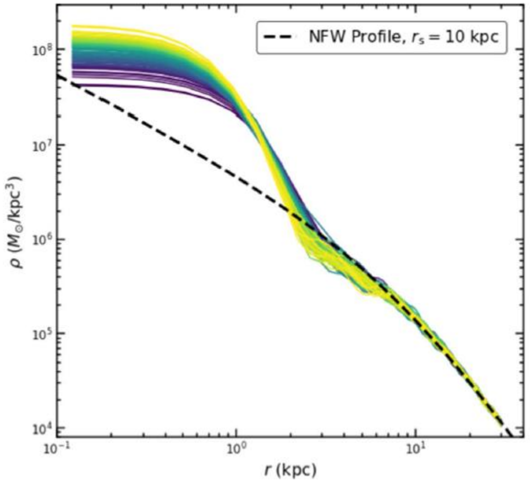
Properties of Fuzzy DM: small scale suppression

- FDM does not change the structure at large scales and while at scales comparable to its wave length the structure is suppressed.

$$\lambda = \frac{h}{mv} \sim 0.5\text{kpc}\left(\frac{10^{-22}\text{eV}}{m}\right)\left(\frac{220\text{km/s}}{v}\right)$$

- The structure suppression within the wave length solves the cusp-core problem.
- The FDM halo is characterized by a profile with a soliton core and an NFW envelope. There is a stationary state of FDM with minimal energy, referred to as soliton;

$$\rho_{\rm FDM}(r) = \begin{cases} \frac{\rho_c}{[1+0.091(r/r_c)^2]^8} & , \; r < kr_c \\ \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2} & , \; r \geq kr_c . \end{cases}$$

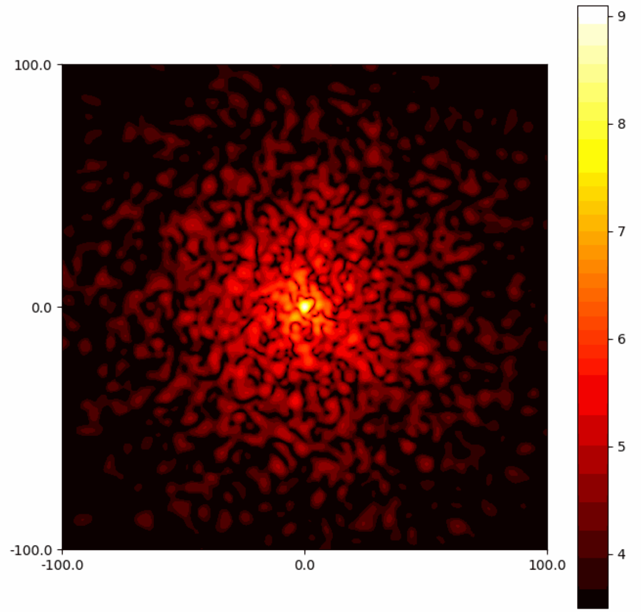


Core-cusp problem

Properties of Fuzzy DM: interference of waves

- Interference between the waves results in many interesting effects.
- These dynamical evolutions lead to **fluctuations of the gravitational field**, which inject energy into the stars residing in it, leading their **velocities to increase** and their spatial distribution to become **more diffuse** over time.
- This effect is referred as the **dynamical heating**.

granules evolution

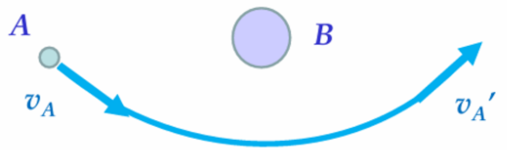


$$\Delta v \sim 2GM/(bv) \qquad M \sim 4\pi\rho(\lambda_{\rm dB}/2)^3/3 \qquad b \sim \lambda_{\rm dB}/2$$

$$\mathrm{rms}\,\Delta v \sim 4\,\mathrm{km/s}\left(\frac{T}{5\,\mathrm{Gyr}}\right)^{1/2}\left(\frac{\rho}{0.01\,\mathrm{M_\odot\,pc^{-3}}}\right)\left(\frac{250\,\mathrm{km/s}}{v}\right)^2\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)^{3/2}$$

Hui, 2101.11735

Yang, **XJB**, Yin, Phys.Rev.D 111 (2025) 6, 063013



Gravitational Slingshot

$m_A \ll m_B$

$v_A' > v_A$

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- Motivation for fuzzy dark matter (FDM)
- An isolated and extremely diffuse galaxy: Nube
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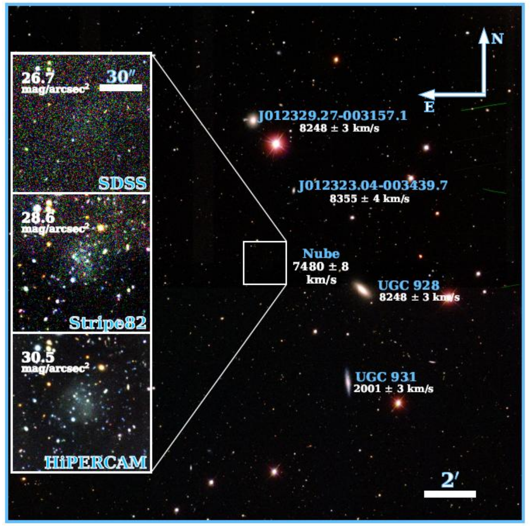
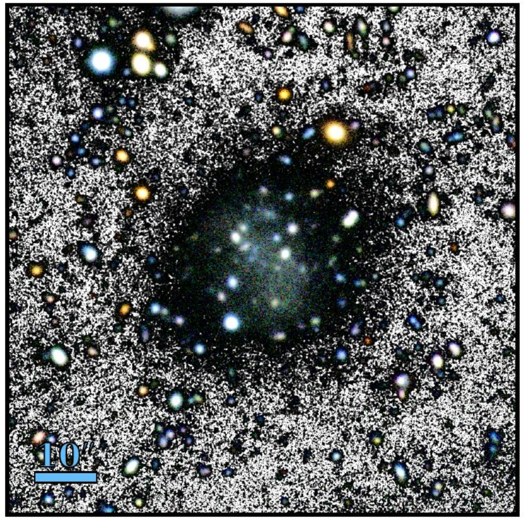
An isolated and extremely diffuse galaxy: Nube





M. Montes et al. Astronomy & Astrophysics681, A15 (2024).

- Age:

$$10.2^{+2.0}_{-2.5}\ \mathrm{Gyr}$$

- Distance:

$$107 \pm 5\ \mathrm{Mpc}$$

- Total stellar mass:

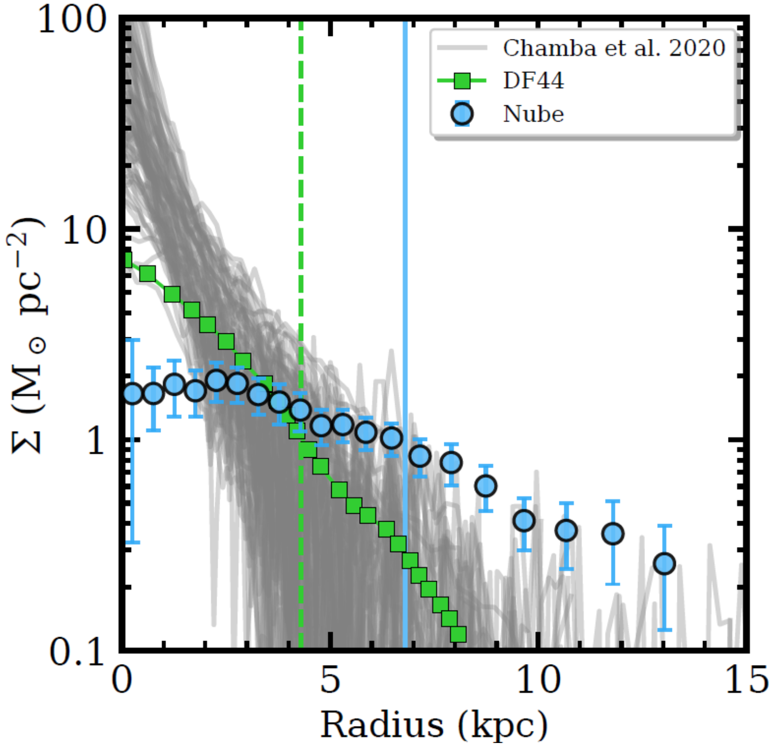
$$M_* = 3.9 \pm 1.0 \times 10^8\ M_\odot$$

- Half-light radius:

$$R_e = 6.9 \pm 0.8\ \mathrm{kpc}$$

- Dynamical mass:

$$2.6 \pm 1.7 \times 10^{10}\ M_\odot \text{ within } 3\,R_e = 20.7\ \mathrm{kpc}$$



anomalous star distribution: low central brightness, large *R_e, exceeding UDGs (R_e~1.5-5kpc)*

- **FDM dynamics** $m \simeq 10^{-22}\mathrm{eV}$
  - Equation of motion $\partial_\mu\left(\sqrt{-g} g^{\mu\nu} \partial_\nu \phi\right) - \sqrt{-g} m^2 \phi = 0$

    ⇓

    度规： $ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Phi)d\mathbf{r}^2$

    non-relativistic limit: $\phi = \frac{1}{\sqrt{2m}}\left(\psi e^{-imt} + \psi^\star e^{imt}\right)$

  - Schrodinger-Poisson (SP) equation:

$$i\partial_t \psi = -\frac{\nabla^2}{2m}\psi + m\Phi\psi,$$
$$\nabla^2\Phi = 4\pi G\rho, \quad \rho = m\left|\psi\right|^2.$$

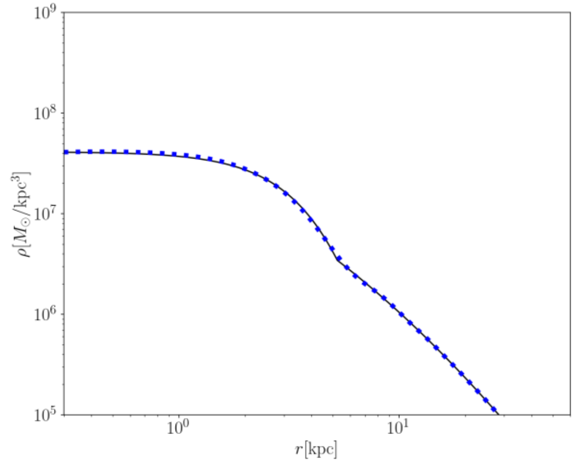
  - Solve the coupled equations numerically

Dynamical heating effect of FDM

- Initial wave function

Soliton+NFW profile

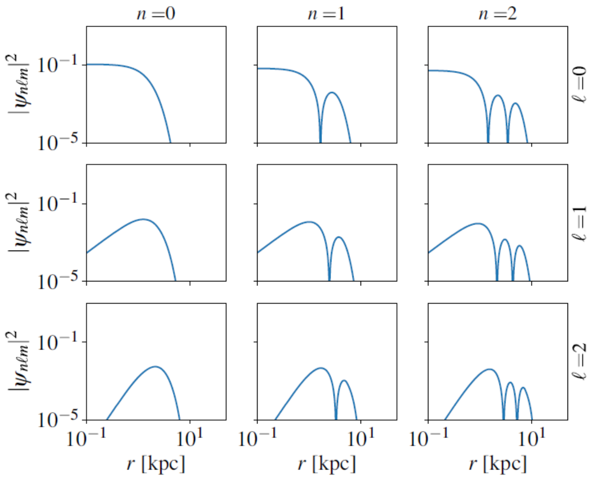
$$\rho_{\rm in}(r) = \begin{cases} \dfrac{\rho_c}{[1+0.091(r/r_c)^2]^8}, & r < kr_c \\ \dfrac{\rho_s}{(r/r_s)\,(1+r/r_s)^2}, & r \geq kr_c, \end{cases}$$



$$\psi(0,\mathbf{x}) = \sum_{nlm} |a_{nl}| e^{i\phi_{nlm}} \Psi_{nlm}(\mathbf{x}),$$

$$-\frac{\hbar^2}{2m_a}\nabla^2\Psi_{nlm}(\mathbf{x}) + m_a\Phi_{\rm in}(r)\Psi_{nlm}(\mathbf{x}) = E_{nl}\Psi_{nlm}(\mathbf{x}).$$

$$\rho_{\rm out}(r) = \frac{m_a}{4\pi}\sum_{nl}(2l+1)|a_{nl}|^2 R_{nl}^2(r).$$



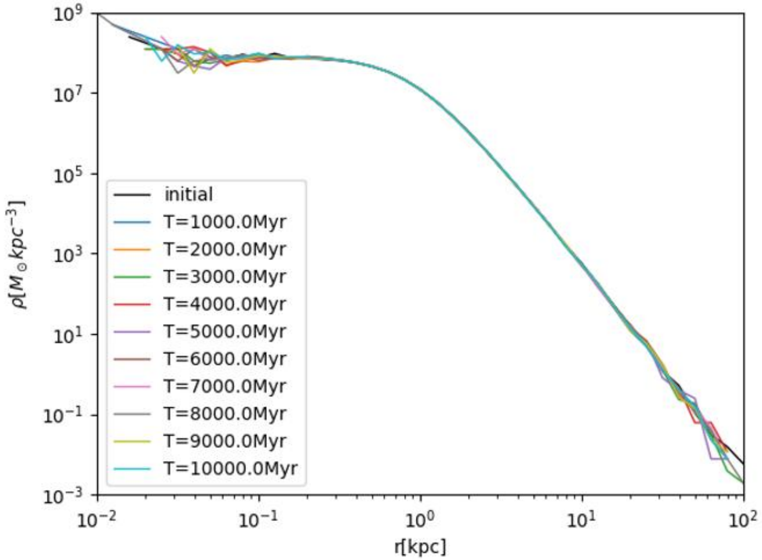
T. D. Yavetz, X Li, and L Hui,
Phys. Rev. D 105 (2022) 2, 023512

- Stellar initial condition
  - Density profile

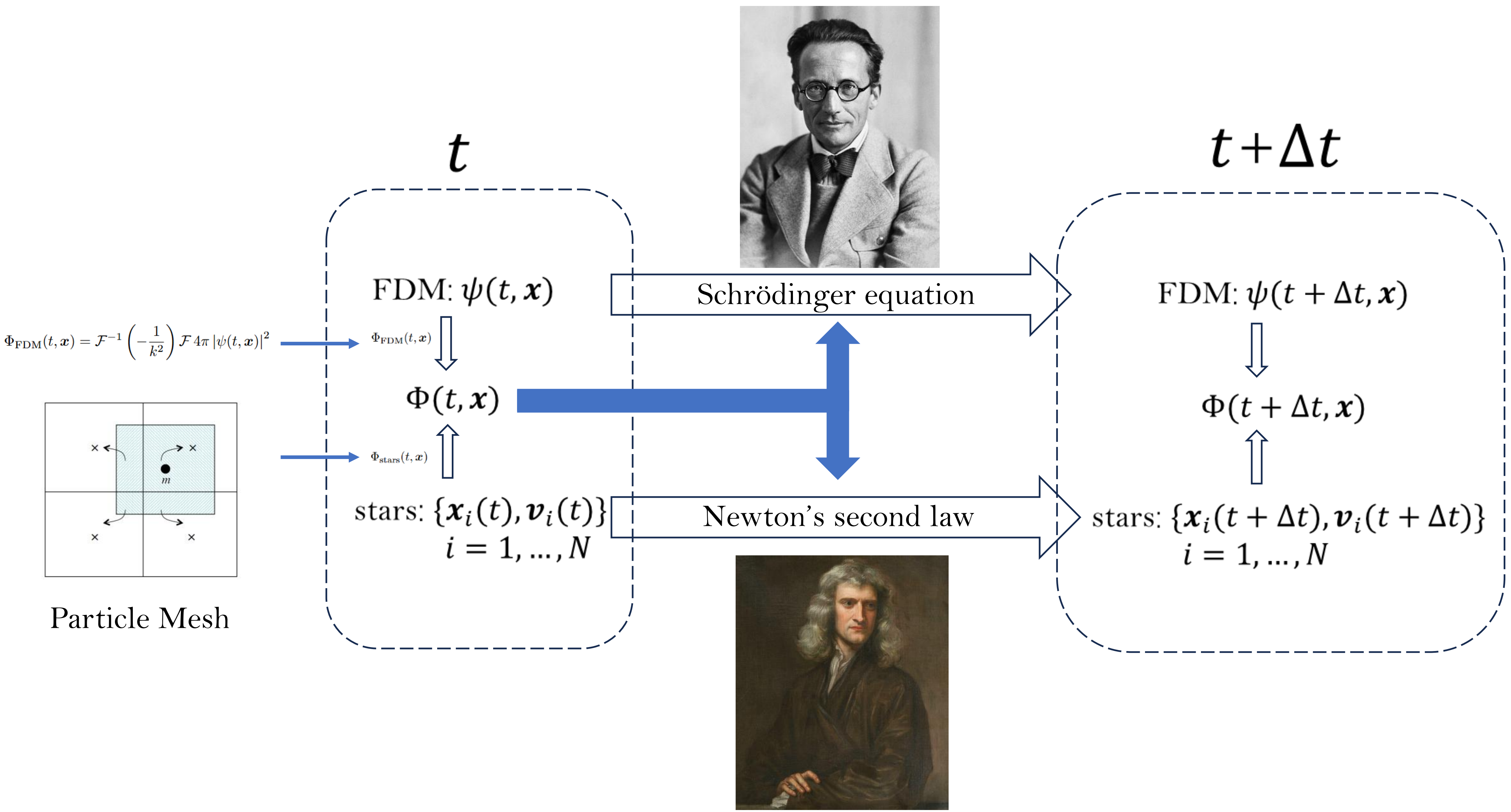
$$\rho_\star(r) = \frac{3M_\star}{4\pi a_i^3}\left(1+\frac{r^2}{a_i^2}\right)^{-5/2}$$

  - Eddington formula

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\frac{\mathrm{d}}{\mathrm{d}\mathcal{E}}\int_0^{\mathcal{E}}\frac{\mathrm{d}\Phi_0}{\sqrt{\mathcal{E}-\Phi_0}}\frac{\mathrm{d}\rho_\star}{\mathrm{d}\Phi_0},$$



Dynamical heating effect of FDM



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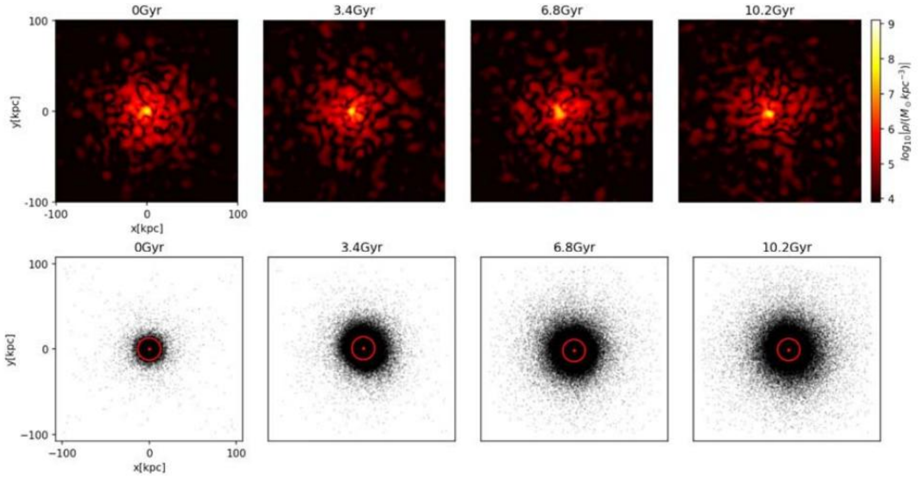

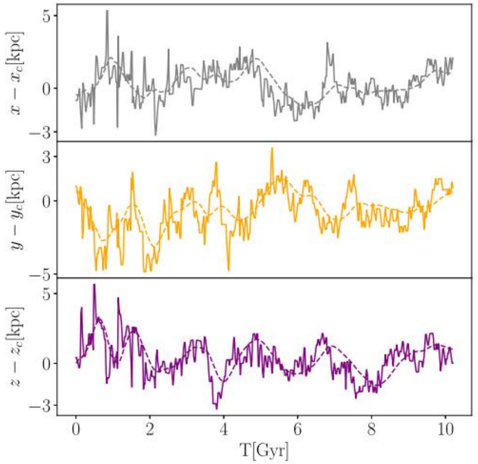

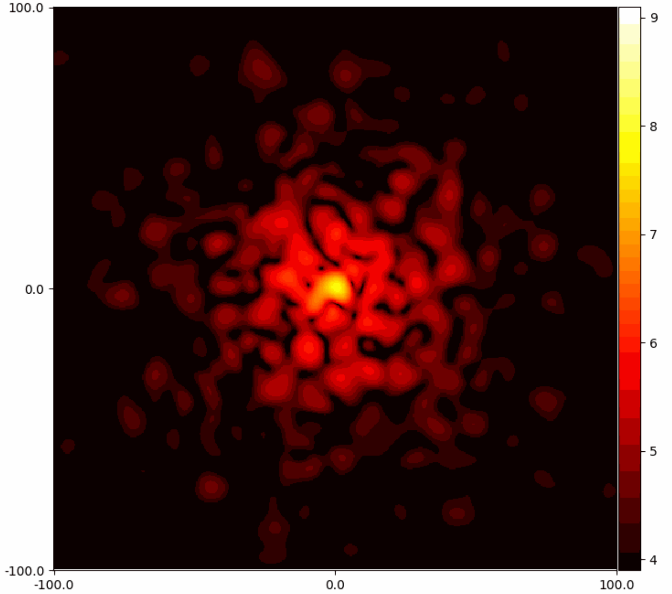

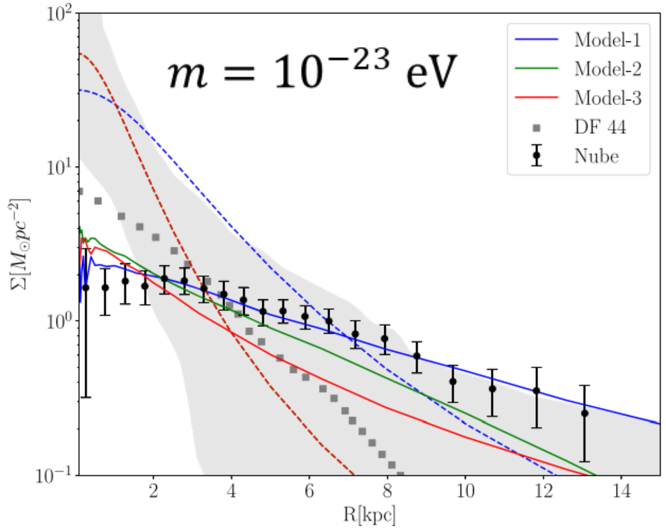

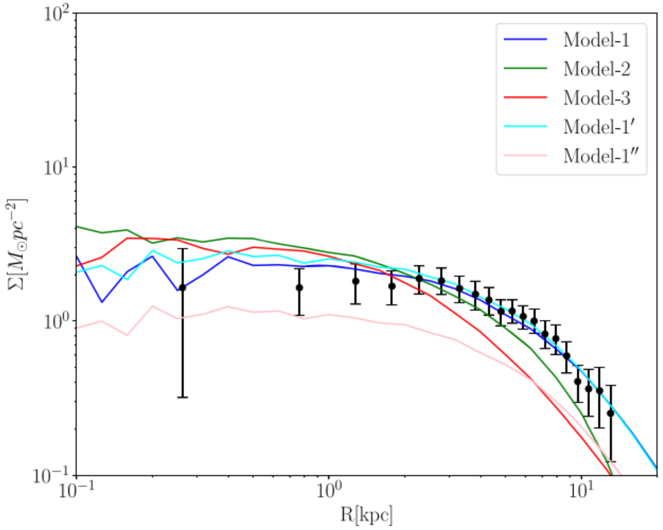

Y.M. Yang, Z.C. Zhang, X.J. Bi, and P.F. Yin, 2025 ApJL 981 L26

Dynamical heating effect of FDM

- A natural consequence in this picture
  - The longer the stars experience heating, the more diffuse their distribution becomes, and the larger their velocity dispersion grows.
- The dynamical heating effect of FDM is most promising in isolated galaxies, and will be affected by environments
- Qualitatively consistent with other observations *Y. M. Yang, X. J. Bi, and P. F. Yin, JCAP 07, 054*

✓ The Milky Way thick (thin) stellar disc is dominated by older (younger) stellar populations, and exhibits higher (lower) velocity dispersion. This is consistent with heating effect of FDM with $m \sim 0.5 - 0.7 \times 10^{-22}$ eV.

B. T. Chiang, J. P. Ostriker, and H. Y. Schive, MNRAS 518, 4045-4063 (2023)

✓ Isolated dwarf galaxies always seem to be young, blue, HI-rich and star-forming.

D.J.Prole et al., MNRAS 488, 2143-2157 (2019)

✓ There is a trend that, compared to younger dwarf galaxies, older dwarf galaxies tend to lie closer to high-density regions.

J. Roman and I.Trujillo, MNRAS 468, 4039-4047 (2017)

✓ Within a dwarf galaxy, older stars tend to have a more diffuse distribution compared to younger stars.

C.R.Higgs et al., MNRAS 503, 176-199 (2021); R.Pucha et al 2019 ApJ 880 104

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Tidal suppression of the heating effect

PHYSICAL REVIEW LETTERS **123,** 051103 (2019)

Strong Constraints on Fuzzy Dark Matter from Ultrafaint Dwarf Galaxy Eridanus II

PHYSICAL REVIEW D **106,** 063517 (2022)

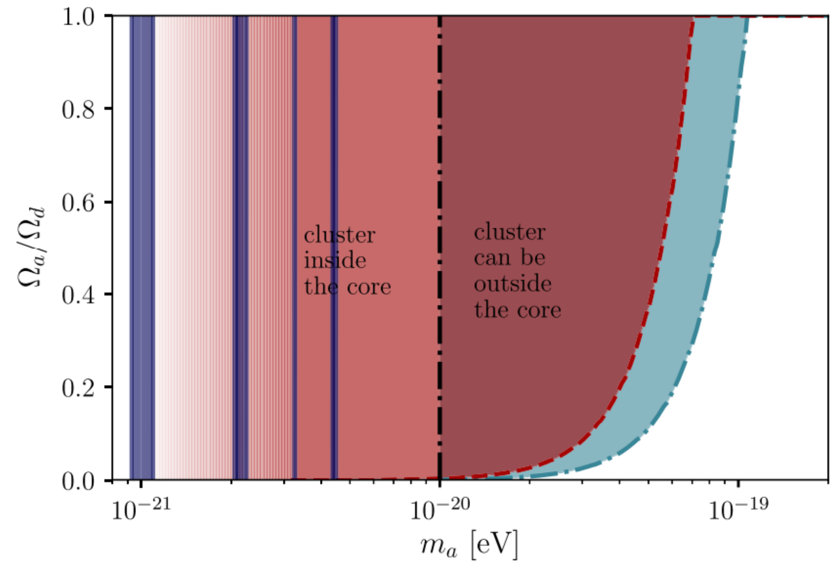
Excluding fuzzy dark matter with sizes and stellar kinematics of ultrafaint dwarf galaxies

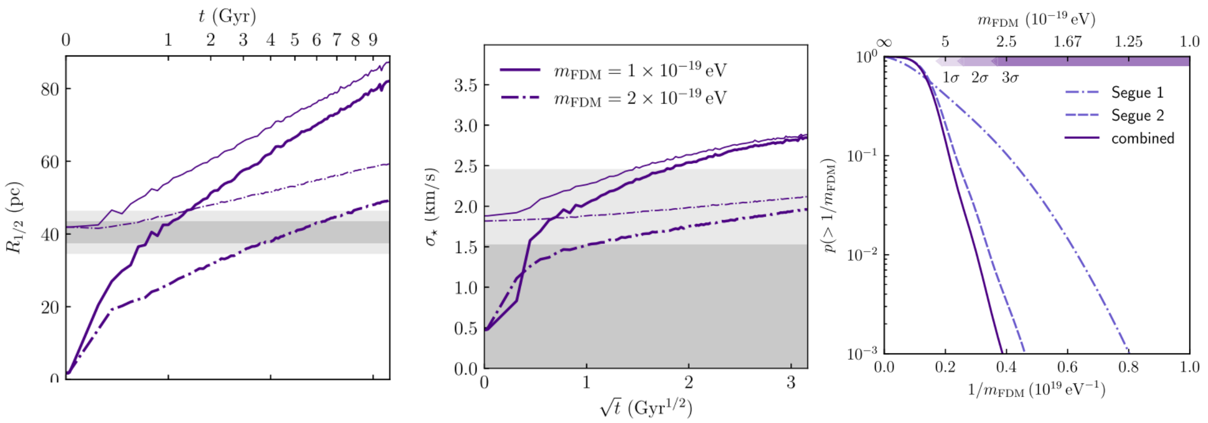
arXiv > astro-ph > arXiv:2501.07631

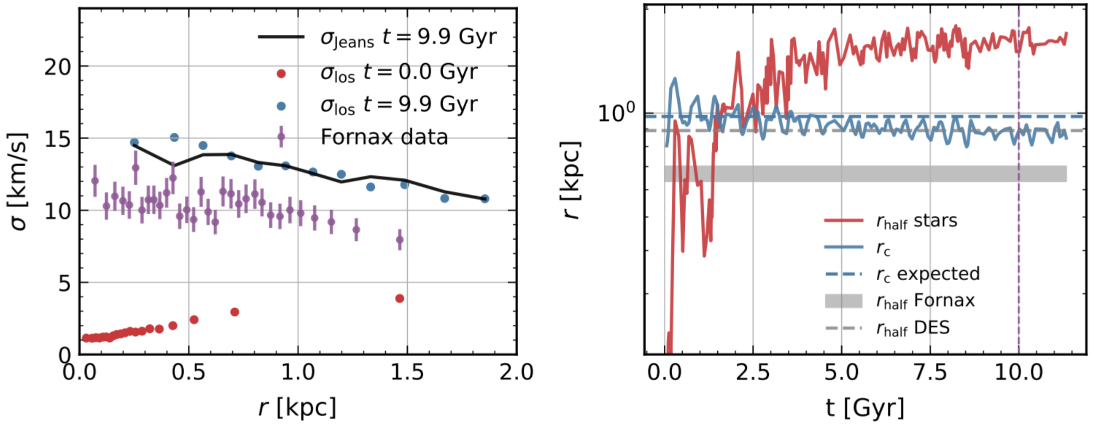
Astrophysics > Astrophysics of Galaxies

[Submitted on 13 Jan 2025]

Ultra-Light Dark Matter Simulations and Stellar Dynamics: Tension in Dwarf Galaxies for $m < 5 \times 10^{-21}$ eV





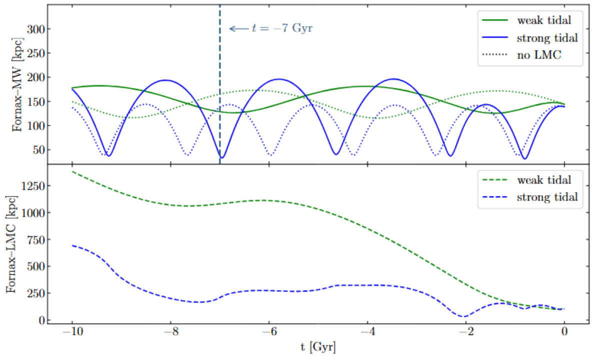


Tidal suppression of the heating effect

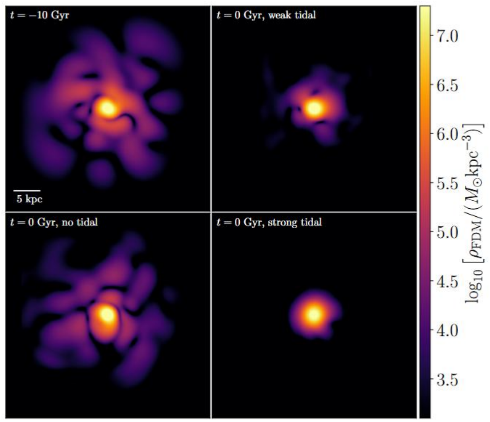
2507.01686, accepted by APJL

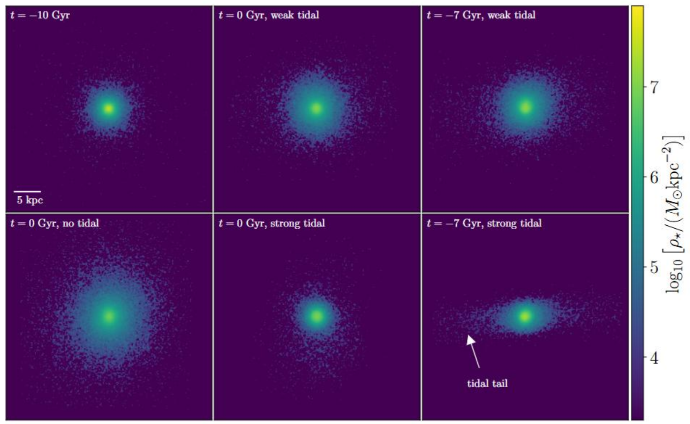
➢Fornax in the Milky Way

➢ Orbit



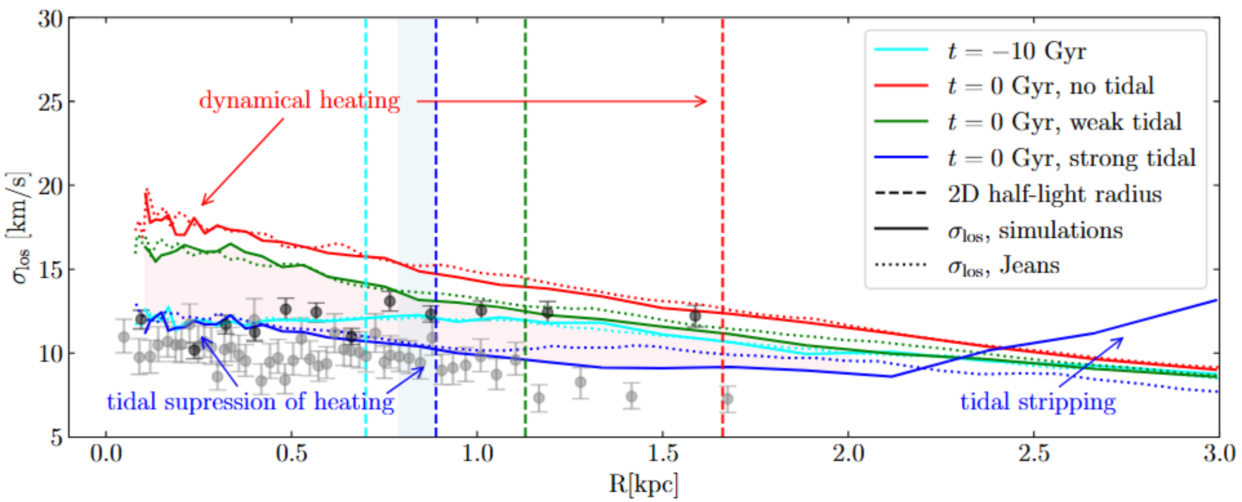
➢ FDM & stellar density





➢ Line-of-sight velocity dispersion

$m=10^{-22}$eV



Summary

- Astronomical observations can probe DM properties in a model-independent way. It is the key to find a suitable system to constrain the properties of dark matter.

- Fuzzy dark matter is proposed to solve the core-cusp problem. The wave interference leads to dynamical heating and explains many observations, including stellar distribution in the Nube galaxy.

- Tidal effect suppresses the heating effects and may relax the previous constraints on the Fuzzy dark matter mass substantially.