Interpreting the Extremely Diffuse Stellar Distribution of the Nube Galaxy through Fuzzy Dark Matter

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QingDao， 2025. 05. 11

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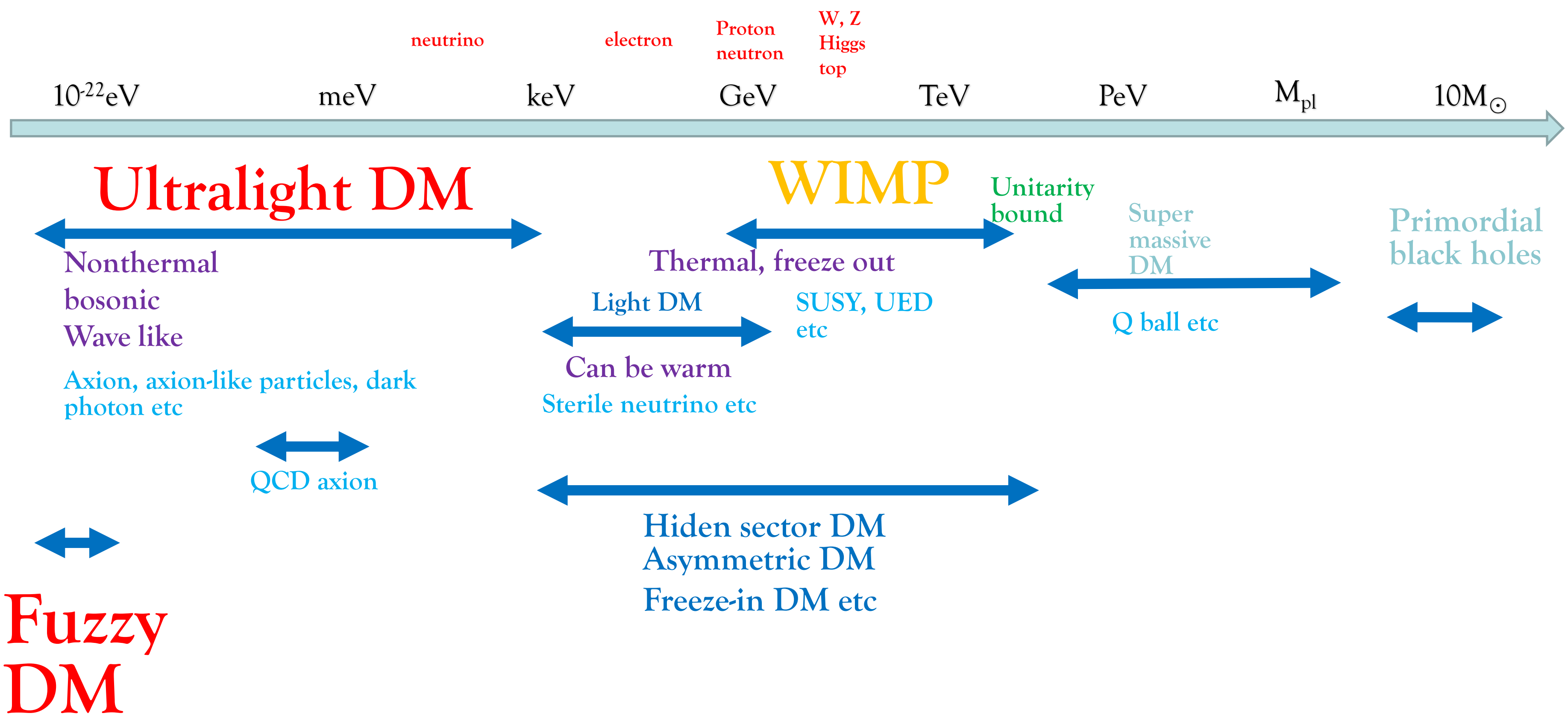
arXiv:2412.01307

Outline

- *The properties of fuzzy dark matter*
- *Observation of the almost dark galaxy Nube*
- *Procedure of the simulation*
- *Simulation results and the FDM interpretation of the stellar distribution of Nube*

Dark matter and Ultra light DM



Wave DM and Fuzzy DM

- *The number of DM particles in a de Broglie volume in the Galaxy*

$$N \sim \frac{\rho\lambda^3}{m} = \frac{\rho}{m}\left(\frac{h}{mv}\right)^3 \sim \left(\frac{\rho}{0.4\mathrm{GeV/cm^3}}\right)\left(\frac{37\mathrm{eV}}{m}\right)^4\left(\frac{220\mathrm{km/s}}{v}\right)^3$$

$N \gg 1$ when $m \ll O(10)$ eV

Such bosonic DM can be effectively described by waves

- *De Broglie wavelength*

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

Such DM has a wavelength at the galactic scale and is called fuzzy DM

Hu, Barkana, Gruzinov, astro-ph/0003365
Peebles, astro-ph/0002495
Hui, Ostriker, Tremaine, Witten, 1610.08297
Ferreira, 2005.03254
Hui, 2101.11735

Dynamics of FDM

- *A scalar field satisfies the Klein-Gordon equation*

  In the non-relativistic limit, the field can be expanded as

$$\phi = \frac{1}{\sqrt{2m}} \left(\psi e^{-imt} + \psi^* e^{imt} \right)$$

ψ satisfies a Schrodinger-like equation (in a flat metric)

$$i\,\partial_t \psi = -\frac{\nabla^2}{2m}\psi + m\Phi\psi \quad \textit{with} \quad k^2/m \ll m$$

It is a complex field, but often referred to as the wave function

- *The gravitational potential should satisfy the Poisson equation*

$$\nabla^2\Phi = 4\pi G\rho \qquad \rho = m|\psi|^2$$

- *The evolution of FDM is determined by the Schrodinger-Poisson (SP) equations*

Another description: fluid

- *ψ can be written as*

$$\psi = \sqrt{\rho/m}\, e^{i\theta}$$

- *It satisfies a conservation function*

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

The velocity of fluid can be defined as

$$\vec{v} = \frac{1}{m} \vec{\nabla} \theta = \frac{i}{2m|\psi|^2} (\psi \vec{\nabla} \psi^* - \psi^* \vec{\nabla} \psi)$$

- *ψ also satisfies an Euler-like equation (the Schrodinger equation is complex)*

$$\partial_t \vec{v} + (\vec{v} \cdot \vec{\nabla})\, \vec{v} = -\vec{\nabla} \Phi + \frac{1}{2m^2} \vec{\nabla} \left(\frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}} \right)$$

The last term is referred to as the quantum pressure term

Properties of FDM: small scales

- *The differences between conventional CDM and FDM would be manifest in the system where the wave length is comparable to the system's size*

  FDM does not change the prediction at large scales and exhibits exotic properties at small scales (galactic scales)

- *Consider an equilibrium system with the viral radius* $r \simeq GM/v^2$

  The wavelength of FDM would be smaller than this radius

$$r_{1/2} \geq 3.925 \frac{\hbar^2}{GMm^2} = 0.335\,\mathrm{kpc}\,\frac{10^9 M_\odot}{M}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)^2$$

Hui et. al, 1610.08297

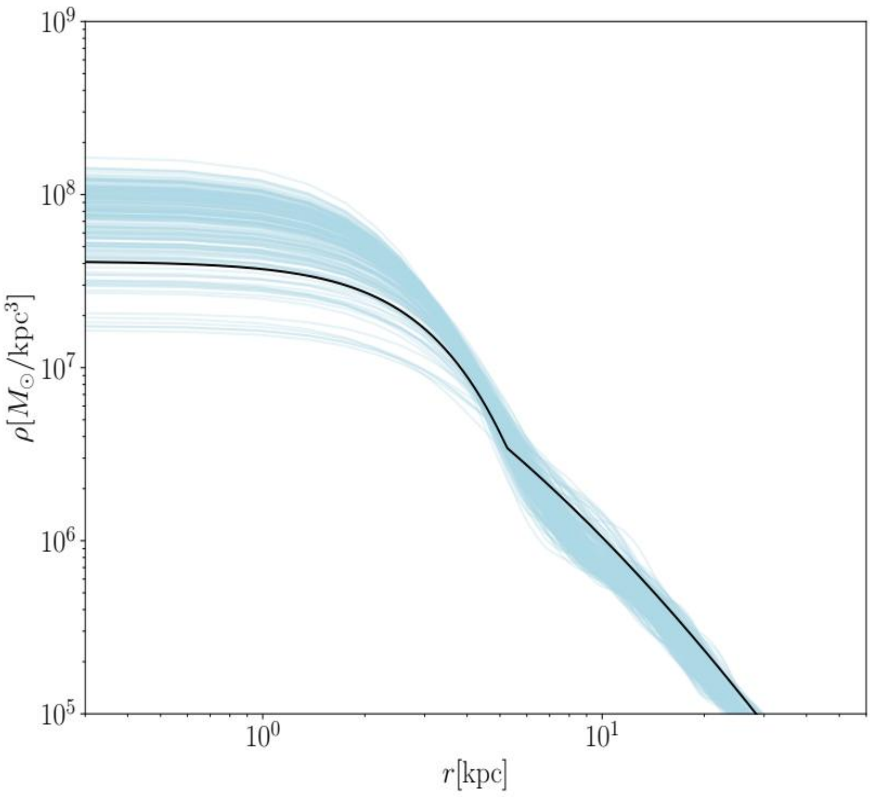
  The small structures are suppressed.
  There is a stationary state with minimal energy, referred to as soliton

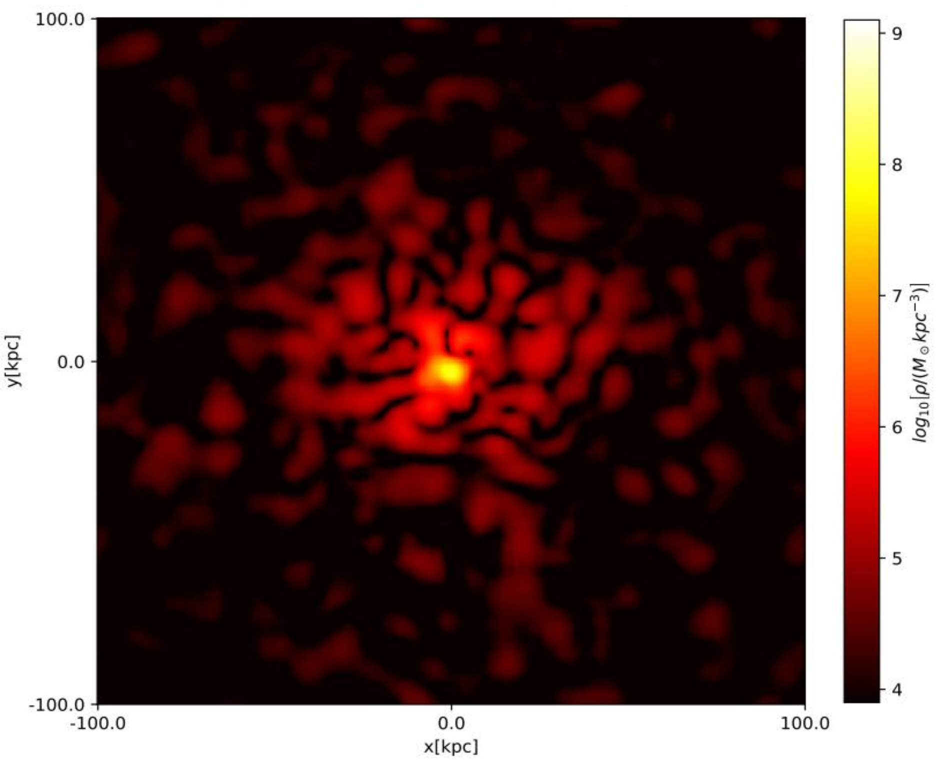
- *The FDM halo is characterized by a profile with a soliton core and an NFW envelope*

Property of FDM: interference

- *The wave function of FDM can be expanded as a superposition of different modes (eigenstates)*

The interference between different modes results in many exotic effects



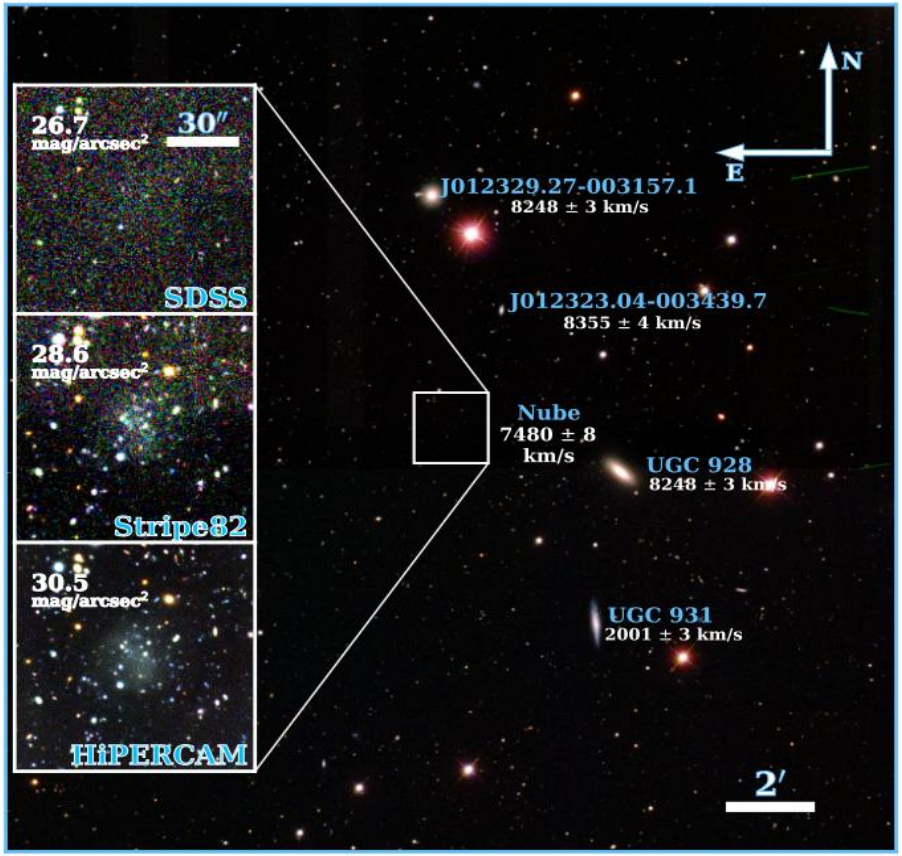


- *Oscillation of the profile*
- *Exotic (unstable) structures*

An almost dark galaxy: Nube

- *Almost dark galaxies are objects that have eluded detection by traditional surveys as the SDSS*

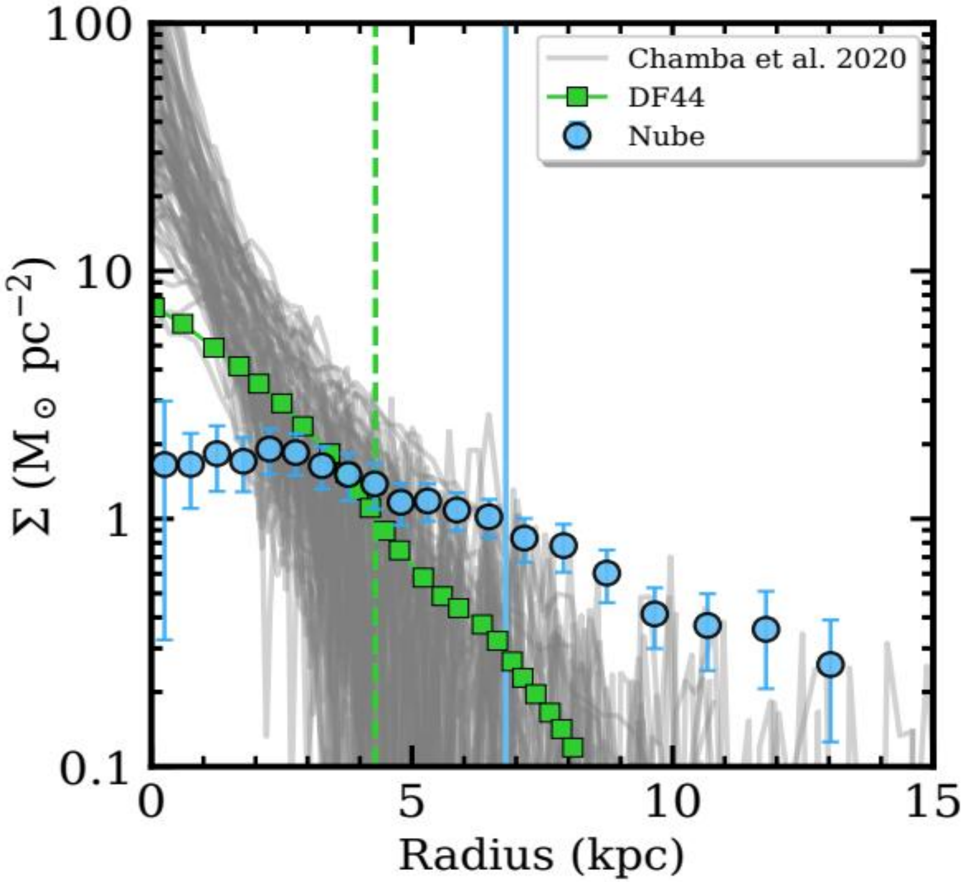
Feedback effects may be inefficient in these galaxies. Thus they are very promising targets for exploring the nature of DM.

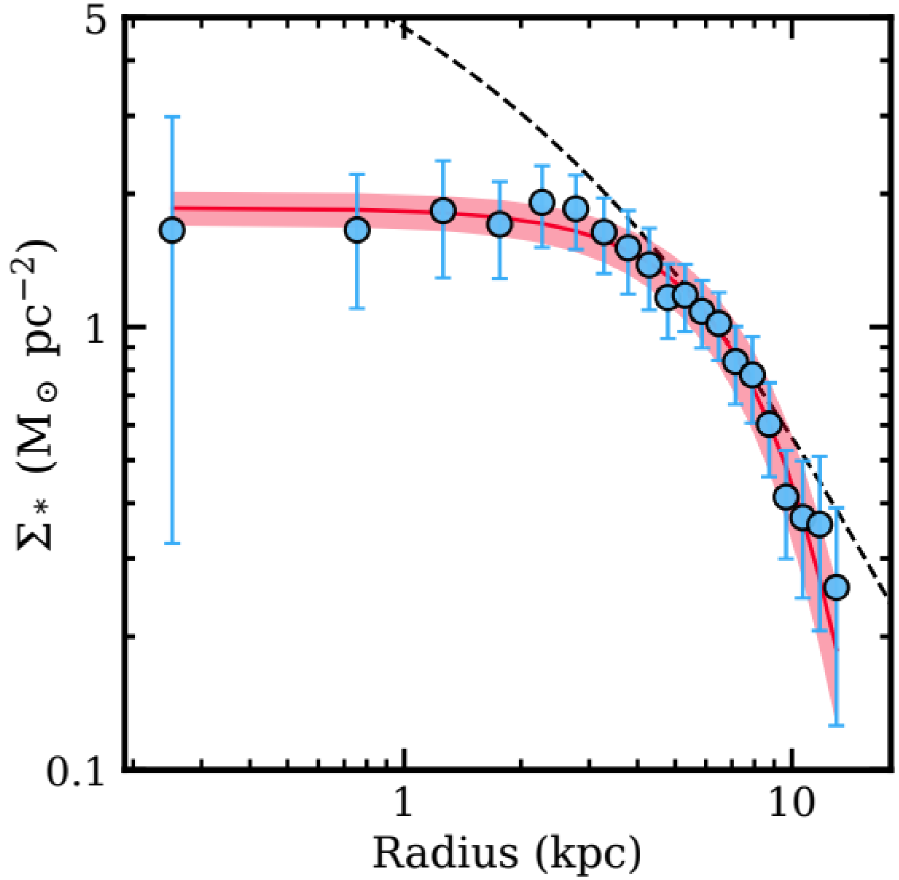


Montes et.al, 2310.12231

- *Nube was discovered by the IAC Stripe82 Legacy Project in 2015*
  Fliri, Trujillo, 2015
  Properties measured by GTC and GBT were reported in 2023
- *Distance ~107 Mpc and lifetime ~ 10.2 Gyr*
- *Stellar mass ~$4*10^8$ M_{sun}, and half-mass radius ~6.9kpc*
- *The most massive and extended object of its kind*
- *An isolated system*

Extremely diffuse stellar distribution



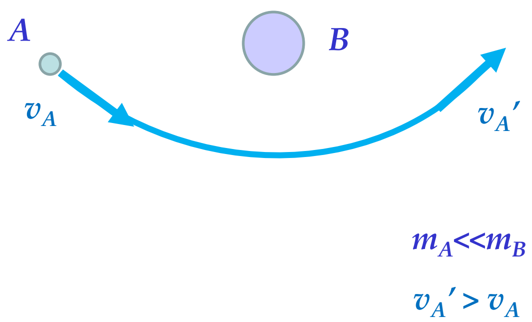


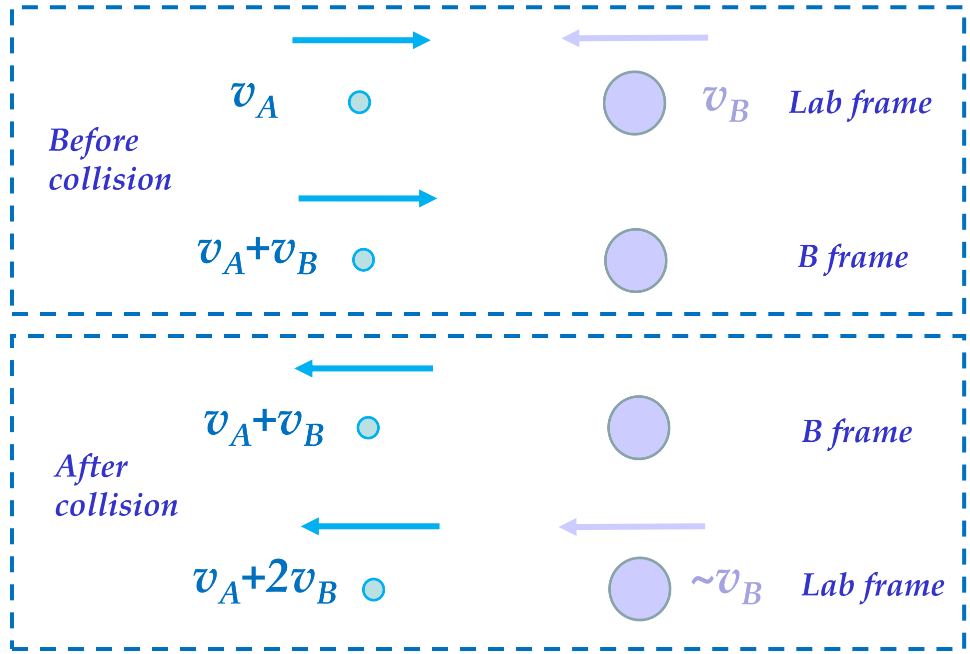
Montes et.al, 2310.12231

- *Nube has a extremely diffuse stellar distribution compared with other galaxies with similar stellar mass*
- *Can be simply fitted by a soliton profile with r_c=6.6 kpc and m~10^{-23}eV*

Dynamic heating effect

- *Gravity assist effect*





- *The kinetic energies of stars would increase via gravitational scattering with structures of FDM*

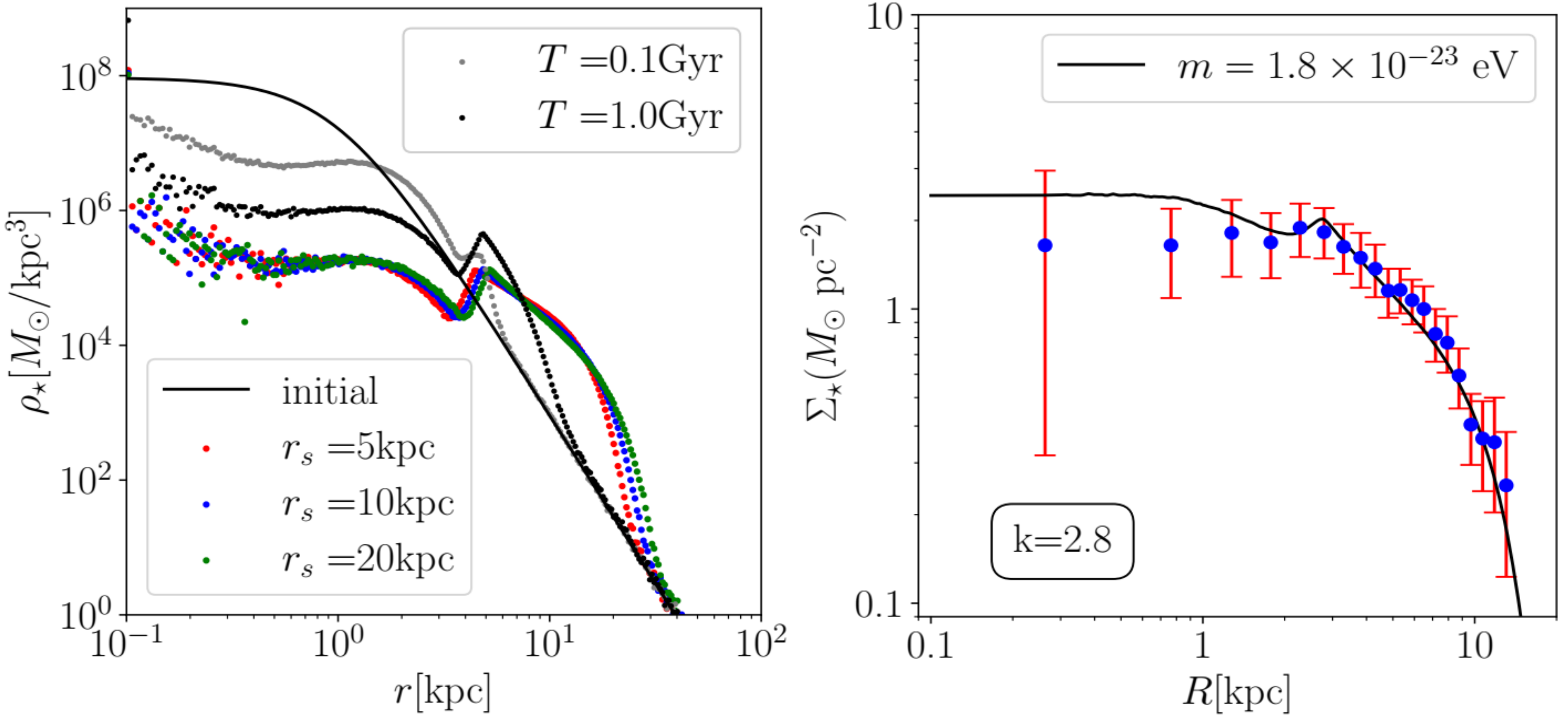
$$\Delta v \sim 2GM/(bv) \qquad M \sim 4\pi\rho(\lambda_{\mathrm{dB}}/2)^3/3 \qquad b \sim \lambda_{\mathrm{dB}}/2$$

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

Hui, 2101.11735

This effect is referred to as the dynamic heating effect

Dynamic heating effect



Yang, Bi, Yin, 2404.05375

- *We use an effective diffusion model (in velocity space) to explain the observation of Nube*
  Bar-Or, Fouvry, Tremaine, 1809.07673
- *More precise analysis requires simulations*

Initial condition of FDM simulation

- *Numerically solve the SP equations to derive the evolution of the FDM halo*
- *The initial wave function as an initial condition is required*
- *Take the initial density profile*

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

Two free parameters k and m_a (using the soliton core density and continuity conditions, and a constant r_s)

- *Note that $\psi = \sqrt{\rho/m}$ is incorrect, since it does not satisfy the SP equations*

We adopt the following procedure to construct the initial wave function

Yavetz, Li, Hui, 2109.06125

Initial wave function

- *Express the initial wave function as a sum of eigenstates of the Schrodinger equation*

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

$$\Psi_{nlm}(\boldsymbol{x}) = R_{nl}(r) Y_l^m(\theta, \varphi)$$

- *The radial functions satisfy the Schrodinger function*

$$-\frac{\hbar^2}{2m_a}\frac{d^2 u_{nl}}{dr^2} + \left[\frac{\hbar^2}{2m_a}\frac{l(l+1)}{r^2} + m_a \Phi_{\rm in}\right] u_{nl} = E_{nl} u_{nl} \qquad u_{nl} \equiv rR_{nl}$$

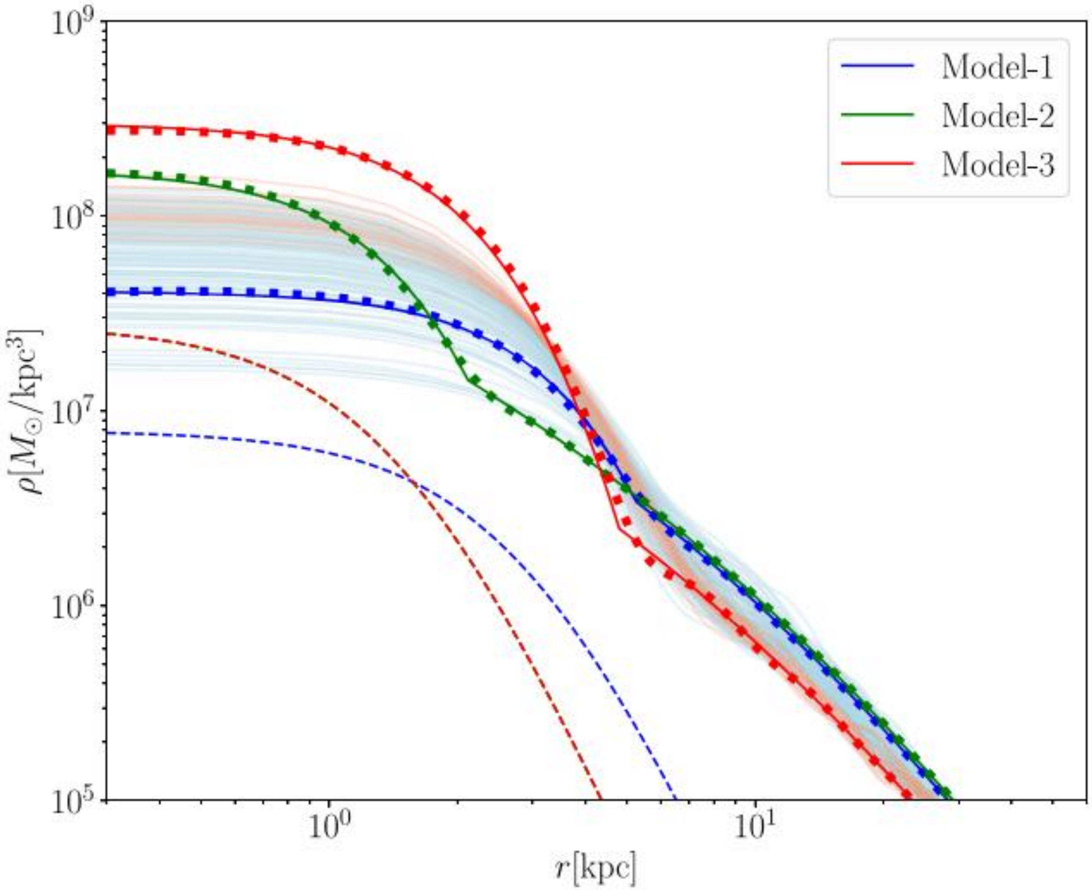
*We derive numerous eigenstates (O(10^3) or more) for combinations of **n** and **l** (omit the m dependence)*

- *Require the following condition and solve coefficients* a_{nl}

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

- *Assign random phases* ϕ_{nl} *to each mode*

Initial wave function



- *The derived wave function can well reproduce the input profile*

Initial stellar condition

- *Stars are taken to be particles in the simulation (10^5 particles here)*
- *The initial position and velocity of each particle are required*
- *Randomly generate positions of particles based on input stellar profile*

  *Take **Plummer** profile with two parameters here*

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

- *Solve the **Eddington** formula to derive the energy distribution of particles in an equilibrium system*

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

  Randomly generate velocities based on this distribution

- *We have tested the stability of this configuration of particles under a static initial potential*

Simulation: evolving the system

- *We use the PYULTRALIGHT package, which adopts the pseudo-spectral method, to evolve the FDM wave function, satisfying the SP equations*

  Edwards, Kendall, Hotchkiss, Easther, 1807.04037

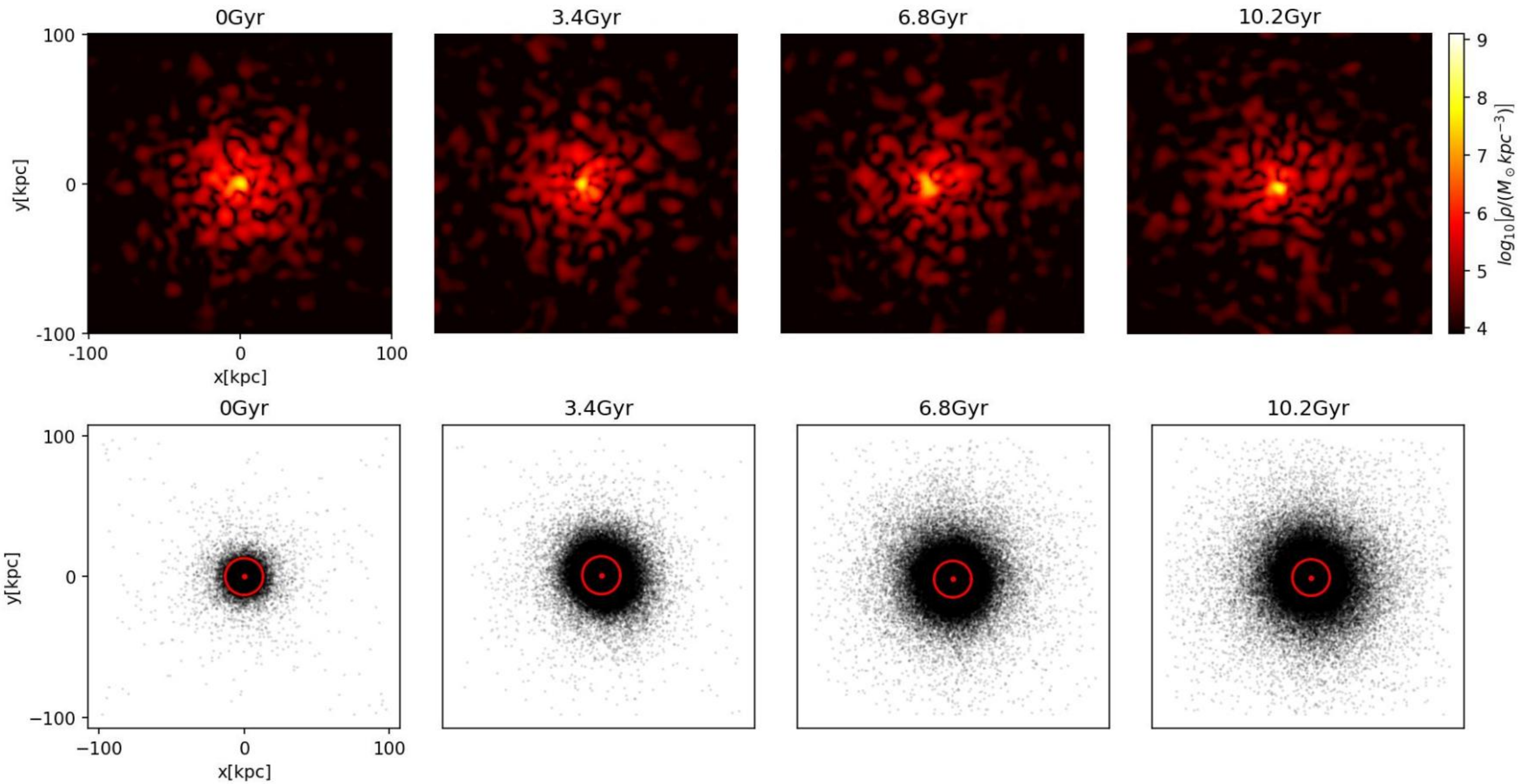
$$\widetilde{\psi}(\tilde{t} + \Delta\tilde{t}_{\mathrm{FDM}}, \tilde{\boldsymbol{x}}) = \exp\left[-\frac{i\Delta\tilde{t}_{\mathrm{FDM}}}{2} \widetilde{\Phi}(\tilde{t} + \Delta\tilde{t}_{\mathrm{FDM}}, \tilde{\boldsymbol{x}}) \right] \times \mathcal{F}^{-1}\left\{ \exp\left(-\frac{i\Delta\tilde{t}_{\mathrm{FDM}}}{2} k^2 \right) \mathcal{F}\left[\exp\left[-\frac{i\Delta\tilde{t}_{\mathrm{FDM}}}{2} \widetilde{\Phi}(\tilde{t}, \tilde{\boldsymbol{x}}) \right] \widetilde{\psi}(\tilde{t}, \tilde{\boldsymbol{x}}) \right] \right\}$$

$$\widetilde{\Phi}(\tilde{t}, \tilde{\boldsymbol{x}}) = \mathcal{F}^{-1}\left\{ -\frac{1}{k^2} \mathcal{F}[4\pi \, |\widetilde{\psi}(\tilde{t}, \tilde{\boldsymbol{x}})|^2] \right\}$$

- *We use the fourth-order Runge-Kutta method to calculate the position and velocity of each star, satisfying the Newton's second law*

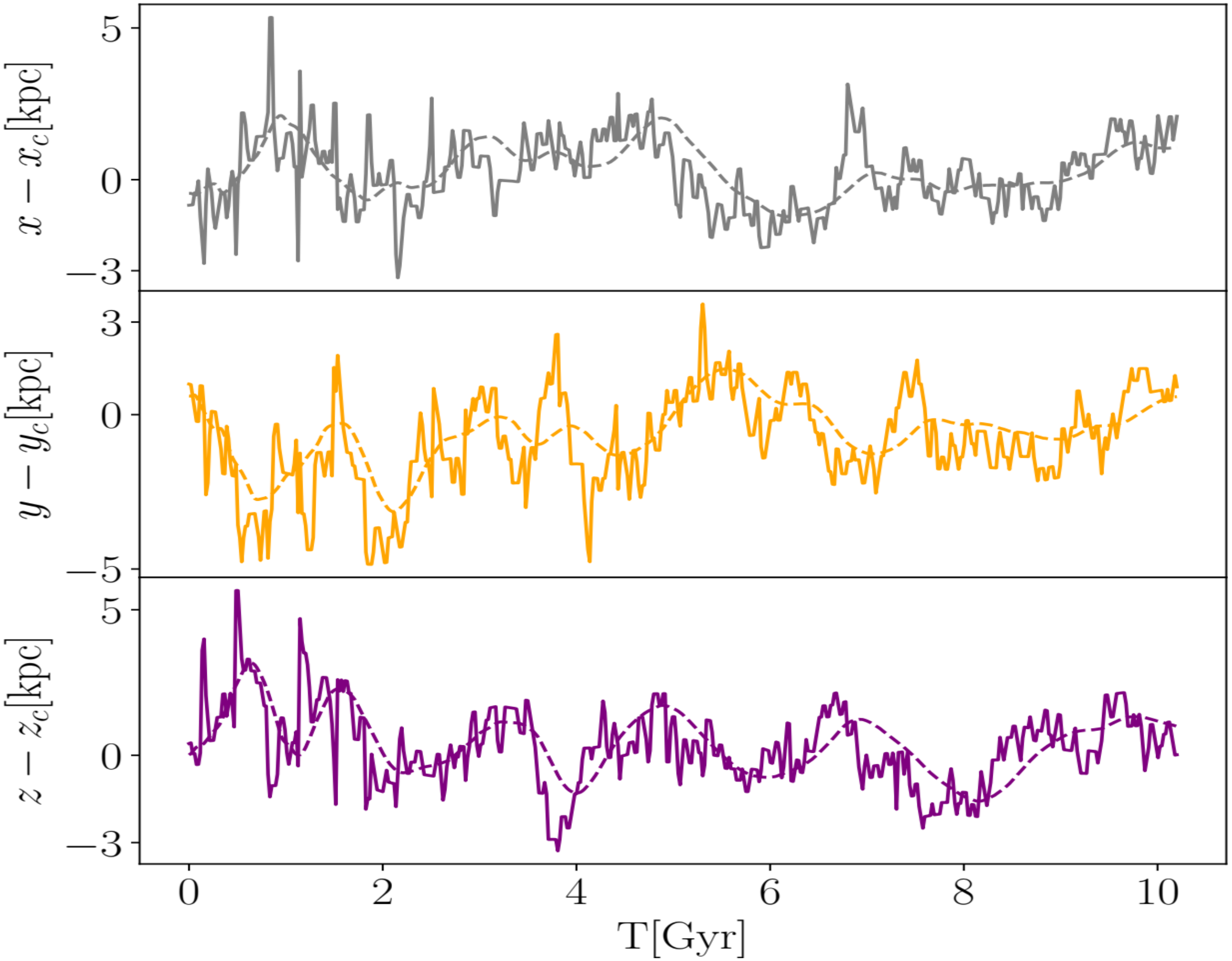
- *We perform the simulation in a (200 kpc)^3 box with a resolution of 512^3*
  time step for FDM: 0.97 Myr, for stars: 0.097 Myr
  Omit the gravity of stars

Evolution results



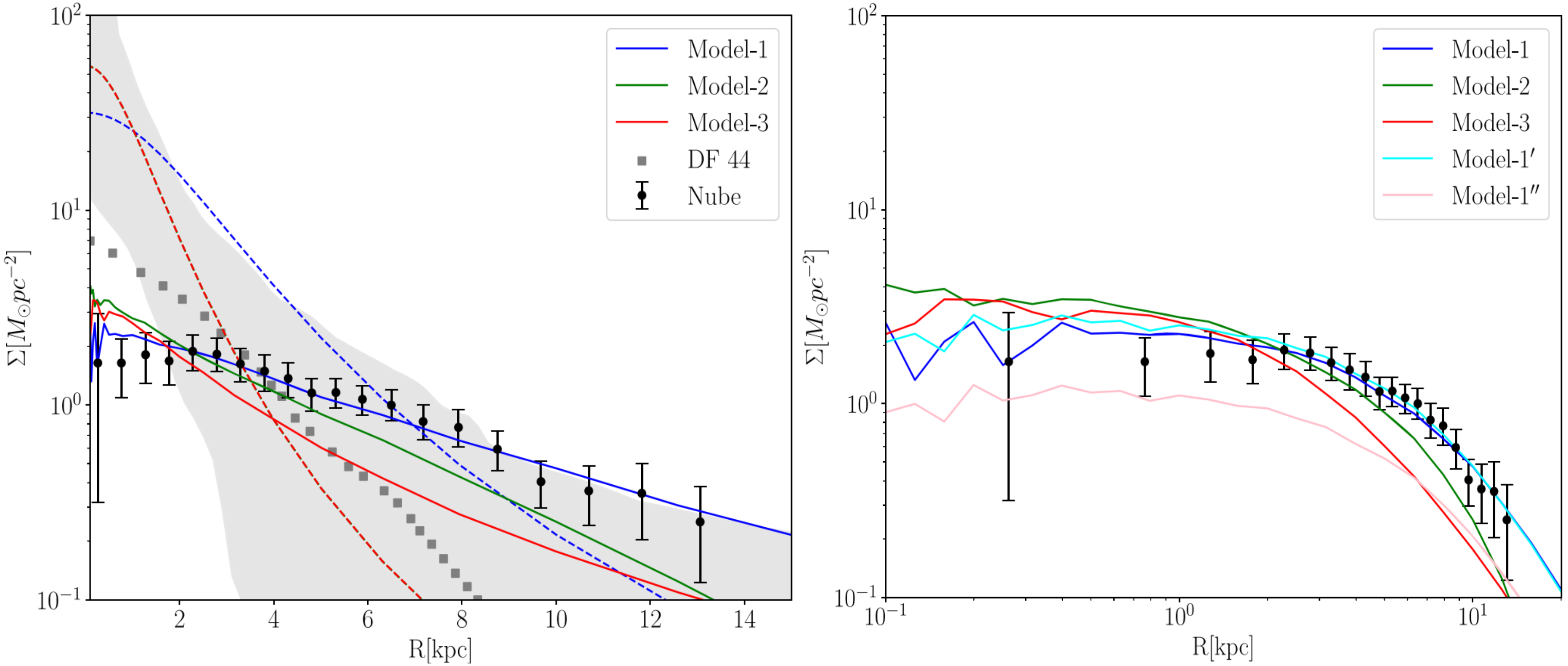
- *Our simulation results show the expansion of the stellar distribution driven by the dynamical heating effect*

Random walk of soliton



- *Relative coordinate of the soliton center (solid) and stellar mass center (dashed) concerning the halo mass center*

Explanation of the Nube observation



- *2D stellar distribution derived from the simulation*
- *The Nube observation can be explained by an FDM mass of ~**O(10^{-23})**eV*

Summary

- *FDM results in many exotic effects at small scales*

- *Almost dark and isolated galaxies provide very promising opportunities to test the nature of DM. Nube is such a good target*

- *We use the dynamical heating effect of FDM to explain extremely stellar distribution of the galaxy Nube. Our results suggest that FDM mass of ~$O(10^{-23})$eV offers a plausible explanation.*

- *We will test this effect in more dark galaxies, and check the constraints on the FDM mass from observations of dwarf satellite galaxies in Milky Way.*

Thank you