Constraining the properties of dark matter by astronomical observations

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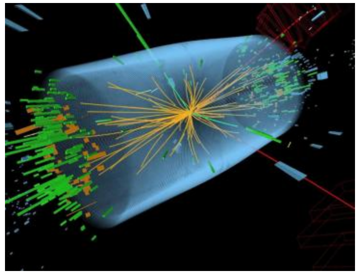
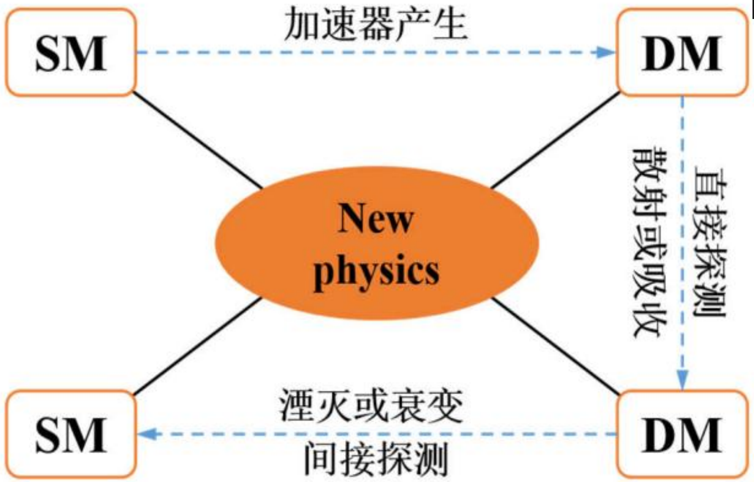
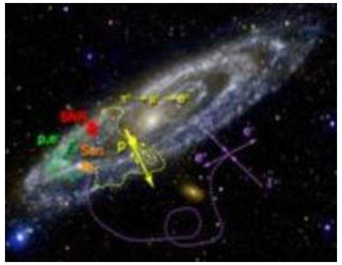
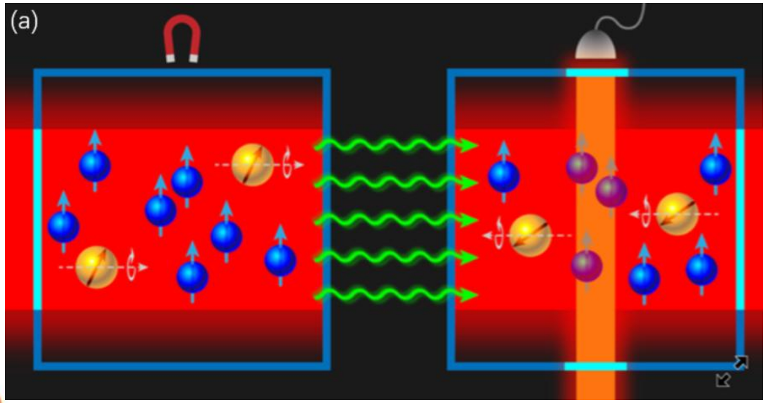
2025/10/24-26

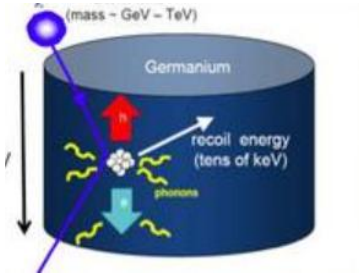
- **Methods to detect dark matter**

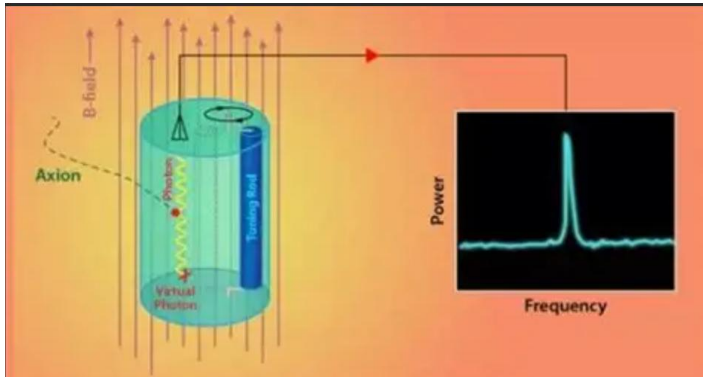


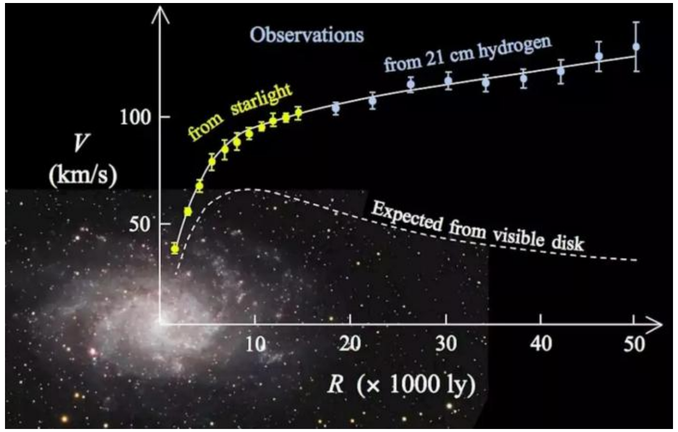










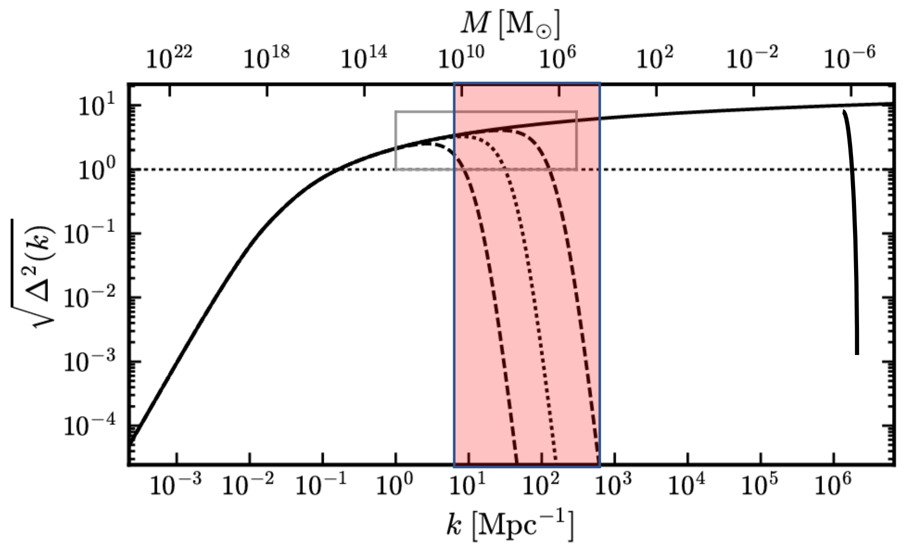


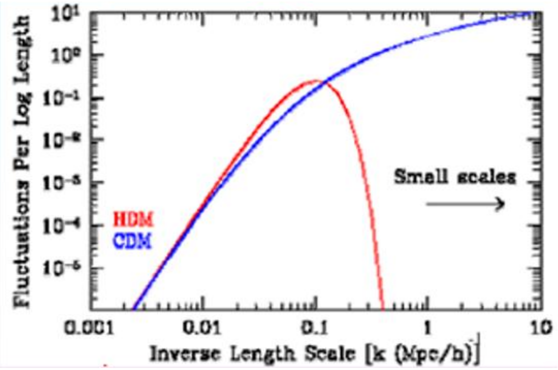
基于粒子物理模型的搜寻

模型无关的天文的搜寻

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, MUST, 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

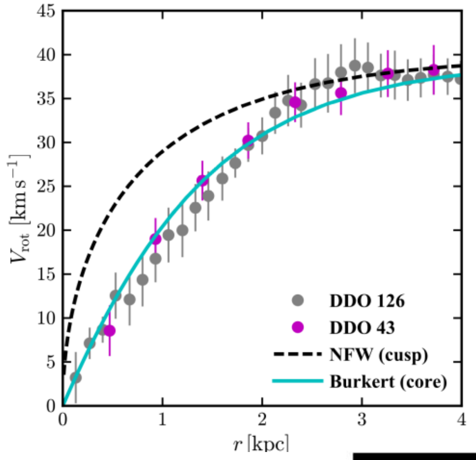
1, core-cusp: The dashed line shows the ΛCDM expectation for a typical rotation curve of a Vmax ≈ 40 km s^{-1} in dwarf galaxies. The data points show the measured rotation curves of two example galaxies of this size requiring a constant DM density core. (LITTLE THINGS survey, Oh et al. 2015)

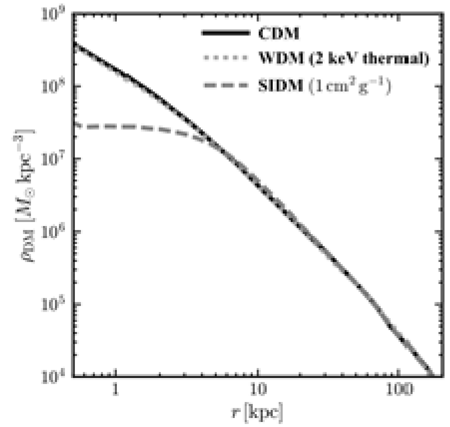
2, missing satellites. Figure show Simulated and observed dwarf galaxies. Deep survey '*seems*' solve the problems. (Garrison-Kimmel et al. 2017)

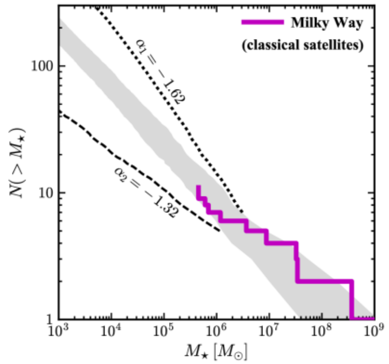
3, diversity problem. The observation of rotation curves shows that the rotation velocity vs maximal velocities have very large dispersion.

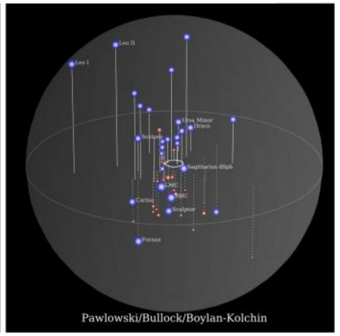
4, too-big-to-fail. Simulation gives rotation curves for biggest subhalos, while only smaller dwarf galaxies are observed. No dwarf corresponds to the biggest ones. this is an independent problem to the 1st one.

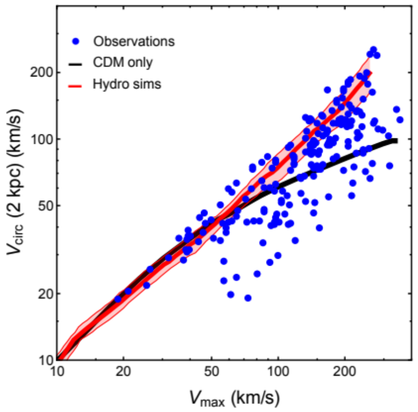
DM or feedback of baryons?

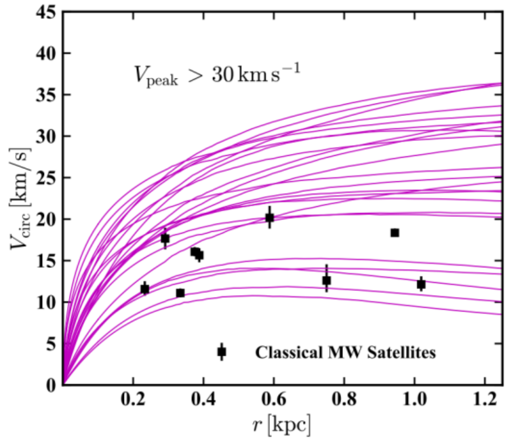












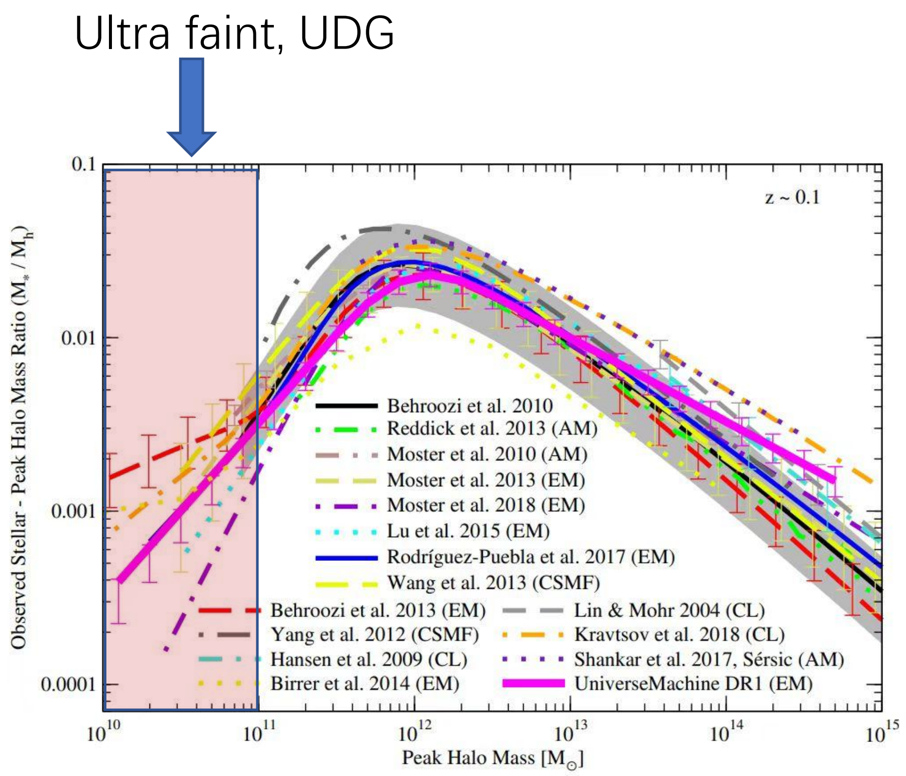
To determine the general properties of DM

- Astronomical observations can constrain the general properties of DM in a model-independent way. This is complementary to the model based researches.
- Try to study the systems which have minimal degeneracy between DM properties and baryon activities, such the ultra faint (diffuse) dwarf galaxies.
- **self-interaction beyond gravity**? Not collisionless
- Properties: **wave-like or particle-like**. Wave-like has long wave length, interference of waves.
- Method: numerical simulation is necessary;

Ultra diffuse(faint) galaxies

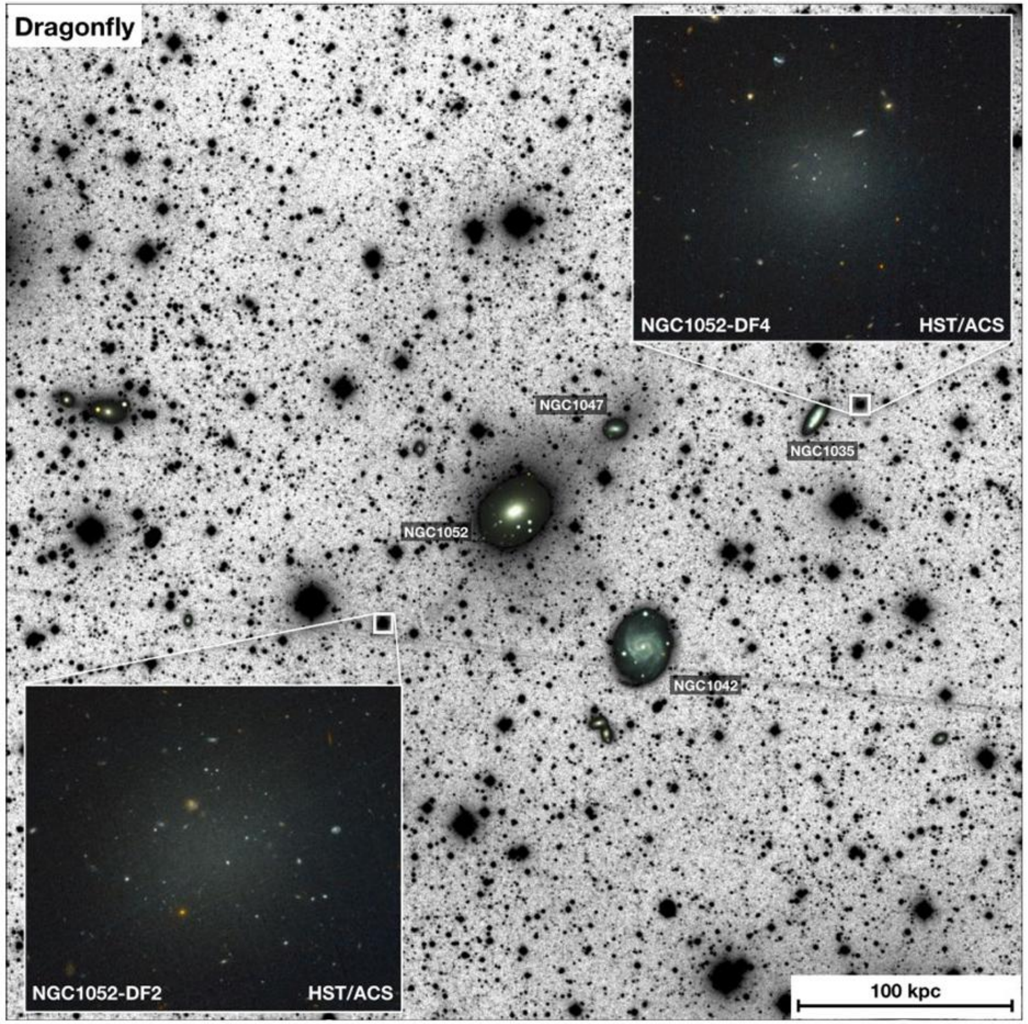
- UDG (ultra-diffuse galaxies)
  - Very dark （μ > 24 mag/arcsec^2）
  - Stars are very diffuse（ R_{eff}>1.5 kpc）

- Usually DM dominated
  - Two extreme DM deficit galaxies DF2、DF4
  - Many globular clusters



- Observations
  - Imaging: Dragonfly, SDSS, HST, Gemini…
  - Spectroscopy of objects in DF2: W. M. Keck Observatory

观测



Distance:

DF2-$20.0^{+2.1}_{-1.1}$ Mpc

DF4-20.0 ± 1.6 Mpc

Distance to NGC1052:

DF2-80 kpc

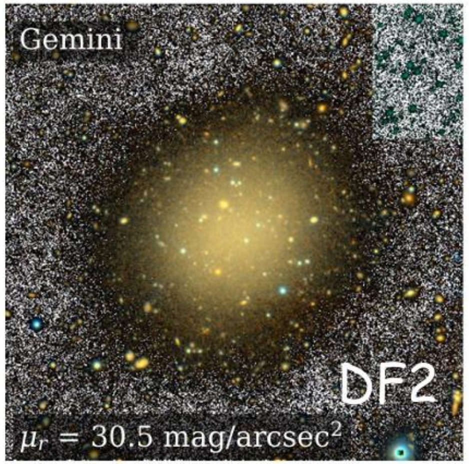
DF4-165 kpc

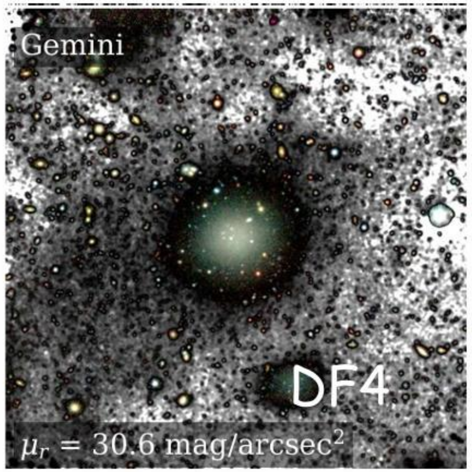
DF2 and DF4 has similar age, size(~9 Gyr), GC population, and velocity dispersion

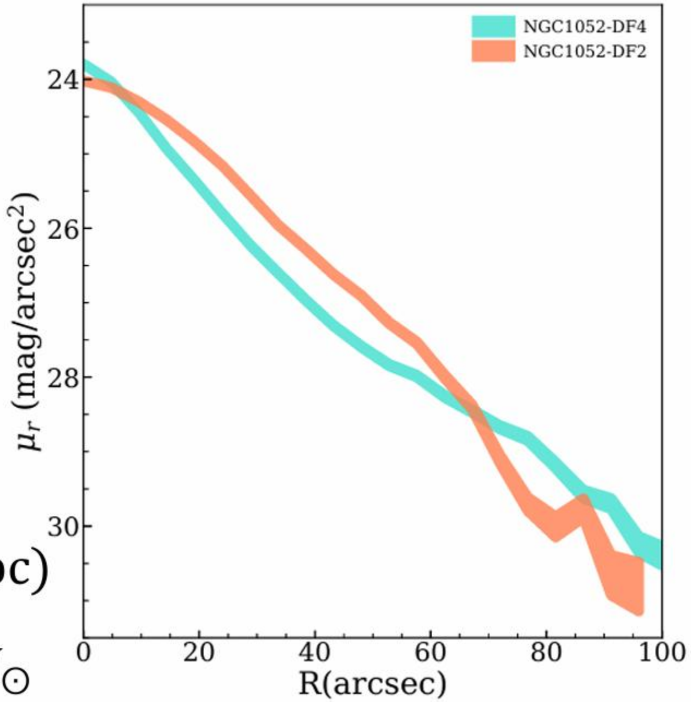
观测

Deep imaging

Both are diffuse !





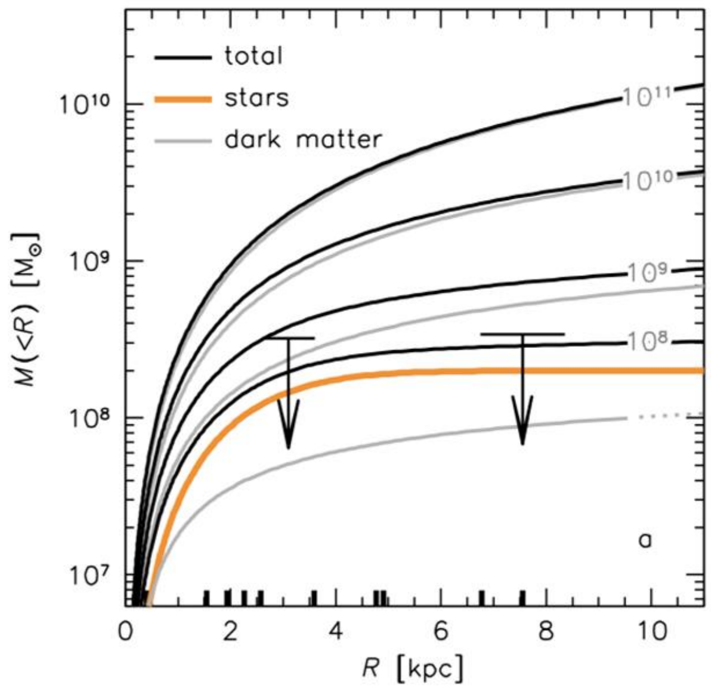


$R_{\mathrm{eff,DF2}} = 22.6'' \ (2.2 \ \mathrm{kpc})$ $R_{\mathrm{eff,DF4}} = 24.5'' \ (2.4 \ \mathrm{kpc})$

$M_{\mathrm{star,DF2}} = 2.0 \times 10^8 \ M_\odot$ $M_{\mathrm{star,DF4}} = 1.5 \times 10^8 \ M_\odot$

The stellar-to-halo mass relation require a halo mass of $O(10^{10} M_\odot)$!

暗物质缺失



NFW profile $\rho(r) = \dfrac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$

$(\rho_s, r_s) \Leftrightarrow (M_{200}, c_{200})$ $\quad c_{200} = \dfrac{r_{200}}{r_s}$

with the mass-concentration relation

$$\boxed{M_{\rm halo} \sim O(10^8\ M_\odot)}$$

Mass ratio in the central region

DF2 $\dfrac{M_{\rm halo}}{M_{star}}(< 2.7\ \mathrm{kpc}) = 0 \sim 1.65$

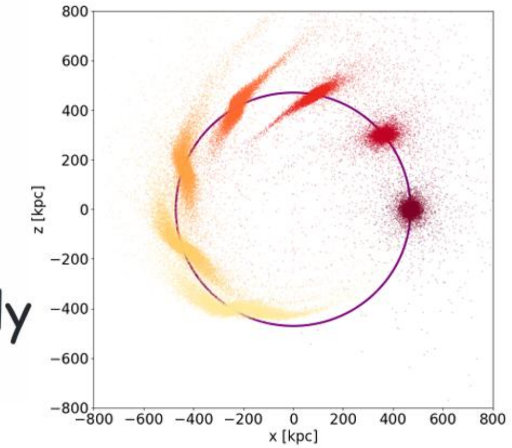
DF4 $\dfrac{M_{\rm halo}}{M_{star}}(< 7\ \mathrm{kpc}) = 0 \sim 0.45$

Extreme dark matter deficiency

Tidal效应造成的暗物质缺失

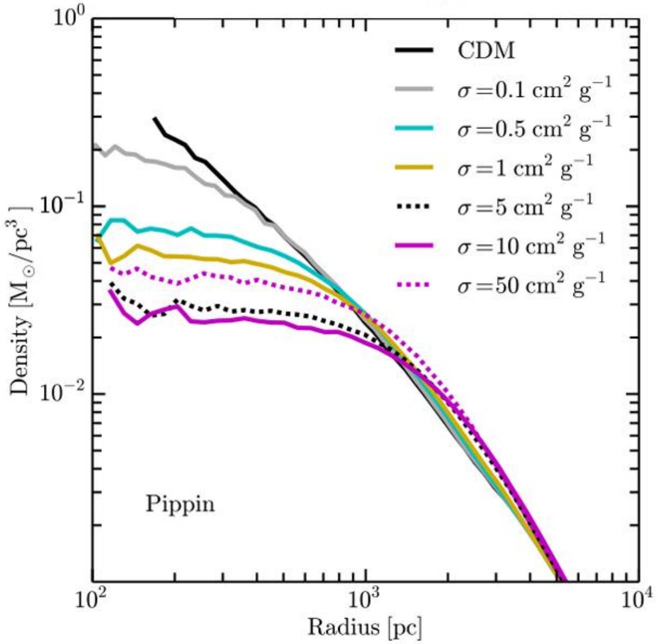
Tidal stripping

- The satellite system experiences gravitational potential in its host halo
- Affect dark matter in the outer region primarily
- Not sufficient to form DF2, DF4



Self-Interaction Dark Matter (SIDM)

- Non-gravitational scatter
- Result in a density core
- Potentially explain the diversity problem, the 'cusp or core' problem, the 'too big to fail' problem



N-body simulation

Zhang, BI, Yin,
2408.01724;
2403.11403

Numerical setting

- N-body code Gadget2 with Tree-PM algorithm
- N-body satellite system consisting of 10^7 particles, with mass of $m = 10^4\ M_\odot$
- softening length of $40\ \mathrm{pc}$

Host system

- accreting dark matter halo resembling NGC1052
- represent by analytical potential
  lead to the absence of evaporation and dynamical friction
- Median values adopted from the mass accretion history and mass-concentration relation
- start at $z_\mathrm{i} = 1.5\ (-9.54\ \mathrm{Gyr})$ to $z_\mathrm{f} = 0\ (0\ \mathrm{Gyr})$

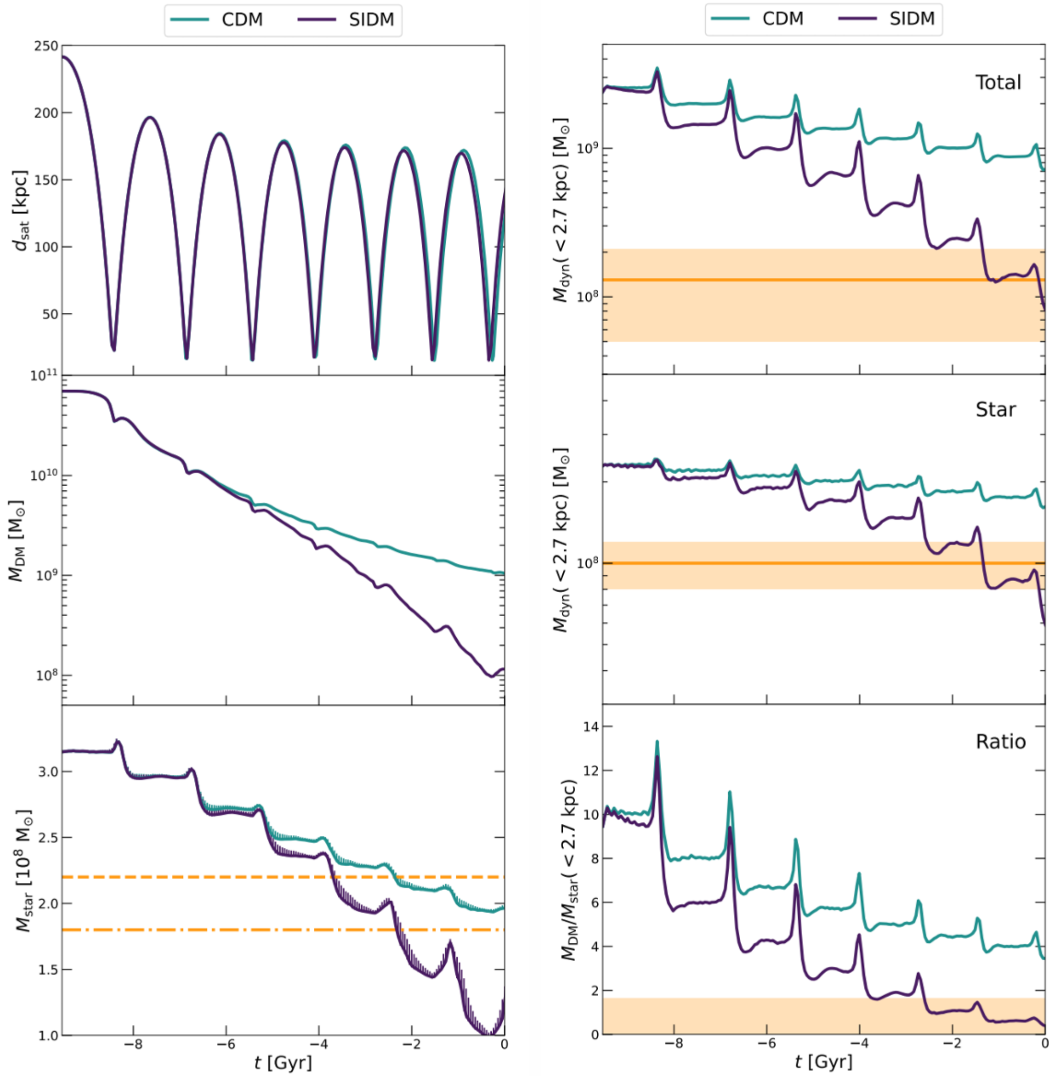
DF2-like 矮星系

Transform a typical dwarf galaxy to a DF2-like galaxy

Initial Conditions

- Halo: NFW profile with $\boxed{M_{200} = 7 \times 10^{10}\ M_\odot}$, $c_{200} = 5.5$
- Star: Hernquist profile with $\boxed{M_{\rm star} = 3.5 \times 10^{8} M_\odot}$, $R_{\rm eff} = 1.25\ \rm kpc$
- Self-interaction strength: $\sigma/m = 5\ \ \rm cm^2/g$
- Orbit: $(x_c = 0.8, \eta = 0.3)$ $\quad r_{\rm peri} = 20.0\ \rm kpc\ (\sim 7.5\ percentile)$
- 10 GCs with mass of $M_{\rm GC} = 10^6 M_\odot$, select GCs from star particles with radius $r_{\rm GC} = 1.8\ \rm kpc$

Results of DF2



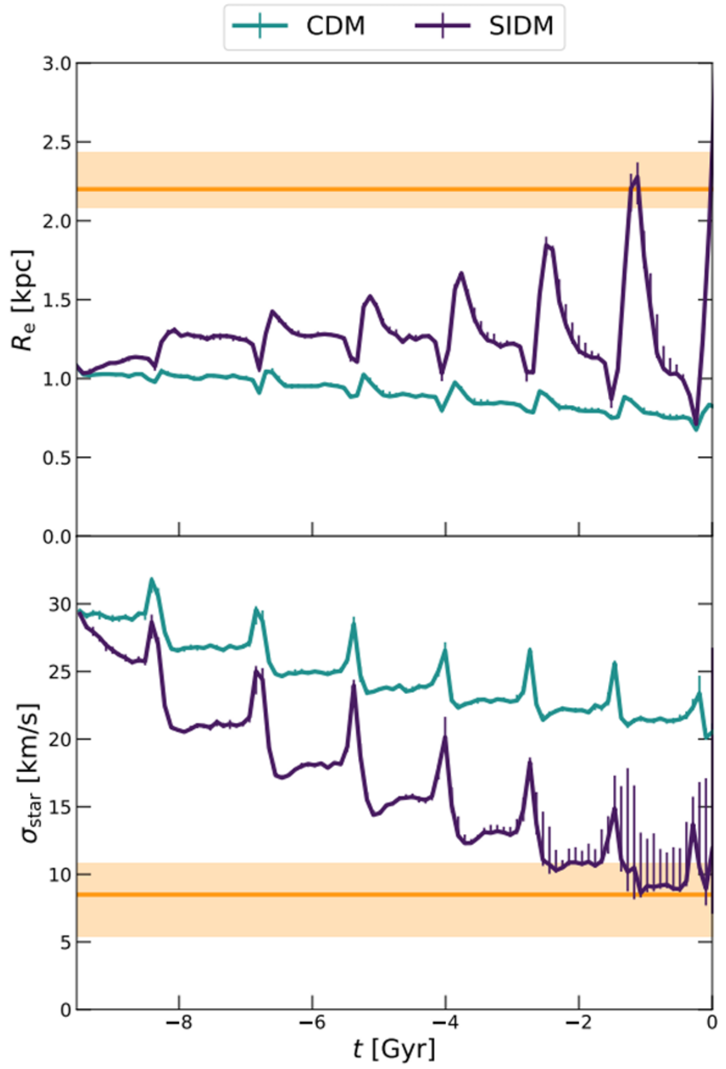
Tidal evolution (total & central region)

- very similar trajectory
- tidal stripping affects dark matter halos more significantly than stars
- DM self-scatters enhance tidal stripping

⇓

DM deficiency

Results of DF2



Star population

- tidal stripping + tidal heating

negative heat capacity of gravitational system

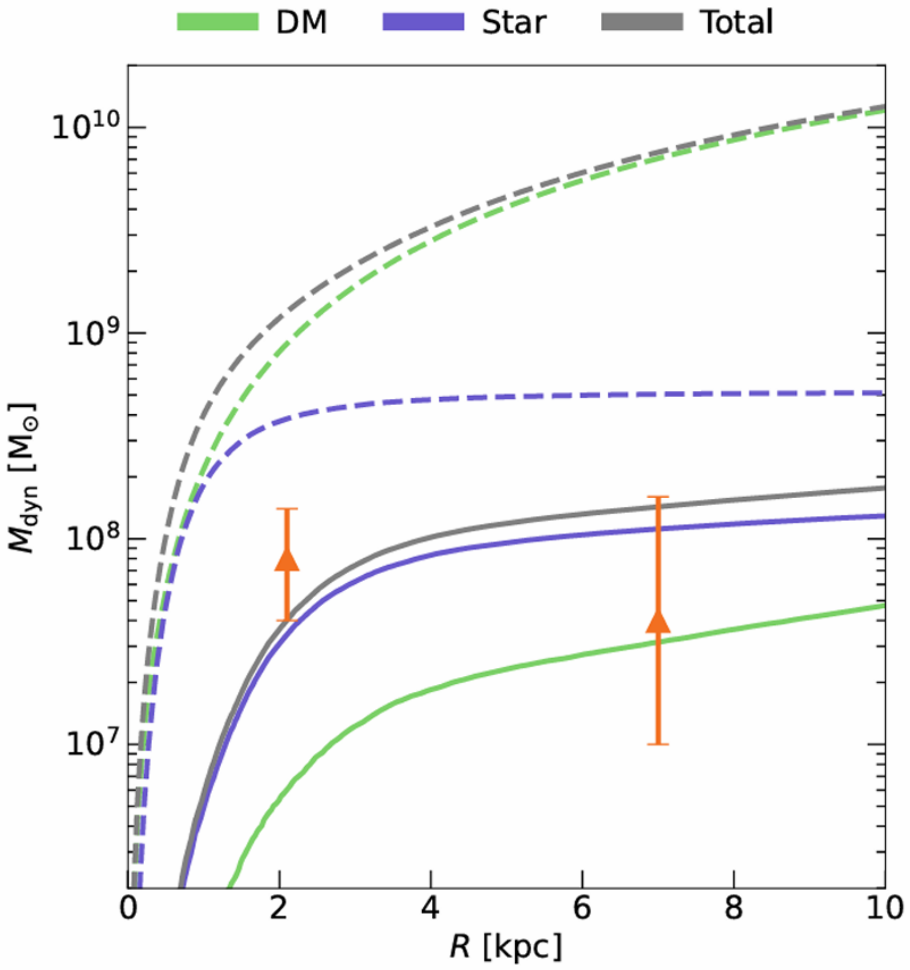
$$E = T + V = -T$$

- more diffuse spatial distribution
- a decrease in velocity dispersion

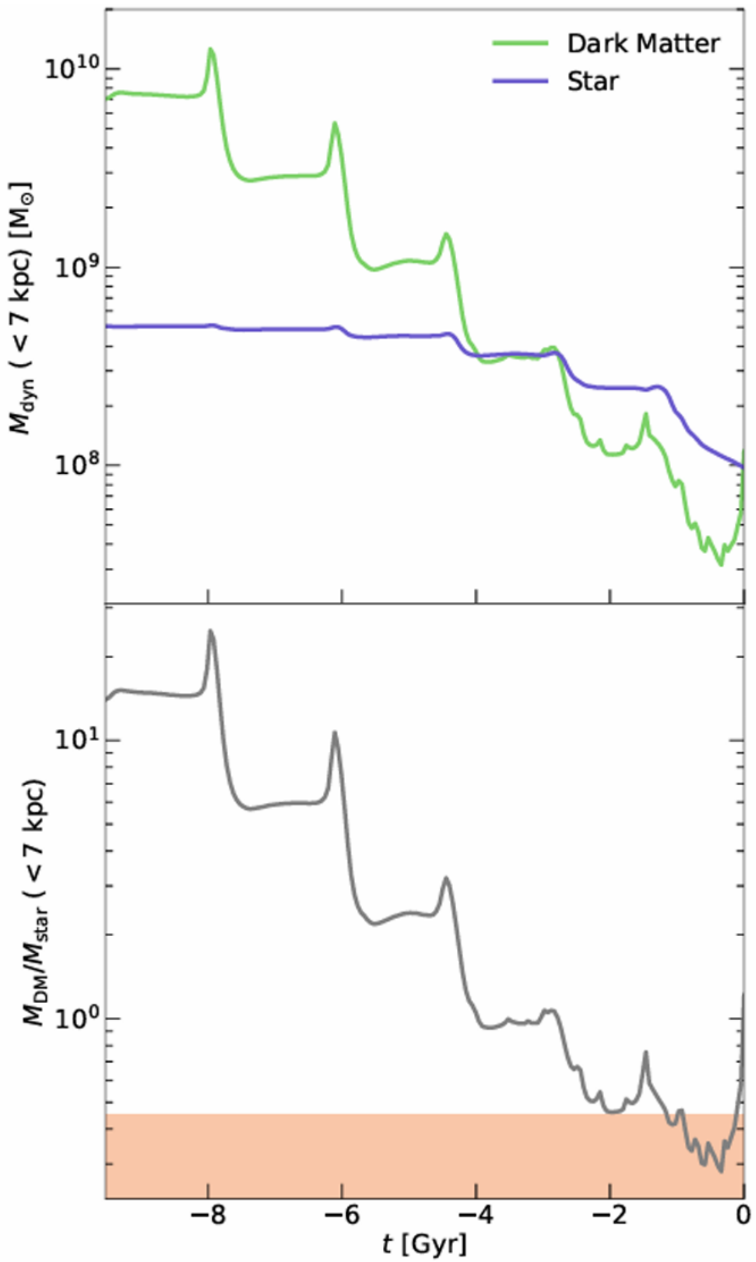
(temperature)

Results of DF4

Dark matter deficiency

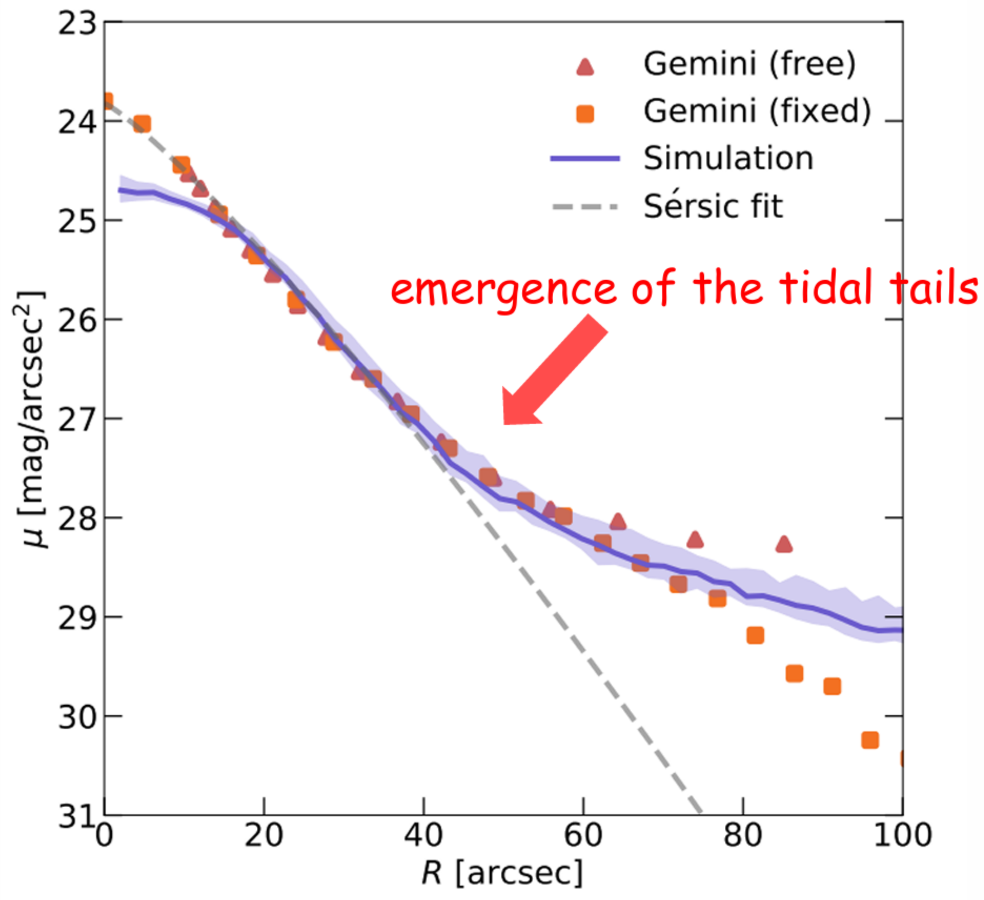


mass profile



The mass ratio in the central region

Results of DF4 – tidal tail



radial surface brightness profile

$R_{\text{distortion}} = 43.4''$

where the slope changes

$R_{\text{break}} = 45.4''$

at least $0.2\ \text{mag/arcsec}^2$ higher than the Sérsic profile

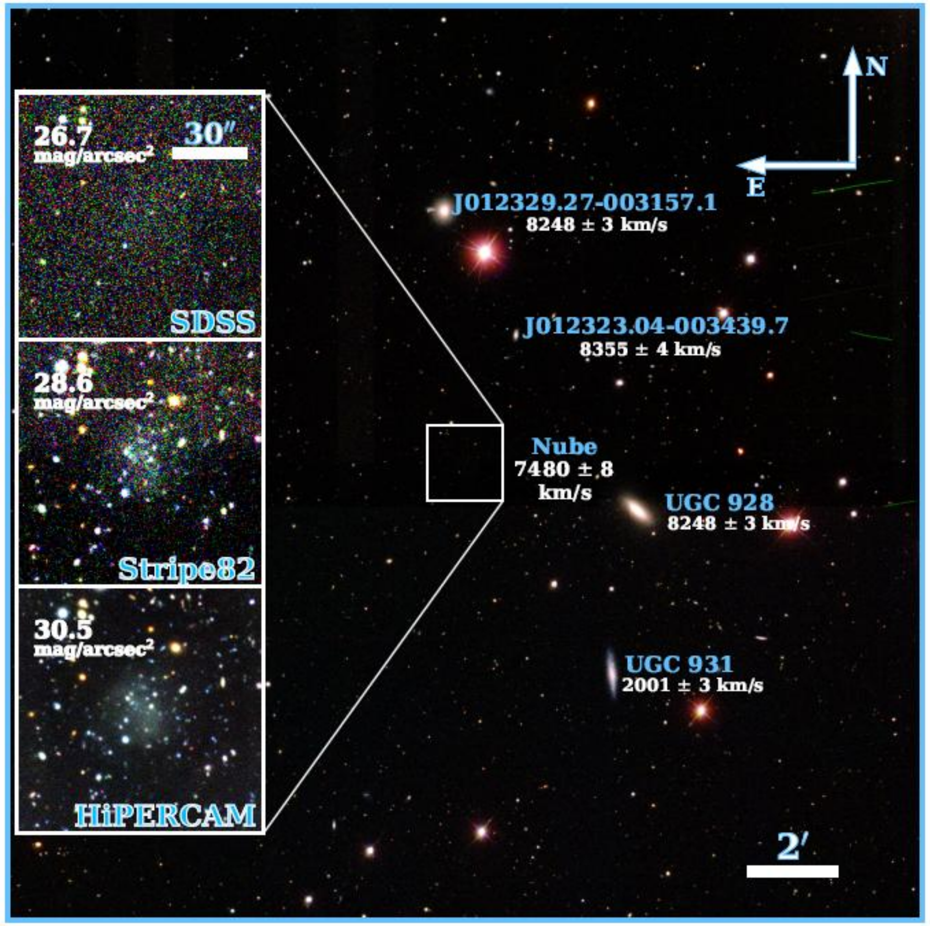
accurately reproduce the tidal tails of DF4

How to explain the tidal tail observed at DF4 if it is generated by collision? How to explain no tidal tail observed at DF2?

- **恒星分布异常的一个矮星系——Nube**

*almost dark galaxy: Nube

A&A 681, A15 (2024)



- 距离：107 ± 5 Mpc
- 恒星总质量：$M_* = 3.9 \pm 1.0 \times 10^8\, M_\odot$
- 有效半径：$R_e = 6.9 \pm 0.8$ kpc
- 动力学质量：

  $2.6 \pm 1.7 \times 10^{10}\, M_\odot$ within $3\, R_e = 20.7$ kpc
- 年龄：$10.2^{+2.0}_{-2.5}$ Gyr
- 位置孤立：没有受到潮汐力的迹象，和最有可能的host halo UGC929 距离是435kpc

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

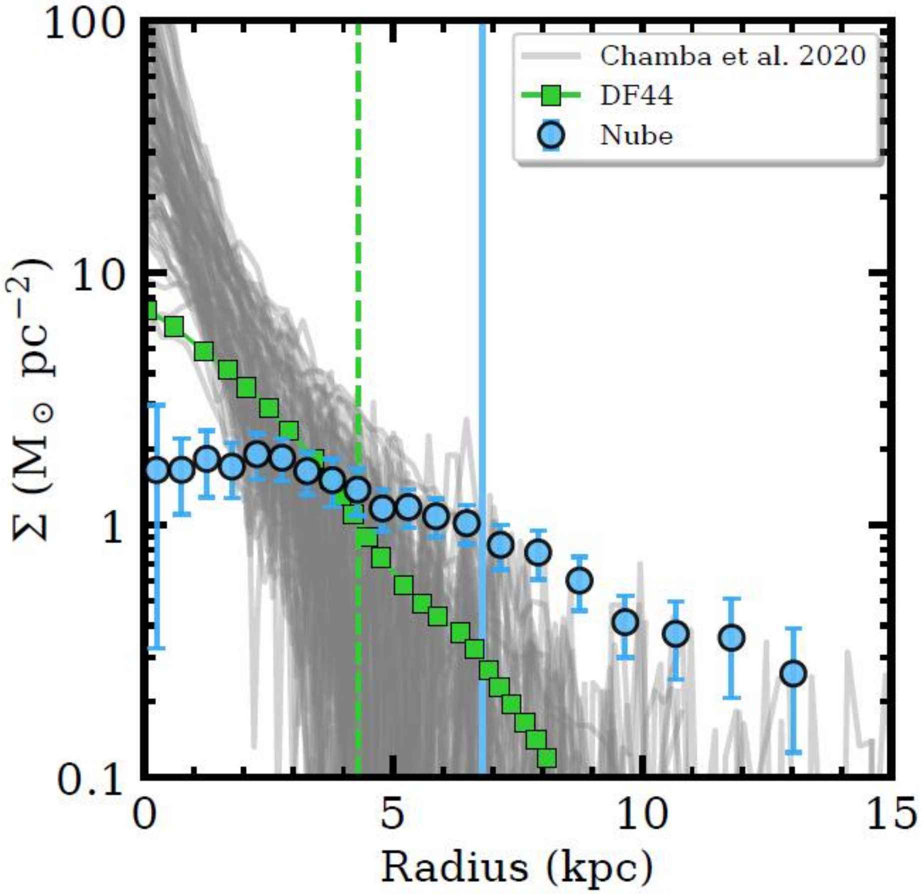
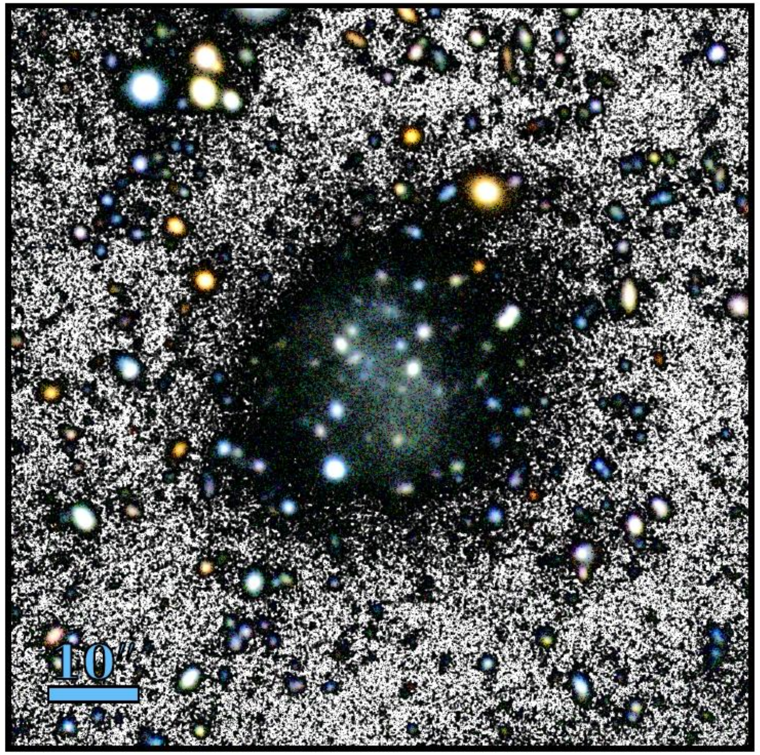


Fig. 9. Surface stellar mass density profile of Nube (blue dots) compared with other galaxies of similar stellar mass. The profiles of dwarf galaxies from Chamba et al. (2020) in the same mass range ($1-5 \times 10^8\ M_\odot$) are plotted. We also show the profile of DF44 (green squares), as it is an iconic large ultra-diffuse galaxy. The vertical lines indicate the half-mass radius (R_e) for Nube (blue solid line) and DF44 (green dashed



Generated by dynamical heating of FDM

May also explain the DF2, DF4

Dark matter and Ultra light DM

neutrino
electron
Proton
neutron
W, Z
Higgs
top

10^{-22}eV | meV | keV | GeV | TeV | PeV | M_{pl} | $10M_{\odot}$

Ultralight DM

Nonthermal
bosonic
Wave like

Axion, axion-like particles, dark photon etc

QCD axion

WIMP

Unitarity bound

Thermal, freeze out

Light DM

SUSY, UED etc

Can be warm

Sterile neutrino etc

Super massive DM

Q ball etc

Primordial black holes

Hiden sector DM
Asymmetric DM
Freeze-in DM etc

Fuzzy DM

- de Broglie wavelength

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

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

waves, N>>1

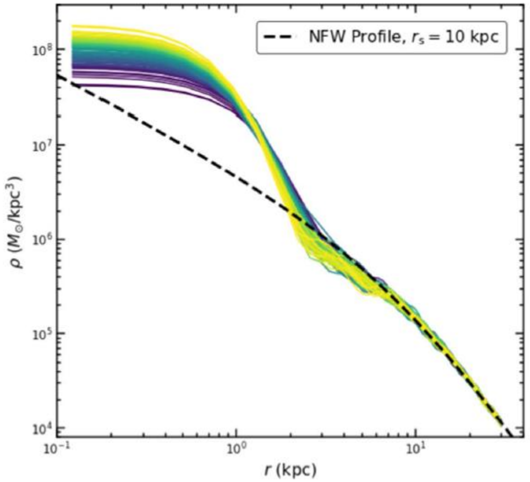
Properties of Fuzzy DM: small scale suppression

- 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;

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

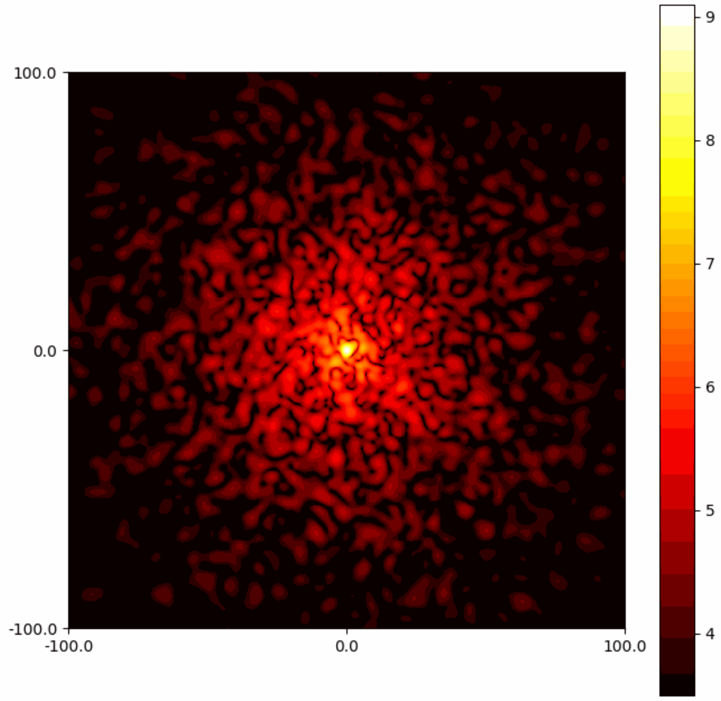


Core-cusp problem

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



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

Analytical treatment of heating

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

Ben Bar-Or *et al* 2019 *ApJ* 871 28

Total mass： $M_\star = 3.9\times 10^8 M_\odot$

Initial half-light radius: a_i as 1kpc （a_i at 0.5-1.5kpc has similar results）

***star distribution is heated by FDM and described by diffusion**

$$D[\Delta E] = \frac{4\sqrt{2\pi}G^2\rho_{\rm FDM}m_{\rm eff}\ln\Lambda_{\rm FDM}}{\sigma_{\rm eff}}e^{-X_{\rm eff}^2}.$$

$$D\left[(\Delta E)^2\right] = 8\sqrt{2}\pi G^2\rho_{\rm FDM}m_{\rm eff}\sigma_{\rm eff}\ln\Lambda_{\rm FDM}X_{\rm eff}\mathbb{G}(X_{\rm eff})$$

$$\Delta r = \frac{2r^2}{GM_{\rm FDM}(r)}\frac{\Delta E}{M}$$

$$m_{\rm eff} = \frac{\pi^{3/2}\rho_{\rm FDM}}{m^3\sigma^3} = \rho_{\rm FDM}\left(\frac{\lambda_\sigma}{2\sqrt{\pi}}\right)^3$$

$$\sigma_{\rm eff} = \sigma/\sqrt{2}$$

$$X_{\rm eff} = v/\sqrt{2}\sigma_{\rm eff} = v/\sigma$$

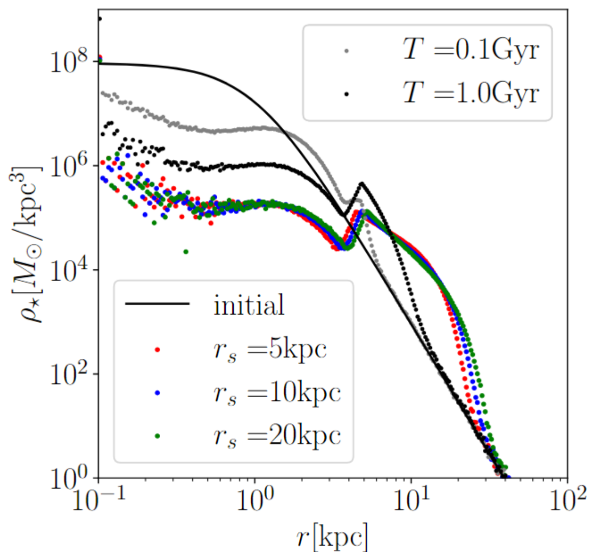
$$\ln\Lambda_{\rm FDM} = \ln\left(\frac{4\pi r}{\lambda_\sigma}\right)$$

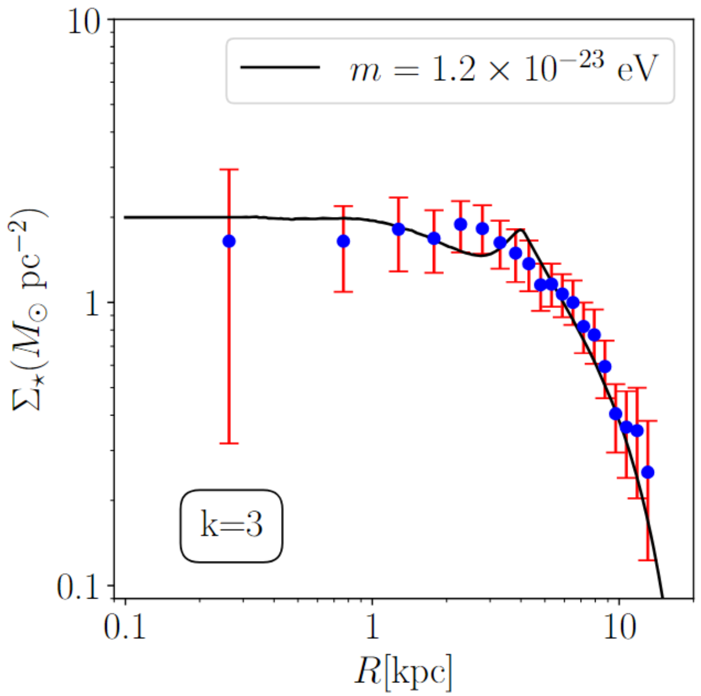
$$\mathbb{G}(X) = \frac{1}{2X^2}\left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}e^{-X^2}\right]$$

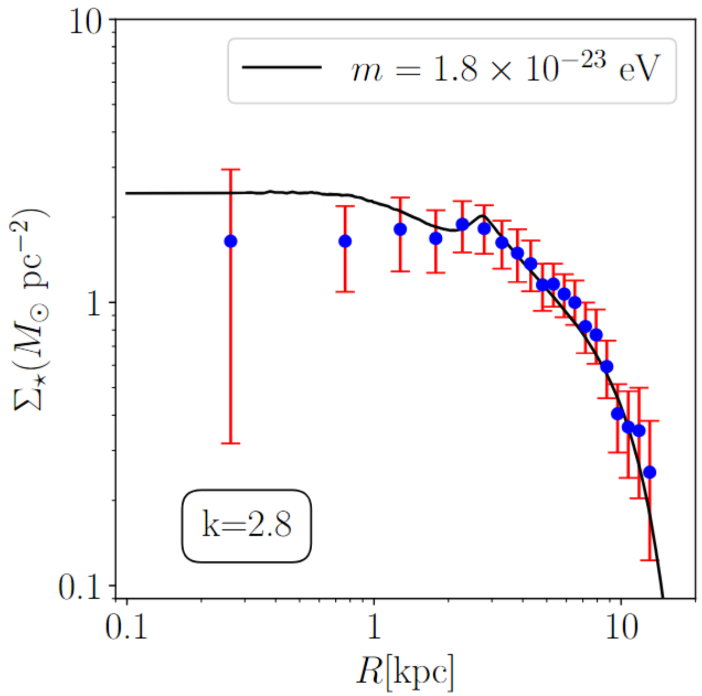
$$\langle\Delta E/M\rangle = D[\Delta E]\Delta t. \qquad \sigma^2(\Delta E/M) = D\left[(\Delta E)^2\right]\Delta t - D[\Delta E]^2\Delta t^2$$

A random walk in the energy space leads to larger energy dispersion

$$
\begin{aligned}
D[\Delta E] &\equiv \frac{\langle \Delta E/M \rangle}{\Delta t} \\
&= \frac{\langle (\mathbf{v}+\Delta\mathbf{v})^2 - \mathbf{v}^2 \rangle}{2\Delta t} \\
&= vD[\Delta v_\parallel] + \frac{1}{2}D[(\Delta v_\parallel)^2] + \frac{1}{2}D[(\Delta v_\perp)^2] \\
&= \frac{4\sqrt{2\pi}G^2 \rho_{\rm FDM} m_{\rm eff} \ln \Lambda_{\rm FDM}}{\sigma_{\rm eff}} e^{-X_{\rm eff}^2}.
\end{aligned}
$$







Yang, **XJB**, Yin, *JCAP* 07 (2024) 054

Numerical simulation

- FDM基本性质 $m \simeq 10^{-22}\mathrm{eV}$
  - 运动方程 $\partial_\mu\left(\sqrt{-g} g^{\mu\nu}\partial_\nu\phi\right)-\sqrt{-g} m^2\phi=0$

    $\Downarrow$

    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:

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

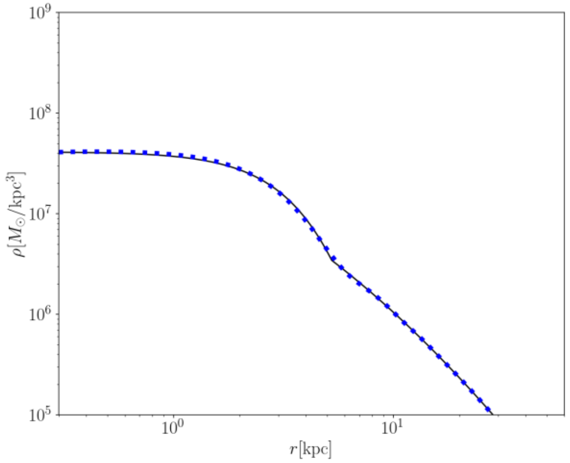
  - de Broglie波长 $\lambda_{\mathrm{dB}} \equiv \frac{2\pi}{mv}=0.48\,\mathrm{kpc}\left(\frac{10^{-22}\ \mathrm{eV}}{m}\right)\left(\frac{250\,\mathrm{km\,s^{-1}}}{v}\right)$

Dynamical heating effect of FDM

- Initial wave function

Soliton+NFW profile

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



- Stellar initial condition
  - Density profile

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

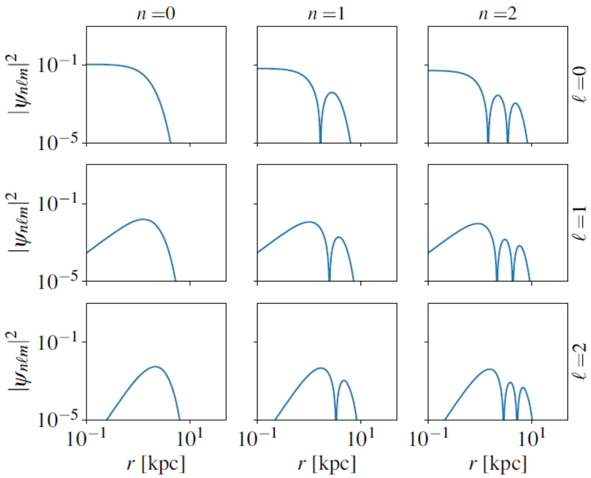
  - Eddington formula

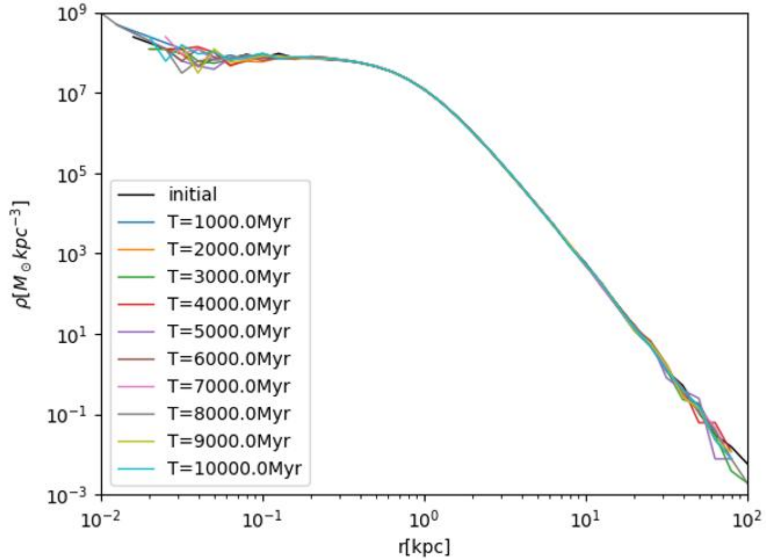
$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\frac{\mathrm{d}}{\mathrm{d}\mathcal{E}}\int_0^{\mathcal{E}}\frac{\mathrm{d}\Phi_0}{\sqrt{\mathcal{E}-\Phi_0}}\frac{\mathrm{d}\rho_\star}{\mathrm{d}\Phi_0},$$

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

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

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



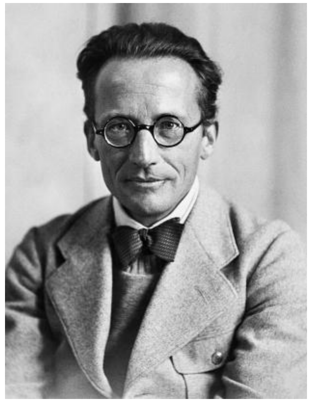


T. D. Yavetz, X Li, and L Hui,
Phys. Rev. D 105 (2022) 2, 023512

Dynamical heating effect of FDM

t

$t+\Delta t$



$\Phi_{\mathrm{FDM}}(t,\boldsymbol{x}) = \mathcal{F}^{-1}\left(-\frac{1}{k^2}\right)\mathcal{F}\,4\pi\,|\psi(t,\boldsymbol{x})|^2$

FDM: $\psi(t,\boldsymbol{x})$

$\Phi_{\mathrm{FDM}}(t,\boldsymbol{x})$

$\Phi(t,\boldsymbol{x})$

$\Phi_{\mathrm{stars}}(t,\boldsymbol{x})$

stars: $\{\boldsymbol{x}_i(t),\boldsymbol{v}_i(t)\}$
$i=1,\ldots,N$

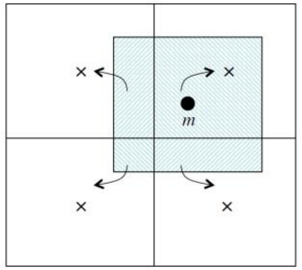
Schrödinger equation

Newton's second law

FDM: $\psi(t+\Delta t,\boldsymbol{x})$

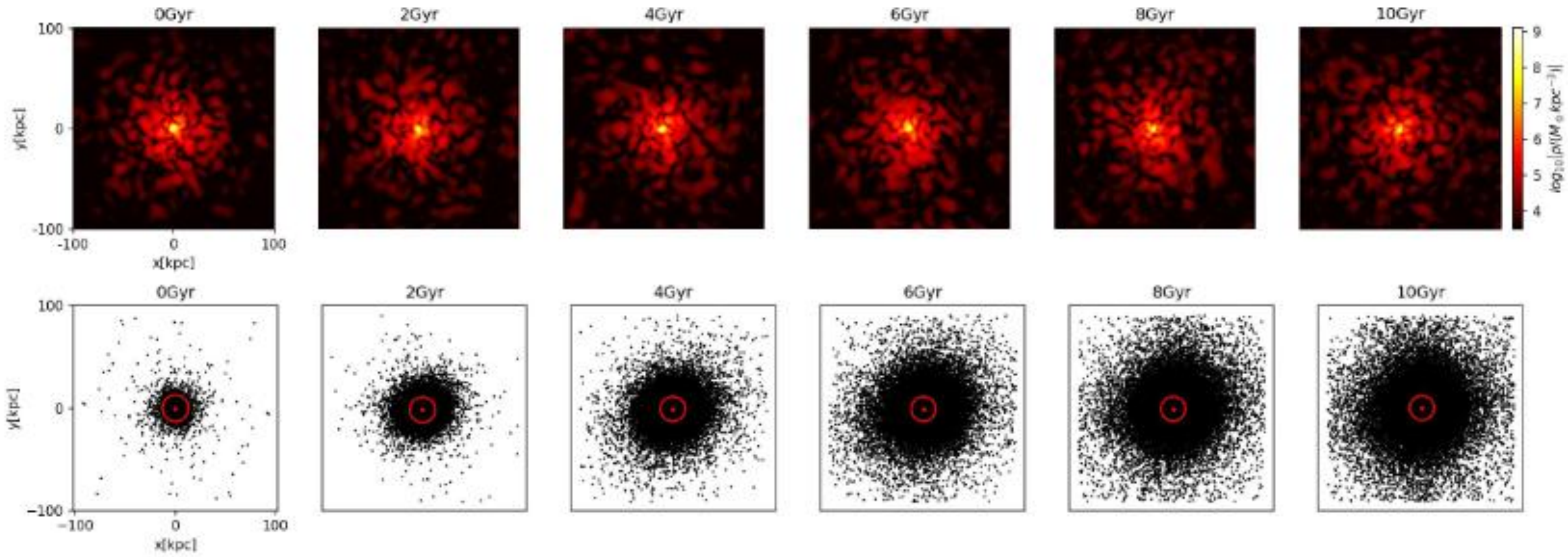
$\Phi(t+\Delta t,\boldsymbol{x})$

stars: $\{\boldsymbol{x}_i(t+\Delta t),\boldsymbol{v}_i(t+\Delta t)\}$
$i=1,\ldots,N$



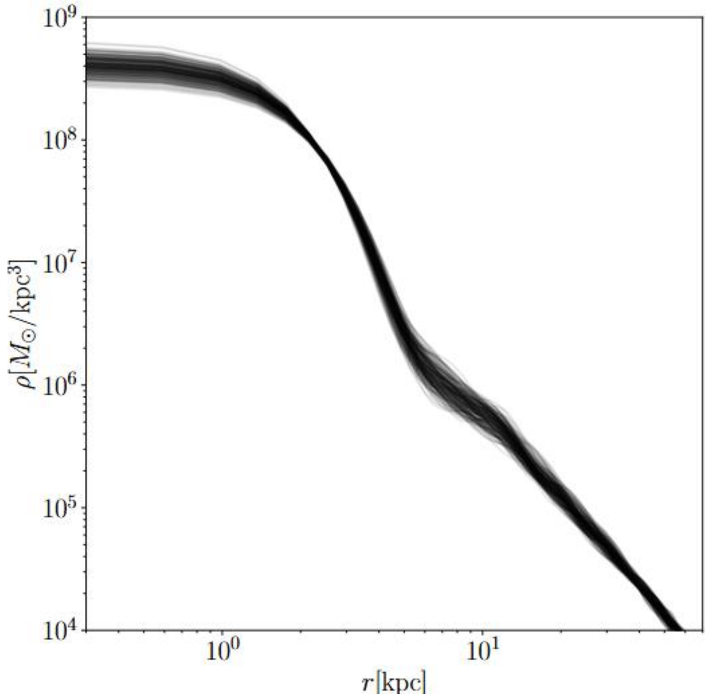
Particle Mesh

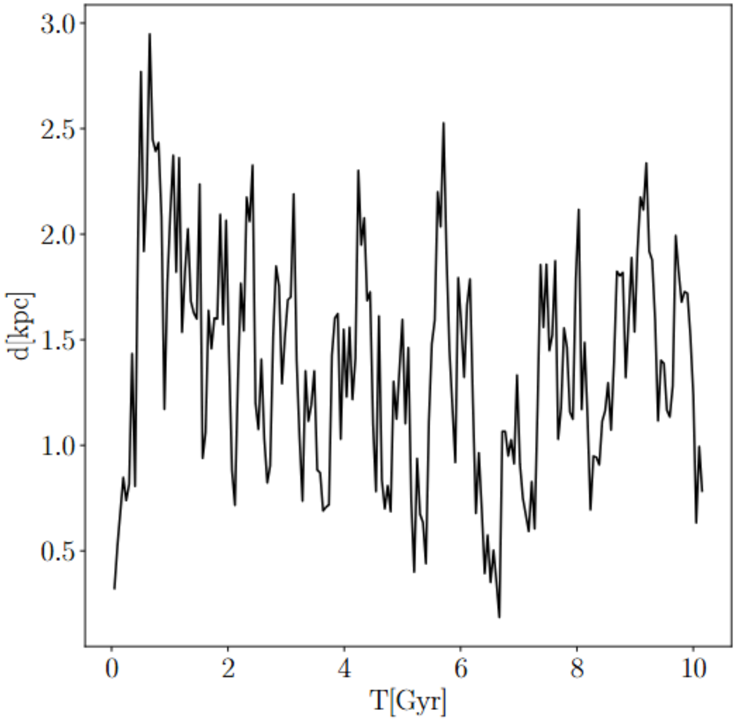
- 模拟结果



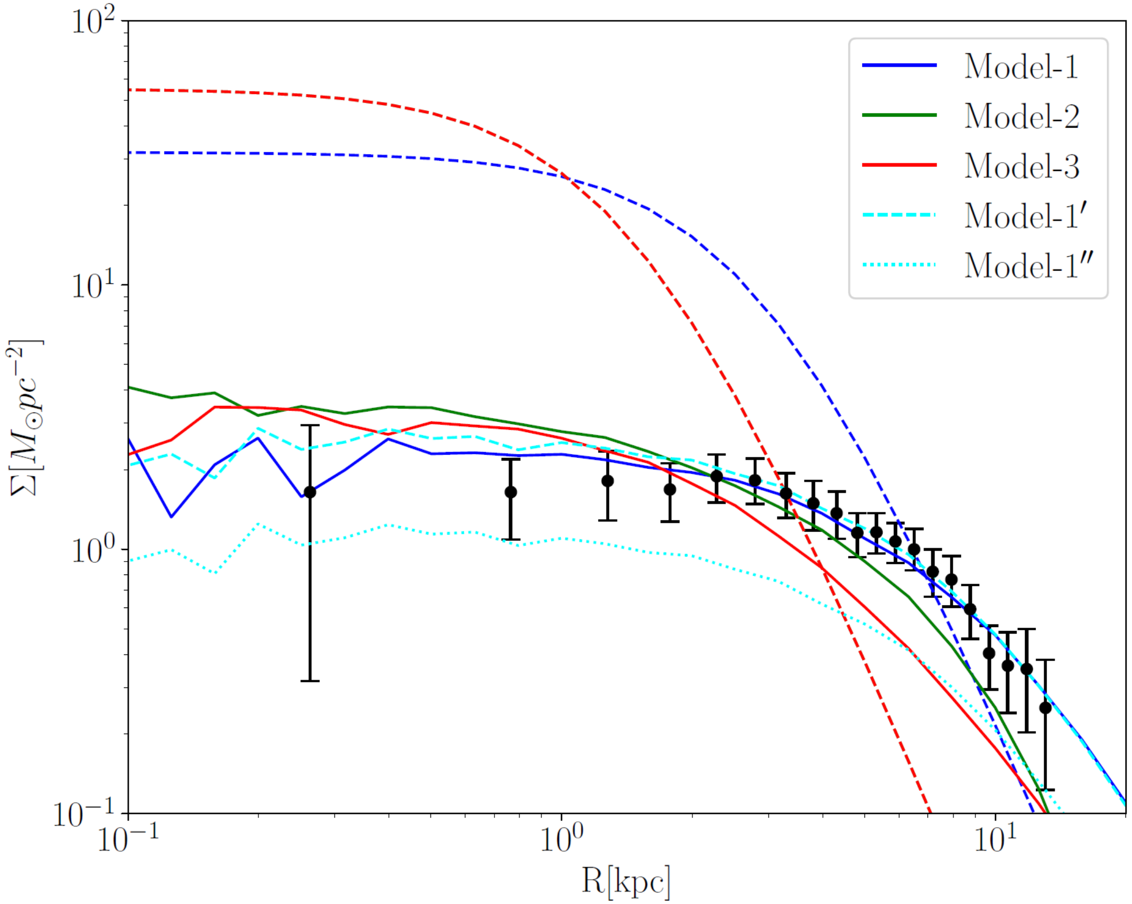
arXiv:2412.01307

arXiv:2412.01307

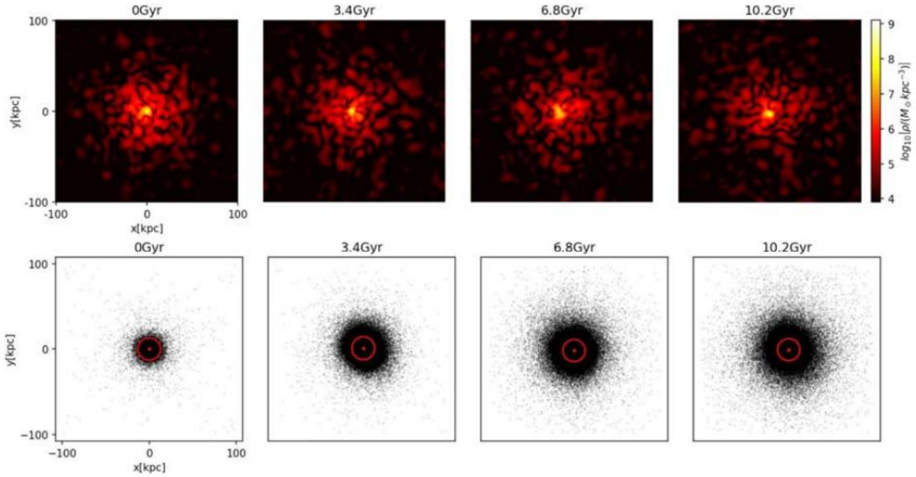


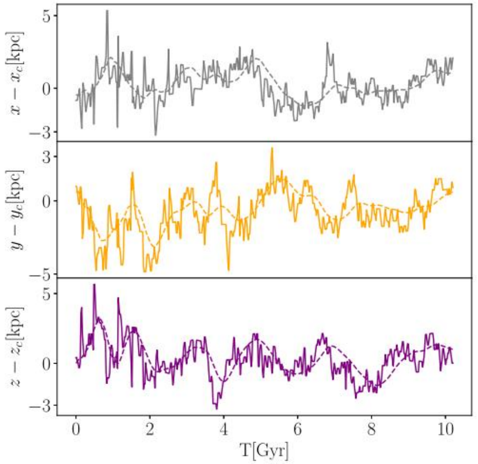


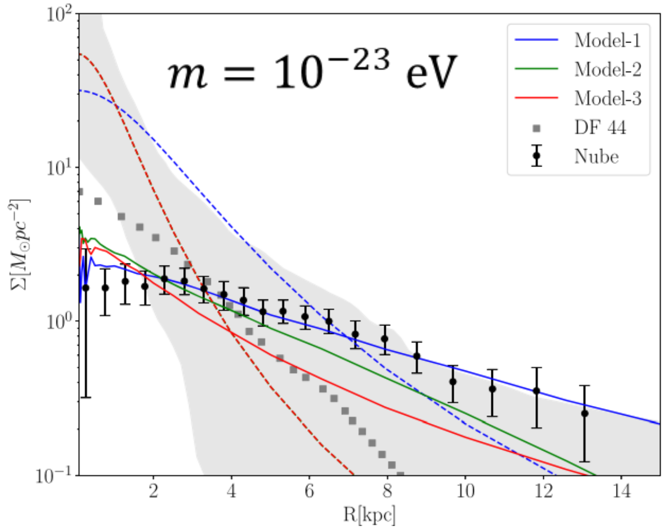
	m_a $[10^{-23}\mathrm{eV}]$	k	$M_\star$ $[10^8 M_\odot]$	a_i [kpc]
Model-1	1	2	8.9	3.0
Model-2	3	2	3.9	1.5
Model-3	1	3	3.9	1.5

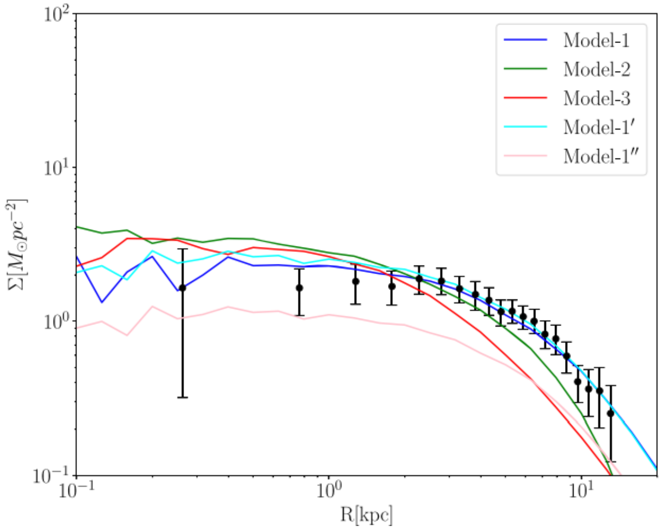


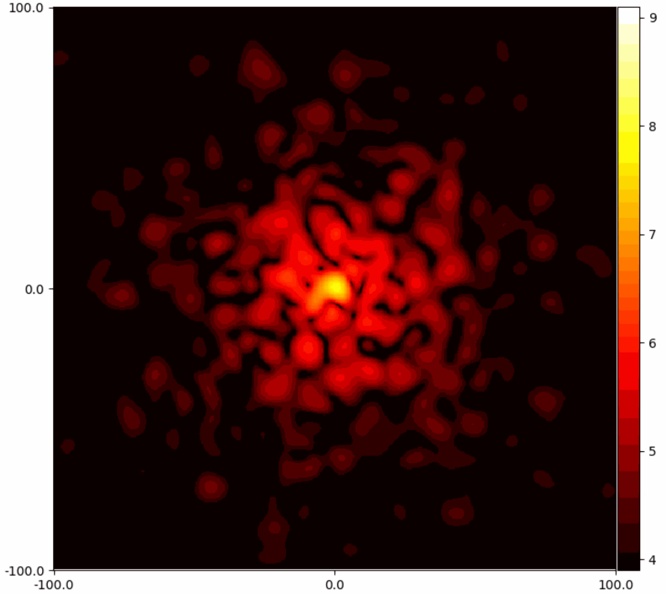
Dynamical heating effect of FDM











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

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)

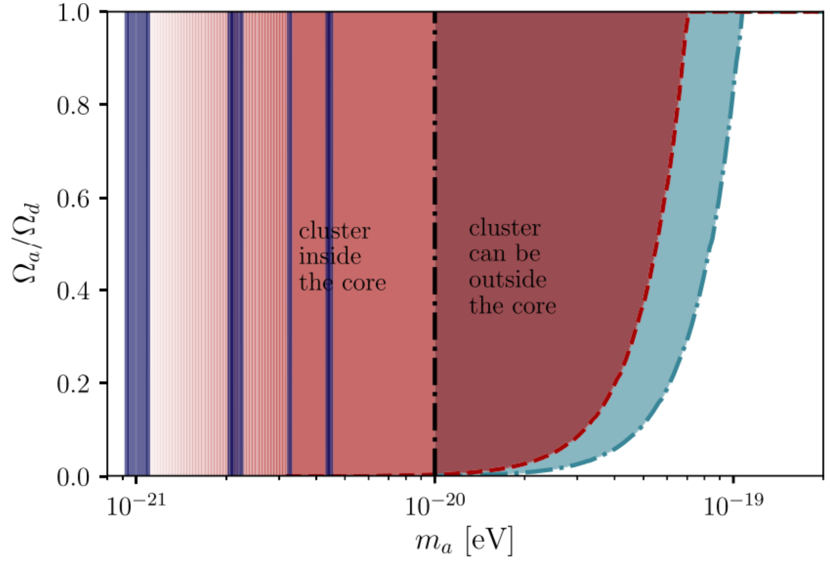
Excluding fuzzy dark matter with sizes and stellar kinematics of ultrafaint dwarf galaxies

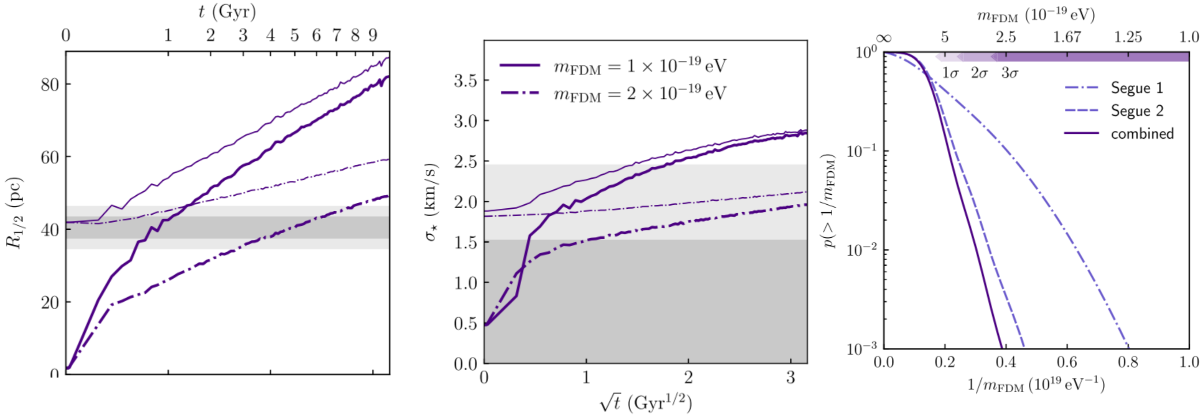
arXiv > astro-ph > arXiv:2501.07631

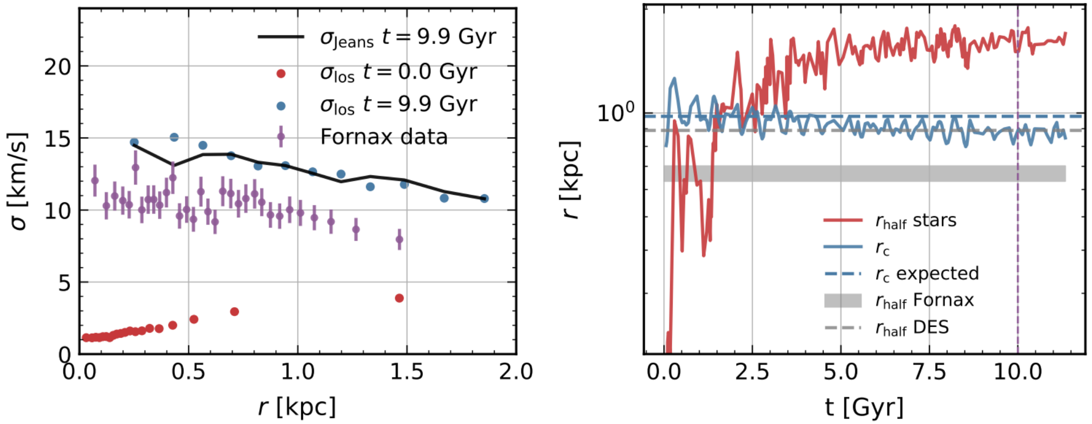
Astrophysics > Astrophysics of Galaxies

[Submitted on 13 Jan 2025]

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





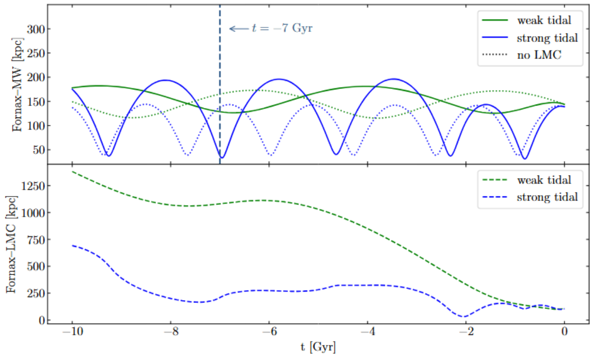


Tidal suppression of the heating effect

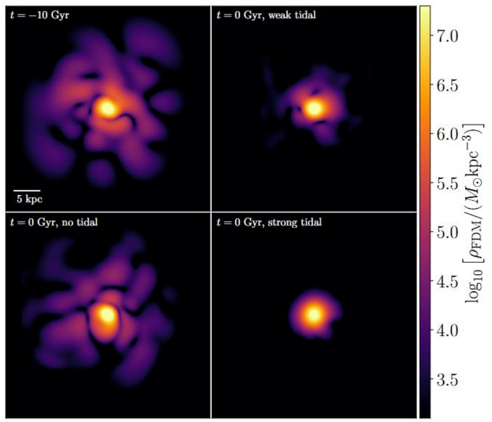
2507.01686, accepted by APJL

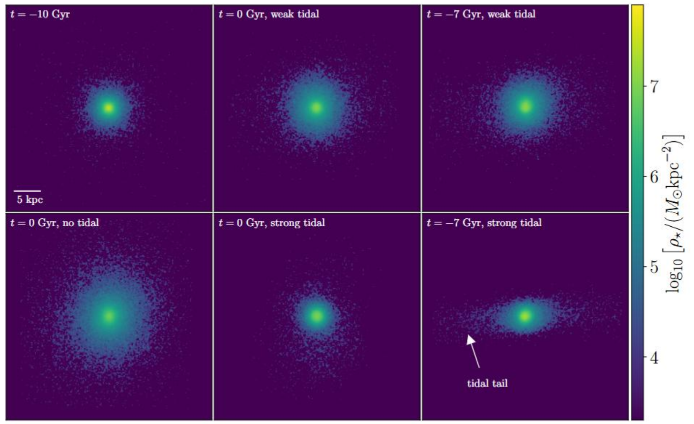
➢Fornax in the Milky Way

- ➢ Orbit



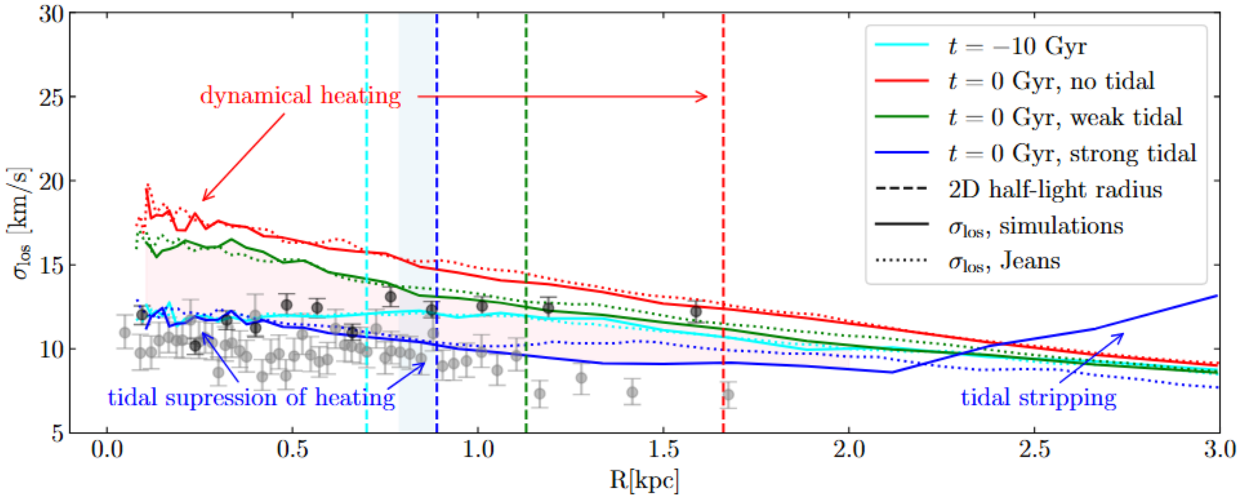
- ➢ FDM & stellar density





- ➢ Line-of-sight velocity dispersion

$m=10^{-22}$eV



Summary

- Astronomical observations can probe DM properties in a model-independent way.

- SIDM/Fuzzy dark matter is proposed to solve the core-cusp problem. The properties help to solve many observations that seem difficult to explain by CDM.

- Core structure enhances the tidal effects to explain DM deficit systems. The wave interference leads to dynamical heating and may explain anomalous stellar distributions in some systems.

- There are also many constraints on DM scenarios beyond the CDM. The available deviation of these DM scenarios from CDM is not clear yet. More observations/simulations are necessary to finally determine the DM properties.