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# Fuzzy Dark Matter Dynamical Friction:

stalling of globular clusters induced by dynamical heating

Adrian Szpilfidel, future PhD at LUX, Obs. de Paris

# Collaborators

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## Fuzzy dark matter dynamical friction

Stalling of globular clusters induced by dynamical heating

Adrian Szipfidel<sup>1\*</sup>, Pierre Boldrini<sup>1</sup>,  Jo Bovy<sup>2</sup> and Paola Di Matteo<sup>1</sup>



arxiv: 2510.00927



**Pierre Boldrini**

*Dark matter - Globular cluster dynamics*

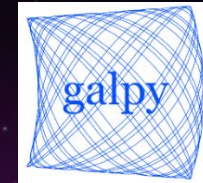


**Paola Di Matteo**

*Galactic dynamics - Milky Way*



**Jo Bovy**



*Galactic dynamics - Milky Way - Developer of GALPY*



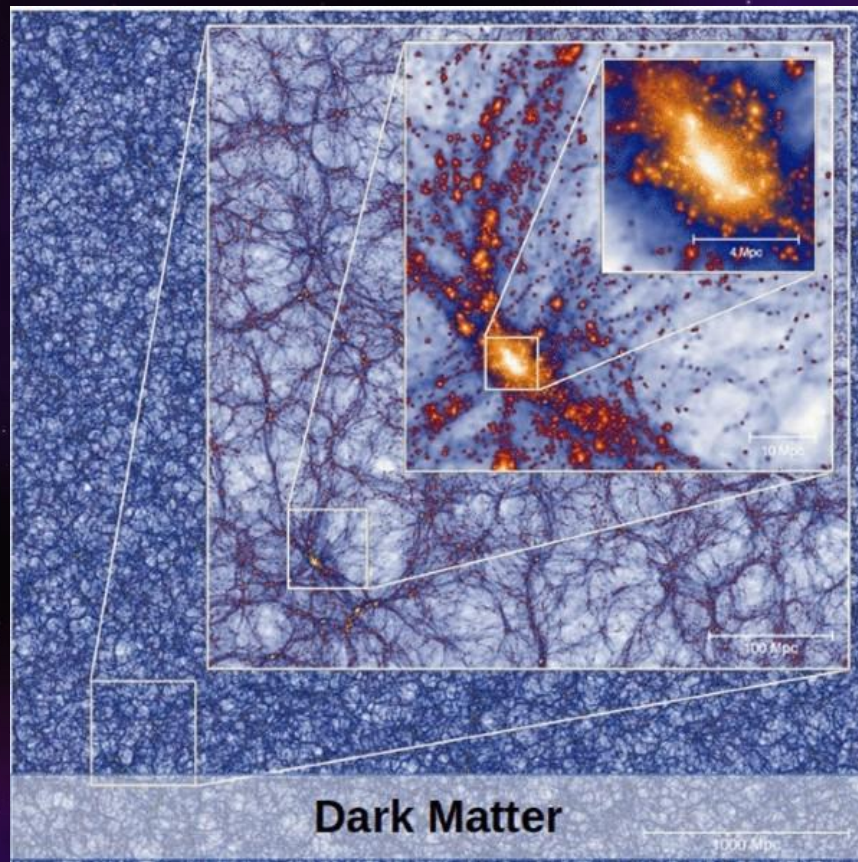
# Introduction

Standard cosmological model:

27% of the Universe is made of **Cold Dark Matter (CDM)**

- Interacts only through gravitation
- Collisionless fluid

Necessary to explain the **large-scale structure formation** of the Universe



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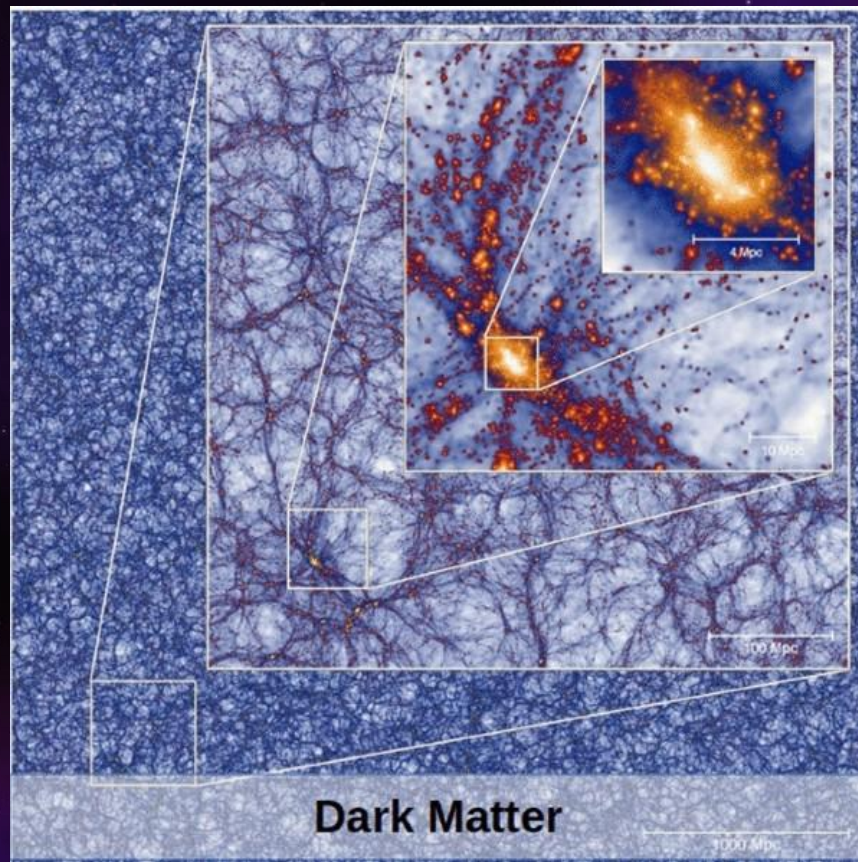
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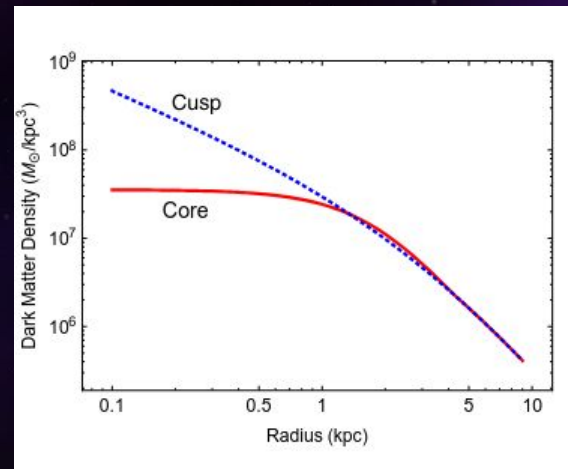
It matches brilliantly the cosmological observations but ...



# Introduction

... but there are **tensions** between observations and predictions on **galactic scales** (1-100 kpc):

- Cusp-core problem
- Fornax globular cluster problem
- Rotation curve diversity problem
- Satellite plane
- ...



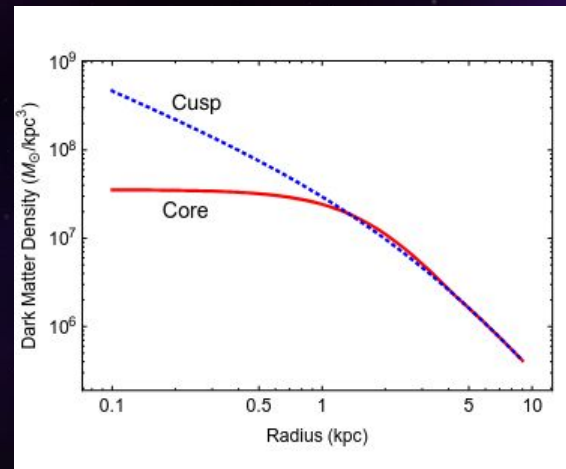
Dark matter density profiles

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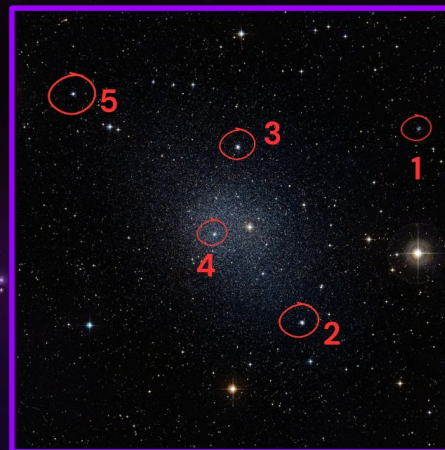
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Dark matter density profiles

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Fornax Dwarf Galaxy  
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Survey 2

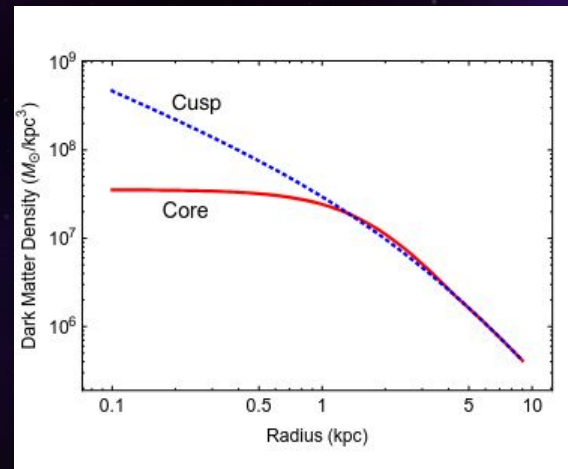
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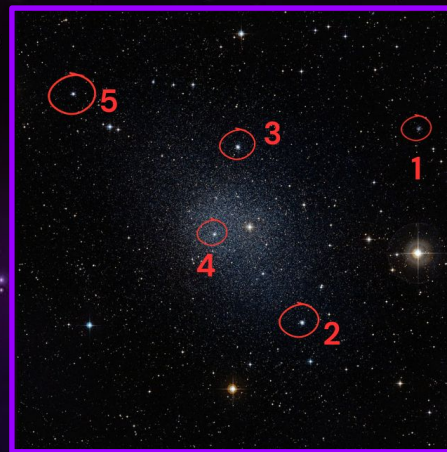
How to address these problems ?

- Baryonic processes
- Build **alternative dark matter model**



Dark matter density profiles

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Fornax Dwarf Galaxy

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# Alternative dark matter models

Several exotic dark matter (DM) models: Warm DM (*Bose et al., +05*),  
Self-Interacting DM (*Spergel et al., 2000*), ...

**Recent alternative: Fuzzy Dark Matter (FDM)** (*Hu et al., 2000*) as an  
ultralight scalar field without interaction. Constituted of a boson with mass

$$m_\chi \sim 10^{-22} \text{ eV}$$

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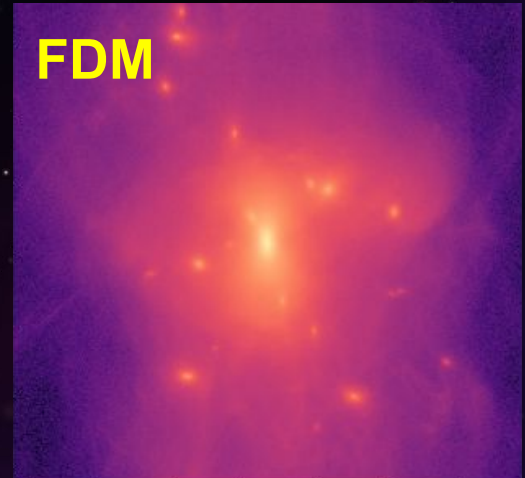
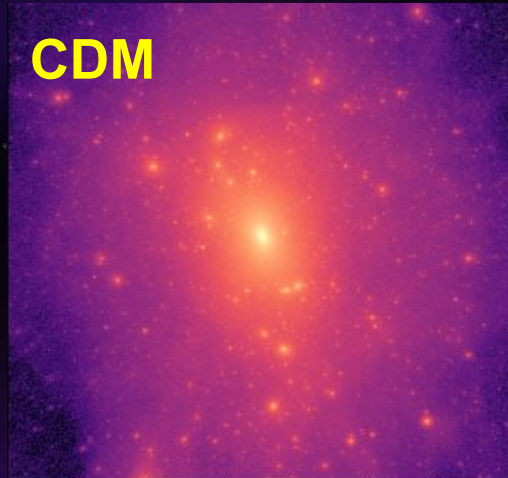
$$m_\chi \sim 10^{-22} \text{ eV}$$

**Modifies the dynamics**

on galactic scales and

**converges to CDM** on

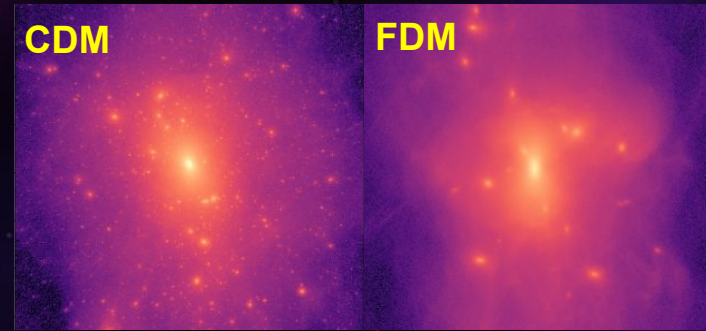
larger scales.



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# Fuzzy Dark Matter (FDM)

**Free parameter:**  $m_{22} = \frac{m_\chi}{10^{-22} \text{ eV}}$

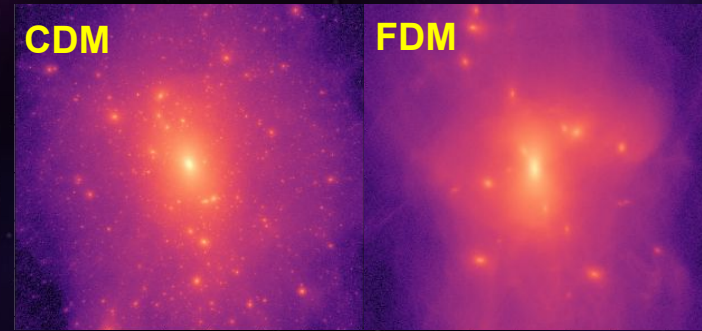


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Quantum wave-like nature of this particle **perturbs the density distribution**: stochastic density fluctuations

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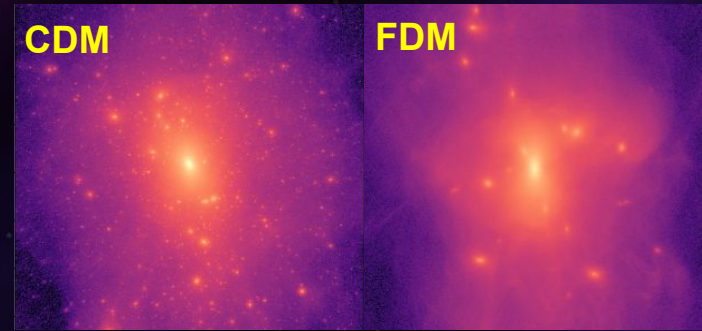
Quantum wave-like nature of this particle **perturbs the density distribution**: stochastic density fluctuations

3 main effects on galaxies:

- Suppression of low-mass halo formation (*Marsh & Silk, +14*)
- Formation of a **dark matter core** in galaxies (*Schive et al, +14*)
- Reduction/suppression of **dynamical friction** (*Hui et al, +17*)

# Fuzzy Dark Matter (FDM)

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**The magnitude of these effects depends on the FDM particle mass**

$m_{22} = 0.1$

→ **Strong effect**

$m_{22} = 100$

→ **Same as CDM**

# How to disentangle dark matter models ?

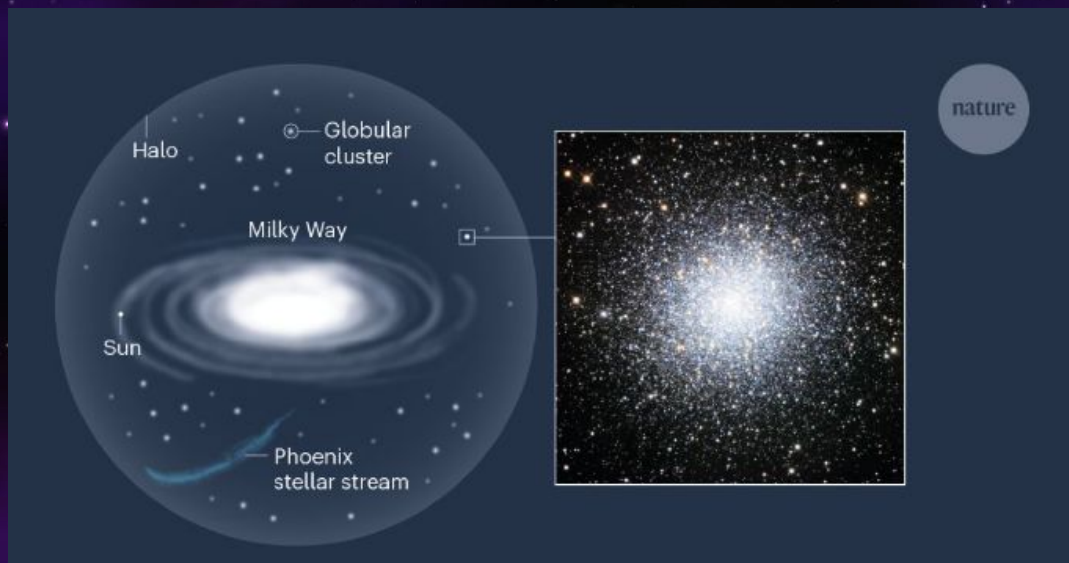
**Globular clusters (GC)** as tracers of DM: dense object composed of millions of stars. Their **dynamics** is sensitive to the **DM background** medium.

Mass:  $M_{GC} \sim 10^4 - 10^6 M_{\odot}$

Half-mass radius:  $r_{hm} \sim 10 \text{ pc}$


Distributed at all radii: 1-100 kpc

for the MW



# Main result

**3 regimes** for GC dynamics:


$$m_{22} = 0.5$$

$$m_{22} = 40$$

- The regimes depend on the value of the **free parameter**

$$m_{22} = \frac{m_\chi}{10^{-22} \text{ eV}}$$

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**3 regimes** for GC dynamics:



**Stalling of  
the GC orbits**

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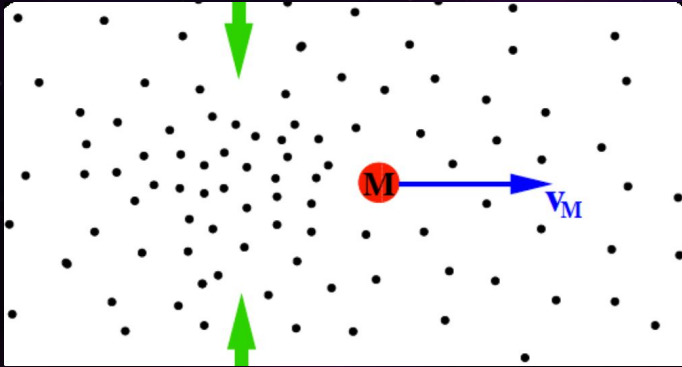
**Same infall as  
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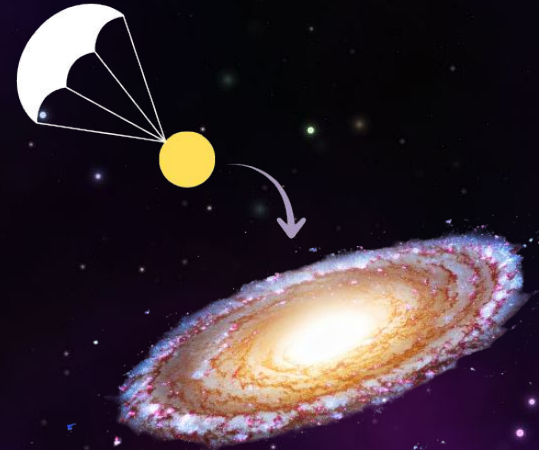
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# Dynamical friction as a probe of dark matter nature

Dynamical friction: **Energy loss** mechanism, drives the **infall of massive objects** (black holes, globular clusters, galaxy satellites)

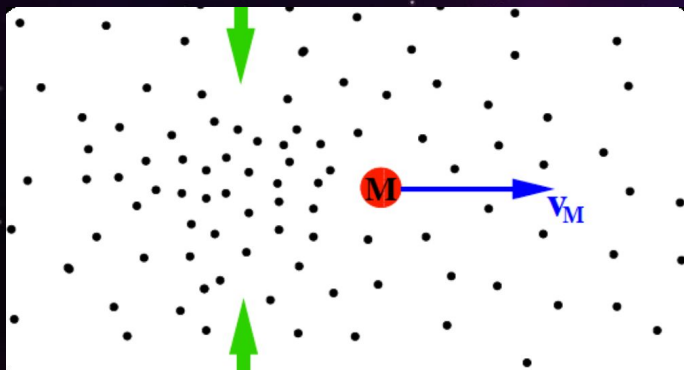


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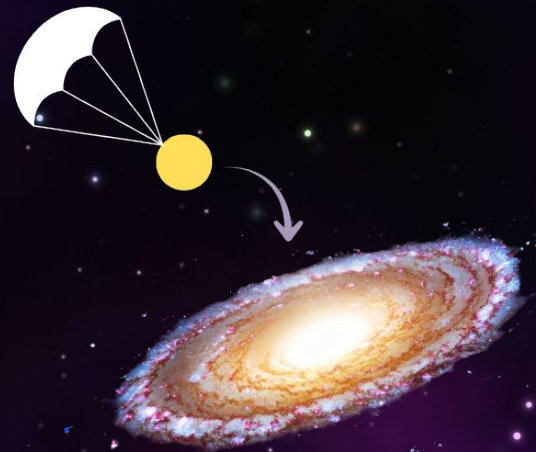
# Dynamical friction as a probe of dark matter nature

Dynamical friction: **Energy loss** mechanism, drives the **infall of massive objects** (black holes, globular clusters, galaxy satellites)



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$$\mathbf{F}_{\text{DF}} \propto -\frac{M_{\text{GC}}^2 \rho_{\text{DM}}(r)}{v^3} \mathbf{v}$$



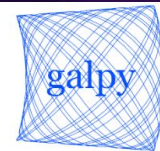
➤ **Looking at the infall of GC provides insight on the DM density profile**

# FDM dynamical friction formalism

**First implementation** of the FDM formalism, **new public instance available in GALPY**

```
class galpy.potential.FMDynamicalFrictionForce(amp=1.0, GMs=0.1, gamma=1.0, rhm=0.0,
m=1e-99, dens=None, sigmar=None, const_lnLambda=False, const_FDMfactor=False, minr=0.0001,
maxr=25.0, nr=501, ro=None, vo=None)
```

[\[source\]](#)



Implements the fuzzy dark matter (FDM) dynamical friction force.

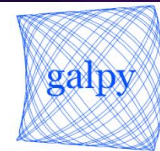
$$\mathbf{F}_{\text{DF}}(r) = -4\pi G^2 M_{\text{GC}}^2 \rho(r) \frac{\mathbf{v}}{v^3} \mathcal{C}(r, v)$$

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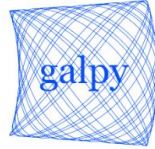
$$\mathcal{C}_{\text{CDM}}(r, v) = \frac{1}{2} \ln(1 + \Lambda^2) \left[ \text{erf}\left(\frac{v}{\sqrt{2}\sigma}\right) - \frac{2v}{\sqrt{2\pi}\sigma} \exp\left(-\frac{v^2}{2\sigma^2}\right) \right] \quad \text{CDM (Chandrasekhar, 1943; Petts et al. +15)}$$

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```

[source]



$$\mathbf{F}_{\text{DF}}(\mathbf{r}) = -4\pi G^2 M_{\text{GC}}^2 \rho(\mathbf{r}) \frac{\mathbf{v}}{v^3} \mathcal{C}(\mathbf{r}, v)$$

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$$C_{\text{CDM}}(r, v) \longrightarrow C_{\text{FDM}}(r, v, m_{22})$$

## 2 physical regimes in FDM:

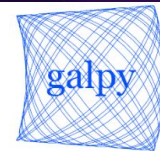
- ❖ Zero velocity dispersion in the medium (Hui et al. +17)
- ❖ Velocity dispersion in the medium (Lancaster et al. +20)

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$$C_{\text{CDM}}(r, v) \longrightarrow C_{\text{FDM}}(r, v, m_{22})$$

$$m_{22} = 0.1$$

$$C_{\text{FDM}} \ll C_{\text{CDM}}$$

$$m_{22} = 100$$

$$C_{\text{FDM}} \rightarrow C_{\text{CDM}}$$

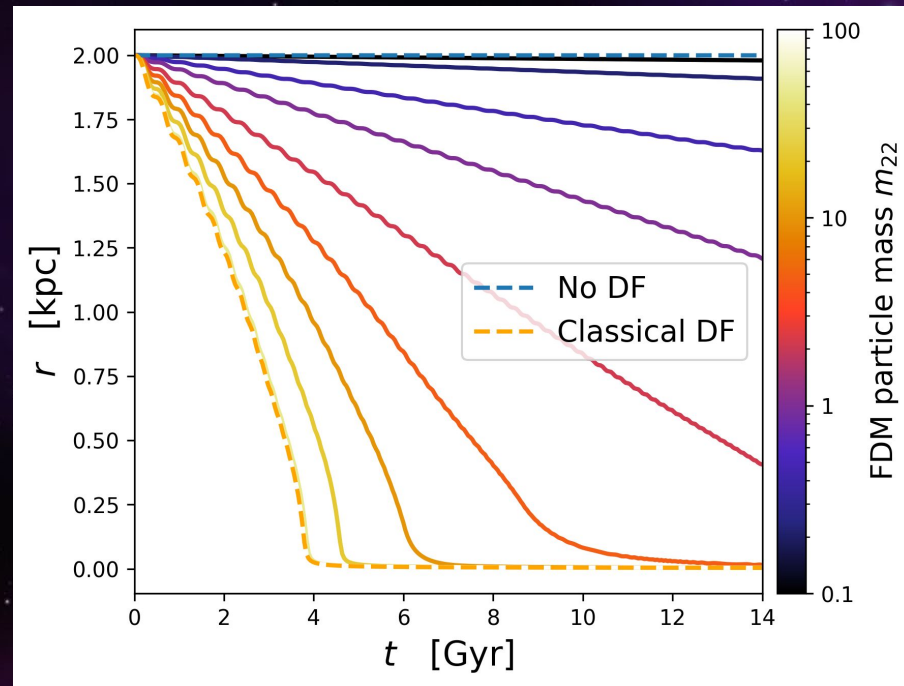
# Dynamical friction in FDM

- Stochastic density fluctuations: granules
- Density fluctuations in FDM **increase kinetic energy** through **dynamical heating**
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$$m_{22} = \frac{m_\chi}{10^{-22} \text{ eV}}$$



$$m_{22} = 0.1$$

- More dynamical heating
- Longer fall-in time

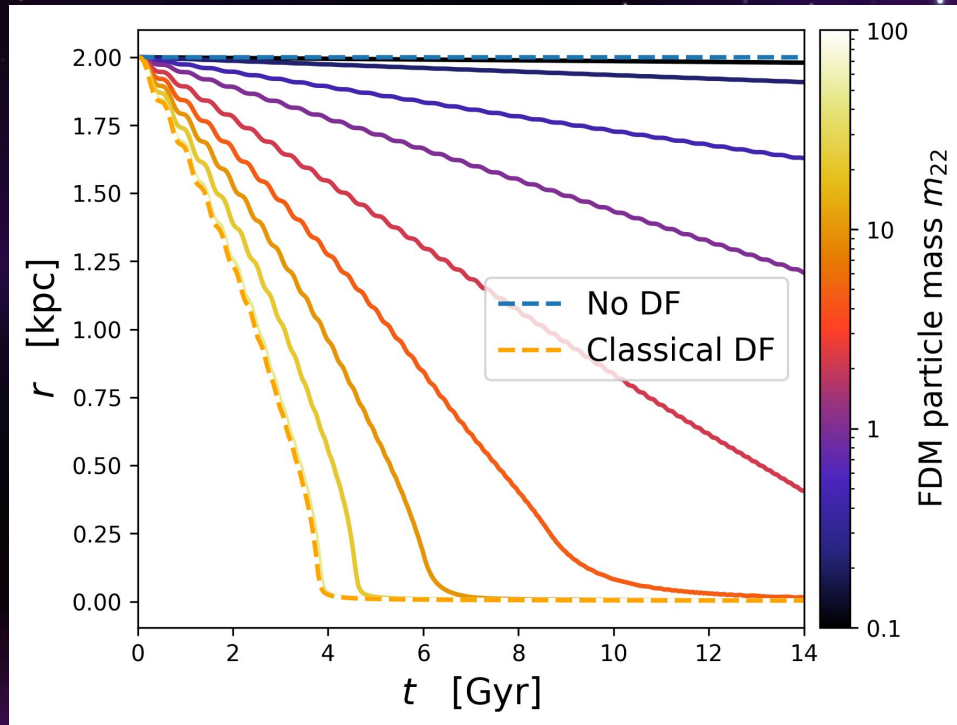
$$m_{22} = 100$$

- Less dynamical heating
- Shorter fall-in time (same as CDM)

# Generalization of the analysis

## Orbital integrations for:

- 1000 GCs with mass  $10^6 M_{\text{sol}}$ , distributed in all the E- $L_z$  space.
- DM halo masses:  $M_{\text{halo}} = 10^9 - 10^{12} M_{\text{sol}}$
- FDM boson mass  $m_{22} = 0.1 - 100$



# Dynamical friction in FDM

$$\text{DF efficiency} = \frac{|r_{\text{apo}}^{\text{DF}} - r_{\text{apo}}^{\text{no DF}}|}{r_{\text{apo}}^{\text{no DF}}} > 5\%$$

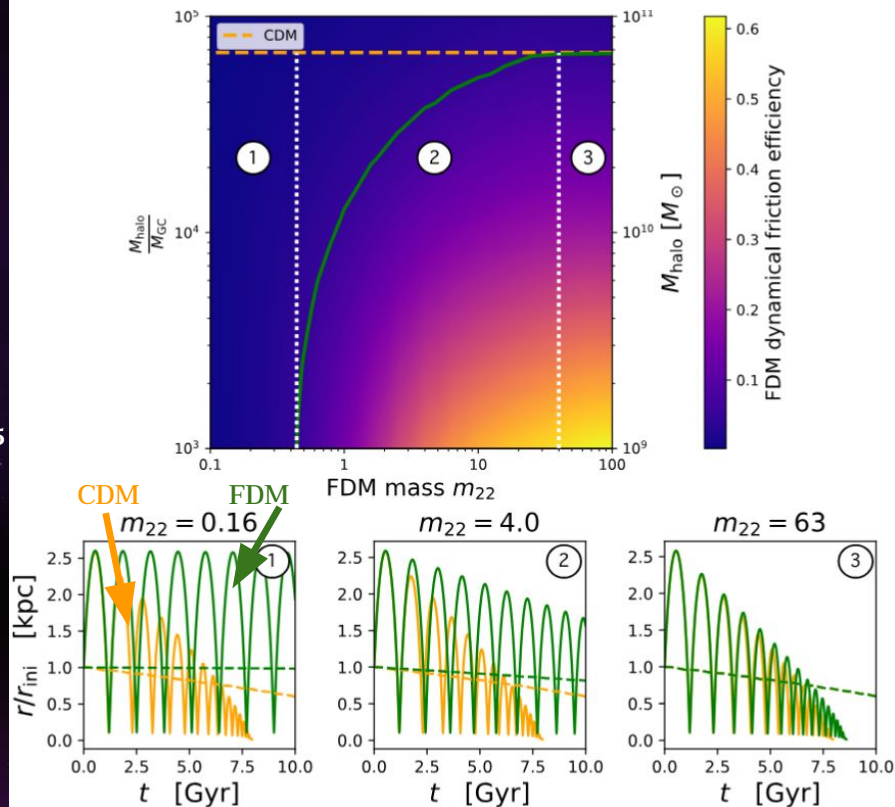
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**Classical DF:** inefficient for mass ratio  $M_{\text{halo}}/M_{\text{GC}} > 10^5$

➤ Dynamical friction is efficient in dwarf galaxies !

## NFW + FDM DF



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**FDM DF: 3 regimes for GC dynamics**

$m_{22} = 0.1$

$m_{22} = 0.5$

$m_{22} = 40$

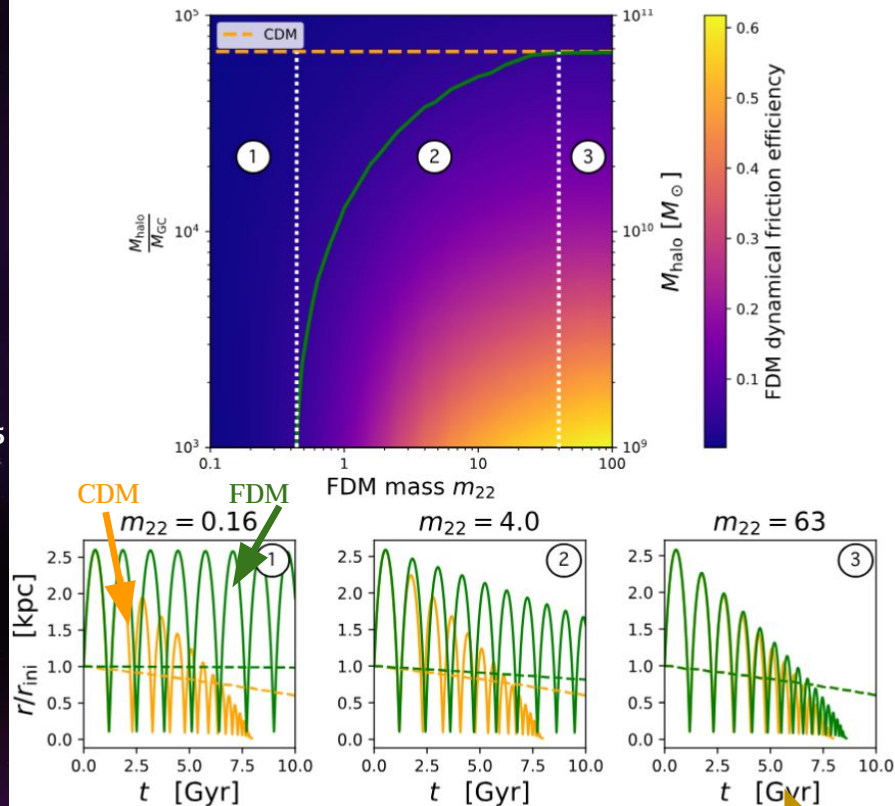
$m_{22} = 100$

➤ DF completely inefficient

➤ DF significantly reduced

➤ FDM DF similar than in CDM

## NFW + FDM DF



# Summary

## 3 regimes for FDM dynamical friction

- ❖ Dynamical heating **vanishes** the dynamical friction  $m_{22} = 0.5$
- ❖ Dynamical heating reduces the friction, **infall time is longer** than found in CDM  $m_{22} = 40$
- ❖ No dynamical heating, **same infall** as found in CDM

Cosmological constraints:  $m_{22} = 7 - 20$  (Lya forest) (*Irsic +17, Kobayashi +17*)

Other galactic constraints:  $m_{22} = 0.5 - 1.5$  (*Amorisco+18a, Chiang+23b*)

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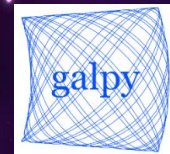
- |  |  |  |
|--|--|--|
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## Perspectives:

- Use GCs dynamics to disentangle FDM and CDM
- Euclid: try to solve the **timing problem** of dwarf galaxies with FDM formalism
- New public package for galactic **dynamics in FDM**



# Summary

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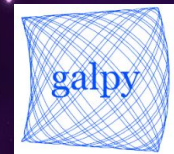
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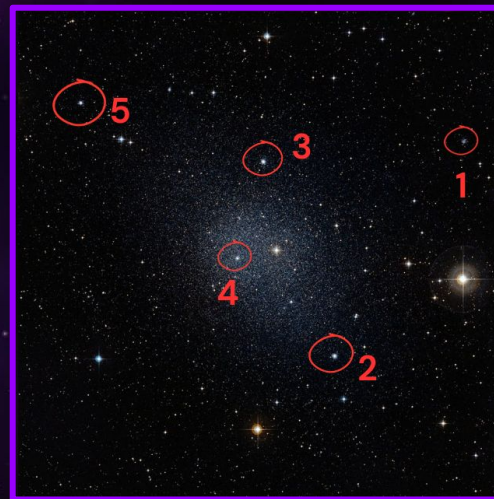
# Thank you!



# Fornax GC problem

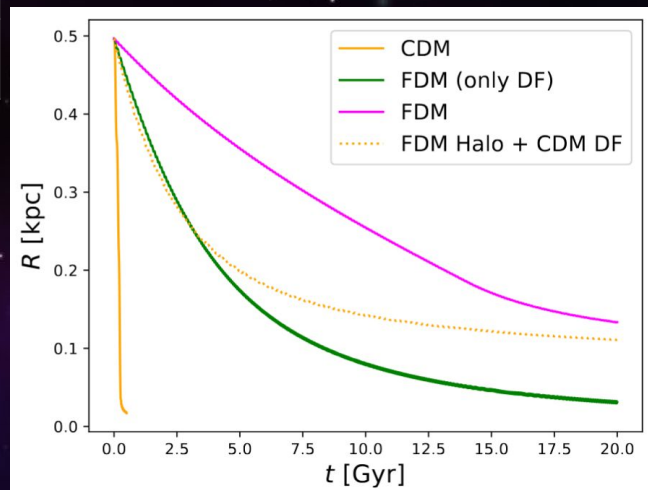
Fall-in time of GCs	CDM (Gyr)	FDM $m_{22}=3$ (Gyr)
Fornax 1	25	393
Fornax 2	2.56	59
Fornax 3	0.3	19
Fornax 4	0.24	24
Fornax 5	5	74

FDM provides an explanation for the survival of Fornax's GCs



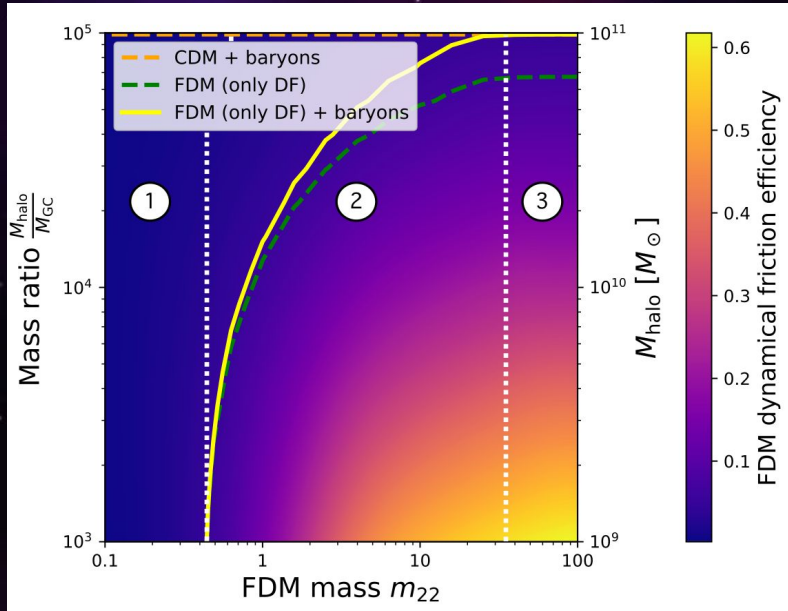
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Fornax 3 orbit



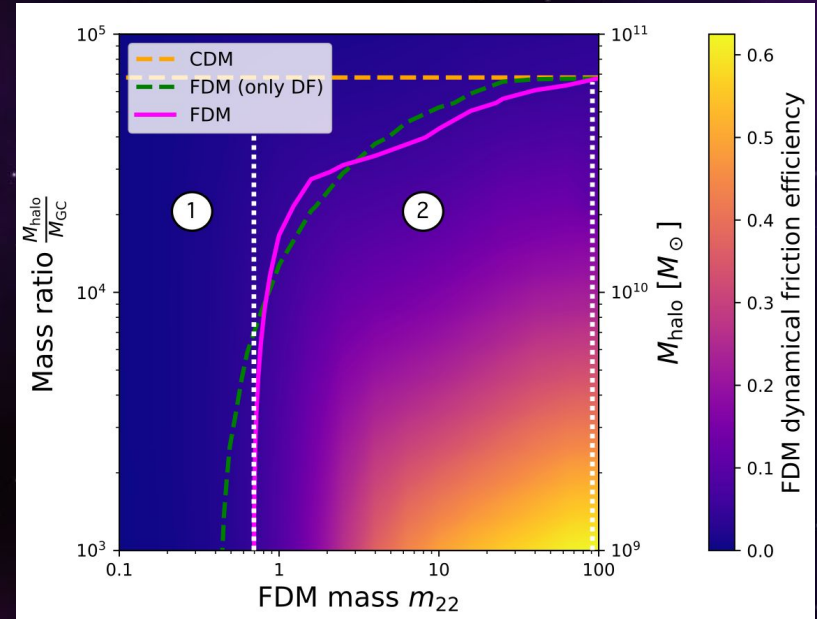
# More complete modelisation

## NFW + FDM DF + Stellar component



DF overall **more efficient** (yellow curve): baryons **increase the density**  
Reduced DF regime slightly tightened.

## DM core + FDM DF



DM core **increase the DF inefficiency**  
Broadening of the reduced DF regime.