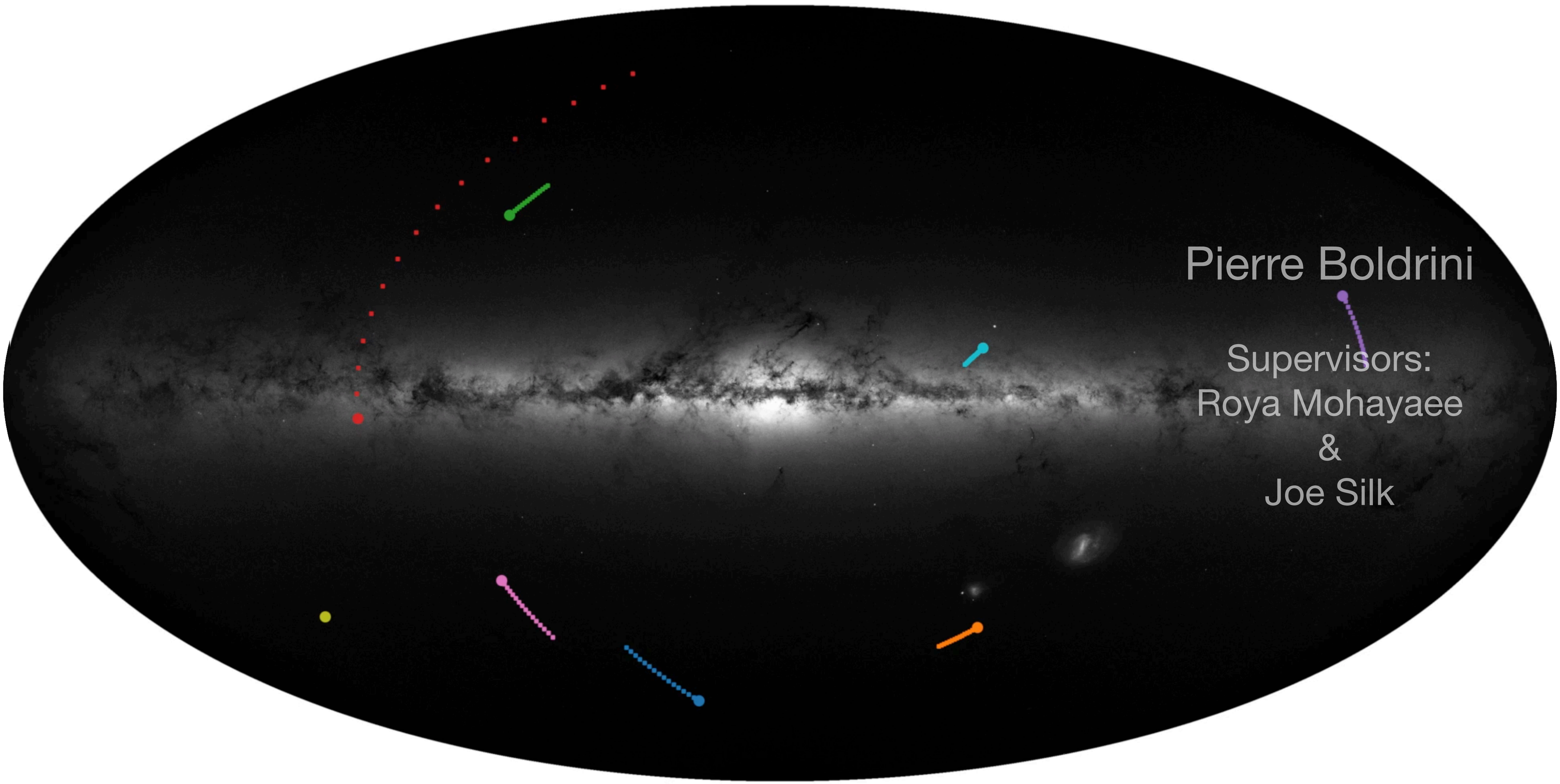
PhD Defense:
The cusp-core problem in dwarf galaxies: New solutions



Pierre Boldrini

Supervisors:
Roya Mohayaee
&
Joe Silk

cnrs

INSTITUT D'ASTROPHYSIQUE DE PARIS
Unité mixte de recherche 7095 · IAP · CNRS - Sorbonne Université

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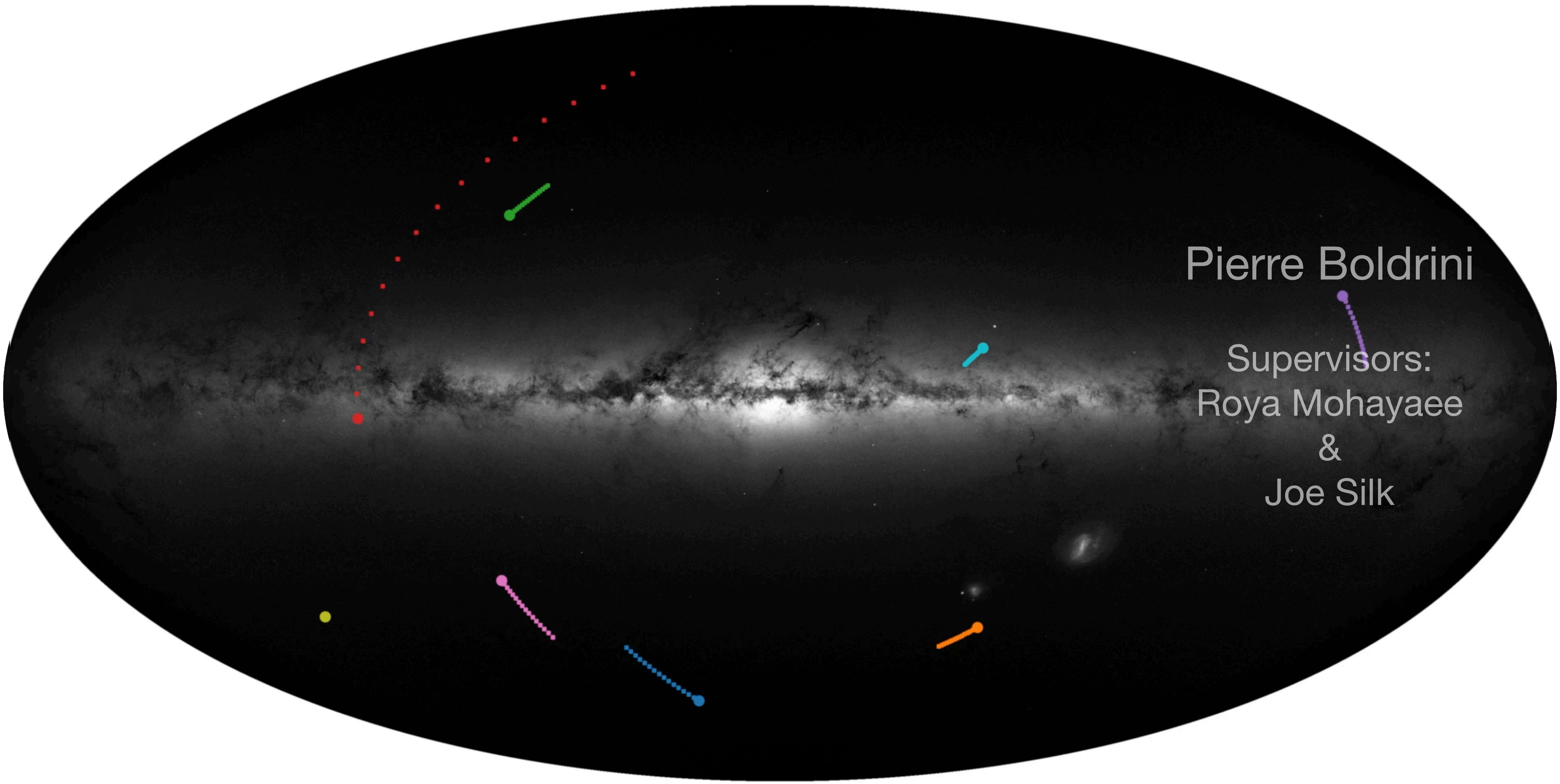

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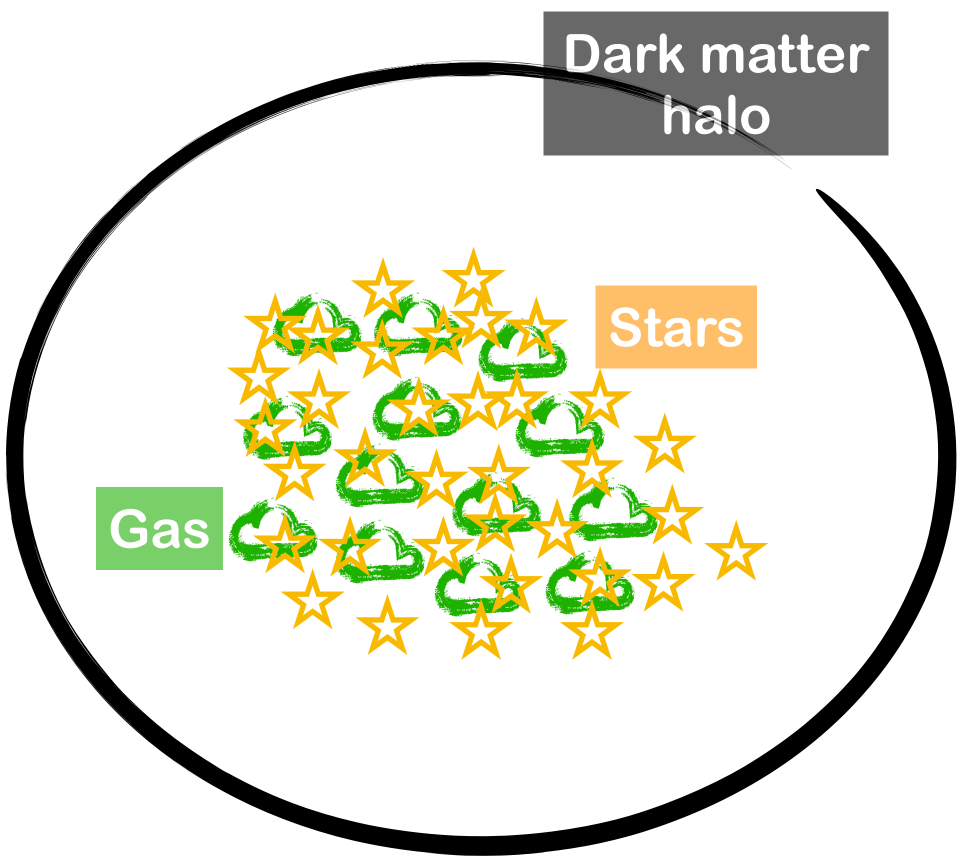
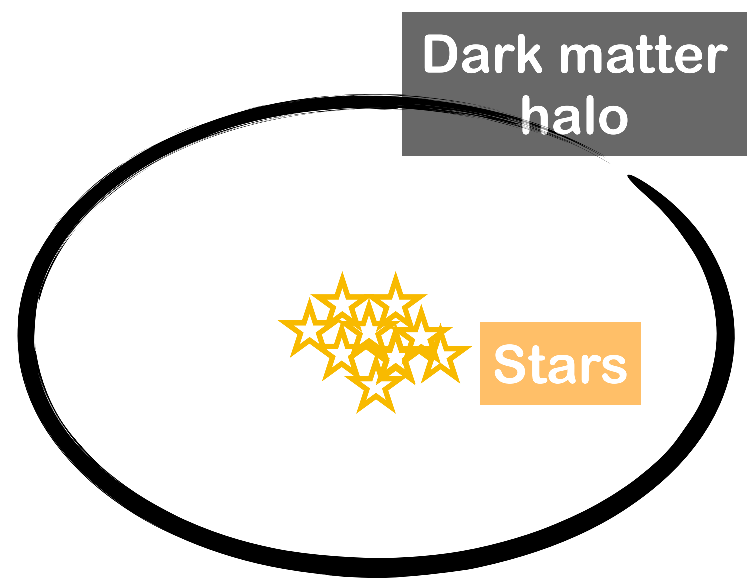
Galaxies

Galaxy



$M_{DM} \sim 10^{11} - 10^{12}\ M_{\odot}$

Dwarf galaxy



- Gas component negligible
- Dominated by dark matter

$M_{DM} \sim 10^{9} - 10^{10}\ M_{\odot}$

Nature of dark matter

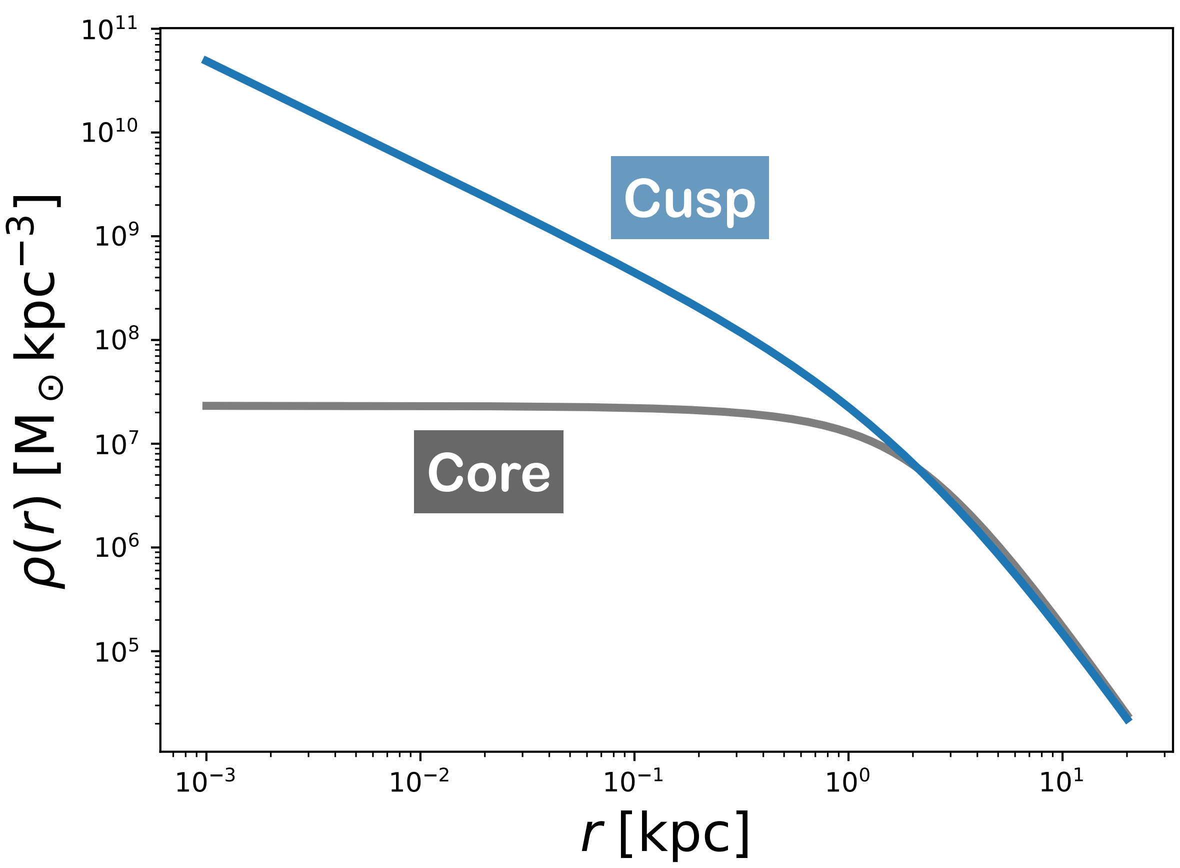
Galaxies are **embedded** in halos of **dark matter**

- Cold dark matter **Current cosmological model**
- Warm dark matter
- Self-interacting dark matter
- Fuzzy dark matter
- Primordial black holes

Alternative theories

Dark matter distributions in different theories

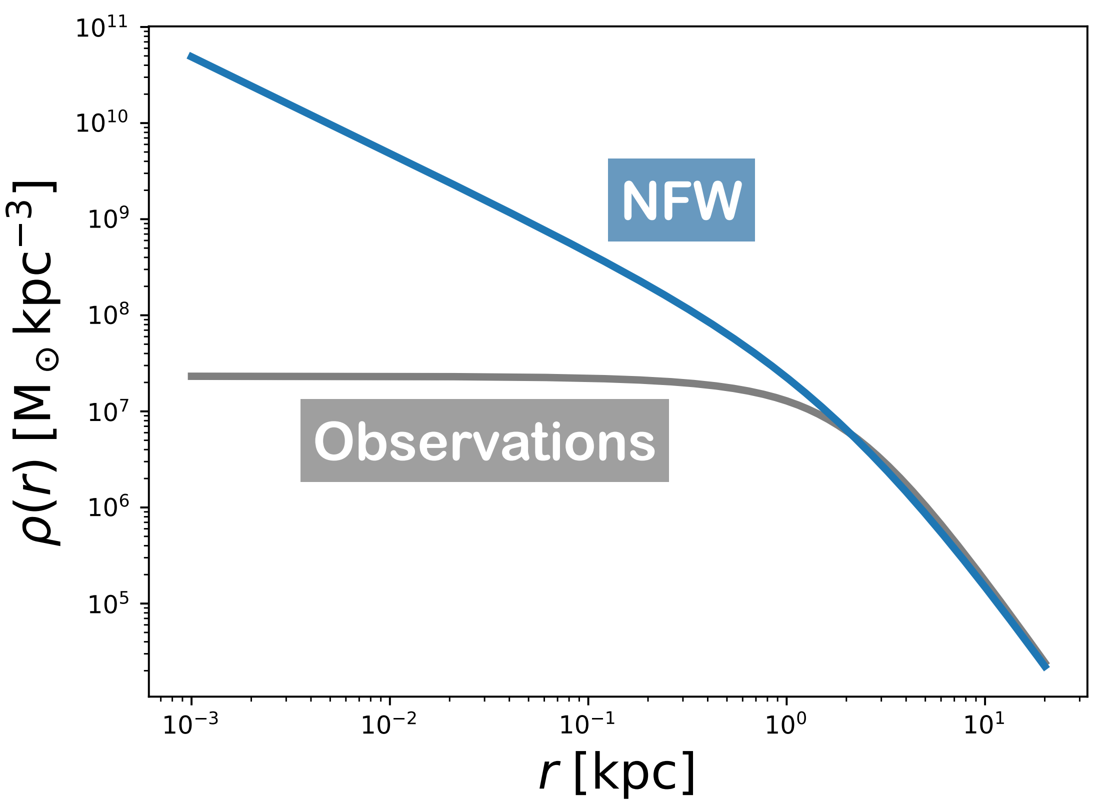
How dark matter is distributed in dwarf galaxies?

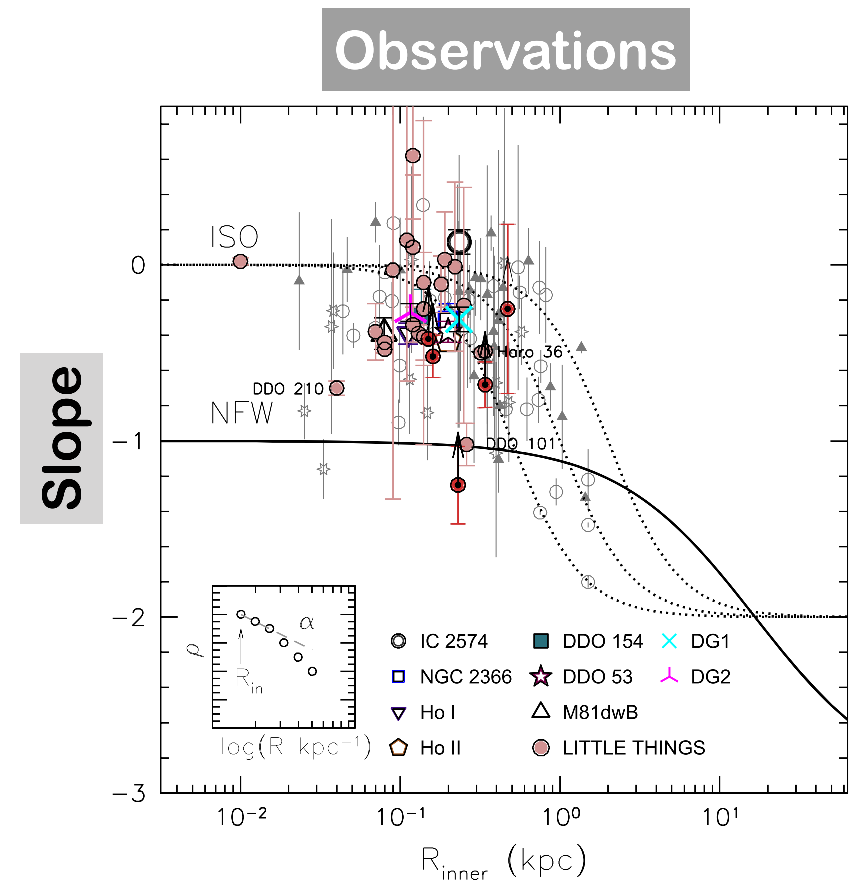


- Cold dark matter **Cusp**
- Warm dark matter **Core**
- Self-interacting dark matter **Cusp** **Core**
- Fuzzy dark matter **Core**
- Cold dark matter + Primordial black holes **???**

Cusp-core problem

The discrepancy between observations and theory



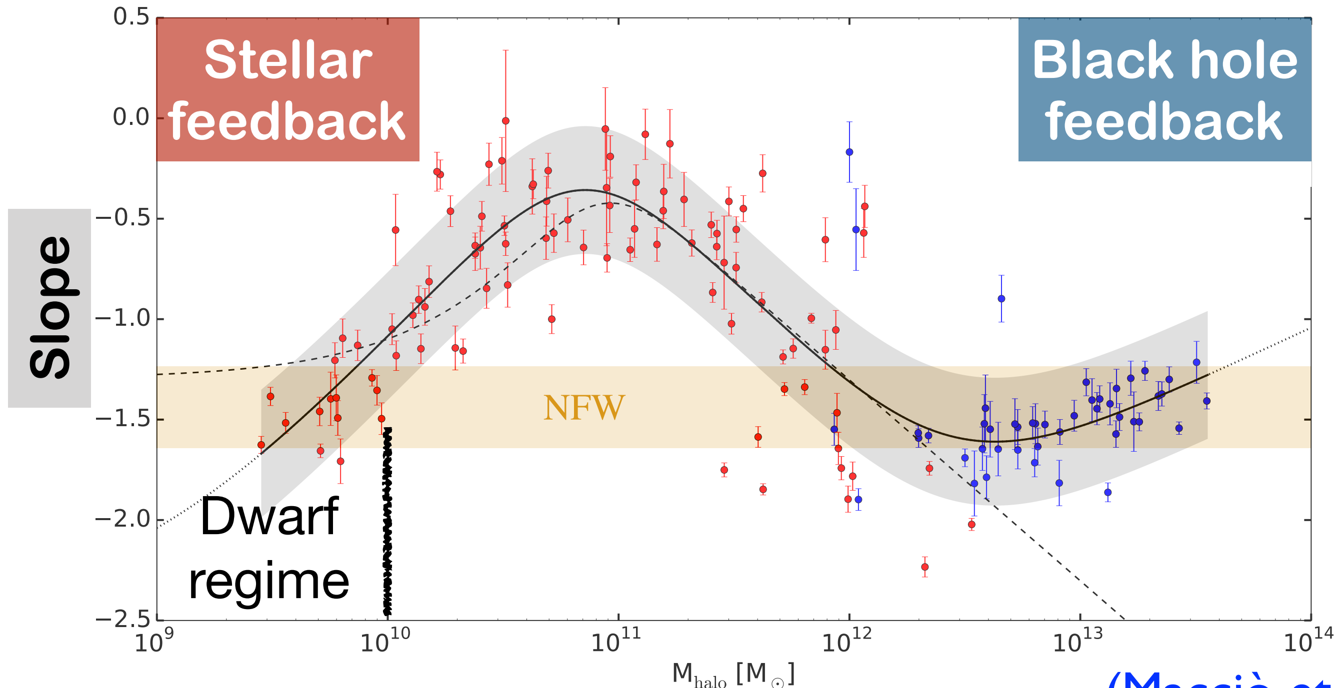


(Oh et al. (2015))

$$\rho(r)_{\rm NFW} = \rho_0 \left(\frac{r}{r_{\rm s}}\right)^{-1} \left(1 + \frac{r}{r_{\rm s}}\right)^{-2}$$

Astrophysical solutions

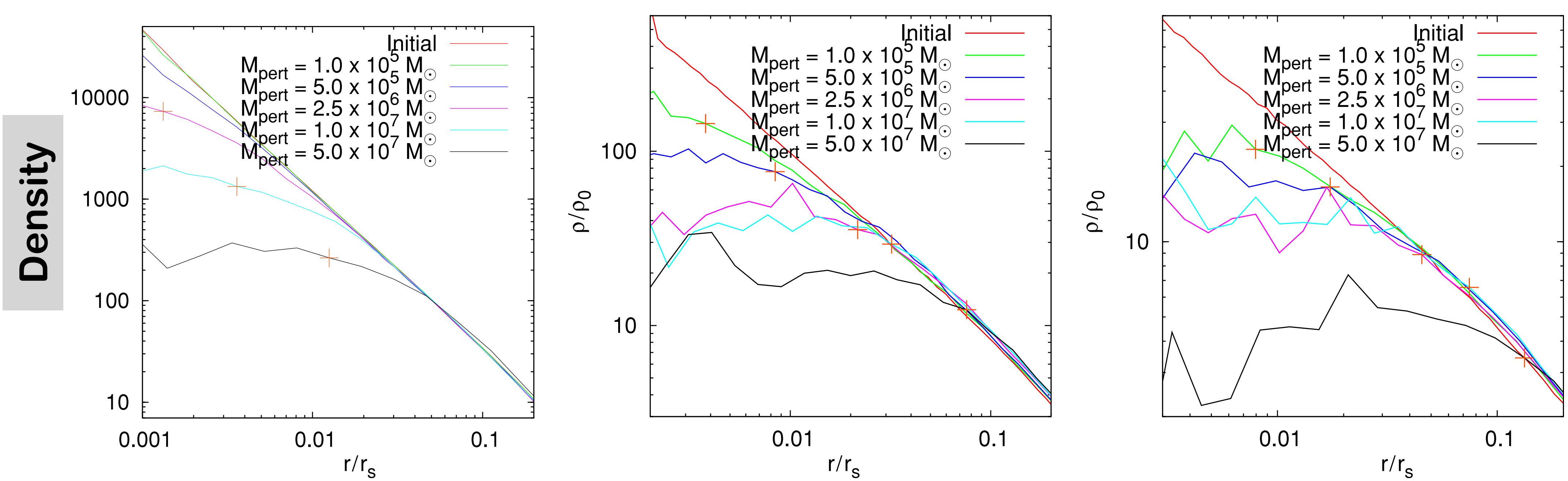
Baryonic feedback



(Macciò et al. (2020))

Sinking massive objects (gas clumps)

(Goerdt et al. (2010))



Astrophysical solutions

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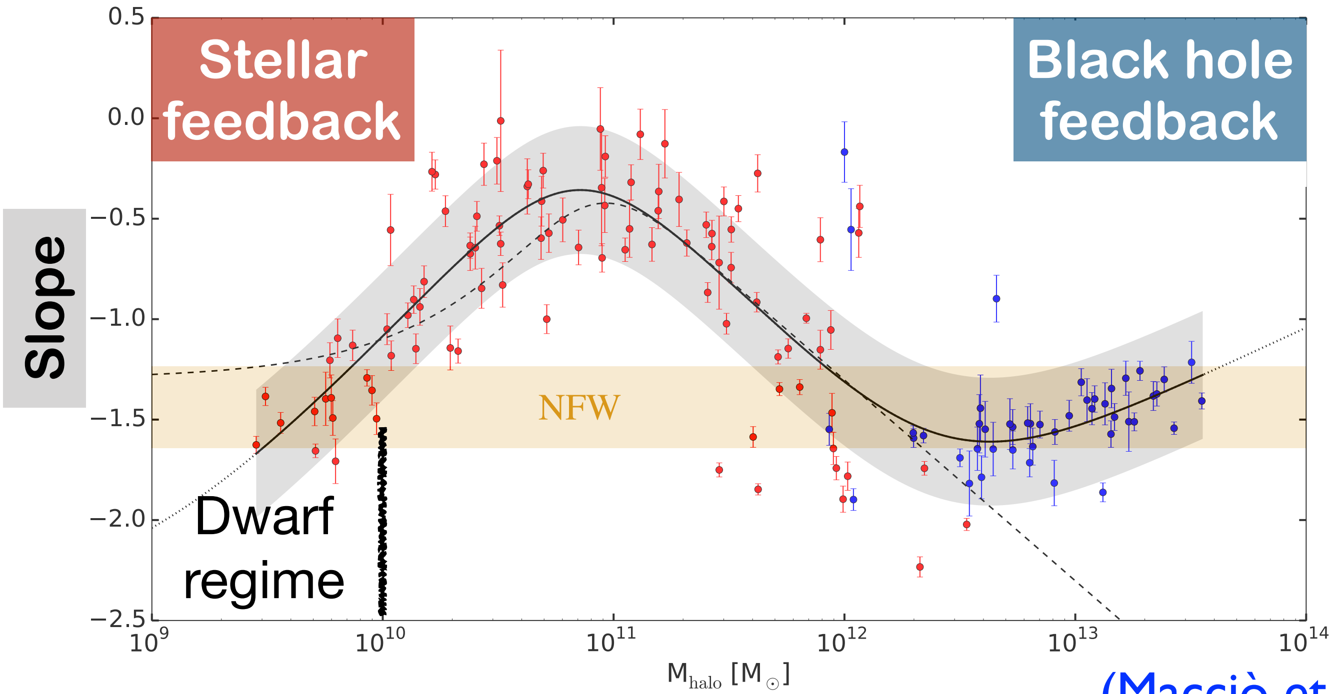

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Sinking massive objects (gas clumps)

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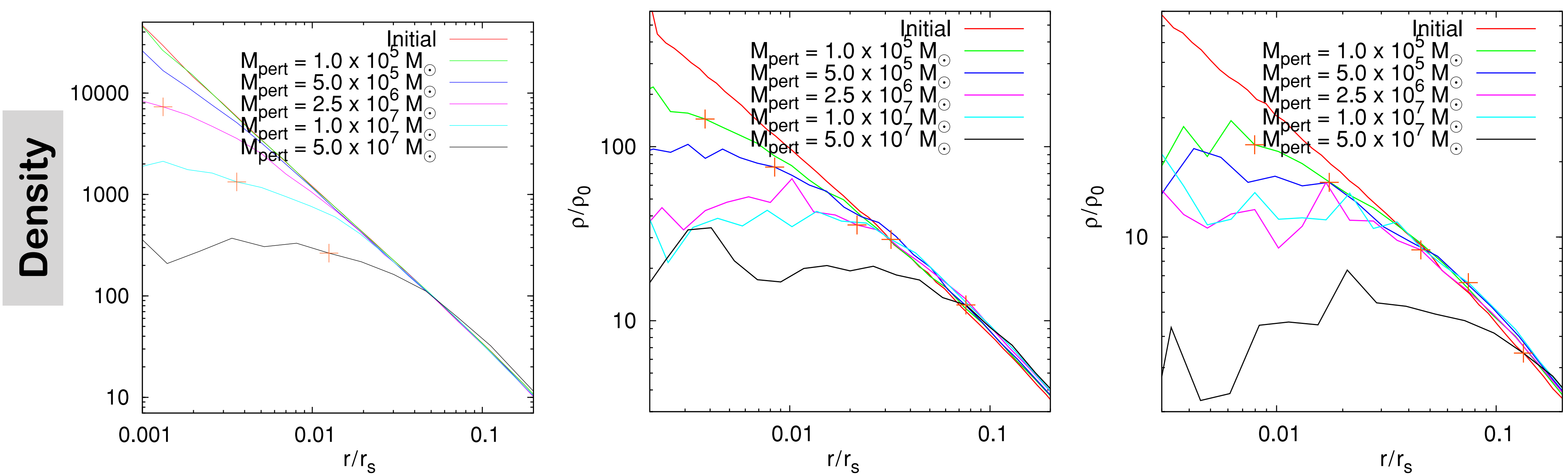
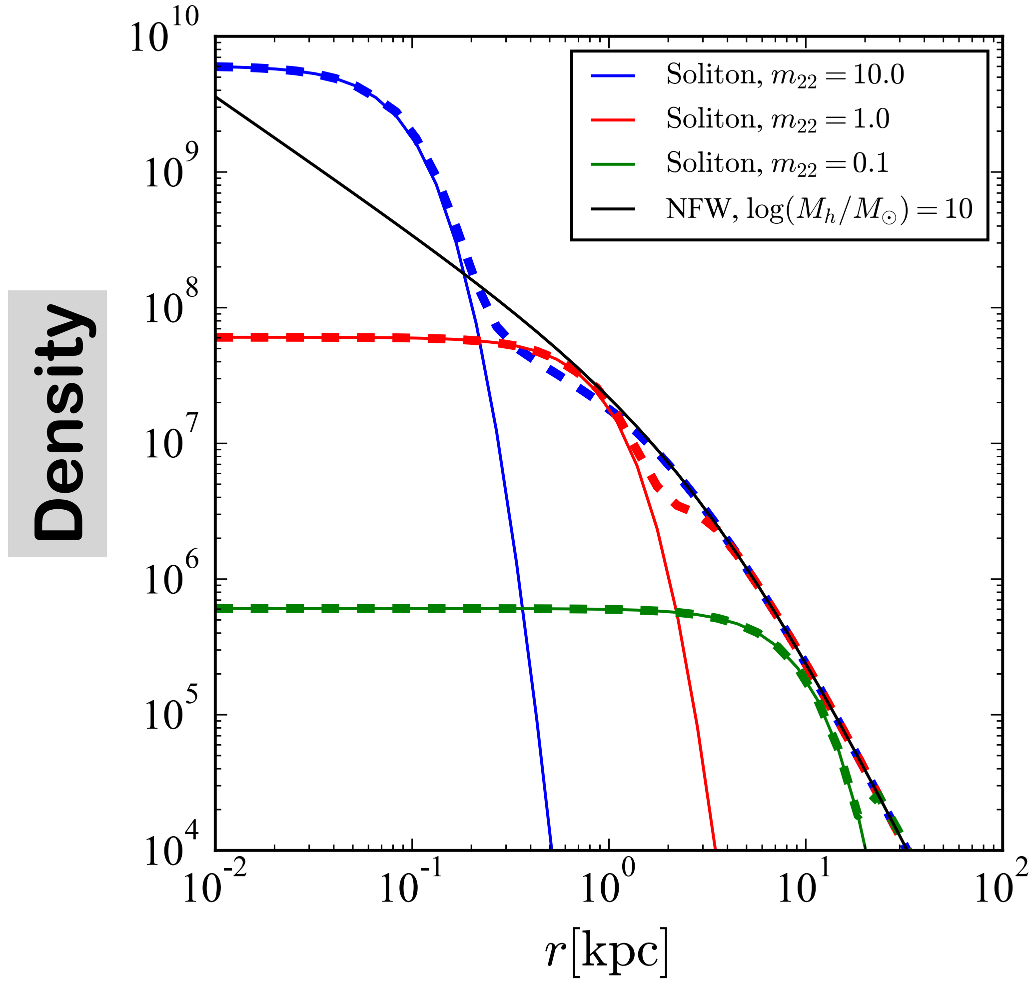


Cosmological solutions

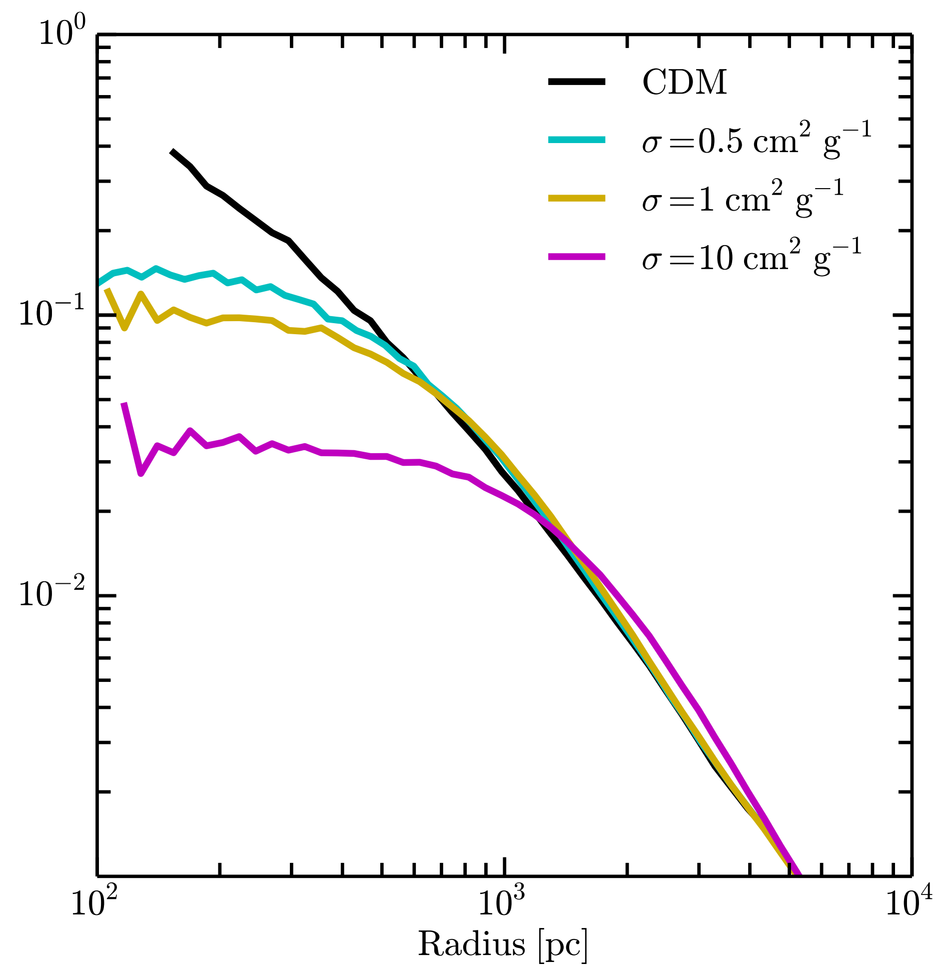
Changing the nature of the dark matter

Fuzzy dark matter



(Safarzadeh et al. (2020))

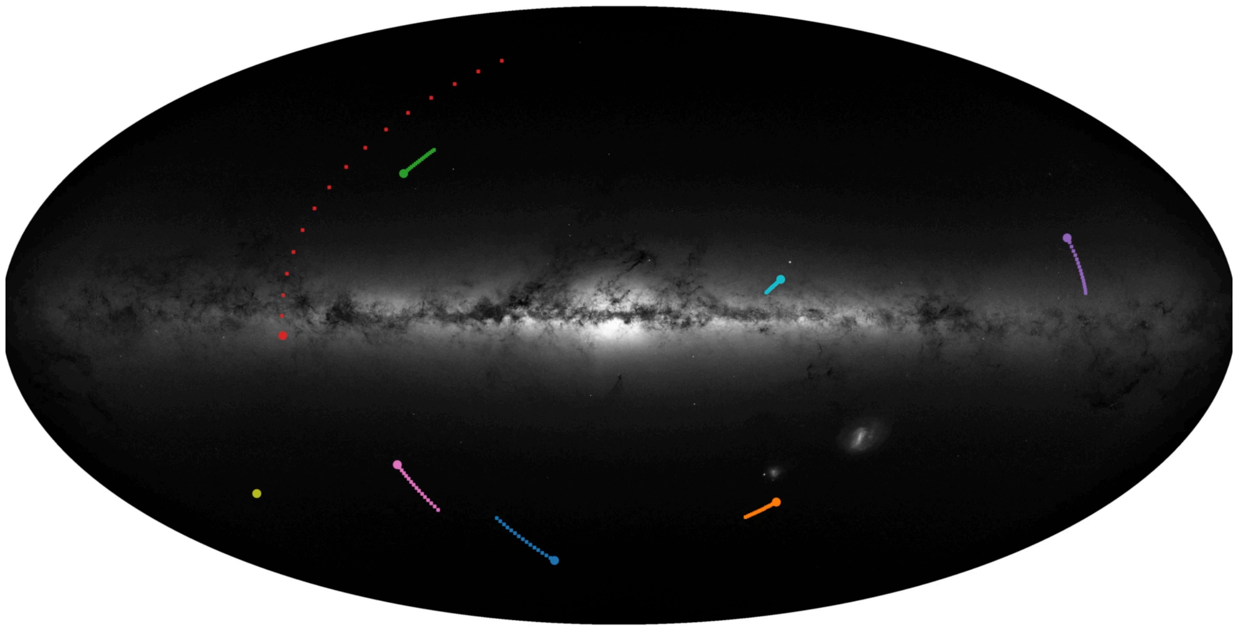
Self-interacting dark matter



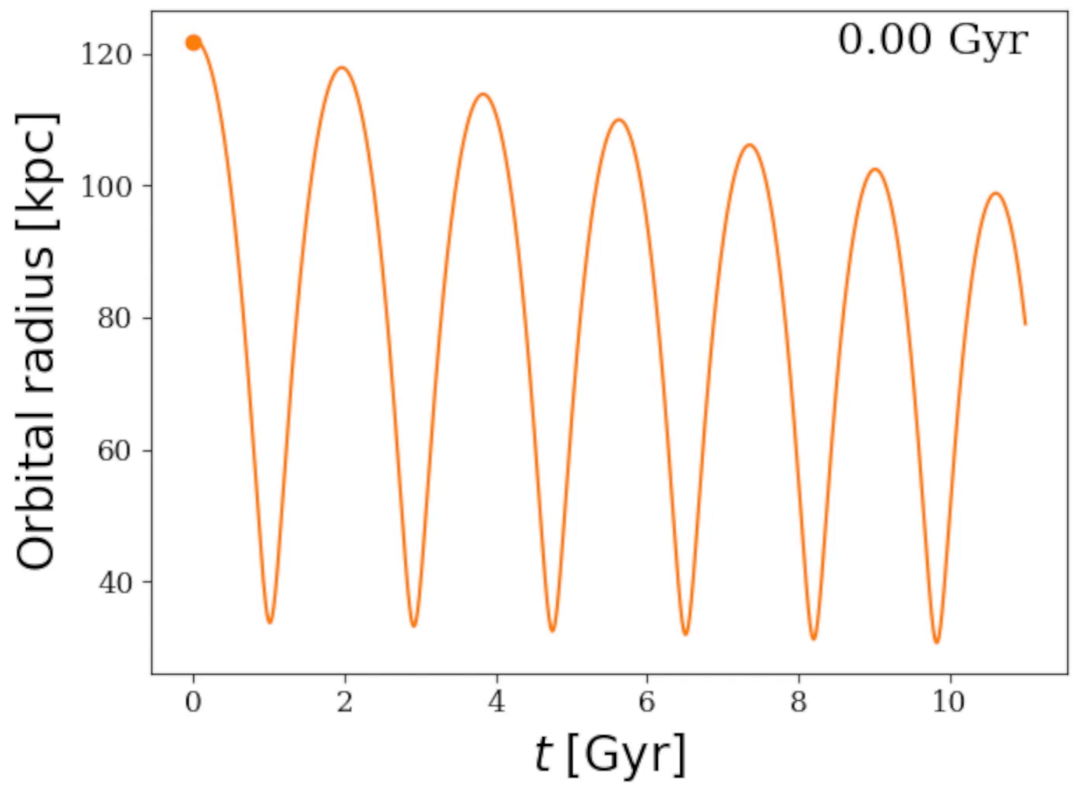
(Elbert et al. (2015))

Orbiting around the Milky Way

Orbits of dwarfs



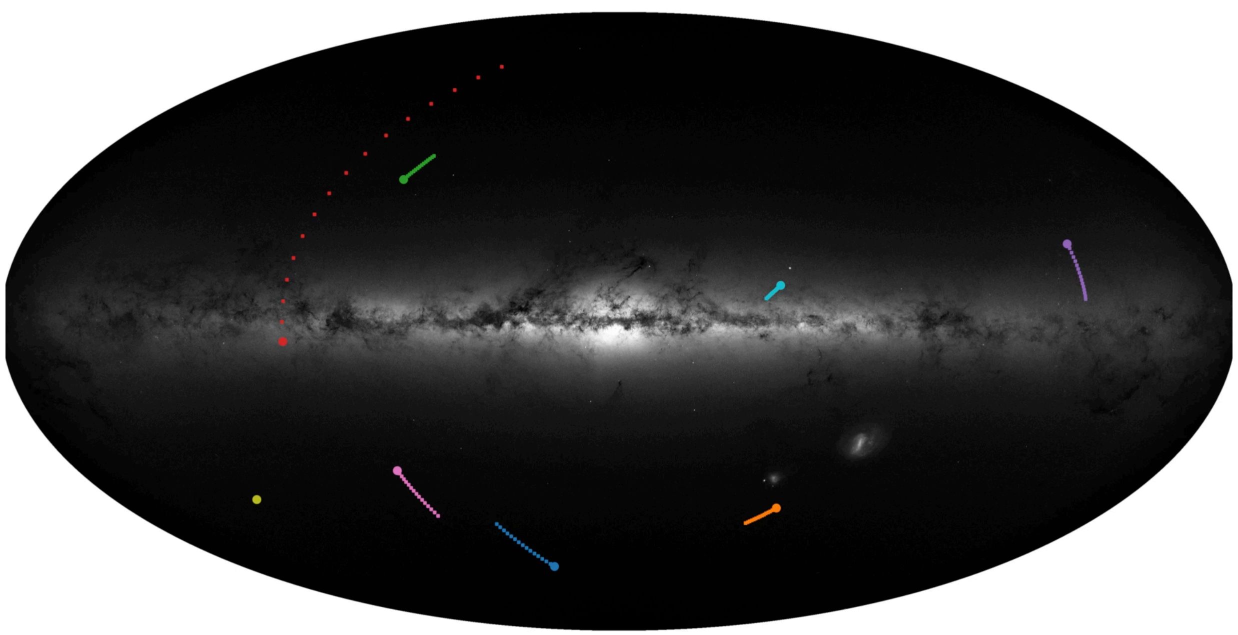
Draco dwarf galaxy



Why the orbit of dwarfs decrease over time?

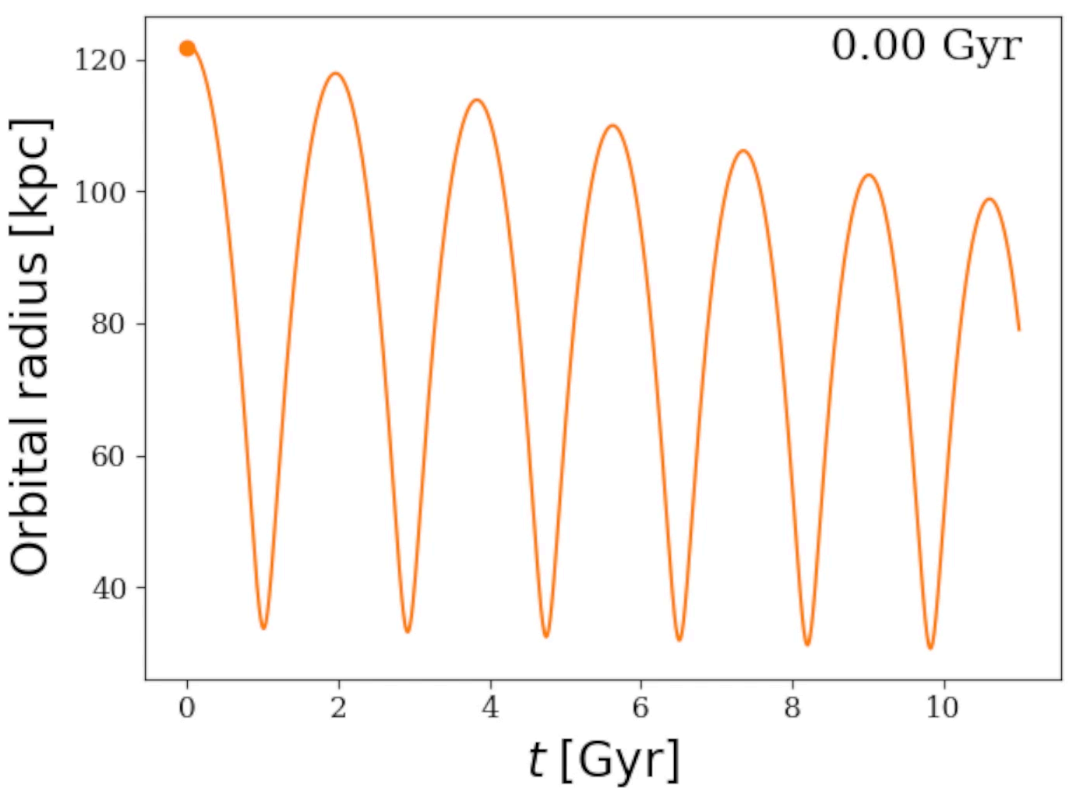
Orbiting around the Milky Way

Orbits of dwarfs



Size of MW halo

Draco dwarf galaxy

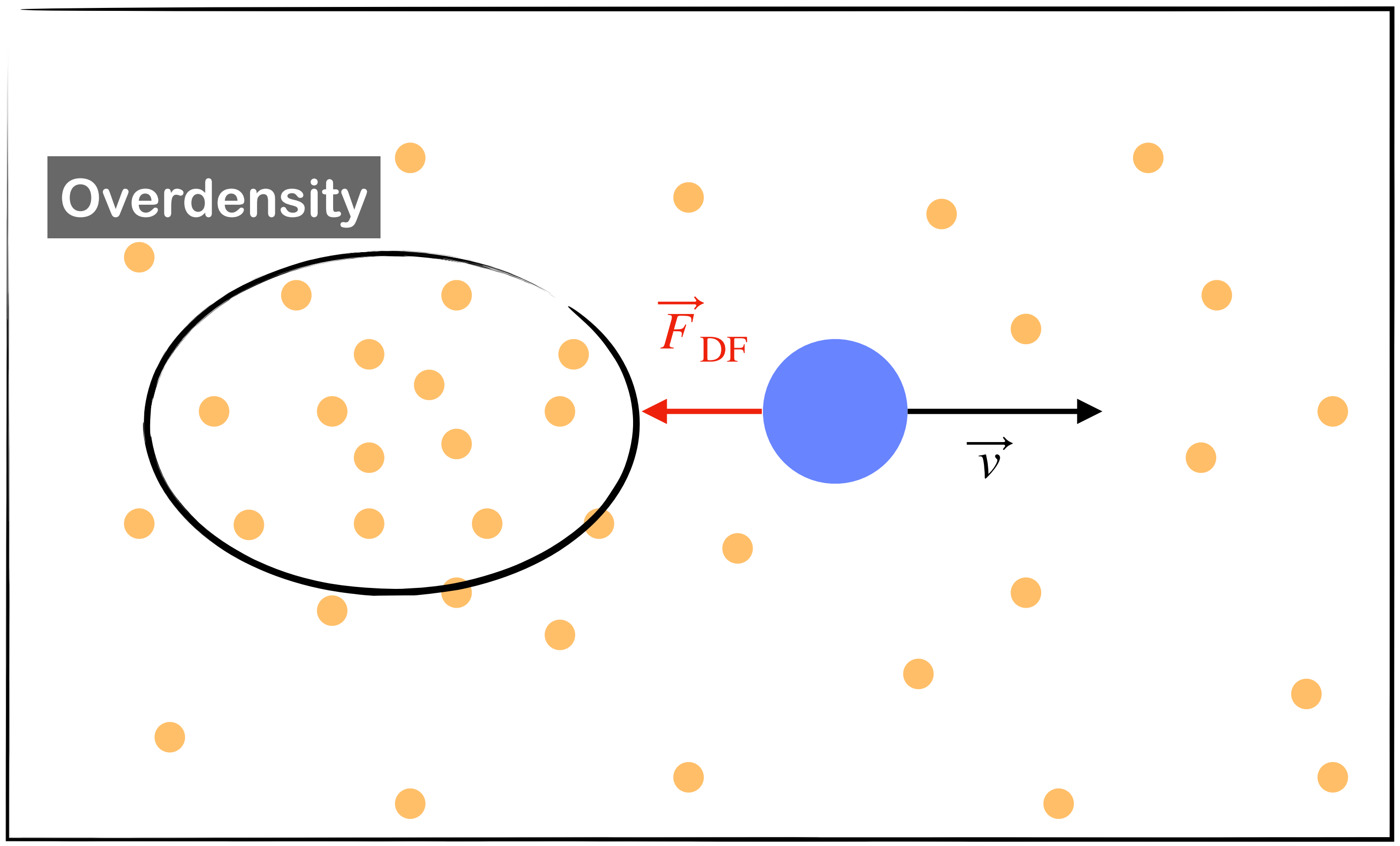


Why the orbit of dwarfs decrease over time?

Dwarf satellites **orbit within the dark matter halo** of the MW
and
feel **dynamical friction**

Dynamical friction

A drag force induced by the DM background



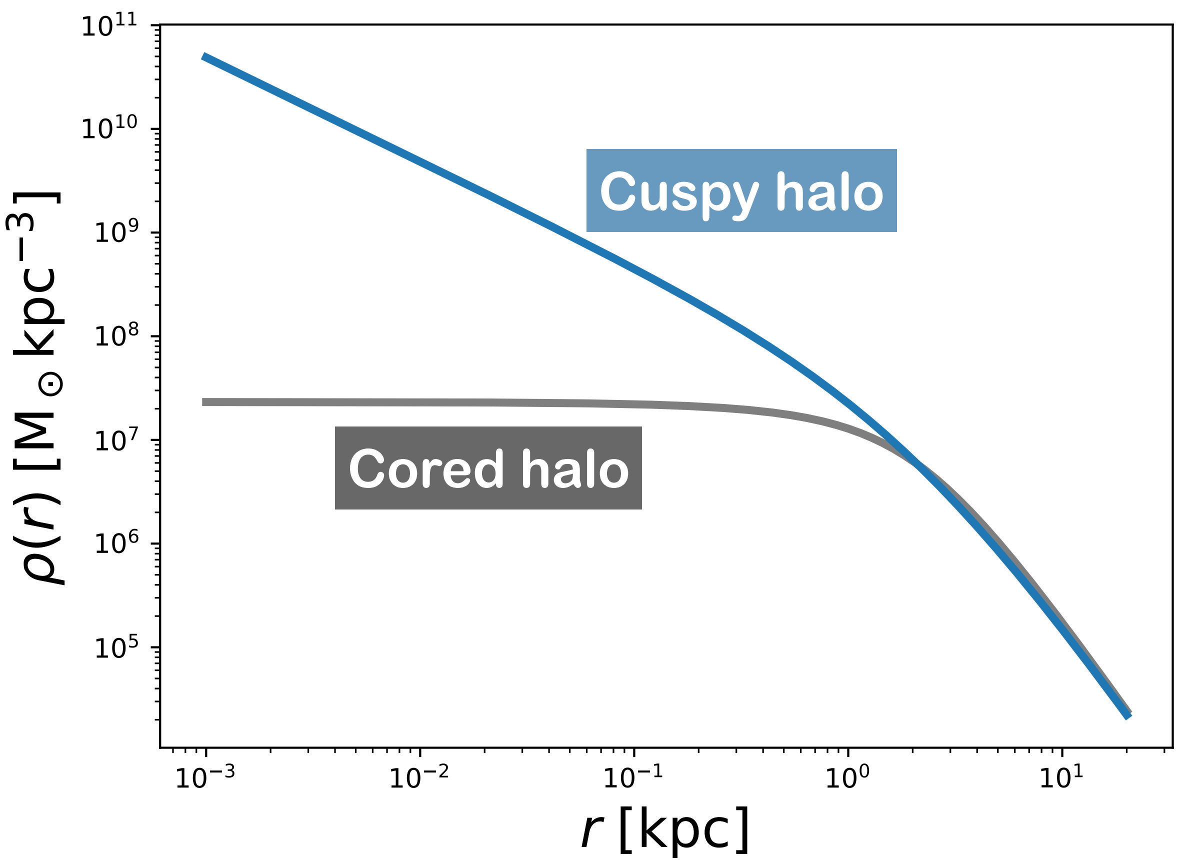
- Slows down the object
- Transfers energy to the background

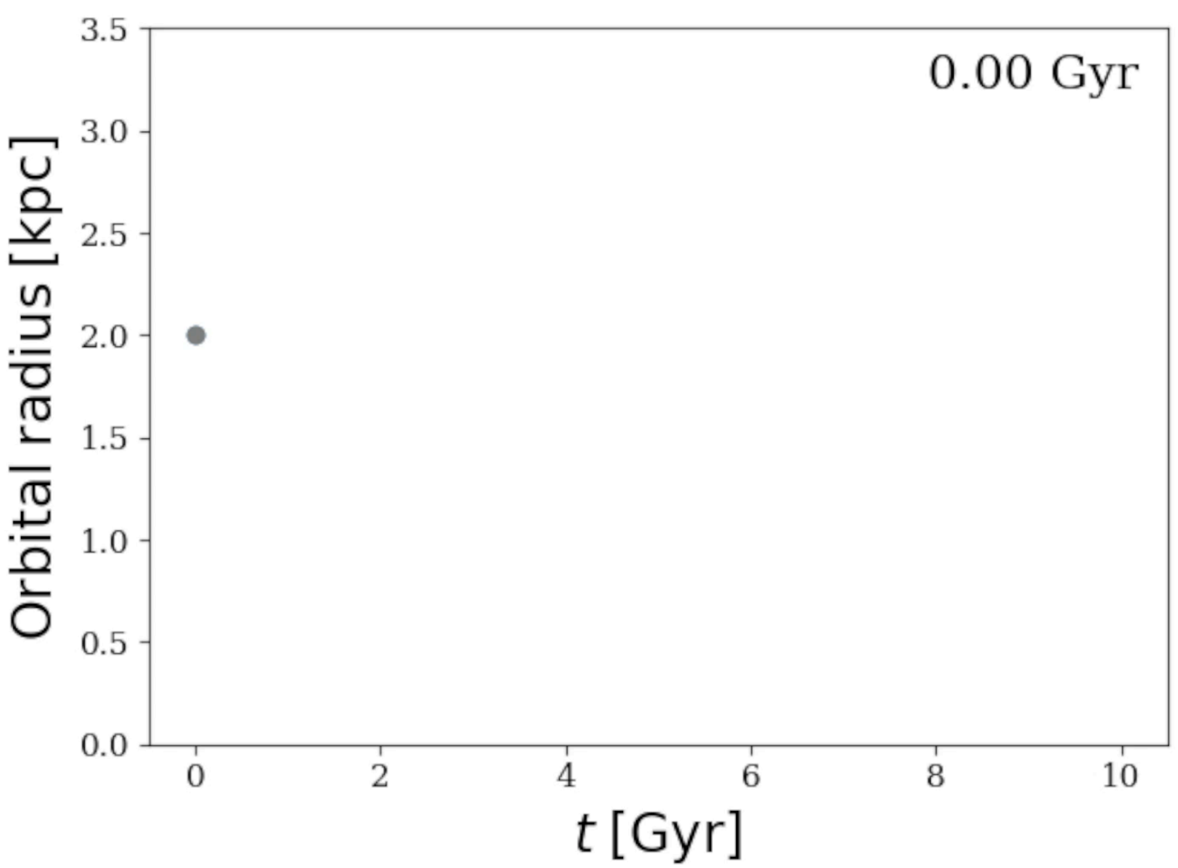
$$\vec{F}_{\rm DF}(x, v) \propto \rho_{\rm DM}(x)\, \mathrm{M}_{\rm perturber}$$ (Chandrasekhar et al. (1943))

The dynamic depends on the **mass of the perturber** and the **DM background density**

Dark matter distribution

$$\vec{F}_{\mathrm{DF}}(x, v) \propto \rho_{\mathrm{DM}}(x)\,\mathrm{M}_{\mathrm{perturber}}$$





How dark matter is distributed in dwarf galaxies?

Dark matter distribution

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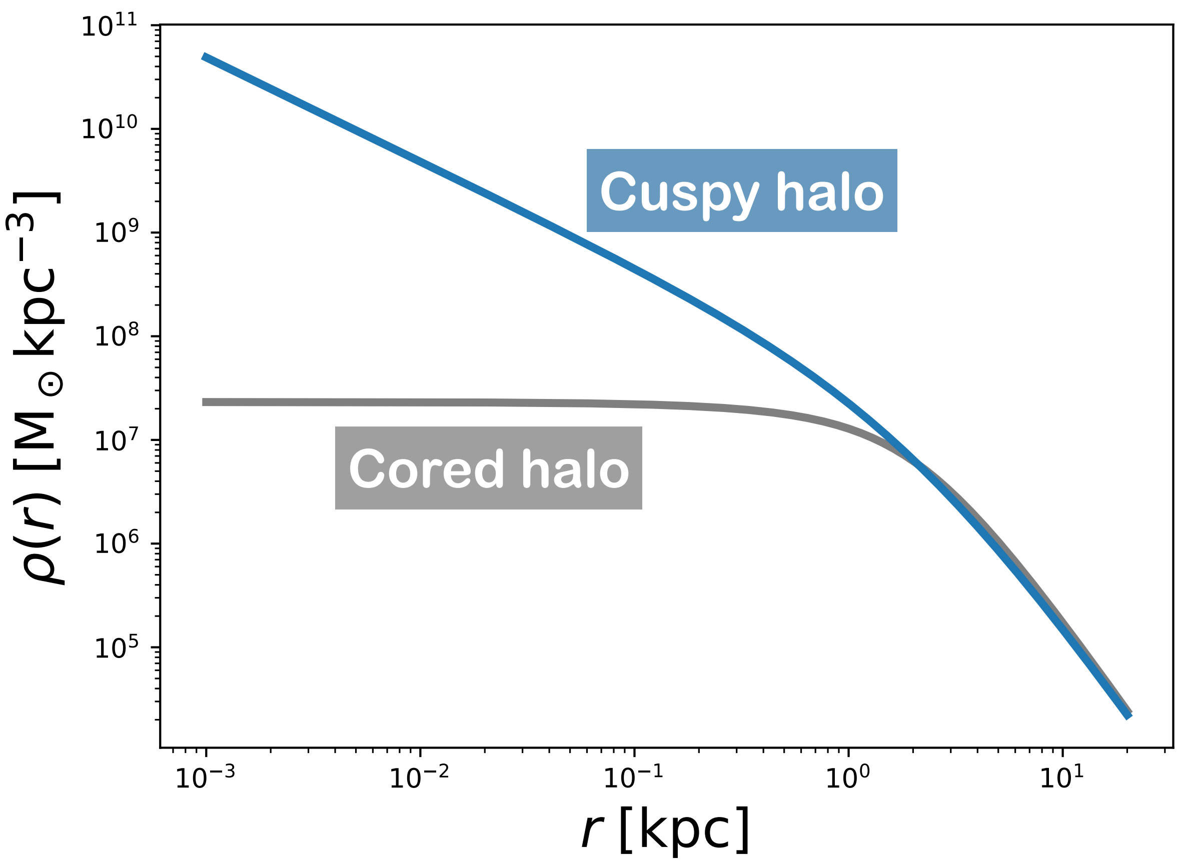
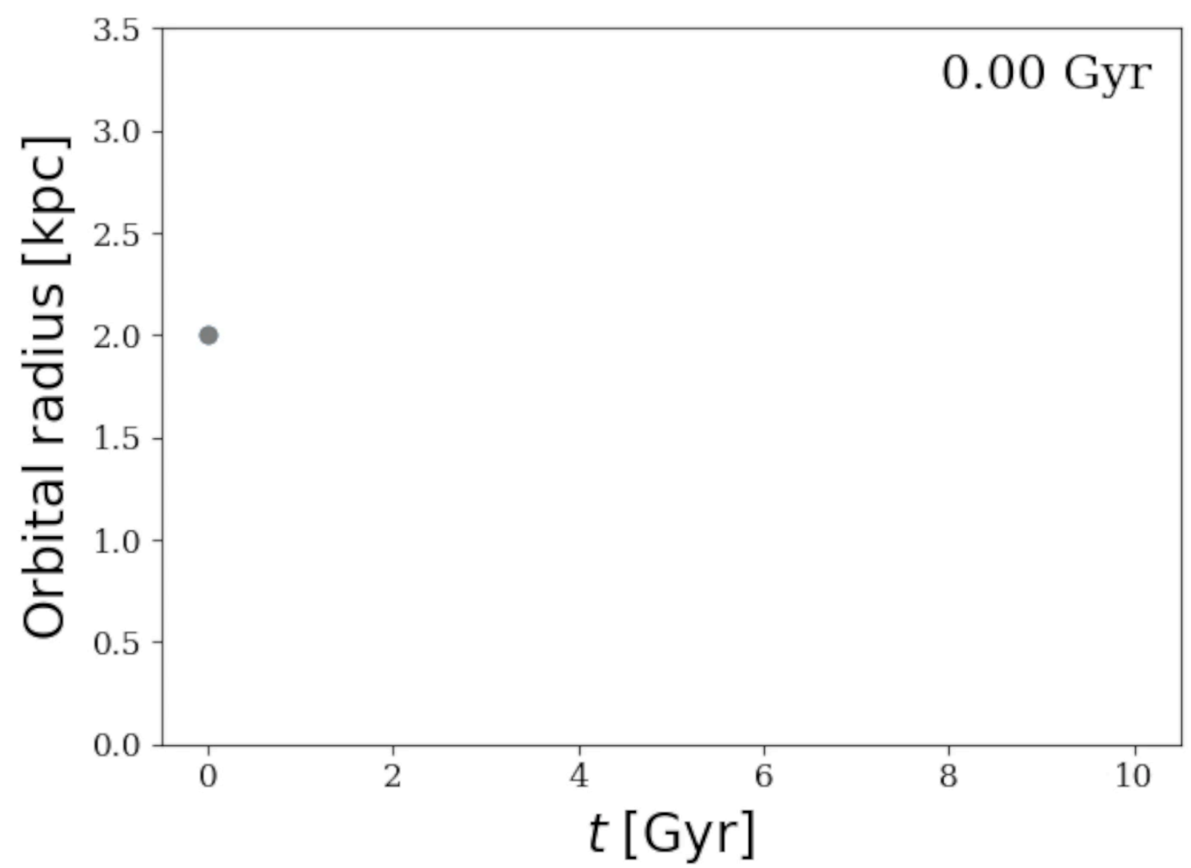




How dark matter is distributed in dwarf galaxies?

=

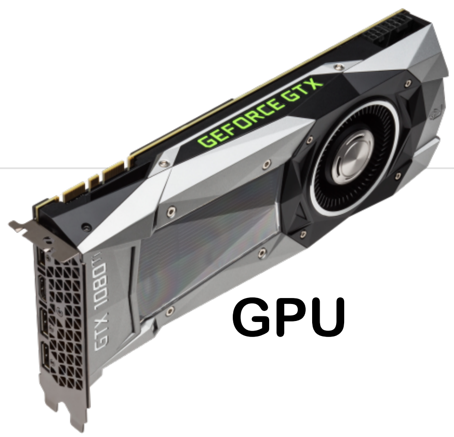
The cusp-core problem

One way to **solve this CDM problem** in dwarf galaxies is studying objects subjected to **dynamical friction**

N-body simulations

Collisionless
N-body code
(like Gadget-2)

\+

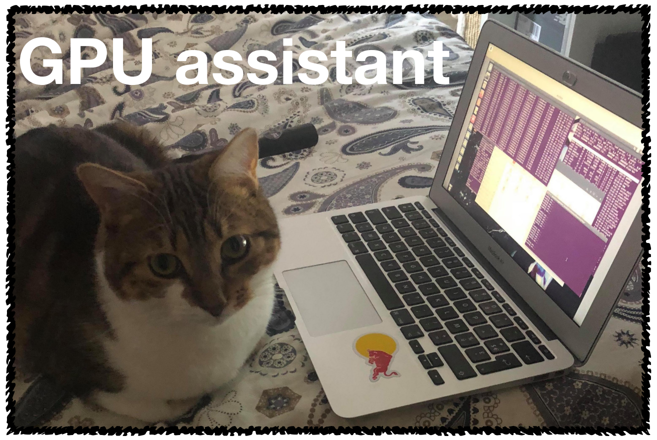


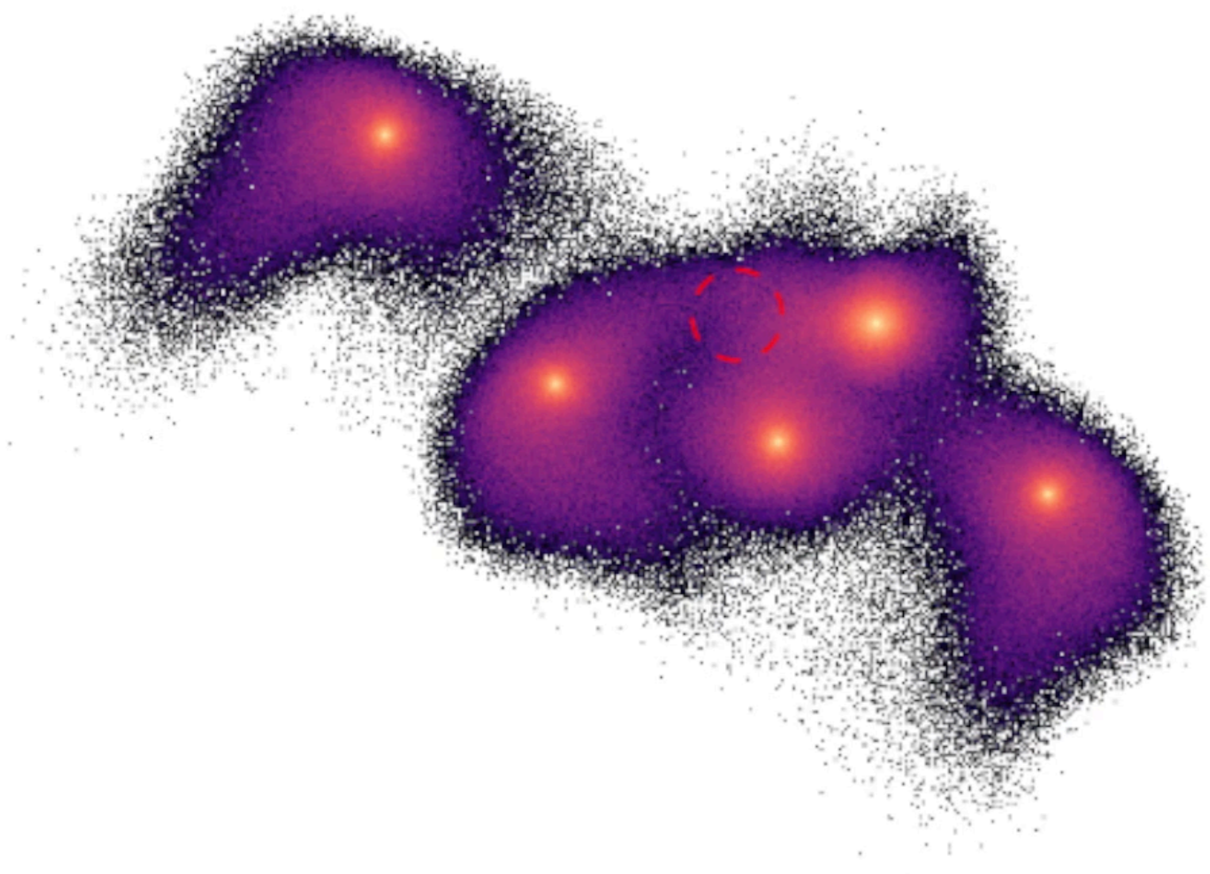
GPU

=

Gravitational
Oct-
Tree code accelerated by
Hierarchical time step
Controlling

(Miki et al. (2017))





Dark matter particles only

Strengths

- Model complex self-gravitating system
- Take into account tidal effects and dynamical friction
- Do movies to catch the physics
- 10^7 - 10^8 particles with 1 GPU

Weaknesses

- computationally costly
- Limited resolution
- Initial conditions

Thesis objectives

Effects of infalling objects on the central region of galaxies

- 🍎 **Globular clusters**
- 🍎 **Satellite galaxy**
- 🍎 **Dark matter subhalos**
- 🍎 **Primordial black holes**

🍦 Finding new plausible solutions to the cusp-core problem in dwarf galaxies 🍦

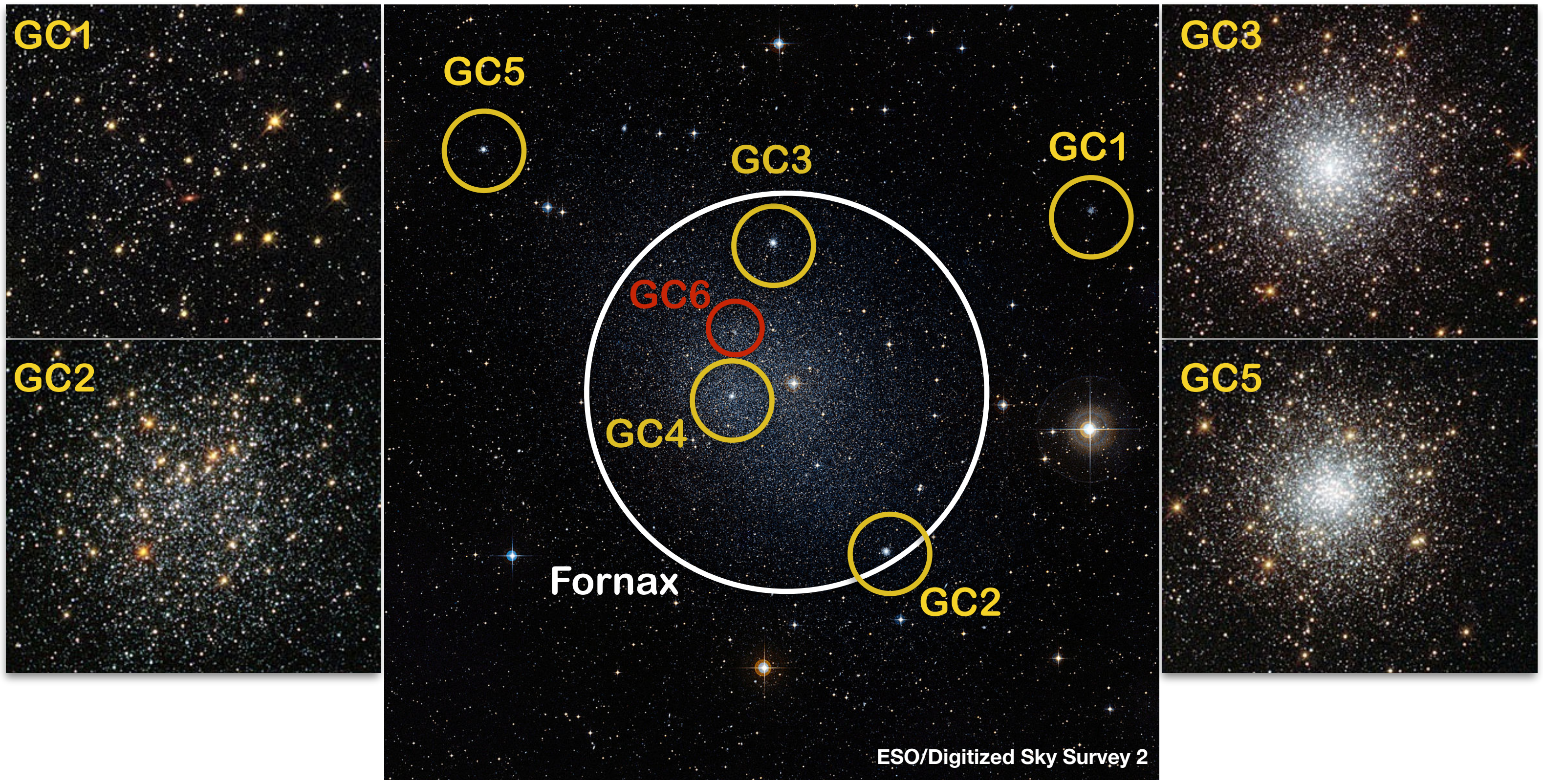
Thesis objectives

Effects of infalling objects on the central region of galaxies

🍎 **Globular clusters**

Globular clusters in Fornax

The most dark matter rich satellites of the Milky Way



Object	M^a [10^5 $M_\odot$]	D_p^b [kpc]
Fornax	382 ± 12	-
GC1	0.42 ± 0.10	1.6
GC2	1.54 ± 0.28	1.05
GC3	4.98 ± 0.84	0.43
GC4	0.76 ± 0.15	0.24
GC5	1.86 ± 0.24	1.43

Masses

Projected distance

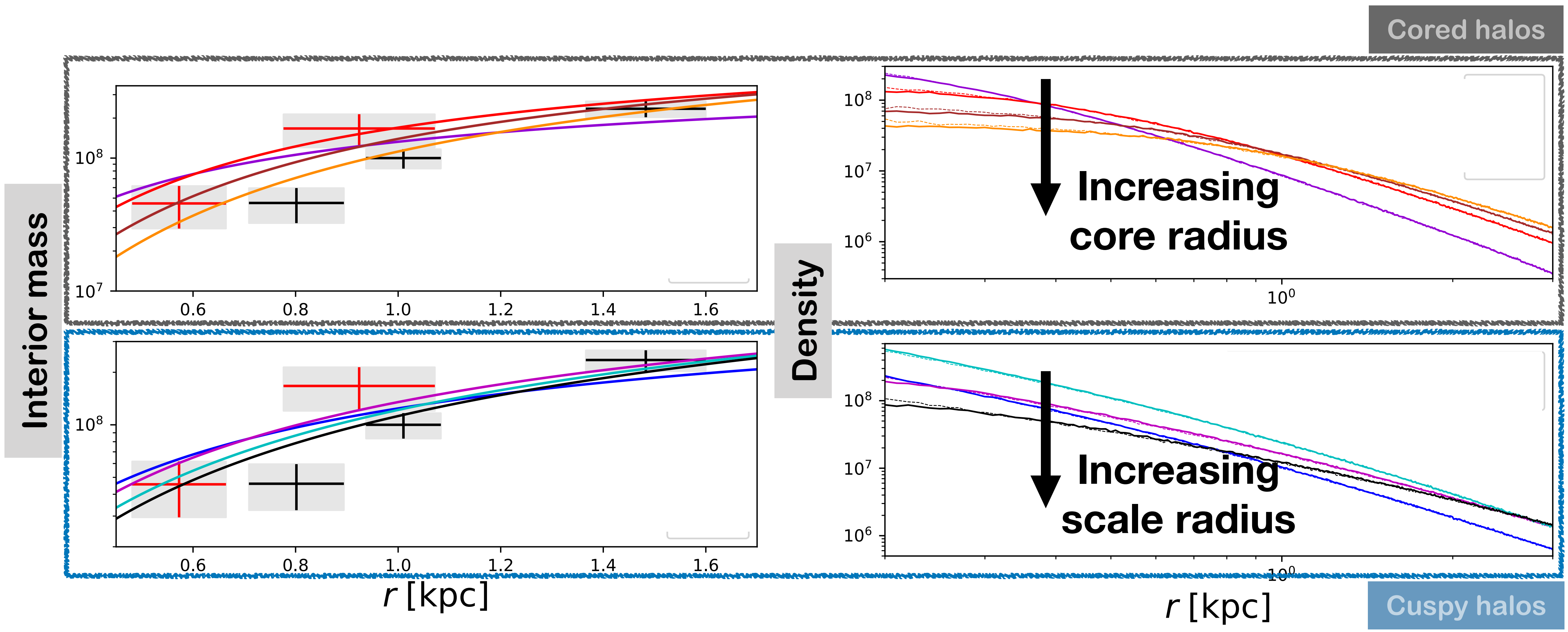
- 10^9 $M_\odot$ DM halo
- ~ 147 kpc
- 5-6 globular clusters (GCs)

Can we constrain the dark matter distribution in Fornax with its globular clusters?

Globular clusters in Fornax

Dark matter halo ~10^9 M$_\odot$

NFW & Burkert



Stellar component ~10^7 M$_\odot$

Plummer profile

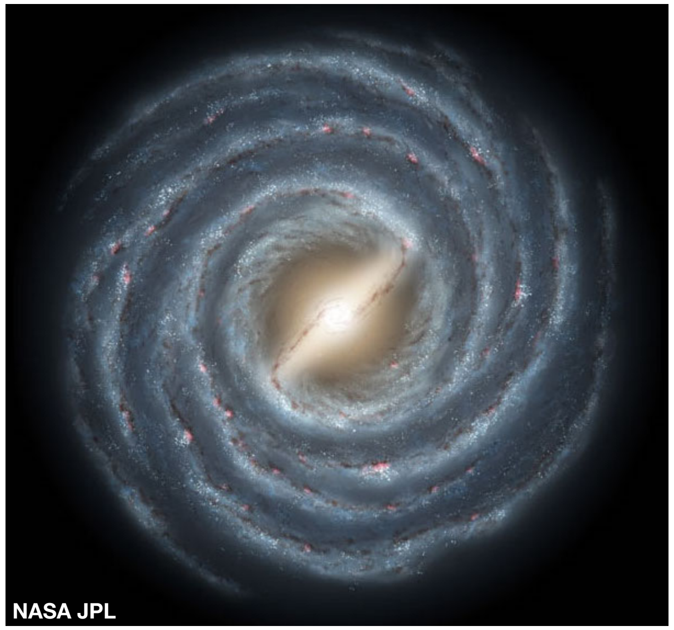
Globular clusters in Fornax

Globular clusters ~10^5 - 10^6 $M_\odot$



- King profile with r_k = 1 pc
- Different initial radii **Ri**, masses **Mi** and eccentricity **e**

Milky Way

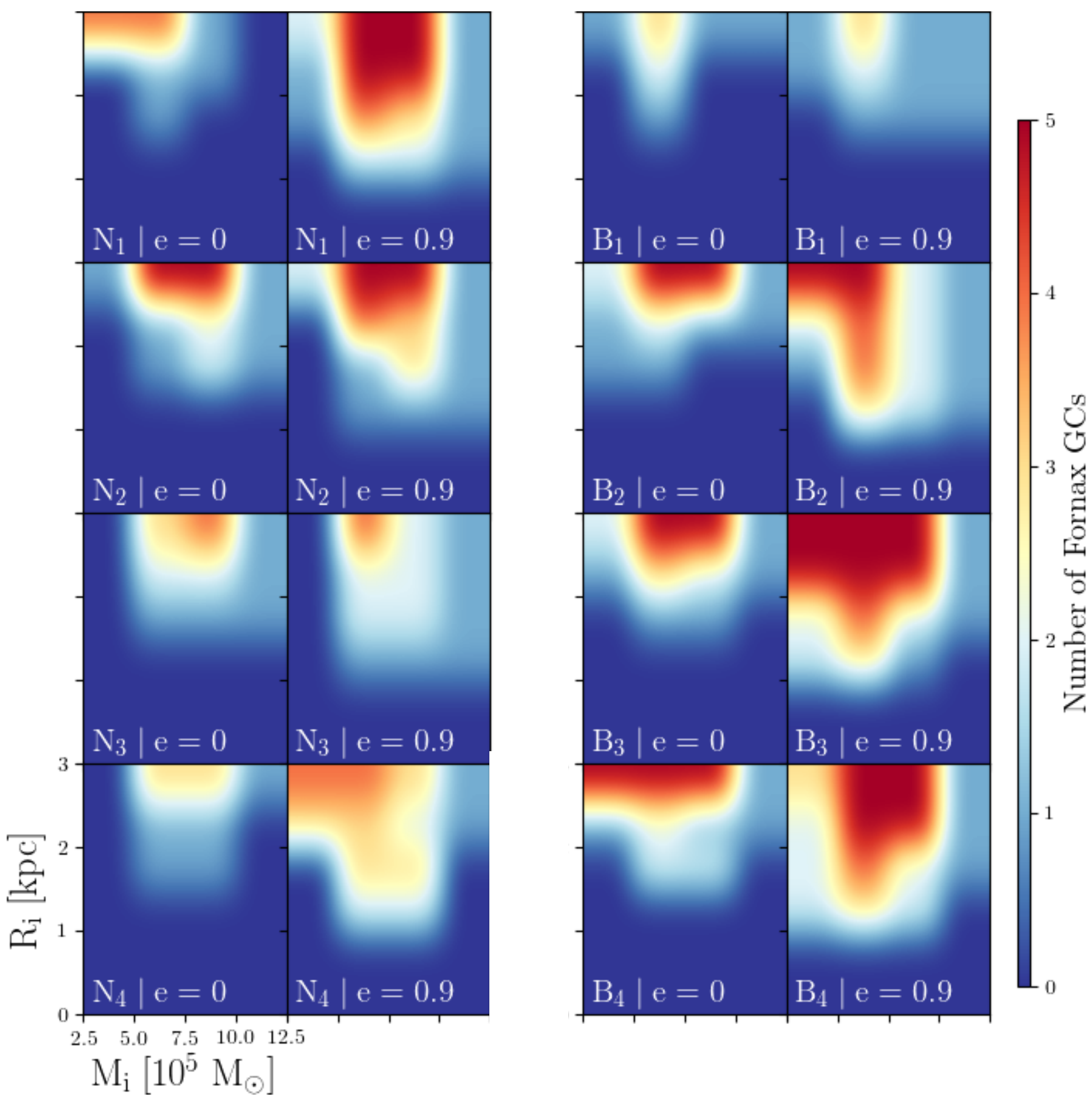


- Static potential (Allen & Santillan (1991), Irrgang et al. (2013))

Globular clusters in Fornax

Constraints on the DM profile from GCs

Cuspy halos | Cored halos



(Boldrini et al. , 2019, MNRAS, 485, 2546)

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Masses | Projected distance

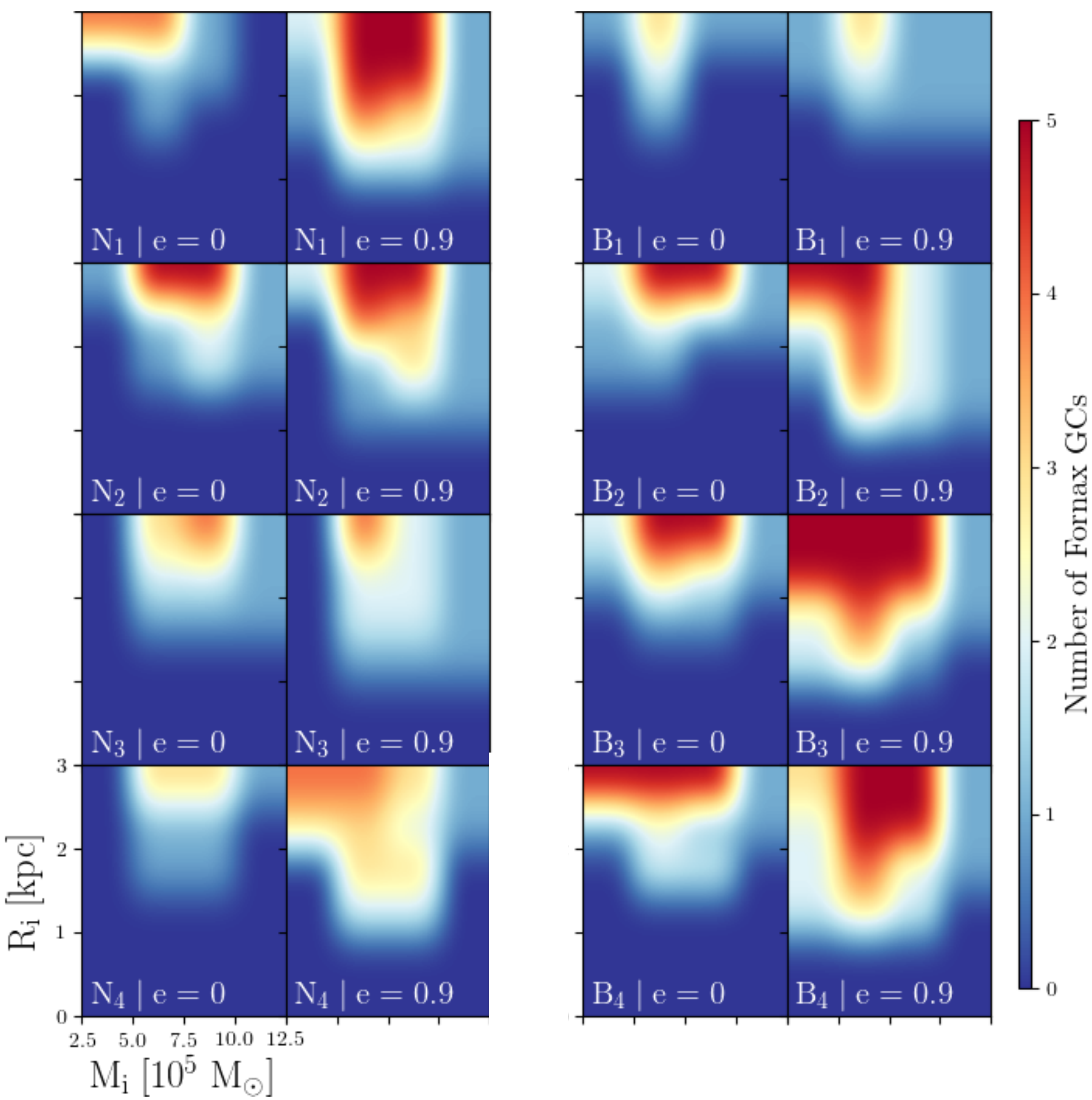
- Cored halo with $r_c \gtrsim$ **0.5 kpc**
- **NFW** profile **not ruled out**

Globular clusters in Fornax

Constraints on the DM profile from GCs

Cuspy halos

Cored halos



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Masses

Projected distance

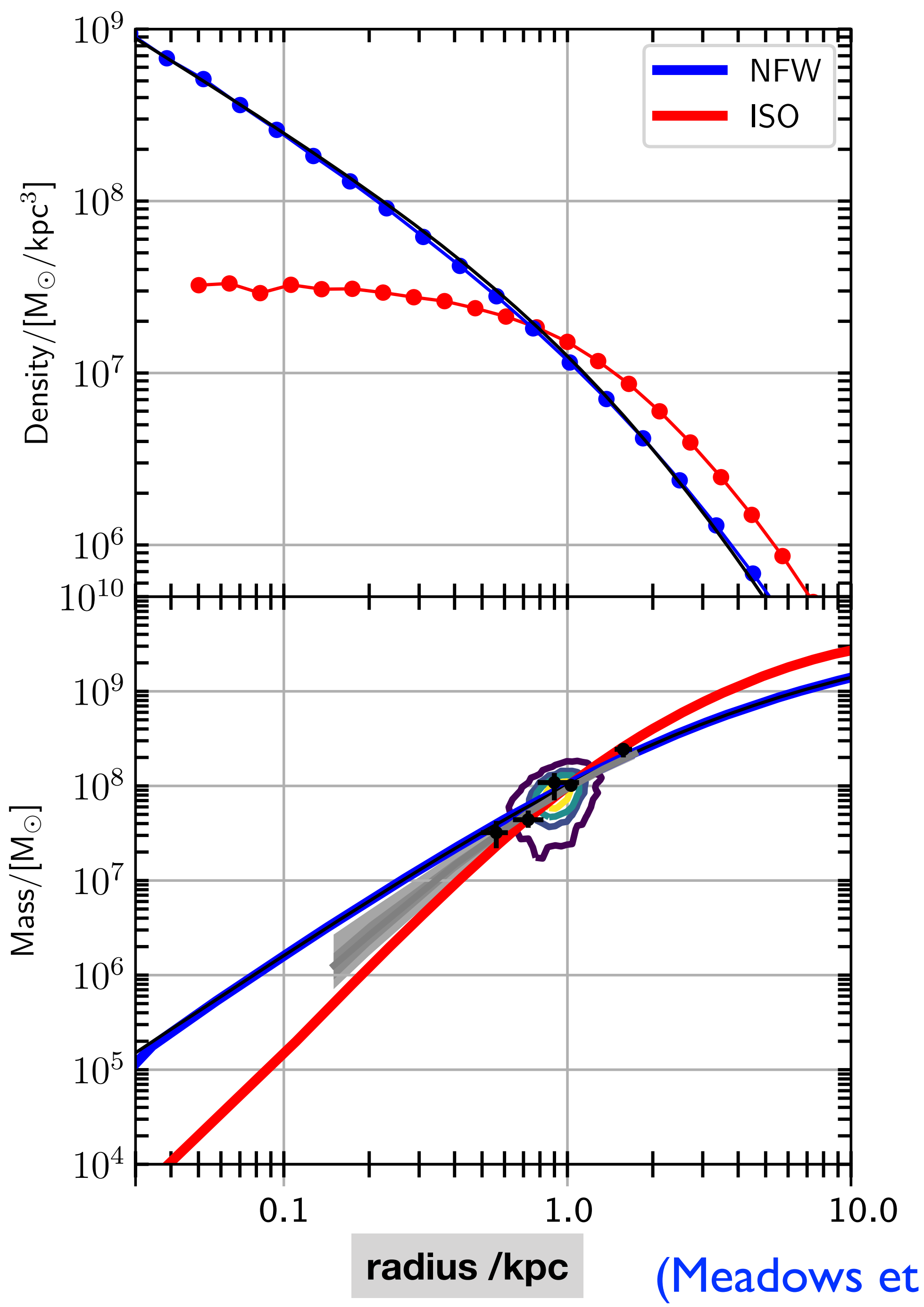
- Cored halo with $r_c \gtrsim 0.5$ kpc
- NFW profile not ruled out

(Boldrini et al. , 2019, MNRAS, 485, 2546)

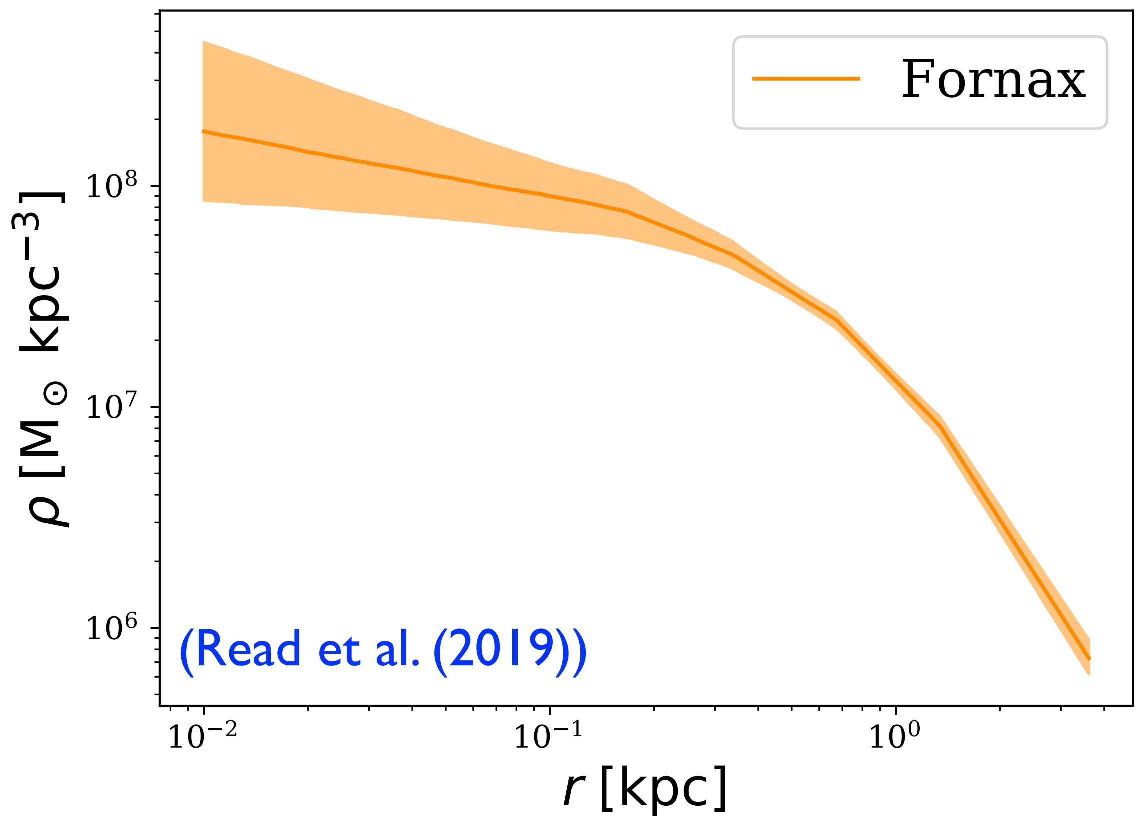
Globular clusters in Fornax

Constraints from stellar kinematics

(Fattahi et al (2016), Walker & Peñarrubia (2011), Amorisco et al. (2013), Read et al. (2019))



(Meadows et al. (2020))



Can we explain a DM core in Fornax within CDM?

Globular clusters in Fornax

Formation of globular clusters: 2 scenarios

- Gravitationally bound gas clouds in the early Universe and formed inside their present-day host galaxies
- Formed around the time of reionization in dark matter minihalos that later merge to become a part of the present-day host galaxy

Not been **detected**, but:

- Maybe observational **signatures**
- **Lost a large** fraction of their DM halo

Adding a new dark component to globular clusters can solve the cusp-core problem in Fornax?

Globular clusters in Fornax

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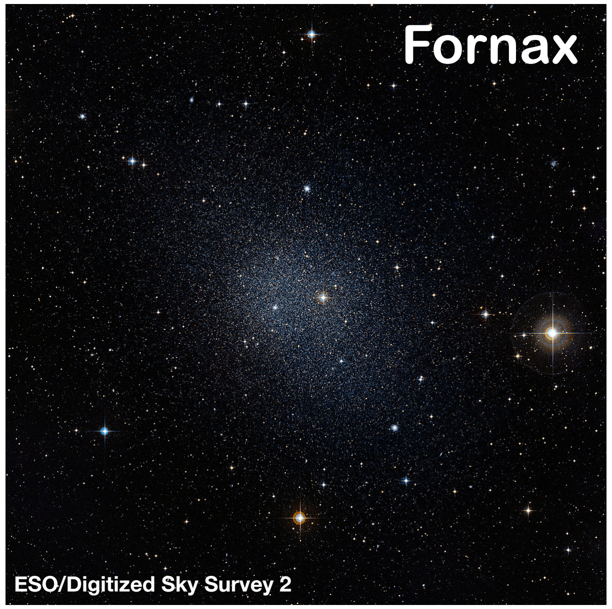
Globular clusters in Fornax

Dark matter halo ~10^9 $M_\odot$

- NFW form with r_s (z) (Prada et al. (2012))

Stellar component ~10^7 $M_\odot$

- Plummer profile



Globular clusters with dark matter

- **Stars:** King profile with r_K = 1 pc ~10^6 $M_\odot$
- **Dark matter:** NFW form with r_s (z) ~2×10^7 $M_\odot$

$M_{DM}/M_* = 20$

Globular clusters in Fornax

Two accretion scenarios for GCs

Early accretion: GCs accreted 12 Gyr ago by Fornax (z=3)

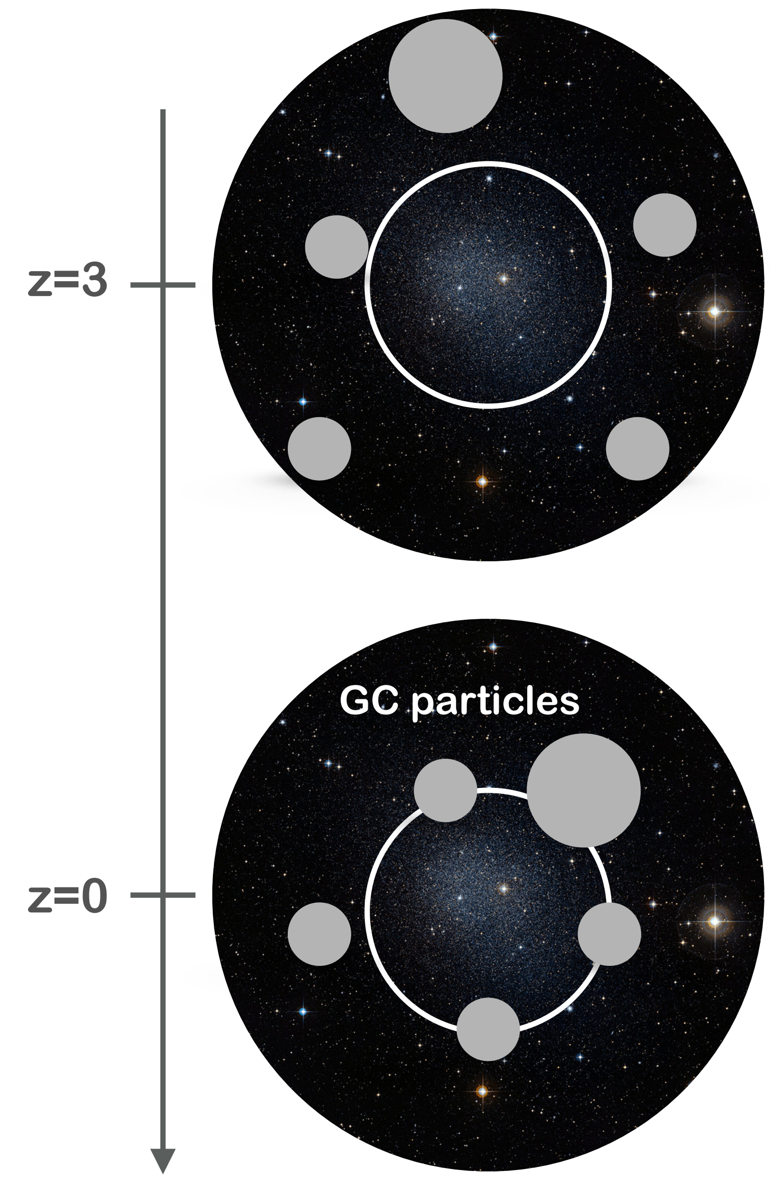
Recent accretion: GCs accreted 4 Gyr ago by Fornax (z=0.36)

Initial positions and velocities of GCs

Object	D_p^b [kpc]
Fornax	-
GC1	1.6
GC2	1.05
GC3	0.43
GC4	0.24
GC5	1.43

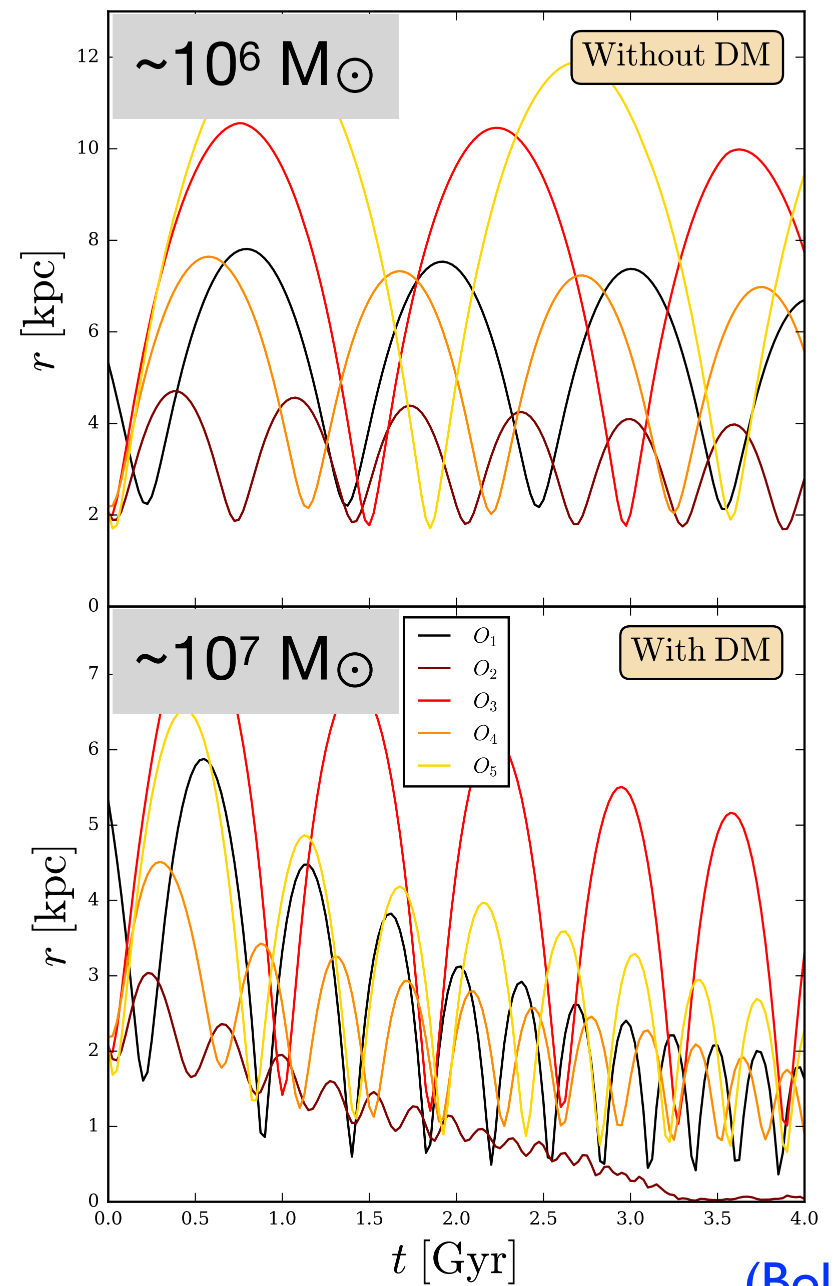
Projected distance

Most prevalent positions and velocities from **Illustris TNG-100** cosmological simulations



Globular clusters in Fornax

Recent accretion scenario

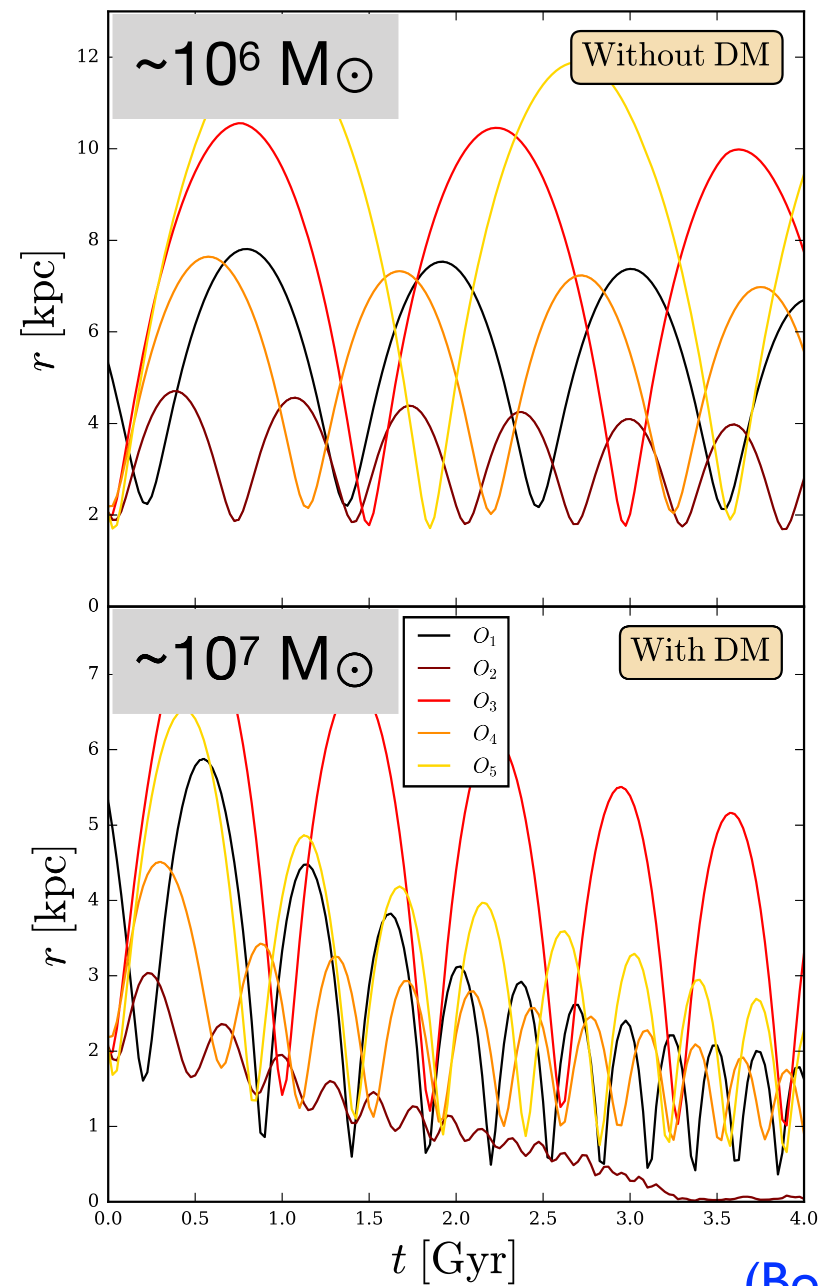


(Boldrini et al. , 2020b, MNRAS, 492, 3169)

With **dark matter** as a **new component** of globular cluster,
we can **reproduce** the **spatial and mass distribution** of observed GCs
if they were **accreted** less than **3 Gyr ago**

Globular clusters in Fornax

Recent accretion scenario



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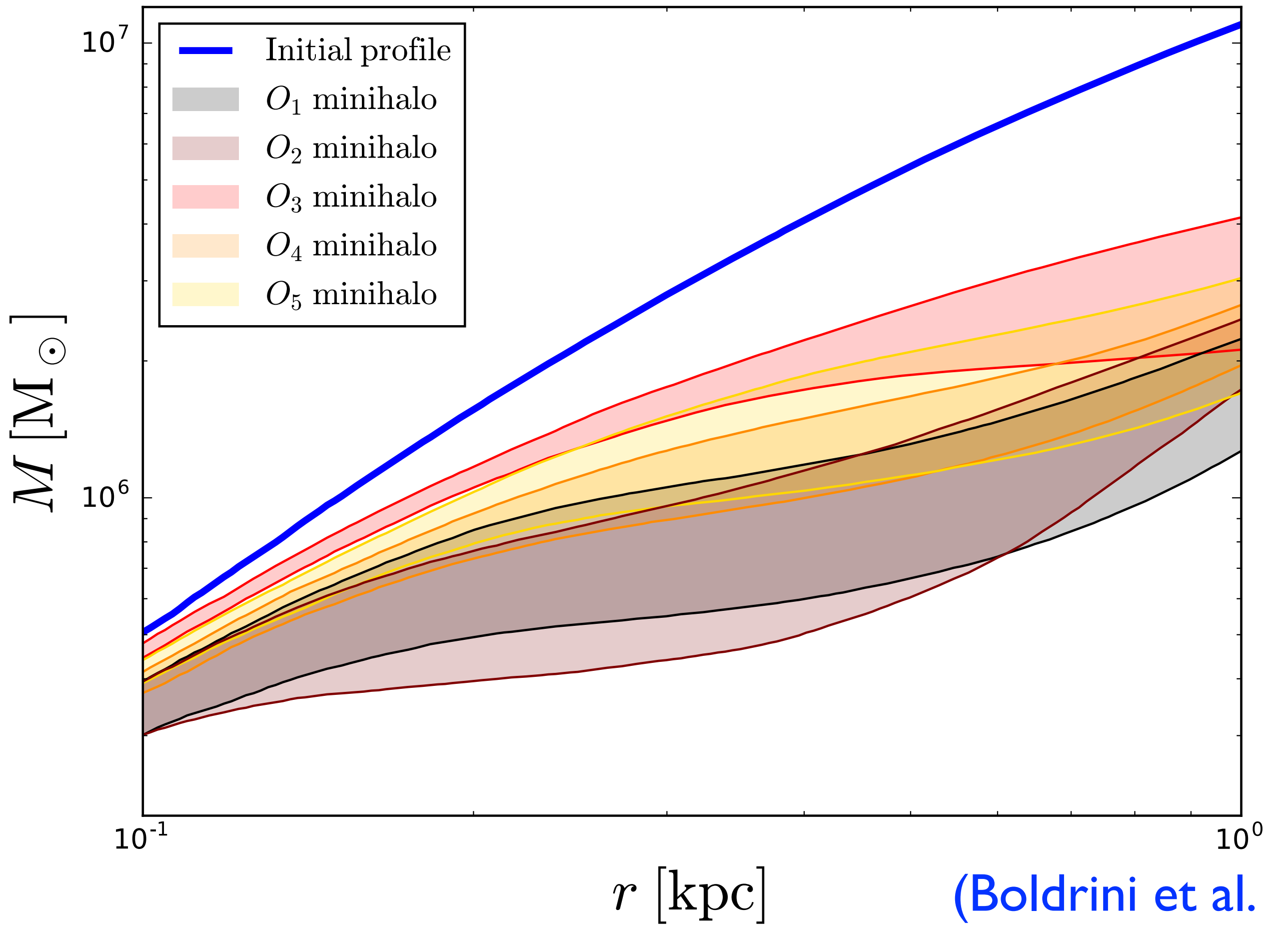
Globular clusters in Fornax

Recent accretion scenario

After 2-3 Gyr



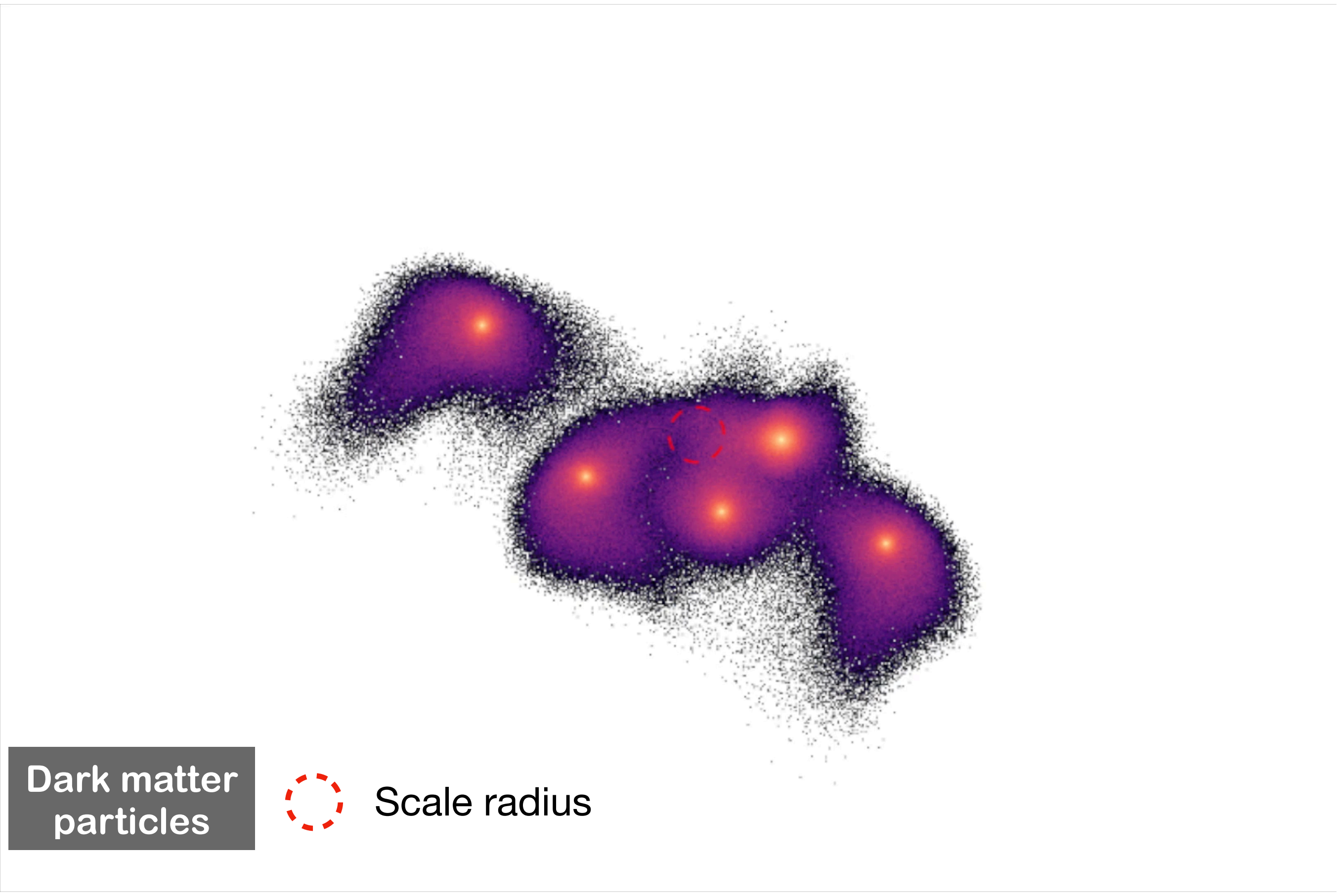
(Boldrini et al. , 2020b, MNRAS, 492, 3169)

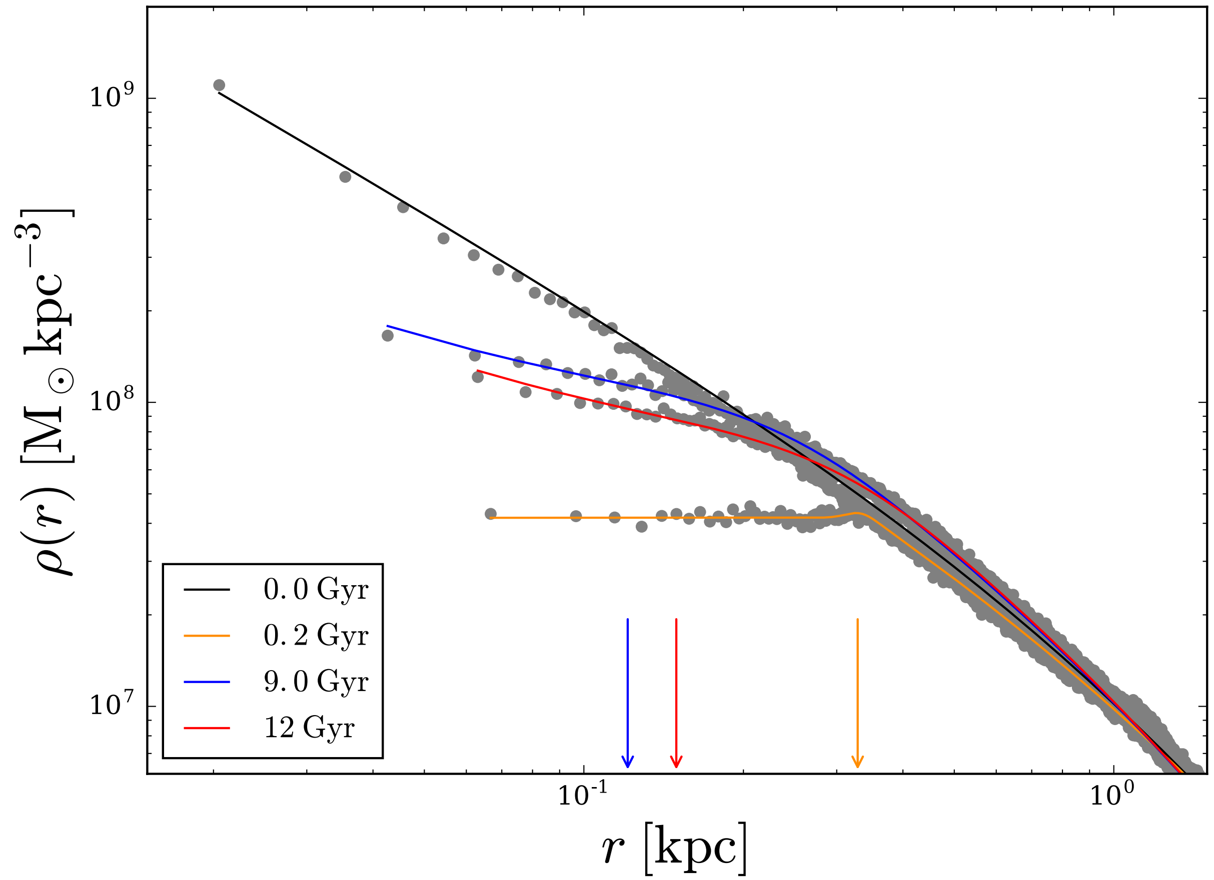
Today, **Fornax GCs** should **be embedded** in **minihalos** less massive than **4×10^6 $M_\odot$** inside the **central 500 pc** of GCS

Agreement with the observed prediction on NGC 2419 (Baumgardt et al. (2009), Ibata et al. (2013))

Globular clusters in Fornax

Cusp-to-core transitions





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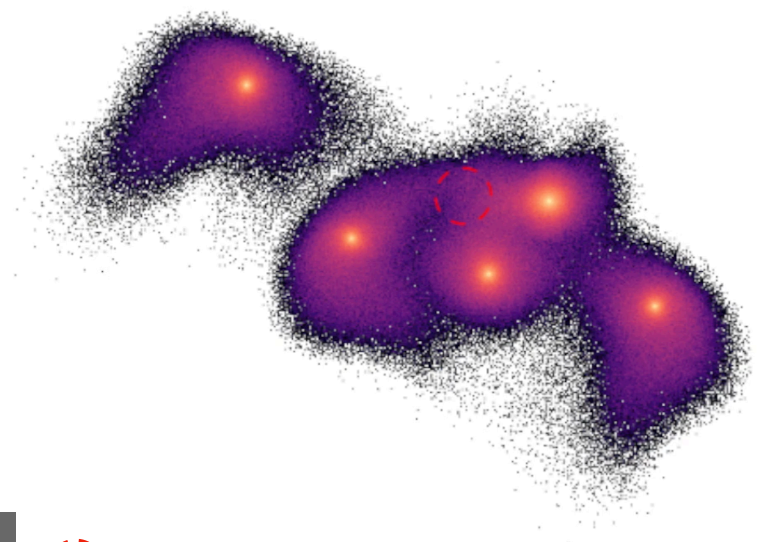
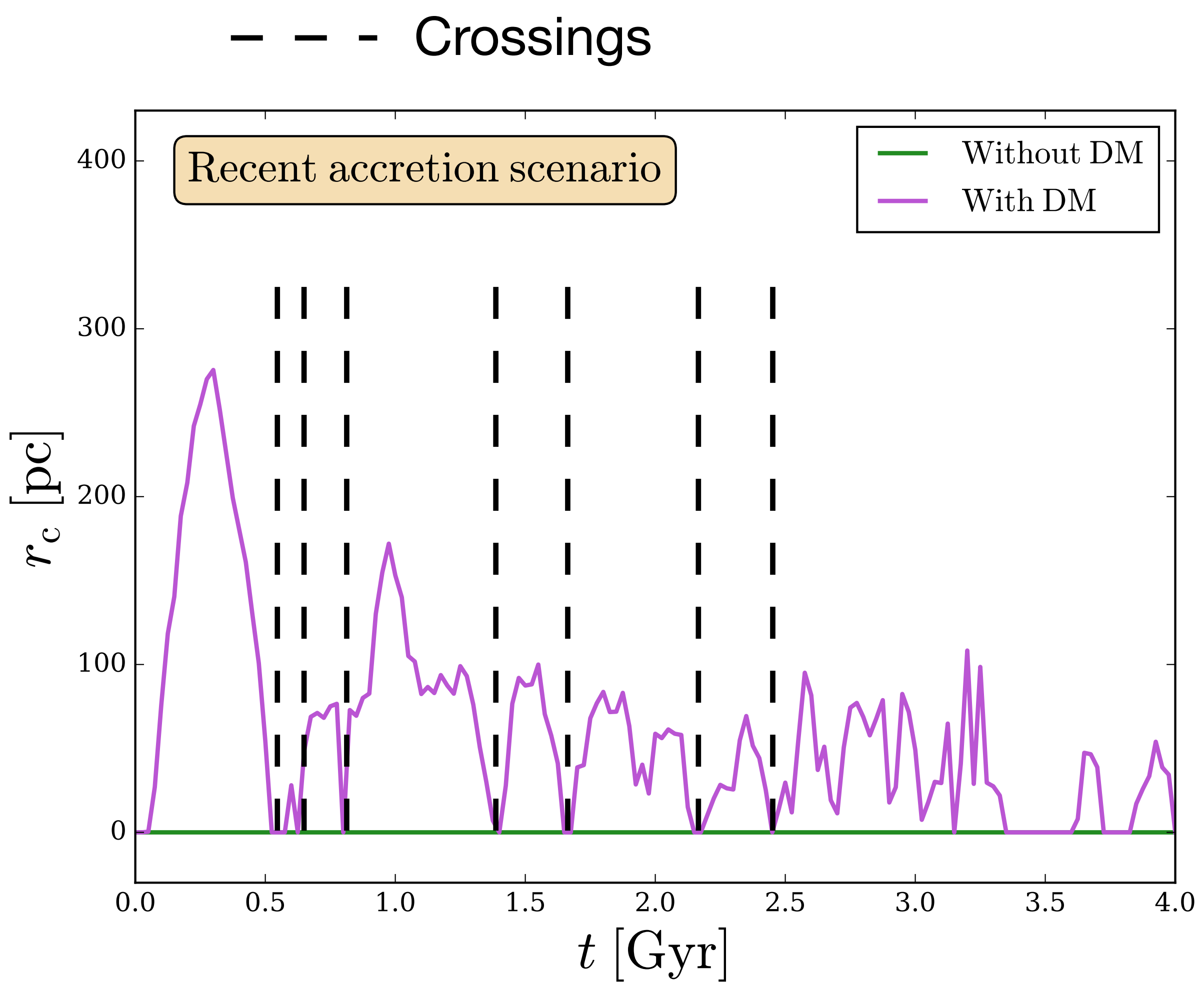
Globular clusters in Fornax

The cusp-core problem





(Boldrini et al. , 2020b, MNRAS, 492, 3169)

A new solution

- Cusp-to-core transition
- Core size depends on the frequency of passages

Goals achieved during the thesis

Effects of infalling objects on the central region of galaxies

🍎 Globular clusters

- Fornax globular cluster dynamic doesn't exclude cuspy profile (Boldrini et al. , 2019, MNRAS, 485, 2546)
- Embedding globular clusters in dark matter minihalos can create cores in Fornax (Boldrini et al. , 2020b, MNRAS, 492, 3169)

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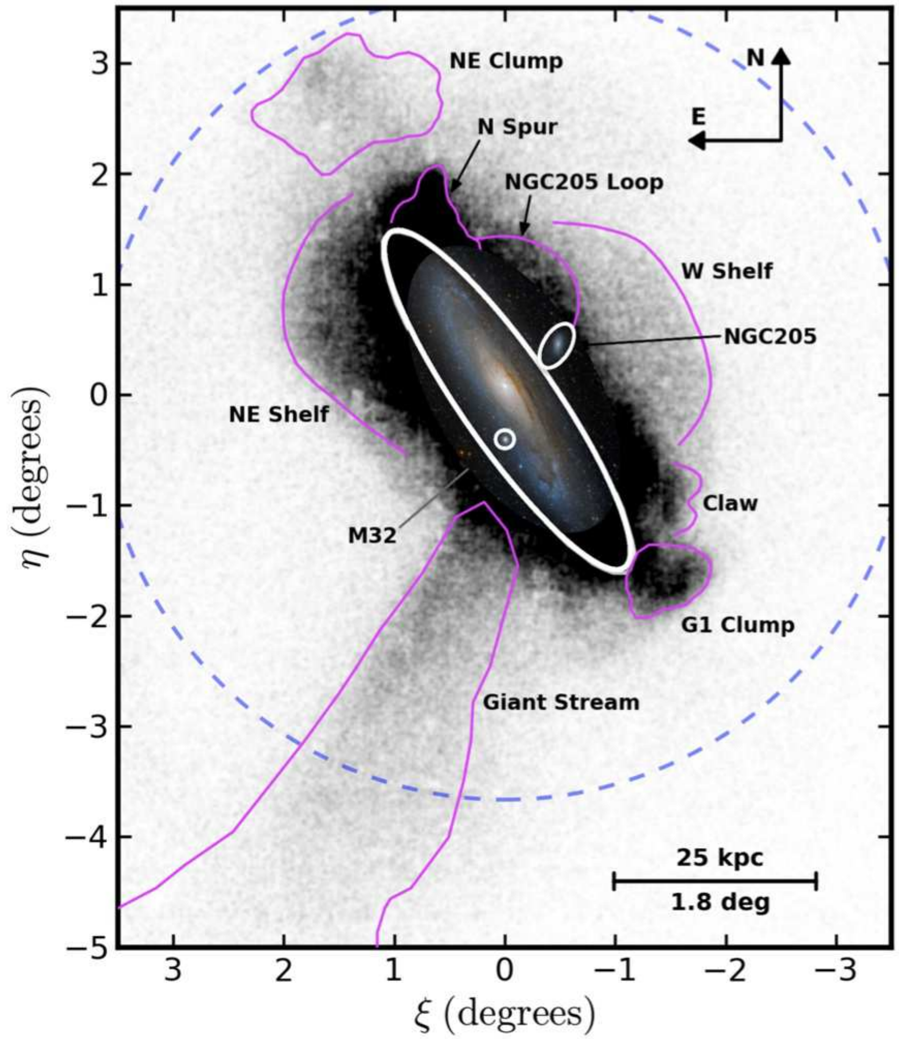
🍎 **Satellite galaxy**

Satellite galaxy in M31

Observations

Tidal features



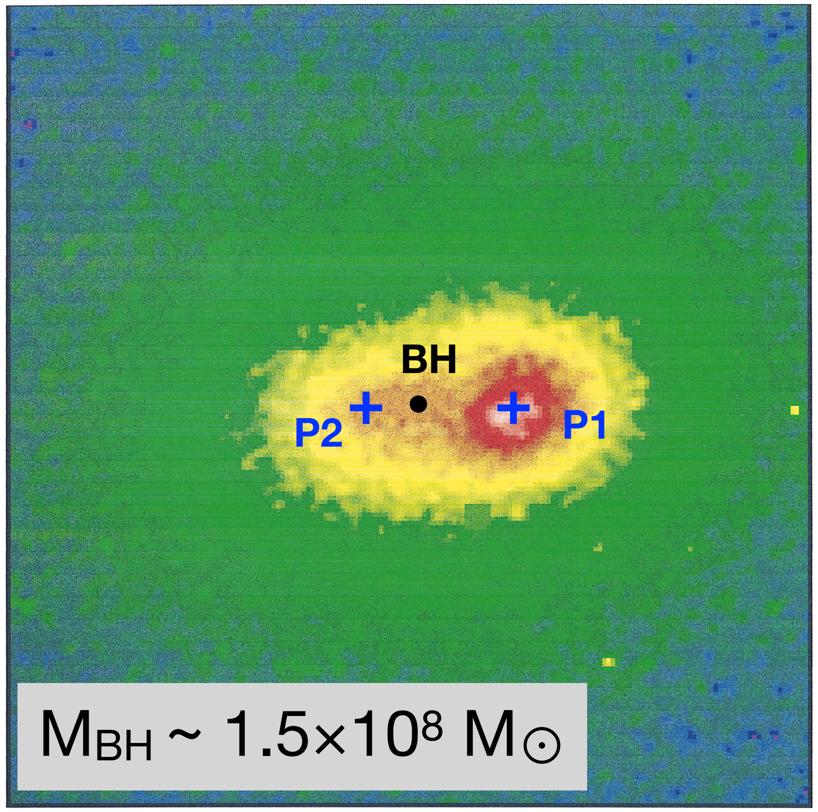
(Ferguson & Mackey (2016))

Phase structures of M31 are results of the **accretion** of a **satellite** galaxy

Satellite galaxy in M31

Observations

Off-centre black hole



(Kormendy & Bender (1999))

The **M31 black hole** is **offset** by **0.26 pc** from P2

Satellite galaxy in M31

Mechanisms for off-centre black holes

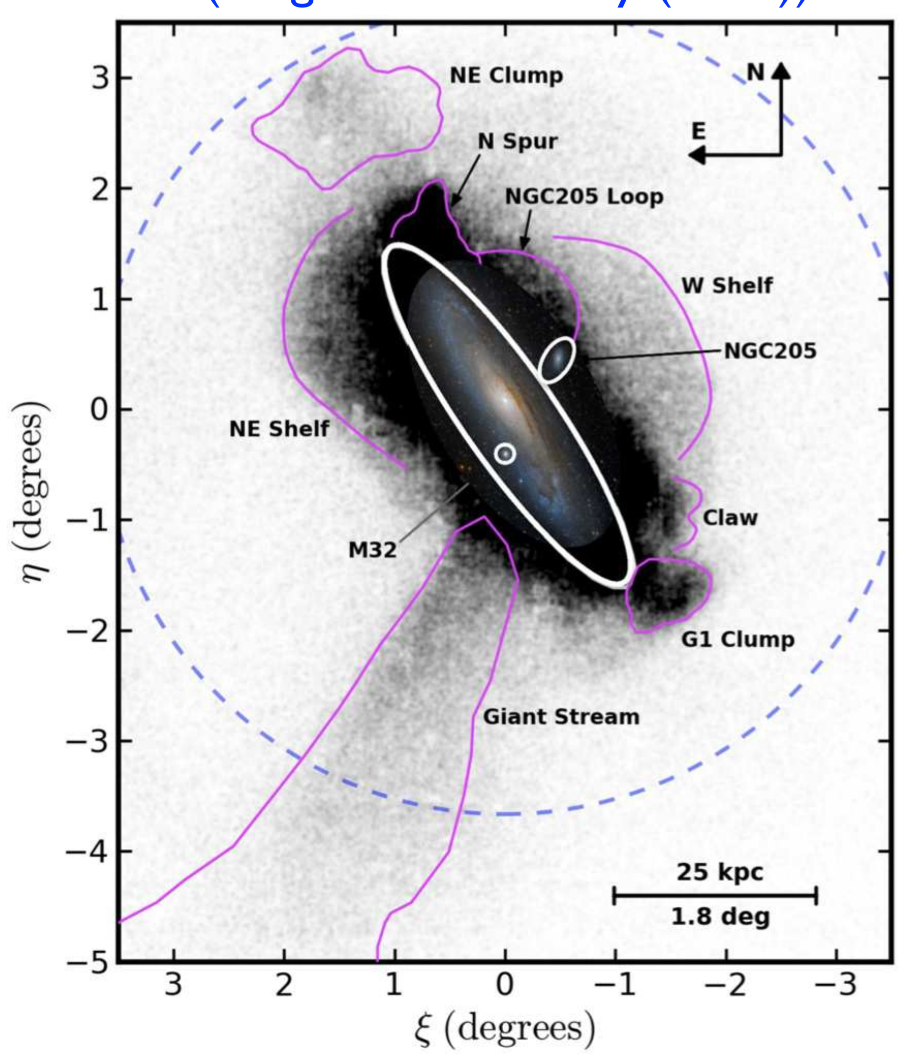
- Binary system before BH merger
- Recoil of merging BHs
- Galaxy mergers

A single minor merger scenario

As the origin of:

- Giant south stream
- Stellar shelves

(Ferguson & Mackey (2016))



Satellite galaxy in M31

Andromeda galaxy M31

Component	Profile	a [kpc]	r_{200} [kpc]	Mass [$10^{10} M_\odot$]
M31 halo	NFW	7.63	195	88
M31 bulge	Hernquist	0.61	-	3.24
M31 disk	Exponential	$R_d = 5.4$	-	3.66
	disk	$z_d = 0.6$	-	-
M31 black hole	Point mass	-	-	0.015

(Geehan et al. (2006))

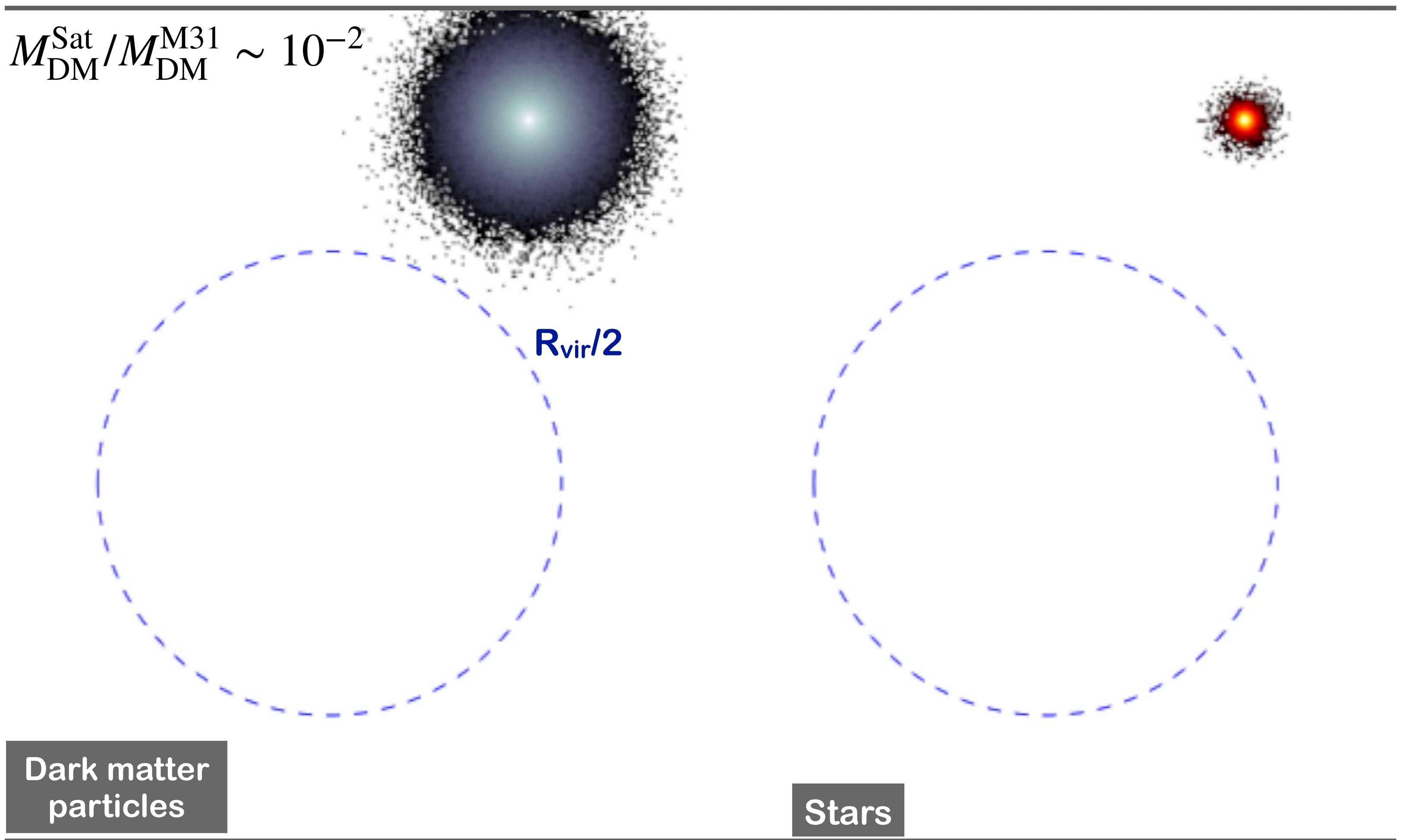
Infalling satellite

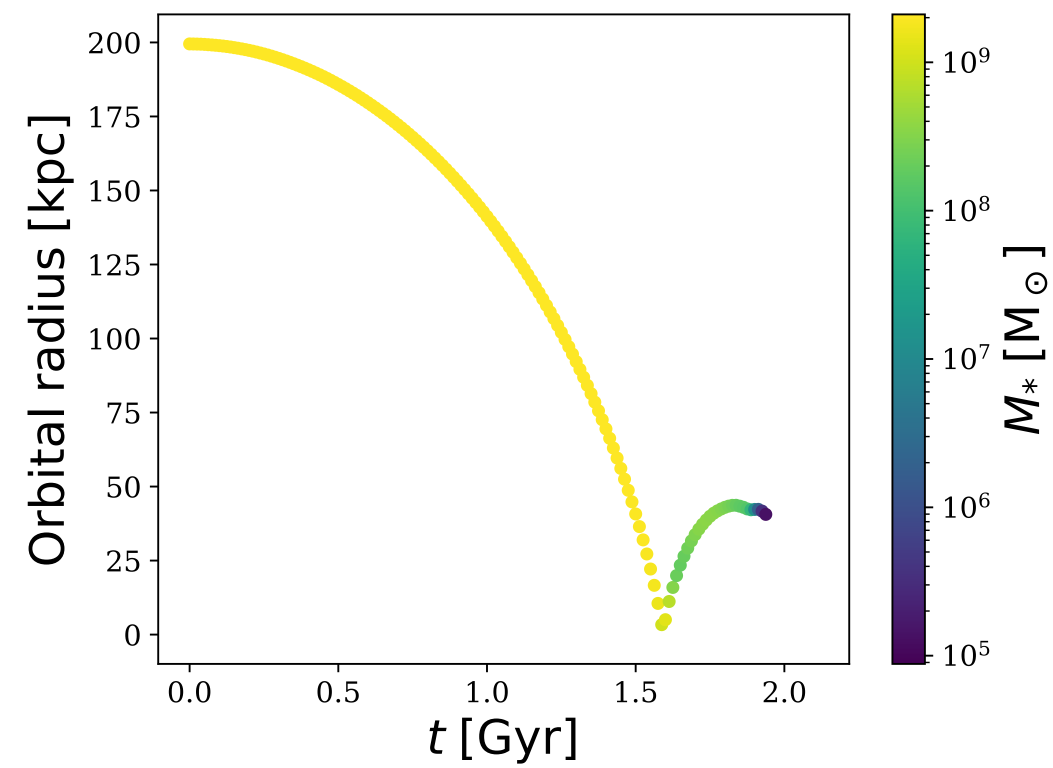
Sadoun, et al. (2014)					
$((M_{DM}/M_*)_{sat} = 20)$	DM halo	Hernquist	12.5	20	4.18
	Stars	Plummer	1.03	-	0.22

The dark matter rich satellite starts at its **first turnaround radius** at **200 kpc** with a **null velocity**

Satellite galaxy in M31

A minor merger scenario with M31 galaxy (Sadoun et al. (2014))



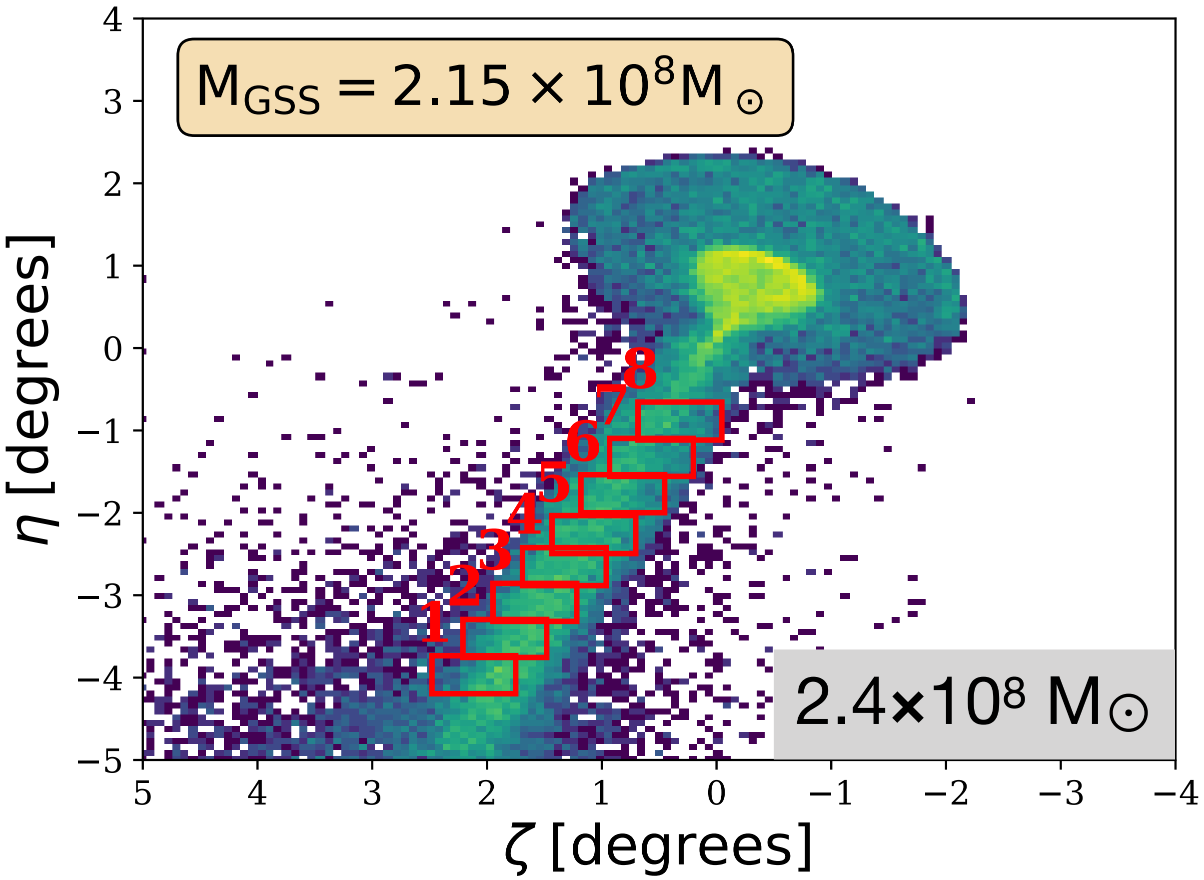


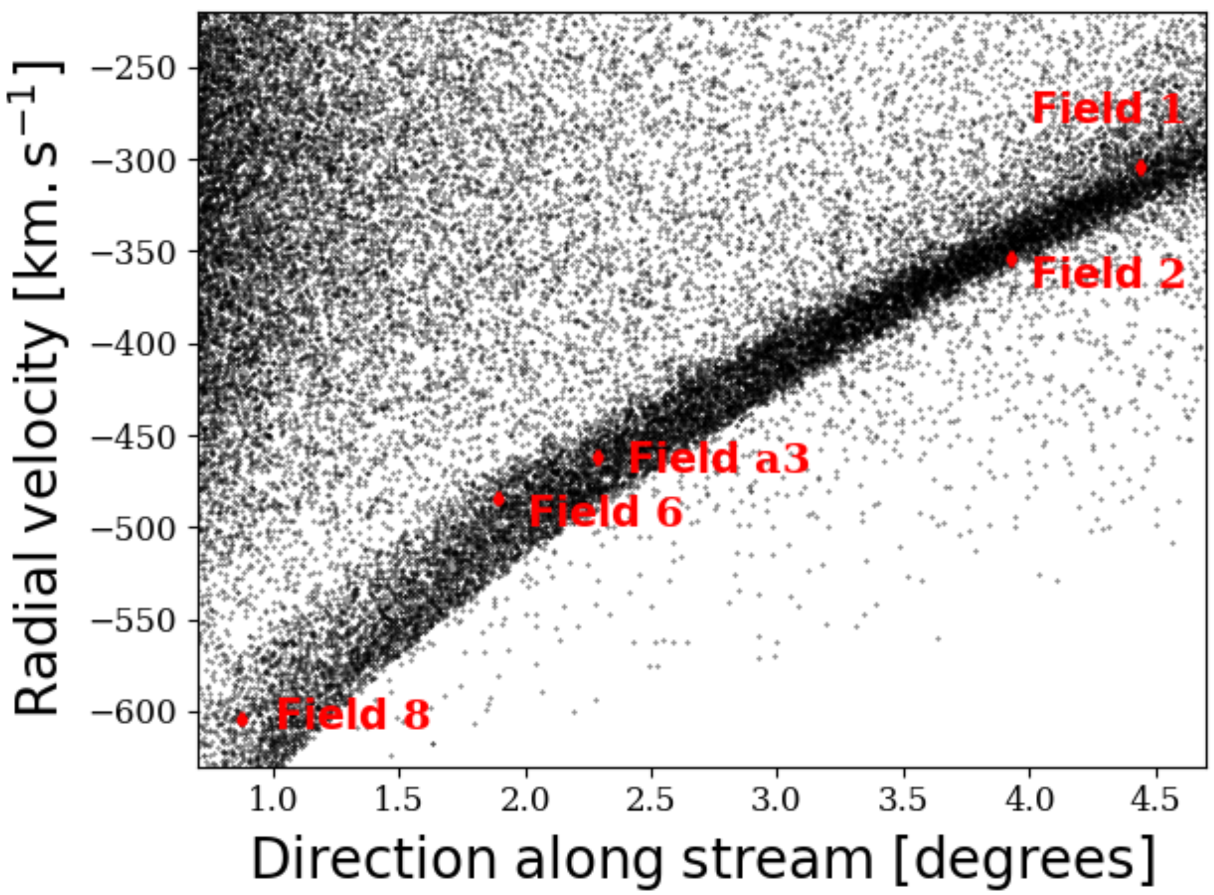
(Boldrini 2020, MNRAS Letters, L137B)

Satellite galaxy in M31

Constraints from observations

At 2.1 Gyr





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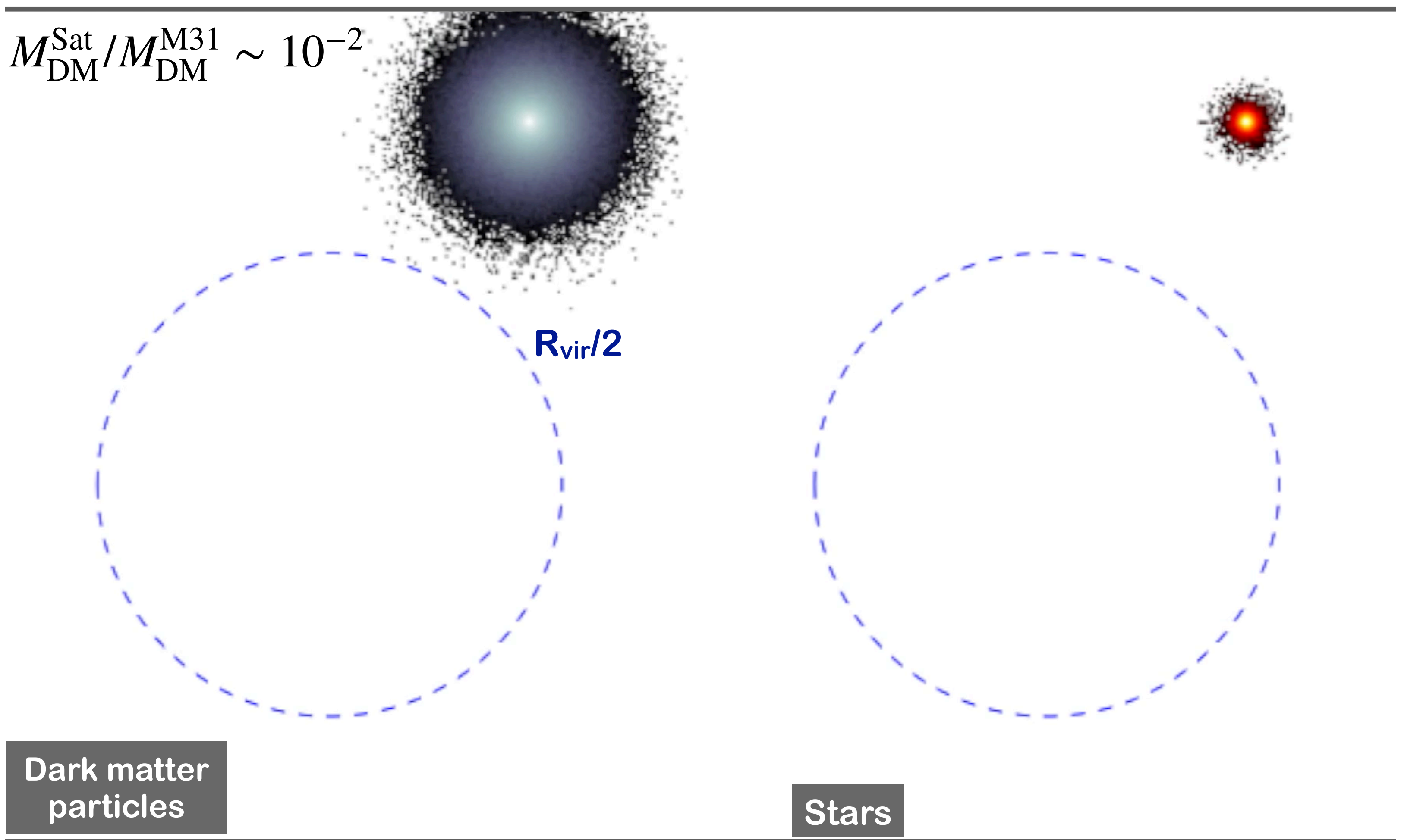
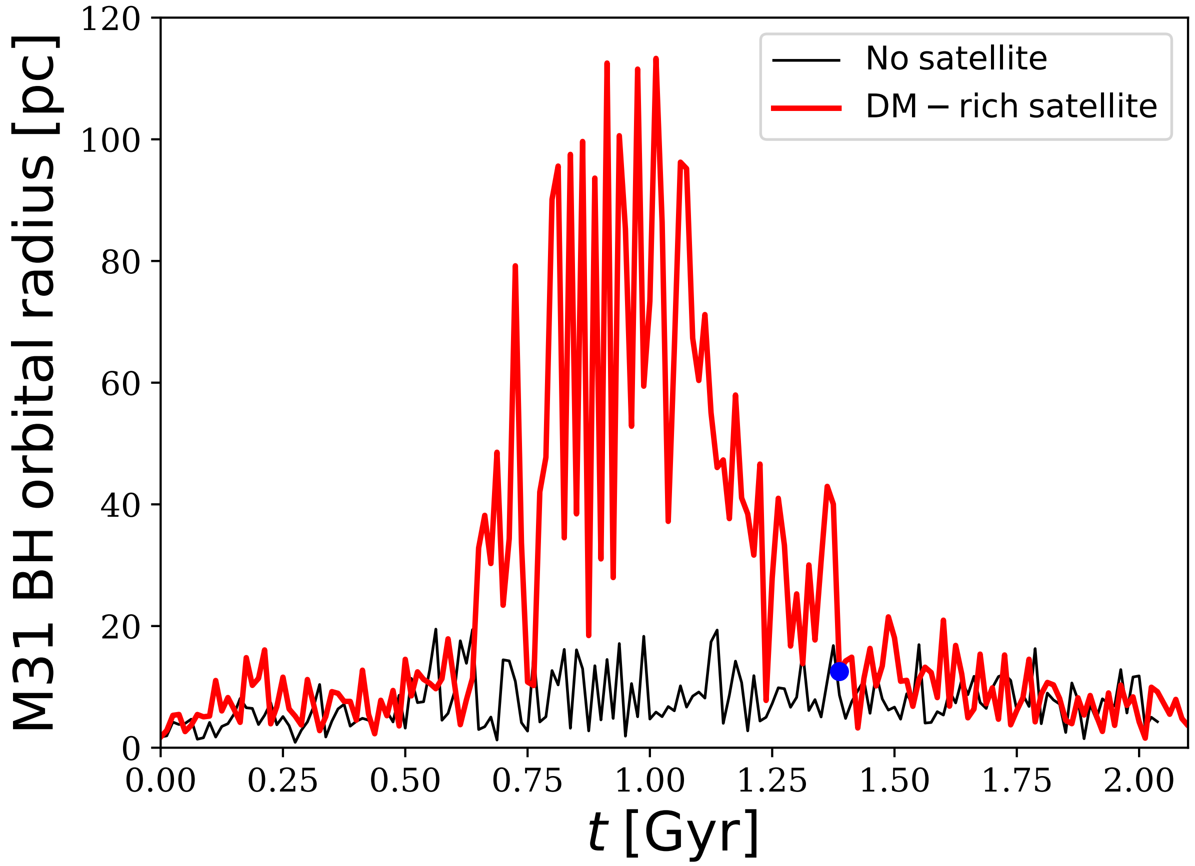


(Boldrini et al. (2020))

What happened to the **M31 central black hole** after this recent merger?

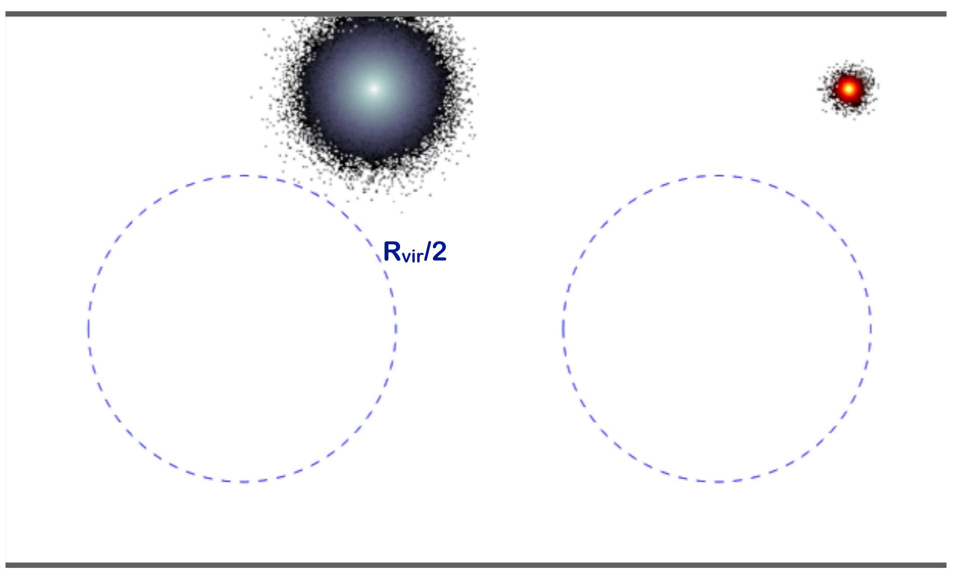
Satellite galaxy in M31

The offset of the M31 black hole



(Boldrini 2020, MNRAS Letters, L137B)

Merger scenario

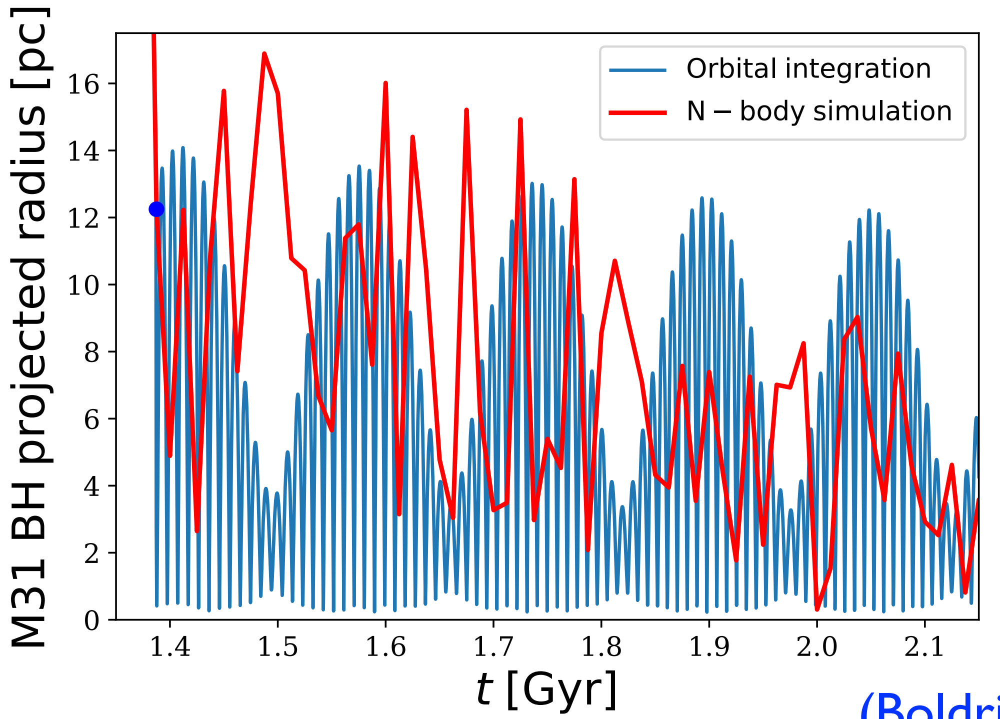


It results in a **kick** of the **black hole** to **hundreds of parsecs** from the galaxy centre

(Boldrini (2020))

Satellite galaxy in M31

Orbit integrations with Galpy (Bovy (2015))



(Boldrini 2020, MNRAS Letters, L137B)

At 2.1 Gyr	Prediction	Observation
Offset by	0.39 pc	0.26 pc

The **infall** of the **accreting satellite** in M31 naturally explains a **black hole offset** by sub-parsecs

Goals achieved during the thesis

Effects of infalling objects on the central region of galaxies

🍎 **Globular clusters**

- Fornax globular cluster dynamic doesn't exclude cuspy profile
  (Boldrini et al. , 2019, MNRAS, 485, 2546)
- Embedding globular clusters in dark matter minihalos create cores in Fornax
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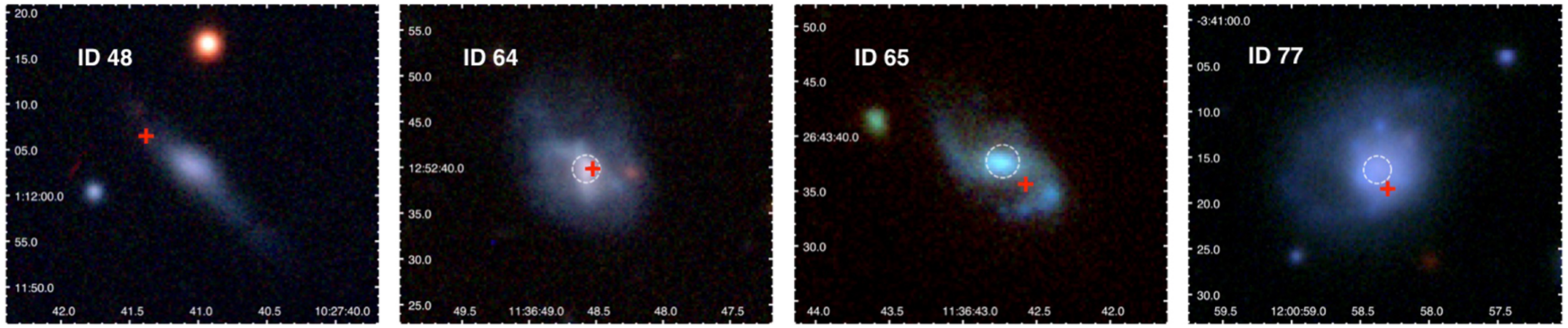
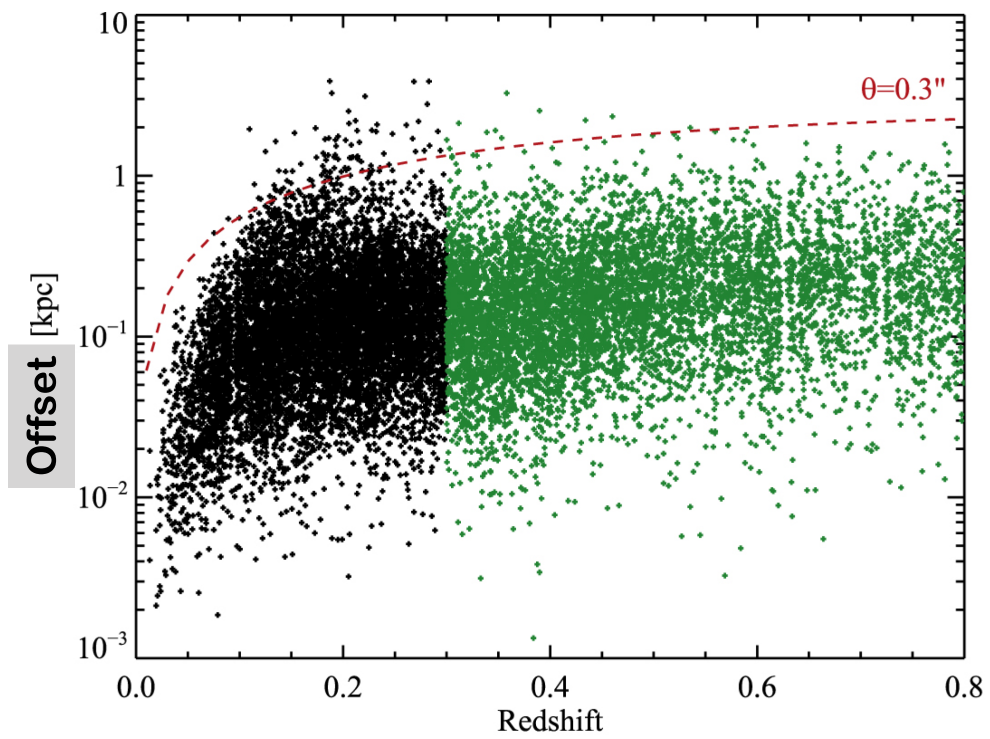
Dark matter subhalos

Off-centre black holes in dwarf galaxies

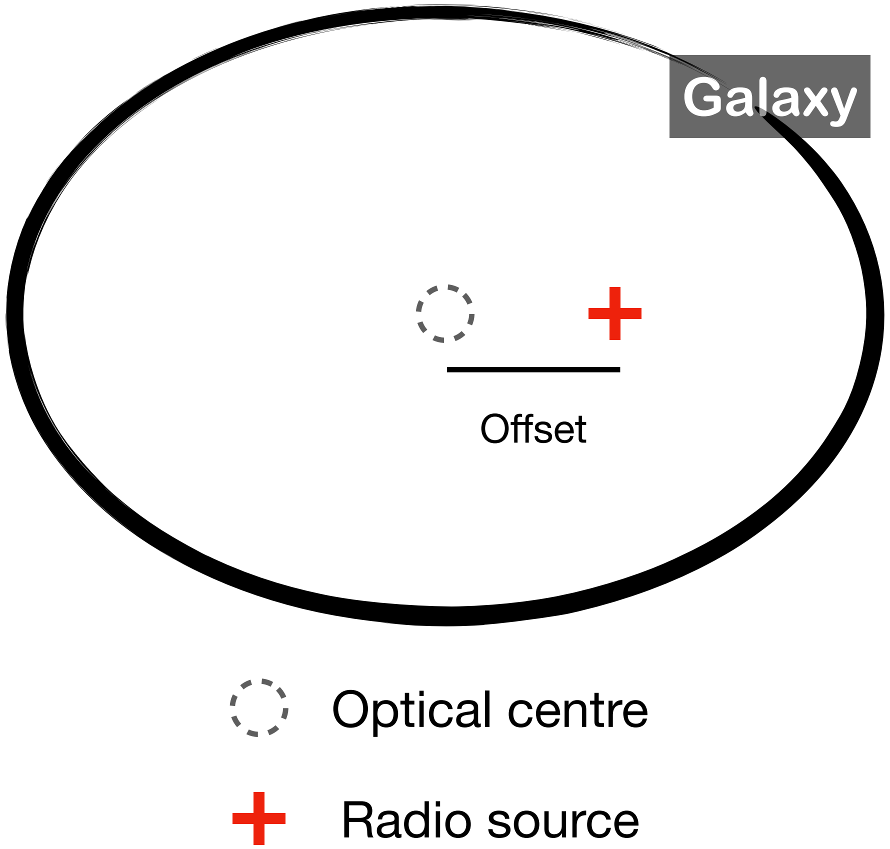
Observations in dwarfs



(Reines et al. (2019))

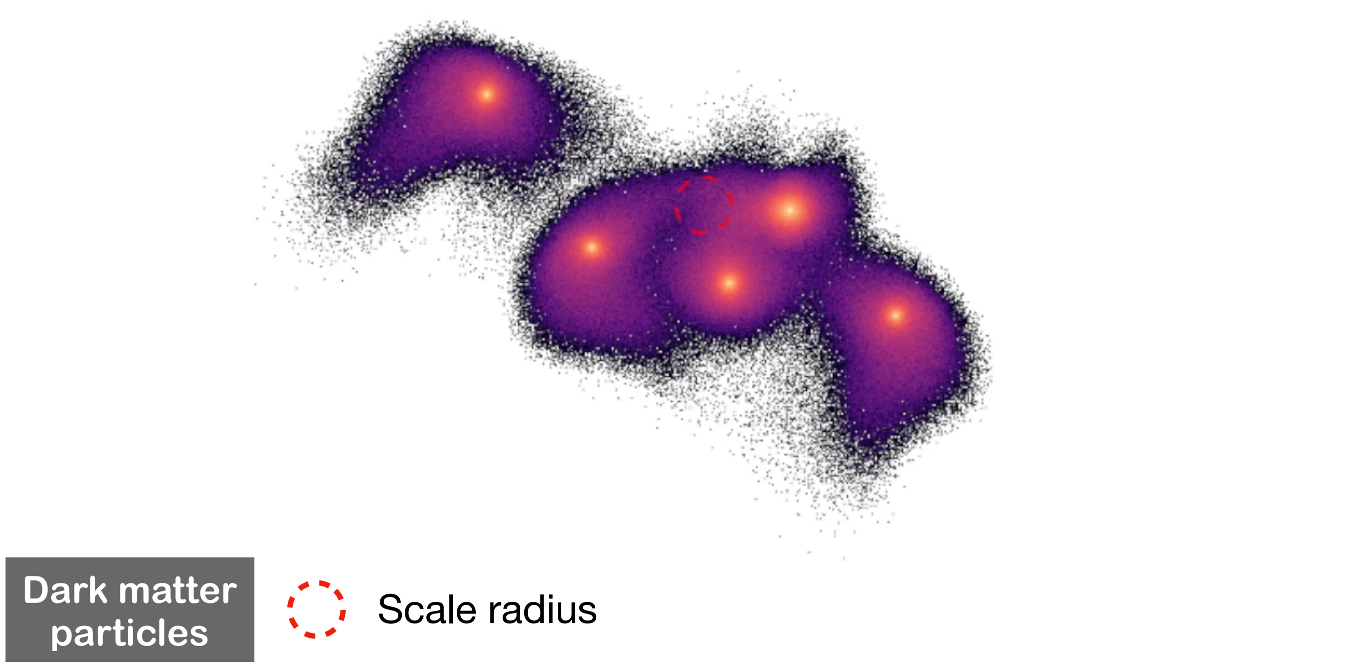


(Shen et al. (2019))



Off-centre black holes in dwarf galaxies

Minihalos of globular clusters in Fornax

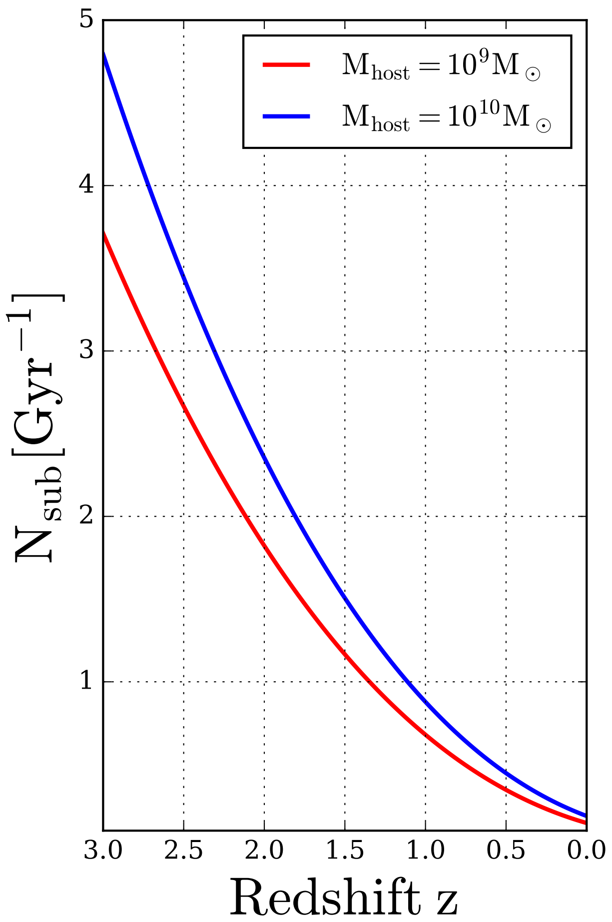


Dark matter subhalos can also be responsible for BH offset?

Off-centre black holes in dwarf galaxies

Subhalo accretions in dwarf galaxies

$10 < M_{host}/M_{sub} < 100$



(Neistein & Dekel (2008))

The **number of subhalo** accretion
in **dwarf galaxies**
can be determined by
the **extended Press-Schecter** formalism

Off-centre black holes in dwarf galaxies

Dwarf galaxies

- NFW form with r_s (z) (Prada et al. (2012)) ~$10^{9\text{-}10}$ $M_\odot$
- Plummer profile

Central massive black hole

- Point mass ~$10^{5\text{-}6}$ $M_\odot$

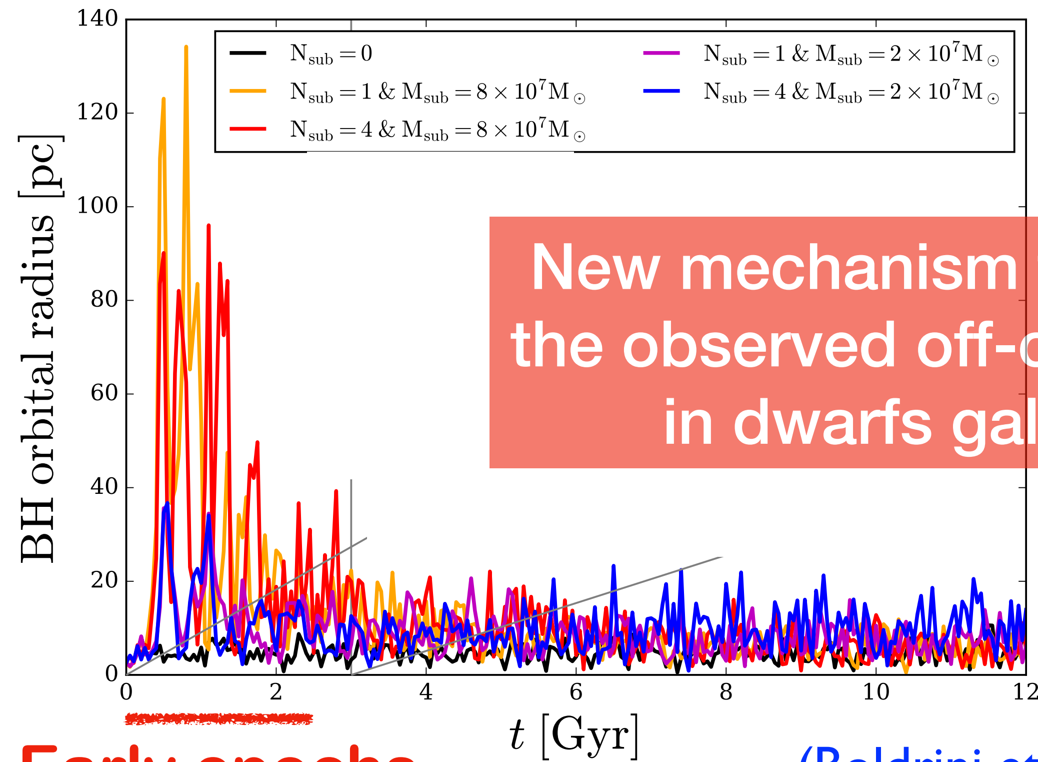
Subhalos ~$10^{7\text{-}8}$ $M_\odot$

- NFW form with r_s (z)
- Initial average circularity (Wetzel (2011))

Off-centre black holes in dwarf galaxies

Heating mechanism

- Sinking of DM subhalos because dynamical friction
- Transferring energy via dynamical friction into the dwarf centre



New mechanism to explain the observed off-centre BHs in dwarfs galaxies

Early epochs

(Boldrini et al. , 2020, MNRAS Letters, 495, L12)

This dynamical heating **kicks** any **central MBH** out to **tens of parsecs**, especially at **early epochs** z=1.5 - 3

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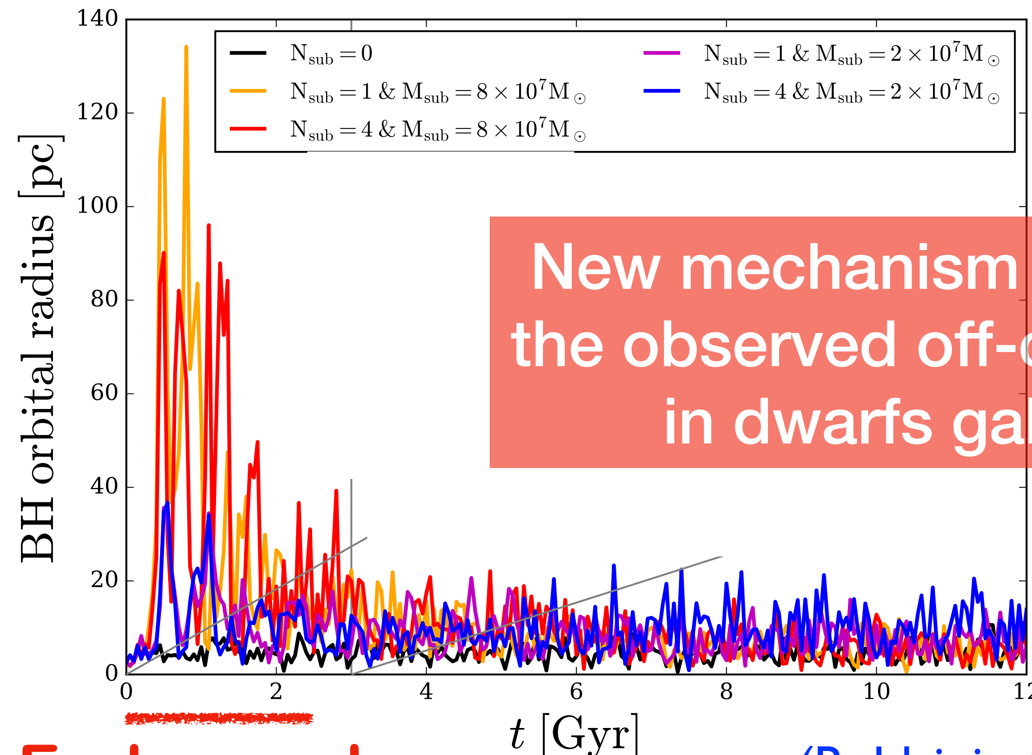

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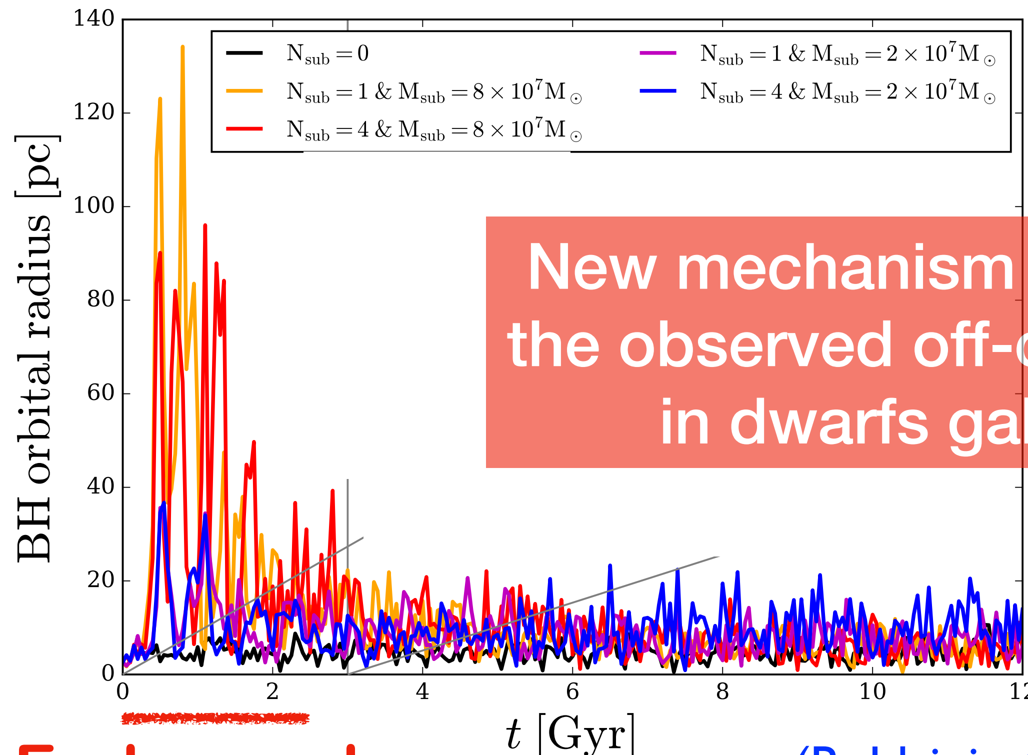

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Off-centre black holes in dwarf galaxies

Cusp-core problem

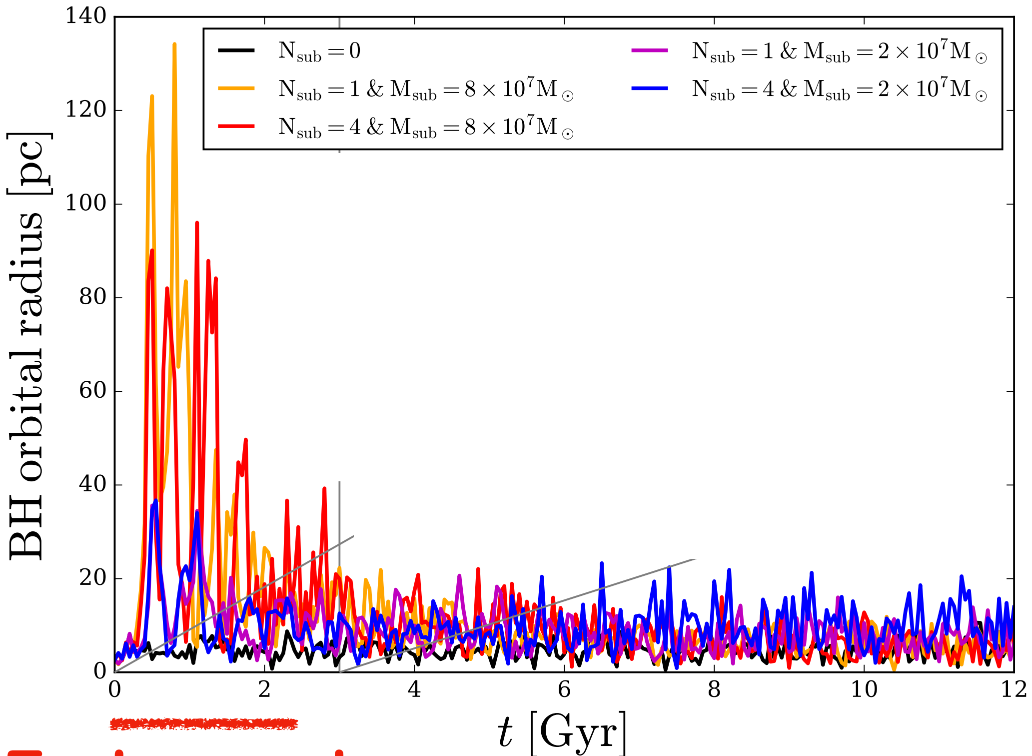
Black hole feedback

- Flattening of the DM density profile
- Peak of BH activity between z~3 and 1.6

BHs **accrete** gas **inefficiently** away from the galaxy centre as **gas clumps** are **centrally located**

(Smith et al. (2018))

Off-centre BH in dwarfs



Early epochs

(Boldrini et al. , 2020, MNRAS Letters, 495, L12)

One consequence of **off-center BHs** during **early epochs** of dwarf galaxies is to **quench any BH feedback**

(Boldrini et al. (2020c))

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🍎 **Primordial black holes**

Nature of cold dark matter

Cold dark matter candidates

Microscopic

WIMPs

Neutralinos

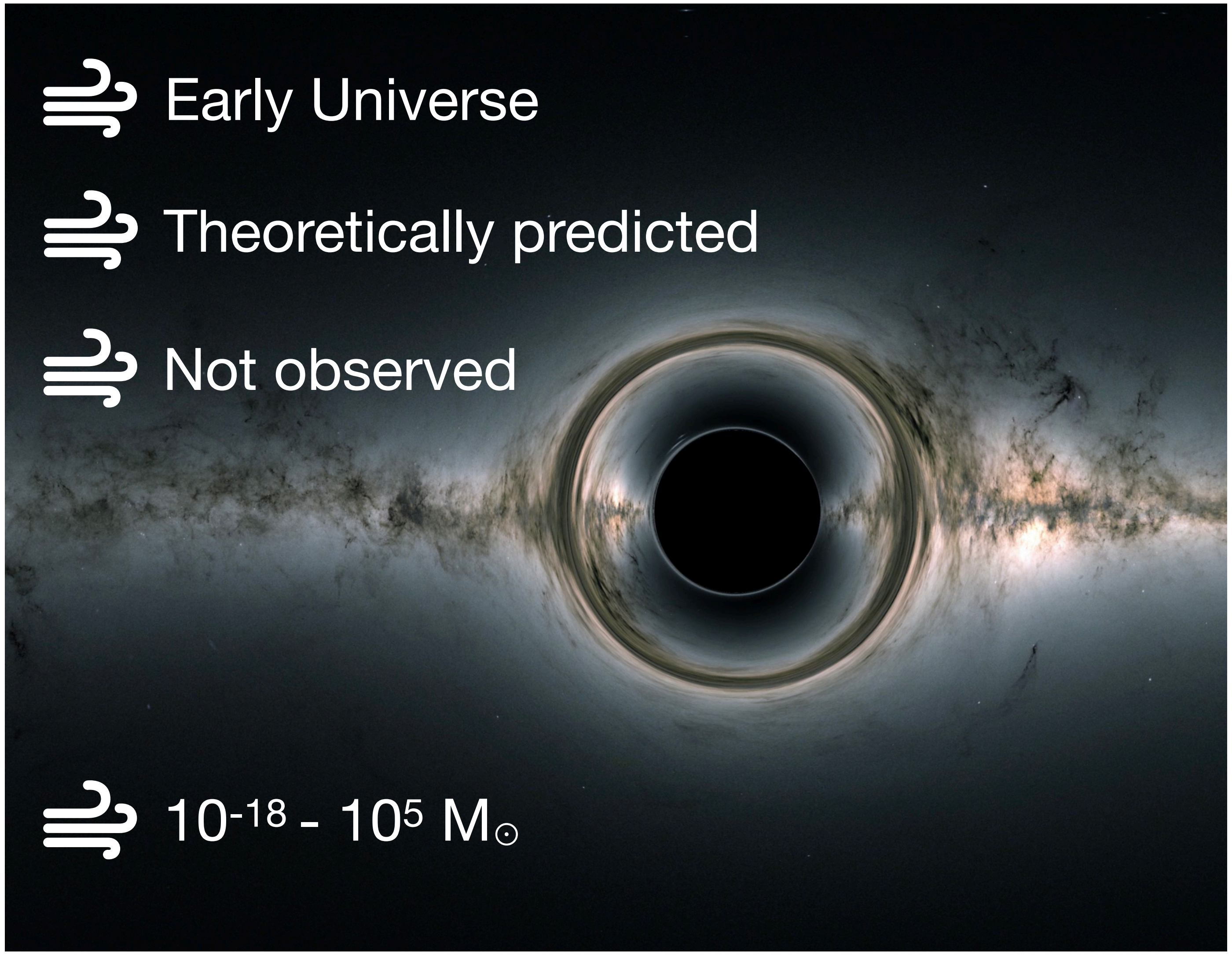
Macroscopic

MACHOs

Neutron stars

Brown and white dwarfs

Primordial black holes



Cold dark matter being composed of PBHs

$$f = \Omega_{PBH} / \Omega_{CDM}$$

Nature of cold dark matter

Cold dark matter candidates

Microscopic	Macroscopic
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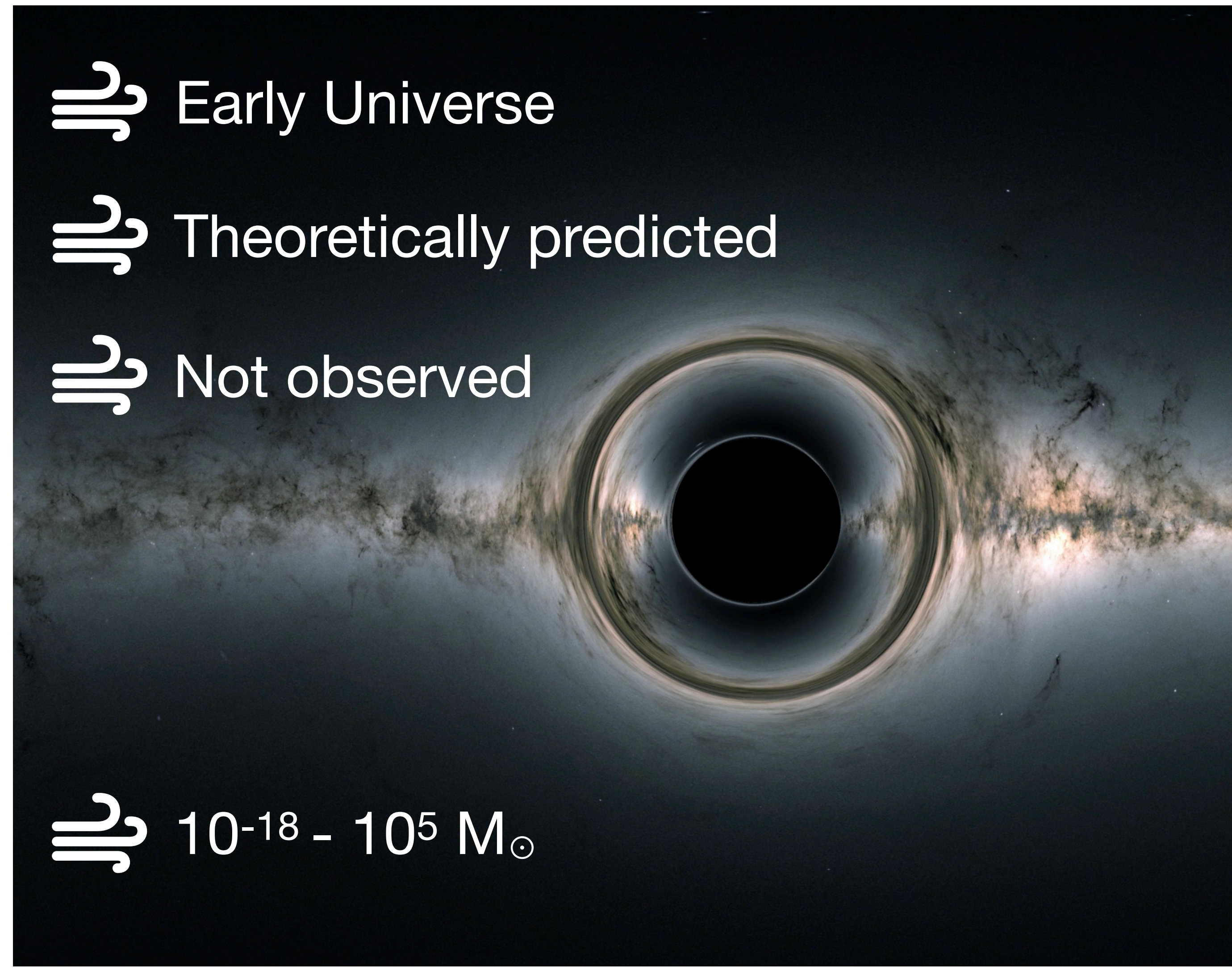


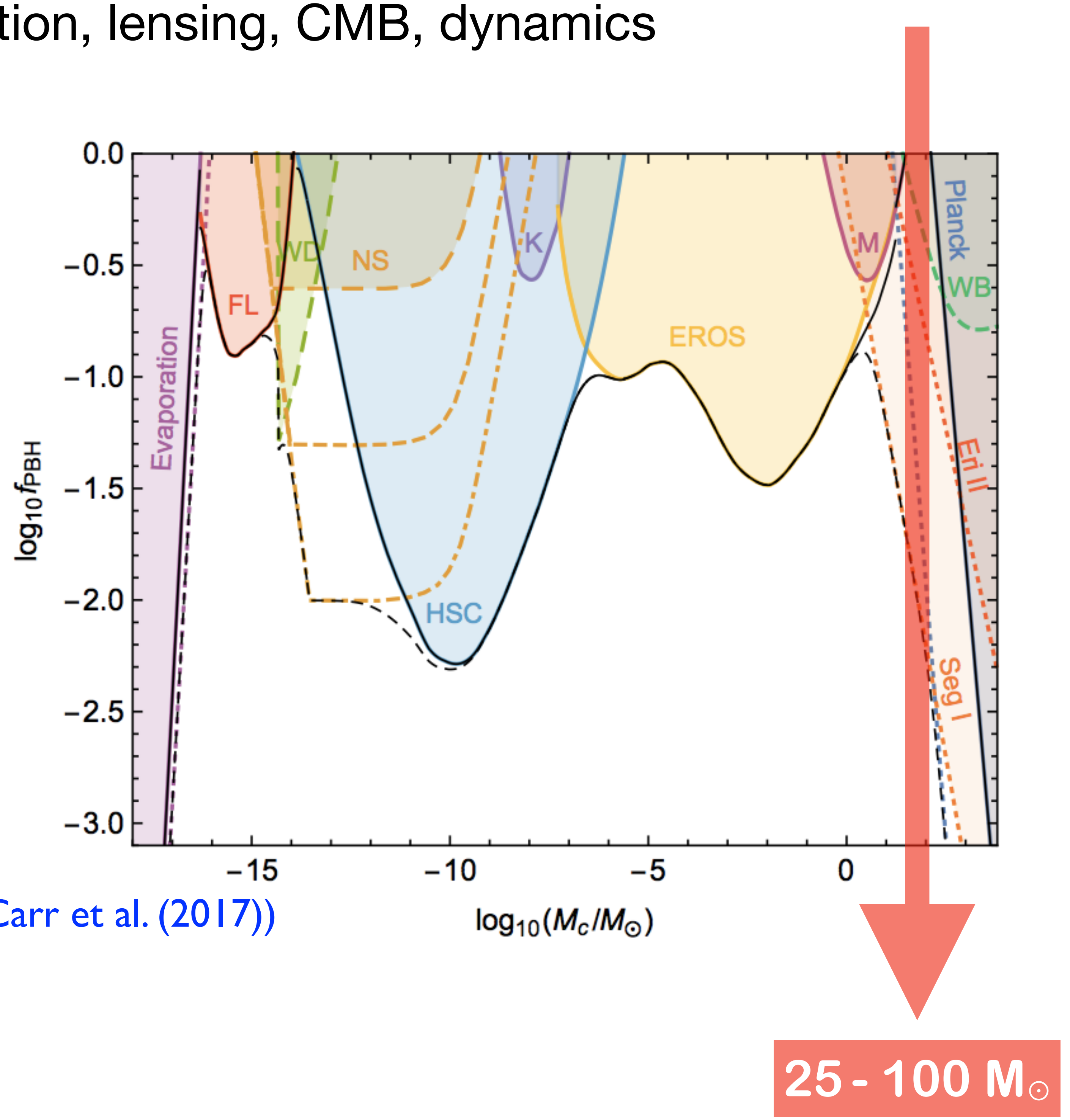
Cold dark matter being composed of PBHs

$$f = \Omega_{PBH}/\Omega_{CDM}$$

Primordial black holes as cold dark matter

Constraints on primordial black holes

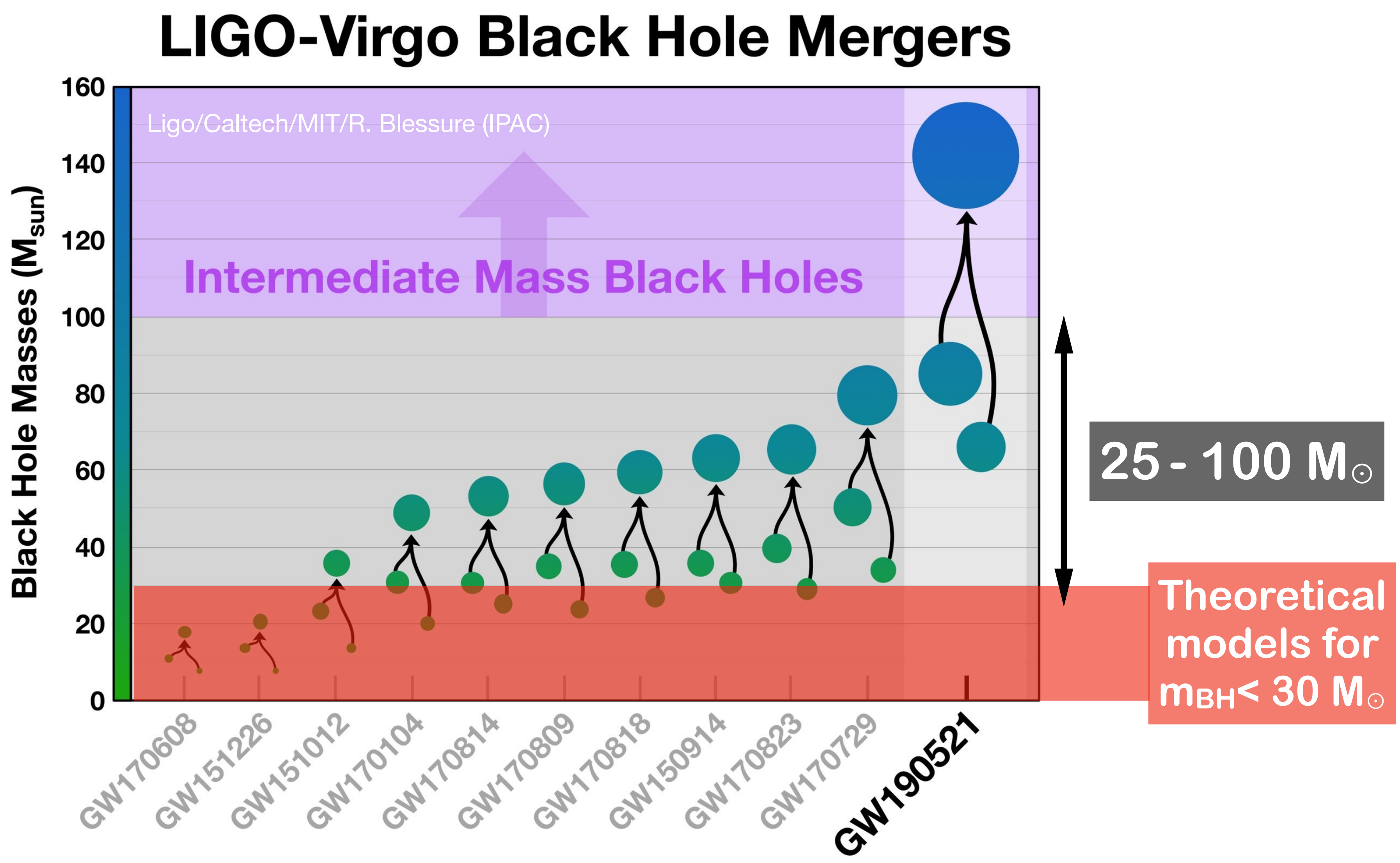
BH evaporation, lensing, CMB, dynamics

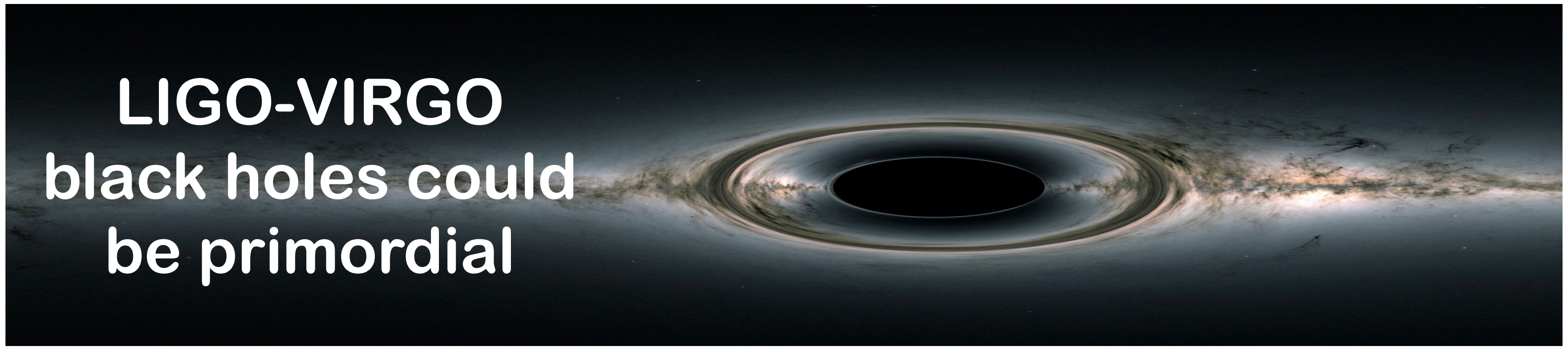


(Carr et al. (2017))

Primordial black holes as cold dark matter

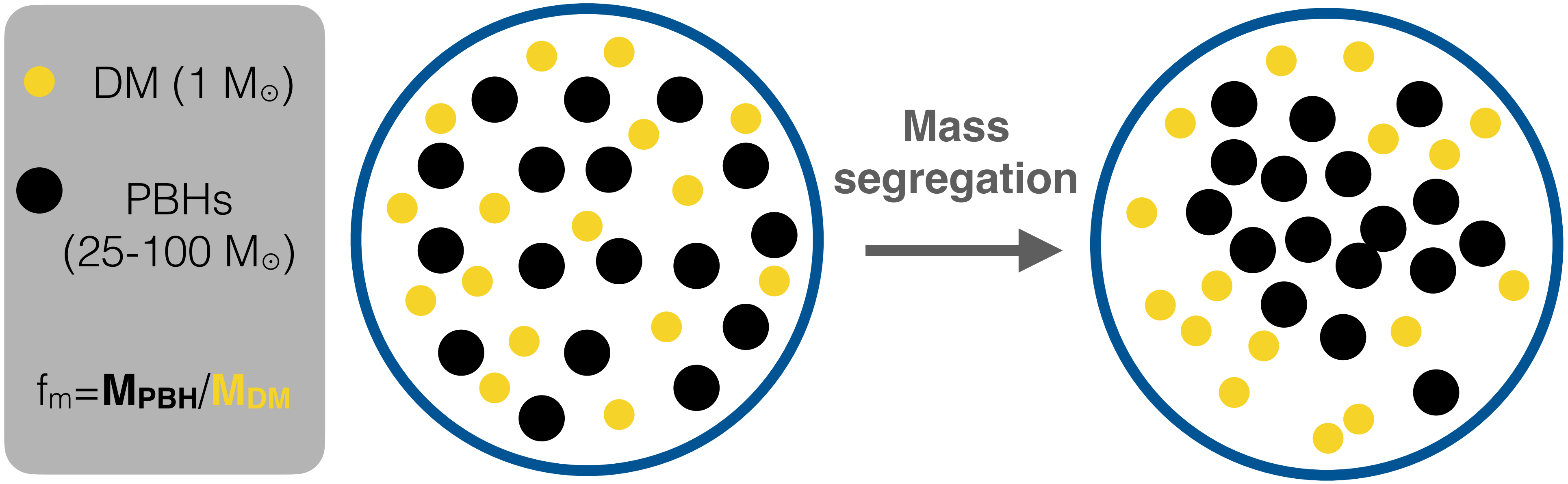
LIGO-VIRGO detections



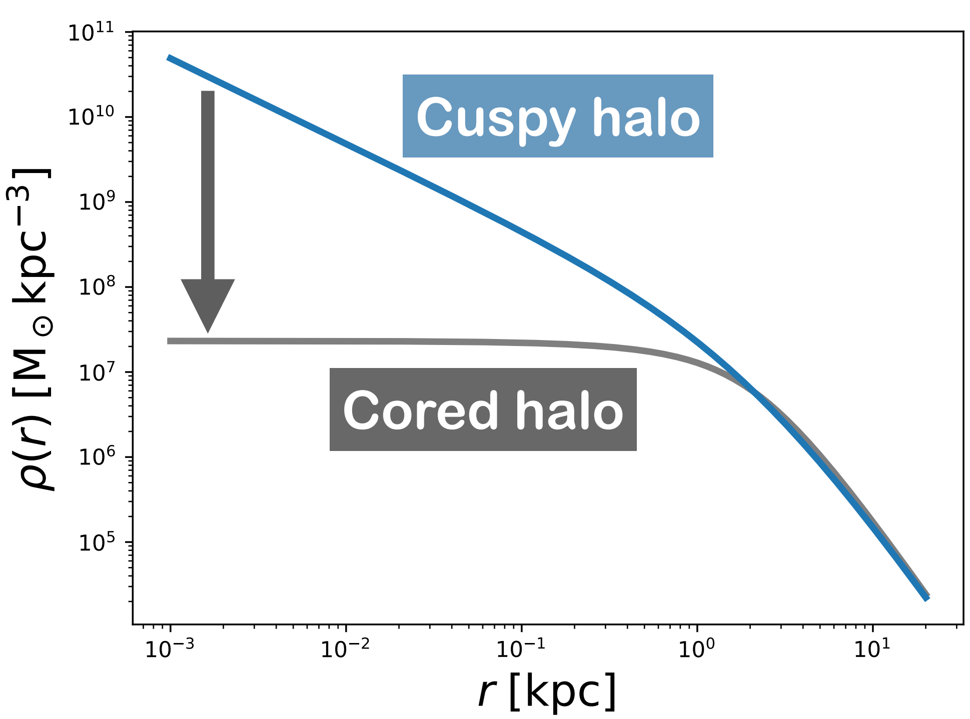


Primordial black holes as dark matter

Galaxy halo composed of PBH and DM particles



Cusp-to-core transition



NFW profile

$$\rho(r) = \rho_0 \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2} \rightarrow \rho_{DM},\ \rho_{PBH}$$

(Navarro et al. (1996))

Primordial black holes as cold dark matter

Relaxation time in CDM+PBH halos

Time needed by a **DM particle** or a **PBH** before it is **significantly perturbed** by **surrounding particles**

$$T_{\rm relax} \propto \frac{M_{\rm h}}{\ln(M_{\rm h})}$$

Dwarf galaxies ~10^{7-9} $M_\odot$

$T_{relax}(10^7\ M_\odot$ halo) ~ 1 - 12 Gyr

$T_{relax}(10^8\ M_\odot$ halo) ~ 9 $T_{relax}(10^7\ M_\odot$ halo)

$T_{relax}(10^9\ M_\odot$ halo) ~ 78 $T_{relax}(10^7\ M_\odot$ halo)

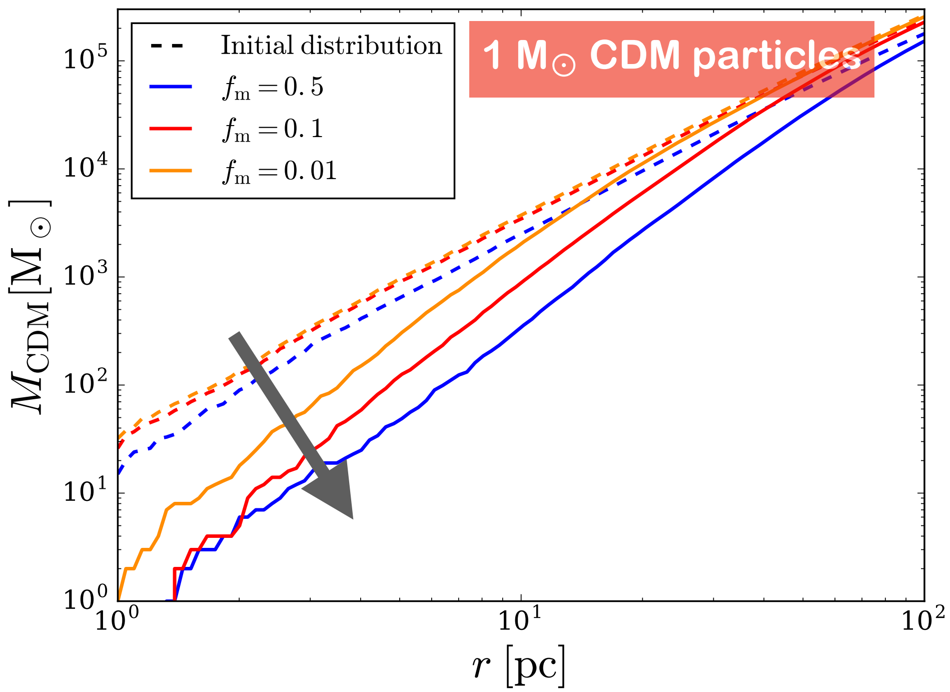
Low mass dwarf halo	~10^7 $M_\odot$	**PBH+CDM halo**
PBHs	25-100 $M_\odot$	
DM particle	1 $M_\odot$	
Mass fraction f_m	0.01-0.5	

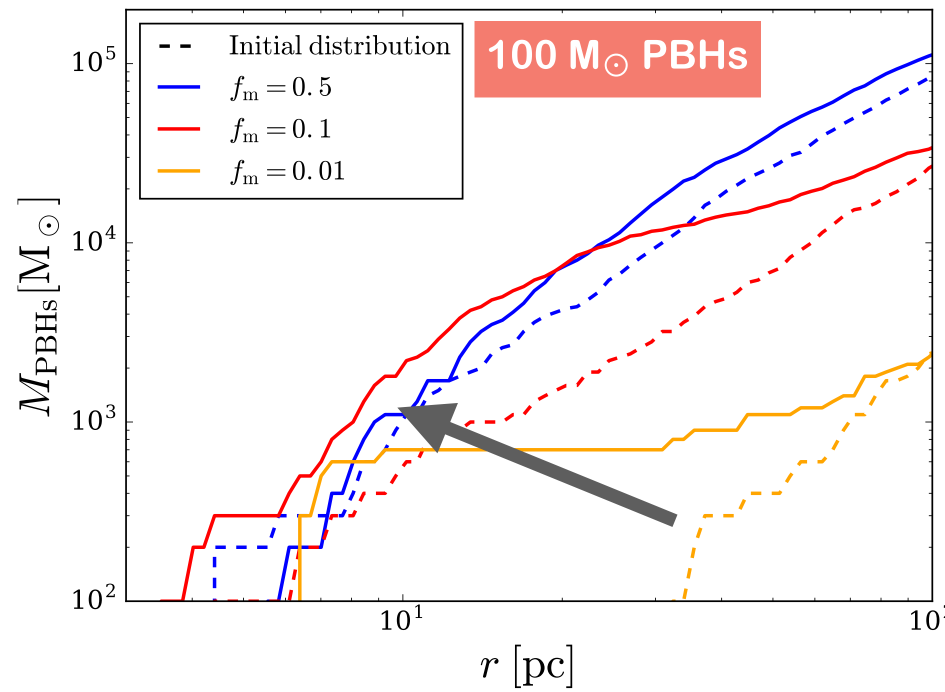
Primordial black holes as cold dark matter

How does this gravitational heating take place?

Interior mass

(Boldrini et al. 2020, MNRAS, 492, 5218)



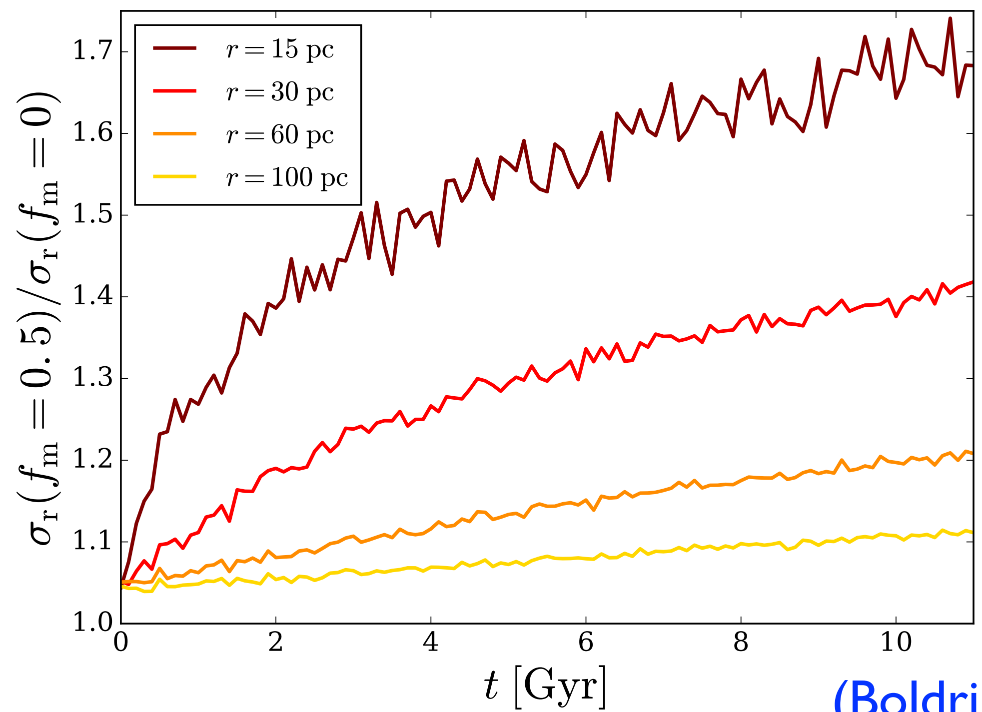


By **falling in**, **PBHs** will **transfer energy** to the **CDM field** via **dynamical friction**

Primordial black holes as cold dark matter

How does this gravitational heating take place?

CDM velocity dispersion



(Boldrini et al. 2020, MNRAS, 492, 5218)

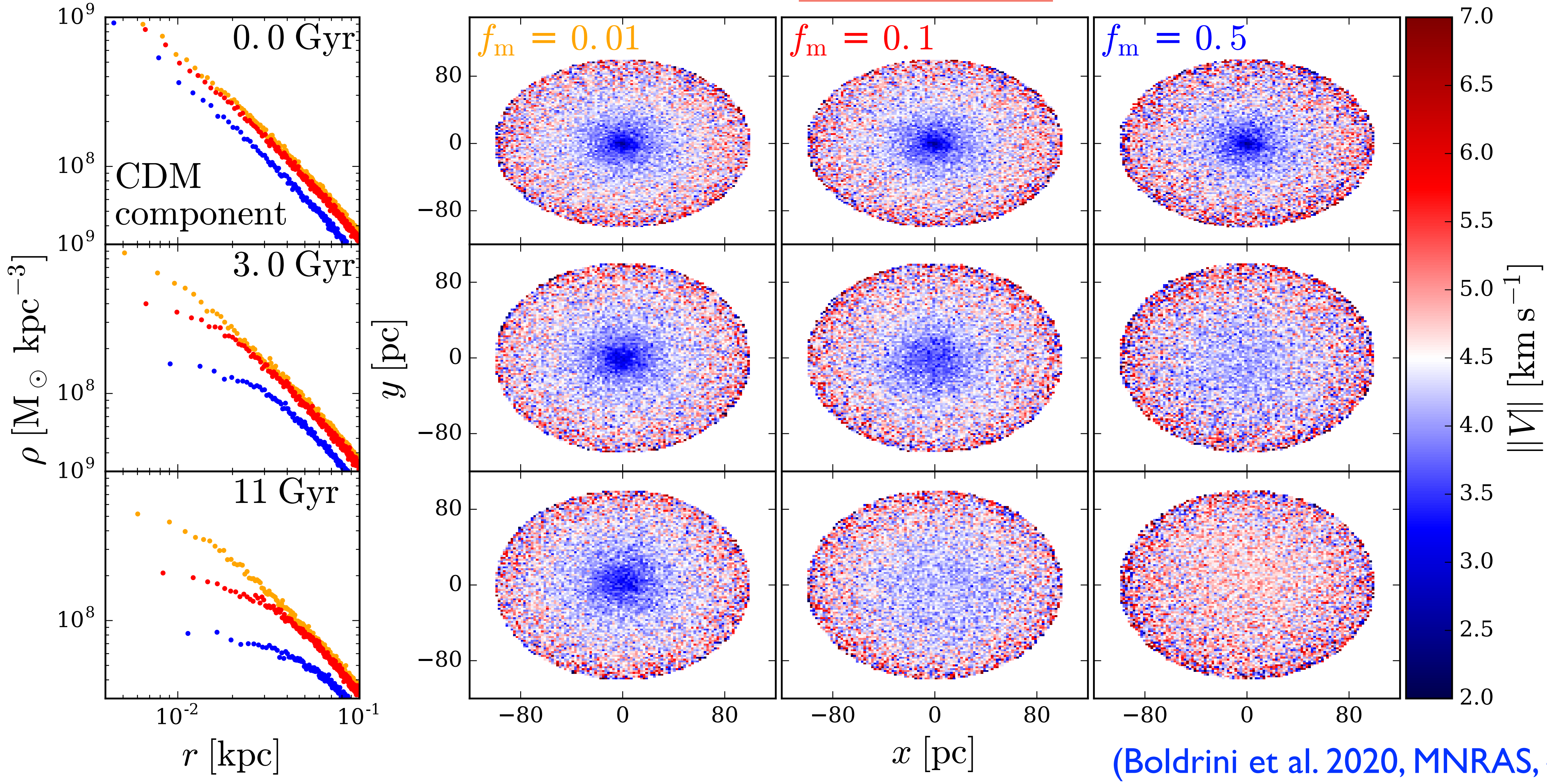
Gravitational heating:

- Dynamical friction induced by PBHs
- Two-body relaxation between PBHs

Primordial black holes as cold dark matter

Cusp-to-core transition in PBH+CDM halo

100 M$_\odot$ PBHs



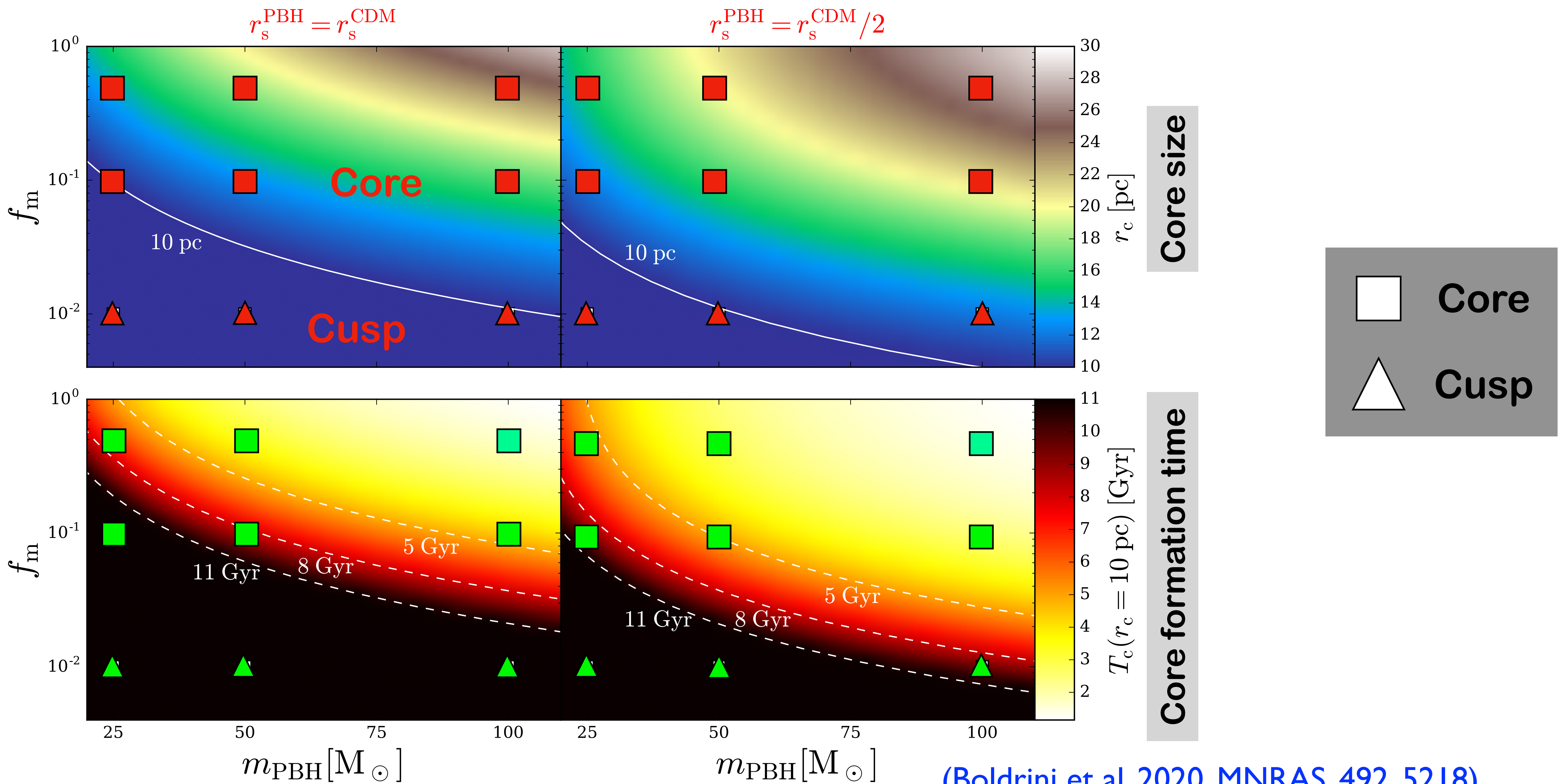
(Boldrini et al. 2020, MNRAS, 492, 5218)

This **gravitational heating** by PBHs leads to **core formation**

Primordial black holes as dark matter

Core size and formation time

$$T_r(r) \simeq \frac{v^3(r)}{8\pi(n_{\rm CDM}m_{\rm CDM}^2 + n_{\rm PBH}m_{\rm PBH}^2)G^2 \ln\left(\frac{r_{200}}{\epsilon}\right)}$$



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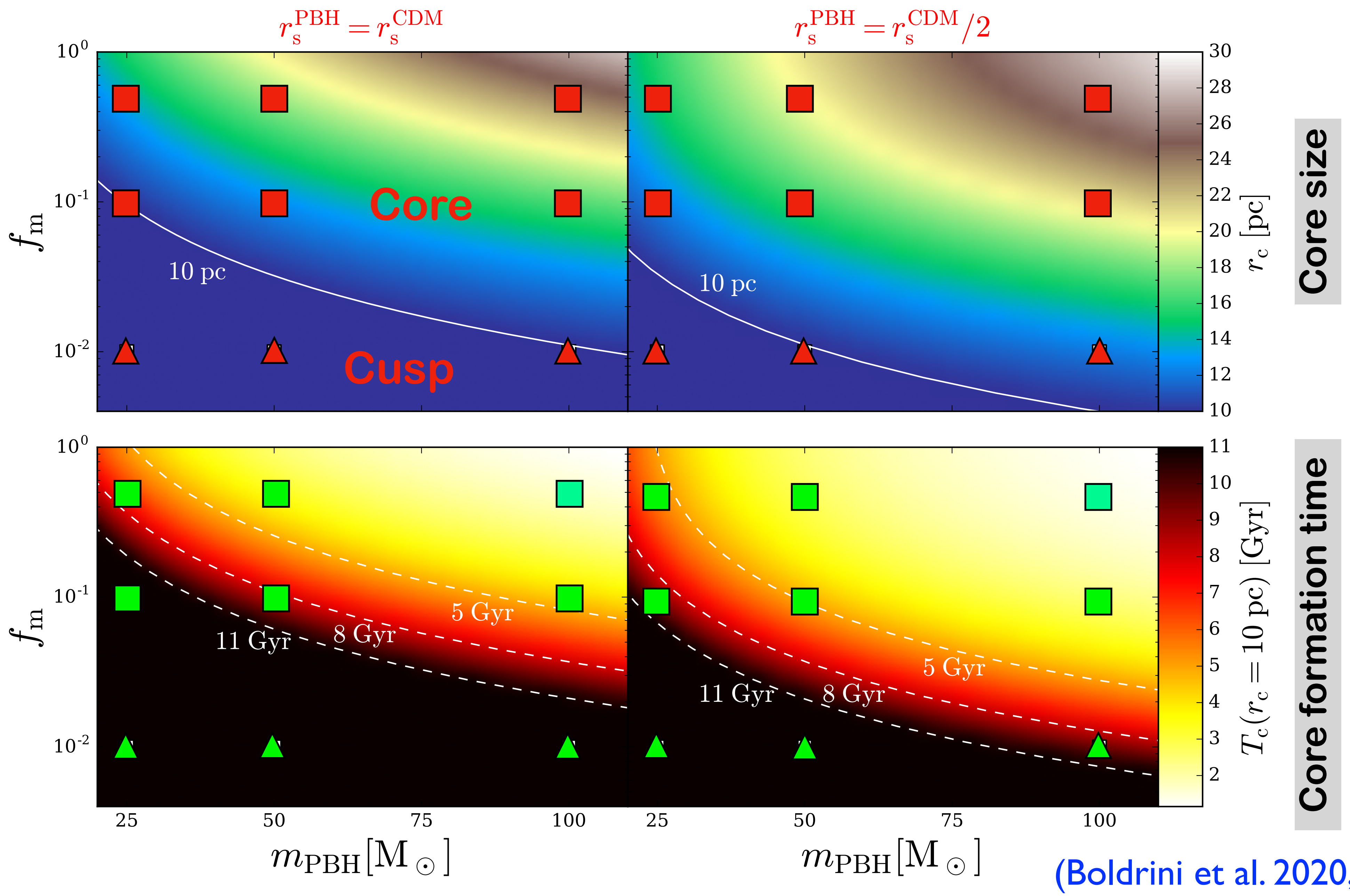

Core

Cusp

(Boldrini et al. 2020, MNRAS, 492, 5218)

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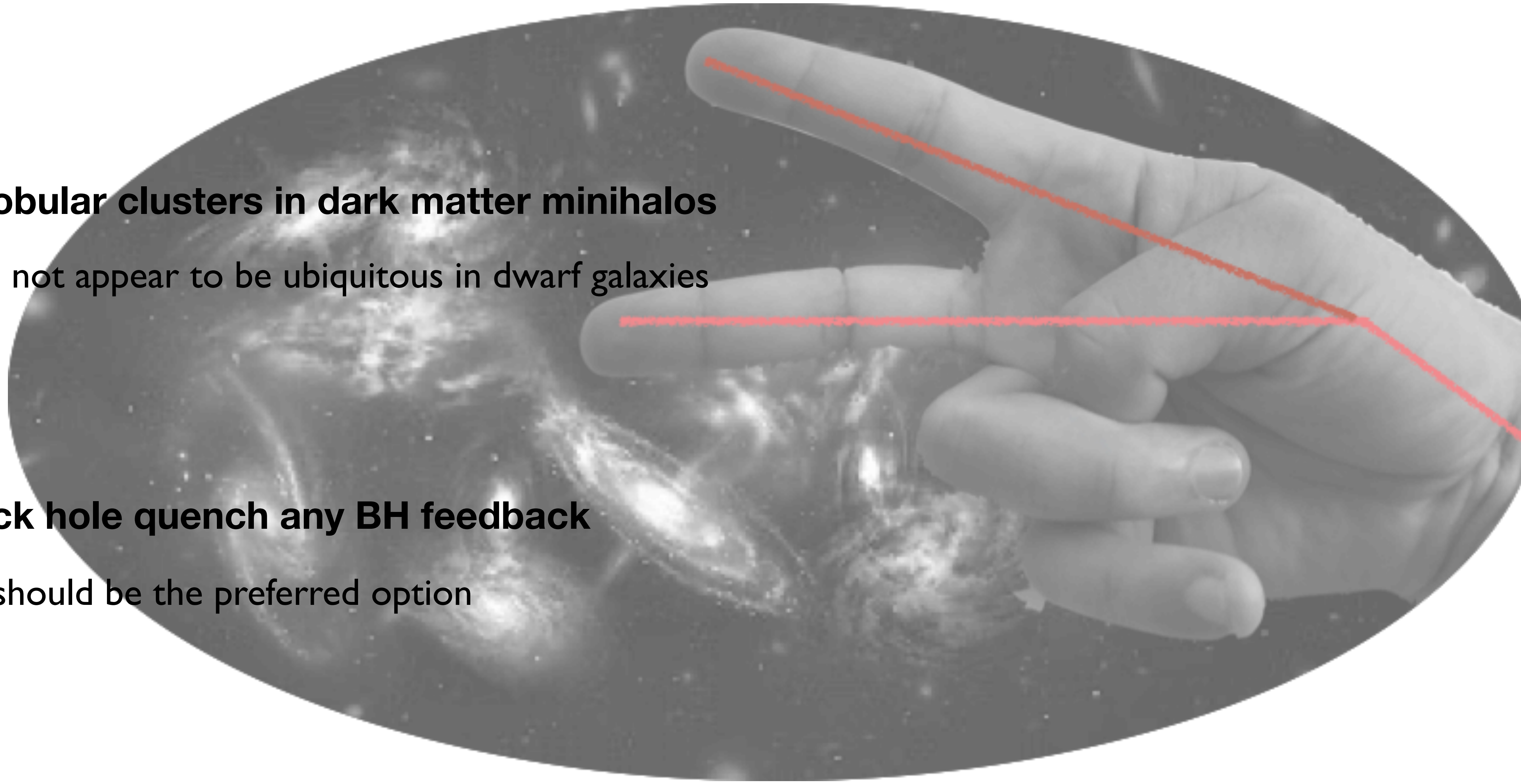
🍎 **Primordial black holes**

- Dark matter cores occur naturally in cold dark matter + primordial black hole halos, without the need to invoke baryonic processes.
  (Boldrini et al. 2020, MNRAS, 492, 5218)

The cusp-core problem



New solutions

- **Embedding globular clusters in dark matter minihalos**

  Orbiting GCs do not appear to be ubiquitous in dwarf galaxies

- **Off-centre black hole quench any BH feedback**

  Stellar feedback should be the preferred option

- **Primordial black holes as dark matter**

  Mergers between low-mass galaxies after core formation in order to form larger cores consistent with observations

Prospects

Globular clusters

- 🍿 Fornax globular clusters in **self-interacting** dark matter and **fuzzy** dark matter
- 🍿 MW globular cluster with **dark matter** (Theoretical predictions and **GAIA data**)
- 🍿 **LISA** mission and **intermediate-mass black hole** in globular clusters

Off-centre black holes

- 🍿 Impact of core formation in **fuzzy** dark matter on central massive black holes

Infalling satellite in M31

- 🍿 Detecting the **remnant** satellite with **HST data**
- 🍿 Looking at the **radio source** in the remnant

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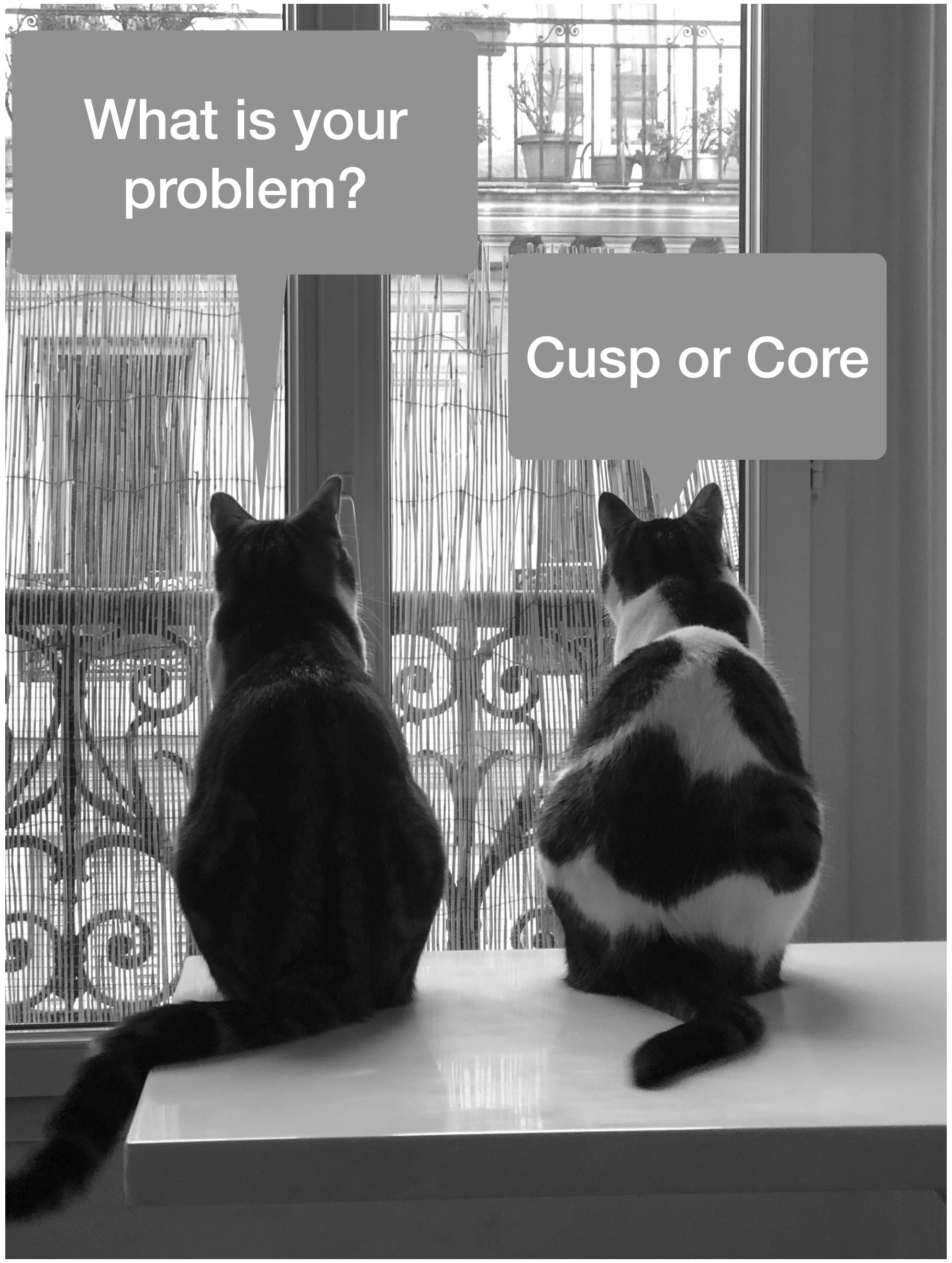
Thank you
for your attention



The future of Gothic

New GPU

Nvidia
geforce GTX 1080 ti

11 GB

2×10^{7} particles

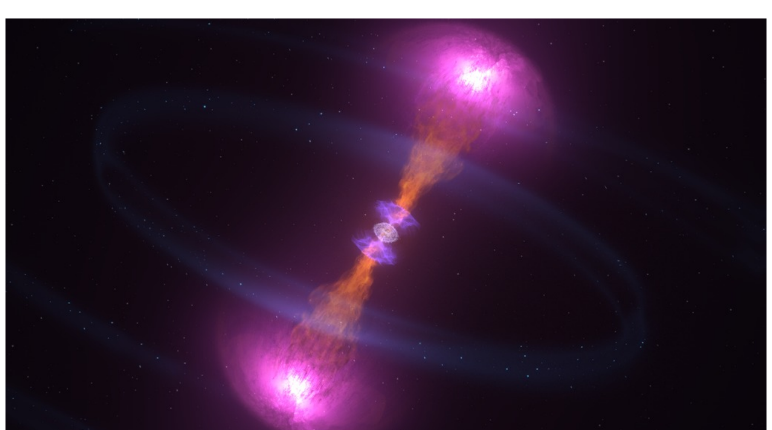
Nvidia
Tesla V100

32 GB

10^{8} particles

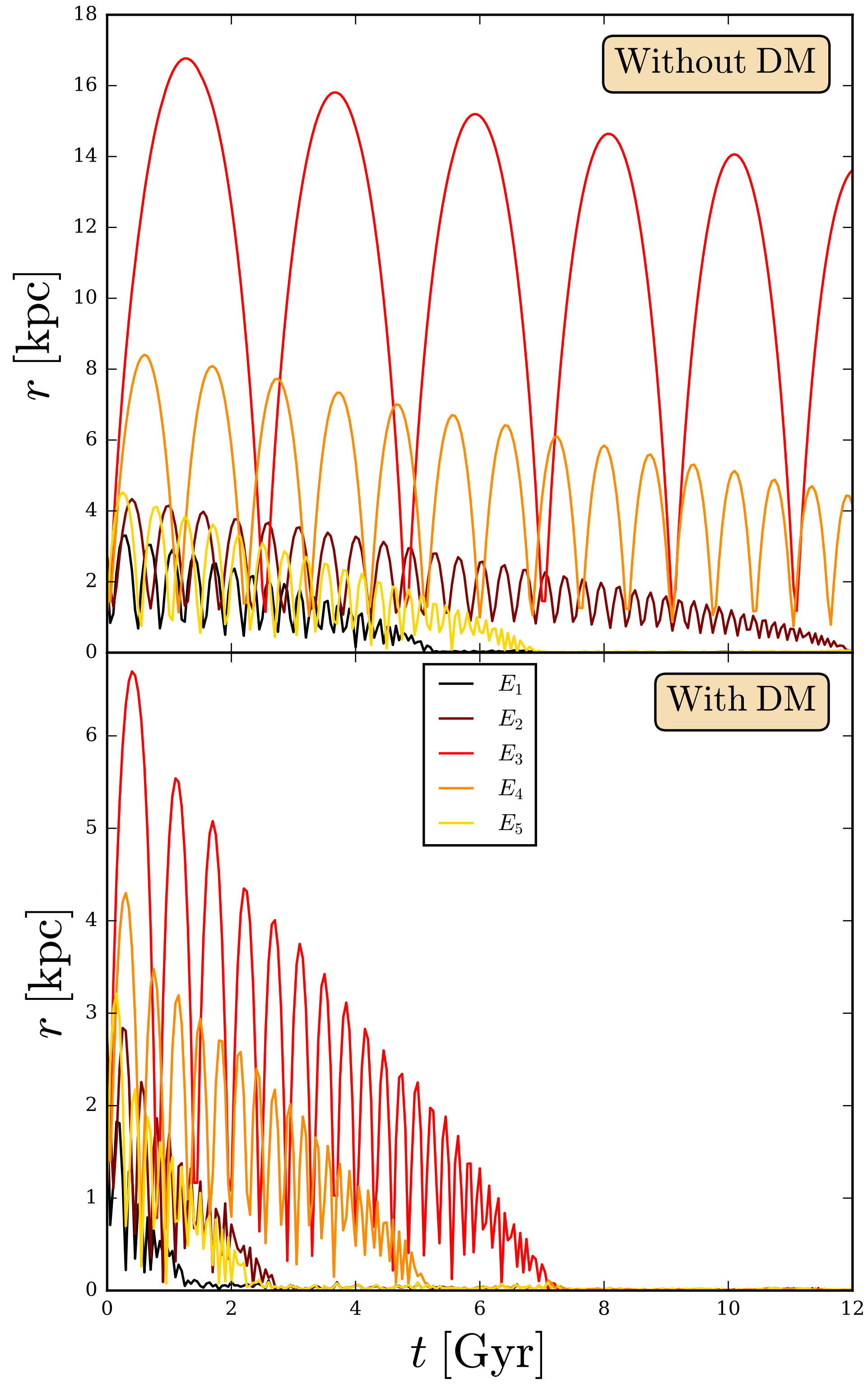
Parallelized soon

Collisional regime



Questions

Disruption of GCs thanks to dark matter



Questions

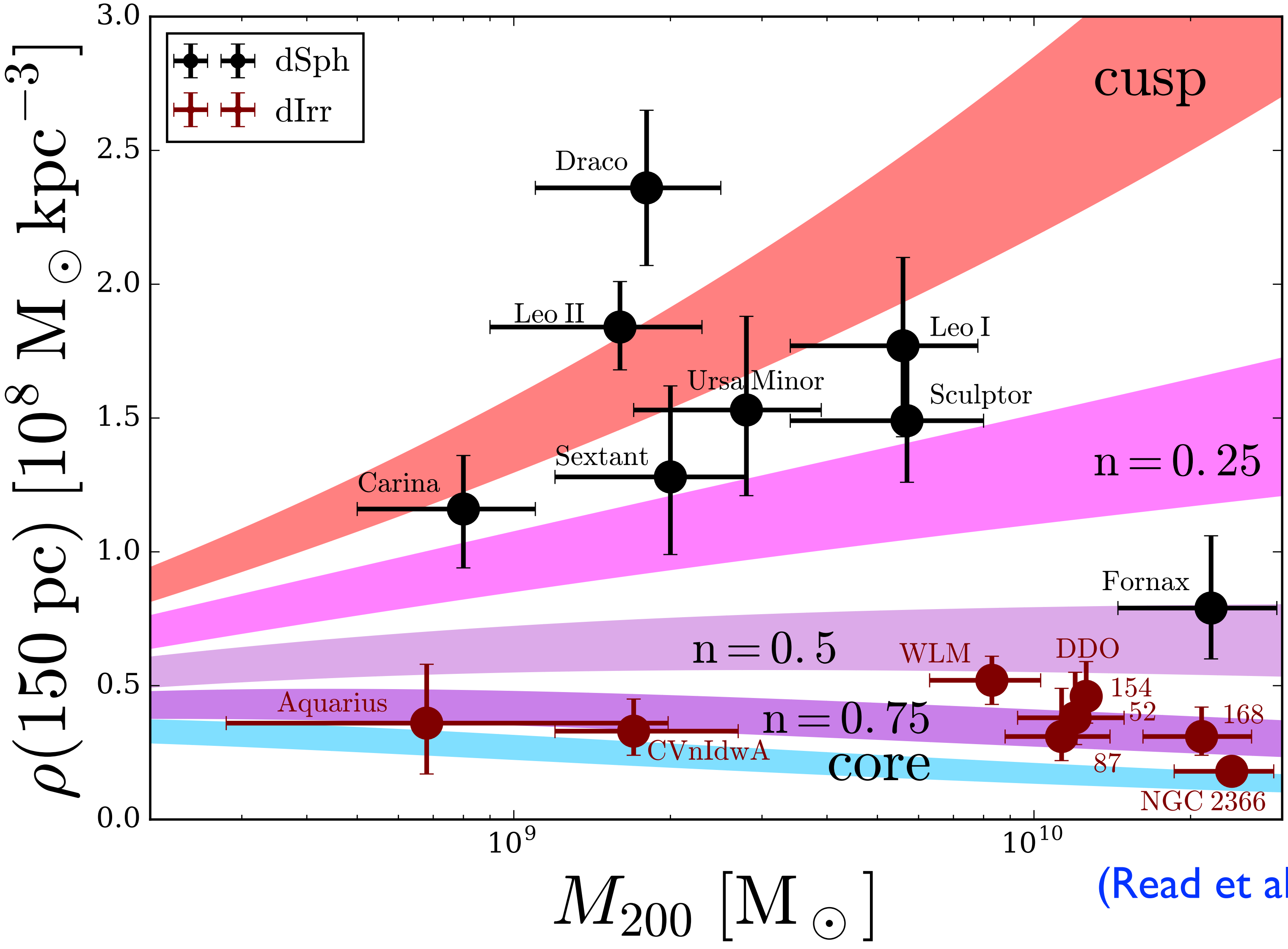
Comparaison between subhalos and GCs with dark matter

	Globular clusters with dark matter	Dark matter subhalos
Initial orbital radius	2-5 kpc	8-10 kpc
Eccentricity	0.6-0.8	0.86-0.88
Mass	$\sim 2\times10^7\ M_\odot$	$\sim 2\times10^7\ M_\odot$

$10 < M_{host}/M_{sub} < 100$

Questions

Cores and cusps in dwarfs



(Read et al. 2019)

Questions

Limitations of our approach

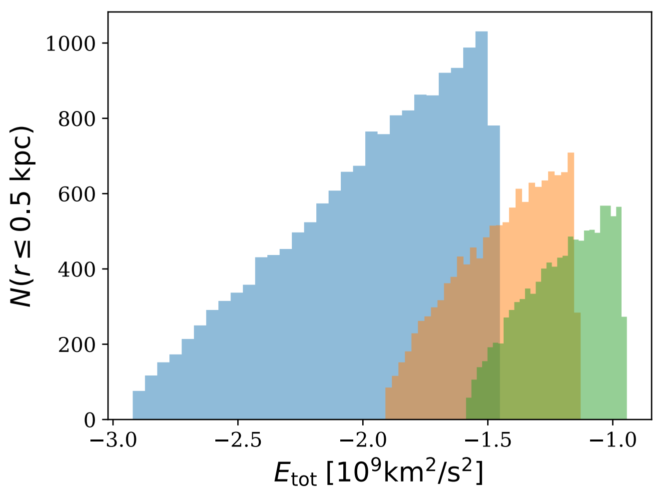
- 🍿 Idealized system
- 🍿 Average initial conditions and exploration of the parameter space

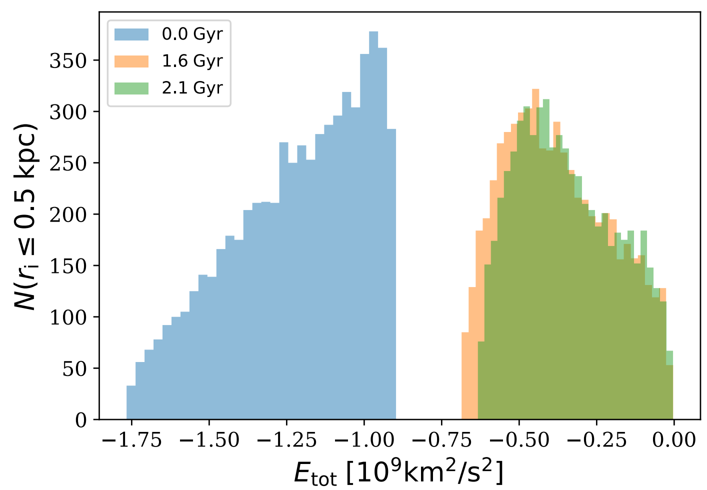
Strengths

- 🍭 Exploring and understanding deeply physical processes **Dynamical friction**
- 🍭 Complementary with Cosmological simulations **Off-centre BHs:** (Bartlett et al. 2020)
- 🍭 Investigating and obtaining constraints from observations

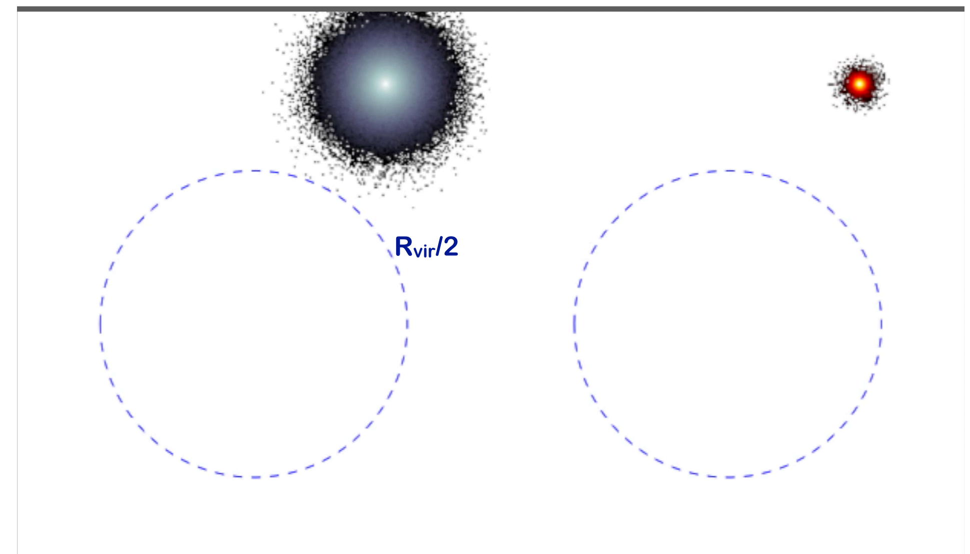
Andromeda galaxy

M31 dark matter halo

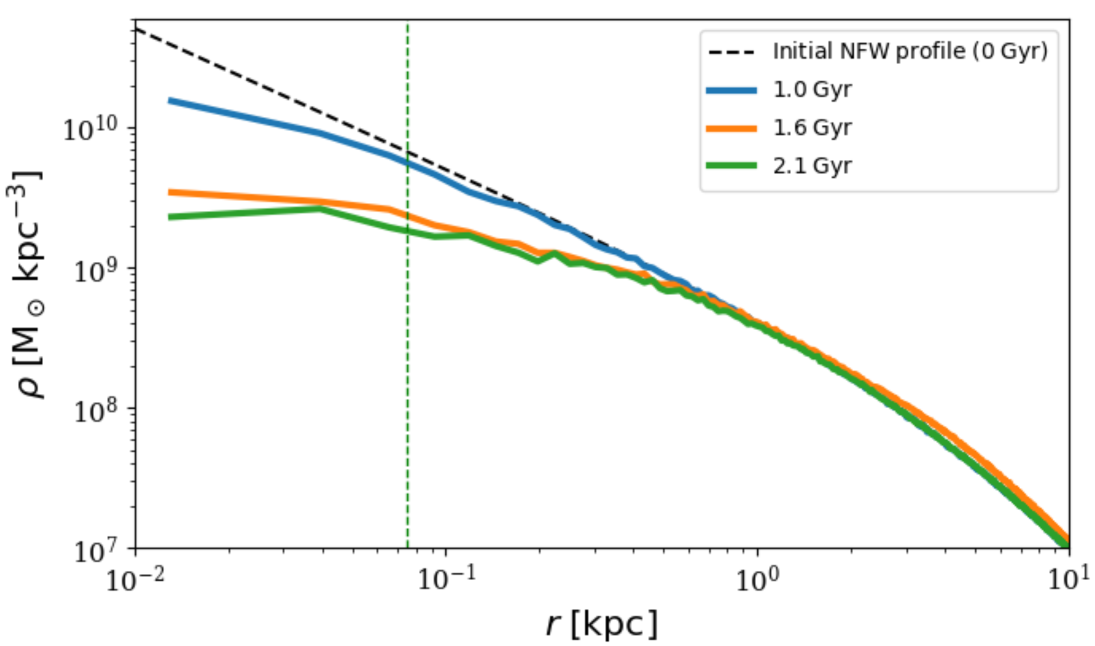


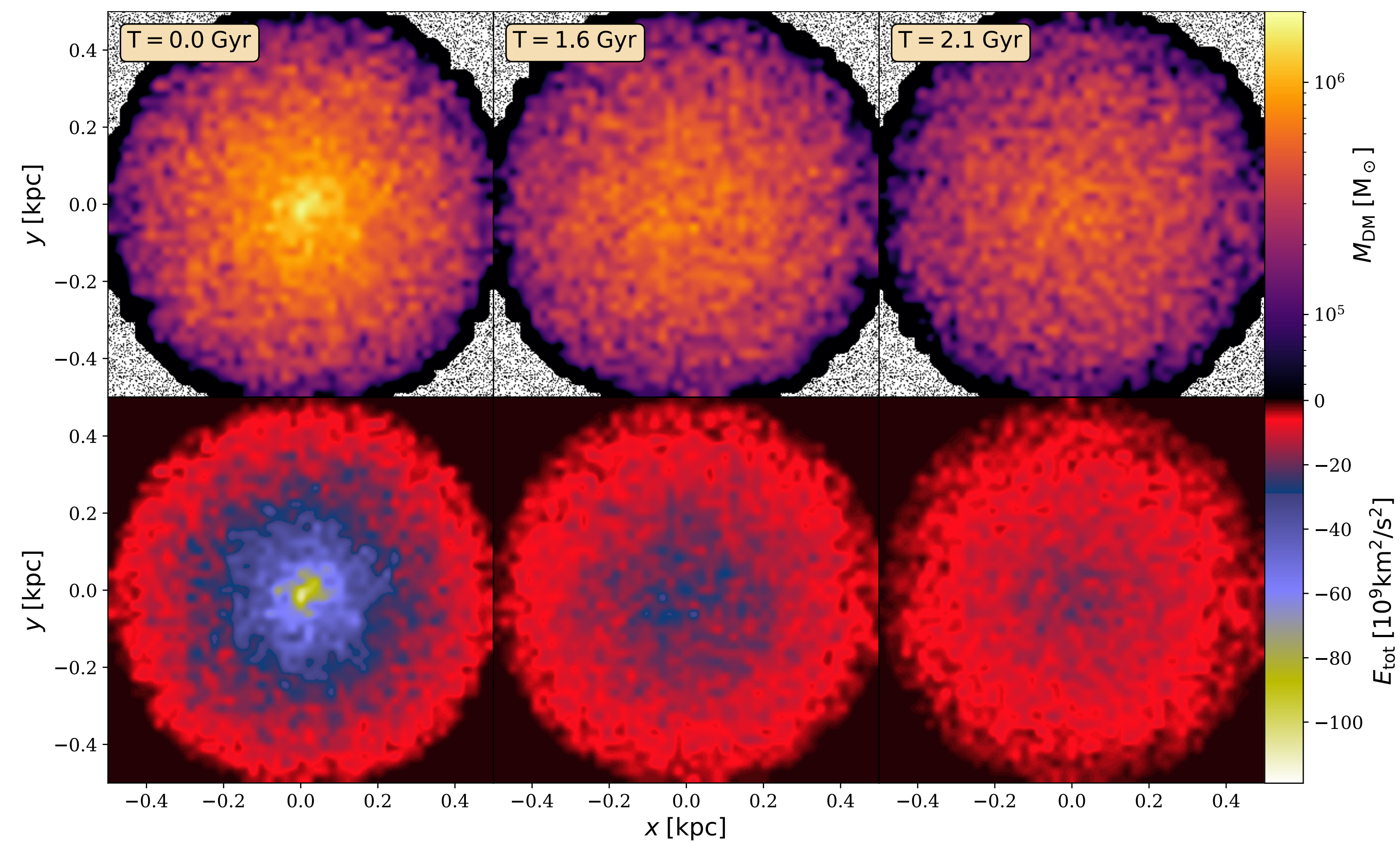


Sadoun scenario



(Boldrini et al. (2020))



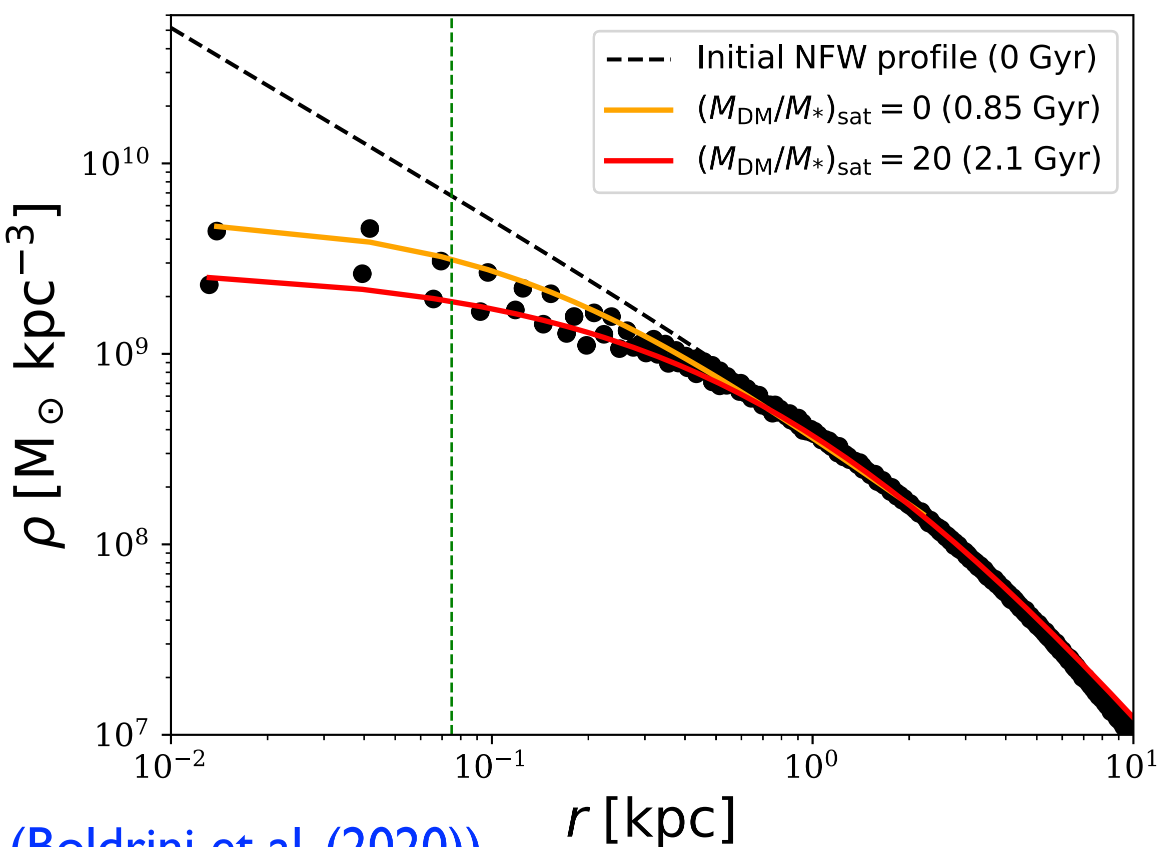


Core formation is due to **heating** and **migration** of **dark matter** in M31

Andromeda galaxy

A dark matter core in M31

Minor merger scenarios	Component	Profile	a [kpc]	r_{200} [kpc]	Mass [$10^{10} M_\odot$]	(x_0, y_0, z_0) [kpc]	(v_{x0}, v_{y0}, v_{z0}) [km.s^{-1}]
Sadoun, et al. (2014)							
$((M_{DM}/M_*)_{sat} = 20)$	DM halo	Hernquist	12.5	20	4.18	(-84.41,152.47,-97.08)	0
	Stars	Plummer	1.03	-	0.22	(-84.41,152.47,-97.08)	0
Fardal, et al. (2007)							
$((M_{DM}/M_*)_{sat} = 0)$	Stars	Plummer	1.03	-	0.22	(-34.75,19.37,-13.99)	(67.34,-26.12,13.5)



(Boldrini et al. (2020))

In both **minor merger** scenarios, the **cusp-to-core transition** takes place, which highlight the formation of a **model-independent dark matter core** in **CDM** Universe

A major merger scenario?

(Hammer et al. (2010, 2018), D'Souza & Bell (2018))