IDM- L'Aquila - July 2024

The Mochima Simulation

The impact of Baryonic physics

The DM distribution and dynamics of the host halo and subhalos of five realizations of the same Milky-Way-like galaxy.

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Colaborations:

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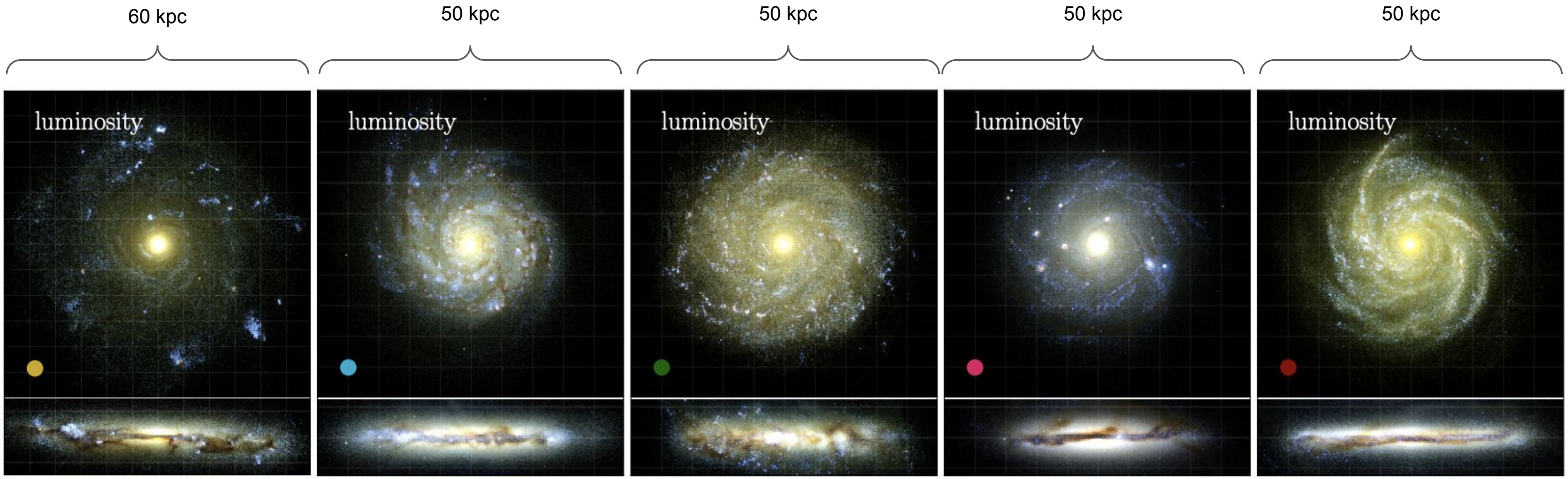


The Mochima simulations

Stellar mass ~5e10 Msun
Total mass ~1.5e12 Msun
5 simulations with baryons + 1 DMO
done using AMR code Ramses (Teyssier et al 2002)

DM is cold dark matter
(very massive ~1e4 Msun collisionless particles)

Zoom-in technique
Resolution 35 pc
In a 36 Mpc box

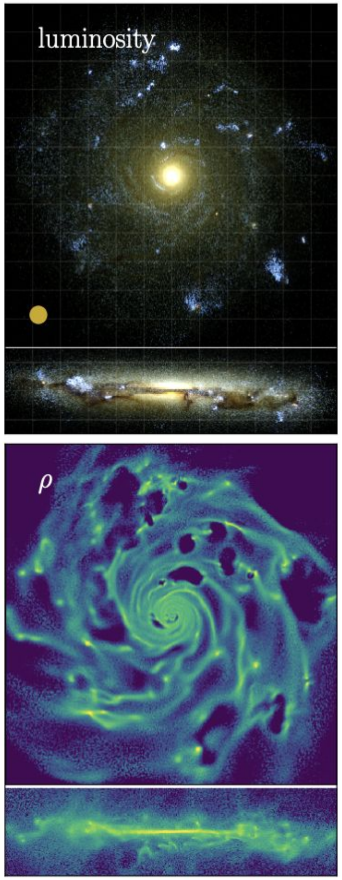
Nunez-Castineyra et al (2020)
(arxiv:2004.06008)

Same galaxy, same initial conditions, different baryonic physics (SN and SF)

The Mochima simulation

Delayed Cooling
(Dubois et al 2015)

Kennicutt-Schmidt SF



Kennicutt-Schmidt SF:

$$\dot{\rho}_\star = \epsilon_{\mathrm{ff}} \frac{\rho_g}{t_{\mathrm{ff}}} \quad for \quad \rho_g > \rho_\star$$

ϵ_{ff} is constant and calibrated to reproduce KS law.

Delayed cooling SN feedback:

Inject directly a non-thermal energy corresponding to the SN explosion

The energy cor assive stars expected to be more massive t ersal IMF.

$$\rho \frac{D\epsilon_{turb}}{Dt} = \dot{E}_{inj} - \frac{\rho \epsilon_{turb}}{t_{\mathrm{diss}}}$$

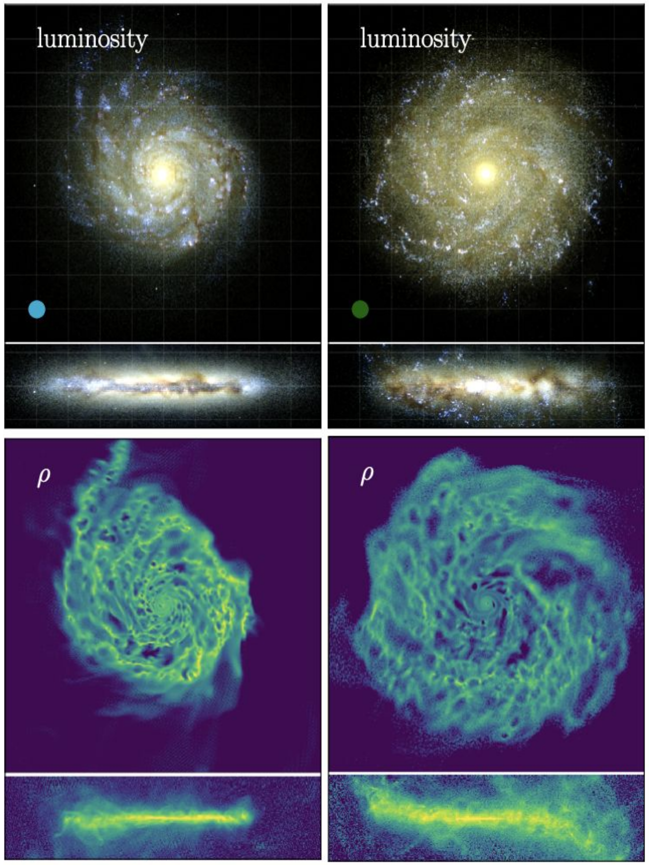
Teyssier et al. 2013, Dubois et al. 2015.

Nunez-Castineyra et al. 2020

The Mochima simulation

Delayed Cooling
(Dubois et al 2015)

Turbulent SF
(multi-ff KN Hennebelle & Chabrier 2011)



Turbulent SF:

Environment dependent efficiency: $\epsilon_{\rm ff} = \epsilon_{\rm ff}(\mathcal{M}, \alpha_{\rm vir})$

$$\epsilon_{\rm ff} = \frac{\epsilon}{2\phi_t} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

where:

$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right) \qquad \mathcal{M} = \frac{\sigma_T}{c_s}$$

$$\rho_{\rm crit} \propto \alpha_{\rm vir} \mathcal{M}^2 \qquad \alpha_{\rm vir} = \frac{\sigma_T^2}{G\rho_0 \Delta^2}$$

Hennebelle & Chabrier 2003

Delayed cooling SN feedback:

Inject directly a non-thermal energy corresponding to the SN explosion

$$\rho \frac{D\epsilon_{turb}}{Dt} = \dot{E}_{inj} - \frac{\rho \epsilon_{turb}}{t_{\rm diss}}$$

Teyssier et al. 2013, Dubois et al. 2015.

Nunez-Castineyra et al. 2020

The Mochima simulation

Mechanical FB
(Kimm et al. 2015)

Turbulent SF
(multi-ff KN Hennebelle & Chabrier 2011)

Turbulent SF:

Environment dependent efficiency: $\epsilon_{\rm ff} = \epsilon_{\rm ff}(\mathcal{M}, \alpha_{\rm vir})$

$$\epsilon_{\rm ff} = \frac{\epsilon}{2\phi_t} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

Mechanical FB:

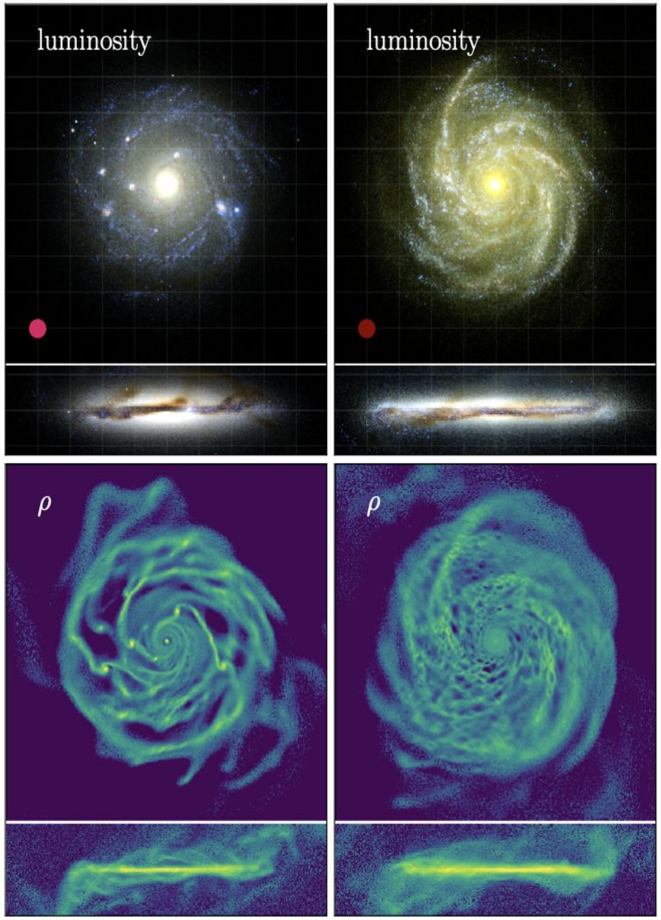
Model the two phases of the SN explosion and inject the corresponding momentum

$$p_{\rm SN,snow} \approx 3 \times 10^5\,{\rm km\,s^{-1}}\,{\rm M_\odot}\,E_{51}^{16/17} n_{\rm H}^{-2/17} Z'^{-0.14}$$

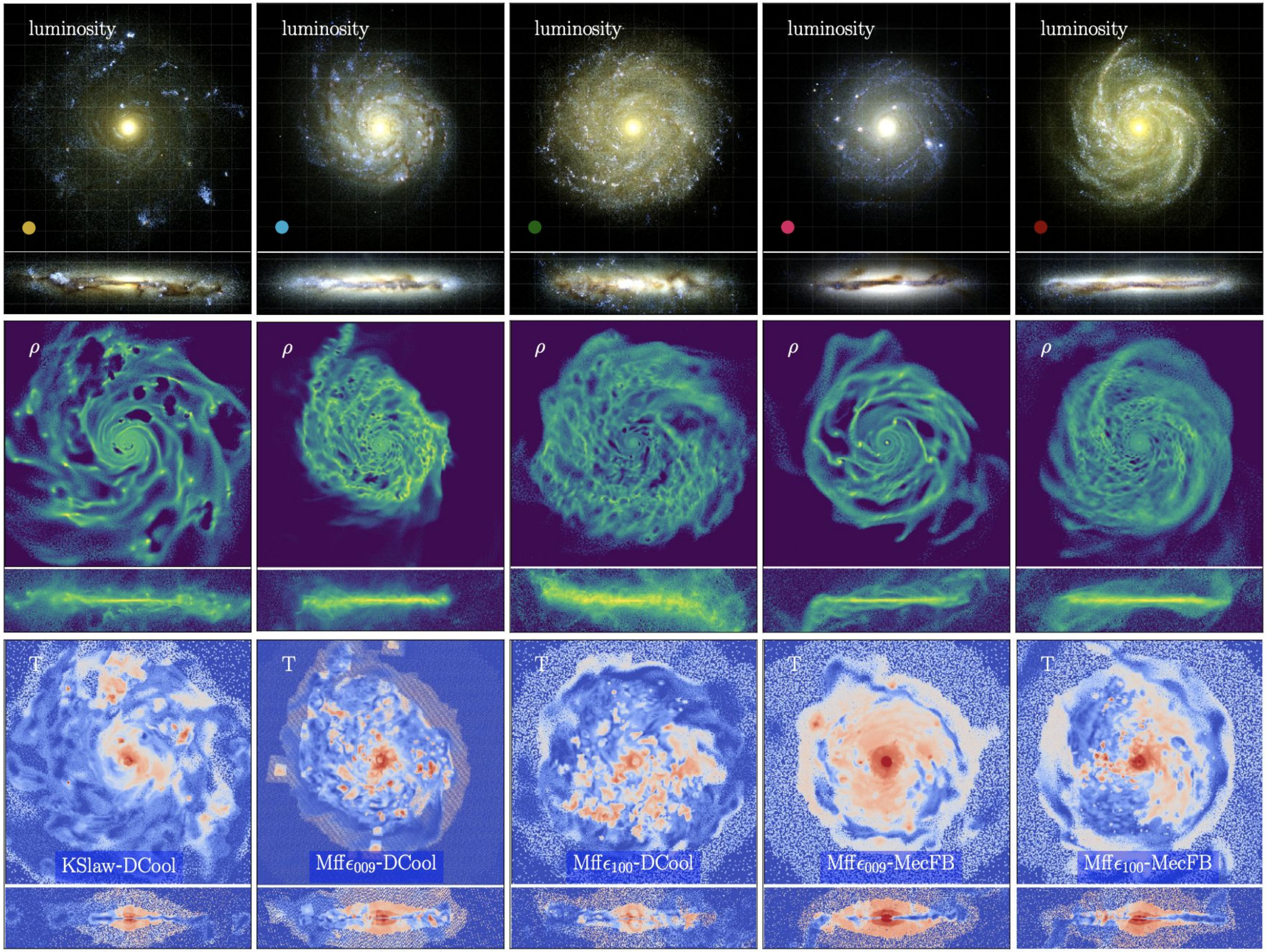
$$p_{\rm SN} = \begin{cases} p_{\rm SN,ad} = \sqrt{2\chi\, M_{\rm ej}\, f_e\, E_{\rm SN}} & (\chi < \chi_{\rm tr}) \\ p_{\rm SN,snow} & (\chi \geq \chi_{\rm tr}) \end{cases}$$

$$\chi \equiv dM_{\rm swept}/dM_{\rm ej} \qquad \chi_{\rm tr} \equiv 69.58\, E_{51}^{-2/17} n_{\rm H}^{-4/17}\, Z'^{-0.28}$$

Kimm & Cen 2014. Kimms et al. 2015.

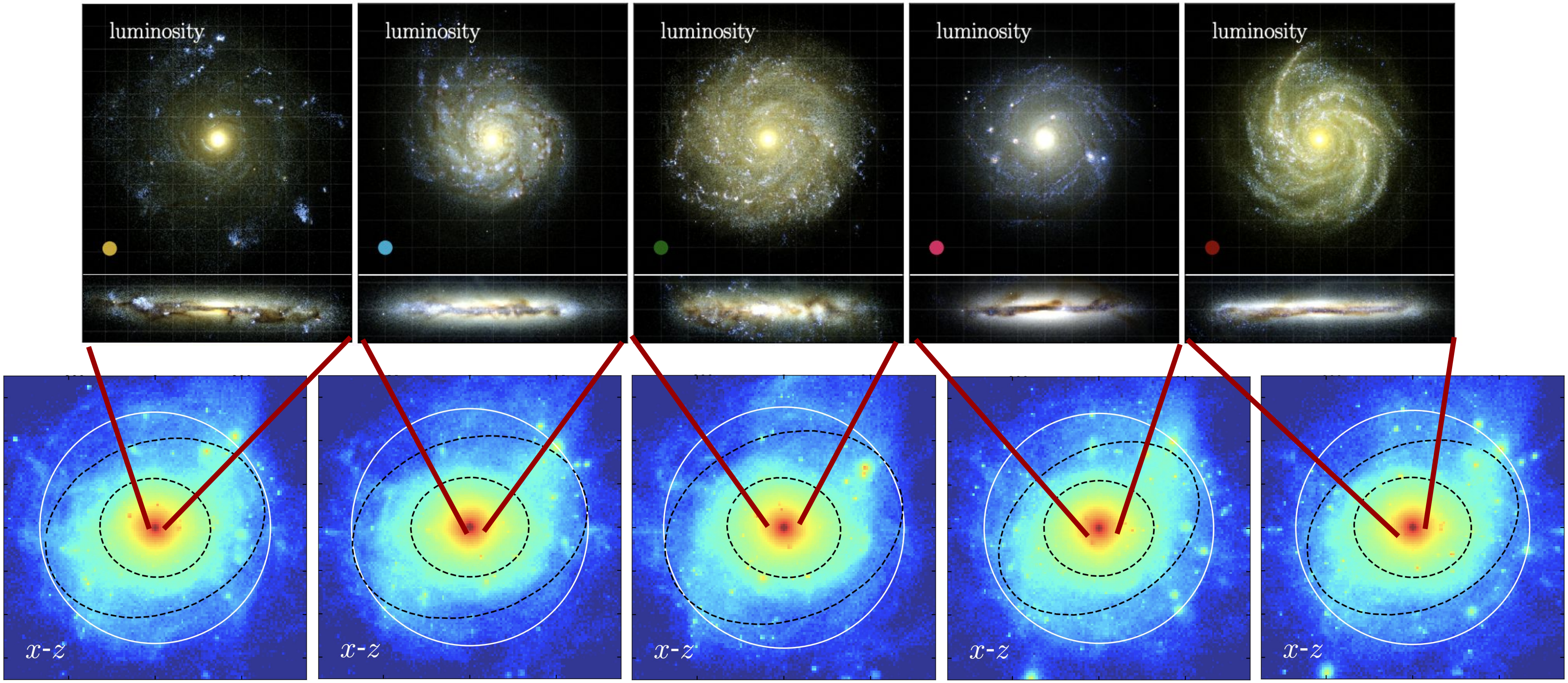


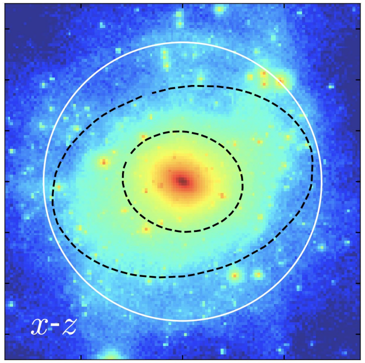
Nunez-Castineyra et al. 2020



Nunez-Castineyra et al
(arxiv:2004.06008)

Same galaxy, same initial conditions, different baryonic physics (SN and SF)





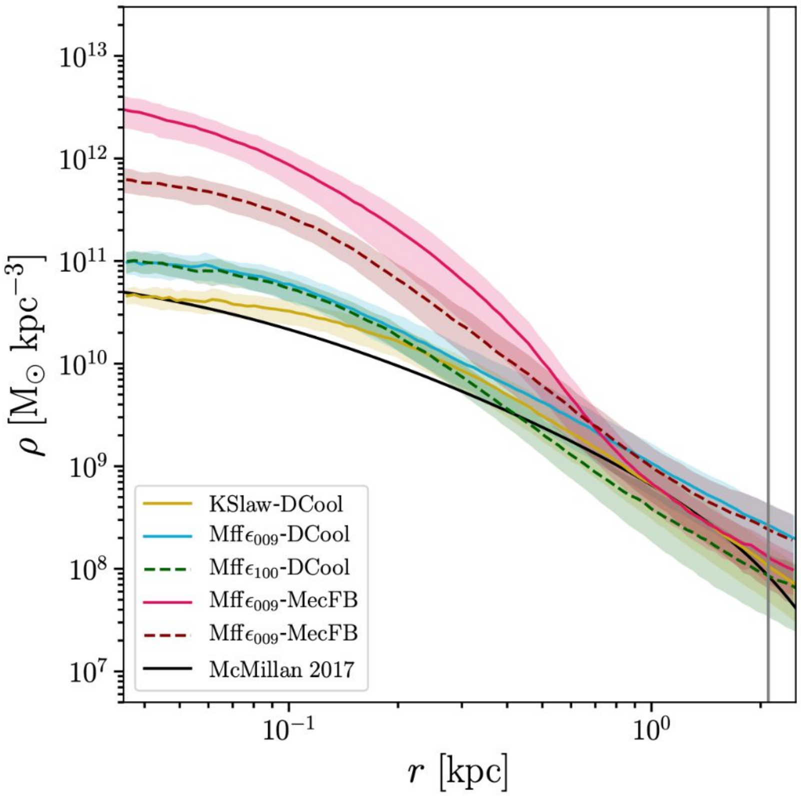
Baryonic Analysis and comparisons
Nunez-Castineyra et al 2020
(arxiv:2004.06008)

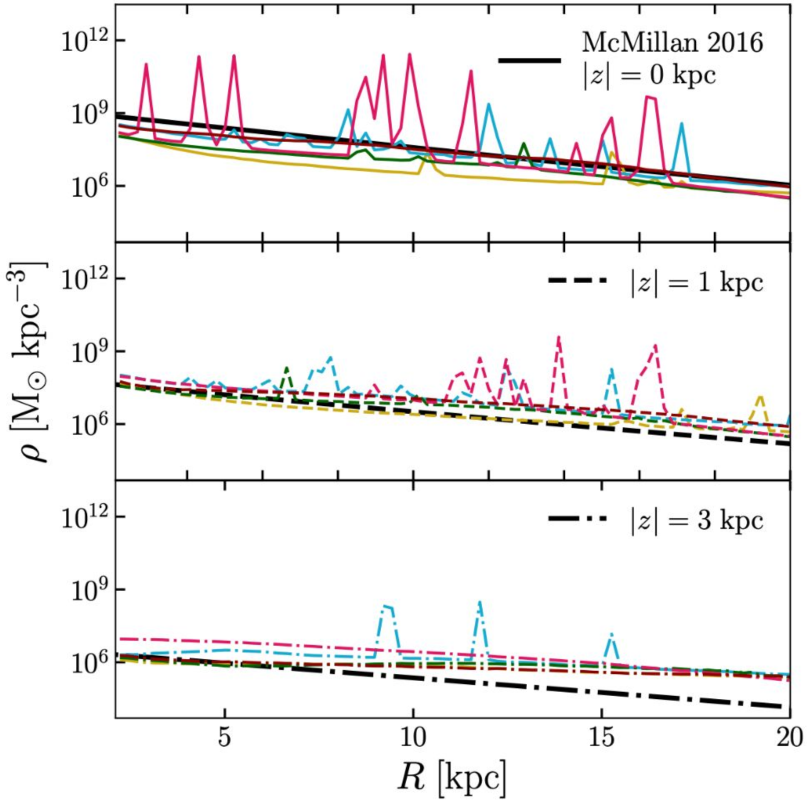
Dark Matter
Main DM halo
Nunez-Castineyra et al 2023
(arxiv:2301.06189)

Satellites subhalos
Nunez-Castineyra in prep
(soon :))

The Mochima simulations

How milky way like is a milky-way-like?

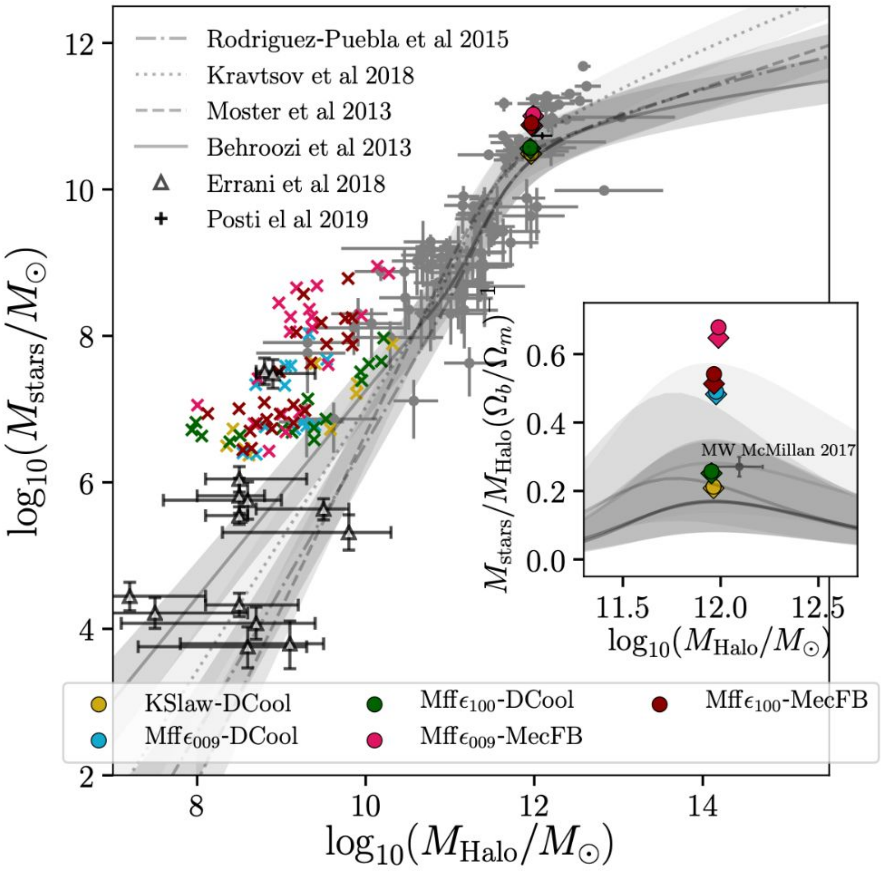


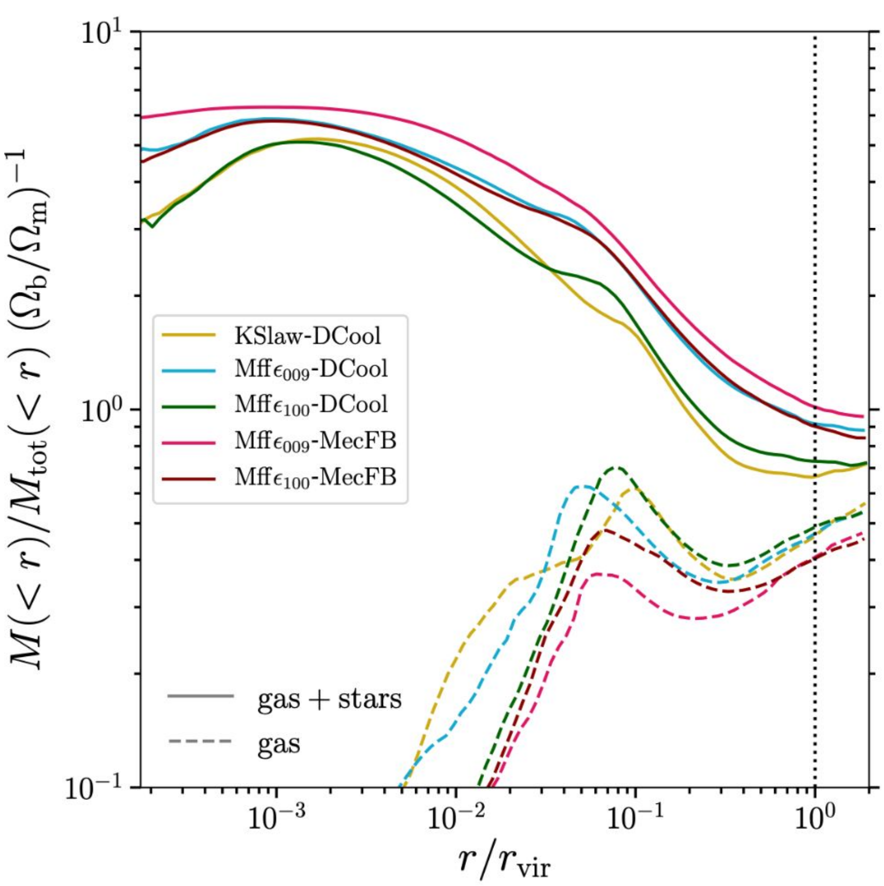


From comparisons with the stellar density profiles of the **MW** we know that these simulations have massive spherical central bulges, and slightly thicker stellar disc far from the center.

Nunez-Castineyra et al (2020) (arxiv:2004.06008)

Dark matter content

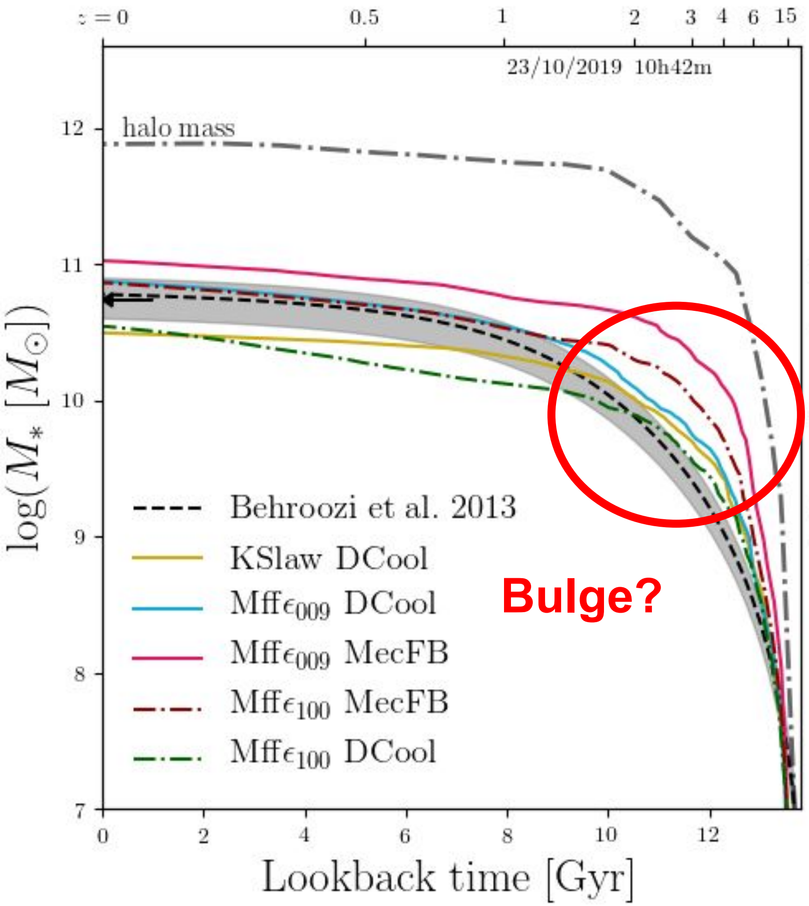




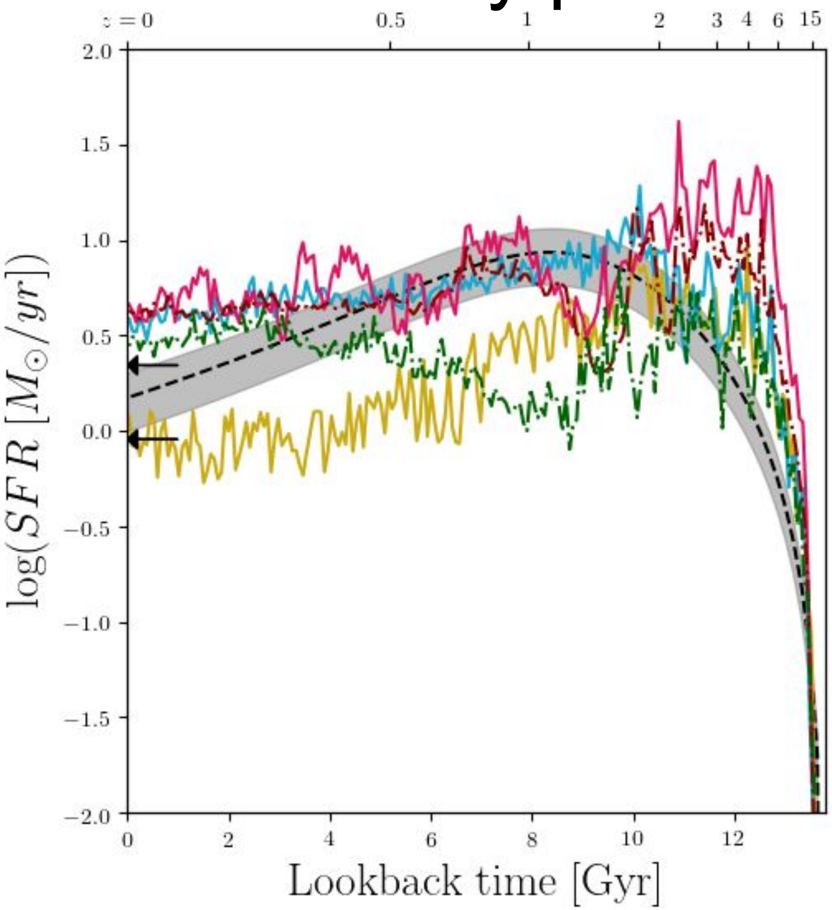
The Mochima suite is in good agreement with SHMR and the cosmological matter content

Nunez-Castineyra et al (2020) (arxiv:2004.06008)

Stellar mass



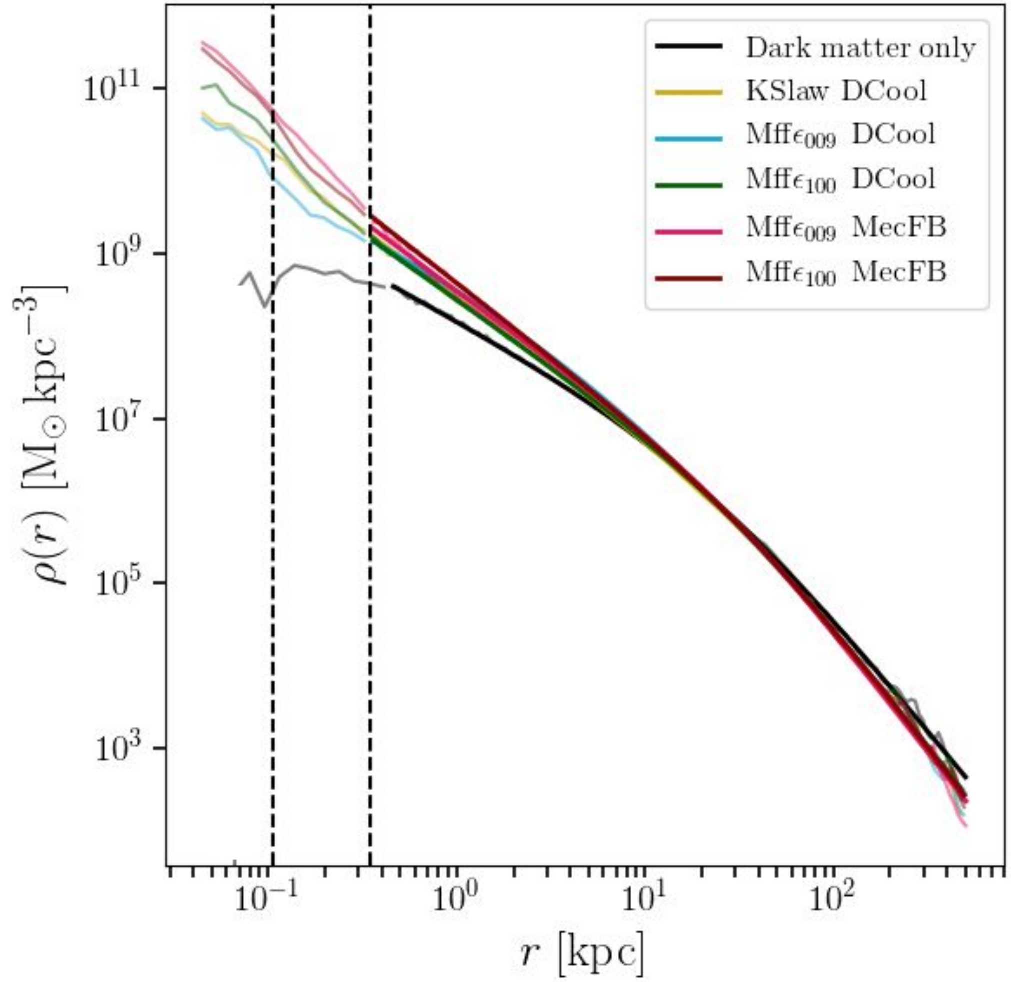
Stellar bulge density profile

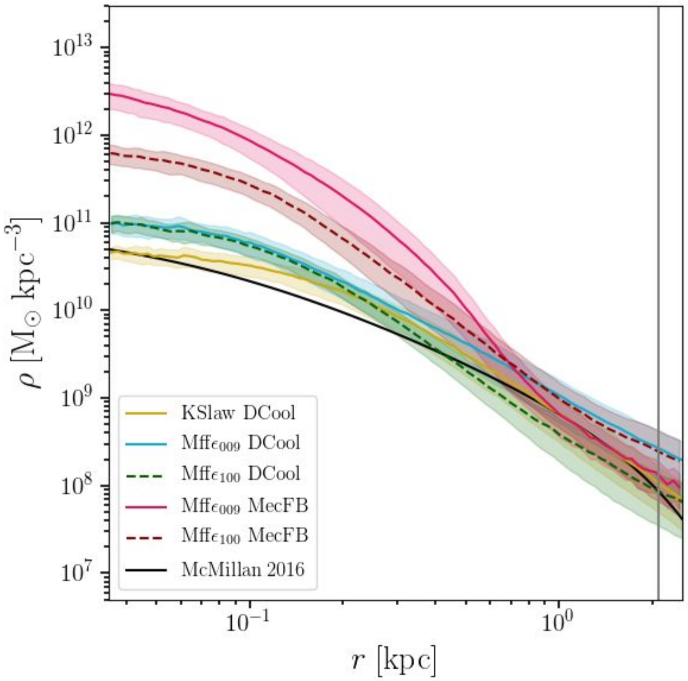


The bulge is composed mainly of old stars formed before z= 2

Nunez-Castineyra et al (2020) (arxiv:2004.06008)

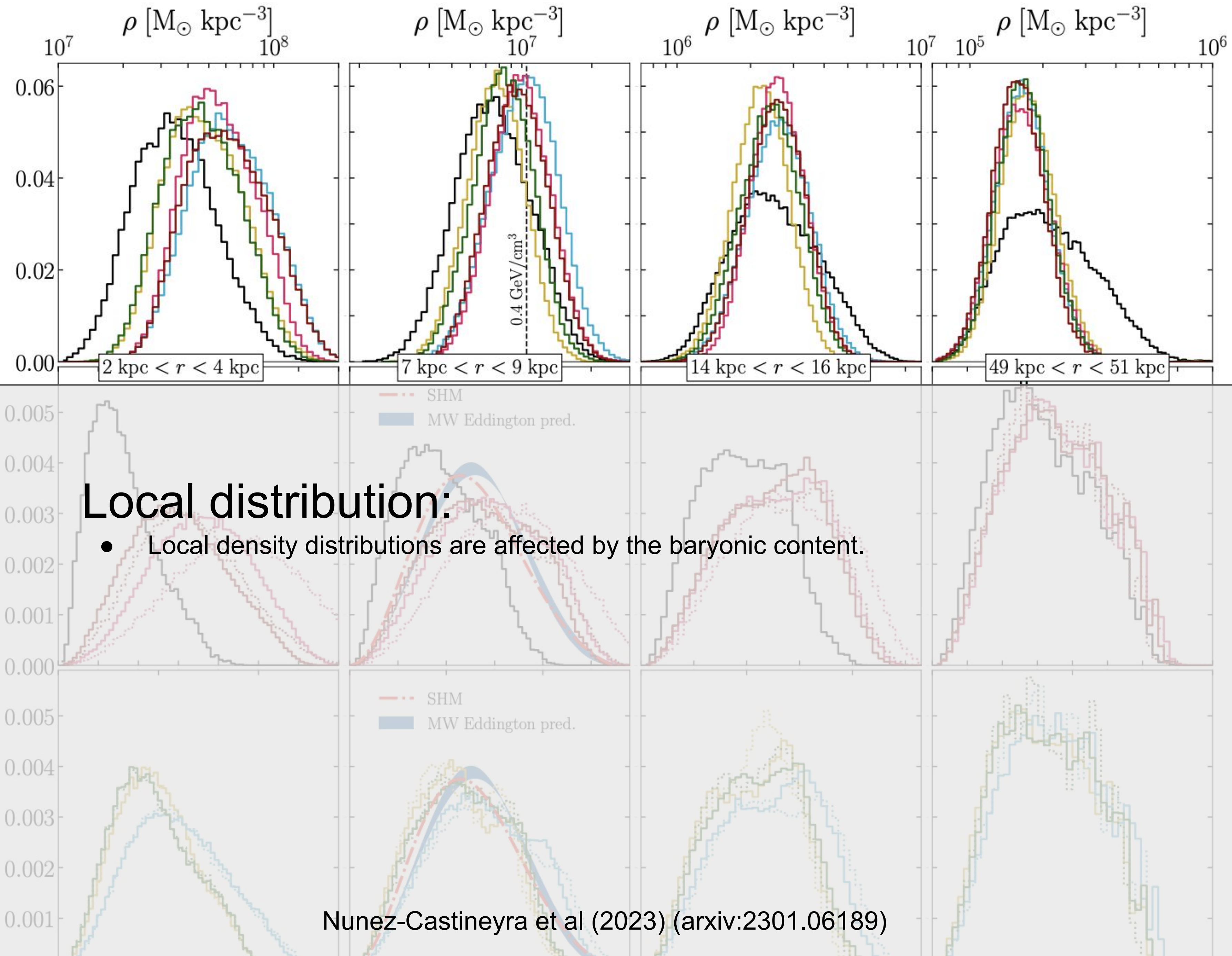
Dark matter distribution





The DM halos are very cuspy. They suffer adiabatic contraction which intensities are related to the bulge size.

Nunez-Castineyra et al (2023) (arxiv:2301.06189)



Local distribution:

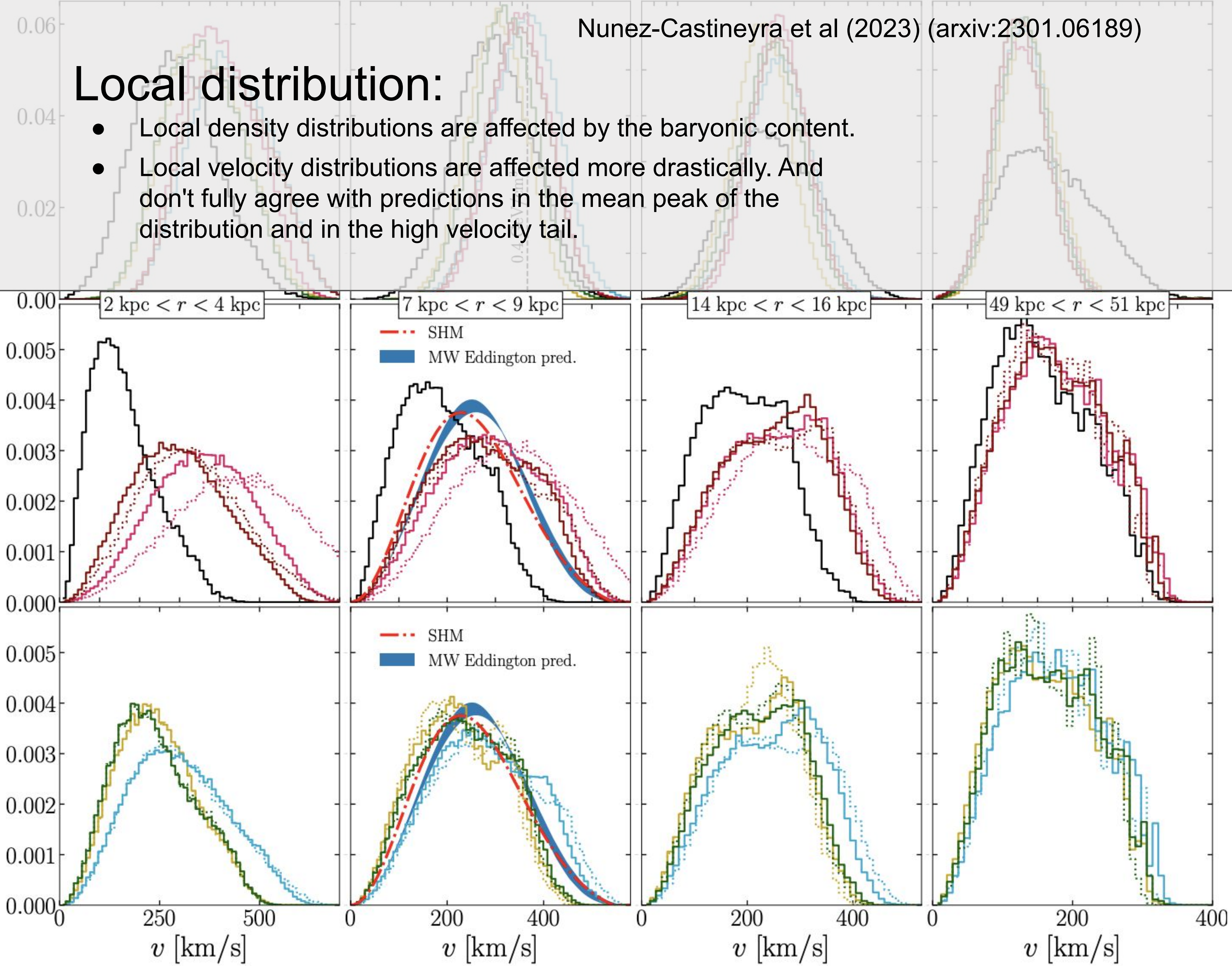
- Local density distributions are affected by the baryonic content.

Nunez-Castineyra et al (2023) (arxiv:2301.06189)

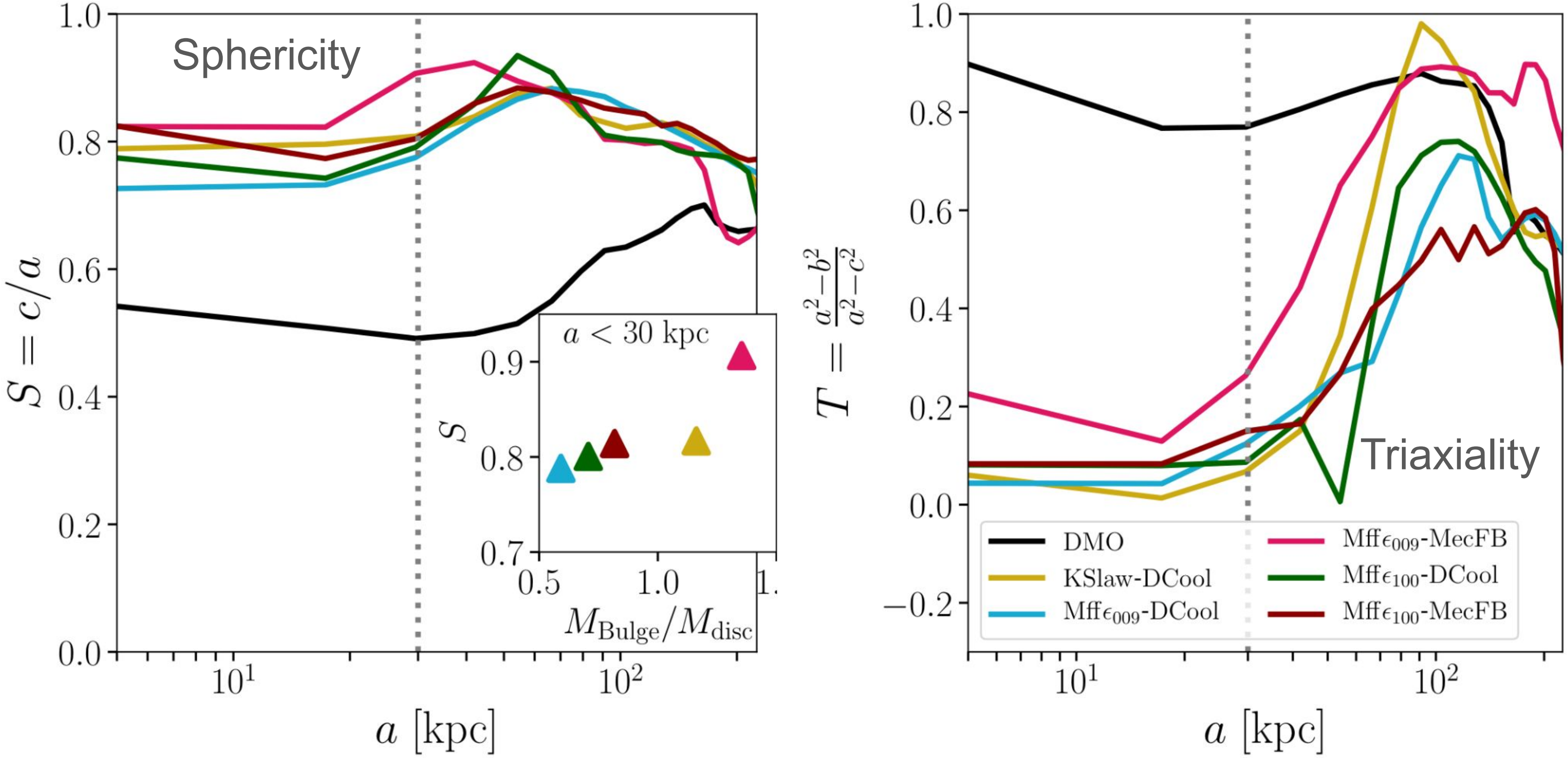
Nunez-Castineyra et al (2023) (arxiv:2301.06189)

Local distribution:

- Local density distributions are affected by the baryonic content.
- Local velocity distributions are affected more drastically. And don't fully agree with predictions in the mean peak of the distribution and in the high velocity tail.



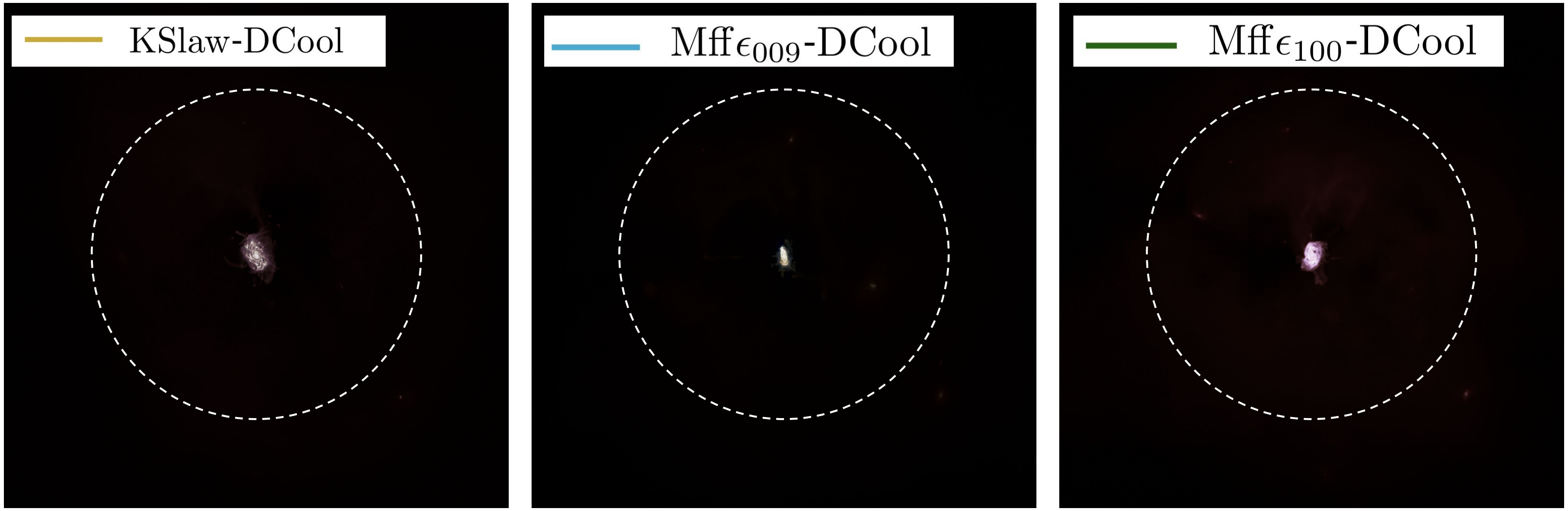
Shape of the DM halo



The presence of subhalos increases the triaxial shape of the outer halo.
Different baryonic physics results in different subhalo populations.

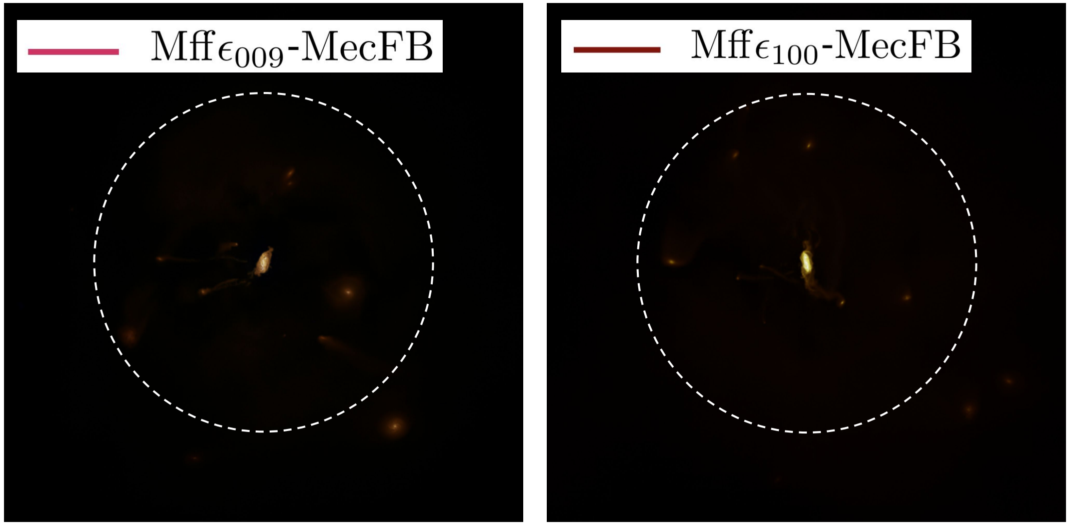
Nunez-Castineyra et al (2023) (arxiv:2301.06189)

Baryons



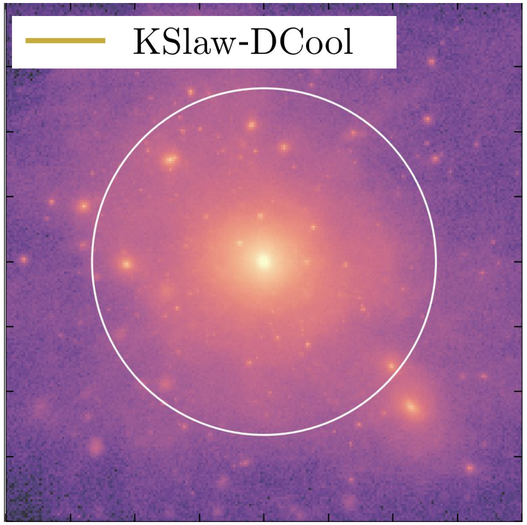
Satellites are impacted by subgrid physics

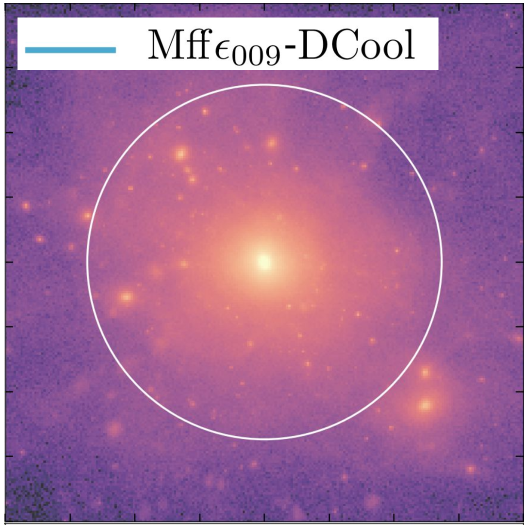
- Central harassment
- Survival ability

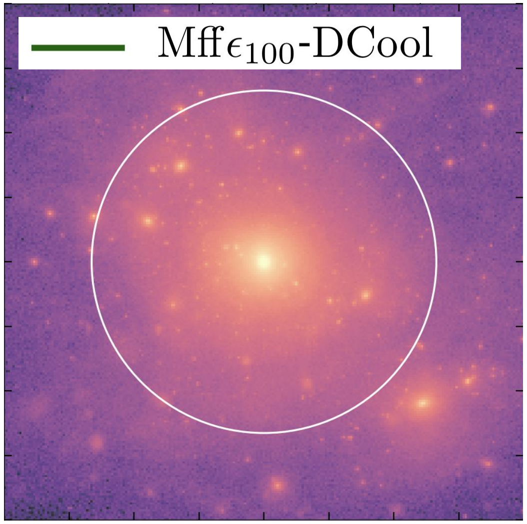


Nunez-Castineyra et al (in prep)

Full dark matter halo







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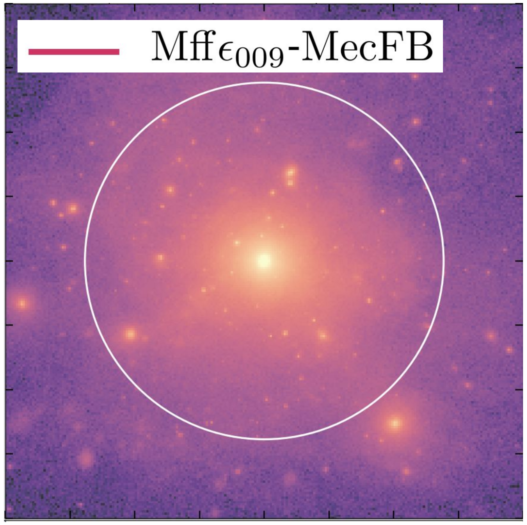
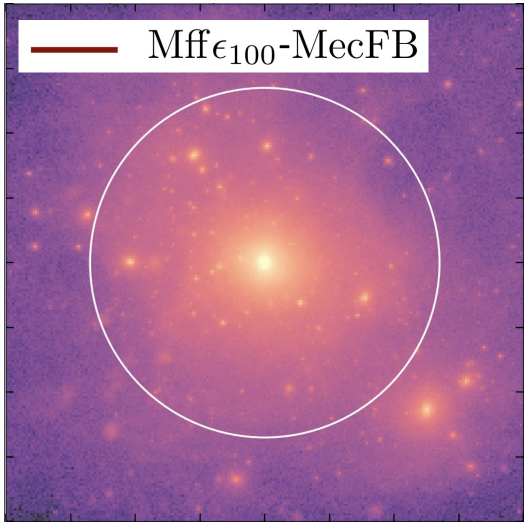
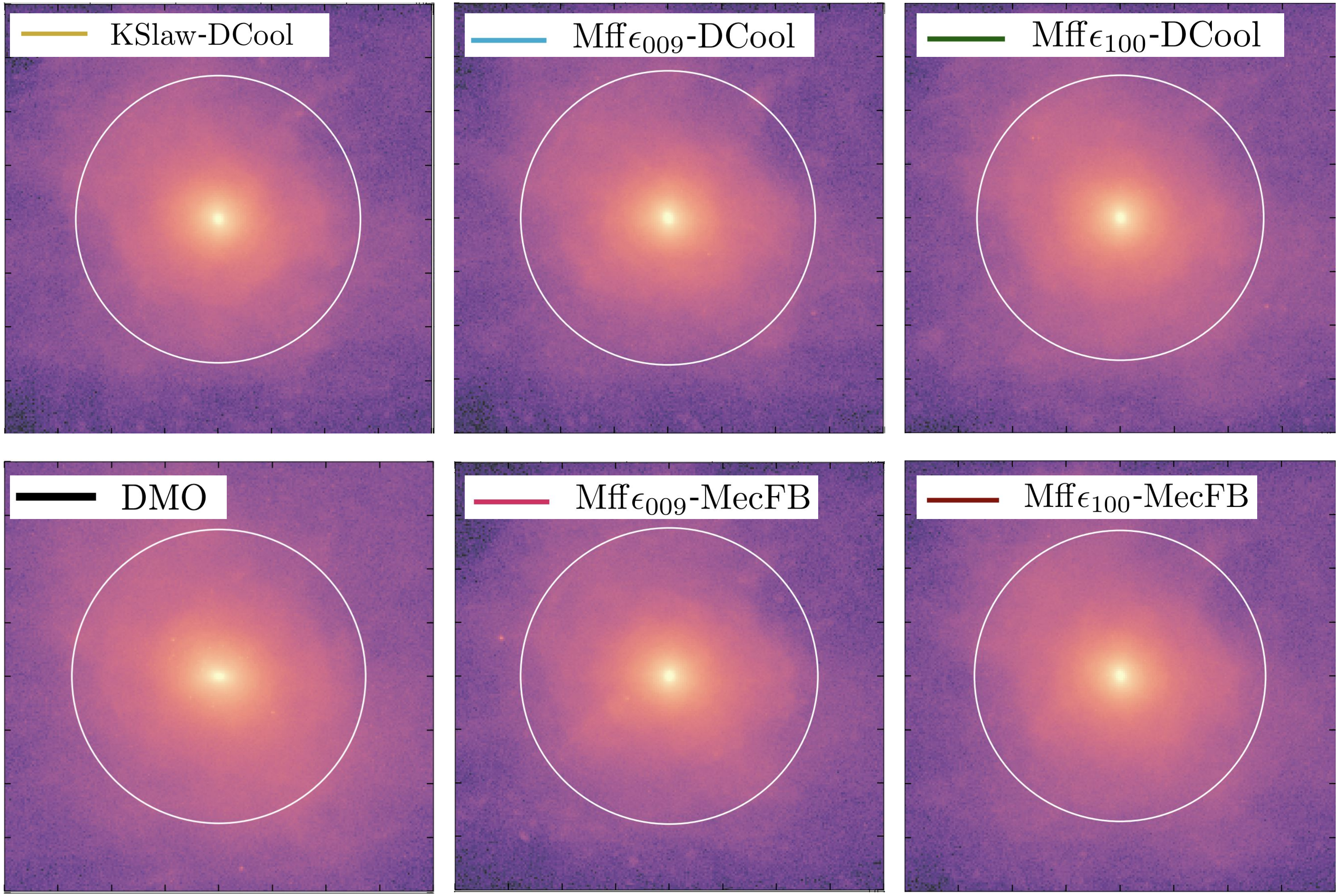


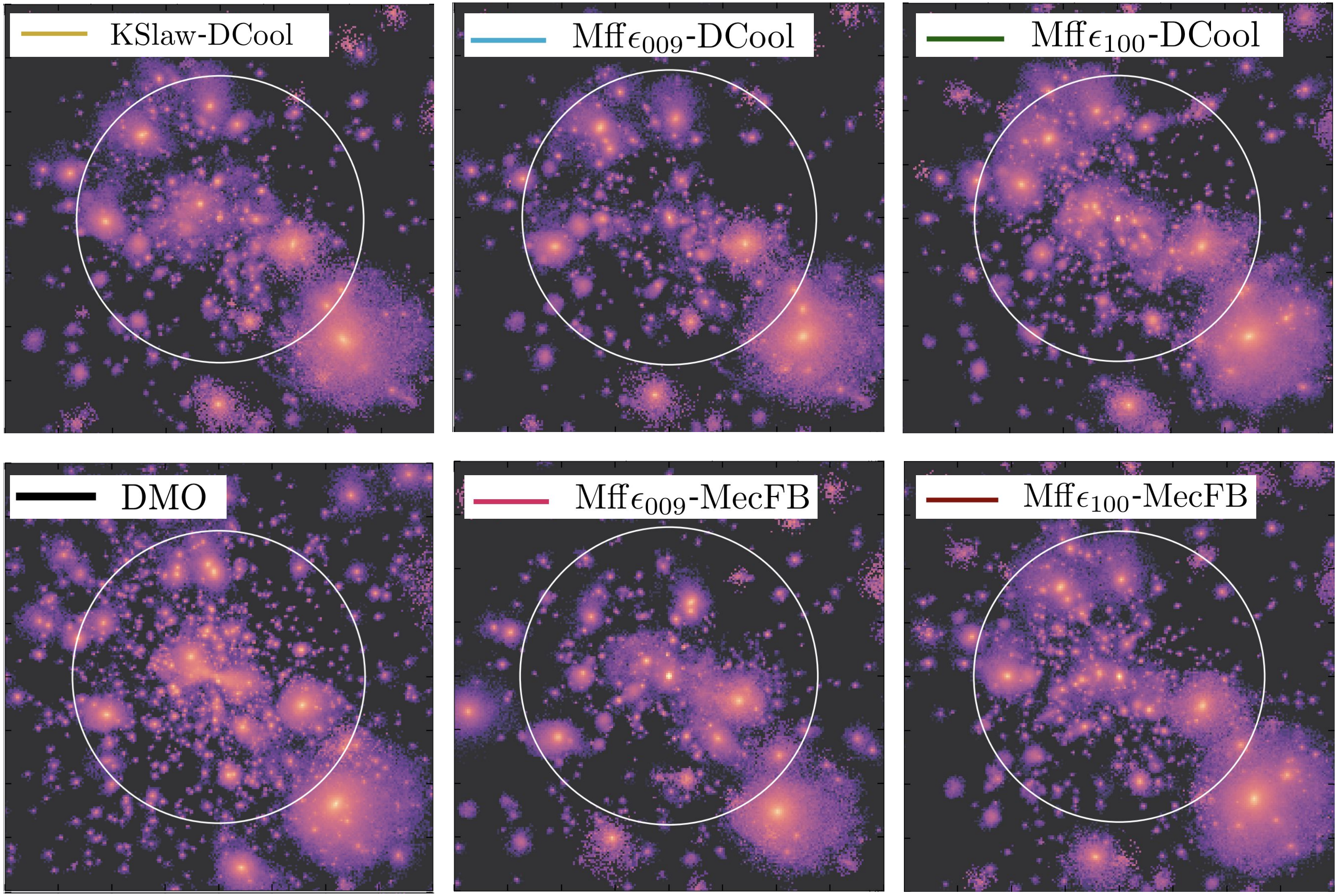


Nunez-Castineyra et al (in prep)

Smooth component of the dark matter halo

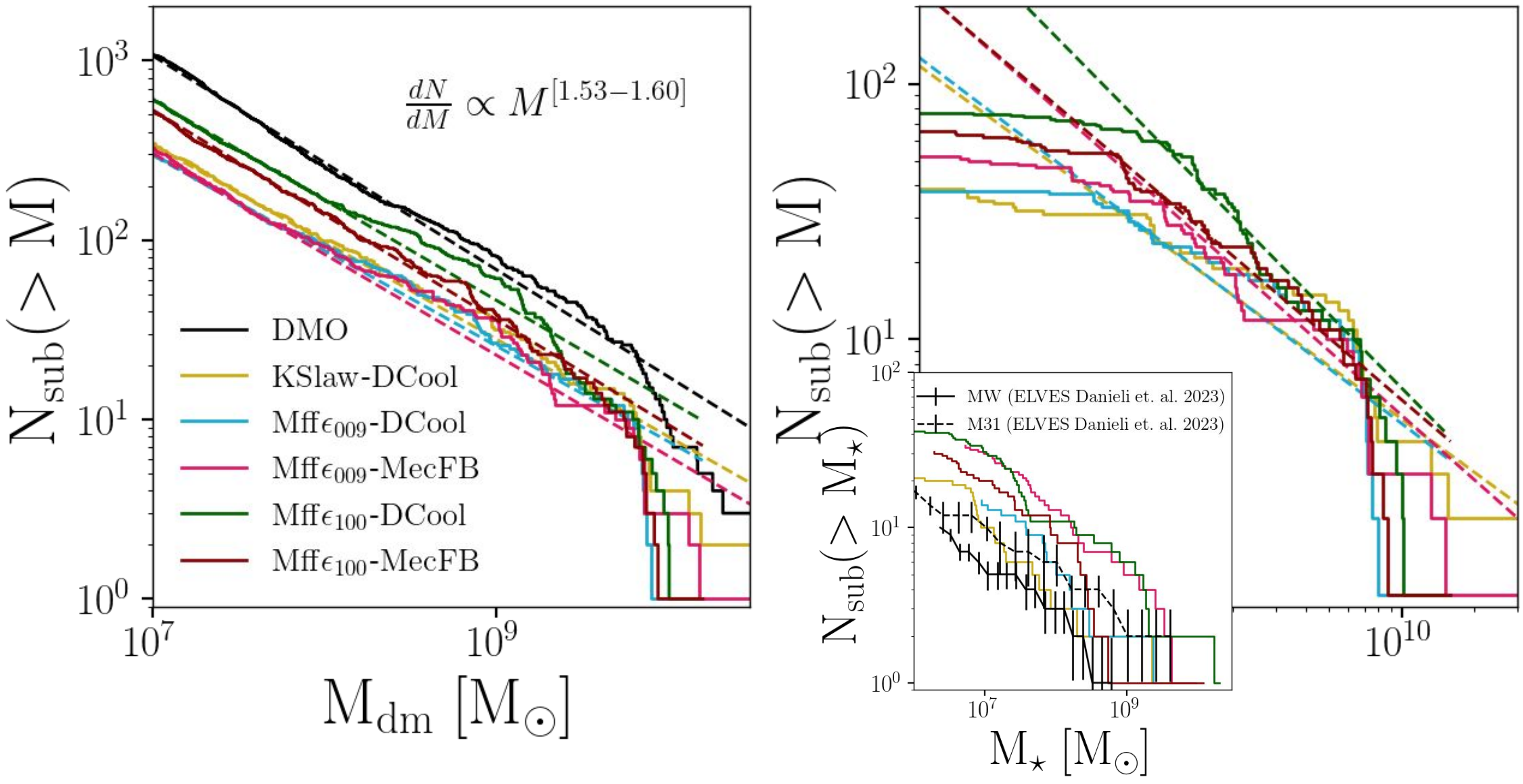


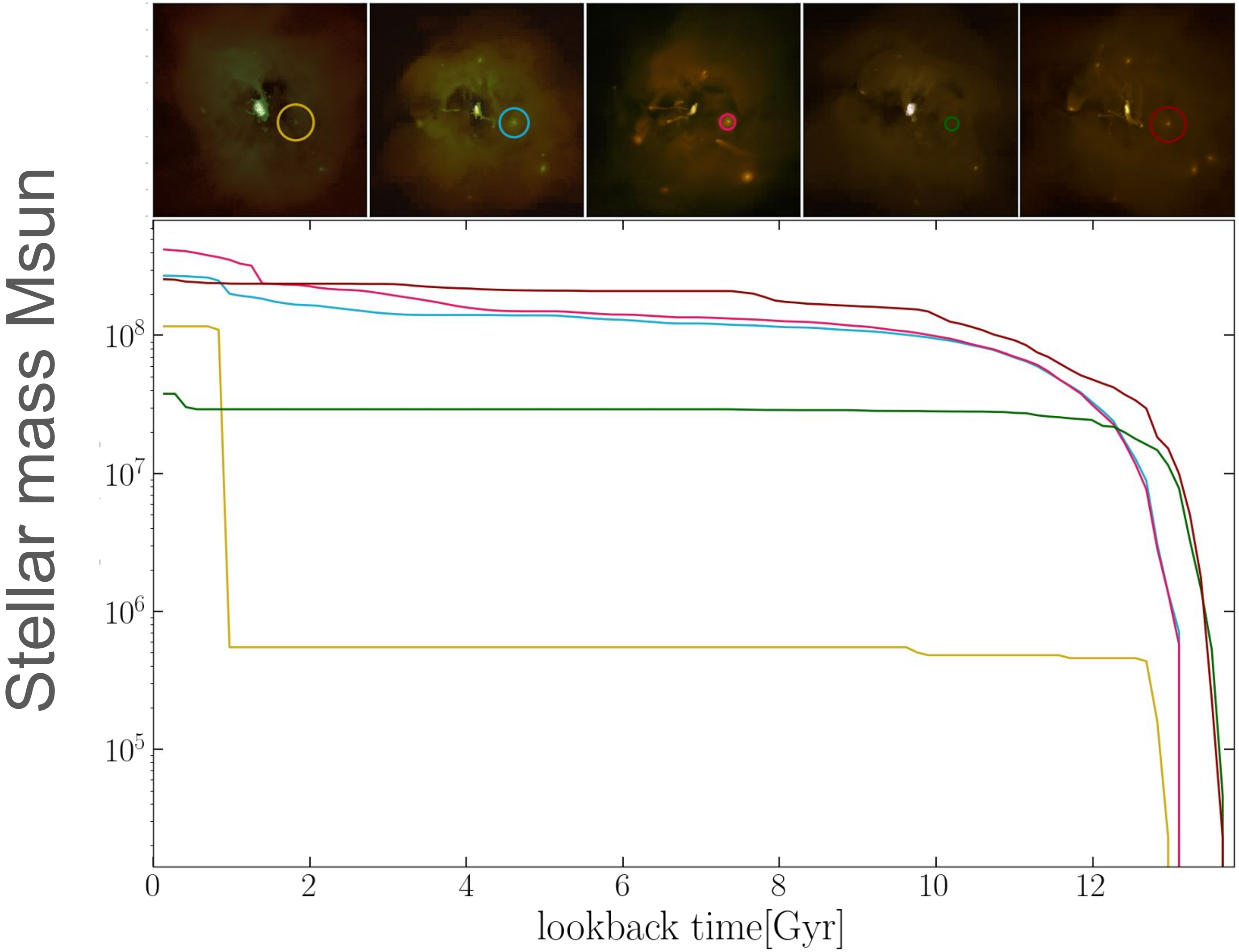
Clumpy component of the dark matter halo



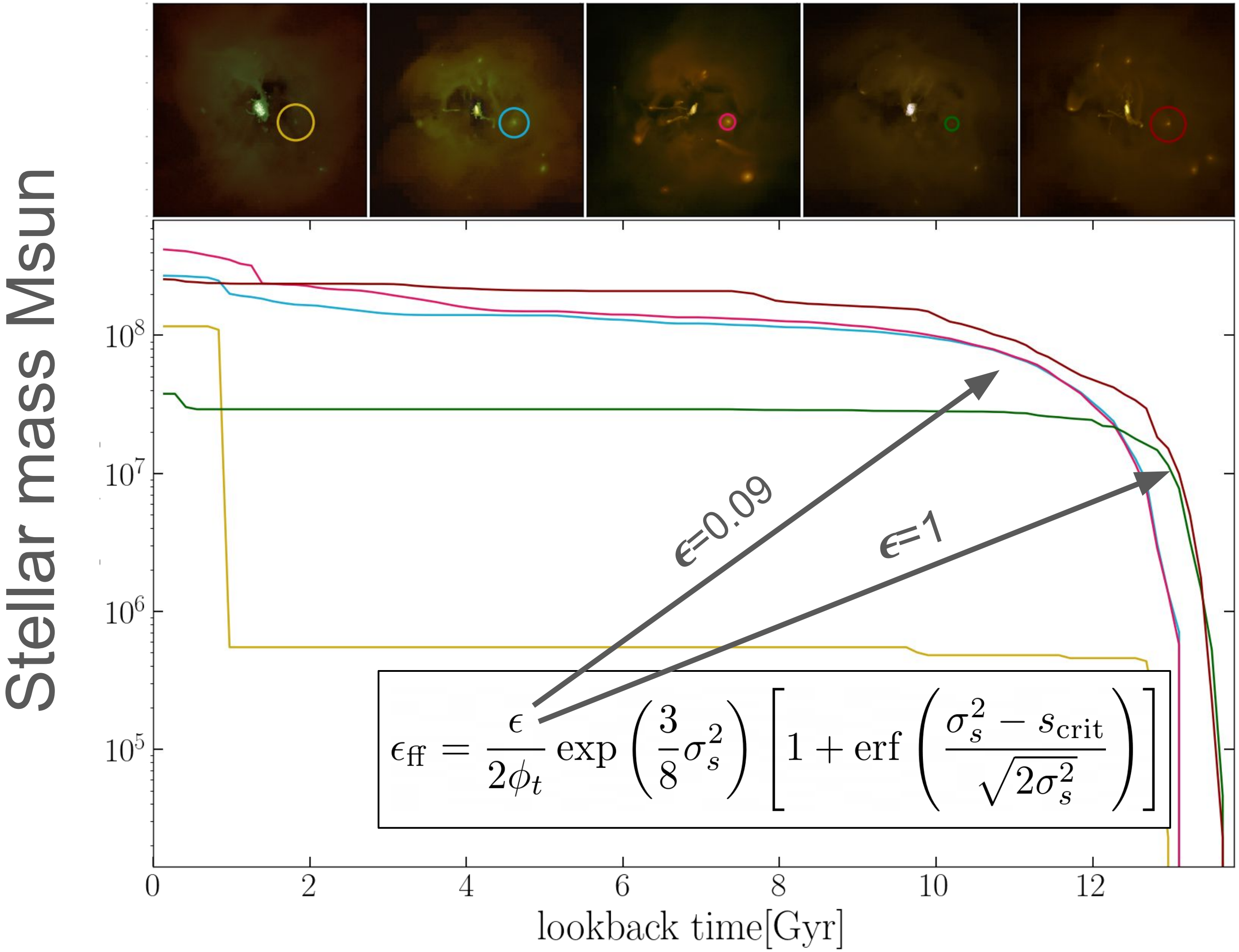
Clumpy component of the dark matter halo

Mass spectrum





Lets take on comon satellite as an example



$$\epsilon_{\rm ff} = \frac{\epsilon}{2\phi_t} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + {\rm erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

Lets take on comon satellite as an example:
Star formation is trigger earlier in the 2 cases with ϵ=1

Summary

- Baryonic physics (SF and SN feedback) will impact the DM distribution
  - Density distribution:
    early SF excesses can induce DM cusps
  - Velocity distribution:
    higher stellar masses → faster vdf
- Subhalos are also impacted
  - Mass spectrum
  - Inner density profiles
  - More to come

Gamma ray and neutrino searches

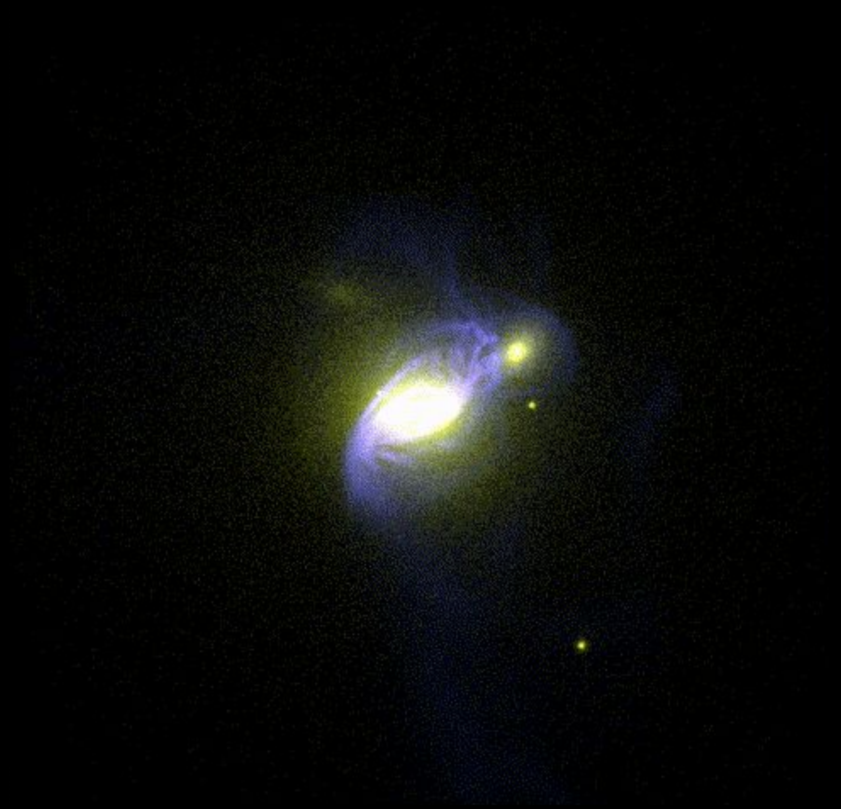
Direct and indirect searches, and Neutrinos from the Sun

Gamma ray and neutrino searches from satellites

Next steps:
AGN feedback (early SF), cosmic rays feedback and others (H2 feedback, IMF non universalities)
Other DM models

We needd to be careful with what we predict from simulations

Thanks

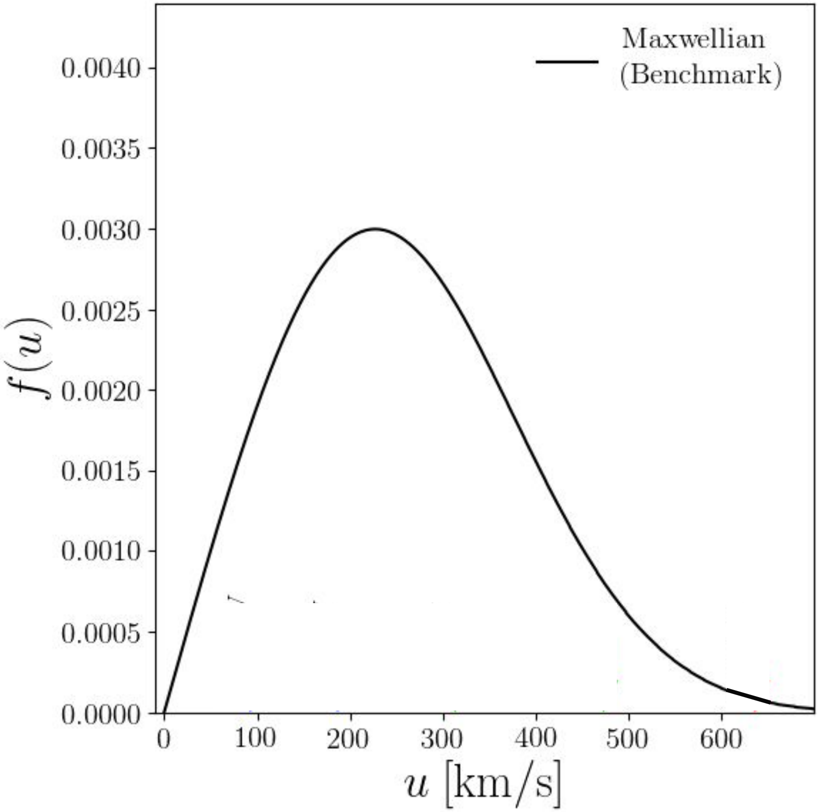


Does this matters for DM detection?

Local dark matter velocity distribution

- The local DM velocity distribution is highly relevant for local dark matter searches depending on the DM candidate
- For typical WIMP searches:
  - the **low-velocity tail** is important for neutrino detection through solar capture
  - The **high-velocity tail** is more relevant for direct detection experiments and directional direct detection experiments.

Therefore, it is necessary to know the local velocity distribution.



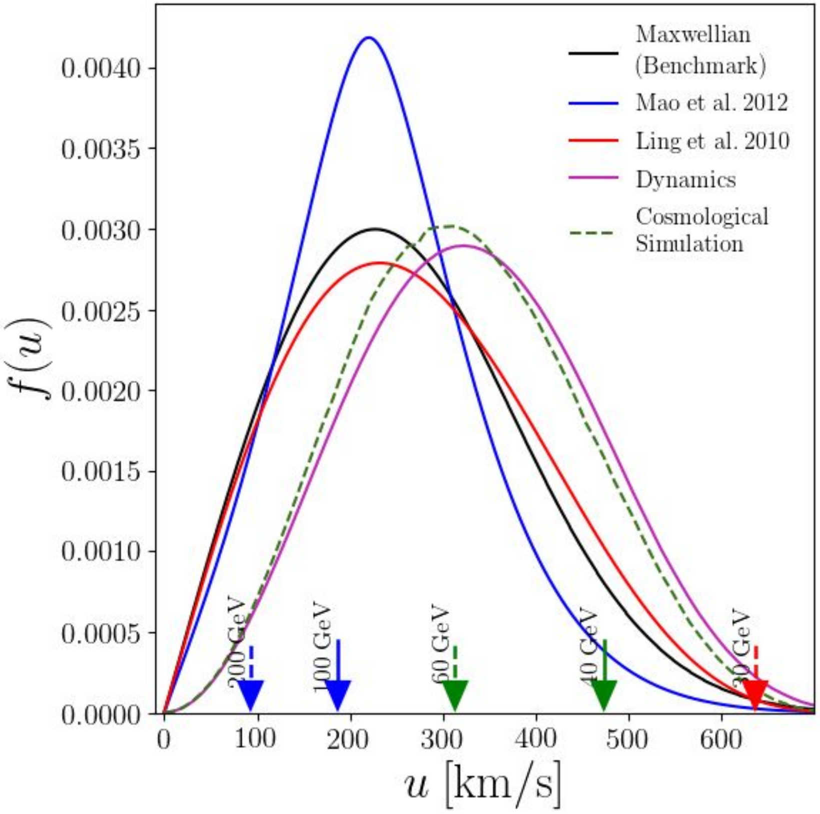
Local dark matter velocity distribution

You either assume a halo:

- SHM: Isothermal DM halo.

Or fit a halo:

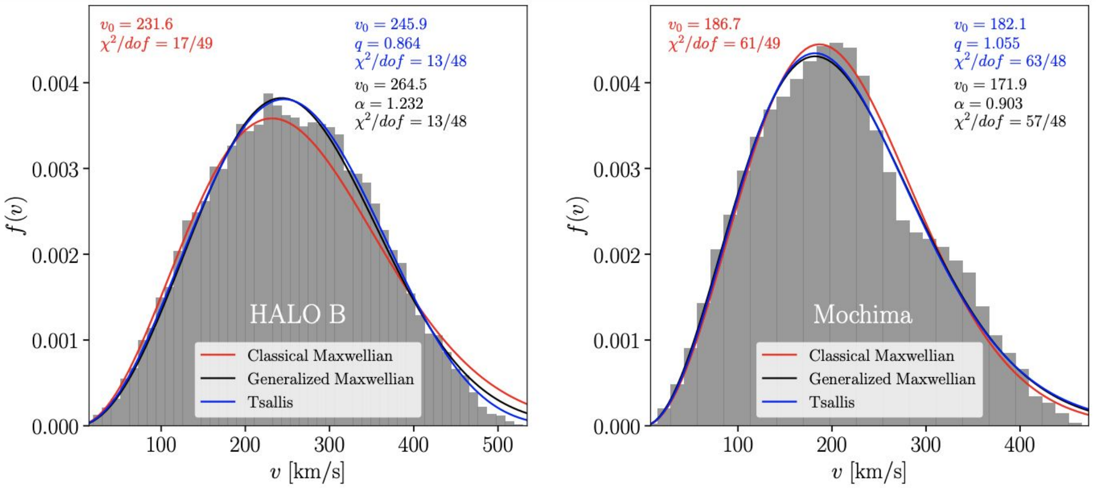
- DM velocity distribution. (Ling 2010, Mao 2012)
- Gravitational potential : Eddington inversion (Lacroix et al 2012, Lacroix+ANC 2020)



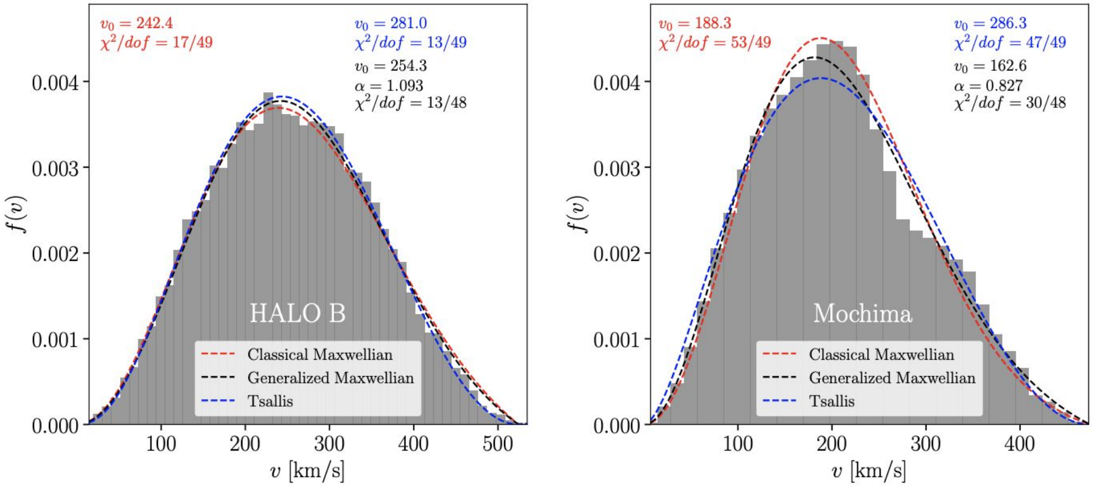
Local dark matter velocity distribution

Typical fitting function overpredict the high velocity tail.

This can be corrected by considering the escape velocity at the solar distance from the galactic center.



(a) Halo B (b) Mochima



(c) Halo B with v_{esc} (d) Mochima with v_{esc}

Nunez-Castineyra et al (2019) (arxiv:1906.11674)

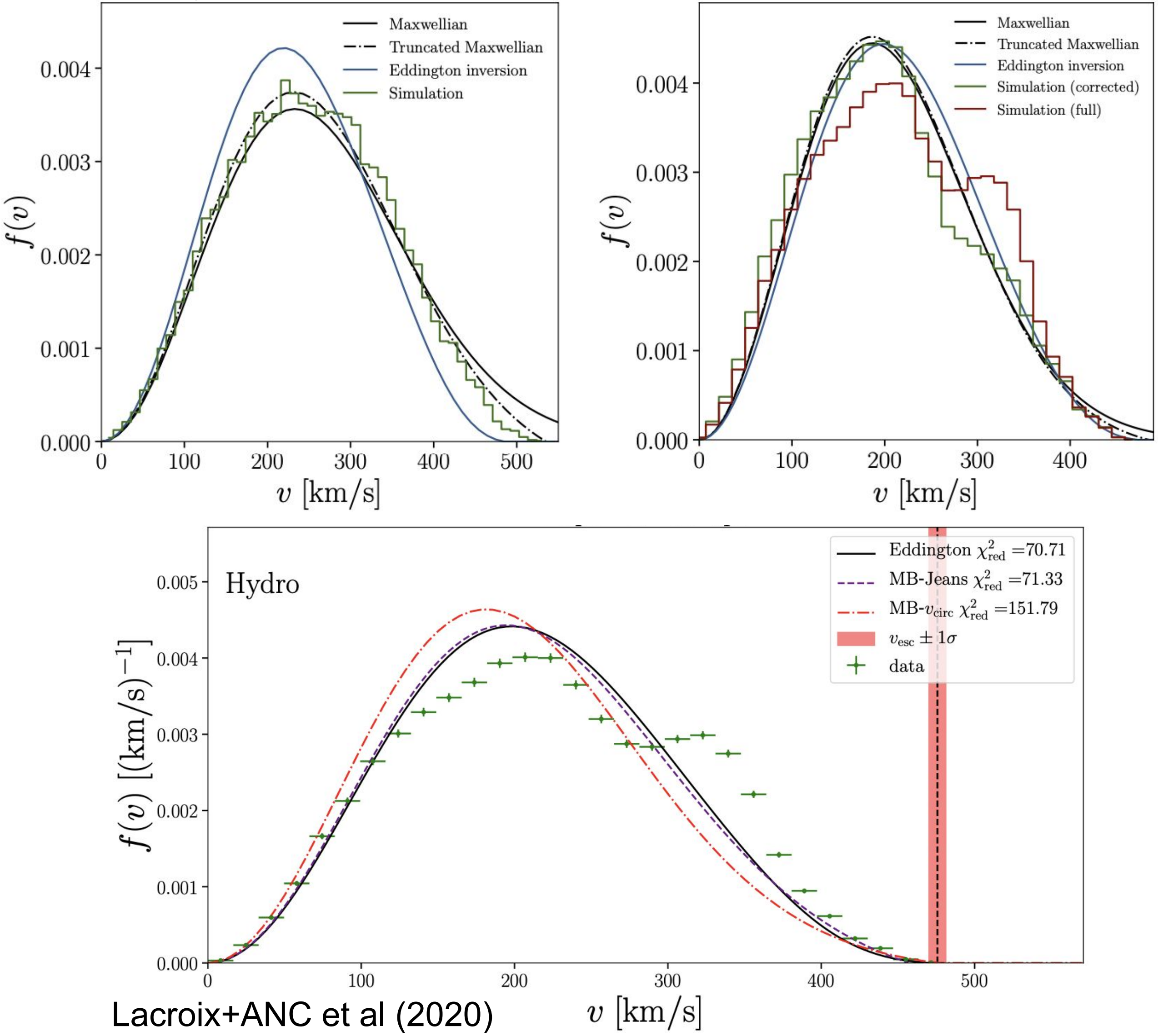
Local dark matter velocity distribution

Typical fitting function overpredict the high velocity tail.

This can be corrected by considering the escape velocity at the solar distance from the galactic center.

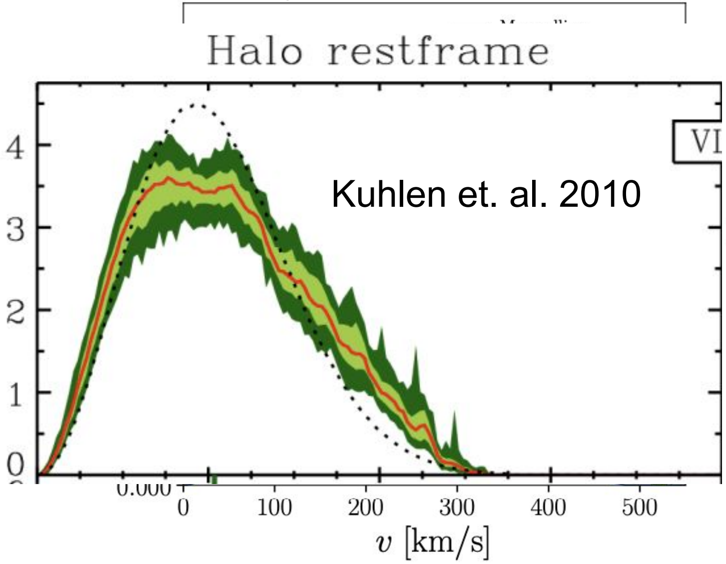
The gravitational potential can also be assumed and recover the phase space distribution.

But the velocity distribution in simulations is not always smooth.

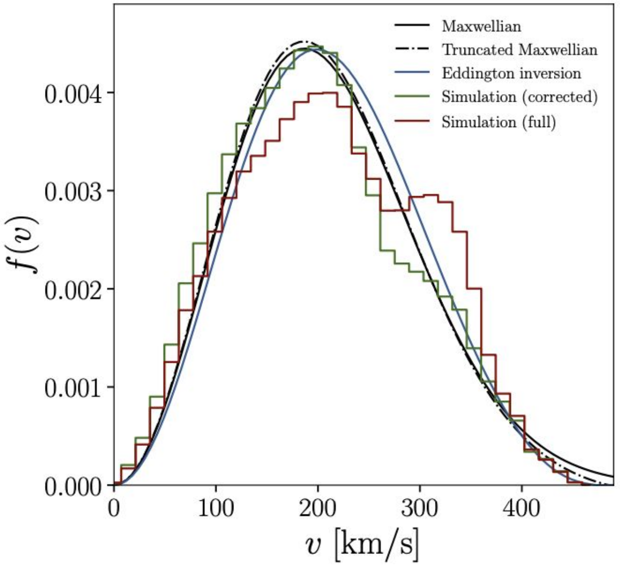


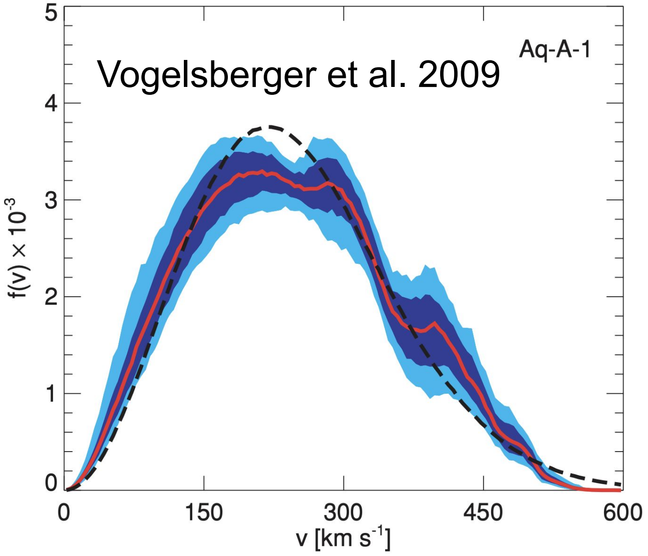
Lacroix+ANC et al (2020)
(arxiv:2005.03955)

Local dark matter velocity distribution



Kuhlen et. al. 2010





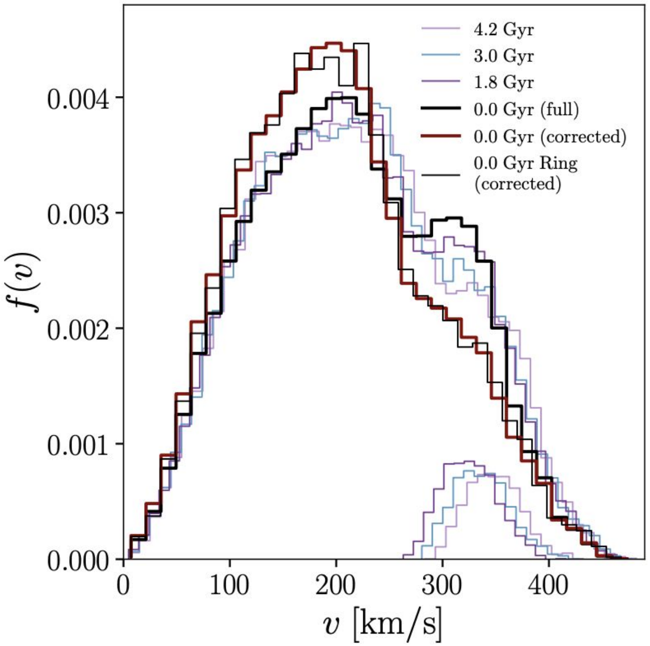
Vogelsberger et al. 2009

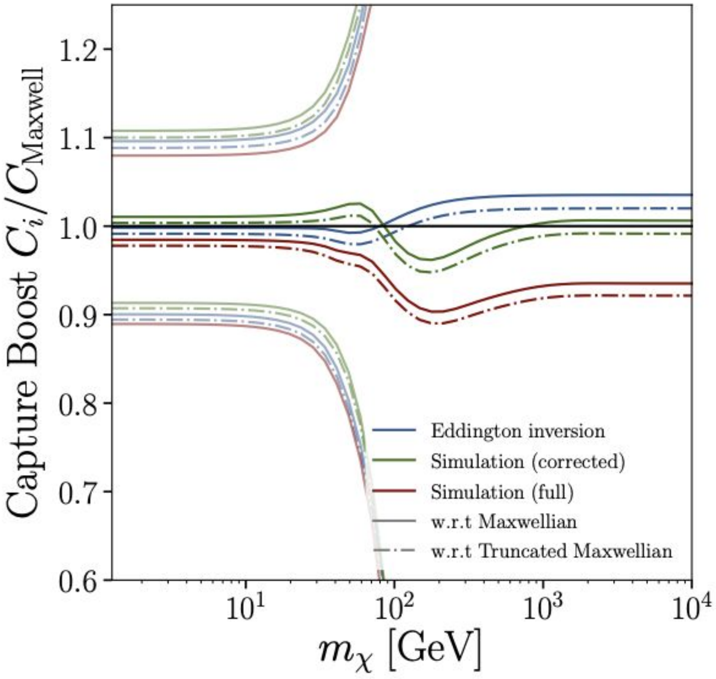
But the velocity distribution in simulations is **not** always smooth.

Effects of the structure of the velocity distribution on DM detection

The presence of the high-velocity excess is weakly impactful for solar DM capture. Since this process is sensitive to the low velocity tail.

Direct detection is likely to be more sensitive to such features.



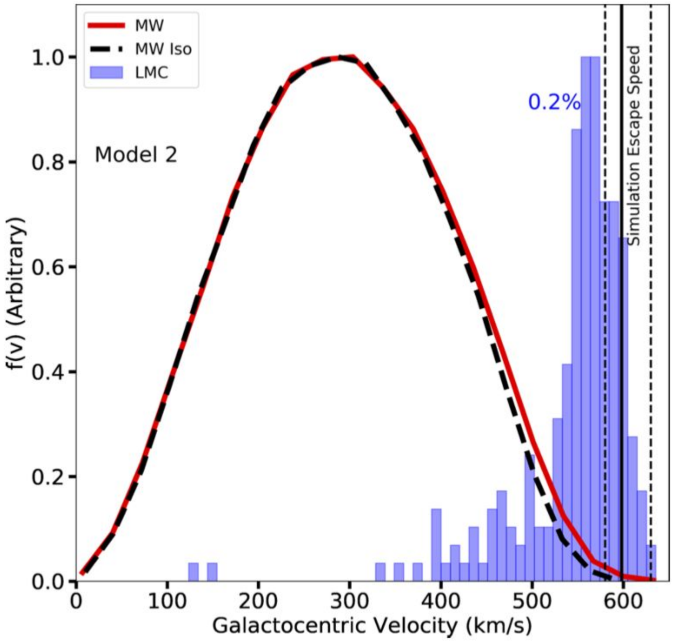


Nunez-Castineyra et al (2019) (arxiv:1906.11674)

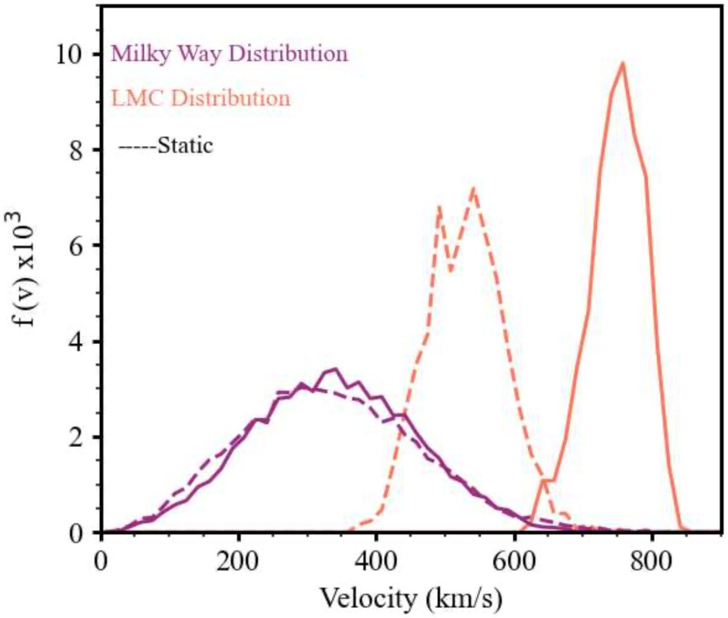
Origin of high velocity particles in the Solar neighbourhood.

Dedicated numerical experiments show that the LMC can be contributing to the local population of DM particles in the high velocity tail.

But Its contribution is rather small



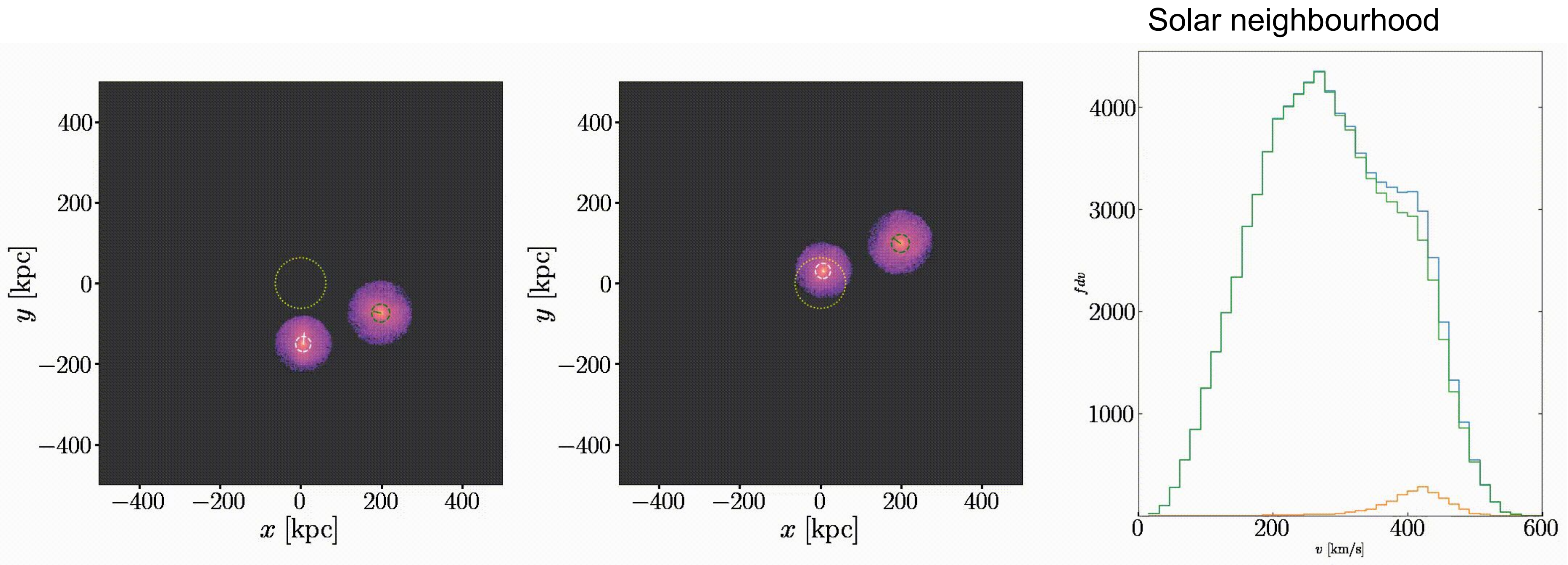
Besla et. al. 2019



Donaldson et. al. 2022

Preliminary

Origin of high velocity particles in the Solar neighbourhood.

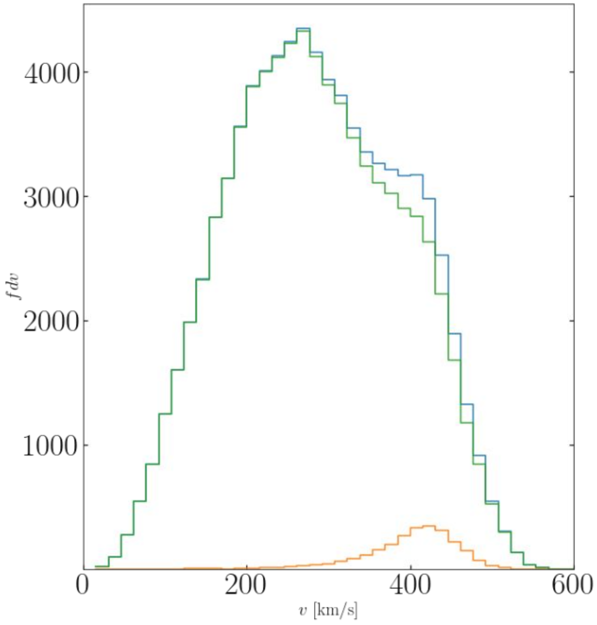


Two subhalos that merge at z=1.7 have been identified to contribute to the "bump" in the local fdv. The movie runs from z=1.7 to z=1

Preliminary

This suggest that even subhalos that merged long time ago can contribute to the high velocity tail of the local velocity distribution

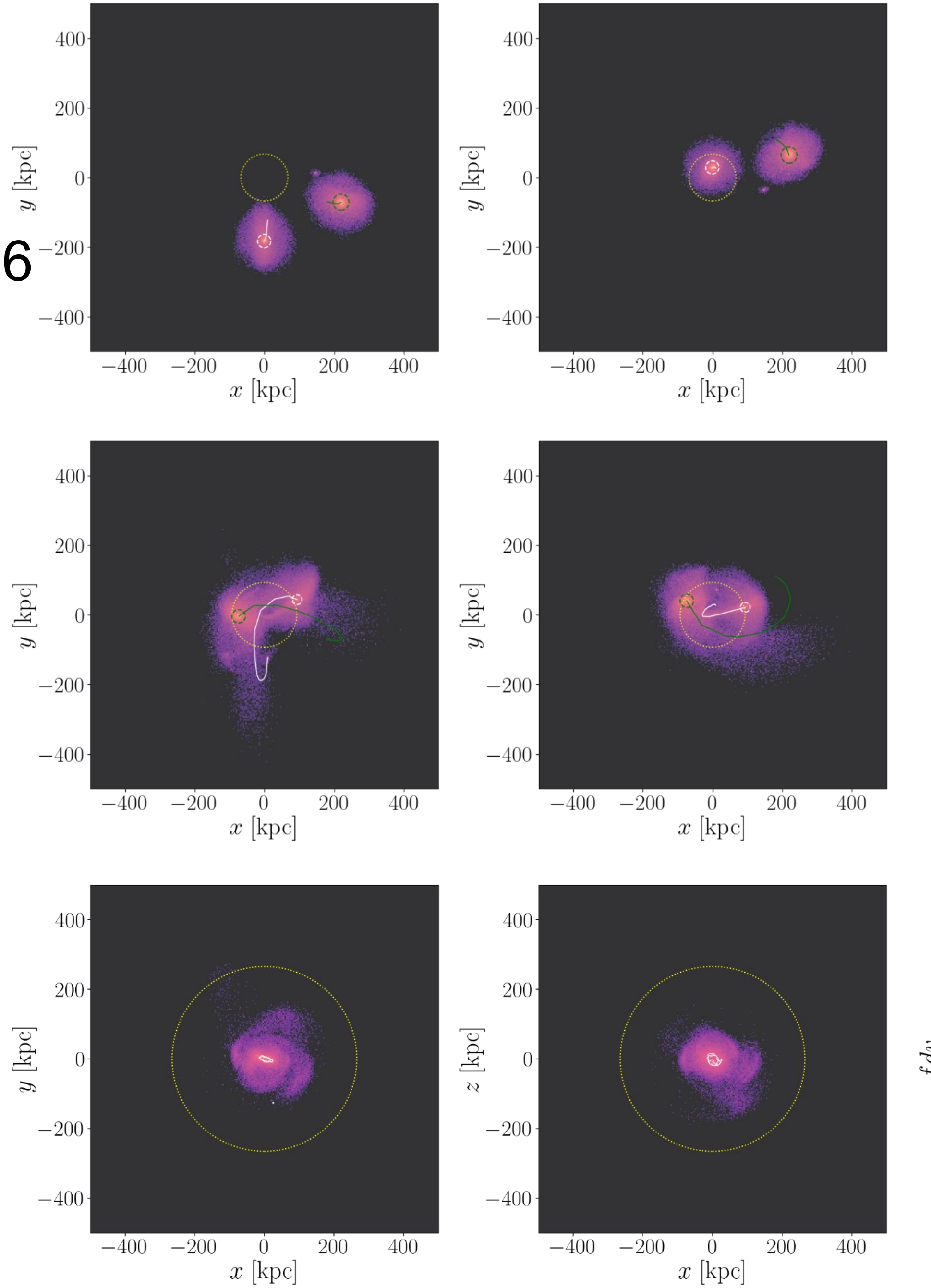
Depending on: orbit? Mass? Merger epoc?



z=1.6

z=1

z=0



Summary

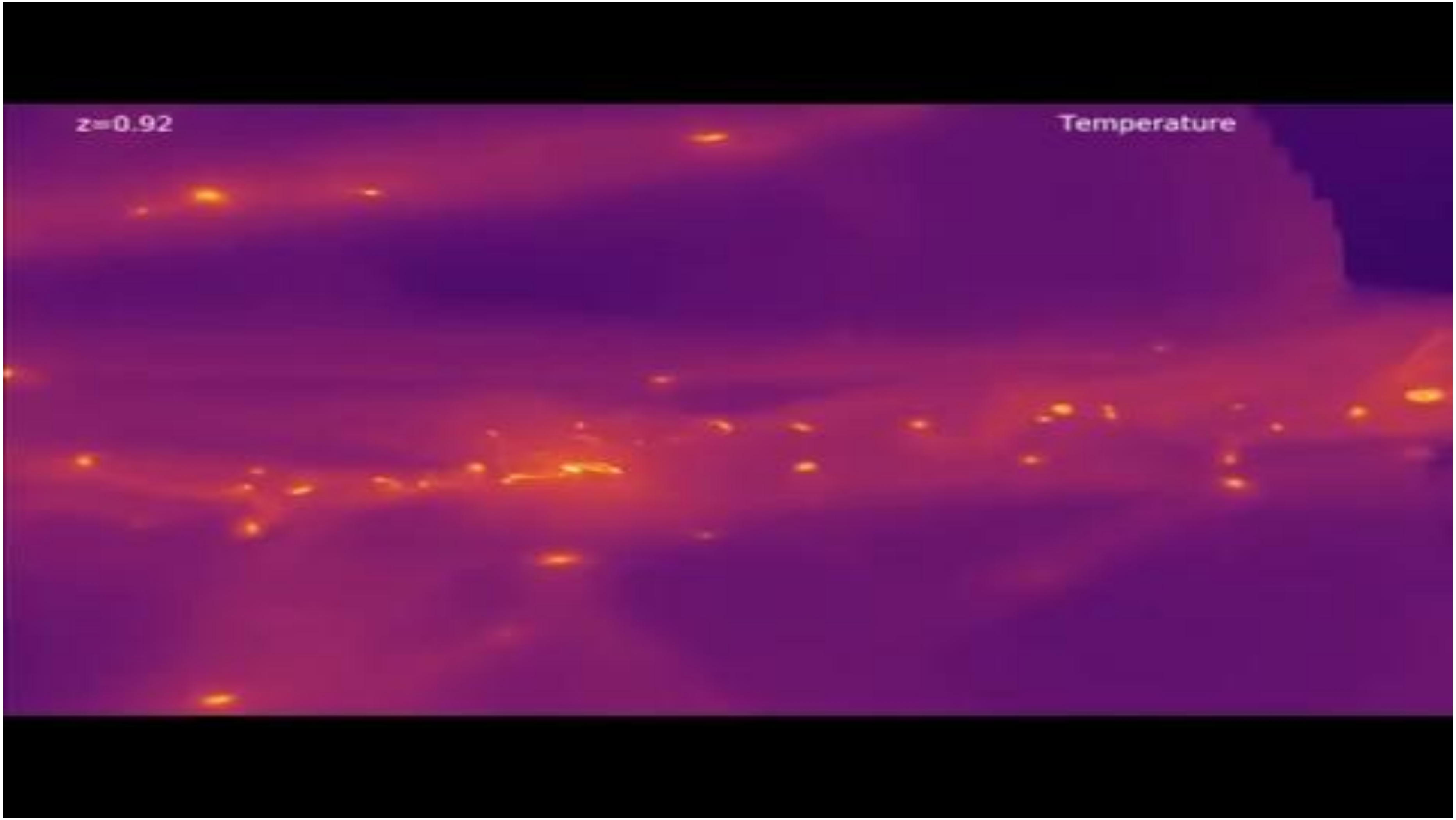
- Cosmological simulations of "MW-analogs" are a powerful tool to understand DM dynamics

- **Not without certain issues:**
    - MW-likeness
    - Resolution
    - Baryonic physics

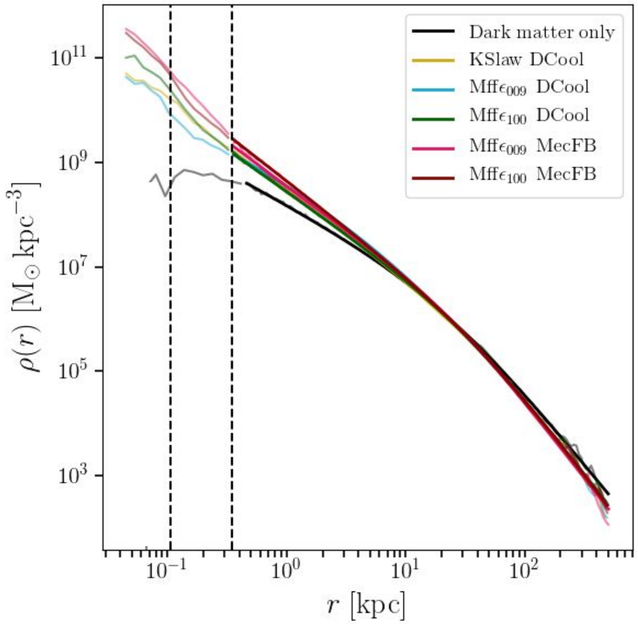
Always ask your local simulator about these aspects

- DM is affected by the baryonic content of the galaxy specifically the baryonic evolution (SFR, Merger history)

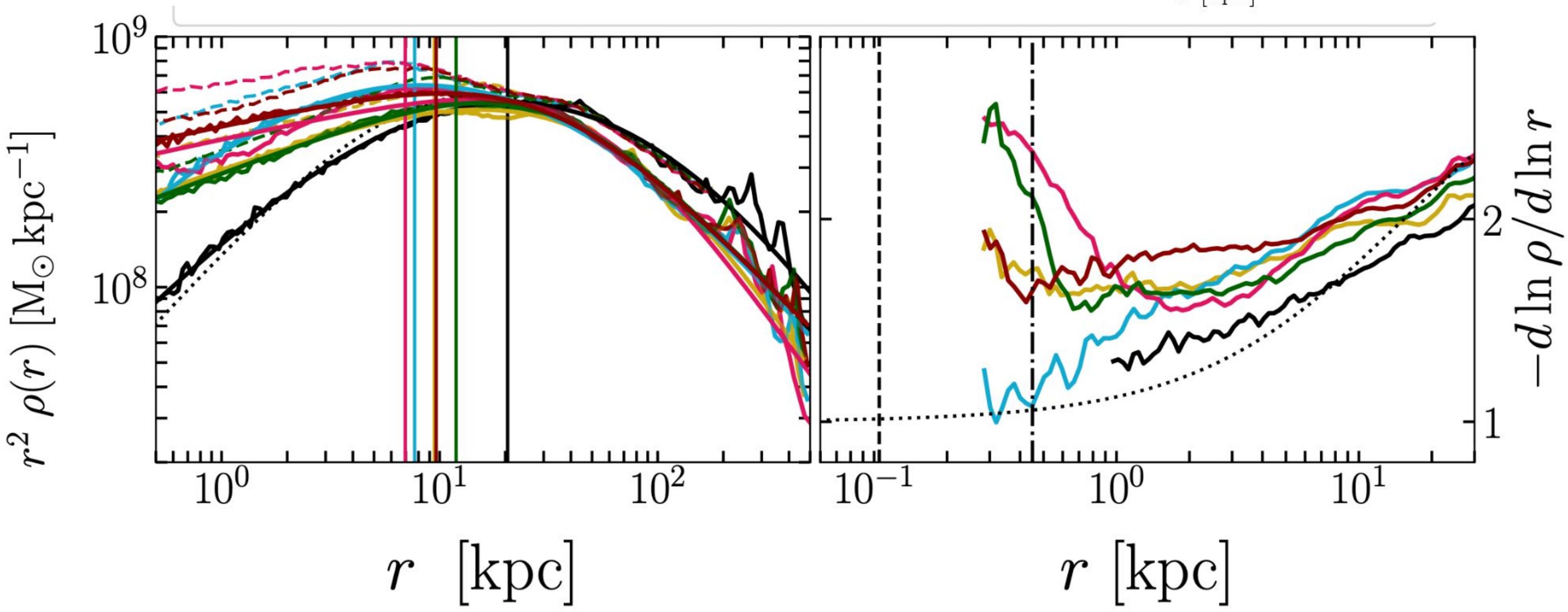
- The phase space distribution could have imprints of the merger history of the galaxy providing an advantage to some detection efforts above others. Direct detection for example


z=0.92
Temperature

Dark matter distribution

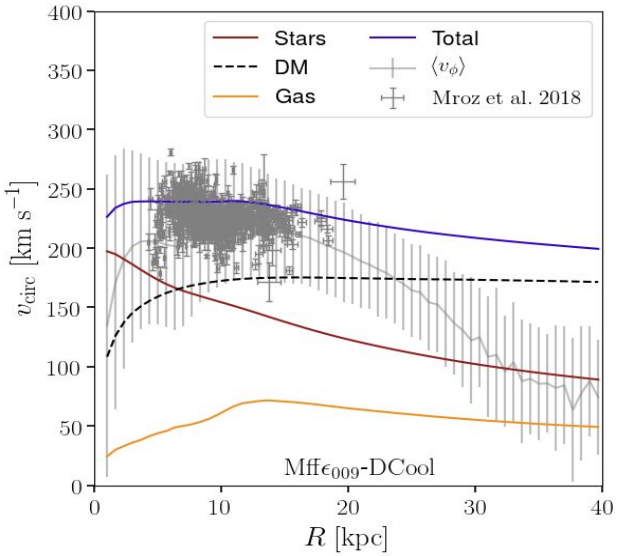


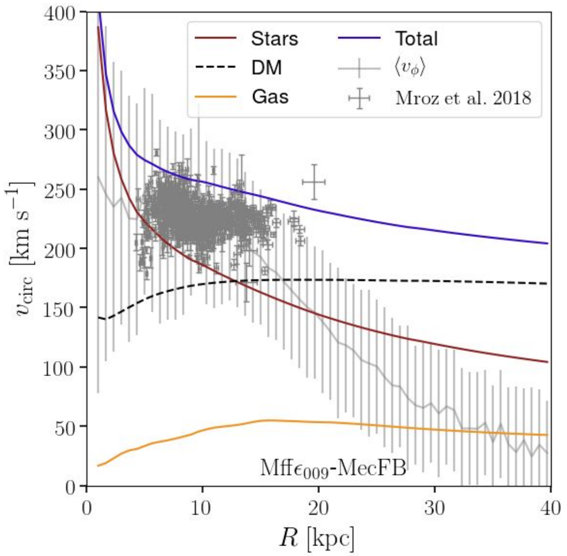
The DM halos are very cuspy.
They suffer adiabatic contraction which intensities are related to the bulge size.



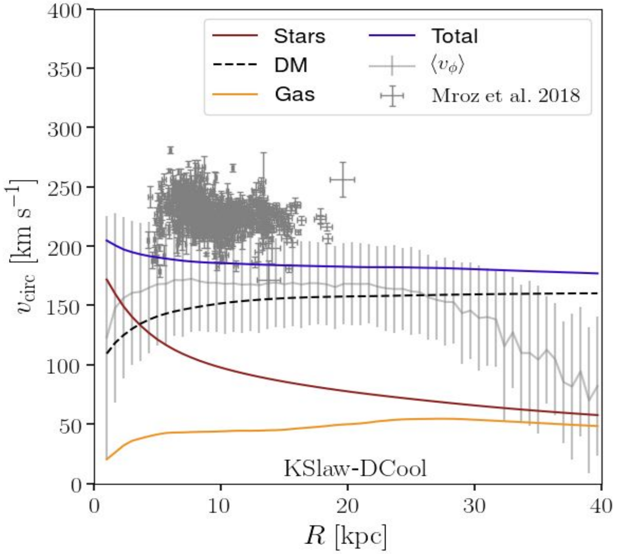
Nunez-Castineyra et al (2023) (arxiv:2301.06189)

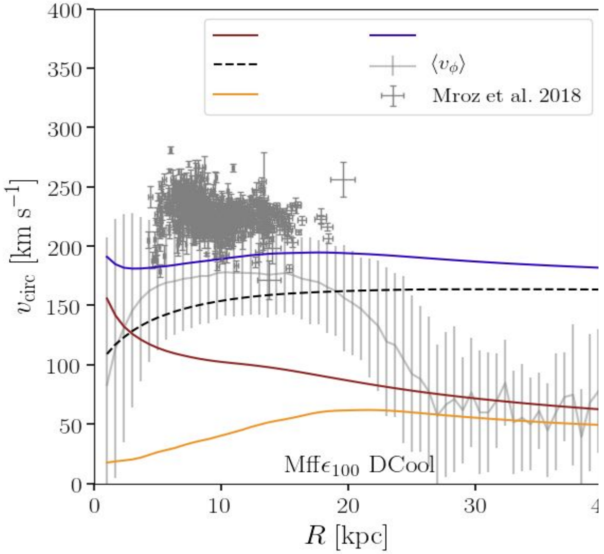
Rotation curves

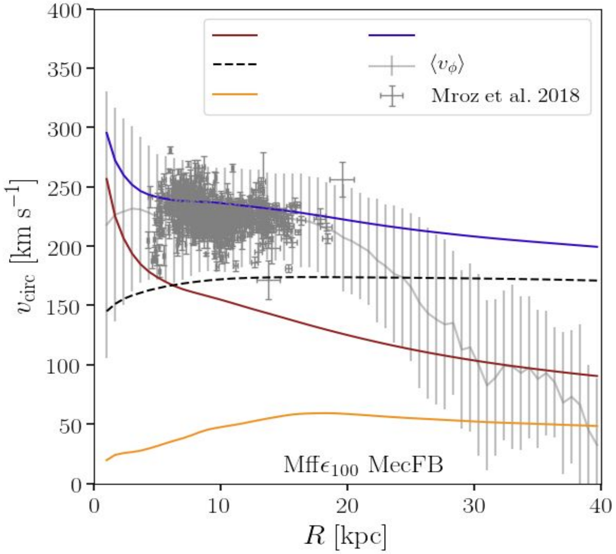




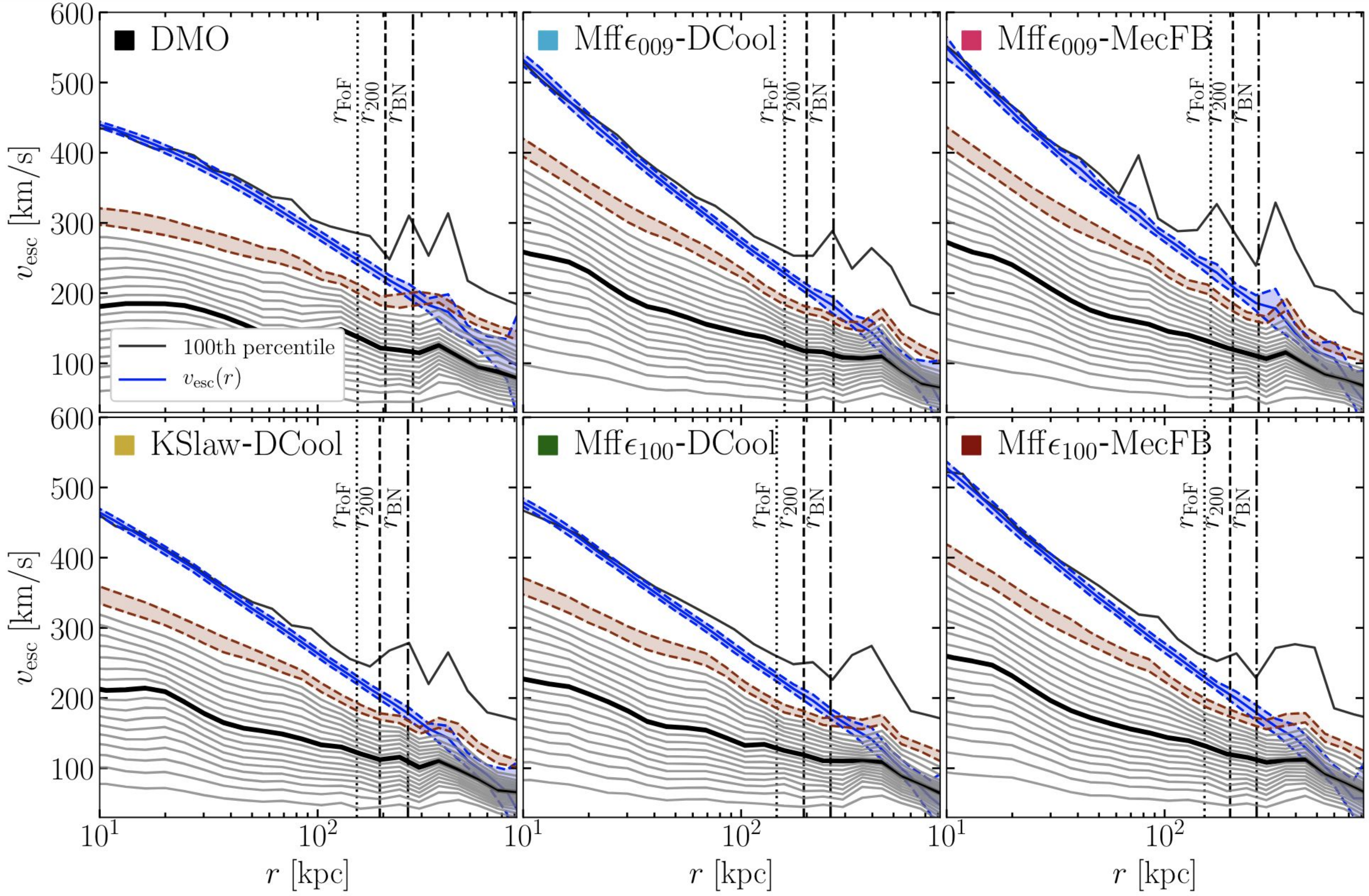
Eilers et al 2018, $5 < R < 25$ kpc
Mroz et al 2019, $4 < R < 18$ kpc
Pato et al 2017, $1.4 < R < 20$ kpc
Huang et al 2016, $4.6 < R < 99$ kpc







Nunez-Castineyra et al (2020) (arxiv:2004.06008)



The edge of the DM halo: the definition by Bryan & Norman 1998 agrees well with the radius where v_esc = v_95%