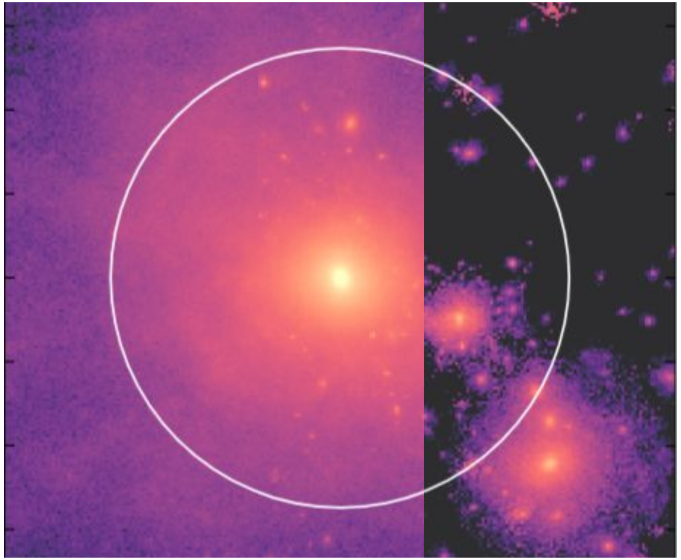
Subhalos in the Mochima simulations

The impact of baryonic physics



Collaborators:
Emmanuel Nezri
Pol Mollitor

News from the dak 9
Marseille
Nov 2024

Arturo Nuñez-Castiñeyra
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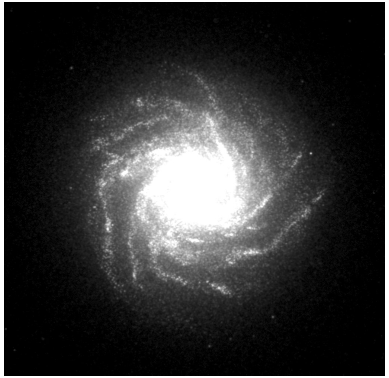
What is a Galaxy and how to simulate it

Cosmological initial conditions and the right ingredients can help the understanding of galaxy formation

What are the right ingredients?

What is a Galaxy and how to simulate it

DM



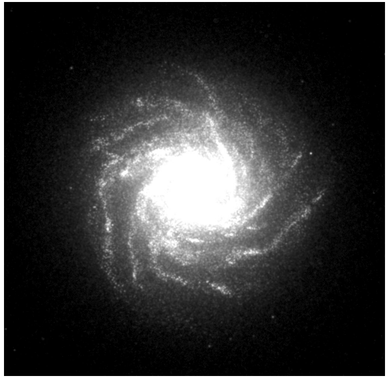
Collisionless limit of the Boltzmann equation:

$$\frac{Df}{Dt} = \frac{\partial}{\partial t} f(\mathbf{x}, \mathbf{v}, t) + \mathbf{v}\frac{\partial}{\partial \mathbf{x}} f + \mathbf{a}\frac{\partial}{\partial \mathbf{v}} f = 0$$

Liouville theorem: number of particles is conserved in phase-space. The gravitational acceleration is given by **Poisson equation**:

$$\Delta\Phi(\mathbf{x}, t) = 4\pi G m\,(n(\mathbf{x}, t) - \bar{n}) \qquad n(\mathbf{x}, t) = \int f(\mathbf{x}, \mathbf{v}, t)\mathrm{d}^3\mathrm{v}$$

What is a Galaxy and how to simulate it



Gas

DM

Gas is a highly collisional system with a Maxwell distribution function.

Hydro. A system of three conservation laws + EoS

$$\partial_t \rho + \nabla \cdot \mathbf{m} = 0$$ (mass)

$$\partial_t \mathbf{m} + \nabla \cdot (\rho \mathbf{u} \times \mathbf{u}) + \partial_x P = 0$$ (momentum)

$$\partial_t E + \nabla \cdot \mathbf{u}(E + P) = 0$$ (energy)

What is a Galaxy and how to simulate it

Gas — DM

Gas is a highly collisional system with a Maxwell distribution function.

A system of three conservation laws + EoS (hydro)

$$\partial_t \rho + \nabla \cdot \mathbf{m} = 0$$ (mass)

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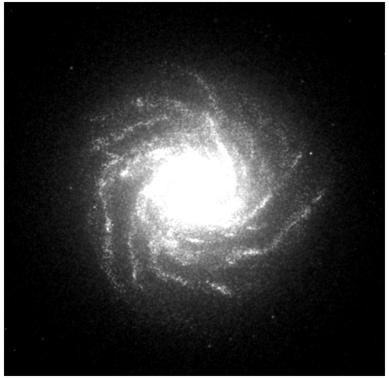
$$\partial_t E + \nabla \cdot \mathbf{u}(E + P) = 0$$ (energy)

Add gravity and heating and cooling rates. (this can be expanded to include magnetic fields as well)



Turbulence

Grav Collapse

What is a Galaxy and how to simulate it

Gas — DM

Stars

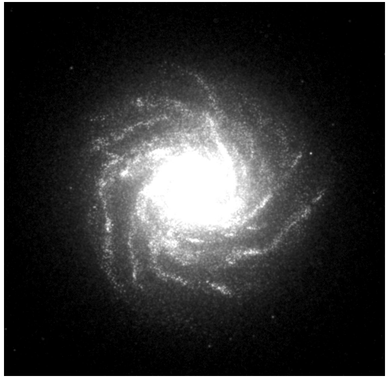
We need an effective model at the scale of the spatial resolution:

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

Ruled by the star formation efficiency

Star formation

Grav Collapse



Turbulence

What is a Galaxy and how to simulate it

Gas — DM

Stars

We need an effective model

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

Ruled by the star formation efficiency

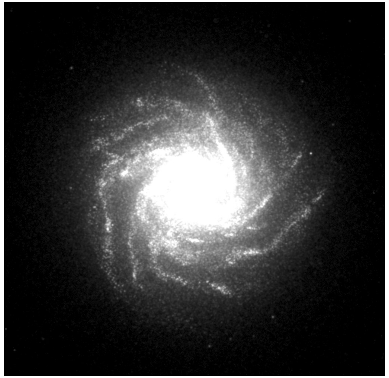
- Constant efficiency galaxy wide
- Environmental dependent efficiency

$$\epsilon_{\rm ff} = \epsilon_{\rm ff}(\mathcal{M}, \alpha_{\rm vir})$$

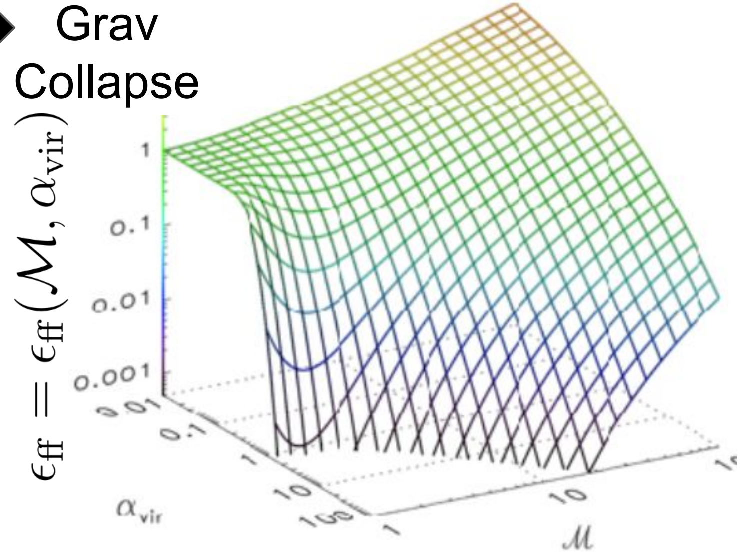
Multi-freefall star formation (Federrath & Klessen (2012))

Star formation

Turbulence



Grav Collapse



What is a Galaxy and how

Star formation

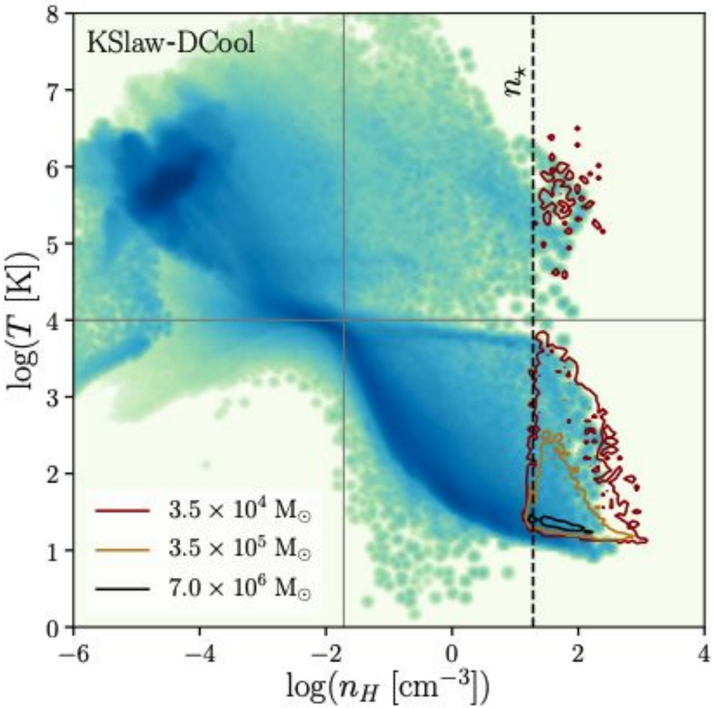
ence

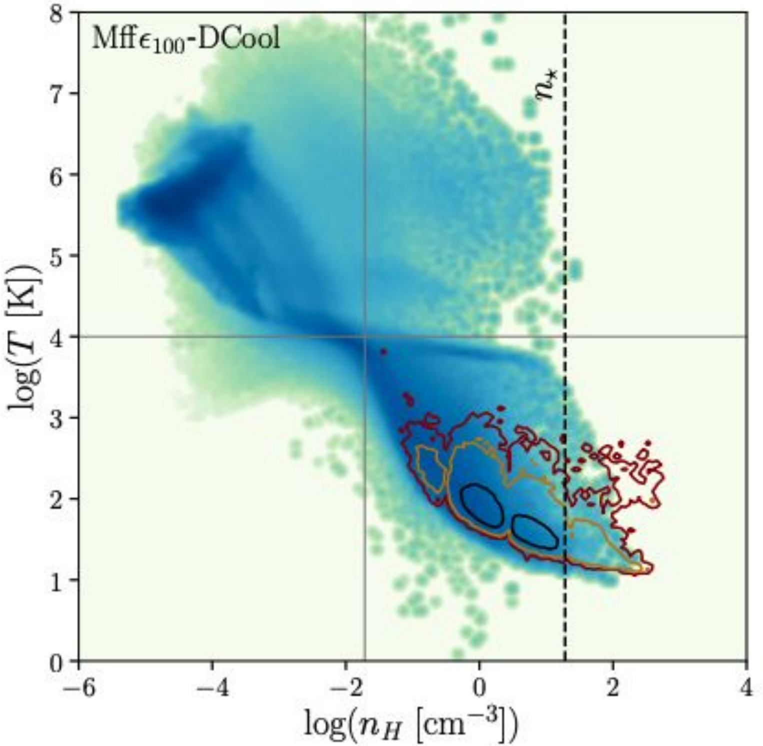
Gas

DM

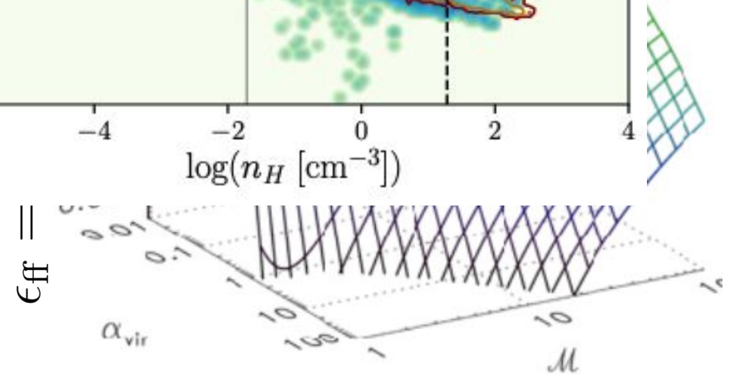
Sta

- Con
- Env



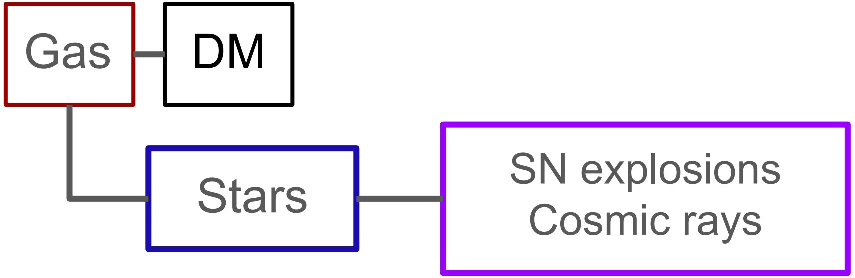


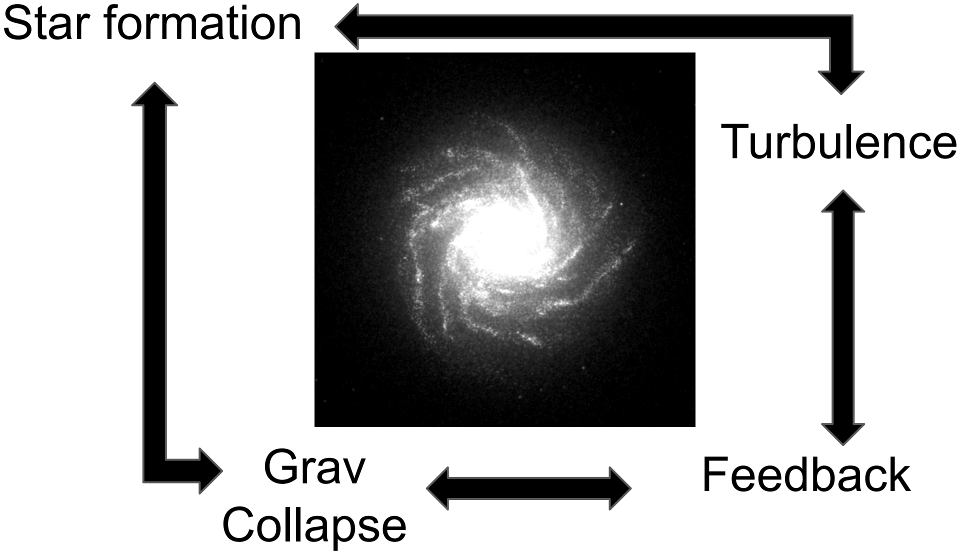
$$\epsilon_{\rm ff} = \epsilon_{\rm ff}(\mathcal{M}, \alpha_{\rm vir})$$



Multi-freefall star formation (Federrath & Klessen (2012))

What is a Galaxy and how to simulate it

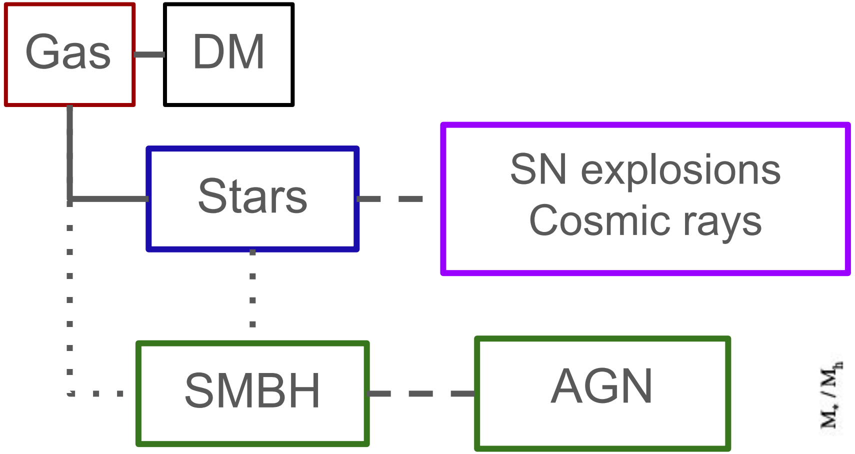


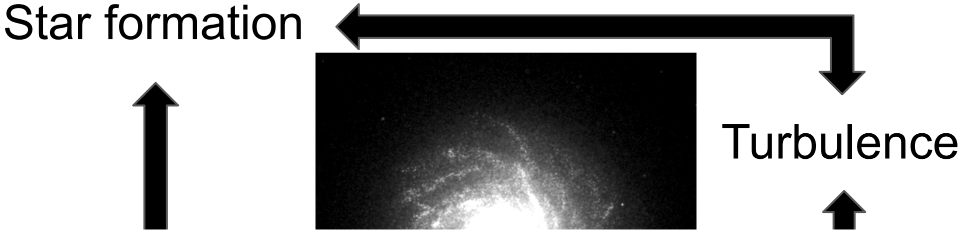


We need effective models:

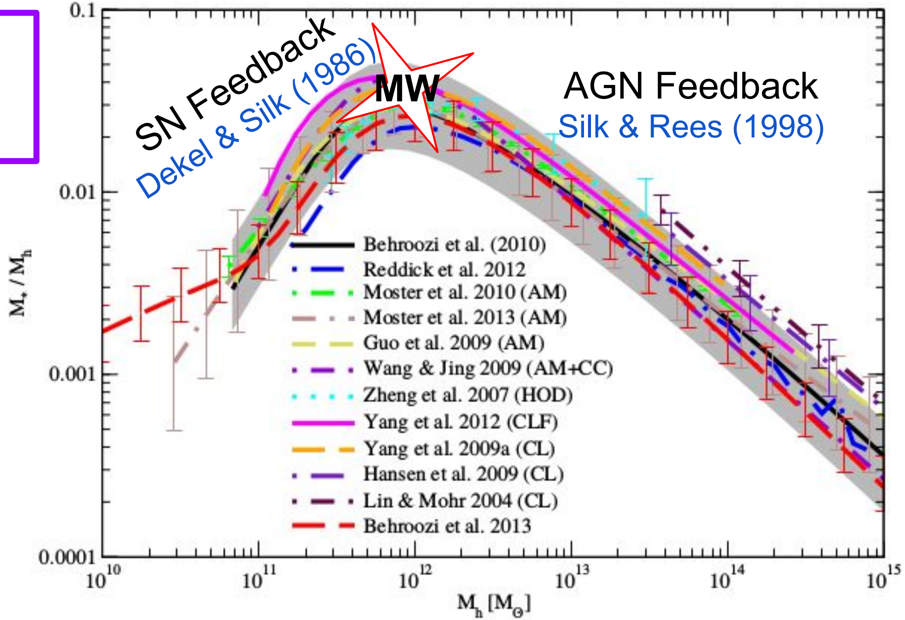
- **SN** : thermal or kinetic energy injections, delayed local cooling, mechanical Sedov taylor phases.(Teyssier et al. 2013, Dubois et al. 2015.Kimm & Cen 2014. Kimms et al. 2015.)
- **Cosmic rays**: relativistic fluid that provides and effective pressure (Low energy GeV) (Dubois & Commerçon 2016)

What is a Galaxy and how to simulate it



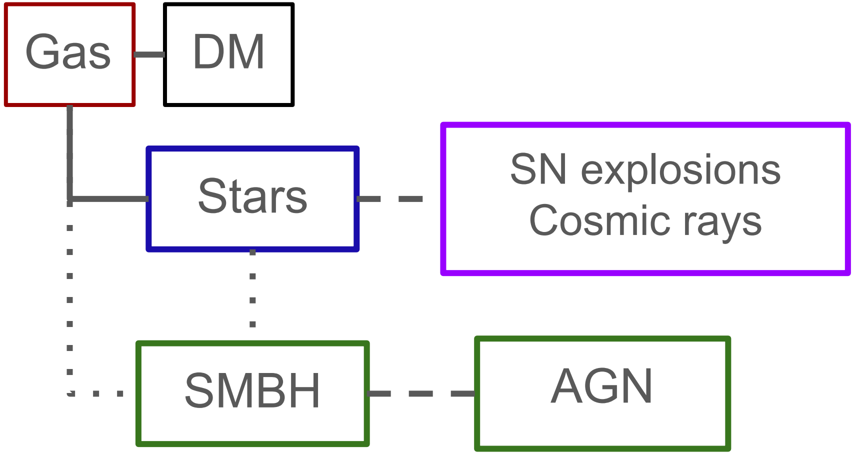


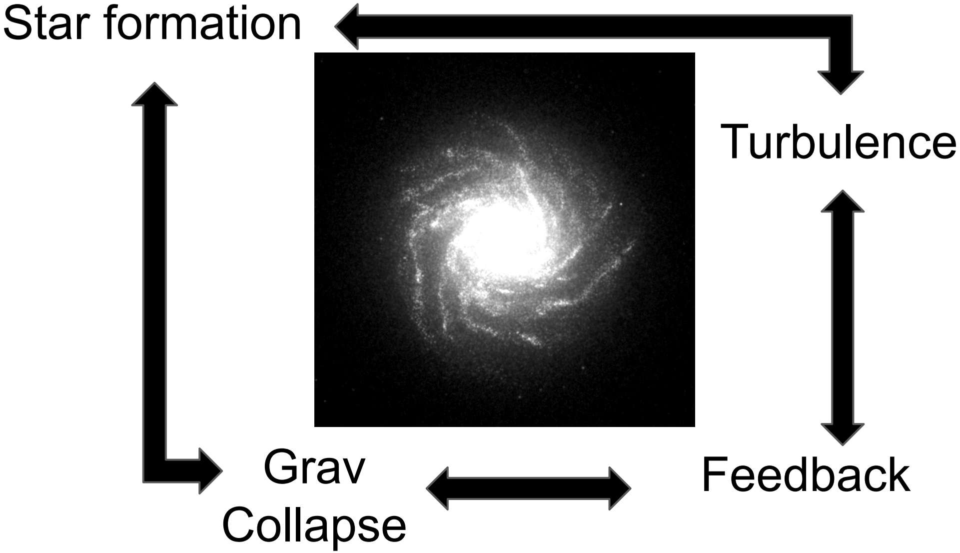
Stellar to Halo Mass Ratio



Behroozi et al. (2013)

What is a Galaxy and how to simulate it





At the end, with these ingredients.. You have a nonlinear environment that evolves with time and can be compared with observation (?)...
giving us information on:

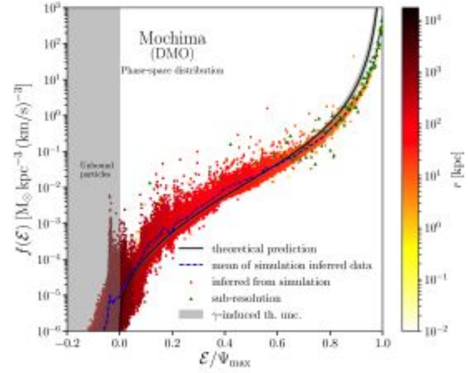
- Galaxy formation
- Galactic dynamics
- Dark matter distribution

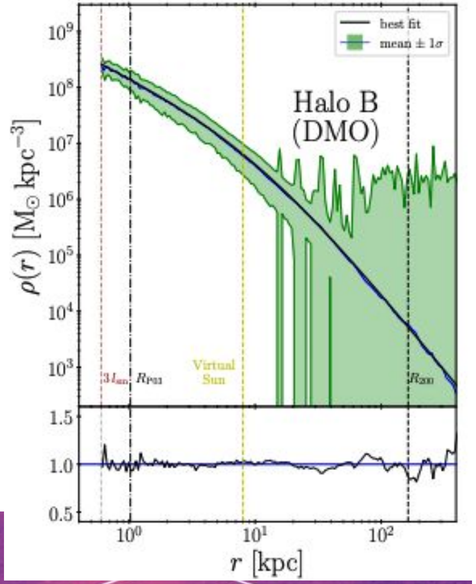
Dark matter content

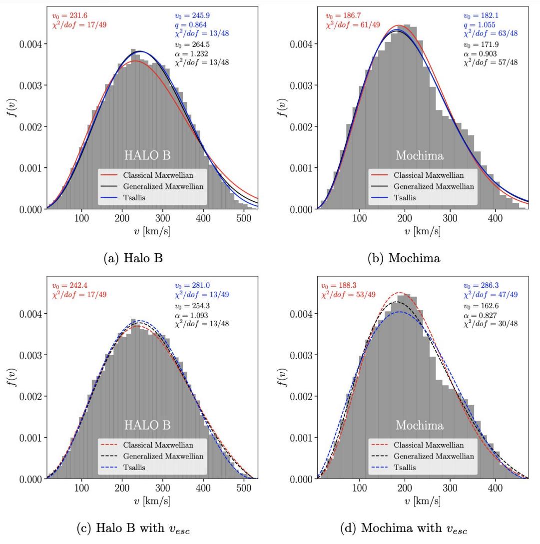
Full access to the DM distribution position and velocity

- Density profiles
- Phase space distribution
- Assembly history

Lacroix. ANC+ 2020

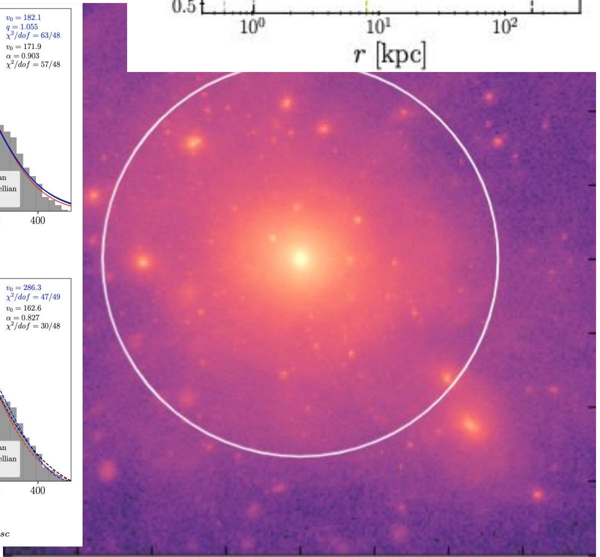






(a) Halo B
(b) Mochima
(c) Halo B with v_{esc}
(d) Mochima with v_{esc}

Nunez-Castineyra et al (2019) (arxiv:1906.1674)



Dark matter content

Full access to the DM distribution position and velocity

- Density profiles
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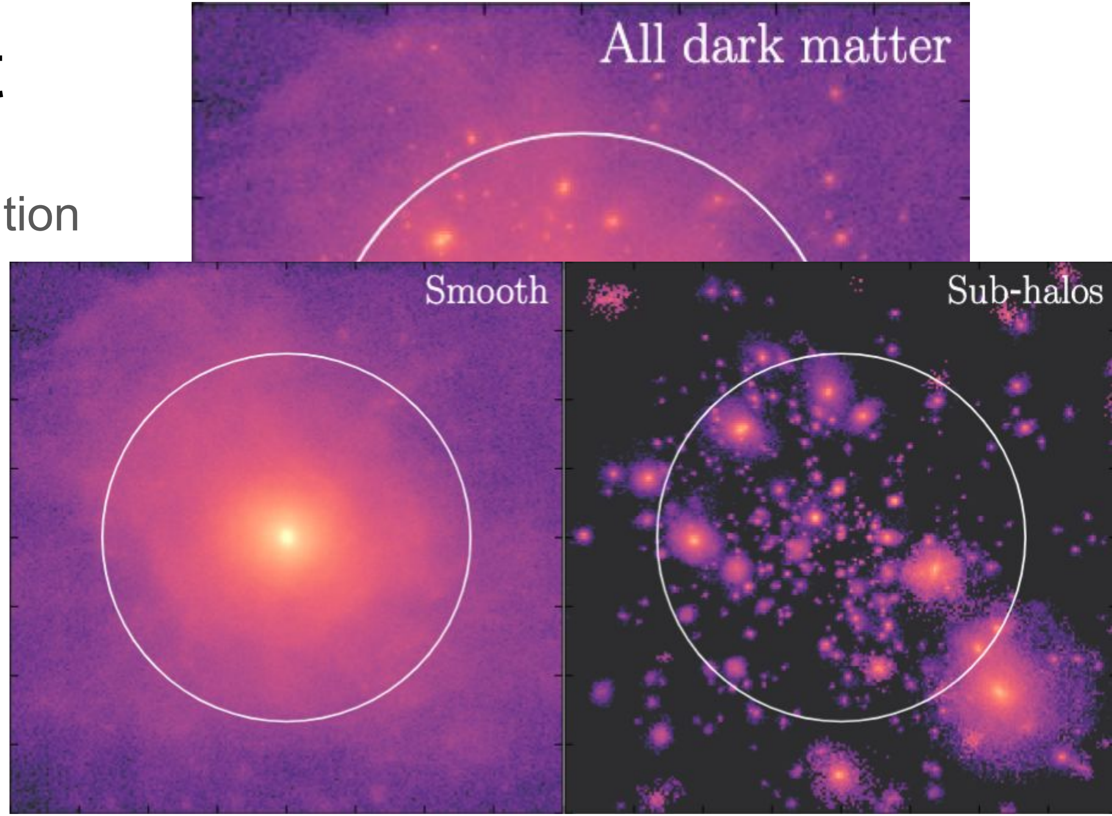
- Assembly history

In a LCDM Universe the a halo is formed from in a bottom up manner.. From small halos to big halos.

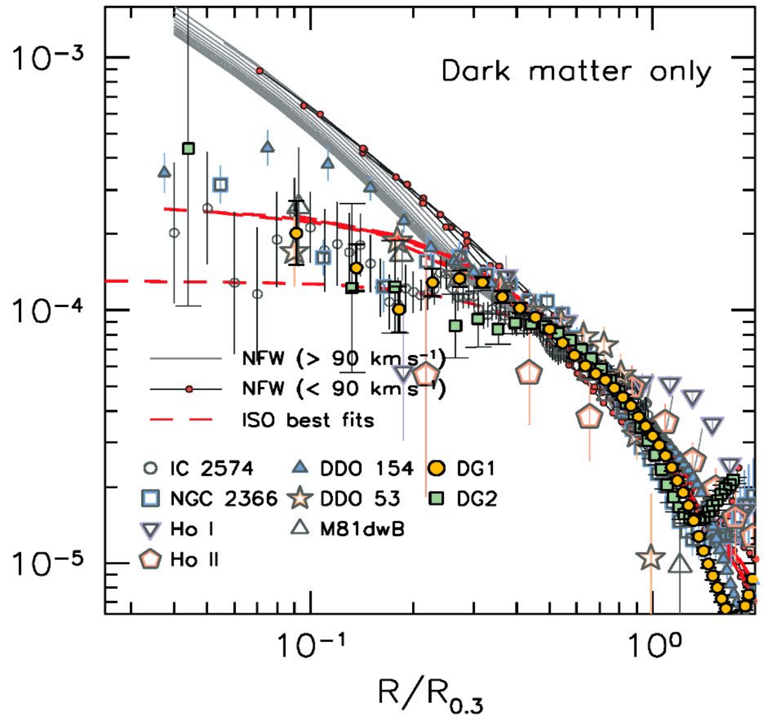


Dark matter content

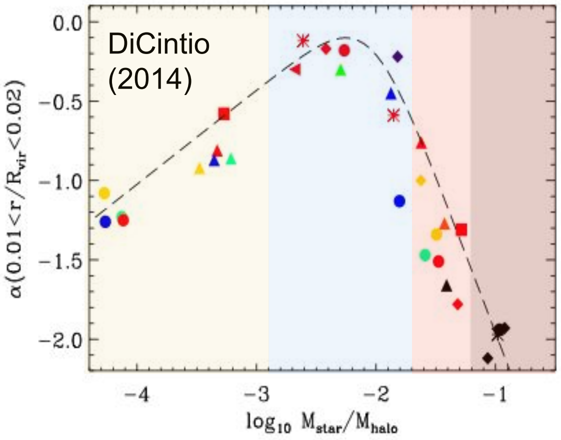
- **Cusp-Core problem (Diversity)**
  When it comes to dark matter halos
  Simulations predict one thing (mostly cusps)
  Observations infer other (mostly cores)

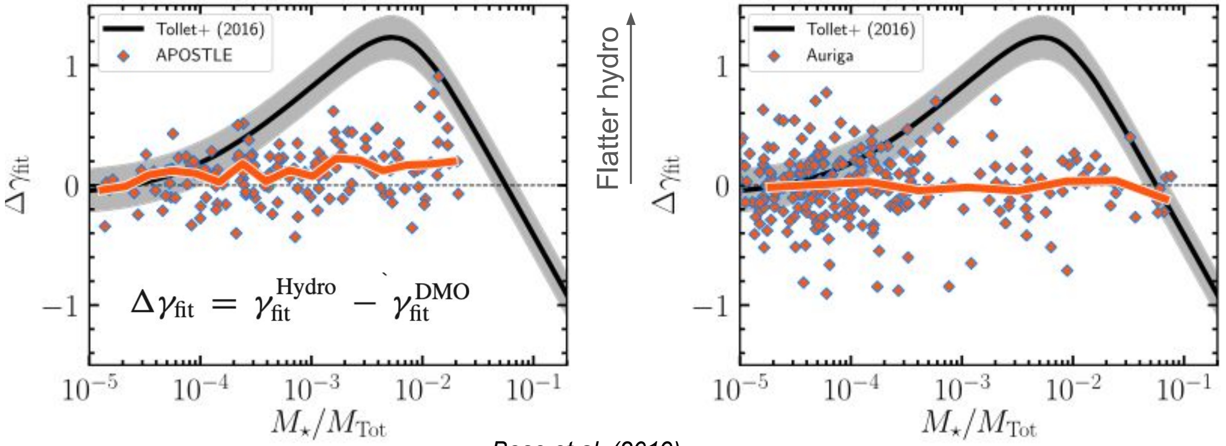
  De Blok (2009), Del Popolo & Le Delliou (2021)

- **Missing satellites situation**(?)
  Simulations predict higher number of satellites than what is observed.



Baryons complicate the story but could solve the problems





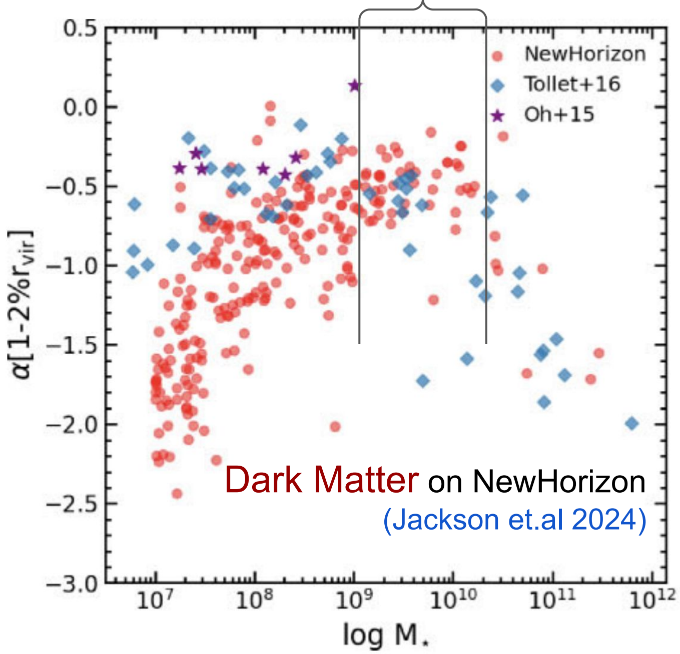
Bose et al. (2019)

- stellar feedback can't alter inner dark matter, so the galaxy remains cuspy.
- feedback expands dark matter, creating cored profiles.
- Central stars deepen gravity enough to counter expansion, resulting in cuspier profiles.

NIHAO: Cores are likely created by a very strong FB

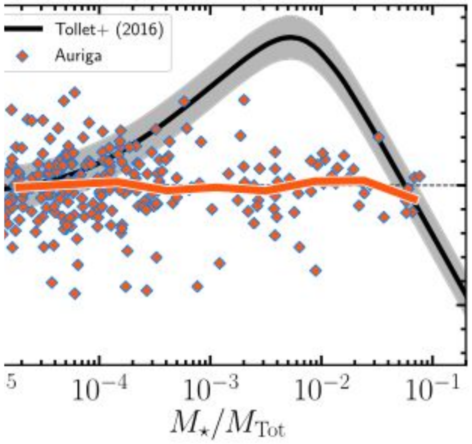
APOSTLE and Auriga: do not find evidence of core formation at *any* mass or any correlation between the inner slope of the DM density profile and temporal variations in the SFH

Baryons complicate the story but could solve the problems



New Horizons: Cores form through supernova-driven gas removal, which alters the central gravitational potential, inducing dark matter to migrate to larger radii.

Similar to what was proposed by Governato et al. 2012; Pontzen & Governato 2012;



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profiles.

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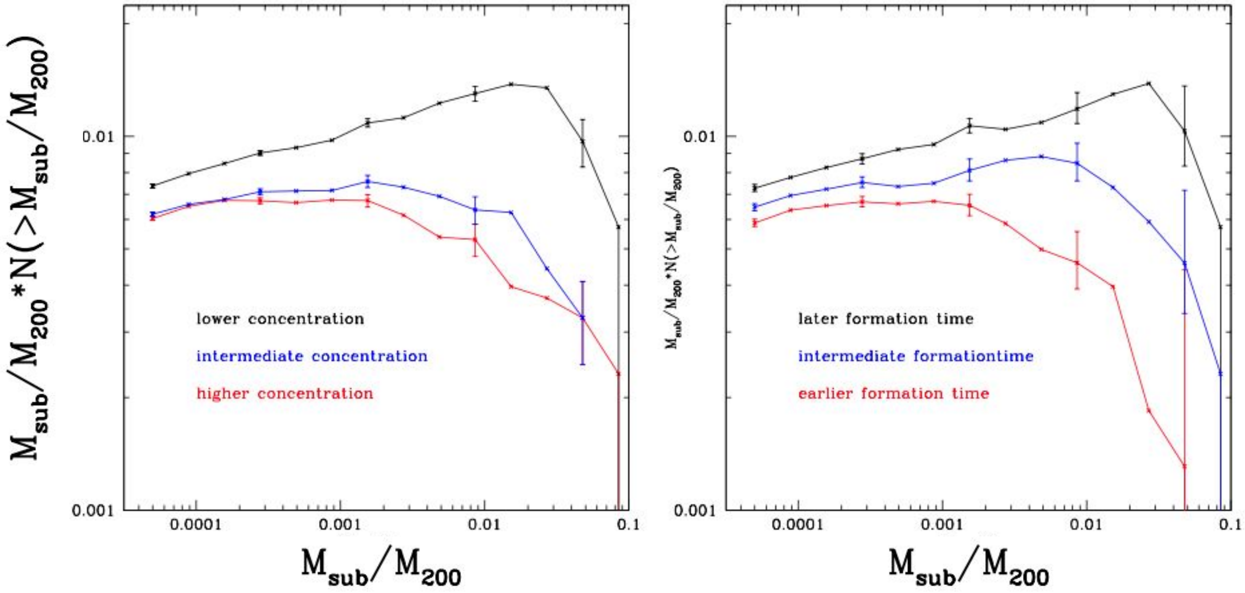
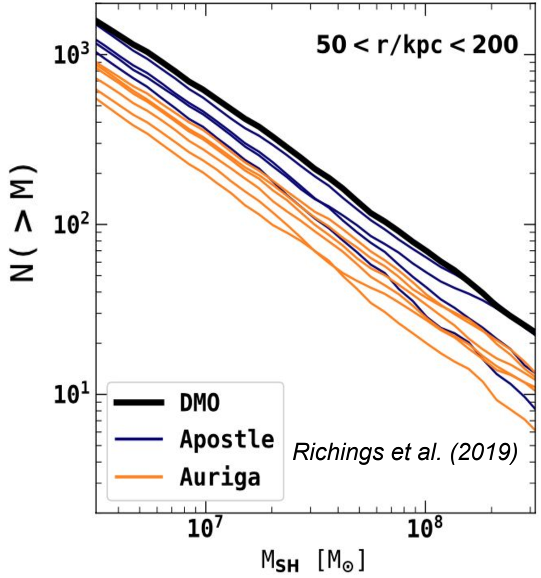
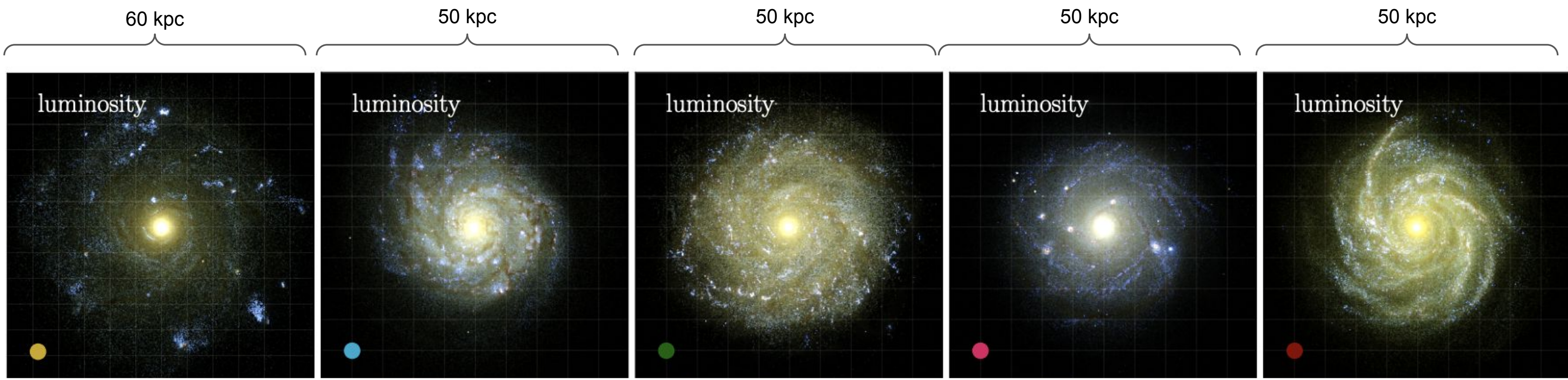




Gao et, al. (2010): The subhalo abundance function correlates with the host halo concentration parameter and formation redshift.

Richings et al. (2019)
less massive halos are more prone to tidal disruption.

The Mochima
Simulations



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

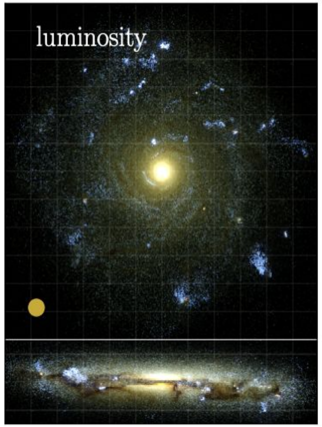
Nunez-Castineyra et al (2020)
(arxiv:2004.06008)

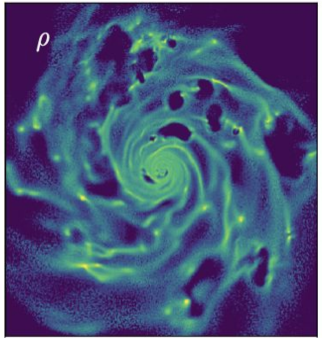
Same galaxy, same initial conditions, different baryonic physics (SN and SF)

The Mochima simulation

Delayed Cooling
(Dubois et al 2015)

Kennicutt-Schmidt SF





Kennicutt-Schmidt SF:

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

$\epsilon_{\rm ff}$ is constant and calibrated to reproduce KS law.

Delayed cooling SN feedback:

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

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

The energy corresponds to the fraction of massive stars expected to be more massive than 8 Msun assuming a universal IMF.

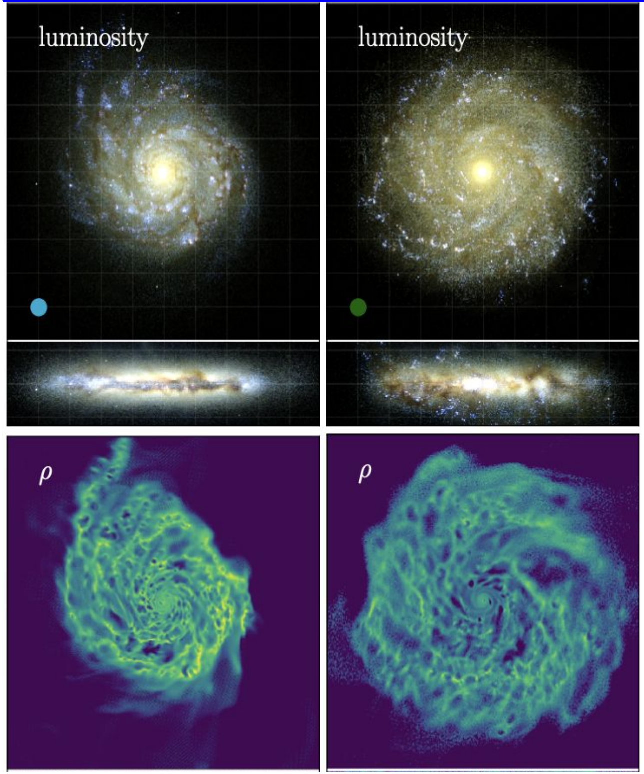
Teyssier et al. 2013, Dubois et al. 2015.

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

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

where: $\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)$ $\mathcal{M} = \frac{\sigma_{\rm T}}{c_s}$

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

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:

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Mechanical FB:

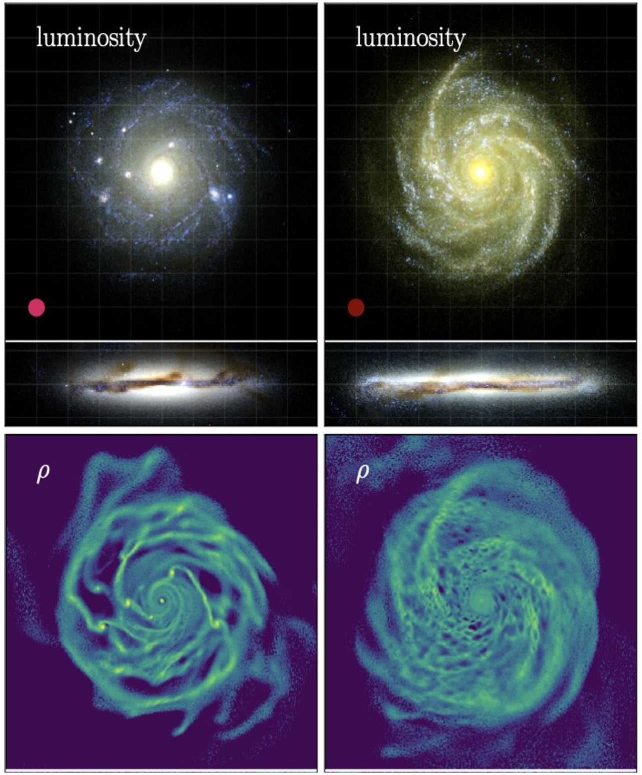
Model the two phases of the SN explosion and inject the corresponding momentum

$$p_{\rm SN,snow} \approx 3\times10^5\,{\rm km\,s^{-1}}\,{\rm M_\odot}\,E_{51}^{16/17} n_{\rm H}^{-2/17} Z'^{-0.14}$$

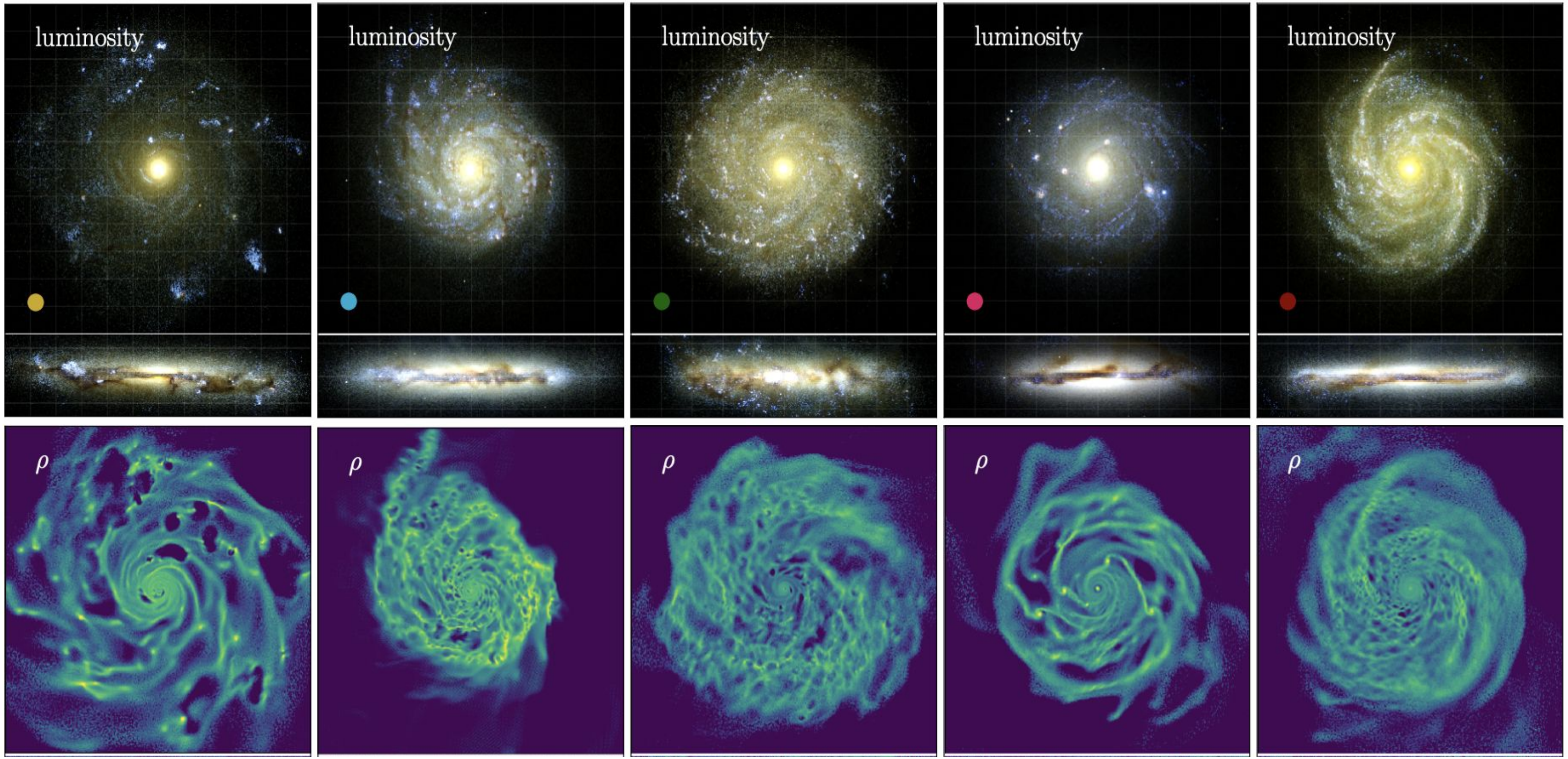
$$p_{\rm SN} = \begin{cases} p_{\rm SN,ad} = \sqrt{2\chi\, M_{\rm ej}\, f_e\, E_{\rm SN}} & (\chi < \chi_{\rm tr}) \\ p_{\rm SN,snow} & (\chi \geq \chi_{\rm tr}) \end{cases}$$

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

Kimm & Cen 2014. Kimms et al. 2015.

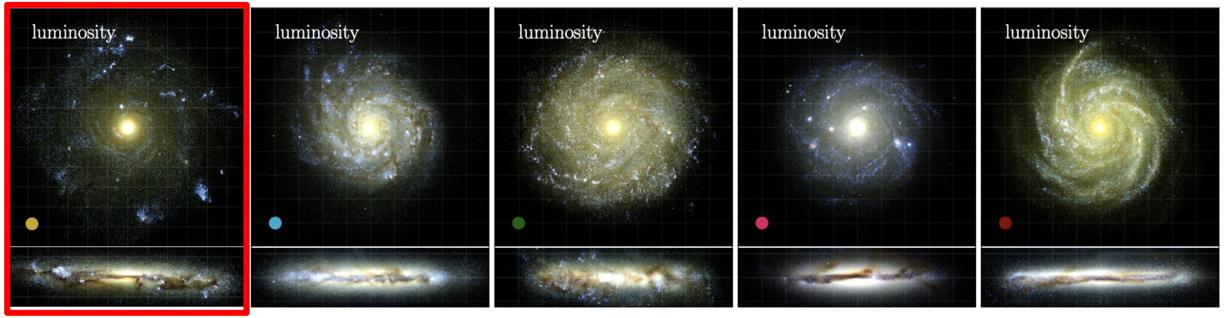


Nunez-Castineyra et al. 2020



Nunez-Castineyra et al
(arxiv:2004.06008)

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



Baryonic Analysis and comparisons

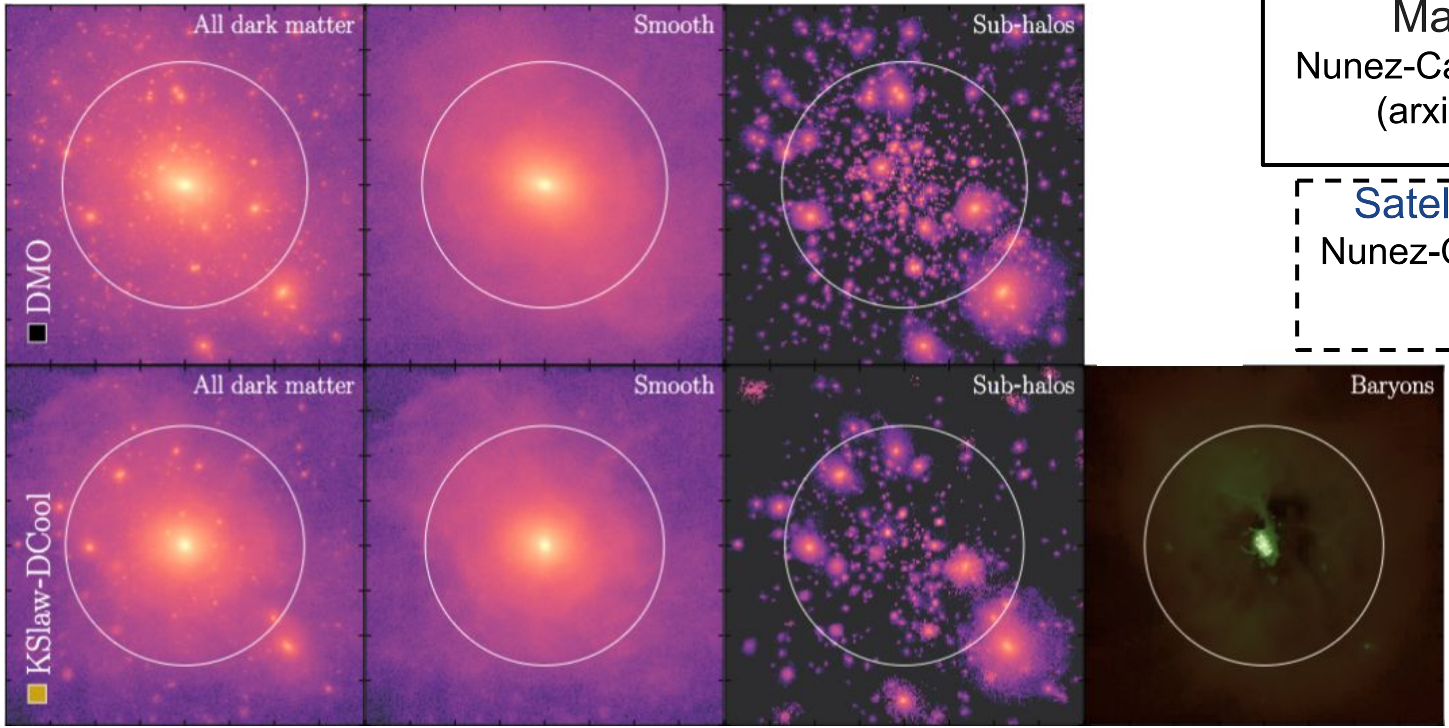
Nunez-Castineyra et al 2020
(arxiv:2004.06008)

Dark Matter
Main DM halo

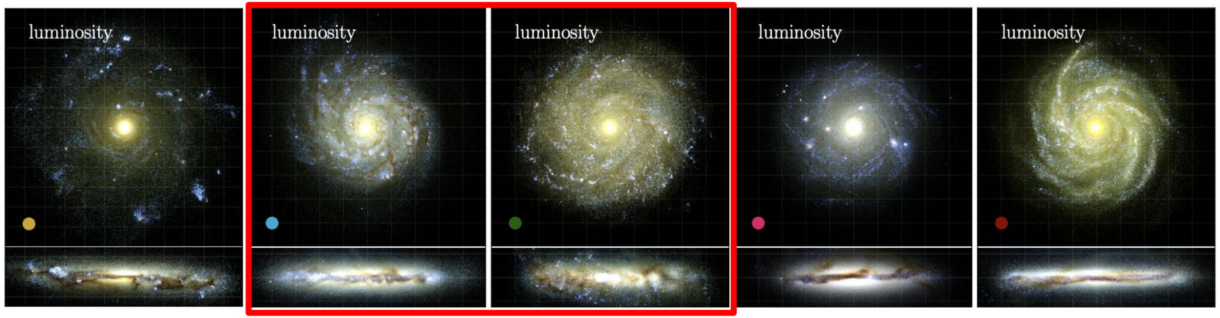
Nunez-Castineyra et al 2023
(arxiv:2301.06189)

Satellites subhalos

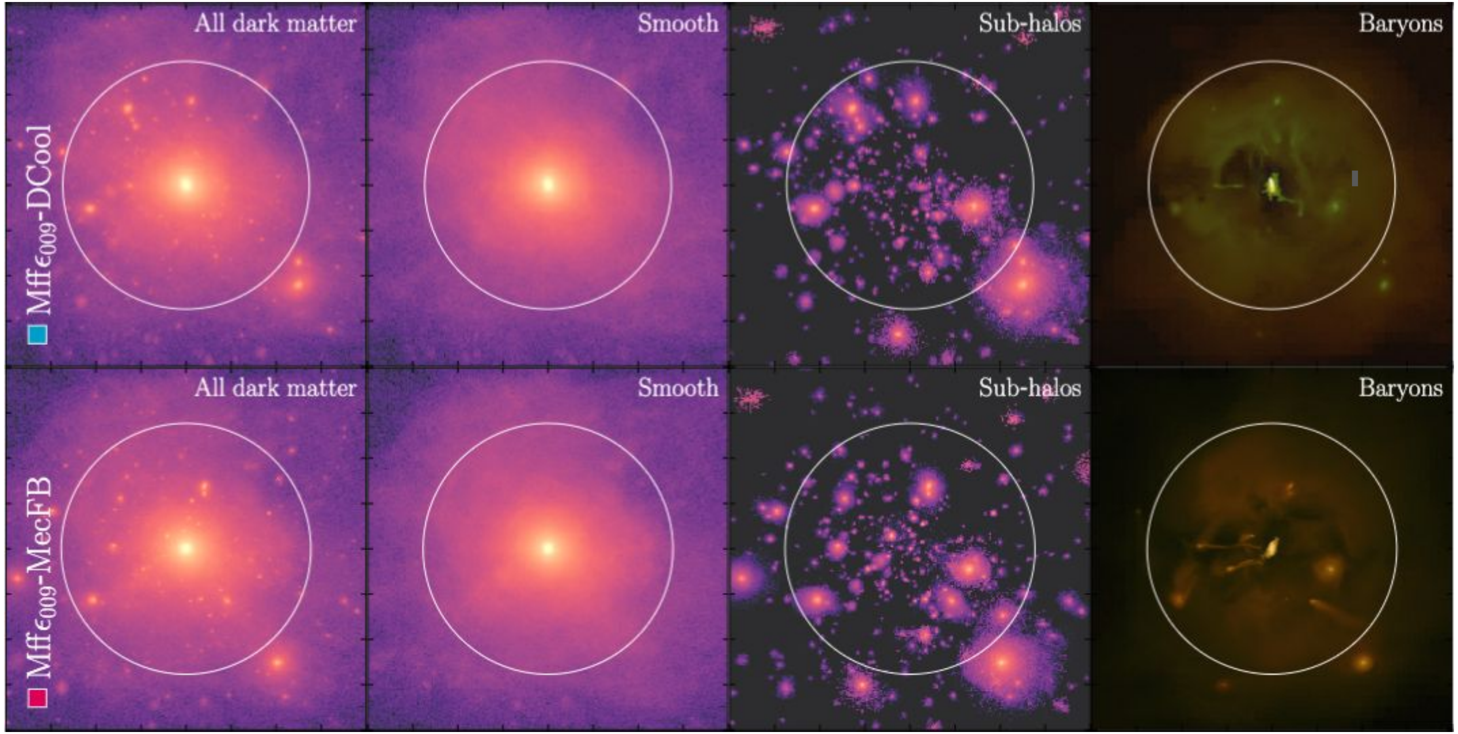
Nunez-Castineyra in prep
(soon :))

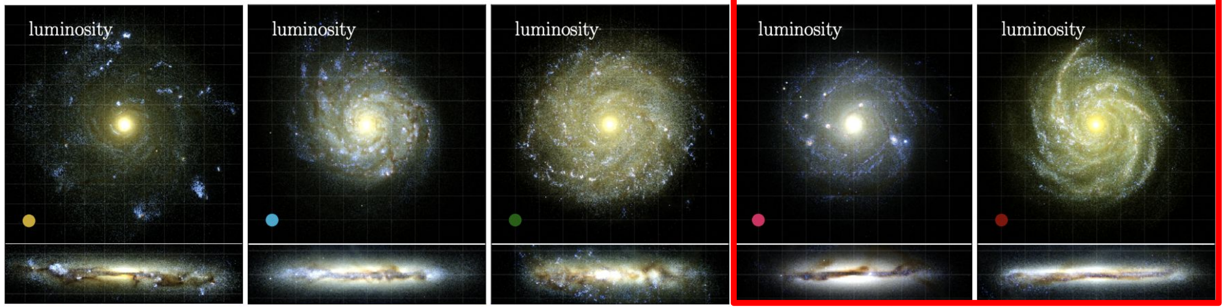


DMO and Benchmark runs

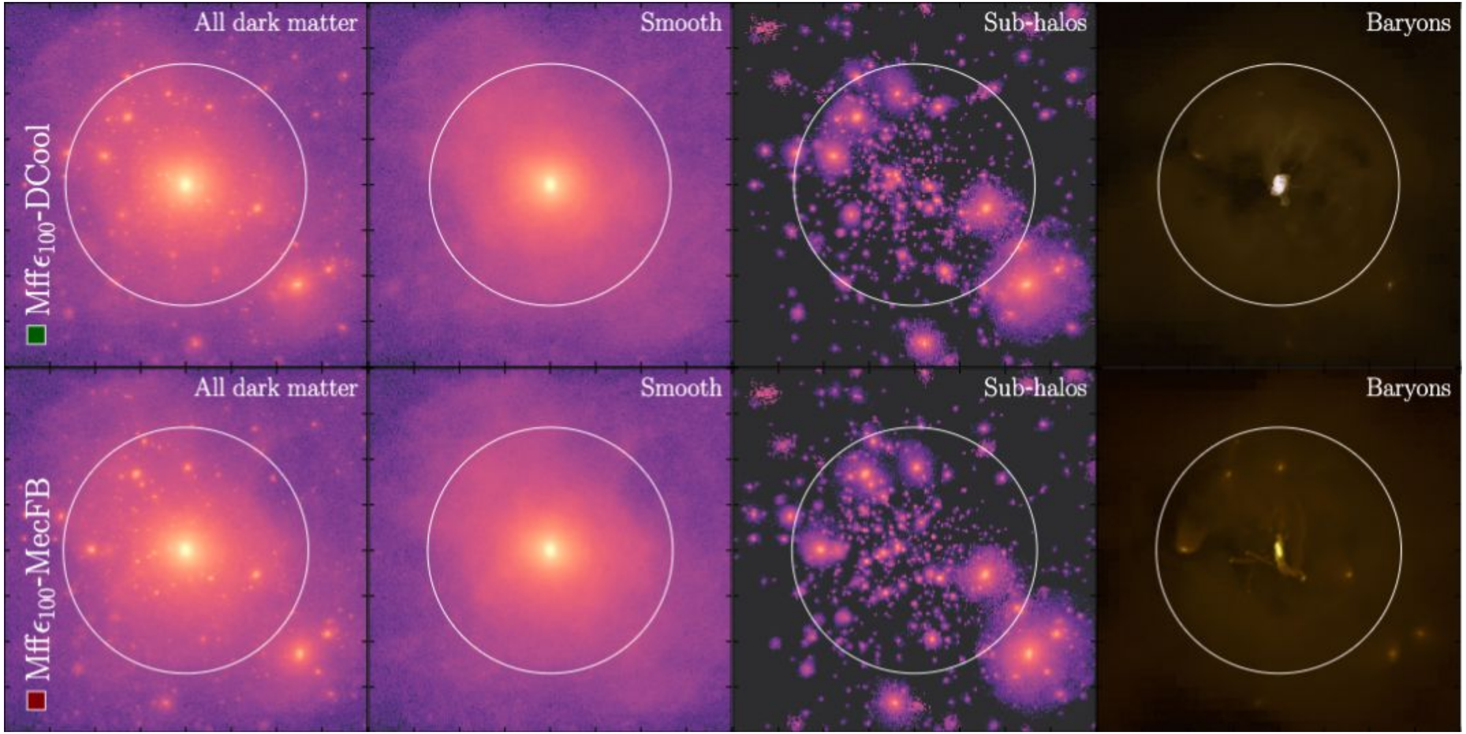


Turbulent SF with protostellar parameter

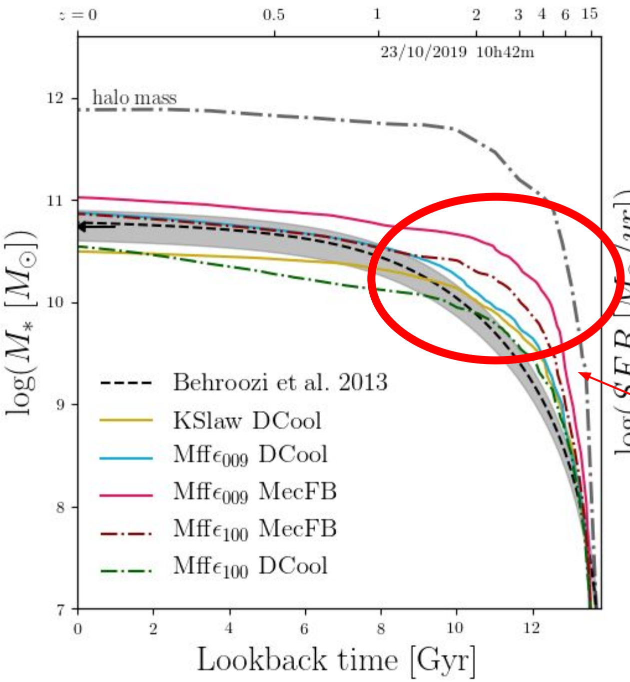




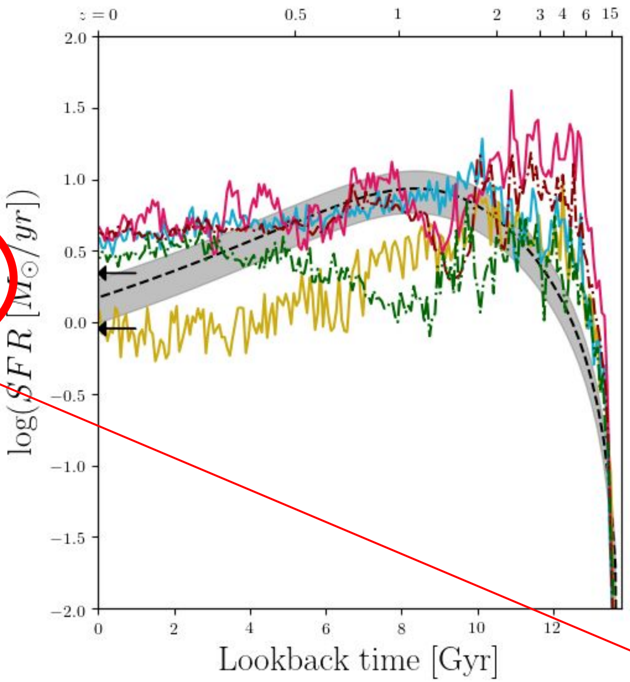
Turbulent SF **without** protostellar parameter



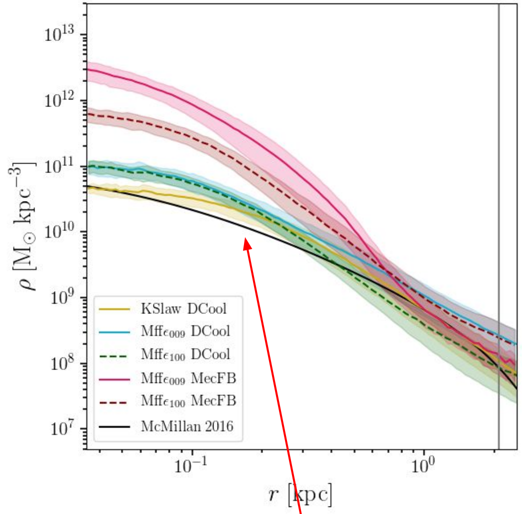
Stellar mass



SFR



Stellar bulge density profile

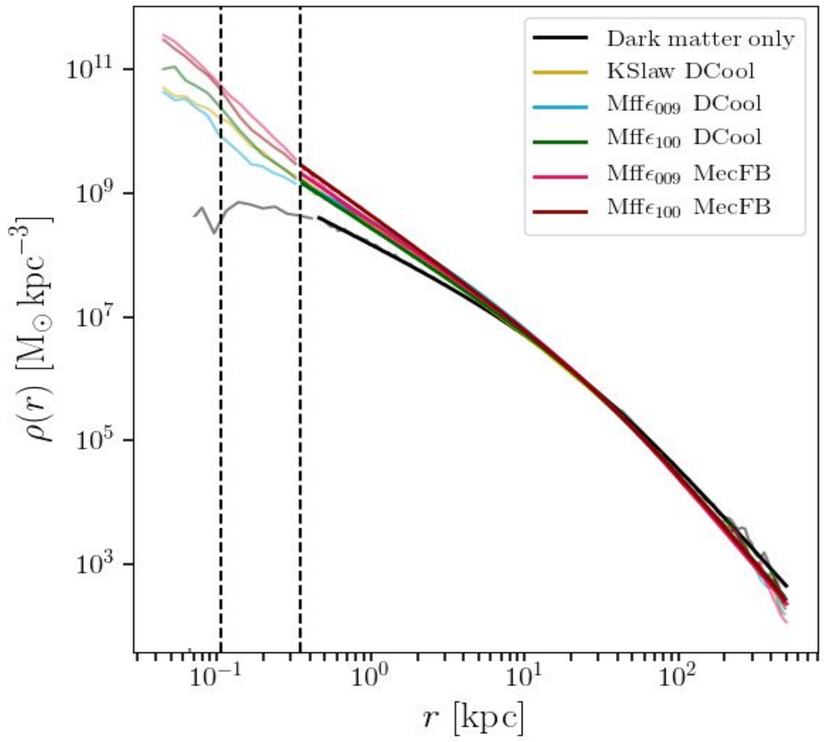


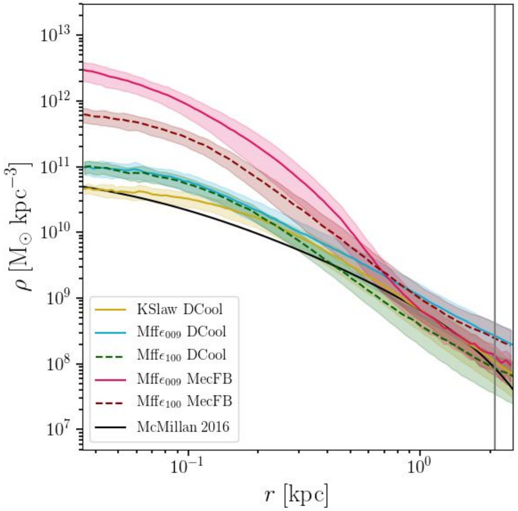
Bulge?

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

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

Dark matter distribution

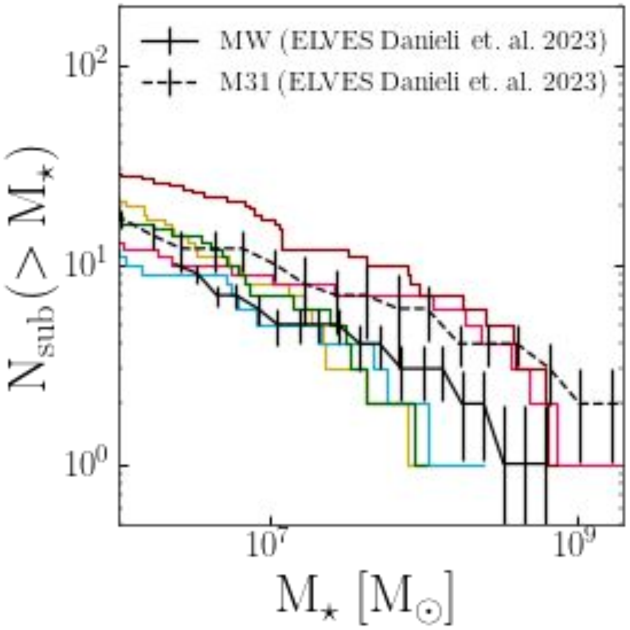




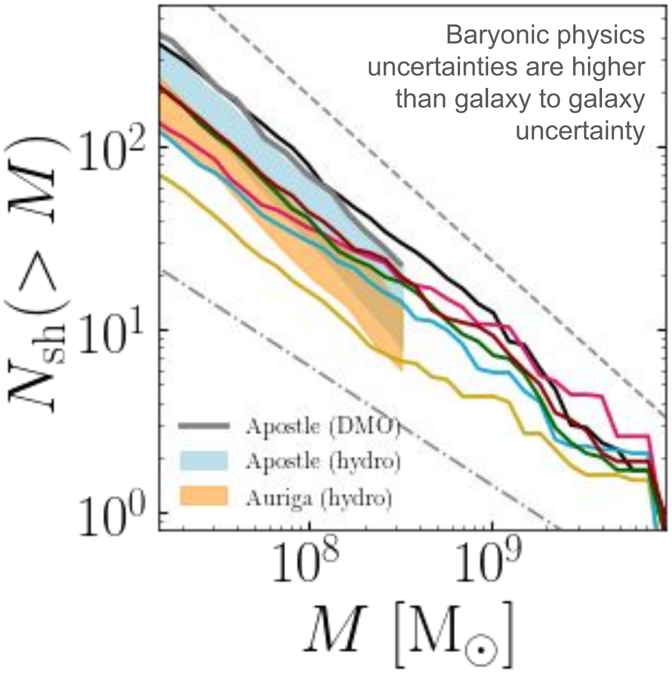
The DM halos are very cuspy. They suffer adiabatic contraction which intensities are related to the bulge size.

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

Subhalos

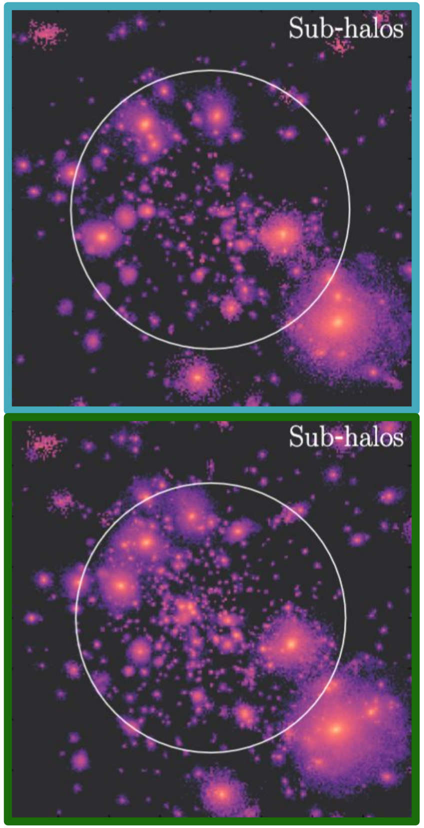


Stellar mass compared to satellites from MW and M31



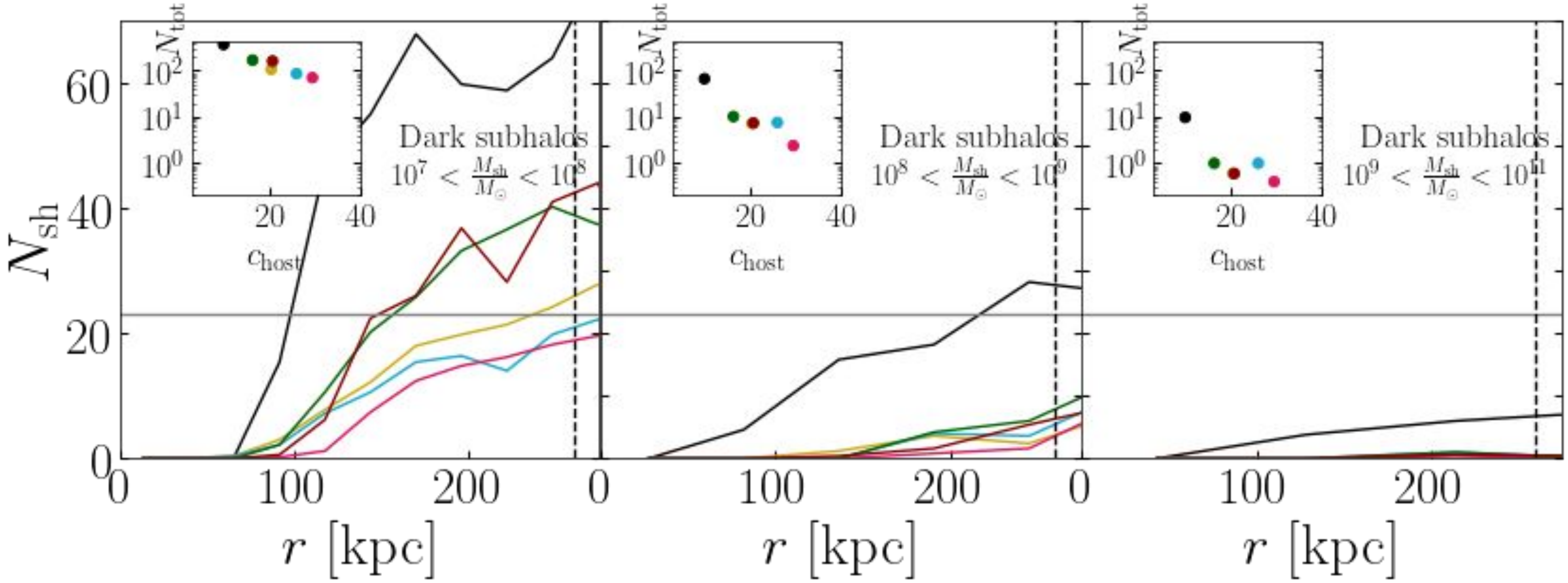
Subhalo dark matter mass

With protostellar parameter ϵ~0.1



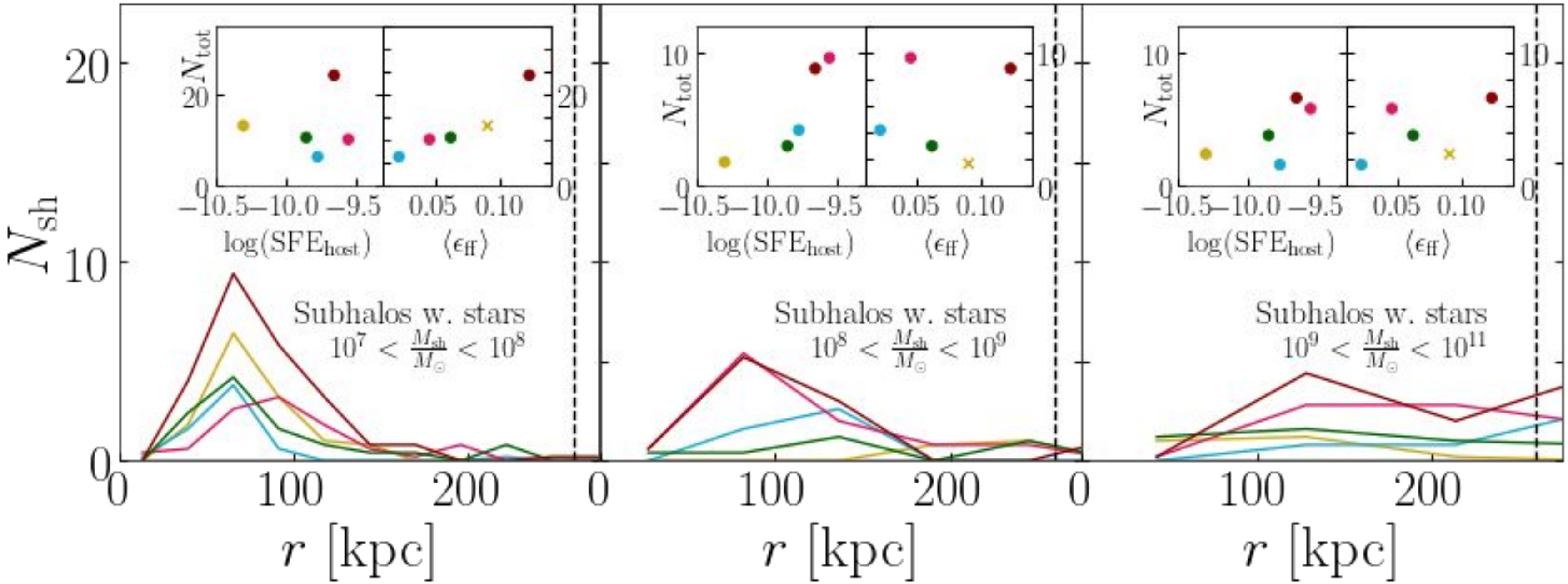
With no protostellar parameter ϵ~1

Subhalos without stars



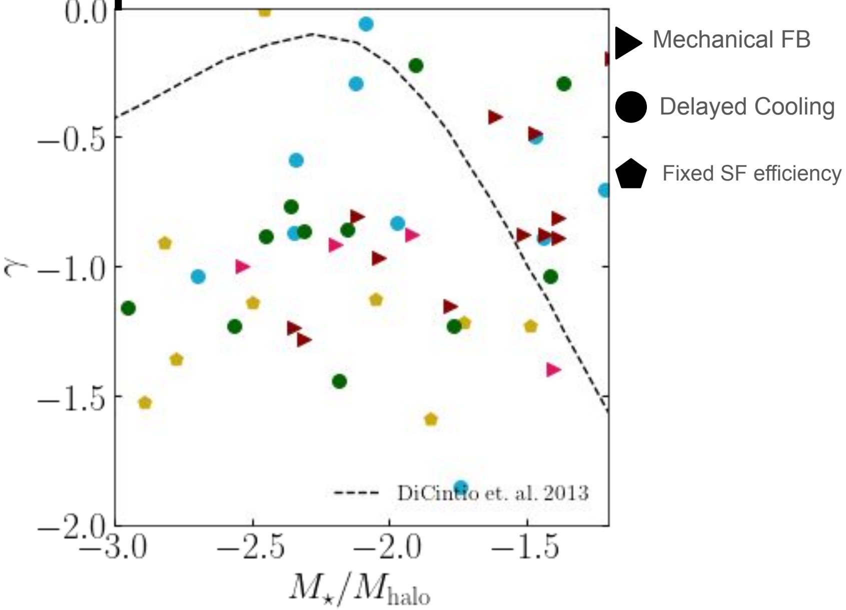
- The fraction of star populated subhalos increases with subhalo mass
- The total number of subhalos is related to the host halo concentration

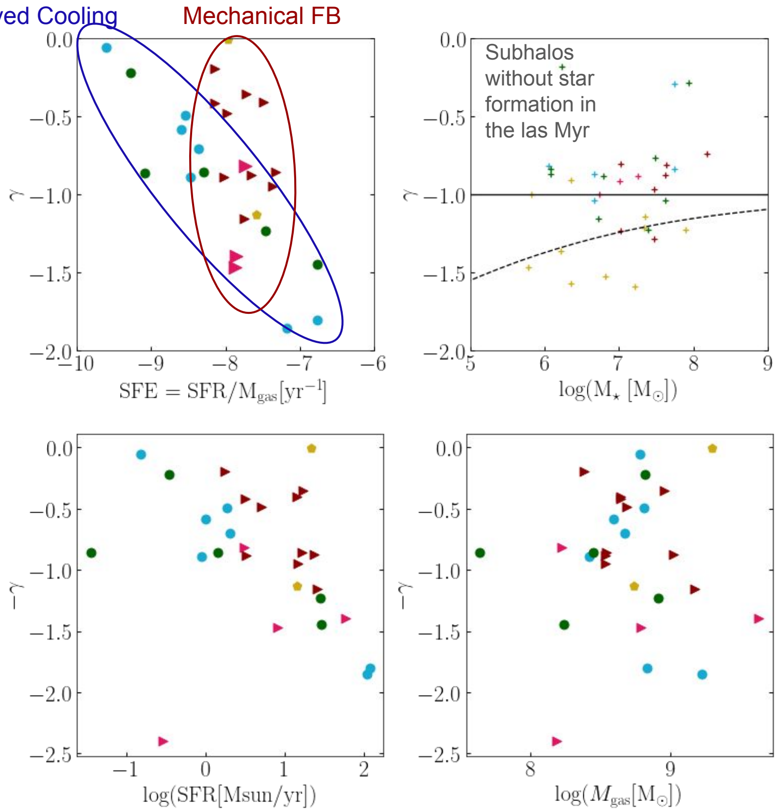
Subhalos with stars



- Low mass star populated subhalos are found in the inner halo and seem to be related to the star formation efficiency in the subgrid physics implementation. (resolution?)
- Higher mass subhalos seem to behave like galactic environment

Subhalos density inner slope





No relation between Mstar/Mhalo is observed

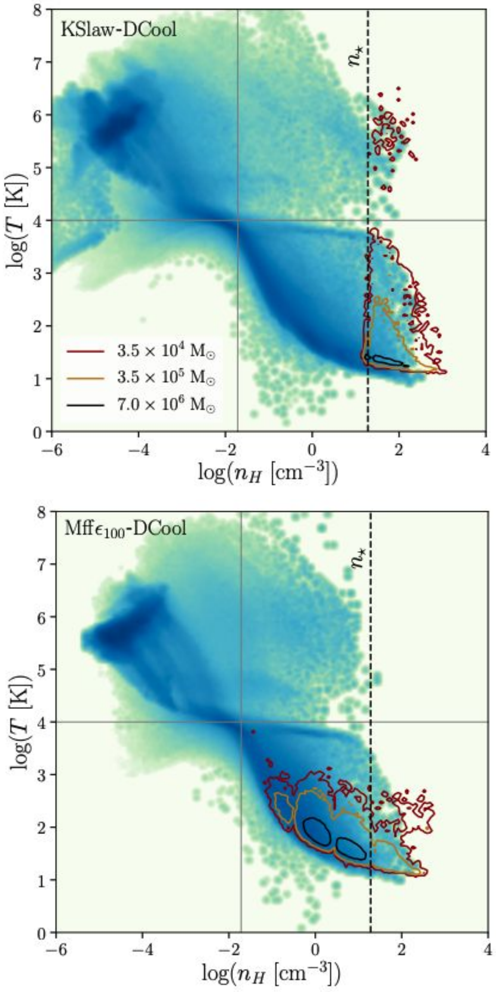
Summary

Baryons can solve many of the current tensions but their modeling is not under control.

We see effect in the subhalo resilience related to the models in baryonic physics

The uncertainties related to the modeling of baryons are important

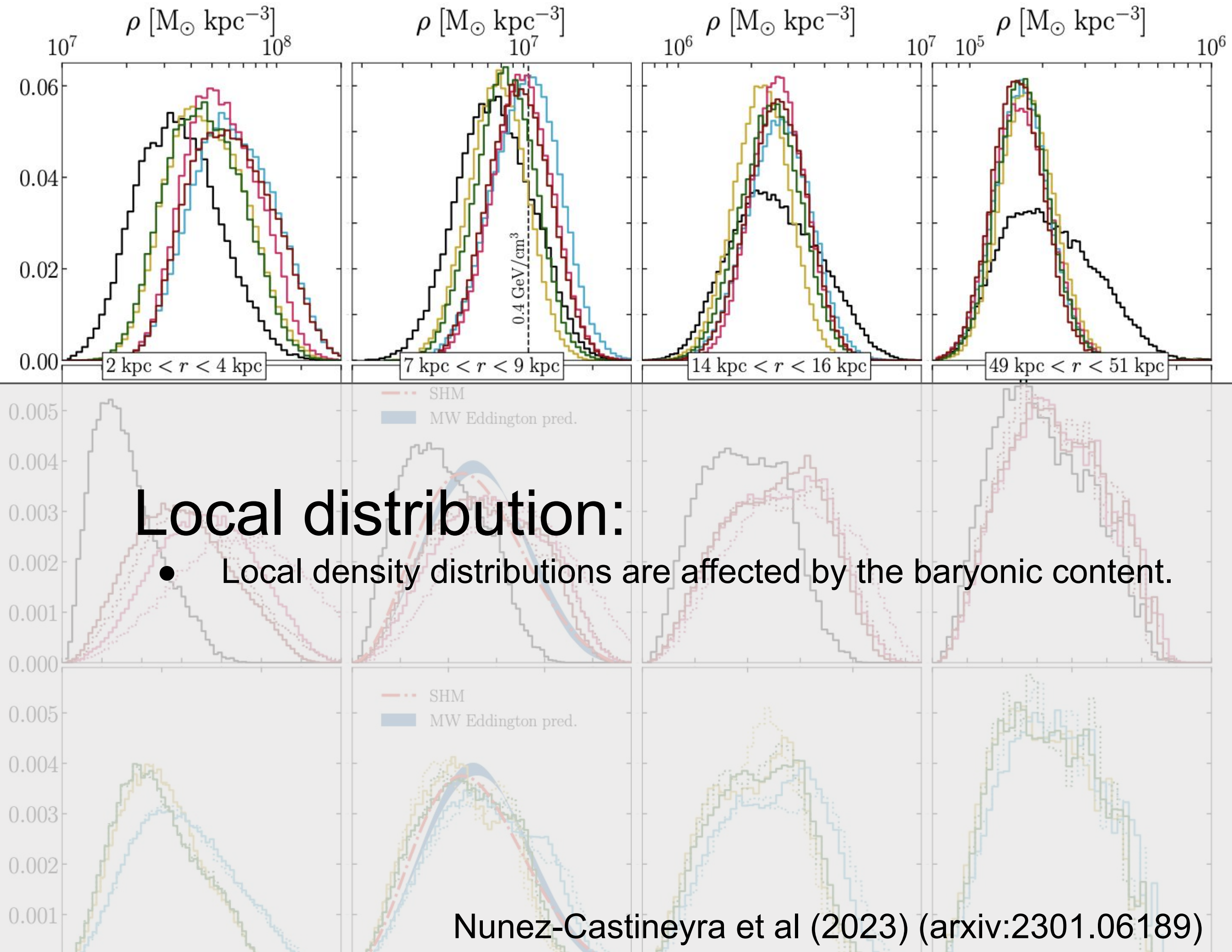
We need to be careful



Thank you

Local distribution:

- Local density distributions are affected by the baryonic content.

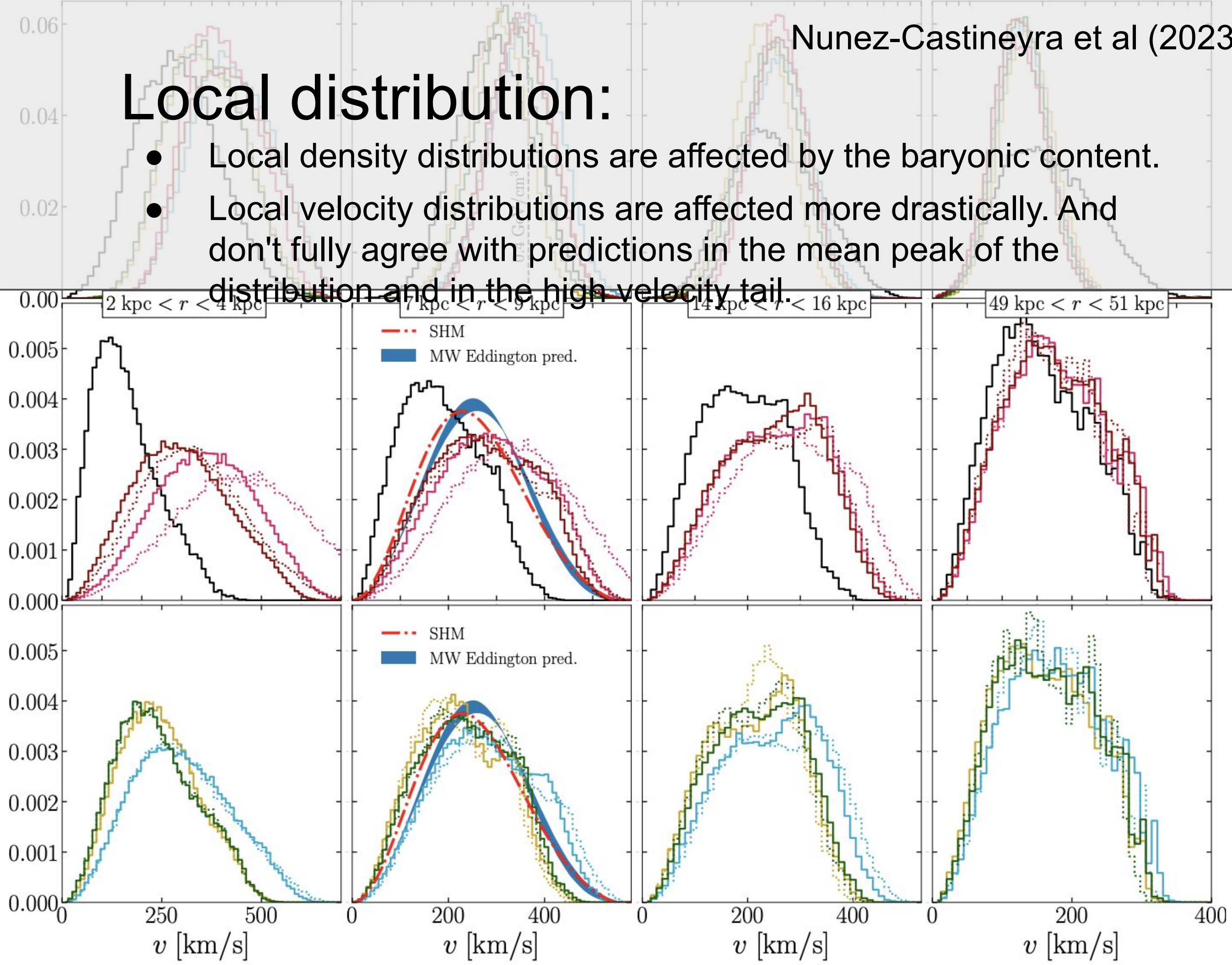


Nunez-Castineyra et al (2023) (arxiv:2301.06189)

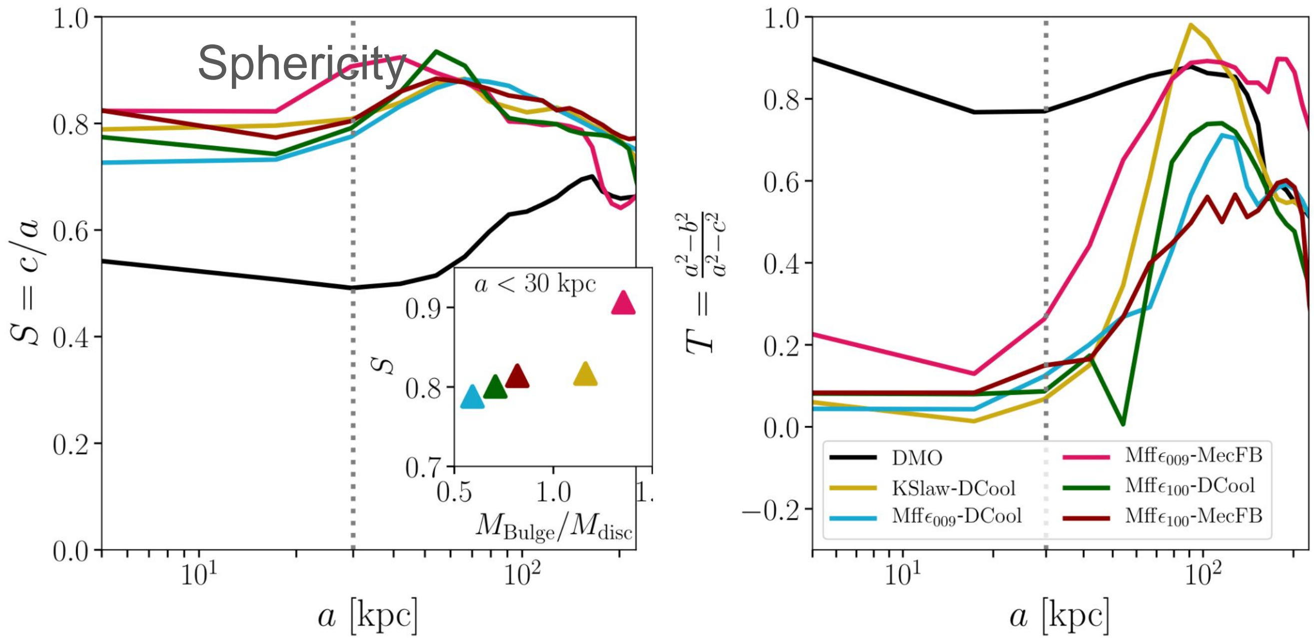
Nunez-Castineyra et al (2023) (arxiv:2301.06189)

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

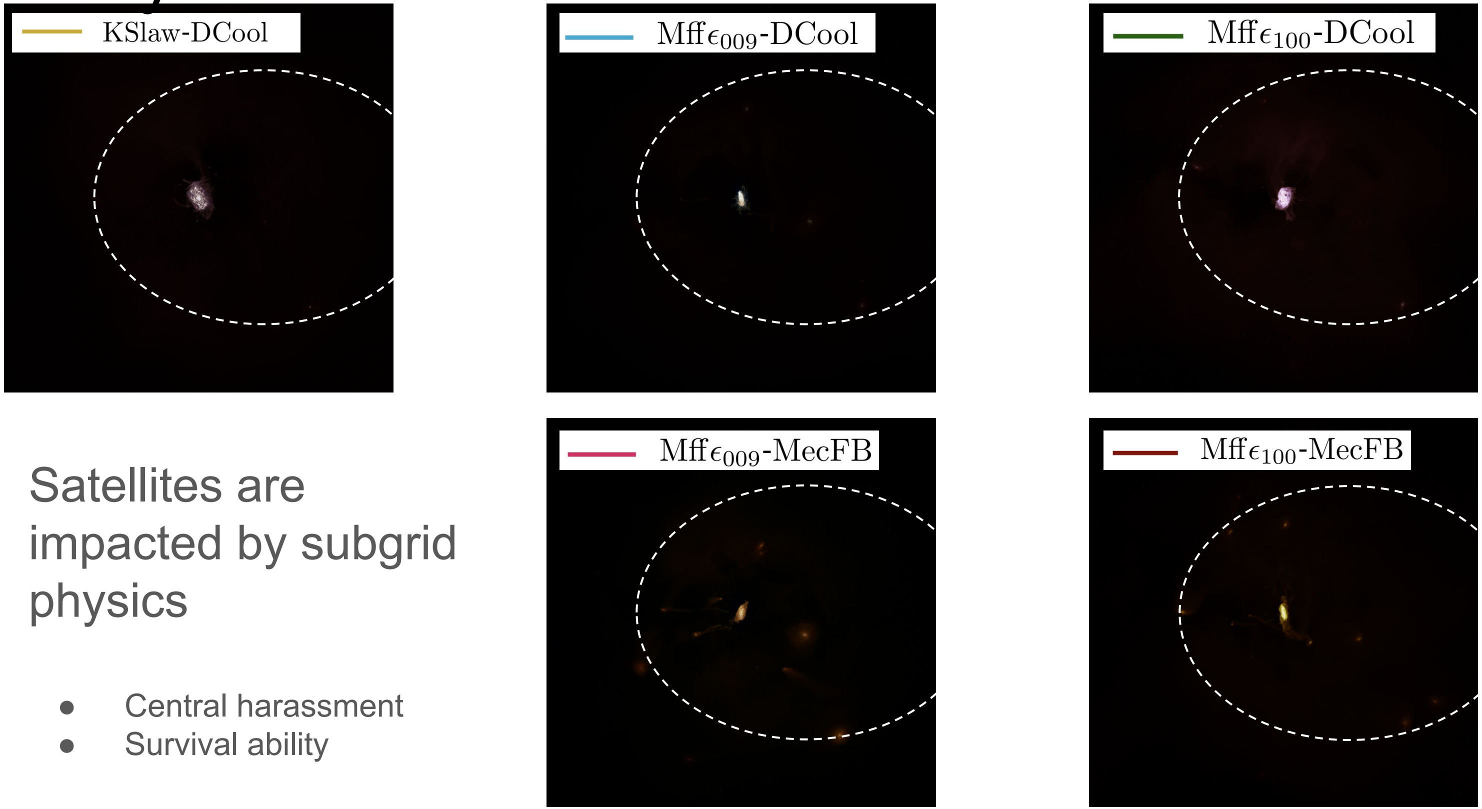


Triaxiality

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

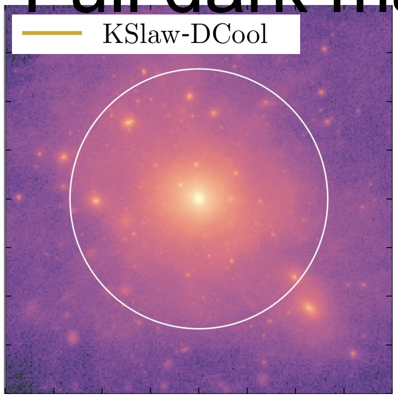


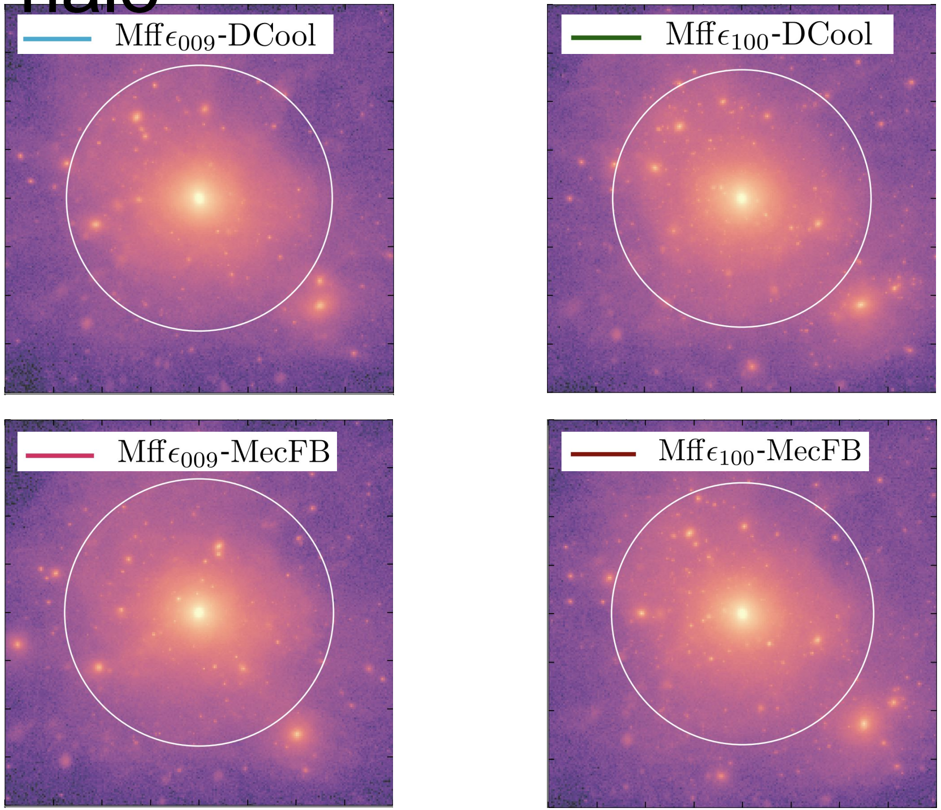
Satellites are impacted by subgrid physics

- Central harassment
- Survival ability

Nunez-Castineyra et al (in prep)

Full dark matter halo



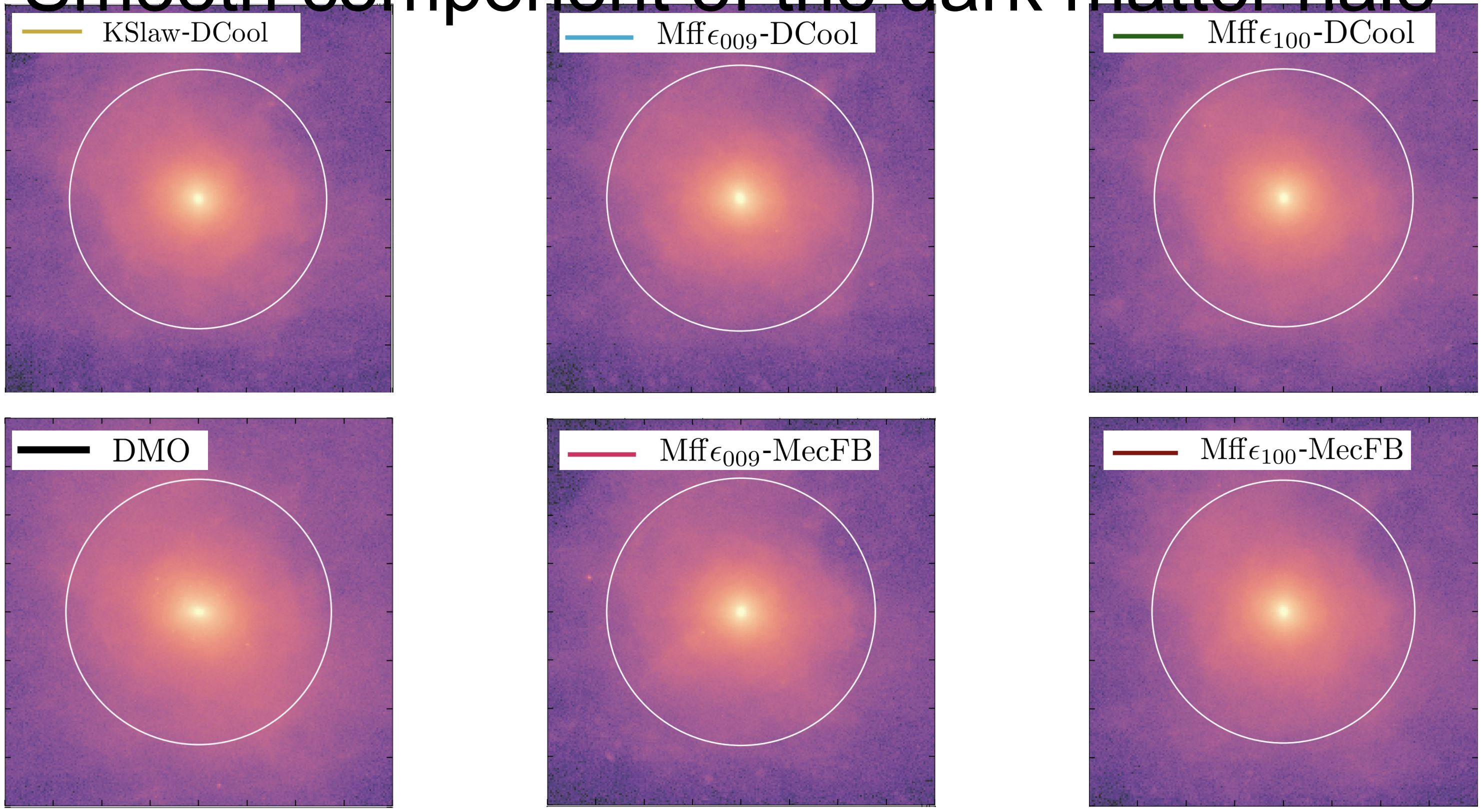


Satellites are impacted by subgrid physics

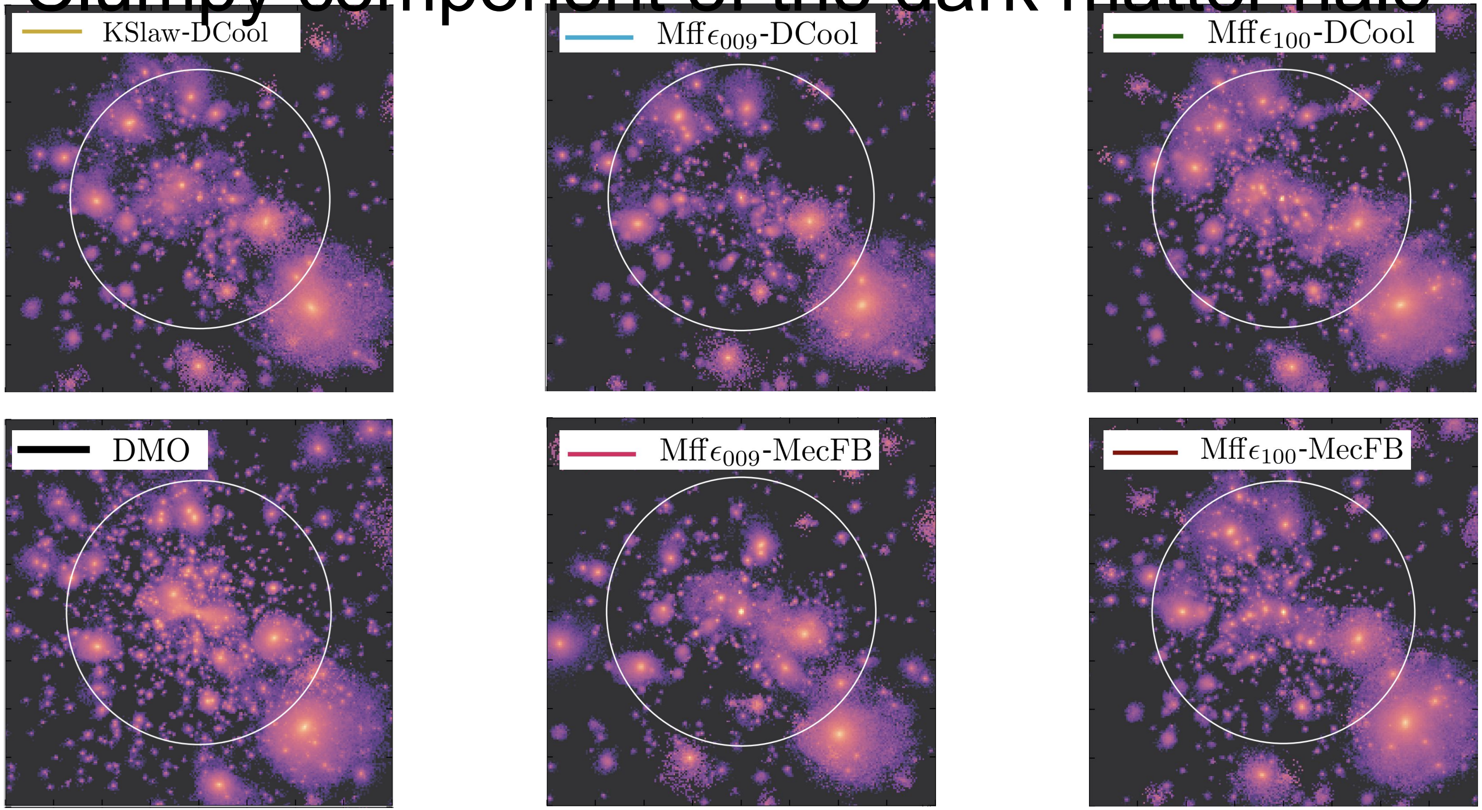
- Central harassment
- Survival ability

Nunez-Castineyra et al (in prep)

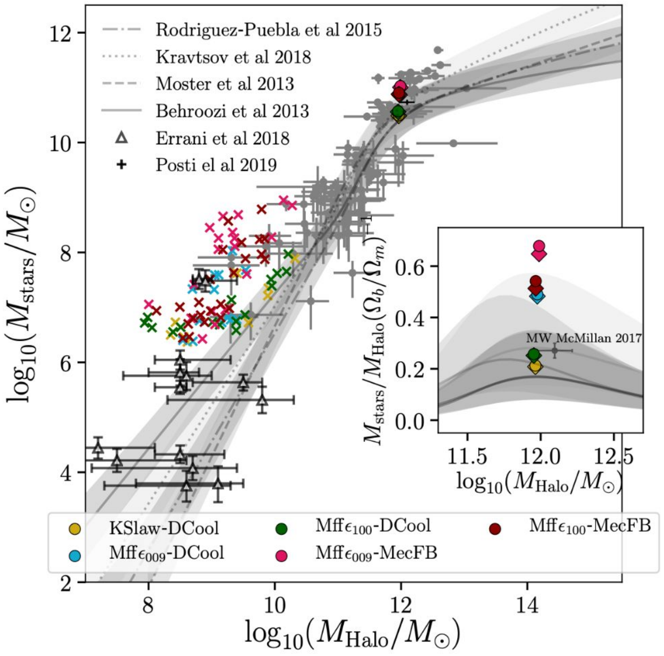
Smooth component of the dark matter halo

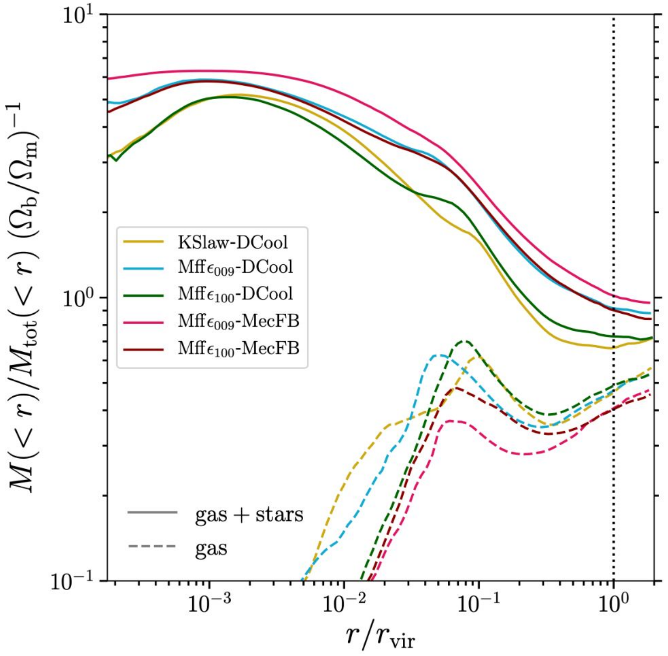


Clumpy component of the dark matter halo



Dark matter content



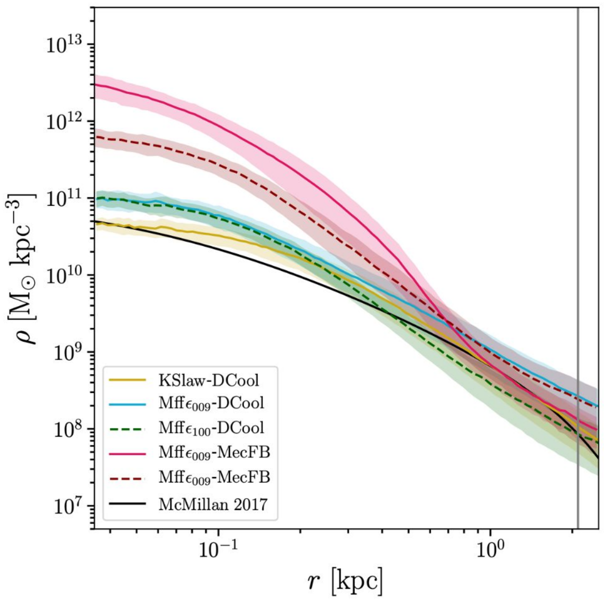


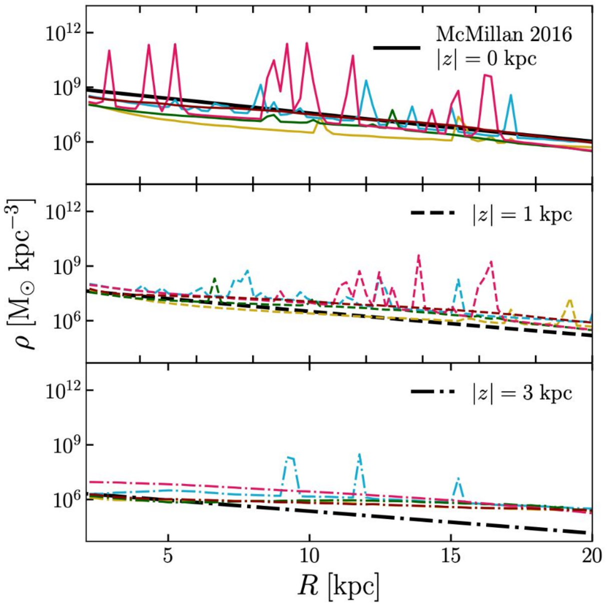
The Mochima suite is in good agreement with SHMR and the cosmological matter content

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

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)