The Mochima simulation

Satellite properties,
the role of baryonic physics and star formation history in shaping dark matter cores/cusps

Arturo Núñez-Castiñeyra

Collaborators:
Emmanuel Nezri, Pol Mollitor, Leo Michel-Dansac,
Julien Devriend and Romain Teyssier

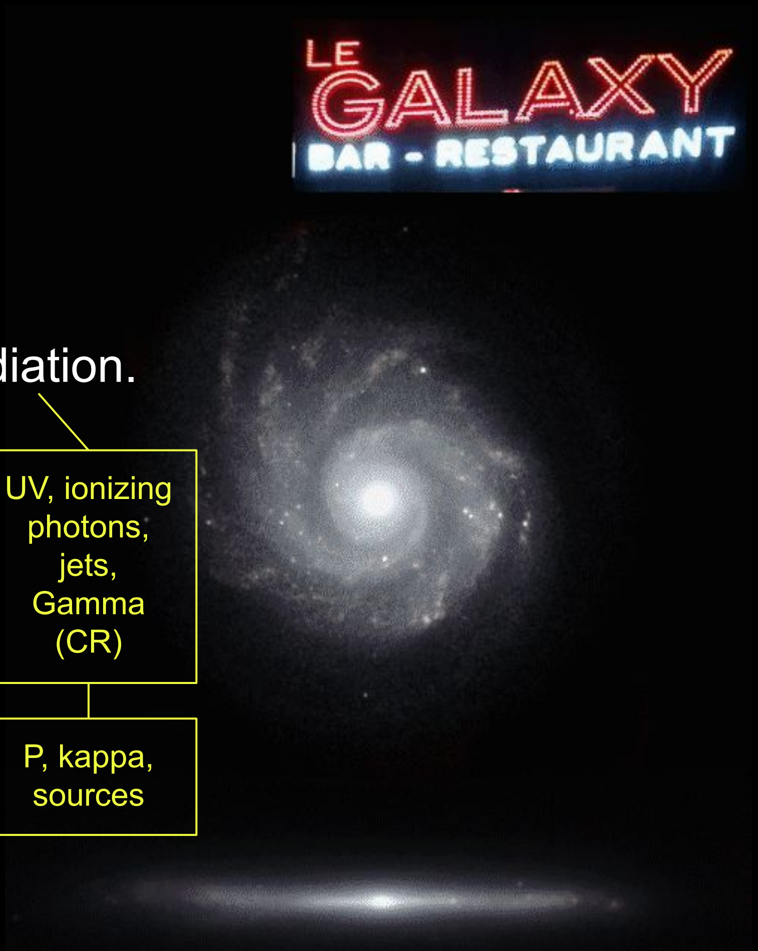
P1:arXiv:2004.06008, P2 :arXiv:2301.06189 and P3: 2509.07470 (submitted)

News from the dark - Montpellier 2025

What is a Galaxy and what can we simulate inside a galaxy

Galaxy : dark matter, stars, gas, black holes, radiation.

- dark matter:
  - Cold
  - Warm
  - Fuzzy
  - SIDM
  - …
  - M, v, x
- stars:
  - M,dwarfs,giants, O/B, Remants
  - M,v,x,age, metallicity
- gas:
  - Atoms, Molecules and Dust
  - M,v,x,T,Ch, heating/cooling rates, metallicity
- radiation:
  - UV, ionizing photons, jets, Gamma (CR)
  - P, kappa, sources



What are the right ingredients?

What is a Galaxy and what can we simulate inside a galaxy

feedback

Galaxy : dark matter, stars, gas, black holes, radiation.

Cold
Warm
Fuzzy
SIDM
…

M, v, x

M,dwarfs, ants, O/B, Remants

Star formation

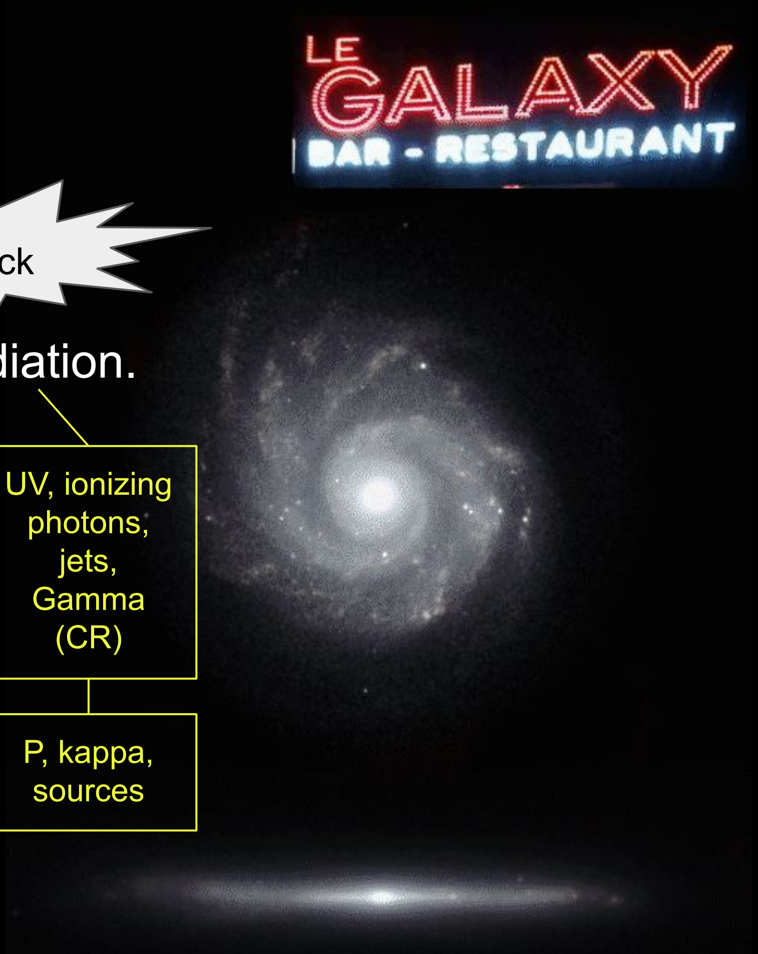
feedback

Atoms, Molecules and Dust

M,v,x,T,Ch, heating/cooling rates, metallicity

UV, ionizing photons, jets, Gamma (CR)

P, kappa, sources



What are the right ingredients?

What is a Galaxy and what can we simulate inside a galaxy

feedback

Galaxy : dark matter, stars, gas, bla ck holes, radiation.

Cold
Warm
Fuzzy
SIDM
…

M, v, x

M,d
ants

star form n

A ms,
cules
D

ates,
met licity

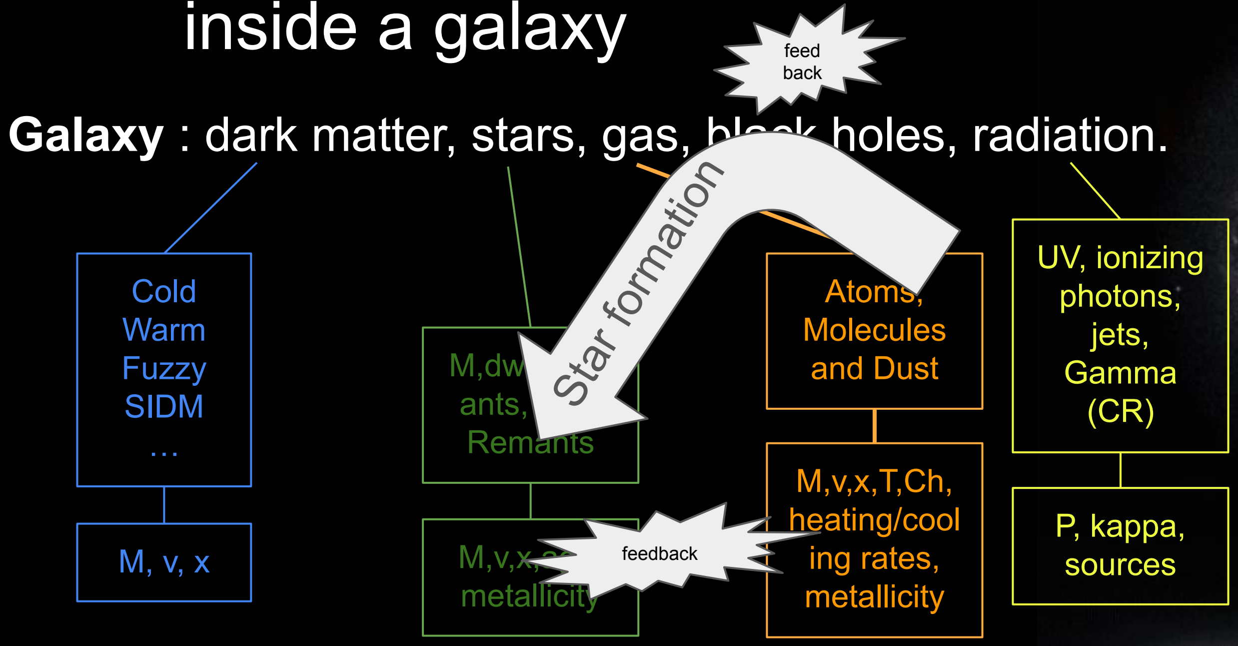
UV, ionizing photons, jets, Gamma (CR)

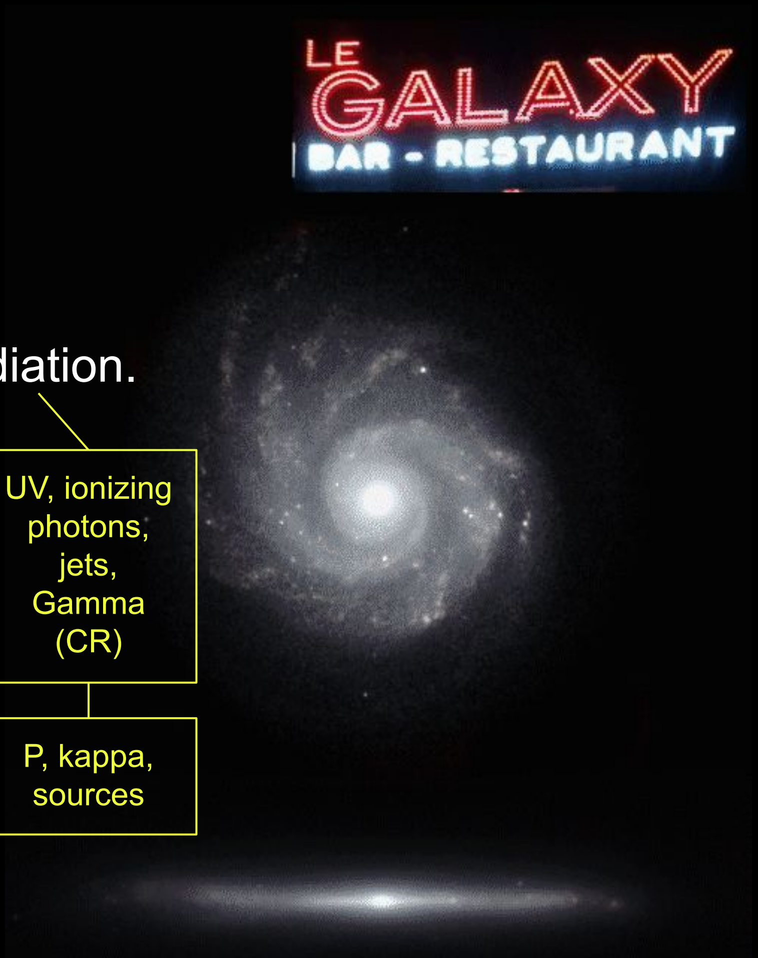
P, kappa, sources

feedback

What are the right ingredients?

What is a Galaxy and what can we simulate inside a galaxy





What are the right ingredients?

dark matter, stars, gas

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**:

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

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

A system of three conservation laws + EoS (hydro)

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

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

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

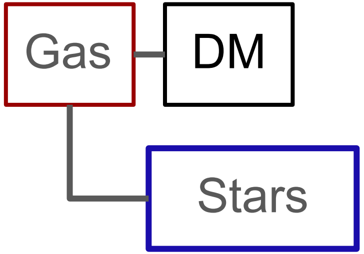
Add gravity and heating and cooling rates. (this can be expanded to include magnetic fields as well)

Plus:

- Clever computing strategies
- heating/cooling rates
- Star formation strategies
- Feedback energy injections

Starting from IC that resemble the early universe → **Realistic galaxies** that we can learn from

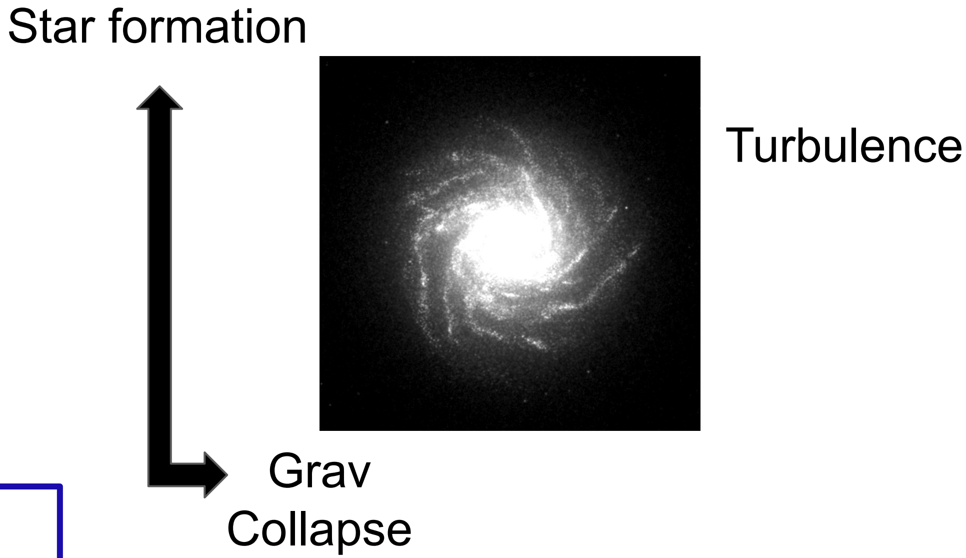
What is a Galaxy and how to simulate it



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



What is a Galaxy and how to simulate it

Gas — DM

Stars

We need an effective model

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

Ruled by the star formation efficiency

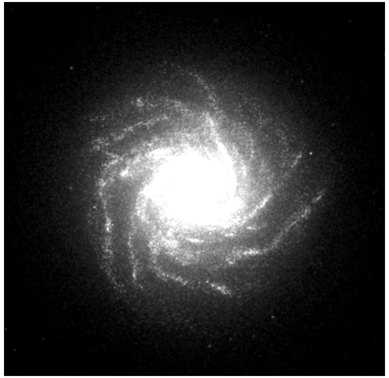
- Constant efficiency galaxy wide
- Environmental dependent efficiency

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

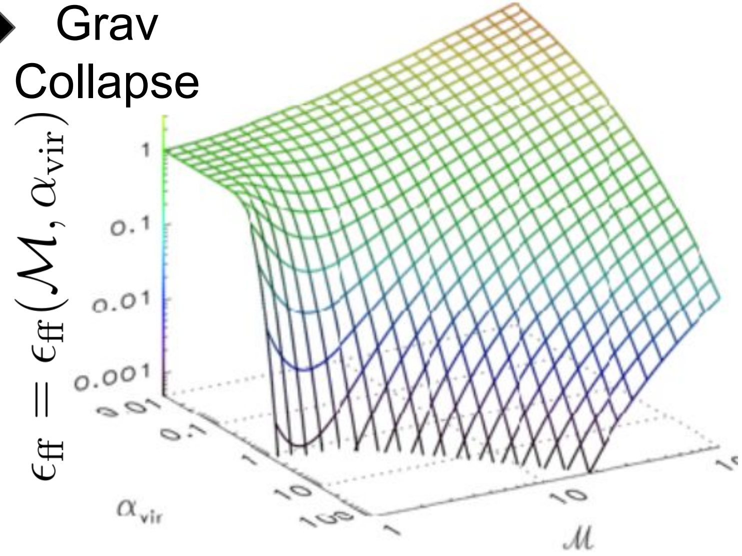
Multi-freefall star formation (Federrath & Klessen (2012))

Star formation

Turbulence



Grav Collapse



What is a Galaxy and how

Star formation

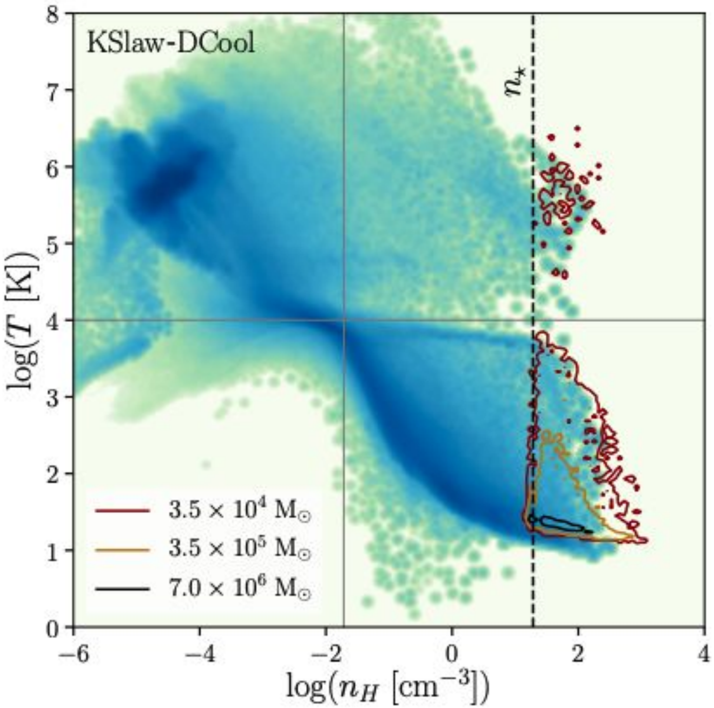
Gas

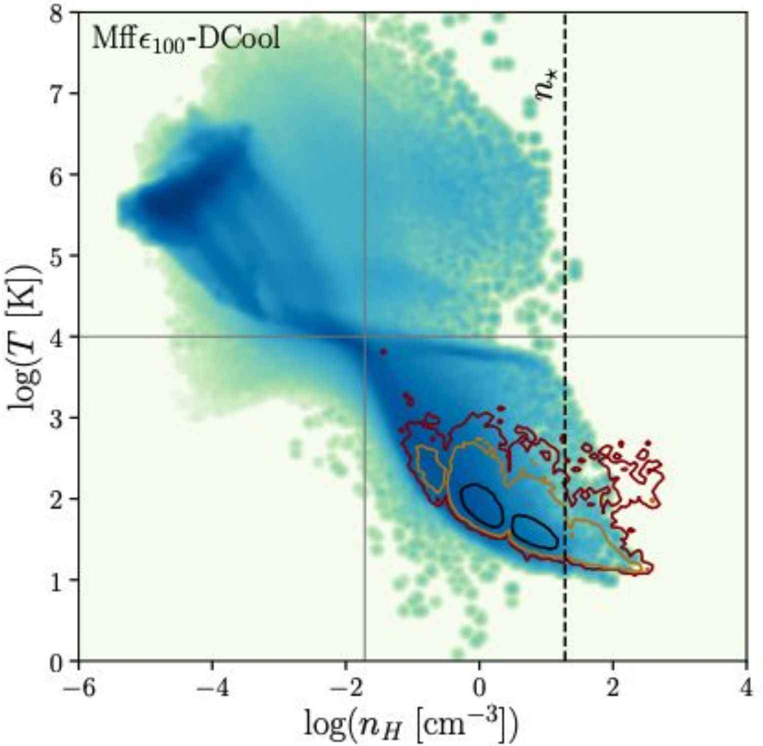
DM

Sta

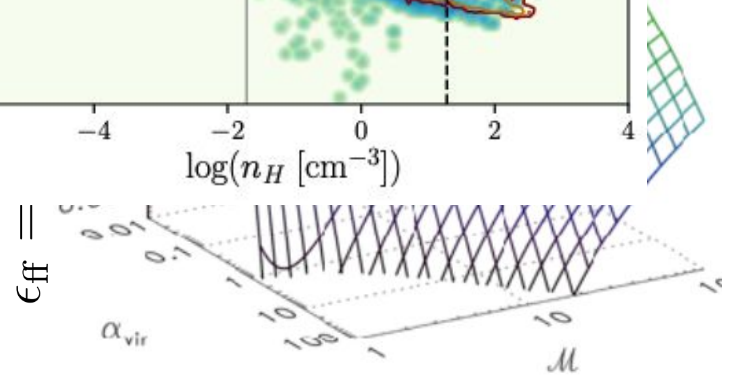
ence

- Con
- Env



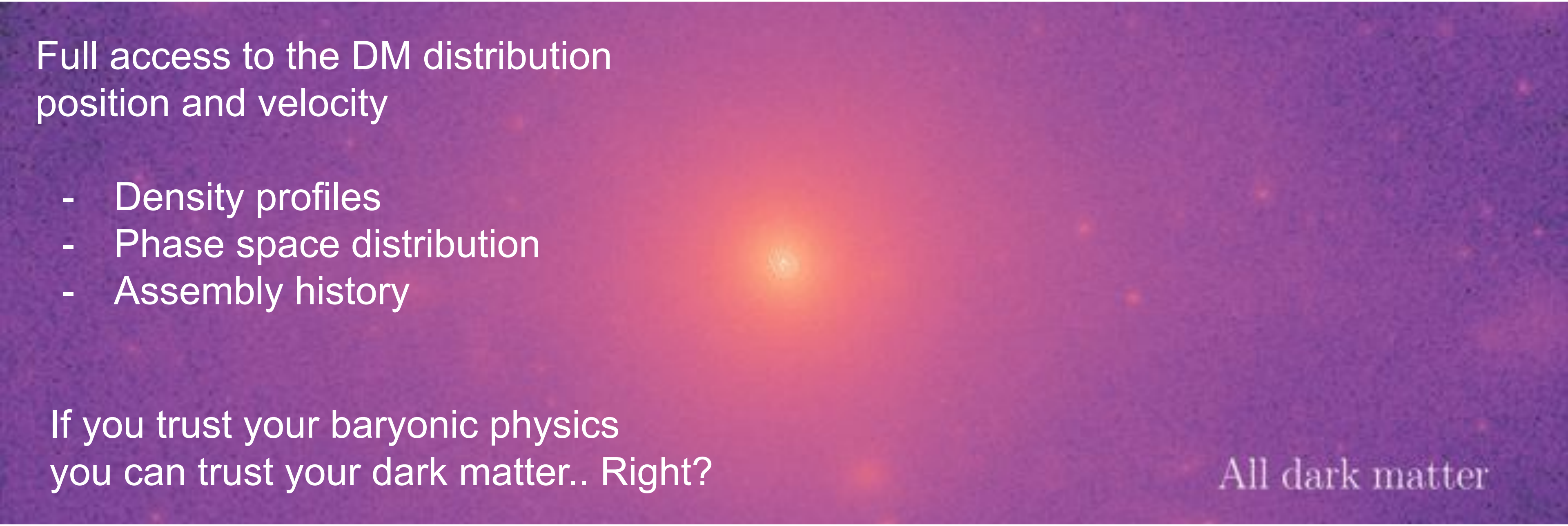


$$\epsilon_{\rm ff} = \epsilon_{\rm ff}(\mathcal{M}, \alpha_{\rm vir})$$



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

Dark matter content



Full access to the DM distribution
position and velocity

- Density profiles
- Phase space distribution
- Assembly history

If you trust your baryonic physics
you can trust your dark matter.. Right?

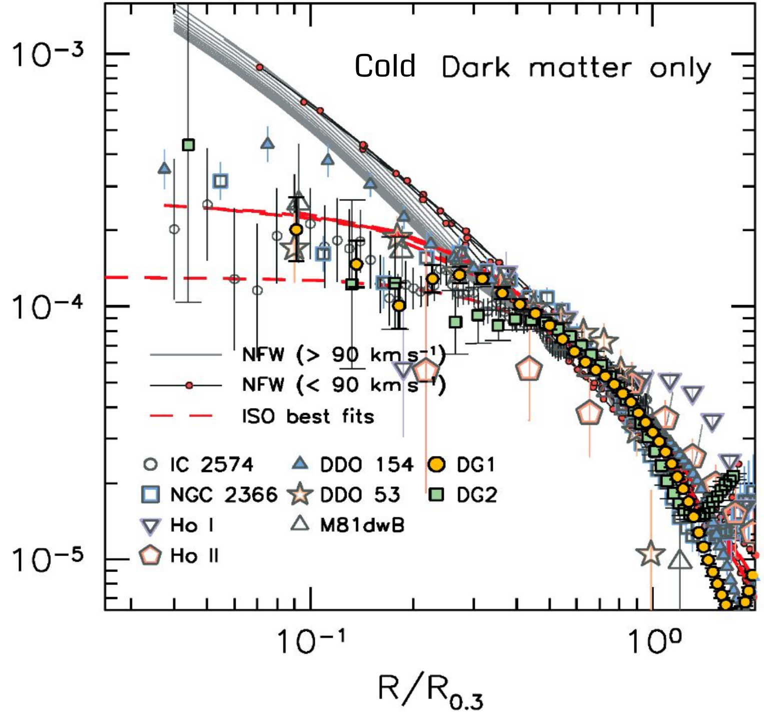
Then you can compare with observations.. Right?

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)

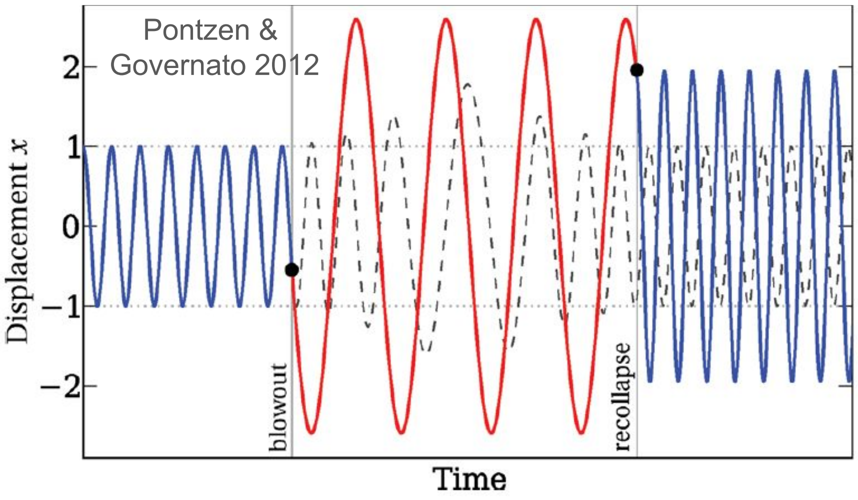
- **Missing satellites situation** (?)
  Simulations predict higher number of satellites than what is observed.

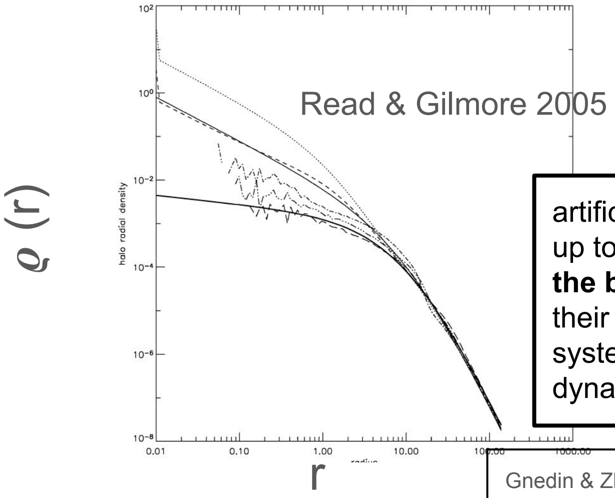


Then you can compare with observations.. Right?

Dark matter cusp core transformation

Dark matter density profile after repeated cycles of gas inflow (slow, adiabatic) and rapid gas removal (impulsive).





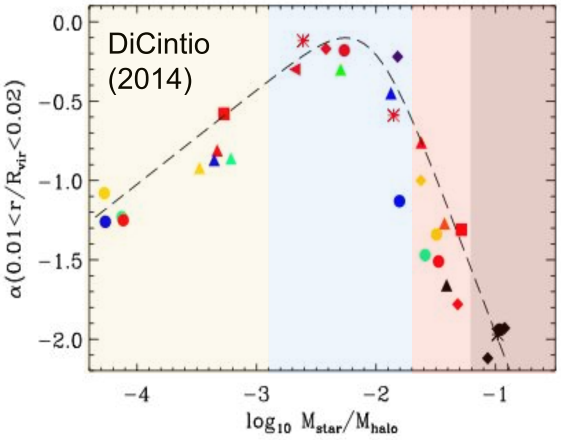
artificially removing up to **95–99% of the baryons** from their N-body systems in one dynamical time

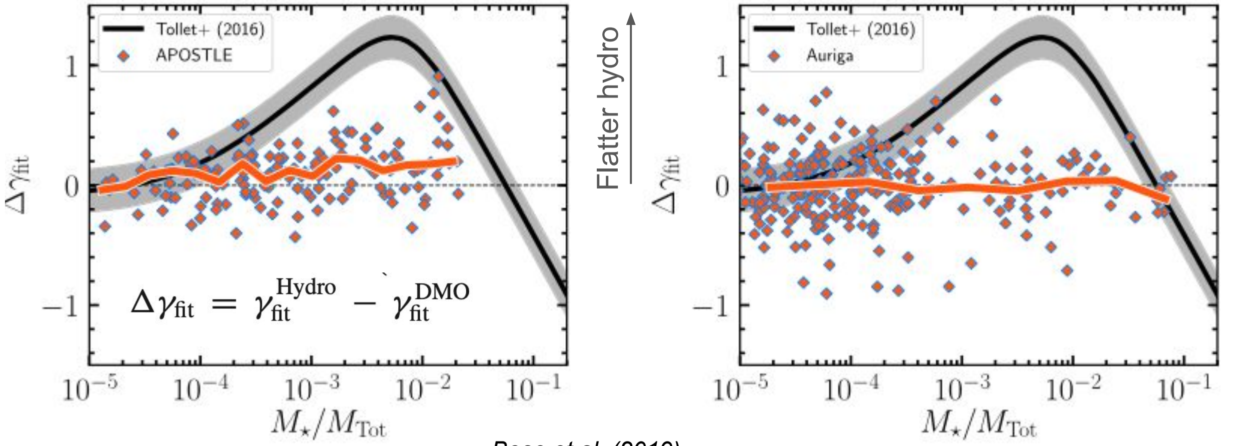
Gnedin & Zhao (2002) showed that one blowout is insufficient

- if the central potential fluctuates **faster than the dynamical time**, changes are *impulsive* and irreversibly transfer energy to the collisionless DM.
- Repeated episodes of gas inflow, star formation, and supernova-driven blowout → repeated potential fluctuations → DM orbits migrate outward → cusps flatten into cores.

Governato 2009, El-Zant et al 2016, Freundlich et al 2020, li et al 2022. (not an exhaustive list)

Baryons complicate the story but could solve the problems





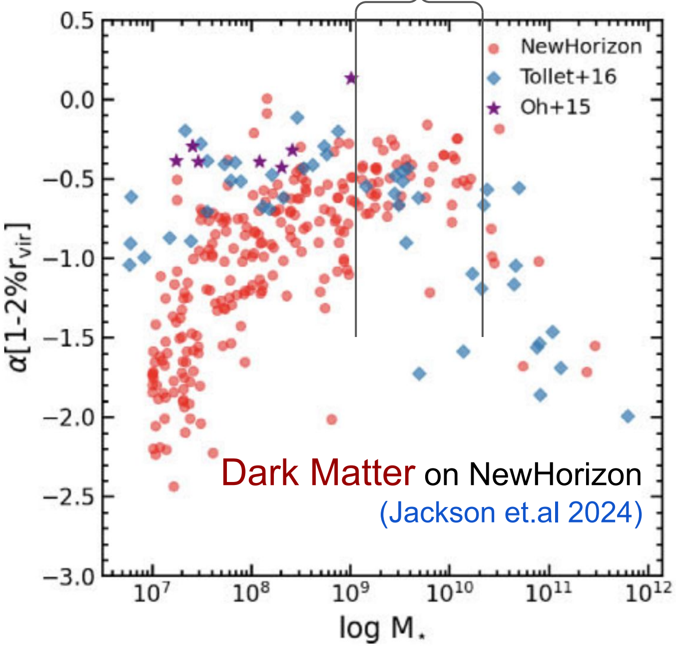
Bose et al. (2019)

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

NIHAO: Cores are likely created by a very strong FB

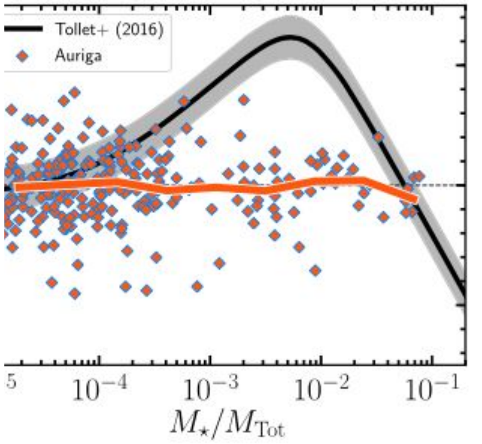
APOSTLE and Auriga: do not find evidence of core formation at *any* mass or any correlation between the inner slope of the DM density profile and temporal variations in the SFH

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;



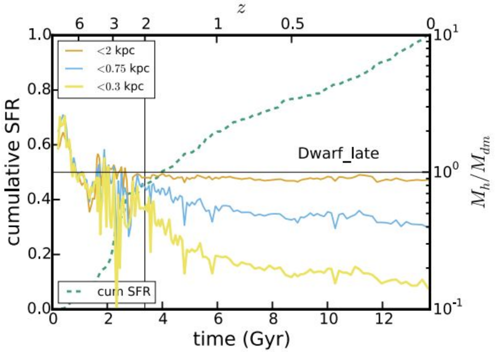
NIHAO: Cores are likely created by a very strong FB

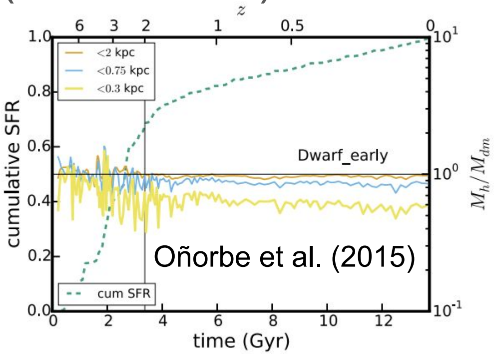
APOSTLE and Auriga: do not find evidence of core formation at *any* mass or any correlation between the inner slope of the DM density profile and temporal variations in the SFH

profiles.

- Central stars deepen gravity enough to counter expansion, resulting in cuspier profiles.

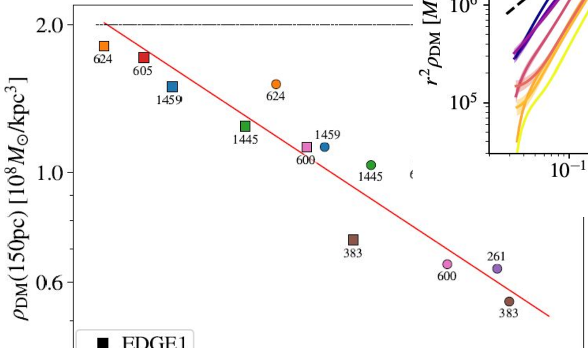
Hints on: Stars vs central DM density
(simulations)

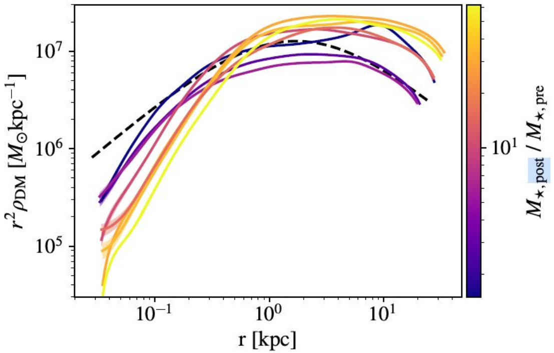




Oñorbe et al. (2015)

$M_{\star,pre}$= Stellar mass pre z~6
$M_{\star,post}$= Stellar mass post z~6



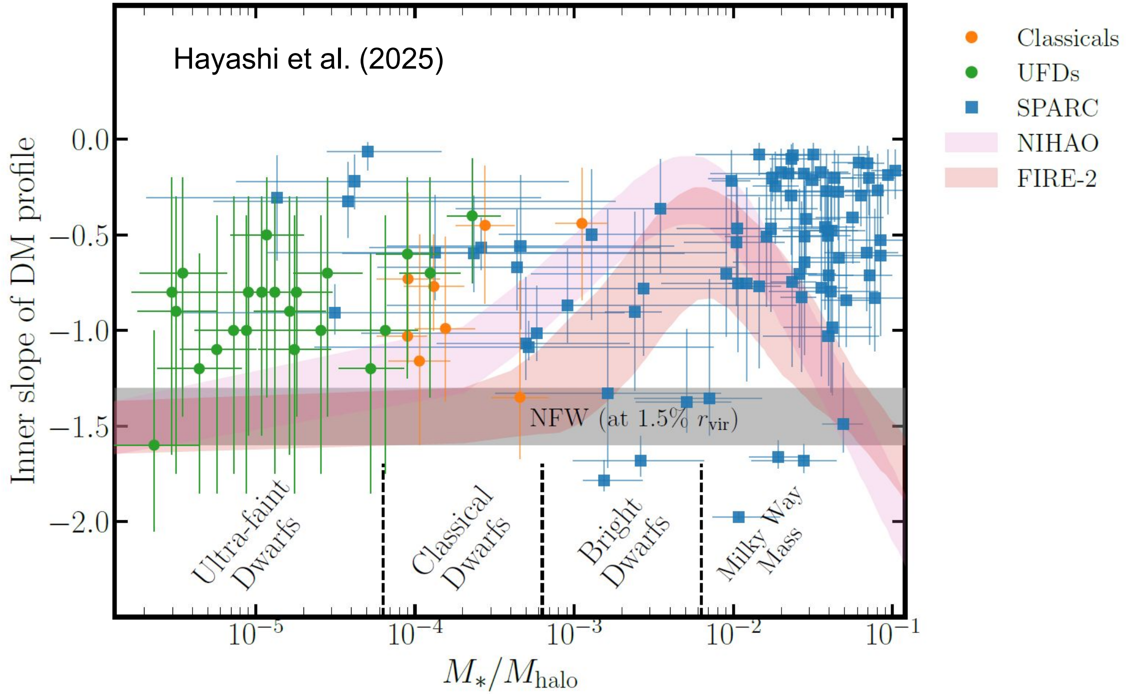


Muni et al. (2025)

- *Single* blowout is insufficient. (Gnedin & Zhao 2002)
- *Repeated, bursty* star formation cycles drive core formation. (Pontzen & Governato 2012)
- *Early, rapid* star formation (concurrent with halo collapse) is inefficient at creating cores. (Chan 2015 FIRE , Jackson 2023 Newhorizons)
- There seems to be a link between extended SFHs and lower central densities. (Oñorbe et al. (2015), Mun et al 2025)

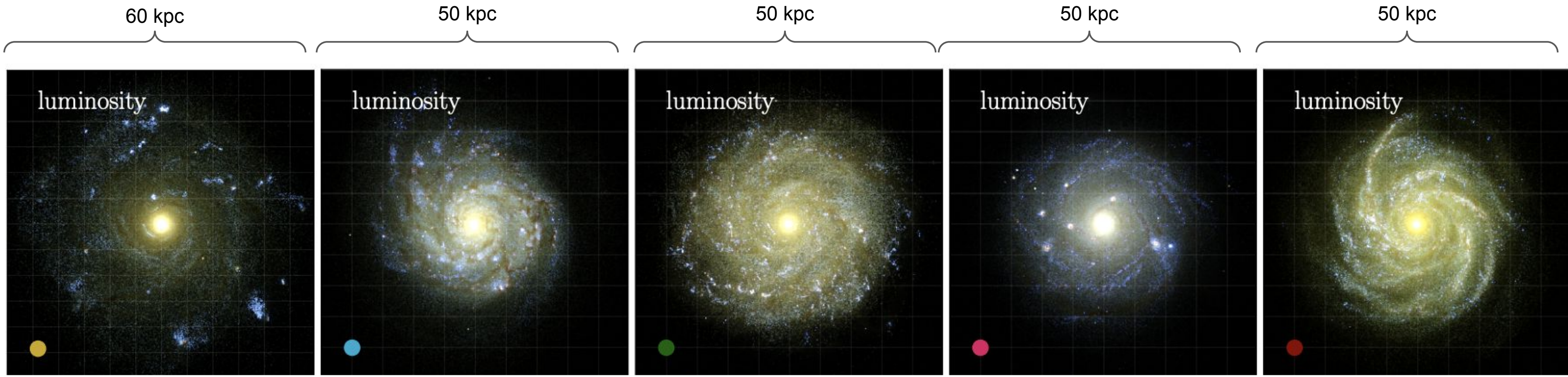
Hints on: Stars vs central DM density

(observations)



"Our findings suggest that baryonic processes may play a significant role in shaping the central dark matter structures and could account for much of the observed diversity, although some discrepancies still remain"

- Oman et al. (2015): large diversity in dwarf galaxy rotation curves at fixed stellar mass, suggesting another parameter (likely SFH) matters.
- Read et al. (2019): extended SFHs→ lower central DM densities.
- Bouché et al. (2022); Collins & Read (2022): correlation between prolonged SF and shallower cores.
- Hayashi et al. (2025): 115 SPARC galaxies, from cores (γ ≈ 0) to cusps (γ ≈ 2). Scatter is larger than in simulations, suggesting baryonic assembly and SF/FB histories drive the diversity.



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
(~2e4 Msun collisionless particles)

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

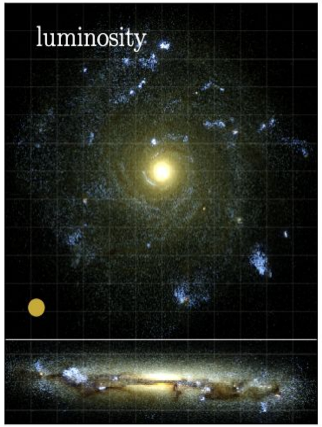
Nunez-Castineyra et al (2020)
(arxiv:2004.06008)

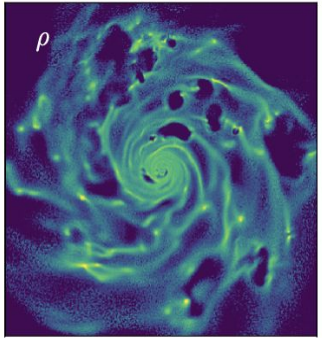
Same galaxy, same initial conditions, different baryonic physics (SN and SF)

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.

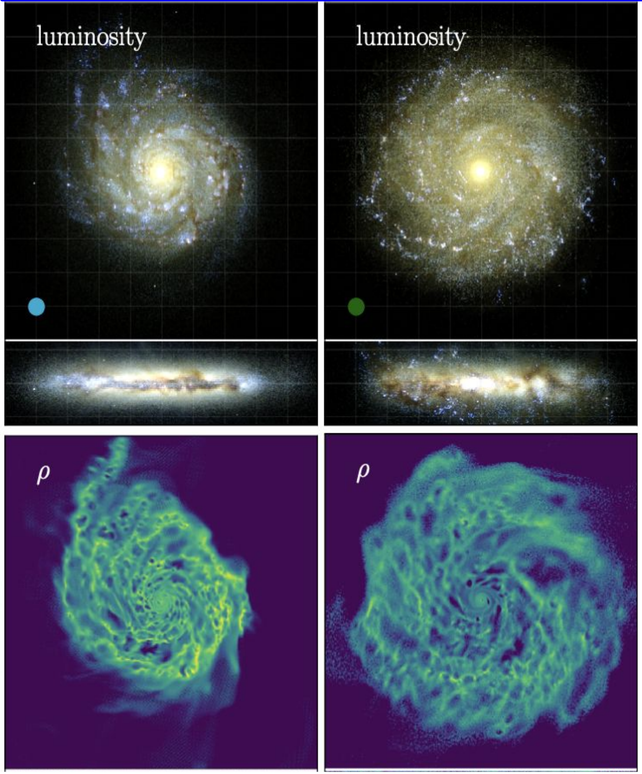
Teyssier et al. 2013, Dubois et al. 2015.

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

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

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:

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

Environment dependent efficiency:

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

Mechanical FB:

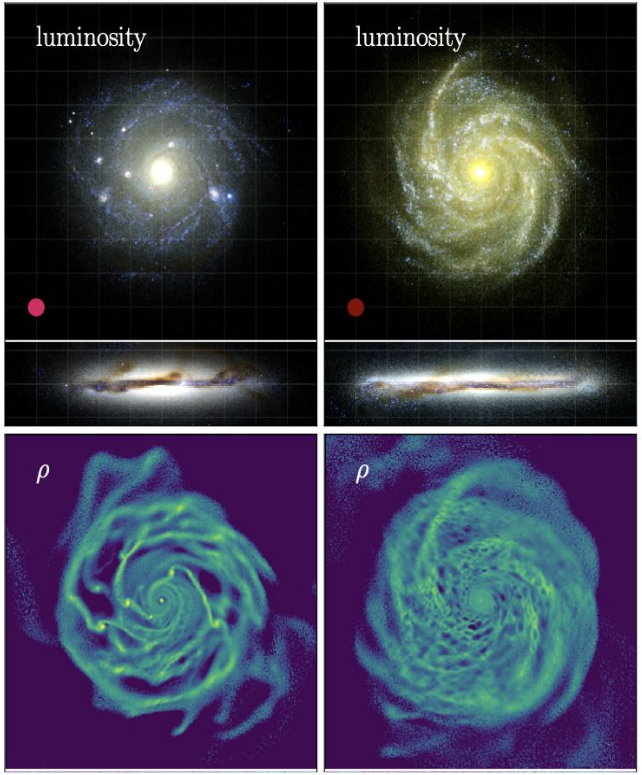
Model the two phases of the SN explosion and inject the corresponding momentum

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

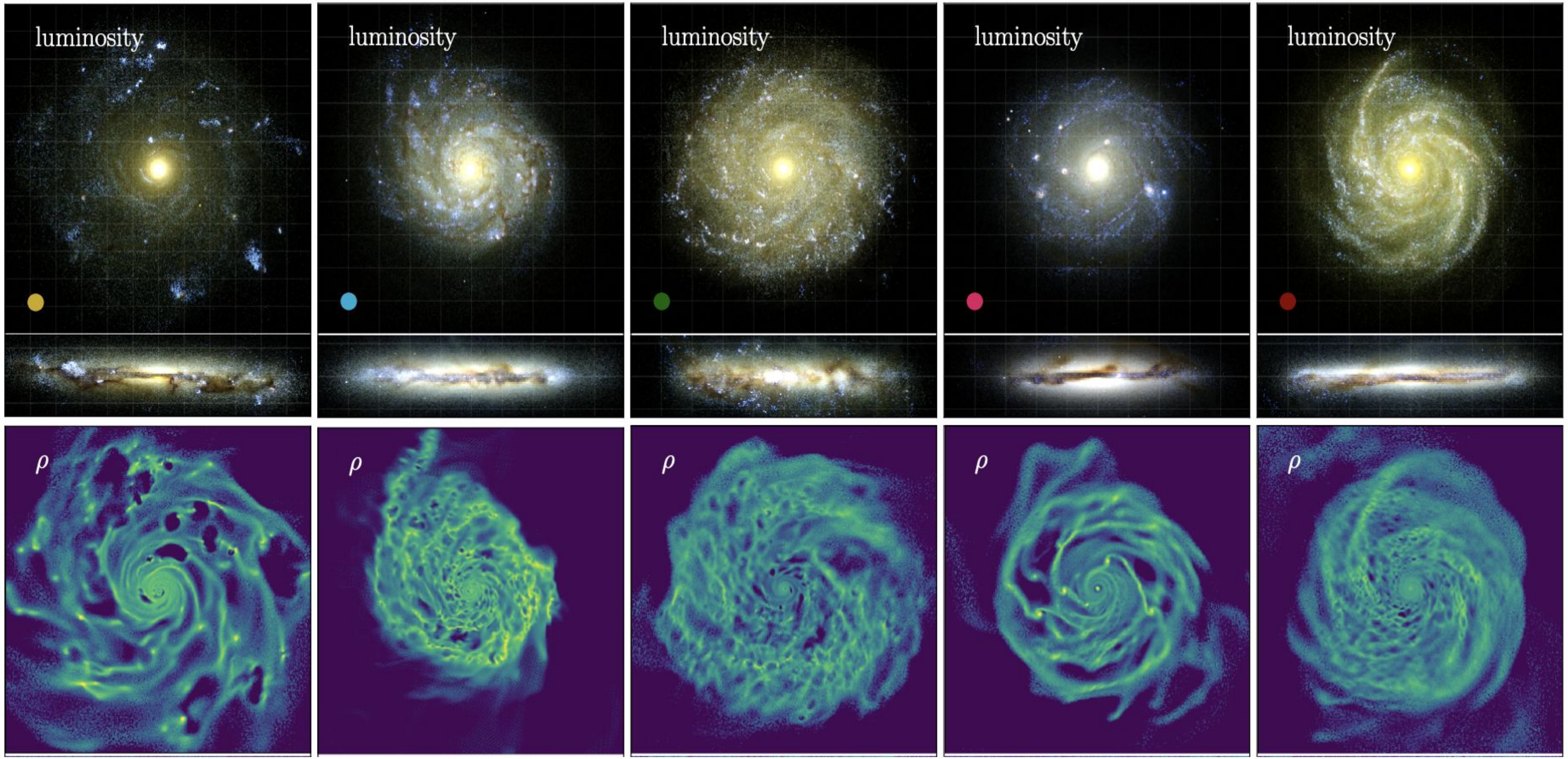
$$p_{\rm SN} = \begin{cases} p_{\rm SN,ad} = \sqrt{2\chi\, M_{\rm ej}\, f_e\, E_{\rm SN}} & (\chi < \chi_{\rm tr}) \\ p_{\rm SN,snow} & (\chi \geq \chi_{\rm tr}) \end{cases}$$

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

Kimm & Cen 2014. Kimms et al. 2015.

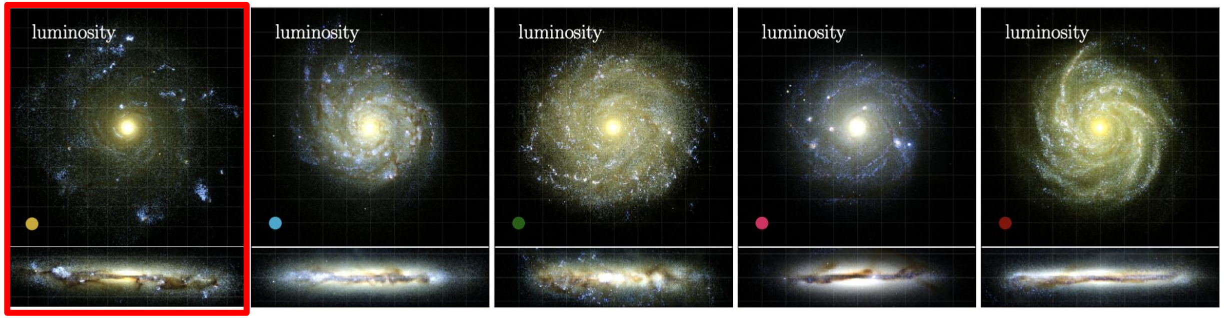


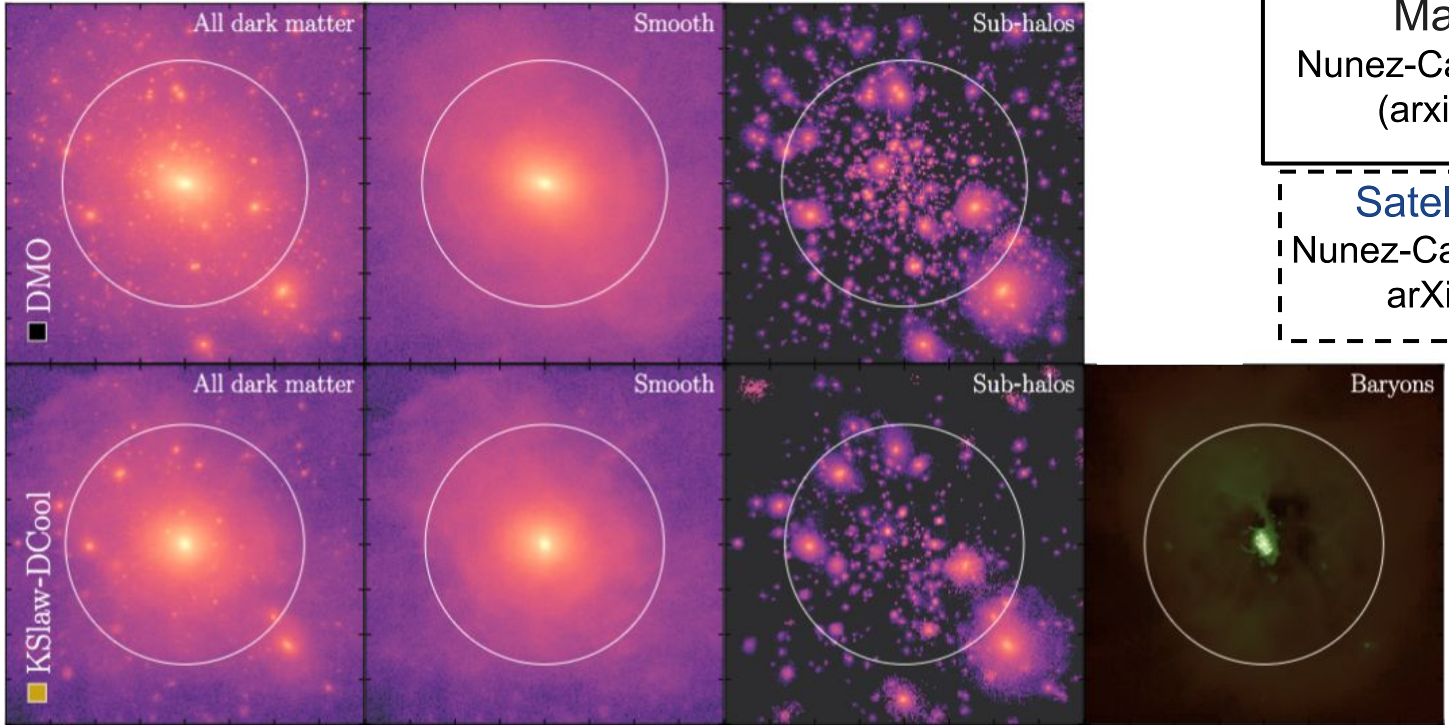
Nunez-Castineyra et al. 2020



Nunez-Castineyra et al
(arxiv:2004.06008)

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



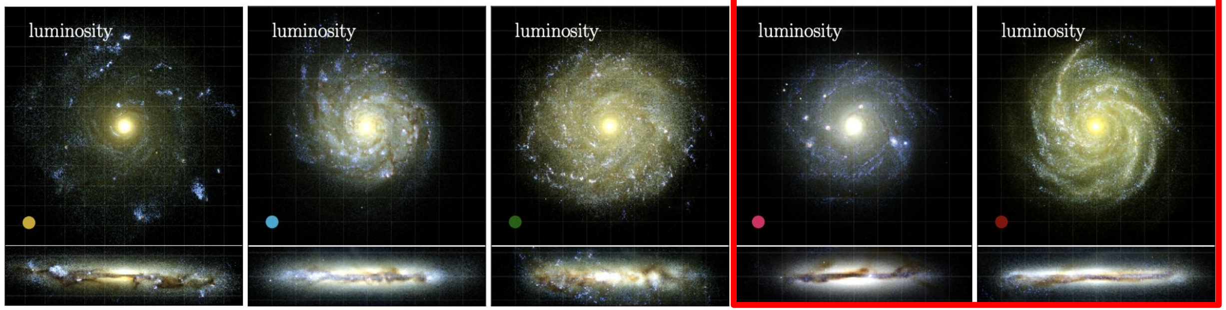


Baryonic Analysis and comparisons
Nunez-Castineyra et al 2020
(arxiv:2004.06008)

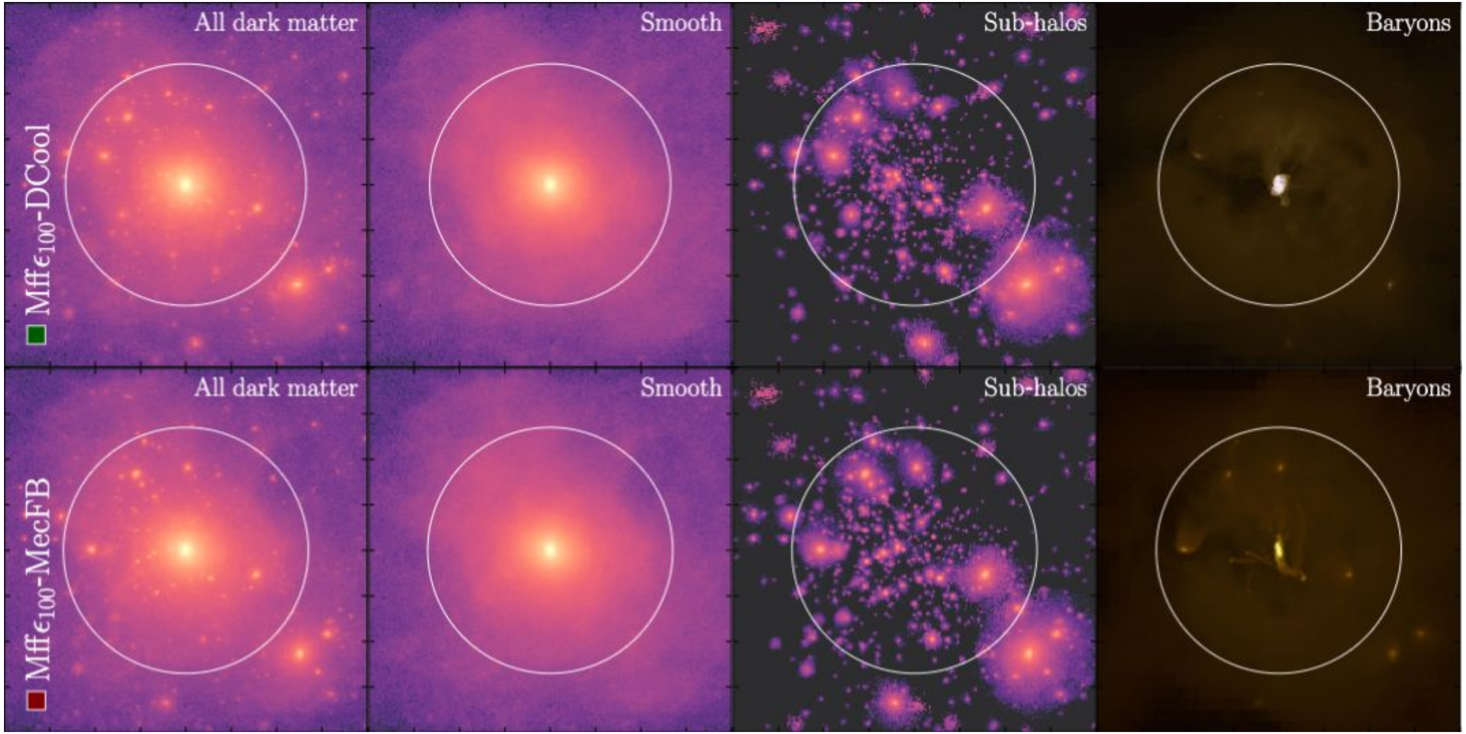
Dark Matter
Main DM halo
Nunez-Castineyra et al 2023
(arxiv:2301.06189)

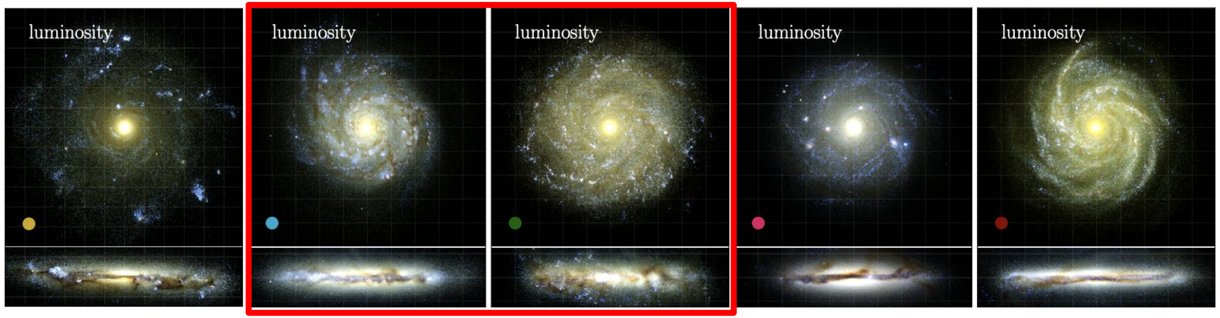
Satellites subhalos
Nunez-Castineyra et al. 2025
arXiv:2509.07470

DMO and Benchmark runs

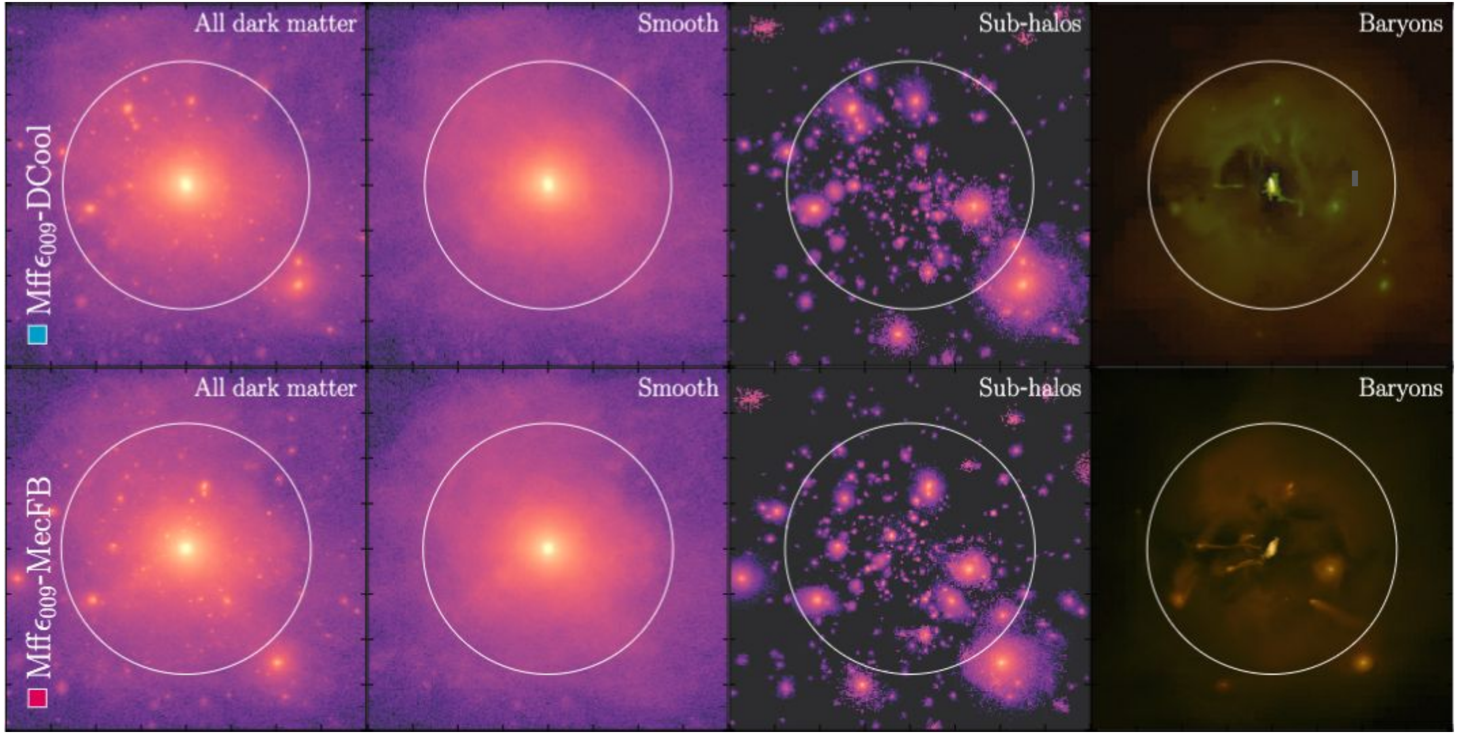


Turbulent SF without protostellar parameter





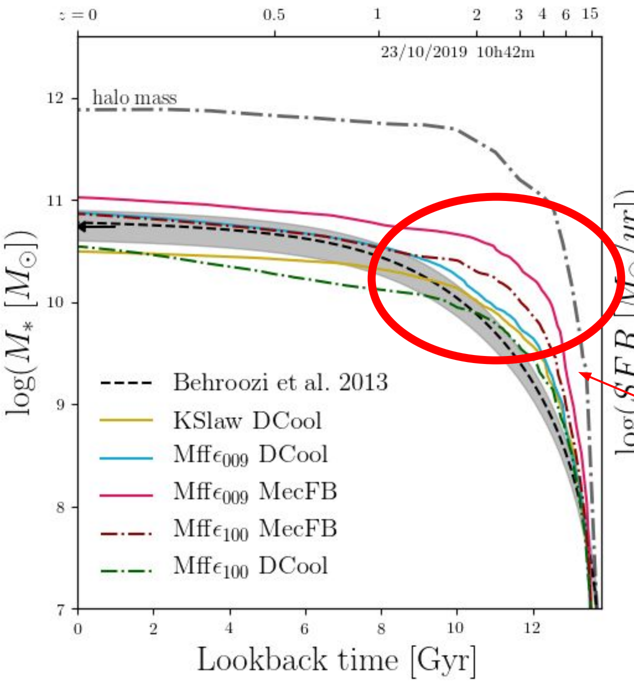
Turbulent SF with protostellar parameter

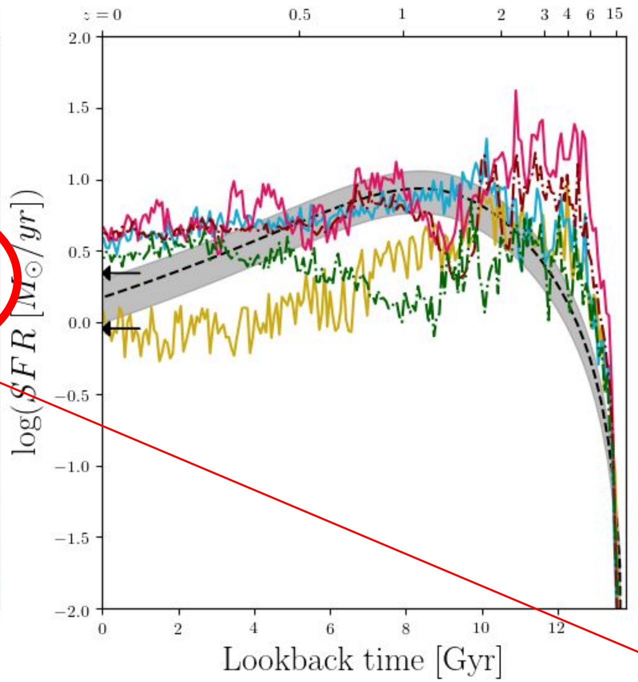


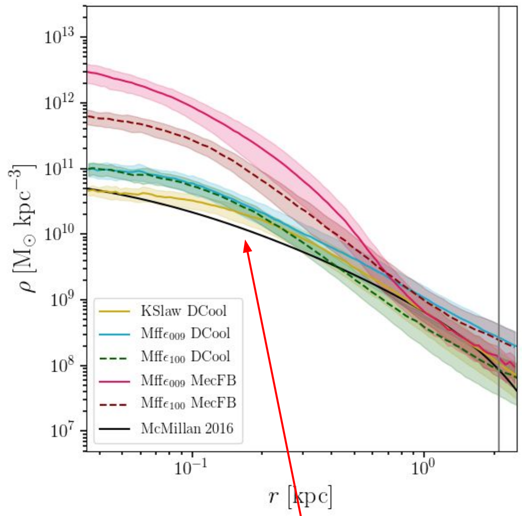
Stellar mass

SFR

Stellar bulge density profile





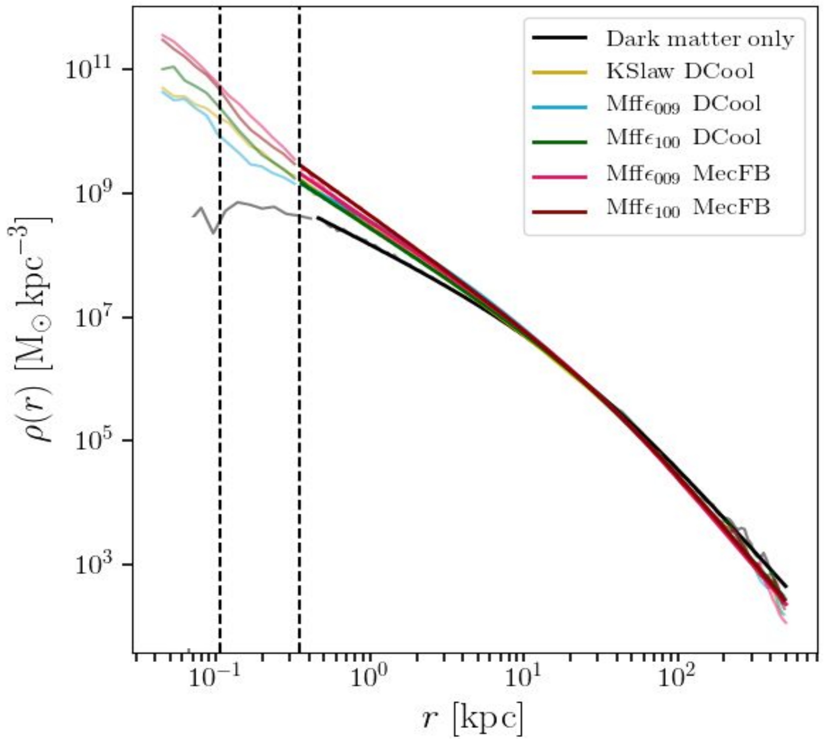


Bulge?

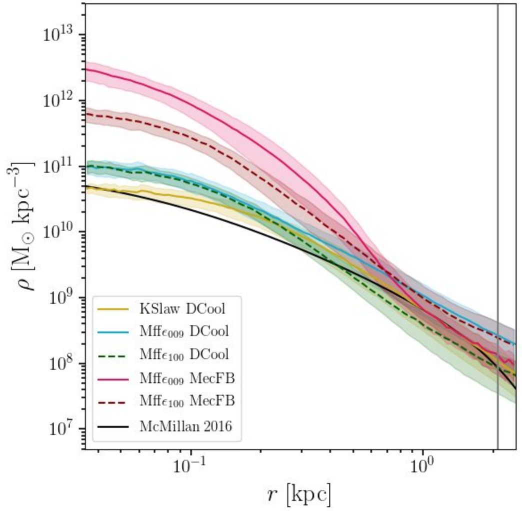
The bulge is composed mainly of old stars formed before z= 2

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

Dark matter distribution



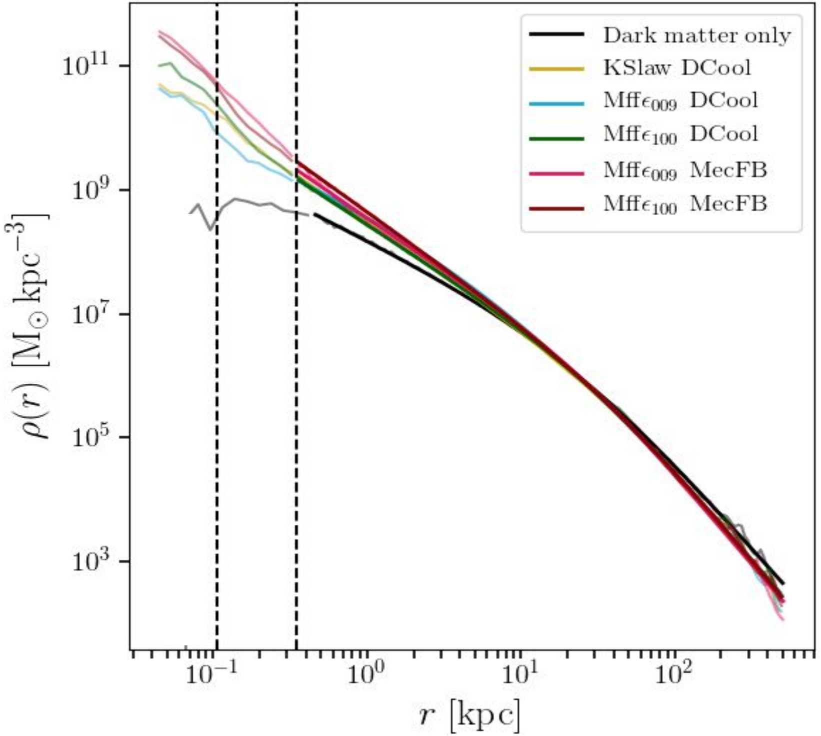
	run	c
6	DMO	9.9
4	KSlaw-DCool	20.4
2	Mffϵ_{009}-DCool	26.0
5	Mffϵ_{100}-DCool	16.3
1	Mffϵ_{009}-MecFB	29.5
3	Mffϵ_{100}-MecFB	20.7



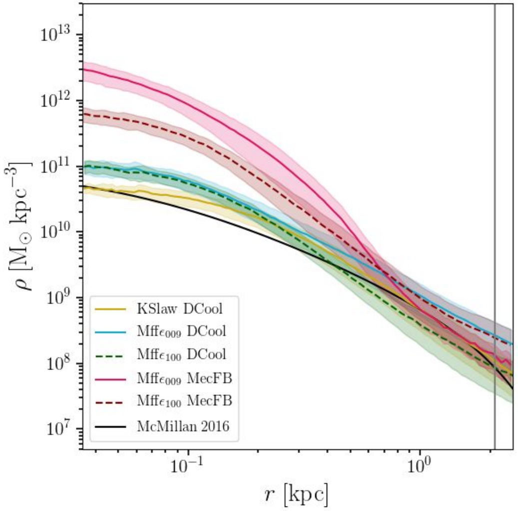
The DM halos are very cuspy.
They suffer adiabatic contraction which intensities are related to the bulge size.

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

Dark matter distribution



	run	c
1	Mffϵ_{009}-MecFB	29.5
2	Mffϵ_{009}-DCool	26.0
3	Mffϵ_{100}-MecFB	20.7
4	KSlaw-DCool	20.4
5	Mffϵ_{100}-DCool	16.3
6	DMO	9.9

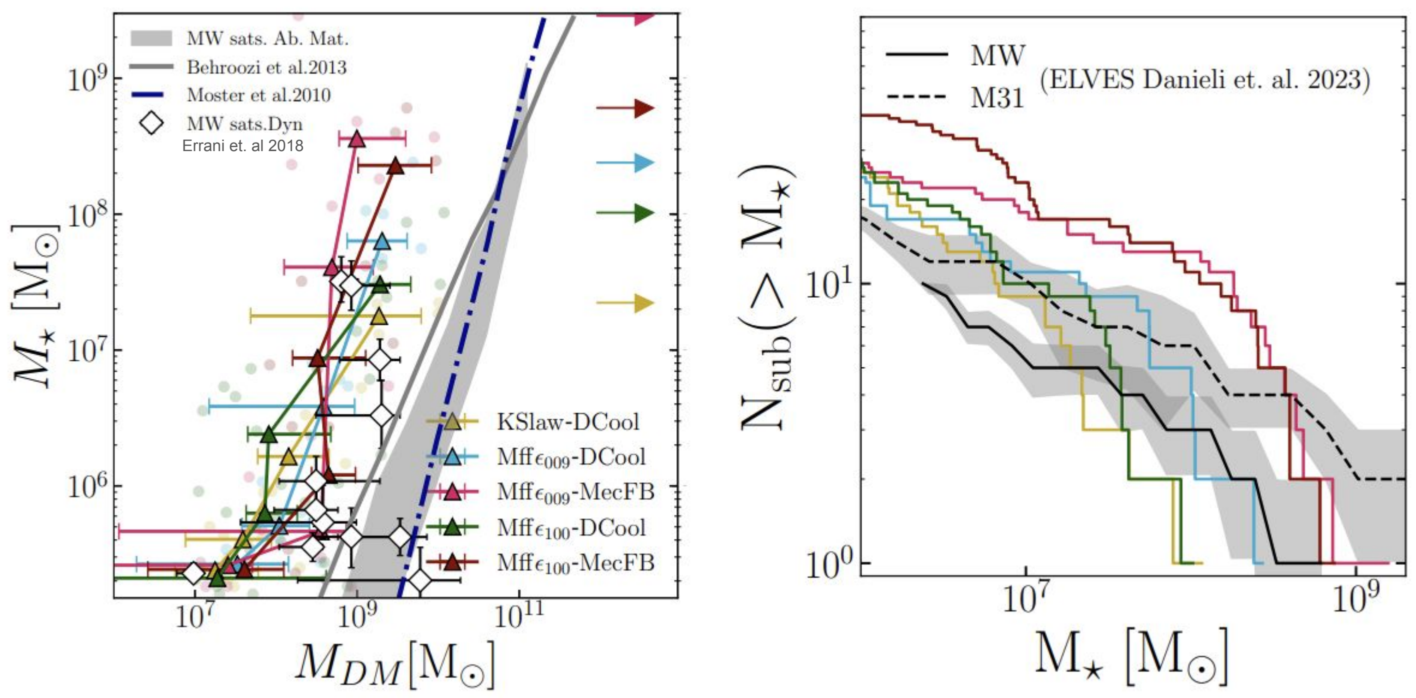


The DM halos are very cuspy.
They suffer adiabatic contraction which intensities are related to the bulge size.

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

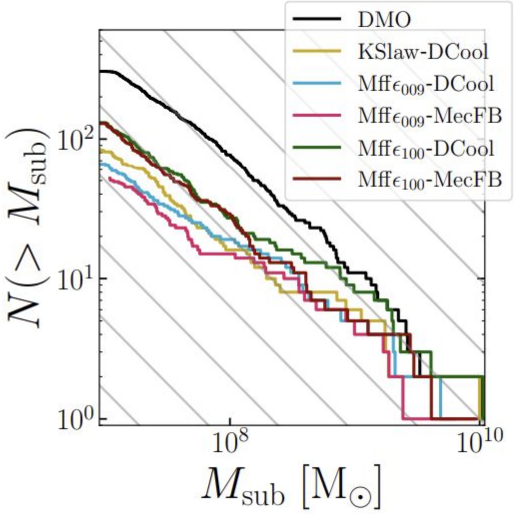
Subhalos
In the Mochima runs

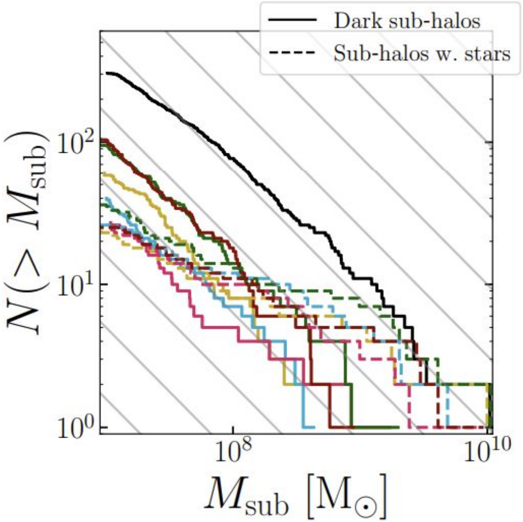
Galaxy halo conexion



Nunez-Castineyra et al. 2025 (arXiv:2509.07470)

Subhalo survival





Baryons alter this spectrum:

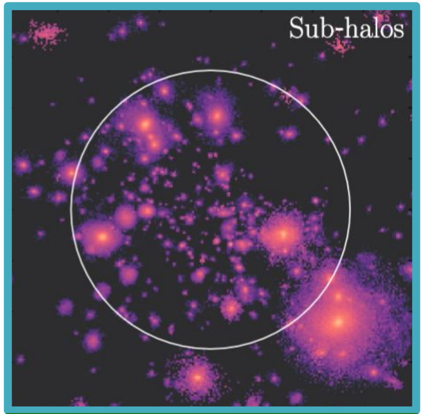
- **Deep central potentials** show strong depletion of massive subhalos.
- Runs with **shallower potentials** retain more subhalos, especially at intermediate masses.
- Runs with **lower concentration** retain more subhalos, especially at low masses.

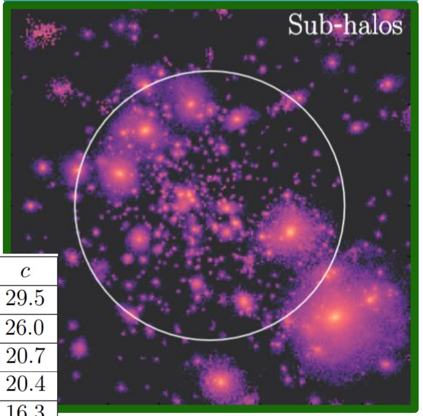
Stellar content matters:

- Subhalos hosting stars are more resilient: their deeper potentials make them harder to disrupt.
- Low-mass dark subhalos (no stars) are preferentially destroyed by tides.

	run	c
1	Mffϵ_{009}-MecFB	29.5
2	Mffϵ_{009}-DCool	26.0
3	Mffϵ_{100}-MecFB	20.7
4	KSlaw-DCool	20.4
5	Mffϵ_{100}-DCool	16.3
6	DMO	9.9

With protostellar parameter ϵ~0.1

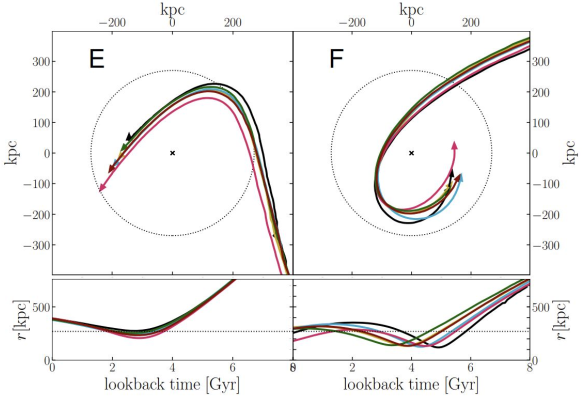




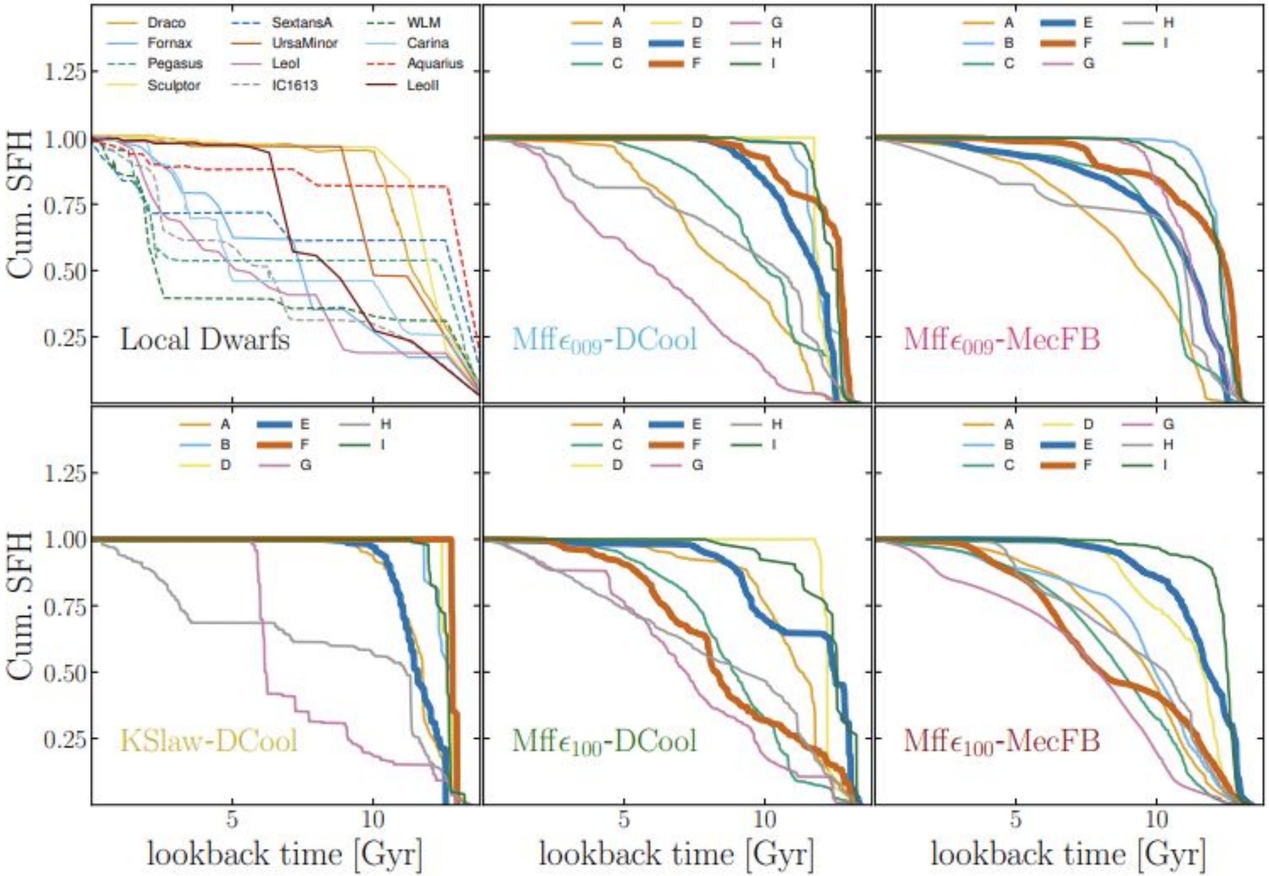
With no protostellar parameter ϵ~1

The SFH

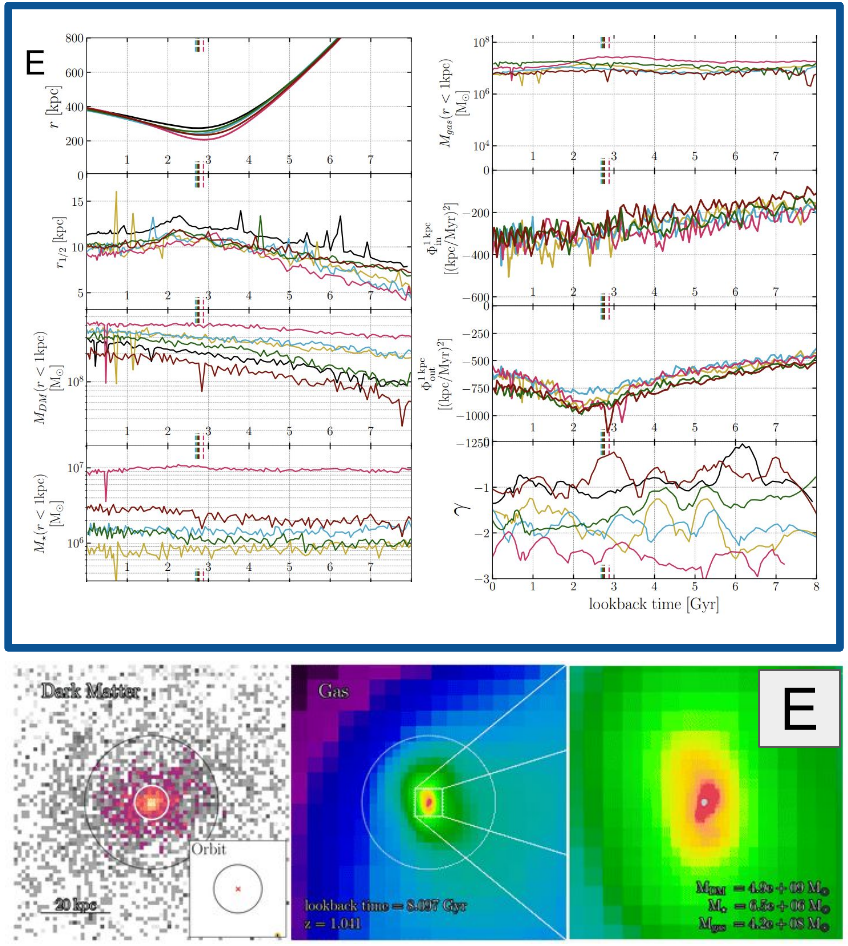
Lets take subhalos with
$10^{8} < M/Msun < 5x10^{10}$
And in particular two halo examples E and F.



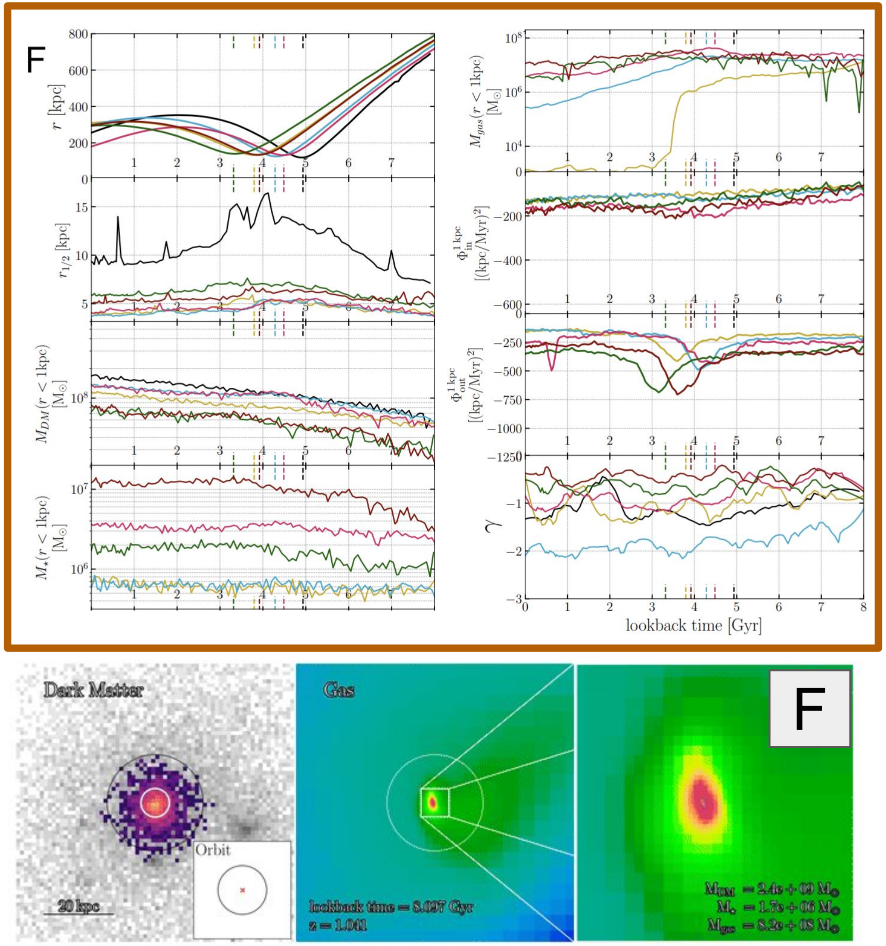
They show a slight variability in the orbits and an important ona in SFH



A subhalo with an easy life

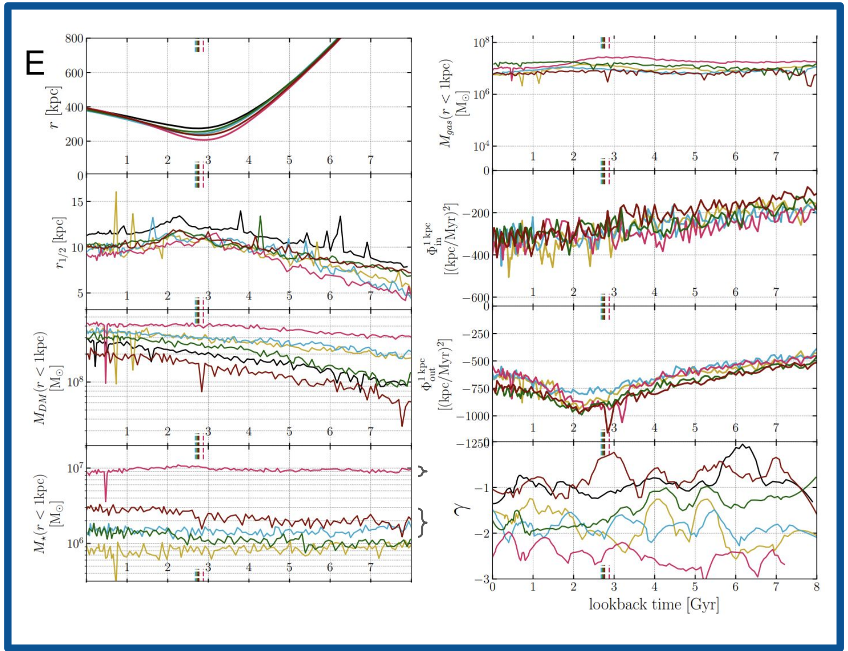


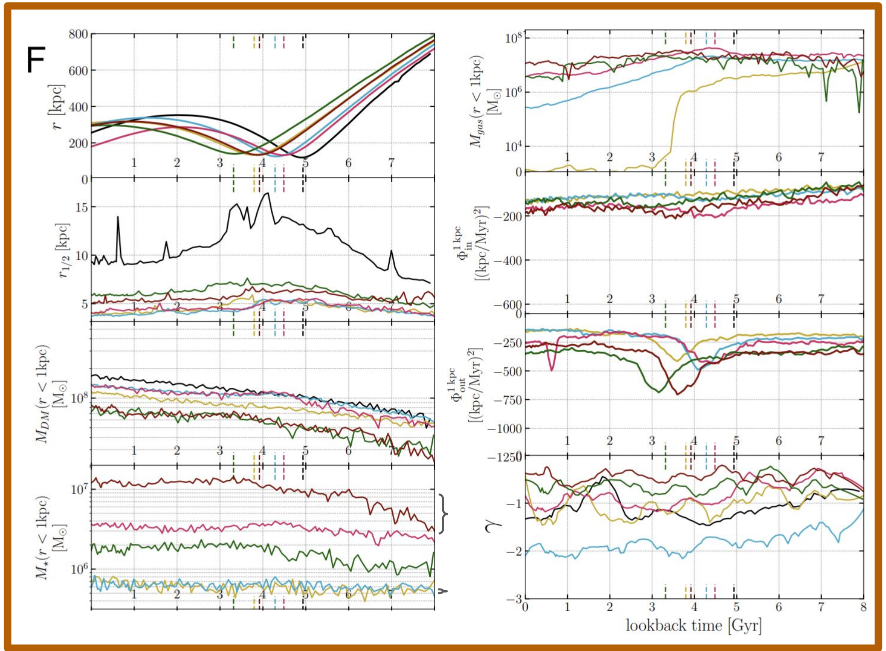
A subhalo with a harsh life



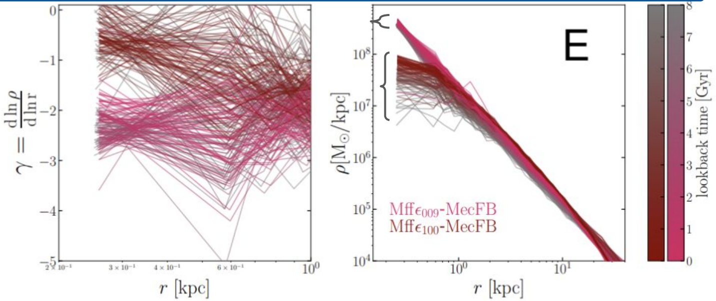
A subhalo with an easy life

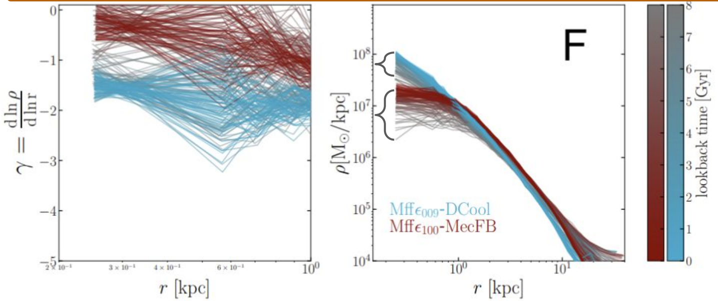
A subhalo with a harsh life





Two extreme inner slope in each case

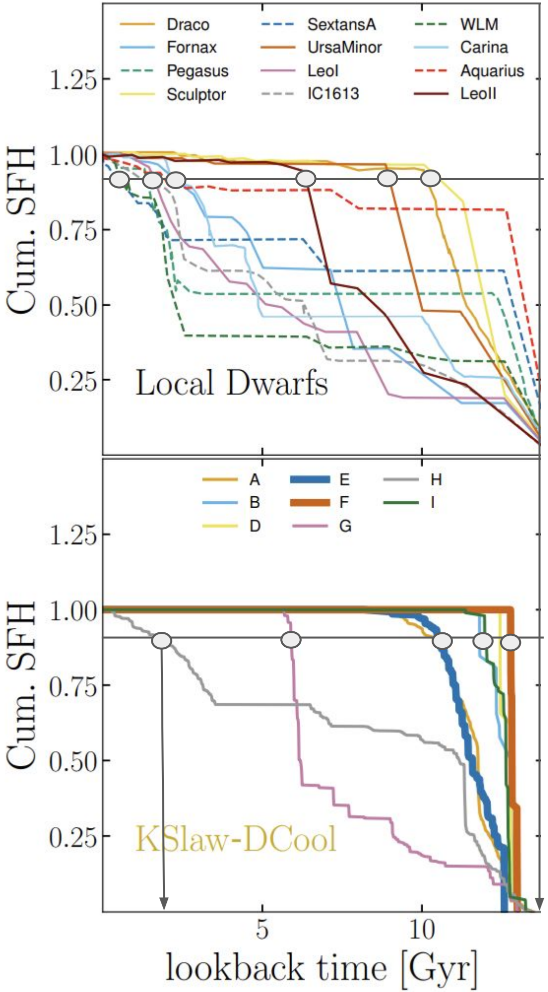




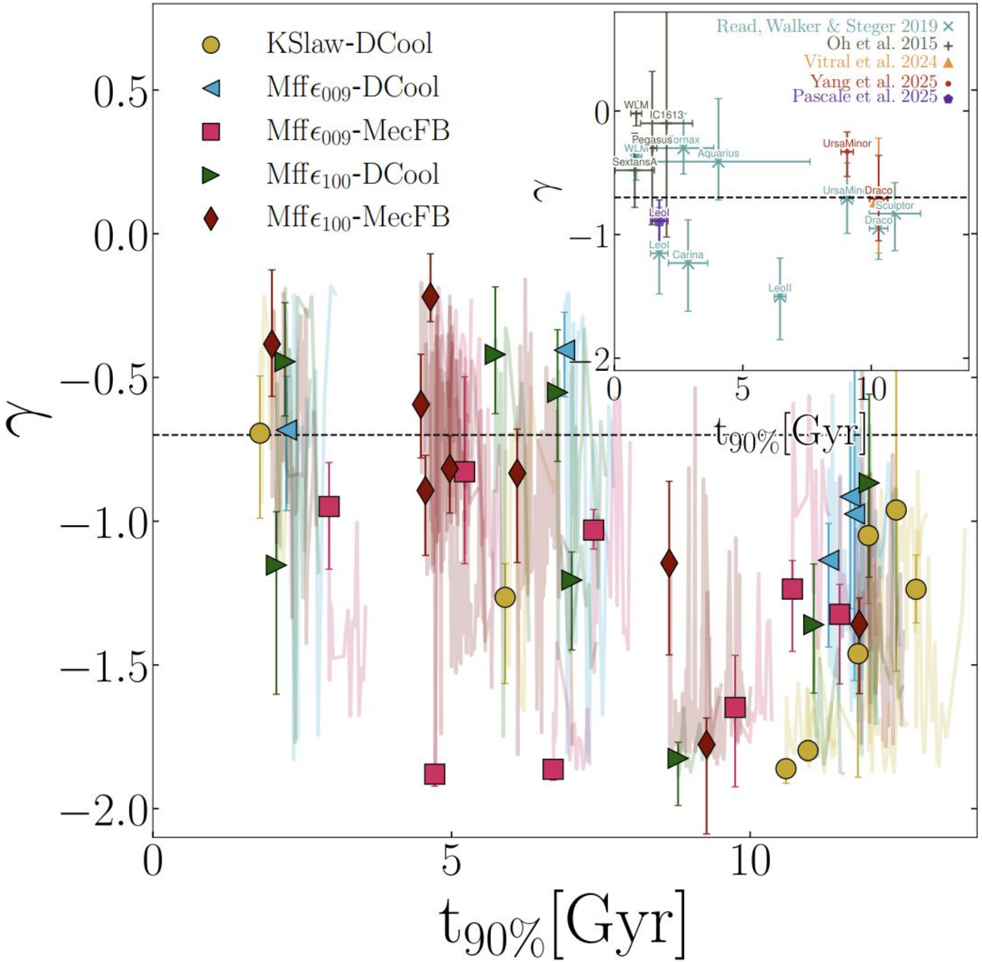
To relate inner slope of dark matter subhalos today with the SFH we define

$$t_{90\%}$$

The **lookback time** at which a dwarf galaxy (or subhalo) has formed **90% of its total stellar mass**



- t90% ≳ 7 Gyr invariably exhibit cusps profiles and show minimal evolution in γ over time.
- In contrast, galaxies with t90% ≲ 7 Gyr show a wide spread in γ and are characterized by significant temporal fluctuations.

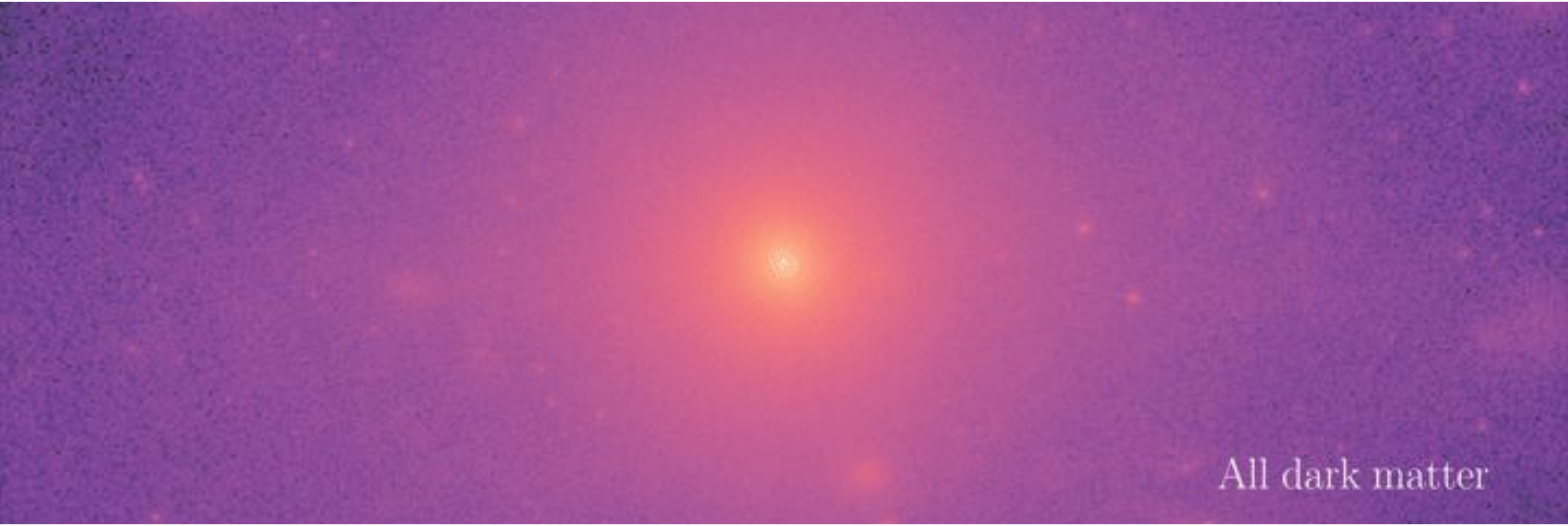


Conclusions

Subhalo survival depends on host concentration and stellar binding;
early SFHs preserve cusps,
While
extended and/or recent SFHs drive fluctuating cores.

- Subhalo survival set by host potential depth and concentration
- Stellar mass in subhalos increases resilience to disruption
- Low-mass, dark subhalos are preferentially destroyed (resolution?)
- Cumulative mass function shallower than DMO; too-big-to-fail alleviated
- Inner slopes show wide diversity (cusps and temporary cores)
- t90% correlates with slope: early → cusps, late → cores

The observed diversity in inner dark matter structure -often viewed as a challenge to cold dark matter models- can arise naturally from the interplay between star formation history and environmental context.


All dark matter