# Baryonic Imprints on Dark Matter Halos and Substructure in the Mochima Simulations


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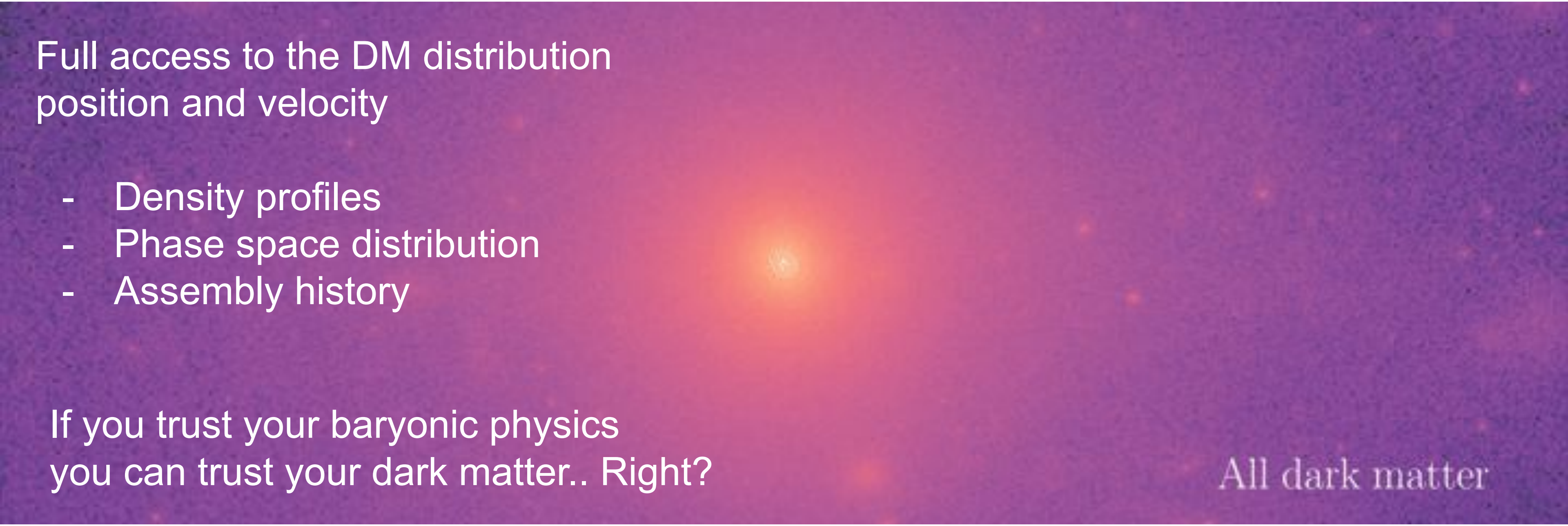
Collaborators:
Emmanuel Nezri, Pol Mollitor, Leo Michel-Dansac,
Julien Devriend and Romain Teyssier

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

TeVPA - 2025 - Valencia

# Dark matter content

## The advantage of using HR cosmological simulations




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 and guide DM searches.. Right?

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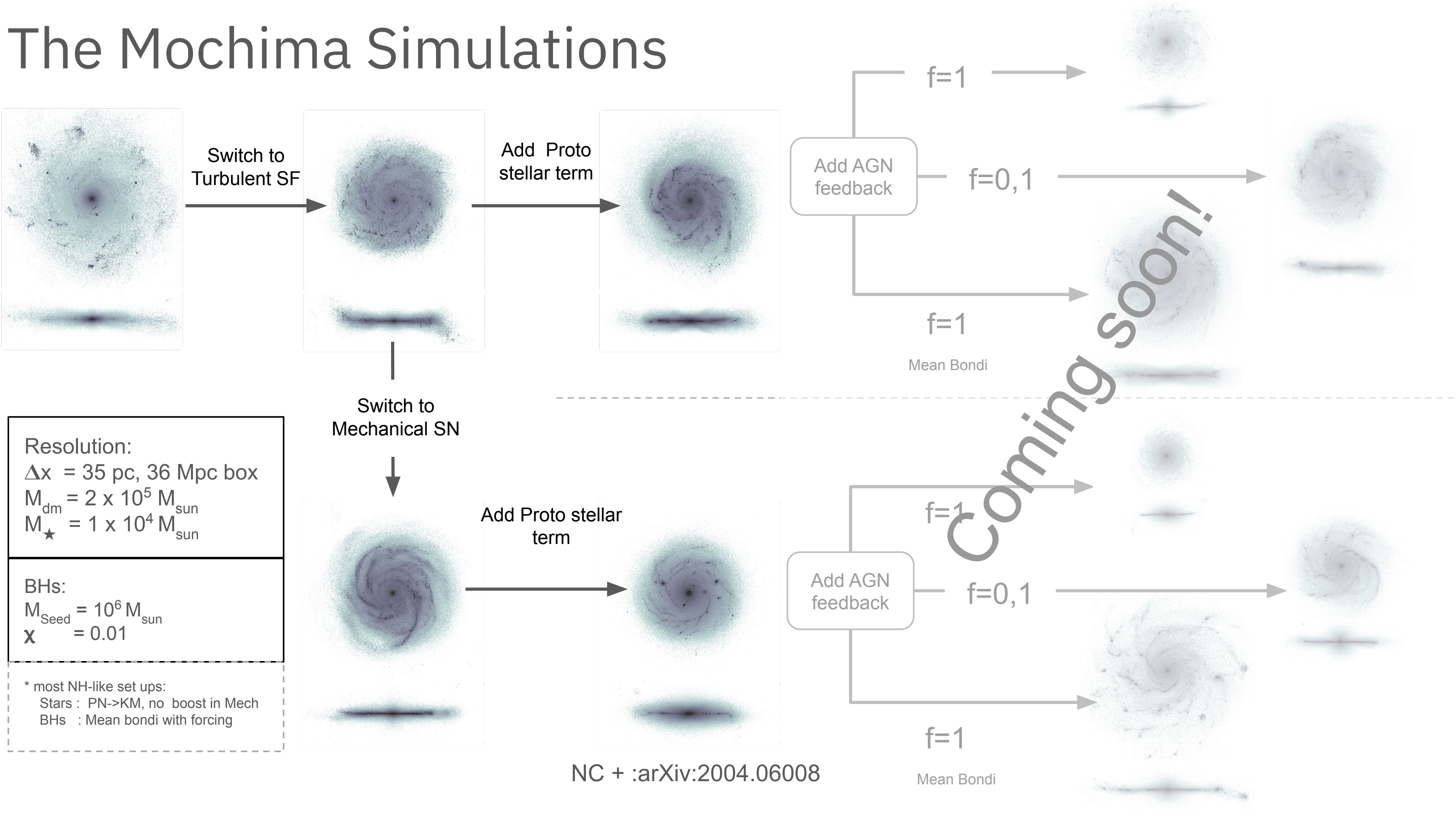
# The Mochima Simulations




Resolution:
$\Delta x$ = 35 pc, 36 Mpc box
$M_{dm}$ = 2 x $10^5$ $M_{sun}$
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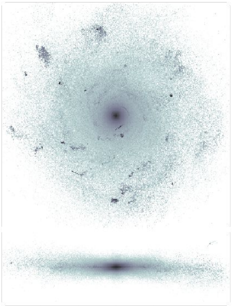
BHs:
$M_{Seed}$ = $10^6$ $M_{sun}$
$\chi$ = 0.01

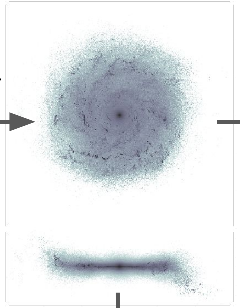
* most NH-like set ups:
Stars : PN->KM, no boost in Mech
BHs : Mean bondi with forcing

NC + :arXiv:2004.06008

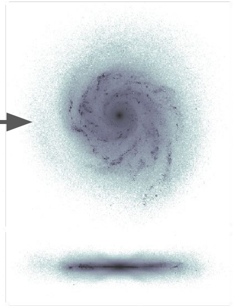
# The Mochima Simulations



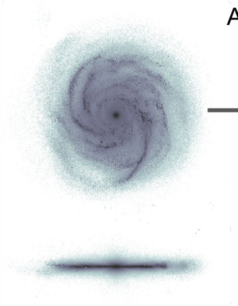
Switch to Turbulent SF



Add Proto stellar term



Switch to Mechanical SN



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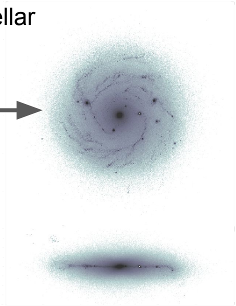

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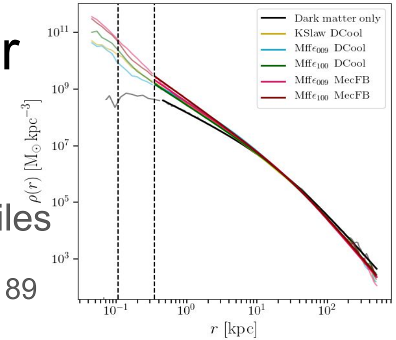
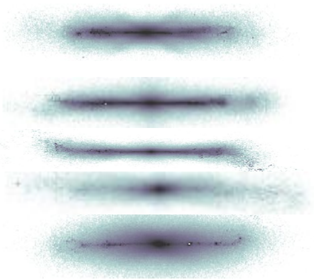
## Dark Matter

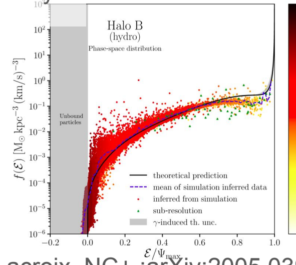
Density profiles

NC+ :arXiv:2301.06189



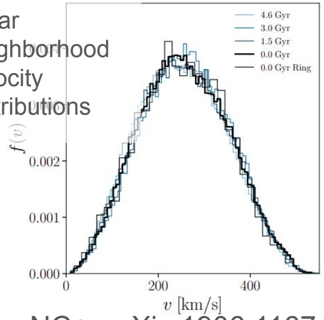



Full phase space density

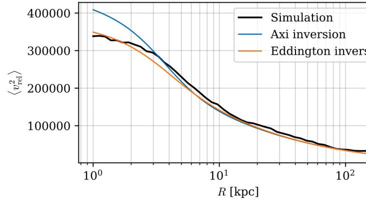



Lacroix, NC+ :arXiv:2005.03

Solar neighborhood velocity distributions




NC+ :arXiv:1906.11674



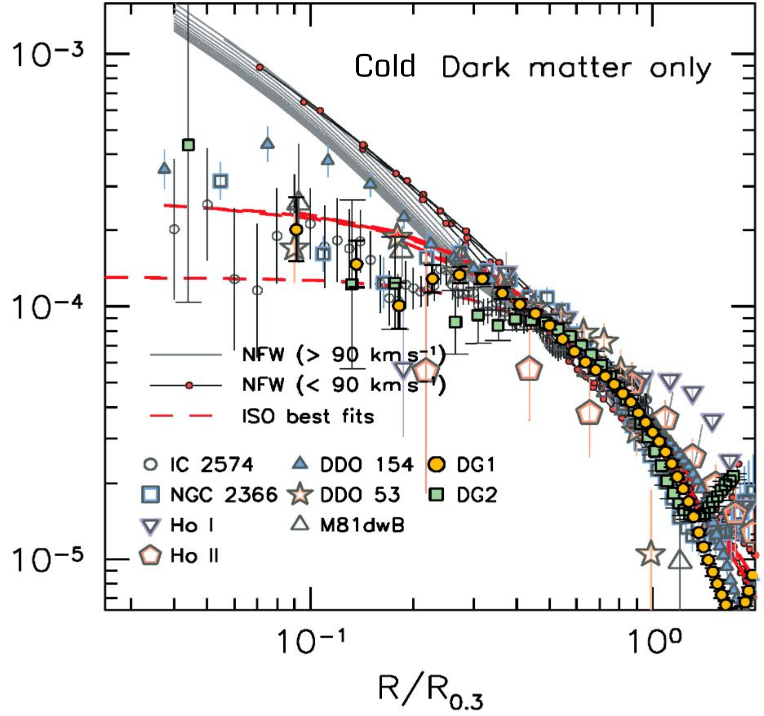

Petac, NC+ :arXiv:2106.0

# Dark matter related problems regarding dwarfs galaxies

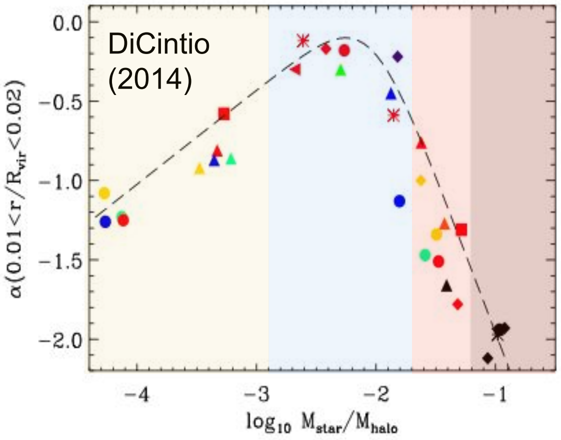
- Cusp-Core problem (Diversity)
  When it comes to dark matter halos
  Simulations predict one thing (mostly cusps)
  Observations infer other ( mostly cores)

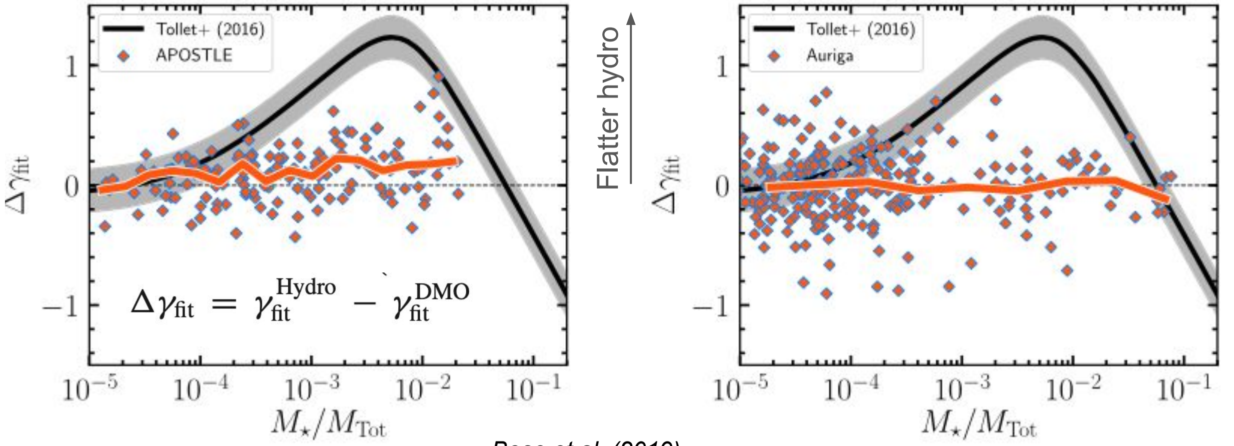
  De Blok (2009), Del Popolo & Le Delliou (2021)

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



# Baryons complicate the story but could solve the problems



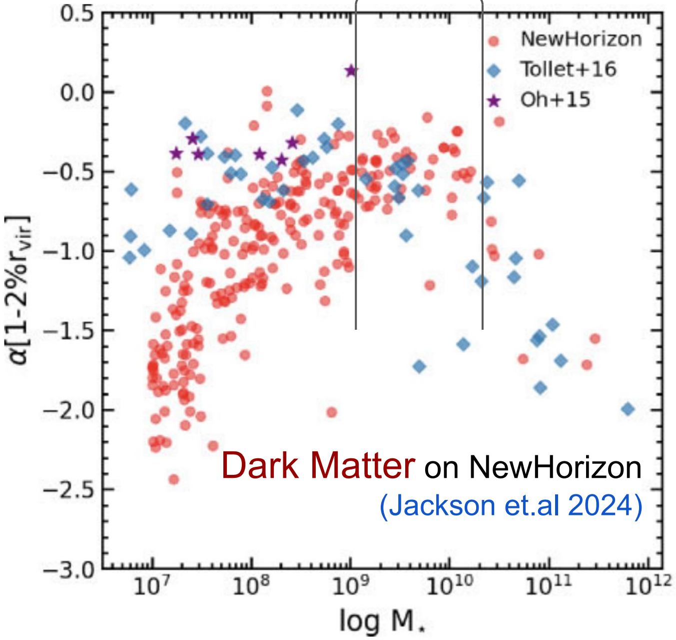

*Bose et al. (2019)*

- 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

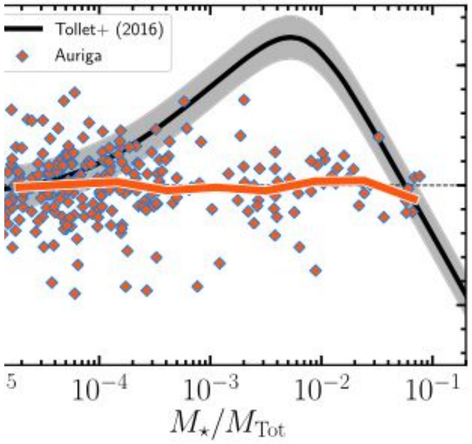
APOSTLE and Auriga: do not find evidence of core formation at *any* mass or any correlation between the inner slope of the DM density profile and temporal variations in the SFH

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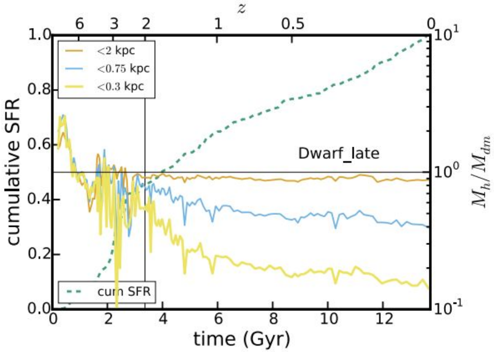
APOSTLE and Auriga: do not find evidence of core formation at *any* mass or any correlation between the inner slope of the DM density profile and temporal variations in the SFH

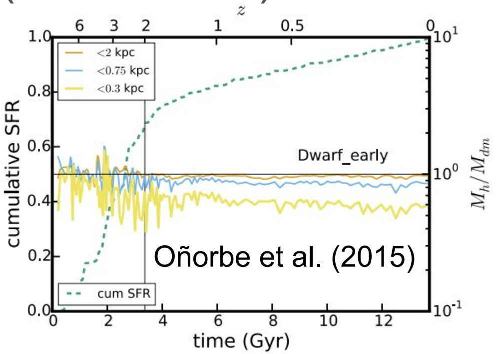
profiles.

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

# Hints on: Stars vs central DM density

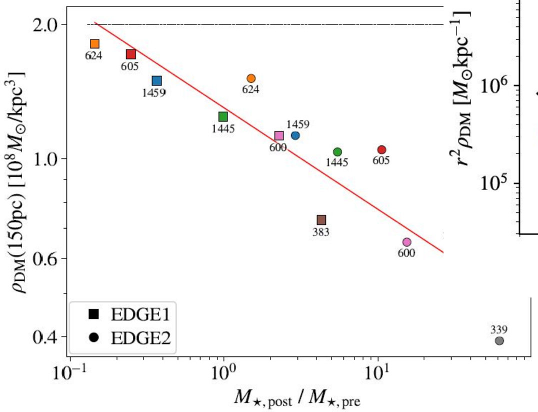
## (simulations)

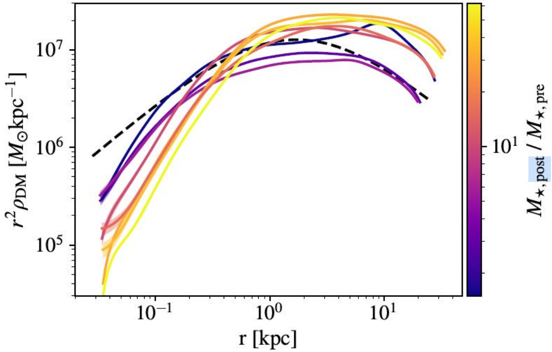



Oñorbe et al. (2015)

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

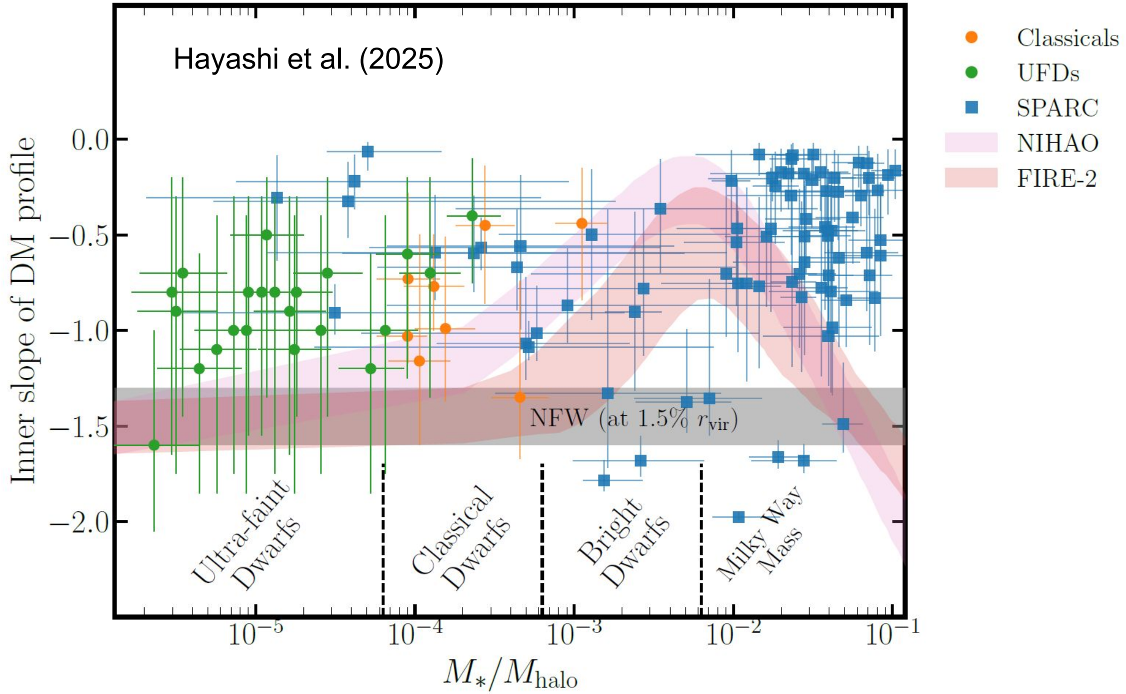



Muni et al. (2025)

- *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)

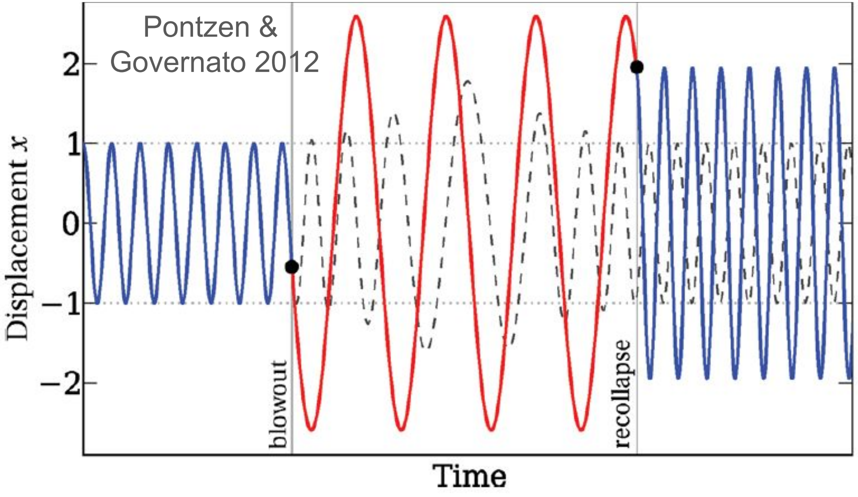


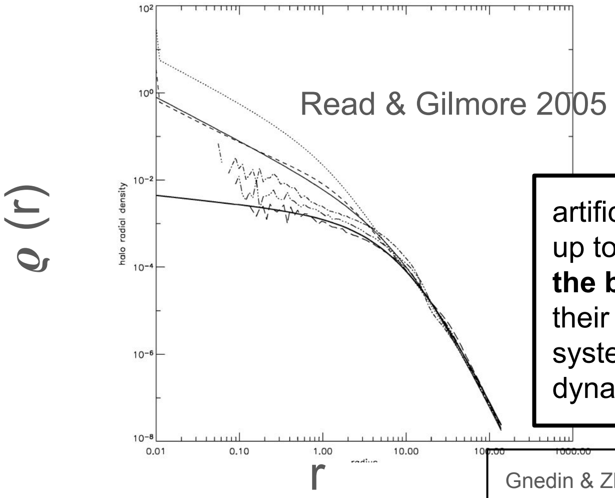

*"Our findings suggest that baryonic processes may play a significant role in shaping the central dark matter structures and could account for much of the observed diversity, although some discrepancies still remain"*

- 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.

# 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

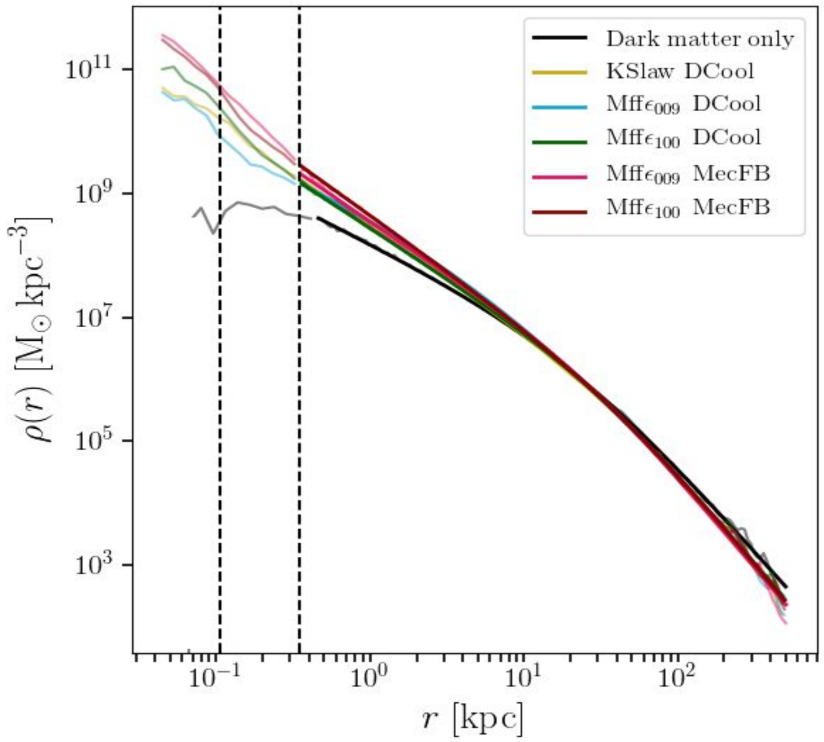
Gnedin & Zhao (2002) showed that one blowout is insufficient

- 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.

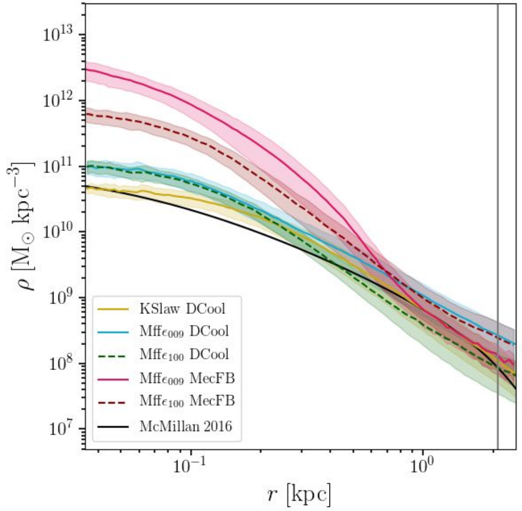
Governato 2009, El-Zant et al 2016, Freundlich et al 2020, li et al 2022. (not an exhaustive list)

# Host halos
# In the Mochima runs

# Dark matter distribution




| | run | $c$ |
|---|---|---|
| 1 | Mff$\epsilon_{009}$-MecFB | 29.5 |
| 2 | Mff$\epsilon_{009}$-DCool | 26.0 |
| 3 | Mff$\epsilon_{100}$-MecFB | 20.7 |
| 4 | KSlaw-DCool | 20.4 |
| 5 | Mff$\epsilon_{100}$-DCool | 16.3 |
| 6 | DMO | 9.9 |

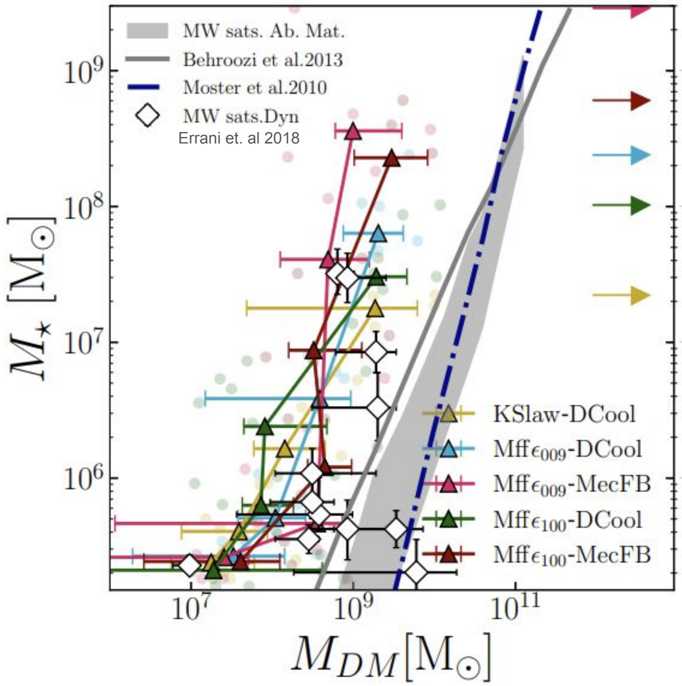


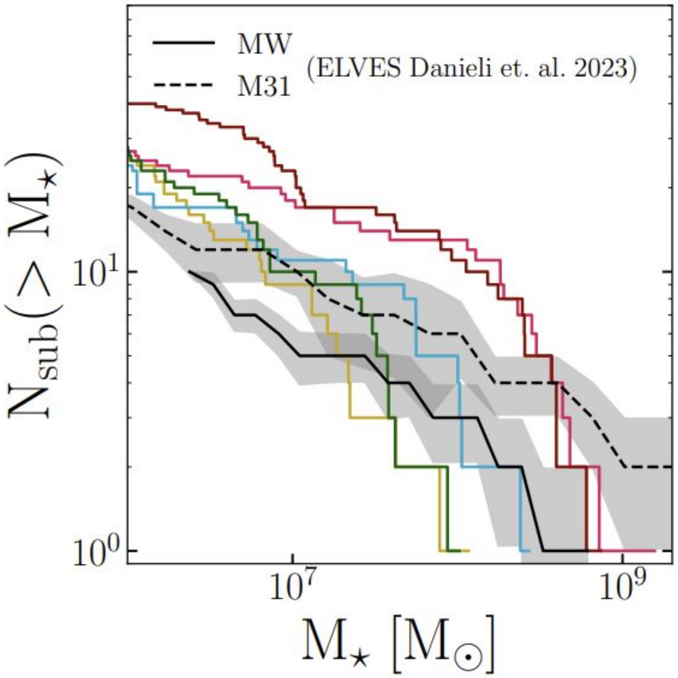

The DM halos are very cuspy.
They suffer adiabatic contraction which intensities are related to the bulge size.

NC+ :arXiv:2301.06189

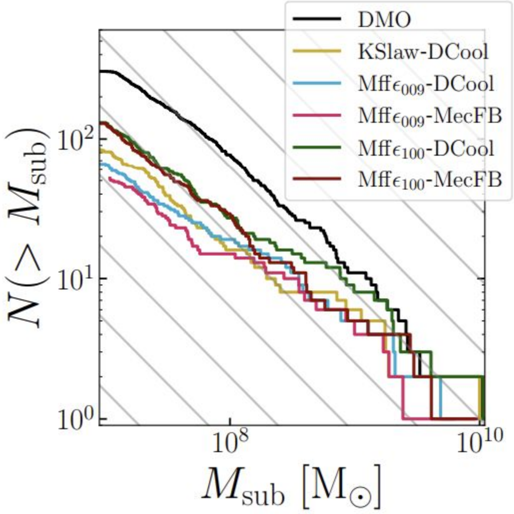
# Subhalos
# In the Mochima runs

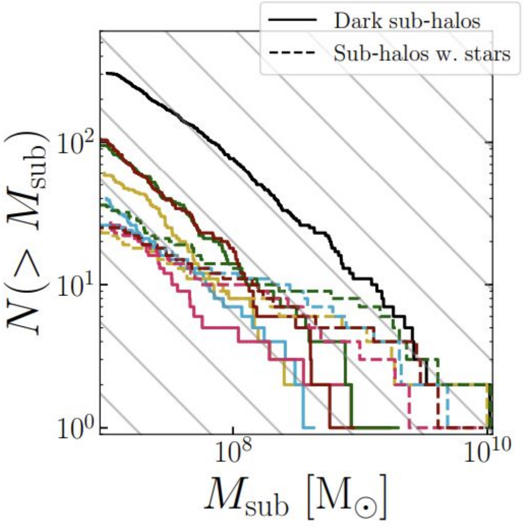
# Galaxy halo conexion




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 | Mff$\epsilon_{009}$-MecFB | 29.5 |
| 2 | Mff$\epsilon_{009}$-DCool | 26.0 |
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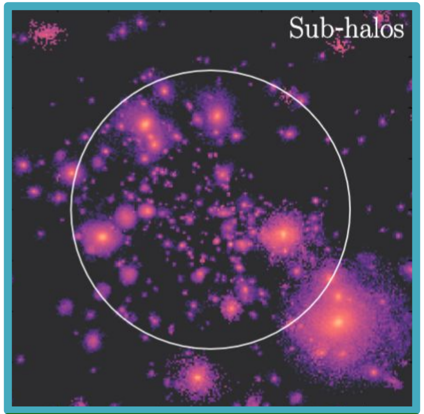
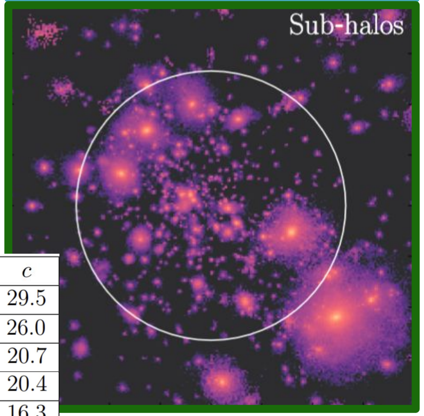
With protostellar parameter $\epsilon$~0.1

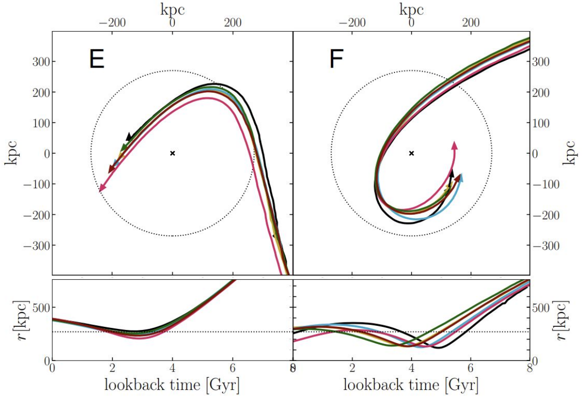


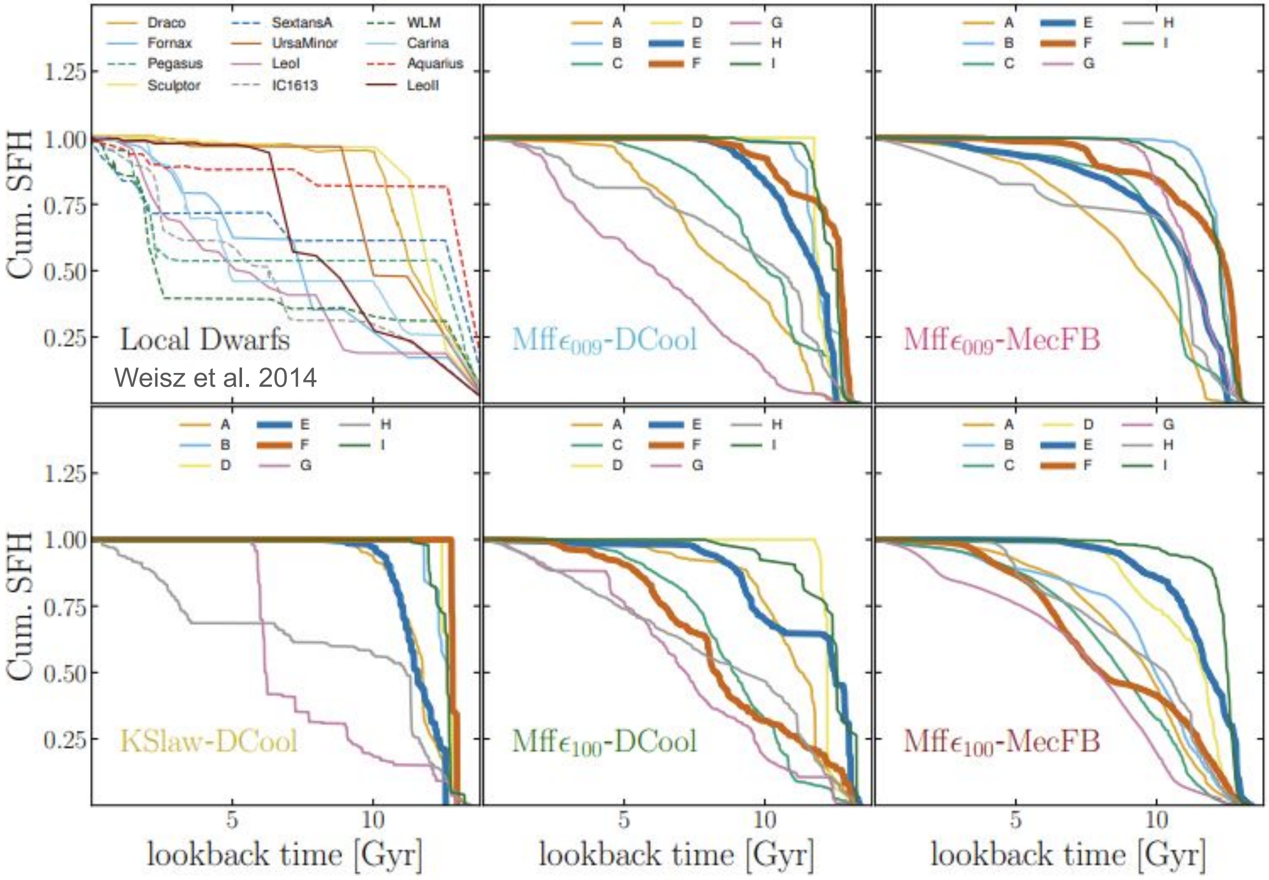

With no protostellar parameter $\epsilon$~1

# The SFH

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

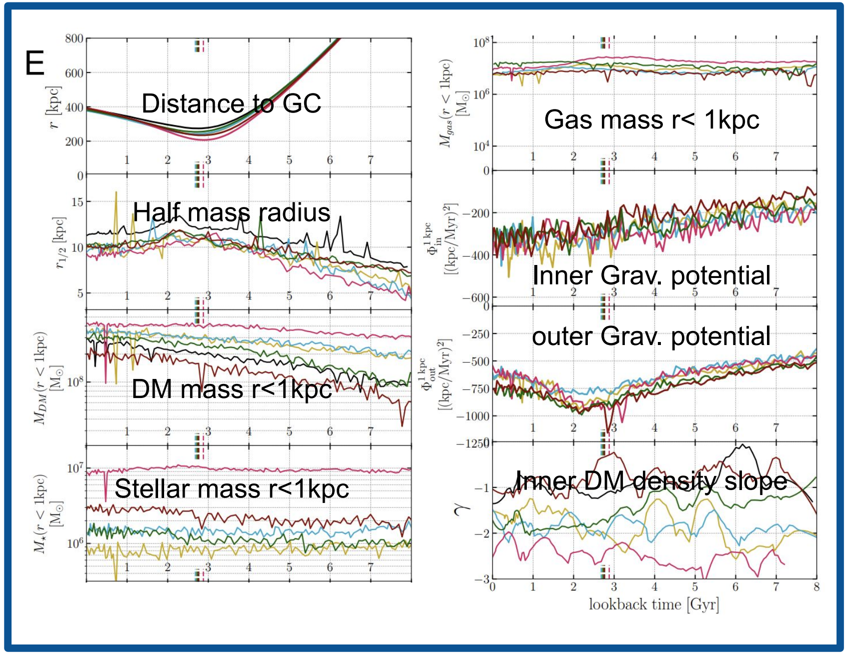


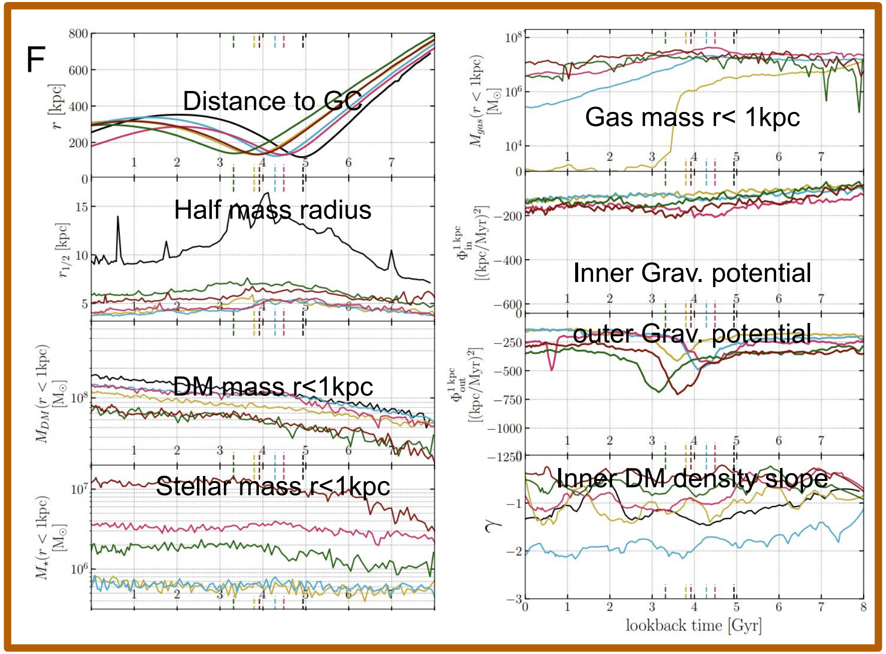

They show a slight variability in the orbits and an important ona in SFH

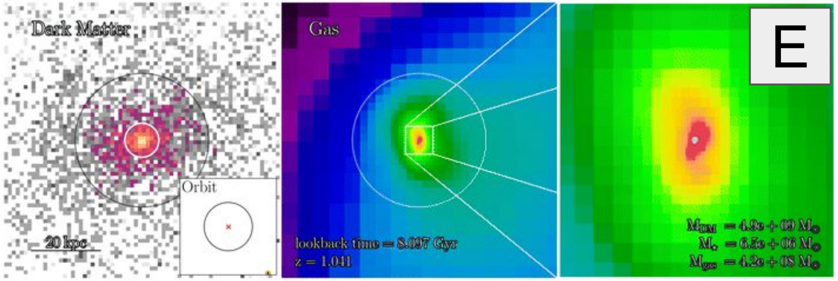


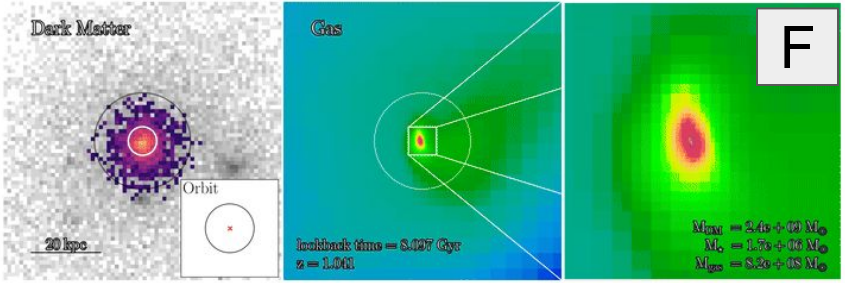
# A subhalo with an easy life

# A subhalo with a harsh life



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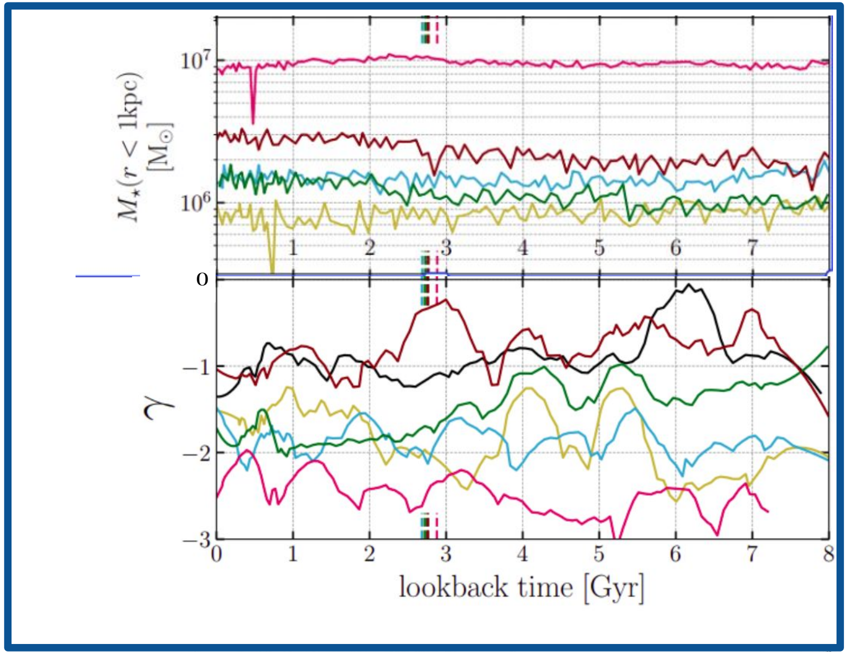


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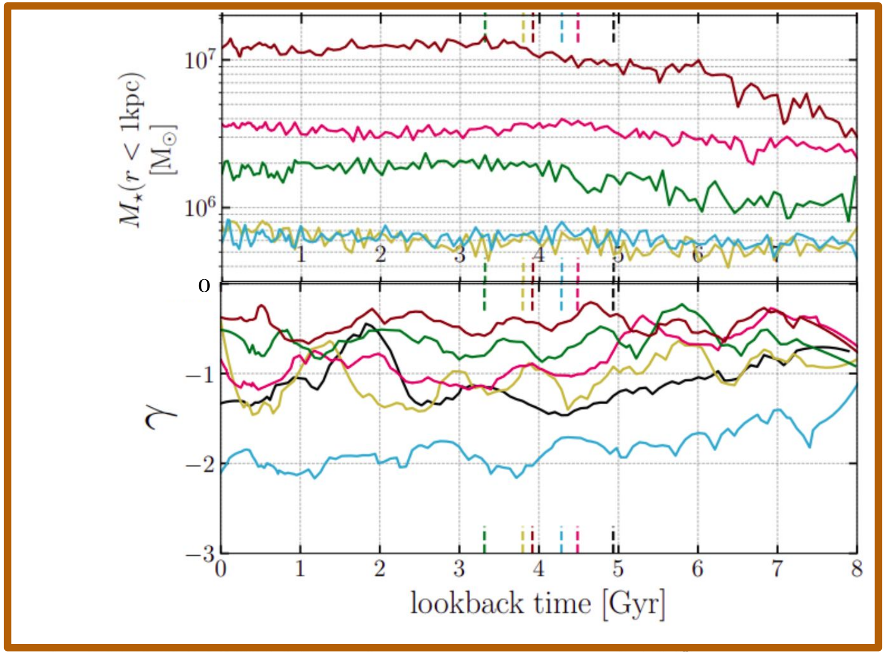
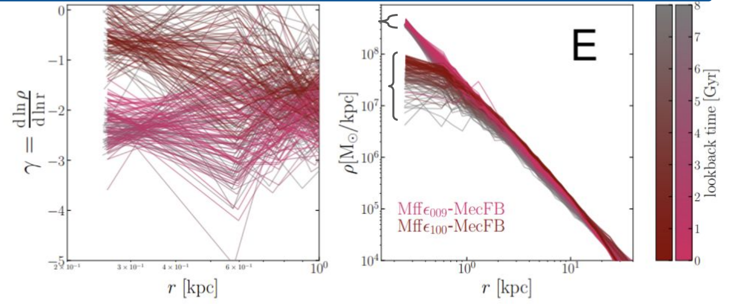
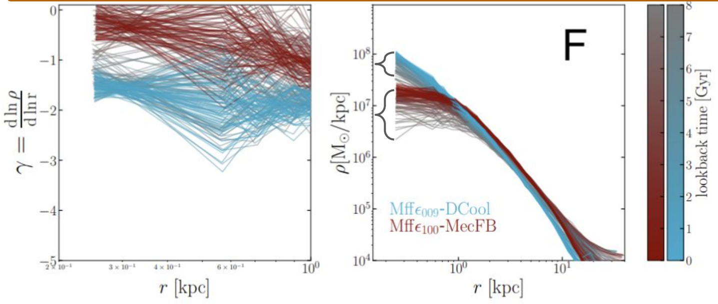



Two extreme inner slope in each case

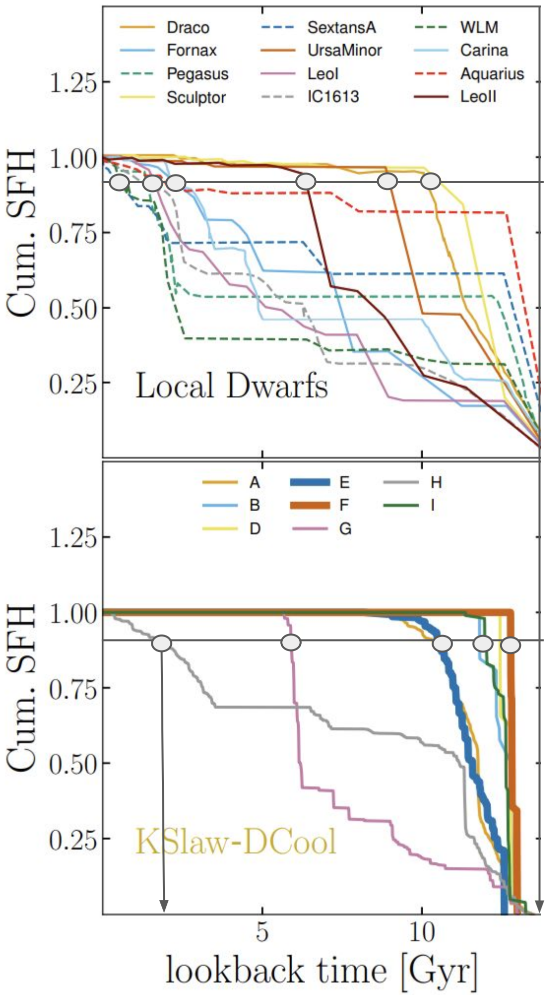


To relate inner slope of dark matter subhalos today with the SFH we define

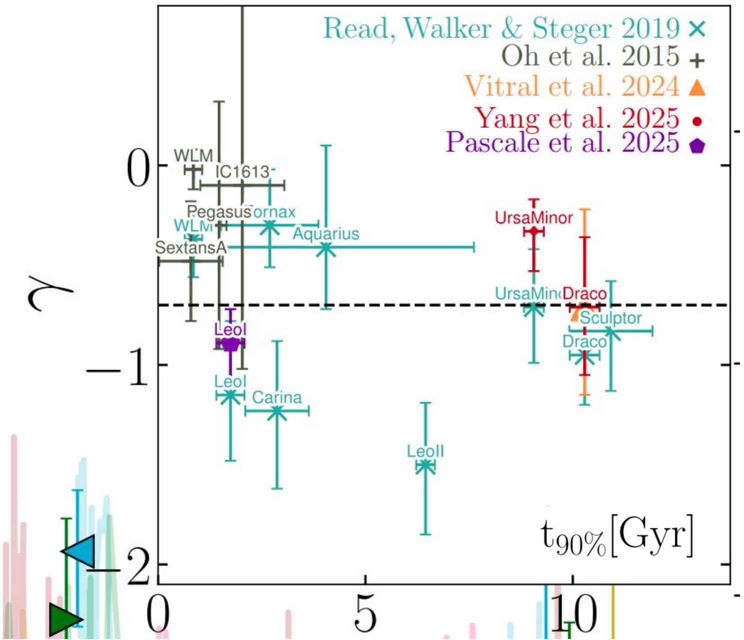
$$t_{90\%}$$

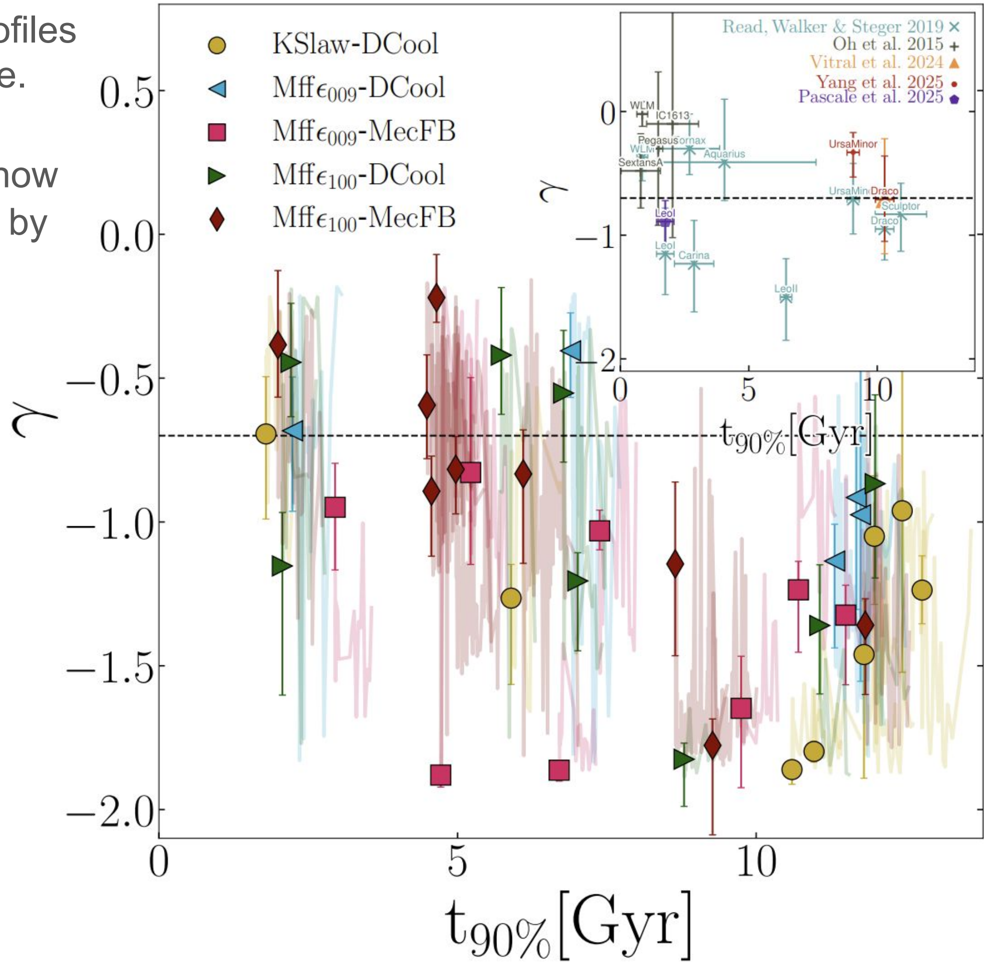
The **lookback time** at which a dwarf galaxy (or subhalo) has formed **90% of its total stellar mass**



- 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.



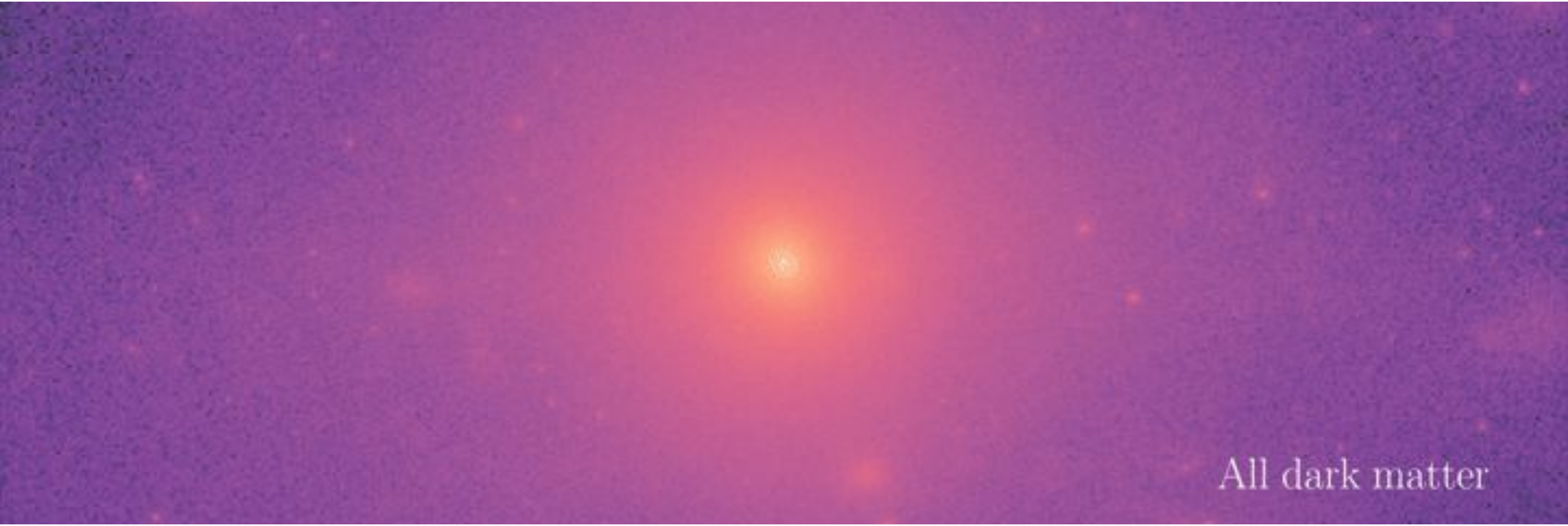



# Conclusions

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