



# Hydrodynamical simulations of galaxy formation: how do baryons affect the dark matter distribution?

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# Overview

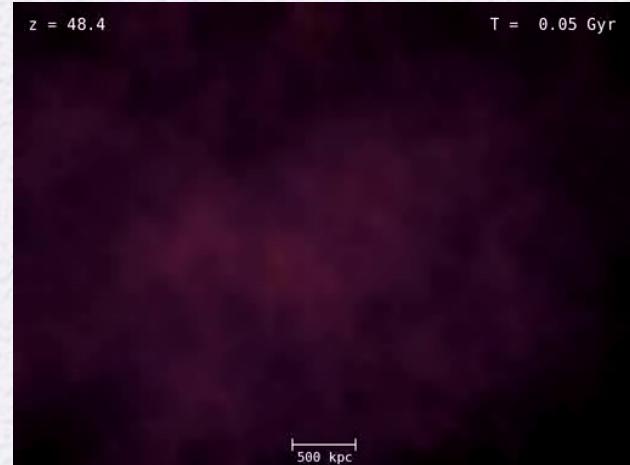
- Structure formation in  $\Lambda$ CDM
  - Properties of DM halos
- Simulations with baryons
  - Baryonic physics in galaxy formation
  - Feedback processes
- Results & Discussion
  - Different codes?
  - Different galaxies?
  - Different environments?
- Summary

# Structure formation in $\Lambda$ CDM

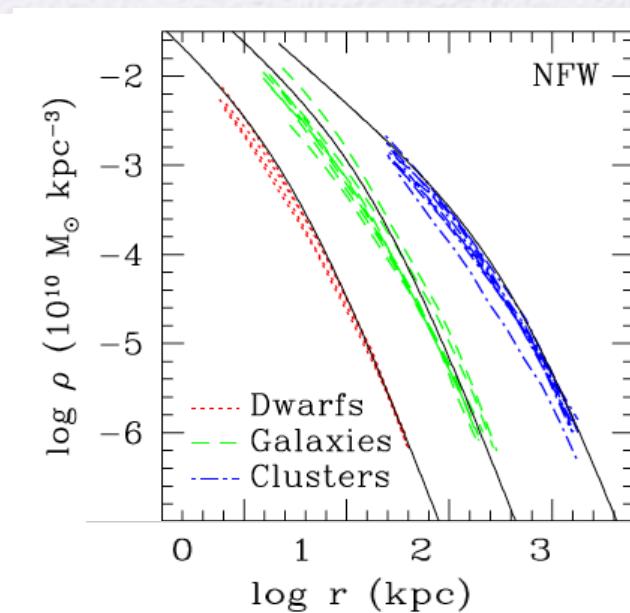
- Structure formation in  $\Lambda$ CDM models is hierarchical
- Dark matter halos form from initial density perturbations and grow via mergers and mass accretion
- Halos have the following properties:
  - “universal” density profiles NFW (Navarro, Frenk & White)

$$\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

Only 2 parameters to describe any halo:  
the mass and the size

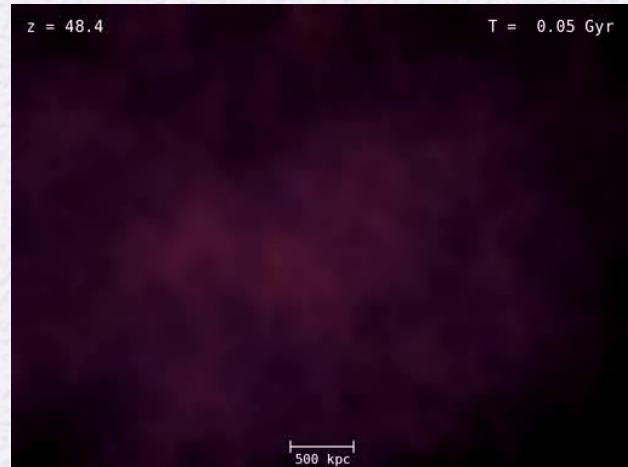


Credit: Volker Springel



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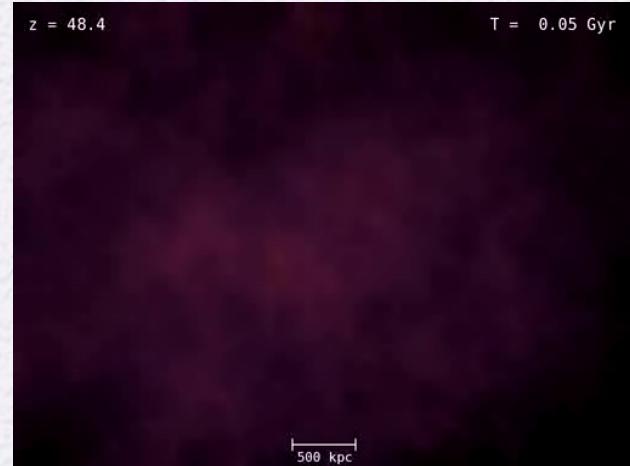


Credit: Volker Springel

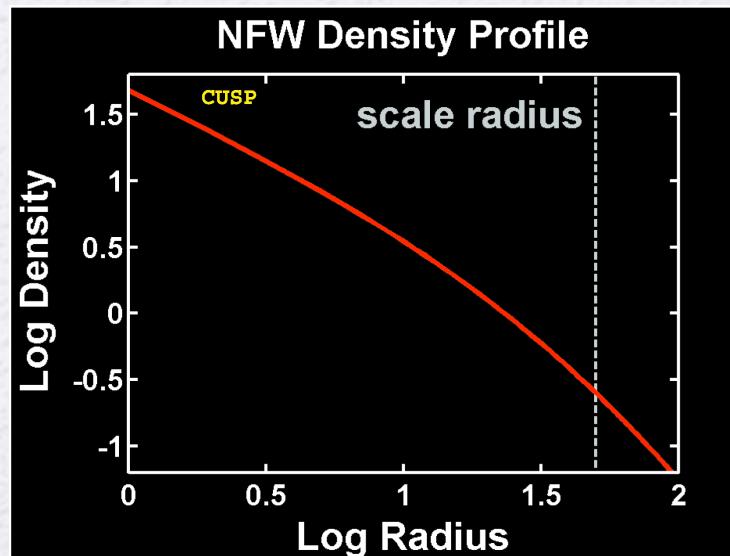


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  - “Cuspy” density profiles

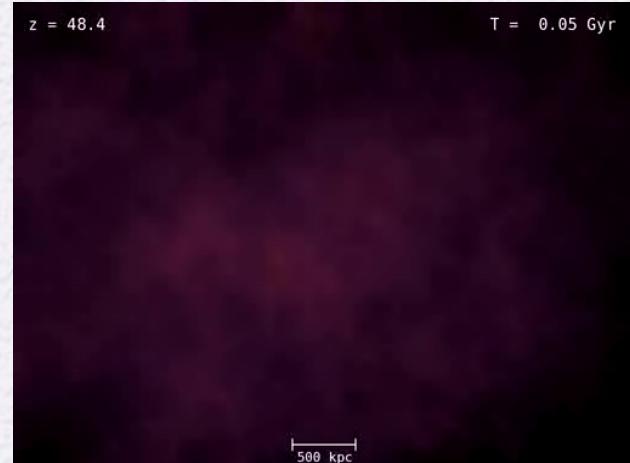


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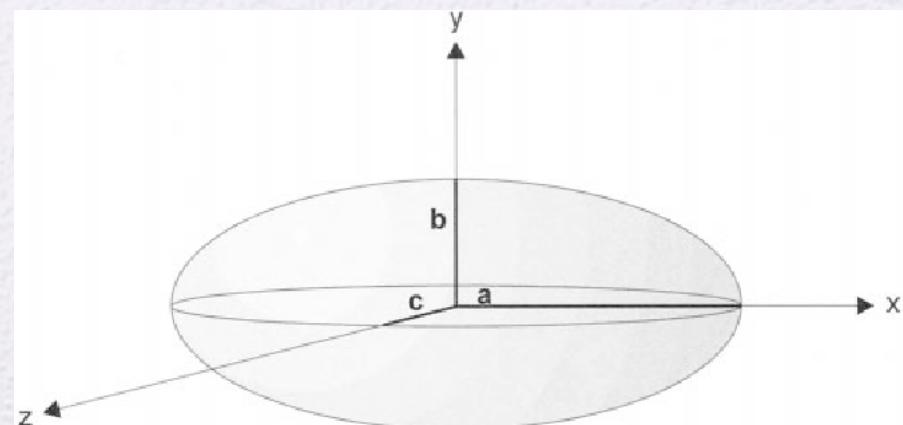


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  - “Cuspy” density profiles
  - Triaxial shapes



Credit: Volker Springel

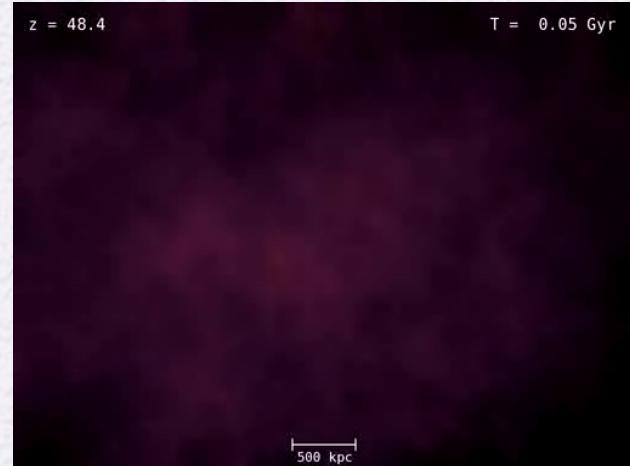


# Tensions in the $\Lambda$ CDM model

- A number of apparent inconsistencies between the predictions of the  $\Lambda$ CDM model and observational results, particularly at the small scales of the dwarf galaxies
  - Too big to fail problem (satellites too massive)
  - Missing satellites problem (too many satellites)
  - Cusped vs cored density profiles (cusps predicted, cores observed)
- Can baryons be the solution?
  - Even though baryons make up only 15% of the total mass, they can have a significant impact in the DM distributions, particularly in the central regions where baryons can dominate the total mass

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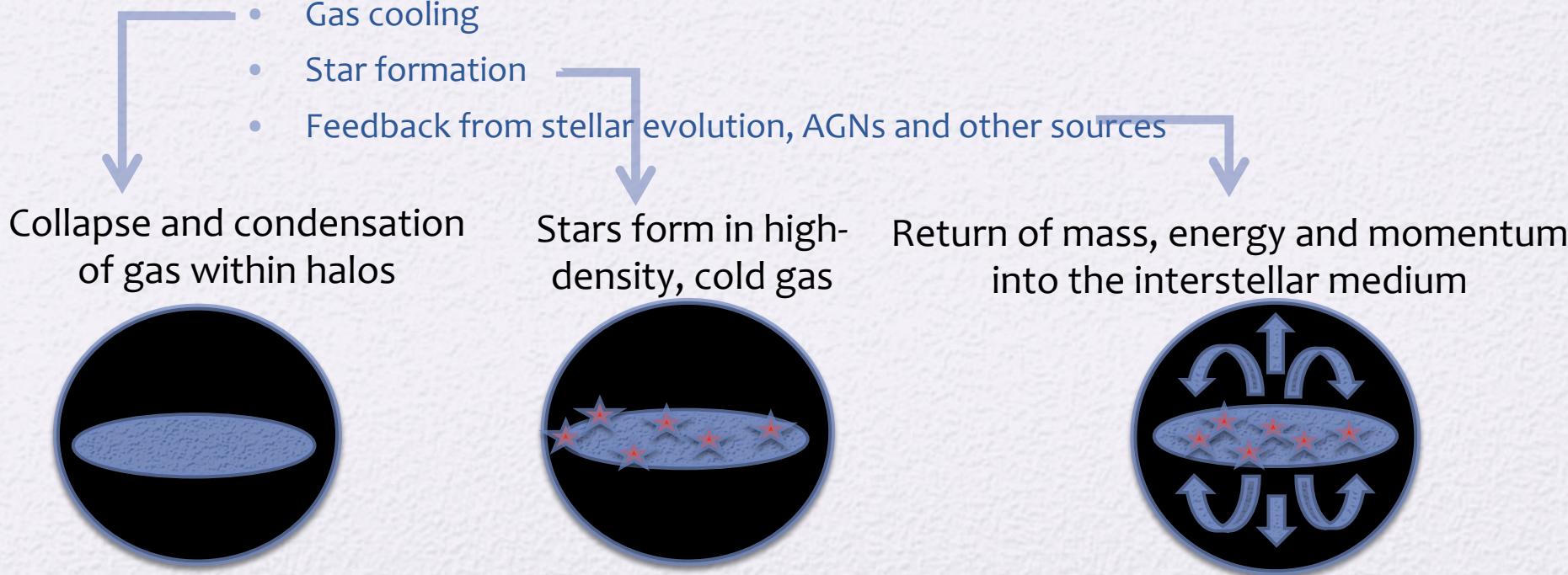
Baryons affect all these properties!

# Simulations with baryons

- Initial (and boundary) conditions
  - These are “known”: given by the CMB observations

# Simulations with baryons

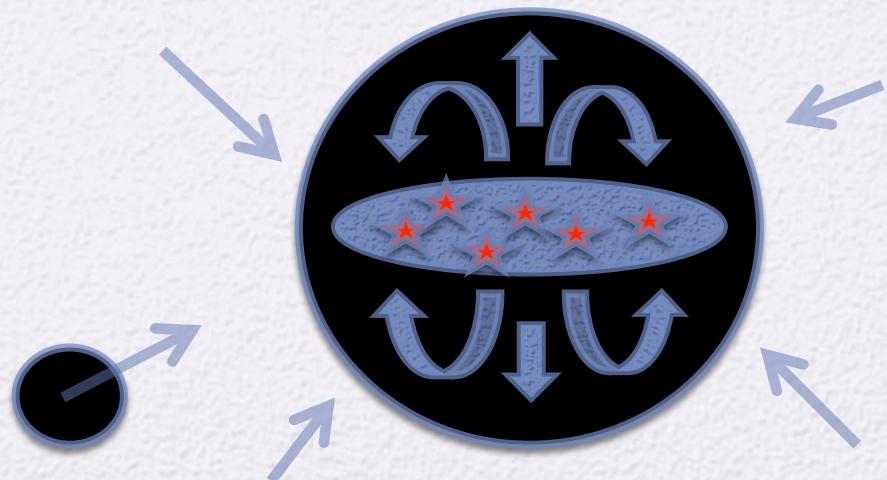
- Initial (and boundary) conditions
- Physical processes which drive evolution
  - Gravity
  - Baryonic evolution:
    - Need to solve hydrodynamics equations + sub-grid physics



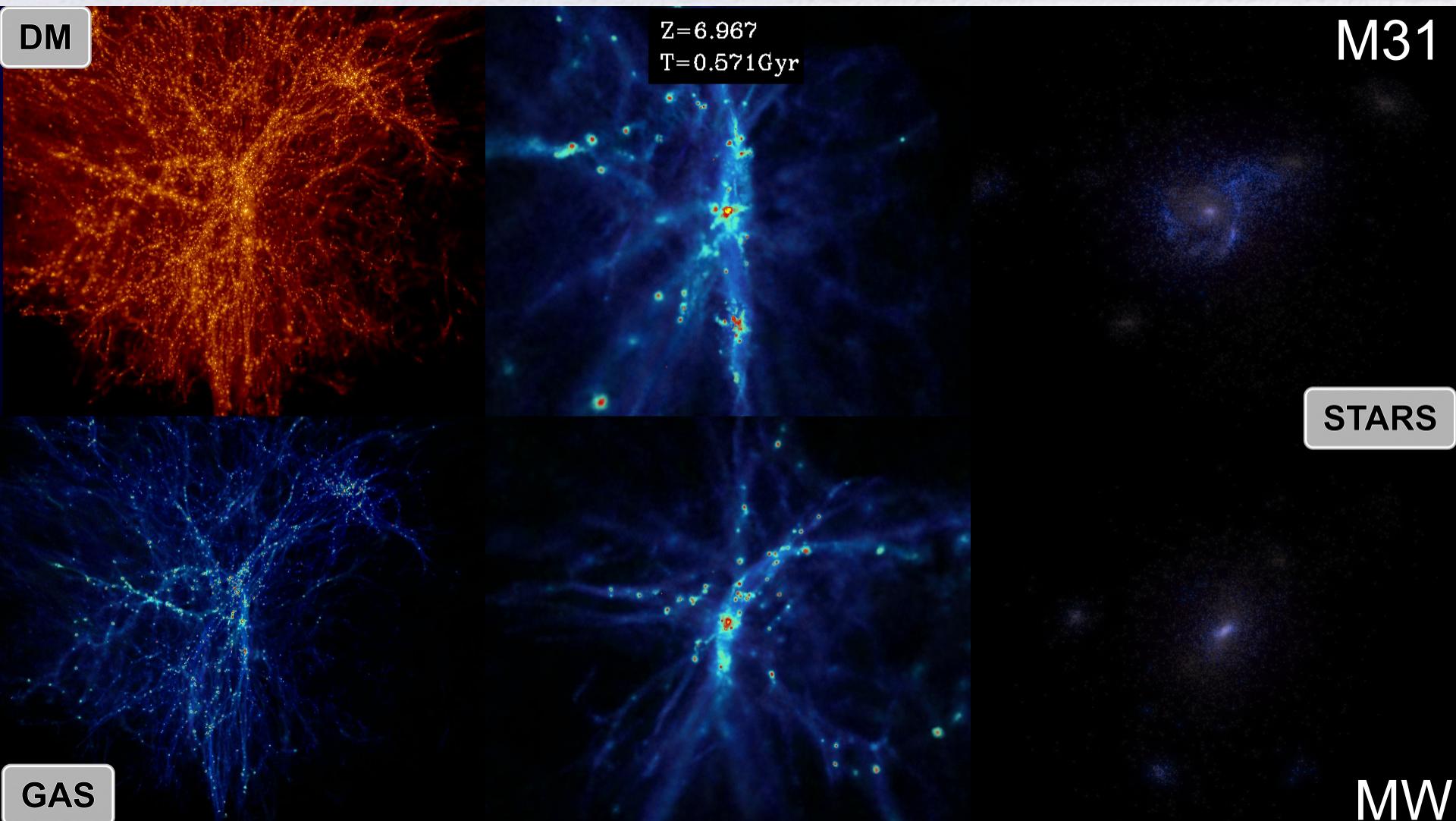
# Simulations with baryons

- Initial (and boundary) conditions
- Physical processes which drive evolution
  - Gravity
  - Baryonic evolution:
    - Need to solve hydrodynamics equations + sub-grid physics
      - Gas cooling
      - Star formation
      - Feedback from stellar evolution, AGNs and other sources

Cosmological effects:  
mass accretion/mergers/  
interactions are naturally  
included in the simulations



# A simulation of the Local Group



# Galaxy formation simulations

- Feedback: a chain of cause-and-effect that forms a closed loop
- Different feedback processes act in galaxies. The most significant feedback in galaxies up to the Milky Way scale is that produced by stellar evolution
  - e.g.: Supernova explosions, mass ejection by stars in the AGB phase
- There are other forms of feedback that are dominant in other regimes:
  - **AGN** feedback: dominant in massive galaxies and galaxy clusters: release significant amounts of energy in the form of radiation/mechanical flows
  - **Cosmic ray** feedback,...

# Stellar feedback: three channels

- Type II Supernova explosions
  - massive stars ( $8M_{\odot} < M < 100M_{\odot}$ ), short-lived ( $10^6$  yr) that end their lives violently
  - **eject significant amounts of energy:  $\sim 10^{51}$  erg per explosion**
  - Eject chemical elements (mainly  $\alpha$ -elements such as O and Mg)
- Type Ia Supernova
  - Low-mass stars/binaries ( $M < 1.4M_{\odot}$ ), long-lived ( $10^{8-10}$  yr)
  - Main contributor of Fe
- AGB stars
  - Low and intermediate-mass stars ( $0.6M_{\odot} < M < 10M_{\odot}$ )
  - Experience significant mass loss, eject chemical elements in winds
  - Main contributors of C, N

# Supernova feedback

## Ingredients of feedback modeling

- Energy feedback comes primarily from SNII explosions  
Initial Mass function: fractional contribution of stars of different mass in a stellar population
- The total energy produced by all SNII in a star particle is easily calculated from the number of “massive stars” in it.
- If we have “N” exploding stars in a star particle of mass  $m$   
→ The energy released is simply  $N \times 10^{51} \text{ erg}$
- The energy is released when the stars explode: given by lifetime of progenitor stars
- Where/how do we inject the energy?
  - This is very hard to implement in simulations
  - Thermal feedback vs kinetic feedback

# Supernova feedback

## Thermal feedback

Add heat to the gas



A star forms in a cold gas cloud



we heat the gas around it



as the cooling is very efficient for cold gas, the energy is lost

Two turnarounds:

→ don't give energy immediately, but wait until a large number of SN have exploded. At some point the energy is high enough so that it does not cool (Scannapieco+2006)

→ Don't allow particles that received energy to cool for a given time (Stinson +2006)

# Energy feedback

## Thermal feedback

Add heat to the gas



A star forms in  
a gas cloud

## Kinetic feedback

Move gas around



give a velocity kick to  
surrounding gas

# Supernova feedback

## Thermal feedback

Add heat to the gas

## Kinetic feedback

Move gas around

Either way, we need to give input parameters, that are not known!

A characteristic radius of the energy injection

For thermal feedback models:

- time scale in which we shut off the cooling

For kinetic feedback models:

- velocity and direction of the “outflows”

# Supernova feedback

## Thermal feedback

Add heat to the gas

## Kinetic feedback

Move gas around

What we are trying to do is mimic the effects of feedback at the scales that are resolved in simulations

What we want:



Gas receiving  
feedback energy



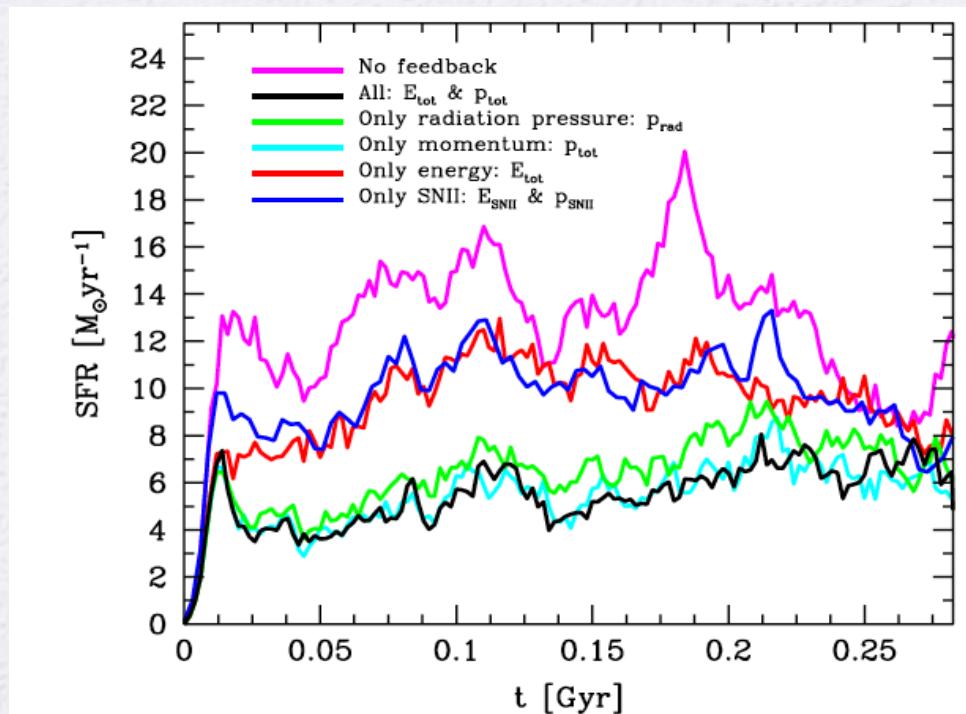
will heat up



and expand

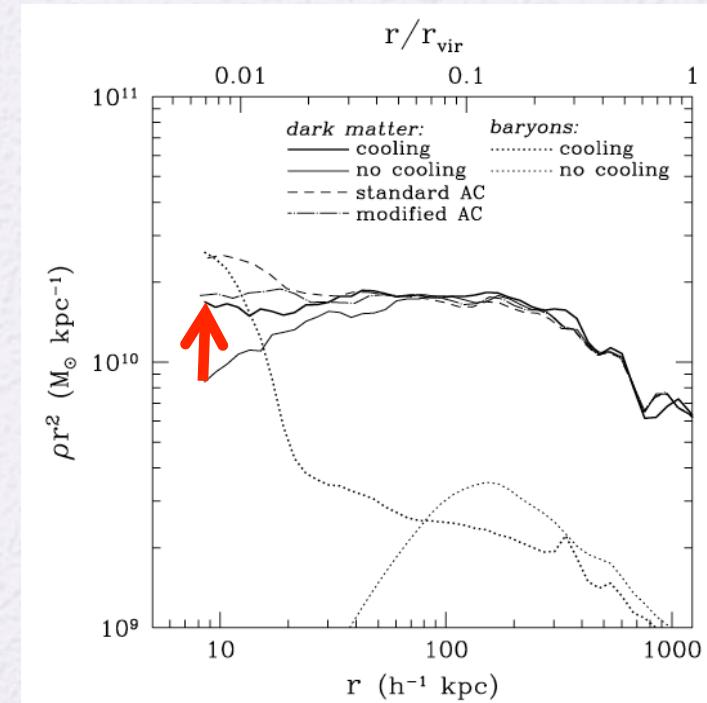
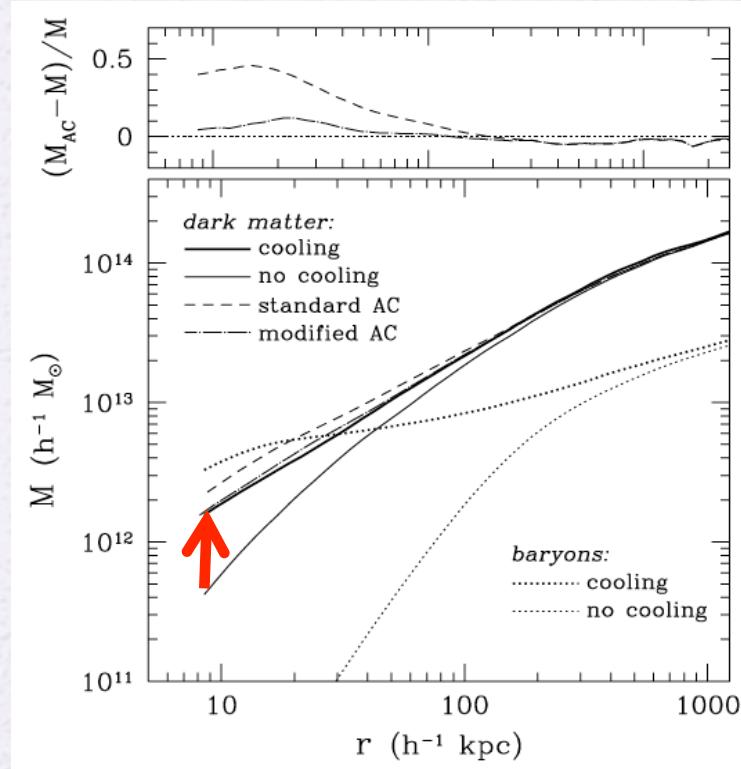
# Radiation-pressure feedback

- Radiation-pressure (RP) feedback: massive, short-lived stars provide additional input of momentum and energy in the form of stellar winds and radiation pressure **prior to their explosion as SNII**
  - No yet consensus on the effects of RP feedback in the surrounding ISM, at the scales resolved in simulations



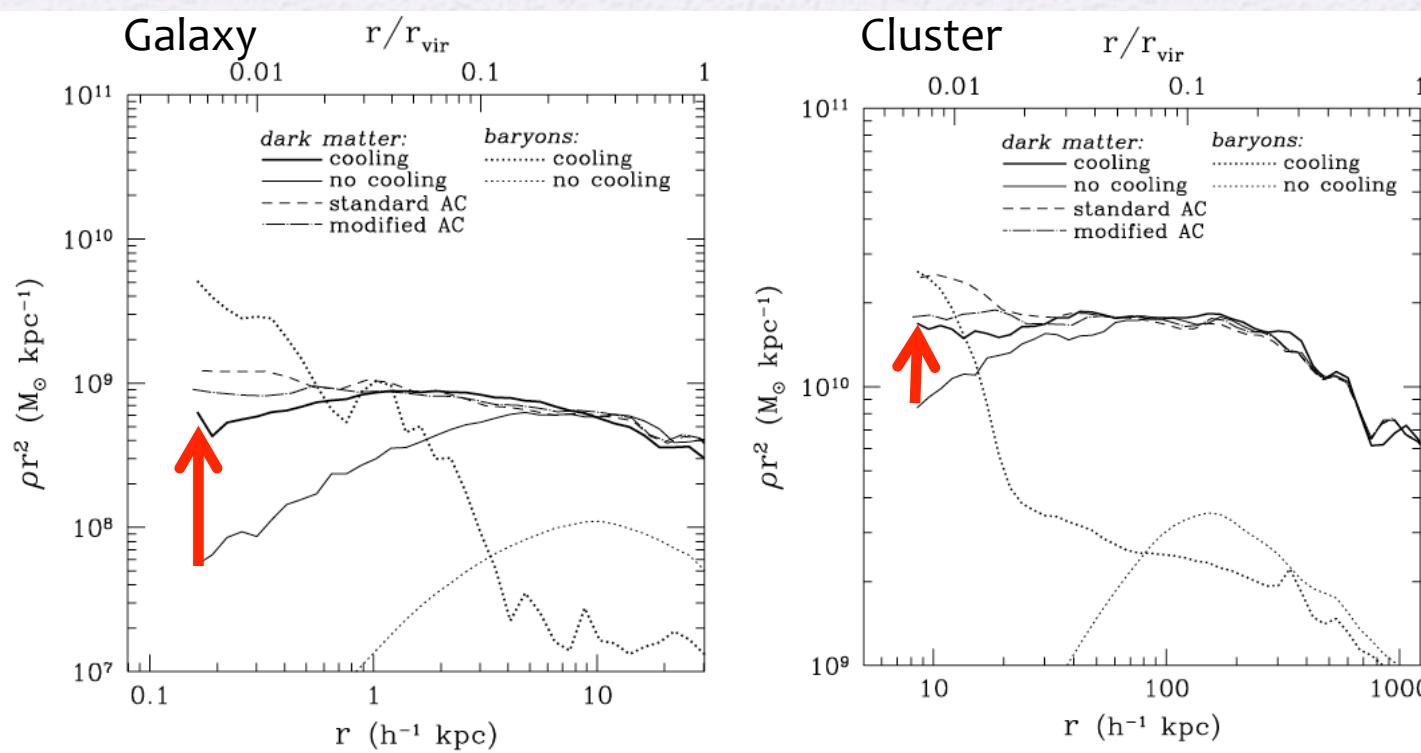
# Effects of baryons on dark matter

- Can baryons be the solution?
  - It is now well established that baryons can significantly modify the properties of the dark matter halos:
    - Contraction due to cooling and condensation of gas



# Effects of baryons on dark matter

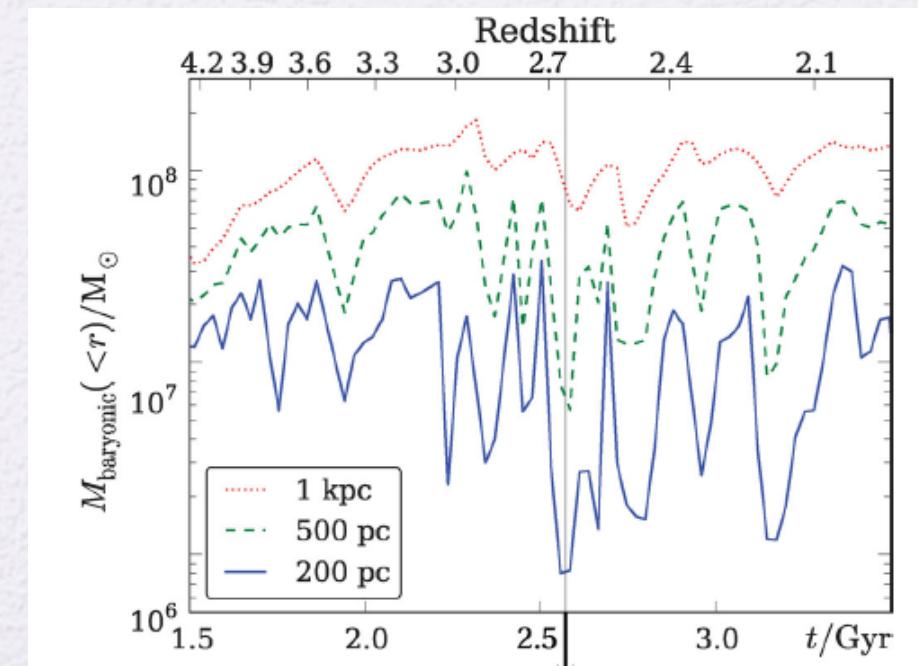
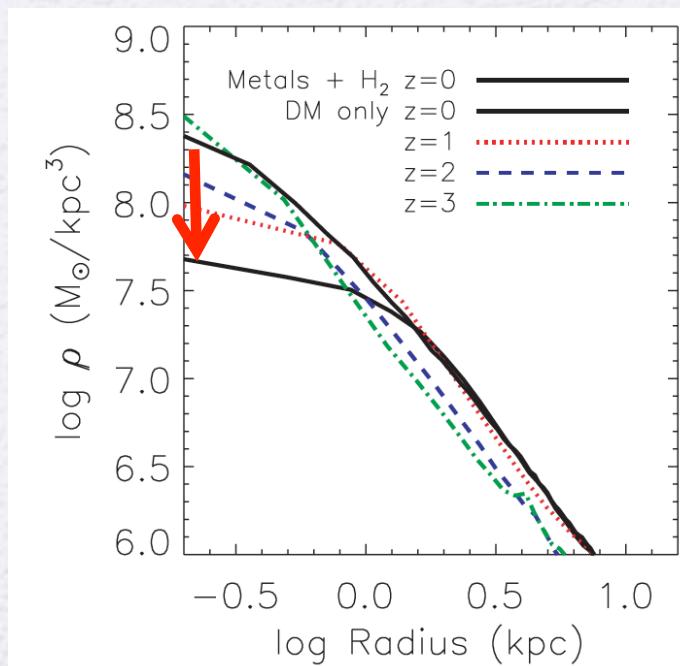
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The final amount of “contraction” will be given by amount of baryons relative to DM in the central region

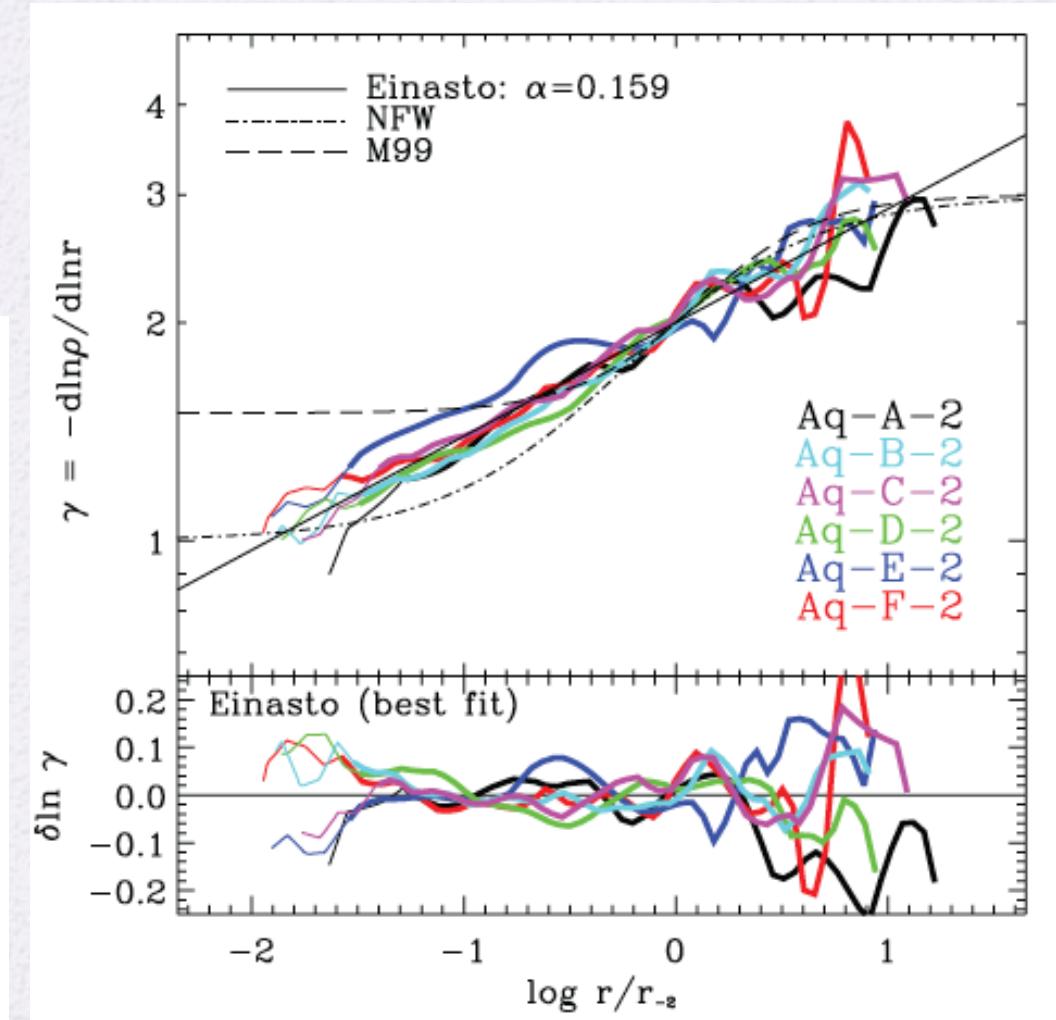
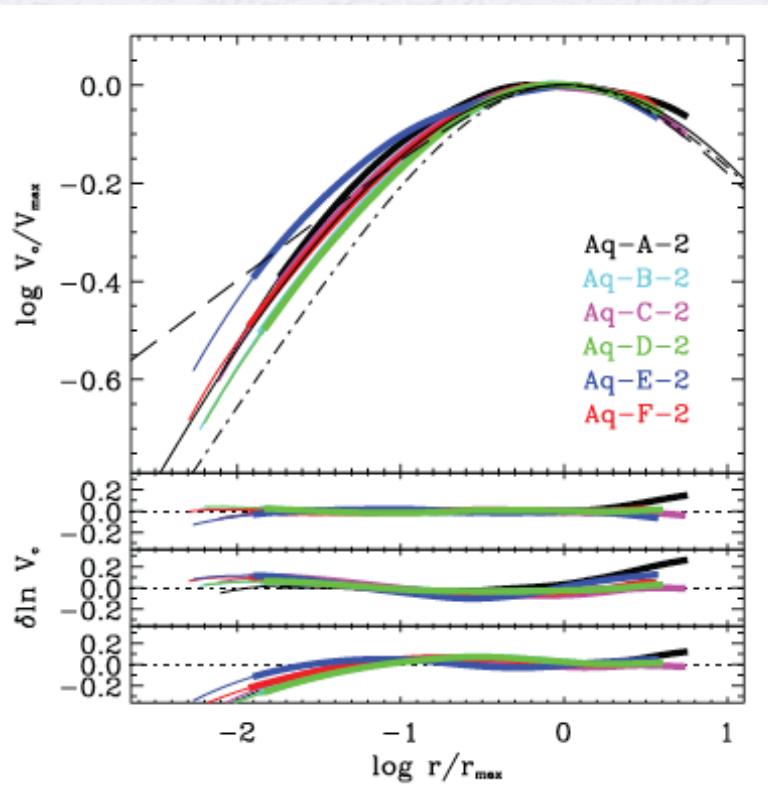
# Effects of baryons on dark matter

- Can baryons be the solution?
  - Simulations show that baryons can significantly modify the properties of the dark matter halos:
    - Contraction due to gas dissipation and condensation
    - Expansion due to strong feedback that removes gas/trigger potential fluctuations/dynamical friction



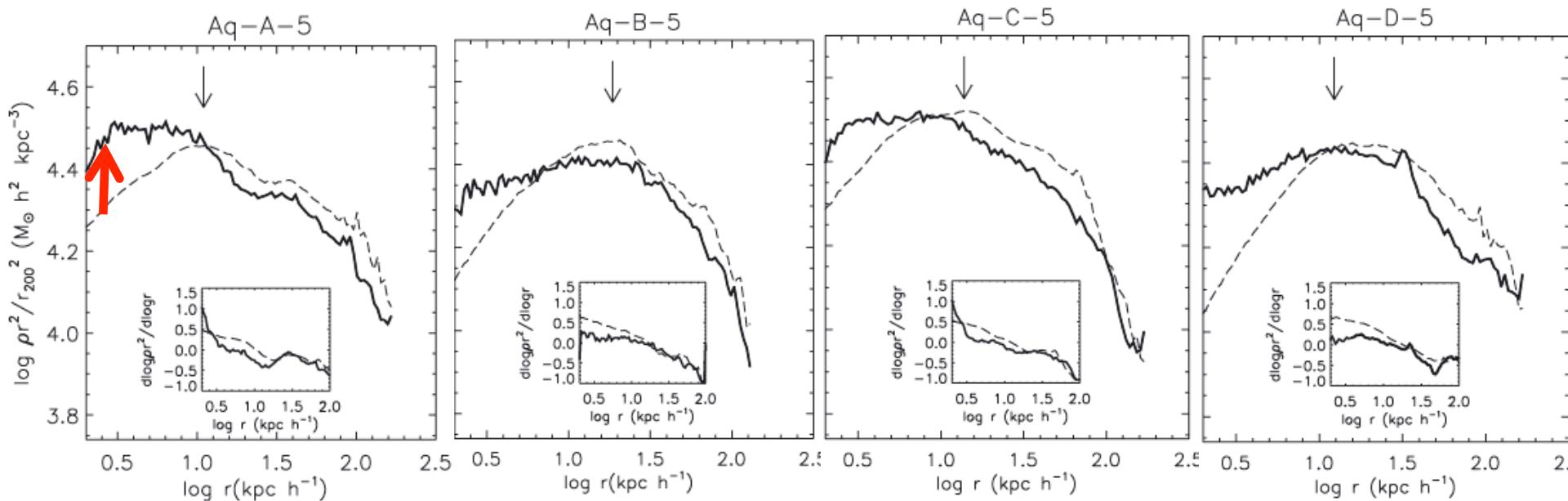
# Different galaxies?

- Pure DM halos are not strictly self-similar



# Different galaxies?

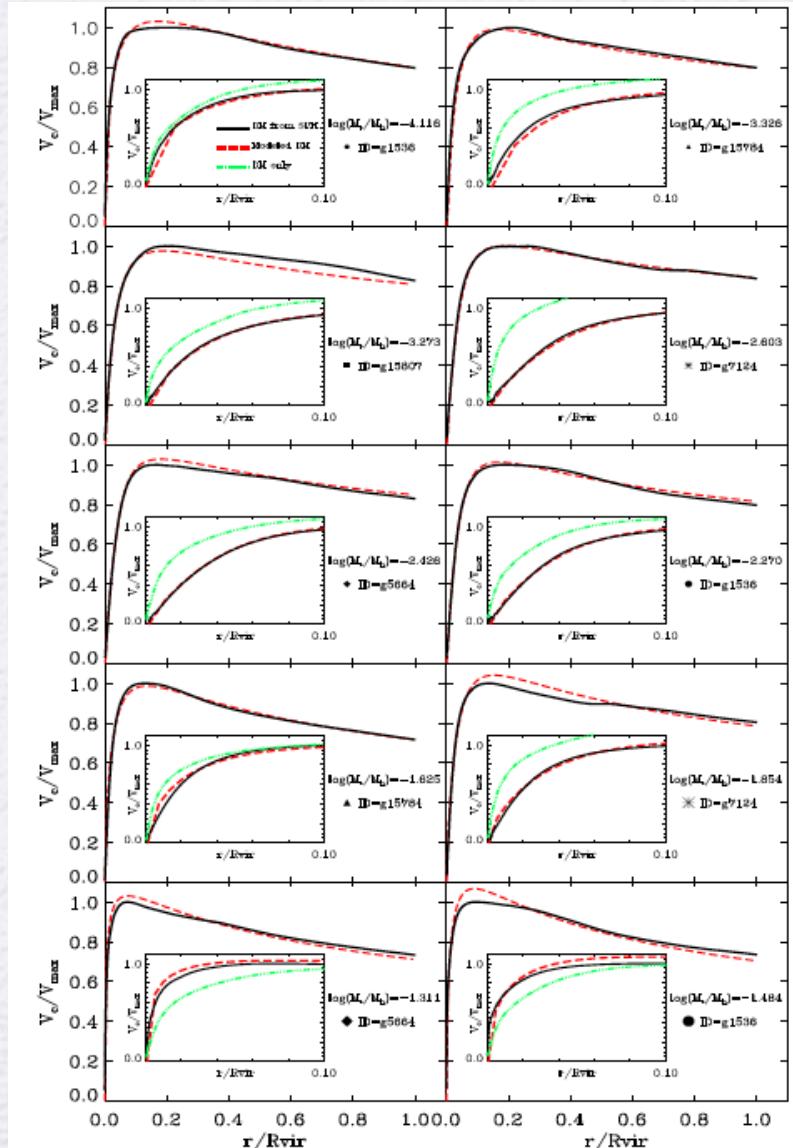
- Different responses of DM halos to baryons in MW-mass galaxies



# Different galaxies?

Di Cintio+ 2014 finds inner slope depends on  $M_*/M_{\text{halo}}$ : the integrated star formation efficiency

- $M_*/M_{\text{halo}} < 10^{-4}$ : maintain the NFW profile of DM only simulations
- Most cored galaxies appear at  $M_*/M_{\text{halo}} \sim 3-5 \times 10^{-3}$  or  $M_* \sim 10^{8.5} M_{\odot}$
- $M_*/M_{\text{halo}} > 5 \times 10^{-3}$  are progressively steeper with increasing mass



# Different codes, different galaxies?

## The Aquila comparison project: the effects of feedback and numerical methods on simulations of galaxy formation

C. Scannapieco,<sup>1</sup> M. Wadevahl,<sup>2</sup> O. H. Parry,<sup>3,4</sup> J. F. Navarro,<sup>5</sup> A. Jenkins,<sup>3</sup> V. Springel,<sup>6,7</sup> R. Teyssier,<sup>8,9</sup> E. Carlson,<sup>10</sup> H. M. P. Couchman,<sup>11</sup> R. A. Crain,<sup>12,13</sup> C. Dalla Vecchia,<sup>14</sup> C. S. Frenk,<sup>3</sup> C. Kobayashi,<sup>15,16</sup> P. Monaco,<sup>17,18</sup> G. Murante,<sup>17,19</sup> T. Okamoto,<sup>20</sup> T. Quinn,<sup>10</sup> J. Schaye,<sup>13</sup> G. S. Stinson,<sup>21</sup> T. Theuns,<sup>3,22</sup> J. Wadsley,<sup>11</sup> S. D. M. White<sup>2</sup> and R. Woods<sup>11</sup>

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<sup>19</sup>INAF, Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025 Pino Torinese, Italy

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# Different codes, different galaxies?

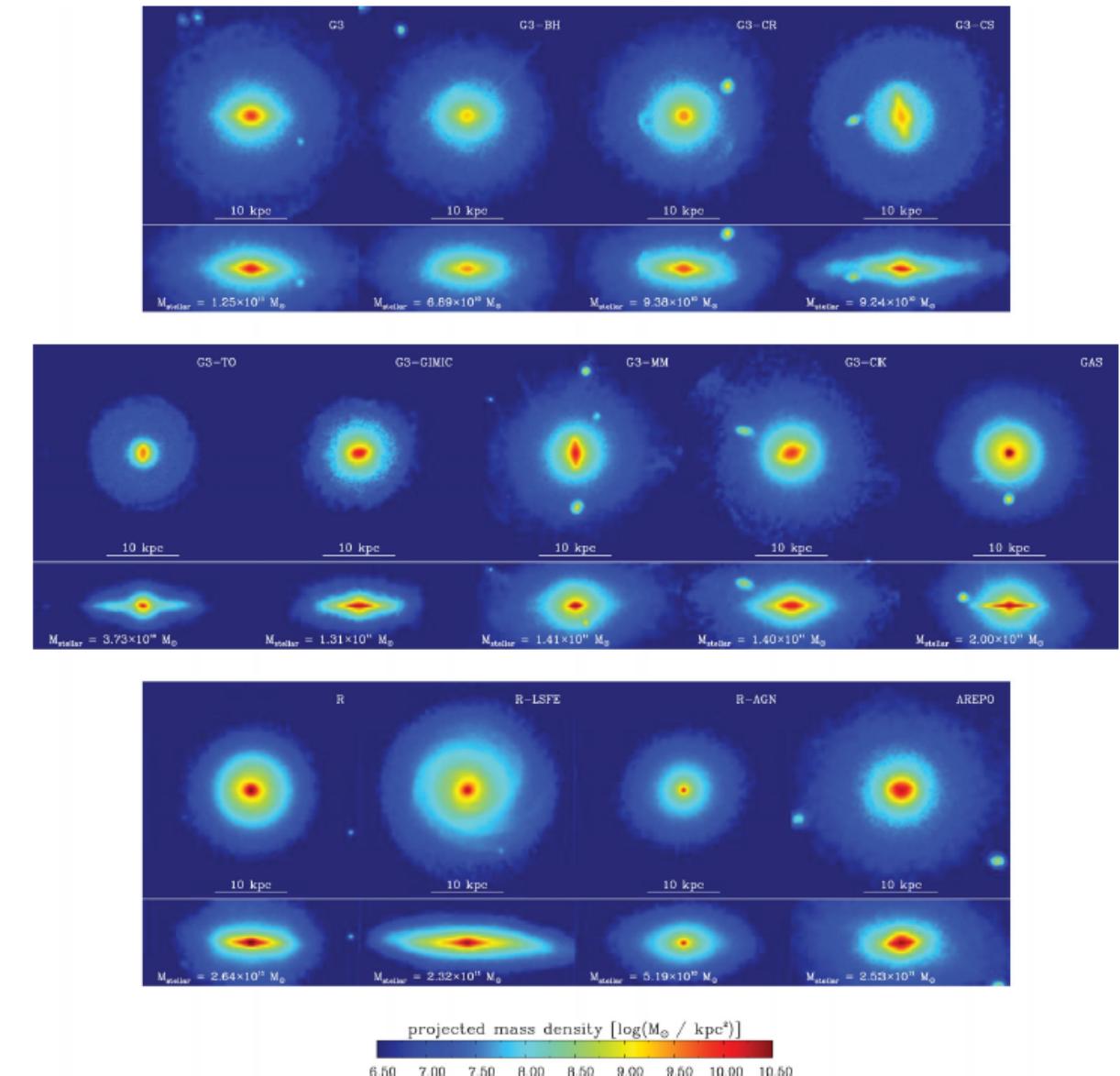
**Table 1.** Summary of code characteristics and subgrid physics.

Code	Reference	Type	UV background		Cooling	Feedback
			(zUV)	(spectrum)		
G3 (GADGET3)	[1]	SPH	6	[10]	Primordial [13]	SN (thermal)
G3-BH	[1]	SPH	6	[10]	Primordial [13]	SN (thermal), BH
G3-CR	[1]	SPH	6	[10]	Primordial [13]	SN (thermal), BH, CR
G3-CS	[2]	SPH	6	[10]	Metal dependent [14]	SN (thermal)
G3-TO	[3]	SPH	9	[11]	Element-by-element [15]	SN (thermal+kinetic)
G3-GIMIC	[4]	SPH	9	[11]	Element-by-element [15]	SN (kinetic)
G3-MM	[5]	SPH	6	[10]	Primordial [13]	SN (thermal)
G3-CK	[6]	SPH	6	[10]	Metal dependent [14]	SN (thermal)
GAS (GASOLINE)	[7]	SPH	10	[12]	Metal dependent [16]	SN (thermal)
R (RAMSES)	[8]	AMR	12	[10]	Metal dependent [14]	SN (thermal)
R-LSFE	[8]	AMR	12	[10]	Metal dependent [14]	SN (thermal)
R-AGN	[8]	AMR	12	[10]	Metal dependent [14]	SN (thermal), BH
AREPO	[9]	Moving mesh	6	[10]	Primordial [13]	SN (thermal)

Note: [1] Springel et al. (2008); [2] Scannapieco et al. (2005), Scannapieco et al. (2006); [3] Okamoto et al. (2010); [4] Crain et al. (2009); [5] Murante et al. (2010); [6] Kobayashi, Springel & White (2007); [7] Stinson et al. (2006); [8] Teyssier (2002), Rasera & Teyssier (2006), Dubois & Teyssier (2008); [9] Springel (2010a); [10] Haardt & Madau (1996); [11] Haardt & Madau (2001); [12] Haardt & Madau (private communication); [13] Katz et al. (1996); [14] Sutherland & Dopita (1993); [15] Wiersma, Schaye & Smith (2009a); [16] Shen, Wadsley & Stinson (2010).

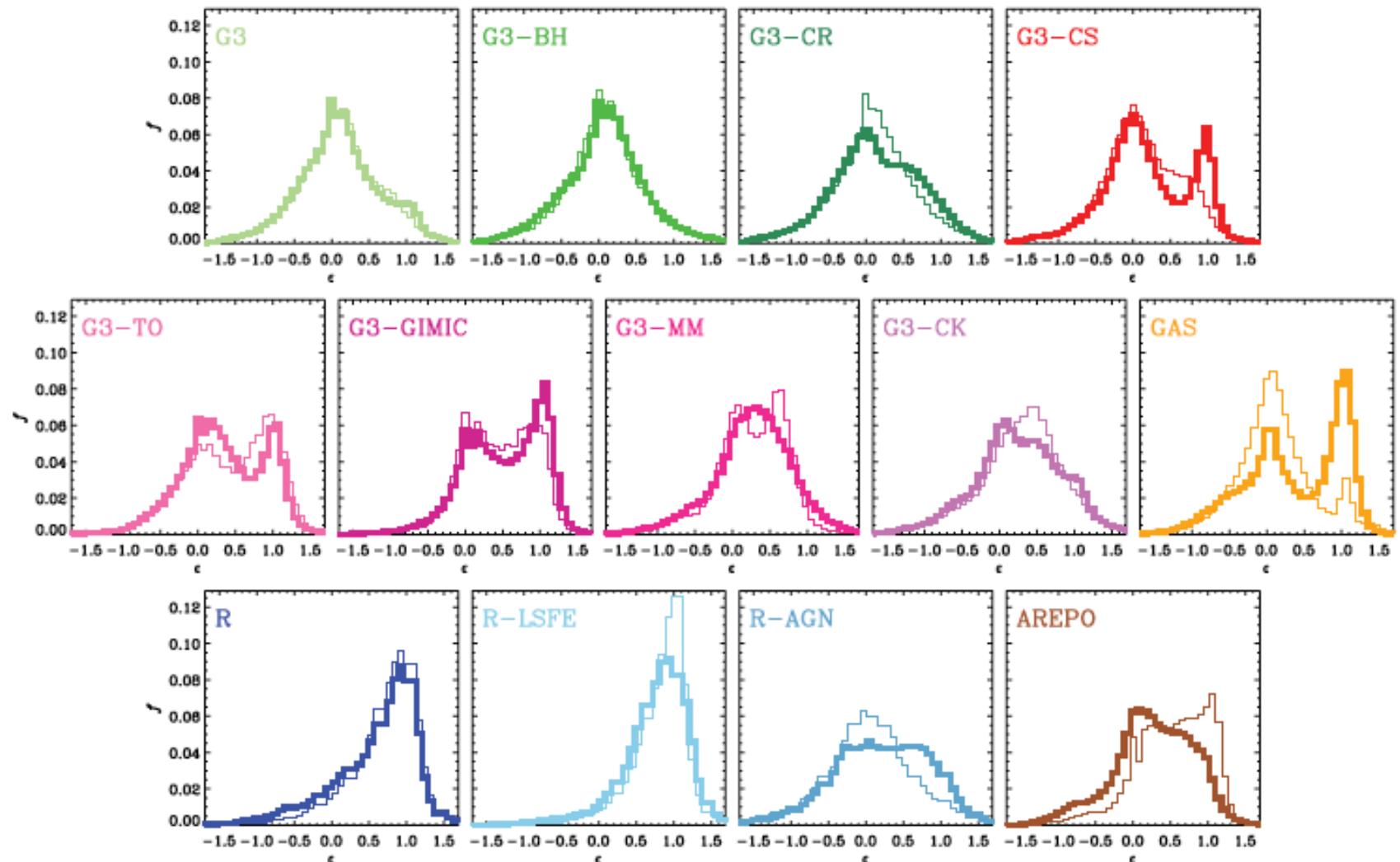
# Different codes, different galaxies?

## Morphologies



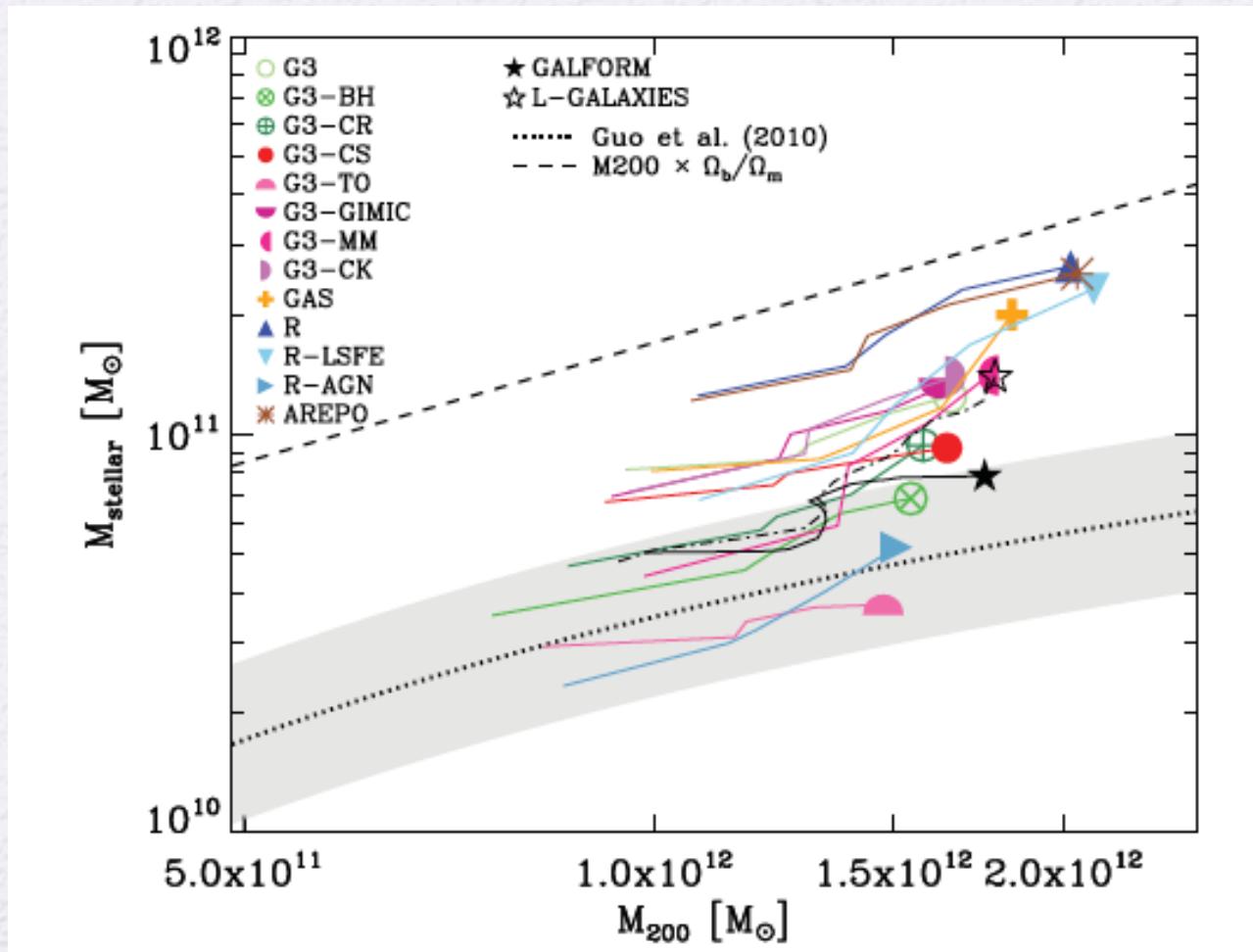
# Different codes, different galaxies?

## Morphologies



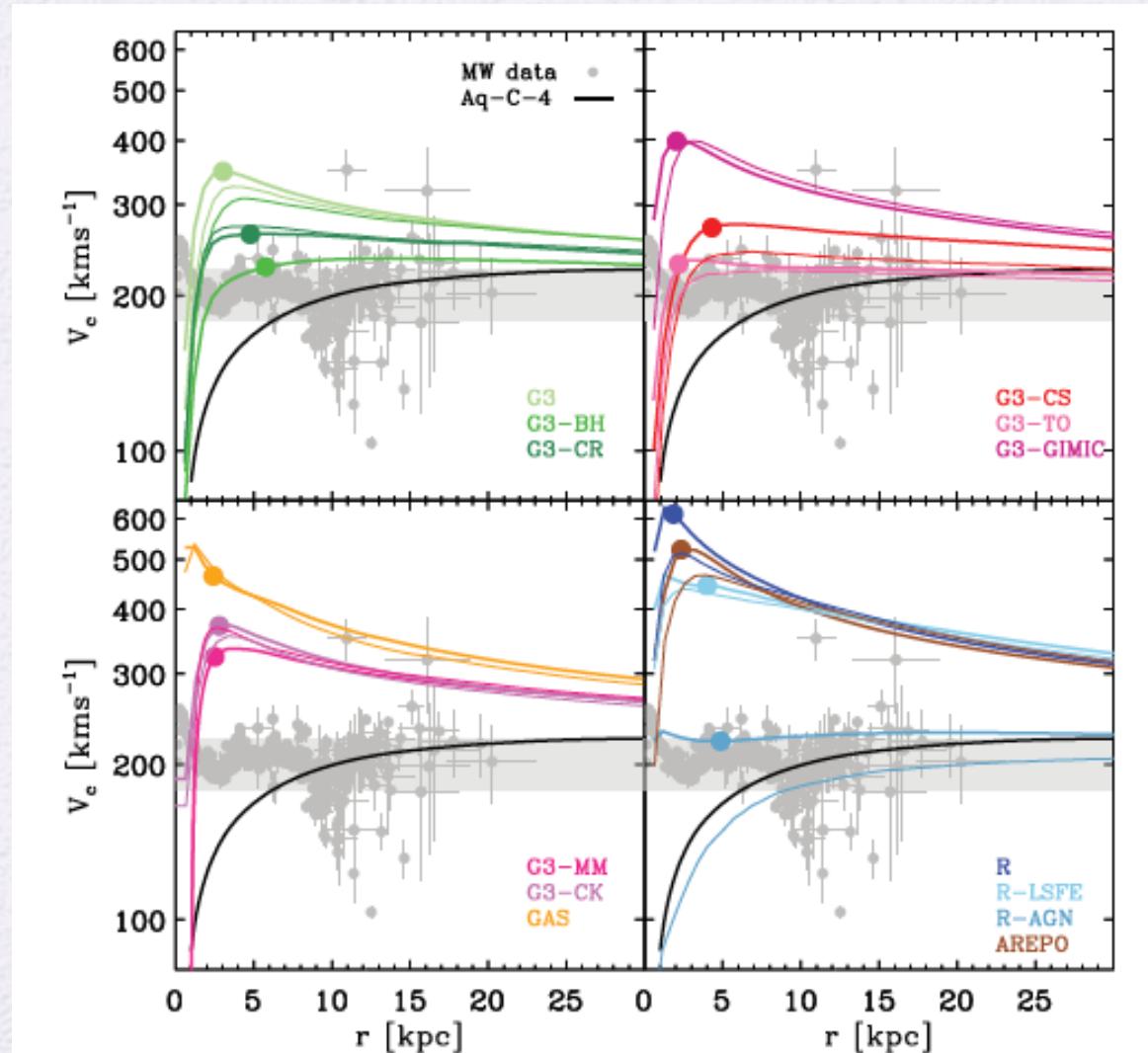
# Different codes, different galaxies?

## Stellar masses



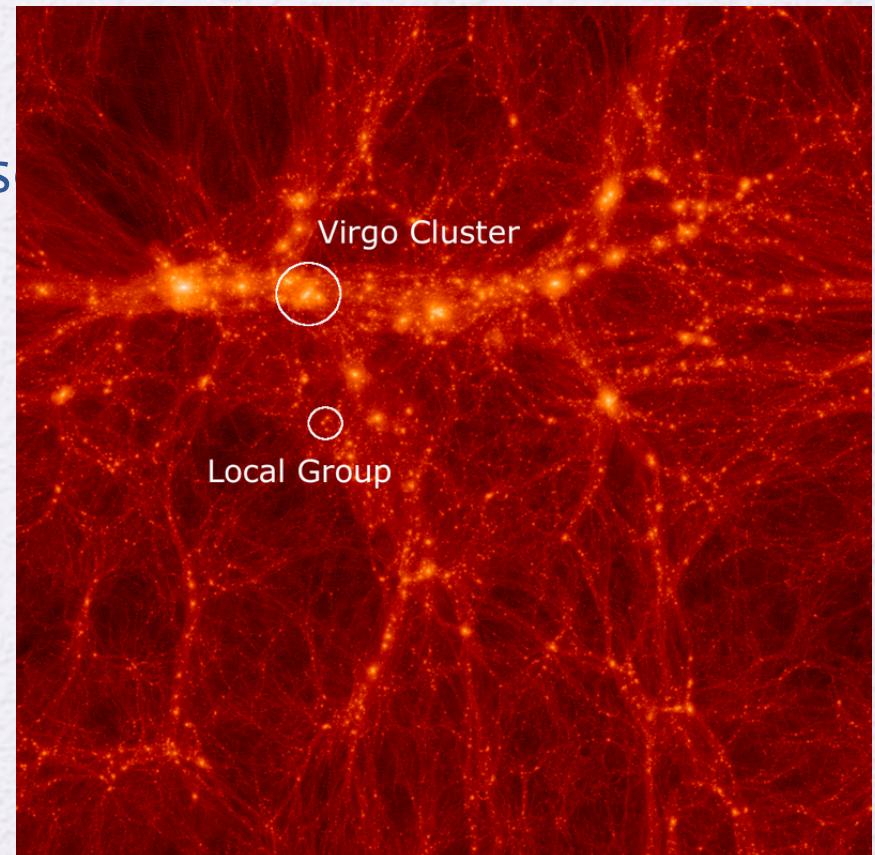
# Different codes, different galaxies?

## Circular velocities



# Different environment, different galaxy properties?

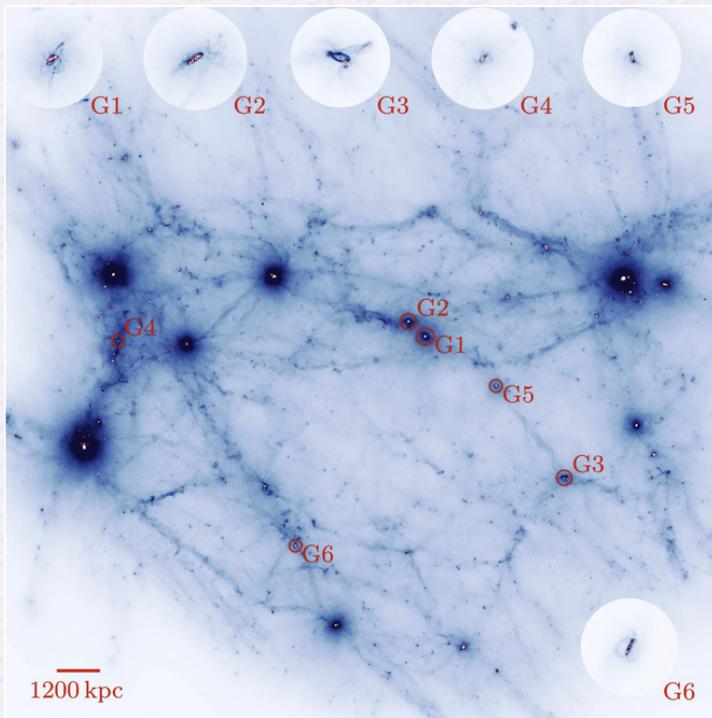
- There are indications that the environment where a galaxy lives might affect its properties
- Given that the Milky Way is part of the Local Group, an overdense region of the Universe it is necessary to understand possible environmental effects
- Constrained Local UniversE simulations: CLUES



<https://www.clues-project.org/>

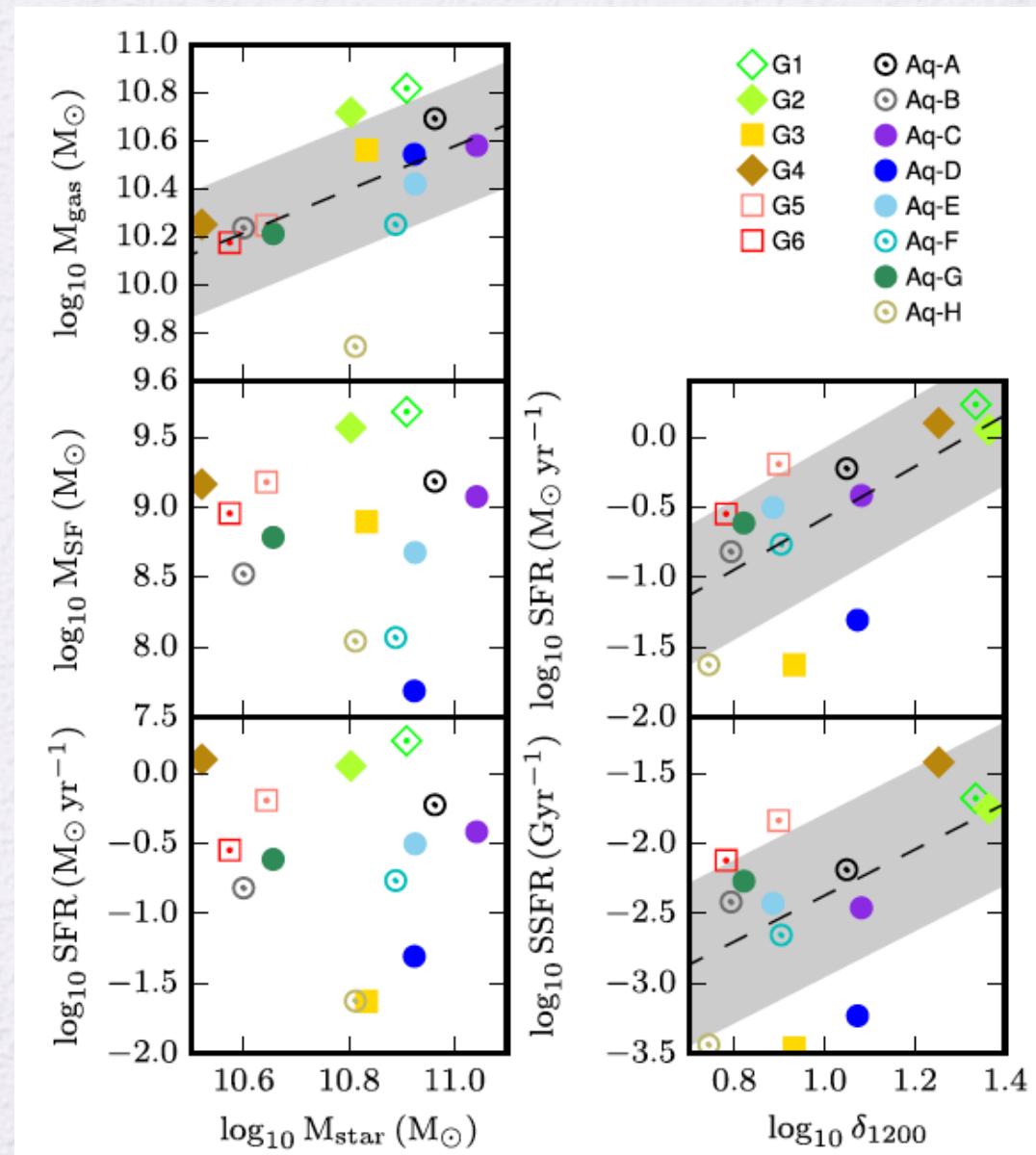
# Environment and galaxy properties

- Environmental effects:  
higher SFRs in richer environments (?)



Creasey+2015

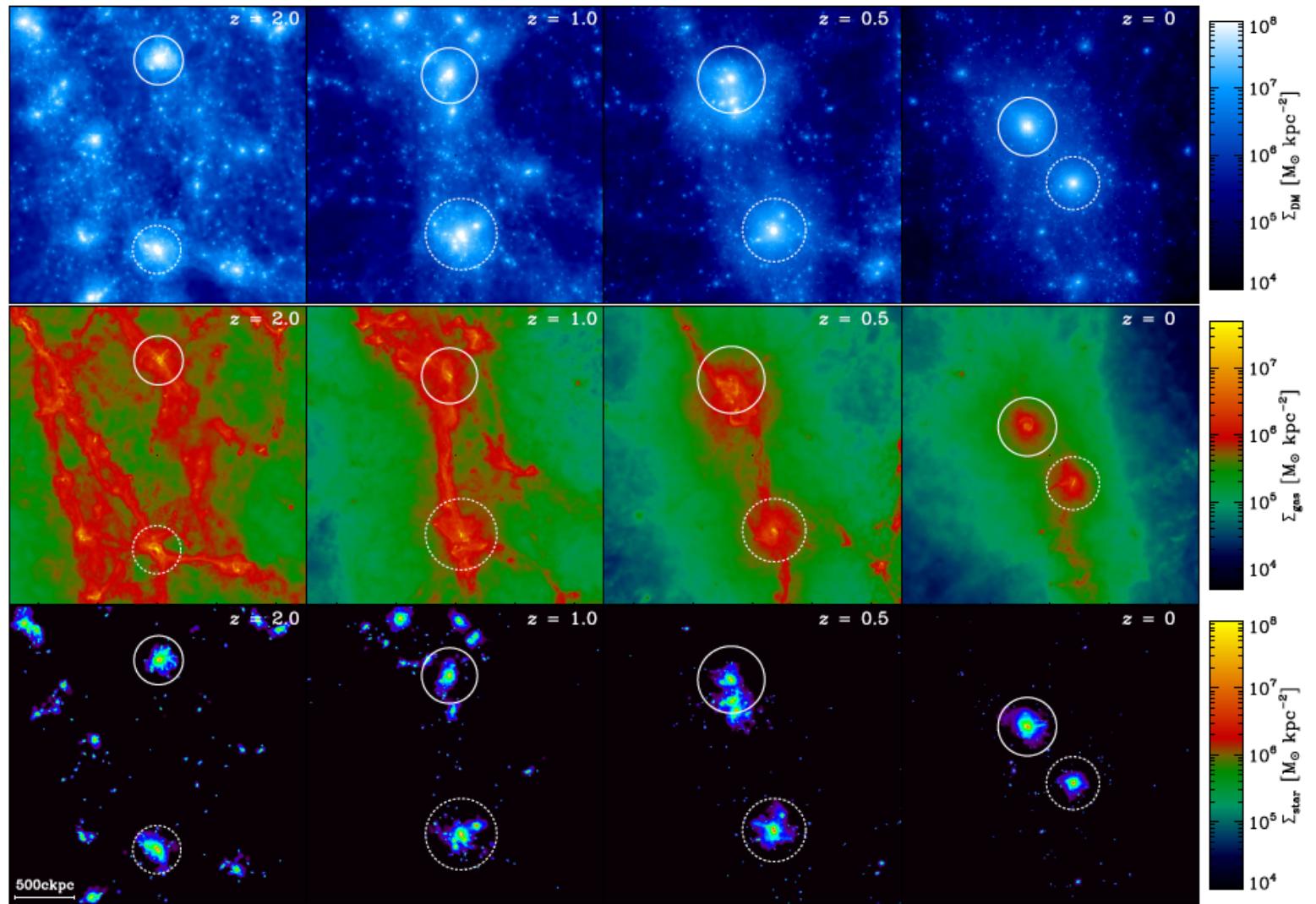
(see also Few+2012, Sawala+2016)



# Different environment, different galaxy properties?

- MW & M31 candidates

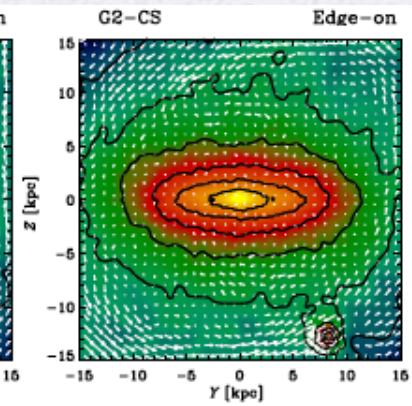
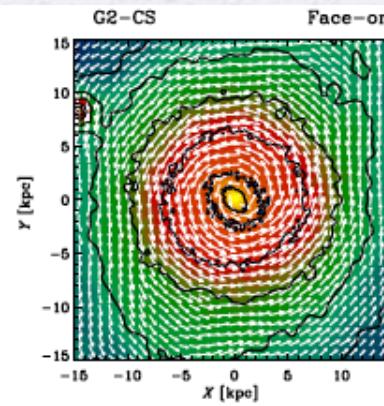
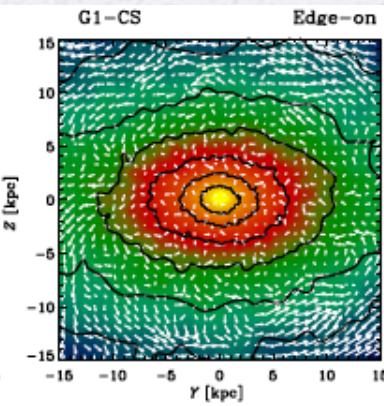
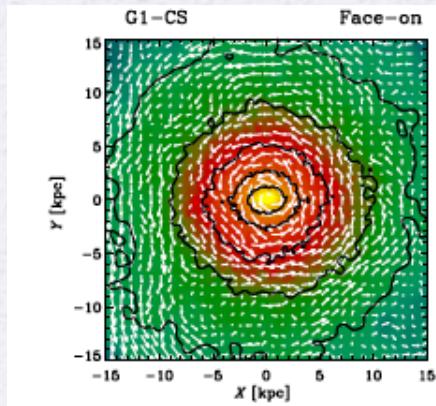
Scannapieco+2015



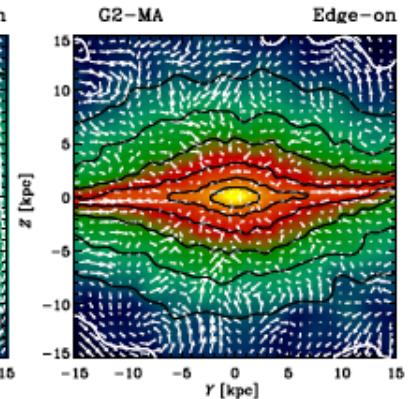
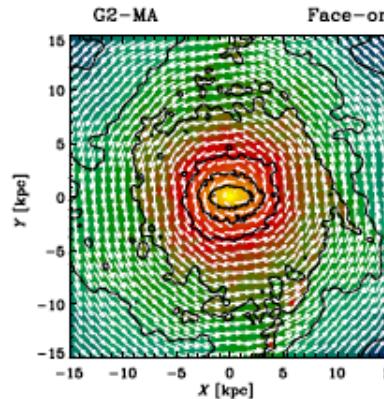
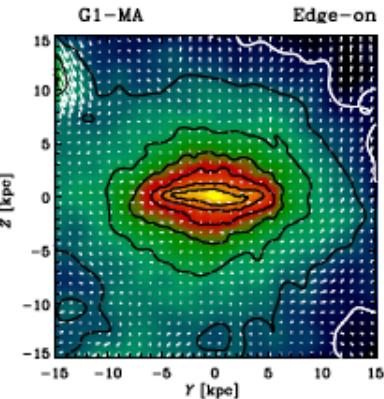
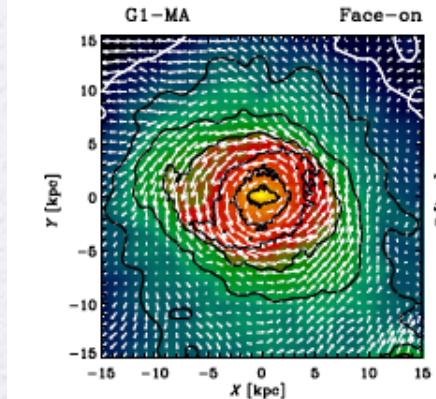
# Different environment, different galaxy properties?

- MW & M31 candidates
- Two runs, Supernova (SN) only, SN + radiation pressure

Only SN feedback



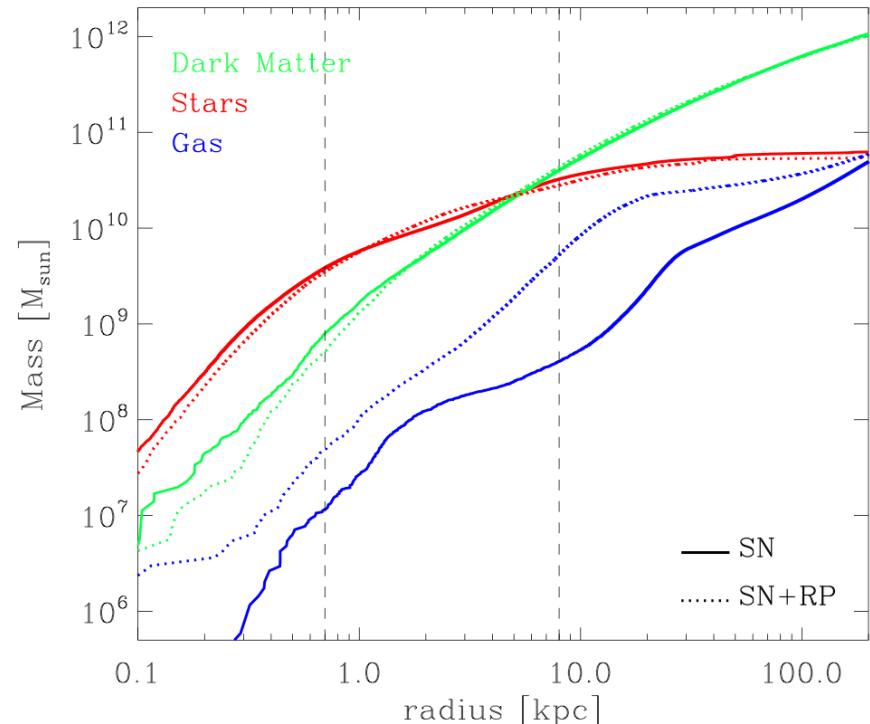
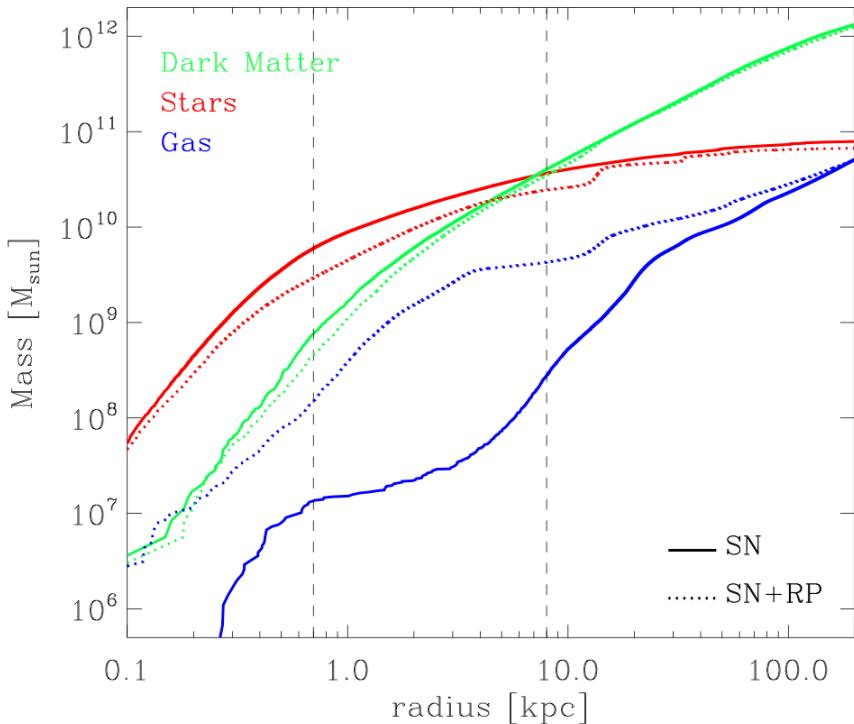
SN+RP feedback



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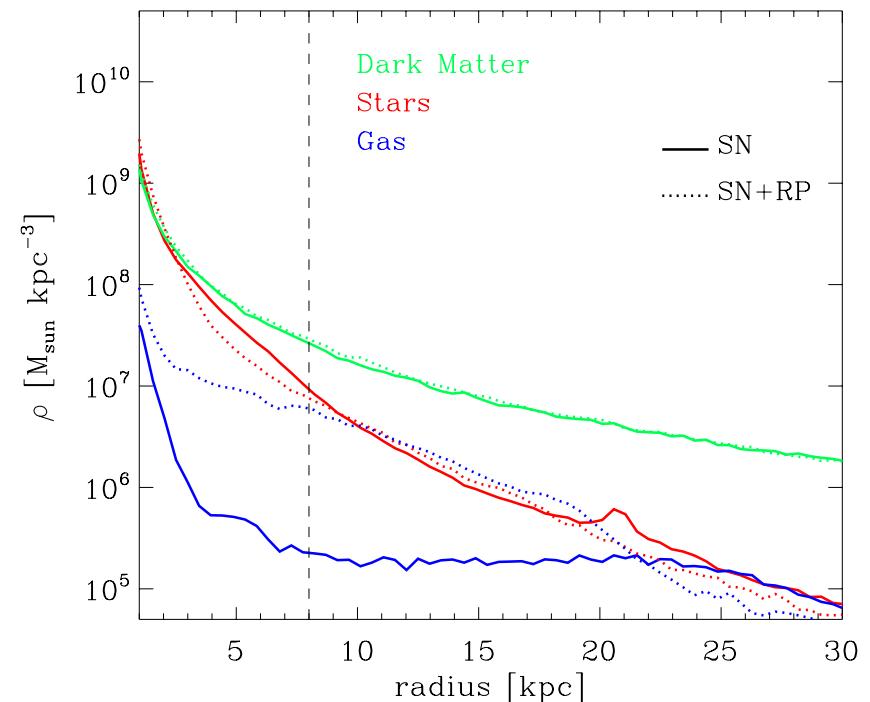
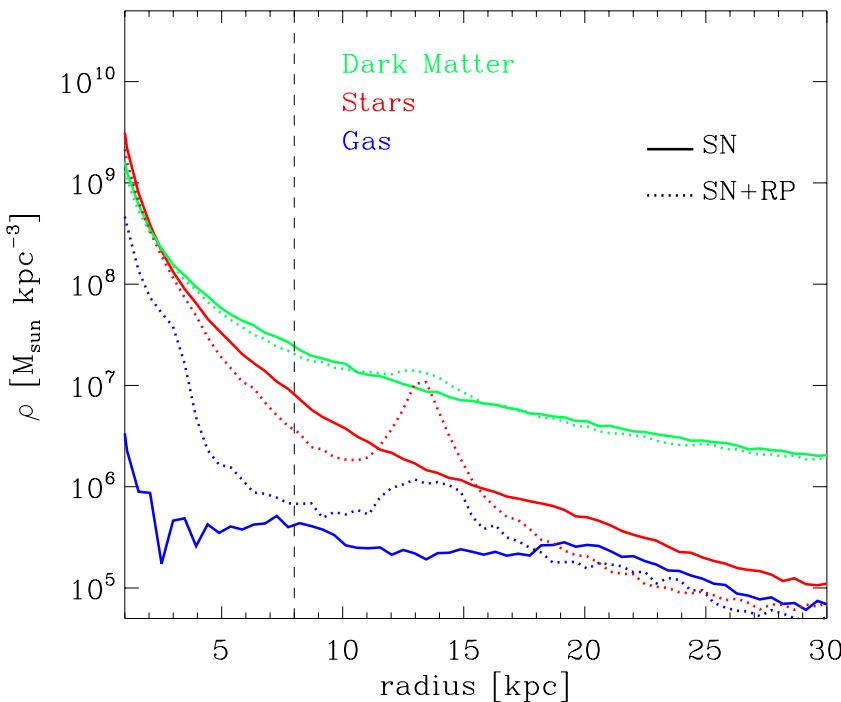
## Mass profiles



# Different environment, different galaxy properties?

- MW & M31 candidates
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## Density profiles



# Summary

- Baryons significantly affect the properties of dark matter halos
- DM halos are diverse as a result of different formation histories. The reaction of DM to the presence of baryons depends on the total amount of stars formed, but also on the particular formation of a halo
- Despite significant variations in the detailed structure of galaxies when different codes are used, at the solar position most models give similar predictions for the DM density regardless of the feedback modelling
- Detailed studies of the DM in the Milky Way would require a deep understanding of environmental effects, and running a larger number of “Local Group” analogues