Beyond N-body simulations: the role of baryons in structure formation

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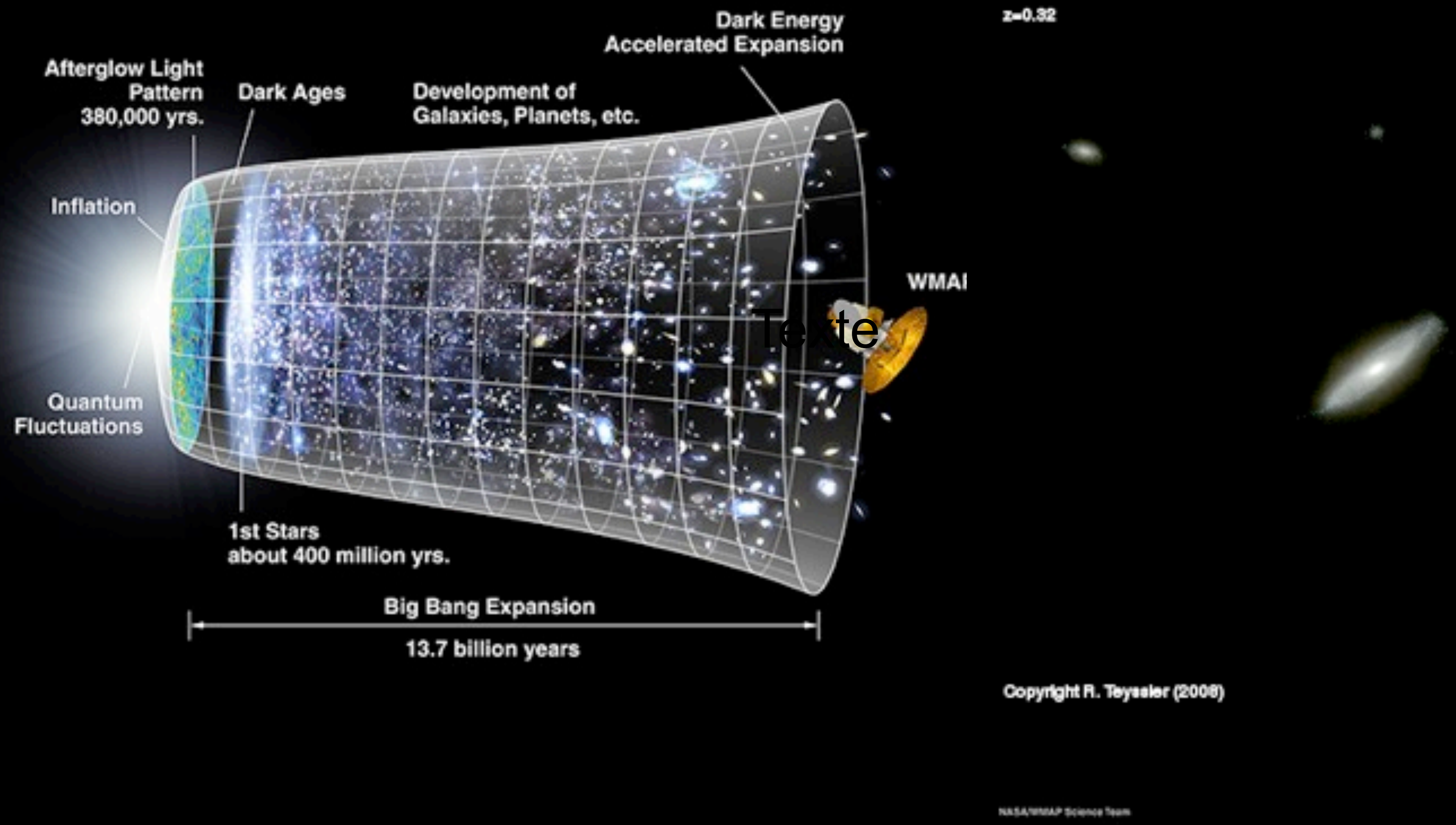
Saclay/Zürich

Cosmic structure formation



Texte

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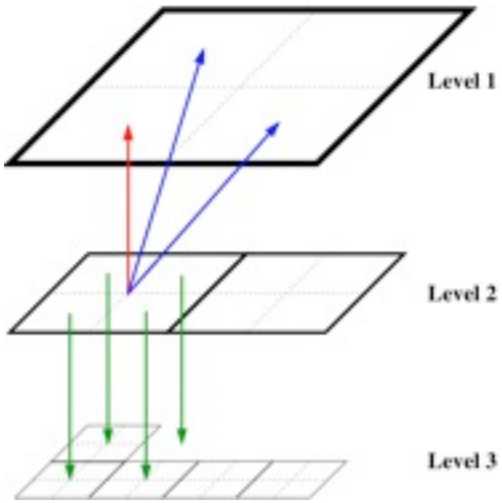
NASA/WMAP Science Team

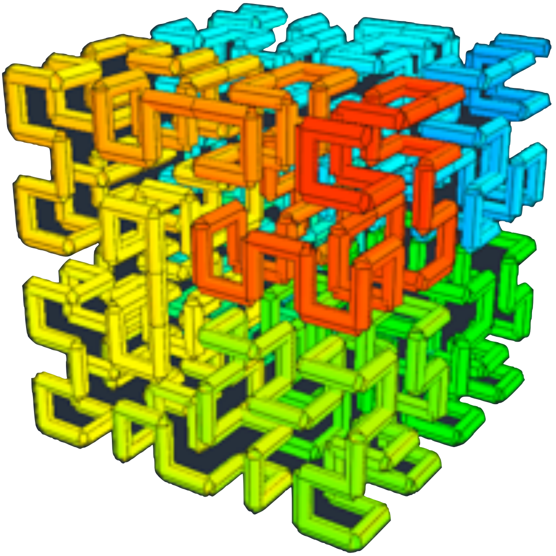
RAMSES: parallel Adaptive Mesh Refinement



- Graded octree structure: the cartesian mesh is refined on a cell by cell basis
- Full connectivity: each oct have direct access to neighboring parent cells and to children octs (memory overhead 2 integers per cell).
- Optimize the mesh adaptivity to complex geometry but CPU overhead can be as large as 50%.

N body module: Particle-Mesh method on AMR grids. Poisson equation solved using a multigrid solver.

Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. New CT-based MHD solver.



Time integration: single time step or sub-cycling.

Other: Radiative cooling/heating, star formation, stellar and AGN feedback, radiative transfer and MHD

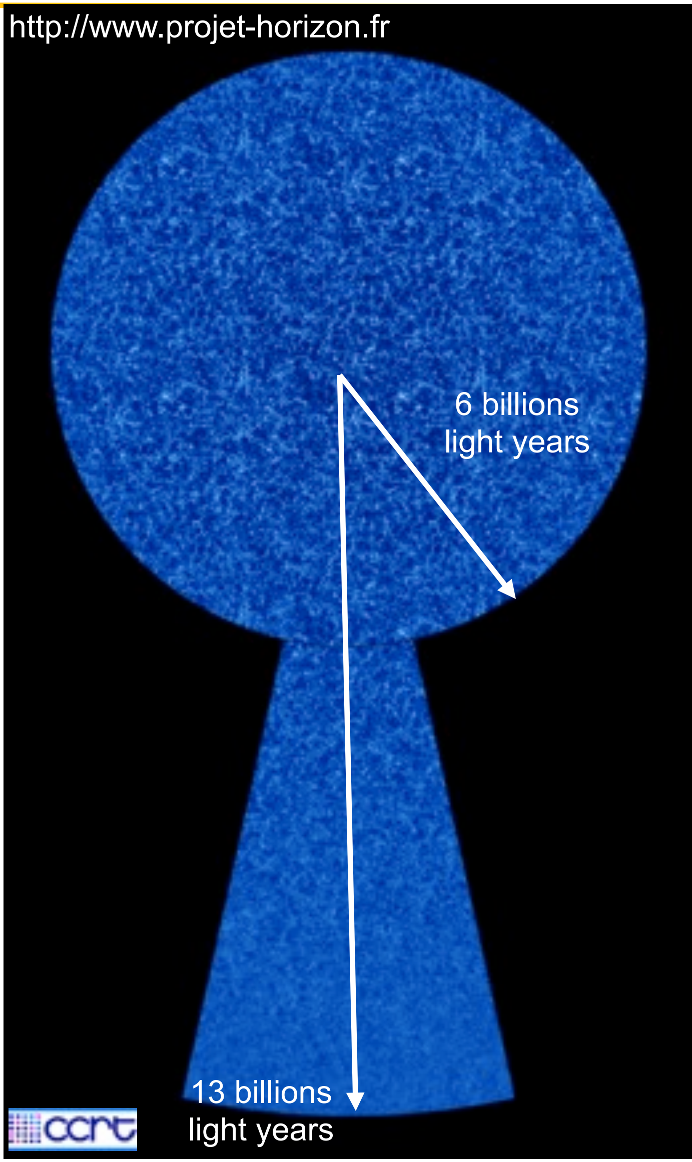
MPI-based parallel computing using time-dependent domain decomposition based on Peano-Hilbert cell ordering.

Download at http://irfu.cea.fr/Projets/Site_ramses

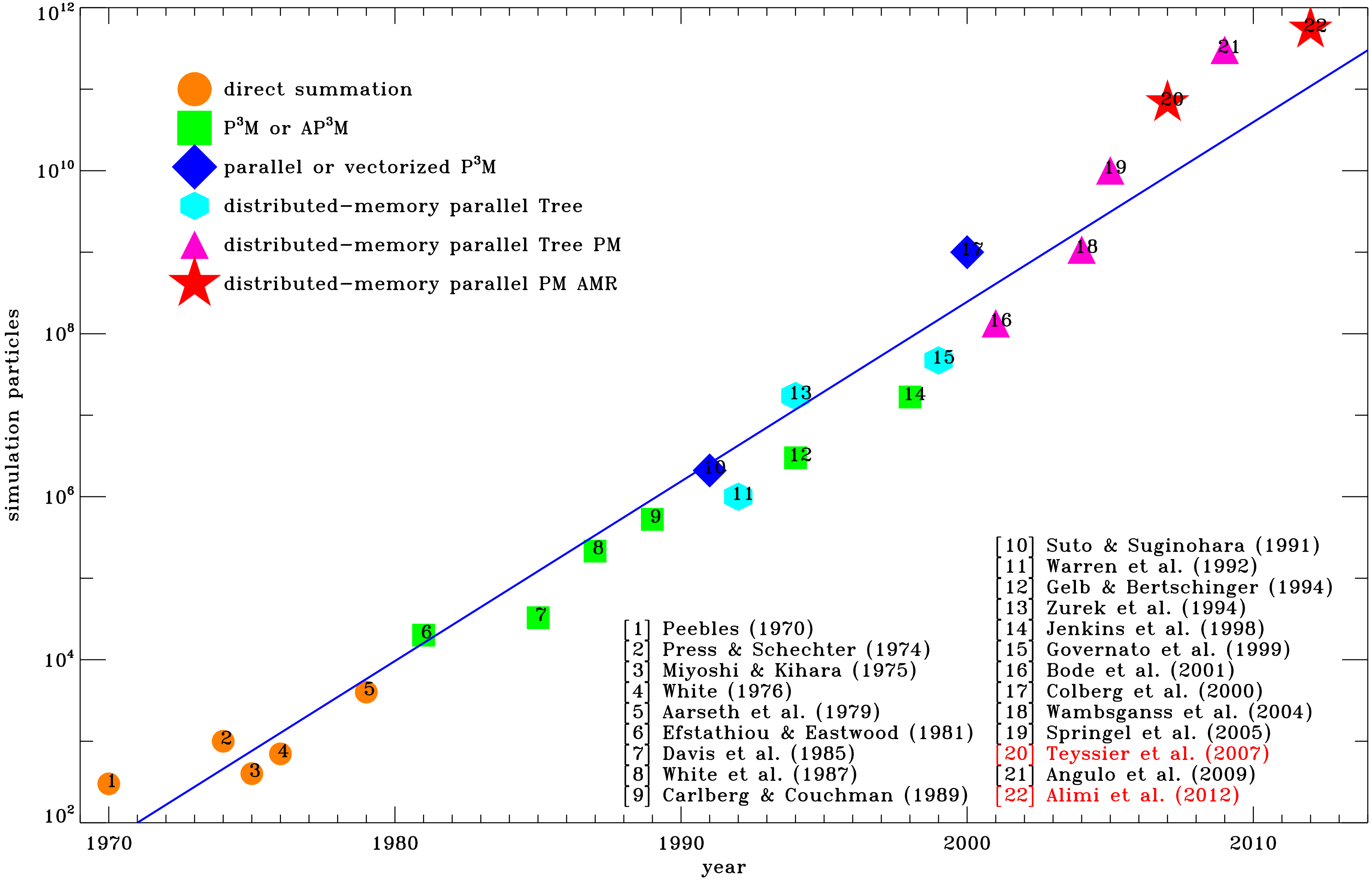
Very large N body simulations with RAMSES

The Horizon simulation (2 Gpc/h)
70 billion dark matter particles and 140 billion AMR cells
6144 core
2.4 GB per core
Wall-clock time 2 month
performed in 2007 on the CCRT BULL Novascale 3045

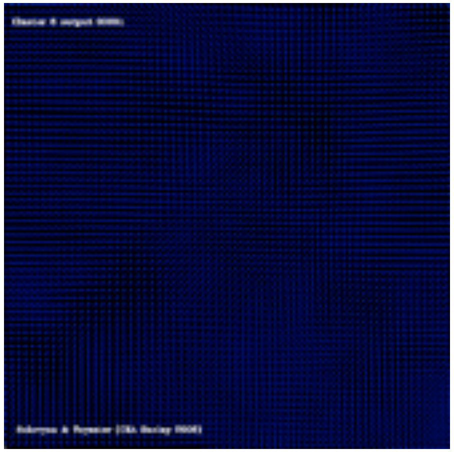
The DEUS simulation (21 Gpc/h)
550 billion dark matter particles and 2 trillion AMR cells
76032 core
4 GB per core
Wall-clock time 1 week
performed in 2012 on the CCRT BULL Bullx S6010



Cosmological N body simulations



Galaxy formation in a nutshell

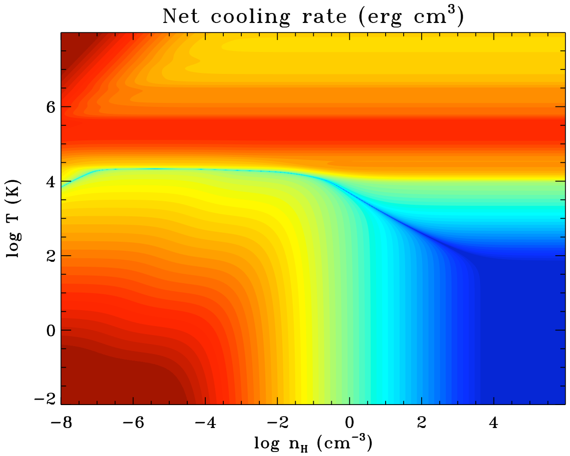


Formation of slowly rotating dark matter halos

- spin from tidal torques
- statistical Virial equilibrium

Hot gas settles in thermal equilibrium

$$\frac{3}{2}\frac{k_{\mathrm{B}}T_{gas}}{\mu m_{\mathrm{H}}} = \frac{1}{2}\frac{GM_{halo}}{R_{halo}}$$



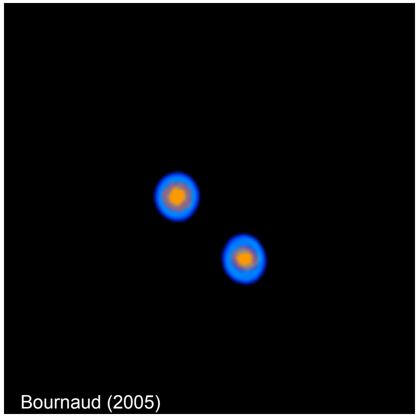
Radiative cooling dissipates pressure support

Dense gas disc settles into centrifugal equilibrium

Atomic physics sets galaxy masses

$$\mathcal{I}_0 = 13.6 \text{ eV}$$

$$M_{\text{galaxies}} \simeq 10^{11} \;\; M_{\odot}$$

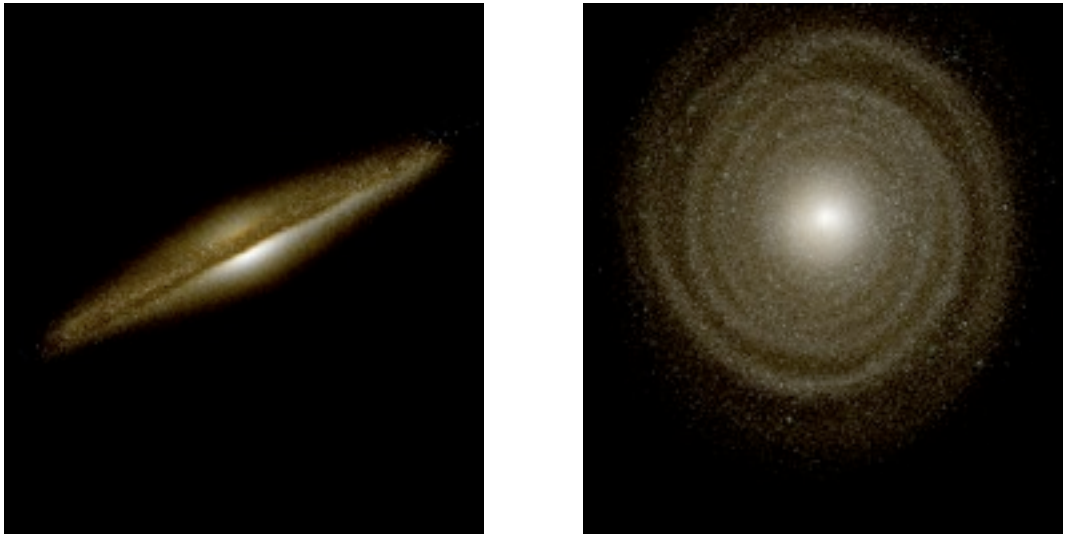

Bournaud (2005)

White and Rees (1978); Dekel and Silk (1986)

Discs form from quiescent gas accretion history

Ellipticals form out of violent mergers

Modern galaxy formation simulations



Mock gri SDSS composite image with dust absorption based on Draine opacity model.

NGC4622 as seen from HST

Okamoto et al. (2009), Governato et al. (2007, 2009, 2010), Piontek & Steinmetz (2009), Scannapieco et al. (2008, 2009); Agertz et al. (2010); Wadephul & Springel (2010)

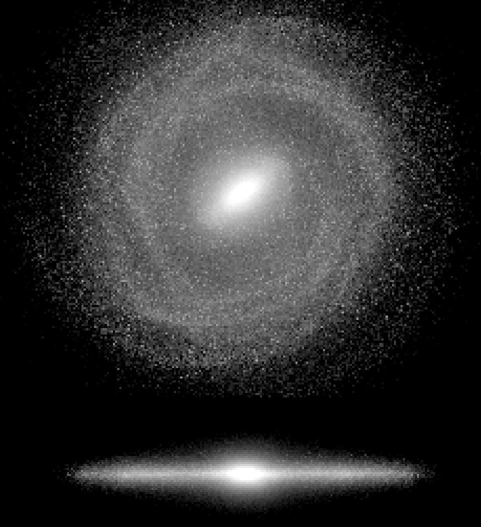
Strong feedback and high resolution are both required.

Agertz *et al.* (2011)

$E_{\mathrm{SNII}} = 10^{51}$ ergs

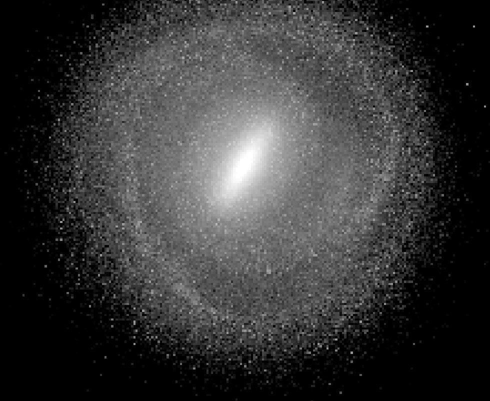
$\epsilon_{\mathrm{ff}} = 5\,\%$

B/D ~ 1.25



$E_{\mathrm{SNII}} = 2 \times 10^{51}$ ergs

B/D ~ 1.16

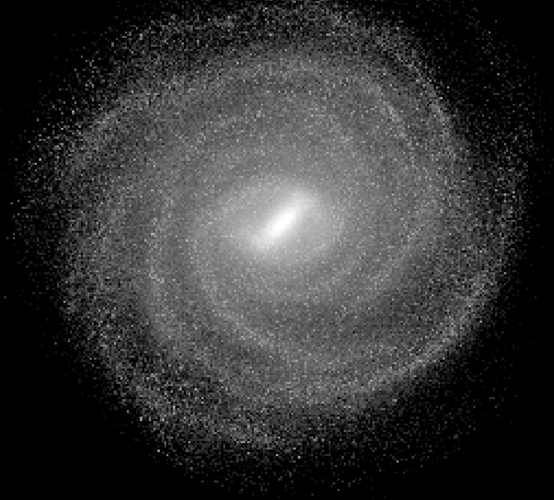


$E_{\mathrm{SNII}} = 5 \times 10^{51}$ ergs

B/D ~ 0.35

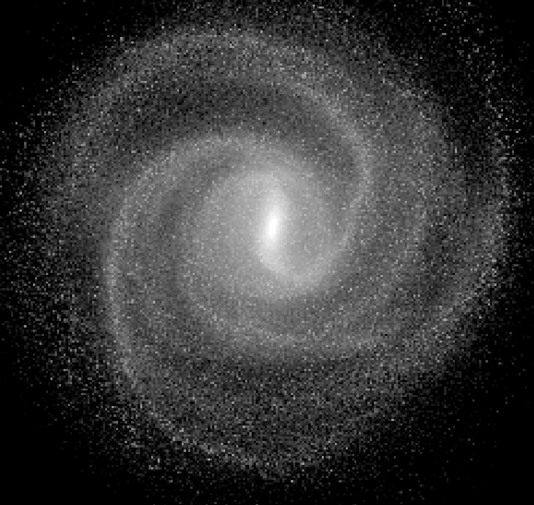
$\epsilon_{\mathrm{ff}} = 2\,\%$

B/D ~ 0.5



$\epsilon_{\mathrm{ff}} = 1\,\%$

B/D ~ 0.25



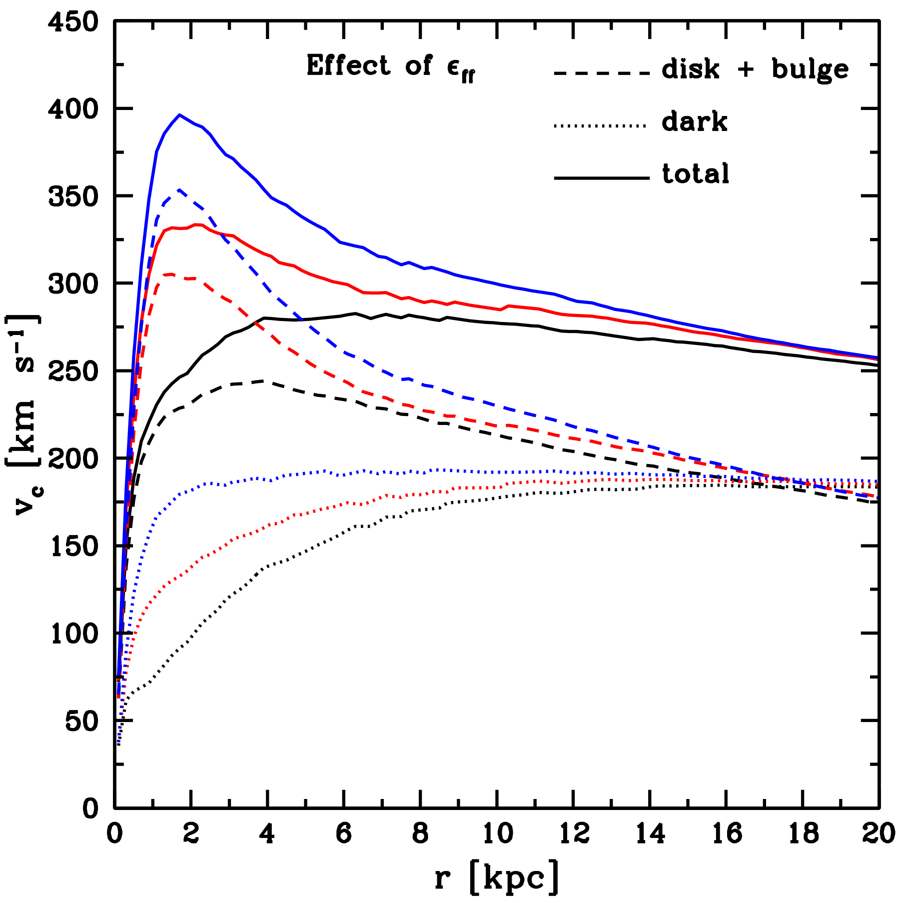
Pseudo bulge!!

Stellar disks at z=0

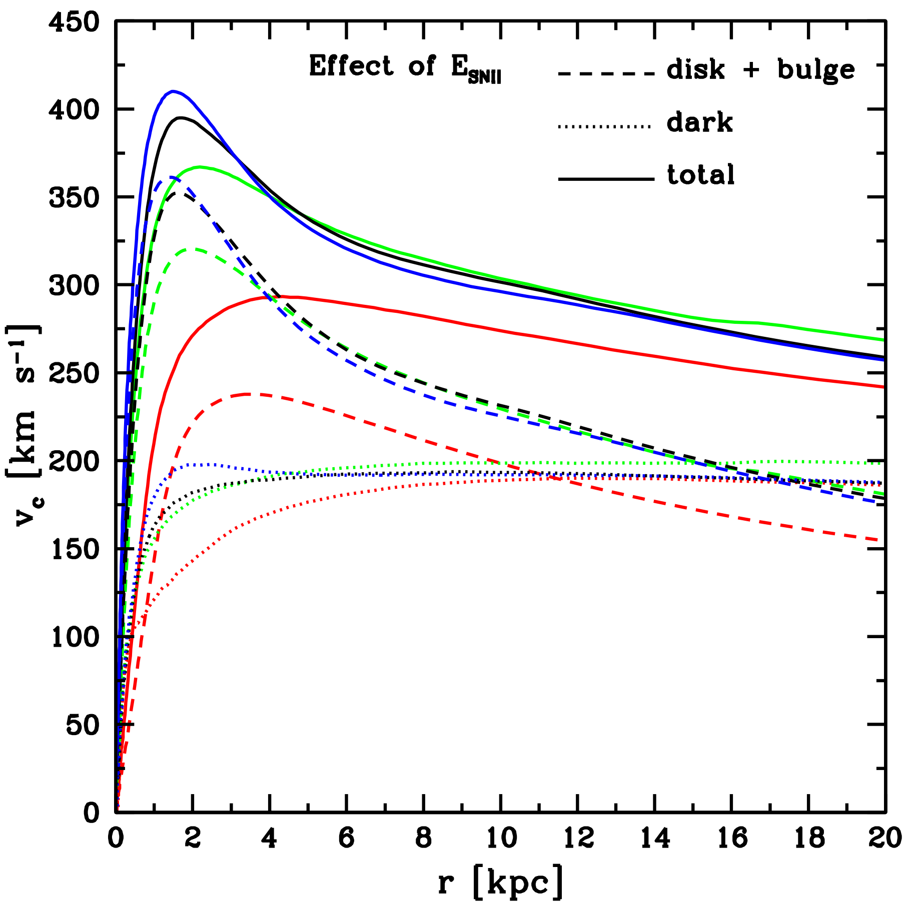
Agertz *et al.* (2011)

Circular velocities

Effect of SFE



Effect of SNe feedback

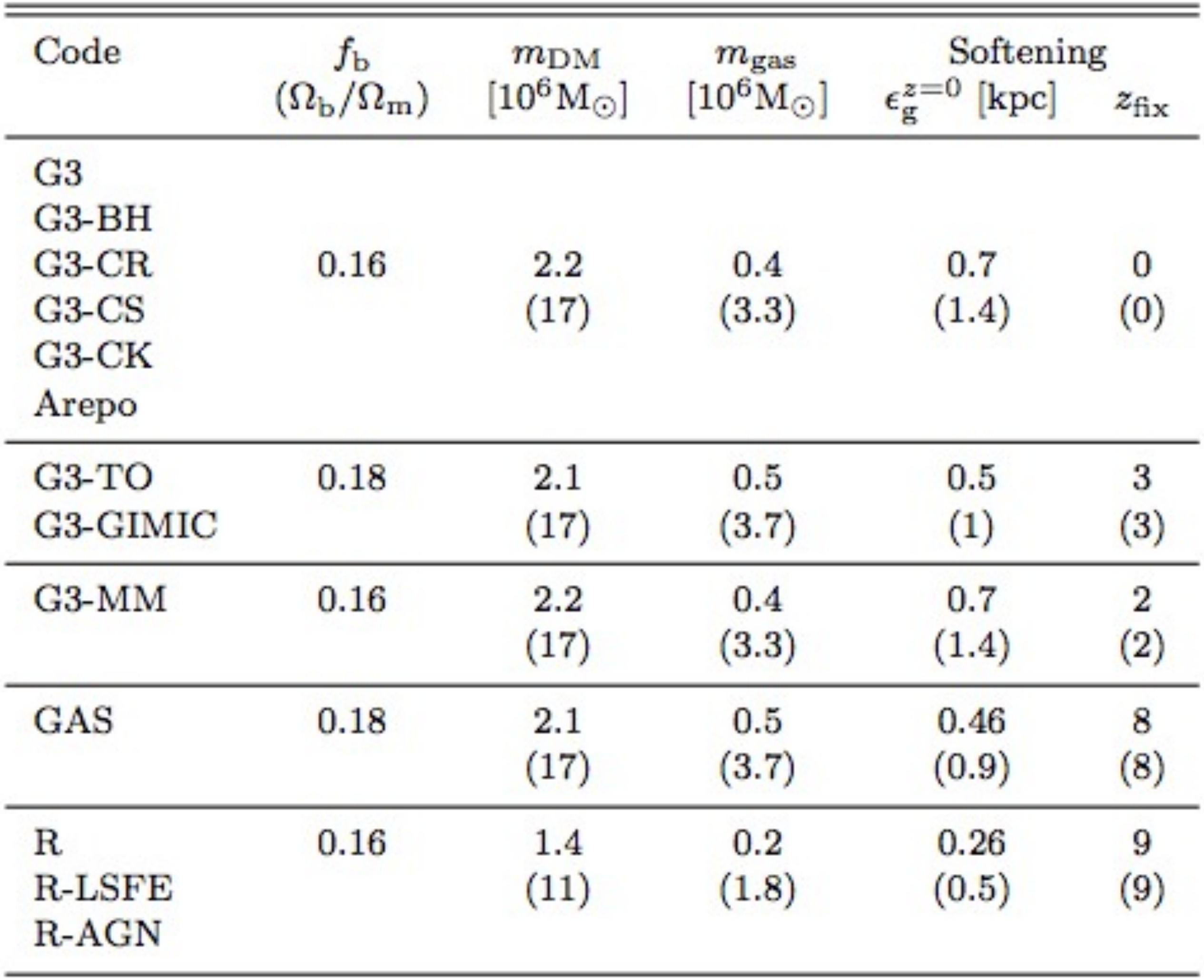


10-20% scaling recovers the Milky Way

MW models with small halo mass (~ 7×10^{11} Msol) are required

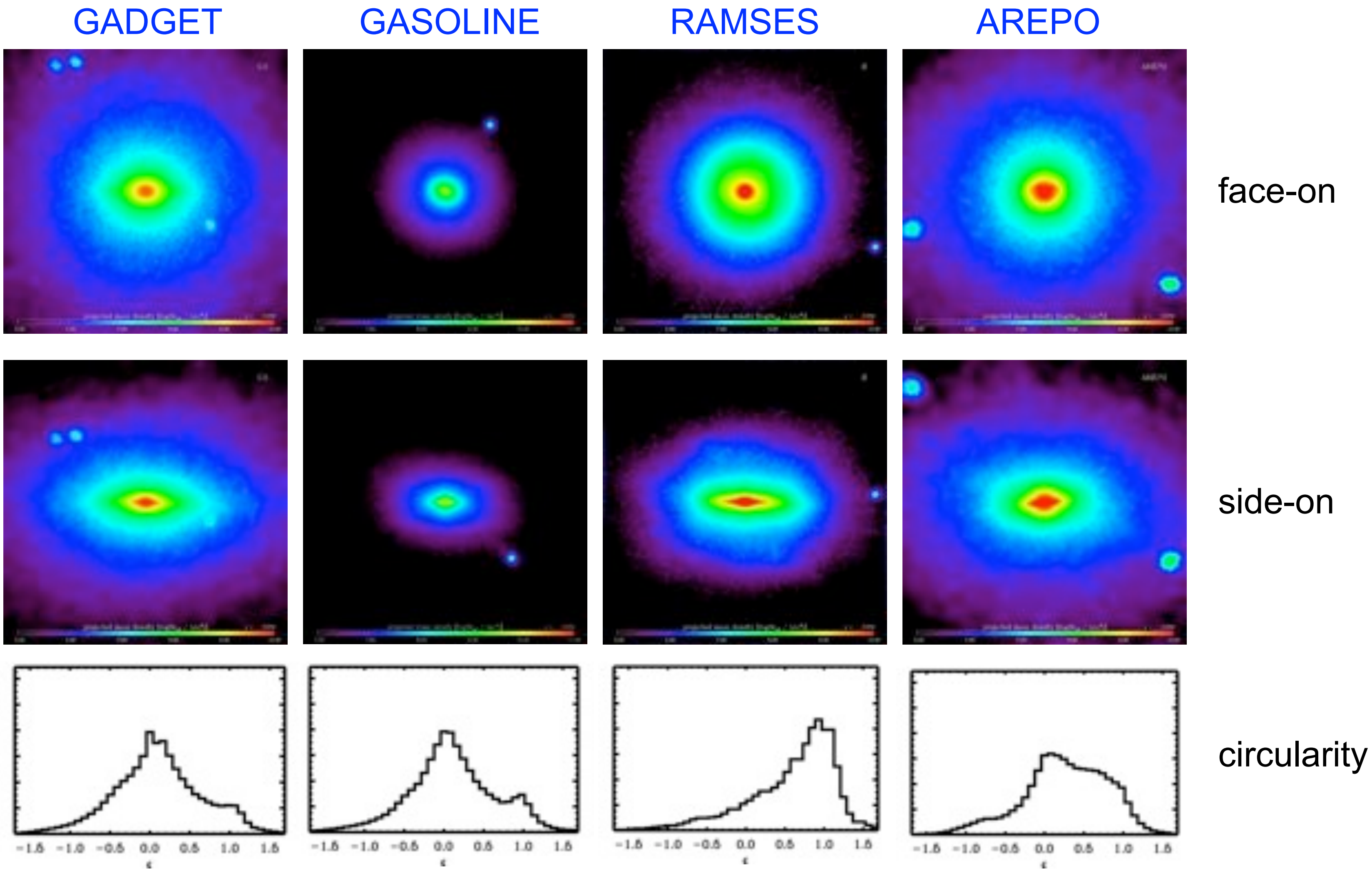
The Aquila project: code comparison

Scannapieco *et al.* (2012) arxiv/1112.0315



Code	f_b $(\Omega_\mathrm{b}/\Omega_\mathrm{m})$	m_DM $[10^6\mathrm{M}_\odot]$	m_gas $[10^6\mathrm{M}_\odot]$	Softening $\epsilon_\mathrm{g}^{z=0}$ [kpc]	Softening z_fix
G3 G3-BH G3-CR G3-CS G3-CK Arepo	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	0 (0)
G3-TO G3-GIMIC	0.18	2.1 (17)	0.5 (3.7)	0.5 (1)	3 (3)
G3-MM	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	2 (2)
GAS	0.18	2.1 (17)	0.5 (3.7)	0.46 (0.9)	8 (8)
R R-LSFE R-AGN	0.16	1.4 (11)	0.2 (1.8)	0.26 (0.5)	9 (9)

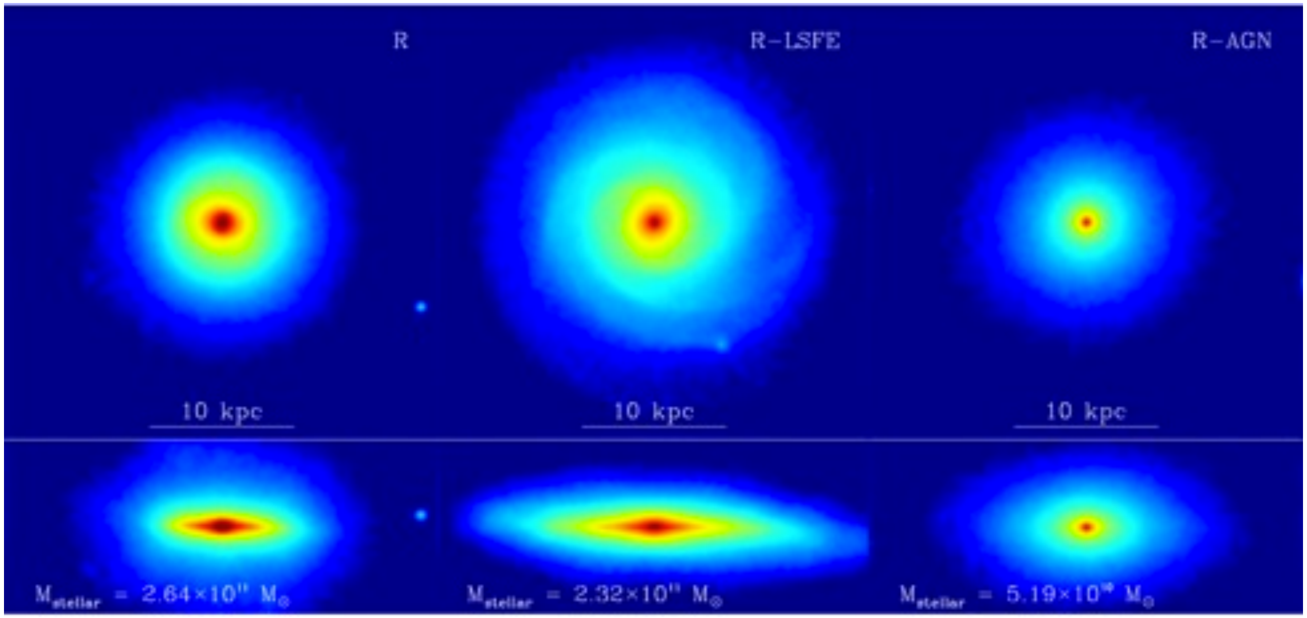
Different codes, same physics, different morphologies...

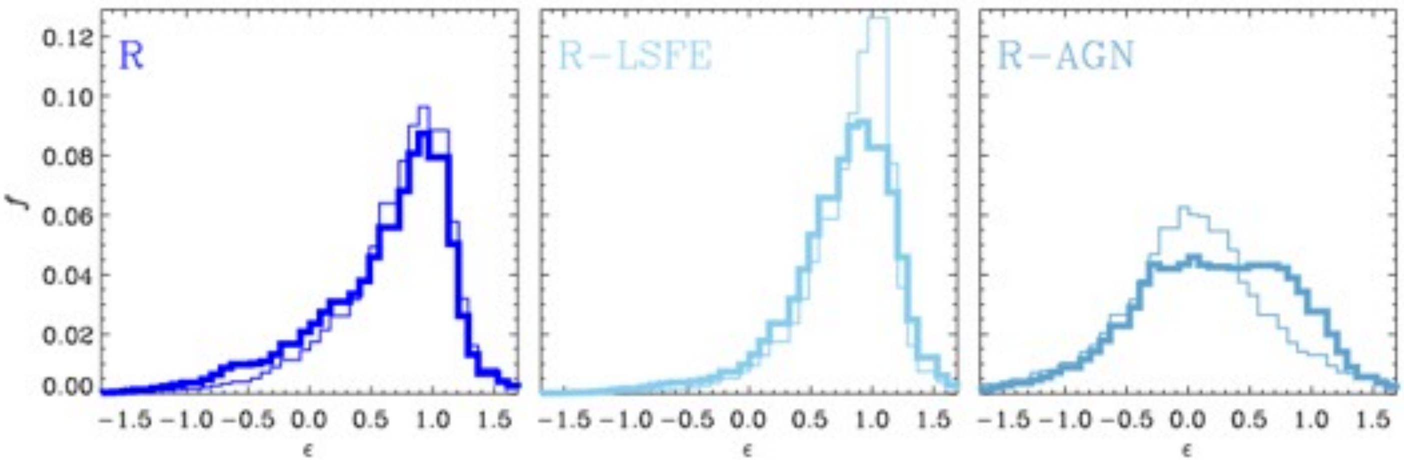


Low resolution runs

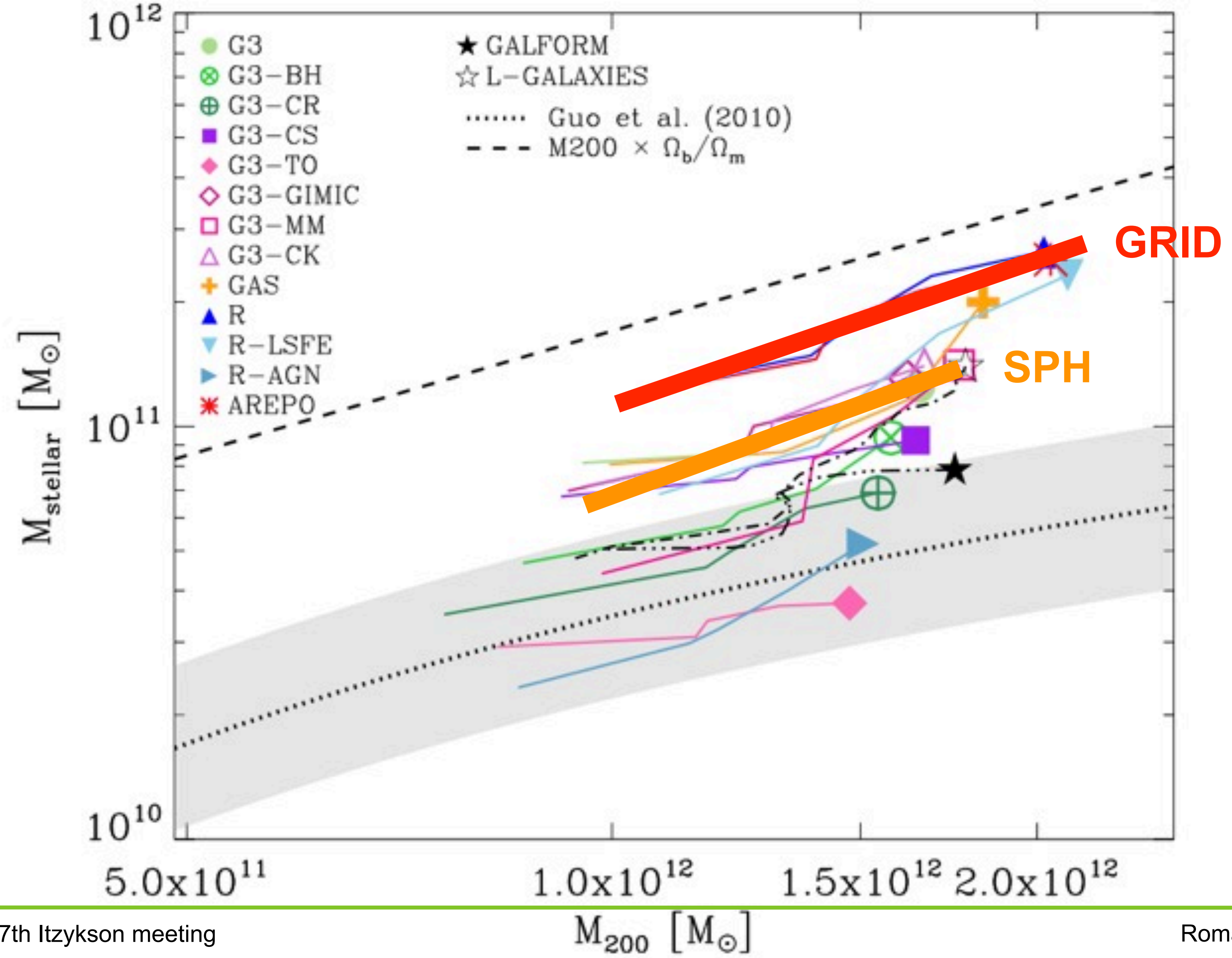
Same code, different subgrid models, different morphologies...

RAMSES





Feedback and SF matter more than code type.



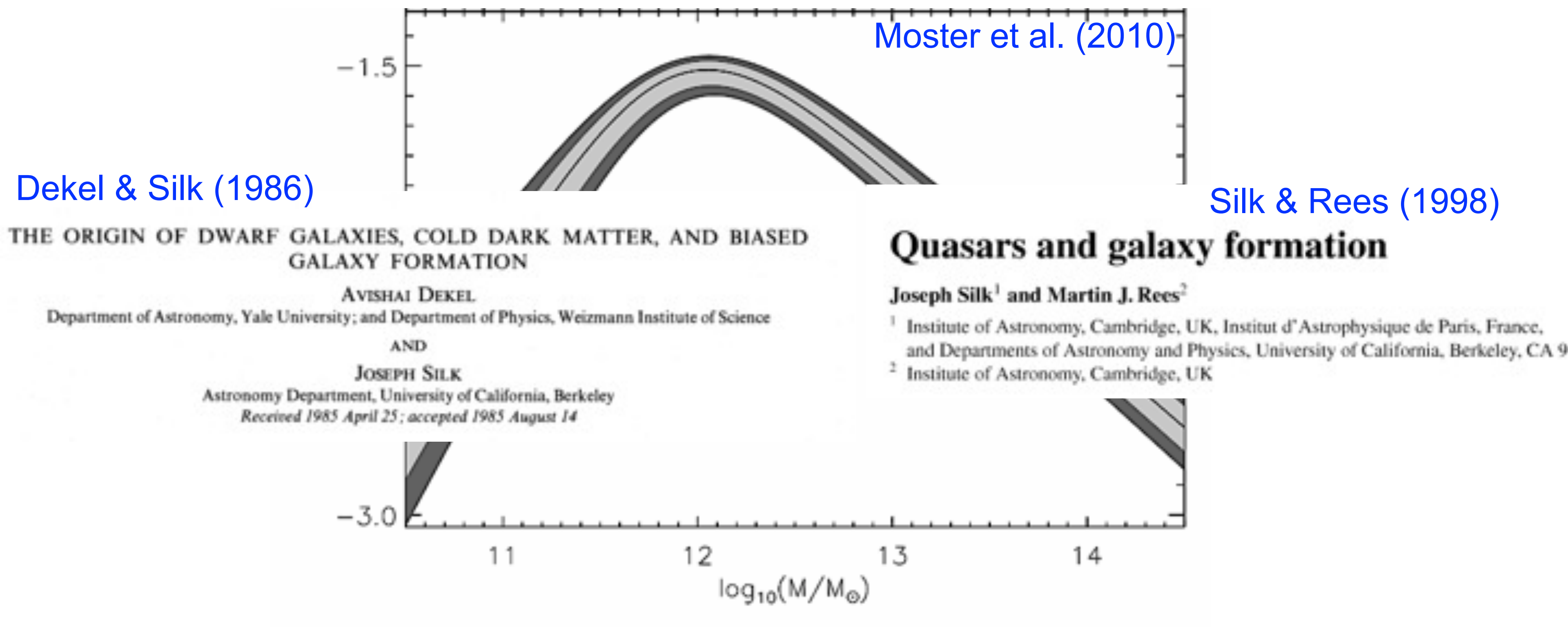
GRID

SPH

The importance of feedback in galaxy formation

Star formation efficiency in the central galaxy as a function of dark halo mass

Stellar-to-halo mass ratio



Moster et al. (2010)

Dekel & Silk (1986)

THE ORIGIN OF DWARF GALAXIES, COLD DARK MATTER, AND BIASED GALAXY FORMATION

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Received 1985 April 25; accepted 1985 August 14

Silk & Rees (1998)

Quasars and galaxy formation

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[2] Institute of Astronomy, Cambridge, UK

A simple model for SMBH growth and feedback

Numerical implementation in cosmological simulations: Sijacki et al. 2007; Booth & Schaye 2010: Teyssier et al. 2011 and many others**...**

In high density regions with stellar 3D velocity dispersion > 100 km/s, we create a seed BH of mass 10^5 M_{sol}.

Accretion is governed by 2 regimes:

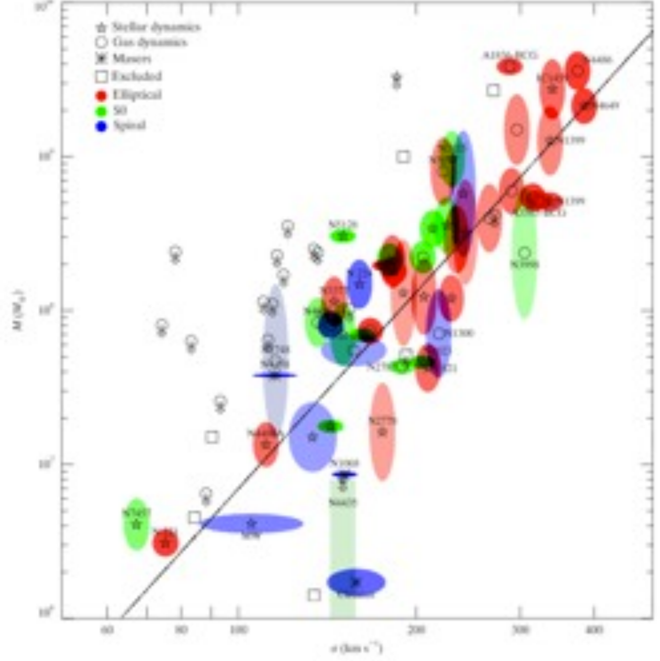
Bondi-Hoyle regime
$$\dot M_{\rm BH} = \alpha_{\rm boost}\frac{4\pi G^2 M_{\rm BH}^2\rho}{(c_s^2+u^2)^{3/2}}$$

Eddington-limited
$$\dot M_{\rm ED} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_r \sigma_{\rm T} c}$$

Feedback performed using a thermal dump
$$\Delta E = \epsilon_{\rm c}\epsilon_{\rm r}\dot M_{\rm acc}c^2\Delta t.$$

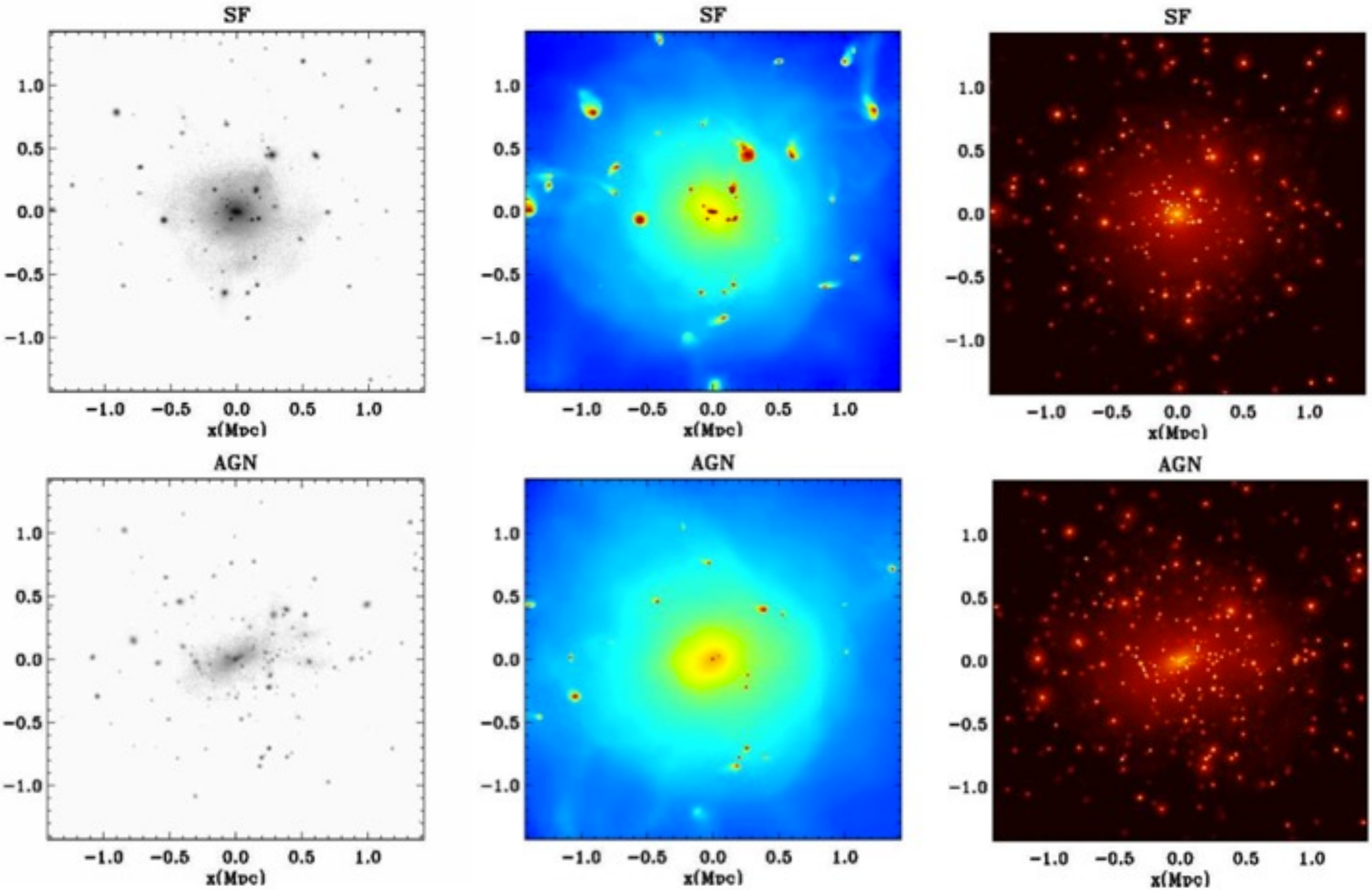
with following trick to avoid overcooling: $E_{\rm AGN} > \frac{3}{2} m_{\rm gas} k_B T_{\rm min}$ $\quad T_{\rm min} = 10^7$ K

Free parameter ε_c calibrated on the M-σ relation.

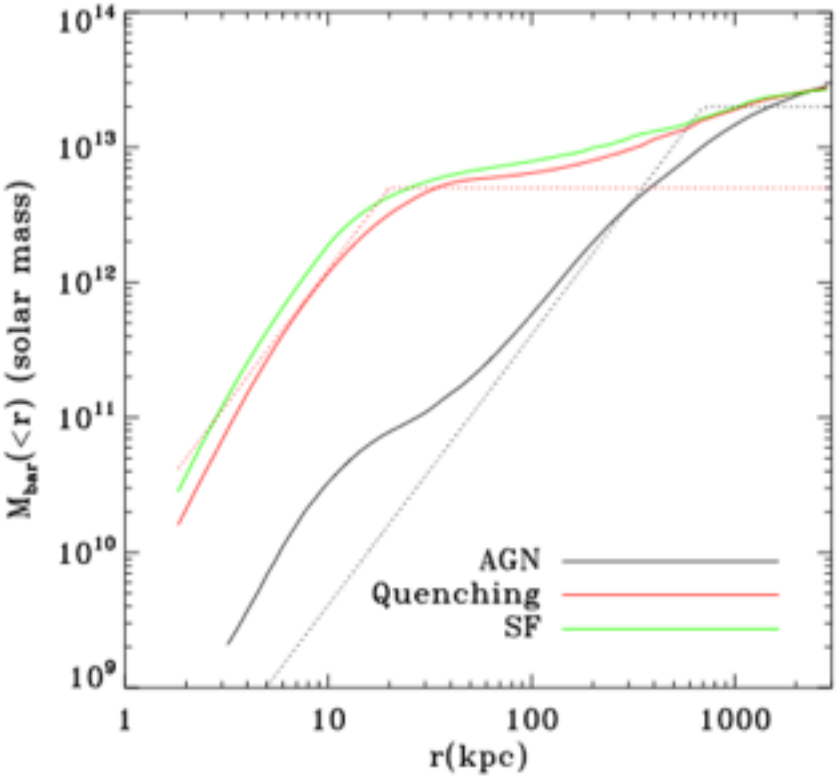


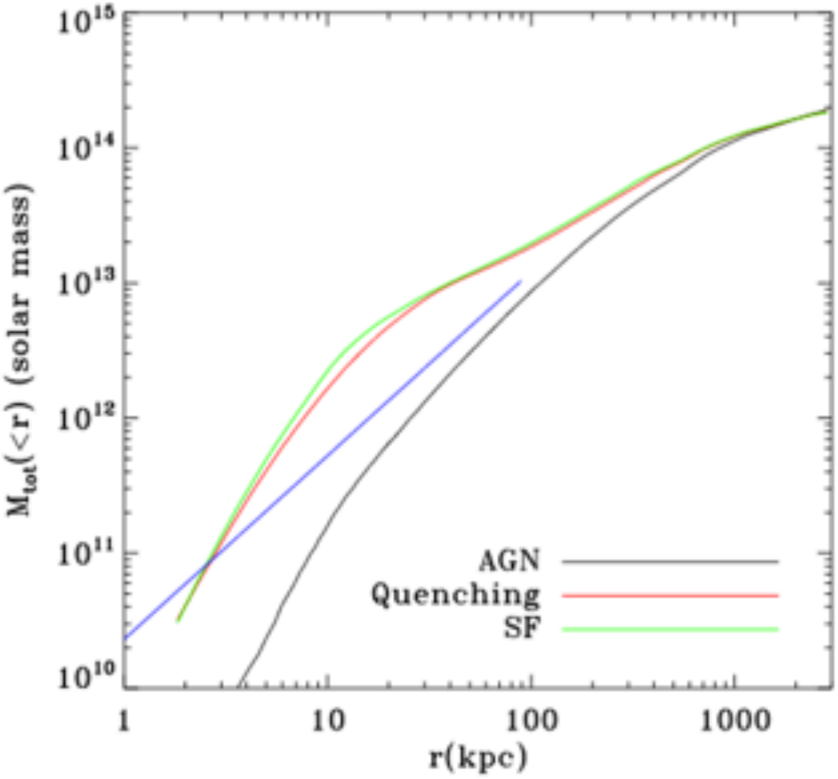
Gültekin *et al.* (2009)

Galaxy formation on cluster scales



AGN feedback regulates the mass distribution



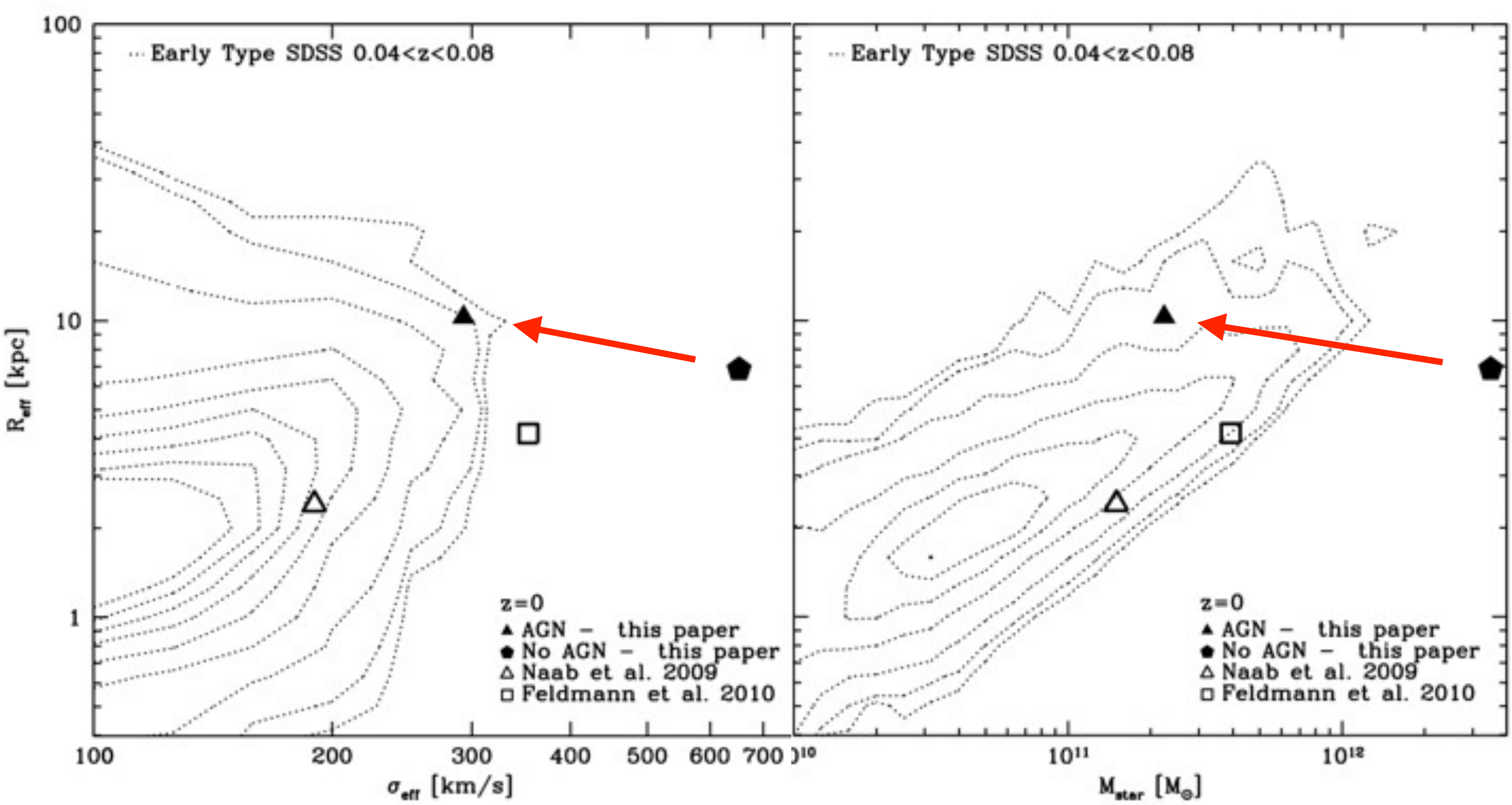


Without AGN feedback, overcooling leads to a strong mass concentration in the center.

With AGN feedback, we see a small adiabatic expansion of the dark halo.

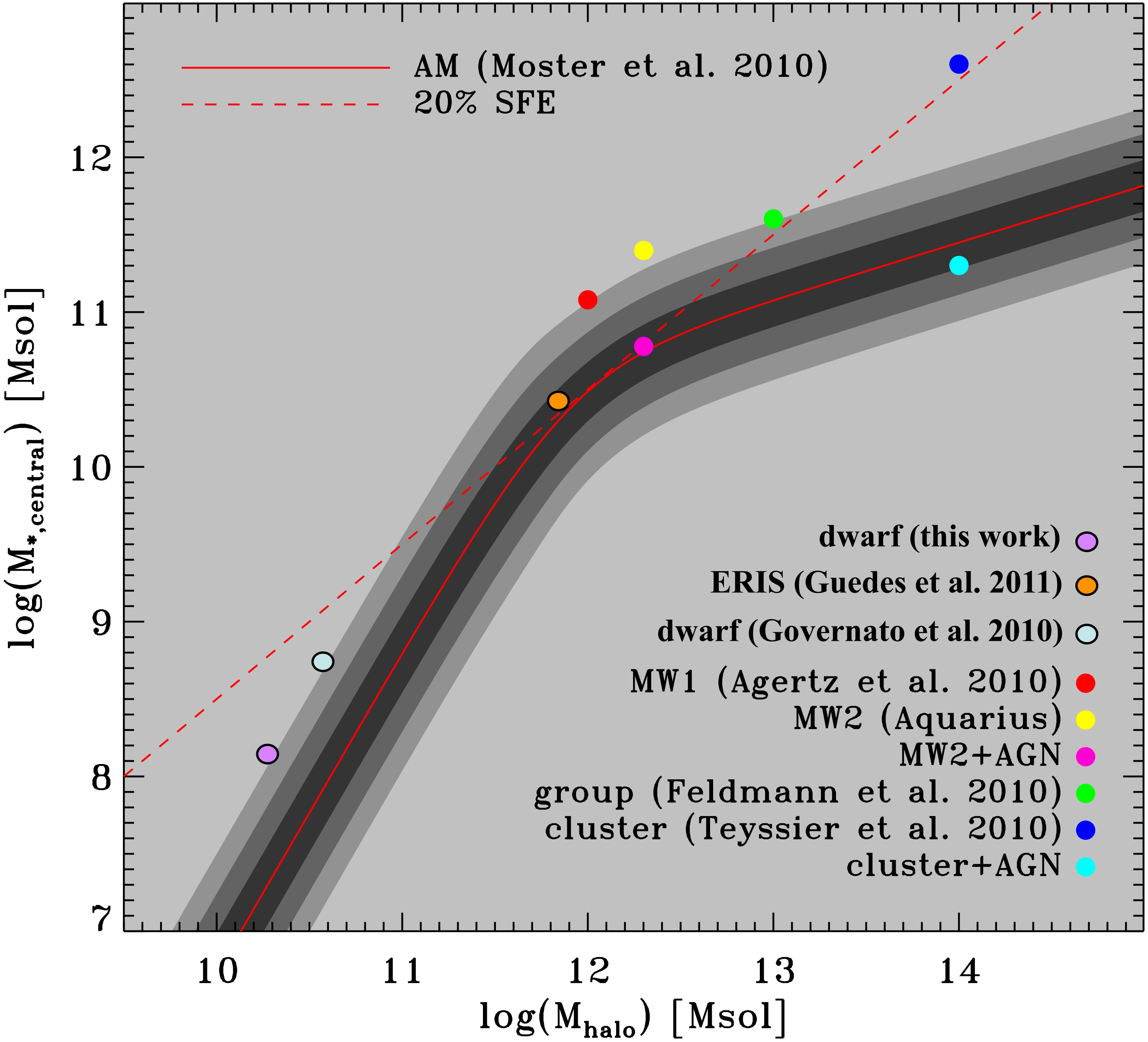
Teyssier *et al.* 2011; Semboloni *et al*. 2011

AGN feedback modifies the BCG properties



Booth & Schaye 10; Teyssier+11; Sembolini+11; Dubois+10,11; Martizzi+11

Constraints from abundance matching



The impact of baryons on the power spectrum

1% accuracy on the theoretical power spectrum is required.

This is a severe challenge for theoretical predictions, even for dark matter only models.

Baryons play an important role (potentially up to 18%) in the matter distribution in the universe. It is therefore of primordial importance to estimate the level of nuisance baryons introduce in 3 important cosmological observables:

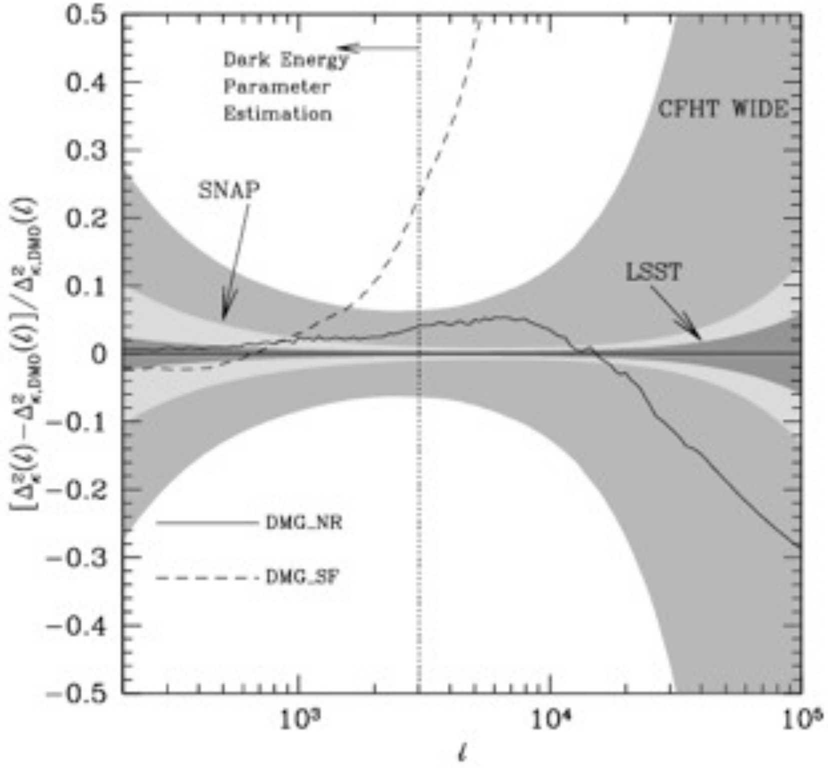
1. The halo mass function
2. The halo mass profile
3. The matter power spectrum

Goal: design a new model for these observables that account for baryonic effects. This (semi-)analytical model will be carefully calibrated on detailed gas and dark matter simulations.

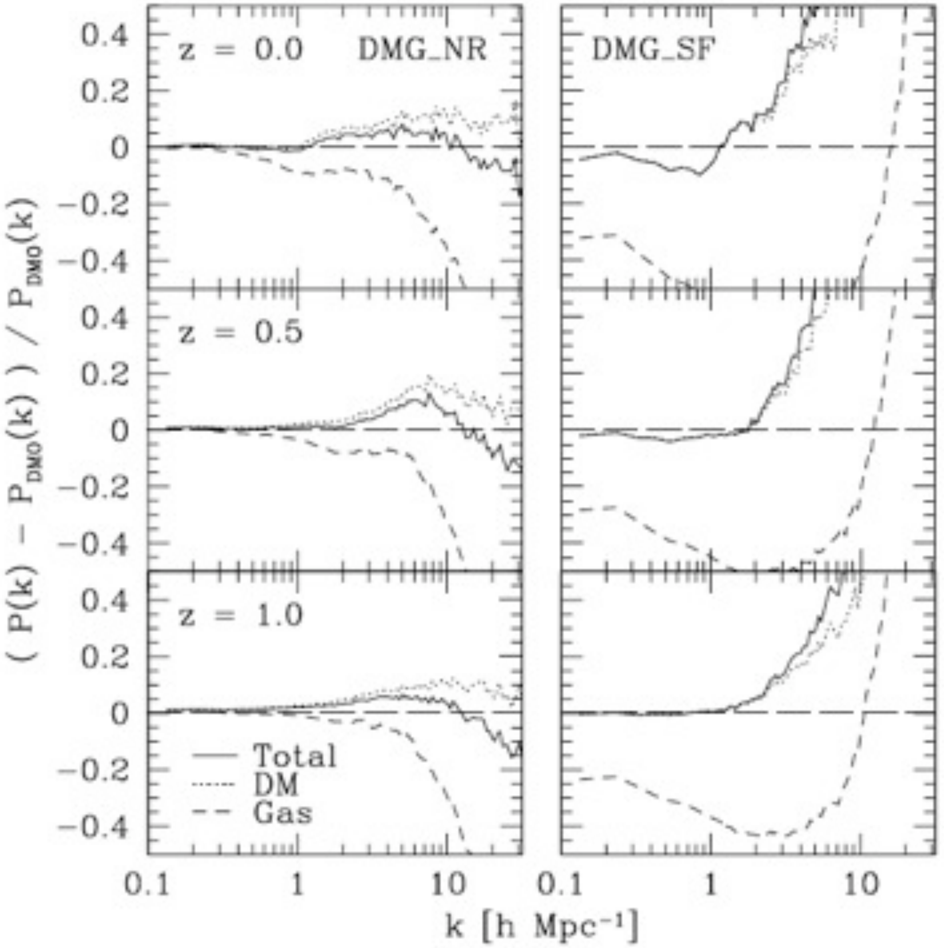
The impact of baryons on the matter power spectrum

Some history: Jing et al. 2006; Rudd et al. 2008
Modify the total power spectrum wrt pure DM spectrum up to 20 percent !
between $l=10^3$ and 10^4

Rudd et al. 2008

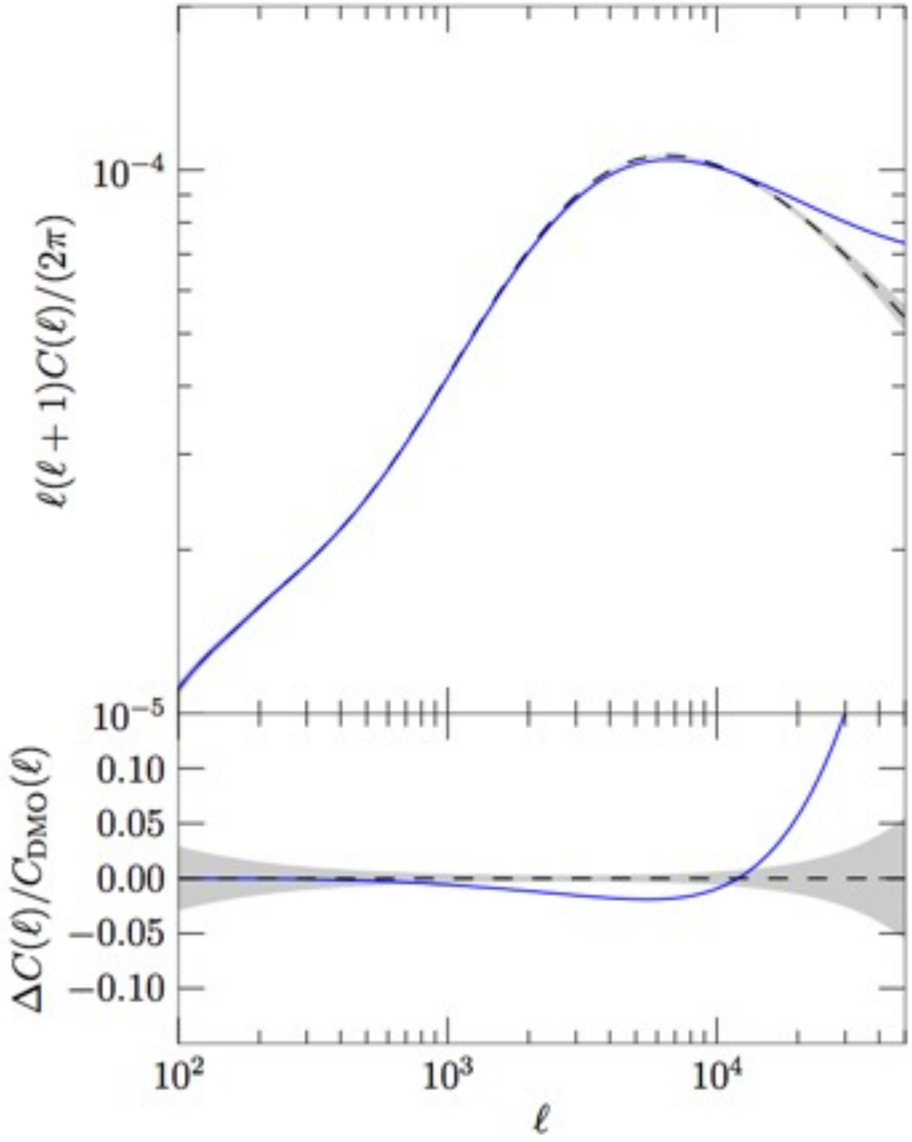


Rudd et al. 2008



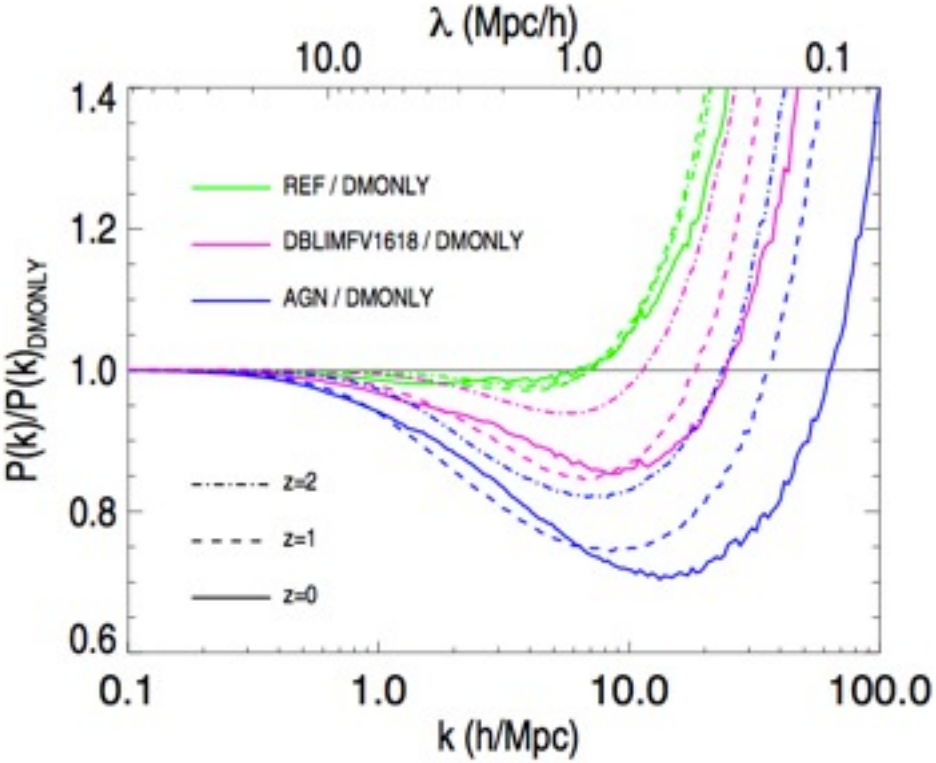
- design halo models that account for baryons
- validate the halo model on numerical data
- use the halo model to fit real data

The impact of baryons on the matter power spectrum



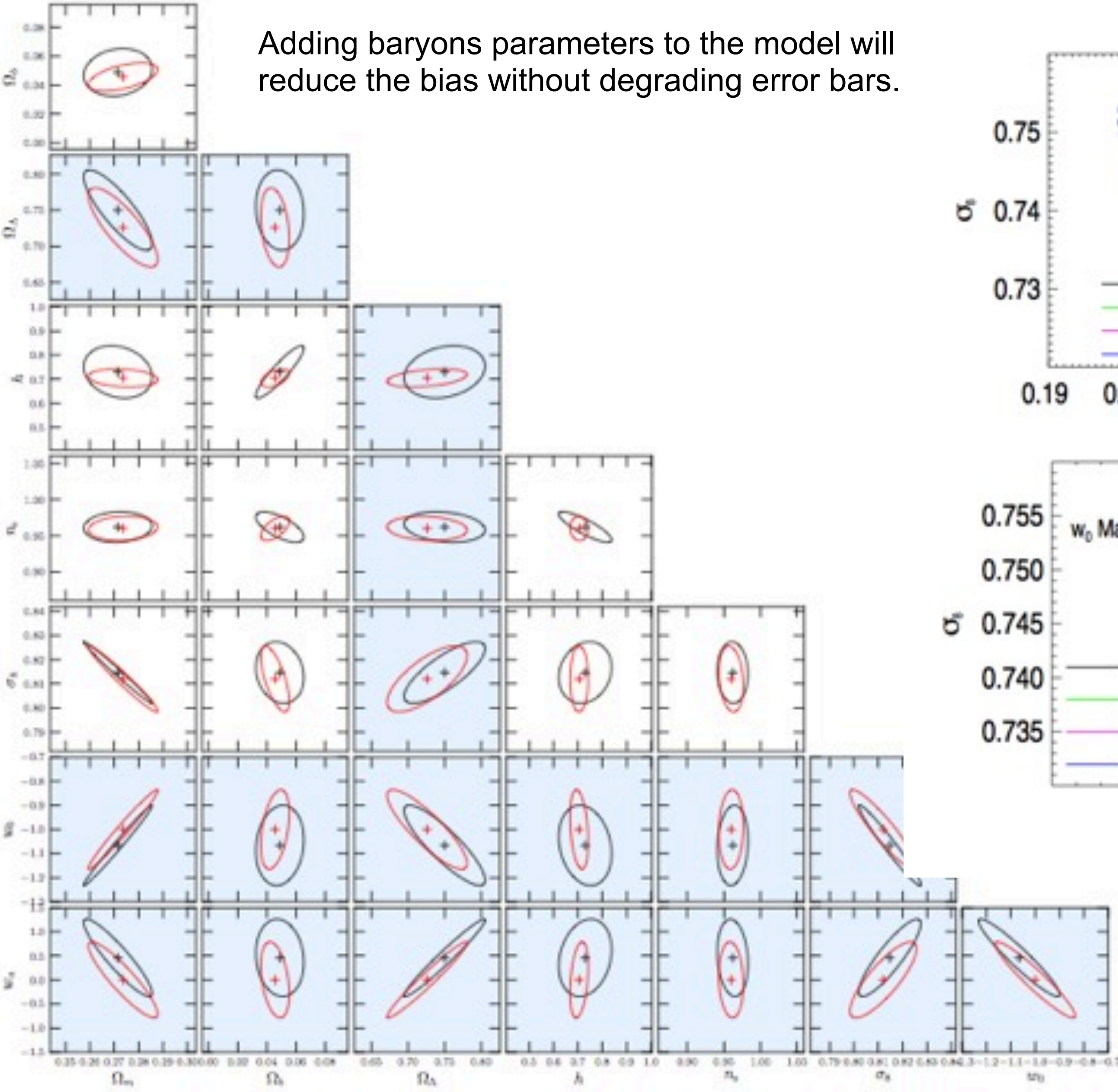
Guillet *et al.* 2010
Analytical model based on AM constraints + adiabatic contraction of DM halos.
100% of baryons are retained inside halos.

Semboloni *et al.* 2011
Numerical model based on AGN feedback.
Up to 50% of the baryons are removed.

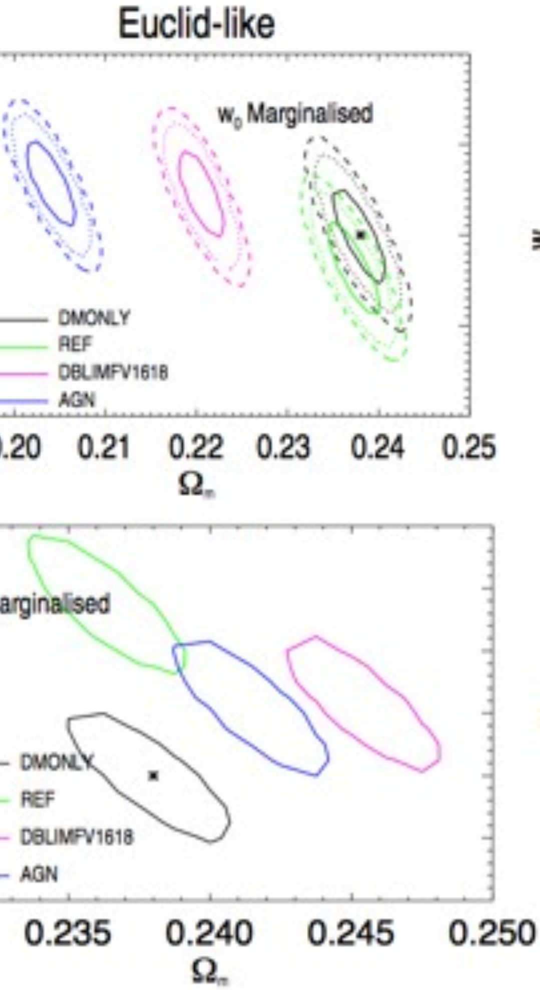


The impact of baryons on the matter power spectrum

Adding baryons parameters to the model will reduce the bias without degrading error bars.



Guillet *et al.* 2010



Semboloni *et al.* 2011

Conclusions

The theory of galaxy formation is still under construction.

Key ingredients are stellar and AGN feedback.

Complex numerical modeling is required.
Numerical results are still affected by poorly understood systematics.

Galaxy formation models are therefore not very accurate.

Baryons can be a large nuisance in estimating the matter power spectrum up to 20% (on small and intermediate scales).

We need to develop theoretical models with baryons and marginalize over mostly unknown baryonic parameter.

Work in progress within the Euclid collaboration.