Disc galaxy formation in Arepo simulations

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Cosmological N-body simulations

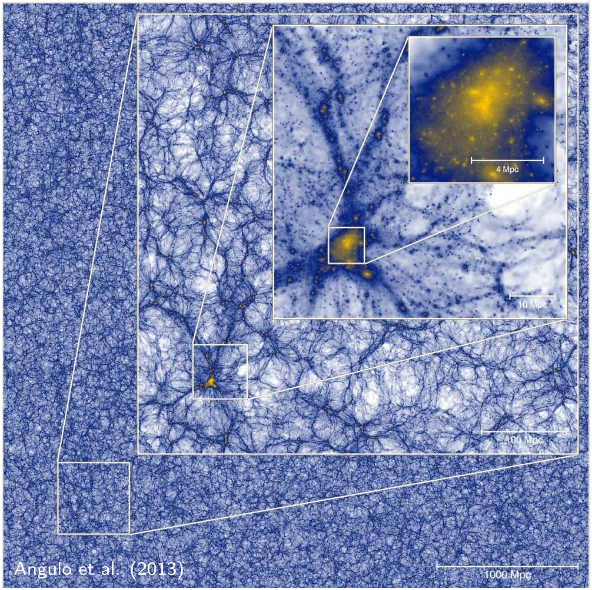
Millennium-XXL

303 billion particles

$\sim$700 millions halos
at $z = 0$

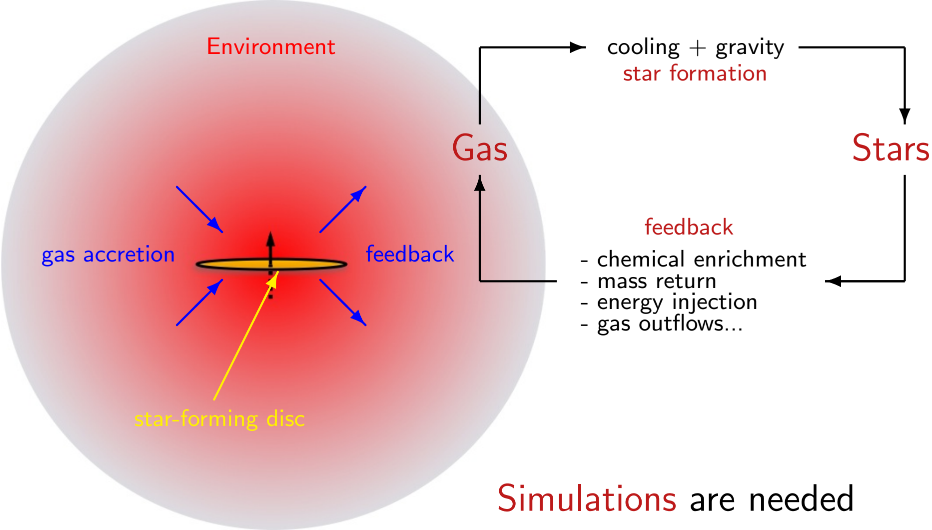
$m_{\mathrm{p}} = 6.1 \times 10^9\ \mathrm{M}_\odot/\mathrm{h}$

run on JuRoPa (Juelich)
12288 cores,
30 TB RAM
2.7 millions CPU-hours



Angulo et al. (2013)

How to form a galaxy



Gas

cooling + gravity
star formation

Stars

feedback
- chemical enrichment
- mass return
- energy injection
- gas outflows…

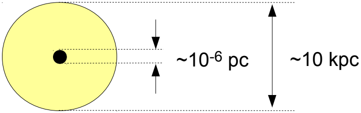
Simulations are needed
to model this complex interplay

Multi-scale physics in galaxy formation

Galaxy formation poses an enormous multi-scale physics problem

THE DYNAMIC RANGE CHALLENGE (slide taken from V. Springel Mind the Gap conference)

A supermassive BH in a galaxy

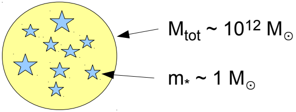


$\sim 10^{-6}$ pc

~ 10 kpc

dynamic range of 10^{10}

Star formation in a normal galaxy



$M_{tot} \sim 10^{12}\ M_{\odot}$

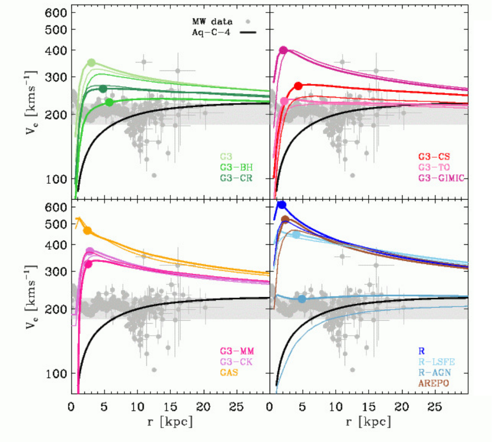
$m_{*} \sim 1\ M_{\odot}$

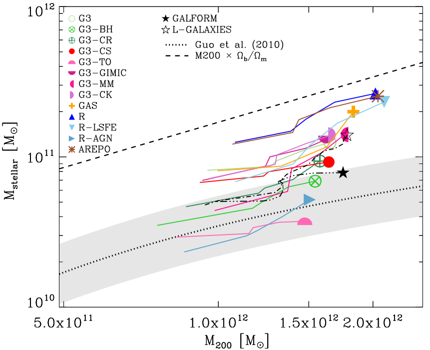
mass dynamic range of 10^{12}

Often euristic prescriptions are implemented to simulate these physical processes

The importance of sub-grid physics

(Scannapieco et al. 2012)

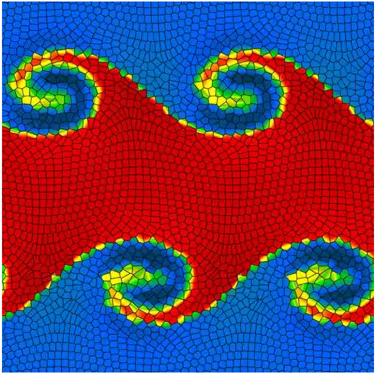




Making disc galaxies is a challenging task in cosmological simulations

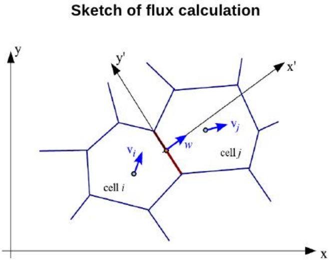
Simulation set-up

The moving-mesh code AREPO



credit: V. Springel

- Very low advection errors and numerical viscosisty
- Fully adaptive and manifestly galileian invariant
- Larger time steps are possible for supersonic flows
- Better convergence rate and accuracy with respect to SPH



Sketch of flux calculation

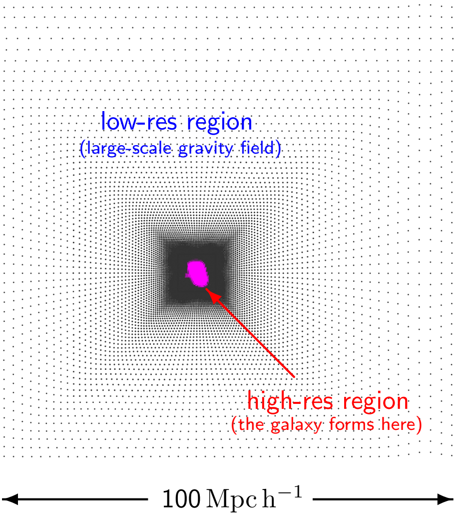
The motion of the mesh generators uniquely determines the motion of all cell boundaries

State left of cell face $\begin{pmatrix} \rho_L \\ \mathbf{v}_L \\ P_L \end{pmatrix}$ **State right of cell face** $\begin{pmatrix} \rho_R \\ \mathbf{v}_R \\ P_R \end{pmatrix}$

Riemann solver (in frame of cell face) $\rightarrow \begin{pmatrix} \rho \\ \mathbf{v} \\ P \end{pmatrix} \rightarrow \mathbf{F}(\mathbf{U})$

Set-up of the simulations

- cosmological hydrodynamic simulations with AREPO of 8 Aquarius haloes (also MHD version)
- baryonic physics includes (Vogelsberger+ 13):
  - sub-resolution model for ISM
  - metal cooling
  - stellar evolution
  - kinetic galactic winds
  - black hole feedback



Galactic wind implementation

Parameterization of wind feedback

ENERGY AND MOMENTUM DRIVEN WINDS **(slide taken from V. Springel Fire down below conference)**

Basic parameterization of energy flux in wind:

$$\frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 = \epsilon_{\rm SN,w}\dot{M}_*$$

Mass loading factor:

$$\eta \equiv \dot{M}_{\rm w}/\dot{M}_*$$

(Springel & Hernquist 2003)

We assume a wind speed proportional to the local potential well depth:

$$v_{\rm w} = \kappa_{\rm w}\,\sigma_{\rm DM}^{1D}$$

In general, one may assume an energy- or momentum scaling of the wind:

$$\eta_{\rm w} = \frac{1}{v_{\rm w}^2}\left({\rm egy}_{\rm w} + \sqrt{{\rm egy}_{\rm w}^2 + v_{\rm w}^2\,{\rm mom}_{\rm w}^2}\right)$$

(see also Openheimer & Dave 2006)

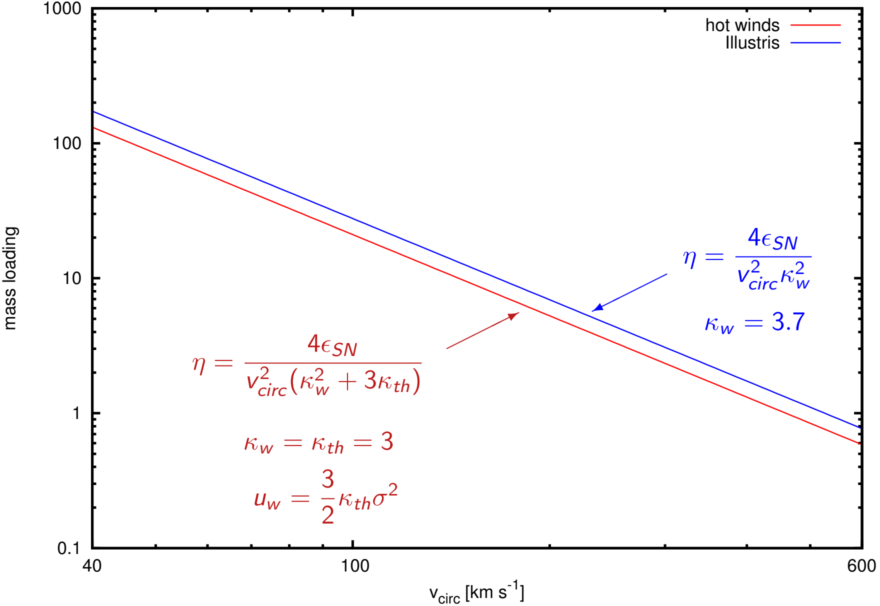
We however achieve the best results with a pure energy-scaling.
(Puchwein & Springel 2013, Vogelsberger et al. 2013)

The two parameters of the model, wind-speed scaling coefficient and energy fraction in the wind are tuned to obtain a reasonable stellar mass function.

Our “Illustris”-Projekt parameters are: $\kappa_{\rm w} = 3.7$

wind kinetic energy flux per supernova: 1.09×10^{51} erg

Wind mass loading



$$\eta = \frac{4\epsilon_{SN}}{v_{circ}^2 \kappa_w^2}$$

$$\kappa_w = 3.7$$

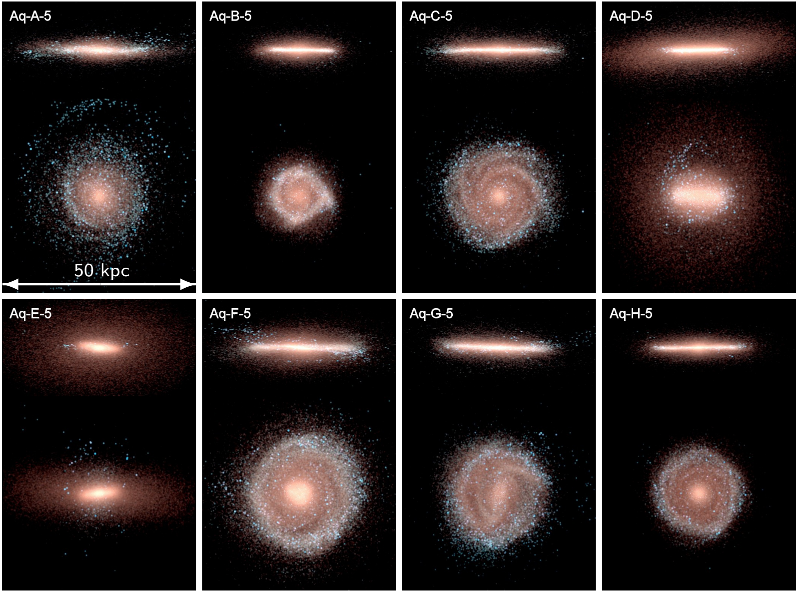
$$\eta = \frac{4\epsilon_{SN}}{v_{circ}^2 (\kappa_w^2 + 3\kappa_{th})}$$

$$\kappa_w = \kappa_{th} = 3$$

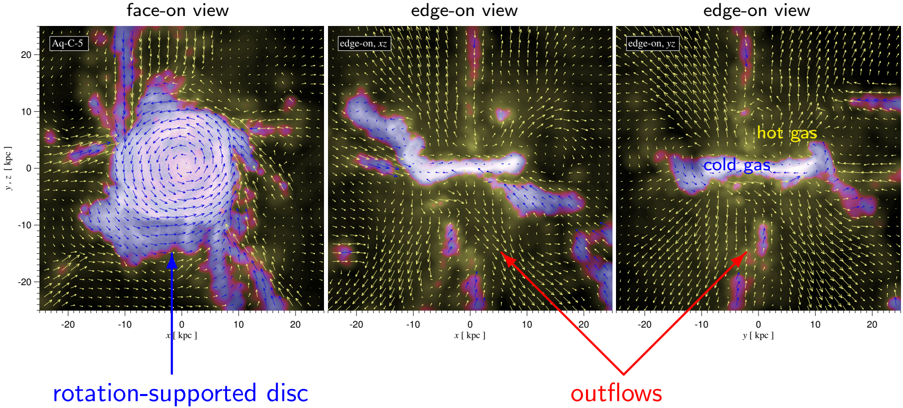
$$u_w = \frac{3}{2}\kappa_{th}\sigma^2$$

Features of the simulated systems

Stellar projections



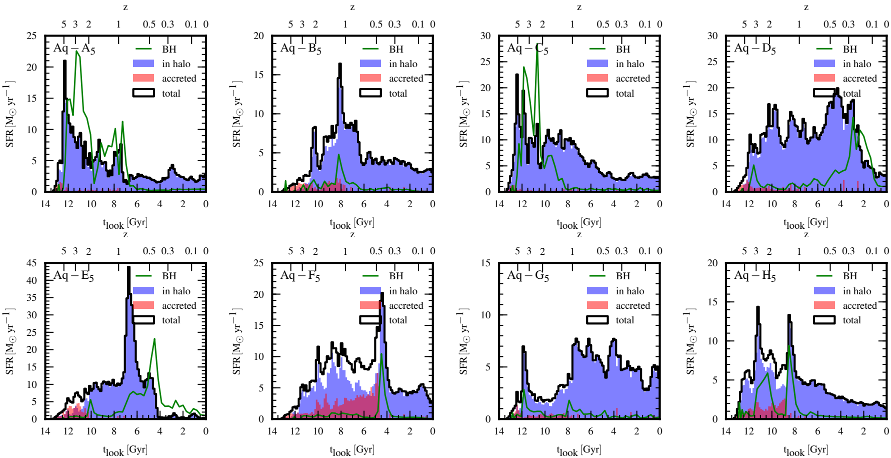
Gas projections



rotation-supported disc

outflows

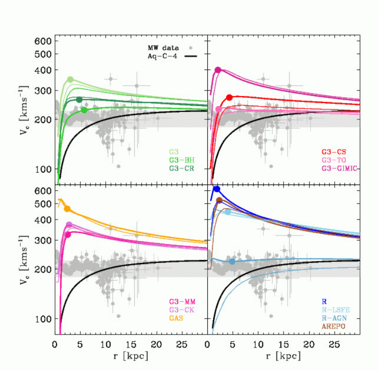
Star formation histories



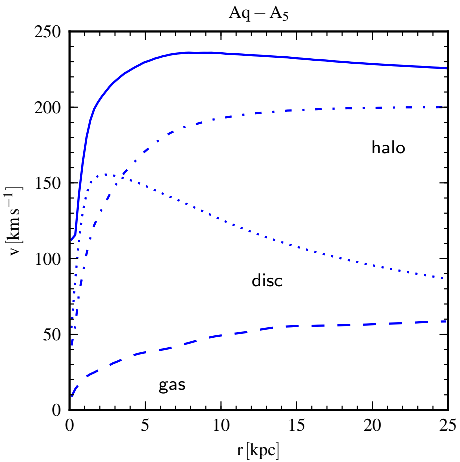
Stars form in-situ, black hole grows by $z \sim 1$

Circular velocities

Flat rotation curve

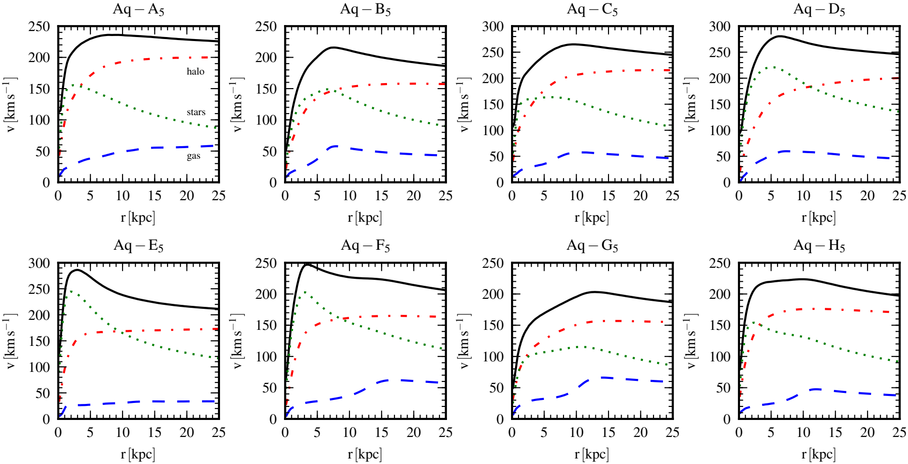


(Scannapieco et al. 2012)



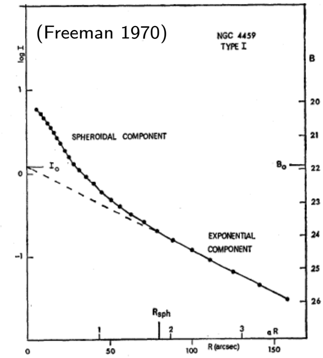
$$v = \sqrt{\frac{GM(<r)}{r}}$$

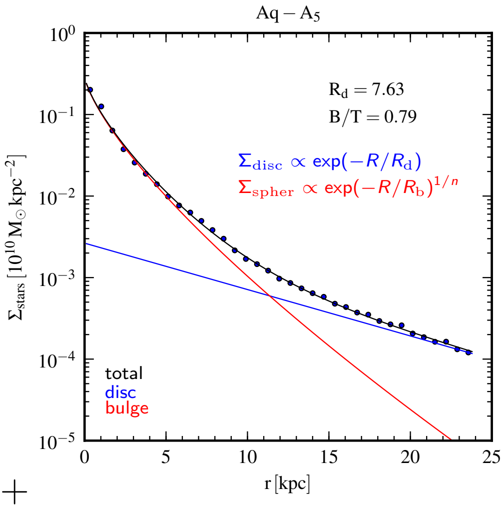
Circular velocities



Realistic (almost flat) rotation curves

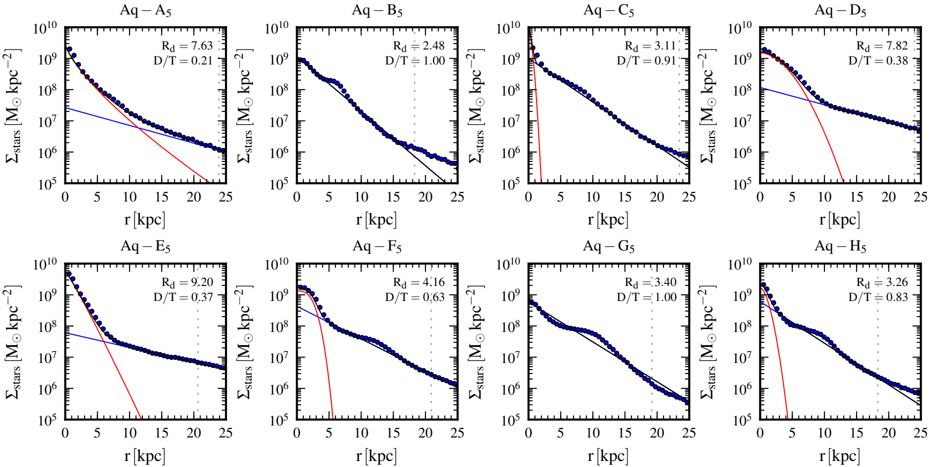
Disc-bulge decomposition





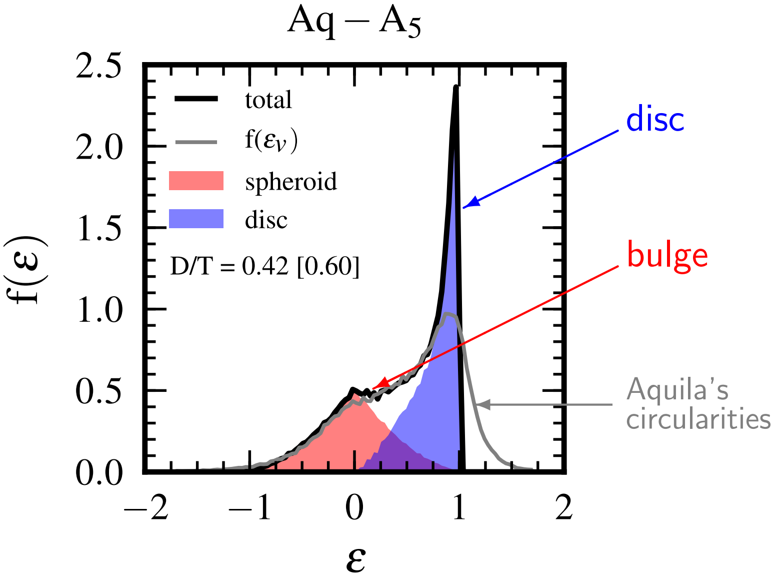
Exponential stellar disc +
luminosity excess in the center

Disc-bulge decomposition

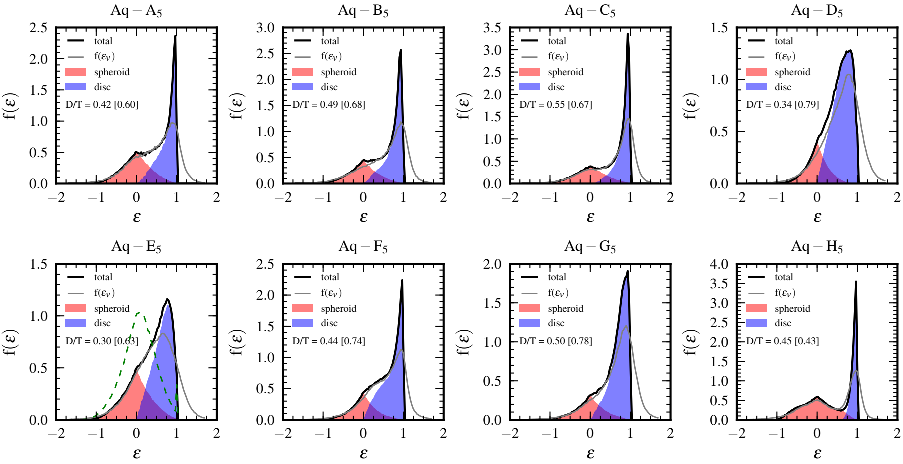


The majority of the systems is disc-dominated

Circularity distributions



Circularity distributions

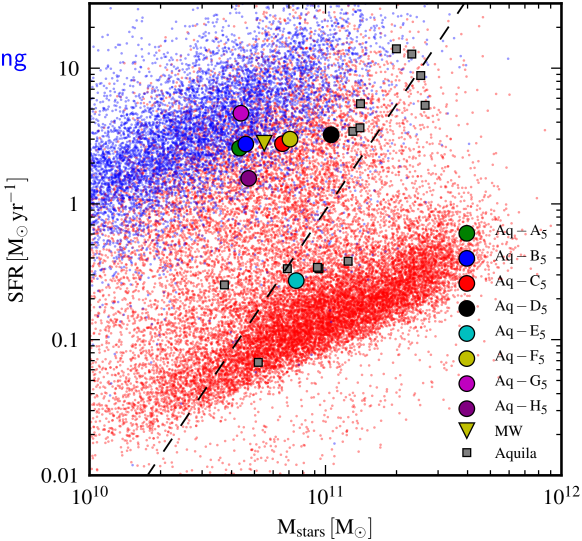


Prominent kinematic disc signature

Star-forming vs “red and dead” galaxies

blue star-forming galaxies

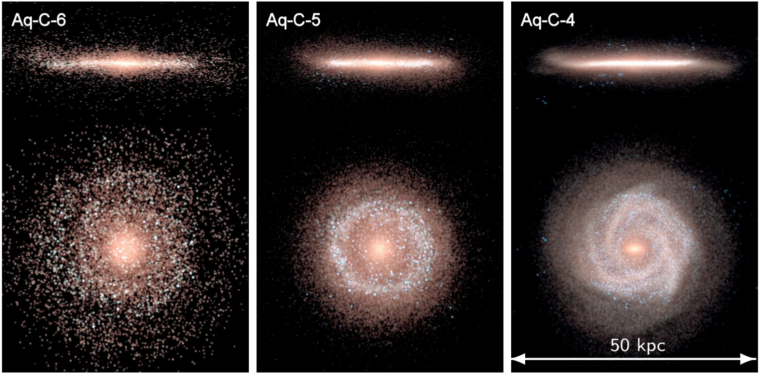
red and dead galaxies



Enough gas is retained for late star formation

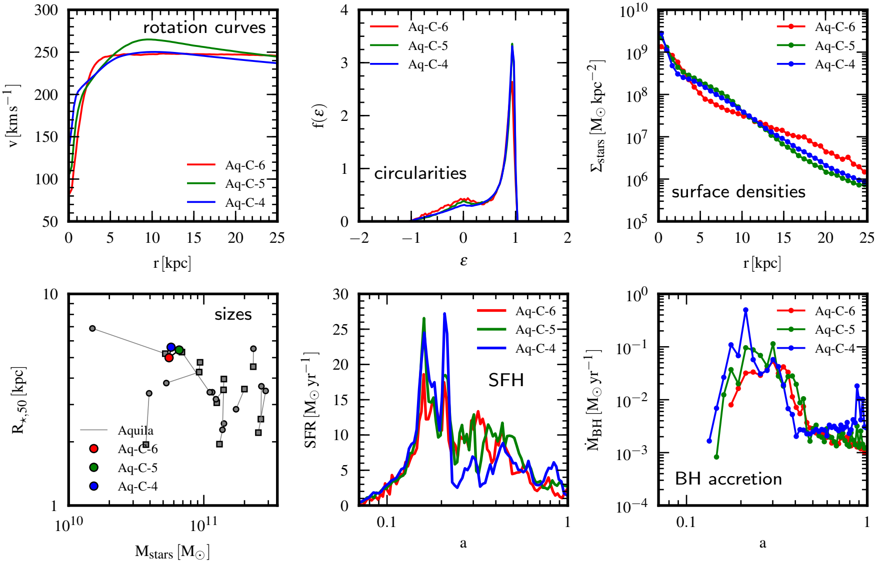
Sub-grid physics & resolution

Stellar disc morphology



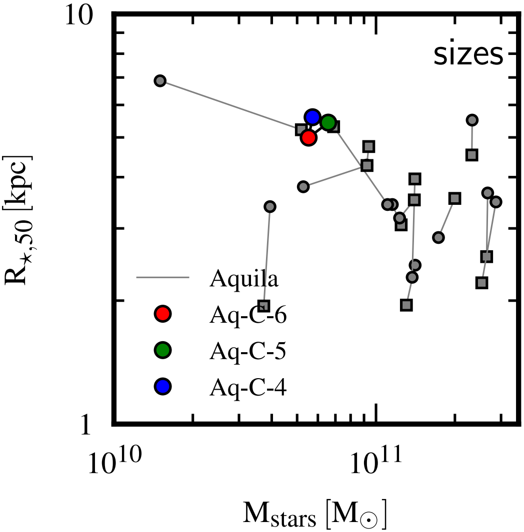
Increasing resolution

Comparison of galaxy properties



Main galaxy properties are well converged

Comparison of galaxy properties



No change in the feedback parameters

Summary

Simulations produce realistic Milky Way-like galaxies:

- well defined discs in most of the simulated systems
- many key observational properties are reproduced
- good convergence properties of the sub-resolution physics