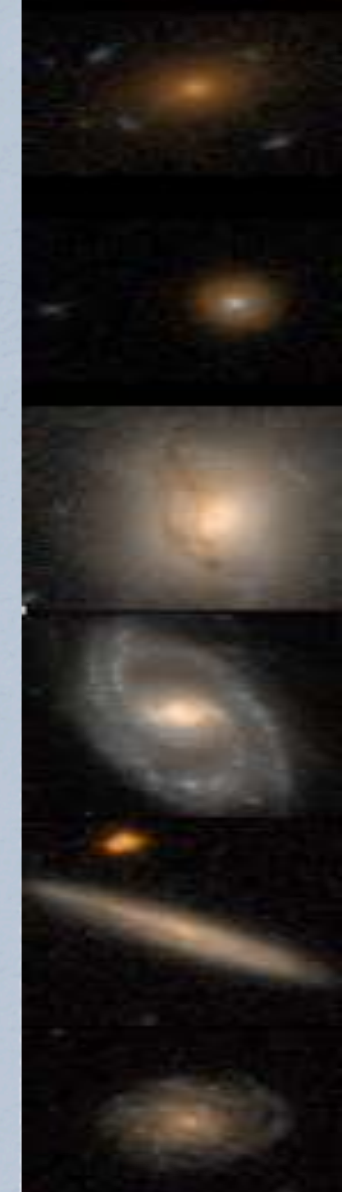
Galaxy formation and evolution



Cecilia Scannapieco

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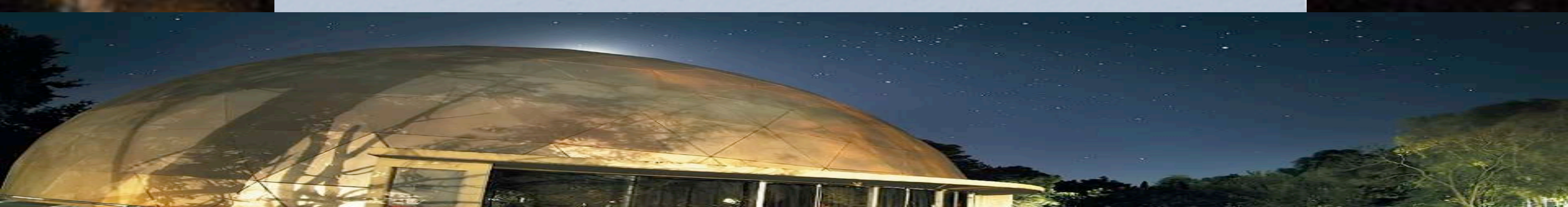
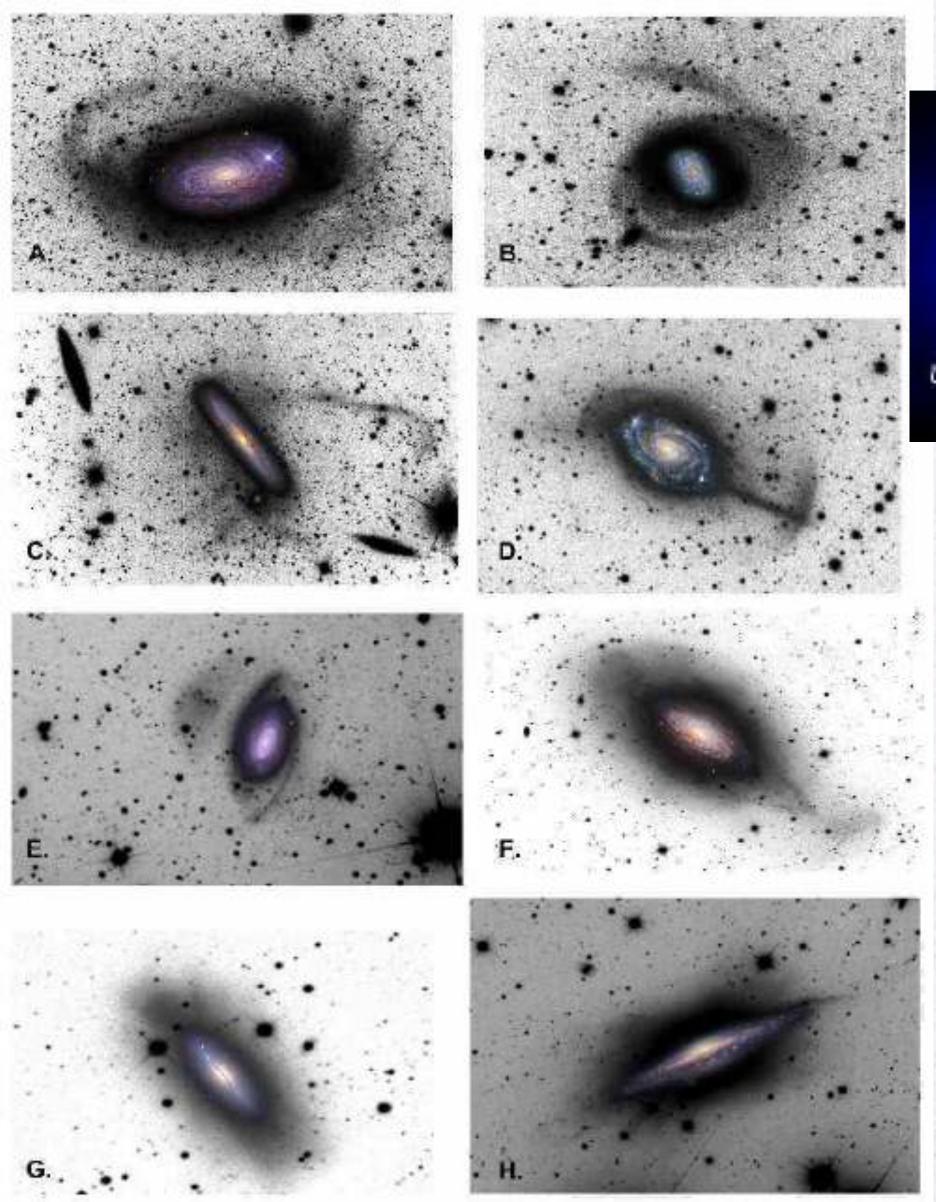
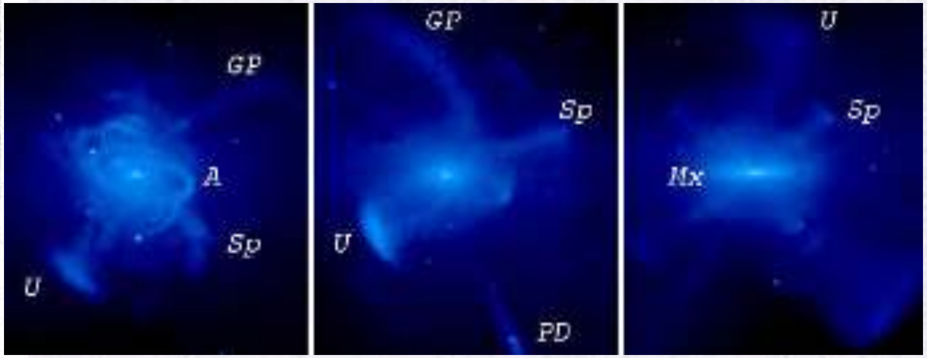
LAPIS 2018



Stellar halos and stellar streams

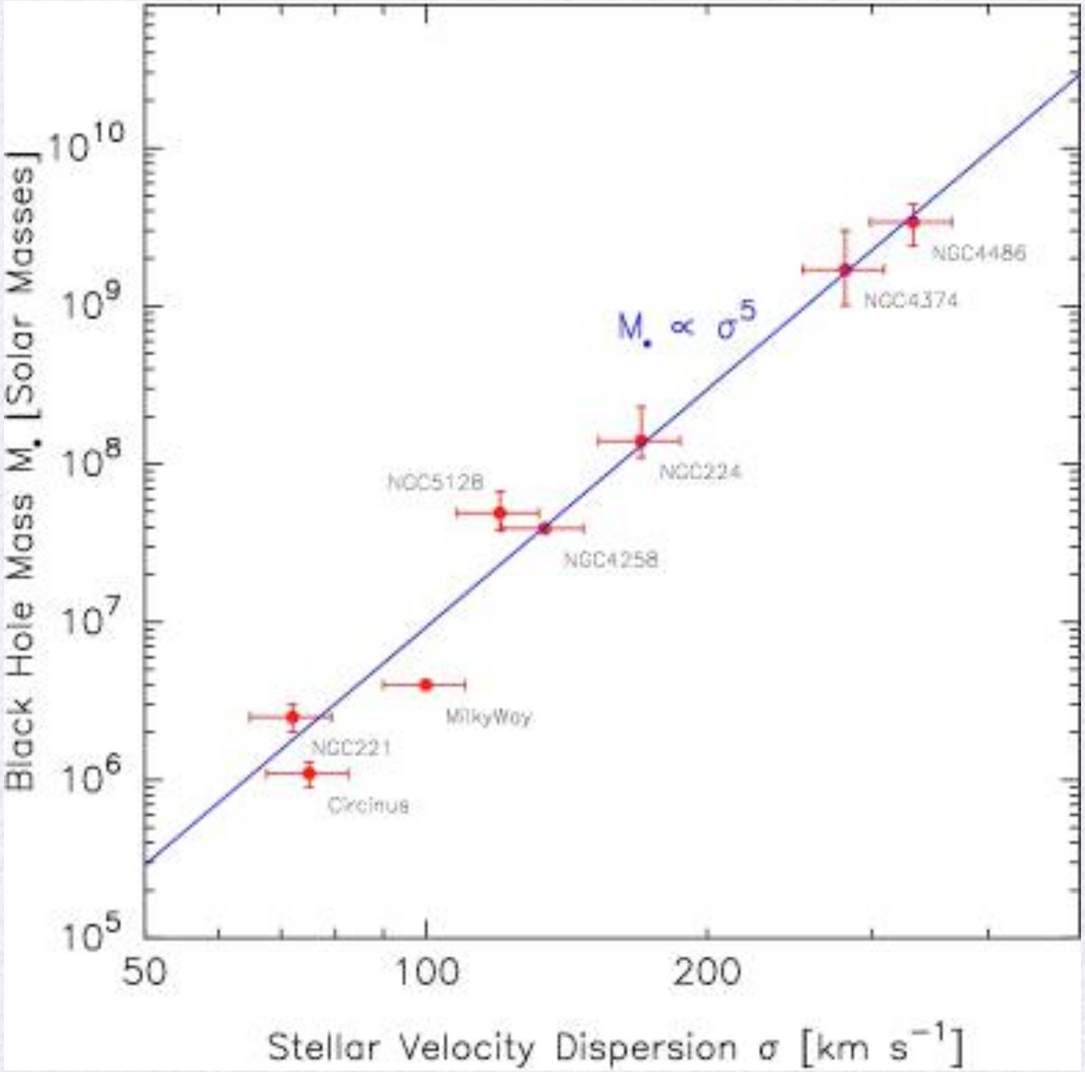




Martínez-Delgado+ 2010

The “m-sigma” relation

A correlation between the bulge mass and the black hole



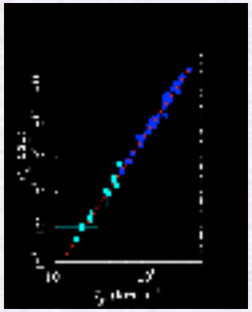
Lectures 1 & 2

Two approaches to study the formation and evolution of galaxies

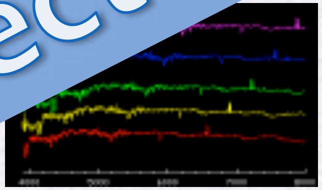
→ Observations → images

→ spectra

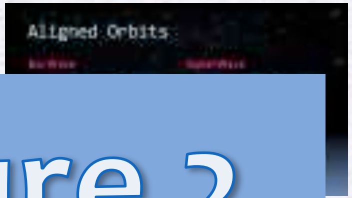
→ statistical r… g relations



→ time e…



Lecture 1

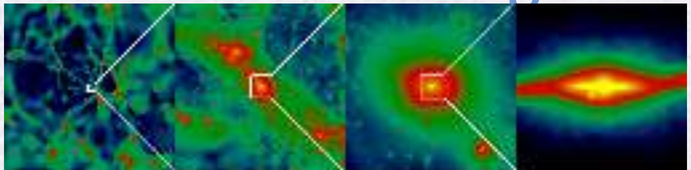


→ Theory → simple …

→ semi-a…

Lecture 2

→ **numerical simulations in cosmological context**



Lecture 2

- Cosmology, structure formation & galaxies
- The physics of galaxy formation
- Numerical Simulations
  - Physical processes
- Results of Simulations
  - The formation of Spiral galaxies
  - Galaxy evolution & merger history
  - Environmental effects

Structure formation and cosmology

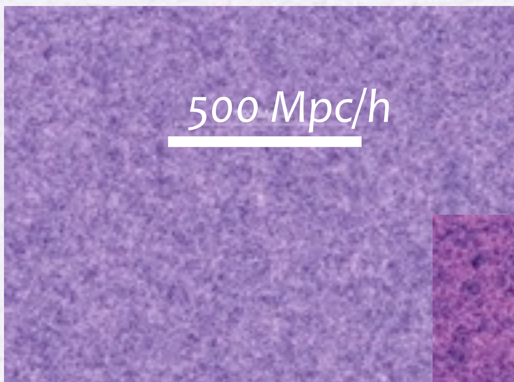
In a theoretical context, a galaxy is more than a collection of stars

- The formation of dark matter haloes & galaxies in ΛCDM is:
  - Highly non-linear
  - Multi-scale
  - Free from any simplifying symmetry
- We need simulations!

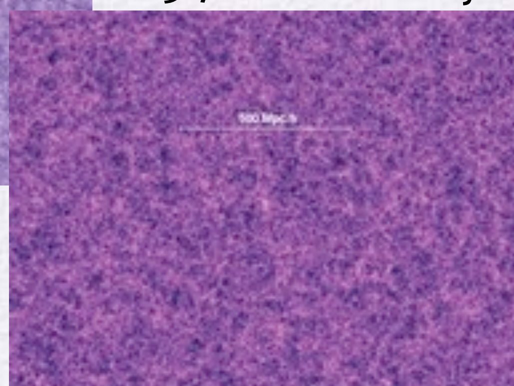
Structure formation and cosmology

Dark matter haloes result from the gravitational amplification of initial density perturbations

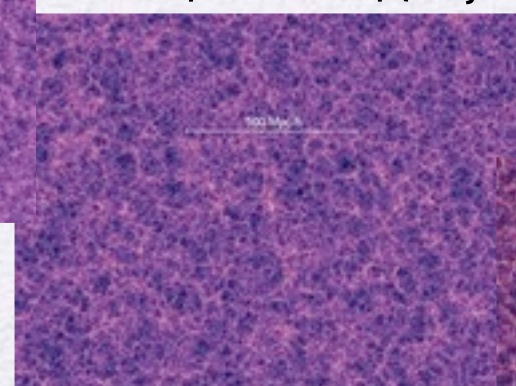
z=18.3 *T* = 0.21 Gyr



z=5.7 *T* = 1 Gyr



z=1.4 *T*=4.7 Gyr



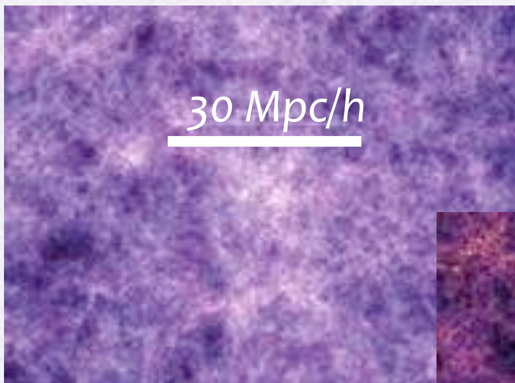
z=0 *T*=13.6 Gyr

Credit: V. SPringel

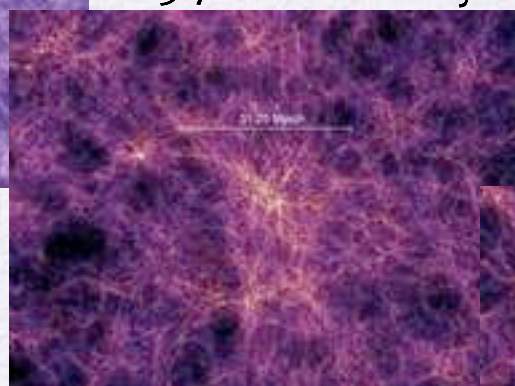
Structure formation and cosmology

Dark matter haloes result from the gravitational amplification of initial density perturbations

z=18.3 *T* = 0.21 Gyr

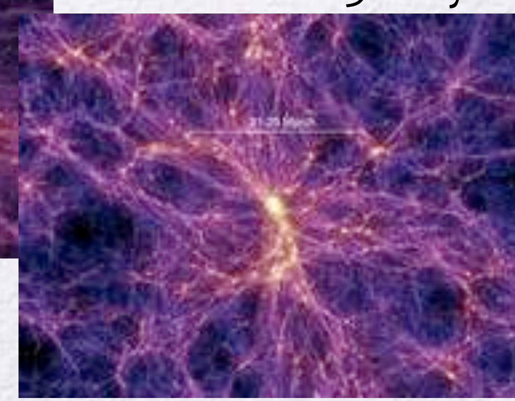


z=5.7 *T* = 1 Gyr



z=1.4 *T*=4.7 Gyr

z=0 *T*=13.6 Gyr

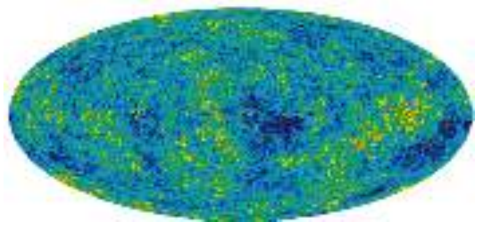


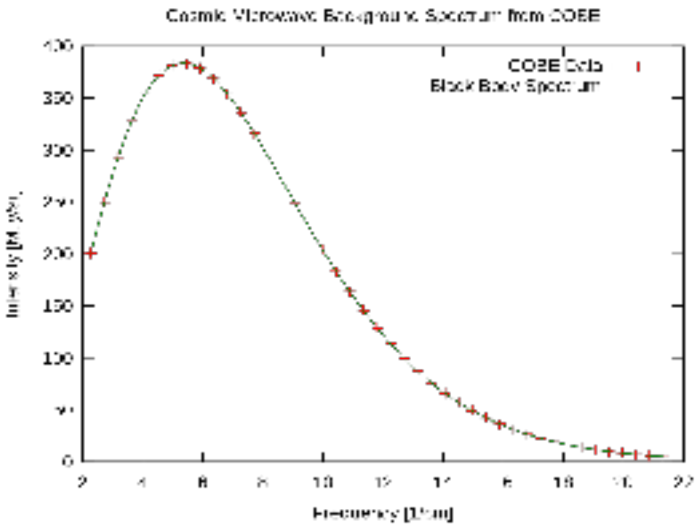
Credit: V. SPringel

Ingredients of simulations

- Initial (and boundary) conditions
  - Set by the processes taking place in early Universe
  - **The initial conditions of galaxy formation are known!!**

Initial conditions
(at convenient time t_0)





CMB spectrum:

→ isotropic to 1 part in 10000, fluctuations $\Delta T/T \sim 10^{-5}$

→ has a perfect blackbody spectrum, T=2.73 K

→ spectrum at recombination, 300000 years after Big Bang

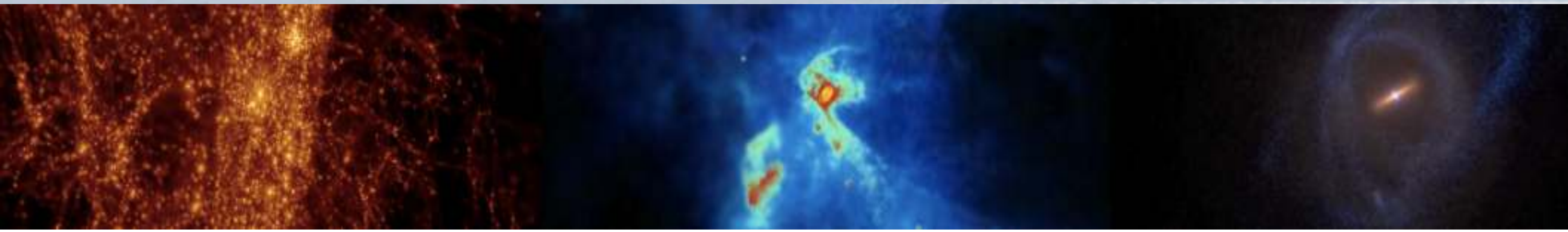
Ingredients of simulations

- Initial (and boundary) conditions

- Physical processes which drive evolution
  - Evolution of dark matter driven by gravitational forces
    - Raúl Angulo's lectures: DM-only, very large volume simulations

  - To study galaxy formation, we need to simulate the evolution of the gas
    - Much more complex, need to solve the Euler equations
    - Still need to simulate relative large volumes, as galaxies and their haloes are affected by the formation of structure at large scales
    - Need to cover a huge dynamical range

Hydrodynamical simulations



Need to cover huge dynamical range

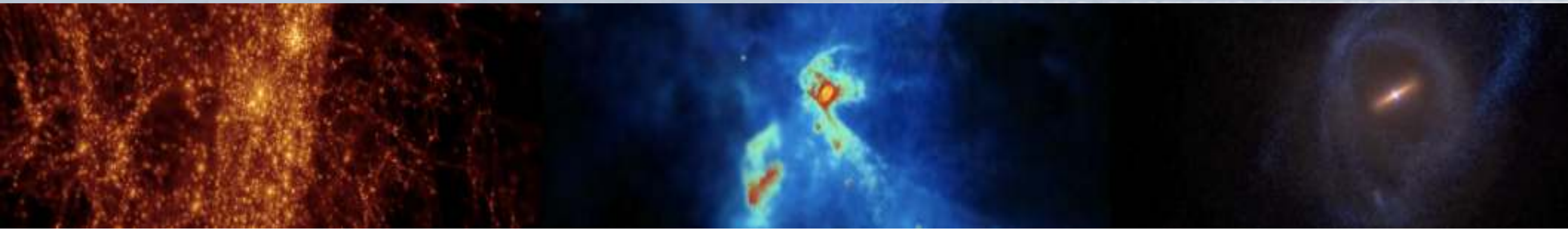
>20 orders of magnitude in size!

- Size of the Universe ~ 3 Gpc ~ 10^9 pc
- Size of stars ~ 10^{-12} pc

For typical galaxies

- Dark matter halo ~ 10^2 kpc
- Influence region ~ 10 Mpc
- Separation between stars ~ 1 pc
  → Still > 7 orders of magnitude!

Structure formation and cosmology



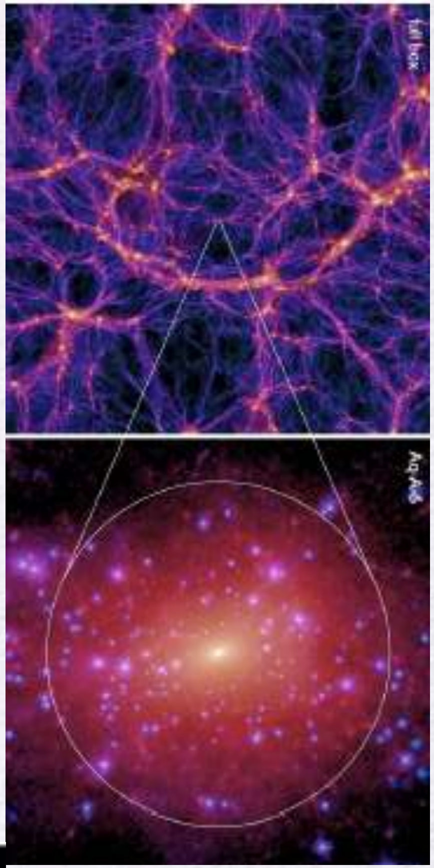
Need to cover huge dynamical range

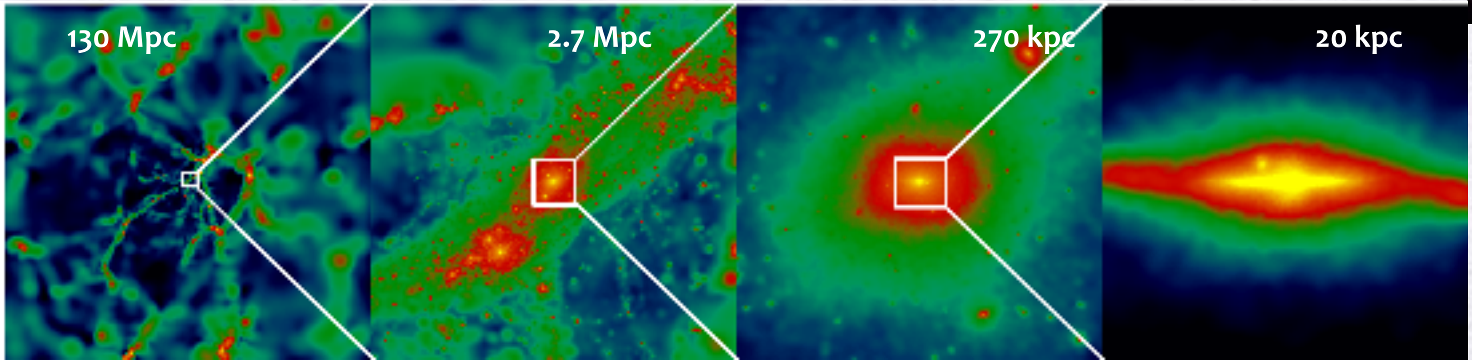
> 4 orders of magnitude in time:

- Time of the Universe ~ 10^{10} yr
- Life-time of stars ~10^{6} yr

Zoom-in simulations

- Run a large-volume, dark-matter only cosmological simulation up to z=0
- Select object of interest (e.g. a quiet galaxy)
- Create a new initial condition, concentrating resolution in a “high-resolution region”, and add gas component
- Run simulation: dark matter + baryons



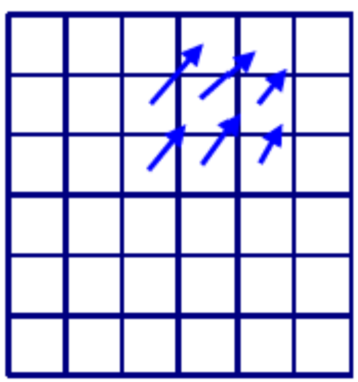


Numerical methods

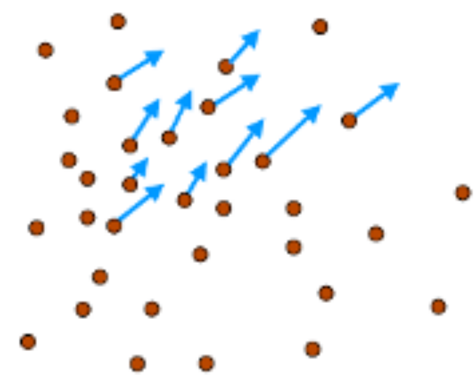
- Discretize matter in terms of particles and follow their trajectories

Two ways of discretizing a continuous distribution

Eulerian
Discretize space
(volume elements)



Lagrangian
Discretize mass
(particles)

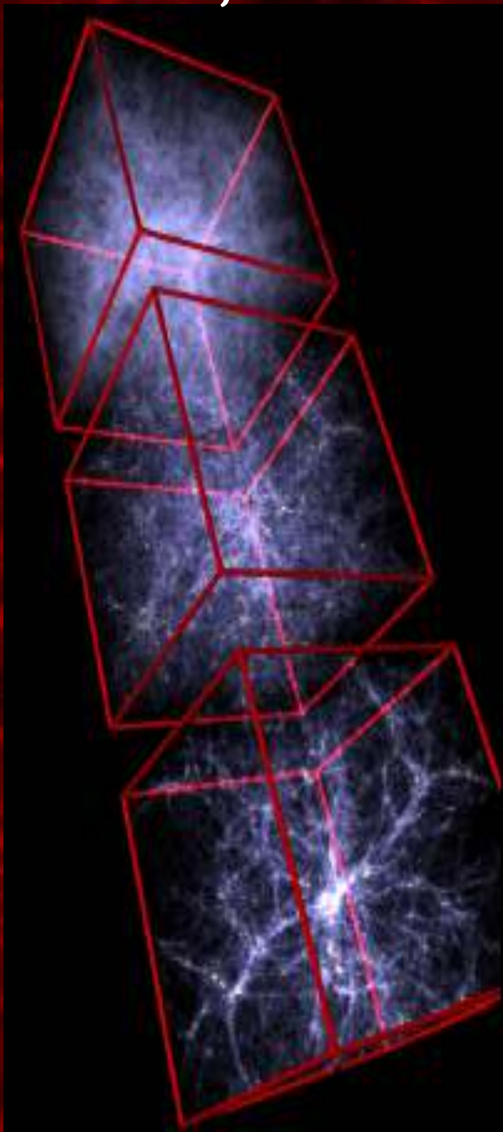


Equations governing flow of physical quantities (mass, momentum, energy) through cell boundaries

Equations governing evolution of physical properties (density, momentum, energy) of particles

Numerical methods

- Discretize matter in terms of particles and follow their trajectories
- Create initial condition:
  - N_{DM} dark matter particles, N_{gas} gas particles
- Solve equations that govern the motion of the particles
  - DM/stars: collisionless → only gravity
  - Gas: collisional → gravity + hydrodynamics
  - Sub-grid physical modules: for important processes that are not resolved, we mimic their effects at the resolved scales
- Solve equations in expanding Universe assuming the standard cosmology



Numerical methods

To solve the hydrodynamical equations we use the SPH technique (SPH: Smoothed Particly Hydrodynamics)

Discrete approximation of a continuous fluid

$$f(\mathbf{r}) = \int_V f(\mathbf{r}')\, \delta(\mathbf{r}-\mathbf{r}')\, \mathrm{d}\mathbf{r}'$$

Generalize the δ function → smoothing kernel *W*

$$f(\mathbf{r}) \approx \sum_i \frac{m_i}{\rho_i} f(\mathbf{r}_i)\, W(\mathbf{r}-\mathbf{r}_i, h)$$

Write the discretized fluid equations + equation of state

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla \Phi$$

$$\frac{\partial u}{\partial t} + \nabla \cdot [(u+P)\mathbf{v}] = 0$$

For each particle *j* , and *I* are the "neighbours"

$$\frac{\mathrm{d}\rho_j}{\mathrm{d}t} = -\rho_j \nabla_j \cdot \mathbf{v}_j$$

$$\frac{\mathrm{d}\mathbf{v}_j}{\mathrm{d}t} = -\sum_i m_i \left(\frac{P_j}{\rho_j^2} + \frac{P_i}{\rho_i^2}\right) \nabla_j W_{ji}$$

$$\frac{\mathrm{d}u_j}{\mathrm{d}t} = \frac{P_j}{\rho_j^2} \sum_i m_i\, (\mathbf{v}_j - \mathbf{v}_i) \cdot \nabla_i W_{ji}$$

Numerical methods

To solve the hydrodynamical equations we use the SPH technique (SPH: Smoothed Particly Hydrodynamics)

Evolution in an expanding universe, with x: comoving coordinate

$$\ddot{\mathbf{x}}_i + 2\frac{\dot{a}}{a}\,\dot{\mathbf{x}}_i = -\frac{G}{a^3}\sum_{\substack{j\neq i\\ \text{periodic}}}\frac{m_j\left(\mathbf{x}_i-\mathbf{x}_j\right)}{|\mathbf{x}_i-\mathbf{x}_j|^3}$$

and for periodic boundary conditions

+ implementation of cooling, etc

+ time integration, parallelization and (many more!) technical issues

Structure formation and cosmology

A typical simulation of galaxy formation

- A box of ~50-100 Mpc side length
- Spatial resolution of ~ 10-100 pc
- Time resolution of ~10^6 yr

Note:

dark matter particles in the simulation are not dark matter particles
DM particles ~ $10^{4\text{-}5}$ $M_\odot$ in the simulations!

star particles in the simulation are not individual stars
Star particles ~ $10^{3\text{-}4}$ $M_\odot$ in the simulations!

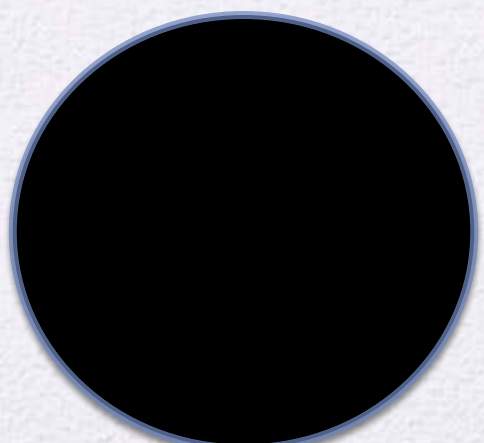
Galaxy formation physics

The formation of a galaxy in the standard cosmological paradigm can be illustrated as follows:

- Collapse and virialization of dark matter haloes
- Cooling and condensation of gas within the halos
- Conversion of cold gas into stars and supermassive black hole
- Evolving stars and active galactic nuclei eject energy, mass and heavy elements into the interstellar medium
- Evolution due to mergers/interactions with other structures which reshape morphologies and trigger further starbursts and AGN activity

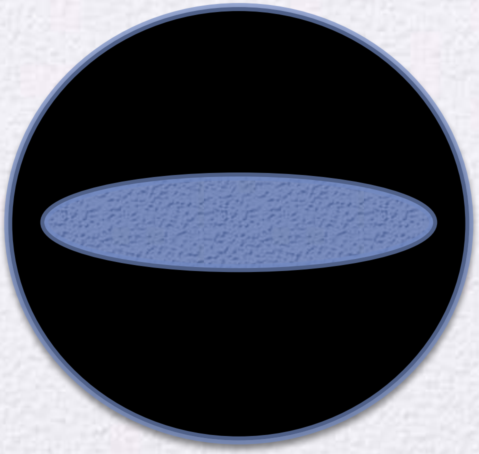
Galaxy formation physics

- Gravity → dark matter halo formation



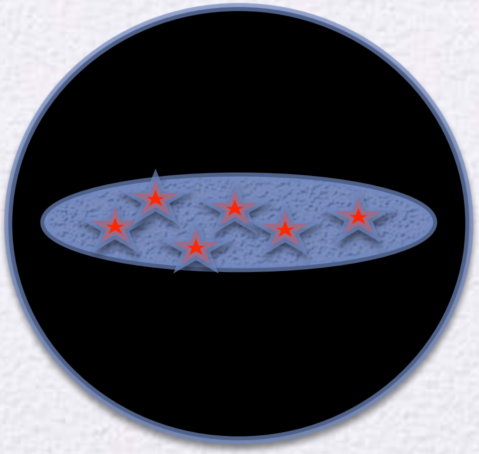
Galaxy formation physics

- Gravity → dark matter halo formation
- Cooling → gas condensation within halos



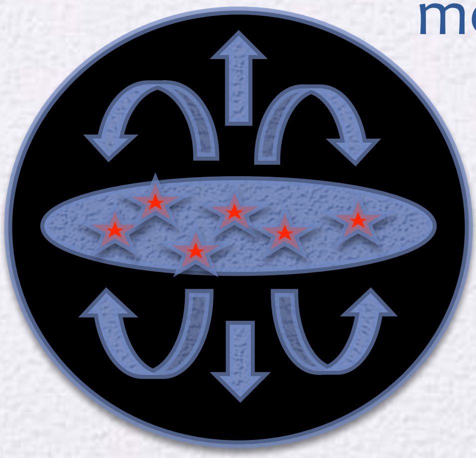
Galaxy formation physics

- Gravity → dark matter halo formation
- Cooling → gas condensation within halos
- Star formation → from high-density, cold gas



Galaxy formation physics

- Gravity → dark matter halo formation
- Cooling → gas condensation within halos
- Star formation → from high-density, cold gas
- "Feedback" → return of chemical elements and/or energy to the interstellar medium

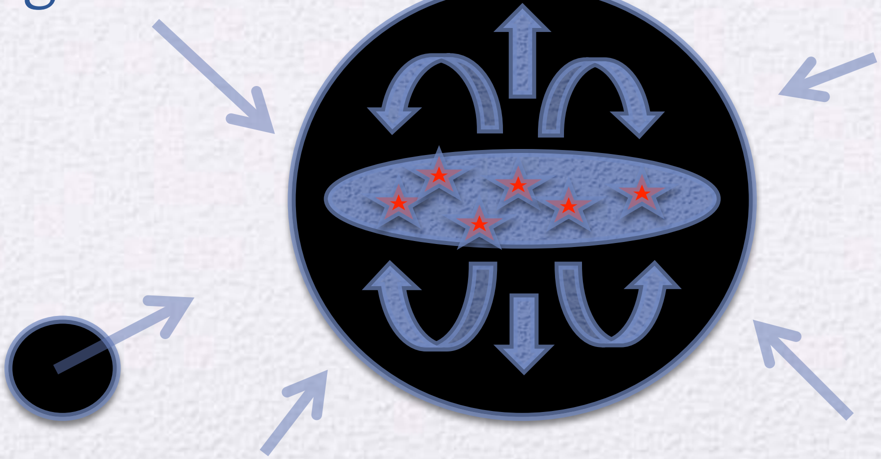


Galaxy formation physics

- Gravity
- Cooling
- Star formation
- “Feedback”

+ Cosmological effects

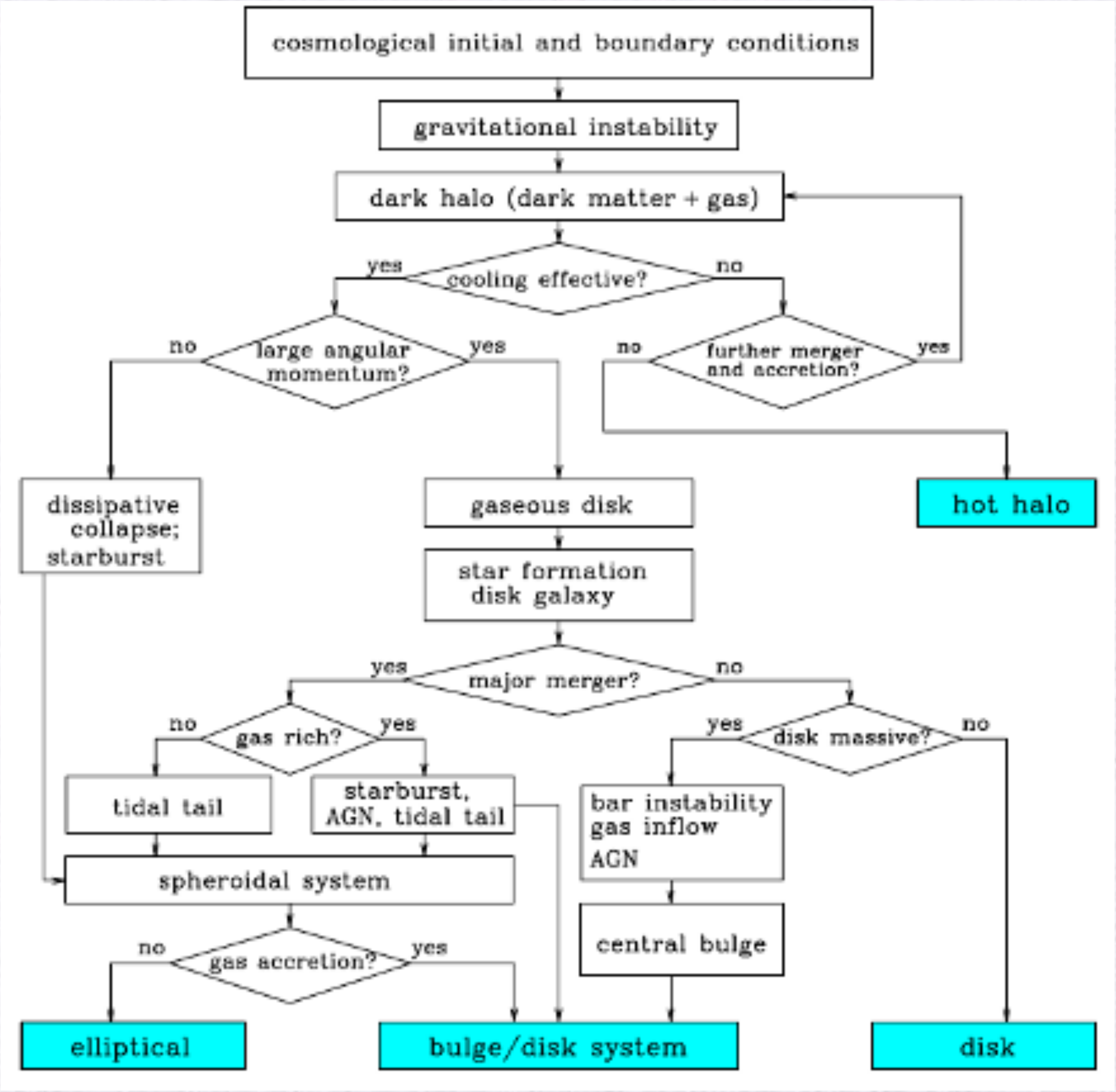
Mass accretion/mergers



Galaxy formation

Flow-chart of processes affecting galaxy formation

Shows our current, **incomplete** view of galaxy formation!

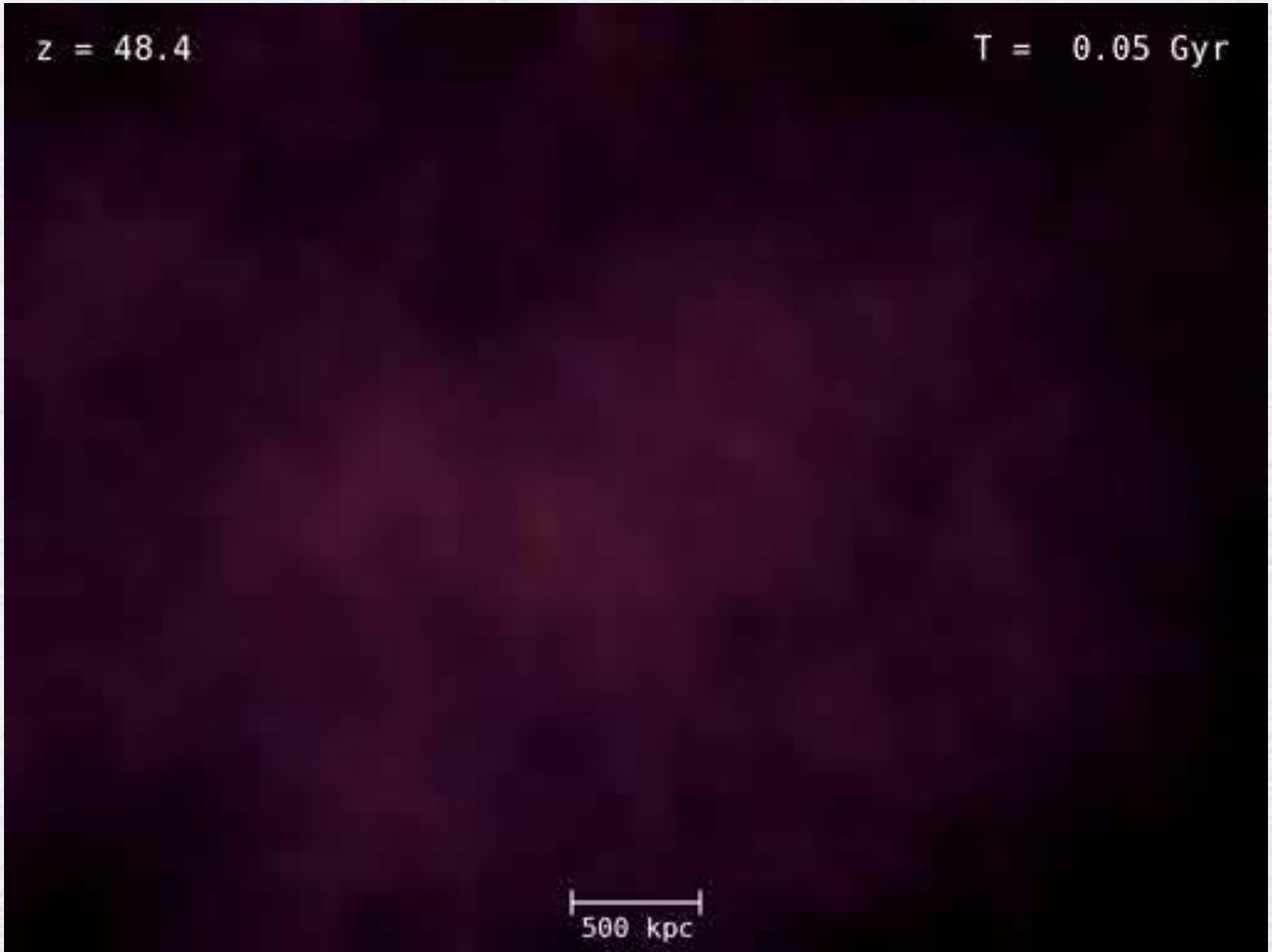


Galaxy formation simulations

- Collapse and virialization of dark matter (DM) halos: in the standard Λ-CDMc cosmology, DM halos form **hierarchically**

Small systems assemble first, larger systems result from mass accretion and mergers

Mergers are more frequent and violent at high redshift (i.e. early times)

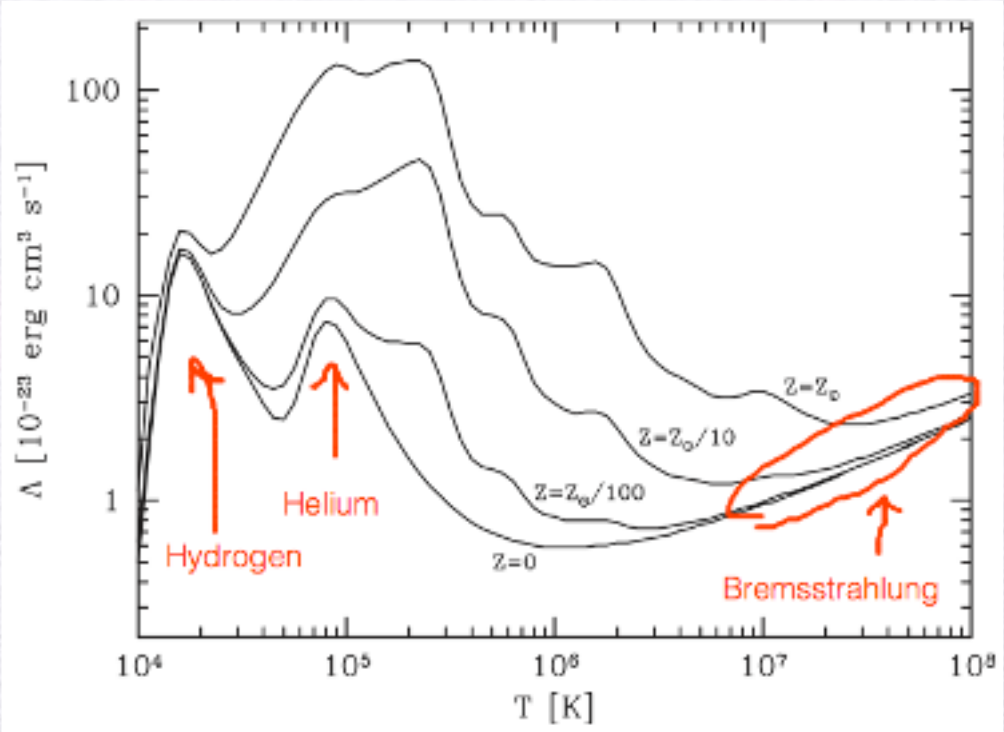


Galaxy formation simulations

- Cooling and condensation of gas within the DM halos
  - Cooling is a crucial ingredient in galaxy formation:
  - Gas cools by various processes, with an efficiency that depends on the temperature, the density and the chemical composition.
  - At "low" temperatures, most cooling happens because particles collide and use their kinetic energy to excite or even ioniza atoms. The atoms subsequently recombine or de-excite, emitting radiation which carries enery away from the system.
  - Most of the gas in the Universe is hydrogen, which cools most efficiently at $T \sim 10^4$ K. At higher temperatures, helium dominates the cooling, as well as various metals depending on their ionization state and density.
  - At very high temperatures ($T>10^7$K), the gas is highly ionized and cooling happens mainly via bremsstrahlung (i.e. deceleration of charged particles by other charged particles).

Galaxy formation simulations

- Cooling and condensation of gas within the DM halos
  - Cooling is a crucial ingredient in galaxy formation:
  - Gas cools by various processes, with an efficiency that depends on the temperature, the density and the chemical composition.
  - In simulations, we use pre-tabulated cooling tables



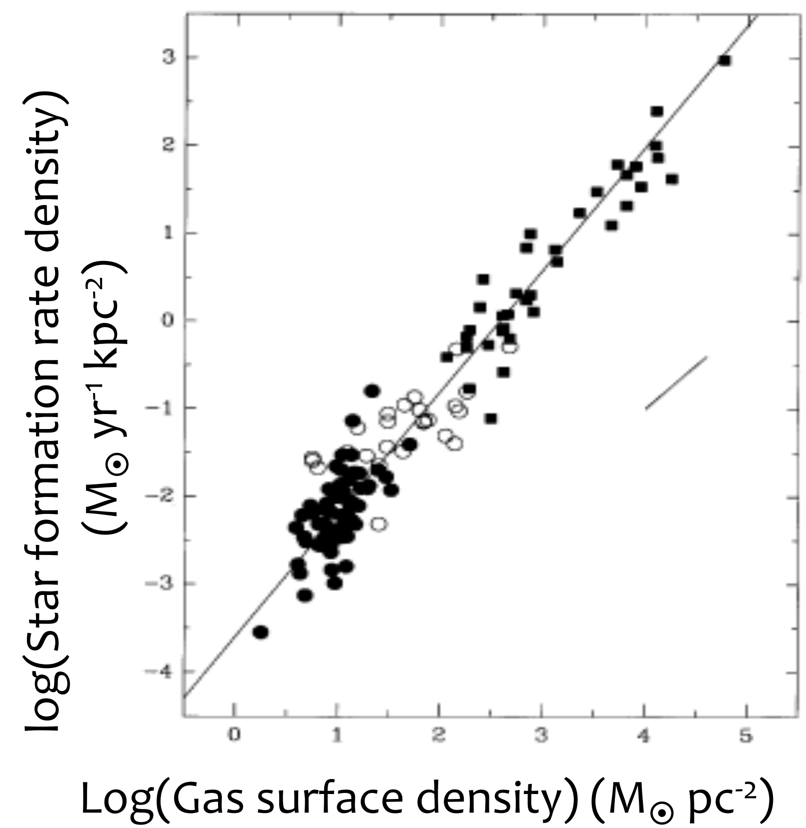
Galaxy formation simulations

- **Star formation**
  - As the gas cools down within the dark matter halo, it reaches sufficiently high densities, fragmenting and forming stars

The "Kennicutt-Schmidt" law

Tight correlation between **star formation rate** density (stellar mass formed per unit time per unit area) and **surface gas density**

$$\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}^{1.4\pm0.15}$$



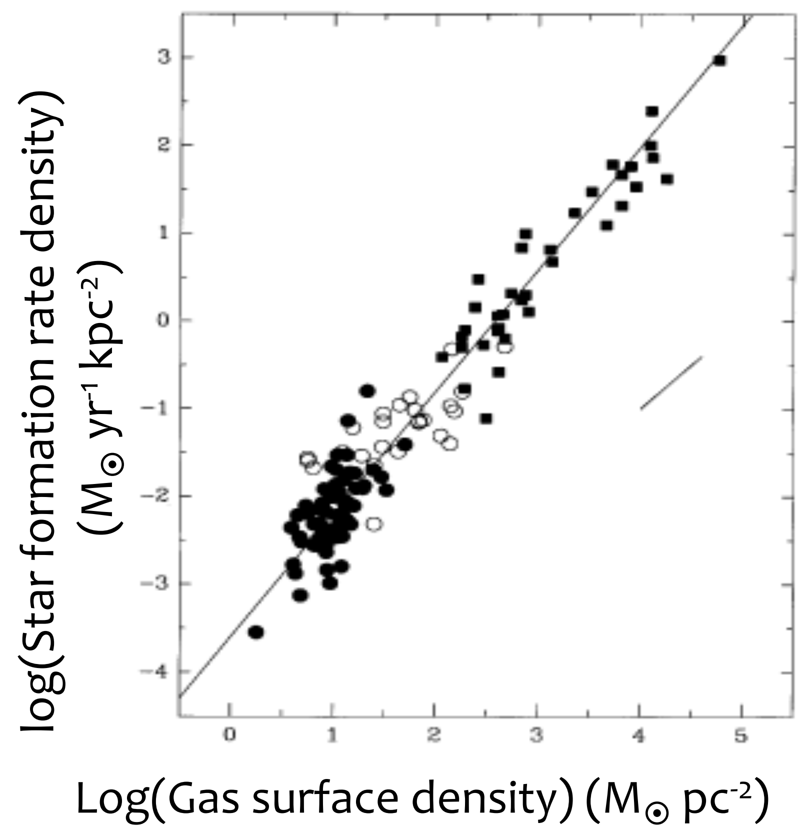
Galaxy formation simulations

Dynamical time

$\tau_{dyn} = (3\pi / 16G\rho)^{1/2}$

Represents the time it would take a star to collapse if the pressure supporting it against gravity were suddenly removed.

he dark matter halo, it reaches
nting and forming stars



We introduce the parameter *c*: efficiency of star formation

c~0.05

$$\dot{\rho}_\star = c \frac{\rho}{\tau_{\rm dyn}}$$

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 like the Milky Way 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, **radiation-pressure** 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 α–elements such as O and Mg)

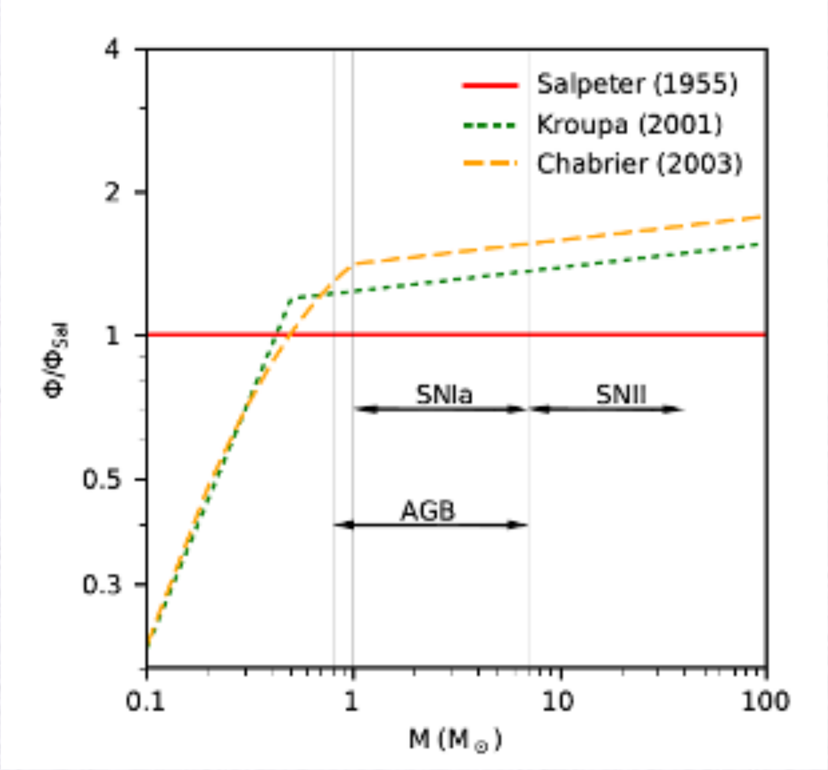
- Type Ia Supernova
  - Low-mass stars/binaries ($M<1.4M_{\odot}$), long-lived ($10^{8\text{-}10}$yr)
  - Main contibutor of Fe

- 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

Stellar feedback: three channels

Ingredients of **chemical enrichment** modeling

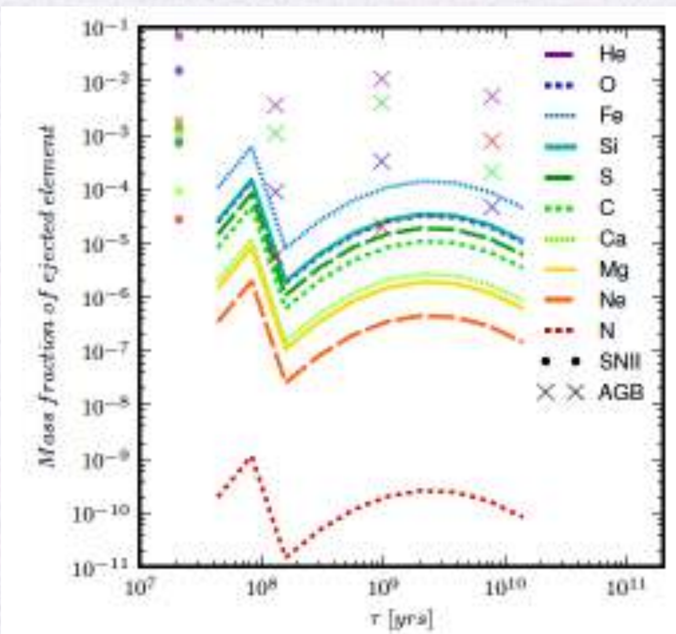
- Initial Mass function: fractional contribution of stars of different mass in a stellar population

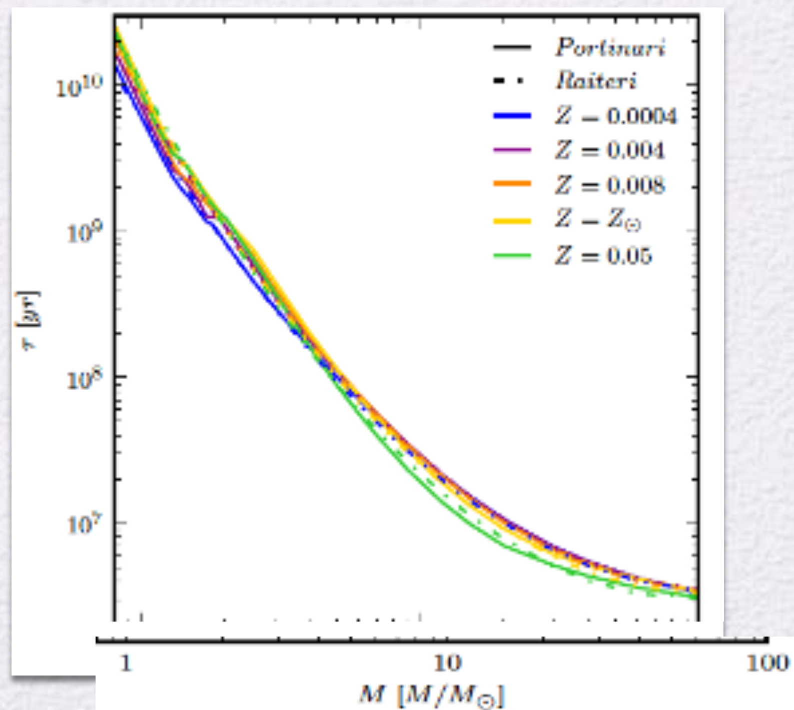


Stellar feedback: three channels

Ingredients of **chemical enrichment** modeling

- Initial Mass function: fractional contribution of stars of different mass in a stellar population
- Typical life-times of progenitor stars, which determine the time of chemical/energy release

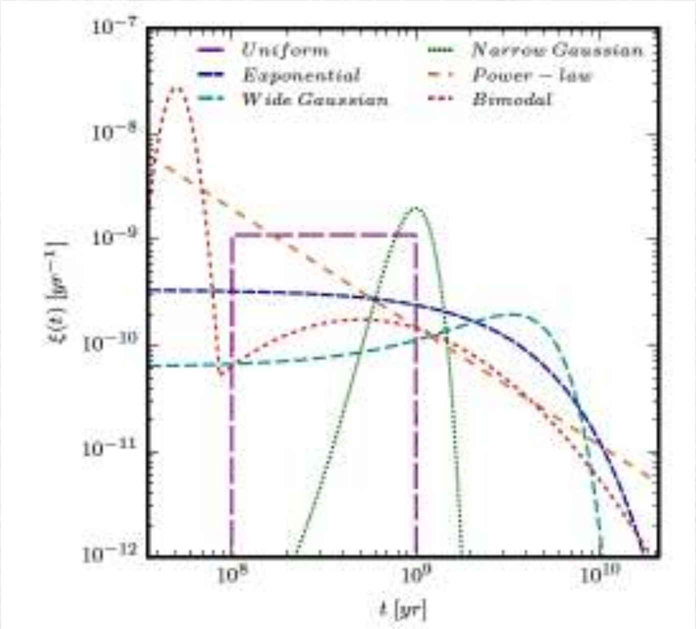




Stellar feedback: three channels

Ingredients of **chemical enrichment** modeling

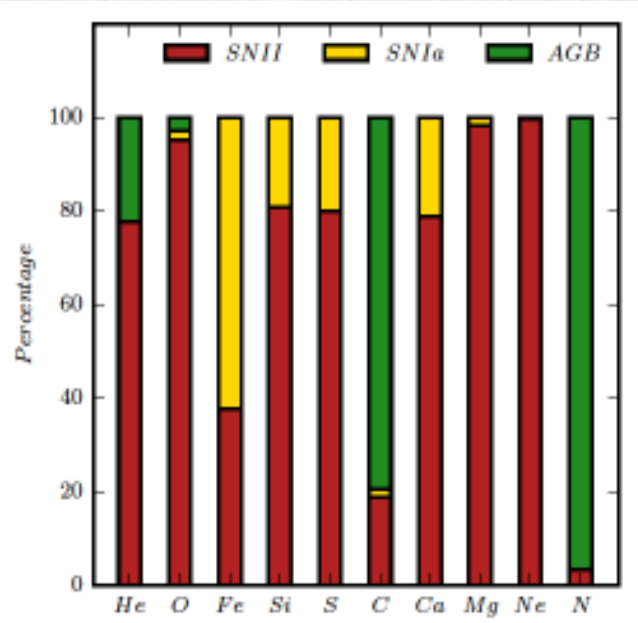
- Initial Mass function: fractional contribution of stars of different mass in a stellar population
- Typical life-times of progenitor stars, which determine the time of chemical/energy release
- Rates of occurrence of SNII, SNIa and AGB stars
    - SNIa rate not well known!



Stellar feedback: three channels

Ingredients of **chemical enrichment** modeling

- Initial Mass function: fractional contribution of stars of different mass in a stellar population
- Typical life-times of progenitor stars, which determine the time of chemical/energy release
- Rates of occurrence of SNII, SNIa and AGB stars
  - SNIa rate not well known!
- Chemical yields: amount of each chemical element ejected into the interstellar medium



Stellar feedback: three channels

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 $N \times 10^{51}$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

Energy feedback

Thermal feedback

Add heat to the gas

Have a cold gas cloud and a star forms

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)

Stellar feedback: three channels

Thermal feedback

Add heat to the gas

Kinetic feedback

Move gas around

A star forms in
a gas cloud

give a velocity kick to
surrounding gas

Stellar feedback: three channels

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"

Stellar feedback: three channels

<u>Thermal feedback</u>

Add heat to the gas

<u>Kinetic feedback</u>

Move gas around

Remember, we are trying to 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

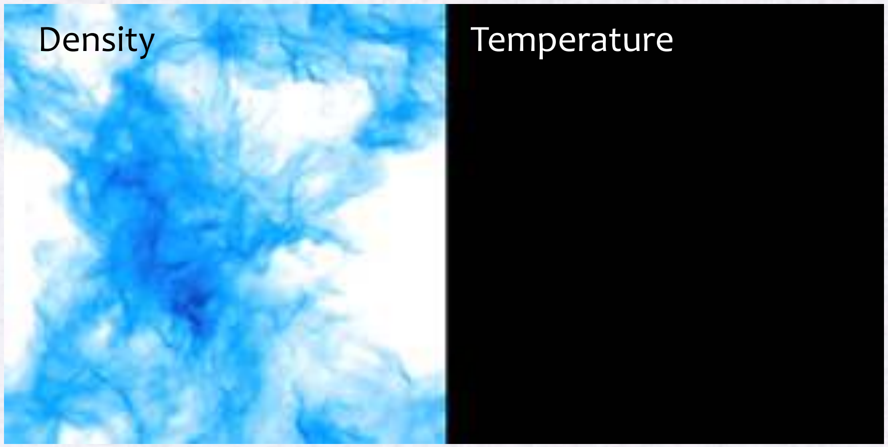
- Radiation-pressure (RP) feedback: massive, short-lived stars provide additional input of momentum and energy in the form of stellar winds and radiation pressure **prior to their explosion as SNII**
  - No yet consensus on the effects of RP feedback in the surrounding ISM, at the scales resolved in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

- Supernova feedback is dominant in Milky Way-mass and smaller galaxies

- Other forms of feedback dominant in more massive galaxies, e.g. black hole feedback

Numerical simulations @ smaller scales

Formation of a massive star cluster (by M. Krumholz)



A Supernova explosion (NASA)

Interstellar medium (by C. Simpson)

Note: much of the baryonic physics involved in galaxy formation is not fully known!

- How stars of different mass form
- How much mass in chemical elements are formed in stars, how much is ejected
- Physics of the interstellar medium?

Simulations: clues to galaxy formation

Results of Simulations

- The formation of Spiral galaxies
- Galaxy evolution & merger history
- Environmental effects

But before, let's "see" how do the dark matter halos look like!

Dark matter halos profiles

The Navarro-Frenk-White (NFW) profile:

A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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Received 1996 November 13; accepted 1997 July 15

ABSTRACT

We use high-resolution *N*-body simulations to study the equilibrium density profiles of dark matter halos in hierarchically clustering universes. We find that all such profiles have the same shape, independent of the halo mass, the initial density fluctuation spectrum, and the values of the cosmological parameters. Spherically averaged equilibrium profiles are well fitted over two decades in radius by a simple formula originally proposed to describe the structure of galaxy clusters in a cold dark matter universe. In any particular cosmology, the two scale parameters of the fit, the halo mass and its characteristic density, are strongly correlated. Low-mass halos are significantly denser than more massive systems, a correlation that reflects the higher collapse redshift of small halos. The characteristic density of an equilibrium halo is proportional to the density of the universe at the time it was assembled. A suitable definition of this assembly time allows the same proportionality constant to be used for all the cosmologies that we have tested. We compare our results with previous work on halo density profiles and show that there is good agreement. We also provide a step-by-step analytic procedure, based on the Press-Schechter formalism, that allows accurate equilibrium profiles to be calculated as a function of mass in any hierarchical model.

Subject headings: cosmology: theory — dark matter — galaxies: halos — methods: numerical

Dark matter halos profiles

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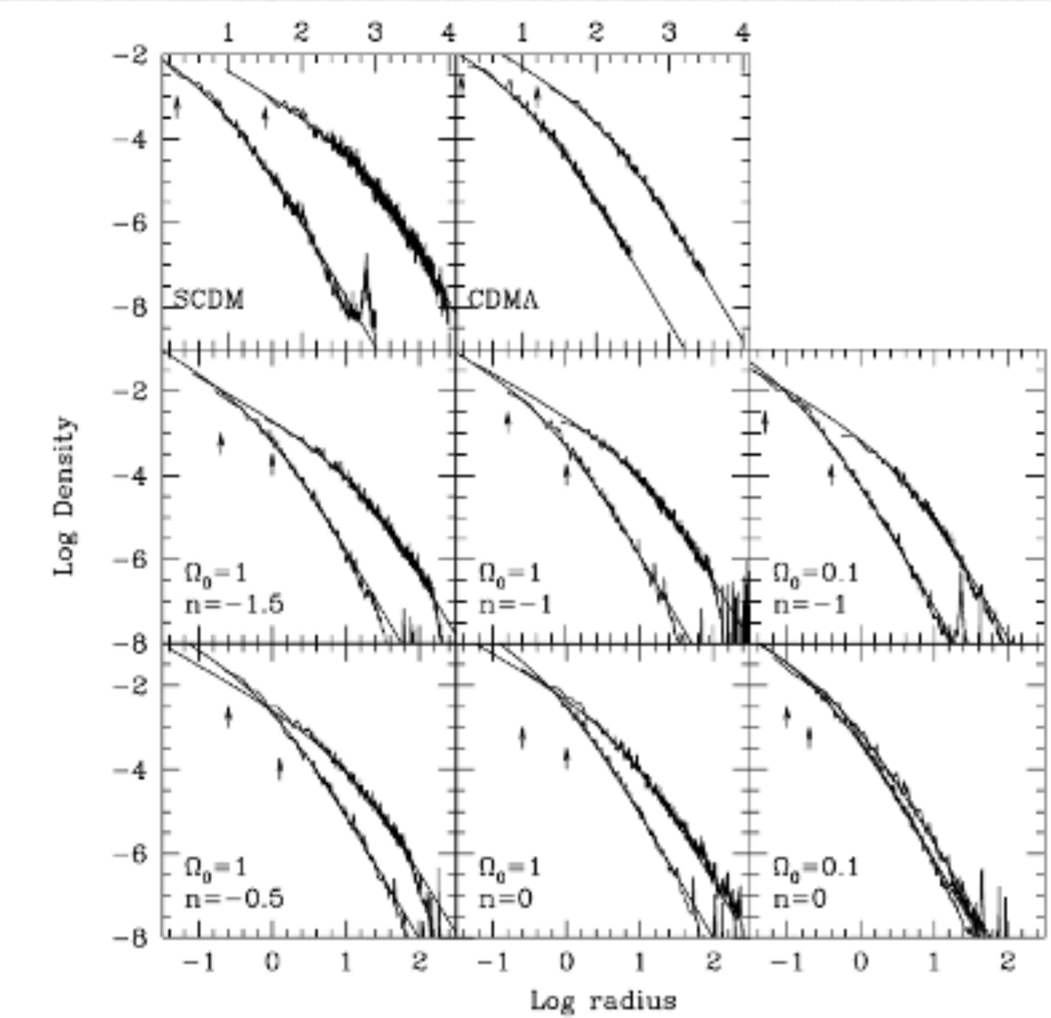
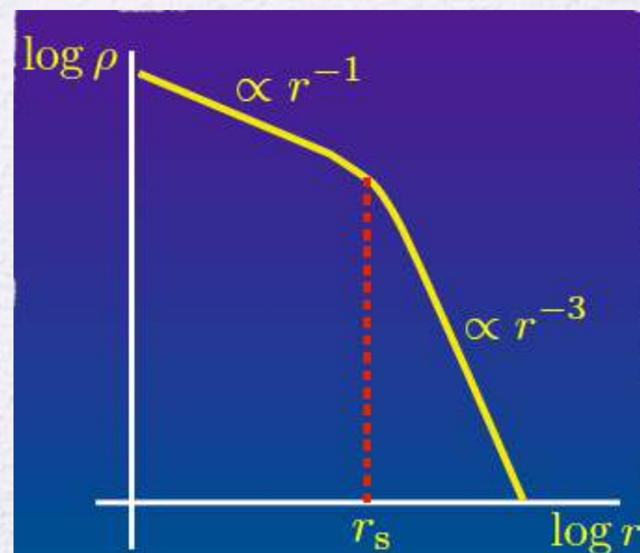


The density profiles of haloes can always be fitted by a universal fitting function:

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



Dark matter halos profiles

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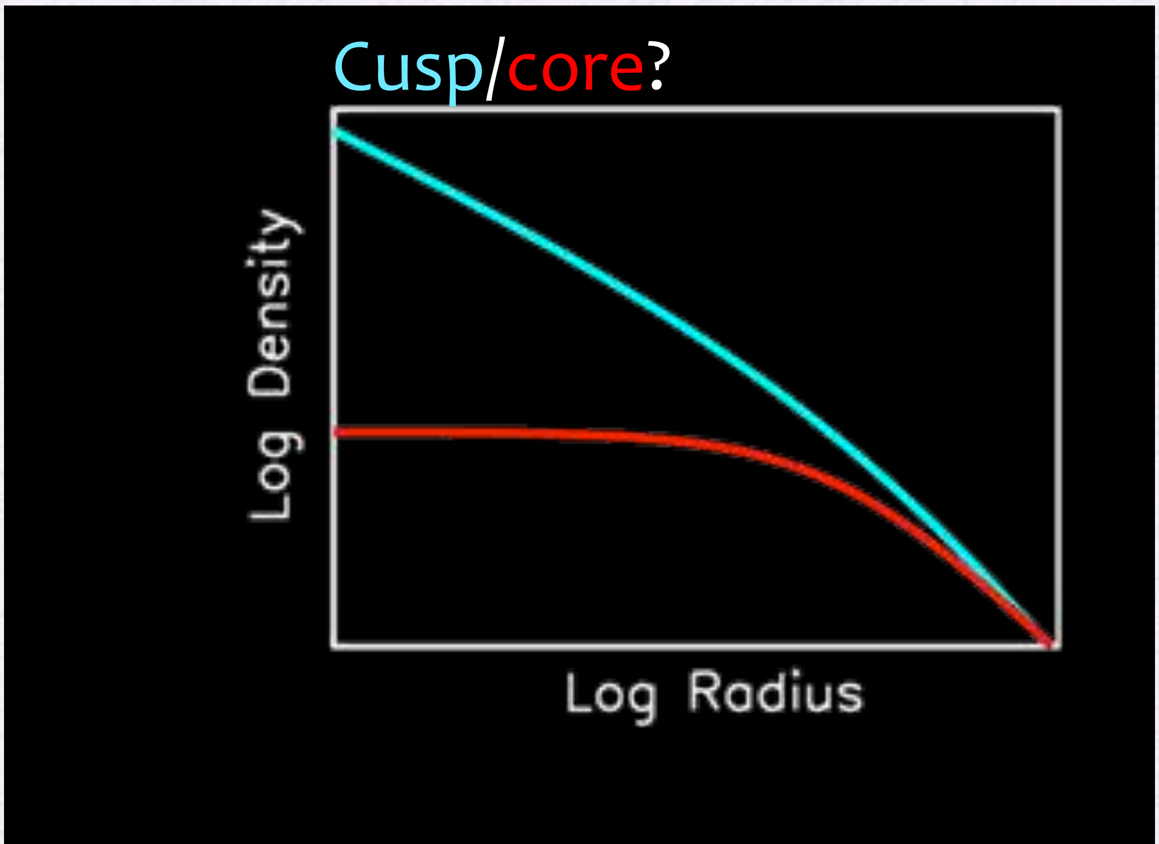
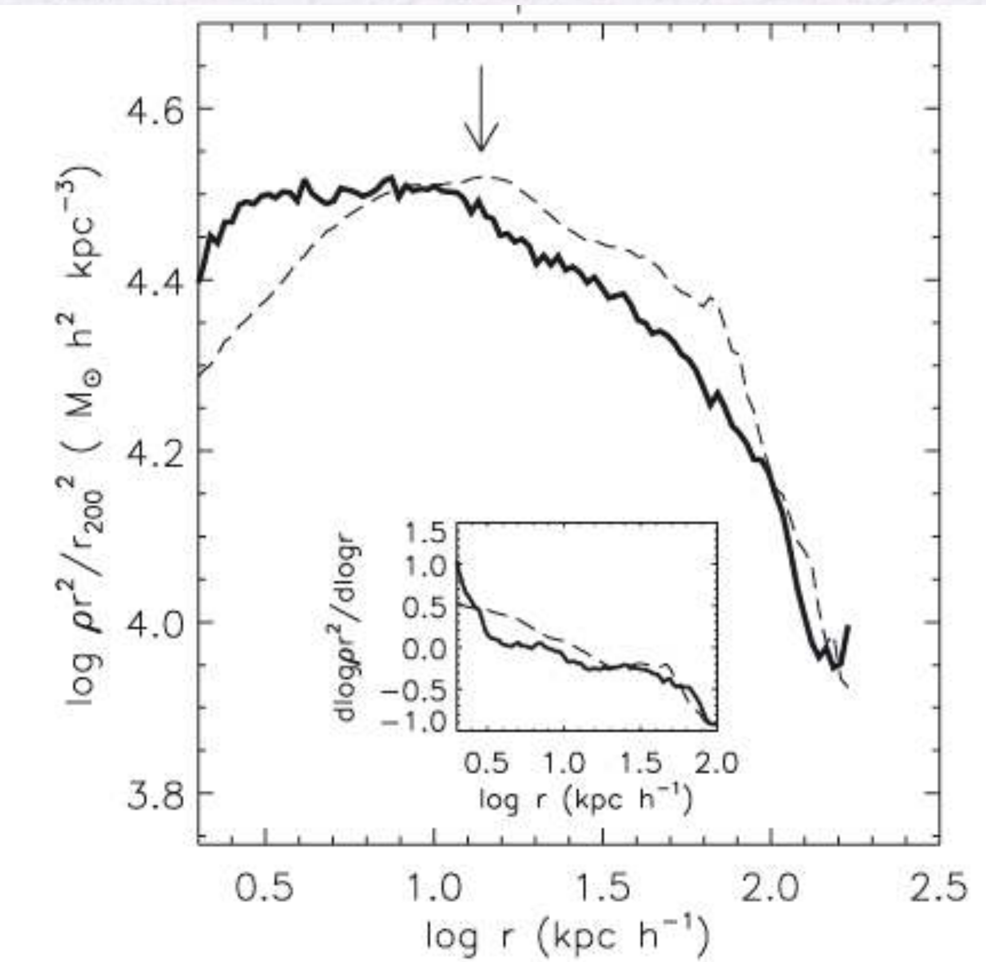


Is this a problem for ΛCDM models?

Dark matter halos profiles

The Navarro-Frenk-White (NFW) profile:



The density profiles of dark matter halos are affected by the presence of baryons!

Tissera+ 2010

The formation of galaxy disks

Standard Model of Disk Formation
Fall & Efstathiou 1980; Mo, Mao & White 1998

Key "assumptions"

- Haloes get initial angular momentum from tidal torques, result of the asymmetries in the mass distribution at early times: cosmological torques
- Gas and dark matter acquire identical specific angular momentum (i.e. angular momentum per mass unit)
- Baryons conserve their angular momentum while cooling

The formation of galaxy disks

Standard Model of Disk Formation

Fall & Efstathiou 1980; Mo, Mao & White 1998

Key “assumptions”

- Ha… the
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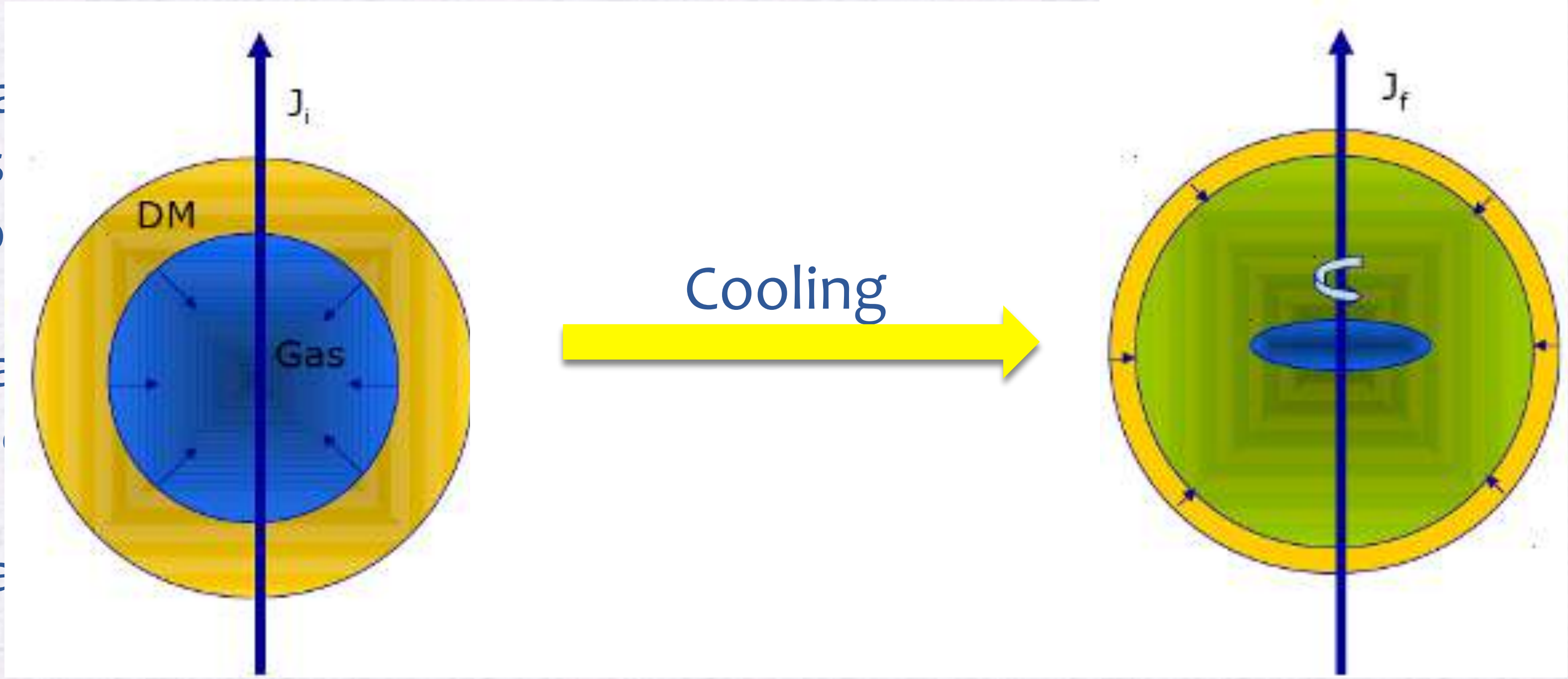
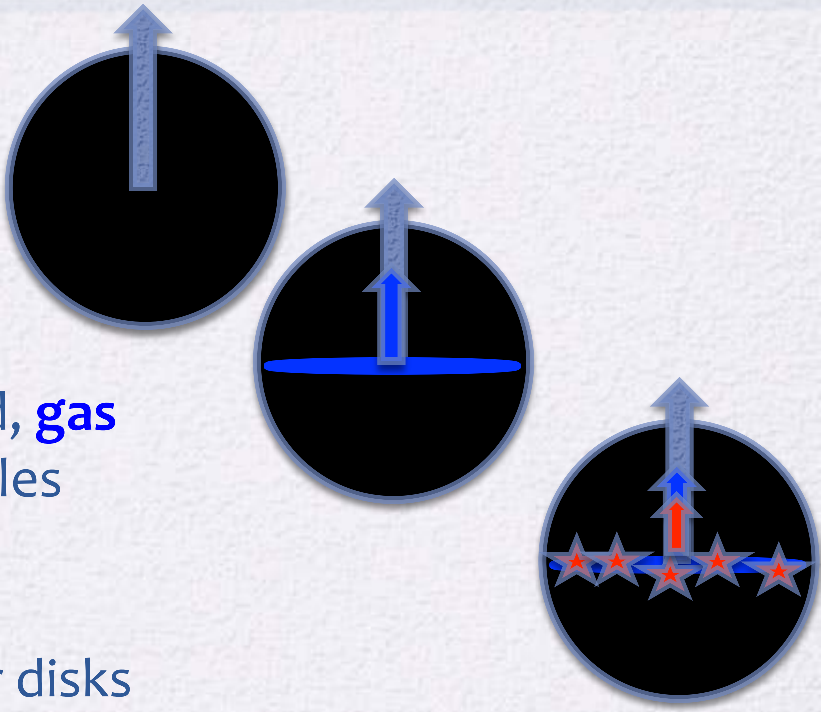
- Ba…



The formation of Spiral galaxies



- **Haloes** obtain angular momentum at early times due to asymmetries in the mass distribution
- Provided angular momentum is conserved, **gas** collapses into dark matter haloes and settles into a disk-like configuration
- **Stars** form in the gas disks, forming stellar disks

The formation of Spiral galaxies

- **Stars** form in the gas disks, forming stellar disks

  - **Disks are unstable against rapid changes in the potential which occur during mergers/interactions/accretion**

The formation of Spiral galaxies

Mergers and interactions significantly affect a galaxy's morphology:

- Turn disks into spheroids
- Induce internal instabilities and the formation of galactic bars

The formation of Spiral galaxies

Mergers and interactions significantly affect a galaxy's morphology:

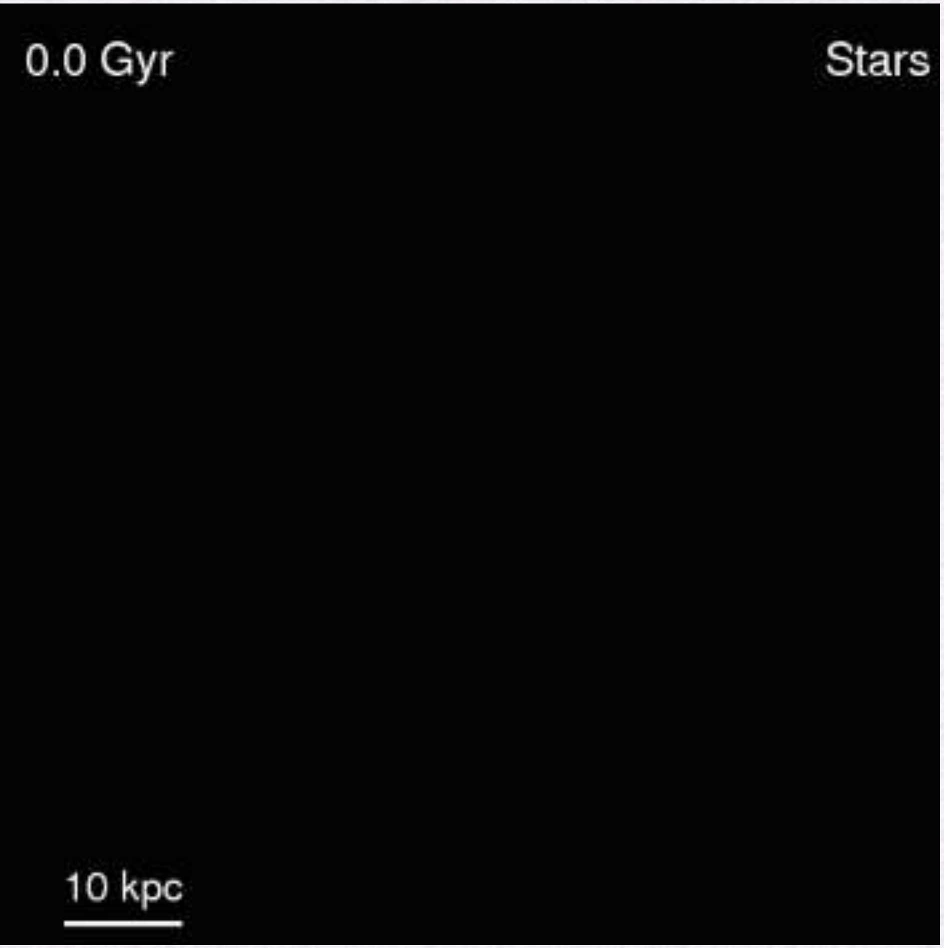
- Turn disks into spheroids
- Induce internal instabilities and the formation of galactic bars

In Λ-CDM models, the merger rates decreases with decreasing redshift

→ The stellar disks we see today were formed late, so they could survive until the present time

The formation of Spiral galaxies

The merger of two galaxies (no cosmology)



Phil Hopkins

The formation of Spiral galaxies

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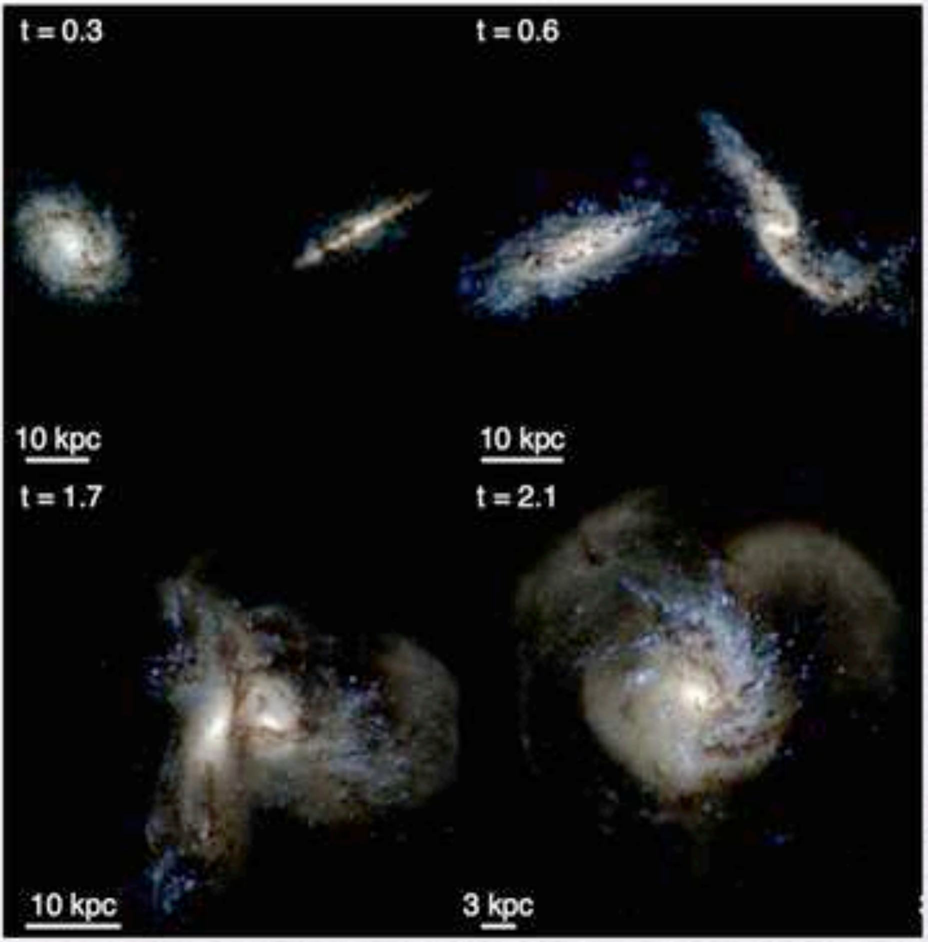

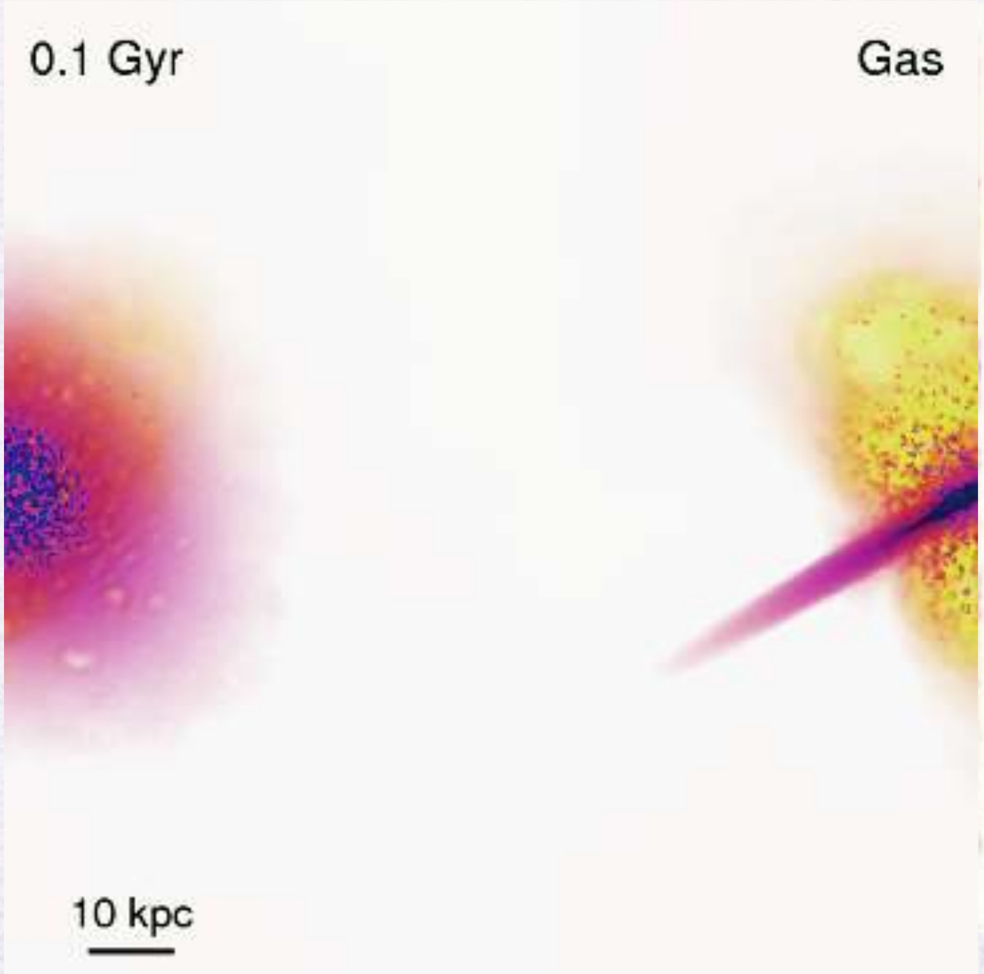

Phil Hopkins

The formation of Spiral galaxies

→ The stellar disks we see today were formed late, so they could survive until the present time

→ Galaxies with massive disks do not experience major mergers during most of their lives

The formation of Spiral galaxies

- → Select a galaxy with quiet merger history
- → Run a simulation including relevant physics
  - → Cosmological
  - → Include hydrodynamics, cooling and star formation

1990s/2000s

The formation of Spiral galaxies

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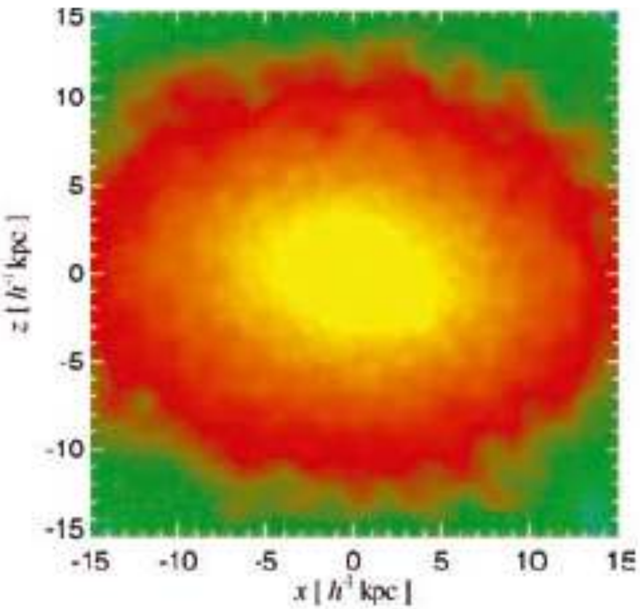
1990s/2000s

Face-on view!



Distribution of stars

At z=0, the galaxy does not look like a disk galaxy!

The formation of Spiral galaxies

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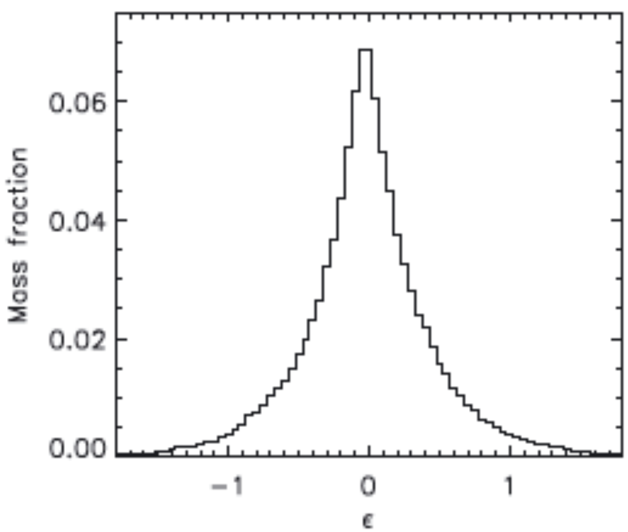
1990s/2000s

Spheroidal distribution
No evidence of rotation



Circularity distribution of stars

At z=0, the galaxy does not look like a disk galaxy!

Dynamical decomposition helps us quantify disk/bulge contributions

$$\varepsilon = j_z \,/\, j_{circ}$$

j_z = angular momentum of a star

J_{circ} = angular momentum expected for a circular orbit (i.e. disk-like)

The formation of Spiral galaxies

2005/2010

- → Select a galaxy with quiet merger history
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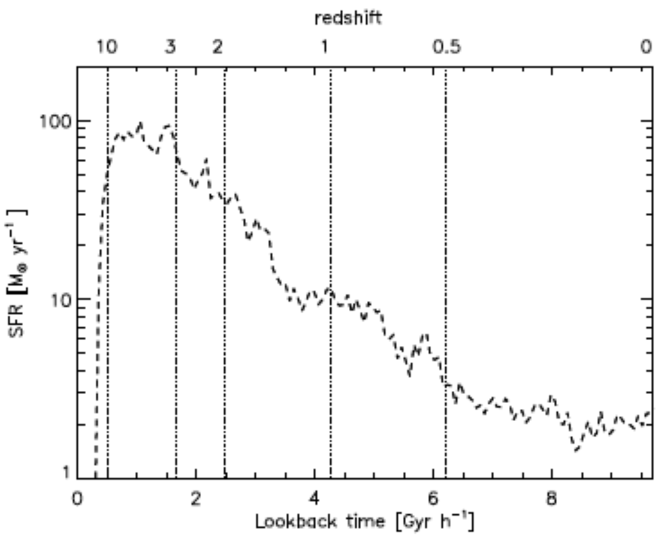
  - → Include more physics… but which?

Star formation rate



Look at the star formation rate of the galaxy with cooling and star formation

SFR peaks at very early times – very little star formation during the last ~6 Gyr

If disks form late, we need high SFRs at late times → need a physical process which regulates SFR early and shifts it to later times

The formation of Spiral galaxies

2005/2010

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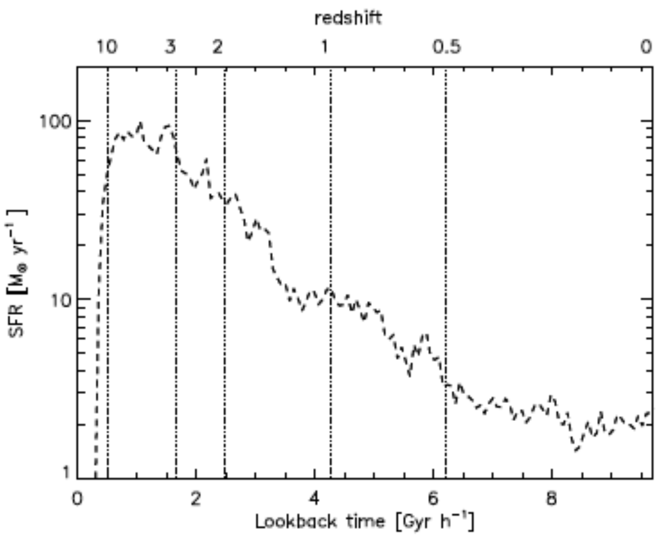

How do we shift the SFR to later times?

Star formation (SF) fuel is cold, dense gas

→ SF regulation if the cold, dense gas mass decreases

- → Heat up the gas
- → Move it from the disks (densest regions)

The formation of Spiral galaxies

2005/2010

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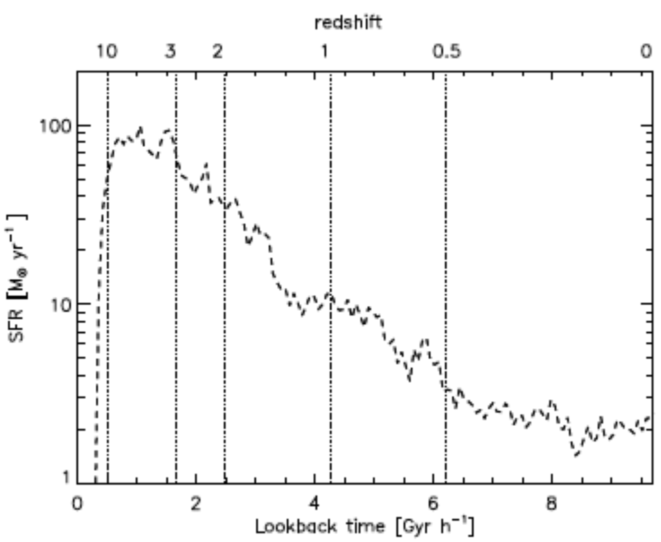

Feedback

A chain of cause-and-effect that forms a closed loop

Stellar feedback, in particular from SNII:

- originated in massive, short-lived stars
  - → Prompt response after SF
  - → Eject large amounts of energy, and provide heat and pressure → winds

The formation of Spiral galaxies

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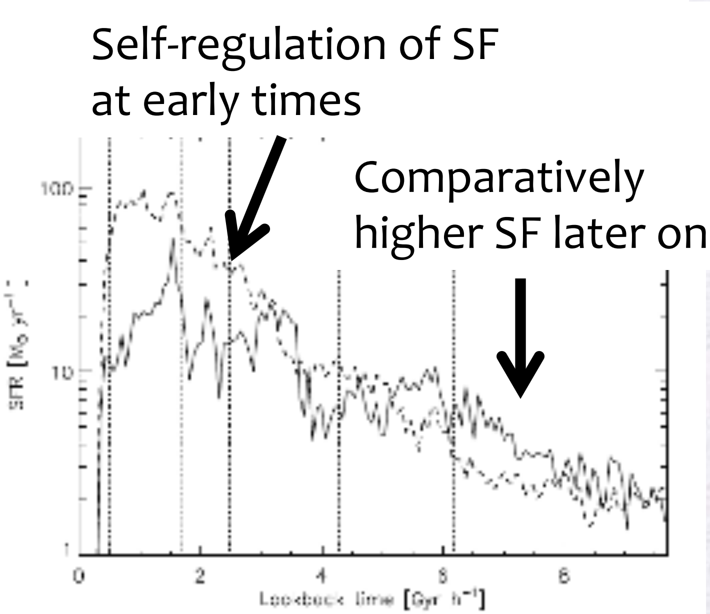

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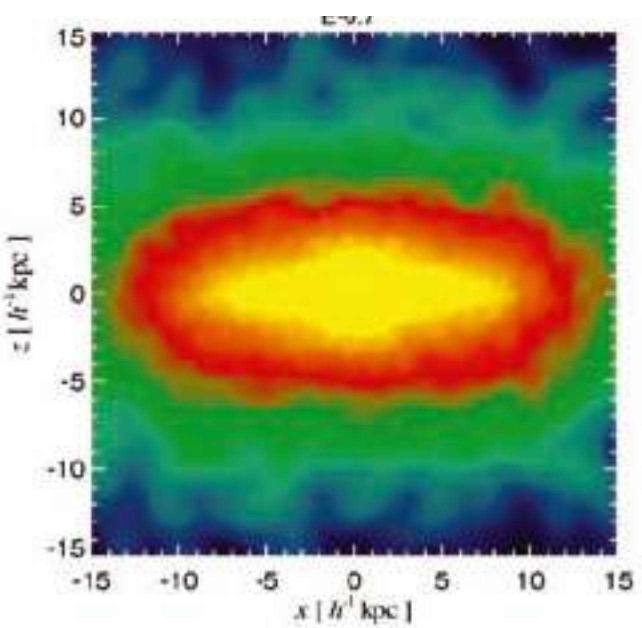
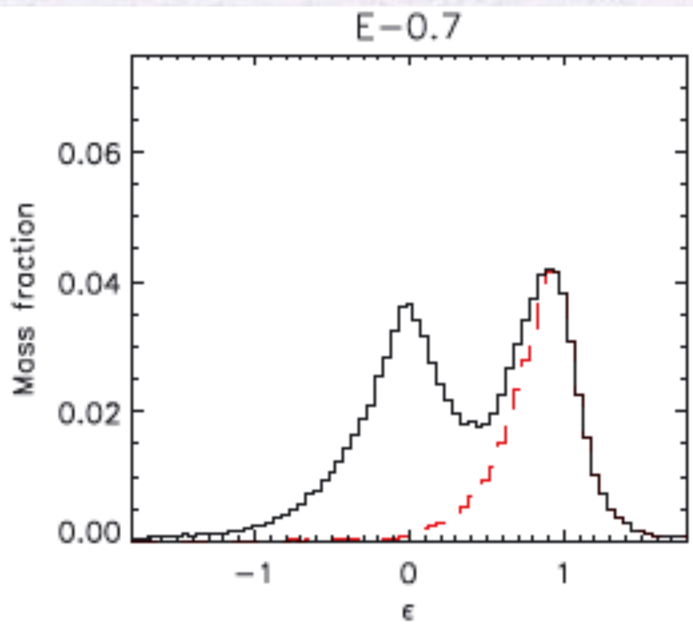
The formation of Spiral galaxies

- If Supernova Feedback is included in simulations, stellar disks can form and survive in cosmological simulations.
- The circularity distribution reveals that the galaxy has a disk-like component, also a spheroid or bulge.

Face-on view



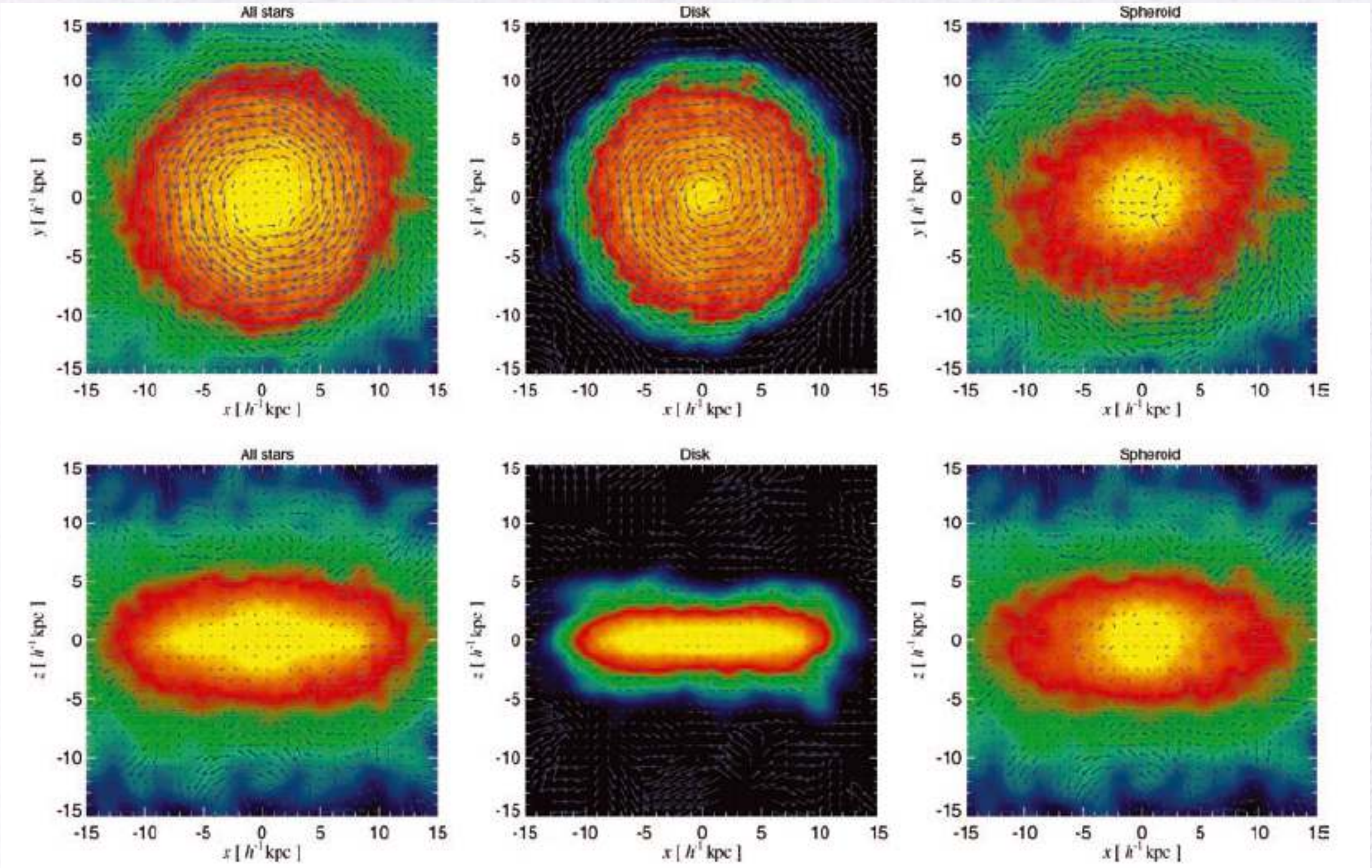
Distribution of stars



Distribution of stellar circularities

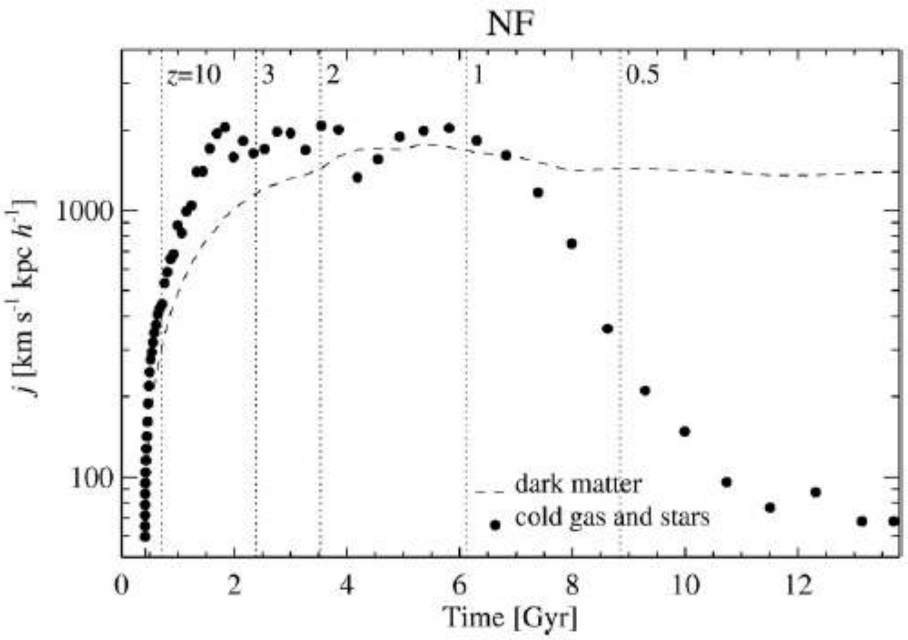
The formation of Spiral galaxies

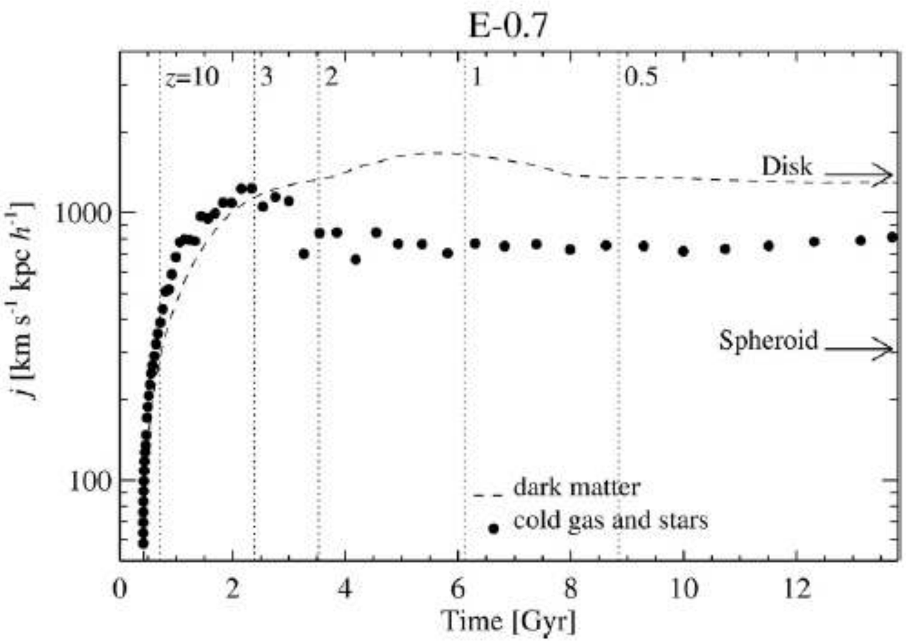
- We can use kinematic decompositions and divide the stellar mass into bulge and disk components, to study their properties



The formation of Spiral galaxies

- Feedback helps regulate star formation, disks form late and can conserve a high fraction of their angular momentum

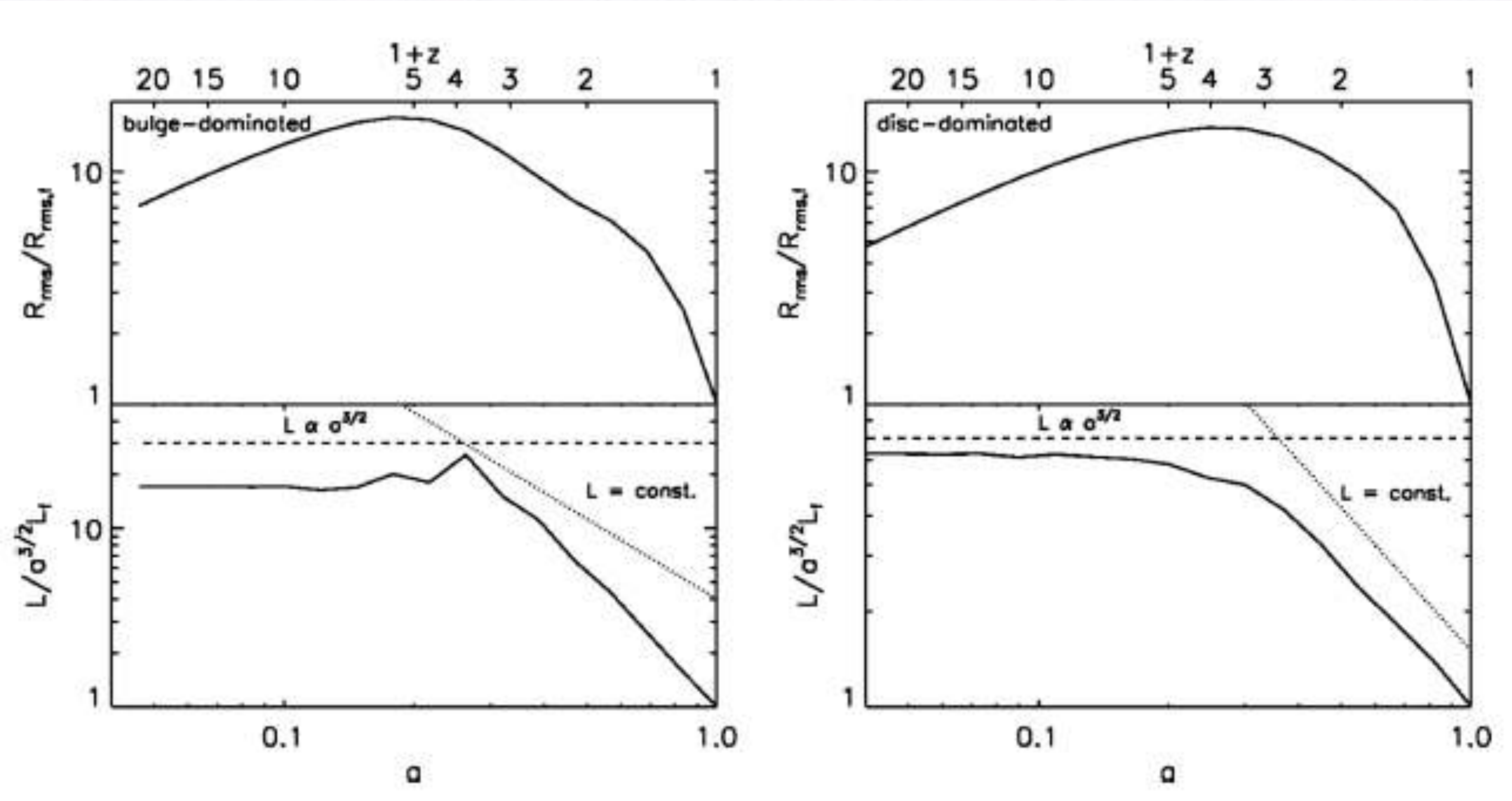




Scannapieco+ 2008

The formation of Spiral galaxies

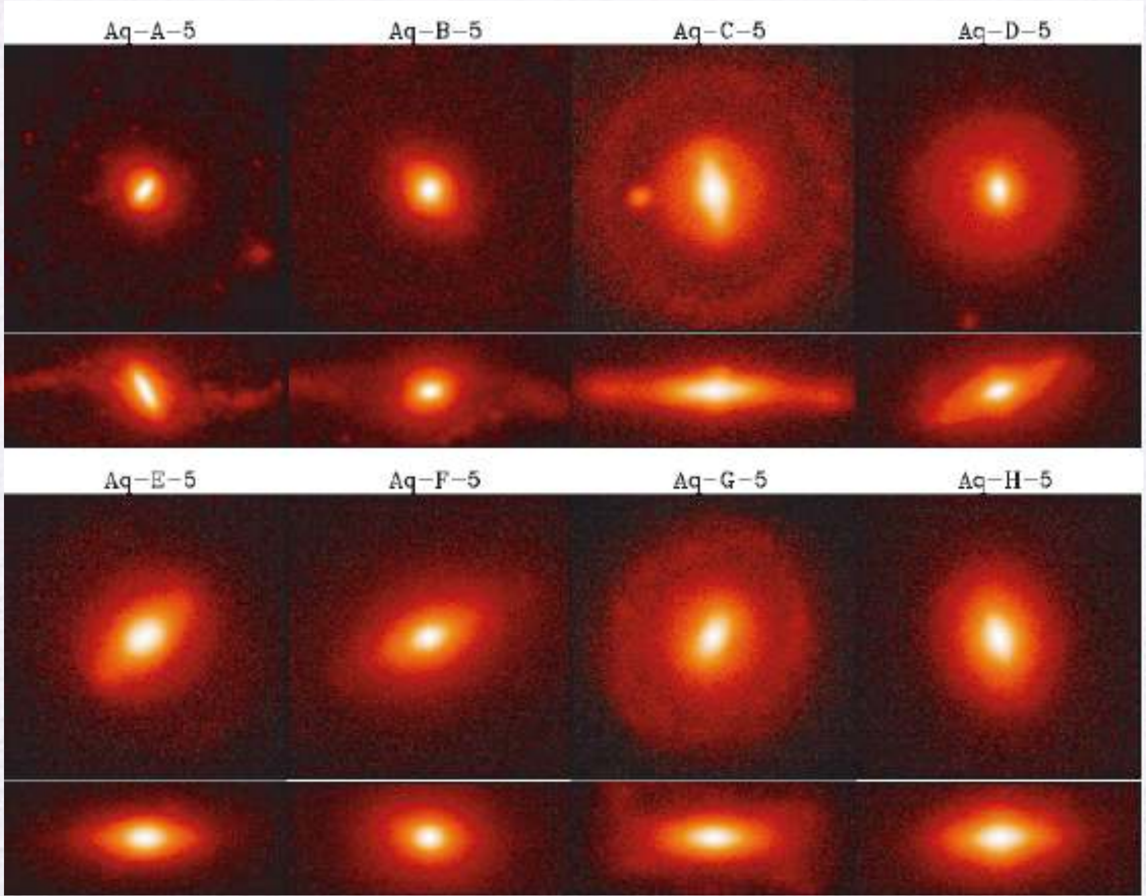
- Evolution of radius and angular momentum in a bulge-dominated and a disk-dominated galaxy
  After the time of maximum expansion, the bulge-dominated galaxy loses a significant fraction of its initial angular momentum



Zavala+ 2007

Morphologies and formation histories

- What about galaxy diversity?
  - We take a "large" number of galaxies, of similar mass
  - A variety of merger histories



Simulations predict morphology diversity

Morphologies and formation histories

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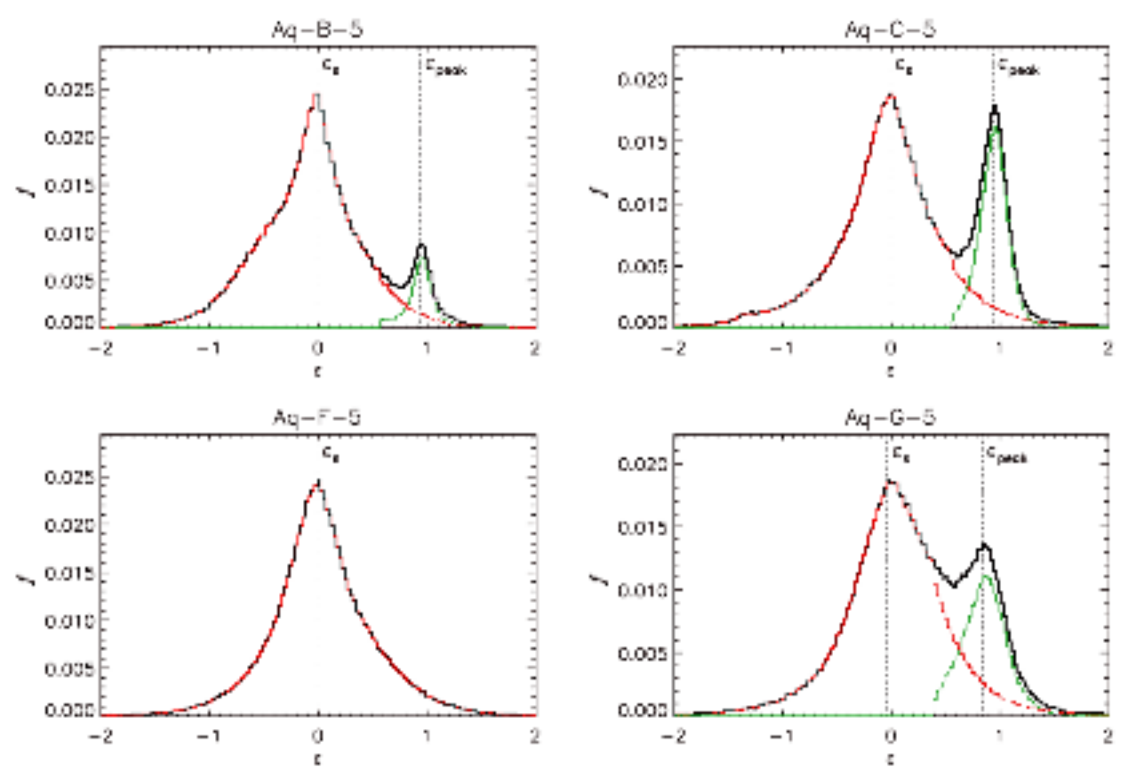

Even if all galaxies have a similar mass, they have different relative contributions of bulge and disk

Morphologies and formation histories

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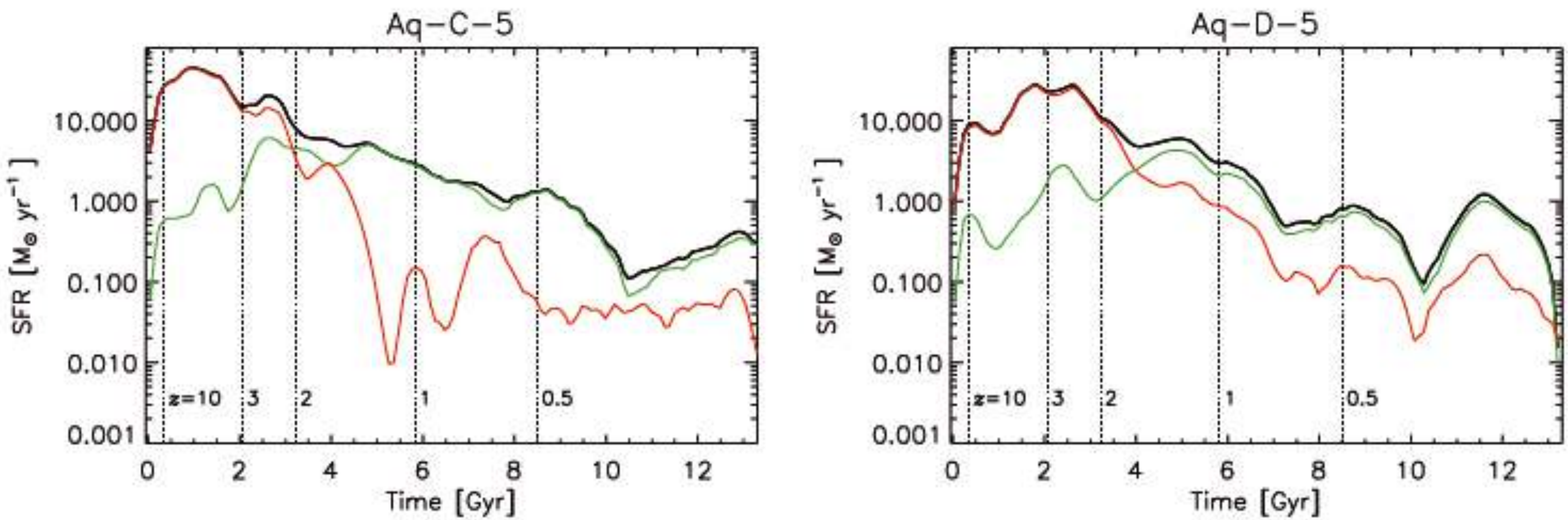
All disks form late!

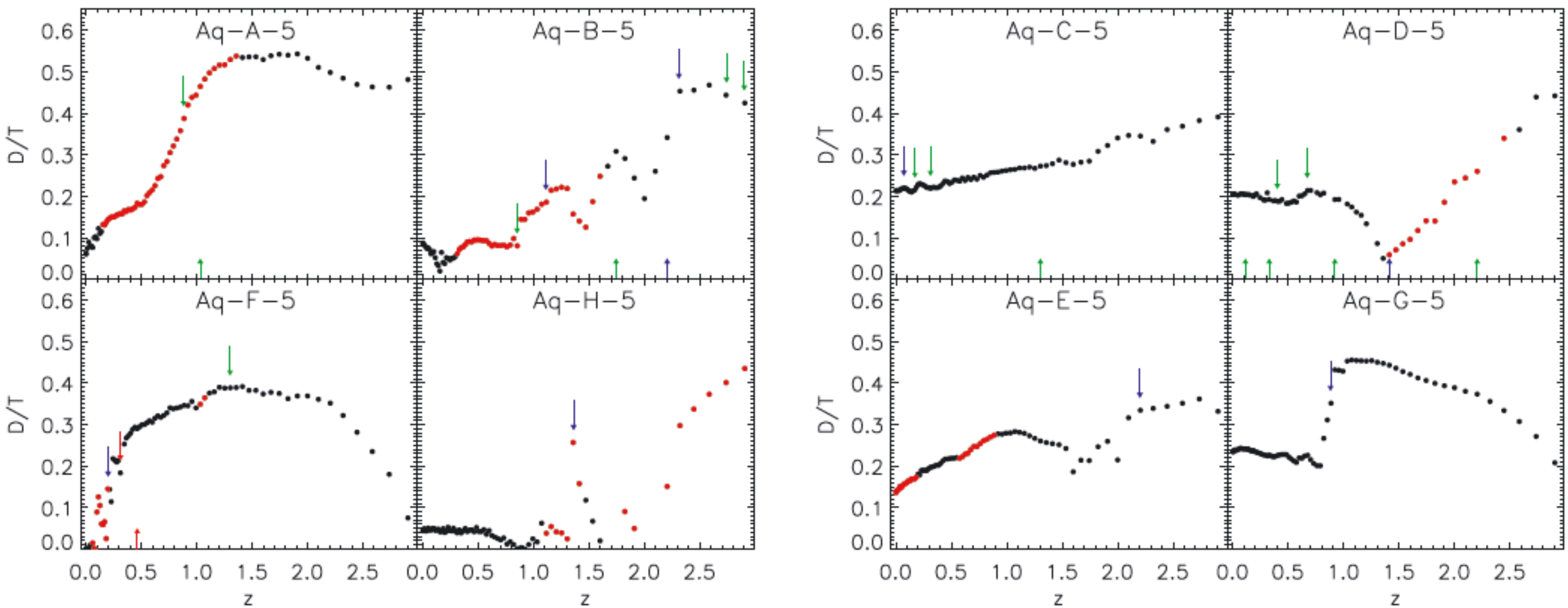


Mergers: effects on morphologies

Mergers significantly affect galaxies, particularly their morphologies

Mergers can not explain the evolution of morphology!

Galaxies with little/no disks at z=0 Galaxies with significant disks at z=0



Scannapieco+ 2009

Gas accretion: effects on morphology

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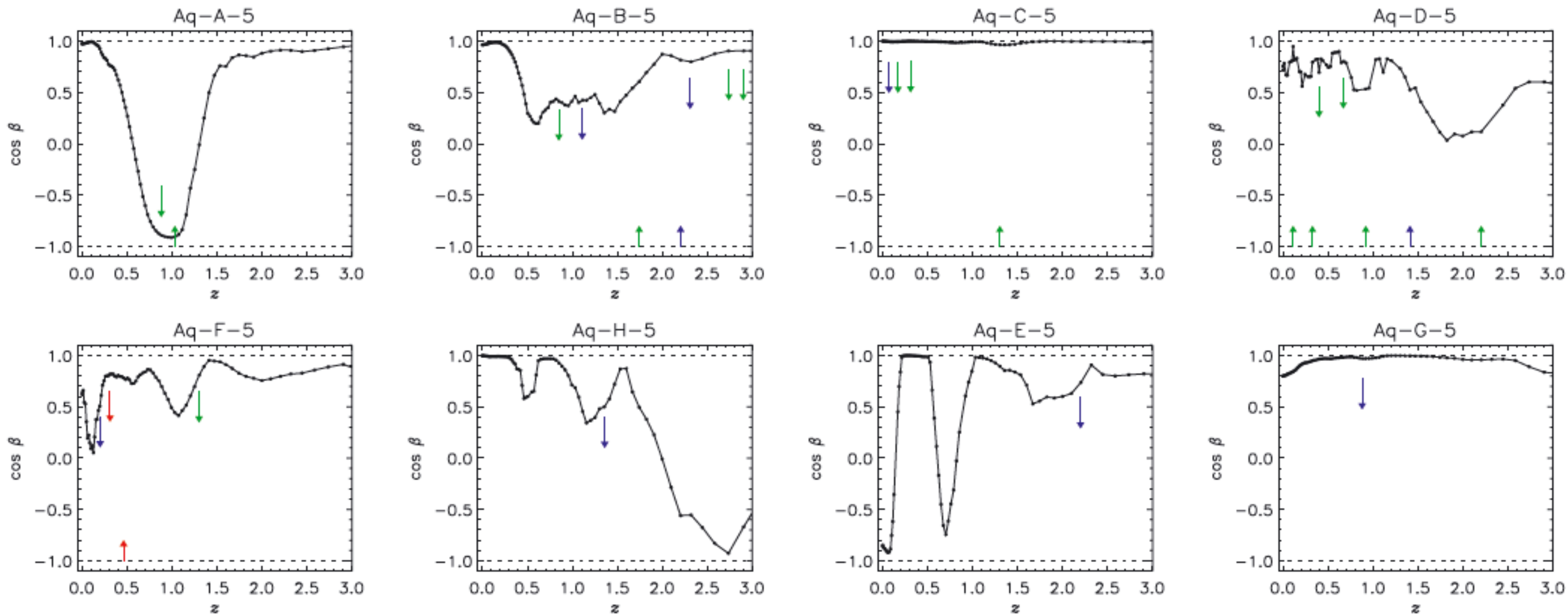
Galaxies with little/no disks at *z*=0 Galaxies with significant disks at *z*=0



Scannapieco+ 2009

Gas accretion & morphologies

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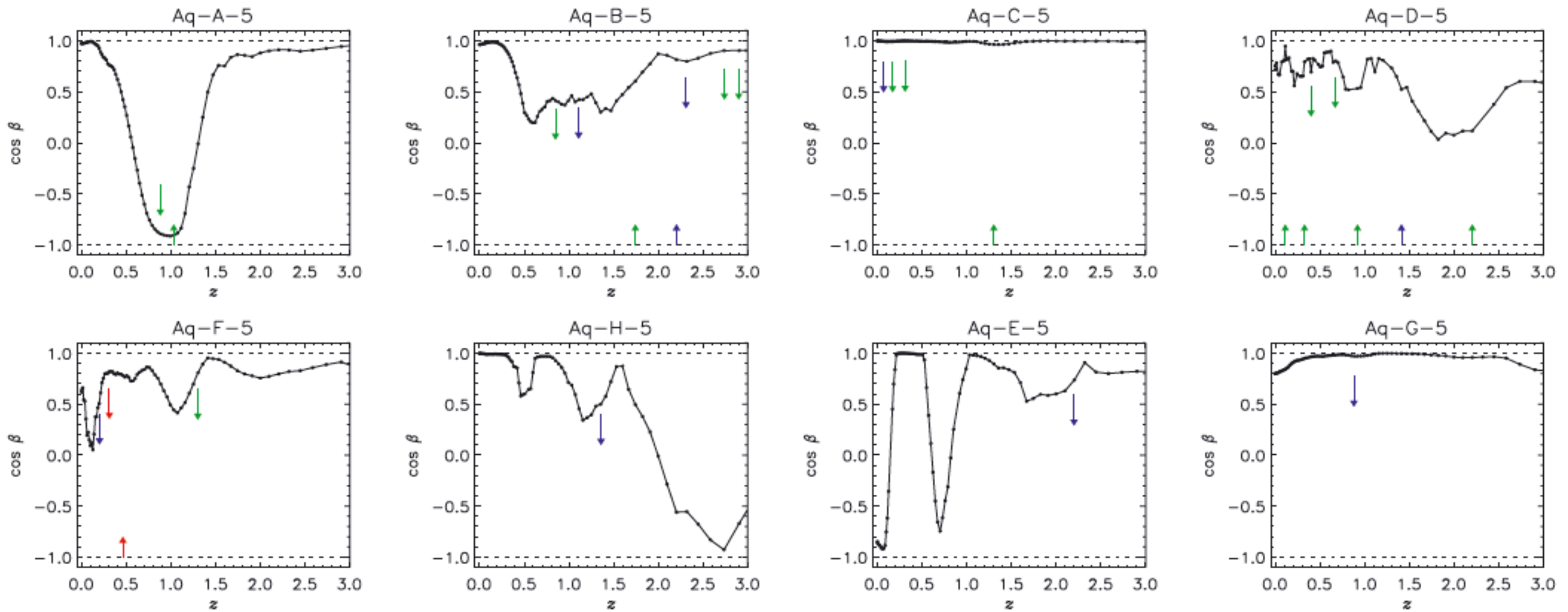
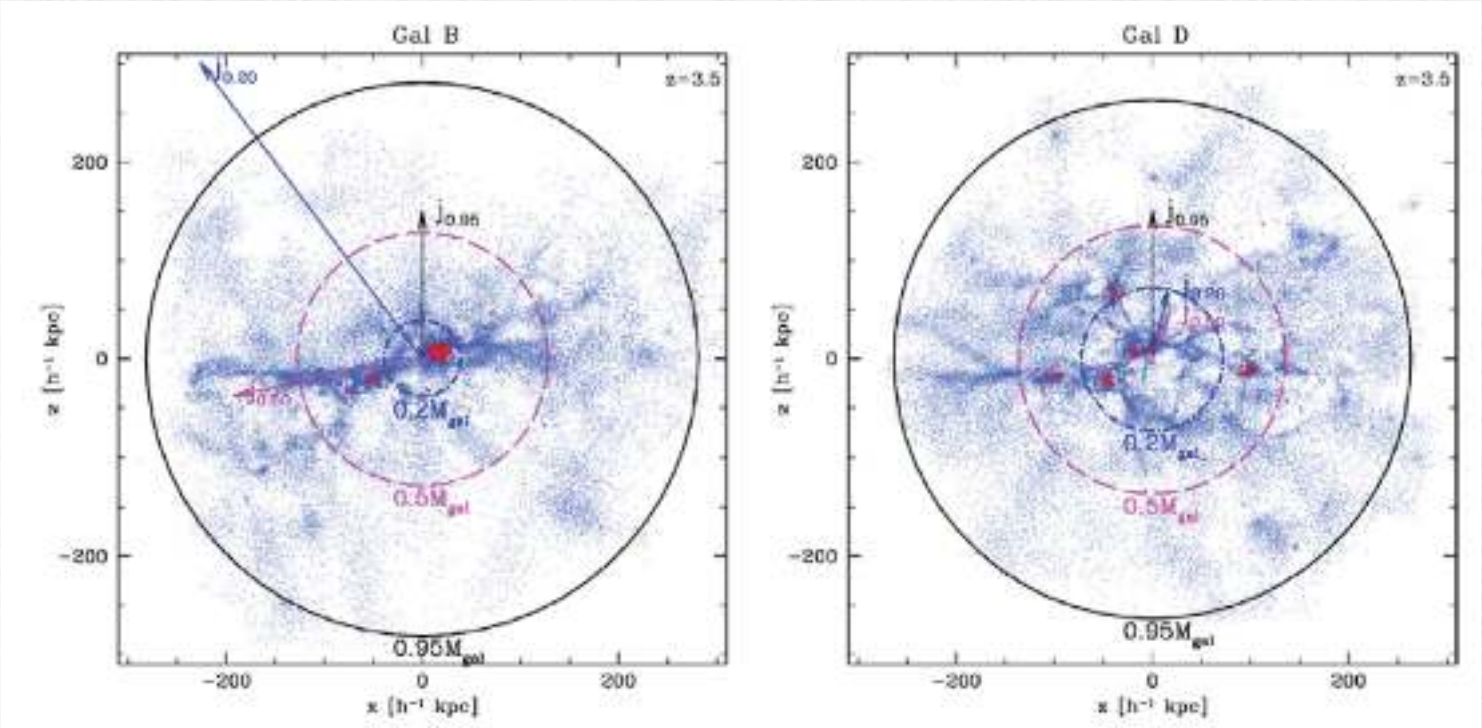


Scannapieco+ 2009

Gas accretion & morphologies

Trace back all gas particles that ended up in a galaxy at z=0.
Take circles enclosing 20, 50 and 95% of total mass.
Calculate angular momentum enclosed in such regions.

Bulge-dominated galaxy @z=0 Disk-dominated galaxy @z=0

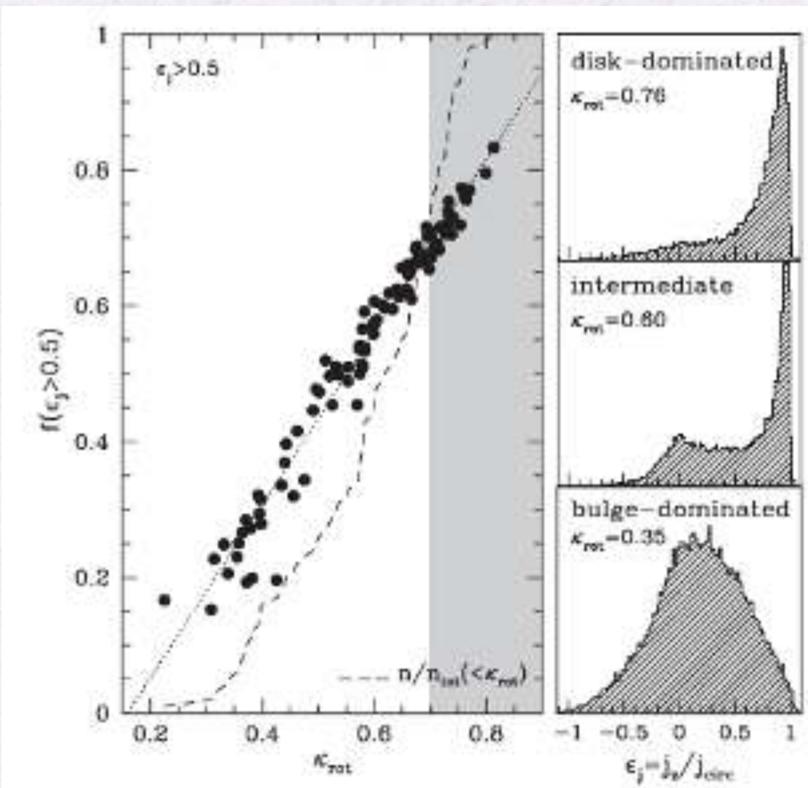


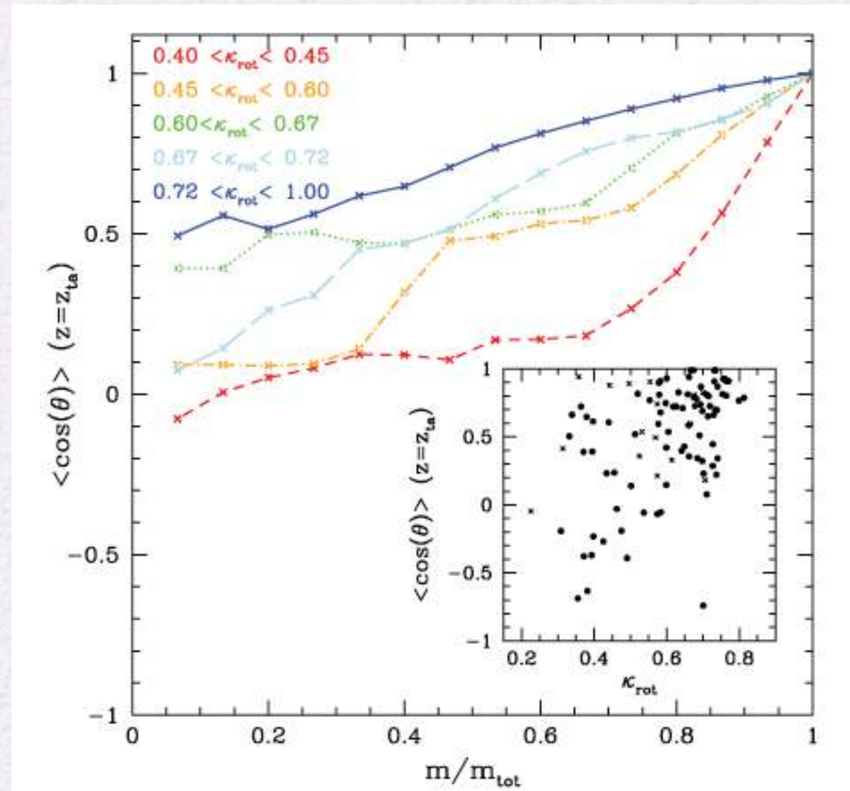
Large sample of simulated galaxies (N=100)

Sales+2012

Gas accretion & morphologies

κ_{rot}: fraction of kinetic energy invested in ordered motion





On average, the accretion of gas in galaxies that are disk-dominated at the present time was much more coherent than in *z*=0 bulge-dominated galaxies

Sales+2012

Summary of disk formation

Conditions for disk formation

- Conservation of angular momentum
- Quiet merger histories, at least in the last ~8Gyr
- Coherent accretion, so that gas and stellar disks are aligned at all times

The formation of Spiral galaxies

2005/2010

- → Select a galaxy with quiet merger history
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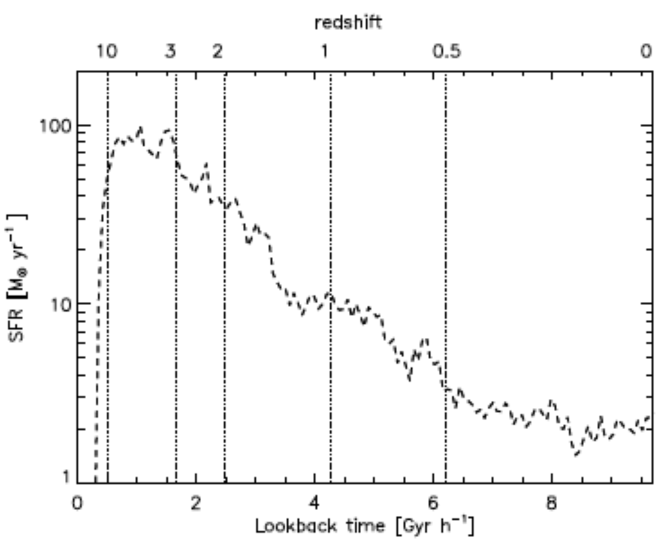
Star formation rate



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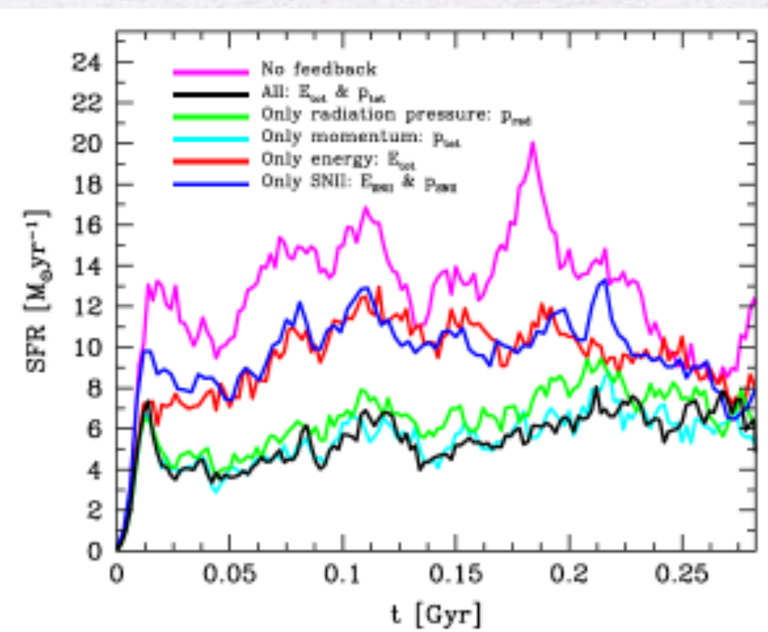
  - → SN feedback

> 2010



Agertz+2013

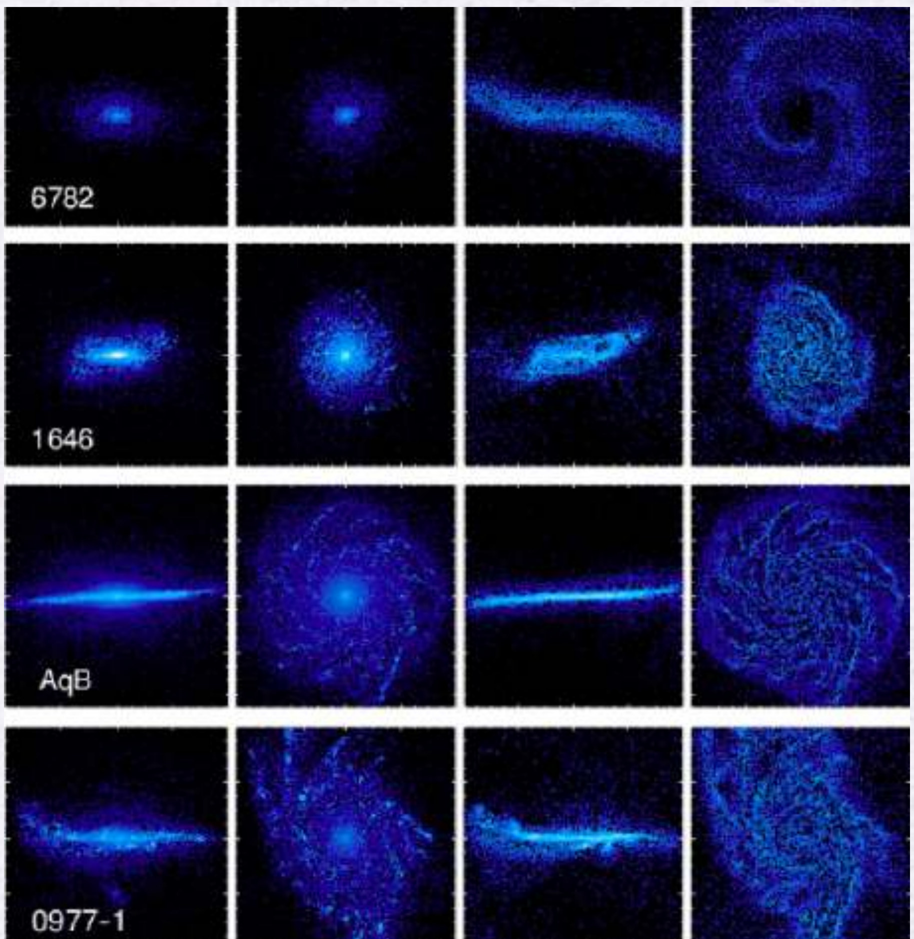
+ Radiative feedback

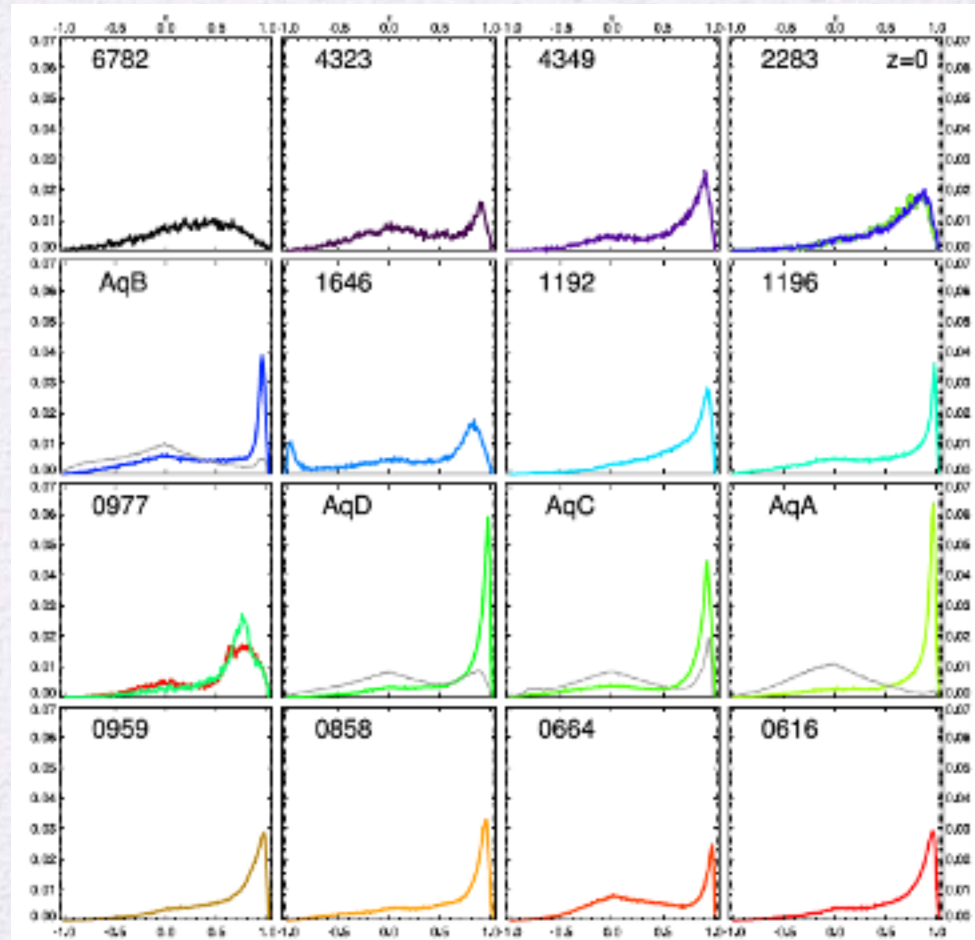
"Radiation-pressure feedback"

Originated in 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**

Radiation-pressure feedback

Simulations including radiation-pressure feedback seem to have significant effect, but large code-to-code variations

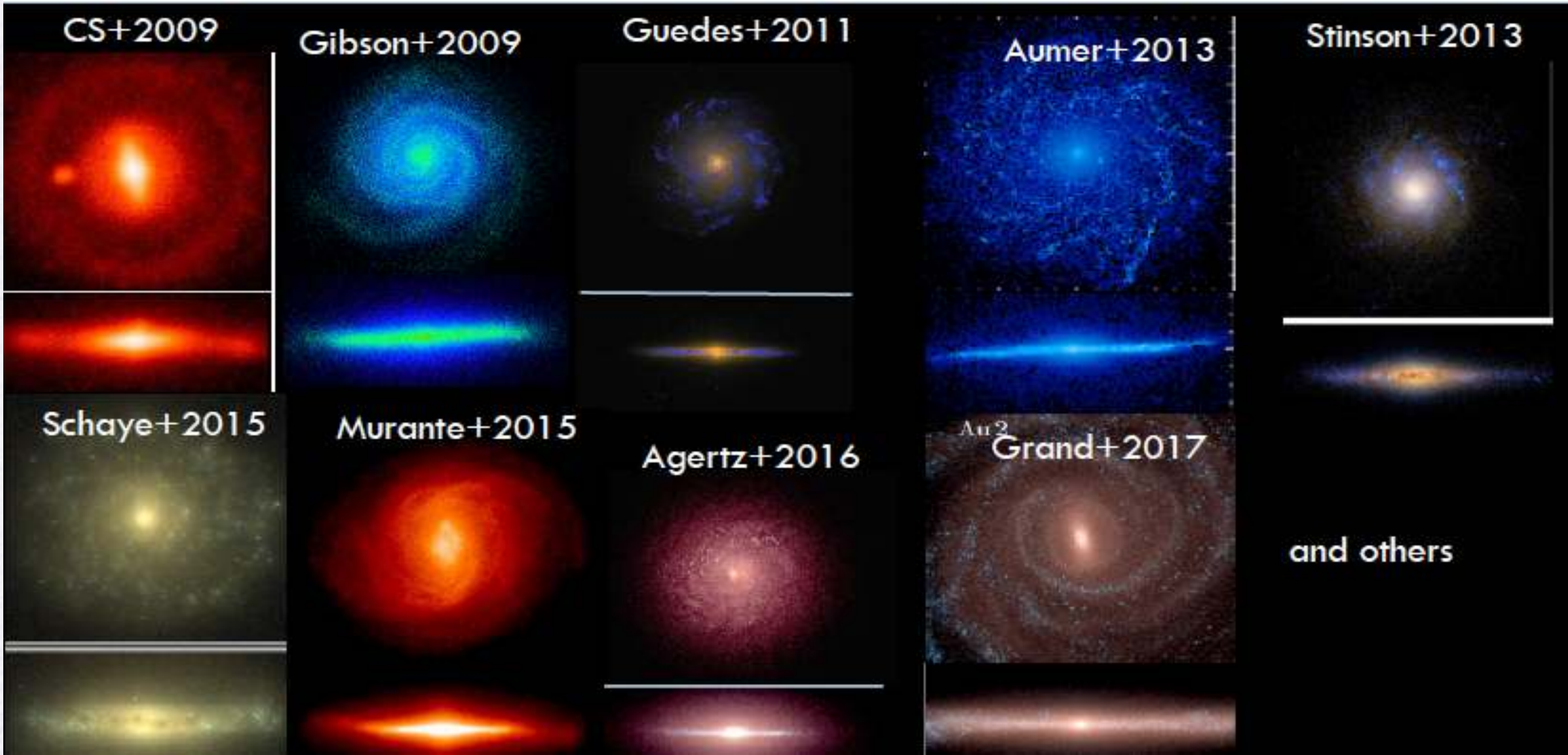




Aumer=2013

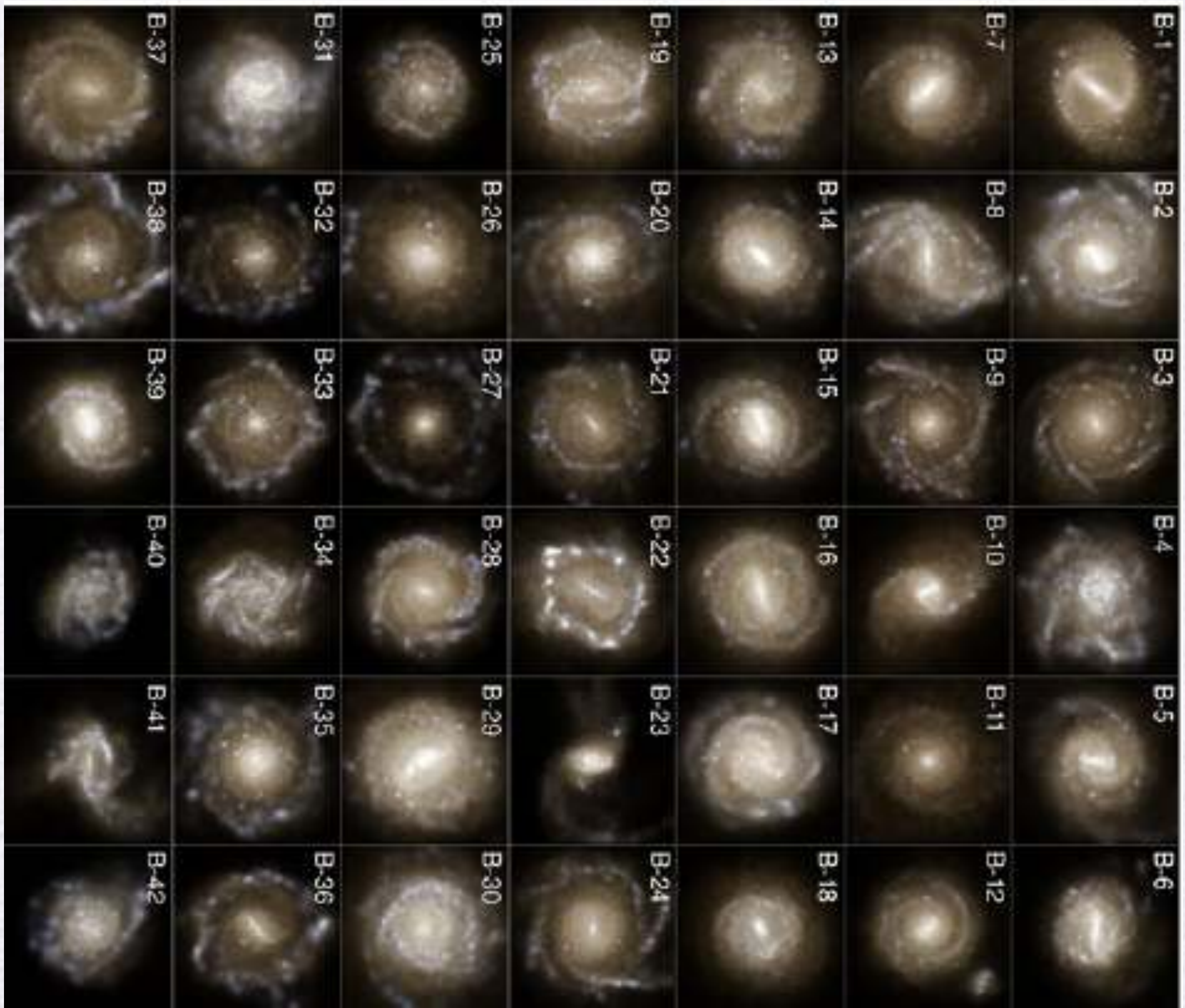
Disk formation simulations

Current state-of-the-art simulations including supernova feedback reproduce the formation of stellar disks in cosmological simulations (only some of them include radiation-pressure feedback as well!)



Disk formation simulations

It is now possible to run very large hydrodynamical simulations, allowing statistical studies of simulated galaxies

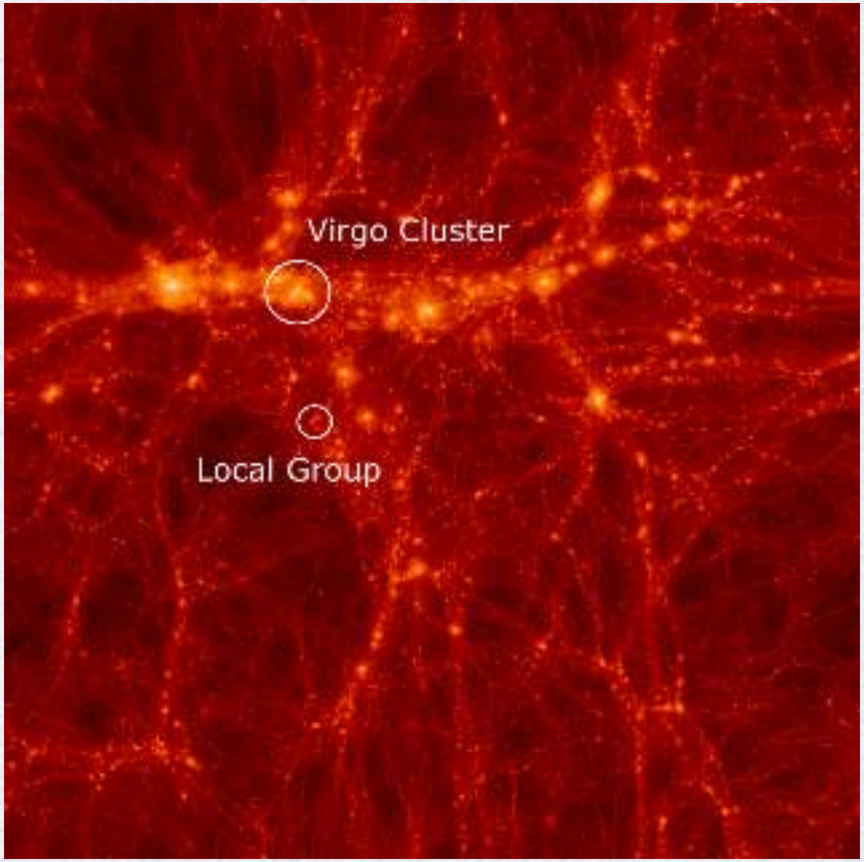


The Illustris Simulation (also EAGLE, Horizon, Auriga, …)

Environment and morphology

- Constrained Local UniversE simulations: CLUES

https://www.clues-project.org/cms/

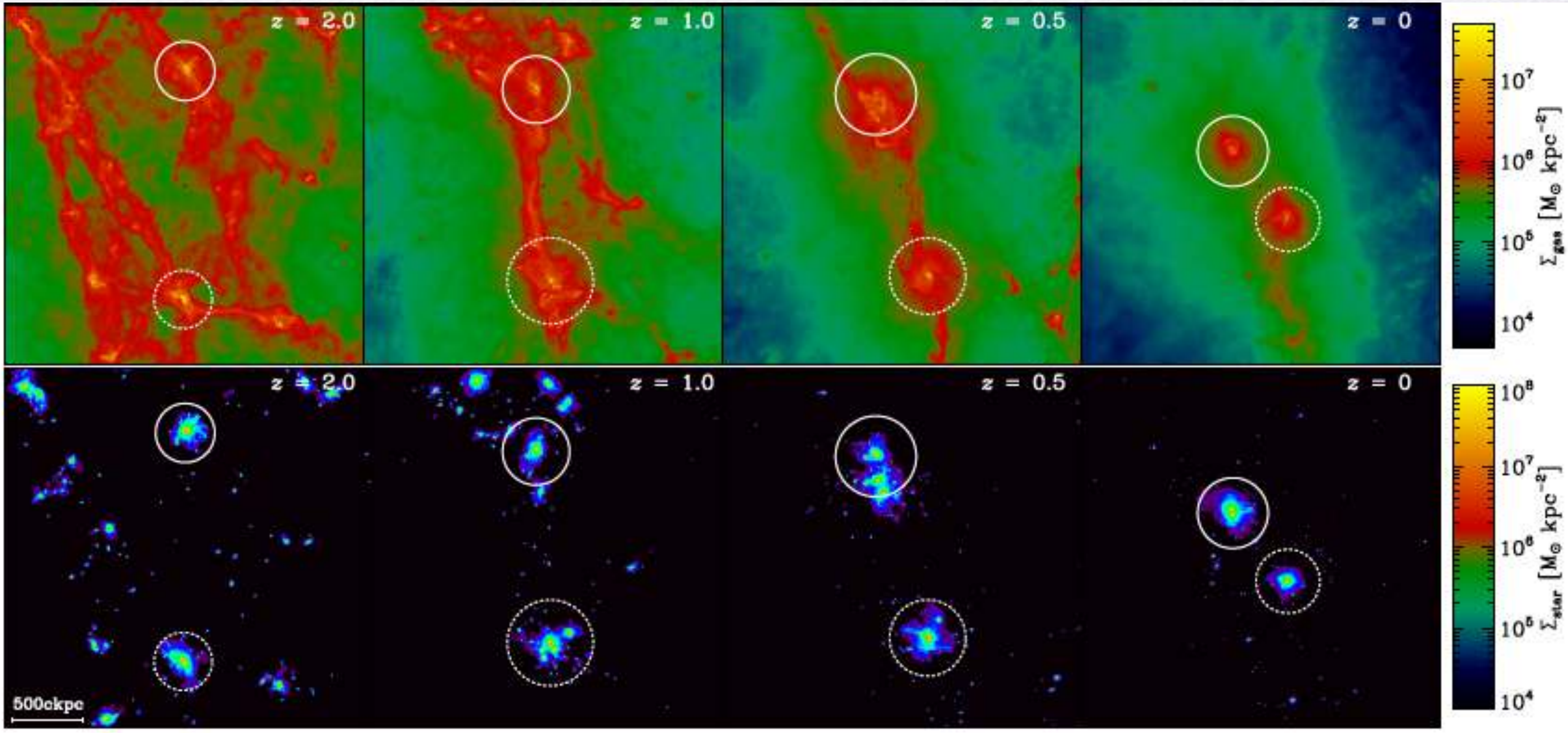


- The Milky Way lives in the "Local Group"
- Massive companion: the Andromeda spiral galaxy
- Local Group is in an overdense region of the Universe, close to a large galaxy cluster

CS+2015

Environment and morphology

- Constrained Local UniversE simulations: CLUES
- Identify MW & M31 candidates

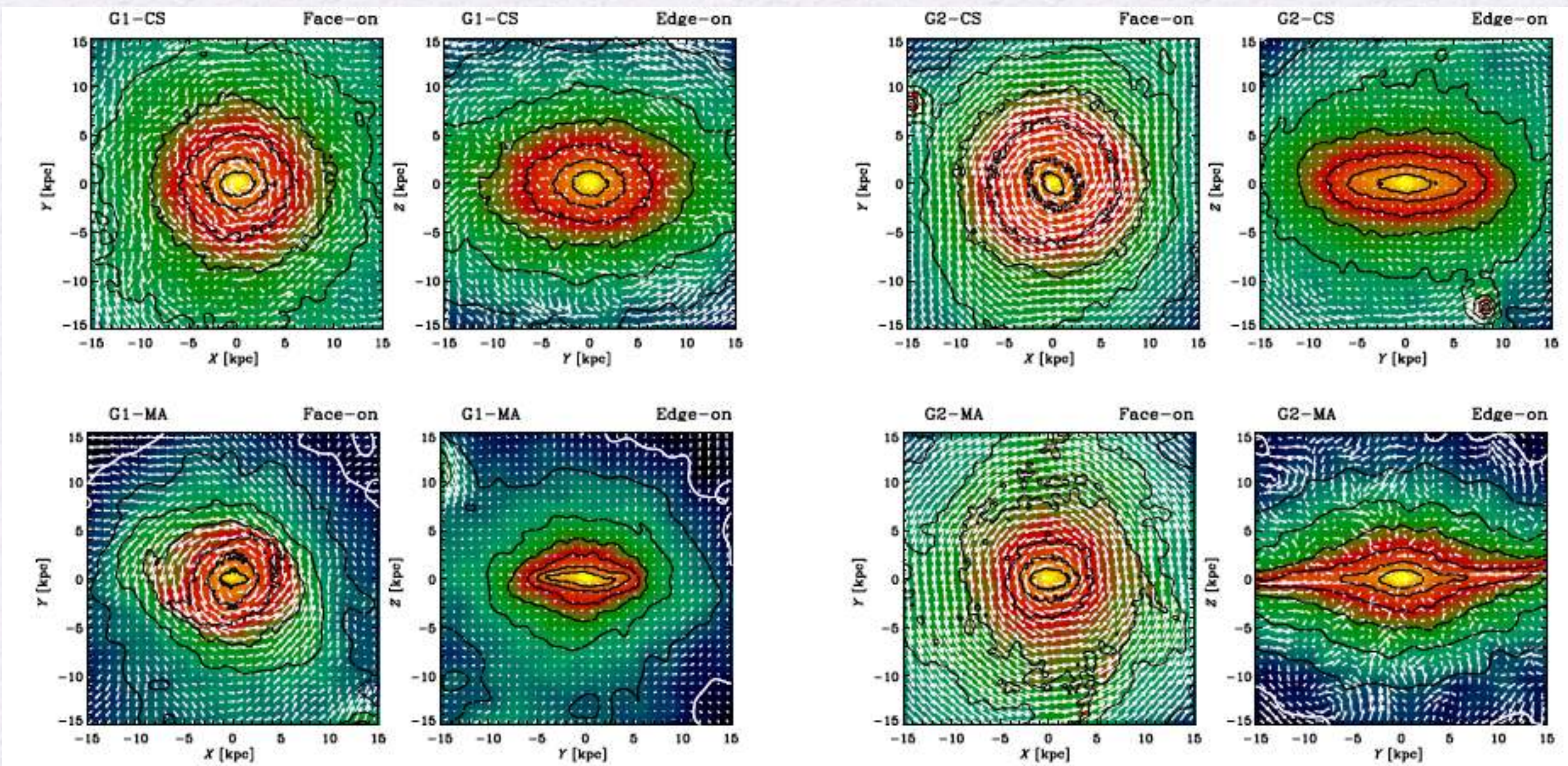


Environment and morphology

Do the simulated galaxies in this richer environment behave similarly compared to galaxies in more isolated systems?

Only SN feedback

SN+RP feedback



Scannapieco+2015

Environment and morphology

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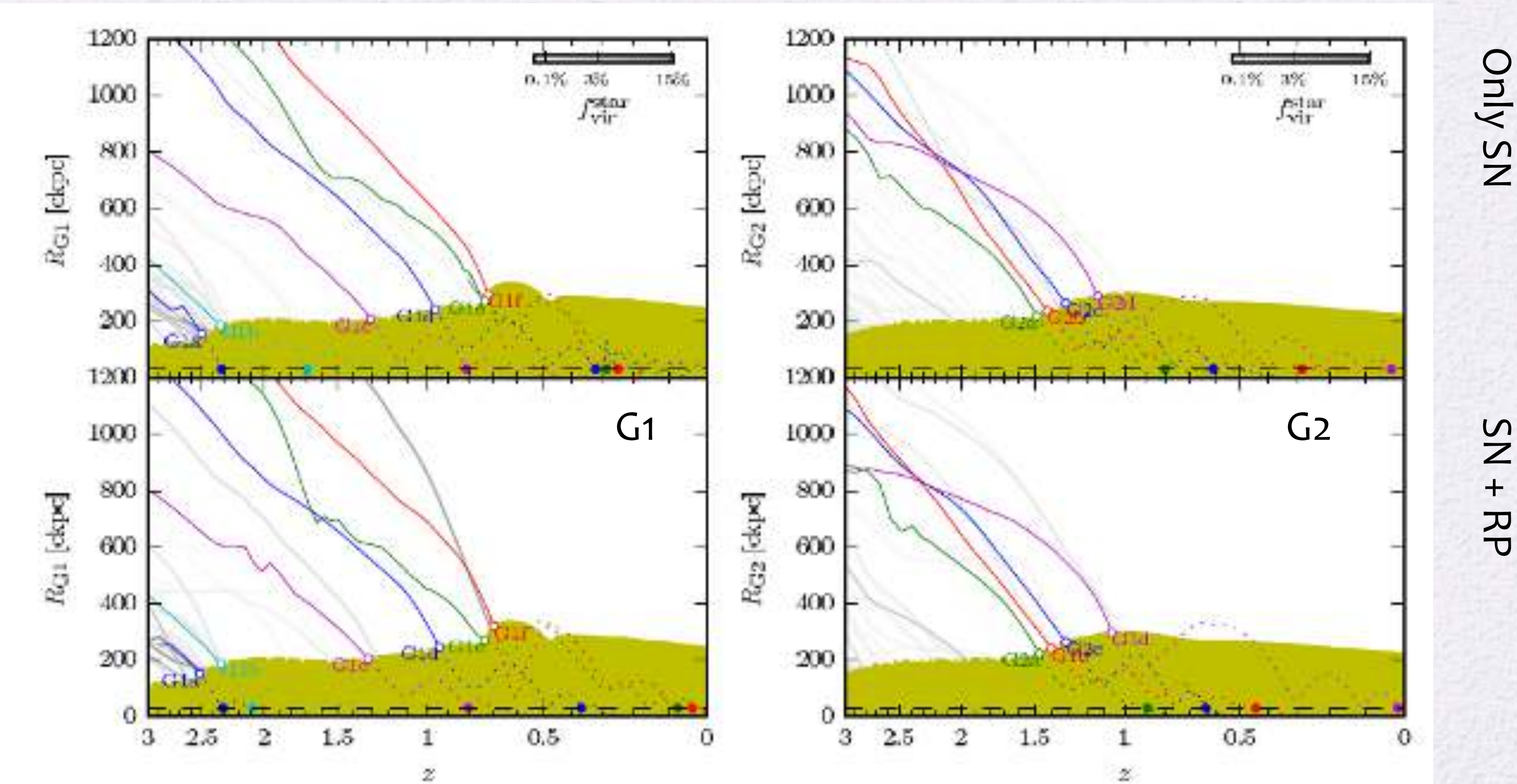

Scannapieco+2015

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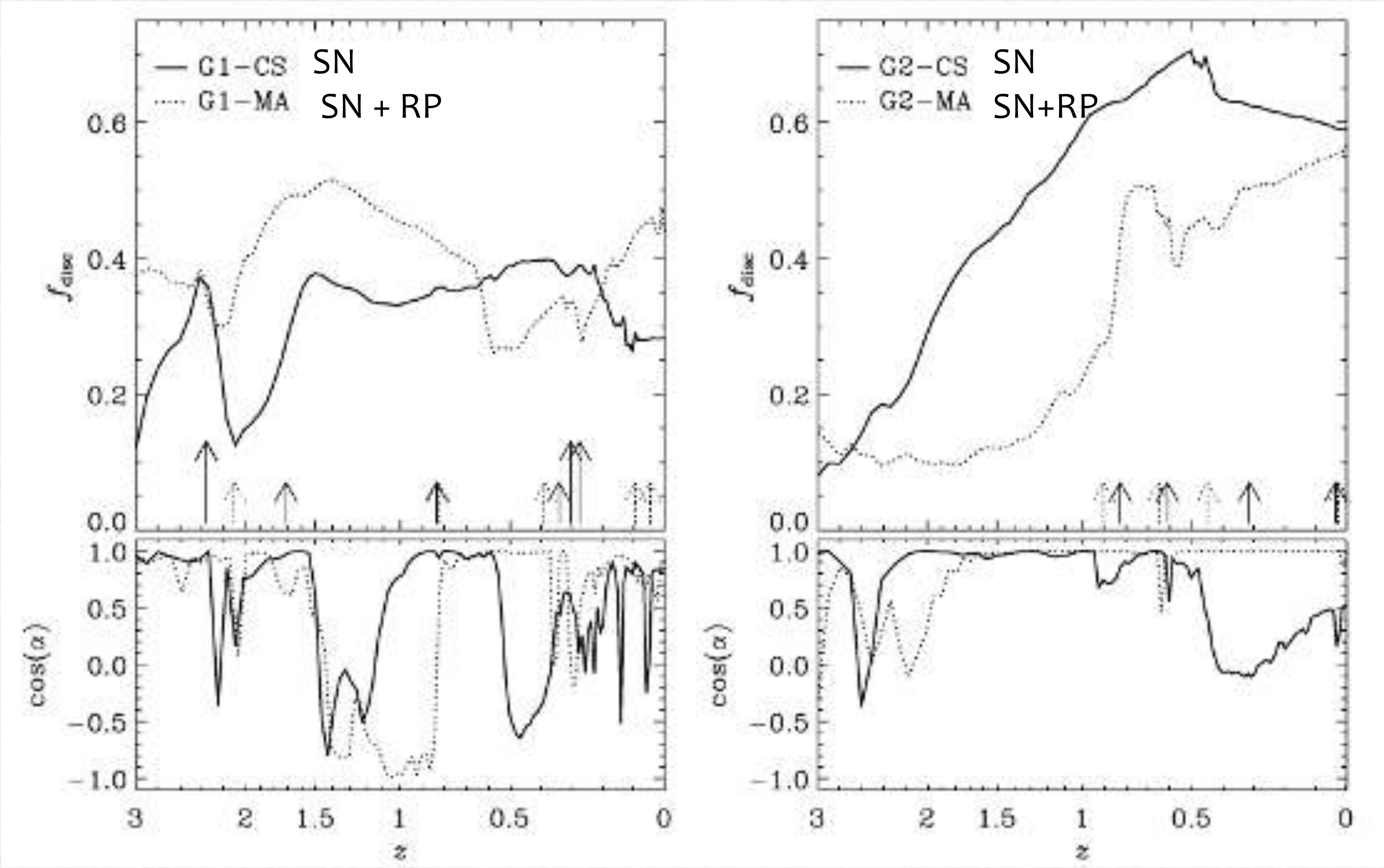


Scannapieco+2015

Environment and morphology

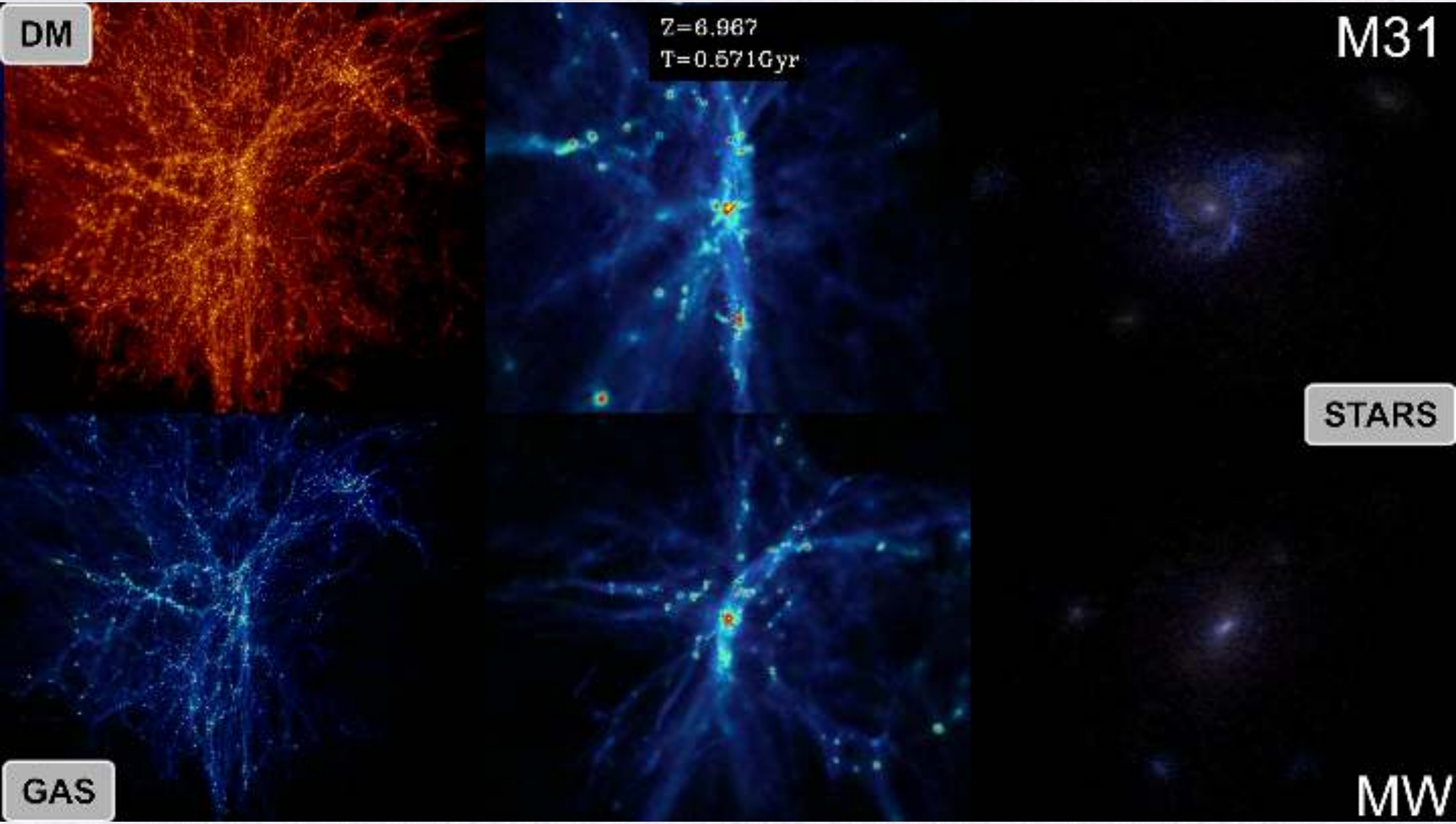
Do the simulated galaxies in this richer environment behave similarly compared to galaxies in more isolated systems?

In terms of the morphologies, these galaxies behave similarly to galaxies in more isolated systems

→ Sensitive to massive mergers and misaligned gas accretion

Scannapieco+2015

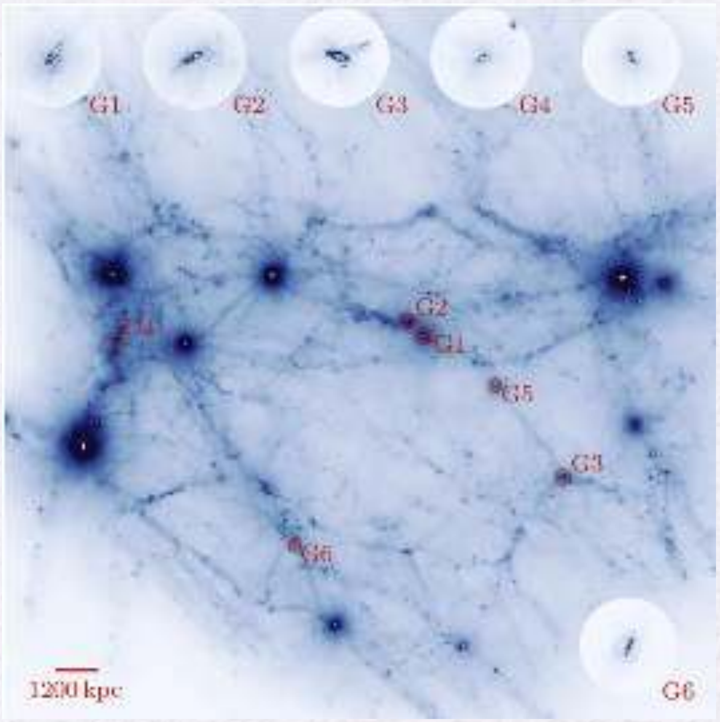
Environment and morphology



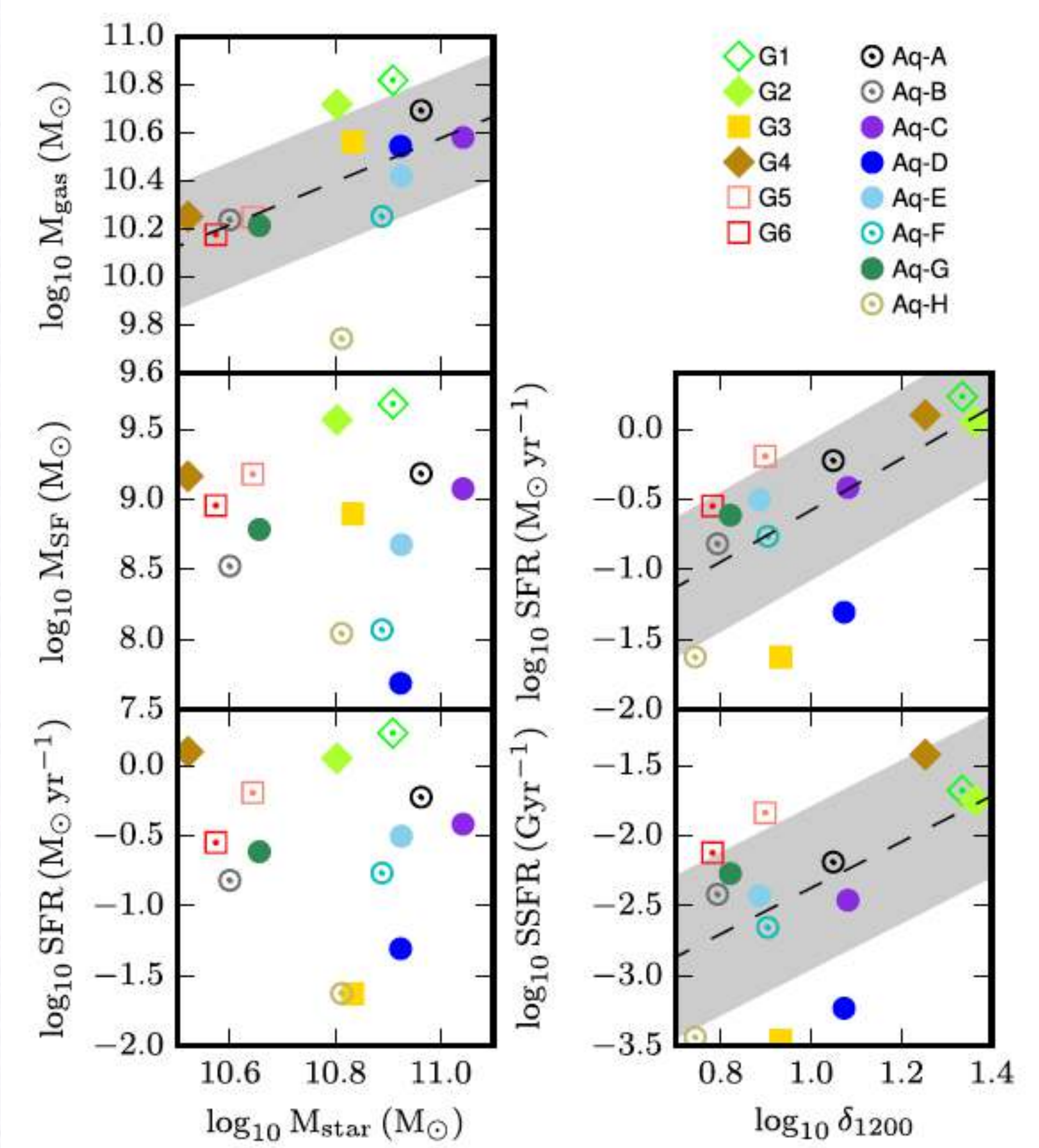
Simulation: C. Scannapieco, Visualization: A. Khalatyan

Environment and morphology

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



Creasey+2015
(see also Few+2012, Sawala+2016)



Summary

- Hydrodynamical simulations are a powerful tool to study galaxy formation and evolution, and to understand links to the formation of structure at large scales
- Despite there are still many uncertainties (incomplete knowledge of underlying physical processes, sub-grid physics, numerical issues), they allow to identify key processes to the formation of galaxies
  - Supernova feedback is a fundamental process whose main effects are the self-regulation of star formation and the generation of galactic winds
  - Other forms of feedback can also be important (e.g. radiation-pressure, black holes for massive systems)
- Simulations provide clues to disk formation process:
  - z=0 disks are young
  - Disks are transient
  - Disks can be rebuilt during evolution
  - Angular momentum of accreted gas & mergers are key to disk survival
- Indications that environmental effects might be relevant