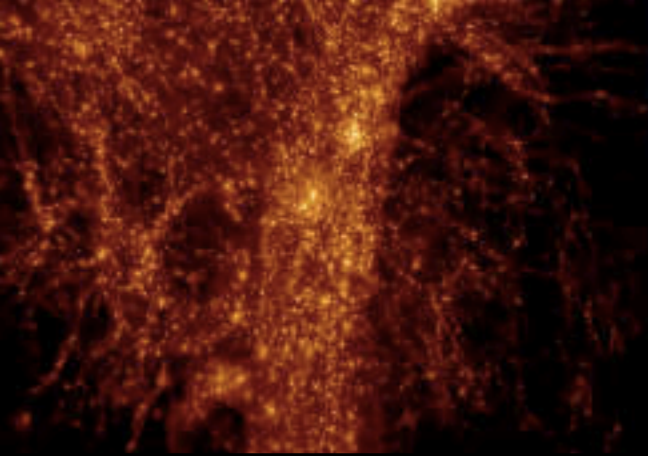
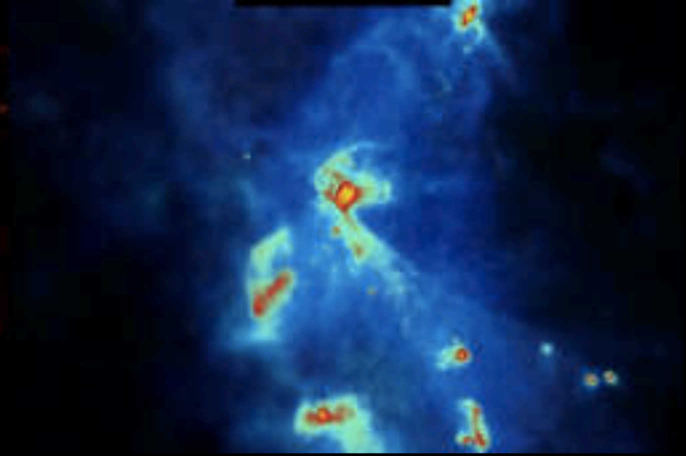




Simulations of galaxy formation and evolution in a cosmological context

Cecilia Scannapieco

Physics Department – University of Buenos Aires

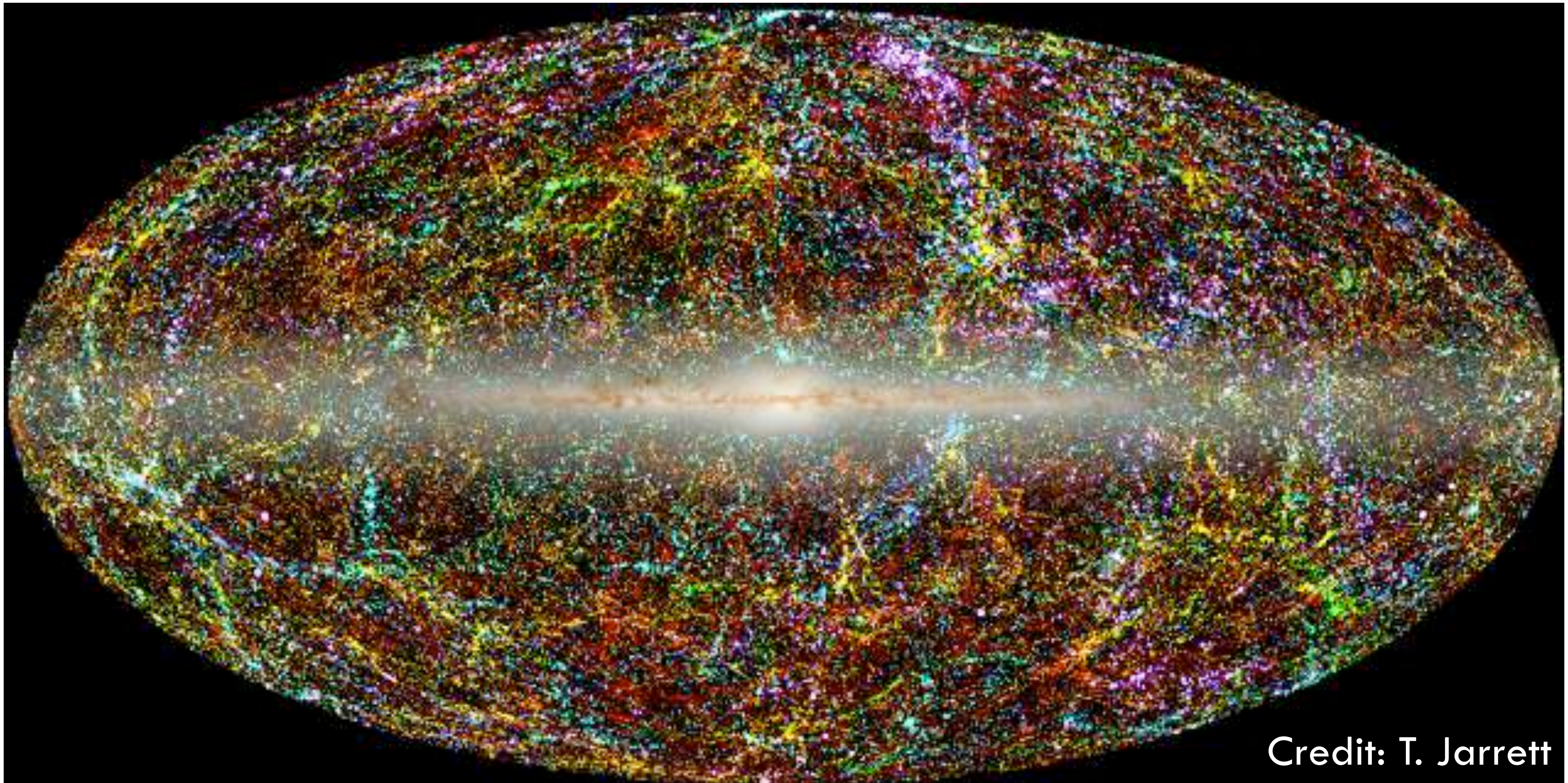
ICTP-SAIFR Colloquium, 21.11.2018

Galaxies & Cosmology

- Galaxies play a pivotal role in our study of the structure and evolution of the Universe:
  - They are bright, long-lived and abundant
  - They can be observed in large numbers over cosmological distances and timescales

Galaxies & Cosmology

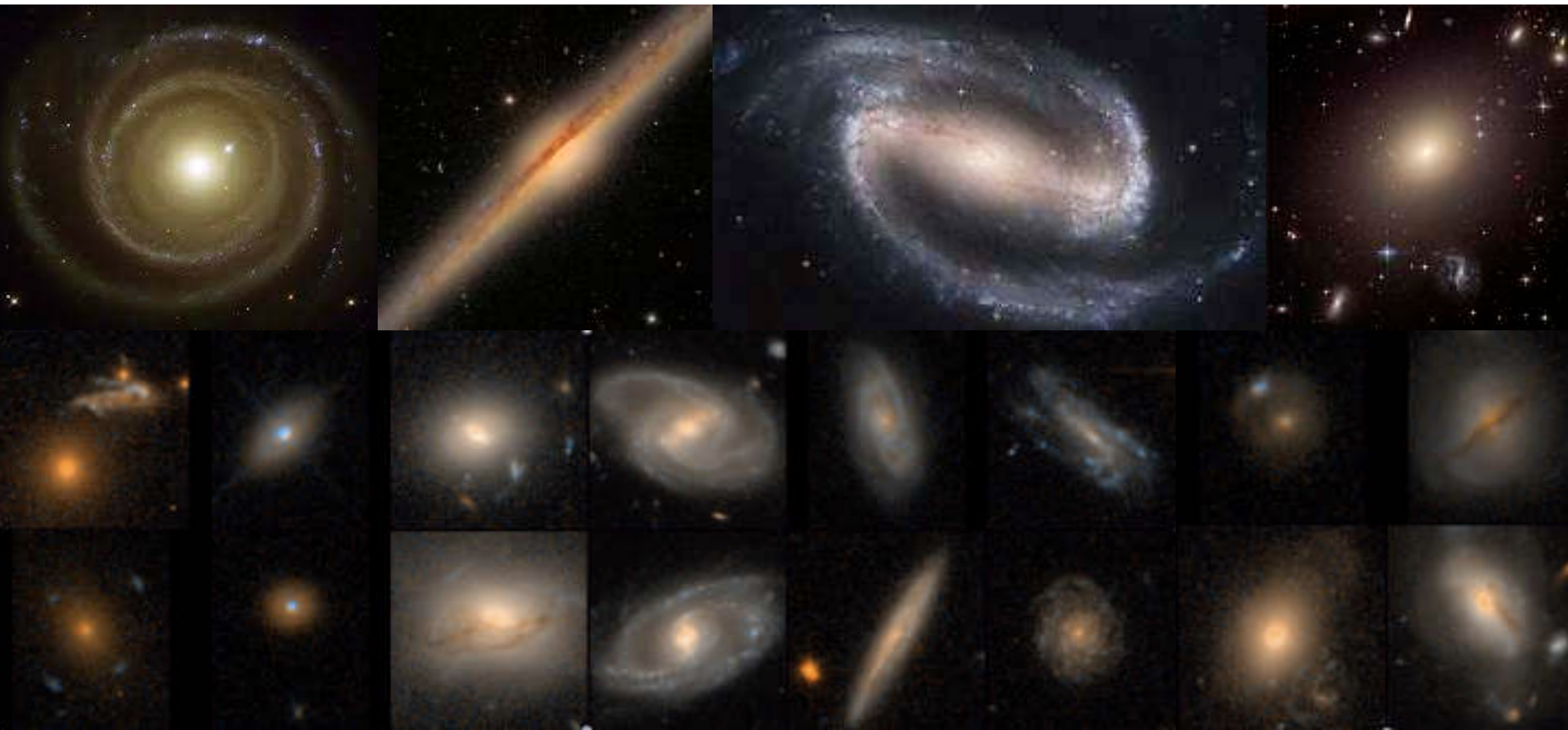
- Galaxies are unique tracers of the large-scale structure of the Universe even though they make up only a small fraction of the total amount of matter in it



Galaxies: observations

- Galaxies are very diverse, and are formed by gas and stars in various configurations: from elliptical to spirals, many have bars

Spiral (face-on) Spiral (edge-on) Spiral+bar Elliptical



Galaxies: observations

- Galaxies are very diverse, and are formed by gas and stars in various configurations: from elliptical to spirals, many have bars

Spiral (face-on) Spiral (edge-on) Spiral+bar Elliptical

- Characterized by:
- Morphology
- Stellar/gas Mass
- SFR: star formation rate
- Colors, size, magnitude, …

Galaxies: observations

- Galaxies are very diverse, and are formed by gas and stars in various configurations: from elliptical to spirals, many have bars

Spiral (face-on)

Spiral (edge-on)

Spiral+bar

Elliptical

- Usually described as the combination of bulge+disk components

Galaxies: observations

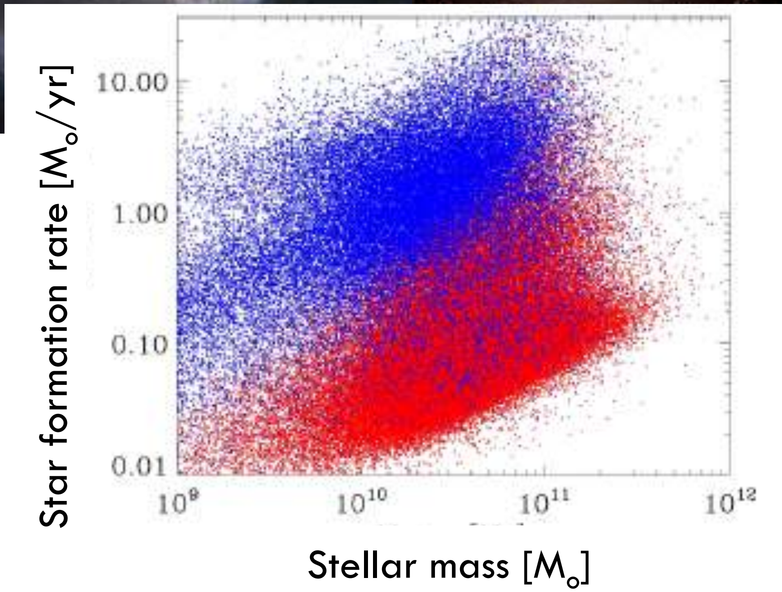
- Galaxies are very diverse, and are formed by gas and stars in various configurations: from elliptical to spirals, many have bars

Spiral (face-on) Spiral (edge-on) Spiral+bar Elliptical

- Great variety of galaxy properties

  even for a fixed stellar mass

  e.g. SFR (star formation rate)



Galaxies: types

Spiral galaxies

- 10^{10} stars
- ~10 kpc radius
- Supported by rotation
- Different components: disk, bulge, halo, bar

A galaxy similar to the Milky Way

Galaxies: observations

Dwarf galaxies

- 10^{5-7} stars
- Ellipticals:1-10 kpc Spheroidals: ~0.1-0.5 kpc
- Also irregular
- **Most abundant** type of galaxy but difficult to detect

A dwarf galaxy

Spiral galaxies

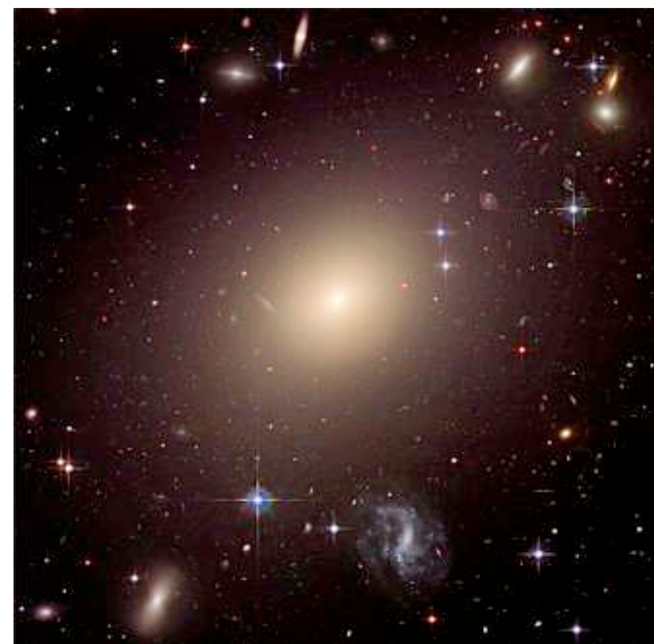
- 10^{10} stars
- ~10 kpc radius
- Supported by rotat
- Different componen disk, bulge, halo, bar

A galaxy similar to the Milky Way

Elliptical galaxies

- Up to 10^{13} stars
- Up to ~100 kpc radius
- Little/no rotation
- Spheroidal shape

An elliptical galaxy

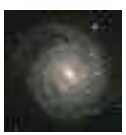


Galaxies: types

Dwarf

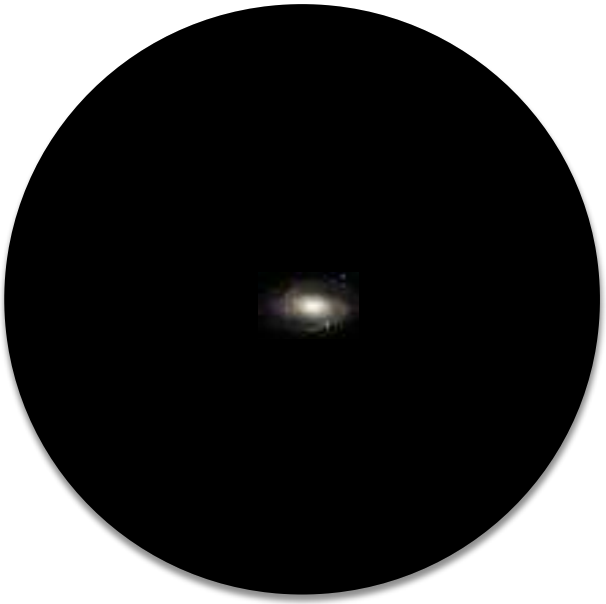
Spiral

Elliptical



Galaxies: dark matter

- Galaxies + Dark matter halos



- Galaxies are composed of gas and stars, and are at the centers of the **dark matter haloes**

Outline

- Galaxies & cosmology
- The simulations
- Galaxy disks: formation, diversity, survival/destruction
- Galaxy diversity: environmental effects
- Discussion: successes, problems, challenges of current simulations
- Summary

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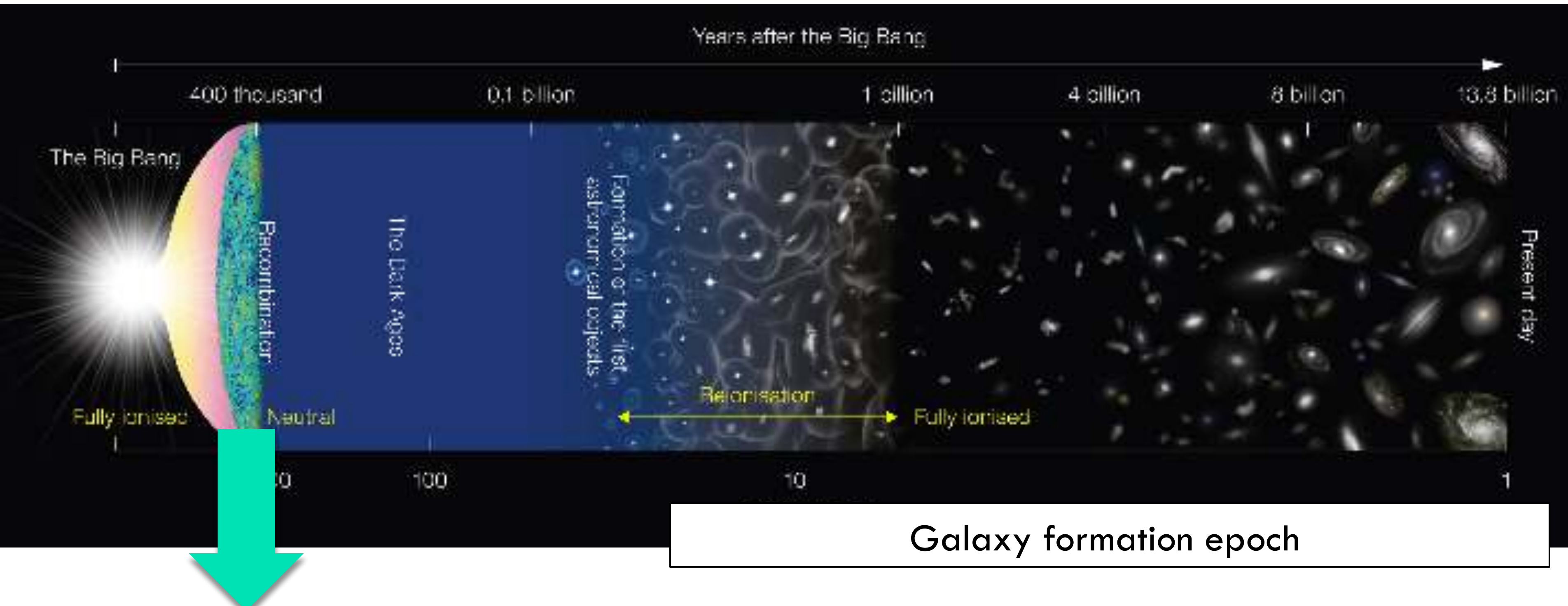
Cosmology & structure formation

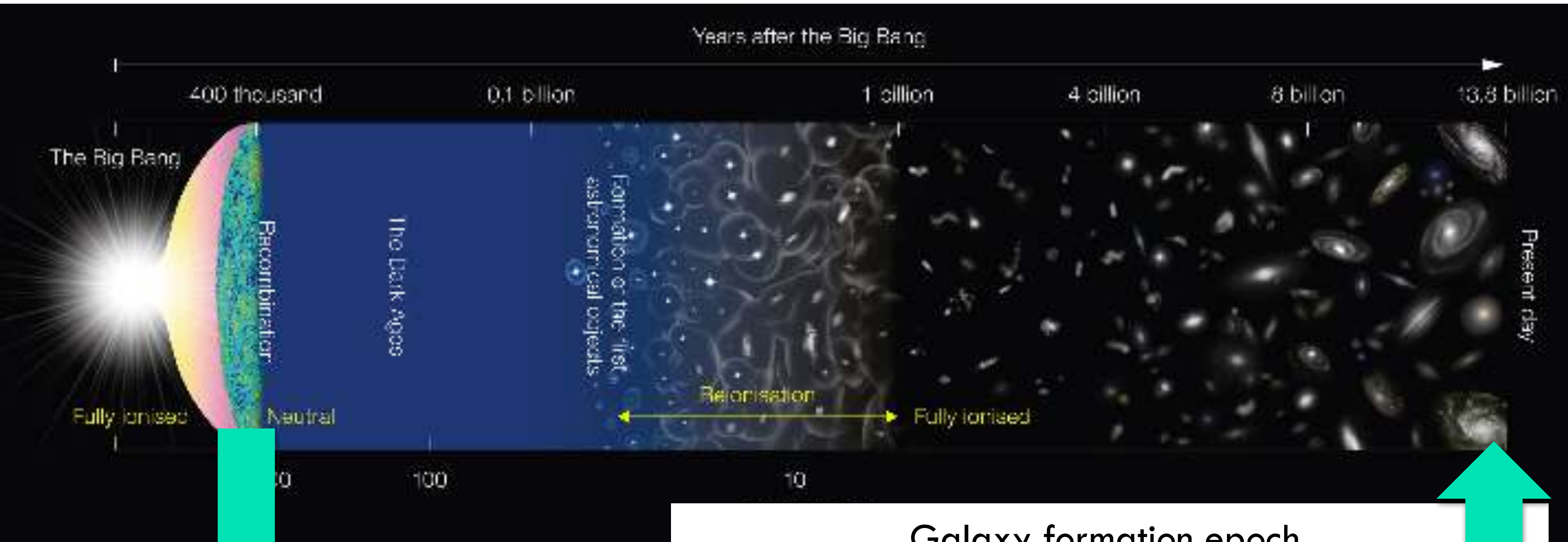
- Cosmological concordance model: Λ-Cold Dark Matter Model



- Small density perturbations in the early universe revealed by observations of the Cosmic Microwave Background (CMB)

Cosmology & structure formation

- Cosmological concordance model: Λ-Cold Dark Matter Model

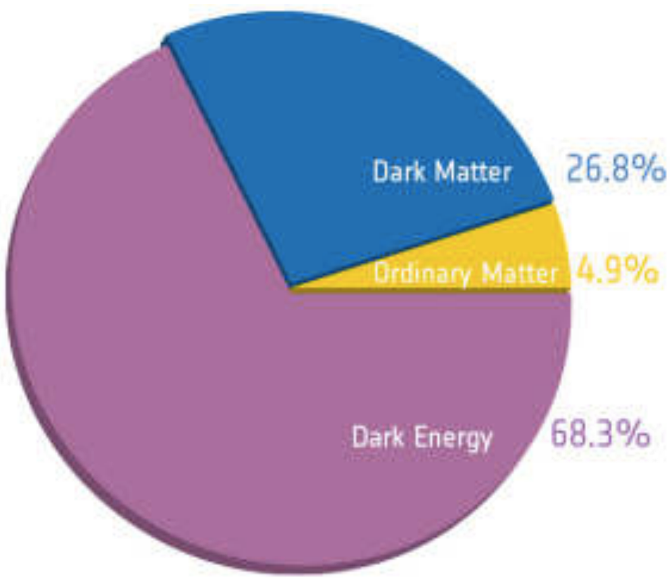


Galaxy formation epoch

Simulations in a cosmological context

Cosmology & structure formation

- Cosmological concordance model: Λ-Cold Dark Matter Model
- Observations give matter-energy content of the universe, which determines its evolution: expanding universe
- ~85% of the matter is dark, only ~15% luminous



Dark Matter is “cold”:
interacts very weakly with ordinary matter and electromagnetic radiation

→ “only” interaction is gravity

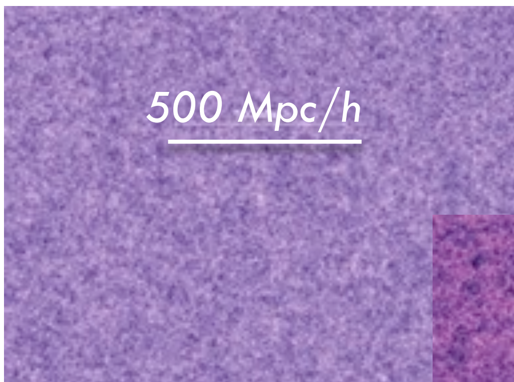
Cosmology & structure formation

In the ΛCDM model, structure formation is hierarchical

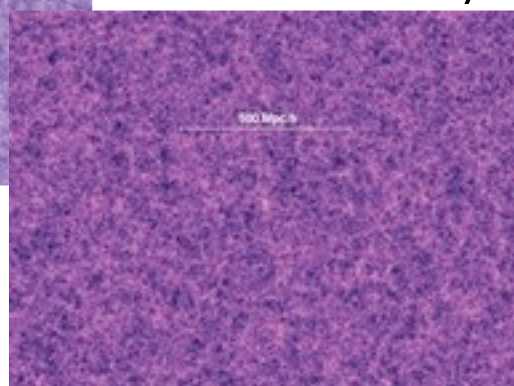
The initial perturbations grow gravitationally, separate from the general expansion of the universe and grow further via mergers and accretion

→ formation of dark matter halos

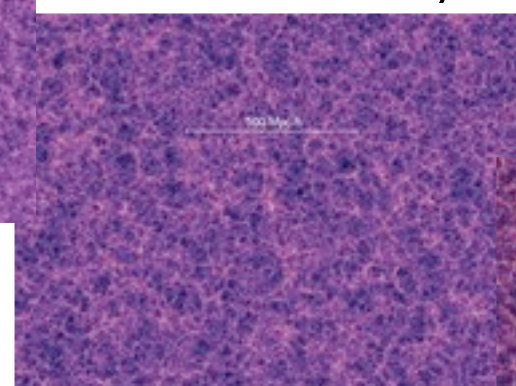
z=18.3 T = 0.21 Gyr



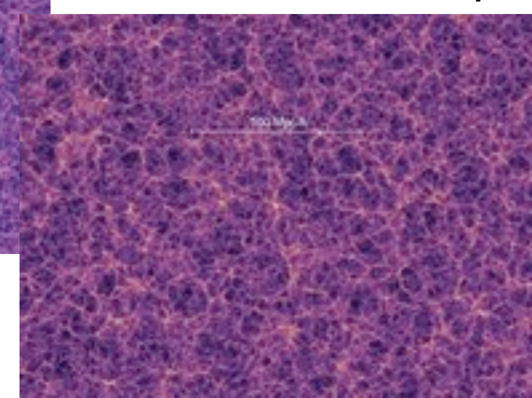
z=5.7 T = 1 Gyr



z=1.4 T=4.7 Gyr



z=0 T=13.6 Gyr



Credit: V. Springel

Cosmology & structure formation

In the ΛCDM model, structure formation is hierarchical

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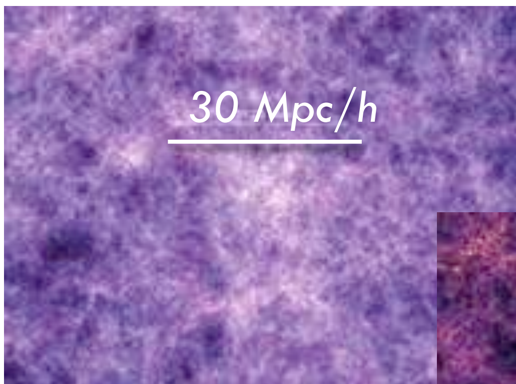
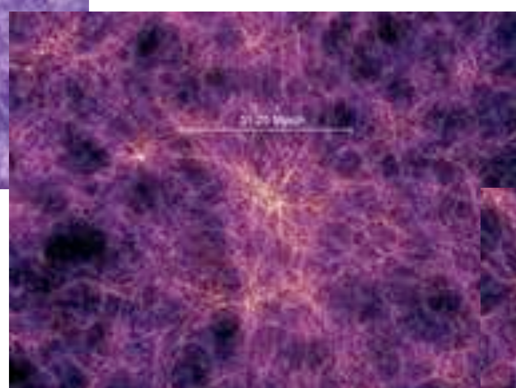


z=5.7 T =

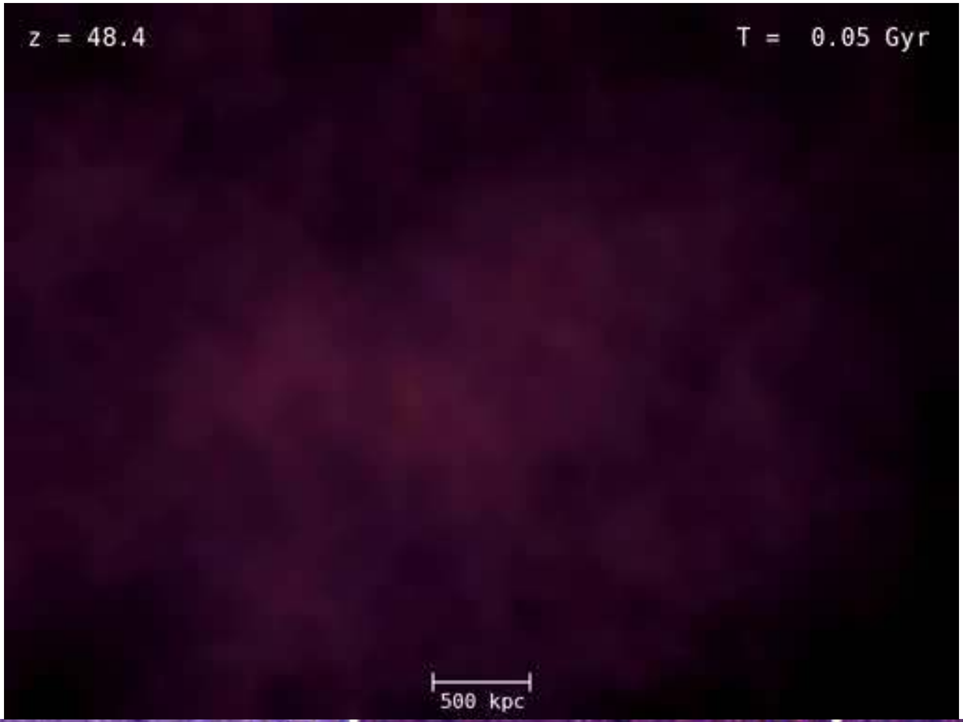


z=1.4 T=4.7

z=0 T=13.6

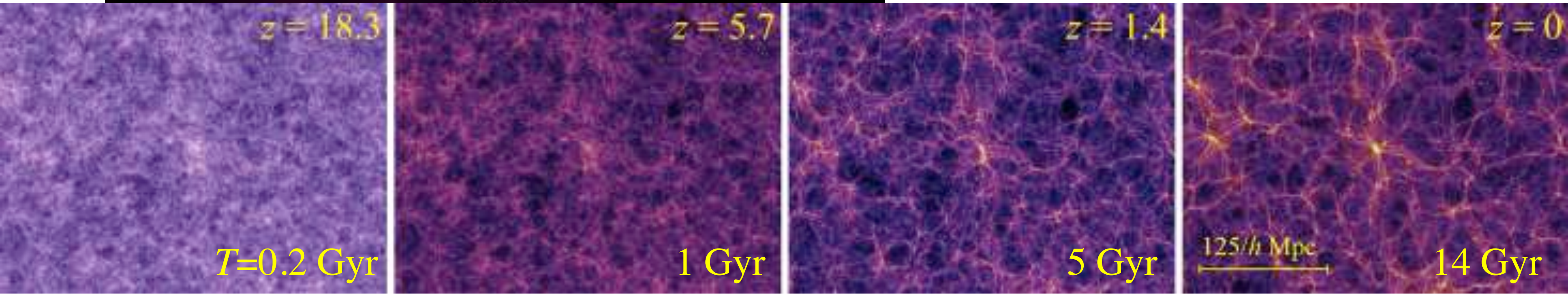
Credit: V. Springel

Cosmology & structure formation



Cosmological structure formation

- Mergers, interactions and mass accretion are major players in the evolution of halos
- Halos are affected by larger scales & other systems



Credit: Volker Springel

Outline

- Galaxies & cosmology
- The simulations
- Galaxy disks: formation, diversity, survival/destruction
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The need for simulations

- Structure formation in Λ-Cold Dark Matter:
  - Highly non-linear
  - Free from any simplifying symmetry
  - Multiscale: large scales affect galaxy-scales

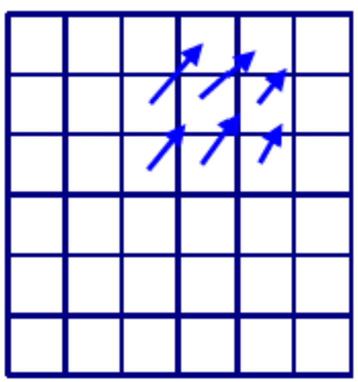
- Numerical simulations → describe growth of structure in a cosmological context, for both dark and gaseous matter:
  - Dark matter described as collisionless fluid
  - Gas dynamics described with hydrodynamical solver

Numerical methods

Discretize matter in terms of particles/cells

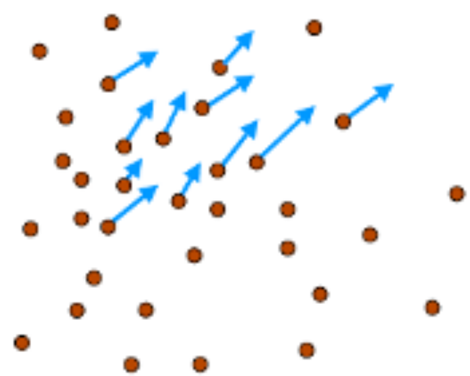
Two ways of discretizing a continuous distribution

Eulerian
Discretize space
(volume elements)



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

Lagrangian
Discretize mass
(particles)



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

Numerical methods

Need to calculate the gravitational force on each particle

Evolve the equations in an expanding universe

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

using periodic boundary conditions

Need to solve hydrodynamics for the gas + sub-grid physics

Efficient codes: time integration, parallelization and (many) technical issues

Numerical methods

2011: Millennium XXL

303 billion particles

L = 3 Gpc/h

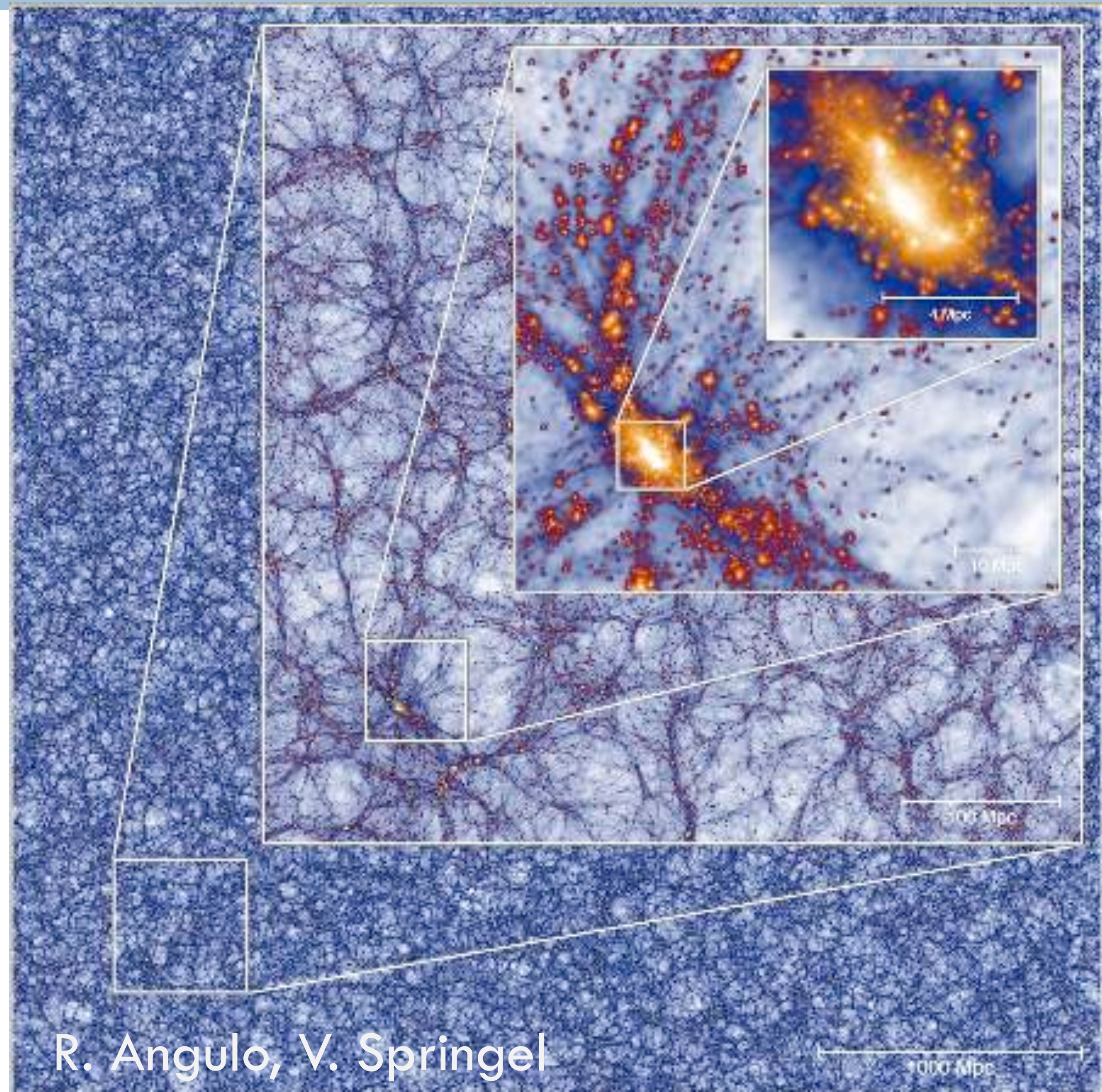
~700 million halos
at z=0

~25 billion (sub)halos
in mergers trees

$m_p = 6.1 \times 10^9\ M_\odot/h$

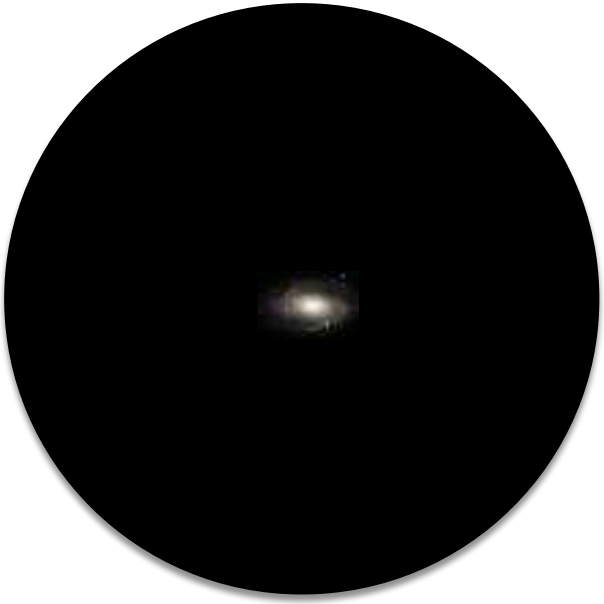
12288 cores,
30 TB RAM on
Supercomputer
JuRoPa in Juelich

2.7 million CPU-hours



Simulations with baryons

Galaxies are not dark!



Simulations with baryons (SPH)

To solve the hydrodynamical equations we use the SPH technique (SPH: Smoothed Particle 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 , i are the "neighbours"

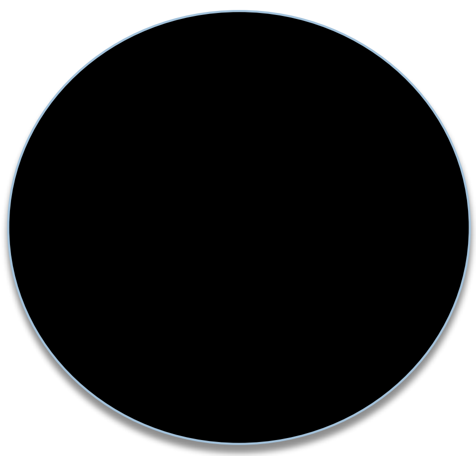
$$\frac{\mathrm{d}\rho_j}{\mathrm{d}t} = -\rho_j \nabla_j \cdot \mathbf{v}_j$$

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

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

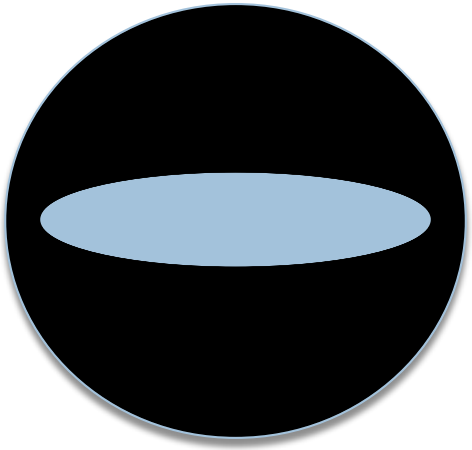
Galaxy formation physics

- Gravity → dark matter halo formation



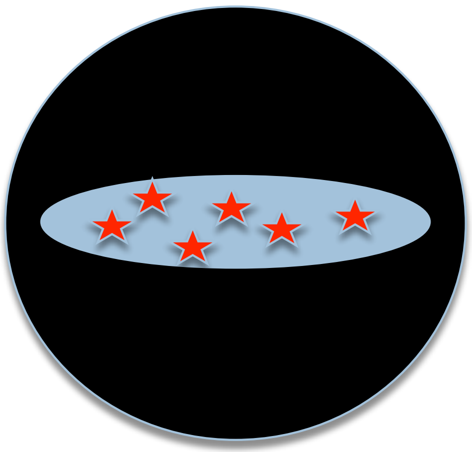
Galaxy formation physics

- 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
- Stellar "Feedback" → return of chemical elements and/or energy to the interstellar medium

Galaxy formation physics

- Gravity → dark matter halo formation
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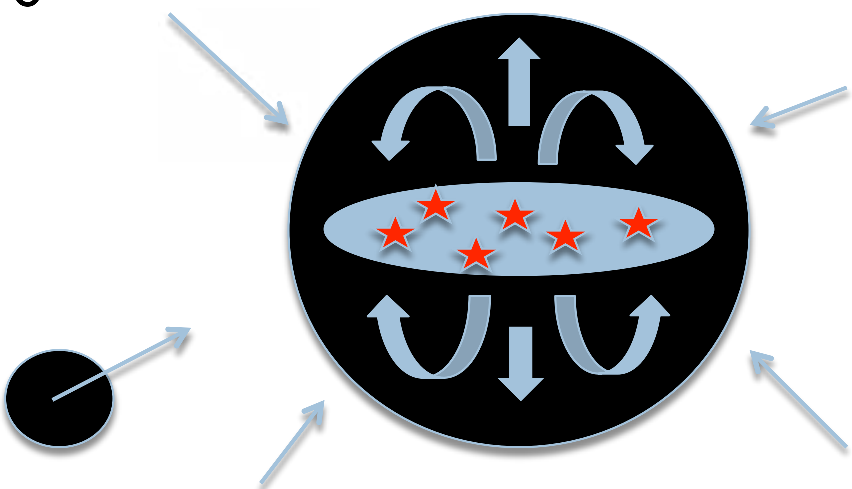
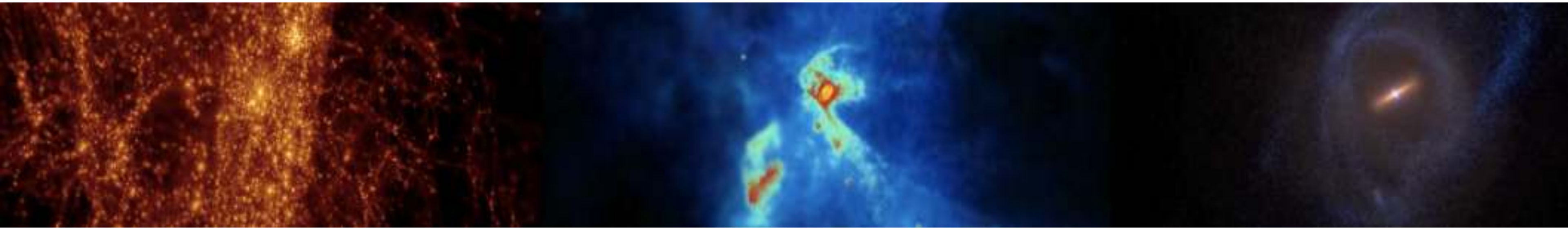
- Stellar "Feedback" → return of chemical elements and/or energy to the interstellar medium

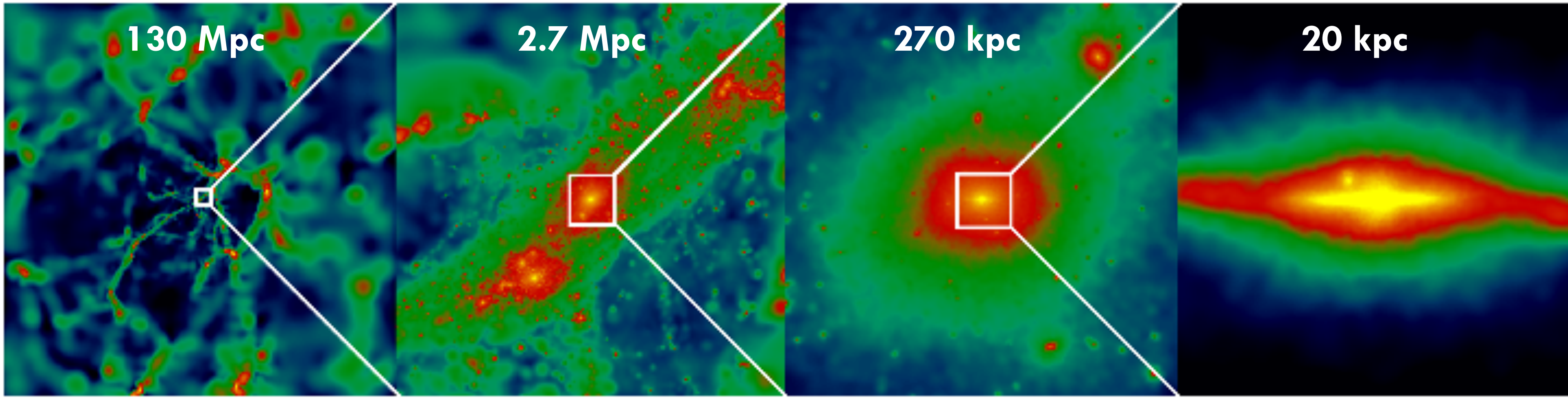
+ Cosmological effects → Mass accretion/mergers



Simulations: computational challenge

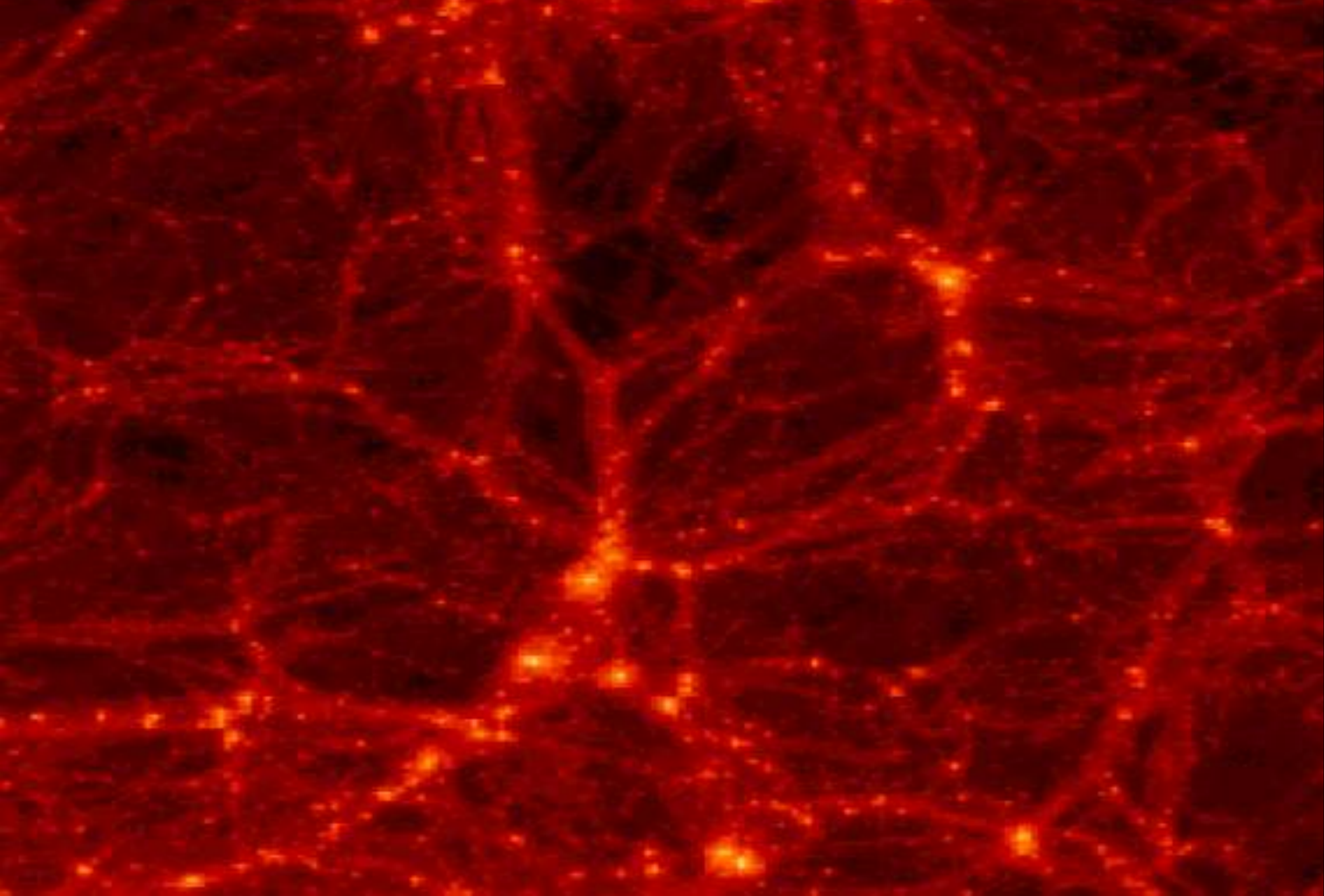


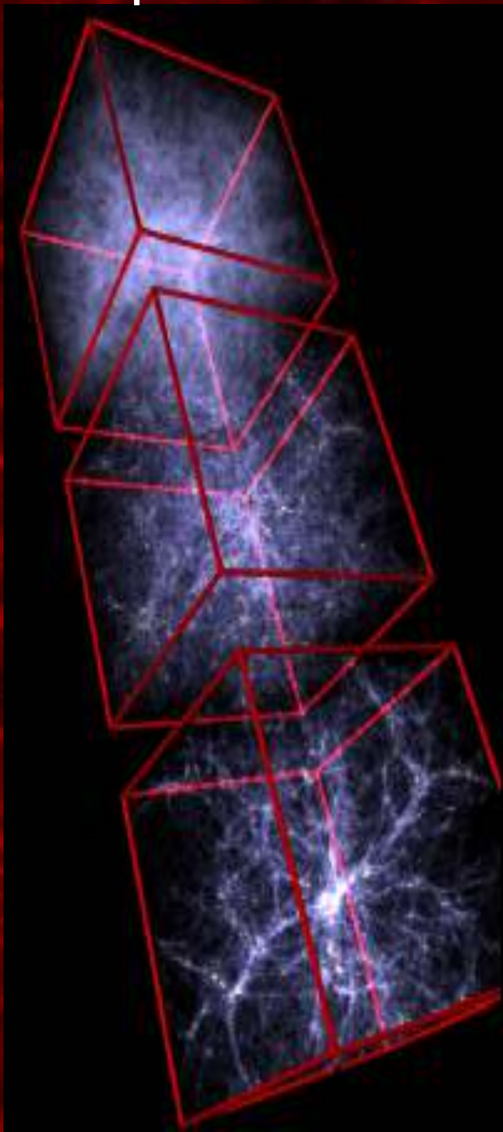
Galaxy formation simulations use the “zoom-in” technique



Numerical methods: summary

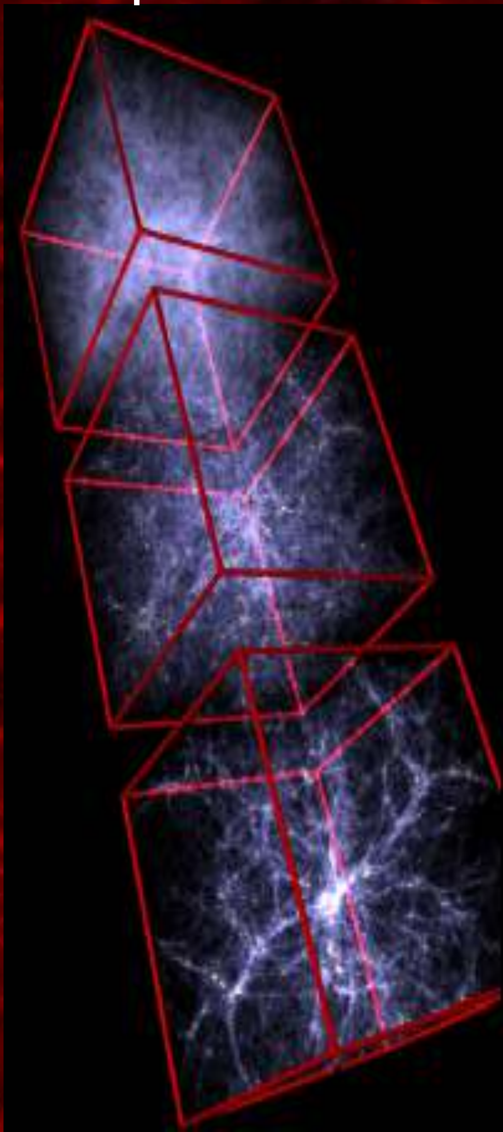
- Discretize matter in terms of particles and follow their trajectories
- Create initial condition:
    - N_{DM} dark matter particles, N_{gas} gas particles





Numerical methods: summary

- 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

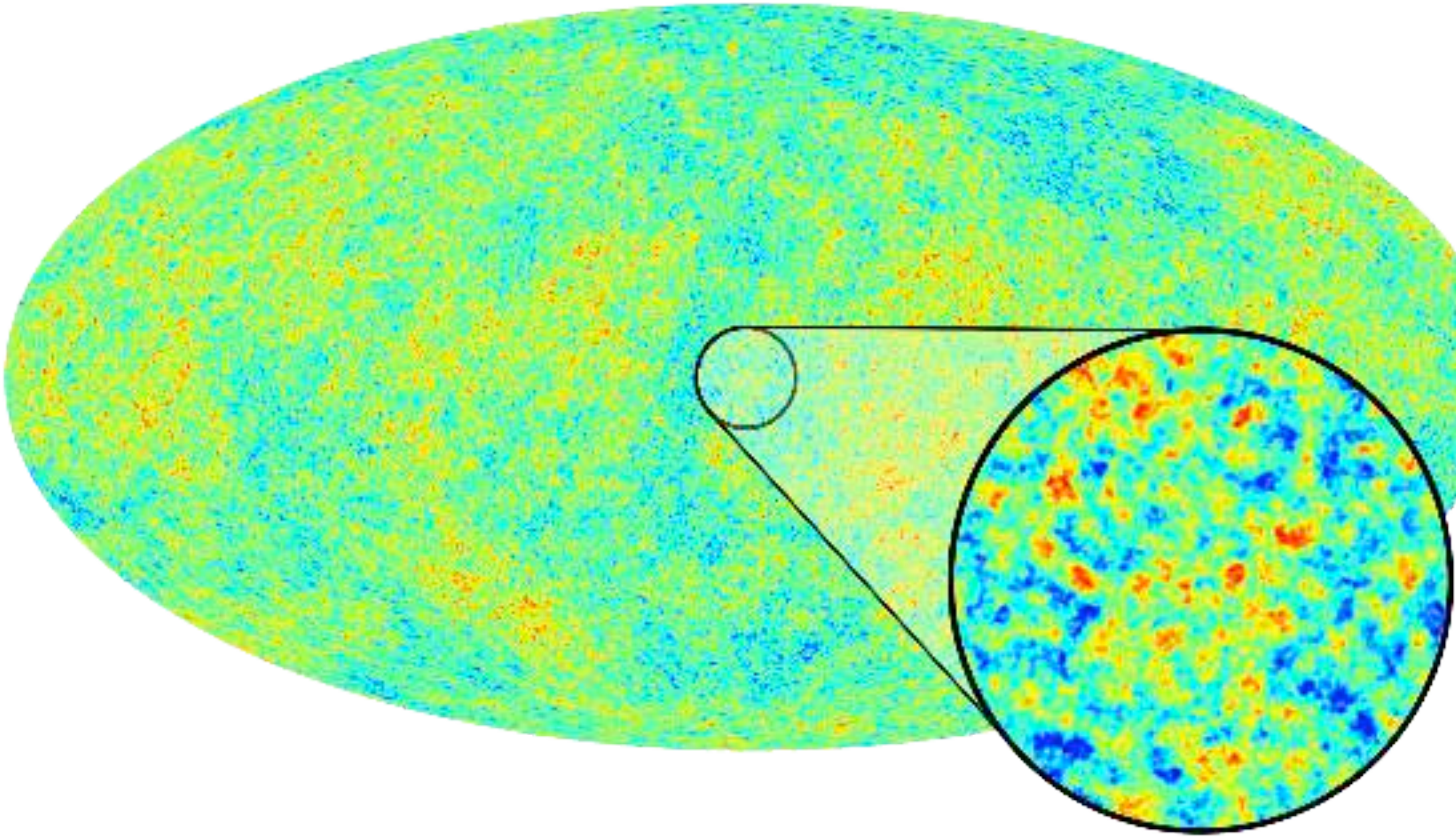


The Simulations: ingredients

- Initial conditions are known:

  given by CMB (cosmic microwave background)

  → spectrum of initial density perturbations



The Simulations: ingredients

- Code to evolve the initial conditions in cosmological context

  GADGET3 (Springel+2008)

  - Gravity solver
  - Smoothed Particle Hydrodynamics to solve gas dynamics

The Simulations: sub-grid physics

- Describe unresolved-physics
  - Star formation, Kennicutt-Schmidt law

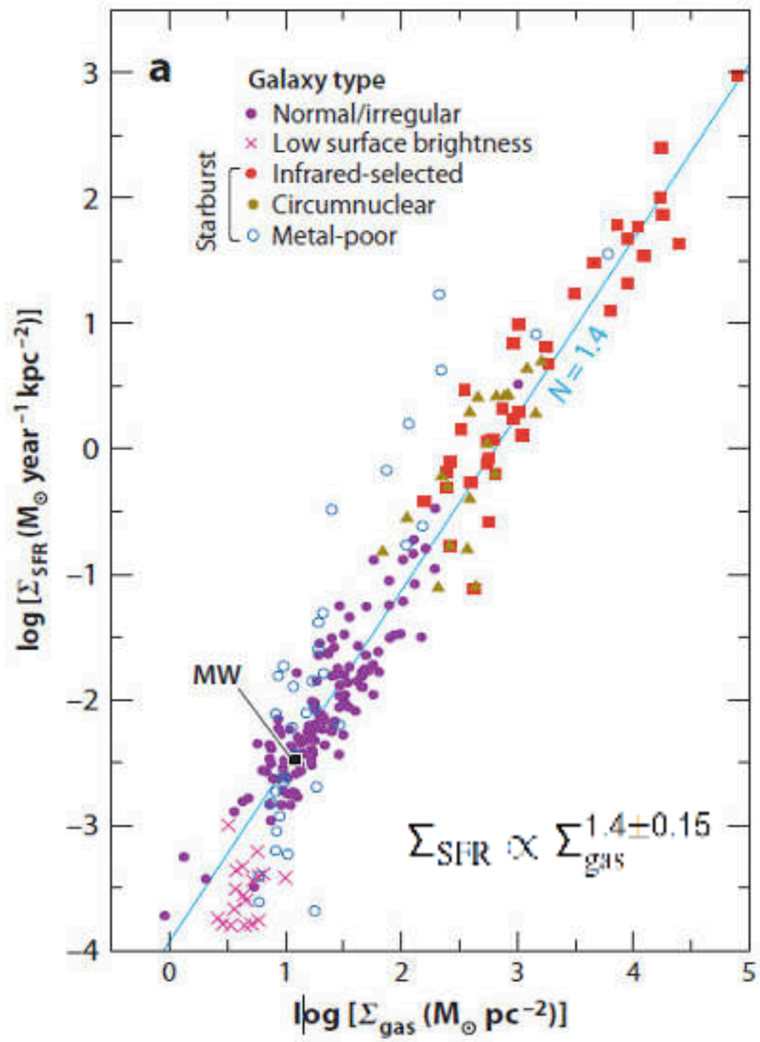
$$\dot{\rho}_\star = c \frac{\rho}{\tau_{\rm dyn}}$$

c: *star formation* efficiency

Dynamical time

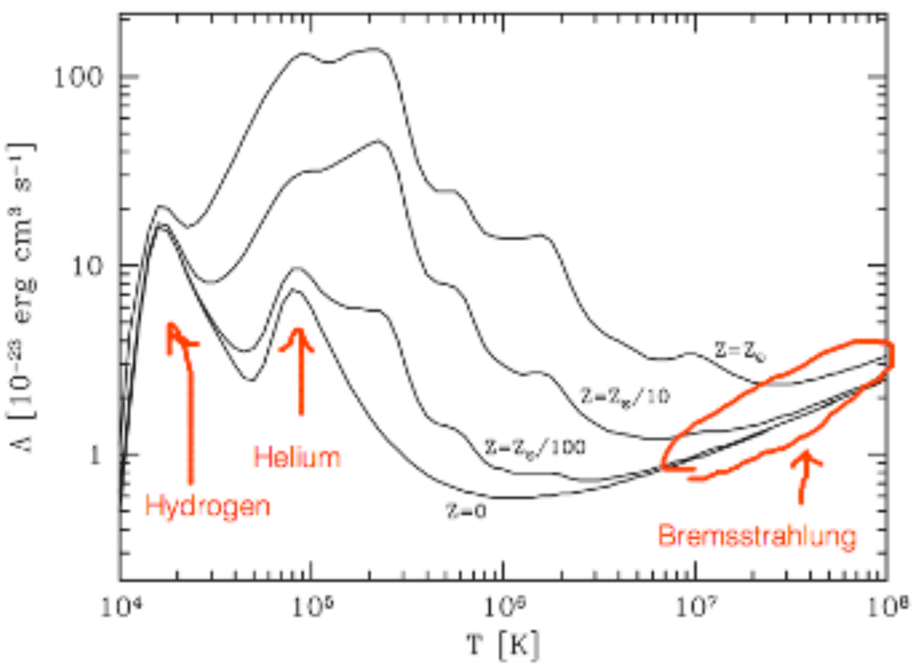
$$\tau_{\rm dyn} = (3\pi / 16 G \rho)^{1/2}$$

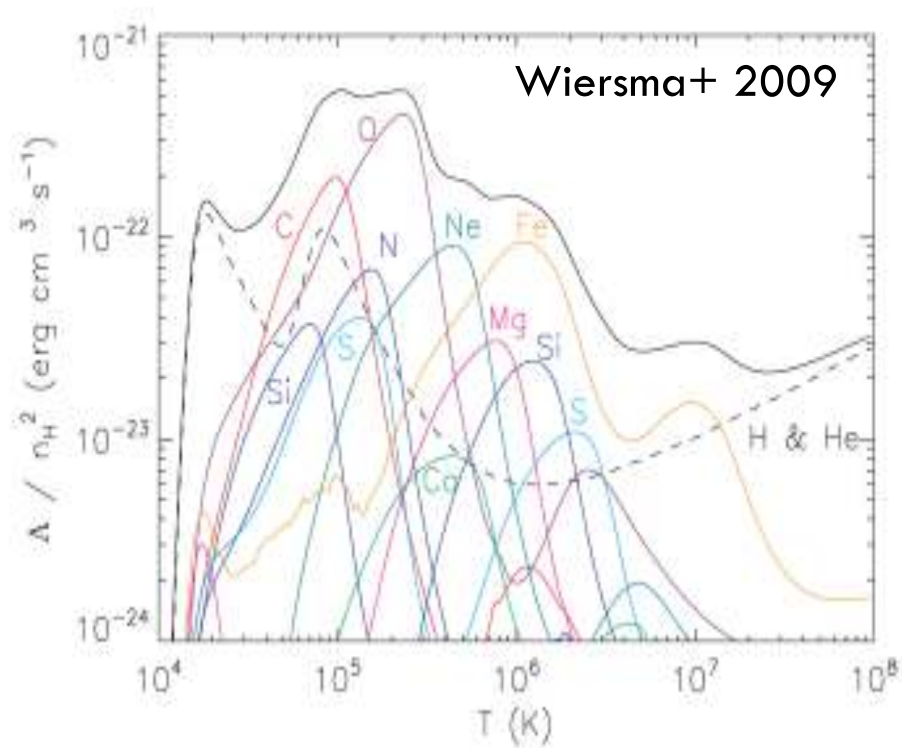
Represents the time it would take a star to collapse if the pressure supporting it against gravity were suddenly removed.



The Simulations: sub-grid physics

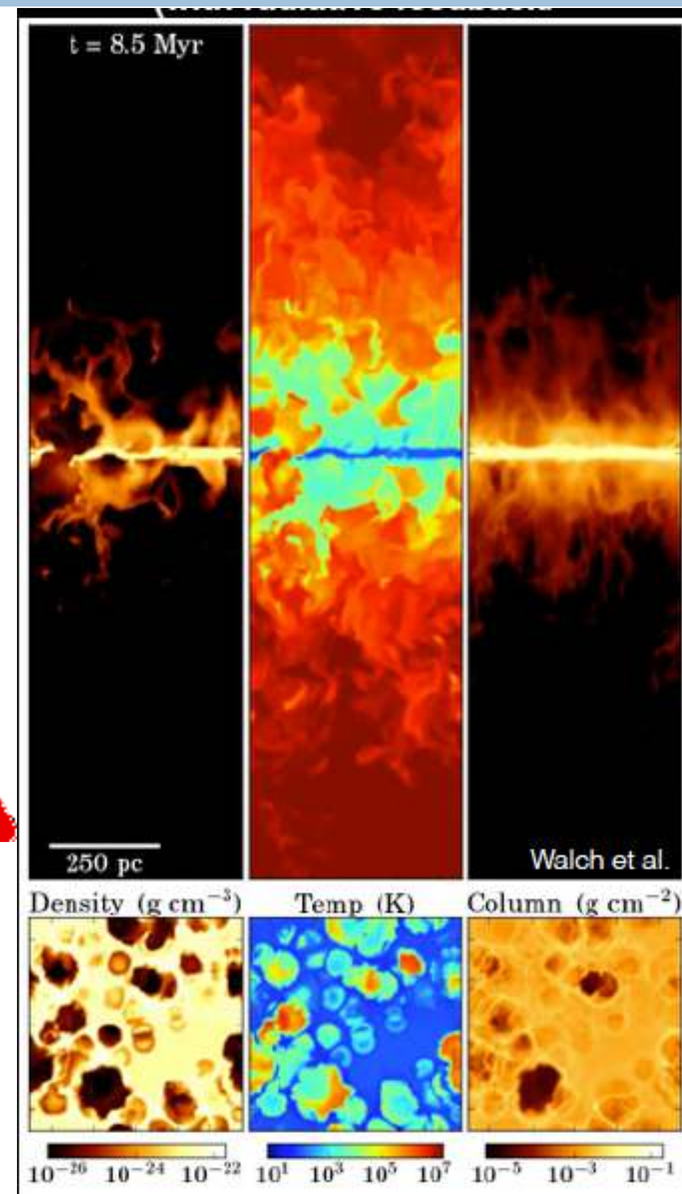
- Describe unresolved-physics
  - Star formation, Kennicutt-Schmidt law
  - Cooling: tabulated cooling functions, depends on density, temperature and chemical composition





The Simulations: sub-grid physics

- Describe unresolved-physics
  - Star formation, Kennicutt-Schmidt law
  - Cooling: tabulated cooling functions, depends on density, temperature and chemical composition
  - Feedback effects
    - **SN feedback**
    - (Radiation-pressure feedback
    - (Black hole 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

<u>Thermal feedback</u>

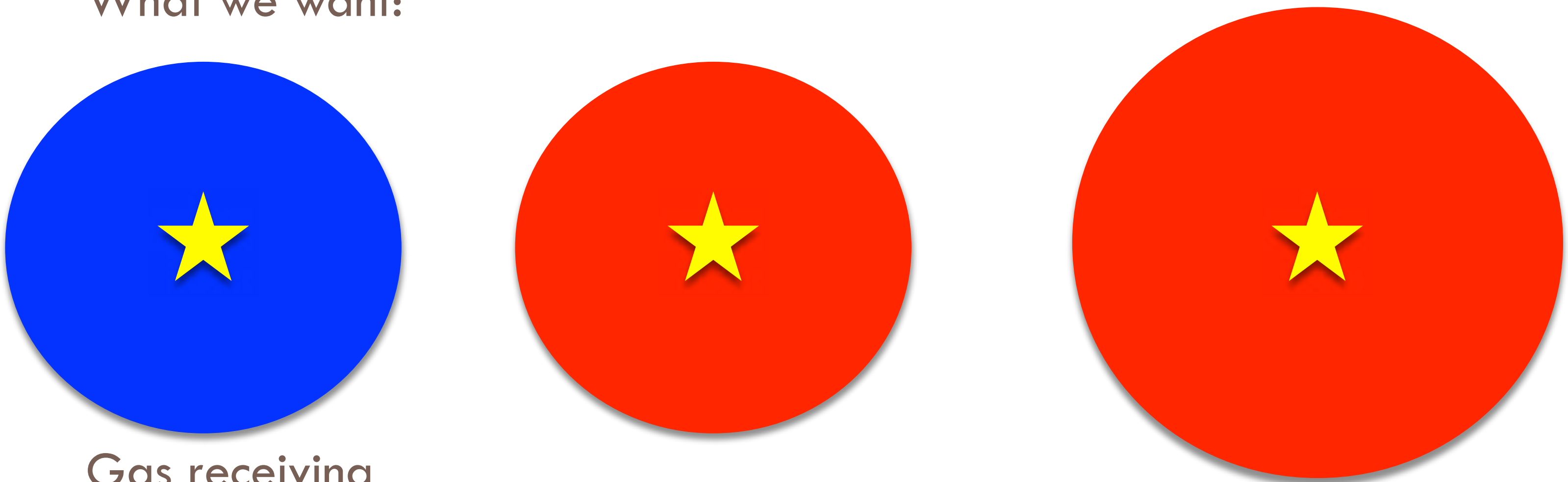
Add heat to the gas

<u>Kinetic feedback</u>

Move gas around

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

Simulations of galaxy formation: state-of-the-art

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}-^{5} $M_\odot$ in the simulations!

star particles in the simulation are not individual stars

Star particles ~ 10^{3-4} $M_\odot$ in the simulations!

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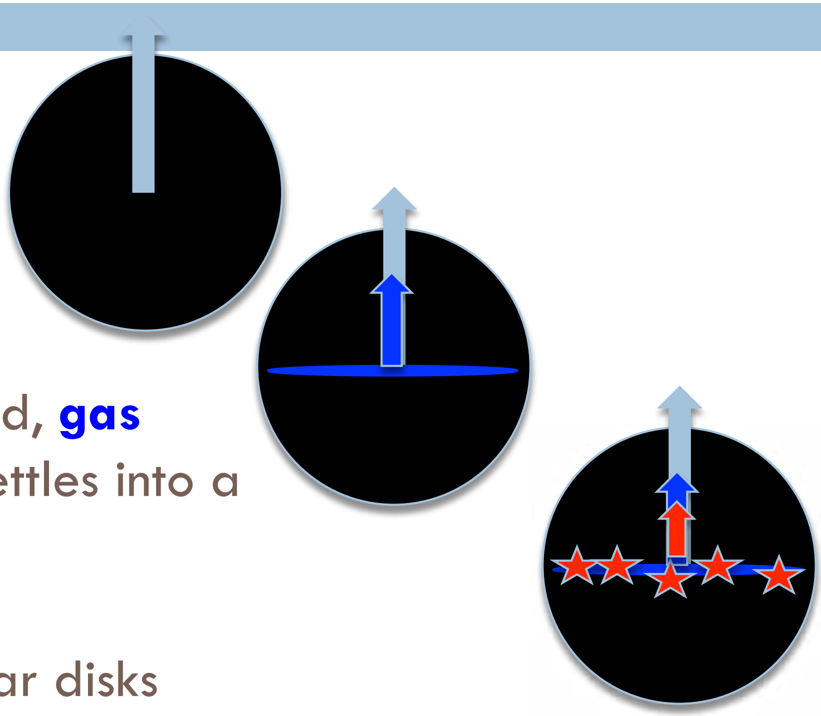
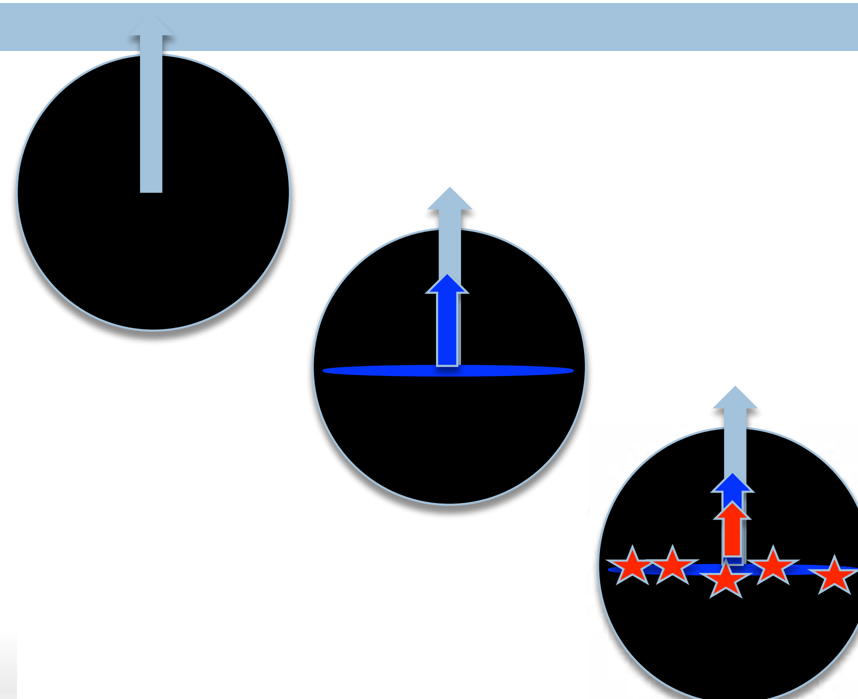
The formation of galaxy disks



- **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 galaxy disks



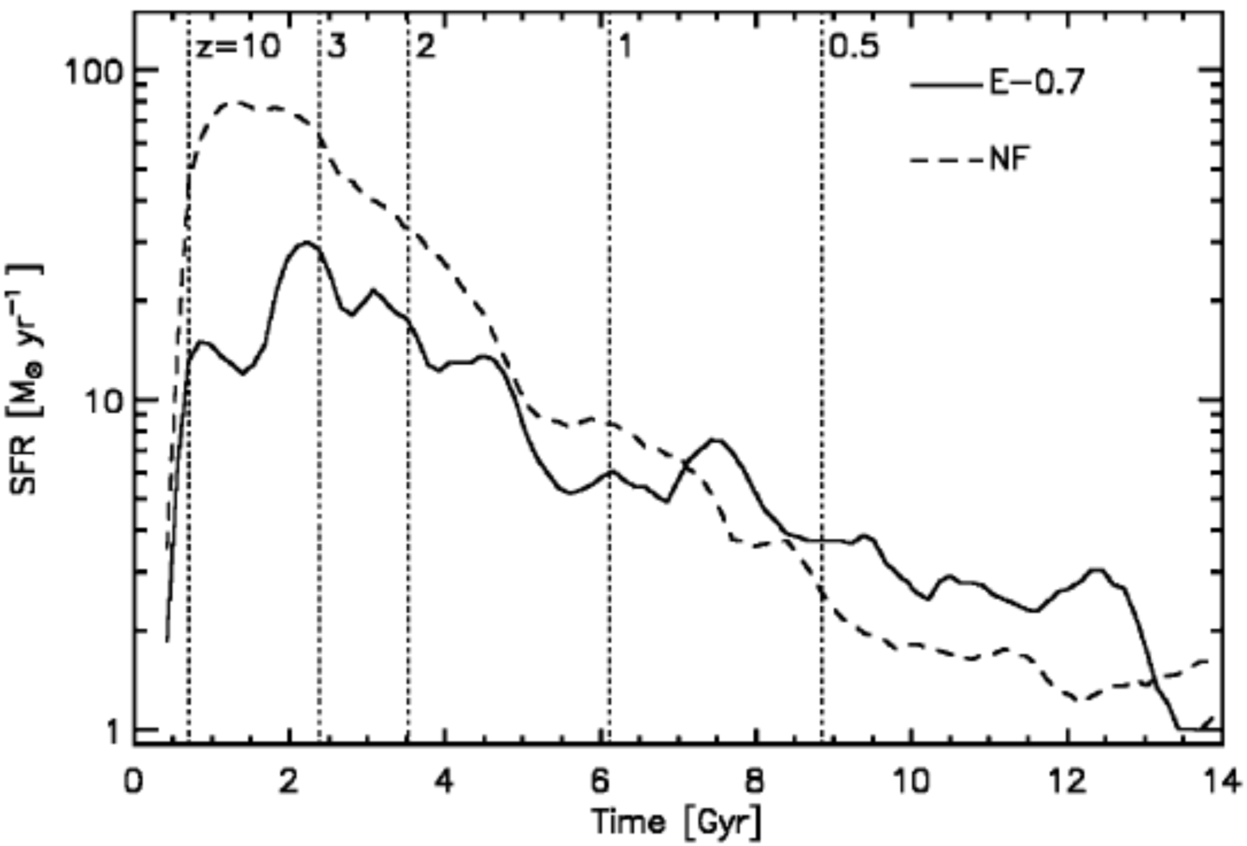
- Disks are unstable against rapid changes in the potential which occur during mergers/interactions/accretion

- Merger rate decreases with time in Λ-CDM
  → stellar disks need to form late to survive until present time

Movies: Volker Springel

Cosmological simulations with feedback

- Feedback regulates star formation through the heating and disruption of cold gas → more gas available to form stars later



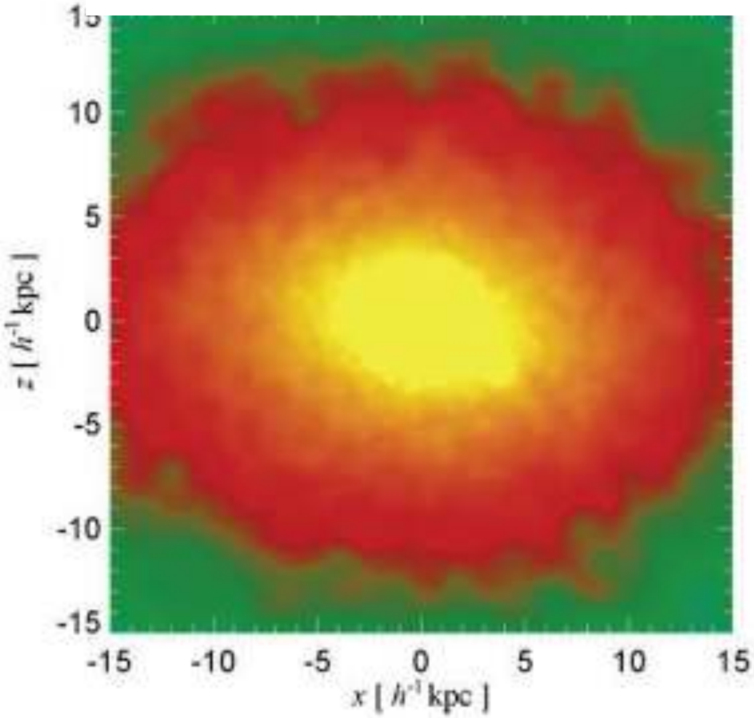
CS+ 2008

Cosmological simulations with feedback

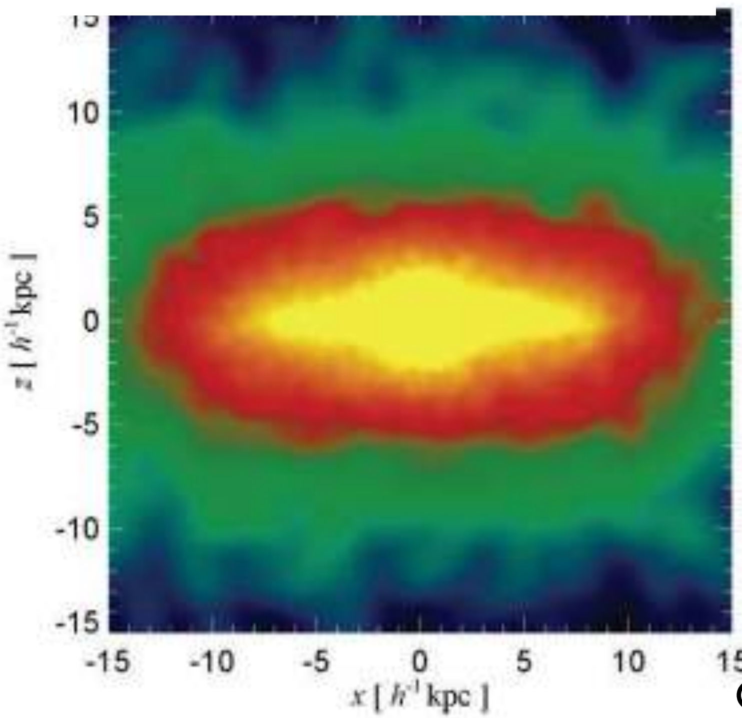
- Feedback regulates star formation through the heating and disruption of cold gas → more gas available to form stars later

  → formation of surviving stellar disks

Without SN feedback



With SN feedback

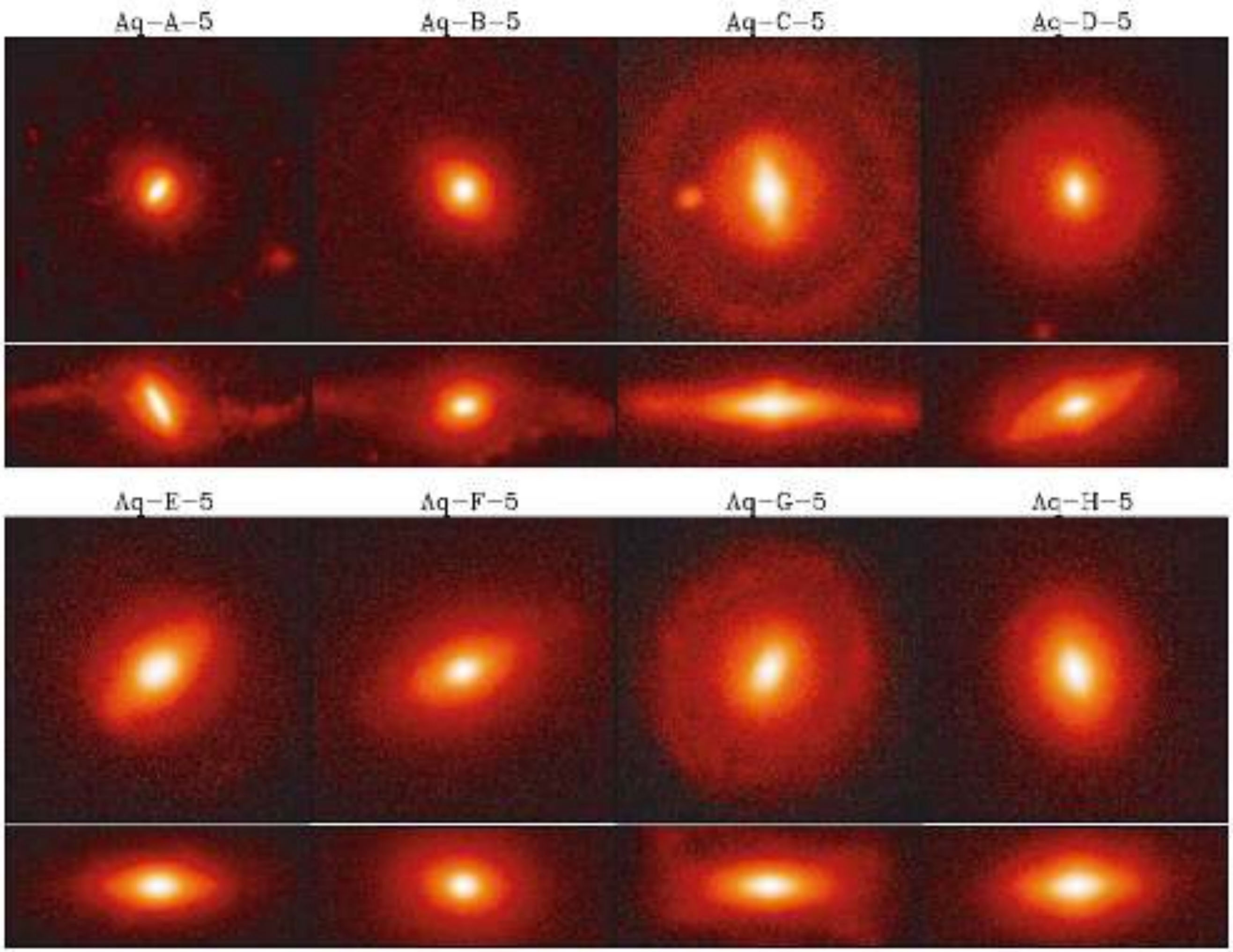


CS+ 2008

Galaxy disks

Simulations of 8 galaxies, MW-mass, mildly isolated

Projected stellar mass density

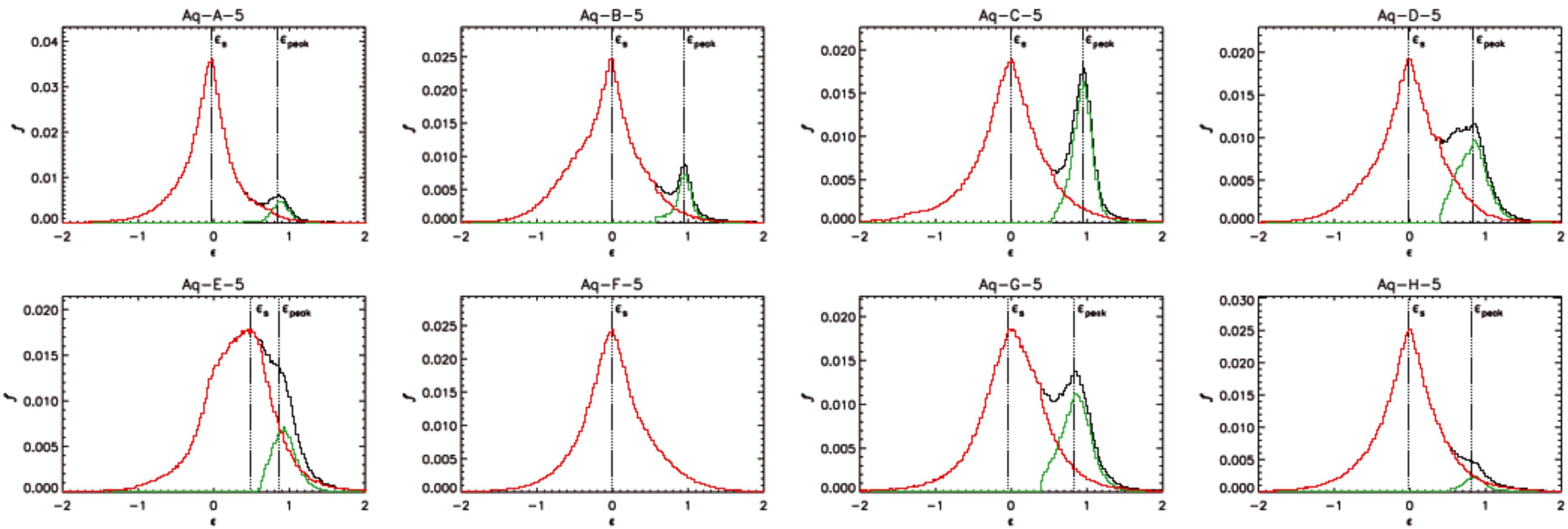


- Galaxies are diverse
- Some have dominant disks, others don't
- Some have bars

CS+ 2009

Galaxy disks

Separate into disk and spheroidal components to study disks

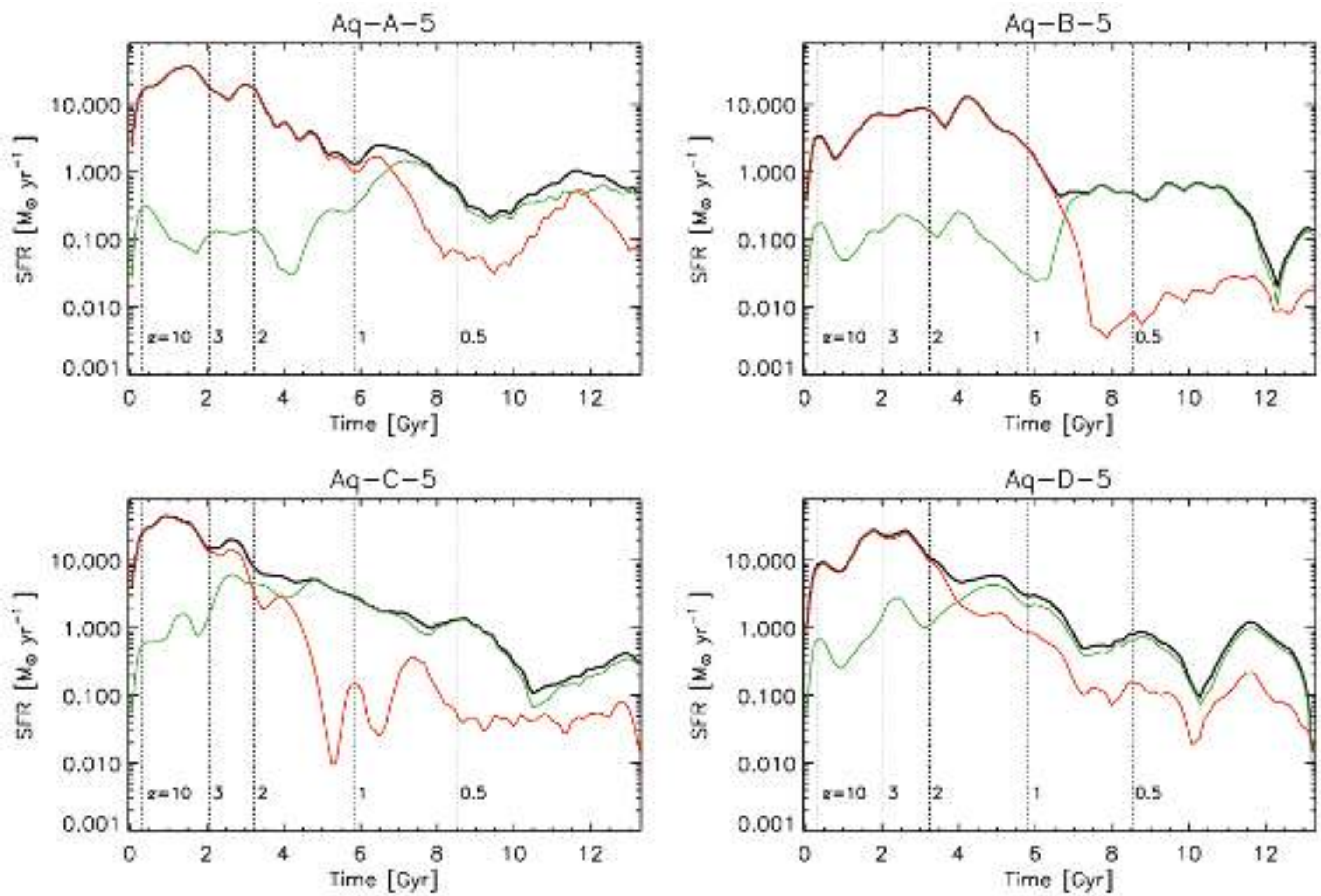


- "Circularity" $\varepsilon = J_Z/J_{circ}$
- Dynamical decomposition based on rotational velocity

CS+ 2009

Galaxy disks

- Disks form from late star formation (disks are young)



Total
Disk
Spheroid

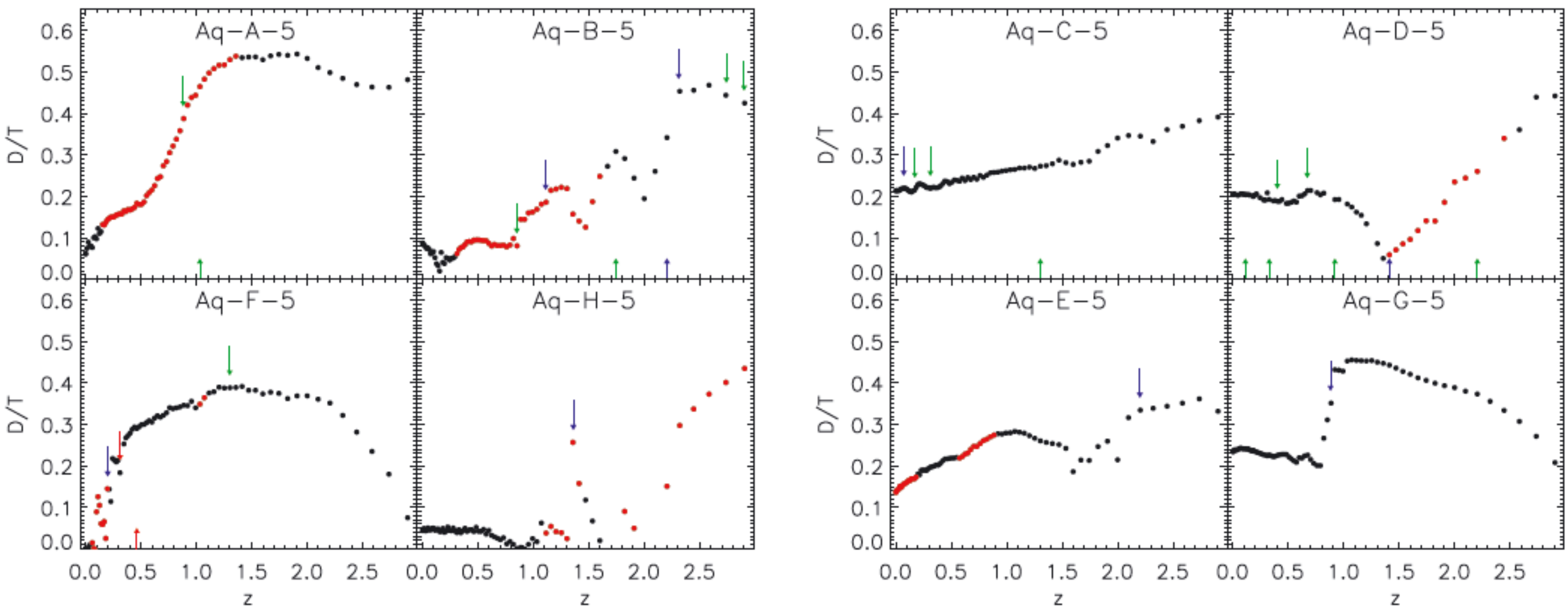
CS+ 2009

Galaxy disks

- Disks easily destroyed due to merger events and misaligned gas accretion

Galaxies with little/no disk at z=0

Galaxies with significant disks at z=0

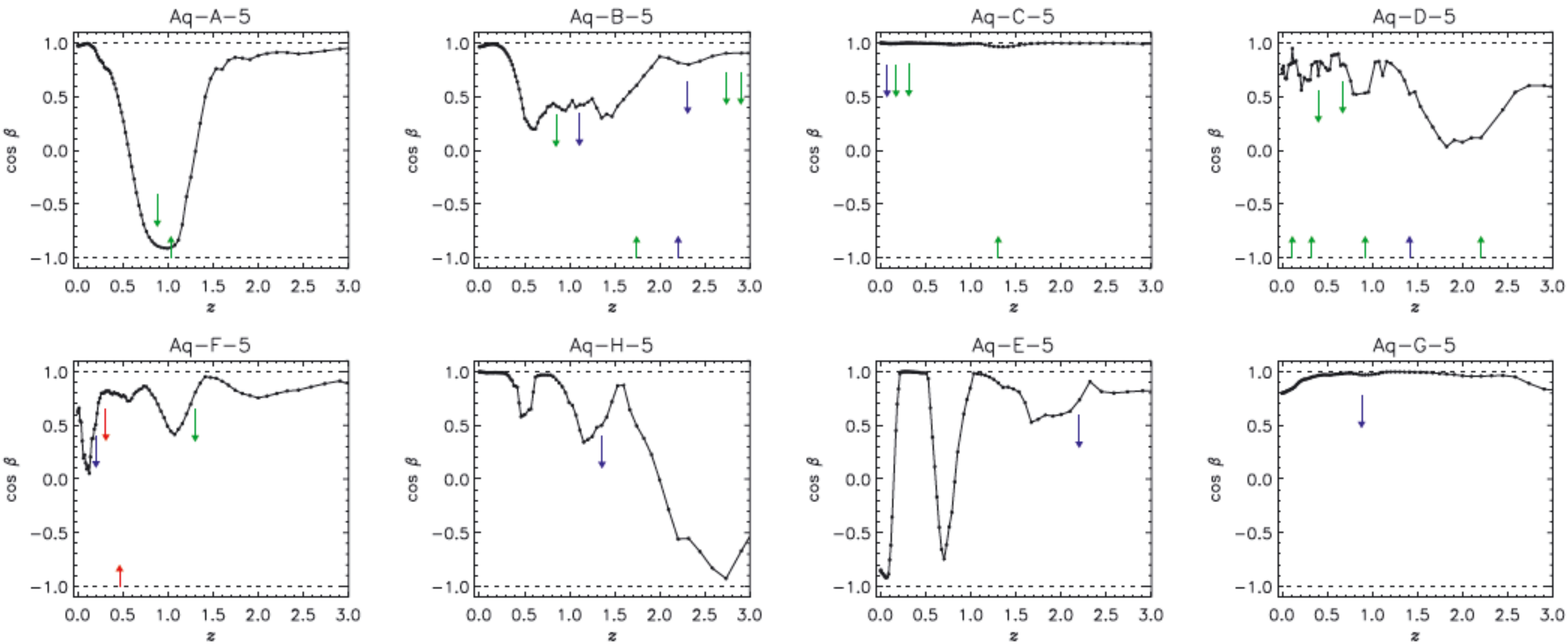


CS+ 2009

Galaxy disks

- Disks partially/totally destroyed during periods of misaligned gas accretion

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



β = angle between gas and stars

CS+ 2009

Outline

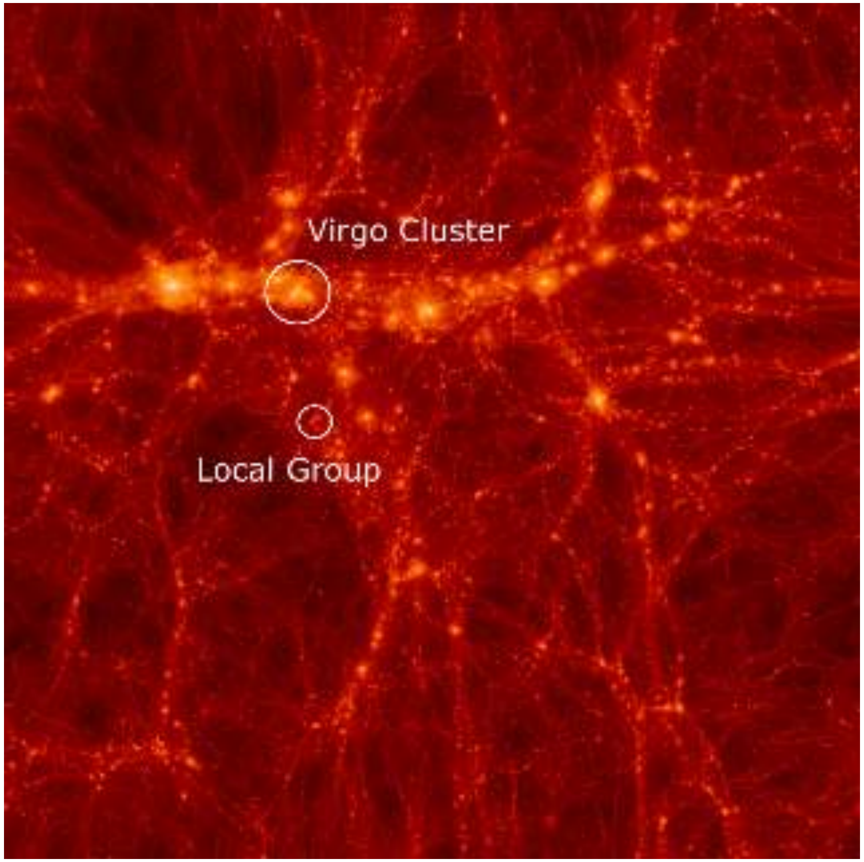
- Galaxies & cosmology
- The simulations
- Galaxy disks: formation, diversity, survival/destruction
- Galaxy diversity: environmental effects
- Discussion: successes, problems, challenges of current simulations
- Summary

The Milky Way: not an isolated galaxy

- Constrained Local UniversE simulations: CLUES

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

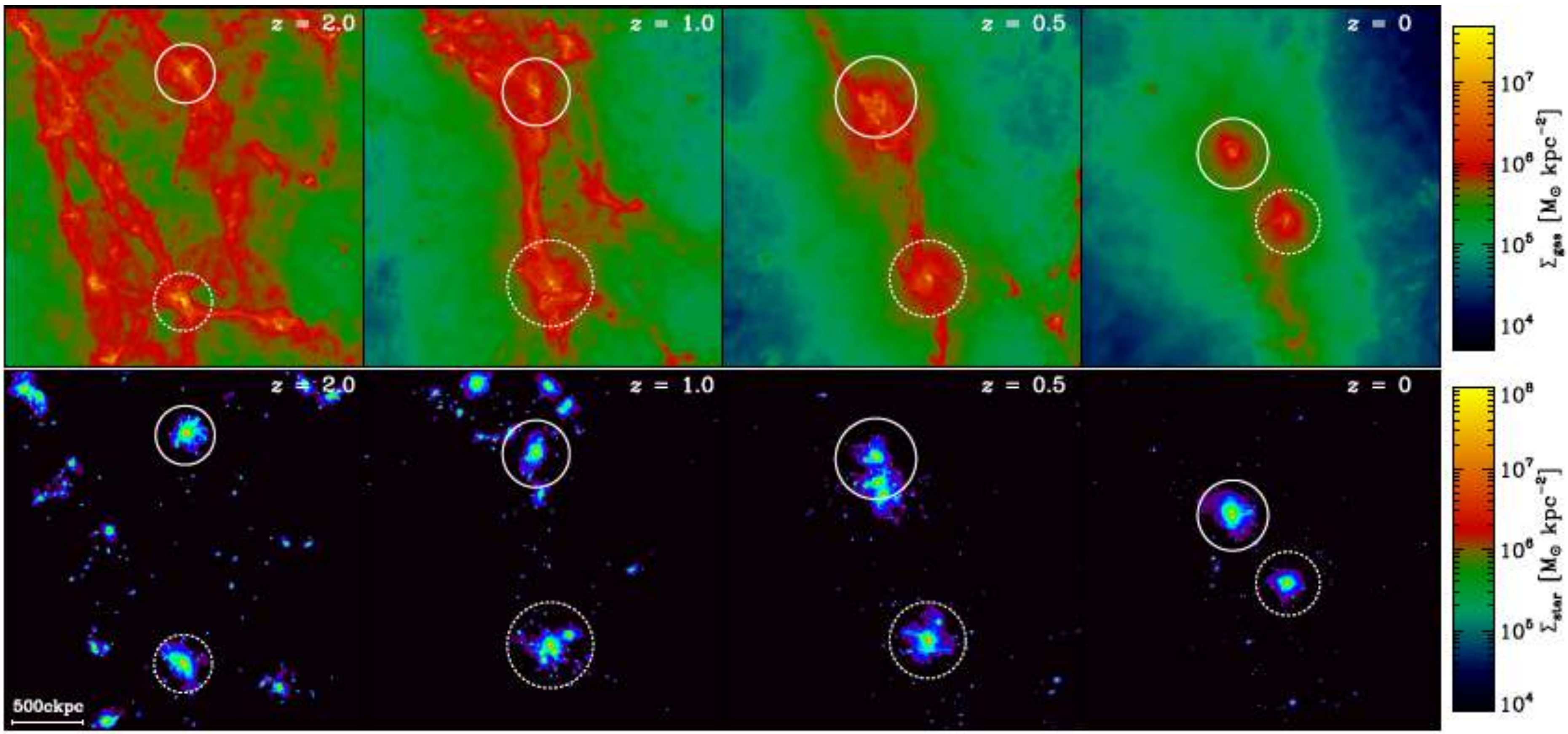
  - The Milky Way lives in the "Local Group"
  - Massive companion: the Andromeda spiral galaxy
  - Local Group is in an overdense region of the Universe, close to a large galaxy cluster



CS+2015

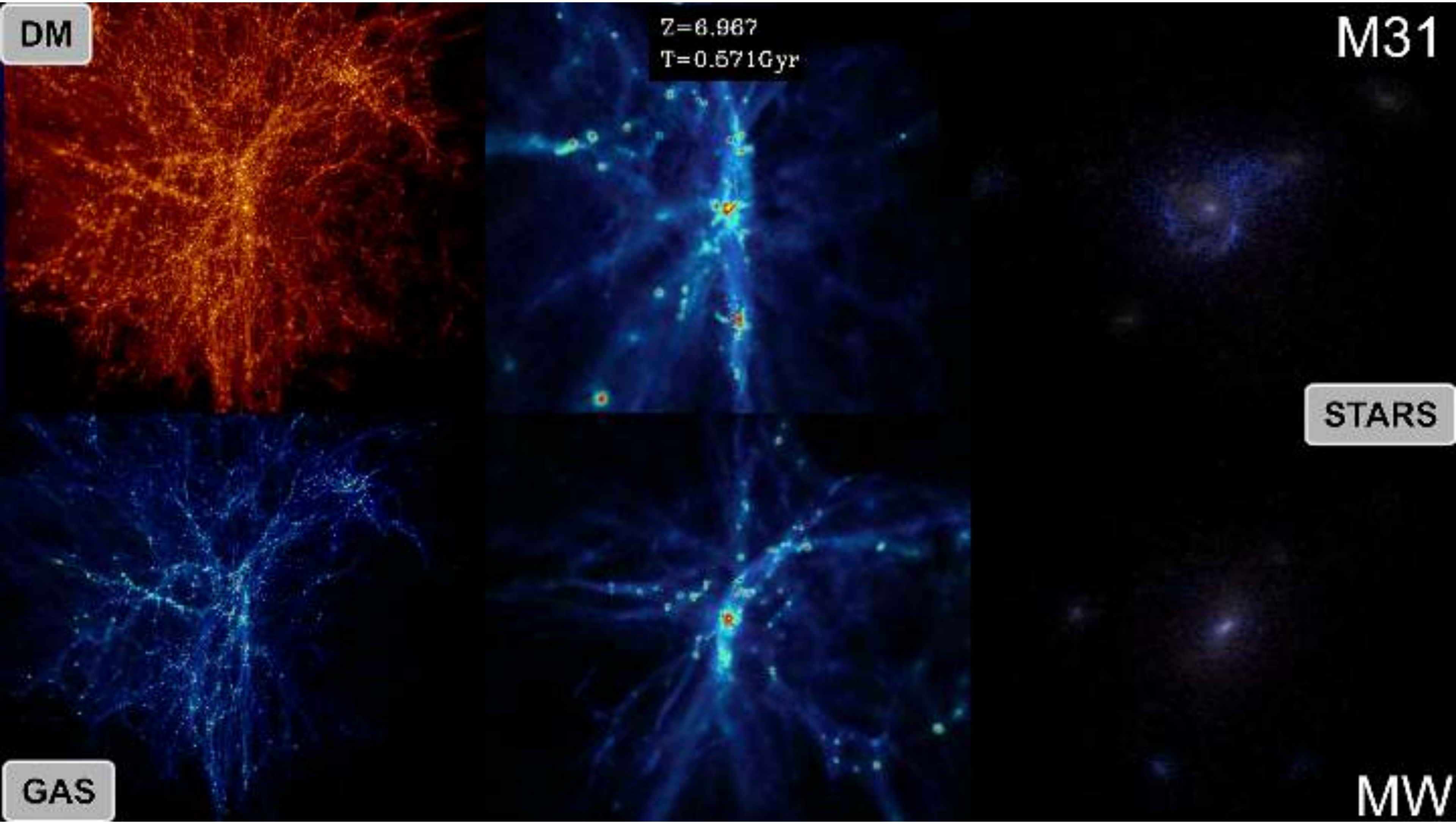
The Milky Way: not an isolated galaxy

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



CS+2015

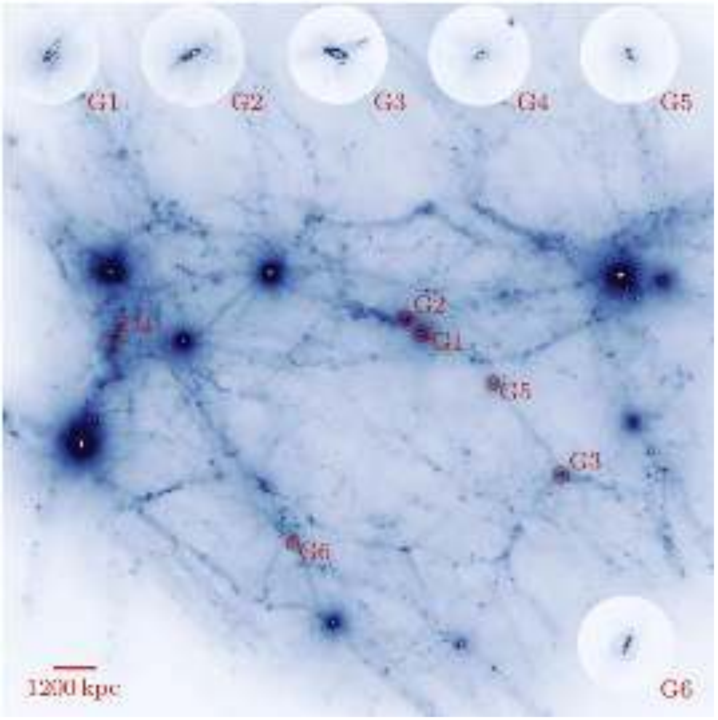
The Milky Way: not an isolated galaxy

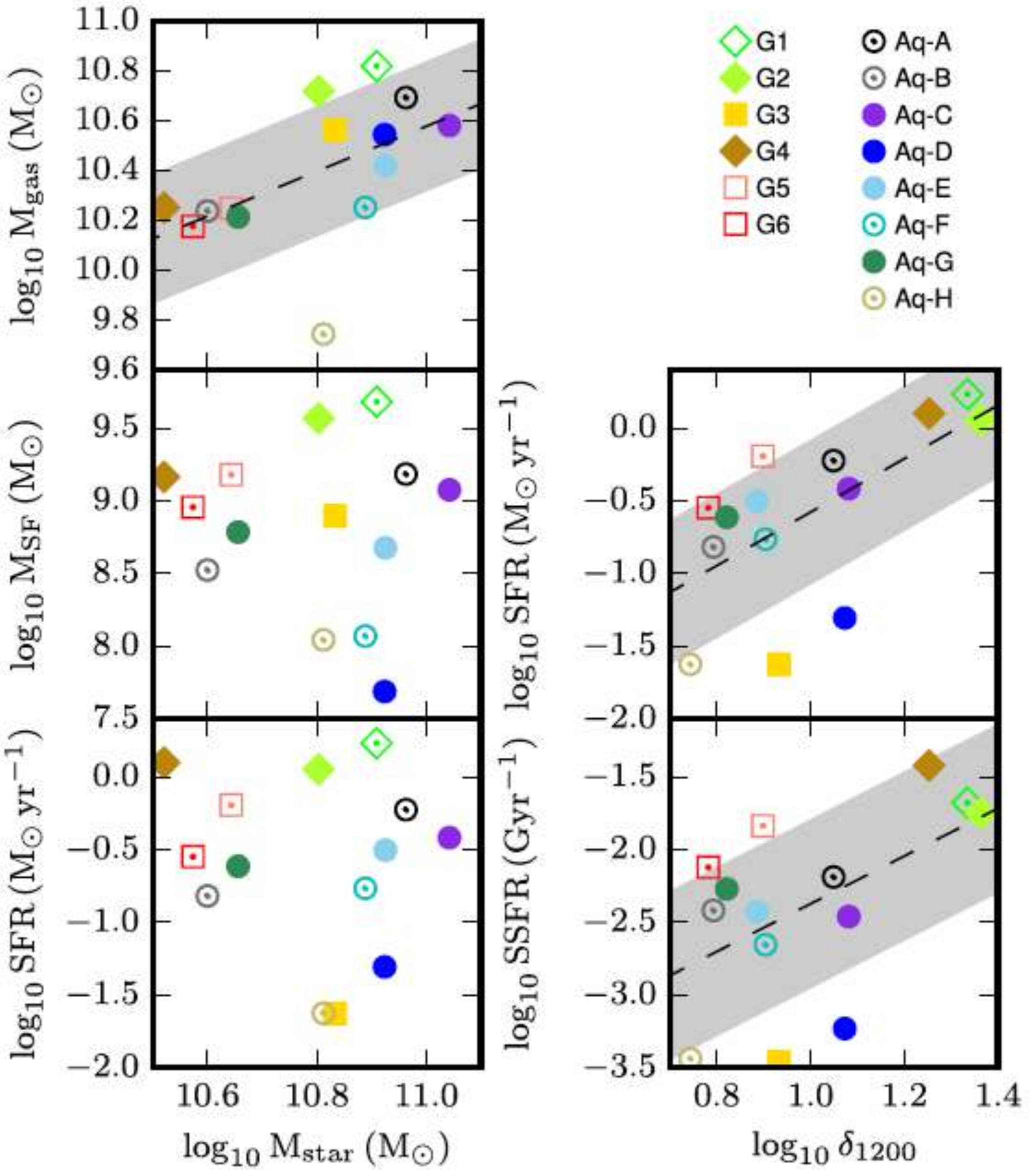


Simulation: C. Scannapieco, Visualization: A. Khalatyan

The Milky Way: not an isolated galaxy

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





Creasey+2015

Outline

- Galaxies & cosmology
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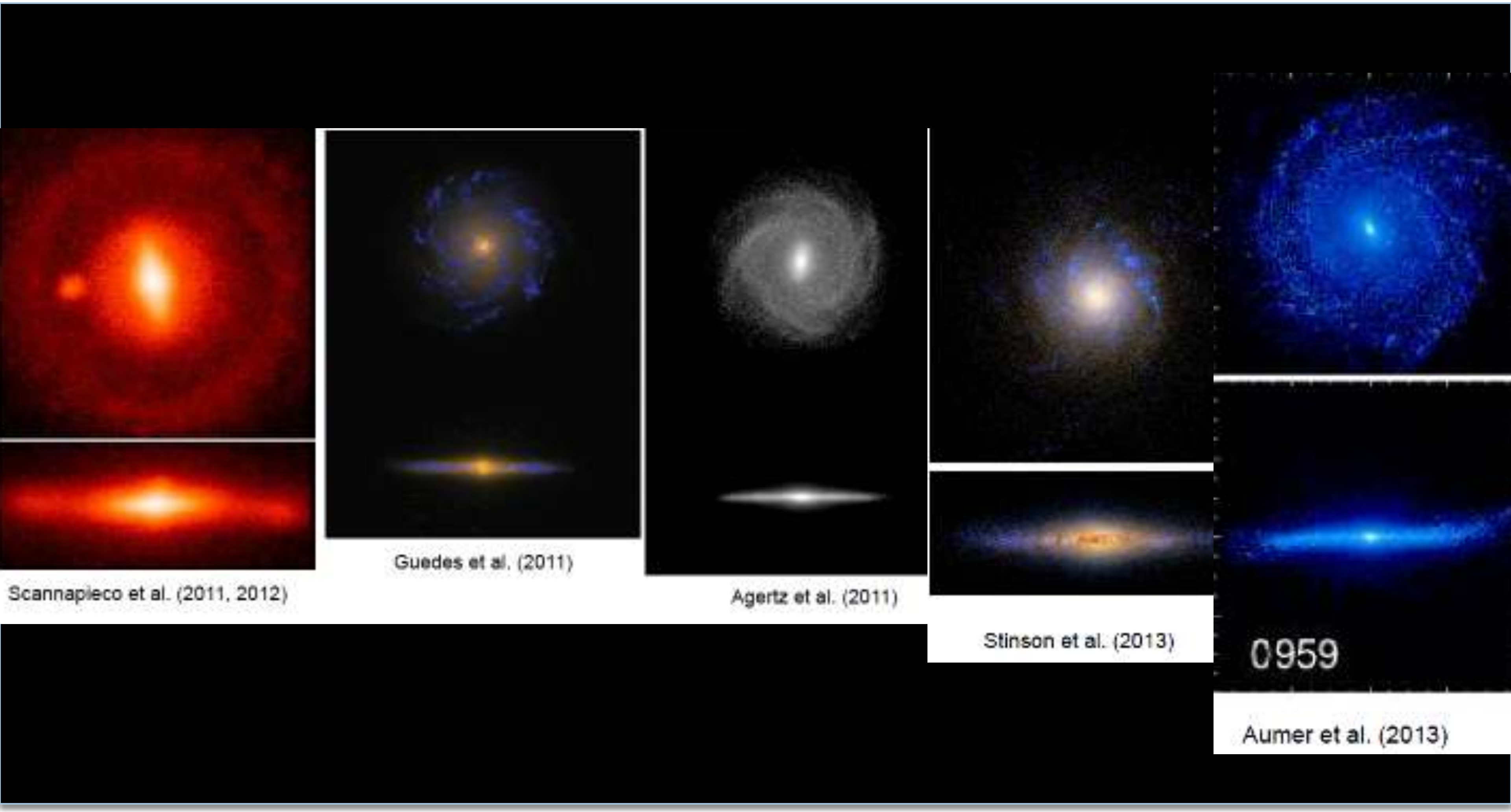
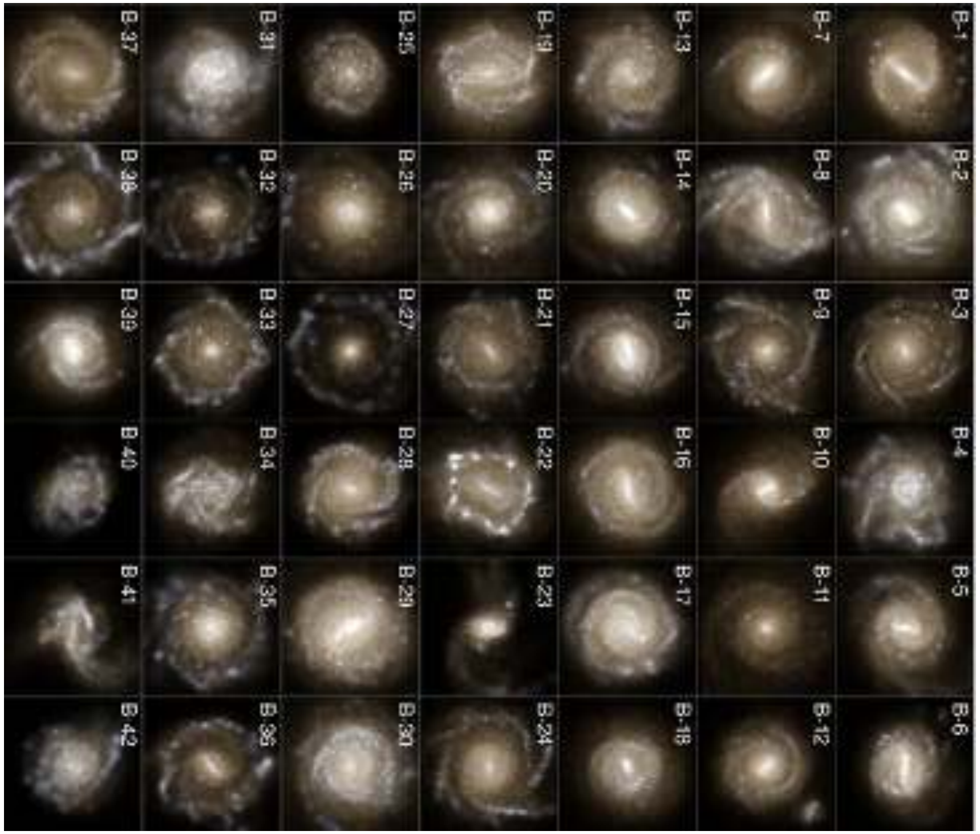
Successes, problems, challenges

- Disks formed in cosmological simulations



Successes, problems, challenges

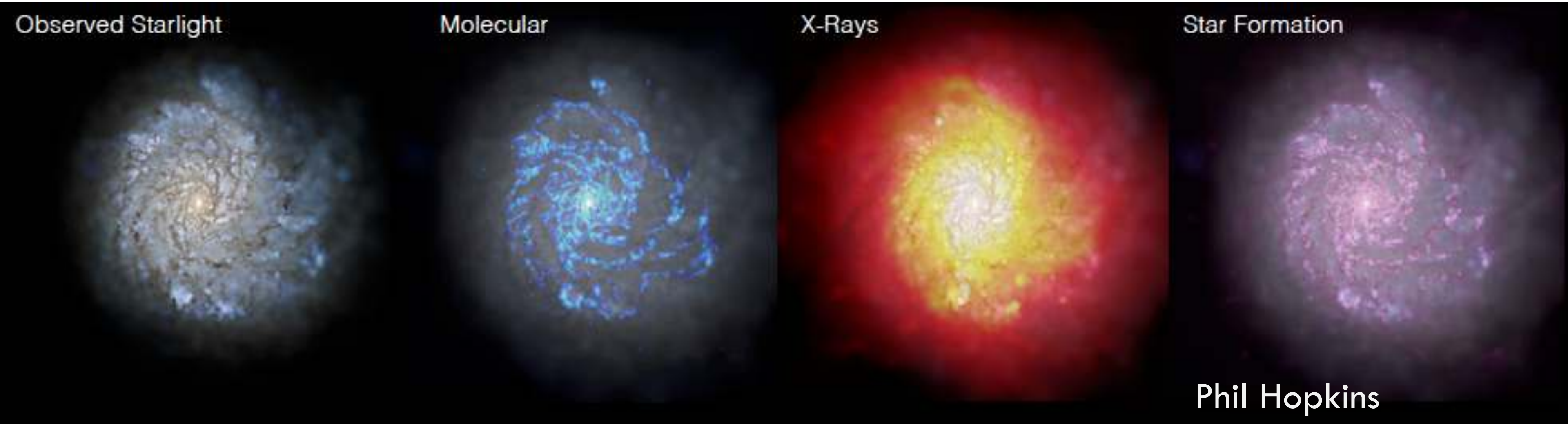
- Disks formed in cosmological simulations
- Codes are starting to simulate large numbers of galaxies and reproducing e.g. relative abundance of disks and bulges



The Illustris Simulation

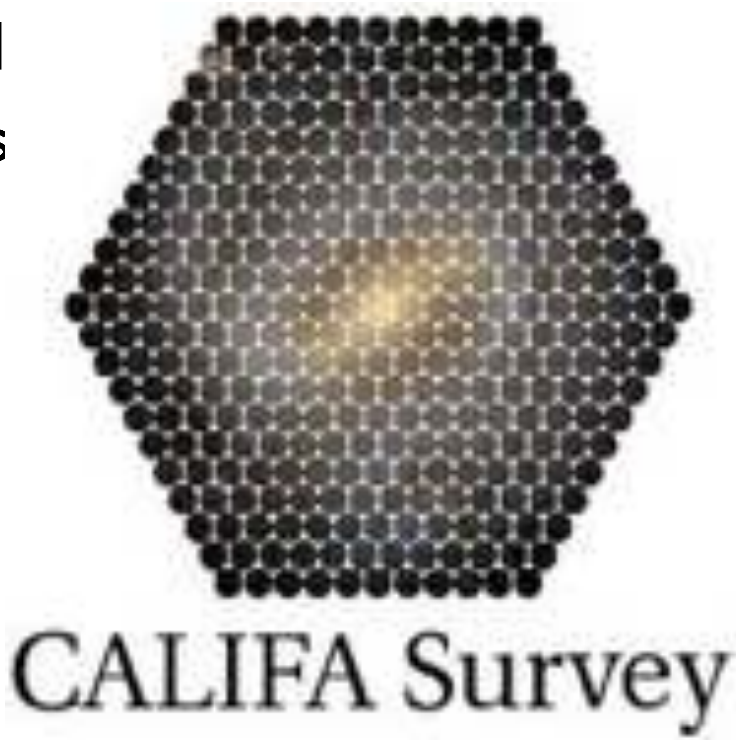
Successes, problems, challenges

- Disks formed in cosmological simulations
- Codes are starting to simulate large numbers of galaxies and reproducing e.g. relative abundance of disks and bulges
- Simulations are giving detailed distribution (& evolution) of stars and gas in different phases



Successes, problems, challenges

- Disks formed in cosmological simulations
- Codes are starting to simulate large numbers of galaxies and reproducing e.g. relative abundance of disks and bulges
- Simulations are giving detailed d of stars and gas in different phas
- New observations provide 2D distribution of stars & gas in galaxies



Successes, problems, challenges

- Different codes, different galaxies?

The Aquila Code Comparison Project (CS+2012)

Monthly Notices
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ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **423**, 1726–1749 (2012) doi:10.1111/j.1365-2966.2012.20993.x

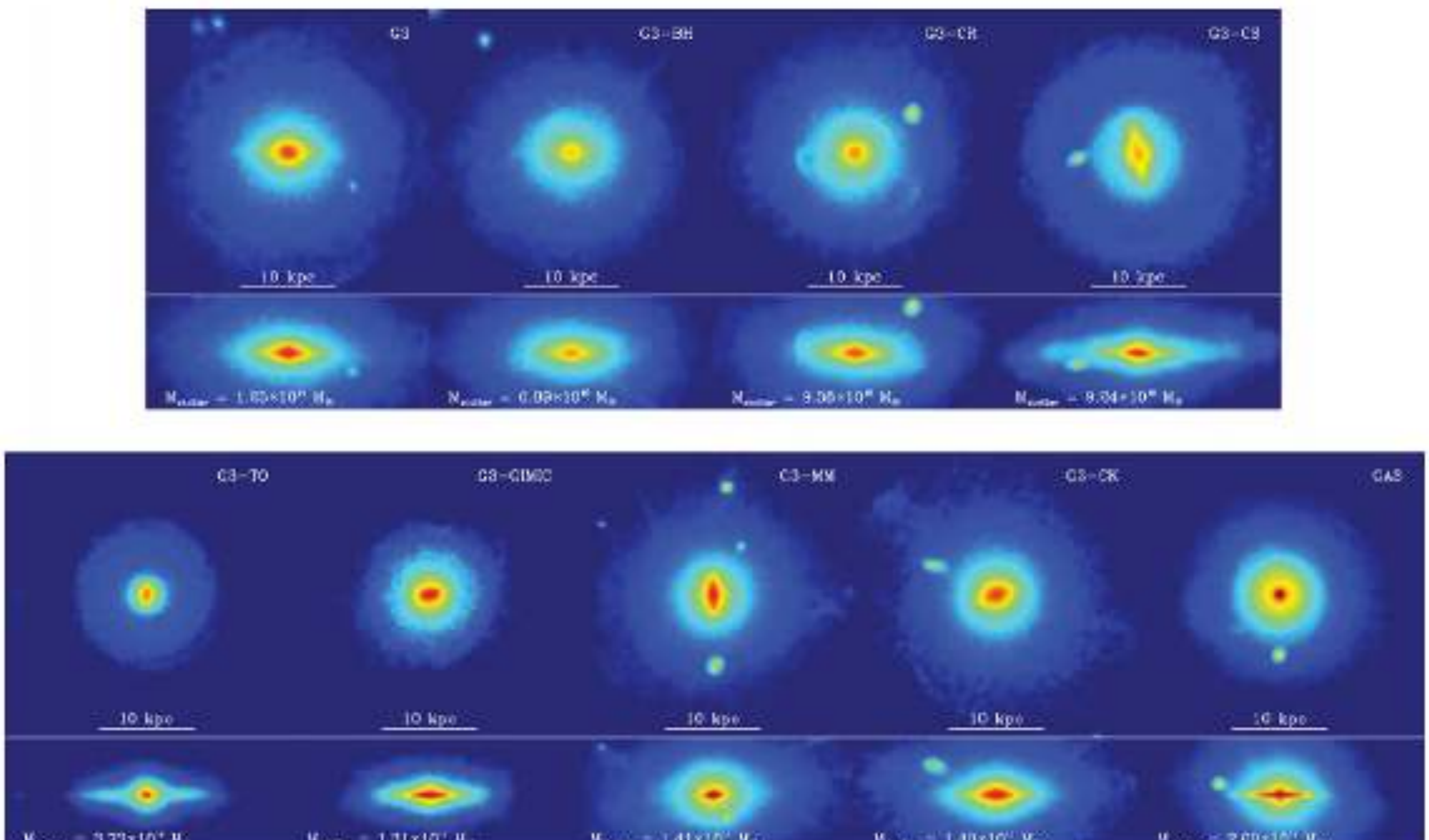
The Aquila comparison project: the effects of feedback and numerical methods on simulations of galaxy formation

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

Successes, problems, challenges

- Different codes, different galaxies?

The Aquila Code Comparison Project (CS+2012)

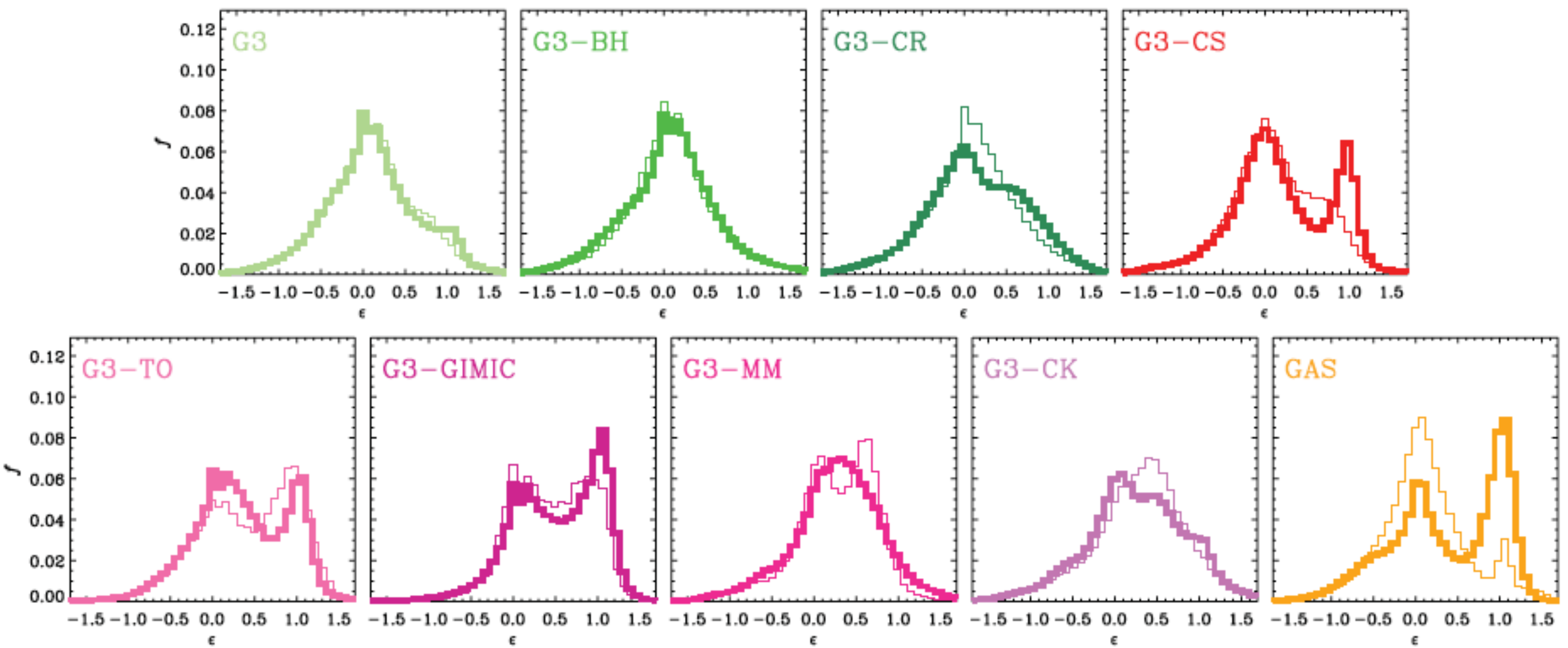


Successes, problems, challenges

- Different codes, different galaxies?

The Aquila Code Comparison Project (CS+2012)

Different codes, different galaxies?

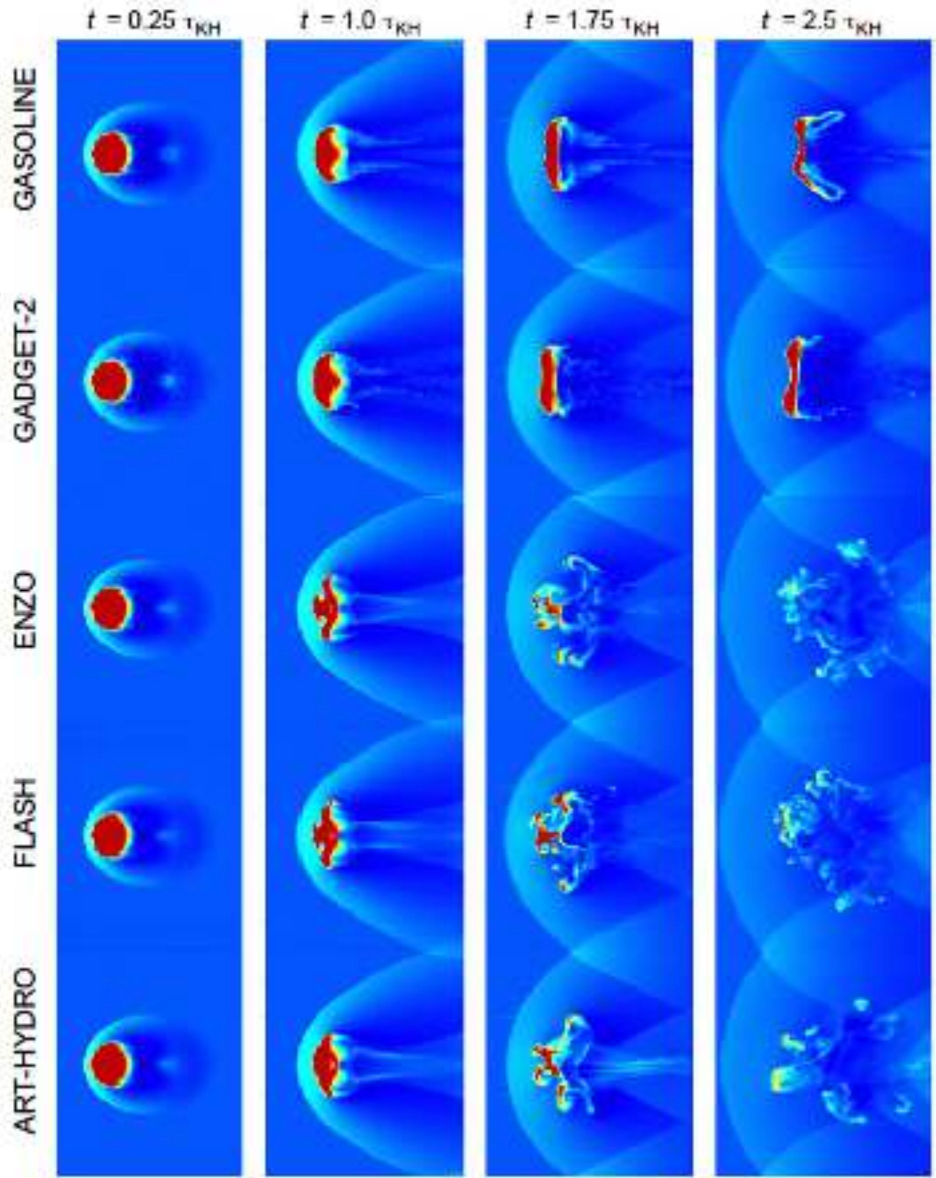


Successes, problems, challenges

- Different codes, differer

The Aquila Code Comparis

- Numerics?



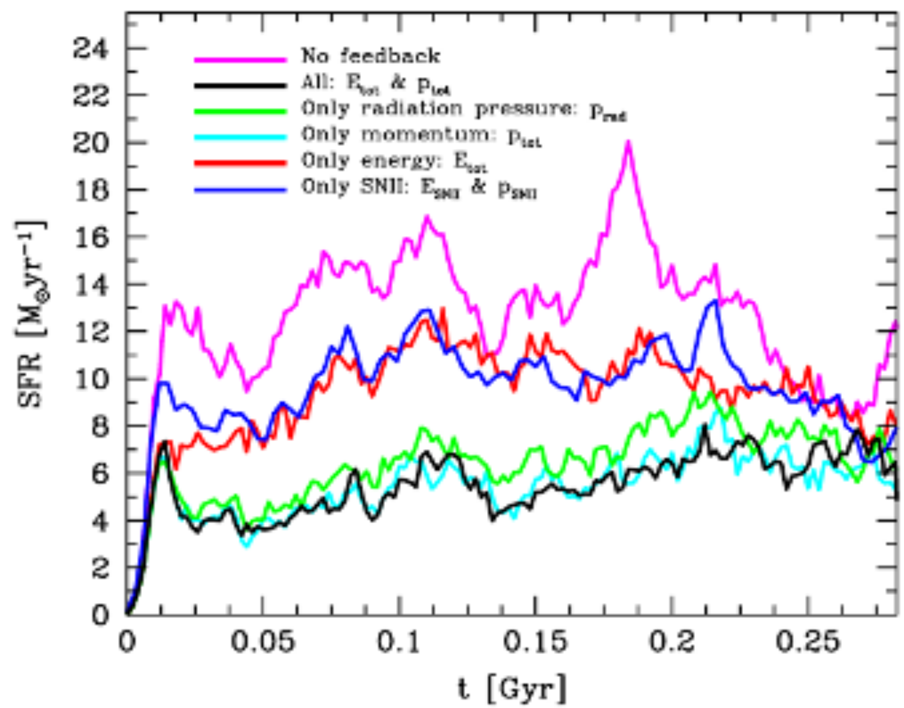
Agertz+ 2007

Successes, problems, challenges

- Different codes, different galaxies?

The Aquila Code Comparison Project (CS+2012)

- Numerics?
- Physics?
  - Only SN relevant for MW-galaxies?
  - Radiation-pressure feedback?
  - Black-hole feedback?



Agertz+ 2007

Summary

- Galaxy formation is a complex process, closely connected to formation of structure at larger scales

- Simulations help us understand relevant physics
  - Galaxy diversity originated in variety of formation histories
  - Disks are young
  - Disks are transient
  - Disks can be rebuilt
  - Environmental effects on Milky Way might be relevant

- Galaxy formation simulations are also needed to understand the structure and evolution of dark matter halos!