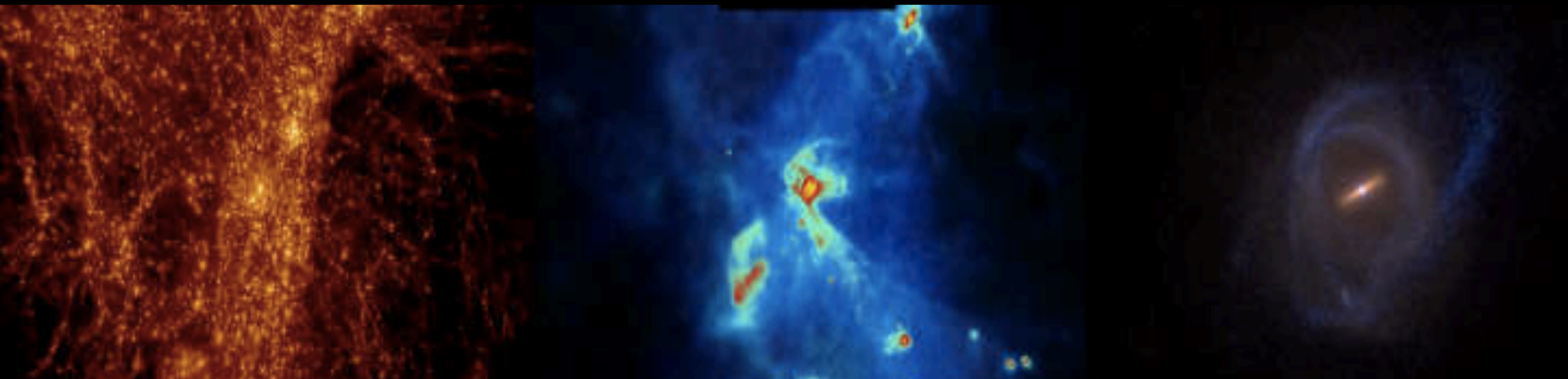
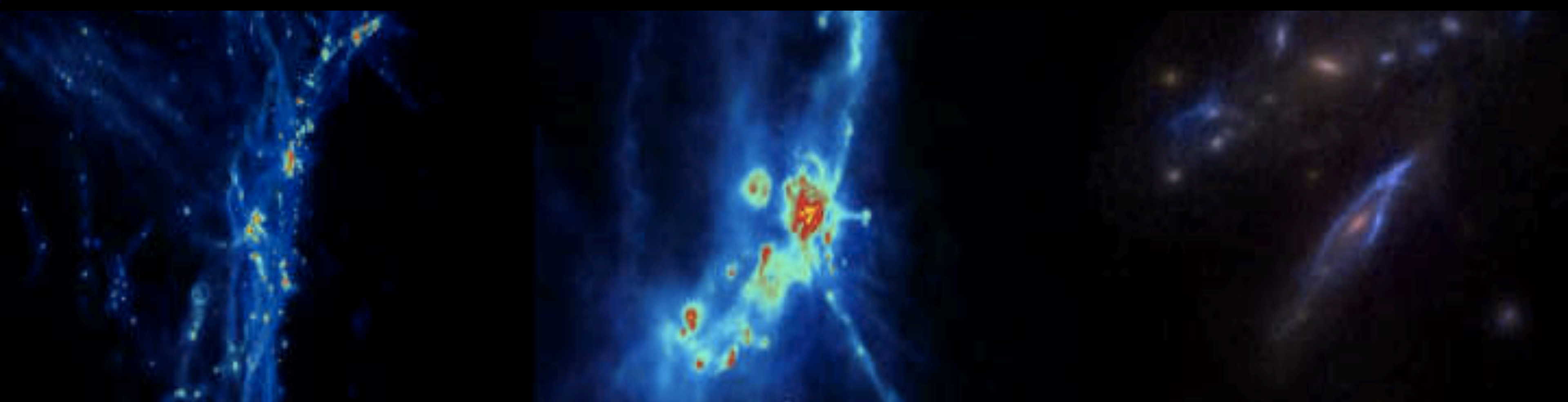
The formation of disc galaxies in computer simulations



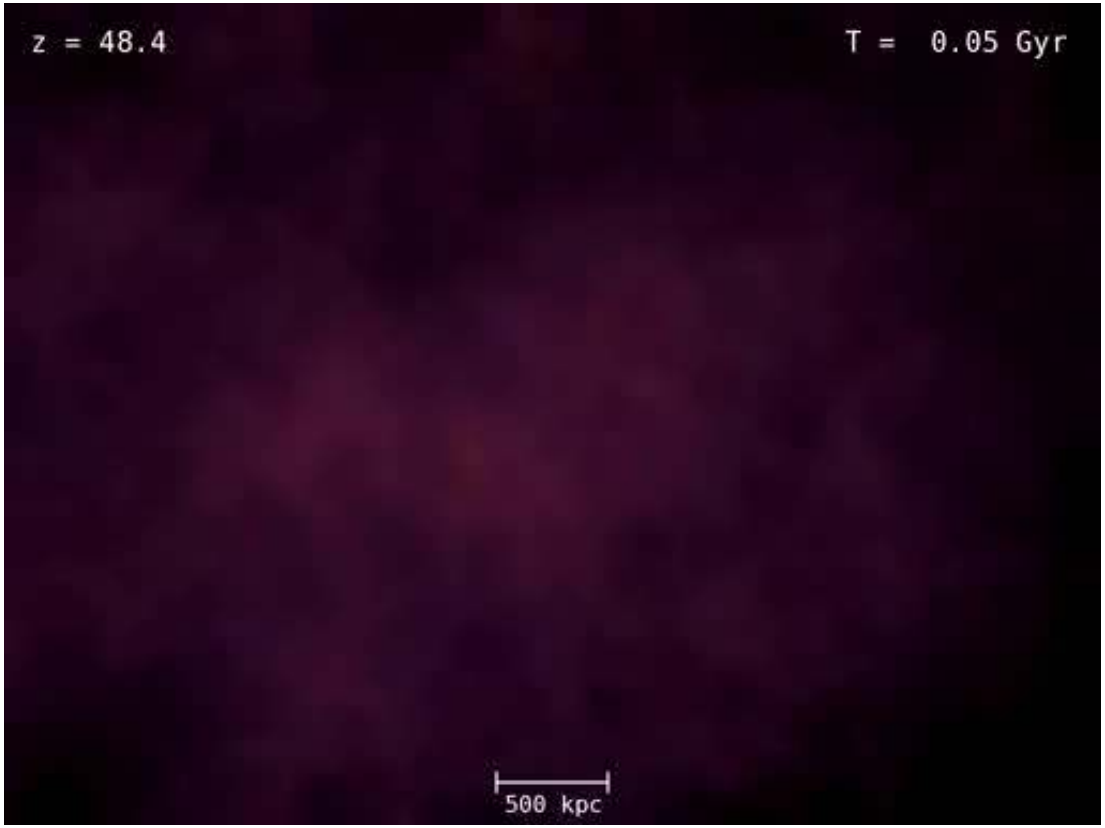
Cecilia Scannapieco

Departamento de Física, FCEyN, Universidad de Buenos Aires



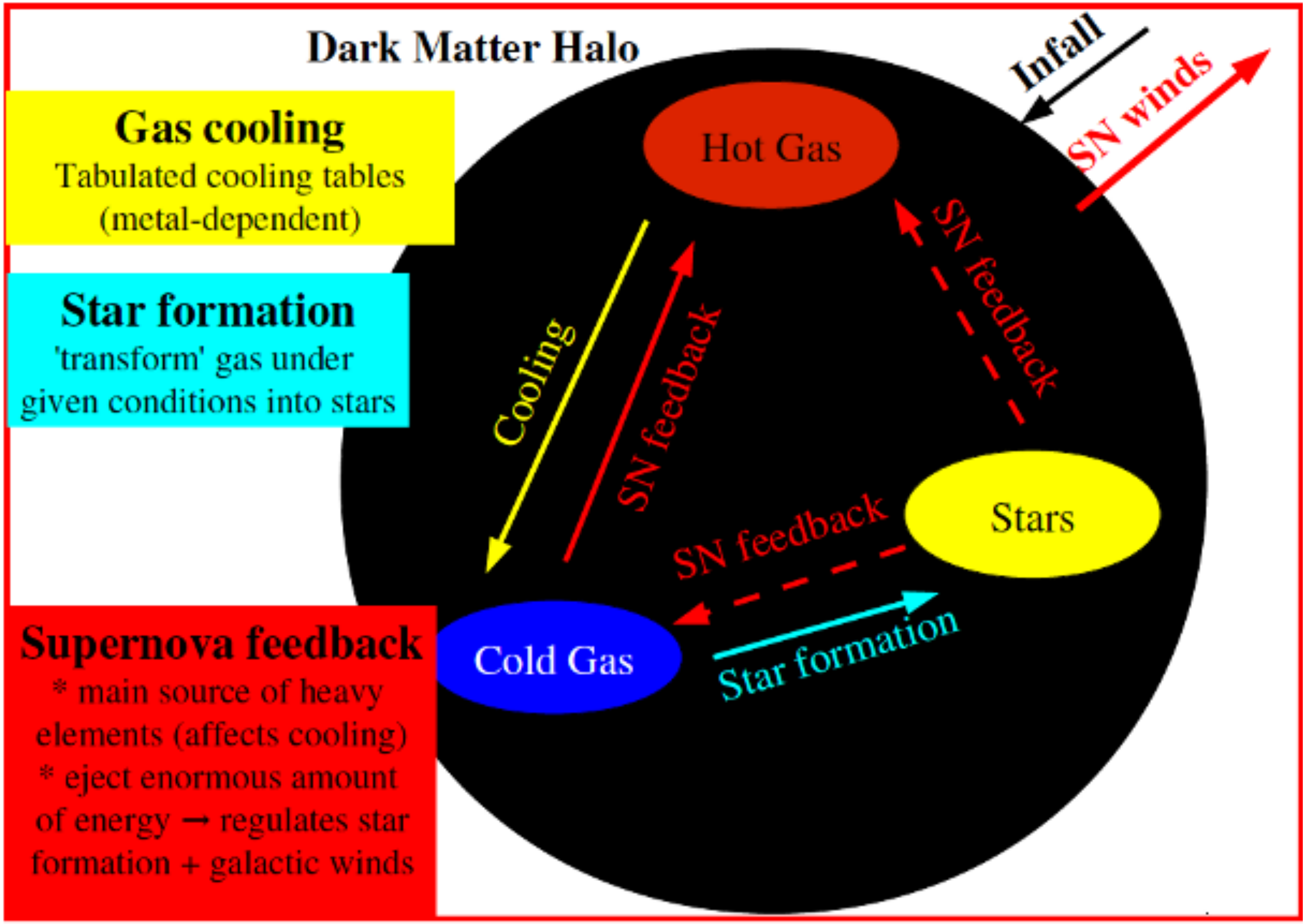
Galaxy formation physics

- Halo & galaxy formation is a highly non-linear, multi-scale process that requires the use of numerical simulations



Credit:
V. Springel

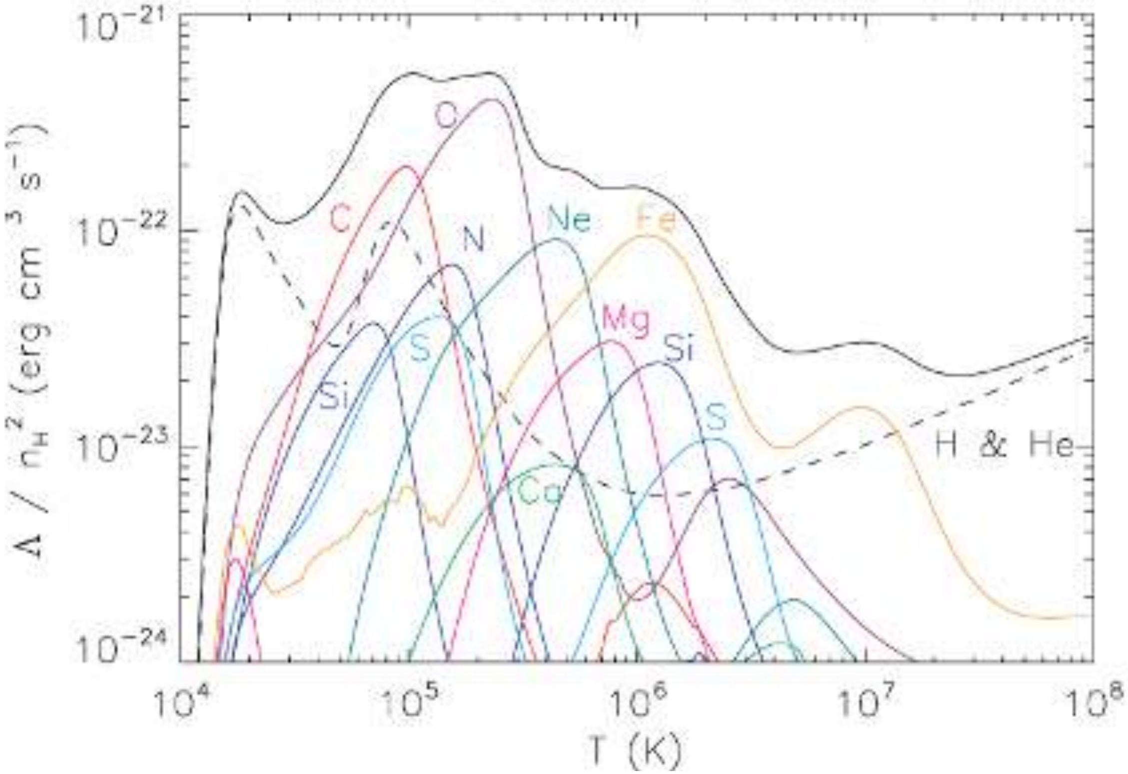
Galaxy formation physics



Galaxy formation physics

Dark Matter halos form via gravitational instability	GRAVITY
Gas cools down and condenses into the centers of the haloes	COOLING
High-density gas fragments and forms stars	STAR FORMATION
Feedback due to stellar evolution returns energy and chemical elements to the interstellar medium	FEEDBACK

Galaxy formation physics



Photoionization & chemical composition effects are important

Wiersma et al. 2009

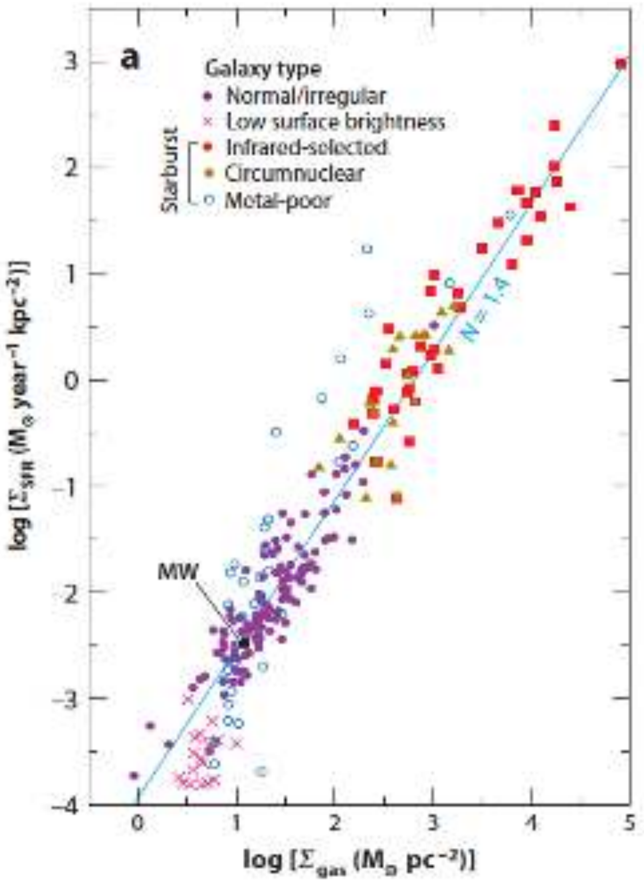
GRAVITY

COOLING

STAR FORMATION

FEEDBACK

Galaxy formation physics



Star formation is unresolved in the simulations.

Still many uncertainties:

- High vs low-mass star formation
- Initial Mass Function (IMF): universal, time-dependent?
- Pop-III (metal-free) stars

In simulations:
Kennicutt-Schmidt law
(Kennicutt+2012)

GRAVITY

COOLING

STAR FORMATION

FEEDBACK

Galaxy formation physics

Feedback: in the absence of feedback, too high SFRs and stellar masses

→ need a physical process that reheats the gas or prevents it from cooling

Supernova (SN) explosions ~ dwarf to MW-mass galaxies

Active Galactic Nuclei (AGN) ~ massive galaxies

Other, under-dominant (?) processes at galaxy scales under debate

GRAVITY

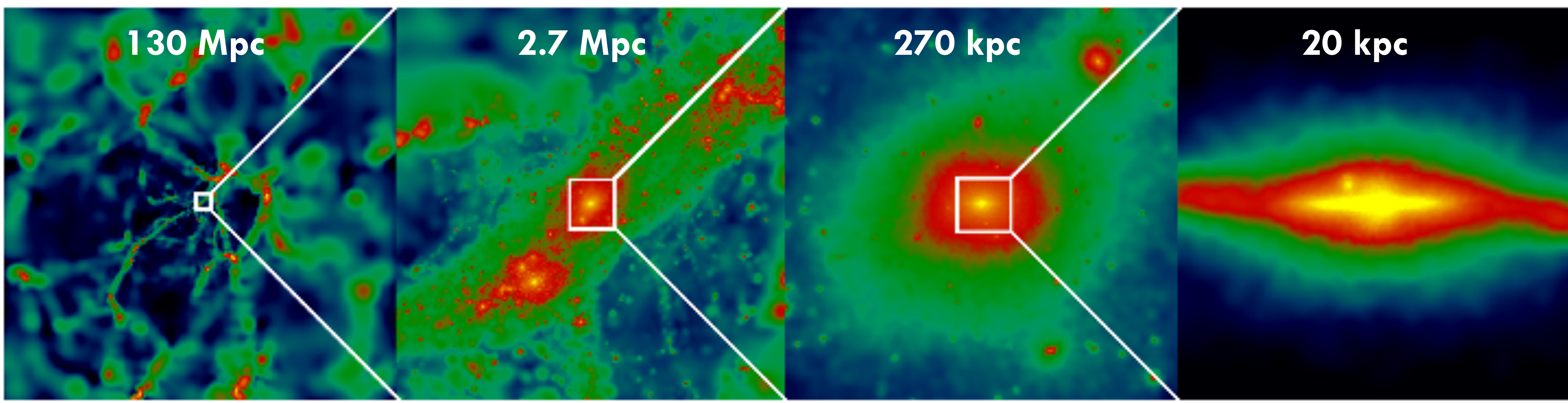
COOLING

STAR FORMATION

FEEDBACK

Galaxy formation simulations

1. Start with an Initial Condition, e.g. consistent with cosmological concordance model
2. Run the simulation (including relevant physics), optimize computational cost, e.g. use zoom-in technique



3. Check whether results are consistent with observational results/ expectations

Galaxy formation physics

- Galaxies are not isolated

- Mergers/interactions with other systems
  - Change galaxy morphology – depends on angular momentum
  - Induce instabilities (e.g. bars)
  - Affect star formation and chemical properties
- Accretion of gas from intergalactic medium (IGM)
  - Contributes gas with different abundance patterns
  - Enhances star formation (provided it penetrates the halo)
- Galactic winds
  - Mixing of gas enriched within galaxies with gas in the IGM
  - Mixing of gas within halos – galactic fountains

Galaxy formation physics

- Galaxies are not isolated

→ GALAXY DIVERSITY!!

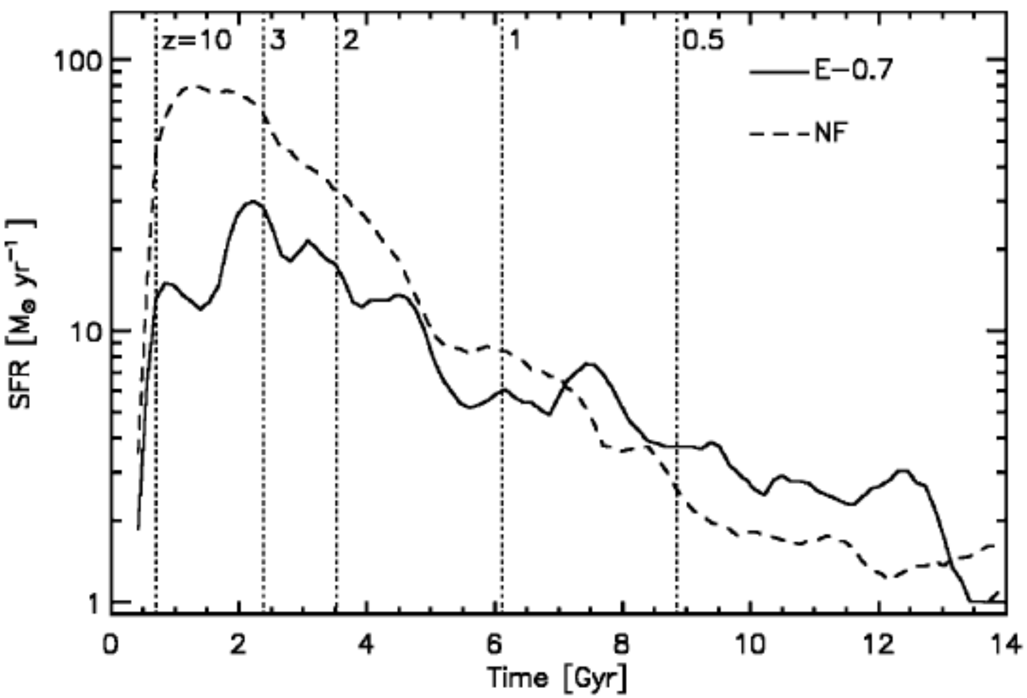
Outline

- Feedback in galaxy formation simulations
  - effects of Supernova (SN) feedback
  - variations between models
- Galaxy disks
  - diversity
  - survival/destruction
- Galaxy diversity
  - environment
- Discussion:
  - other types of feedback?
- Summary

SN Feedback in galaxy formation

Without feedback mechanisms, the gas efficiently cools down and forms stars. In a cosmological context, this results in:

→ inconsistent with observed SFRs/galaxy stellar masses



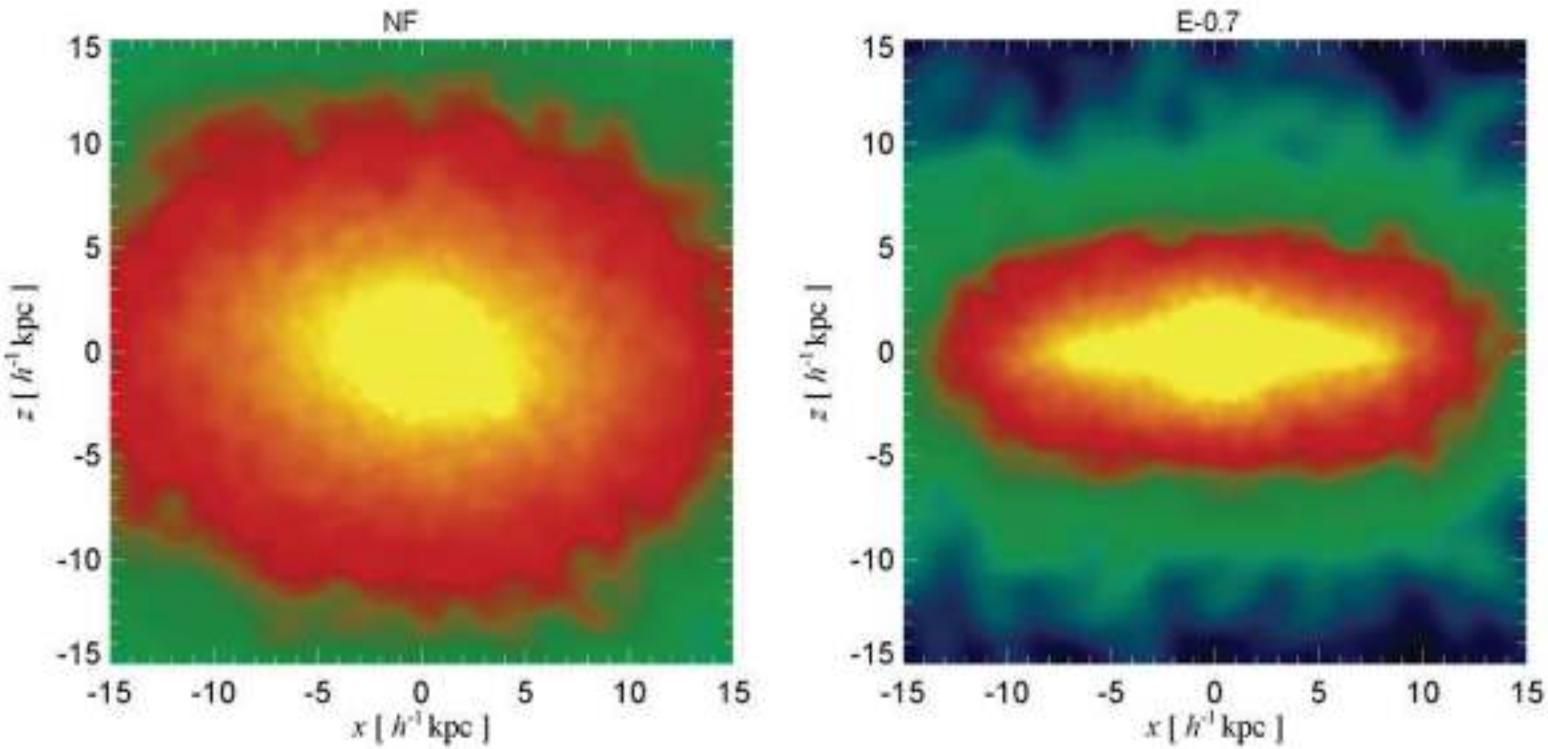
CS+ 2008

SN Feedback in galaxy formation

Without feedback mechanisms, the gas efficiently cools down and forms stars. In a cosmological context, this results in:

→ inconsistent with observed SFRs/galaxy stellar masses

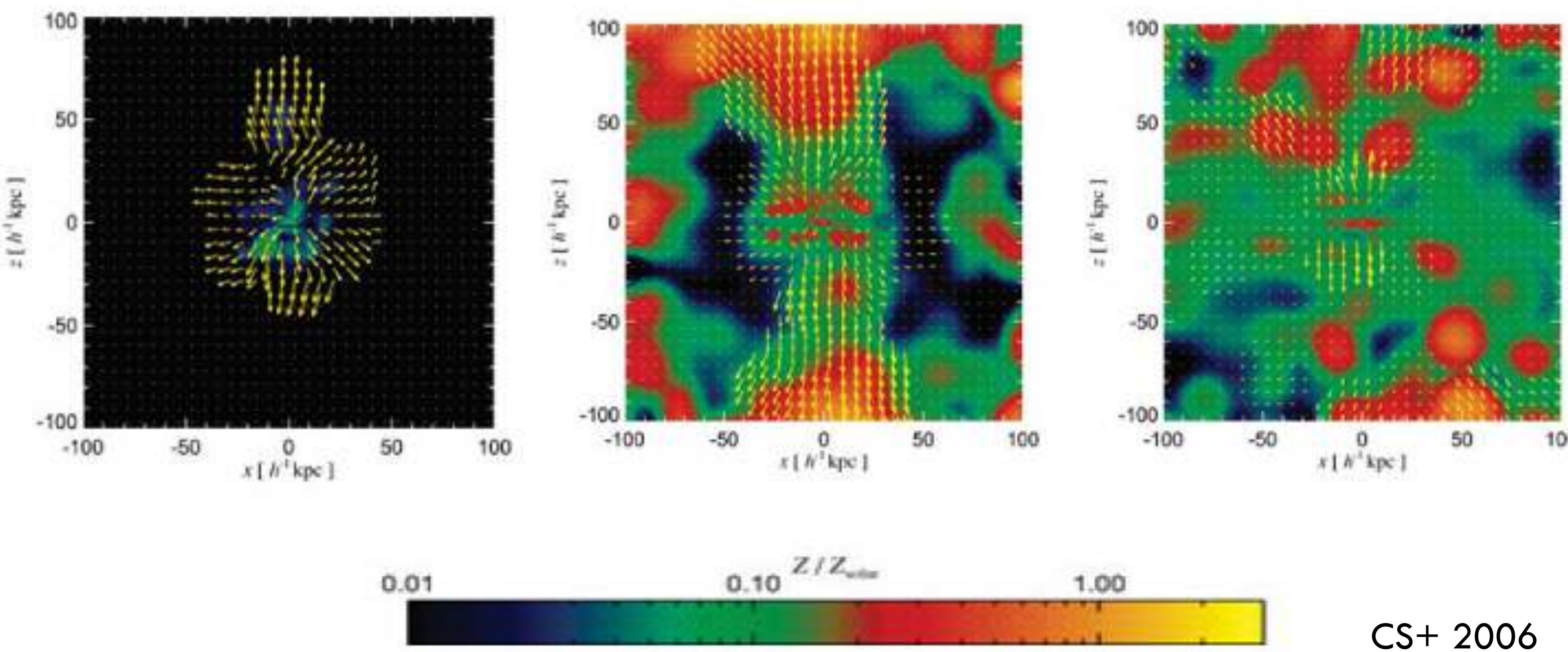
→ very high SFRs at early times → spheroidal, old galaxies



CS+ 2008

SN Feedback and metallicity

Winds triggered by SN explosions transport mass and metals into the ISM and IGM of galaxies



CS+ 2006

SN Feedback - problems

- How to implement feedback in simulations?
  - Ad-hoc winds versus cooling shutoff/delayed feedback
  - Input parameters needed, fine-tuning
  - Dependence on numerical choices, resolution

SN Feedback - problems

- How to implement feedback in simulations?
  - Ad-hoc winds versus cooling shutoff/delayed feedback
  - Input parameters needed, fine-tuning
  - Dependence on numerical choices, resolution

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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

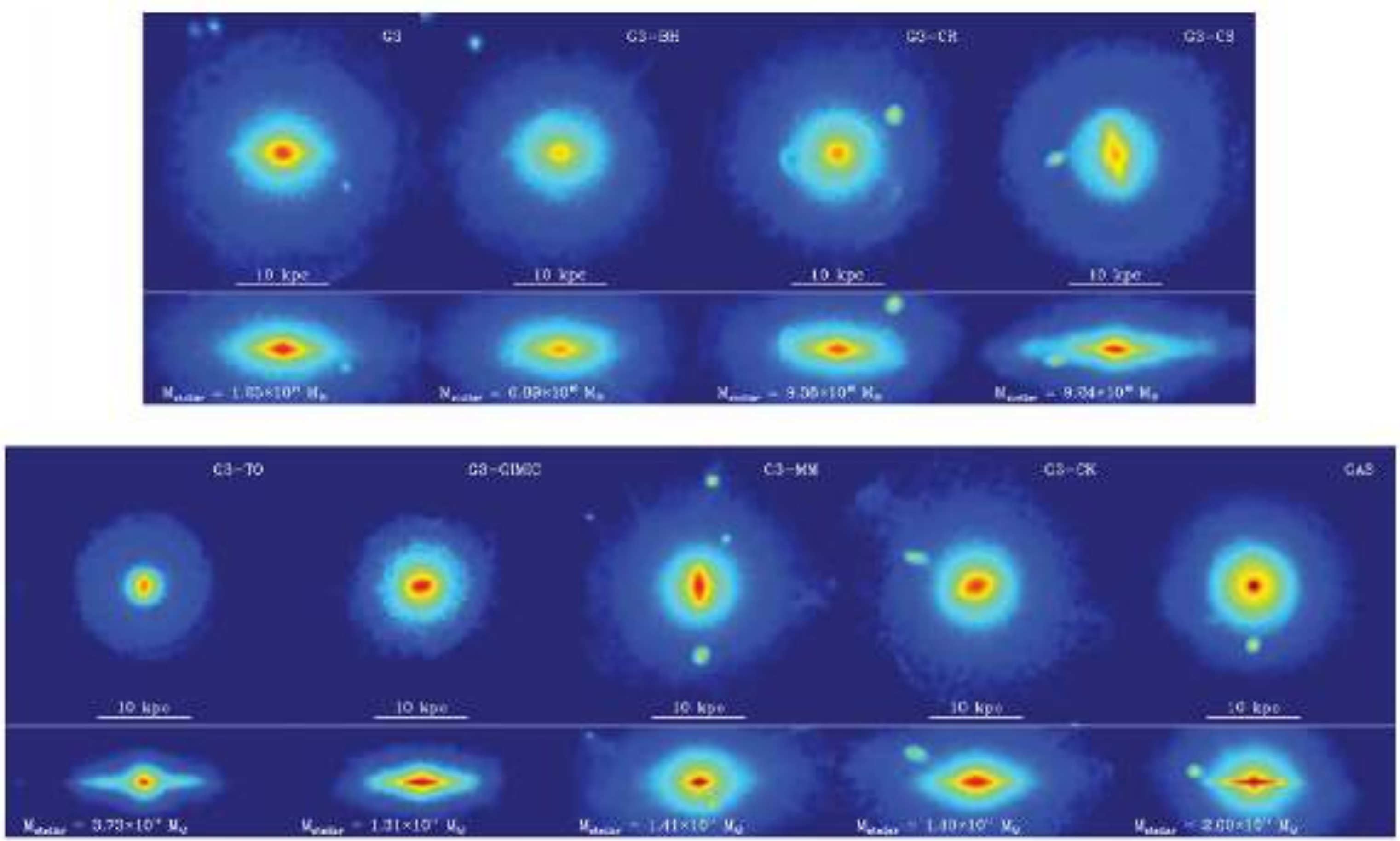
The Aquila comparison project: the effects of feedback and numerical methods on simulations of galaxy formation

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]

Aquila Project results

- Different codes predict different galaxy properties

  e.g. morphologies, gas fractions, SFRs, stellar masses, sizes



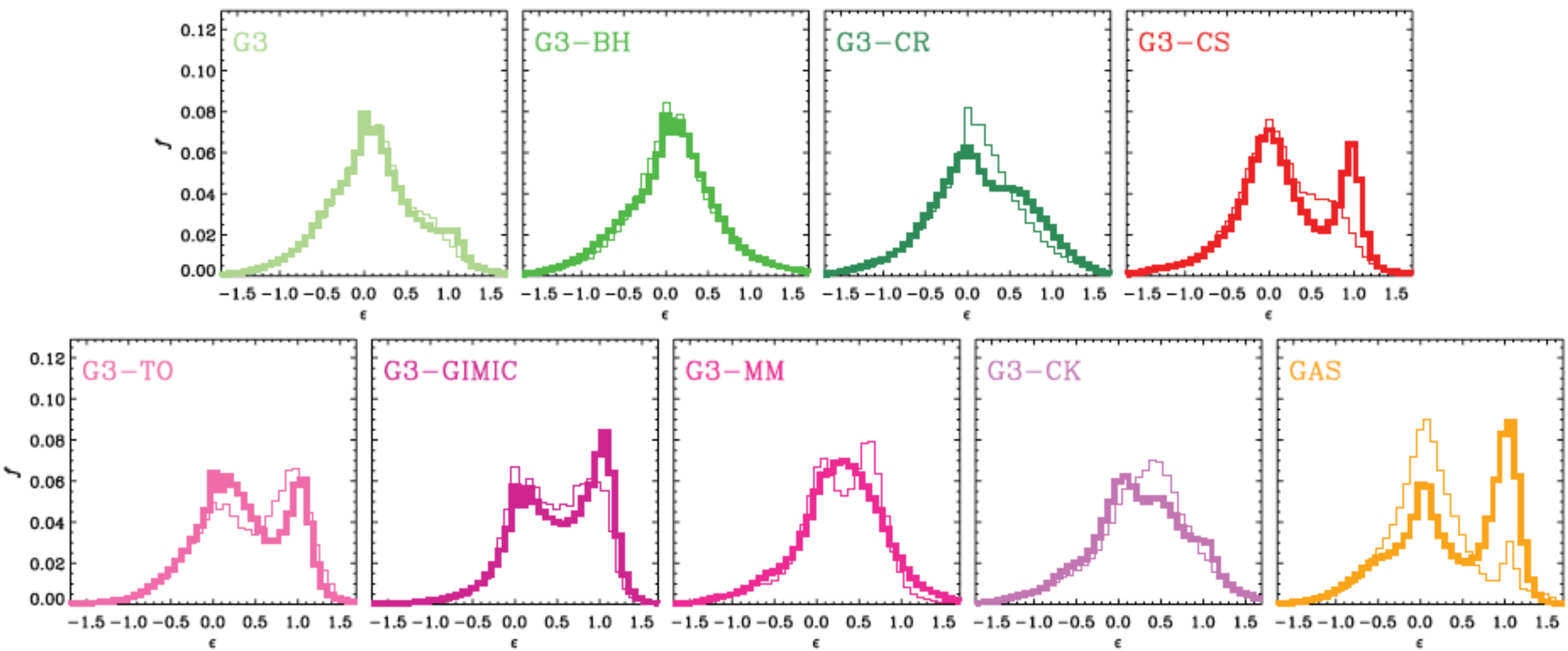
CS+ 2012

Aquila Project results

- Different codes predict different galaxy properties

  e.g. morphologies, gas fractions, SFRs, stellar masses, sizes

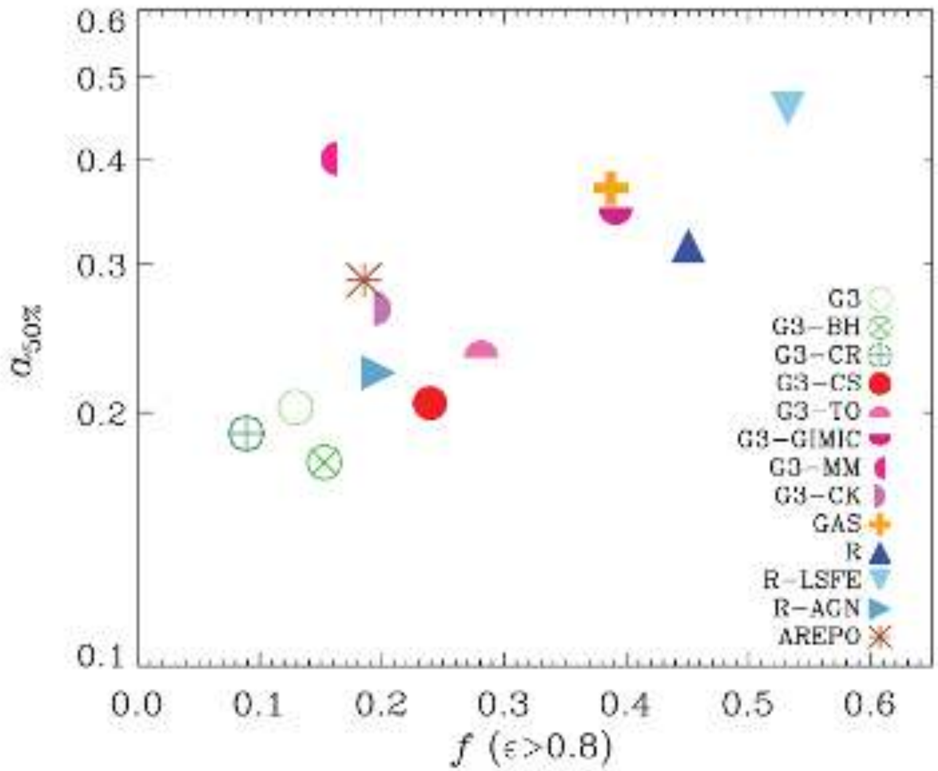
  The circularity parameter ε measures rotation, $\varepsilon \sim 1$: disk-like rotation



CS+ 2012

Aquila Project results

- Hints on e.g. disk formation from common results

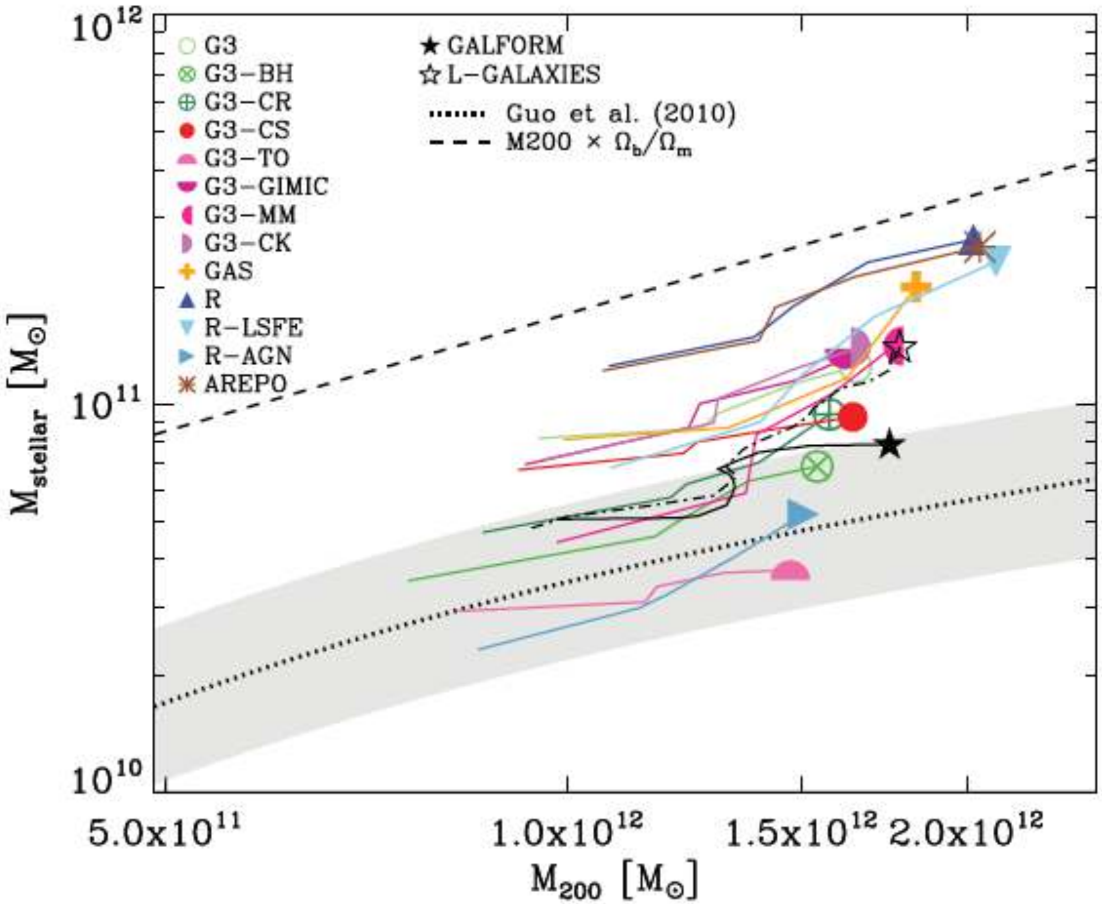


- Galaxies with higher late-time SFRs have more significant disks

CS+ 2012

Aquila Project results

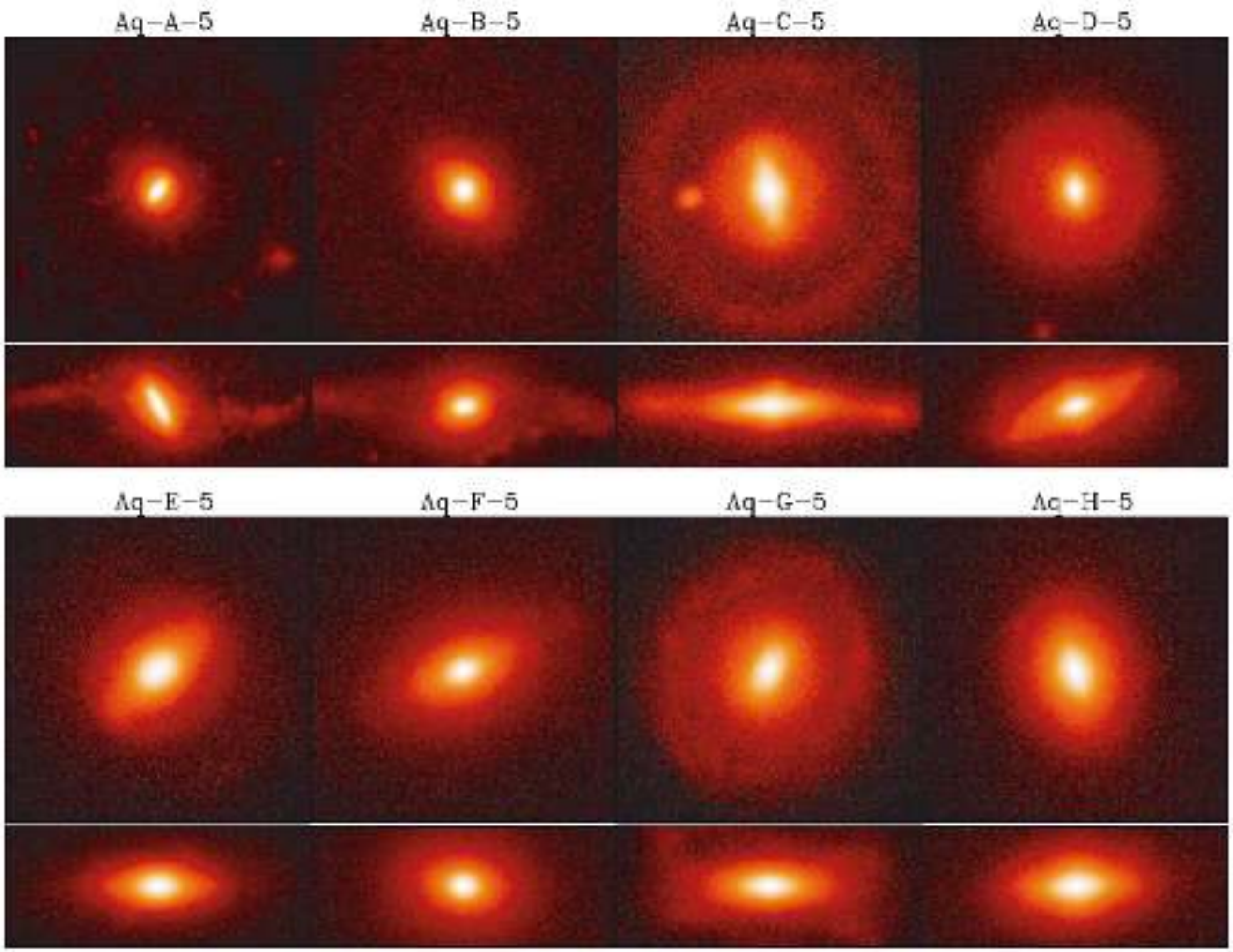
- All simulations predict galaxies with too large $M_{stellar}$?



CS+ 2012

Galaxy disks

Simulations of 8 galaxies, MW-mass, mildly isolated

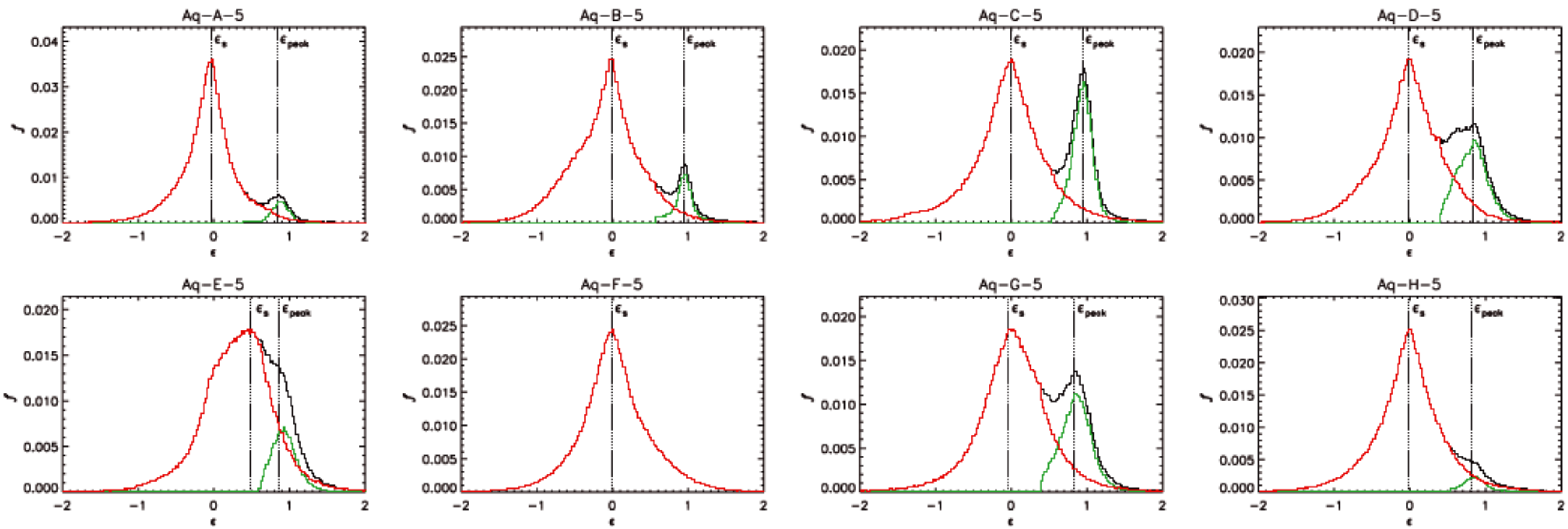


- Galaxies are diverse
- Some have dominant disks, others don't
- Some have bars

CS+ 2009

Galaxy disks

Separate into disk and spheroidal components to study disks

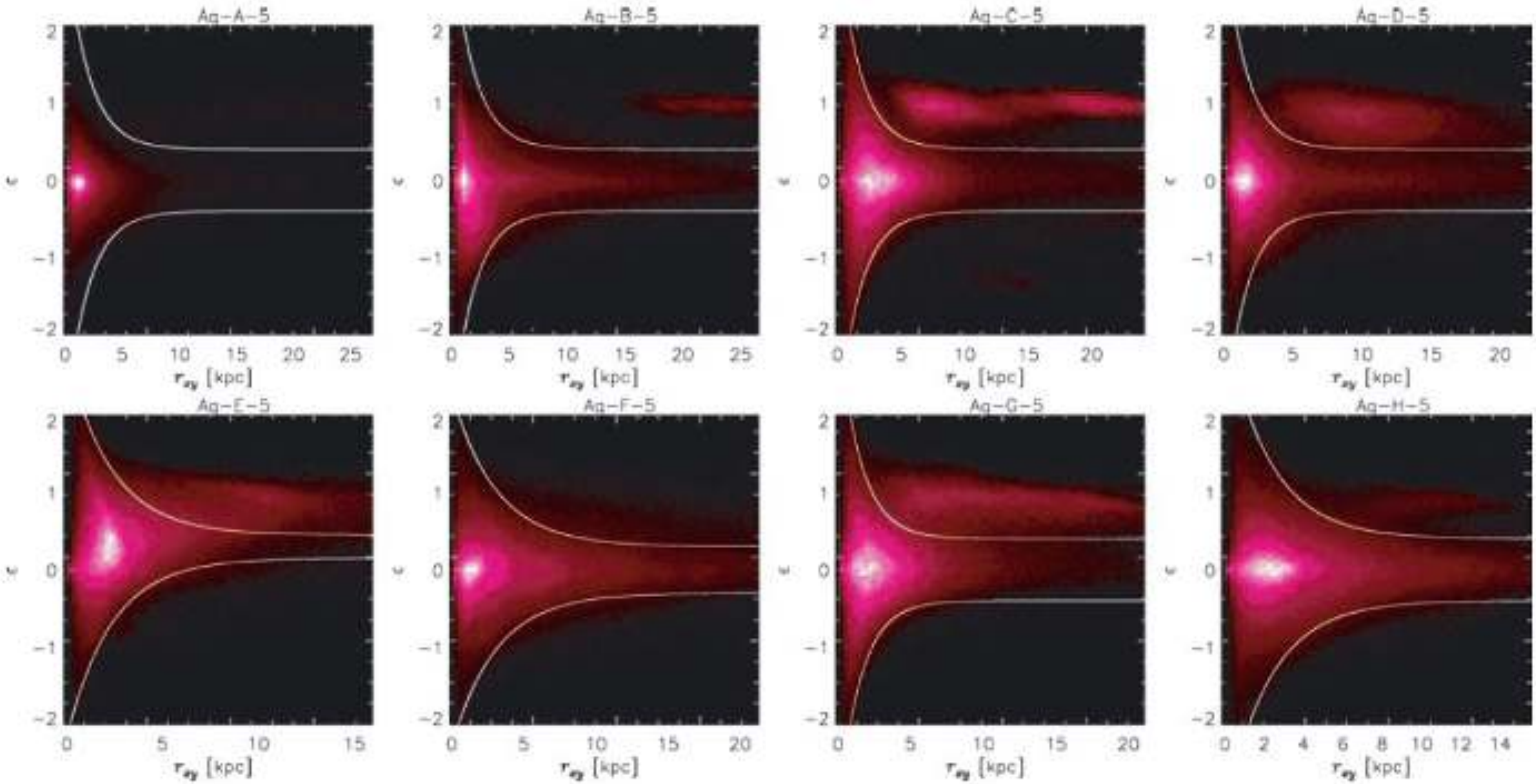


- "Circularity" $\varepsilon = J_Z/J_{circ}$
- Dynamical decomposition based on rotational velocity

CS+ 2009

Galaxy disks

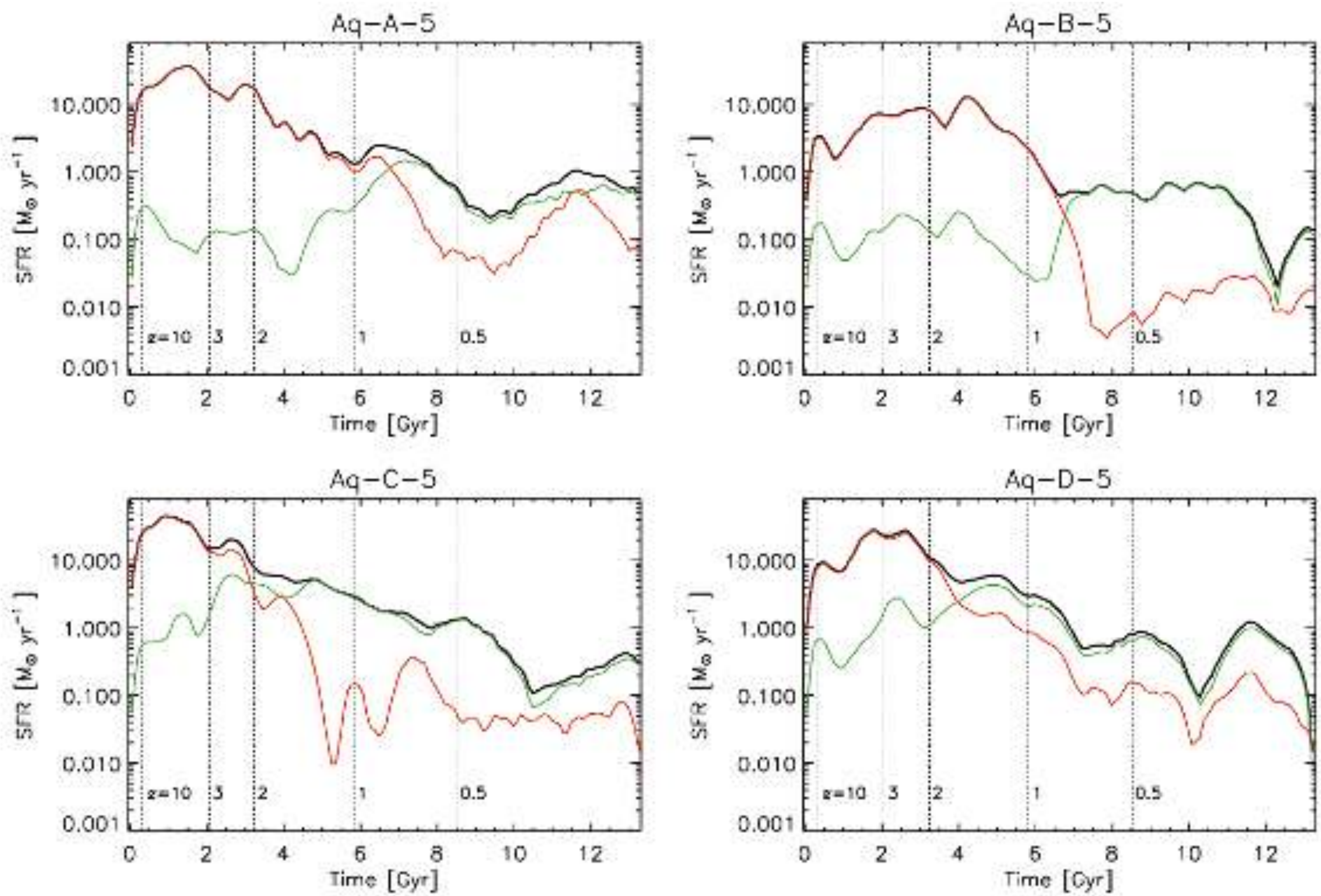
- Disk particles populate outer regions



CS+ 2009

Galaxy disks

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

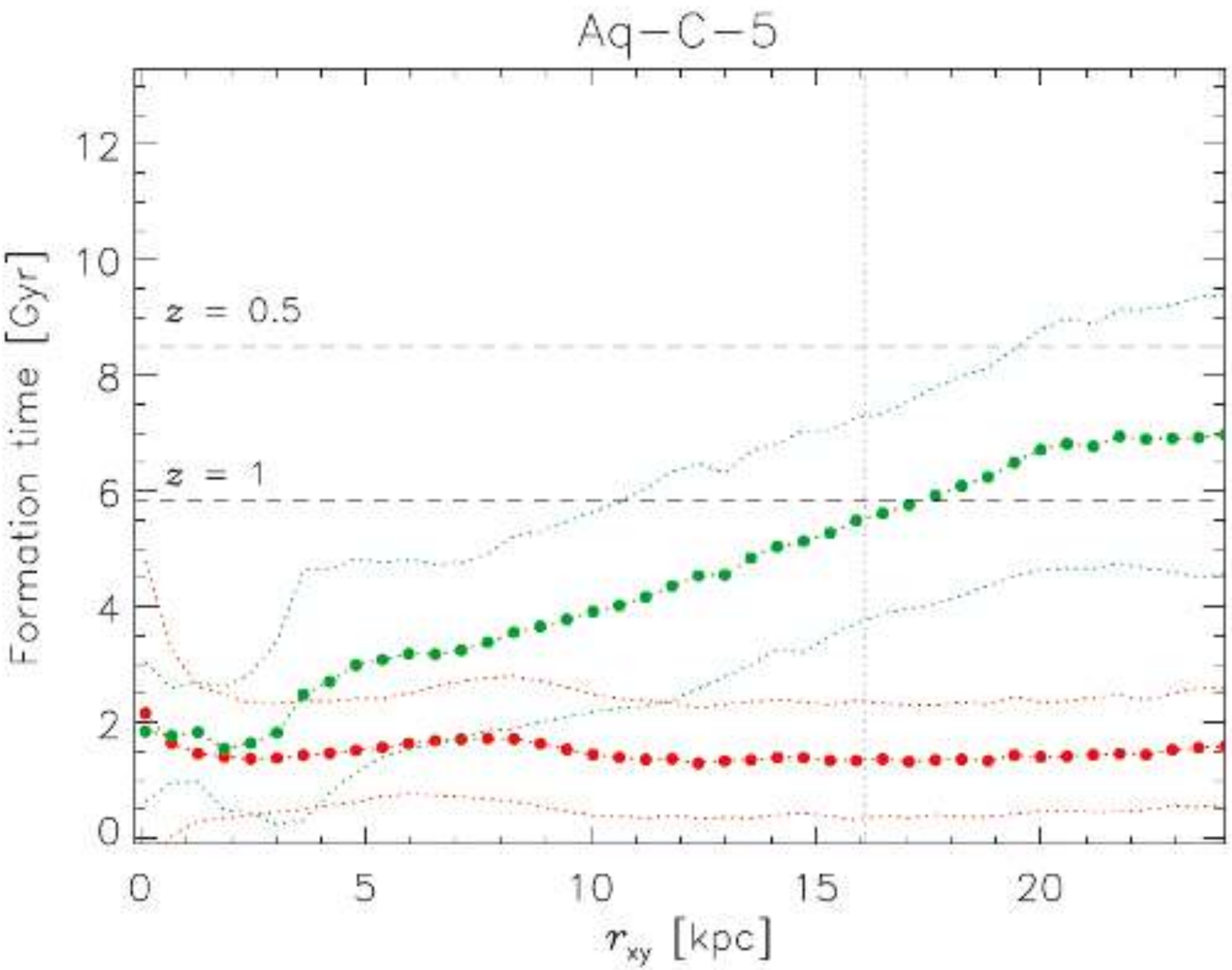


Total
Disk
Spheroid

CS+ 2009

Galaxy disks

- Disks form from the inside-out



Disk
Spheroid

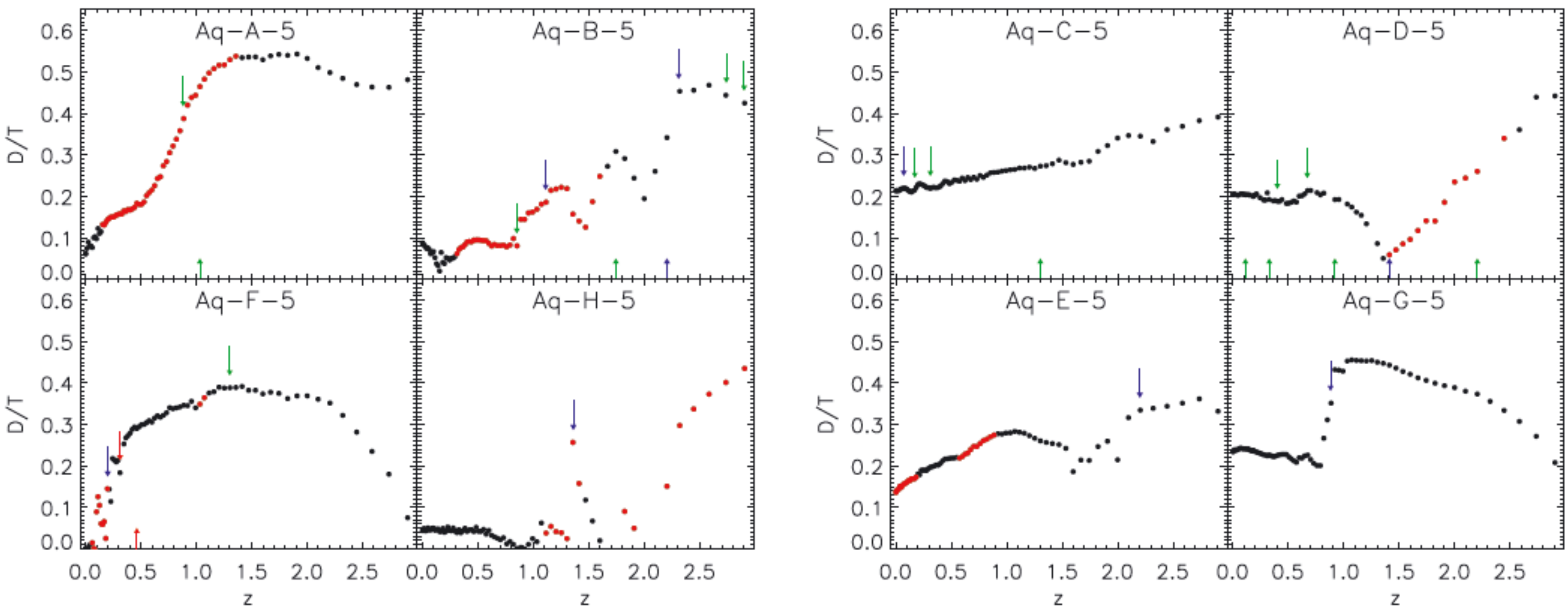
CS+ 2009

Galaxy disks

- Disks easily destroyed due to merger events

Galaxies with little/no disk at z=0

Galaxies with significant disks at z=0



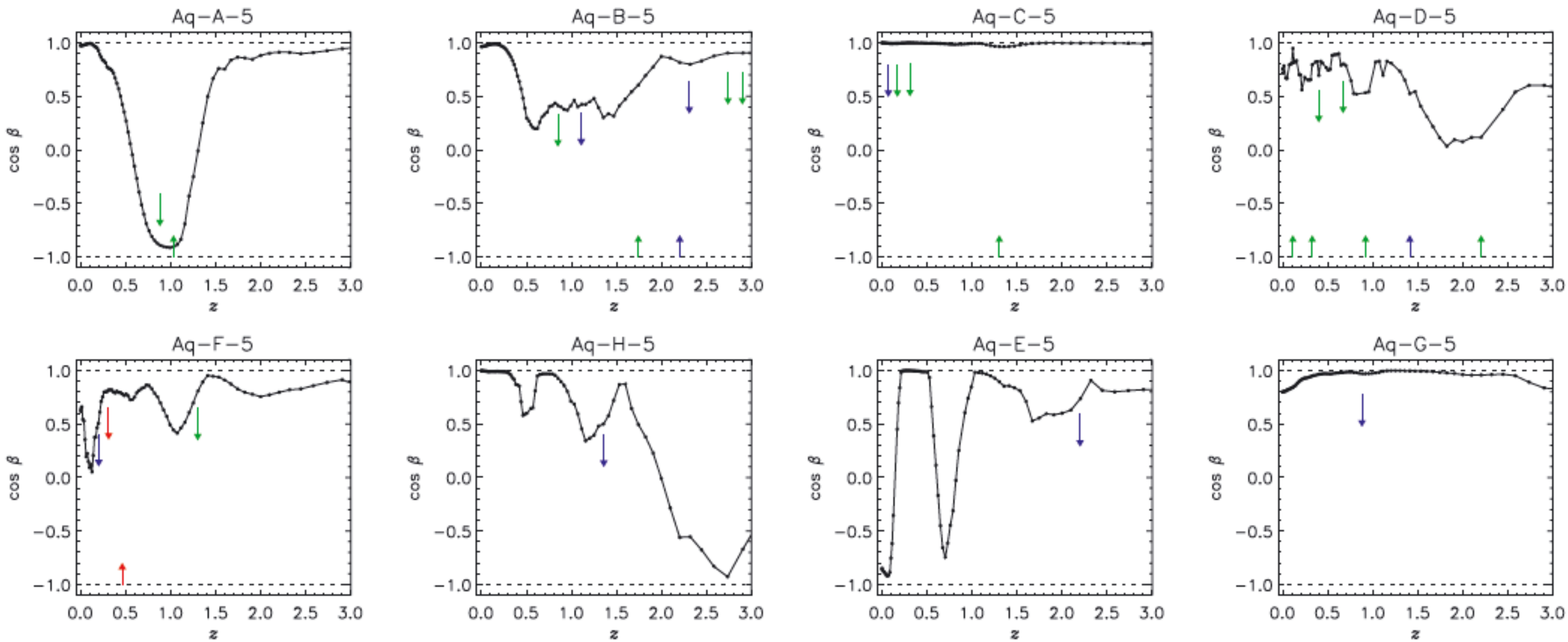
- Other process affecting disk destruction?

CS+ 2009

Galaxy disks

- Disks destroyed/shrinked during periods of misaligned gas accretion

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

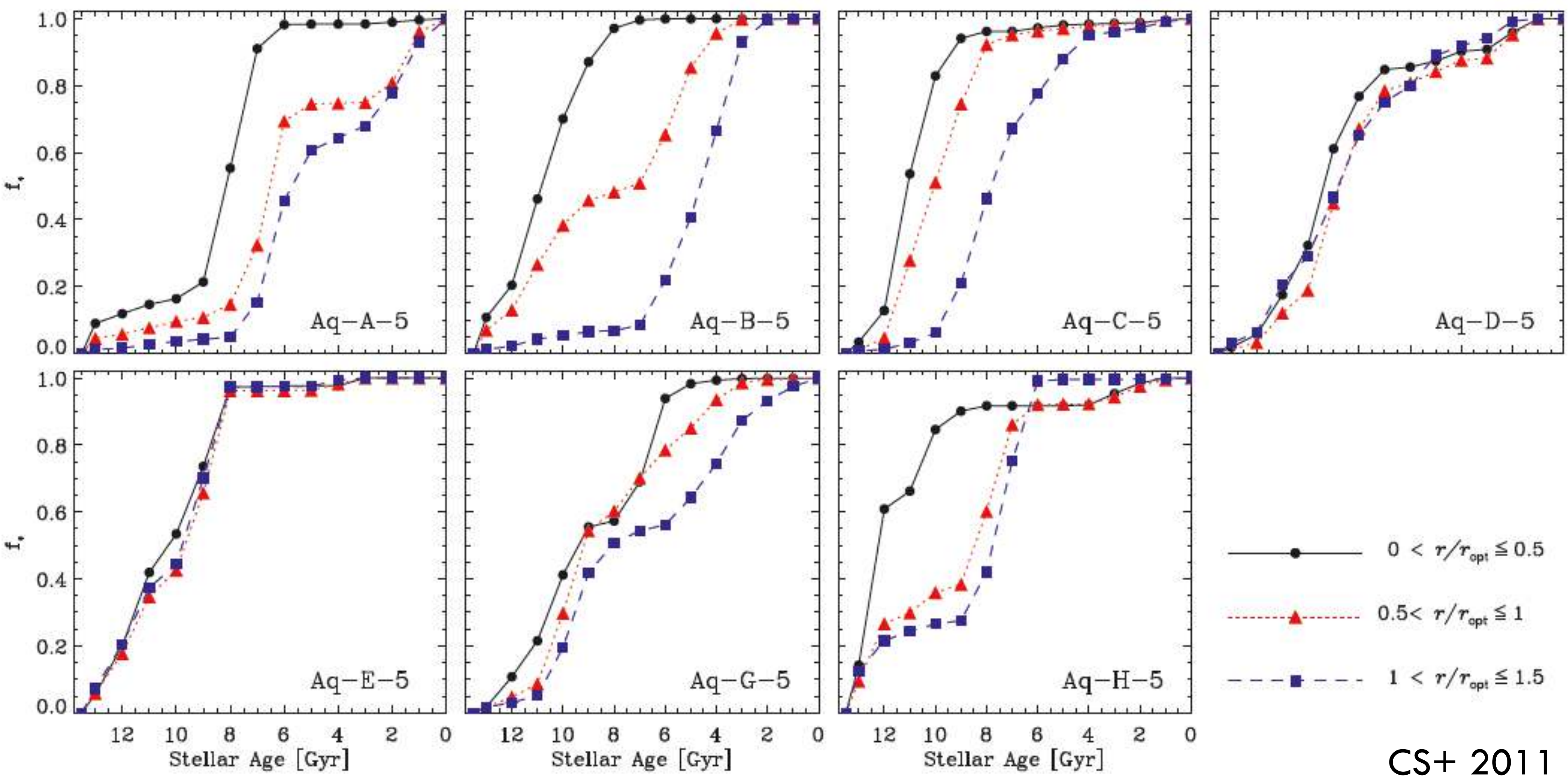


β = angle between gas and stars

CS+ 2009

Galaxy diversity

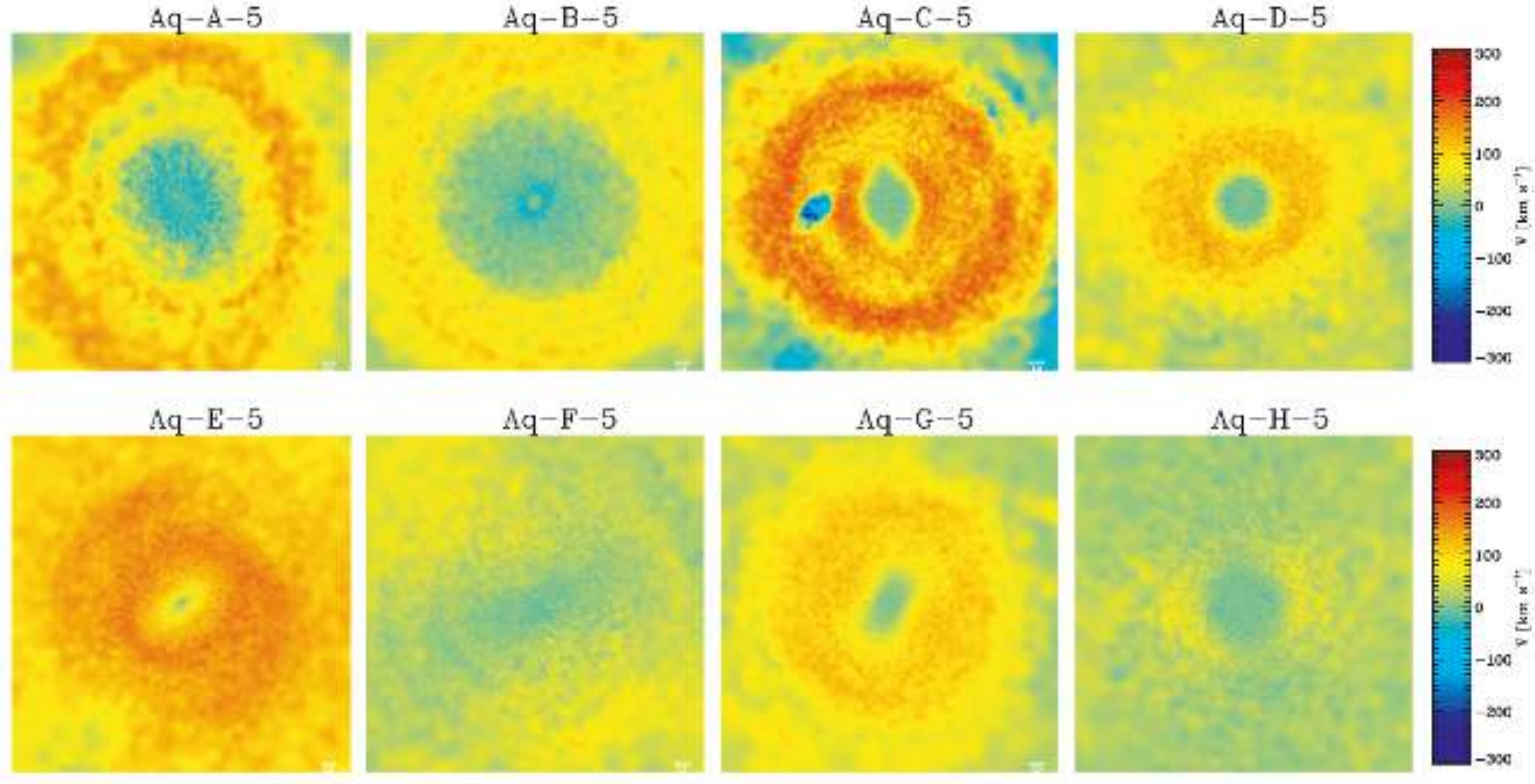
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. inside-out formation



CS+ 2011

Galaxy diversity

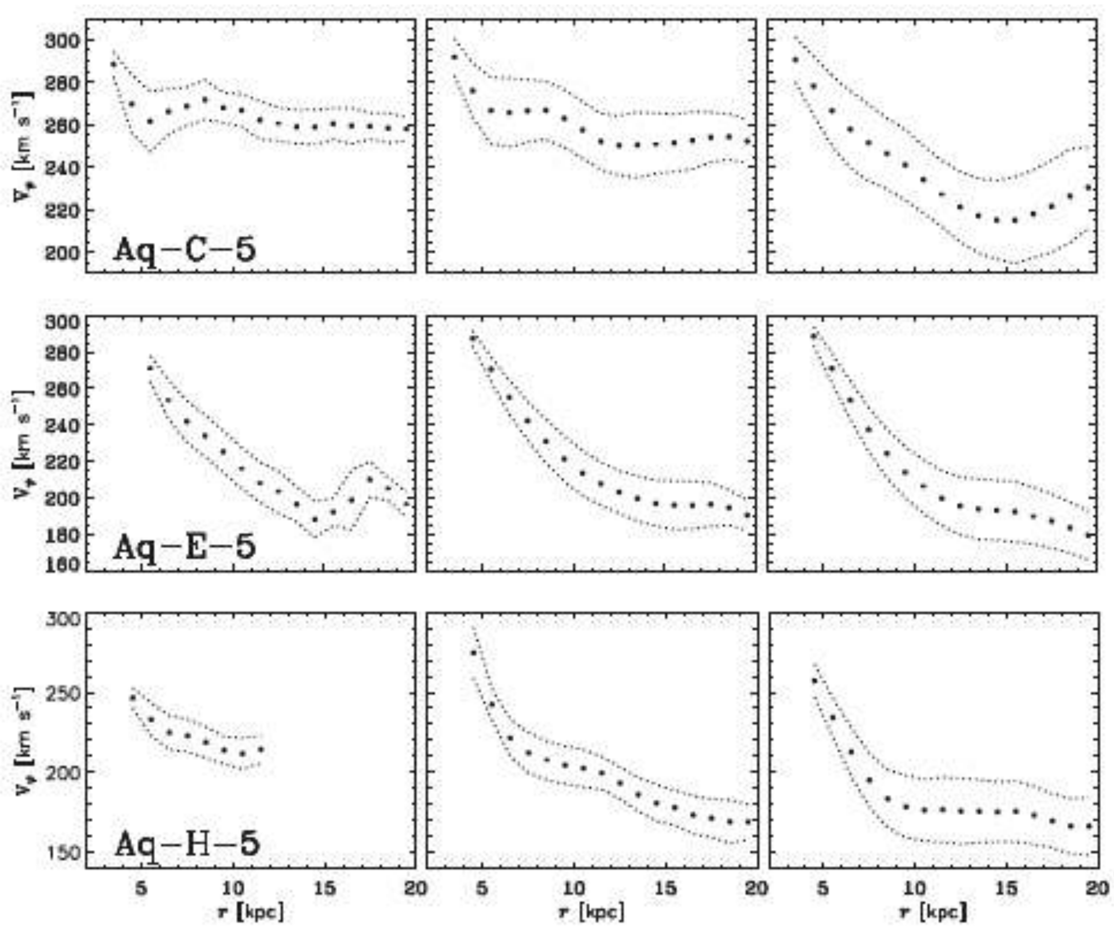
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. dynamics (morphology)



CS+ 2011

Galaxy diversity

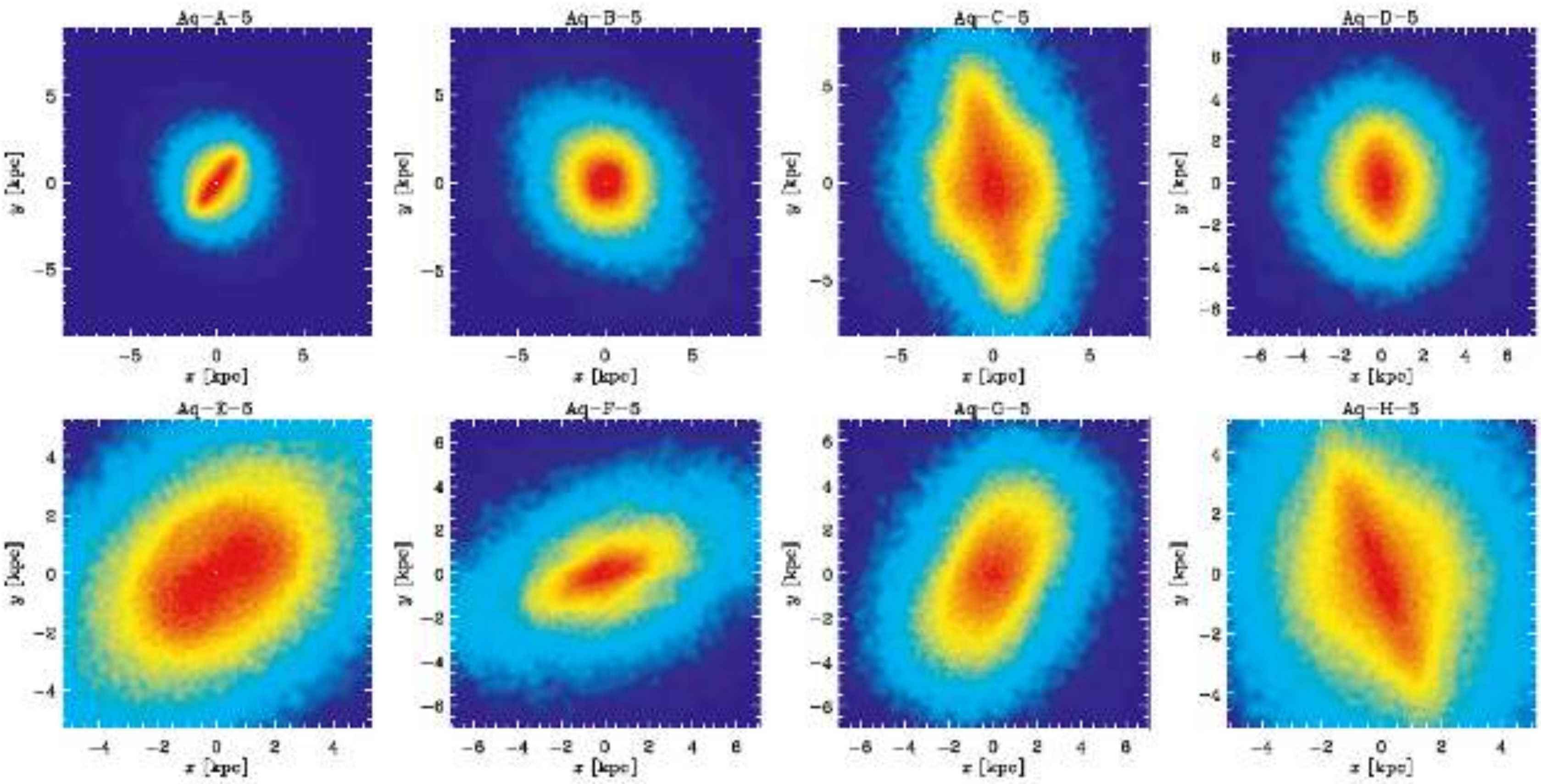
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. disk rotation



CS+ 2011

Galaxy diversity

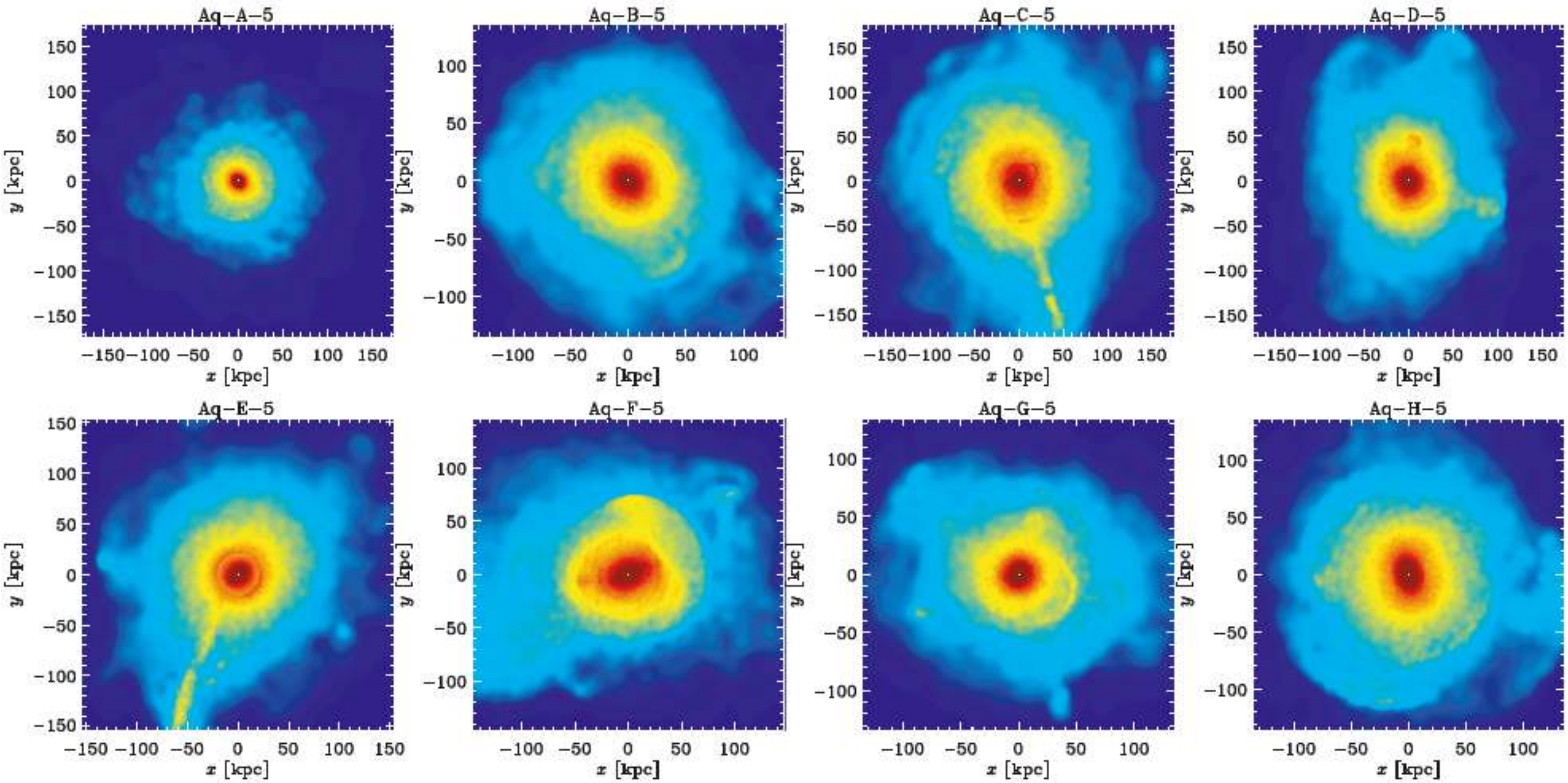
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. inner structure



CS+ 2011

Galaxy diversity

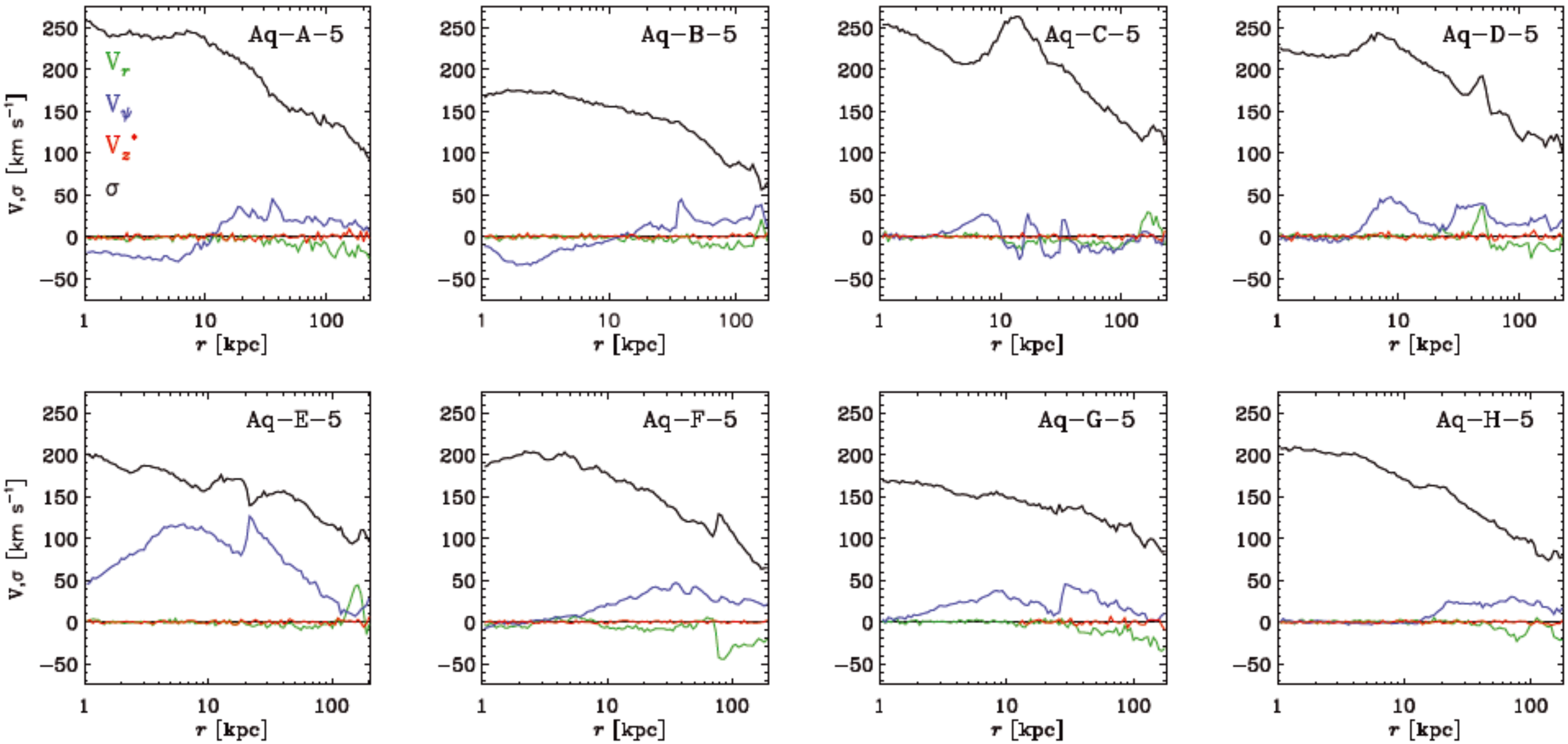
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. outer structure



CS+ 2011

Galaxy diversity

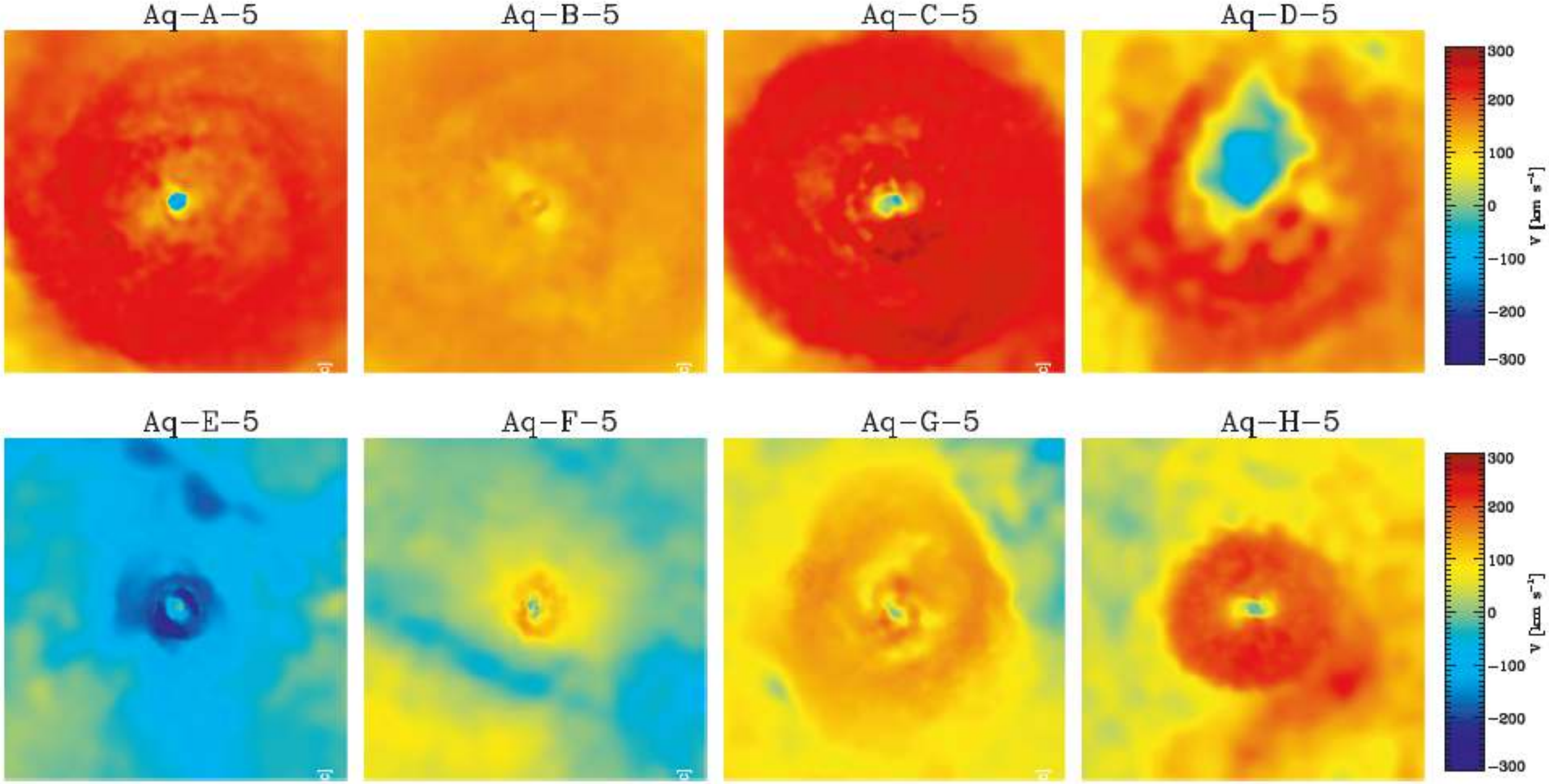
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. spheroid dynamics



CS+ 2011

Galaxy diversity

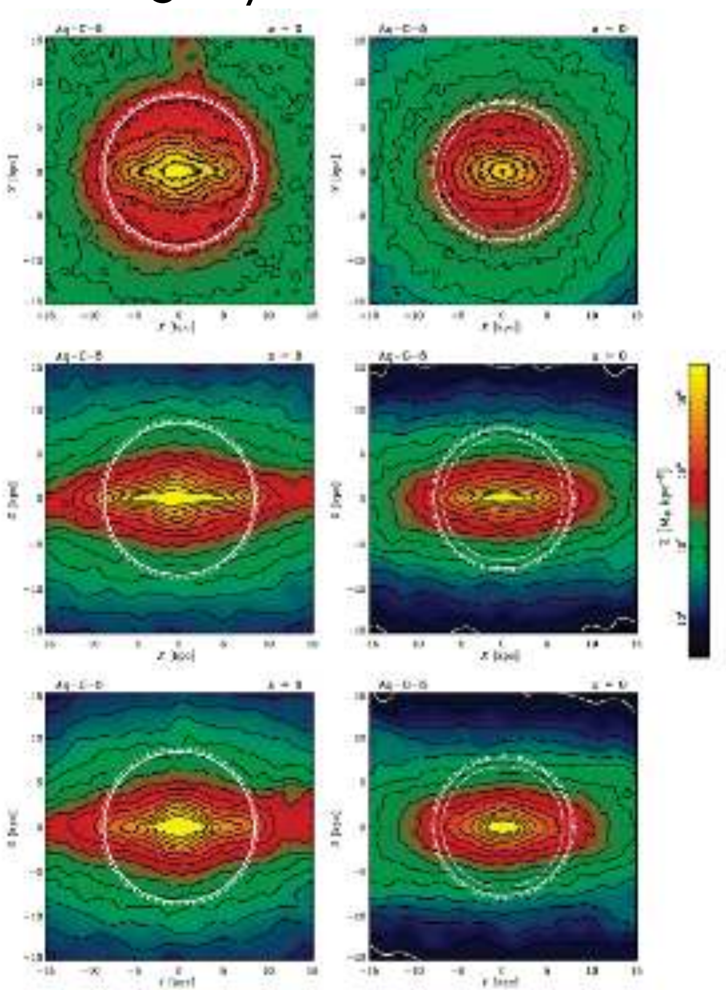
- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. gas dynamics

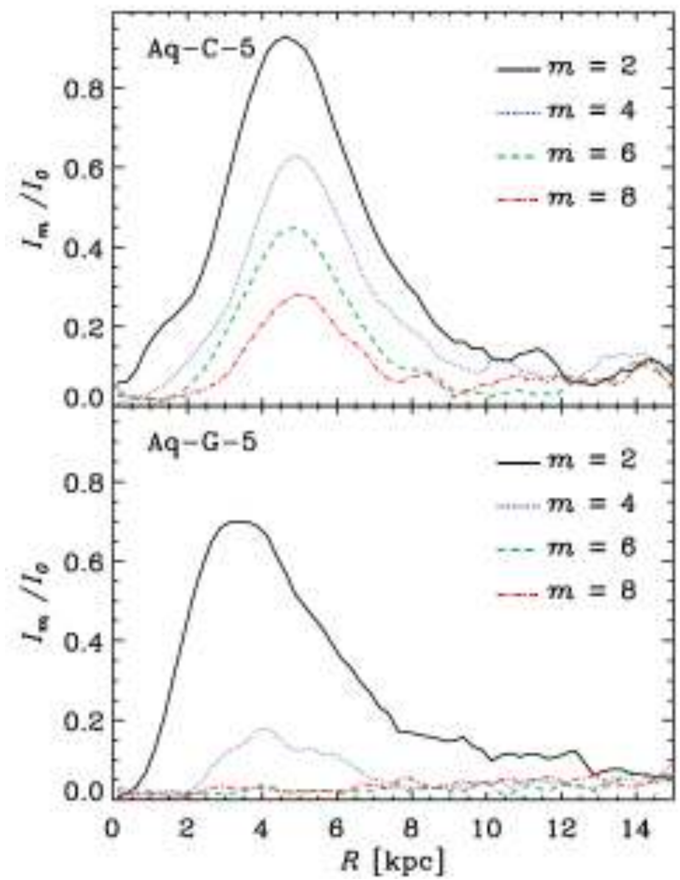


CS+ 2011

Galaxy diversity

- Diversity expected in ΛCDM coming from diverse merger/accretion histories. E.g. bar formation

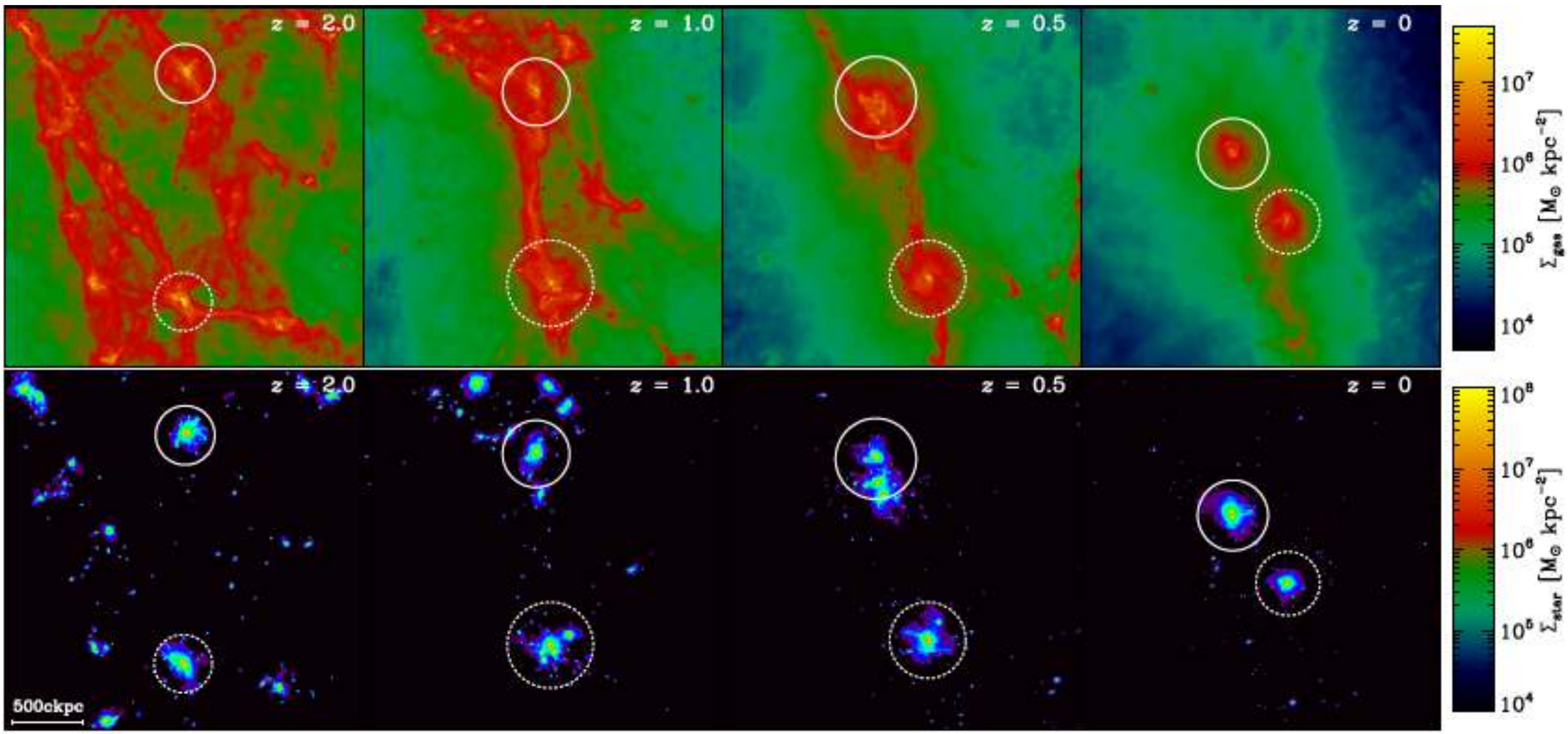




CS & Athanassoula 2012

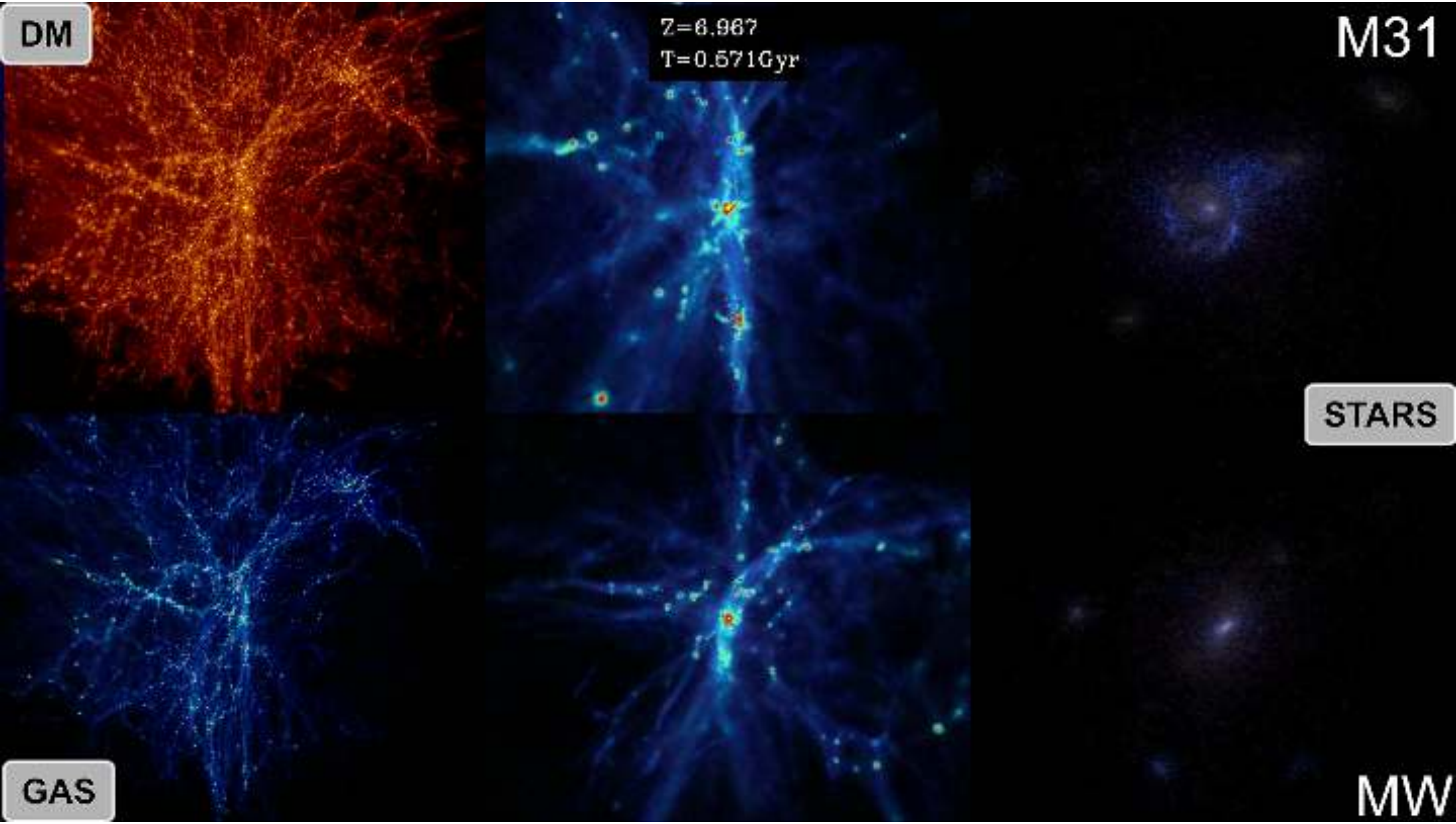
The Milky Way: not an isolated galaxy

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



CS+2015

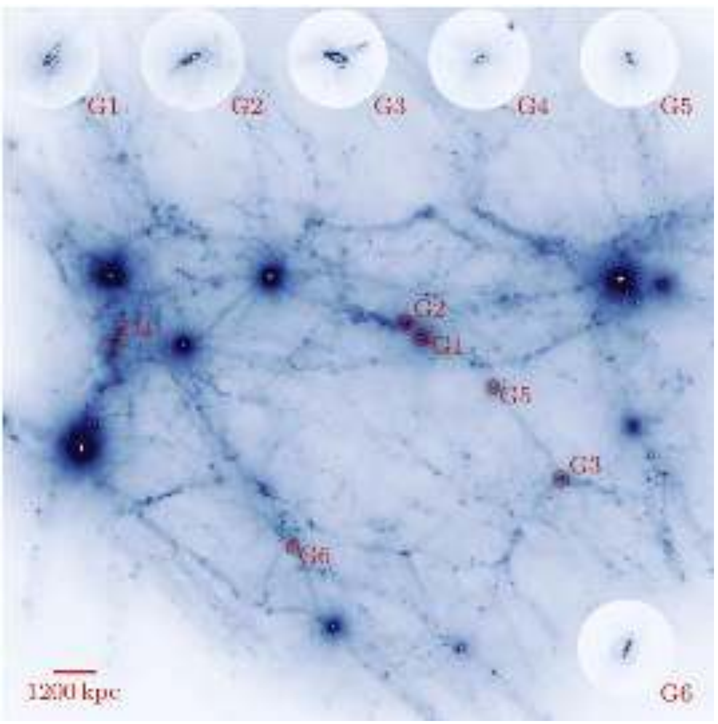
The Milky Way: not an isolated galaxy

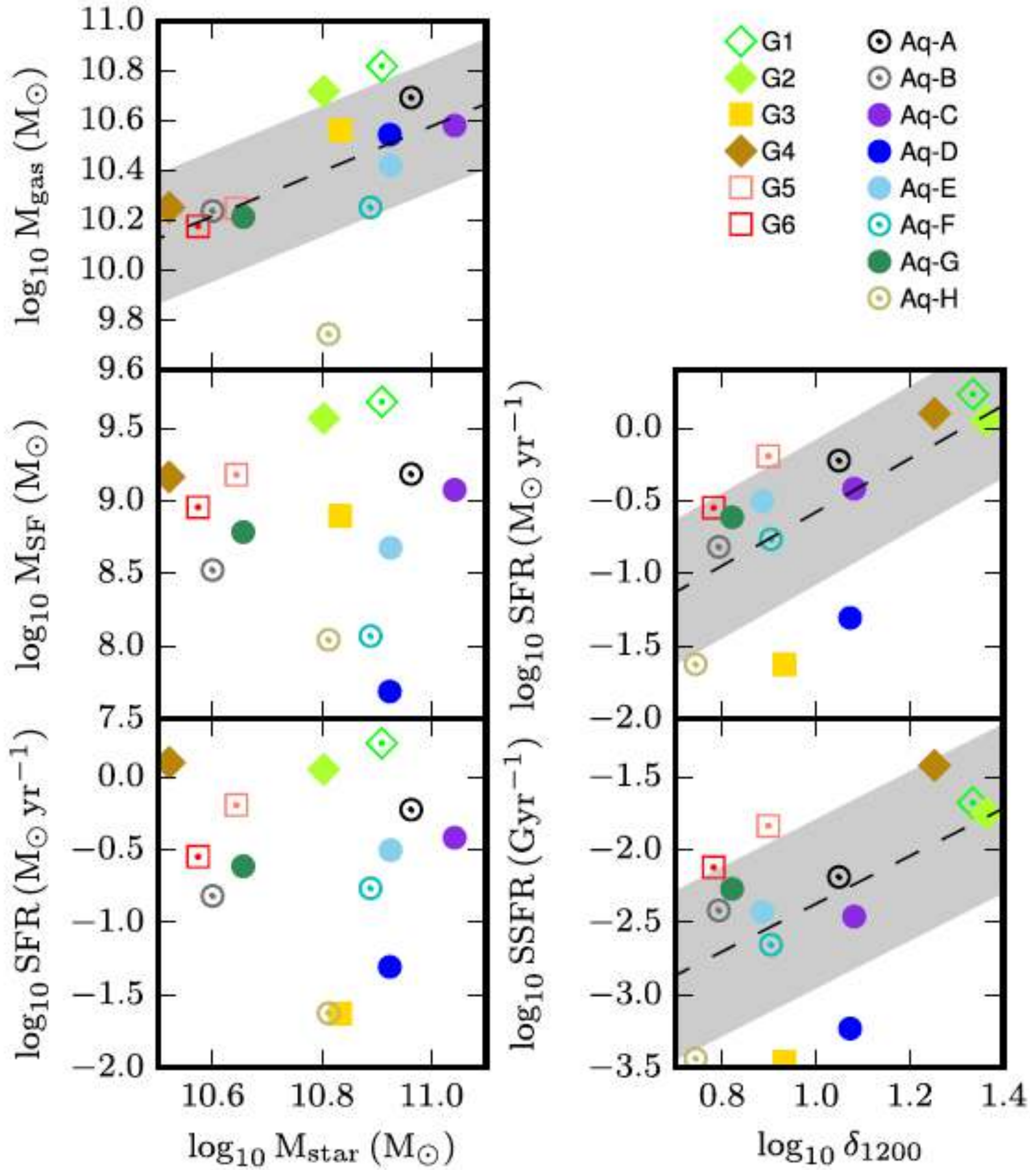


Creasey+ 2015, CS+2015

The Milky Way: not an isolated galaxy

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





Creasey+2015

Other feedback mechanisms?

- Most simulations including only SN feedback still have too high SFRs at early times, consuming most of the gas which becomes unavailable for later star formation.

Radiation pressure from young, massive stars:
effects on ISM comparable to SN feedback?
(e.g. Hopkins+2011, Agertz+2013, Aumer+2013, Stinson+2013)

- Observations of young star clusters in GMCs show that the gas disperses *before* the first SNe explode

→ The radiation from a young stellar population carries large amounts of energy and momentum

Other feedback mechanisms?

- How to implement radiation pressure in simulations?

Momentum-driven feedback, parametrized in general as:

$$\dot{p}_{\rm rad} = (\eta_1 + \eta_2 \tau_{\rm IR}) \frac{L(t)}{c}$$

$L(t)$: luminosity of the stellar population

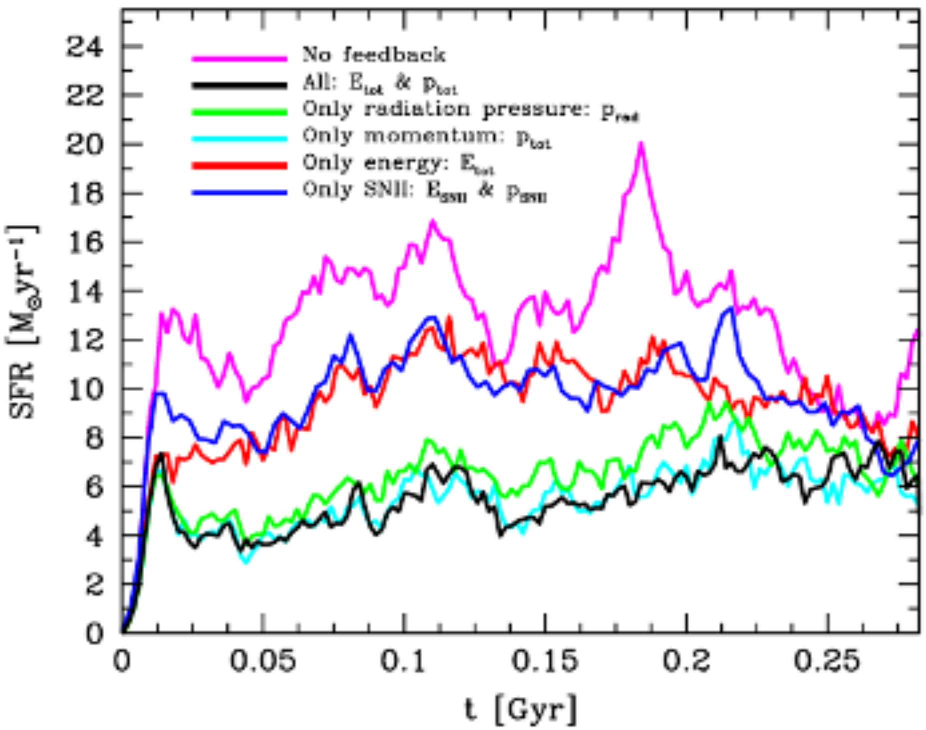
η_1 : efficiency of radiation absorption/scattering

η_2: efficiency of momentum transfer from IR photons (re-radiated by dust and scattered by dust grains)

τ_{IR}: optical IR depth (depends on ρ, Z, σ ?)

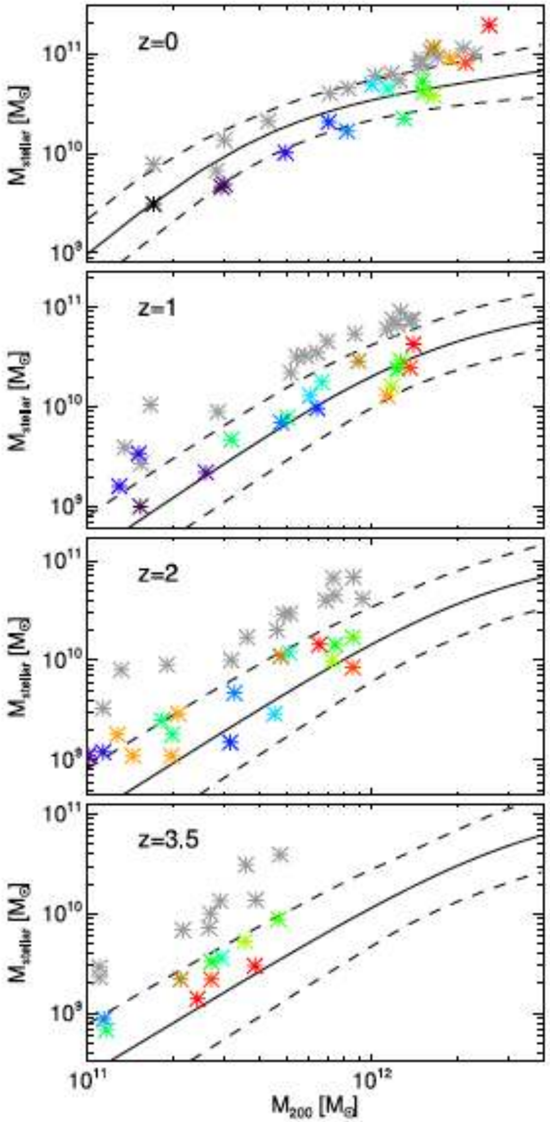
Effects of radiation-pressure feedback

- Reduce star formation at early times

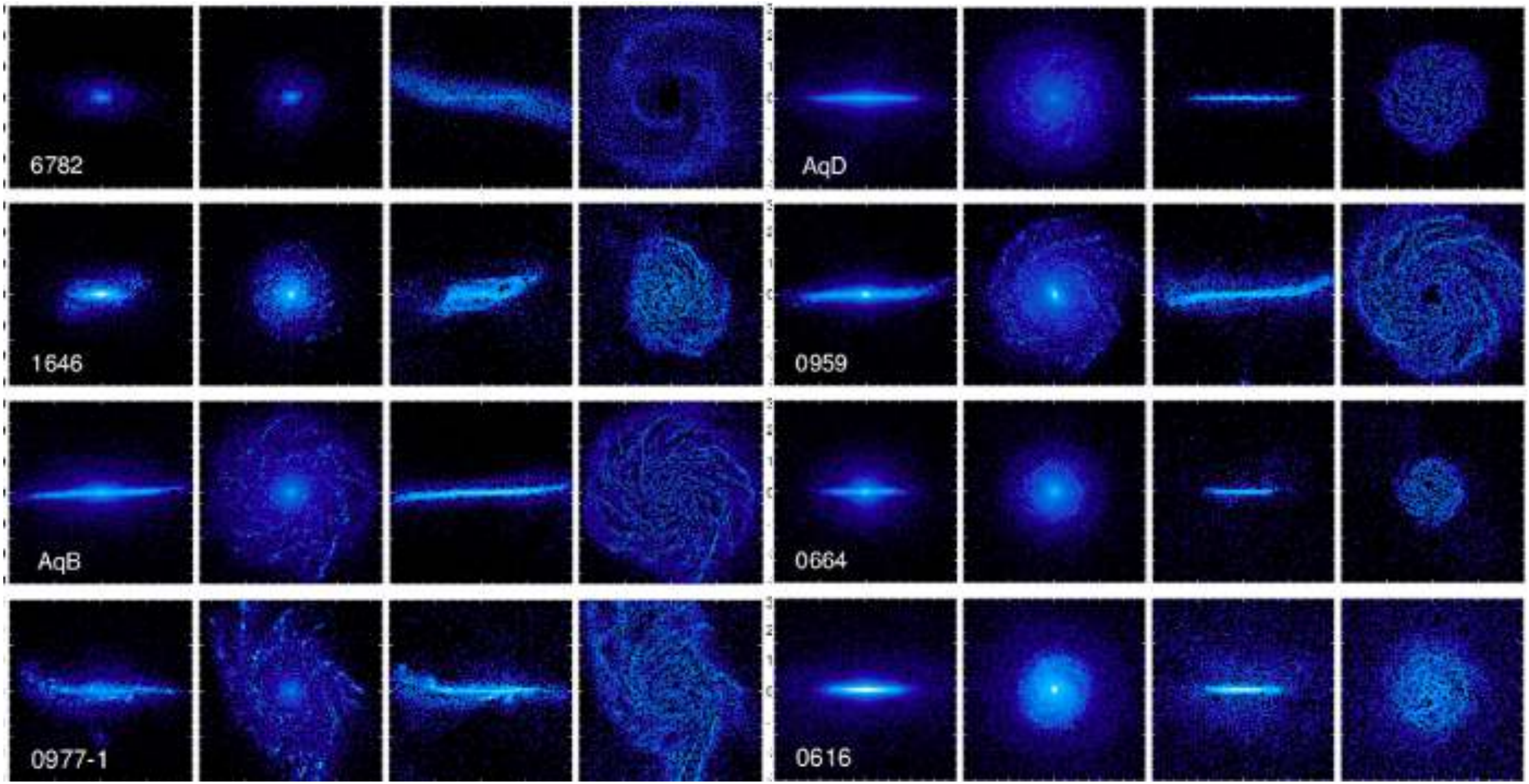


Isolated galaxy simulations
Agertz+2013

Aumer+2013



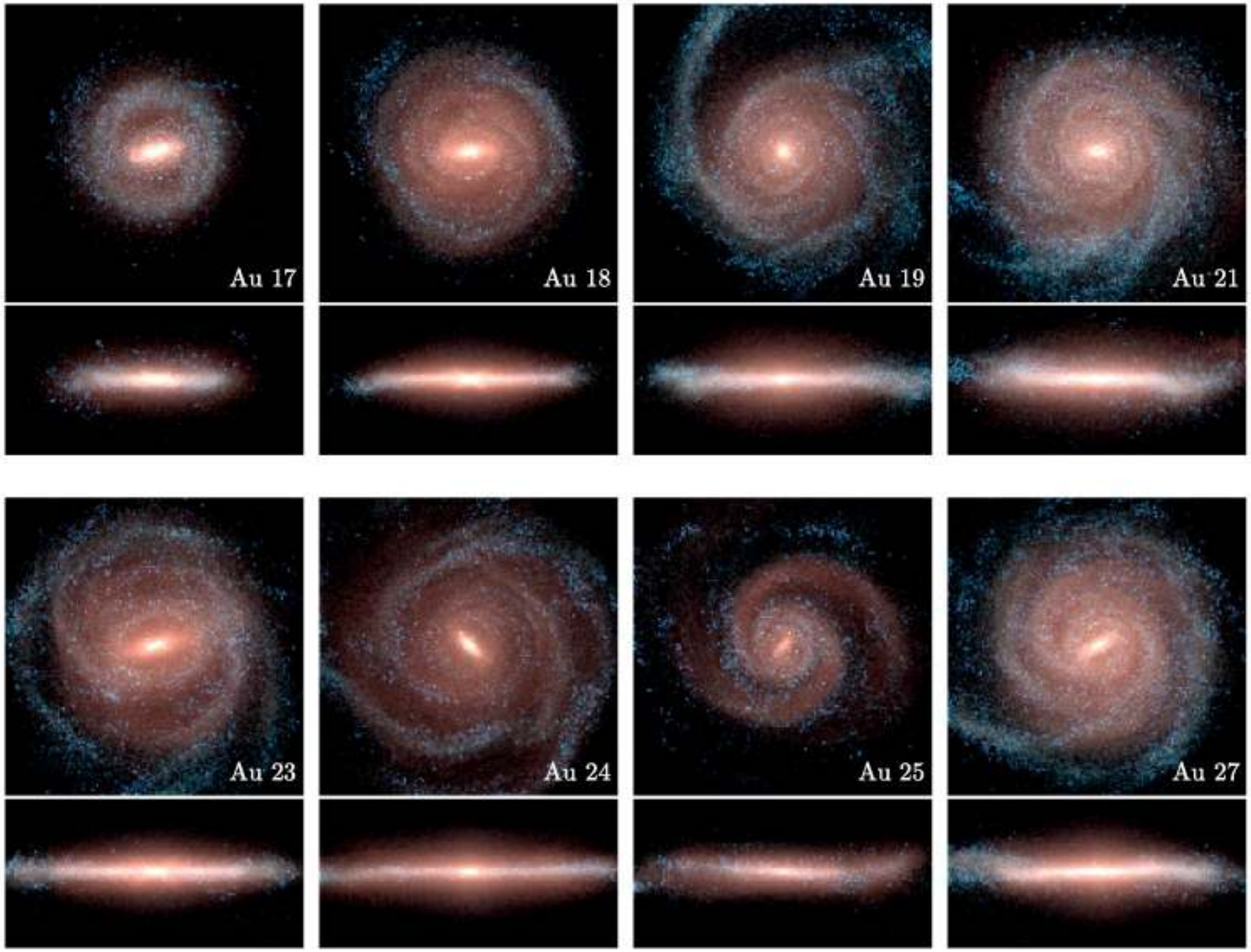
Abundance of disks: invariant to assumptions?



SN + Radiation pressure feedback

Aumer+ 2013

Abundance of disks: invariant to assumptions?



Ad-hoc winds & ISM model

Grand+ 2016

Summary

- Feedback mechanisms regulate star formation in galaxies, but:
  - Significant uncertainties in physical details
  - Not clear how to implement at resolved scales
  - SN: thermal versus kinetic
  - Radiation pressure (?)
- Still, simulations help understand relevant physics of disk formation
  - Disks are young
  - Disks can be destroyed by mergers and by misaligned gas accretion
  - Disks can be rebuilt provided gas is available
  - Environmental effects on Milky Way might be relevant
- Galaxies are diverse in ΛCDM, even at a fixed stellar mass
  - Codes should reproduce such diversity