Galaxy Formation from simulation side

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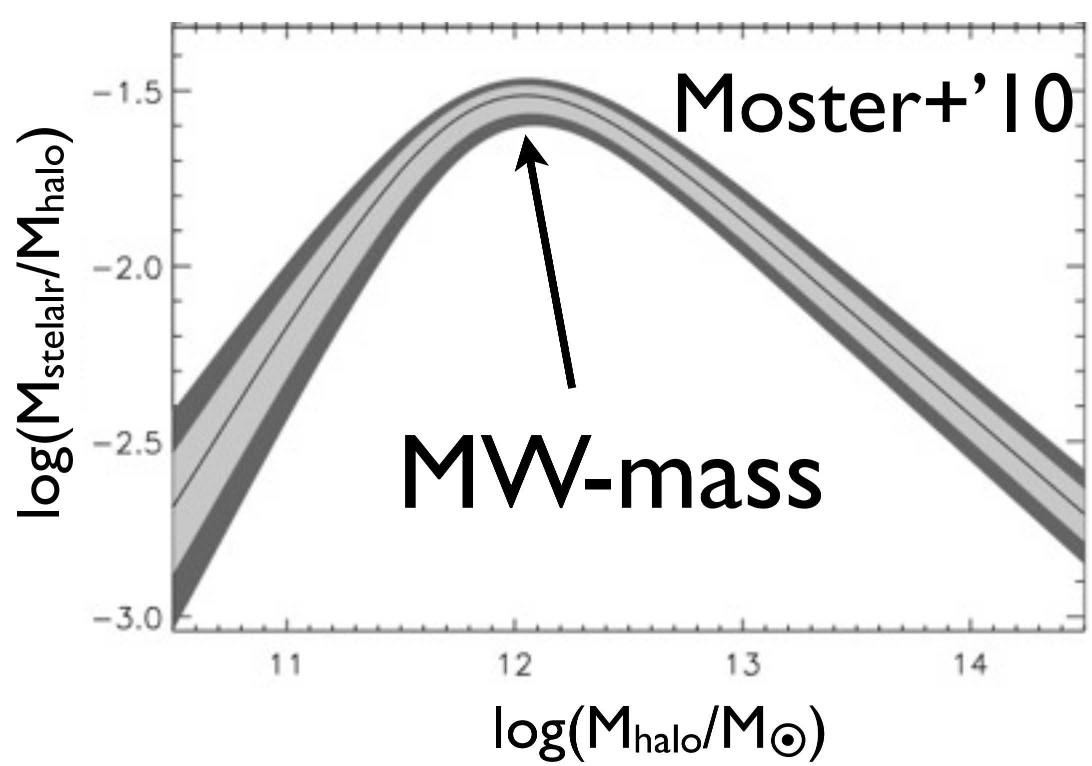
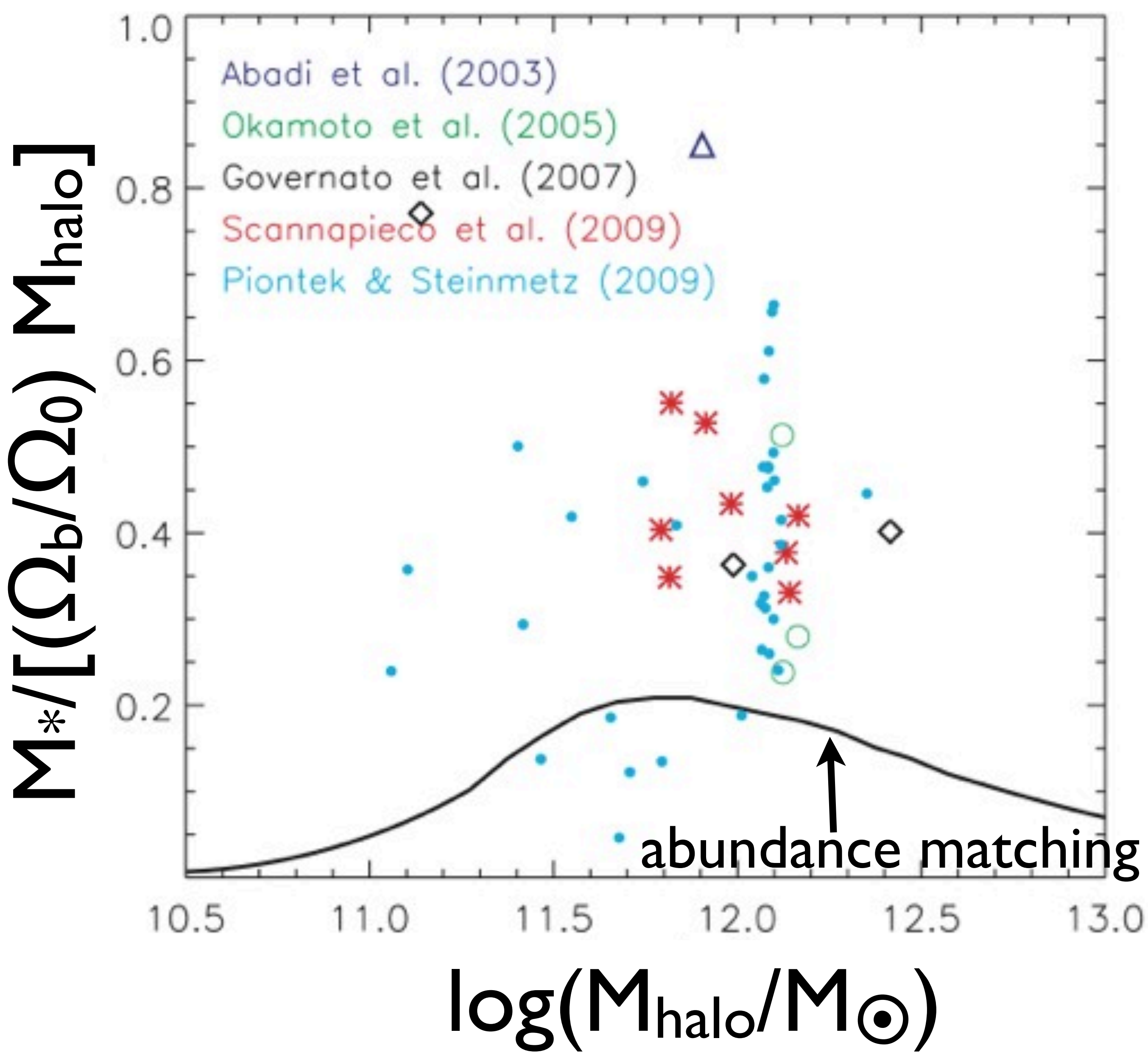
Milky Way-mass galaxies

- Why Milky Way-mass galaxies?
  - dominate the stellar mass density of the local Universe
  - at the knee of the luminosity/mass function
  - Highest efficiency to convert baryons into stars



Feedback is matter

Guo+'10



- Most of simulations convert too many barons into stars.
- Need stronger feedback

Feedback in simulations

- Feedback is modelled as "**subgrid physics**"
  - Individual SN remnants cannot be resolved
  - Simply put feedback energy into star-forming regions as thermal energy has little or no effect
  - Putting feedback energy as kinetic form do not have strong impact either because kinetic energy immediately thermalizes in the dens gas.

Stronger feedback

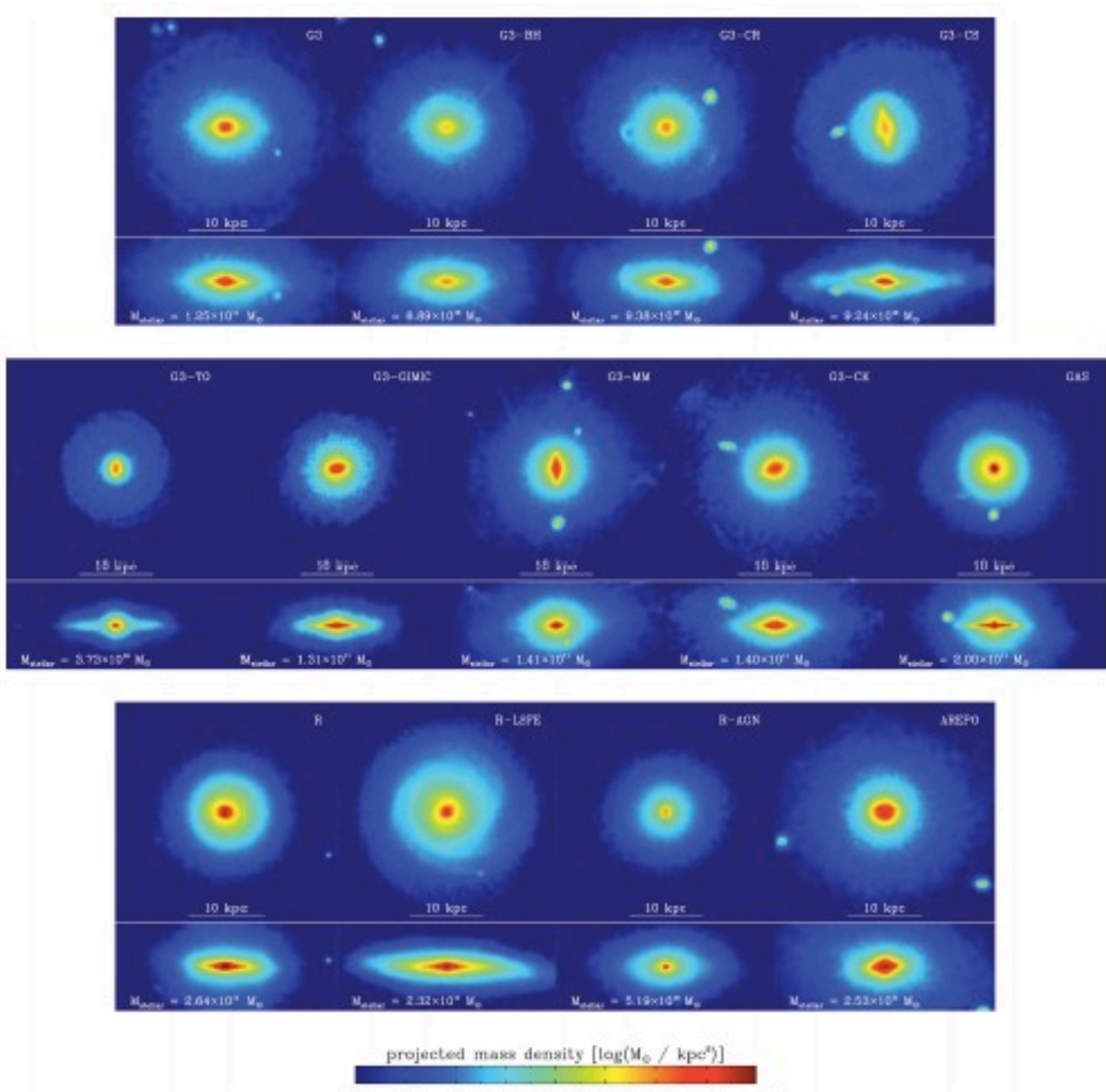
- Thermal feedback + delayed cooling
  - e.g. Tacker & Couchman'01, Stinson+'06
  - Shutting off cooling of heated gas for a while (~ 10 Myr)
  - Forms realistic disk galaxies (e.g. Guedes+'11)
- Kinetic feedback (winds) + decoupling
  - e.g. Springel & Hernquist'03, Oppenheimer & Dave'06, Okamoto+'10
  - Give the momentum to wind particles and they are decoupled from hydrodynamic interactions until they leave star-forming regions.
  - Successes in reproducing many properties of galaxies (e.g. Okamoto+'10, Okamoto'13, Vogelsberger+'13)

Feedback efficiency is rather unclear

Subgird makes difference

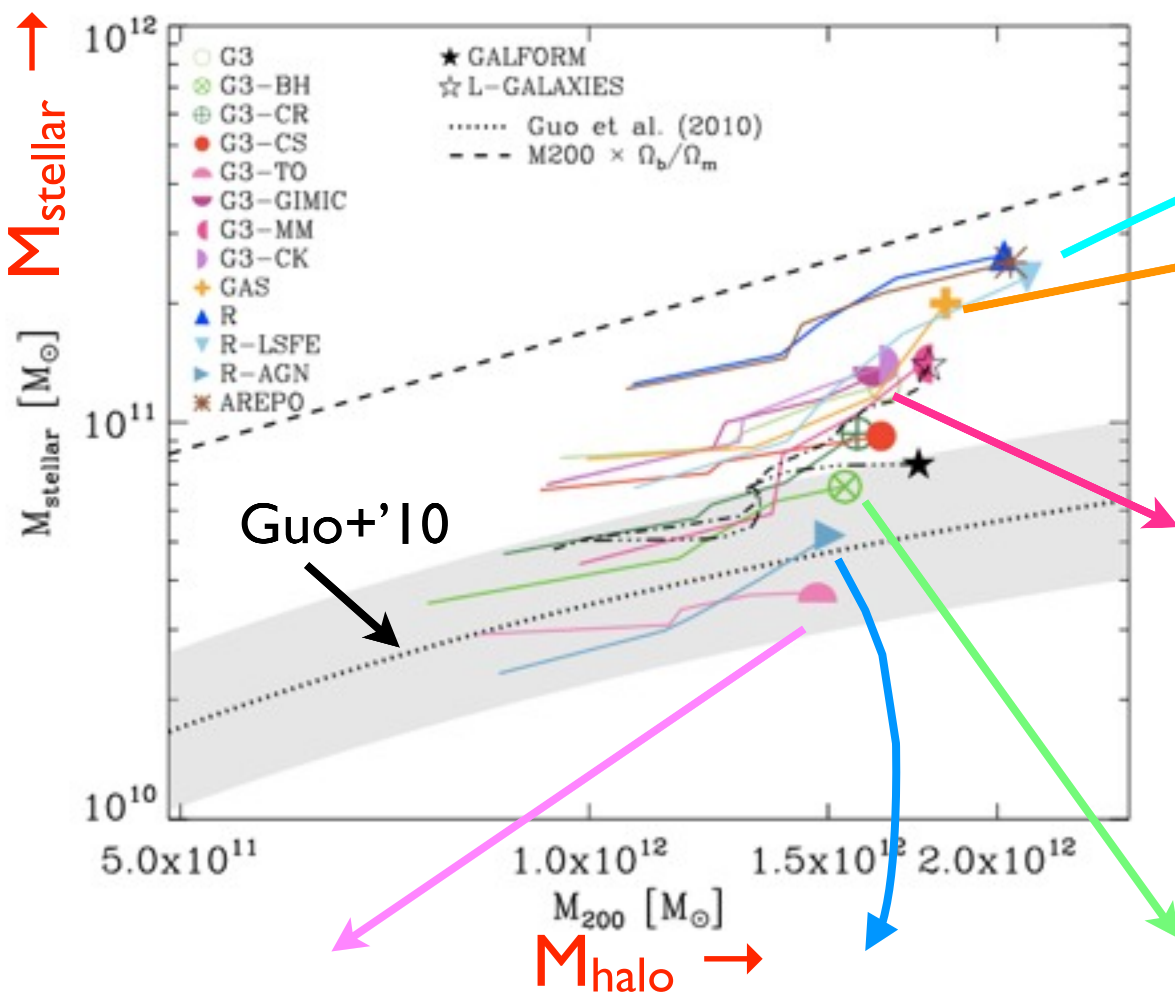
- Aquila comparison project
  (Scannapieco, Okamoto+'12)
  - Cosmological simulations from the identical initial condition with favorite codes and models.
  - MW-mass halo with a quiet merger history
  - Codes: SPH, AMR, and moving mesh

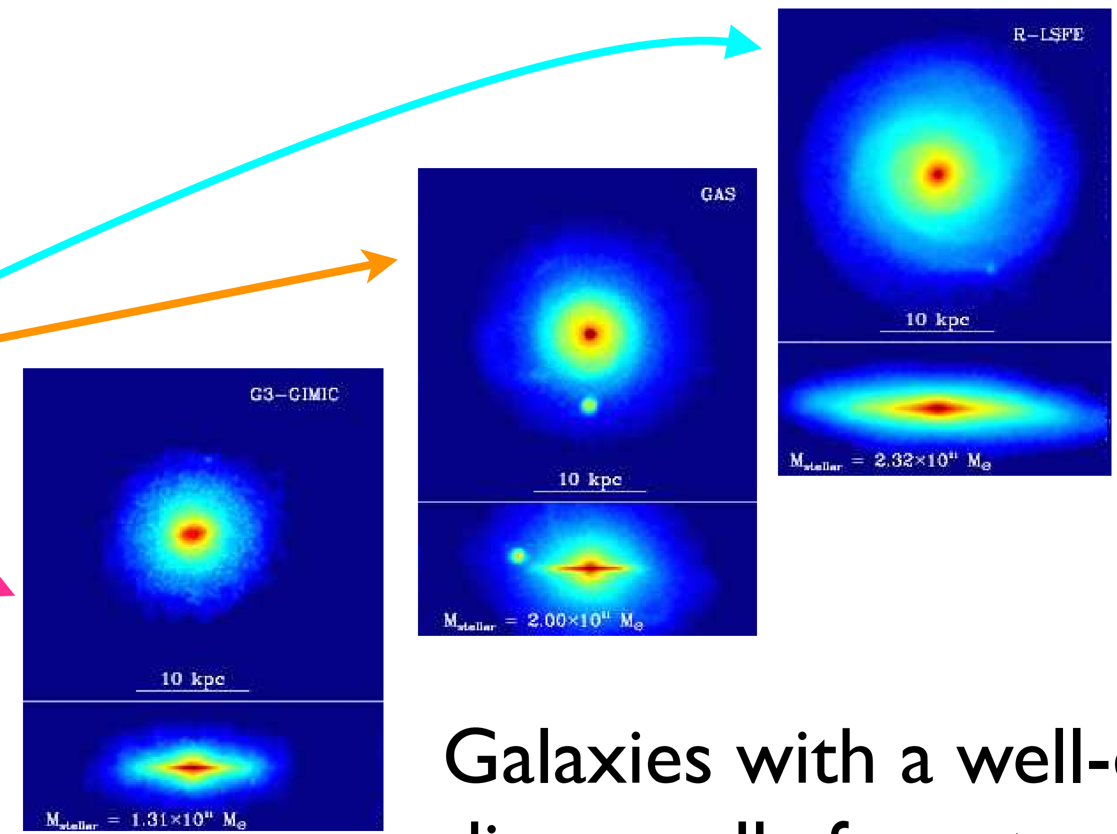
Results



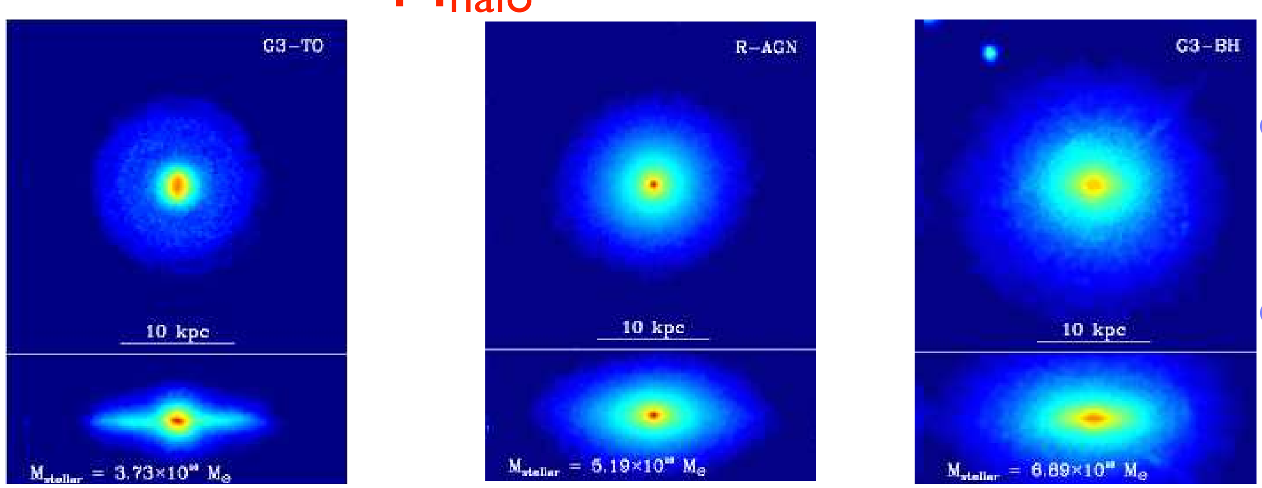
- Projected stellar density
  - Wide range of morphology from the same initial condition...

Stellar mass and morphology





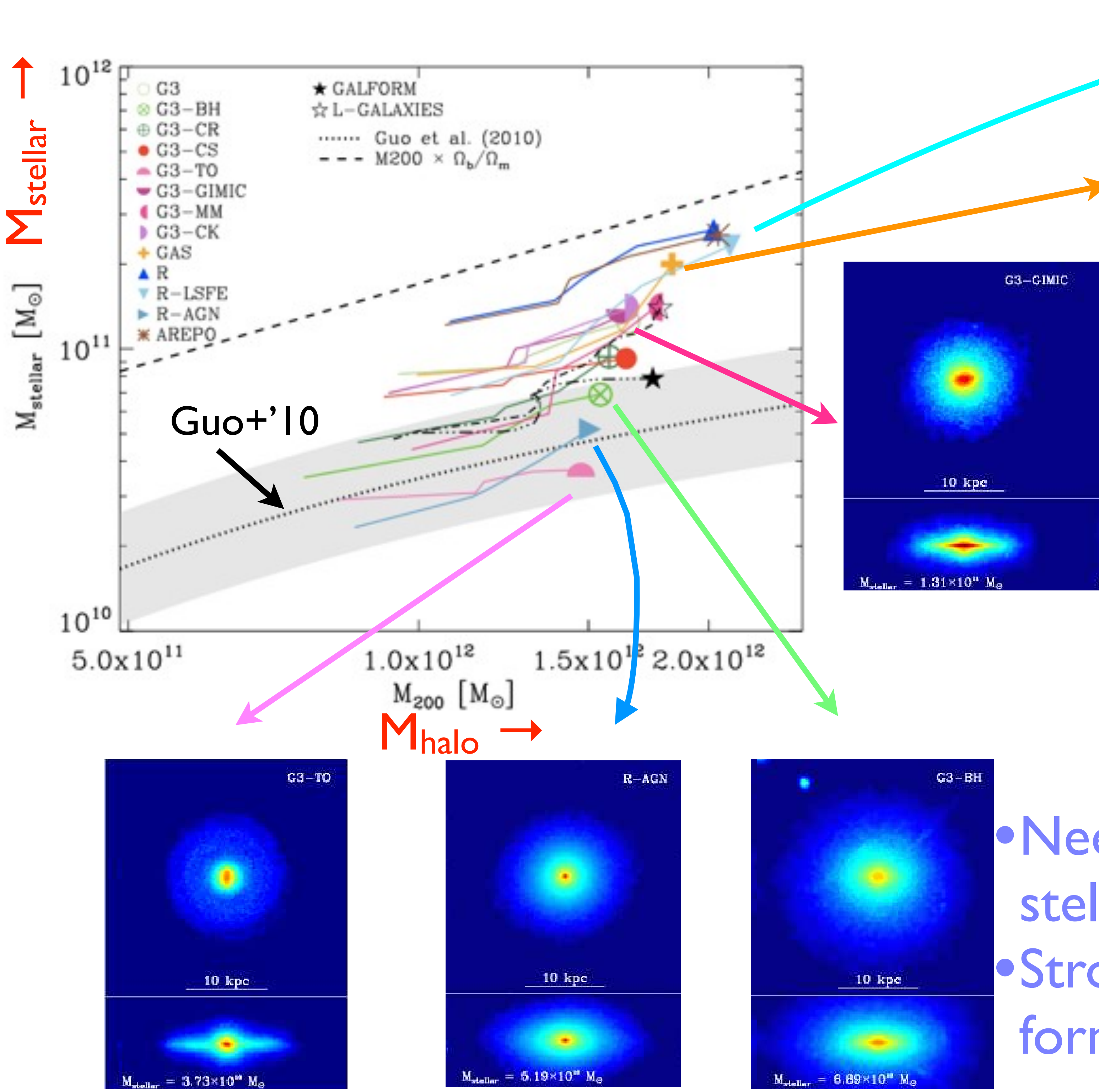
Galaxies with a well-defined disc usually form too many stars.



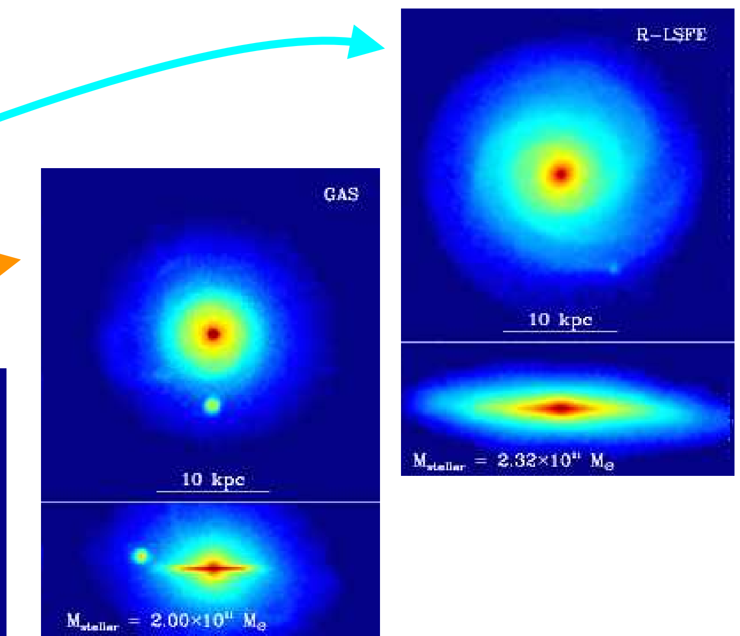
- Need strong feedback to match the stellar mass.
- Strong feedback often prevents disc formation

(Scannapieco+'12)

Stellar mass and morphology



Mine!



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(Scannapieco+'12)

Evolution of Milky Way-mass galaxies by high-resolution cosmological simulations

The simulations

- Two Milky Way-sized halos from the Aquarius simulation (Springel+'08) in a comoving 100 h^{-1} Mpc box
  - Labelled as Aq-C and Aq-D
    (Aq-C is the halo used in the Aquila project)
  - The same physics used in the Aquila
  - Higher resolution
- How does bulge-disk system develop?

Aq-C

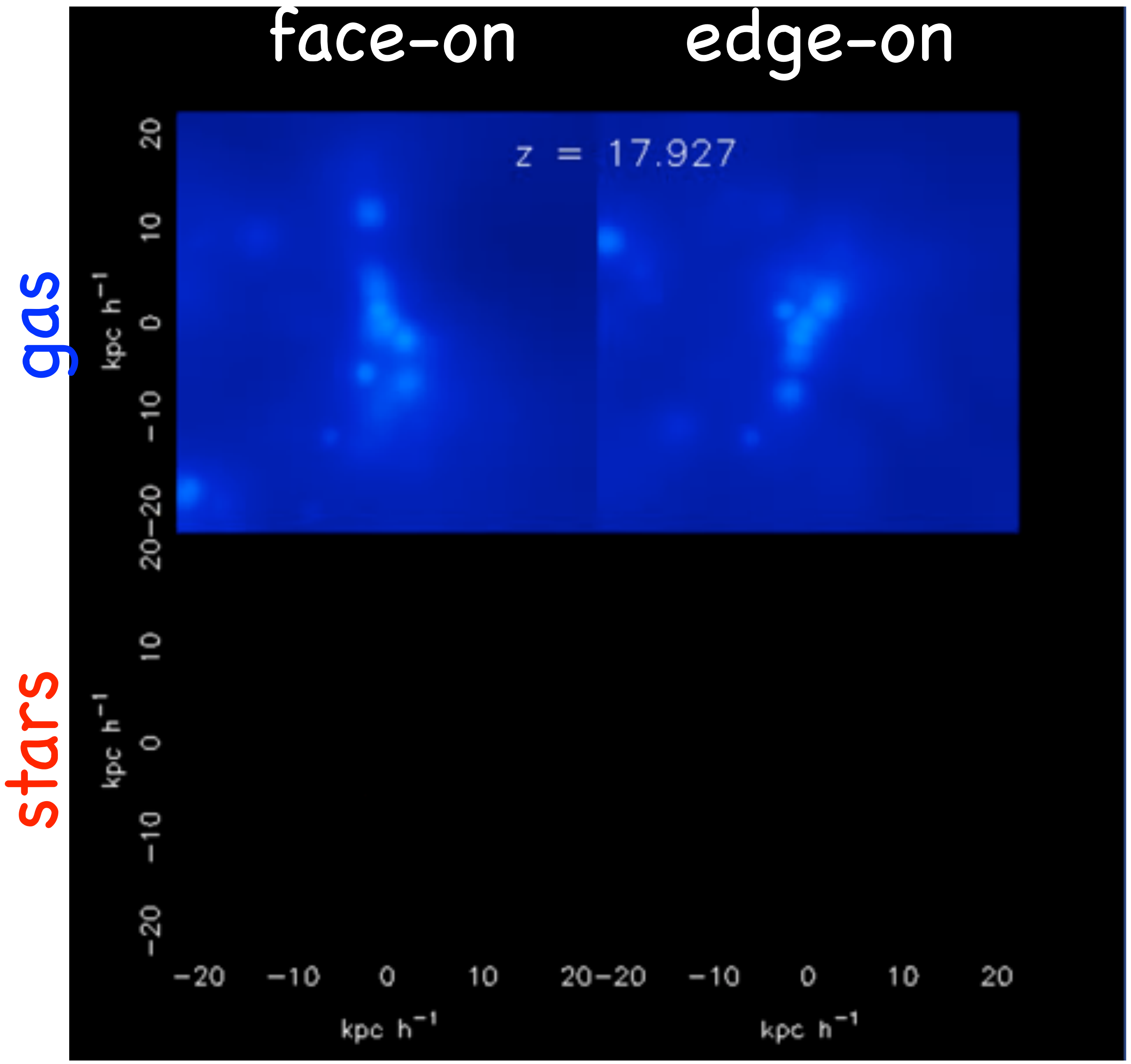
gas

stars

- no significant mergers below redshift 4
- disc formation begins around redshift 2
- there is a bar below redshift 1
- The orientation of the disc changes with redshift

(Okamoto'10)

Aq-C



- no significant mergers below redshift 4
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Aq-D

gas

stars

- no significant mergers below redshift 4
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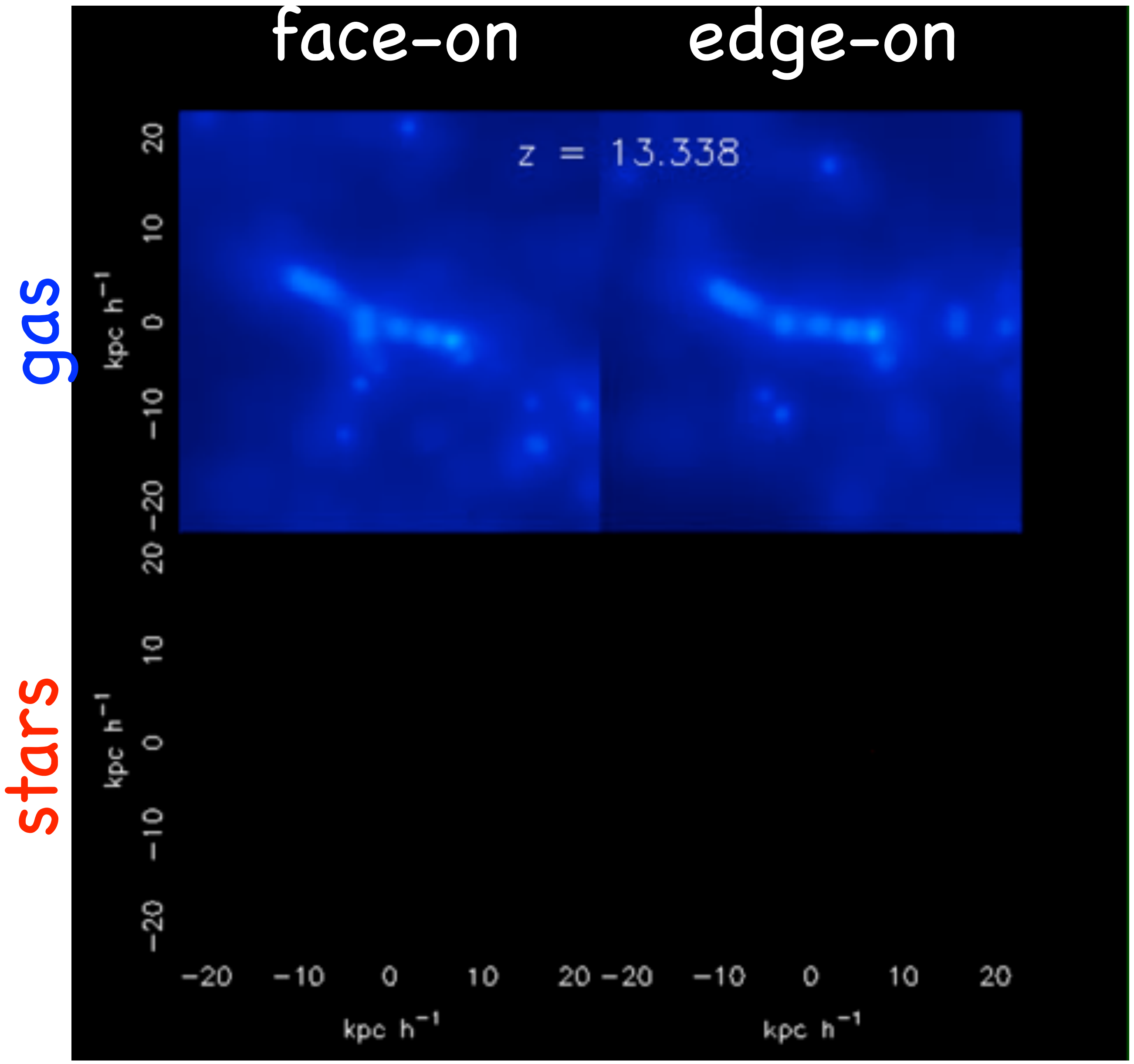
- can't see bar-like structure
- clumpy star formation below redshift 1

(Okamoto'10)

Aq-D



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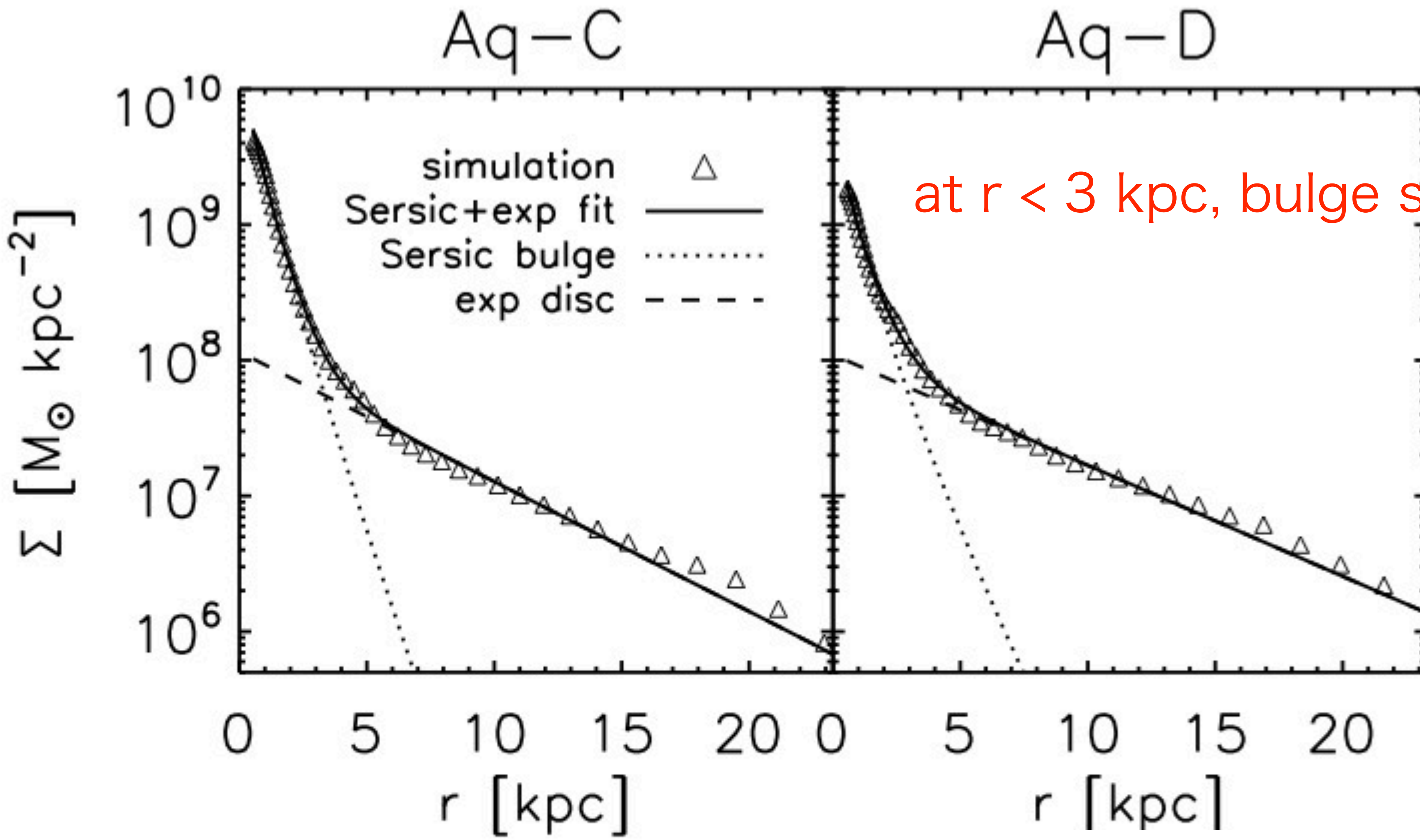
Surface density profiles



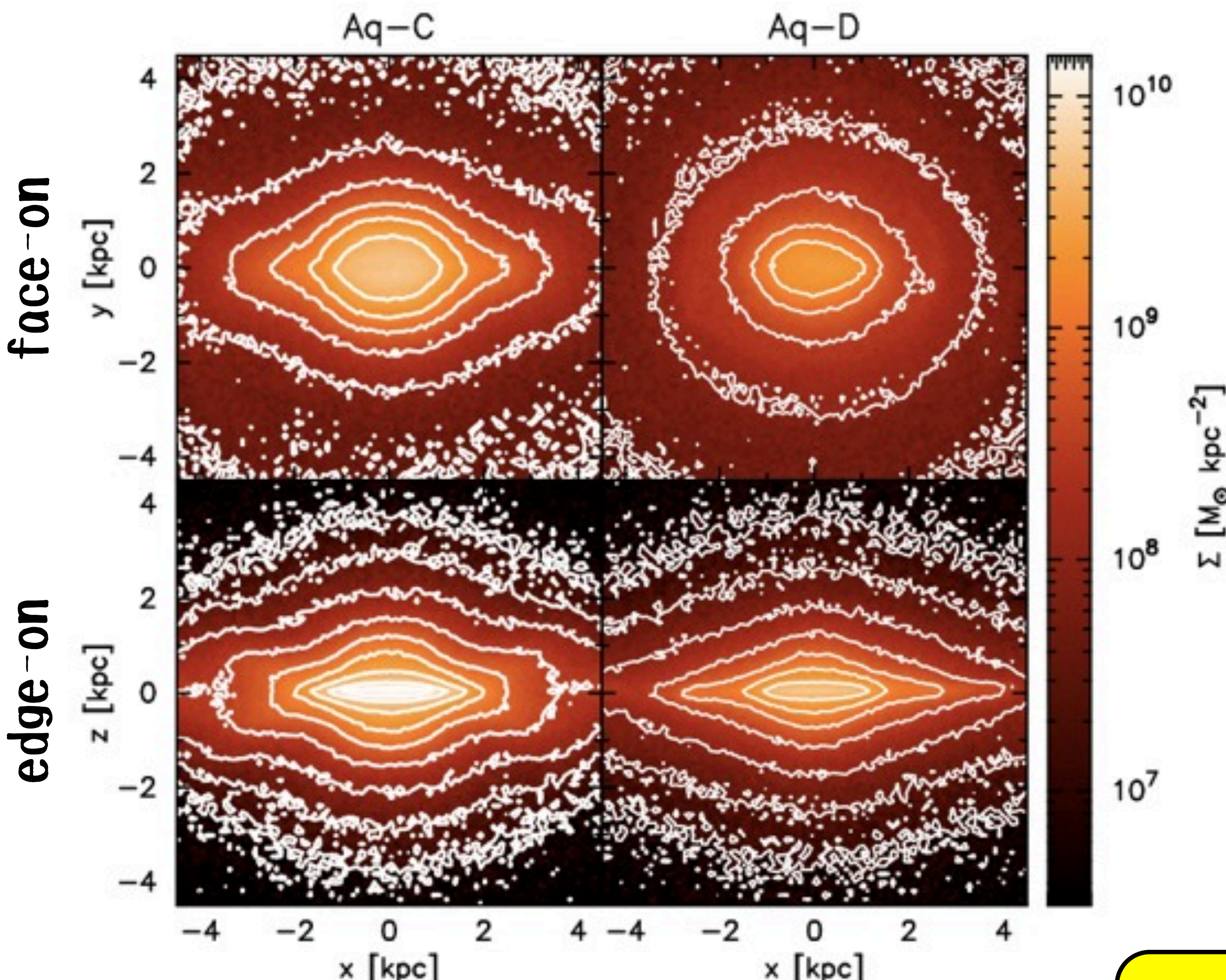
at r < 3 kpc, bulge stars dominate

- Fit the bulge by the Sérsic profile: $\Sigma(r) = \Sigma_e \exp\left[-b_n\left\{\left(\frac{r}{R_e}\right)^{\frac{1}{n}} - 1.0\right\}\right]$
- Aq-C: n = 1.2
- Aq-D: n = 1.4

pseudobulge-like

(Okamoto'10)

Bulge shapes

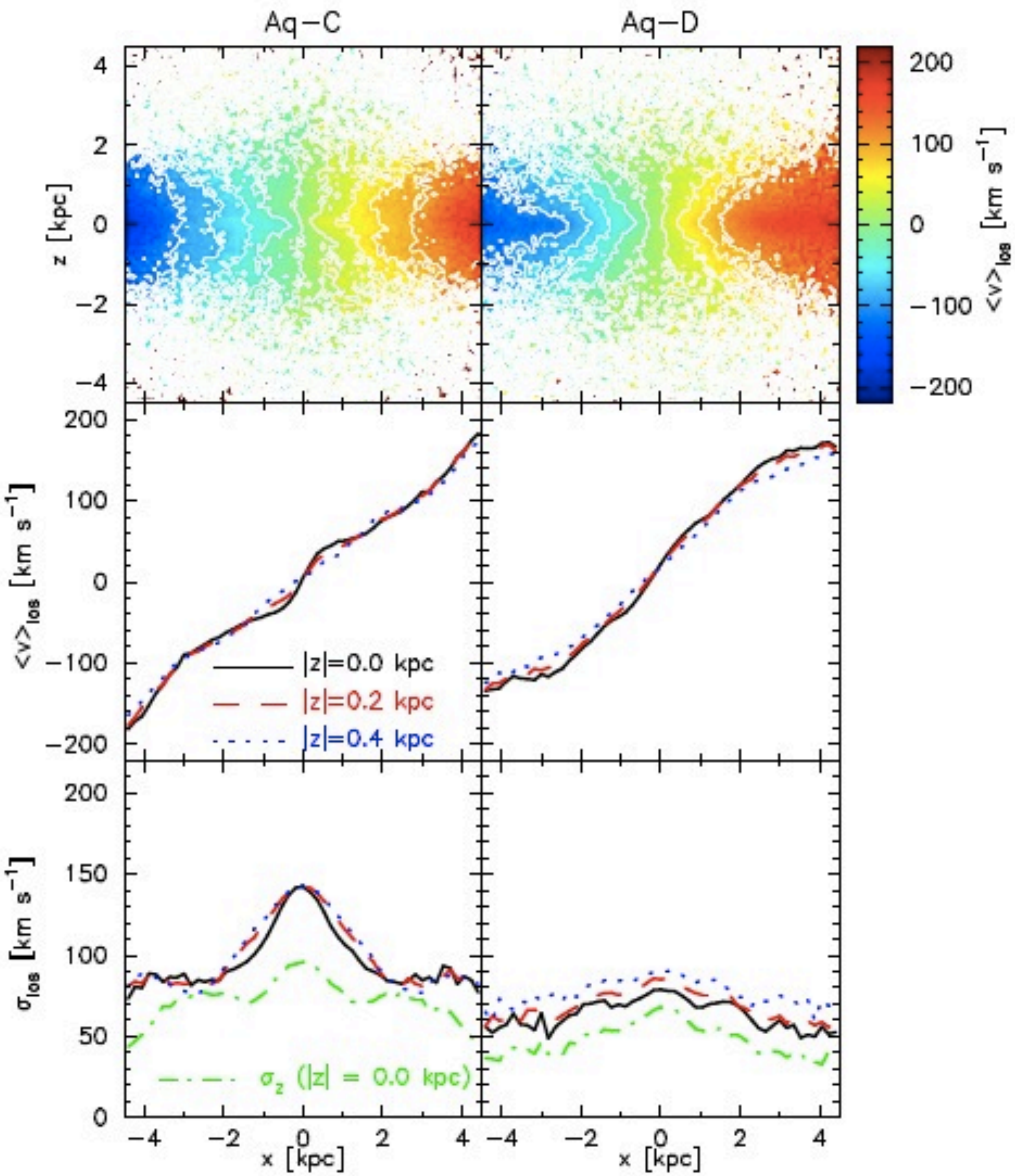


- A bar in Aq-C
- Both bulges have disky contour shapes in edge-on
- Weak signature of boxy-bulge in Aq-C
- Diamond shape of Aq-D's bulge is a strong evidence of disky bulges

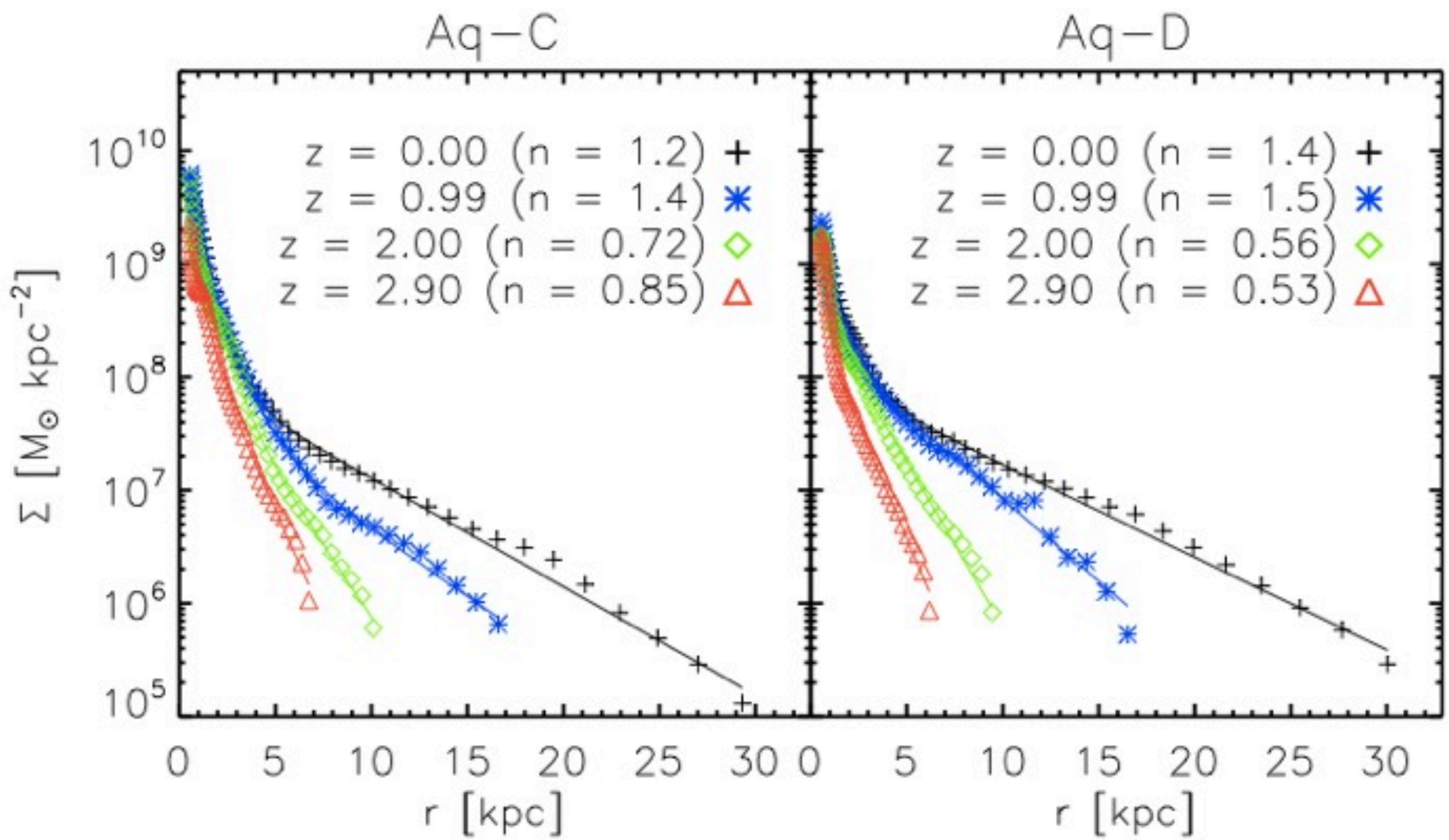
Both bulges are pseudo-bulges

(Okamoto'10)

Kinematic properties of bulges



Evolution of surface density profiles

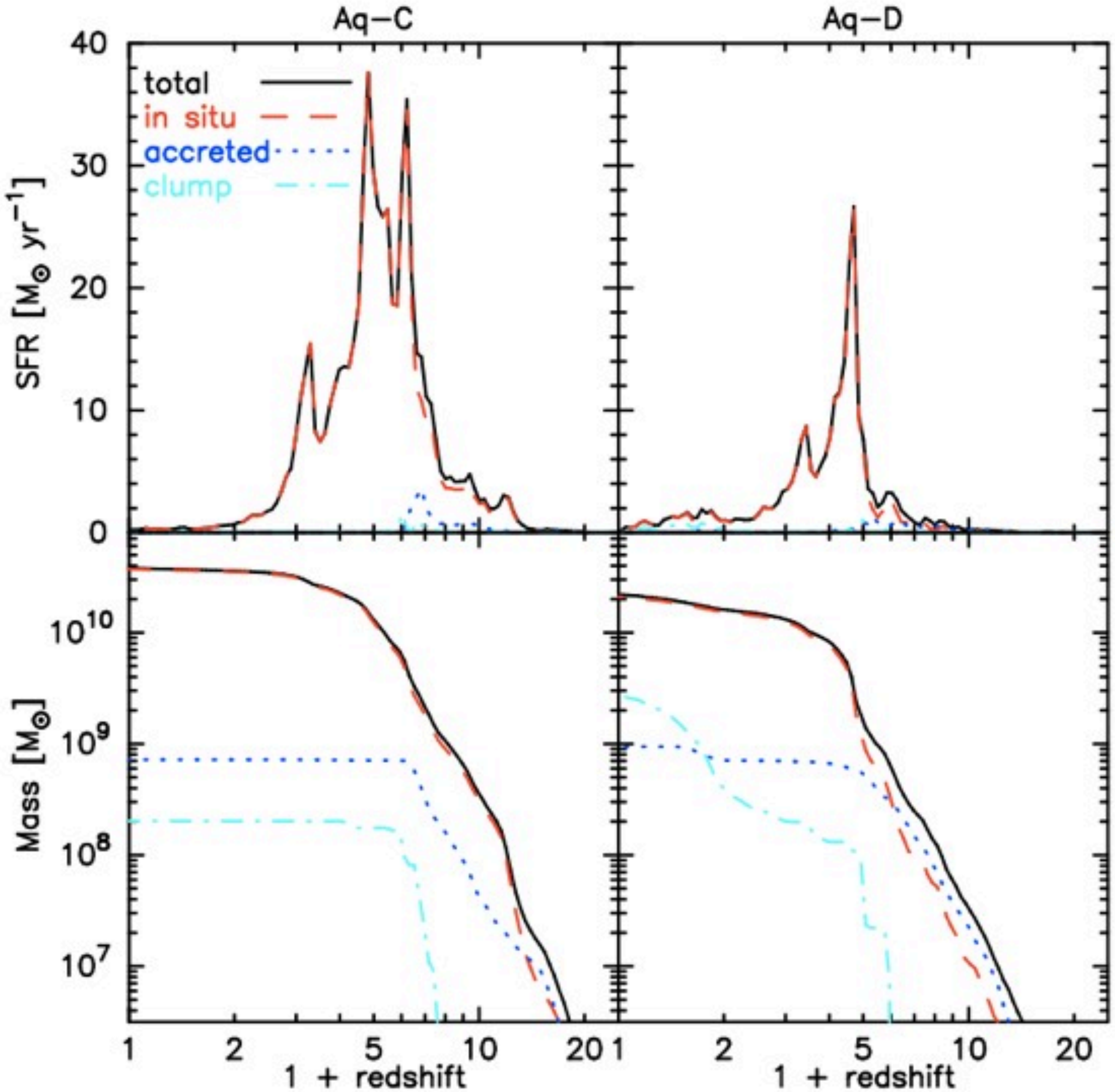


- By z = 2—3, the bulges have formed as disks with small scale length.
- From z ~ 2, the main disks with large scale length form around the disky bulges.
- The bulge masses at z = 2 account for 70% (Aq-C) and 87%(Aq-D) of those at z = 0.

The main process of the pseudo-bulge formation is NOT the secular evolution in these simulations

(Okamoto'10)

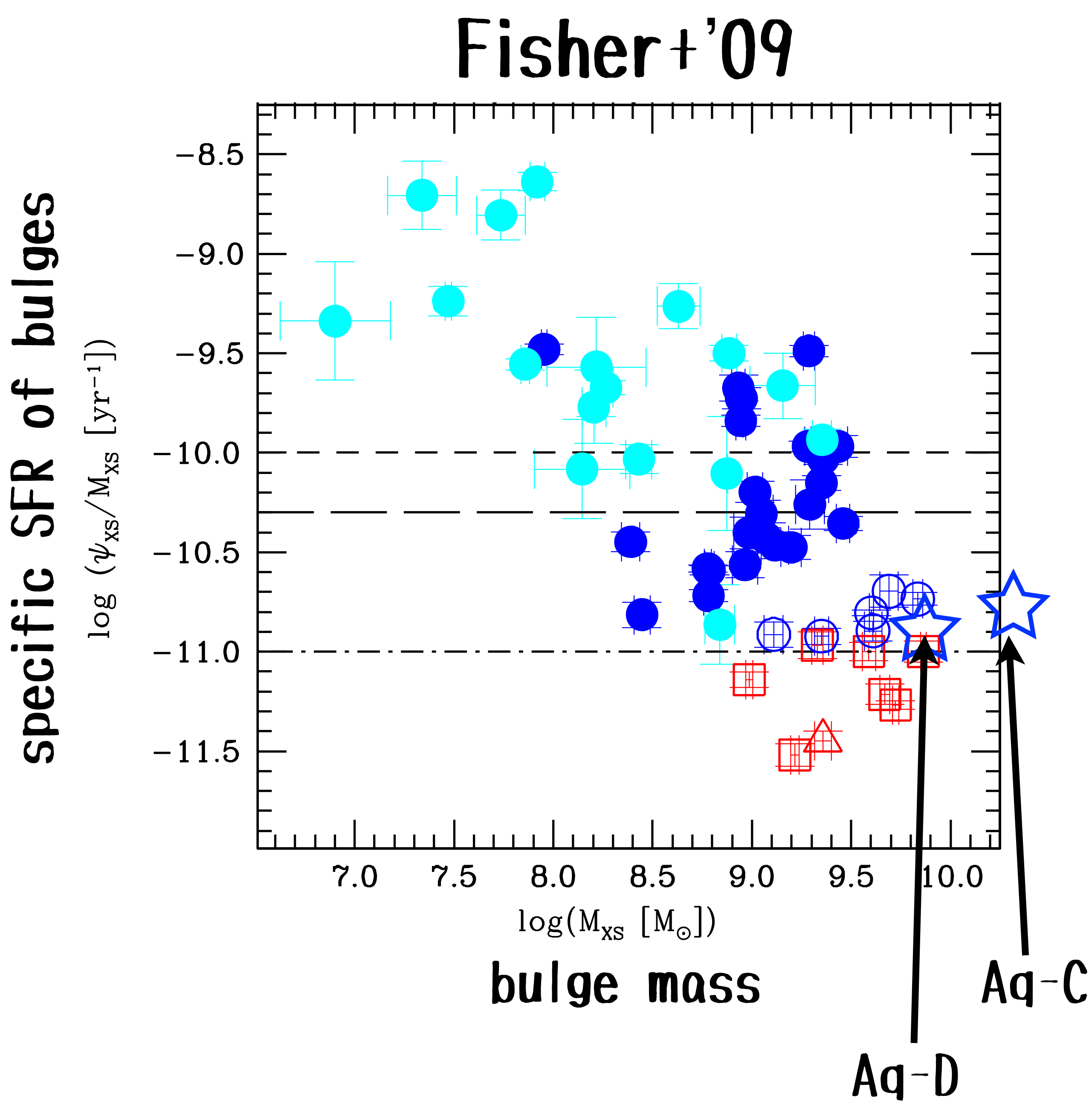
Star formation histories of the bulges



- Formation histories of stars with in 3 kpc at z = 0
- Bulge stars are mainly formed by high-redshift starbursts
- Mostly *in situ*.

(Okamoto'10)

Formation time-scale of the bulges



- blue **filled** circles: **pseudo-bulges**
- cyan **filled** circles: **pseudo-bulges in late-type disks**
- blue **open** circles: **inactive pseudo-bulges**
- red open squares: **classical bulges**

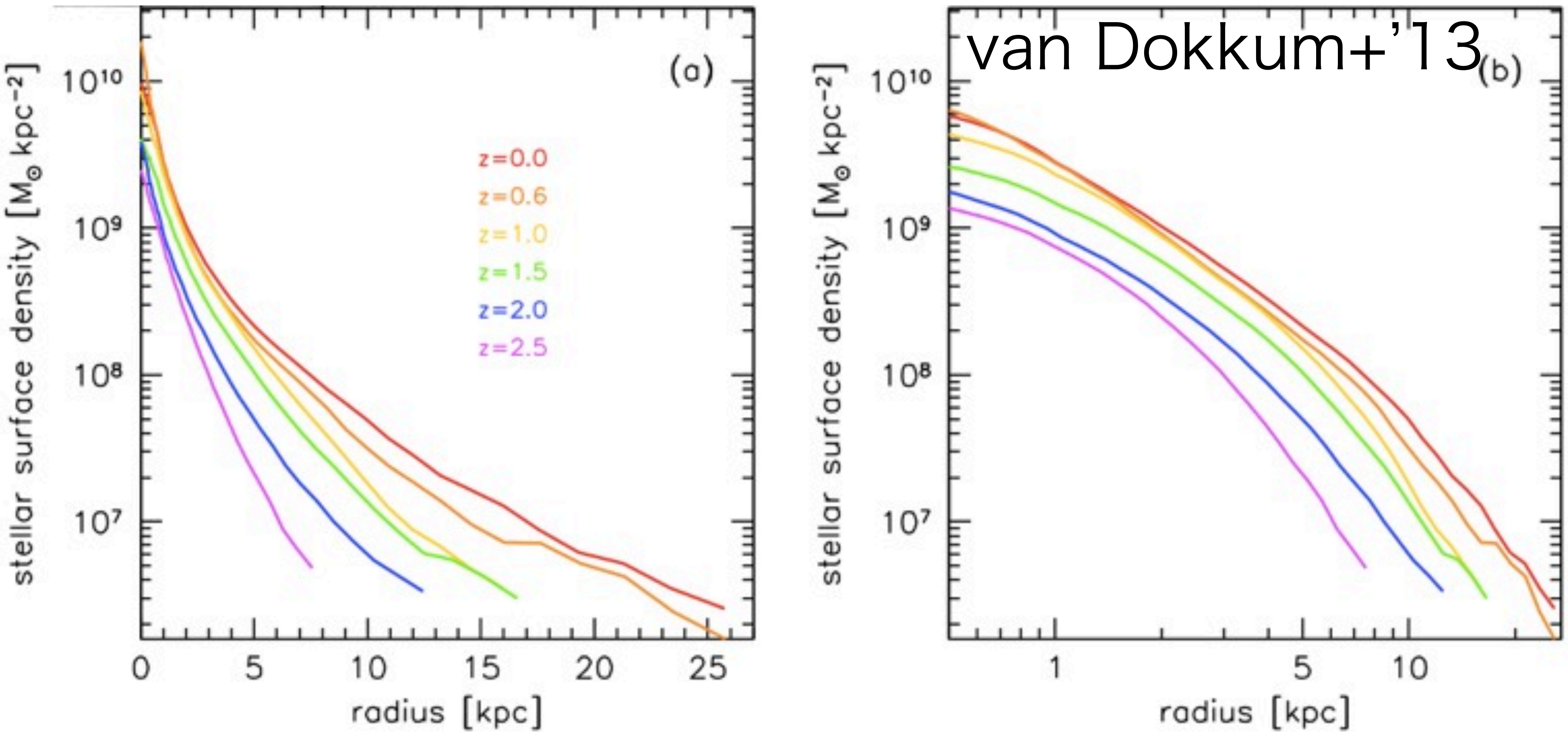
Simulated bulges are inactive pseudo-bulges

(Okamoto'10)

Summary of the simulation results

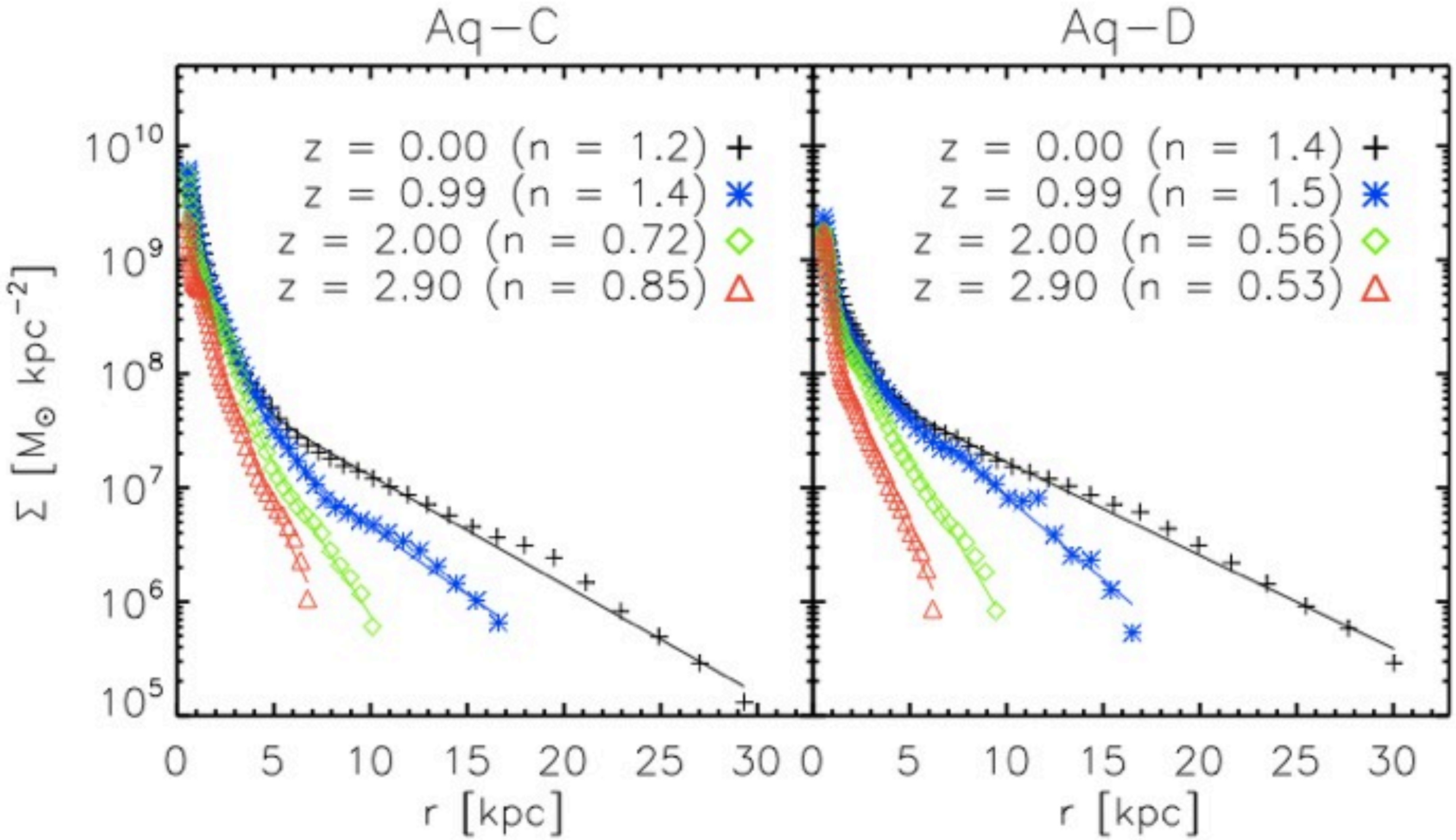
- No agreed model of feedback
- (Inactive) pseudo-bulges form in MW-mass galaxies with non-secular process (high-redshift starbursts)
  - A similar result is reported by an independent study (Guedes+'12)
- Observed counterparts do exist. But are they typical?

Observational indications



- The stellar surface density evolution of the "progenitors" of the MW-mass galaxies
- the central and outer parts built up at the same rate between z = 2.5 and 1.

In simulations



- The bulge masses at z = 2 account for 70% (Aq-C) and 87%(Aq-D) of those at z = 0.
- Early bulge formation and inside-out galaxy formation

Non inside-out formation of observed galaxies

- Need to suppress the starbursts that build up bulges at early times in simulations
  - Early stellar feedback? (feedback by radiation and stellar winds, e.g. Stinson+'12): SN feedback is too late
- Need to bring high angular momentum material to the center
  - Secular processes such as bars and clump migration
  - High-resolution imaging of high-redshift progenitors with kinematic information is a key to understand the physical processes.

Non inside-out formation of observed galaxies

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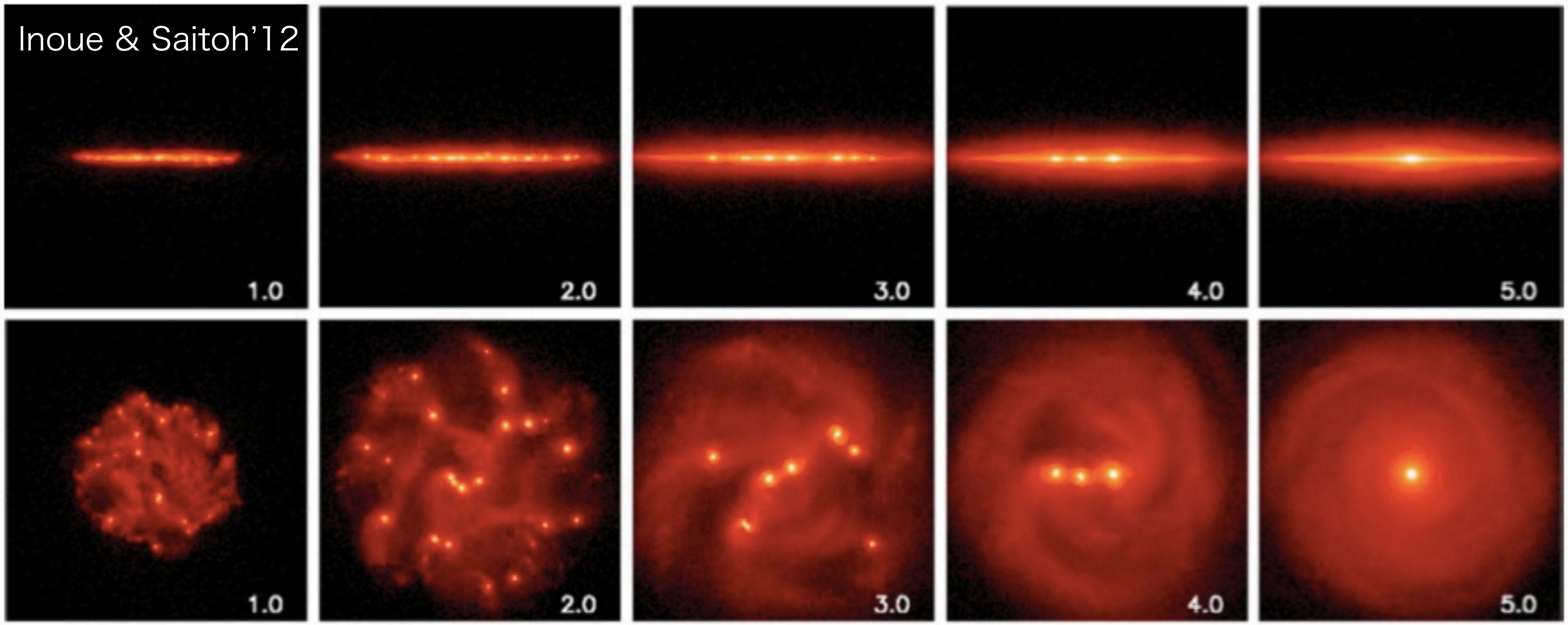

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Answers to the questions

THE ANSWER
to the questions

I’d rather buy a supercomputer.

Q. 1

- Which instrument is essentially important for your science cases?
  1. Wide-Field Near-IR Imager
  2. Wide-Field NIR Imager and Multi-Object Spectrograph
  3. Multi-Object Integral Field Spectrograph

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- Ans.
  Option 3, of course. I'd like to have kinematic information.
  Option 2 might be OK (c.f. Tadaki-san's talk)

Q. 2

- What is the optimal plate scale / FoV for your science cases?

Q. 2

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- Ans.
  The baseline specification seems reasonable.

Q. 3

- Can you highlight synergies between this instrument and the TMT?

Q. 3

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- Ans.
  No, I can’t.

Q. 3

- Can you highlight synergies between this instrument and the TMT?

- Ans.
  No, I can't.

  To find interesting high-z objects.

Q. 4

- Does this instrument have competitive (or complementary) capabilities with planned Near-IR space missions such as JWST, Euclid and WISH?

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- Does this instrument have competitive (or complementary) capabilities with planned Near-IR space missions such as JWST, Euclid and WISH?
- Ans.
  To be honest... It doesn't look like so. too late.
  But space missions are expensive, often delay, and launch operations sometimes fail...

  Maybe NB imaging and emission lines according to Minowa-san's and Akiyama-san's talks.

Done!