# Galactic discs forming through clump clusters

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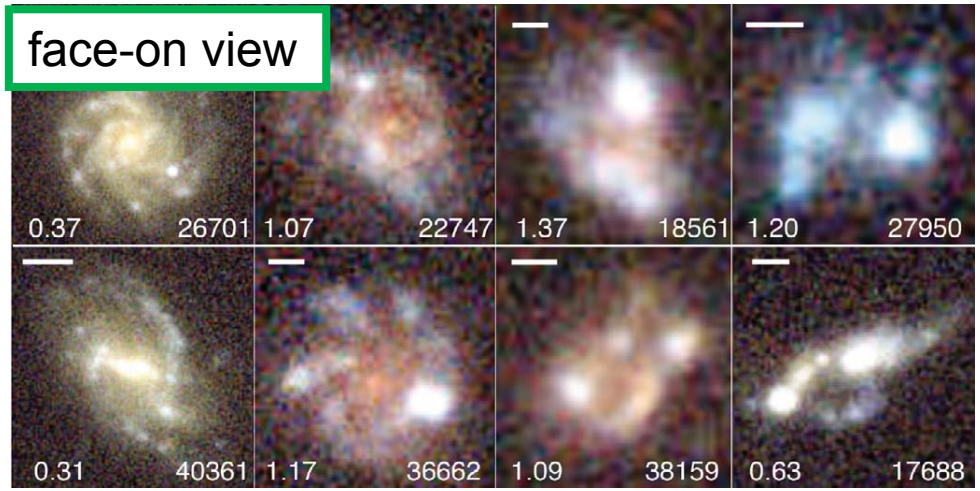
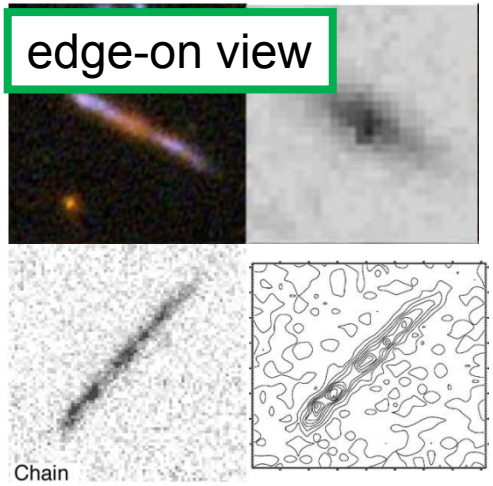
# clump cluster / chain galaxy

- In the high-z Universe（1 < z < 3）
  - clump clusters / chain galaxies




Elmegreen et al. (2009)

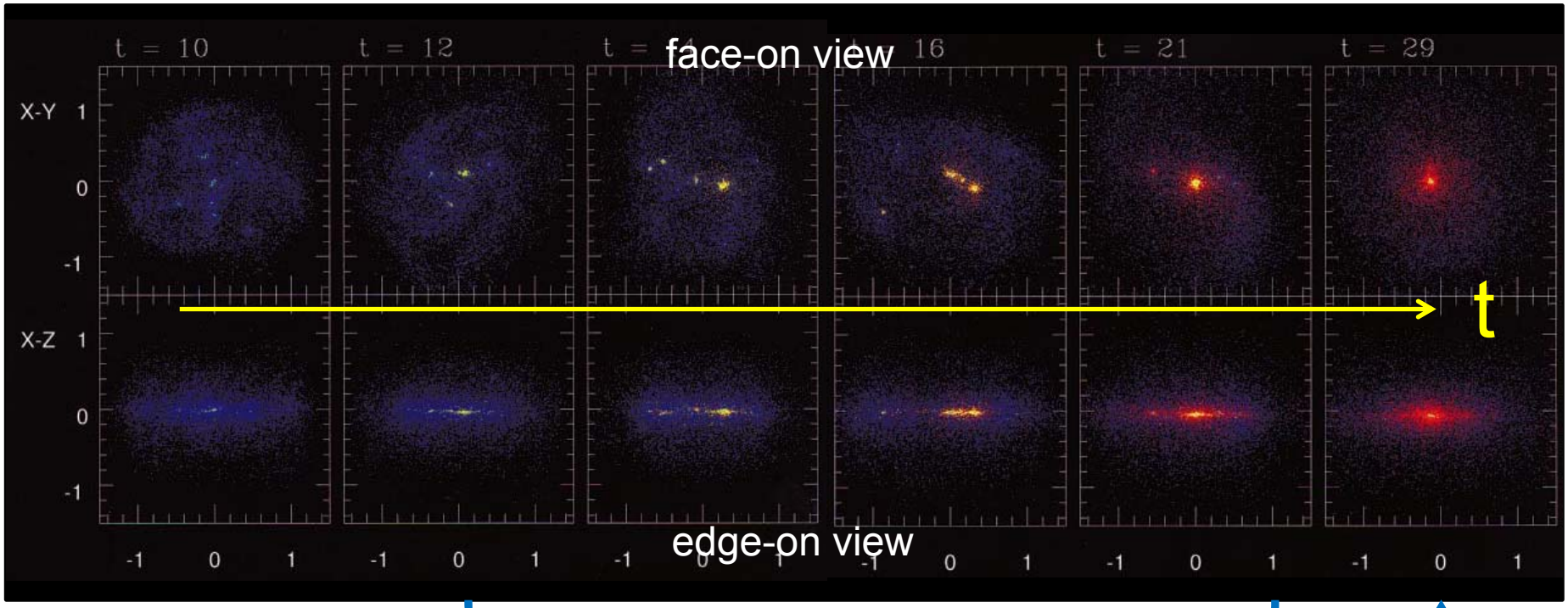
Elmegreen et al. (2009)



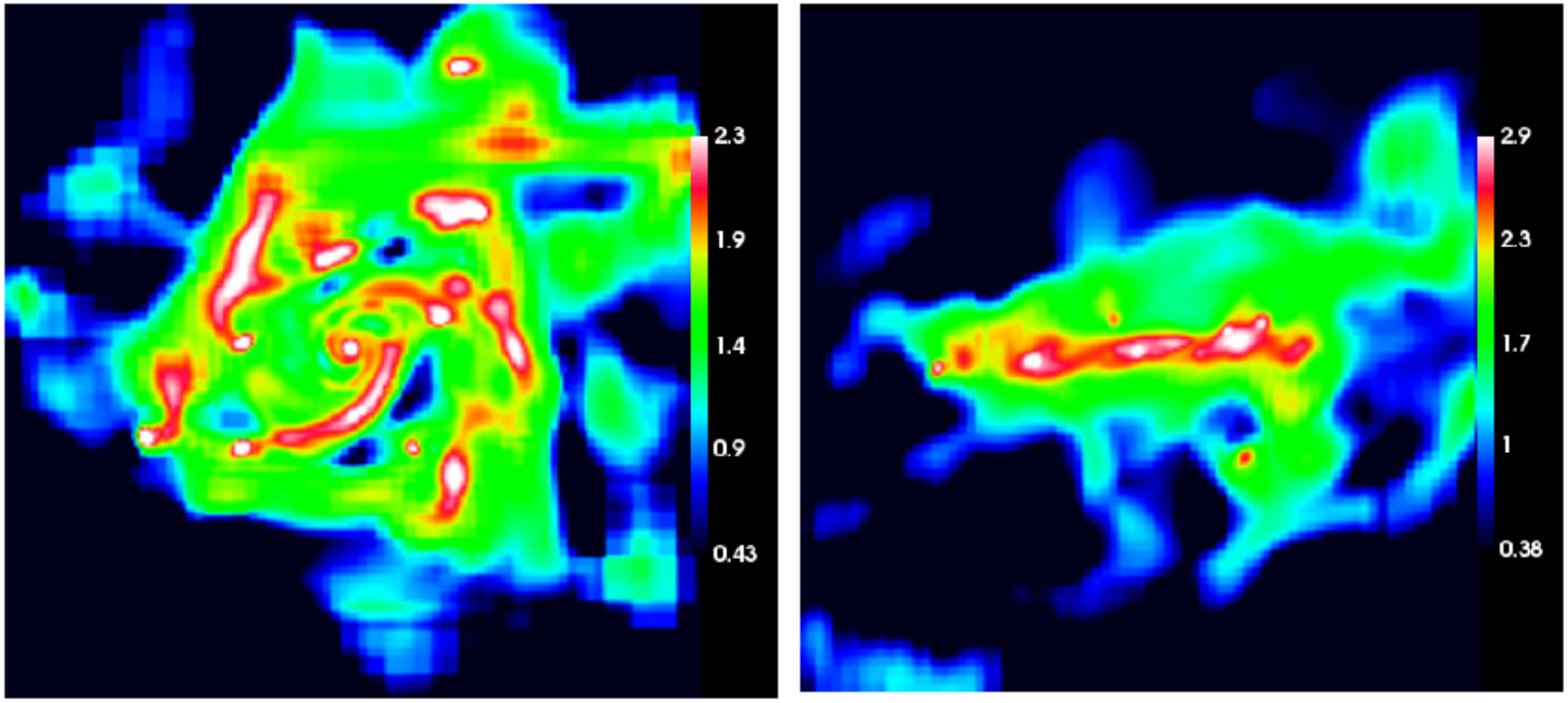

Elmegreen et al. (2004)

- **“Clumpy” galaxies are discs in their formative stages.**
  - “Giant clumps” (massive star clusters) in premature discs.
  - Clump mass ~ $10^9$ $M_\odot$ at the largest.

- Demonstration by numerical simulations
  - Noguchi (1998, 1999) etc…
    - Gas-rich discs in formative stages can cause dynamical instability.
    - Giant clumps form in the discs and may merge into central bulges.



- Demonstration by numerical simulations
  - Dekel, Sari & Ceverino (2009) etc…
    - Cosmological simulation




Dekel, Sari & Ceverino (2009)

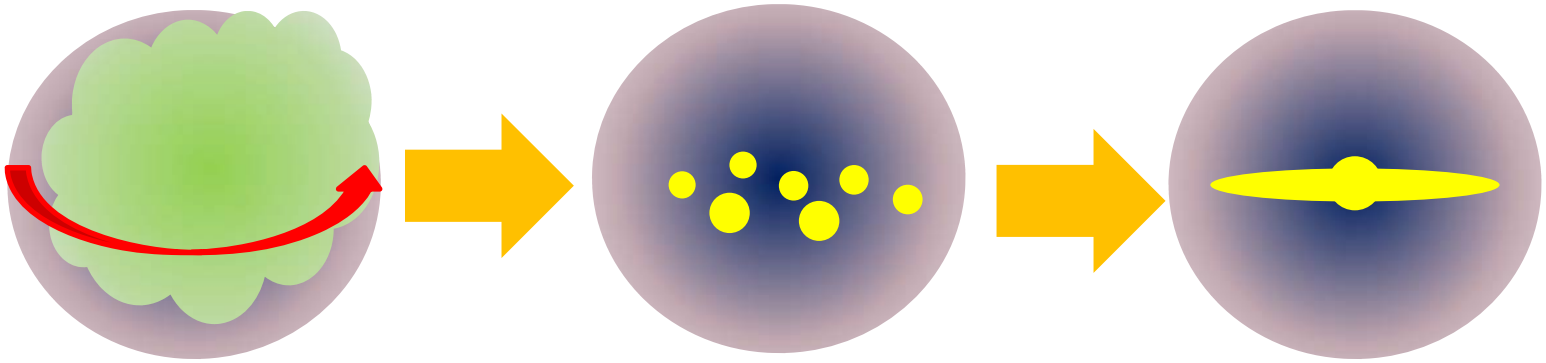
## Problems

- The clump clusters in current observations are too massive to evolve into MW-sized galaxies.

- The clumpy disc phase may not be a common stage of disc-galaxy formation.
  - Some disc galaxies may experience quiet formation processes.

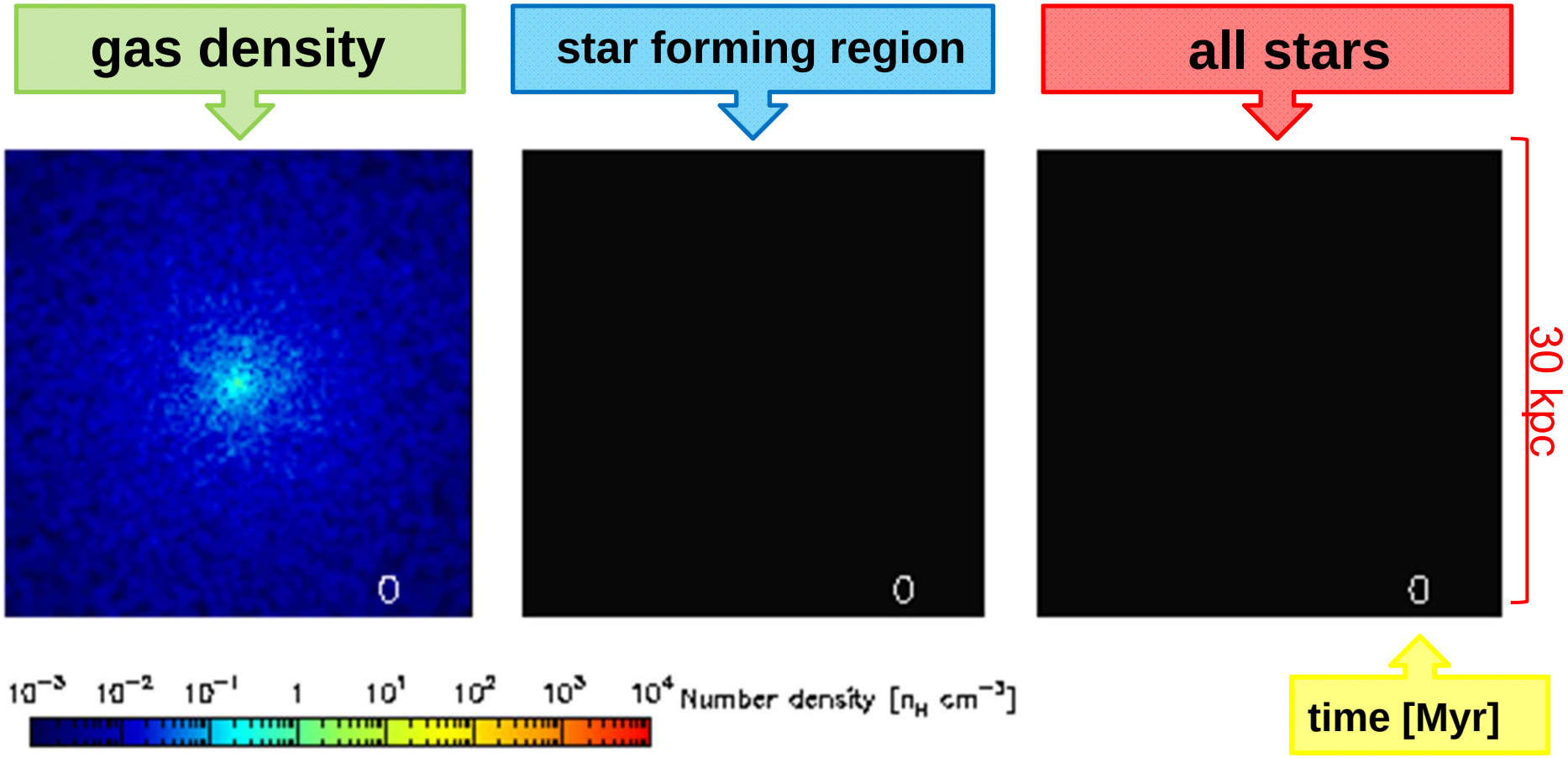
**Was our Galaxy once a clump cluster?**

# A spherical gas-collapse model using SPH



- NFW profile
  - $M_{vir} = 5\times10^{11}\,M_\odot$
  - gas fraction = 6 %
  - $N_{DM} = 10^7$, $N_{gas} = 5\times10^6$
  - $\varepsilon$ = 10 pc
- spin parameter $\lambda = 0.04$
  - AM distribution $j \propto r$
  - virial temperature

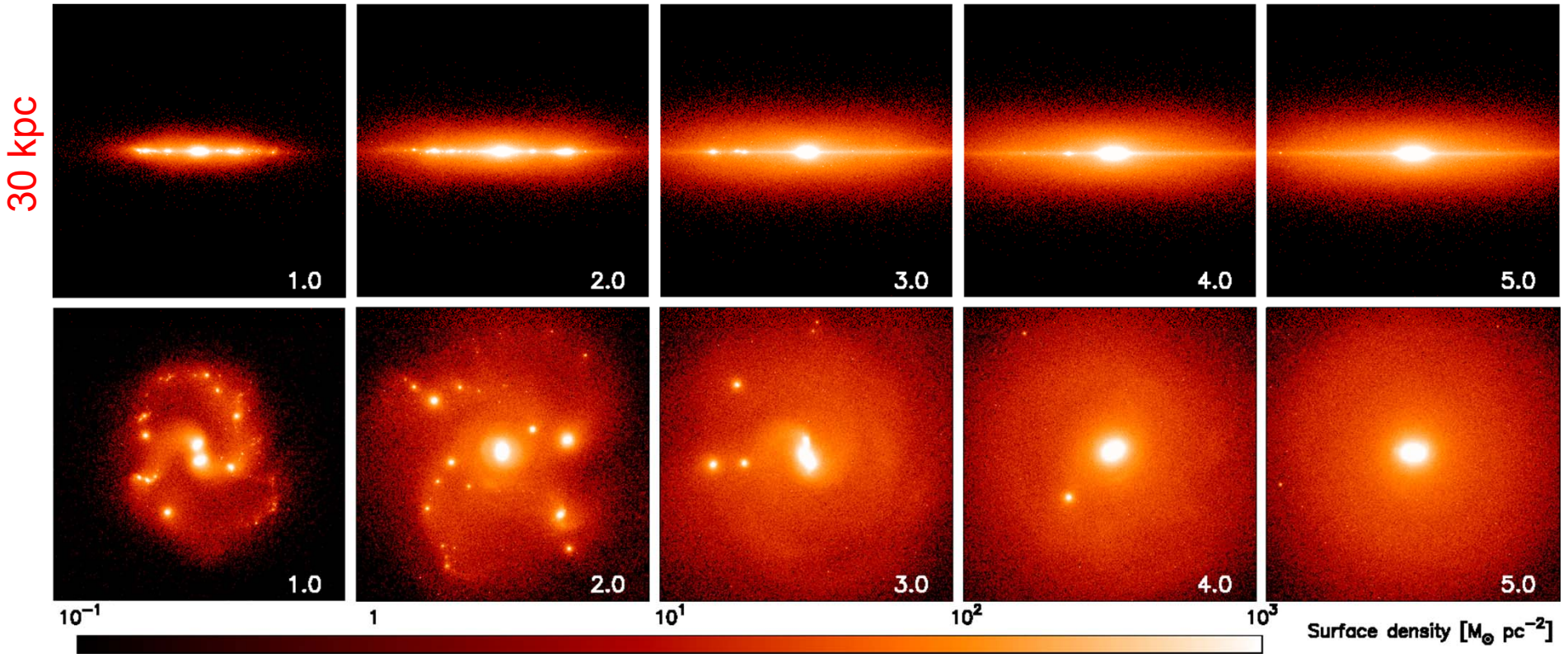
- w/ ASURA (SPH Saitoh+ '08,'09)
  - radiation cooling
  - SN II & FUV background
- star-formation criteria
  - $\nabla \cdot v < 0$
  - T < 100 K
  - $\rho_{gas}$ > 100 atm / cm$^3$




Inoue & Saitoh (2011, 2012)

30 kpc

Inoue & Saitoh (2011, 2012)




at t = 6 Gyr

- DM mass = $4.7\times10^{11}\,M_\odot$
- Stellar mass = $2.8\times10^{10}\,M_\odot$ scale radius = 4 kpc
- Gas mass = $2.1\times10^{9}\,M_\odot$ Bulge/Total = 0.37

The clump-origin bulge is a classical or pseudo-bulge?

# BULGE

# classical bulge or pseudo-bulge?

- Galactic bulges are generally classified into two types.
  - classical bulge
    - **made by galactic mergers**
    - de Vaucouleur's profile
    - spherical shape with little rotation
    - old component
  - pseudo-bulge (discy bulge, boxy/peanut bulge)
    - **made by secular evolution (by spiral arms, bars etc…)**
    - exponential profile
    - oblate (boxy/peanut) shape with a significant rotation
    - relatively young

- **Which type is the clump-origin bulge? New type?**

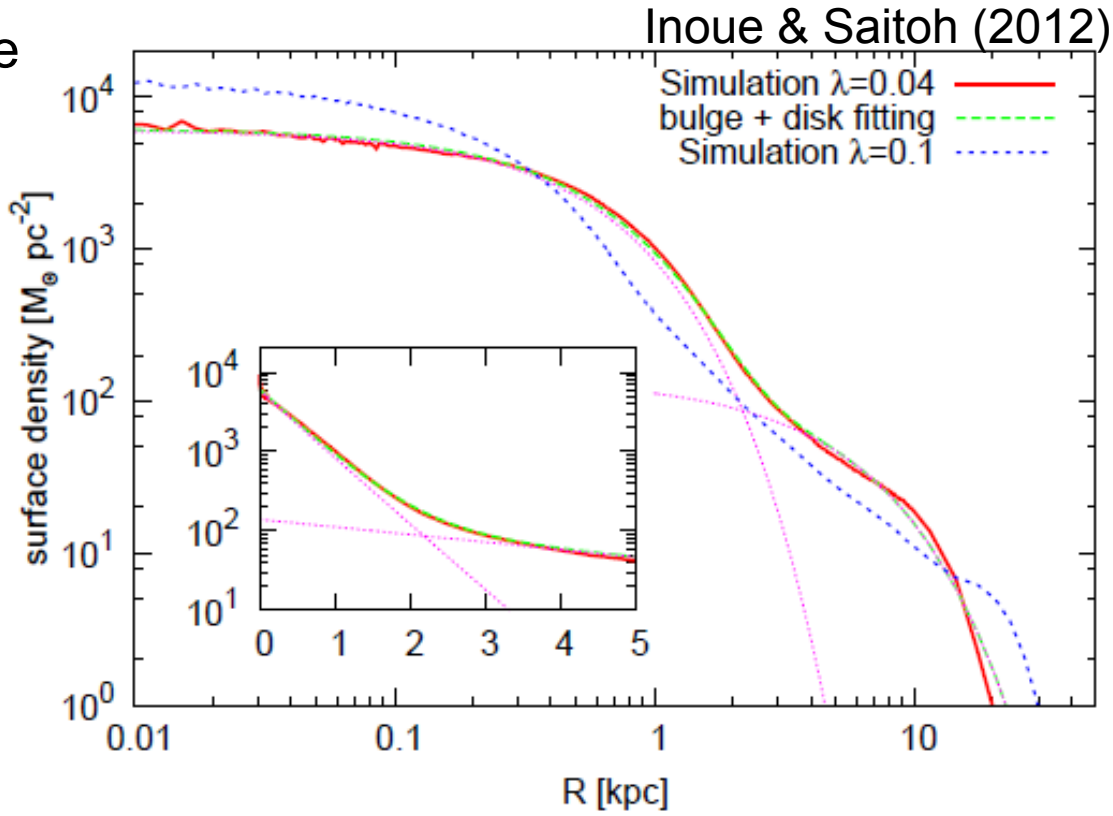
# Sersic profile fit

$$\Sigma(R) = \underbrace{\Sigma_0 \exp\left[-(R/R_e)^{1/n}\right]}_{\text{Sersic profile bulge}} + \underbrace{\Sigma_d \exp\left(-R/R_d\right)}_{\text{exponential disc}}$$

- n>2.0 ⇒ classical bulge
- n<2.0 ⇒ pseudo-bulge

- **n=1.02**
  - **pseudo-bulge**

- bulge mass = $1.0\times10^{10}\,M_\odot$

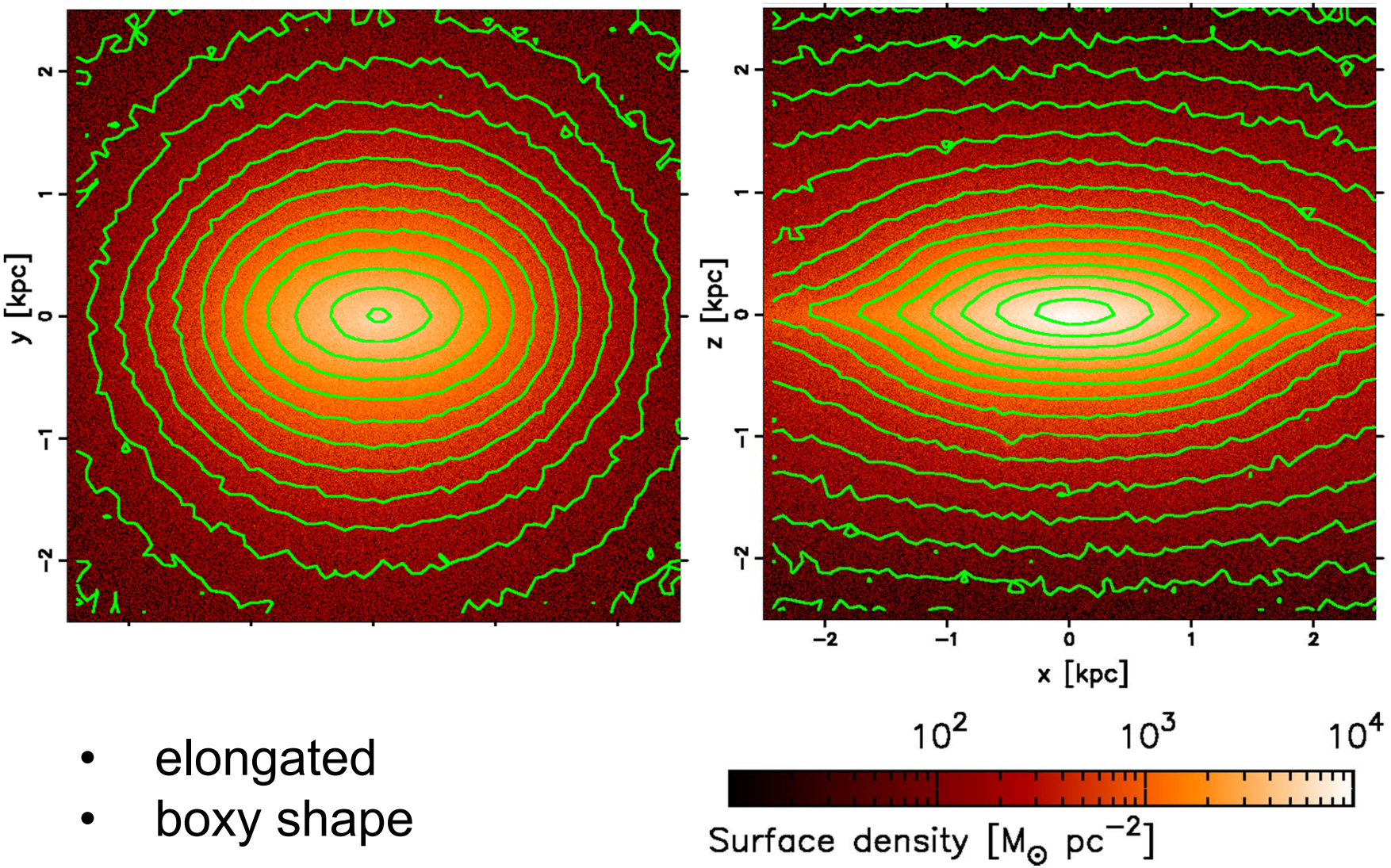


# bulge shape

Inoue & Saitoh (2012)

face-on

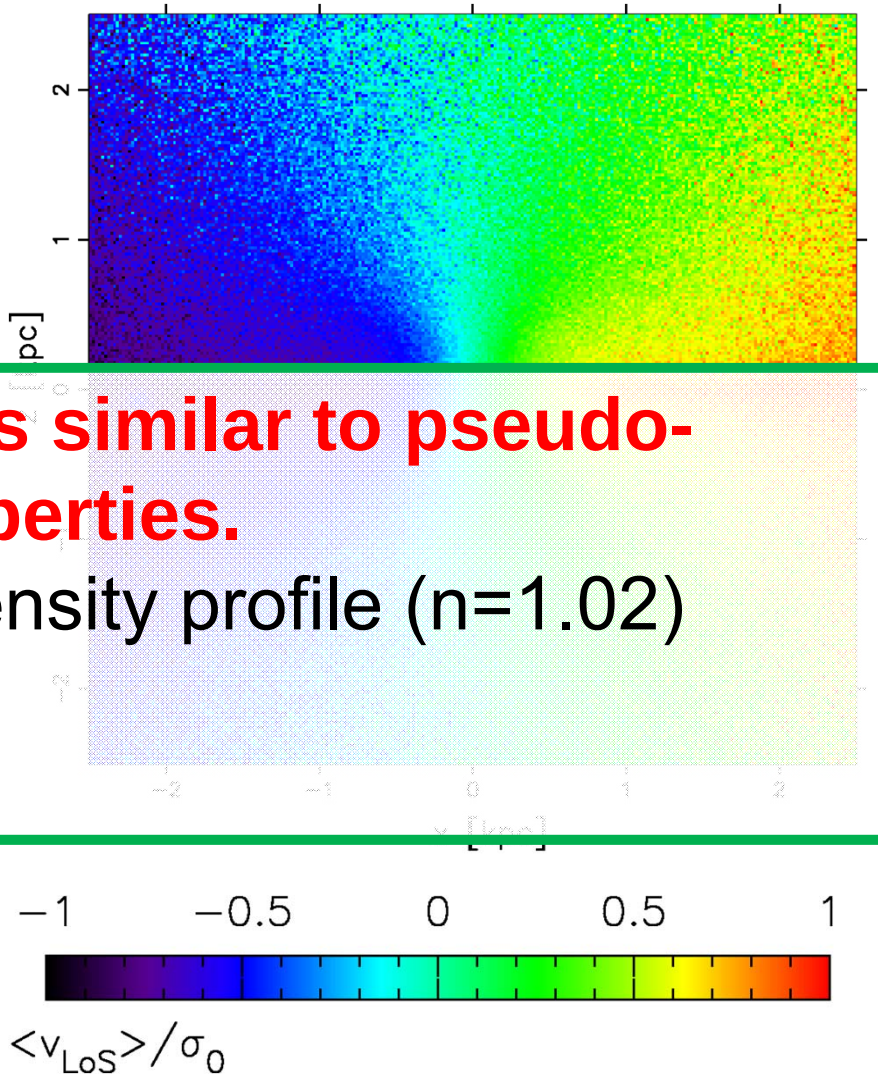
edge-on




- elongated
- boxy shape

# rotation

Inoue & Saitoh (2012)



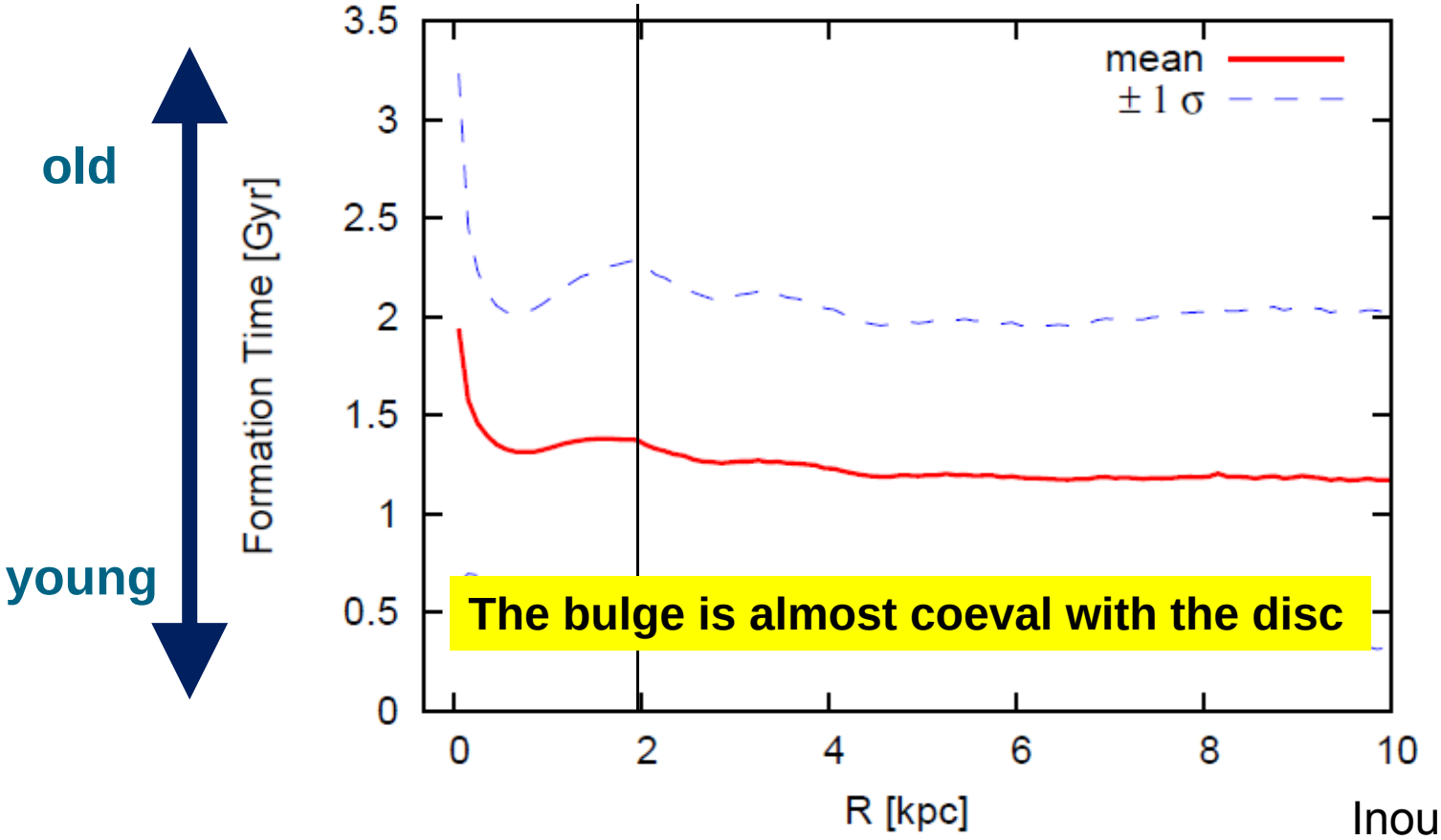

- a significant rotation
  - comparable to velocity dispersion

**The clump-origin bulge is similar to pseudo-bulges in dynamical properties.**

- almost exponential density profile (n=1.02)
- boxy shape
- a significant rotation

# Age

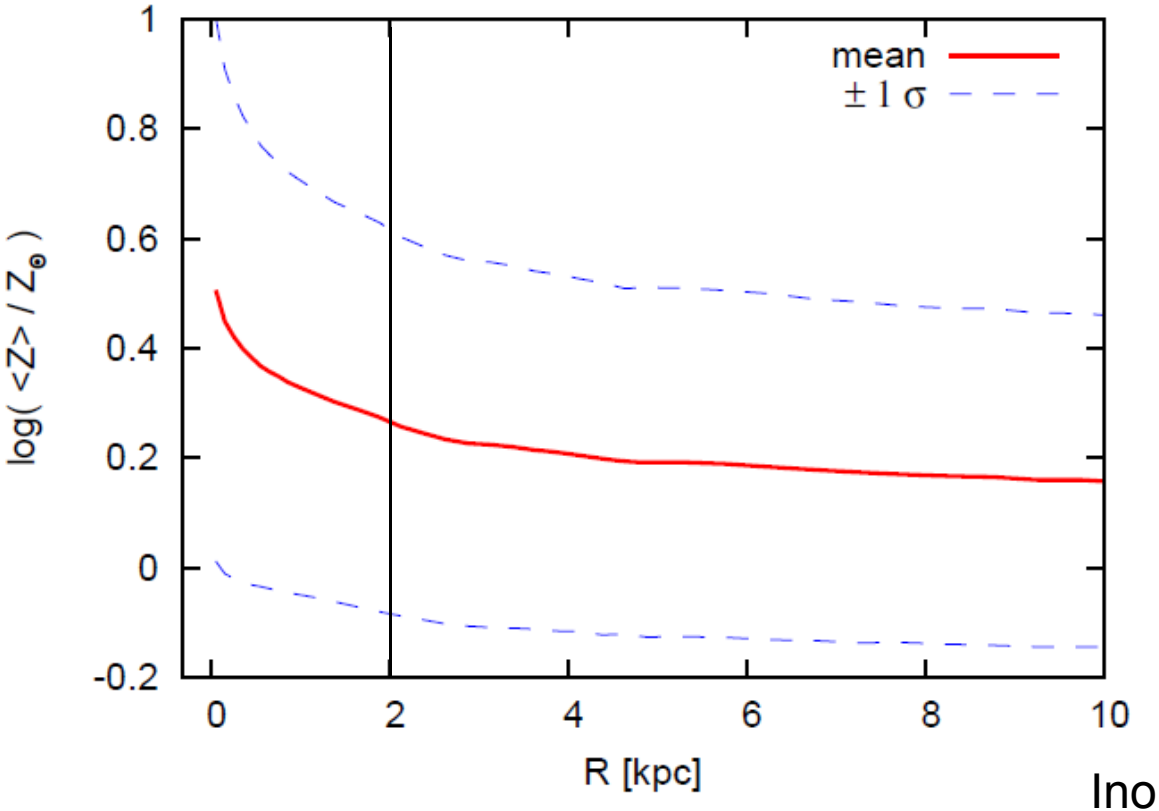
- The clump-origin bulge is an old component.
  - Clump clusters can be observed in the high-redshift Universe.
    - Clump-origin bulges form in an early stage of galaxy formation.




Inoue & Saitoh (2012)

# Metallicity

- The clump-origin bulge consists of metal-rich stars
  - Metal enrichment in clumps.
  - The metal-enriched clumps form the clump-origin bulge.




Inoue & Saitoh (2012)

# The property of the clump-origin bulge

**The clump-origin bulge is similar to pseudo-bulges in dynamical properties.**

- nearly exponential density profile (n=1.02)
- boxy shape
- a significant rotation

**The clump-origin bulge better resembles classical bulges on stellar population.**

- early formation
- old & metal-rich

- The clump-origin bulge is neither a classical bulge nor a pseudo-bulge.

# The Milky Way bulge

- The MW bulge is supposed to be a **pseudo-bulge.**
  - Exponential profile (e.g., Kent et al. 1991)
  - Oblate and X-shape (e.g., Kinman et al. 1966)
  - Significant rotation (e.g., Minniti et al 1995)
- But, the stellar population is like a **classical bulge.**
  - Old age ~11-13 Gyr. (e.g., Sandage 1986)
  - High metallicity (e.g., McWilliam & Rich 1994)

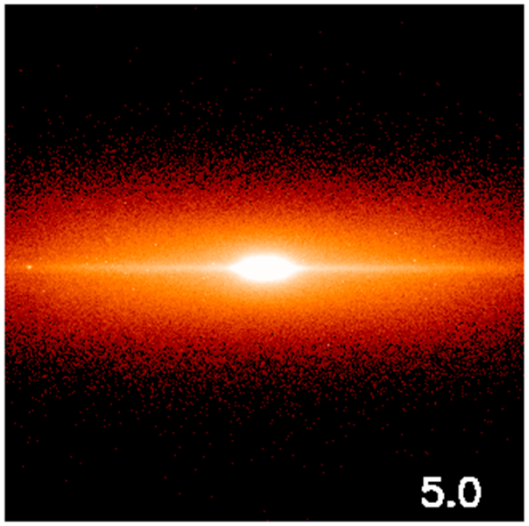
- **The clump-origin bulge resembles the Milky Way bulge.**

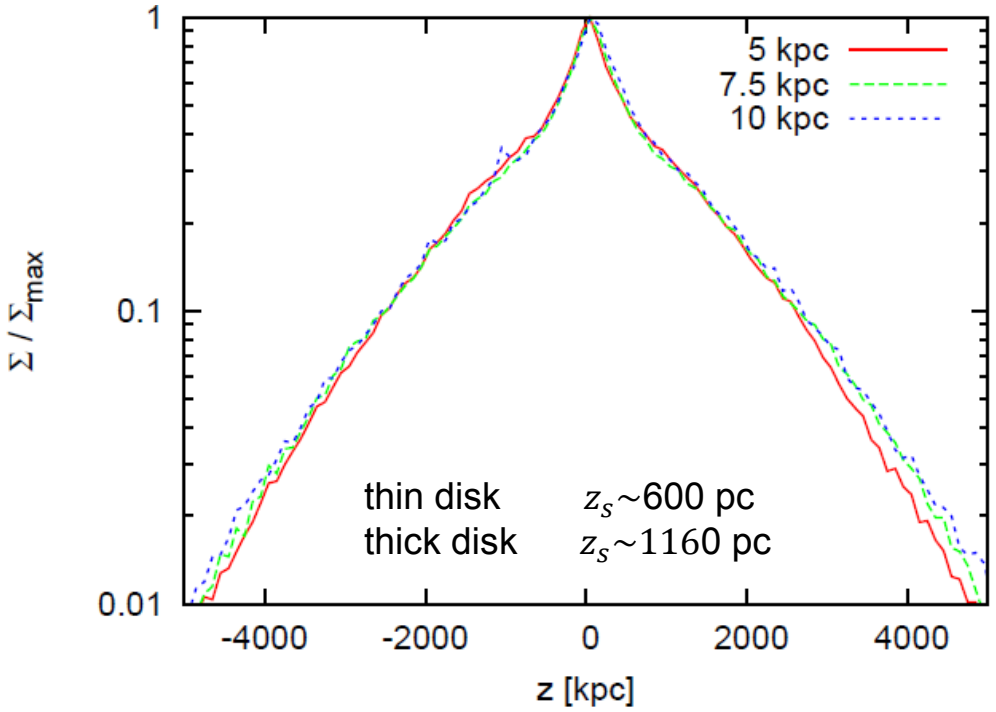
  - However, Elmegreen et al. (2008) have shown that clump-origin bulges are like classical bulges.
    - an initial condition of a pre-existing disc
    - a sticky-particle method for hydrodynamics

A possible thick disc formation scenario?

# DISC

# A thick disc is formed in a clump cluster




- A thin disc has hardly formed in my simulation.
  - Thin disc formation needs later gas accretion.
    - Bournaud, Elmegreen & Martig (2009)

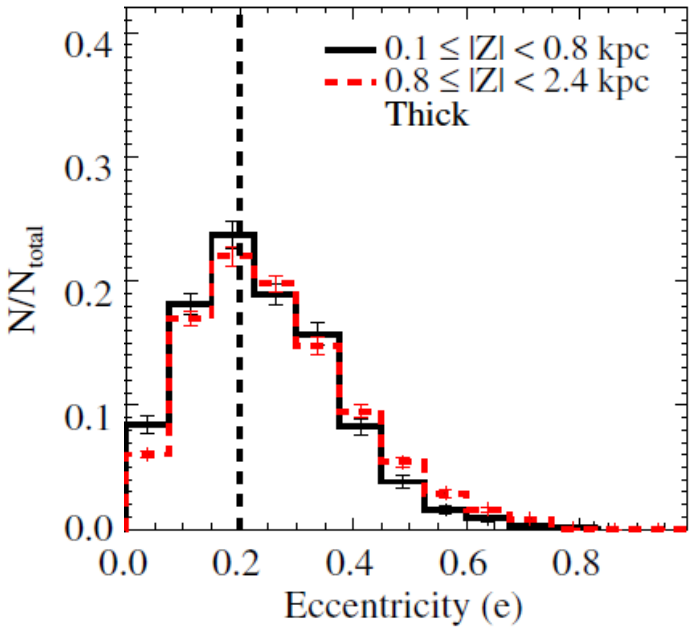
# Thick disc formation scenarios

- Many scenarios have been suggested…
  - ① stellar accretion from dwarf galaxies
    - Abadi et al. (2003)
  - ② thin-disc heating by dwarf galaxies
    - Villalobos & Helmi (2008)
  - ③ radial migration of thin disc stars
    - Sellwood & Binney (2002)
  - ④ multiple gas-rich minor mergers
    - Brook et al. (2004, 2005)
  - ⑤ **thick disc formation in clump clusters**
    - Bournaud et al. (2009)

# Orbital eccentricity distribution

- Distribution of orbital eccentricities can be used as a probe of the thick disc formation scenarios.
  - Sales et al. (2009)

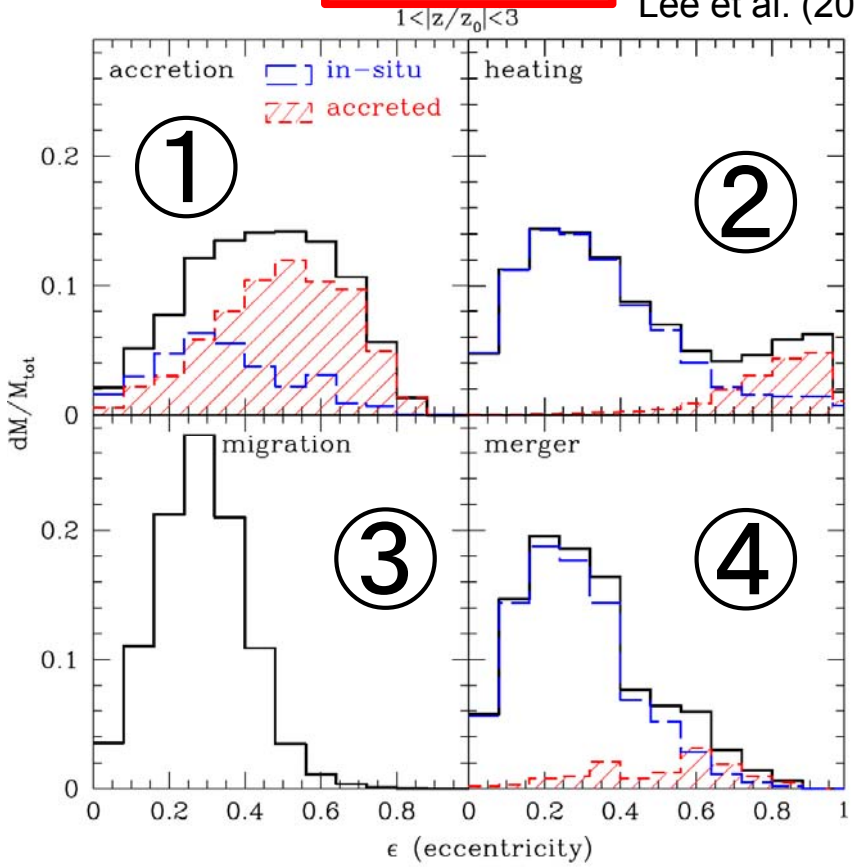
the Milky Way




Lee et al. (2011)

simulations

Lee et al. (2011)

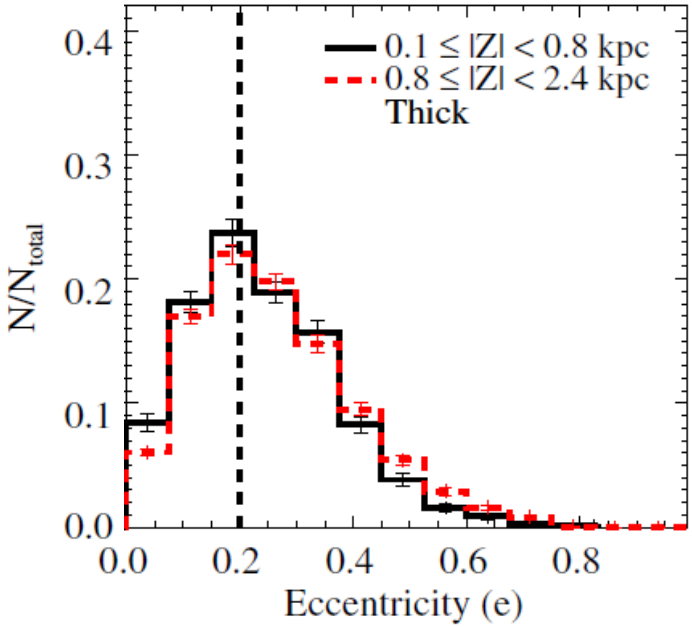


# Orbital eccentricity distribution

- Distribution of orbital eccentricities can be used as a probe of the thick disc formation scenarios.
  - Sales et al. (2009)

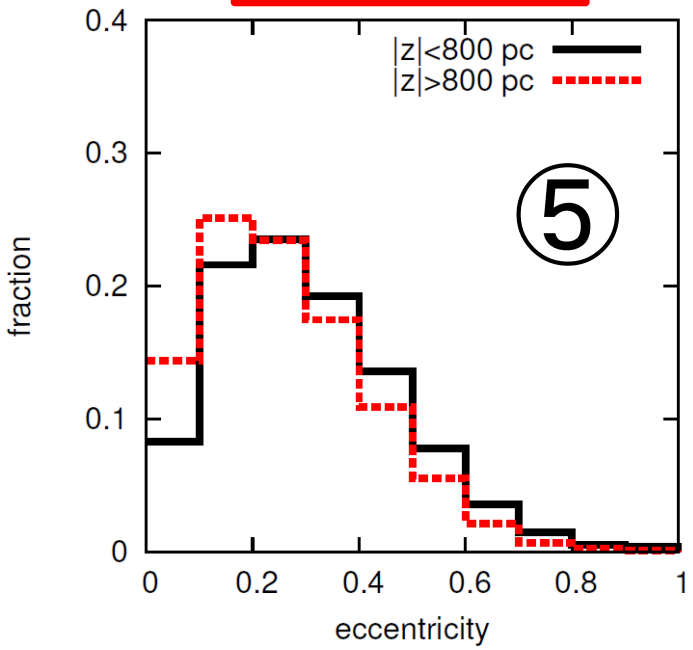
Inoue & Saitoh in prep.

the Milky Way




Lee et al. (2011)

my simulation



## Summary

- bulge
  - The clump-origin bulge seems to be a pseudo-bulge-like structure,
  - but consist of old stars, like classical bulges.
  - These properties are similar to the Milky Way bugle.
- thick disc
  - Orbital eccentricity distribution can be a prove of thick disc scenario.
  - I didn't find clear discrepancies from the MW thick disc.
- However…
  - My simulation may be still insufficient in stellar feedback.
    - over-cooling problem

# Clump-origin bulges are classical bulges?

- However, Elmegreen et al. (2008) have argued that their clump-origin bulges are like classical bulges.
  - Low Sersic index, dispersion-dominant system, round shape.
    - Different hydrodynamics scheme? (sticky particle vs SPH)
    - Different initial conditions?