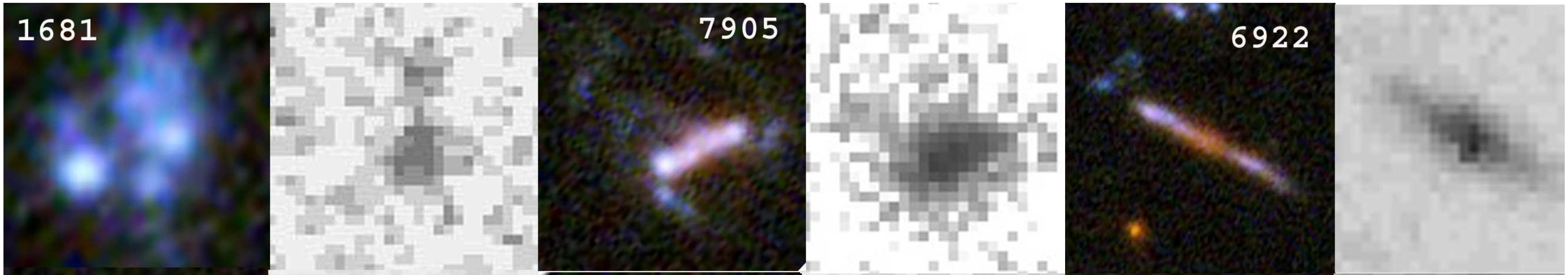
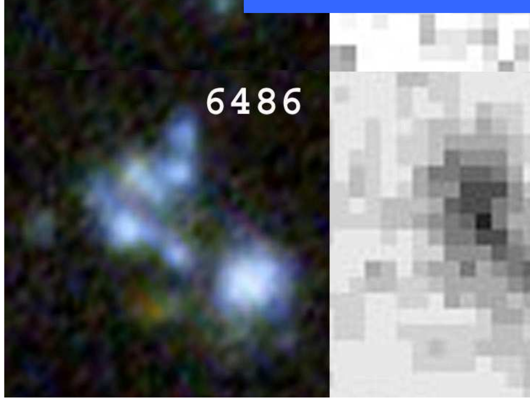
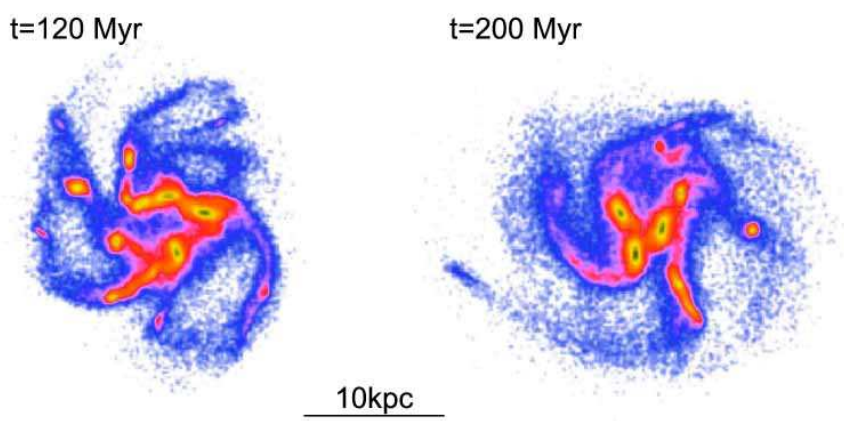
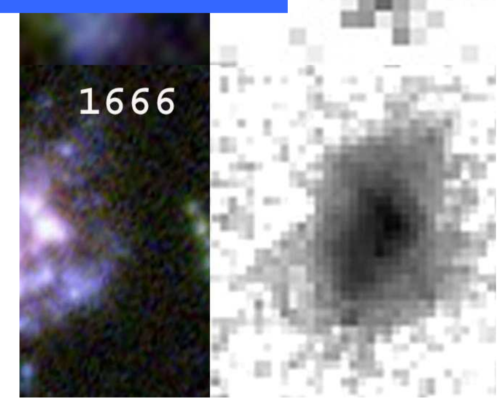


Simulations of Star Formation in Clumpy High-Redshift Galaxies

Bruce Elmegreen, Frederic Bournaud, and Debra Elmegreen
IBM, CEA-Saclay, Vassar College







Summary of Clumpy Galaxies

- New galaxy morphology at $z>0.1$: clumpy
    - chains (Cowie +95), clump clusters (EEH04), "*clumpies*"
  - chains are edge-on clump-clusters (EE05)
    - statistics of W/L, Distribution of positions in chains, clump & galaxy properties
    - clumpy types dominate at $z>2$ but even present at $z=0.1$-1, which suggests the structure is not just bandshifted star formation or mergers & interactions

- Likely precursor to modern spirals
  - combined co-moving density like spirals, $\sim 10^{-3}$ /Mpc^3 (E+07)
  - visible optically to $z\sim5$ (E+07)

- Possible evolution to bulges & smooth disks
  - mass, age, surface density

Working Model

- Clump formation by <u>gravitational instabilities</u> in <u>rapidly assembled</u> gas disks
  - clumps are confined to within 100 pc of mean disk (EE06)
  - clumps are young star-forming regions (not diverse merged galaxies)
  - clump masses of 10^7 - $10^8 M_\odot$, approaching 10^9 $M_\odot$, could be M_{Jeans} if turbulent speeds & gas column densities are high
    - $M_{Jeans} \sim \sigma^4/G^2\Sigma \sim 10^8\ M_\odot$ if $\sigma \sim 30\text{-}50$ km s^{-1} and $\Sigma gas \sim 100\ M_\odot\ pc^{-2}$
      - dispersions consistent with observed HII dispersions (Forster-Schreiber+06; Weiner +06; Genzel +06,08; Puech +07)
      - column density typical for inner disks today
- Possible consequences of large clump masses:
  - massive clumps interact, migrate to the center to make a classical bulge and smooth the disk to make an exponential (Noguchi 99; Immeli +04).
  - Possible connection with nuclear black holes if clump cores form IMBH (EBE+08)
- Relevance to Kennicutt-Schmidt law:
  - check if SFR/Area , M_{clump} , σ , Σ_{gas} , and Q make sense
  - high σ is a possible explanation to the Wolfe & Chen 06 effect:
    - which is that the threshold column density is 10x higher than locally (from DLAs)
- Good analogy with local Dwarf Irregulars:
  - high σ/V, high H/R, high L_J/R, high gas fraction, “youthful”

Check if SFR/Area, M_{clump}, Σ_{gas} make sense

- SFR in clump clusters (at z~1):
  ~in a clump: 0.3 M_O/kpc^2/yr
  ~in whole galaxy: 3 M_O/(25 kpc^2)/yr ~ 0.12M_O/kpc^2/yr

- SFR in MW:
  - star complex: 5x10^5 M_O in R=300 pc in 50 Myr = 0.035 M_O/kpc^2/yr
  - whole galaxy: 5M_O/yr/(300 kpc^2)=0.017 M_O/kpc^2/yr
  - factor of ~10 higher SFR/Area for both clumps and whole galaxies

- If SFR/Area ~ $\Sigma^{1.5}$ (Kennicutt 98) then
  - clump Σ_{gas} higher than in MW by factor of $10^{2/3}$=5,
  - which means Σ_{gas} should be 100 M_O/pc^2 if local <Σ> ~ 20 M_O/pc^2
    - consistent with M~M_{Jeans}

Implications of the KS law

- A sensible explanation for KS law:
  - SFR/Area = effic. * Σ_{gas} * GI growth rate ~ 0.01 Σ_{gas} ($\pi G \Sigma_{gas}/\sigma$)

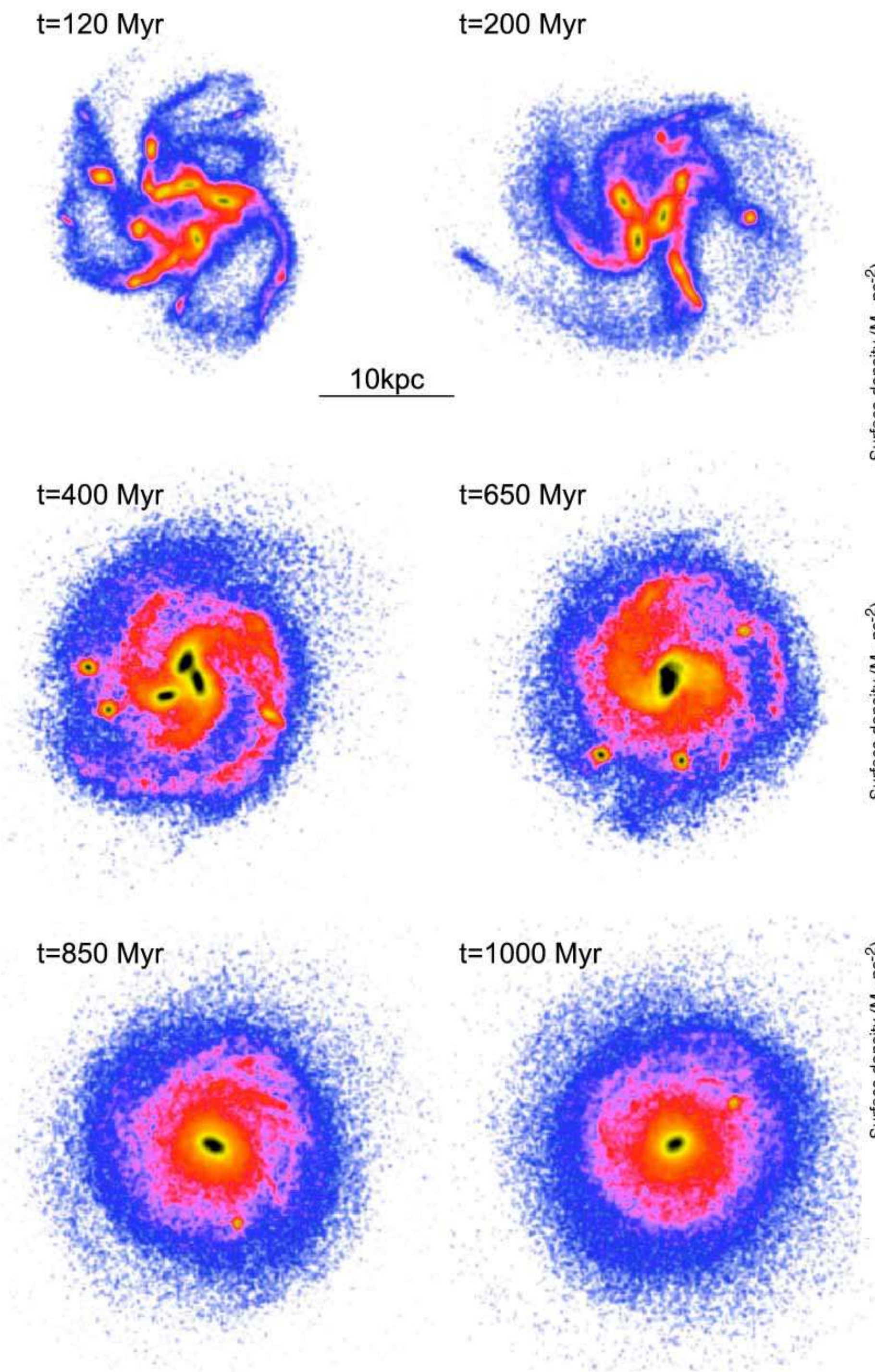
- <u>If</u> high redshift galaxies satisfy the local KS law then Σ^2_{gas}/σ must scale only with $\Sigma^{1.5}_{gas}$ (there is no σ in the KS law)
  - which means σ must scale with $\Sigma^{0.5}_{gas}$
  - so clump mass ~ $\sigma^4/G^2\Sigma_{gas}$ scales with Σ_{gas} or σ^2
  - and Q ~ $\kappa\sigma/\pi G\Sigma_{gas}$ scales with $\kappa/\Sigma^{0.5}_{gas}$ or κ/σ
    - either more unstable or κ higher (inner disks of massive galaxies)

- Also, gas scale height ~ $\sigma^2/\pi G\Sigma_{\text{total mass in gas layer}}$
  - scales only with $\Sigma_{gas}/\Sigma_{\text{total in gas layer}}$ and therefore decreases over time.

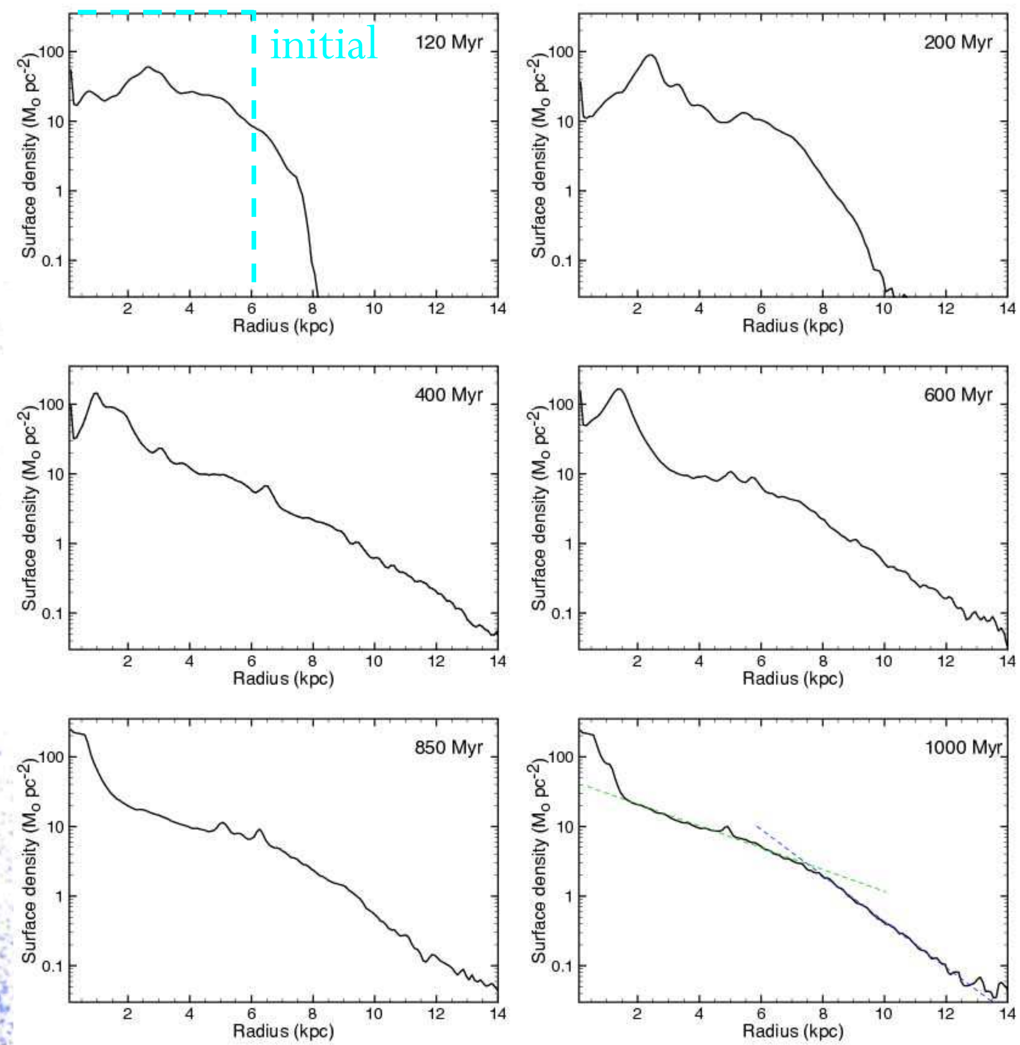
Simulations of Clumpy Galaxy Evolution

(ApJ 07, 08ab, 09ab with Frederic Bournaud & others)

- Particle-mesh, sticky particle gas (β=0.7)
  - grid resolution 110 pc (some runs 28 pc)
  - 10^6 particles each for halo, stars, gas (some runs 3x)
    - halo = Plummer sphere with scale length 15 kpc (some runs cuspy DM)
- Schmidt-law star formation
  - probability particle converts to a star is proportional to the local density to the power 1.4; feedback in some models
- Initial disk profile flat, bulgeless, 6 kpc radius, 7×10^{10} M_O total disk
- Initial Q_{star}=1.5
- Example here: 50% disk gas fraction initially, disk/halo inside disk=2



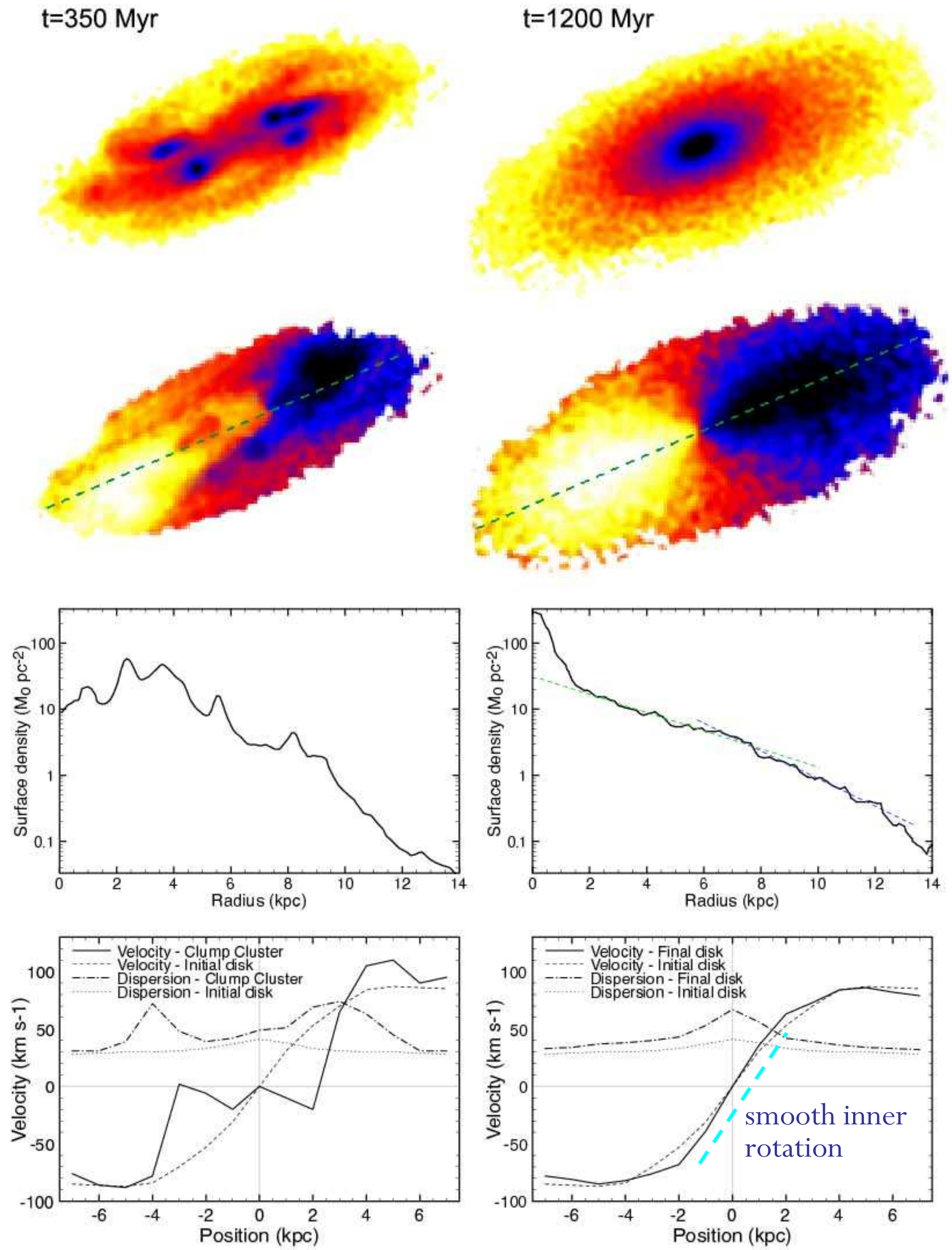
New models show evolution to exponential disk & bulge



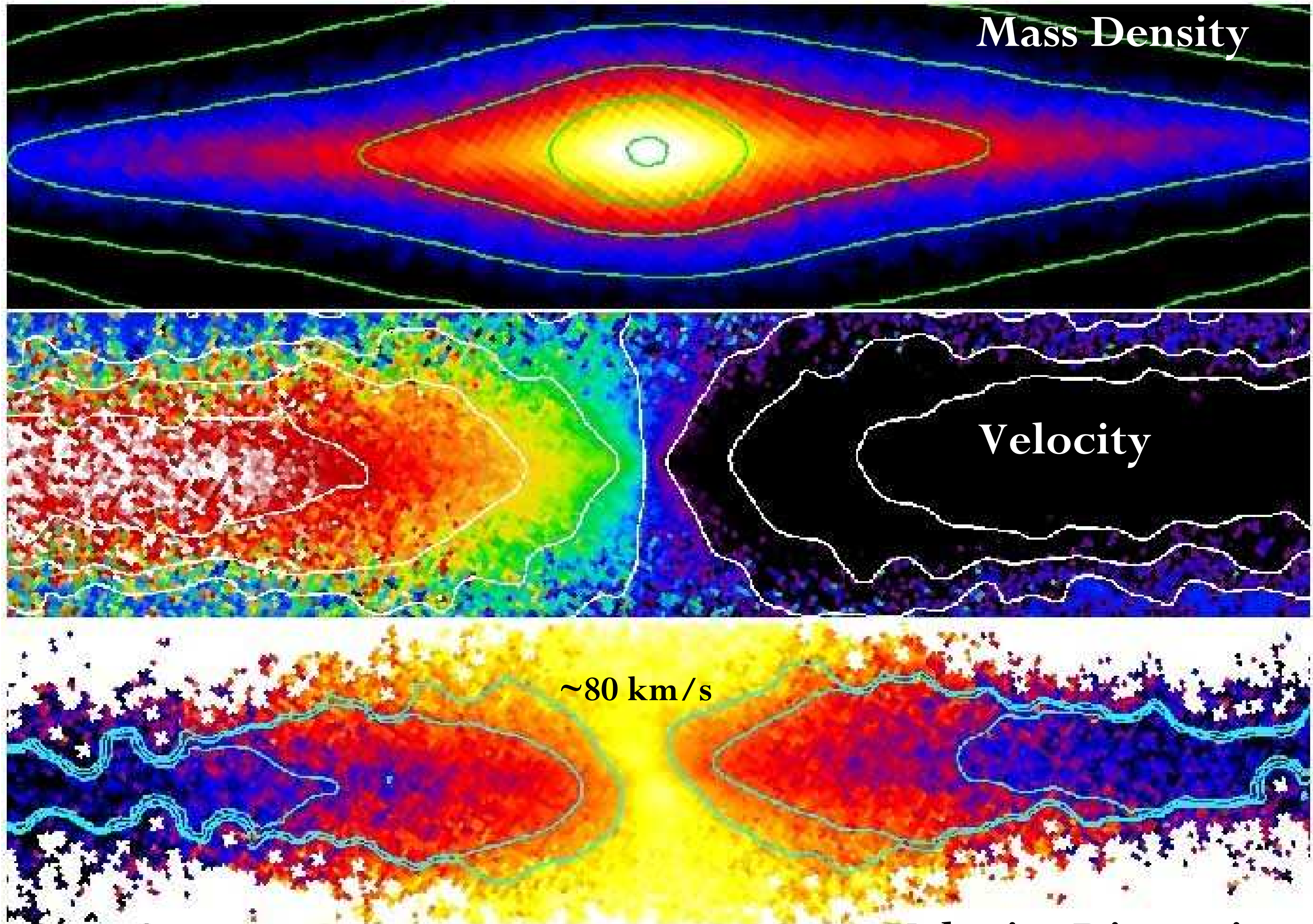
Bournaud, Elmegreen & Elmegreen 07

The rotation curve for the early phase is irregular because of the clump motions.

The stellar velocity dispersion is high.



Bournaud, Elmegreen & Elmegreen 07

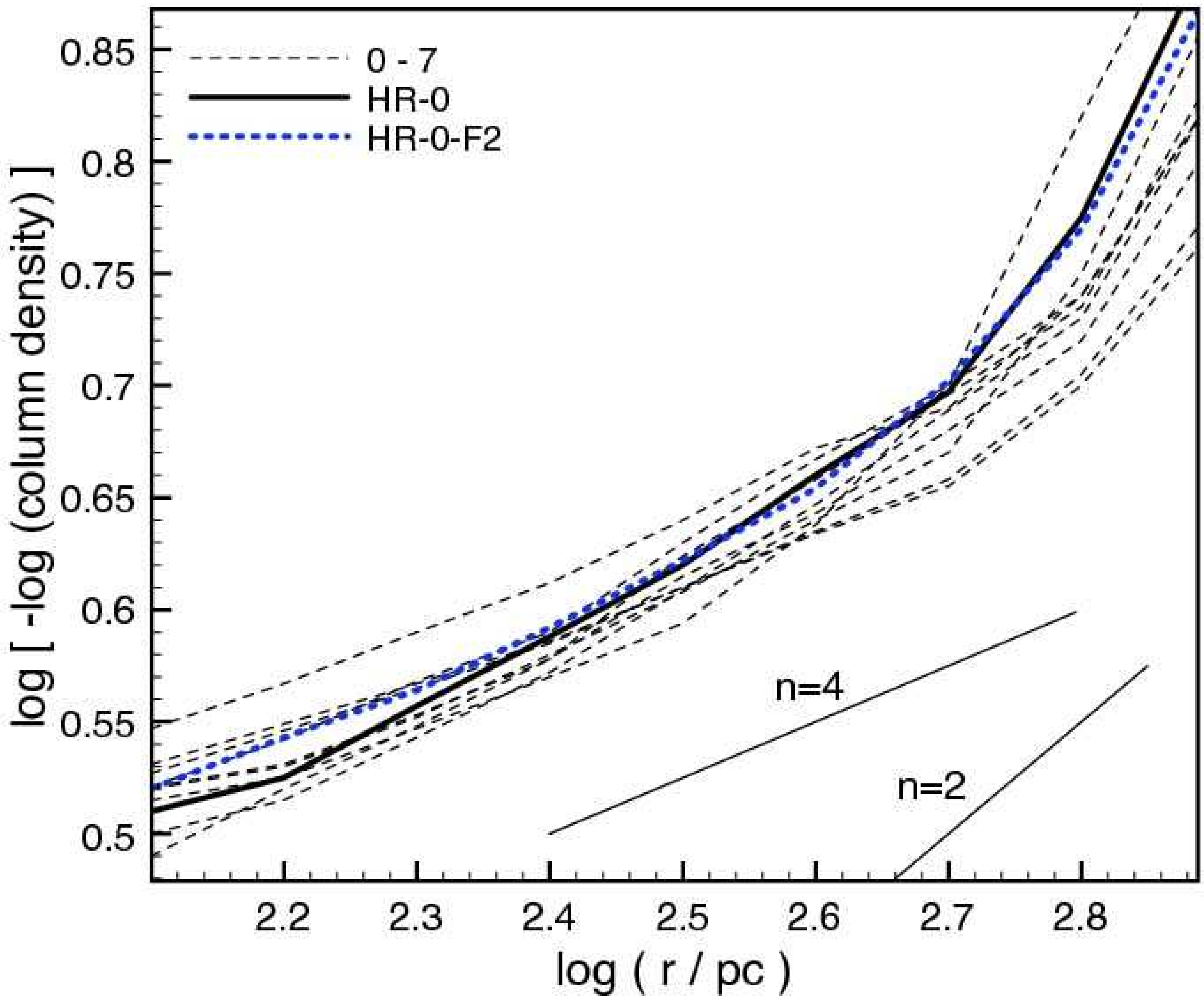


High resolution: Nx3, L_{soft}=28 pc inside 4 kpc

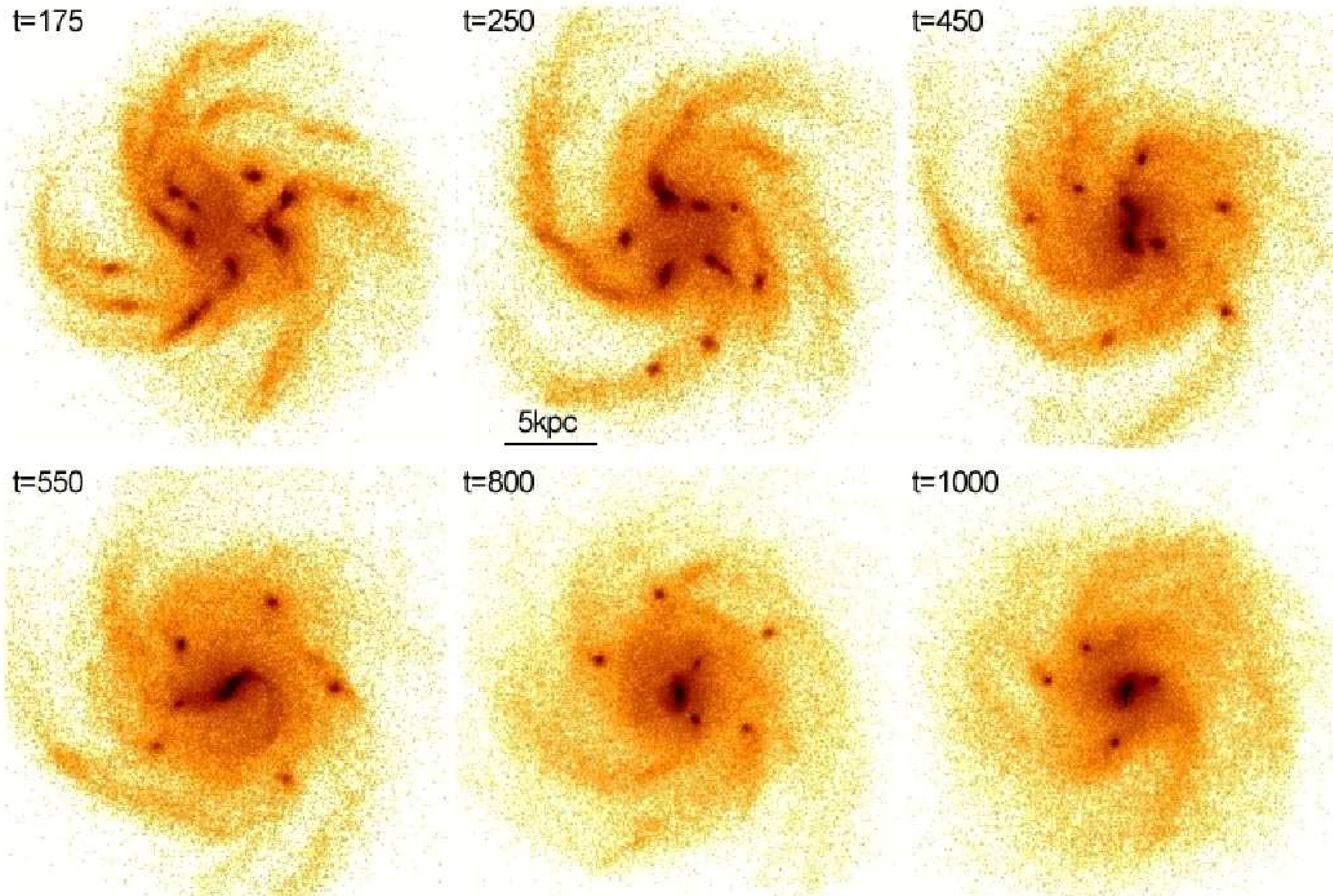
(Elmegreen +08)

Bulge radial profiles have high Sersic – n

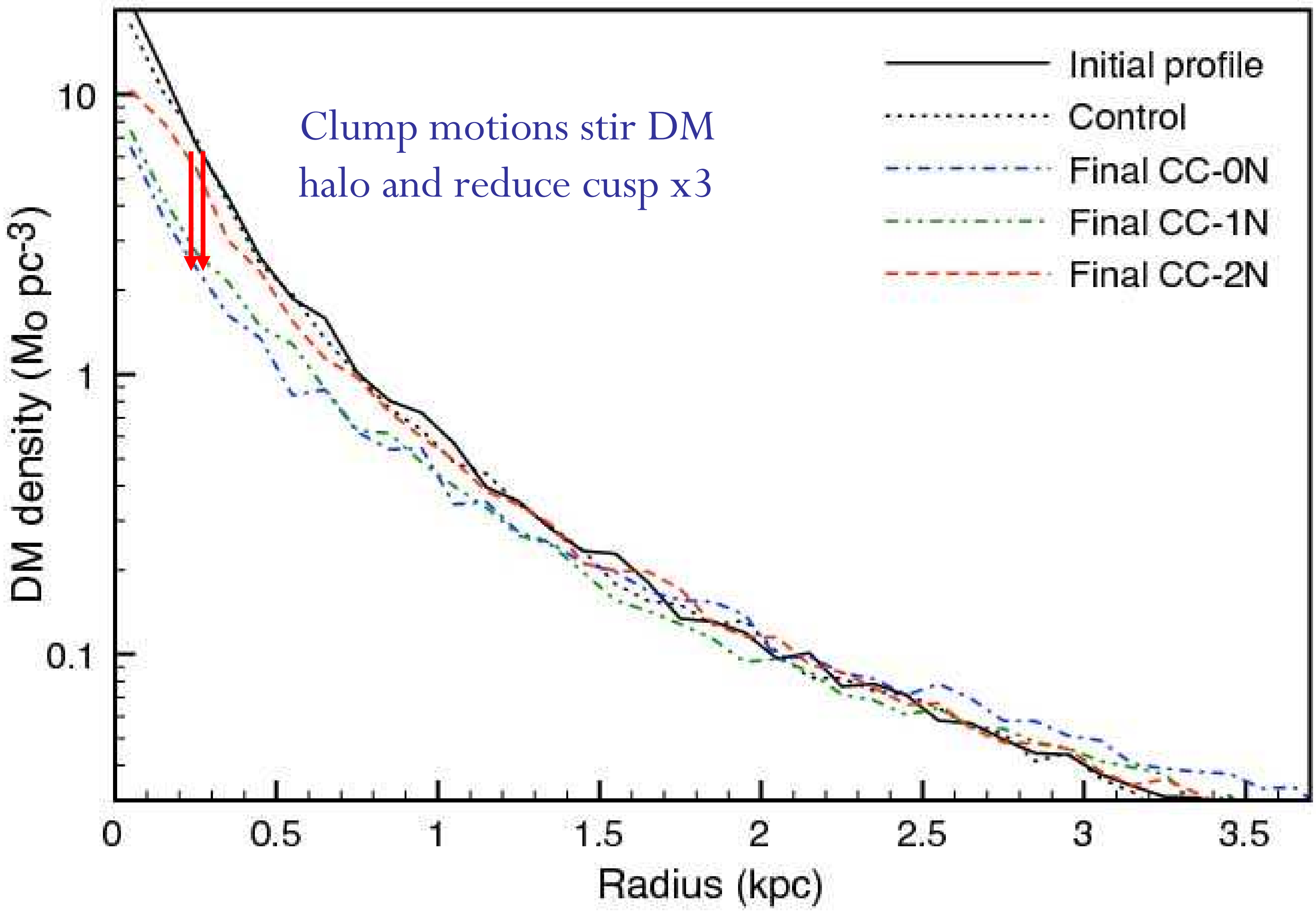
Classical or "de Vaucouleurs" bulge, n~3-4



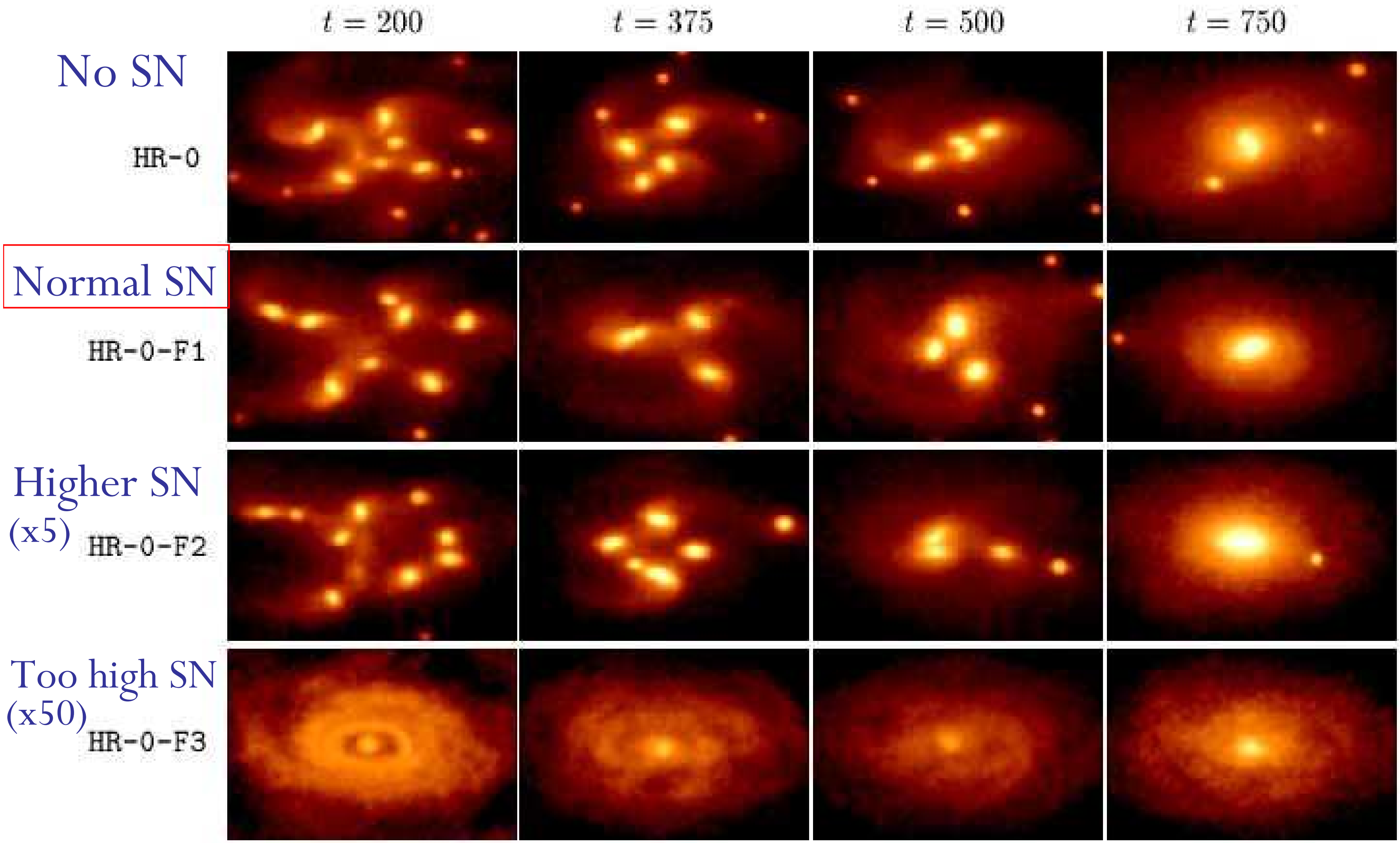
(EBE08)



With cuspy DM halo (gas+stars shown)

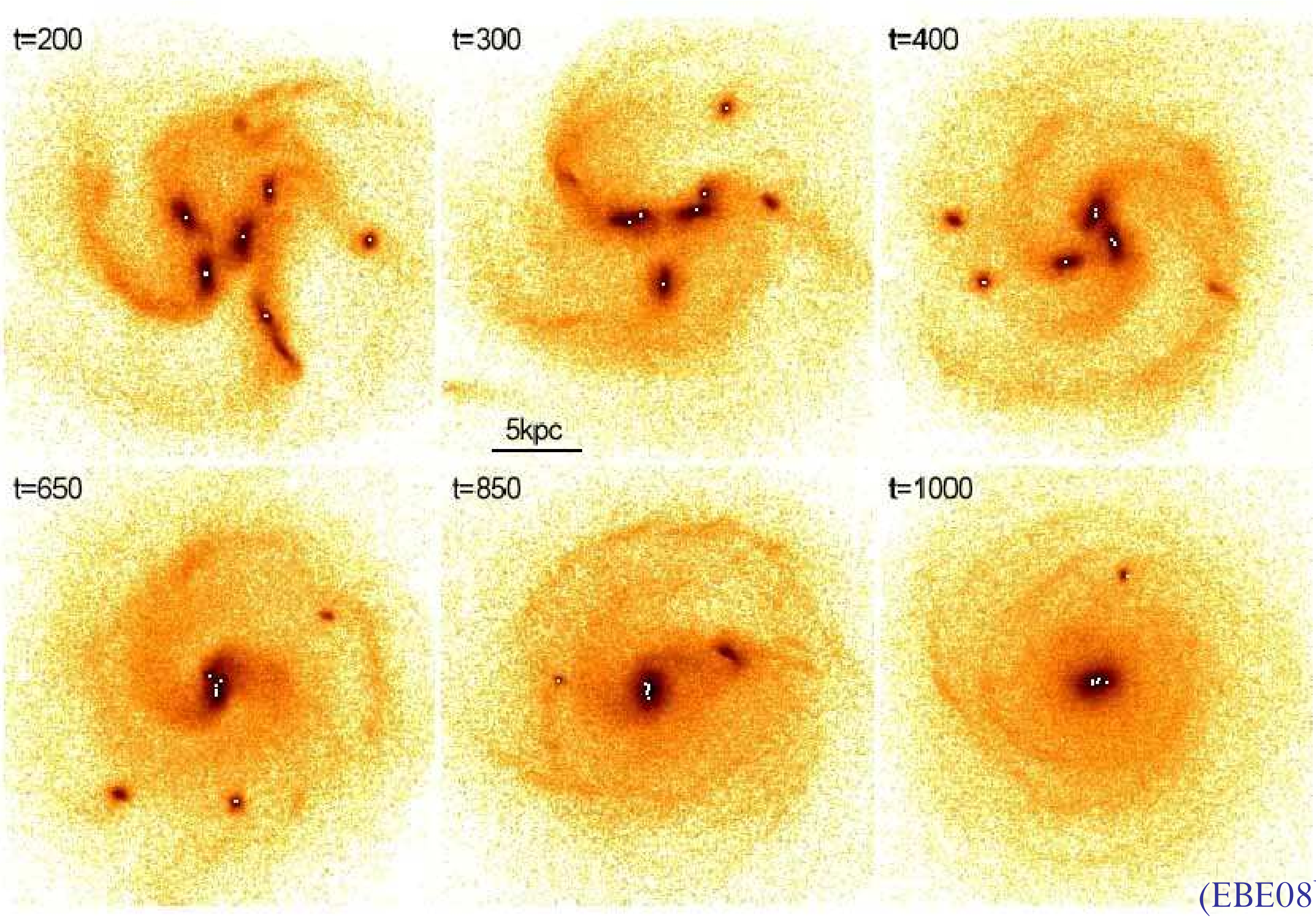


Control: rigid disk; others 50% gas, CC-[0,1,2]N: σ_{gas}=[9,5,15] km/s



Feedback Models

High-resolution models: Nx3, softening length 2x less everywhere and 4x less at R<4 kpc (28 pc resol.). Without SN (top) and with SN feedback: $\varepsilon = 0.0002$ (Mihos & Hernquist '94), 0.001, 0.01. (images inclined 30 deg)

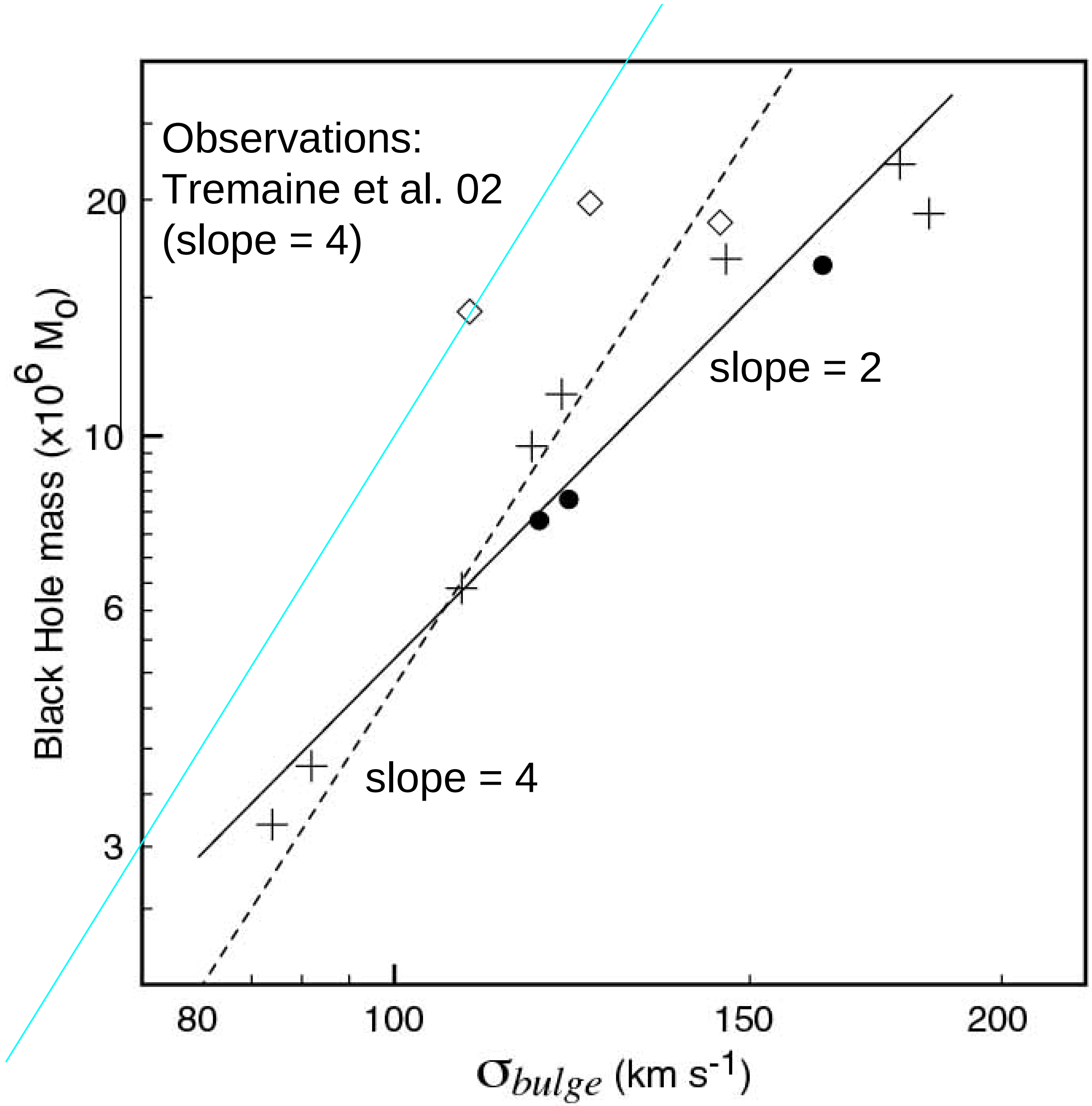


(EBE08b)

If giant clumps contain dense clusters that form IMBH
(e.g., Ebisuzaki +01; Portegies-Zwart +02,04,06; Freitag +06;…)
then these IMBH can also spiral into the center and make a SMBH

BH mass – bulge σ relation

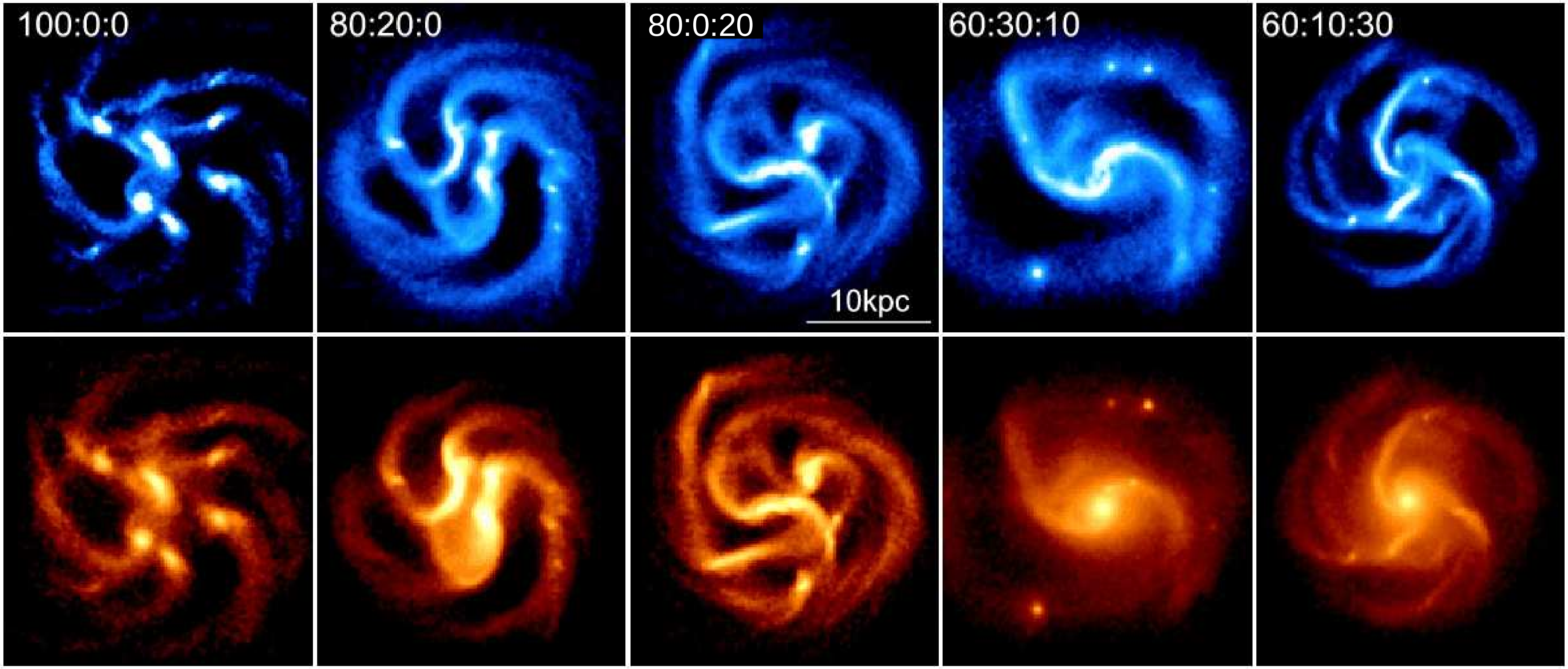
Because $M_{BH}/M_{clump} = 10^{-3}$ was put in, this relation indicates that the bulge size is coming out correctly



Clump Clusters as Evidence for Cold Flows

(Murali +02; Semelin & Combes 05; Dekel, Birnboim +03-09, Keres 08; Ocvirk +08; Agertz +09)

- Simultaneous formation of several similar clumps implies rapid assembly of gas disk
  - otherwise SF will eat away at the gas slowly
- Clump roundness suggests that the gravitational instability is strong
  - in local disks, which are marginally stable, GIs produce spiral waves in the stars, or flocculent spirals in star formation when there are no stellar spirals
- Strong instability requires a cool stellar disk and this seems to rule out significant mergers, even minor mergers for primary gas accretion
  - (Bournaud & Elmegreen 2009)



σ_{gas}=50 km s^{-1}, 3x10^6 particles each for gas, stars, DM;
30 pc resolution, M_{gas}=M_{stars} =6x10^{10} M_O, M_{halo}=0.5(M_{stars}+M_{gas})
stellar mass fraction in disk:bulge:halo indicated

Bournaud & Elmegreen 09

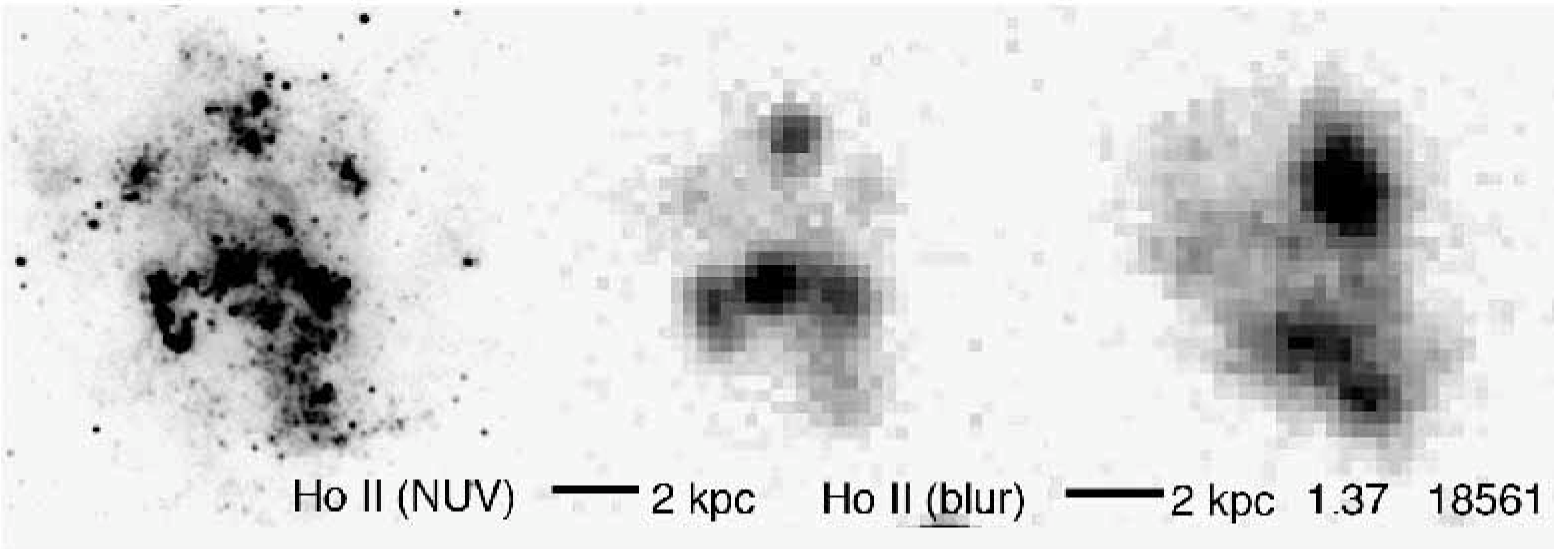
Giant clump formation requires >80% of the stars (and all of the gas) in a disk. Makes even minor mergers (10:1) unlikely during galaxy build-up. Requires smooth gas accretion.

The Trouble with Mergers…
too much Stellar Spheroid

- Disks built by galaxy mergers are embedded in stellar spheroids
  - Springel & Hernquist 05: 25% of its stars the final disk, 50% in bulge & 25% in halo
  - Robertson et al. 06: f_{gas}=0.4-0.6, 1:1 mergers end up with <10% of stars in the disk
  - Robertson et al. 06: f_{gas}=0.8, 1:1 mergers end up with 40%-45% of the stars in the disk
  - Robertson et al. 06: f_{gas}=0.4-0.8, 8:1 merger, final stellar disk fraction=60%-75%
  - Hopkins et al. 08: 8:1 merger gets final stellar disk fraction = 70%-85%; 2:1 merger, disk<50% of stars; 1:1 merger, disk < 30% of stars

- If a galaxy doubles its mass by mergers:
  - for 1:1 major merger or six successive 8:1 minor mergers, and for f_{gas}=50% in the progenitors (likely for $z \sim 2$; Daddi et al. 2008), such mergers will leave only 20% or less of the stellar mass in the rotating disk, the vast majority being in the bulge and halo.

- If the last mass doubling was half by mergers and half by smooth accretion:
  - for one 2:1 merger or 3-4 8:1 mergers, 40%-50% of the stellar mass will be in the disk



Morphologically, clump clusters are well matched to dwarf Irregulars

(except for mass: CC's ~30 x more massive than dwarf Irrs)

Dwarf Irrs as Analogs of Clump Clusters

- CC's resemble local dwarf irregulars because:
  - both have high gas fractions (e.g., Linda Tacconi, …)
  - both have high velocity dispersions relative to the rotation speed
  - neither have spiral density waves

- In general, L_{Jeans}/Galaxy Size ~ H_{disk}/Galaxy Size ~ $(\sigma/V)^2$

- So, high σ/V means
  - large complexes relative to the galaxy size
  - only a few complexes in the whole galaxy
  - relatively thick disks
  - difficulty organizing stars into a coherent spiral wave

- In addition, the high gas fraction may cause the high σ/V because of stirring by self-gravity

- Finally, both types are relatively young!
  - another example of "down sizing"
  - "young" galaxies (in terms of rotation times) are gas-rich and clumpy

The Wolfe & Chen '06 Result

- DLA gas does not obviously form stars even though Σ_{gas}>local Σ_{crit} (5-10 M_O pc^{-2}) (see also Wolfe, Rafelski, here).
- Wolfe & Chen 06 suggested Σ_{crit} is 10x higher at z~2 than locally
- Can the high Σ_{crit} result from low metallicities and low H_2 fractions (W&C06)?
  - Maybe not: local dwarfs have low metals and low H_2 fractions too, but they have low Σ_{crit} (Hunter + 98)
- Can the high Σ_{crit} result from high κ (W&C06)? i.e., DLAs are inner disks which are thought to require high Σ_{crit} even in local galaxies
  - Possibly, and clump clusters are a little smaller than local galaxies (x2 maybe), but inner disks have star formation in other z~2 galaxies
- <u>New explanation</u>: high Σ_{crit} comes from high σ (Elmegreen +09)

- Recall, $\Sigma_{crit} = \sigma\kappa/\pi G$
- Use $(\sigma/V)^2 \sim L_{Jeans}/R$ (valid if disk dominates dark matter in inner region)
- Then $\Sigma_{crit} \sim (L_{Jeans}/R)^{1/2}\ (V^2/R)\ /\ 2.2G$
- For given V, clumpy structure (large L_{Jeans}/R) implies Σ_{crit} should be high (the Wolfe & Chen result)
  - a spiral galaxy of the same size has lower Σ_{crit} because L_{Jeans}/R is lower
- Perhaps DLAs are $\Sigma<\Sigma_{crit}$ whole disks or $\Sigma<\Sigma_{crit}$ parts of clumpy disks with modest SF rates

Summary

- Clumpy galaxy morphology at high z seems to result from GIs in turbulent, gas-rich disks
- For instabilities $L_{Jeans} \sim \sigma^2/G\Sigma$, $M_{Jeans} \sim \sigma^4/G^2\Sigma$
  - Scale-up implies:
    - $\sigma \sim 5$ x local $\sigma \sim 40$ km/s
      - Forster Schreiber + 06; Genzel + 06, 08; Weiner et al. 2006, Puech et al.2007, …
    - $\Sigma \sim 10$ x local $\Sigma \sim 100\ M_{O}/pc^2$ in gas (1×10^{22} H cm^{-2})
- Clumpy galaxies appear to be forming the inner disks (thick disks?) and bulges of today's spirals
- Process of star formation is the same as locally, but at higher σ and Σ
  - and higher gas fraction: clumps form instead of swing-amplified spirals
- Significant merging unlikely: puts too much stellar mass in a bulge or spheroid and then the instabilities look like spirals and not clumps
- Wolfe & Chen KS law anomaly could result from high σ

THE END