Violent Disk Instability at z=1-4
Outflows; Clump Evolution; Compact Spheroids

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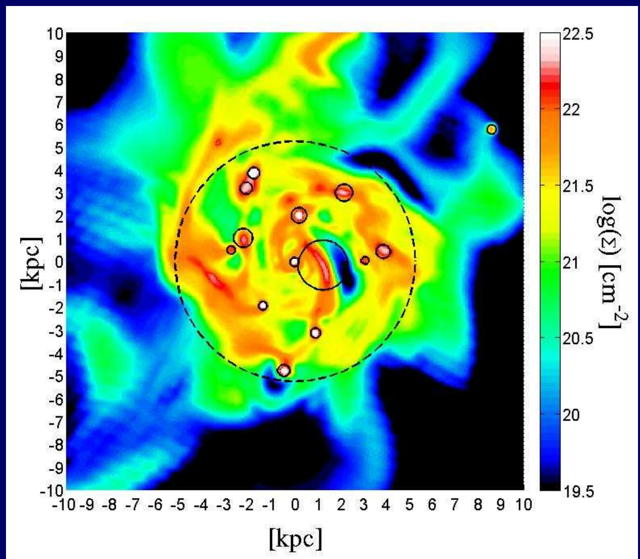
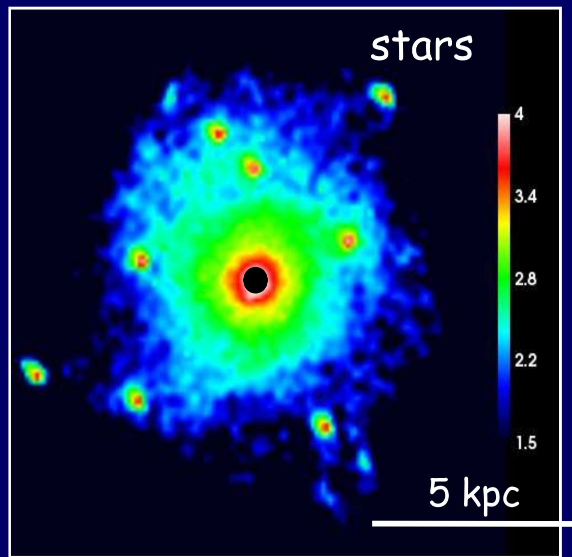
Santa Cruz, August 2013



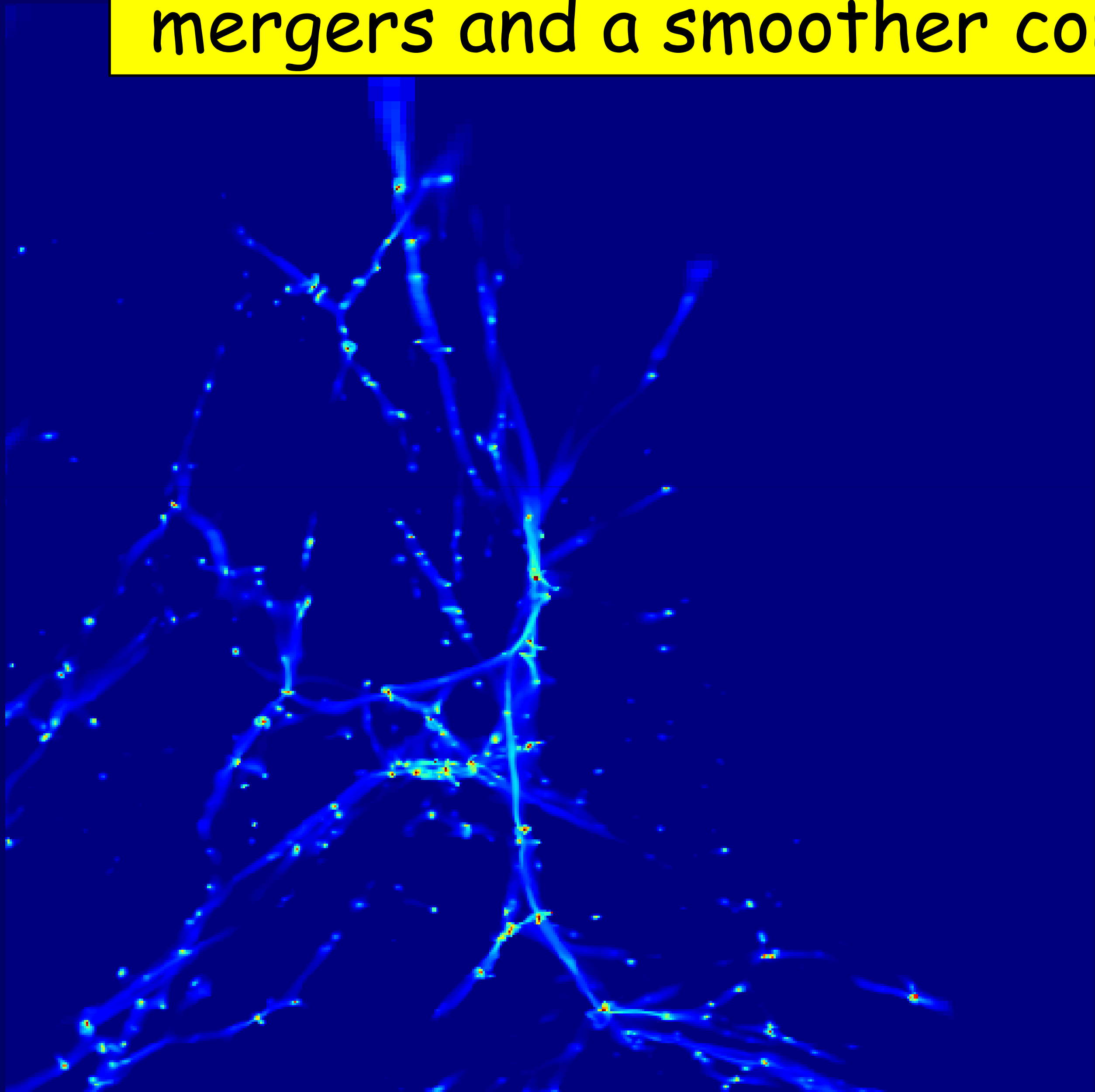


Outline

1. Inflows and Outflows
2. Evolution of giant clumps in VDI disks
3. Formation of compact spheroids: blue & red

1. Inflows and Outflows

Cosmic-web Streams feed galaxies: mergers and a smoother component



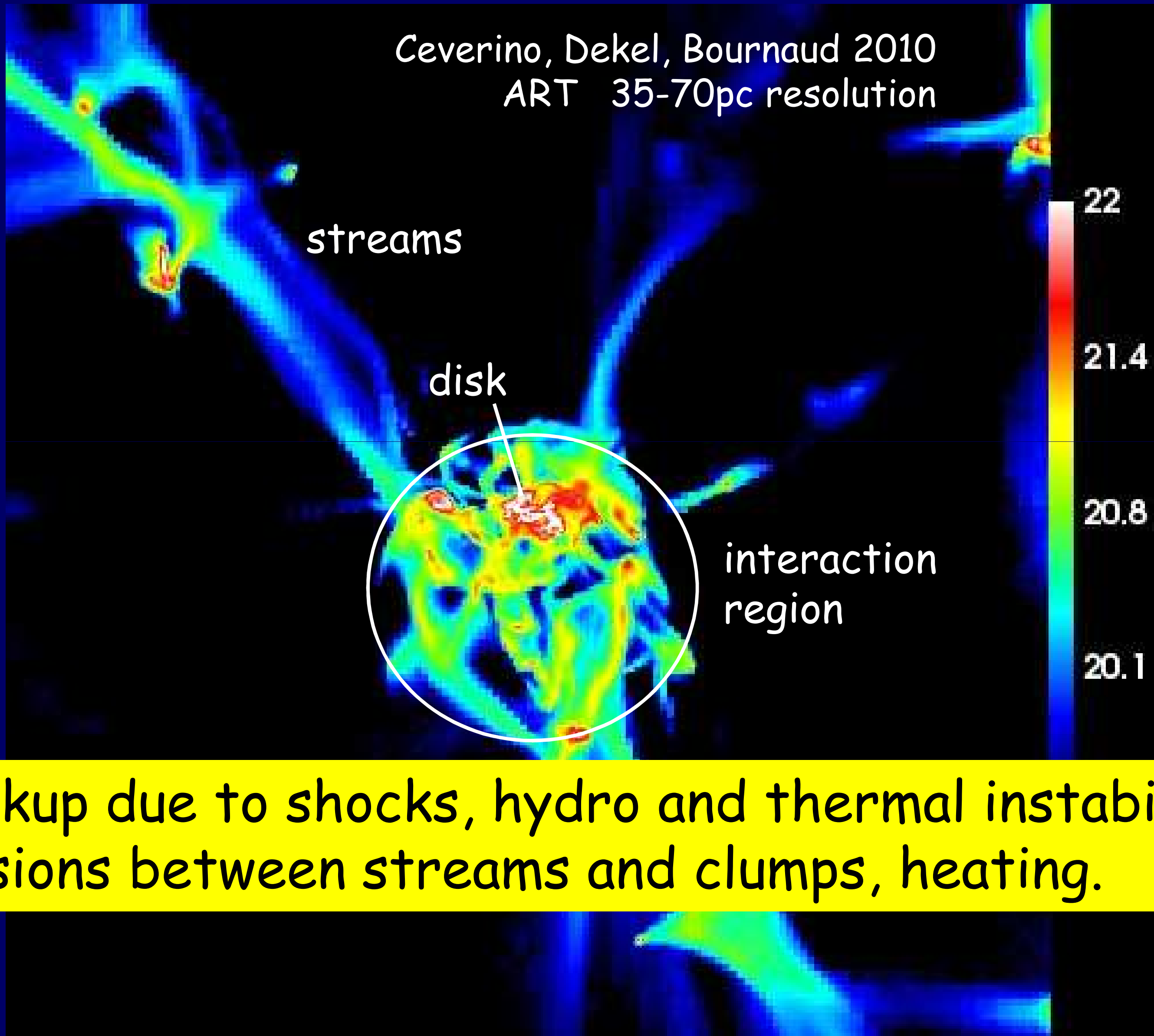
AMR RAMSES
Teyssier, Dekel

box 300 kpc

res 30 pc

z = 5.0 to 2.5

Streaming to the disk - a Messy Region

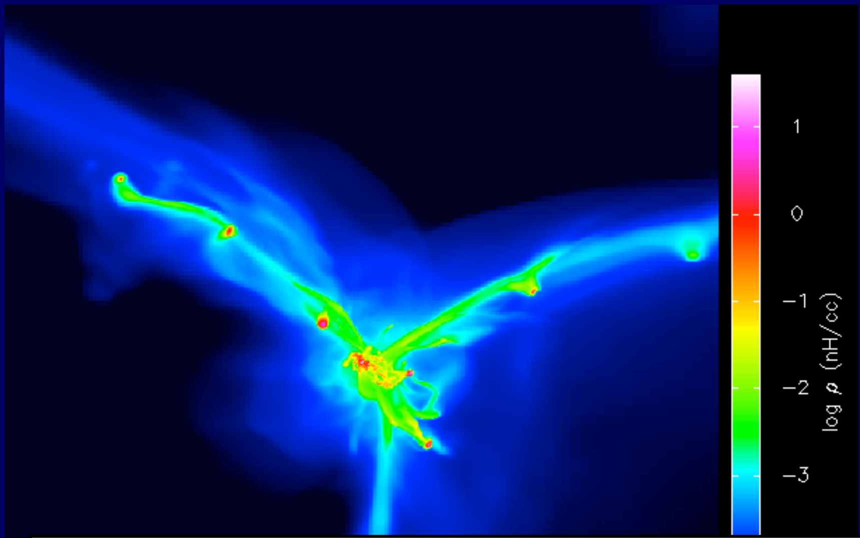


Breakup due to shocks, hydro and thermal instabilities, collisions between streams and clumps, heating.

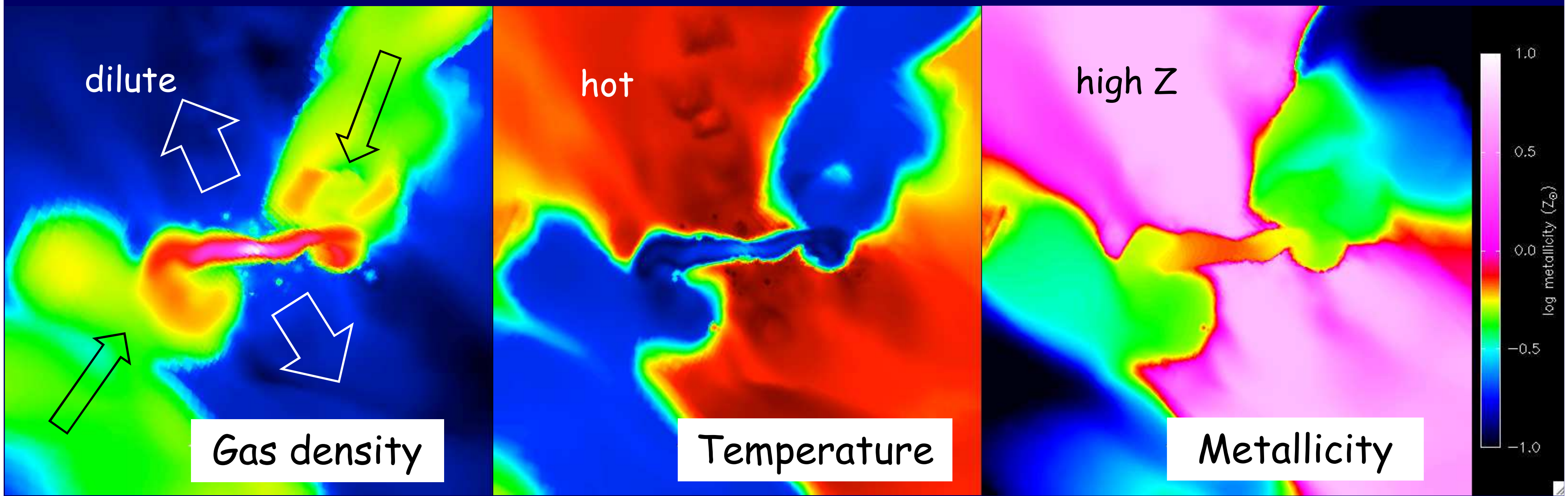
Inflows & Outflows

Tweed, Dekel, Teyssier

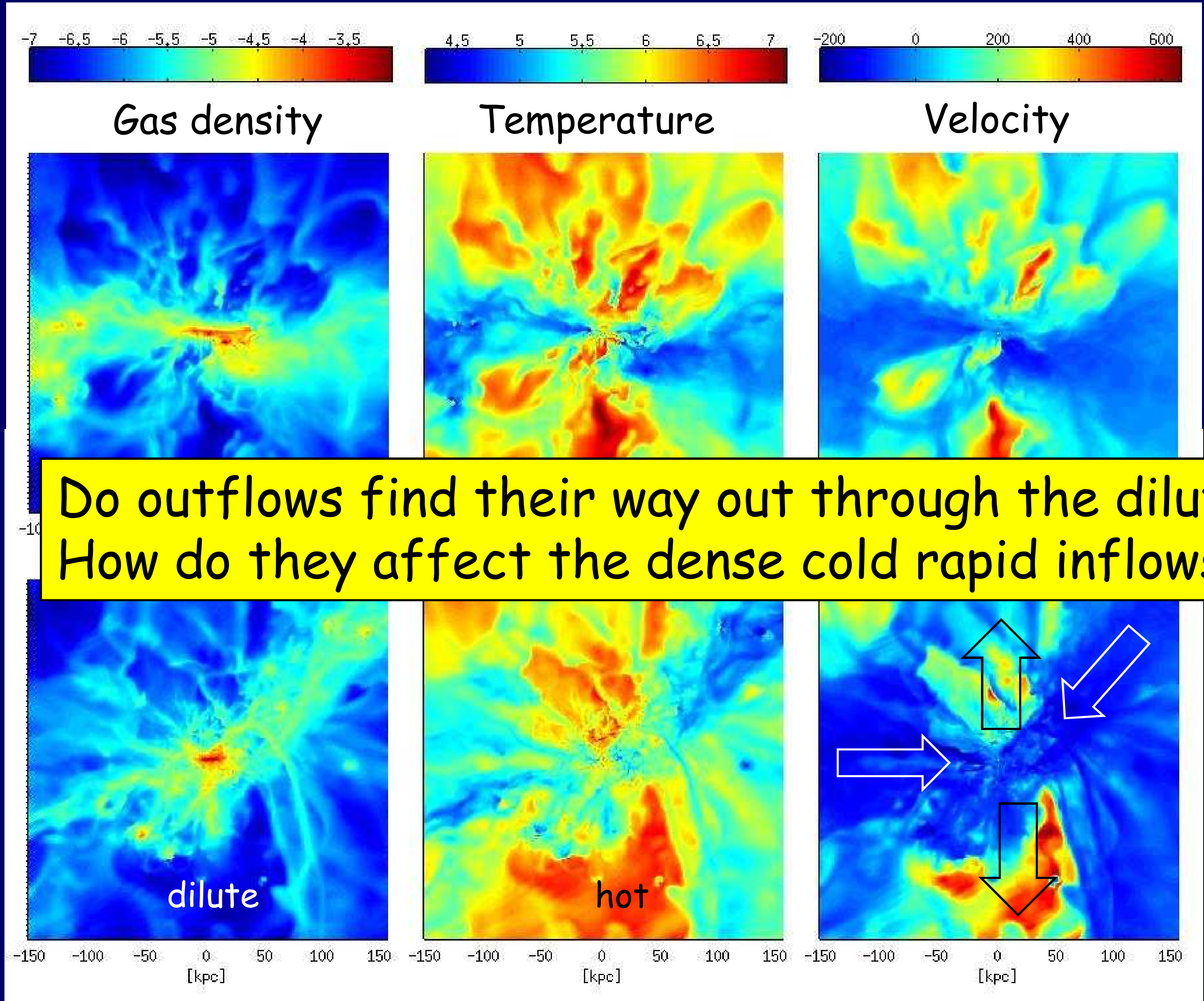
RAMSES 70-pc resolution



Do outflows find their way out through the dilute medium with no noticeable effect on the dense cold rapid inflows?



Inflows and Outflows



Do outflows find their way out through the dilute medium?
How do they affect the dense cold rapid inflows?

House, Ceverino, et al. in prep.

ART cosmological

radiative fdbk
outflow η~1-7

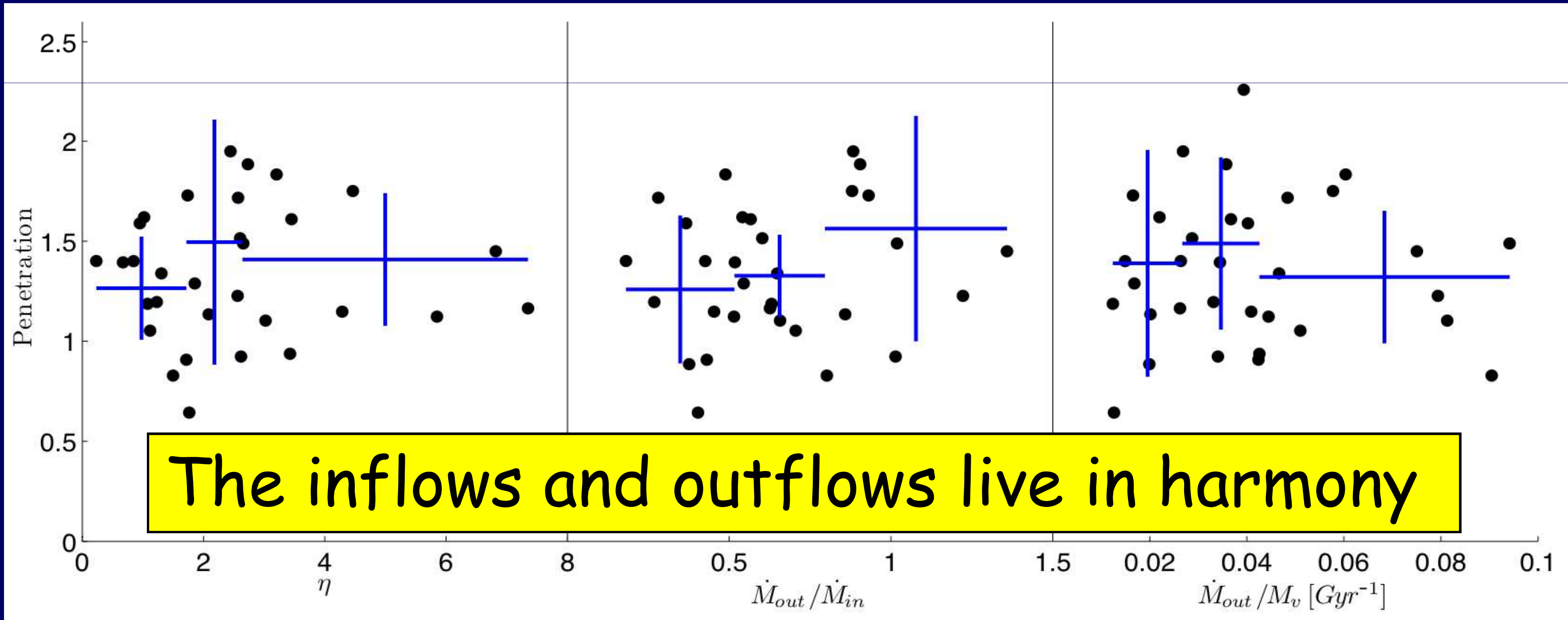
z=2.6
M_v=7x10^{11}

Interaction of Outflows and Inflows

House, Ceverino,Tweed, et al. 13

ART cosmological simulations at 25pc resolution
with radiative feedback

Inflow penetration $\dot{M}(0.1R_v)/\dot{M}(R_v)$

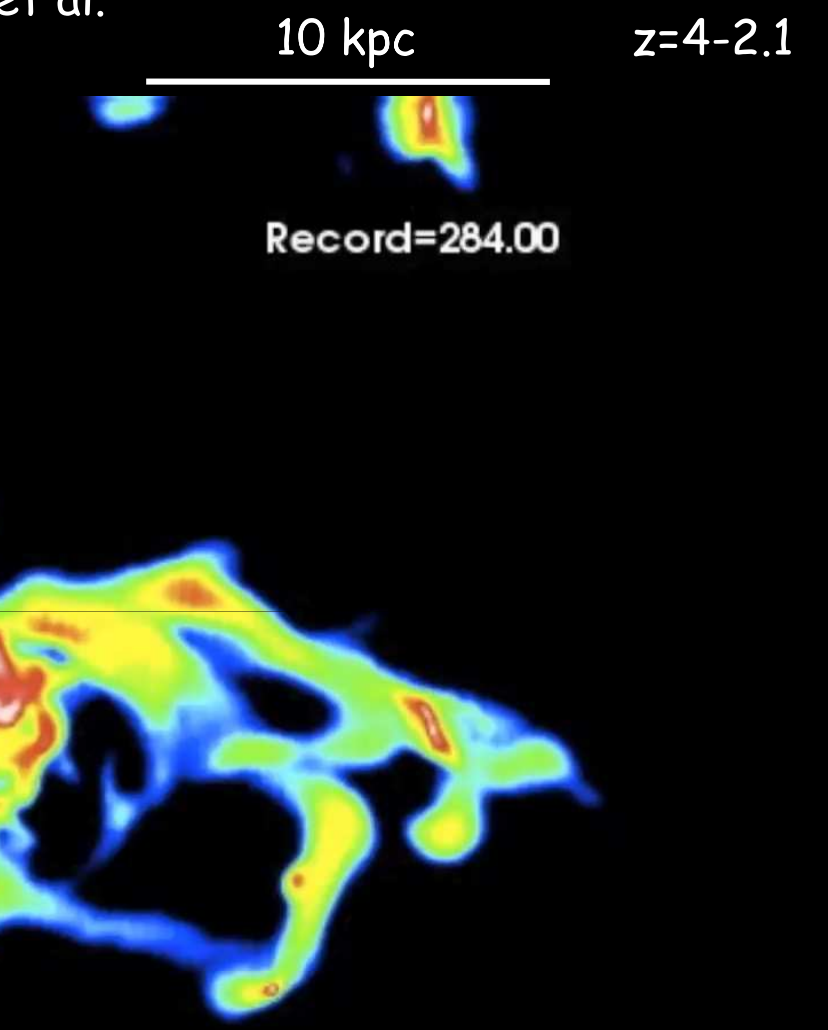


The inflows and outflows live in harmony

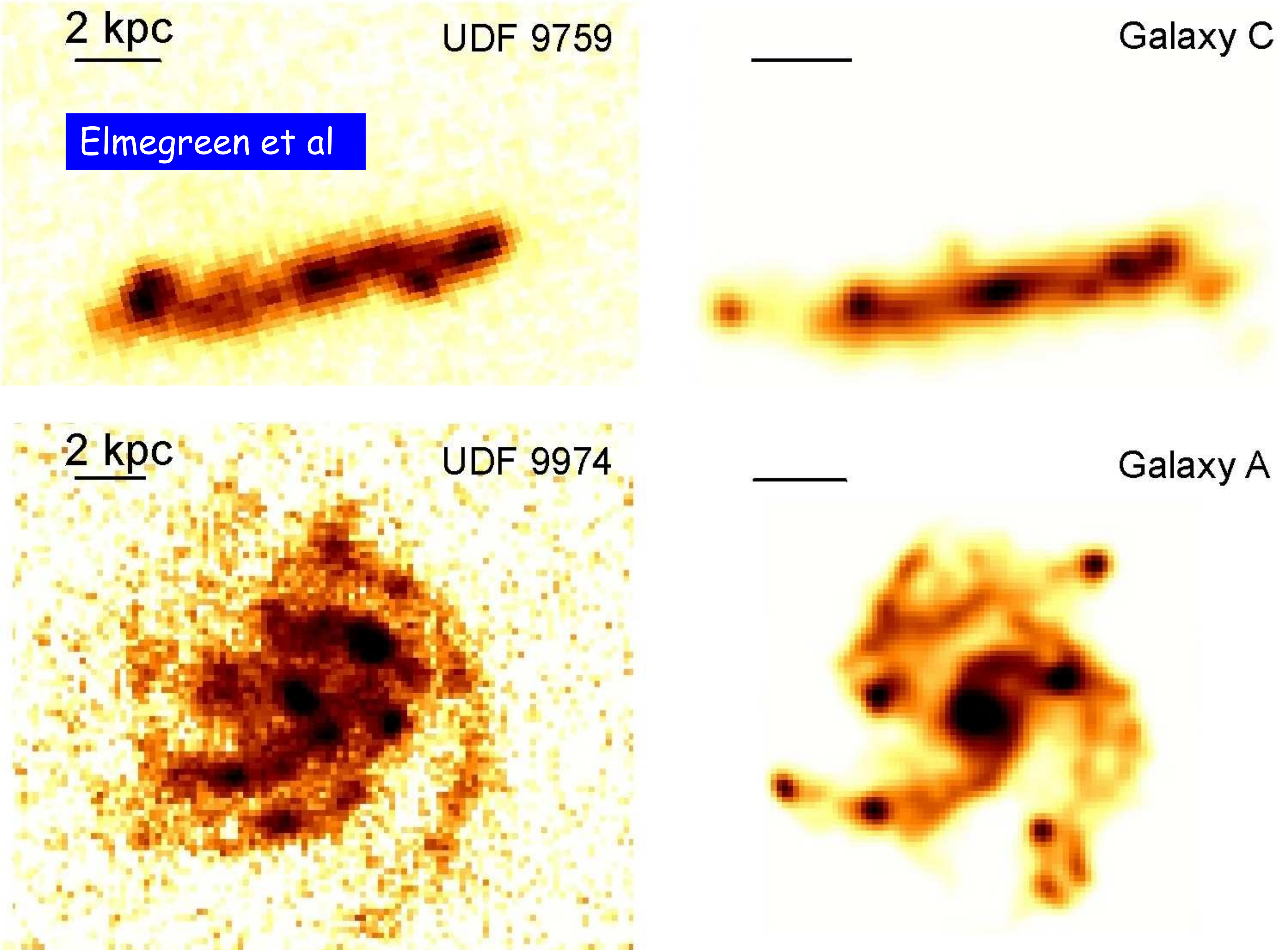
Outflow strength

2. Evolution of Giant Clumps in VDI Disks

Clumpy Disk Ceverino, Dekel et al.



Observations vs. Simulations



Violent Disk Instability (VDI) at High z

High gas density → disk unstable

Giant clumps and transient features
→ rapid evolution on dynamical time

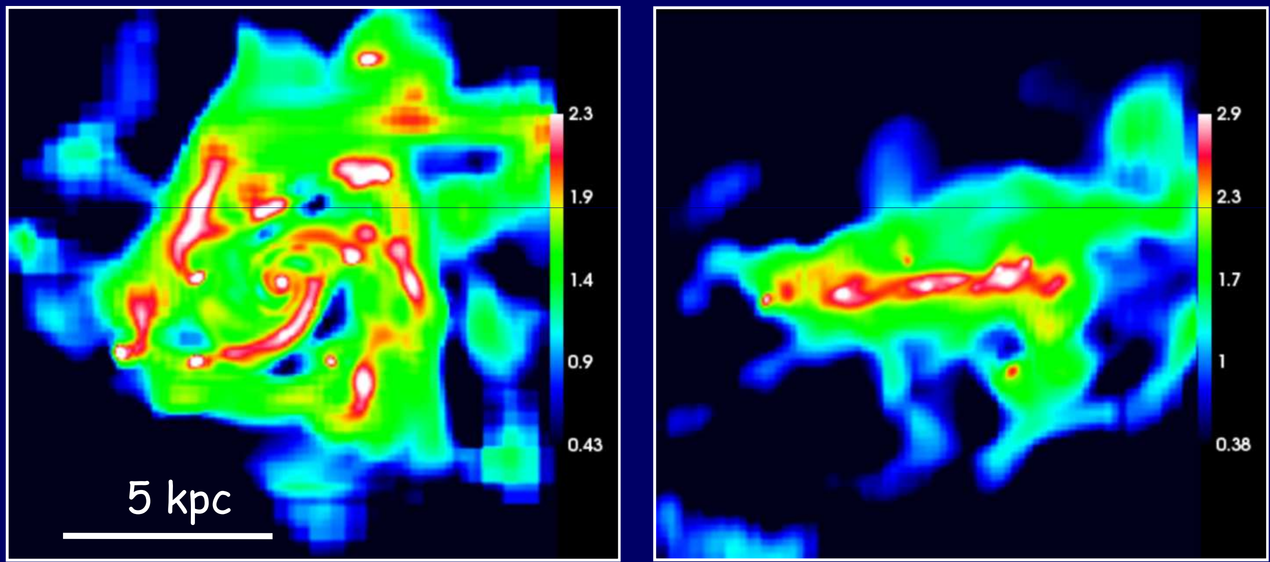
$$Q \propto \frac{\sigma\Omega}{G\Sigma} \leq 1$$

$$R_{\rm clump} \propto \frac{G\Sigma}{\Omega^2}$$

Toomre 64;

Isolated galaxies:
Noguchi 99; Immeli et al. 04; Bournaud, Elmegreen, Elmegreen 06, 08; Hopkins et al. 12; Bournaud et al. 13

In cosmology:
Dekel, Sari, Ceverino 09
Agertz et al. 09
Ceverino, AD, Bournaud 10
Ceverino et al. 11
Cacciato, AD, Genel 12a,b
Genel et al. 12
Forbes et al. 12, 13



Self-regulated at Q~1 by torques and inflow → high σ/V~1/4

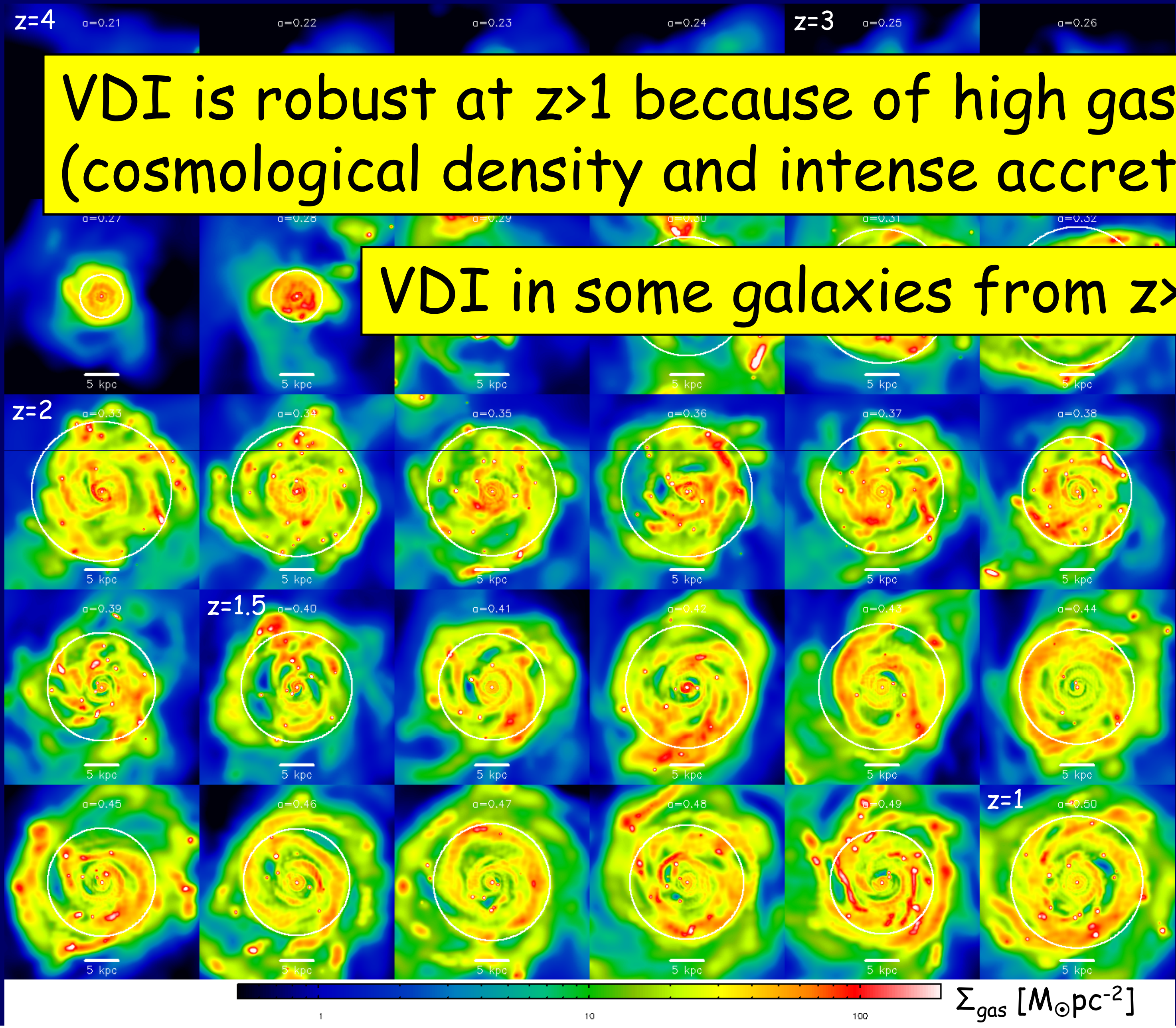
Inflow → compact bulge and BH

Steady state: disk draining and replenishment, bulge ~ disk

Clumpy Disk in a cosmological steady state

VDI is robust at z>1 because of high gas density (cosmological density and intense accretion)

VDI in some galaxies from z>7 to z<1

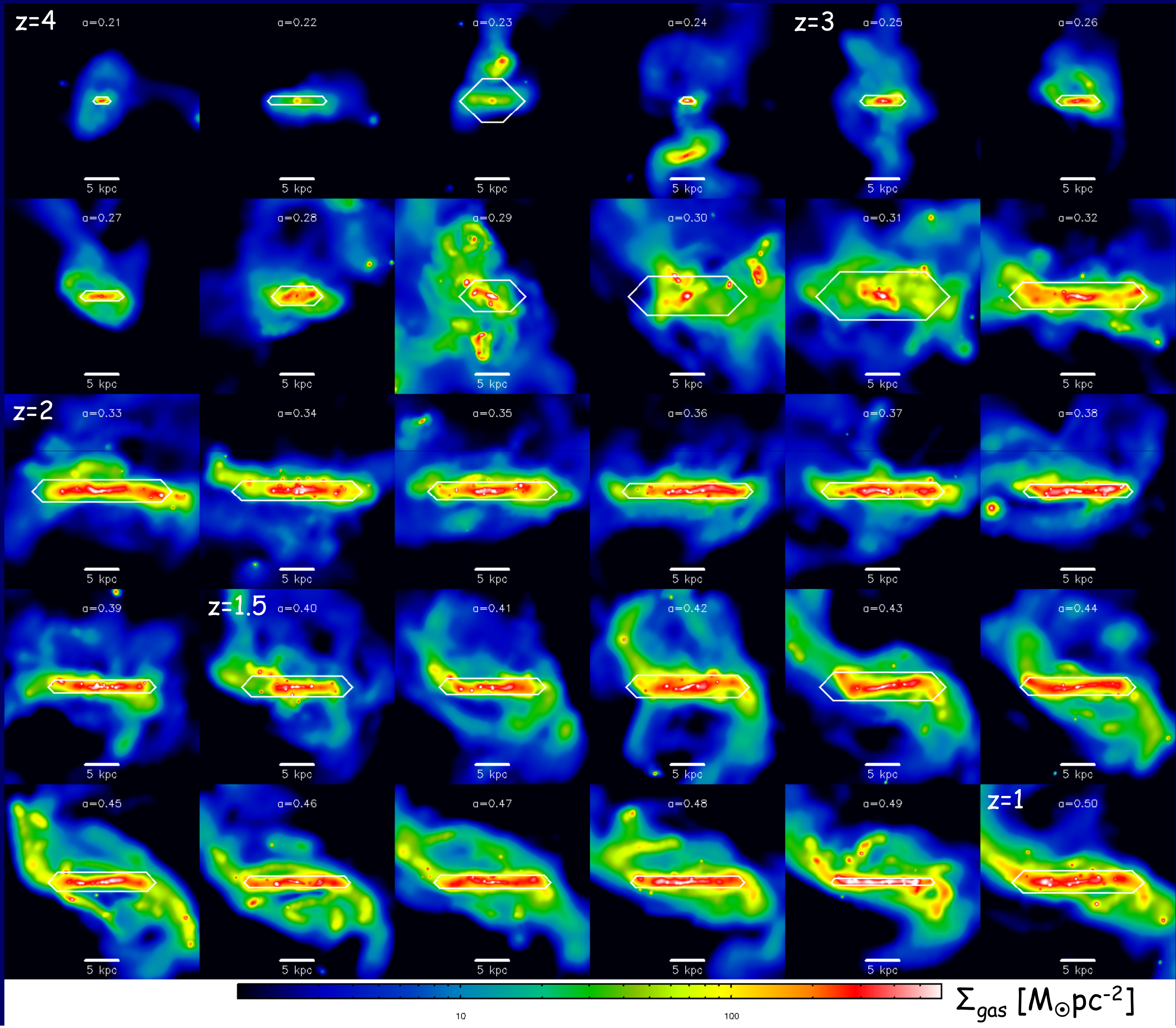


Dekel, Sari, Ceverino 09;

Ceverino, Dekel, Bournaud 10

Mandelker et al. 13

Clumpy Disk in a cosmological steady state



Dekel, Sari, Ceverino 09;

Ceverino, Dekel, Bournaud 10

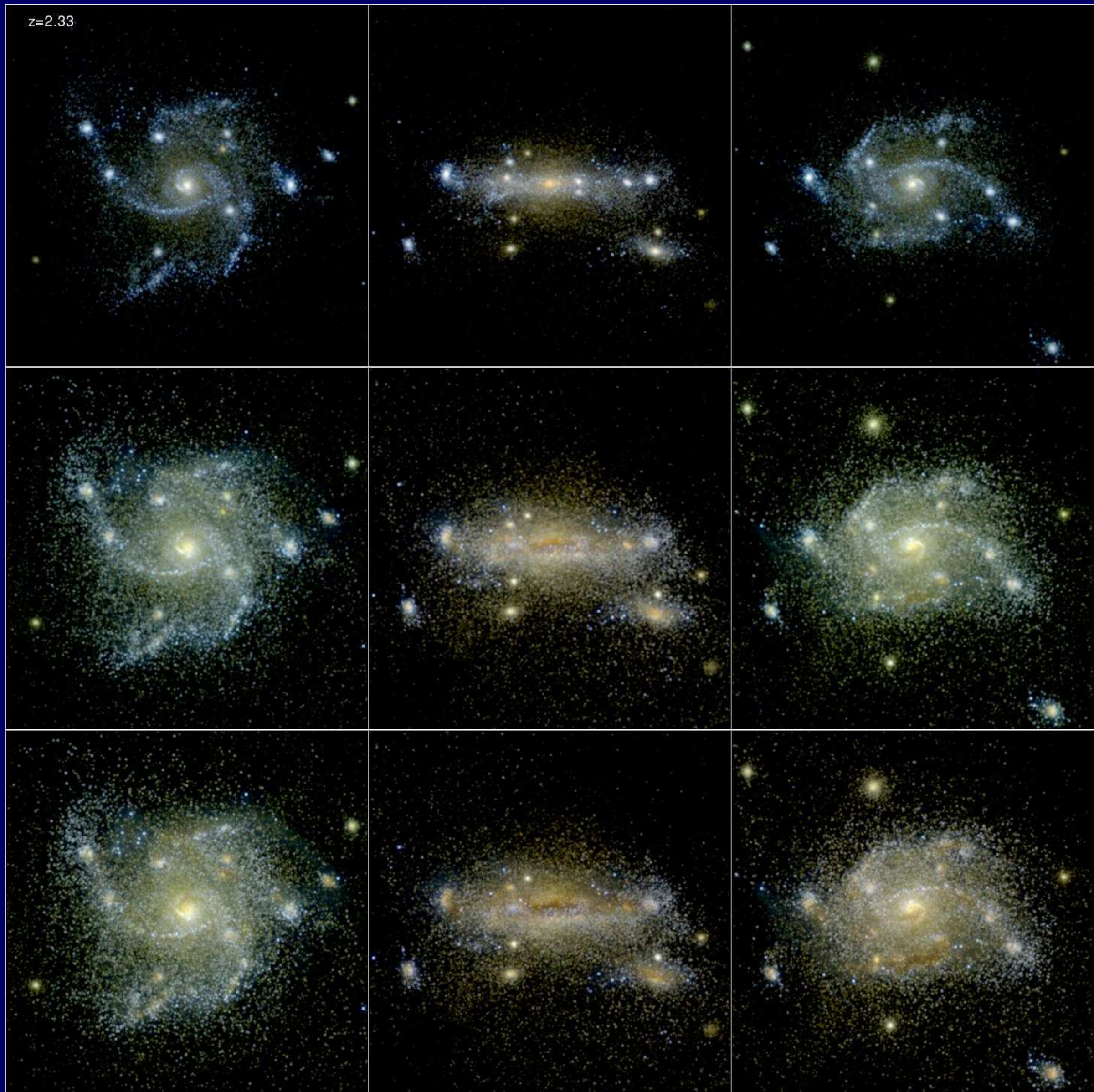
Mandelker et al. 13

Simulated hi-z galaxy through Dust

low dust

medium

high



SUNRISE

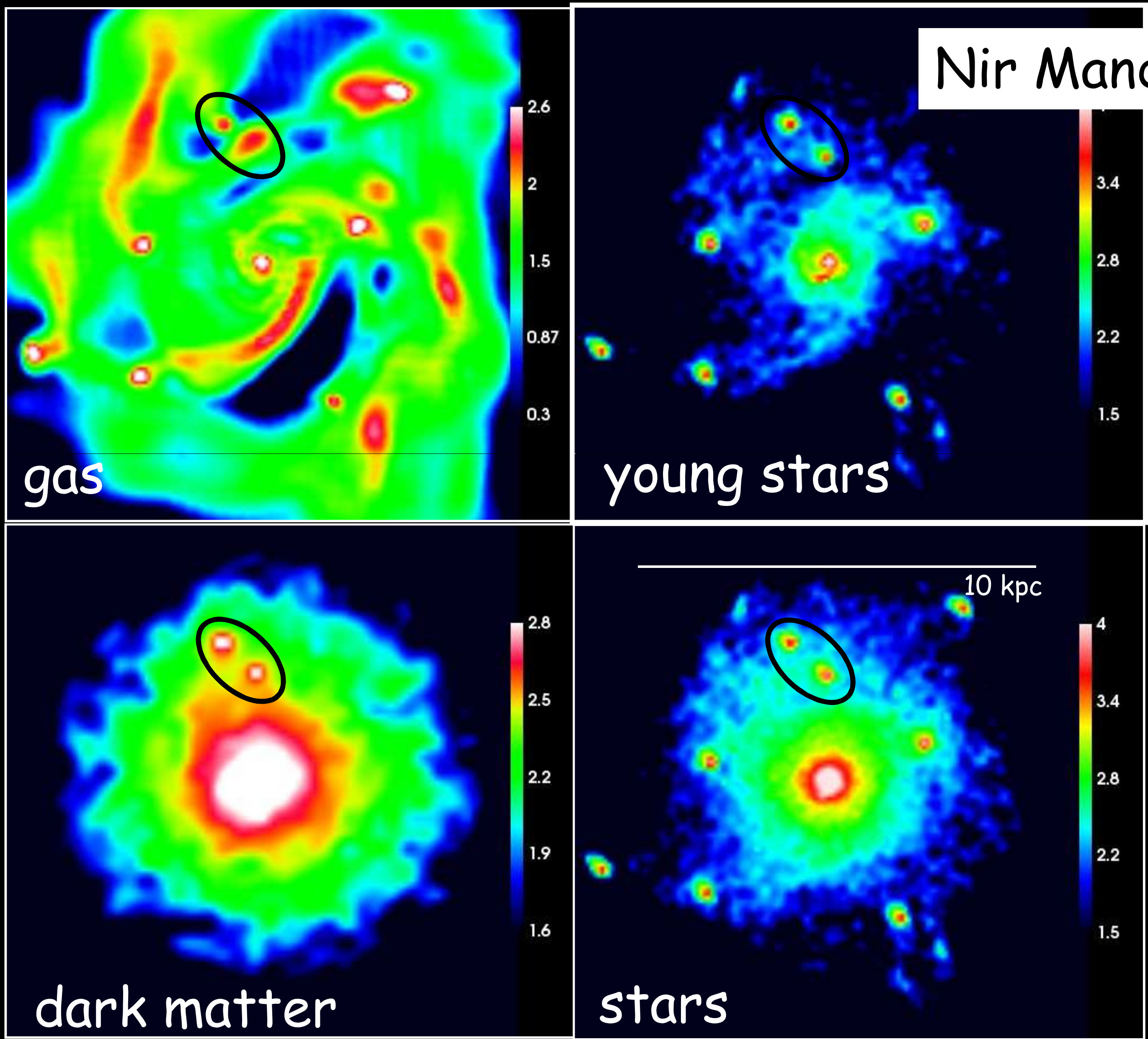
RGB colors

MW3
z=2.33

Moody,
Ceverino,
Mozena,
Dekel,
Primack

In-situ (VDI) and Ex-situ (merger) Clumps

Nir Mandelker



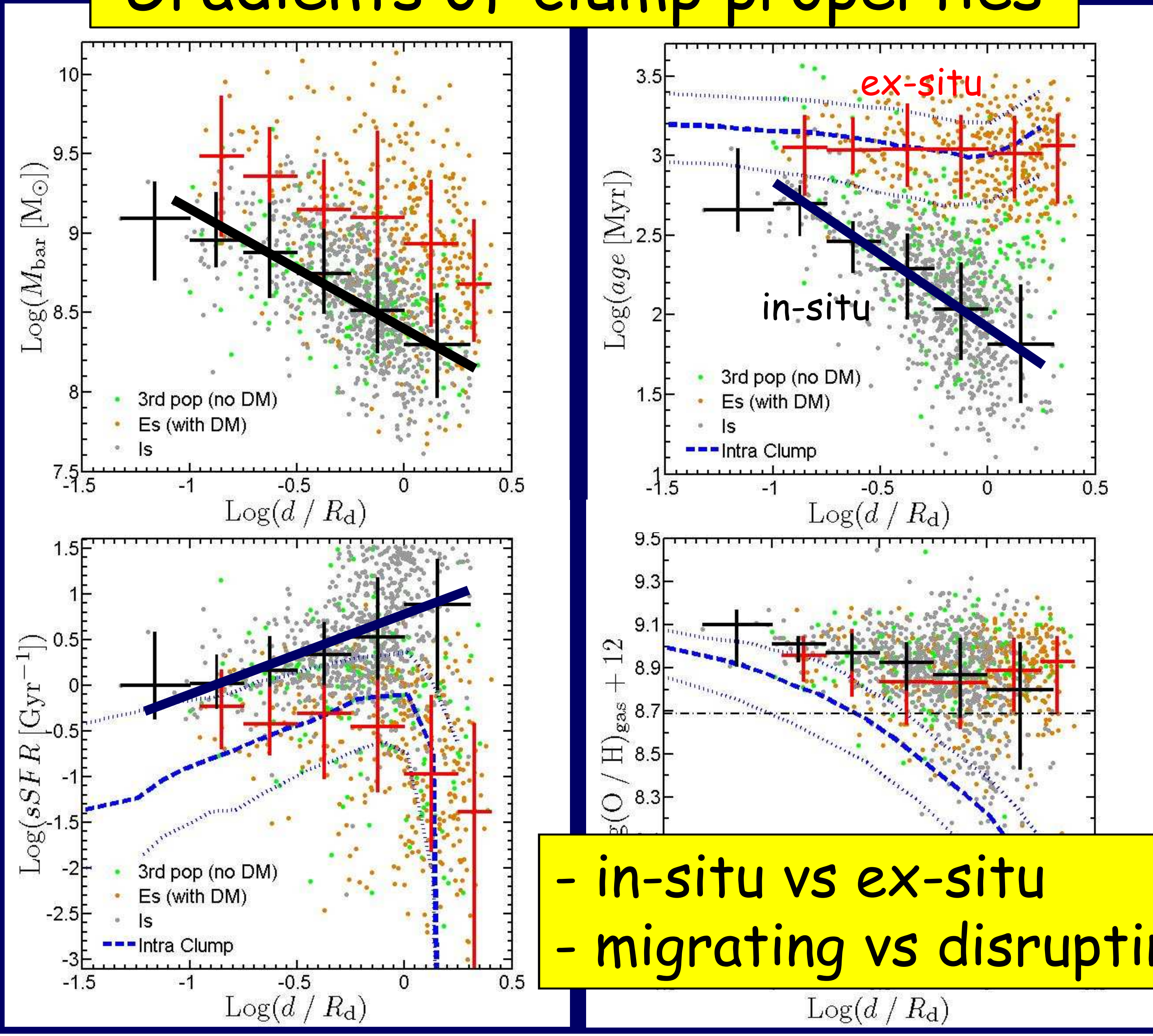
Clumps in Cosmological Simulations

Ceverino, Dekel, Bournaud 10; Ceverino et al. 12; Mandelker et al. 2013

Gas disks in 83% of the galaxies
Off-center clumps in 70% of disks, compact & round, 3-4 per galaxy

	In-situ clumps	**Ex-situ, merging clumps**
Dark matter	no	yes
Kinematics	rotating disk	50/50% disk/off disk
Number	70%	30%
Mass	45%	55%
SFR	75%	25%
M_{clump}/M_{disk}	0.02	0.06
Stellar age (Myr)	180	1200
sSFR (Gyr^{-1})	4.0	0.3
Gas fraction	0.3	0.03
Metallicity	low tail	no low tail

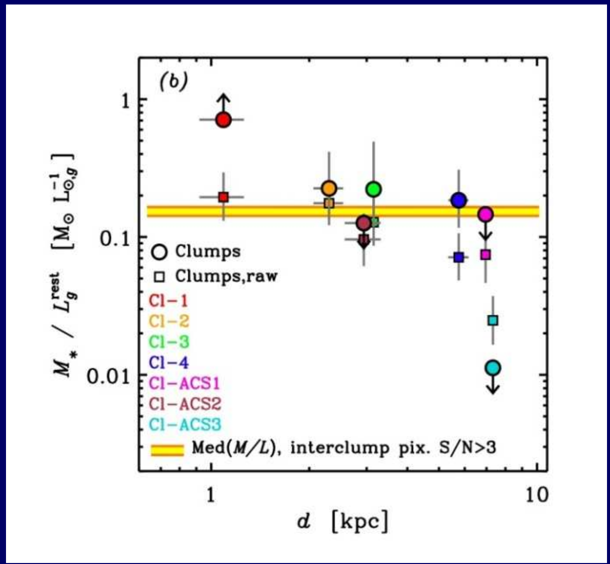
Gradients of clump properties

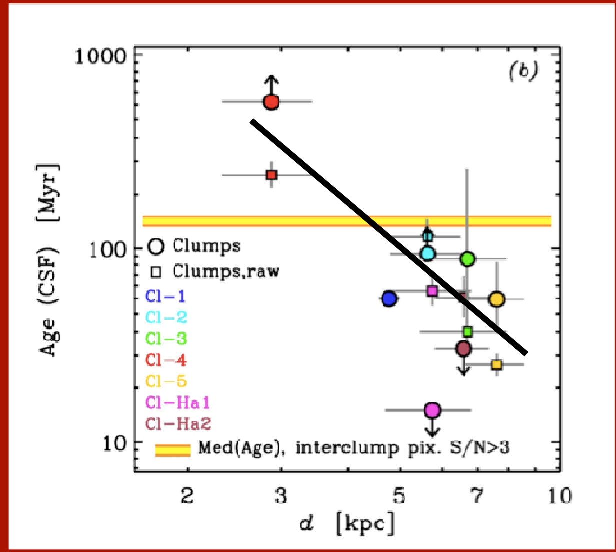


- in-situ vs ex-situ
- migrating vs disrupting

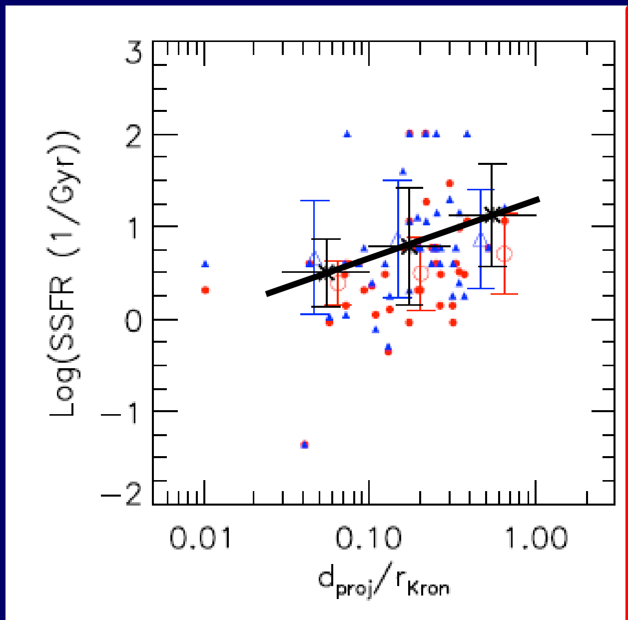
Observational indications for clump survival?

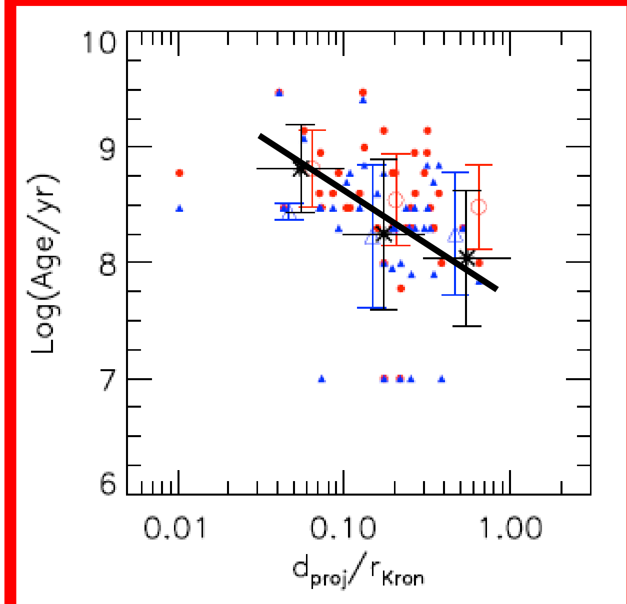
Forster Schreiber et al. 11





Guo et al 11



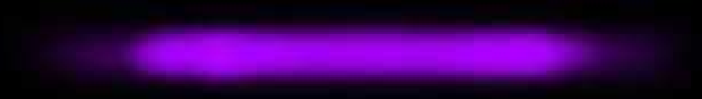


Isolated, gas-rich, turbulent disk - giant clumps - migration - bulge

Formation of an exponential spiral disk
and a central bulge

from the evolution of a gas-rich primordial disk

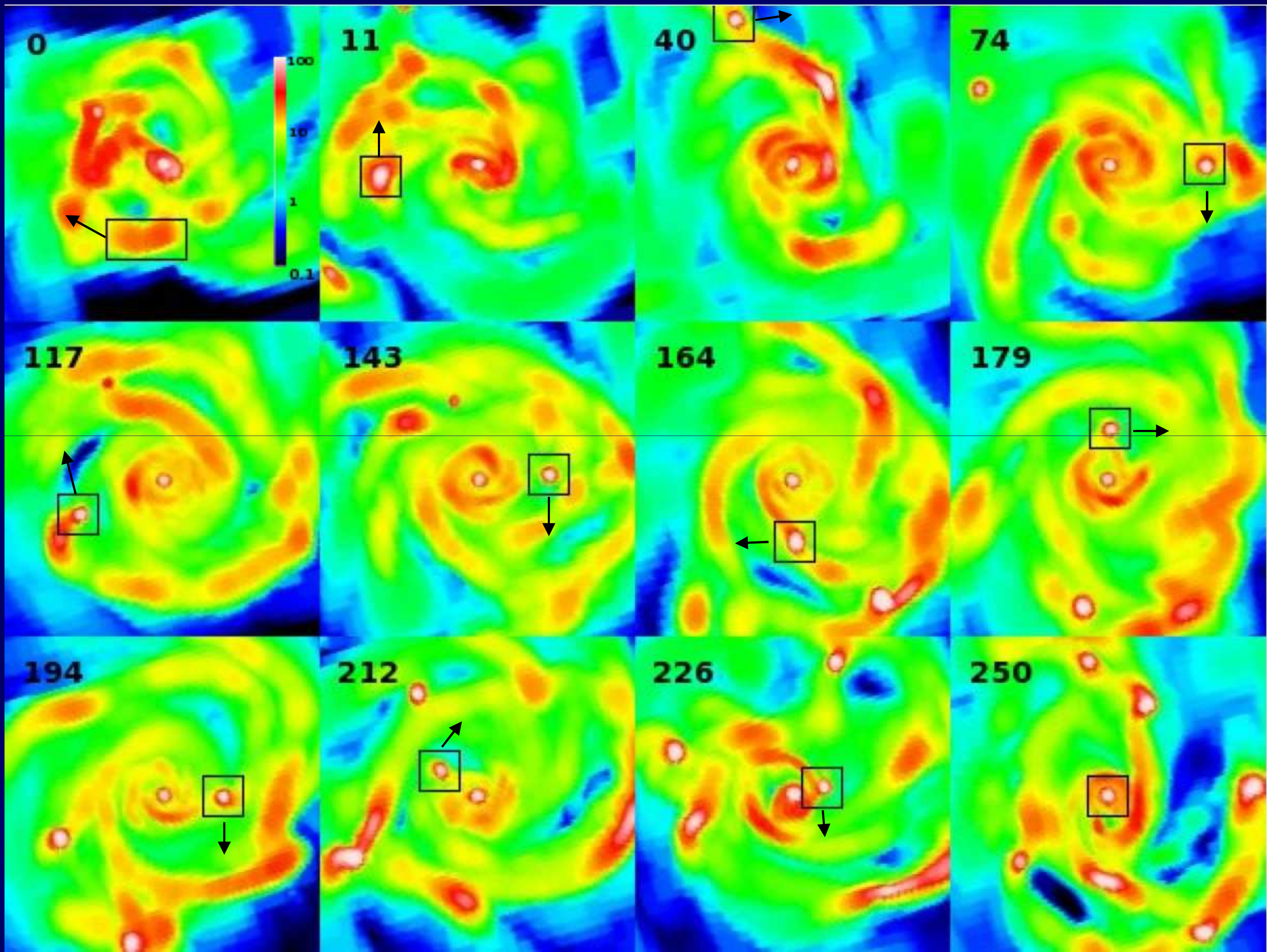
evolving through a clumpy phase



Models from Bournaud, Elmegreen & Elmegreen 2007

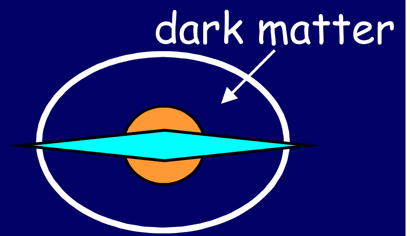
Noguchi 99; Immeli et al. 04; Bournaud, Elmegreen, Elmegreen 06, 08

Clump Migration on an Orbital Timescale



Ceverino, Dekel, Bournaud 10

Clump Evolution during Migration



Toomre instability $1 \approx Q \approx \delta^{-1} \frac{\sigma}{V}$ $\delta \equiv \frac{M_{\rm disk}}{M_{\rm tot}(R_{\rm disk})}$

- Migration to center: torques, encounters, dyn. friction

$$t_{\rm mig} \approx \delta^{-2}\, t_{\rm dyn} \approx 8 t_{\rm dyn} \approx 250\,{\rm Myr}$$

Dekel, Sari, Ceverino 09

- Mass gain $\dot{M}_{\rm acc} \approx \rho_{\rm d} R_{\rm T}^2\, \sigma_{\rm d}$ → $t_{\rm acc} \approx 8\, t_{\rm dyn} \approx t_{\rm mig}$

Dekel, Krumholz 13 Mandelker et al 13 Bournaud et al 13

- Star formation

$$t_{\rm sfr} \approx (3\varepsilon_{\rm sfr})^{-1}\, t_{\rm dyn} \approx 30\, t_{\rm dyn} \approx 3 t_{\rm mig}$$

- Momentum-driven outflows; steady wind

$\dot{p}_{\rm w} = \psi_{\rm w} V_L \dot{M}_*$ $L/c = V_L \dot{M}_*$ $V_L \approx 160\ {\rm km\ s^{-1}}$ Dekel, Krumholz 13

STARBURST99

Simulations of wind instability Krumholz, Thompson 13

+proto-stellar winds + stellar winds + supernovae → $\psi_{\rm w} \approx 2.5$ $\eta \approx 1\!-\!2$

Consistent with observed

$$t_{\rm out} \approx (3\eta\varepsilon_{\rm sfr})^{-1} t_{\rm dyn} \approx \eta^{-1} t_{\rm sfr} \approx (1-2)\, t_{\rm mig}$$

$$t_{\rm mig} \approx t_{\rm acc} \leq t_{\rm out} \leq t_{\rm sfr}$$

Clump Evolution during Migration

$$\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - \dot{M}_{\rm sfr} - \dot{M}_{\rm out}$$

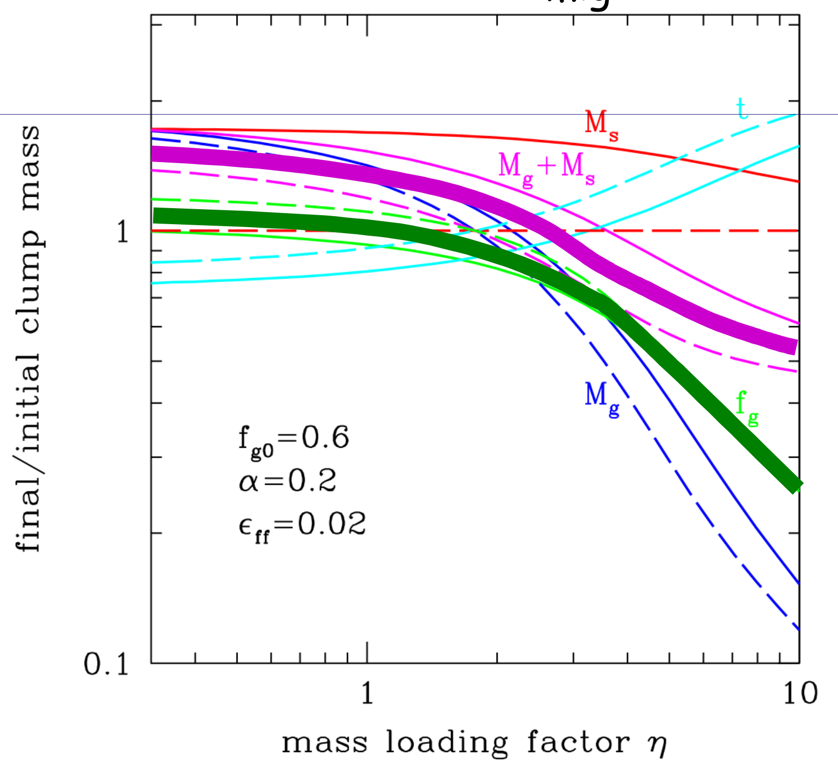
$$0 \le \dot{M}_{\rm stars} \le 3\varepsilon_{\rm sfr}\, t_{\rm dyn}^{-1}\, M_{\rm gas}$$

max tidal stripping SFR only

$$\dot{M}_{\rm gas} = t_{\rm gas}^{-1}\, M_{\rm gas}$$

$$t_{\rm gas}^{-1} = t_{\rm dyn}^{-1}\,[(8 f_{\rm gas})^{-1} - 3(1+\eta)\varepsilon_{\rm sfr}]$$

final mass at t_{mig} /initial



any η, mass varies by < x2

η~2-4, M_{clump} ~ const.

η<<1, M_{clump} ~ x2

η>>1, $M_{clump} \rightarrow 0$

for η<4, f_{gas} ~ const.

$$M_{\rm gas} \propto \exp(t/t_{\rm gas})$$

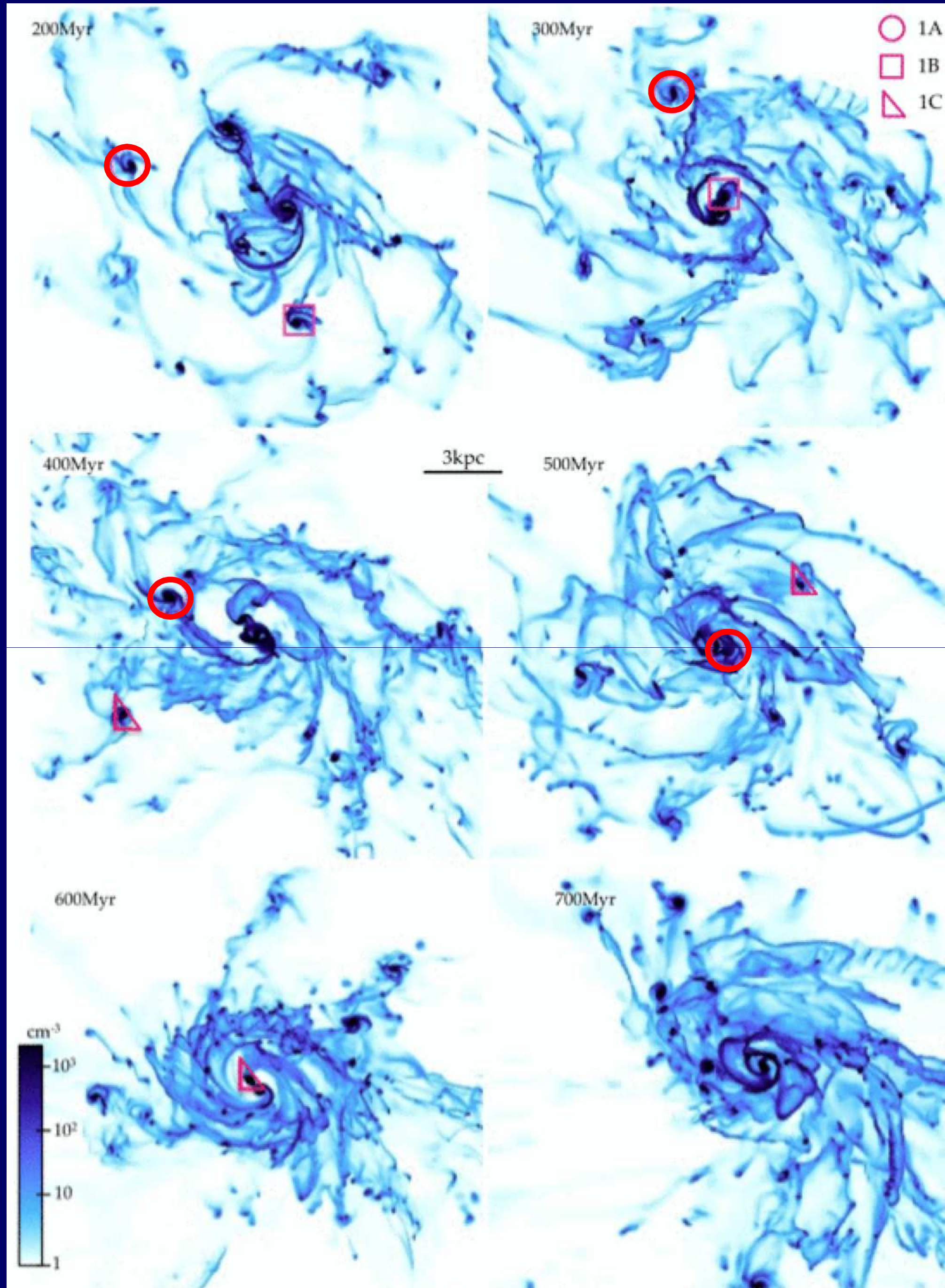
η~2-4 $\rightarrow$ t_{mig}<<t_{gas} $\rightarrow$ M_{gas} ~ const.

Confirmed in simulations
Bournaud et al. 13,
Mandelker et al. 13

Clump Survival

RAMSES simulations of isolated gas-rich disks at 5pc resolution with radiative feedback η~2
Bournaud, AD, Elbaz et al. 13

Migration ~300 Myr
Massive clumps survive with mass ~constant



Clump Evolution during Migration: Summary

- SFR in clumps drives η~1-2 steady winds
- Gas gain by accretion
- Stellar loss by tidal stripping
- The massive clumps keep ~constant mass
- They live for t_{mig}~ 300 Myr
- They feed gas & stars to the bulge
- Less massive clumps disrupt

Expect a weak gradient of clump mass in disks
Certain gradient in age/color

3. Formation of Compact Spheroids
Blue and Red

Violent Disk Instability ↔ Inflow to Center

Self-regulated Toomre instability $Q \approx \frac{\sigma\Omega}{\Sigma} \approx \delta^{-1}\frac{\sigma}{V} \approx 1 \;\rightarrow\; \frac{M_{\text{cold}}}{M_{\text{tot}}} \equiv \delta \approx \frac{\sigma}{V}$

1. Torques between perturbations drive AM out and mass in (e.g. clump migration)
Gammie 01; Dekel, Sari, Ceverino 09

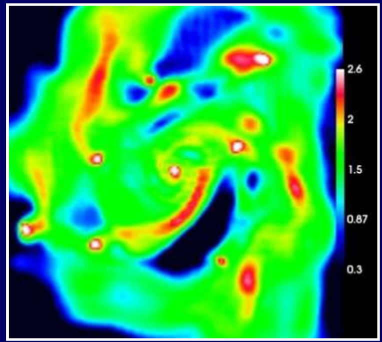
2. Inflow down the potential gradient provides the energy for driving σ to Q~1 compensating for the dissipative losses Krumholz, Burkert 10; Bournaud et al. 11; Cacciato et al. 12; Forbes et al. 13; Dekel et al. 13

$$\dot{M}_{\text{inflow}} V^2 \approx \frac{M\sigma^2}{t_{\text{dyn}}} \;\rightarrow\; t_{\text{inflow}} \approx t_{\text{dyn}}\,\delta^{-2}$$

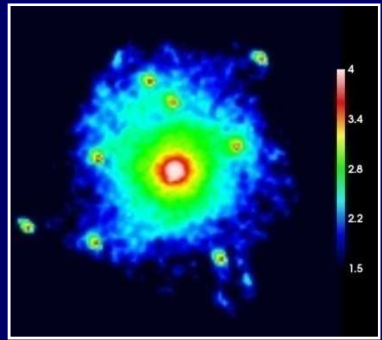
$$\boxed{\dot{M}_{\text{inflow}} \approx 25\, M_{\odot}\,\text{yr}^{-1}\, M_{\text{cold},10.5}\,(1+z)_3^{3/2}\,\delta_{0.2}^2}$$

Inflow of gas (and stars), not limited to clump migration

clumpy gas disk

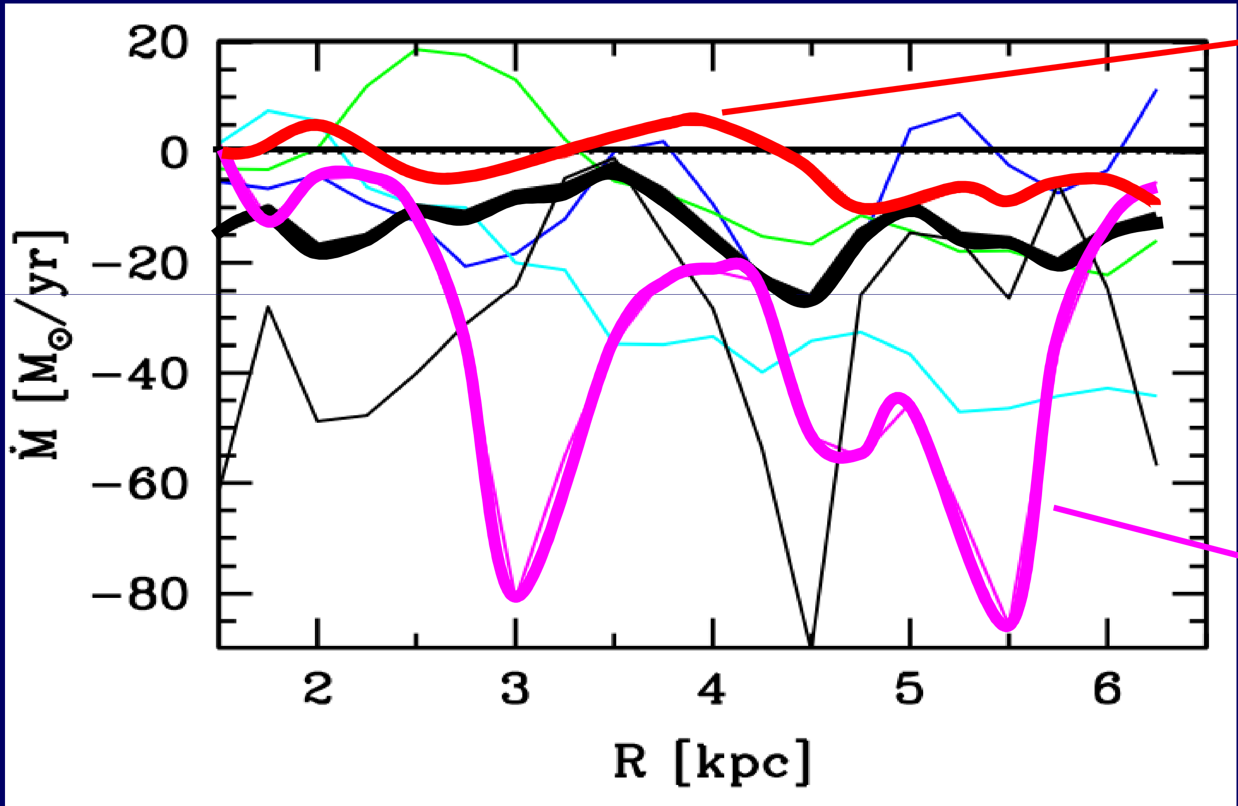


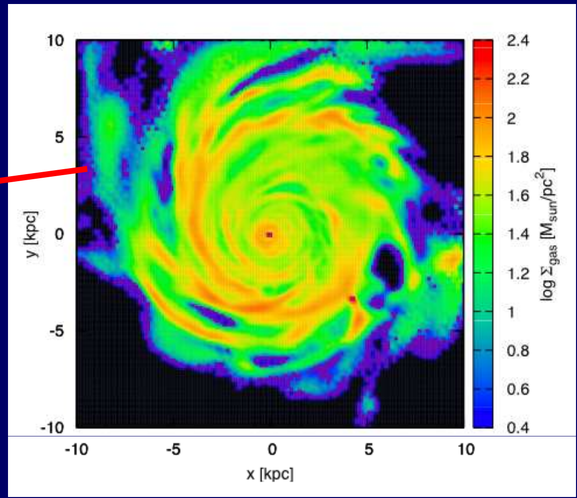
compact stellar bulge



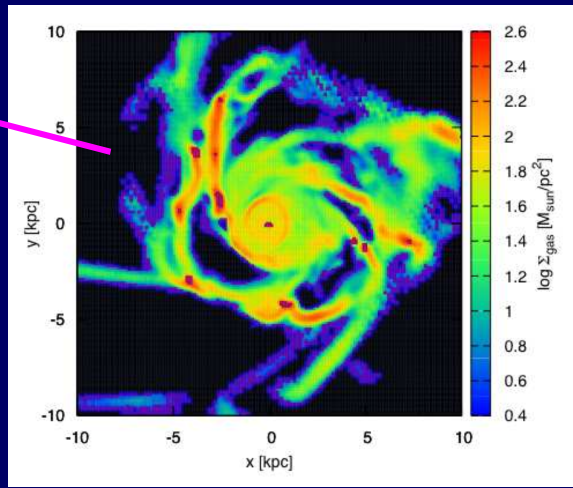
VDI-driven Inflow in Simulations

Dekel et al. 2013; Cacciato





stable



VDI

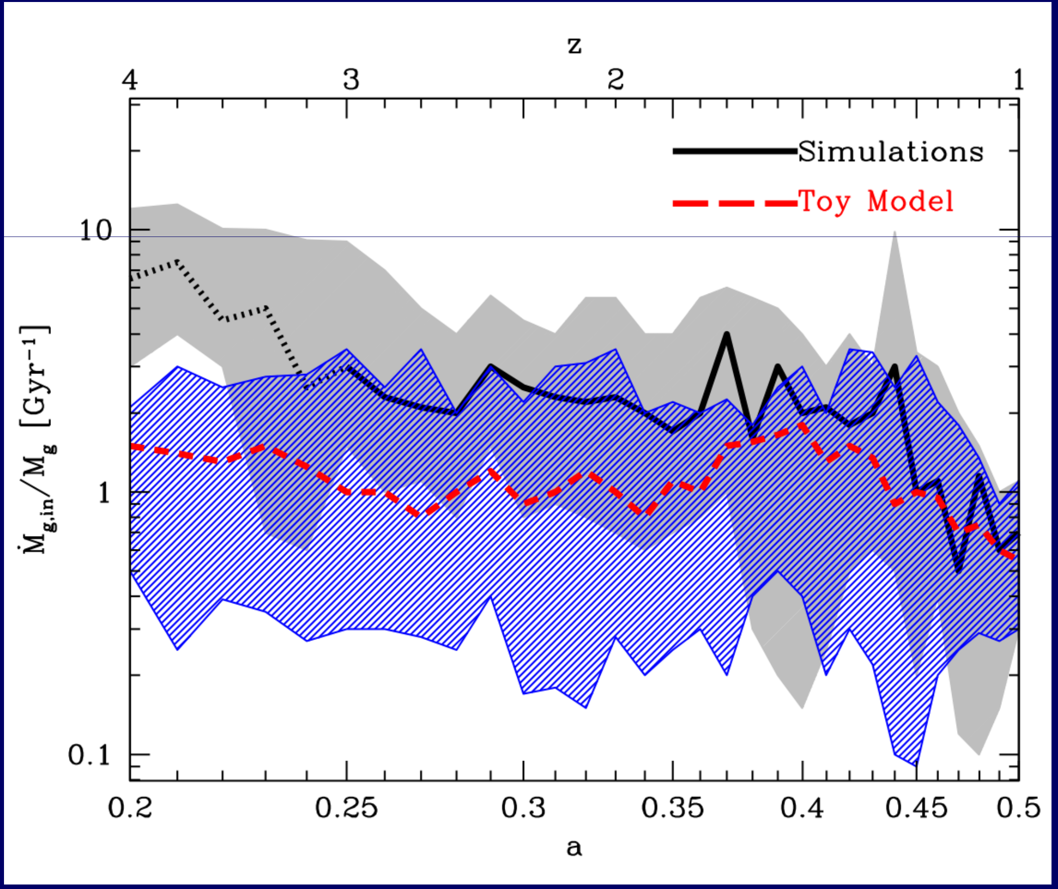
$$\dot{M}_{\text{inflow}} \approx 25\, M_\Theta \text{yr}^{-1}\, M_{\text{cold},10.5}\, (1+z)_3^{3/2}\, \delta_{0.2}^2$$

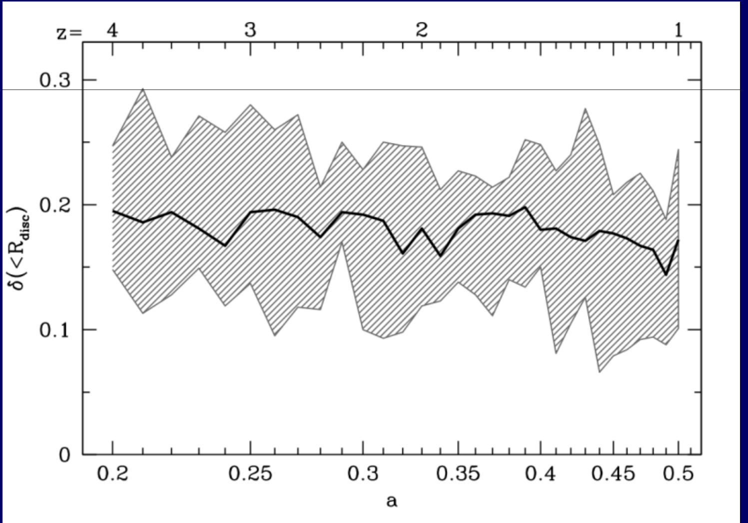
VDI-driven Inflow in simulations

Dekel et al. 2013

$$\frac{\dot{M}_{\rm inflow}}{M_{\rm cold}} \approx \frac{1}{2t_{\rm dyn}}\delta^2$$

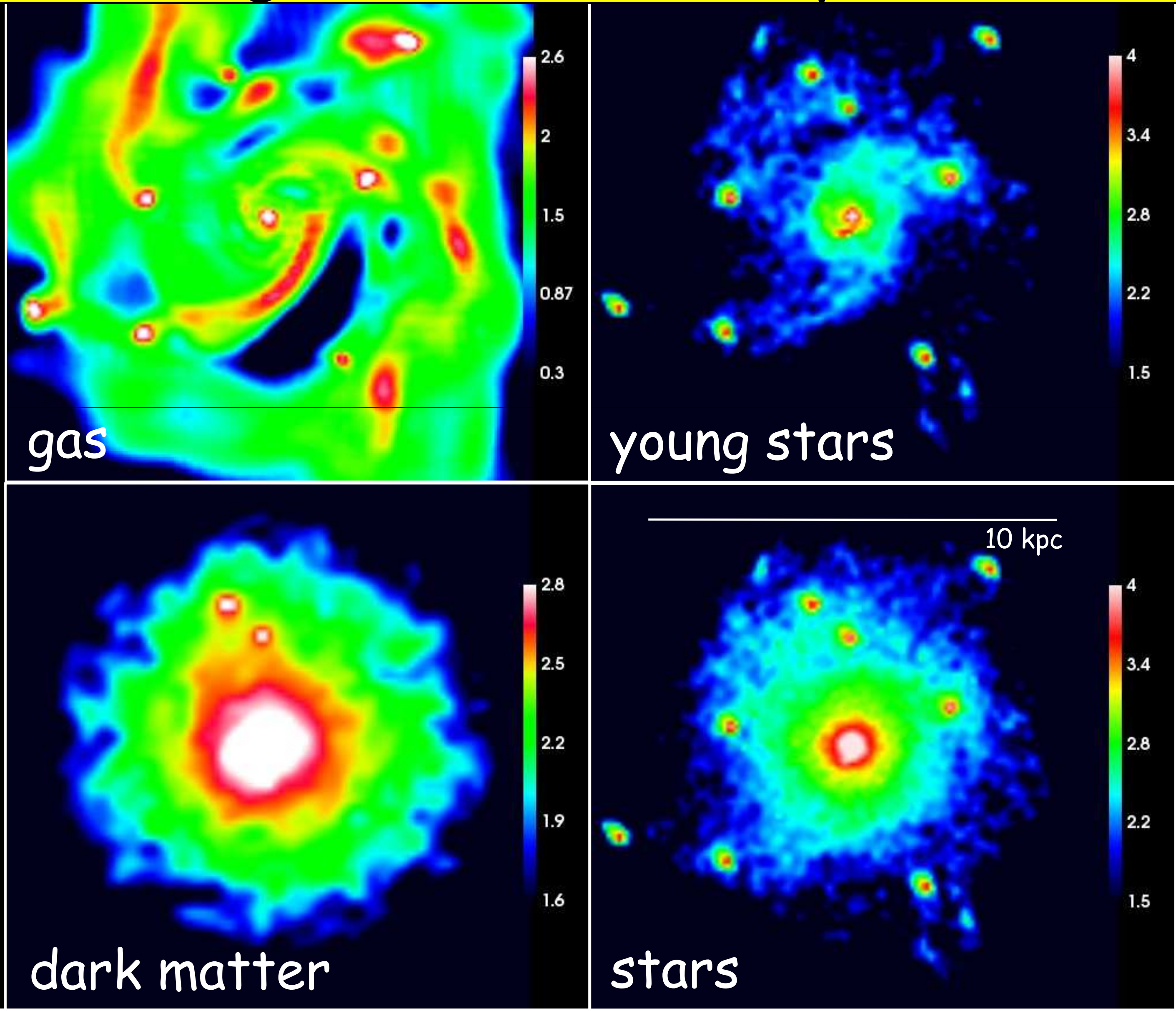
$$\dot{M}_{\rm inflow} \approx 25\,M_{\odot}{\rm yr}^{-1}\,M_{\rm cold,10.5}\,(1+z)_3^{3/2}\,\delta_{0.2}^2$$





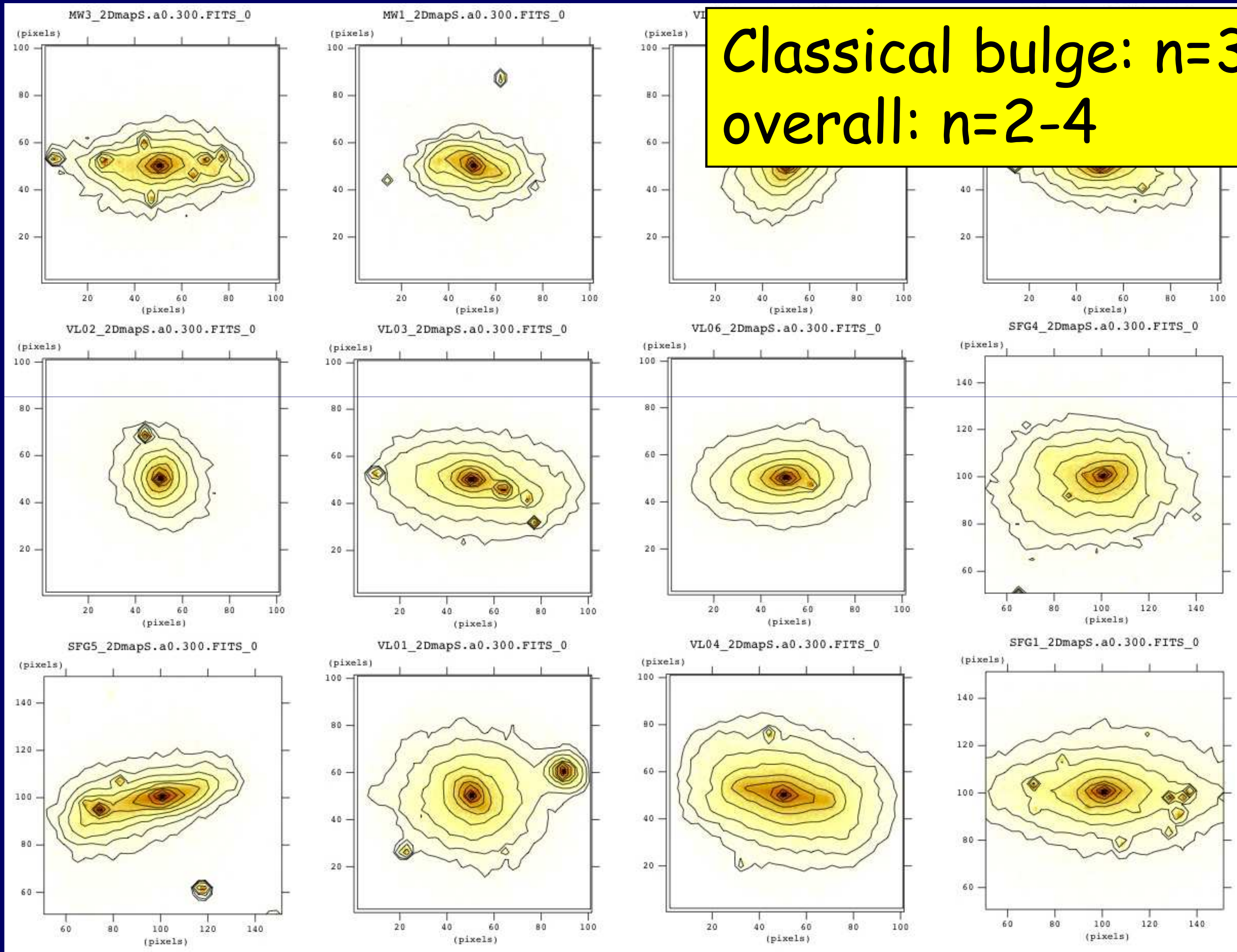
$$\frac{M_{\rm cold}}{M_{\rm tot}} \equiv \delta \approx \sqrt{2}\,\frac{\sigma}{V}$$

Formation of a Compact Spheroid by VDI
Bulge~Disk in Steady State



Stellar Component z=2.3 Edge-on

Ceverino et al. 2013



Classical bulge: n=3-5
overall: n=2-4

Red Nuggets and Blue Nuggets

Dekel & Burkert 2013; Zolotov et al. 2013

Compact stellar spheroid → dissipative "wet" inflow to a "blue nugget", by mergers or VDI

VDI inflow is "wet" if $t_{inflow} \ll t_{sfr}$

Self-regulated instability $Q \sim 1$

$$\frac{M_{cold}}{M_{tot}} \equiv \delta \approx \frac{\sigma}{V}$$

$$\delta \approx \frac{\Sigma_g}{\Sigma_g + \Sigma_* + \Sigma_{dm}}$$

Wetness parameter

$$w \equiv \frac{t_{sfr}}{t_{inflow}} \approx \varepsilon_{sfr}^{-1} \delta^2 > 1$$

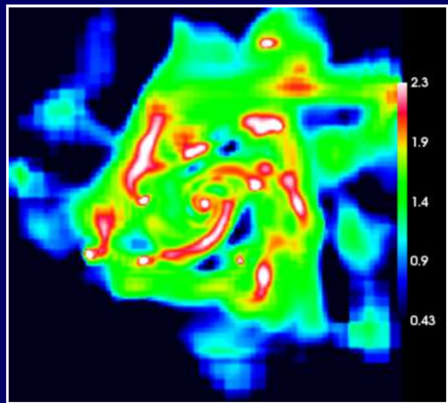
$$\varepsilon_{sfr} \leq 0.02 \quad \delta \geq 0.2$$

Bi-modality in Σ: either compact nuggets or extended disks

Start wet inflow → Σ up → w up → wetter inflow

Blue nuggets are dispersion dominated: $\sigma/V \sim \delta$

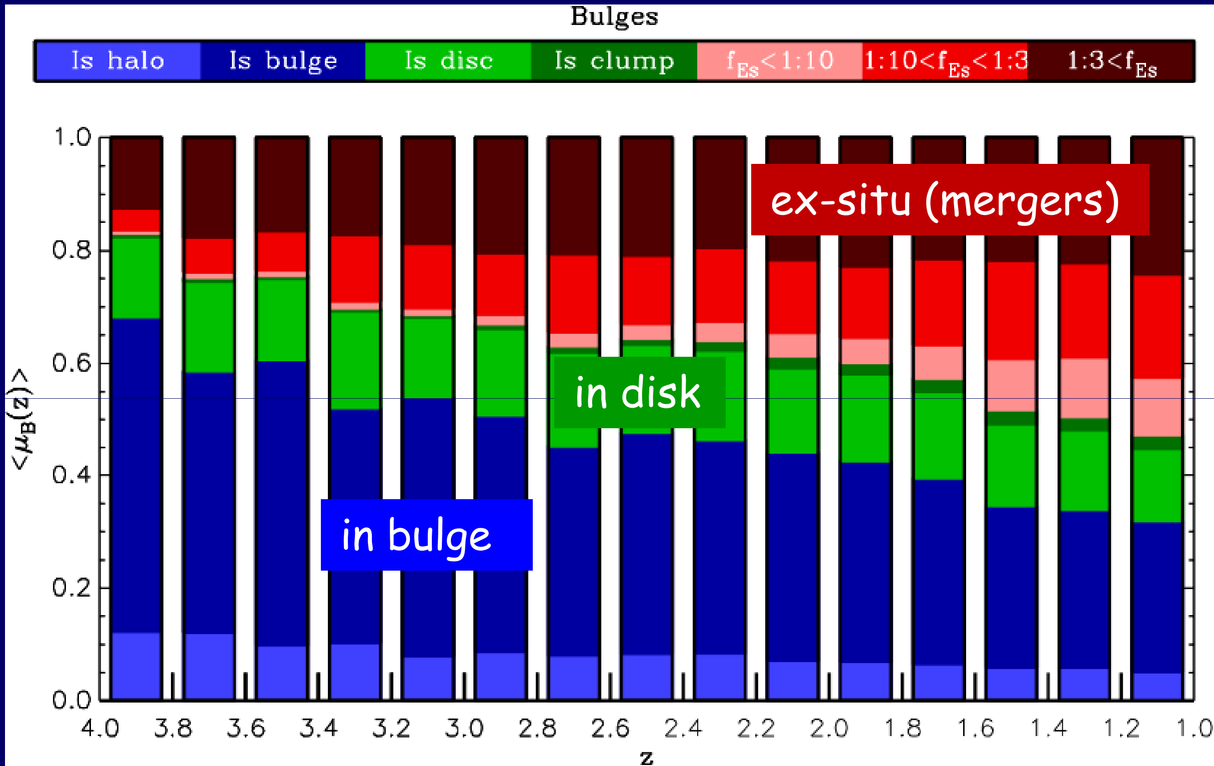
Expect VDI-driven nuggets:
- at high z, where f_{gas} is high
- for low spin λ, where R_{gas} is low
- for high mass, where outflows are weak, Σ hi, λ low



Wet Origin of Bulge: Stellar Birthplace

Simulations: Tweed, Zolotov, Dekel, Ceverino, Primack 2013

Fraction of bulge stars born in

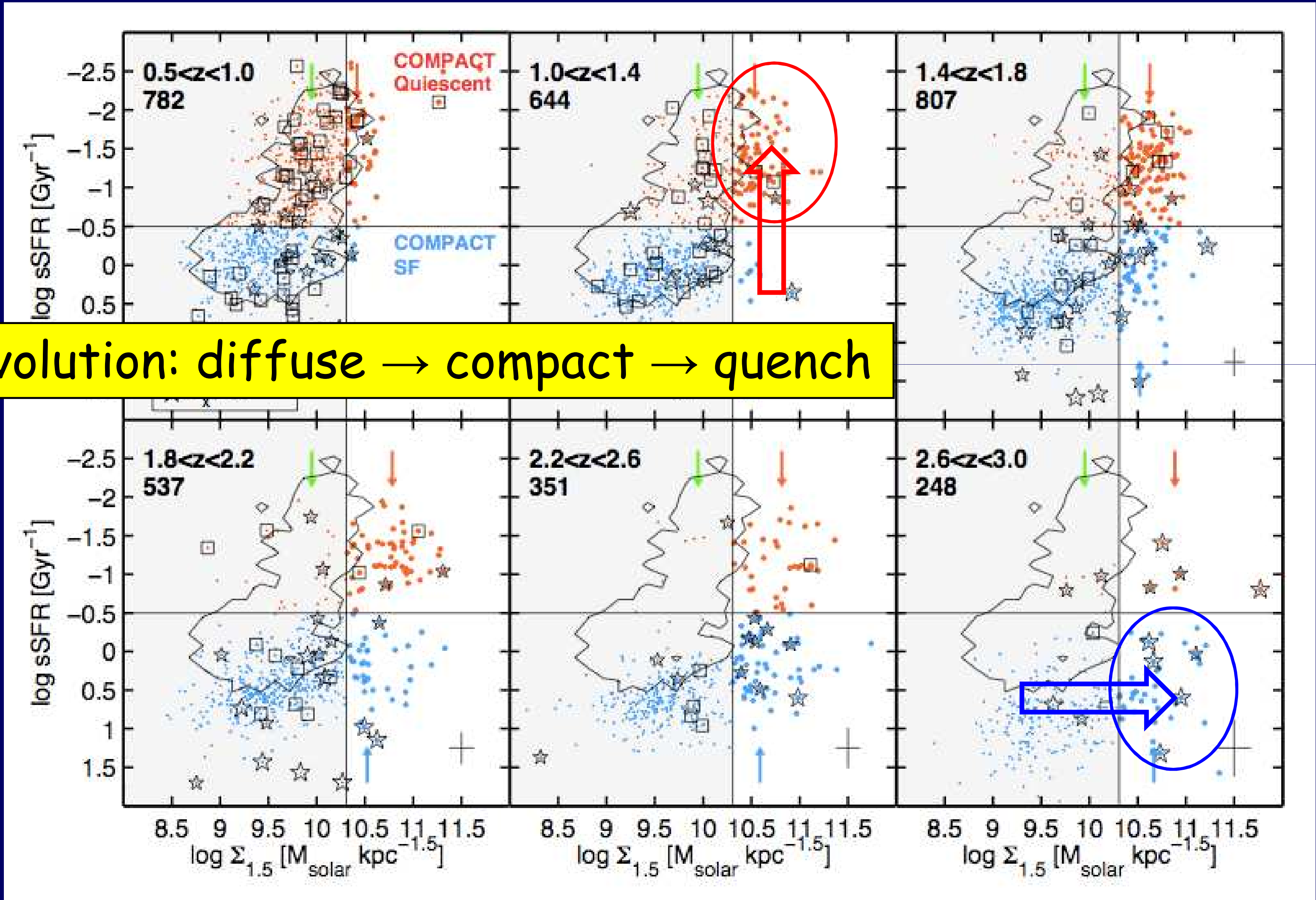


60-30% of the bulge stars form in the bulge → wet inflow

Driven by wet VDI or wet mergers

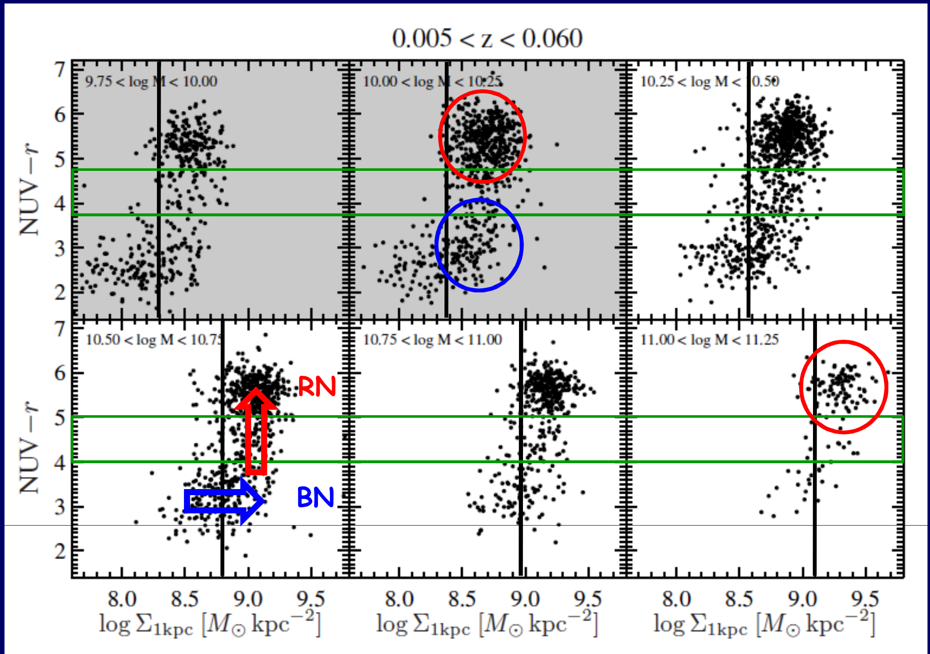
Observations: Blue Nuggets -> Red Nuggets

Barro et al. CANDELS z=1-3

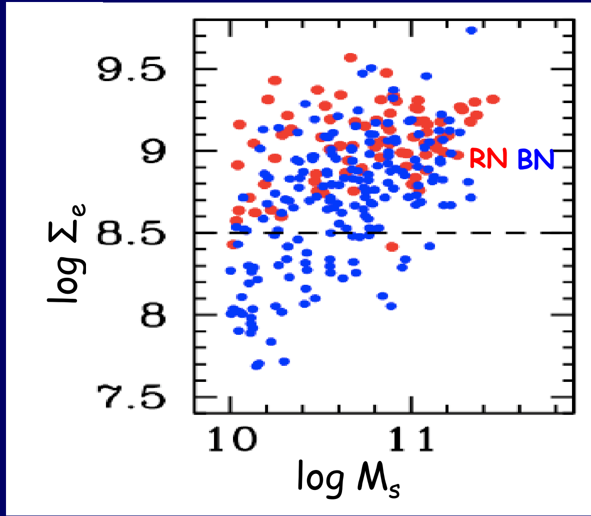


Evolution: diffuse → compact → quench

Observations: Blue Nuggets -> Red Nuggets

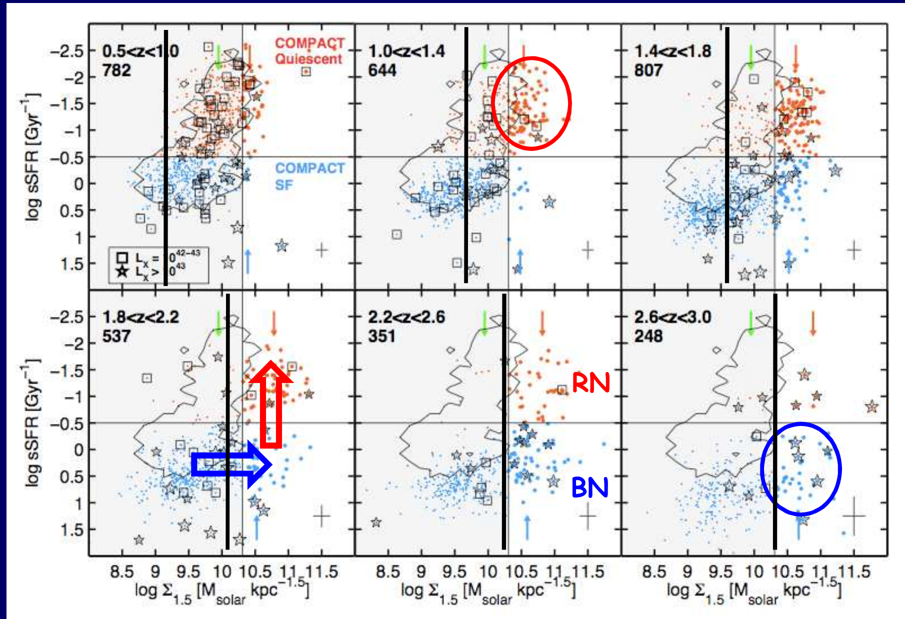


Fang et al. (z=0), Cheung et al. (z~1)



Kauffmann et al. gas z=0

Barro et al. z=1-3



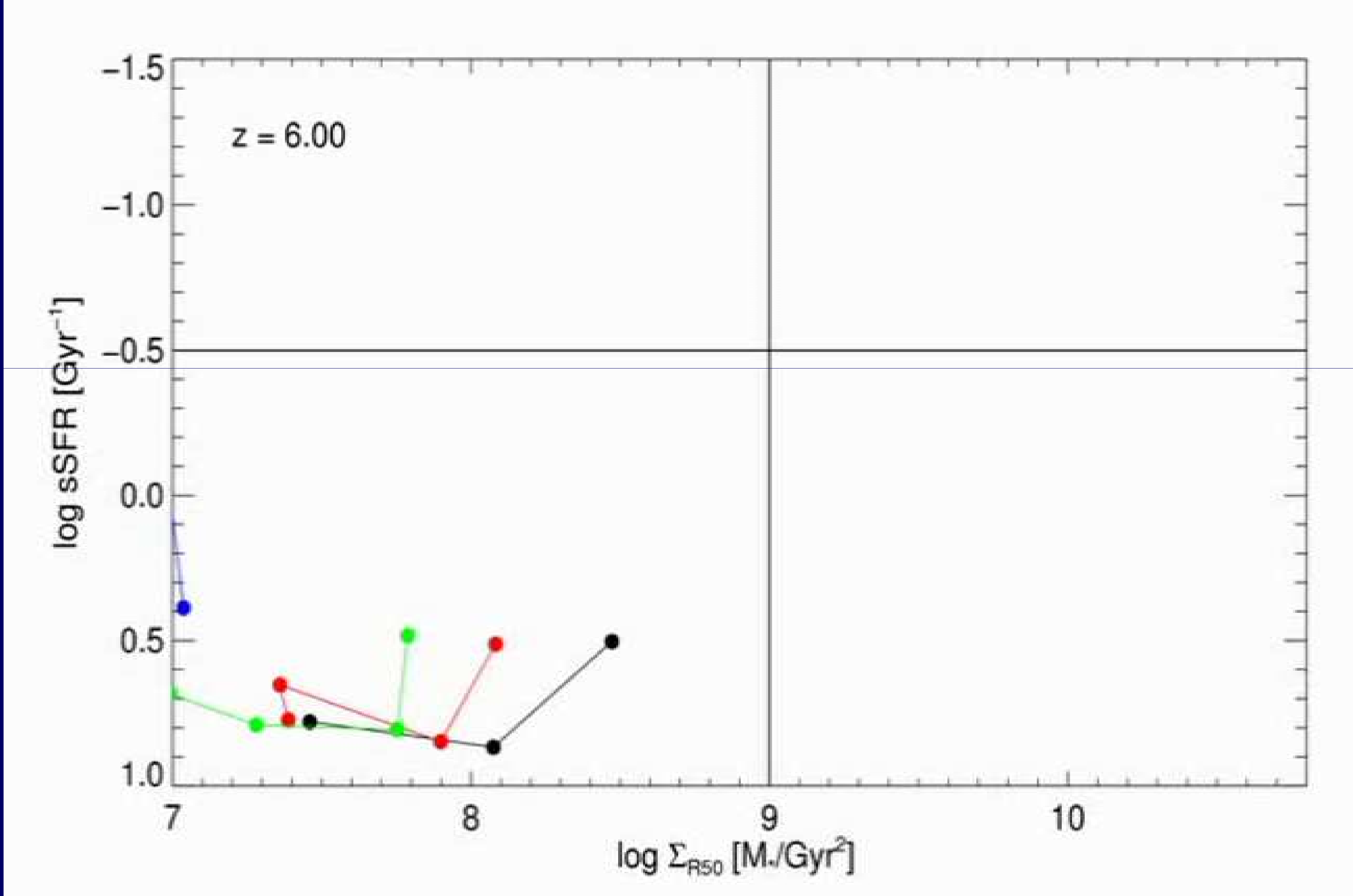
Red and blue nuggets

Evolution:
diffuse → compact → quench

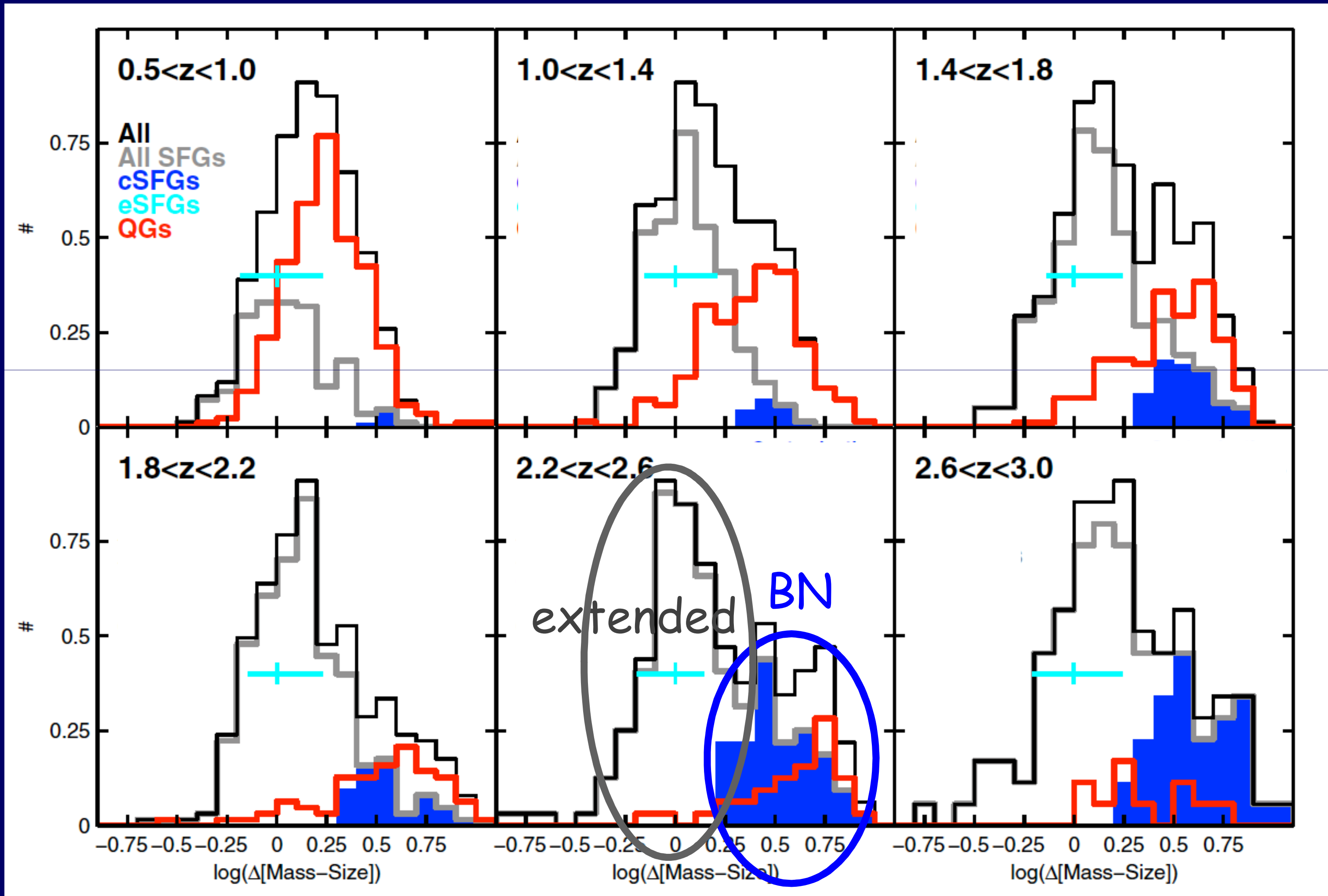
downsizing of quenching

ART Cosmological Simulations with Fdbk

Zolotov et al. 2013



Bimodality in Compactness: Blue Nuggets at Hi z



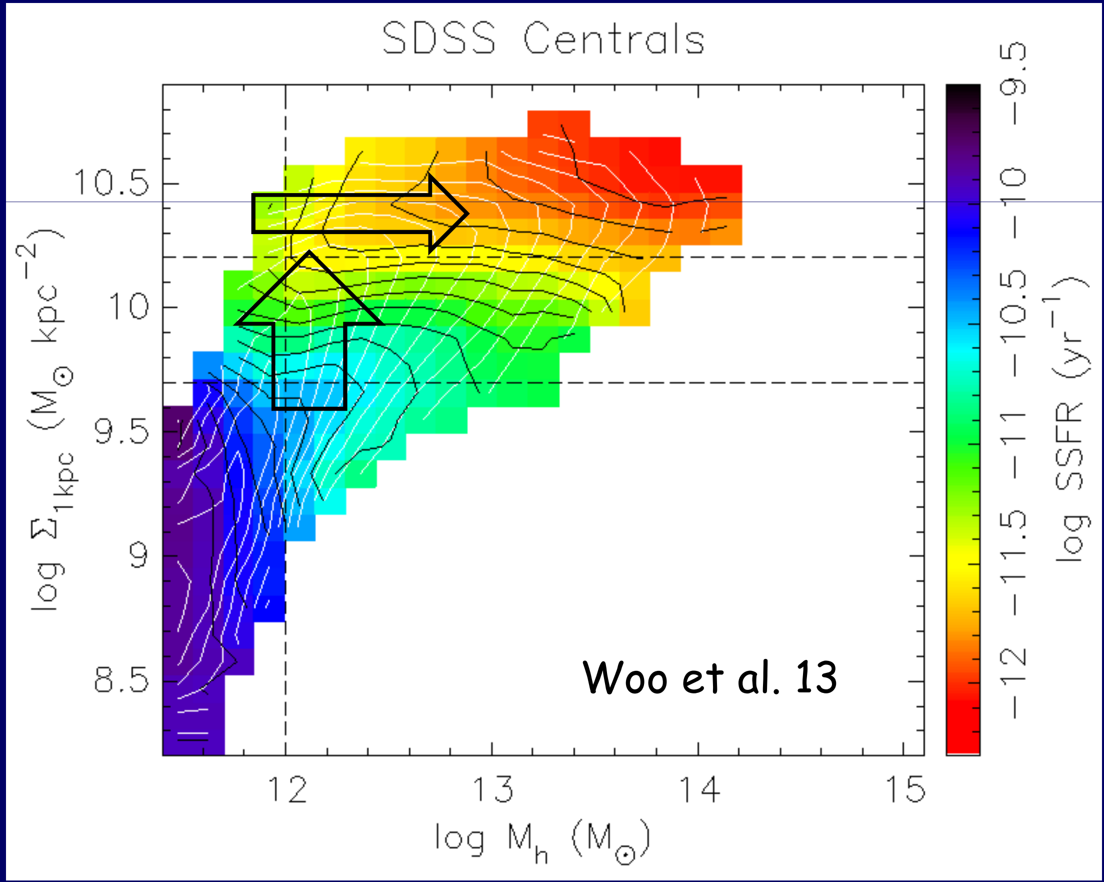
Compactness →

Barro et al. 2013

Quenching: BN to RN

Compact gaseous bulge ->
1. starburst -> gas removal by star formation & outflow
2. AGN feedback -> gas removal by outflow

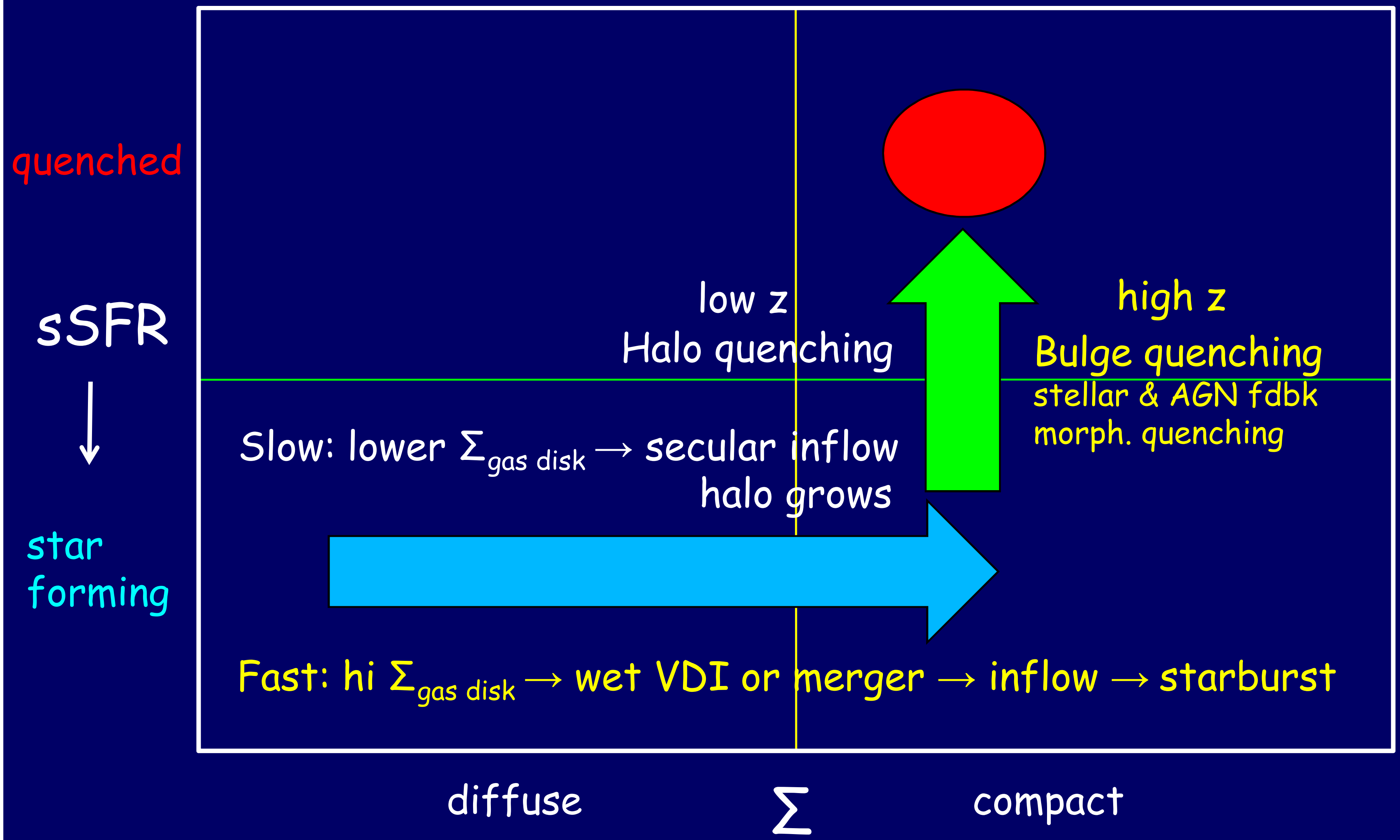
In halos > $10^{12}\ M_\odot \rightarrow$
long-term shutdown of gas supply by virial shock heating



Need both bulge and halo quenching

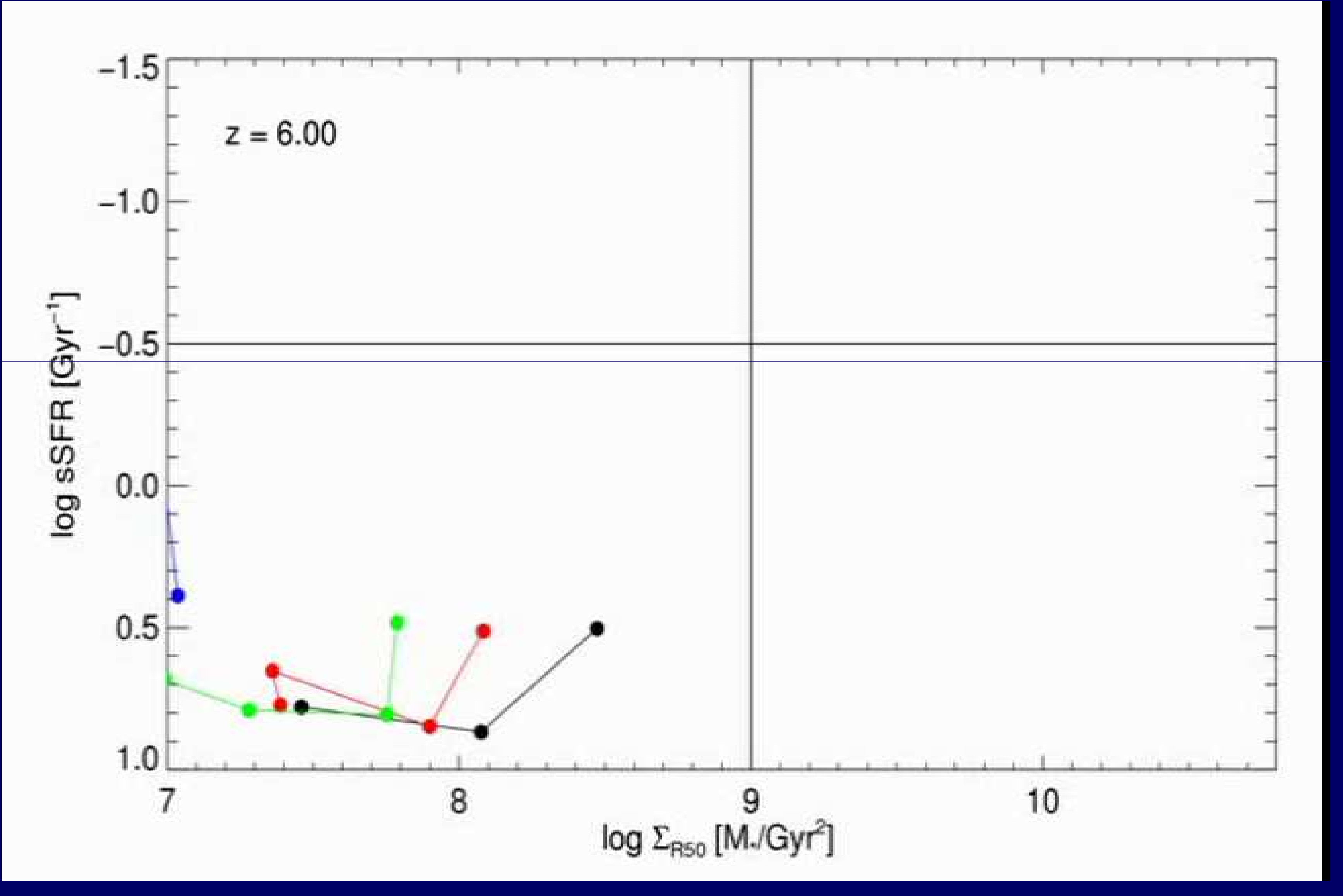
Two Modes of Evolution: Fast and Slow

Barro, Fang, Yesuf, Woo …



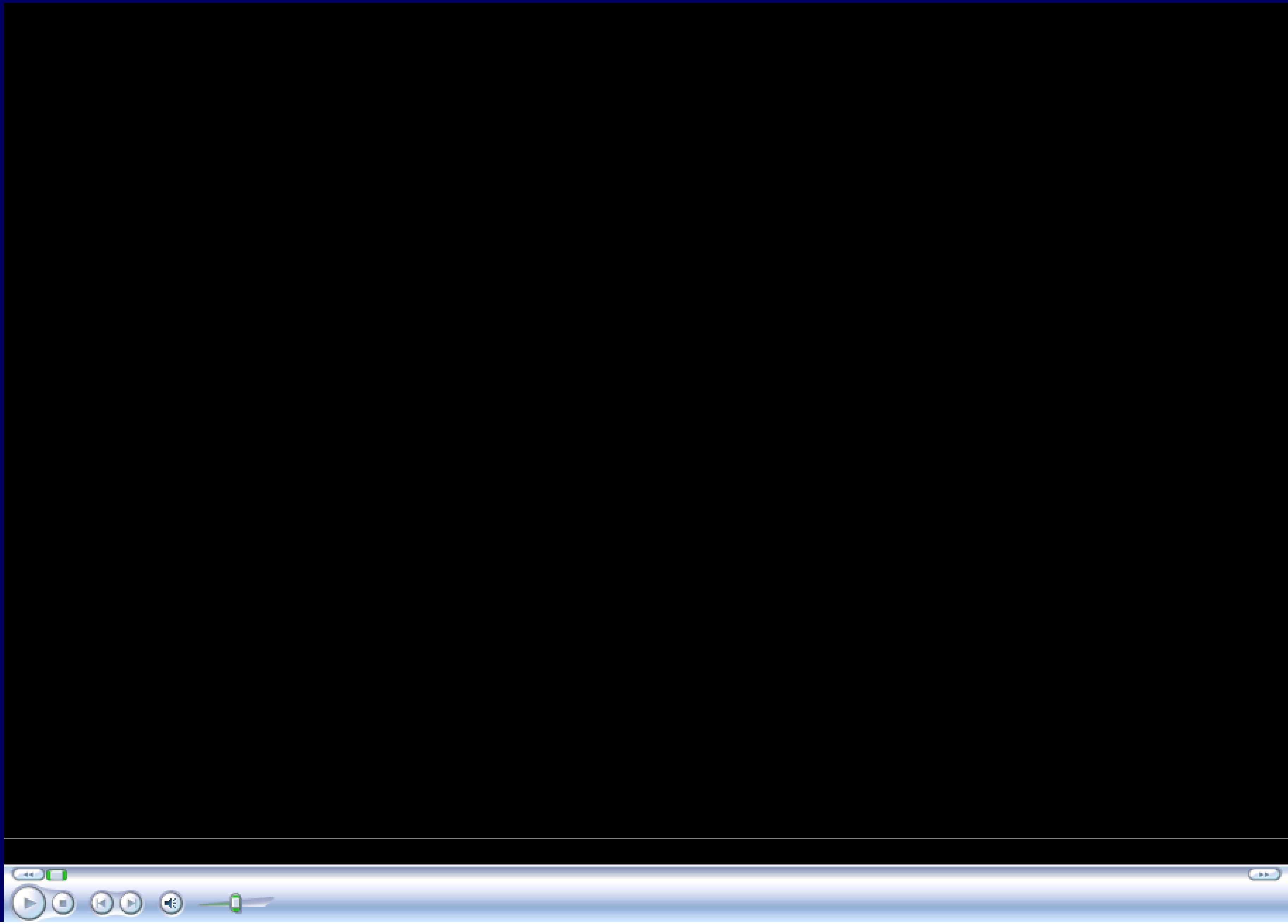
ART Cosmological Simulations with Fdbk

Zolotov et al. 2013



ART Cosmological Simulations with Fdbk

Zolotov et al. 2013



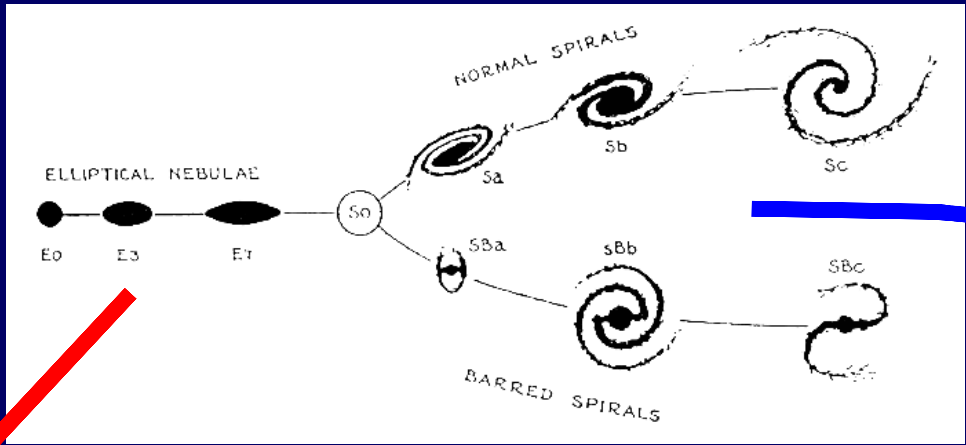
Conclusions

1. Disks are fed by cosmic-web cold streams: smooth + mergers
   - Interphase streams-disk: to be studied
   - Outflows and inflows live in harmony

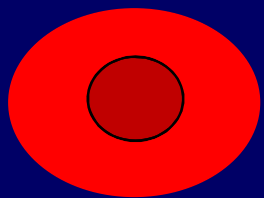
2. Violent disk instability (VDI): by intense gas in-streaming and high density
   - In-situ clumps and transient features, plus merged clumps
   - In-situ clumps are 70% in number and SFR but 45% in mass, younger higher sSFR (blue), lower Z, showing certain gradients due to migration
   - Steady mass loss by momentum-driven outflows from clumps, η~1-2
   - The clumps grow by accretion from the disk during migration, M~const.

3. VDI-driven inflow to disk center $\rightarrow$ classical compact bulge
   - Blue nuggets (and AGN) when the inflow is "wet", i.e. faster than SFR VDI and mergers.
     This is when Σ_{gas} is high, at high z and in galaxies of low spin or high mass
   - The nuggets are dispersion-dominated
   - Fast mode: bulge quenching to red nuggets by stellar/AGN feedback, maintained by halo heating.
   - Slow mode: dominated by halo quenching

The High-z "Hubble" Sequence

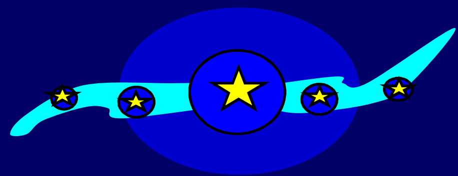


Red nuggets



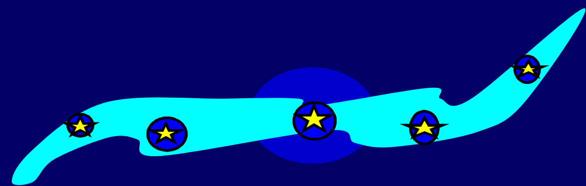
Compact ellipticals

Blue nuggets



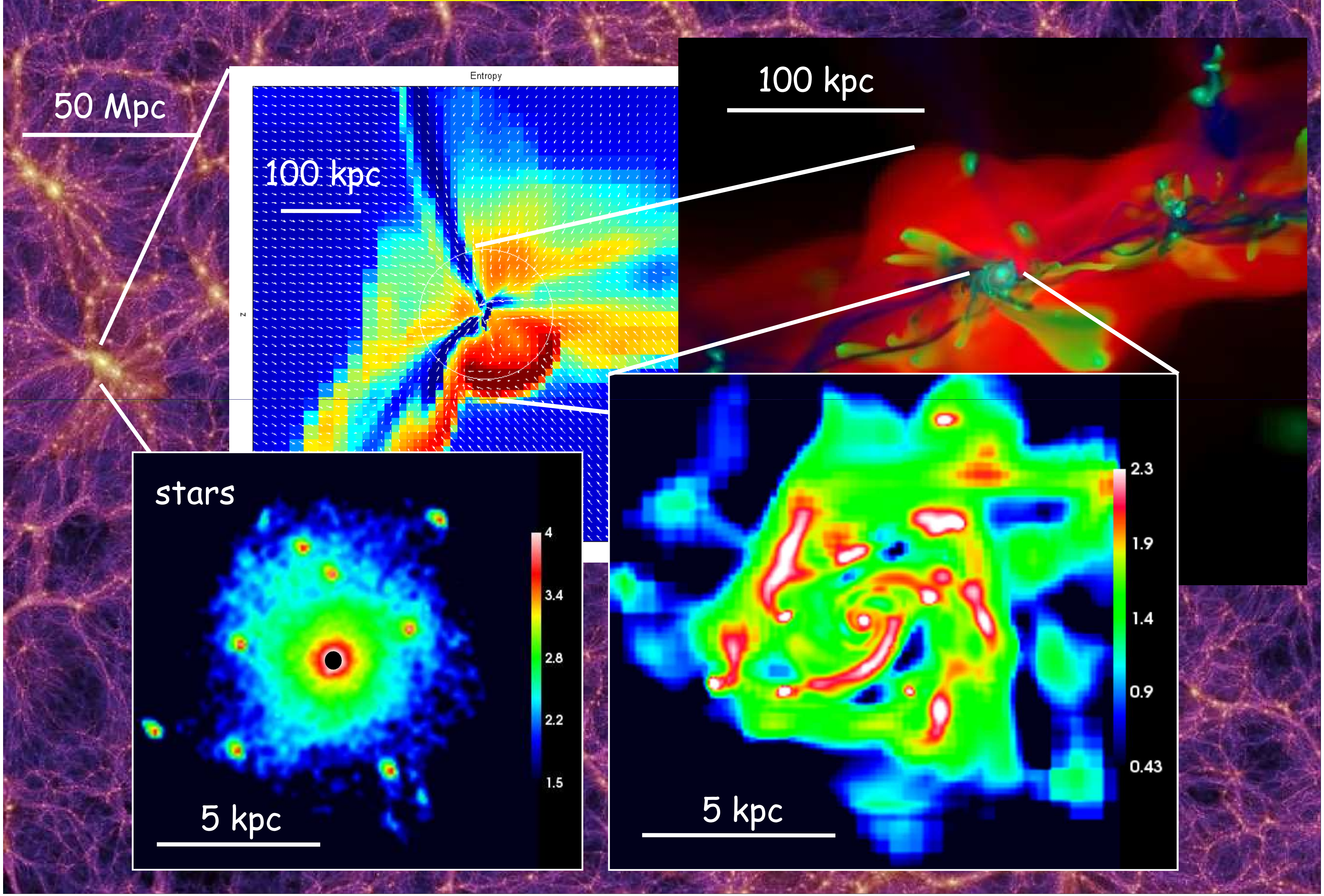
Starburst in a
compact bulge

Clumpy disks



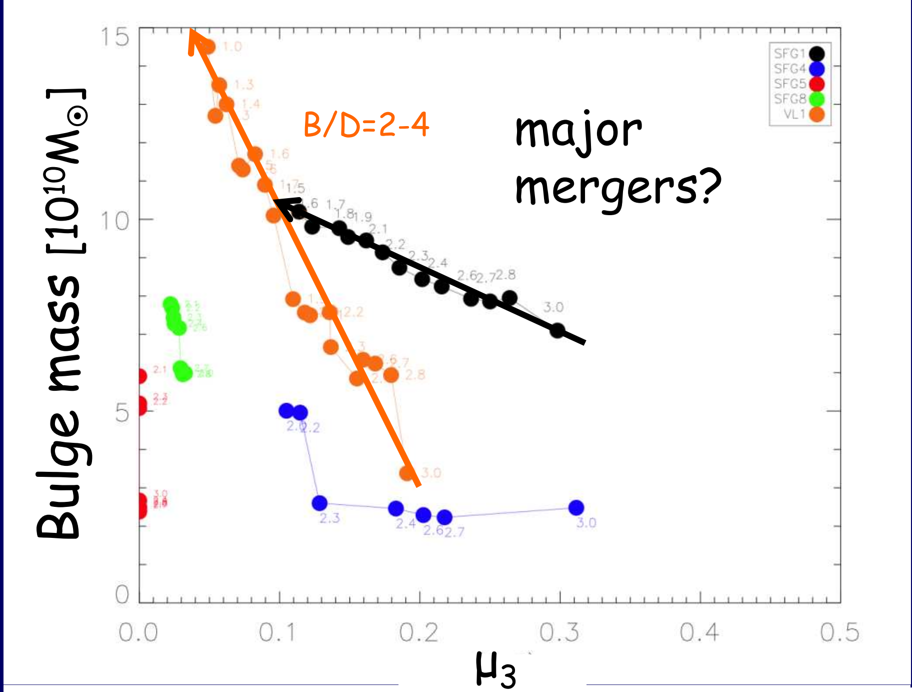
No bars
Perturbed spiral patterns

Cosmic Web, Cold Streams, Clumpy Disks & Spheroids

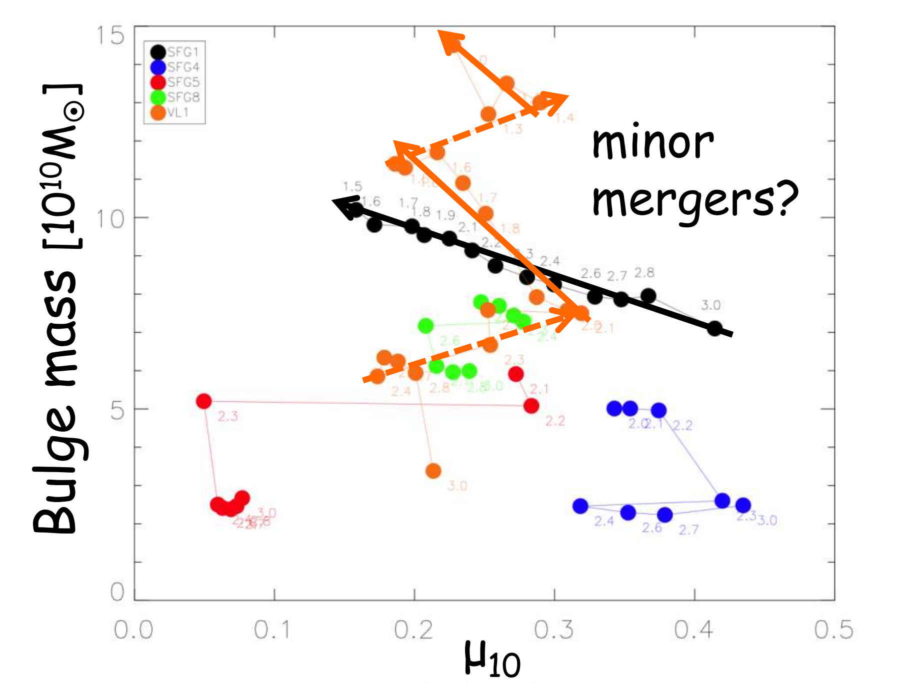


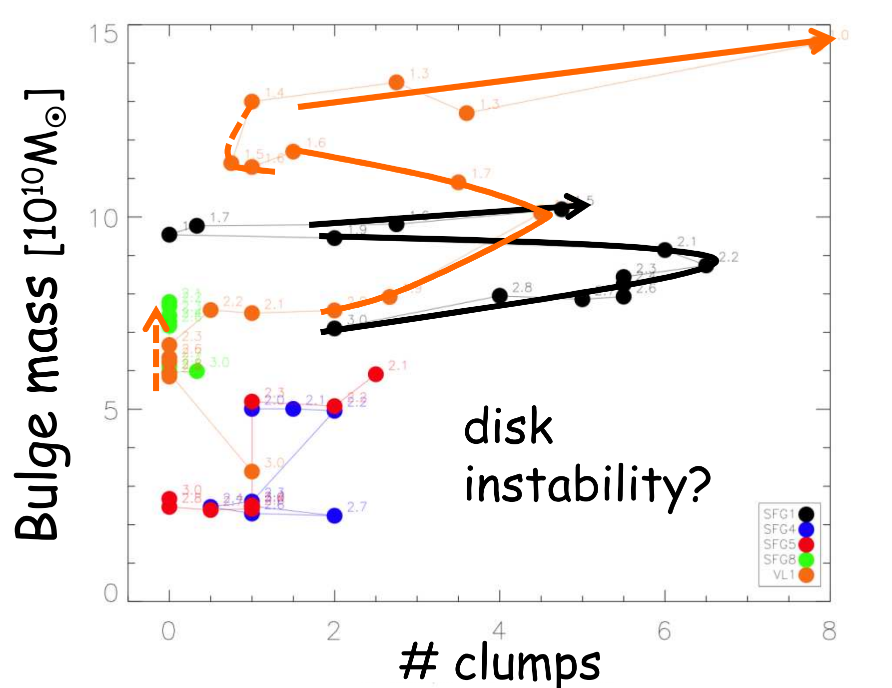
Bulge growth by mergers versus disk instability

Tweed, Zolotov



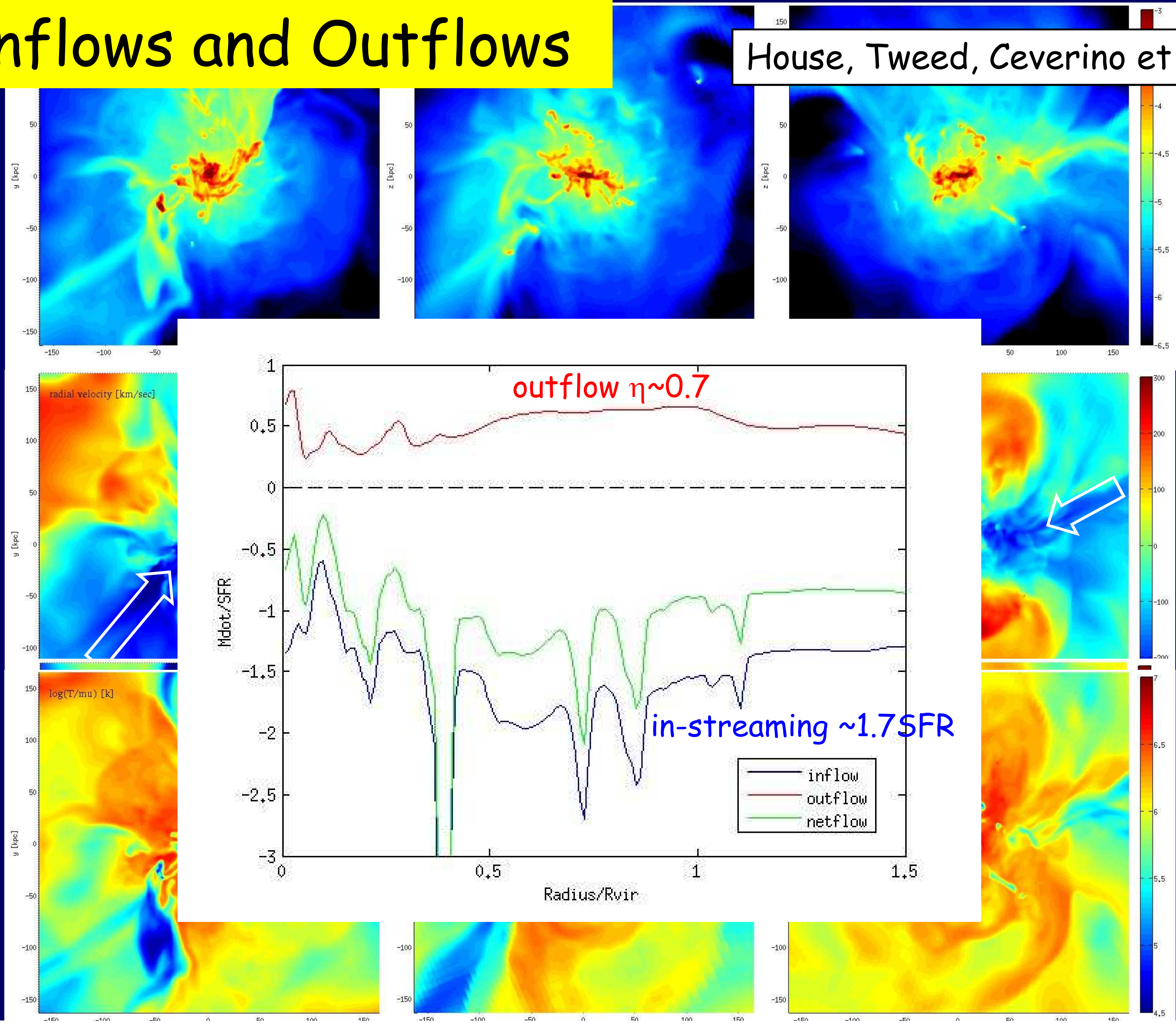
μ_m = fraction of mass added in mergers of 1:m





Inflows and Outflows

House, Tweed, Ceverino et al.



Outflow and Inflows