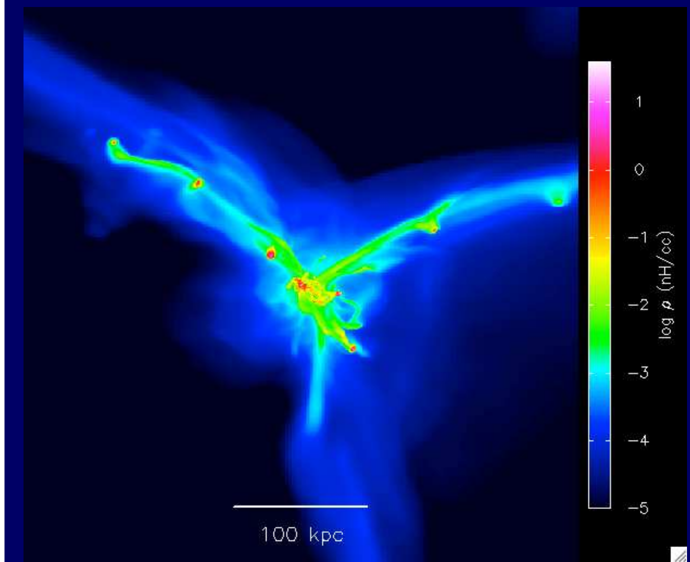
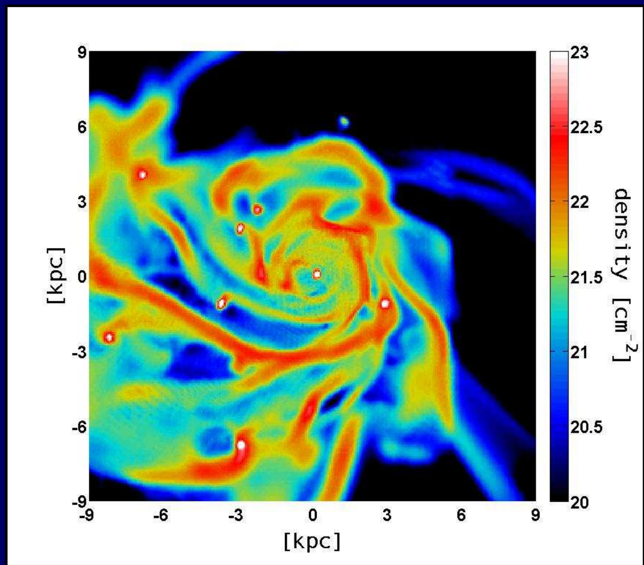
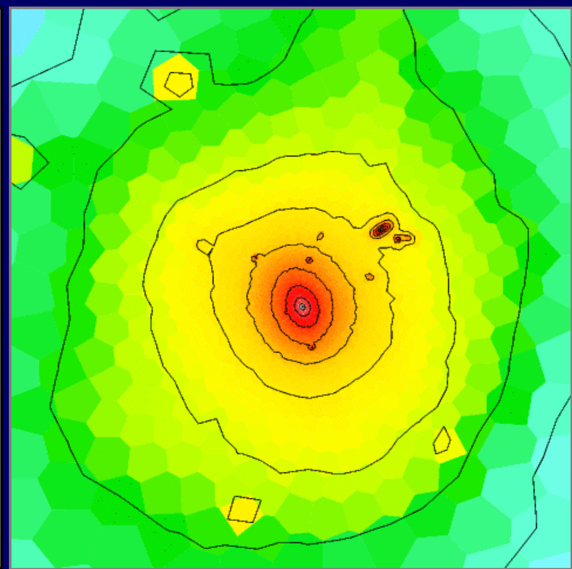
# High-z Galaxy Evolution: VDI and (mostly minor) Mergers

Avishai Dekel
The Hebrew University of Jerusalem

UCSC, August 2012



# Outline:
# in-situ (VDI) and ex-situ (mergers)

1. Cold streams: smooth and clumpy

2. Disk-clumps: in-situ and ex-situ

3. Blue Nuggets and BH by wet inflows

4. Two-zone kinematics

# AMR Cosmological Simulations

Zoom-in individual galaxies: 30 sims ~50pc resolution
HART (Kravtsov, Klypin) : Ceverino, Dekel, Primack, …

RAMSES (Teyssier): Tweed, Dekel,
Bournaud (isolated, ~1pc res)

HUJI:
Daniel Ceverino, Tobias Goerdt, Loren Hoffman,
Nir Mandelker, Dylan Tweed, Joanna Woo, Adi Zolotov

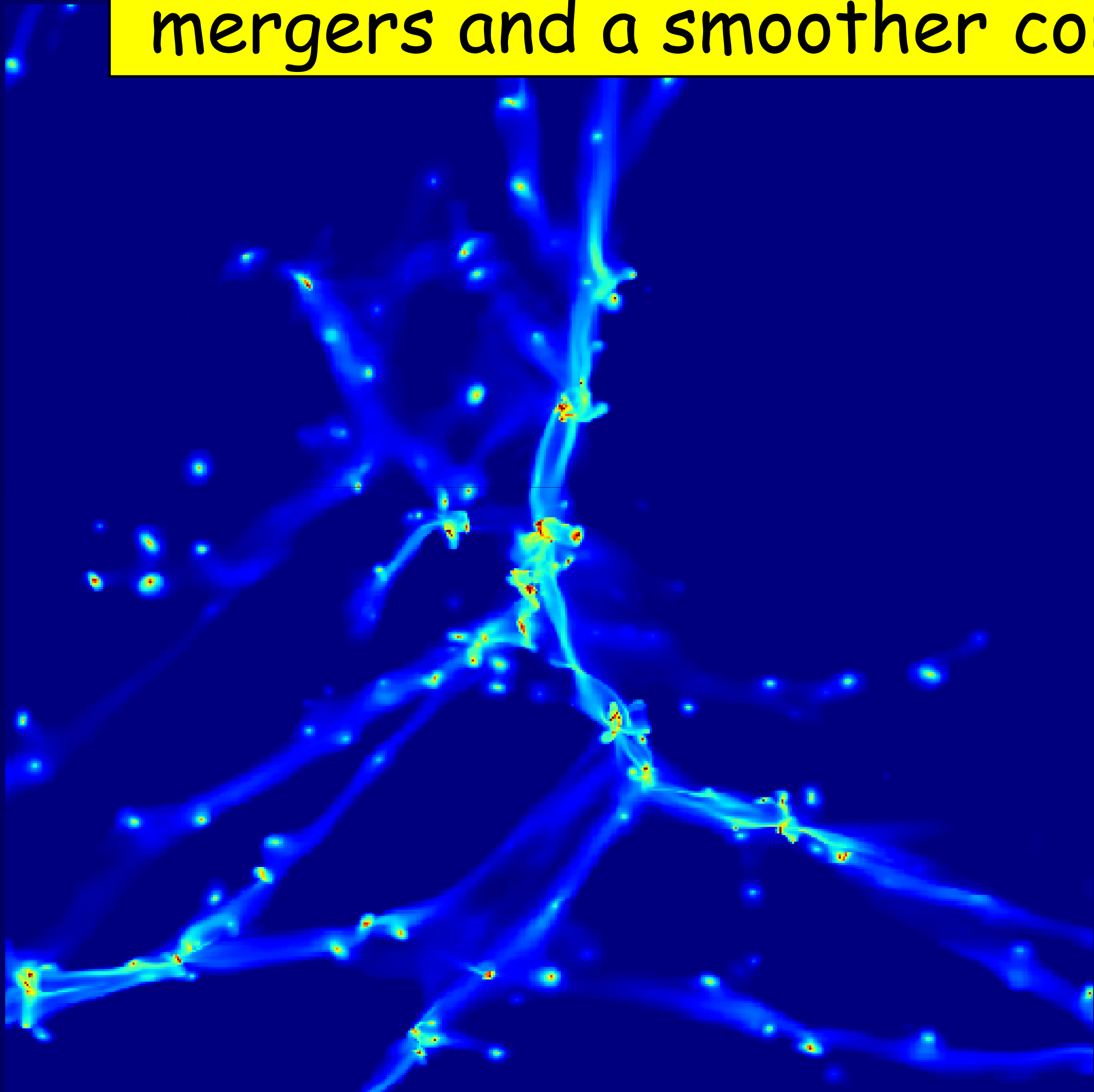
UCSC:
Michele Fumagalli, John Forbes, Chris Moody,
Mark Mozena, Loren Porter, the CANDELS team

# 1. Cold Streams: Smooth and Clumpy

Dekel et al. 2009
Fumagalli et al. 2011
Danovich, Dekel, Hahn, Teyssier 2012

Tweed, Ceverino, Goerdt, Mandelker…

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



AMR RAMSES
Teyssier, Dekel

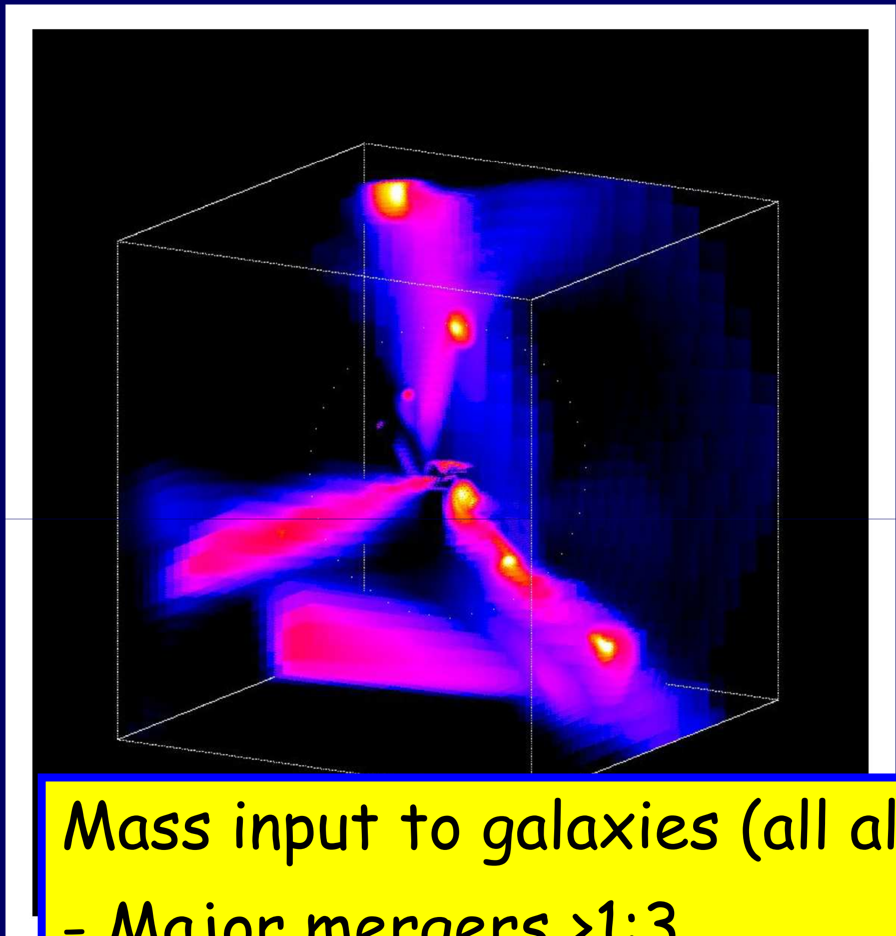
box 300 kpc

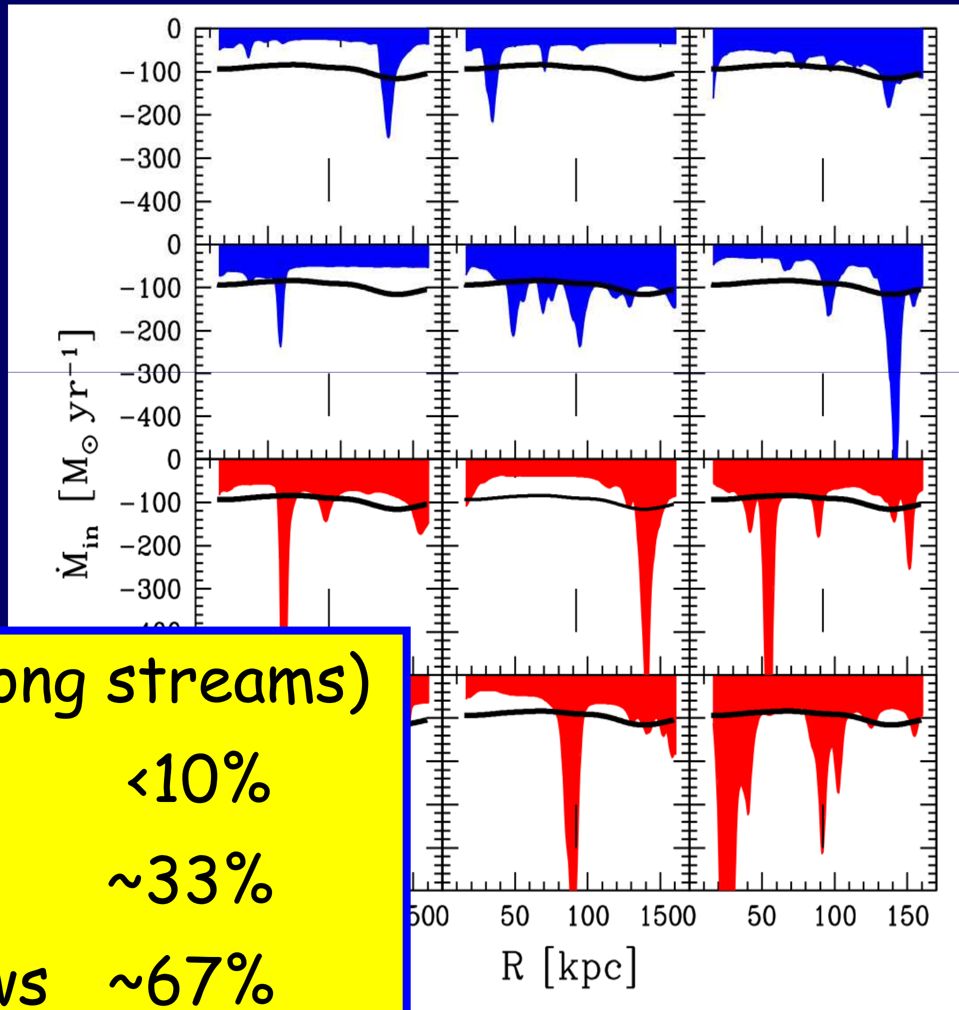
res 30 pc

z = 5.0 to 2.5

# Stream Clumpiness - Mergers

Dekel, Teyssier et al 09;
MareNostrum RAMSES sims 1kpc res



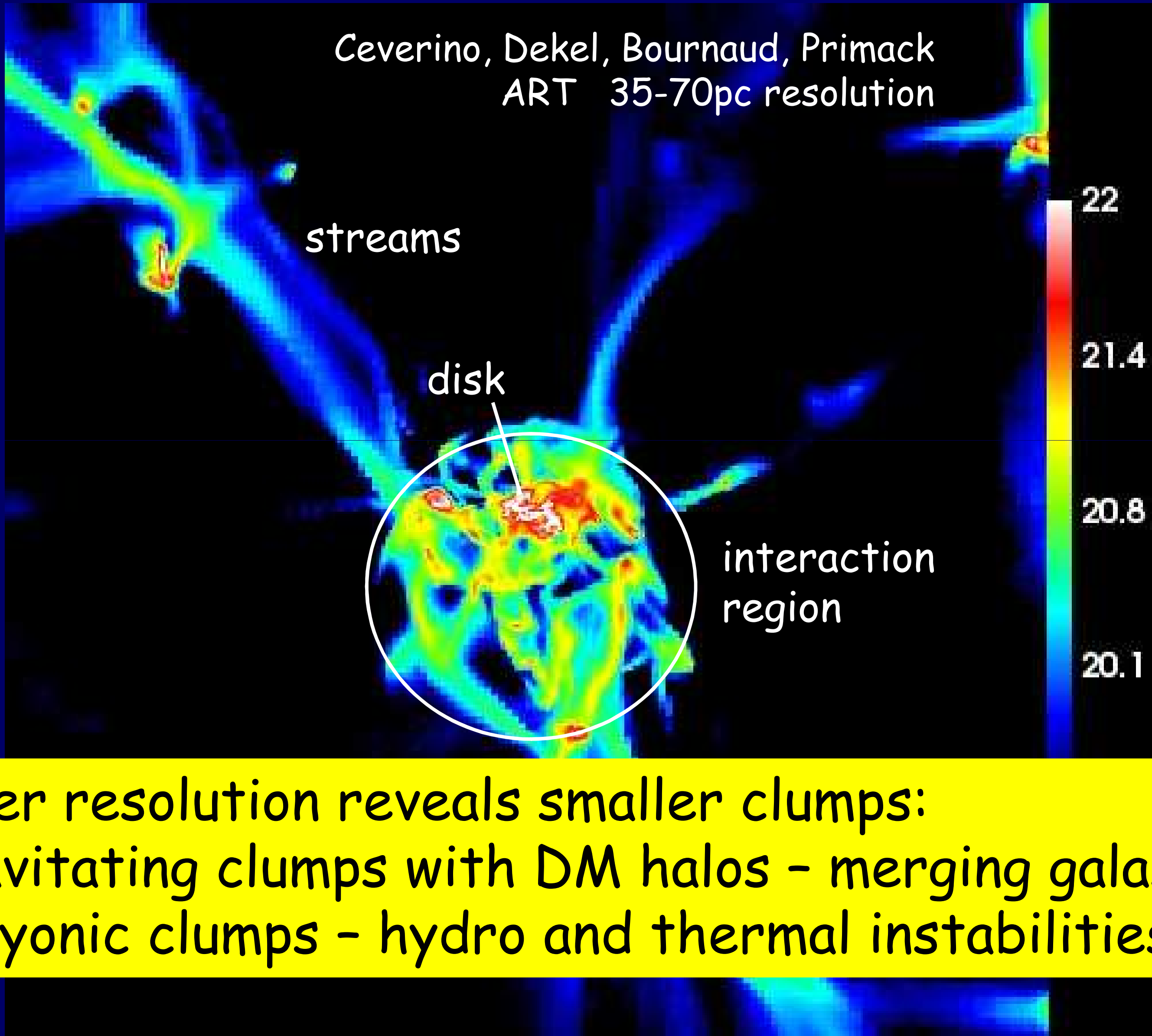



Mass input to galaxies (all along streams)

- Major mergers >1:3 <10%
- Major+minor mergers >1:10 ~33%
- Miniminors and smooth flows ~67%

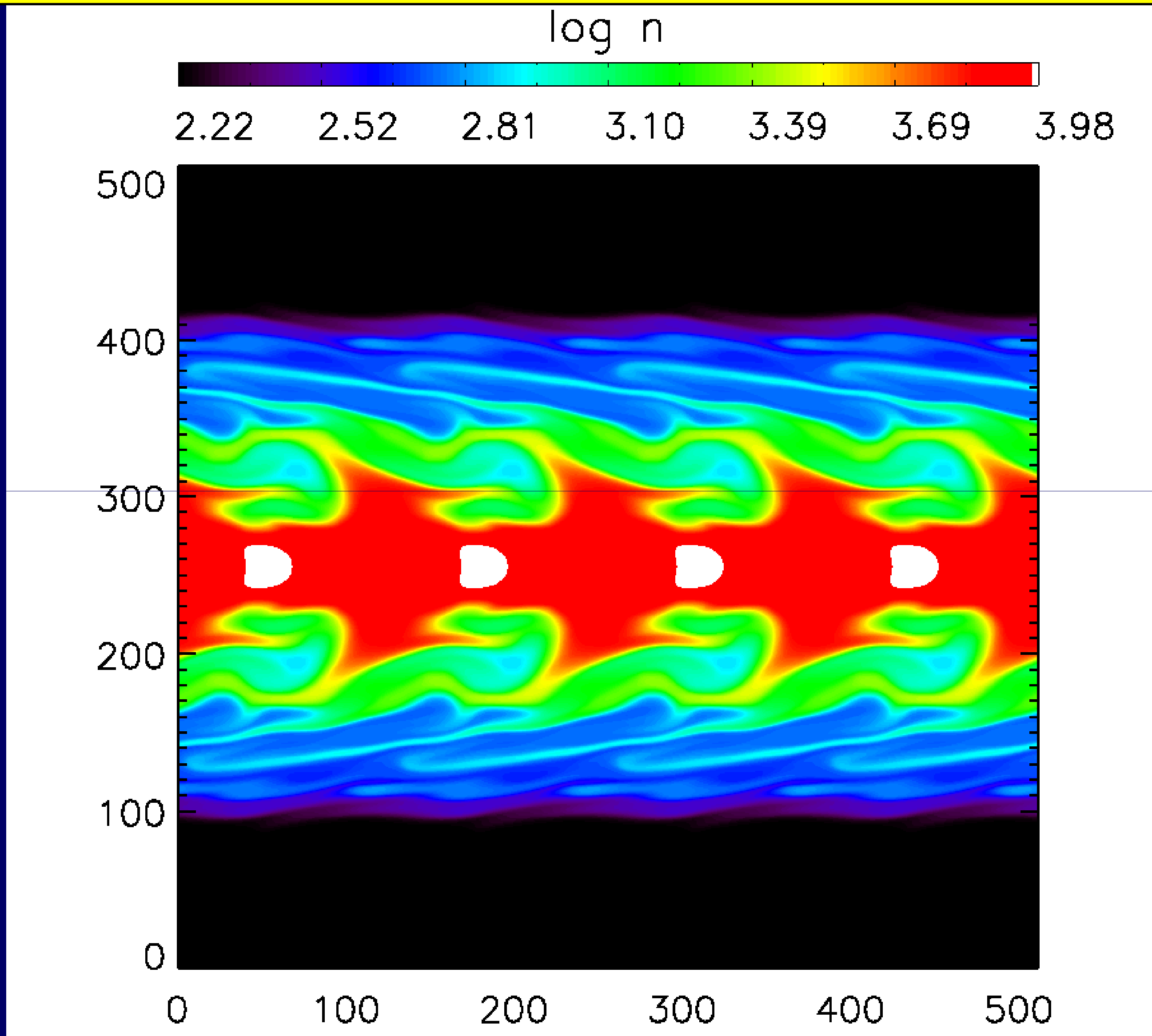
$M=10^{12}M_\odot$ $z=2.5$

# Streams Break Up - the "Messy" Region



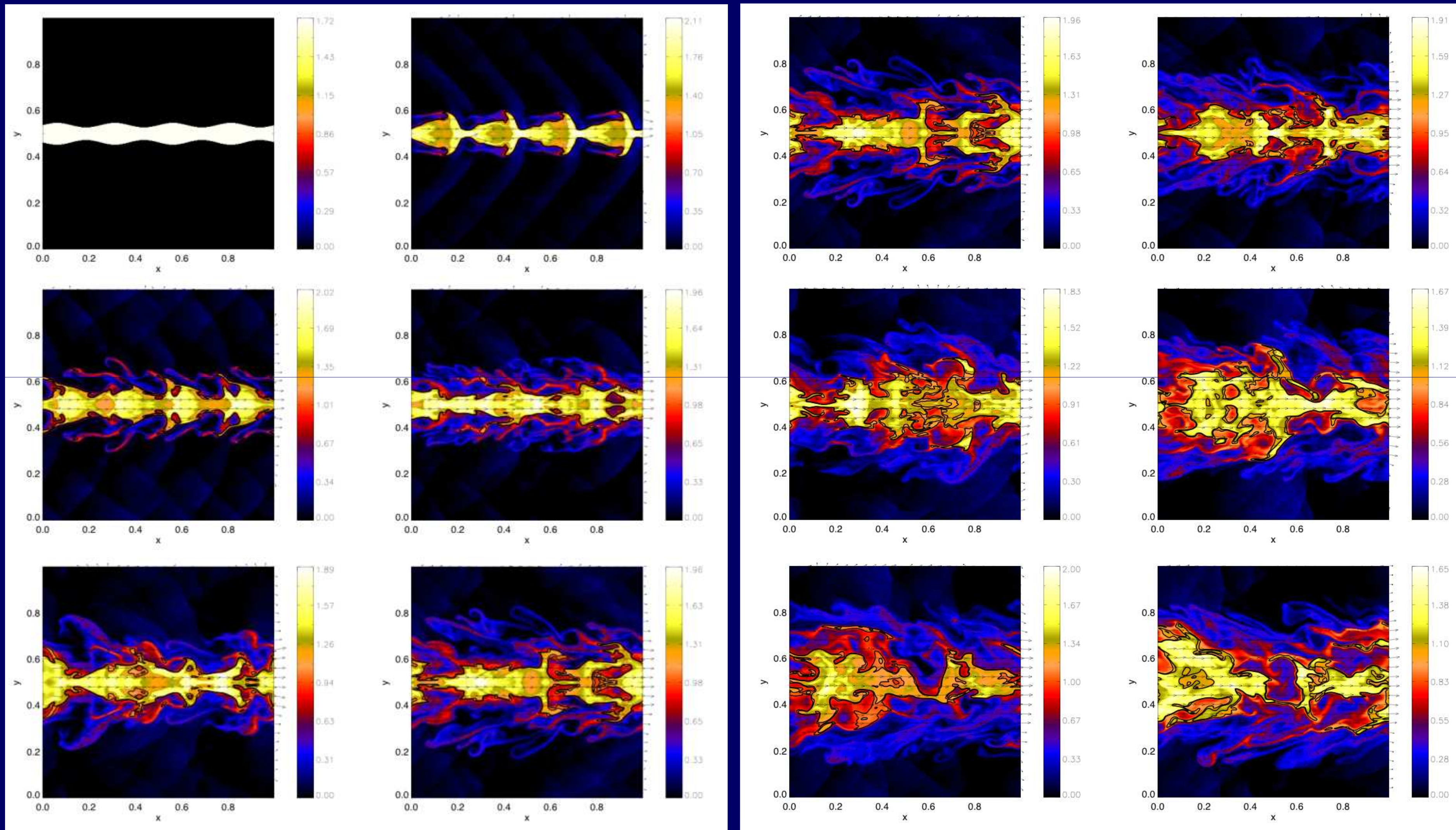

Higher resolution reveals smaller clumps:
- Gravitating clumps with DM halos – merging galaxies
- Baryonic clumps – hydro and thermal instabilities (?)

# Supersonic cold stream in a hot medium (2D)

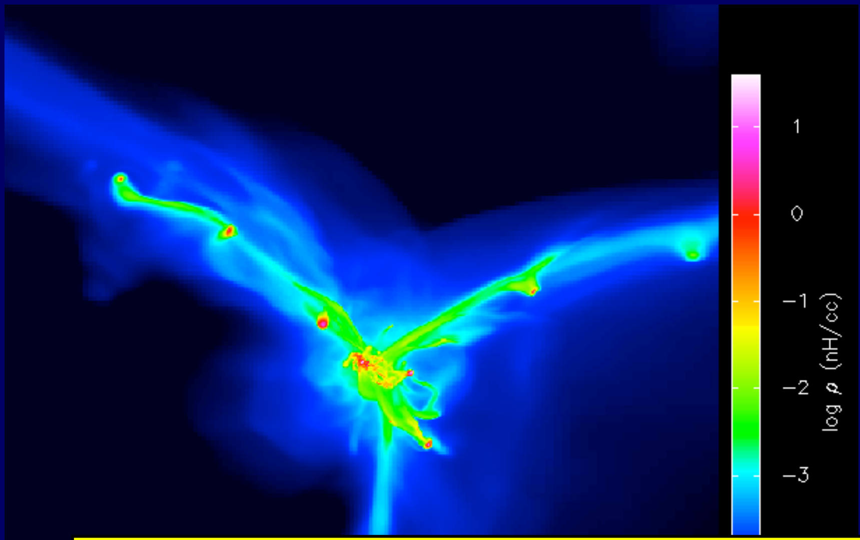



Burkert, Ntormousi, Forbes, Dekel, Birnboim...

# Supersonic cold stream in a hot medium (2D)



Burkert, Ntormousi, Forbes, Dekel, Birnboim...

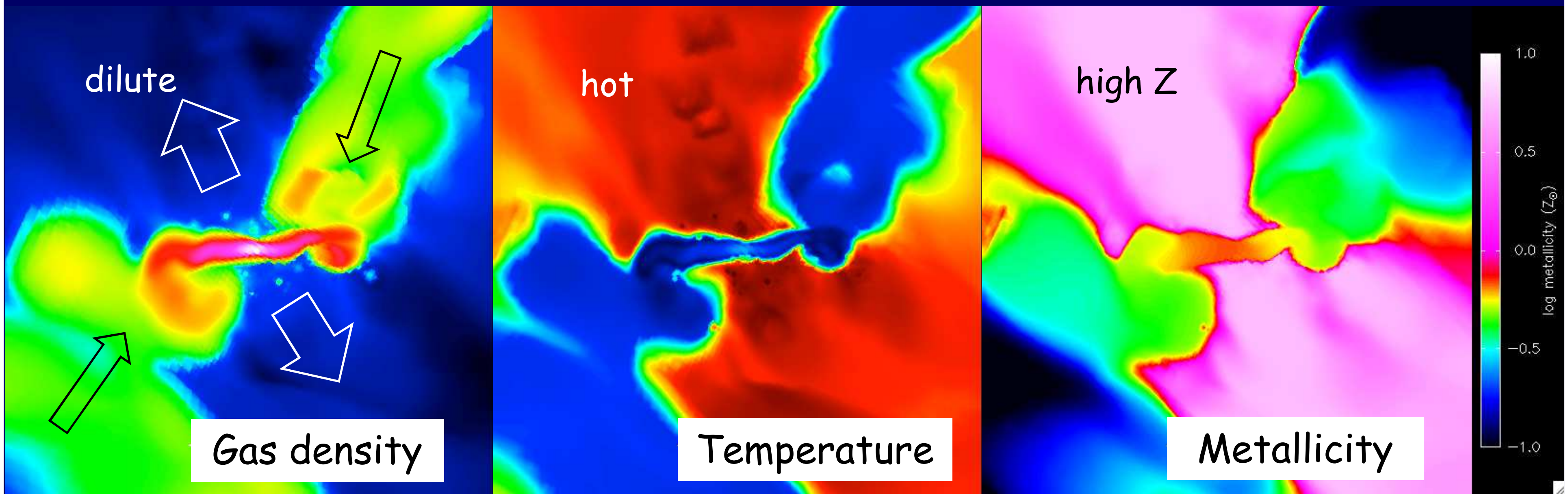



# Inflows & Outflows

Tweed, Dekel, Teyssier

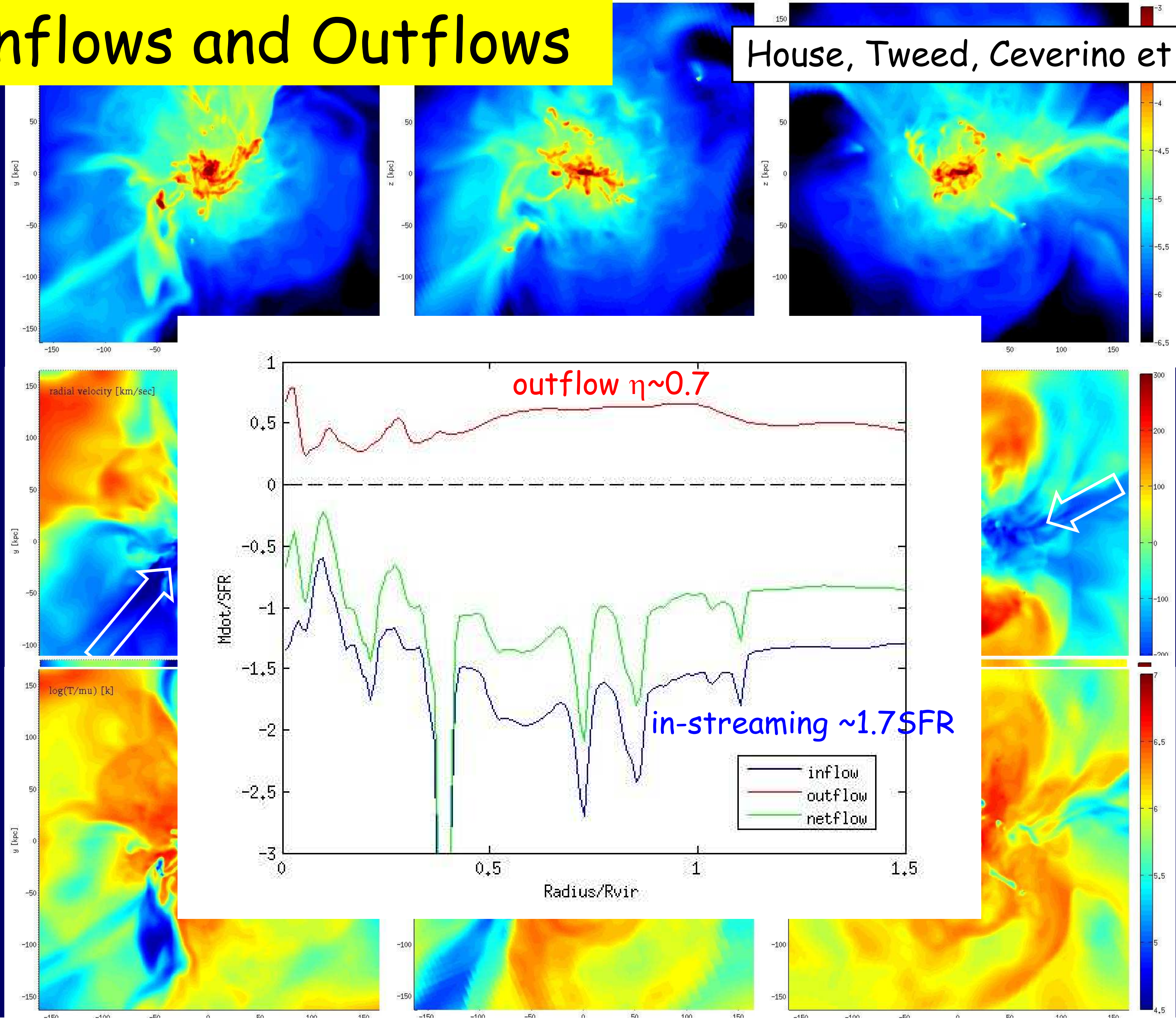
RAMSES 70-pc resolution

Outflows find their way out through the dilute medium
no noticeable effect on the dense cold rapid inflows



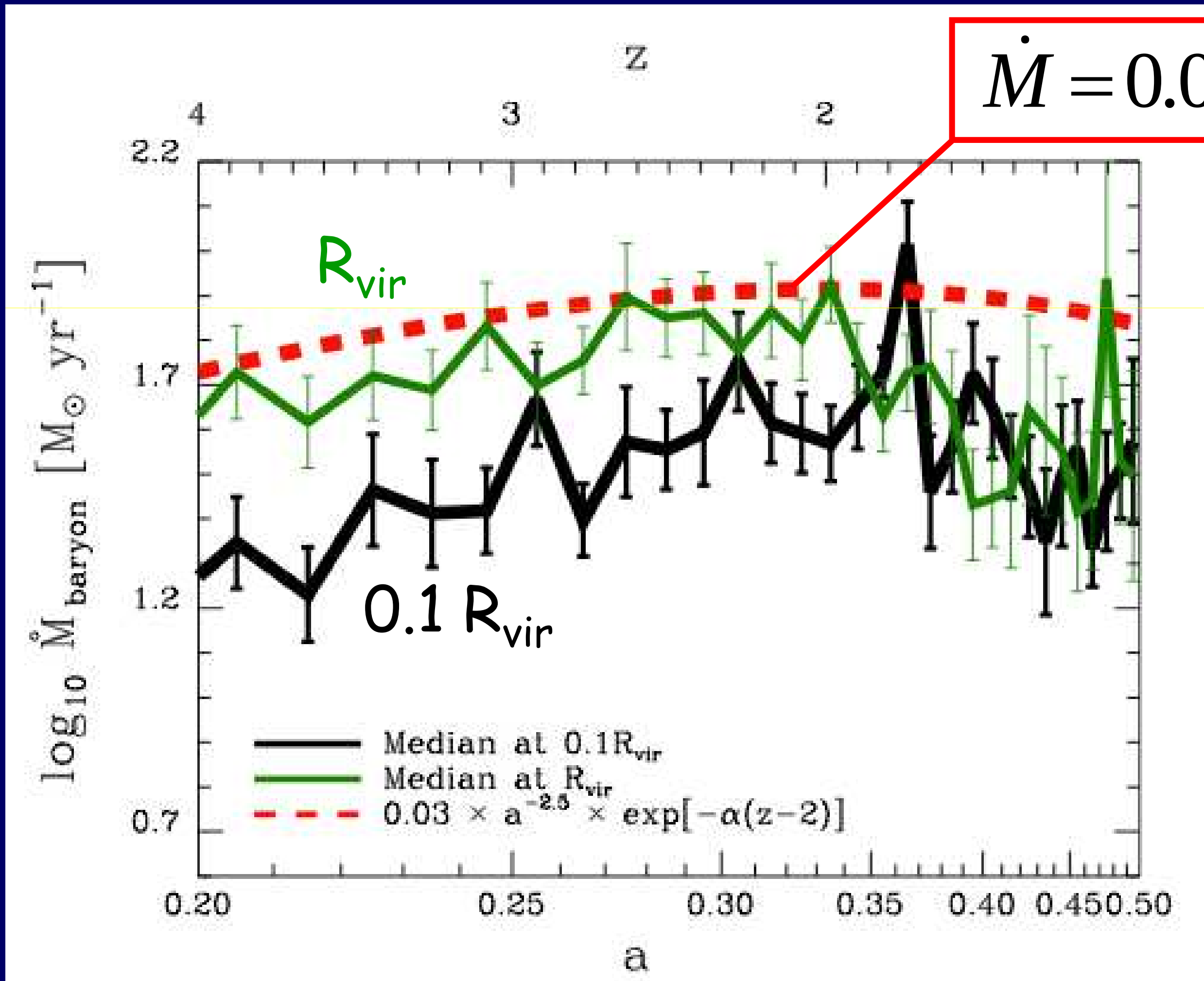
# Inflows and Outflows

House, Tweed, Ceverino et al.



# Baryon Penetration to the Disk: ~50%

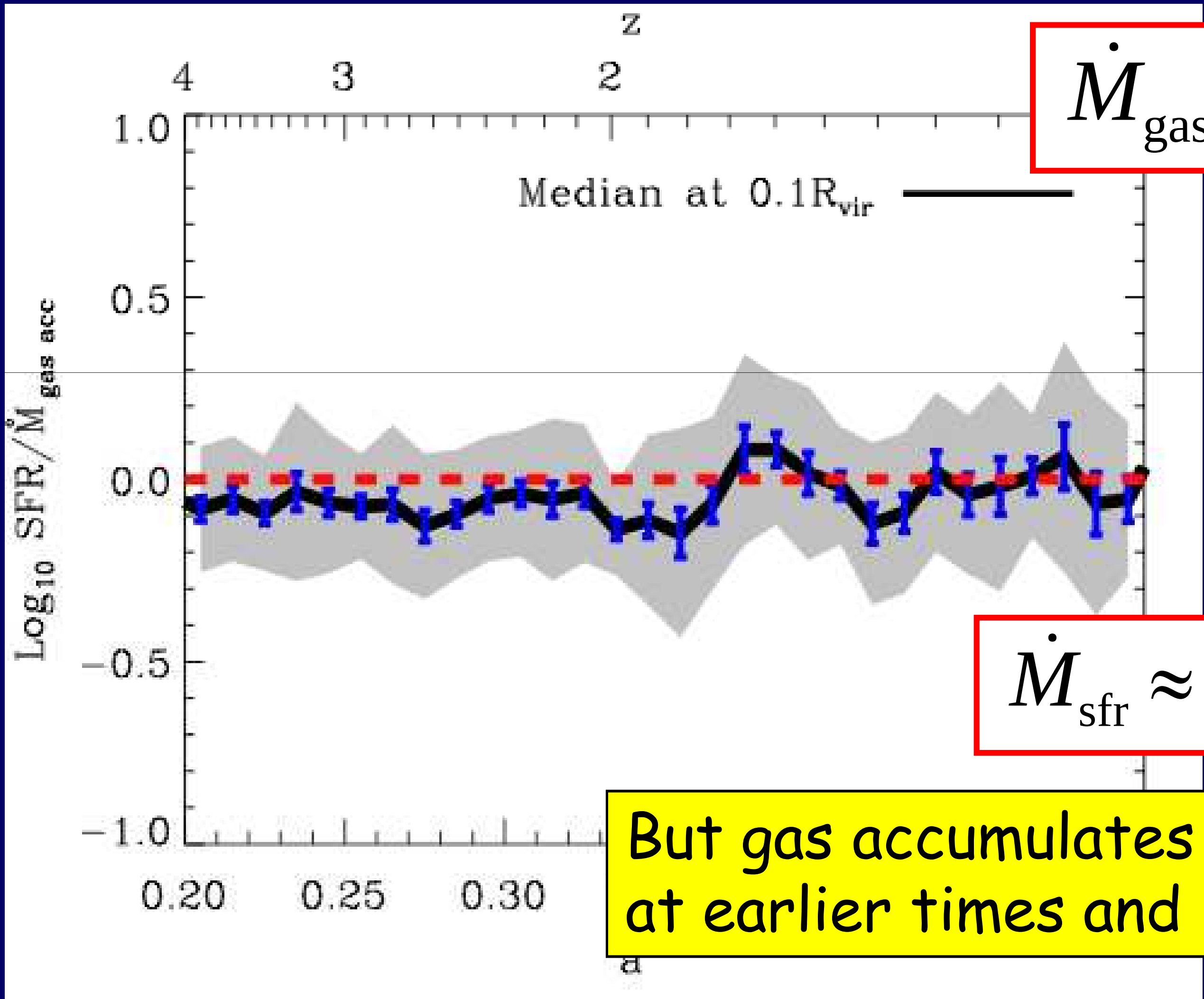
Toy models versus simulations:
Dekel, Zolotov, Tweed, Cacciato, Ceverino, Primack
HART 30 simulations 35-70pc res




$$\dot{M} = 0.03\,Gyr^{-1} M\,(1+z)^{5/2}$$

$$M = M_0 e^{-0.8(z-z_0)}$$

# Steady State: SFR ~ accretion rate into the disk




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

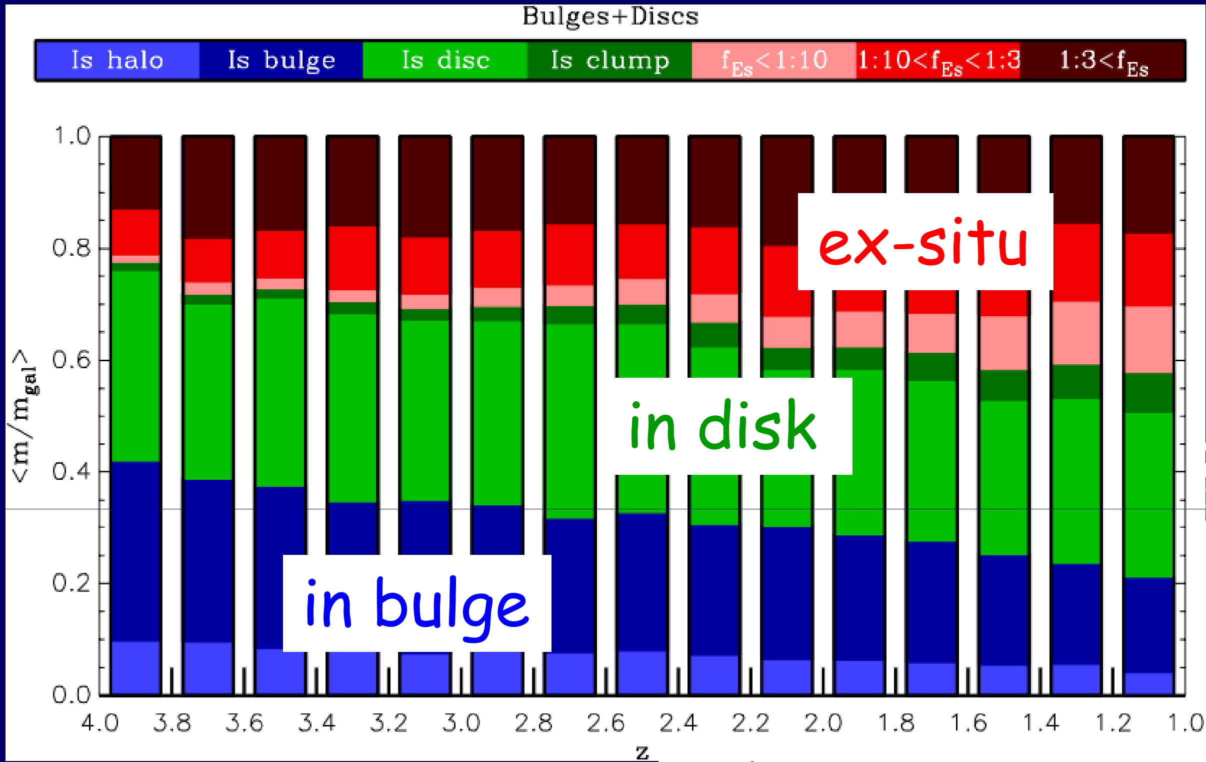
$$\dot{M}_{sfr} = \frac{M_{gas}}{\tau_{sfr}}$$

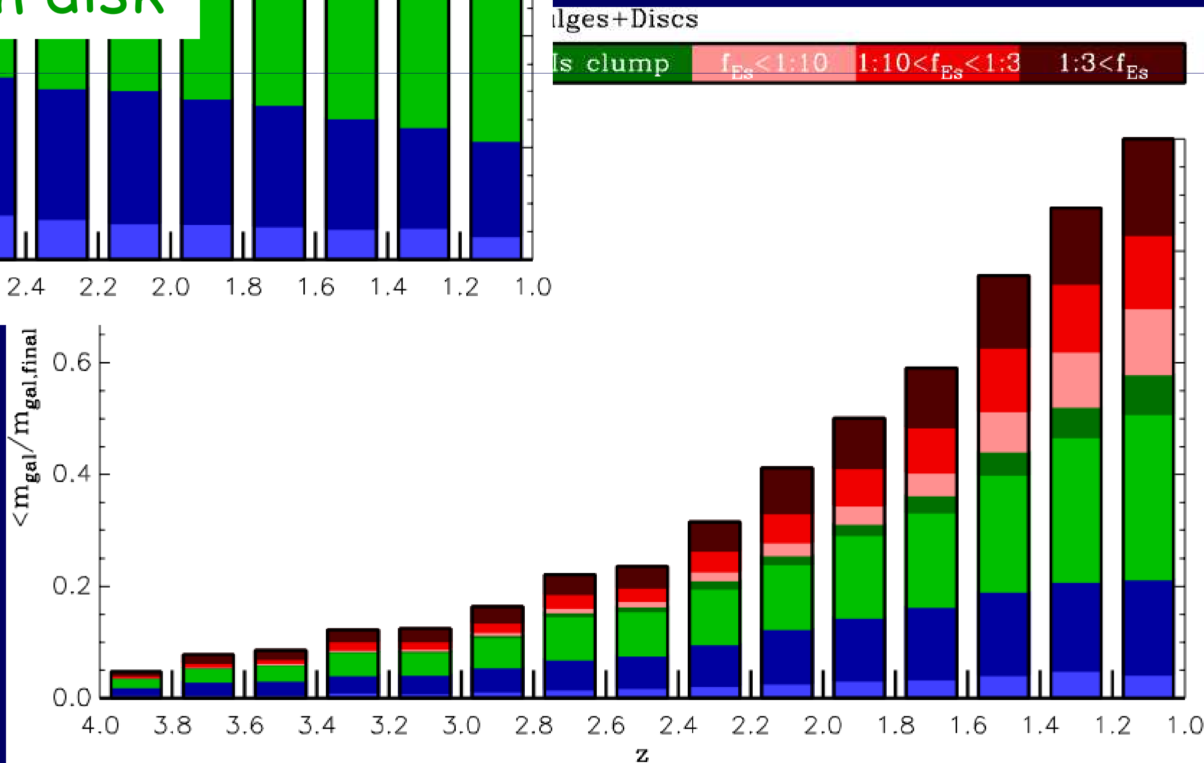
$$\dot{M}_{sfr} \approx \dot{M}_{gas,acc} \quad \dot{M}_{gas} \approx 0$$

But gas accumulates in disks
at earlier times and in smaller masses

# In-situ vs Ex-situ Star Formation

Tweed, Zolotov, …



# 2. Disk-clumps: in-situ (VDI) and ex-situ (mergers)

Ceverino et al 2010, 2011

Mandelker, Tweed, …

Mozena, Moody, …

# Violent Disk Instability (VDI)

High gas density → disk unstable

Giant clumps and transient features: processes on dynamical timescales

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

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

Noguchi 99

Immeli et al. 04

Bournaud, Elmegreen, Elmegreen 06, 08

In cosmology:

Dekel, Sari, Ceverino 09

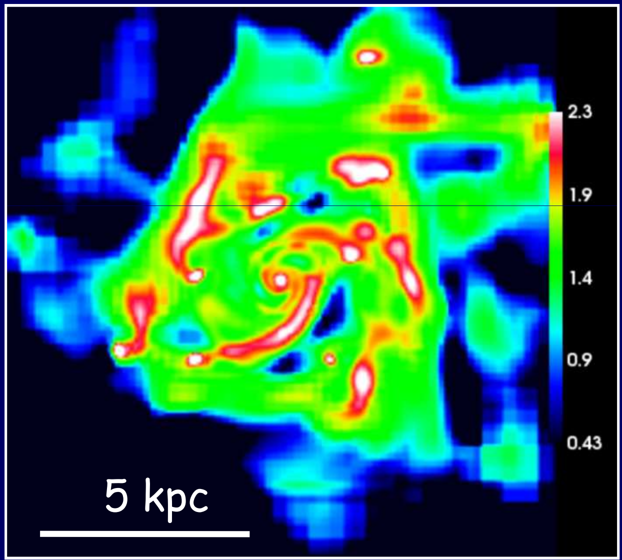
Agertz et al. 09

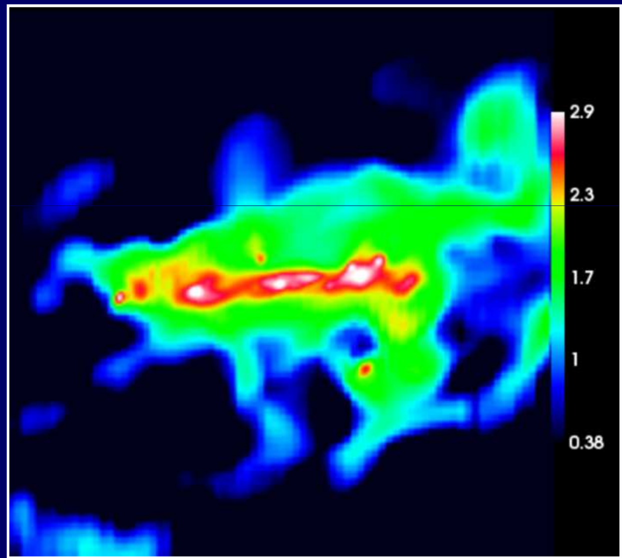
Ceverino, Dekel, Bournaud 10

Ceverino et al. 11

Cacciato et al. 11

Krumholz, Forbes et al. 12



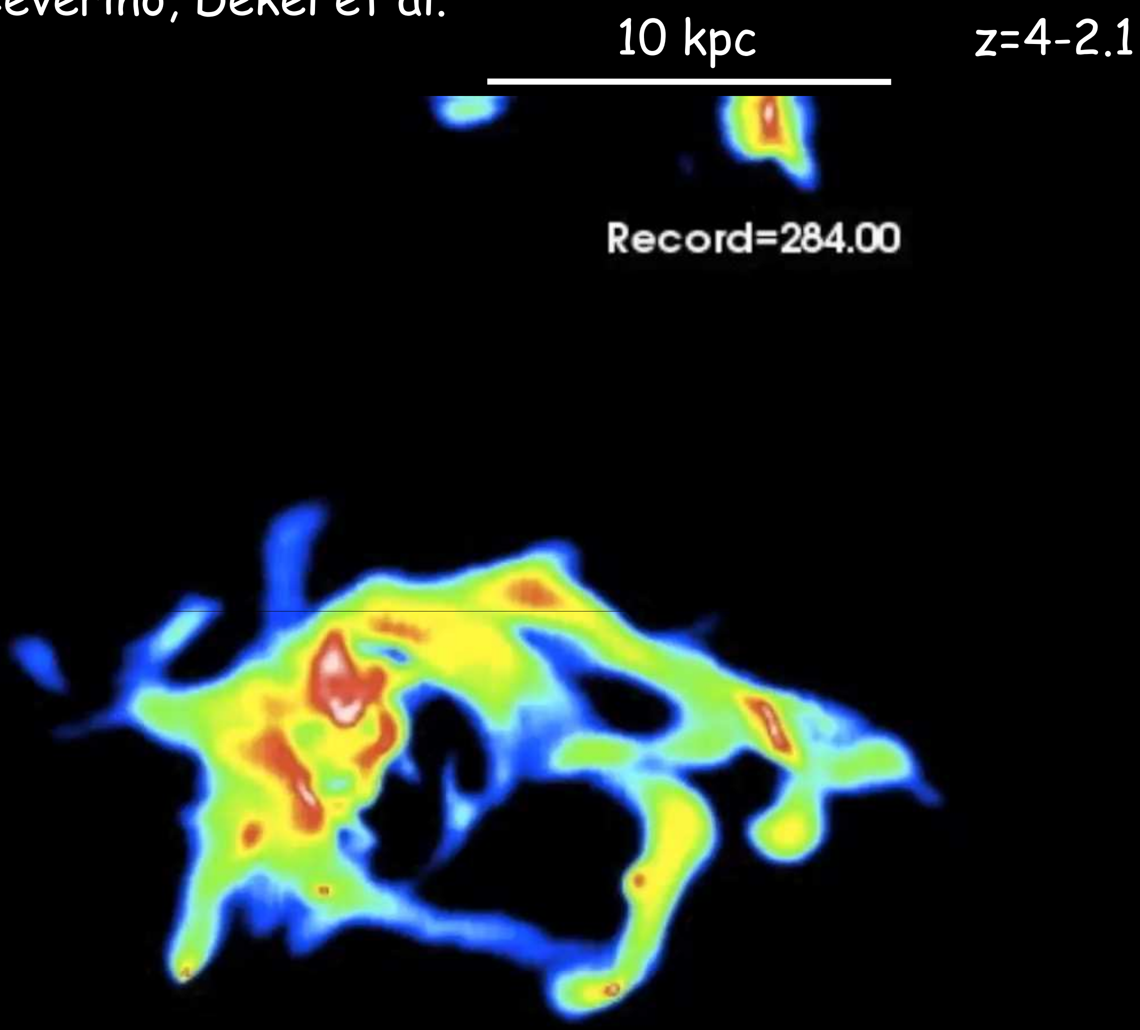

Self-regulated at Q~1 by torques → high σ/V~1/4

Torques induce inflow → formation of a compact bulge and BH

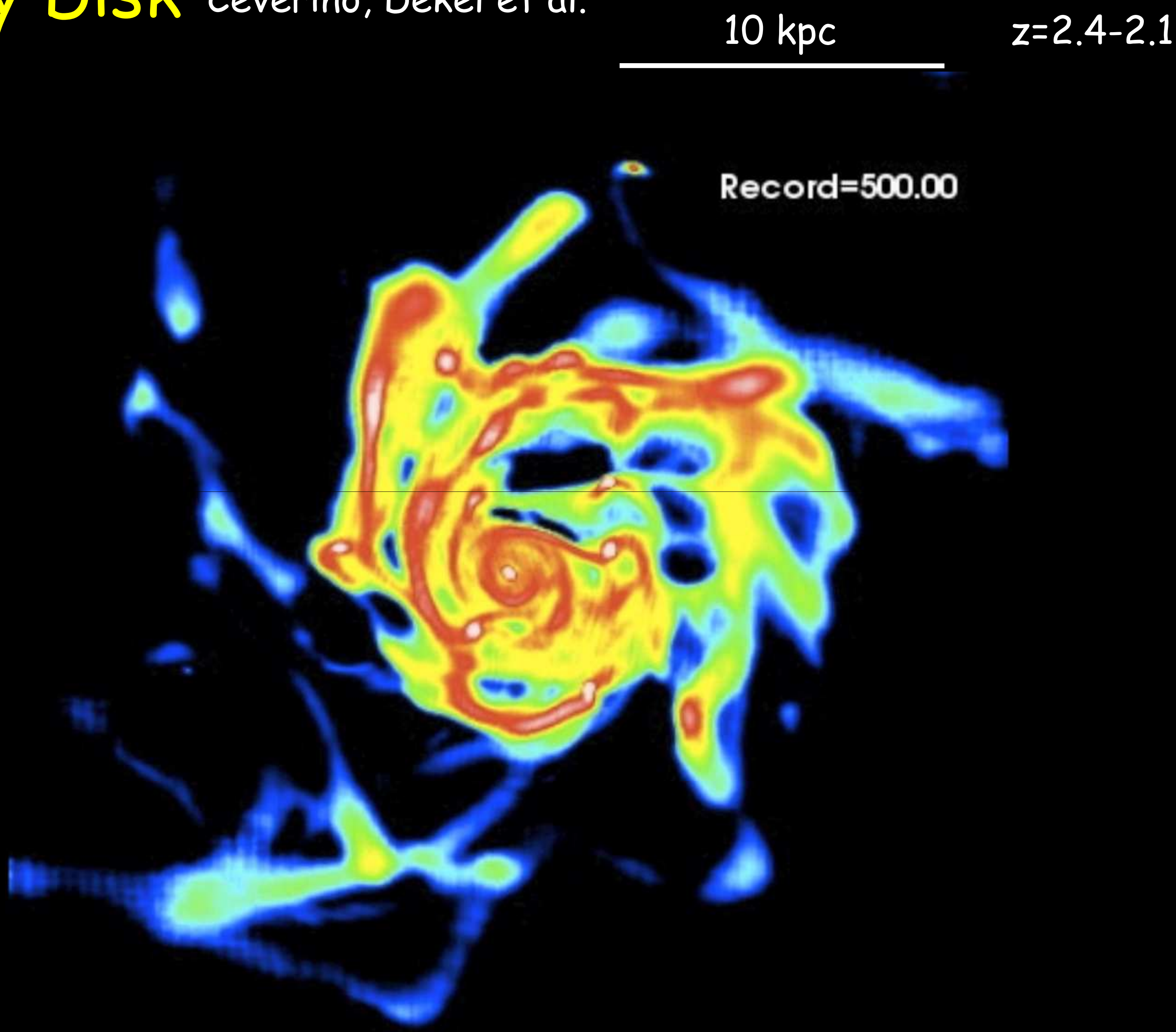
Cosmological steady state: disk draining and replenishment, bulge ~ disk

Star formation and feedback in clumps

# Clumpy Disk Ceverino, Dekel et al.



# Clumpy Disk Ceverino, Dekel et al.



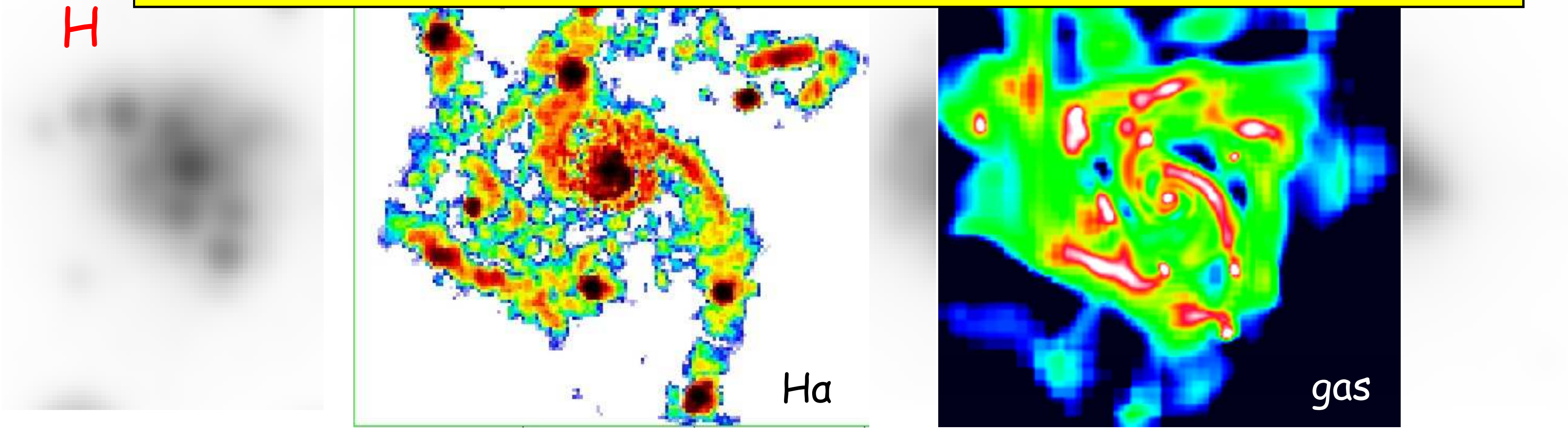
# Stellar images of z~2 simulated disks "observed" with HST bands and PSF

Mozena, Moody, Mendelker, Ceverino, et al. - CANDELS

B

Needed: a new morphological classification scheme for high-z galaxies, emphasizing the in-situ clumpy disks

H



# Disk Clump Classification

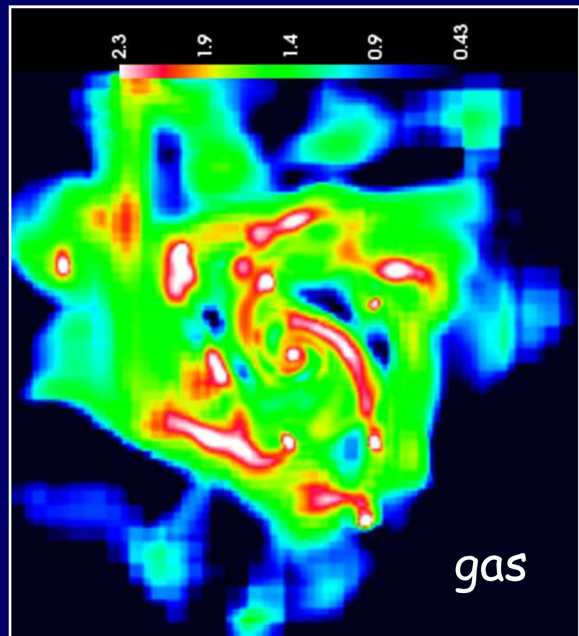
Mandelker et al. 2012

bulge - off-center
>0.9 2 per galaxy

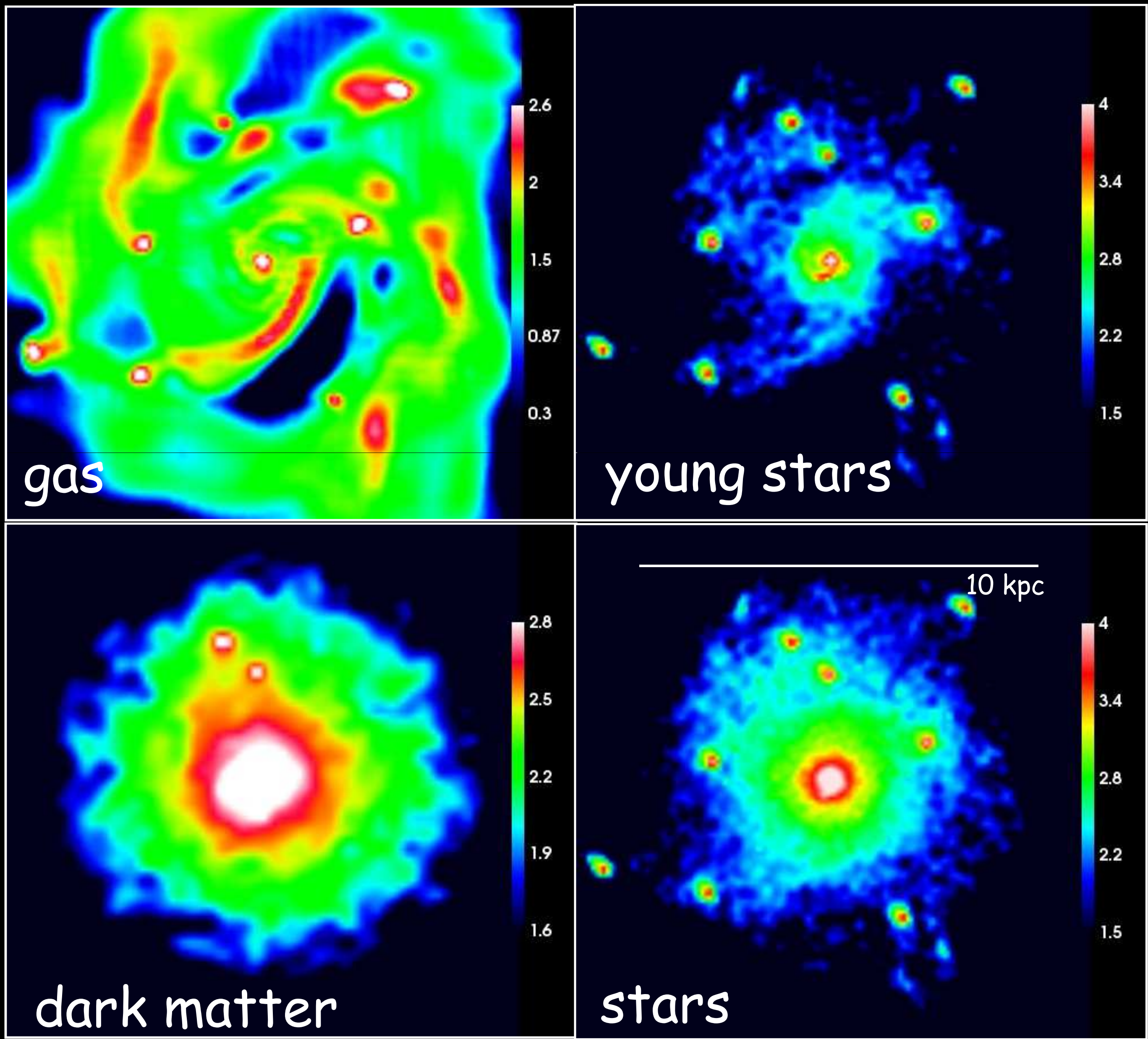
compact, round - diffuse, elongated
90% of mass

| | in-situ | ex-situ |
|---|---|---|
| # | 70% | 30% |
| mass | 45% | 55% |
| SFR | 75% | 25% |

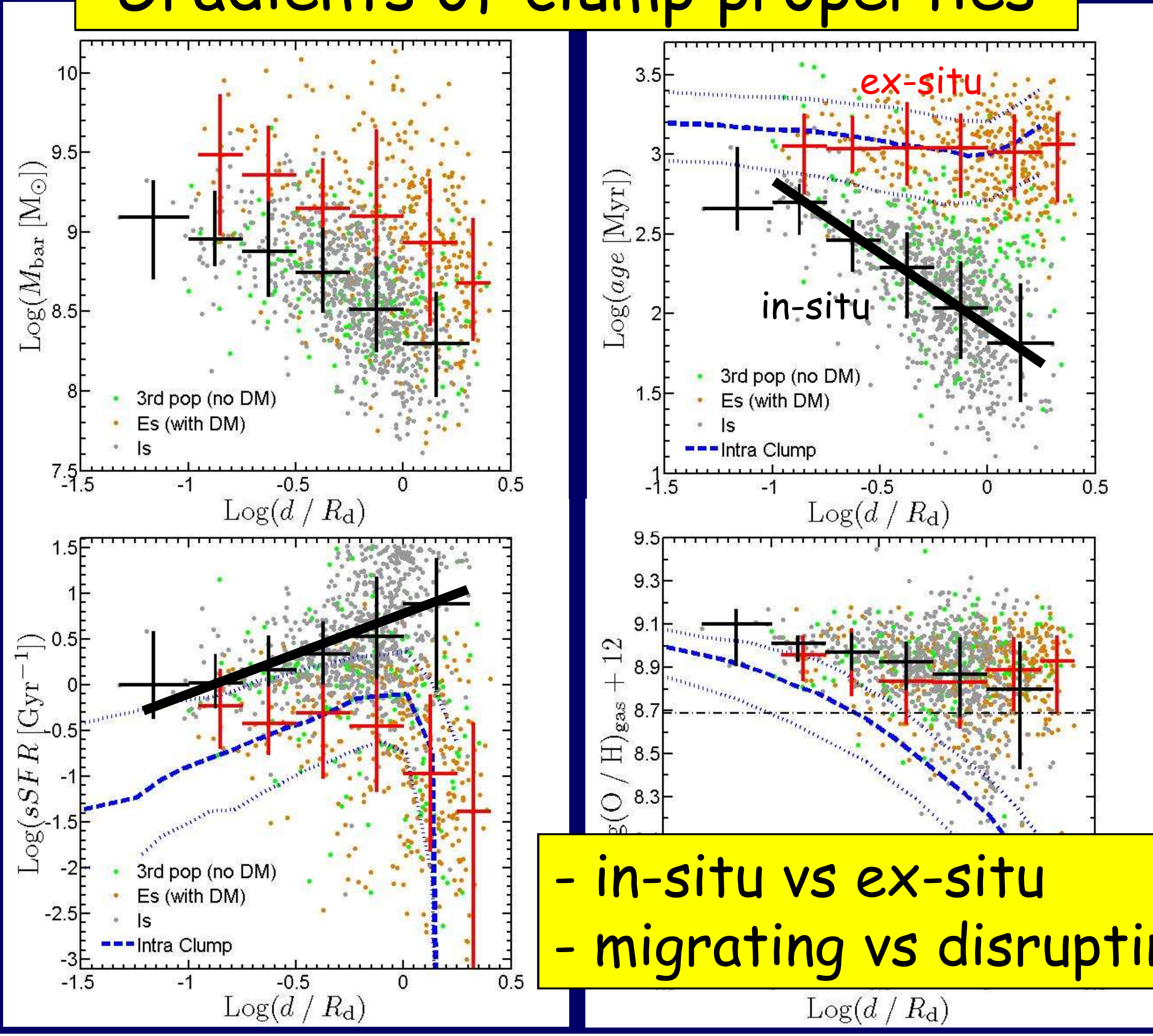
rotating - non-rotating
2/3 1/3



# Bulge mass ~ Disk mass



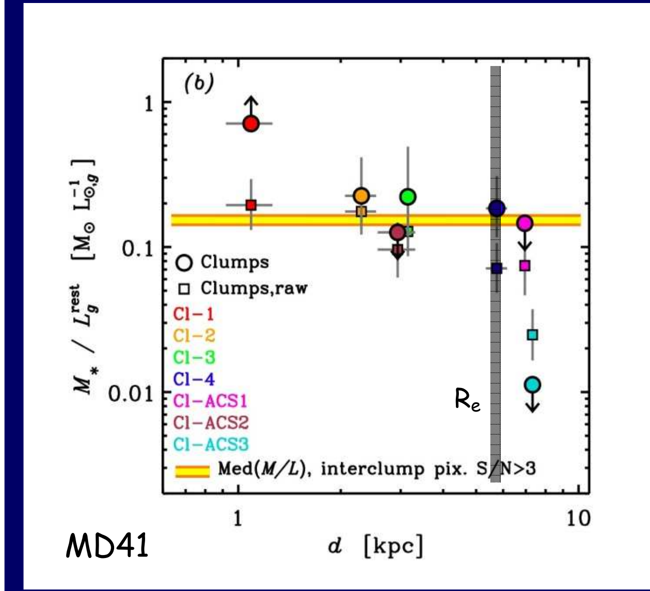
# Gradients of clump properties

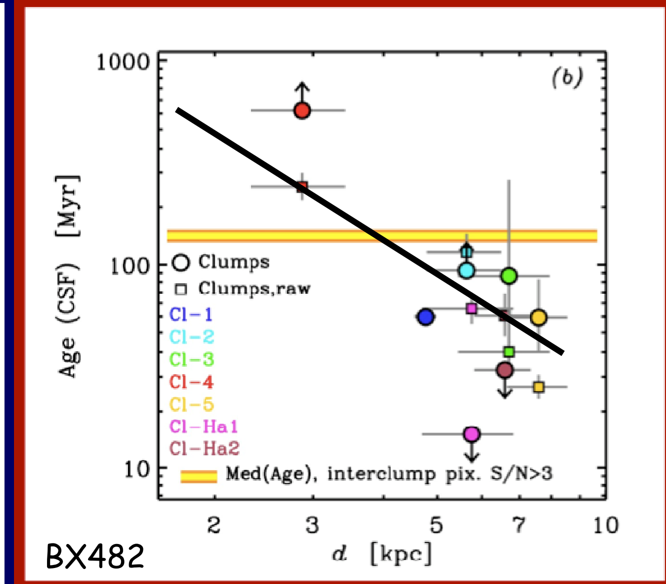



- in-situ vs ex-situ
- migrating vs disrupting

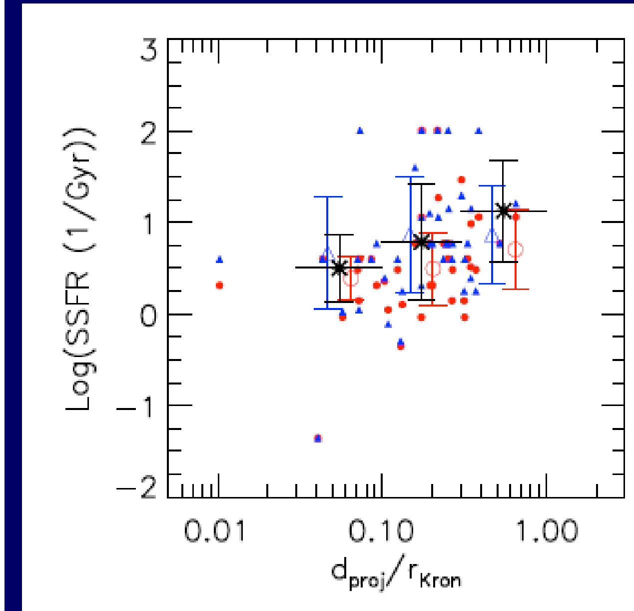
# Observational indications for clump survival?

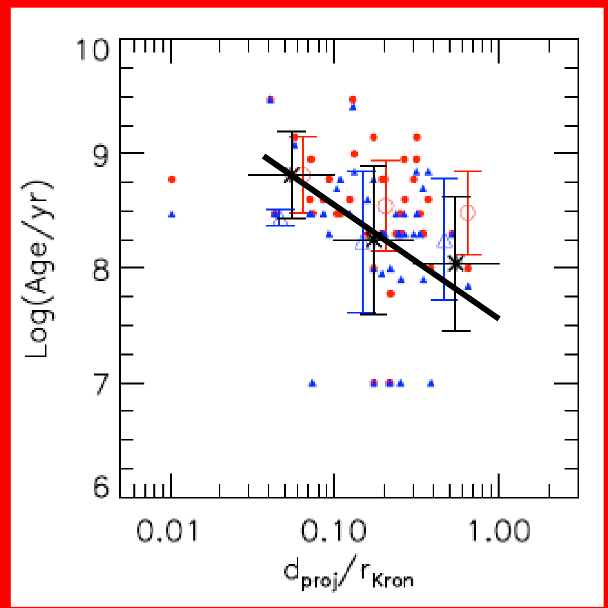
Forster Schreiber et al. 11

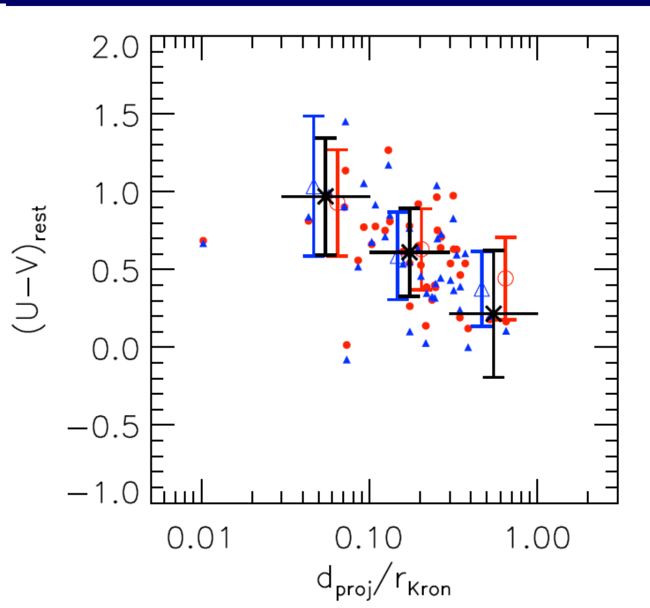



Guo et al 11



# 3. Blue Nuggets and BH by Wet Inflow: VDI and Mergers

Dekel, Sari, Ceverino 2009
Ceverino, Dekel, Bouraud 2010
Bournaud, Dekel et al. 2011
Cacciato, Dekel, Genel 2011

Krumholz, Forbes, Burkert 2011

Spheroid: Ceverino, Cacciato, Hoffman, Zolotov, Tweed, …

# Violent Disk Instability ↔ Inflow to Center

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

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

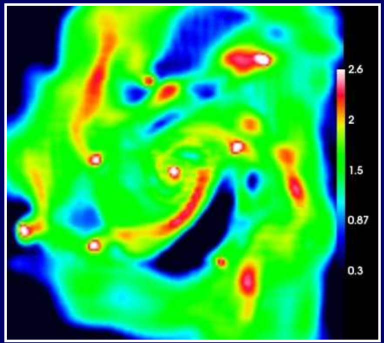
2. Inflow down the potential gradient provides the energy for driving σ to Q~1 and it compensates for dissipative losses
   Krumholz, Burkert 10; Cacciato, Dekel 11

$$\dot{M}_{\rm inf} V^2 \approx \frac{M\sigma^2}{\gamma t_{\rm dyn}} \quad \rightarrow \quad t_{\rm inf} \approx \gamma t_{\rm dyn} \delta^{-2}$$

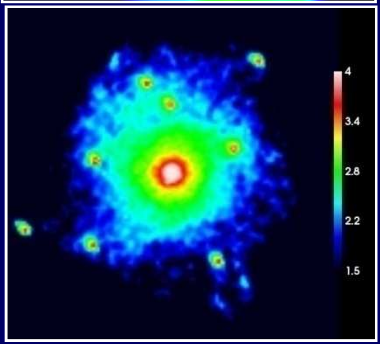
$$\dot{M}_{\rm inflow} \approx 25 M_{\odot} yr^{-1} M_{\rm cold,10.5} (1+z)_3^{3/2} \delta_{0.2}^2 \gamma^{-1}$$

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

clumpy gas disk

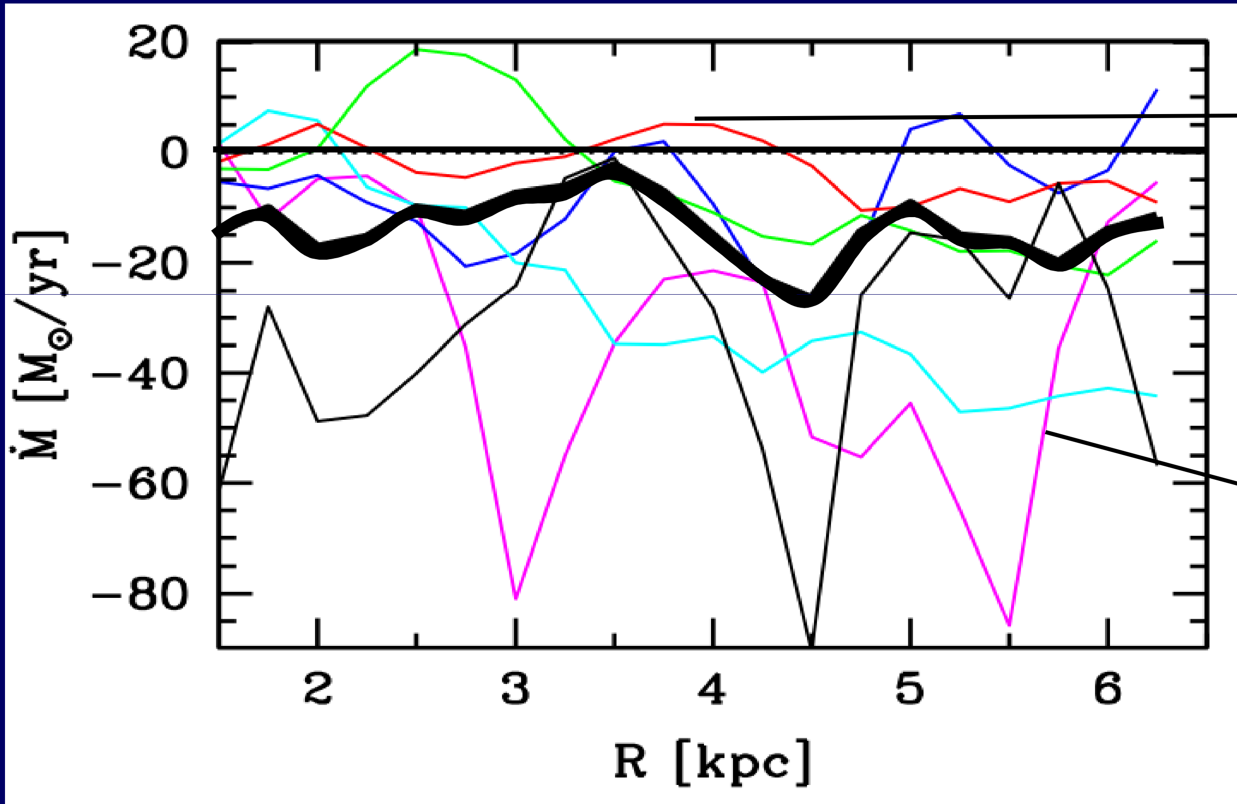


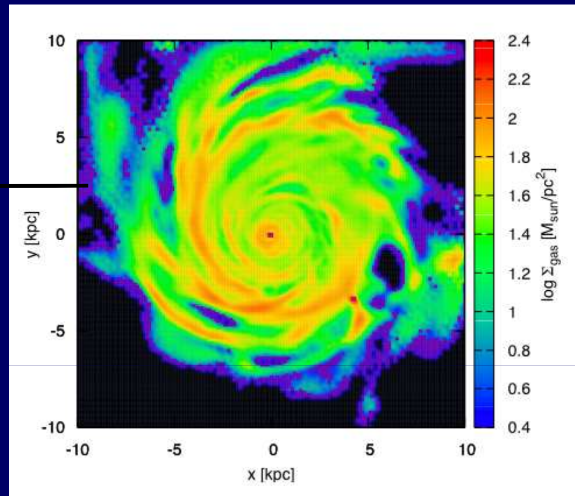

compact stellar bulge

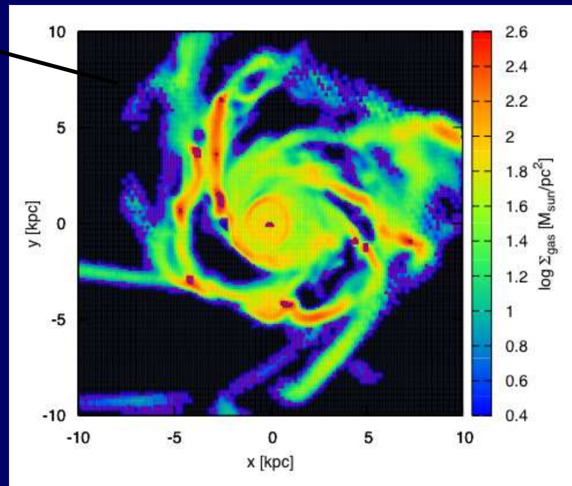


# Disk-instability-driven Inflow in Cosmological Simulations

Cacciato et al.



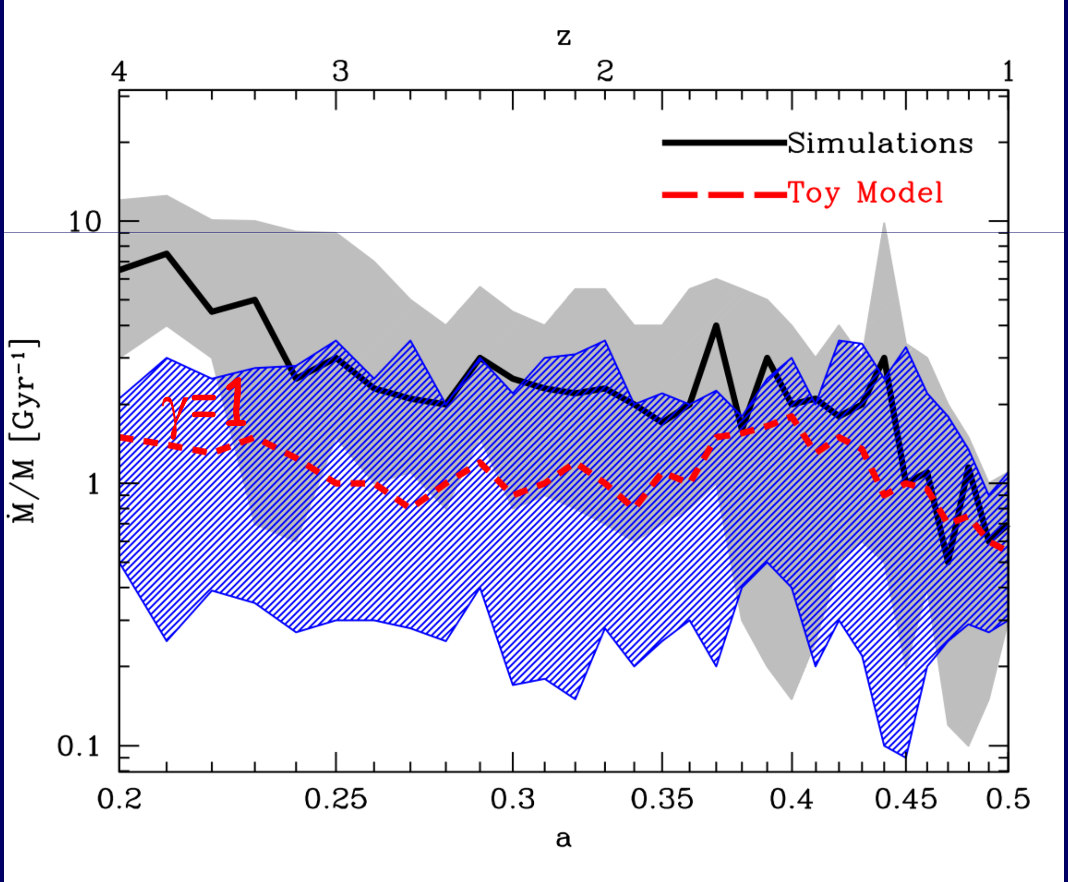



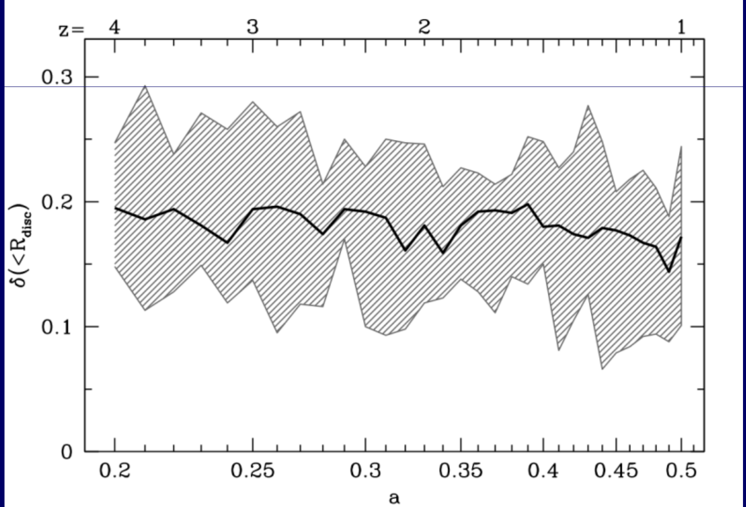

$$\dot{M}_{\rm inflow} \approx 25 M_{\Theta} yr^{-1} M_{\rm disk,11} (1+z)_3^{3/2} (\sigma/V)_{0.2}^2 \gamma^{-1}$$

# DVI-driven Inflow in simulations

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

Cacciato et al




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

# VDI wet inflow if $t_{inflow} \ll t_{sfr} \rightarrow$ blue nugget

Dekel & Burkert

Self-regulated Toomre instability at $Q \sim 1 \rightarrow$

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

$$t_{inf} \approx 2\gamma t_{dyn} \delta^{-2}$$

$$t_{sfr} \approx \varepsilon^{-1} t_{dyn}$$

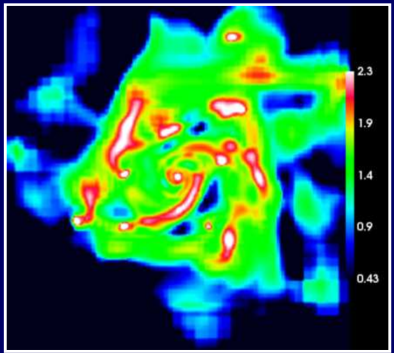
$$\rightarrow \frac{t_{inf}}{t_{sfr}} \approx (2\gamma\varepsilon)\ \delta^{-2} < 1$$

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

Runaway: wet inflow $\rightarrow \Sigma_g$ up $\rightarrow t_{inf}/t_{sfr}$ down $\rightarrow$ wetter inflow

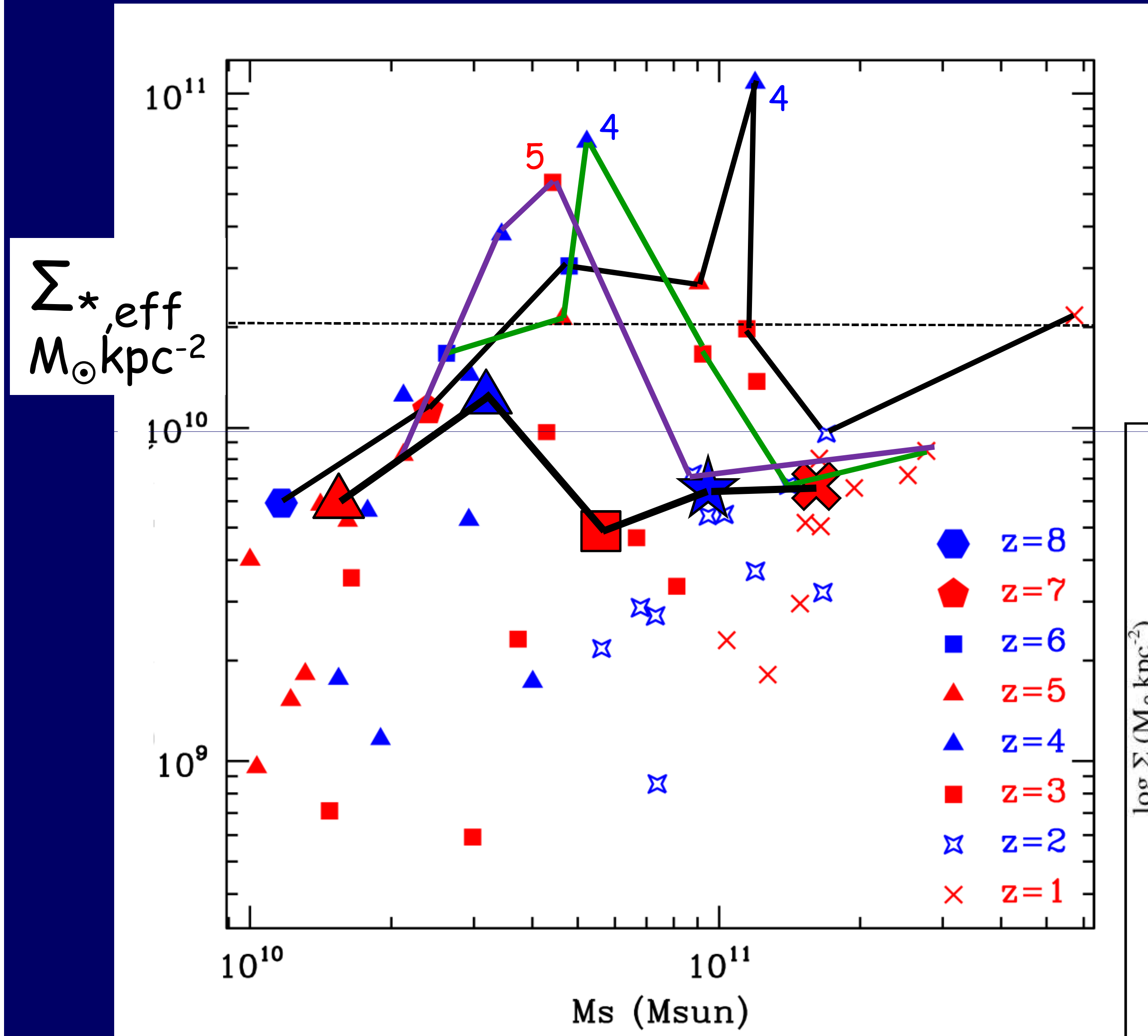
Expect VDI-driven blue nuggets:
- at high z, where $f_g$ is high
- for low $\lambda$, where $R_g$ is low

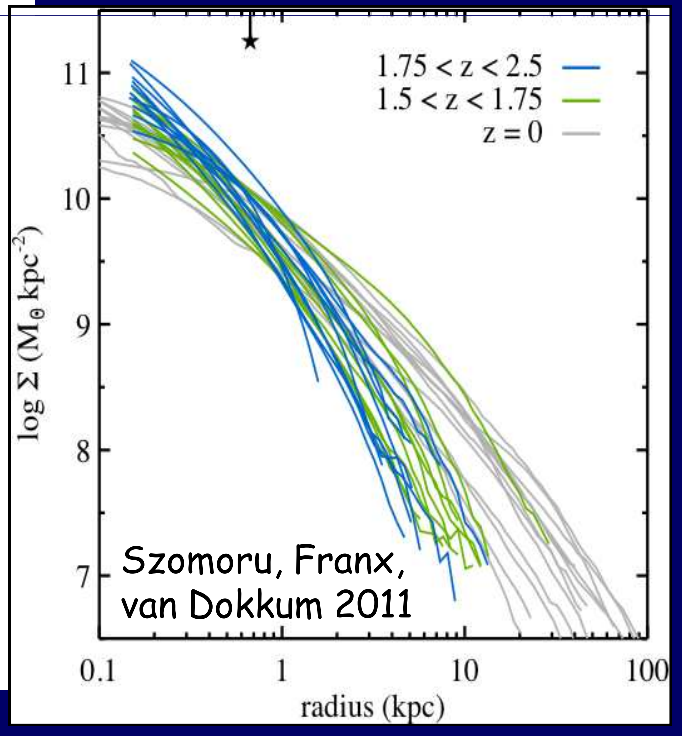
Quenching of blue to red nuggets by:
- gas consumption
- stellar feedback
- AGN feedback



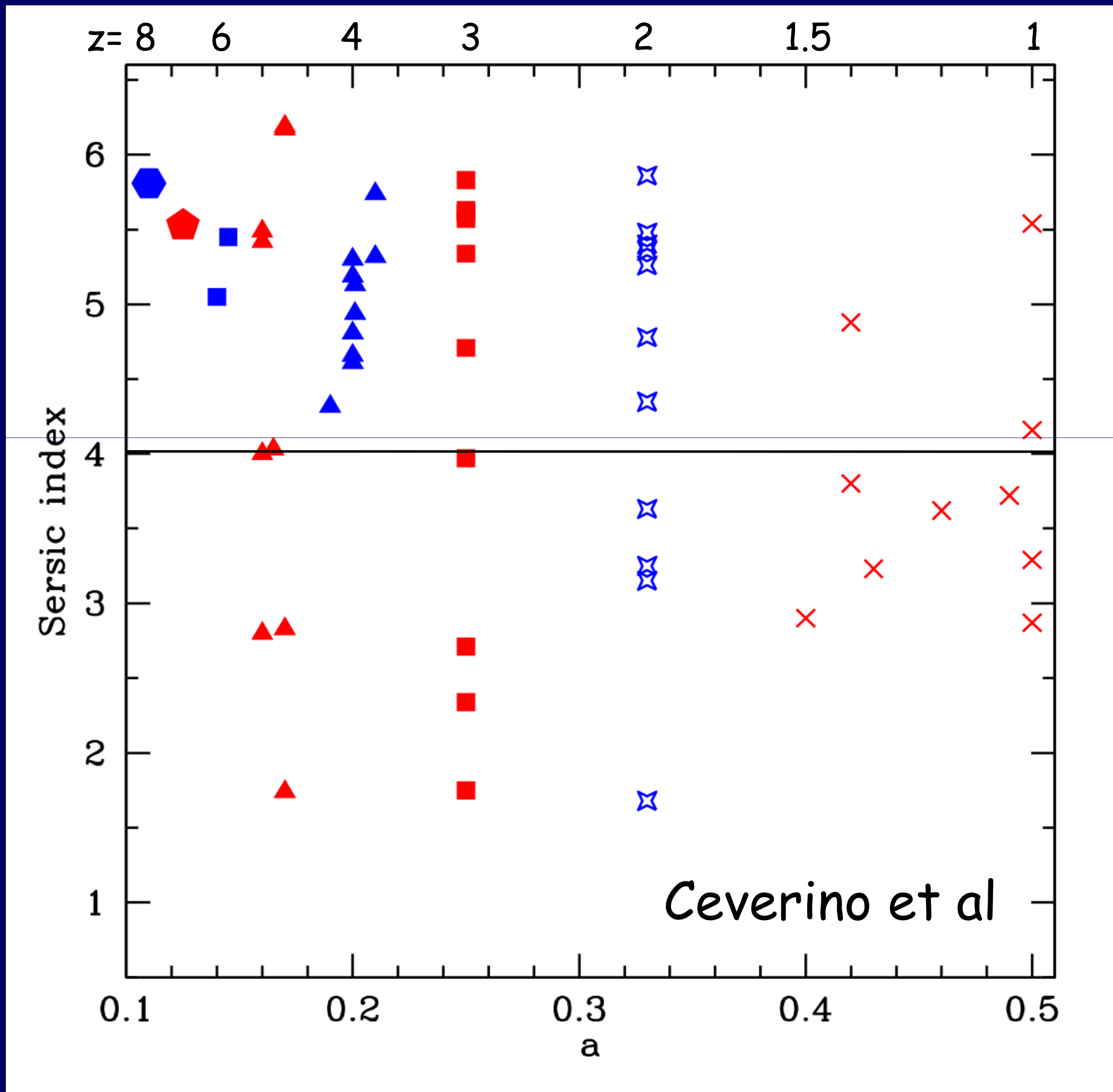
# Blue Nuggets from Wet Inflow

Ceverino et al

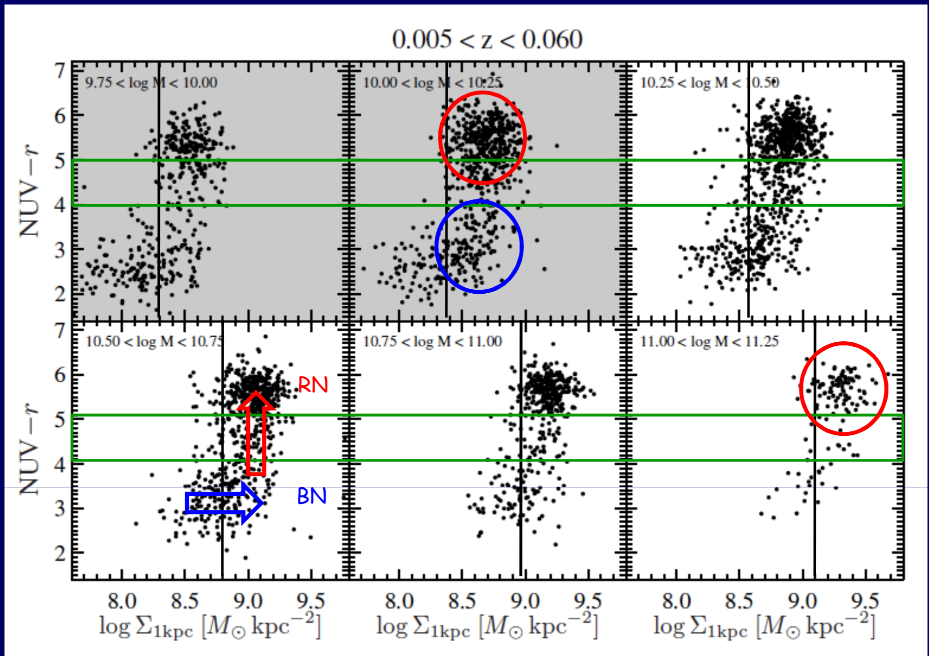


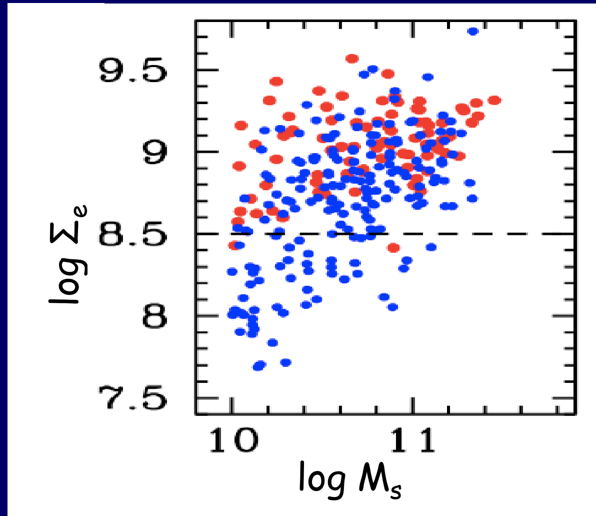
# Classical Bulges from Wet Inflow



# Observations: Blue Nuggets - Red Nuggets

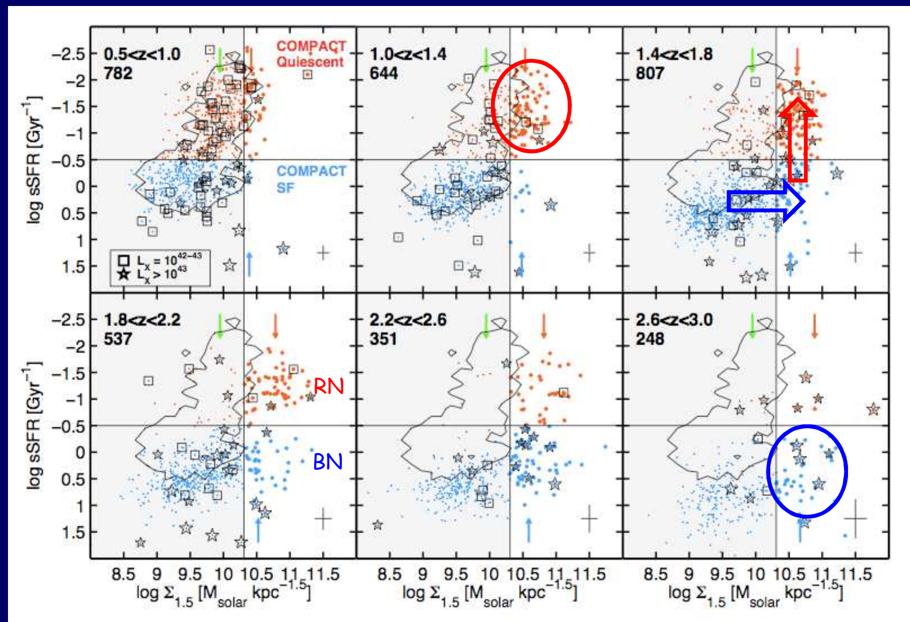



Fang et al., Cheung et al.




Kauffmann et al.

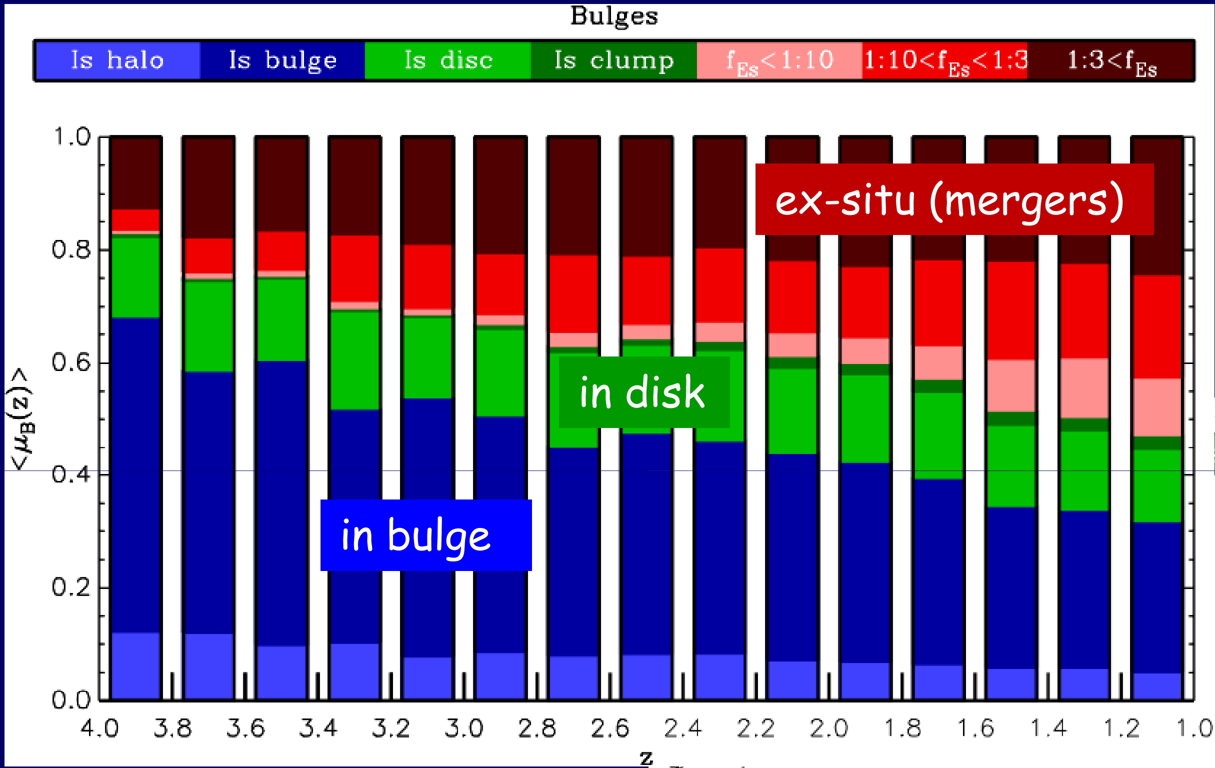
diffuse → compact → quench
downsizing of quenching



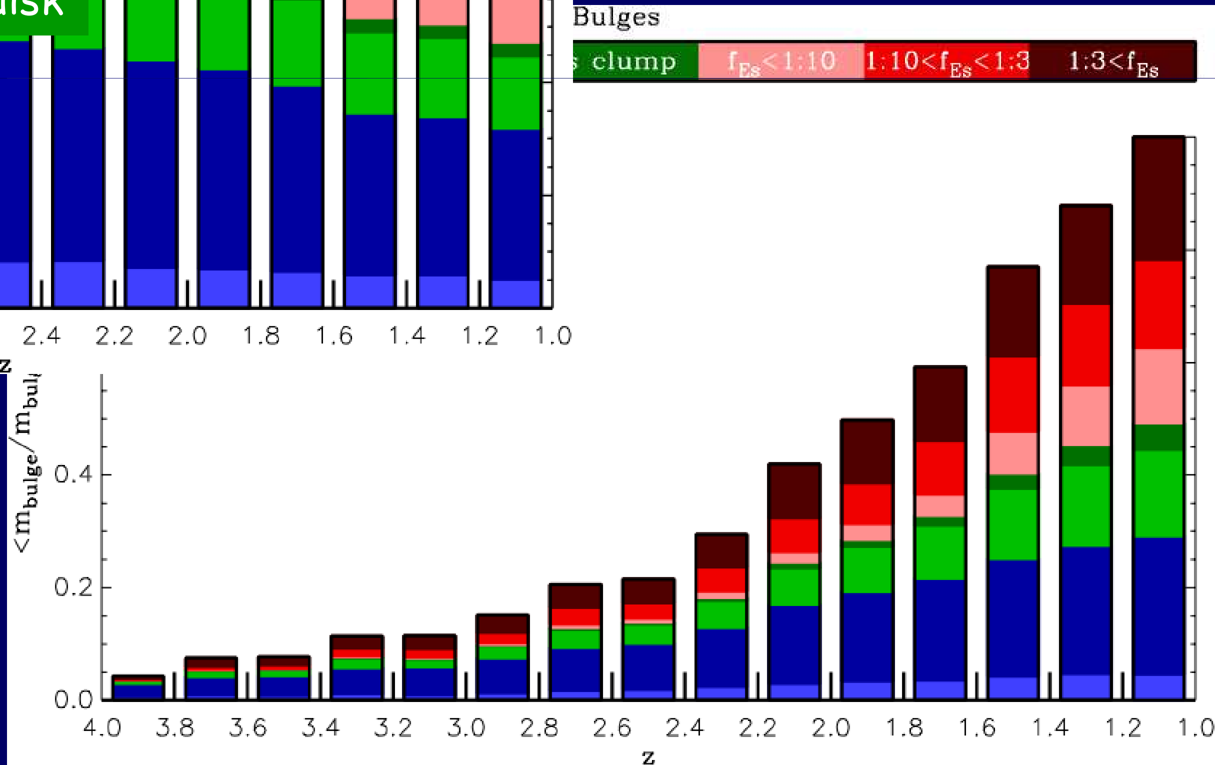

Barro et al.

# Origin of Bulge: Stellar Birthplace

Tweed, Zolotov, …



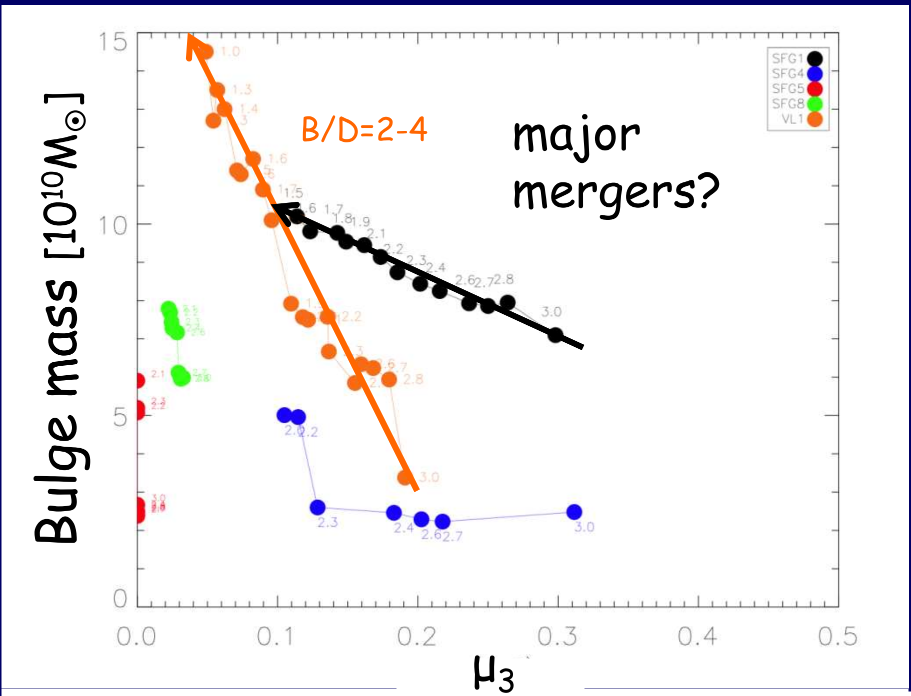

60-30% of the bulge stars form in the bulge
→ wet inflow

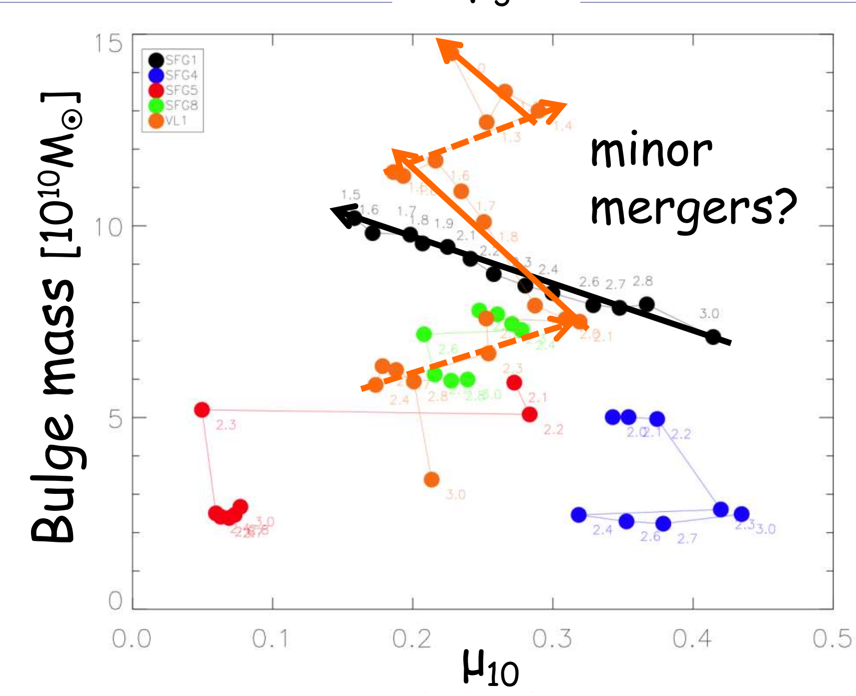


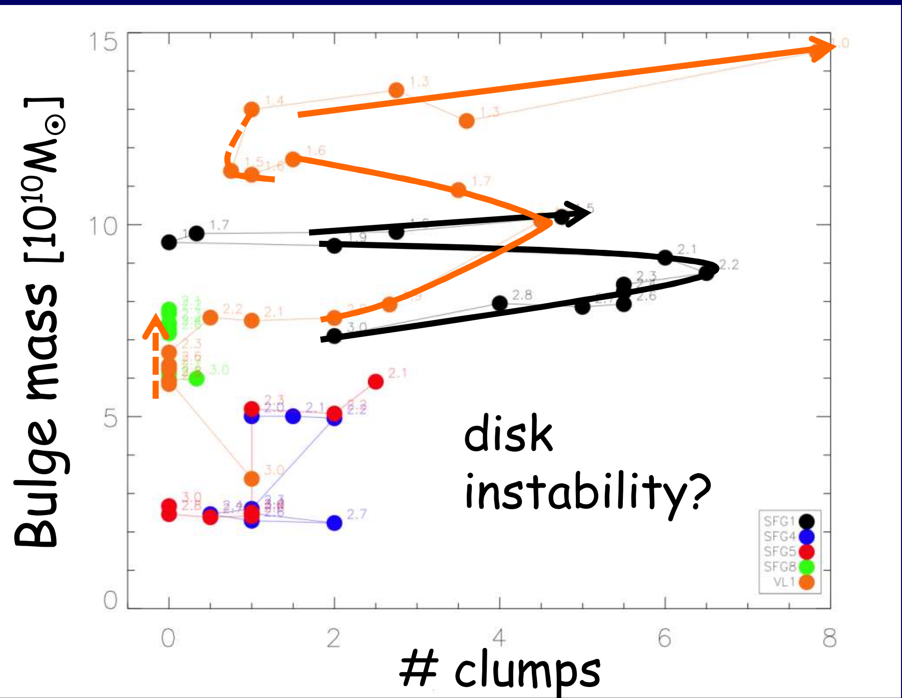
# Bulge growth by mergers versus disk instability

Tweed, Zolotov

$\mu_m$ = fraction of mass added in mergers of 1:m



# Bulge – Black Hole - AGN

Bournaud, Dekel, Teyssier, Cacciato, Daddi, Juneau, Shankar 11

Black hole growth by VDI-driven inflow in the disk

2% Sub-Eddington AGN, $L_x \sim 10^{42-43}$ erg $s^{-1}$

Bright episodes by clump coalescence

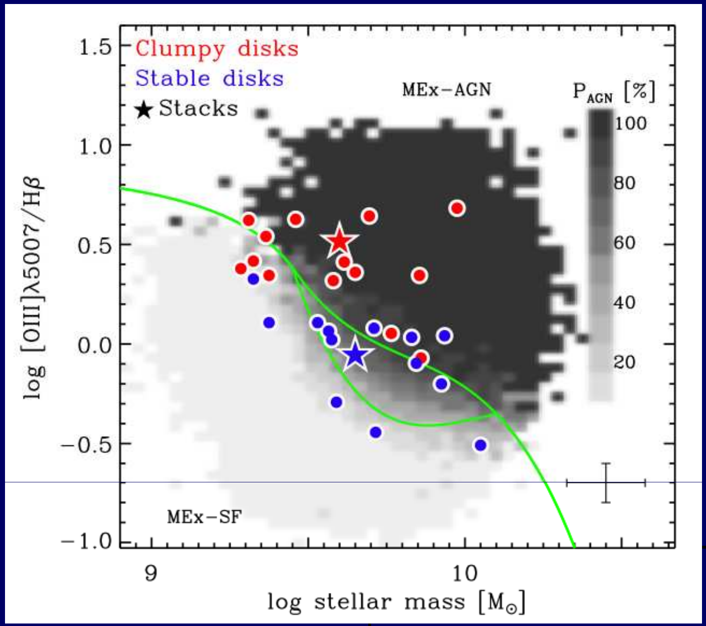
Obscured by $\Sigma_{gas} \sim 10^{23-24}$ $cm^{-2}$

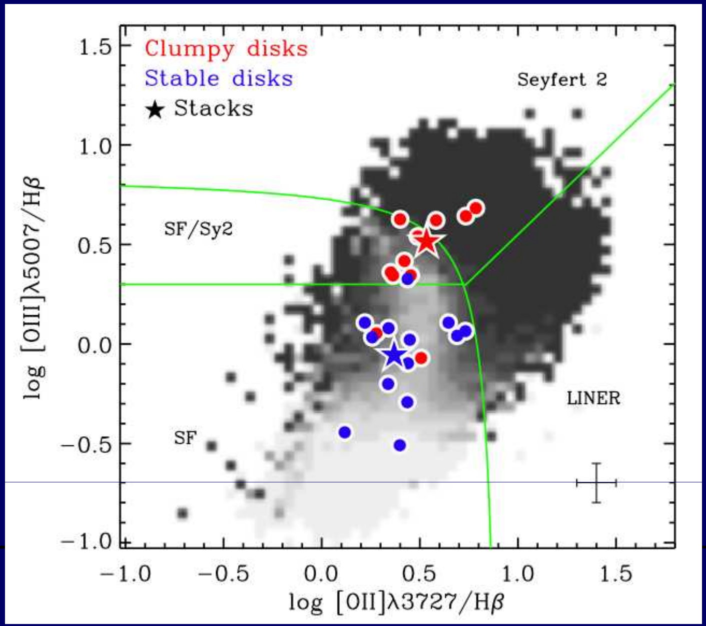
Similar to major mergers, but more abundant

At z>6: VDI inflow allows Eddington accretion onto the BH
By z~6 grow $M_{BH} \sim 10^9 M_\odot$ from a seed $\sim 5 \times 10^4 M_\odot$ at z~10

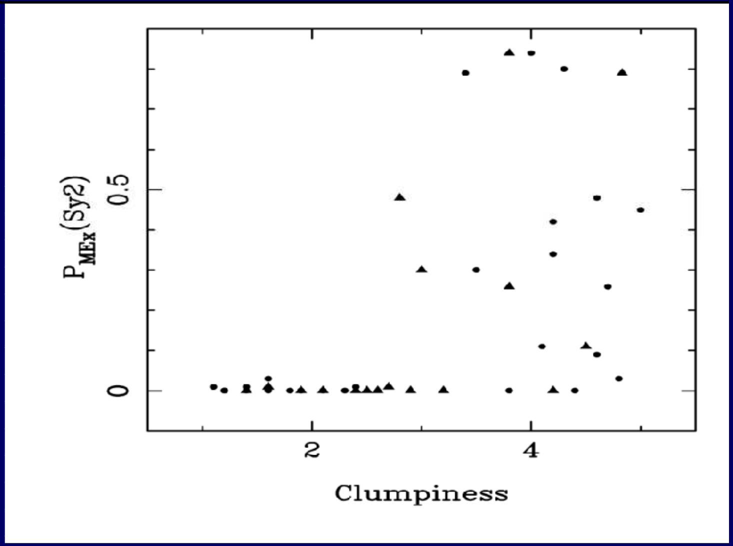
# AGN associated with Clumpy Disks

Bournaud, Juneau, Le Floch, Mullaney, Daddi, Dekel, Duc, Elbaz, Salmi, Dickinson 11



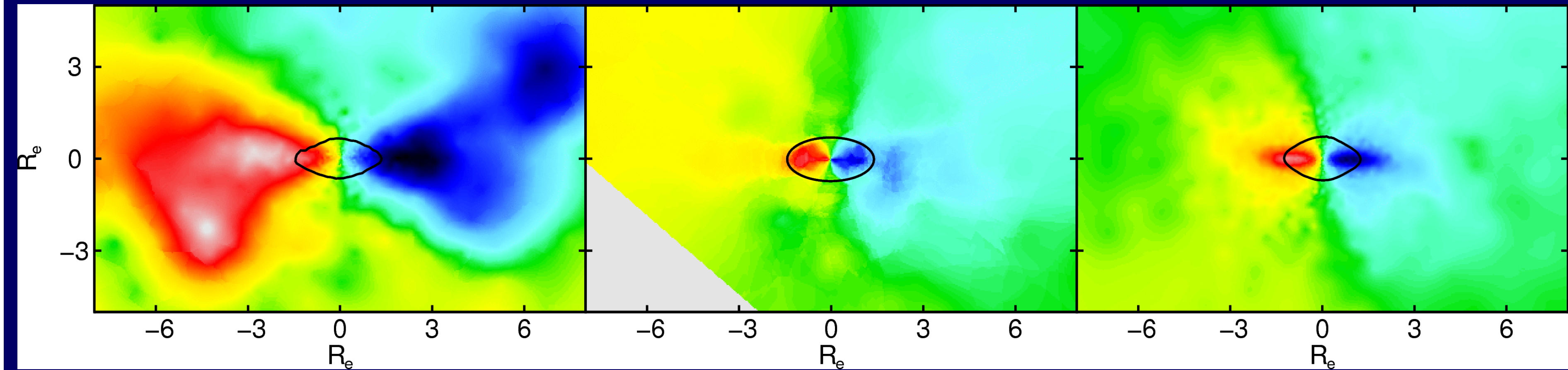

z=0.5-1.0



# 4. Two-Zone Rotation in Ellipticals: Disk Instability and Minor Mergers

Romanowsky, Dekel, Arnold, Hoffman, Ceverino, Brodie, Primack, …

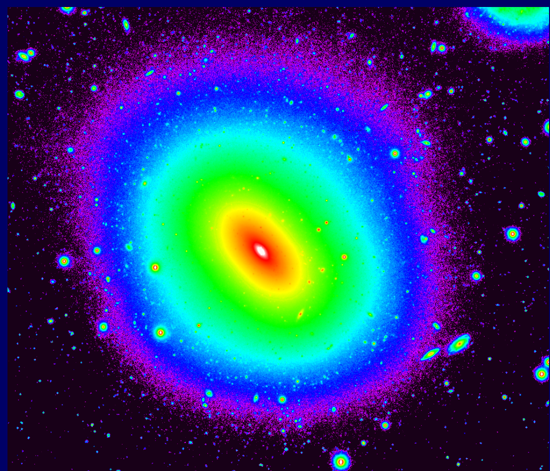
# Outer vs Inner Rotation




Binary major merger simulation, gas-rich 1:3 (Burkert et al.)

Disky elliptical (NGC 3377; Romanowsky et al.)

Cosmological simulation (Ceverino et al.)



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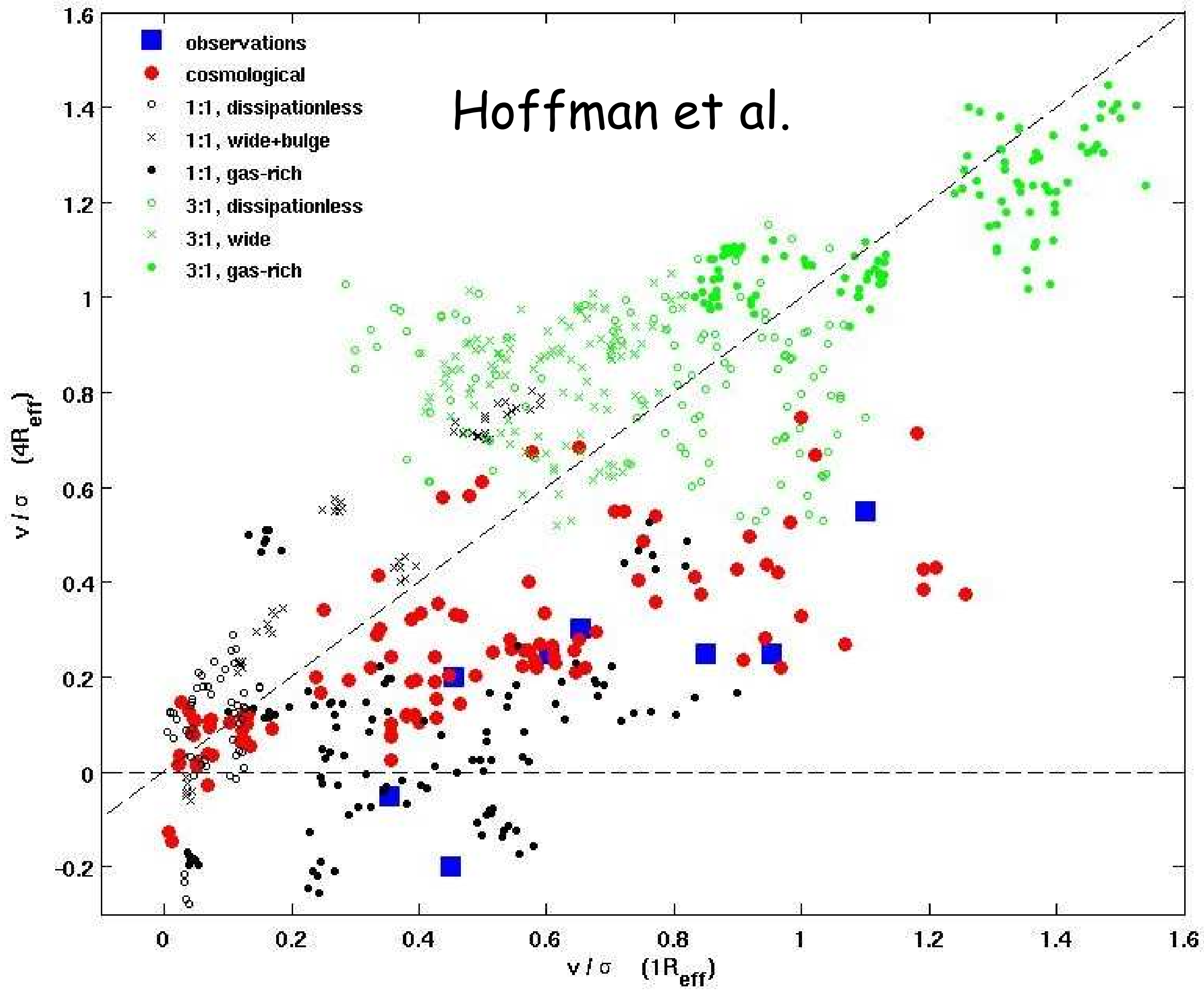
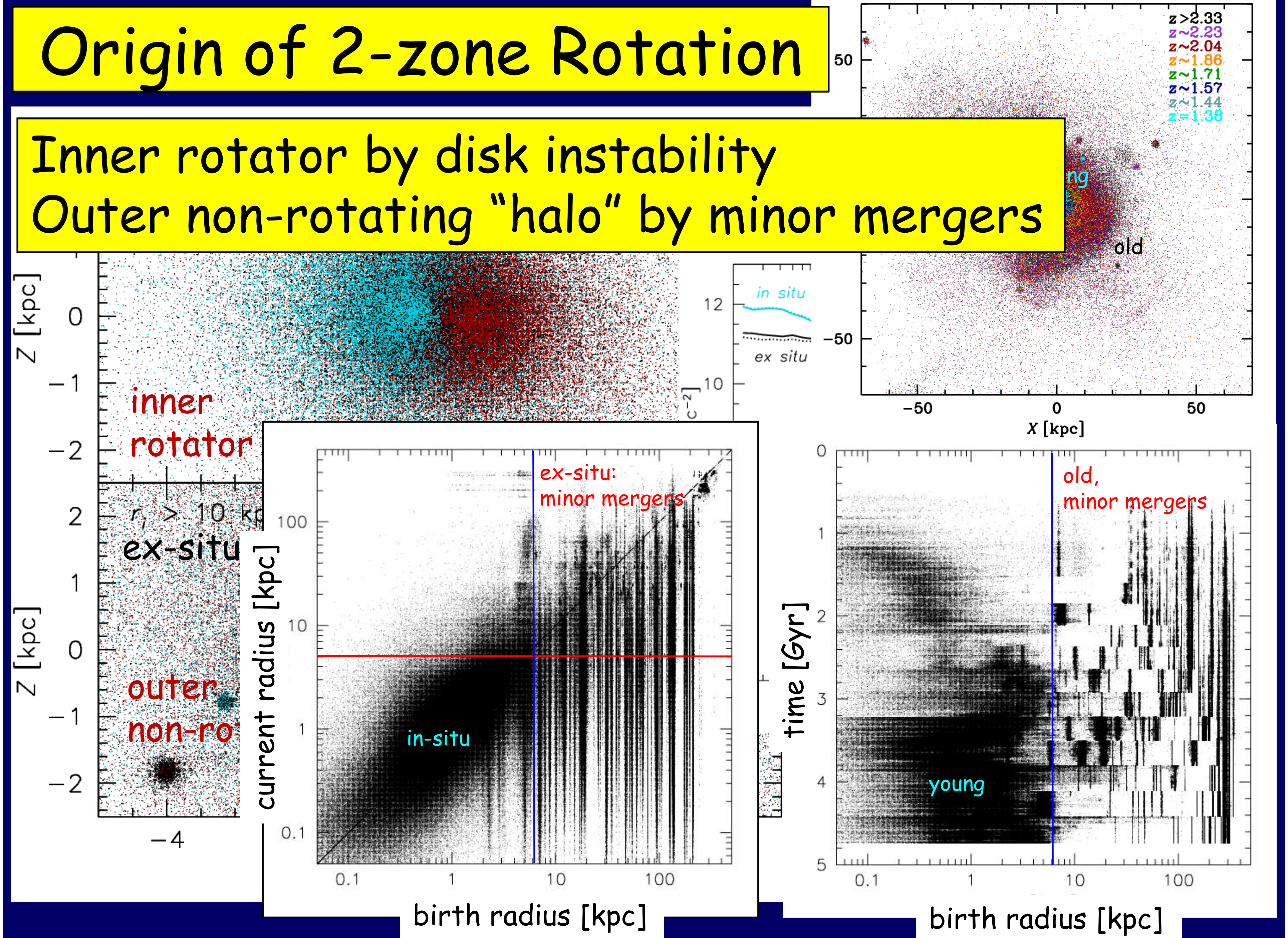


# Origin of 2-zone Rotation

Inner rotator by disk instability
Outer non-rotating "halo" by minor mergers



# Conclusions

The cold streams feeding hi-z galaxies include ex-situ clumps:
- merging galaxies with DM halos (30% mass in m/M > 0.1)
- baryonic clumps by hydro and thermal instabilities (?)

Disk-clumps are in-situ (VDI) and ex-situ (mergers):
70-30% in number, 45-55% in mass, 75-25% in SFR
In-situ are less massive, young, high sSFR (blue), low Z,
showing strong gradients due to migration (as opposed to disruption).

Blue Nuggets and AGN are formed by wet inflow: VDI and mergers
VDI-driven inflow is wet when $\Sigma_{gas}$ is high $\rightarrow$ $t_{inf} \ll t_{sfr}$ (hi z, low $\lambda$)
Classical bulges
Quenching by stellar and AGN feedback (?)

Two-zone kinematics of Es:
Inner rotator by VDI, Outer non-rotator by minor mergers

# Cosmic Web, Cold Streams, Clumpy Disks & Spheroids