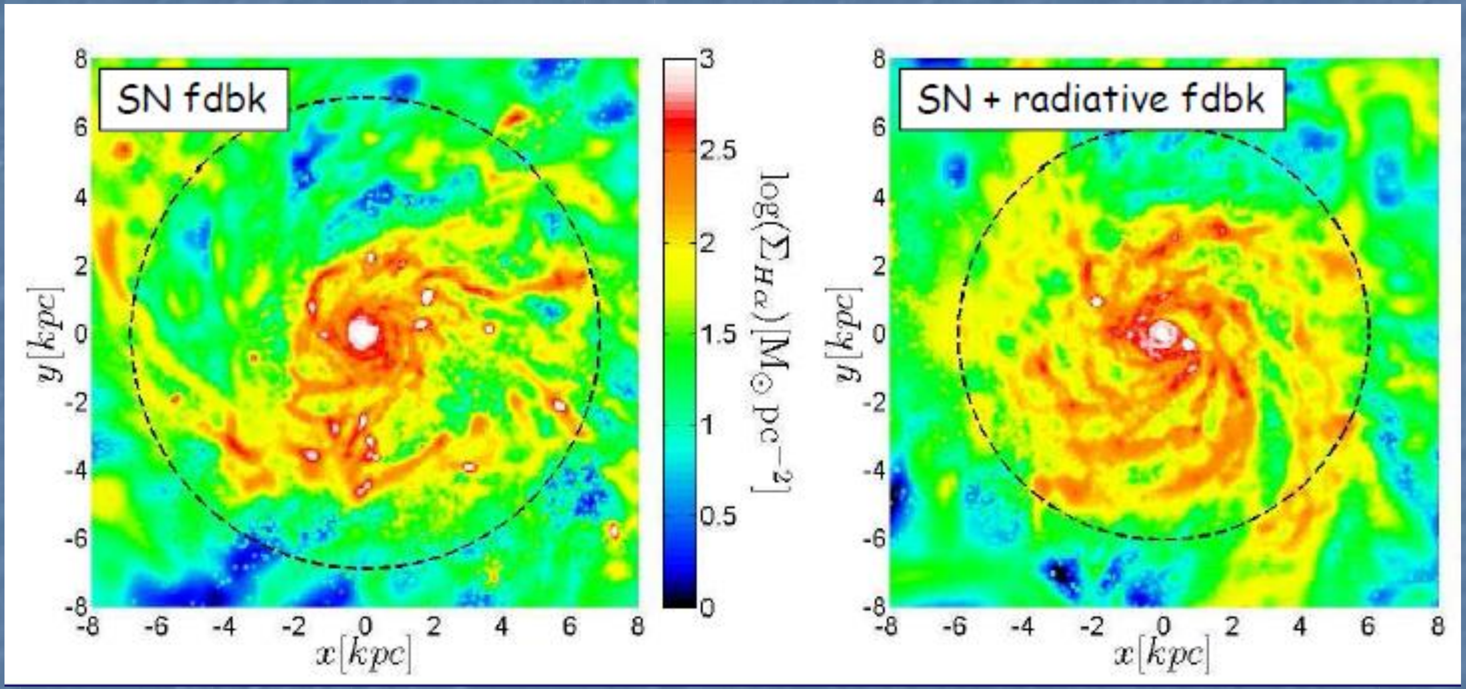
Evolution of Giant Clumps in High *z* Disc Galaxies



Nir Mandelker, H.U.J.I.

UCSC Galaxy Workshop, August 13 2014

Collaborators: Avishai Dekel, Daniel Ceverino, Frederic Bournaud, Yicheng Guo, Chris Moody, Joel Primack

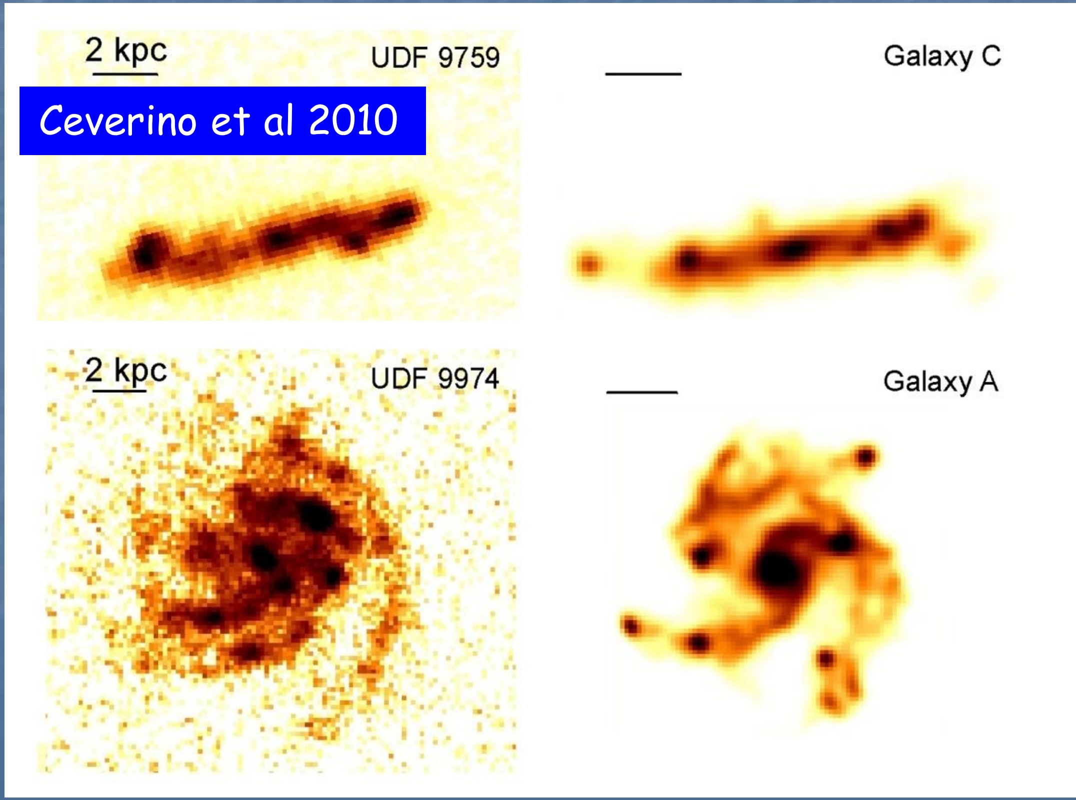
What Do We Know About Clumpy Discs?

Many SFGs at z~2 exhibit clumpy morphology

Robust in both observations and simulations

Cowie+ 95
van den Bergh 96
Elmegreen+ 04, 05
Forster Schreiber+ 06, 11
Genzel+ 08, 12
Jones+ 10
Guo+ 12
Wisnioski+ 12

Ceverino+ 10
Agertz+ 09
Bournaud+ 06, 08, 13
Genel+ 12
Ceverino, Dekel, **N. Mandelker**+ 12
N. Mandelker+ 14



What Do We Think We Know About Clumpy Discs?

High gas fractions cause giant clumps to form in situ in the disc through VDI

Toomre 64
Noguchi 99
Immeli+ 04
Bournaud+ 06, 08
Dekel+ 09, 13
Krumholz+ 10
Genel+ 12
Cacciato+ 12
Forbes+ 12, 13
Ceverino, Dekel, **N. Mandelker**+ 12

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

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

Is it really Toomre? (talks by Burkert, Inoue, Dekel)

Clumpy discs may also be merging systems

Clumps should survive feedback, migrate to the center and form a bulge

Krumholz, Dekel 2010   Dekel, Krumholz 2014   Bournaud+ 14   **N. Mandelker**+ 14

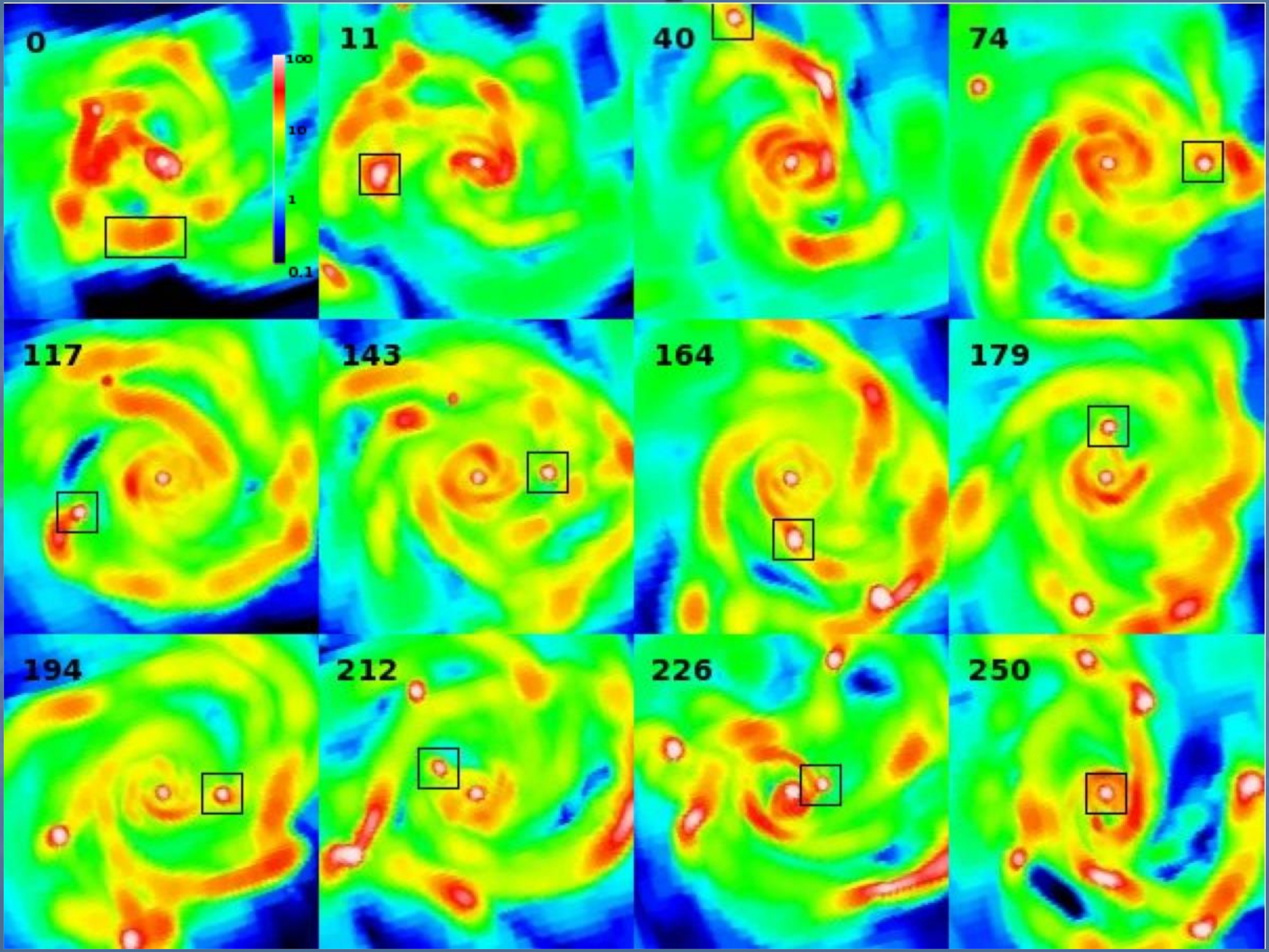
Clumps should not survive feedback, destroyed in t_{dyn}

Mauuray+ 10   Genel+12   Hopkins+ 13

What Would We Like to Know About Clumpy Discs?

- What is the fraction of clumpy discs as a function of disc mass / redshift?
- How many of the clumps were formed through VDI? What is the origin of instability?
- Can these be distinguished from mergers?
- Do clumps survive feedback and migrate to the disc center?
- Do they contribute to bulge formation?

Clump Survival



Ceverino+ 10

Also:
Ceverino, Dekel, Mandelker+ 12
Dekel & Krumholz 14
Mandelker+ 14

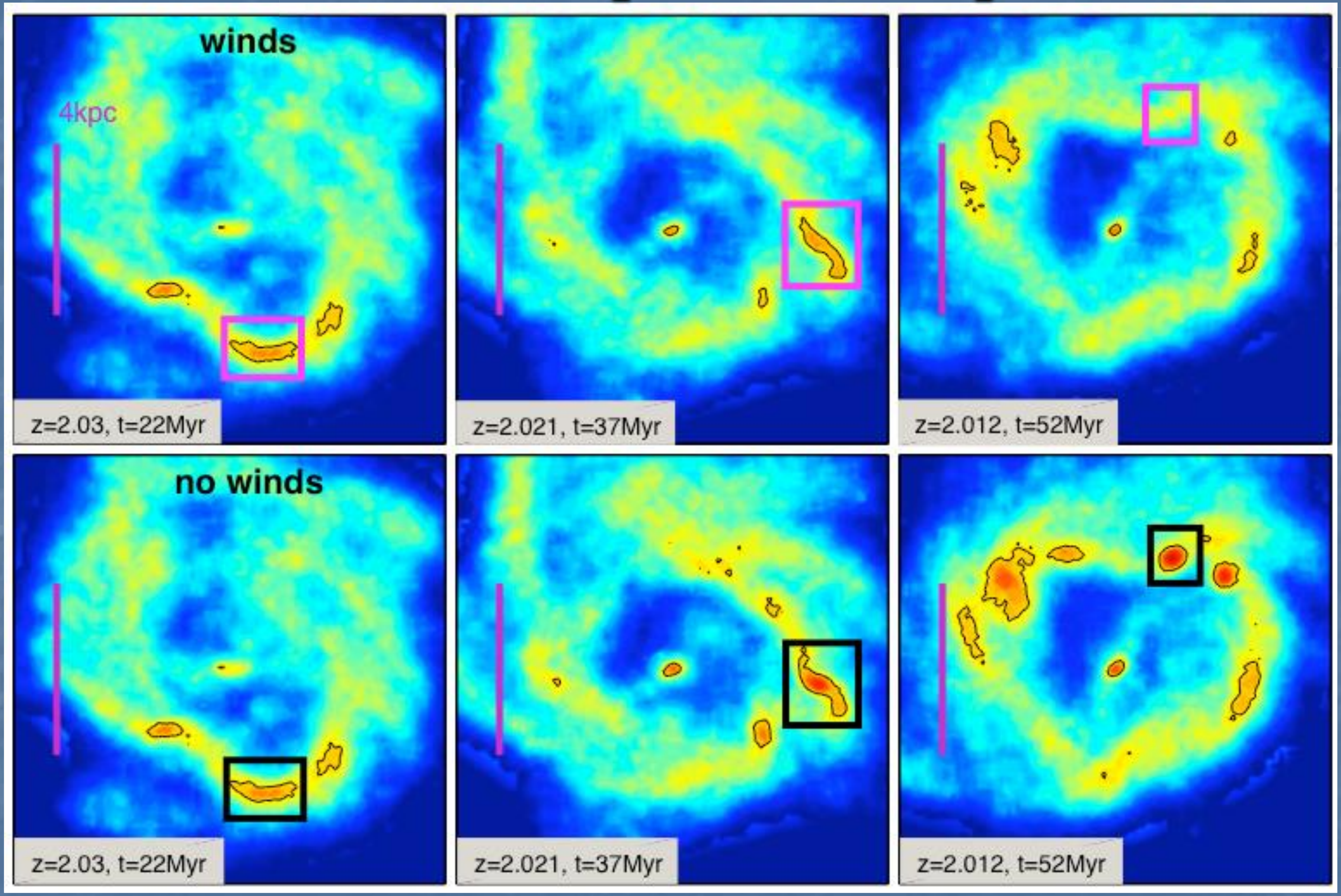
Hydro ART "Generation 1"

~50 pc resolution

SN feedback only

Clumps migrate to bulge in orbital timescale

Clump Disruption?



Genel+ 12

Also:
Hopkins+ 13
Murray+ 10

Gadget 2

~100 pc resolution

artificial strong winds put in (Oppenheimer and Dave)

Winds cause clumps to disrupt in a dynamical time. Without winds, clumps migrate

A Bathtub Model for Clump Evolution

Dekel, N. Mandelker, Bournaud 2014 (in prep)

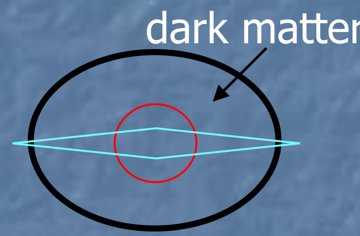
$$\dot{M}_{gas} = \dot{M}_{acc} - \dot{M}_{SFR} - \dot{M}_{out}$$

$$\dot{M}_{stars} = \dot{M}_{SFR} - \dot{M}_{stripping}$$

Toomre Instability:

$$1 \approx Q \approx \frac{\sigma\Omega}{G\Sigma} \approx \delta^{-1}\frac{\sigma}{V}$$

$$\delta \equiv \frac{M_{\rm disk}}{M_{\rm tot}(R_{\rm disk})} \sim 0.3$$



Migration to center due to DF, torques and clump encounters

$$t_{mig} \approx \delta^{-2} t_{dyn} \approx 10 t_{dyn} \sim 250 - 500 Myr$$

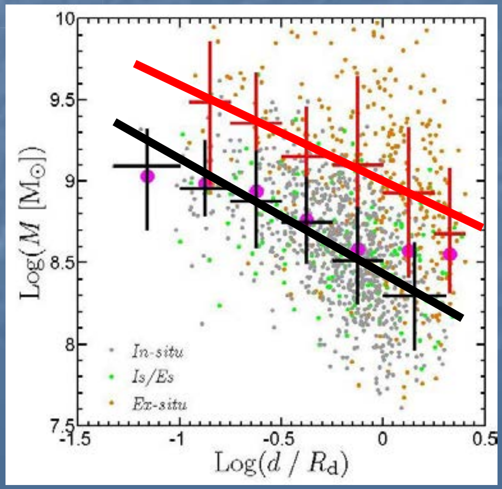
Dekel, Sari, Ceverino 2009

Mass gain by accretion of gas from the disc

$$\dot{M}_{acc} \approx \alpha\, \rho_d\, R_T^2\, \sigma_d$$

$$t_{acc} \approx \frac{2}{\alpha} t_{dyn} \approx 10 t_{dyn} \approx t_{mig}$$

N. Mandelker+ 2014; Dekel & Krumholz 2014; Bournaud+ 2014



Without outflows, clump mass can > double during migration

Seen in weak feedback simulations

N. Mandelker+ 2014

A Bathtub Model for Clump Evolution

Dekel, N. Mandelker, Bournaud 2014 (in prep)

Star formation $\epsilon_{SF} \sim 0.02, \ t_d \geq 3t_{ff}$

$$t_{SFR} \approx \epsilon_{SFR}^{-1} t_{ff} \approx 30t_{dyn} \approx 3t_{mig}$$

Momentum driven outflows –

a steady wind, with minimal photon trapping

Krumholz & Thompson 2012, 2013; Dekel & Krumholz 2014

$$\dot{p}_w \approx 3\, L/c \quad \rightarrow \quad \eta \approx 1-2$$

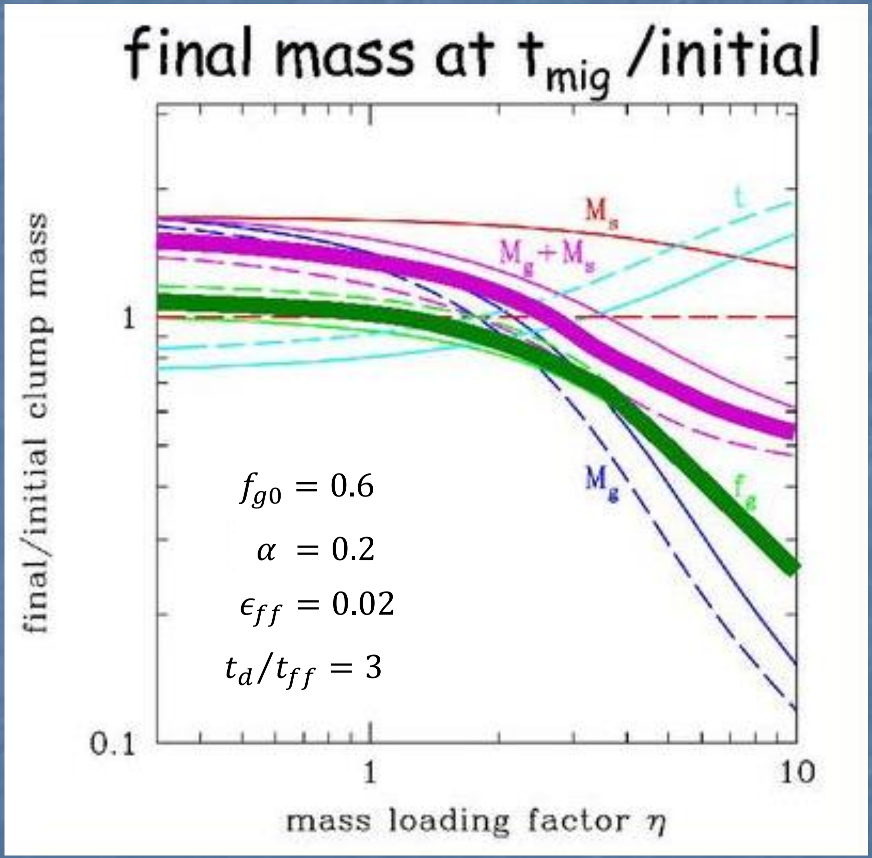
Consistent with Genzel+ 2012; Newman+ 2013

$$t_{out} \approx \eta^{-1} t_{SFR} \approx (1-2) t_{mig}$$

$$t_{mig} \approx t_{acc} \leq t_{out} \leq t_{SFR}$$

A Bathtub Model for Clump Evolution

Dekel, N. Mandelker, Bournaud 2014 (in prep)



At any η, mass varies by less than factor 2

For $\eta{\sim}2-4$, mass is ~ constant

$\eta \ll 1$, mass grows by factor ~2

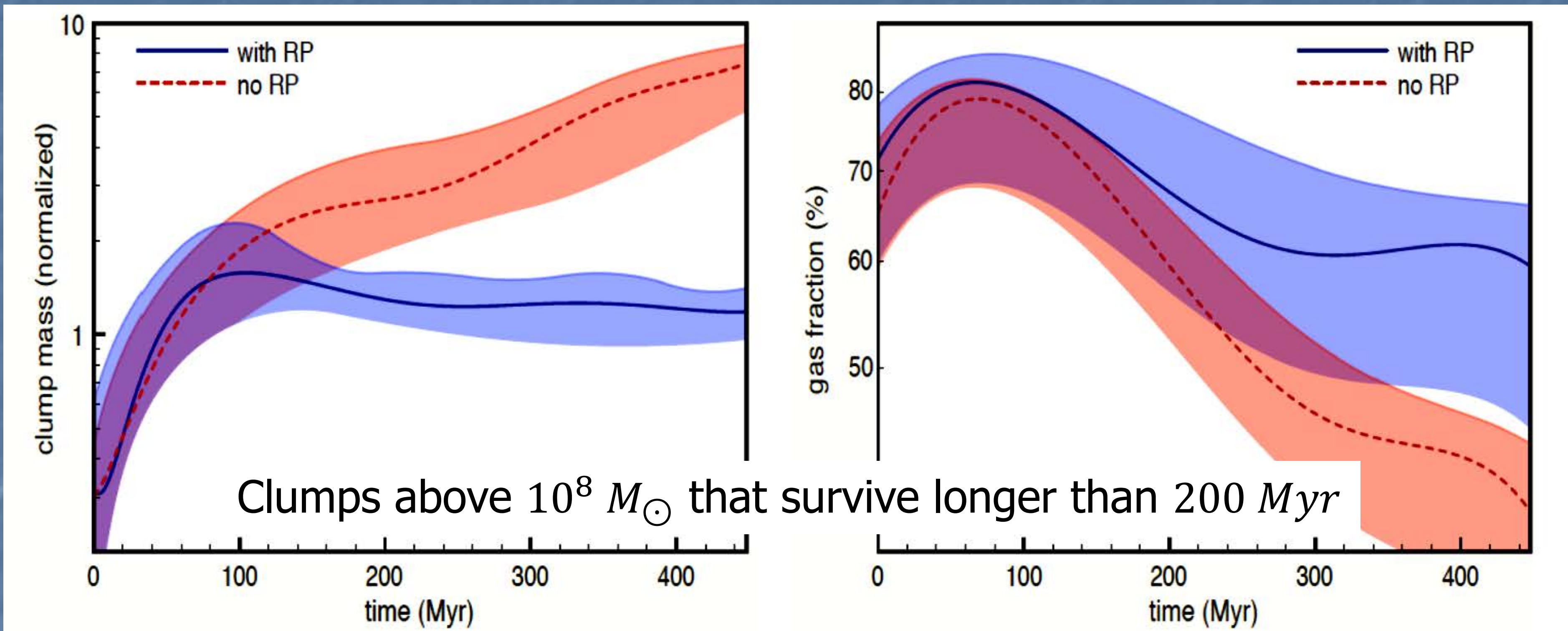
$\eta \gg 1$, mass goes to 0

(robust)

For $\eta < 4$ gas fraction ~ constant (sensitive to t_d/t_{ff})

Isolated Disc Simulations with RAMSES

Dekel, N. Mandelker, Bournaud 2014 (in prep)



Simulations by Bournaud+ 2014

Maximal AMR resolution of 3.5 pc

Galaxy baryonic masses of $4 \times 10^{10} - 4 \times 10^{11} M_\odot$

60% gas fraction

Zoom in Cosmological Simulations with ART

Kravtsov+ 1997, 2003; Ceverino+ 2009, 2010, 2014

~30 pairs of simulations with identical ICs

Halo masses of $10^{11} - 10^{12} M_{\odot}$ at $z \sim 1$

Maximal AMR resolution of ~25 pc

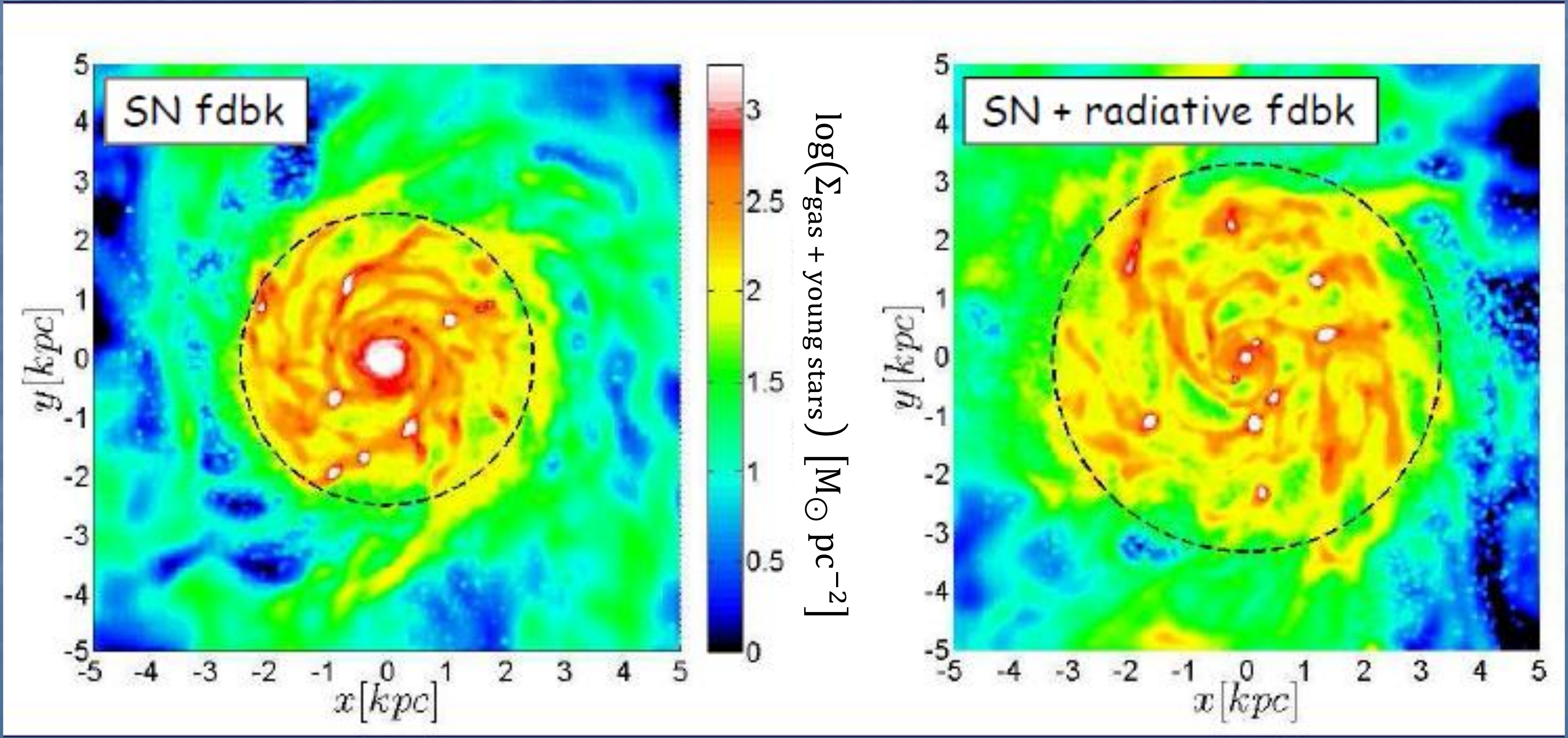
Thermal feedback from stellar winds and SNae - no shutdown of cooling, ~30% runaway stars

Run with and without radiation pressure feedback with $\tau_{IR} = 1$
Produces $\eta \sim 2\ (0.2 - 10)$ globally

3D clump finder (Mandelker+ 14) run on both gas and stars
Outputs every ~100 Myr, clumps tracked by stellar particles

The Effect of Radiative Feedback on Clumps

Gas disc expands, bulge may loose gas, giant clumps survive, small clumps disrupt

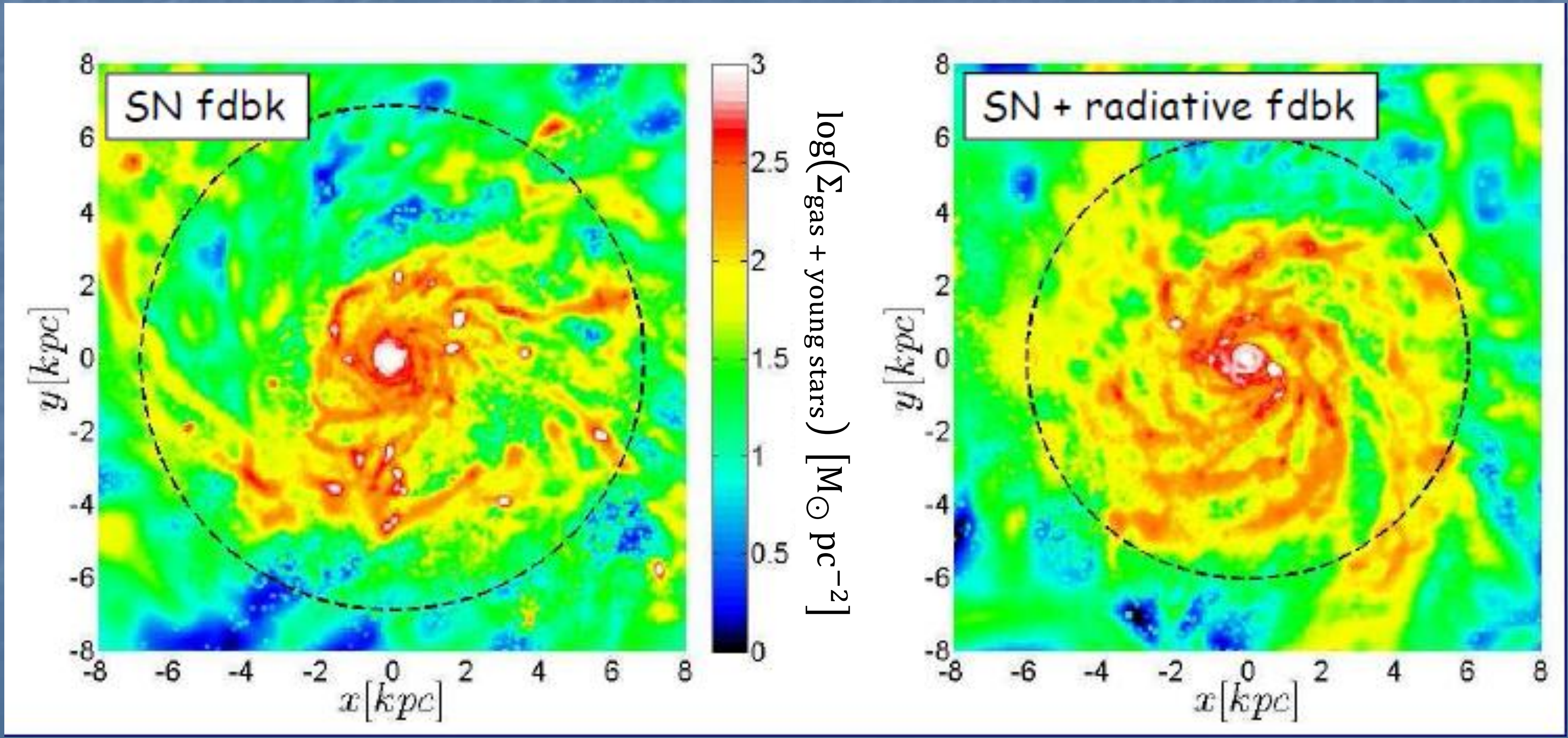


VELA15 z~4.6

N. Mandelker + 14, in prep

The Effect of Radiative Feedback on Clumps

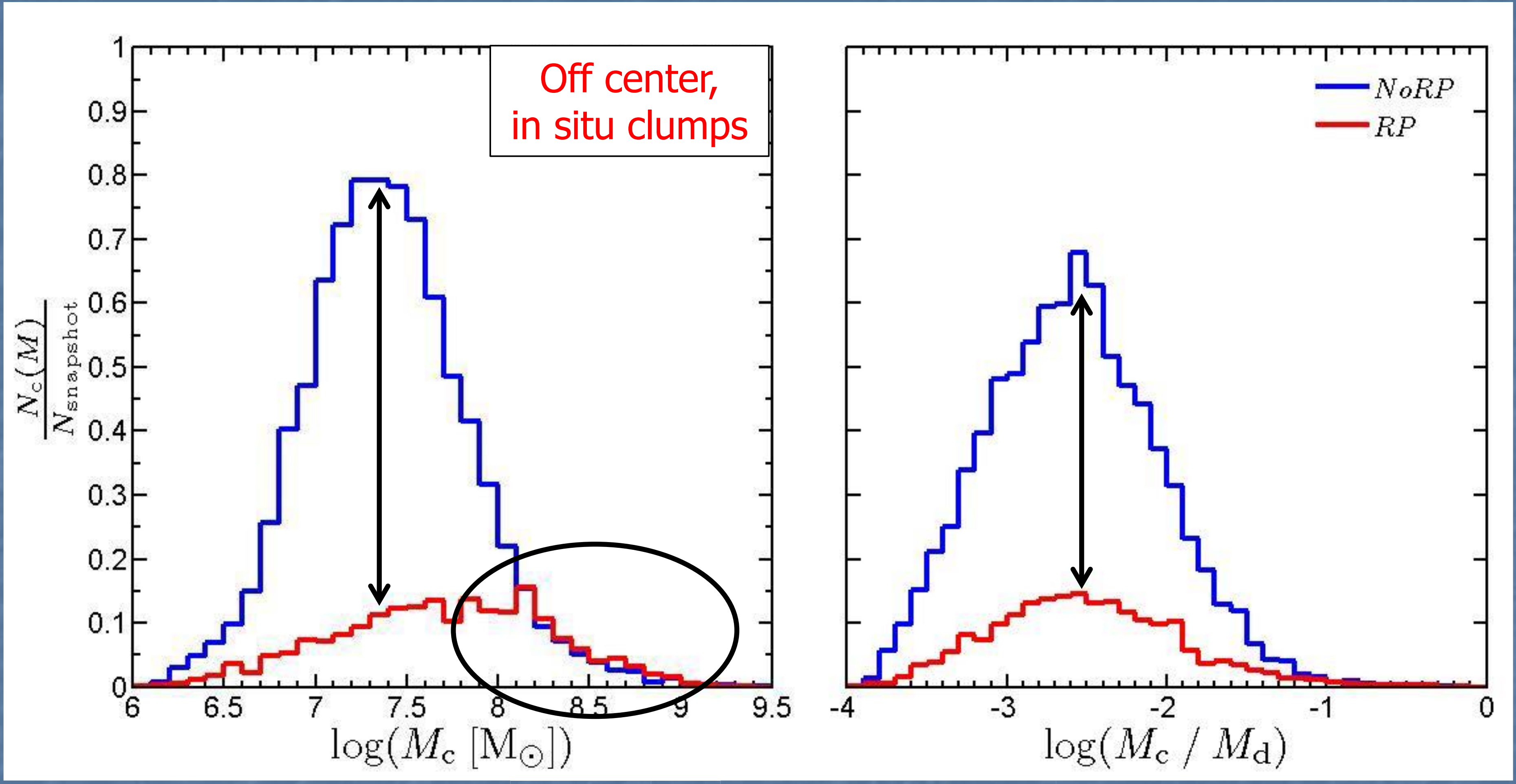
Gas disc expands, bulge may loose gas, giant clumps survive, small clumps disrupt



VELA07 z~2.8

N. Mandelker + 14, in prep

The Effect of Radiative Feedback on Clumps

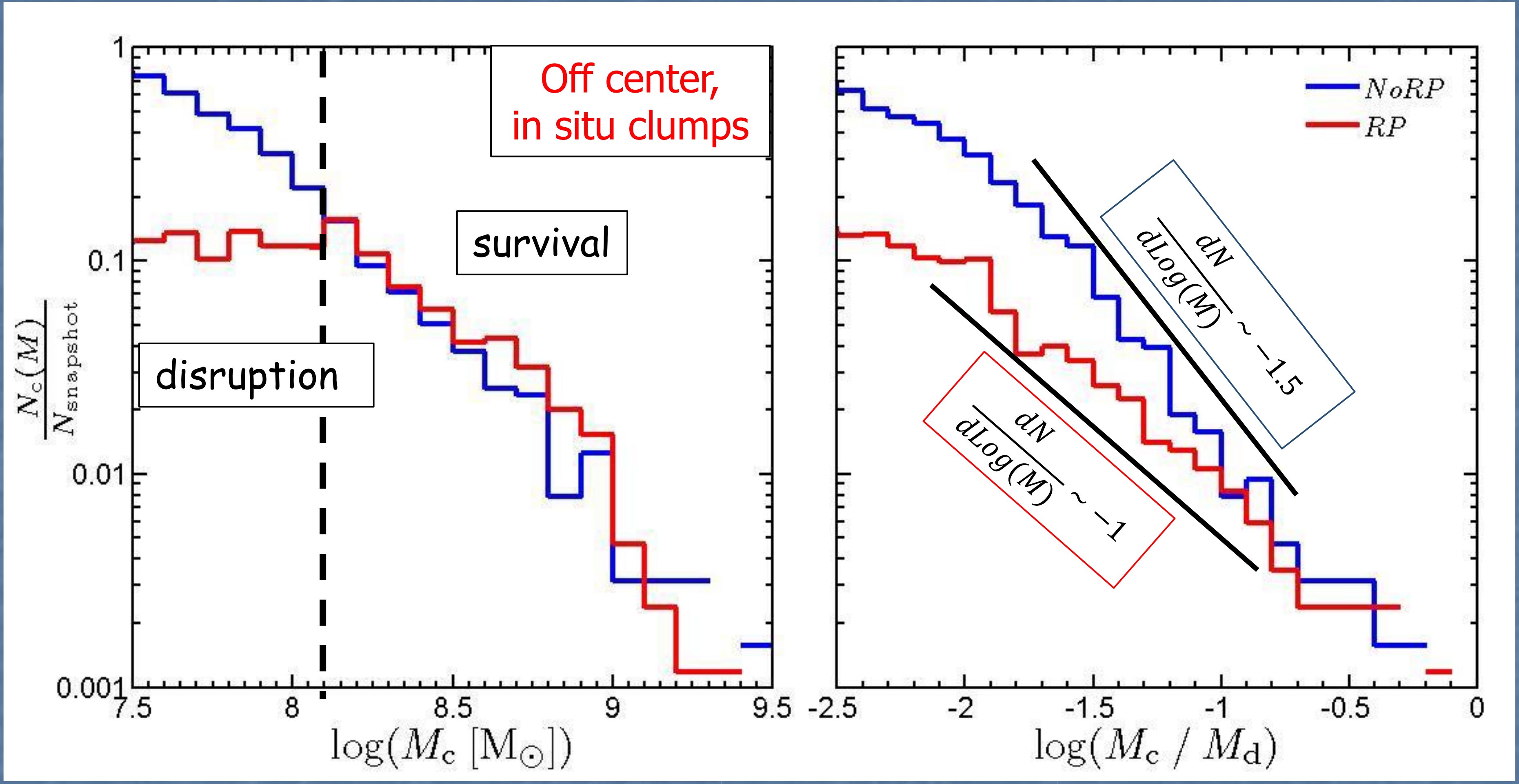


Moody, Guo, N. Mandelker+ 14
N. Mandelker + 14, in prep

Small clumps disrupt

Giant clumps survive

The Effect of Radiative Feedback on Clumps



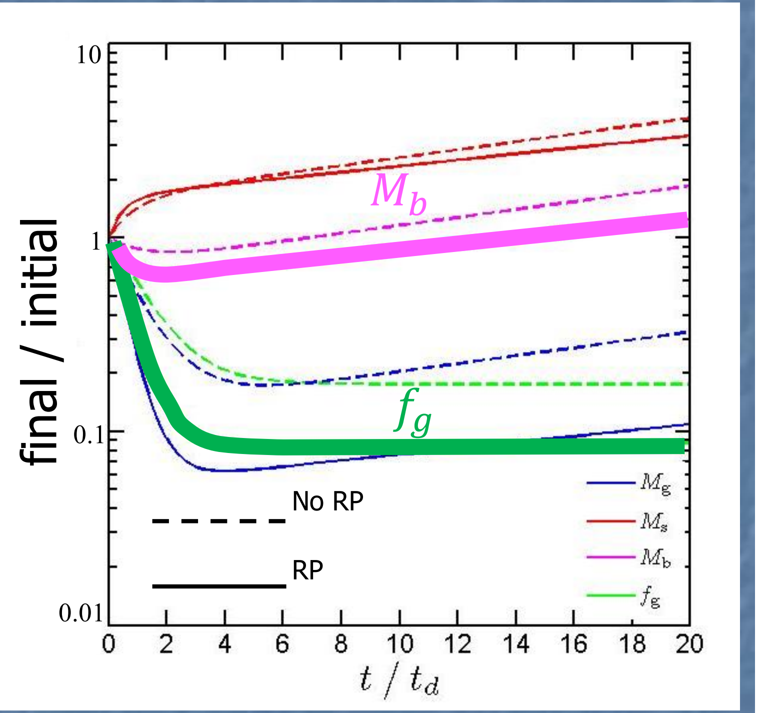
N. Mandelker + 14, in prep

Small clumps disrupt

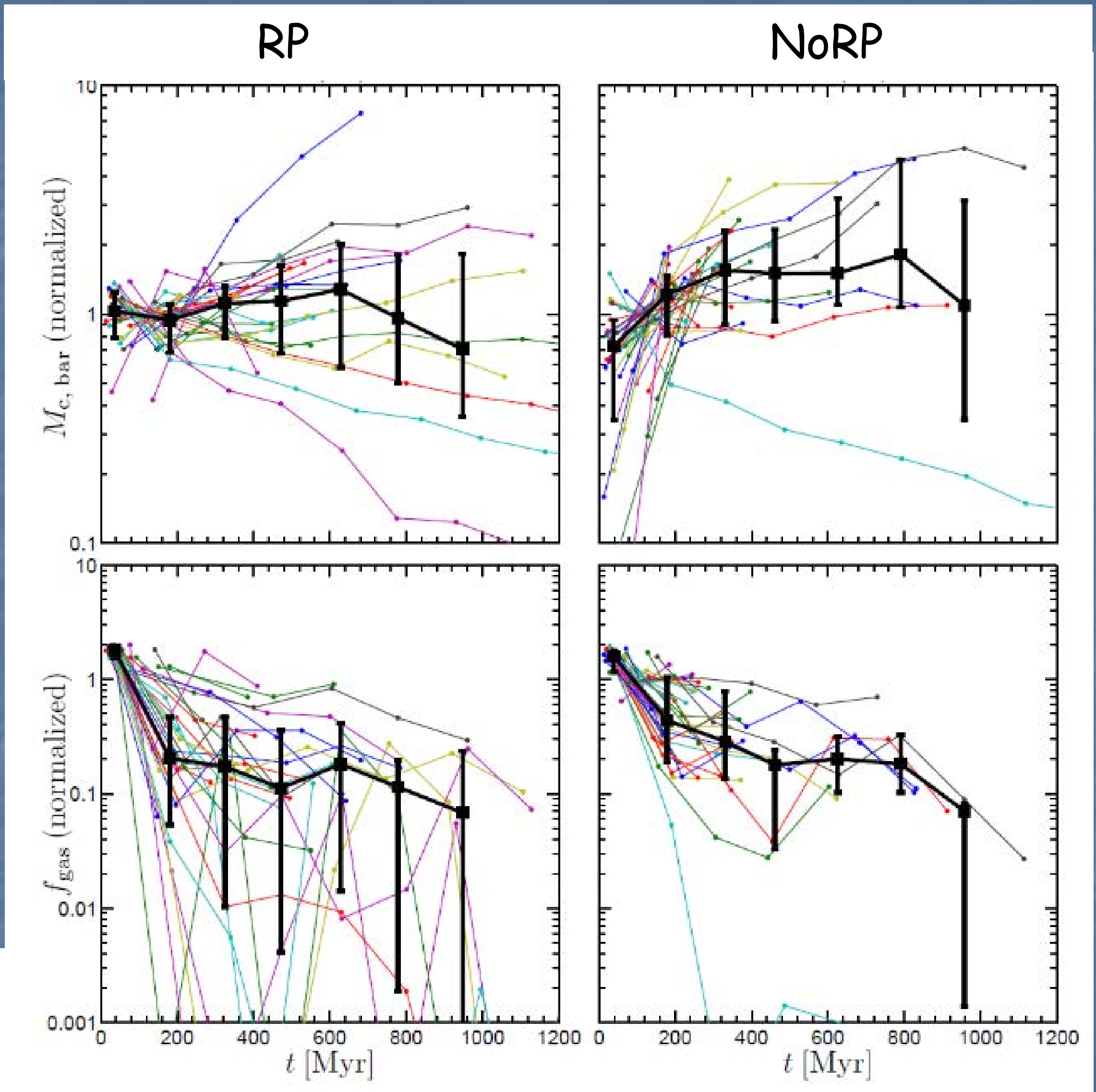
Giant clumps survive

Evolution of Massive Clumps

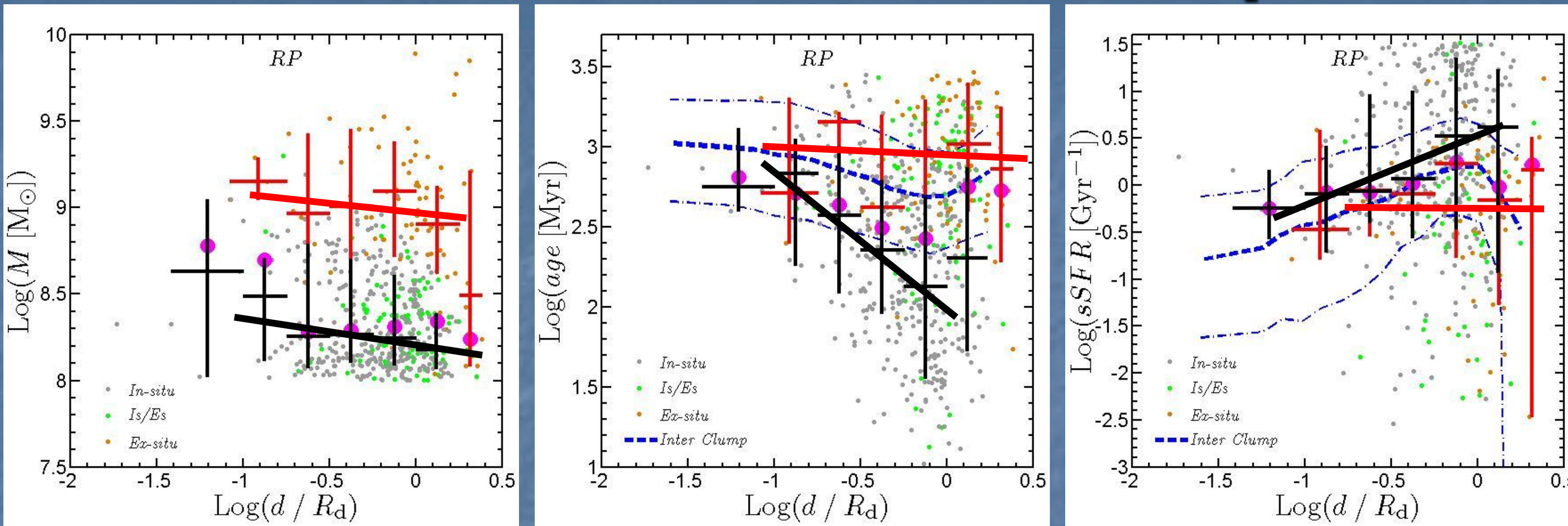
Measure typical values for
$\eta,\ \alpha,\ \epsilon_{sf},\ t_d/t_{ff},\ f_{g0}$
and stellar tidal stripping



Clumps above $10^8\ M_\odot$ that survive longer than $200\ Myr$



Gradients of Massive Clumps

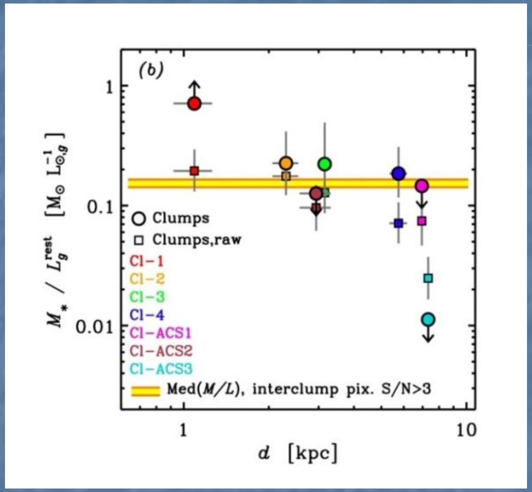


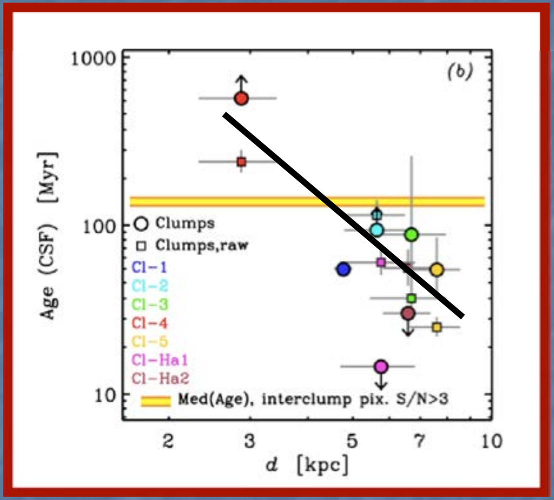
N. Mandelker+ 14 MNRAS in press; N. Mandelker+ 14 in prep

IN-SITU: **Closer to the disc center, clumps are older and with lower sSFR (i.e. redder).**
Age gradient <u>much steeper</u> than the background disc.
Only very weak mass gradient

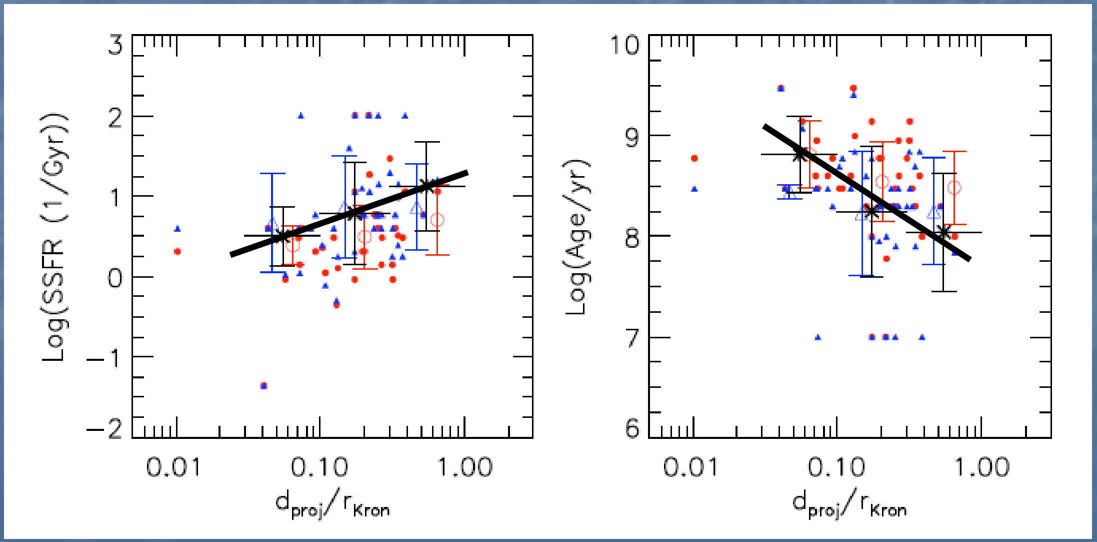
EX-SITU: **Gradients much weaker. Age and sSFR simillar to local disc → May hide overall clump gradient.**
Old clumps with low sSFR in the outer disc → *Ex-Situ*.

Observed Gradients - Evidence for Clump Survival





Forster Schreiber+ 11



Guo+ 12

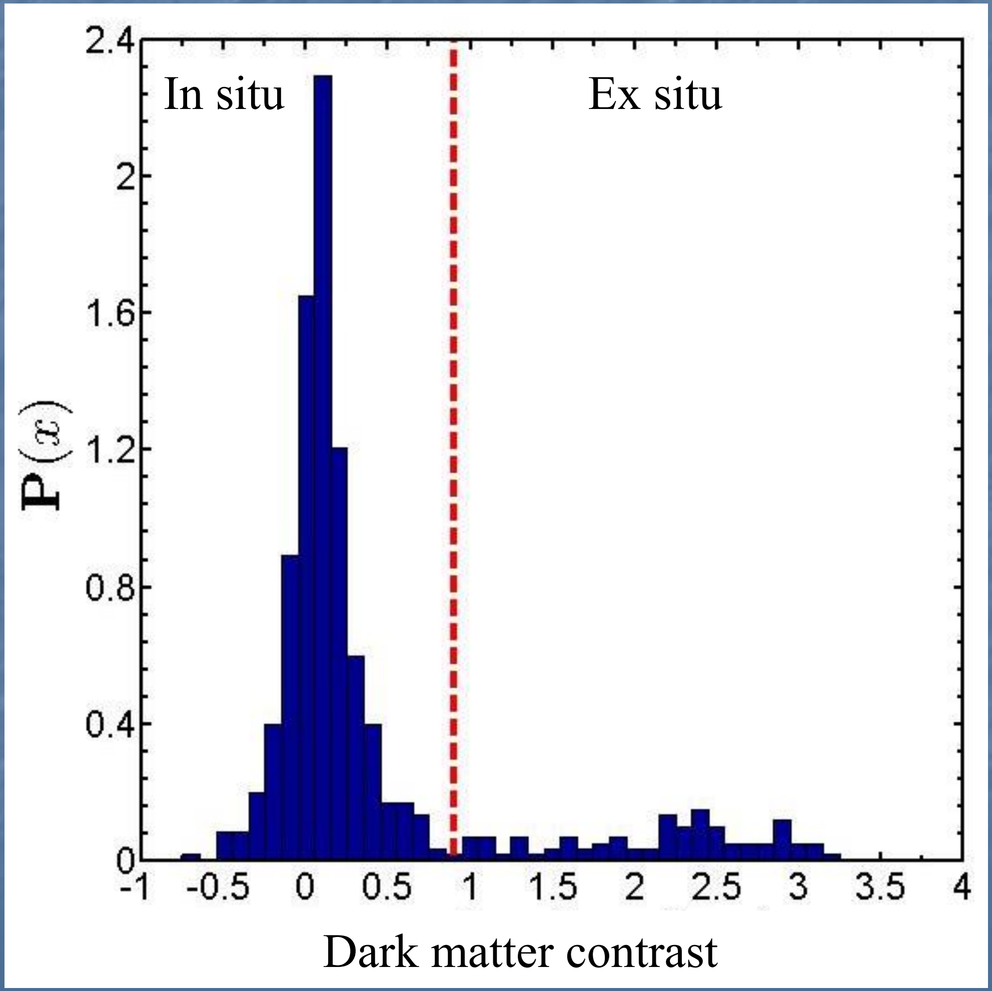
Ex Situ Massive Clumps in RP Simulations

Ex situ clumps are minor mergers with dark matter and external stars

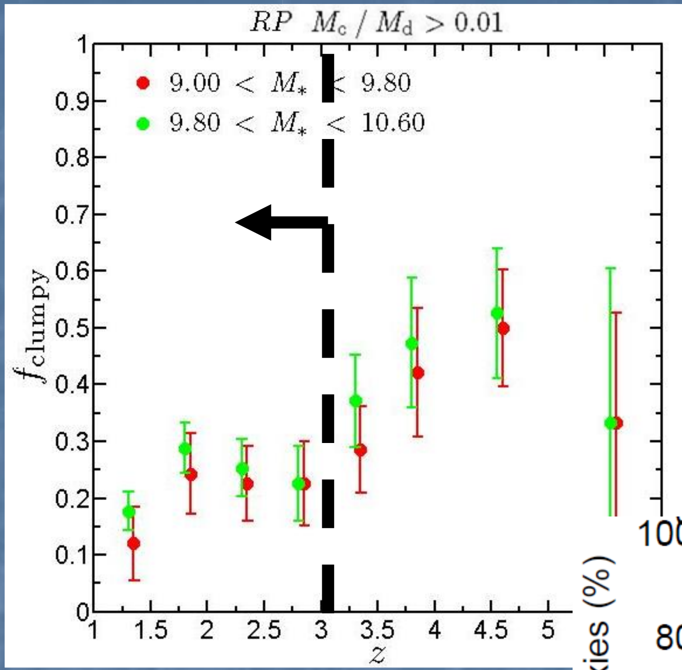
~15% of massive clumps are ex situ

They contain ~50% of the mass in massive clumps

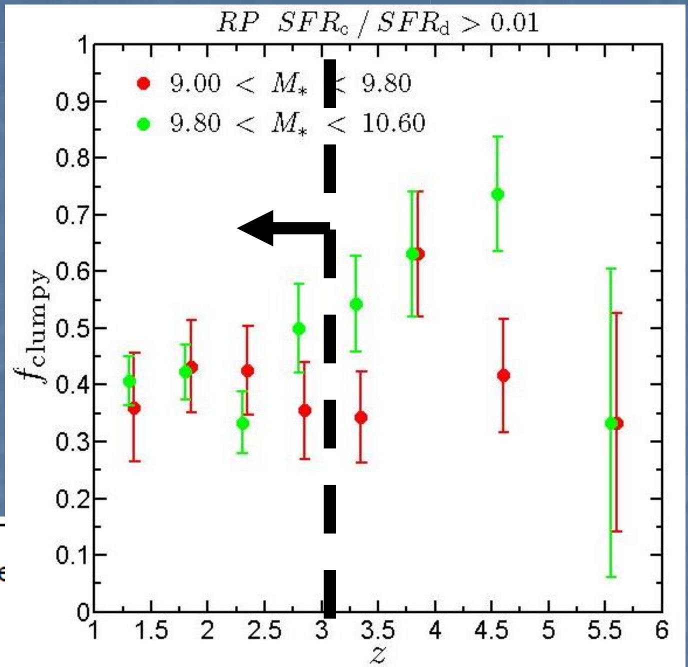
They contain ~35% of the SFR in massive clumps

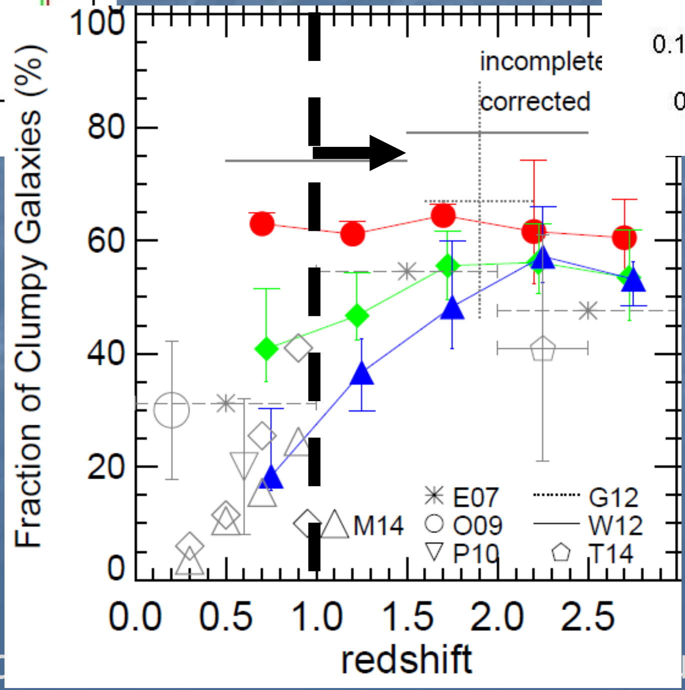


Clumpy Fraction of Discs



Work in progress





$L_{UV,clump} \geq 0.05 L_{UV,gal}$

Guo+ 14, submitted

Disc Clumpiness

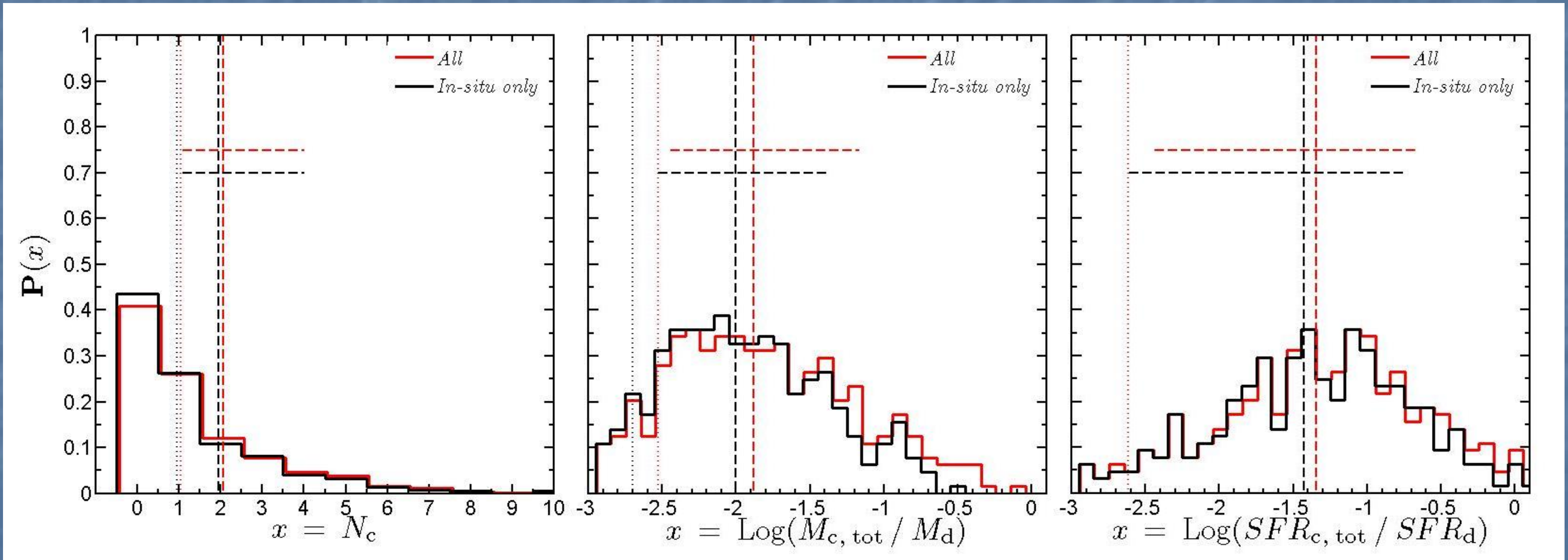
$10.6 > \log(M_*) > 9.0$

60% of discs are clumpy

~2 clumps per galaxy

~0.5-3% of the disc mass

~1-30% of the disc SFR



Mandelker+ 14 in prep

Summary and Conclusions

- Violent Disc Instability (VDI) by intense gas inflow and high density
- In situ giant clumps and transient features form, ex situ clumps merge

- Small clumps disrupt due to feedback
- Massive clumps survive a steady wind with $\eta \sim 1$ and keep roughly constant mass
- Gradients in age and color due to migration and accretion from the disc No mass gradient

- Ex situ clumps are ~15% in number, ~35% in SFR and ~50% in mass
- In situ younger, higher sSFR + gas fraction (bluer), lower mass + metallicity than ex-situ clumps
- ~ half the galaxies are clumpy, with $\leq 30\%$ SFR in the clumps in broad agreement with observations

THANK YOU!!