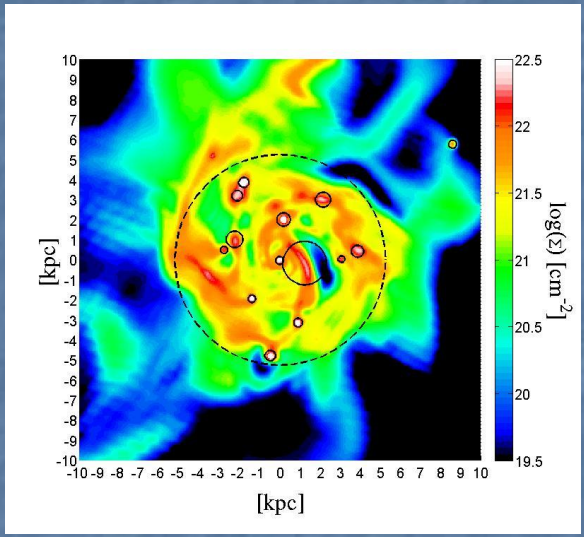
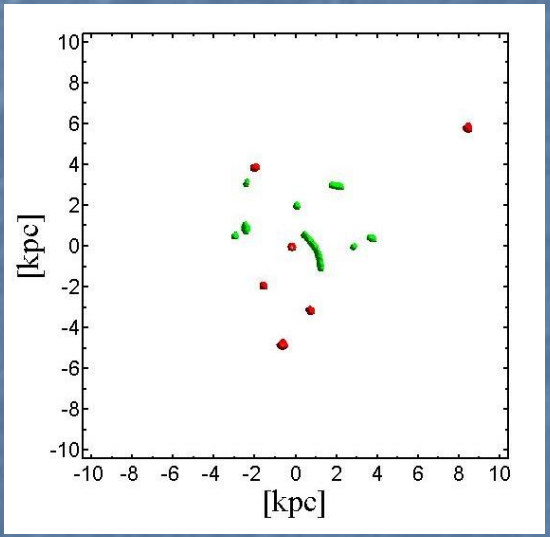
Properties of Giant Clumps in the ART Simulations

In situ vs. Ex situ, Statistics and Migration





Nir Mandelker, H.U.J.I.

UCSC Galaxy Workshop, August 13, 2013

Collaborators: Avishai Dekel, Daniel Ceverino, Dylan Tweed, Joel Primack

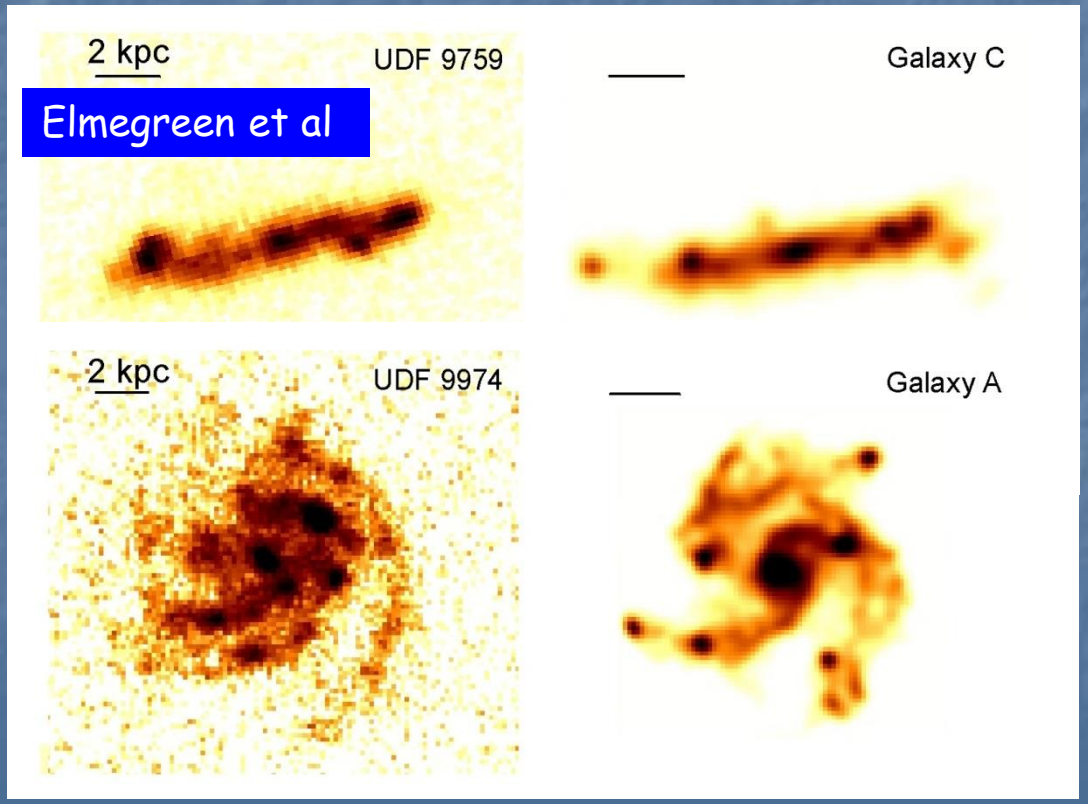
What Do We Know About Clumpy Discs?

Galaxies 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



What Do We Think We Know About Clumpy Discs?

High gas fractions can cause giant clumps to form in situ in the disc through VDI (talk by A. Dekel)

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

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

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

Clumpy discs may also be merging systems

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

Krumholz, Dekel 2010 Dekel, Krumholz 2013 Bournaud+ 13

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?
- Can these be distinguished from mergers?
- Do clumps survive feedback and migrate to the disc center?
- Do they contribute to bulge formation?

Galaxy Formation Simulations with ART

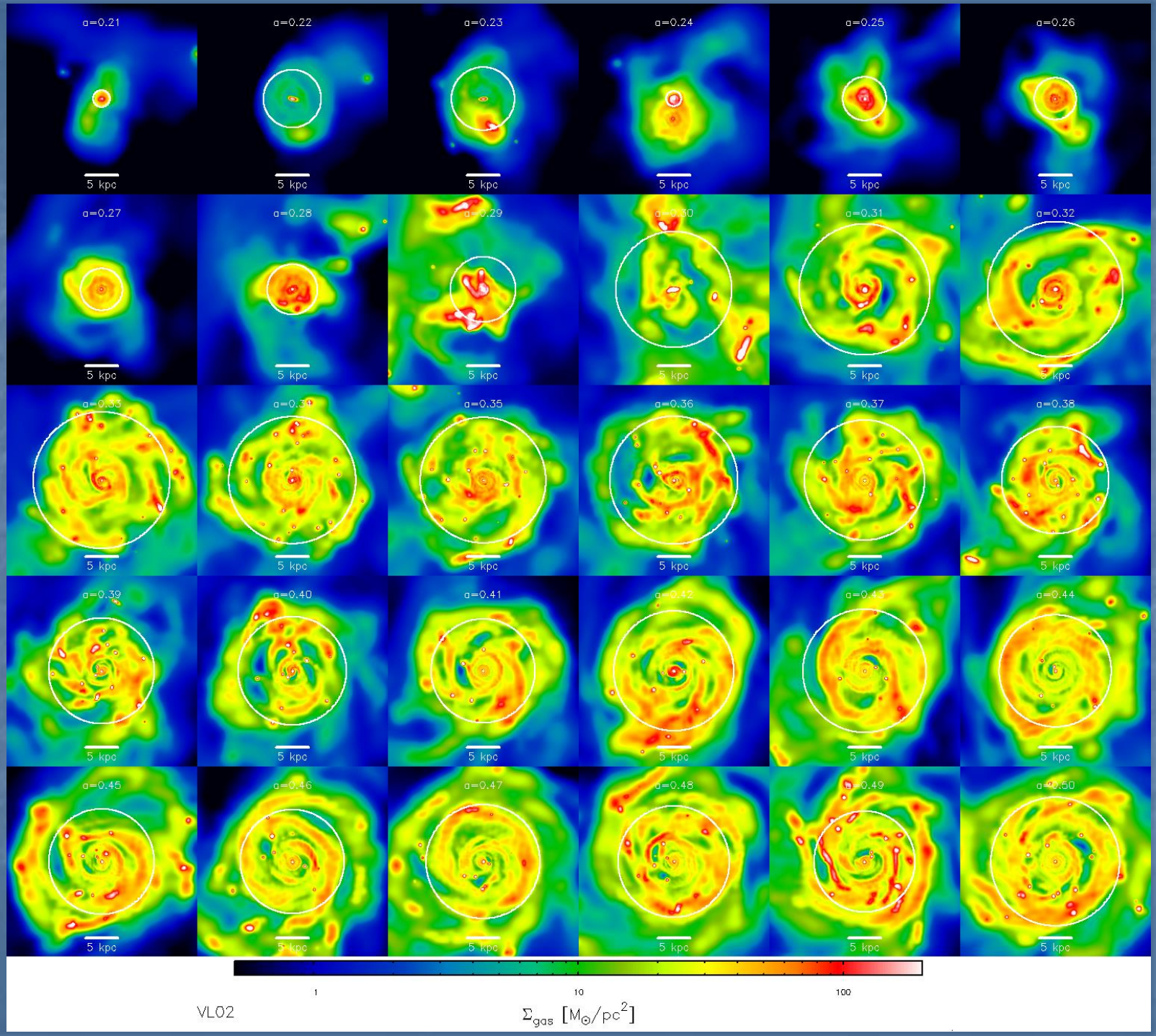
- Adaptive Mesh Refinement (grid based) code: HYDRO-ART (Kravtsov et al 1997, Kravtsov 2003)
- Gas Cooling, Star Formation, Stellar Feedback, Metal Enrichment (Ceverino & Klypin 2009; Ceverino, Dekel and Bournaud 2010)
  - Cooling below 10^4 K (minimum temperature of 300 K)
  - Thermal feedback (supernovae, stellar winds) + runaway stars
- Maximum resolution of 35-70 pc → clumps are resolved

>750 snapshots from ~30 galaxies in the redshift range

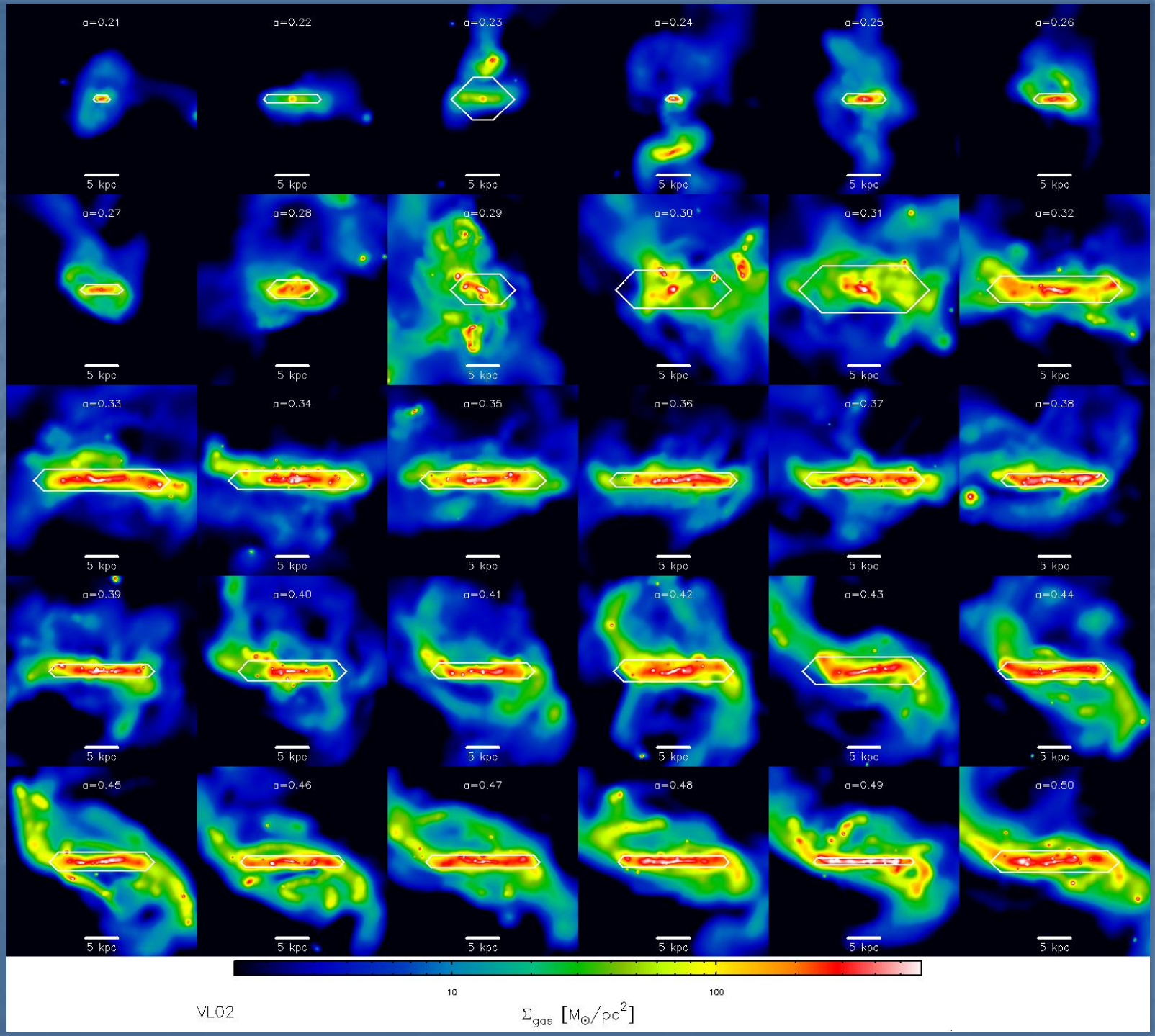
$1 \leq z \leq 4$

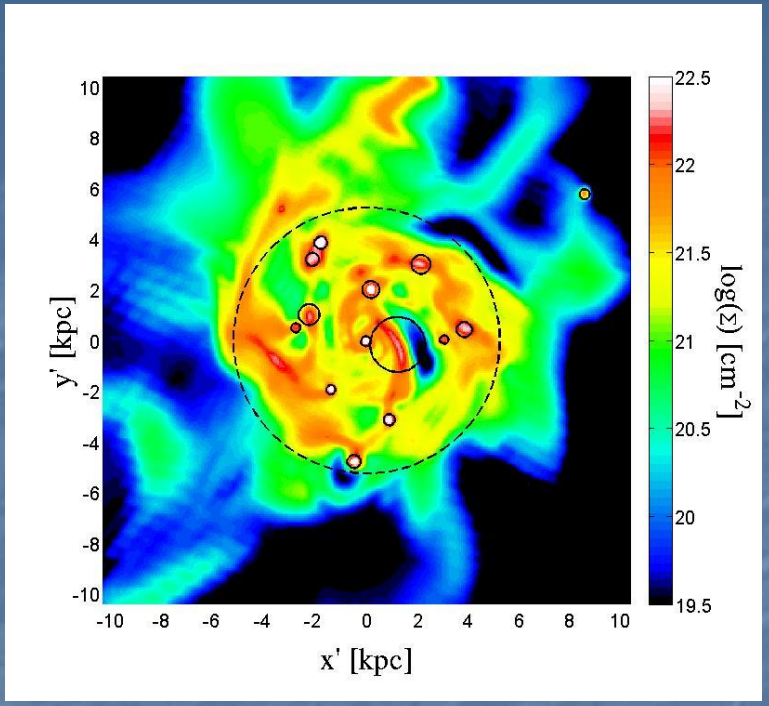
Identify clumps in **3D gas**

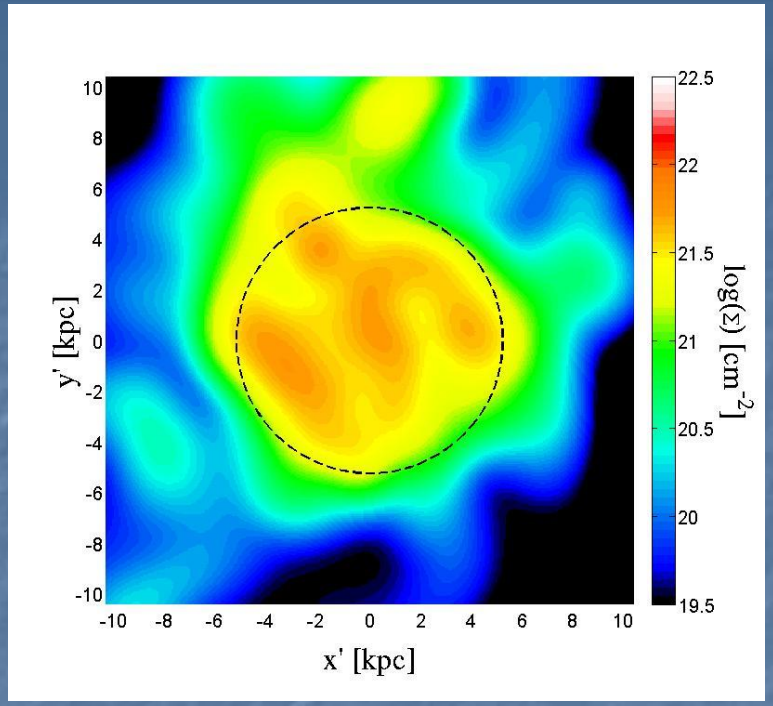
VL02 from z=3.8 to z=1



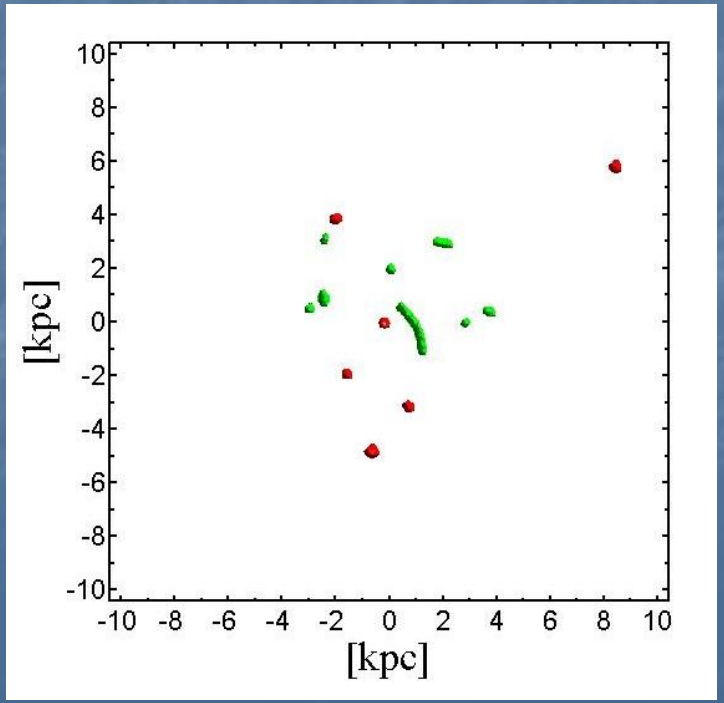
VL02 from z=3.8 to z=1







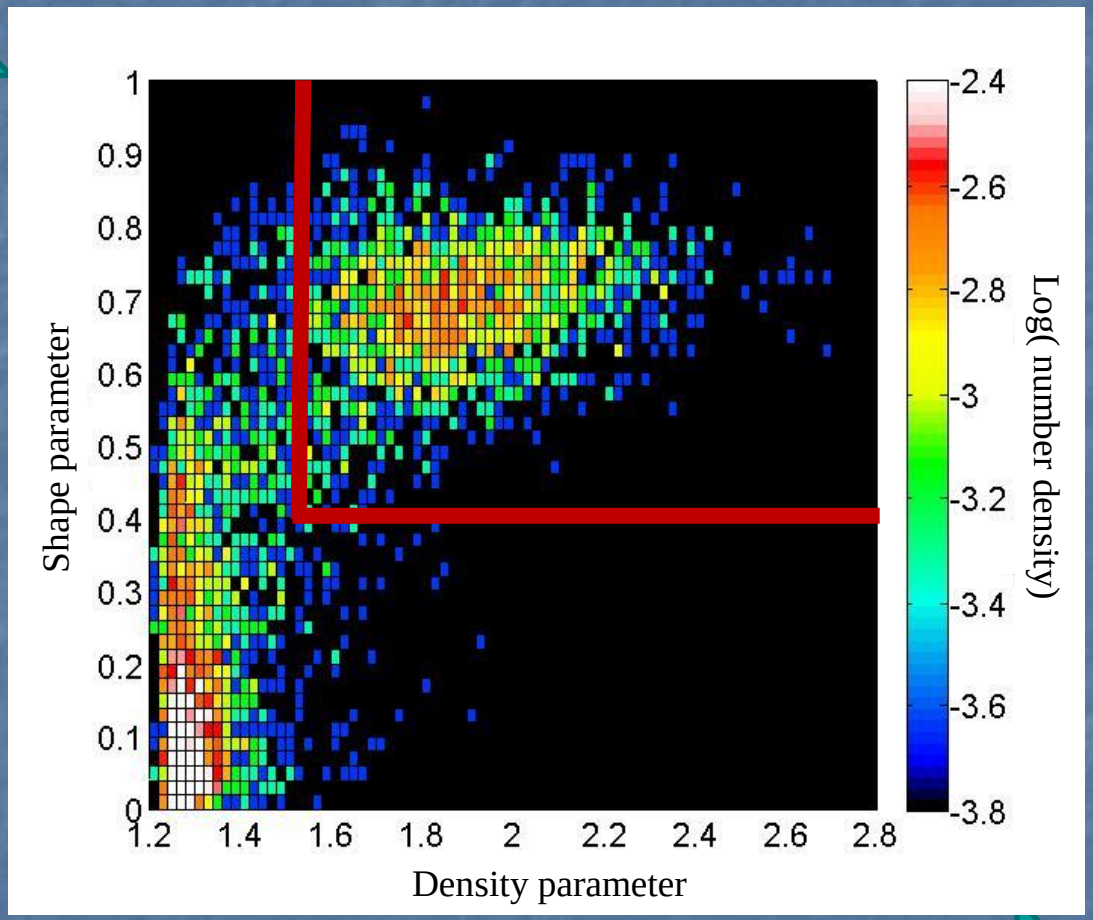
MW3
at z=2.3



Mandelker+ 13 in prep

Clumps Come in All Shapes and Sizes!

SPHERICAL

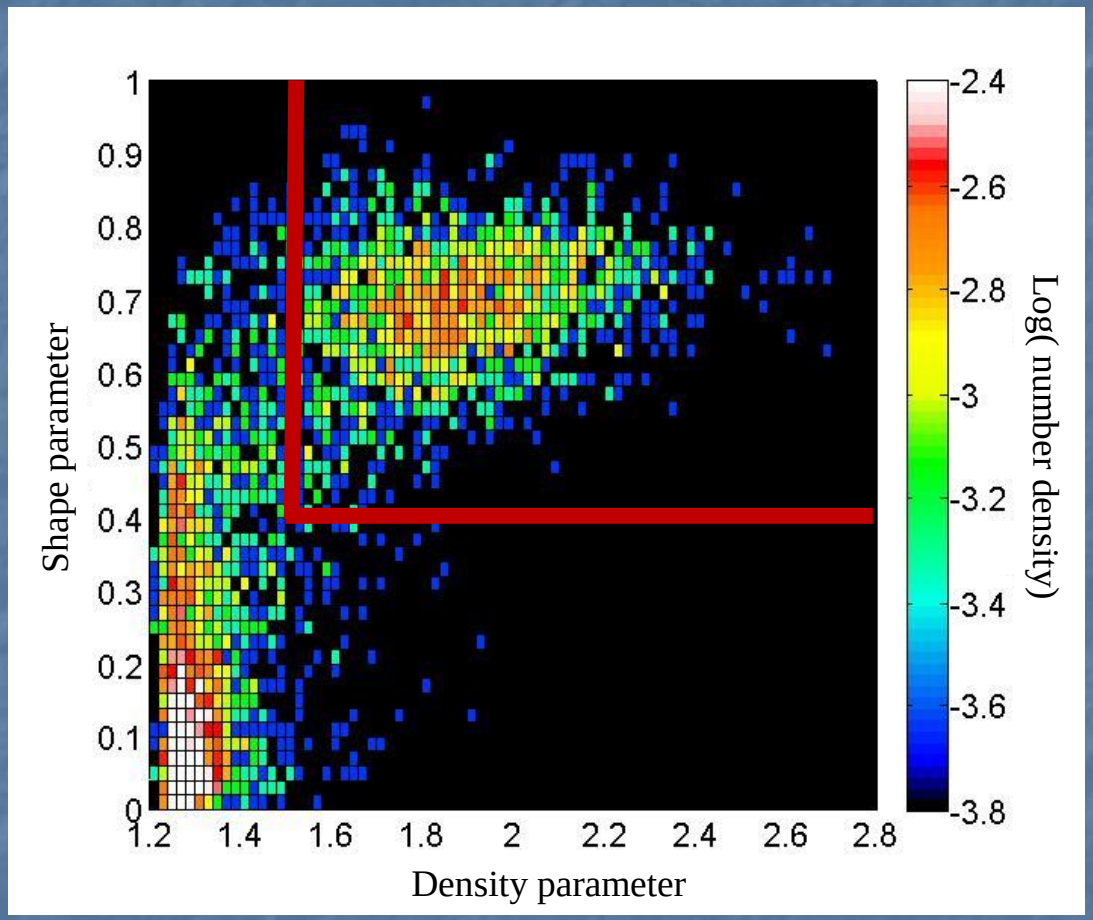


FILAMENTARY

HIGHER CONTRAST

N. Mandelker+ 13

Clumps Come in All Shapes and Sizes!



Diffuse or Elongated

Compact & Spherical

~ 45 % in number

> 90 % in mass

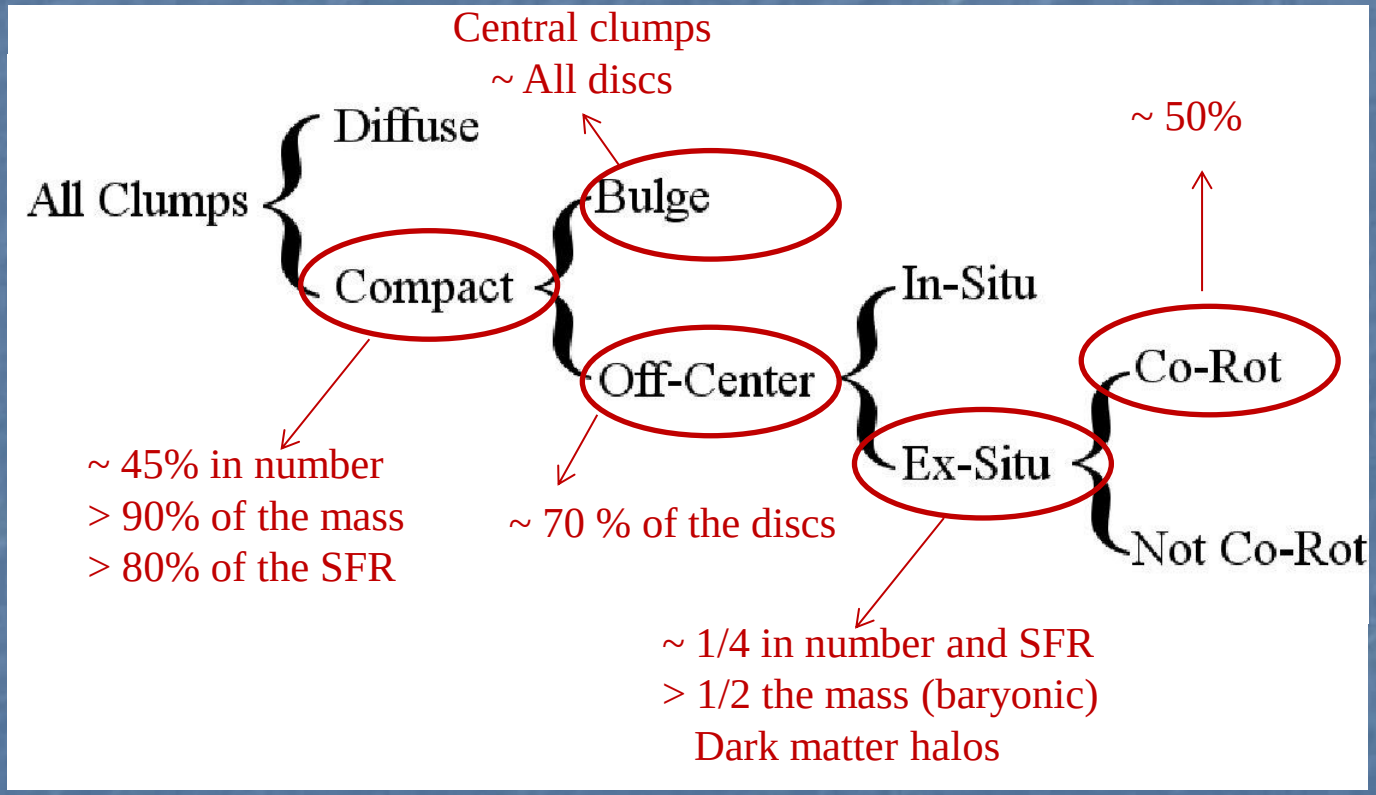
> 80 % in SFR

~ 2000 clumps

N. Mandelker+ 13

Clumps in the Simulations

Gas discs in ~83% of the galaxies



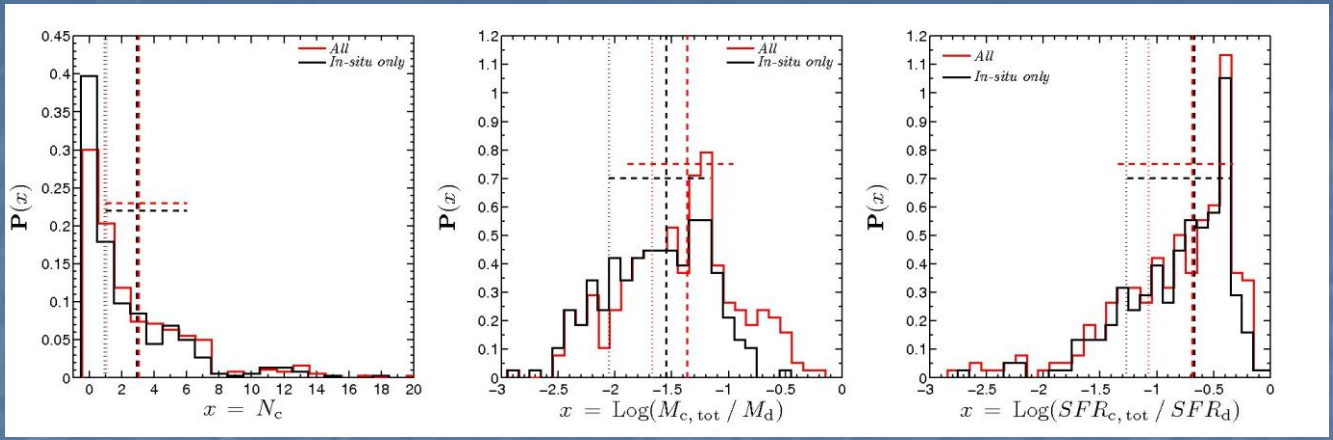
Mandelker+ 13 in prep

Disc Clumpiness

$1 < z < 3$, $\log(M_d) > 10.25$

70% of discs are clumpy
60% undergoing VDI

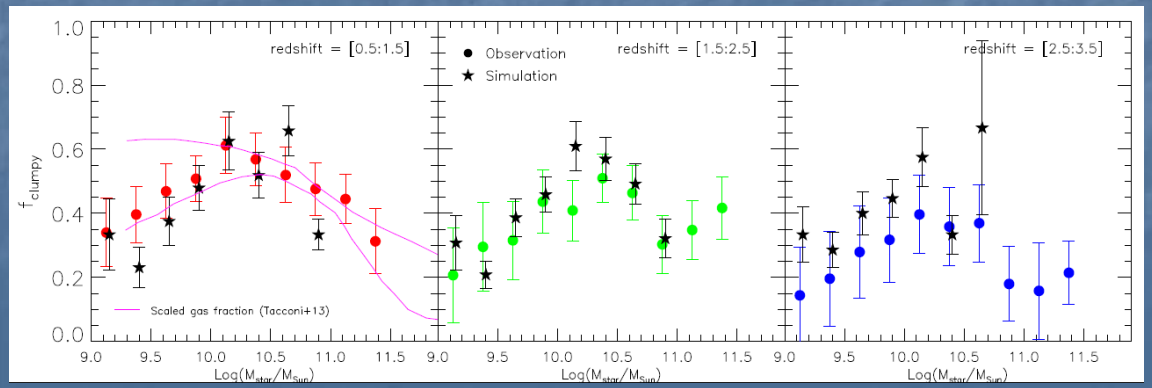
~3-4 clumps per galaxy
~1-7% of the disc mass
~5-45% of the disc SFR

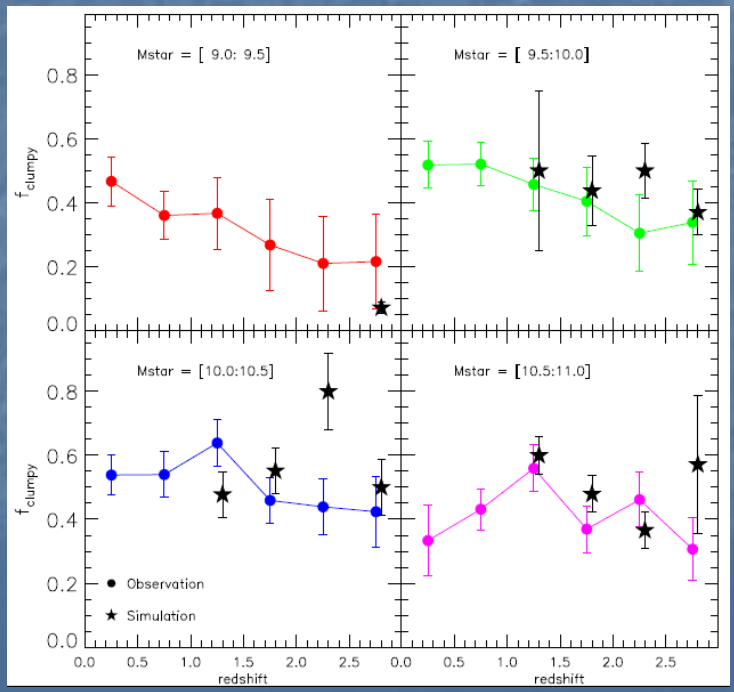


Mandelker+ 13 in prep

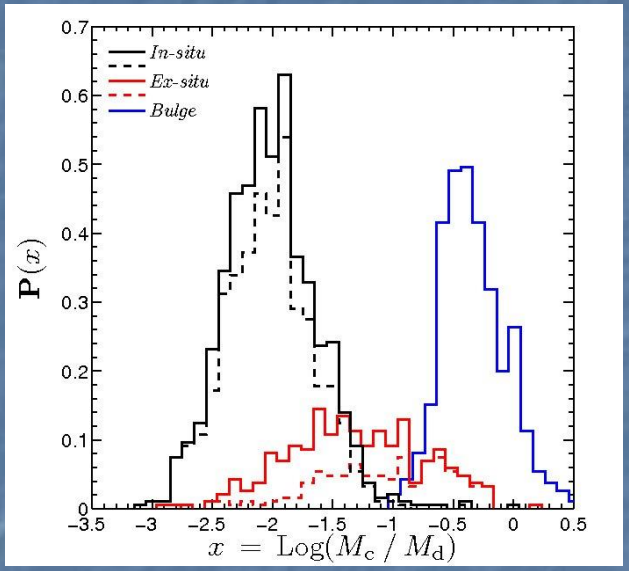
Clumpy fraction agrees with observations

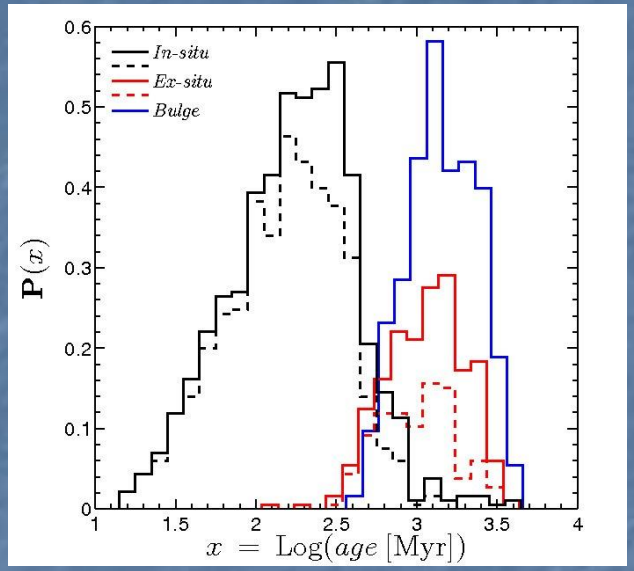
Guo+

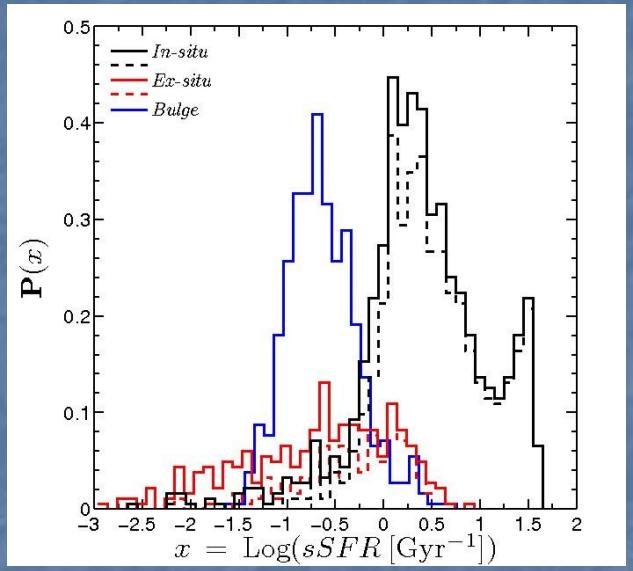




Clump Properties



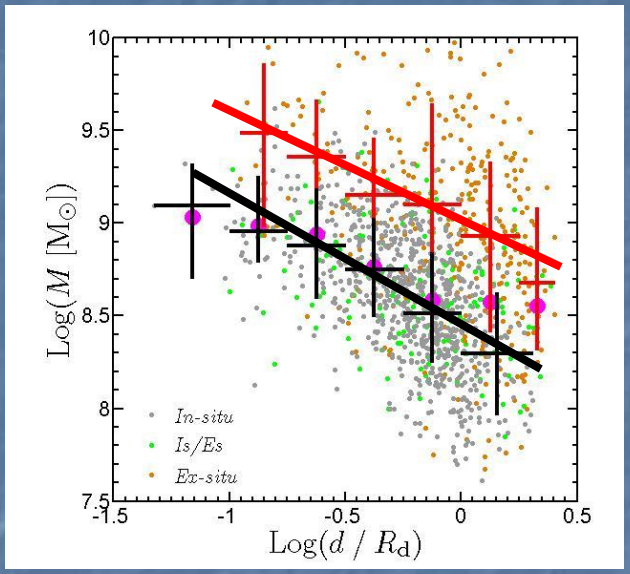


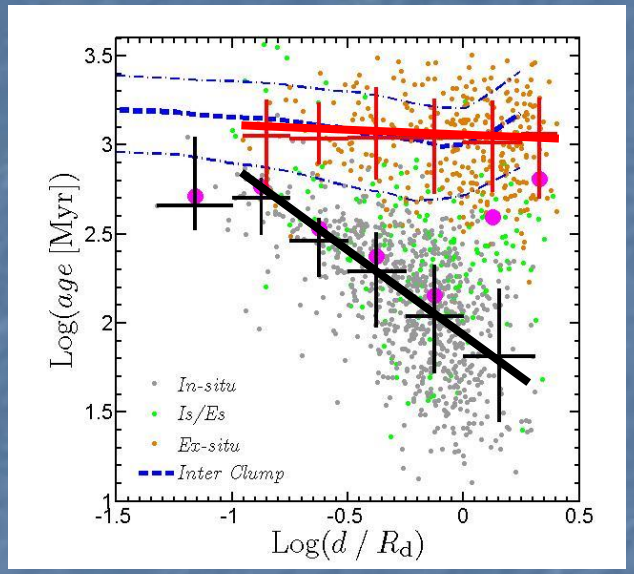


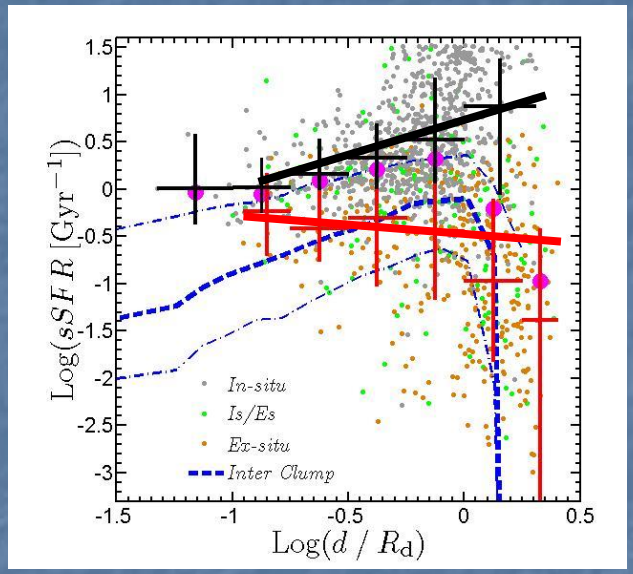
IN-SITU **CLUMPS ~ 1 - 2% OF THE DISC MASS**	**~ 150 - 300 MYR OLD (MIGRATION TIME)**	**HIGH SSFR (BLUE)**
EX-SITU **CLUMPS FACTOR ~ 2 - 4 MORE MASSIVE**	**AS OLD AS THE DISC ~ 1 GYR**	**CAN HAVE MUCH LOWER SSFR (REDDER)**
BULGE **CLUMPS FACTOR ~ 10 MORE MASSIVE**	**>1 GYR OLD**	**LOW SSFR (REDDER)**

Mandelker+ 13 in prep

Clump Gradients





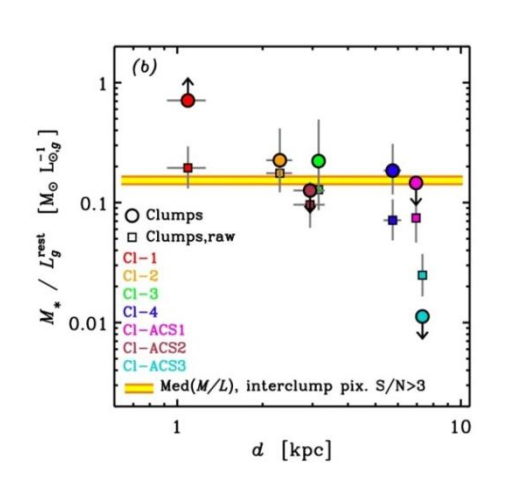


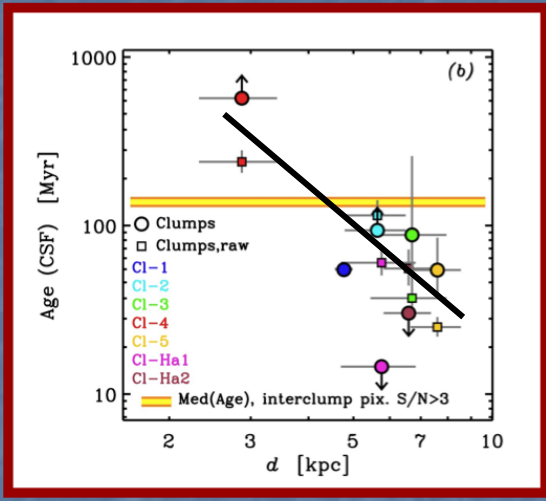
IN-SITU: **Closer to the disc center, clumps are more massive, older and with lower sSFR (i.e. redder).**
Age gradient much steeper than the background disc.
Consistent with clump survival, migration and accretion.

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*.

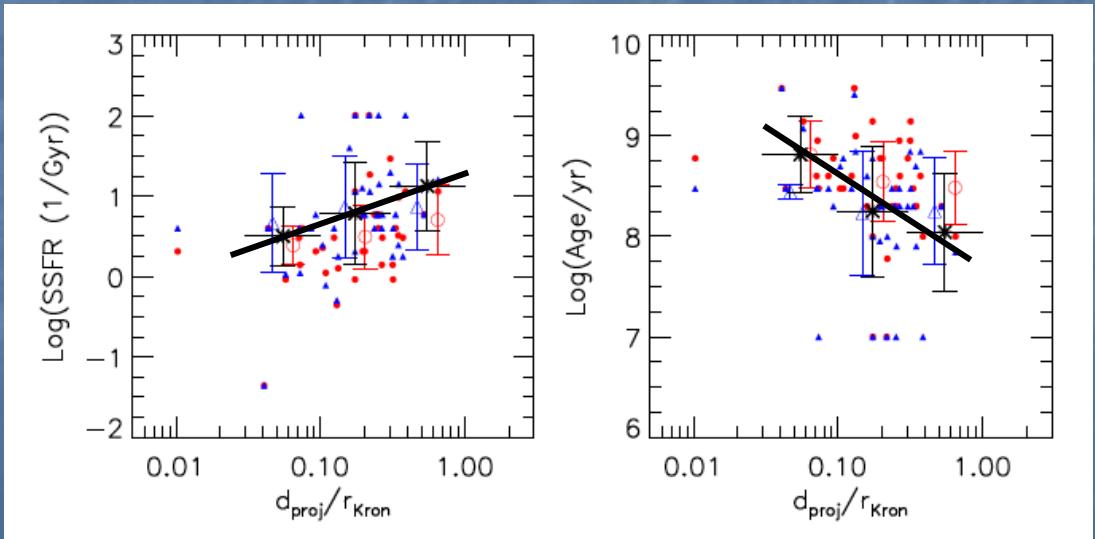
Mandelker+ 13 in prep

Observed Gradients - Evidence for Clump Survival?





Forster Schreiber+ 11



Guo+ 12

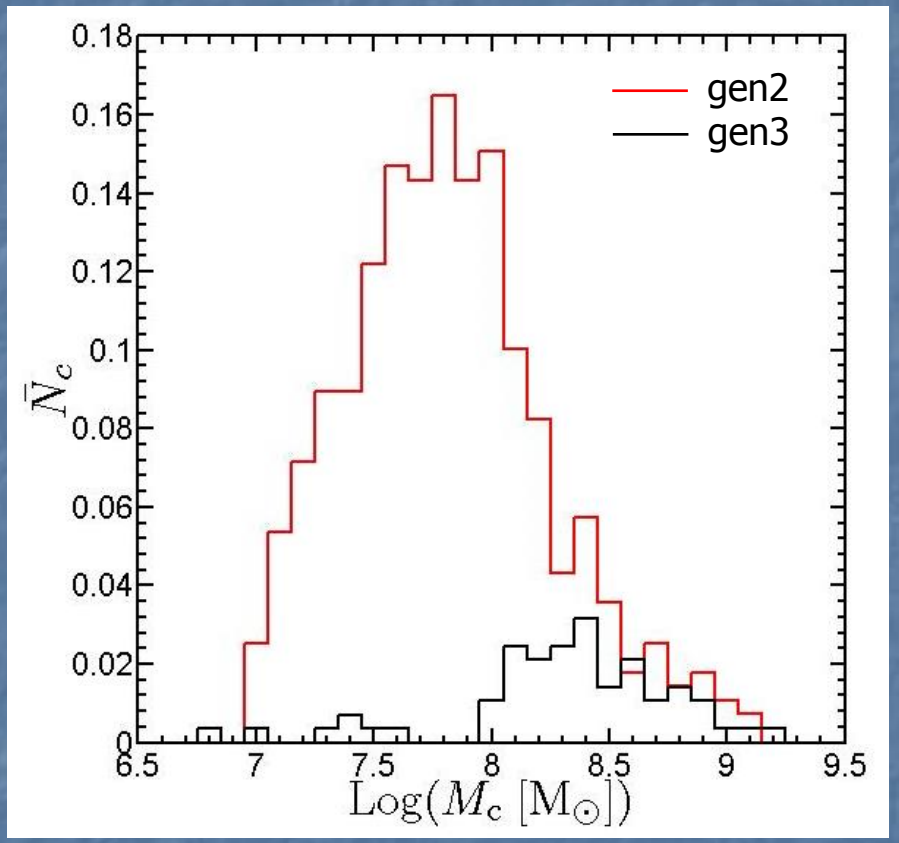
Preliminary

New suites of simulations (30 galaxies each):

Generation 2: Twice the resolution + improved recipe for star formation

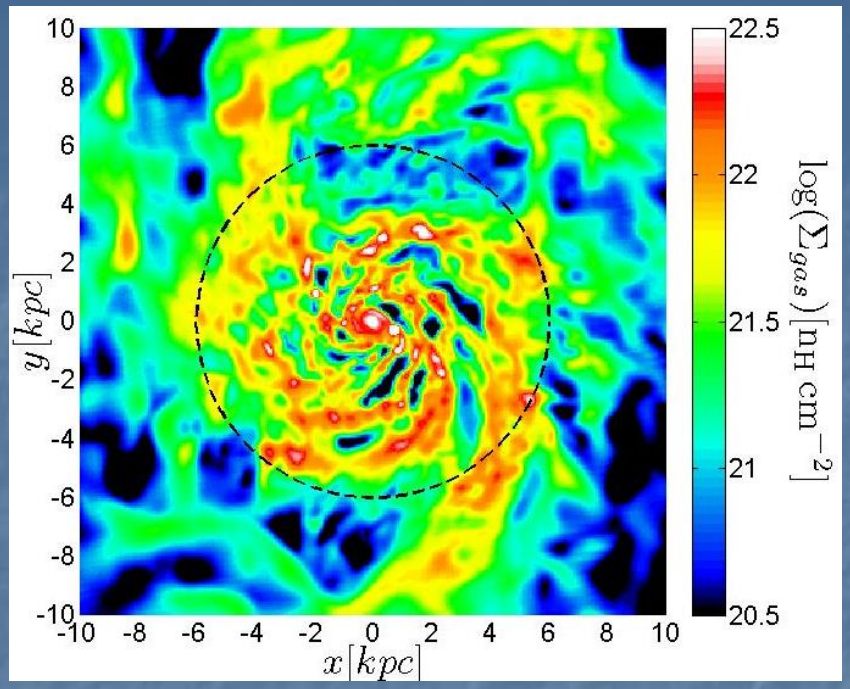
Generation 3: Gen2 + non-thermal radiative feedback

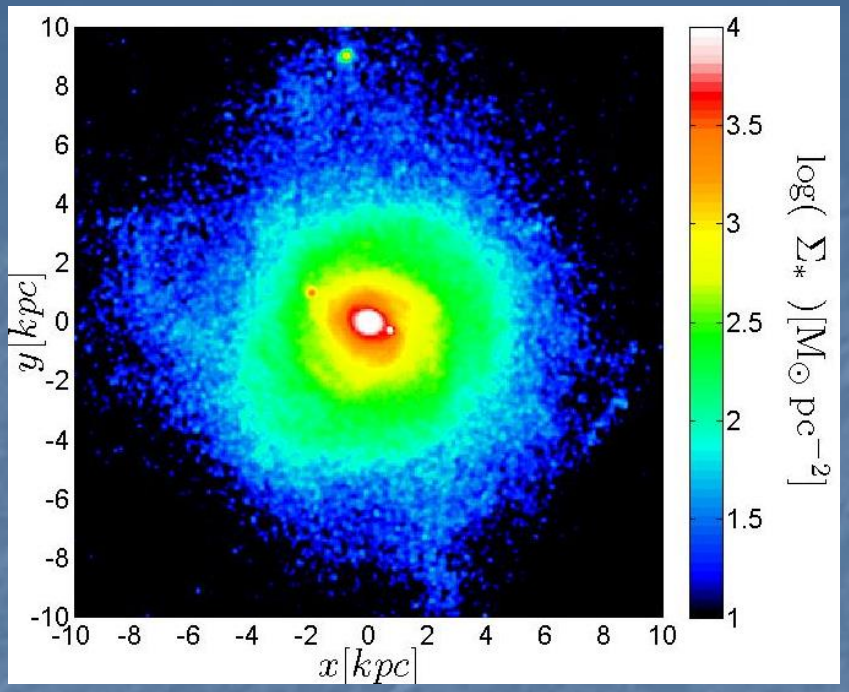
Up to factor 10 **less** massive than generation 1 simulations ($M_{vir} \sim 10^{11} M_{\odot}$ @ $z \sim 2$)

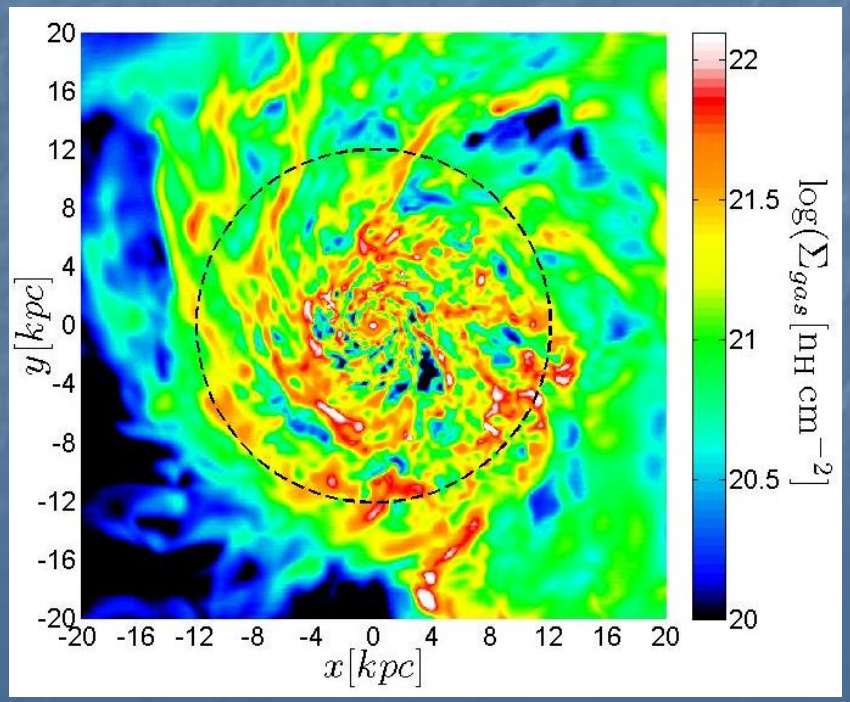


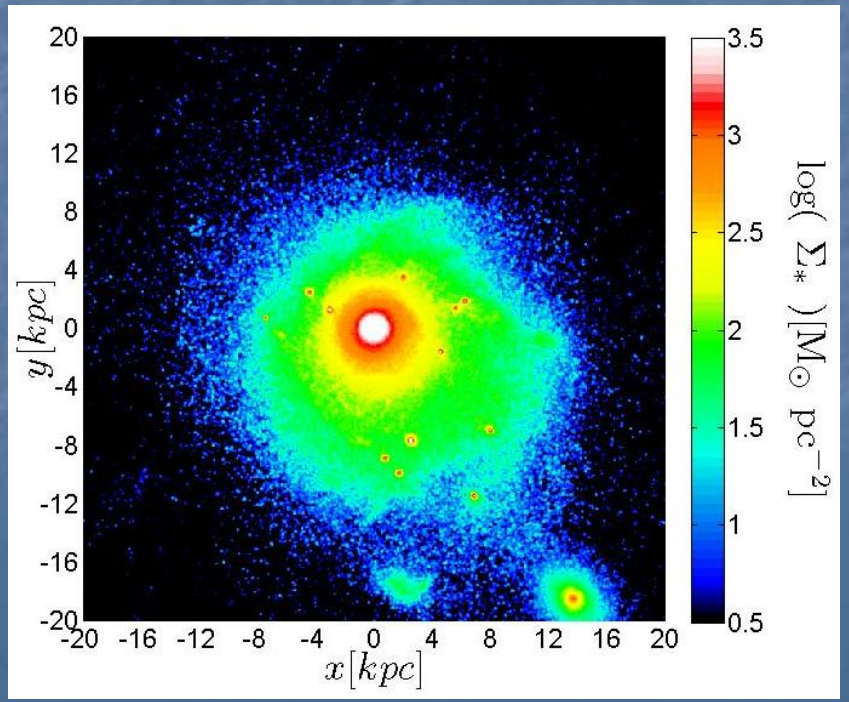
Using the same algorithm to detect clumps in 3D gas

Beware: Stellar clumps can differ from gas clumps


$y\,[kpc]$
$x\,[kpc]$
$\log(\Sigma_{gas})\,[\mathrm{n_H\ cm^{-2}}]$


$y\,[kpc]$
$x\,[kpc]$
$\log(\ \Sigma_{*}\ )\,[\mathrm{M_\odot\ pc^{-2}}]$


$y\,[kpc]$
$x\,[kpc]$
$\log(\Sigma_{gas}\,[\mathrm{n_H\ cm^{-2}}]$


$y\,[kpc]$
$x\,[kpc]$
$\log(\ \Sigma_{*}\ )\,[\mathrm{M_\odot\ pc^{-2}}]$

Summary and Conclusions

- Violent Disc Instability (VDI) causes in-situ giant clumps and transient features
- In situ clumps are ~70% in number and SFR, but only ~45% in mass
- In situ younger, higher sSFR + gas fraction (bluer), lower mass + Z than ex-situ clumps
- Strong gradients due to migration and accretion from the disc
- Massive clumps survive feedback from radiation pressure

Coming up

- Further study of new simulations with / without radiation pressure
- Comparison of gas and stellar clumps in 3D/2D
- Modeling clump evolution with inflows and outflows

THANK YOU!!