Violent Disk Instability: Clump Formation and Survival

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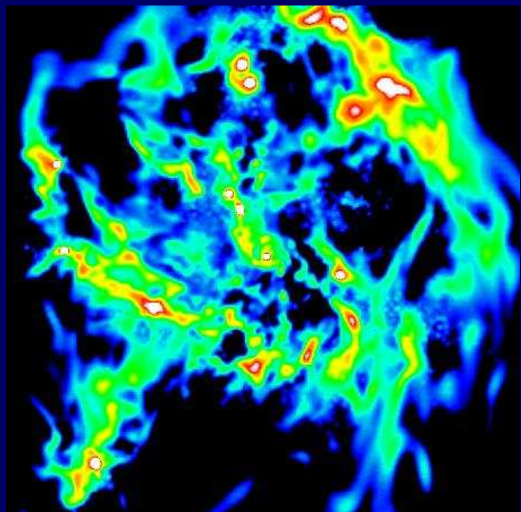
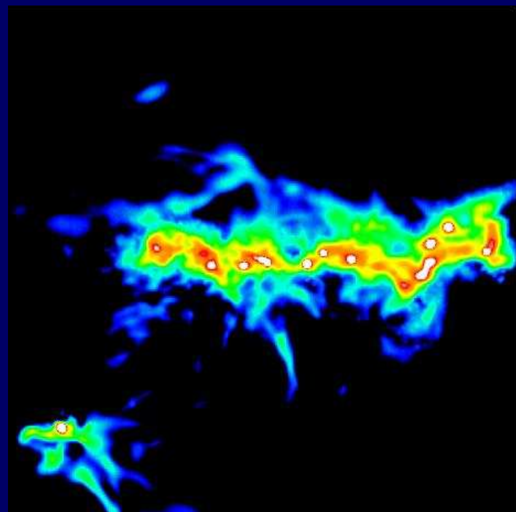
The Hebrew University of Jerusalem & UCSC

CANDELS, UCSC, July 2017

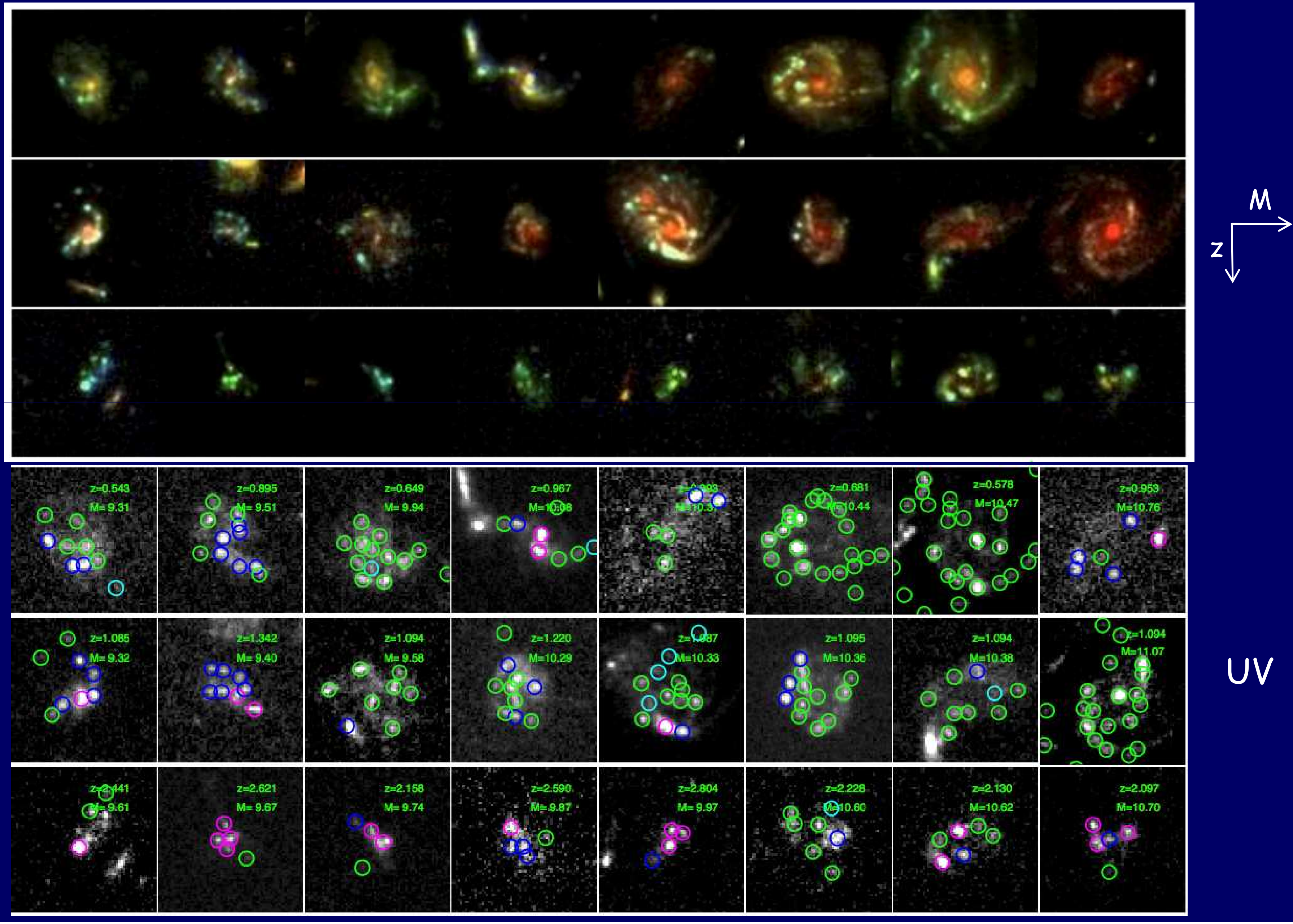
Outline

1. Clump formation: stimulated violent disk instability (VDI)
   Q>1 - compressive turbulence by compressive tides

2. Clump evolution: survival versus disruption
   theory vs observations

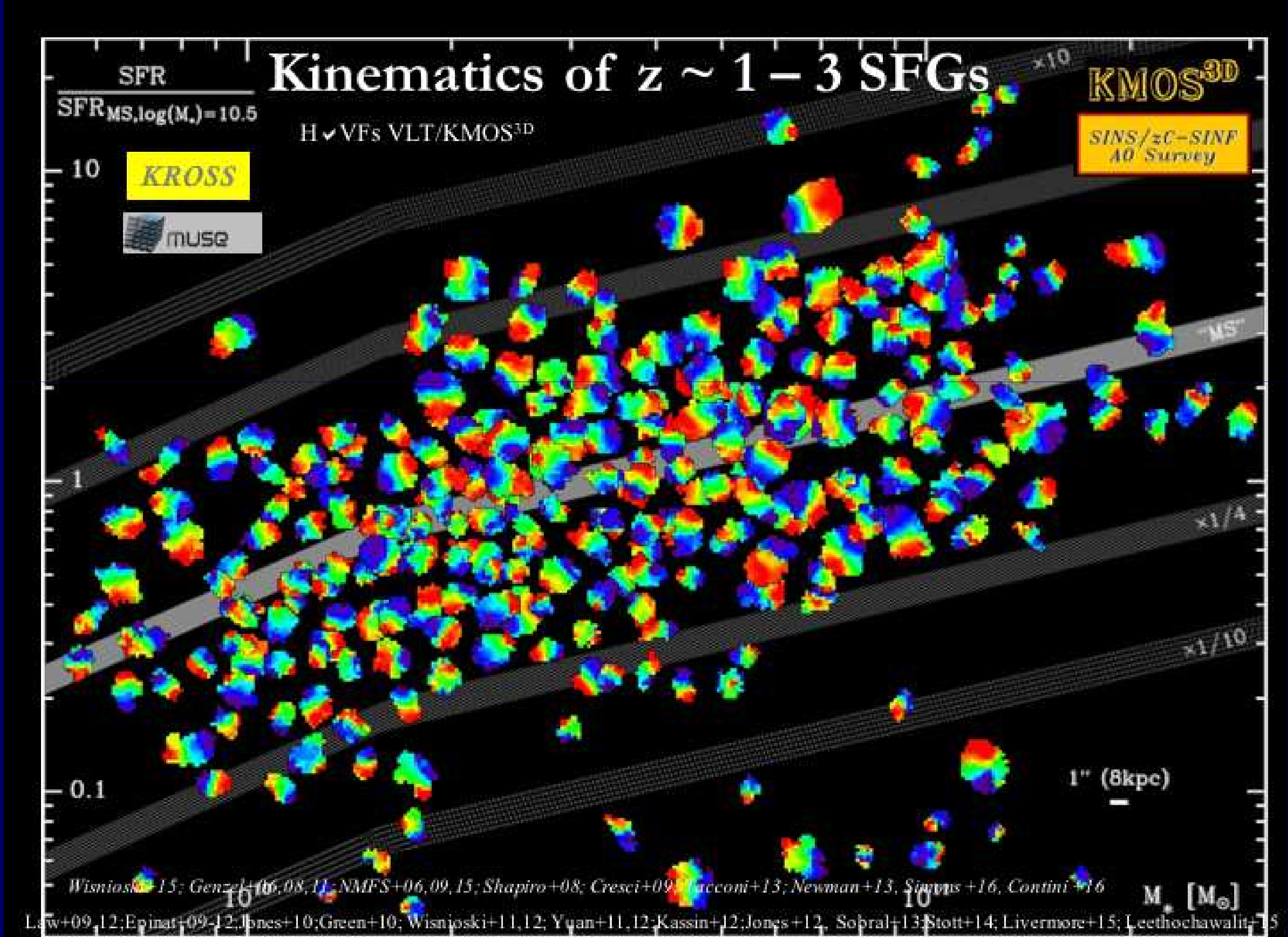
High-z Clumpy Disks

Guo+ 17 CANDELS
3187 clumps in 1269 galaxies, z=0.5-3



Most hi-z SFGs are Rotating Turbulent Disks

Wisnioski+15, Stott+16, Contini+16



AMR Cosmological Simulations

Cosmological simulations VELA (Ceverino, Dekel, Primack)
zoom-in individual galaxies, ART code (Kravtsov, Klypin)
25 pc resolution, stellar+SN+radiative fdbk (6x35 galaxies)

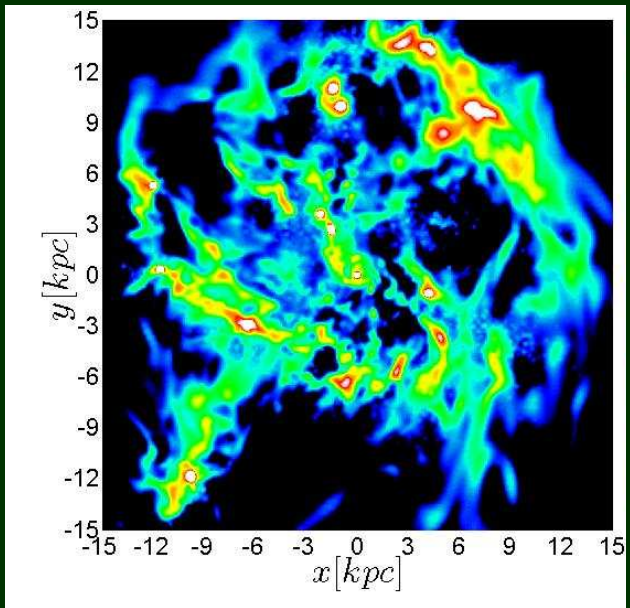
Isolated galaxies, 1-10 pc resolution, RAMSES (Bournaud+)

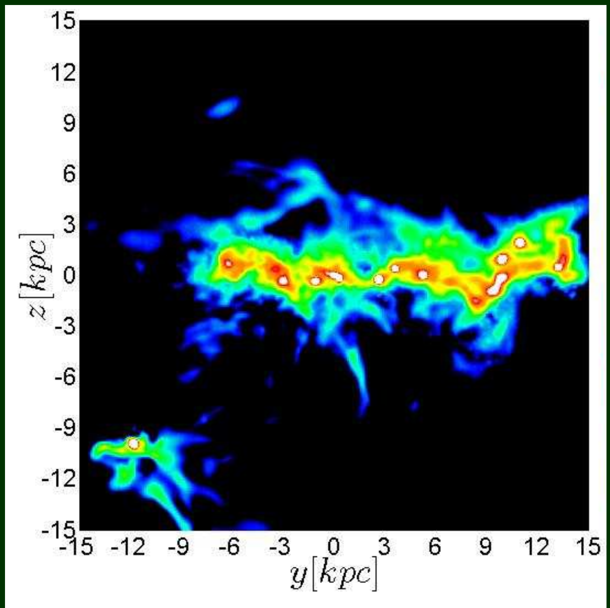
Collaborators on disk instability:
Ceverino, Forbes, Guo, Mandelker, Inoue
Bournaud+, Burkert+,Teyssier+, Klypin+, Krumholz+,
Primack+, Genzel+, Faber & Koo+, Carollo+, …

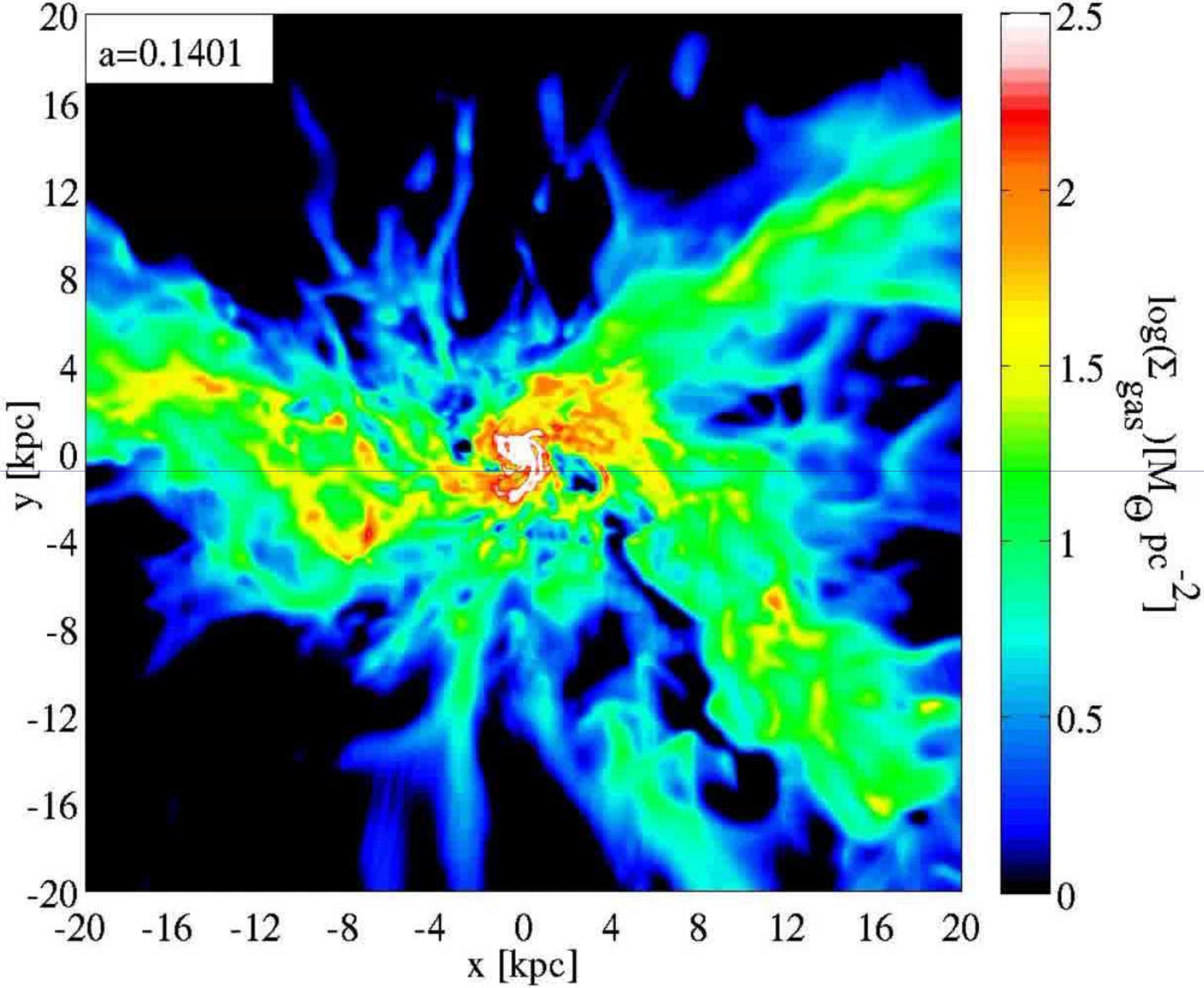
Clump Formation

Violent Disk Instability- Nonlinear and Stimulated

Dekel, Sari, Ceverino 2009; Ceverino+ 2010, 2012
Mandelker+ 2014, 2016; Moody+ 2014; Forbes+ 2014a,b
Inoue+ 2015, Mandelker+ 2017





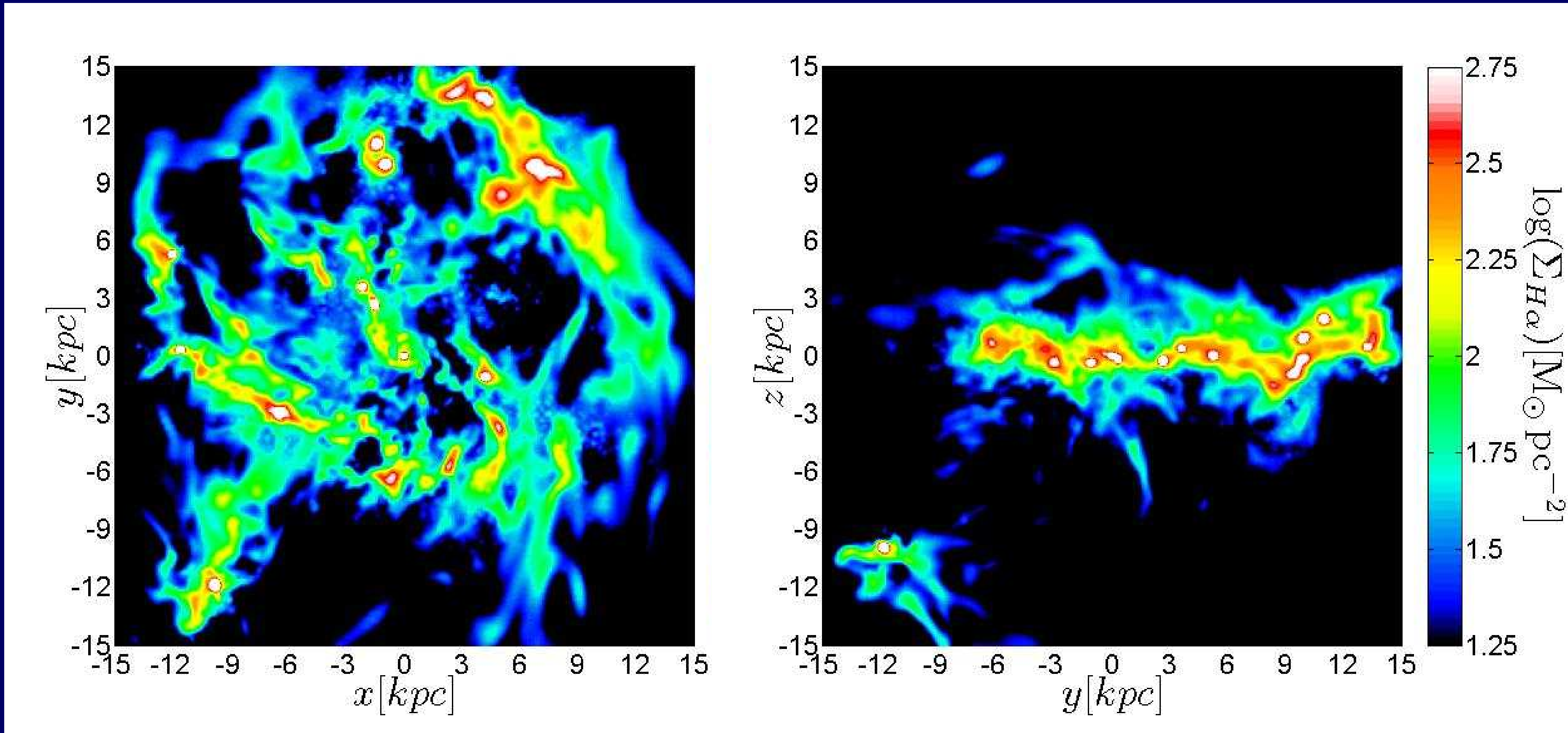


a=0.1401
x [kpc]
y [kpc]
$\log(\Sigma_{gas})[M_\odot\,pc^{-2}]$

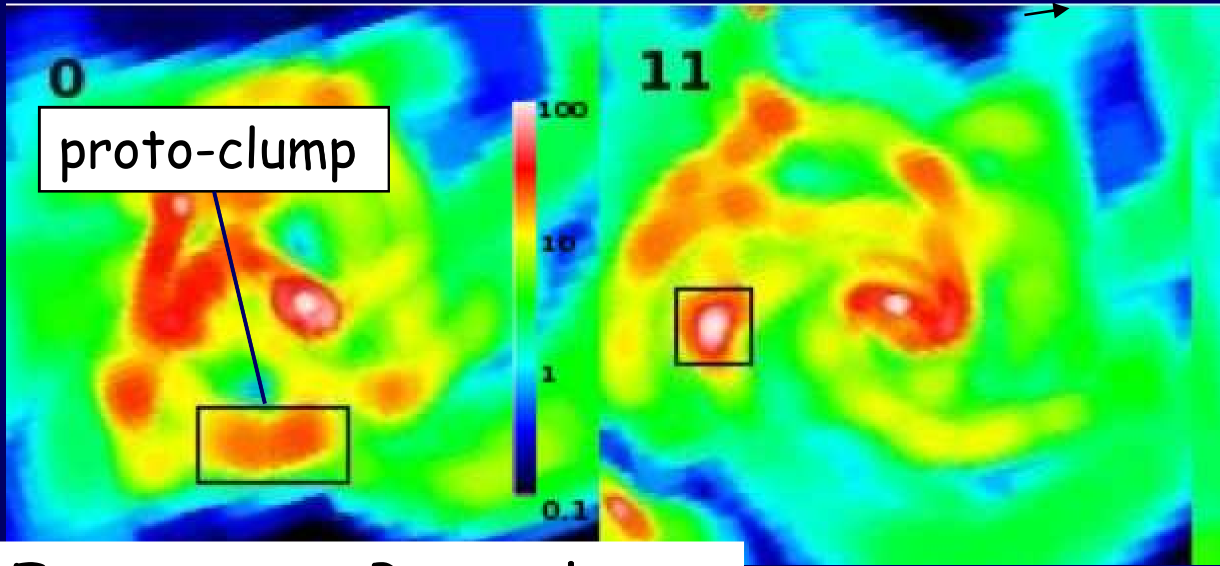
Violent Disk Instability (VDI) at High z

Ceverino+ VELA (ART-AMR) cosmological simulations at 25pc resolution

A typical massive SFG at z~2: gas-rich, highly perturbed, clumpy rotating disk: H/R ~ σ/V ~ f_{cold} ~ 0.2



High Gas Fraction -> Violent Disk Instability



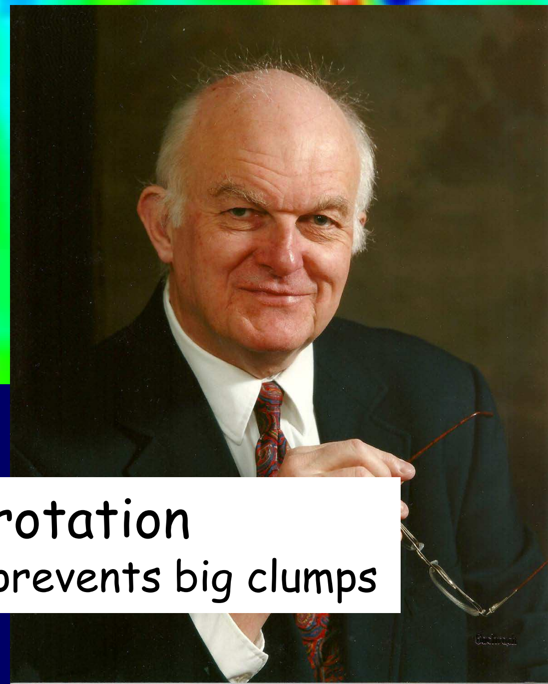
Forces on a Protoclump:

pressure
prevents small clumps

rotation
prevents big clumps

$$Q \propto \frac{\sigma \Omega}{\Sigma_{\text{gas}}} \approx 1$$

self-gravity attraction



Toomre 64

Gravity wins when Q<1

Clumps by Toomre Instability?

$$Q \propto \frac{\sigma\Omega}{\Sigma_{\mathrm{gas}}}$$

Toomre is linear analysis of small fluctuations, but cosmological disks are continuously, nonlinearly perturbed

$Q<1$ in clump regions because Σ is high after collapse
-> not very meaningful

-> Measure Q in proto-clump regions,
where the local perturbations may be small

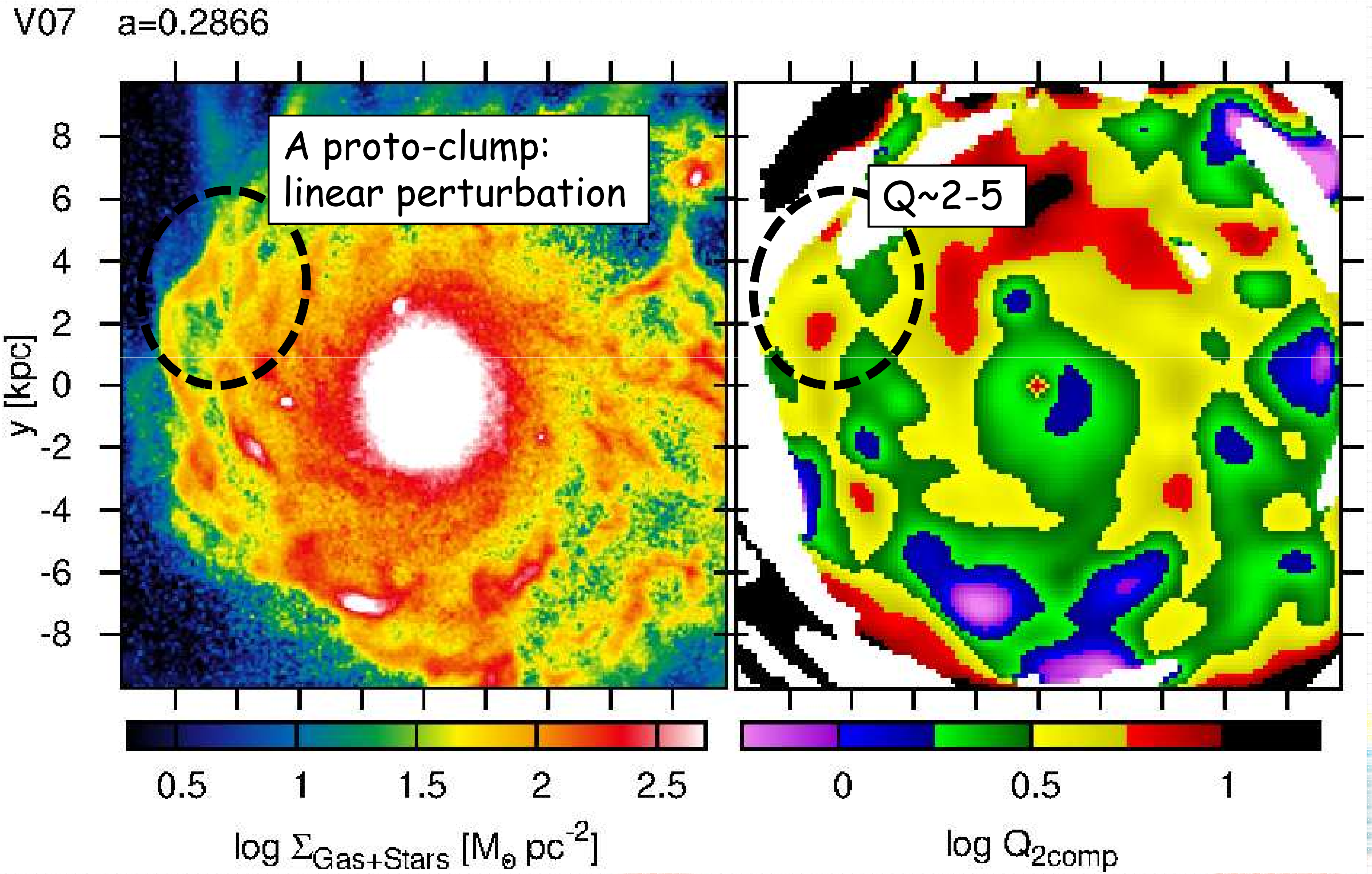
Find in simulations

Isolated: Q~1 e.g. Bournaud+ ~10pc res.

Cosmological: Q~1-3 Inoue+16 ~25pc res.

high σ on small <100pc scales

Clump Formation in Q~3 Protoclump Regions



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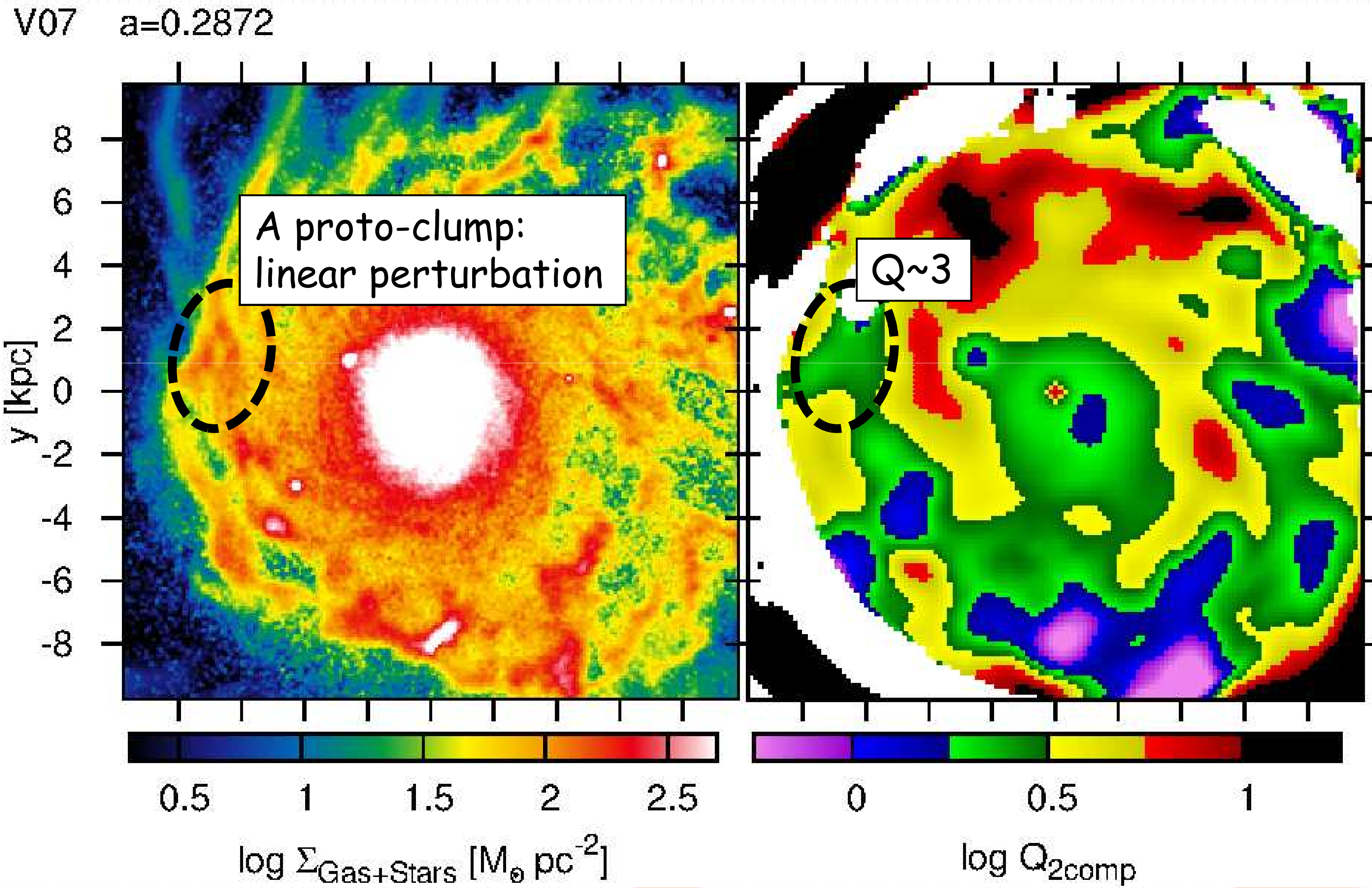

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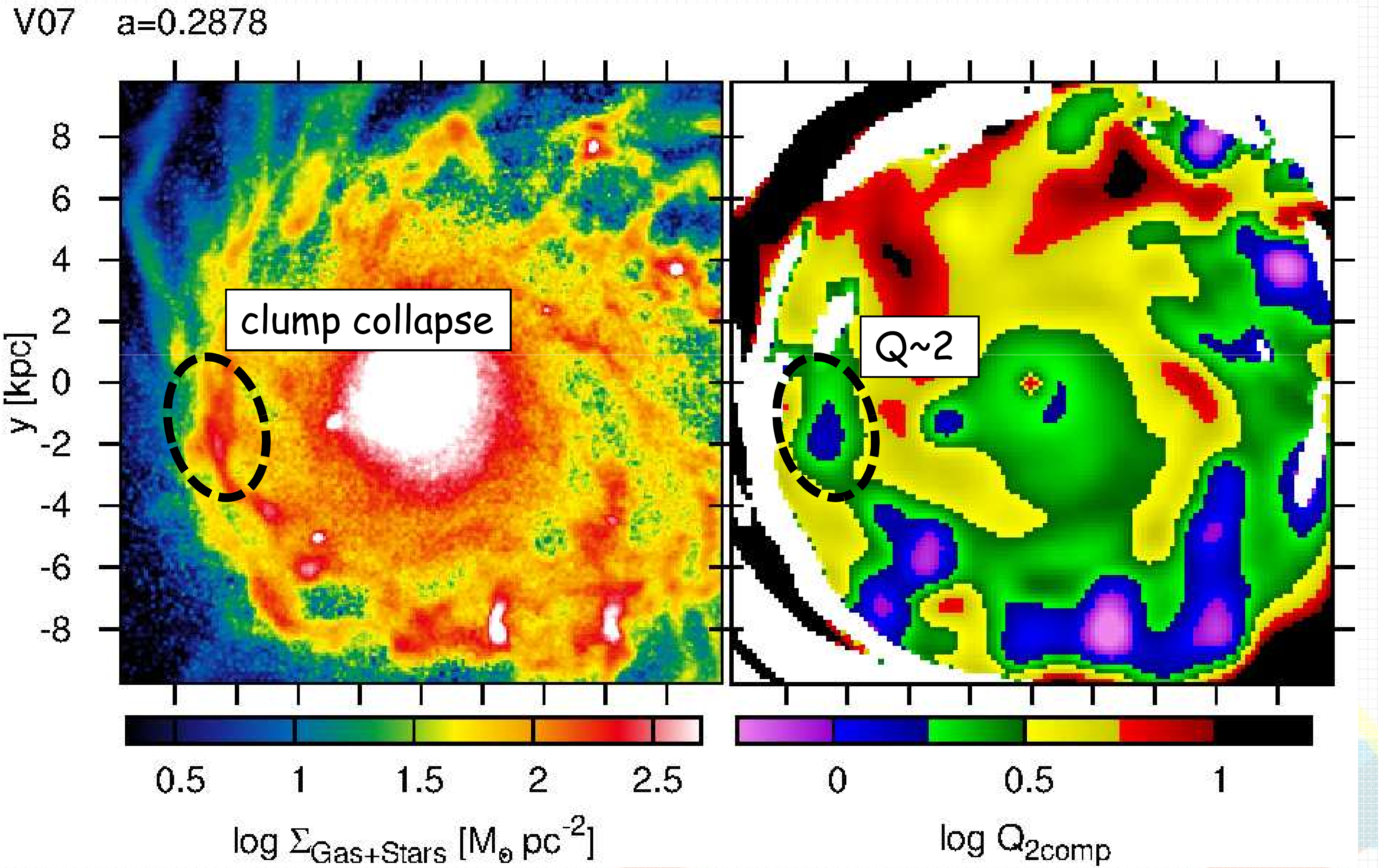
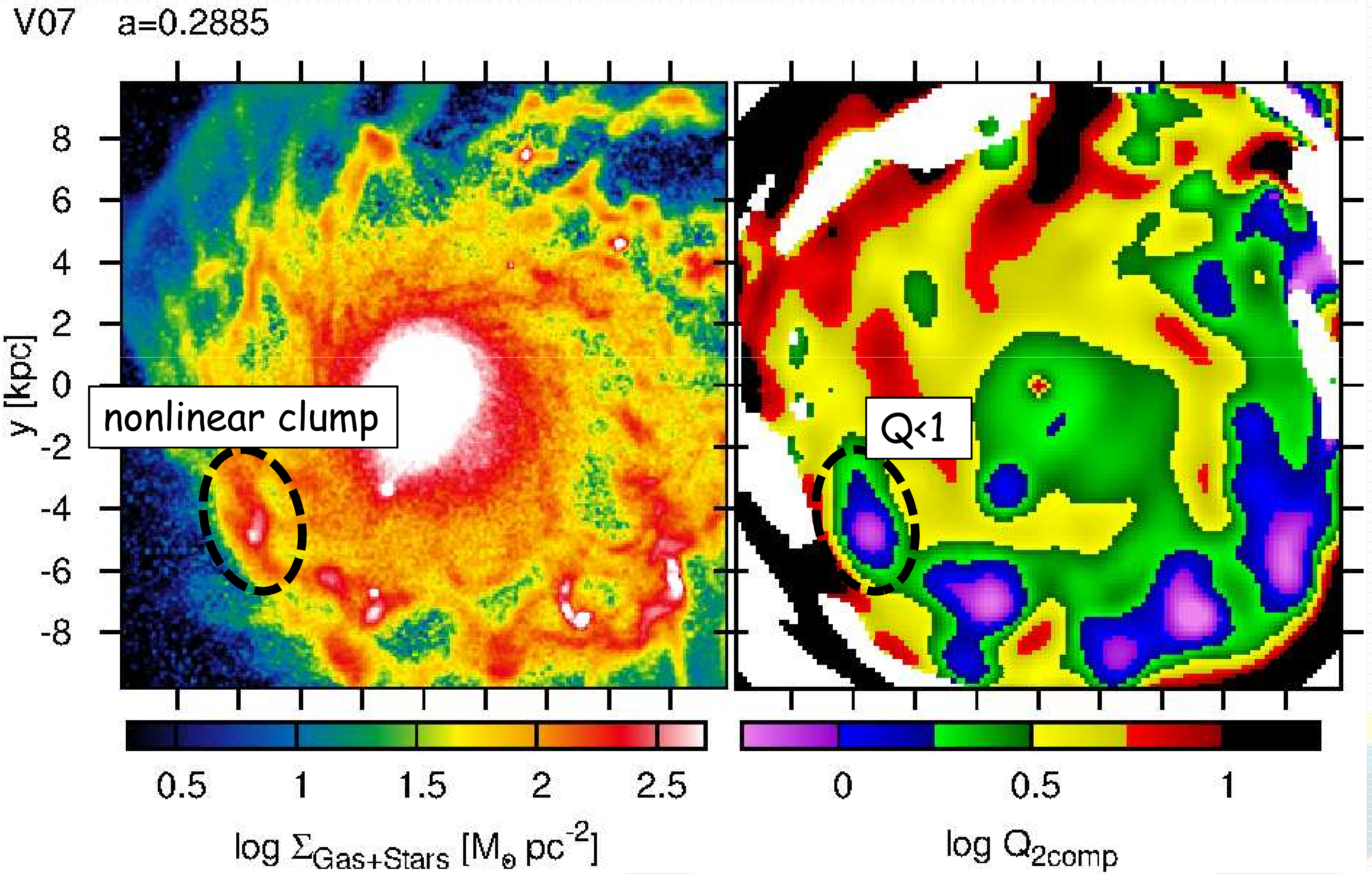
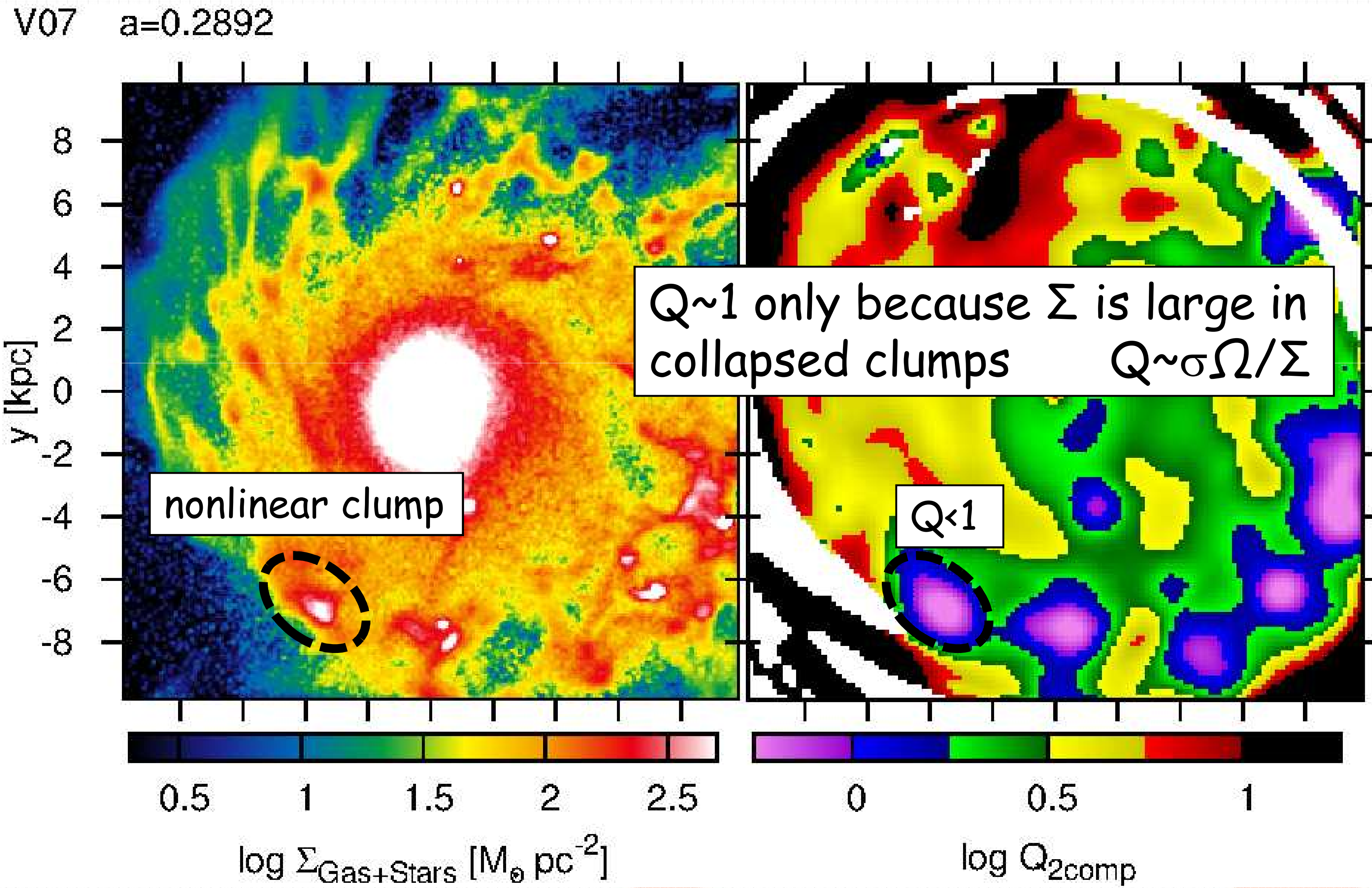


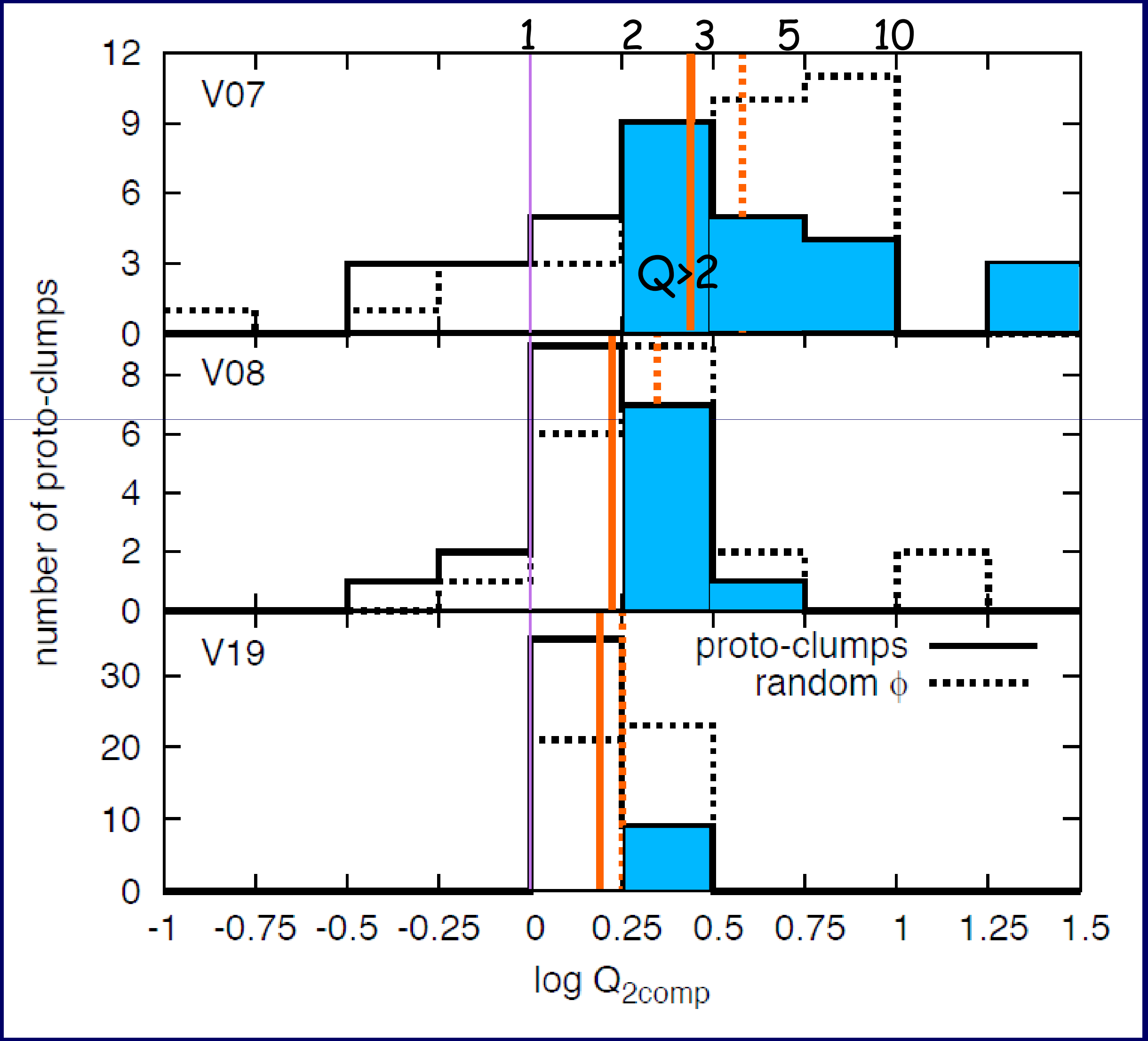
Clump Formation in Q~3 Protoclump Regions



Clump Formation in Q~3 Protoclump Regions



Distribution of Q in Proto-clumps



Stimulated Non-linear Instability

$$Q \propto \frac{\sigma\,\Omega}{\Sigma}$$

Tentative ideas for instability with Q>1

- Rapid decay of turbulence (Elmegreen)
  no time for pressure buildup against clump self-gravity

- Clumps generate new clumps

- Irregular rotation – counter-rotating streams
  no centrifugal force against clump self-gravity

- Compressive mode of turbulence (Renaud+; Mandelker+)
  - triggers local collapse, while σ is high, before gravity takes over
  - induced by tidal compression, generated by external perturbers (e.g. mergers)

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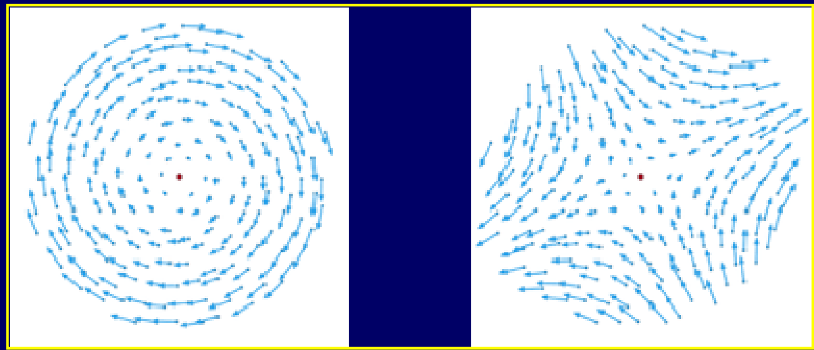
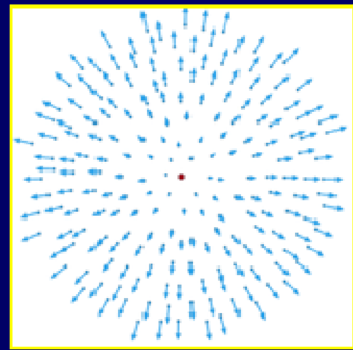
Compressiev Modes of Turbulence

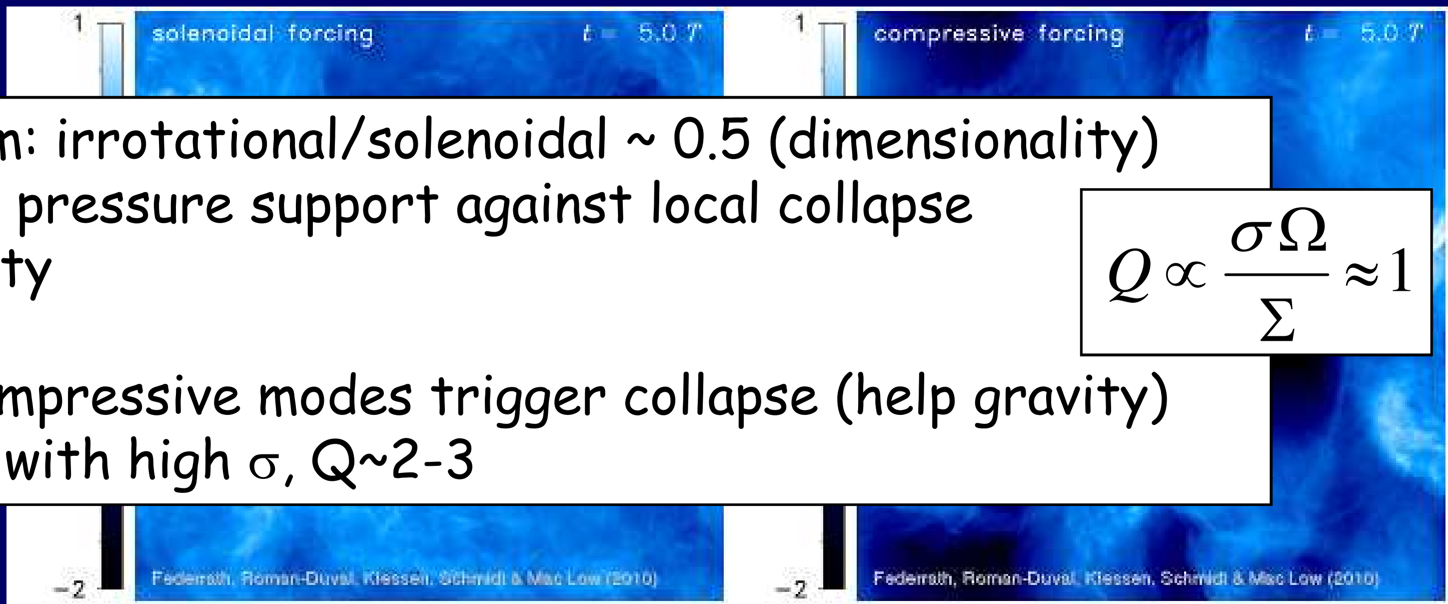
$$\vec{\sigma} = \vec{\sigma}_{\text{irrotational}} + \vec{\sigma}_{\text{solenoidal}} = -\vec{\nabla}\phi + \vec{\nabla} \times \vec{A}$$

solenoidal



irrotational



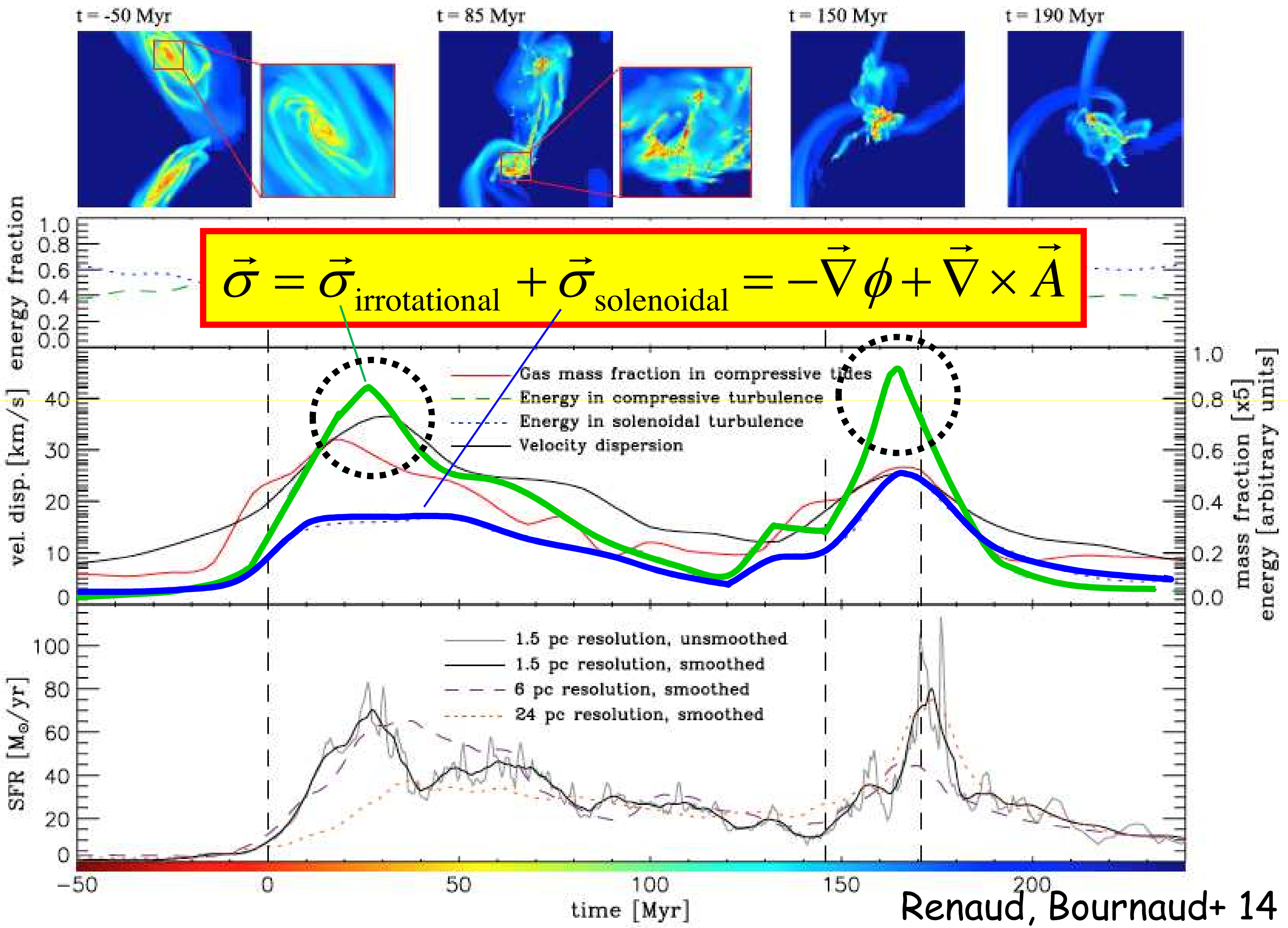


In equilibrium: irrotational/solenoidal ~ 0.5 (dimensionality)
σ represents pressure support against local collapse
Q>1 -> stability

$$Q \propto \frac{\sigma \Omega}{\Sigma} \approx 1$$

Excessive compressive modes trigger collapse (help gravity)
-> instability with high σ, Q~2-3

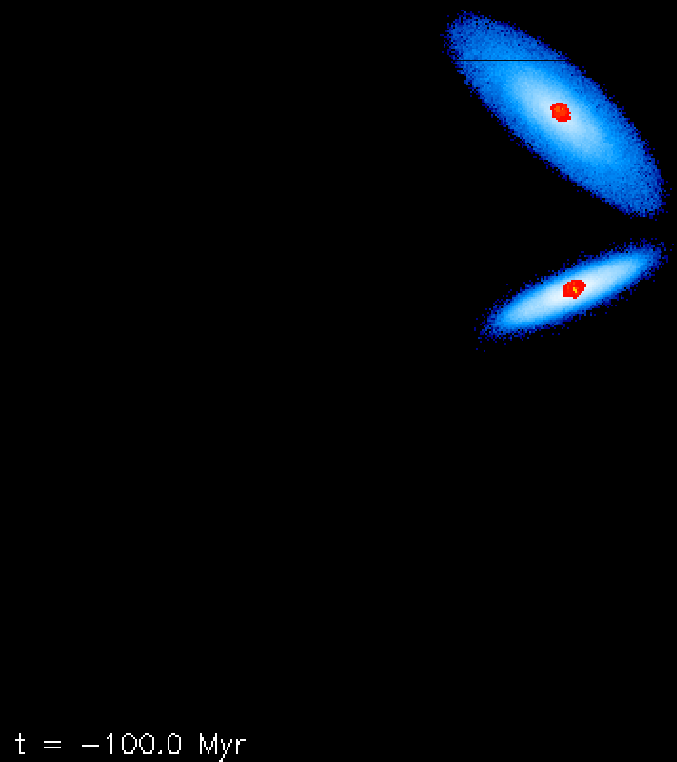
Compression Modes of Turbulence in a Merger



$$\vec{\sigma} = \vec{\sigma}_{\text{irrotational}} + \vec{\sigma}_{\text{solenoidal}} = -\vec{\nabla}\phi + \vec{\nabla} \times \vec{A}$$

Renaud, Bournaud+ 14

Excessive Compressive Mode of Turbulence by Compressive Tides (red) in Mergers

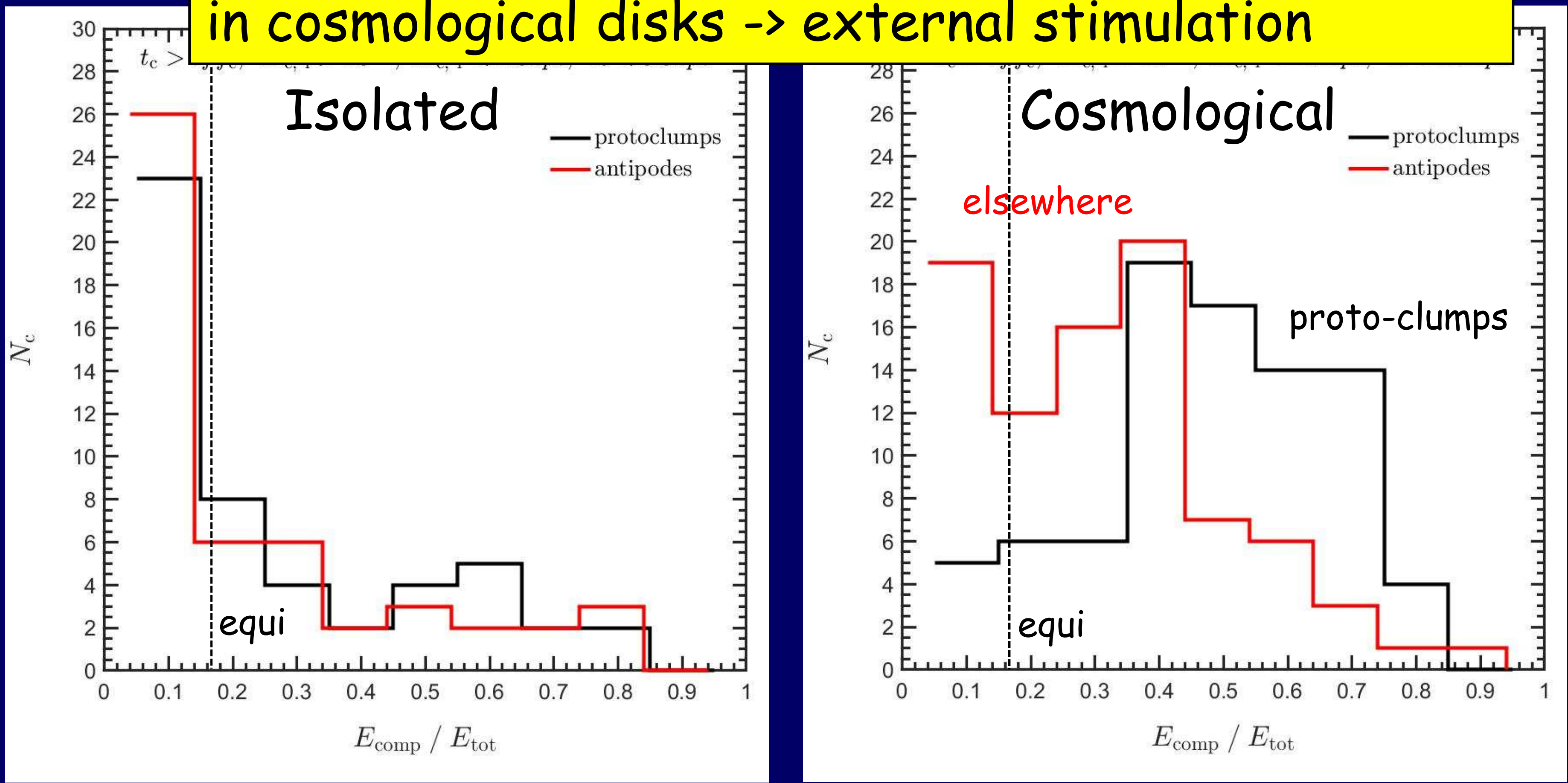


Renaud+15

Compression in Proto-clumps: Isolated vs Cosmological Galaxies

Mandelker, Dekel, Bournaud 17

Excess of compressive turbulence in proto-clumps in cosmological disks -> external stimulation



Compressive Mode of Turbulence

Find in simulations:

In isolated galaxies: $E_{compress}/E_{tot} \sim 0.16$
-> standard equilibrium

In cosmological galaxies: $E_{compress}/E_{tot} \sim 0.5$
-> excessive compression

Conclusions: Clump Formation
Stimulated Nonlinear Violent Disk Instability

Inoue+ 16; Mandelekr+17b

Cosmological disks are continuously nonlinear, and externally perturbed – not linear Toomre instability

In protoclump regions in cosmological simulations Q ~ 1-3, while Q ~ 1 in isolated disks

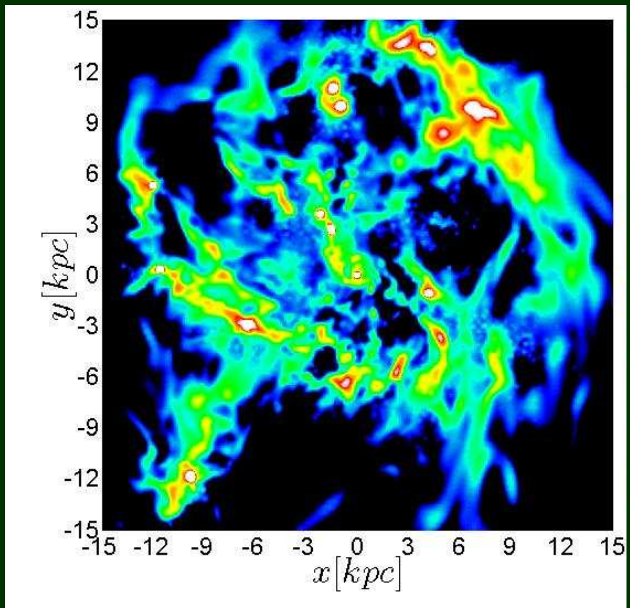
Excessive compressive turbulence, induced by tides, initiates clump collapse before gravity takes over while Q (σ) is high

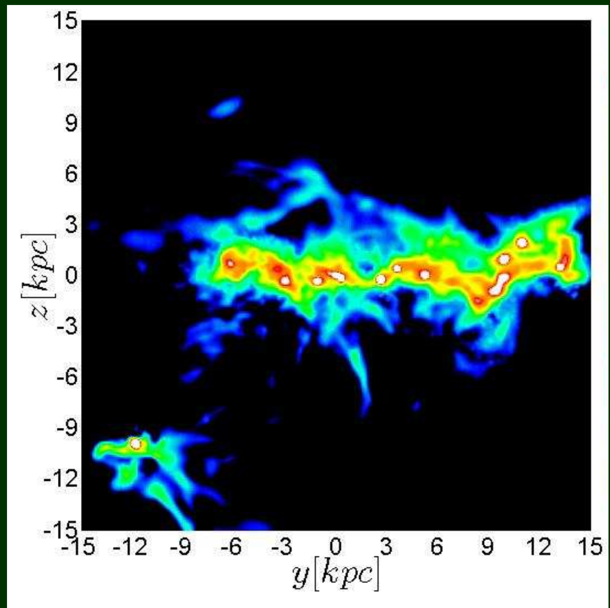
See Nir Mandelker's talk

Clump Survival or Disruption?

Mandelker + 17
Dekel, Mandelker, Bournaud + 17 (in prep.)

VELA Simulations Ceverino, Dekel, Primack





Massive In-situ Clumps in High-z Disks: Long-lived or Short-lived?

Scenario 1: "bound clumps"

- Clumps $>10^8 M_\odot$ are compact, bound and survive feedback.
  Migration to center in ~300 Myr
  -> medium lifetimes 0-500 Myr, gradients of age, mass, sSFR
- Clumps $<10^8 M_\odot$ are diffuse and elongated – short lived
- Ex-situ merged clumps: massive and old

Dekel+ 09; Ceverino+10,12; Bournaud+14; Mandelker+14,17; Dekel+Krumholz 12,13

Scenario 2: "Xmas tree"

Clumps are unbound, disrupt by feedback in a dynamical time <50 Myr
-> short lifetimes <50 Myr, no migration -> weaker gradients
(due to contamination?)

Genel+12; Murray+10; Hopkins+12; Oklopcic+16

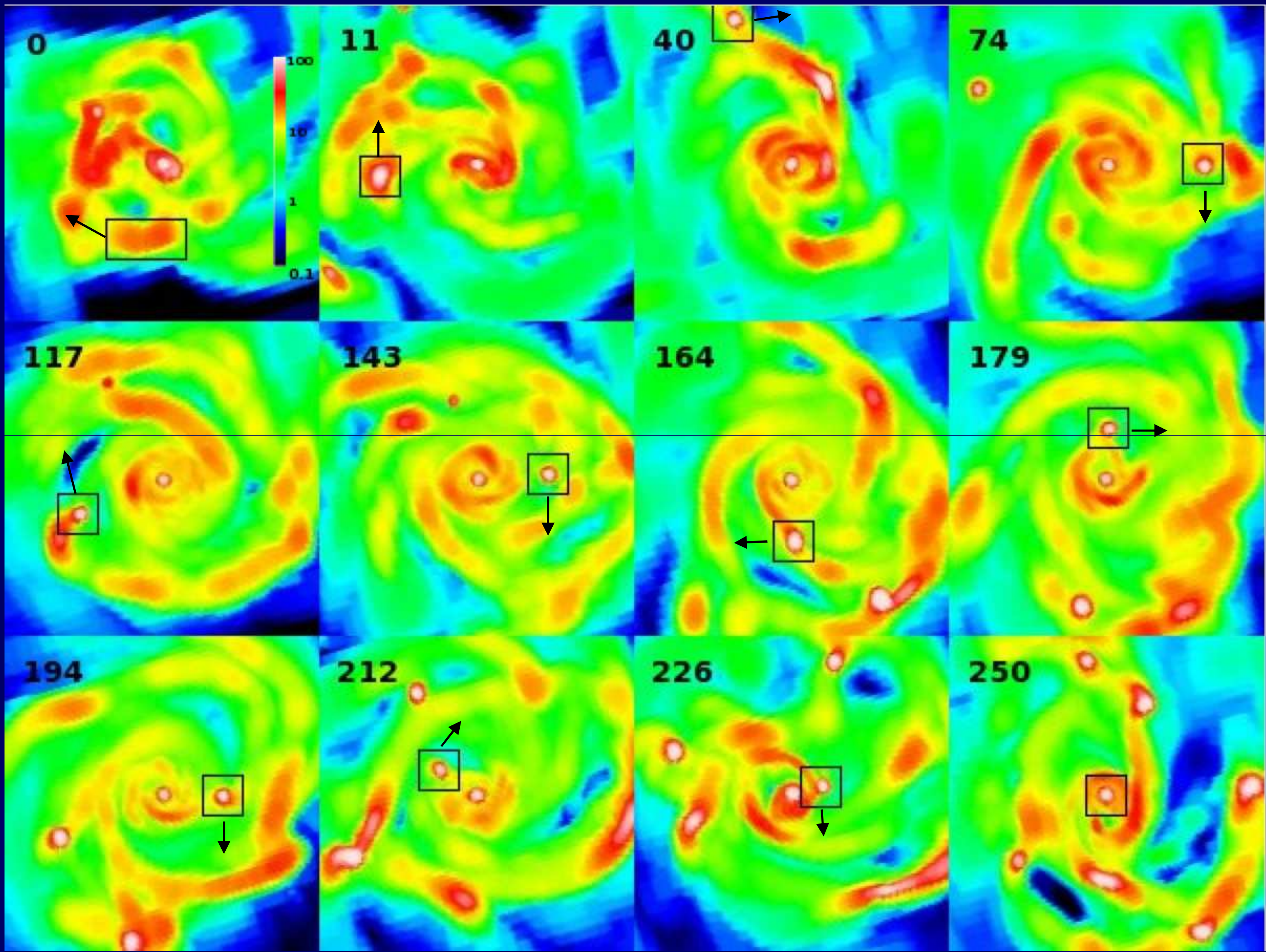
~~Scena~~ violates observations

~~Bound massive clumps do not form (in some isolated-galaxy simulations)~~

Mayer, Tamburello+ 16-17

Feedback model? Resolution? External stimulation is needed?

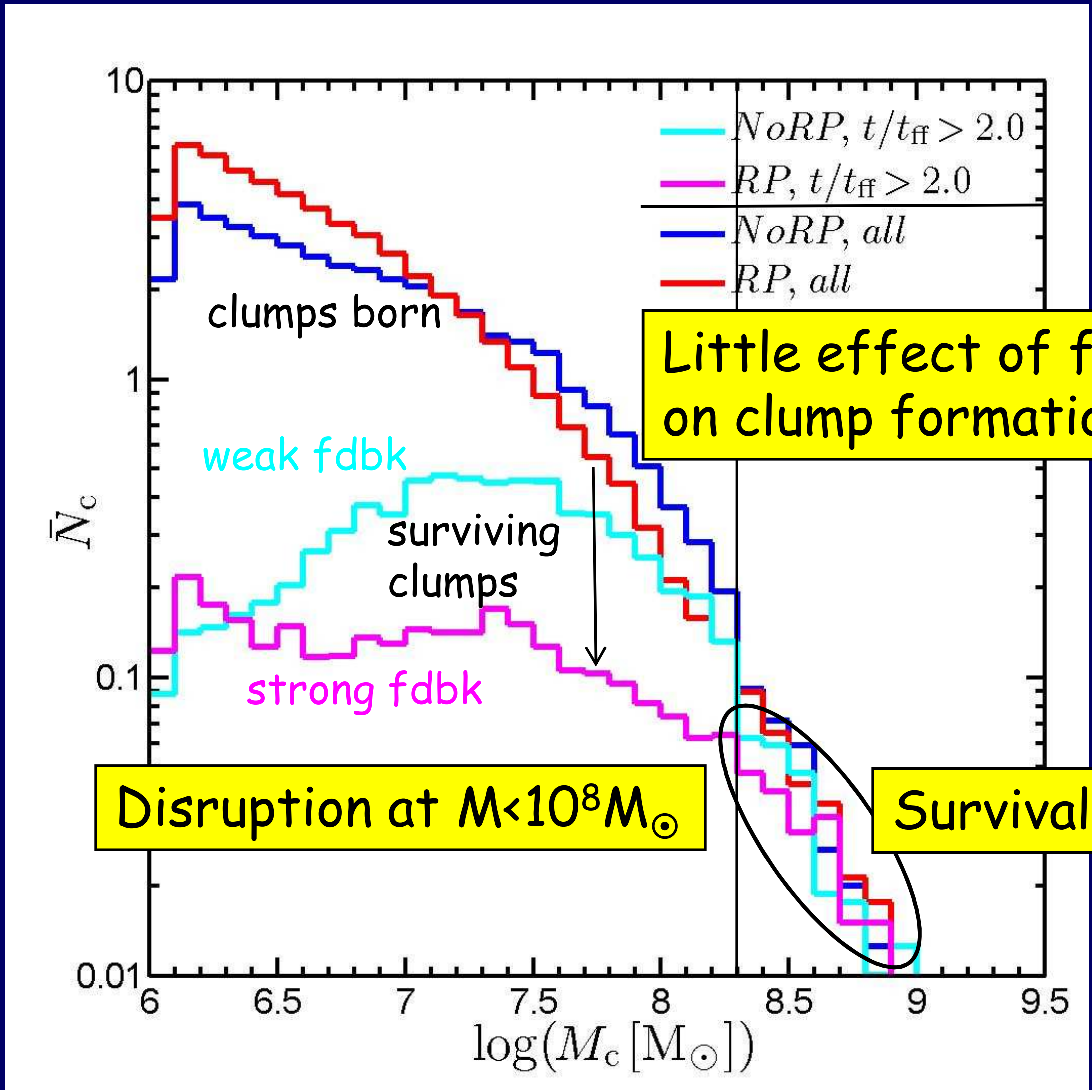
Clump Migration in a Few Orbits



Ceverino, Dekel, Bournaud 10

The Effect of SN+Radiative Fdbk on Clumps

Mandelker+17 ART-AMR cosmological simulations, 25pc resolution

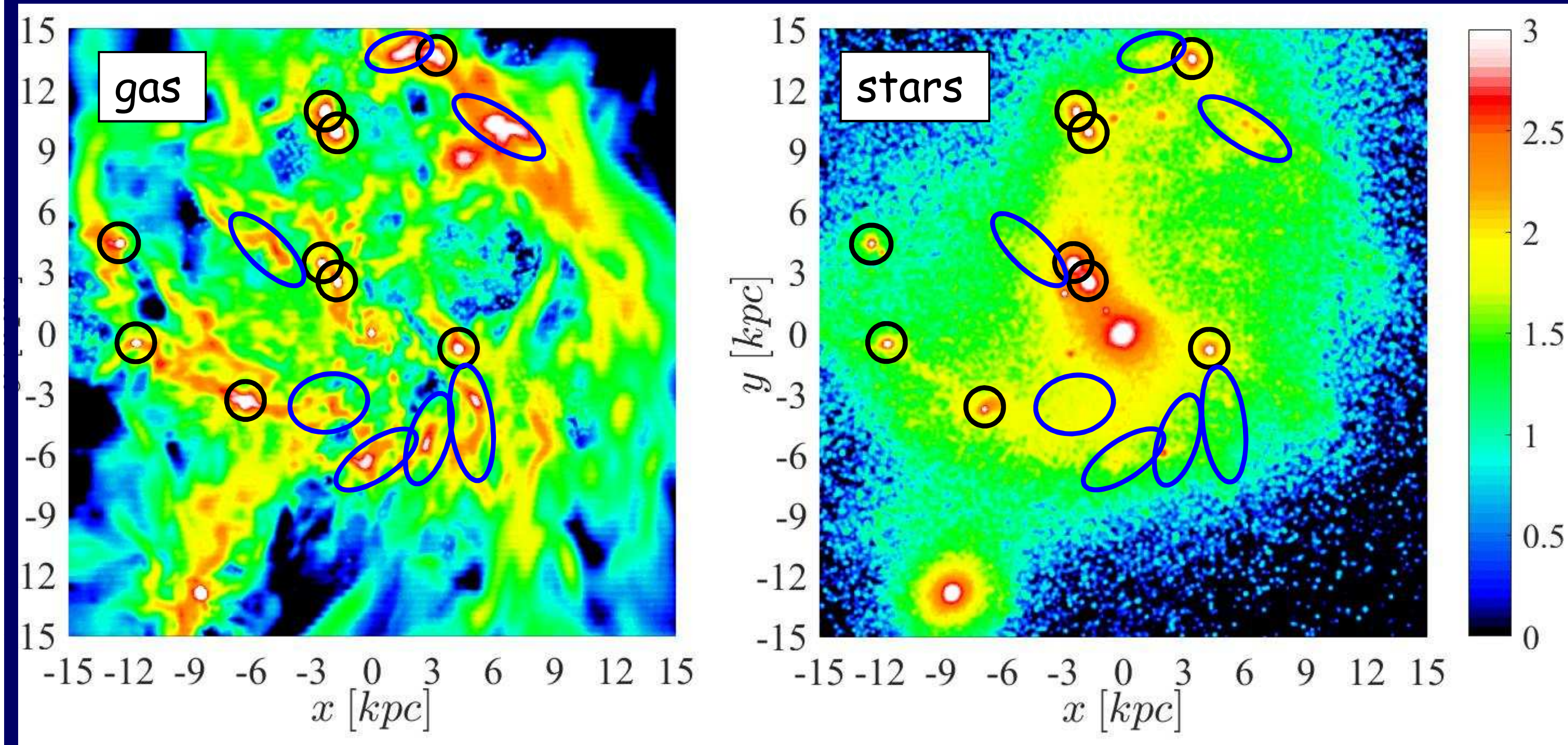


Little effect of feedback on clump formation

Disruption at $M<10^8 M_\odot$

Survival at $M>10^{8.3} M_\odot$

Short-lived vs Long-lived Clumps



Long-lived clumps in gas & stars, >10^8$M_\odot$, compact & round

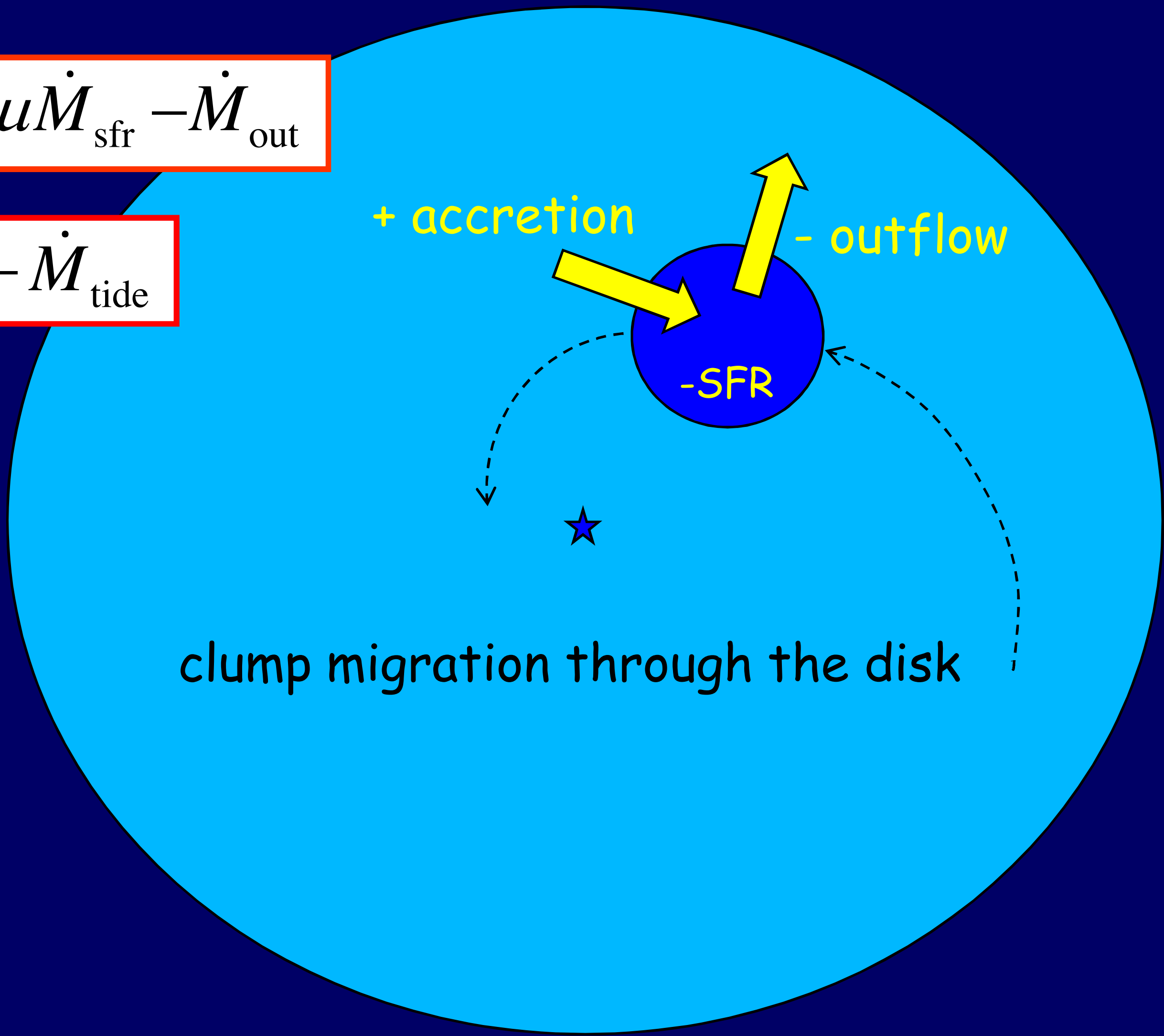
Short-lived clumps only in gas, <$10^{8.5}M_\odot$, diffuse & elongated

Bathtub Model for a Bound Clump in a Disk

Dekel, Mandelker, Bournaud 17

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

$$\dot{M}_{\rm star} = \mu \dot{M}_{\rm sfr} - \dot{M}_{\rm tide}$$



Bathtub Model for a Bound Clump in a Disk

Dekel, Mandelker, Bournaud 17

Migration $t_{\rm mig} \approx 10 t_{\rm dyn} (M_{\rm Toomre} / M_{\rm clmp})$

Bathtub $\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - \mu \dot{M}_{\rm sfr} - \dot{M}_{\rm out}$ $\quad \dot{M}_{\rm star} = \mu \dot{M}_{\rm sfr} - \dot{M}_{\rm tide}$

Accretion $\dot{M}_{\rm acc} = \alpha \rho_{\rm disk} \pi R_{\rm tide}^2 \sigma_{\rm disk} = 0.5 \alpha t_{\rm d}^{-1} M_{\rm clmp}$

SFR $\dot{M}_{\rm sfr} = \varepsilon_{\rm ff} t_{\rm ff}^{-1} M_{\rm gas} = \varepsilon_{\rm d} t_{\rm d}^{-1} M_{\rm gas}$

Outflow $\dot{M}_{\rm out} = \eta_{\rm g} \dot{M}_{\rm sfr}$ $\quad \dot{M}_{\rm tide} = \eta_{\rm s} \dot{M}_{\rm sfr}$

parameters

$\alpha \approx 0.2,\ \varepsilon_{\rm d} \approx 0.1$

$\eta_{\rm g} \approx 1,\ \eta_{\rm s} \approx 0$

For a galaxy $\dot{M}_{\rm gas} = \dot{M}_{\rm acc}(M_{\rm halo}) - (\mu + \eta) \varepsilon_{\rm d} t_{\rm d}^{-1} M_{\rm gas}$

Solution $M_{\rm gas}(t) \propto \dot{M}_{\rm acc} (1 - e^{-t/\tau})$ $\rightarrow$ QSS $\dot{M}_{\rm gas} = 0 \quad {\rm SFR} \propto \dot{M}_{\rm acc}$

For a clump $\dot{M}_{\rm gas} = 0.5 \alpha t_{\rm d}^{-1} M_{\rm star} + [0.5\alpha - (\mu + \eta) \varepsilon_{\rm d} t_{\rm d}^{-1}] M_{\rm gas}$

Solution $M_{\rm gas}(t) = m_1 e^{t/\tau_1} + m_2 e^{-t/\tau_2}$

$\tau_i^{-1}(\alpha, \varepsilon_d, \eta_g)$ roots of a polynomial

m_i by initial $M_{gas,in}$

Bathtub Model for a Clump in a Disk

Dekel, Mandelker, Bournaud 17

$$M_{gas}(t) = m_1 e^{t/\tau_1} + m_2 e^{-t/\tau_2}$$ $$\tau_1 \approx 10 t_d$$

$t_{in} < t < \tau_1$

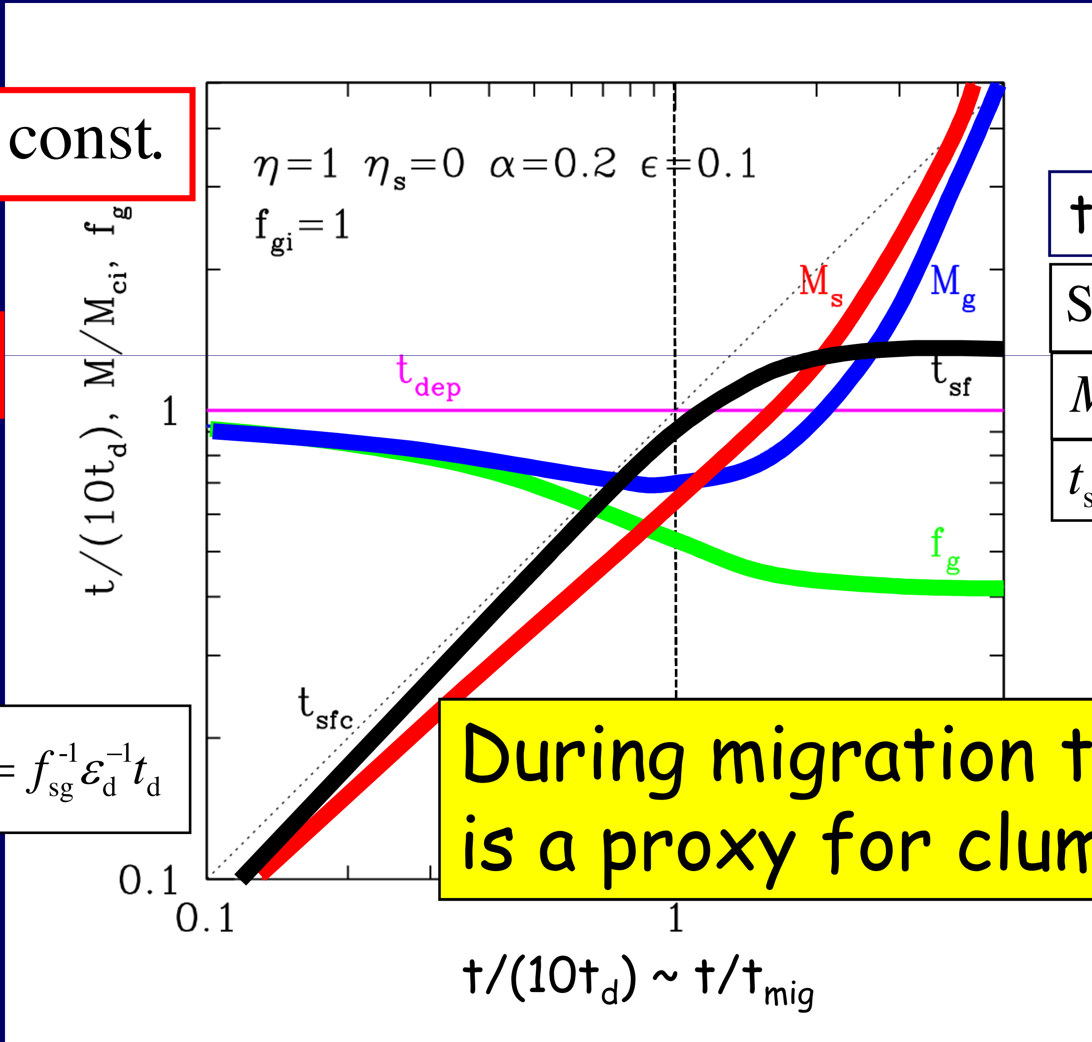
$$\mathrm{SFR} \propto M_{gas} \approx \mathrm{const.}$$

$$M_{star} \propto t$$

$$t_{sf} \approx (\mu - \eta_s) t$$

$$t_{dep} = \frac{M_{gas}}{\mathrm{SFR}} = \varepsilon_d^{-1} t_d$$

$$t_{sf} = \mathrm{sSFR}^{-1} = \frac{M_{star}}{\mathrm{SFR}} = f_{sg}^{-1} \varepsilon_d^{-1} t_d$$



$t > \tau_1$ QSS

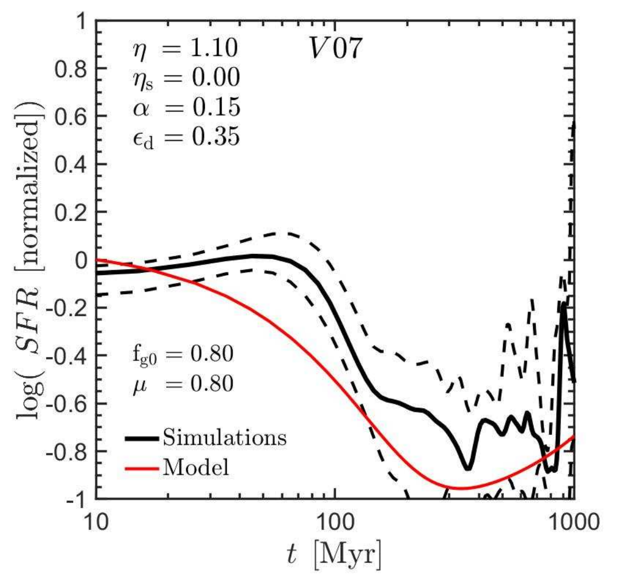
$$\mathrm{SFR} \propto M_{gas} \propto e^{t/\tau_1}$$

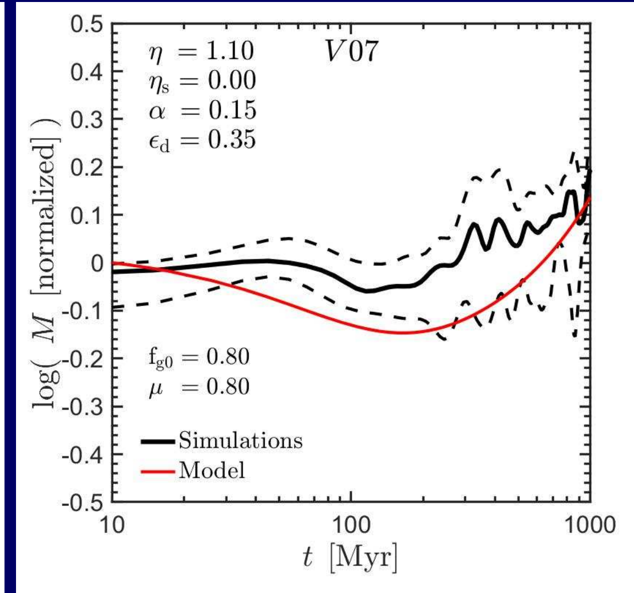
$$M_{star} \propto e^{t/\tau_1}$$

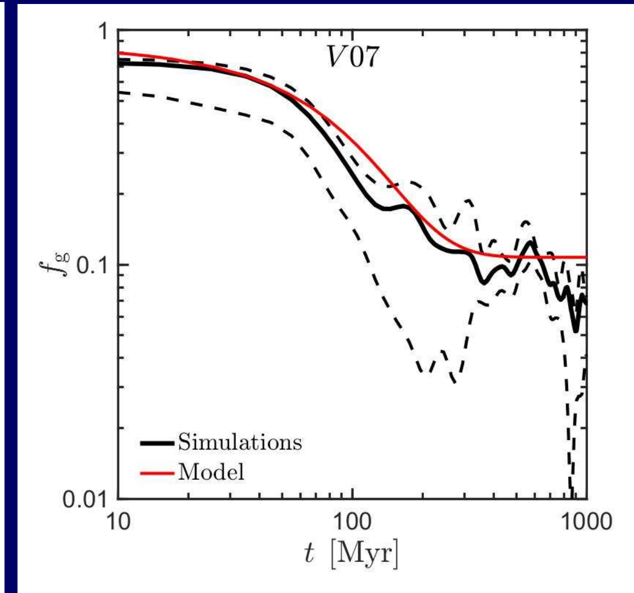
$$t_{sf} = (\mu - \eta_s) \tau_1$$

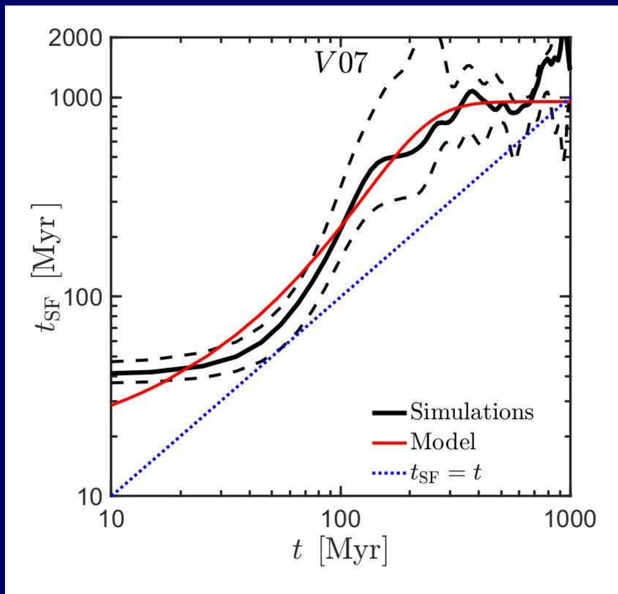
During migration $t_{sf} = \mathrm{sSFR}^{-1}$ is a proxy for clump lifetime

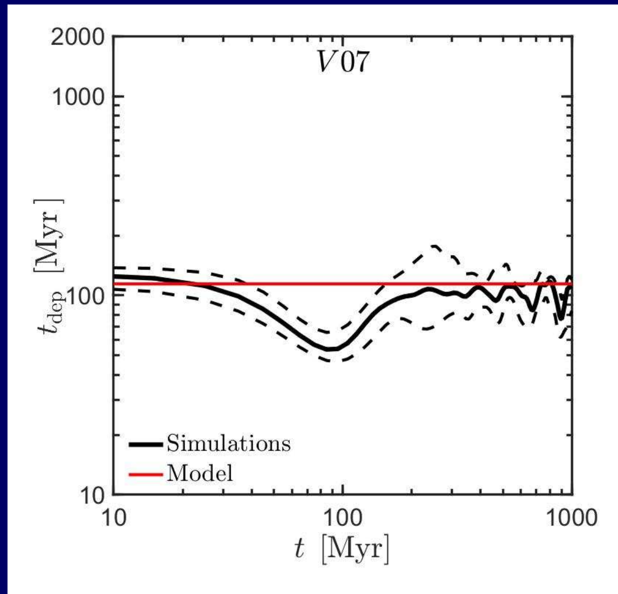
Model vs Cosmological Simulations











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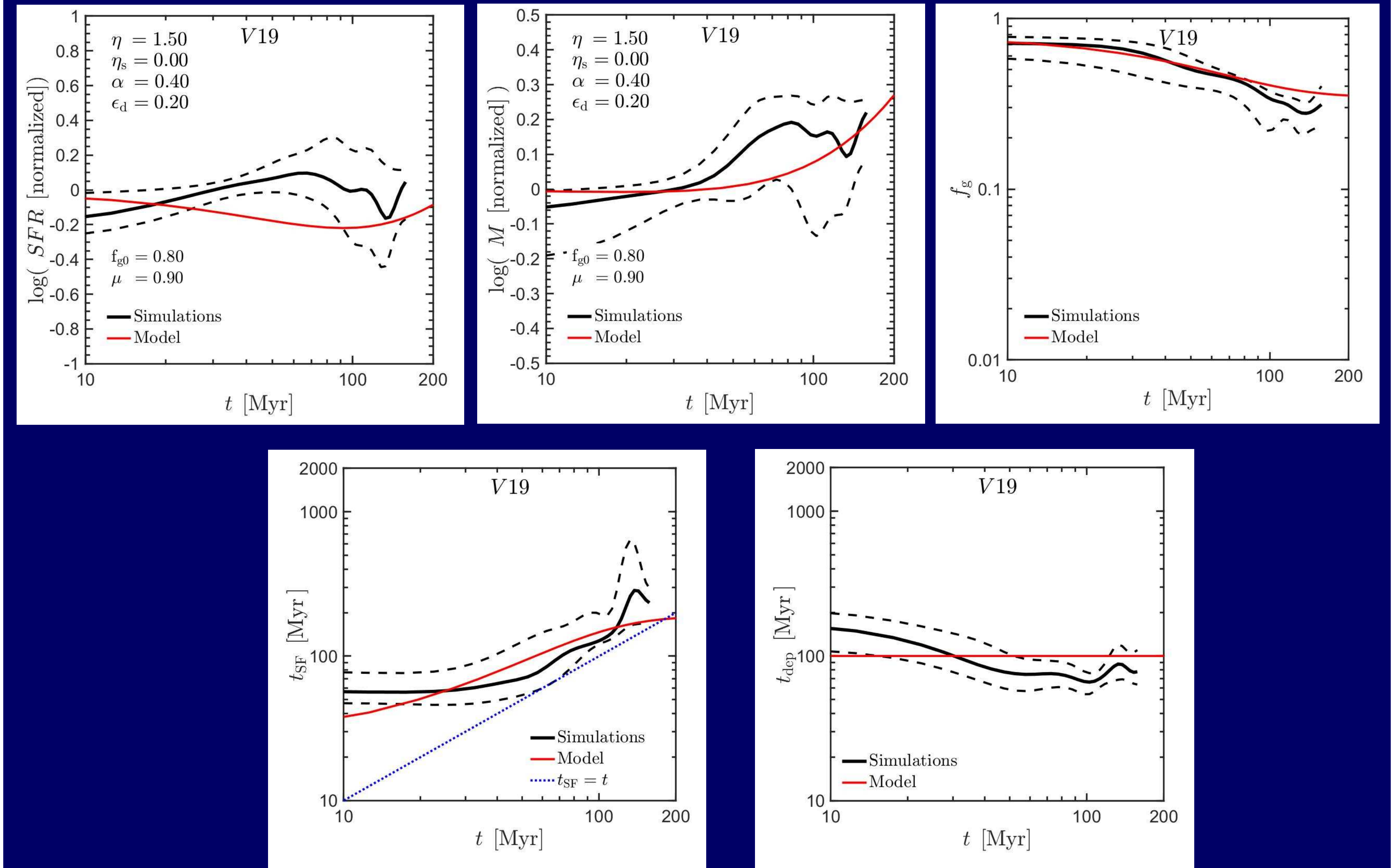
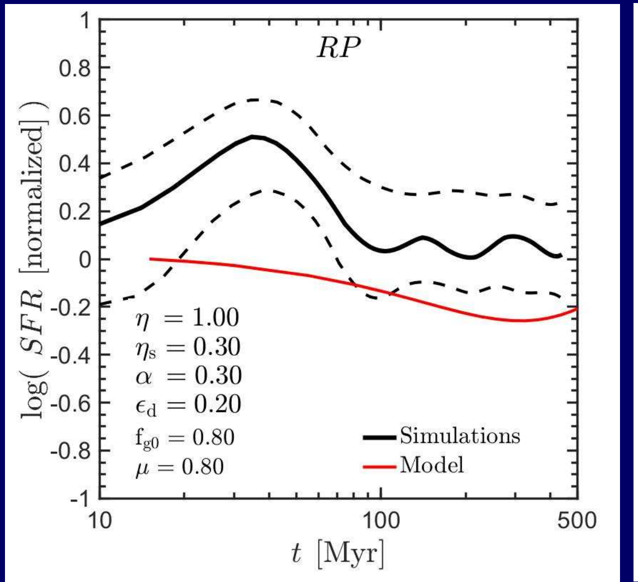
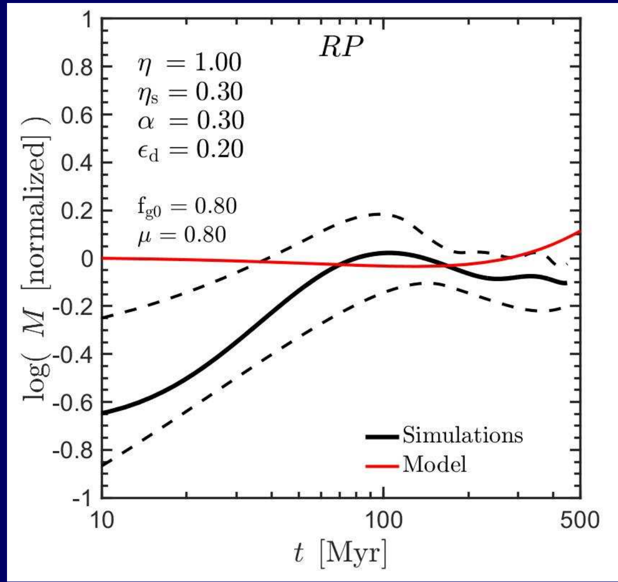
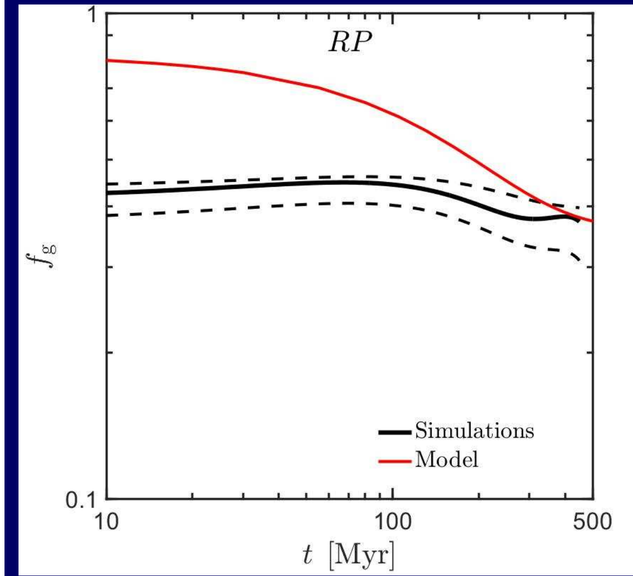
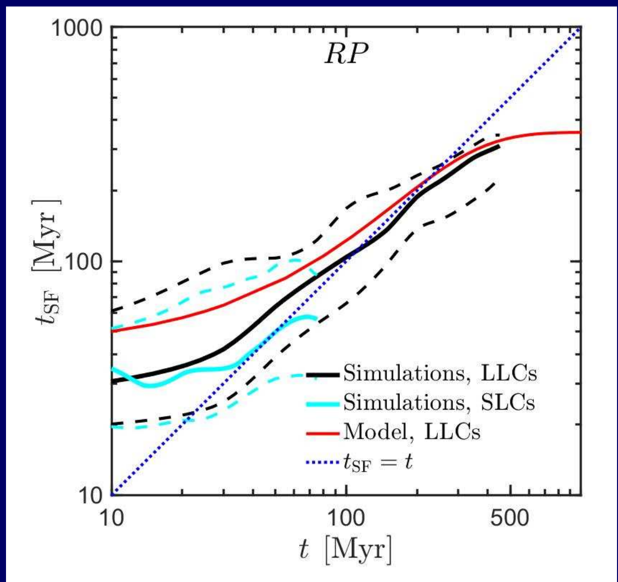


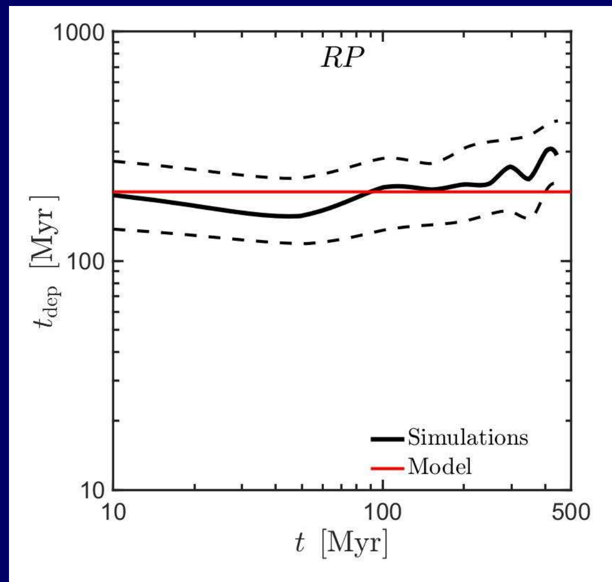
Model vs Isolated Simulations





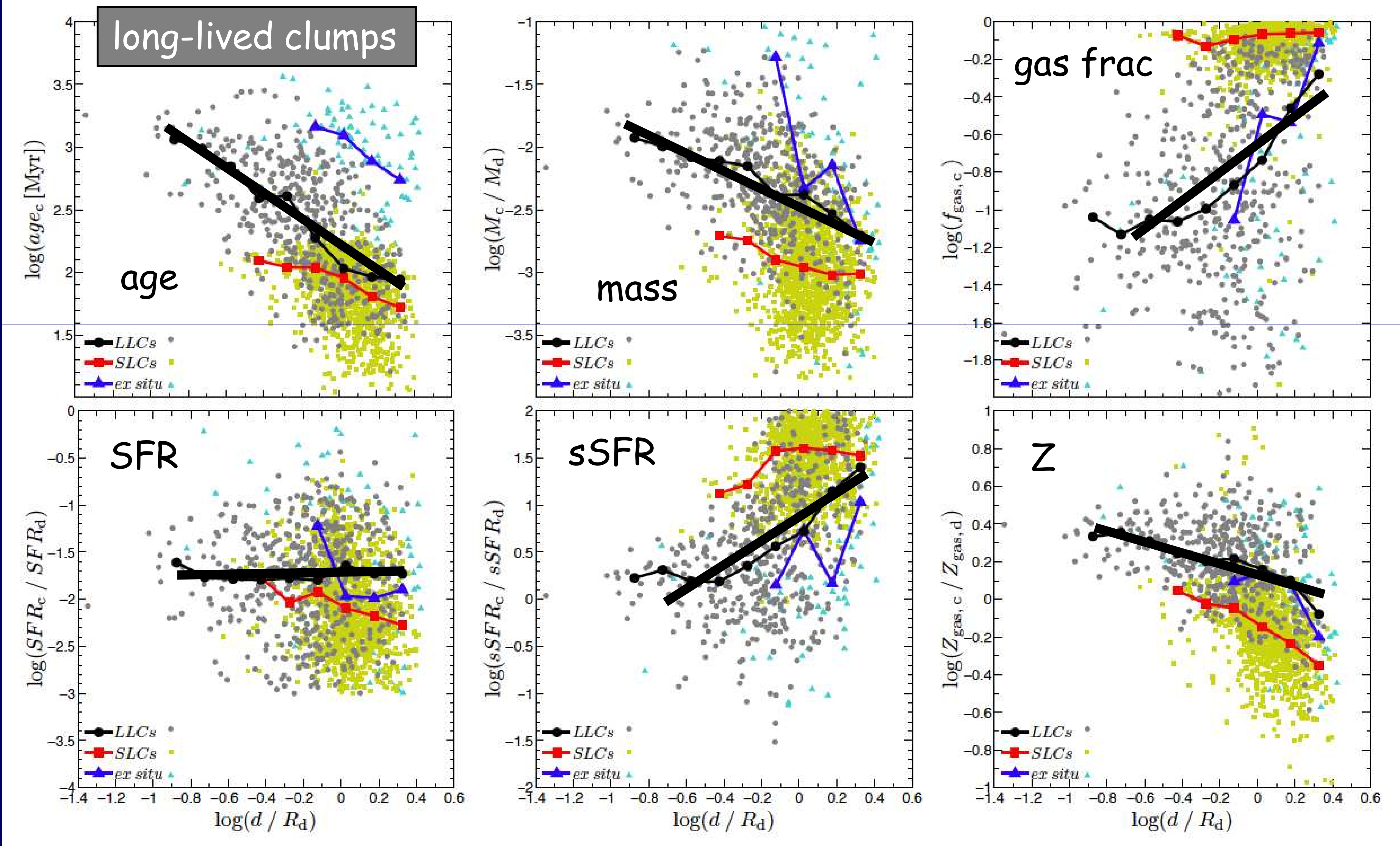




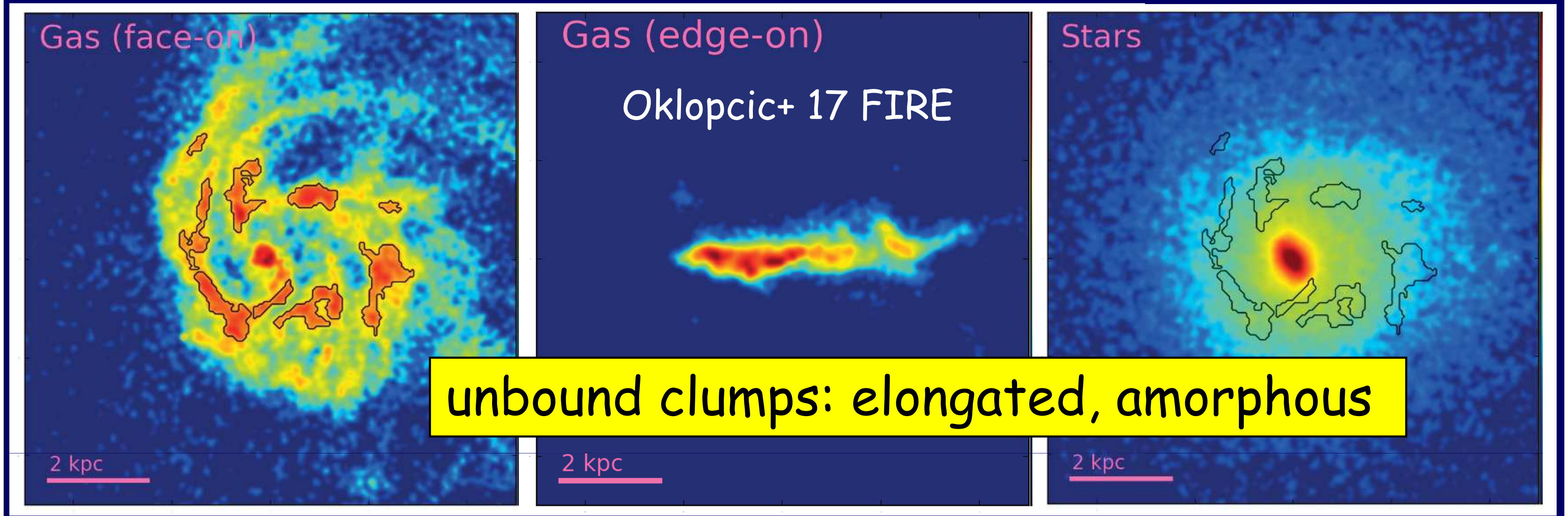


Gradients of Clump Properties

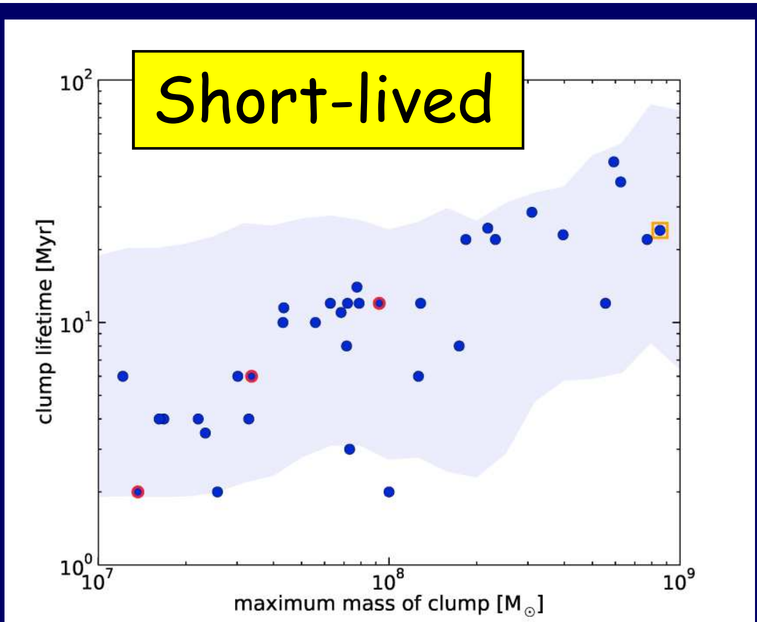
Mandelker+17 ART-AMR cosmological simulations, 25pc resolution



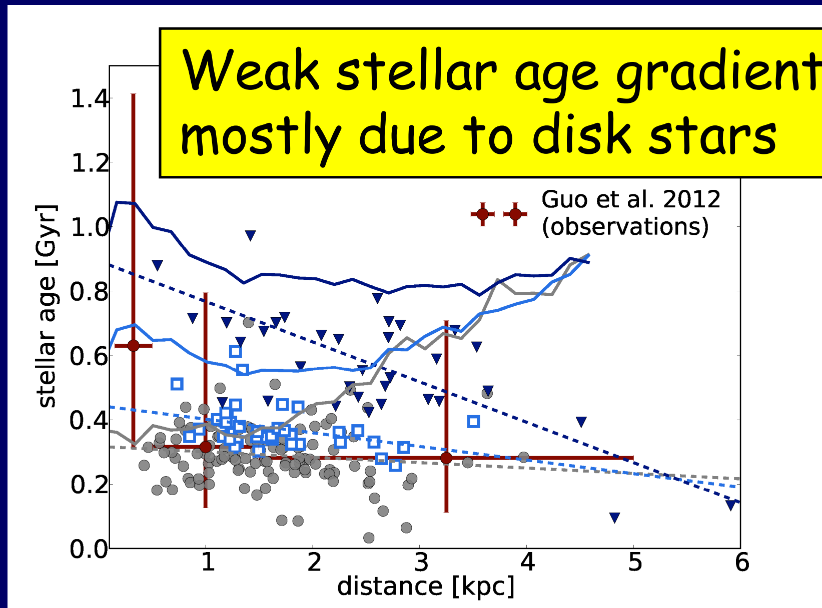
The Xmas-tree Scenario



unbound clumps: elongated, amorphous



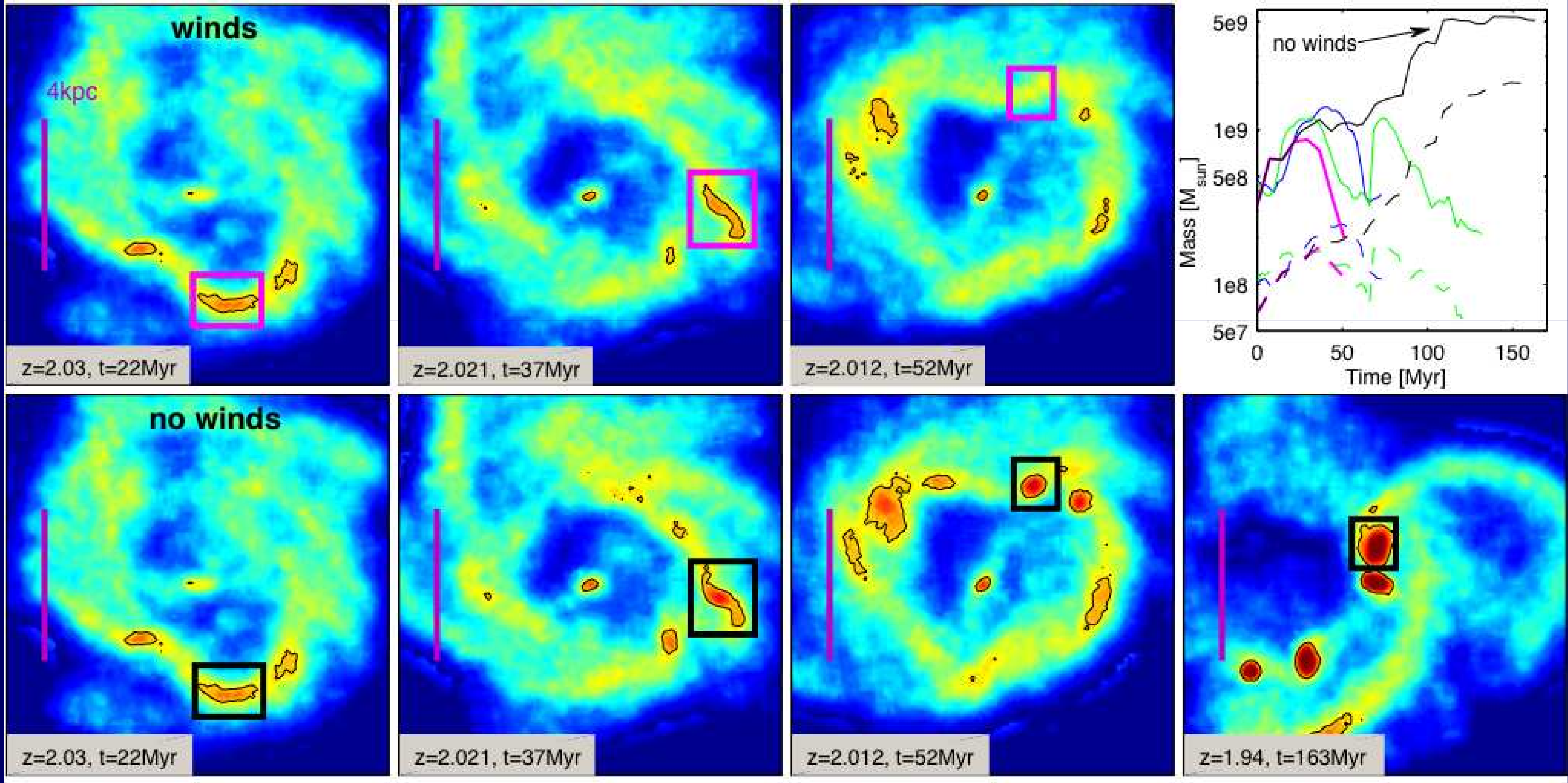
Short-lived



Weak stellar age gradient, mostly due to disk stars

The Xmas-Tree Scenario

Genel et al. 11



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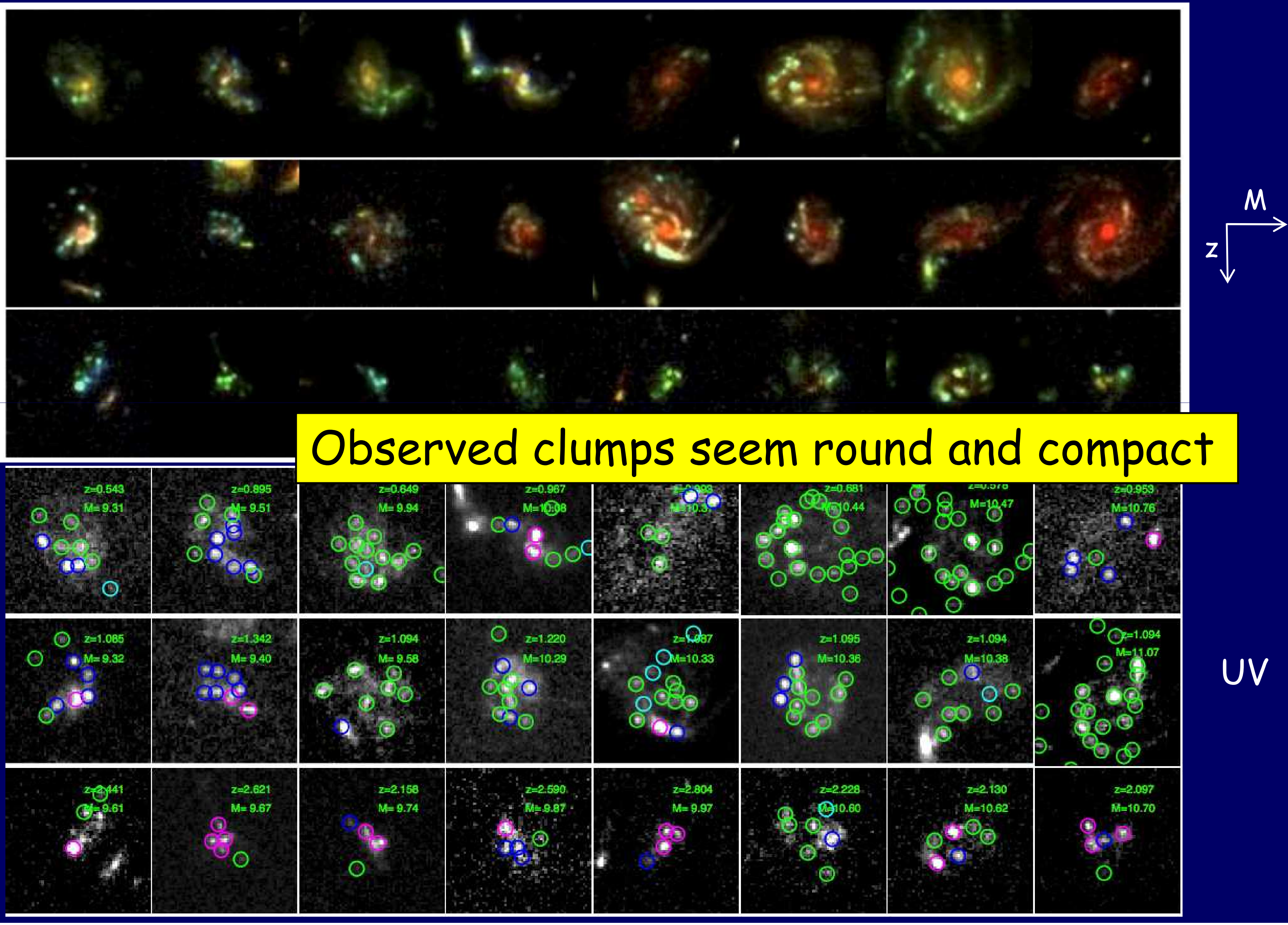
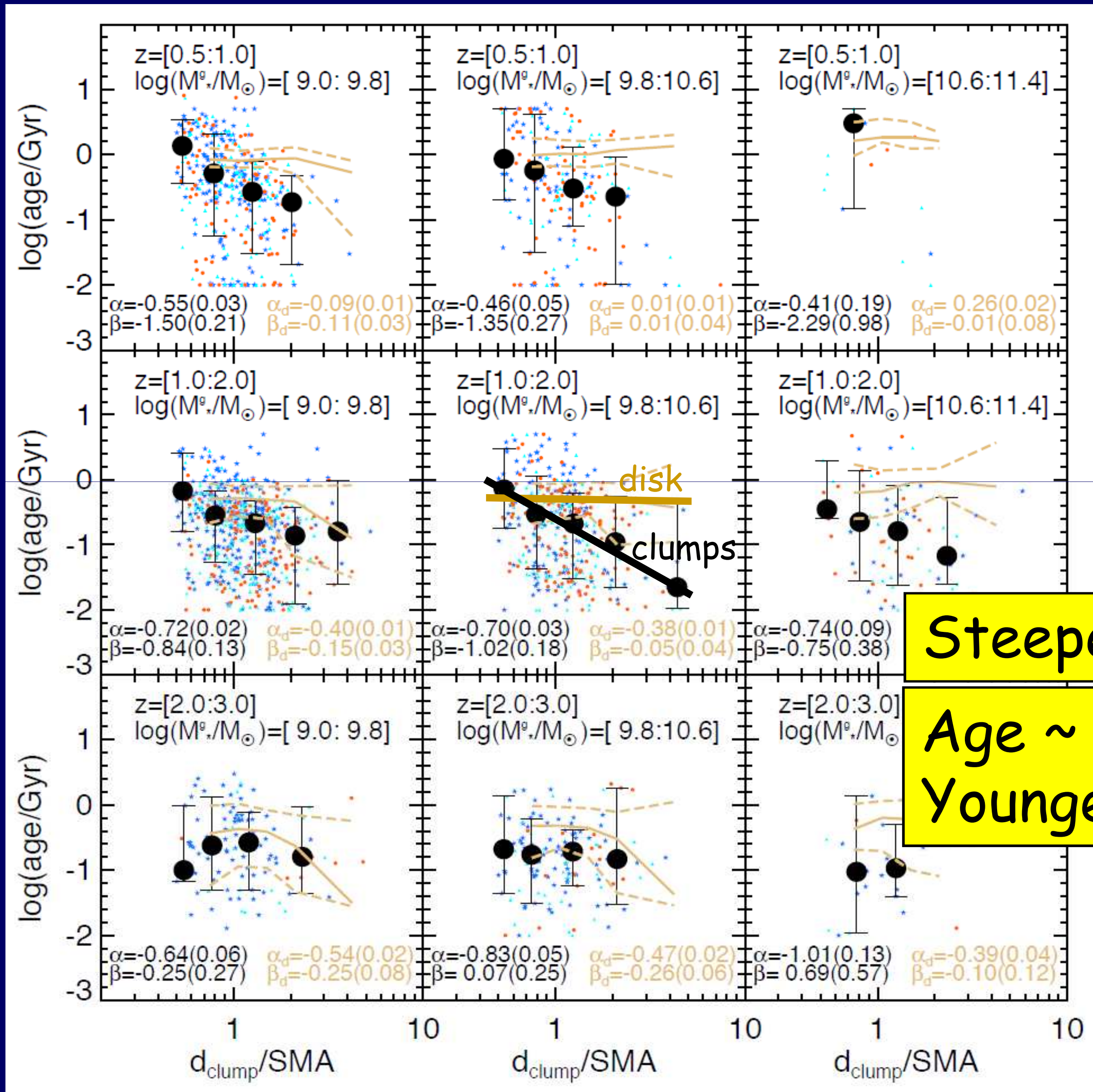


Observed clumps seem round and compact

Observed Clump Gradients

Guo+17 CANDELS

Age



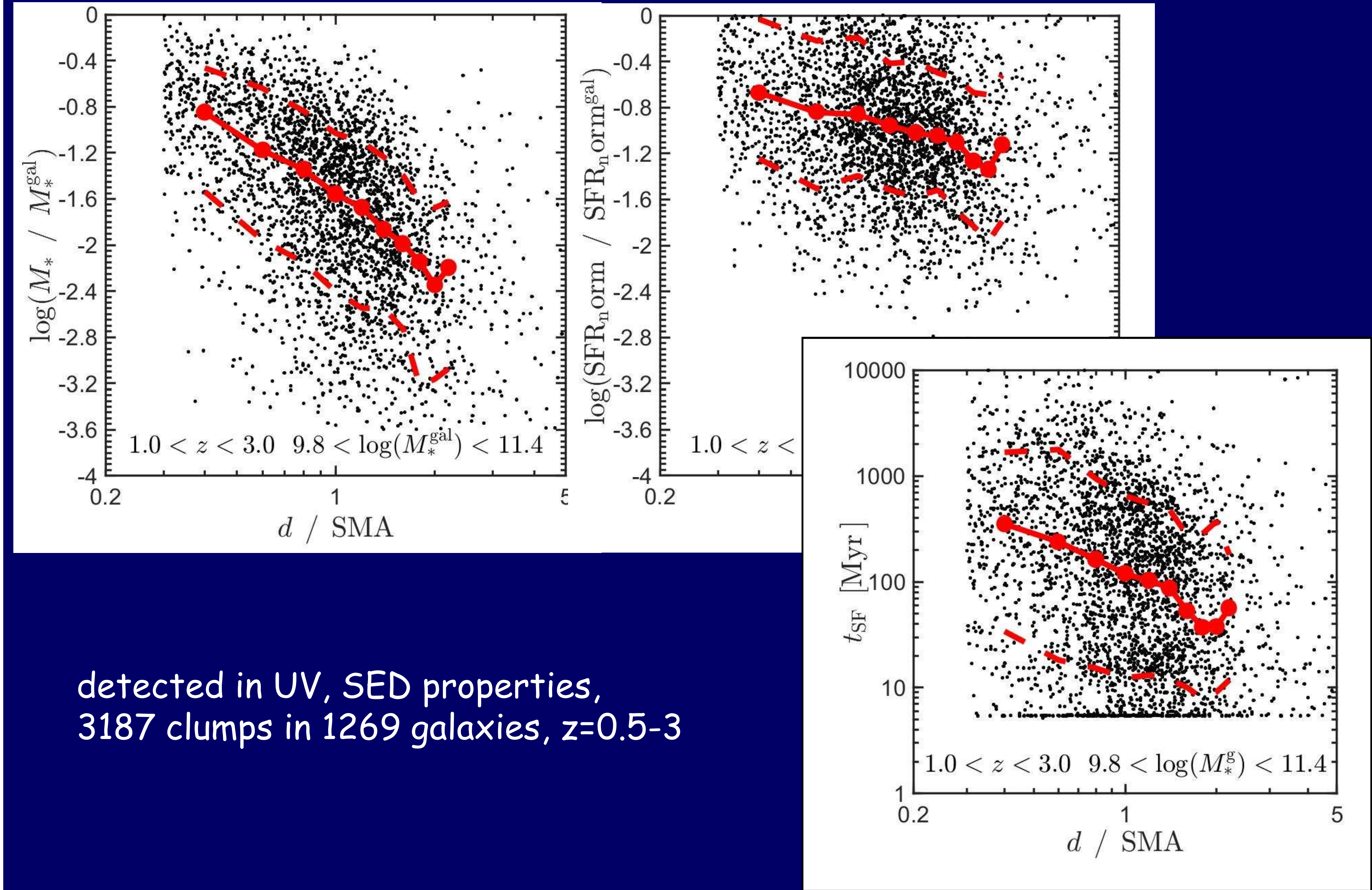
detected in UV
SED properties
3187 clumps
in 1269 galaxies
z=0.5-3

Steeper than in disk

Age ~ 0-500 Myr
Younger at large d

Observed Clump Gradients

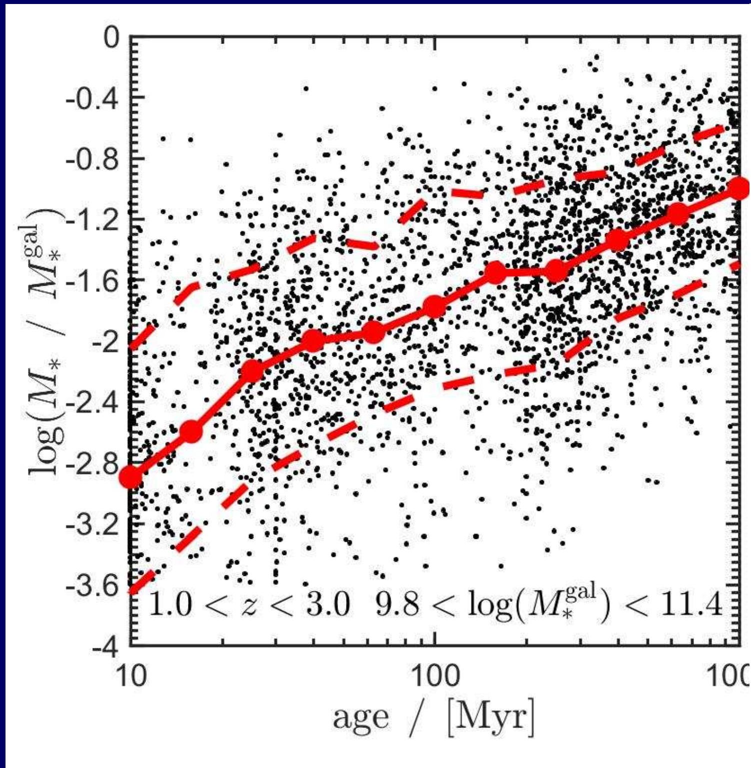
Guo+17 CANDELS

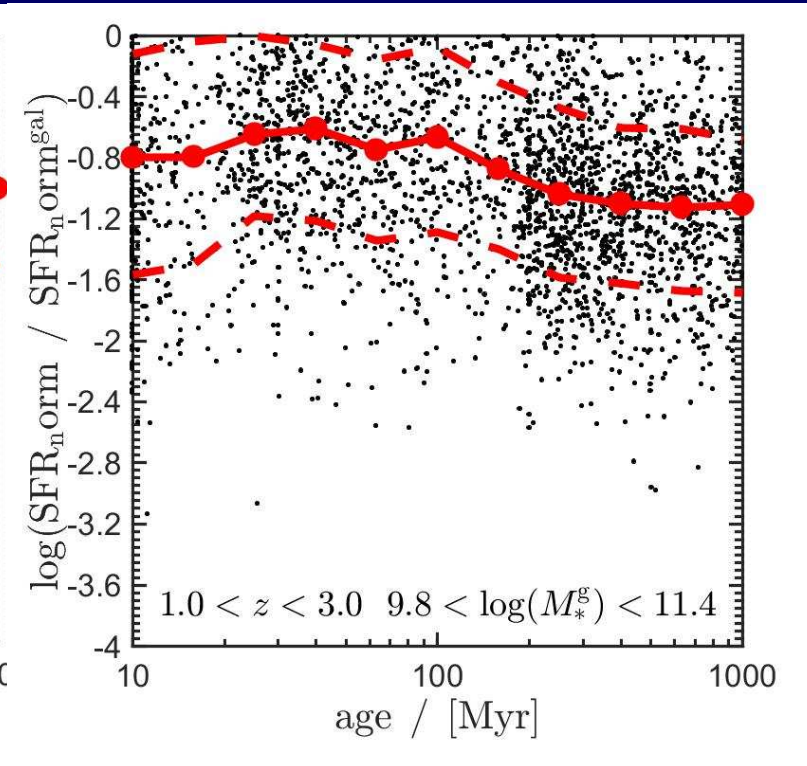


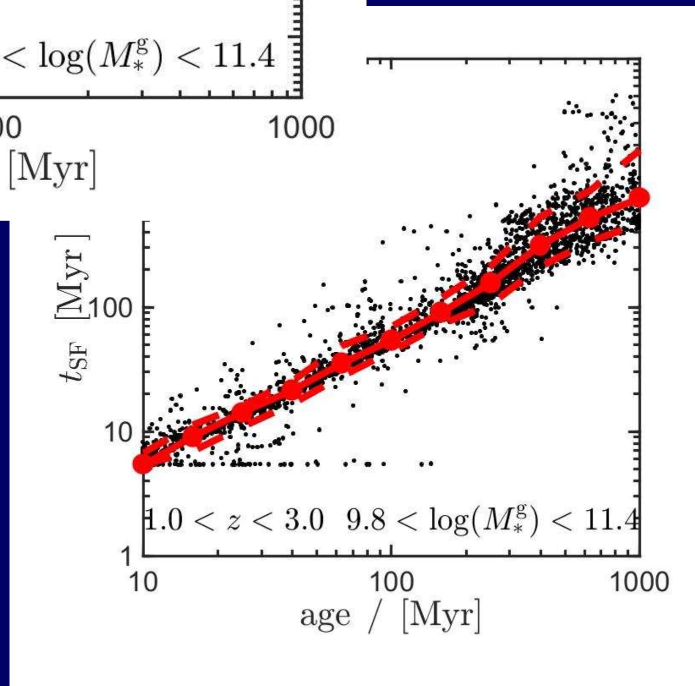
detected in UV, SED properties,
3187 clumps in 1269 galaxies, z=0.5-3

Observed Clumps vs Age

Guo+17 CANDELS



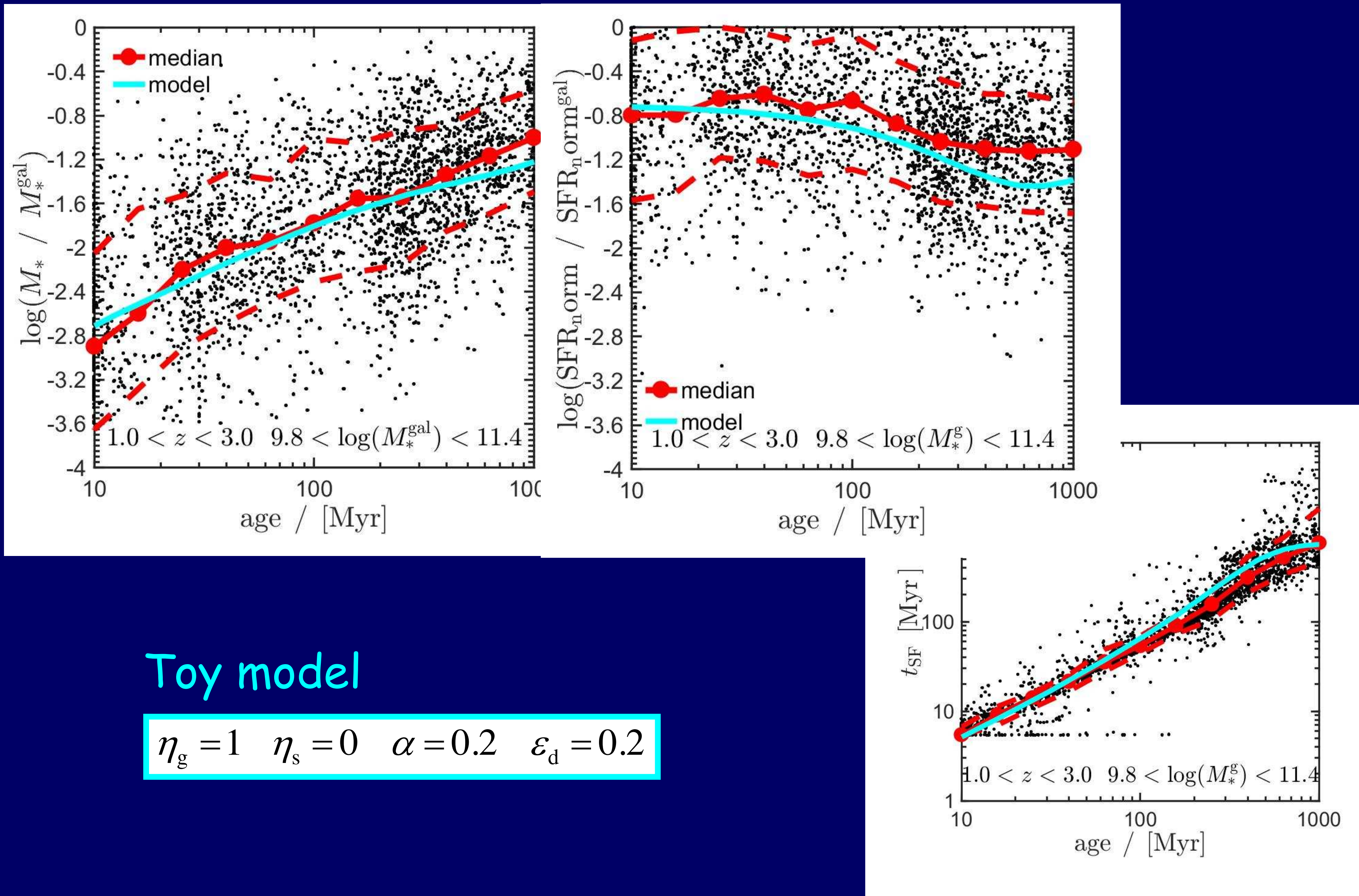




detected in UV, SED properties,
3187 clumps in 1269 galaxies, z=0.5-3

Observed Clumps vs Age

Guo+17 CANDELS



Toy model

$$\eta_g = 1 \quad \eta_s = 0 \quad \alpha = 0.2 \quad \varepsilon_d = 0.2$$

Conclusions: Clump Survival vs Disruption

- Long-lived clumps: massive >$10^8 M_\odot$, bound, compact & round
  Lifetimes 0-500 Myr. Gradients due to migration
  (plus short-lived clumps, and old massive ex-situ clumps)

- Short-lived clumps (Xmas-tree): unbound, diffuse, elongated
  Lifetimes <50Myr. Weak gradients due to disk stars

- Observed Clumps at z=0.5-3 (CANDELS) compact & round ?
  Ages 0-500 Myr and strong gradients
  Seem consistent with bound clumps

- A bathtub toy model reproduces the clump evolution in
  simulations and observations. Can be useful.