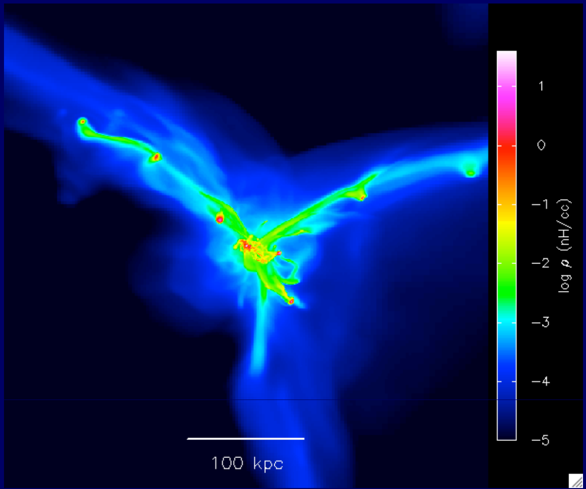
# Key Processes in High-z Galaxies

z=3-10

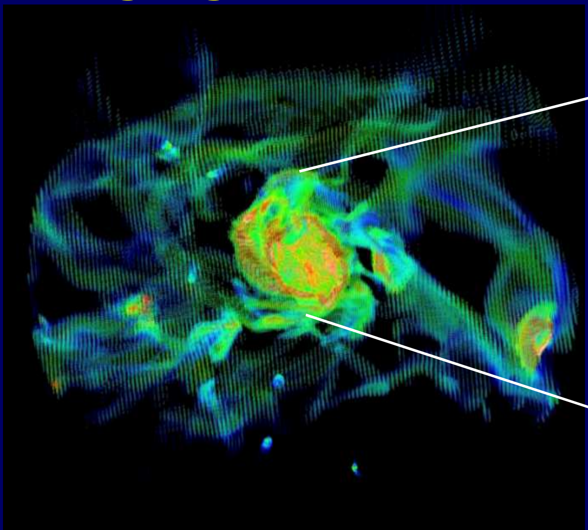
cosmic-web streams



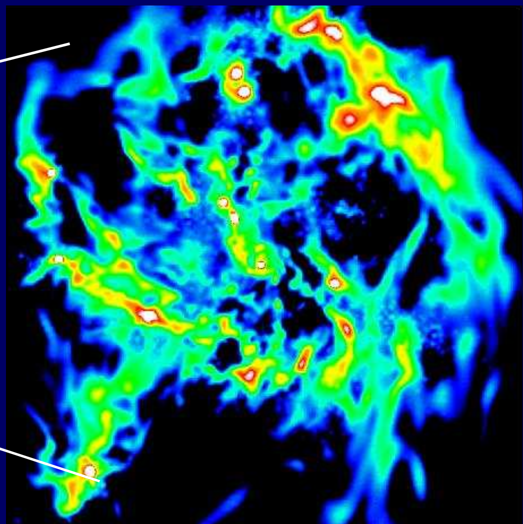

Avishai Dekel
The Hebrew University of Jerusalem

IAP, June 2016

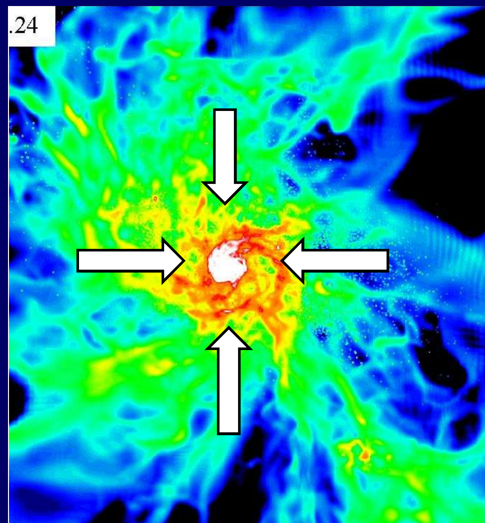
ring + gas-rich disk



violent instability



compaction



# Immediate Lessons from Timescales

Disk orbital time $t_{\rm orb} \approx \lambda t_{\rm vir} \approx 1(1+z)^{-3/2}\, Gyr$ $\quad t_{\rm orb} = 2\pi\, t_{\rm dyn}$

SFR time $t_{\rm sfr} = \varepsilon^{-1} t_{\rm ff} \approx 6\,(1+z)^{-3/2}\, Gyr$ $\quad t_{\rm ff} \approx t_{\rm dyn}/3$ in SF clumps

Accretion time $t_{\rm acr} \approx 25\,(1+z)^{-5/2}\, Gyr$

Dekel+13

| z | $t_{acc}/t_{orb}$ | $t_{acc}/t_{sfr}$ |
|---|---|---|
| 0 | 25 | 4.2 |
| 3 | 6.2 | 1 |
| 10 | 2.3 | 0.38 |

At z>3: $t_{acc}<t_{sfr}$ -> gas accumulates -> high $f_{gas}$

At z>3: accretion on a few orbital times
-> violent dynamical effects

# Minimal Bathtub Toy Model

Dekel, Mandelker 14
Dave+ Lilly+

Continuity gas: $\dot{M}_{\rm g} = f_{\rm ga}\dot{M}_{\rm acc} - (\mu+\eta)\dot{M}_{\rm sf}$

mass loading $\eta = \dot{M}_{\rm loss}/\dot{M}_{\rm sf} = \eta_{\rm out} - \eta_{\rm rec}$

stars: $\dot{M}_{\rm s} = f_{\rm sa}\dot{M}_{\rm acc} + \mu\dot{M}_{\rm sf}$

$\mu \approx 0.5$ fraction left in stars

Accretion rate $\dot{M}_{\rm acc}/M_{\rm acc} = 0.03\,Gyr^{-1}(1+z)^{5/2}$ $M_{\rm a} = M_{\rm ai}e^{-0.8(z-z_i)}$

SFR $\dot{M}_{\rm sf} = M_{\rm g}/t_{\rm sf}$ $t_{\rm sf} = \varepsilon^{-1}t_{\rm ff} \propto t$

-> Simple equation $\dot{M}_{\rm g} = A - \tau^{-1}M_{\rm g}$

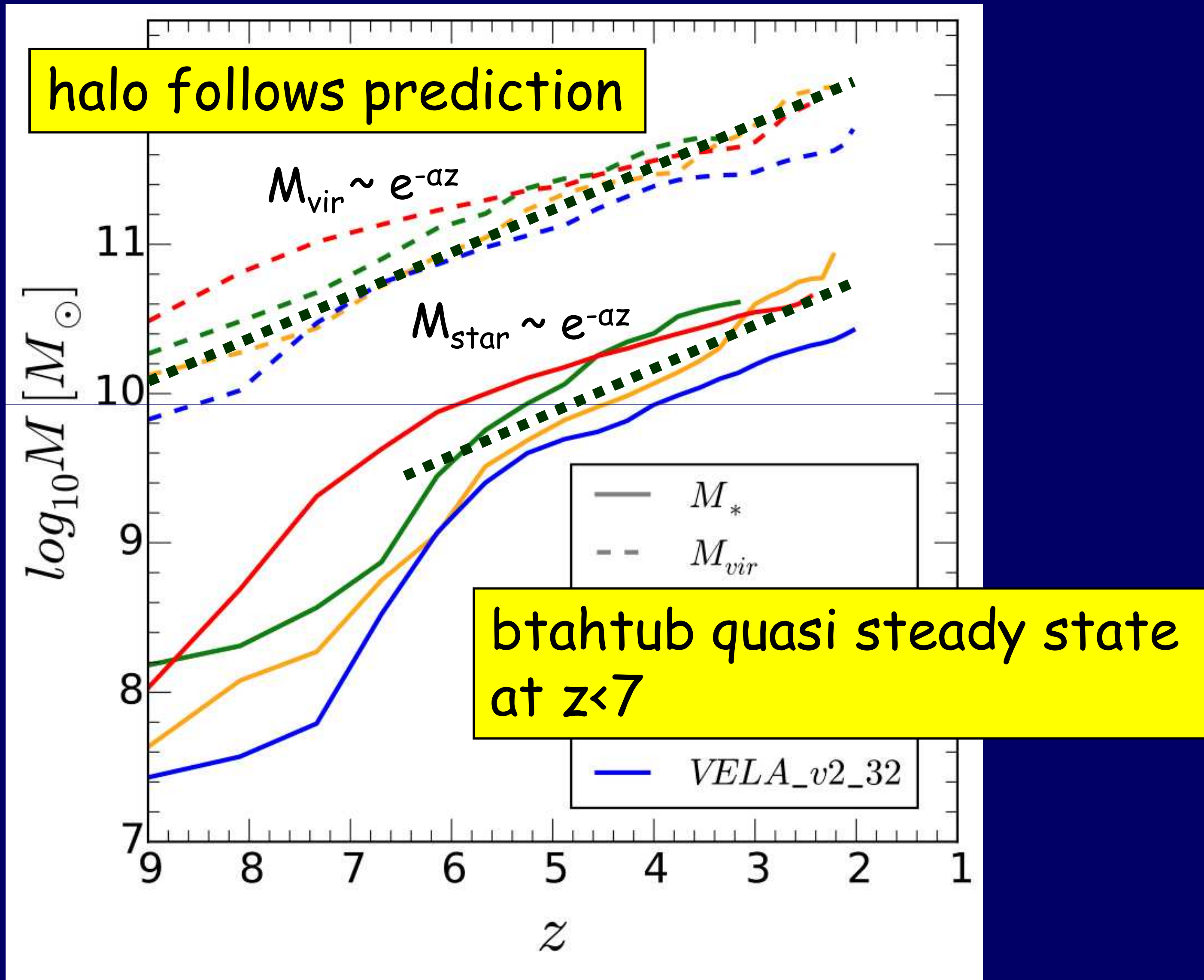
Quasi-steady-state solution $\dot{M}_{\rm g} \approx 0$ $M_{\rm g} \approx A\tau$

$$\mathrm{SFR} \approx \frac{f_{\rm ga}}{\mu+\eta}\dot{M}_{\rm acc}$$

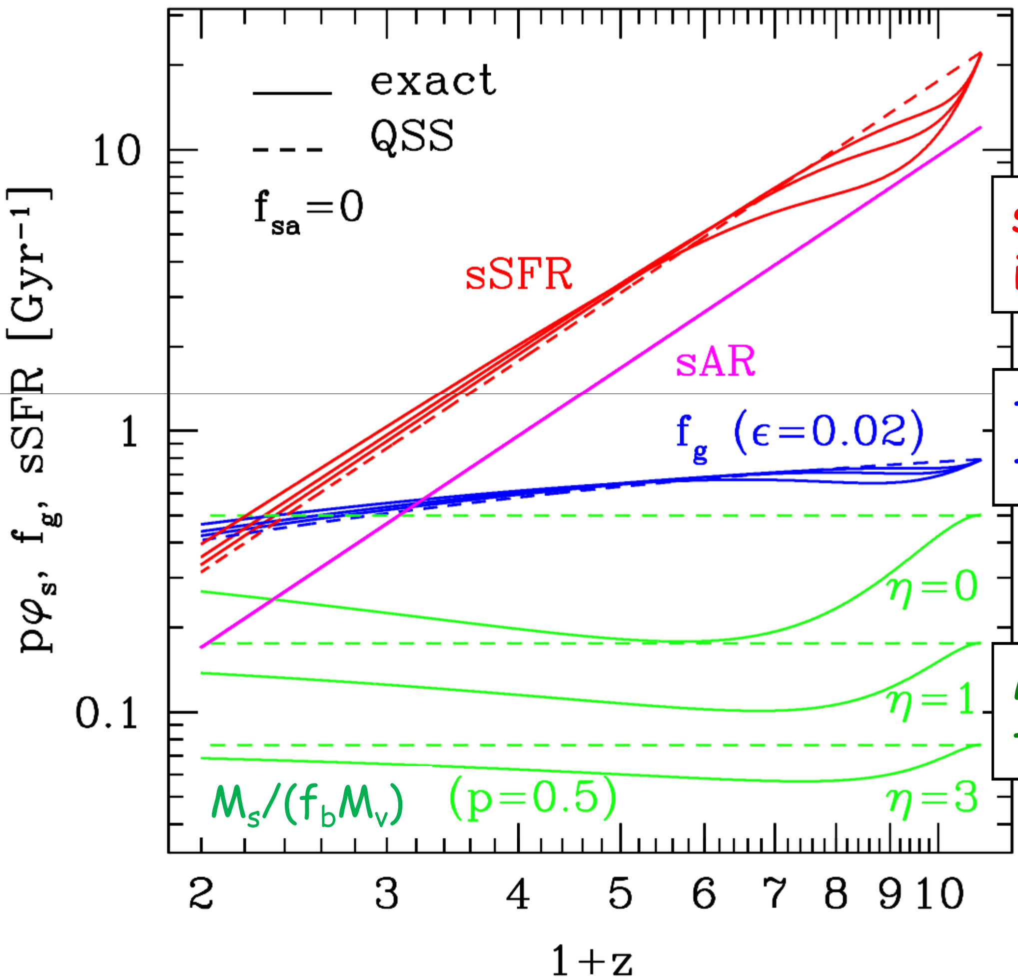
insensitive to ε and η

$$\mathrm{sSFR} = \frac{f_{\rm ga}}{\mu+f_{\rm sa}\eta}\,\mathrm{sAR}$$

# Mass Growth in Sumulations



# Bathtub Toy Model: Solution



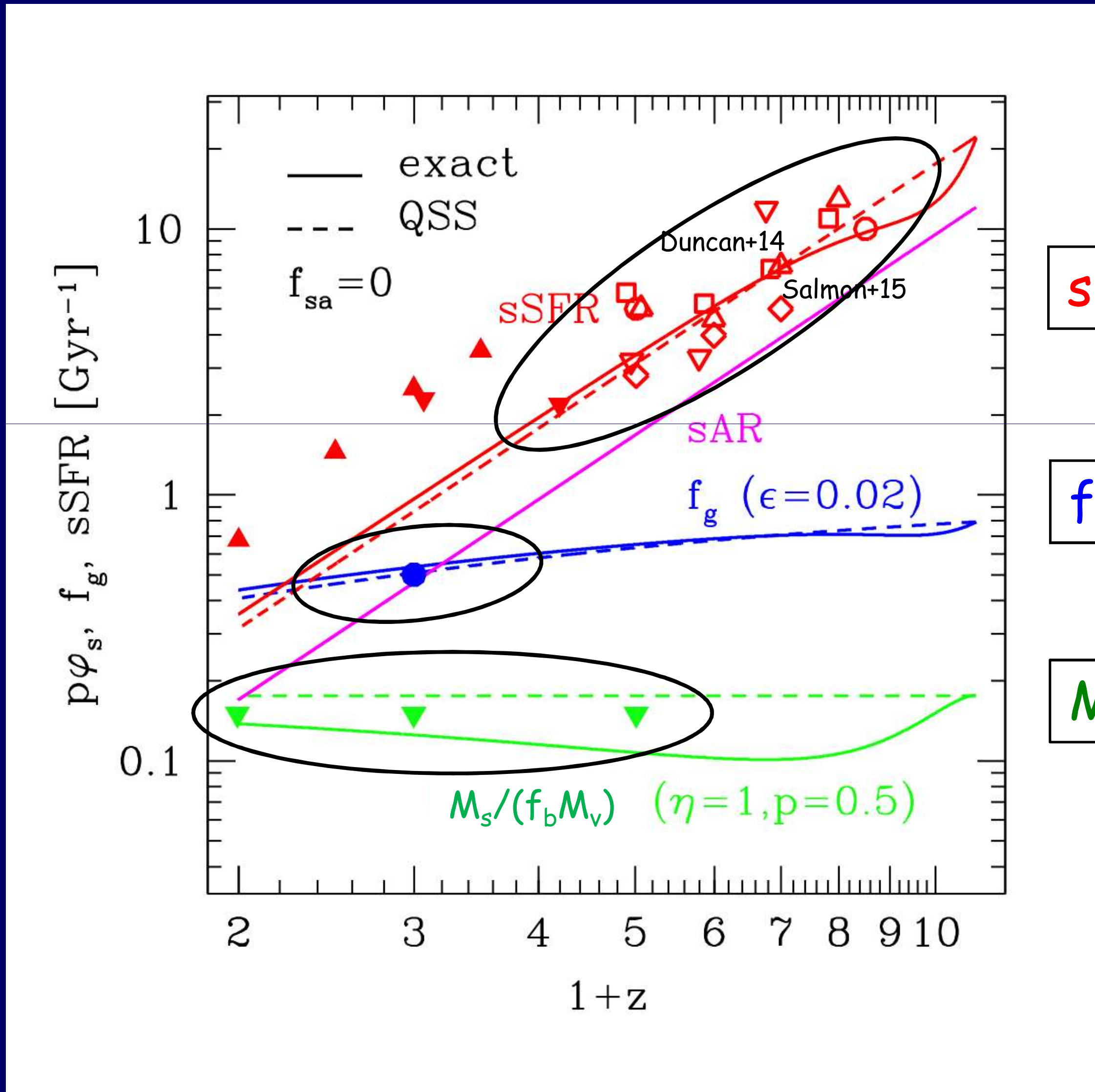

sSFR > sAR
insensitive to ε,η

$f_g$ declines slowly
f(ε)

$M_s/M_v$ ~const.
f(η)

# Bathtub Toy Model vs Observations

If *gaseous accretion* (high z): a good fit at z>3




sSFR > sAR

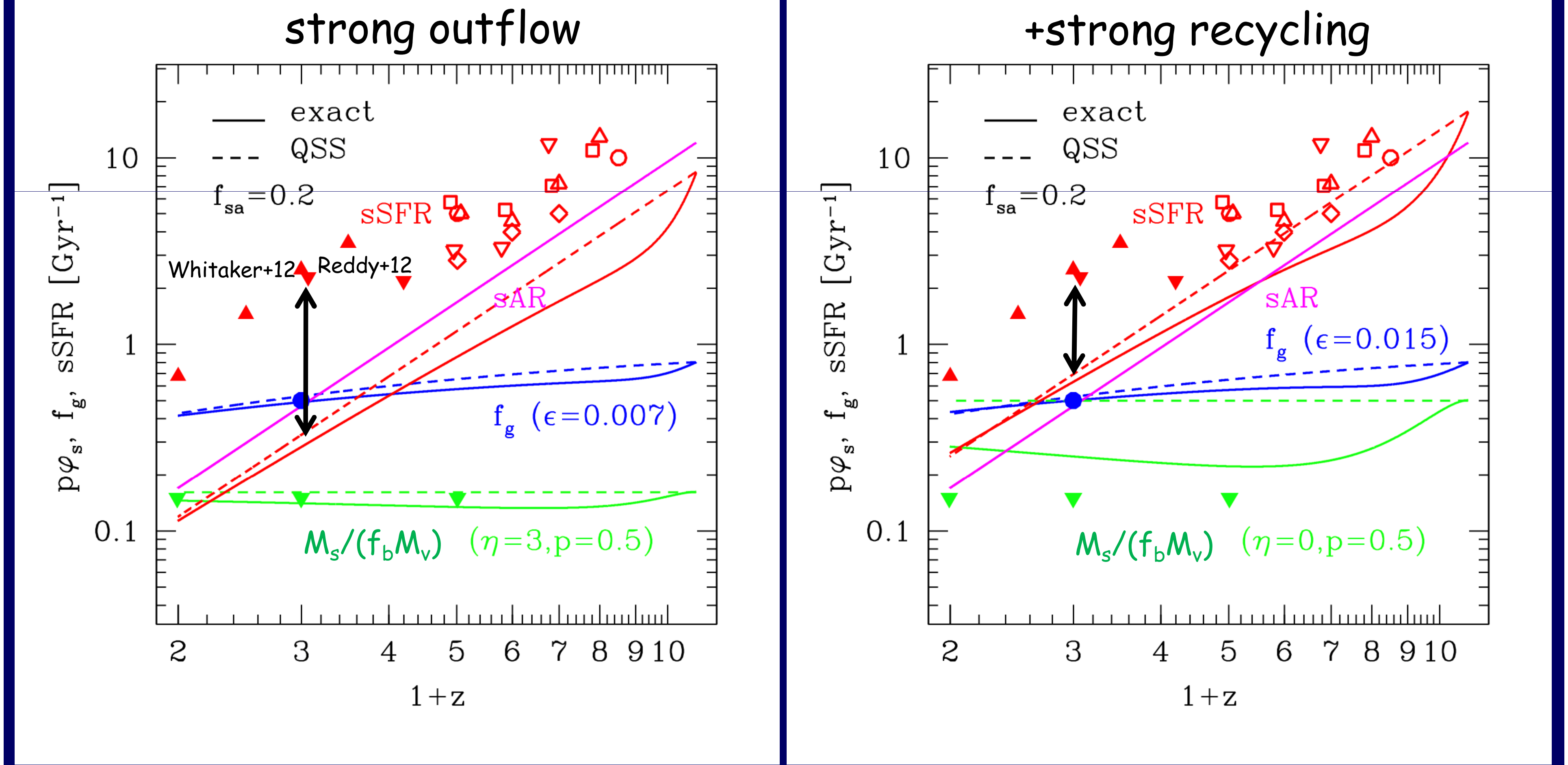
$f_g \rightarrow \varepsilon \sim 0.02$

$M_s/M_v \rightarrow \eta \sim 1$

# Bathtub Toy Model vs Observations

If some stellar accretion: can't match the high sSFR at z~2

Modeling recycling?  Observational bias?  Toy model invalid?



# AMR Cosmological Simulations

Cosmological box, RAMSES (Teyssier), resolution 1 kpc

Zoom-in individual galaxies, ART (Kravtsov, Klypin)
Ceverino, Dekel, Primack, Klypin:
25 pc resolution, stellar+SN+radiative fdbk (3x35 galaxies)

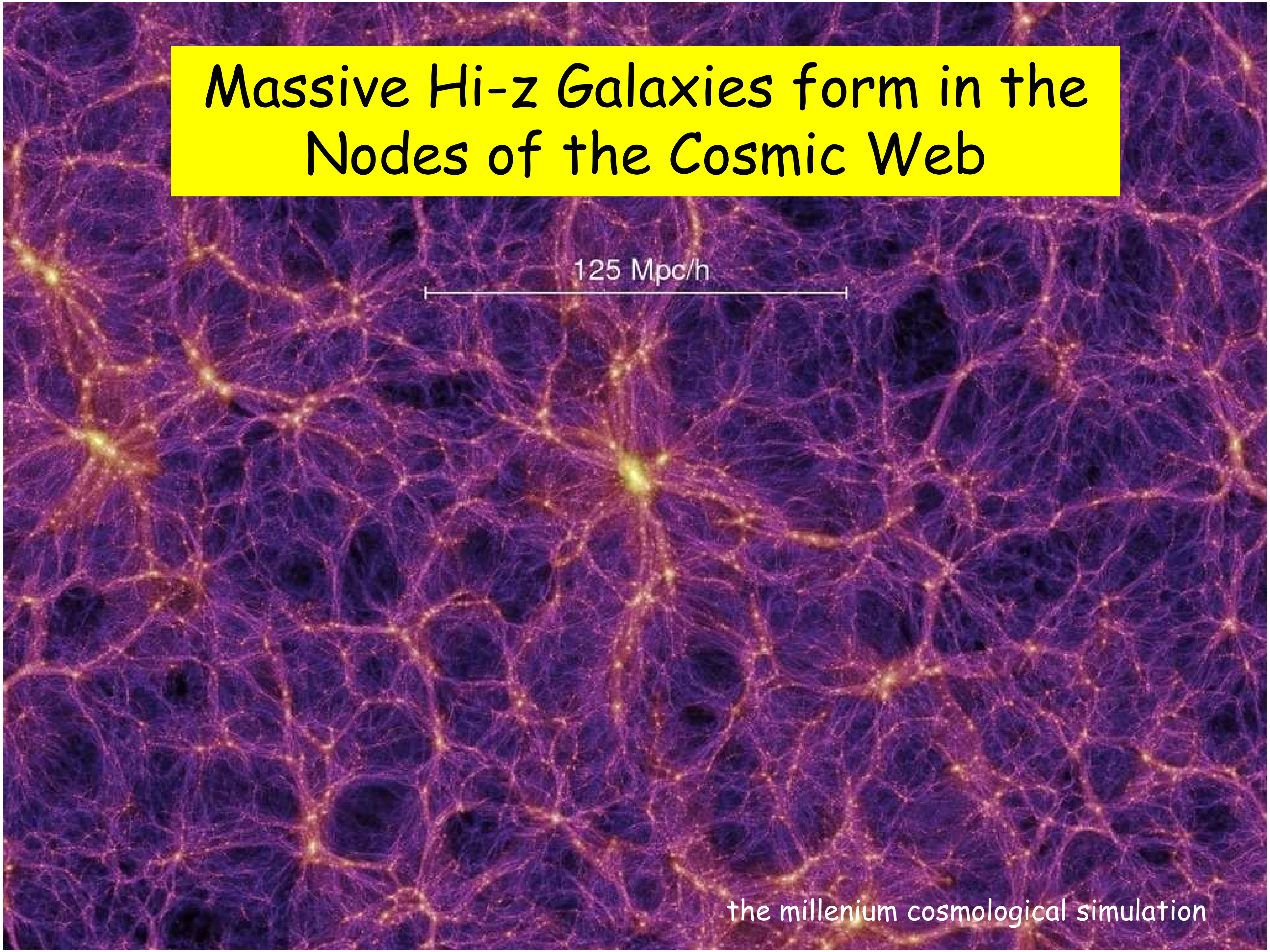
Isolated galaxies, resolution 1-10 pc, RAMSES (Bournaud),
ENZO (Forbes)

HUJI: Ceverino, Danovich, Mandelker, Padnos, Zolotov, Lapiner,
Kertschmer, DeGraf, Inoue, Tomassetti, Roca-Fabrega …

UCSC: Forbes        ETH: Tacchella

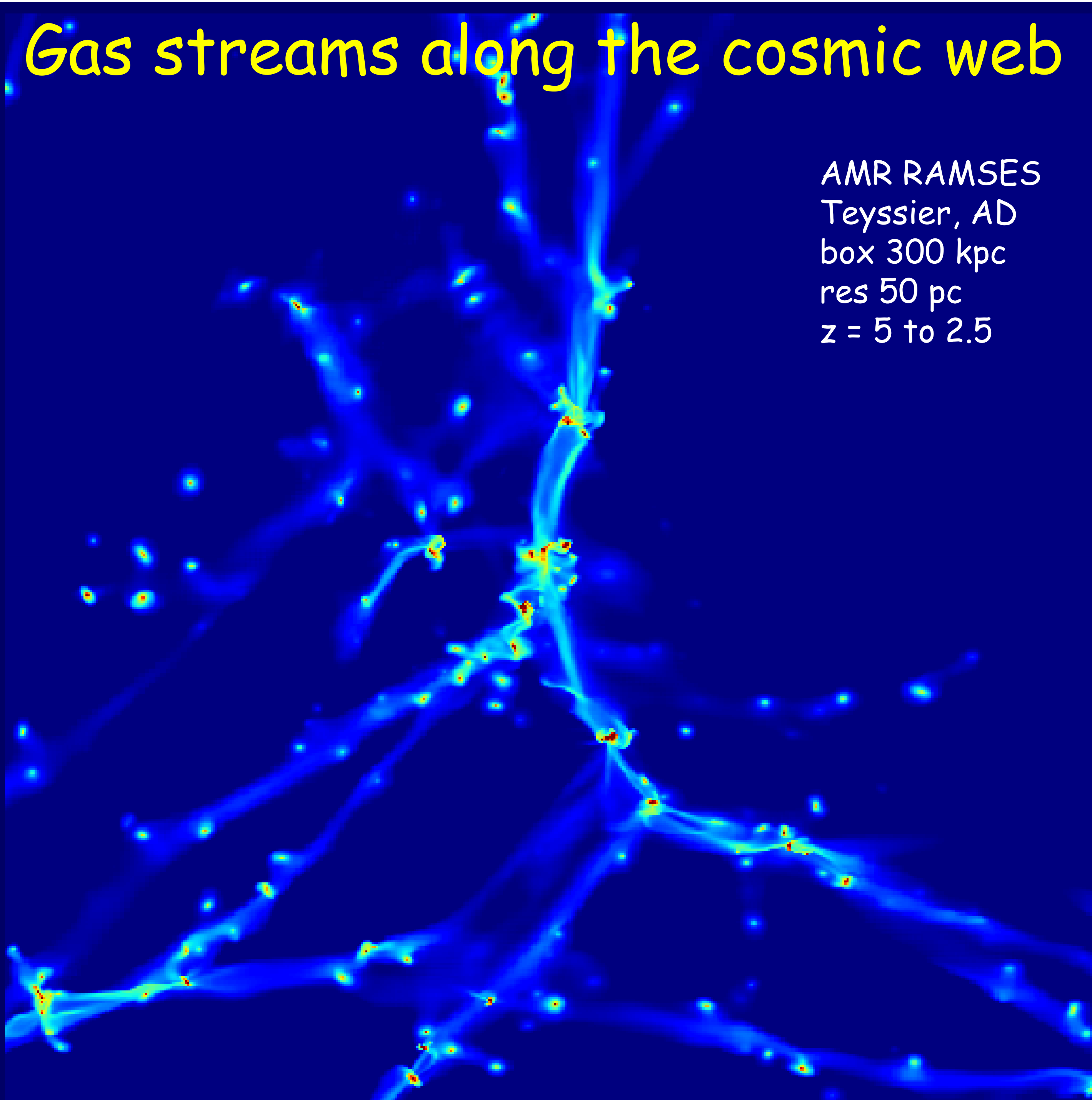
Collaborators: Bournaud+, Teyssier+, Klypin+, Krumholz+, Burkert+,
Primack+, Genzel+, Faber+, Carollo+, …

# Massive Hi-z Galaxies form in the Nodes of the Cosmic Web




the millenium cosmological simulation

# Gas streams along the cosmic web

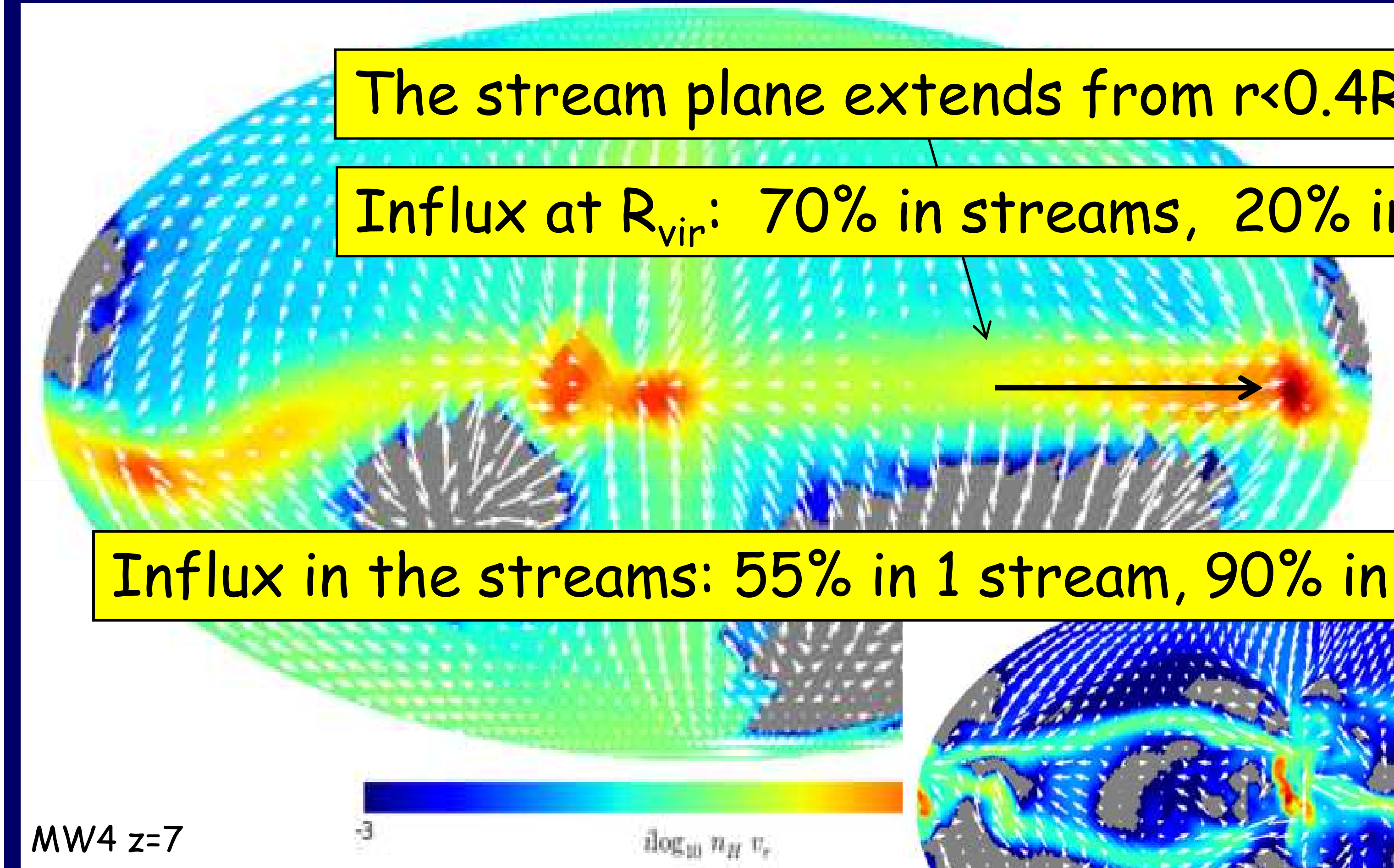


# Flows into pancakes, and along pancakes to filaments

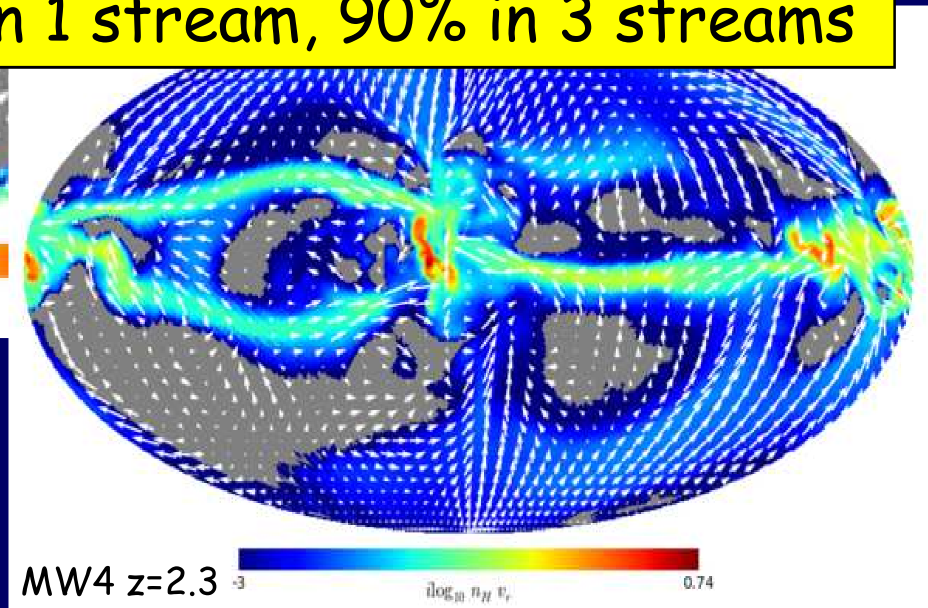
The stream plane extends from r<0.4Rv to r>5Rv

Influx at $R_{vir}$: 70% in streams, 20% in pancakes

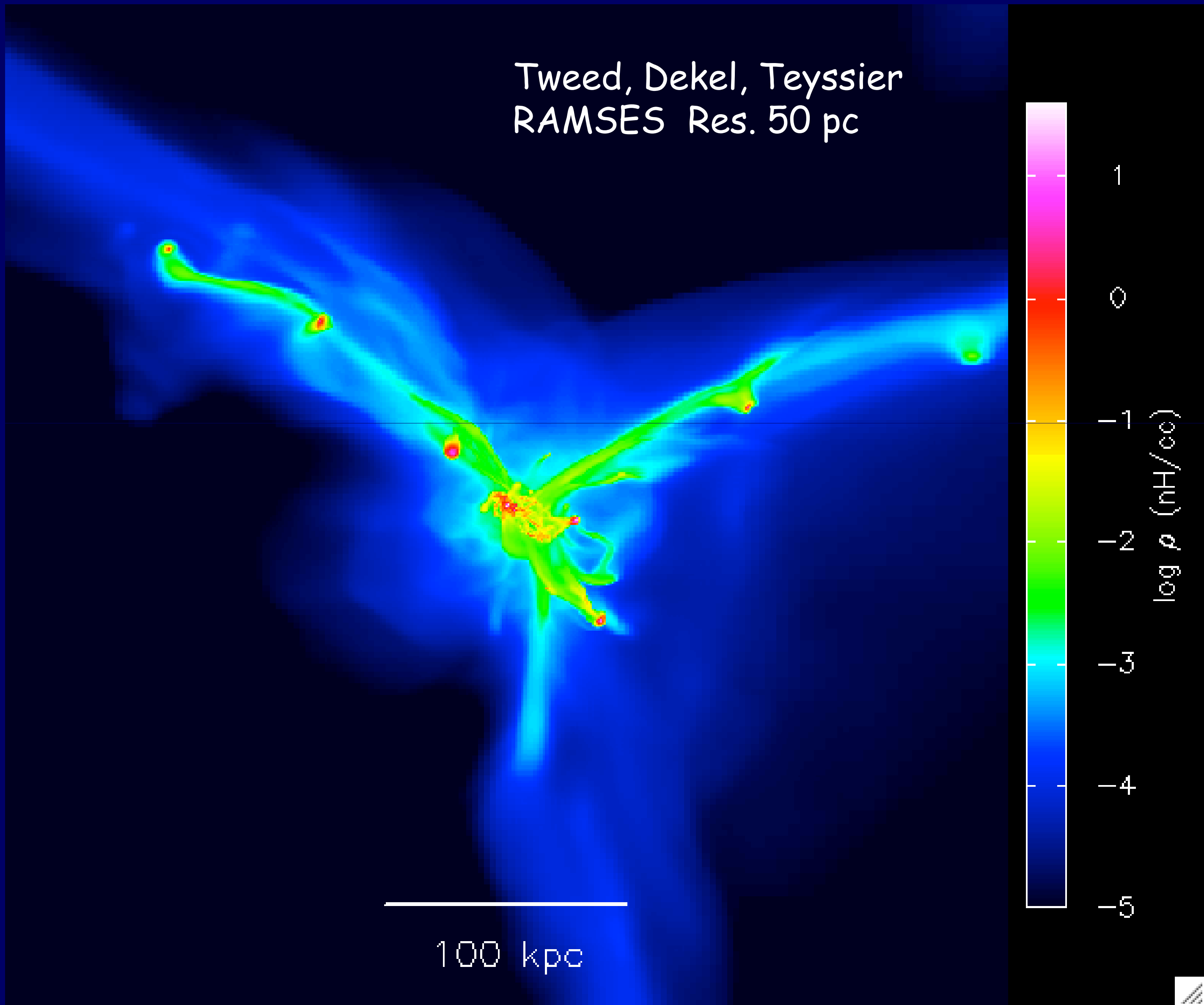
Influx in the streams: 55% in 1 stream, 90% in 3 streams



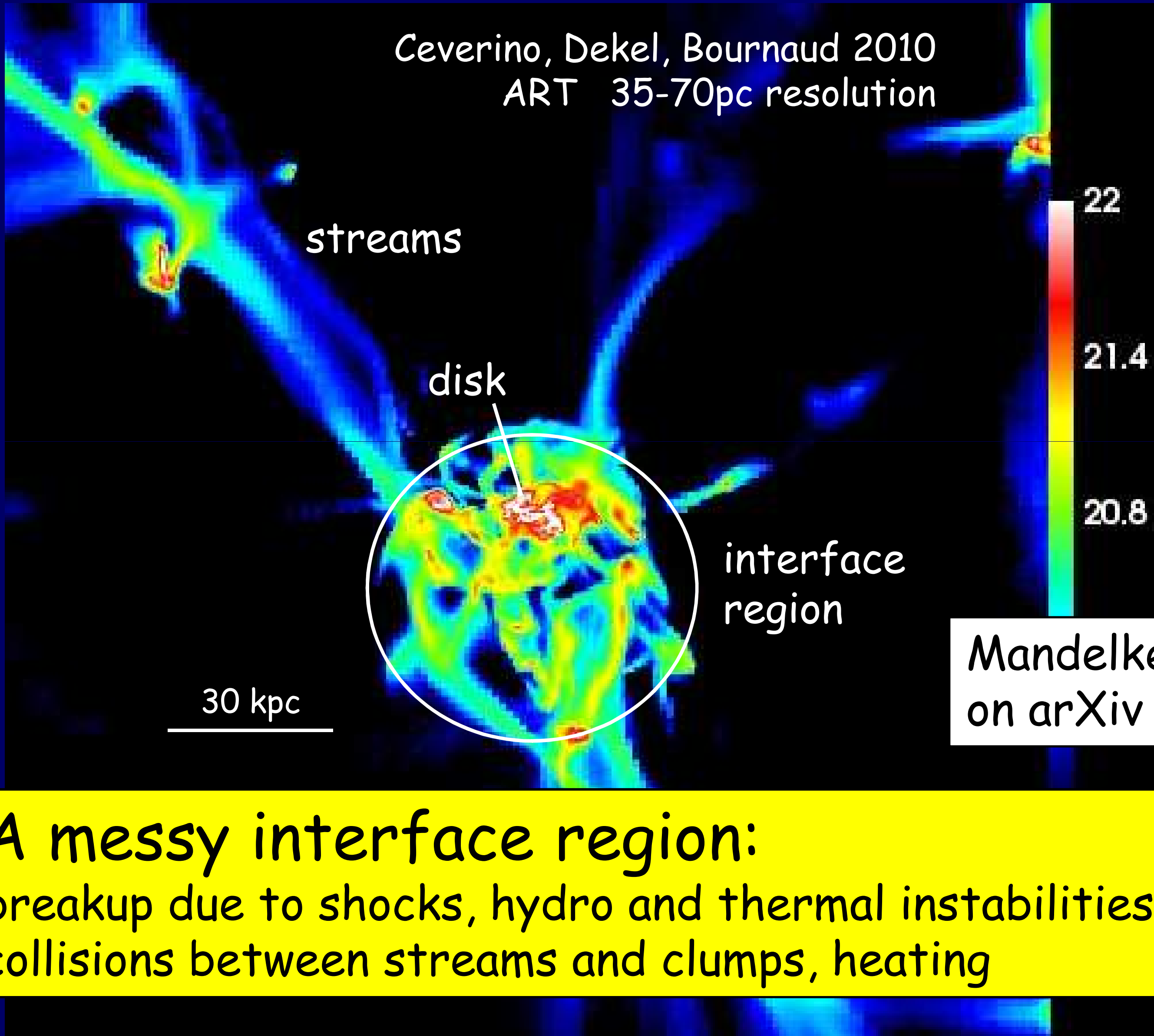

influx $M_{\odot} yr^{-1} rad^{-2}$



# Streams Feeding a Hi-z Galaxy



# How do the streams join the disk?

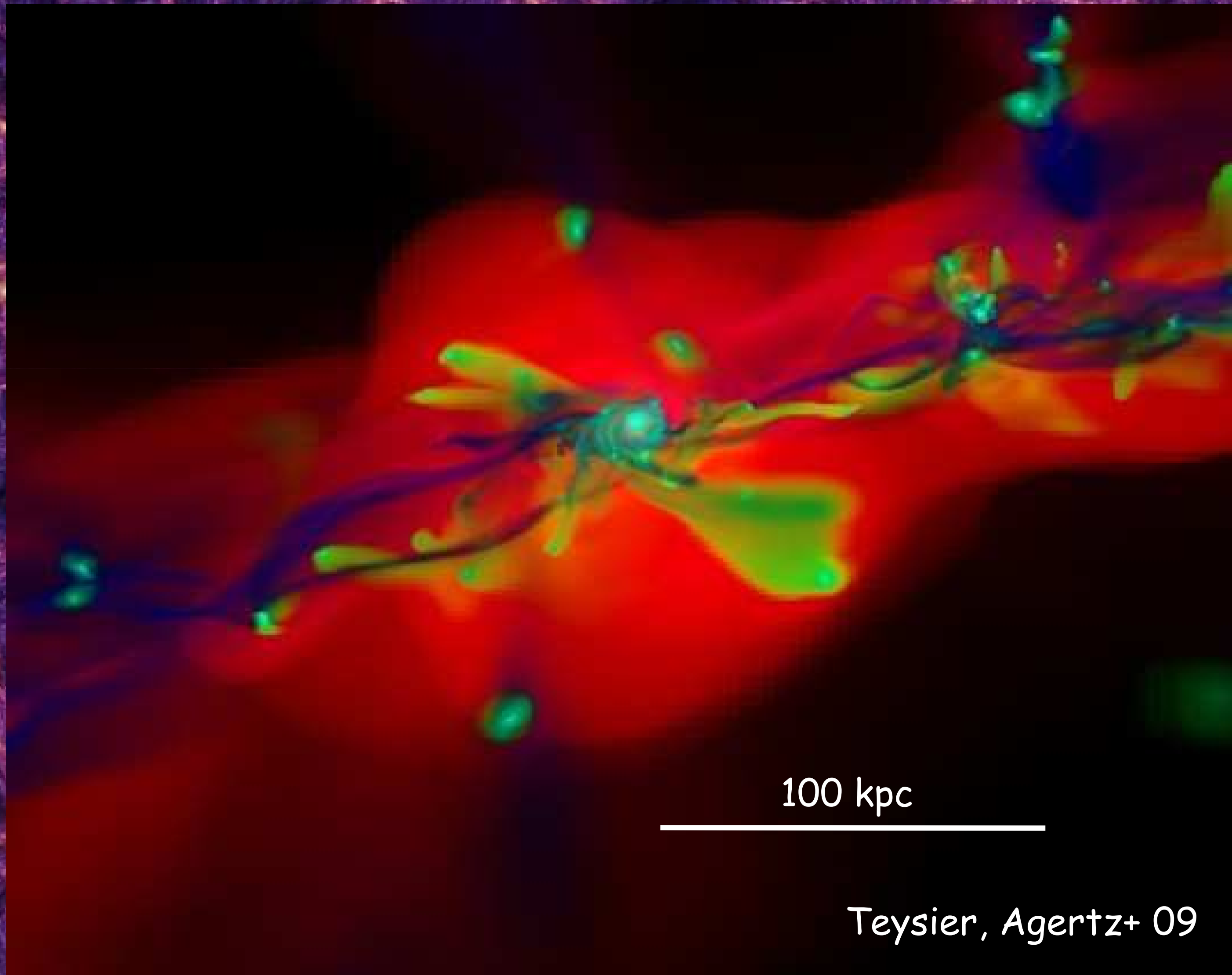



Mandelker+ 16 on arXiv today

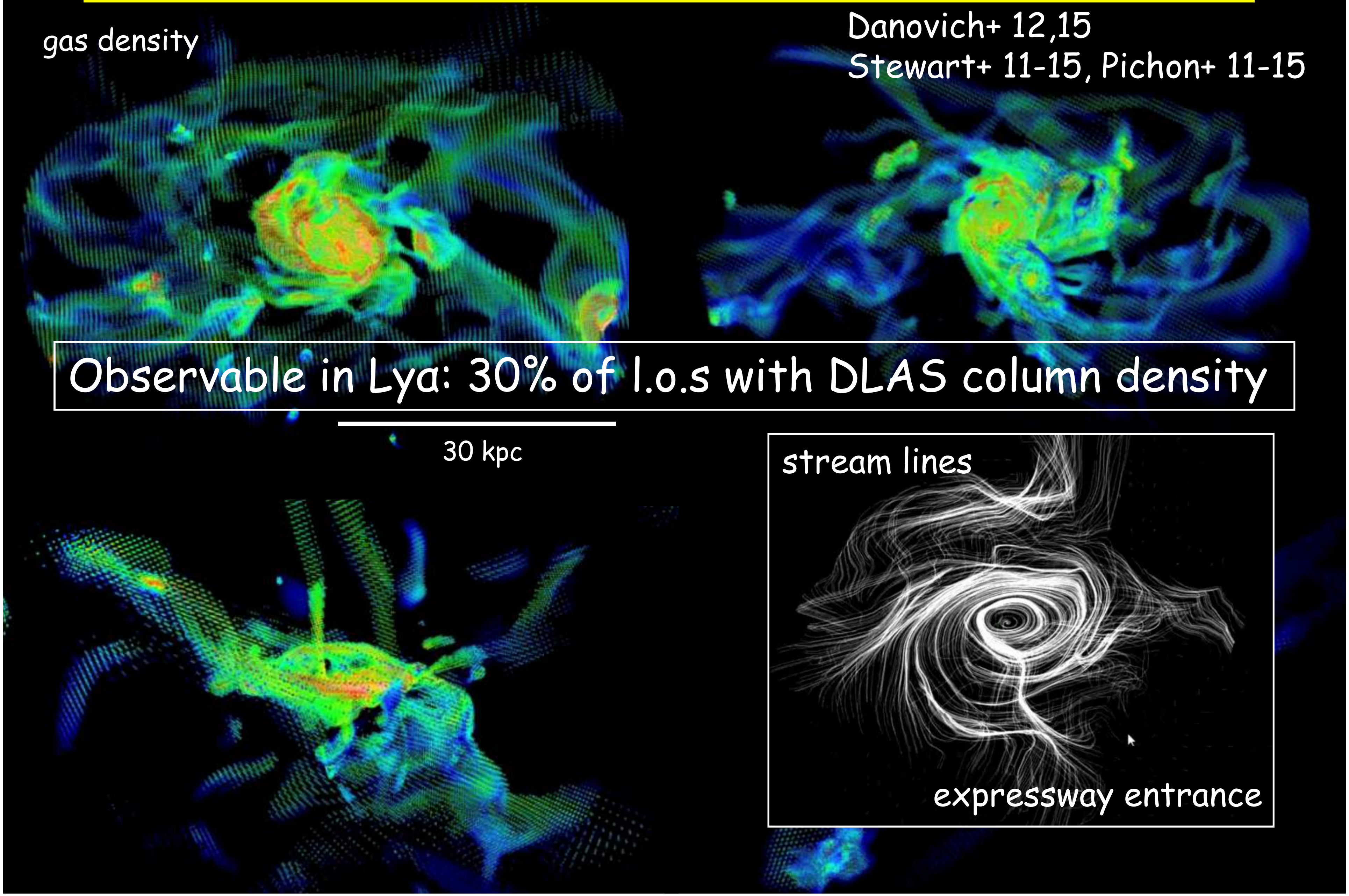
## A messy interface region:

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

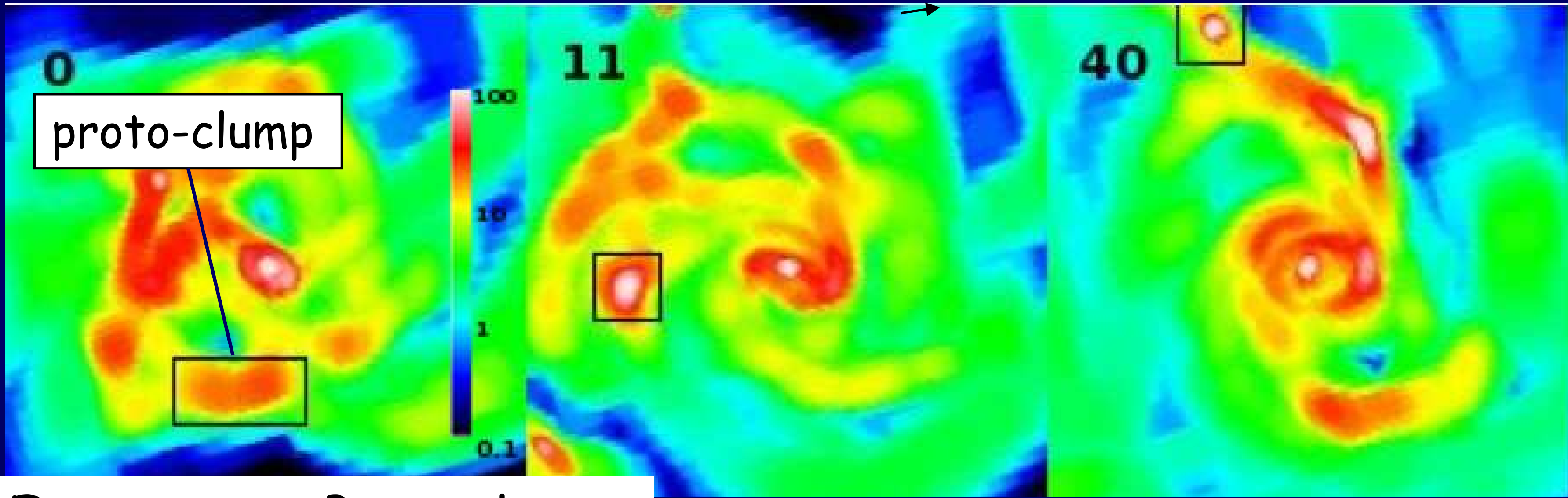
# Angular momentum buildup in the context of galaxy growth by cosmic-web streams



# An Extended Tilted Ring about the Disk



# High Gas Fraction -> Violent Disk Instability




Forces on a Protoclump:

pressure
prevents small clumps

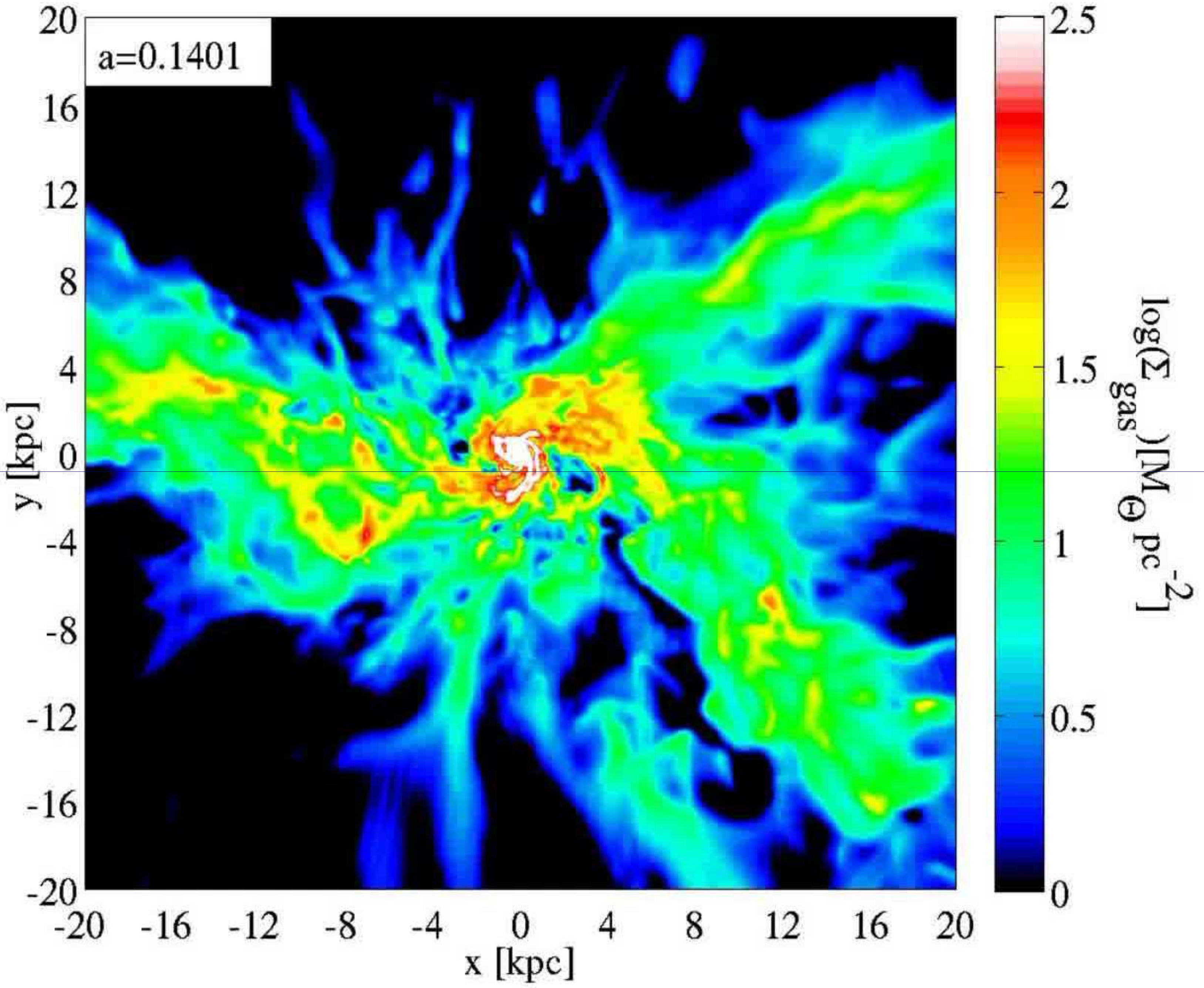
rotation
prevents big clumps

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

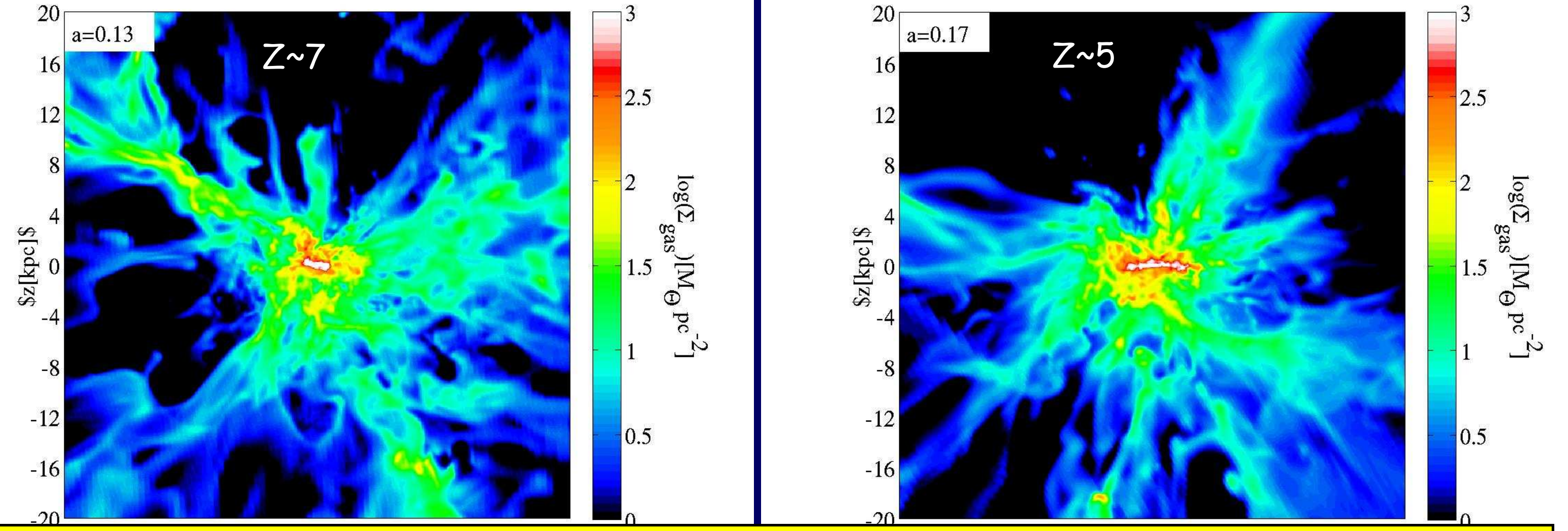
Toomre 64

self-gravity attraction

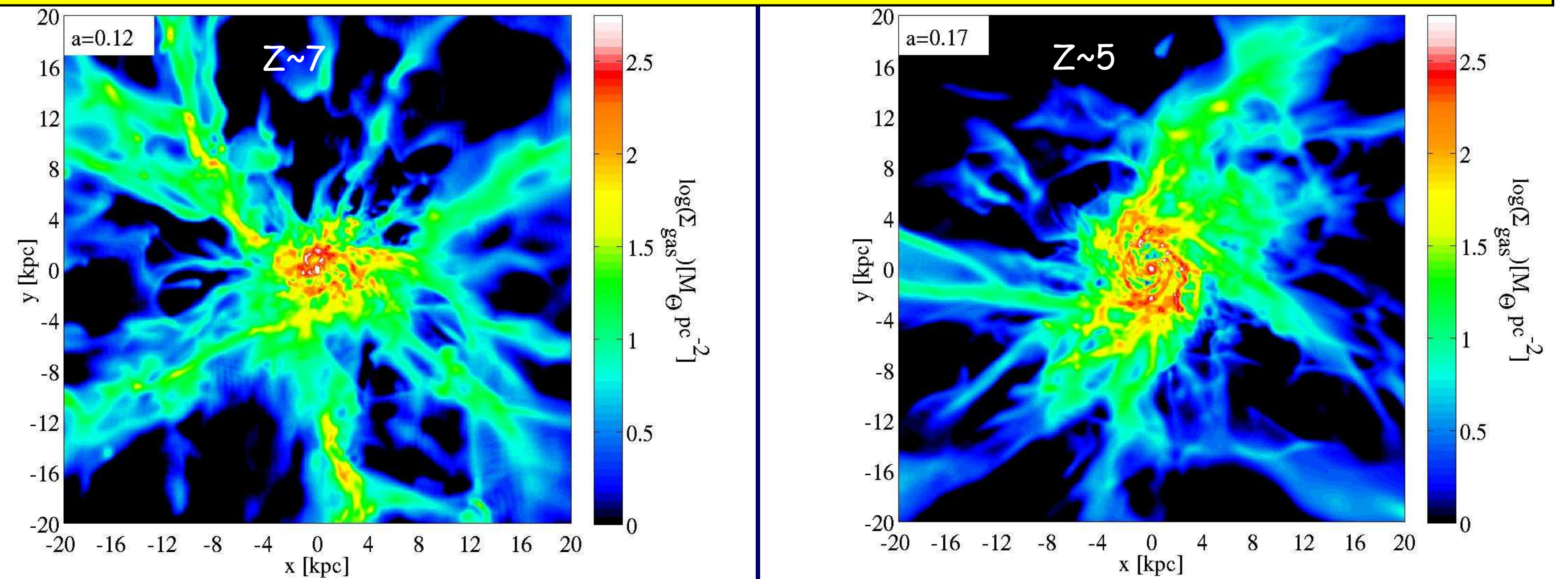
Gravity wins when Q<1




V19



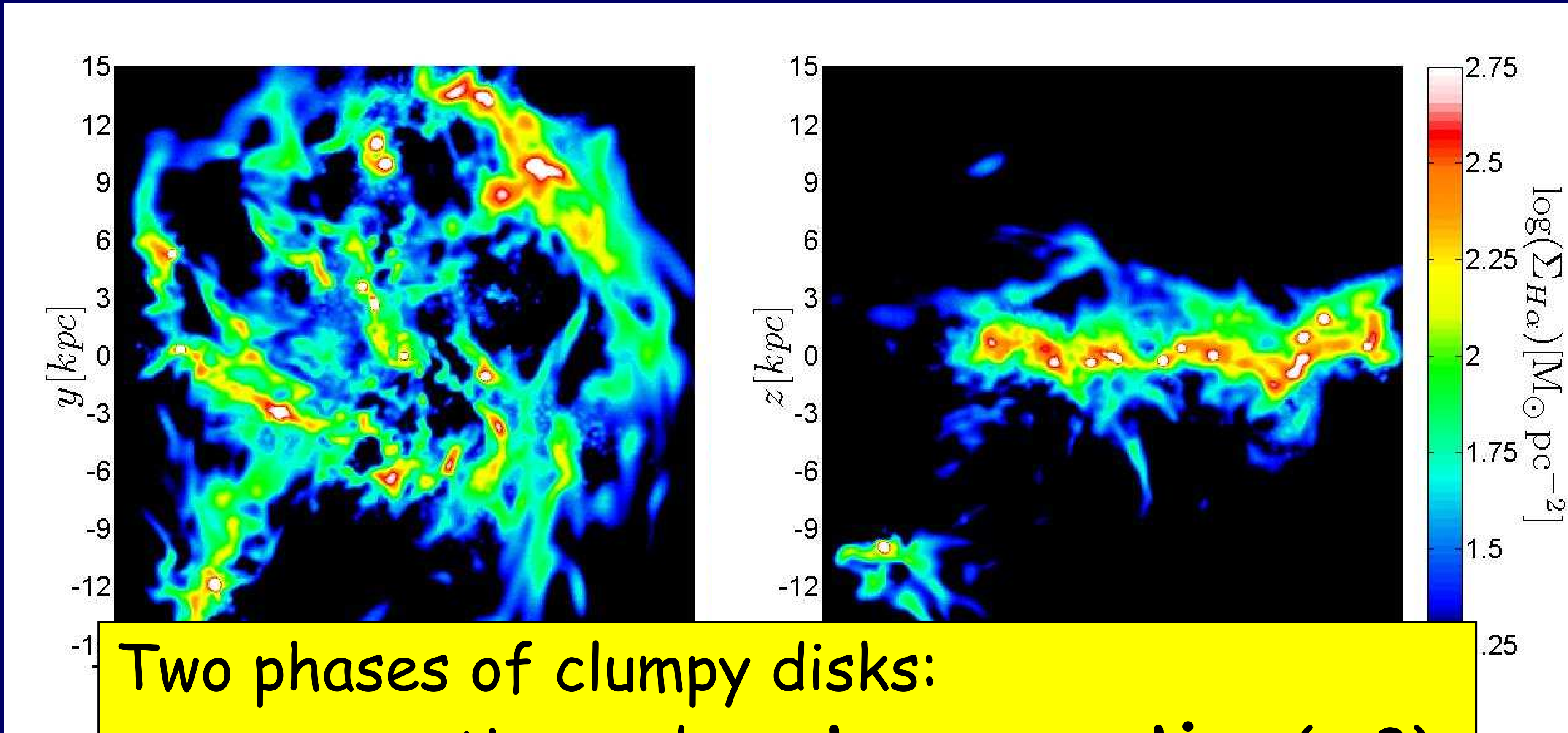

# Expect clumpy disks (~5kpc) already at z~7



# Violent Disk Instability (VDI) at z~2

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

highly perturbed, clumpy rotating disk: $H/R \sim \sigma/V \sim f_{cold} \sim 0.2$

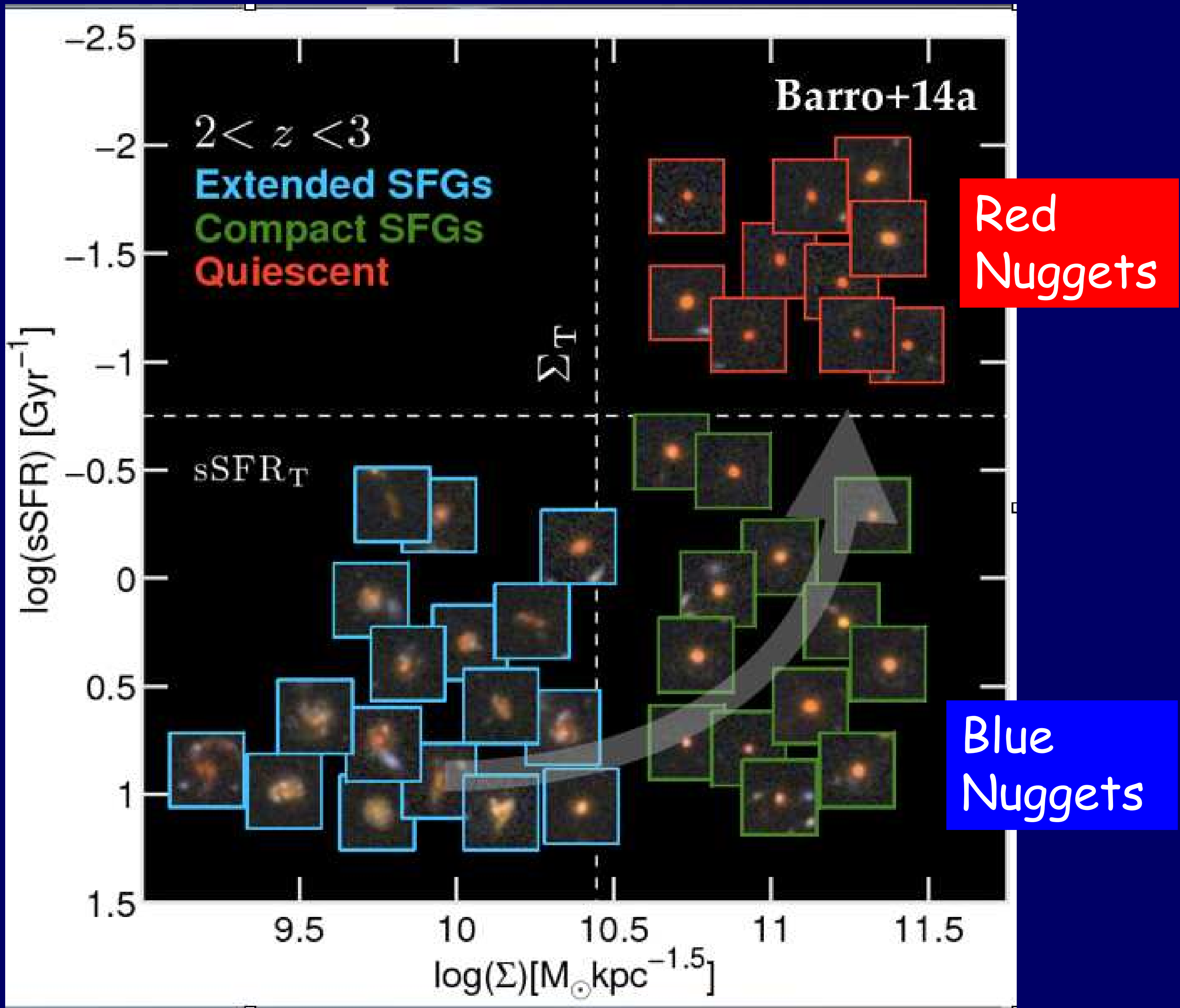



Two phases of clumpy disks:
pre-compaction and **post-compaction** (z<3)

Violent disk instability (VDI) and mergers (mostly minor) work in concert

VDI may deviate from linear Toomre instability
Q=2-5 -> nonlinear instability
stimulated by in-streams with minor mergers

Inoue+ 15; Mandelekr+16



Barro+14a
2< z <3
Extended SFGs
Compact SFGs
Quiescent
sSFR$_T$
$\Sigma_T$
Red Nuggets
Blue Nuggets
log(sSFR) [Gyr$^{-1}$]
log(Σ)[M$_\odot$kpc$^{-1.5}$]
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
9.5
10
10.5
11
11.5

# Wet Compaction

Dekel & Burkert 2013

Compact stellar spheroid → dissipative inflow to a "blue nugget"

Inflow is "wet" if inflow > SFR

In violent disk instability (VDI): torques drive AM out and mass in

Wetness parameter

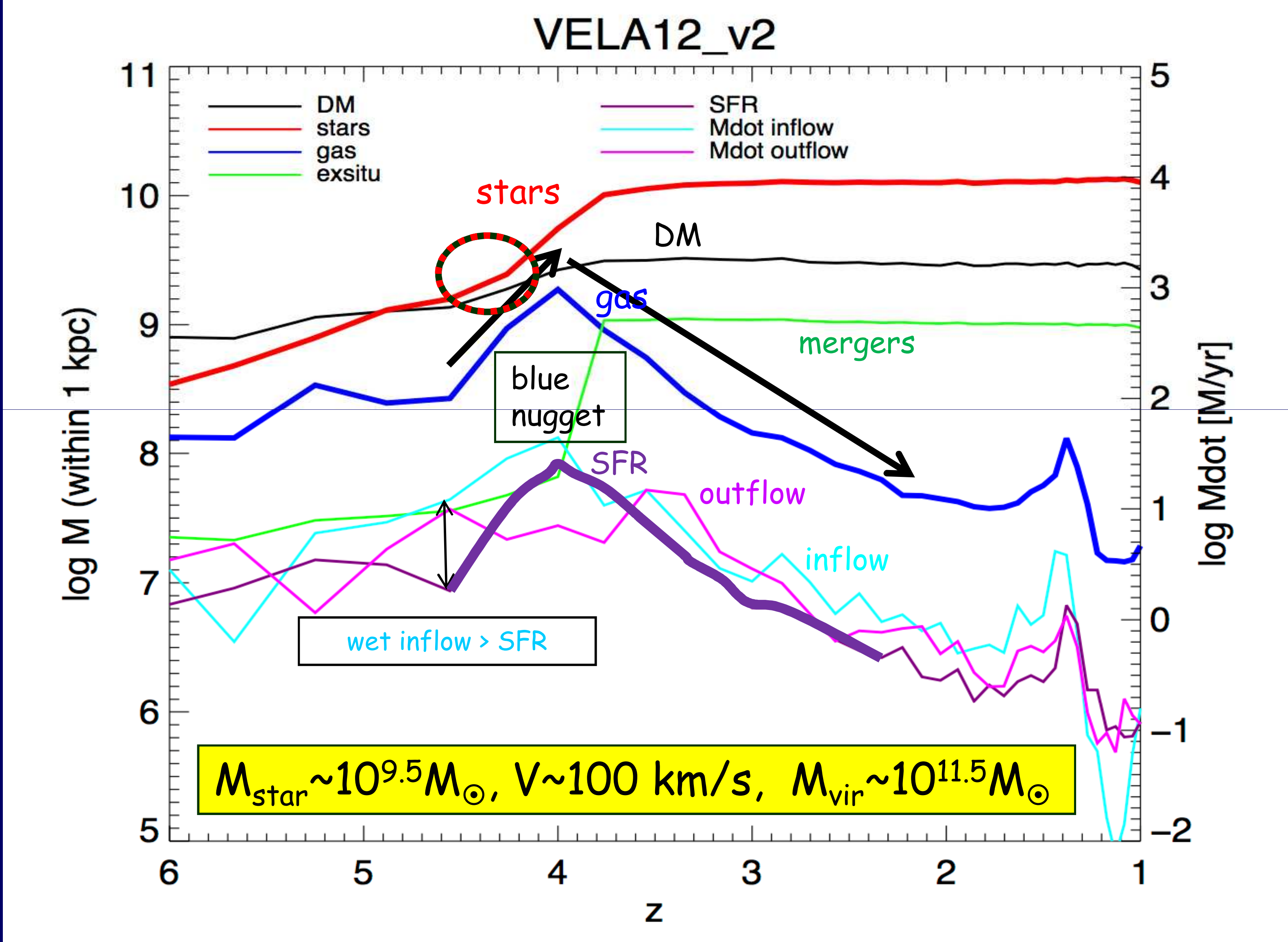
$$w \equiv \frac{\text{inflow}}{\text{SFR}} \approx \varepsilon_{\text{sfr}}^{-1} f_{\text{cold}}^{\;2} > 1$$

$$\varepsilon_{\text{sfr}} \le 0.02 \qquad f_{\text{cold}} \ge 0.2$$

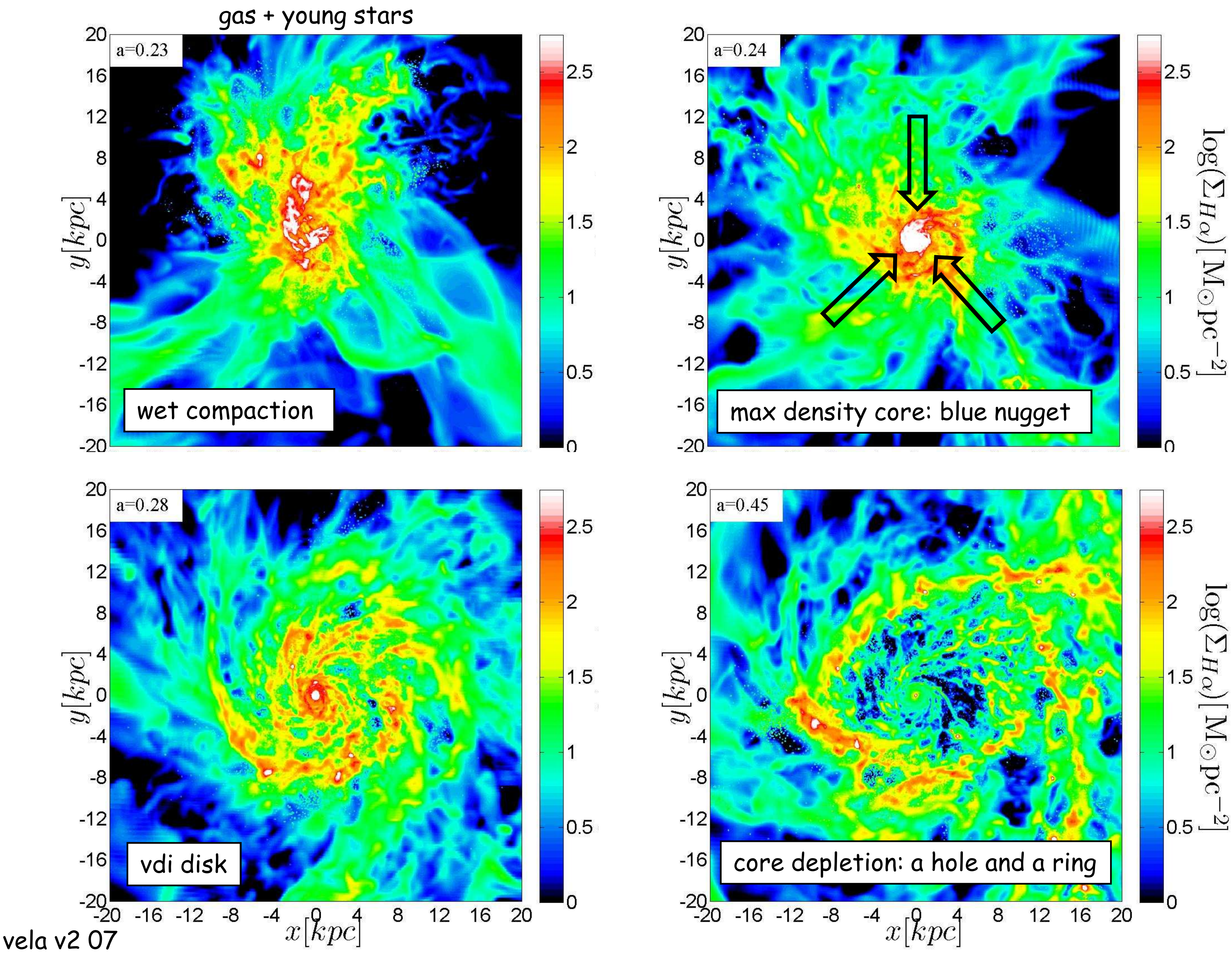
Expect compact nuggets:
- at high z, where $f_{gas}$ is high
- for low spin $\lambda$, where initial $R_{gas}$ is low

# Compaction and quenching

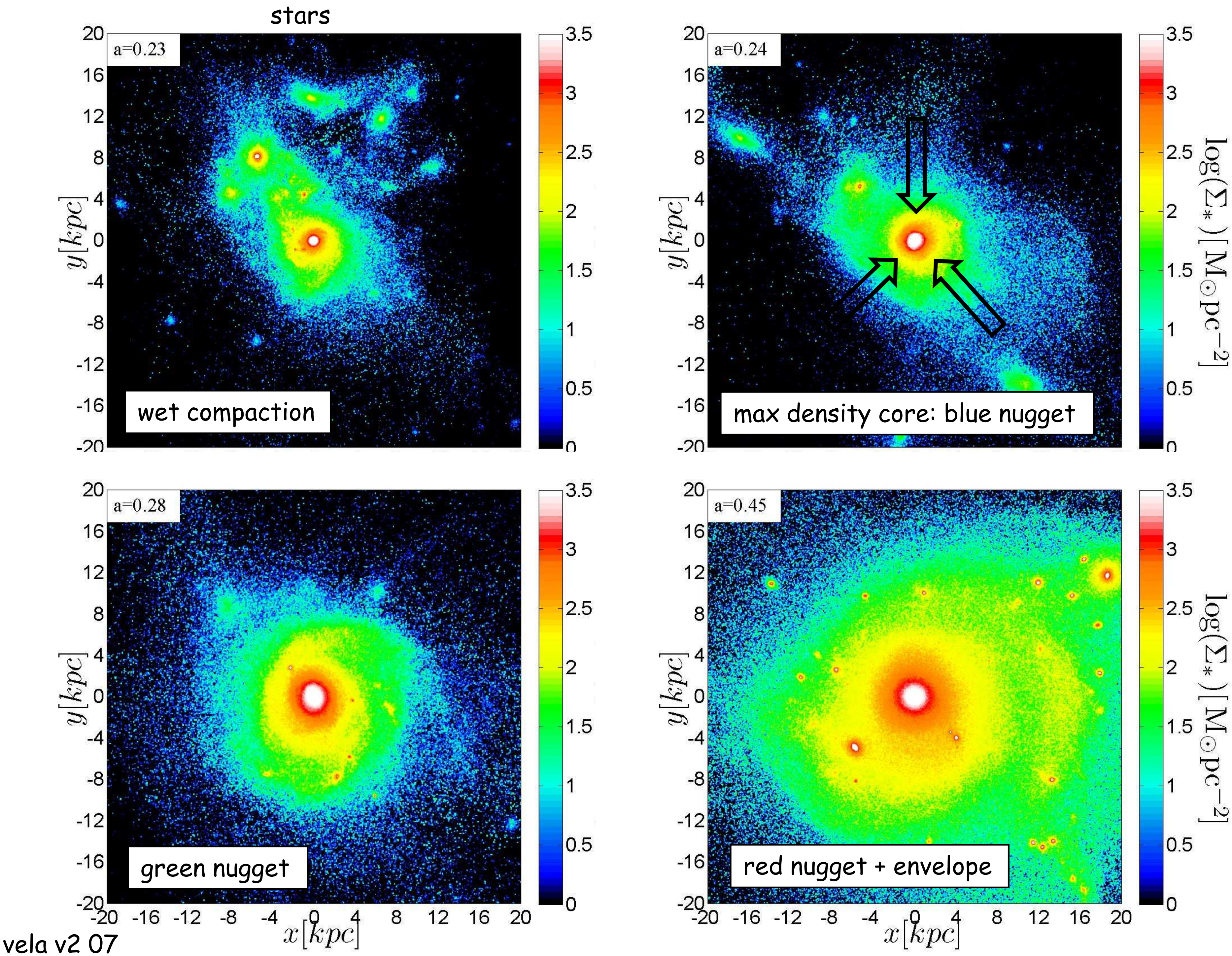
Zolotov+ 15,
Tacchella+ 16a,b




$M_{star}$~$10^{9.5}M_{\odot}$, V~100 km/s, $M_{vir}$~$10^{11.5}M_{\odot}$

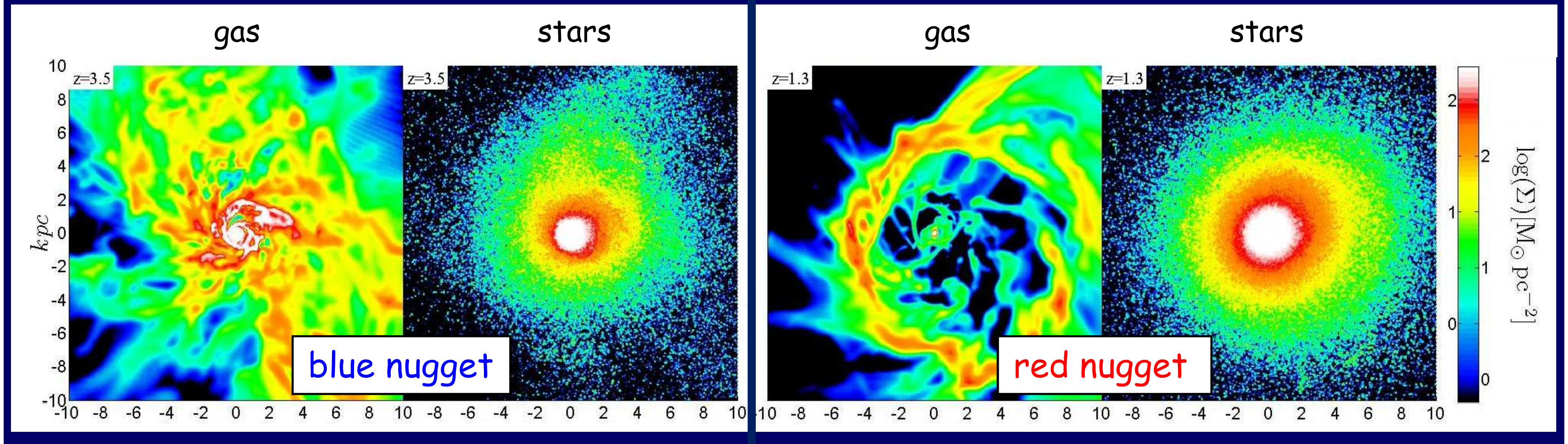


gas + young stars
a=0.23
wet compaction
a=0.24
max density core: blue nugget
a=0.28
vdi disk
a=0.45
core depletion: a hole and a ring
$\log(\Sigma_{H\alpha})\,[\mathrm{M_\odot pc^{-2}}]$
$y[kpc]$
$x[kpc]$
vela v2 07



stars
a=0.23
wet compaction
a=0.24
max density core: blue nugget
a=0.28
green nugget
a=0.45
red nugget + envelope
y[kpc]
x[kpc]
log(Σ*)[M⊙pc^-2]
vela v2 07

# Blue Nugget --> Red Nugget



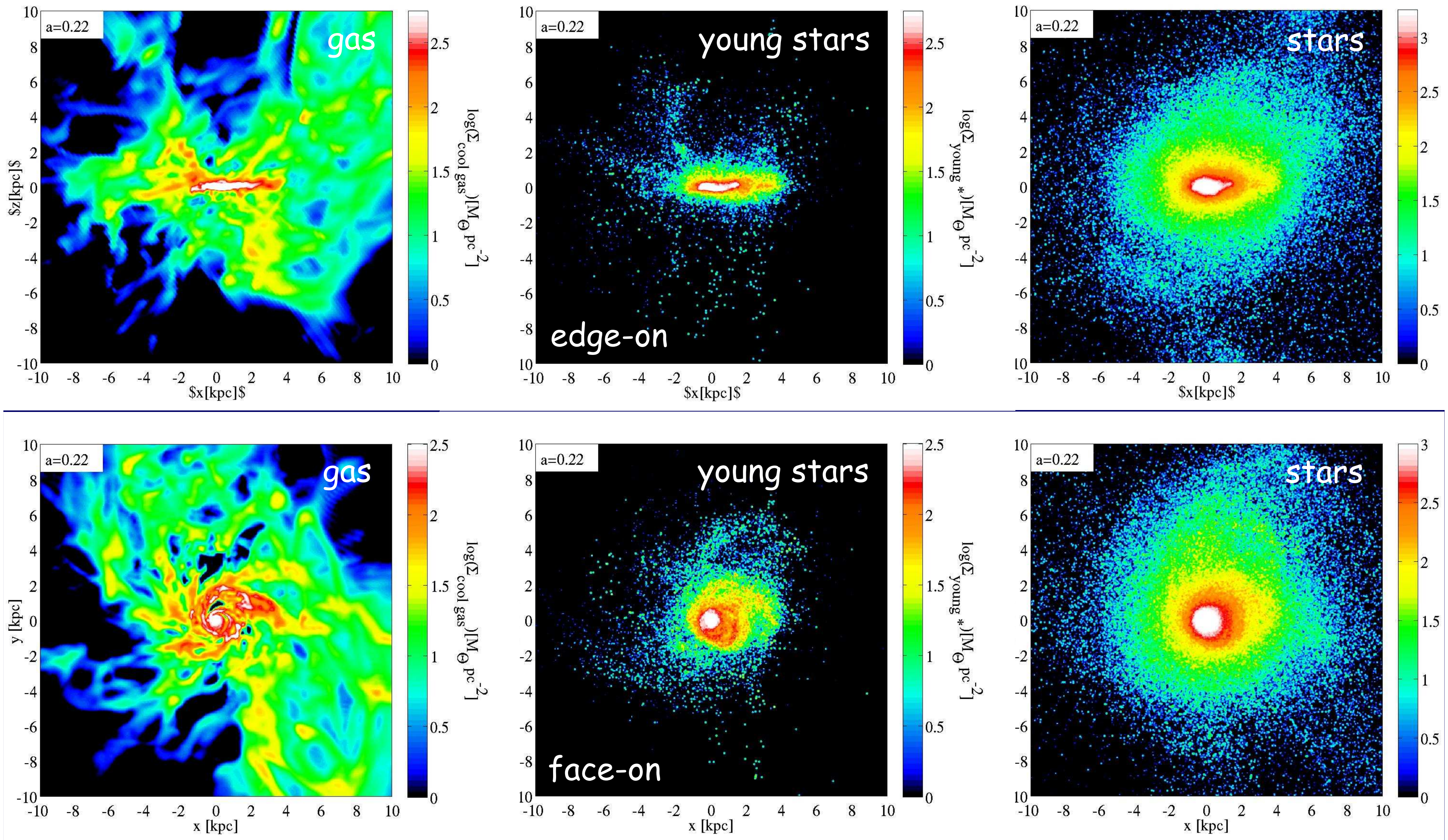

dense gas core -> dense stellar core

gas depletion from core,
gas ring may form,
-> inside-out quenching

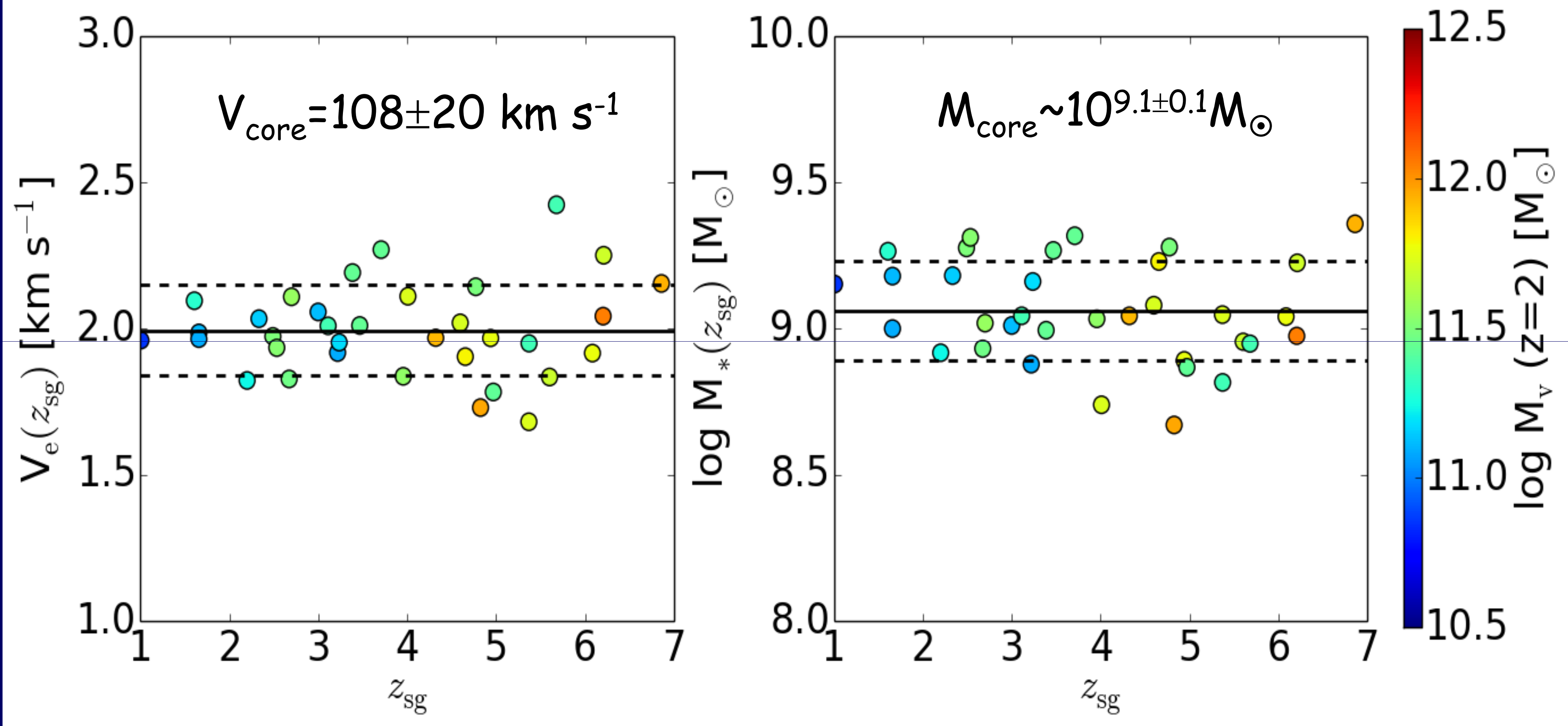
stellar core remains dense
from BN to RN

# Blue Nuggets: Compact Disks of Young Stars

V12 at z=3.55

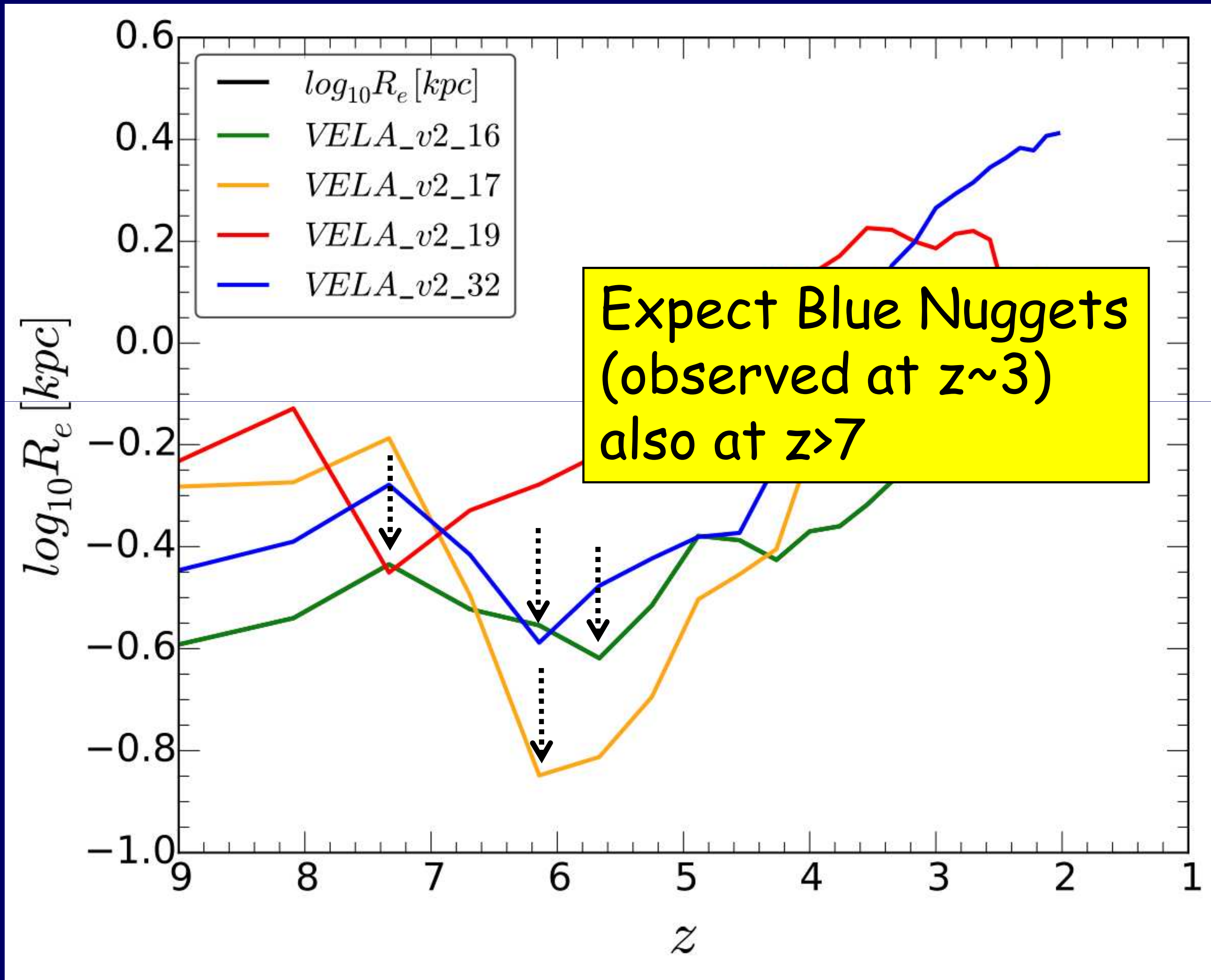


# Blue Nugget & Transition DM to Self-Gravity at a Critical $M_{star}$~$10^{9.5}M_\odot$ & V

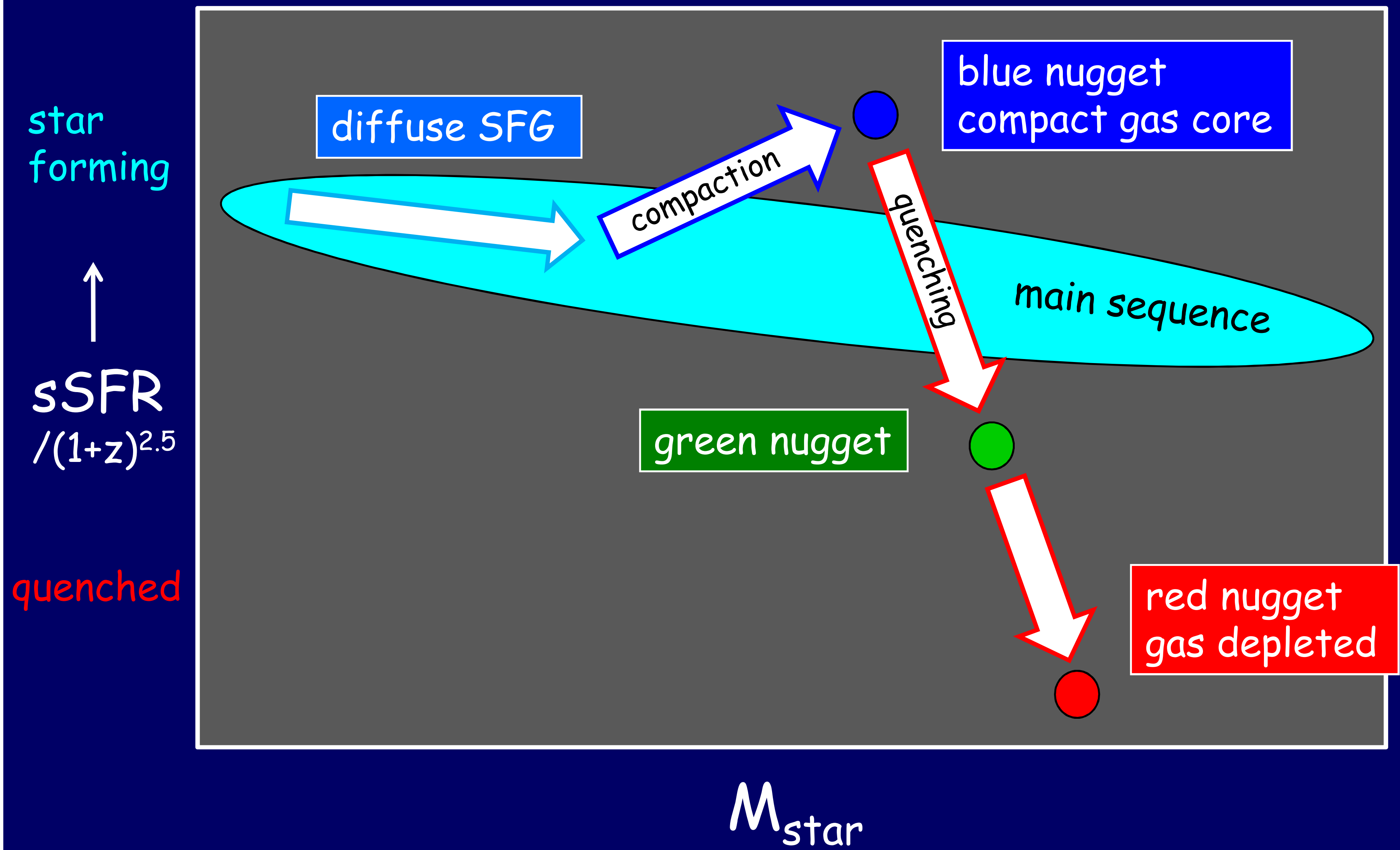



A clue: V~100 km/s
critical depth of potential well for SN-driven outflows (Dekel & Silk 86) ?

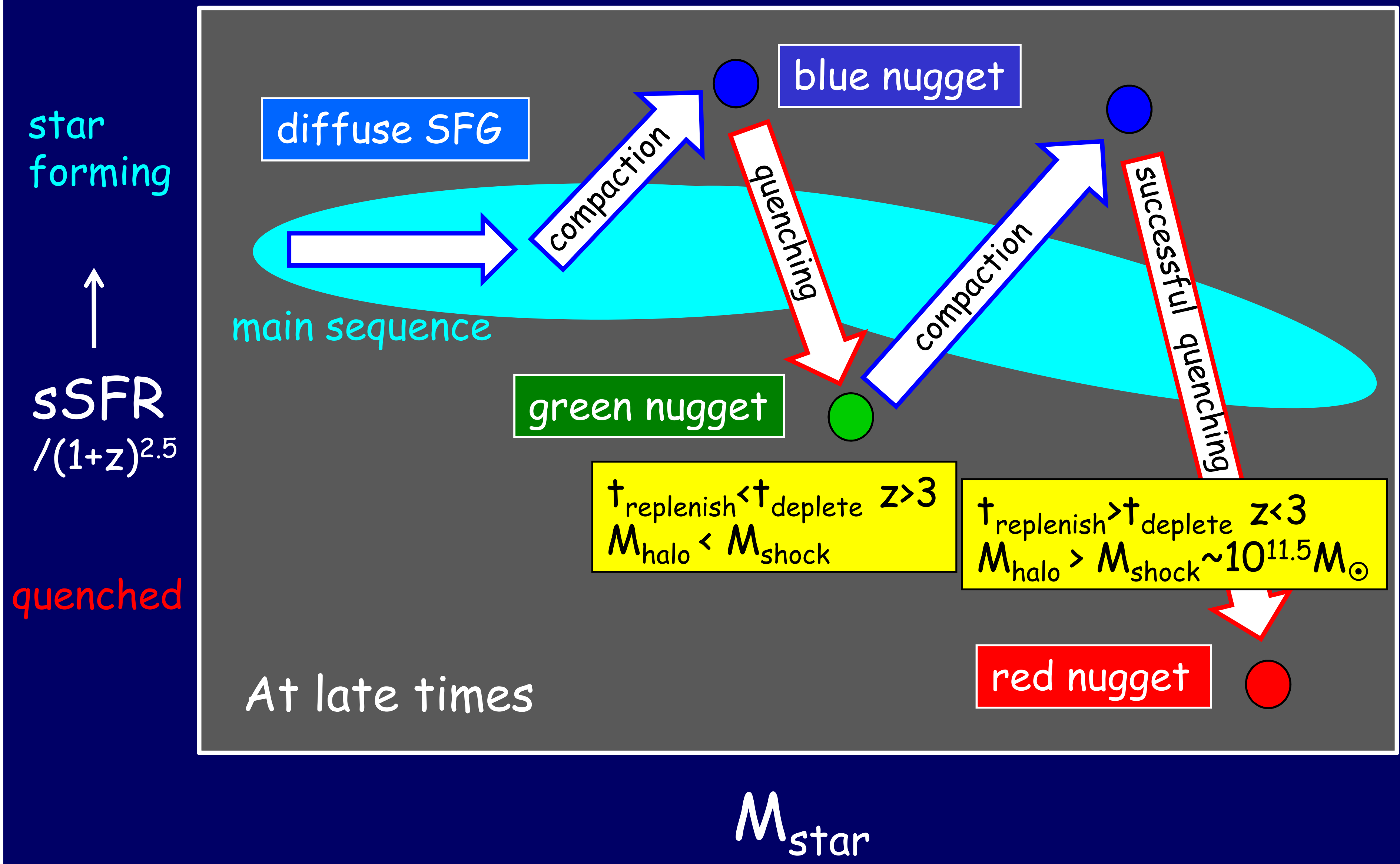
# Compaction at $M_{star} \sim 10^{9.5}\ M_\odot$

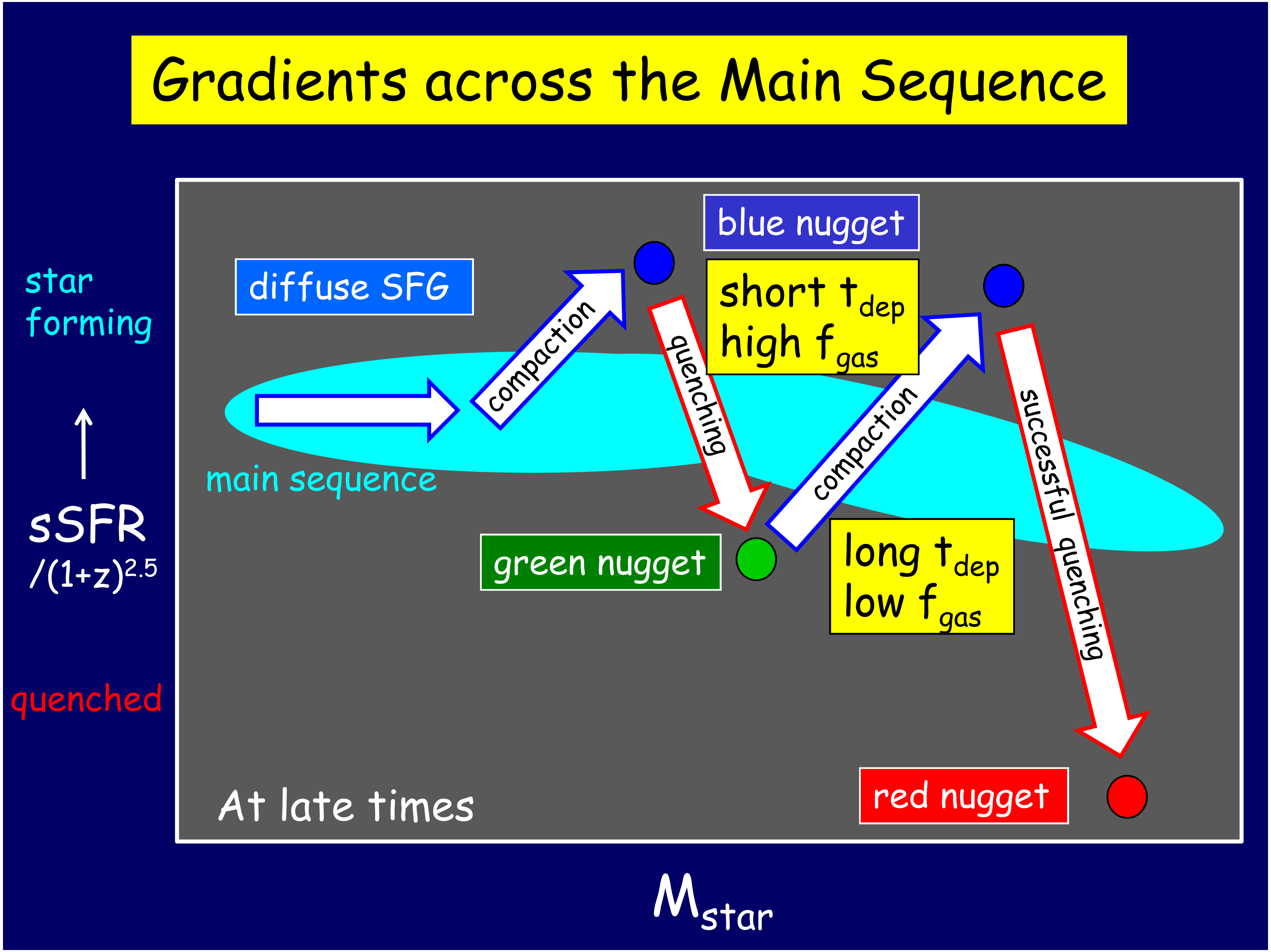


# Evolution About the Main Sequence



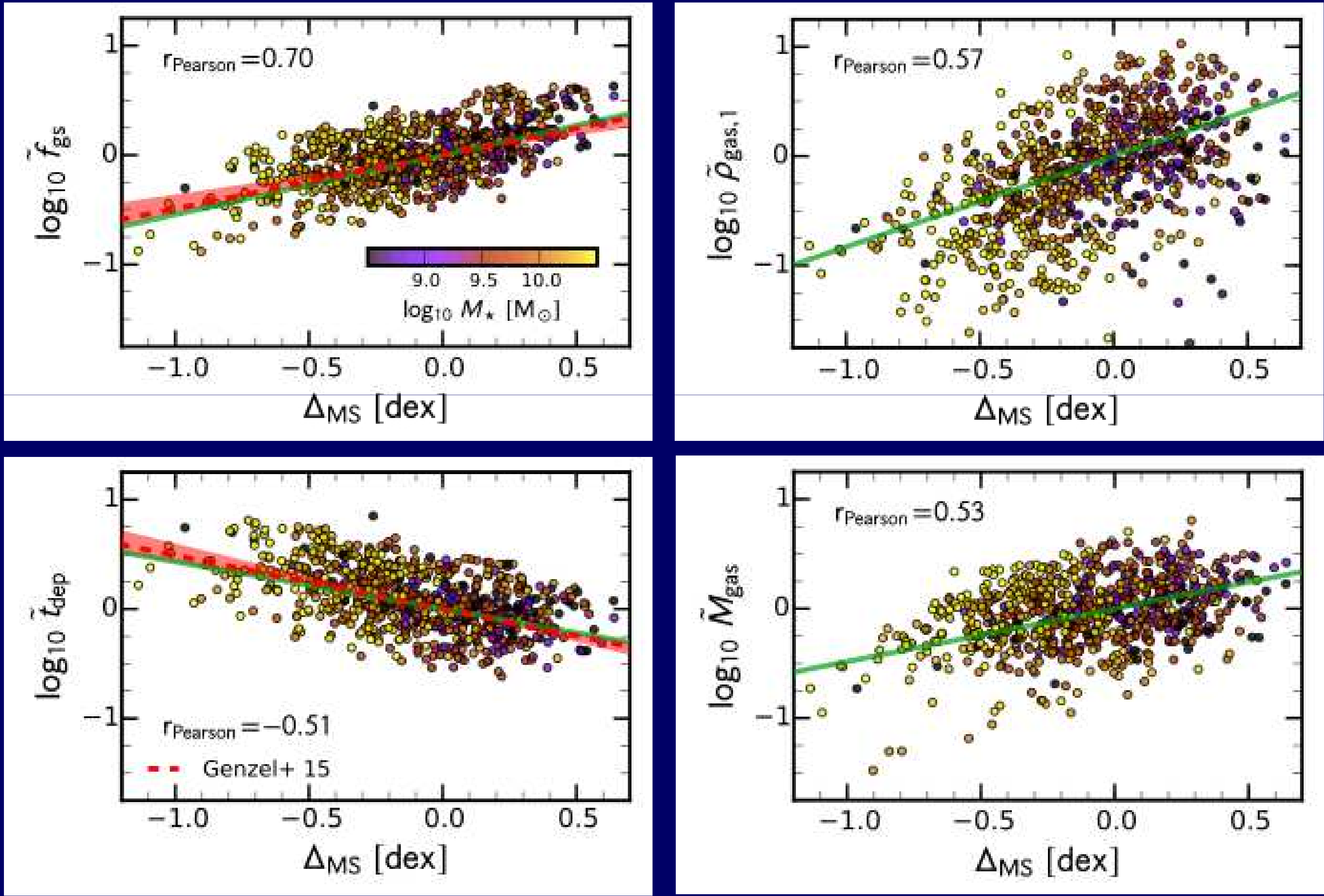
# Confinement of the Main Sequence



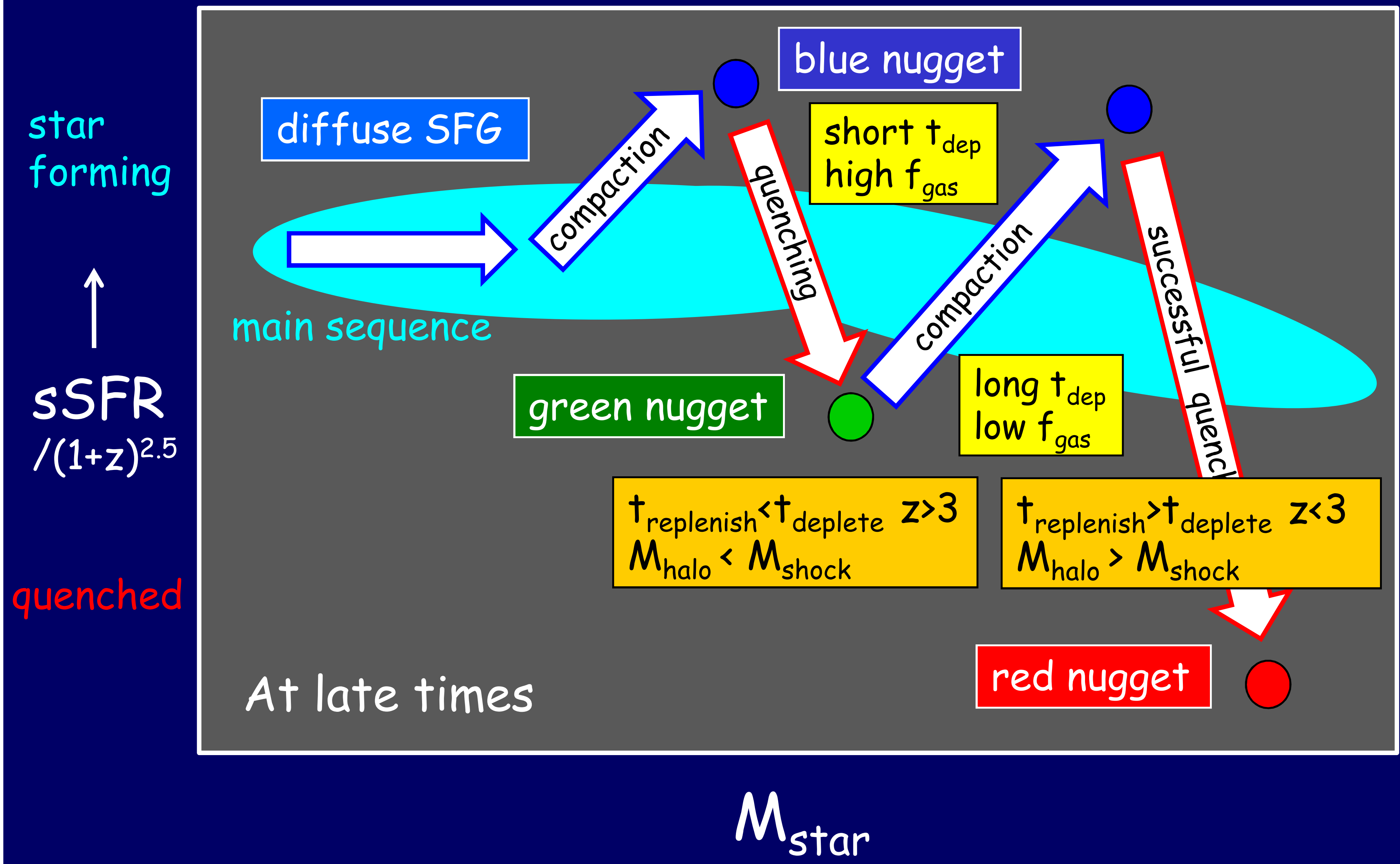


Gradients across the Main Sequence
star forming
sSFR
/(1+z)^2.5
quenched
diffuse SFG
compaction
blue nugget
short t_dep
high f_gas
quenching
main sequence
compaction
green nugget
long t_dep
low f_gas
successful quenching
red nugget
At late times
M_star

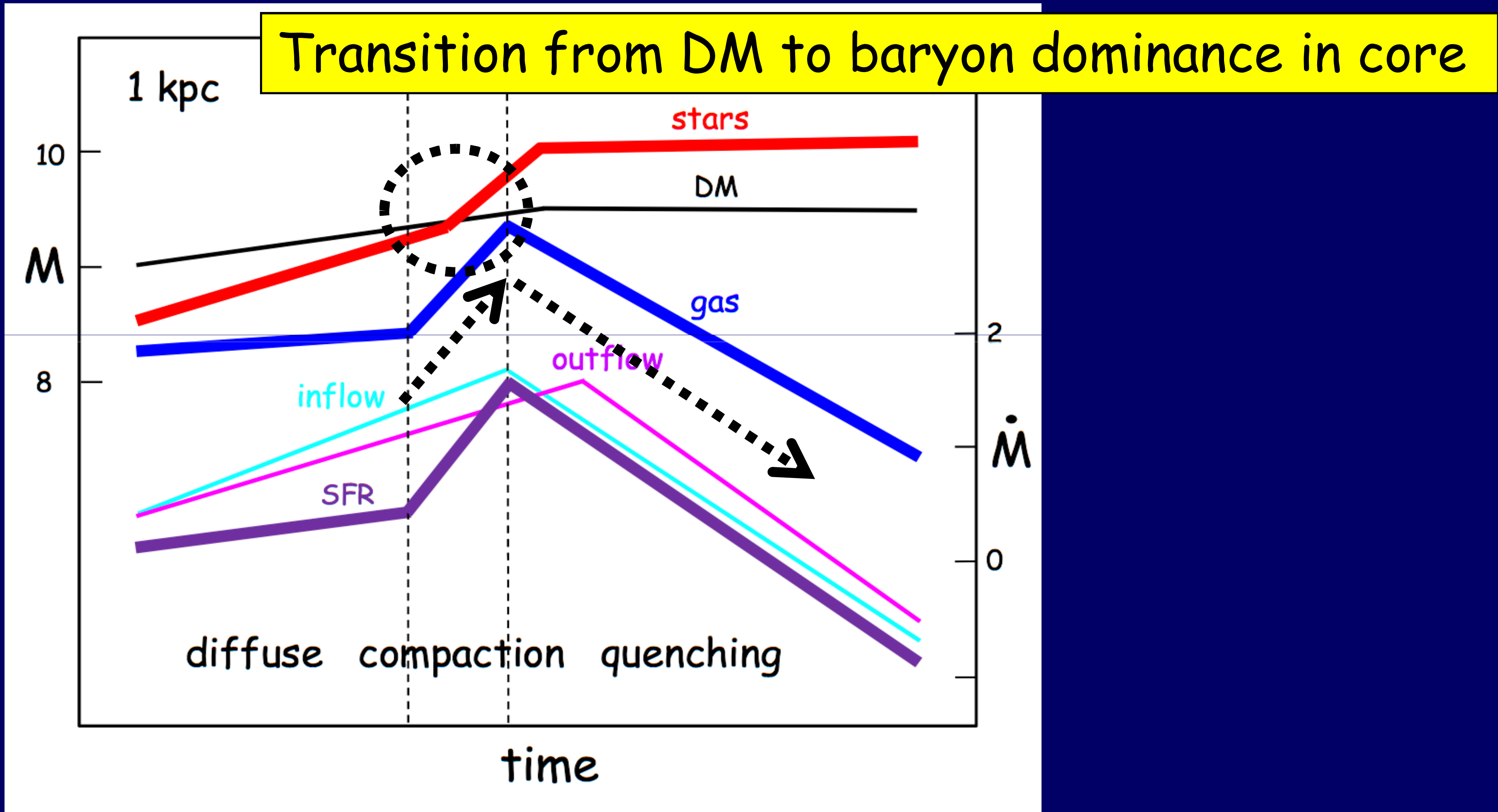
# Gas Gradients across the Main Sequence



# Summary: Evolution in the Main Sequence



# Compaction and Quenching in the Inner 1 kpc

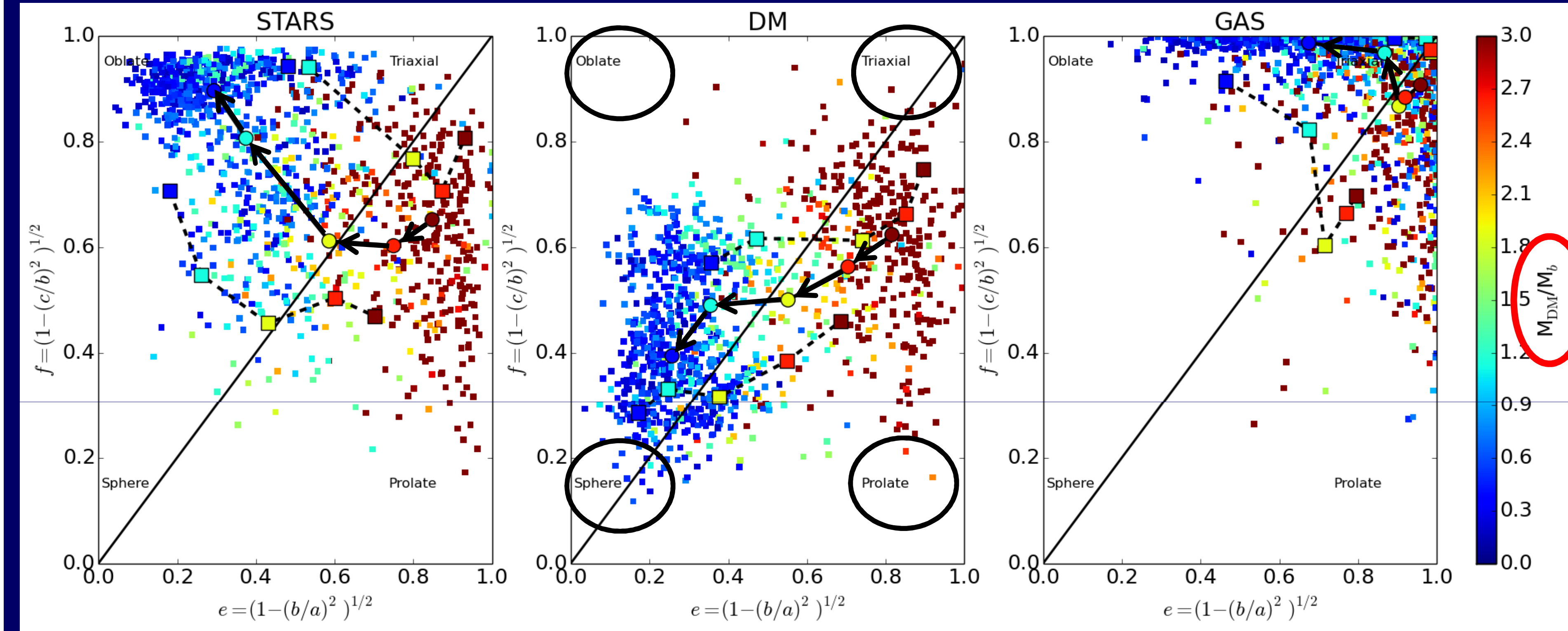



inner 1 kpc

Debattista+ 06-15

# Evolution of Shape

Ceverino+ 15
Tomassetti+ 16




Pre-compaction: DM-dominated core, $M_*<10^9\ M_\odot$ V<100 km/s -> outflows
--> prolate (triaxial) DM & stellar system, anisotropic dispersion

Post-compaction: baryonic core, $M_*>10^9\ M_\odot$ V>100 km/s – no outflow
--> box orbits deflected --> oblate, rotation-dominated

Gas: triaxial --> disk

Transition at V~100 km/s - feedback?

# Predictions for Galaxies at z~3-10

Fed by cold streams at the nodes of the cosmic web
build up mass & angular momentum on orbital time scales,
highly perturbed disks, fed by observable inspiraling streams

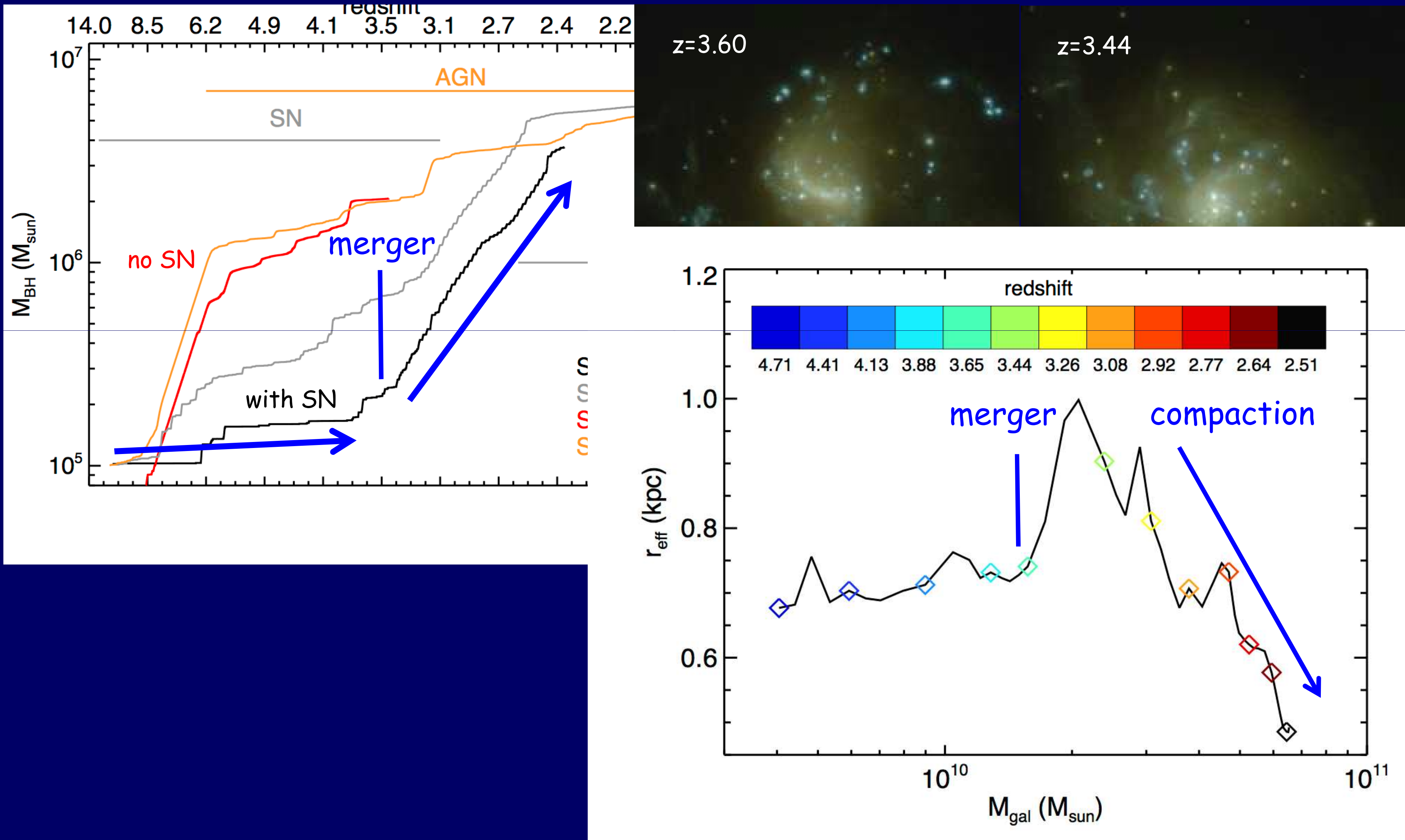
High gas fraction 0.5-0.8 sSFR ~ sAR ~ $(1+z)^{5/2}$ $M_{star}/M_{halo}$~const.

Violent disk instability, Q>1, stimulated by streams (w mergers)

Wet compaction to star-forming blue nuggets at $M_{star} \sim 10^{9.5} M_\odot$
($V_{core}$>100 km/s, $M_{halo} > 10^{11.5} M_\odot$) induced by streams (w mergers)
A major transition point:
- from SFG to quenching – gradients across the main sequence
- from DM to baryon dominance - prolate to oblate stellar systems
- from perturbed disks ($V/\sigma \sim 1$) to rings ($V/\sigma \sim 4$) around red nuggets
- trigger of BH growth and AGN activity

# Compaction Activates AGN

Simulation by Dubois+ 15: SN feedback suppresses BH growth



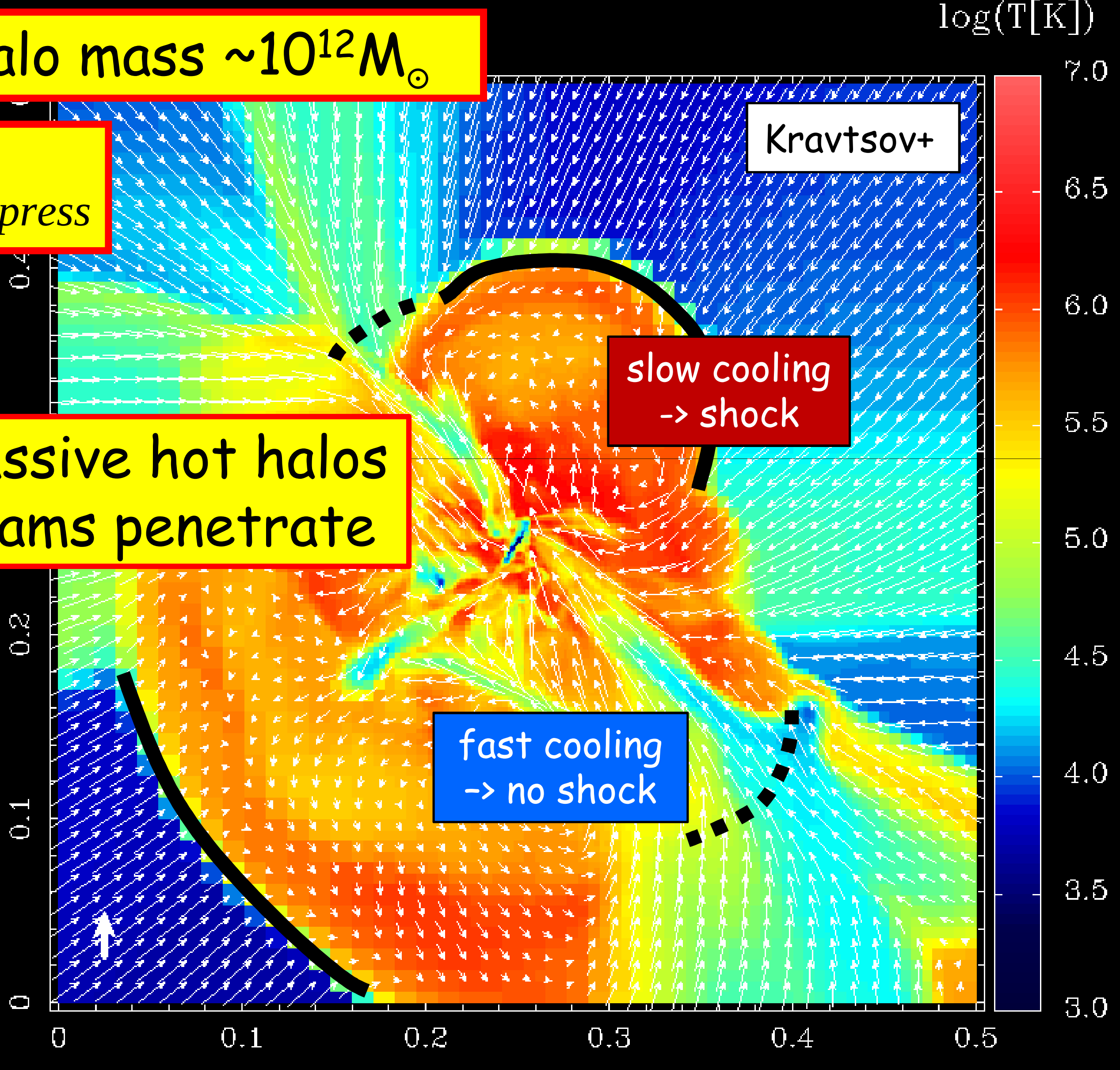
# Virial Shock Heating

Dekel & Birnboim 2006

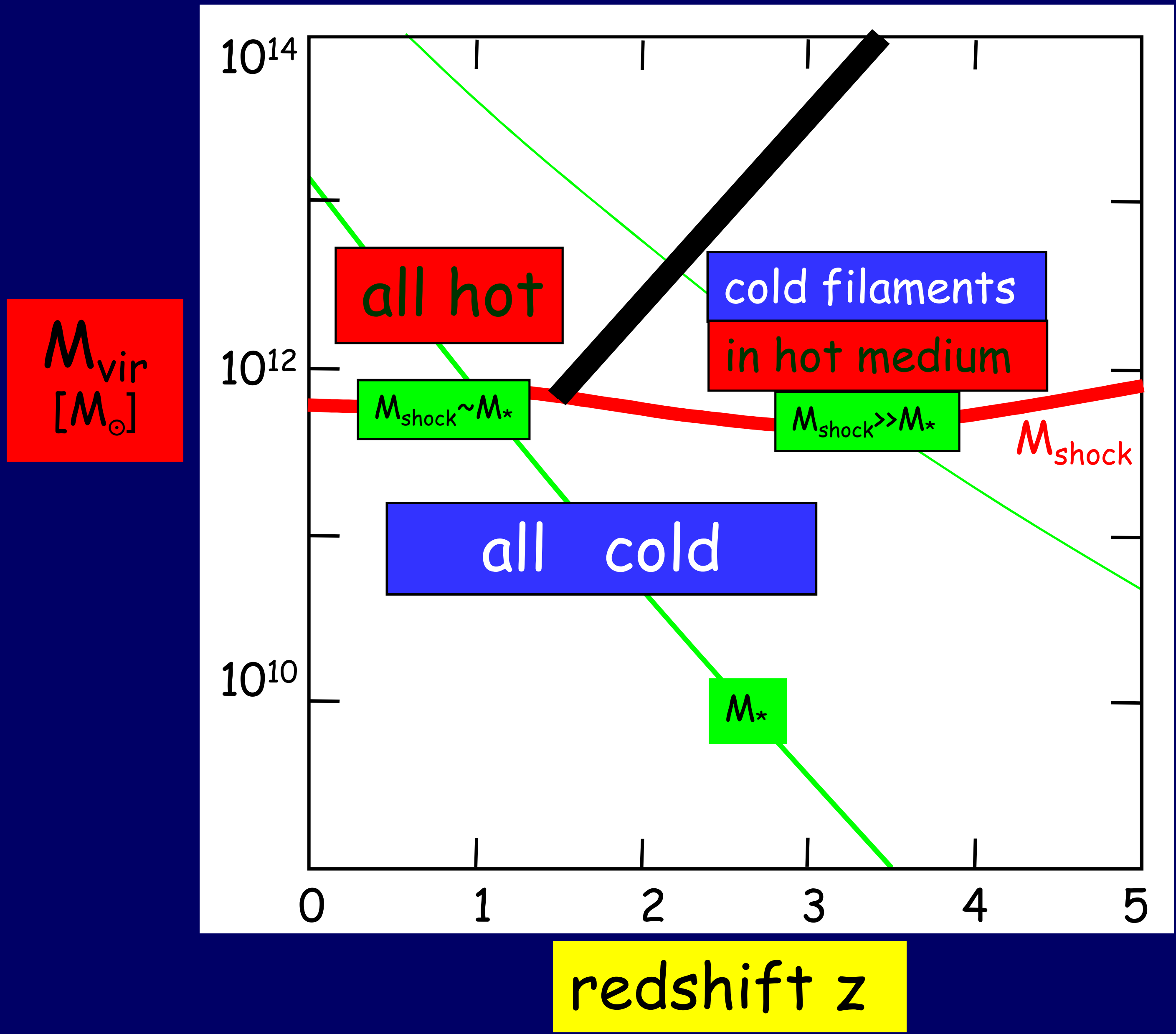
critical halo mass ~$10^{12} M_\odot$

$t_{cool}^{-1} < t_{compress}^{-1}$

in hi-z massive hot halos cold streams penetrate



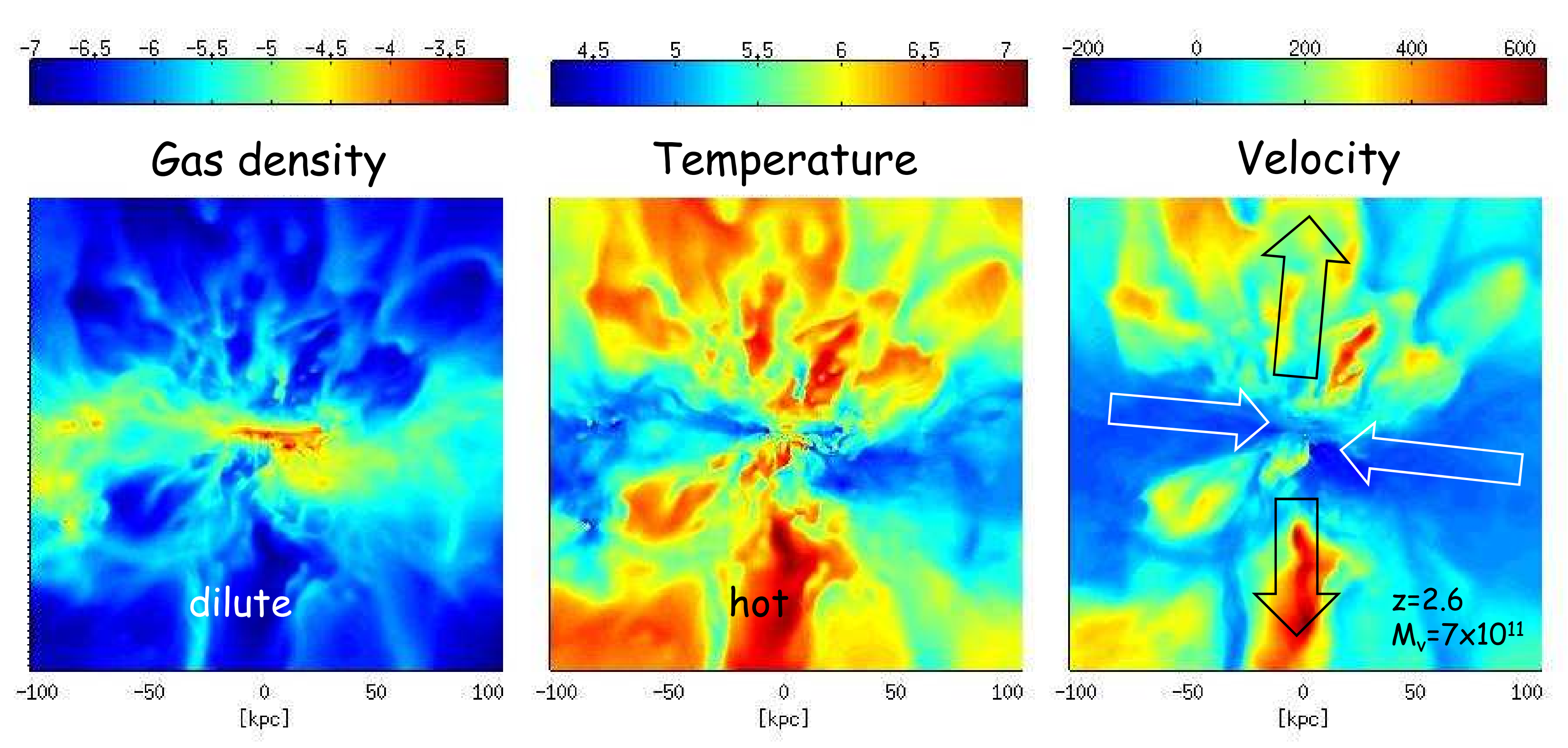
# Cold Streams in Big Galaxies at High z




Dekel & Birnboim 06

# Outflows do not halt the Inflows

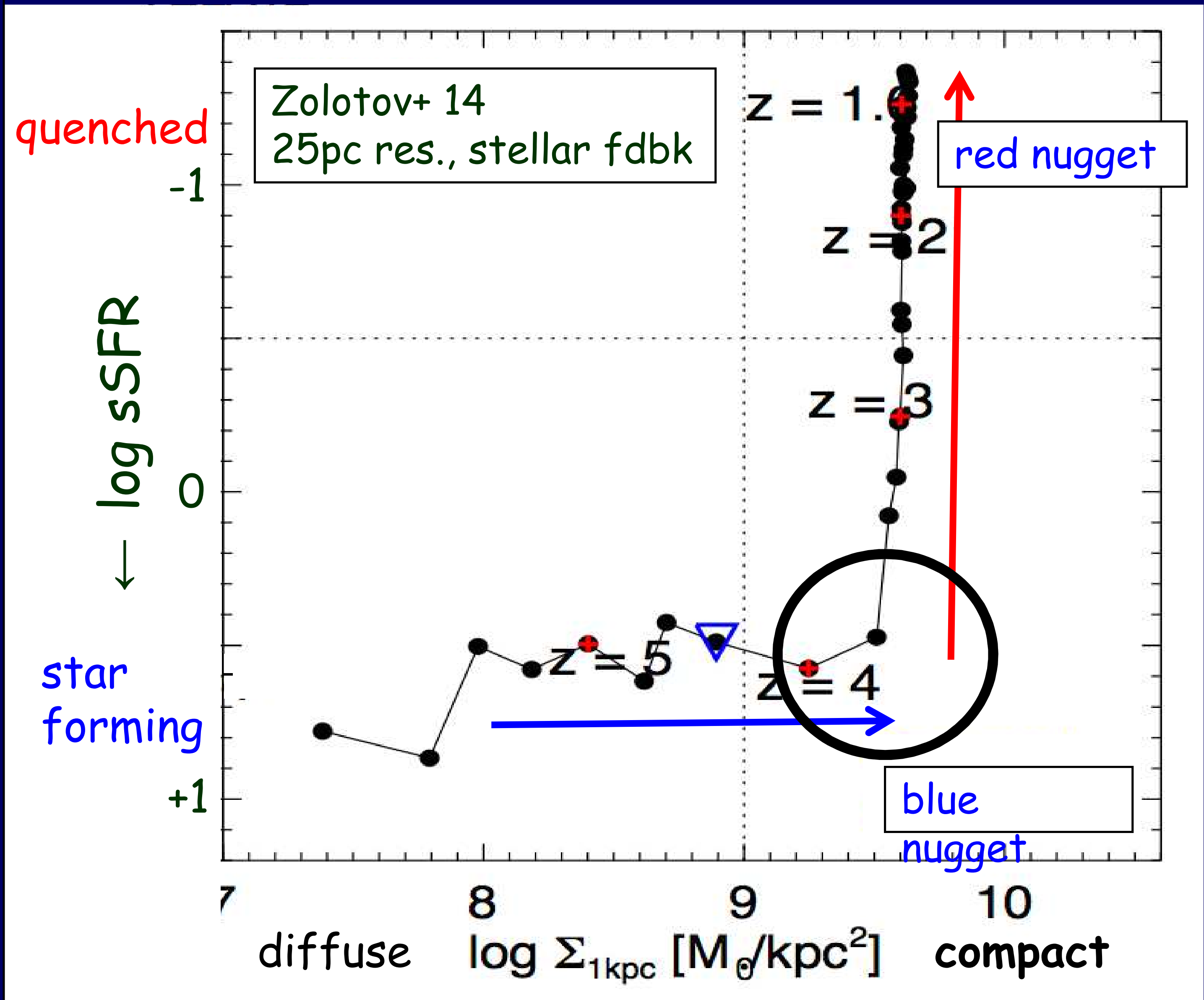
DeGraf+ 15




- Dense, cold, metal-poor inflows penetrate into the galaxy
- Hot, metal-rich, fast outflows fly through the dilute CGM

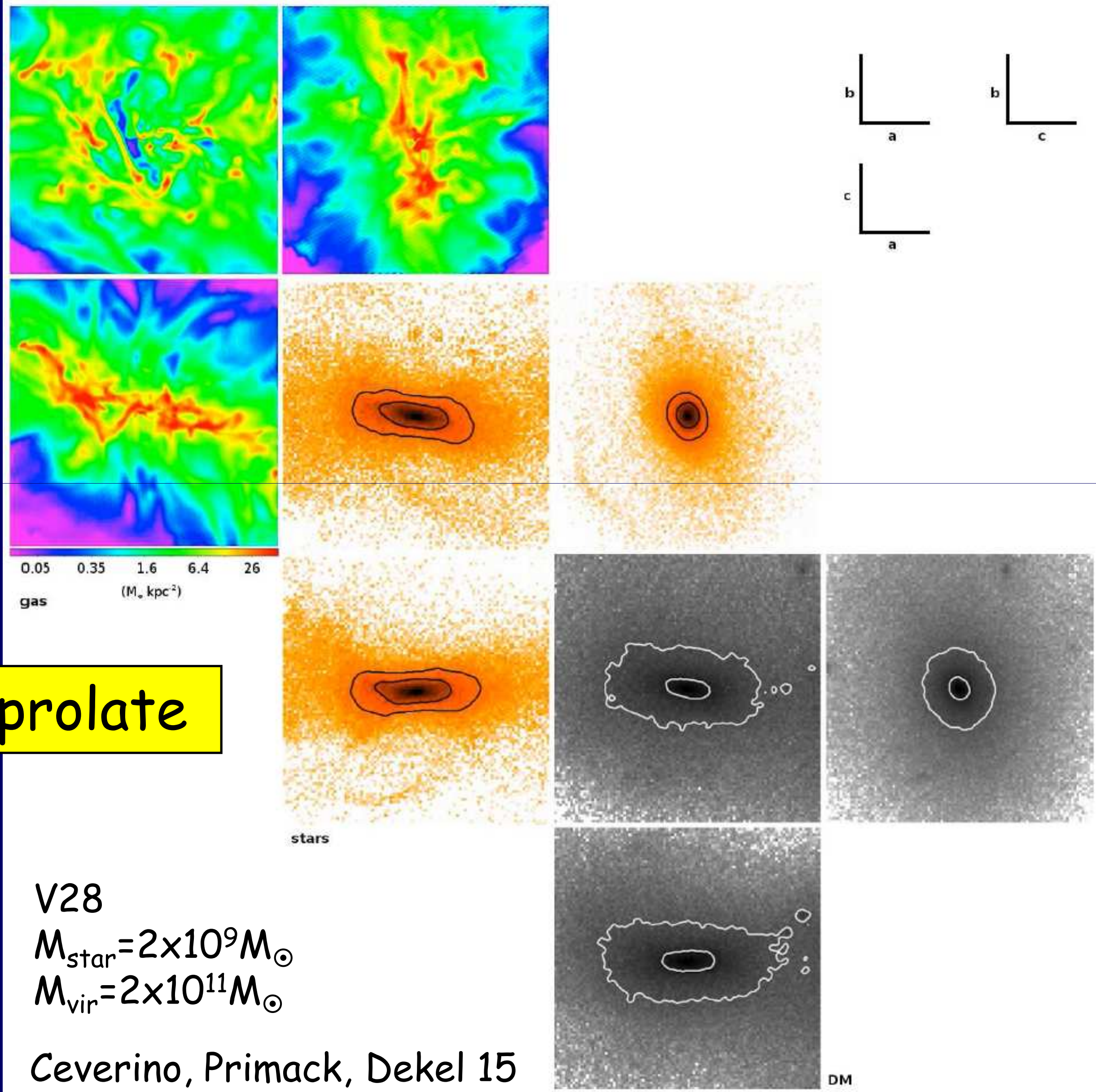
- Outflows remove low-angular-momentum gas from center?
- Outflows dominate the quenching of SFR?

# Compaction and Quenching in Simulations



# A Prolate Low-Mass Galaxy at z=2.2

Gas: disk




Stars and DM: prolate

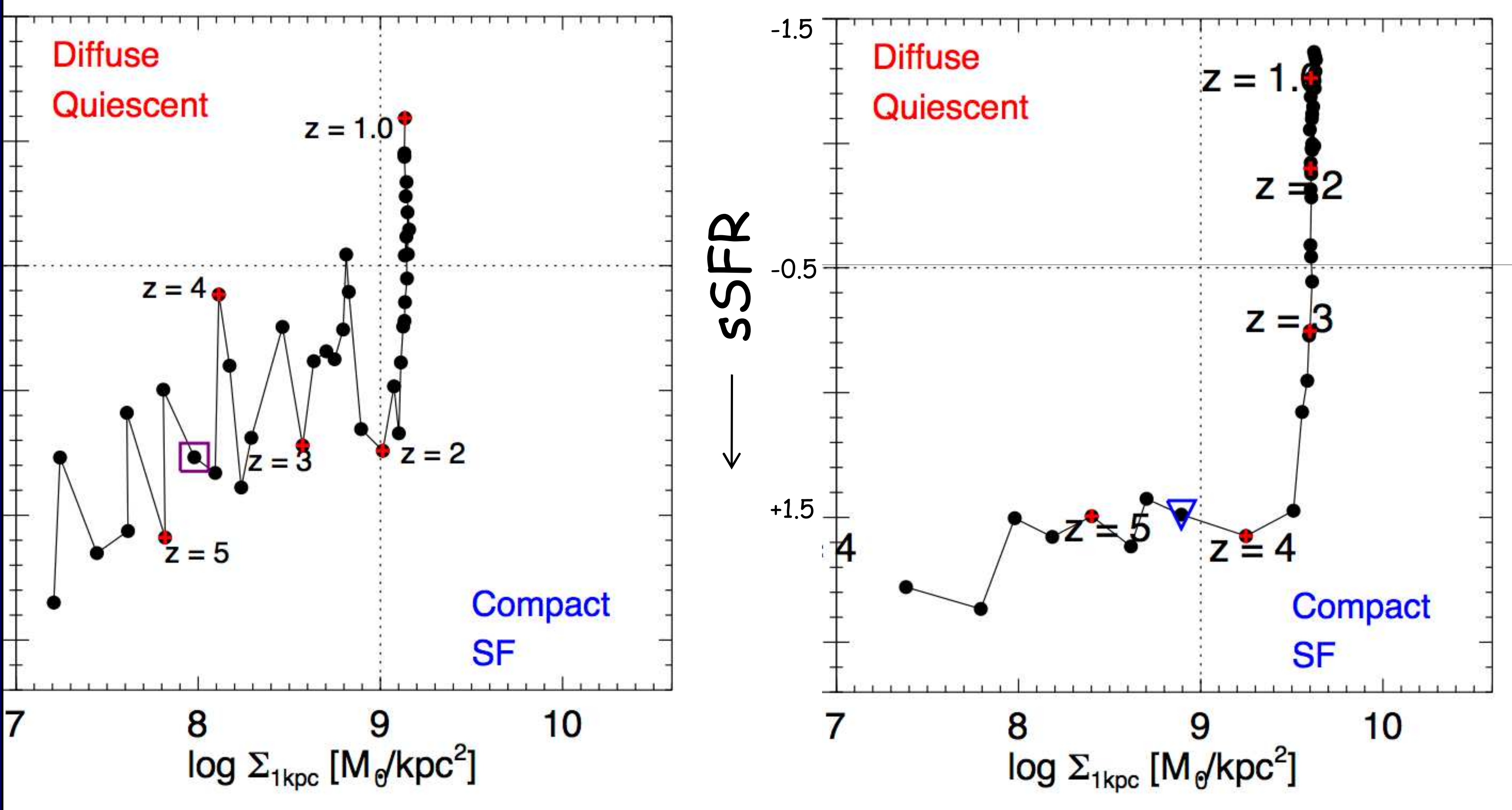
Consistent with van der Wel+ 14 CANDELS

V28
$M_{star}=2\times10^{9}M_{\odot}$
$M_{vir}=2\times10^{11}M_{\odot}$

Ceverino, Primack, Dekel 15

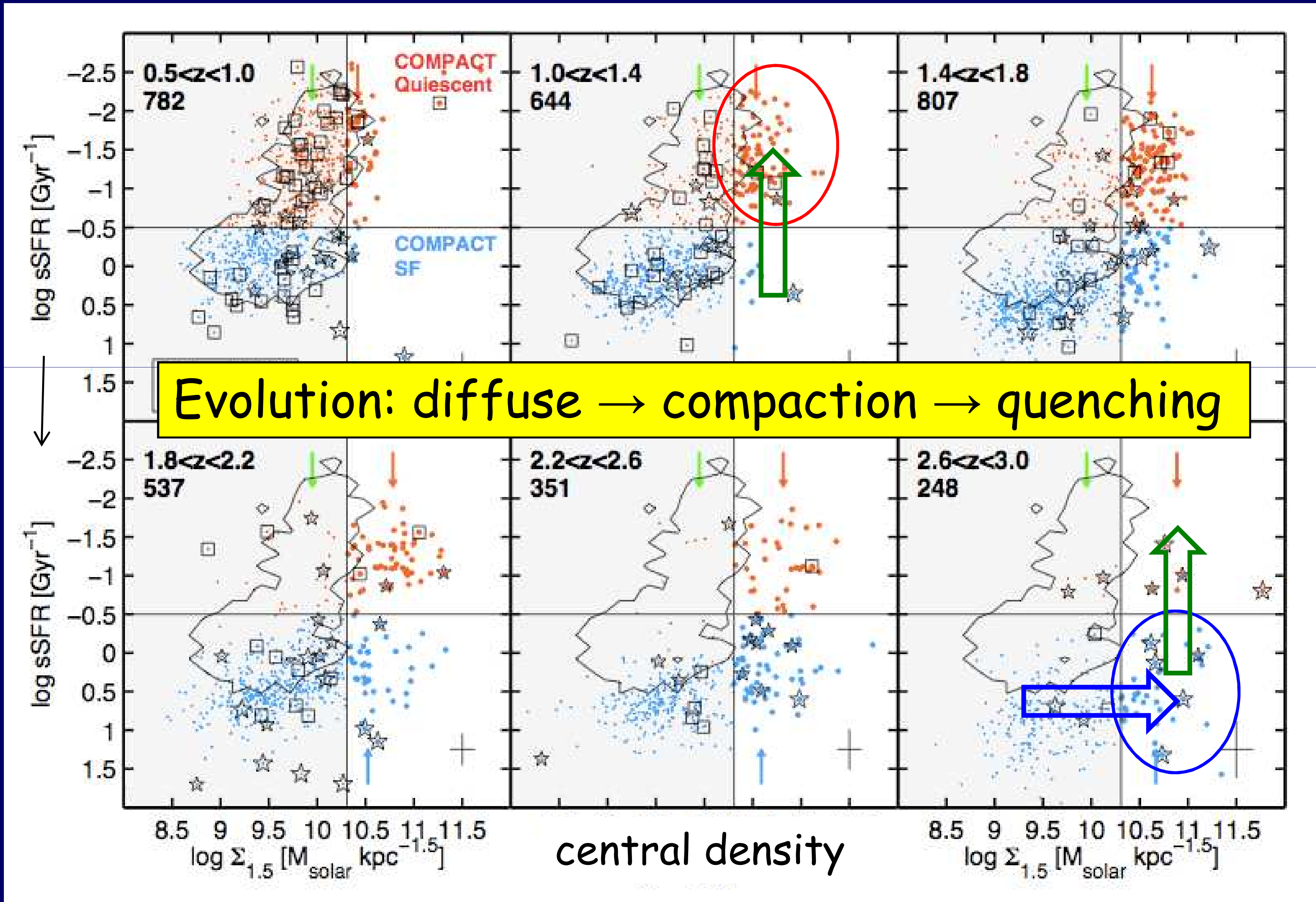
# Hesitatnt vs. Decisive Quenching

low mass, low z　　　　high mass, high z

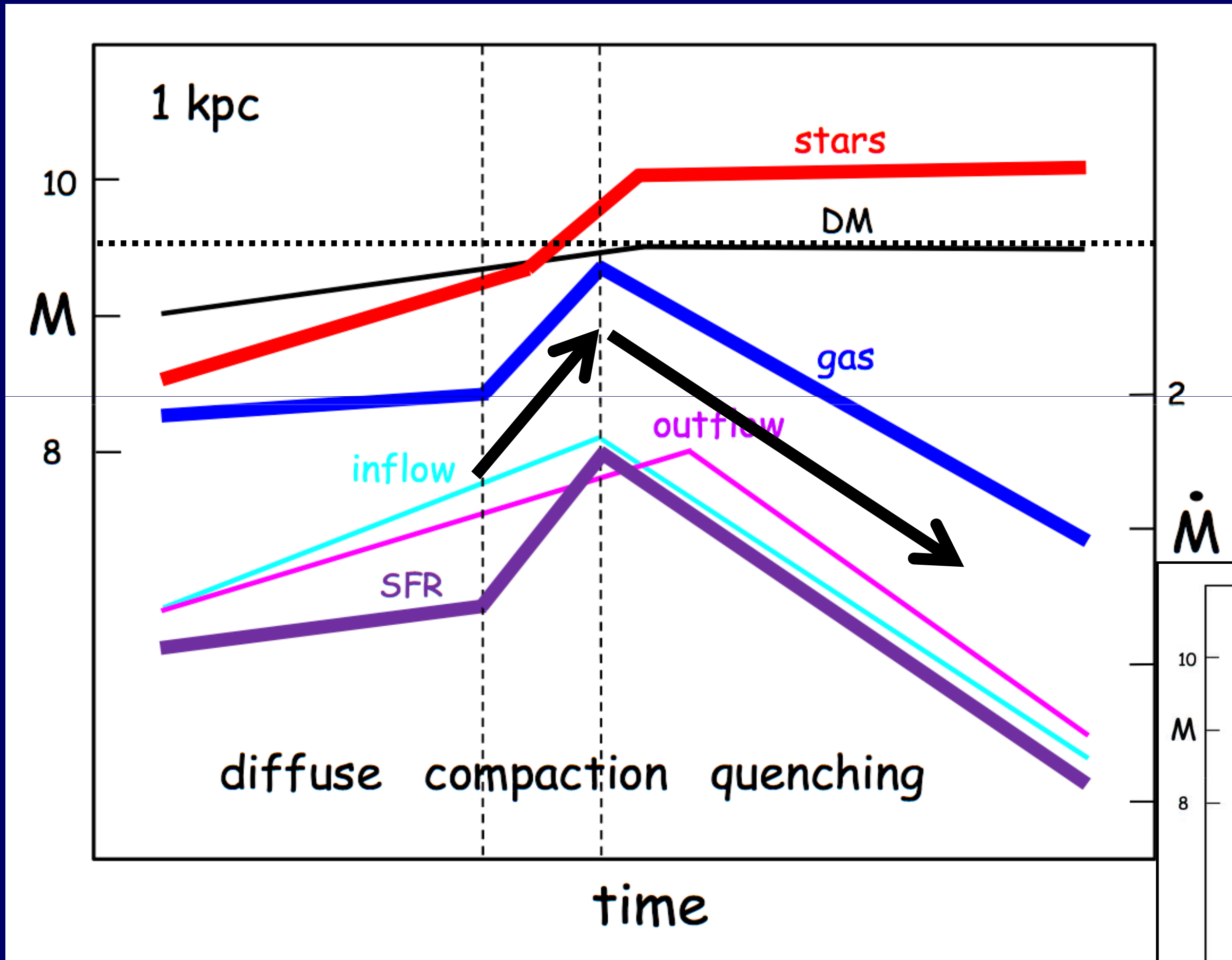


# Observations: Blue Nuggets -> Red Nuggets

Barro+ 13 CANDELS z=1-3

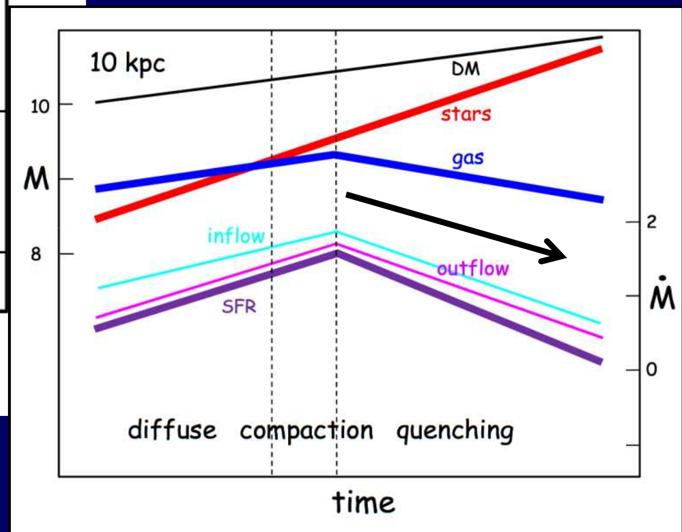


# Compaction and Quenching in the Inner 1 kpc

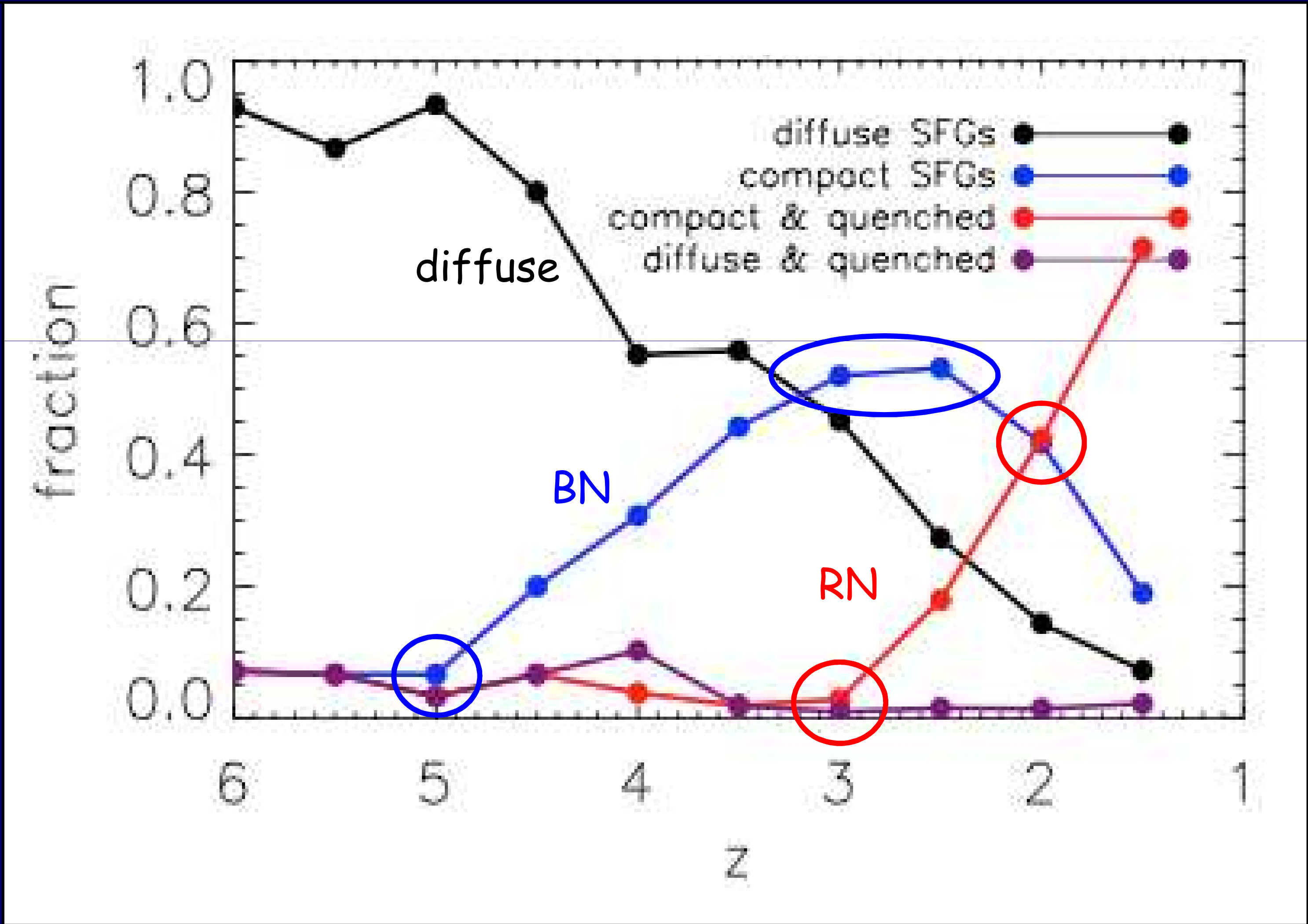


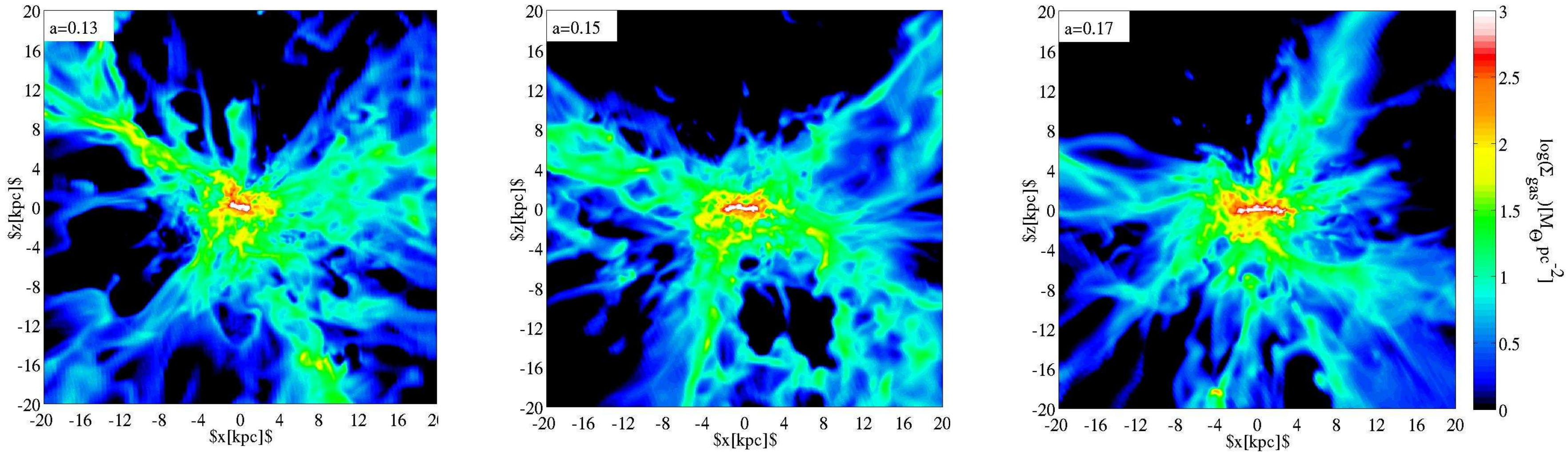

inner 1 kpc

whole galaxy

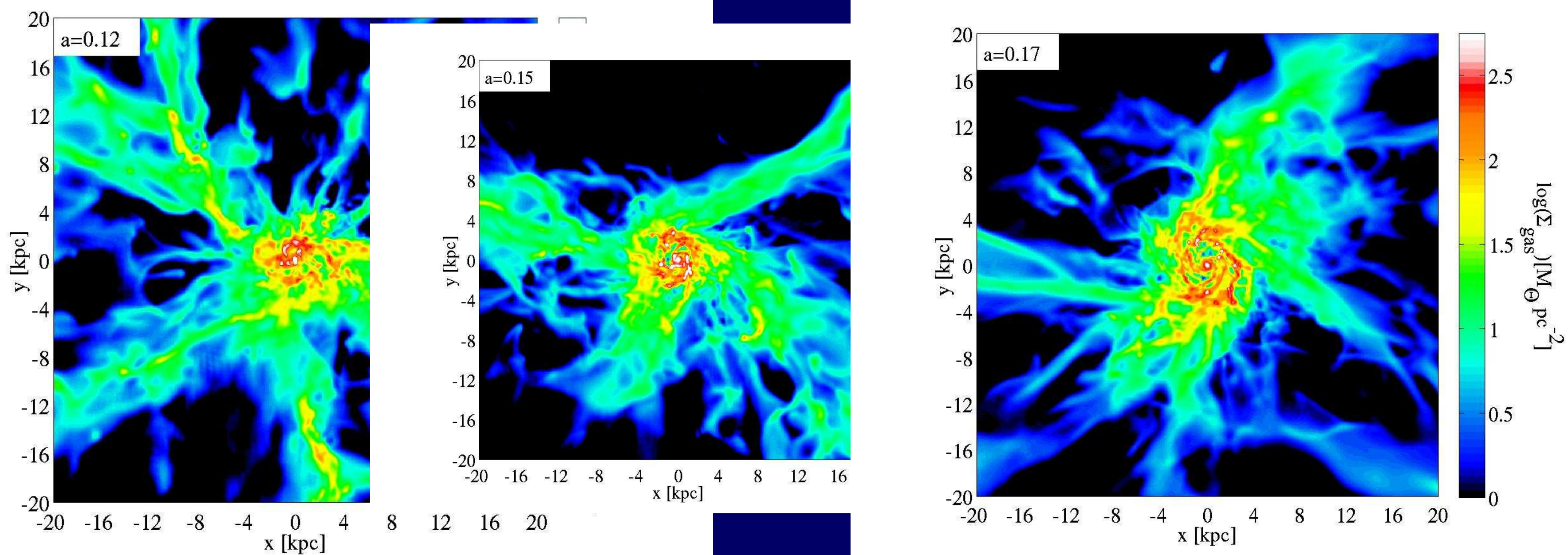


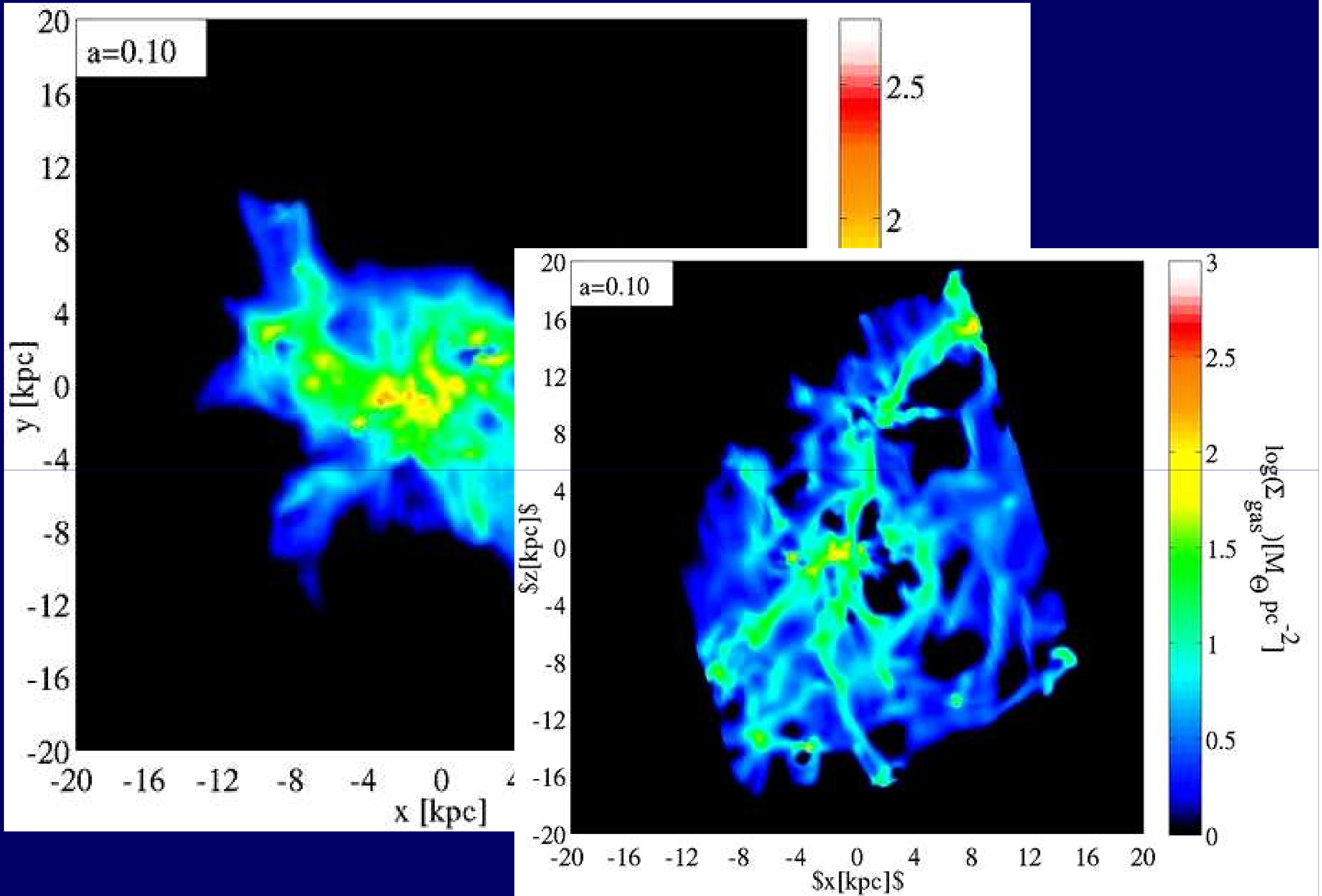
# Evolution of Populations:
## Diffuse SFG -> Blue Nuggets -> Red Nuggets




a=0.13
a=0.15
a=0.17
$z[kpc]$
$x[kpc]$
$\log(\Sigma_{gas})[M_\Theta pc^{-2}]$

Z=7 5


a=0.12
a=0.15
a=0.17
y [kpc]
x [kpc]
$\log(\Sigma_{gas})[M_\Theta pc^{-2}]$


a=0.10
y [kpc]
x [kpc]
20
16
12
8
4
0
-4
-8
-12
-16
-20
2.5
2
a=0.10
$z[kpc]$
$x[kpc]$
-20 -16 -12 -8 -4 0 4 8 12 16 20
3
2.5
2
1.5
1
0.5
0
log(Σgas)[MΘ pc-2]

V32

# Stimulated Non-linear VDI

Typical SFGs have perturbed rotating disks undergoing violent disk instability (VDI)

- Massive clumps (>$10^8 M_\odot$) survive feedback
- off-center in-situ young clumps <300 Myr, showing age/gas gradient
- older ex-situ clumps

Nonlinear instability (sometimes Q>1)
Stimulated by inflow+mergers?   Compressive turbulence?
Irregular rotation due to counter-rotating streams?

VDI and (minor) mergers actually work in concert