Compaction, Quenching, and the Main Sequence of SFGs

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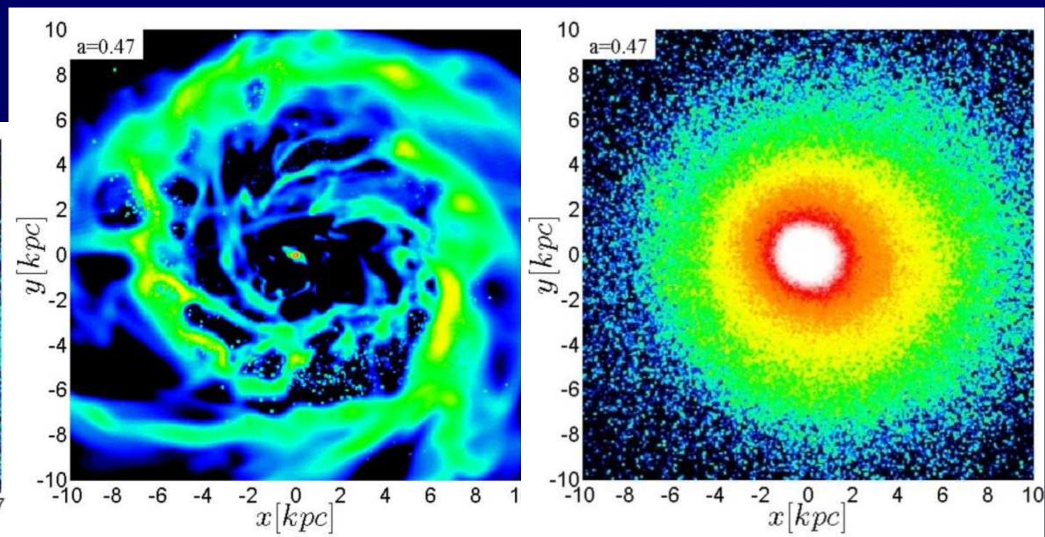
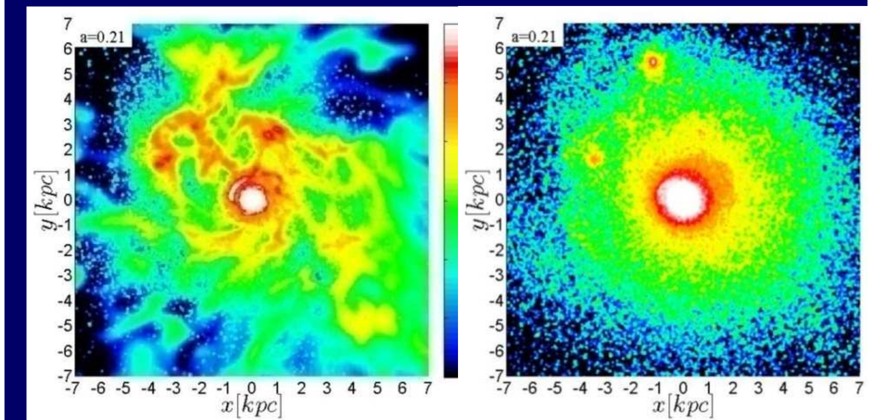
Barro+ 2013-15; Dekel & Burkert 2014; Zolotov+ 2015;
Tacchella+ 2015a,b,c; Ceverino+ 2015; Tomassetti+ 2015

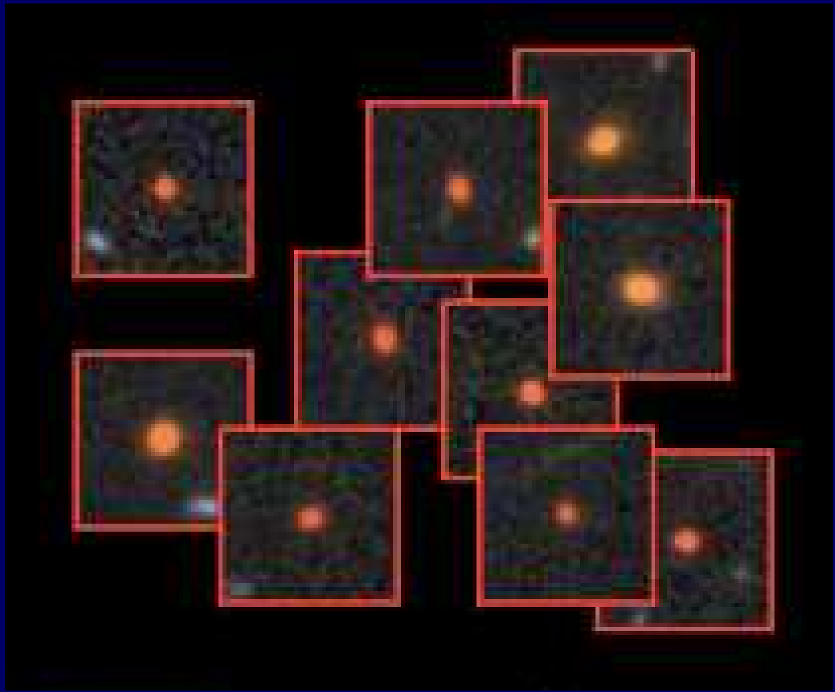
Red Nugget



Blue Nugget



Red Nuggets



$z \sim 2$ $M \sim 10^{11} M_{\odot}$ $R_e \sim 1$ kpc low-SFR
the progenitors of the cores of today's Es?

Van Dokkum, Franx, Kriek, Bouwens, Labbe+ 08,10,14, Damjanov+09, Newman+10, Damjanov+11, Whitaker+12, Bruce+12, …

Wet Compaction

Dekel & Burkert 2013

Compact stellar spheroid → dissipative "wet" 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

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

$\varepsilon_{\rm sfr} \le 0.02 \quad f_{\rm cold} \ge 0.2$

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

Cosmological Simulations

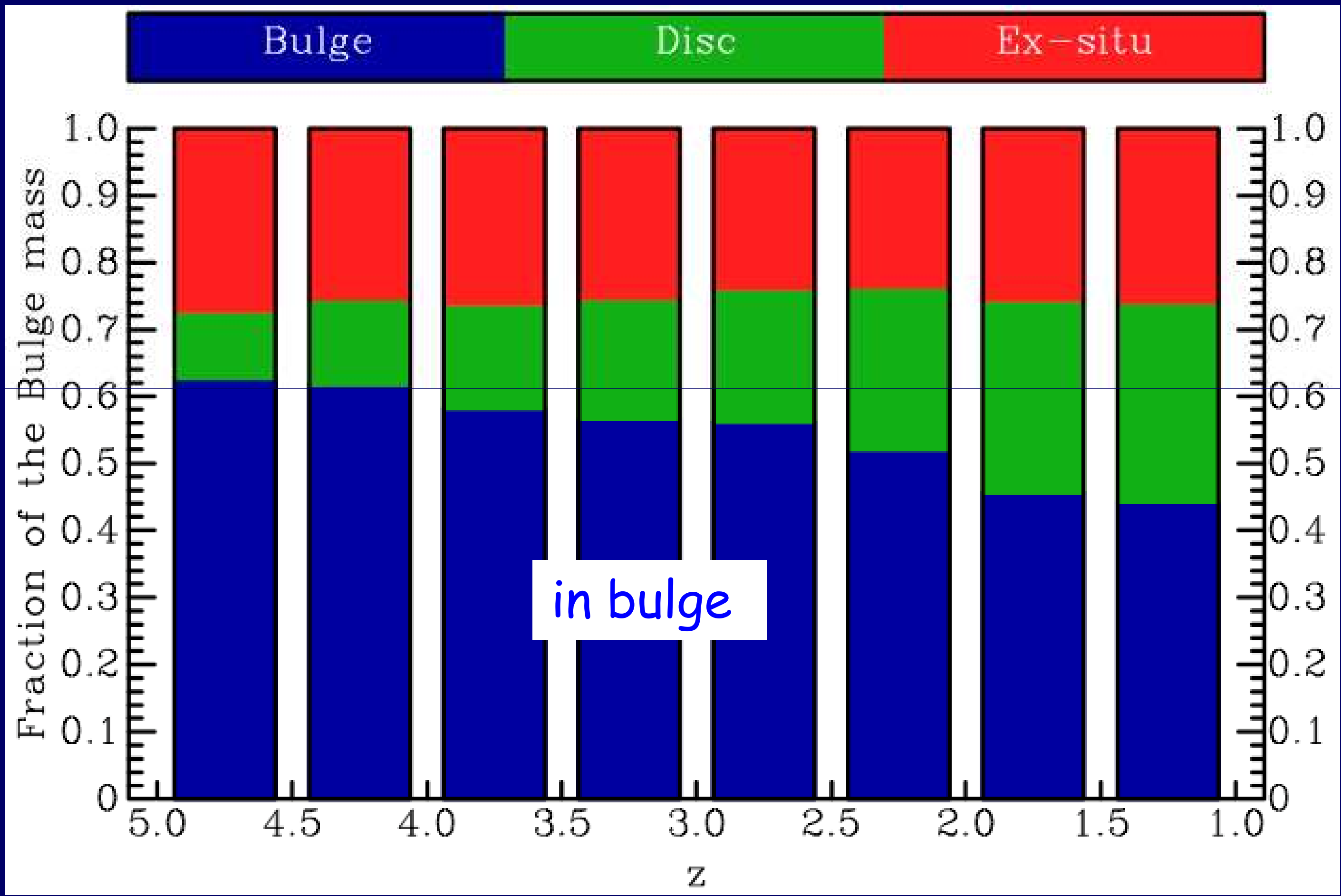
Run by Ceverino
Code: AMR ART (Kravtsov, Klypin)
3x30 galaxies zoom-in
Max resolution 25 pc
SN and radiative feedback

Collaborators:
Danovich, DeGraf, Inoue, Lapiner, Mandelker, Tacchella, Tomassetti, Tweed, Zolotov,
Bournaud+, Burkert+, Krumholz+, Primack+,
Carollo+, Faber+, Genzel+

Wet Origin of Bulge in Simulations

Zolotov+15

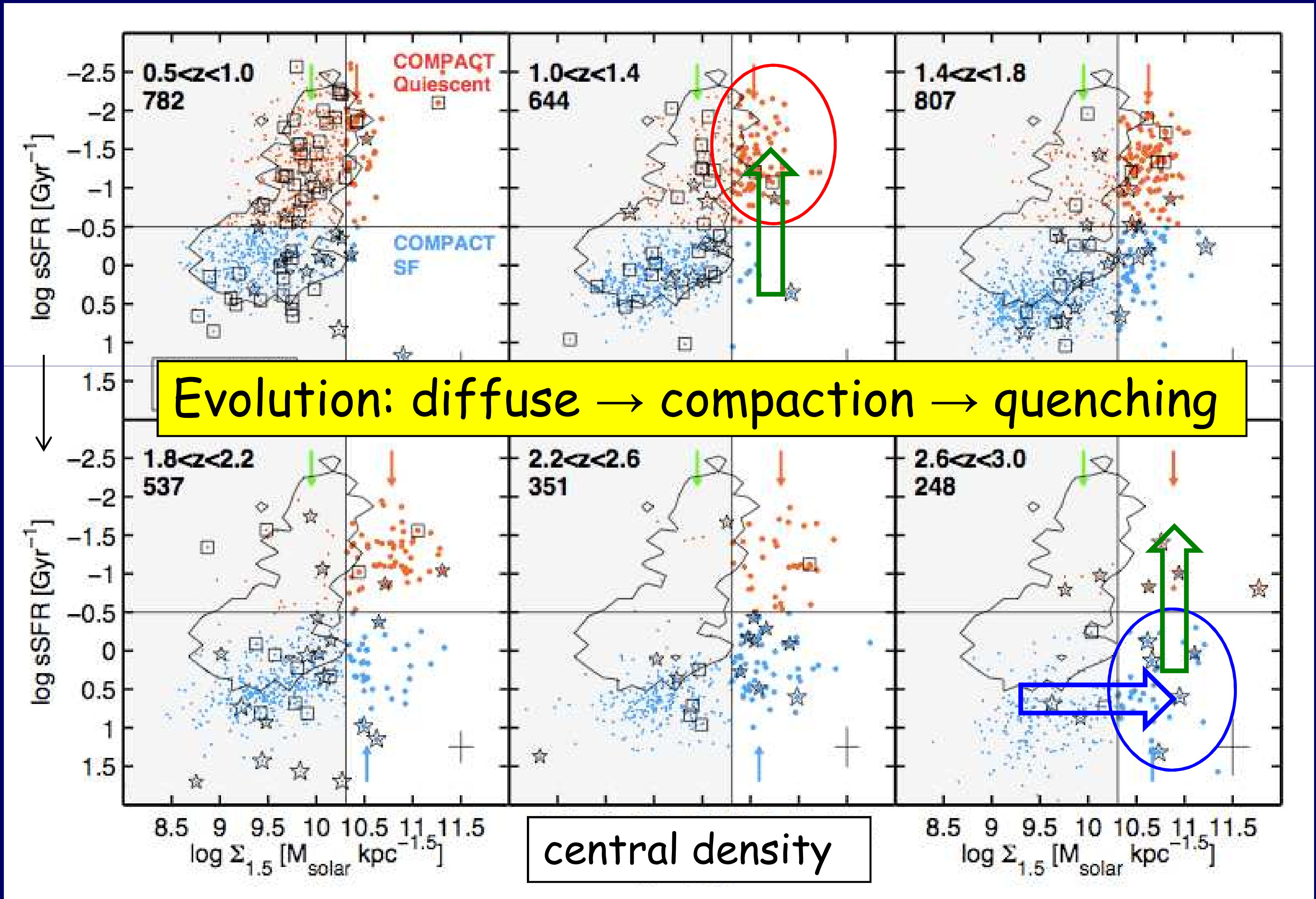
Fraction of bulge stars born in different components

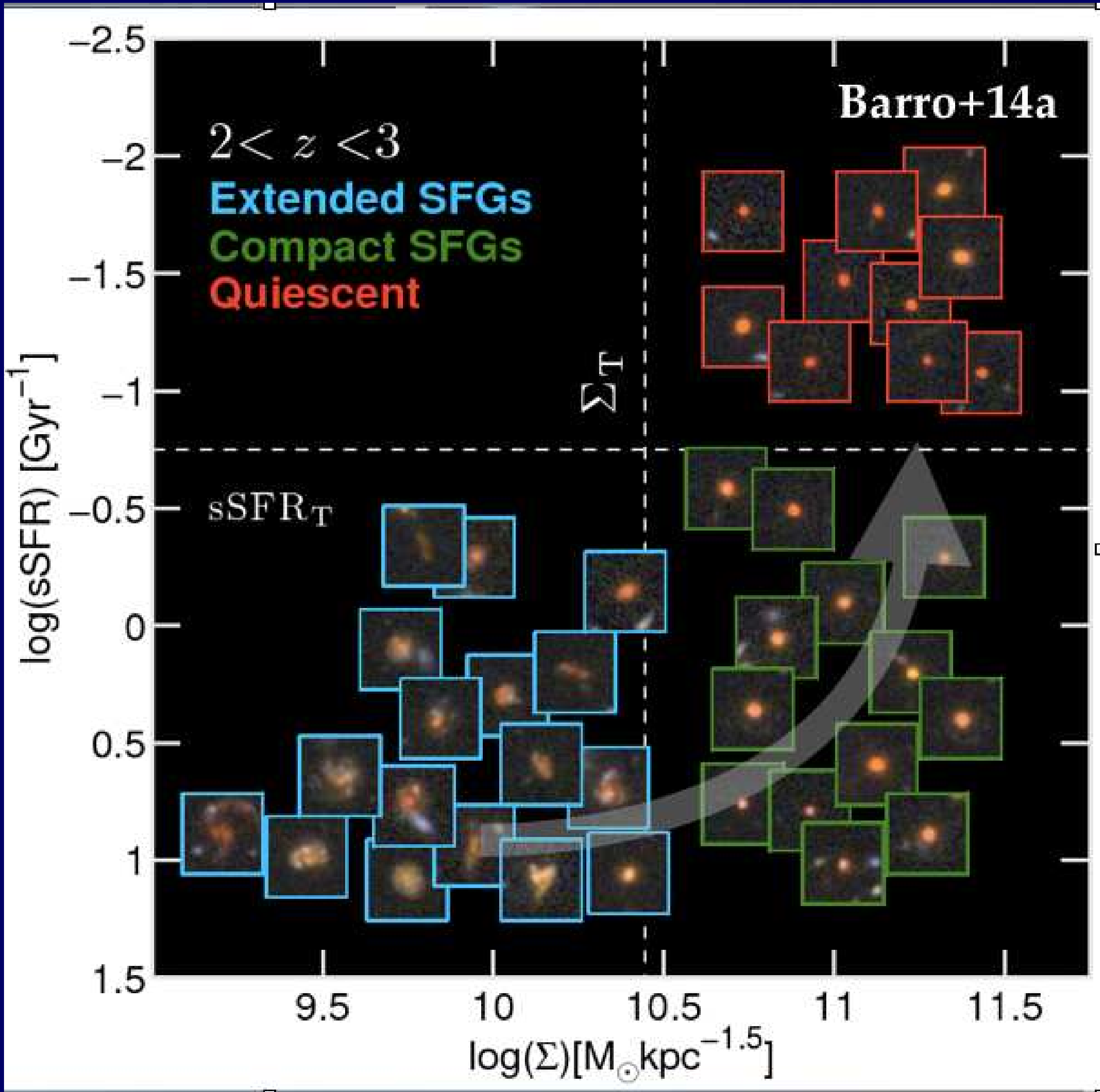


~half the bulge stars formed in the bulge → wet inflow

Observations: Blue Nuggets -> Red Nuggets

Barro+ 13 CANDELS z=1-3



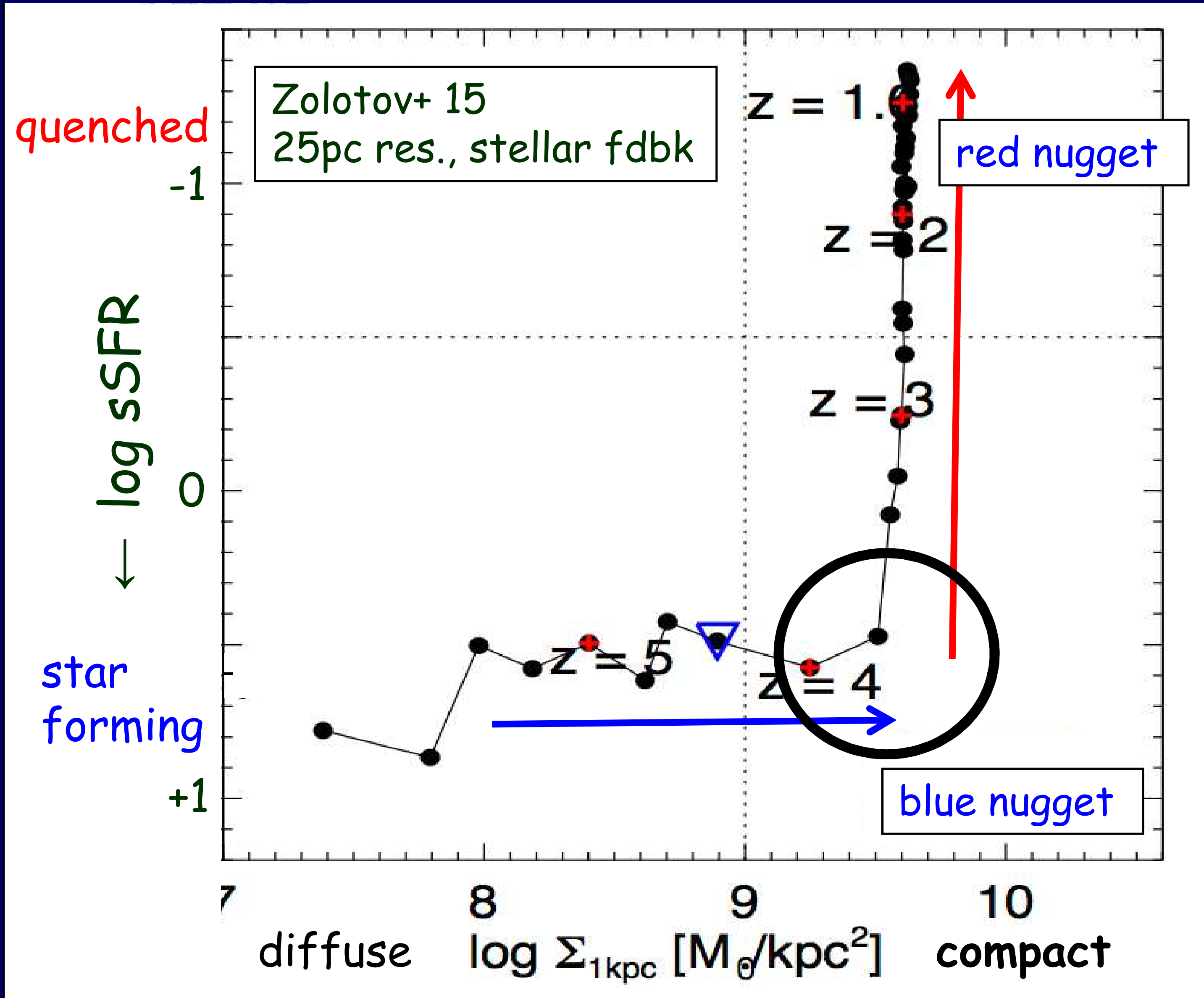


Barro+14a
2< z <3
Extended SFGs
Compact SFGs
Quiescent
Σ_T
sSFR$_T$
log(sSFR) [Gyr^{-1}]
log(Σ)[M$_\odot$ kpc$^{-1.5}$]
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
9.5
10
10.5
11
11.5

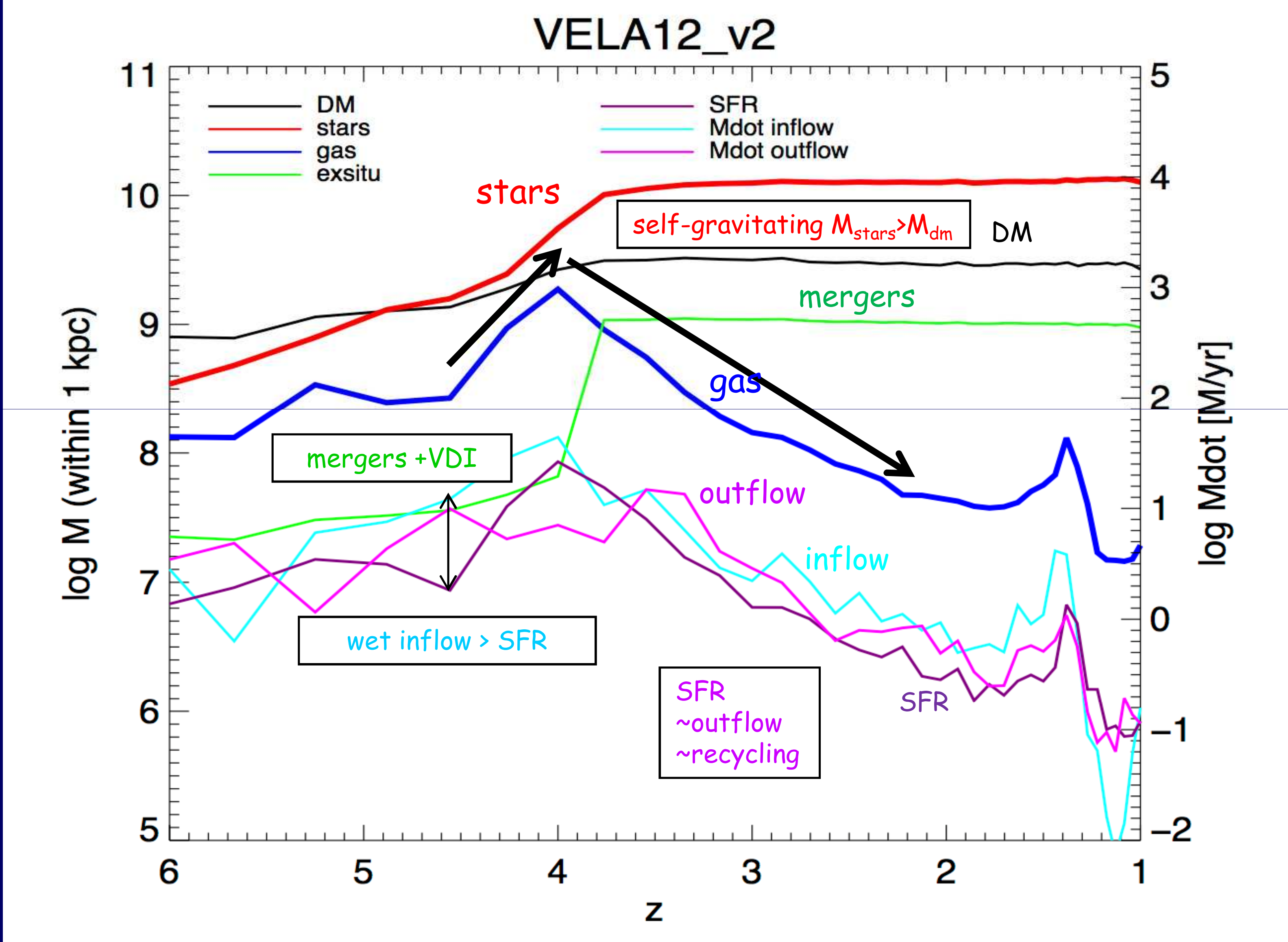
RN

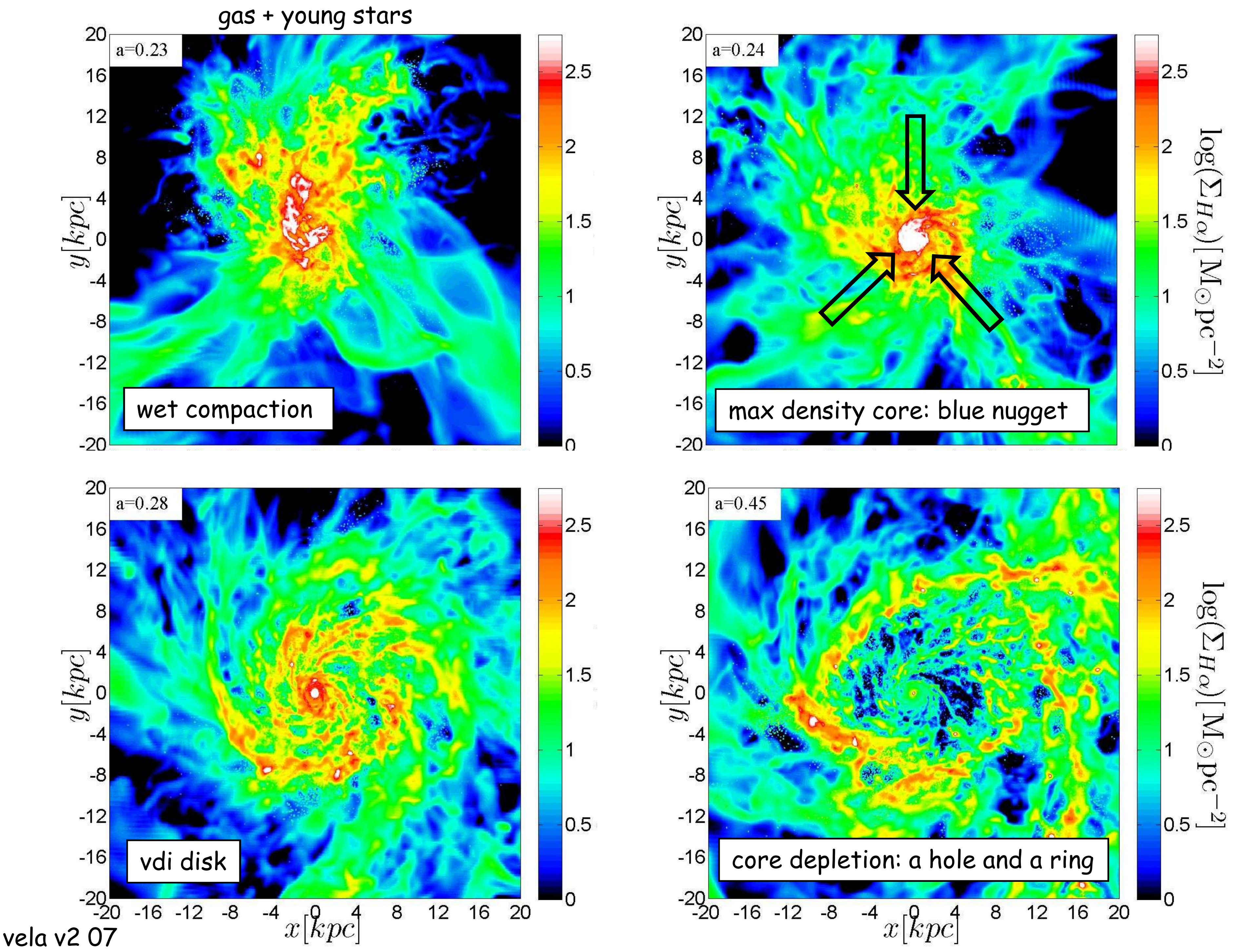
BN

Compaction and Quenching in Simulations

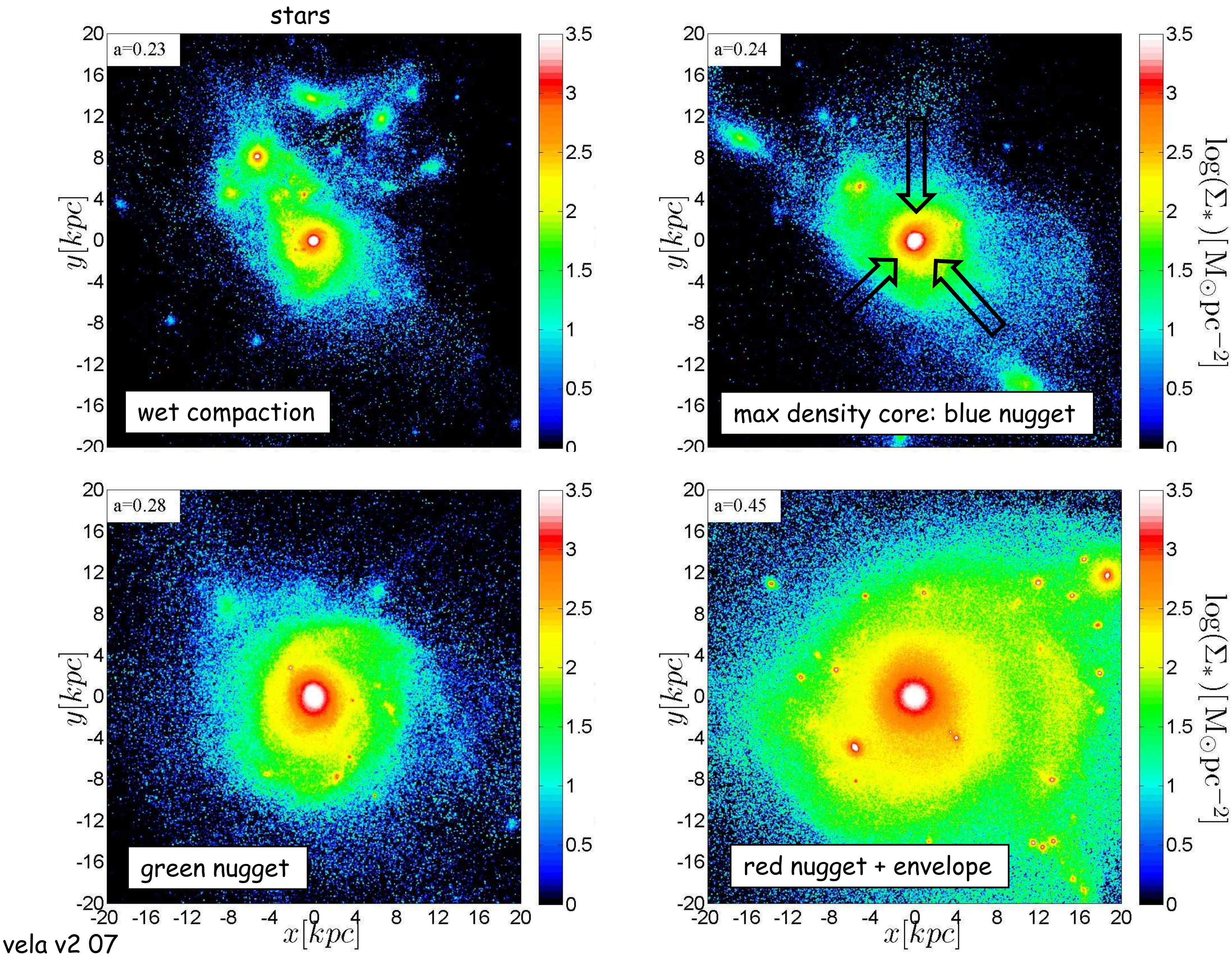


Compaction and quenching





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
$y[kpc]$
$x[kpc]$
$\log(\Sigma_{H\alpha})[M_\odot pc^{-2}]$
vela v2 07


stars
a=0.23
wet compaction
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max density core: blue nugget
a=0.28
green nugget
a=0.45
red nugget + envelope
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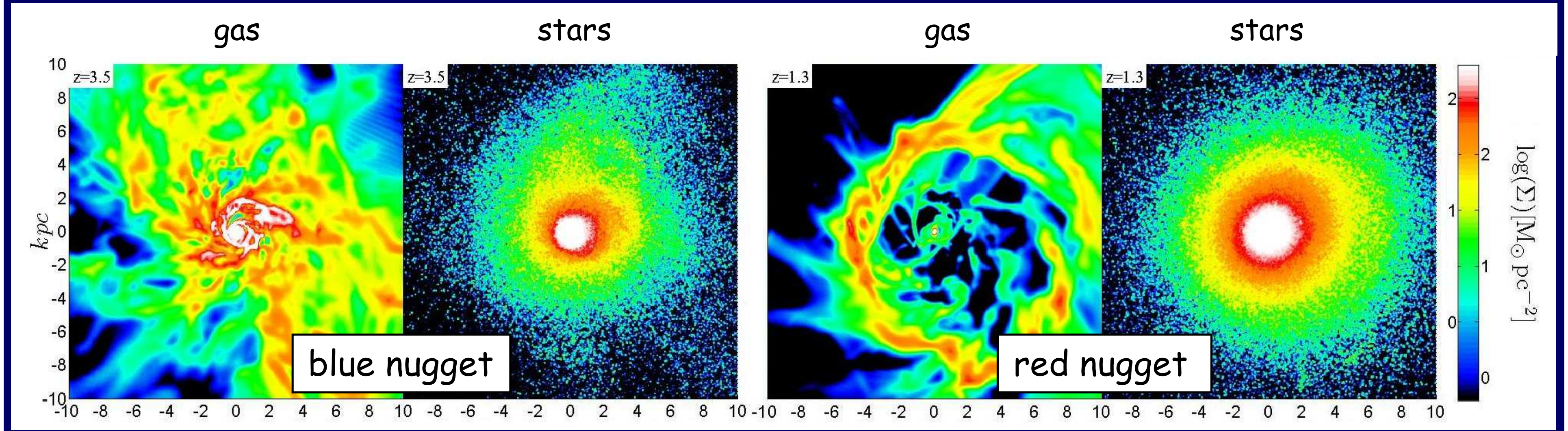
$\log(\Sigma_*)[M_\odot pc^{-2}]$
vela v2 07

Blue Nugget - Red Nugget



Pre-BN: ouside-in quenching

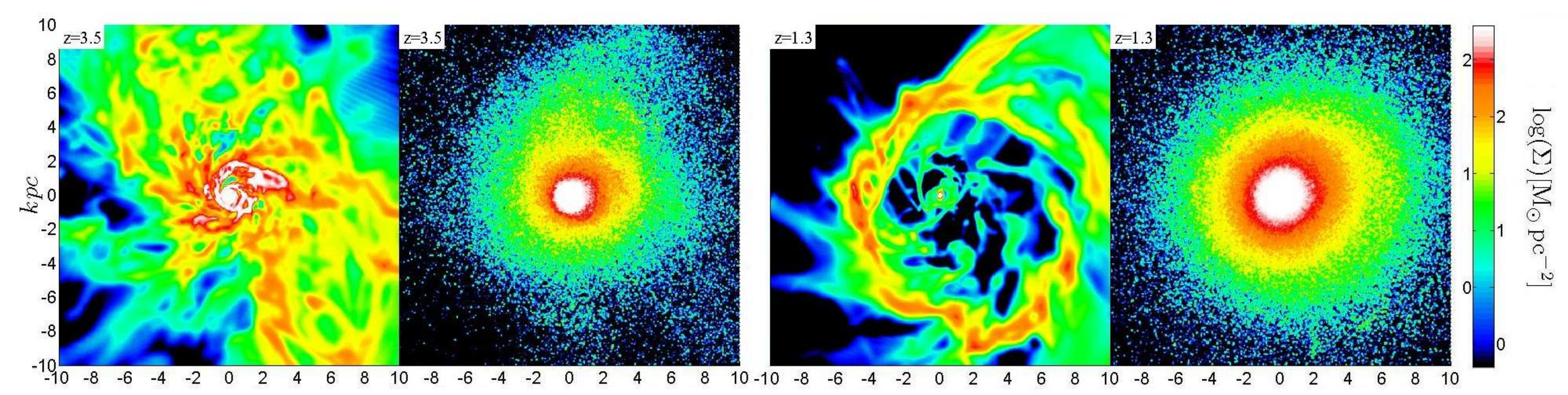
Dense gas core -> dense stellar core

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

Stellar core remains dense from BN to RN

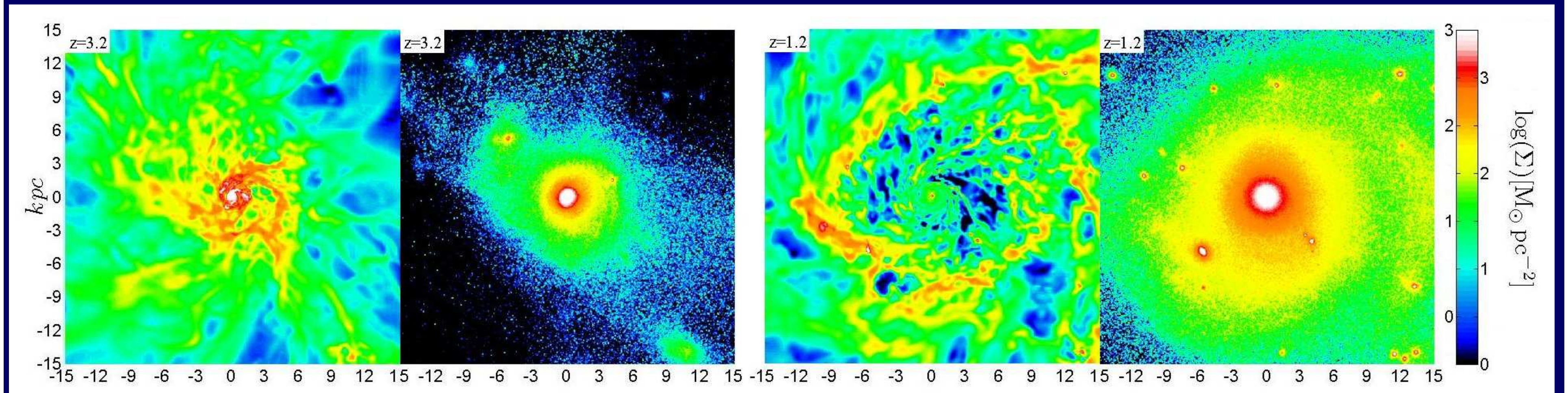
Blue Nugget - Red Nugget

naked red nugget



A stellar envelope may gradually grow by dry mergers

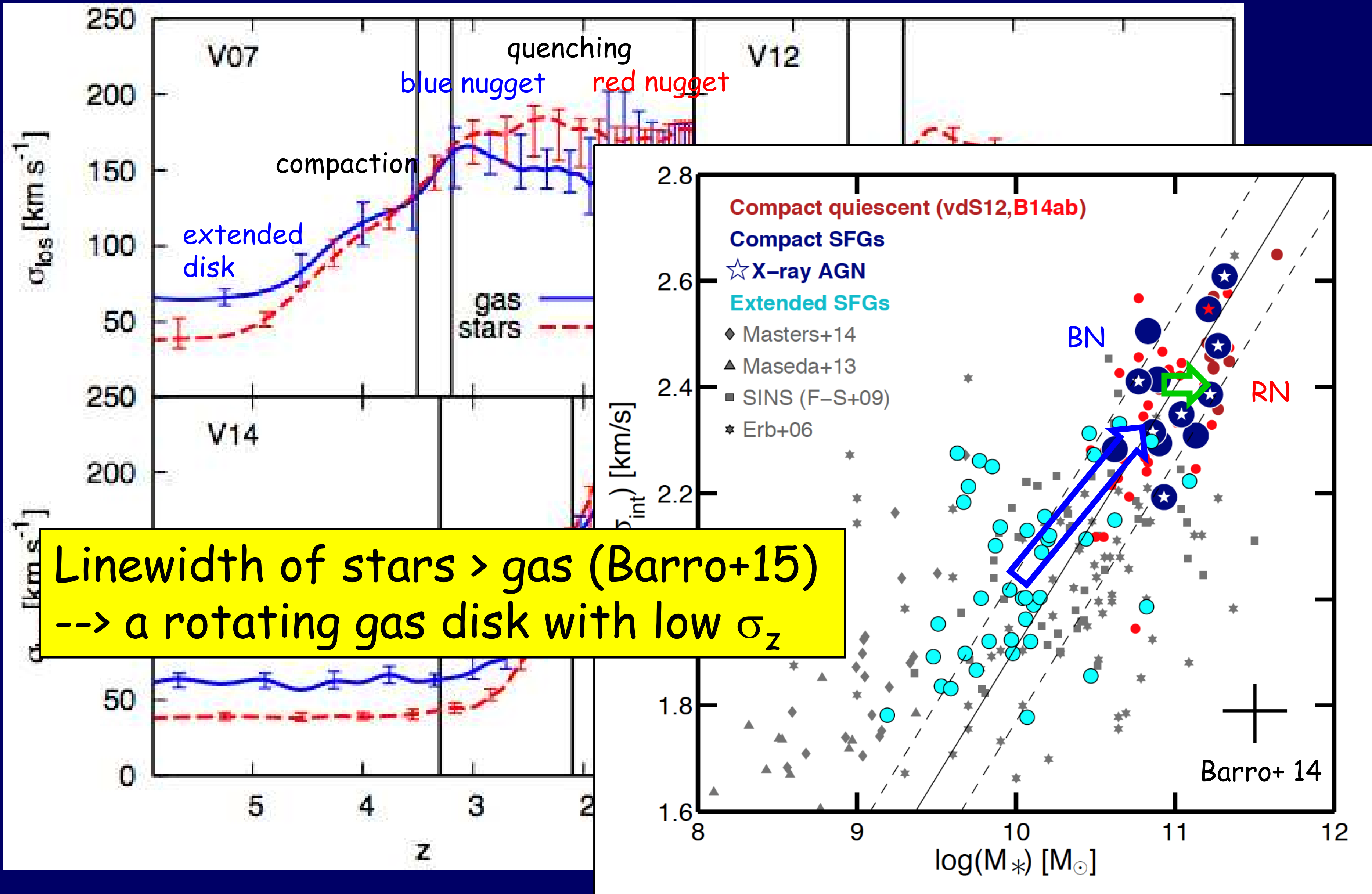
red nugget + envelope = elliptical



Profiles

Tacchella+ 2015b

"line width" evolution in simulated galaxies

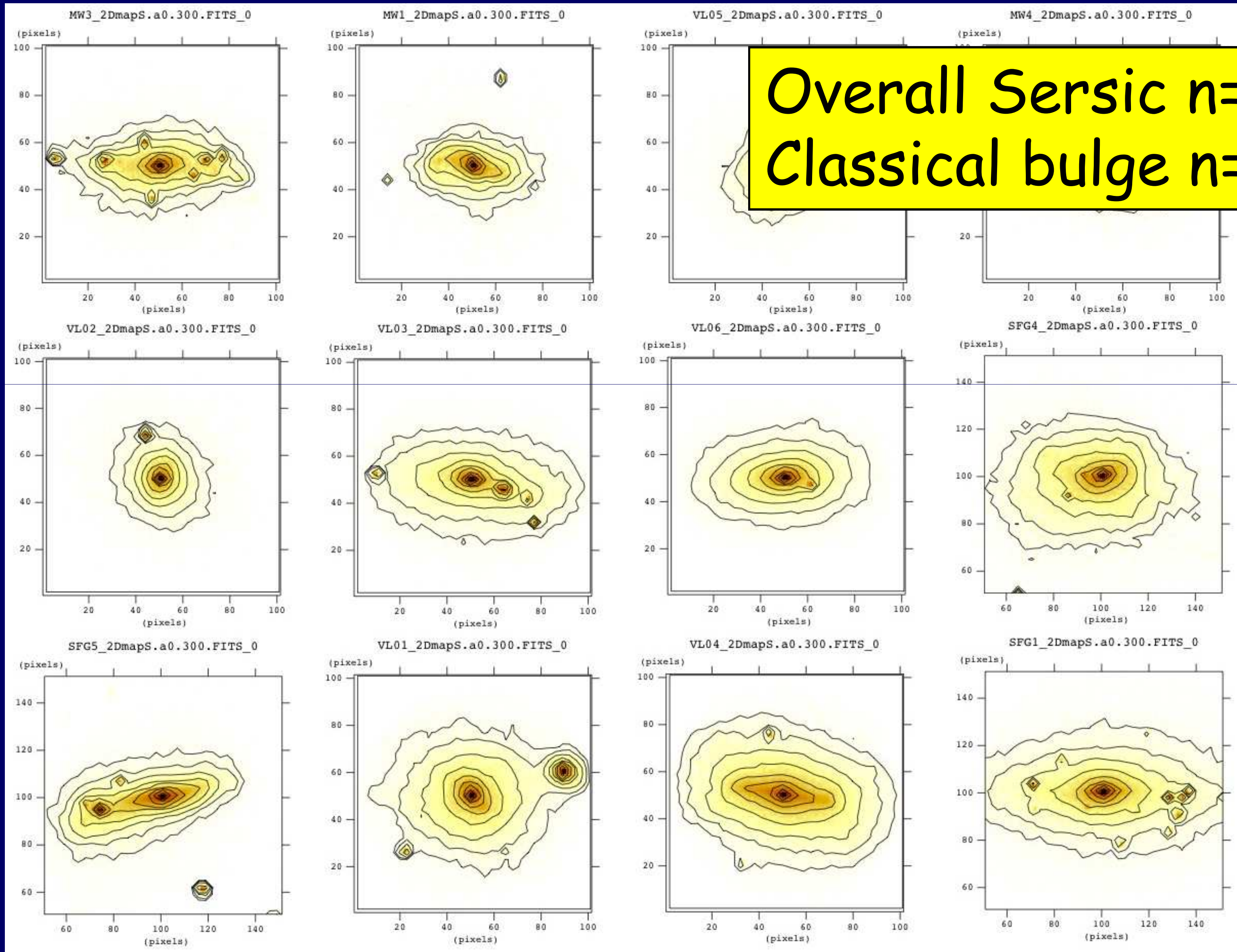


Linewidth of stars > gas (Barro+15)
--> a rotating gas disk with low σ_z

Stellar Red Nuggets z=2.3, edge-on

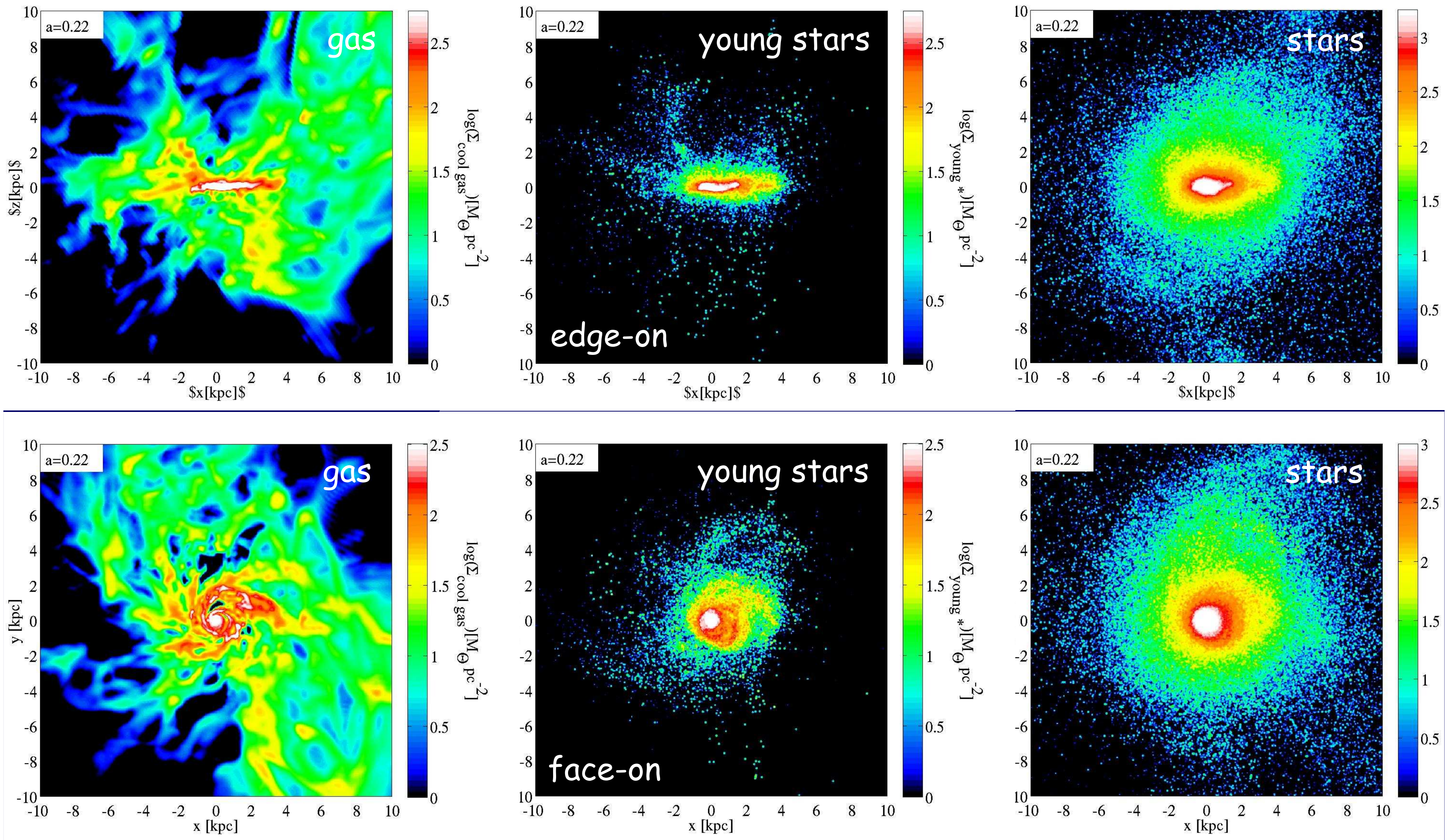
Ceverino+ 2015

Overall Sersic n=2-4
Classical bulge n=3-5



Blue Nuggets: Disks of Young Stars

V12 at z=3.55



Trigger of Wet Compaction

What is the Trigger of wet Compaction?

- VDI-driven inflow (Dekel, Burkert 14)
- Mergers (major, minor) (Barnes, Hernquist 91; Hopkins+ 06)
- Tidal compression (Dekel+ 03; Renaud+ 14)
- Counter-rotating streams (Danovich+ 14, Nir+ 15)
- Triaxial halo core (Ceverino+15, Tomassetti+ 15)
- Return of recycled low-AM gas (Elmegreen+ 14)

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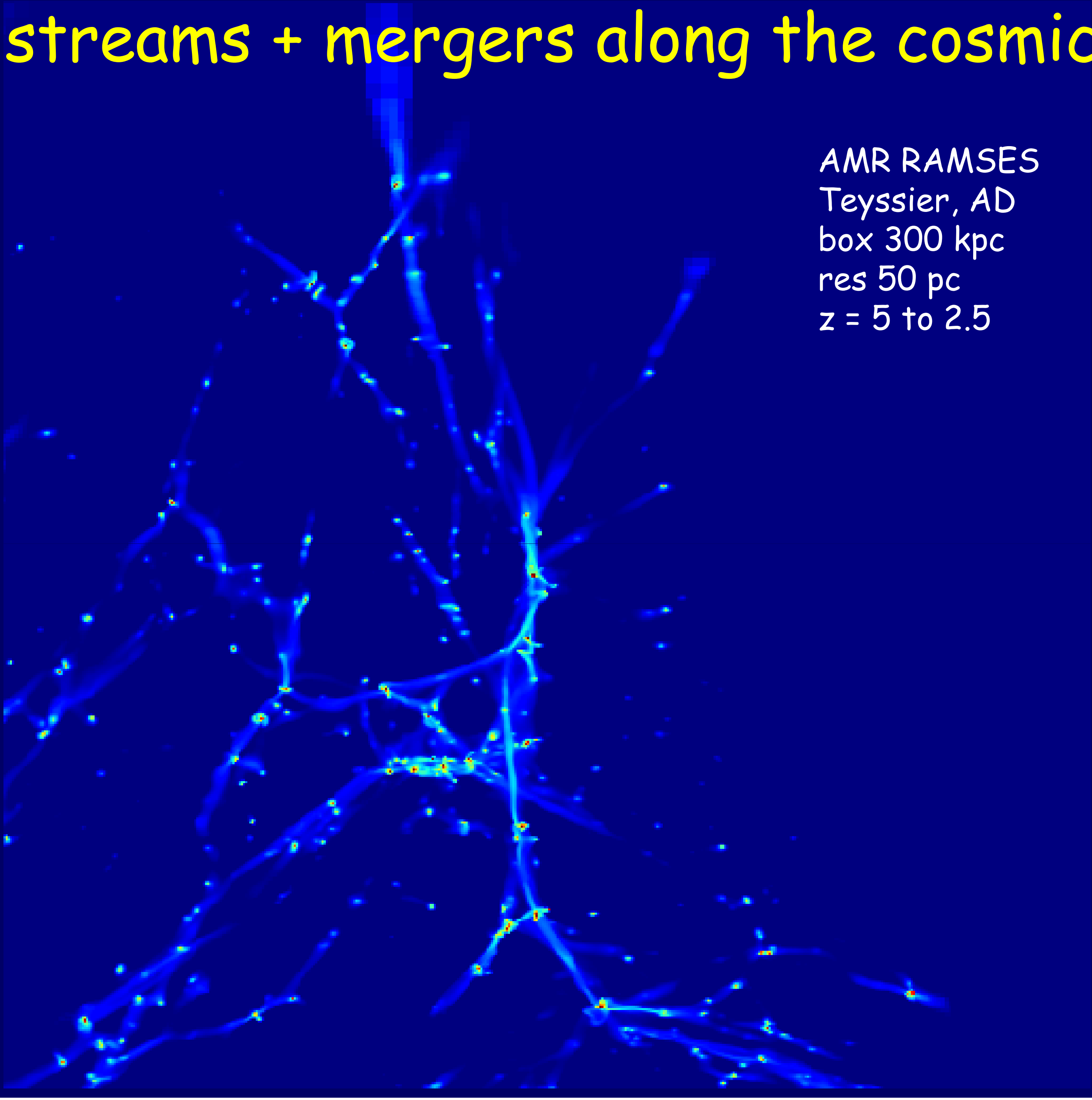
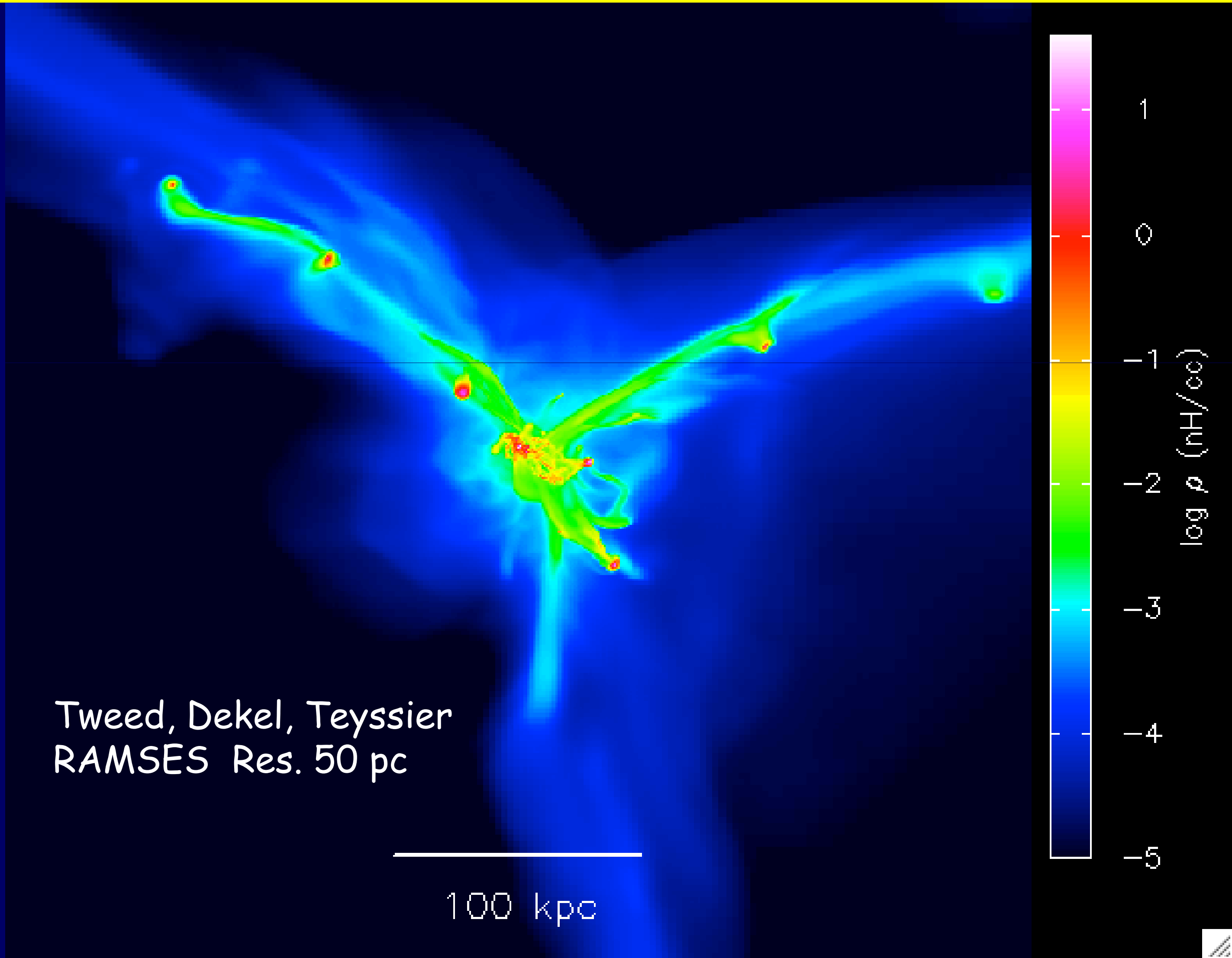
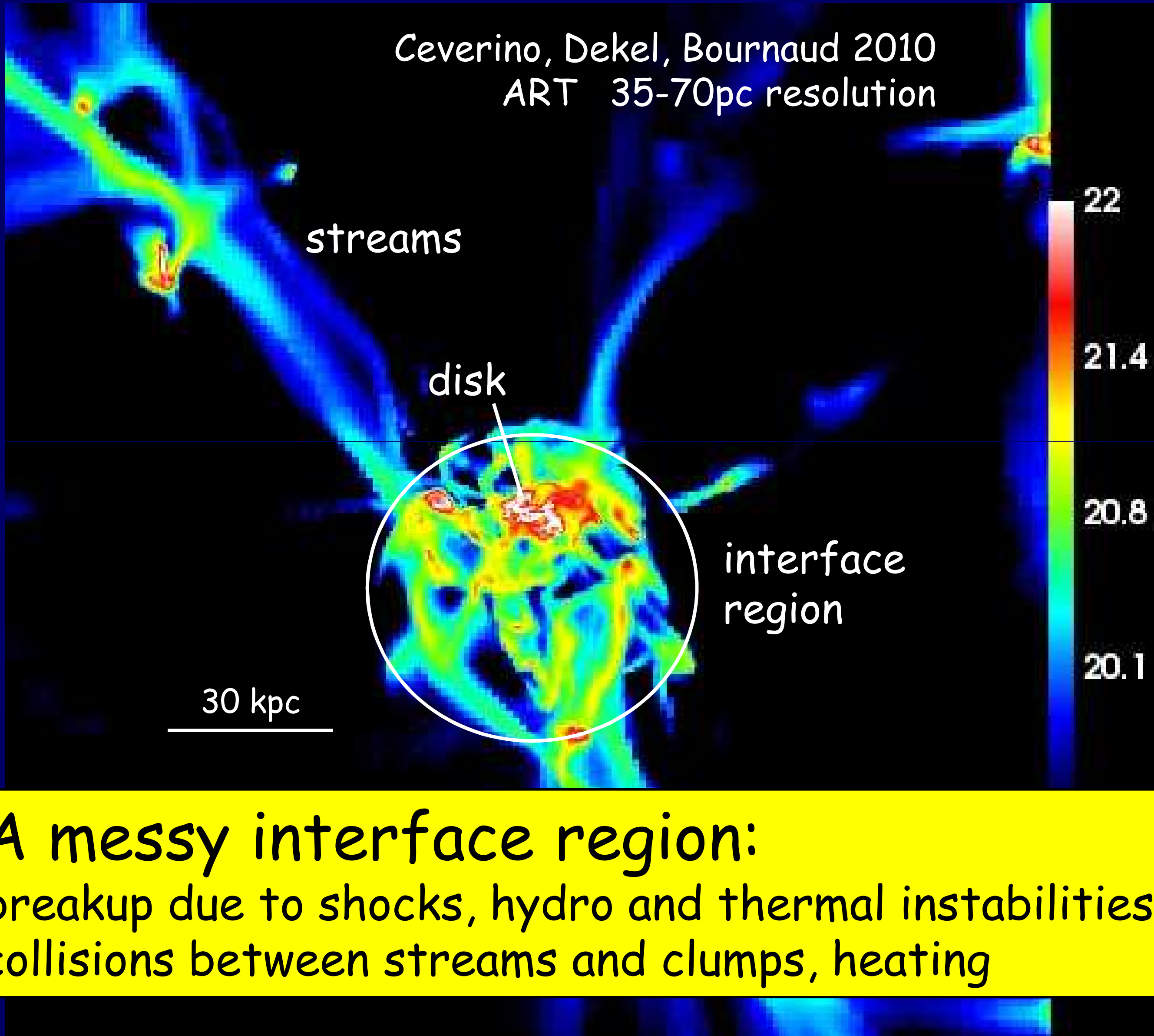
Gas streams + mergers along the cosmic web



Hi-z galaxies are fed by intense streams, including minor and major mergers

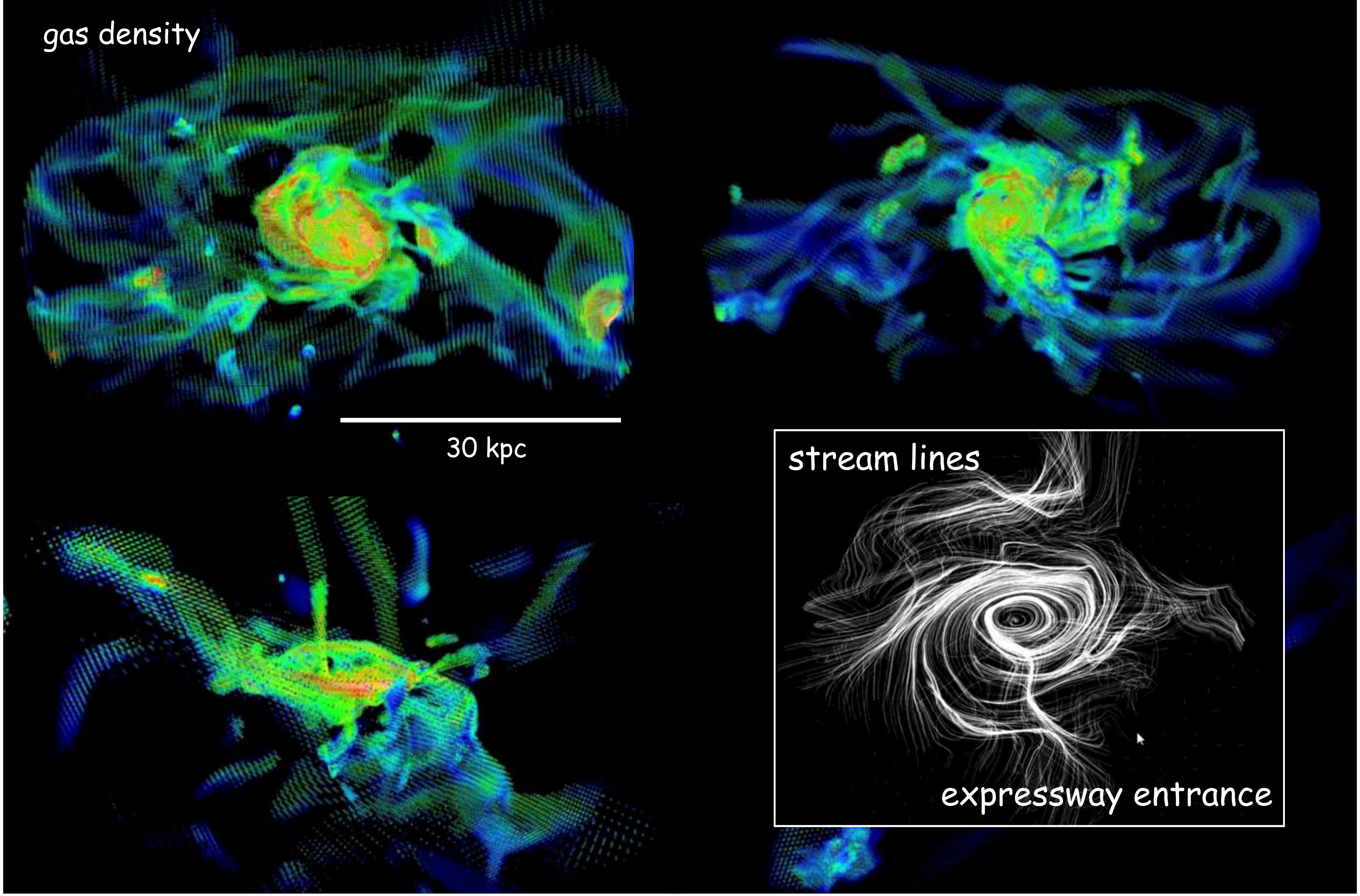


How do the streams join the disk?



A messy interface region:
breakup due to shocks, hydro and thermal instabilities, collisions between streams and clumps, heating

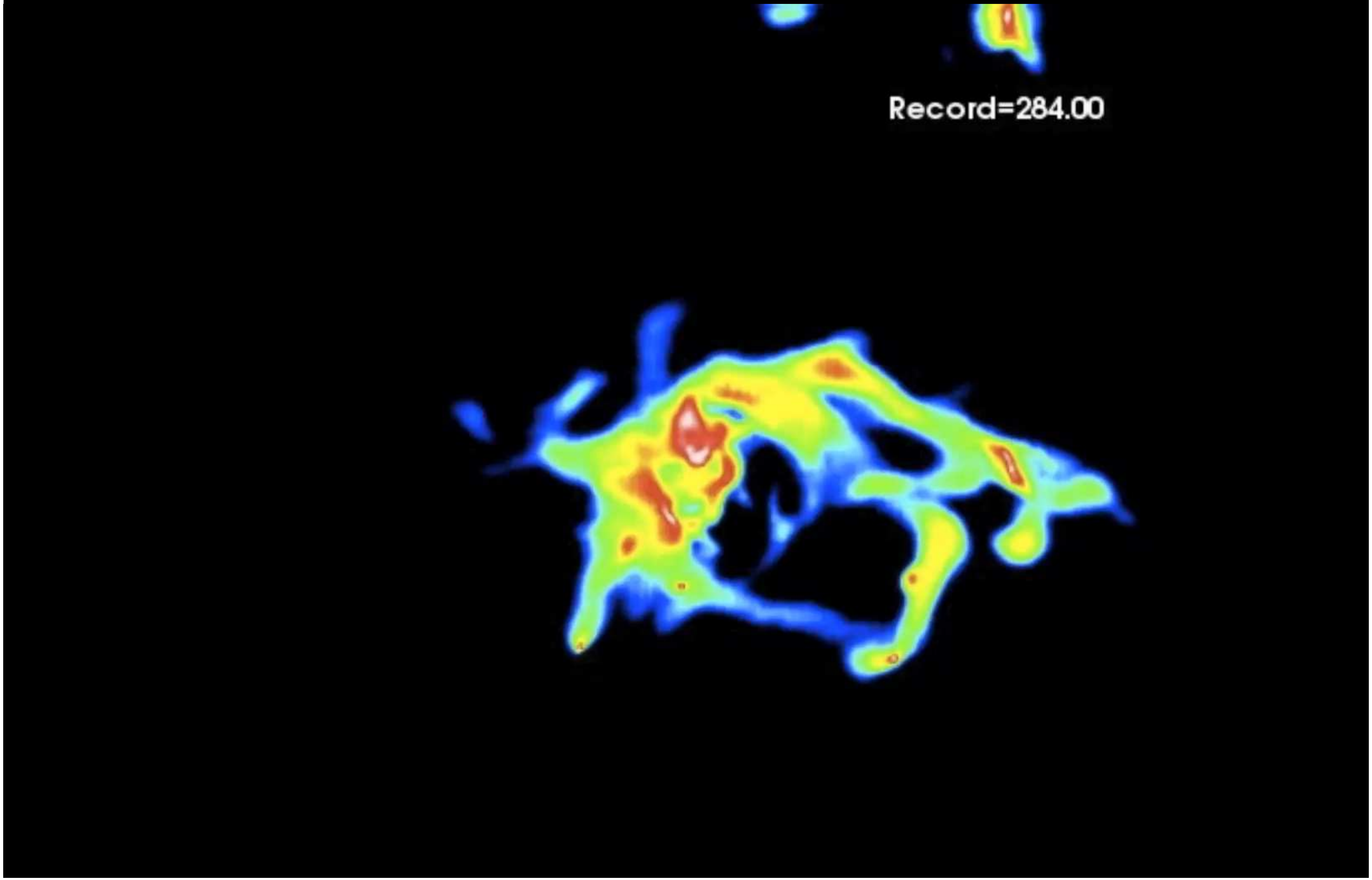
An Extended Tilted Ring about the Disk



Clumpy Disk: streams & mergers

Ceverino, Dekel et al.

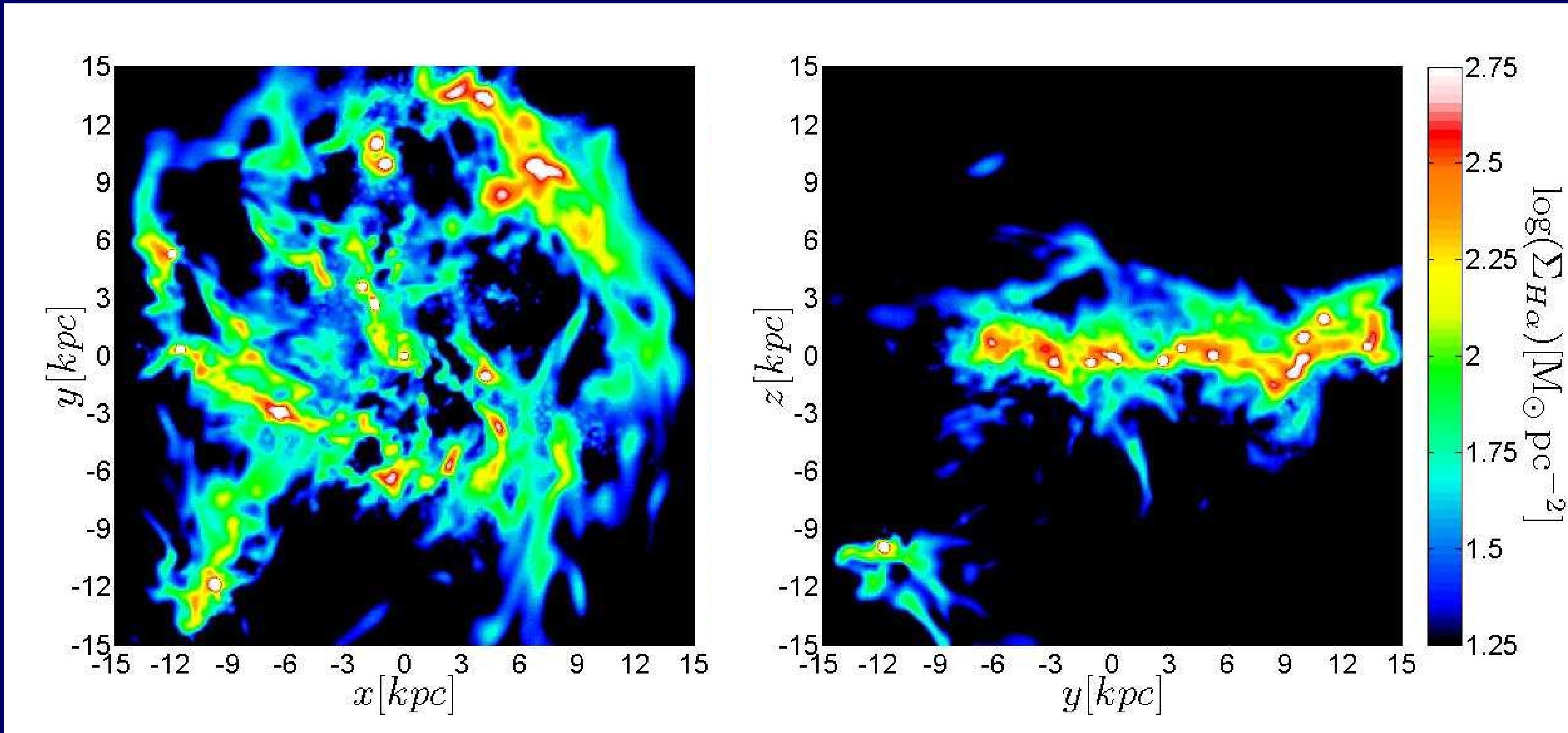
10 kpc z=4-2.1



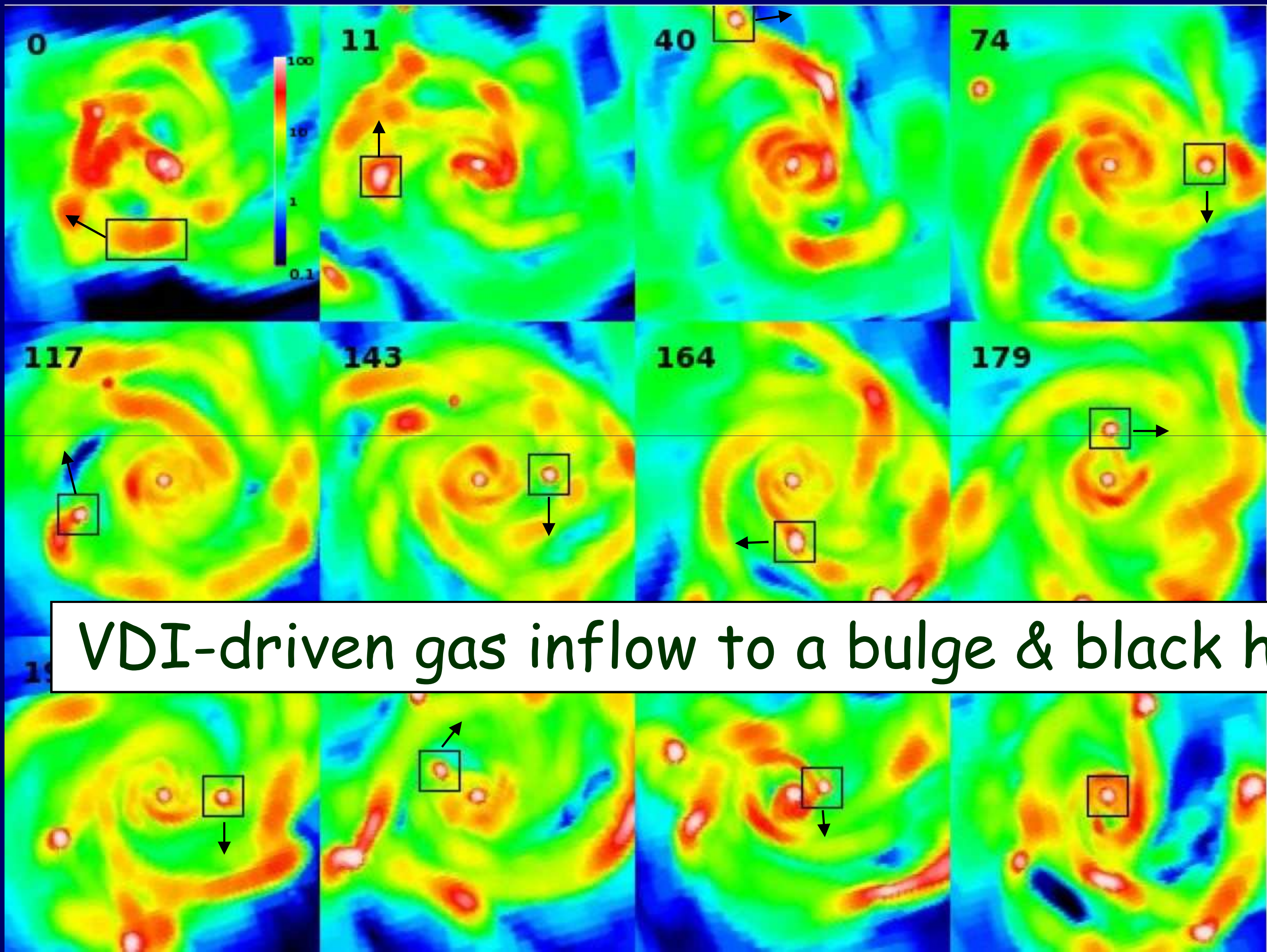
Violent Disk Instability (VDI) at High z

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

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



Clump Formation & Migration



VDI-driven gas inflow to a bulge & black hole

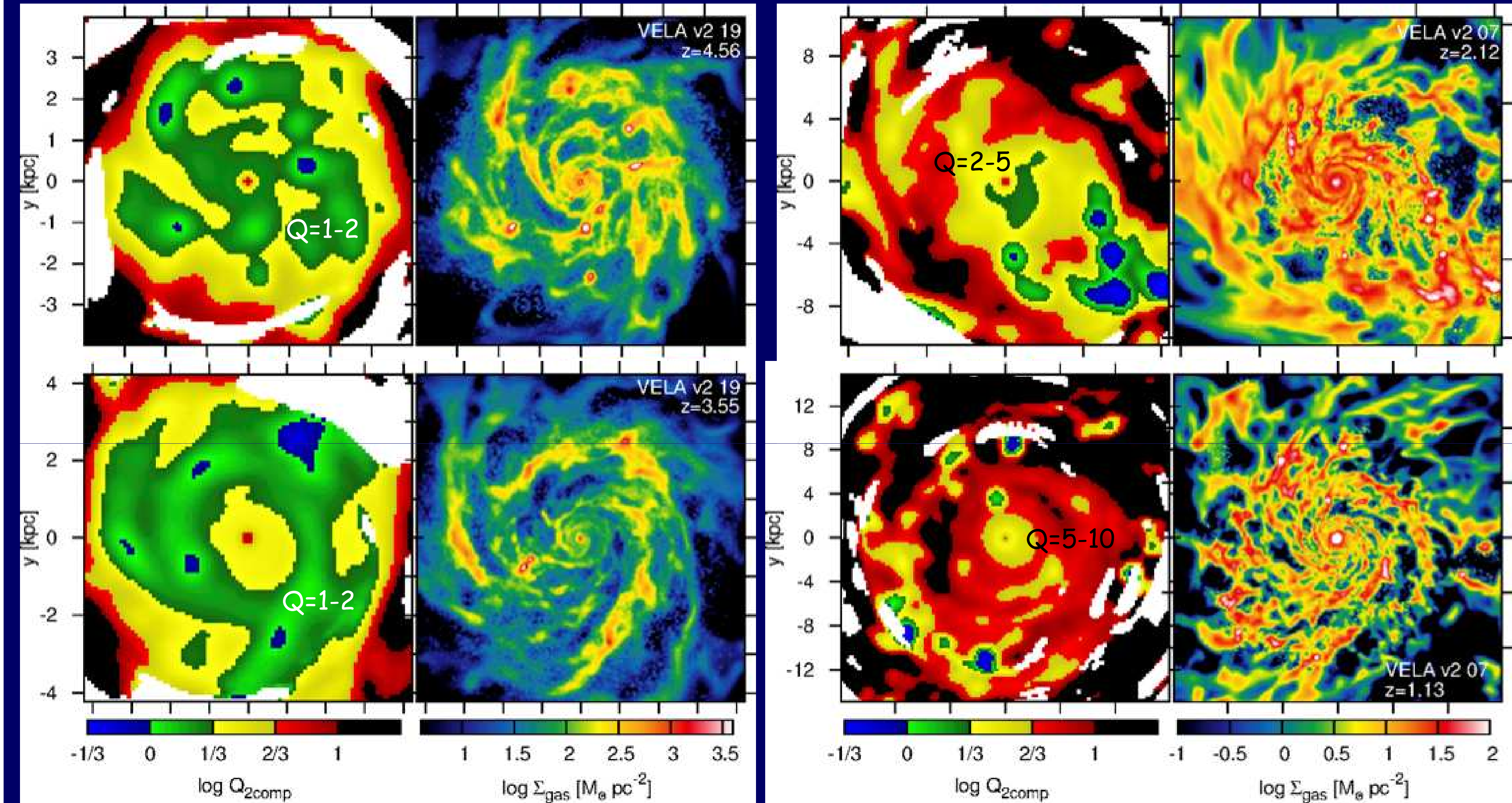
Ceverino, Dekel, Bournaud 10

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

VDI deviates from linear Toomre instability
Q=2-5 -> nonlinear instability
stimulated by in-streams with minor mergers
(Inoue+)

Violent Instability with Q~2-3

Toomre $Q \propto \Omega\sigma/\Sigma \approx 1$



Nonlinear instability – stimulated by intense inflows with minor mergers, or by the non-linear clumps themselves

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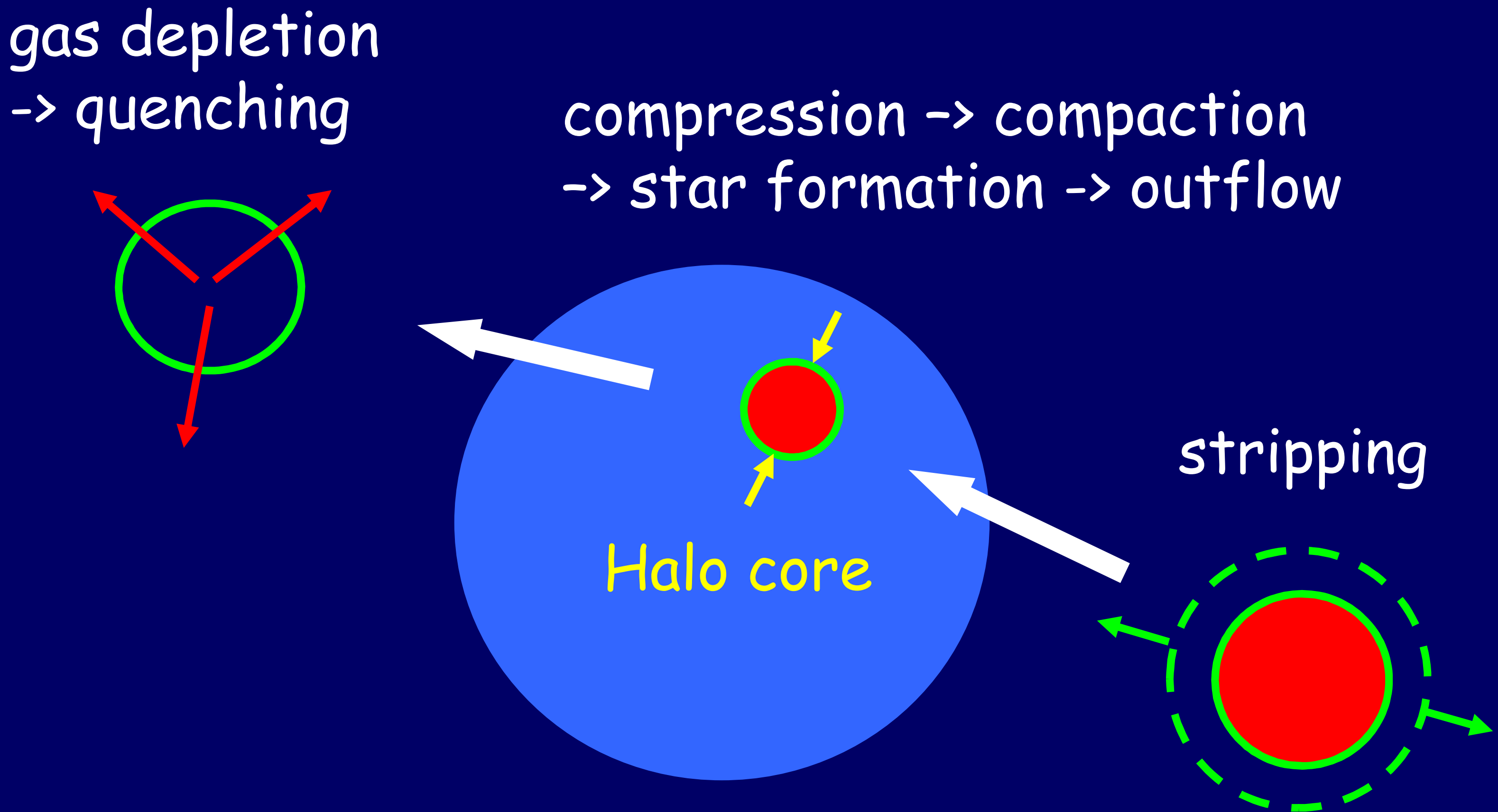
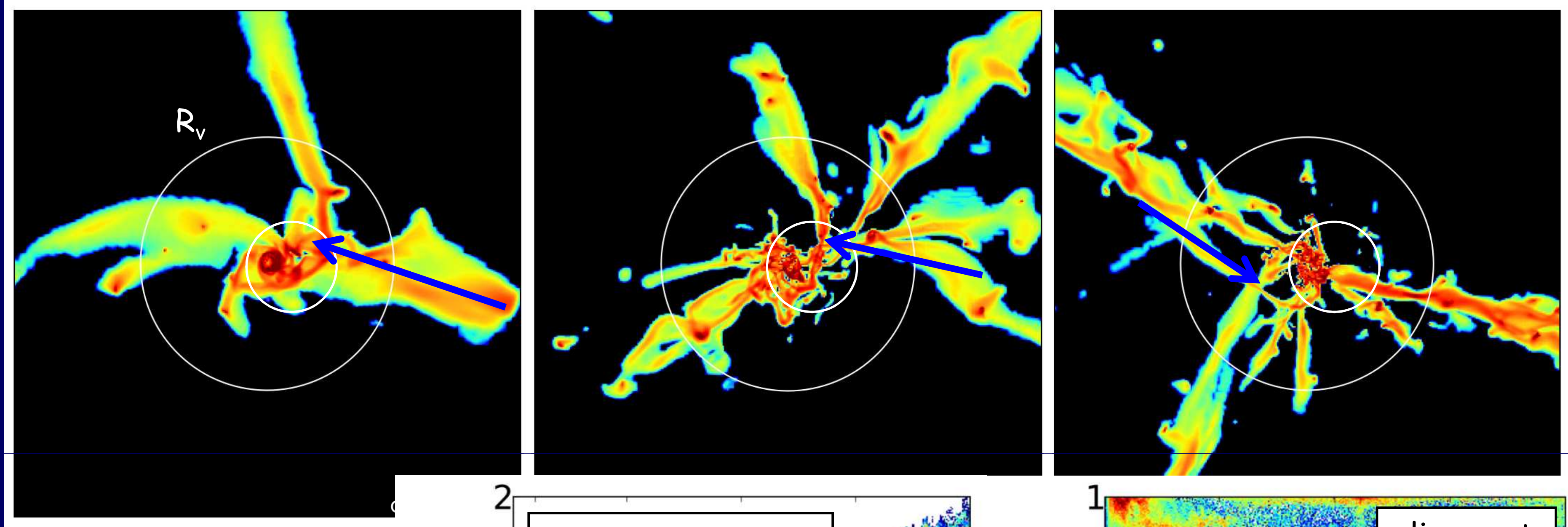
Compaction by Tidal Compression

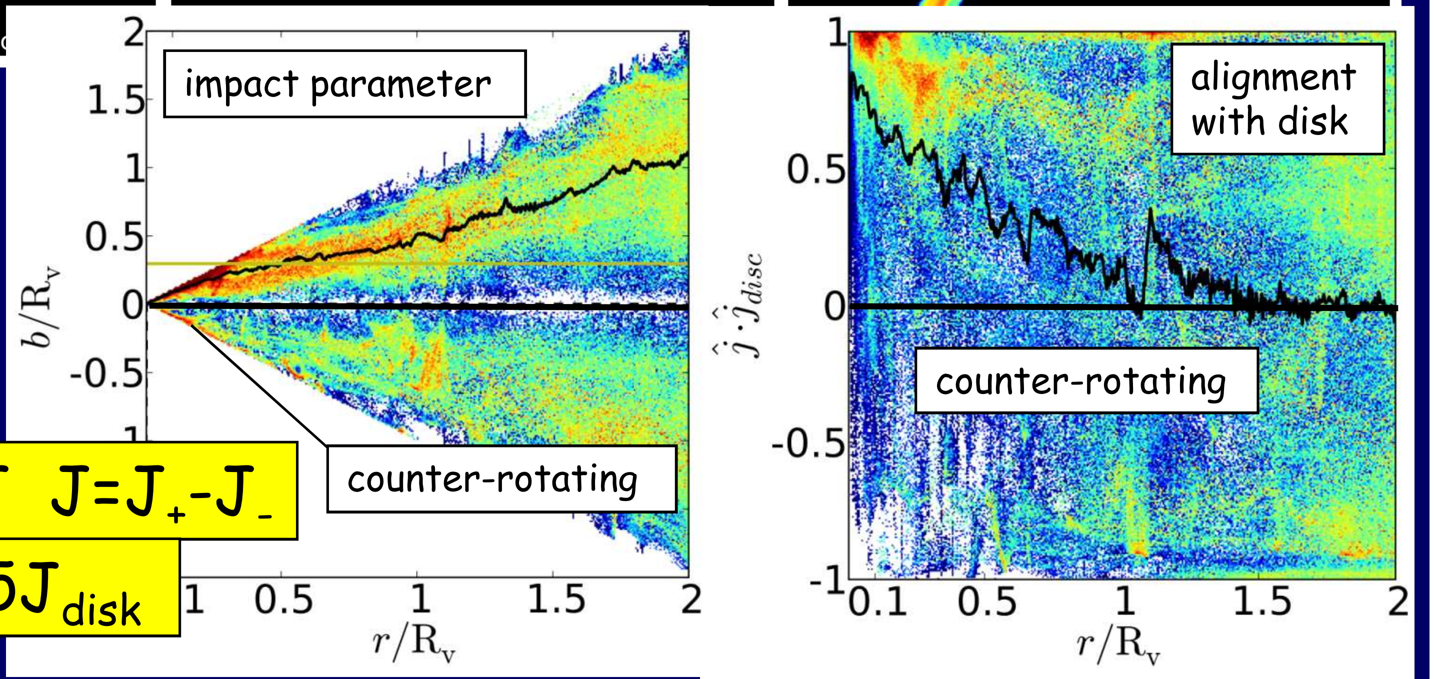
Dekel, Devor, Hetzroni 2003



Counter-rotating Streams

Danovich+15





inflow: J_{-}~0.7J $J=J_{+}-J_{-}$

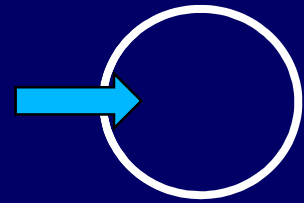
in t_{orbit}: J_{-}~0.15J_{disk}

The Quenching Mechanism(s)

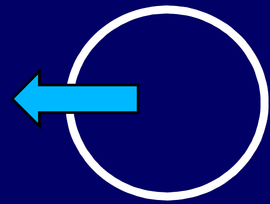
Zolotov+ 2015, Tacchella+ 2015

The Quenching Mechanism

Wet compaction: inflow > SFR+outflow



High SFR and no gas supply to the center:
inflow < SFR+outflow → quenching attempt

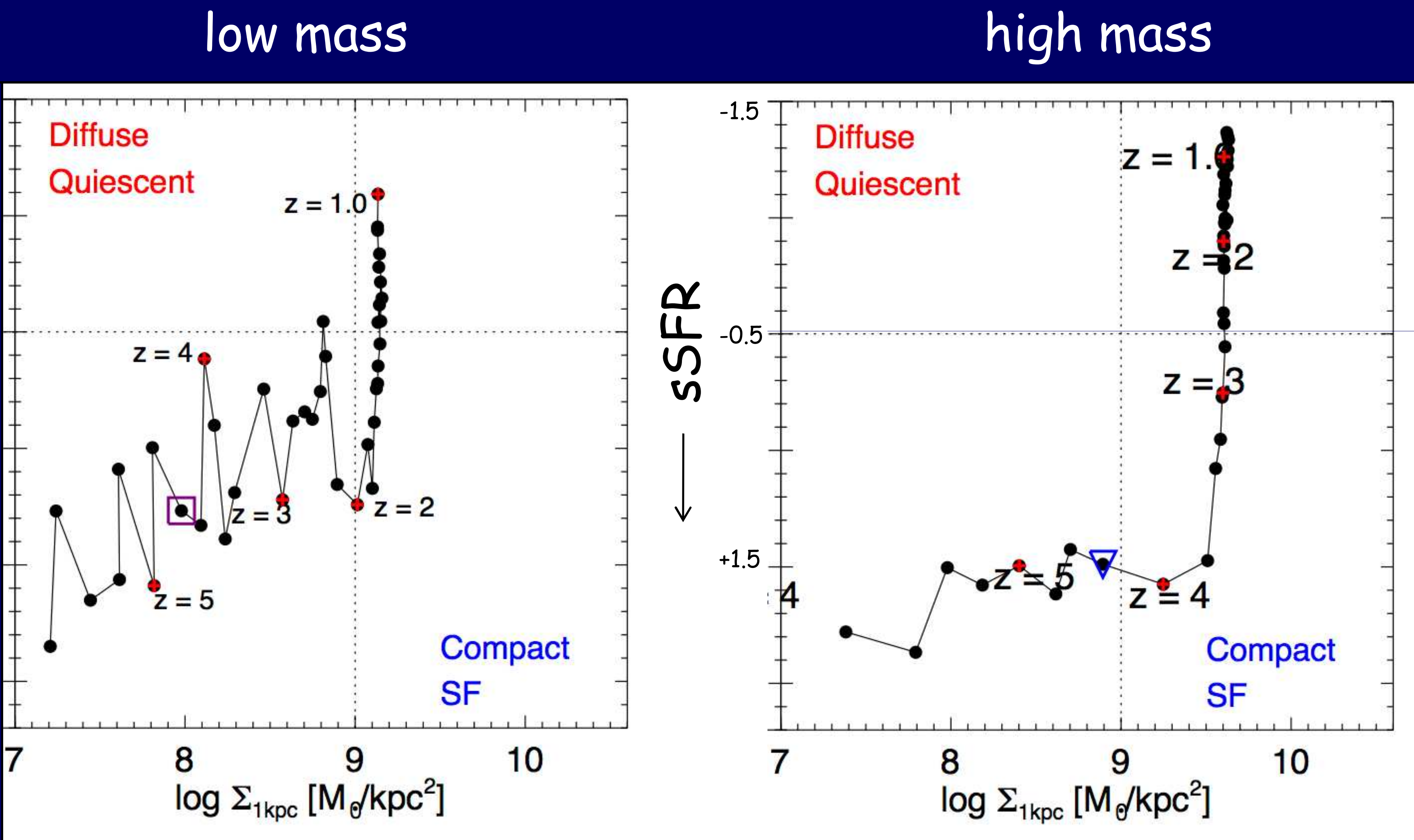


- disk has shrunk → no immediate gas supply to center
- massive bulge suppresses VDI-driven inflow (morphological quen.)
- V<100 km s^{-1} shallow potential -> stellar, SN, AGN outflows

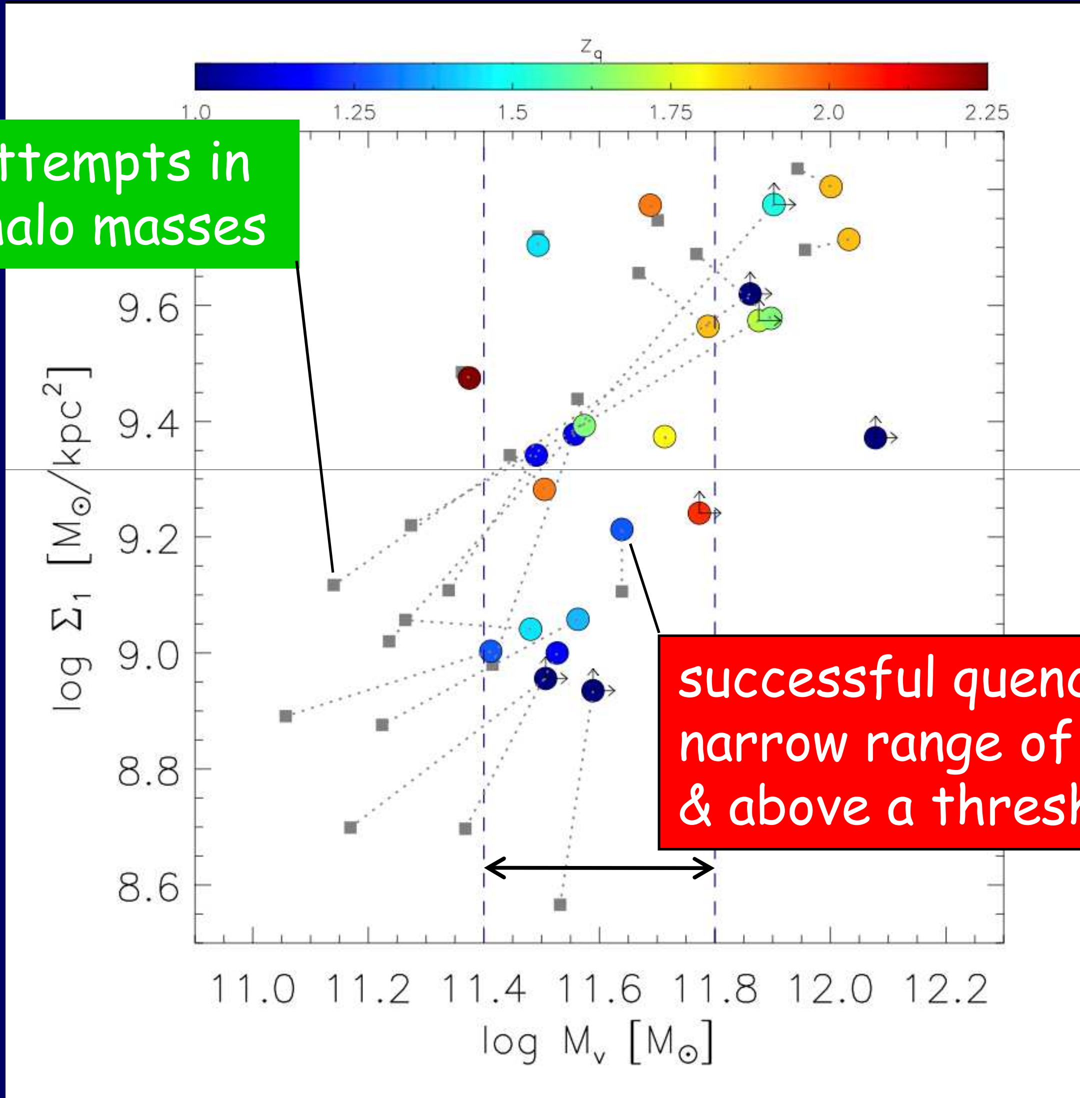
Long-term quenching?

- $t_{deplete} < t_{replenish}$ $z<3$
- hot massive halo $M>10^{11.5}M_{\odot}$

Hesitatnt vs. Decisive Quenching



Halo Mass and Central Density at Quenching



quenching attempts in a range of halo masses

successful quenching in a narrow range of halo masses & above a threshold $\sim 10^{11.5} M_\odot$

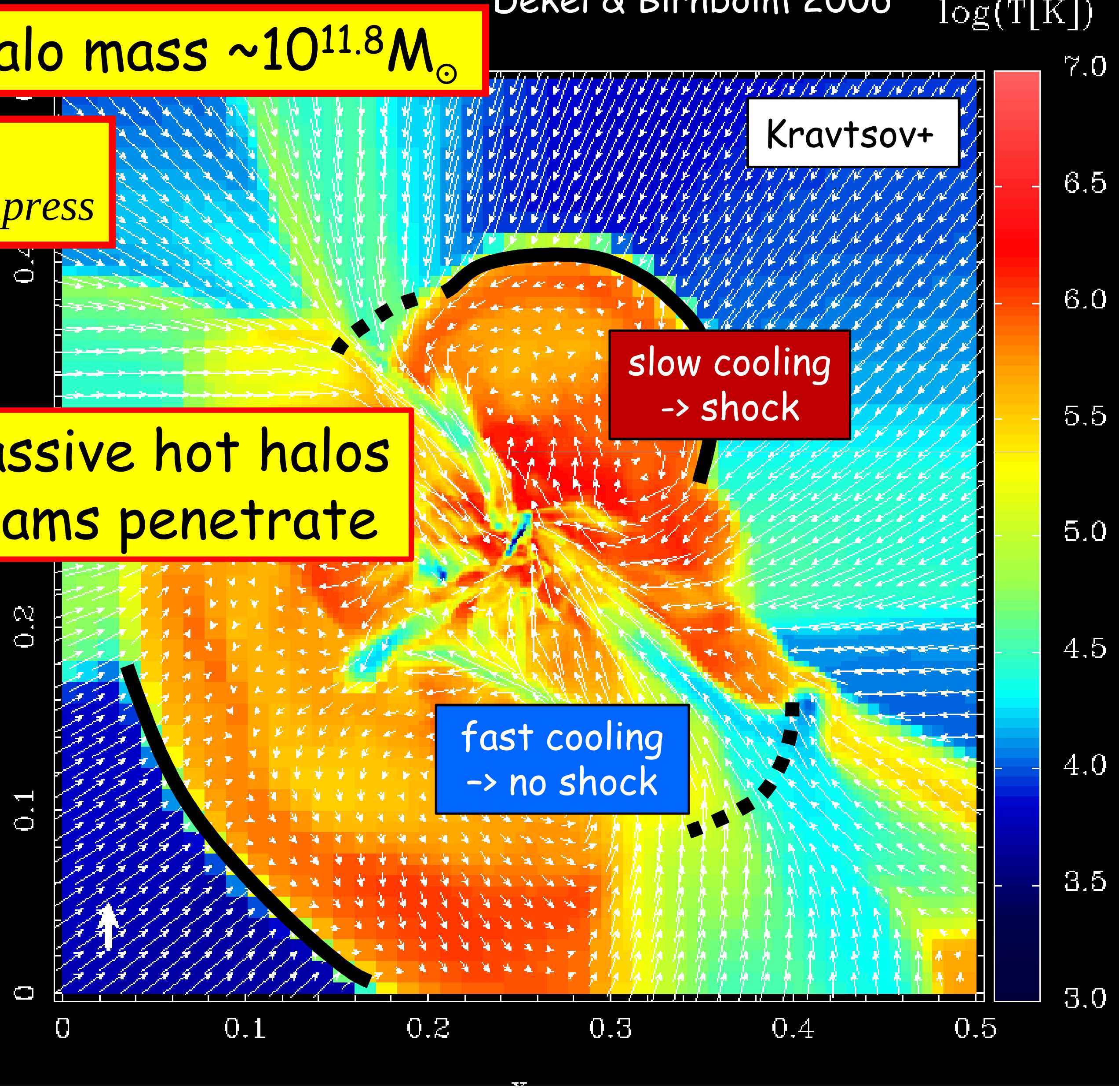
Virial Shock Heating

Dekel & Birnboim 2006

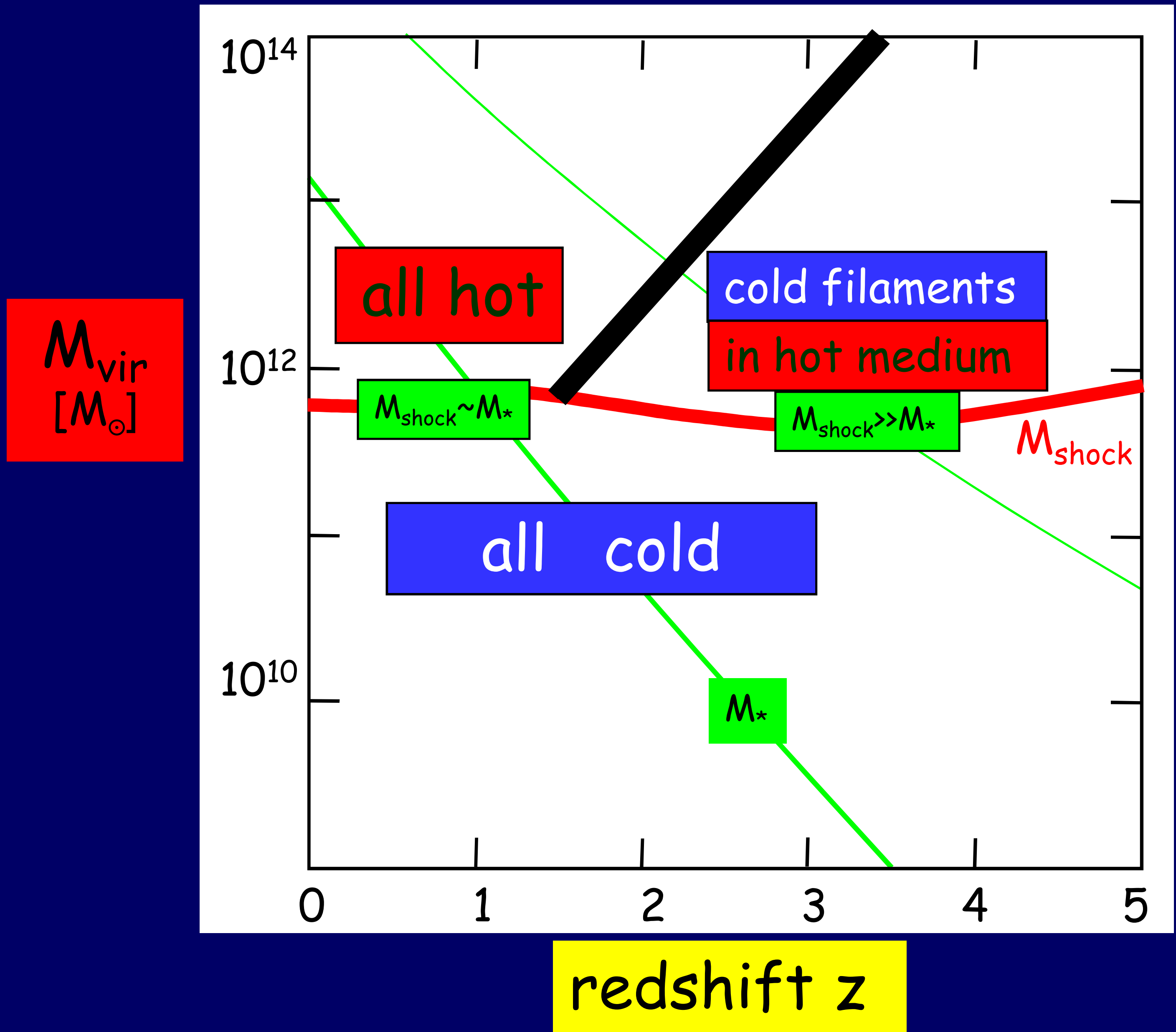
critical halo mass ~$10^{11.8} M_\odot$

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

in hi-z massive hot halos
cold streams penetrate



Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06

The Quenching Mechanism

Wet compaction: inflow > SFR+outflow

High SFR and no gas supply to the center:
inflow < SFR+outflow → quenching attempt

- disk has shrunk → no immediate gas supply to center
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- $V<100$ km s^{-1} shallow potential -> stellar, SN, AGN outflows

If halo is massive (hot) → starvation of gas supply
→ long-term quenching

If halo is less massive → gas supply to a new disk
→ new compaction and SFR … until the halo is massive (hot)

Main Sequence

Zolotov+ 2015; Tacchella+ 2015c

The Universal Main Sequence of SFGs

star forming

↑

sSFR

quenched

bathtub model:

$$\dot{M}_{\rm gas} \approx \dot{M}_{\rm in} - \dot{M}_{\rm SF}(1+\eta)$$

$$\dot{M}_{\rm SF} \approx \varepsilon M_{\rm gas} / t_{\rm ff}$$

main sequence SFGs

±0.3 dex

→ steady state: $\dot{M}_{\rm SF} \approx \dot{M}_{\rm in}$

→ time evolution of main-sequence zero point:

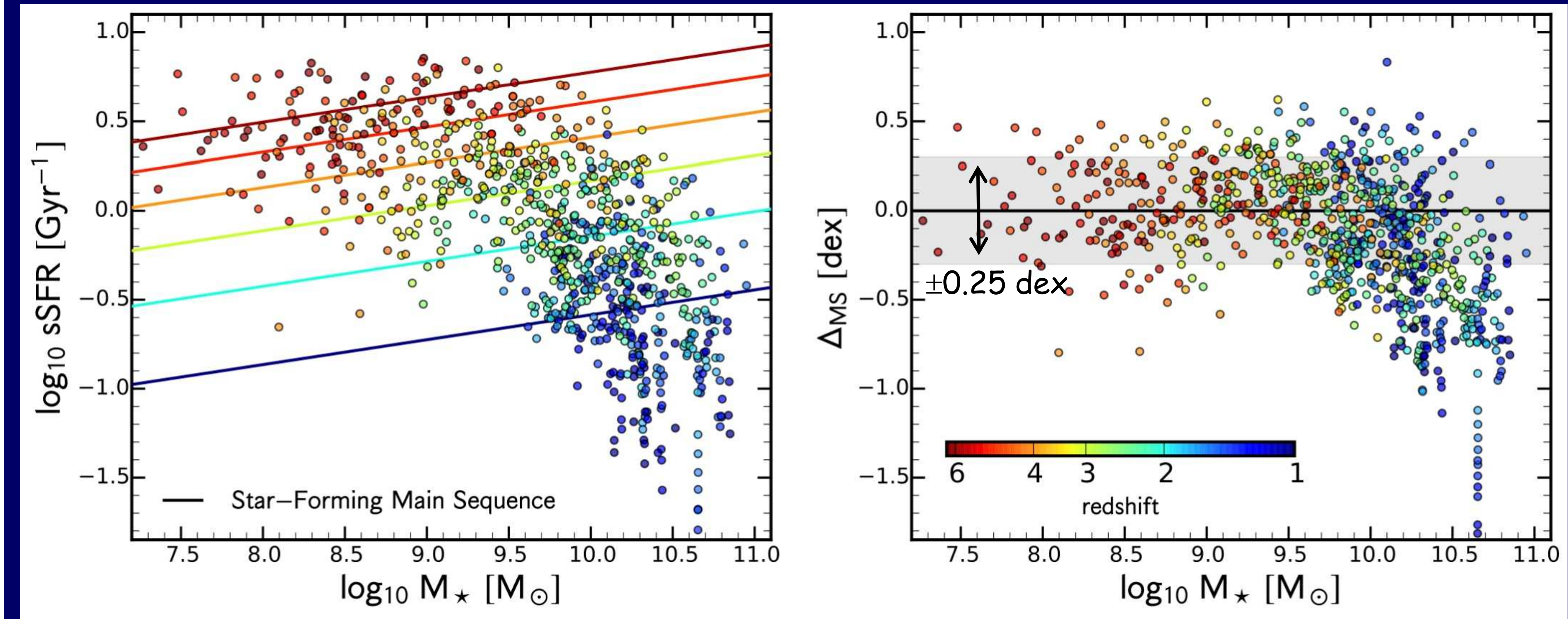
$$< sSFR > \approx < \frac{\dot{M}_{\rm in}}{M} > \approx 0.04\,{\rm Gyr}^{-1}(1+z)^{5/2}$$

$M_{\rm star}$

The Universal Main Sequence of SFGs

MS ridge $$sSFR_{MS} \approx 1.5\, Gyr^{-1}\, M_{*10}^{0.14}\, (1+z)_{z=3}^{5/2}$$

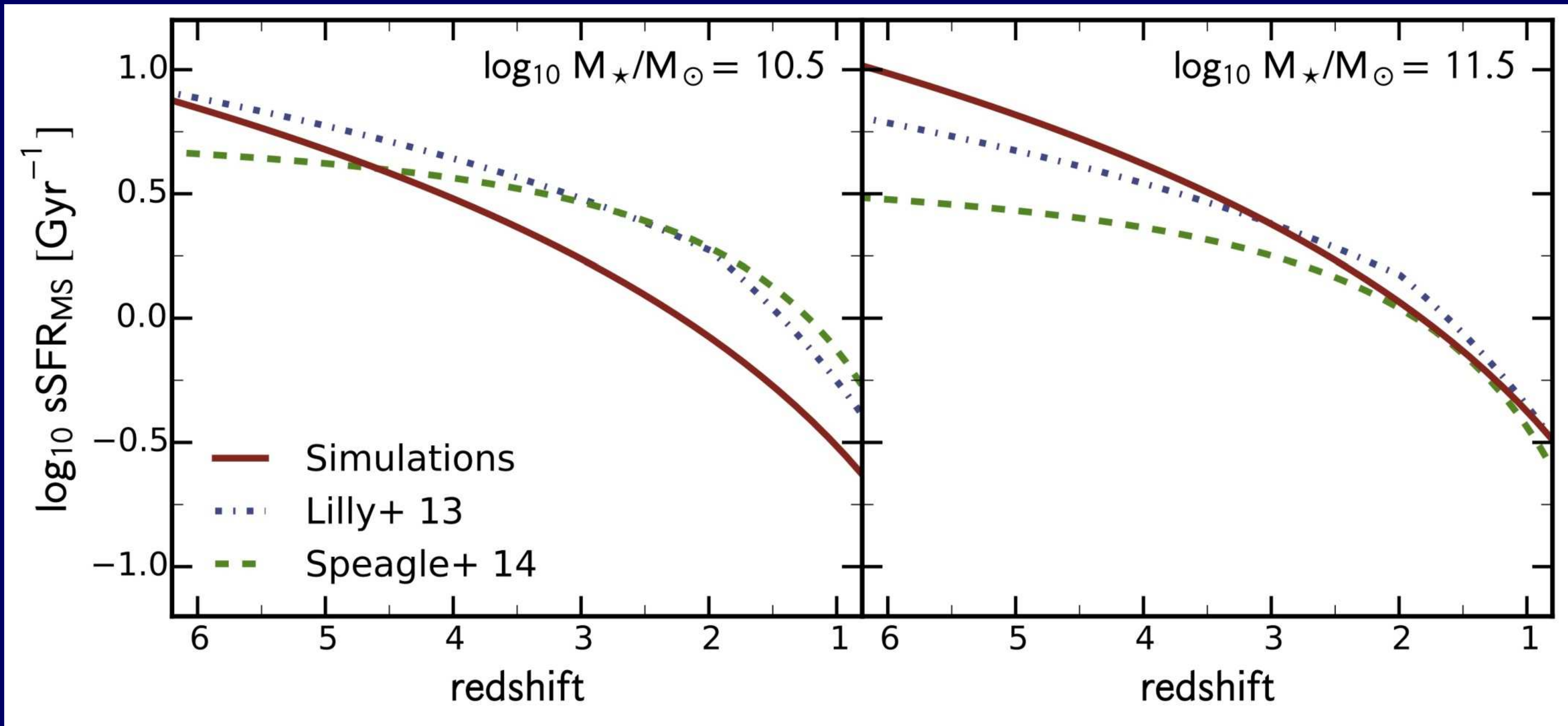
Deviation from MS ridge $$\Delta_{\mathrm{MS}} = \log\left(sSFR / sSFR_{\mathrm{MS}}\right)$$



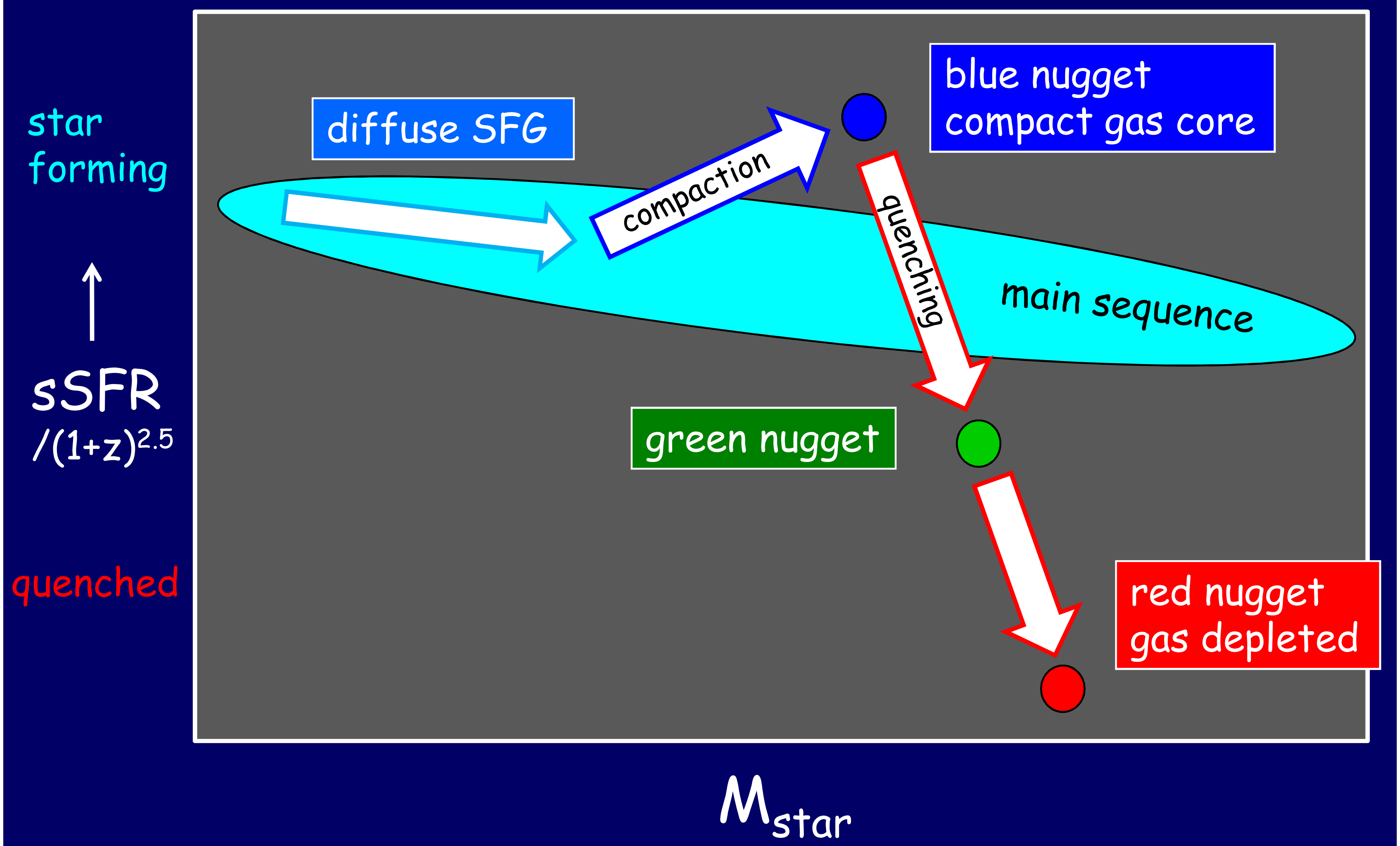
Tacchella+ 2015c

sSFR in Simulations vs Observations

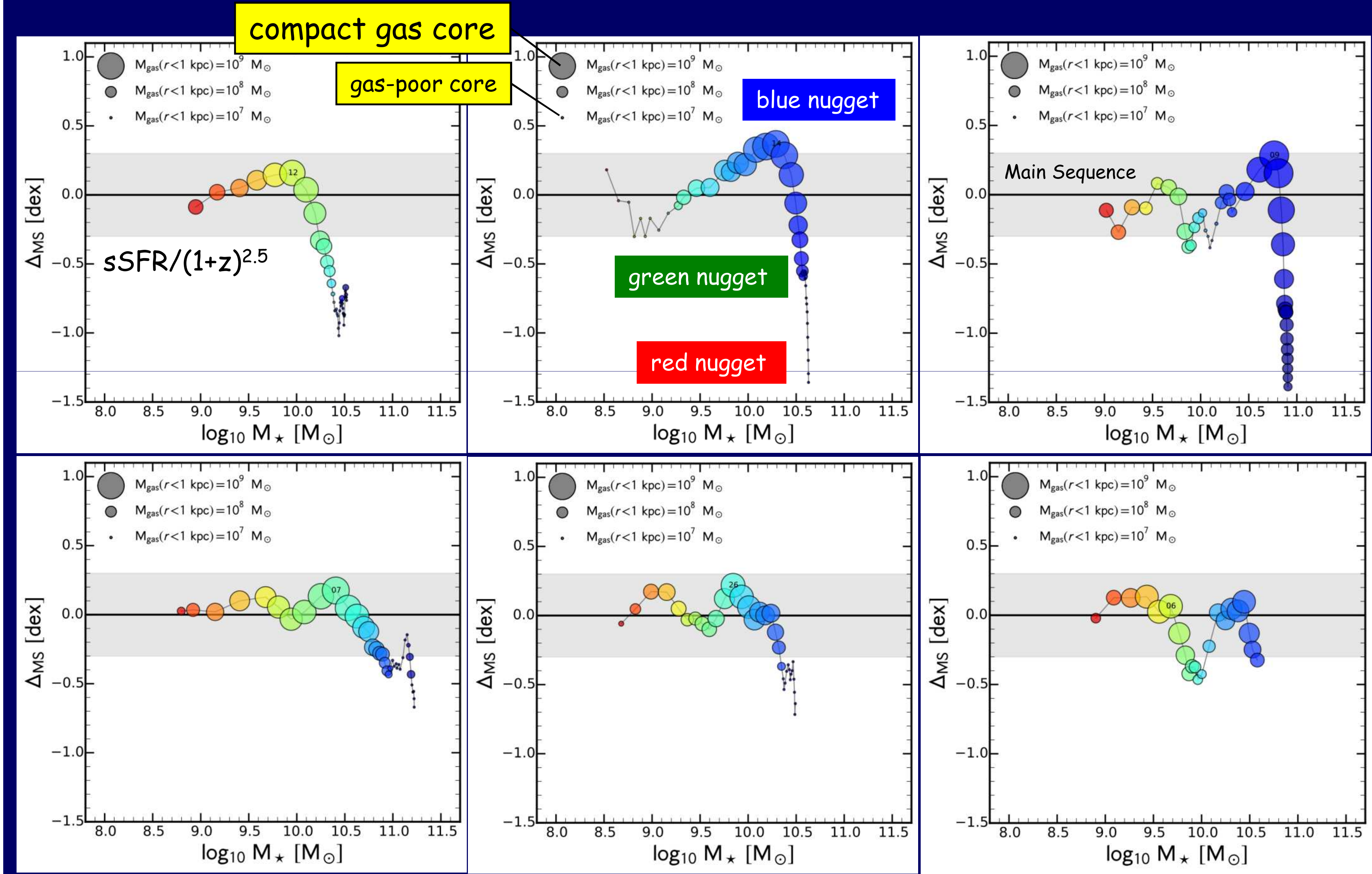
Robust: hard to match the high observed sSFR at z~2



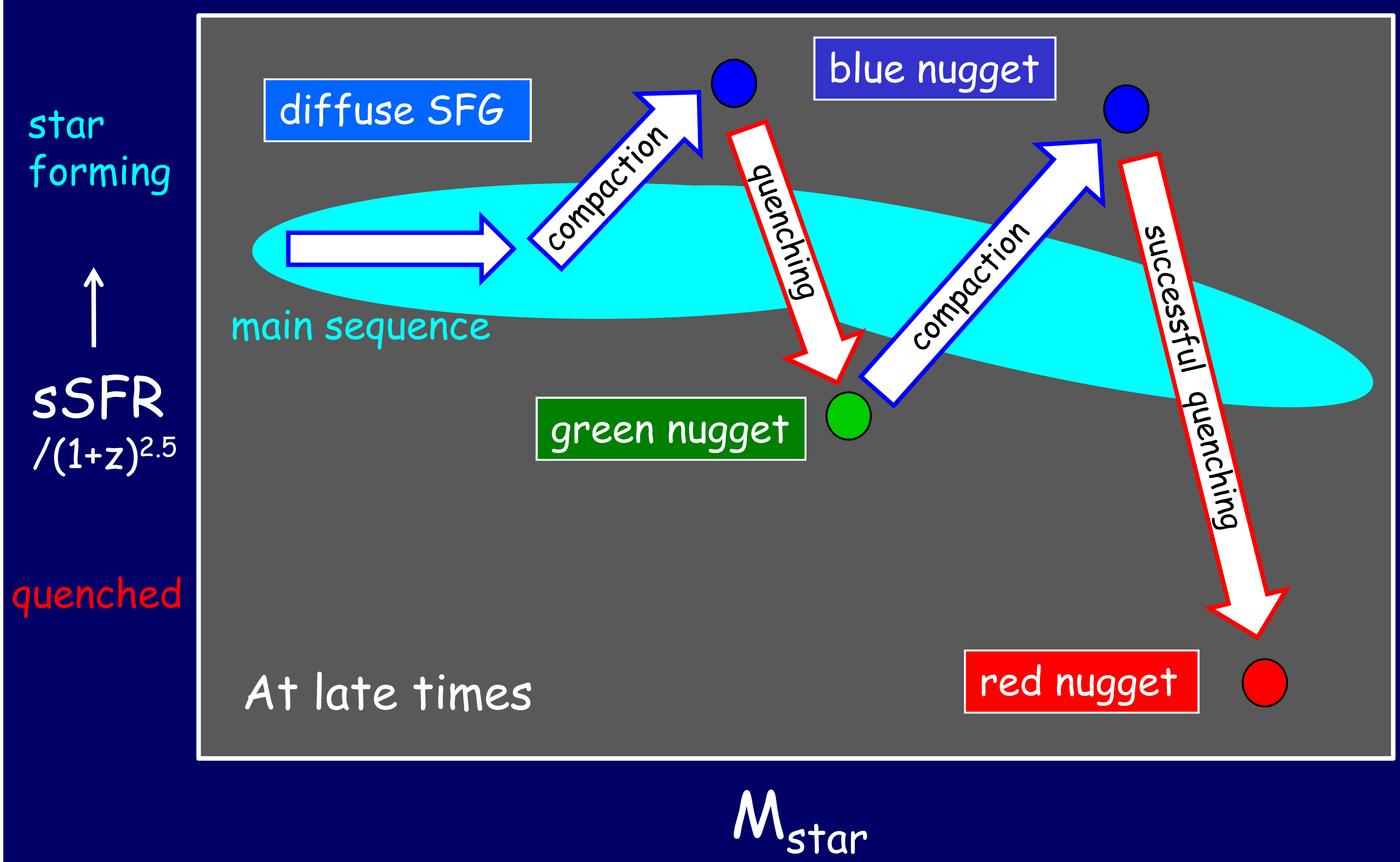
Evolution About the Main Sequence



Blue Nuggets: Tip of the Main Sequence



Confinement of the Main Sequence



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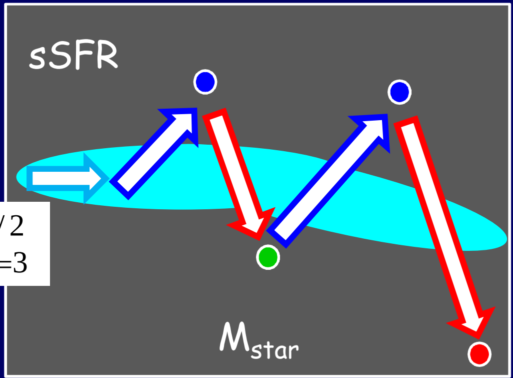


- MS ridge (cosmic accretion) $sSFR_{MS} \approx 1.5\,Gyr^{-1}\,(1+z)^{5/2}_{z=3}$

- sSFR up: wet compaction to BN **inflow > SFR**

$t_{compact} \approx 0.3\,t_{hubble} \approx 0.7\,Gyr\,(1+z)^{-3/2}_{z=3}$

in simulations ~ halo crossing (mergers)
~ VDI-driven inflow

- Upper bound: at BN onset of quenching **inflow < SFR+outflow**

- Lower bound: new compaction at GN
need disk replenishment and a new trigger

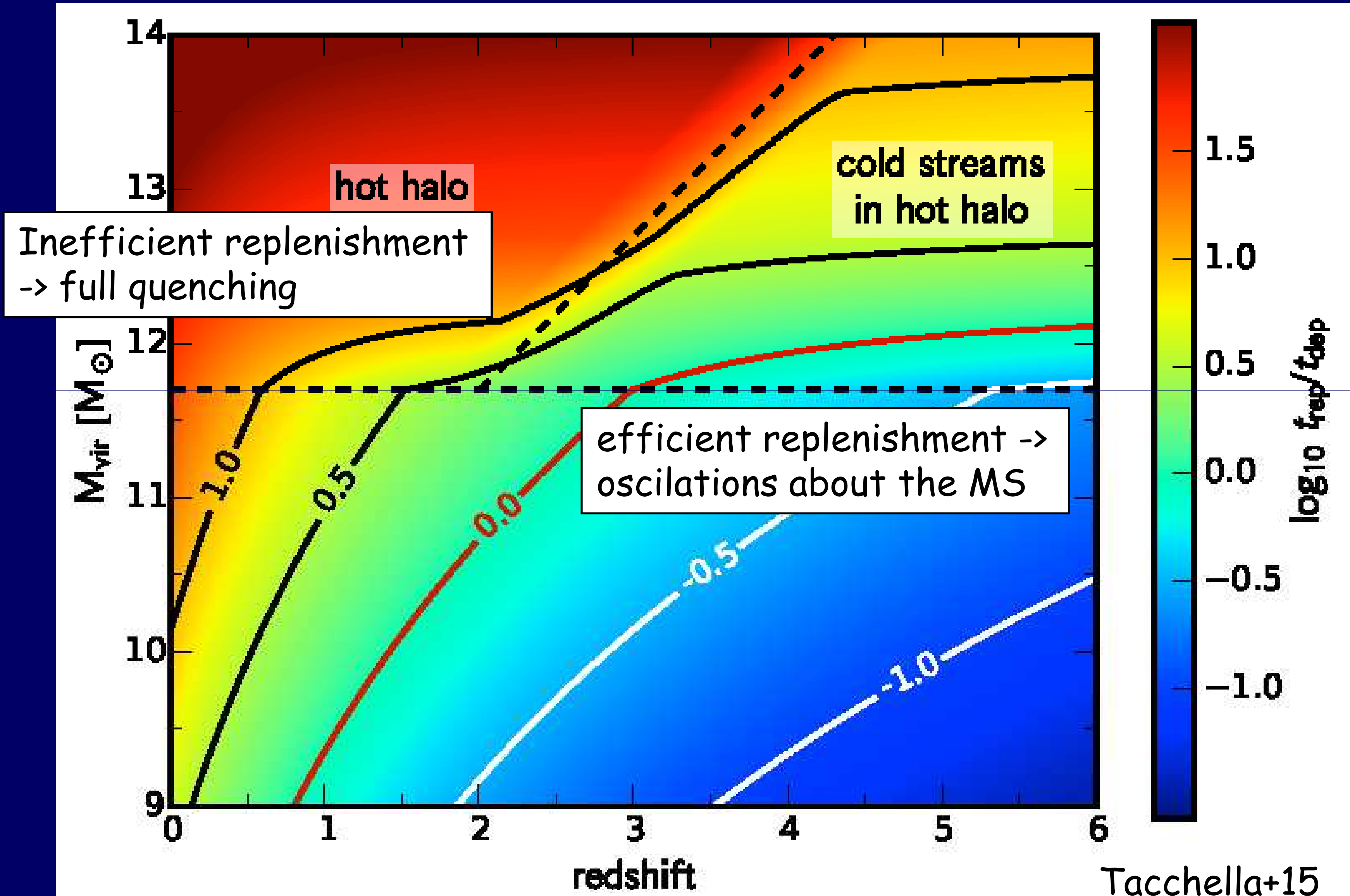
$t_{replenish} < t_{depletion}$

$t_{replenish} \approx 0.7\,Gyr\,(1+z)^{-5/2}_{z=3}$ $t_{depletion} \approx 0.7\,Gyr$ $\propto M^{-1/3}$

new compaction at z>3 , preferentially for lower M (halo)

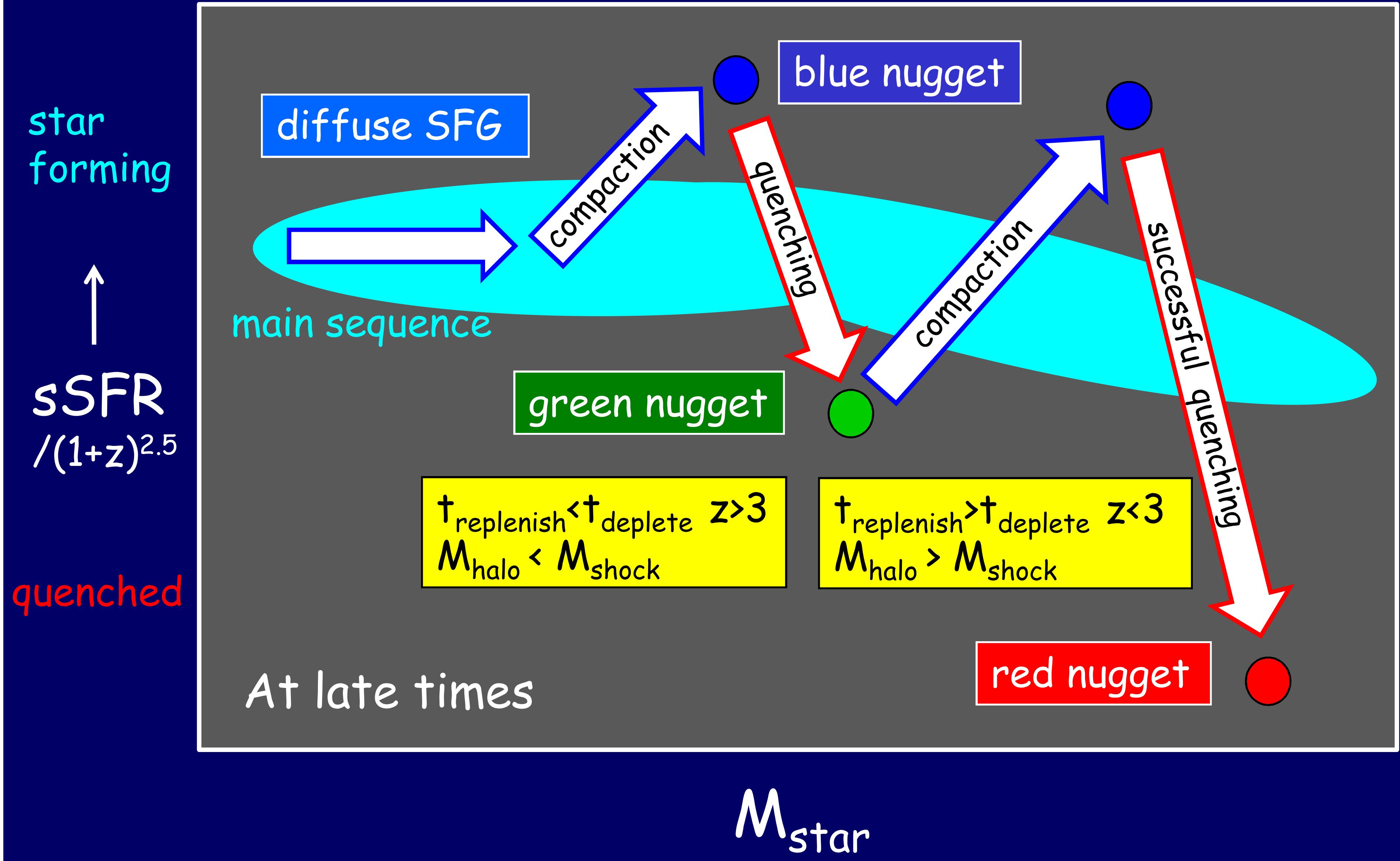
- Quenching to RS (+bending down of MS): full quenching if $t_{rep} > t_{dep}$
-> Preferentially at z<3
downsizing: earlier for massive galaxies (t_{rep} large by M_{halo} & t_{dep} small)

Full Quenching vs Quenching Attempt



Tacchella+15

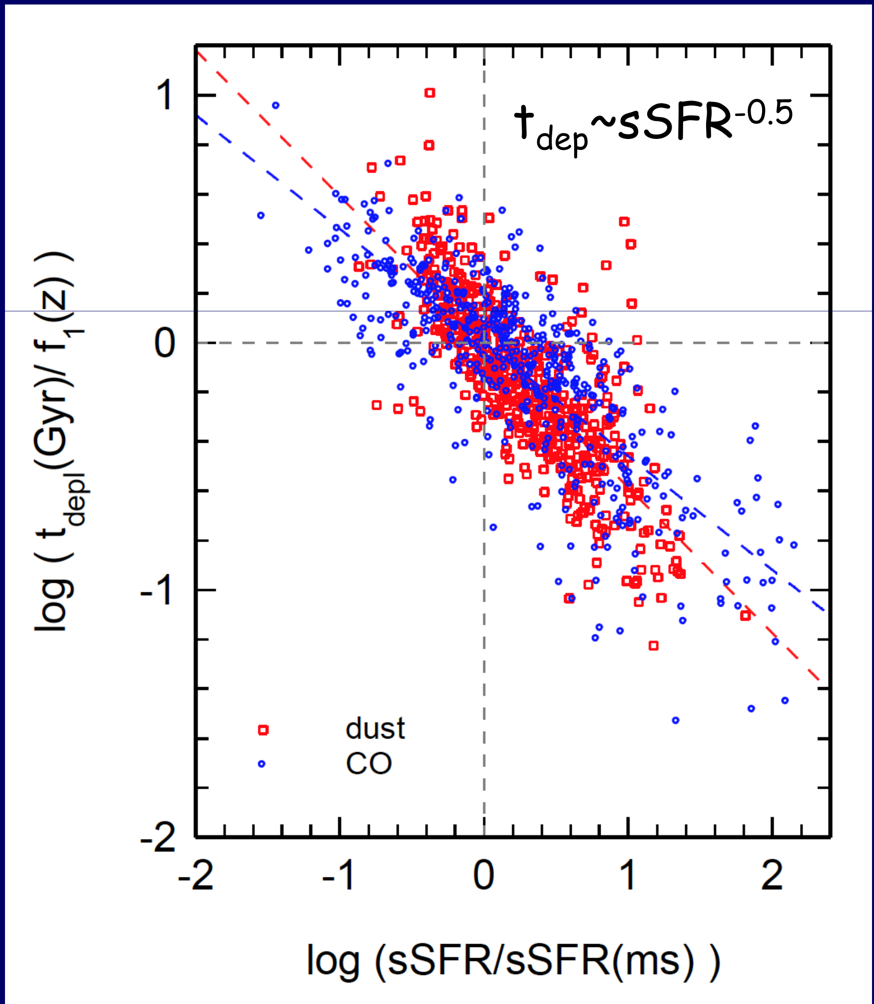
Confinement of the Main Sequence



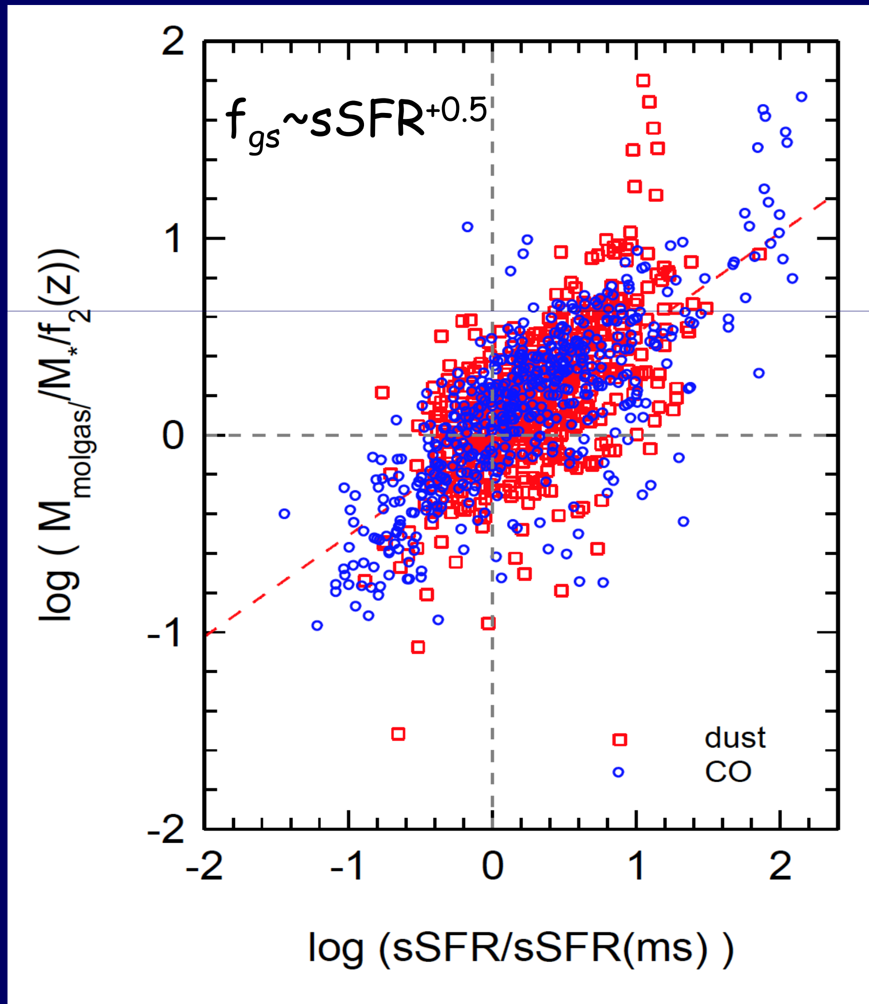
Observed Gradients across the MS

Genzel, Tacconi+ 2015 z=0-2.5

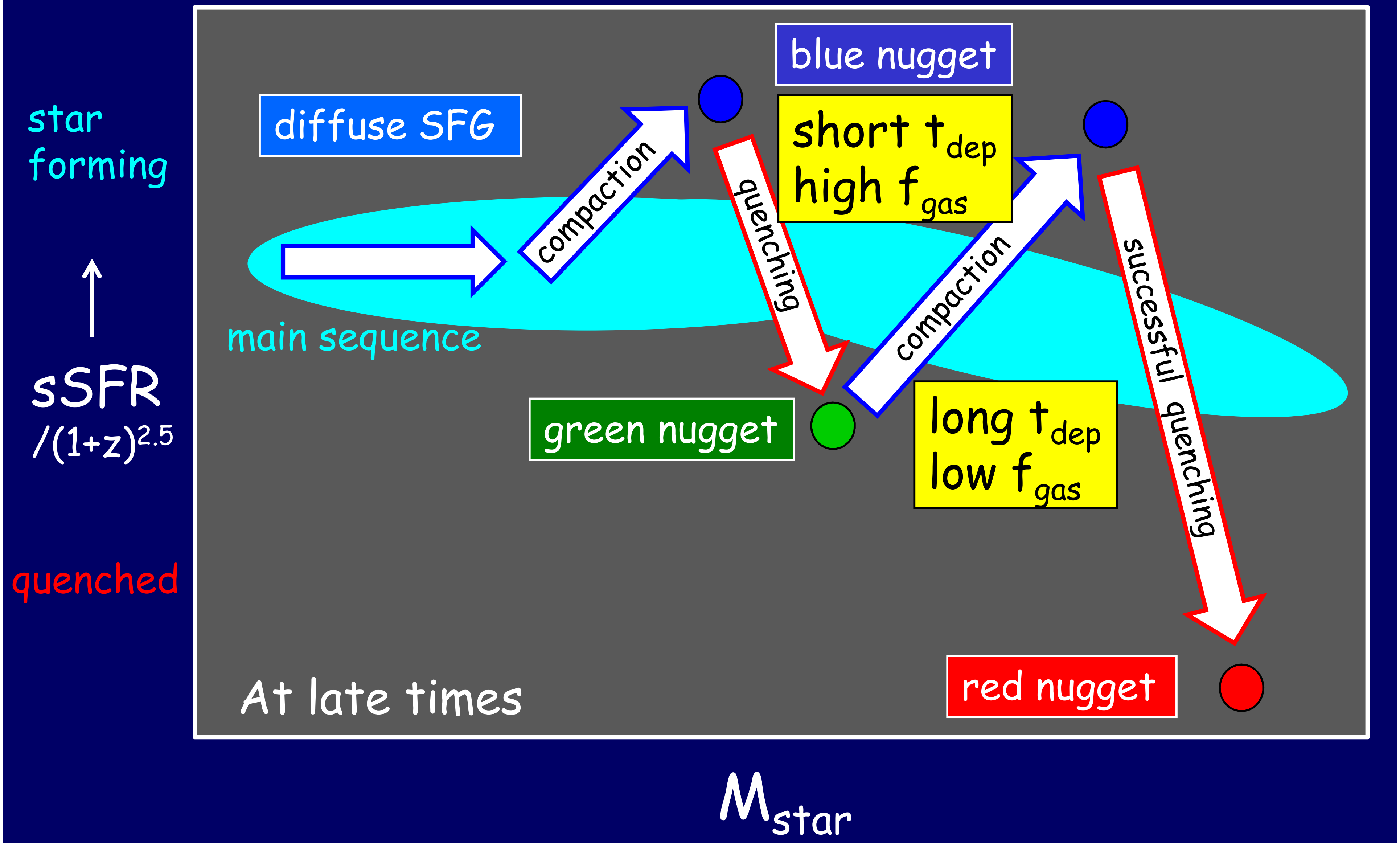
$t_{dep}=M_{gas}/SFR$



$f_{gs}=M_{gas}/M_{stars}$



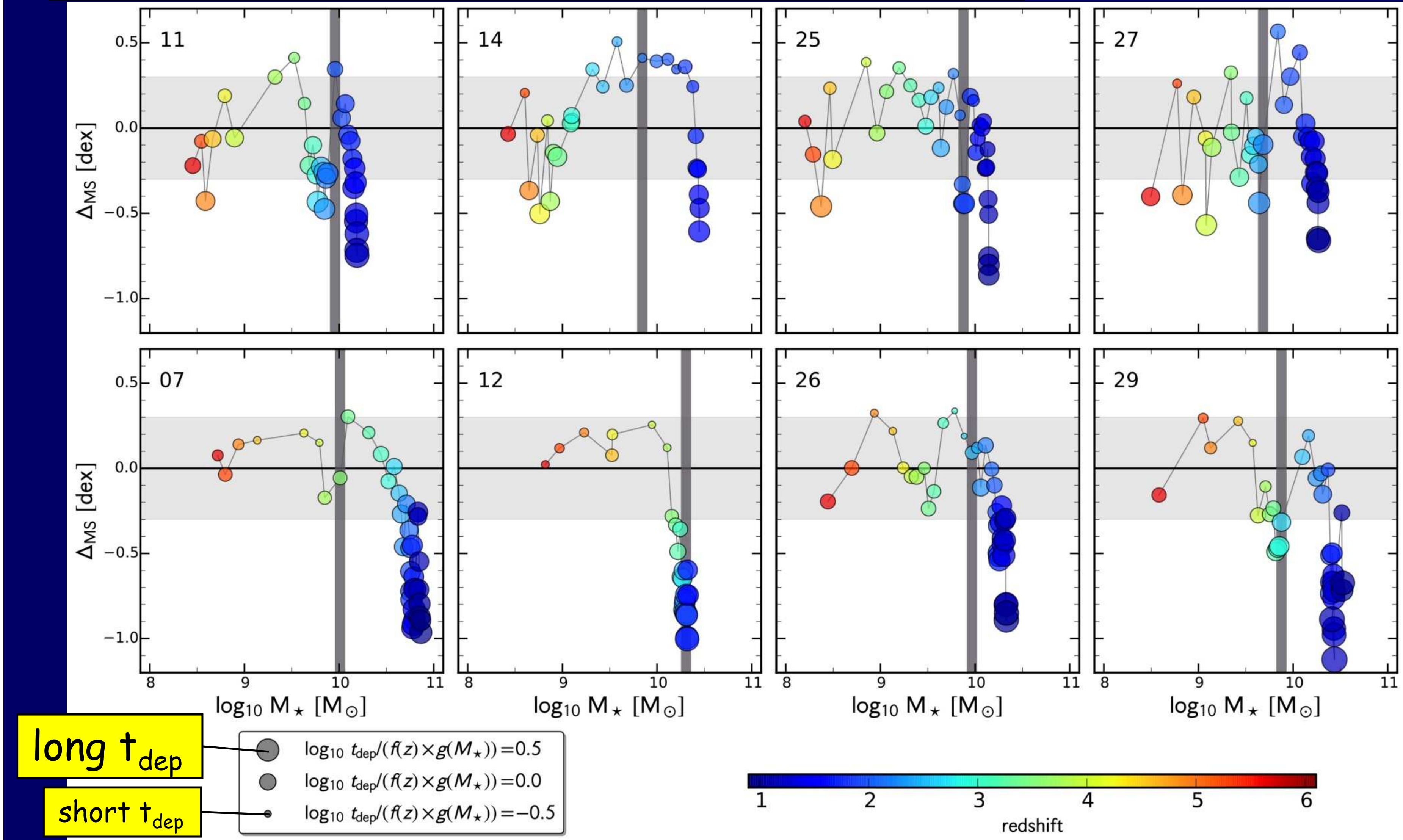
Gradients across the Main Sequence



Depletion Time

= gas mass/SFR

BN at top of MS: minimum depletion time

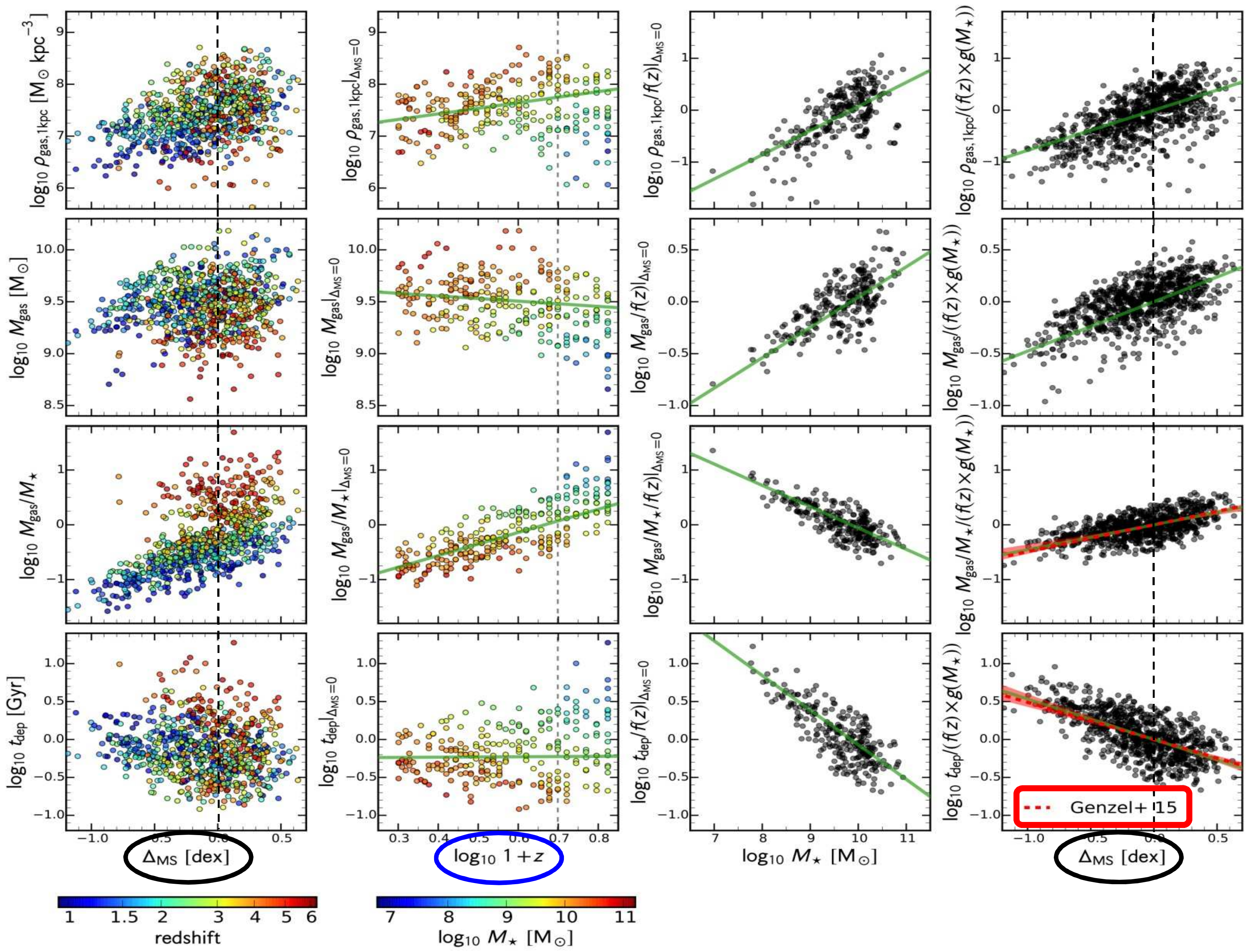


Gradients across the Main Sequence

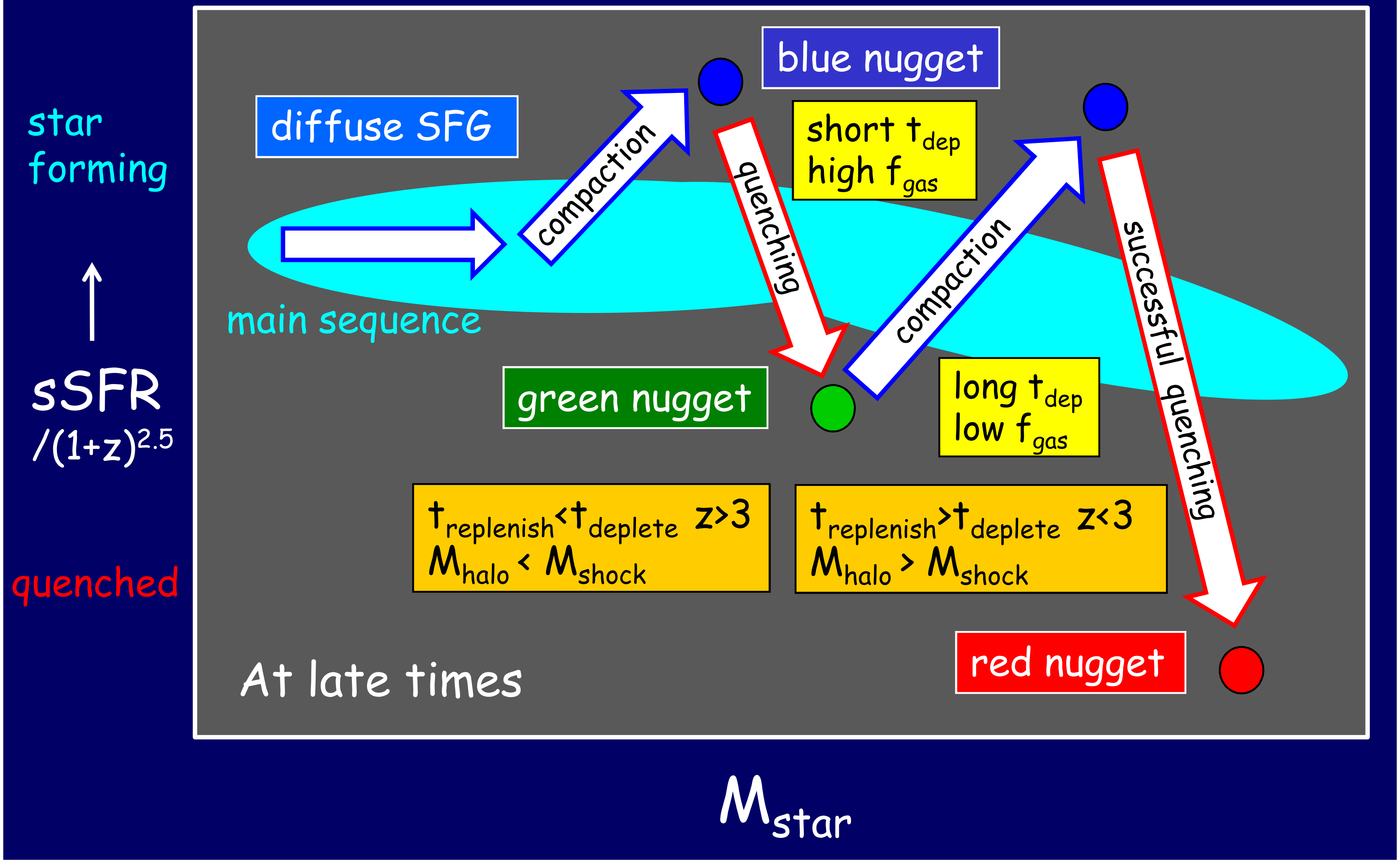
core gas density

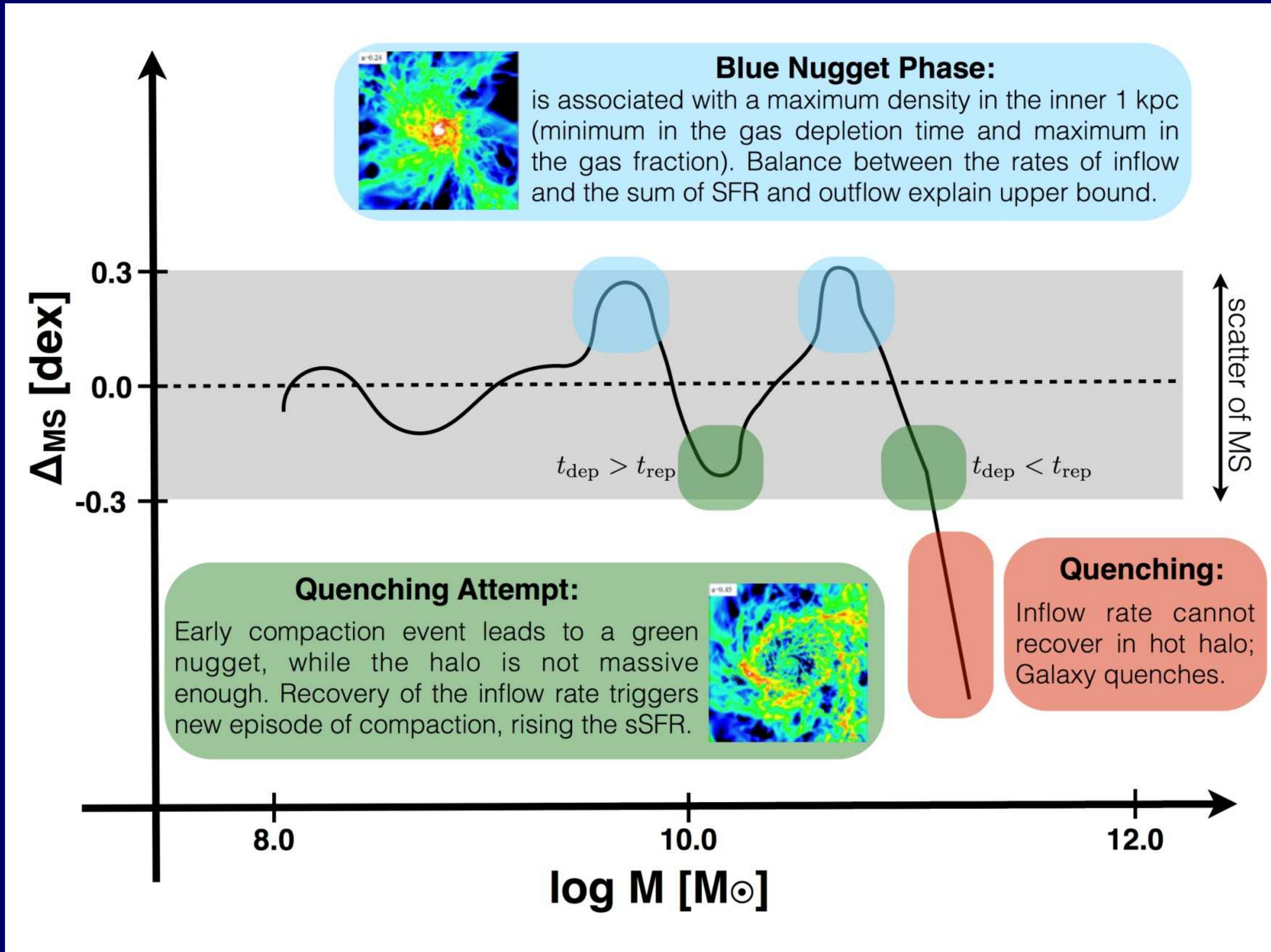
gas fraction

depletion time



Summary: Evolution in the Main Sequence




Blue Nugget Phase:
is associated with a maximum density in the inner 1 kpc (minimum in the gas depletion time and maximum in the gas fraction). Balance between the rates of inflow and the sum of SFR and outflow explain upper bound.
0.3
0.0
-0.3
Δ_{MS} [dex]
$t_{\rm dep} > t_{\rm rep}$
$t_{\rm dep} < t_{\rm rep}$
scatter of MS
Quenching Attempt:
Early compaction event leads to a green nugget, while the halo is not massive enough. Recovery of the inflow rate triggers new episode of compaction, rising the sSFR.
Quenching:
Inflow rate cannot recover in hot halo; Galaxy quenches.
8.0
10.0
12.0
log M [M⊙]

Elongated Galaxies

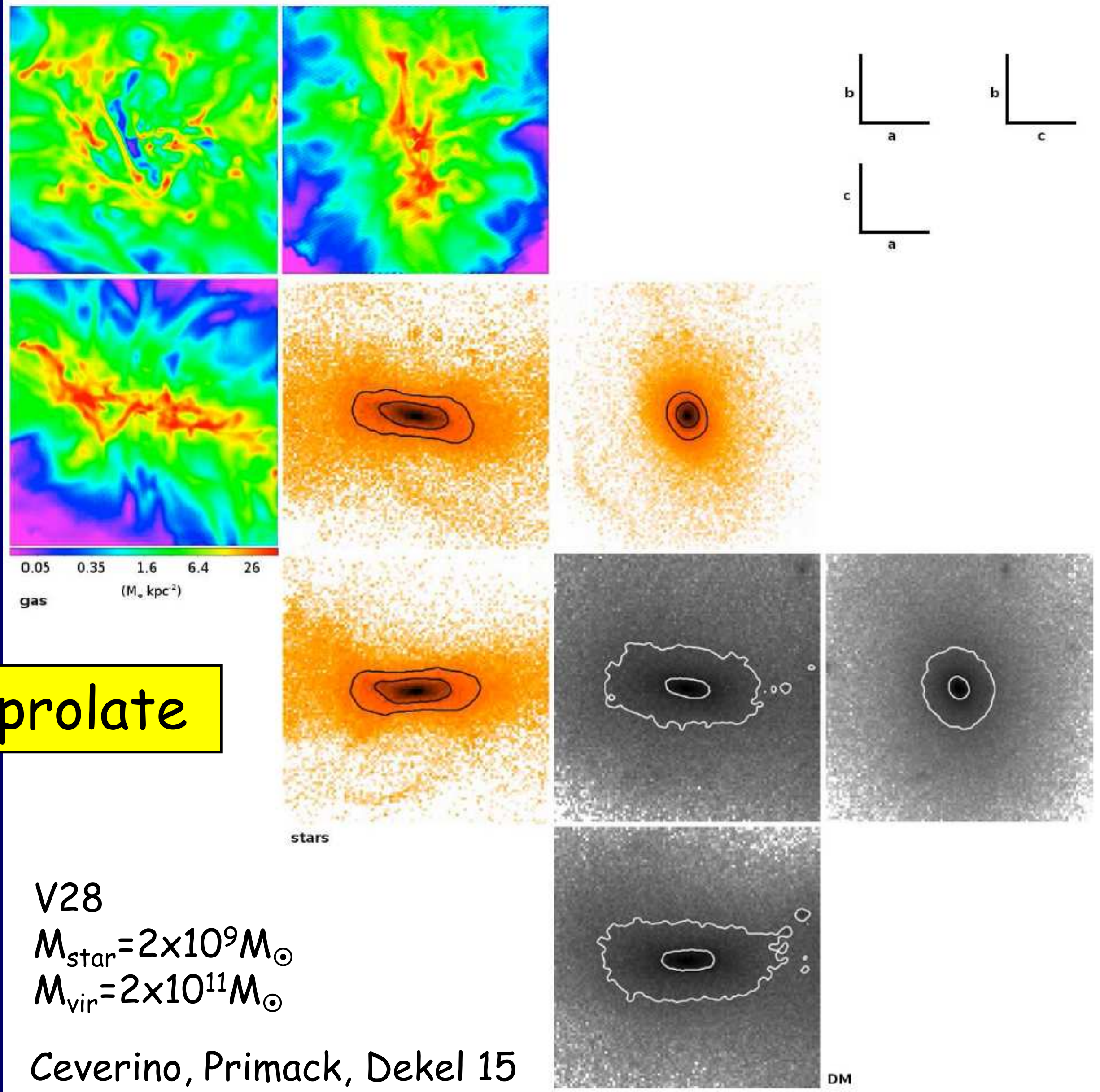
Ceverino+ 2015, Tomassetti+ 2015

A Prolate Low-Mass Galaxy at z=2.2

Gas: disk

Stars and DM: prolate

Consistent with van der Wel+ 14 CANDELS

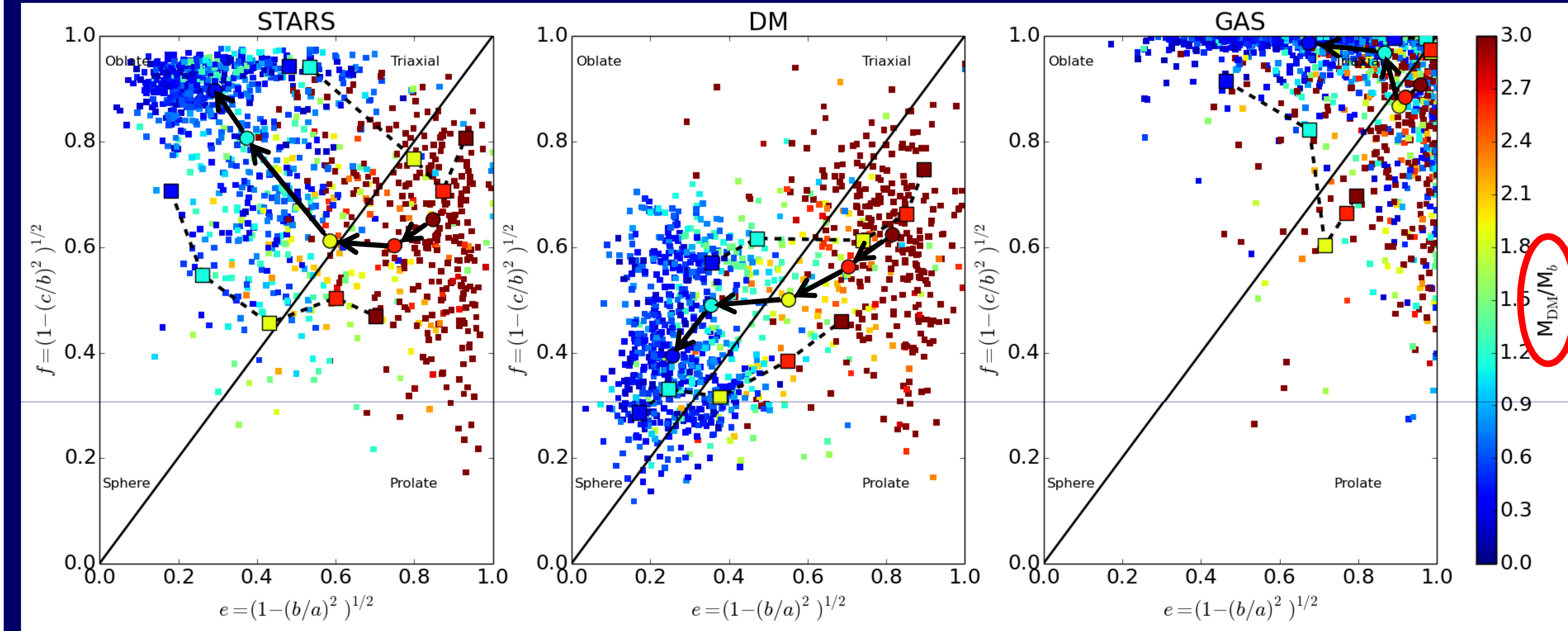


V28
$M_{star}=2\times10^9 M_\odot$
$M_{vir}=2\times10^{11} M_\odot$

Ceverino, Primack, Dekel 15

Evolution of Shape

Tomassetti+15



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 --> oblate, rotation-dominated

Gas: triaxial --> disk

Conclusion: a generic sequence of events

High-z massive galaxies fed by cosmic-web streams + mergers
-> gas-rich, dense disks - violent disk instability (VDI)

Wet compaction to Blue Nuggets: by streams + mergers + VDI (in low-spin galaxies) -> compact gas disks, high SFR, flattened stellar spheroids

Quenching inside-out to Red Nuggets: SFR(+AGN) + outflows > inflow -> central gas depletion. Then SFR in gas rings & stellar envelopes (ETGs)

Repeated compactions in low-mass halos at high z, when inflow resumes
Long-term quenching in hot massive halo at low z, when $t_{replenish}>t_{depletion}$

Quenching downsizing: massive galaxies quench earlier, efficiently, at higher densities. Low-mass galaxies oscillate till inflow shutdown (halo)

Confinement of the Main Sequence and gradients across it
due to the evolution through episodes of compaction and quenching

Shape evolution from prolate to oblate stellar system at compaction:
transition from DM-dominated to baryon-dominated core , at V~100 km/s