High-z Compaction to "Blue" Nuggets and Quenching to Red Nuggets

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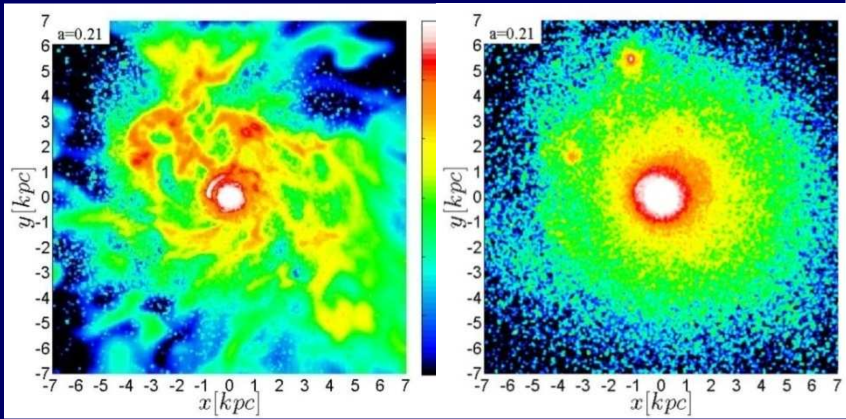
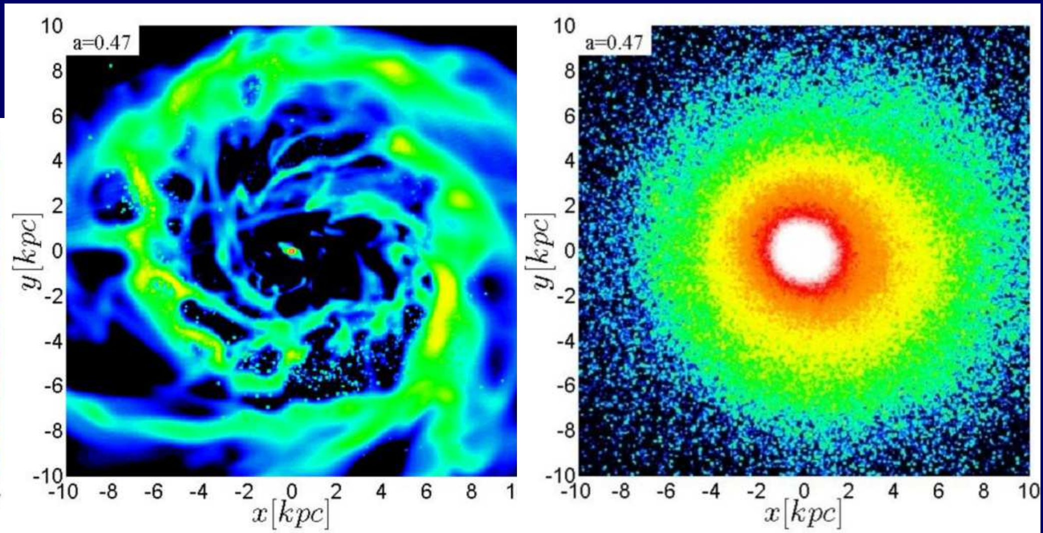
Barro+ 2013-14; Dekel & Burkert 2014; Zolotov+ 2014

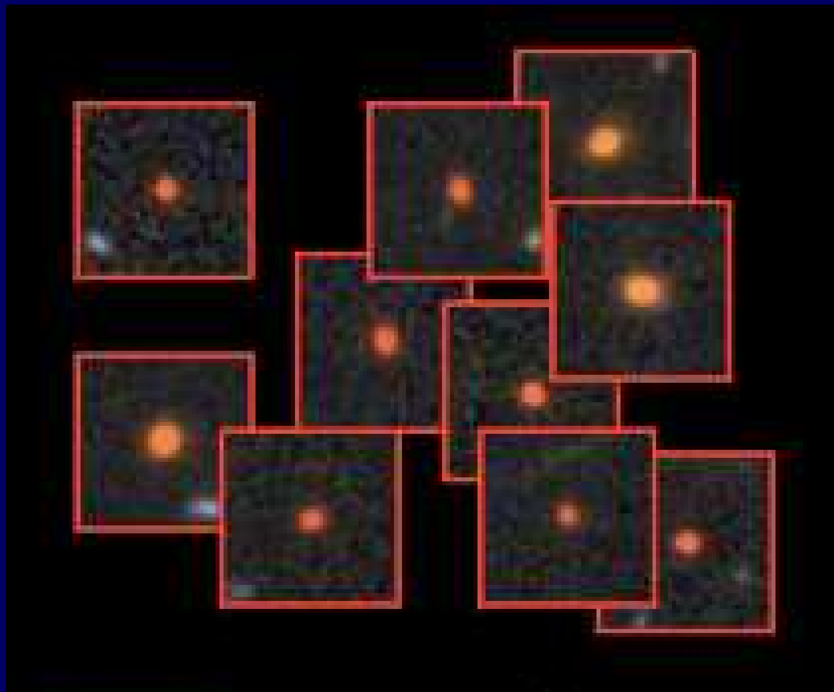
"Blue" Nugget



Red Nugget



Red Nuggets



$z \sim 2$ $M \sim 10^{11} M_\odot$ $R_e \sim 1$ kpc low-SFR

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

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

$$\varepsilon_{\text{sfr}} \leq 0.02 \qquad f_{\text{cold}} \geq 0.2$$

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

Cosmological Simulations

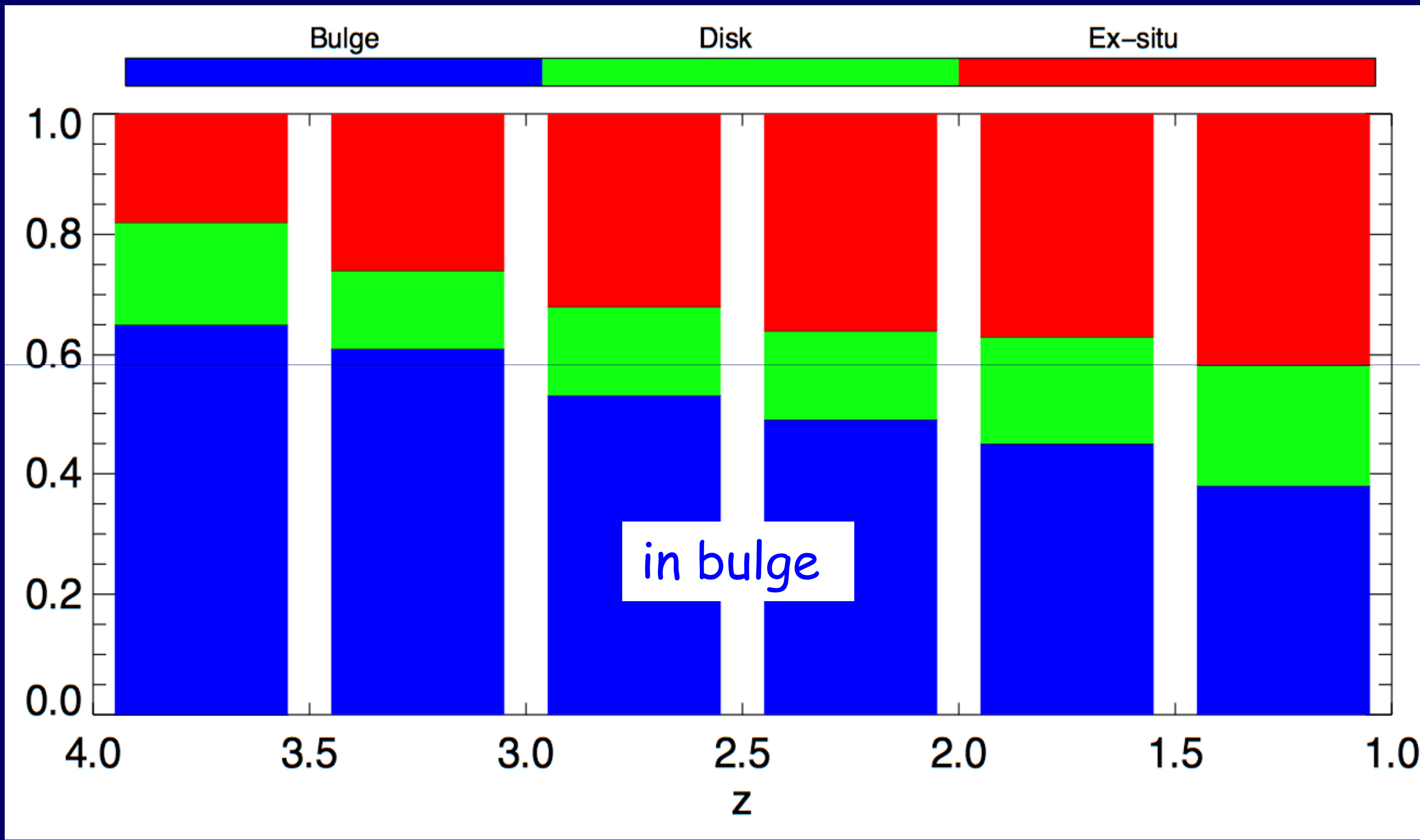
Run by Ceverino
Code: AMR ART (Kravtsov, Klypin)
3x30 galaxies zoom-in
Max resolution 25 pc
SN and radiative feedback

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

Wet Origin of Bulge in Simulations

Zolotov, Dekel, Mandelker, Tweed, DeGraf, Ceverino, Primack 2014

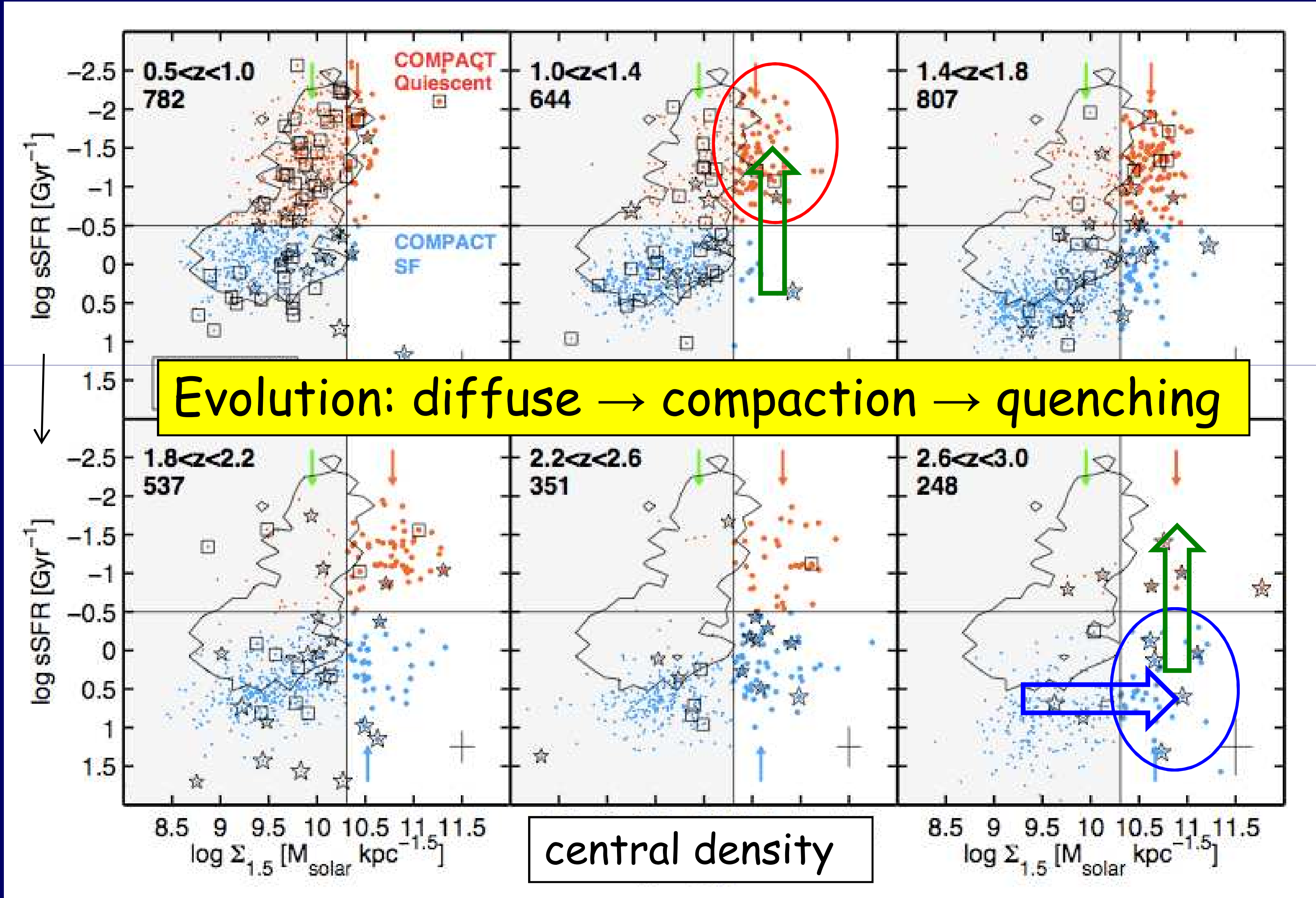
Fraction of bulge stars born in different components

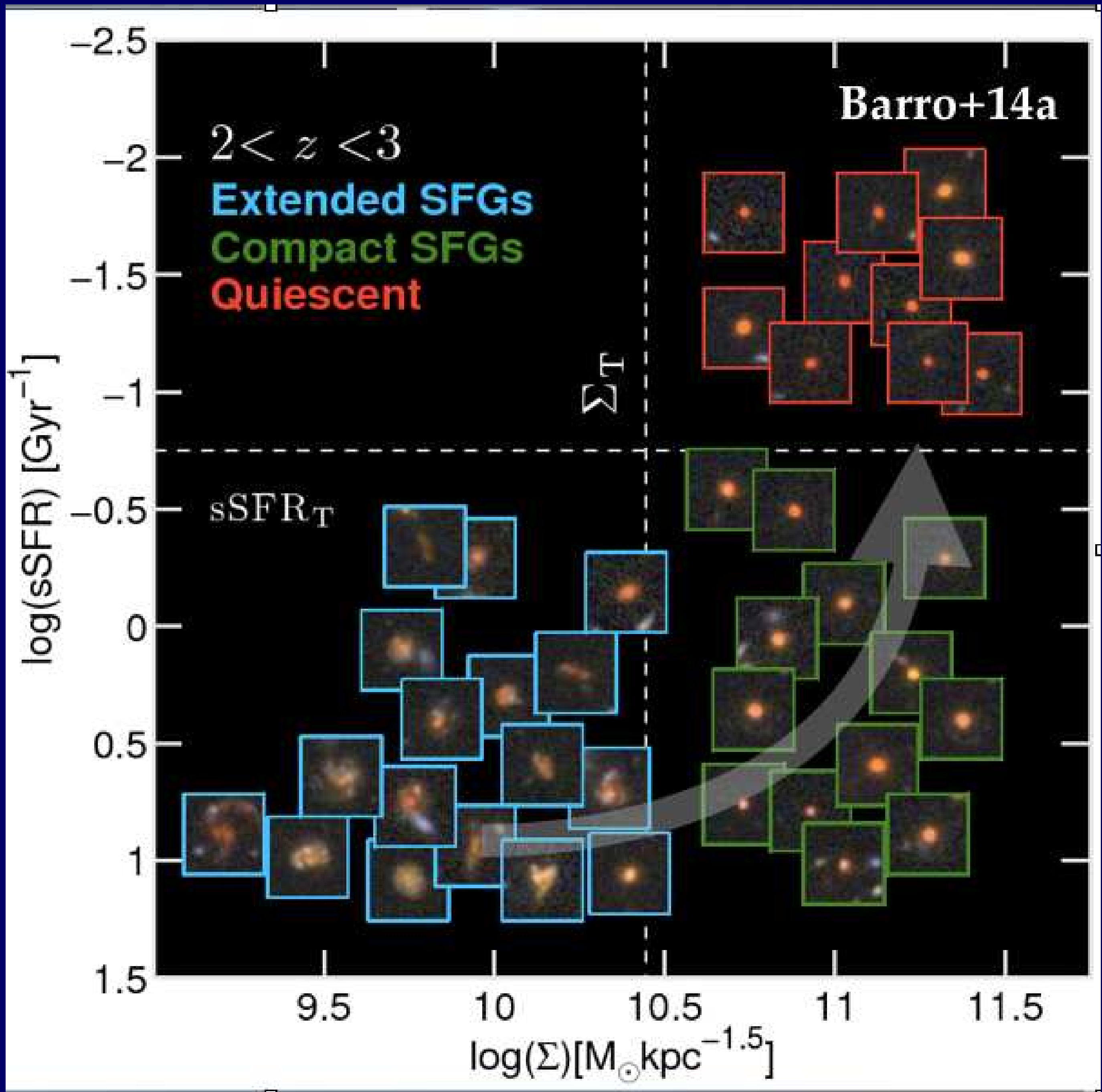


Most of the bulge stars formed in the bulge → wet inflow

Observations: Blue Nuggets -> Red Nuggets

Barro+ 13 CANDELS z=1-3





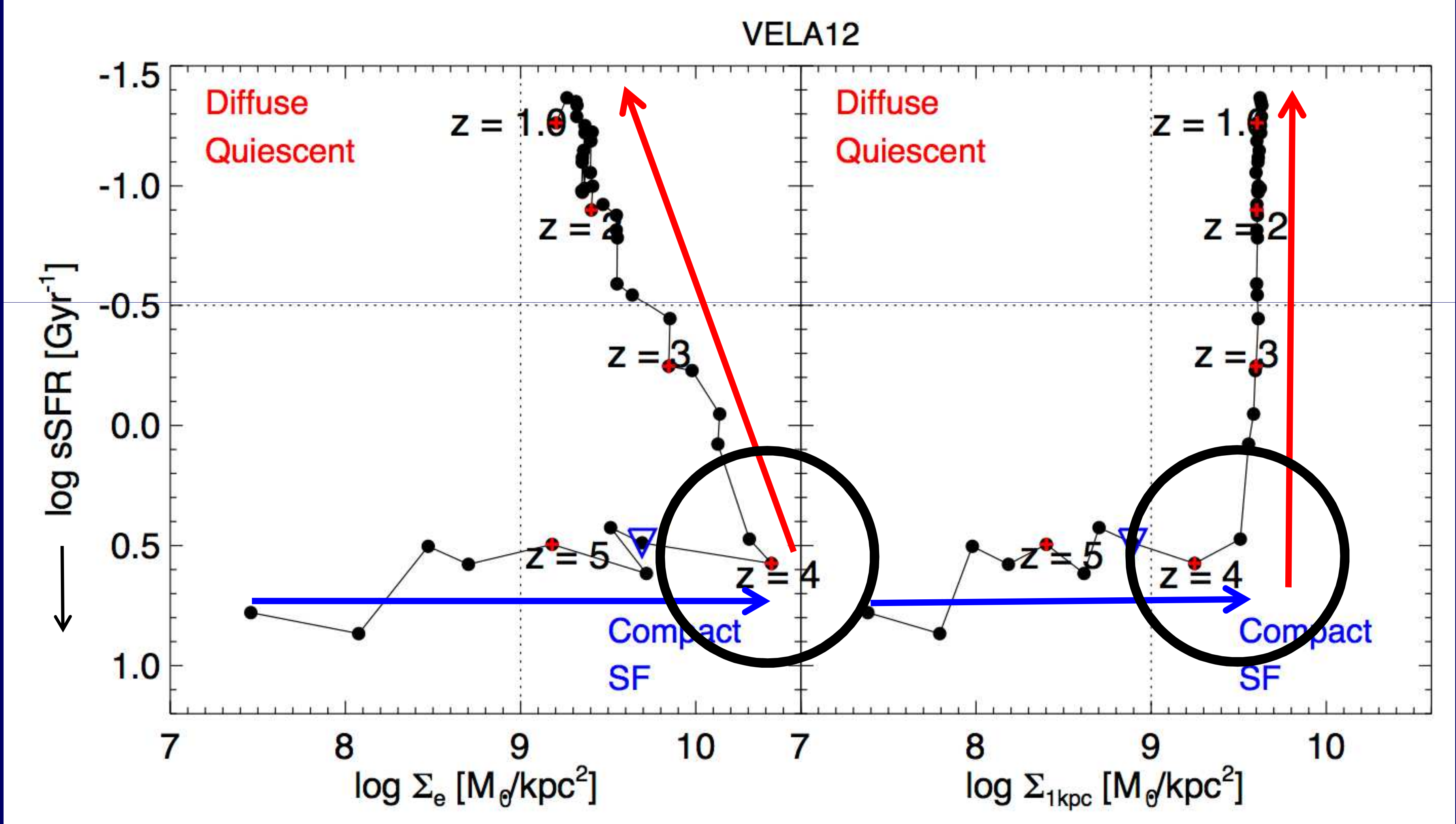
Barro+14a
2< z <3
Extended SFGs
Compact SFGs
Quiescent
sSFR$_T$
Σ_T
log(sSFR) [Gyr^{-1}]
log(Σ)[M$_\odot$kpc$^{-1.5}$]
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
9.5
10
10.5
11
11.5

RN

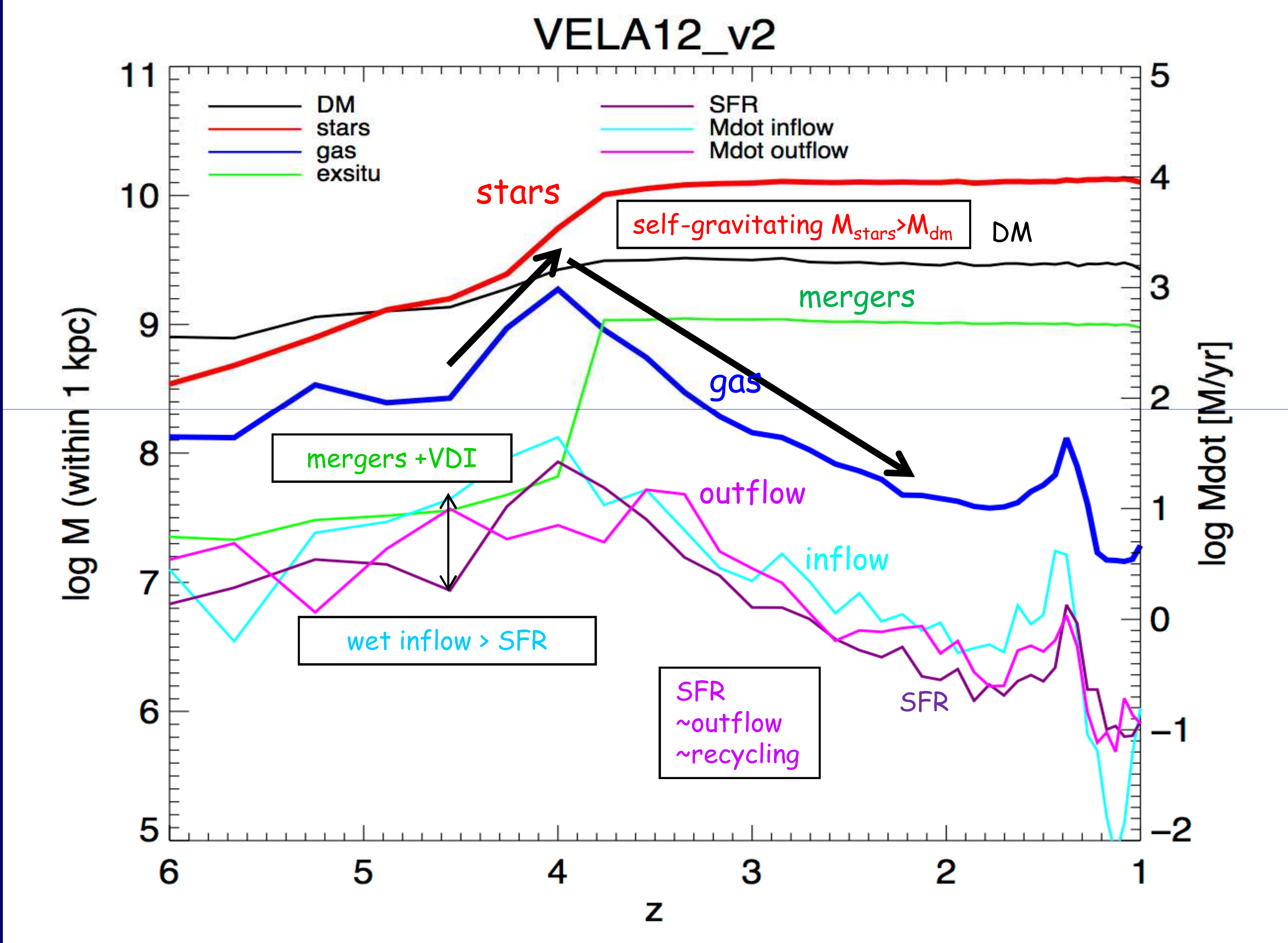
BN

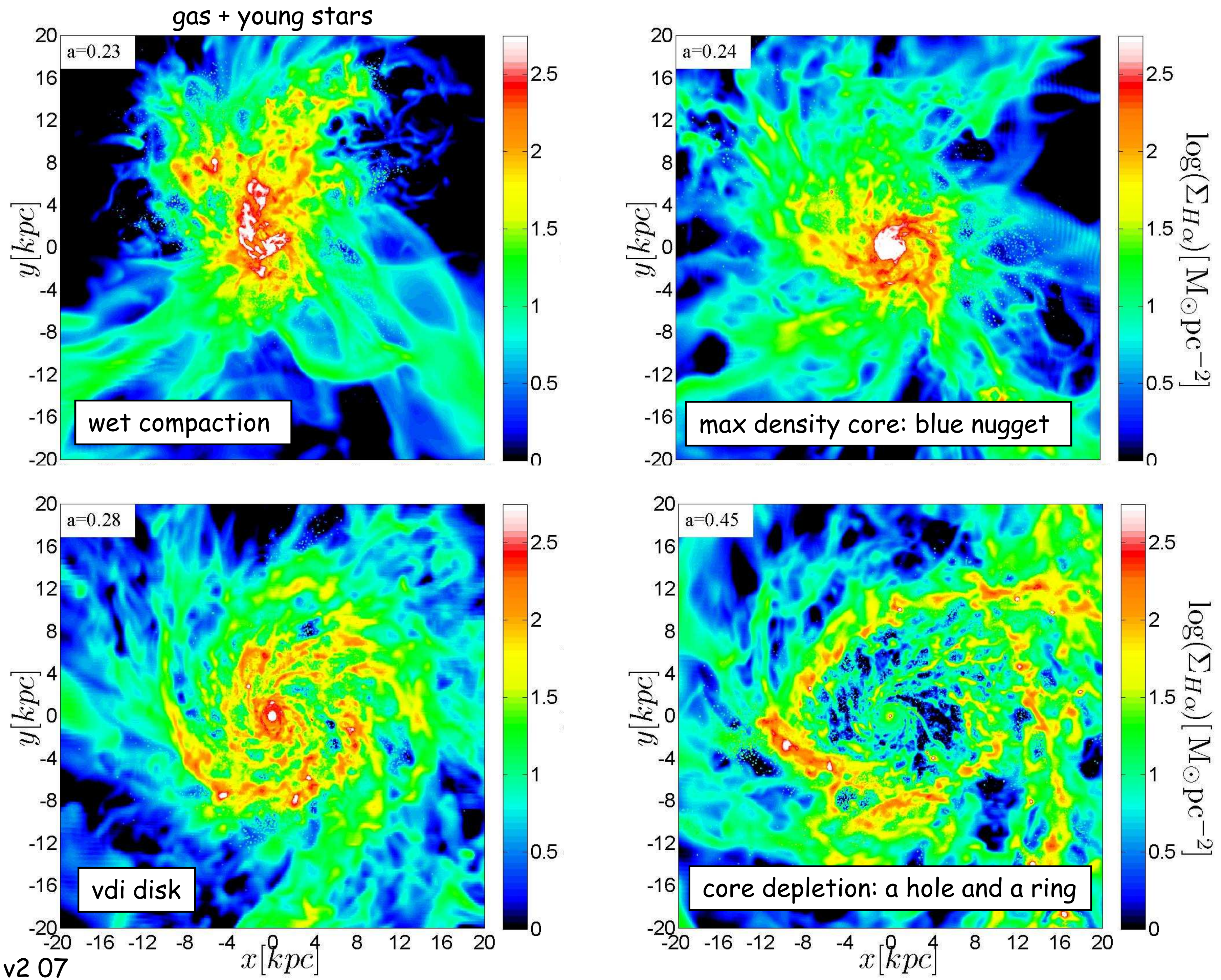
Compaction and quenching

Zolotov+ 14 ART cosmological simulations, res. 25pc, rad fdbk, no AGN



Compaction and quenching

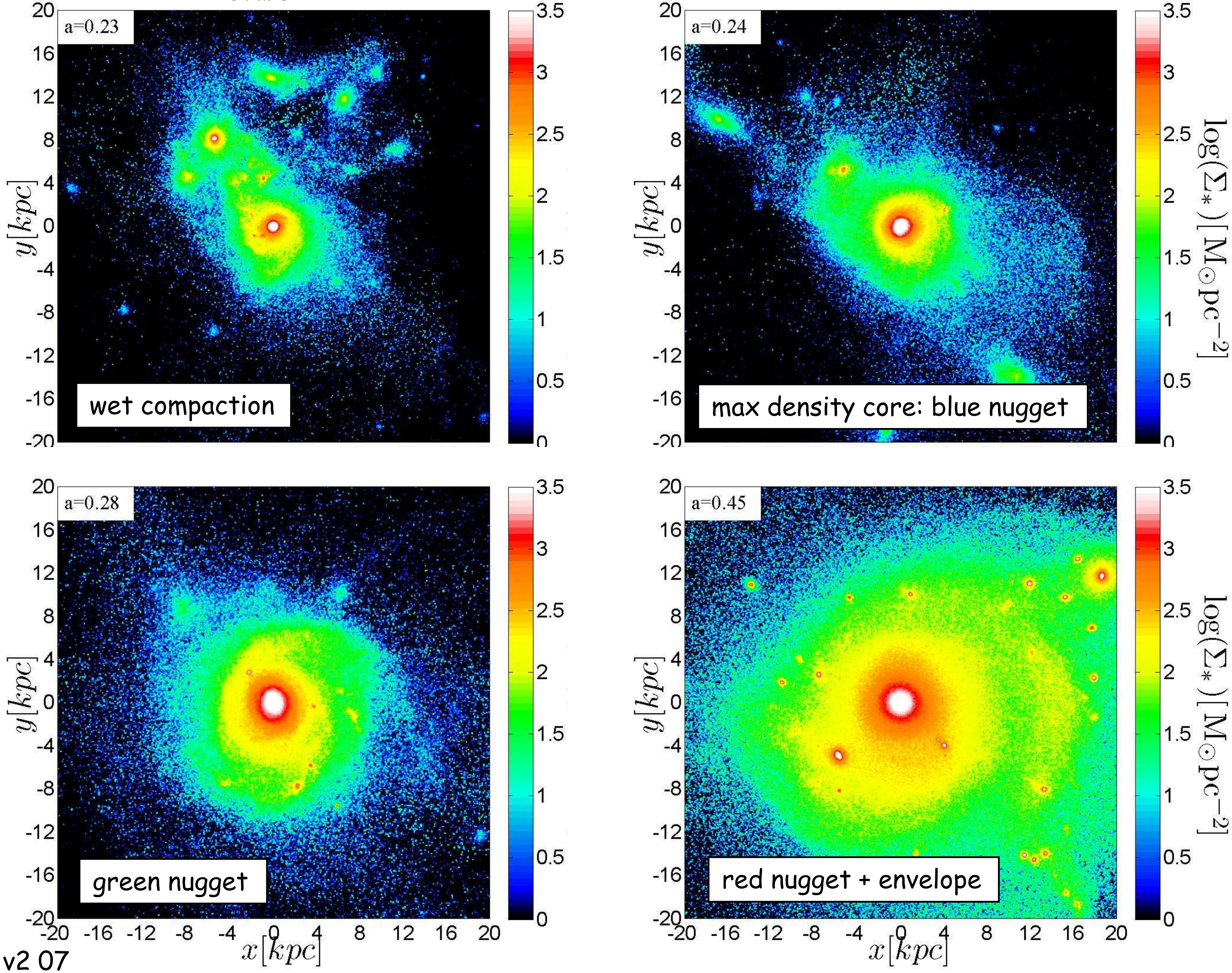




gas + young stars
a=0.23
wet compaction
a=0.24
max density core: blue nugget
a=0.28
vdi disk
a=0.45
core depletion: a hole and a ring
$y[kpc]$
$x[kpc]$
$\log(\Sigma_{H\alpha})[M_\odot pc^{-2}]$

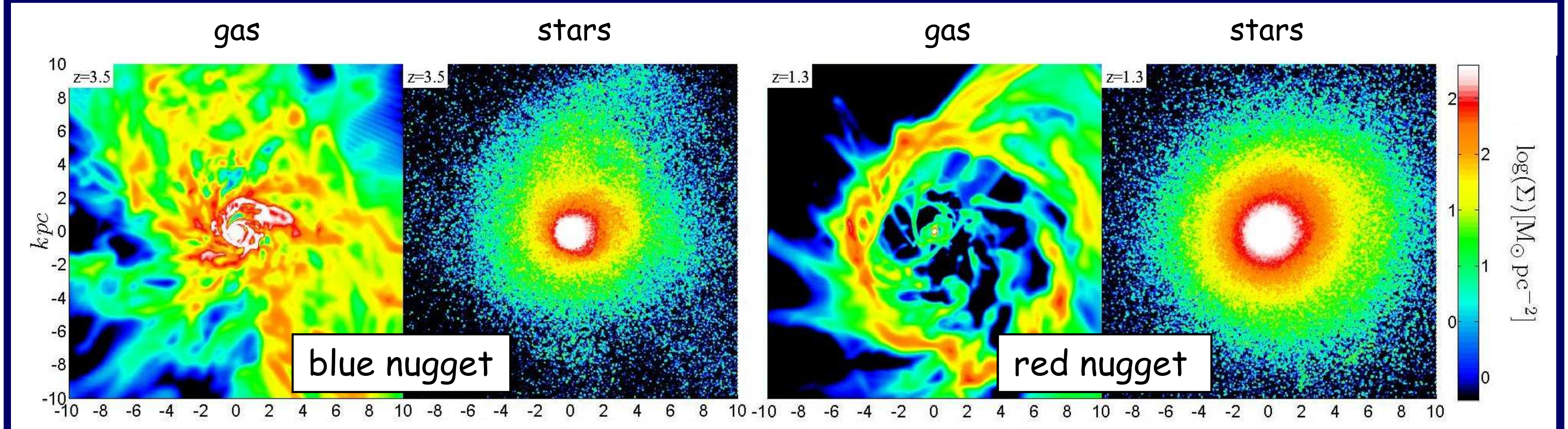
vela v2 07

stars



vela v2 07

Blue Nugget - Red Nugget



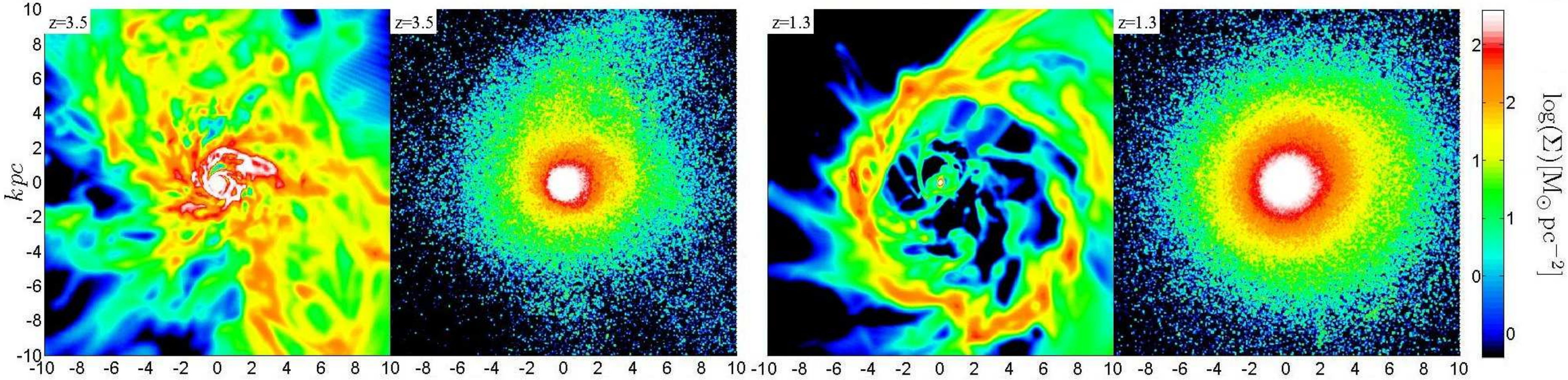
dense gas core -> dense stellar core

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

stellar core remains dense
from BN to RN

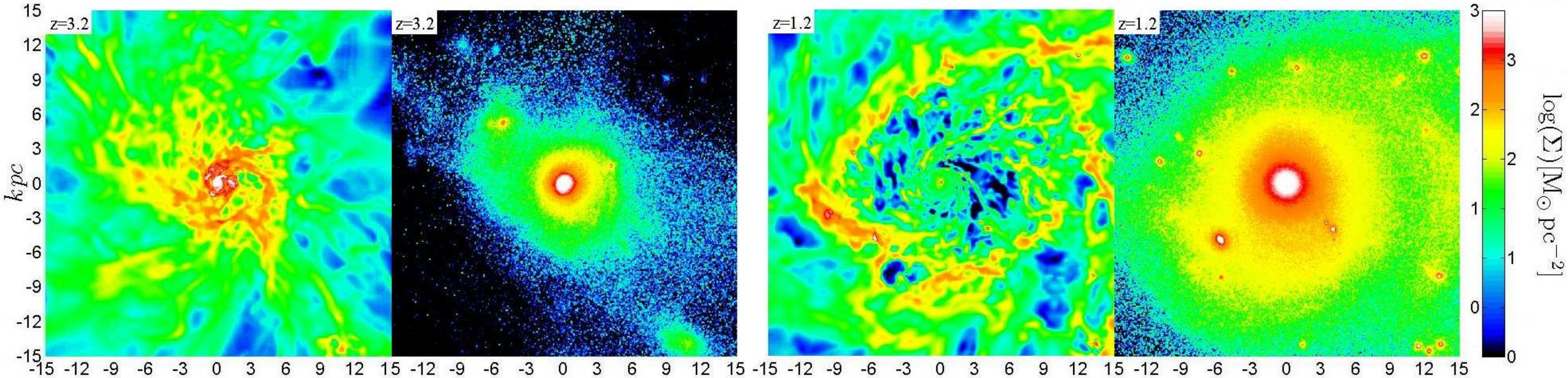
Blue Nugget - Red Nugget

naked red nugget

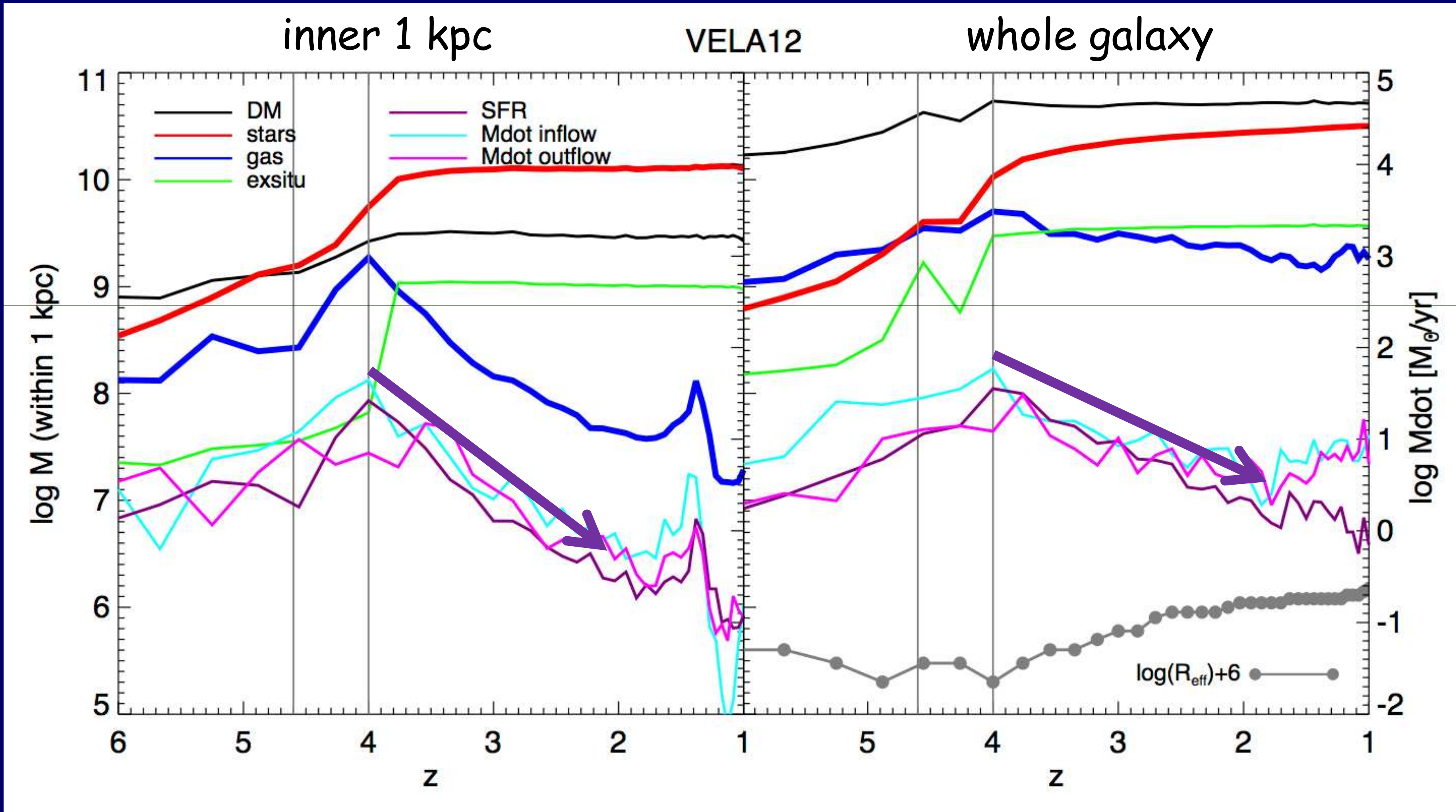


a stellar envelope may gradually grow by dry mergers

red nugget + envelope = elliptical

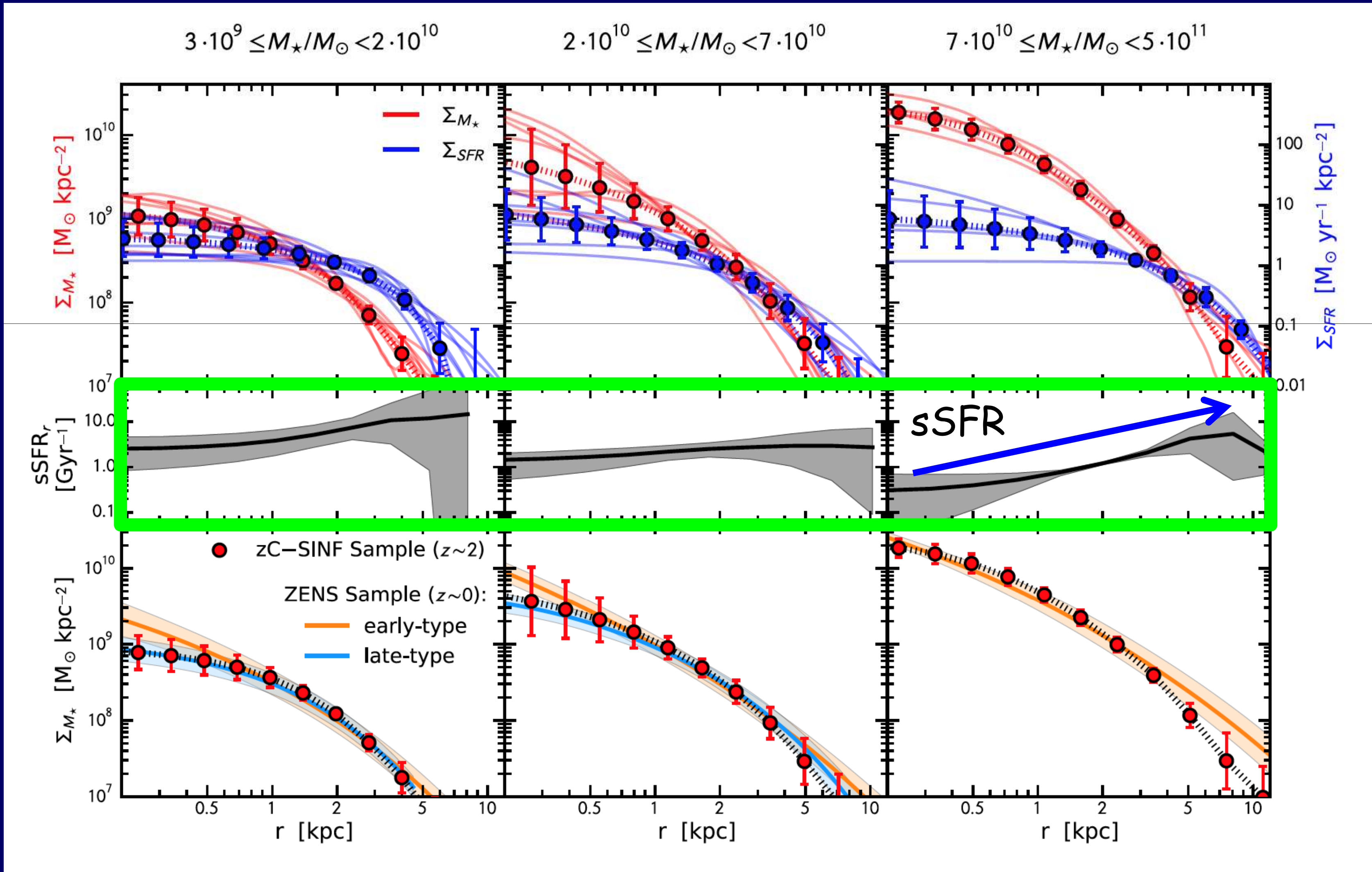


Inside-Out Quenching: Slower Quenching in the Outer Disk



Inside-Out Quenching

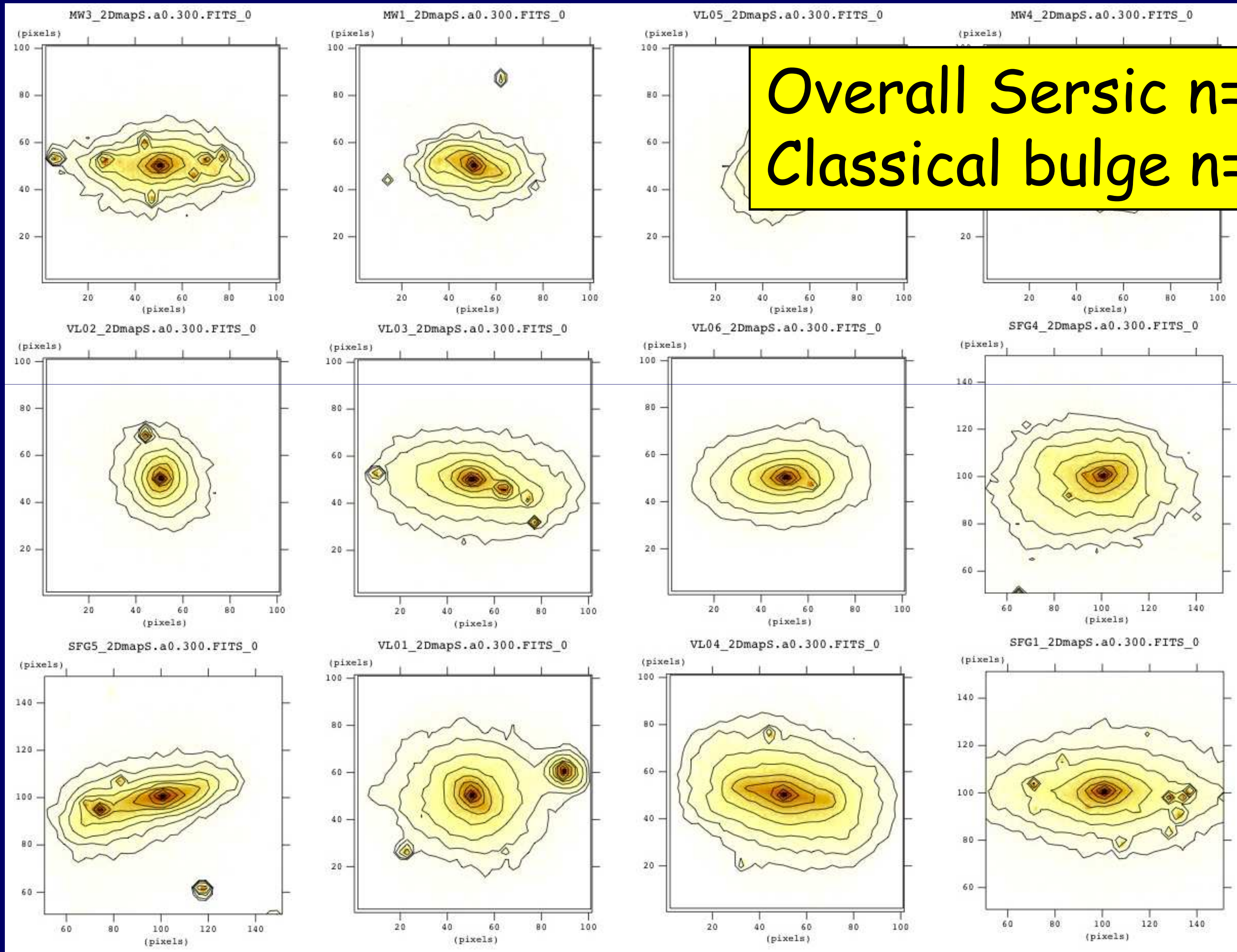
Tacchella+ 2014 profiles of sSFR (=SFR/M_{star}) at z~2 galaxies



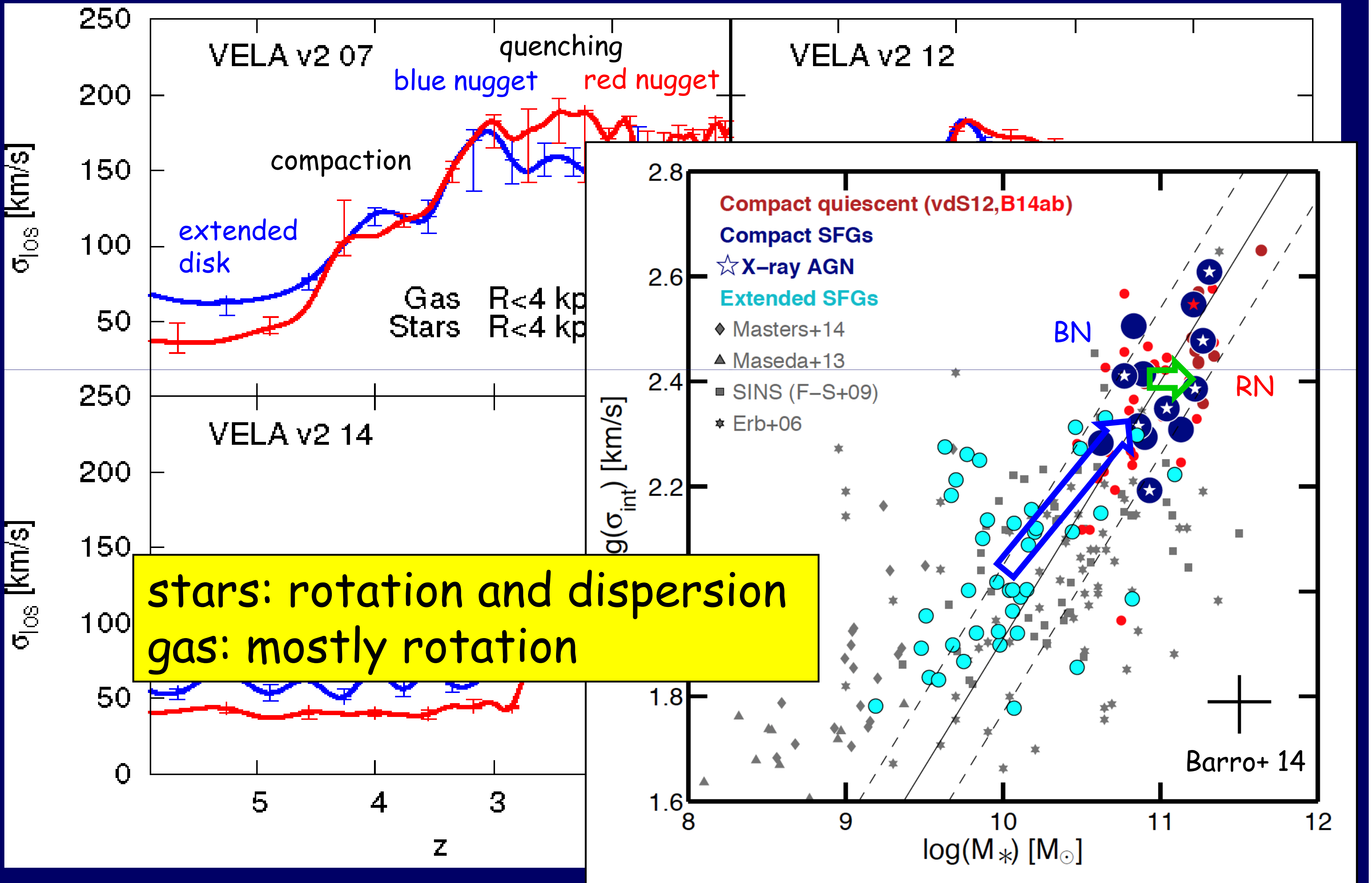
Stellar Component at z=2.3, edge-on

Ceverino+ 2014

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



“line width” evolution in simulated galaxies

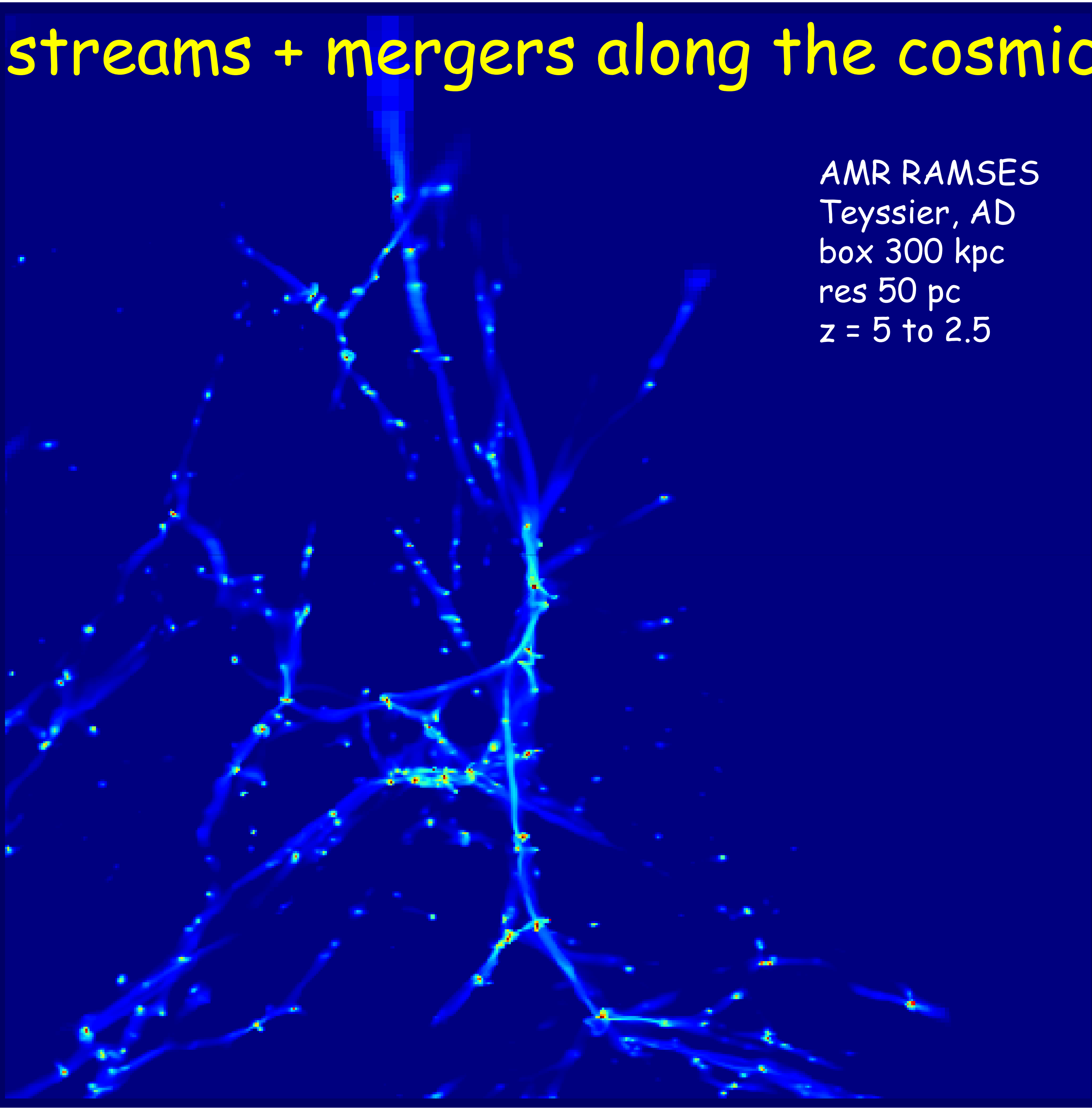


stars: rotation and dispersion
gas: mostly rotation

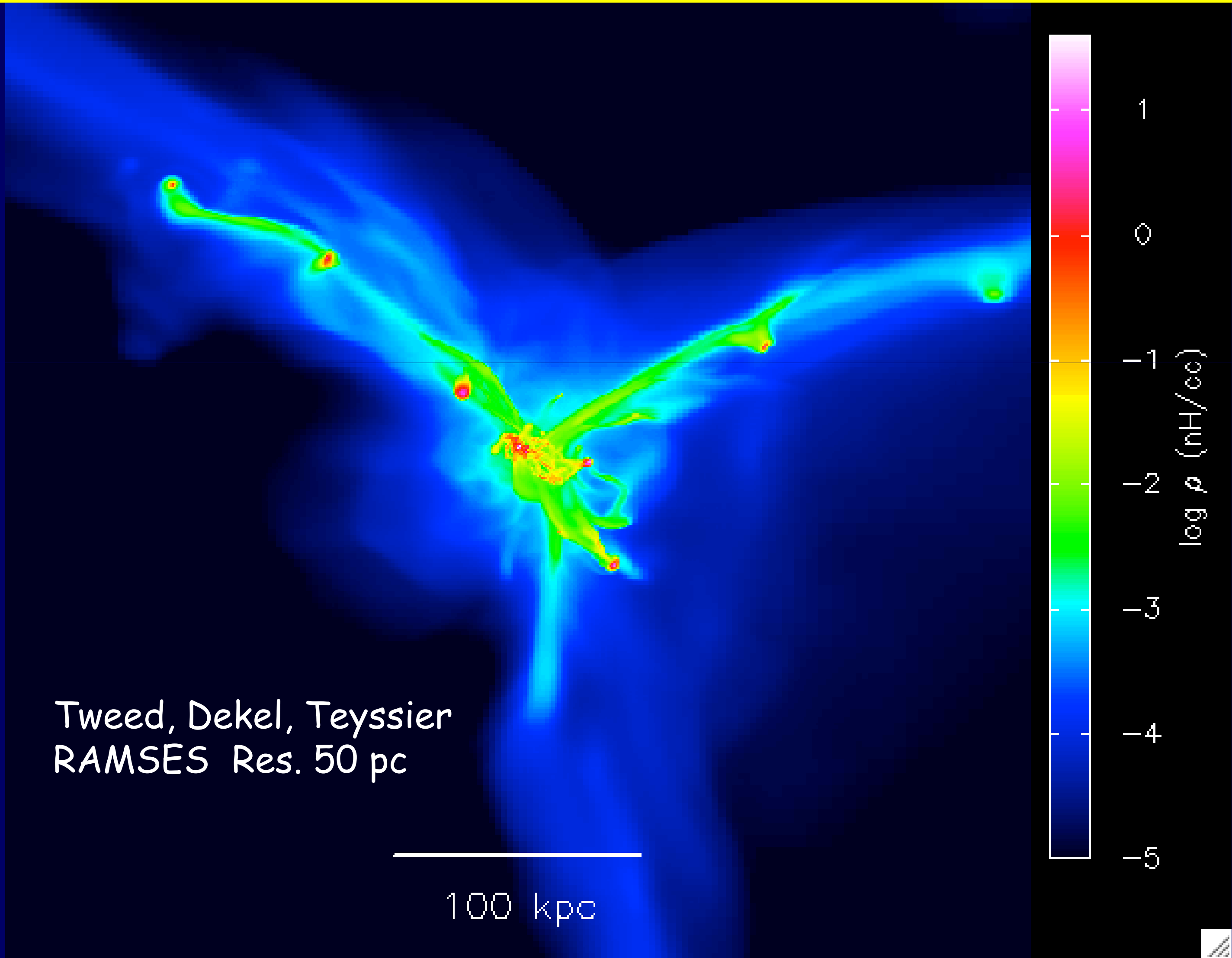
What is the Trigger of wet Compaction?

- 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)
- Return of recycled low-AM gas (Elmegreen+ 14)

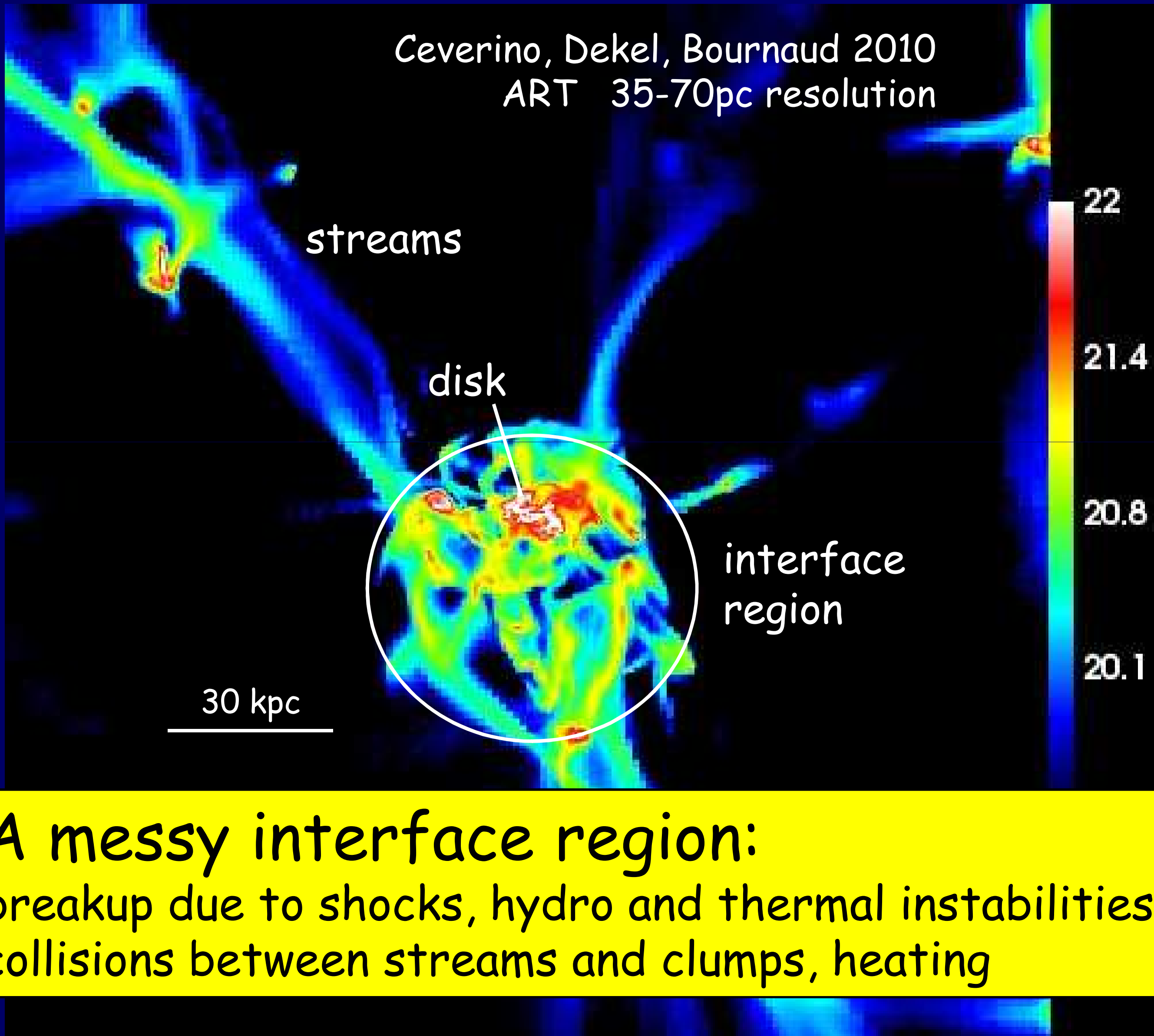
Gas streams + mergers along the cosmic web



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

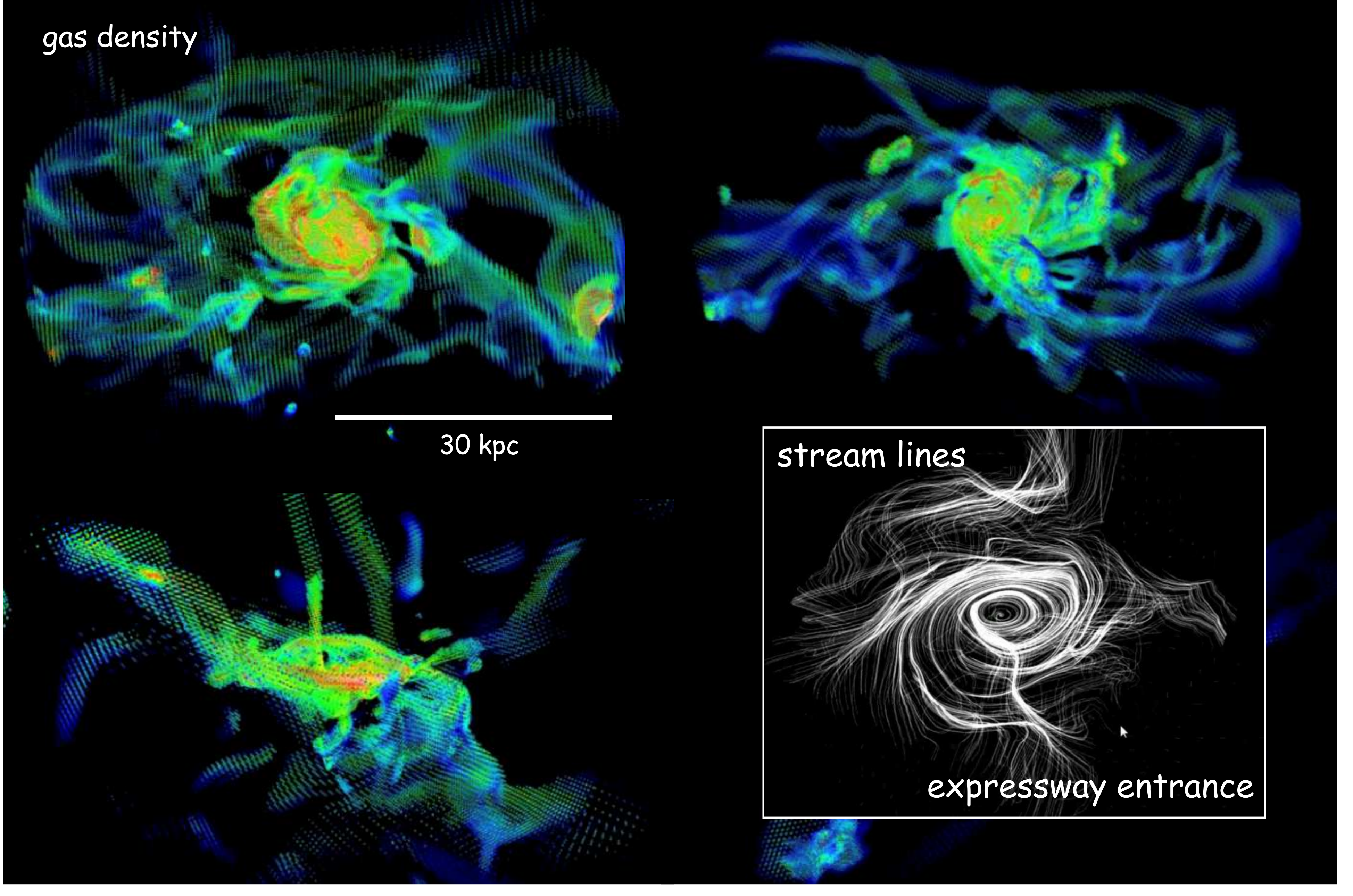


How do the streams join the disk?



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

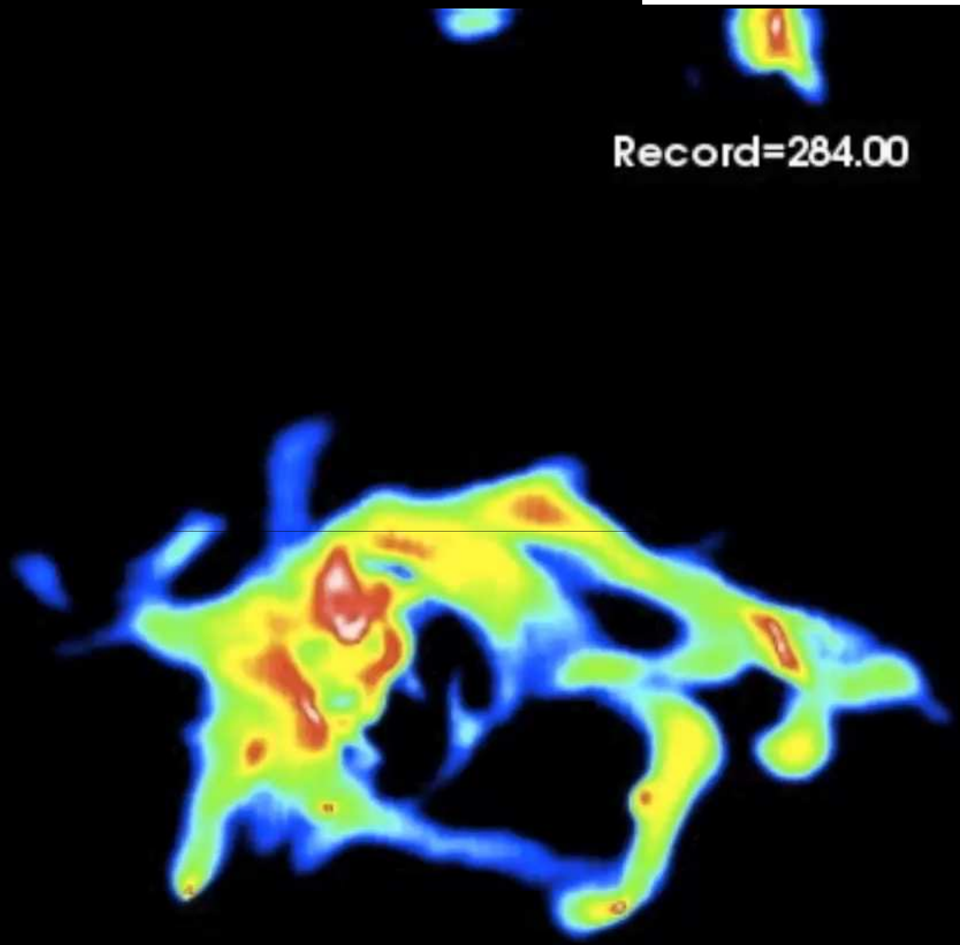
An Extended Tilted Ring about the Disk



Clumpy Disk: streams & mergers

Ceverino, Dekel et al.

10 kpc z=4-2.1



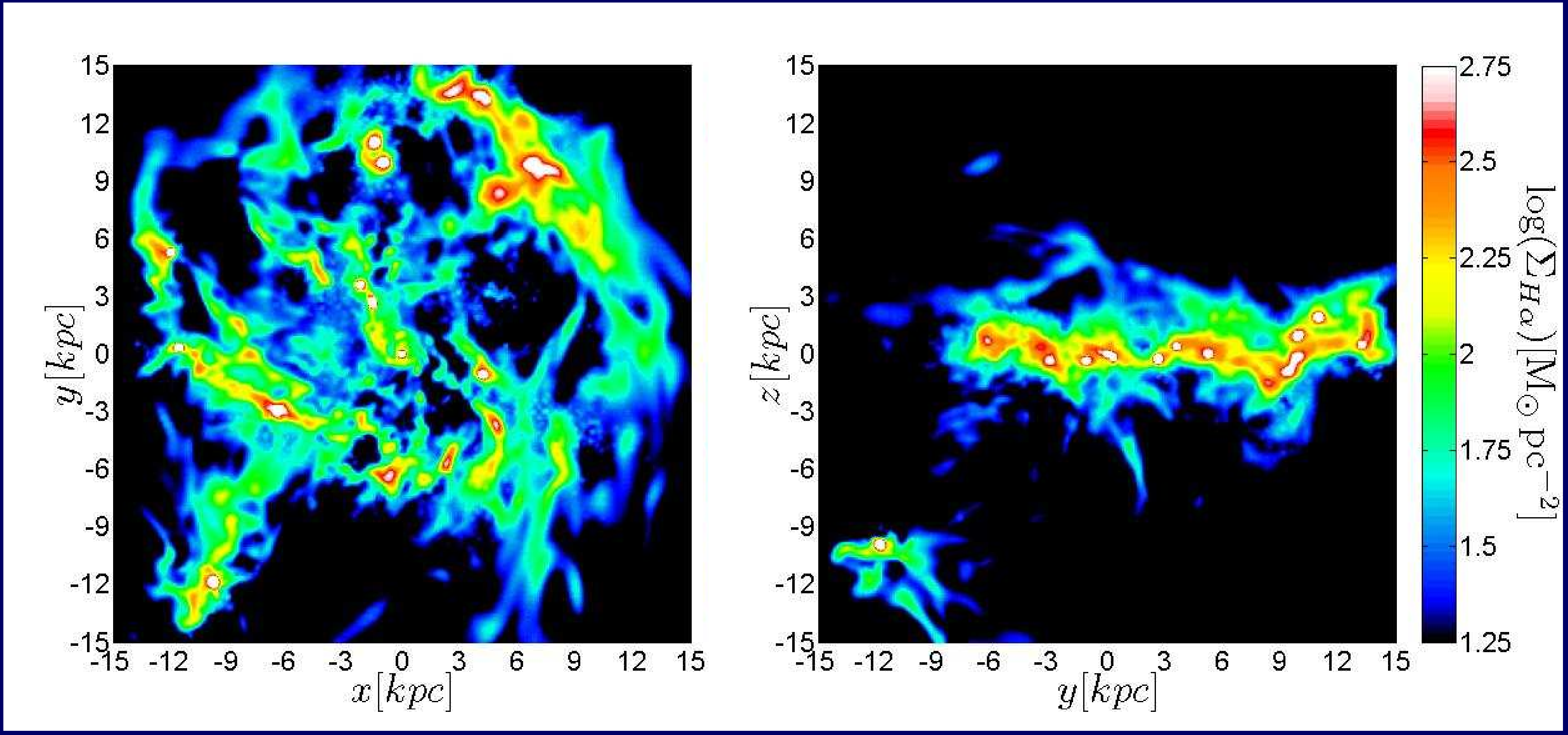
Violent disk instability (VDI) and mergers (mostly minor) work in concert

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

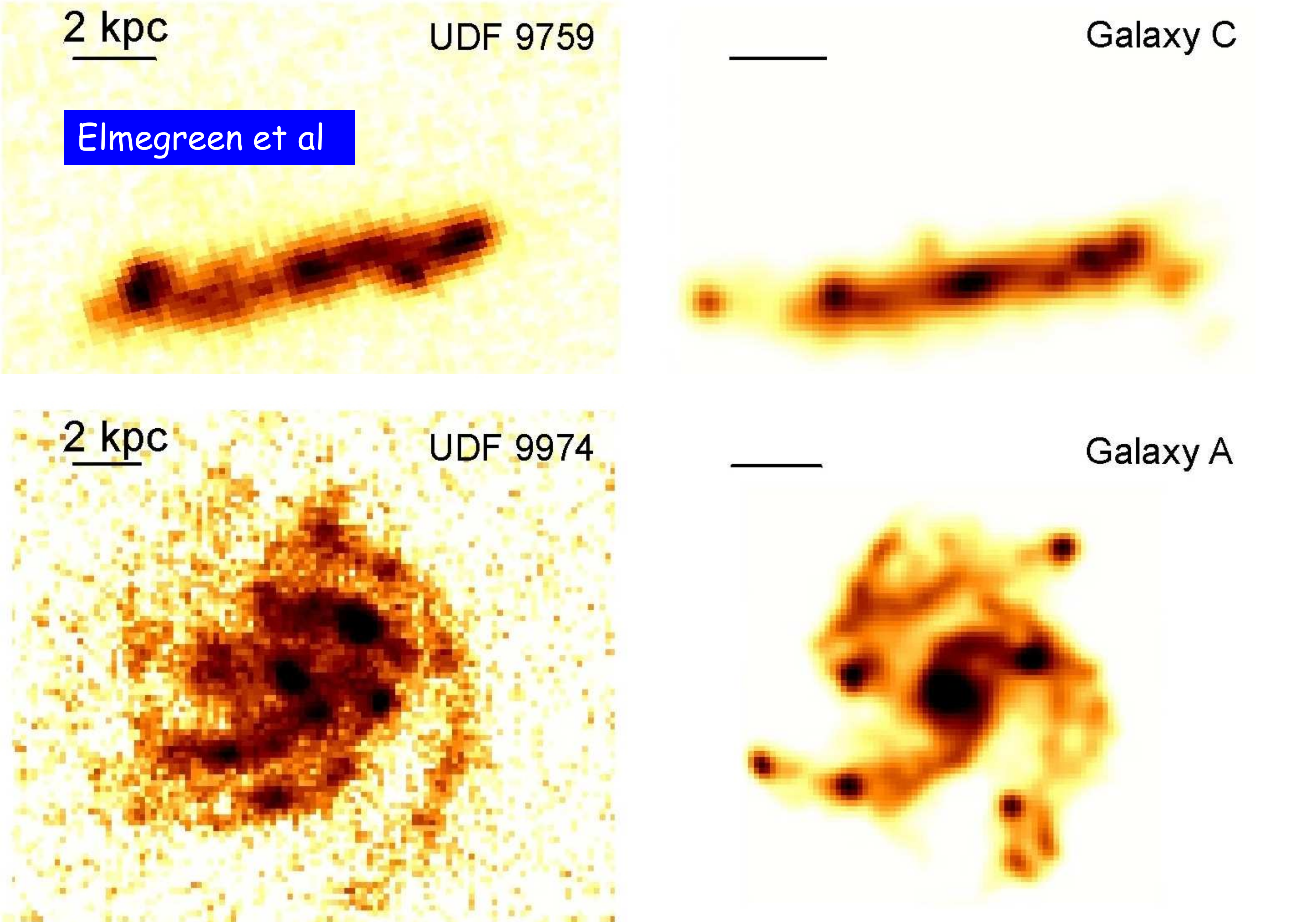
Violent Disk Instability (VDI) at High z

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

highly perturbed, clumpy rotating disk: H/R ~ σ/V ~ f_{cold} ~ 0.2



Observations vs. Simulations



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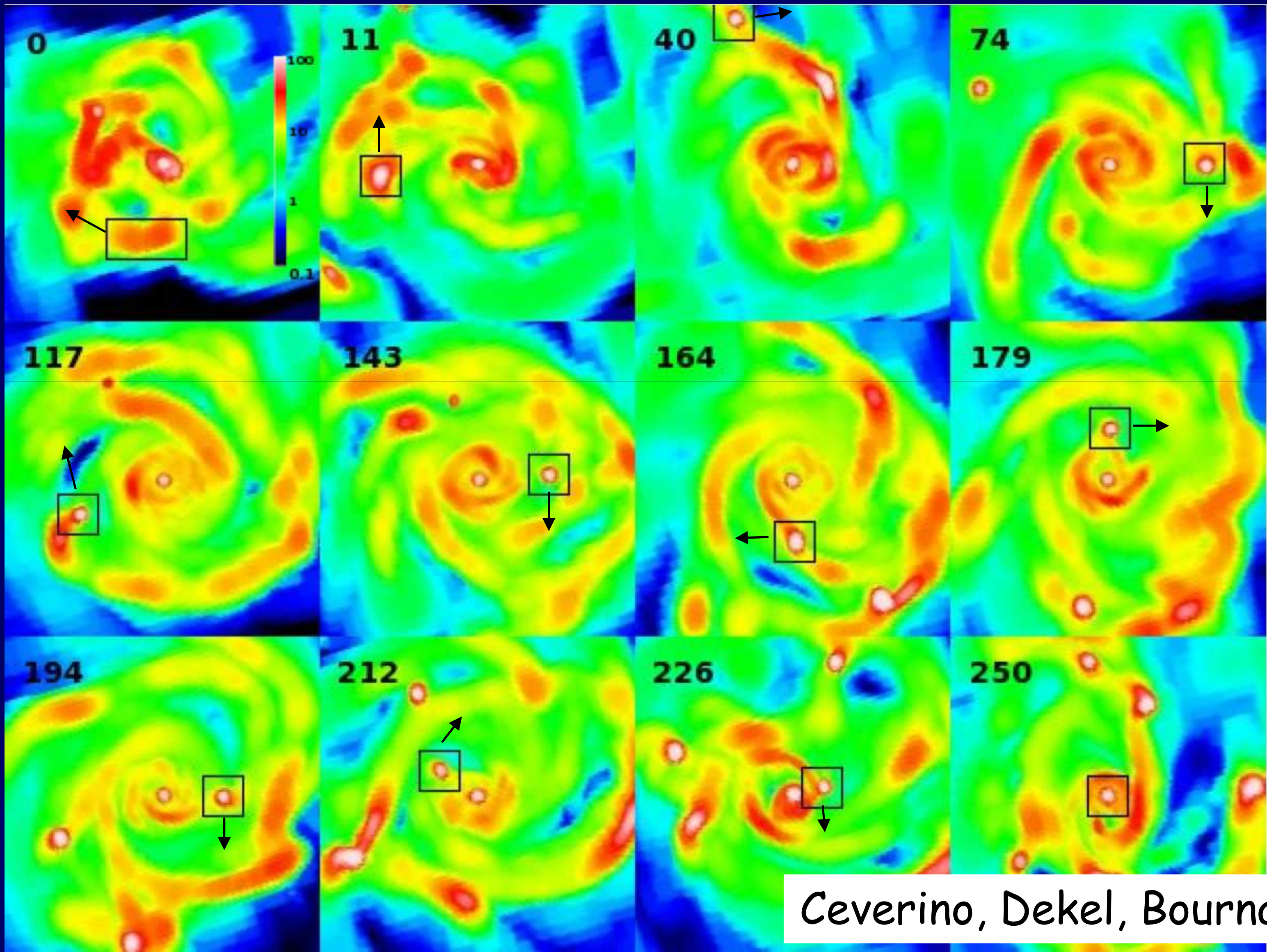
- Return of recycled low-AM gas (Elmegreen+ 14)

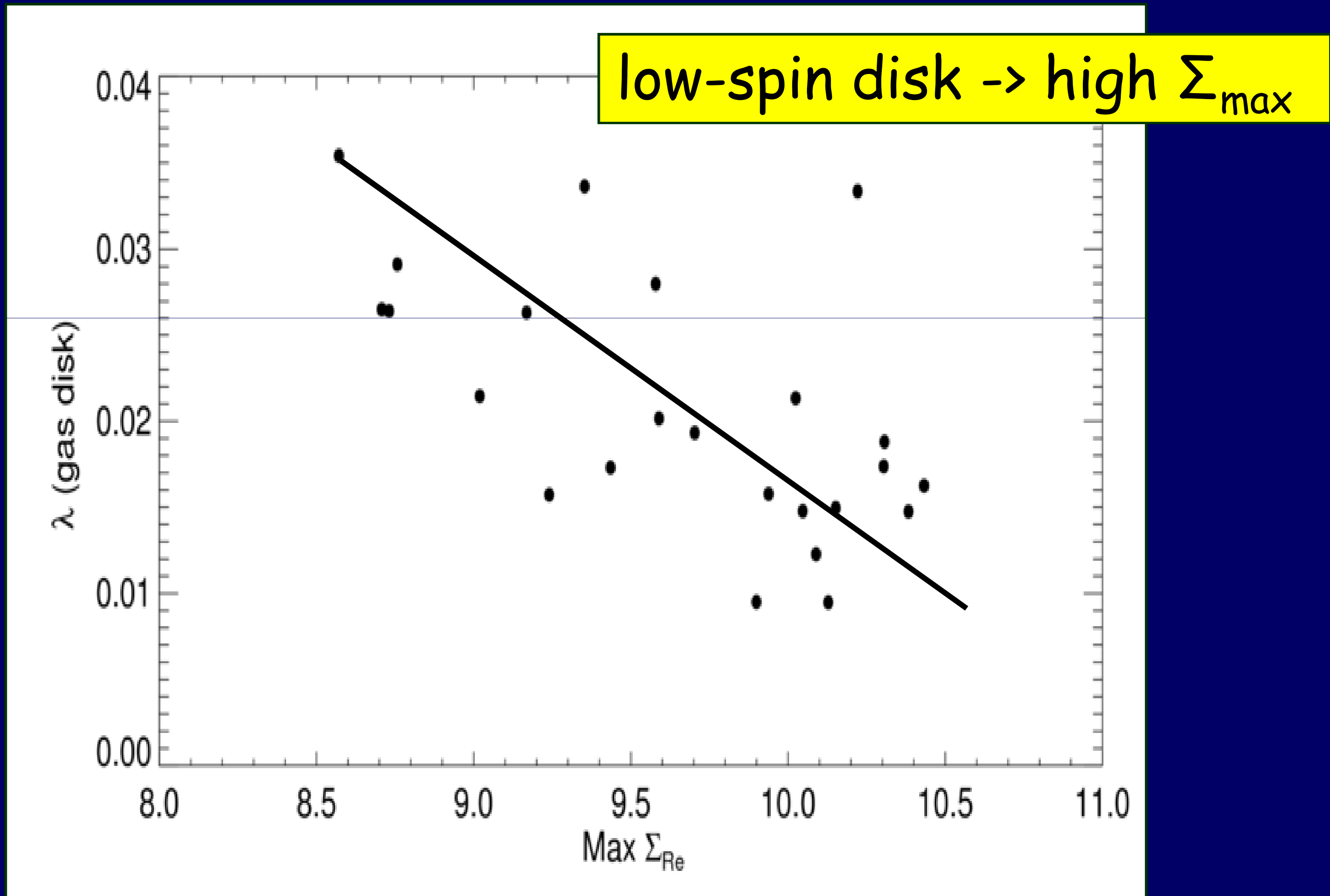
VDI-Driven Inflow: Gas + Clump Migration



Ceverino, Dekel, Bournaud 10

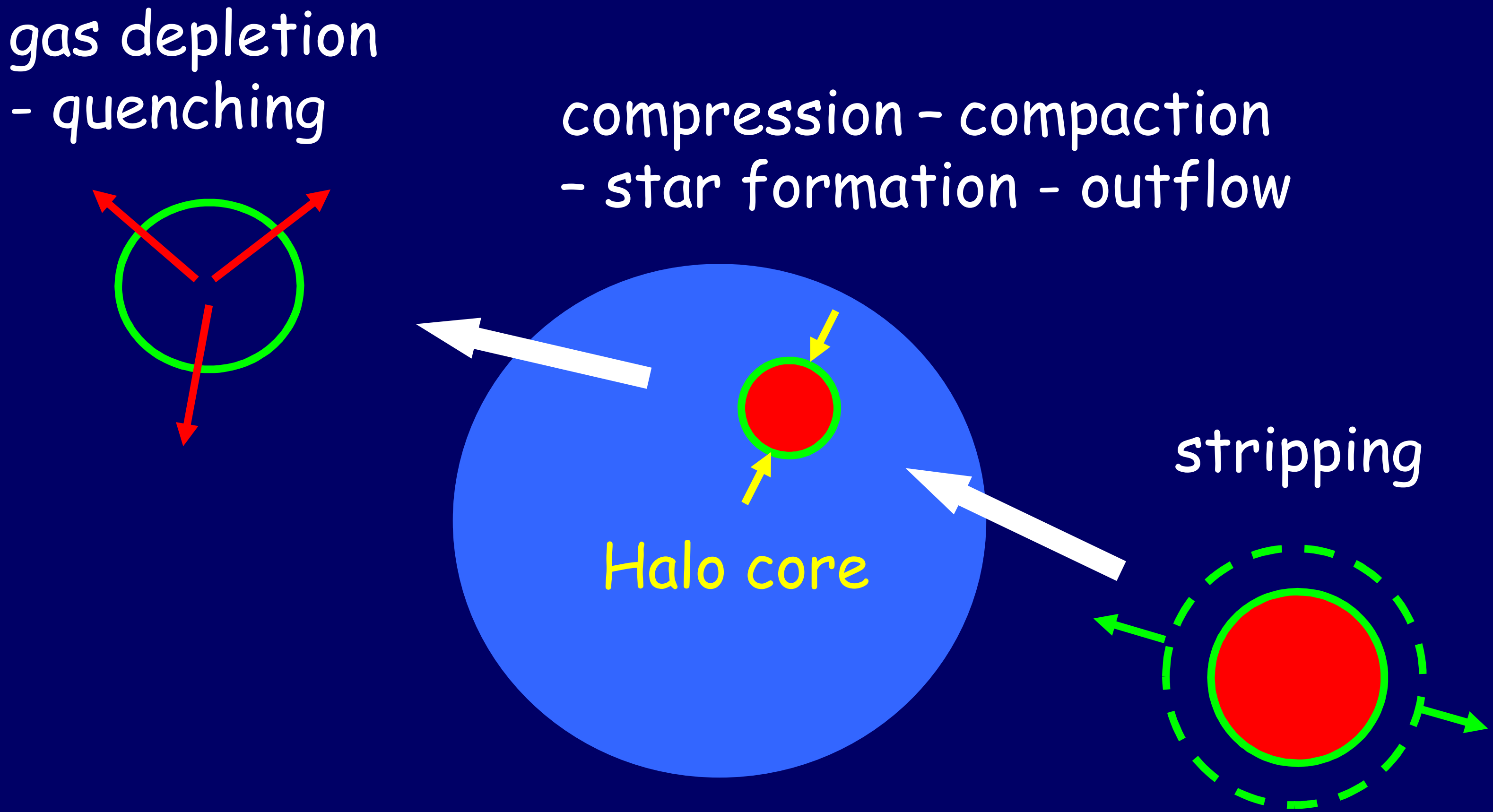
Wet Inflow when Gas Disk has Low Spin

Simulations (Zolotov+14) confirm model predictions (Dekel, Burkert 14)

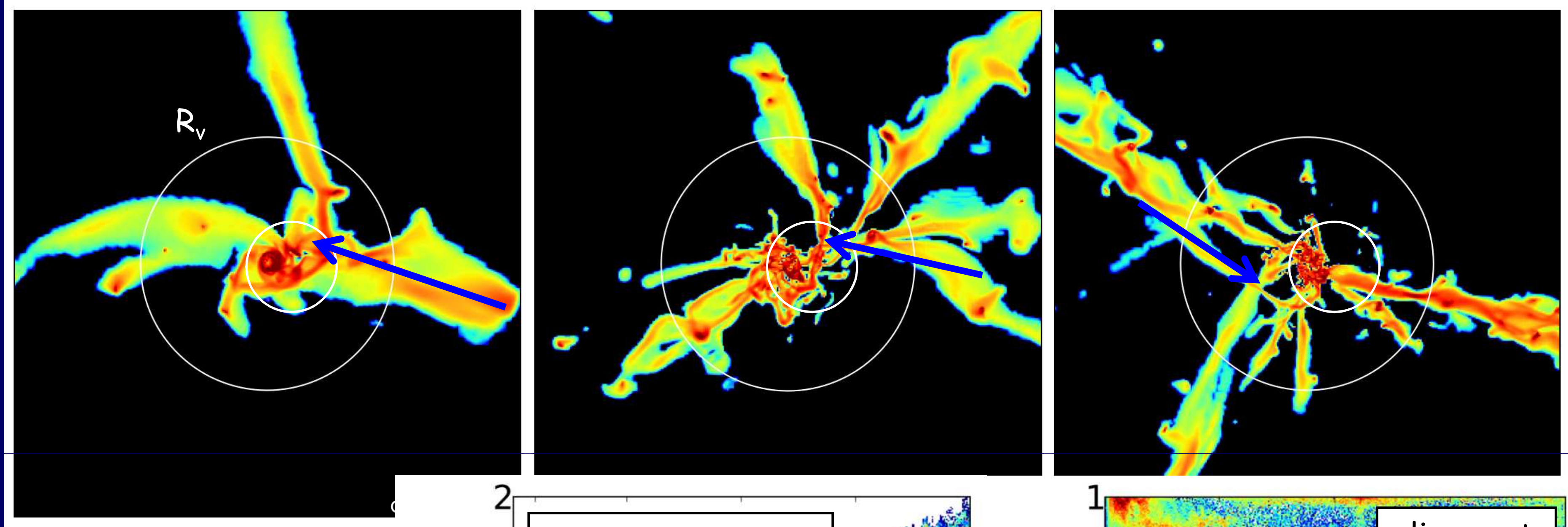


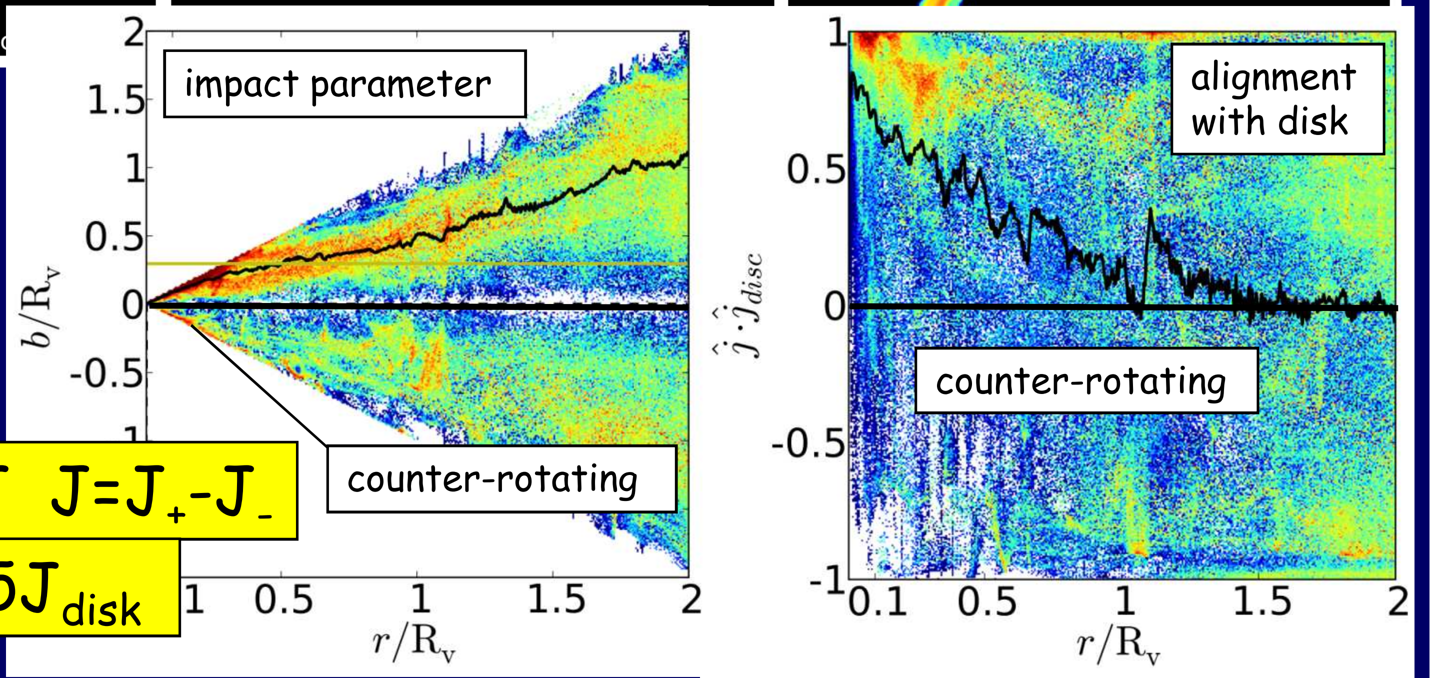
Compaction by Tidal Compression

Dekel, Devor, Hetzroni 2003



Counter-rotating Streams





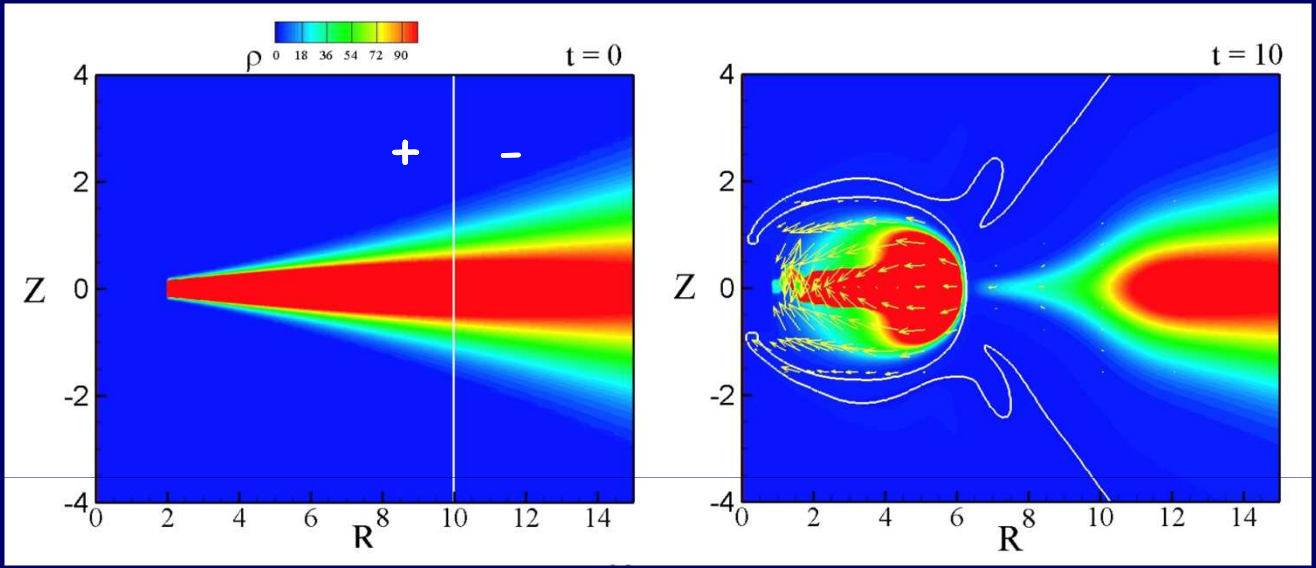
inflow: J_{-}~$0.7J$ $J=J_{+}-J_{-}$

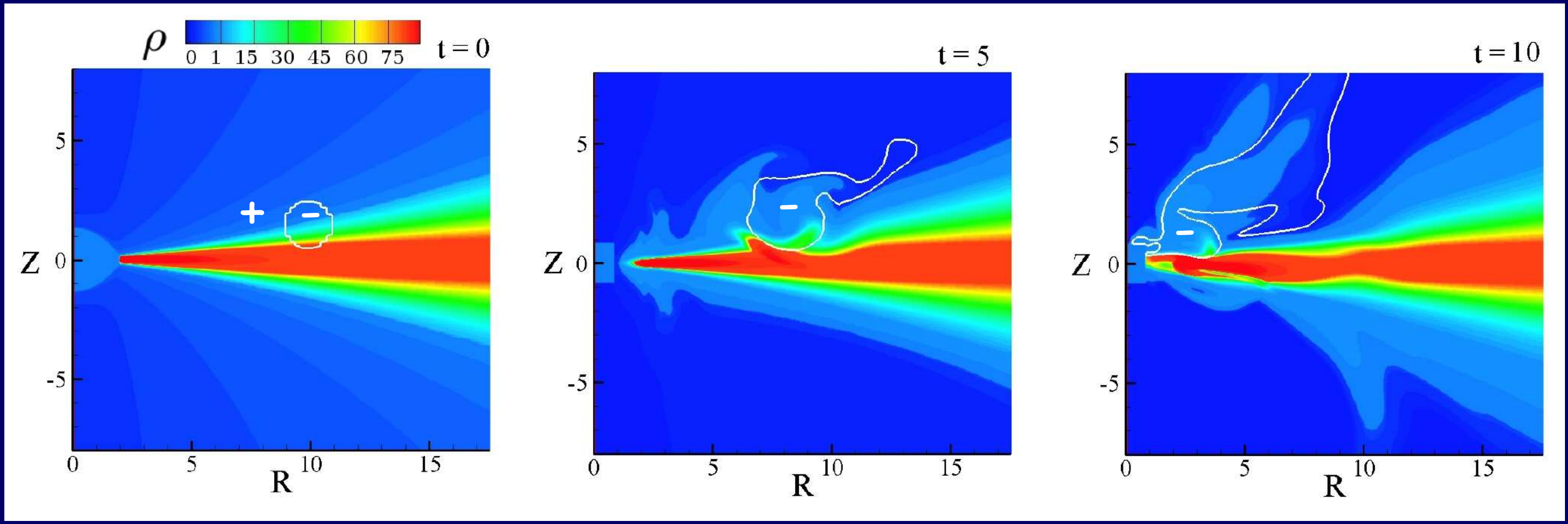
in t_{orbit}: J_{-}~$0.15J_{disk}$

Counter-rotation -> Compaction

Dyda, Lovelace+14
(proto-stellar disks)

+ oscilations





The Quenching Mechanism

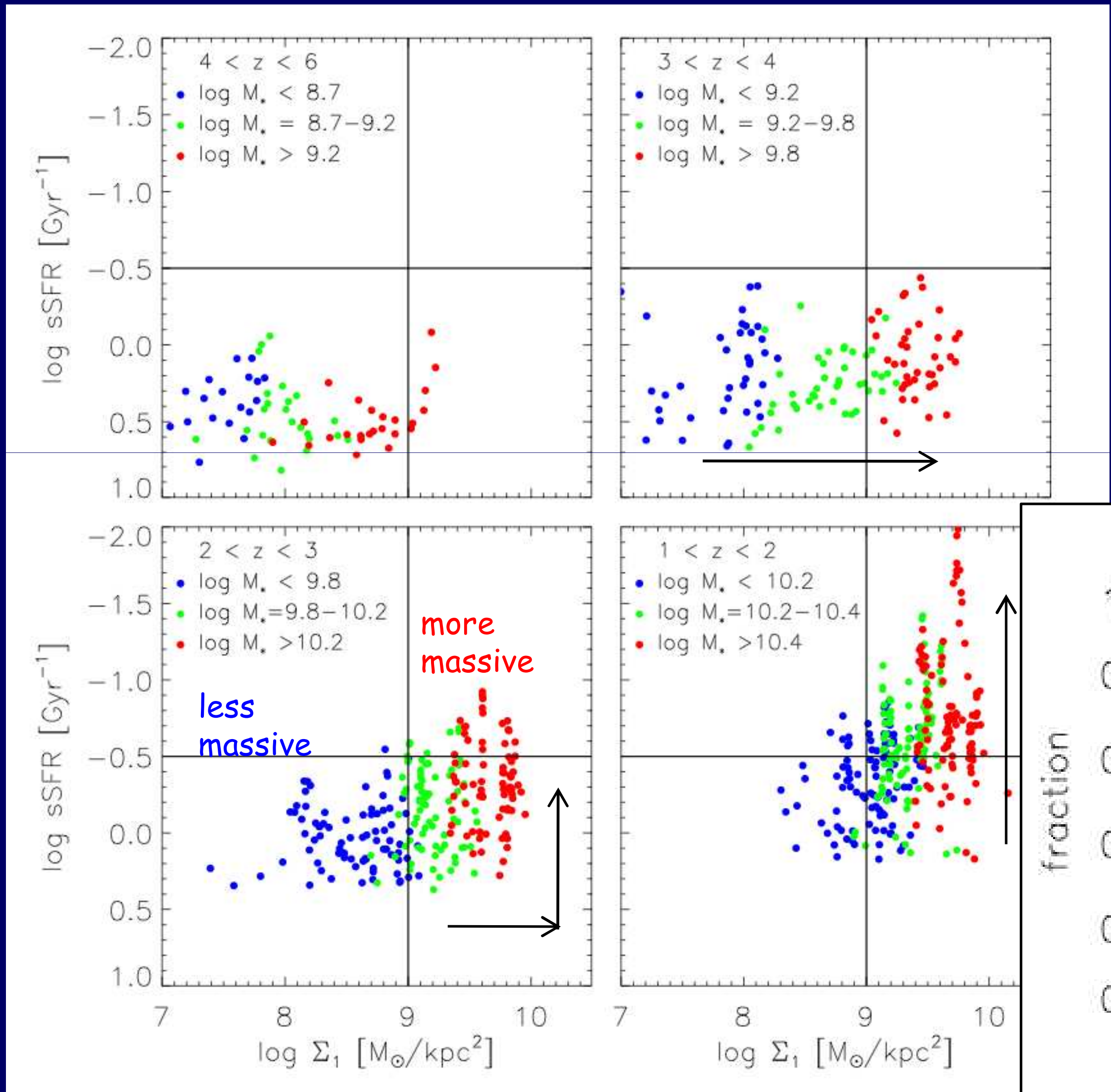
Wet compaction: inflow > SFR+outflow

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.)
- AGN outflow

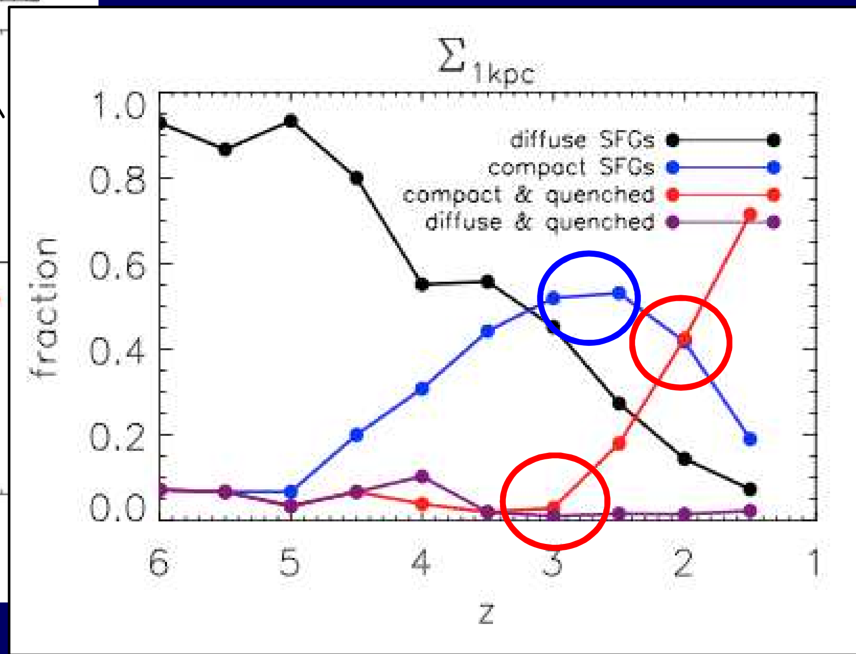
Long-term quenching? Hot Halo

Diffuse SFG -> "Blue" Nuggets -> Red Nuggets



Downsizing:

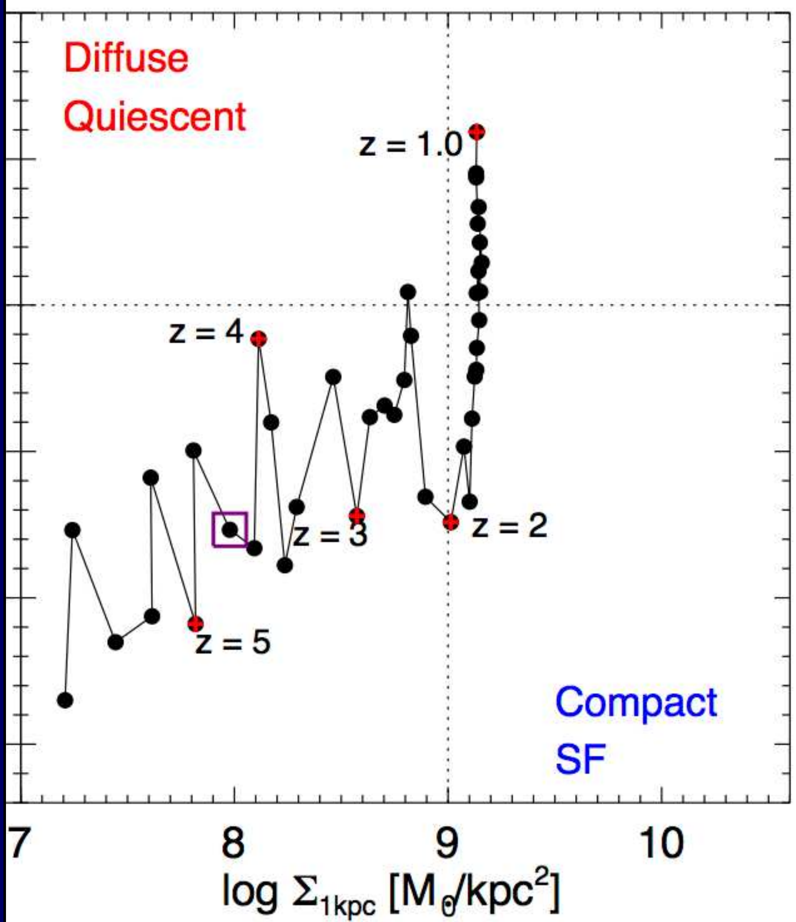
More massive galaxies
- compactify earlier
- to higher density Σ_1 , Σ_e
- quench more efficiently

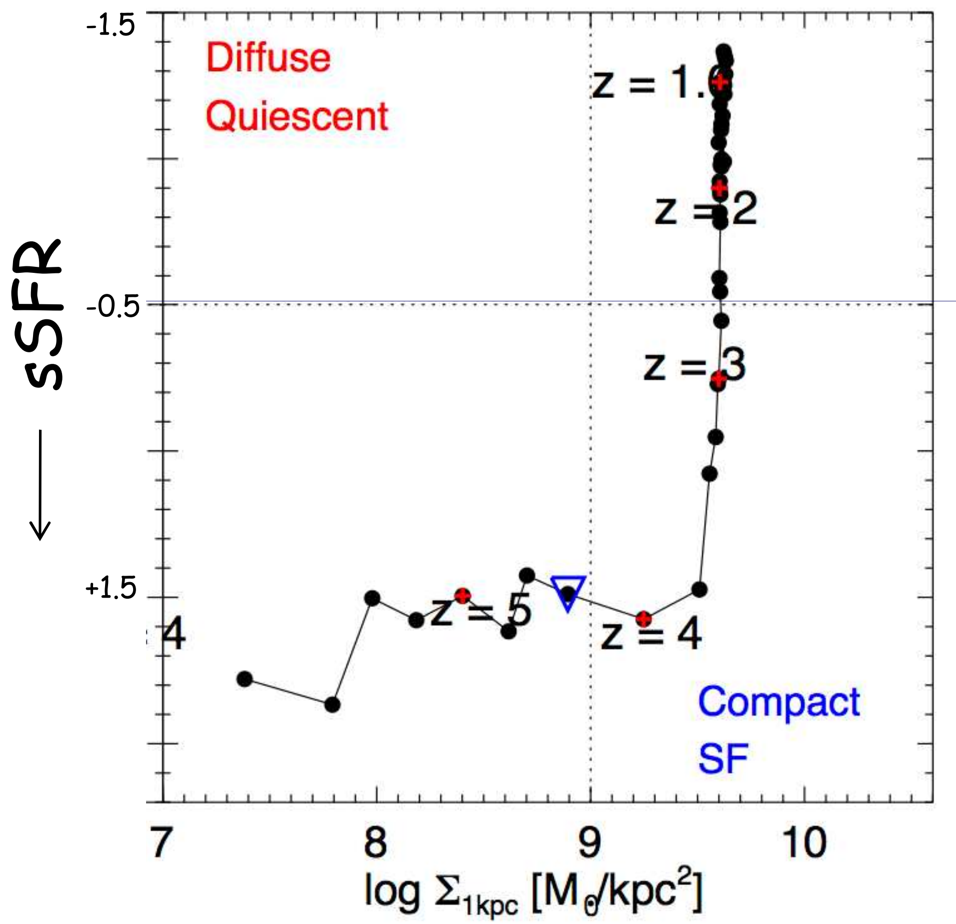


Hesitatnt vs. Decisive Quenching

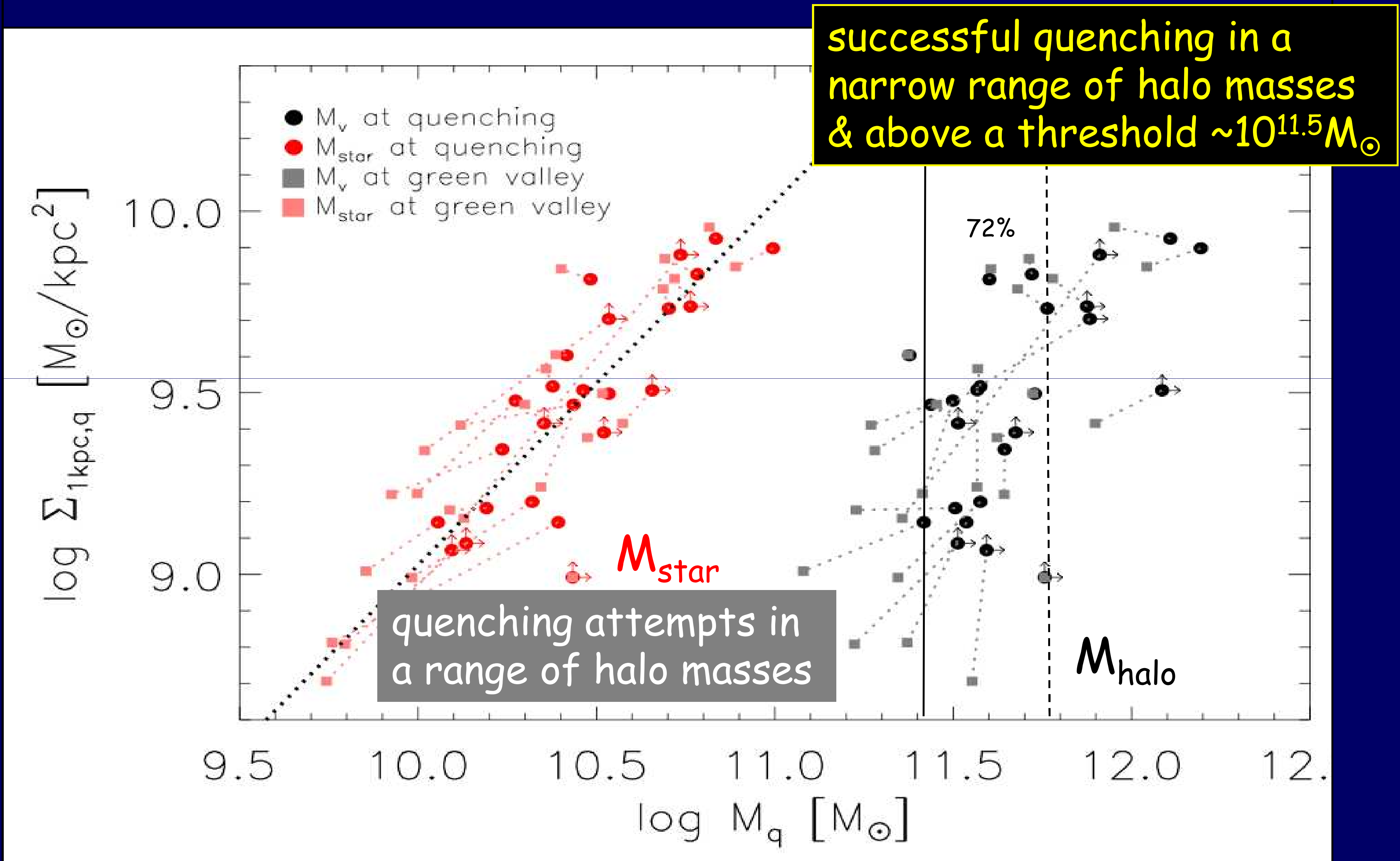
low mass, low z

high mass, high z





Mass and Central Density at Quenching



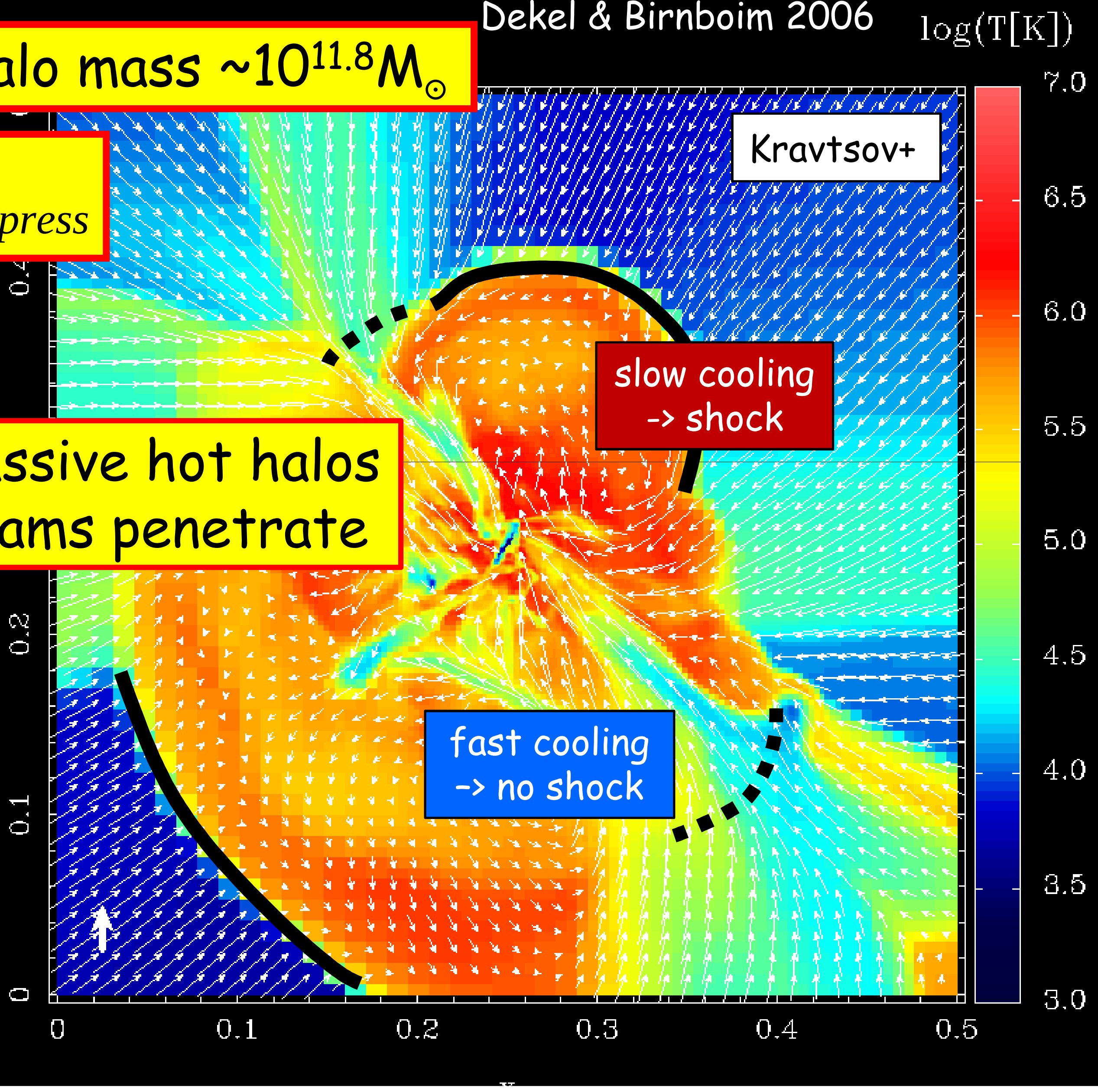
Virial Shock Heating

Dekel & Birnboim 2006

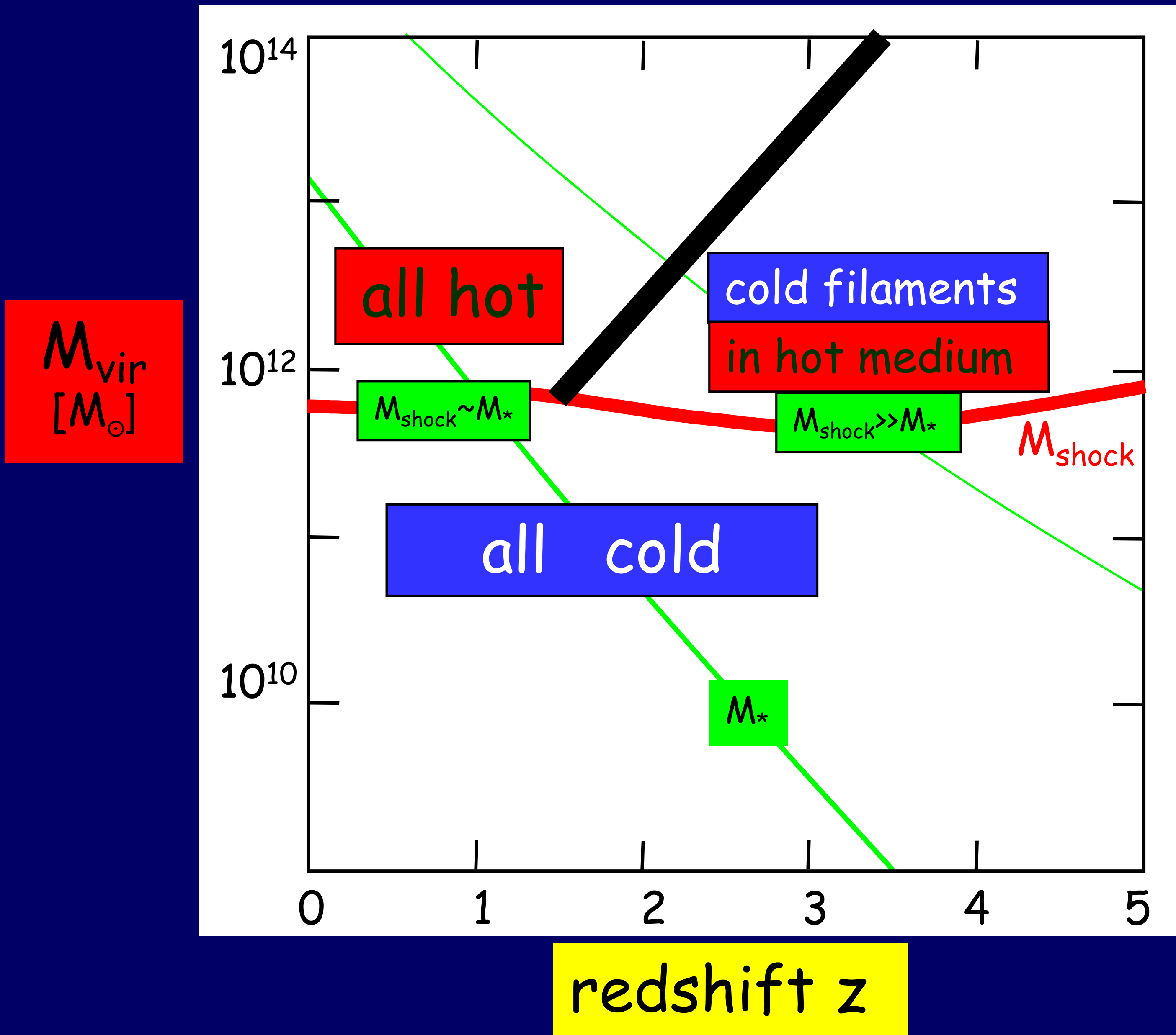
critical halo mass ~$10^{11.8} M_\odot$

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

in hi-z massive hot halos cold streams penetrate

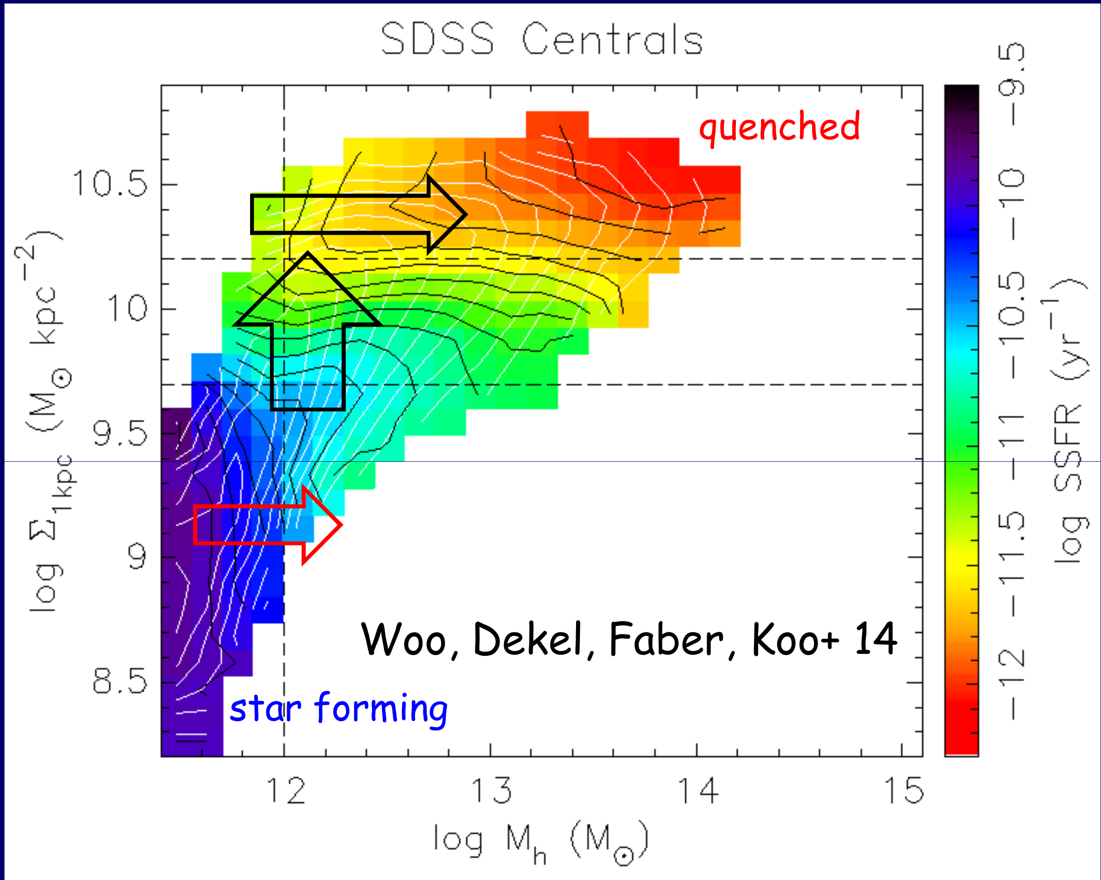


Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06

Two Quenching Mechanisms: Bulge & Halo



Compact gaseous bulge

-> gas removal by high SFR, outflow, AGN, Q-quenching

In halos > 10^{12} $M_\odot$

-> long-term shutdown of gas supply by virial shock heating

Compact bulge and halo quenching

But each can quench by itself

The Quenching Mechanism

Wet compaction: inflow > SFR+outflow

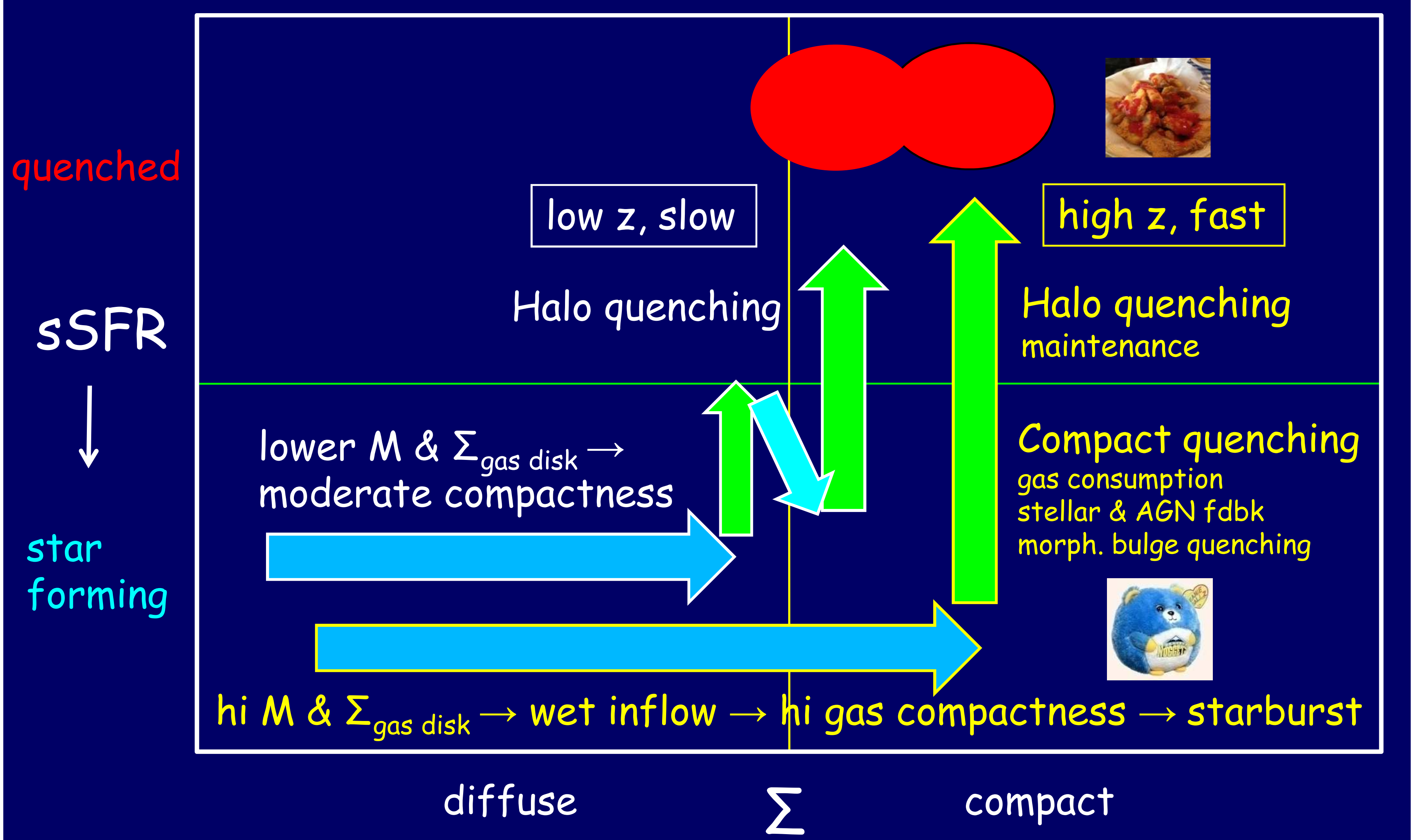
High SFR and no gas supply to the center:
inflow < SFR+outflow → quenching attempt

- disk has shrunk → no immediate gas supply
- massive bulge suppresses VDI-driven inflow
- AGN outflow

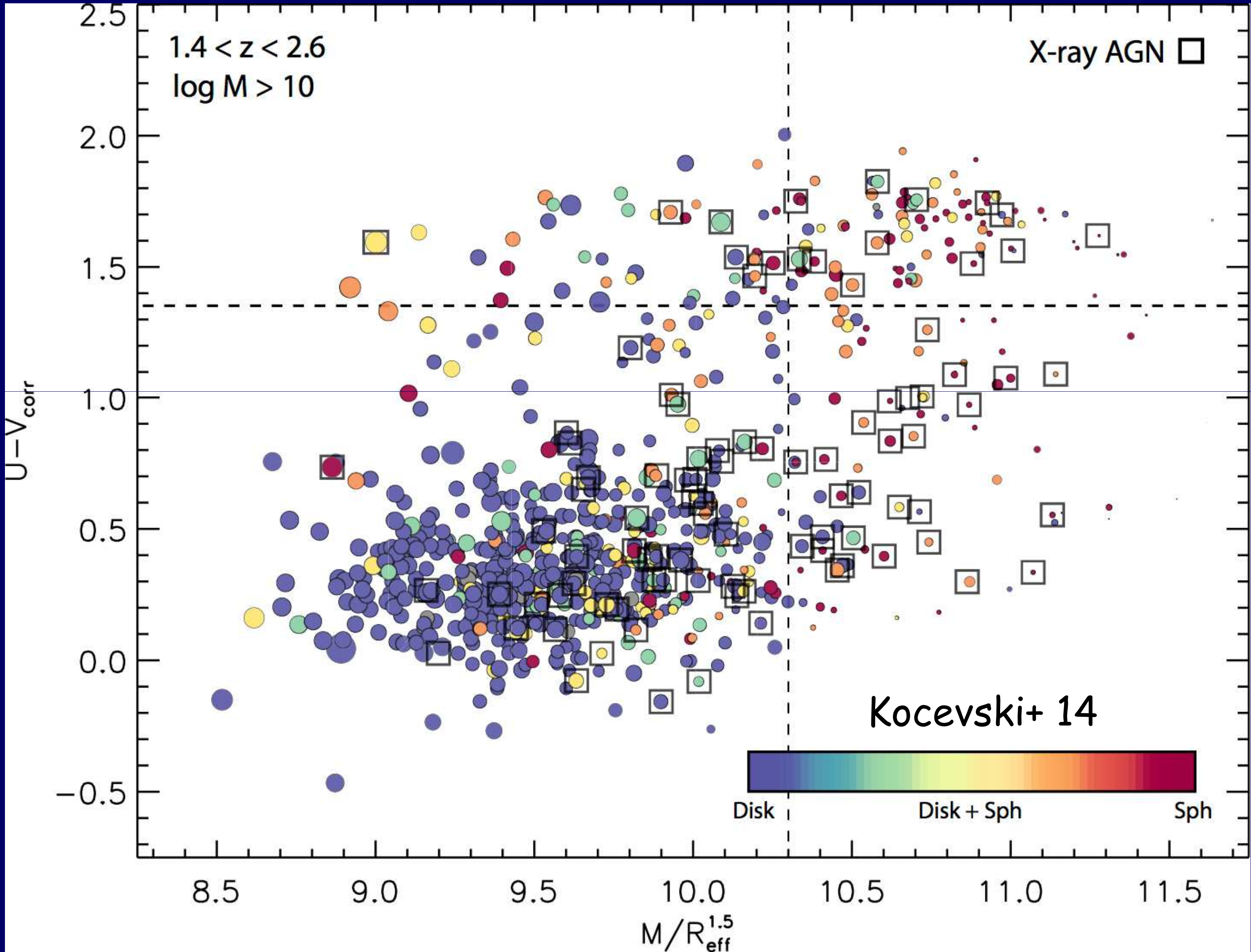
If halo is massive (hot) → starvation of gas supply
→ long-term quenching

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

Modes of Evolution



Role of AGN Feedback in Quenching?



Gradients Across the Main Sequence

star forming

sSFR

quenched

bathtub model:

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

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

main sequence SFGs

±0.3 dex

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

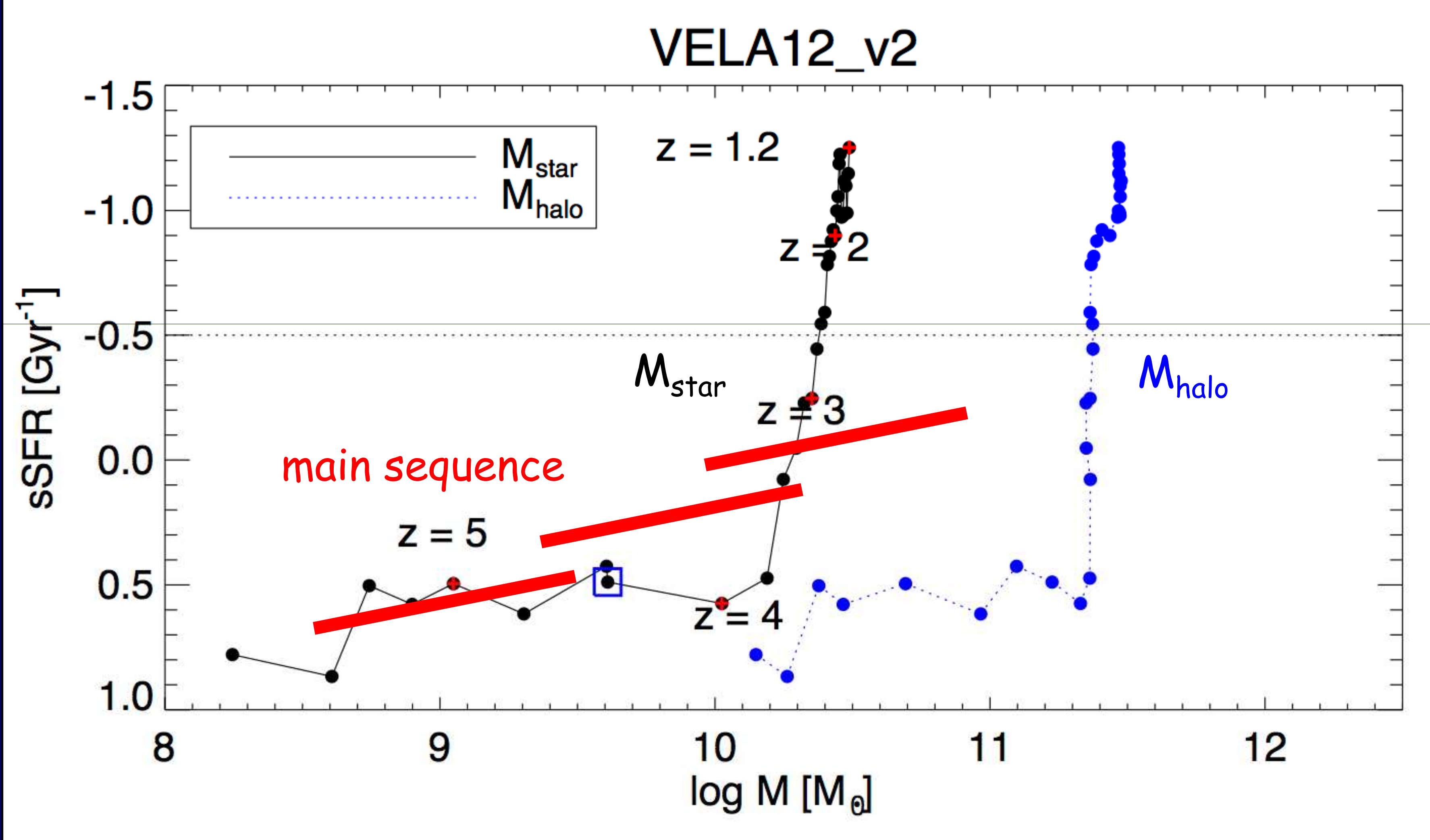
→ time evolution of main-sequence zero point:

$$< sSFR > \approx < \frac{\dot{M}_{in}}{M} > \approx 0.03\,\mathrm{Gyr}^{-1} (1+z)^{5/2}$$

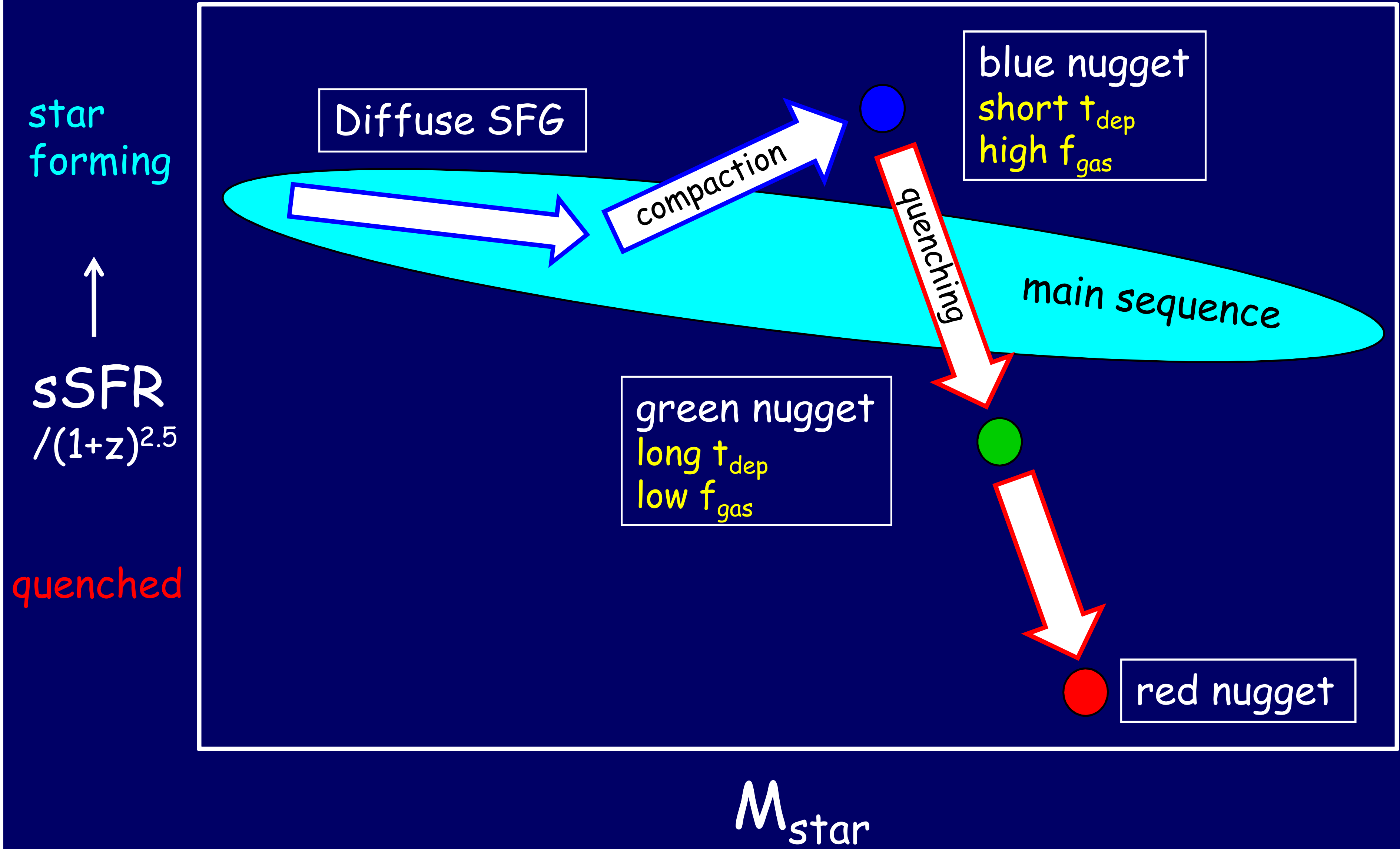
M_{star}

Compaction and quenching

Zolotov+ 14 ART cosmological simulations, res. 25pc, rad fdbk, no AGN



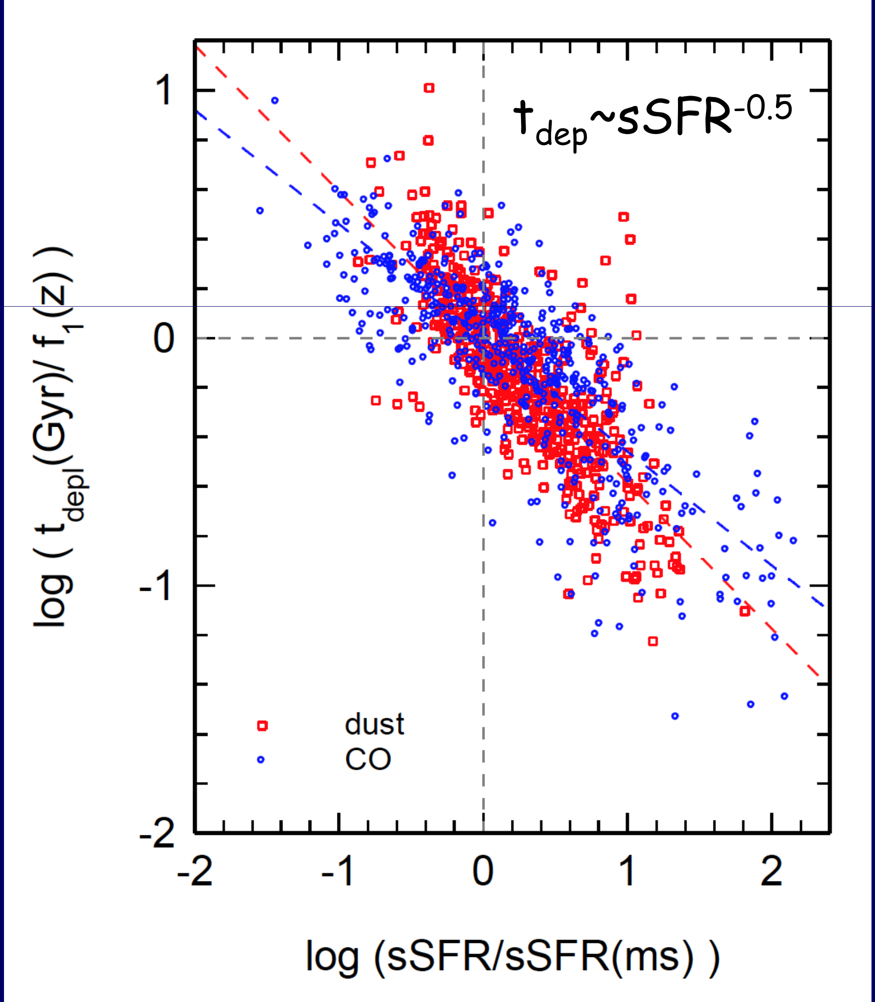
Gradients Across the Main Sequence



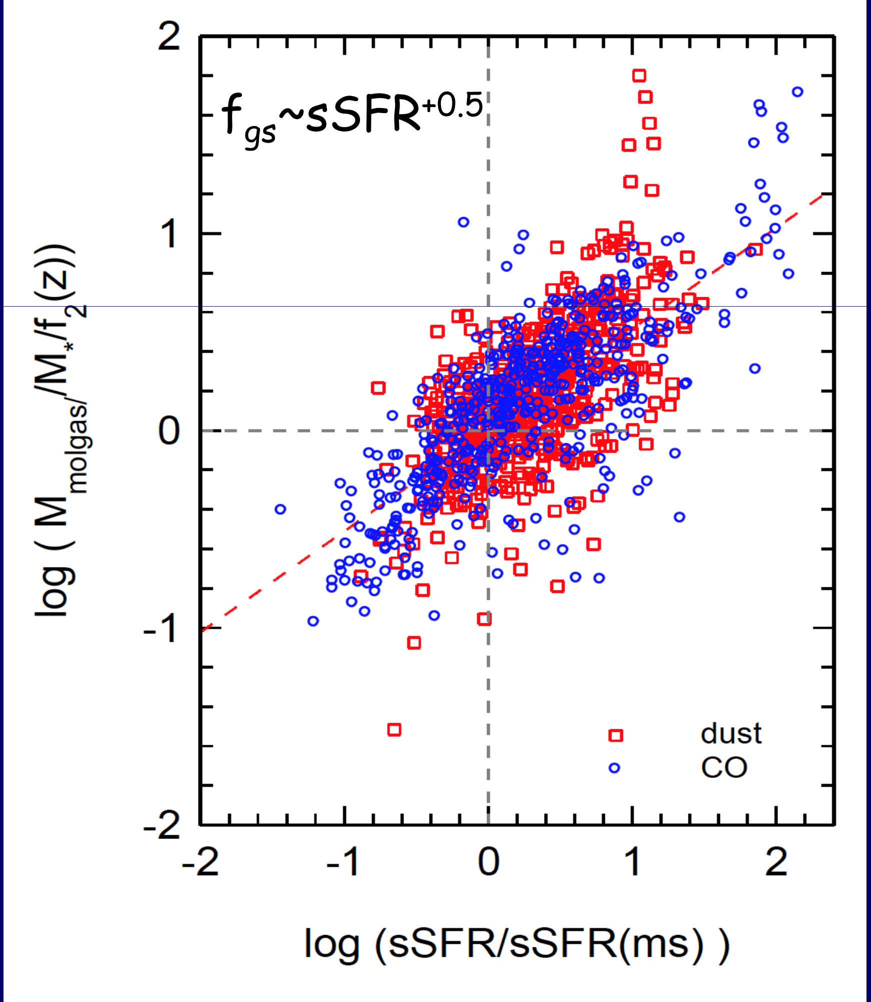
Gradients Across the Main Sequence

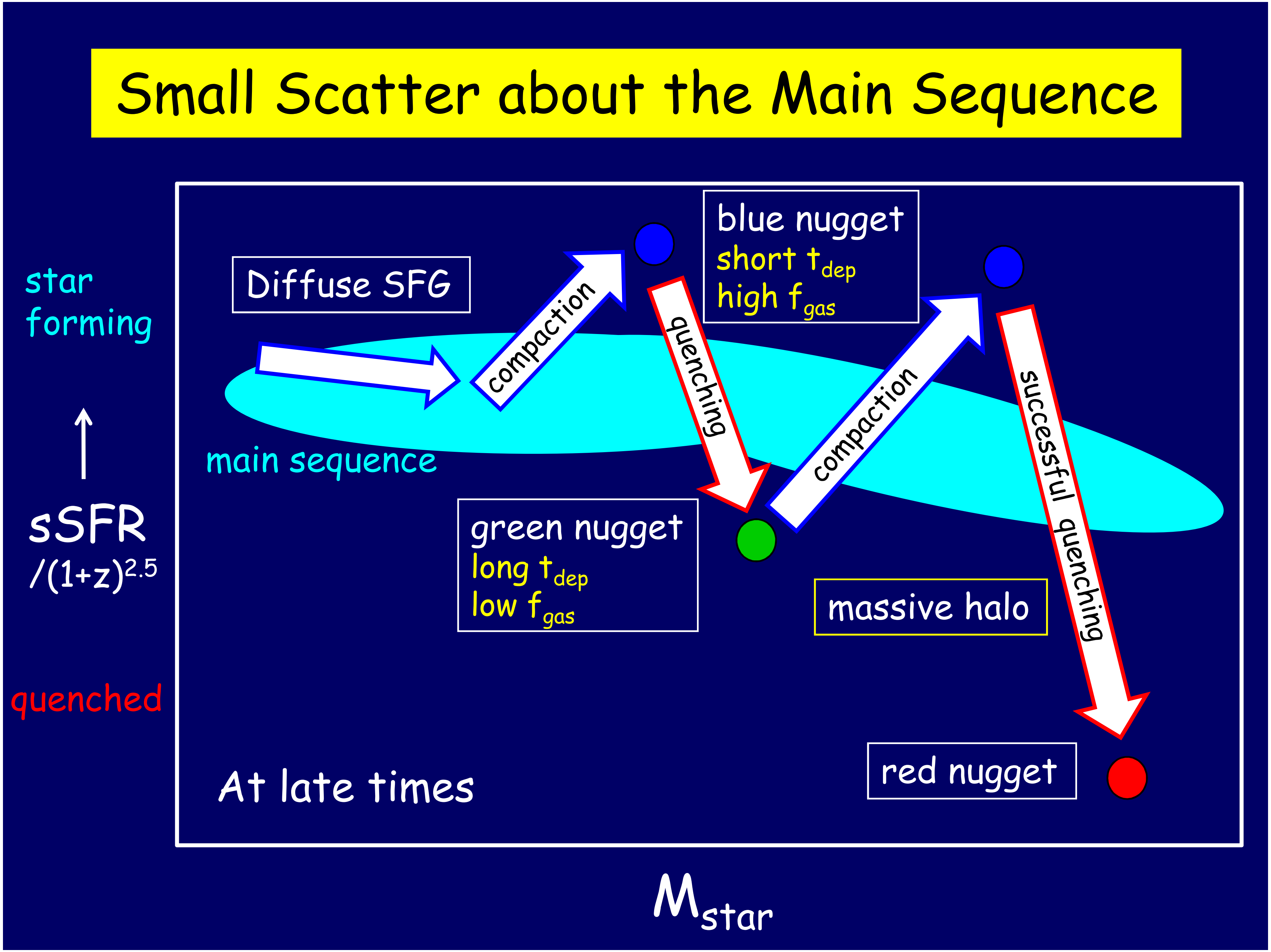
Genzel+ 2014 z=0-2.5

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



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




Small Scatter about 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
successful quenching
green nugget
long t_dep
low f_gas
massive halo
red nugget
At late times
M_star

Conclusions

High-z massive galaxies are fed by cosmic-web streams with mergers: they are gas-rich disks undergoing violent disk instability (VDI)

A characteristic sequence of events in most galaxies:

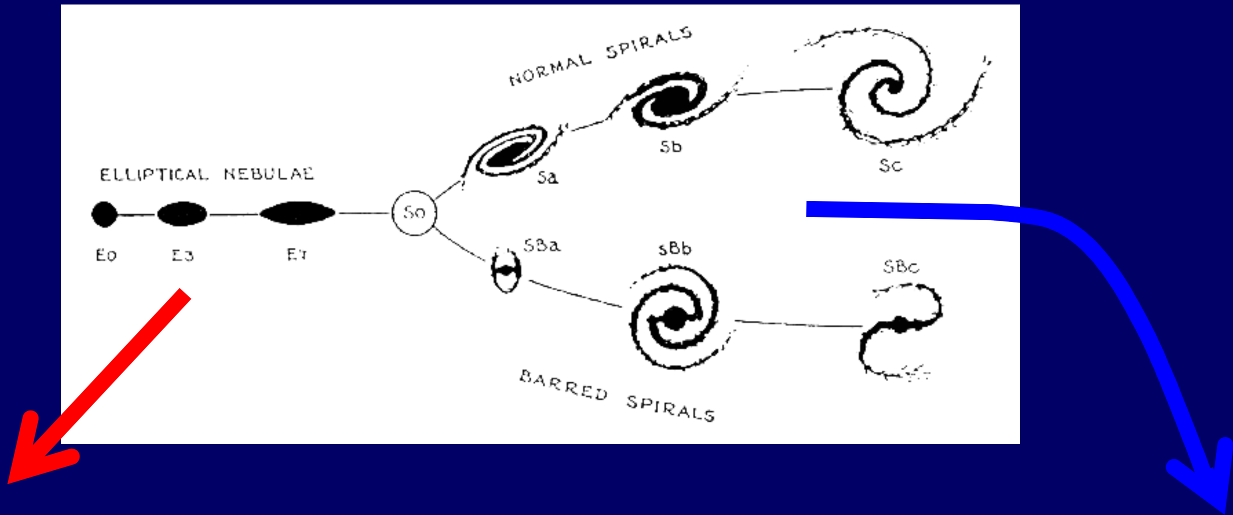
- Wet compaction by streams with mergers and VDI to compact SFGs ("blue" nuggets): rotating flattened spheroids with high dispersion, above the main-sequence, short depletion time, high gas fraction

- High SFR+AGN, outflows, massive self-gravitating bulge → fast quenching inside-out to compact spheroids (red nuggets) then star-forming gas rings and stellar envelopes (ellipticals)

- Long-term quenching by hot massive halo

- Quenching downsizing:
  massive galaxies quench earlier, efficiently, at higher central densities
  less massive galaxies : hesitant quenching till halo shutdown

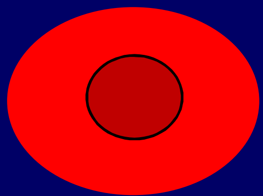
The High-z "Hubble" Sequence

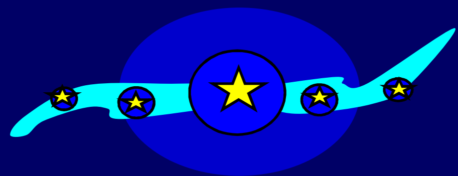


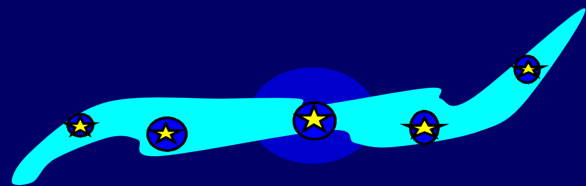
Red nuggets

Blue nuggets

Clumpy disks







Compact ellipticals

Starburst in a
compact bulge

No bars
Perturbed spiral patterns