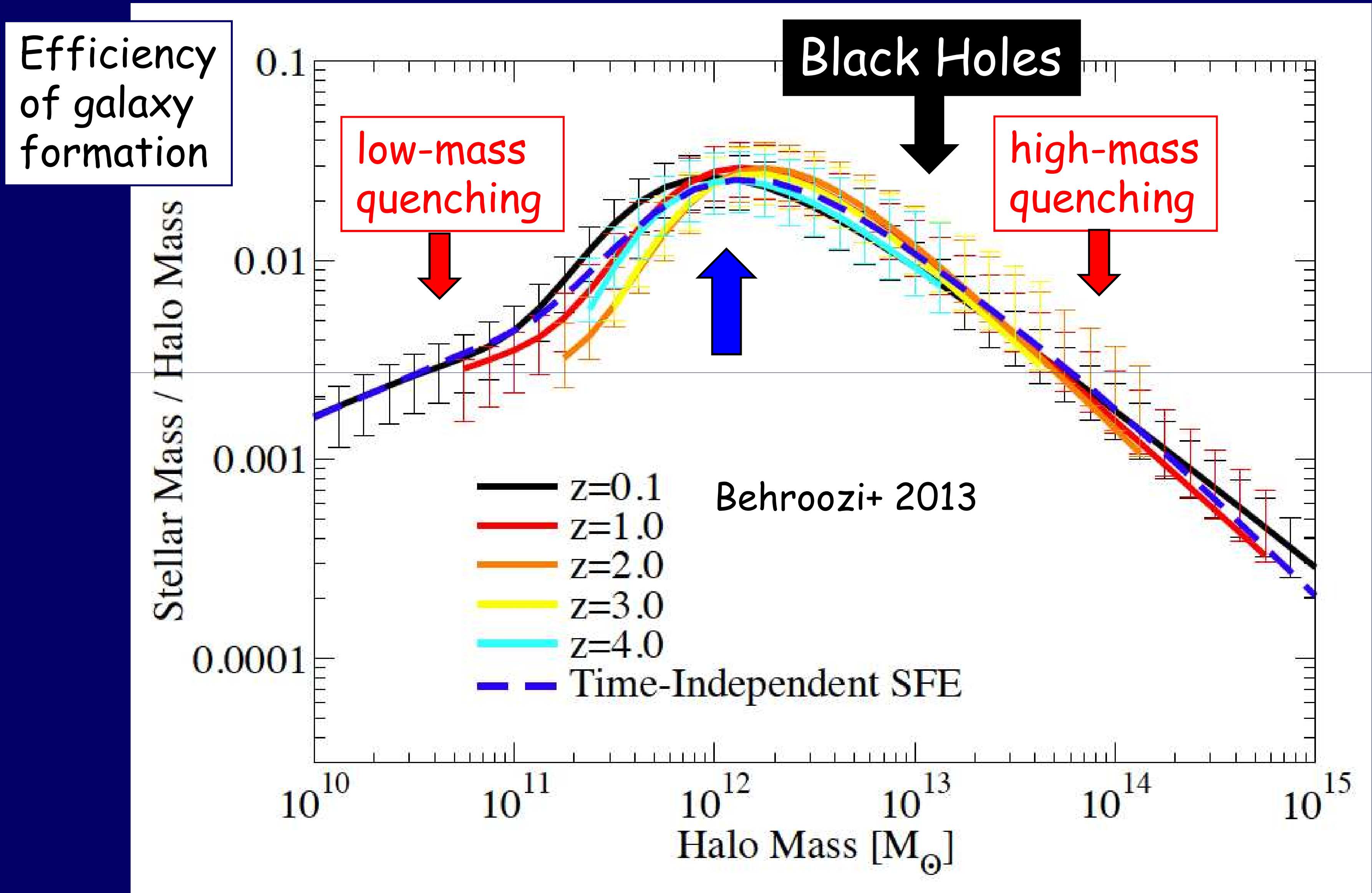
The Magic Scale of Galaxy Formation:
SNe & Hot CGM --> Compaction & BHs

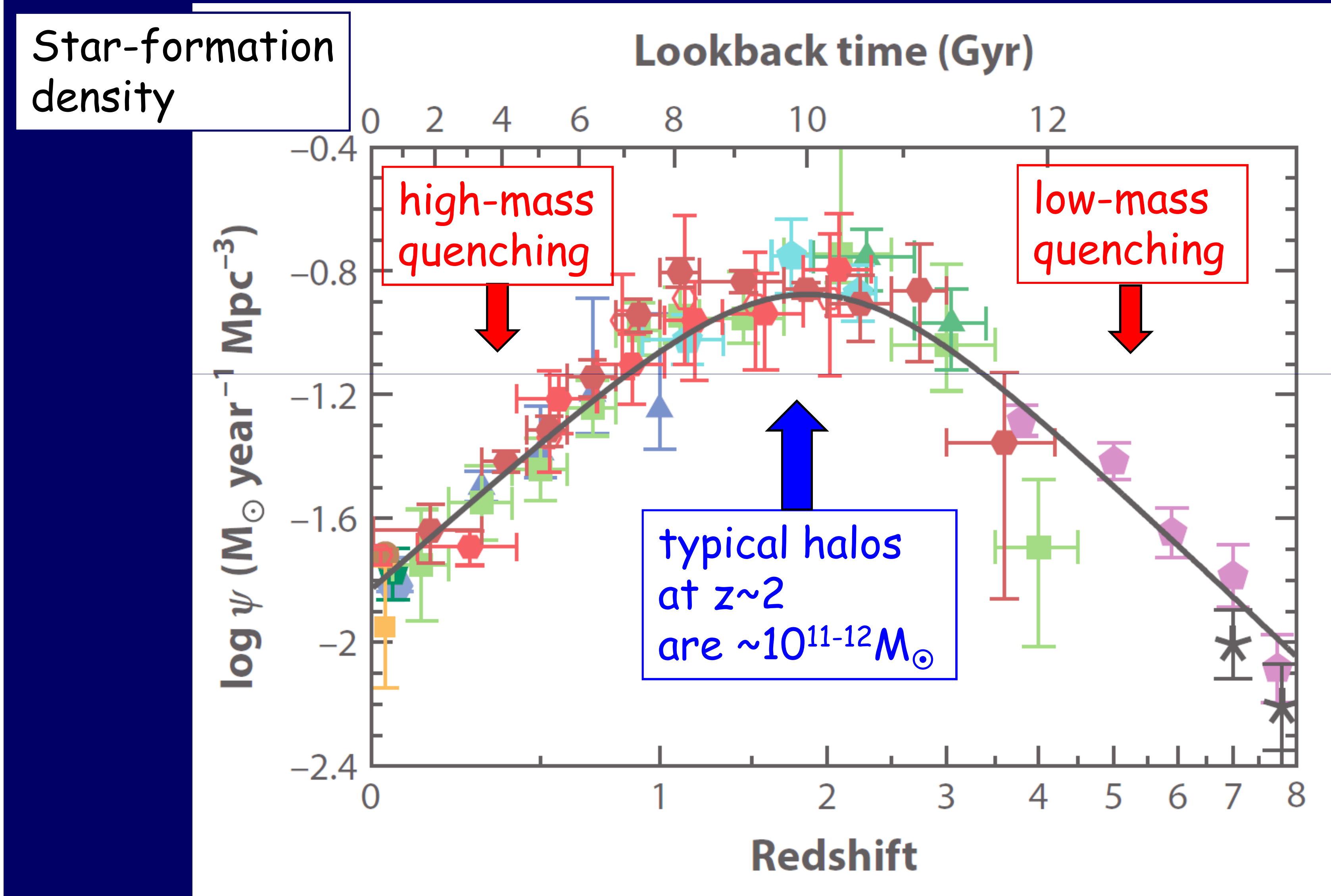
Avishai Dekel
The Hebrew University of Jerusalem & UCSC

Silk 75, December 2017

A Characteristic Mass for Galaxy Formation



A Characteristic Mass for Galaxy Formation



A Characteristic Mass for Galaxy Formation

$M_{star} \sim 10^{10.5} M_\odot$ $M_{vir} \sim 10^{12} M_\odot$ $V_{vir} \sim 100$ km/s

- Hot CGM (virial shock heating) at $M > M_{crit}$

Rees & Ostriker 77, Silk 77, Binney 77, Dekel & Birnboim 06

- SN feedback efficient at $M < M_{crit}$ (V_{crit})

Larson 74, Dekel & Silk 86

-> Compaction to Blue Nuggets + quenching at $\sim M_{crit}$ (any z)

Zolotov+15, Tacchella+16, Dekel+17

-> BH suppressed by SN at $M < M_{crit}$, BH growth at $M > M_{crit}$

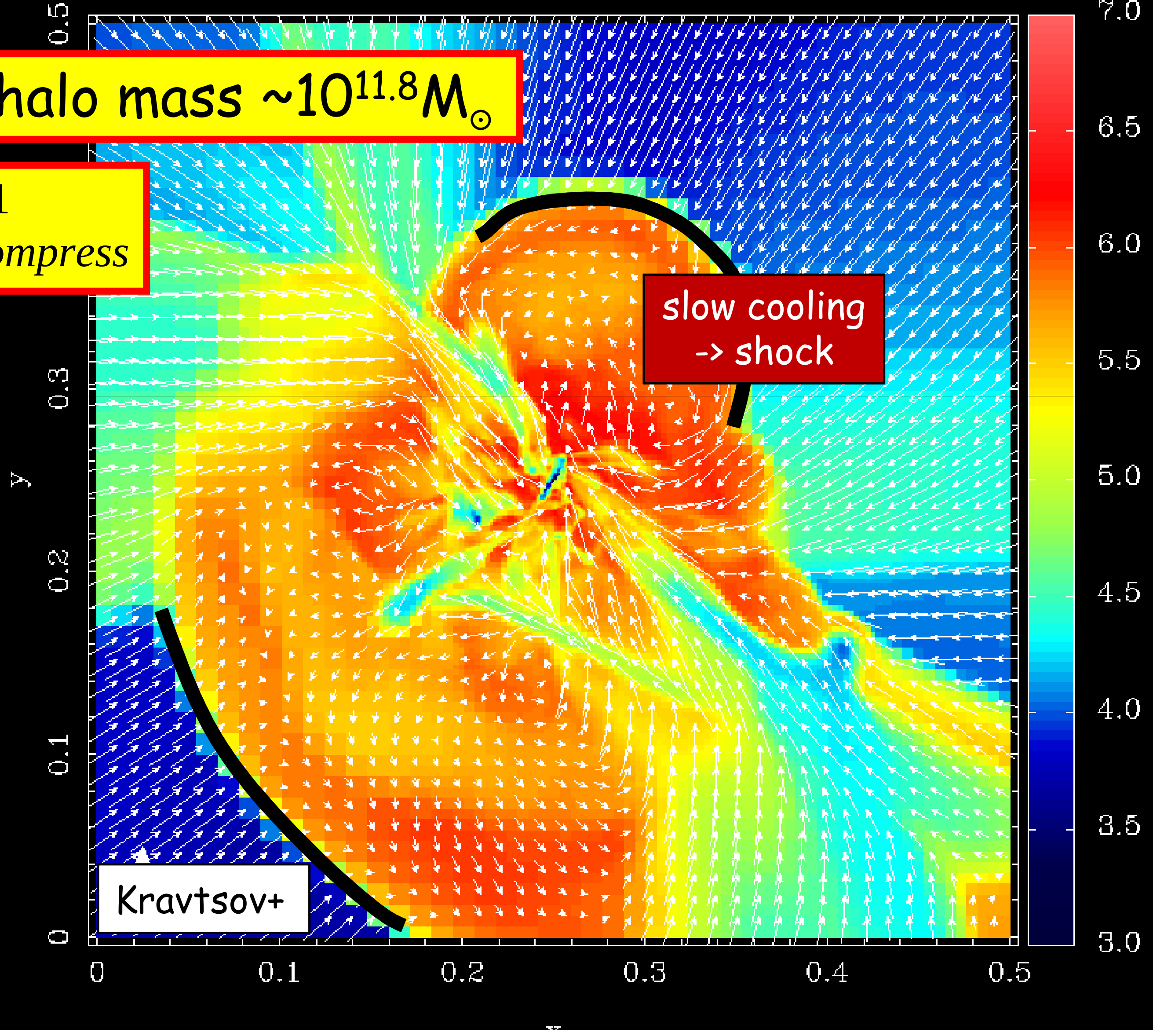
-> Quenching at $M > M_{crit}$
triggered by compaction, maintained by hot CGM & AGN

1. Hot CGM Scale: shutdown of cold gas supply

Dekel & Birnboim 06, Rees & Ostriker 77, Silk 77, Binney 77

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

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



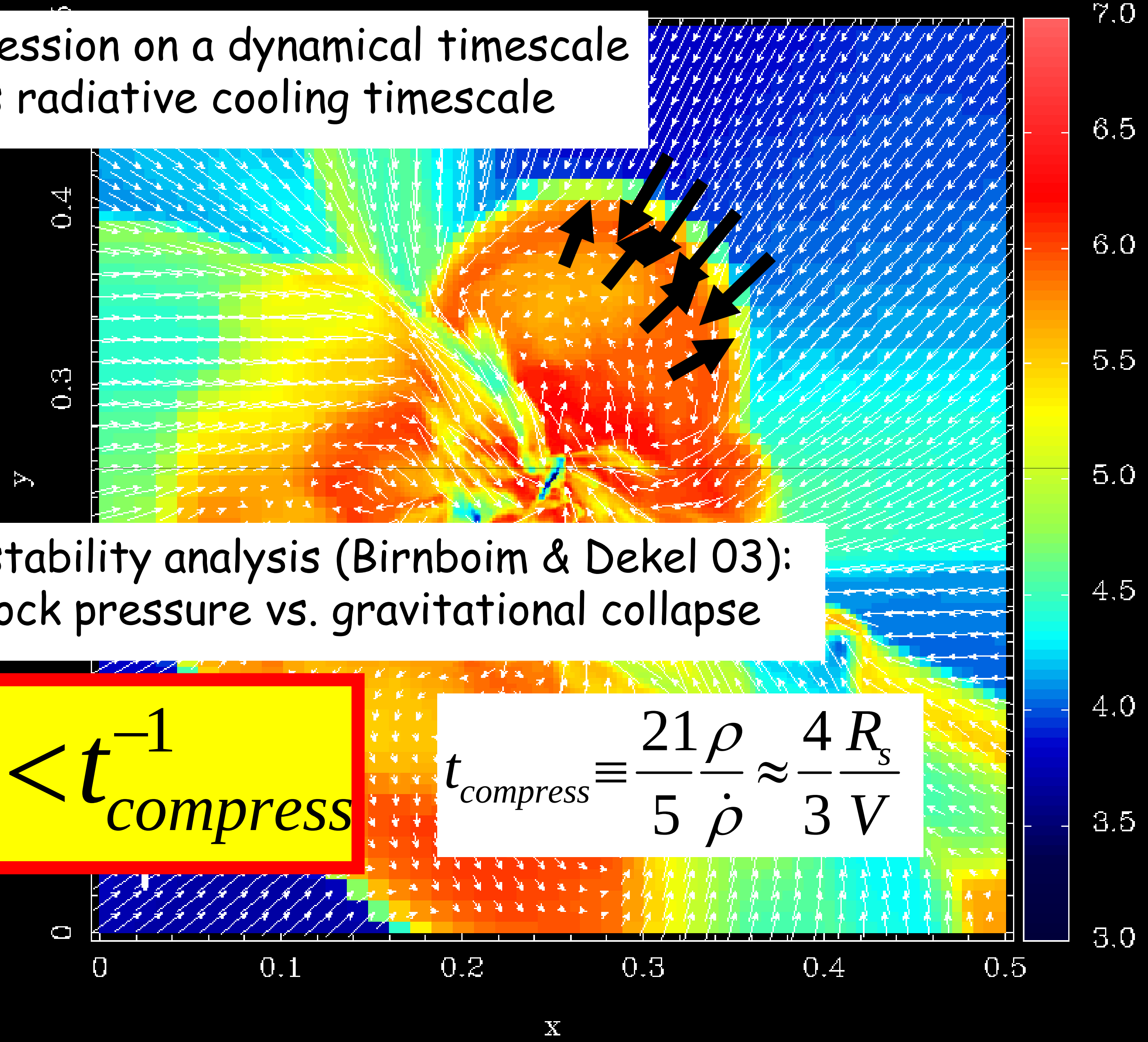
Gas through shock: heats to virial temperature

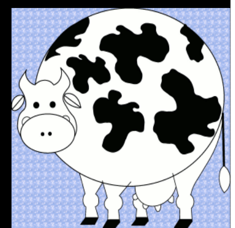
compression on a dynamical timescale
versus radiative cooling timescale

Shock-stability analysis (Birnboim & Dekel 03):
post-shock pressure vs. gravitational collapse

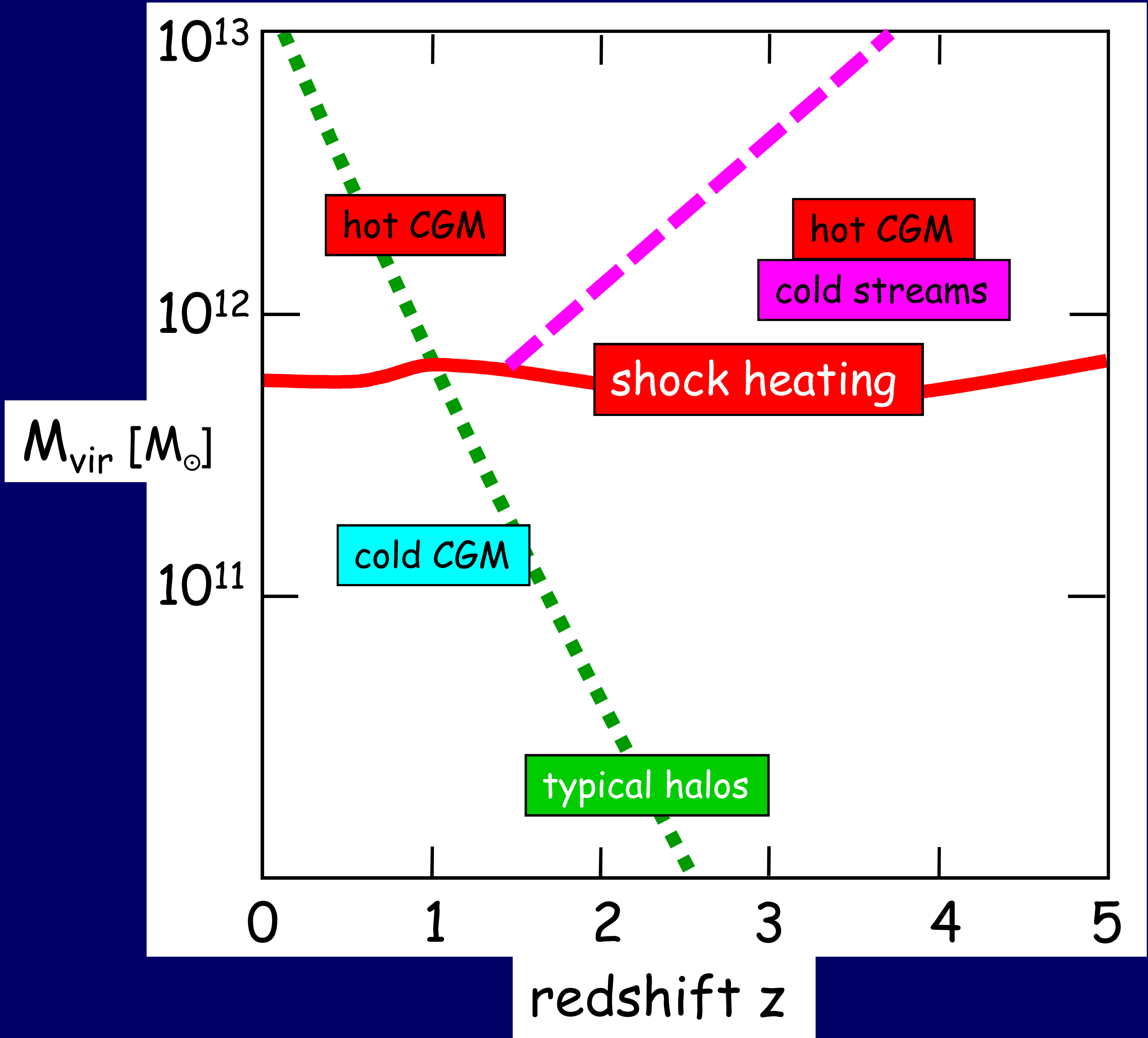
$$t_{cool}^{-1} < t_{compress}^{-1}$$

$$t_{compress} \equiv \frac{21}{5}\frac{\rho}{\dot{\rho}} \approx \frac{4}{3}\frac{R_s}{V}$$





M_{crit} by Shock Heating: $M_{vir} \sim 10^{11.5-12} M_\odot$



Simulations: Ocvirk, Pichon, Teyssier 08; Dekel+ 09

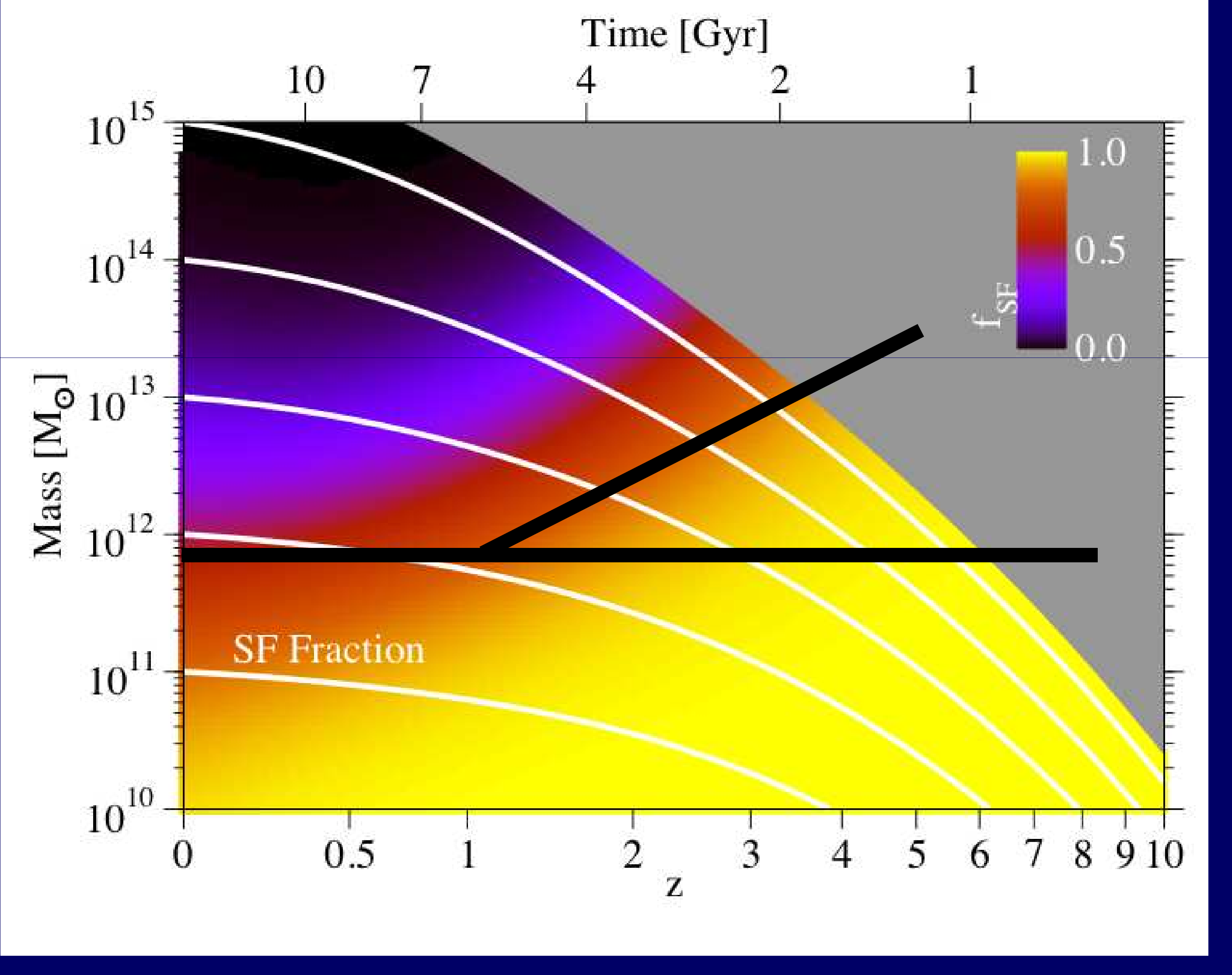
Dekel & Birnboim 06

Press & Schechter 74

Empirical Model From Observations

Behroozi+

Fraction of star-forming galaxies



Cooling Time vs Dynamical Time

2. Supernova Fdbk Scale V_{vir}~100 km/s

Dekel & Silk 86

Energy fed to the ISM during the SN adiabatic phase:

$$E_{SN} \approx \nu_{SN}\, \varepsilon_{SN}\, \dot{M}_*\, t_{cool} \qquad \approx M_*\, \varepsilon_{ff}\, (t_{cool}/t_{ff})\, \nu_{SN}\, \varepsilon_{SN}$$

#SN per M_* — energy per SN

$$\dot{M}_* = \varepsilon_{ff}\, M_* / t_{ff}$$

$t_{cool}/t_{ff} \approx 0.01$

$\Lambda \propto T^{-1}$ at $T \sim 10^5 K$

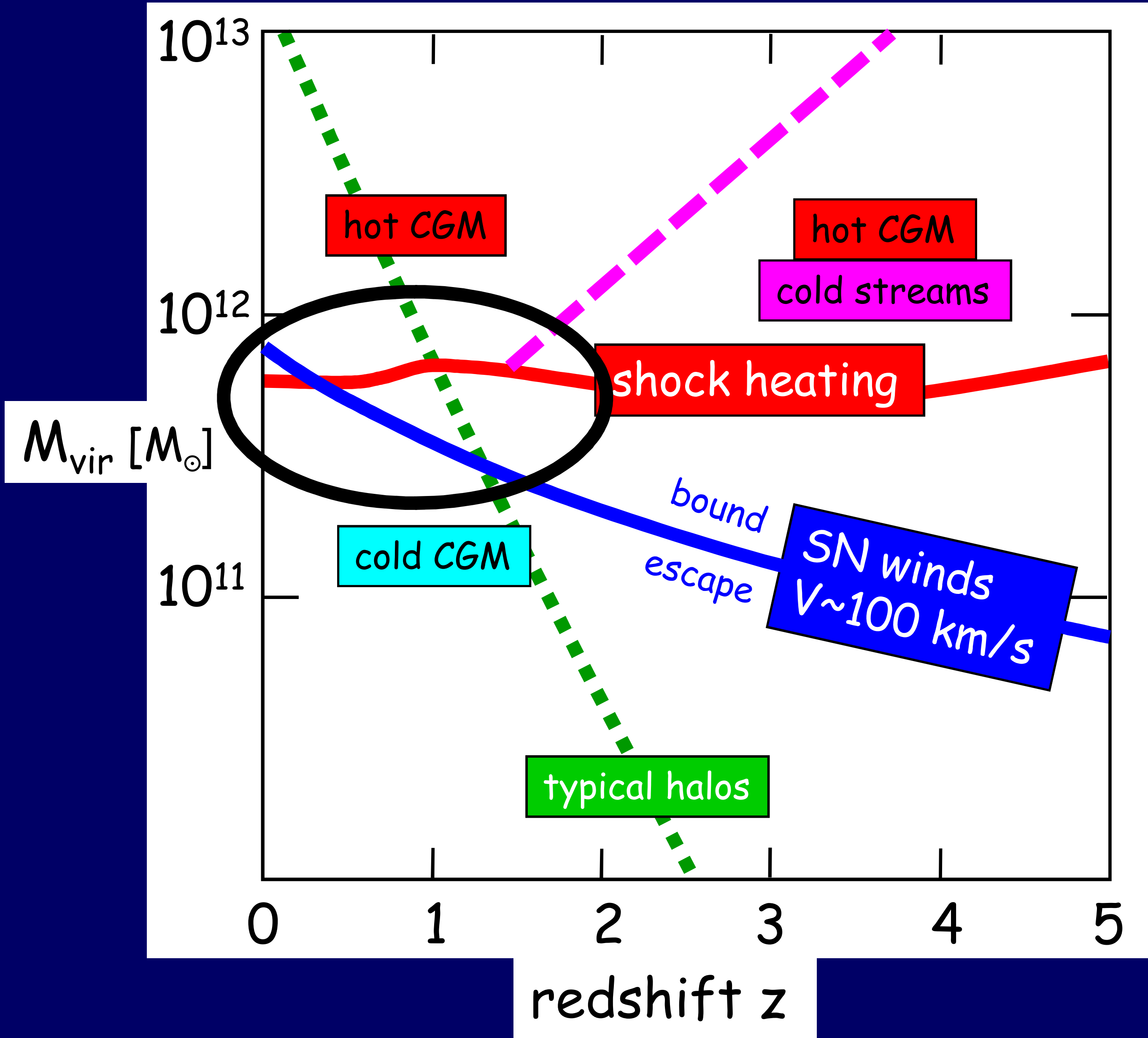
$$\rightarrow \quad E_{SN} \approx M_* V_{SN}^2, \quad V_{SN} \approx 120\,\mathrm{km/s}$$

Energy for heating/ejecting the CGM: $E_{CGM} \approx M_{gas} V_{vir}^2$

E_{SN}~E_{CGM}, peak efficiency SF M_*~M_{gas} -> a critical scale:

$$V_{vir,SN} \approx 120\ \mathrm{km/s} \ \rightarrow M_{vir,SN} \approx 7\times10^{11} M_\odot \ (\mathrm{at}\ z=0)$$

M_{crit} by SN Feedback: M_{vir}~$10^{11.5-12} M_\odot$



Dekel & Birnboim 06

Dekel & Silk 86

Press & Schechter 74

Stellar to Halo Mass Ratio

Dekel & Woo 03

$$E_{SN} \approx M_* V_{SN}^2, \quad V_{SN} \approx 120\,\mathrm{km/s}$$

$$E_{CGM} \approx M_{gas} V_{vir}^2$$

For $V_{vir} \ll V_{SN}$ -> SN fdbk is effective -> $M_* \ll M_{gas} \propto M_{vir}$

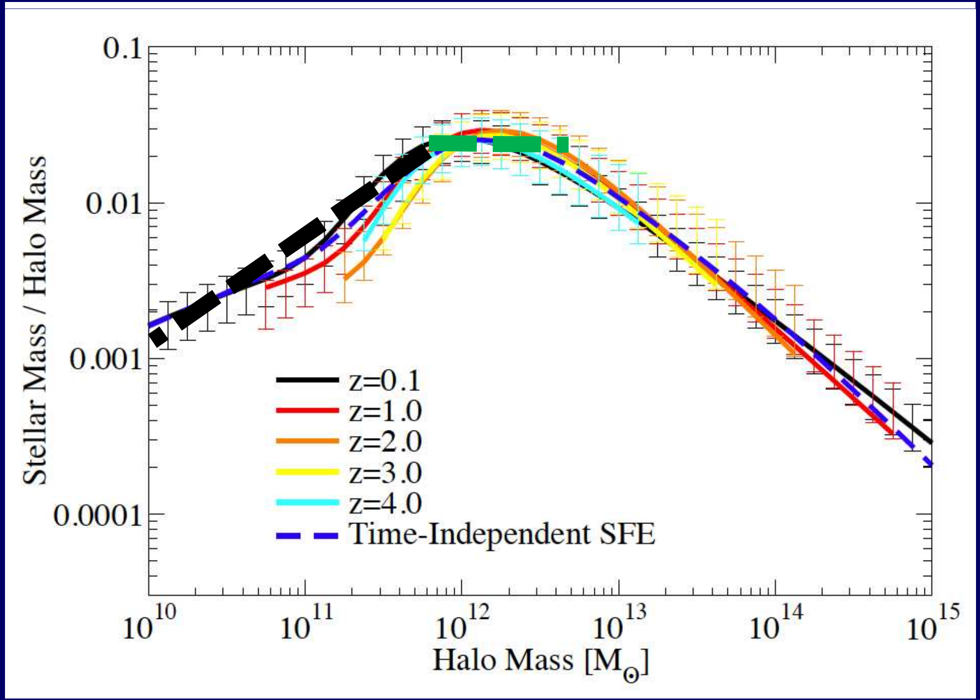
$$\frac{M_*}{M_{vir}} \propto \left(\frac{V_{vir}}{V_{SN}}\right)^2 \approx \left(\frac{M_{vir}}{M_{vir,SN}}\right)^{2/3}$$

$$M_{vir,SN} \approx 10^{12} M_\otimes$$

For $V_{vir} \sim V_{SN}$ ->
SN fdbk is ineffective
-> $M_* \sim M_{gas} \propto M_{vir}$

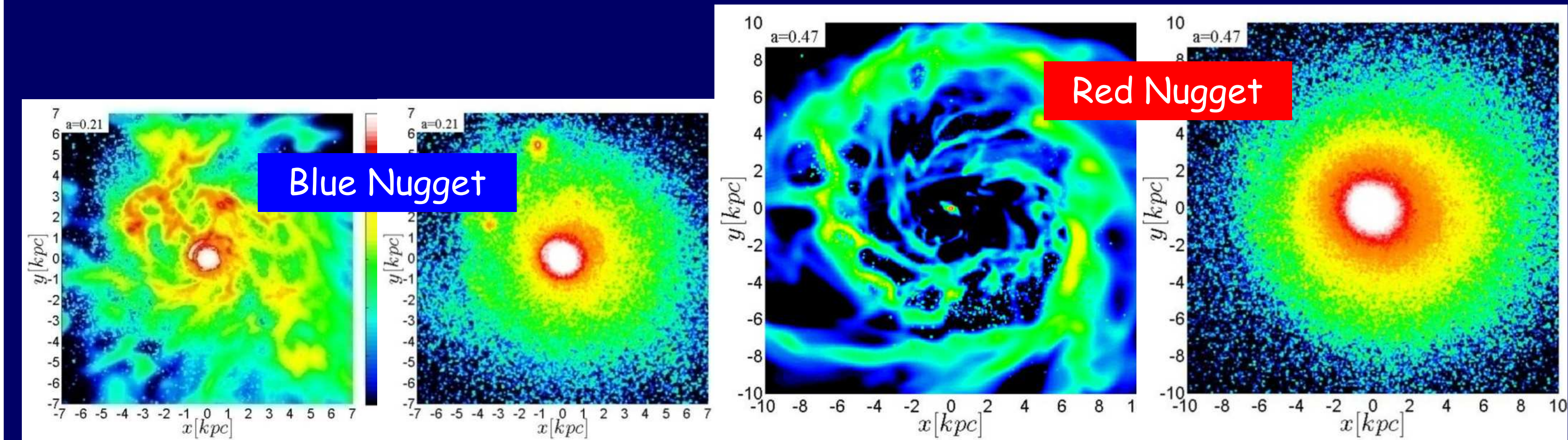
$$\frac{M_*}{M_{vir}} \approx const.$$

peak of SF efficiency



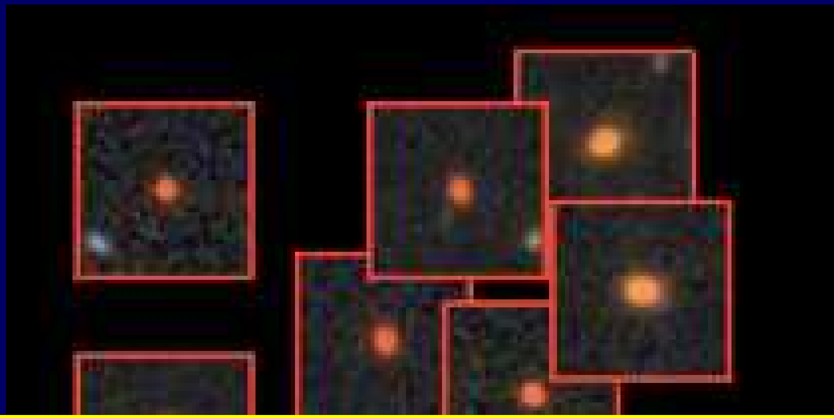
3. Wet Compaction to Blue Nuggets

Dekel & Burkert 14, Zolotov+15, Tacchella+16a,b, Dekel, Lapiner+17



Red Nuggets (RNs)

Damjanov,
Abraham,
McCarthy,
Glazebrook
2009



What is the origin of the compact Red Nuggets?

Wet Compaction:
dissipation & drastic loss of angular momentum

$z\sim2$ $M\sim10^{11}M_\odot$ $R_e\sim1$ kpc low-SFR
the progenitors of the cores of today's Es?

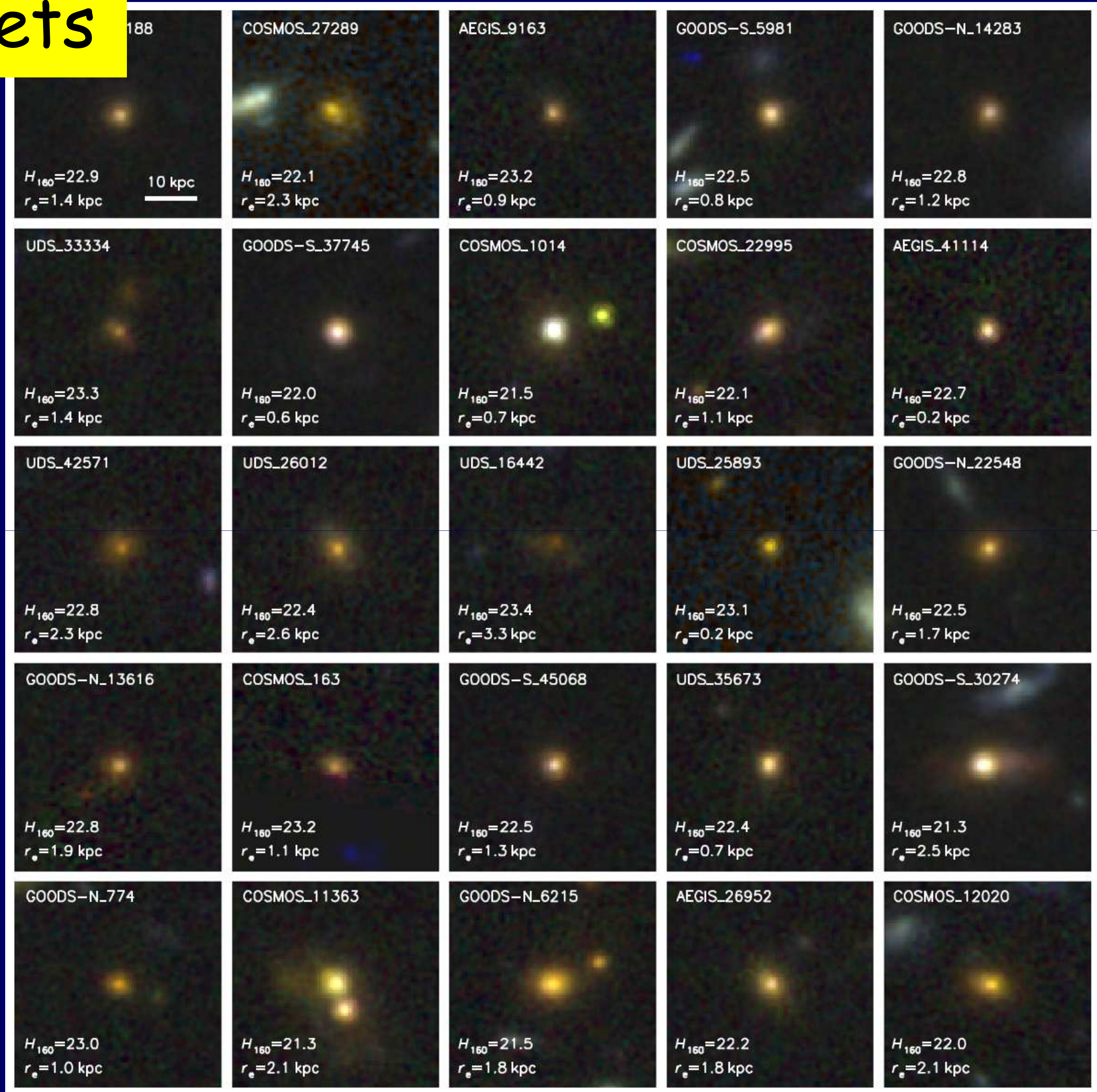
Van Dokkum, Franx, Kriek, Bouwens, Labbe+ 08,10,14, Damjanov+09, Newman+10, Damjanov+11, Whitaker+12, Bruce+12, …

"Blue" Nuggets

Barro+13-17
van Dokkum+ 15

Compact, star forming, at z~2

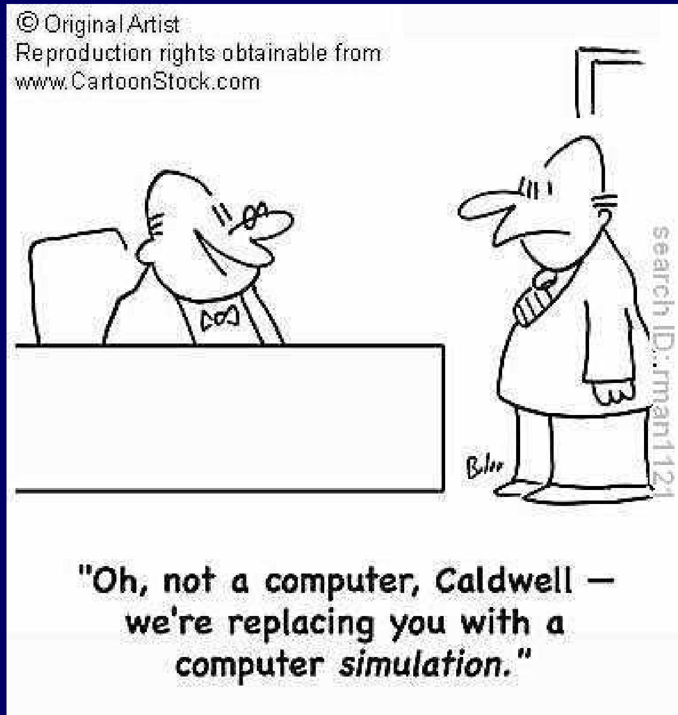
The BNs are actually red…



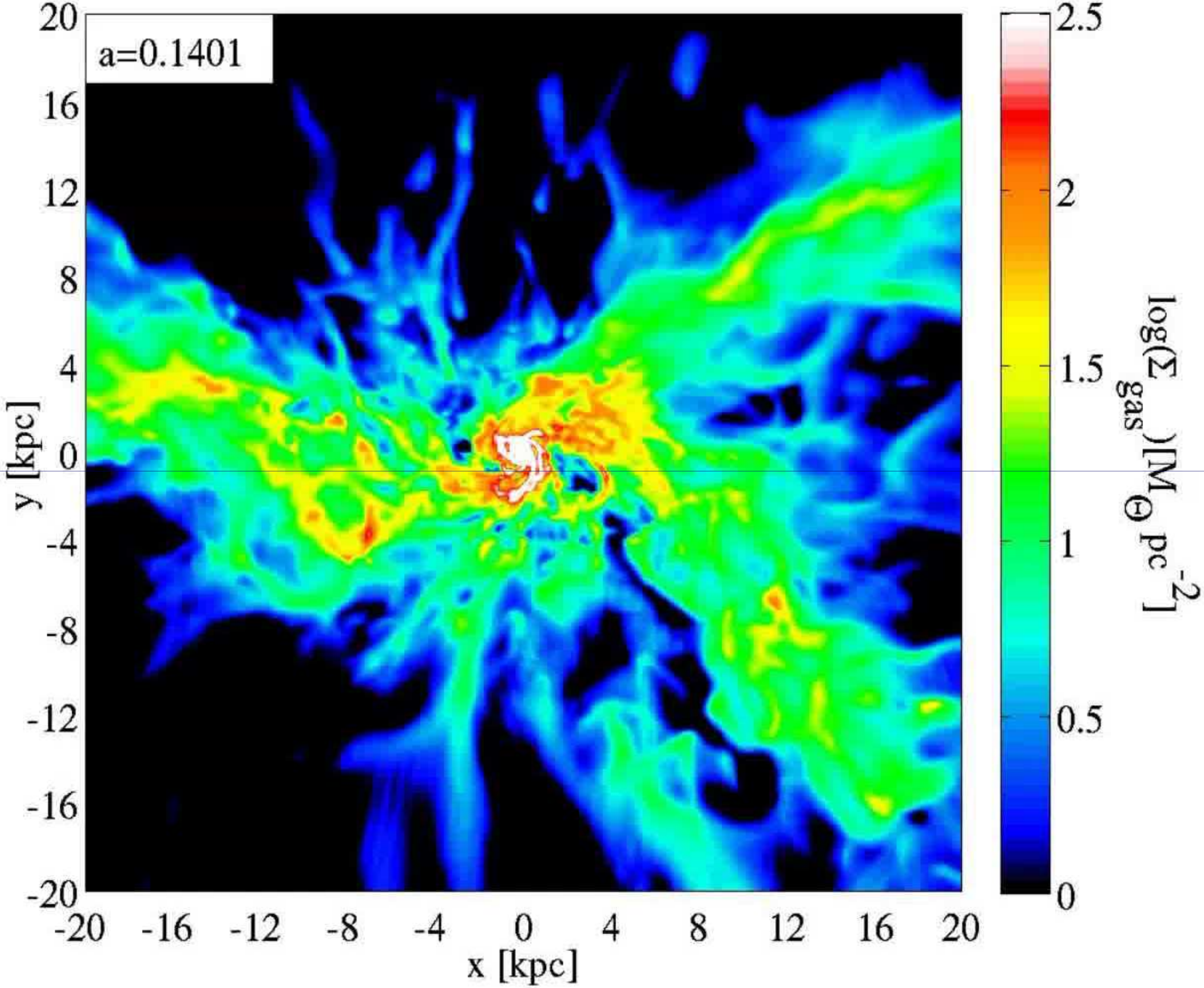
Cosmological Simulations

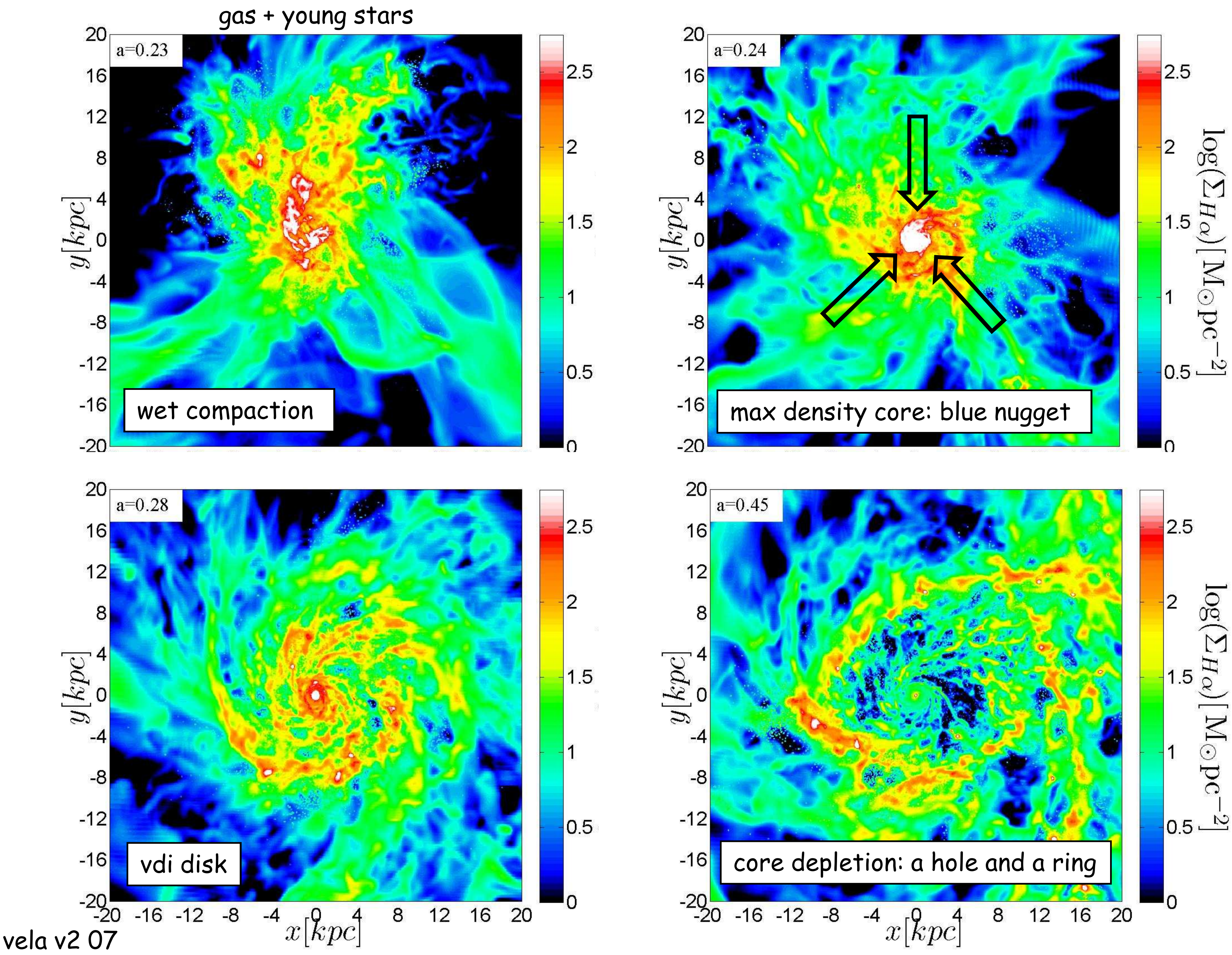
VELA by Daniel Ceverino+
Code: AMR ART (Kravtsov, Klypin)
Max resolution 25 pc
5x35 galaxies zoom-in
SN and radiative feedback

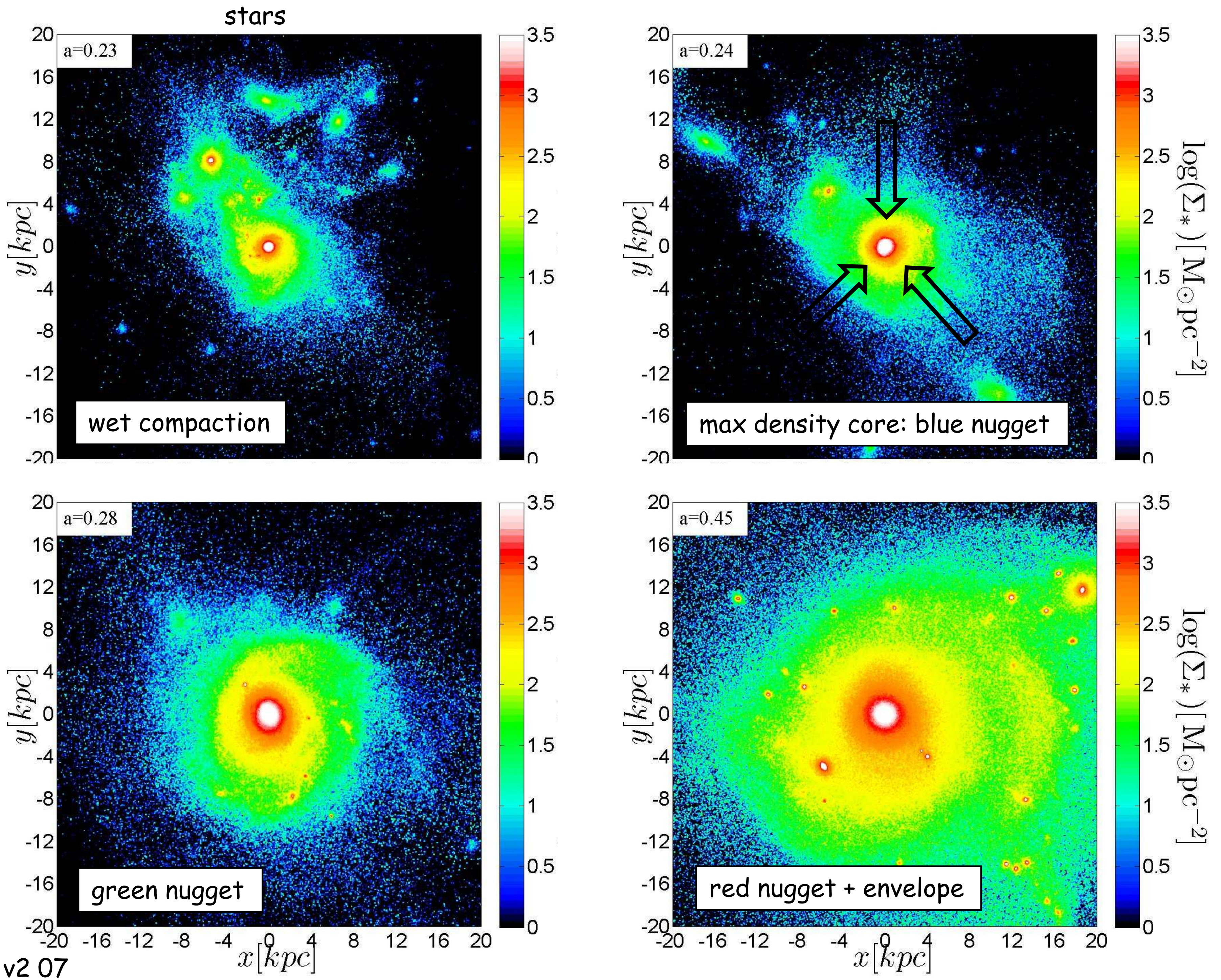
+RAMSES, ENZO, GASOLINE



Collaborators:
Ceverino, Danovich, DeGraf, Freundlich, Inoue, Jiang, Lapiner, Kretschmer, Mandelker, Roca-Fabrega, Tacchella, Tomassetti, Tweed, Zolotov,
Bournaud+, Burkert+, Krumholz+, Primack+, Teyssier+,
Carollo+, Faber+, Genzel+


a=0.1401
y [kpc]
x [kpc]
20
16
12
8
4
0
-4
-8
-12
-16
-20
-20
-16
-12
-8
-4
0
4
8
12
16
20
$\log(\Sigma_{gas})[M_\odot\,pc^{-2}]$
2.5
2
1.5
1
0.5
0

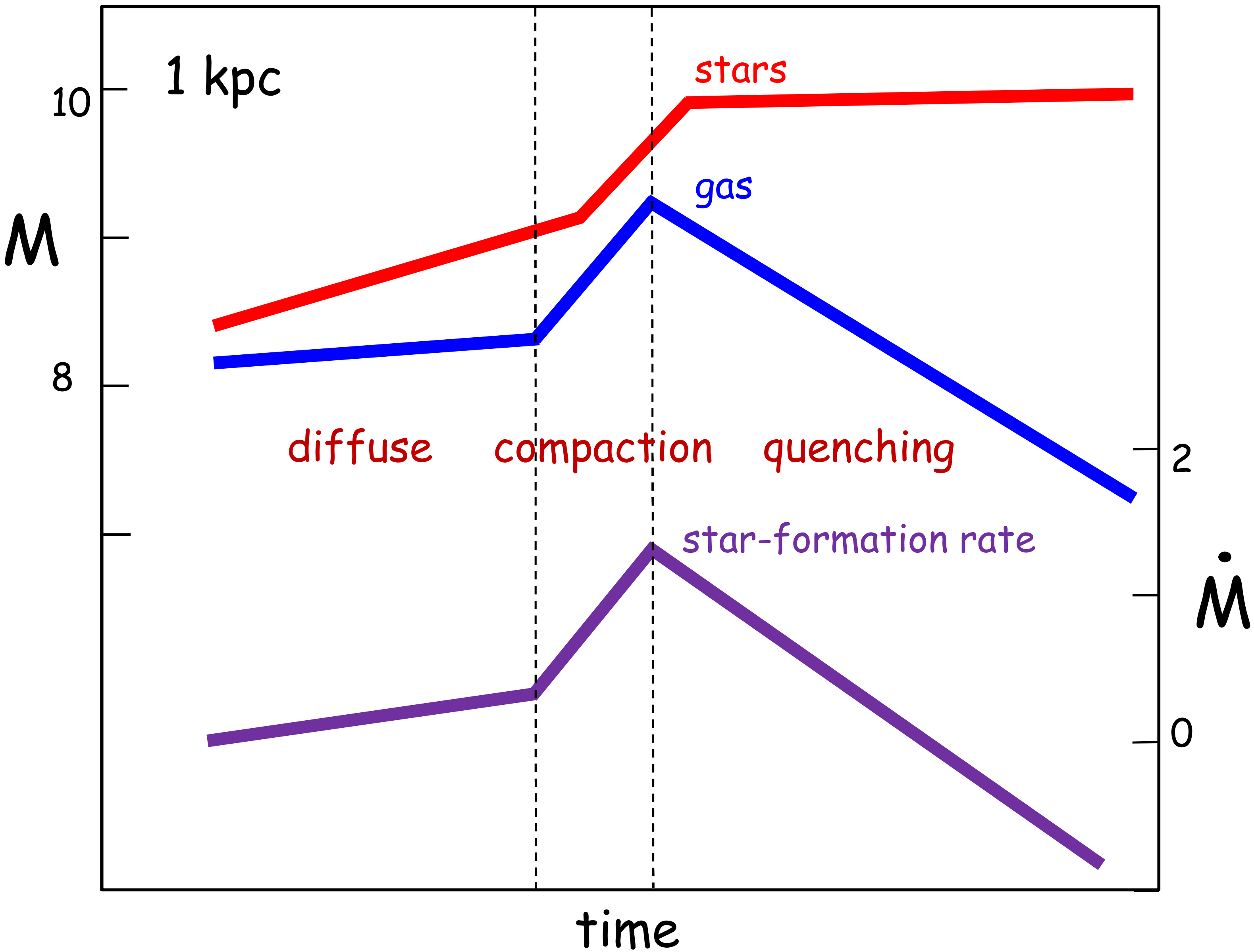

gas + young stars
a=0.23
wet compaction
a=0.24
max density core: blue nugget
a=0.28
vdi disk
a=0.45
core depletion: a hole and a ring
y[kpc]
x[kpc]
log(Σ_{Hα}) [M⊙pc^{-2}]
vela v2 07



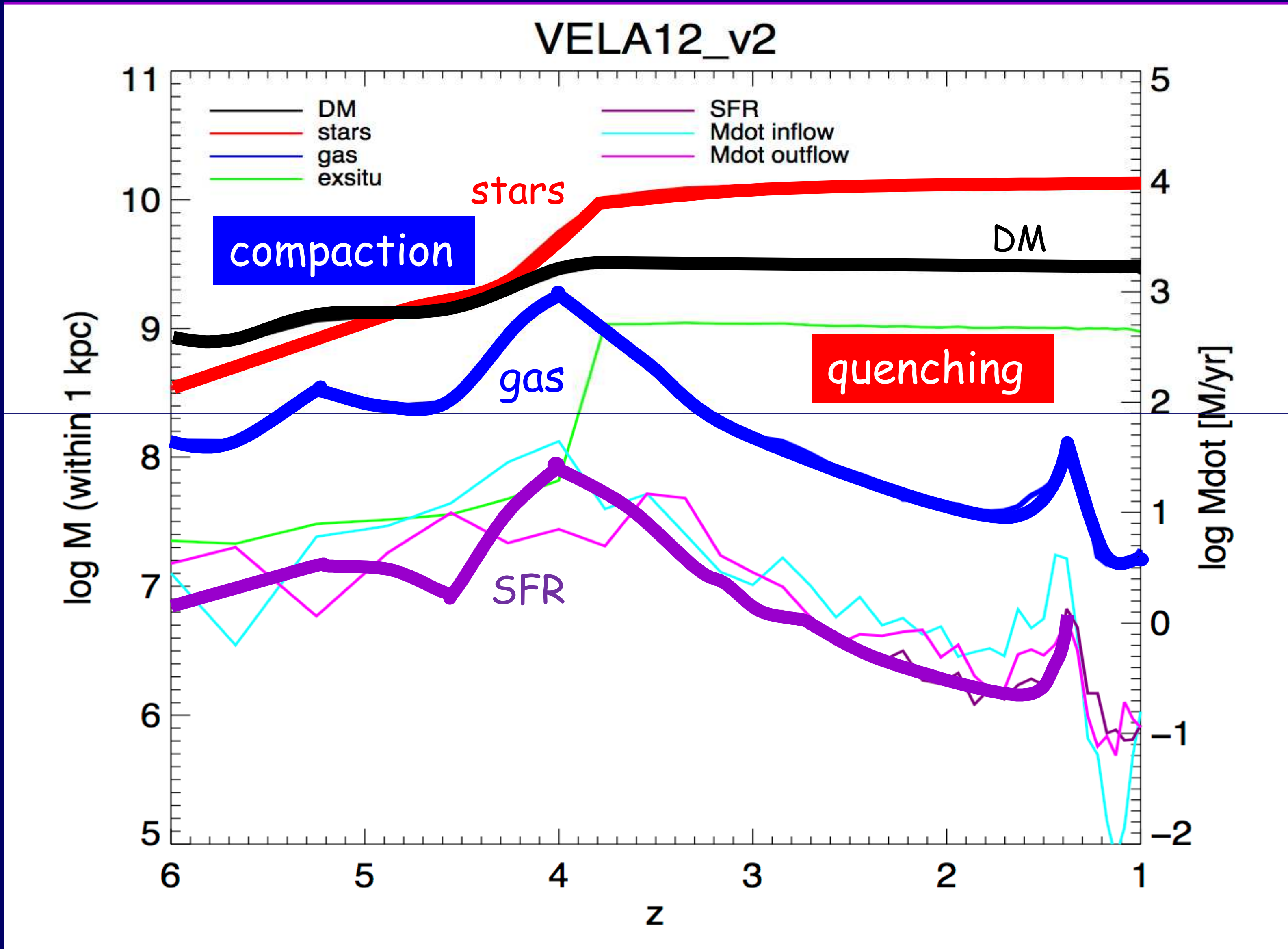
stars
a=0.23
wet compaction
a=0.24
max density core: blue nugget
a=0.28
green nugget
a=0.45
red nugget + envelope
y[kpc]
x[kpc]
log(Σ*)[M⊙pc^-2]

vela v2 07

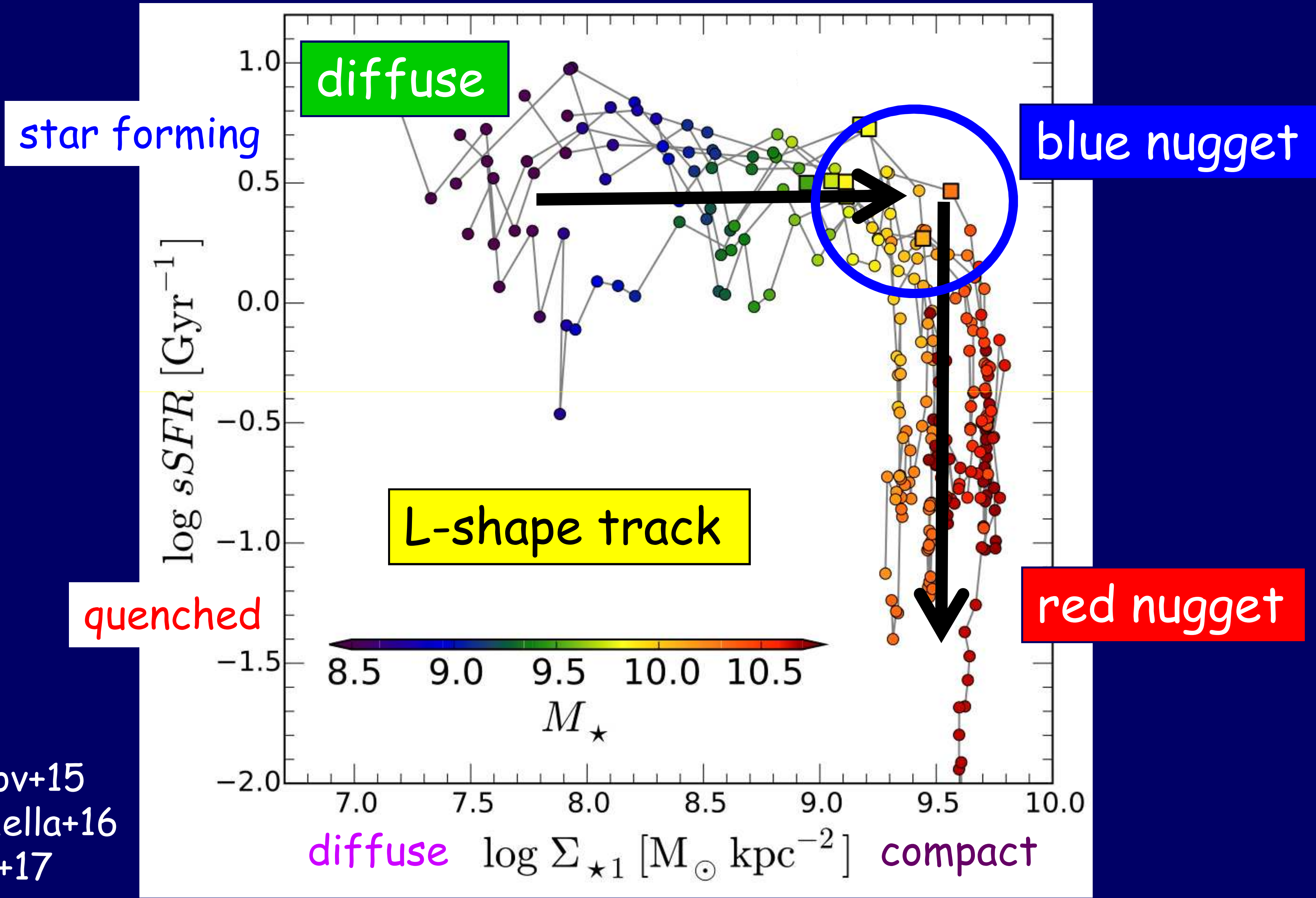
Compaction -> Quenching



Compaction and quenching in the inner 1 kpc



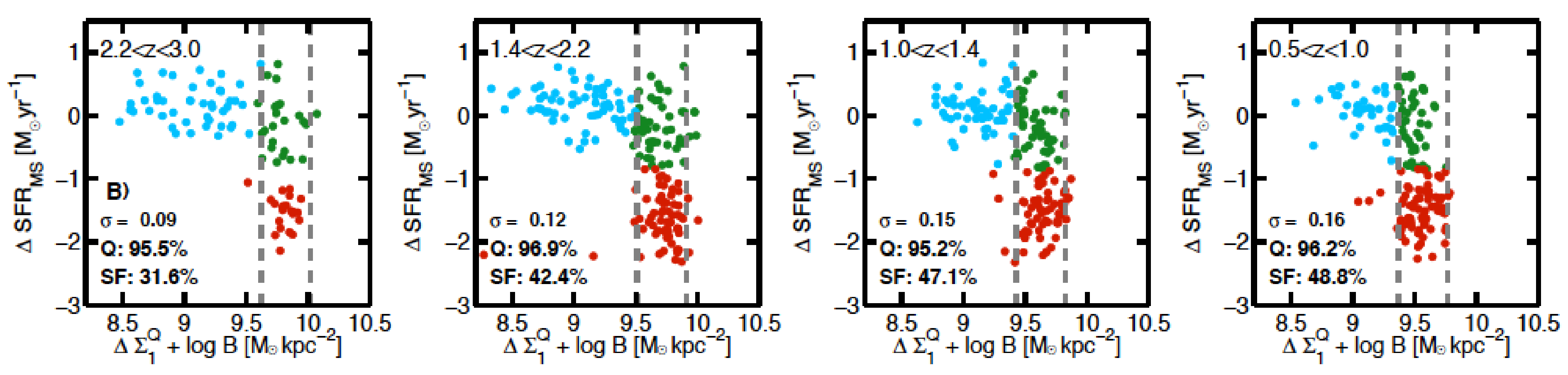
Compaction and Quenching in Simulations

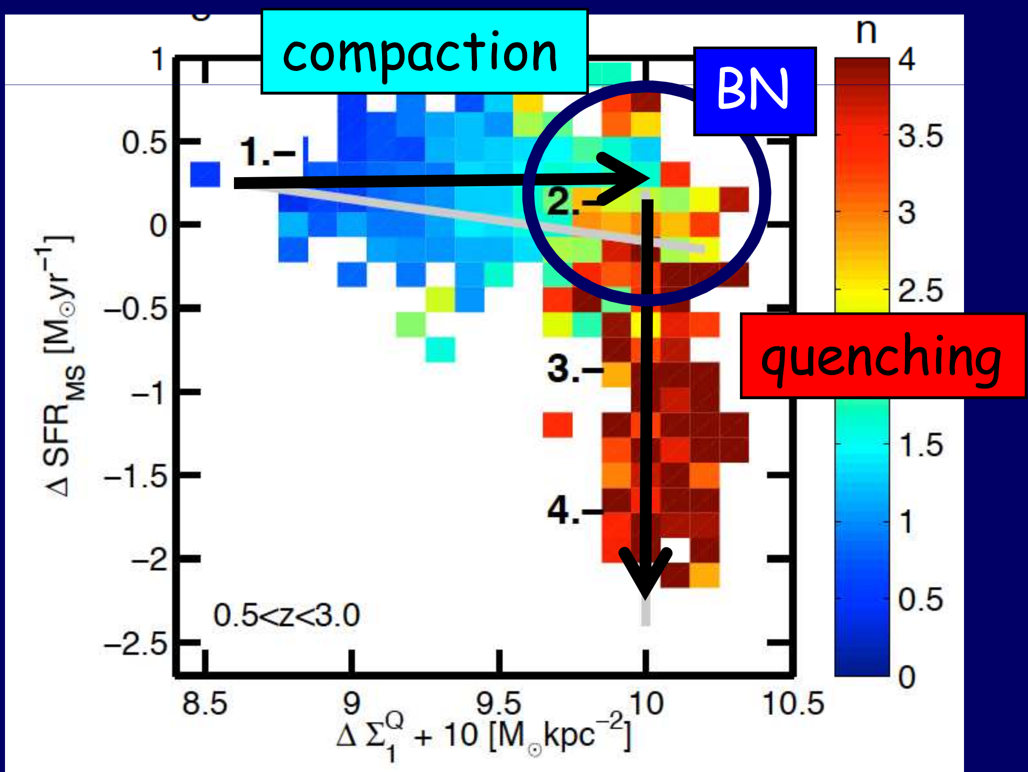


Zolotov+15
Tacchella+16
Dekel+17

Observed L-Shape Track

Barro+17





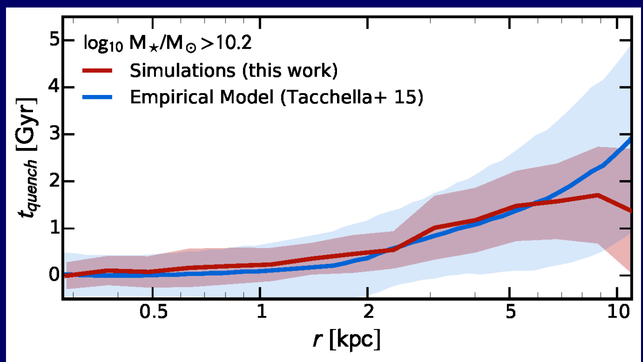
Profiles Evolution - Stacked in Phases

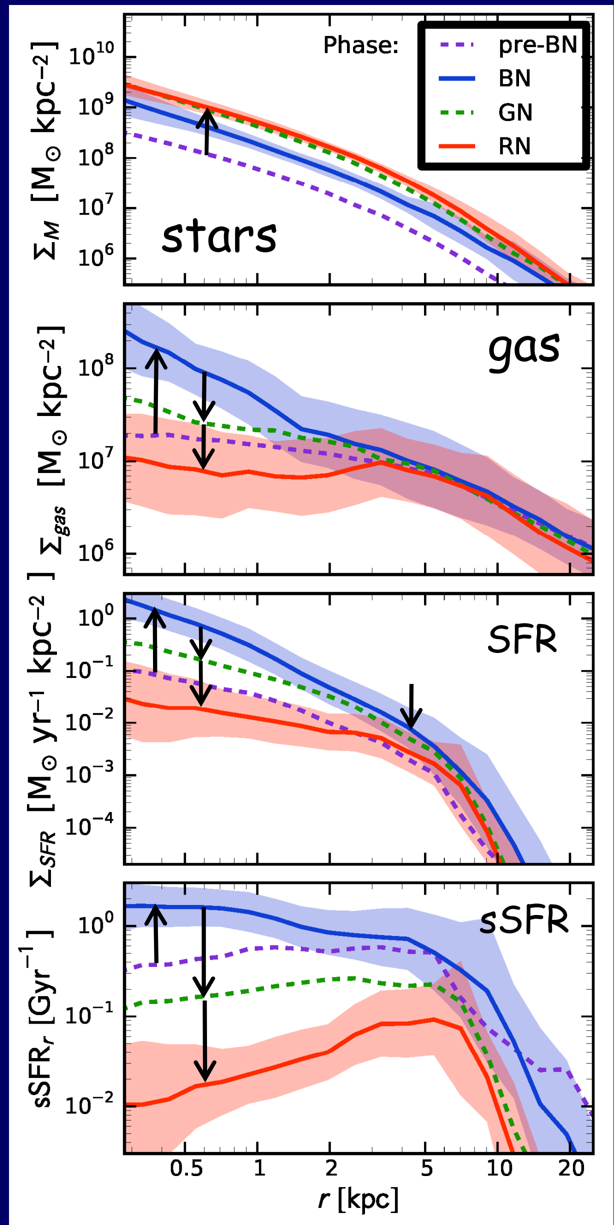
Self-similar growth of stellar profile (sSFR flat)
Saturation of core post-BN

1. Gas central cusp
Wet compaction to BN
Quenching outside-in

2. Central gas depletion
Quenching inside-out

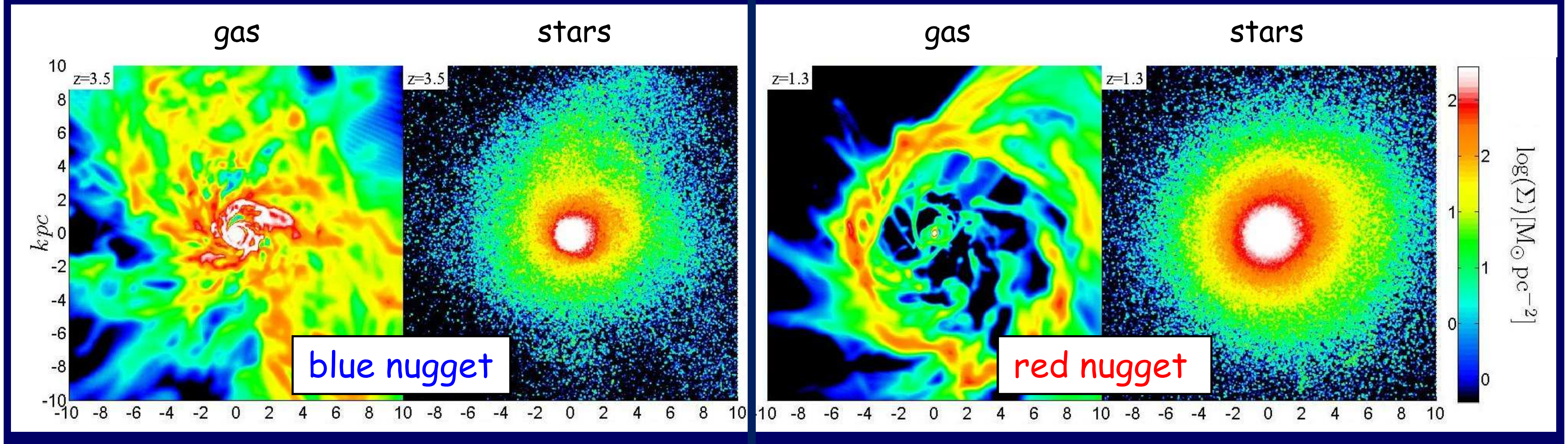
sSFR profile rising post-BN
Quenching inside-out





Tacchella+ 2016

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

What is the Trigger of wet Compaction?

Drastic loss of angular momentum

- Mergers (major, minor) (Barnes, Hernquist 91; Hopkins+ 06)

- VDI-driven inflow (Dekel, Burkert 15)

- Counter-rotating streams (Danov

- Tidal compression (Deke ; Renaud+ 14; Mandelker+ 16)

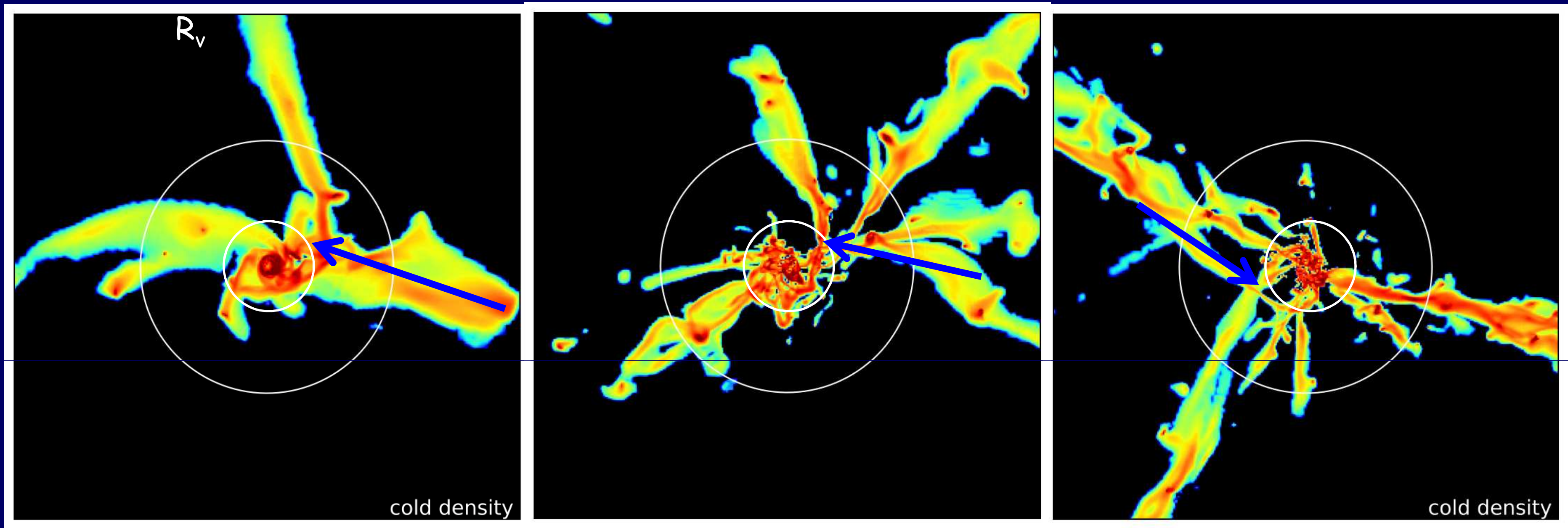
- Triaxial halo core (Ceverino+ 15; Tomassetti+ 16)

- Return of recycled low-AM gas (Elmegreen+ 14; DeGraf+ 16)

50% mergers, 30% no mergers

Counter-rotating Streams

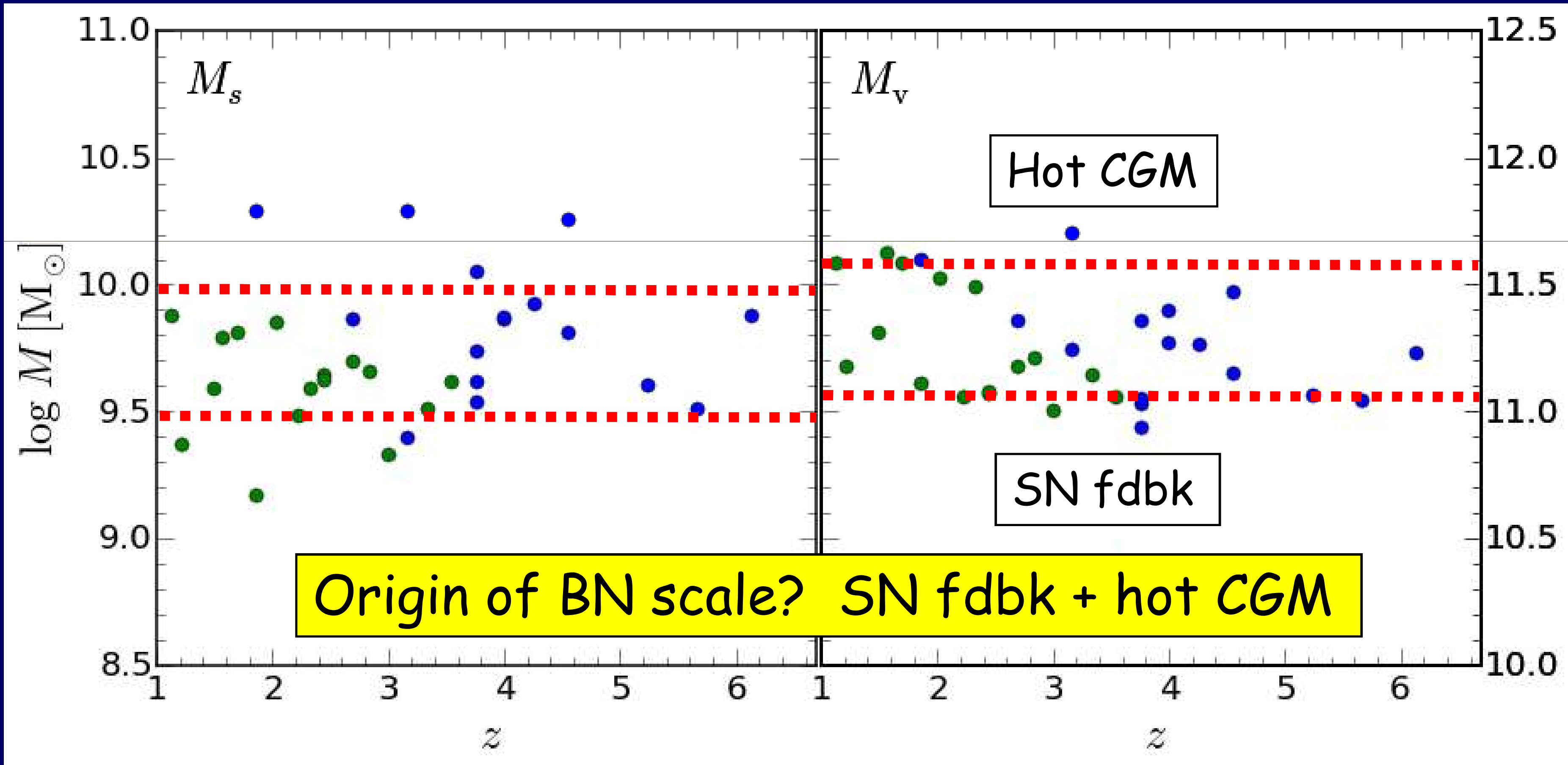
Danovich+15



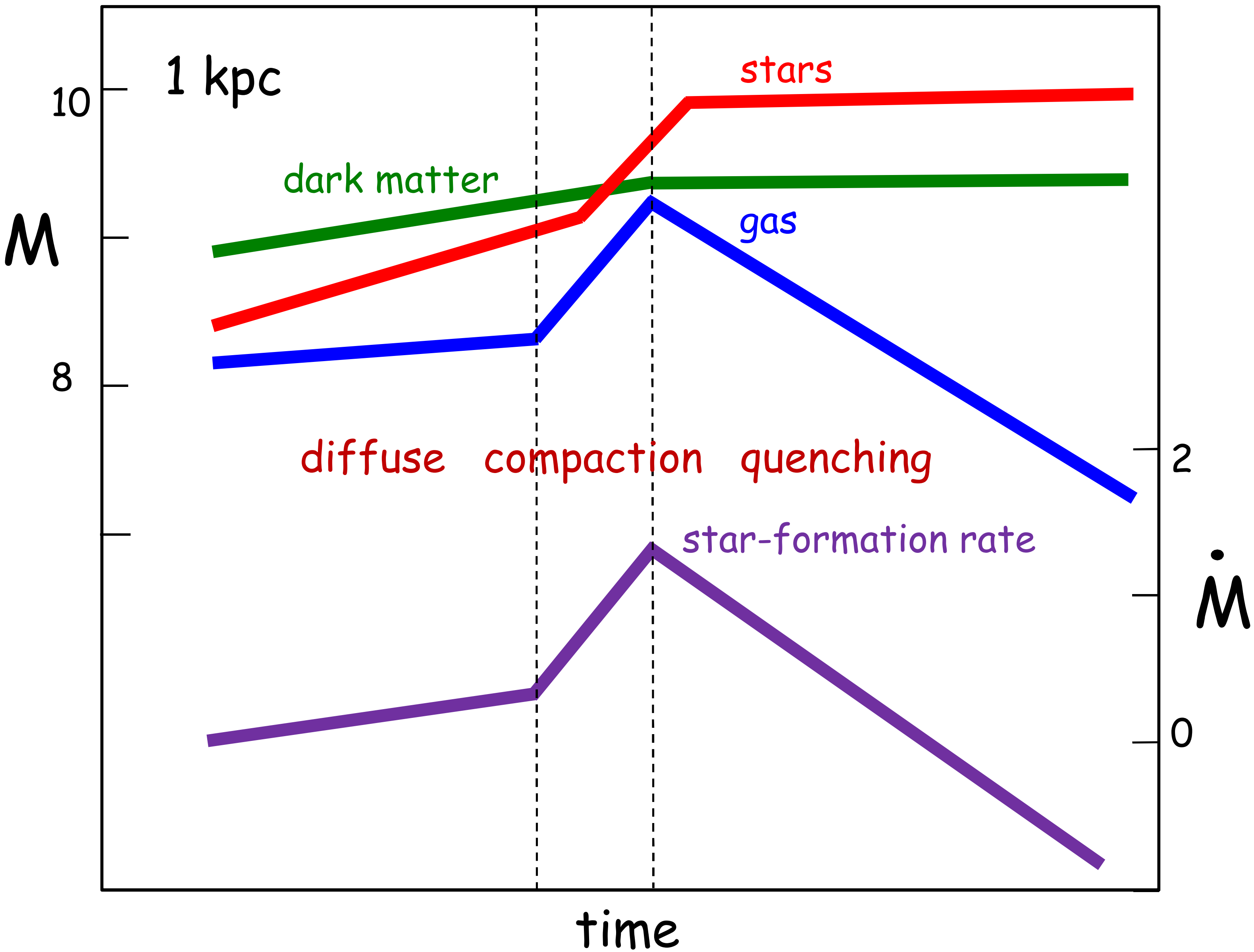
1/3 streams are counter-rotating

A Critical Mass for Blue Nuggets (at all z)

$M_{star} \sim 10^{10} M_\odot$ $M_{vir} \sim 10^{11.5} M_\odot$

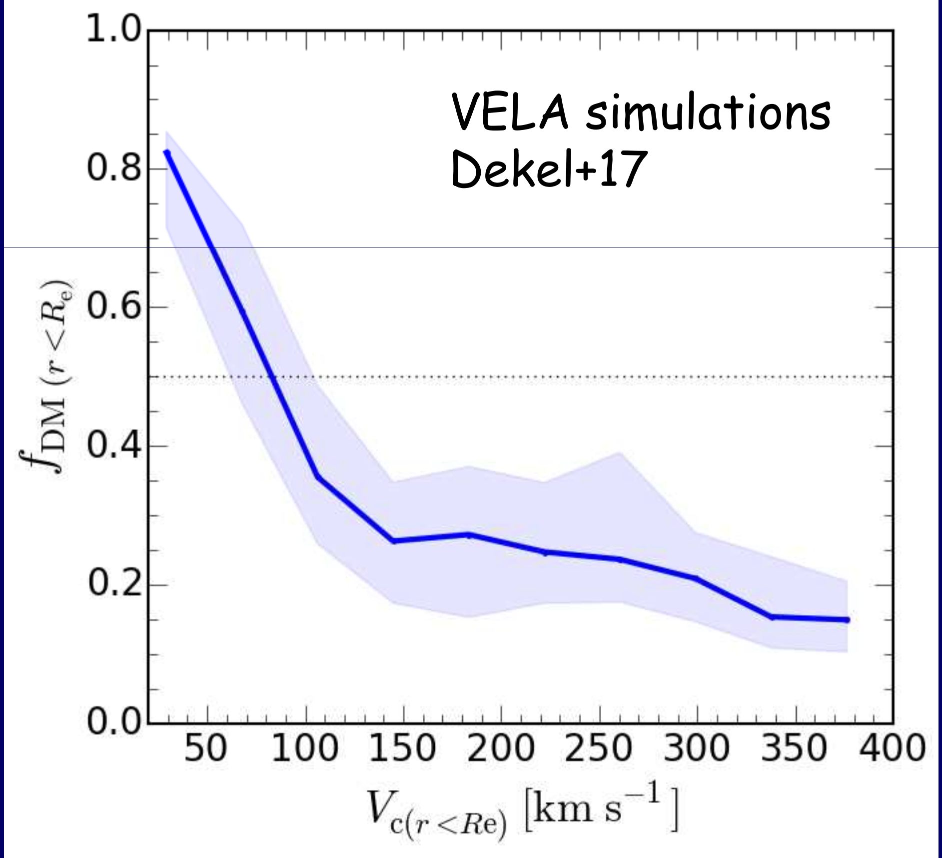


Dark Matter to Baryon Dominance

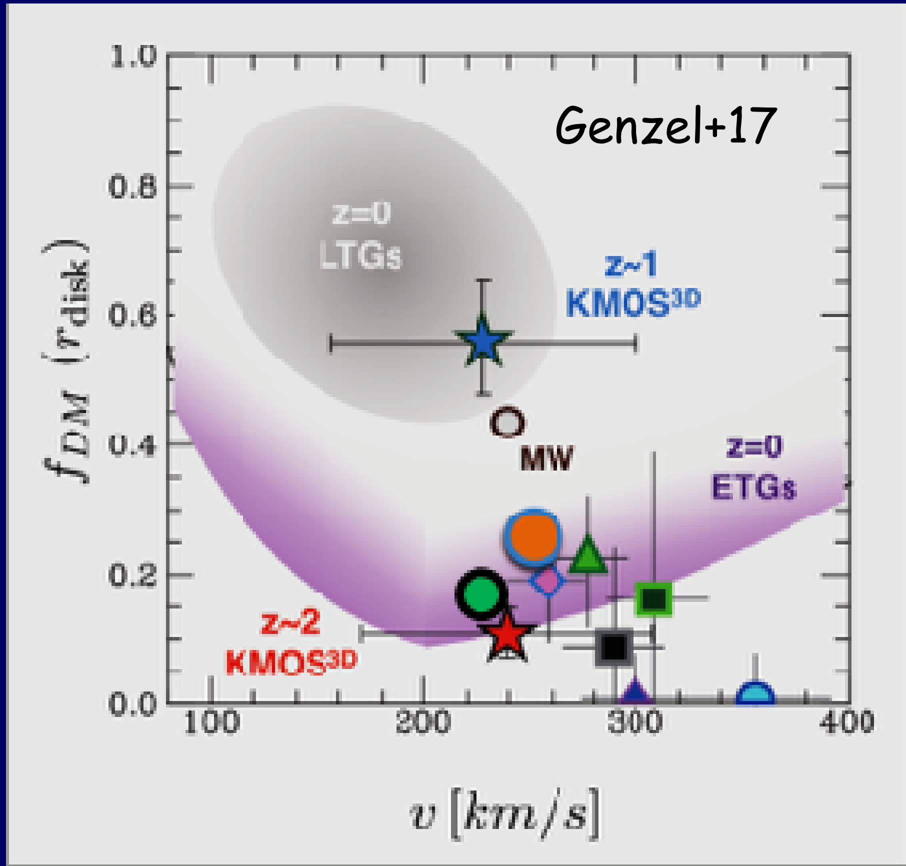


Baryon Dominance in Massive Galaxies

Transition from dark-matter to baryon dominance due to compaction into a Blue Nugget at $M_* > 10^{10} M_\odot$



mass



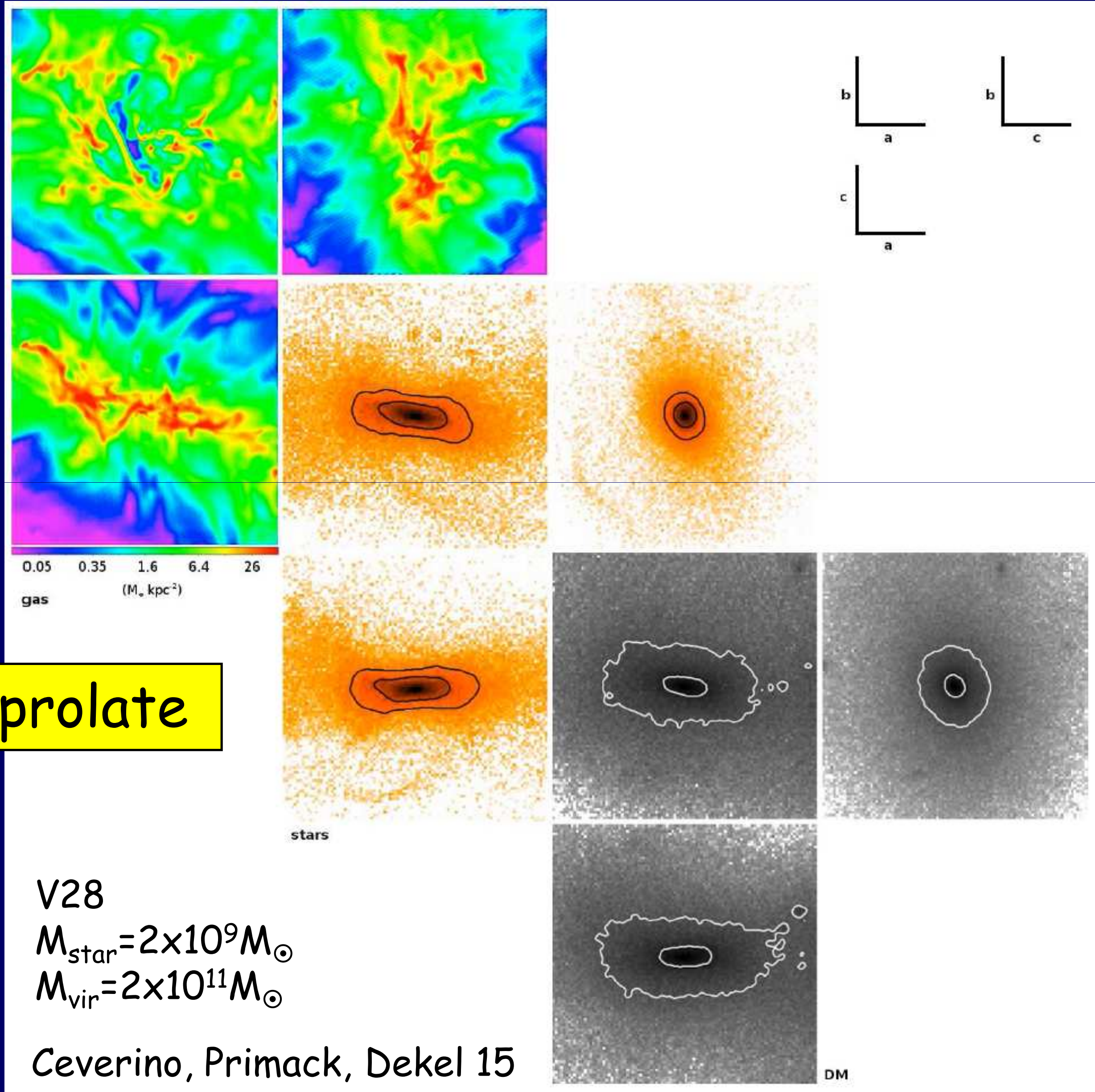
mass

A Prolate Low-Mass Galaxy at z=2.2 in Sims

Gas: disk

Stars and DM: prolate

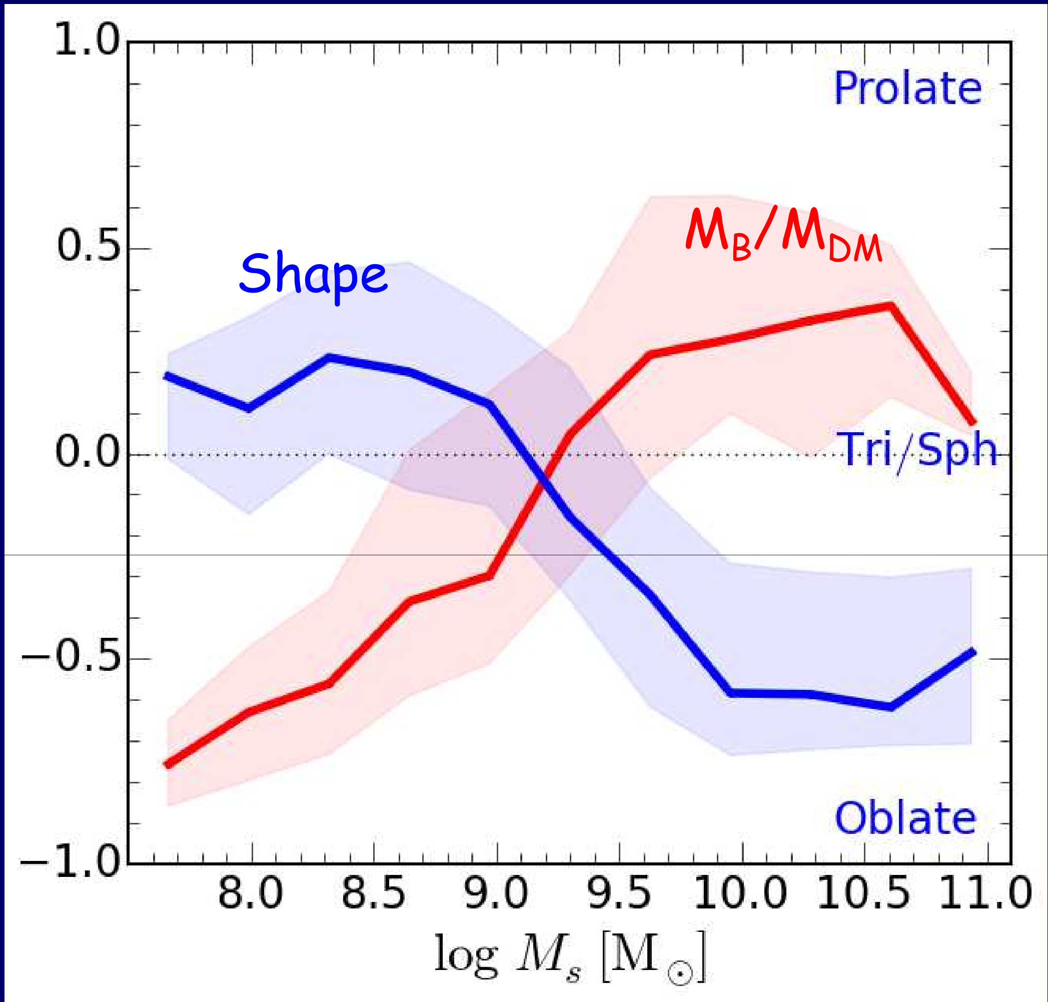
Consistent with van der Wel+ 14 CANDELS



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

Ceverino, Primack, Dekel 15

Transition of Shape: Prolate to Oblate



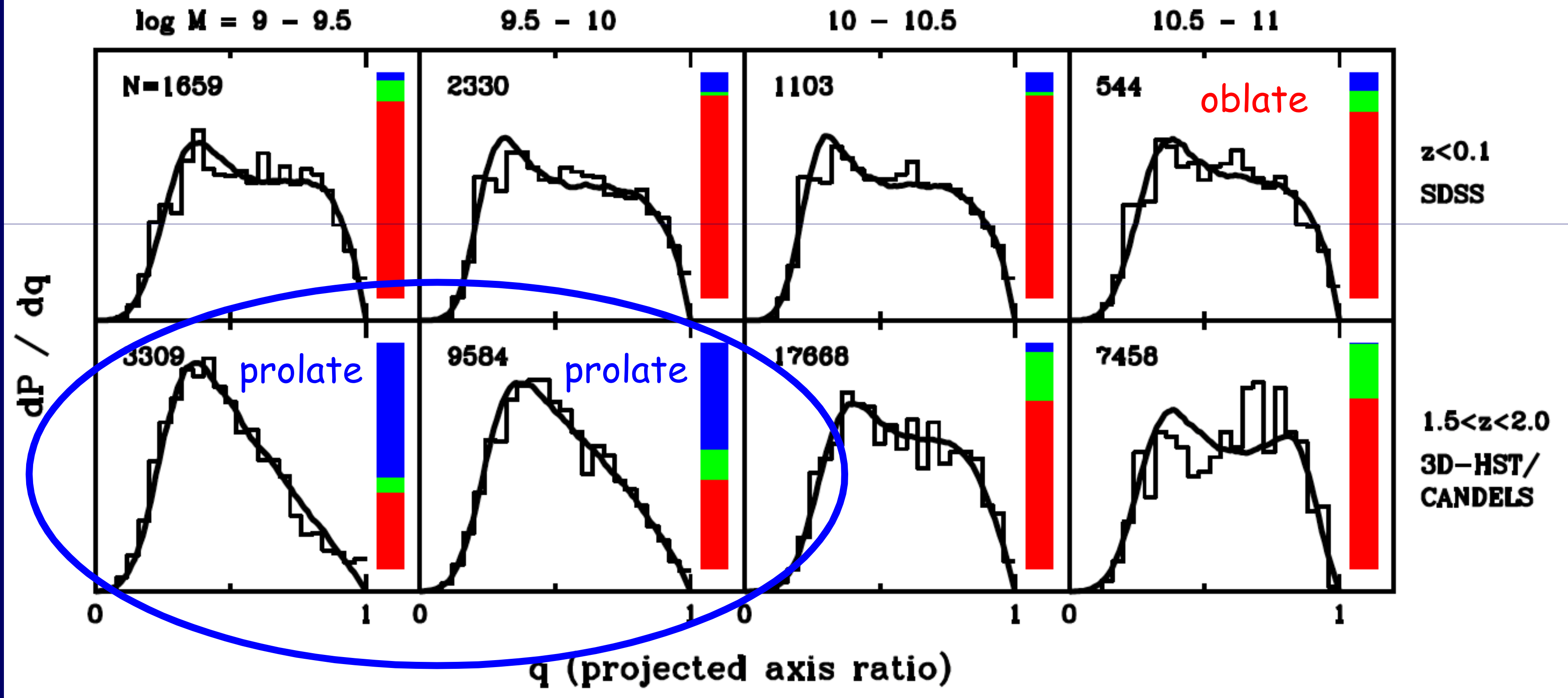
Ceverino+ 15
Tomassetti+ 16

Pre-BN, $M_* < 10^{9.5} M_\odot$, DM-dominated
-> prolate DM & stars,
anisotropic dispersion

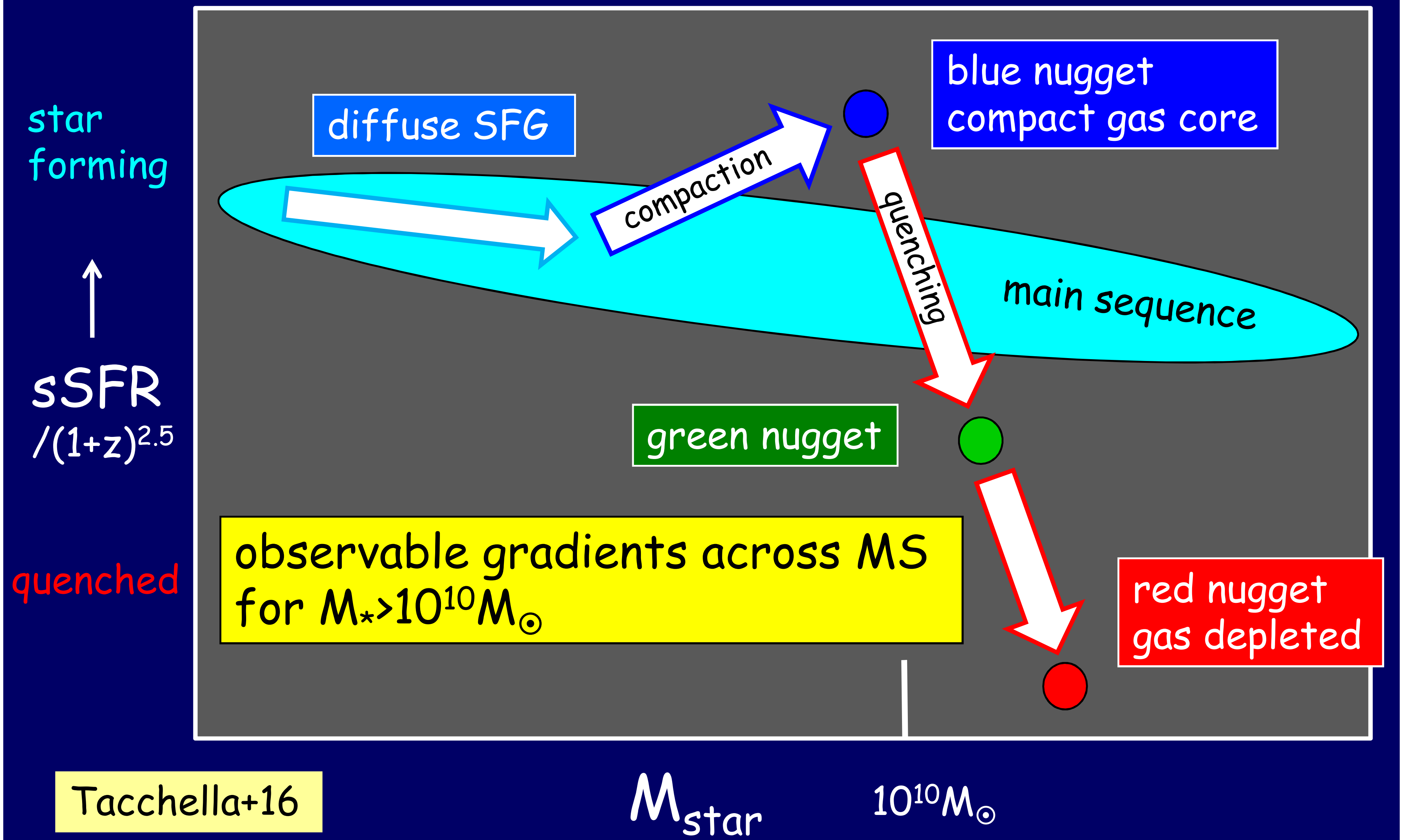
Post-BN baryon-dominated
-> box orbits deflected
-> oblate, rotation-dominated

Obs. Galaxies at z~2, $M<10^{10}M_\odot$ are prolate

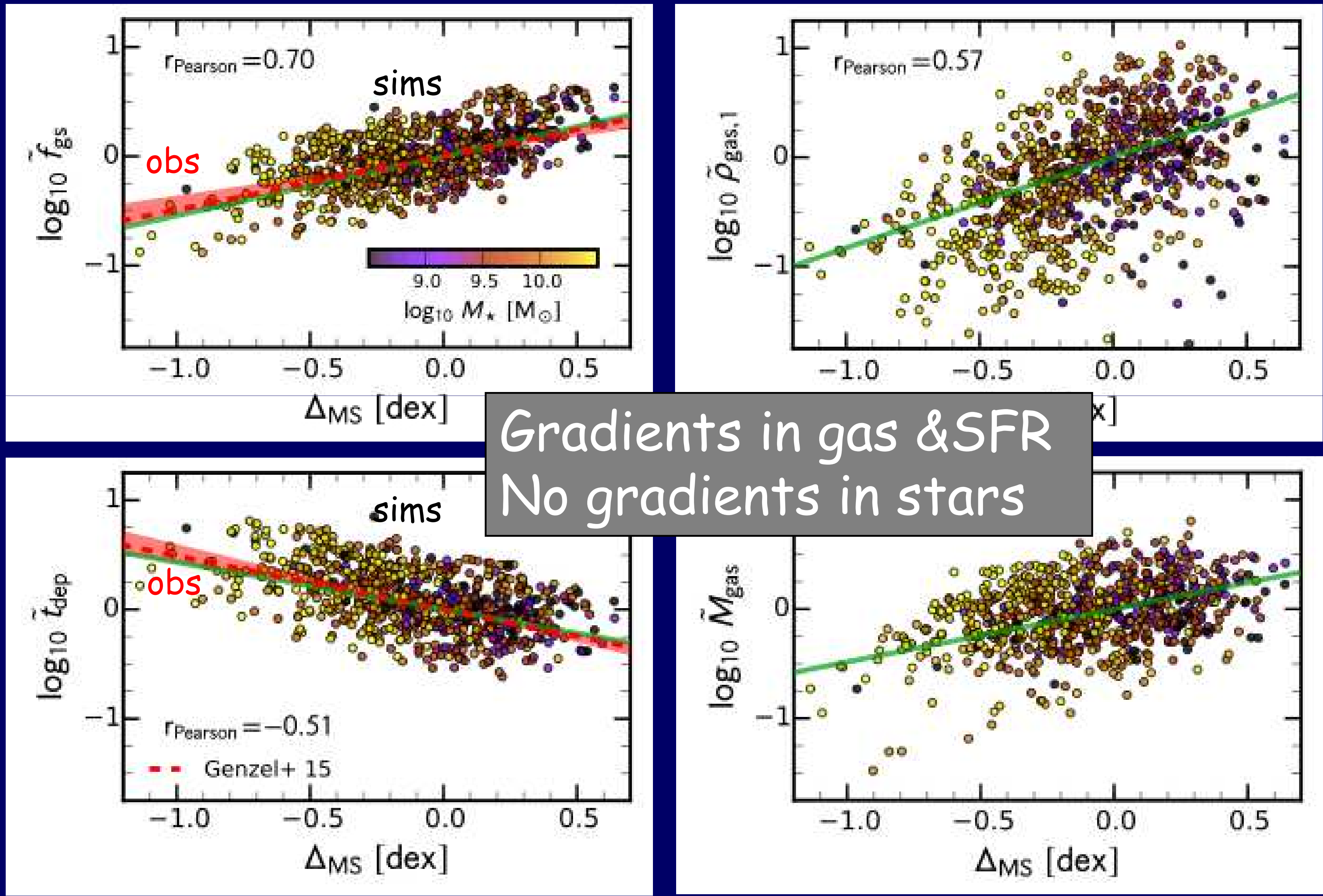
Van der Wel+ 14 CANDELS



Evolution About the Main Sequence in Sims

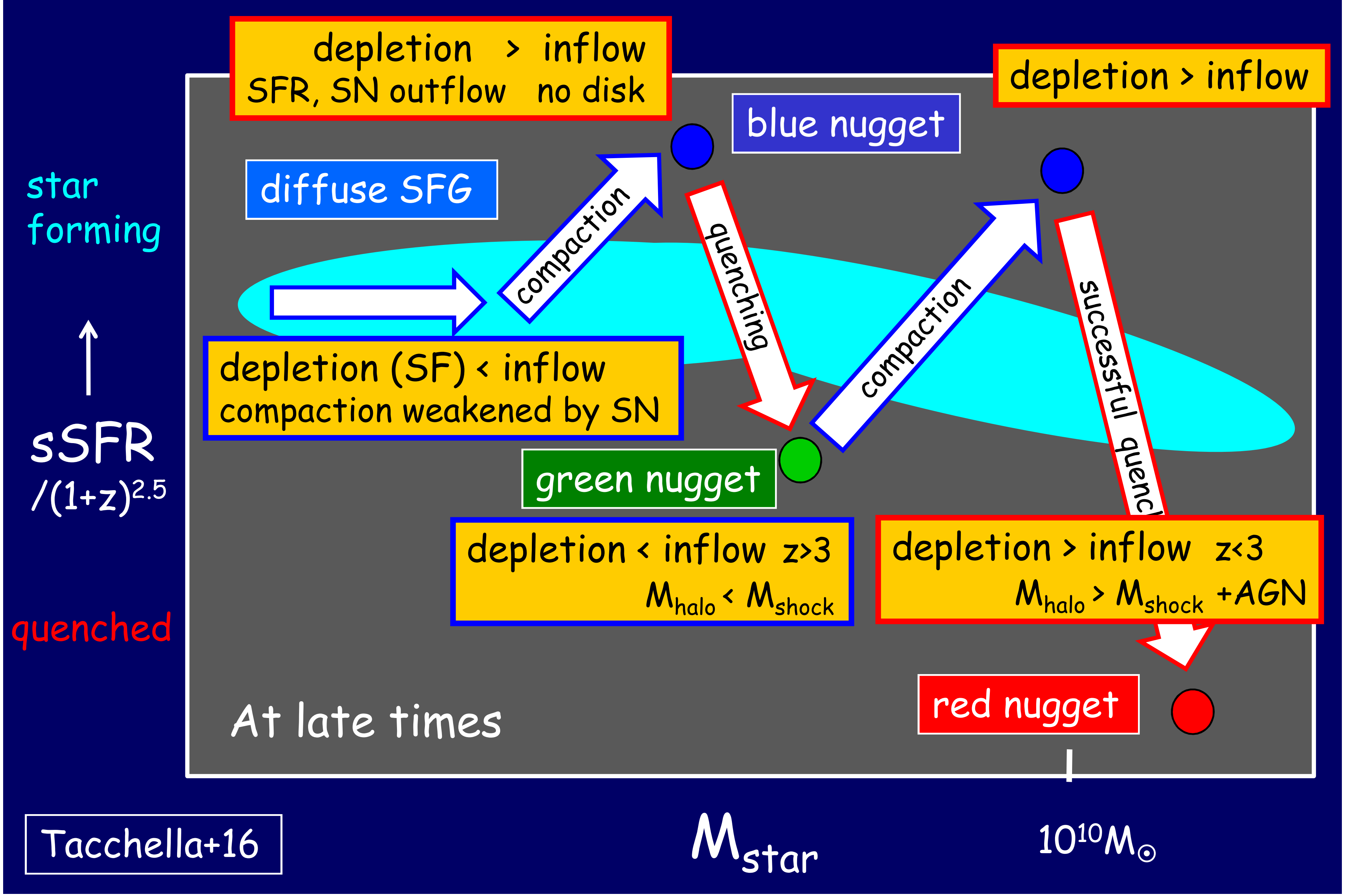


Gas Gradients across the Main Sequence

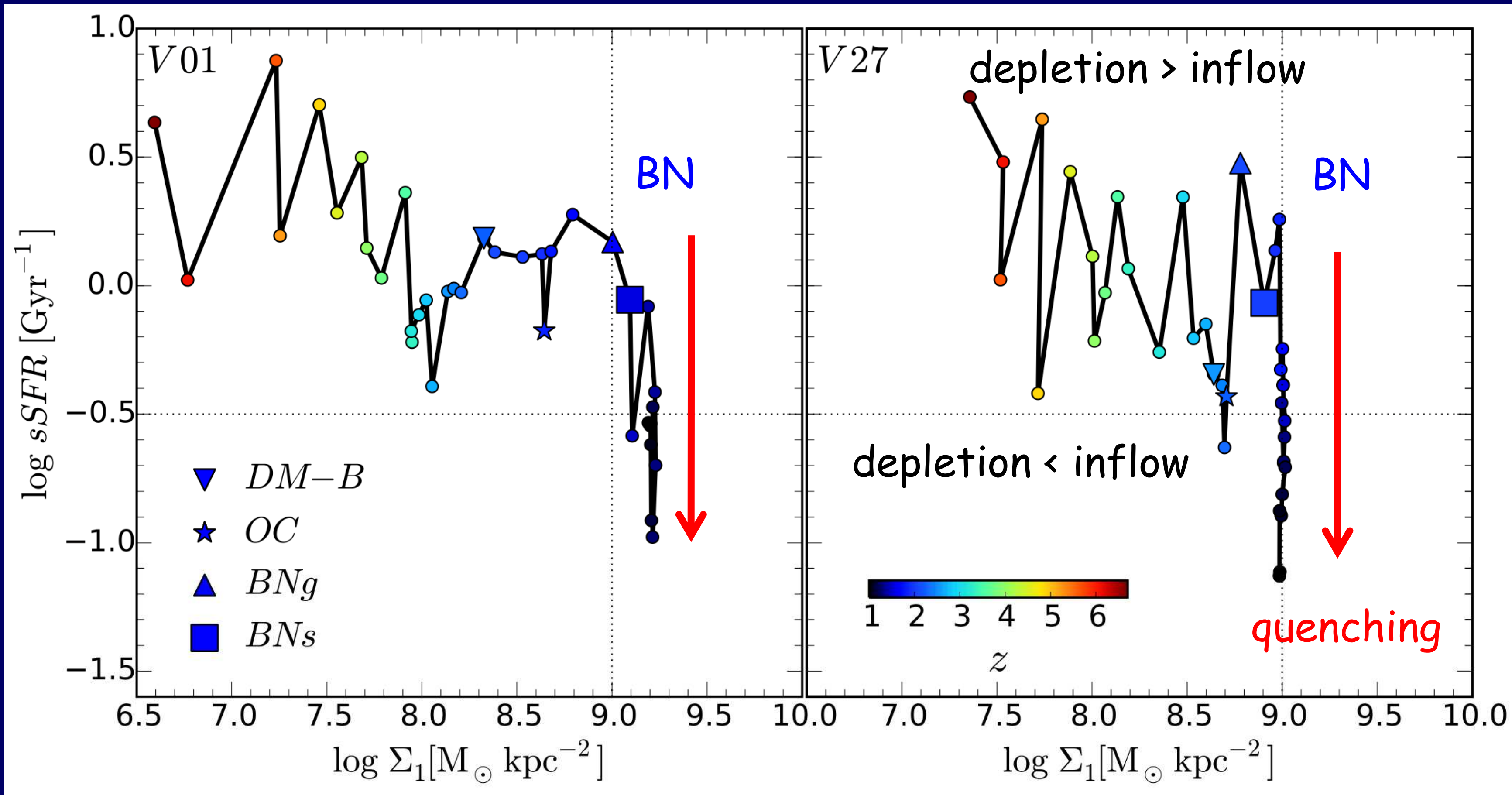


Gradients in gas &SFR
No gradients in stars

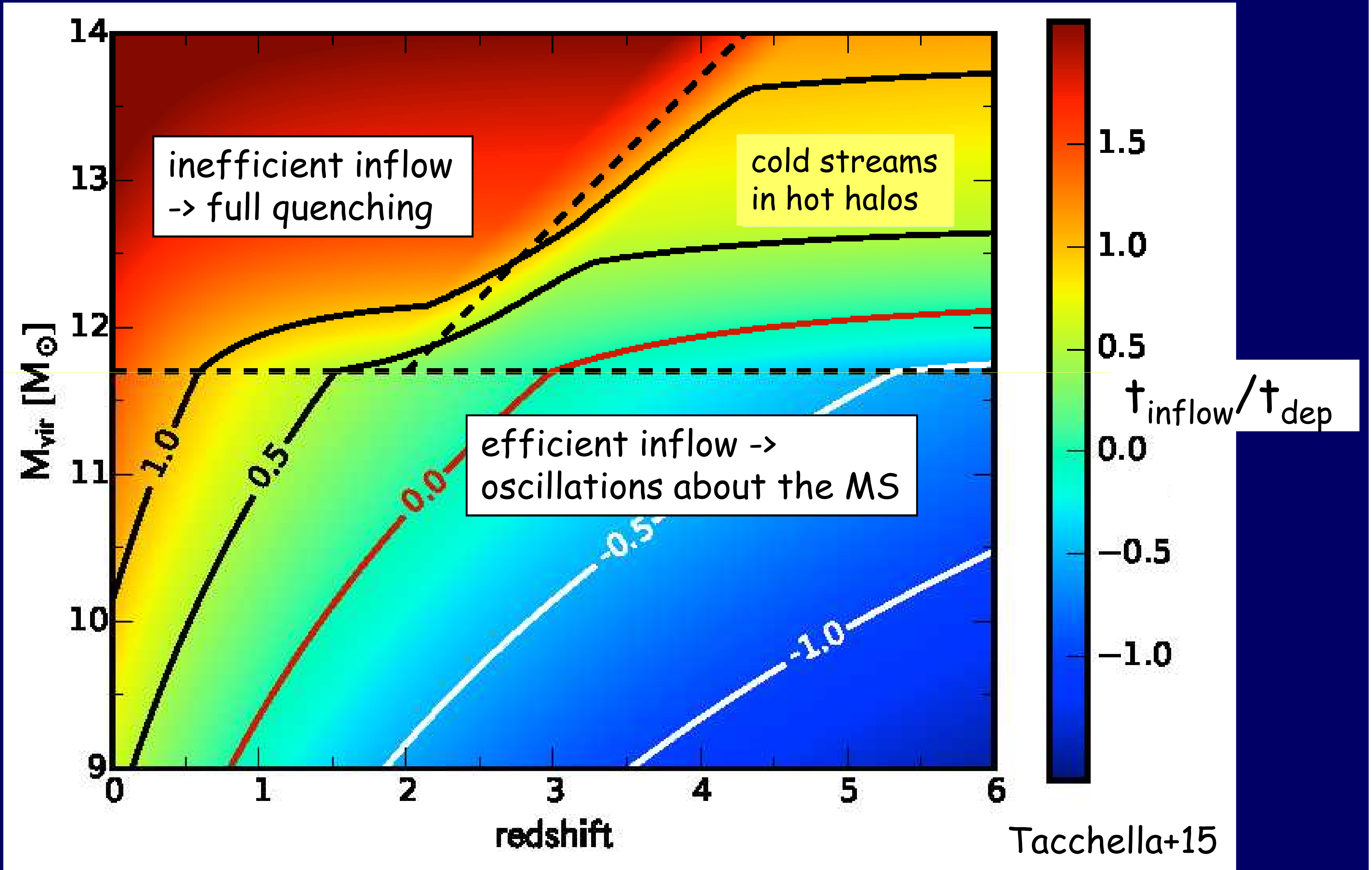
Evolution Along & Across the Main Sequence



A Sequence of Compactions and Quenching Attempts



Full Quenching vs Quenching Attempt

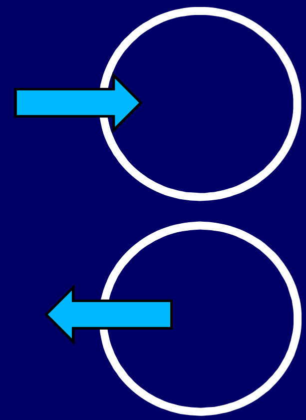


The Quenching Mechanism

Wet compaction: inflow > SFR+outflow

Post-BN: high SFR and no gas supply to center

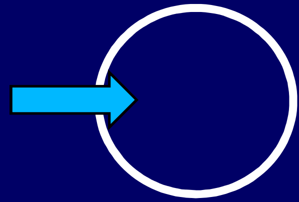
Central gas depletion inflow < SFR+outflow



- disk shrunk -> no gas supply to center
- bulge suppresses VDI-driven inflow (morph. quench.)
- V<100 km s^{-1} shallow potential -> outflows

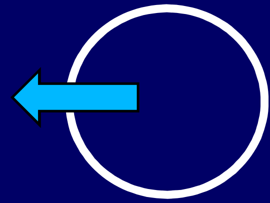
The Quenching Mechanism

Wet compaction: inflow > SFR+outflow



Post-BN: high SFR and no gas supply to center

Central gas depletion inflow < SFR+outflow

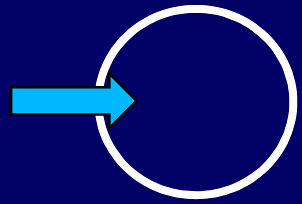


Long-term quenching?

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

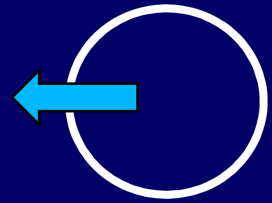
The Quenching Mechanism

Wet compaction: inflow > SFR+outflow



Post-BN: high SFR and no gas supply to center

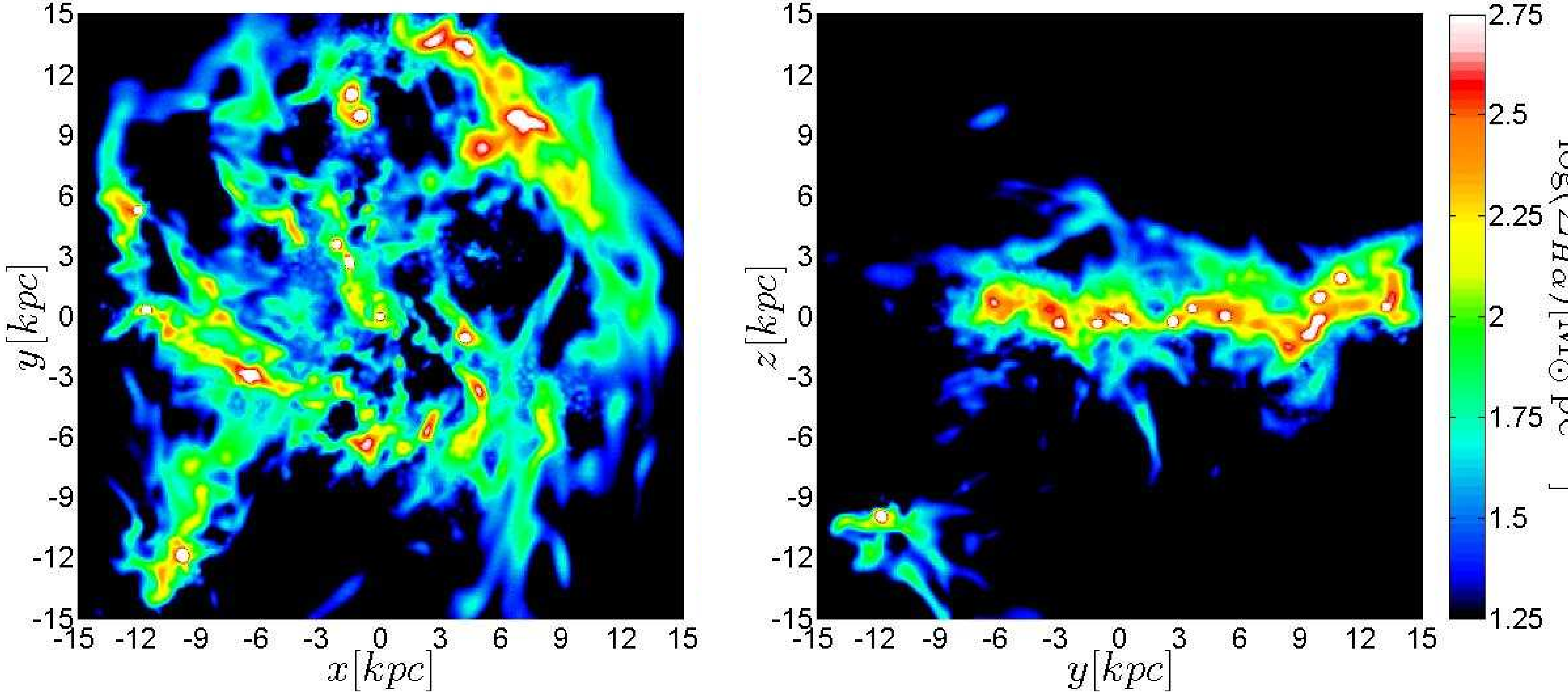
Central gas depletion inflow < SFR+outflow



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

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

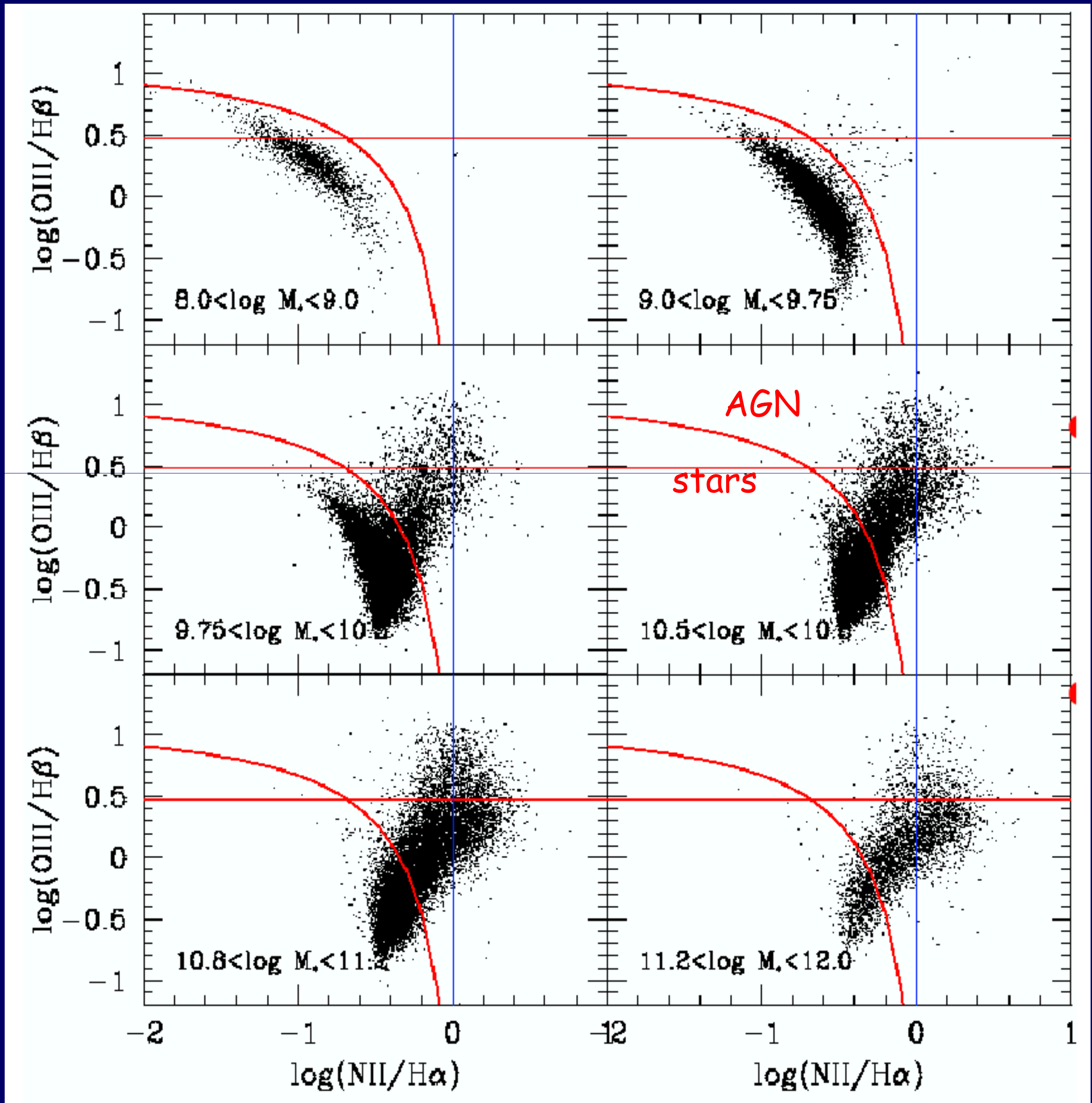
Post-BN: An Extended Clumpy Gas Ring around a Passive Core



4. Compaction and Black-Hole Growth

Dekel, Lapiner, Dubois+ 2017

AGN or Star Formation Emission vs Mass



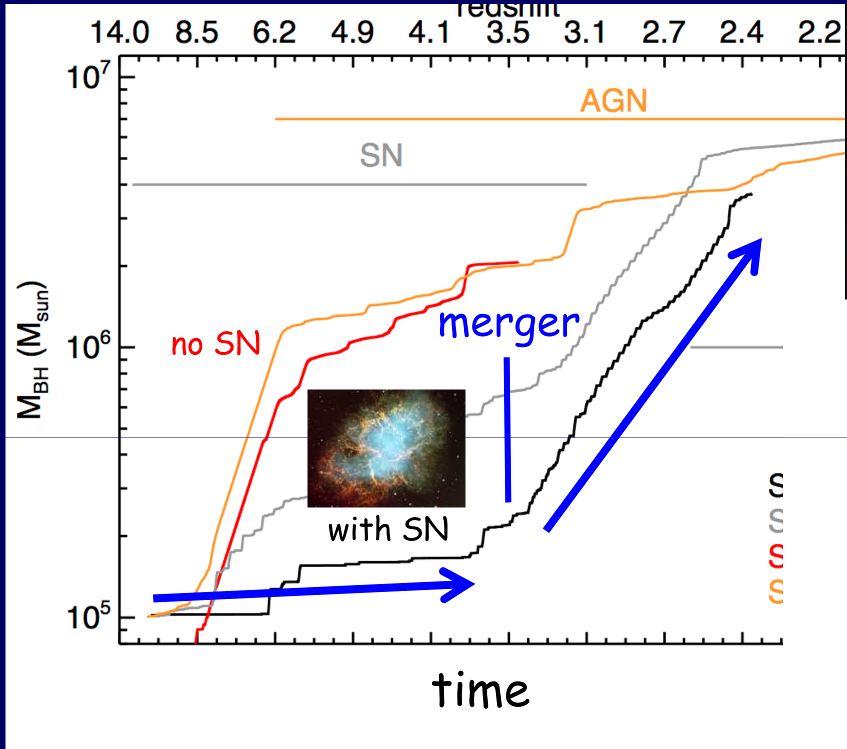
AGN emission only at high masses:

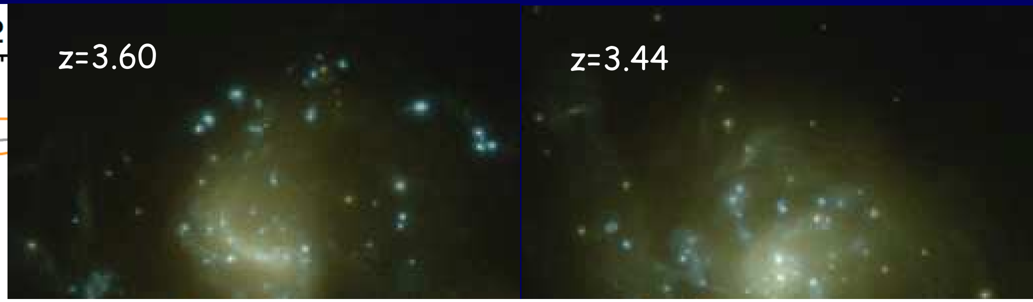
log M_{star} > 9.8
log M_{vir} > 11.5

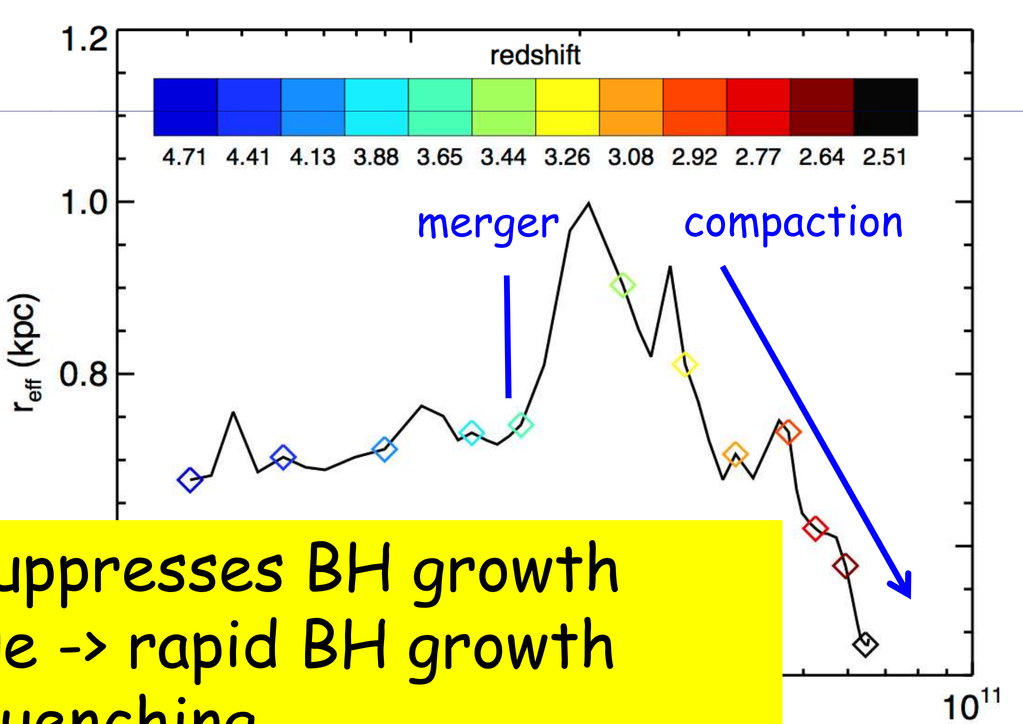
Kauffmann et al. 2004

Interplay between SNe and BHs

RAMSES Simulation SN+BH by Dubois+ 15



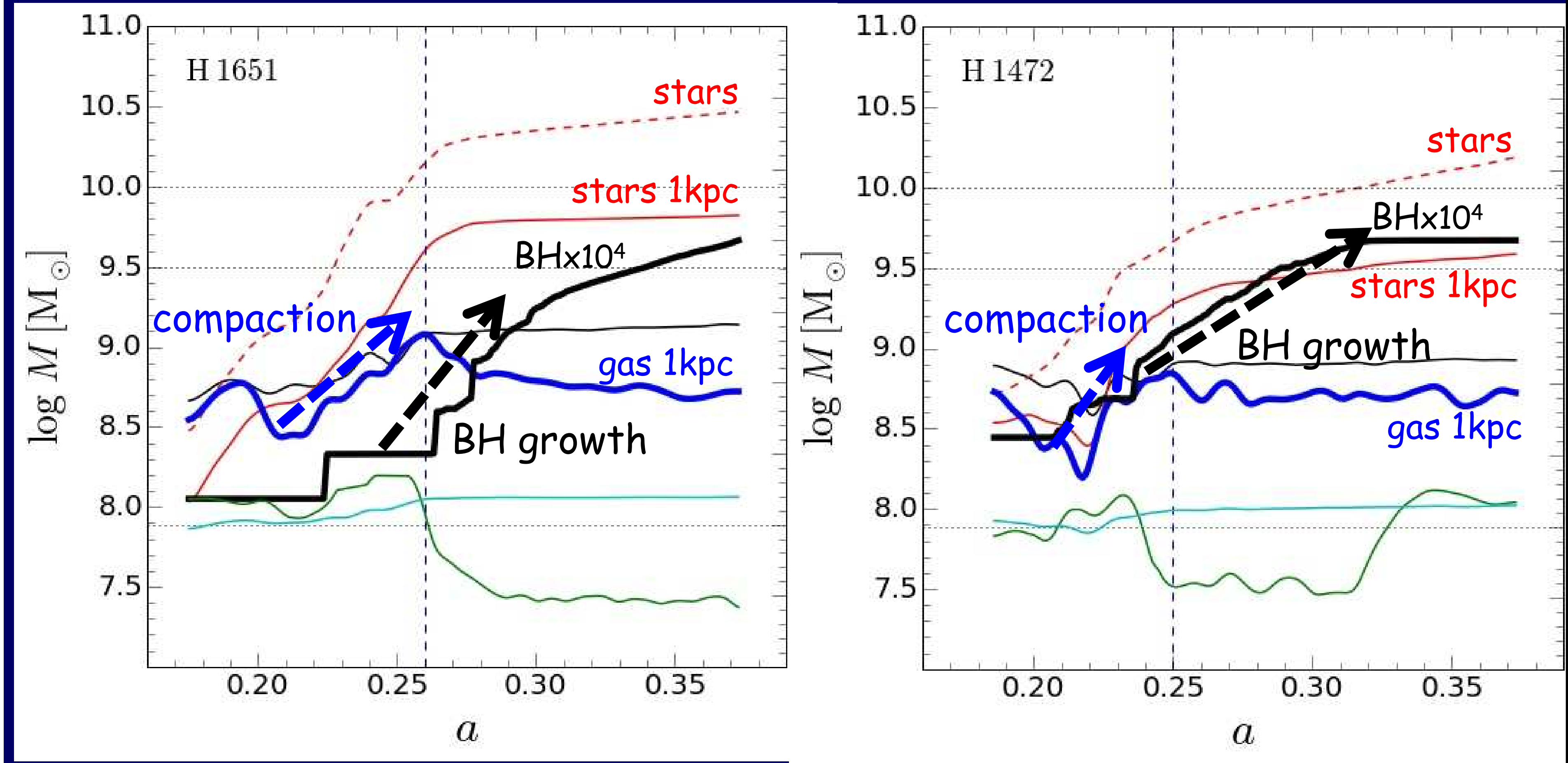




- $M<M_{crit}$: strong SN fdbk suppresses BH growth
- Compaction overcomes SNe -> rapid BH growth
- $M>M_{crit}$: AGN fdbk helps quenching

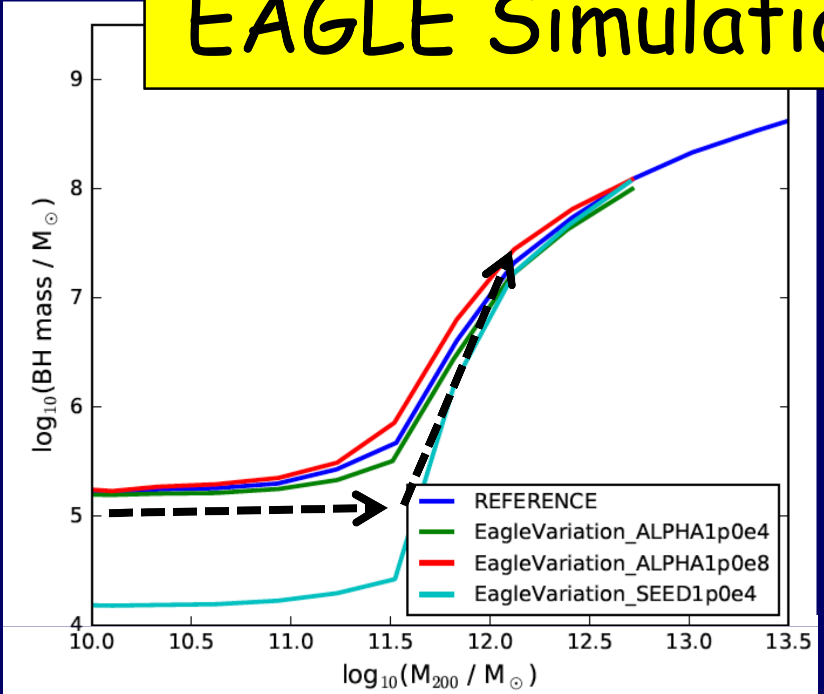
Compaction driving BH Growth

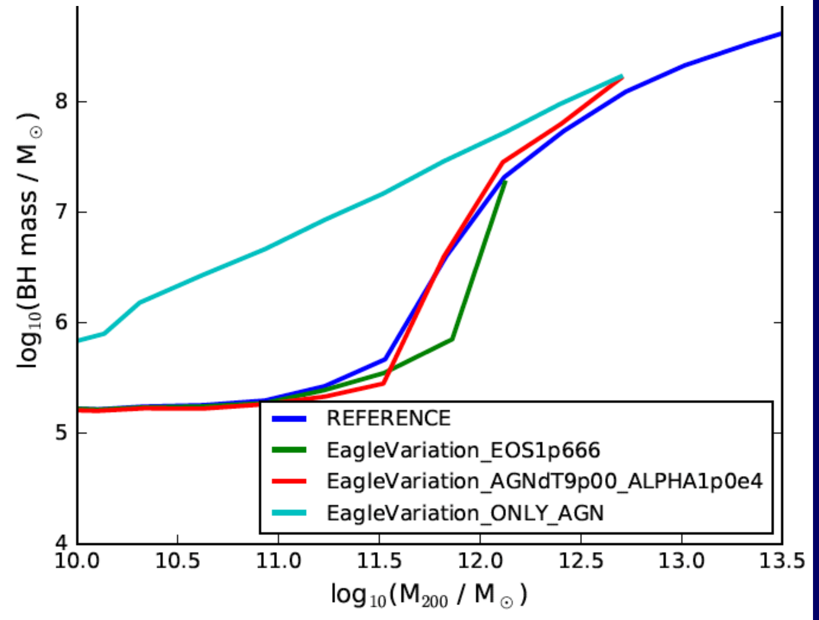
New Horizon simulations SN+BH Dubois+ Lapiner+

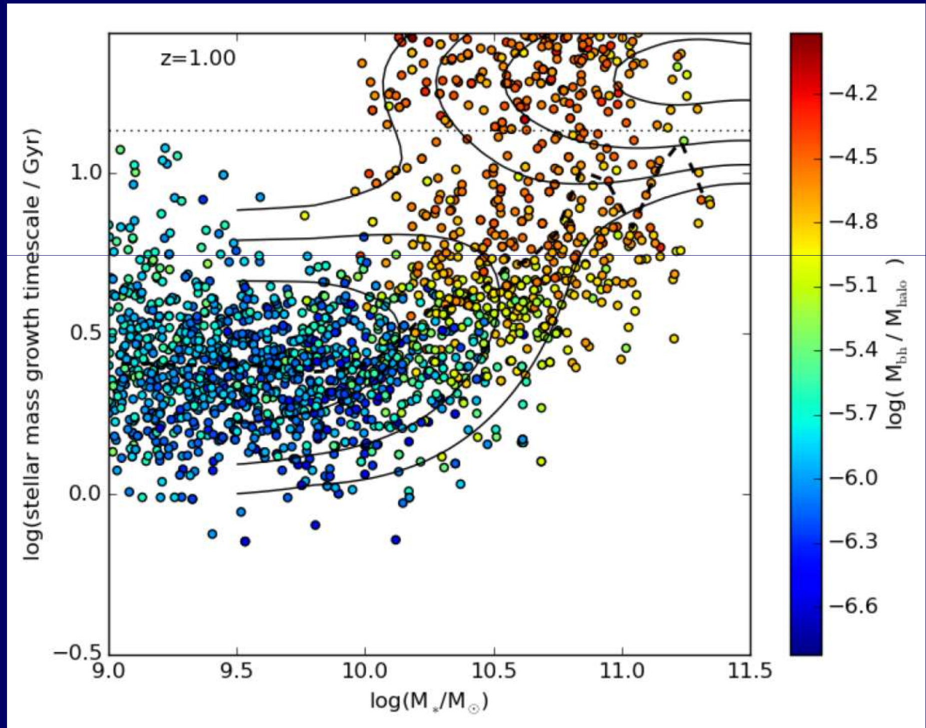


EAGLE Simulations: Similar Results

Bowers+ 2016







BH Growth by Compaction at M_{vir}~$10^{11.5-12}M_\odot$

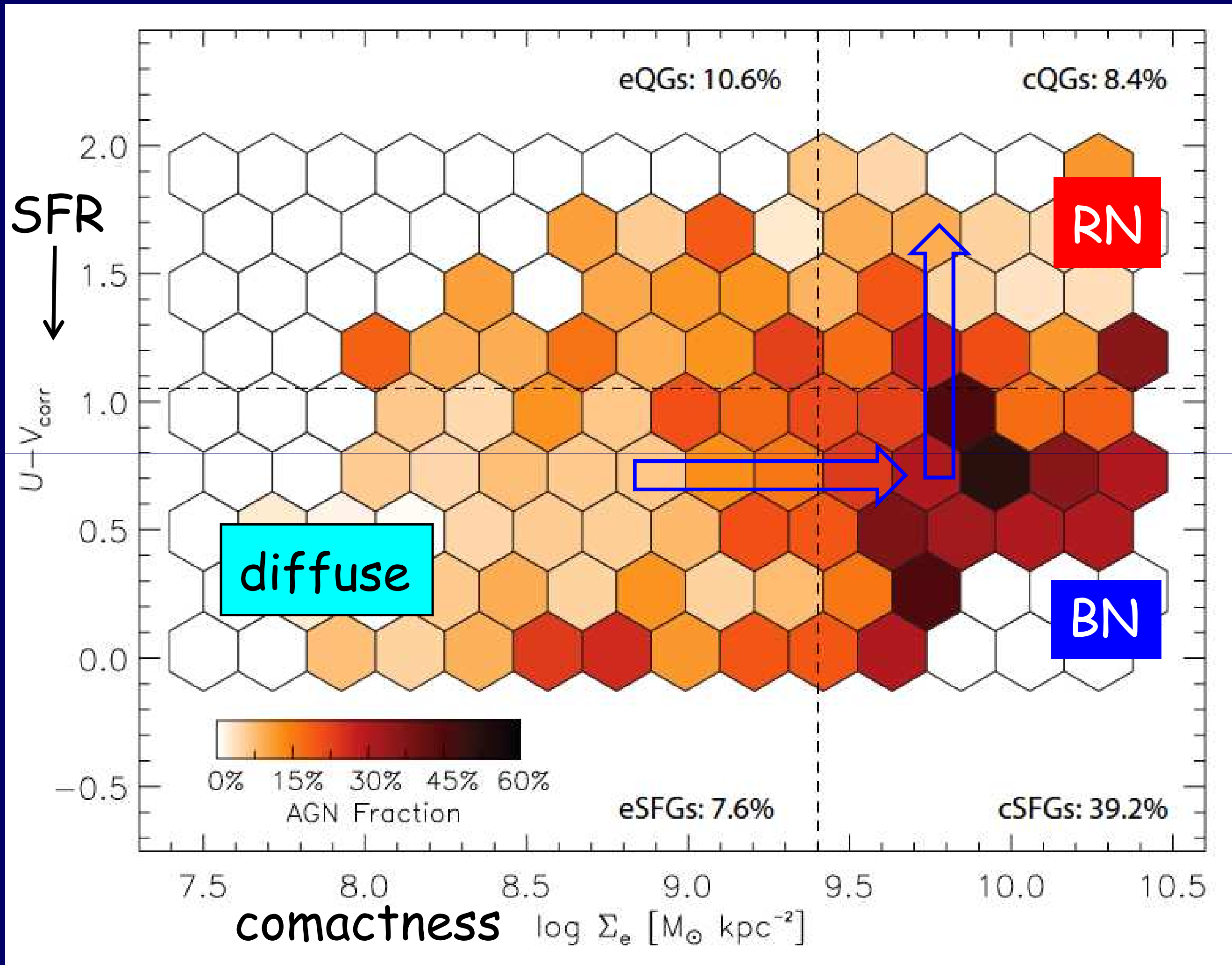
- $M_{vir} < M_{crit}$, pre-compaction SN phase:
  V_{esc} < 100 km/s -> SN winds of 100 km/s escape and evacuate the core
  -> BH growth is suppressed , BN formation is suppressed

- $M_{vir} \sim M_{crit}$, compaction overcoming SN fdbk:
  The compressed gas activates rapid BH growth

- $M_{vir} > M_{crit}$, post-compaction hot CGM phase:
  V_{esc} > 100 km/s -> SN winds are bound (by halo potential and hot gas)
  -> gas falls back in -> BH growth continues
  -> AGN self-regulates with the accretion,
  AGN fdbk keeps the CGM hot and suppresses SFR long term

Observed High Fraction of AGN in BN Pase

Kocevski+17



-> Compaction triggers BH growth and AGN -> quenching

AGN Feedback Can Actually Be Positive

A Characteristic Mass for Galaxy Formation

$M_{star} \sim 10^{10.5} M_\odot$ $M_{vir} \sim 10^{12} M_\odot$ $V_{vir} \sim 100$ km/s

- Hot CGM (virial shock heating) at $M > M_{crit}$

Rees & Ostriker 77, Silk 77, Binney 77, Dekel & Birnboim 06

- SN feedback efficient at $M < M_{crit}$ (V_{crit})

Larson 74, Dekel & Silk 86

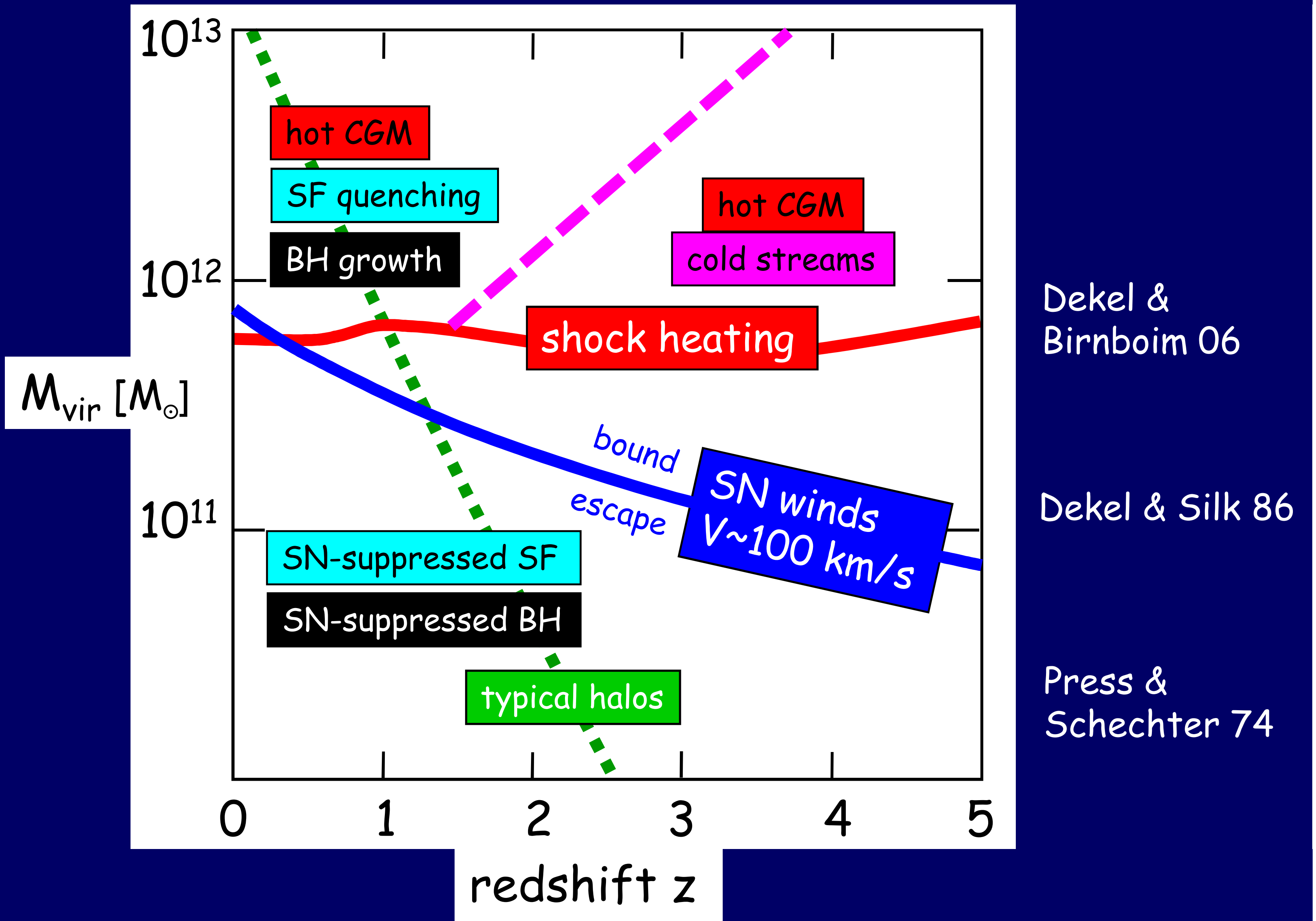
-> Compaction to Blue Nuggets + quenching at $\sim M_{crit}$ (any z)

Zolotov+15, Tacchella+16, Dekel+17

-> BH suppressed by SN at $M < M_{crit}$, BH growth at $M > M_{crit}$

-> Quenching at $M > M_{crit}$
triggered by compaction, maintained by hot CGM & AGN

M_{crit} by SN Feedback: $M_{vir}\sim10^{11.5-12}M_\odot$



Happy Birthday Joe!