The Golden Mass of Galaxies and Black Holes

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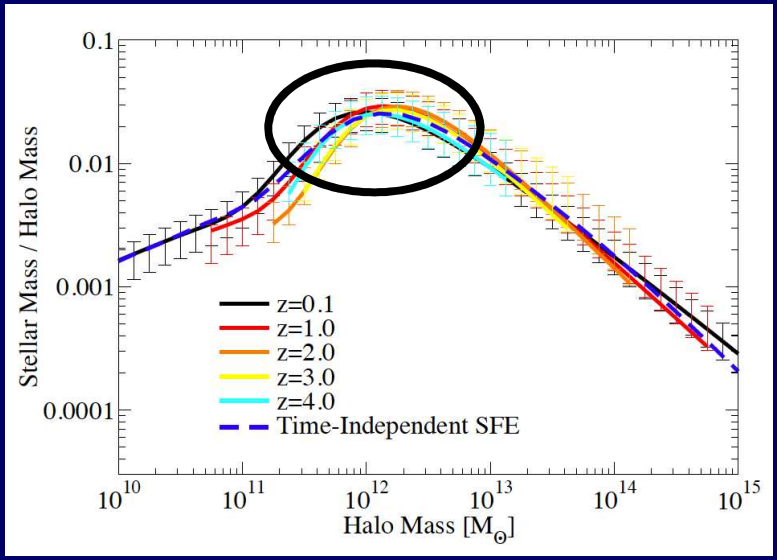
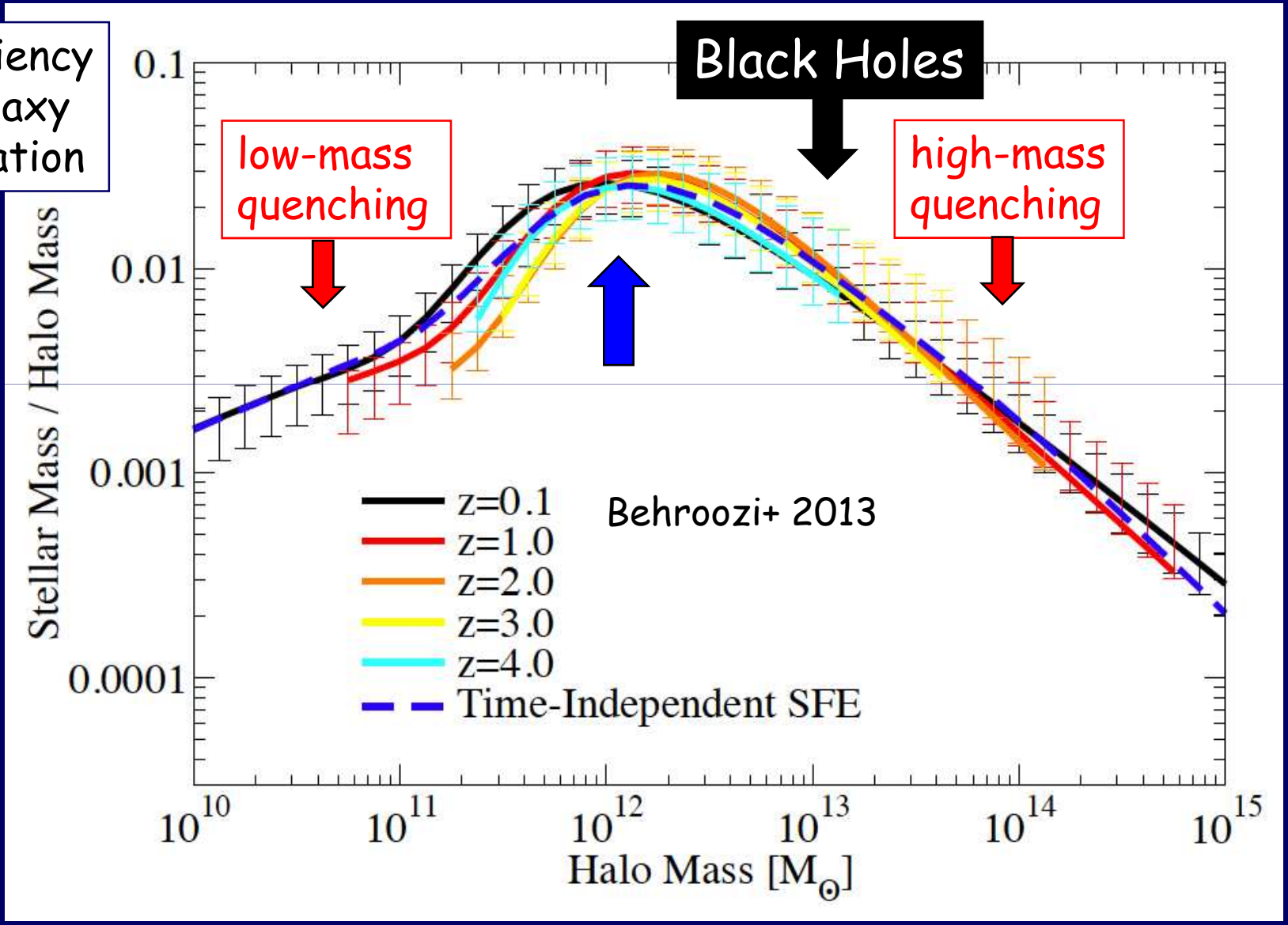
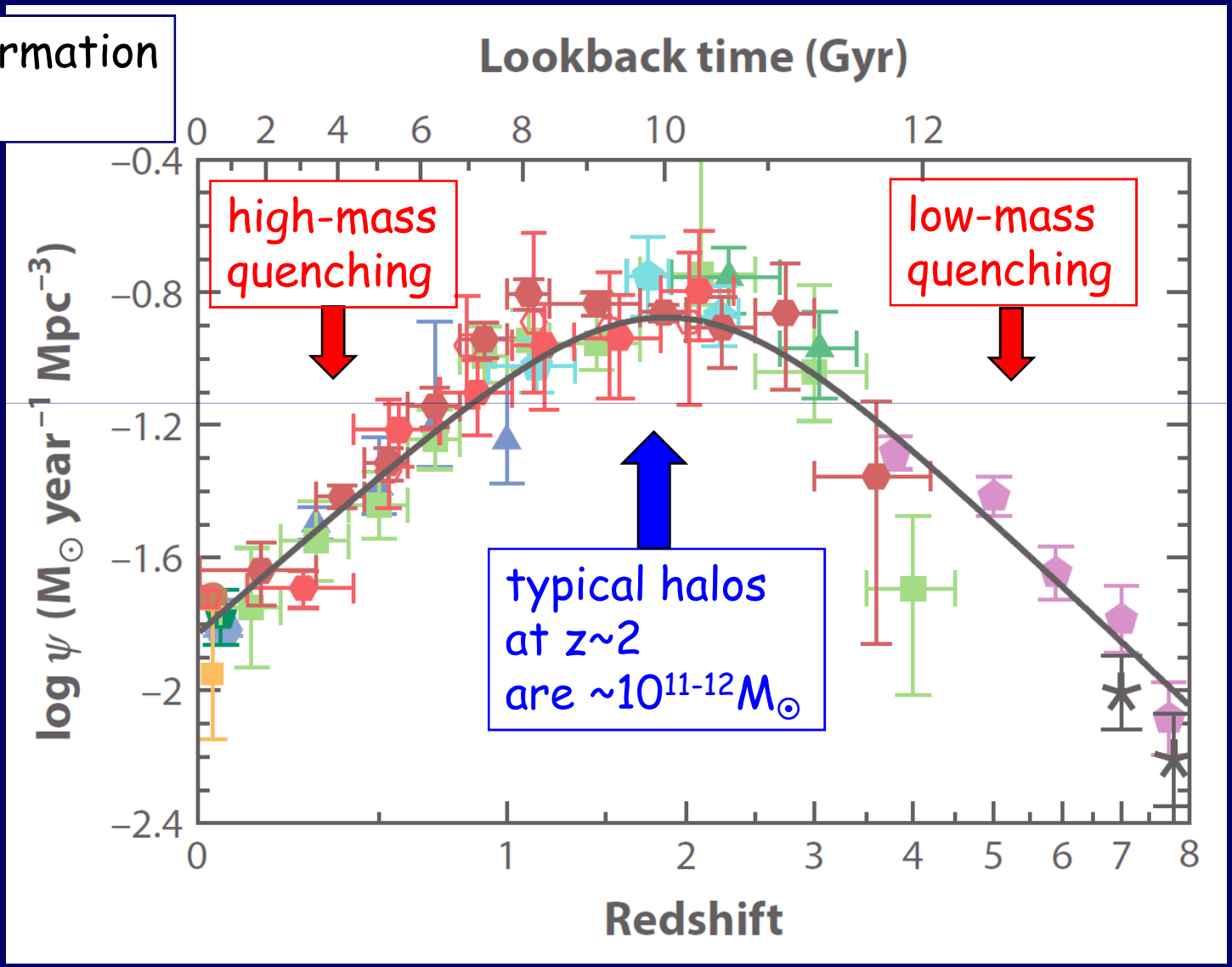


A Characteristic Mass for Galaxy Formation



A Characteristic Mass for Galaxy Formation

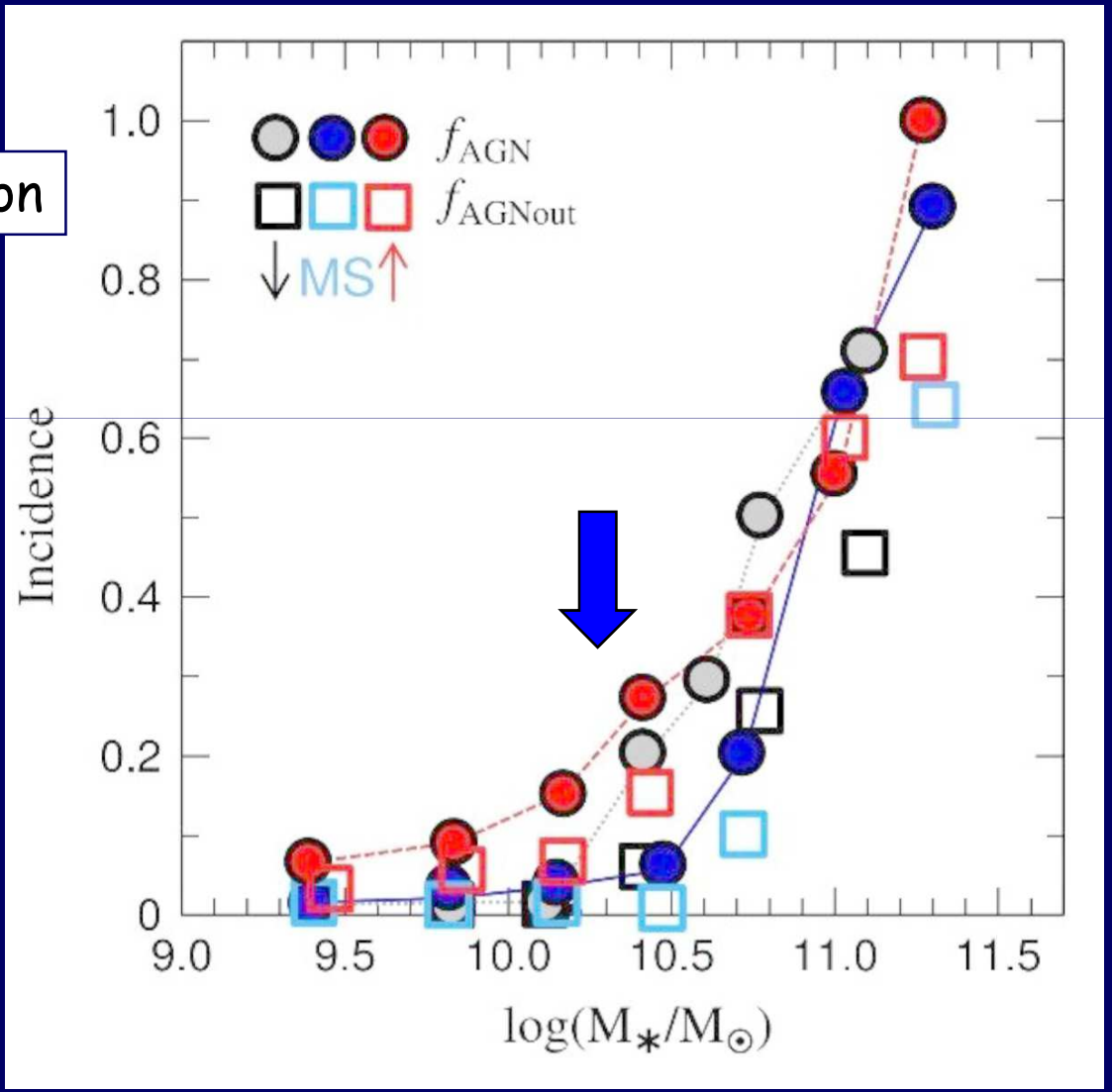
Star-formation density



AGN Activation at the Critical Mass

Forster-Schreiber+18 KMOS^{3D} z=0.6-2.7 599 galaxies

AGN fraction



Why do **galaxies** tend to form near the golden mass (and time)?

Why do **black holes** grow rapidly once their host galaxies are above the golden mass?

A Characteristic Mass for Galaxy Formation

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

- Supernova feedback effective at $M<M_{crit}$ (V_{crit})

Larson 74, Dekel & Silk 86

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

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

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

Zolotov+15, Tacchella+16ab, Dekel+19

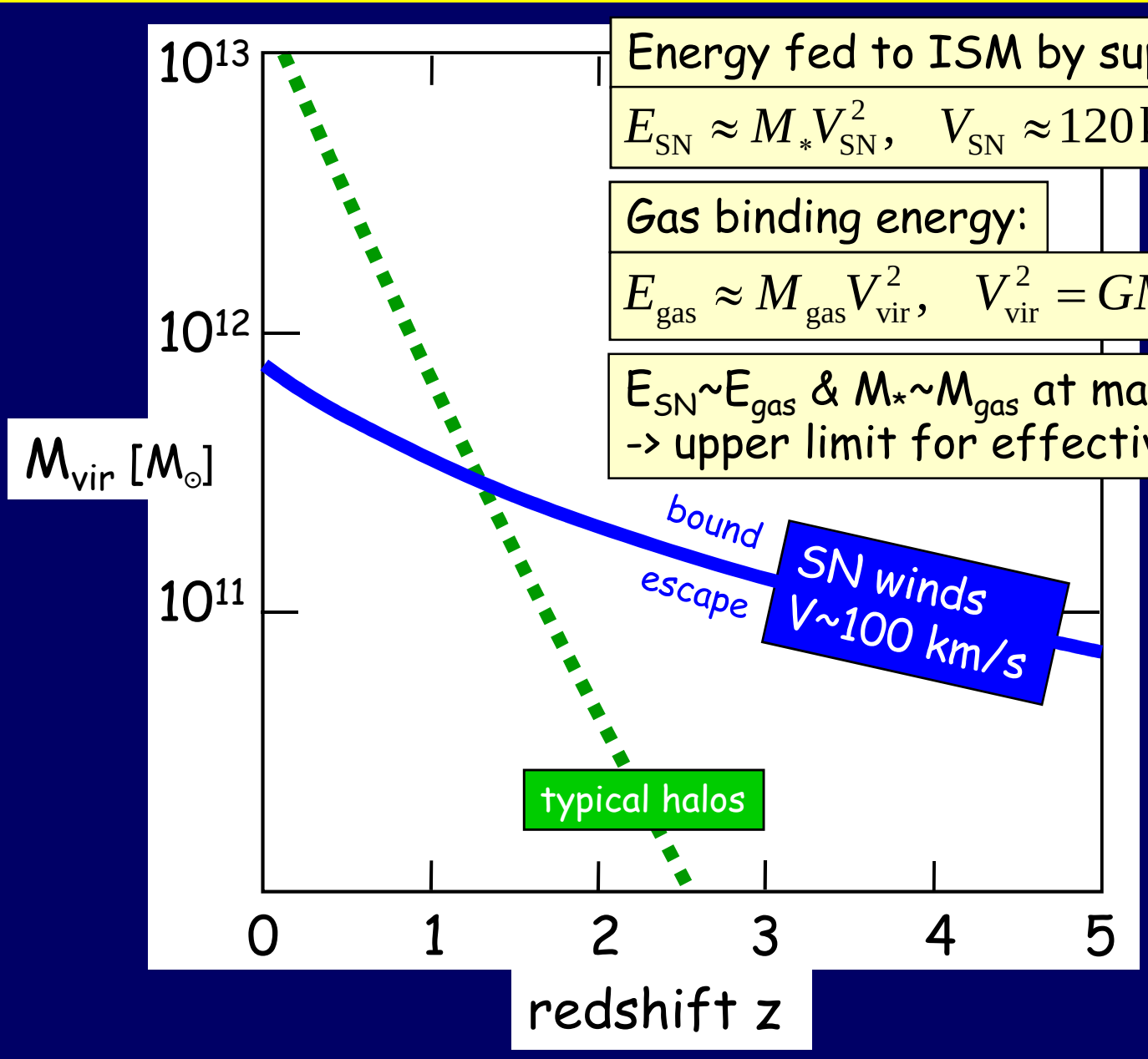
-> Black-Hole growth suppressed by supernovae at $M<M_{crit}$,
Compaction-driven black-hole rapid growth at $M>M_{crit}$

-> Quenching of star formation at $M>M_{crit}$
triggered by compaction, maintained by hot halo & black hole

1. Supernova Feedback in Low-mass Halos

Larson 74, Dekel & Silk 86

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



Energy fed to ISM by supernovae:

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

Gas binding energy:

$$E_{gas} \approx M_{gas} V_{vir}^2, \quad V_{vir}^2 = GM/R$$

E_{SN}~E_{gas} & M_*~M_{gas} at max efficiency
-> upper limit for effective SN fdbk:

Dekel & Silk 86

Press & Schechter 74

2. Virial Shock Heating in Massive Halos

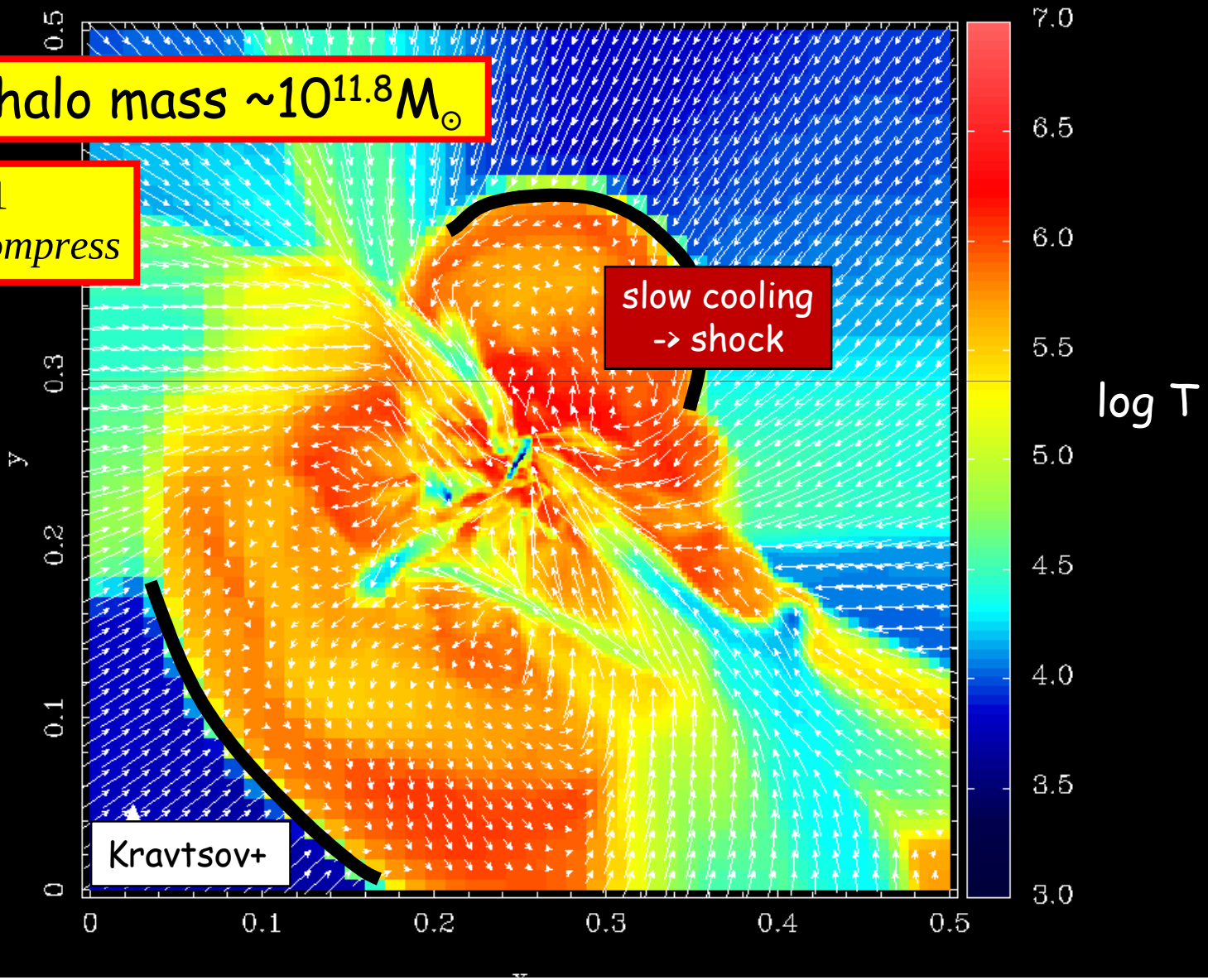
Dekel & Birnboim 06, Rees & Ostriker 77, Silk 77, Binney 77

Hot Halo Scale: shutdown of cold gas supply

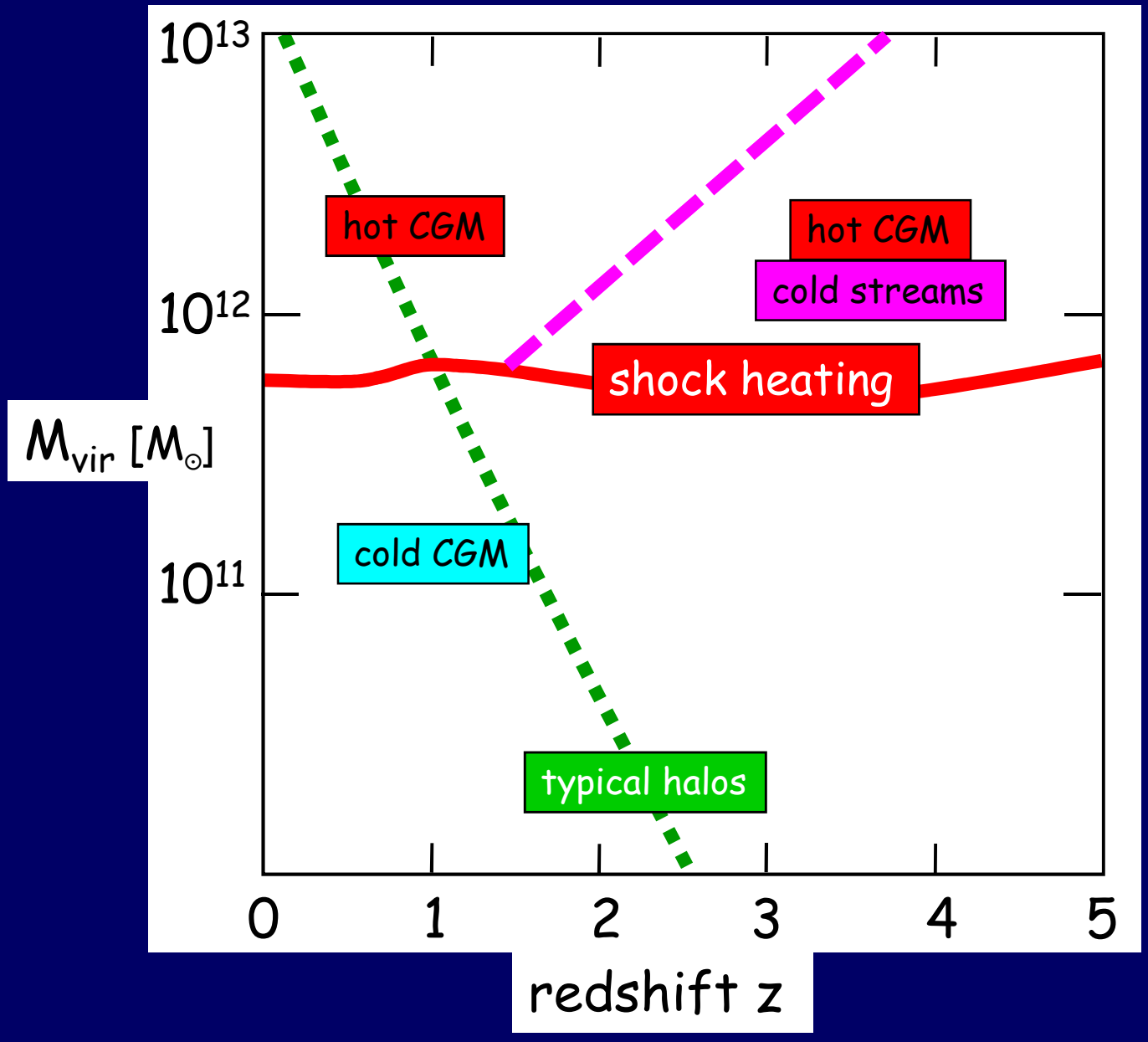
Dekel & Birnboim 06, Rees & Ostriker 77, Silk 77, Binney 77

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

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



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



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

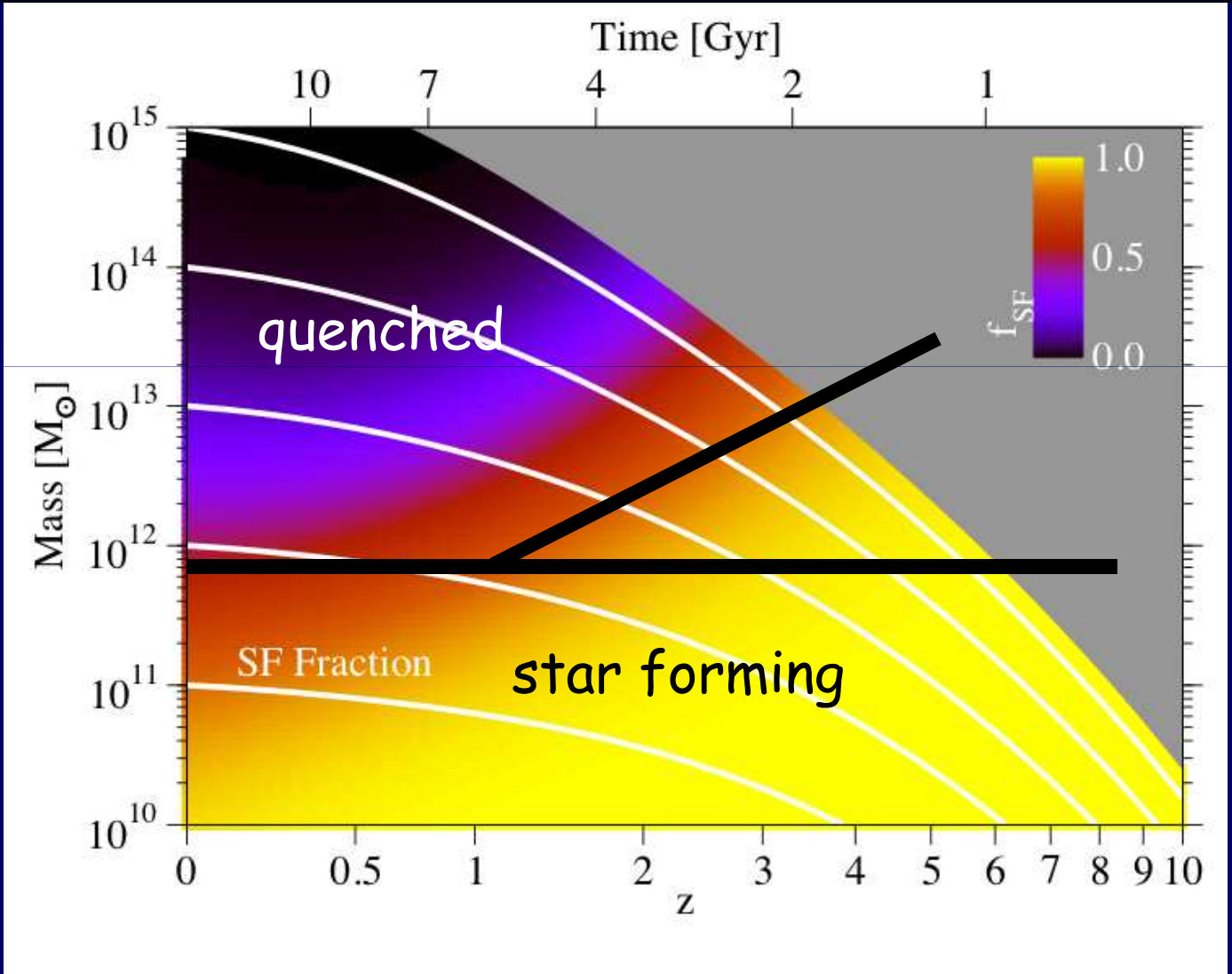
Dekel & Birnboim 06

Press & Schechter 74

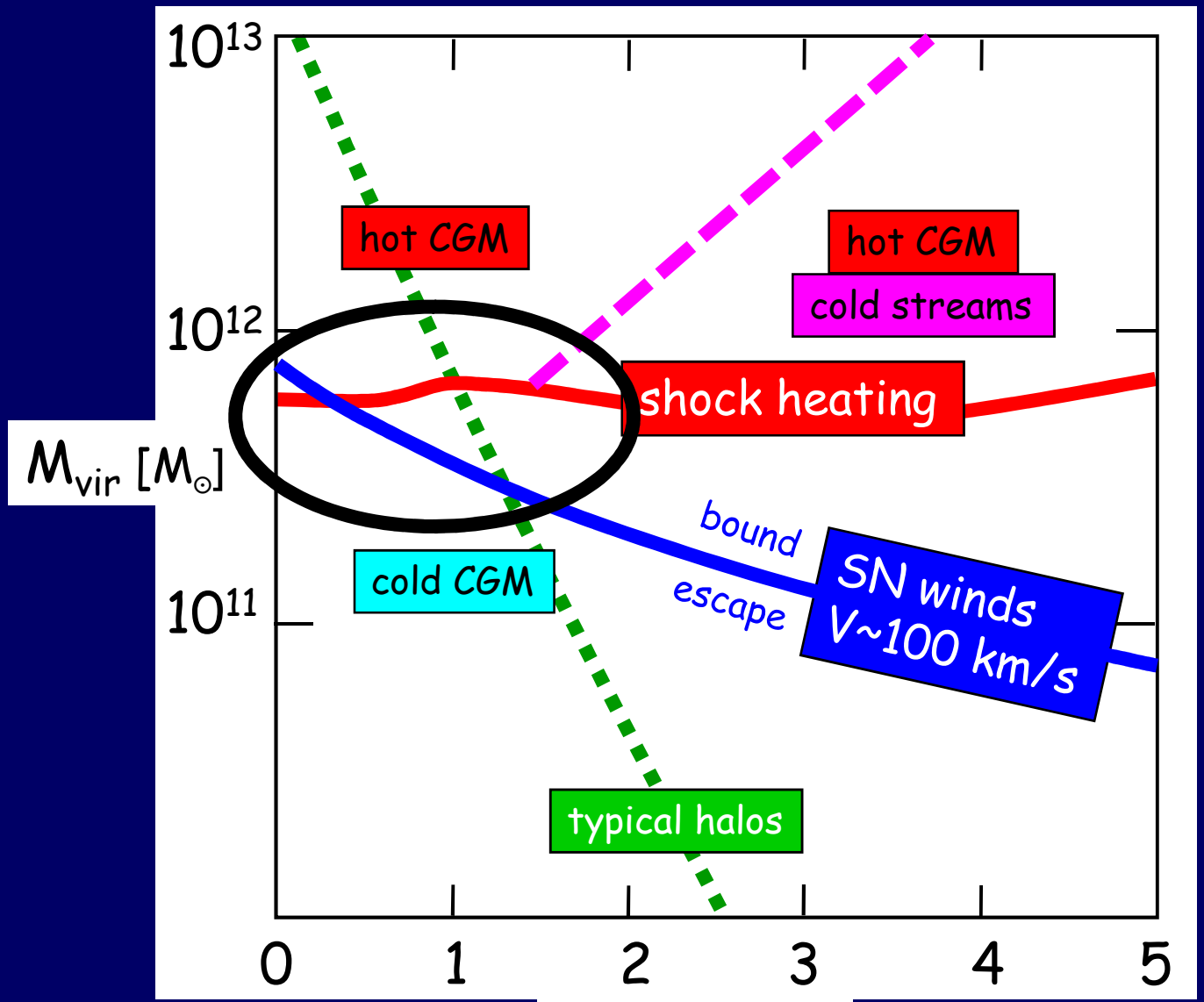
Empirical Model From Observations

Behroozi+18

Fraction of star-forming galaxies



Golden Mass: $M_{vir} \sim 10^{11.5\text{-}12} M_\odot$



Dekel & Birnboim 06

Dekel & Silk 86

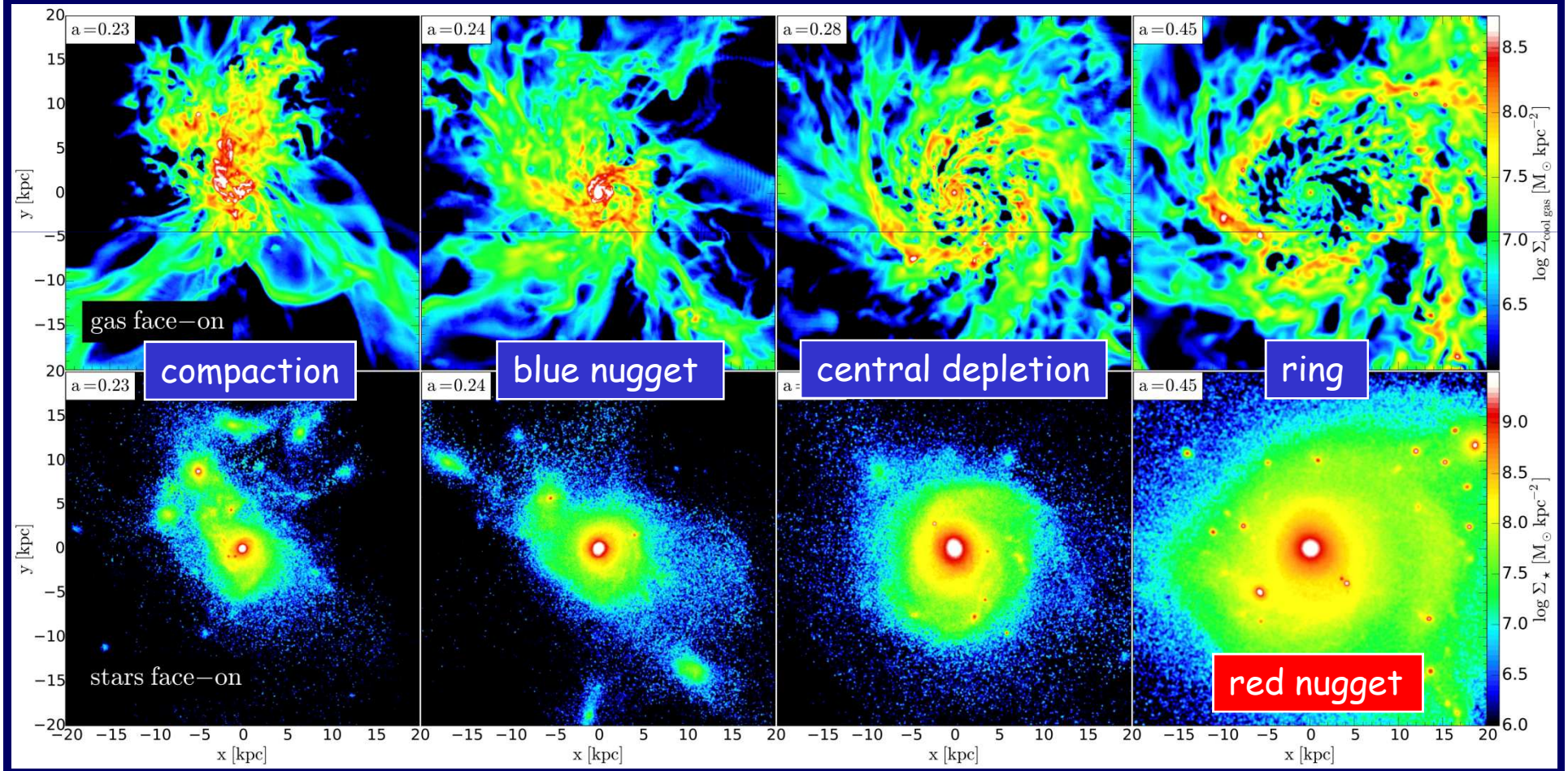
Press & Schechter 74

3. Wet Compaction to Blue Nuggets at the Golden Mass

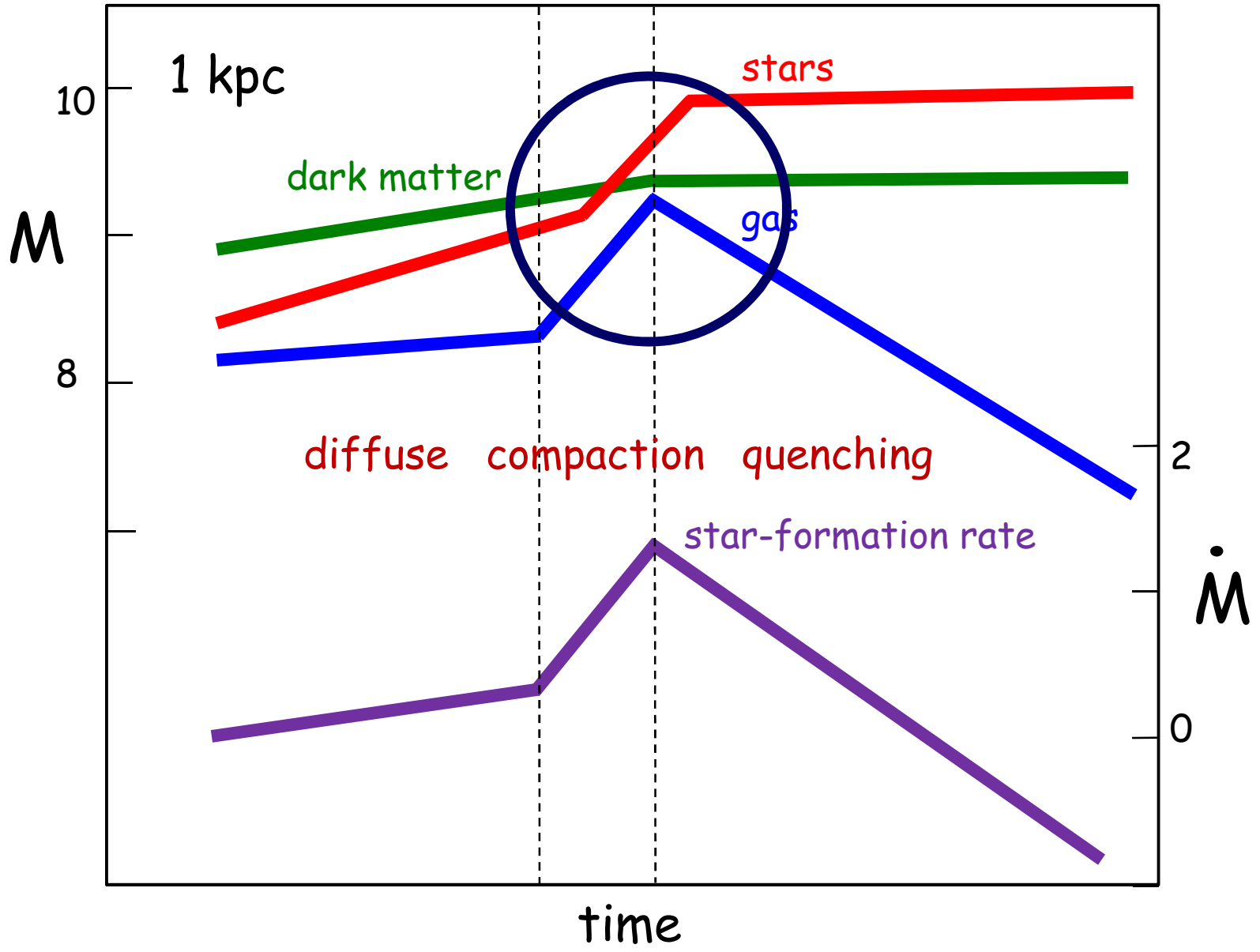
Dekel & Burkert 14, Zolotov+15, Tacchella+16a,b, Tomassetti+16, Dekel, Lapiner+19

Wet Compaction to a Blue Nugget and Disk/Ring Formation

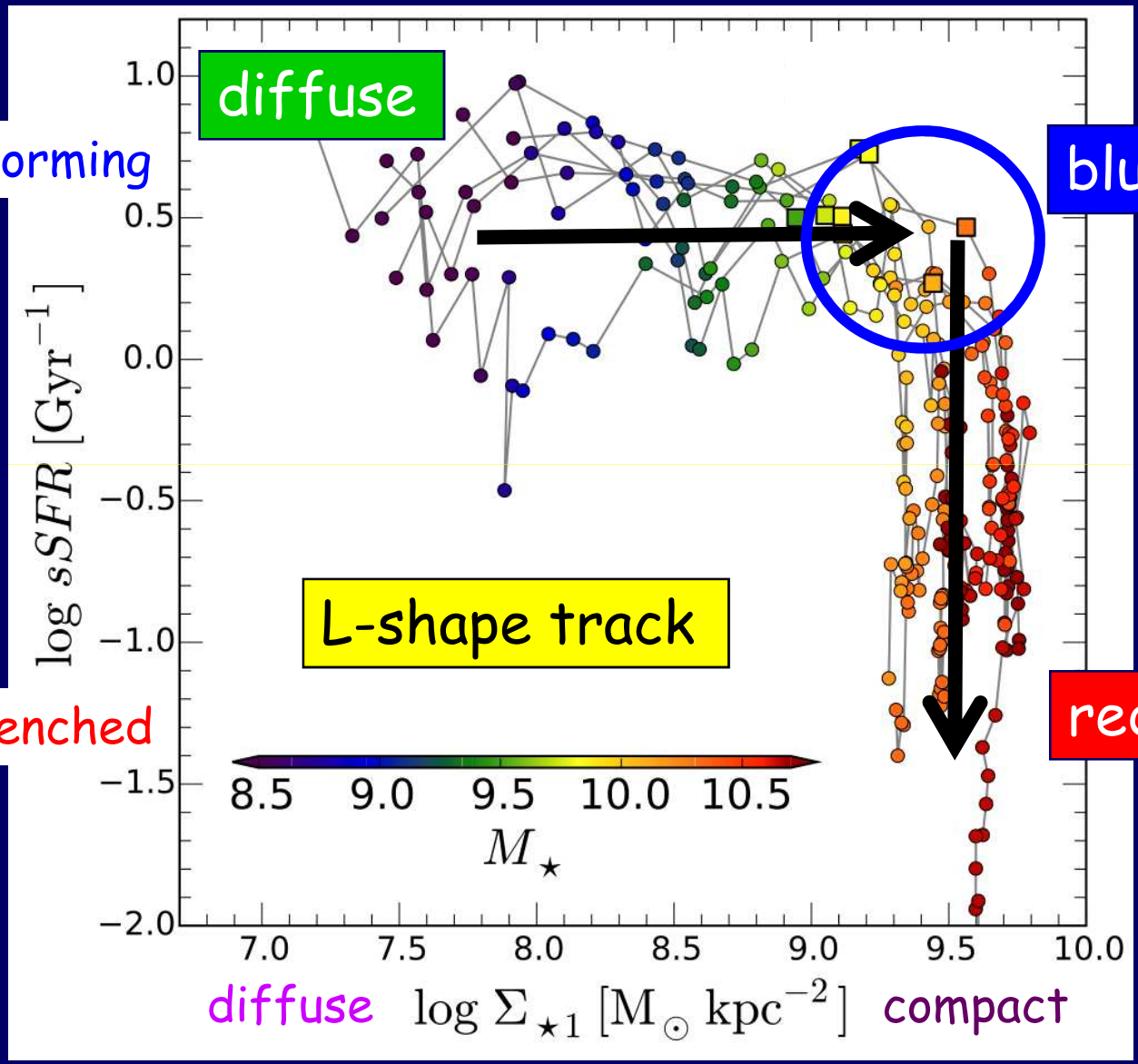
VELA-3 cosmological simulations 25pc res (Ceverino, Dekel, Primack)



Compaction -> quenching in the inner 1 kpc



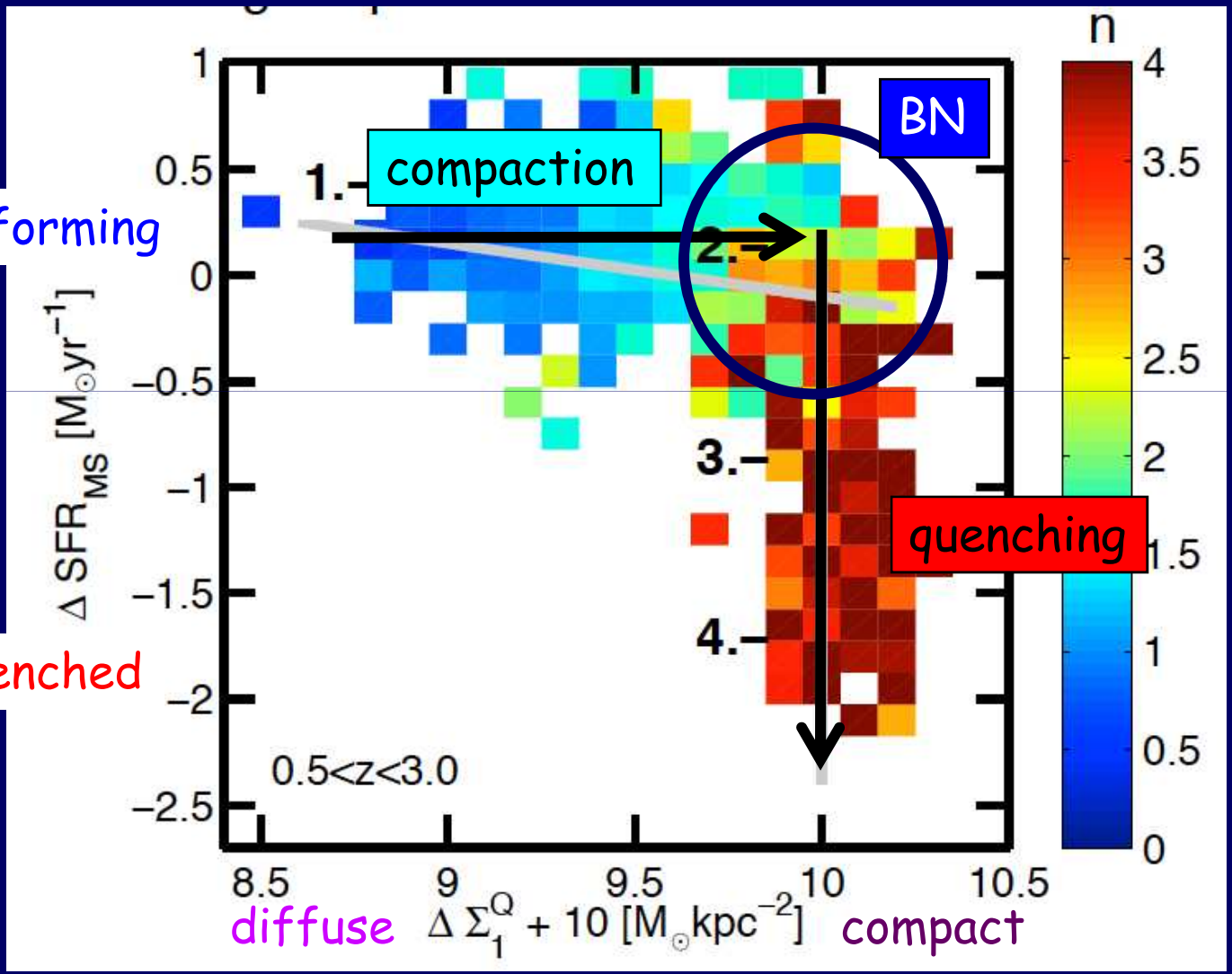
Compaction and Quenching in Simulations



Zolotov+15
Tacchella+16
Dekel+17

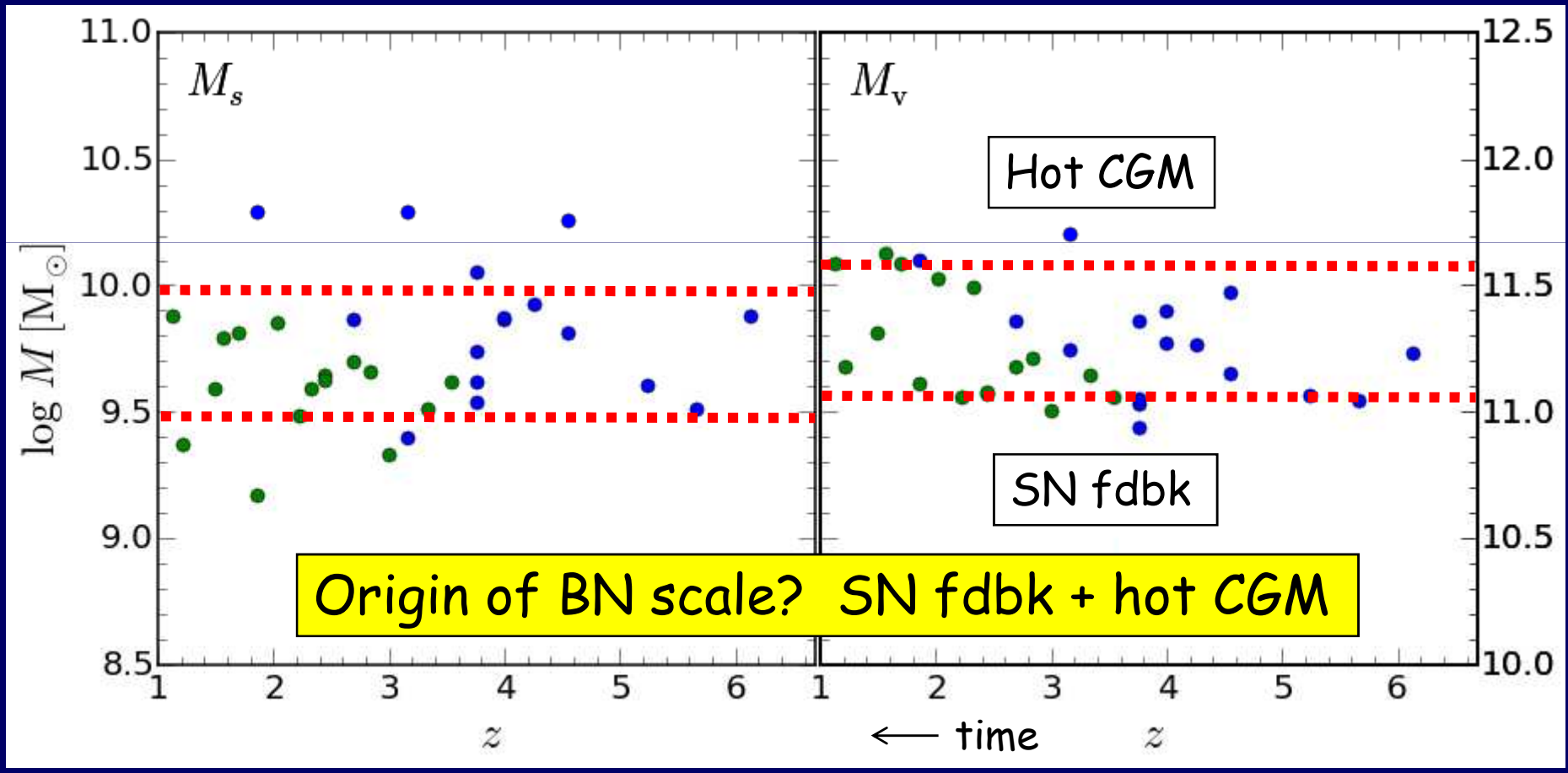
Observed L-Shape Track

Barro+17



A Critical Mass for Blue Nuggets (at all z)

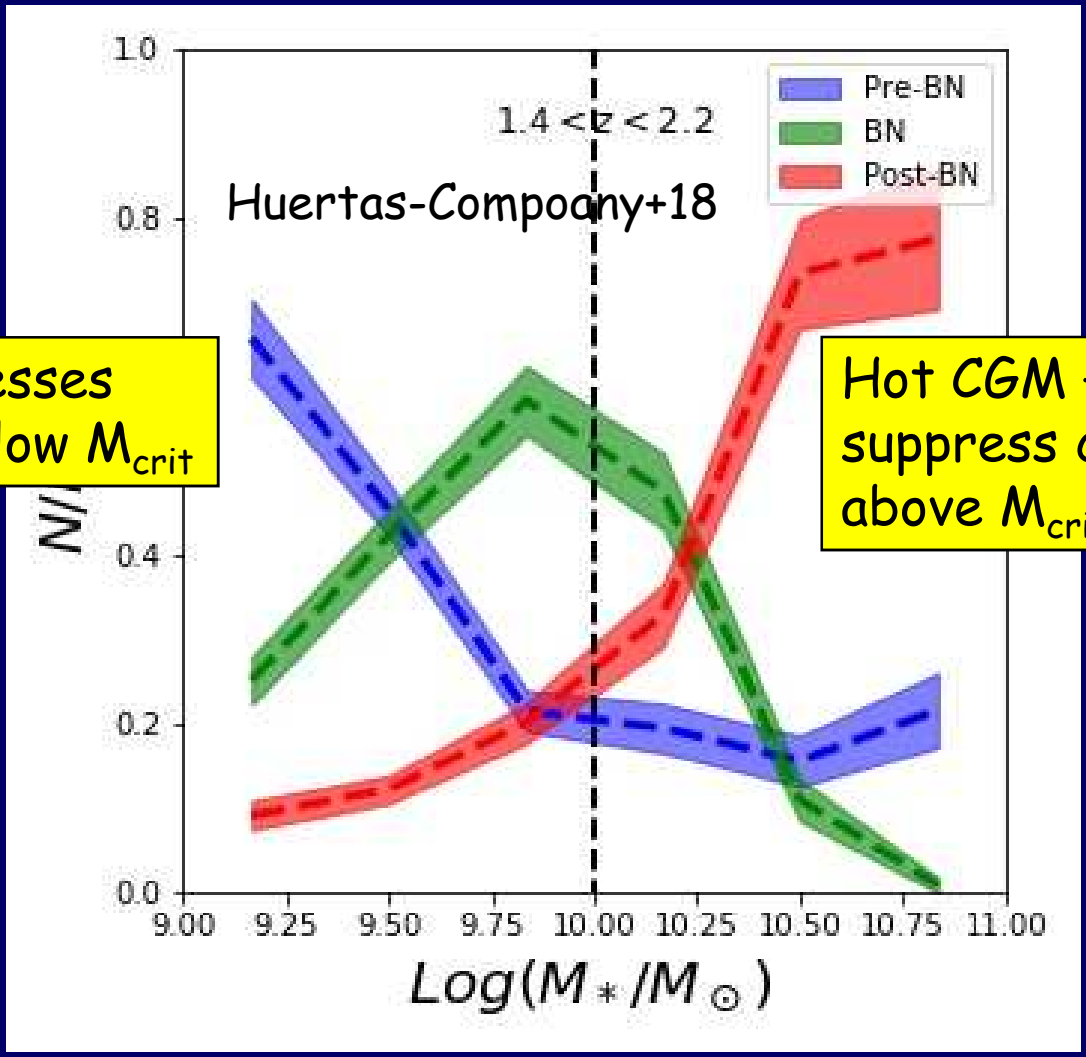
$M_{star} \sim 10^{10} M_\odot$ $M_{vir} \sim 10^{11.5} M_\odot$



Origin of BN scale? SN fdbk + hot CGM

Blue Nuggets at ~M_{crit} in Simulations & CANDELS via Deep Learning

M_{star}~$10^{10}M_{\odot}$ M_{vir}~$10^{11.5}M_{\odot}$ Zolotov+15, Tomassetti+16



SN fdbk suppresses compactions below M_{crit}

Hot CGM + AGN fdbk suppress compactions above M_{crit}

Transition in Galaxy Properties at the BN

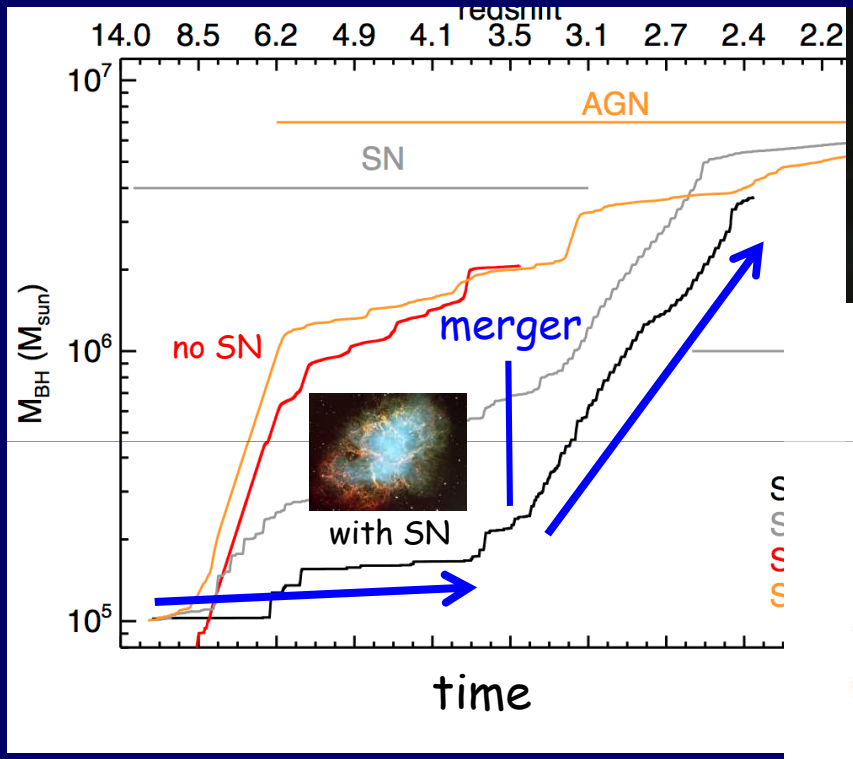
- Diffuse -> compact core + extended disk/ring
- Star forming -> quenched
- Oscillations across the Main Sequence -> quenching
- Dark-matter -> baryon dominated core
- Prolate -> oblate stellar system
- $V/\sigma \sim 1$ -> $V/\sigma \sim 4$, dispersion -> rotation dominated, ring
- ...

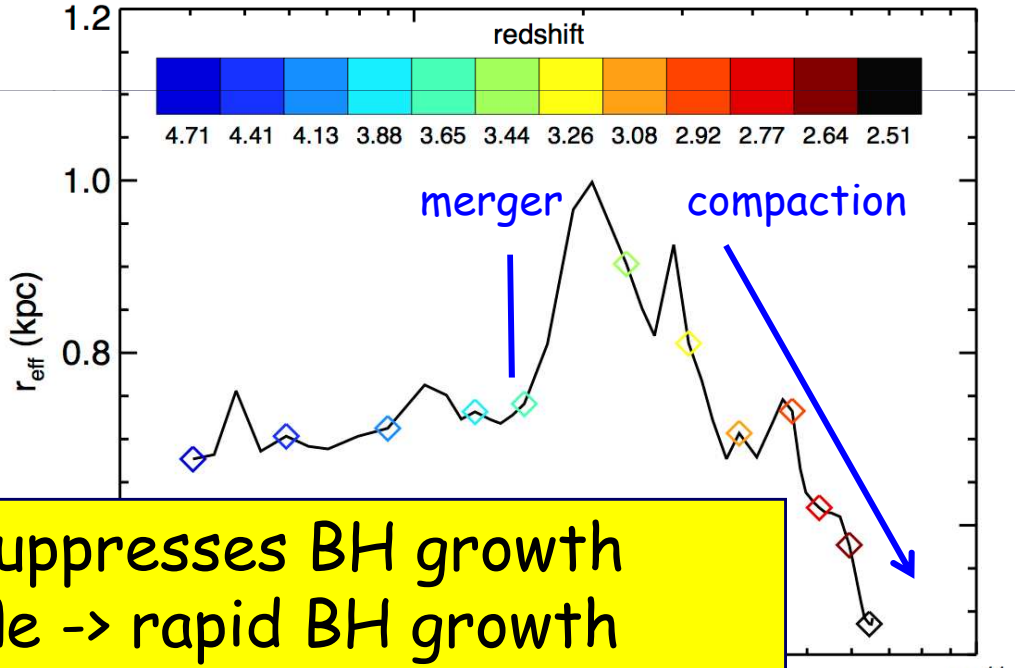
4. Compaction-Driven Black-Hole Growth

Dekel, Lapiner, Dubois+ 2017

Interplay between SNe and BHs

RAMSES Simulation SN+BH by Dubois+ 15

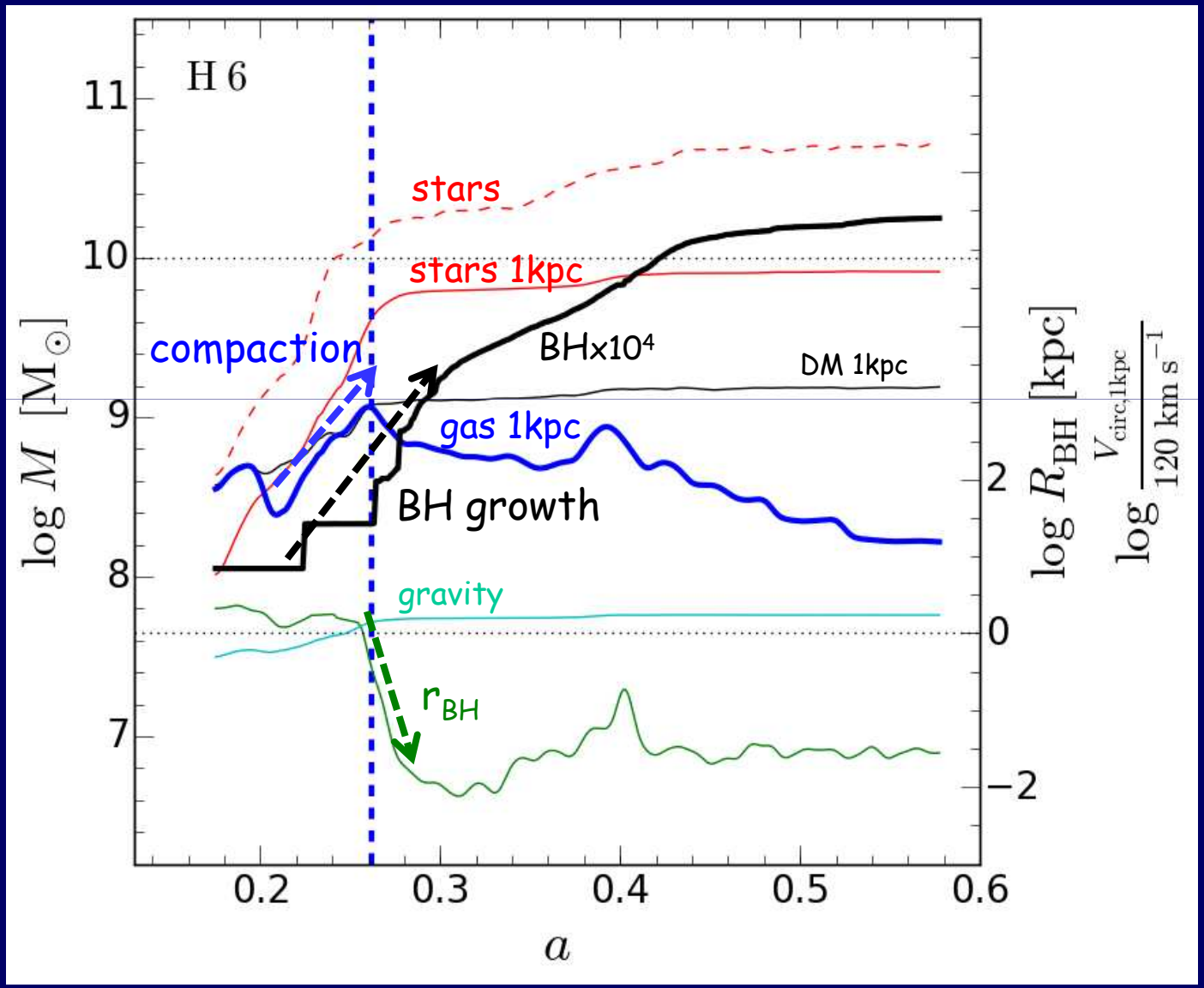




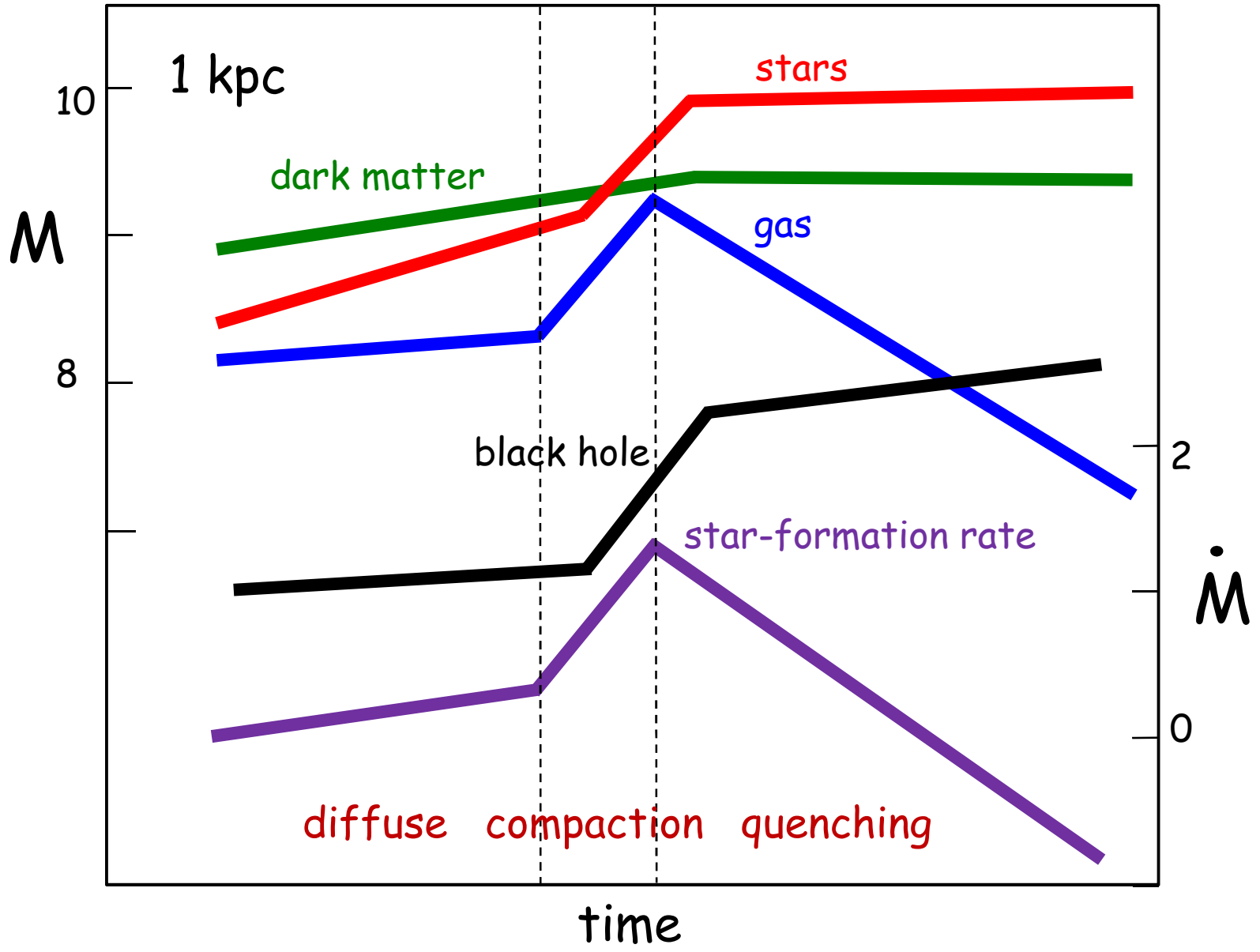
- $M<M_{crit}$: strong SN fdbk suppresses BH growth
- Compaction overcomes SNe -> rapid BH growth
- $M>M_{crit}$: AGN fdbk helps quenching

Compaction driving BH Growth

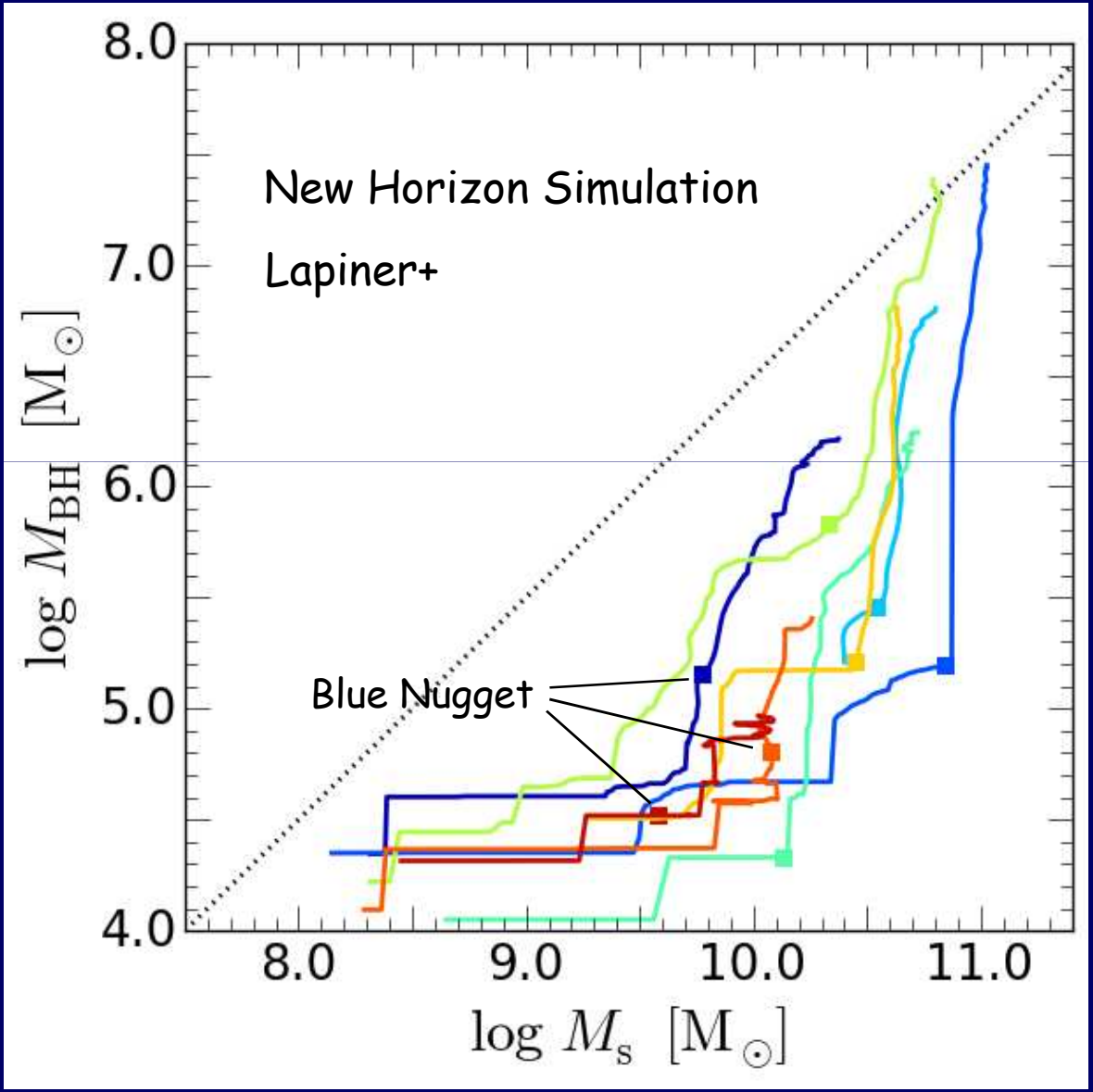
New Horizon simulations SN+BH Dubois+ Lapiner+



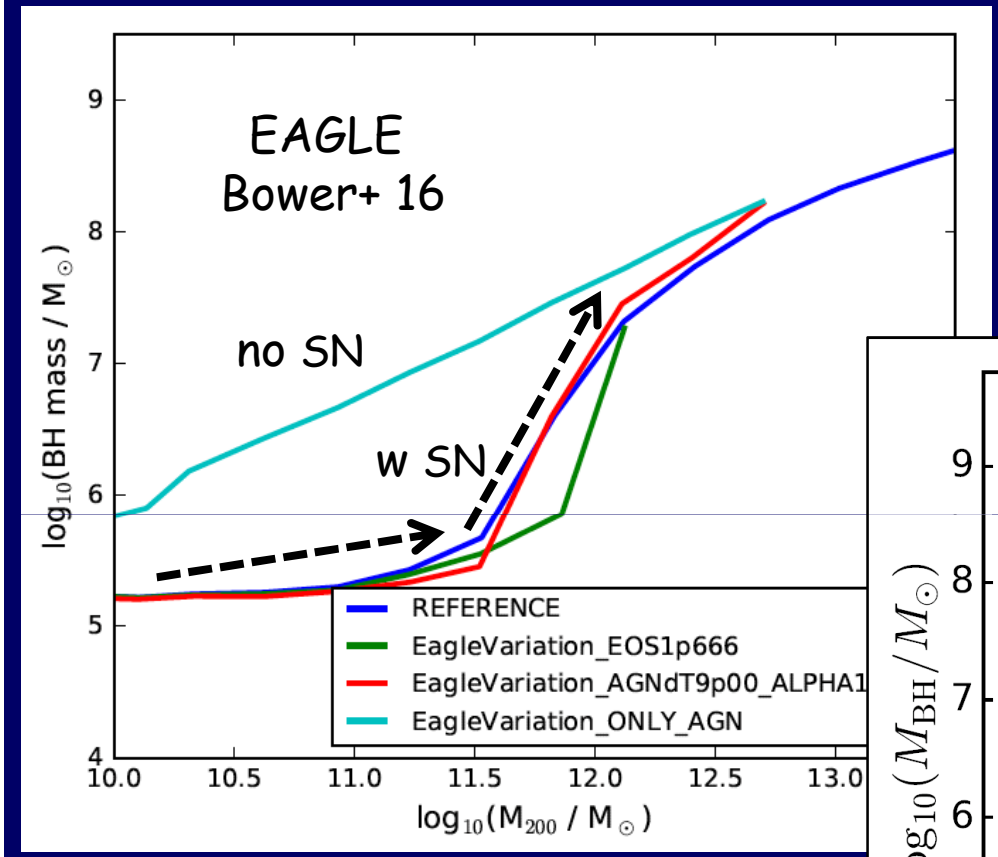
Compaction -> BH Growth



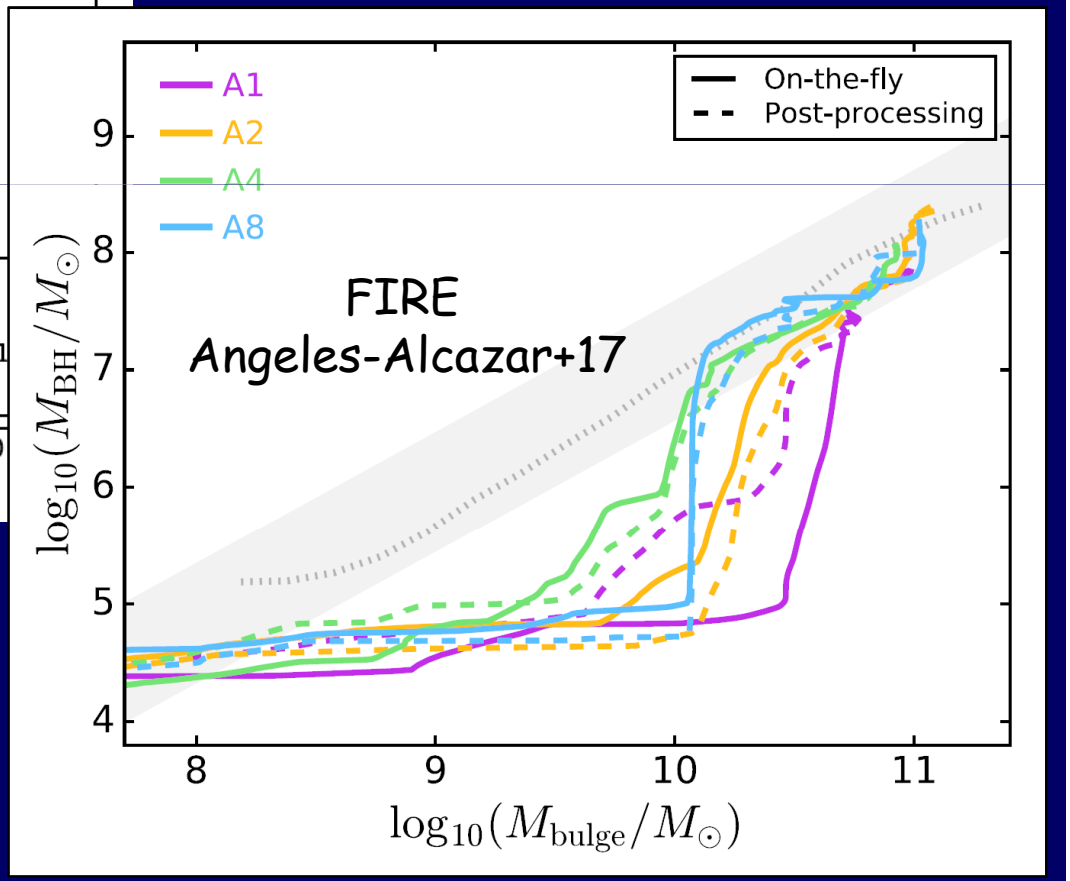
BH Below the Linear Relation for M_{BH}~$10^5 M_\odot$



Golden Mass for BH is Robust in Simulations



Illustris TNG
Habouzit+18



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

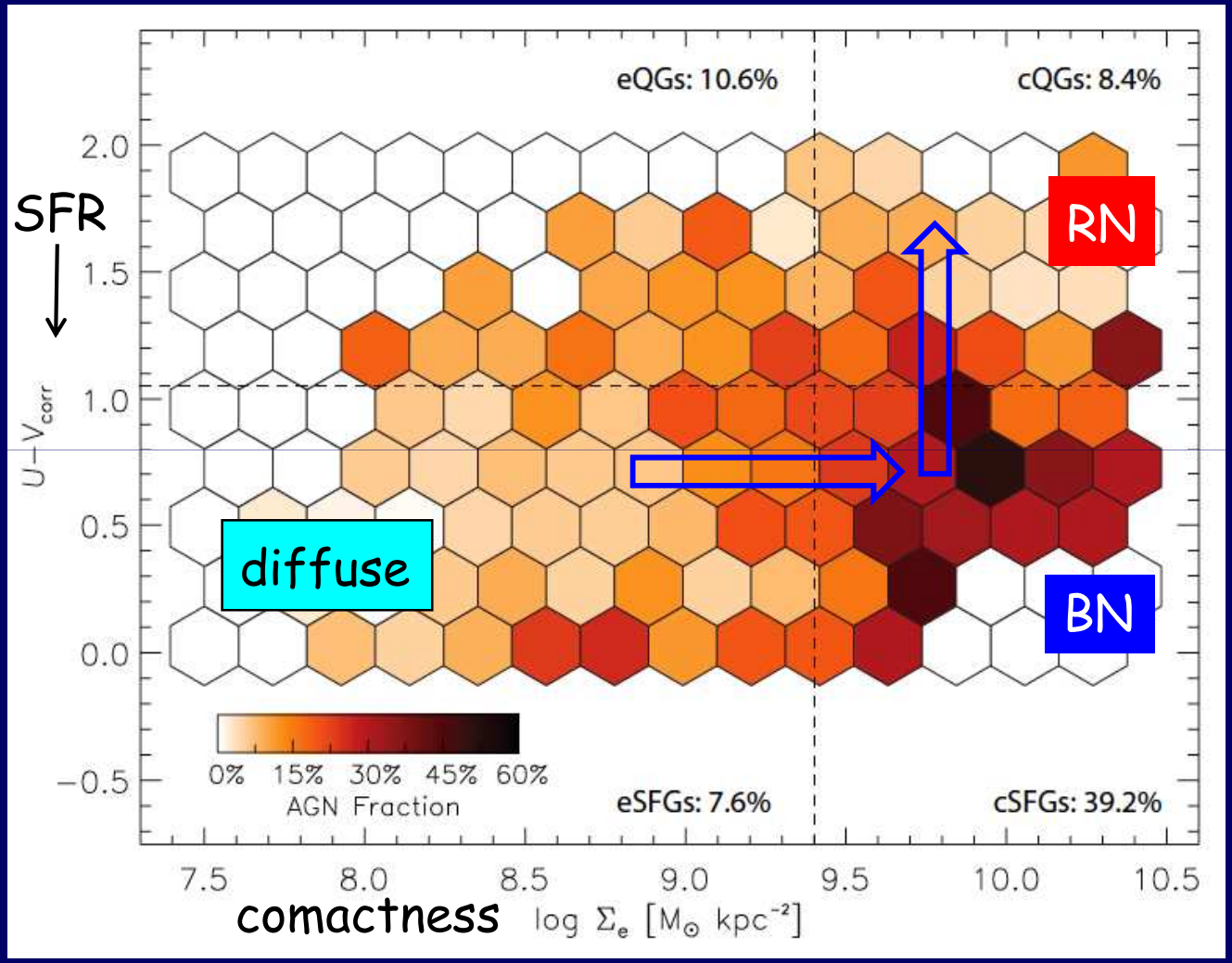
- $M_{vir} < M_{crit}$, pre-compaction SN phase:
  V_{esc} < 100 km/s -> SN winds of 100 km/s evacuate the core
  -> BH growth is suppressed , Blue-Nugget formation is suppressed

- $M_{vir} \sim M_{crit}$, 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 Phase

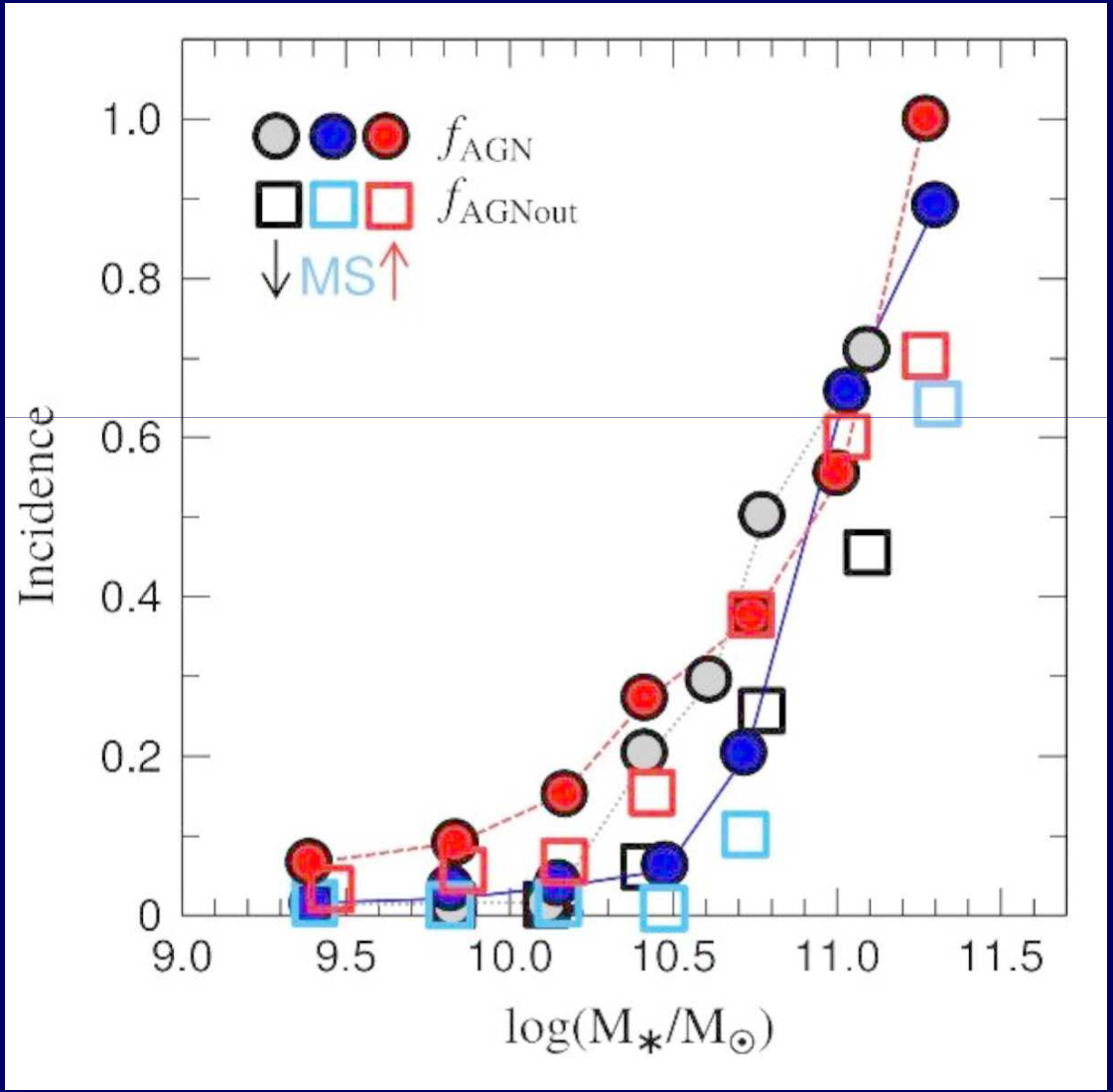
Kocevski+17



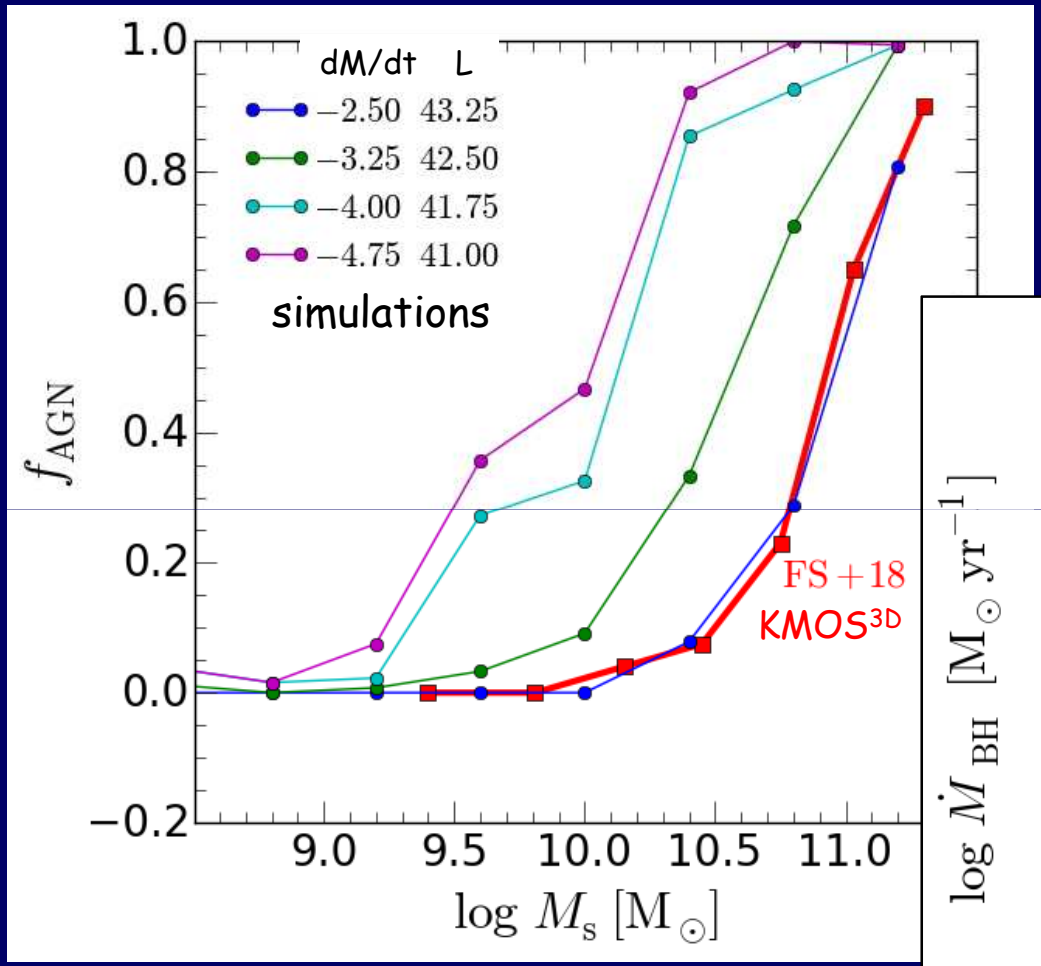
-> Compaction triggers BH growth and AGN -> quenching

AGN Activation at the Critical Mass

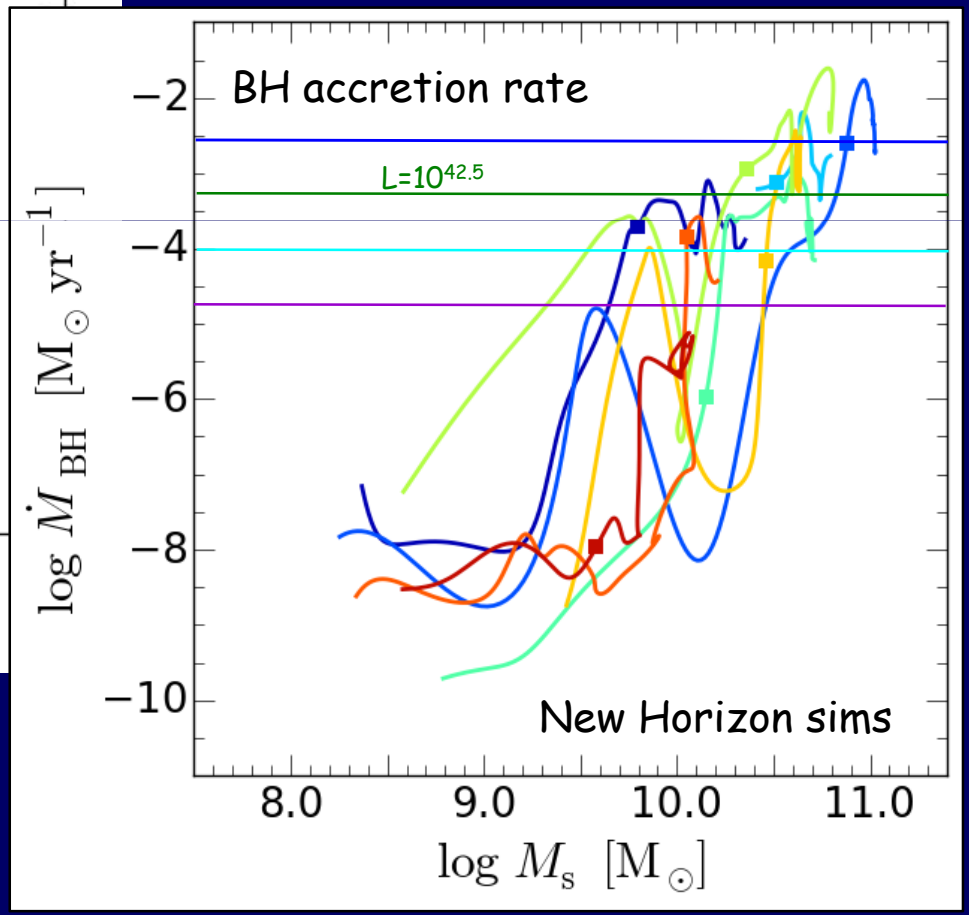
Forster-Schreiber+18 KMOS^{3D} z=0.6-2.7 599 galaxies



Fraction of AGN

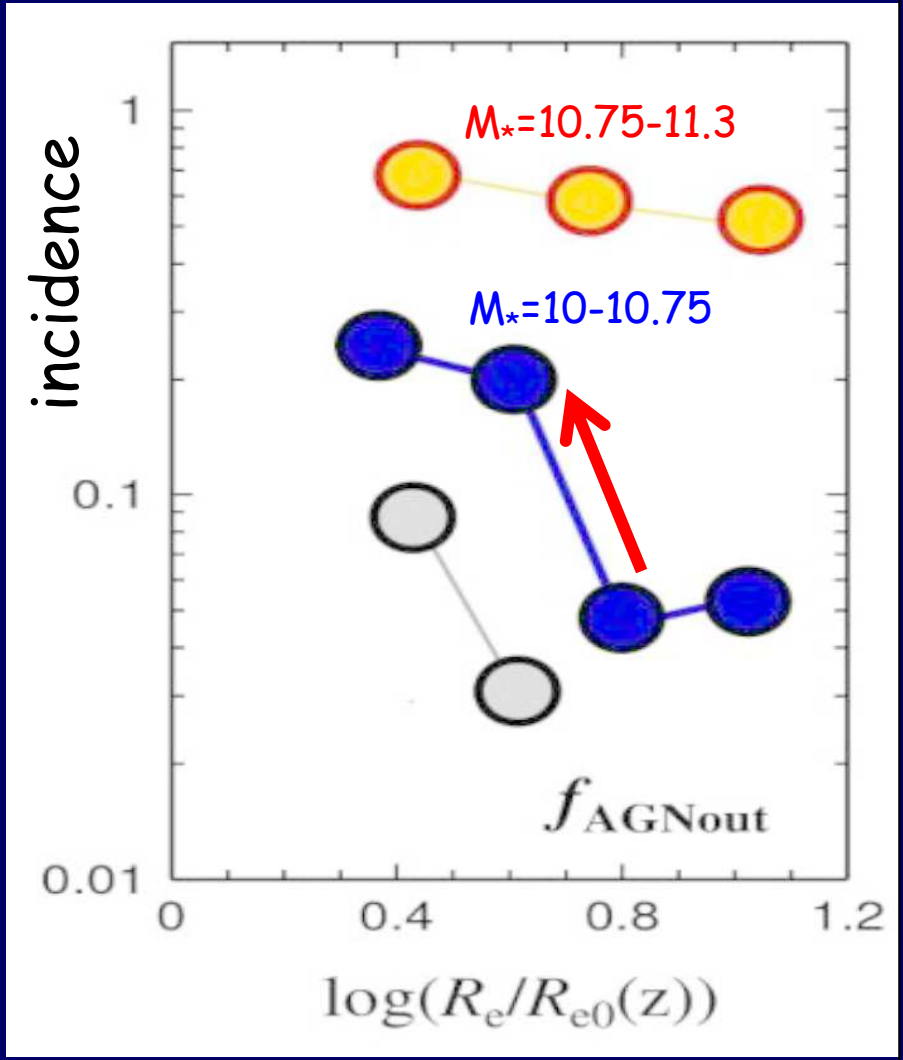


$L = 0.1\ dM_{bh}/dt\ c^2$



AGN Correlate with Compactness

Forster-Schreuer+18 KMOS^{3D} z=0.6-2.7 599 galaxies

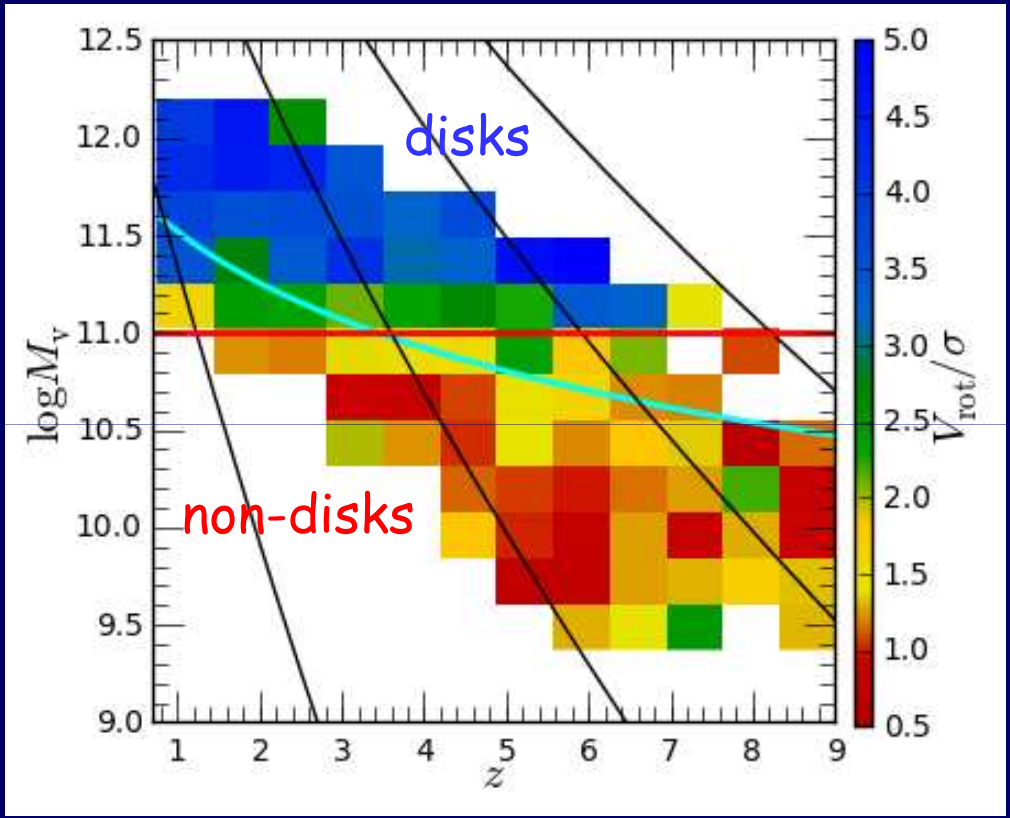


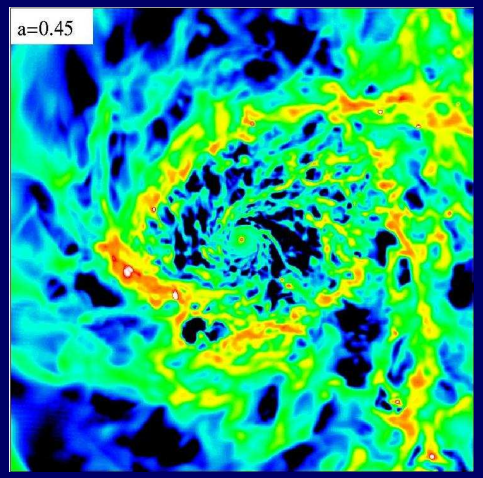
5. Compaction-Driven Rings

Dekel et al. 2019

A Mass Threshold for Disks/Rings

VELA-3 cosmological simulations 25pc res (Ceverino, Dekel, Primack)





Disks in $M_{vir}>2\times10^{11}\ M_\odot$

$M_{star}>10^9\ M_\odot$

No significant redshift dependence

Compaction -> Extended Ring

In an unstable disk: AM out -> mass in (e.g. clump migration)

Rapid inflow $t_{\rm inflow} \approx 2\delta_{\rm disk}^{-2} t_{\rm orbit}$

$\delta_{\rm disk} \equiv (M_{\rm cold}/M_{\rm tot})$ cold mass fraction

Dekel, Sari, Ceverino 09

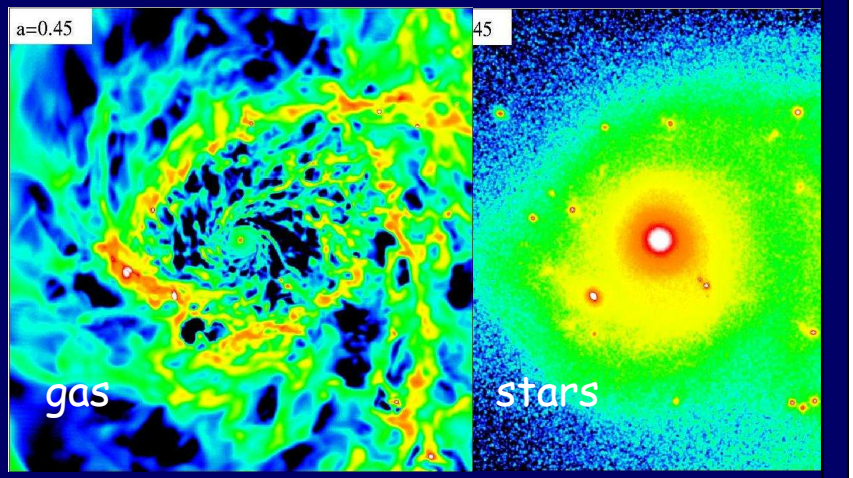
Why long-lived ring post compaction?

Torques by spiral structure on ring:

Dekel+ 19

- pitch angle $\tan^2\alpha \approx 4\delta_{\rm disk}^2$

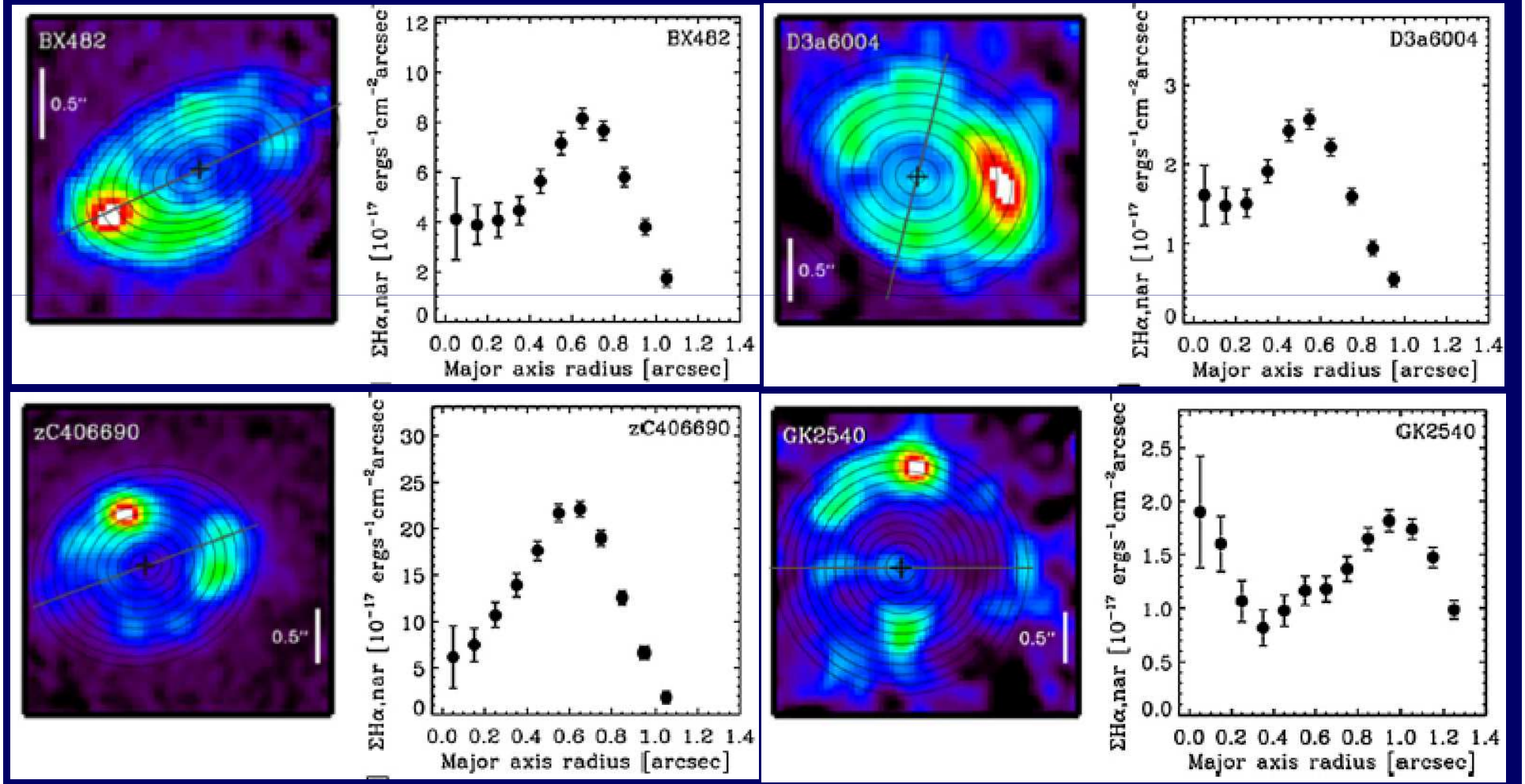
- slow inflow $t_{\rm inflow} \approx \delta_{\rm disk}^{-3} t_{\rm orbit}$



- in-streams with hi AM -> extended ring
- Gas depletion + bulge -> $Q_{\rm in}$>>1 -> no perturbations -> ring, weak torques
- Massive bulge (or DM) -> $\delta_{\rm disk}$ <<1 -> ring, $t_{\rm inflow}$ >> 10 $t_{\rm orbit}$ > $t_{\rm accretion}$

Observed Hα Rings & Massive Bulge

z ~ 2 Genzel+ 14



Conclusions

The golden mass M_*~$10^{10}M_\odot$ (and z~2) is due to suppression of SFR by SN fdbk at low masses and CGM heating at high masses (+AGN)

Wet compaction to a Blue Nugget is a dramatic event in the history of many galaxies (~40% by mergers, 30% counter-rotating streams)

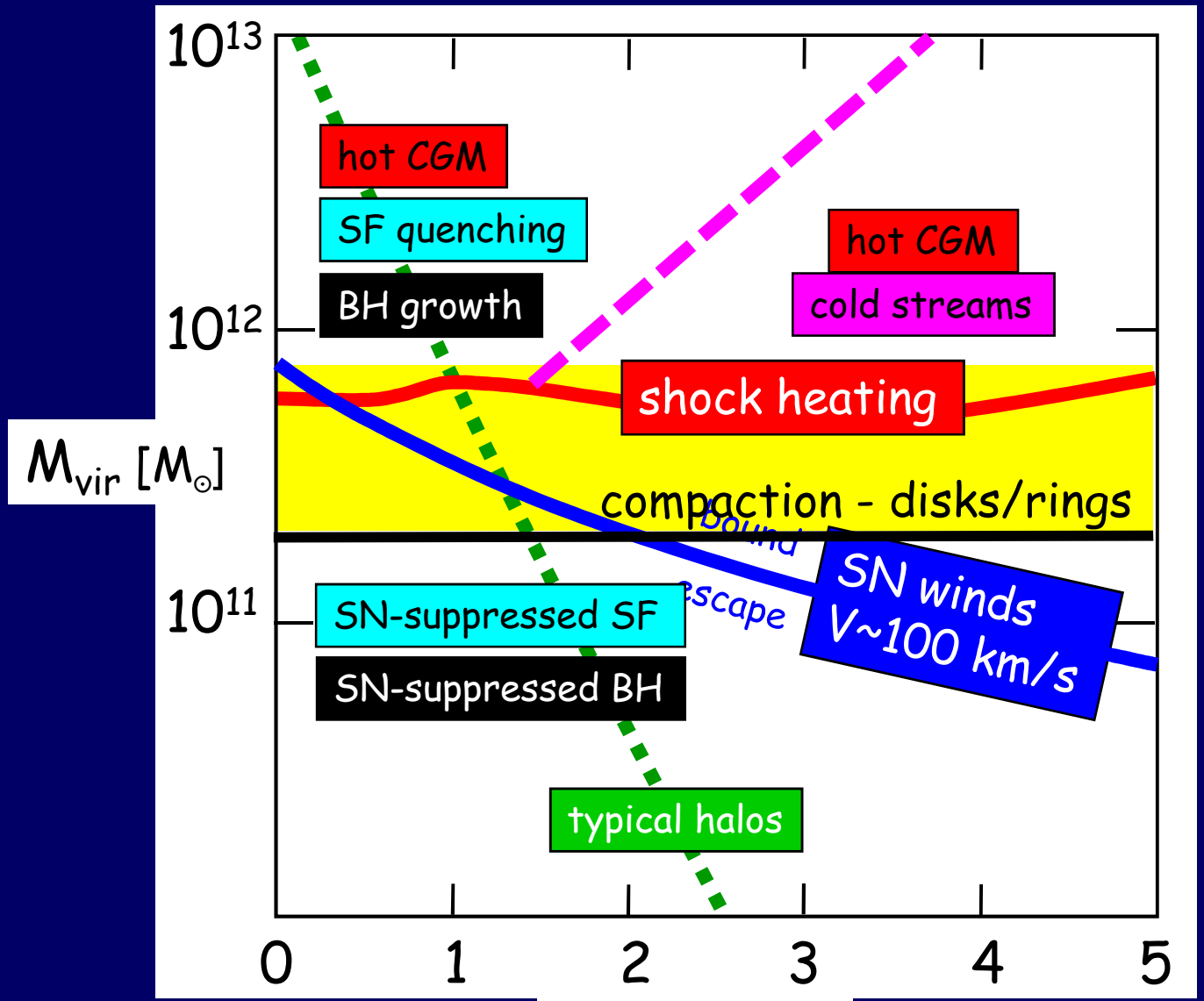
The major compaction is typically at the golden mass, when SN fdbk becomes ineffective and cold streams penetrate the hot CGM

The Blue Nugget marks transitions in most galaxy properties:
mass, size, SFR, gas fraction, metallicity, dust,
dark-matter dominance, shape, kinematics, …

BH growth is suppressed by SN feedback in $M<M_{crit}$ halos,
and is triggered by Wet compaction in $M>M_{crit}$ halos,
where SNe are ineffective & the CGM is shock heated.
The resulting AGN helps maintaining the quenching

Extended, clumpy, star-forming rings above the golden mass
supported by a massive post-compaction bulge (or central dark matter)

The Golden Mass M_{vir}~$10^{11.5\text{-}12} M_\odot$



Dekel & Birnboim 06

Dekel & Silk 86

Press & Schechter 74