Three comments on High-z Galaxy Formation

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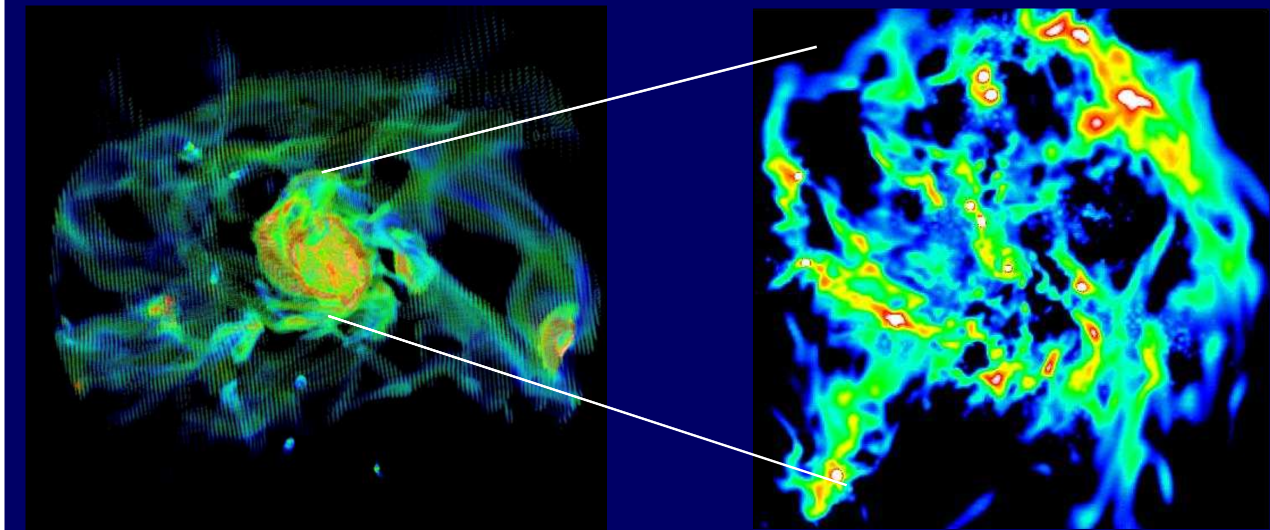
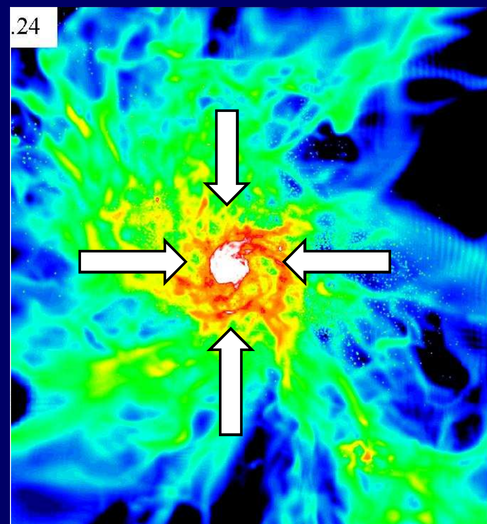




Outline

1. Angular momentum: buildup in 4 phases

2. Violent disk instability: Nonlinear, Stimulated

3. Quenching: by compaction and by a hot halo

AMR Cosmological Simulations

Cosmological box, RAMSES (Teyssier), resolution 1 kpc

Zoom-in galaxies, ART (Kravtsov, Klypin), RAMSES (Teyssier)

Ceverino, Dekel, Primack:
- 50 pc res. (30 galaxies)
- 25 pc res., lower SFR, w/o rad. fdbk (2x30 galaxies)
- same with stronger RP feedback

DeGraf, Dekel, Gabor, Bournaud:
- with BHs and AGN feedback (isolated and cosmological)

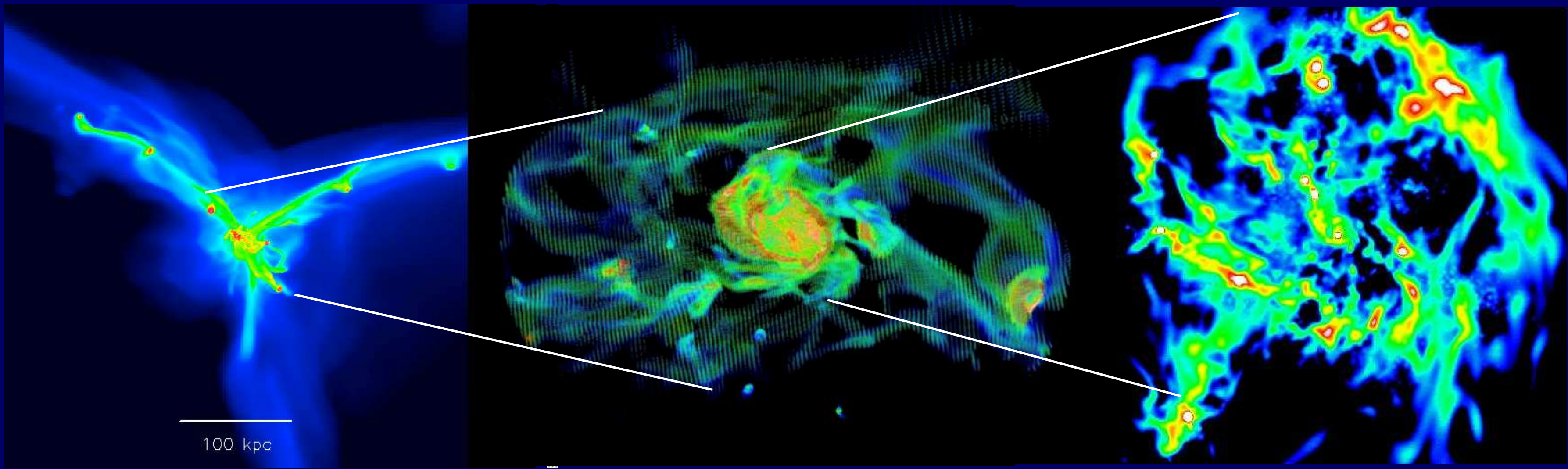
Isolated galaxies, resolution 1-10 pc, RAMSES, Bournaud et al.

HUJI: Ceverino, Mandelker, Danovich, Tweed, Zolotov, DeGraf, Inoue
Groups of Krumholz+, Burkert+, Bournaud+, Primack+

Angular Momentum Buildup in High-z Galaxies

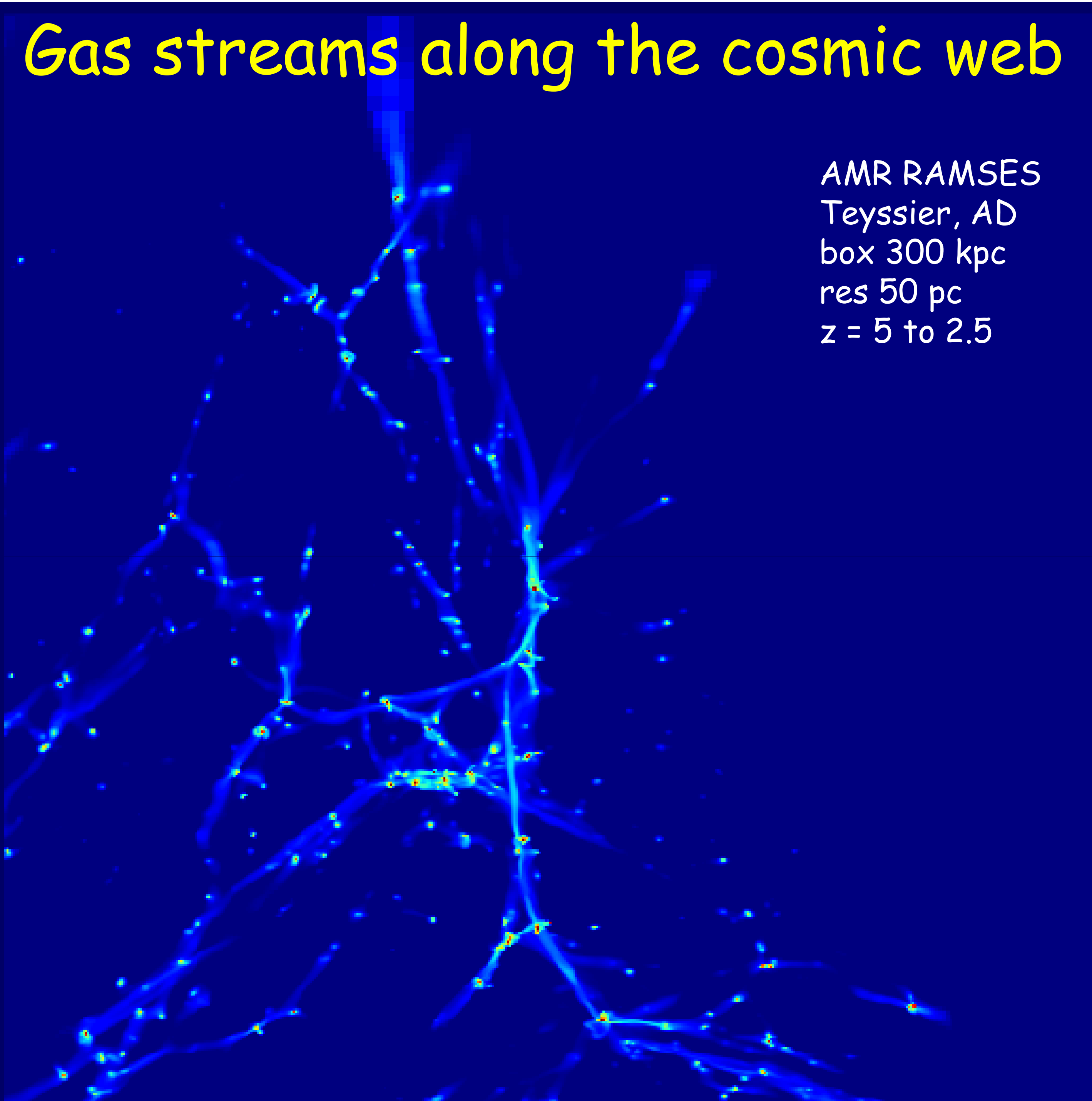
Pichon, Devriendt+ 2011-2014
Stewart, Bullock+ 2011, 2013
Danovich, Dekel, Hahn, Ceverino, Primack 2012, 2014

Kyle Stewart's talk

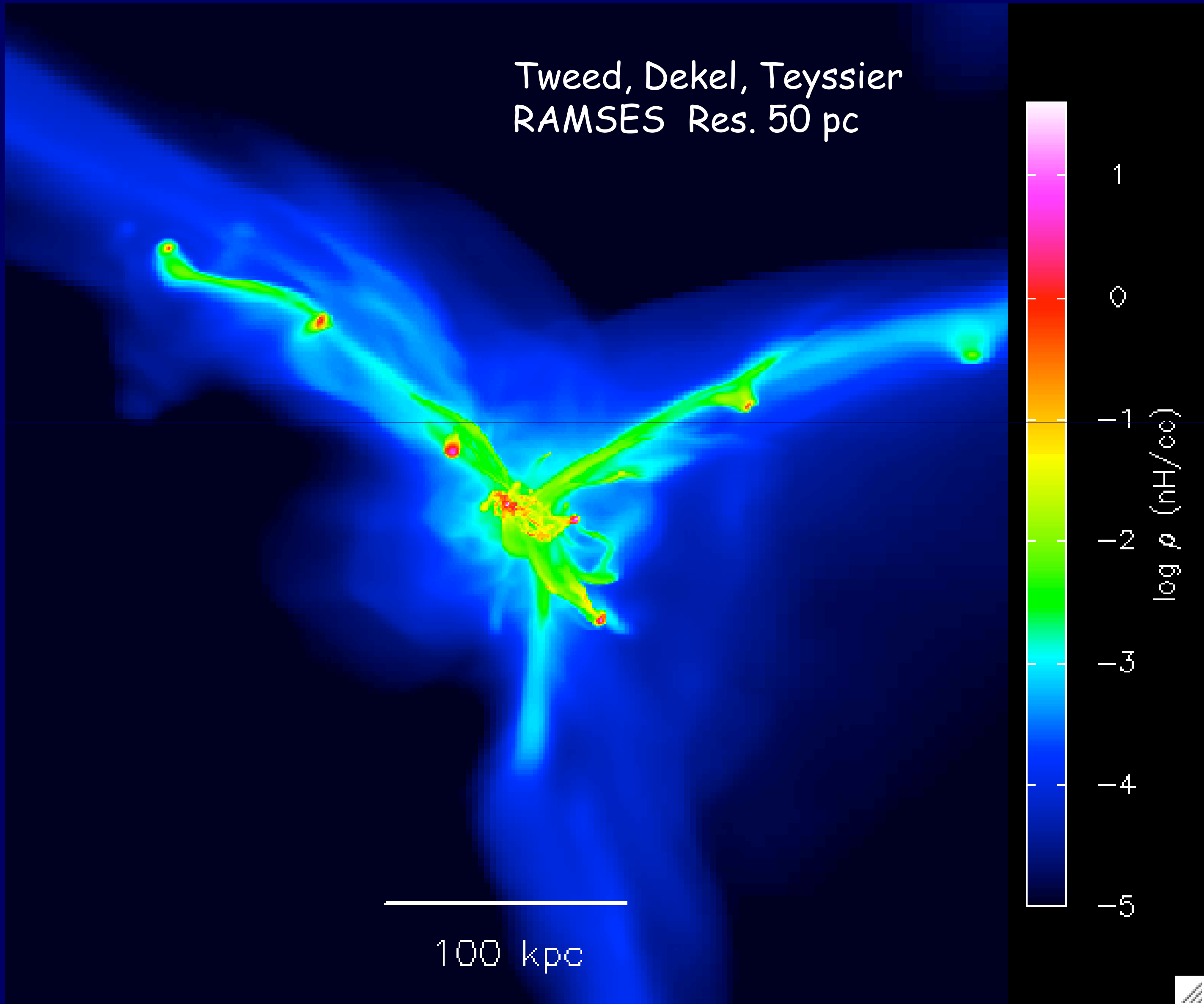


Is the naïve model of smooth cylindrical infall with disk spin ~ halo spin (SAM) valid at high redshift?

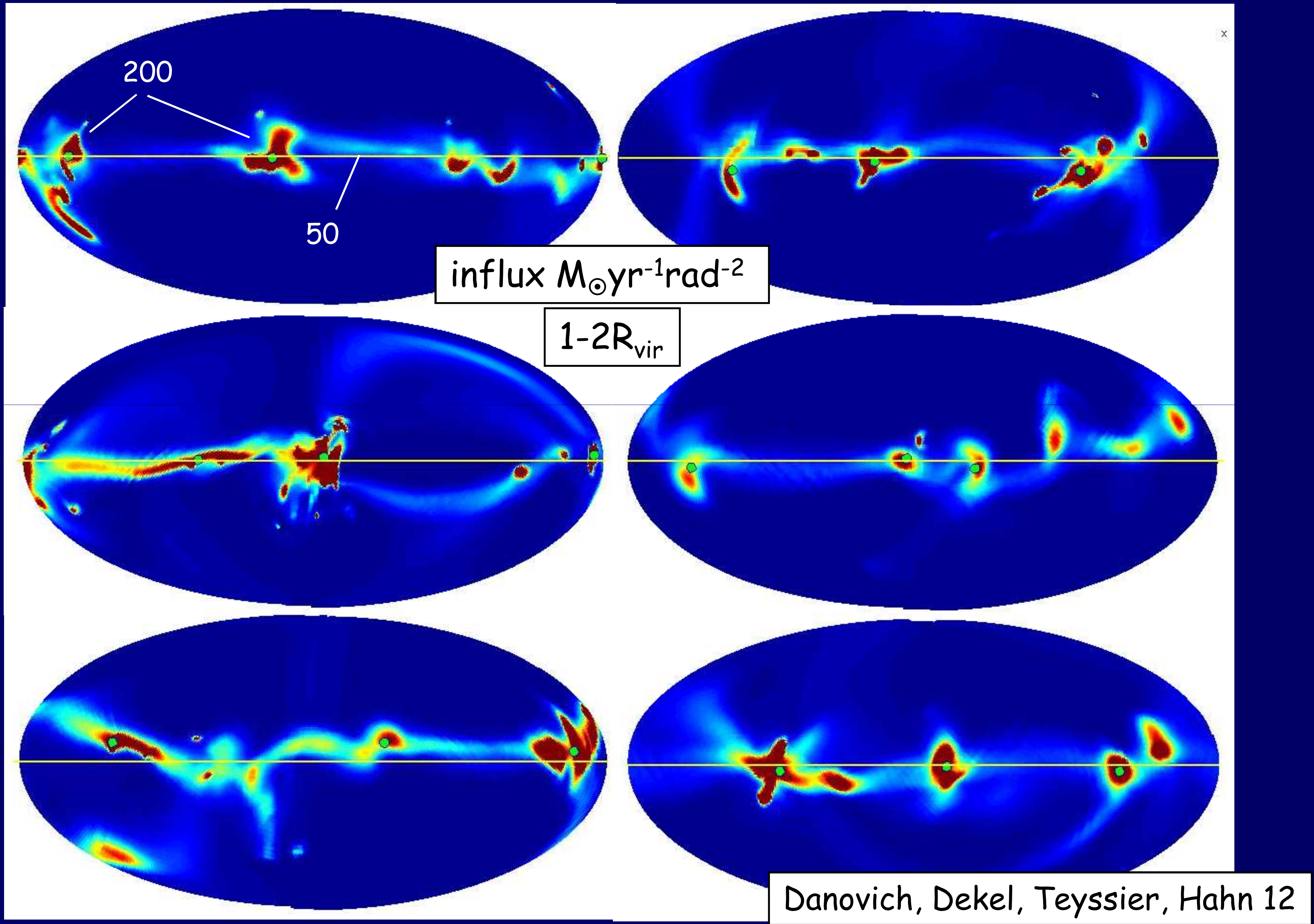
Gas streams along the cosmic web



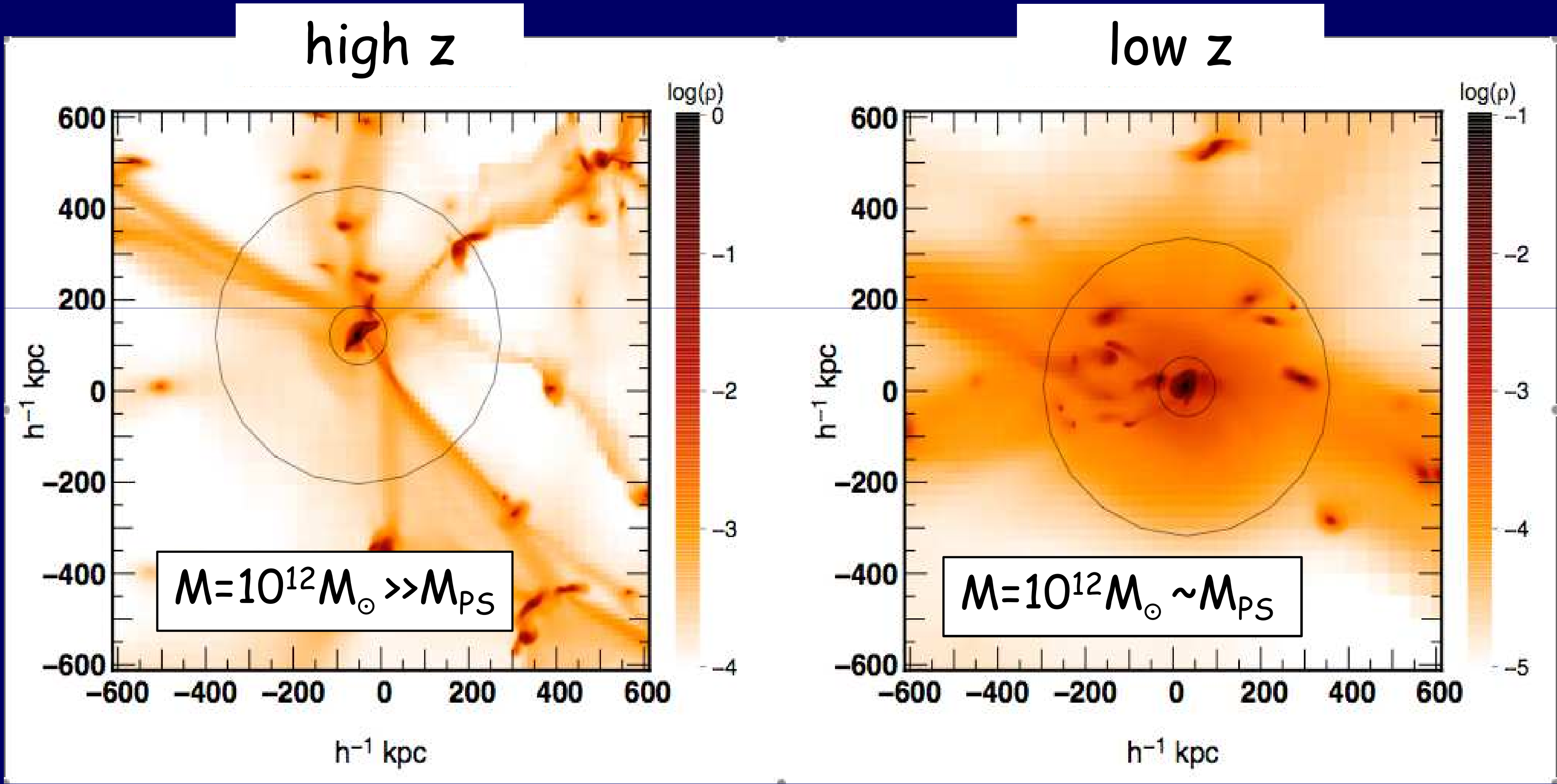
Streams Feeding a Hi-z Galaxy



Co-planar ~3 Streams (in a pancake)



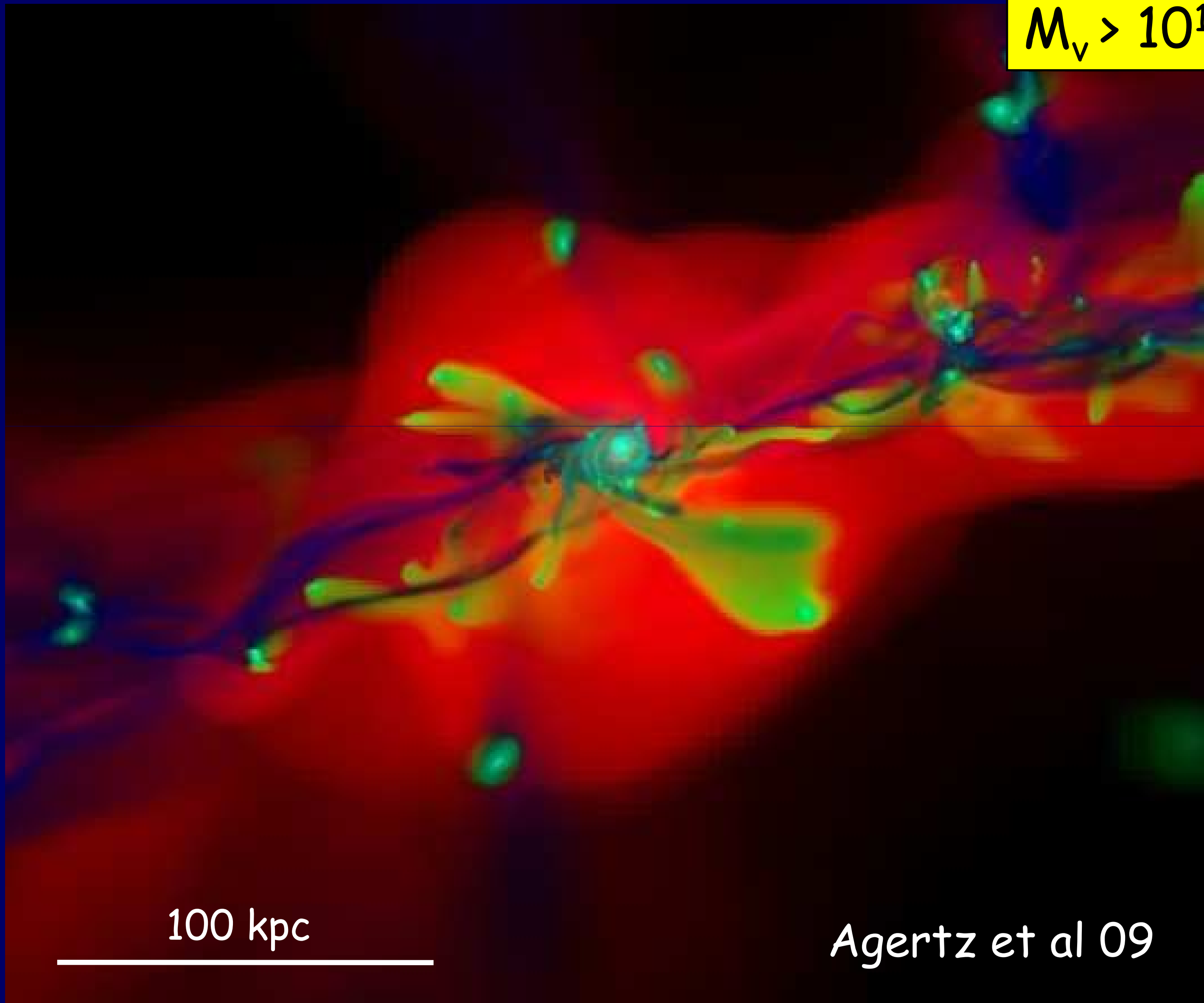
Narrow dense gas streams at high z versus spherical infall at low z



Ocvirk, Pichon, Teyssier 08

Cold Streams Penetrate through Hot Halos

$M_v > 10^{12}\ M_\odot$



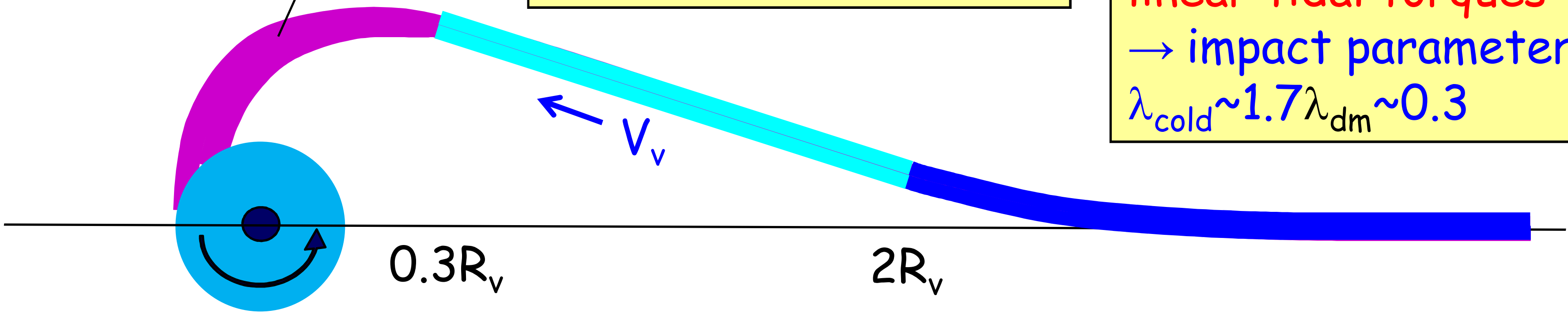
AM Buildup by Cold Gas in 4 Phases

Danovich, Dekel, Hahn+ 14

III. inner halo – extended tilted ring
non-linear torques, dissipation
AM loss $\lambda_{cold} \rightarrow 0.04$ & alignment

II. outer halo
AM transport, j~const.
$\lambda_{cold} \sim 3\lambda_{dm} \sim 0.1$ DM mix

I. cosmic web
linear tidal torques
→ impact parameter
$\lambda_{cold} \sim 1.7\lambda_{dm} \sim 0.3$

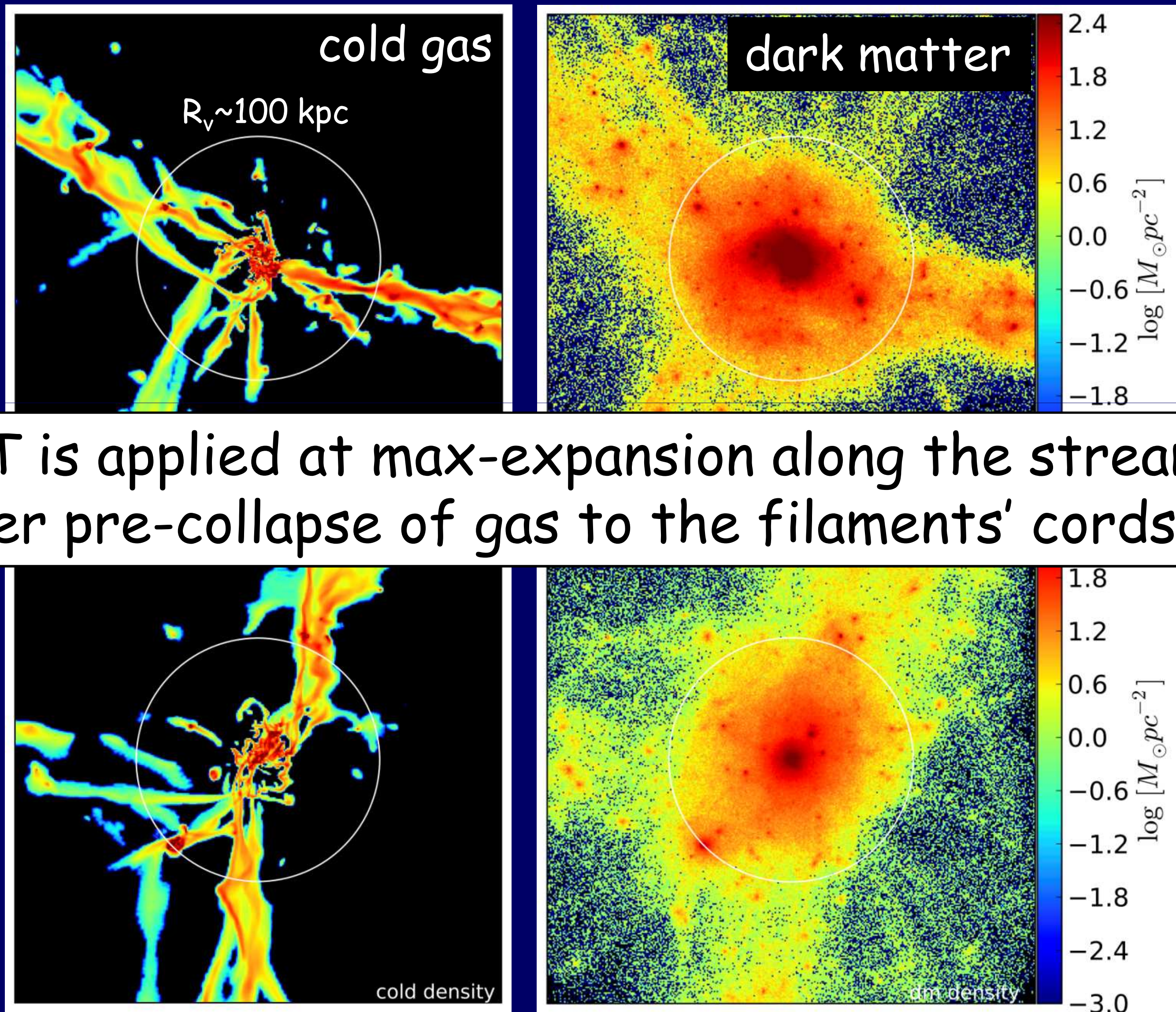


IV. inner disc (+ bulge)
disk instability, outflows
$\lambda_{baryons} \sim 0.03$

spin parameter $\lambda \sim \frac{J/M}{\sqrt{2} R_V V_V}$

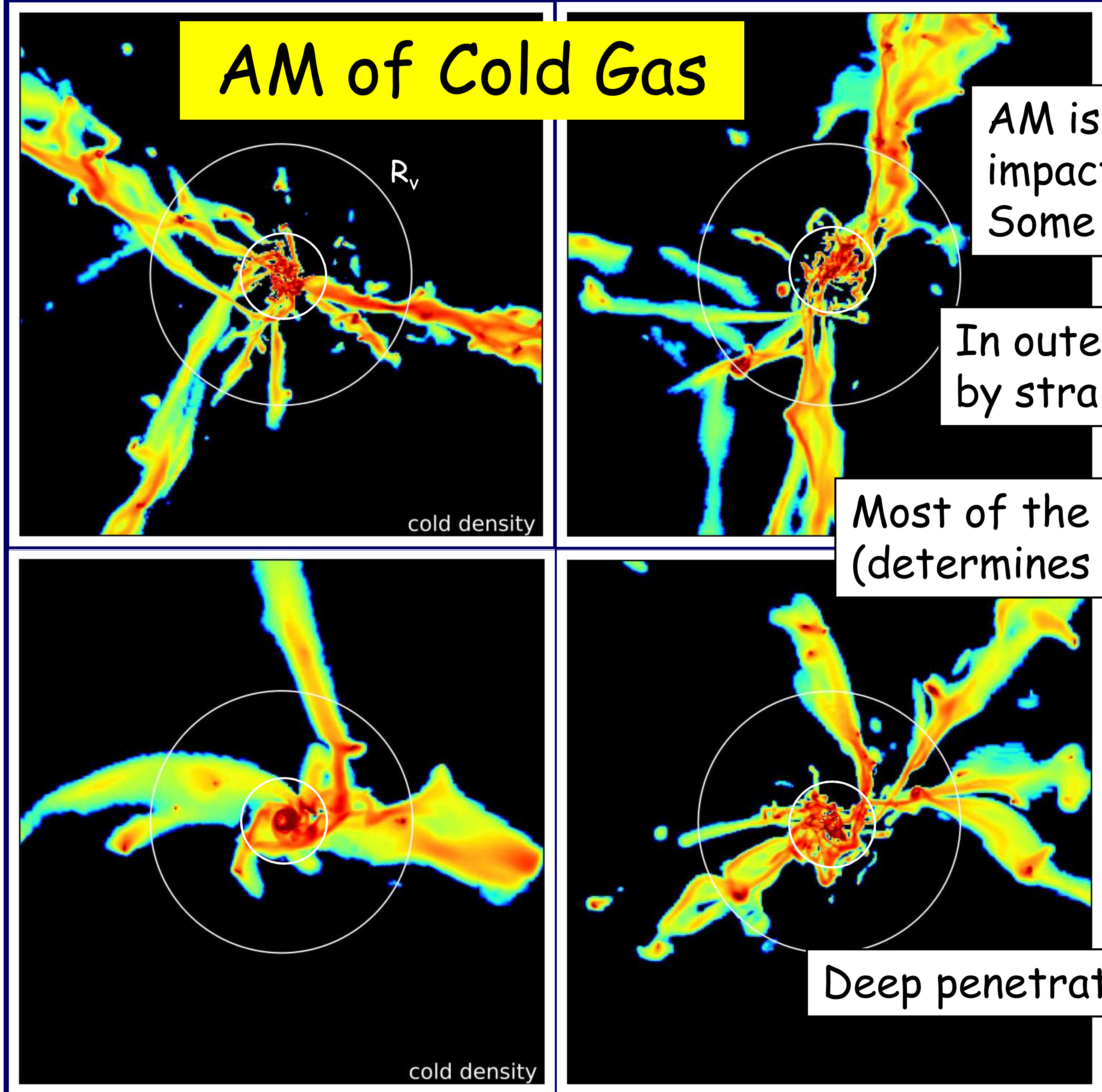
TTT outside the halo: $\lambda_{cold} \sim 1.7 \lambda_{DM}$ due to quadrupole moment of inertia

$$J_i \propto t\, \varepsilon_{ijk} T_{jl} I_{lk}$$



TTT is applied at max-expansion along the streams, after pre-collapse of gas to the filaments' cords

AM of Cold Gas



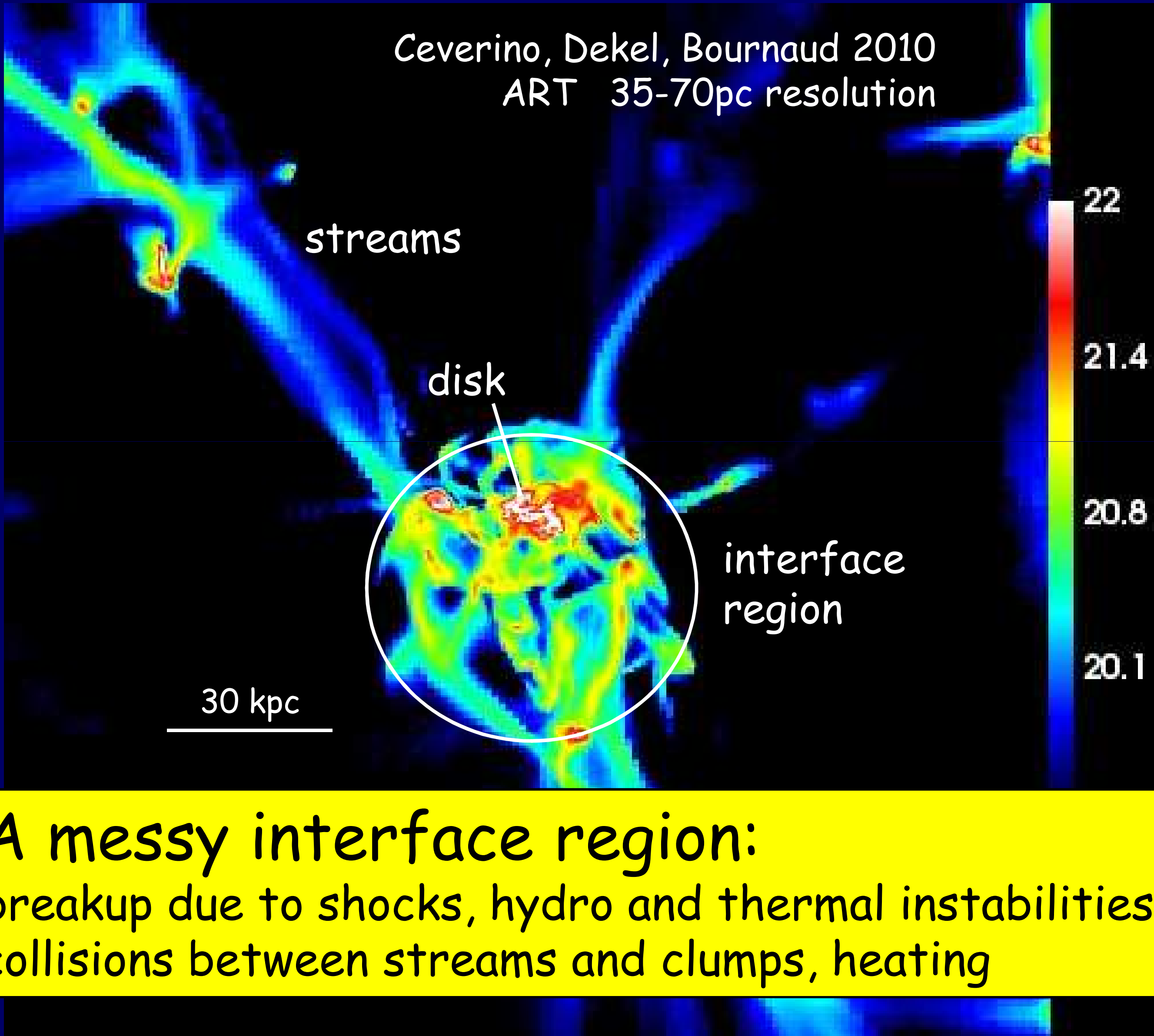
AM is represented by impact parameters <0.3R$_v$
Some counter-rotating

In outer halo AM transport by straight streams

Most of the AM is in one stream (determines the AM plane at R$_v$)

Deep penetration of the streams

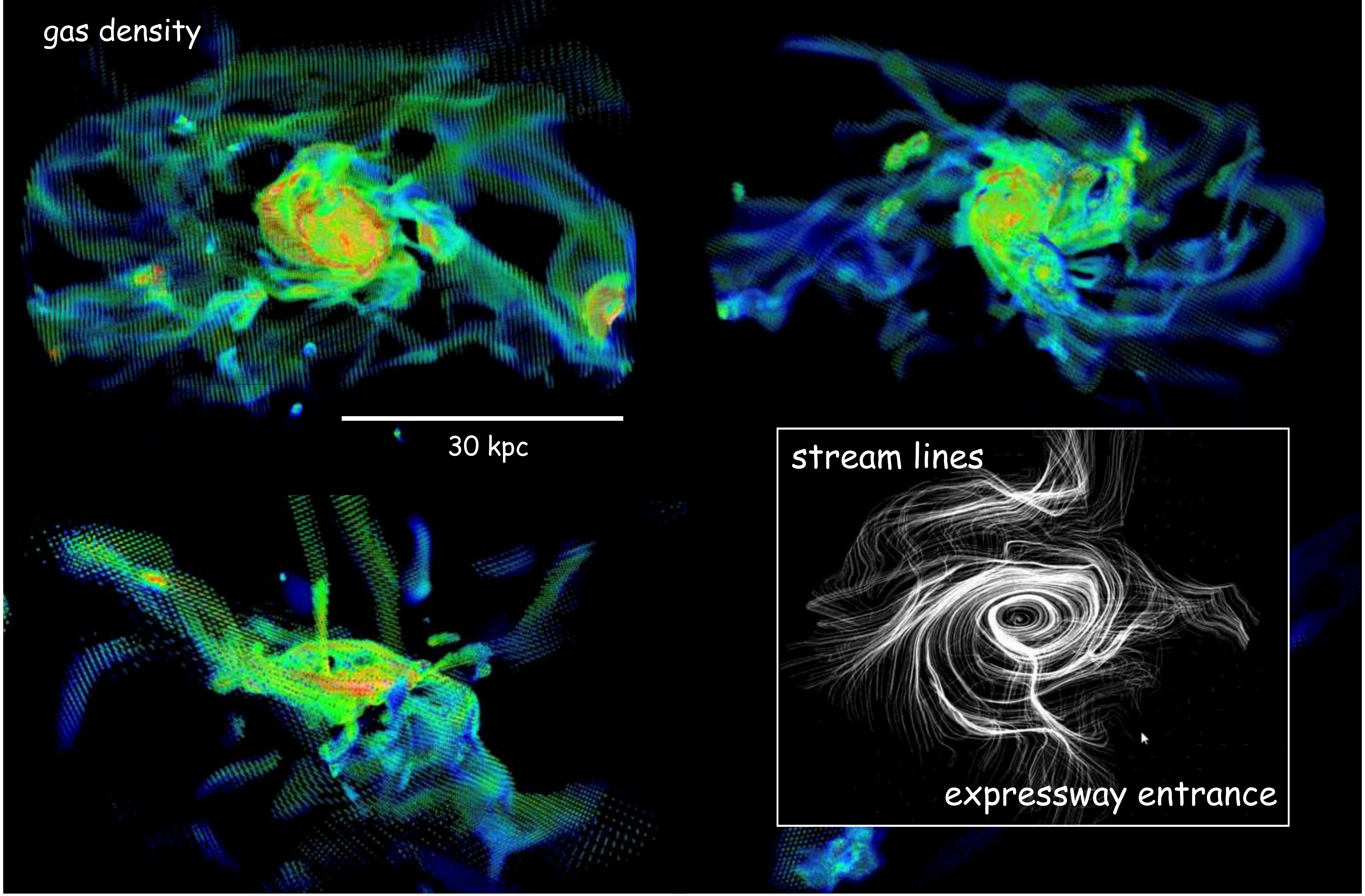
How do the streams join the disk?



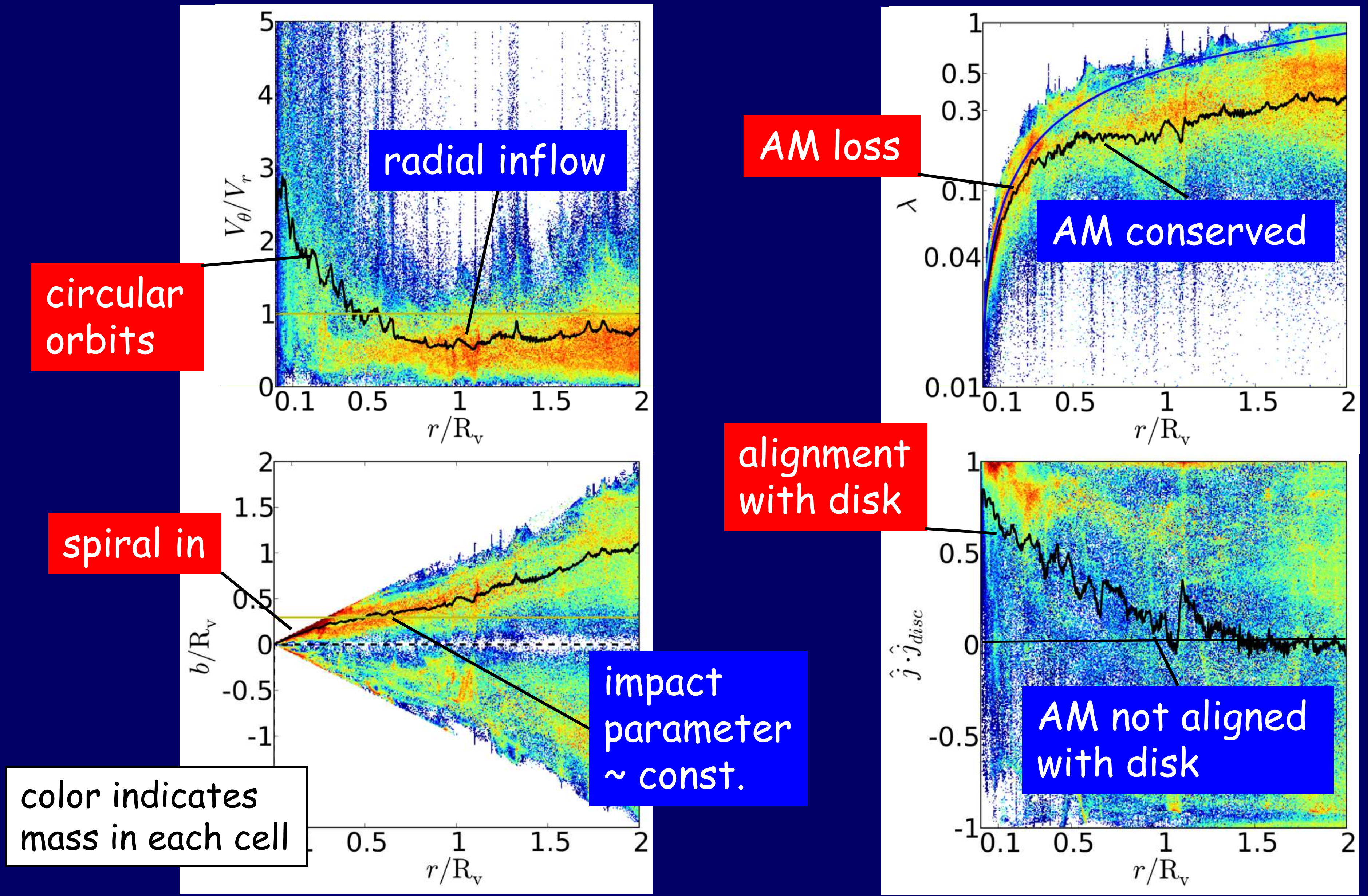
A messy interface region:

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

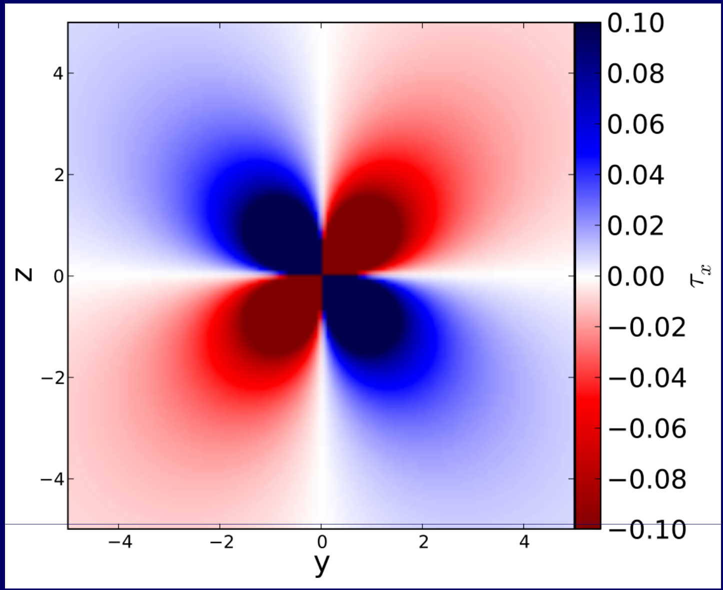
An Extended Tilted Ring about the Disk



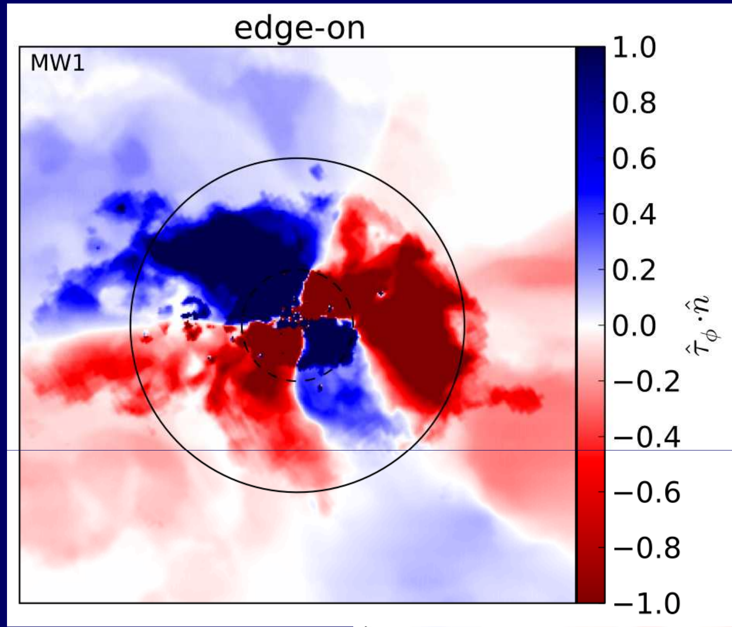
A tilted rotating ring in the inner halo

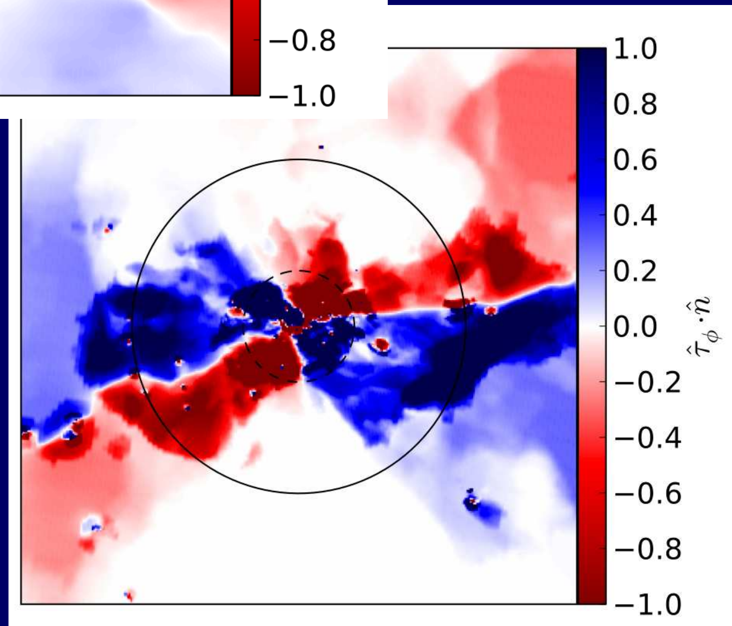


AM Exchange in the Ring: Torques by Disk



torques by an
idealized disk

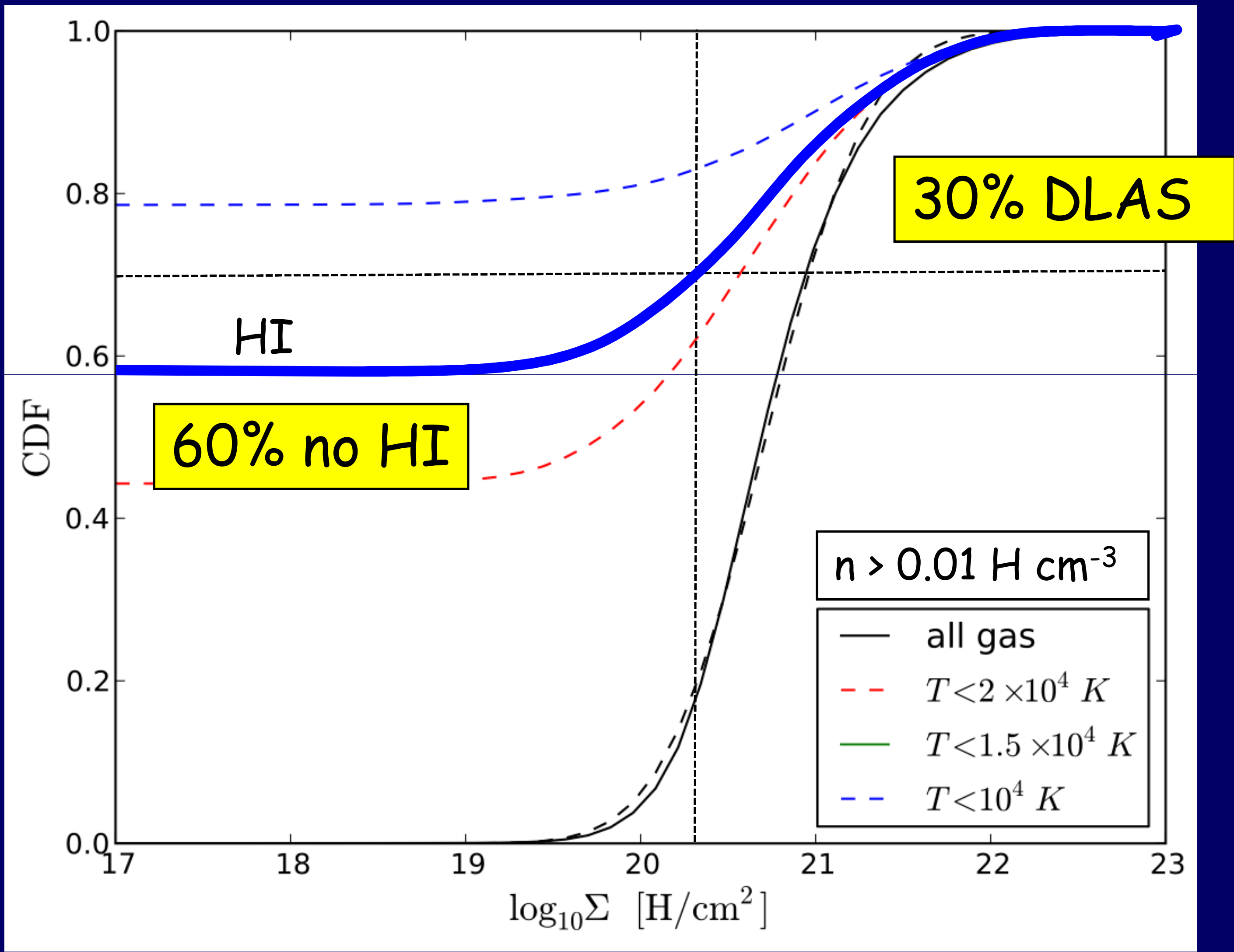




Torques in the
simulated galaxies

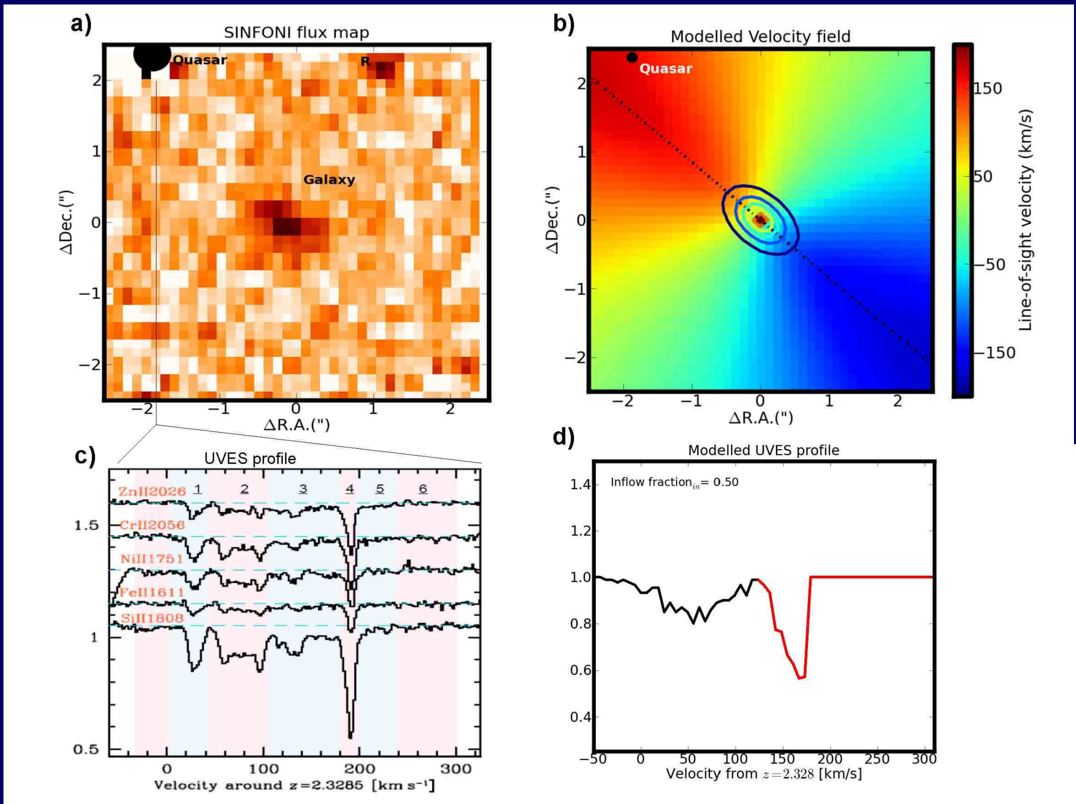
Extended Ring: HI Column Density

Random lines of sight through (0.1-0.3)R_v

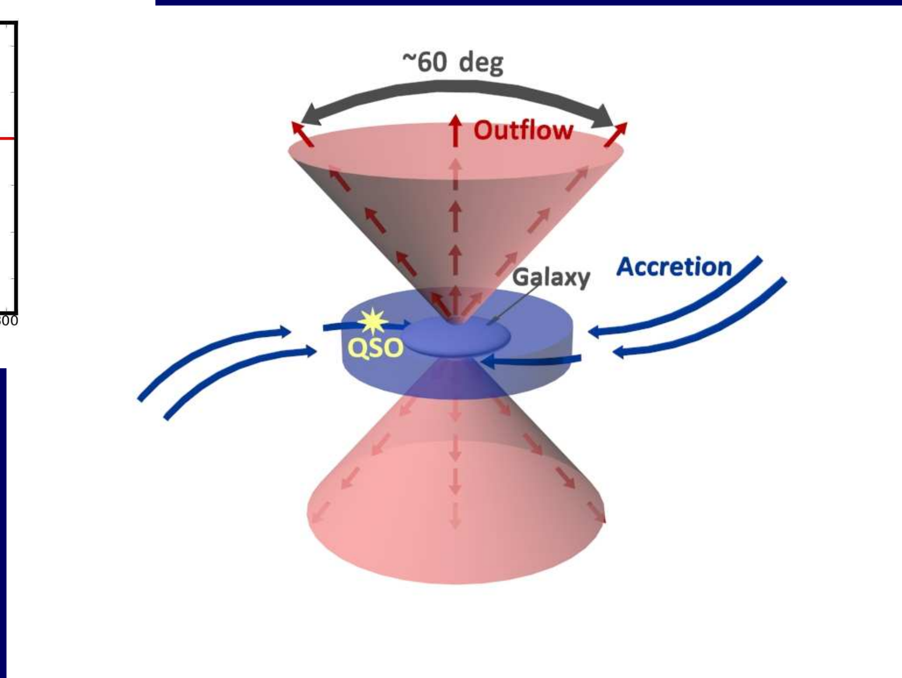


Detection of an Extended Ring?

Bouche+ 2013



z=2.3
Low-Z gas
26 kpc from center
V=180 km/s

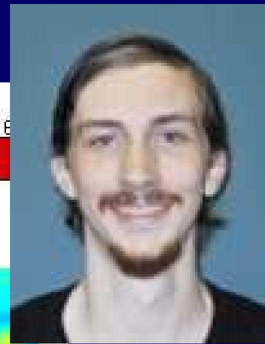


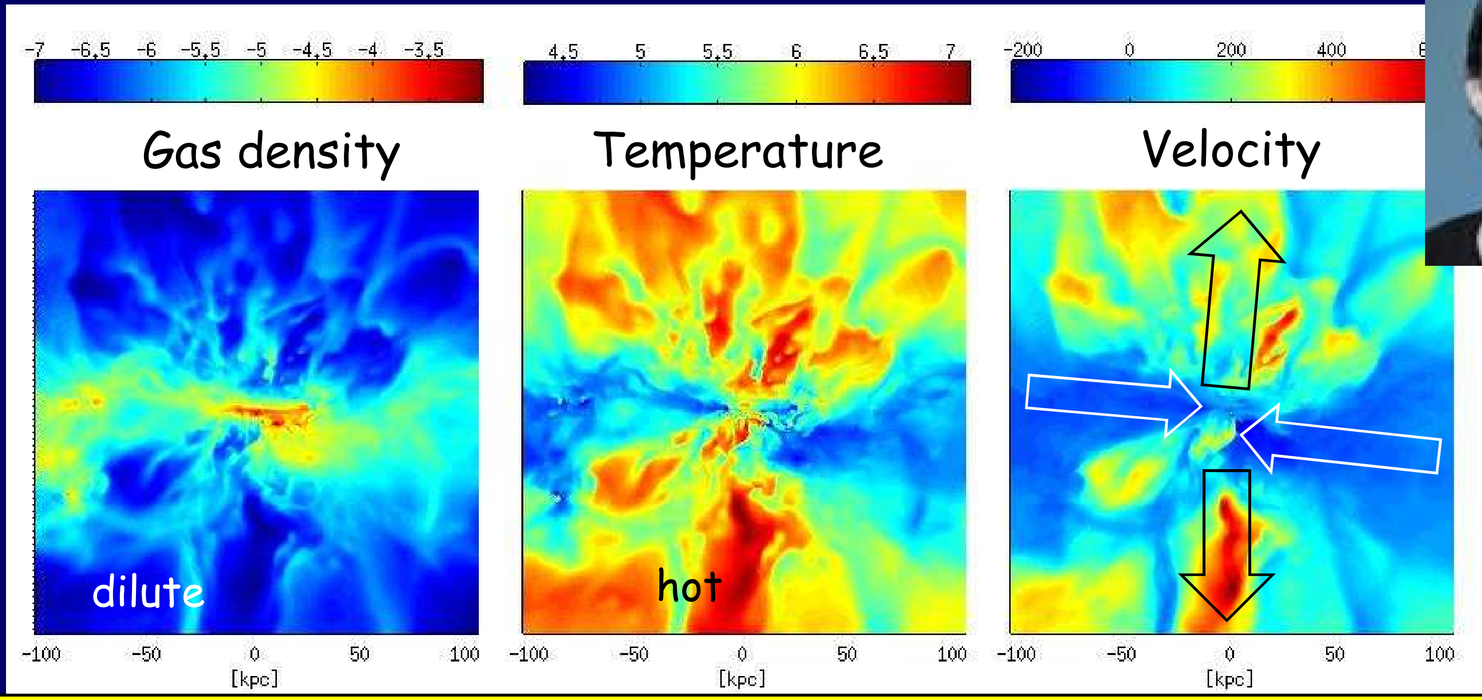
Crighton+ 2013 z=2.4, 54 kpc

Steidel+ 2002, Kacprzak+ 2010

Outflows do not halt the Inflows

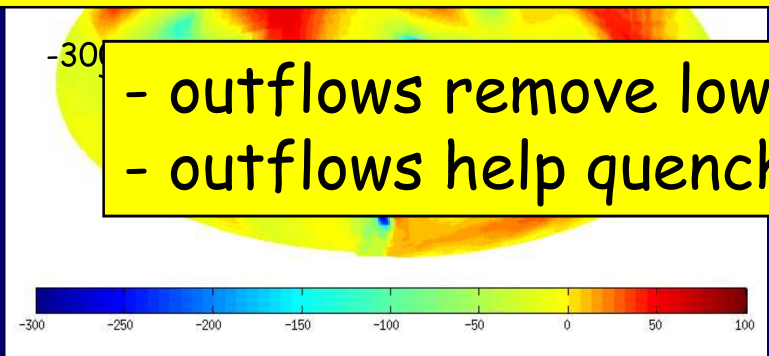
DeGraf+ 14

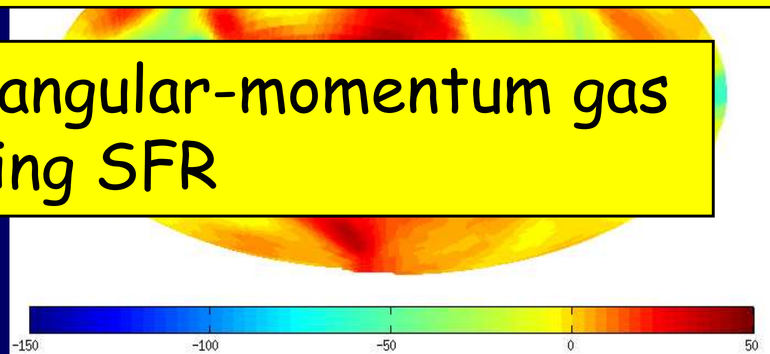




z=2.6
M_v=7x10^{11}

- 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
- outflows help quenching SFR

AM Evolution in Disks

Gas-rich -> violent disk instability (VDI) (Noguchi 99; Dekel+ 09)
-> torques -> AM outflow and mass inflow (Gammie 01)
-> massive spheroids (+BHs) with low AM (Genzel+ 08; Bournaud+11; Dekel+ 13)

Stellar and AGN feedback -> outflows remove low-AM gas from galaxy centers (Maller & Dekel 02; Governato+ 10; Guedes+ 11)

$\lambda_{gal} < \lambda_{disk} \sim 0.03$

λ_{disk} is only slightly smaller than λ_{DM} -> the naïve model is a crude approximation despite the different AM evolution

Conclusions: AM Buildup

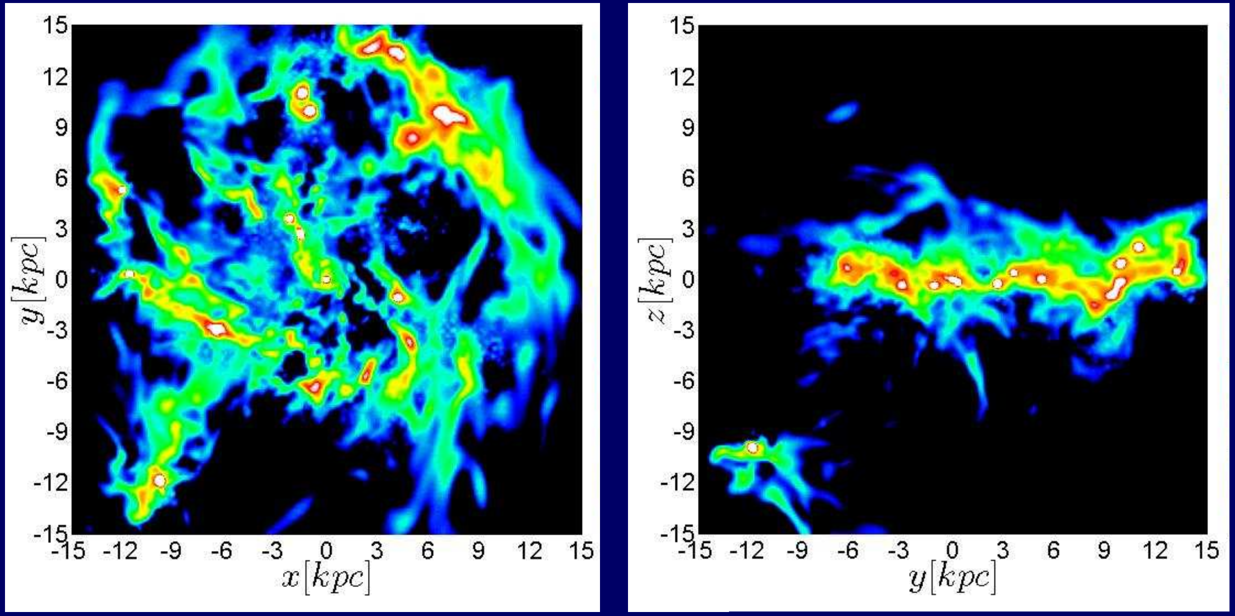
High-z massive galaxies form at cosmic-web nodes
Fed by ~3 co-planar streams penetrating hot CGM

4 Phases of angular-momentum buildup:
- effective tidal torques on pre-collapsed gas streams,
- AM transport through outer halo to inner halo
- spiral-in through an extended tilted rotating ring (DLAS?)
- redistribution within the disk by VDI and feedback

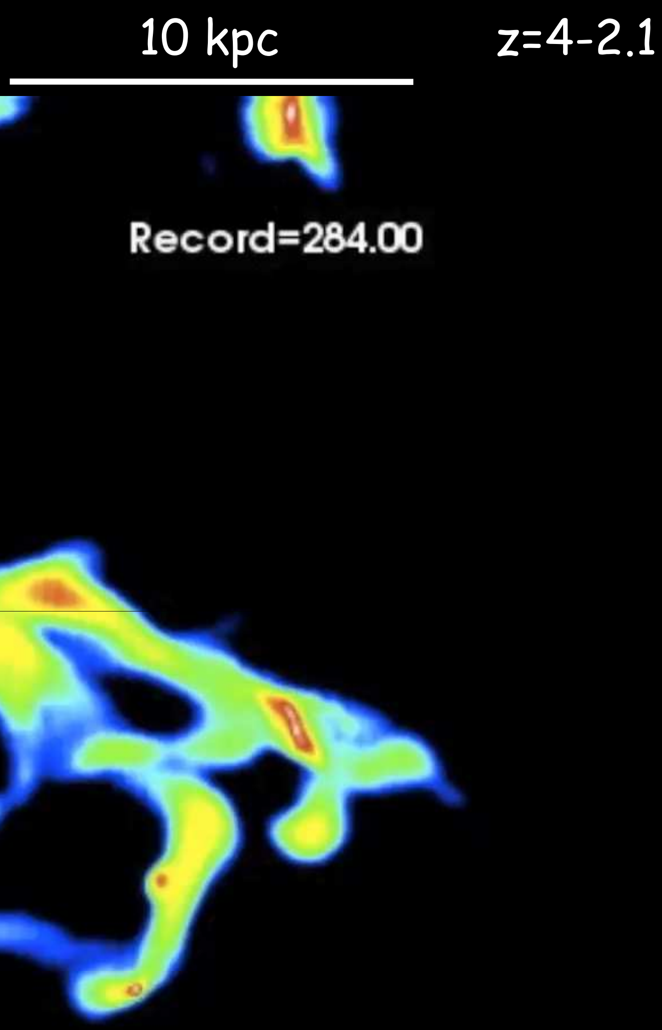
disk spin ~ halo spin (fac 2) despite the very different evolution

Violent Disk Instability: Nonlinear and Stimulated

Dekel, Sari, Ceverino 2009; Ceverino+ 2010, 2012
Mandelker+ 2014; Moody+ 2014; Forbes+ 2014a,b
Dekel, Bournaud, Mandelker+ 2014;
Inoue+ 2014



Clumpy Disk Ceverino, Dekel et al.



Violent Disk Instability (VDI) at High z

High gas density → disk unstable

$$Q \propto \frac{\sigma \Omega}{G\Sigma} \leq 1$$

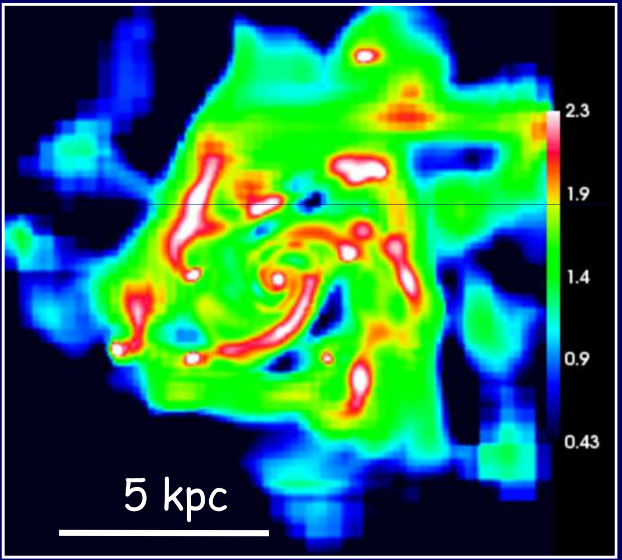
Giant clumps and transient features
→ rapid evolution on dynamical time

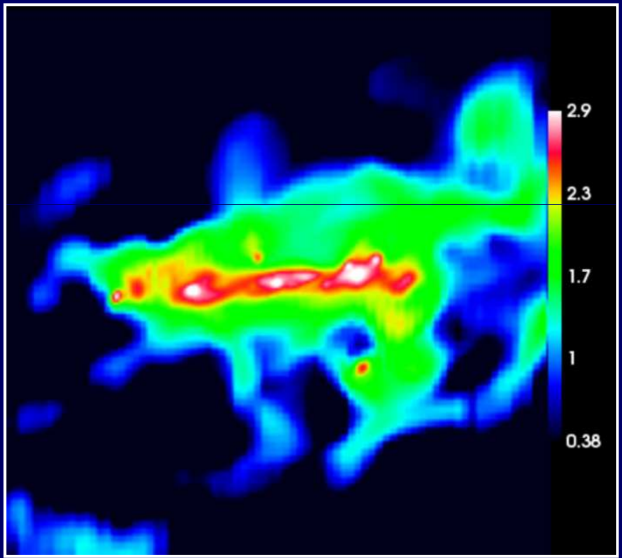
$$R_{\text{clump}} \propto \frac{G\Sigma}{\Omega^2}$$

Toomre 64

Isolated galaxies:
Noguchi 99
Immeli+ 04a,b
Bournaud, Elmegreen+ 06, 08
Hopkins+ 12
Bournaud+ 13

In cosmology:
Dekel, Sari, Ceverino 09
Agertz et al. 09
Ceverino, AD, Bournaud 10
Ceverino+ 11
Cacciato, AD, Genel 12a,b
Genel+ 12
Forbes et al. 12, 13, 14





Self-regulated at Q~1 by torques and inflow → turbulent with high σ/V~1/5

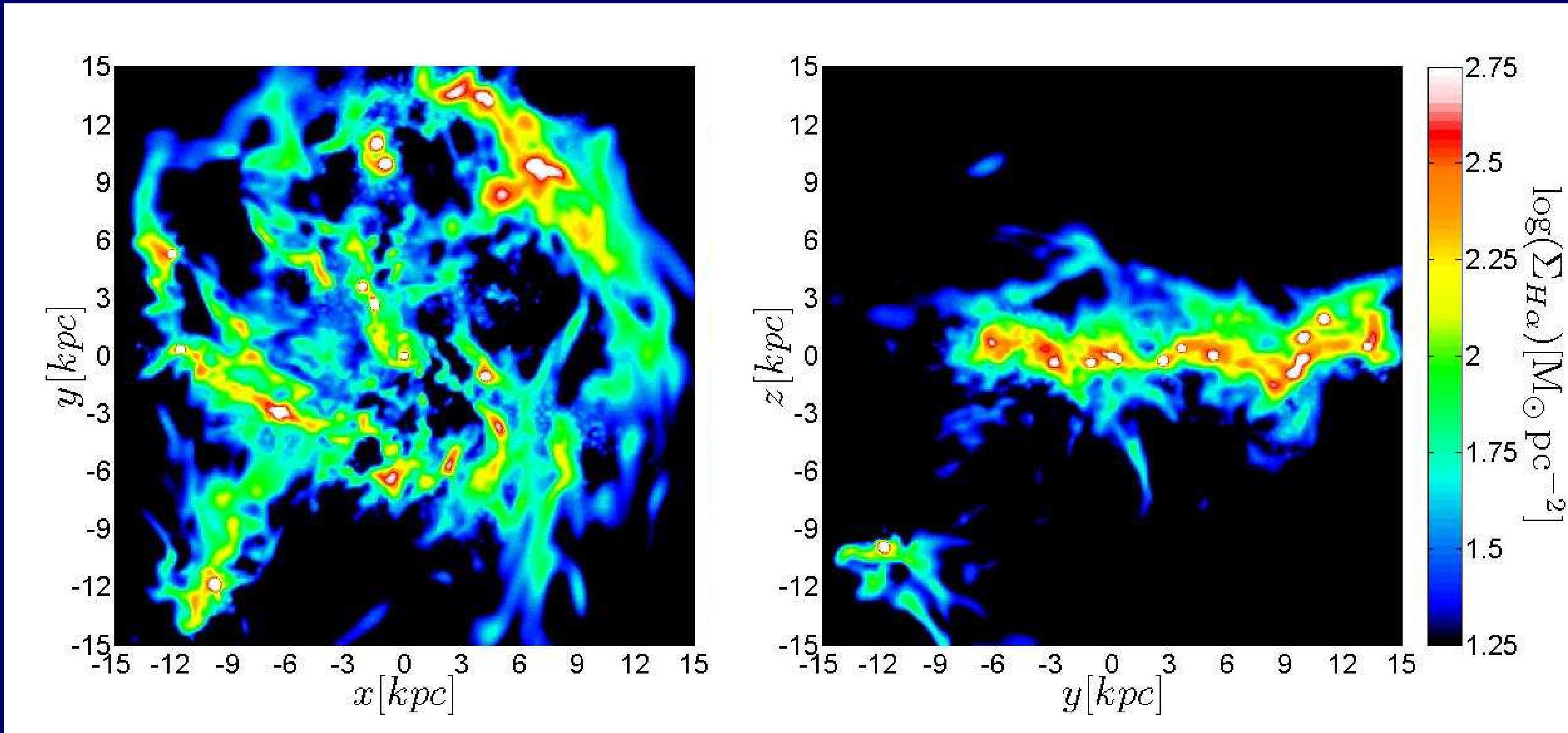
Inflow in disk → compact bulge and BH

Steady state: disk draining and replenishment, bulge ~ disk

Violent Disk Instability (VDI) at High z

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

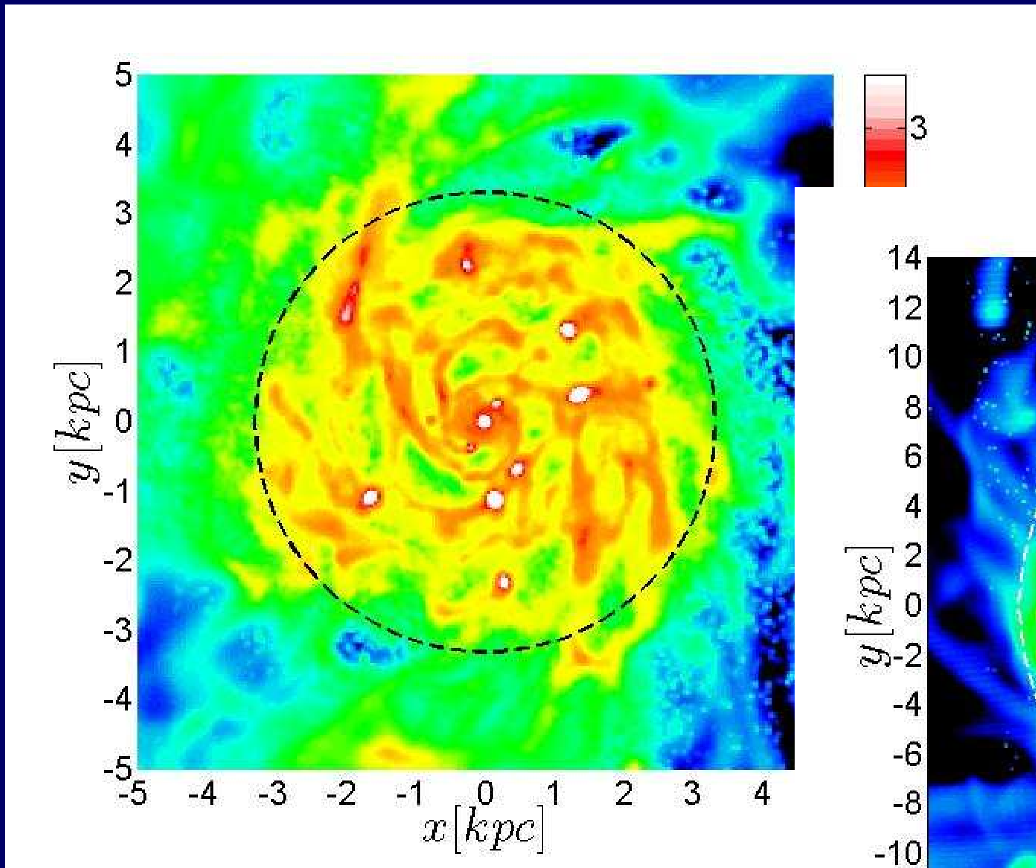
highly perturbed, clumpy rotating disk: $H/R \sim \sigma/V \sim f_{cold} \sim 0.2$

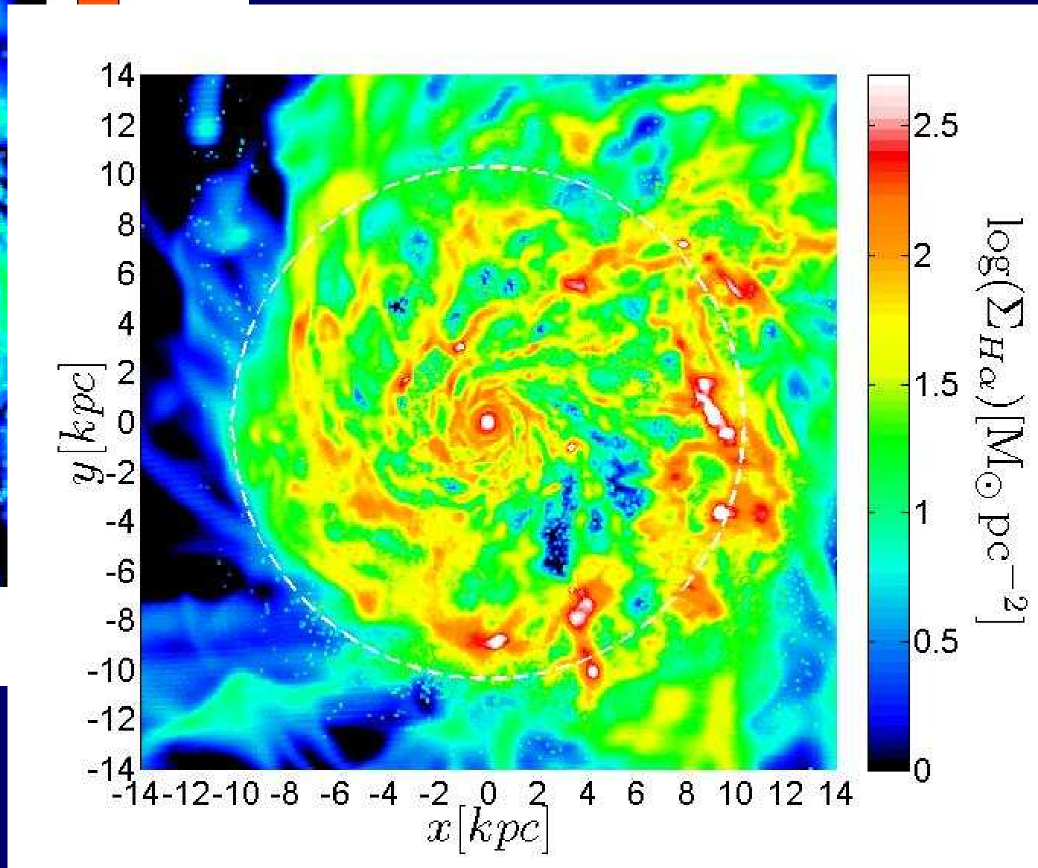


Violent Disk Instability (VDI) at High z

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

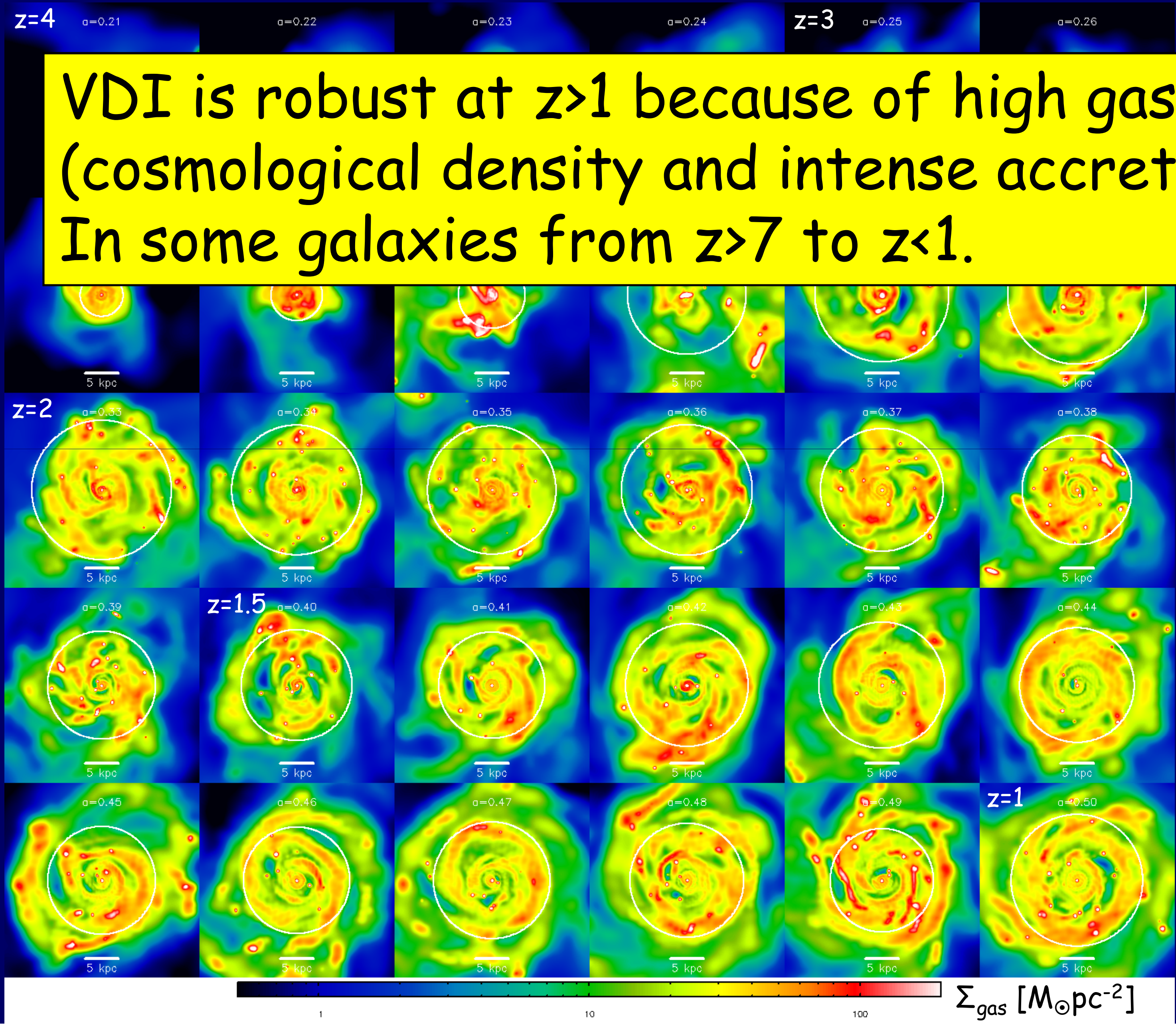
$H/R \sim \sigma/V \sim f_{cold} \sim 0.2$





Clumpy Disk in a cosmological steady state

VDI is robust at z>1 because of high gas density (cosmological density and intense accretion).
In some galaxies from z>7 to z<1.

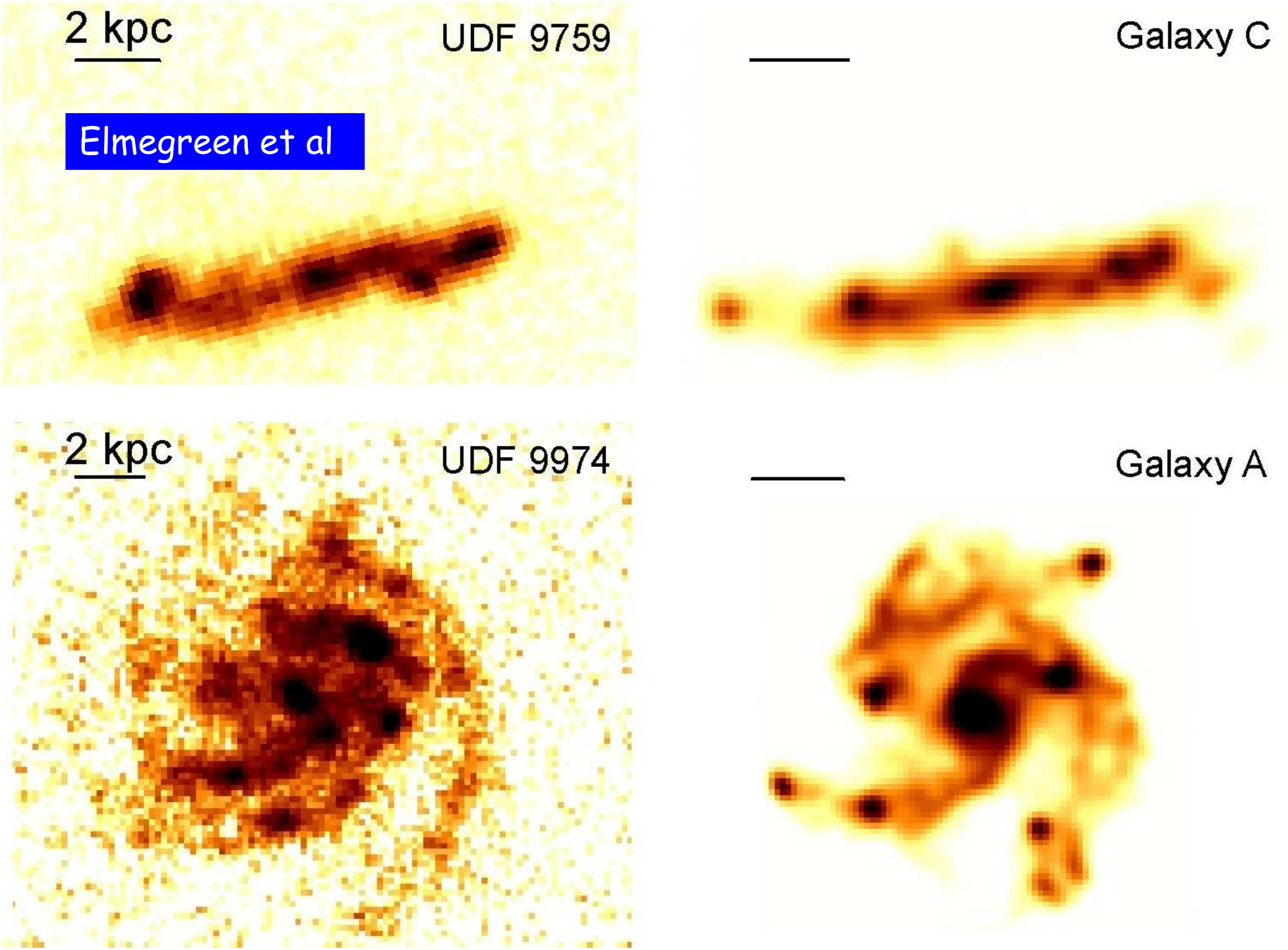


Dekel, Sari, Ceverino 09;

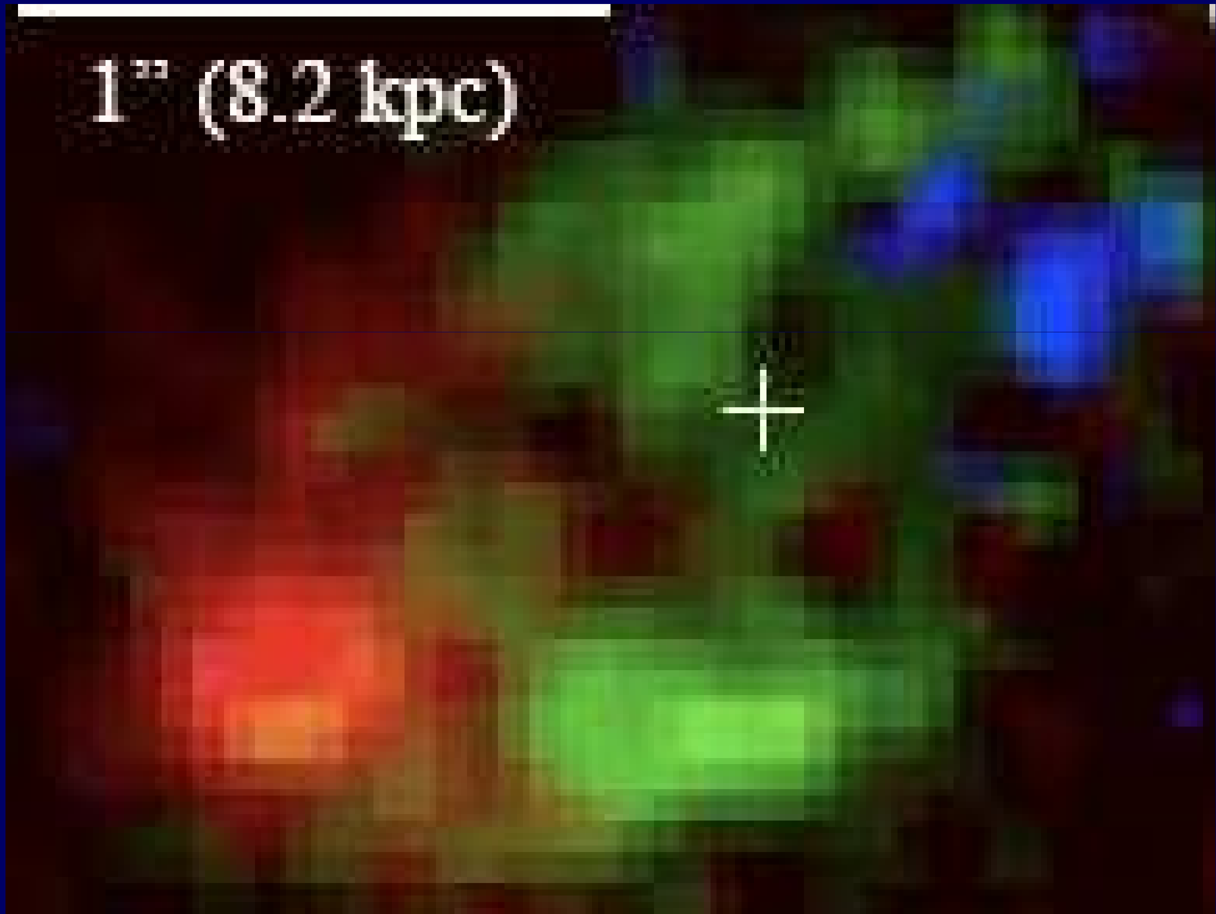
Ceverino, Dekel, Bournaud 10

Mandelker et al. 14

Observations vs. Simulations



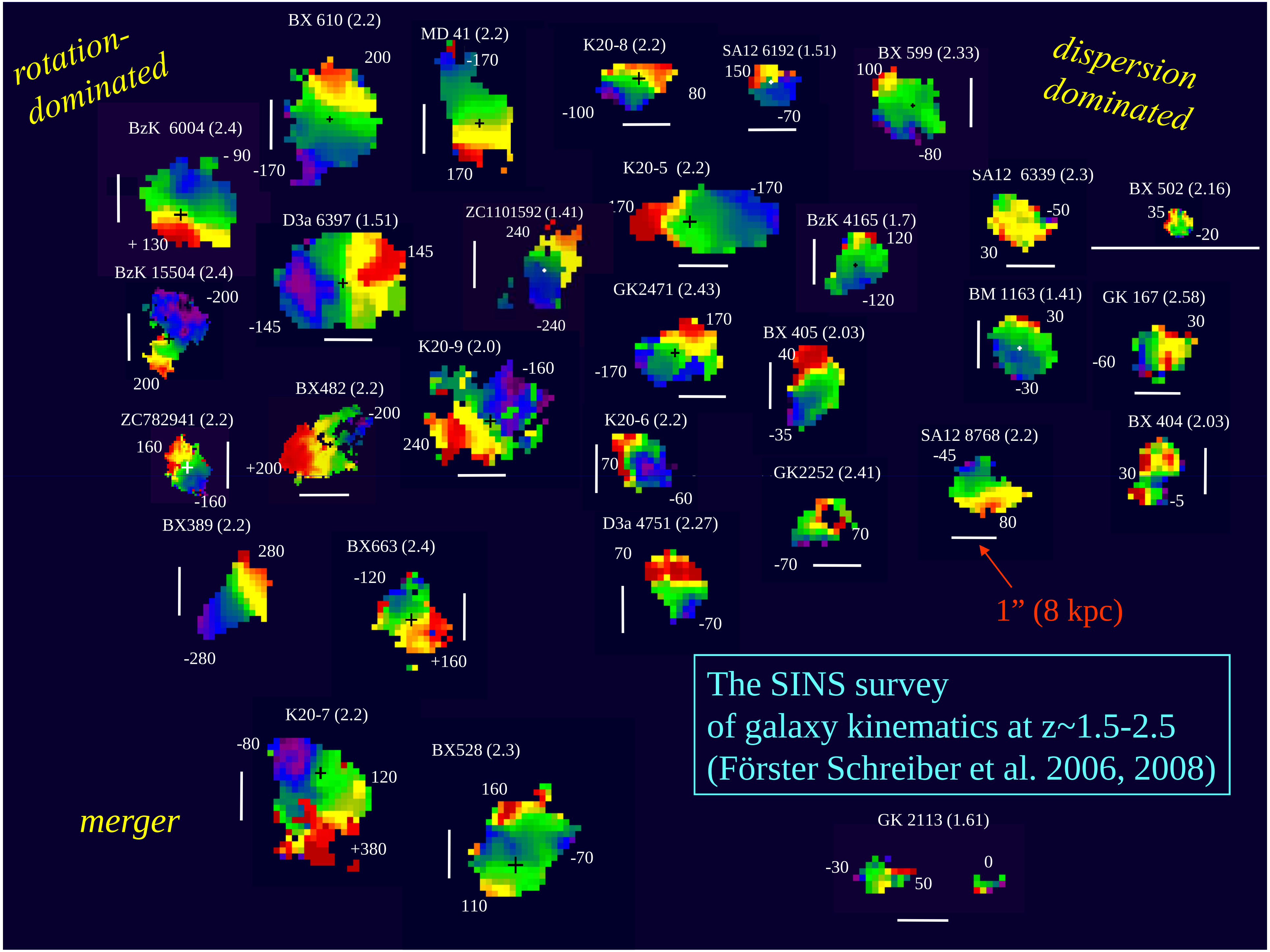
A typical star-forming galaxy at z=2:
clumpy, rotating, extended disk & a bulge



Ha star-forming regions

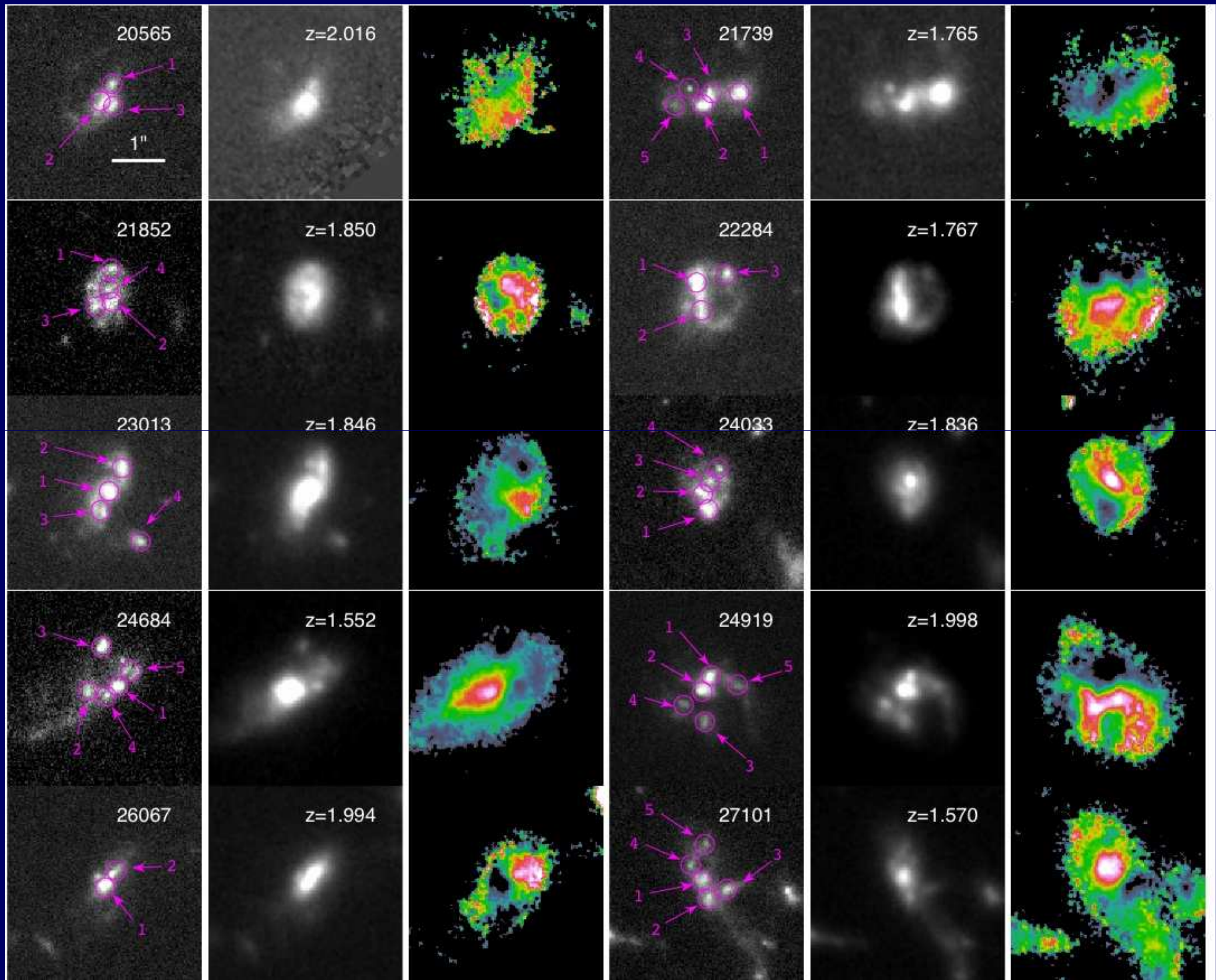
color-code velocity field

Genzel et al 08



rotation-dominated
dispersion dominated
merger
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
BzK 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
BzK 4165 (1.7)
BzK 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
K20-9 (2.0)
BX 405 (2.03)
BX482 (2.2)
ZC782941 (2.2)
K20-6 (2.2)
SA12 8768 (2.2)
BX 404 (2.03)
GK2252 (2.41)
BX389 (2.2)
D3a 4751 (2.27)
BX663 (2.4)
1" (8 kpc)
The SINS survey
of galaxy kinematics at z~1.5-2.5
(Förster Schreiber et al. 2006, 2008)
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)

High-z Disks with Giant Clumps



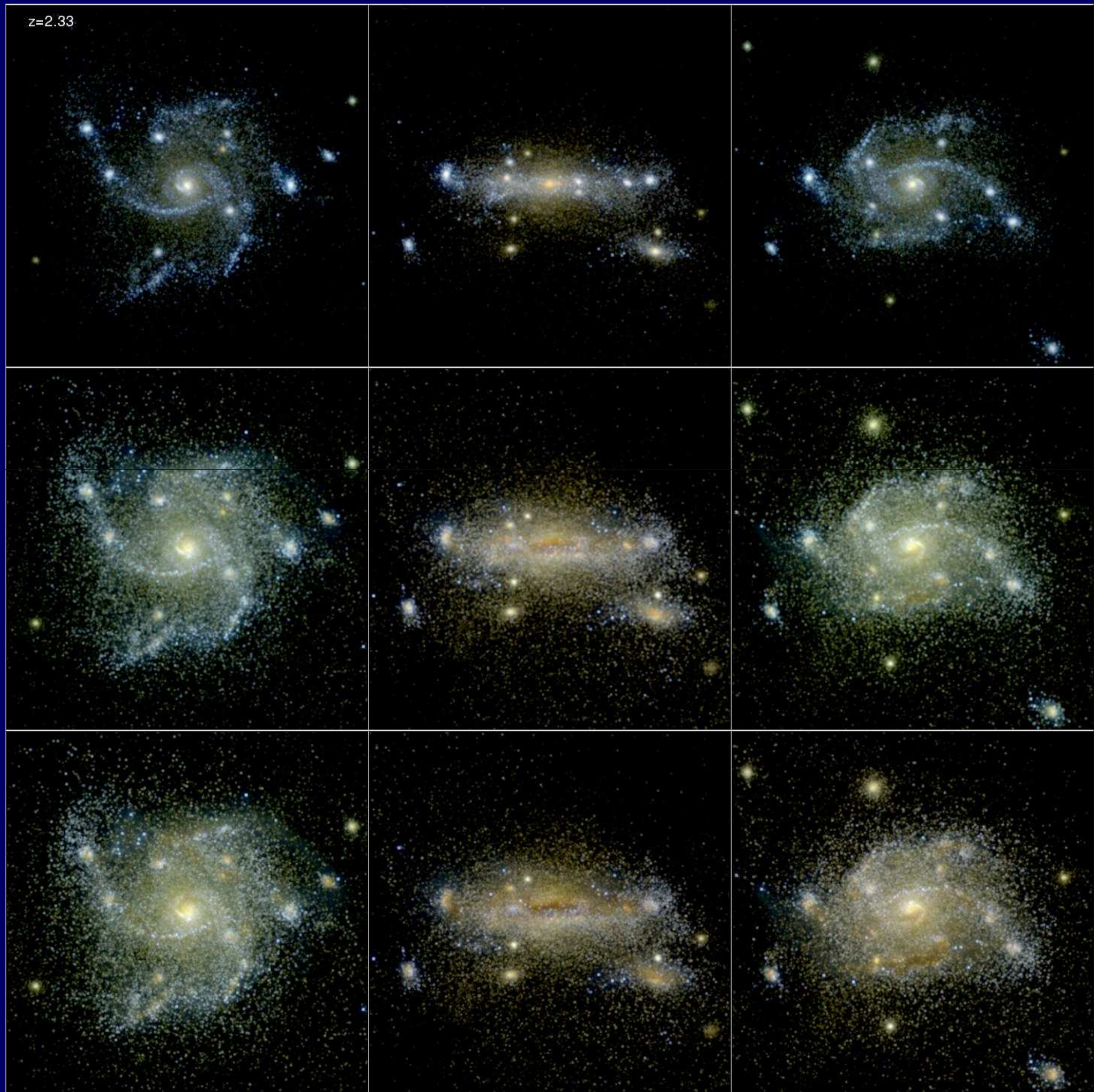
Guo et al. 12
CANDELS

Simulated hi-z galaxy through Dust

low dust

medium

high



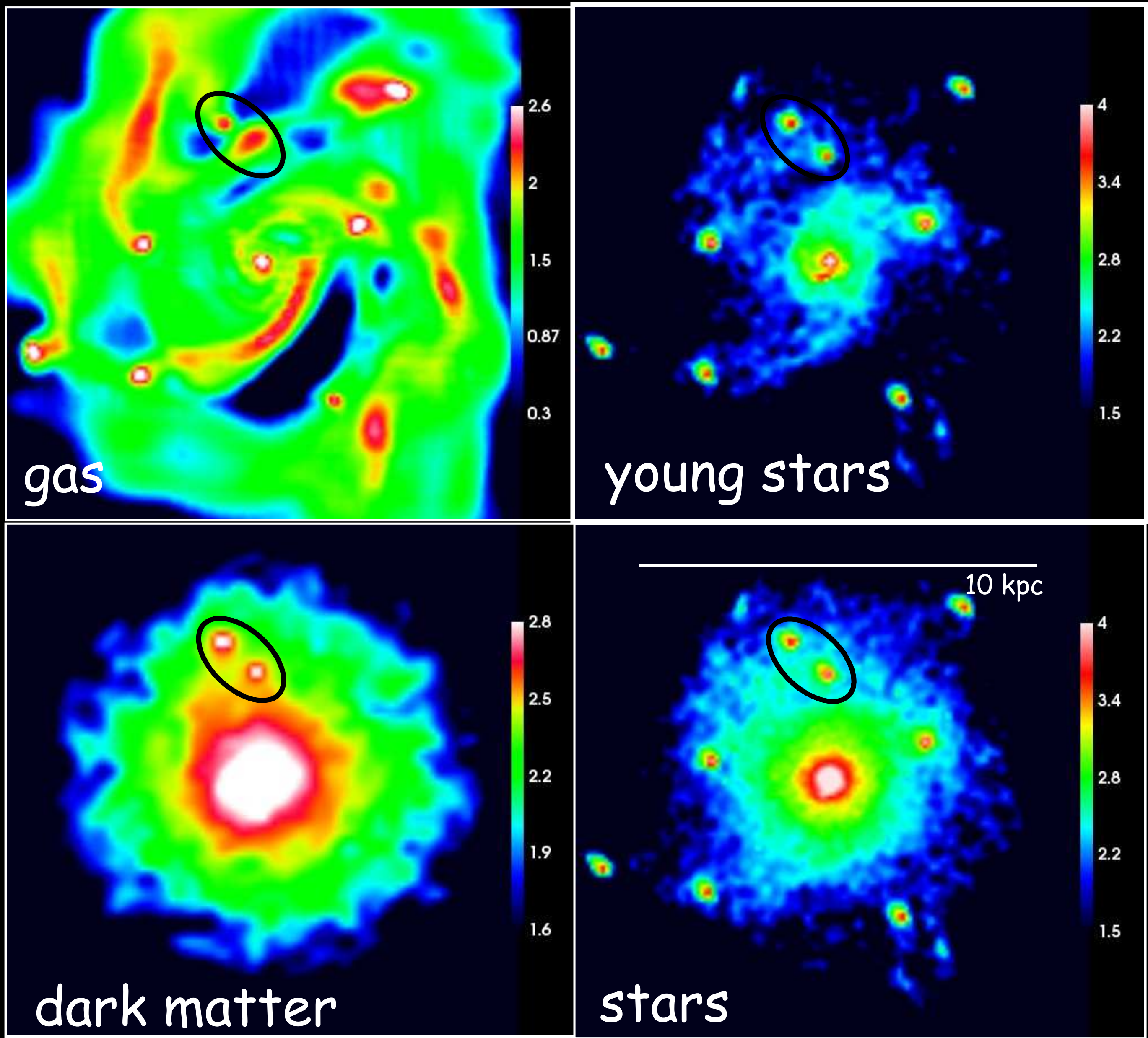
SUNRISE

RGB colors

MW3
z=2.33

Moody+

In-situ (VDI) and Ex-situ (merger) Clumps



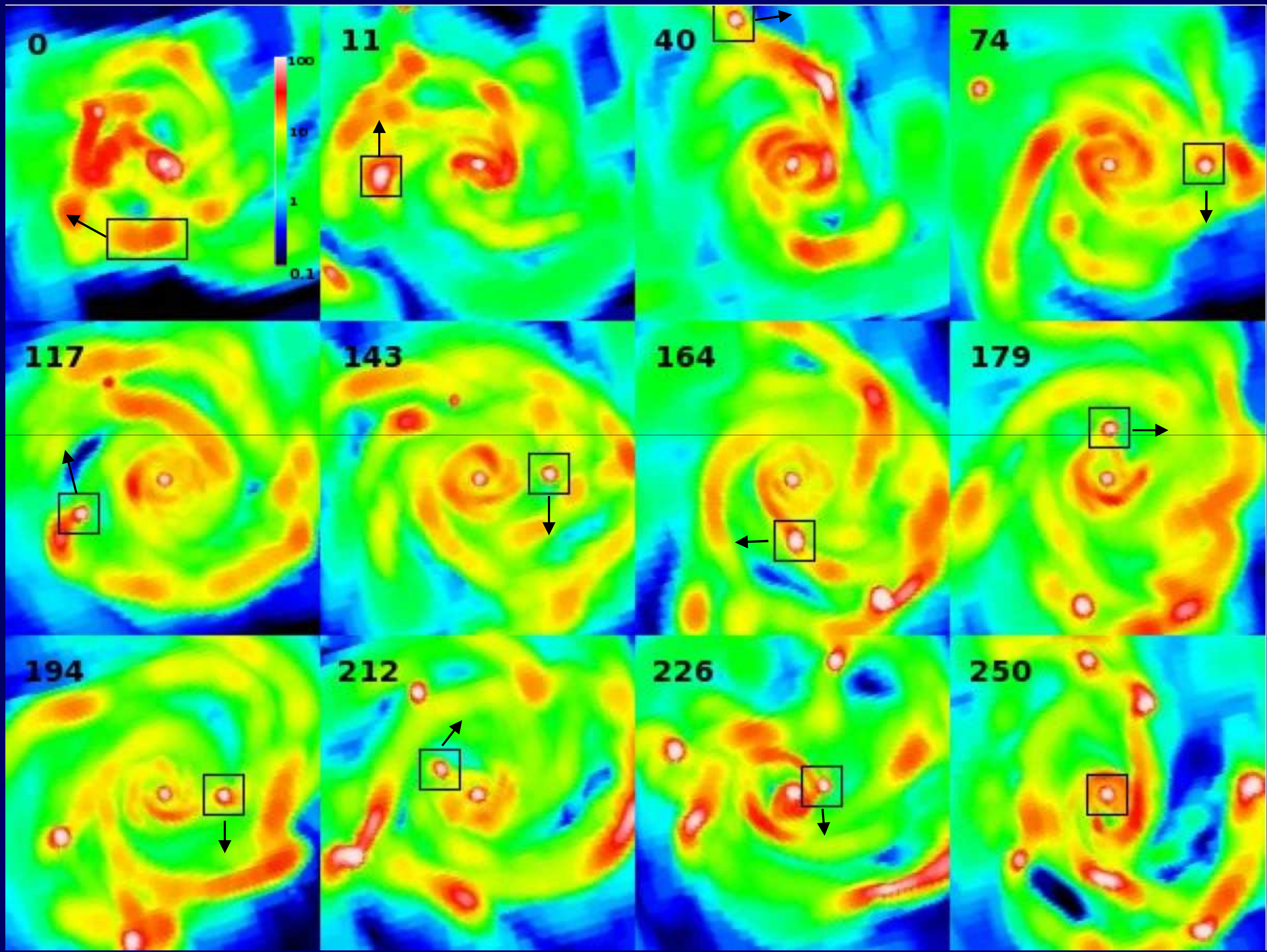
Clumps in VDI Disks

Nir Mandelker
Greg Snyder

- most hi-z galaxies go through a VDI phase
- perturbed by intense inflows including minor mergers
- bulge ~ disk in cosmological steady state
- giant clumps $M \sim 10^{8-9} M_\odot$ $R<0.5$kpc
- in-situ (gaseous, SFR) and ex-situ (stellar, mergers)
- half the SFR in clumps
- migration to center in ~300 Myr → gas+ young stars
- clumps $>10^8 M_\odot$ survive outflows with mass~constant
  $\eta \sim 1$-2 winds, gas accretion, tidal stripping
- less massive clumps disrupt
- VDI feed gas & stars to the bulge and BH

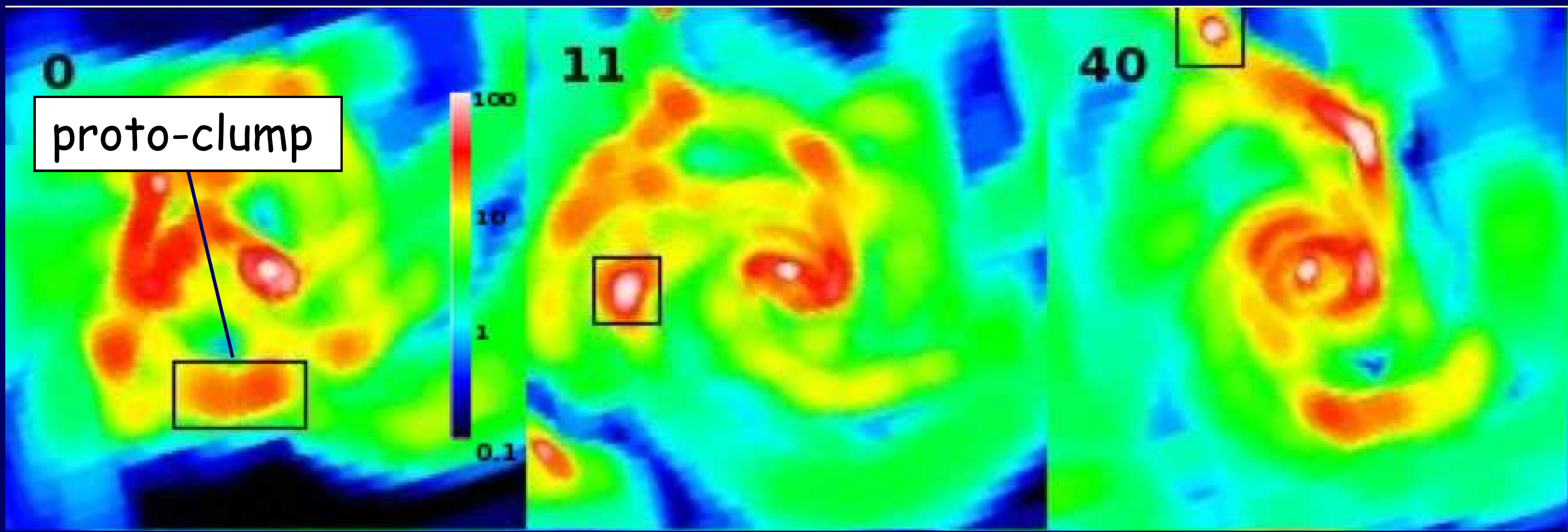
Expect a weak gradient of clump mass in disks
Certain gradient in age/color for in-situ clumps

Clump Formation & Migration



Ceverino, Dekel, Bournaud 10

Local Instability: Forces on Protoclump



pressure
prevents small clumps

rotation
prevents big clumps

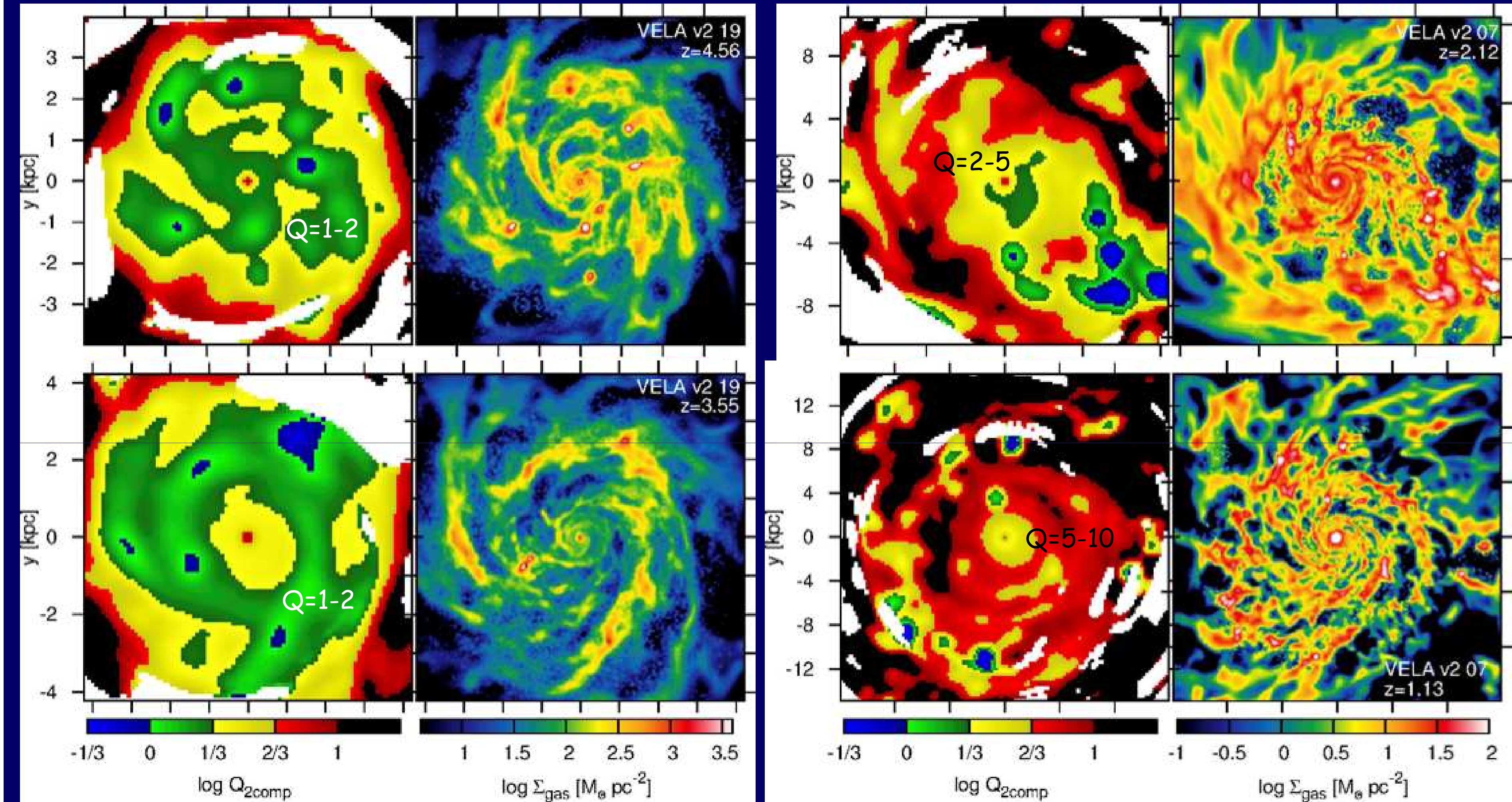
$$Q \propto \frac{\sigma \Omega}{\Sigma} \approx 1$$

self-gravity attraction

Gravity wins when Q<1

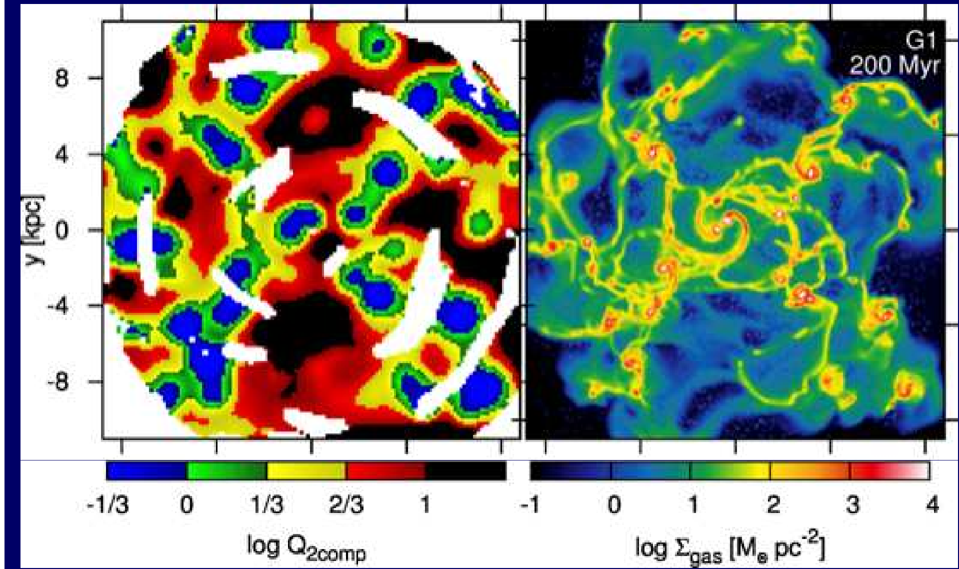
Violent Instability with Q~2-3

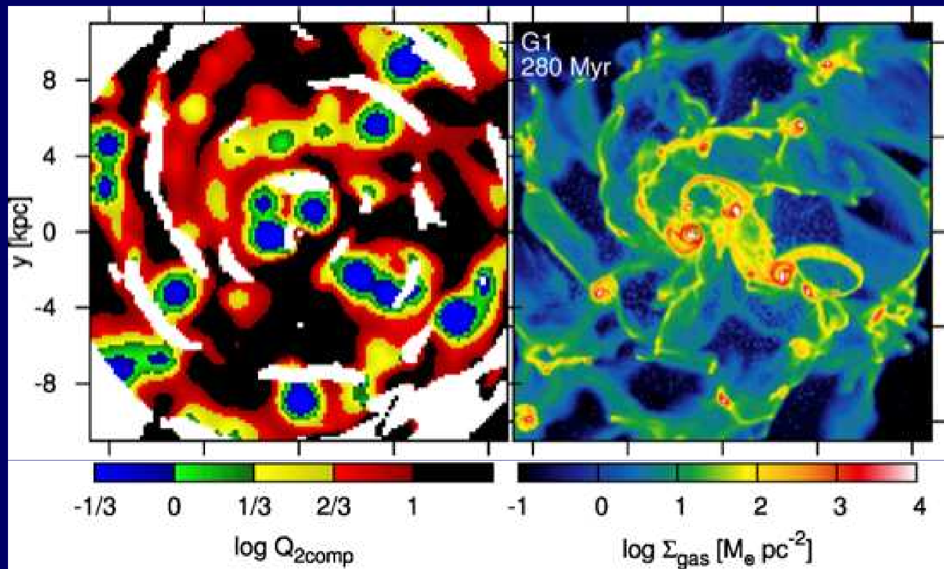
Toomre $Q \propto \Omega\sigma/\Sigma \approx 1$

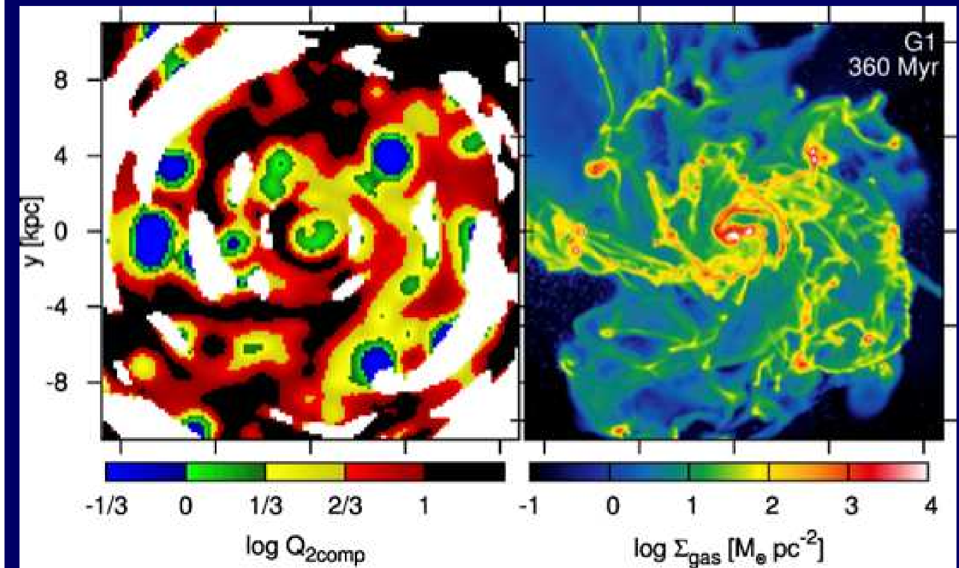


Nonlinear instability – stimulated by intense inflows with minor mergers, or by the non-linear clumps themselves

VDI with Q>1: Isolated galaxy







But no new clump formation where Q>1

Non-linear Instability

Toomre $$Q \propto \frac{\sigma \Omega}{\Sigma} \approx 1$$

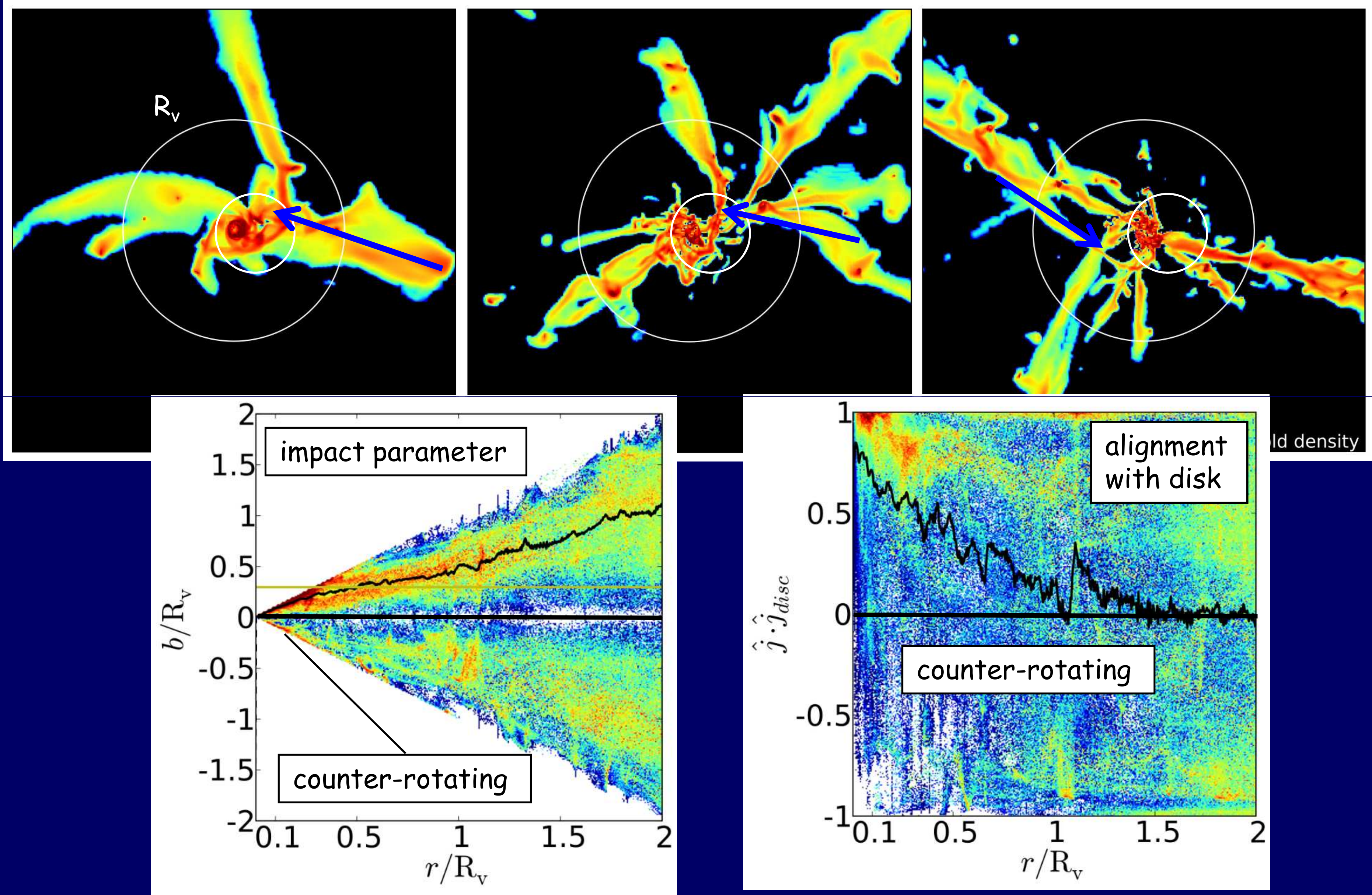
Tentative ideas for Q>1 instability:

- Rapid decay of turbulence (Elmegreen)

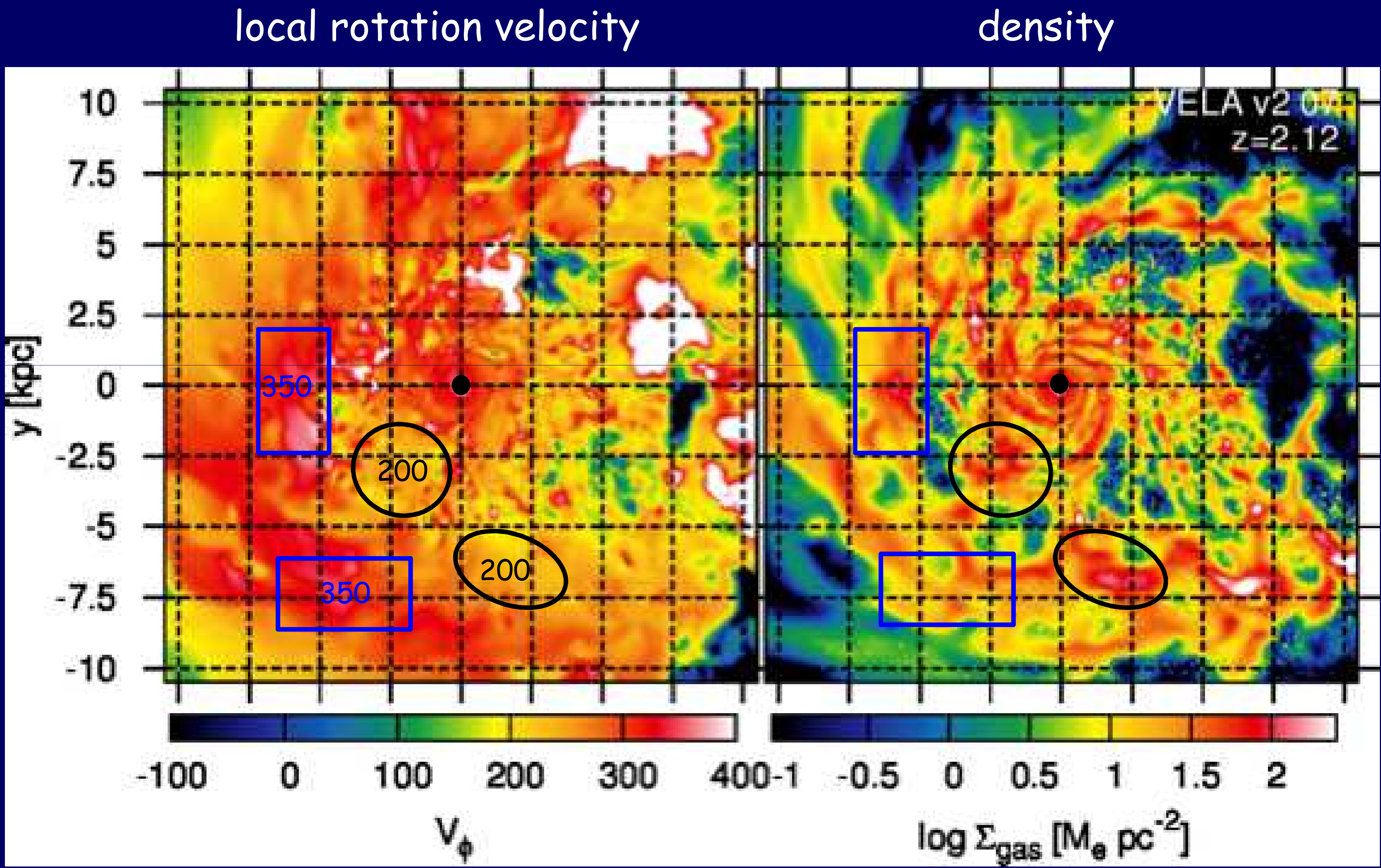
- Irregular rotation – counter-rotating streams (Lin)

- Compression modes of turbulence (Bournaud, Renaud)

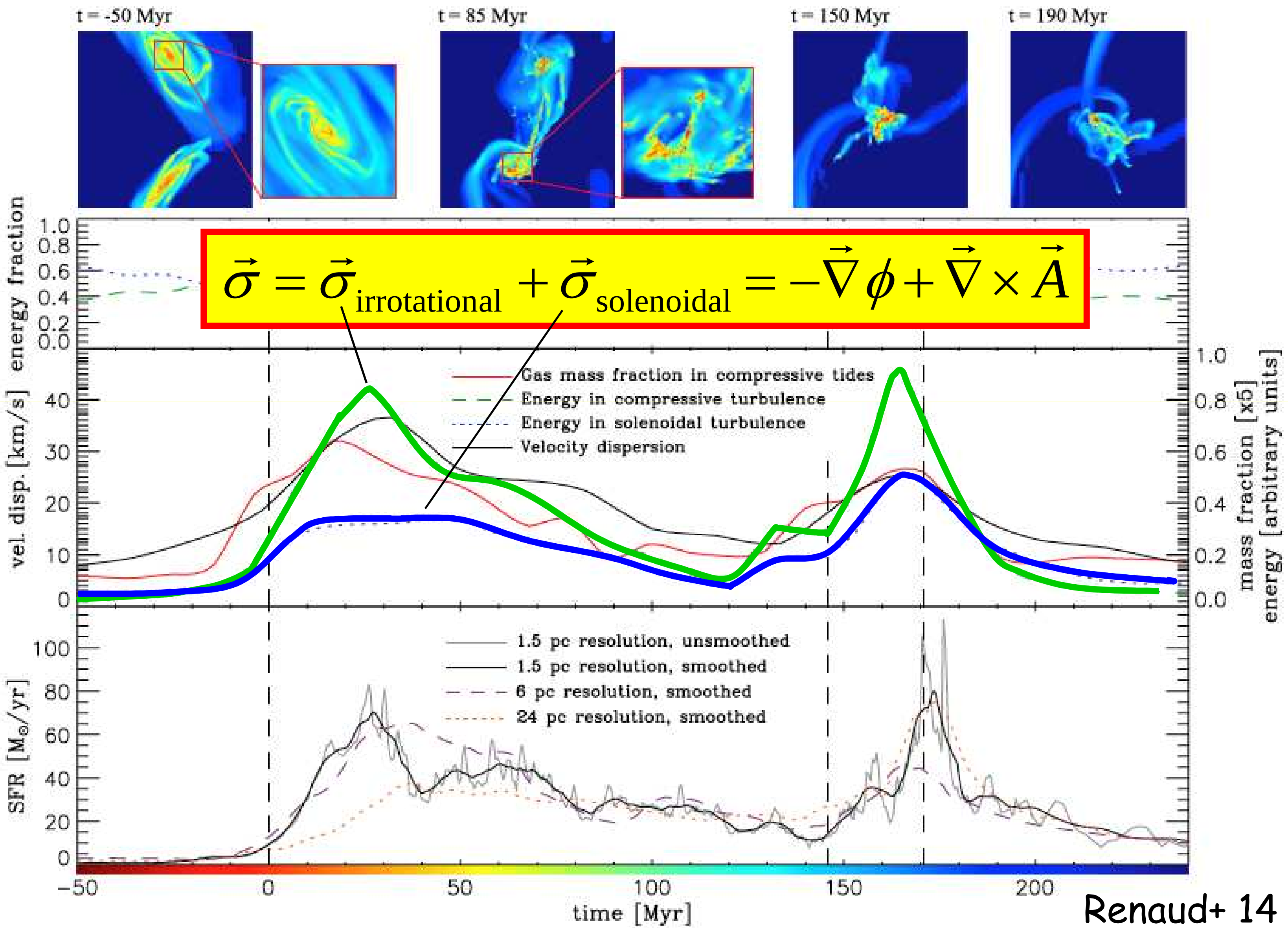
Counter-rotating Streams



Irregular Rotation



Compression Modes of Turbulence: Merger



$$\vec{\sigma} = \vec{\sigma}_{\text{irrotational}} + \vec{\sigma}_{\text{solenoidal}} = -\vec{\nabla}\phi + \vec{\nabla}\times\vec{A}$$

Renaud+ 14

Conclusions: 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
Stimulated by inflow+mergers? Compressive turbulence? Irregular rotation?

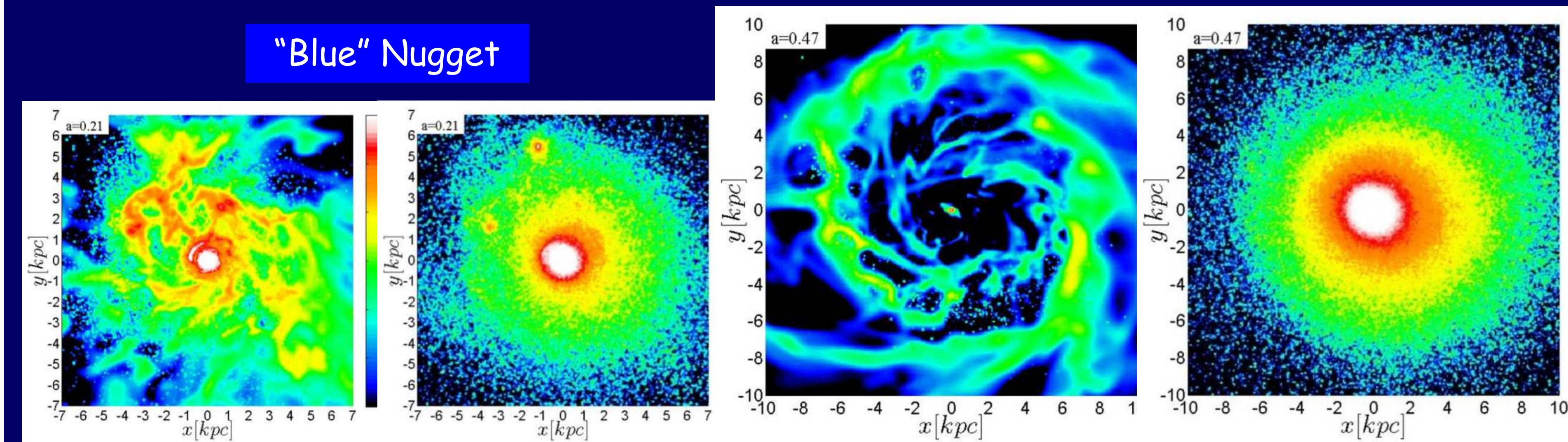
VDI and (minor) mergers actually work in concert

Quenching by Compaction and by Hot Halo

Dekel & Burkert 2014; Zolotov et al. 2014
Dekel & Birnboim 2003, 2006

Red Nugget

"Blue" Nugget



Inflow in unstable disks

Clump migration in ~300 Myr
Massive clumps survive feedback

Elmegreen, Bournaud+ 07, 08; Genzel+ 06, 08;
Dekel, Sari, Ceverino 09;
Bournaud+ 14; Dekel+ 14

Inflow in disk, evaluated by torques, dynamical friction, clump encounters, self-regulated instability

$$t_{\text{inflow}} \approx f_{\text{cold}}^{-2} t_{\text{dyn}} \approx (V/\sigma)^2 t_{\text{dyn}} \approx 10 t_{\text{dyn}}$$

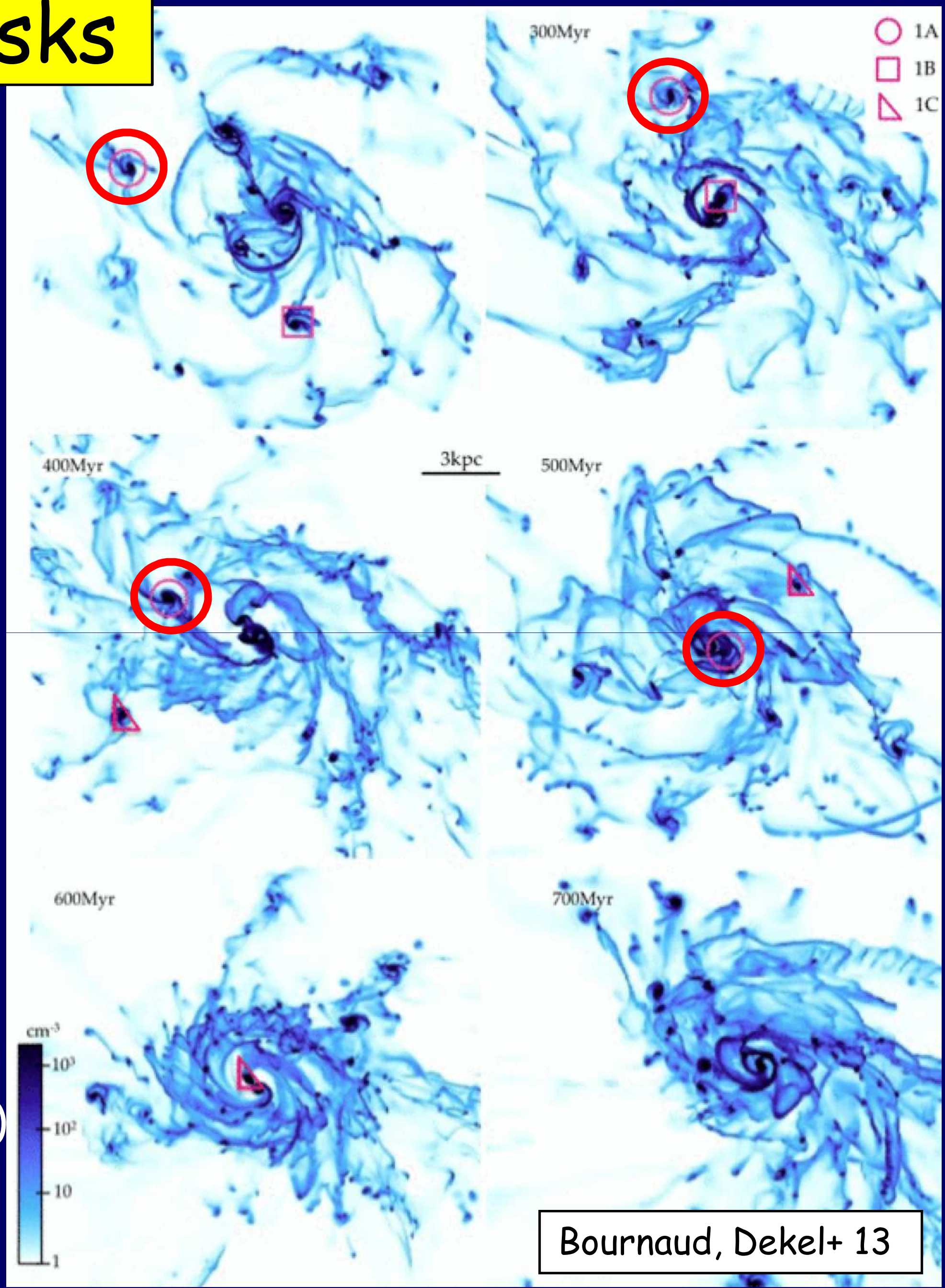
Gammie 01; Dekel, Sari, Ceverino 09

Wet compaction if

$$t_{\text{inflow}}/t_{\text{sfr}} \approx \varepsilon_{\text{sfr}}\, f_{\text{cold}}^{-2} < 1$$

valid when gas fraction is high (high z) and spin is relatively low

Dekel, Burkert 14



Bournaud, Dekel+ 13

Wet Compaction

Dekel & Burkert 2013; Zolotov et al. 2014

Compact stellar spheroid → dissipative "wet" inflow to a "blue nugget" by mergers and/or VDI

Inflow is "wet" if $t_{inflow} \ll t_{sfr}$

Inflow in self-regulated VDI disk Q~1, evaluated by torques, dynamical friction, clump encounters, energy conservation, …

$$t_{\rm inflow} \approx f_{\rm cold}^{-2}\, t_{\rm dyn} \approx (V/\sigma)^2\, t_{\rm dyn} \approx 10\, t_{\rm dyn}$$

Gammie 01; Dekel, Sari, Ceverino 09

$$\frac{M_{\rm cold}}{M_{\rm tot}} \equiv f_{\rm cold} \approx \frac{\sigma}{V}$$

Wetness parameter

$$w \equiv \frac{t_{\rm sfr}}{t_{\rm inflow}} \approx \varepsilon_{\rm sfr}^{-1}\, f_{\rm cold}^{\;2} > 1$$

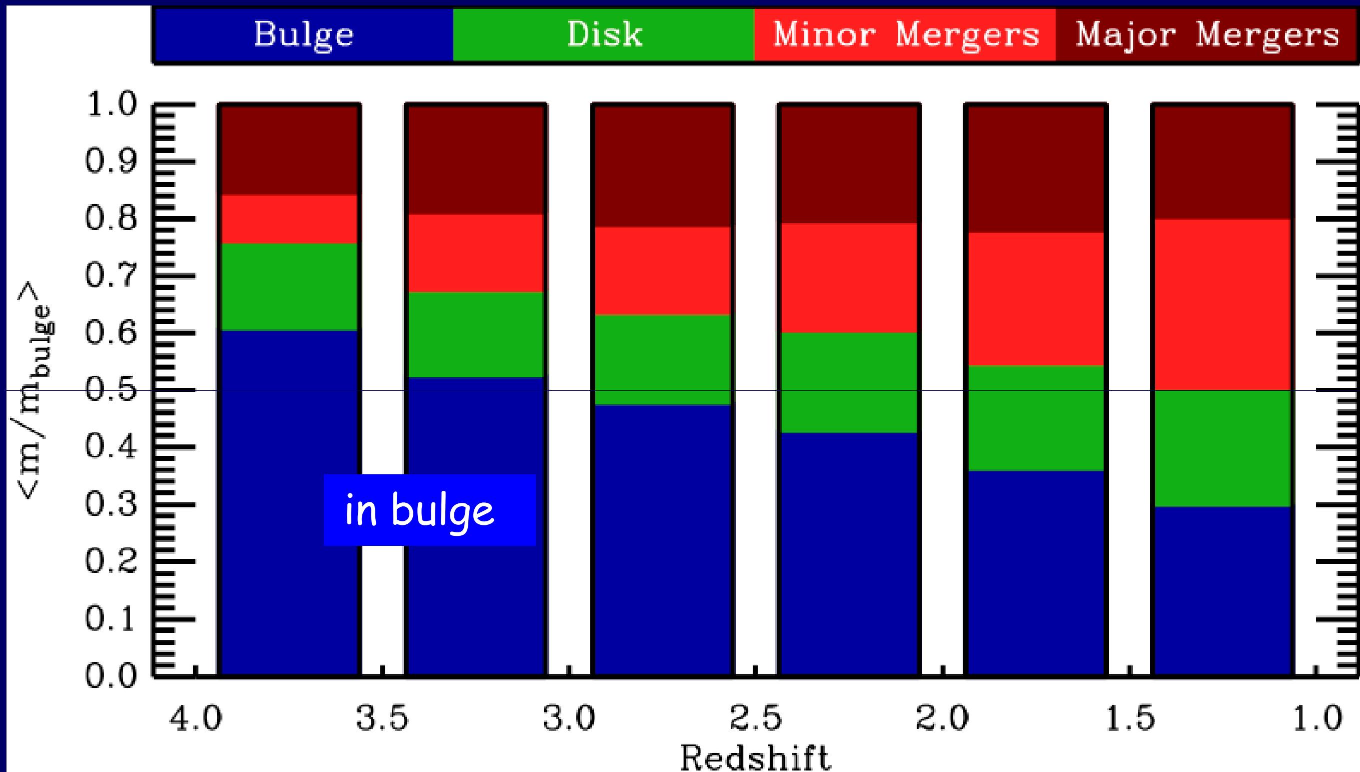
$$\varepsilon_{\rm sfr} \le 0.02 \qquad \delta \ge 0.2$$

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

Wet Origin of Bulge: Stellar Birthplace

Zolotov, Dekel, Mandelker, Tweed, Ceverino, Primack 2013

Fraction of bulge stars born in different components

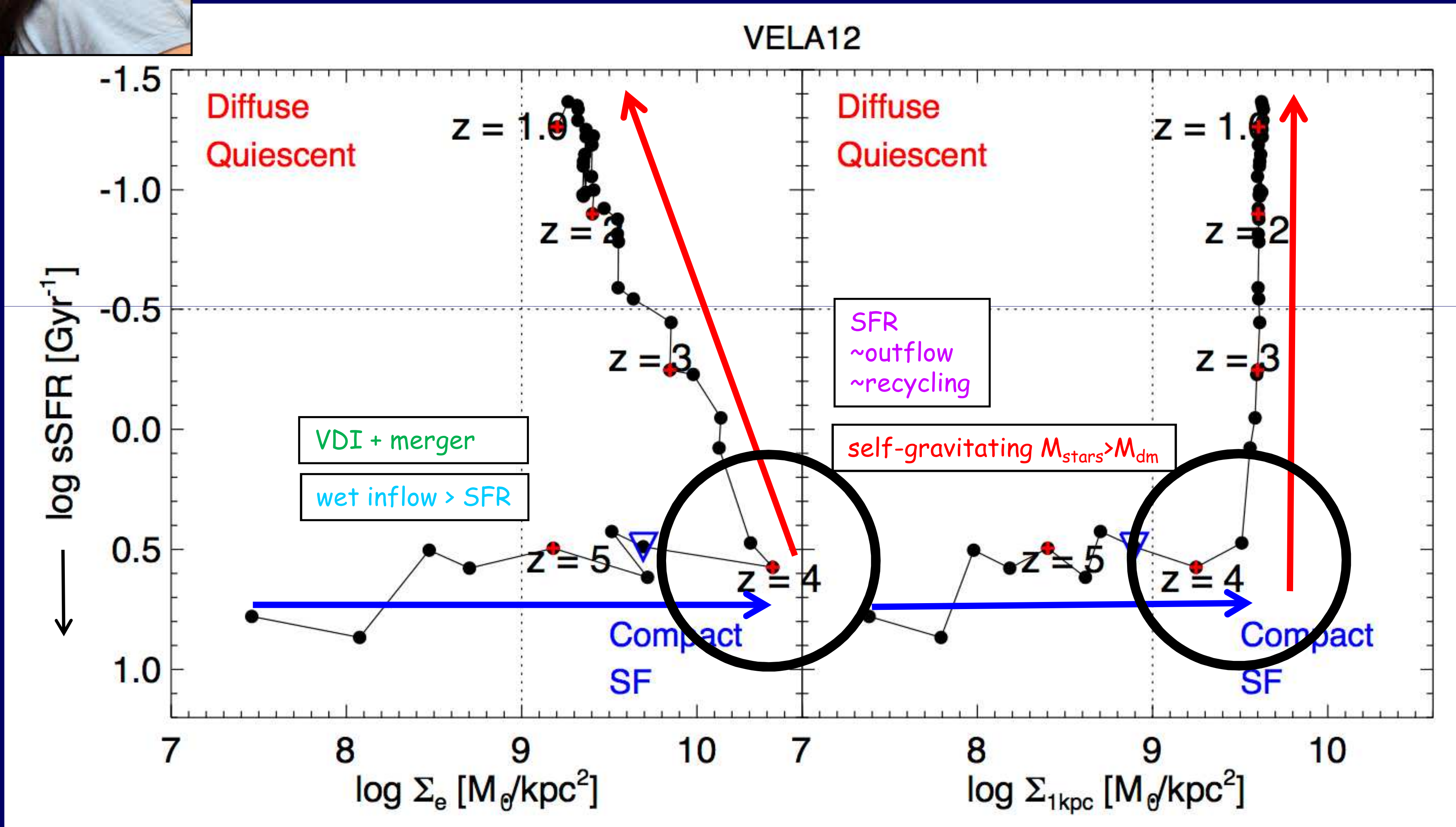


60-30% of the bulge stars form in the bulge → wet inflow

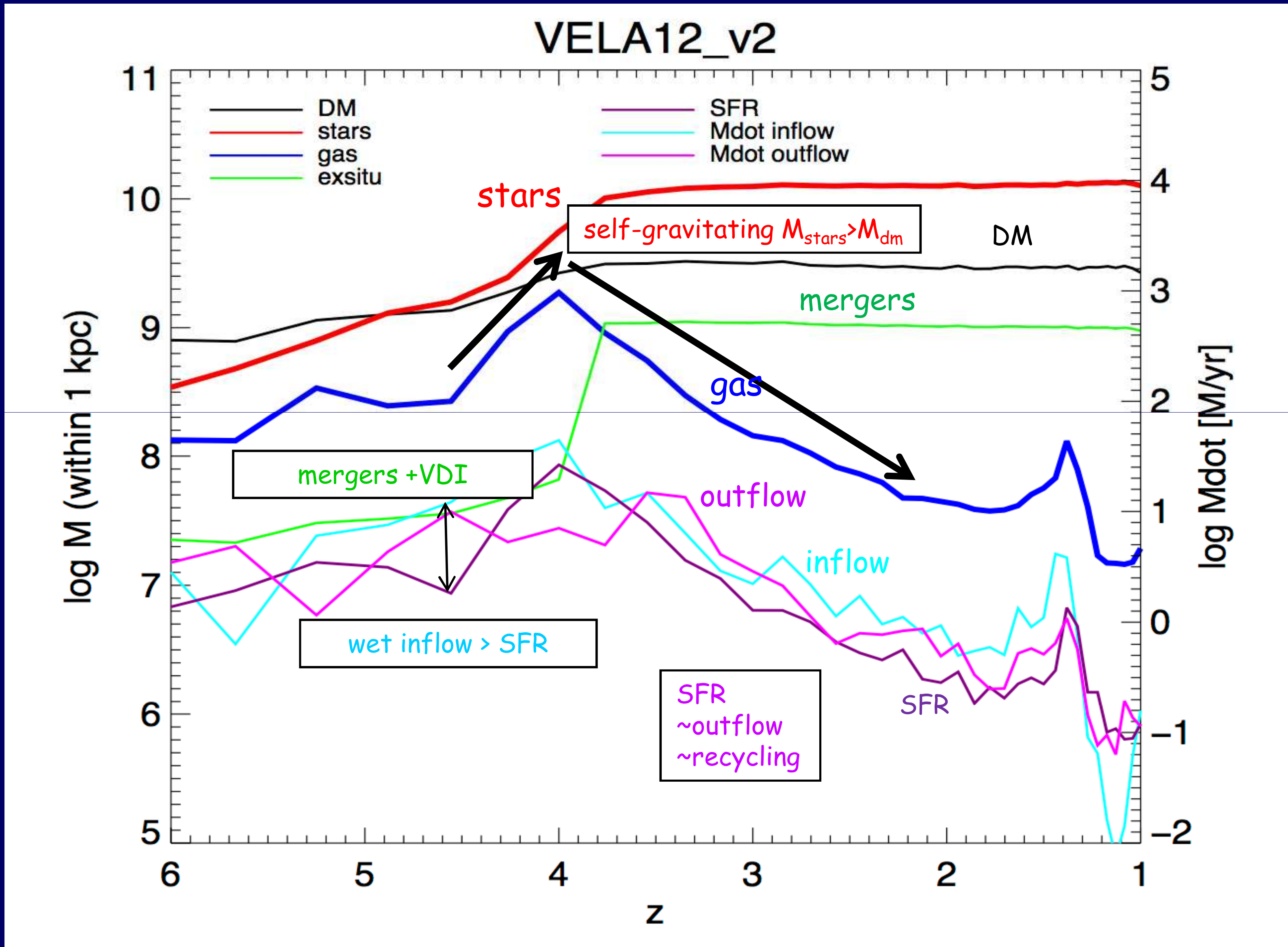
Driven by wet VDI or wet mergers

Compaction and quenching

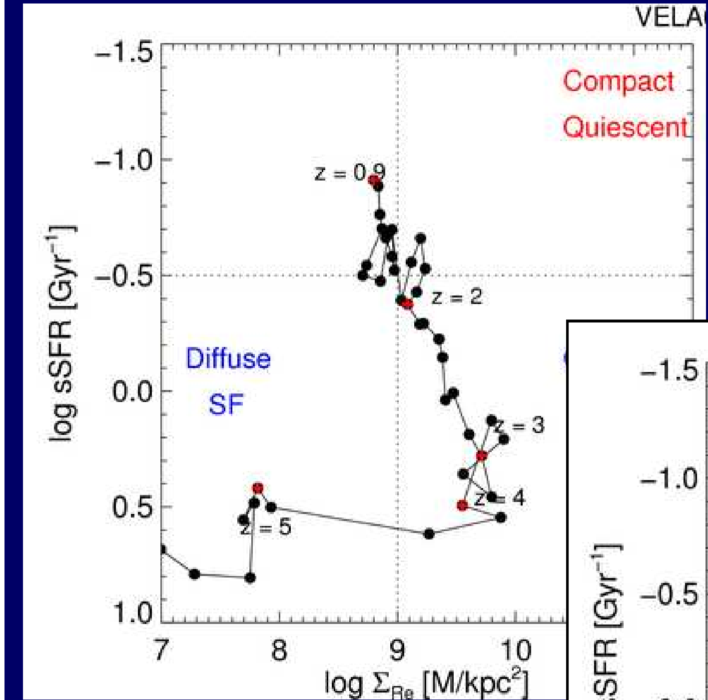
Zolotov+ 14 ART cosmological simulations, res. 25pc, rad fdbk, no AGN

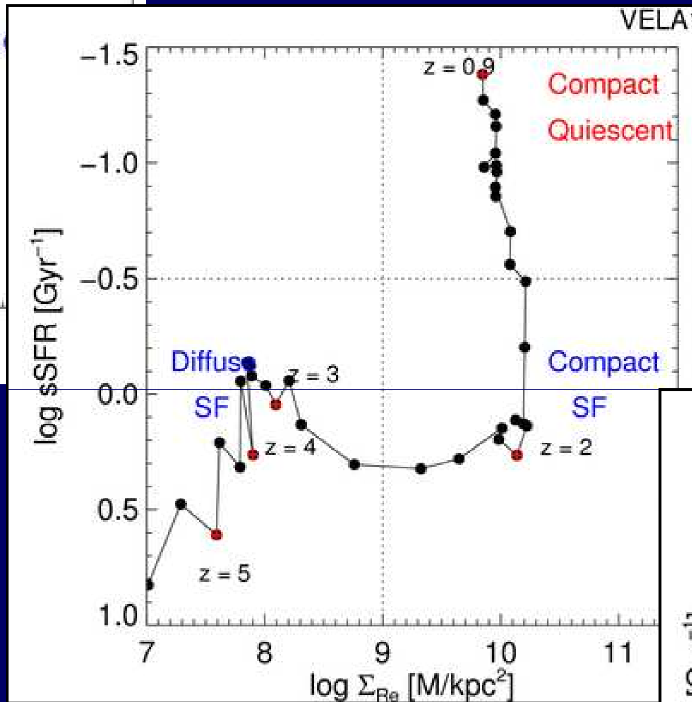


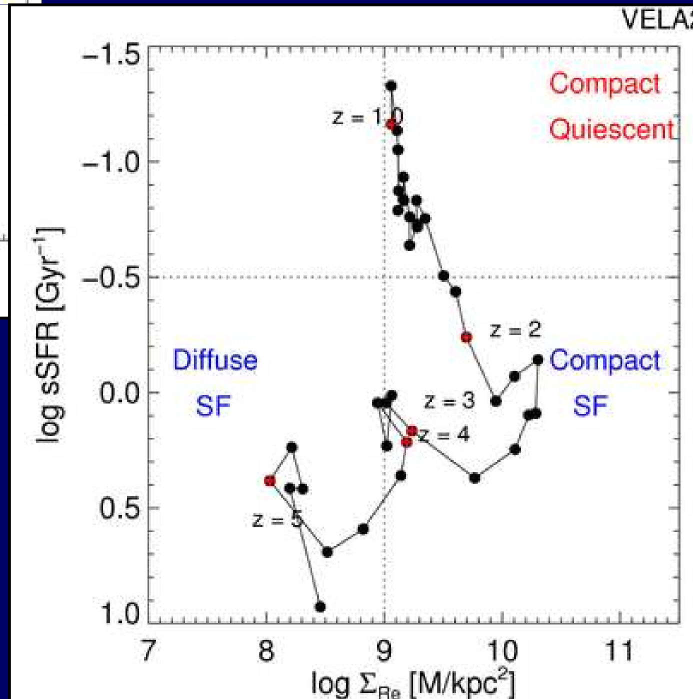
Compaction and quenching

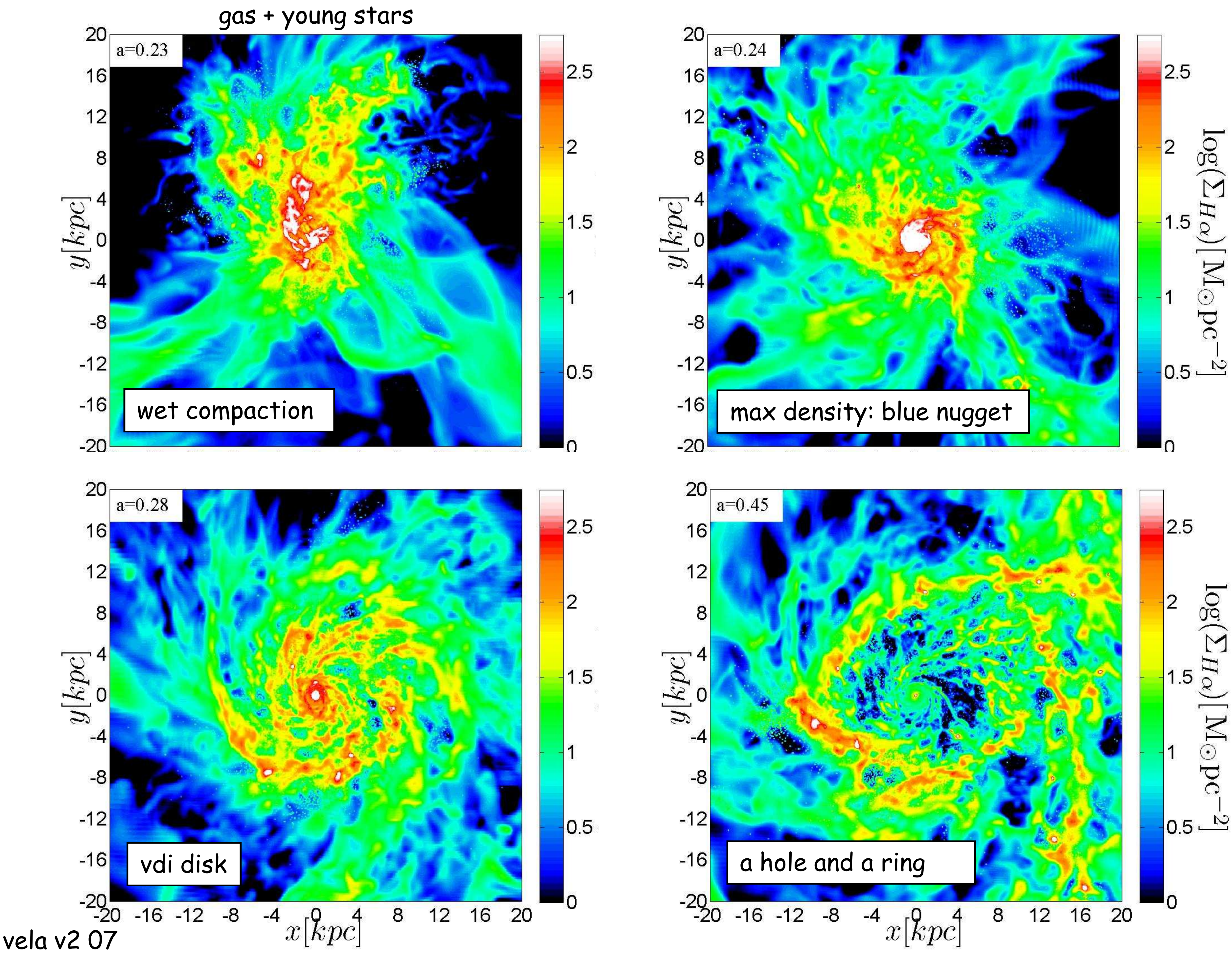


More Galaxies

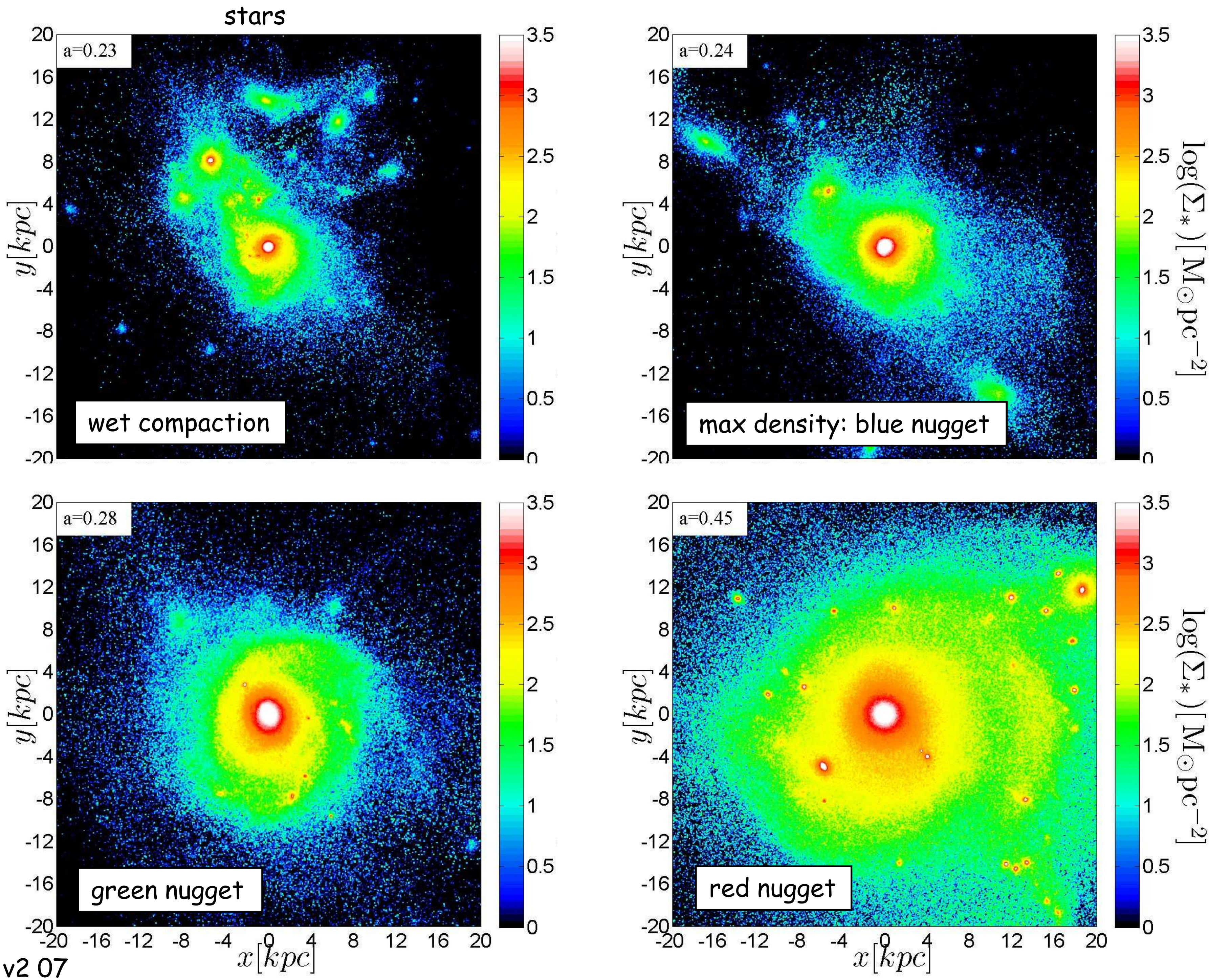








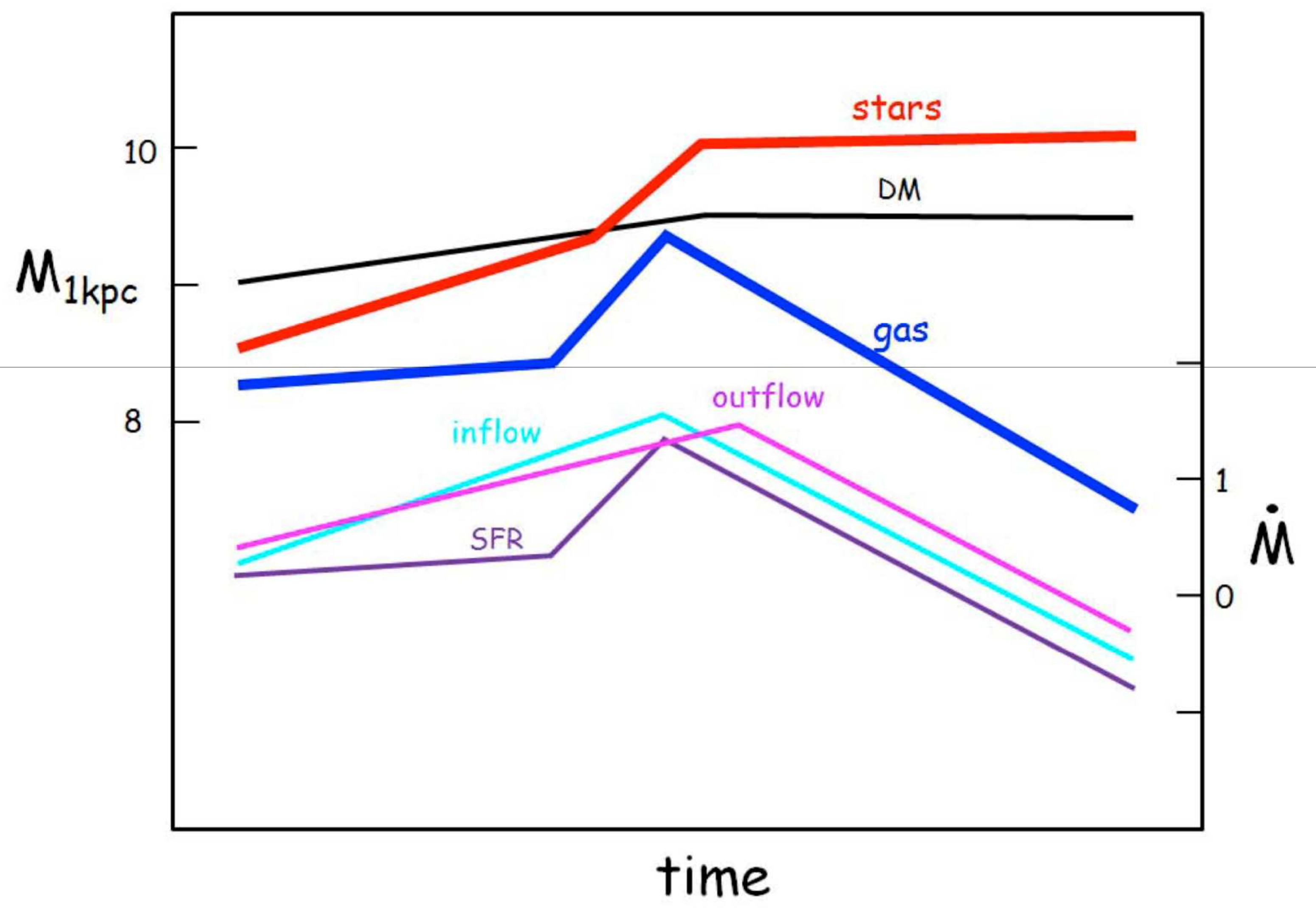
gas + young stars
a=0.23
wet compaction
a=0.24
max density: blue nugget
a=0.28
vdi disk
a=0.45
a hole and a ring
y[kpc]
x[kpc]
log(Σ_{Hα}) [M⊙pc^{-2}]
vela v2 07



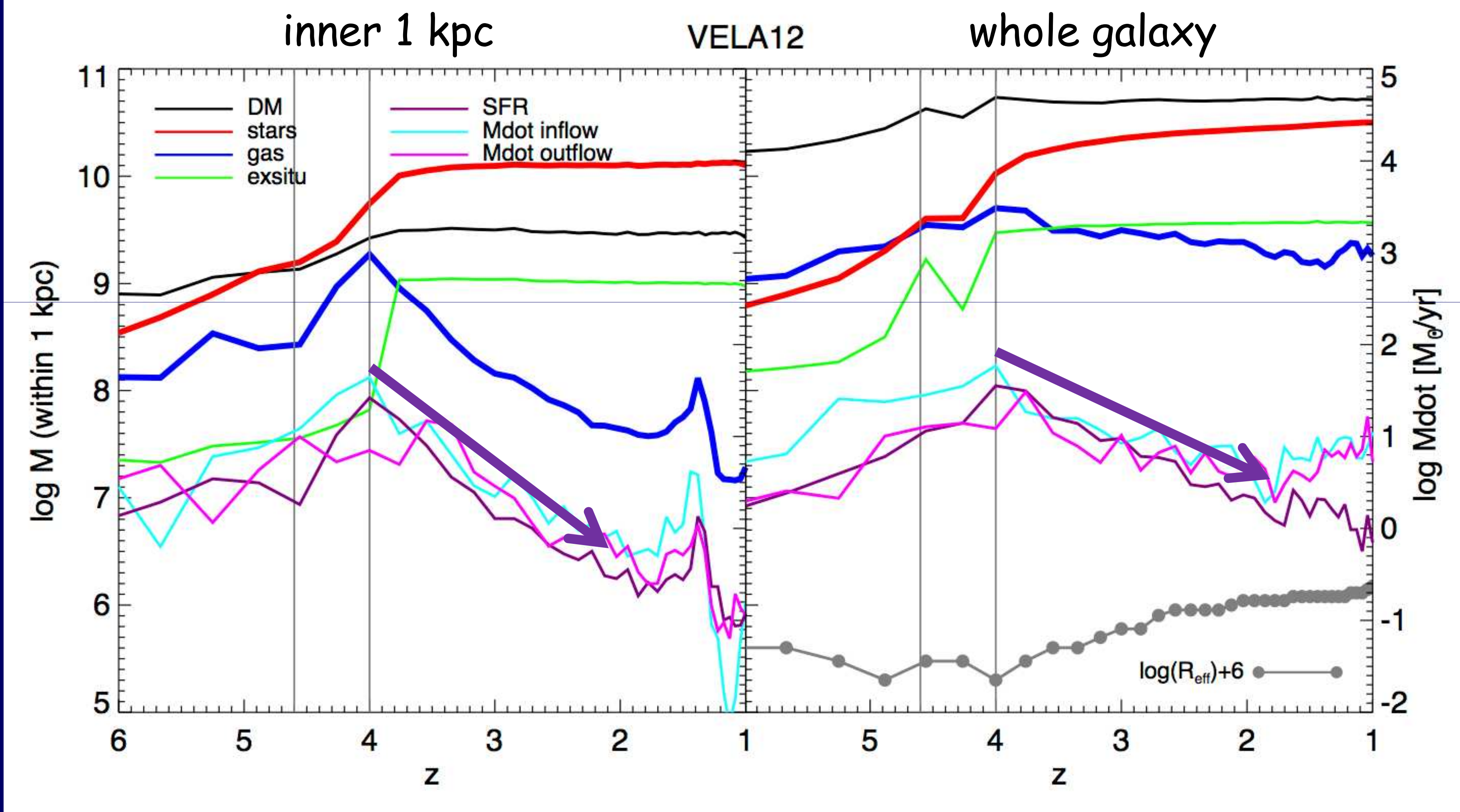
stars
a=0.23
wet compaction
a=0.24
max density: blue nugget
a=0.28
green nugget
a=0.45
red nugget
y[kpc]
x[kpc]
log(Σ*)[M⊙pc^-2]

vela v2 07

Typical Event: Compaction & quenching

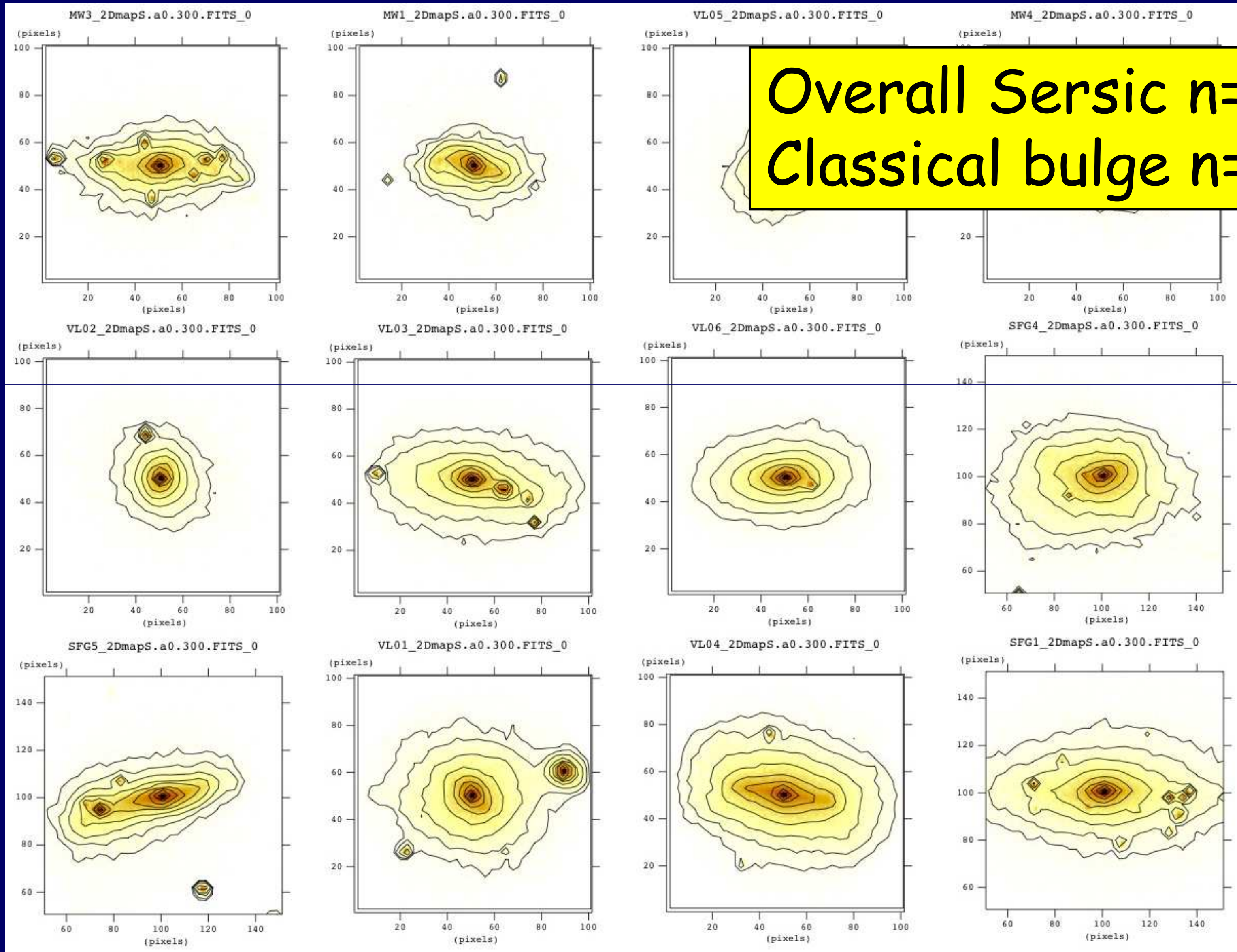


Inside-Out Quenching: Slower Quenching in the Outer Disk



Stellar Component at z=2.3, edge-on

Ceverino+ 2014

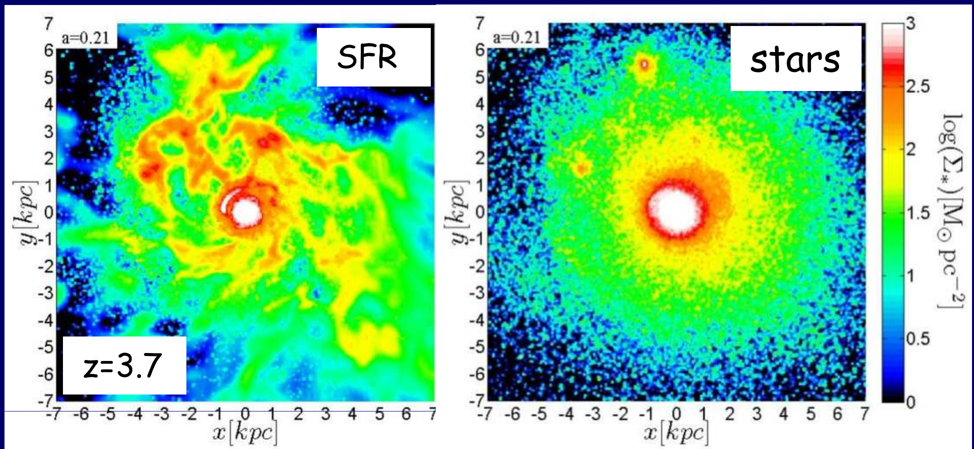


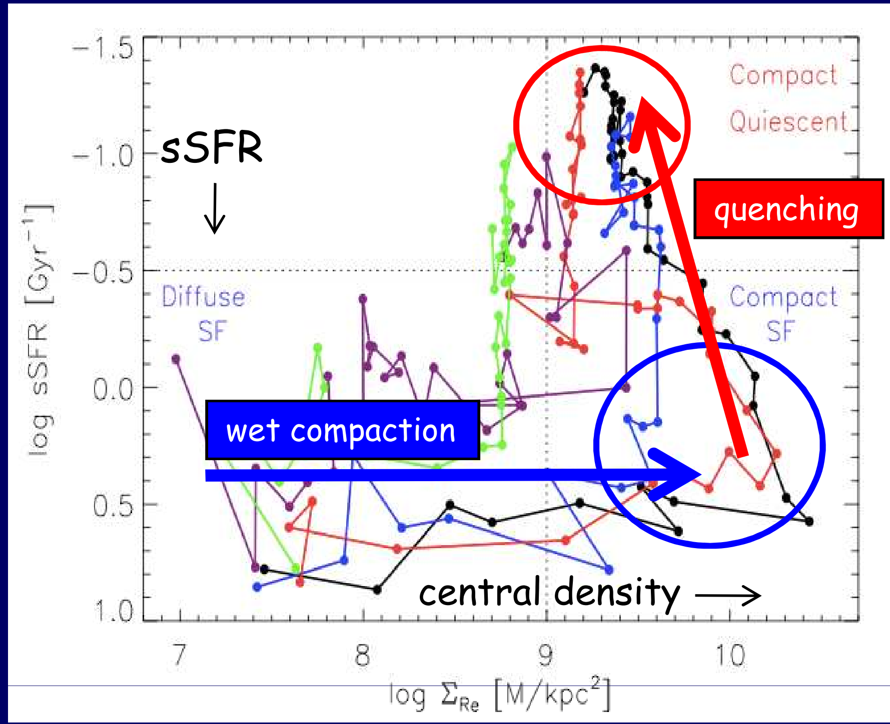
Overall Sersic n=2-4
Classical bulge n=3-5

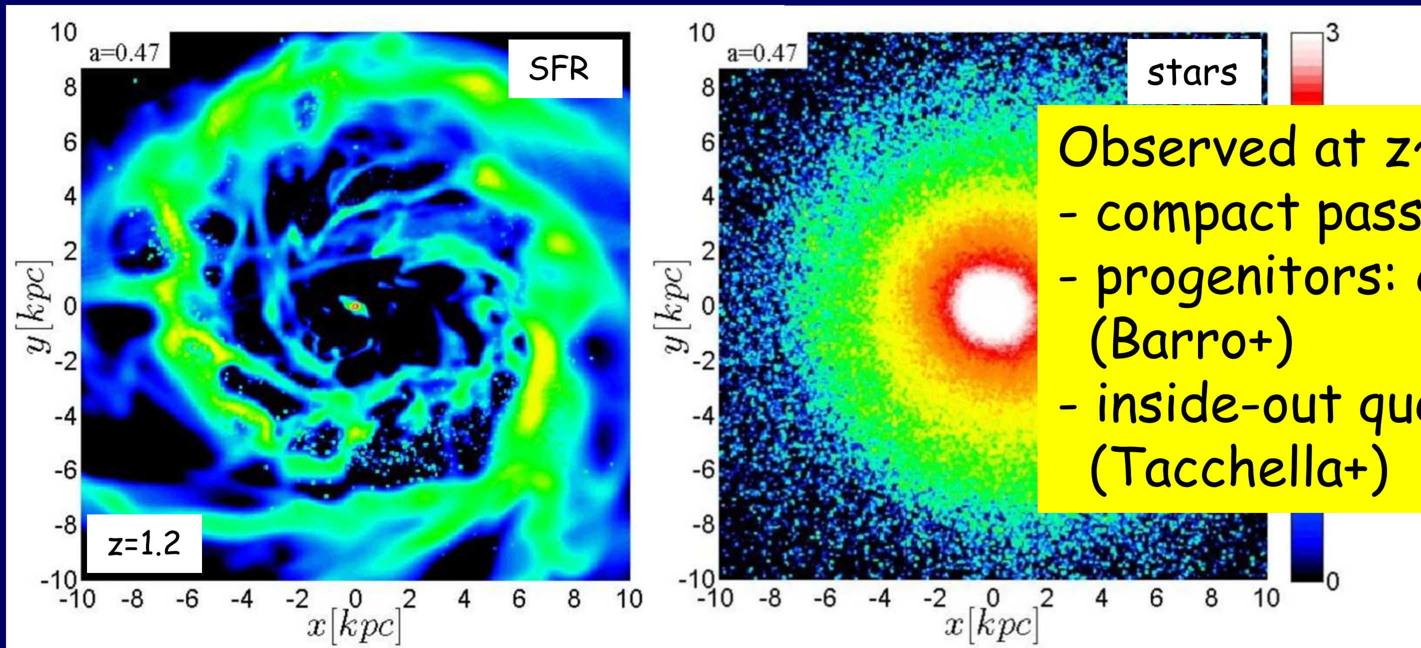
Blue and Red Nuggets

Zolotov, AD+ 14

blue nugget

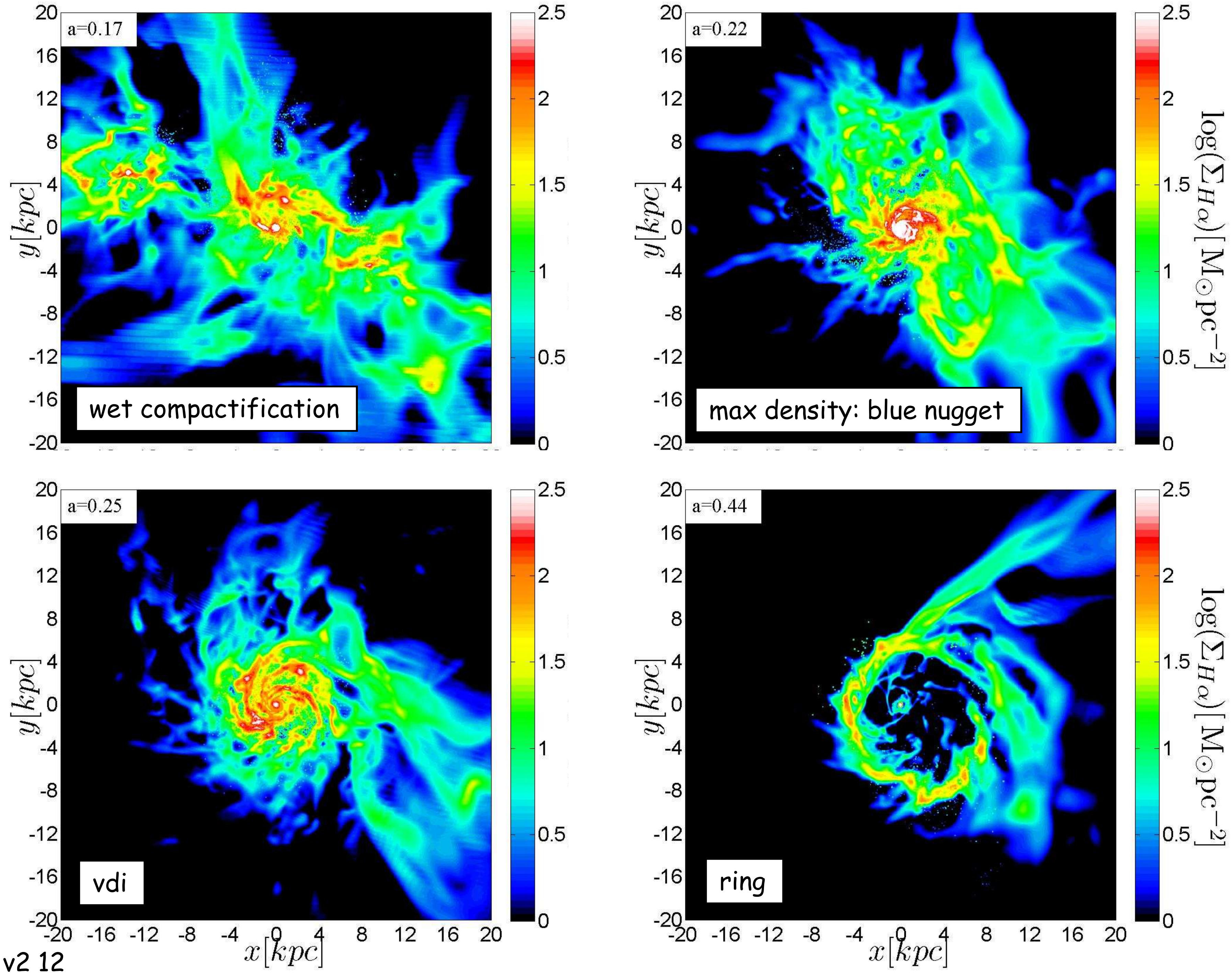




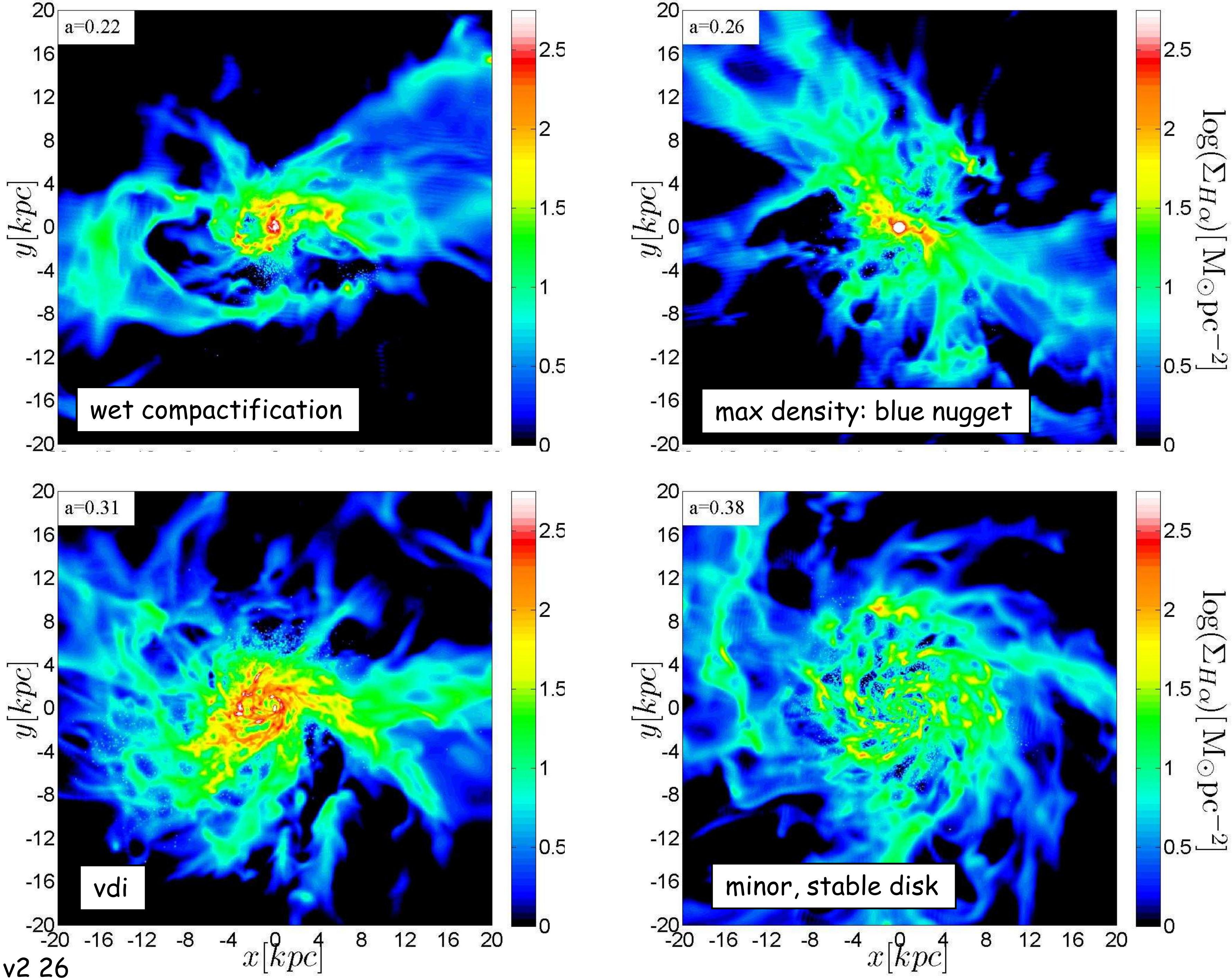


Observed at z~2-3:
- compact passive ellipticals
- progenitors: compact SFGs (Barro+)
- inside-out quenching – ring SF (Tacchella+)

red nugget


a=0.17
wet compactification
a=0.22
max density: blue nugget
a=0.25
vdi
a=0.44
ring
$y[kpc]$
$x[kpc]$
$\log(\Sigma_{H\alpha})[\mathrm{M_\odot pc^{-2}}]$

vela v2 12

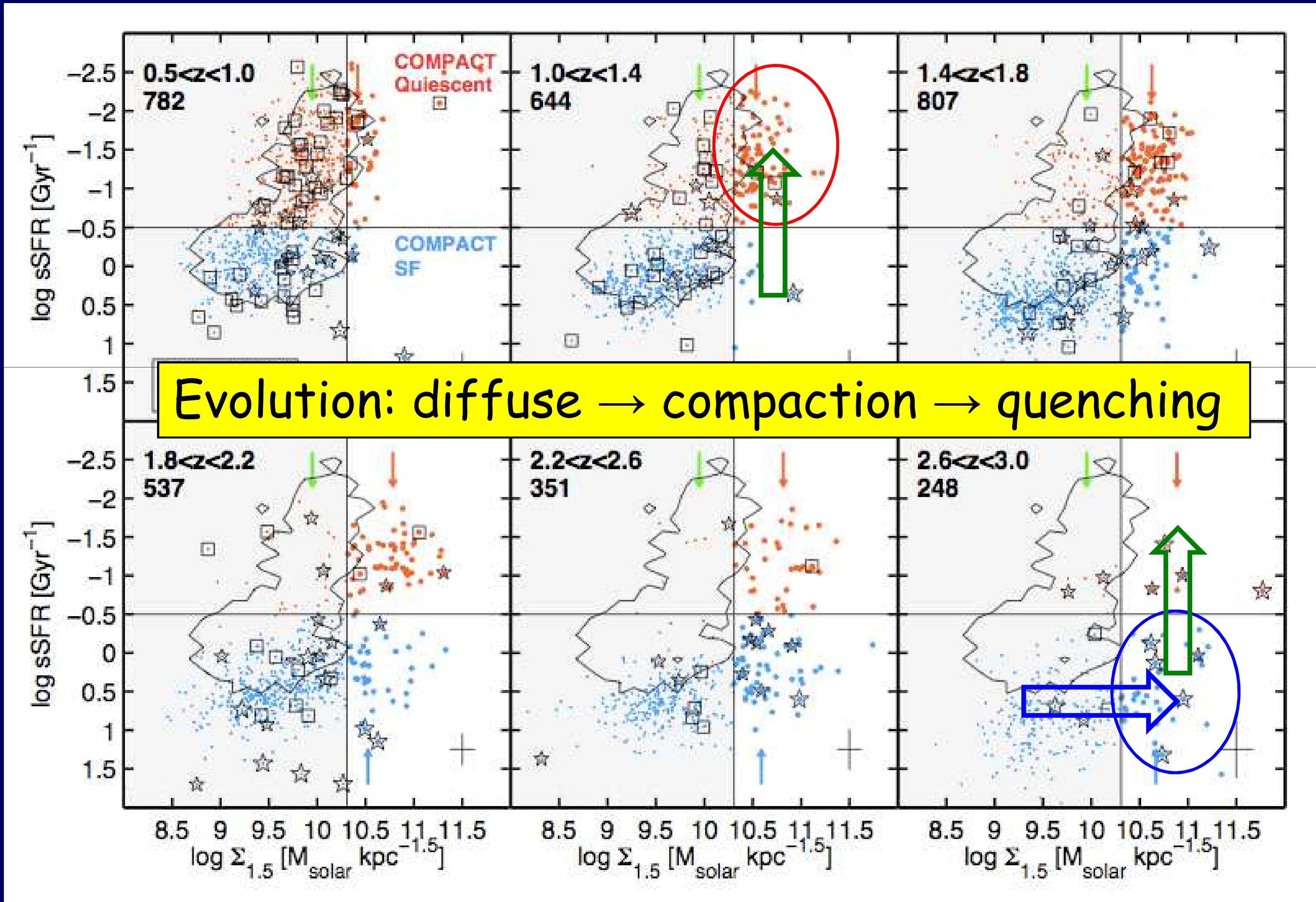


a=0.22
wet compactification
a=0.26
max density: blue nugget
a=0.31
vdi
a=0.38
minor, stable disk
$y[kpc]$
$x[kpc]$
$\log(\Sigma_{H\alpha})\,[\mathrm{M}_\odot\,\mathrm{pc}^{-2}]$

vela v2 26

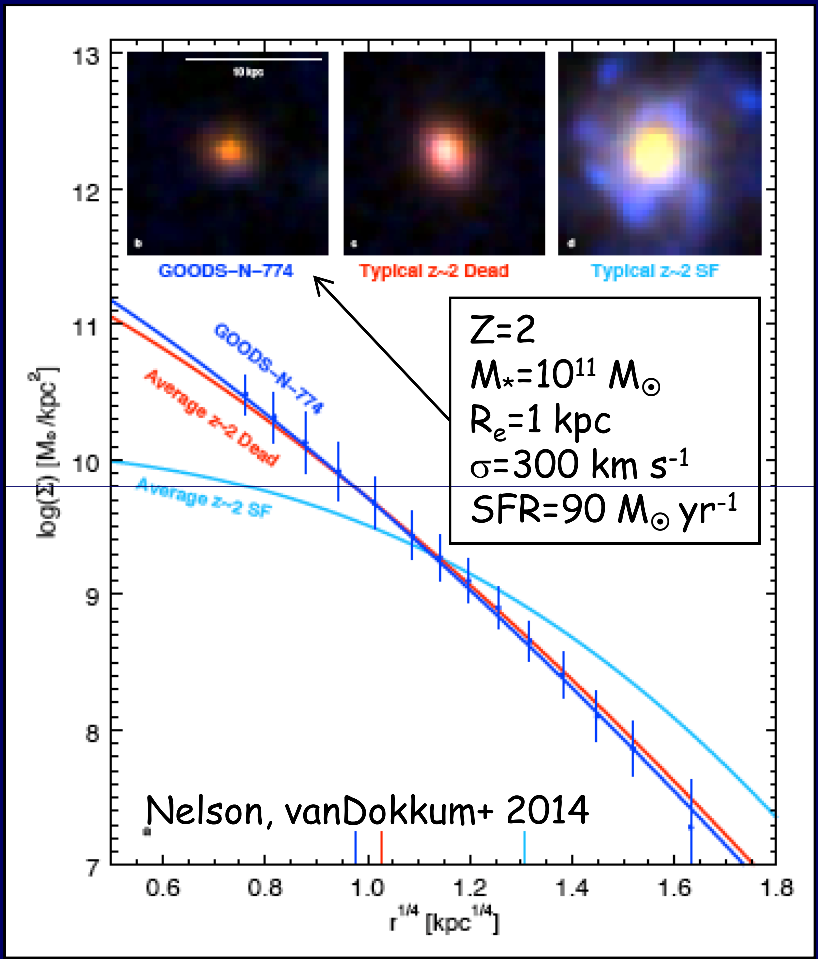
Observations: Blue Nuggets -> Red Nuggets

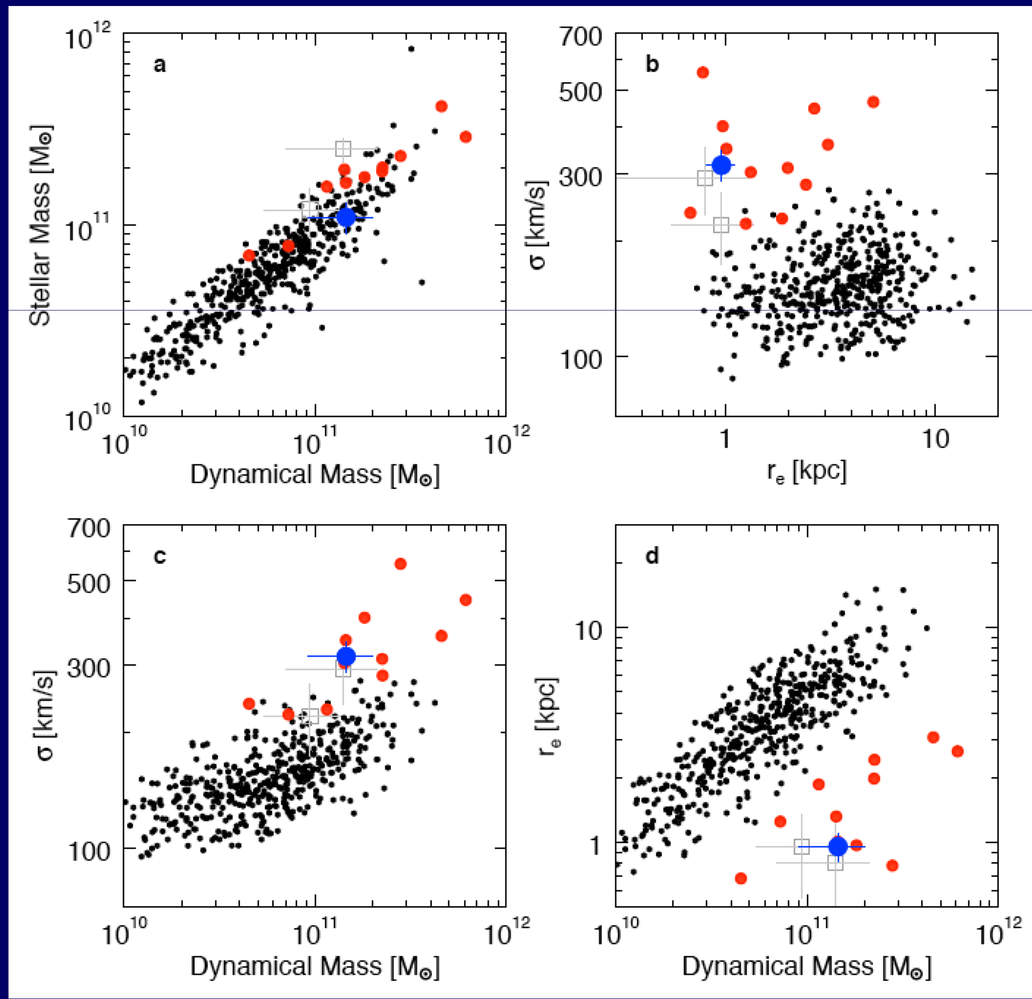
Barro+ 13 CANDELS z=1-3



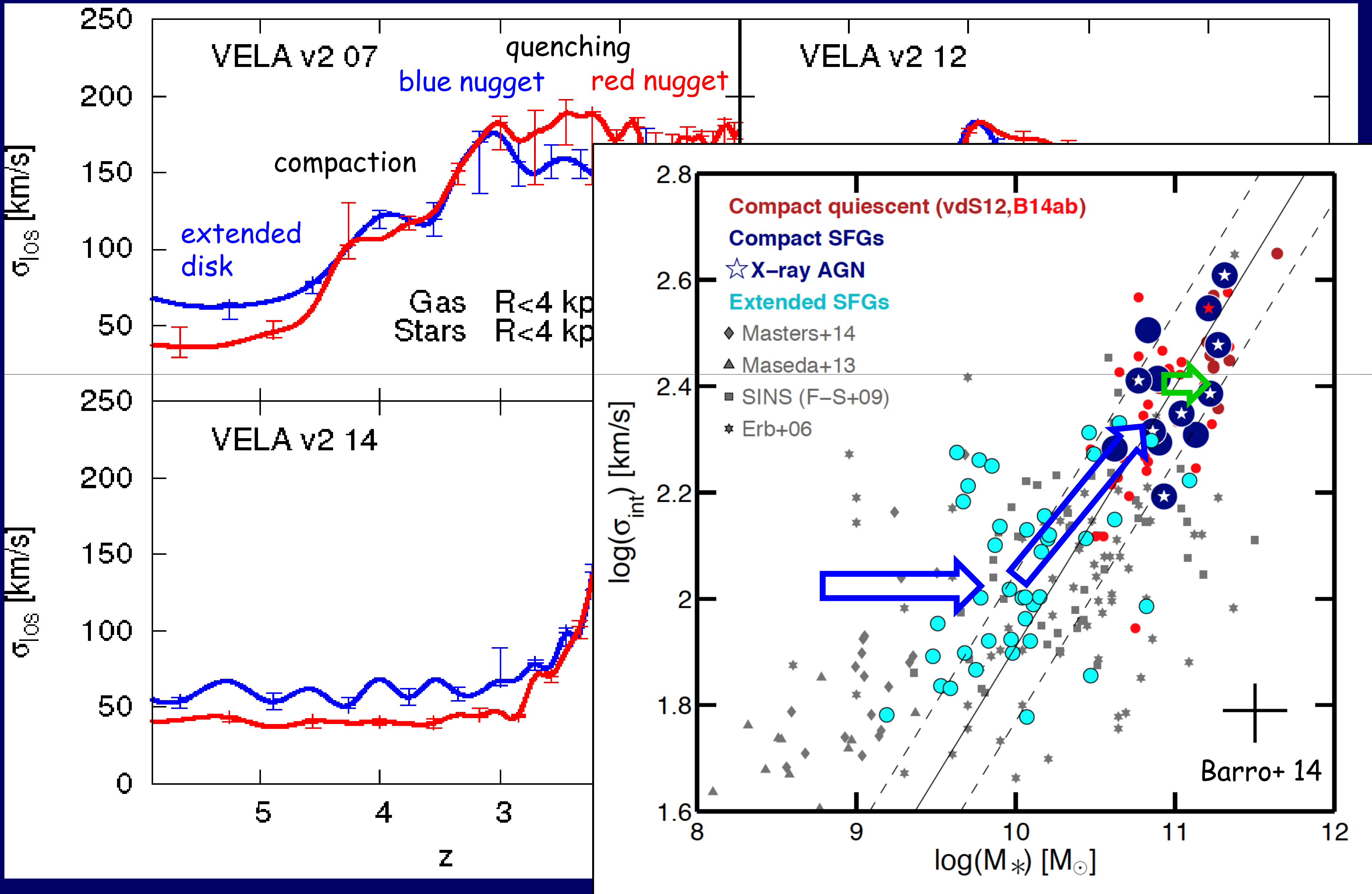
Evolution: diffuse → compaction → quenching

Similar Structure for Blue & Red Nuggets

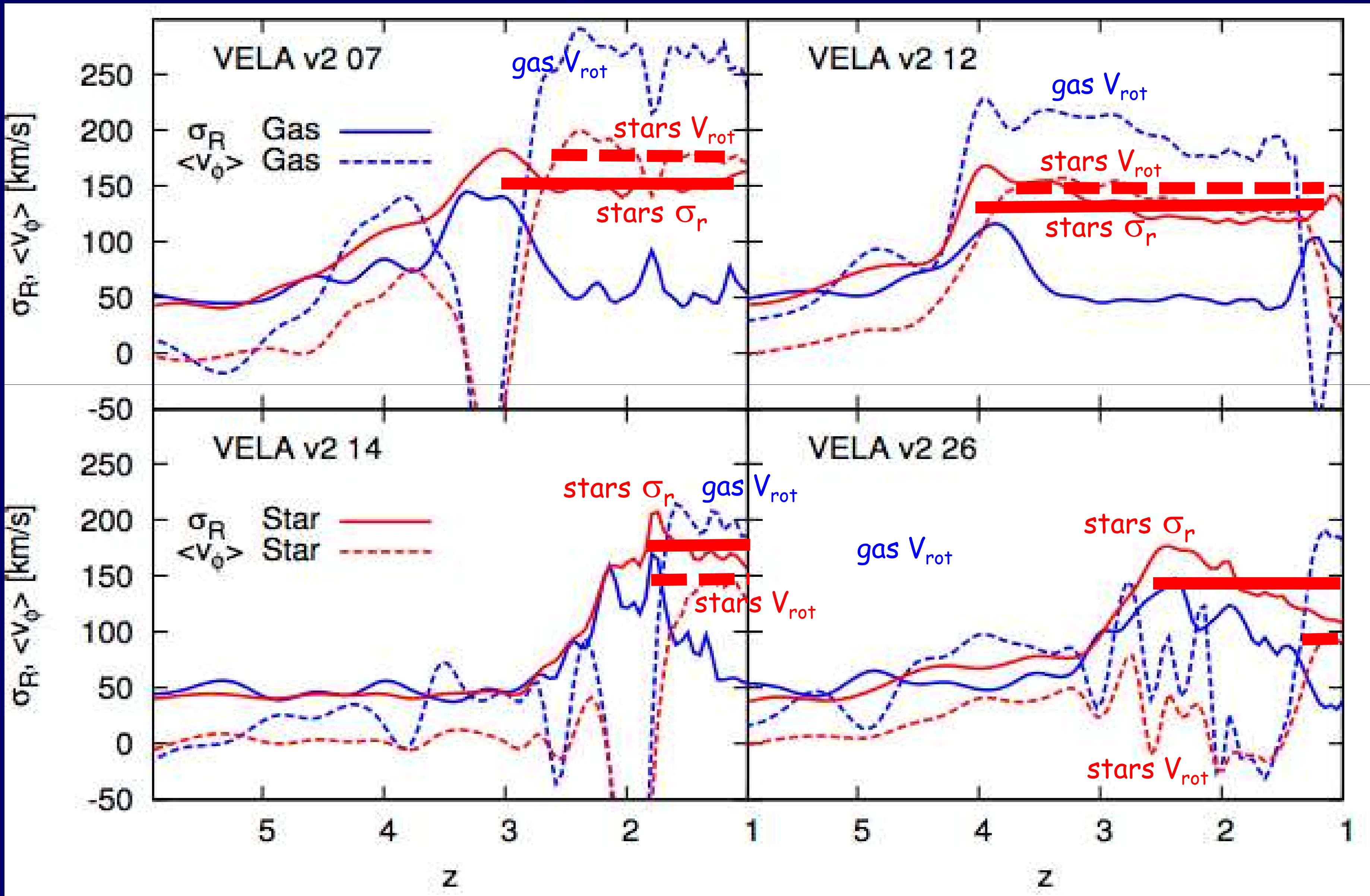




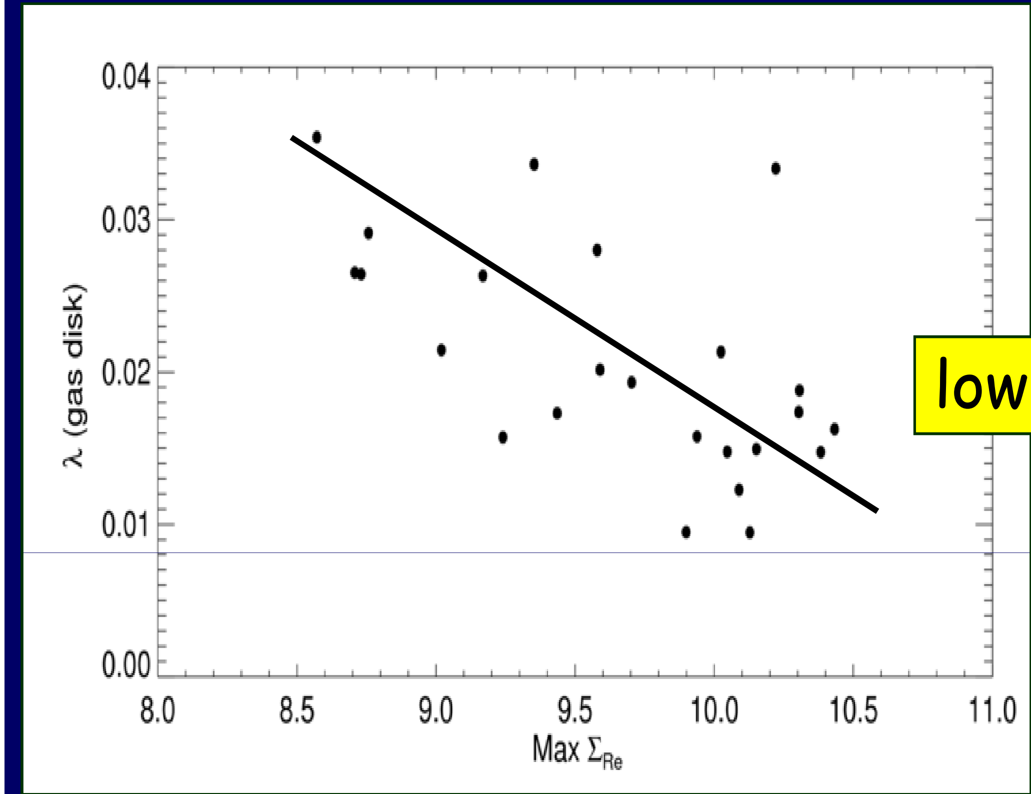
“line width” evolution in simulated galaxies



Nuggets: Rotation and Dispersion



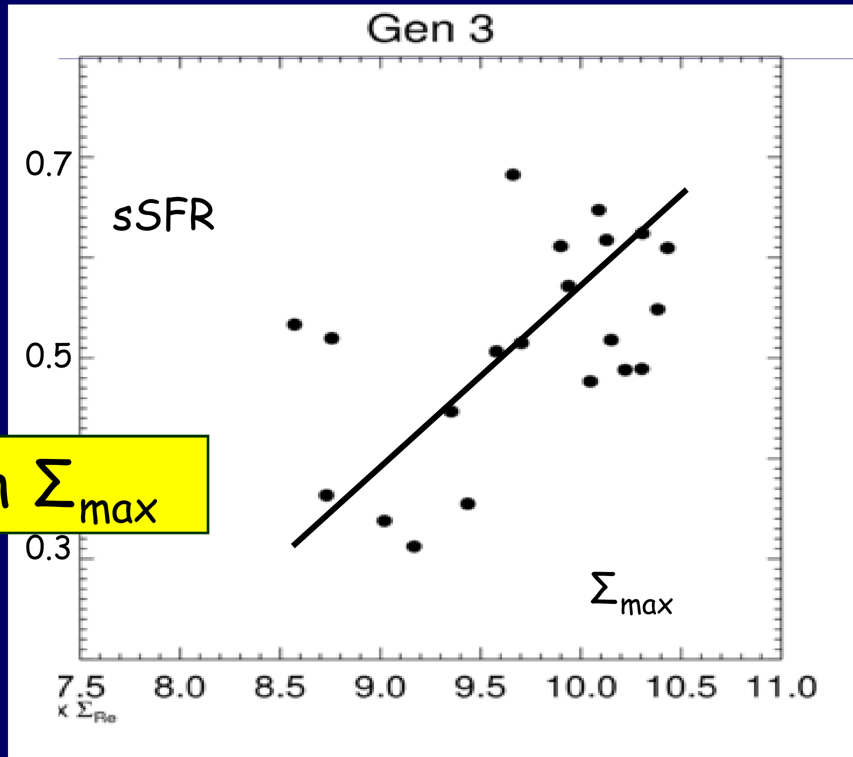
Blue Nuggets by Wet Inflow: Spin and sSFR



Simulations confirm model predictions

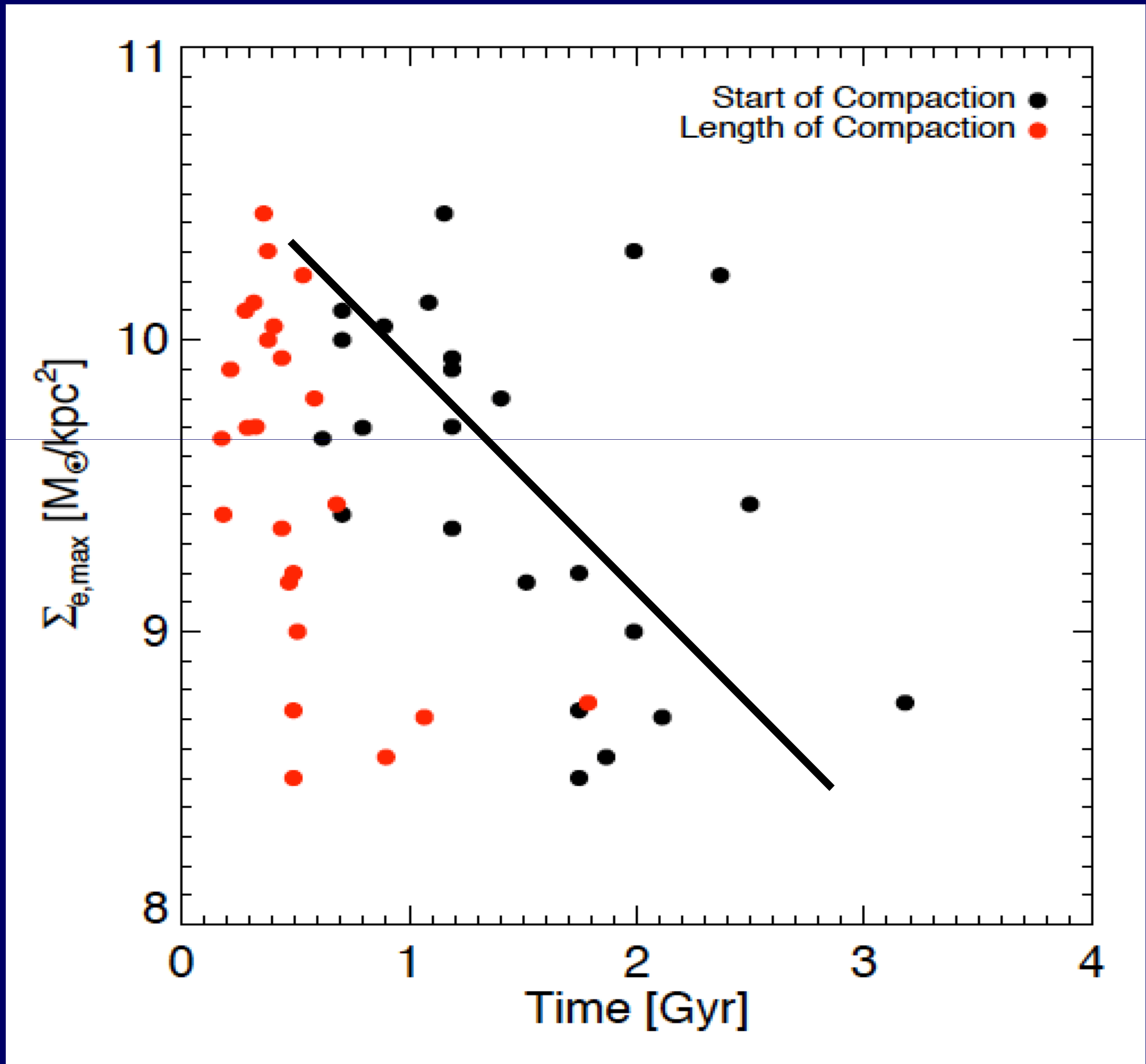
Dekel, Burkert 14; Zolotov+ 14

low-spin disk -> high Σ_{max}



high-sSFR disk -> high Σ_{max}

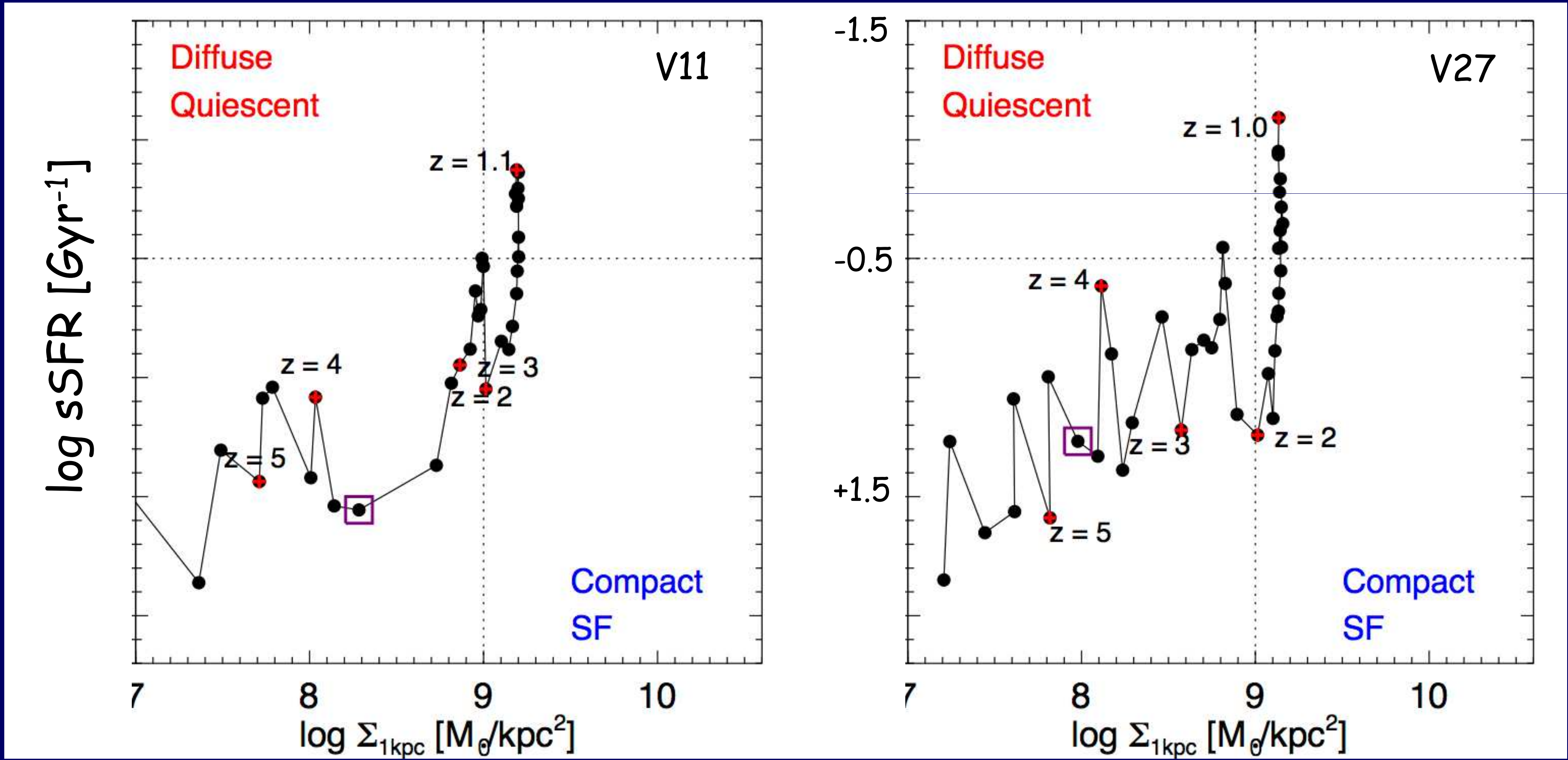
More Compact at Earlier Redshift



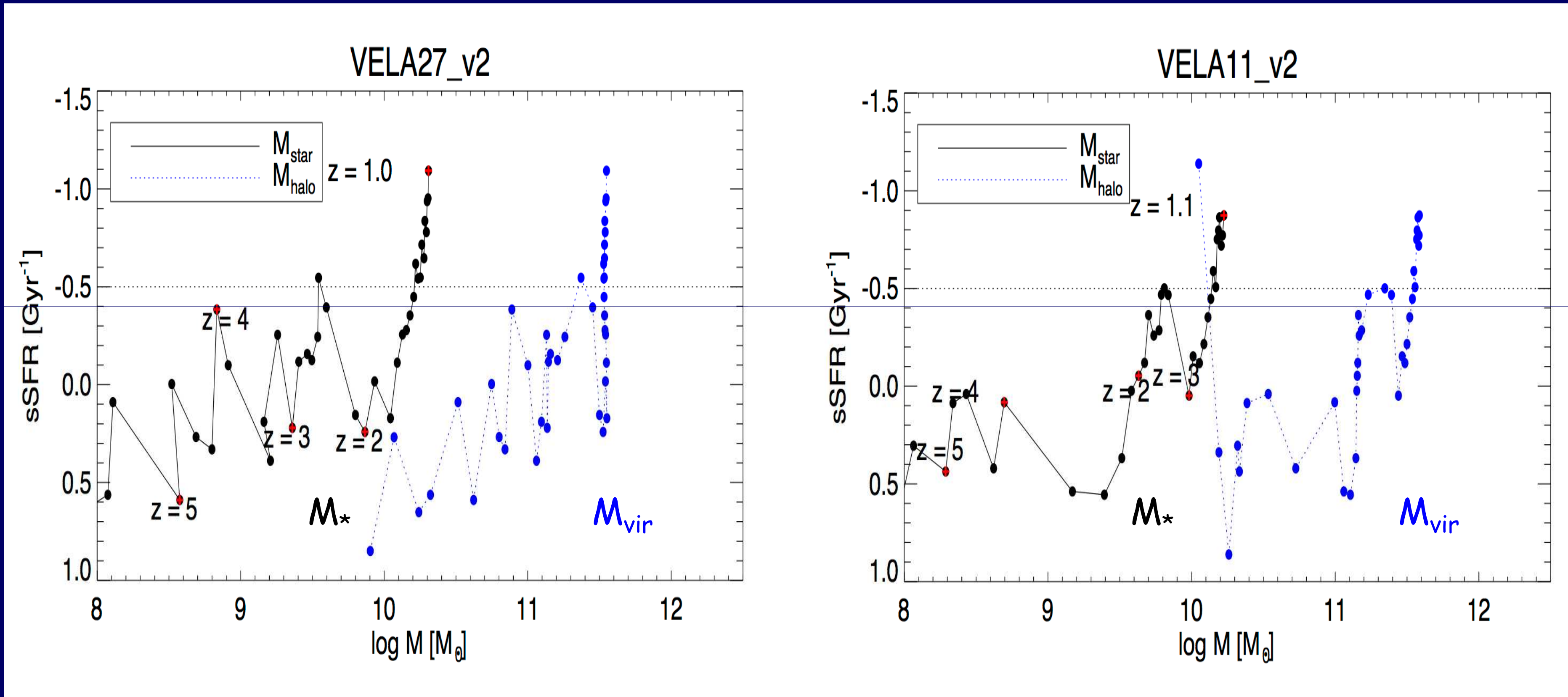
Hesitant quenching at moderate compactness

At lower redshift, higher spin, lower sSFR

What allows the final quenching?



Halo Mass >$10^{11.5}M_\odot$ for Final Quenching



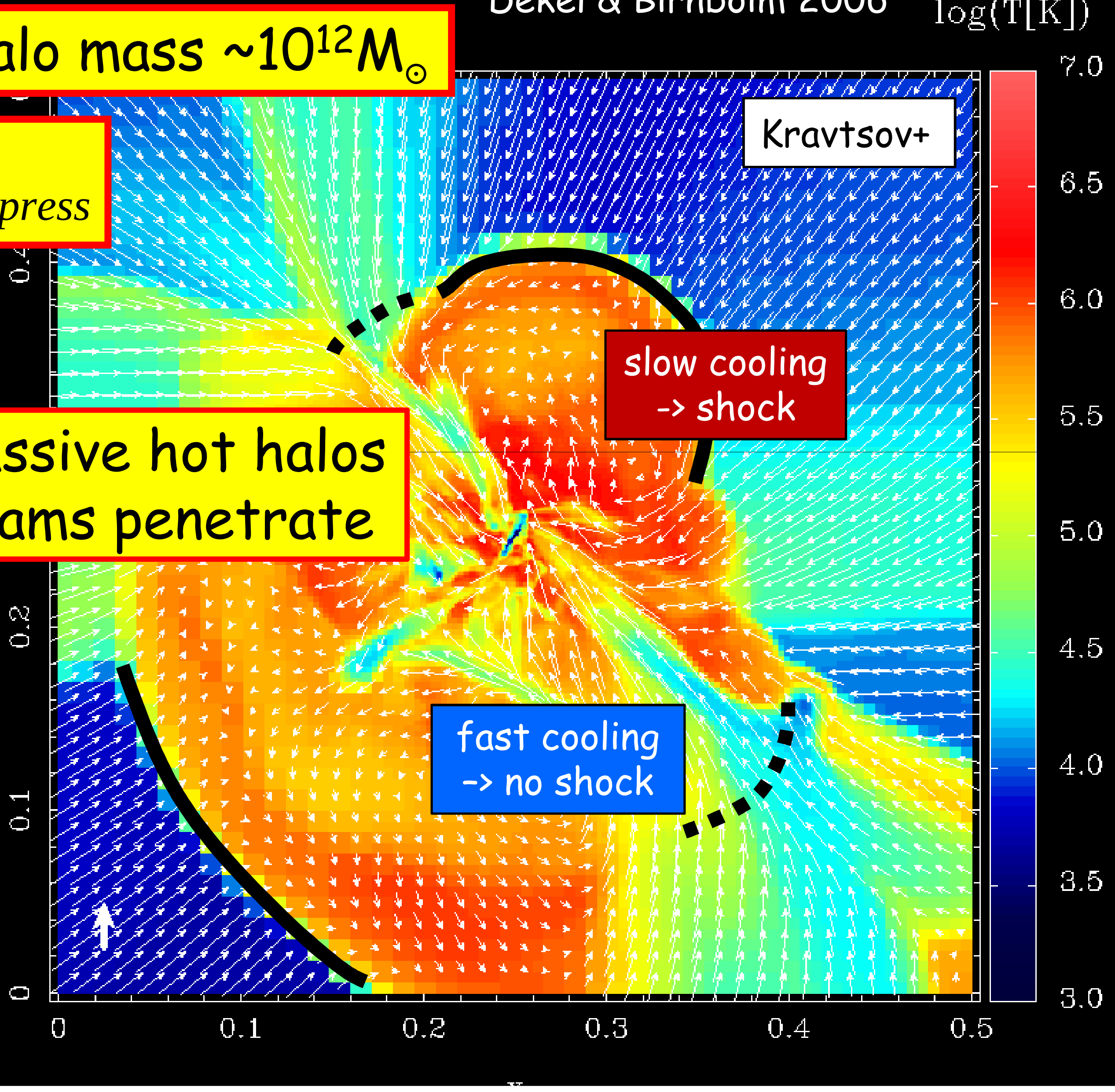
Virial Shock Heating

Dekel & Birnboim 2006

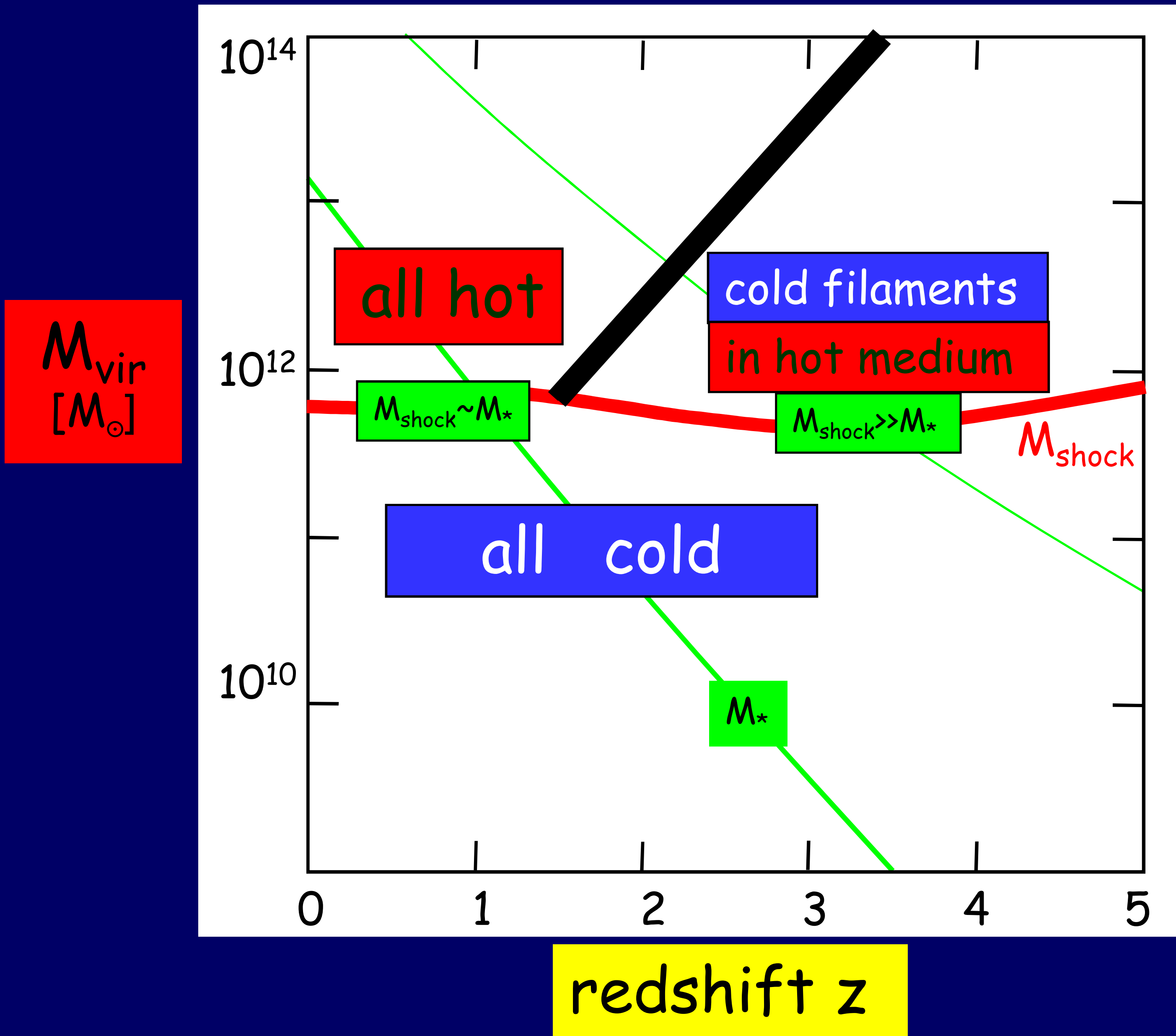
critical halo mass ~$10^{12} M_\odot$

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

in hi-z massive hot halos
cold streams penetrate



Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06

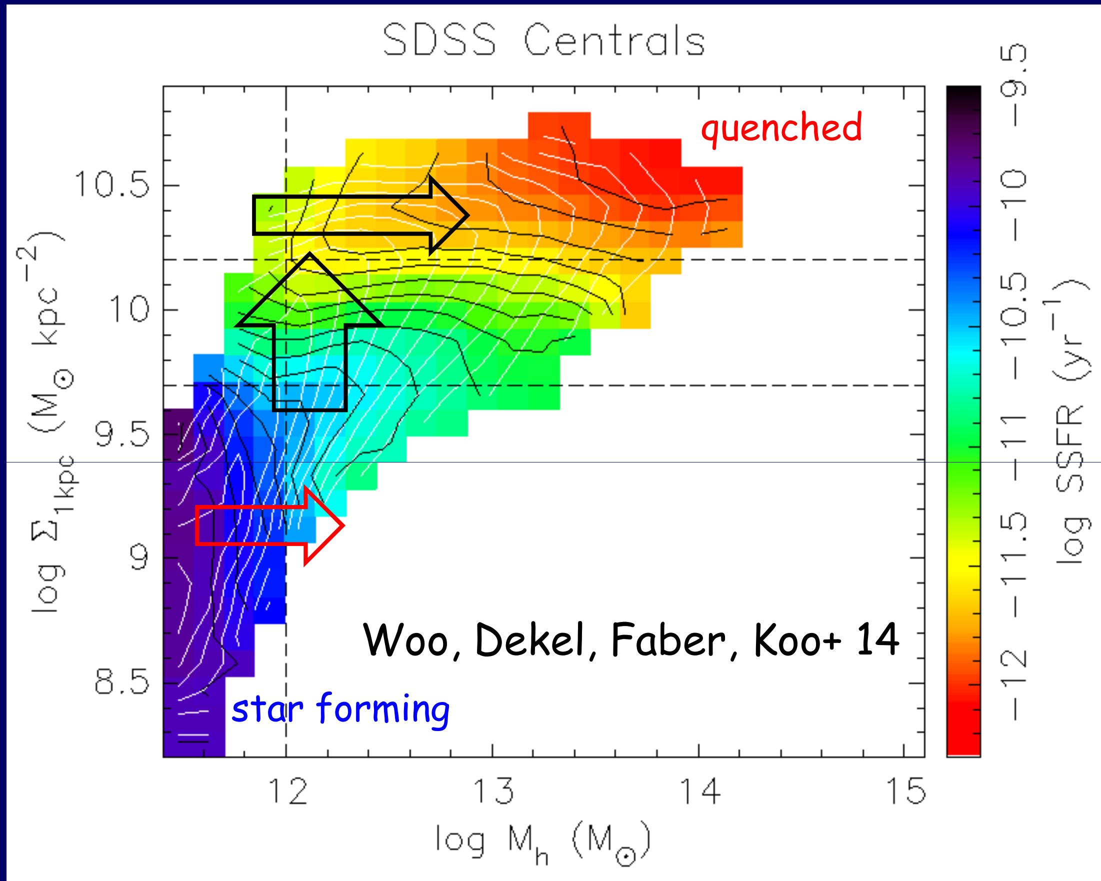
Two Quenching Mechanisms: Bulge & Halo

Compact gaseous bulge

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

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

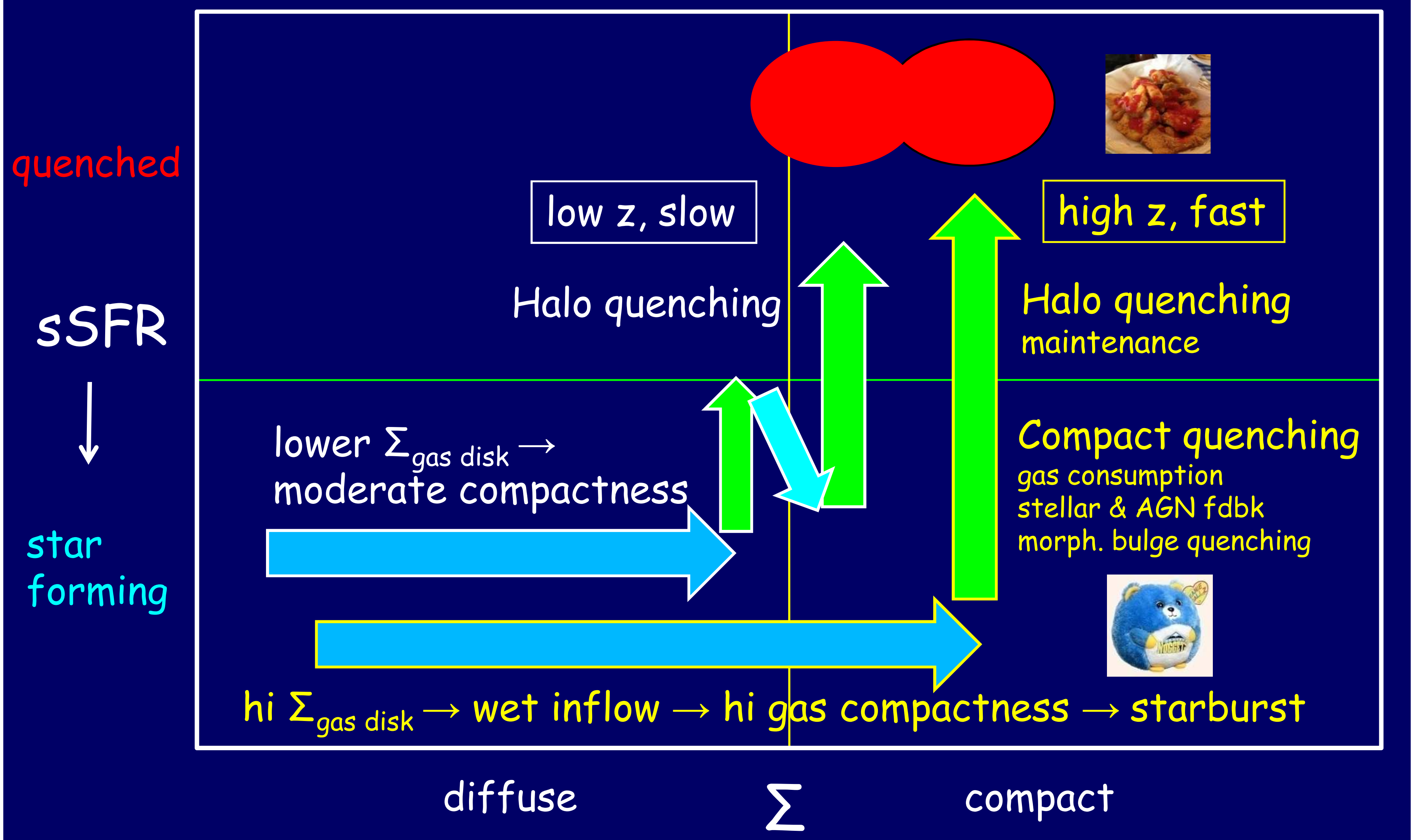
-> long-term shutdown of gas supply by virial shock heating



Compact bulge and halo quenching

But each can quench by itself

Modes of Evolution



Conclusions

A characteristic sequence of events at high z in almost every galaxy:

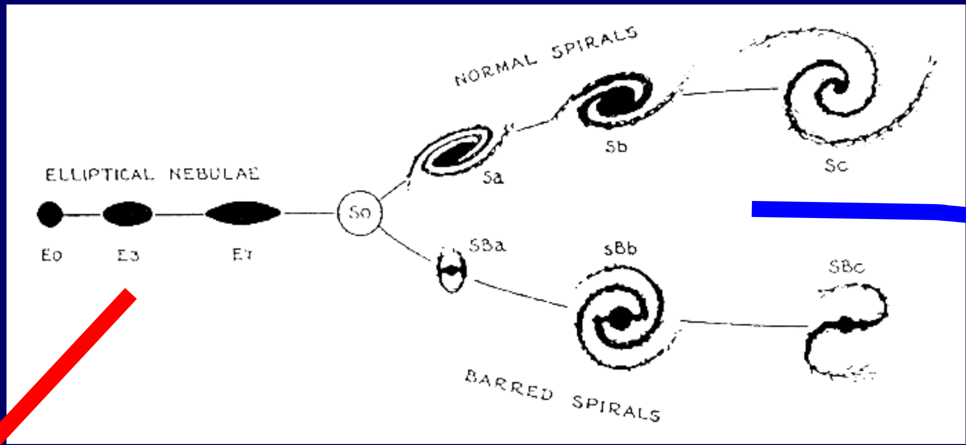
- wet compaction by mergers and VDI to compact SFGs (blue nuggets)
  rotating flattened spheroids with high dispersion

- high SFR+AGN, outflows, massive self-gravitating bulge →
  fast quenching to compact ellipticals (red nuggets)
  +gas rings (?)

- long-term quenching by hot massive halo

- Fast evolution, at hi z: compact quenching, long-term halo quenching
  Slow evolution, at low z: mostly halo quenching, some compact q

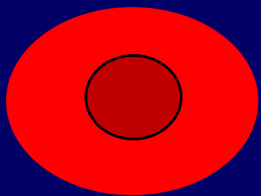
The High-z "Hubble" Sequence

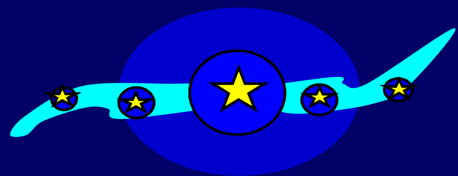


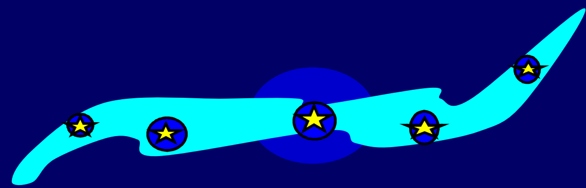
Red nuggets

Blue nuggets

Clumpy disks





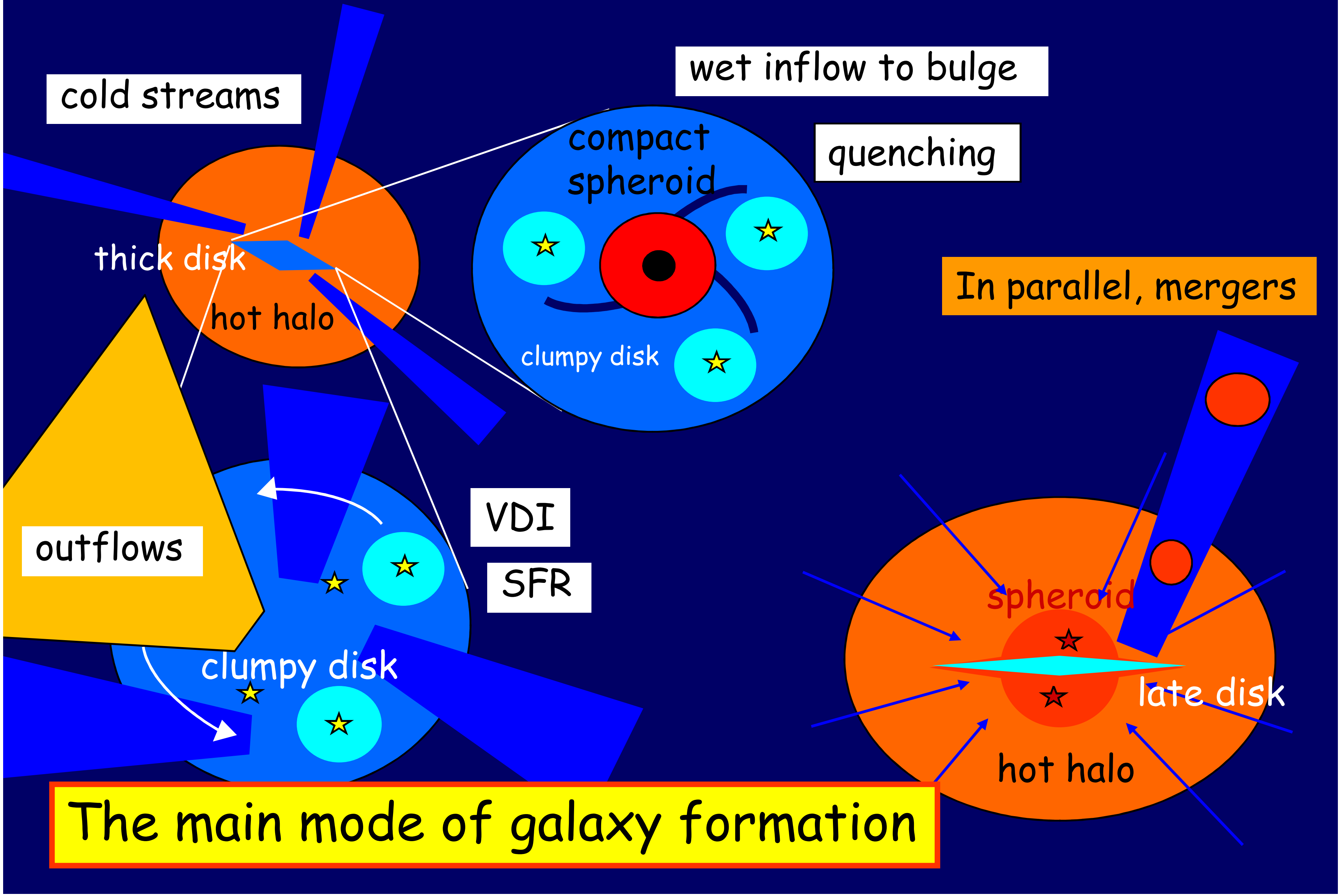


Compact ellipticals

Starburst in a compact bulge

No bars
Perturbed spiral patterns

Stream-Fed Galaxies at High z



The main mode of galaxy formation