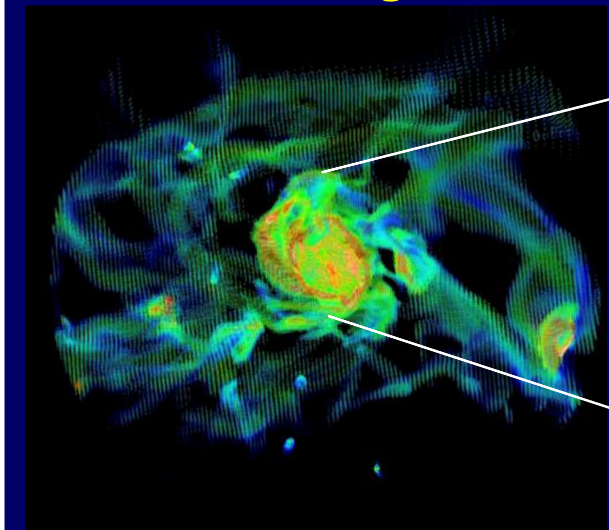
Key Issues at the Peak of Galaxy Formation

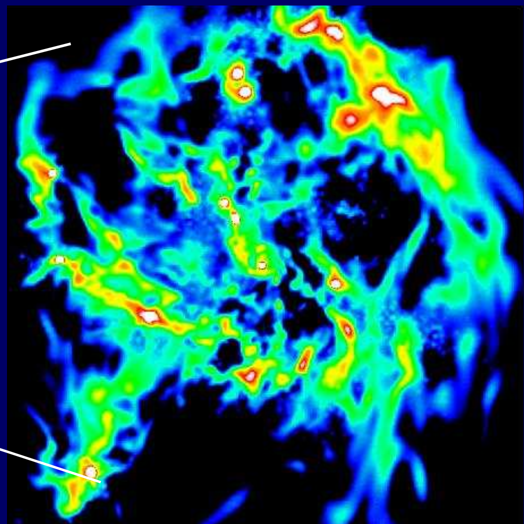
Avishai Dekel
The Hebrew University of Jerusalem

IAP, October 2014

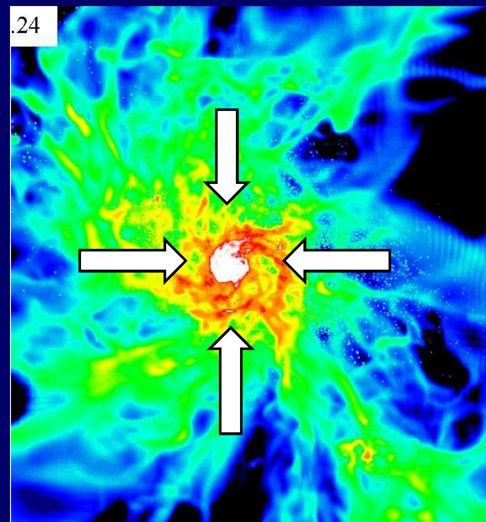
streams – ring – disk



instability



compaction



The most active phase of galaxy formation is during the first few Gyr, z=1-4

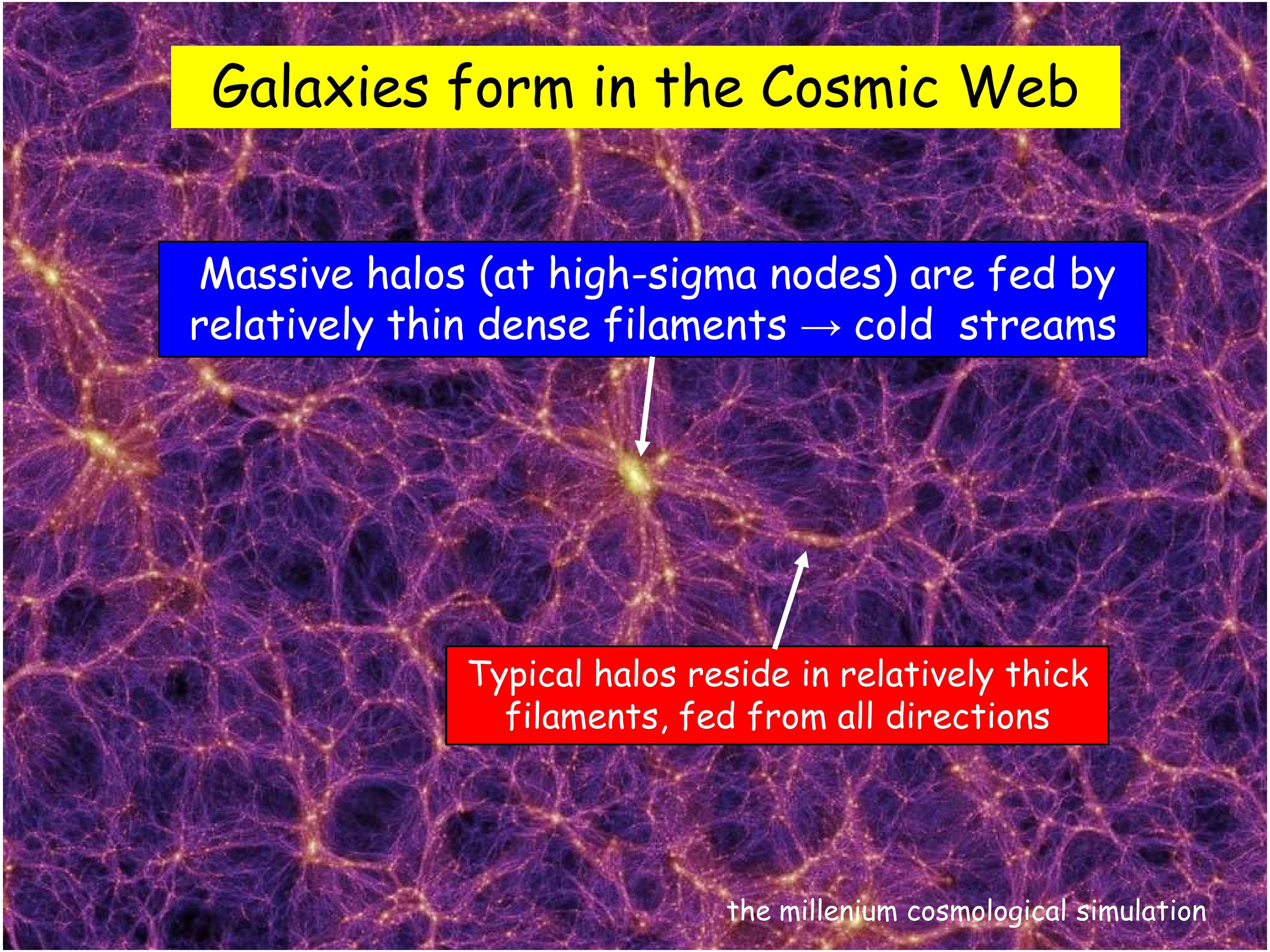
Rapid mass assembly: $dM/dt \sim M\,(1+z)^{2.5}$
→ at z~2 significant mass growth per orbital time

High gas fraction: ~ 50%

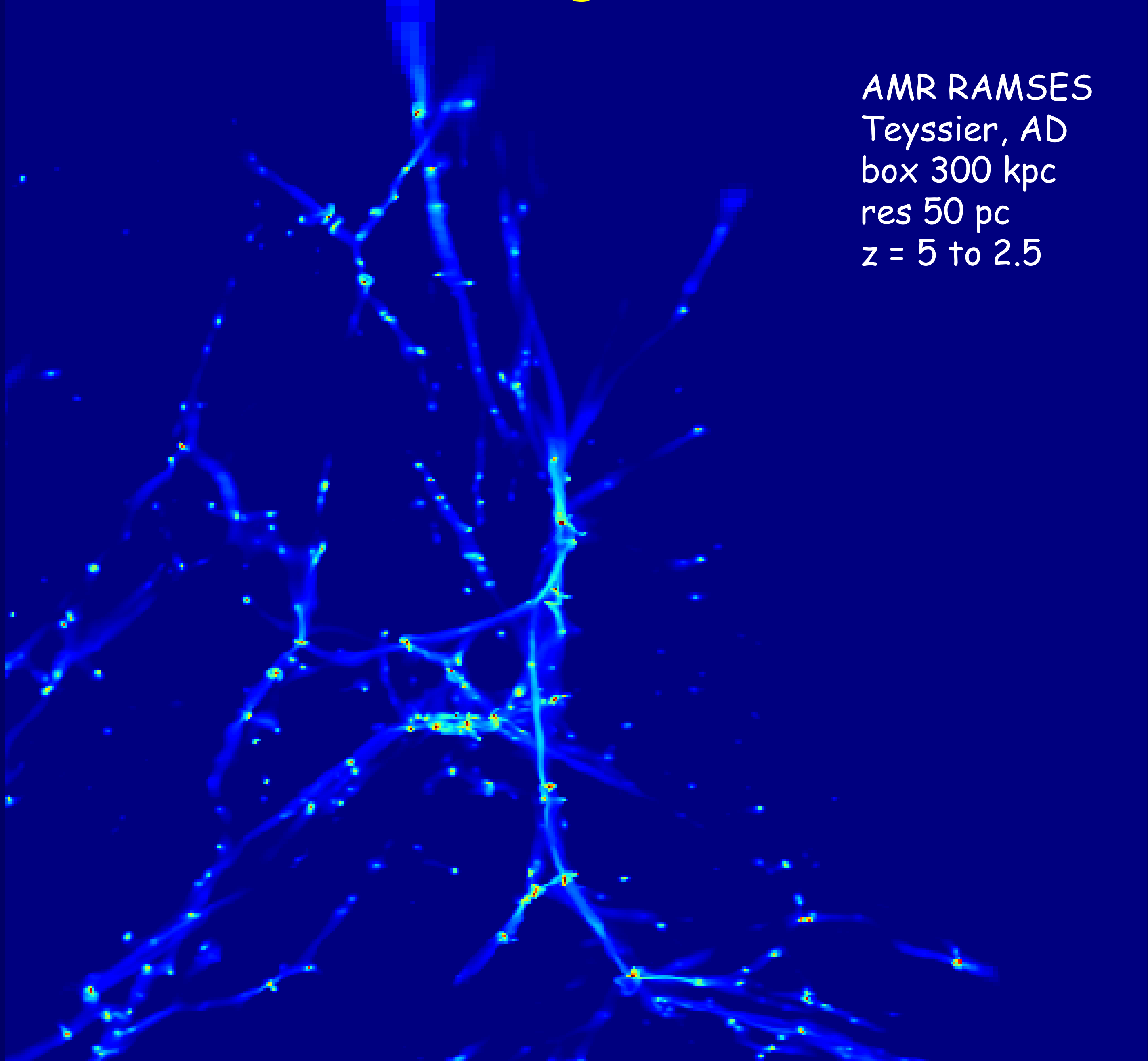
Fast star formation: $SFR \sim 100\ M_\odot\ yr^{-1}$

The processes are intensified compared to z=0
→ best for studying galaxy formation

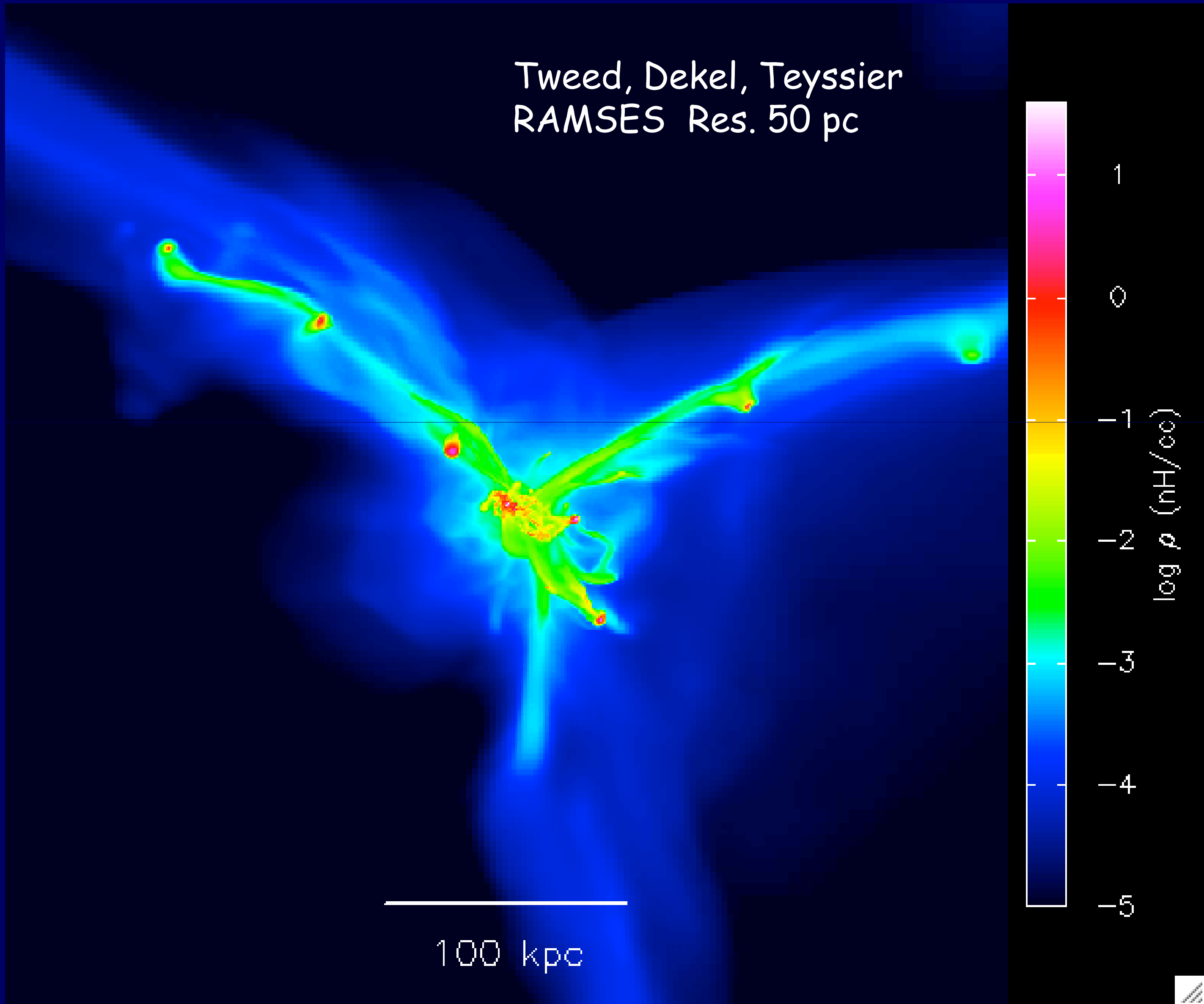
Galaxies form in the Cosmic Web



Gas streams along the cosmic web

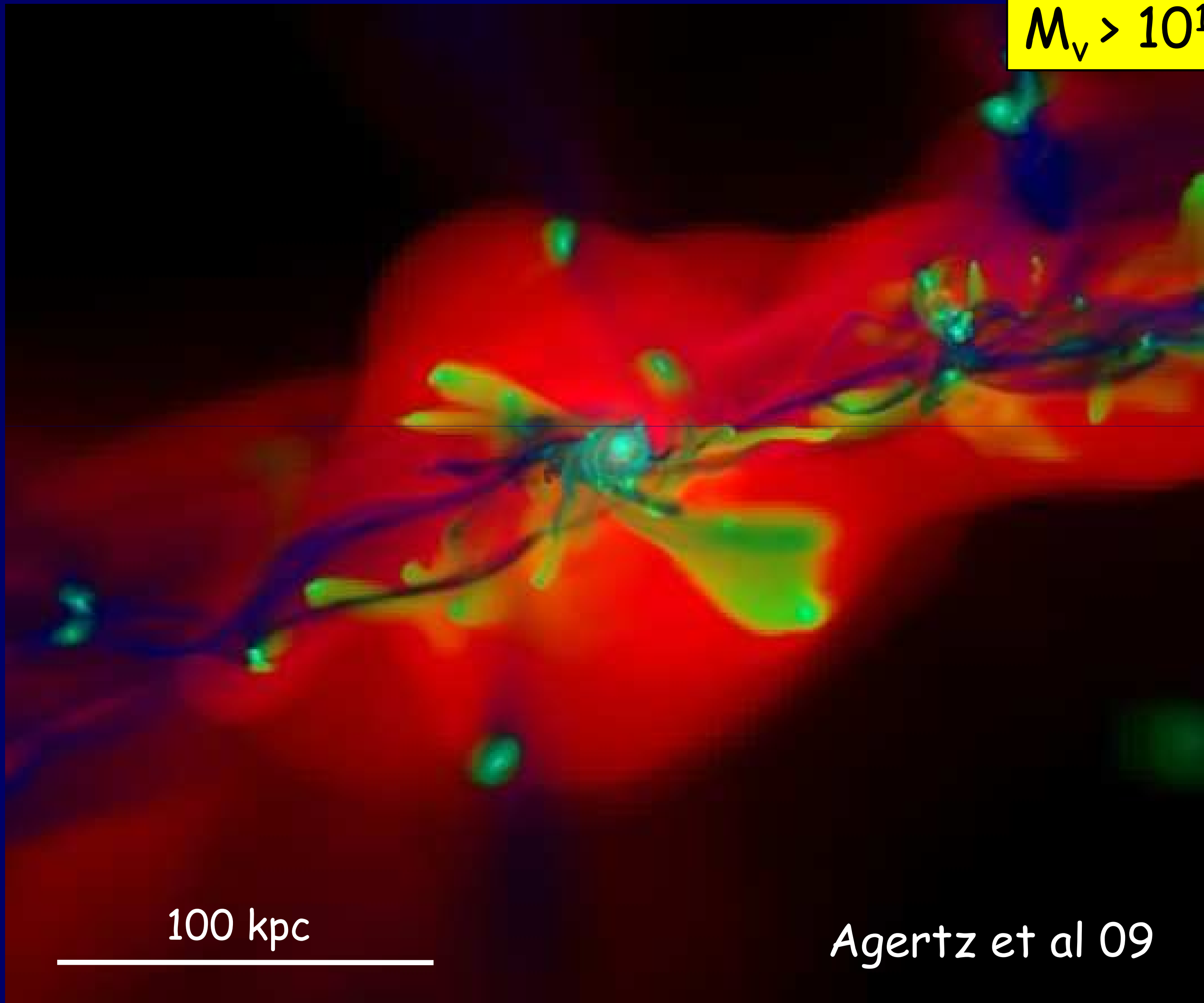


Streams Feeding a Hi-z Galaxy

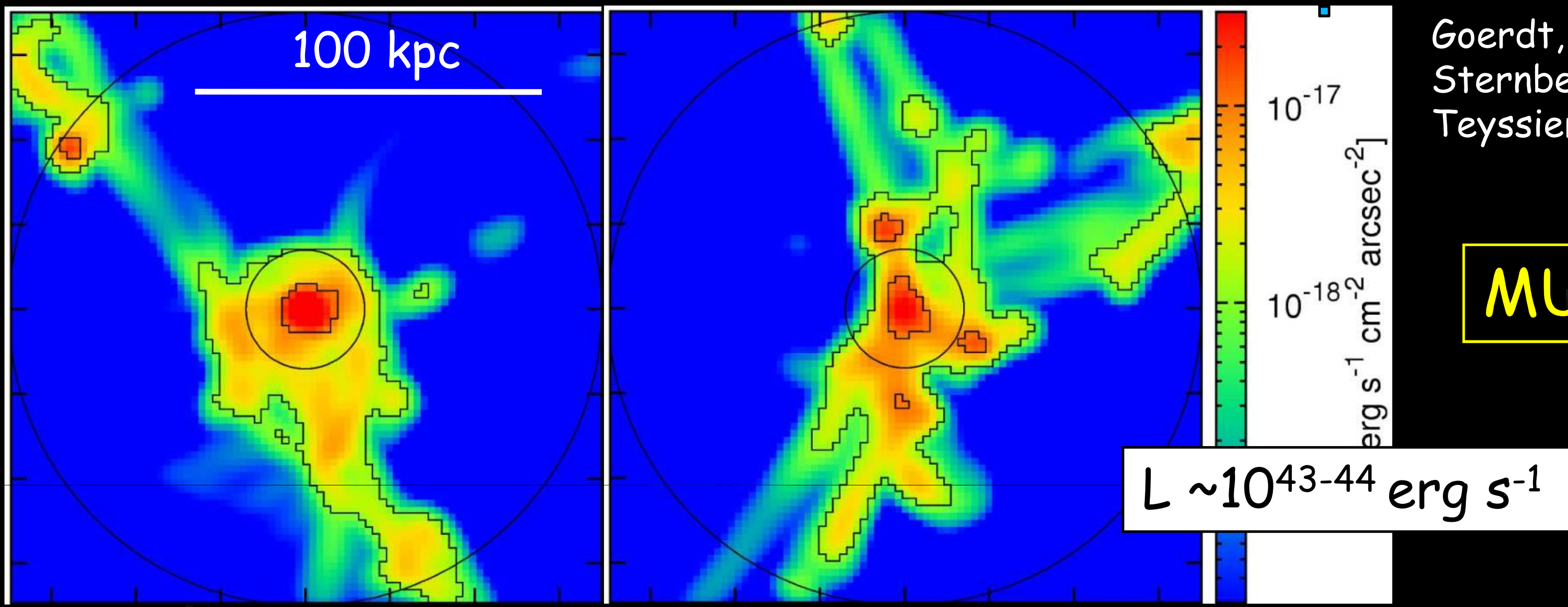


Cold Streams Penetrate through Hot Halos

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



Cold streams Observable: Lyman-alpha Blobs

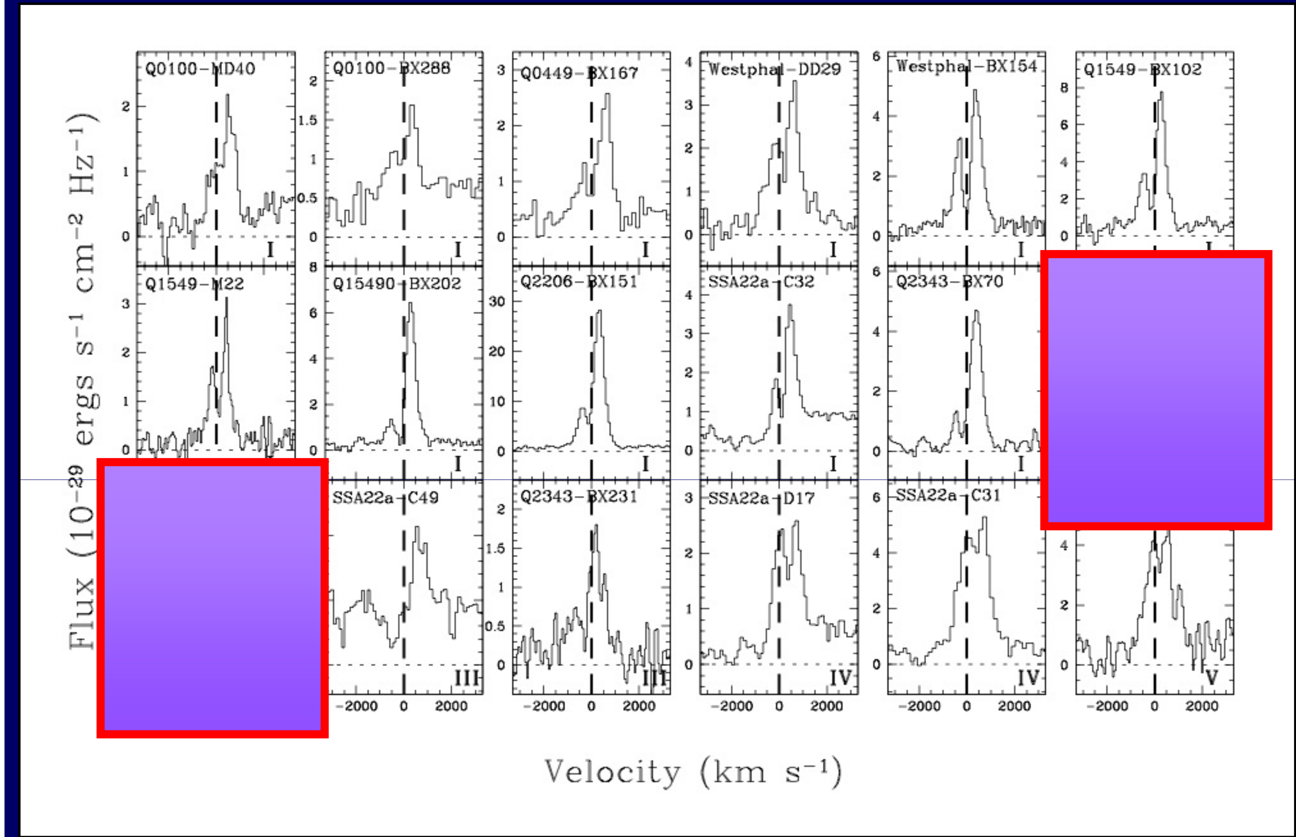


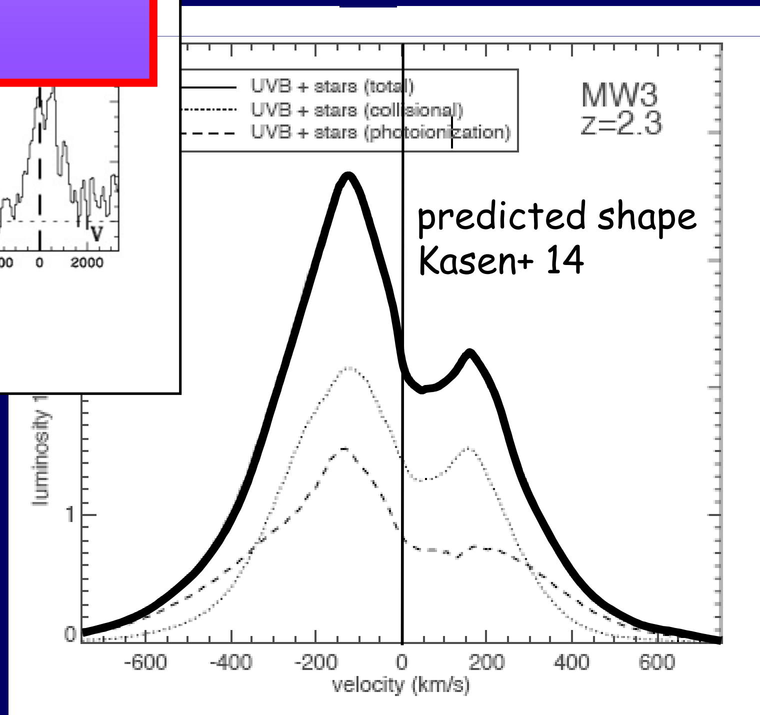
Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 10

MUSE?

Matsuda et al 06-09

Detection of Inflow in Lya Emission





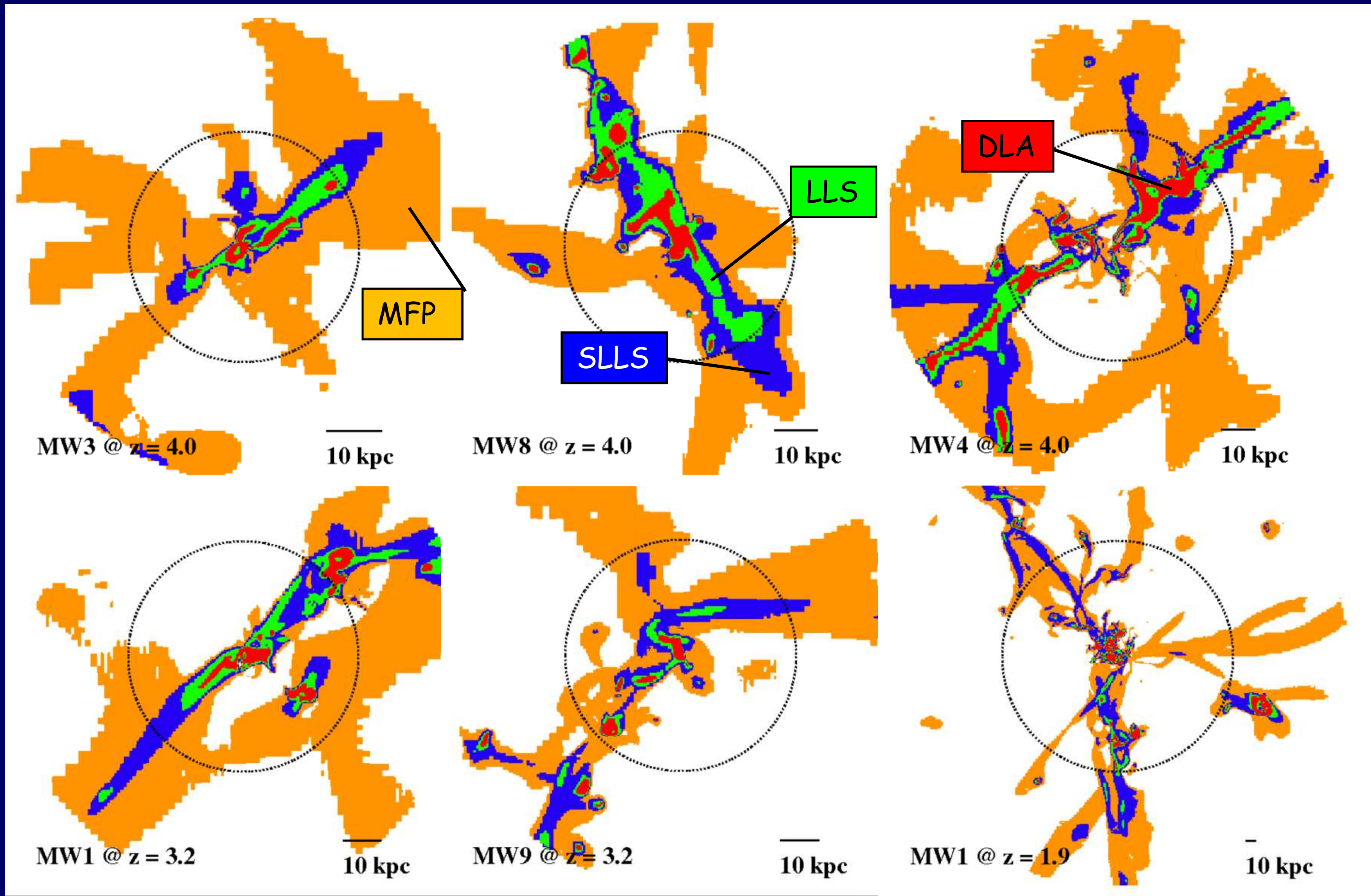
predicted shape
Kasen+ 14

Kulas, Shapley+ 2012: Systemic z from Hα

Most are red-shifted -> outflows
Some are blue-shifted -> inflow

Cold Streams & Pancakes in Ly-a Absorption

Fumagalli, Prochaska, Kasen, Dekel, Ceverino, Primack 11



High-z massive galaxies are fed by intense thin streams of smooth gas and frequent mergers (minor, major)

New challenges for galaxy formation

1. Galaxy angular momentum from the cosmic web

2. Violent disk instability: nonlinear, stimulated

3. Quenching by compaction + hot halo

AMR Cosmological Simulations

Cosmological box, RAMSES (Teyssier), resolution 1 kpc

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

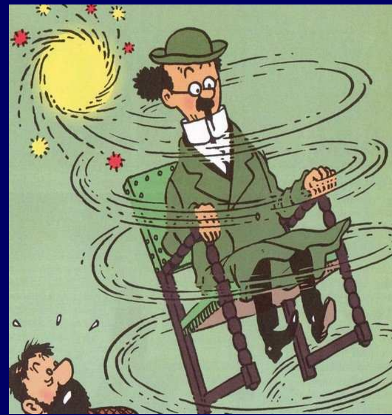
Ceverino, Dekel, Primack:
- 50 pc res. (30 galaxies)
- 25 pc res., lower SFR, w/o rad. fdbk (2x30 galaxies)
- same with stronger RP feedback

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

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

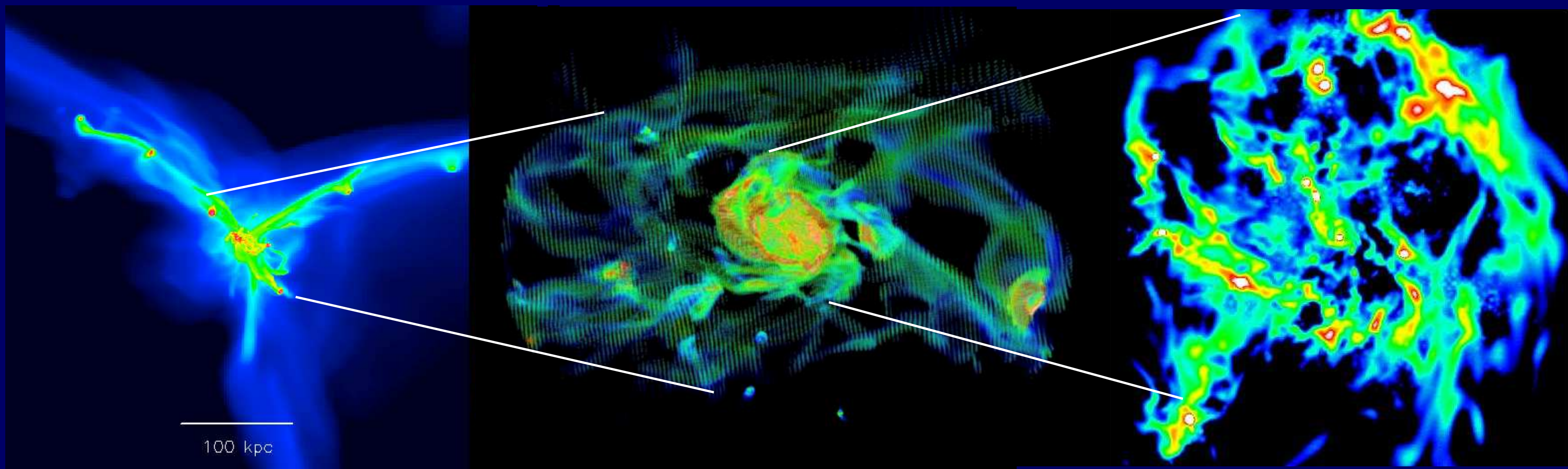
HUJI: Ceverino, Mandelker, Danovich, Tweed, Zolotov, DeGraf, Inoue
Groups of Krumholz+, Burkert+, Bournaud+, Teyssier+, Primack+

Angular Momentum Buildup in High-z Galaxies



Prof. tournesol

Pichon, Pogosyan, Devriendt, Dubois, Colombi+ 2011-2014
Stewart, Bullock+ 2011, 2013
Danovich, Dekel, Hahn, Teyssier, Ceverino, Primack 12, 14

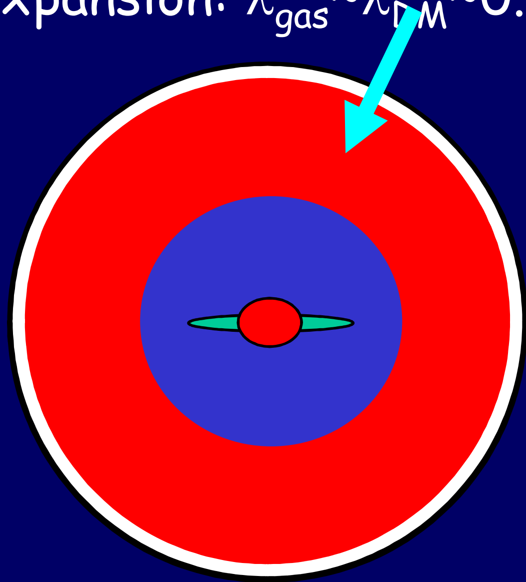


Standard Picture: Spherical Collapse

Rees & Ostriker 77, Silk 77, White & Rees 78, Fall & Efstathiou 80 …

Proto-halo expansion, turnaround,
collapse to a virialized DM halo

AM by tidal torques (TTT) prior to maximum expansion: $\lambda_{gas} \sim \lambda_{DM} \sim 0.04$



Spherical gas infall into the halo with the DM
Virial shock heating to $T_v \sim 10^6$K

$\lambda_{gas} \sim \lambda_{DM}$

Radiative cooling, cylindrical accretion to disk

AM is conserved

Halo AM determines disk size and structure

$$const. = J_{gas} / M_{gas} \sim \lambda R_{vir} V_{vir} \sim R_{disk} V_{disk} \quad \rightarrow \quad \frac{R_{disk}}{R_{vir}} \approx \lambda \approx 0.04$$

Bulge by mergers, disk AM is conserved

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

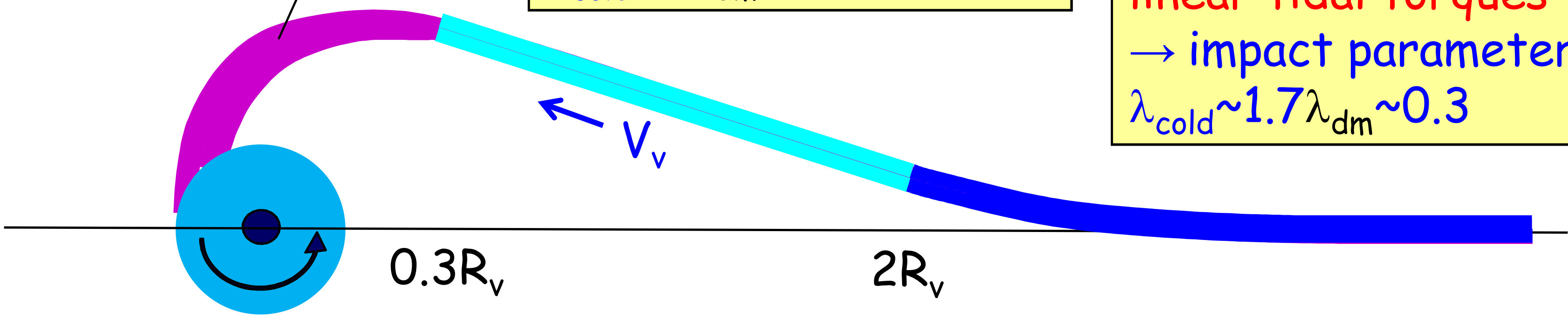
AM Buildup by Cold Streams in 4 Phases

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
$\lambda_{cold} \sim 1.7\lambda_{dm} \sim 0.3$

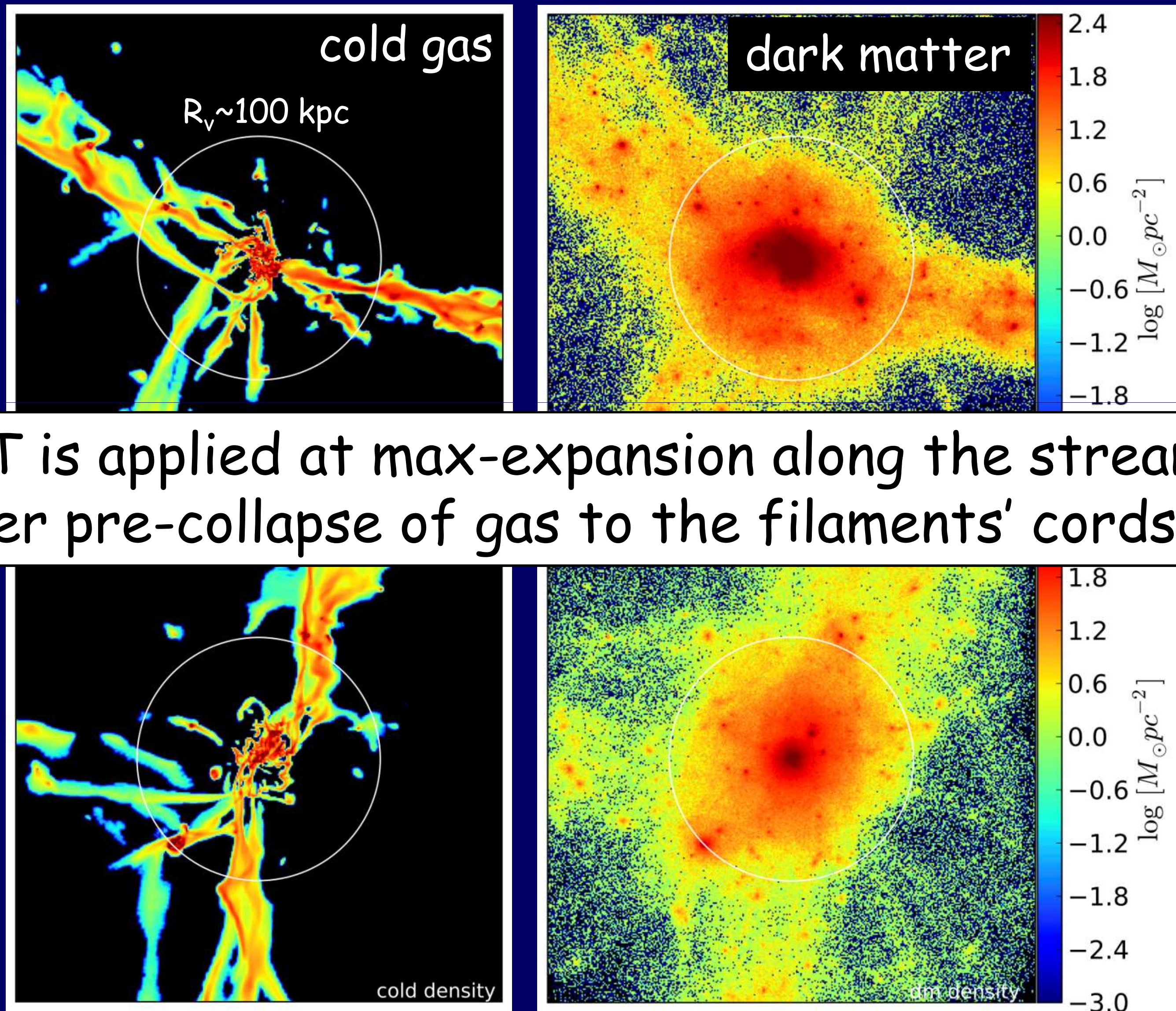


IV. inner disc (+ bulge)
disk instability, outflows
$\lambda_{baryons} \sim 0.03$

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

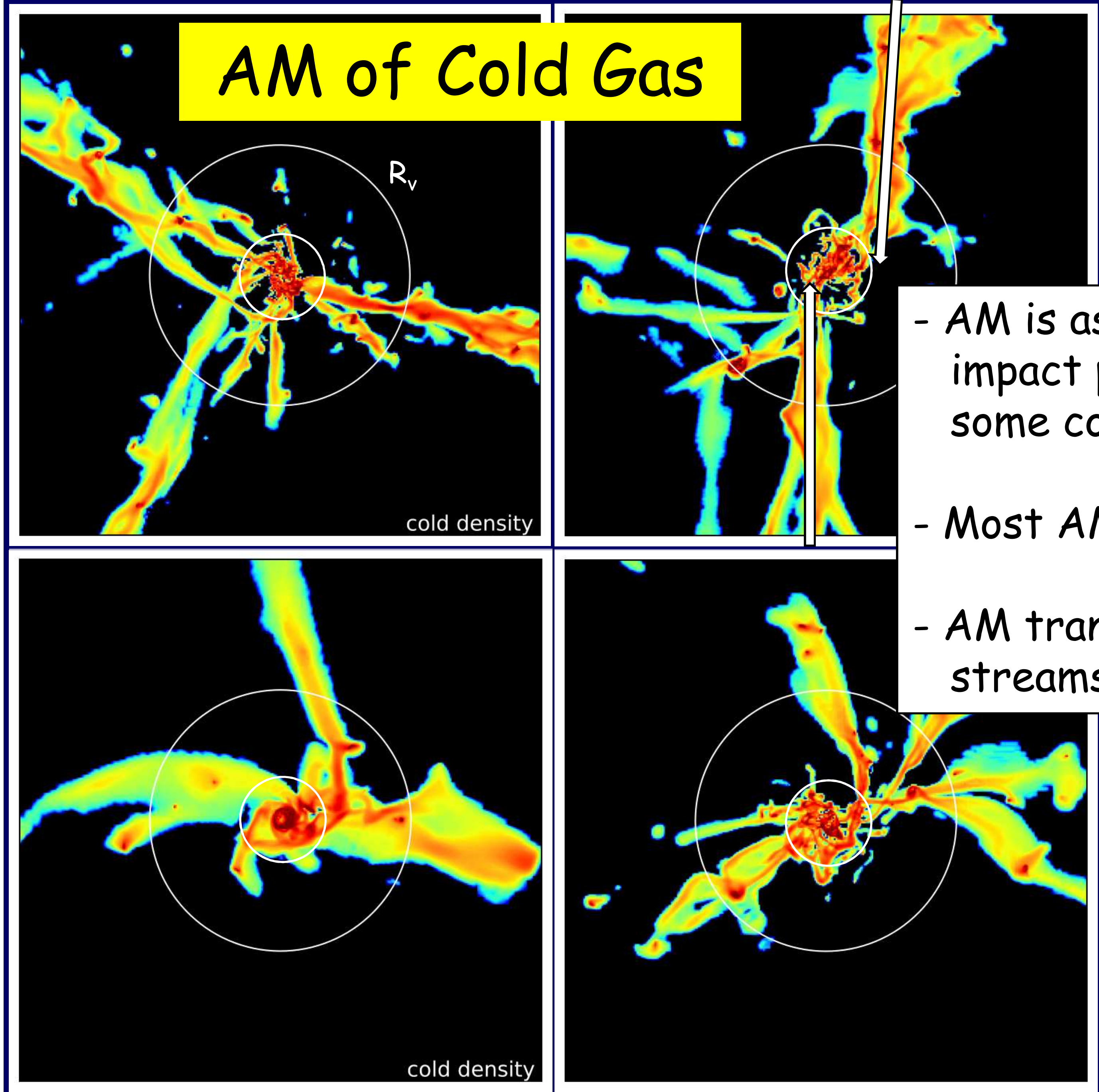
TTT outside the halo: λ_{cold}~1.7λ_{DM} due to quadrupole moment of inertia

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



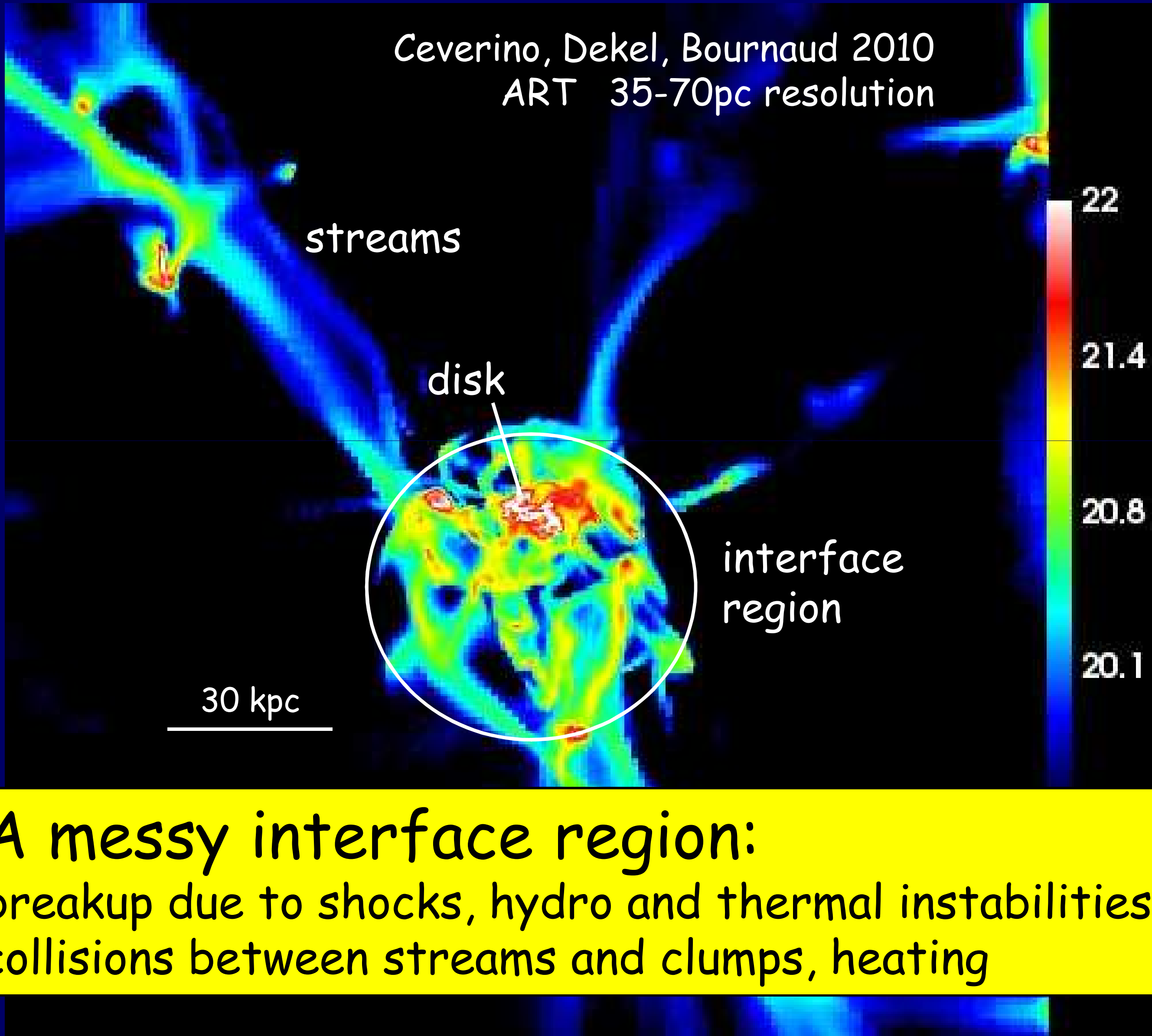
TTT is applied at max-expansion along the streams, after pre-collapse of gas to the filaments' cords

AM of Cold Gas



- AM is associated with impact parameters $<0.3R_v$ some counter-rotating
- Most AM in one stream
- AM transport by straight streams to inner halo

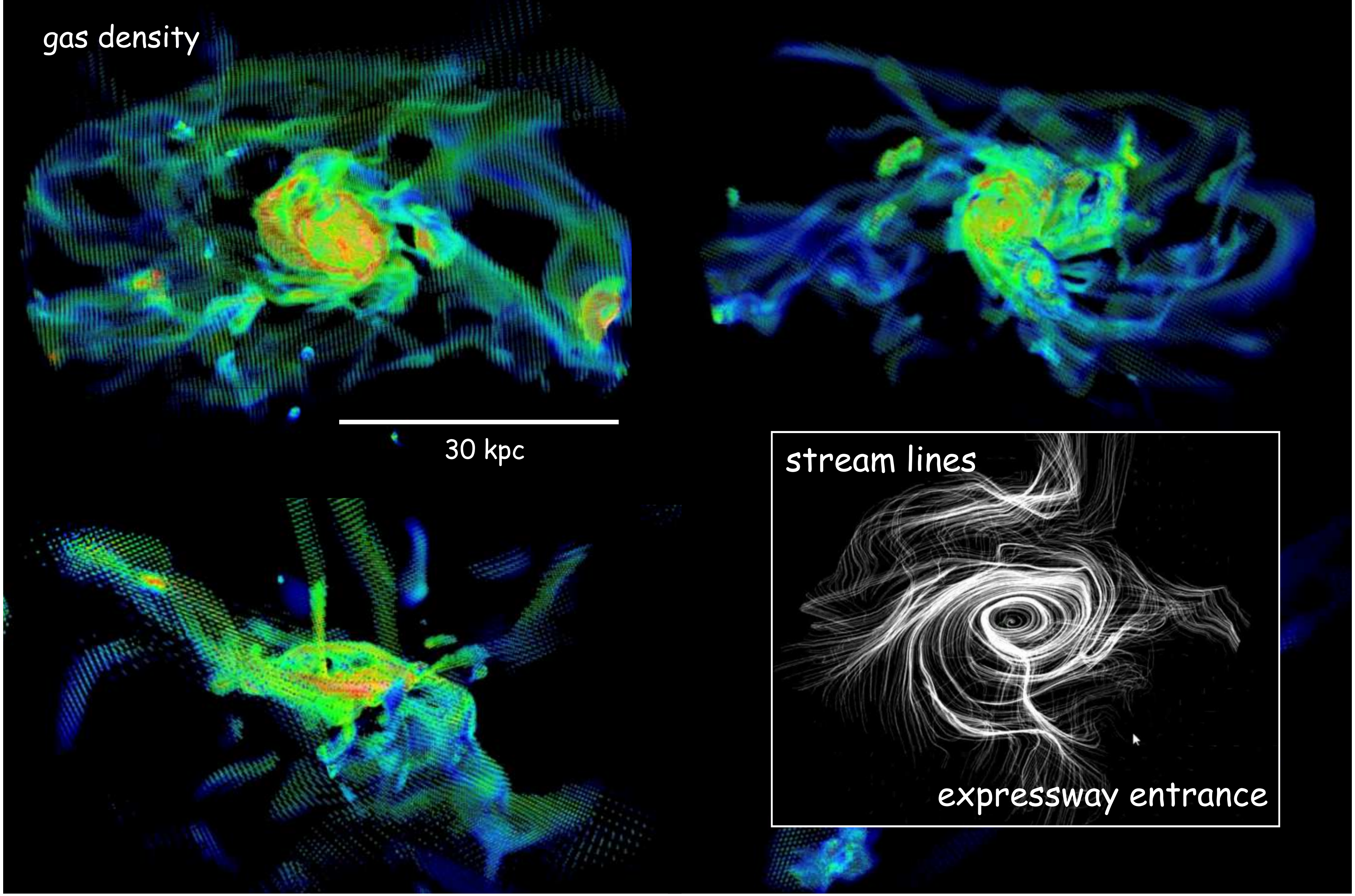
How do the streams join the disk?



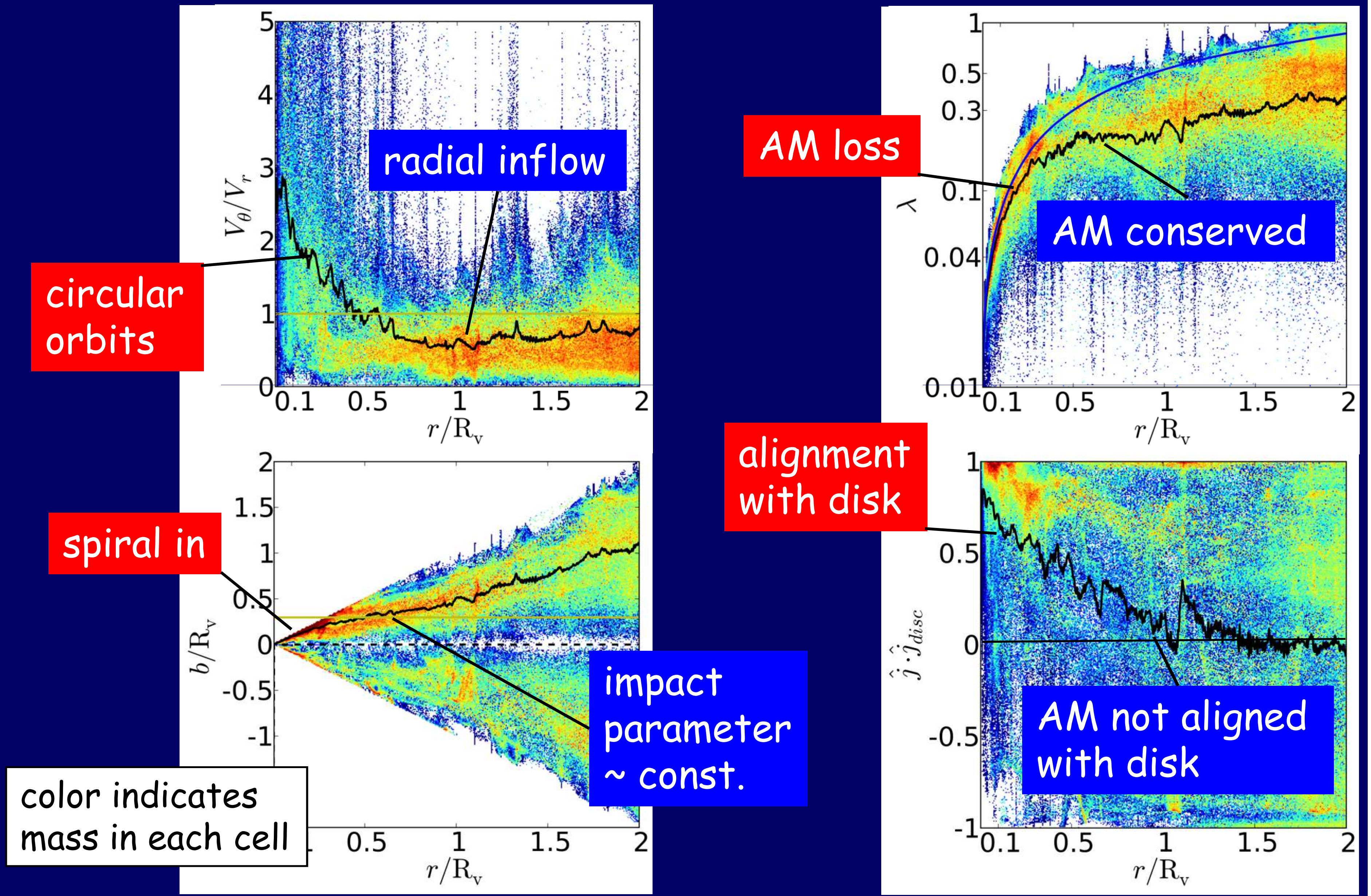
A messy interface region:

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

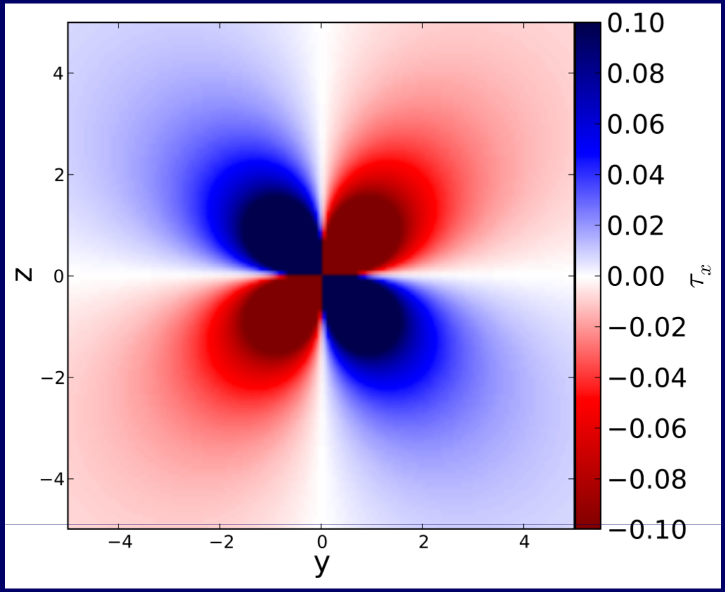
An Extended Tilted Ring about the Disk



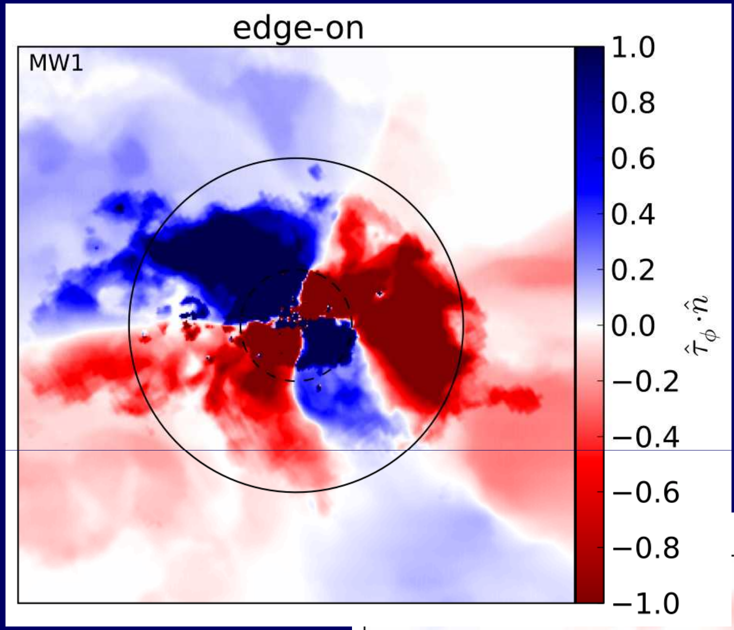
A tilted rotating ring in the inner halo

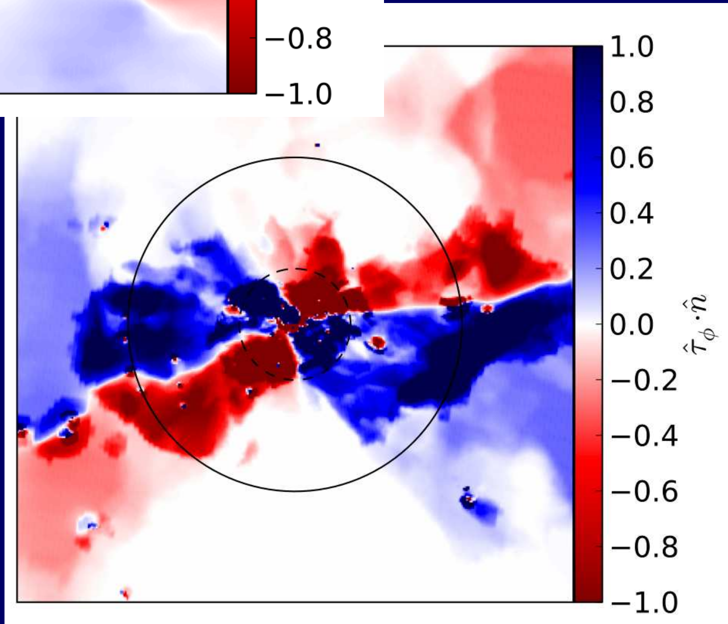


AM Exchange in the Ring: Torques by Disk



torques by an idealized disk

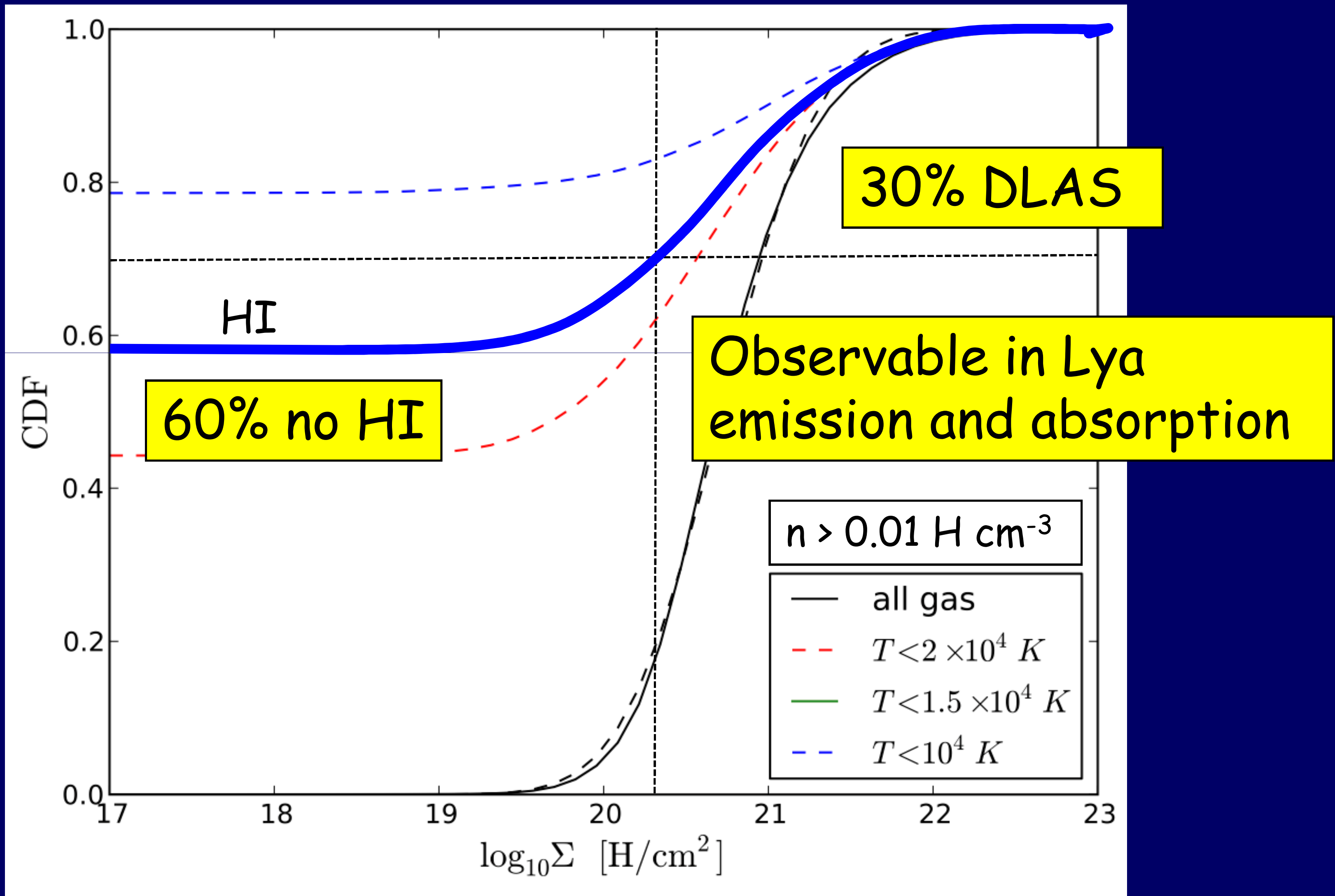




Torques in the simulated galaxies

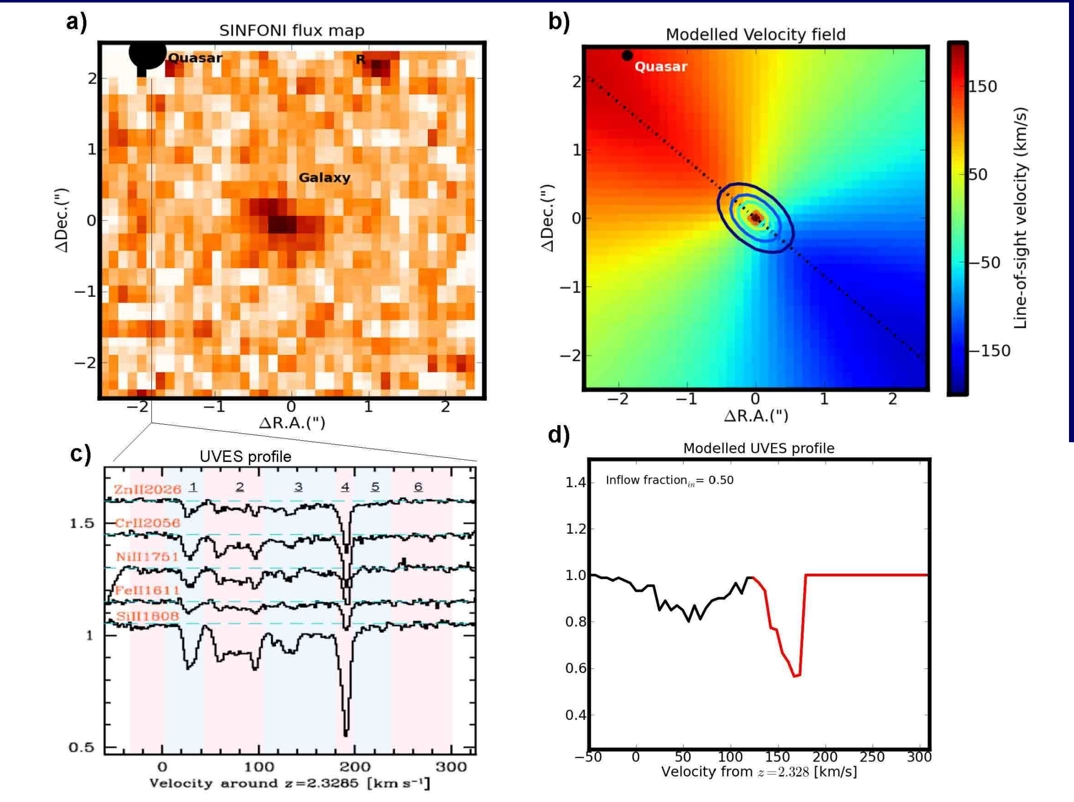
Extended Ring: HI Column Density

Random lines of sight through (0.1-0.3)R_v

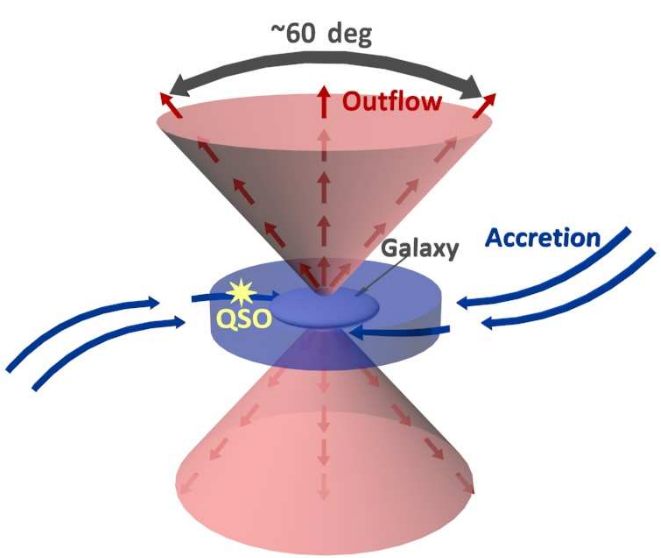


Detection of an Extended Ring?

Bouche+ 2013



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

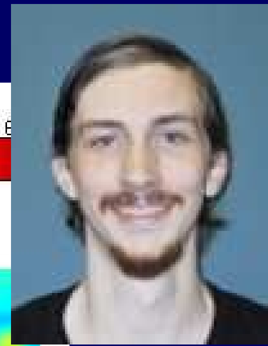


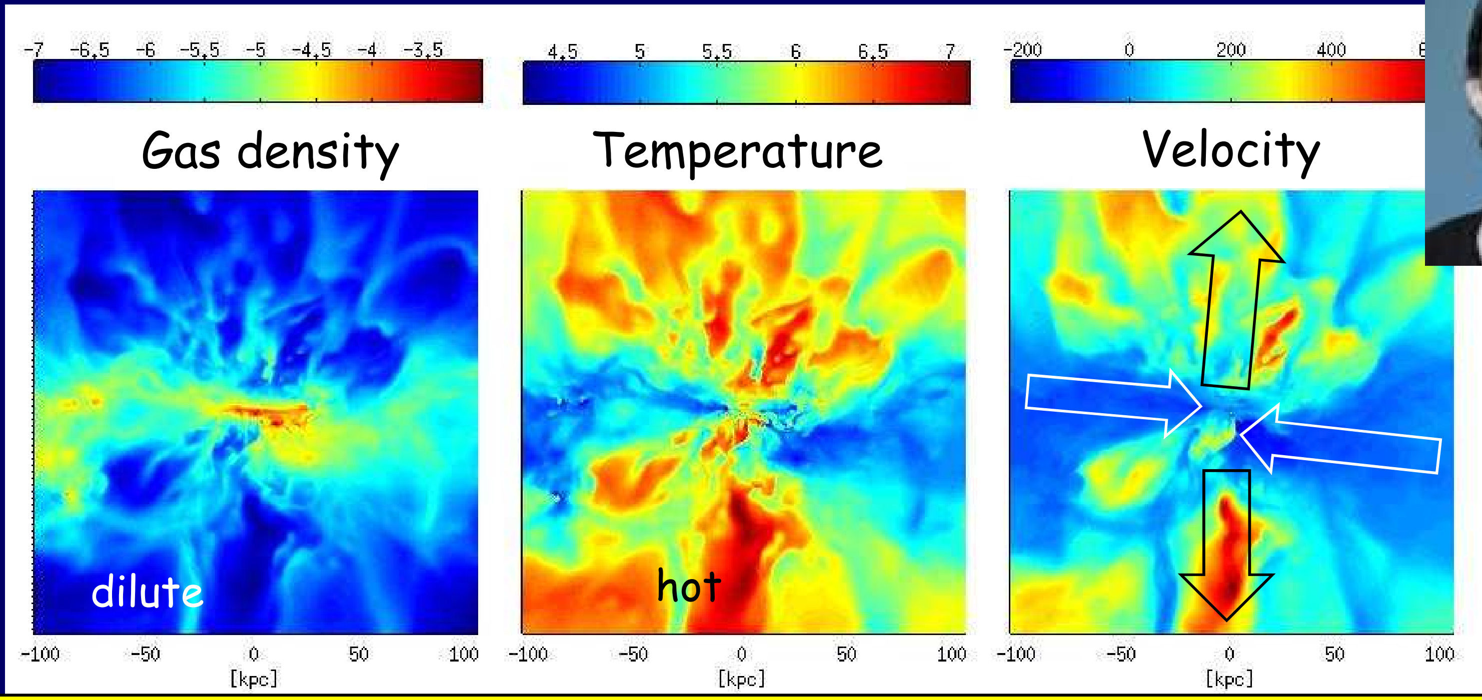
Crighton+ 2013 z=2.4, 54 kpc

Steidel+ 2002, Kacprzak+ 2010

Outflows do not halt the Inflows

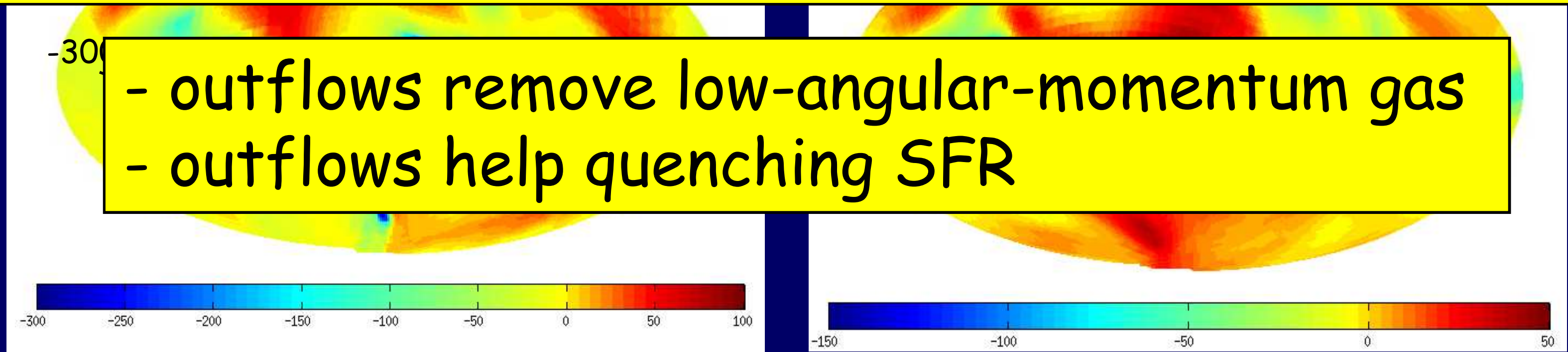
DeGraf+ 14





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: Angular-Momentum Buildup

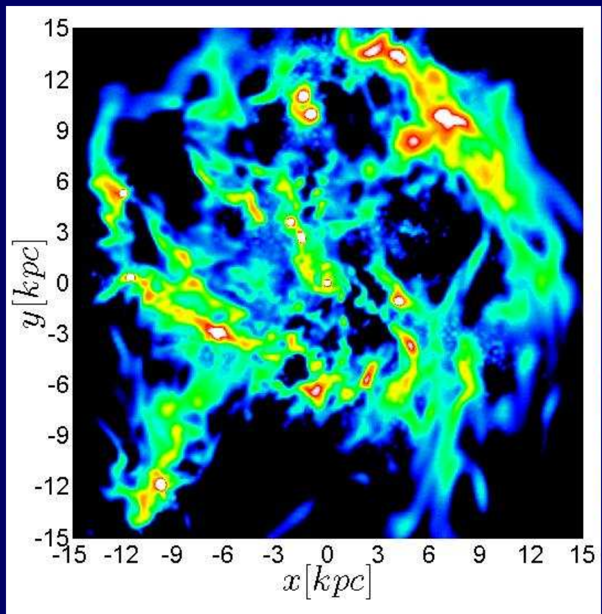
High-z massive galaxies form at cosmic-web nodes
Fed by ~3 co-planar streams penetrating hot CGM

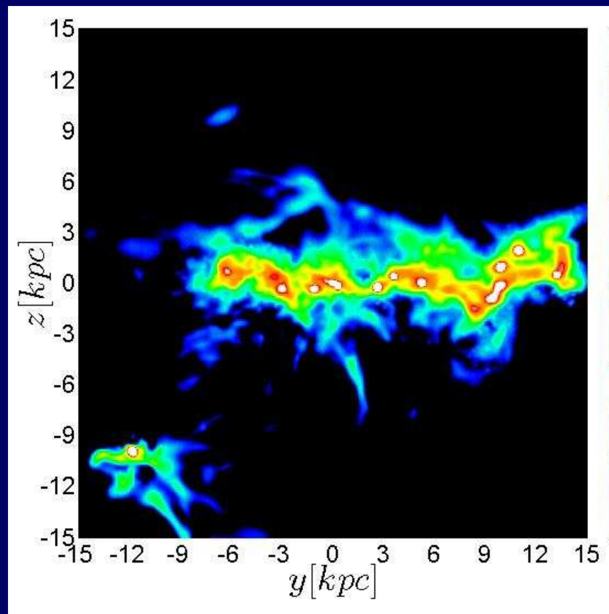
4 Phases of AM buildup:
- effective tidal torques on pre-collapsed gas streams,
- AM transport through outer halo to inner halo
- spiral-in through an extended tilted rotating ring (DLAS?)
- redistribution within the disk by VDI and feedback

disk spin ~ halo spin (within x2) despite different evolution
→ moderate changes to semi-analytic models

Violent Disk Instability: Nonlinear and Stimulated

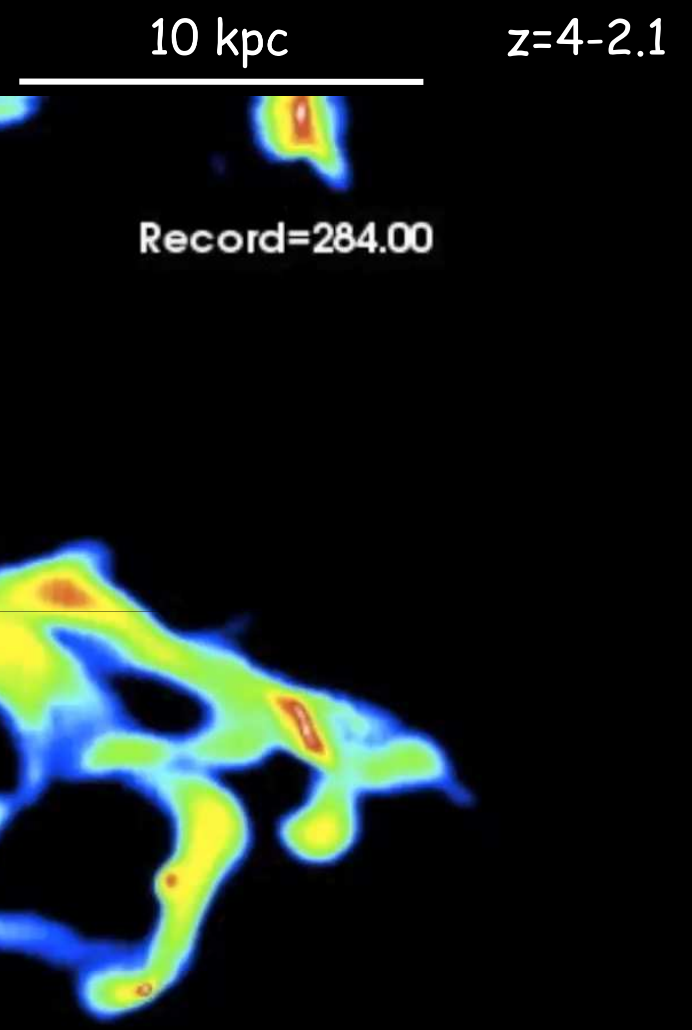
Dekel, Sari, Ceverino 2009; Ceverino+ 2010, 2012
Mandelker+ 2014; Moody+ 2014; Forbes+ 2014a,b
Dekel, Bournaud, Mandelker+ 2014;
Inoue+ 2014



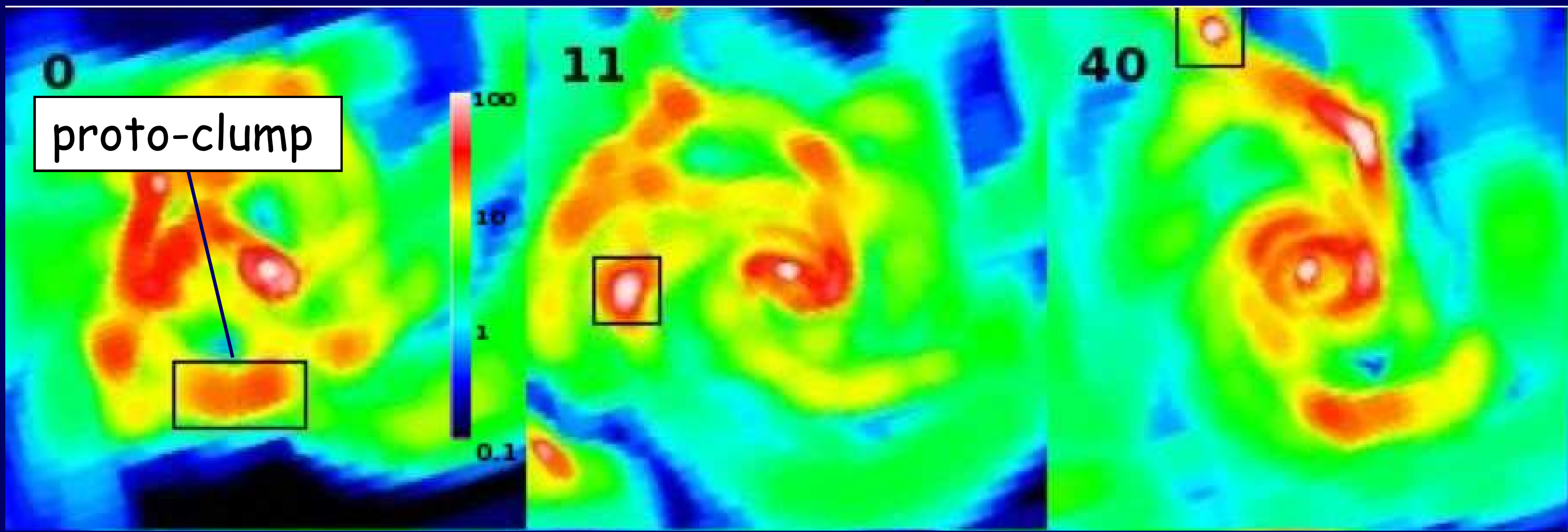


Clumpy Disk

Ceverino, Dekel et al.



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 Disk Instability (VDI) at High z

High gas density → disk unstable

Giant clumps and transient features
→ rapid evolution on dynamical time

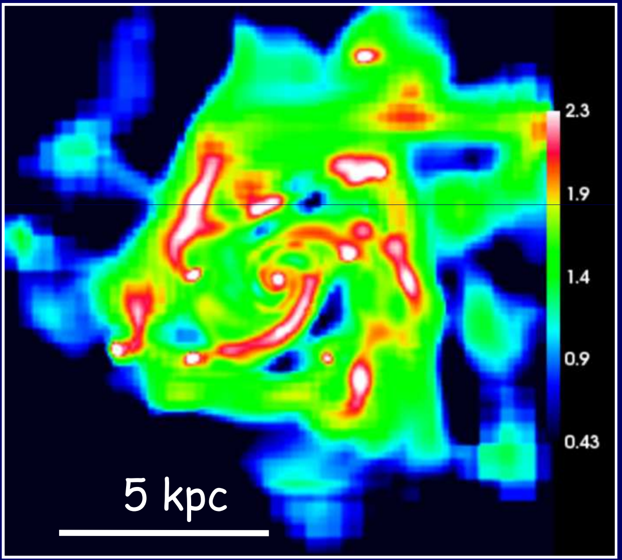
$$Q \propto \frac{\sigma \Omega}{G \Sigma} \leq 1$$

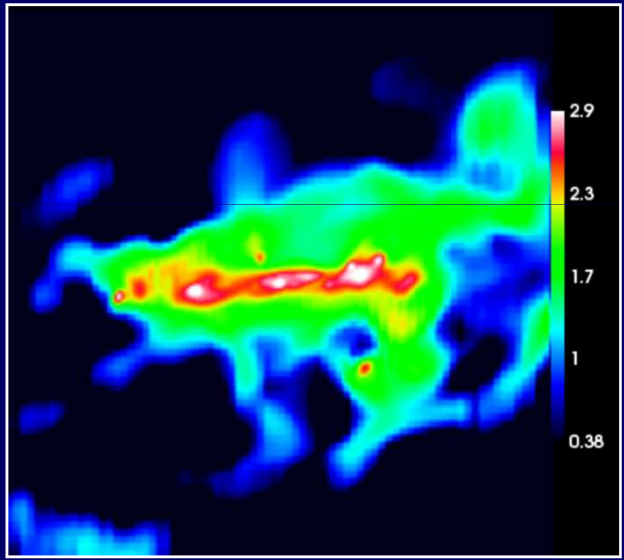
$$R_{\text{clump}} \propto \frac{G \Sigma}{\Omega^2}$$

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

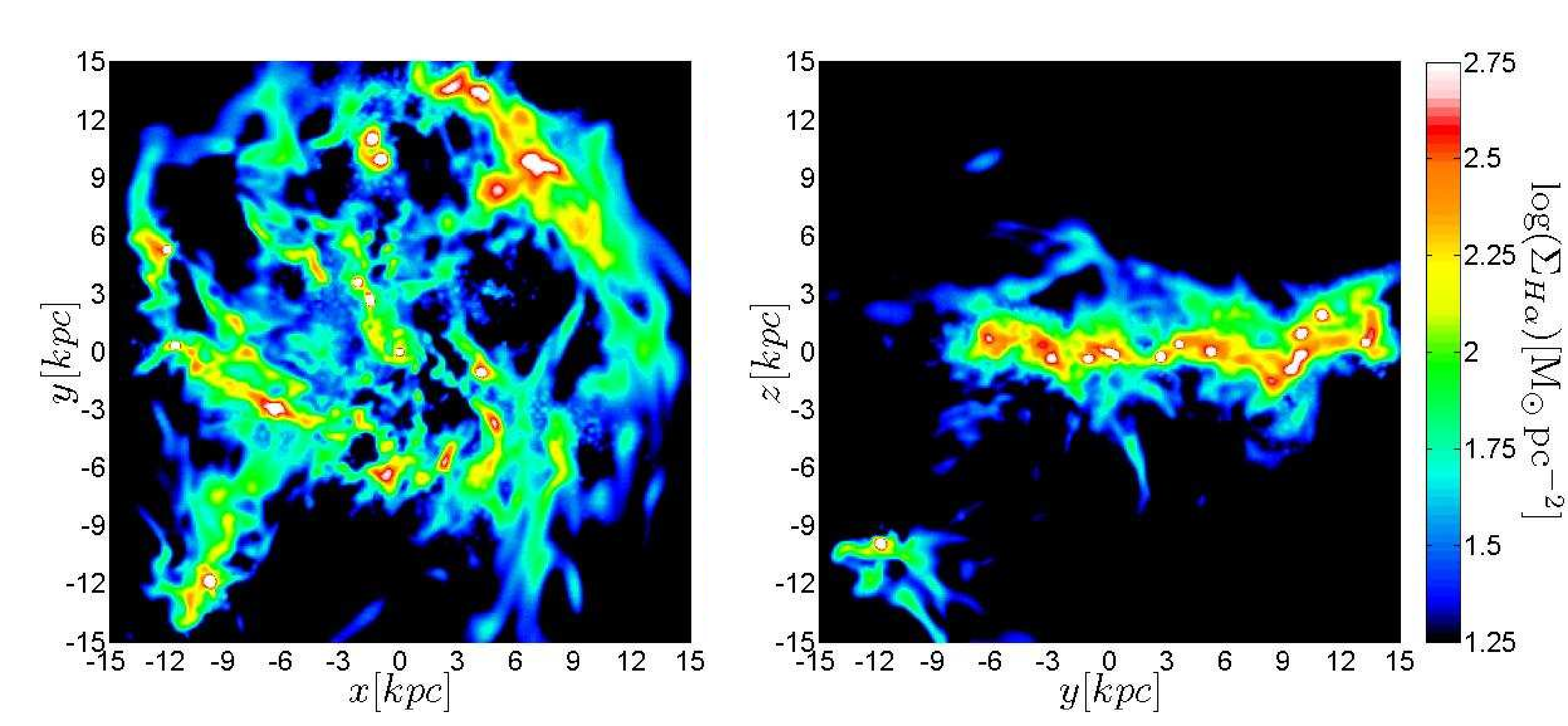
Inflow in disk → compact bulge and BH

Steady state: disk draining and replenishment, bulge ~ disk

Violent Disk Instability (VDI) at High z

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

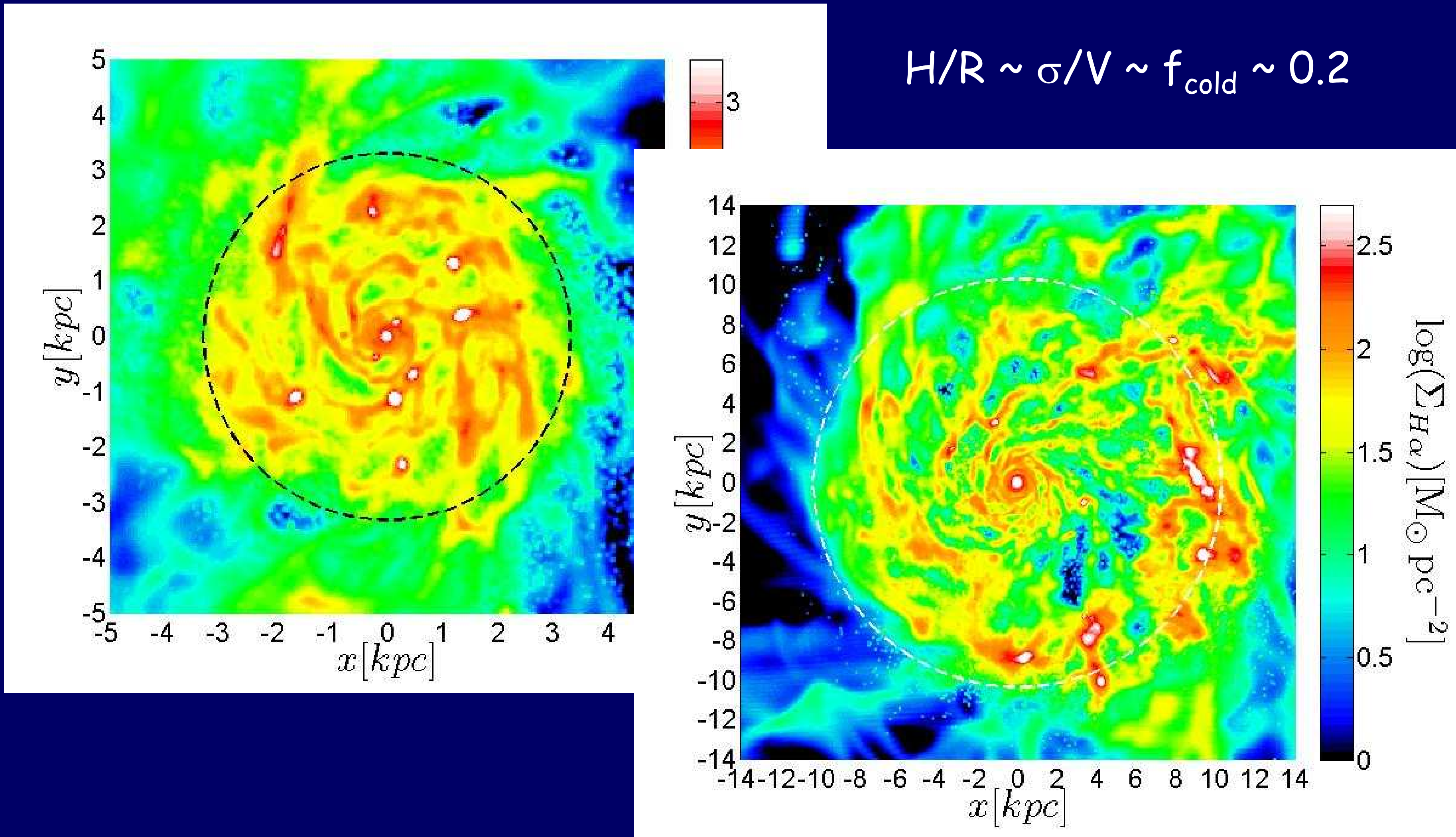
highly perturbed, clumpy rotating disk: H/R ~ σ/V ~ f_{cold} ~ 0.2



Violent Disk Instability (VDI) at High z

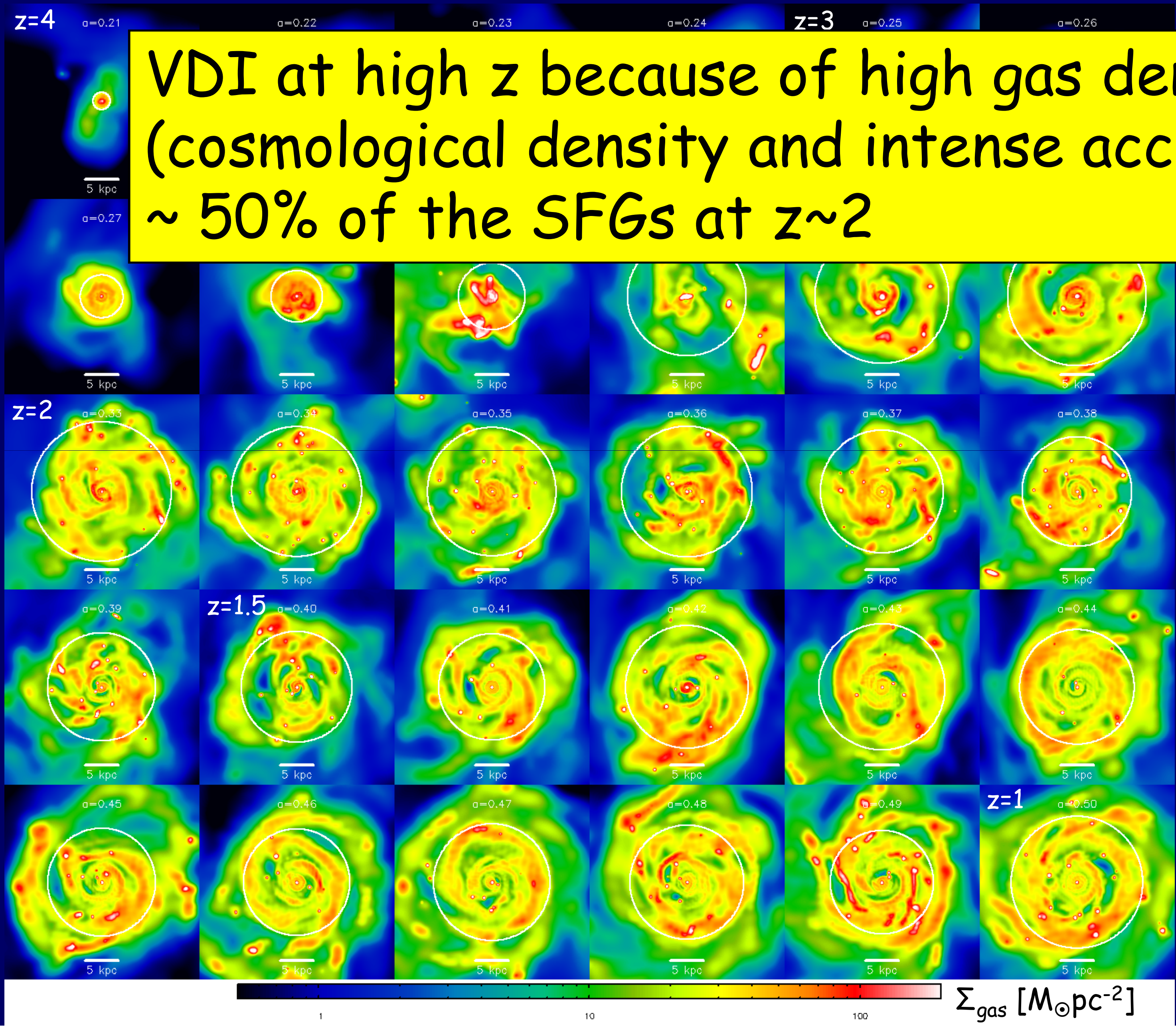
Ceverino+ ART-AMR cosmological simulations at 25pc resolution

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



Clumpy Disk in a cosmological steady state

VDI at high z because of high gas density
(cosmological density and intense accretion)
~ 50% of the SFGs at z~2

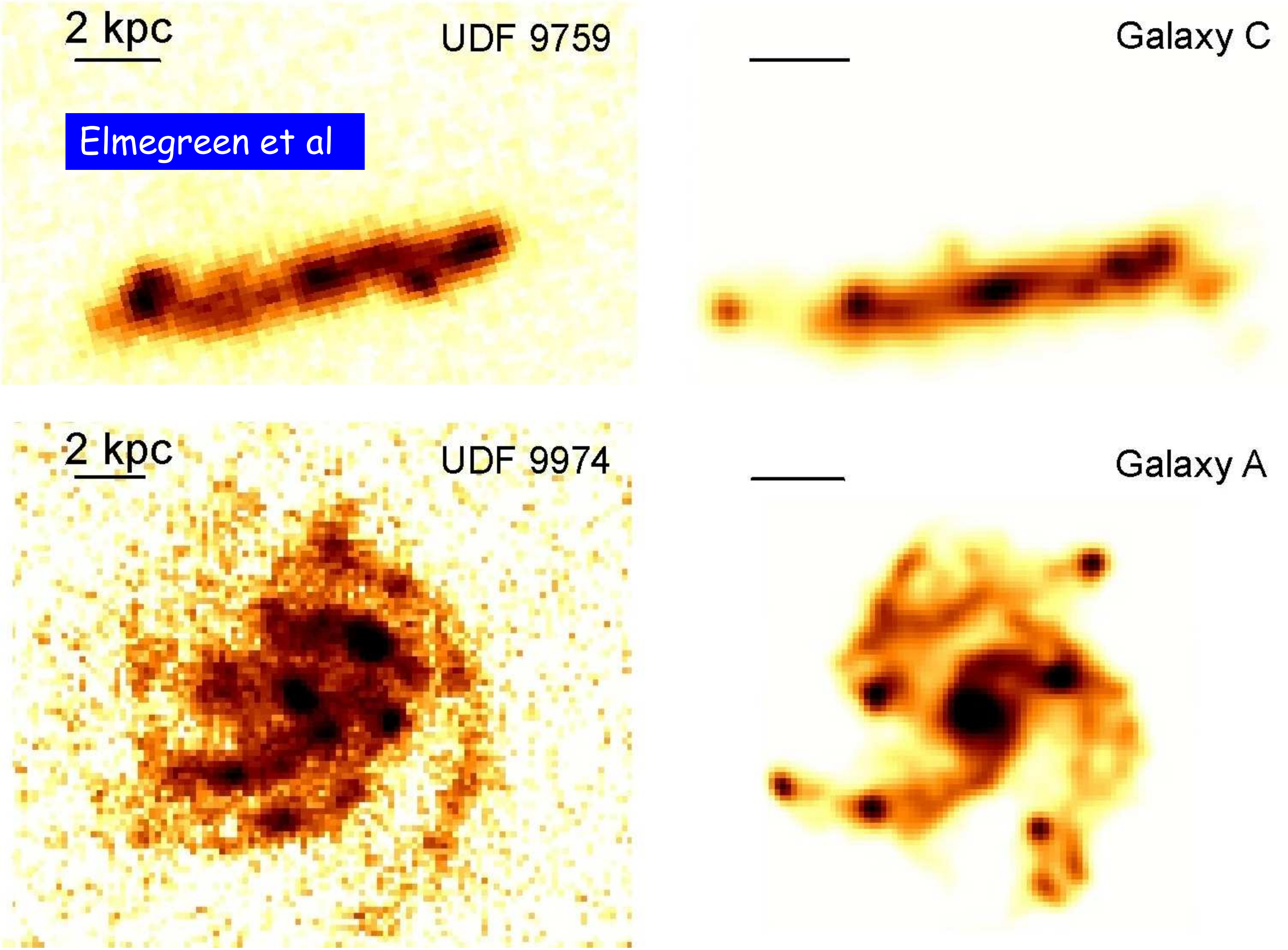


Dekel, Sari, Ceverino 09;

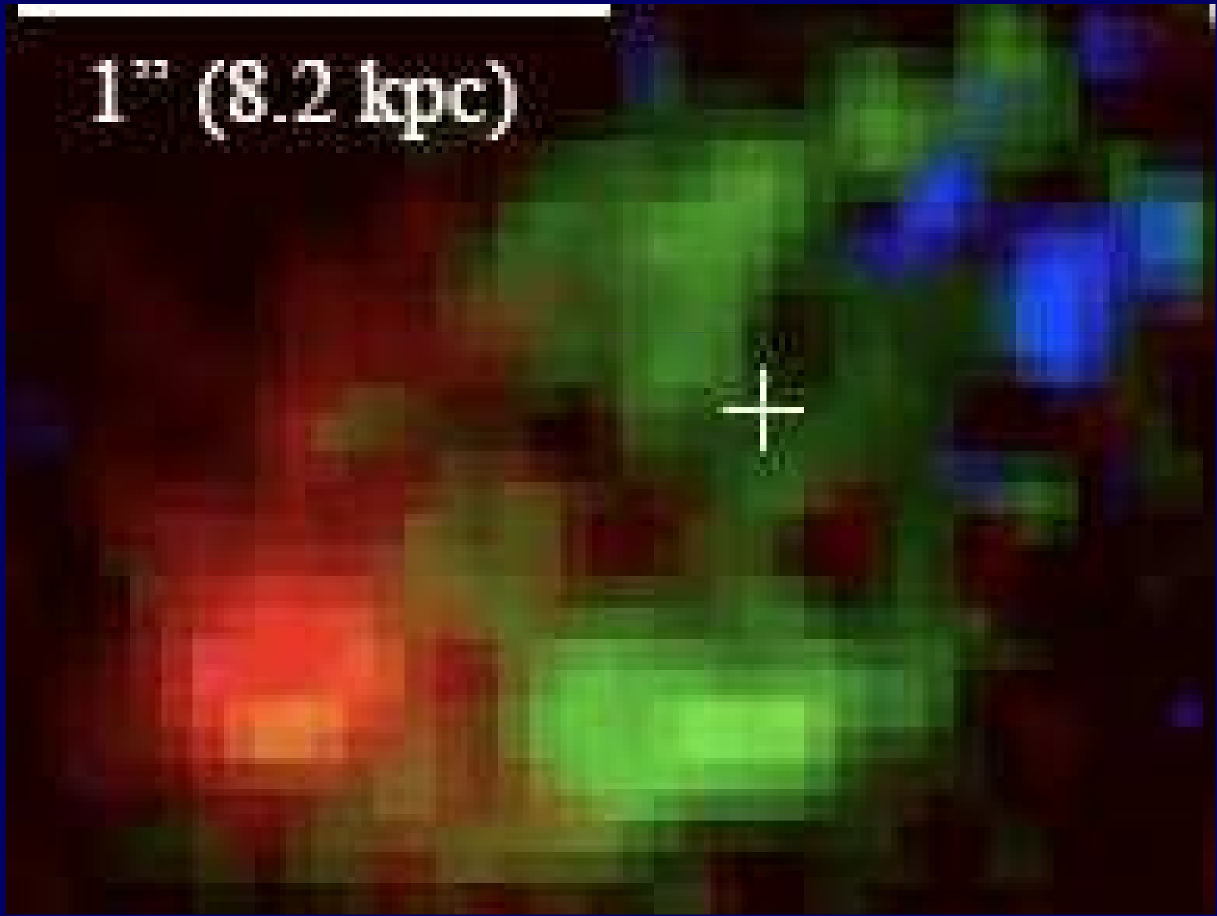
Ceverino, Dekel, Bournaud 10

Mandelker et al. 14

Observations vs. Simulations



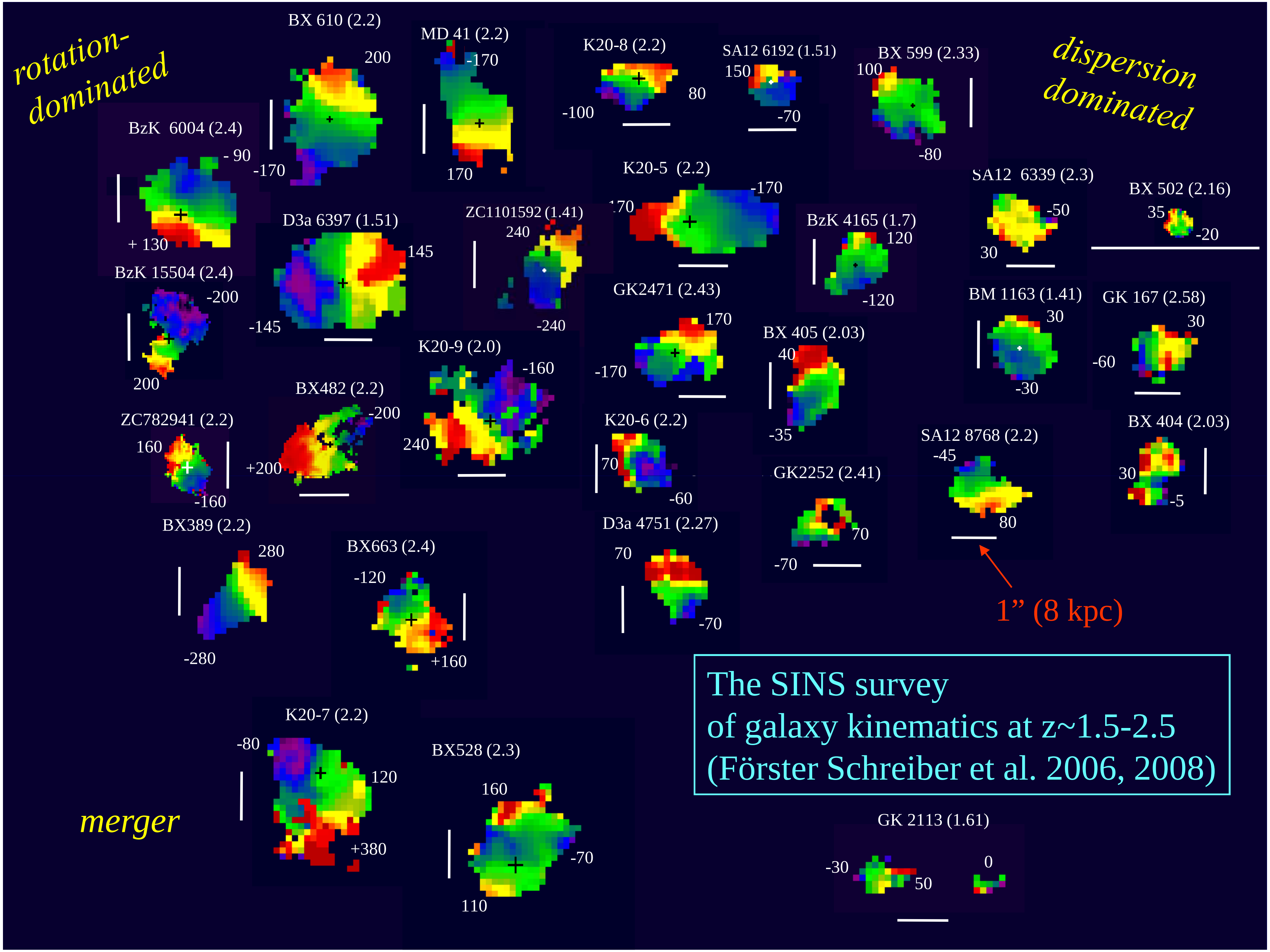
A typical star-forming galaxy at z=2:
clumpy, rotating, extended disk & a bulge



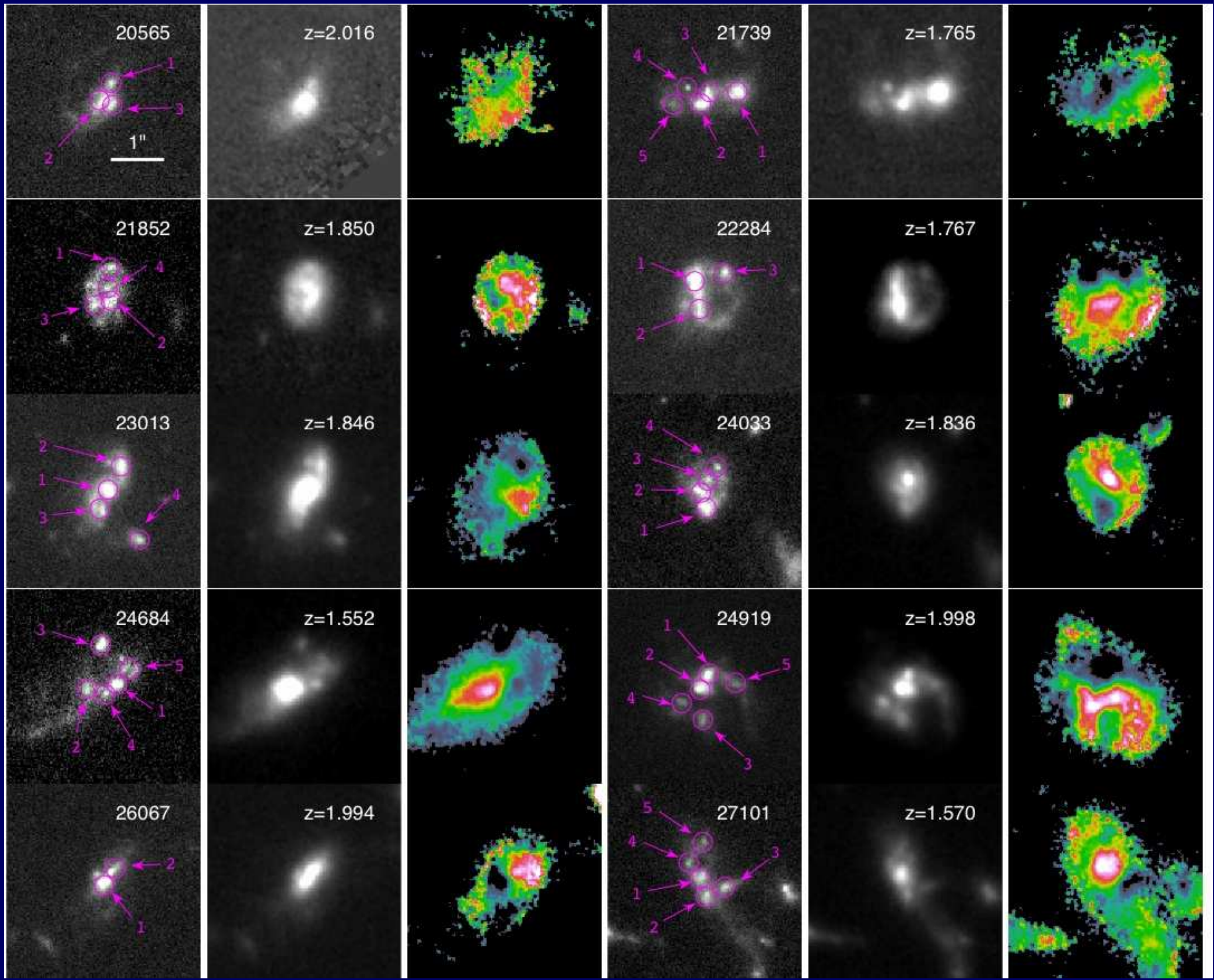
Hα star-forming regions

color-code velocity field

Genzel et al 08


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

High-z Disks with Giant Clumps



Guo et al. 12
CANDELS

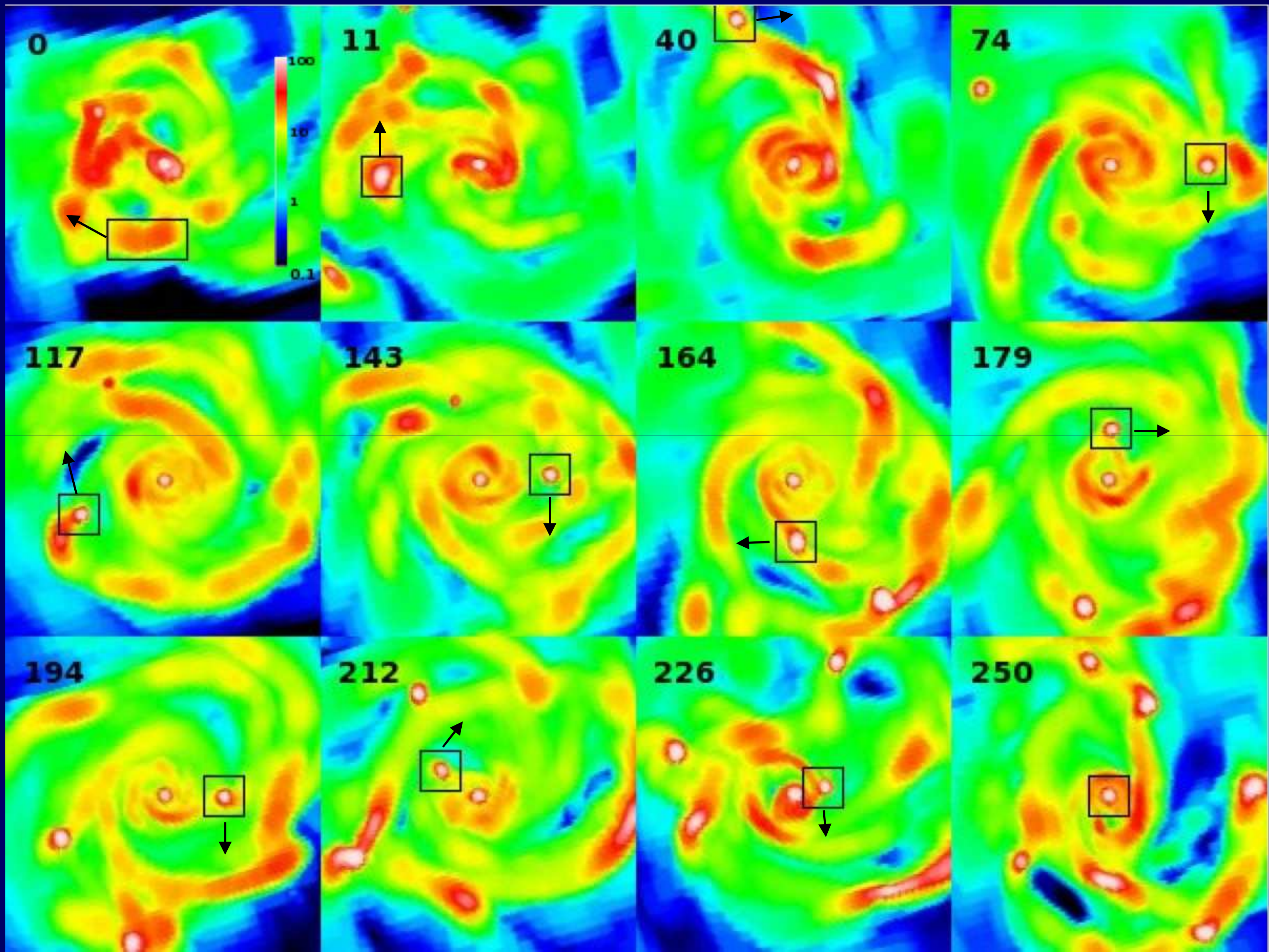
Clumps in VDI Disks

Mandelker+14
Bournaud+14
Dekel, Krumholz 14
Moody+14, Snyder+14

- 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 gradient of clump mass and age/color

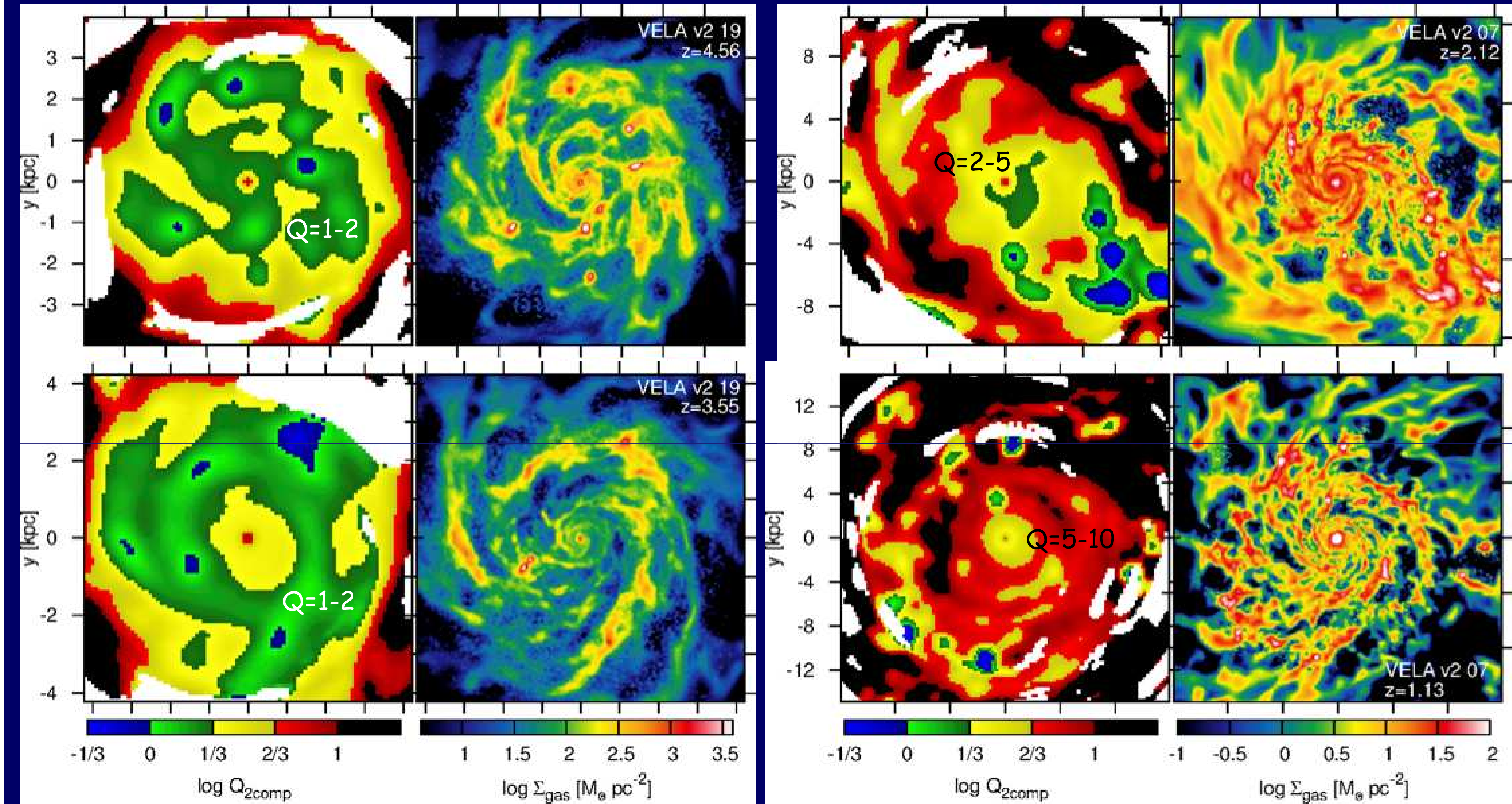
Clump Formation & Migration



Ceverino, Dekel, Bournaud 10

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

Stimulated Non-linear Instability

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

Tentative ideas for Q>1 instability:

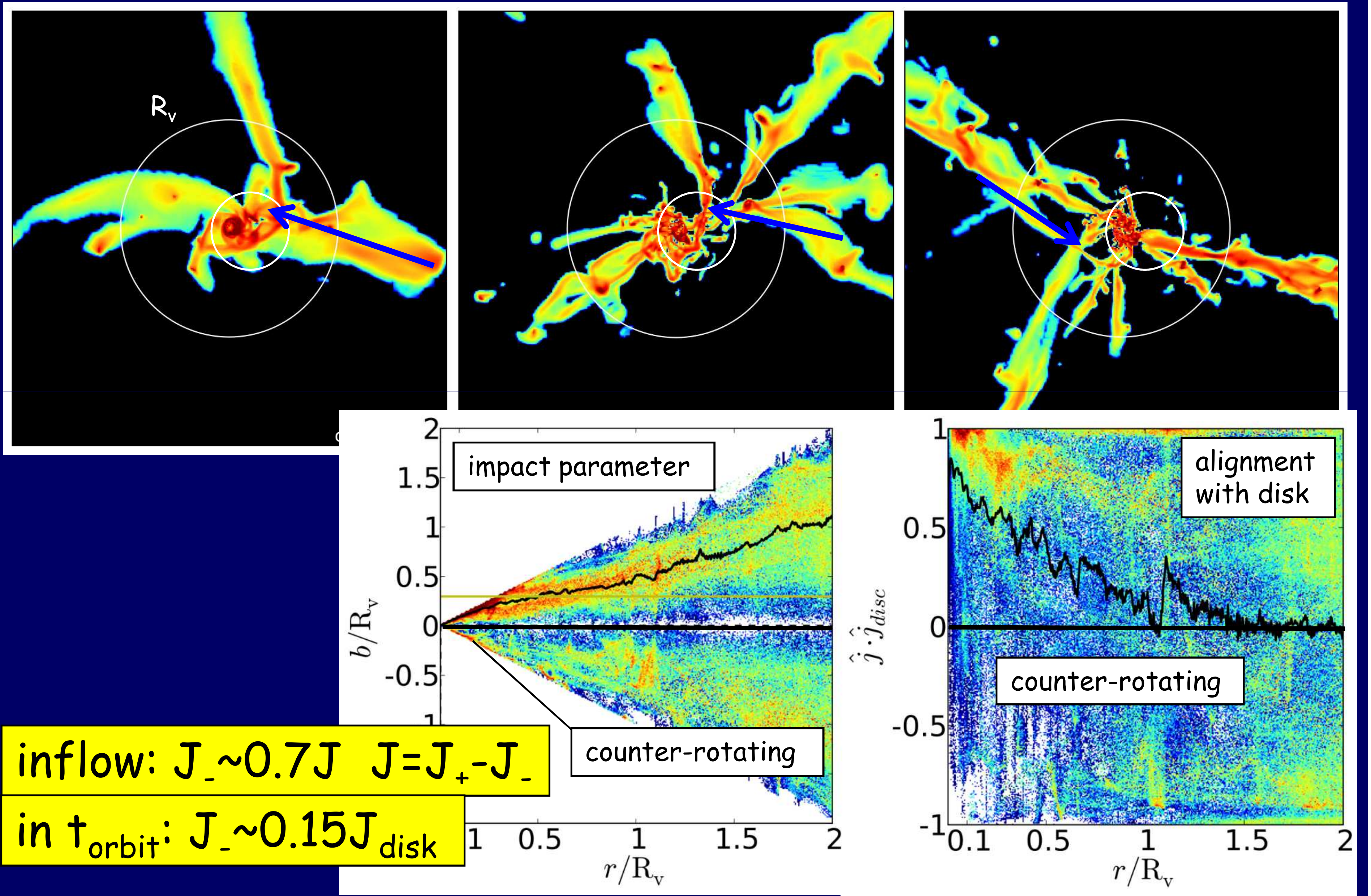
- Rapid decay of turbulence (Elmegreen)
  no time for pressure buildup against clump self-gravity

- Irregular rotation – counter-rotating streams (Lin)
  no centrifugal force against clump self-gravity

- Compression modes of turbulence (Bournaud, Renaud)
  by tidal compression? trigger local collapse

- Clumps generate new clumps

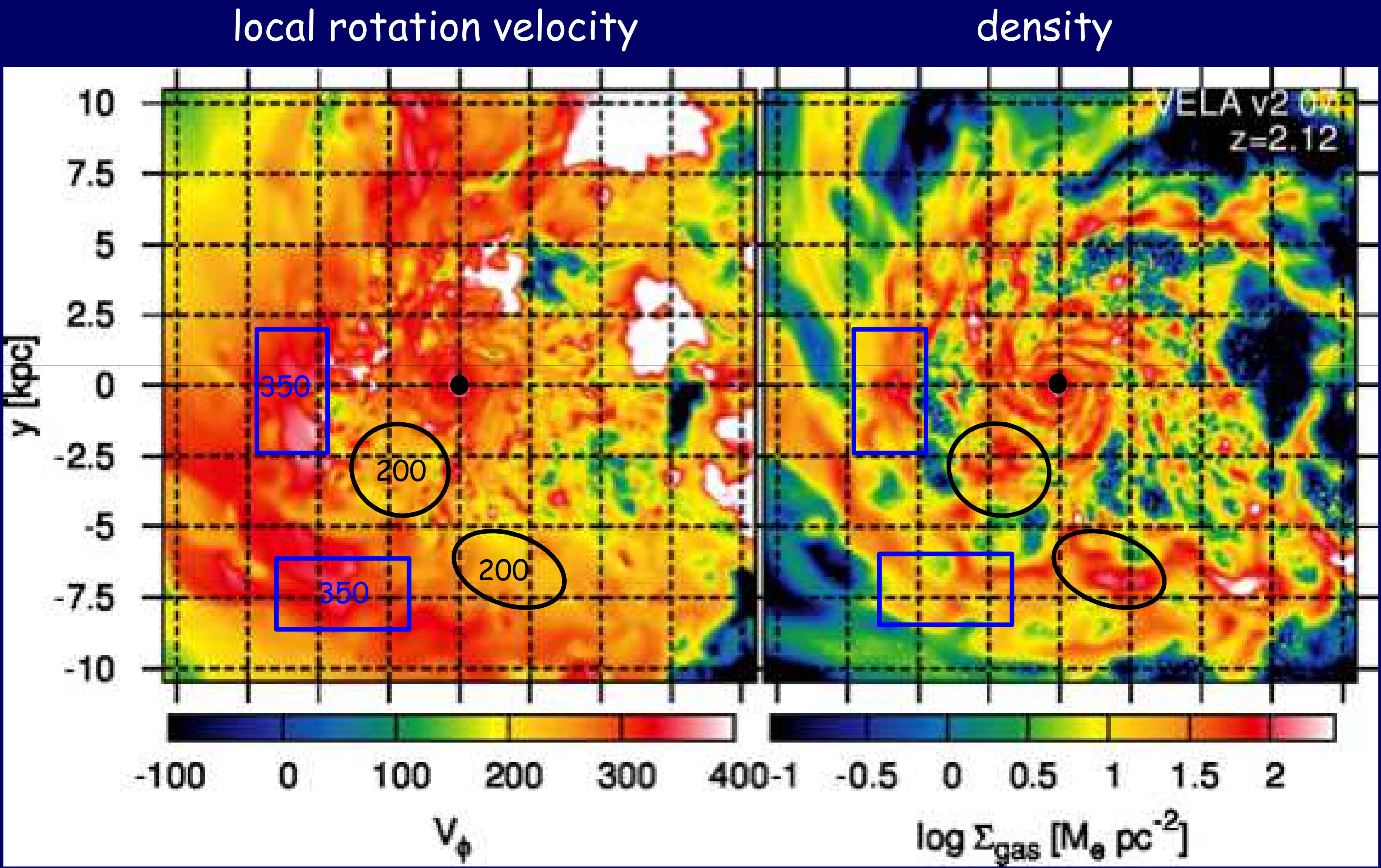
Counter-rotating Streams



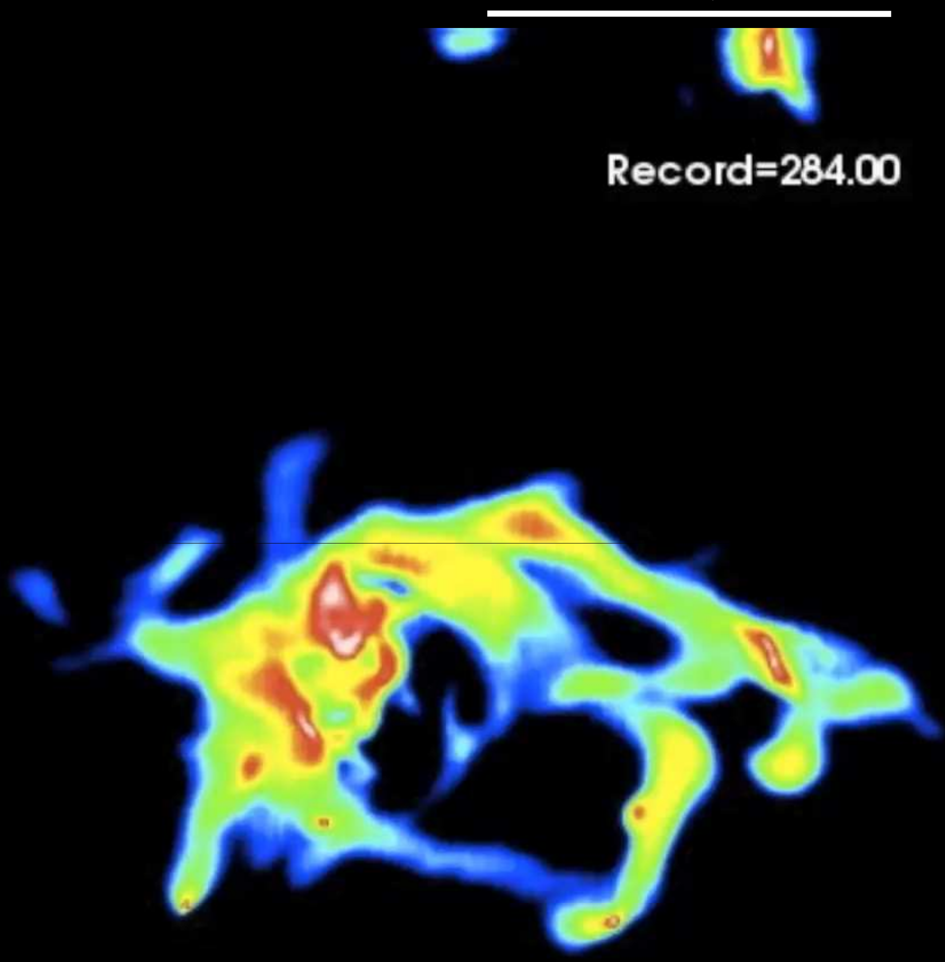
inflow: $J_{-} \sim 0.7J \quad J=J_{+}-J_{-}$

in t_{orbit}: $J_{-} \sim 0.15 J_{disk}$

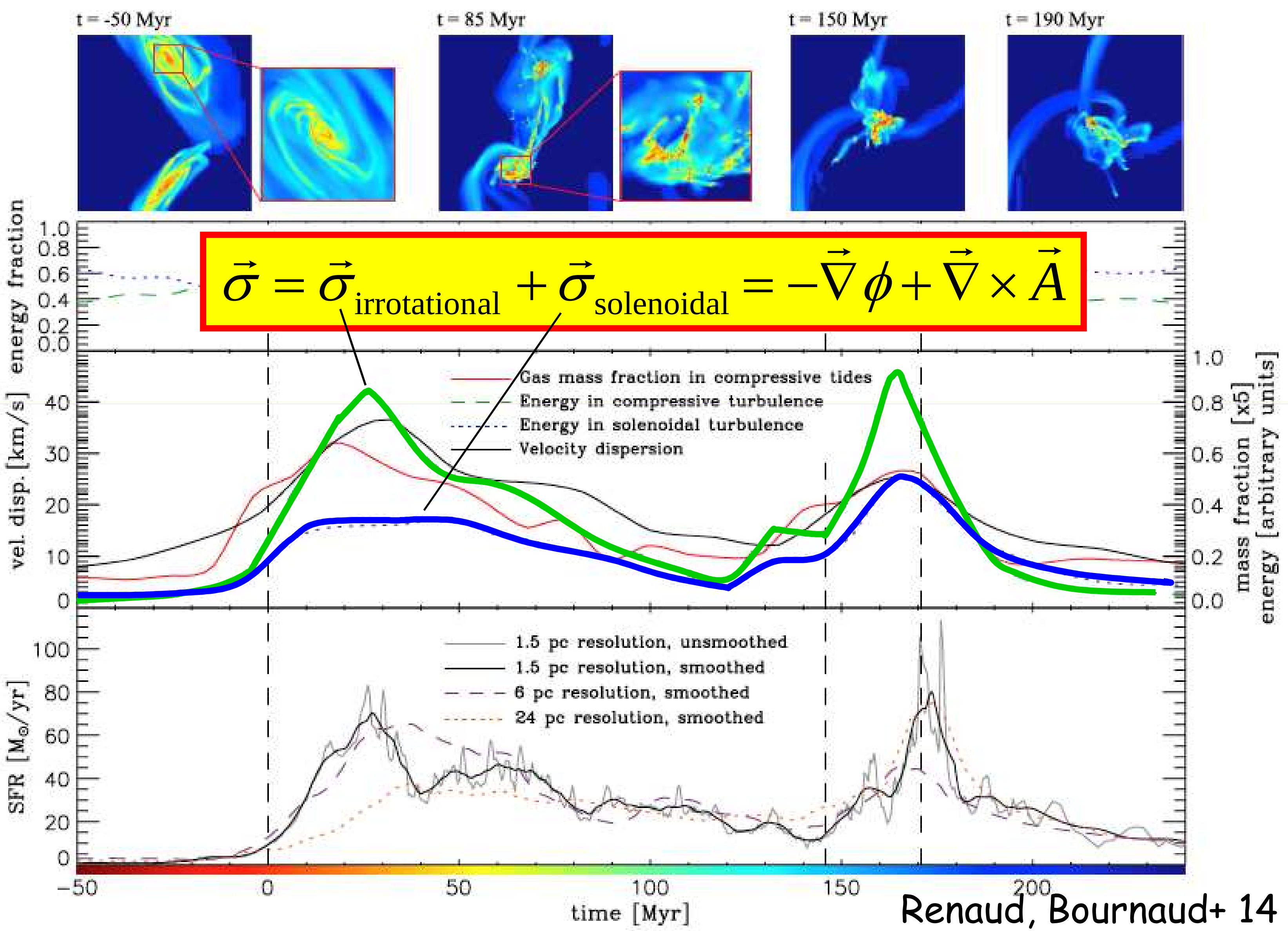
Irregular Rotation



Clumpy Disk Ceverino, Dekel et al.



Compression Modes of Turbulence: Merger



Renaud, Bournaud+ 14

Conclusions: Stimulated Non-linear 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

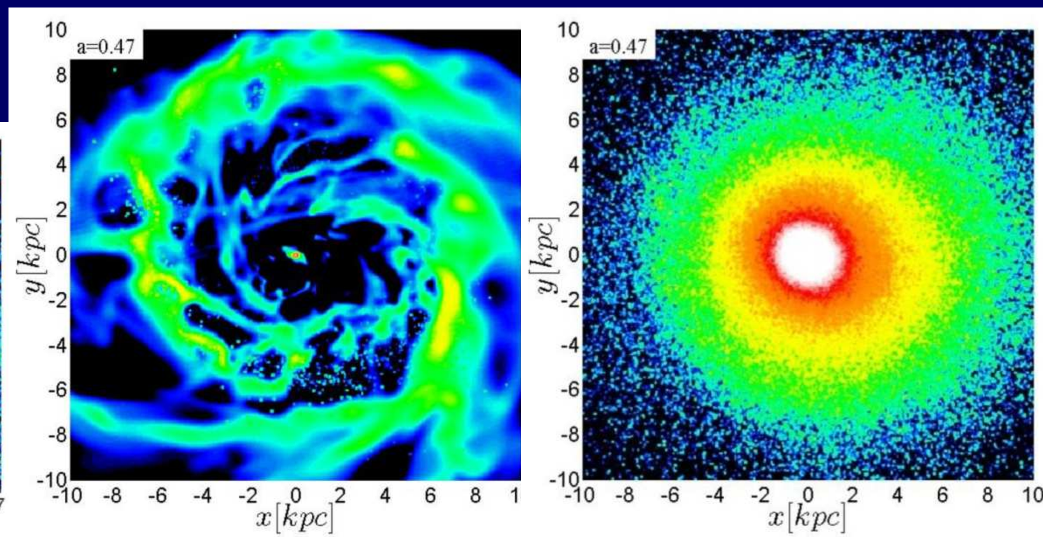
Nonlinear instability
Stimulated by inflow+mergers? Compressive turbulence?
Irregular rotation due to counter-rotating streams?

VDI and (minor) mergers actually work in concert

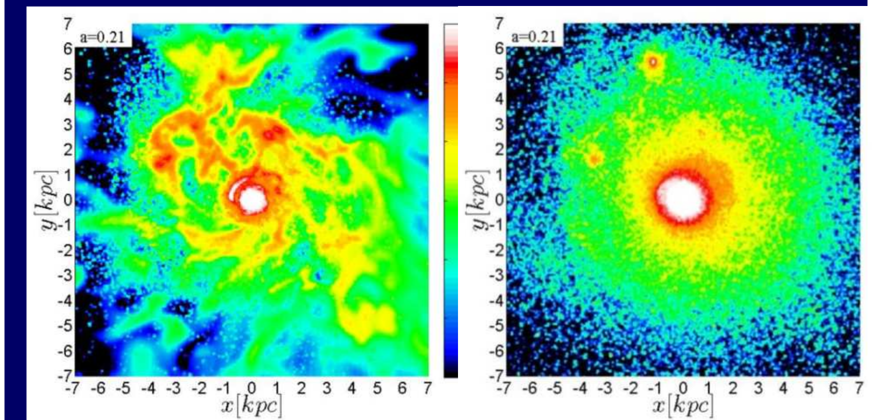
Quenching by Compaction and by a Hot Halo

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

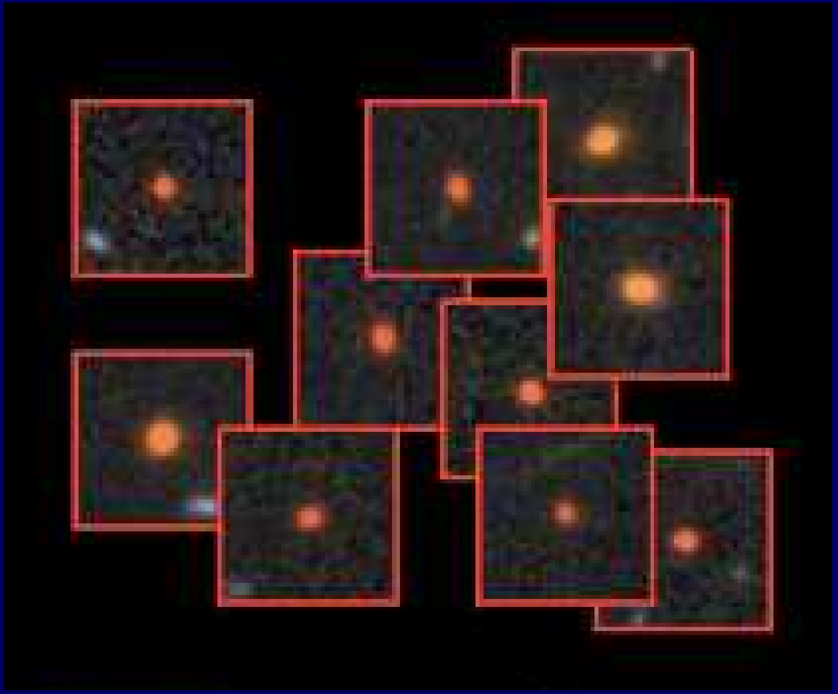
Red Nugget



"Blue" Nugget



Red Nuggets



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

Van Dokkum+08,10,14, Damjanov+09, Newman+10, Damjanov+11, Whitaker+12, Bruce+12, …

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

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

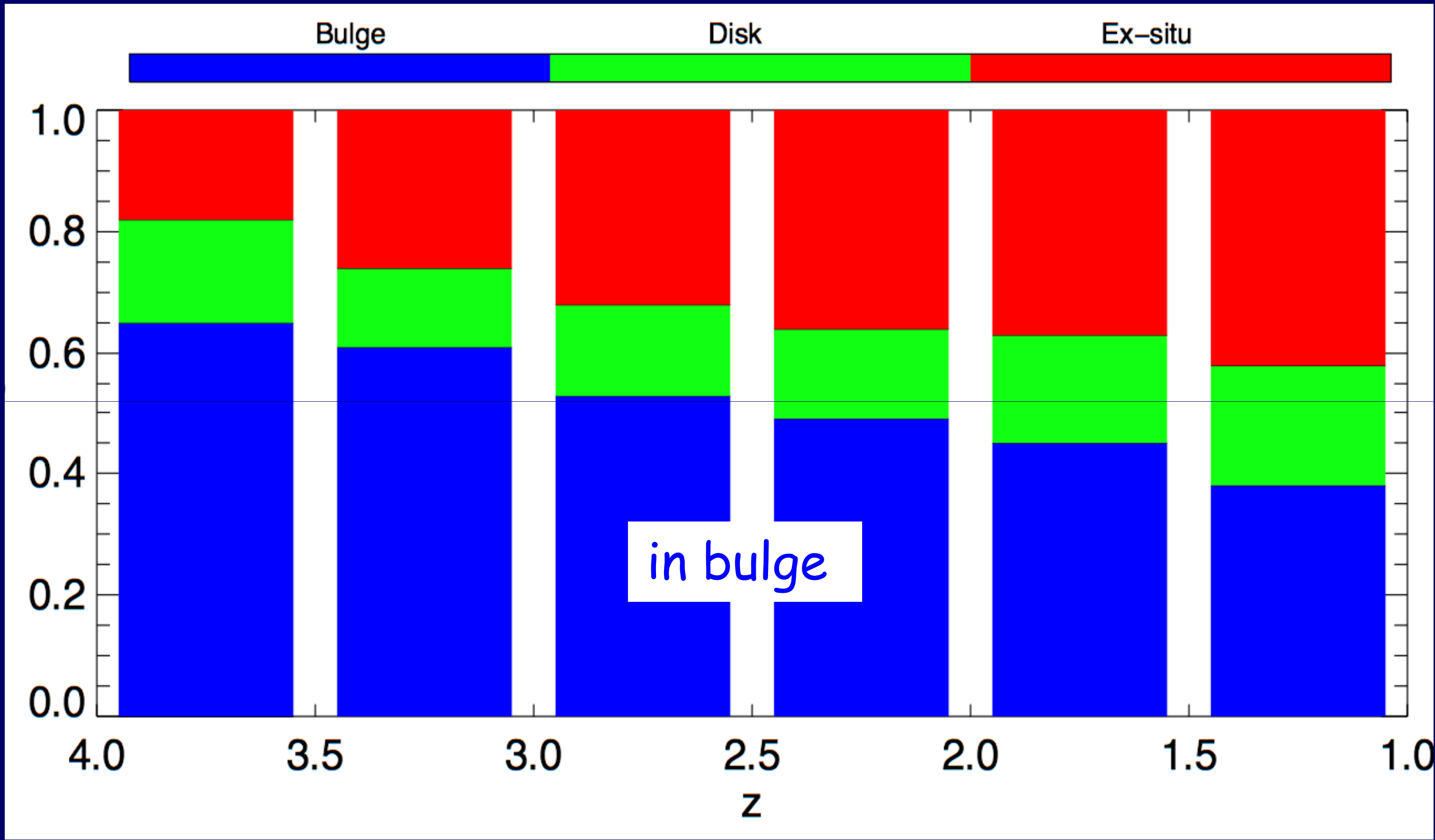
$$\varepsilon_{\rm sfr} \le 0.02 \quad \delta \ge 0.2$$

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 in Simulations

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

Fraction of bulge stars born in different components

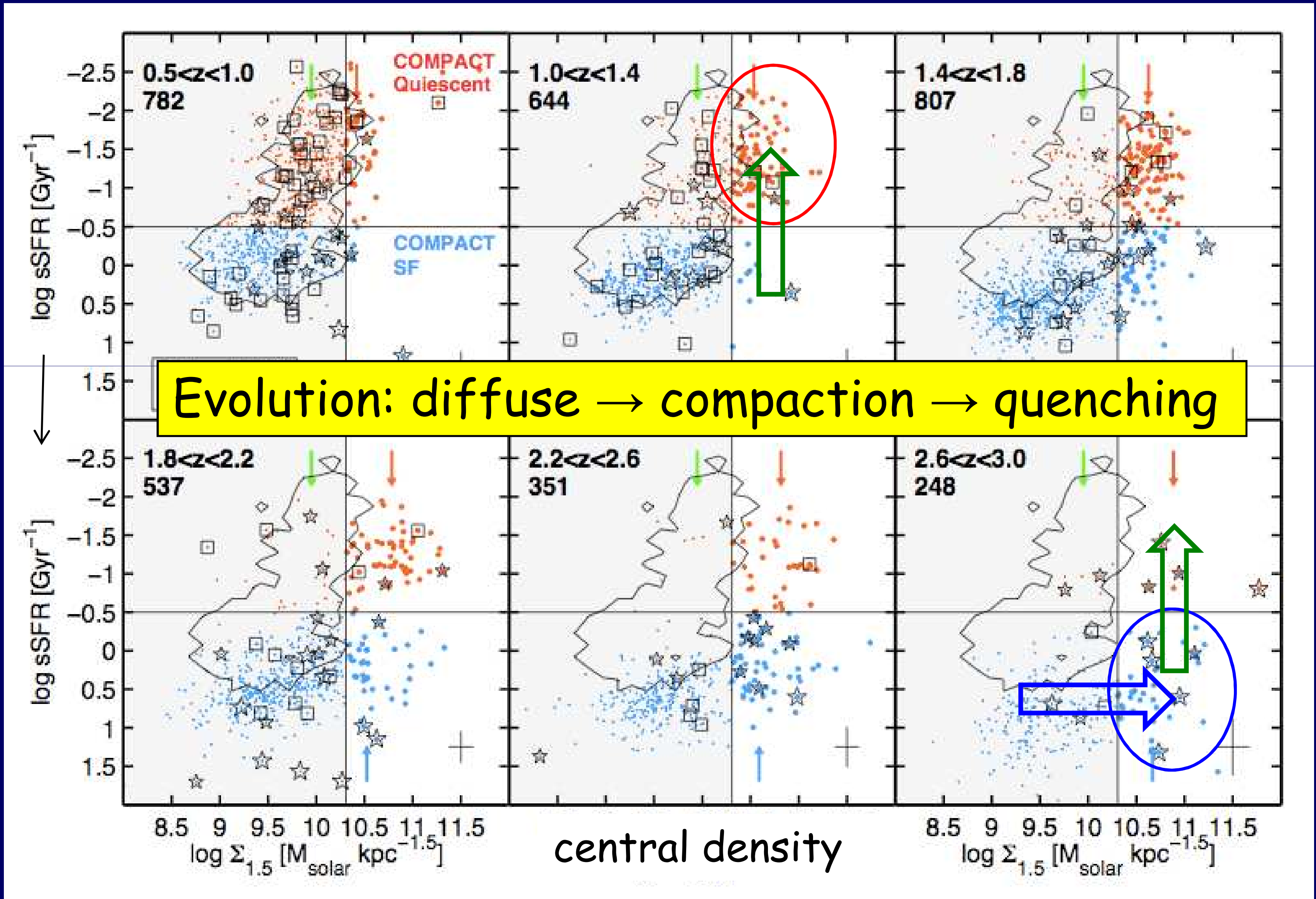


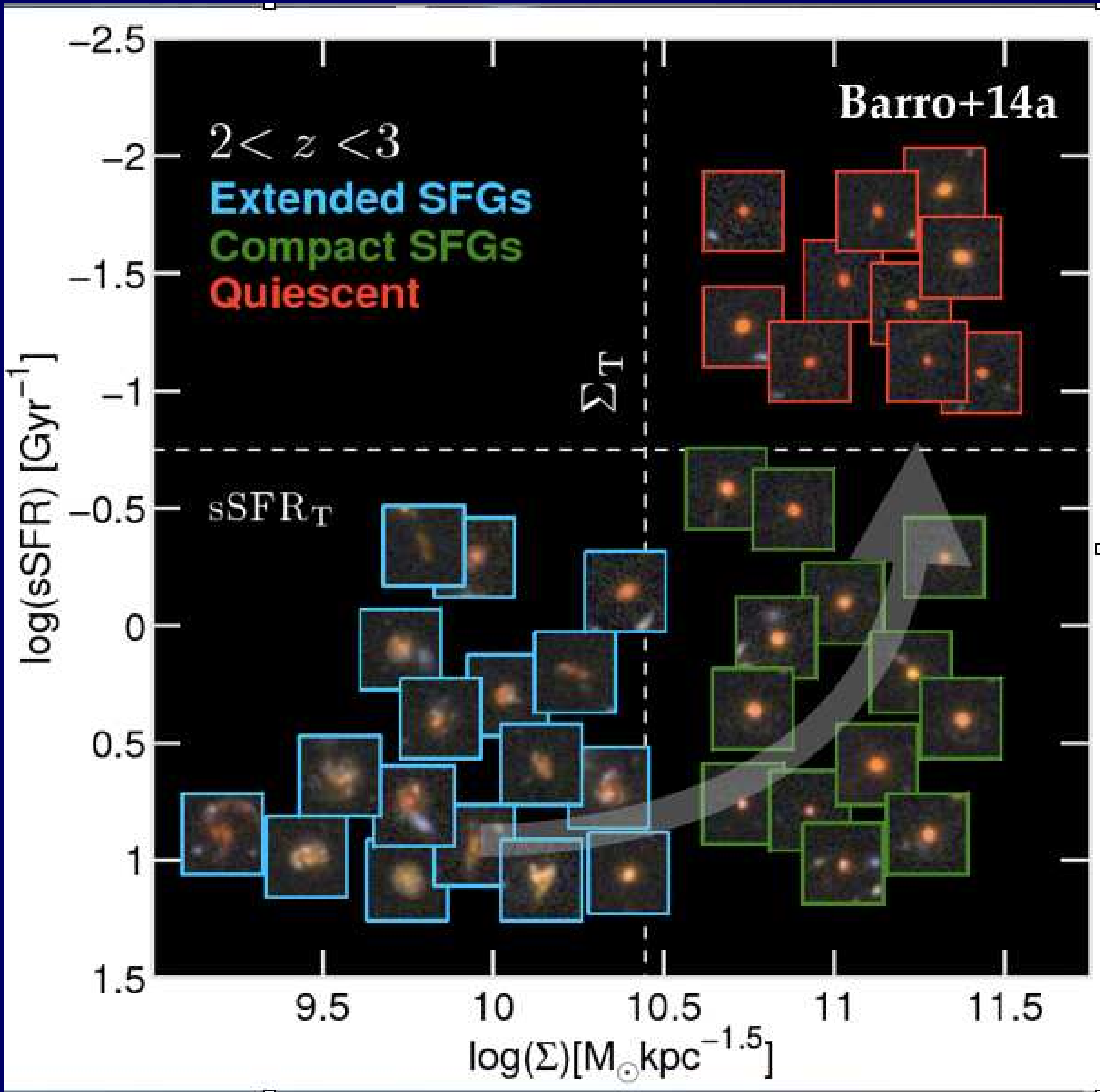
65-38% of the bulge stars formed in the bulge → wet inflow

Driven by wet VDI or wet mergers

Observations: Blue Nuggets -> Red Nuggets

Barro+ 13 CANDELS z=1-3



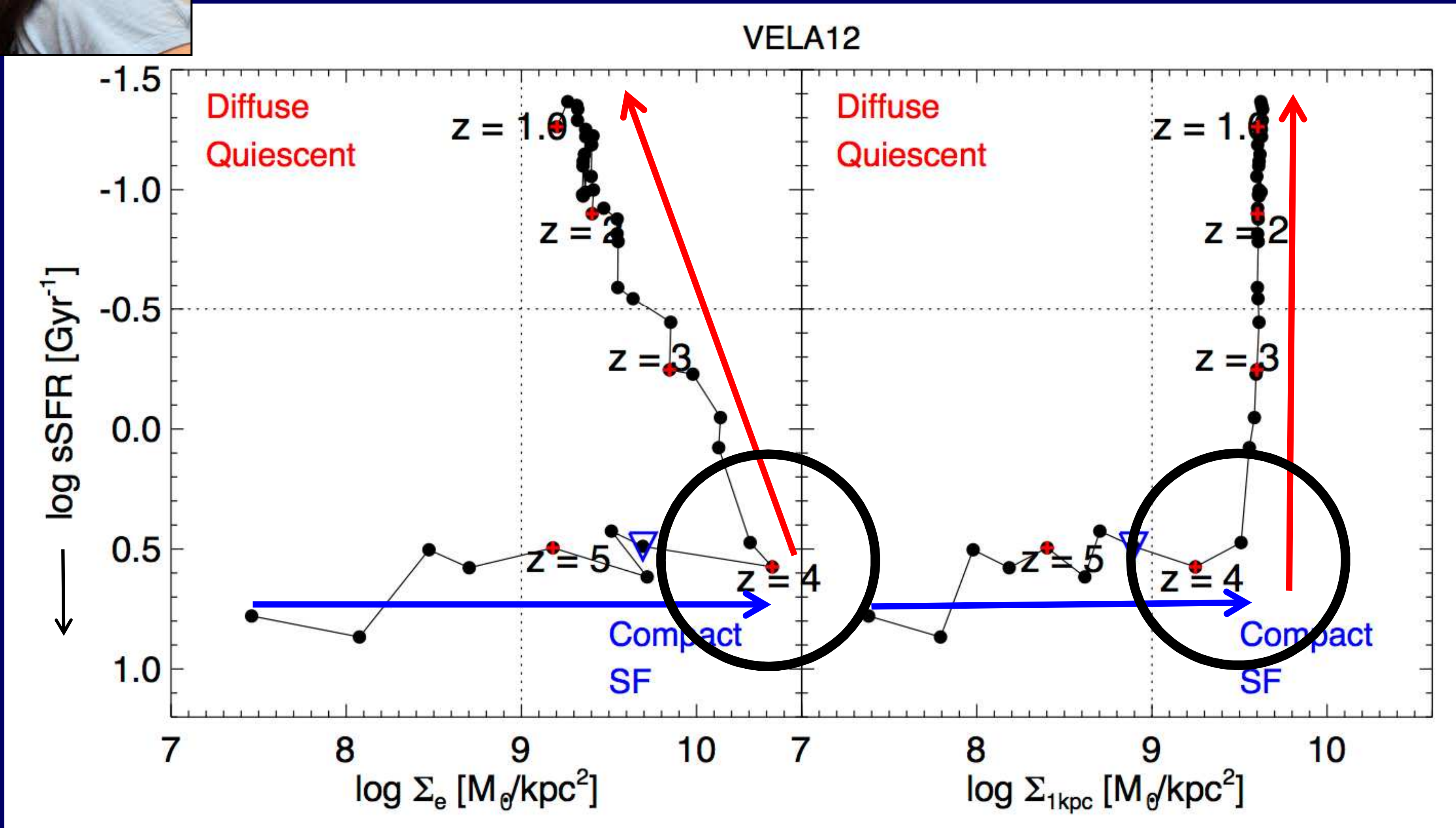

Barro+14a
2< z <3
Extended SFGs
Compact SFGs
Quiescent
sSFR$_T$
Σ_T
log(sSFR) [Gyr^{-1}]
log(Σ)[M$_\odot$ kpc$^{-1.5}$]
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
9.5
10
10.5
11
11.5

RN

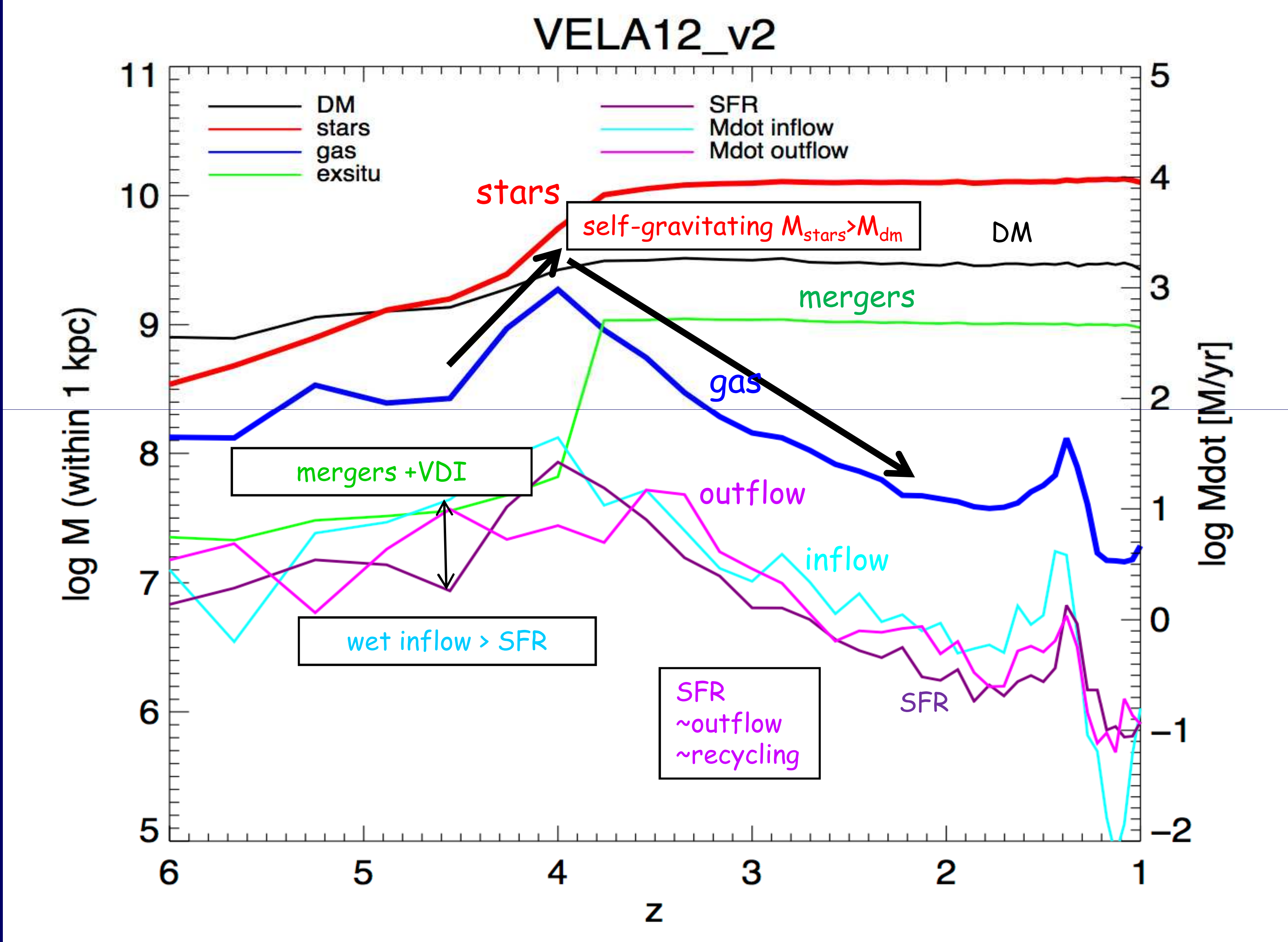
BN

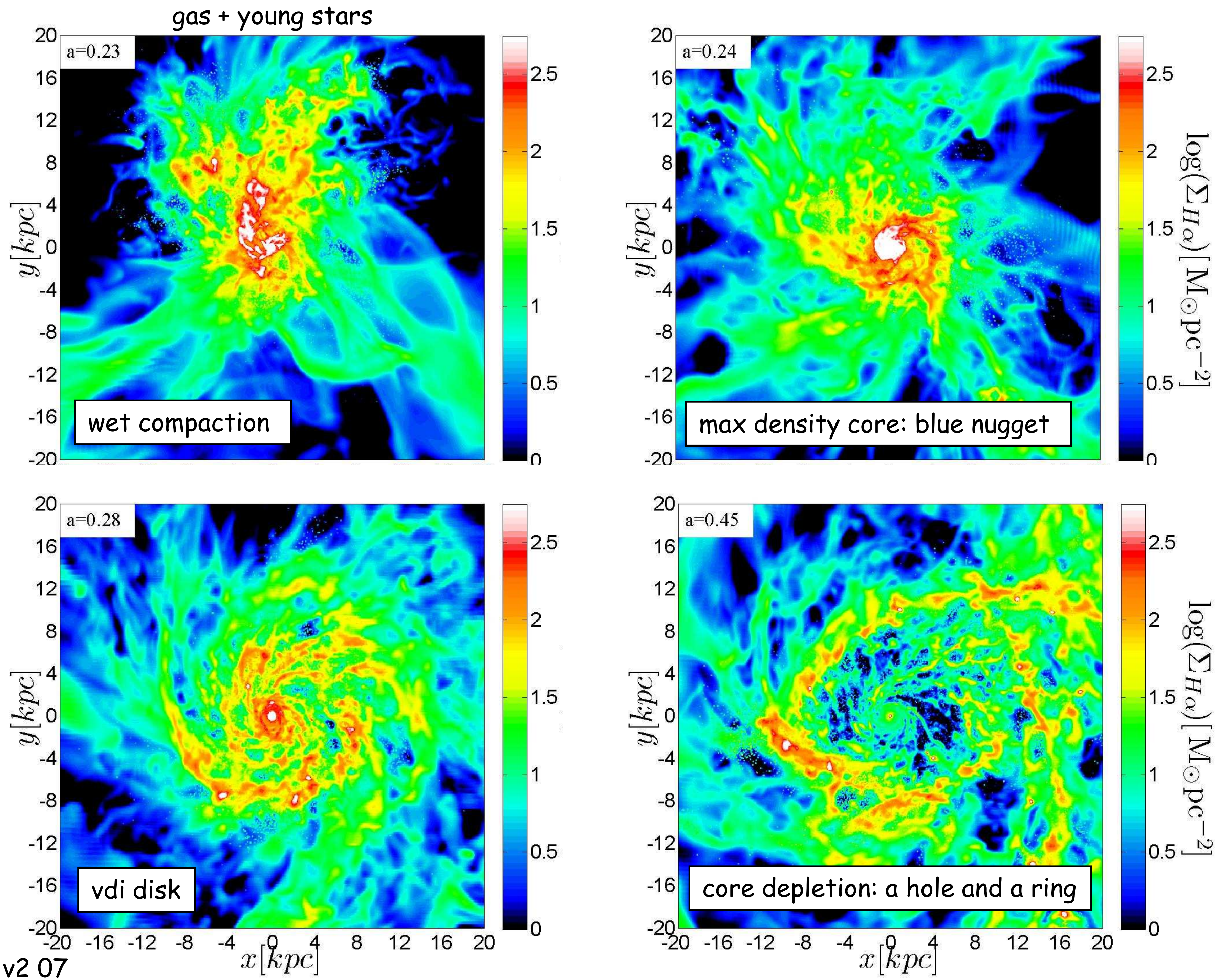
Compaction and quenching

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

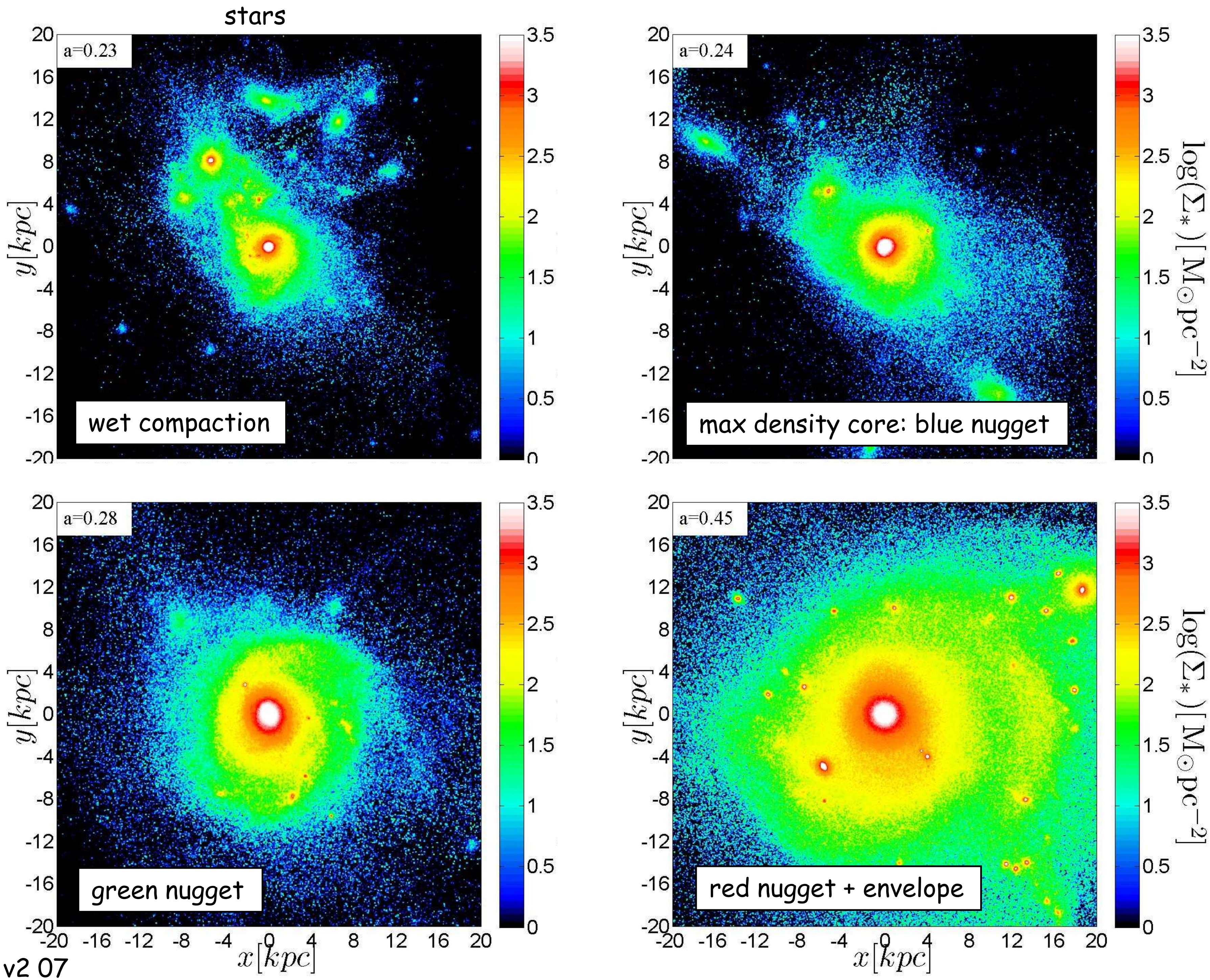


Compaction and quenching




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

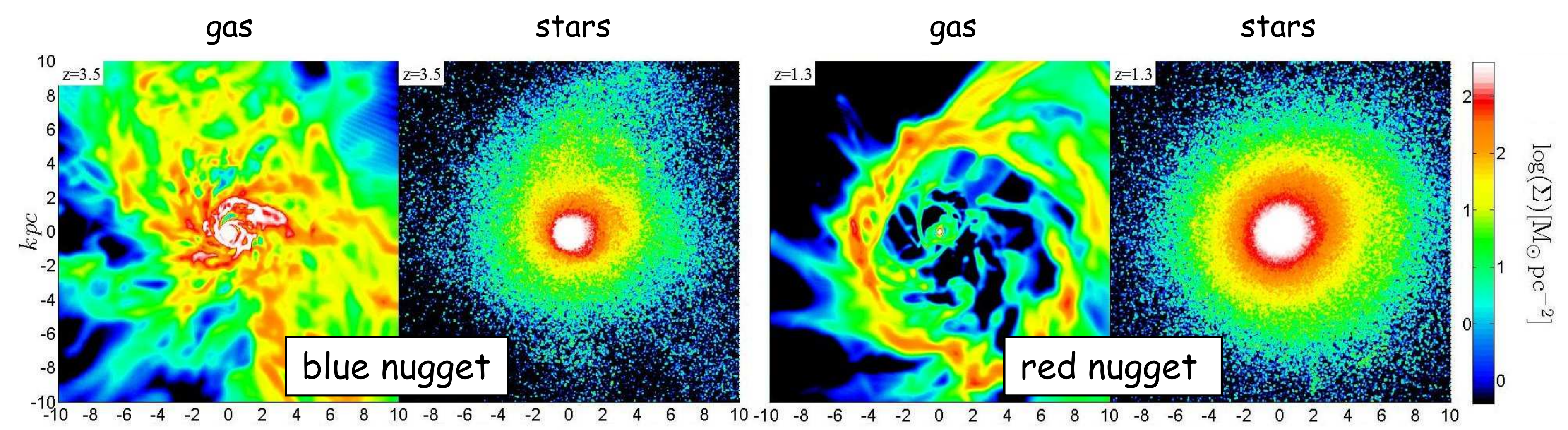
vela v2 07



stars
a=0.23
wet compaction
a=0.24
max density core: blue nugget
a=0.28
green nugget
a=0.45
red nugget + envelope
$y[kpc]$
$x[kpc]$
$\log(\Sigma_*)[\mathrm{M}_\odot \mathrm{pc}^{-2}]$

vela v2 07

Blue Nugget - Red Nugget



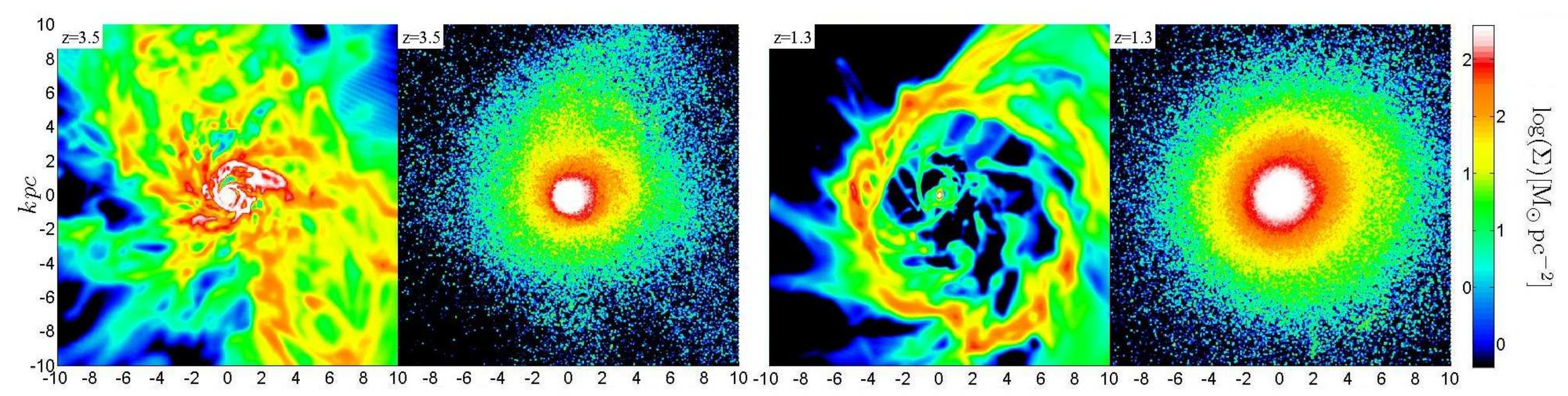
dense gas core -> dense stellar core

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

stellar core remains dense
from BN to RN

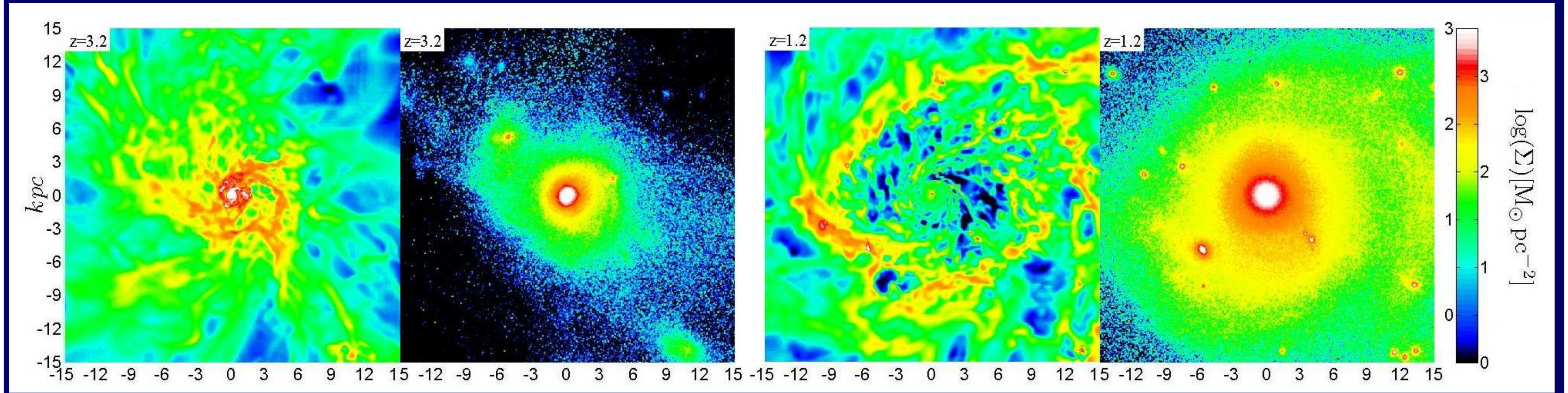
Blue Nugget - Red Nugget

naked red nugget

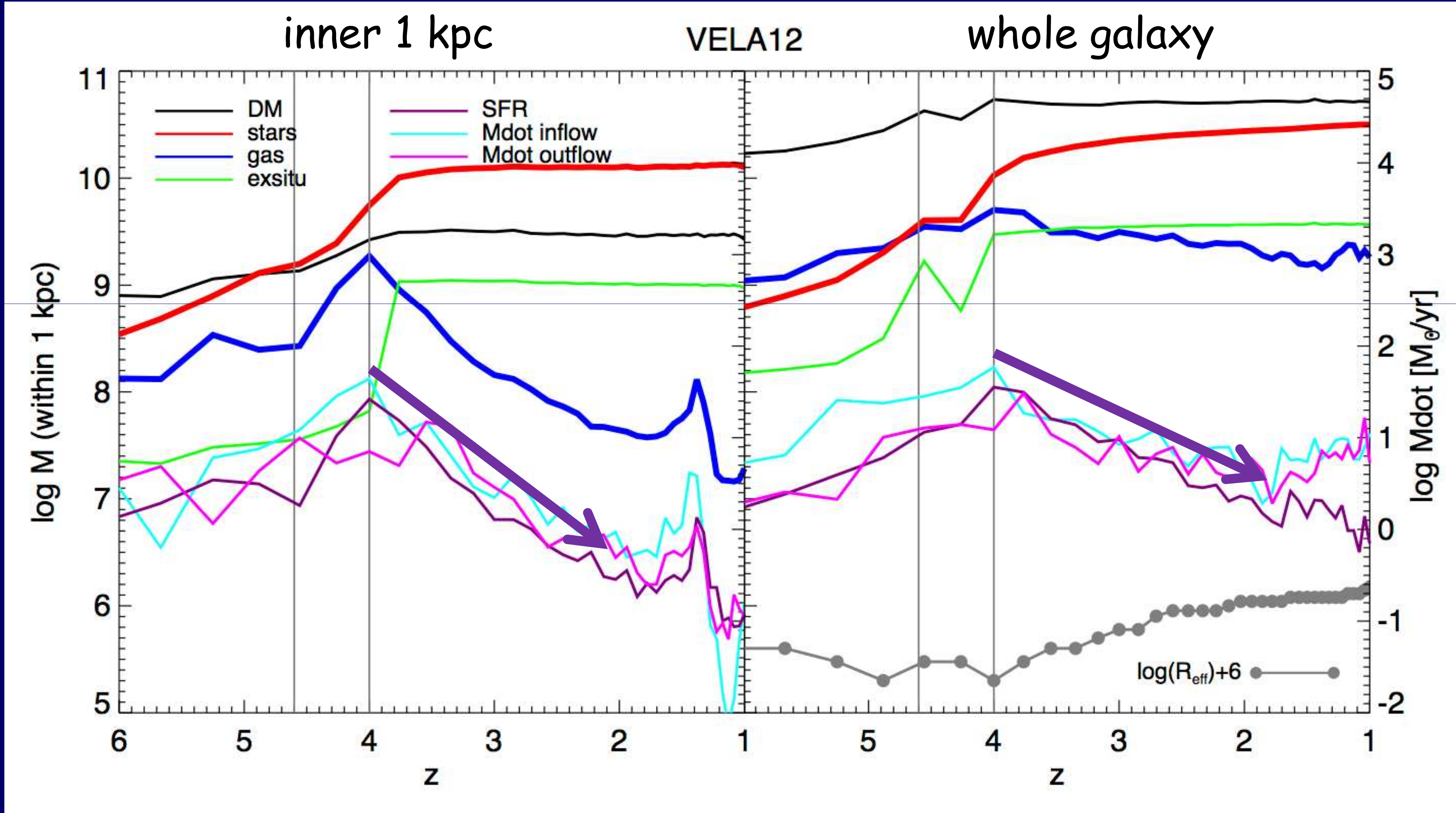


a stellar envelope may gradually grow by dry mergers

red nugget + envelope = elliptical

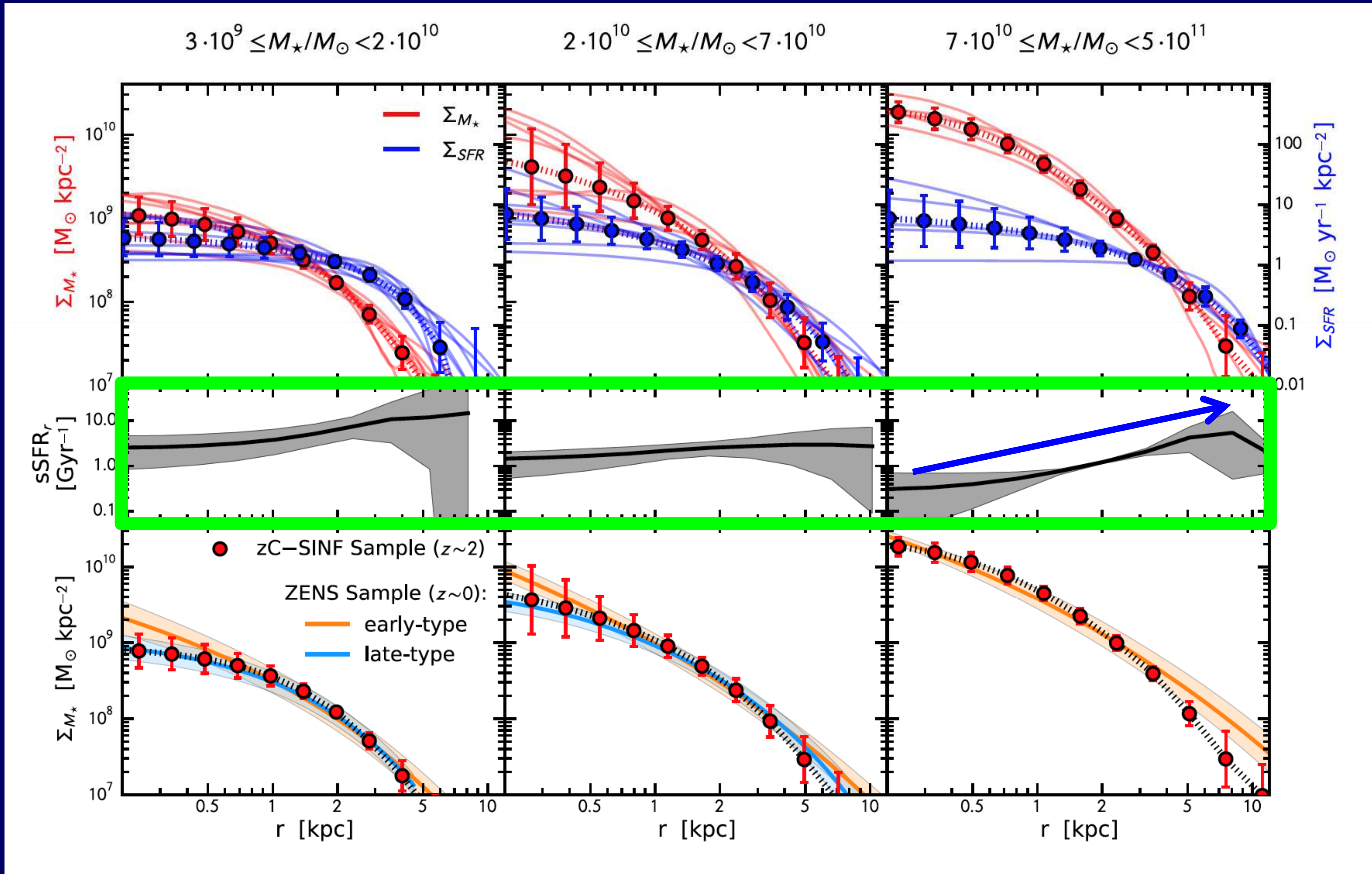


Inside-Out Quenching: Slower Quenching in the Outer Disk



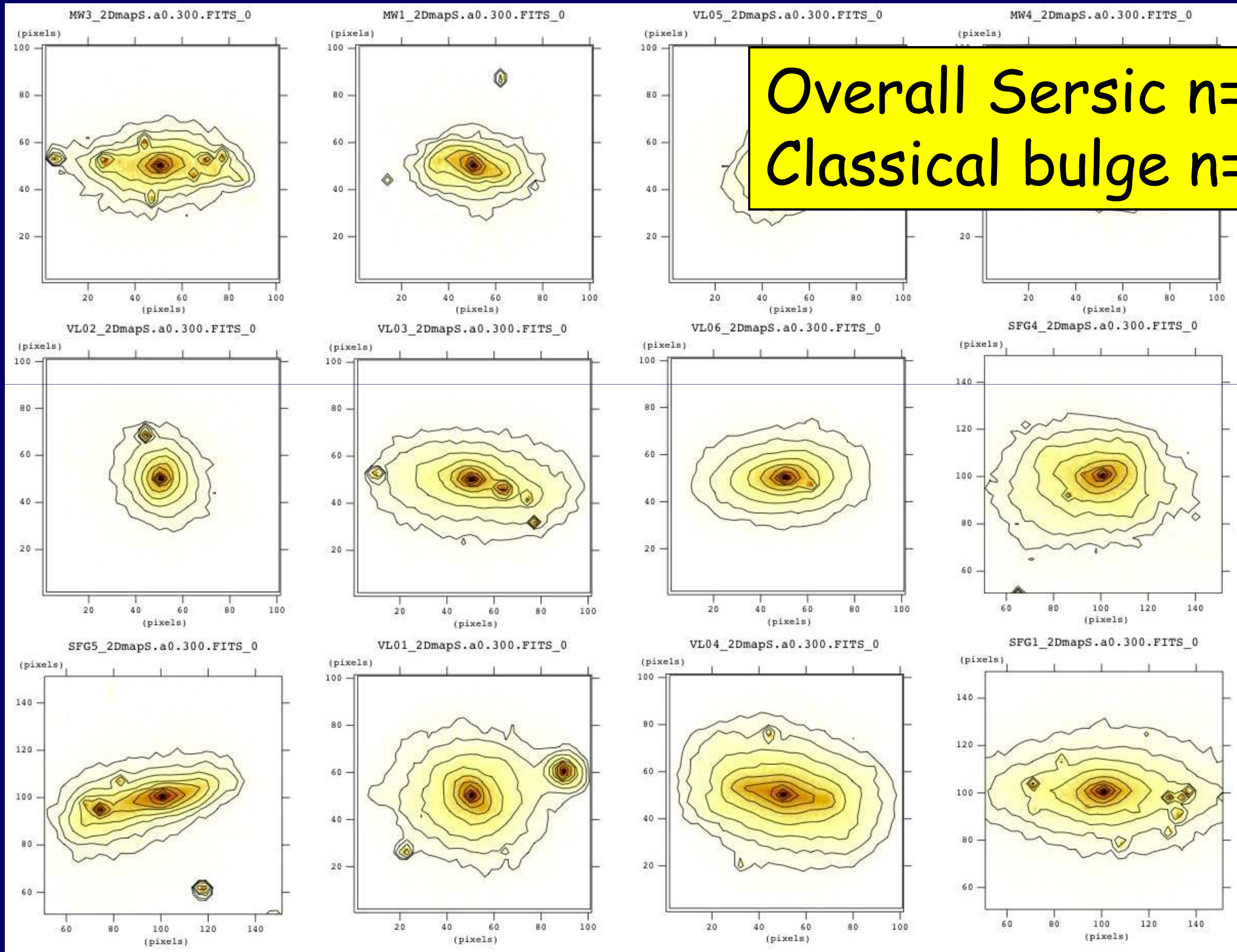
Inside-Out Quenching

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



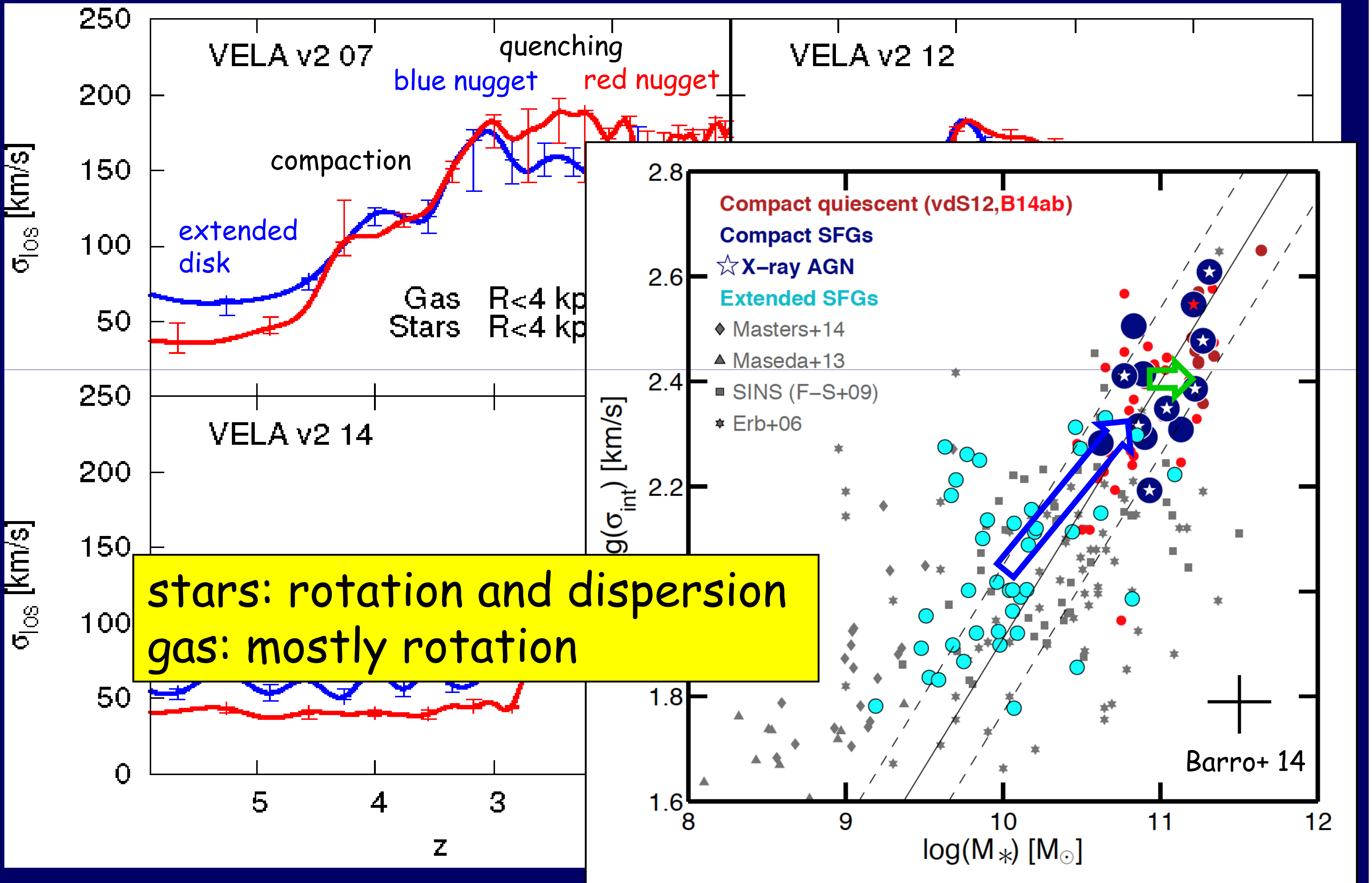
Stellar Component at z=2.3, edge-on

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

The Trigger of wet Compaction?

- VDI-driven inflow

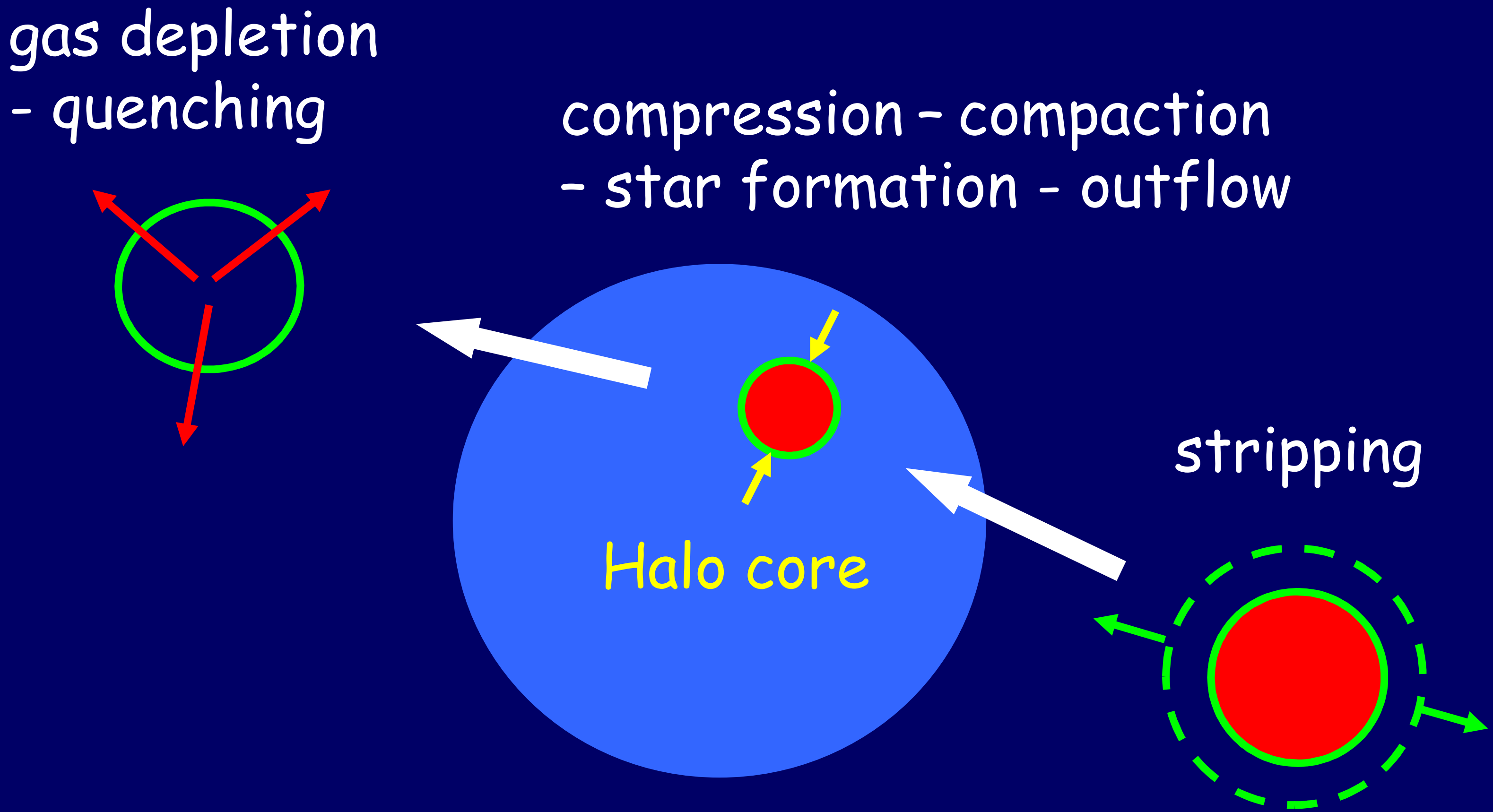
- Mergers

- tidal compression

- Counter-rotating streams

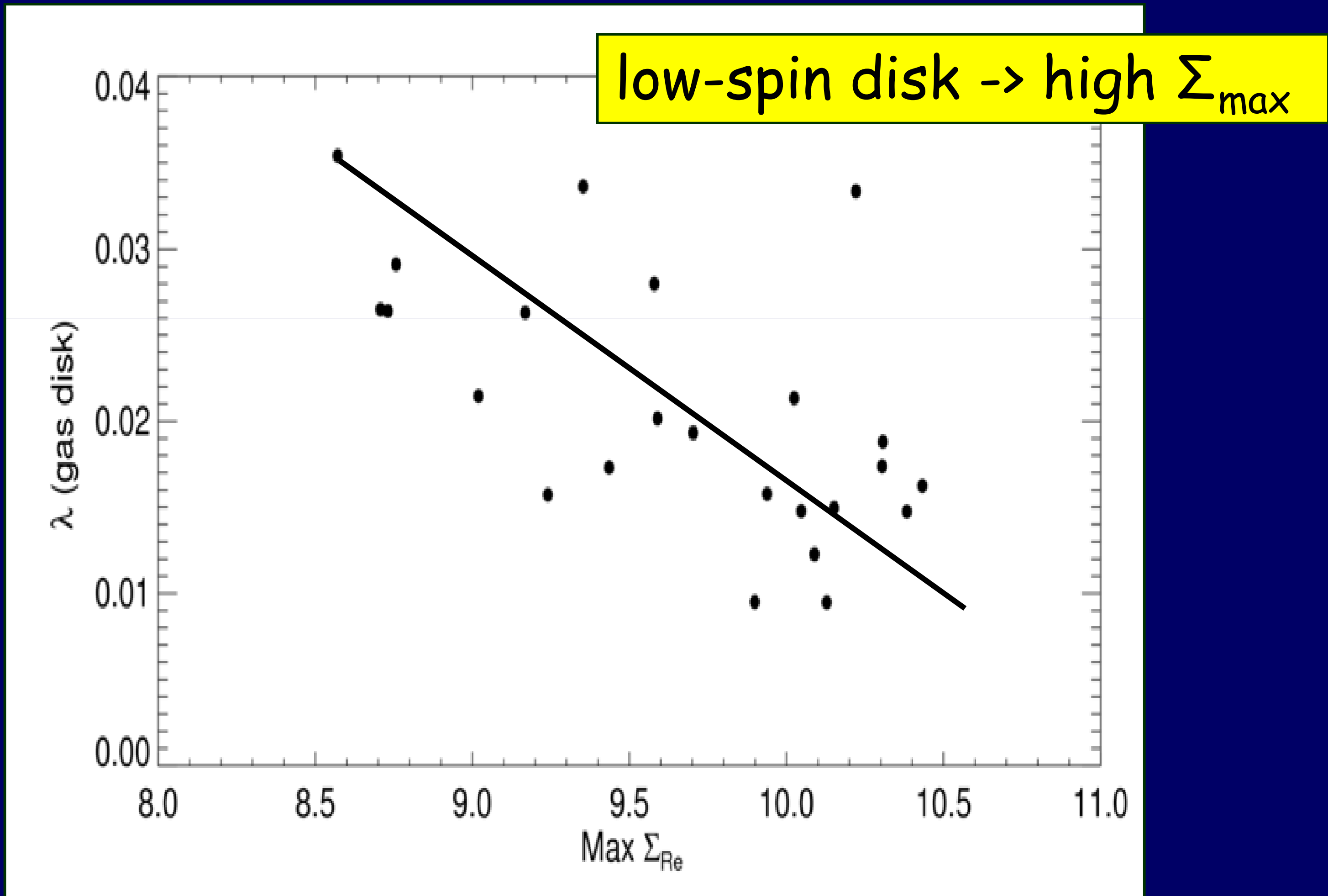
Compaction by Tidal Compression

Dekel, Devor, Hetzroni 2003

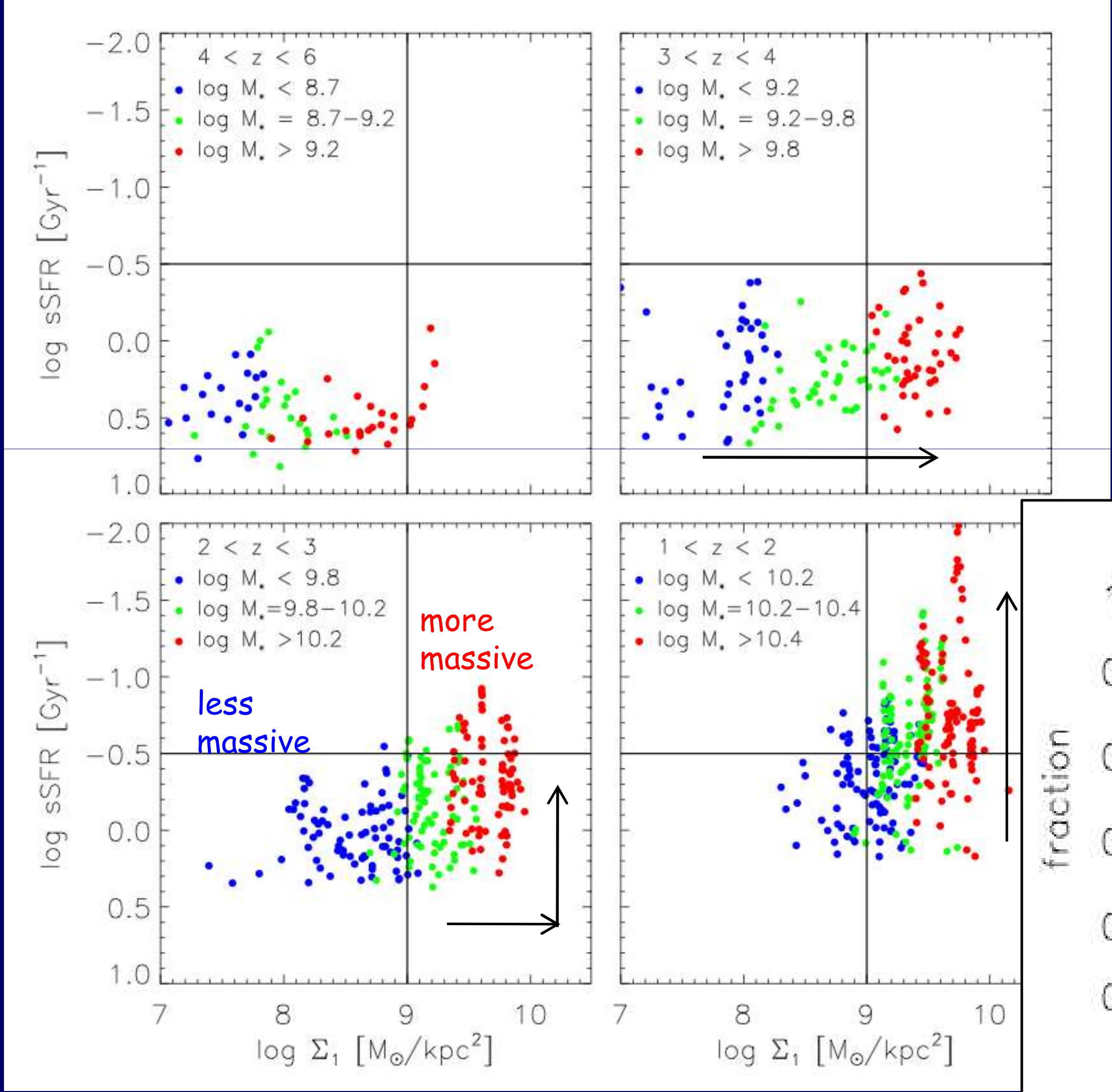


Blue Nuggets by Wet Inflow: Low Spin

Simulations confirm model predictions Dekel, Burkert 14; Zolotov+ 14

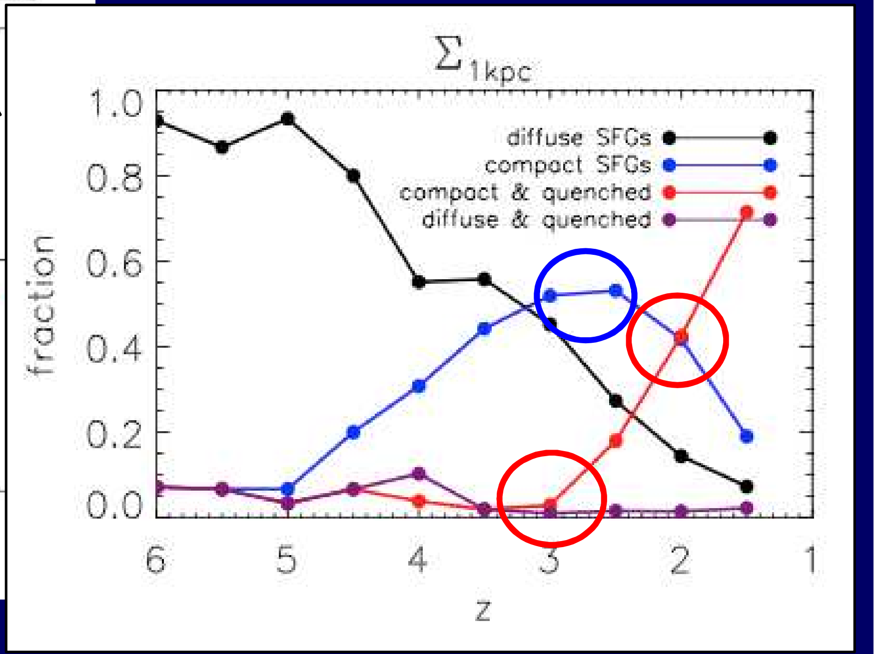


Diffuse SFG -> "Blue" Nuggets -> Red Nuggets



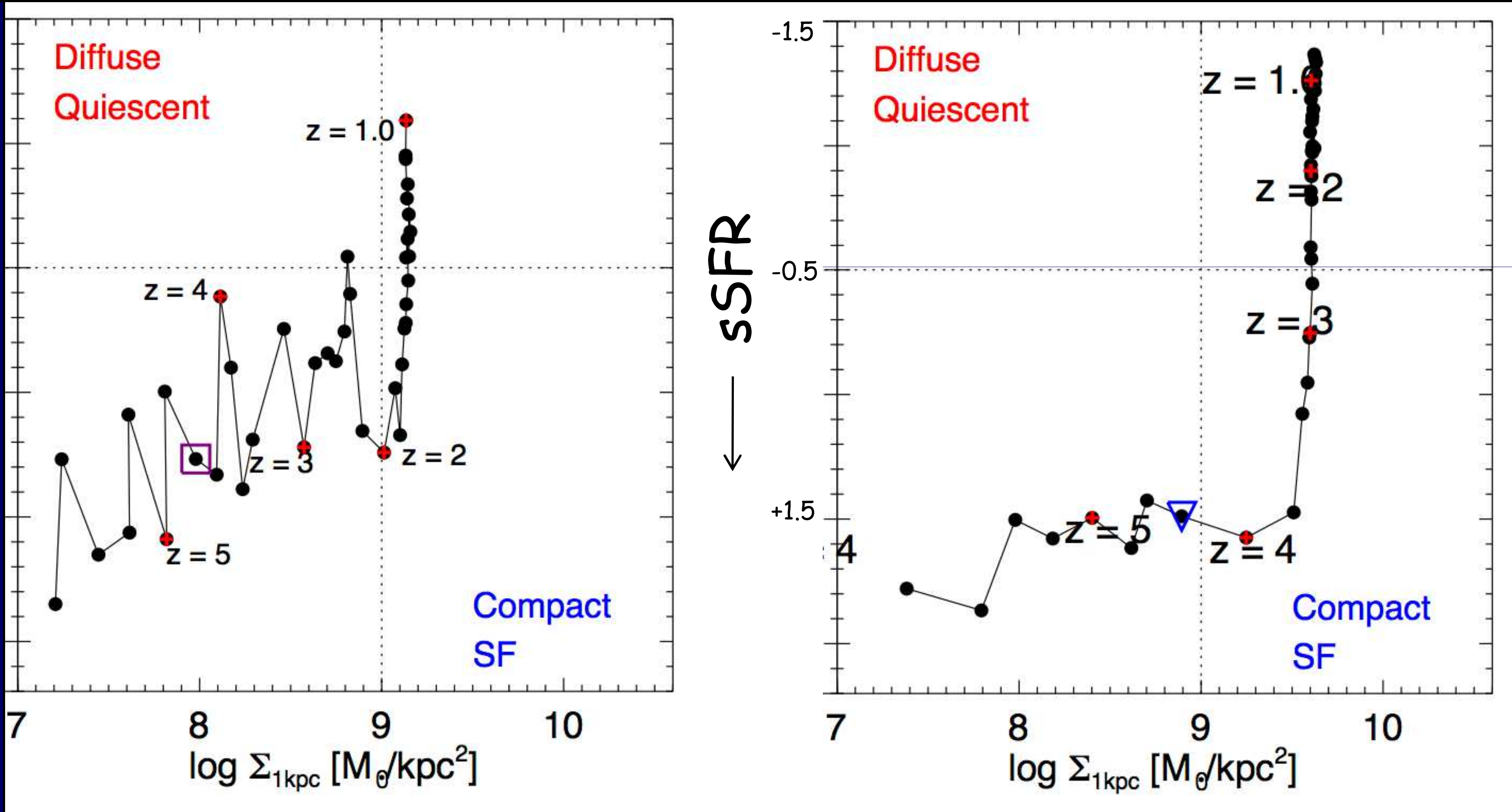
Downsizing:

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

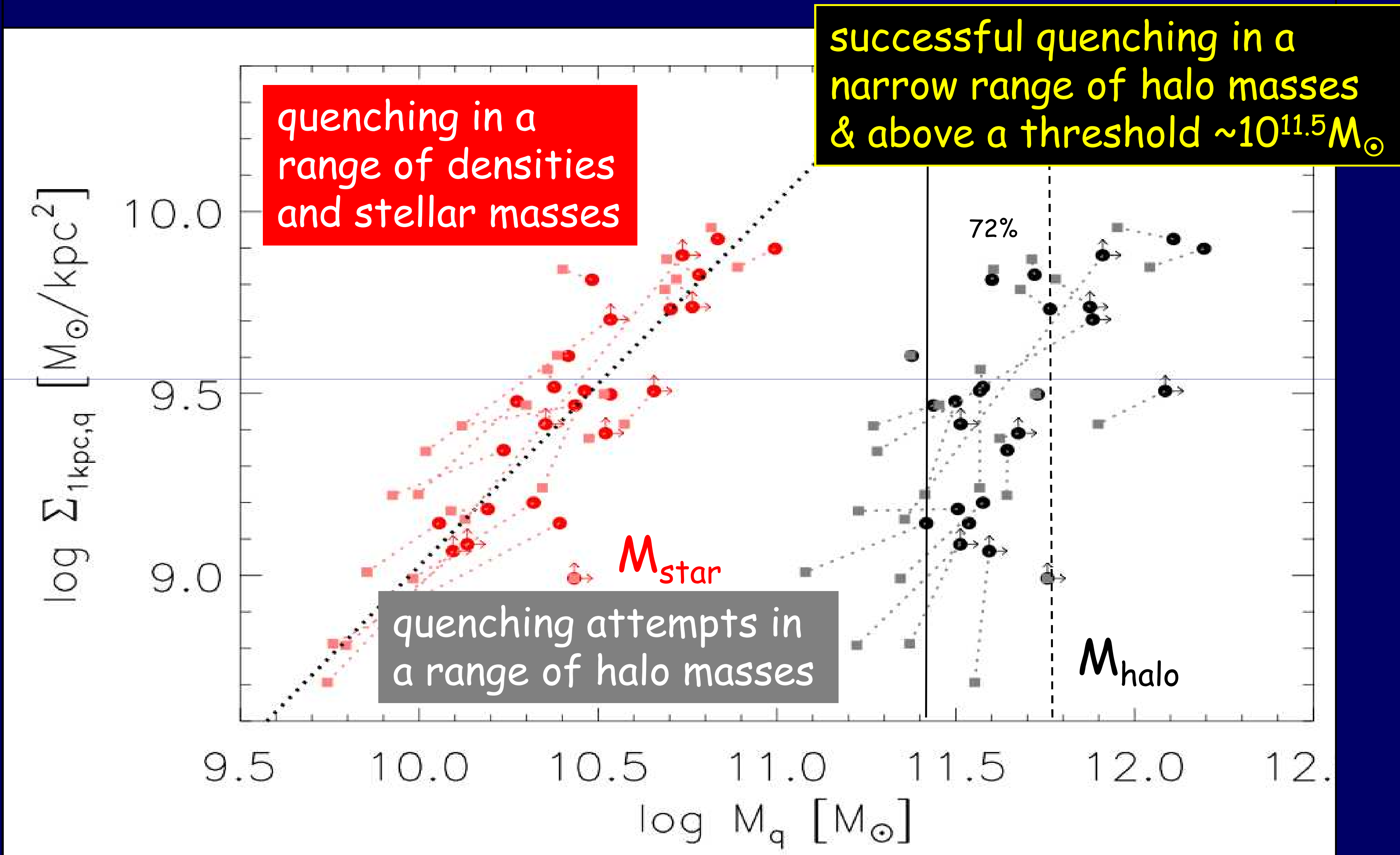


Hesitatnt vs. Decisive Quenching

low mass, low z | high mass, high z



Mass and Central Density at Quenching



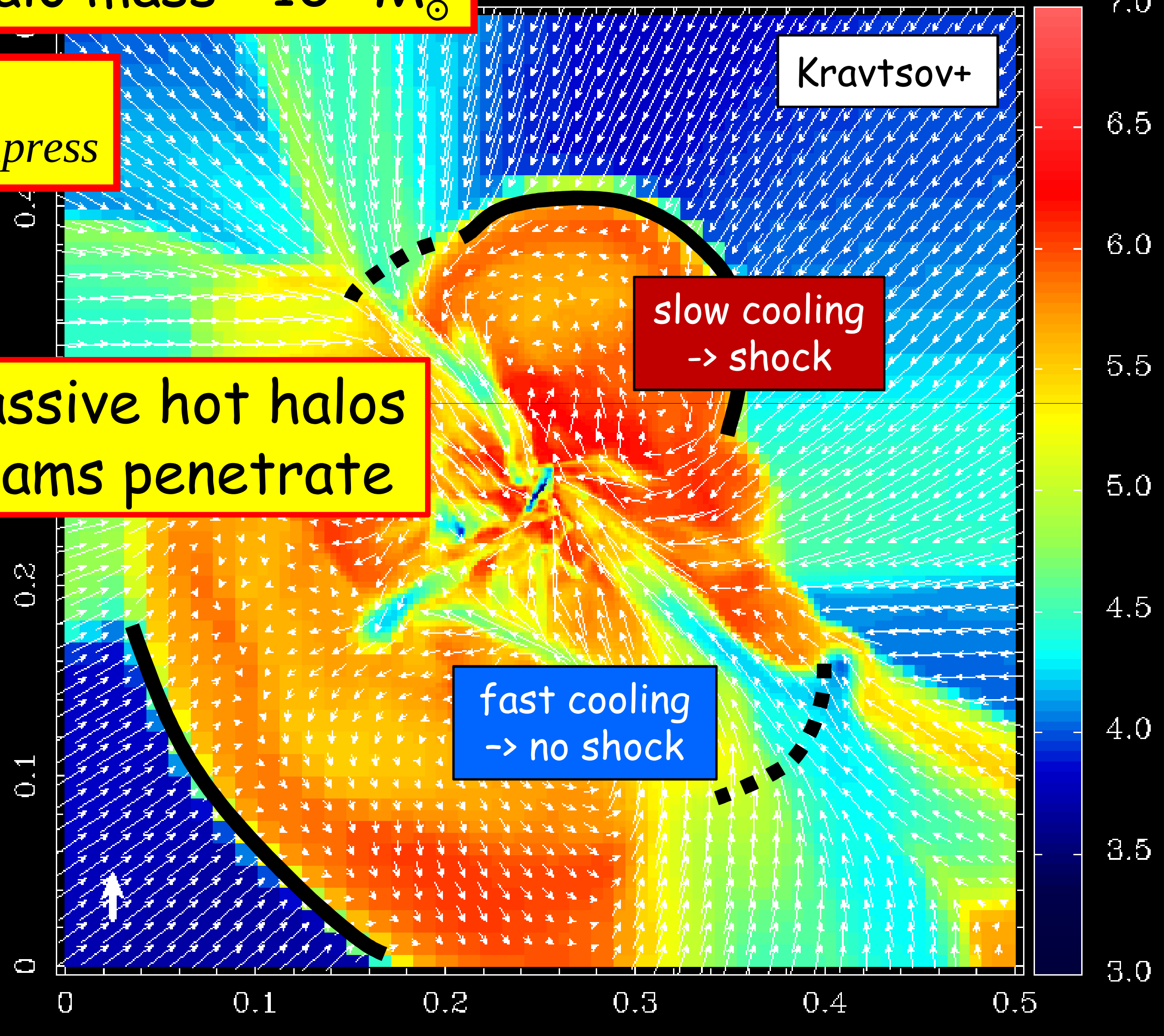
Virial Shock Heating

Dekel & Birnboim 2006

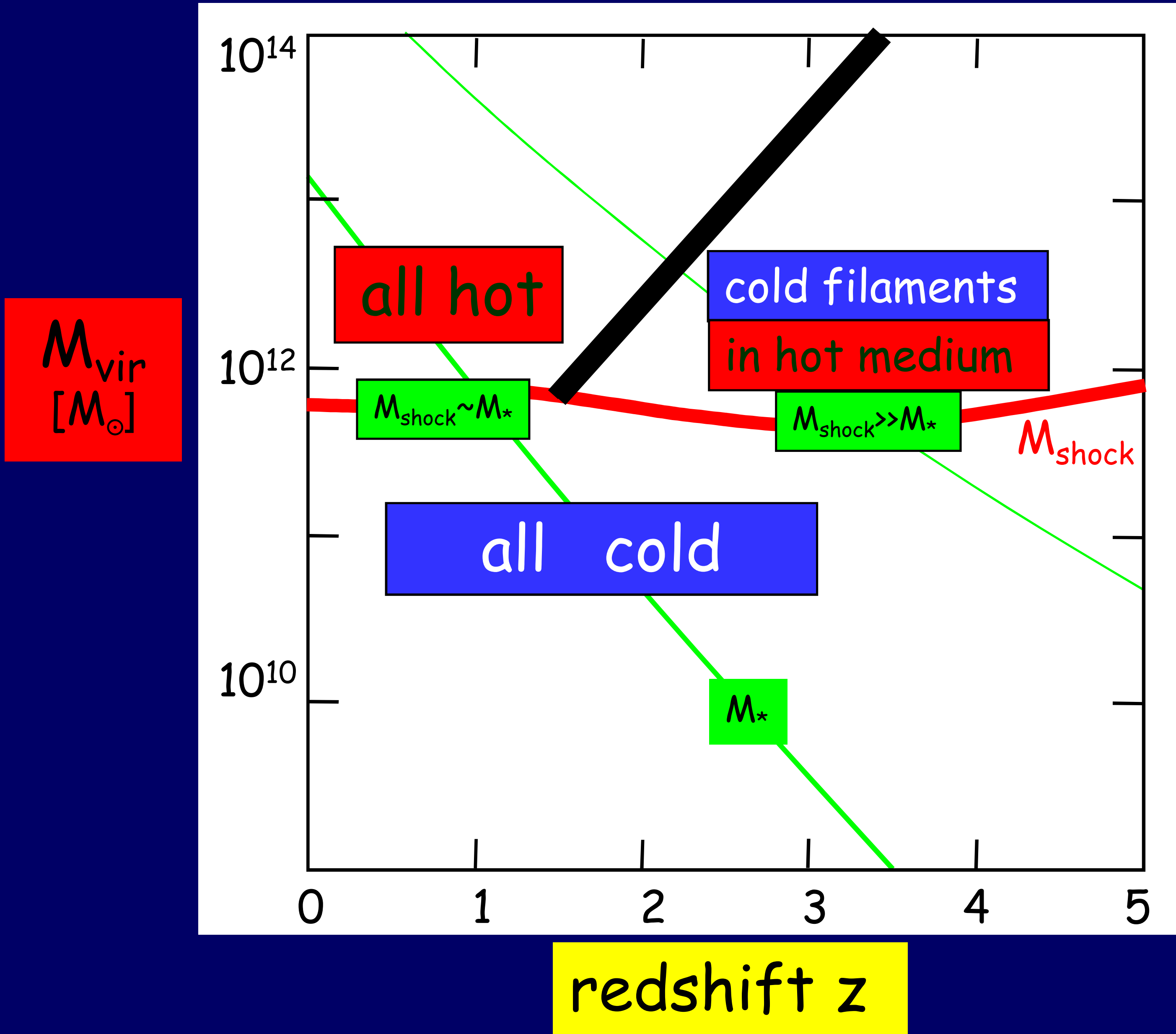
critical halo mass ~$10^{12}M_\odot$

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

in hi-z massive hot halos cold streams penetrate

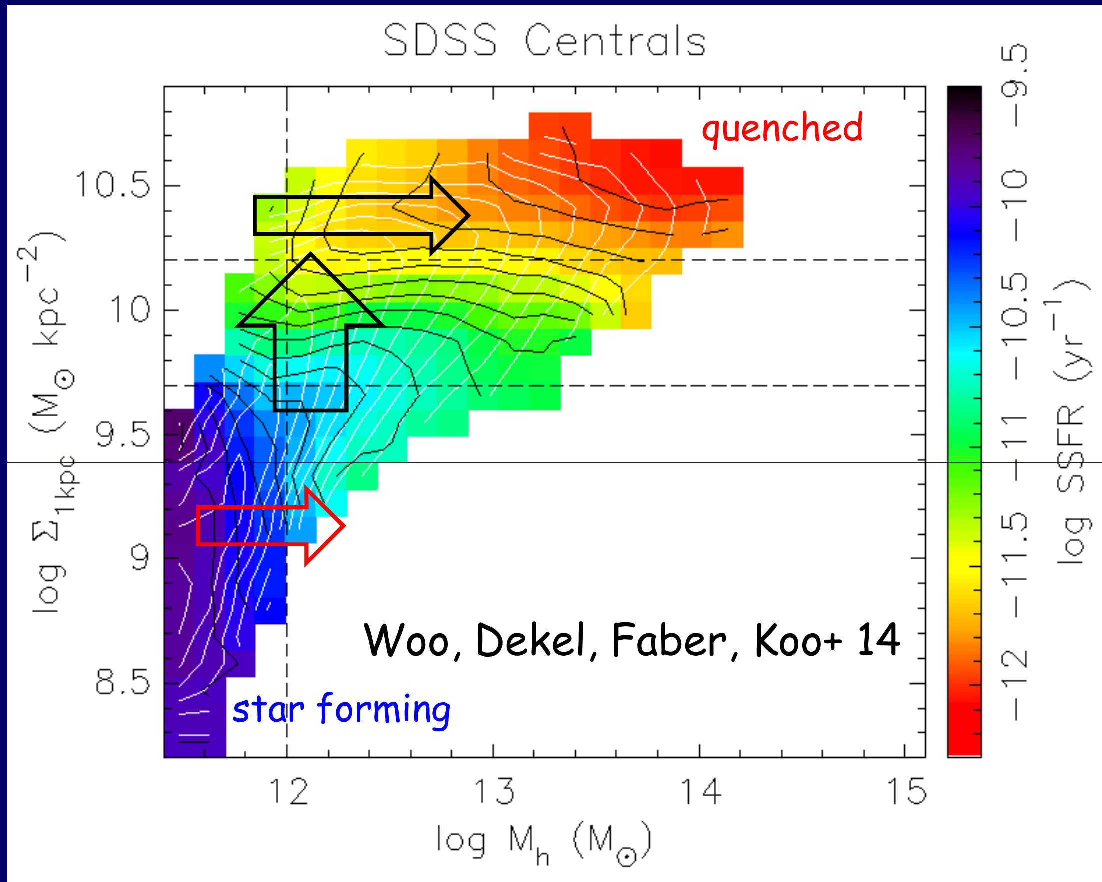


Cold Streams in Big Galaxies at High z



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

The Quenching Mechanism

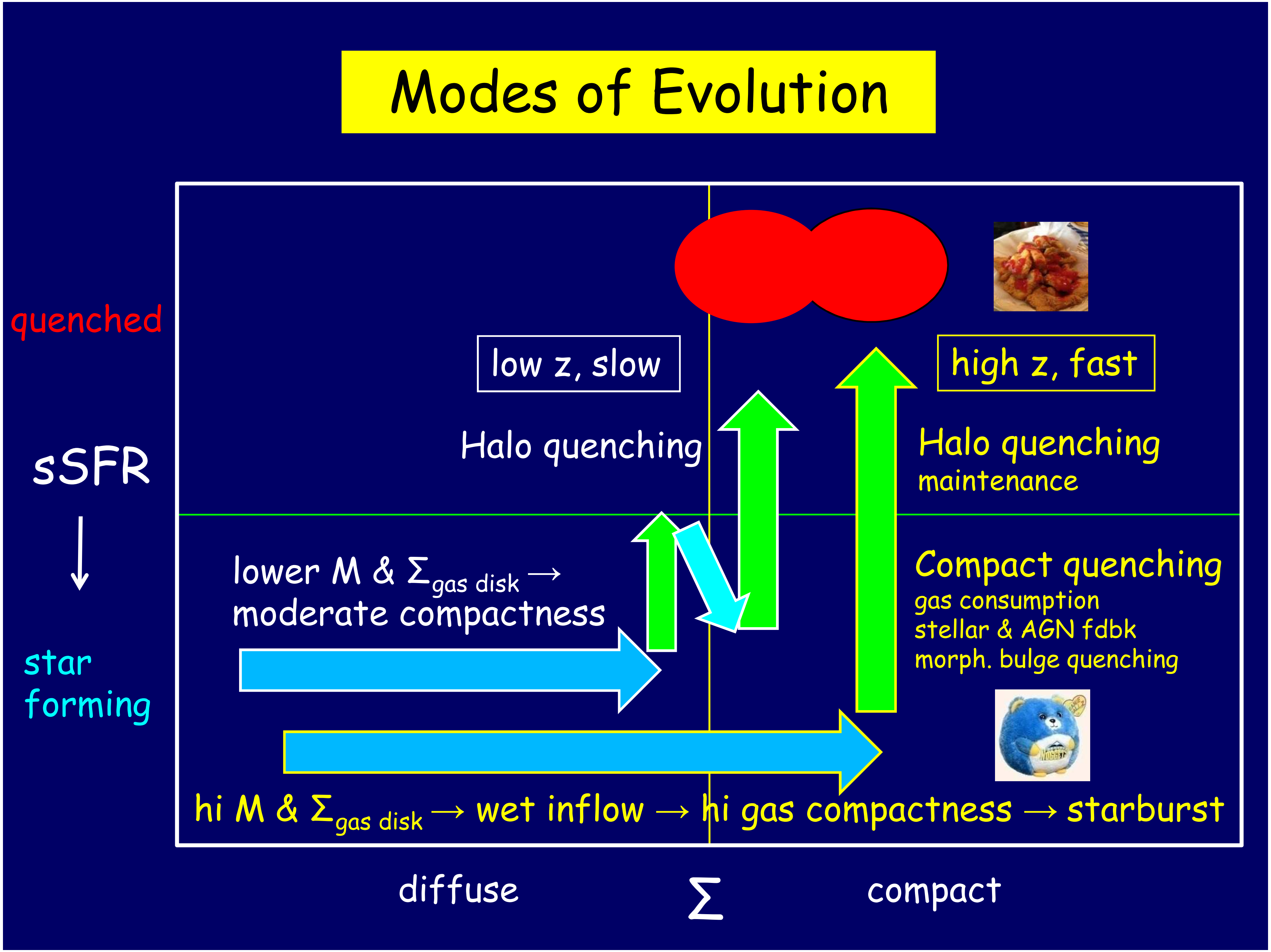
Wet compaction triggered by streams/mergers/VDI
in low-spin galaxies: inflow > SFR+outflow

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

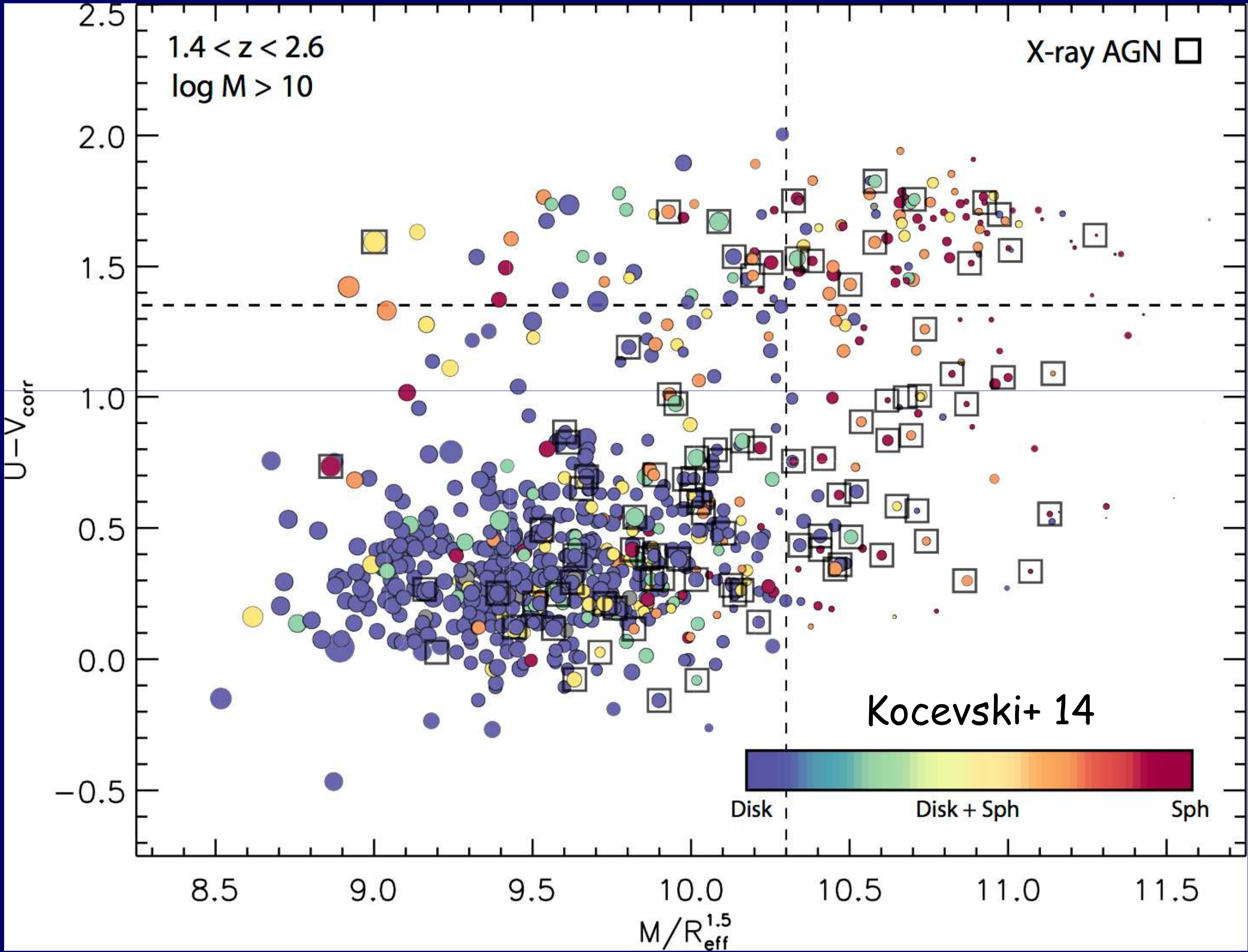
- disk has shrunk → no immediate gas supply
- massive bulge suppresses VDI-driven inflow
- AGN outflow

If halo is massive (hot) → no further gas supply
→ long-term quenching

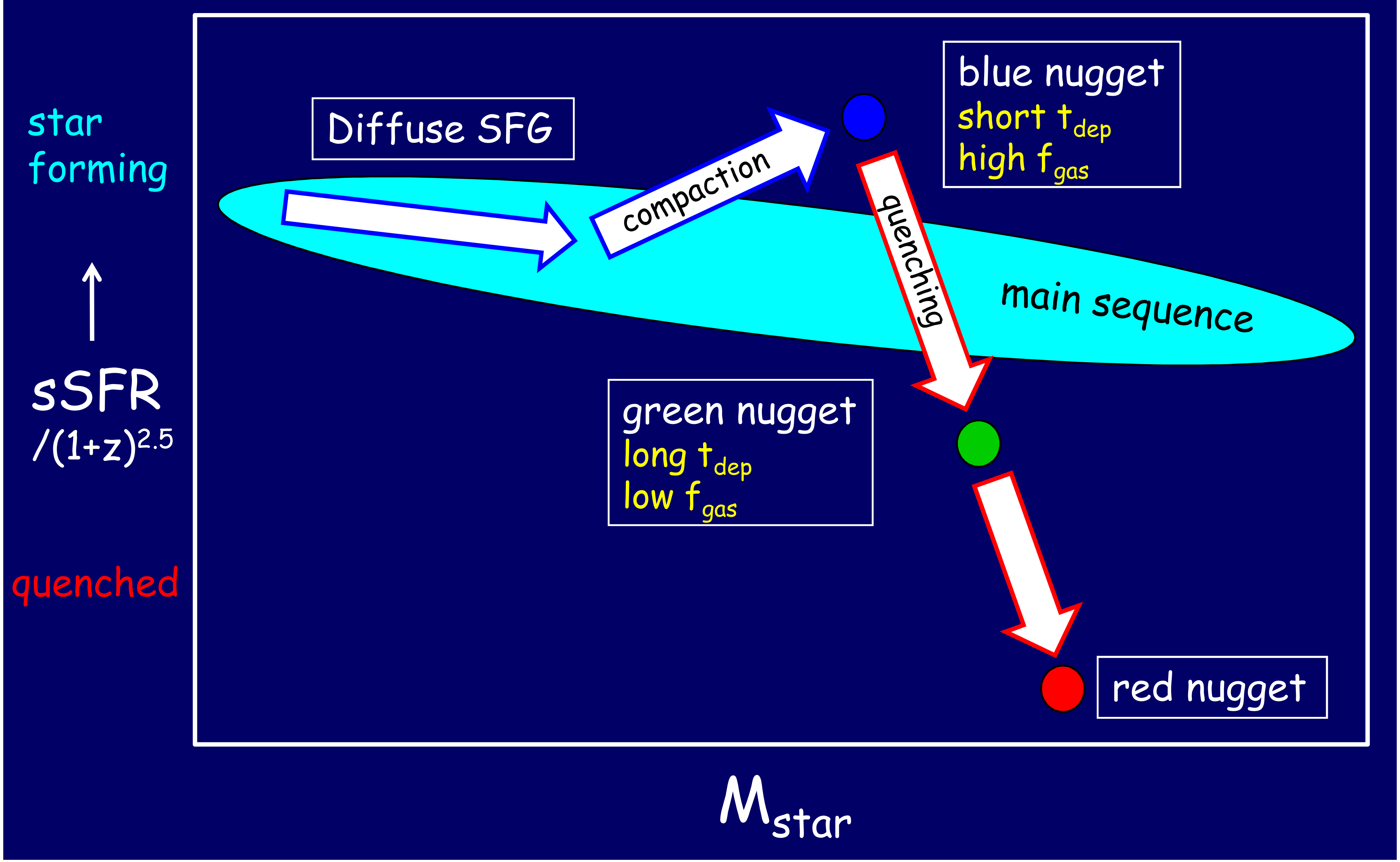
If halo is less massive → gas supply to a new disk
→ new compaction and SFR … until the halo is massive (hot)


Modes of Evolution
quenched
sSFR
star forming
low z, slow
high z, fast
Halo quenching
Halo quenching
maintenance
Compact quenching
gas consumption
stellar & AGN fdbk
morph. bulge quenching
lower M & $\Sigma_{gas\ disk}$ →
moderate compactness
hi M & $\Sigma_{gas\ disk}$ → wet inflow → hi gas compactness → starburst
diffuse
Σ
compact

Role of AGN Feedback in Quenching?



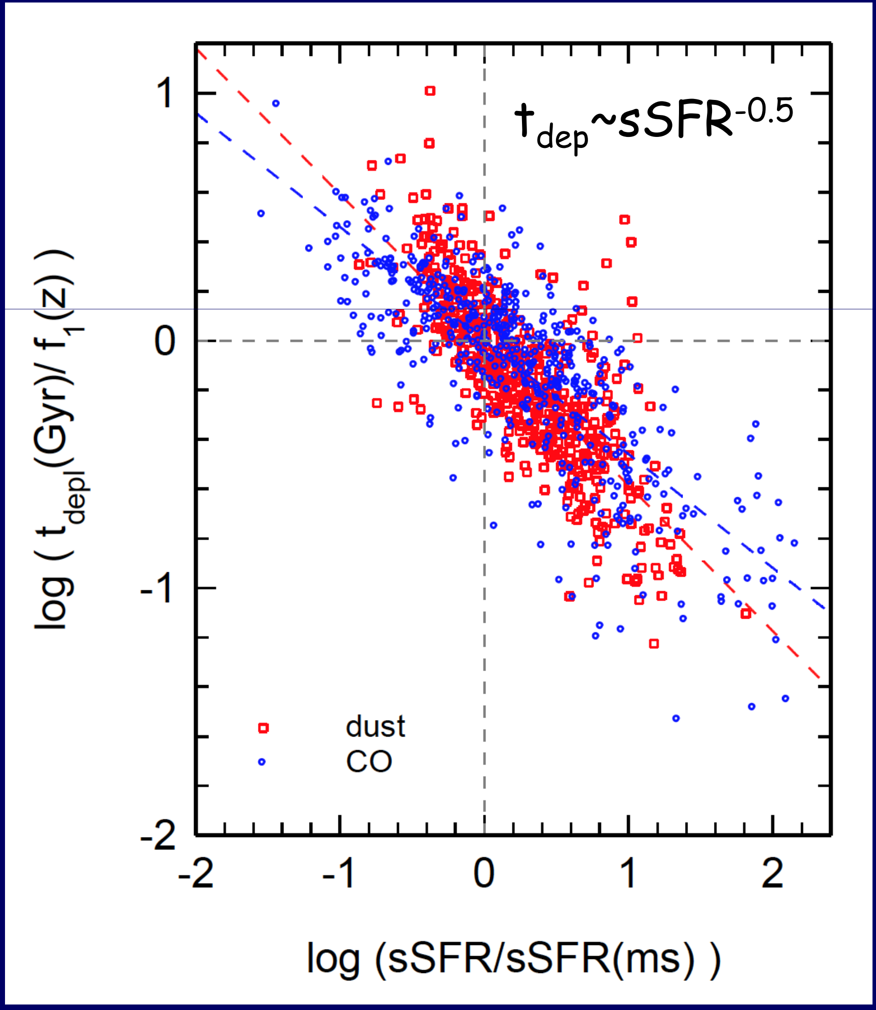
Gradients Across the Main Sequence



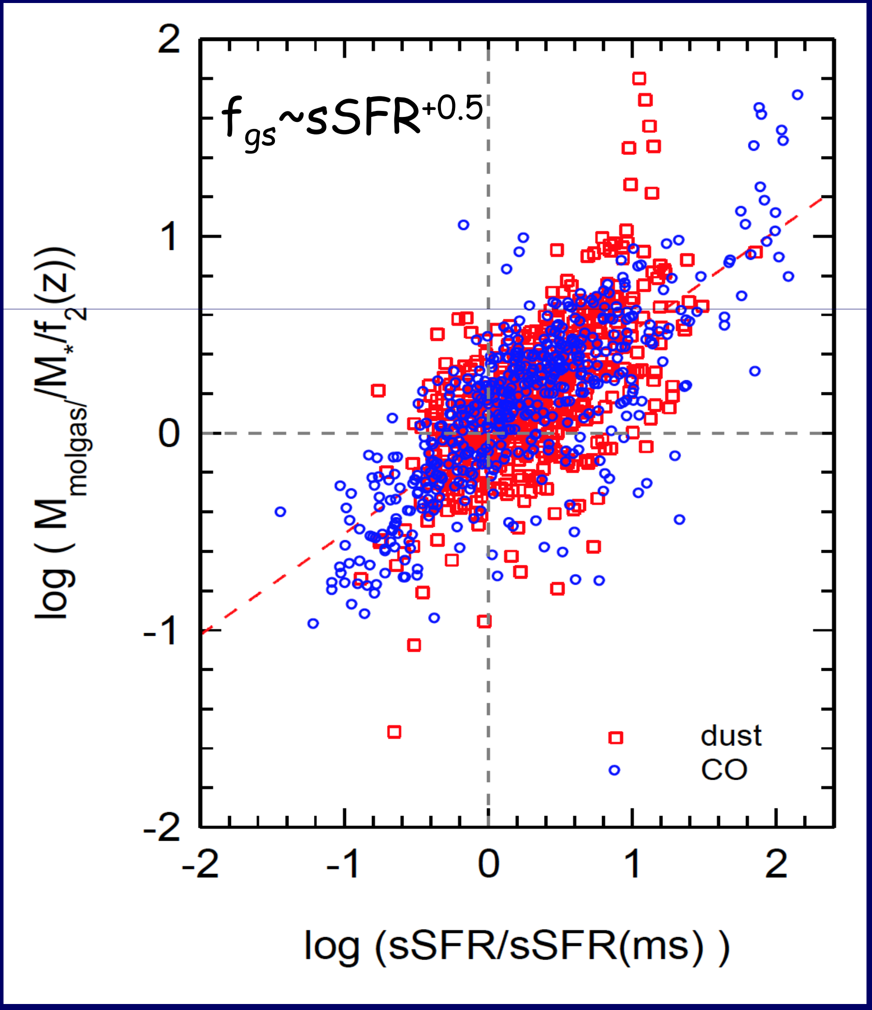
Gradients Across the Main Sequence

Genzel+ 2014 z=0-2.5

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



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



Conclusions: Quenching

A characteristic sequence of events at high z in most galaxies:

- wet compaction by 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)
  +gas rings

- 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

Conclusions

High-z massive galaxies at cosmic-web nodes
Fed by ~3 co-planar streams penetrating hot CGM
Angular-momentum:
- effective tidal torques on gas streams, AM transport to inner halo
- spiral-in through an extended rotating tilted ring (DLAS?)
- disk spin ≤ halo spin

Typical SFGs have perturbed rotating disks at violent 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 driven by inflow+mergers. Compressive turbulence?

A characteristic sequence of events:
- wet compaction by mergers and VDI into compact SFGs (blue nuggets)
- high SFR+AGN, outflows, massive self-gravitating bulge
  -> fast quenching to compact ellipticals (red nuggets) +gas rings (?)
- long-term quenching by hot massive halo -> downsizing of quenching

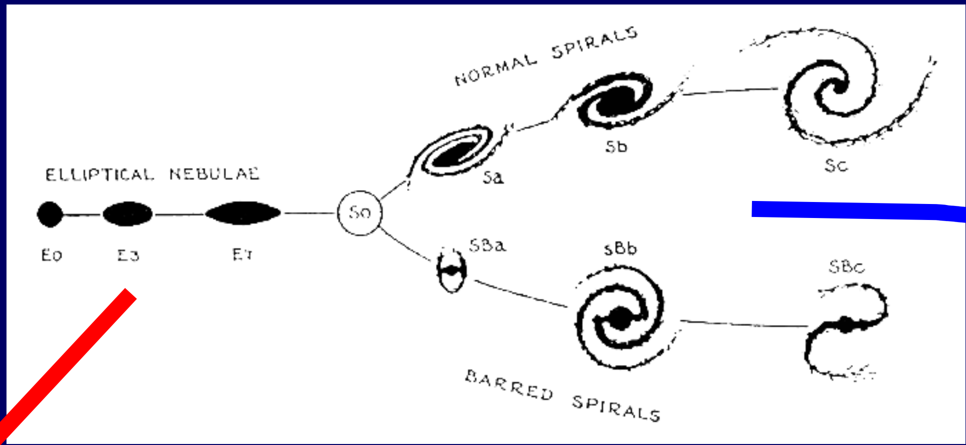
Conclusions

High-z massive galaxies at cosmic-web nodes
Fed by ~3 co-planar streams penetrating hot CGM
Angular-momentum:
- effective tidal torques on gas streams, AM transport to inner halo
- spiral-in through an extended rotating tilted ring (DLAS?)
- disk spin ~ halo spin, despite different history

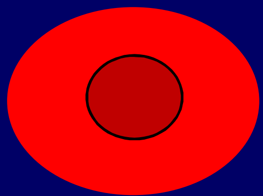
Typical SFGs have perturbed rotating disks at violent instability (VDI)
- Massive clumps ($>10^8 M_\odot$) survive feedback
- in-situ young clumps showing age gradient. Older ex-situ clumps
Stimulated nonlinear instability, by inflow+mergers.
compressive turbulence? Compressive tides? counter-rotating streams?

A characteristic sequence of events:
- wet compaction by mergers and VDI into compact SFGs (blue nuggets)
- high SFR+AGN, outflows, massive self-gravitating bulge
-> fast quenching to compact ellipticals (red nuggets) +gas rings (?)
- long-term quenching by hot massive halo -> downsizing of quenching

The High-z "Hubble" Sequence

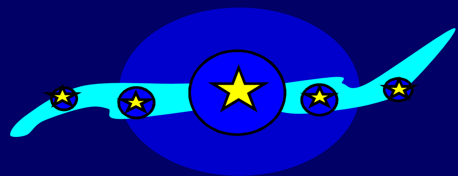


Red nuggets



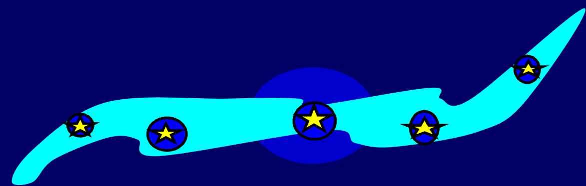
Compact ellipticals

Blue nuggets



Starburst in a
compact bulge

Clumpy disks



No bars
Perturbed spiral patterns

z=0

z=2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z=8