Feedback in High-z Galaxies

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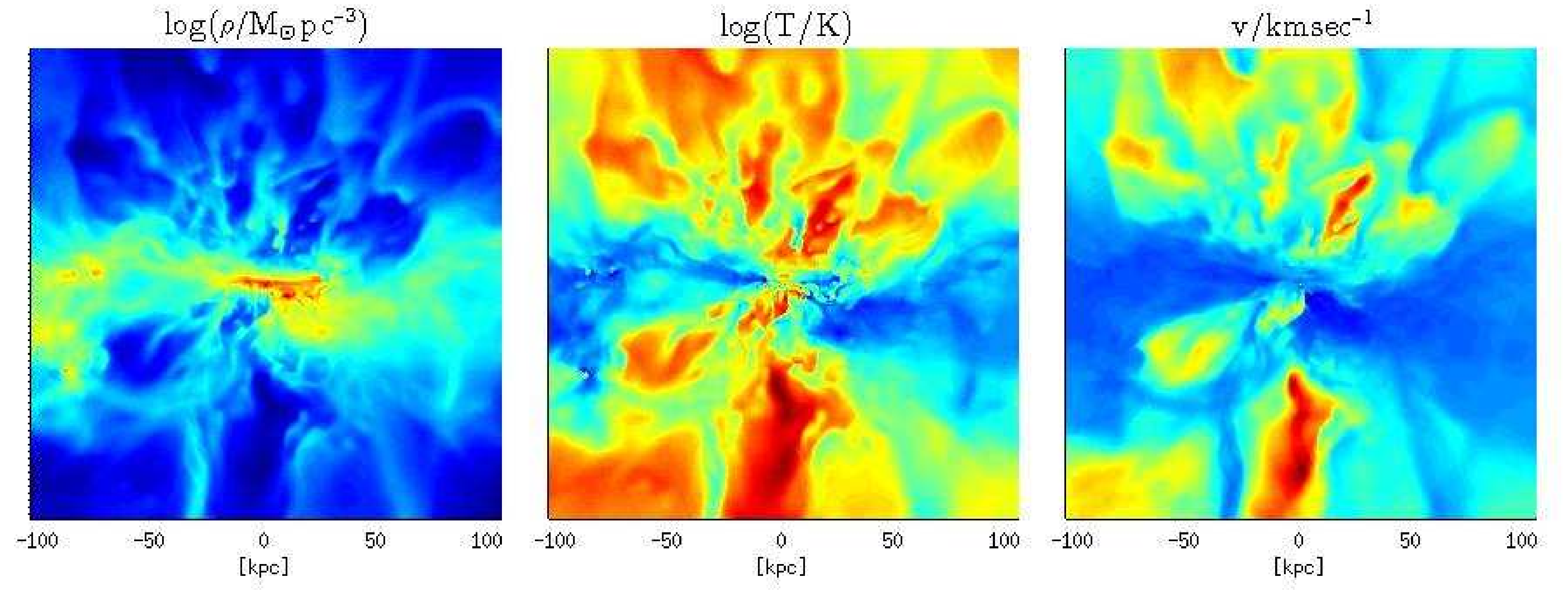


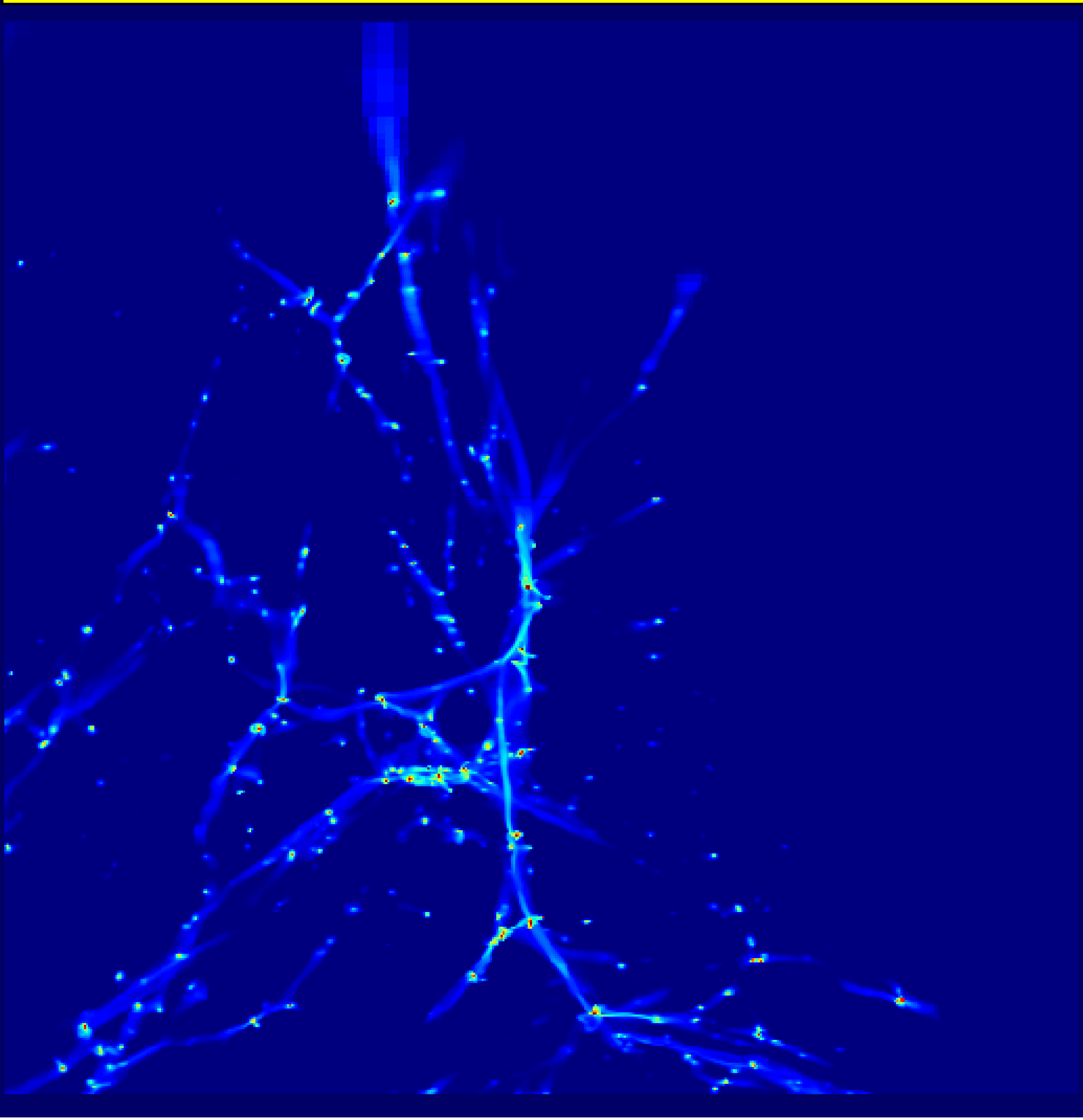
Outline

1. Inflows and outflows
2. Evolution of disk giant clumps
3. Compactification and quenching:

   blue nuggets and red nuggets

1. Inflows and Outflows

Cosmic-web Streams feed galaxies



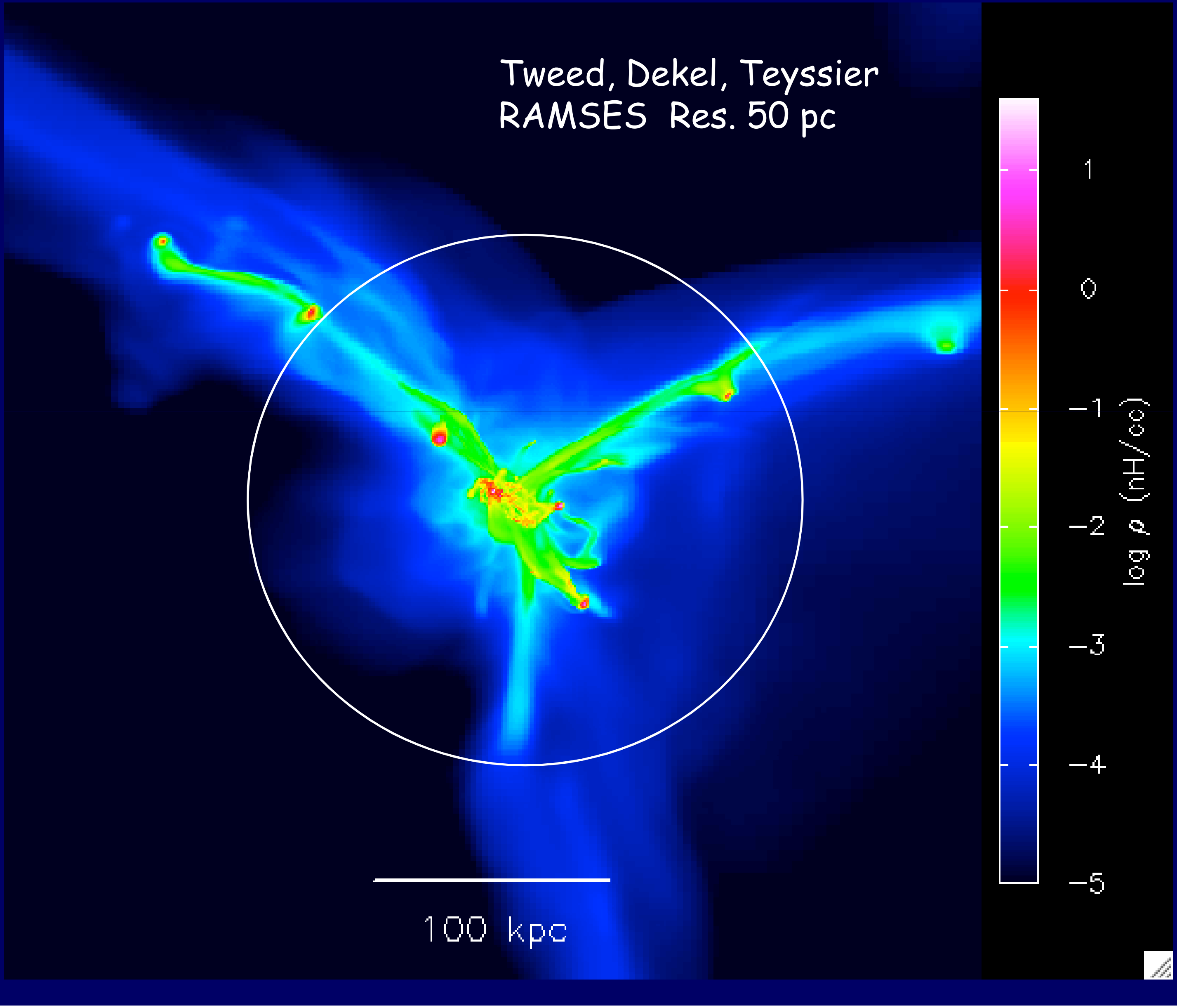
AMR RAMSES
Teyssier+

box 300 kpc

res 30 pc

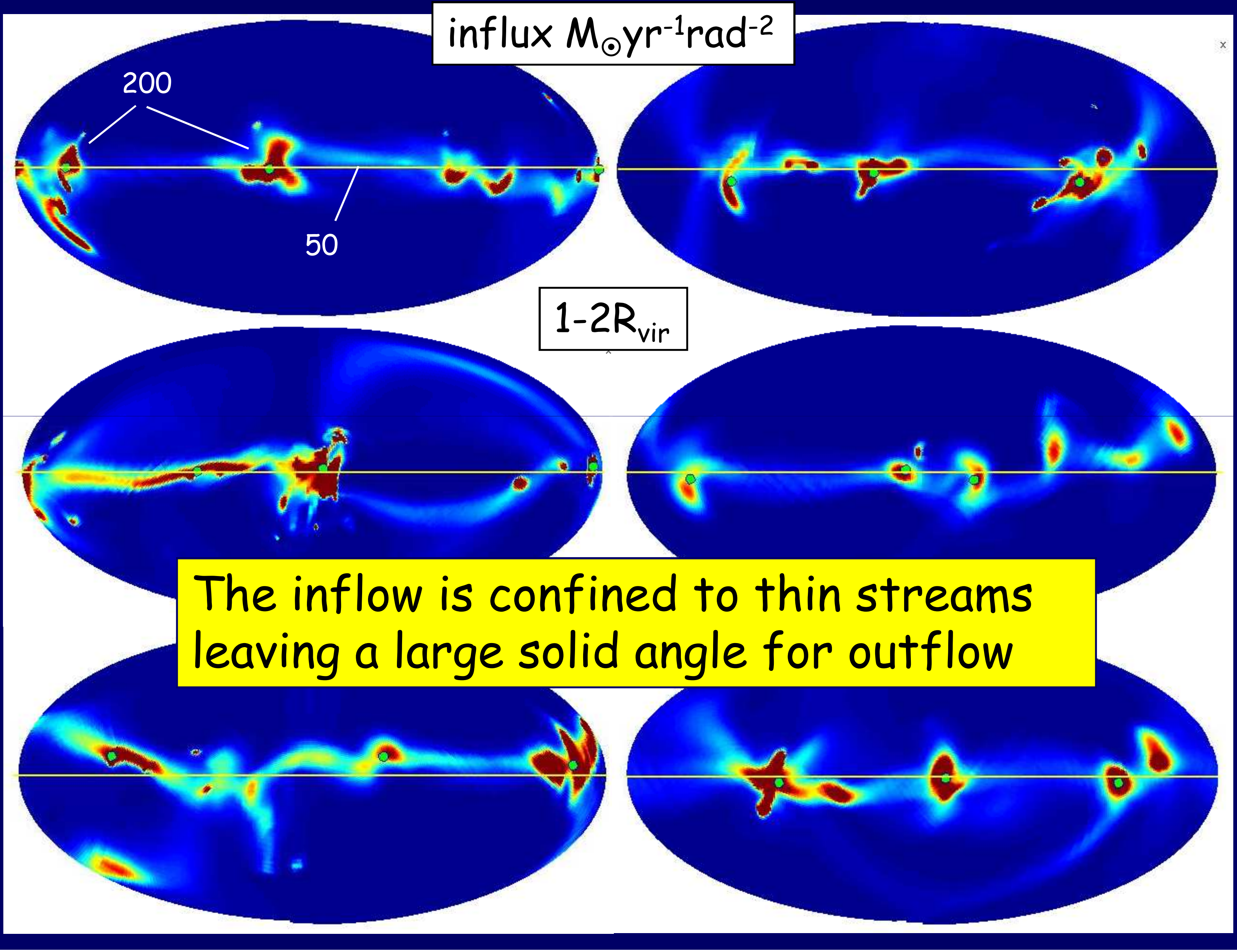
z = 5.0 to 2.5

Streams Feeding a High-z Galaxy



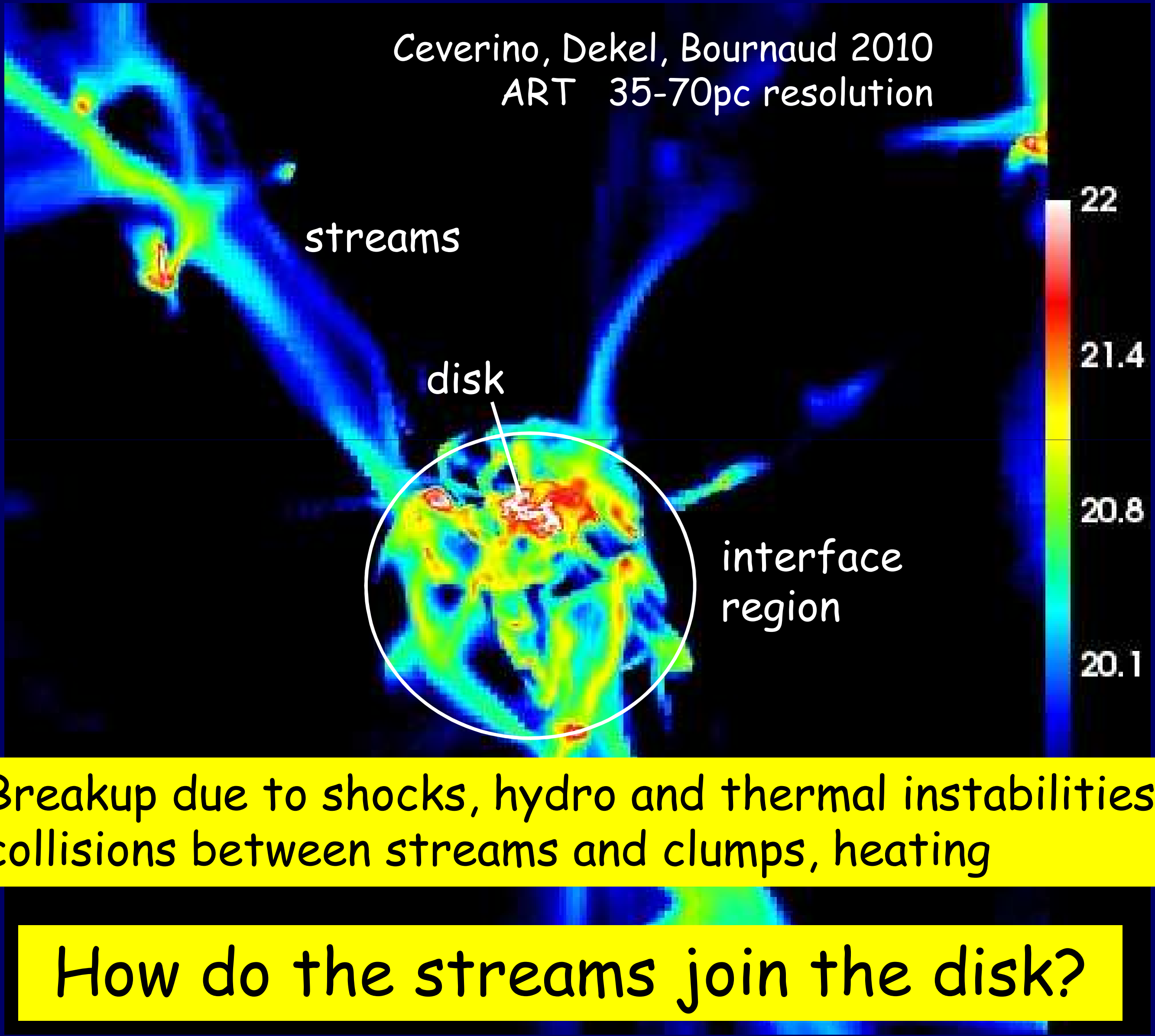
Co-planar Streams and Pancakes

Danovich, Dekel, Teyssier, Hahn 12



The inflow is confined to thin streams leaving a large solid angle for outflow

The Interface of Streams and Disk



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

How do the streams join the disk?

Angular Momentum Buildup by Cold Gas in 4 Phases

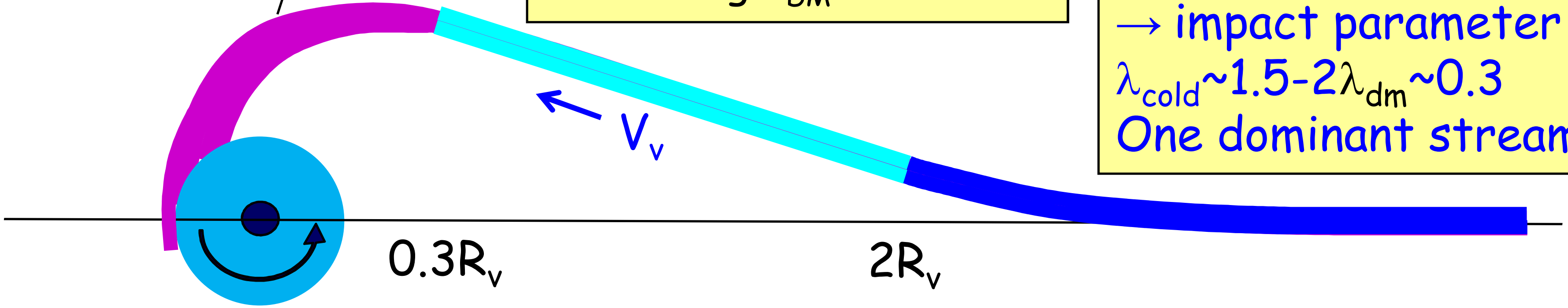
Danovich, Dekel, Hahn+ 2012, 2014
ART cosmological simulations, res 25pc

Pichon, Kimm, Devriendt, Slyz+
Stewart+

III. inner halo – outer tilted ring
non-linear torques, dissipation
AM loss $\lambda_{cold} \to 0.035$ & alignment

II. outer halo
AM transport, j~const.
$\lambda_{cold} \sim 3\lambda_{dm} \sim 0.1$
DM mixing $\lambda_{DM} \sim 0.035$

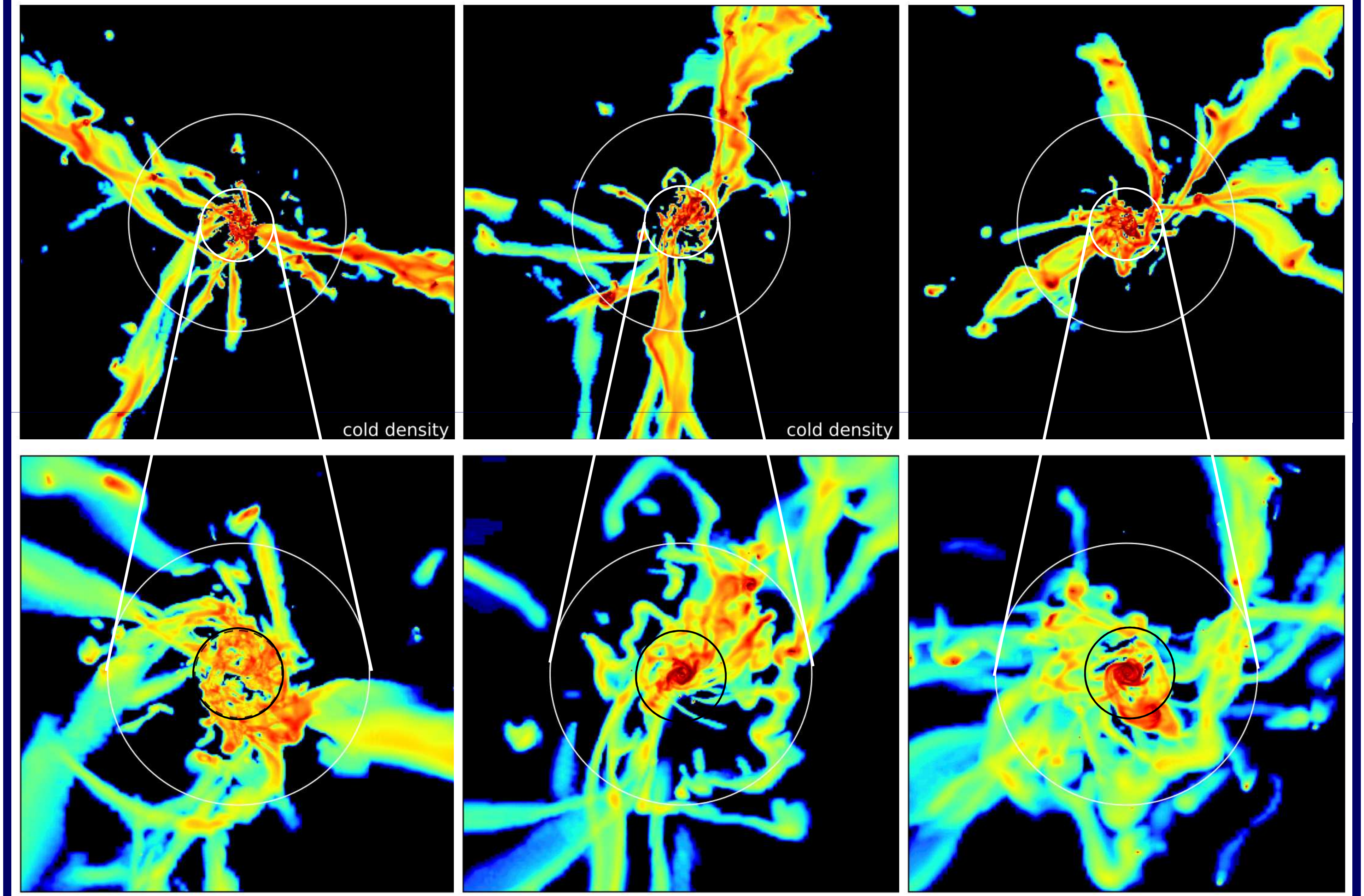
I. cosmic web
linear tidal torques
→ impact parameter
$\lambda_{cold} \sim 1.5\text{-}2\lambda_{dm} \sim 0.3$
One dominant stream



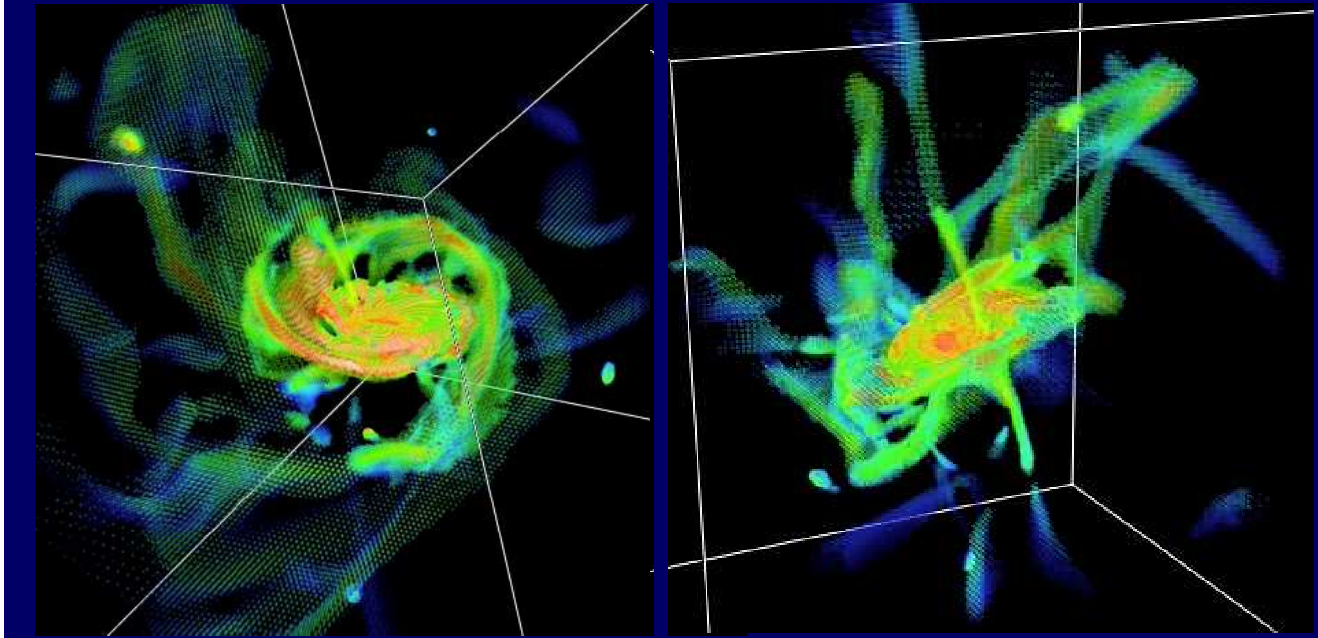
IV. inner disc + bulge
disk instability, outflows
$\lambda_{cold} \sim 0.035$

spin parameter
$\lambda = J/(MR_vV_v)$

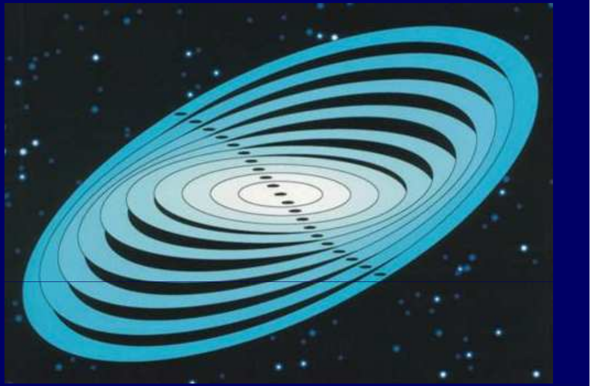
Outer Ring in the Inner Halo

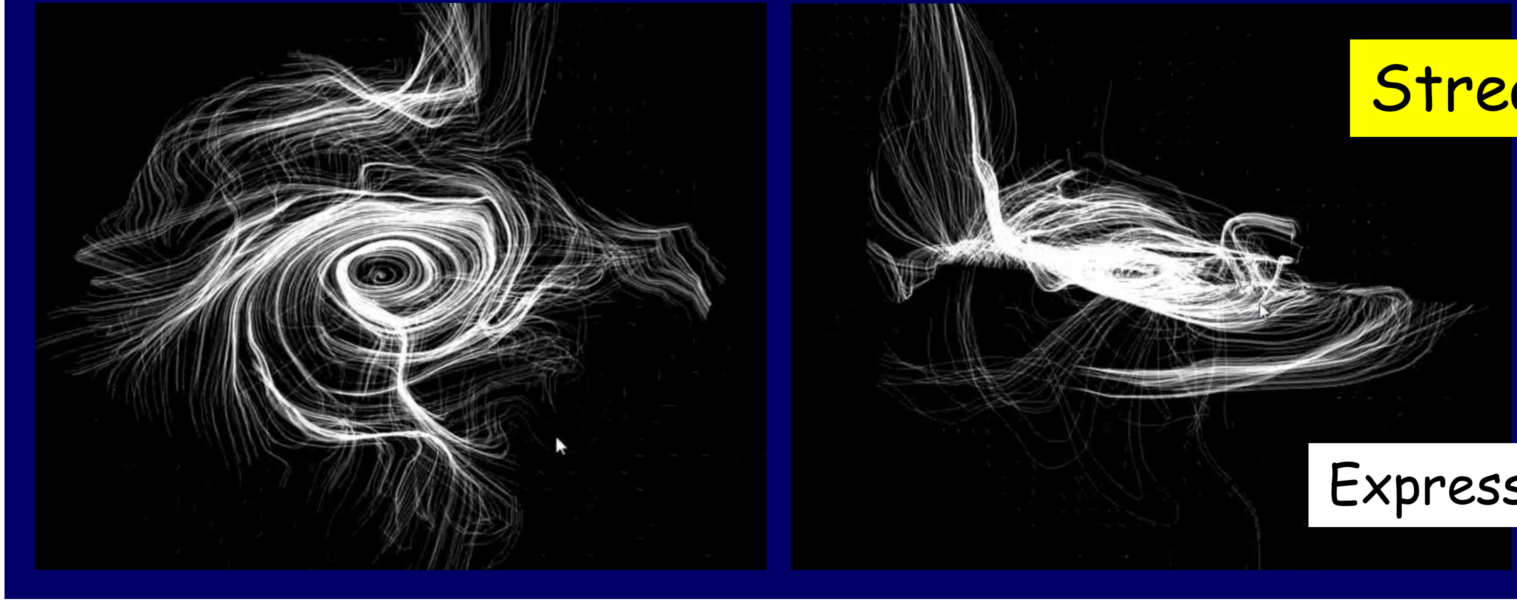


Disk and Tilted Outer Ring



Gas density

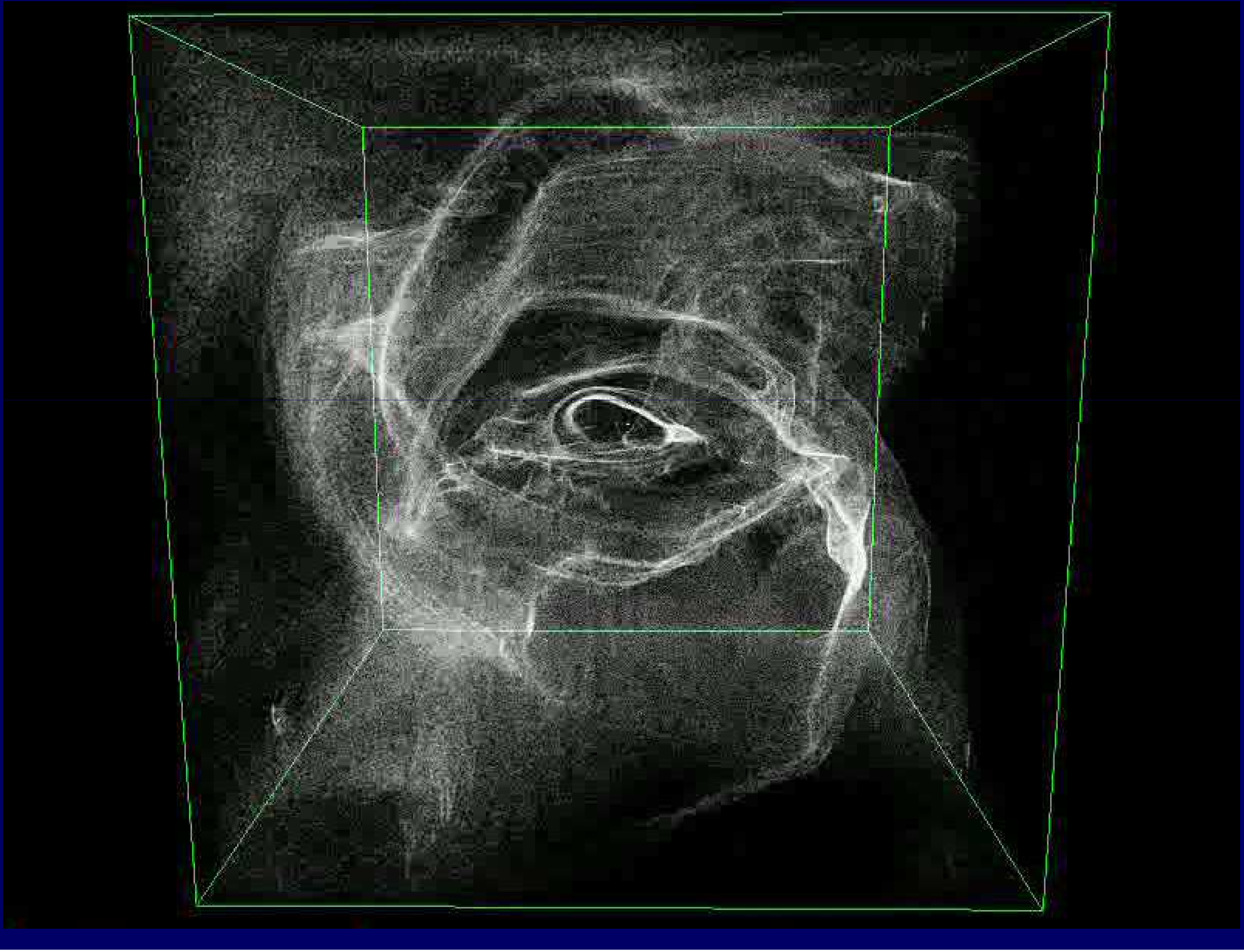




Stream lines

Expressway entrance

Inner disk and outer ring: stream lines



Feeddback in Cosmological Simulations

Ceverino, Klypin+ 14; House, Dekel, Ceverino+ 14

60 ART cosmological zoom-in simulations, resolution 25 pc

Main feedback mechanisms:

- SN feedback (energy):
  Heating for 40 Myr, no time delay, 30% runaway stars

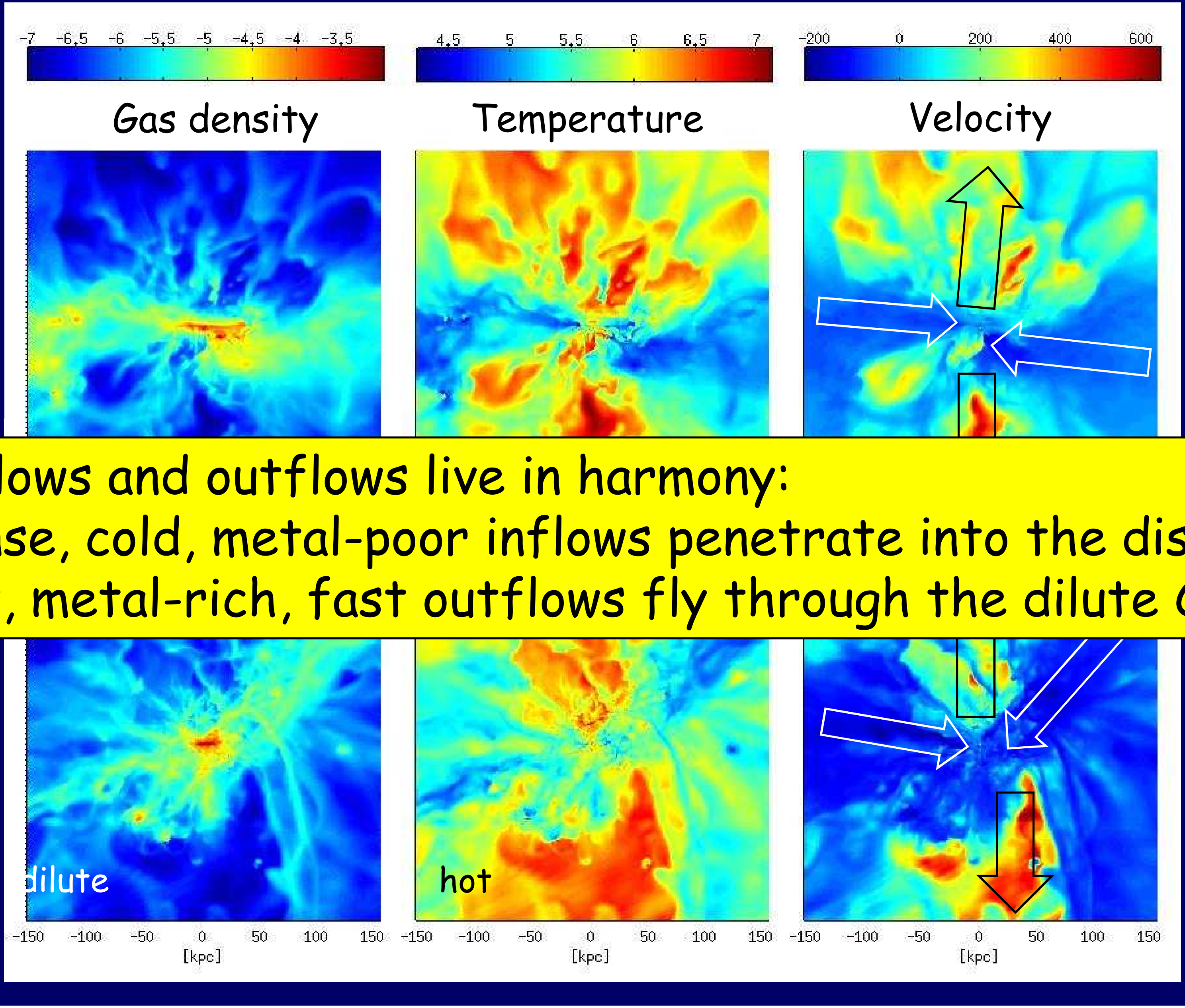
- Photo-heating and photo-ionization

- Radiation pressure (momentum):
  $P_{rad}=L/(cR^2)$ in adjacent cells, where $n_H>10^{21}$ cm^{-2}, for 5 Myr

Mass loading factor $\eta \sim 2$ (0.2-10)

Inflows and Outflows

House, Dekel,
Ceverino+ 14



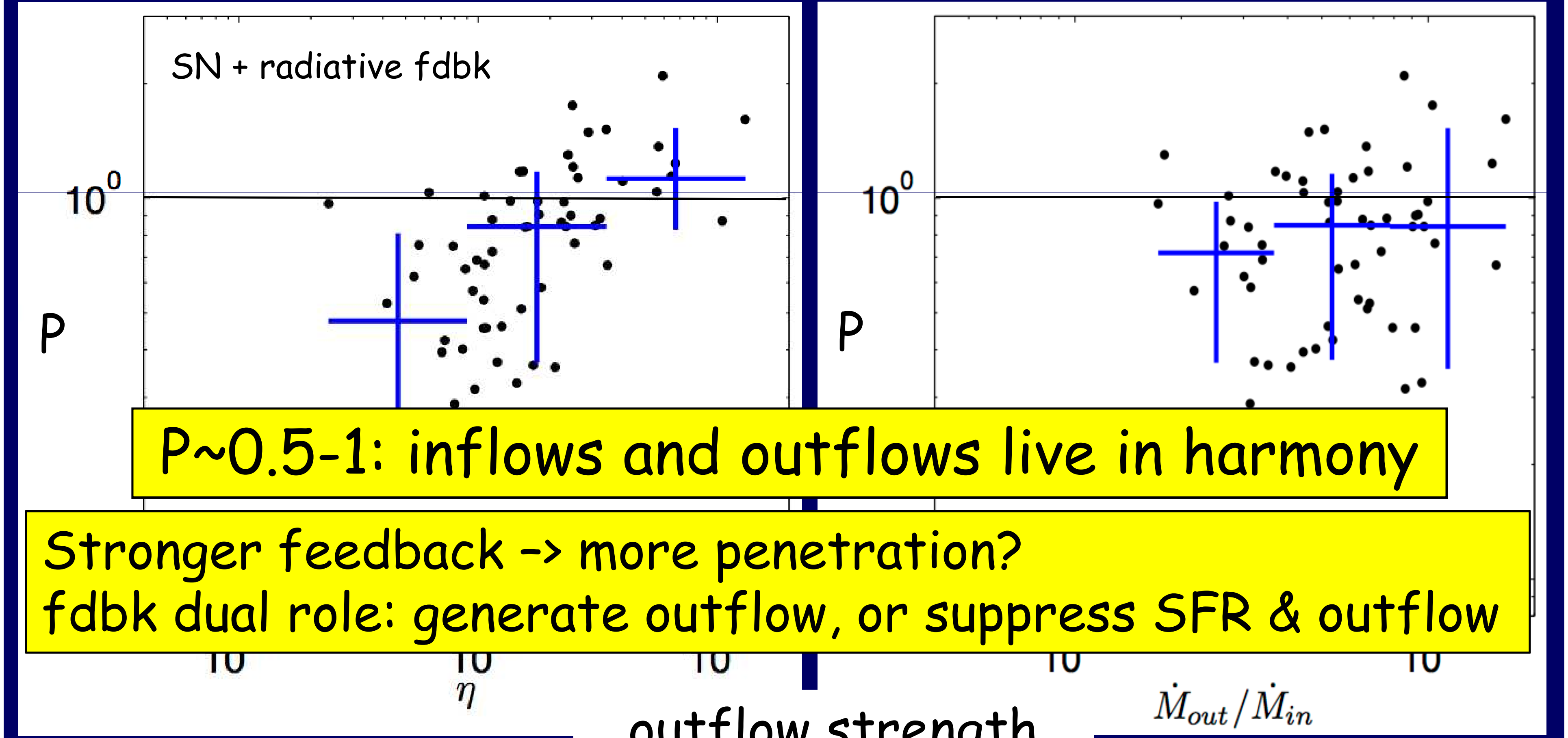
Inflows and outflows live in harmony:
Dense, cold, metal-poor inflows penetrate into the disk
Hot, metal-rich, fast outflows fly through the dilute CGM

$z=2.6$
$M_v=7\times10^{11}$

Inflow Penetration

House, Dekel, Ceverino+14: ART cosmological simulations 25pc res.

$$P = \dot{M}_{\rm in}(0.1R_{\rm v}) / \dot{M}_{\rm in}(R_{\rm v}) \quad Z < 0.1$$



P~0.5-1: inflows and outflows live in harmony

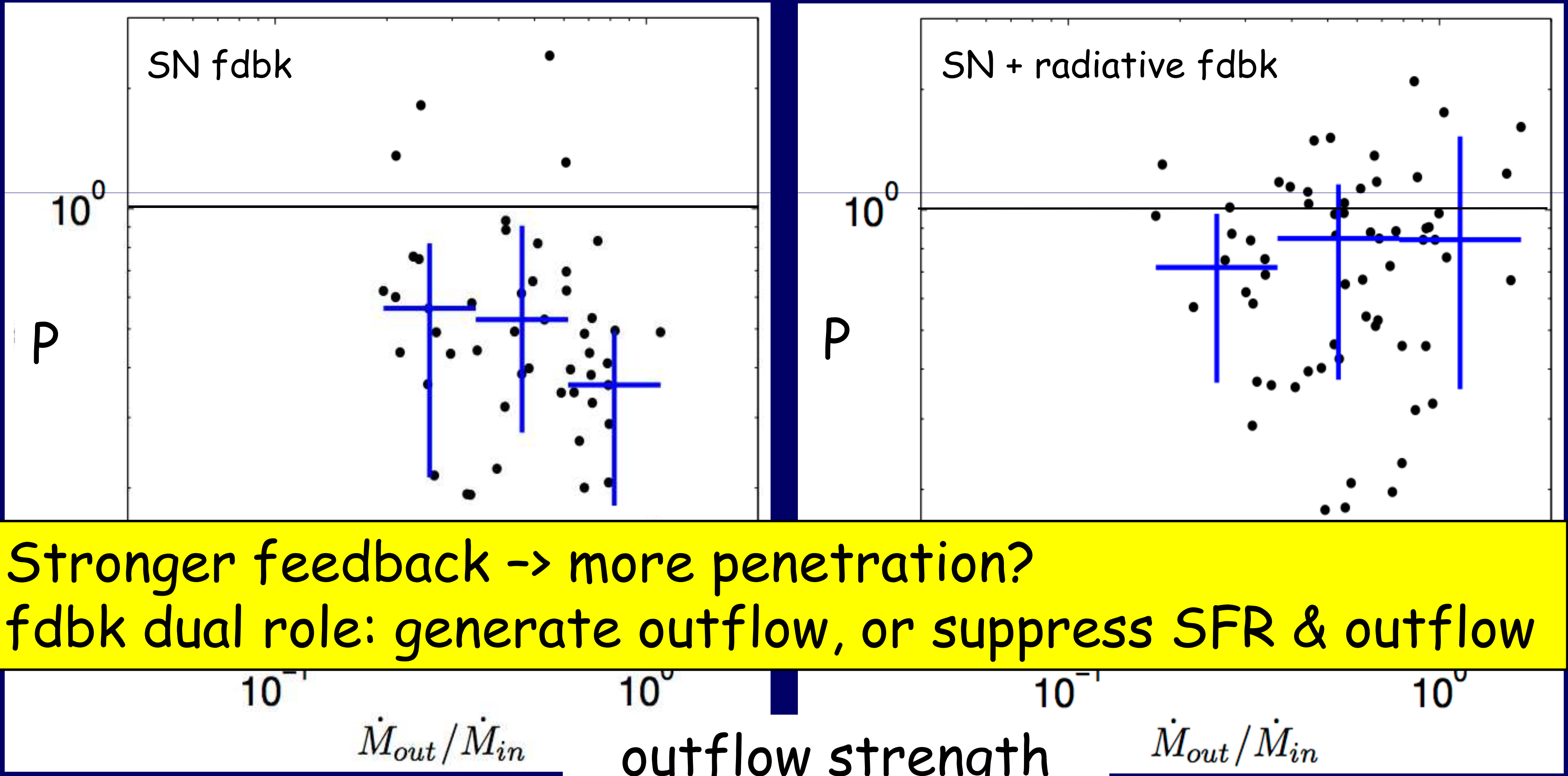
Stronger feedback -> more penetration?
fdbk dual role: generate outflow, or suppress SFR & outflow

outflow strength

Inflow Penetration

House, Dekel, Ceverino+14: ART cosmological simulations 25pc res.

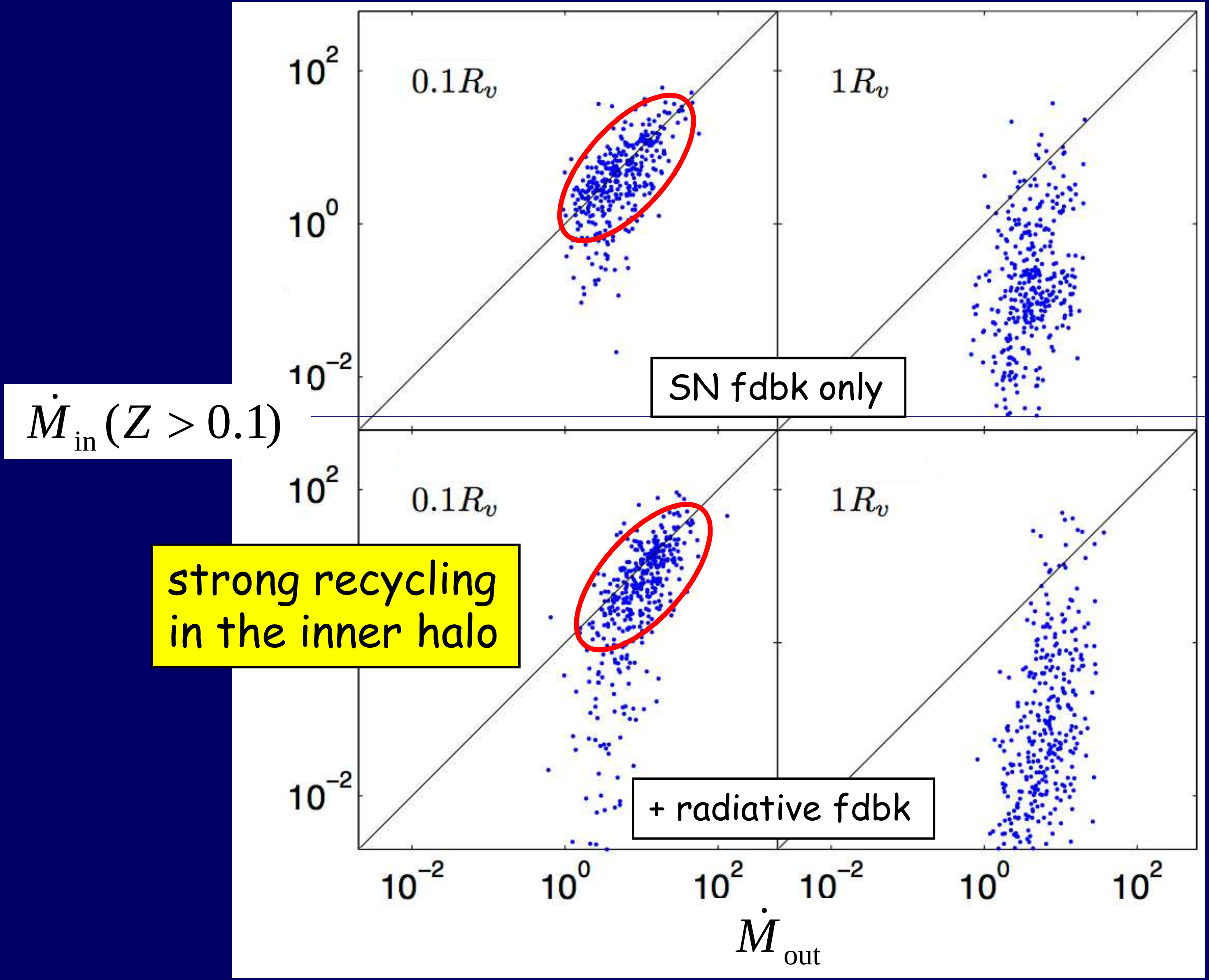
$$P = \dot{M}_{\rm in}(0.1R_{\rm v}) / \dot{M}_{\rm in}(R_{\rm v}) \quad Z < 0.1$$



Stronger feedback -> more penetration?
fdbk dual role: generate outflow, or suppress SFR & outflow

outflow strength

Strong Recycling of Outflows



SN fdbk only

+ radiative fdbk

strong recycling
in the inner halo

Bathtub Toy Model

Dekel, Mandelker 14

Continuity

$$\dot{M}_{\rm g} = f_{\rm ga}\dot{M}_{\rm a} - (\mu+\eta)\dot{M}_{\rm sf}$$

$$\dot{M}_{\rm s} = f_{\rm sa}\dot{M}_{\rm a} + \mu\dot{M}_{\rm sf}$$

$$\eta = \dot{M}_{\rm loss}/\dot{M}_{\rm sf} = \eta_{\rm out} - \eta_{\rm rec}$$

$\mu \approx 0.5$ fraction left in stars

Accretion rate

$$\dot{M}_{\rm a}/M_{\rm a} = 0.03\,Gyr^{-1}(1+z)^{5/2}$$

$$M_{\rm a} = M_{\rm ai}e^{-0.8(z-z_i)}$$

Neistein, Dekel 08; Dekel et al 13

SFR

$$\dot{M}_{\rm sf} = M_{\rm g}/t_{\rm sf} \qquad t_{\rm sf} = \varepsilon^{-1}t_{\rm d} \propto t$$

$$\dot{M}_{\rm g} = A - \tau^{-1}M_{\rm g}$$

Quasi-steady-state: $M_{\rm g} \approx A\tau$

Observables:

gas fraction

$$f_{\rm g}^{-1} = 1 + \frac{\mu + \cancel{f_{\rm sa}\eta}}{f_{\rm ga}\,t_{\rm sf}/t_{\rm a}}$$

$$t_{\rm sf}/t_{\rm a} \propto \varepsilon^{-1}(1+z)$$

f(ε), slowly declining with t

star/halo fraction

$$\frac{M_{\rm s}}{M_{\rm v}} = pf_{\rm b}\frac{\mu + \cancel{f_{\rm sa}\eta}}{\mu+\eta}$$

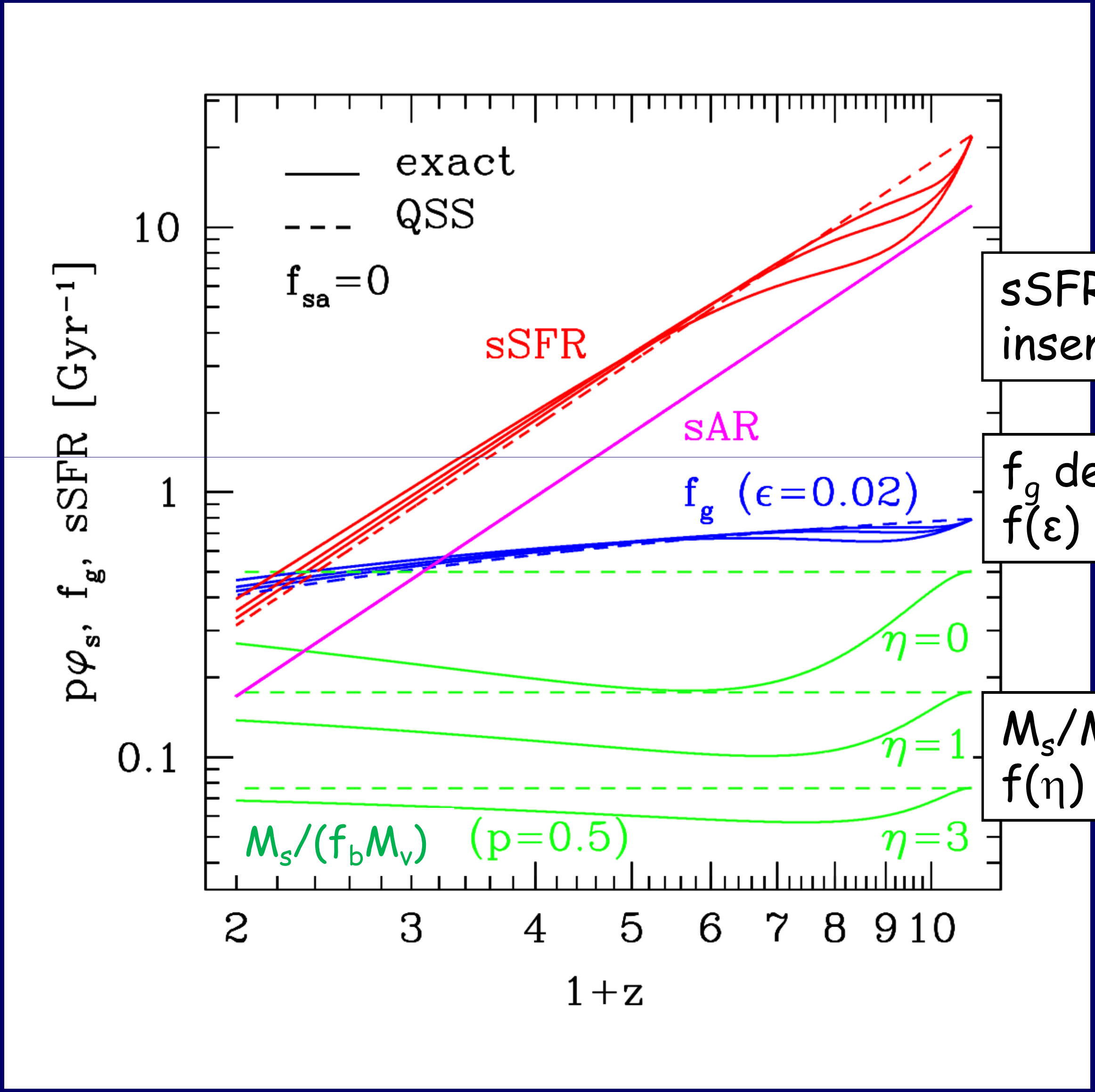
f(η), constant

sSFR

$$\frac{\dot{M}_{\rm sf}}{M_{\rm s}} = \frac{f_{\rm ga}}{\mu + \cancel{f_{\rm sa}\eta}}\frac{\dot{M}_{\rm a}}{M_{\rm a}}(t)$$

independent of ε,η, >sAR

Bathtub Toy Model: Solution



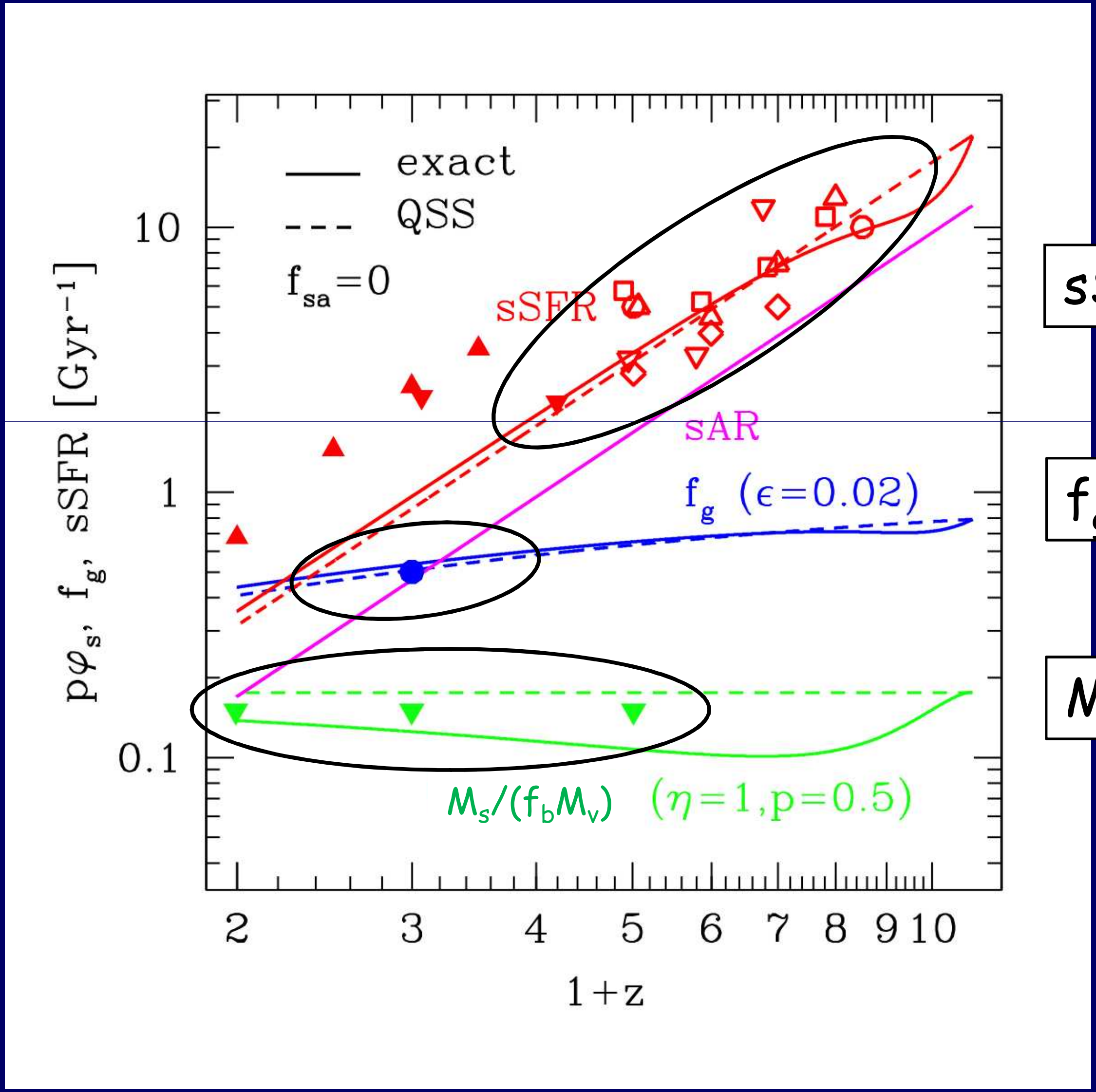
sSFR > sAR
insensitive to ε,η

f_g declines slowly
f(ε)

M_s/M_v ~const.
f(η)

Bathtub Toy Model vs Observations

If gaseous accretion (high z?): a good fit at z>3



sSFR > sAR

$f_g \rightarrow \varepsilon$~0.02

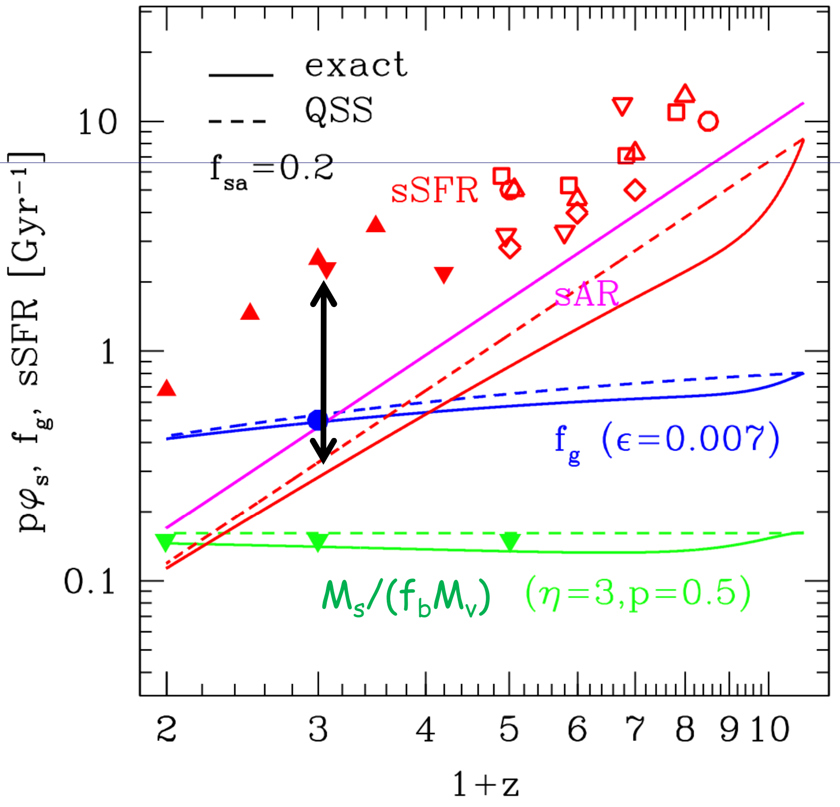
$M_s/M_v \rightarrow \eta$~1

Bathtub Toy Model vs Observations

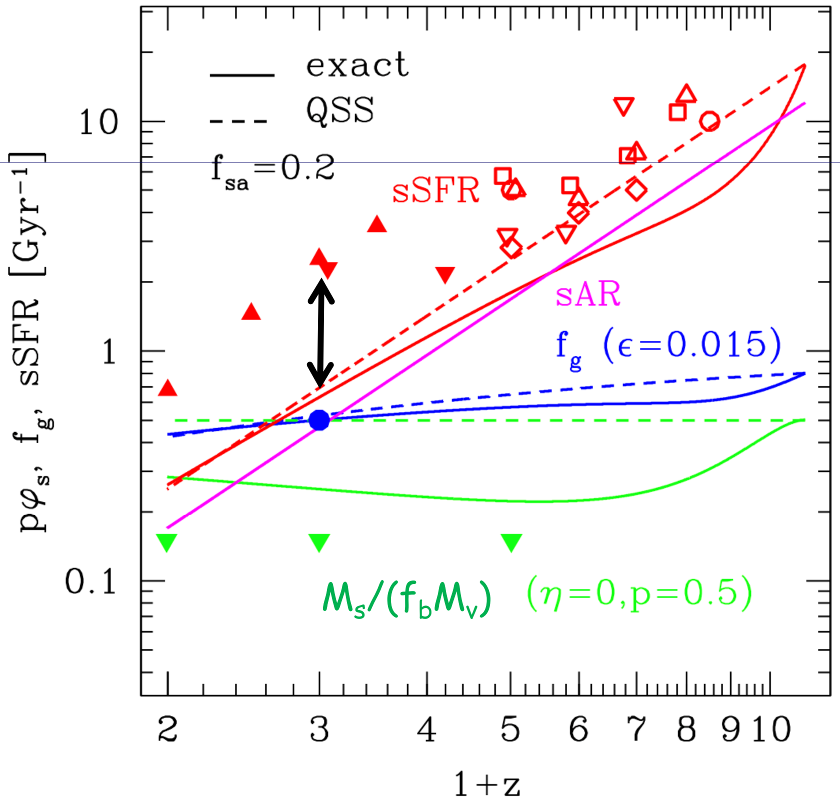
If some stellar accretion: can't match the high sSFR at z~2

Modeling recycling? Observational bias? Toy model invalid?

strong outflow



+strong recycling



2. Evolution of Disk Giant Clumps

Violent Disk Instability (VDI) at High z

High gas density because
- denser universe
- high accretion rate $\dot{M} / M \approx 0.03\,(1+z)^{2.5}\ \mathrm{Gyr}^{-1}$
- suppressed SFR

Neistein, Dekel 08; Dekel et al 13

→ Toomre disk instability

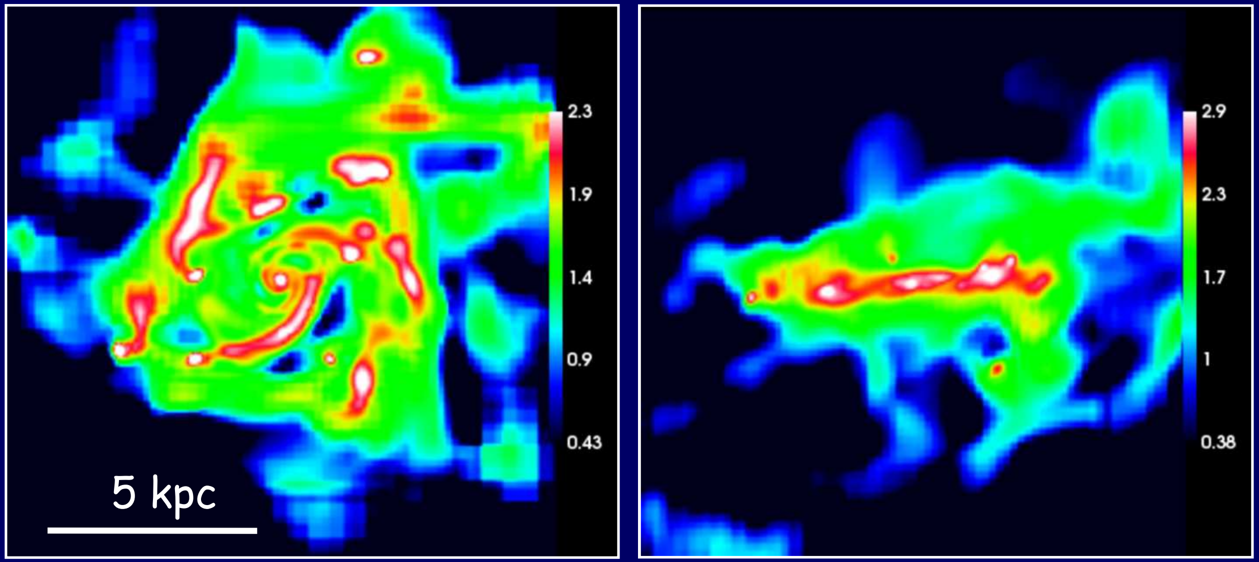
$$Q \propto \frac{\sigma_{\mathrm{cold}}\,\Omega}{G\Sigma_{\mathrm{cold}}} \leq 1$$

→ giant clumps and transient perturbations ~$10^9 M_\odot$

$$R_{\mathrm{clump}} \propto \frac{G\Sigma_{\mathrm{cold}}}{\Omega^2}$$

affecting the disk dynamics,
rapid evolution on a disk dynamical timescale

→ violent, not secular



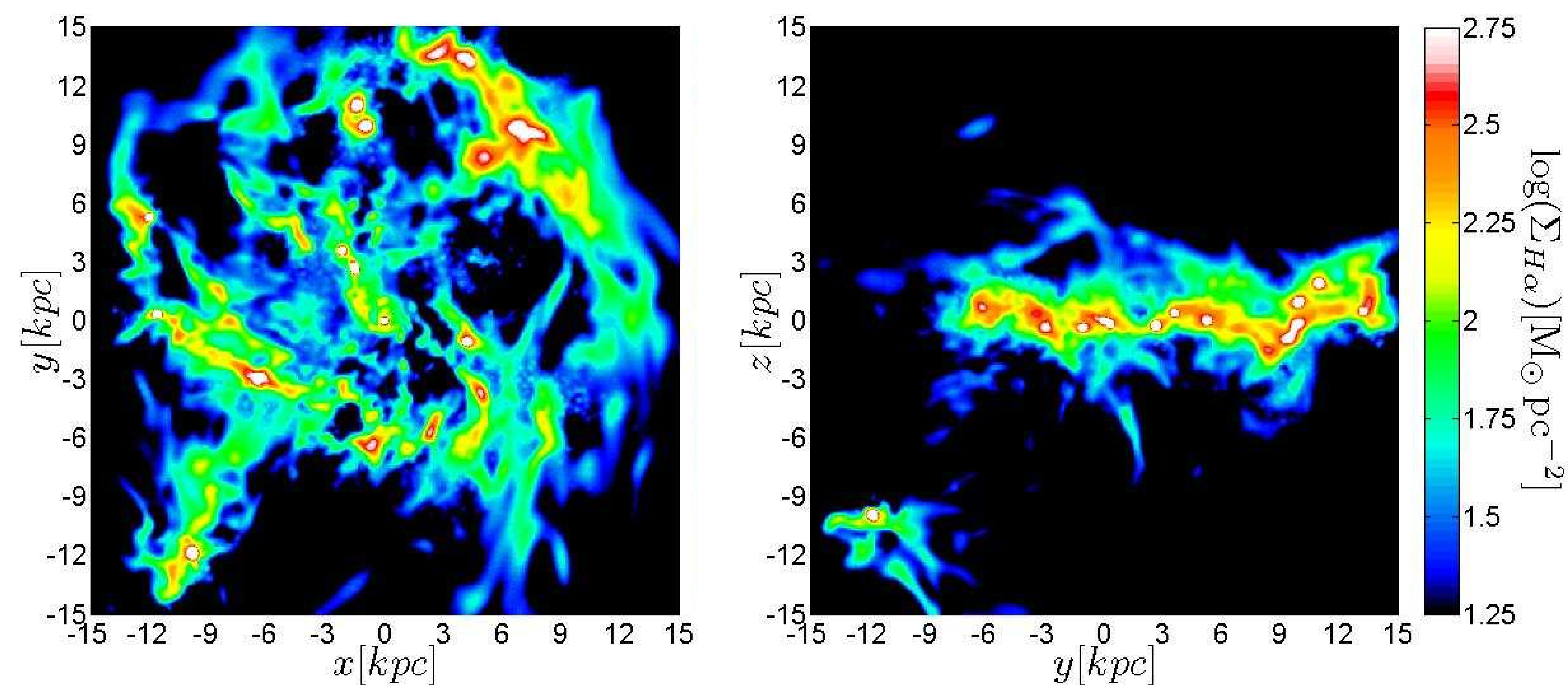
Toomre 64;

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

In cosmology:
Dekel, Sari, Ceverino 09; Agertz + 09; Ceverino + 09,11; Genel + 12; Cacciato + 12; Forbes +13; Dekel + 13

Violent Disk Instability (VDI) at High z

Ceverino+ ART-AMR cosmological simulations at 25pc resolution

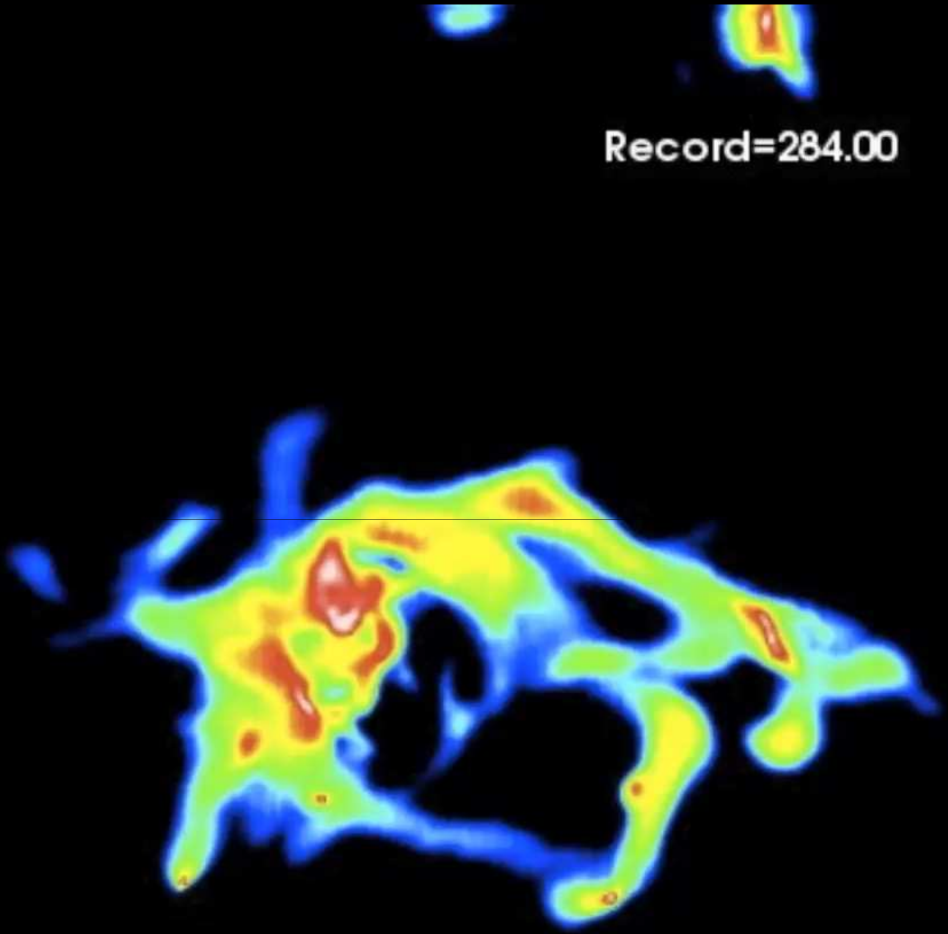


Clumpy Disk

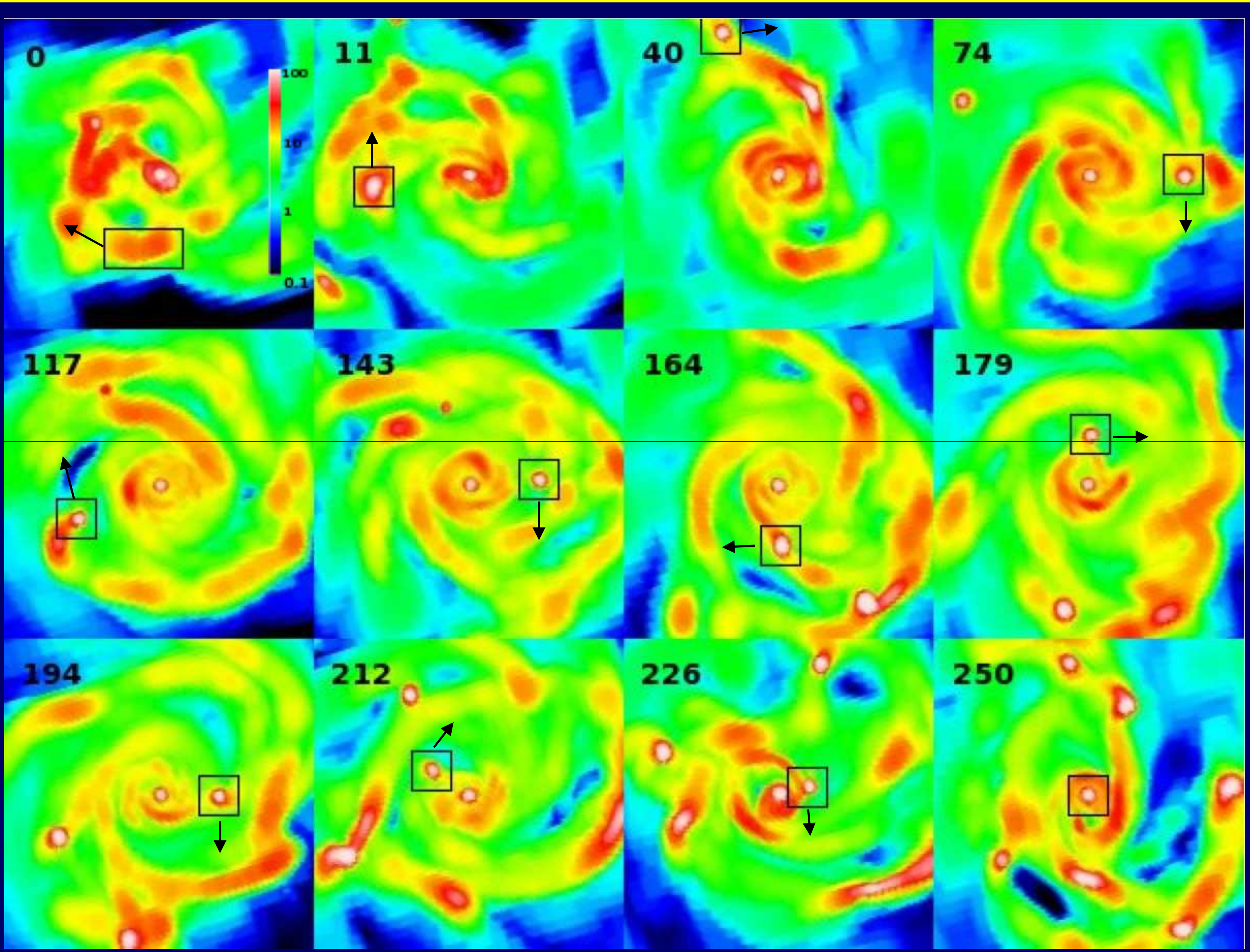
Ceverino, Dekel+ 2010
res 50 pc

10 kpc

z=4-2.1

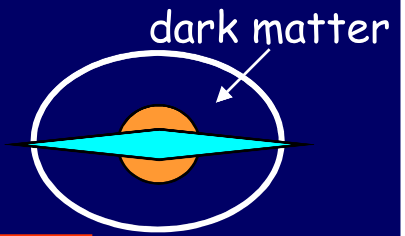


Clump Migration on an Orbital Timescale



Ceverino, Dekel, Bournaud 10

Clump Evolution during Migration



Toomre instability $1 \approx Q \approx \delta^{-1} \dfrac{\sigma}{V}$ $\delta \equiv \dfrac{M_{\rm disk}}{M_{\rm tot}(R_{\rm disk})}$

- Migration to center: torques, encounters, dyn. friction $\boxed{t_{\rm mig} \approx \delta^{-2}\, t_{\rm dyn} \approx 8 t_{\rm dyn} \approx 250 {\rm Myr}}$

Dekel, Sari, Ceverino 09

- Mass gain $\dot{M}_{\rm acc} \approx \rho_{\rm d} R_{\rm T}^2\, \sigma_{\rm d}$ $\longrightarrow$ $\boxed{t_{\rm acc} \approx 8 t_{\rm dyn} \approx t_{\rm mig}}$

Dekel, Krumholz 13; Bournaud+ 13; Mandelker+ 14

- Star formation $\boxed{t_{\rm sfr} \approx (3\varepsilon_{\rm sfr})^{-1}\, t_{\rm dyn} \approx 30\, t_{\rm dyn} \approx 3 t_{\rm mig}}$

- Momentum-driven outflows; steady wind

$\dot{p}_{\rm w} = \psi_{\rm w} V_L \dot{M}_*$ $L/c = V_L \dot{M}_*$ $V_L \approx 160\ {\rm km\ s}^{-1}$

Dekel, Krumholz 13

STARBURST99

Simulations wind instability Krumholz, Thompson 13; Davis+ 14

+proto-stellar winds + stellar winds + supernovae → $\psi_{\rm w} \approx 2.5$ $\eta \approx 1\!-\!2$

Consistent with observed

$\boxed{t_{\rm out} \approx (3\eta\varepsilon_{\rm sfr})^{-1} t_{\rm dyn} \approx \eta^{-1} t_{\rm sfr} \approx (1-2)\, t_{\rm mig}}$

$$\boxed{t_{\rm mig} \approx t_{\rm acc} \le t_{\rm out} \le t_{\rm sfr}}$$

Clump Evolution during Migration

$$\dot M_{gas} = \dot M_{acc} - \dot M_{sfr} - \dot M_{out}$$

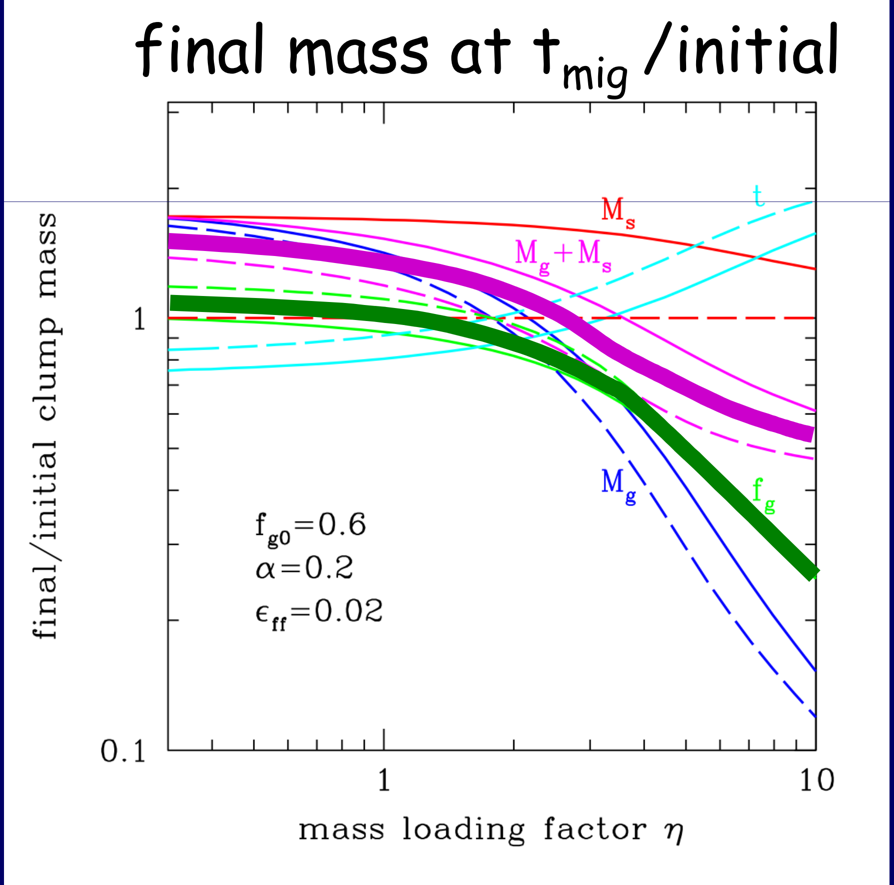
$$0 \le \dot M_{stars} \le 3\varepsilon_{sfr} t^{-1}_{dyn} M_{gas}$$

max tidal stripping SFR only

$$\dot M_{gas} \equiv t^{-1}_{gas} M_{gas}$$

$$t^{-1}_{gas} = t^{-1}_{dyn} [(8 f_{gas})^{-1} - 3(1+\eta)\varepsilon_{sfr}]$$

final mass at t_{mig} /initial



any η, mass varies by < x2

η~2-4, M_{clump} ~ const.

η<<1, M_{clump} ~ x2

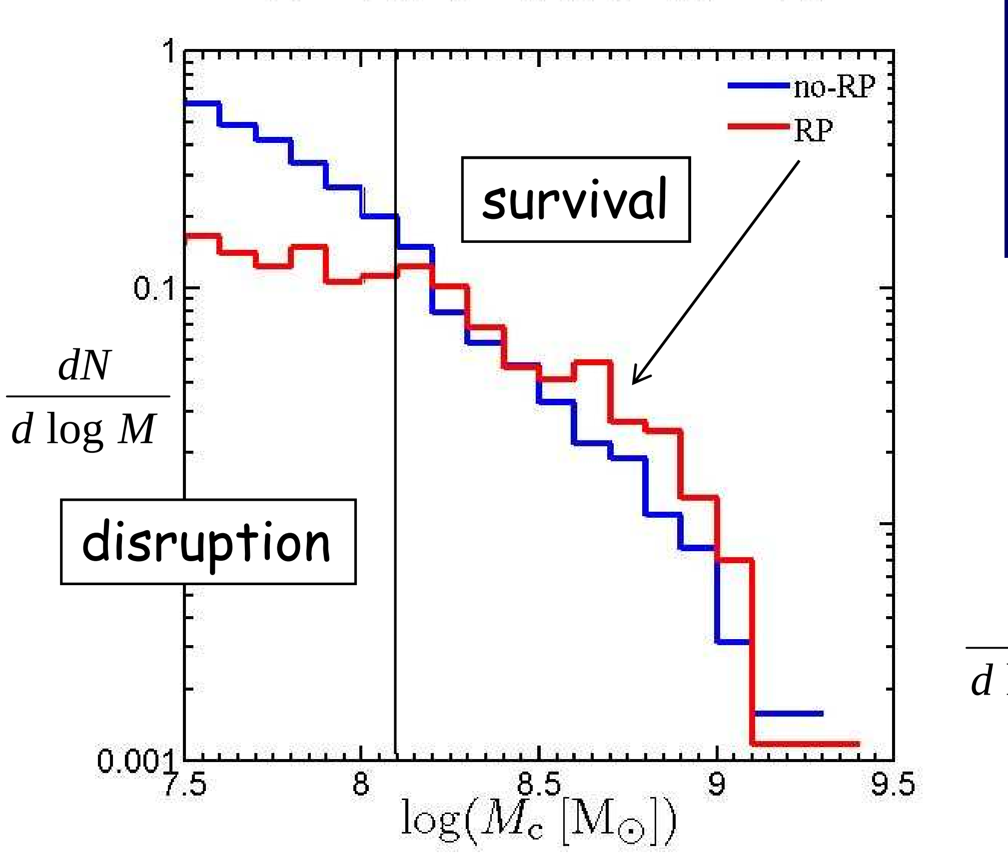
η>>1, $M_{clump} \rightarrow 0$

for η<4, f_{gas} ~ const.

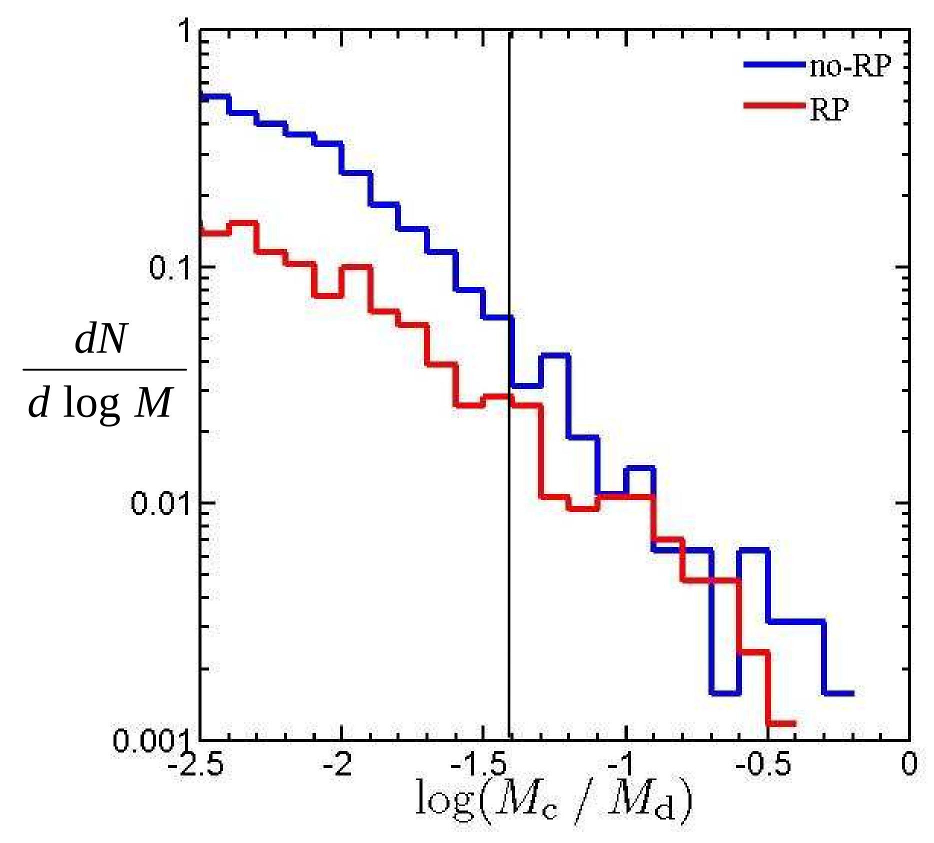
Confirmed in simulations
Bournaud+ 13, Mandelker+ 14

The Effect of Radiative Fdbk on Clumps

Mandelker, Ceverino+ ART-AMR cosmological simulations, 25pc resolution



giant clumps survive, small clumps disrupt

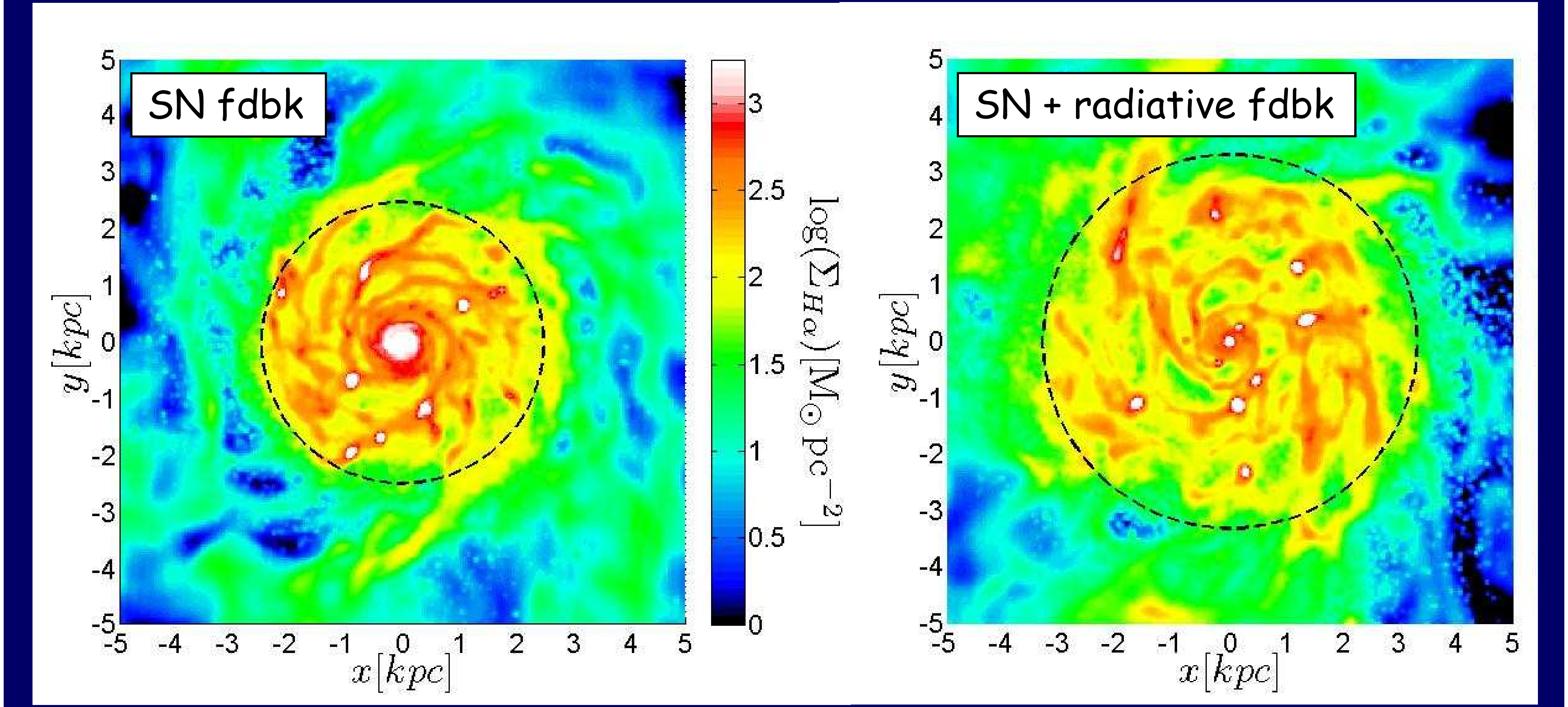


The Effect of Radiative Fdbk on Clumps

Mandelker, Ceverino+ ART-AMR cosmological simulations, 25pc resolution

gas disk expands, bulge may lose gas
giant clumps survive, small clumps disrupt

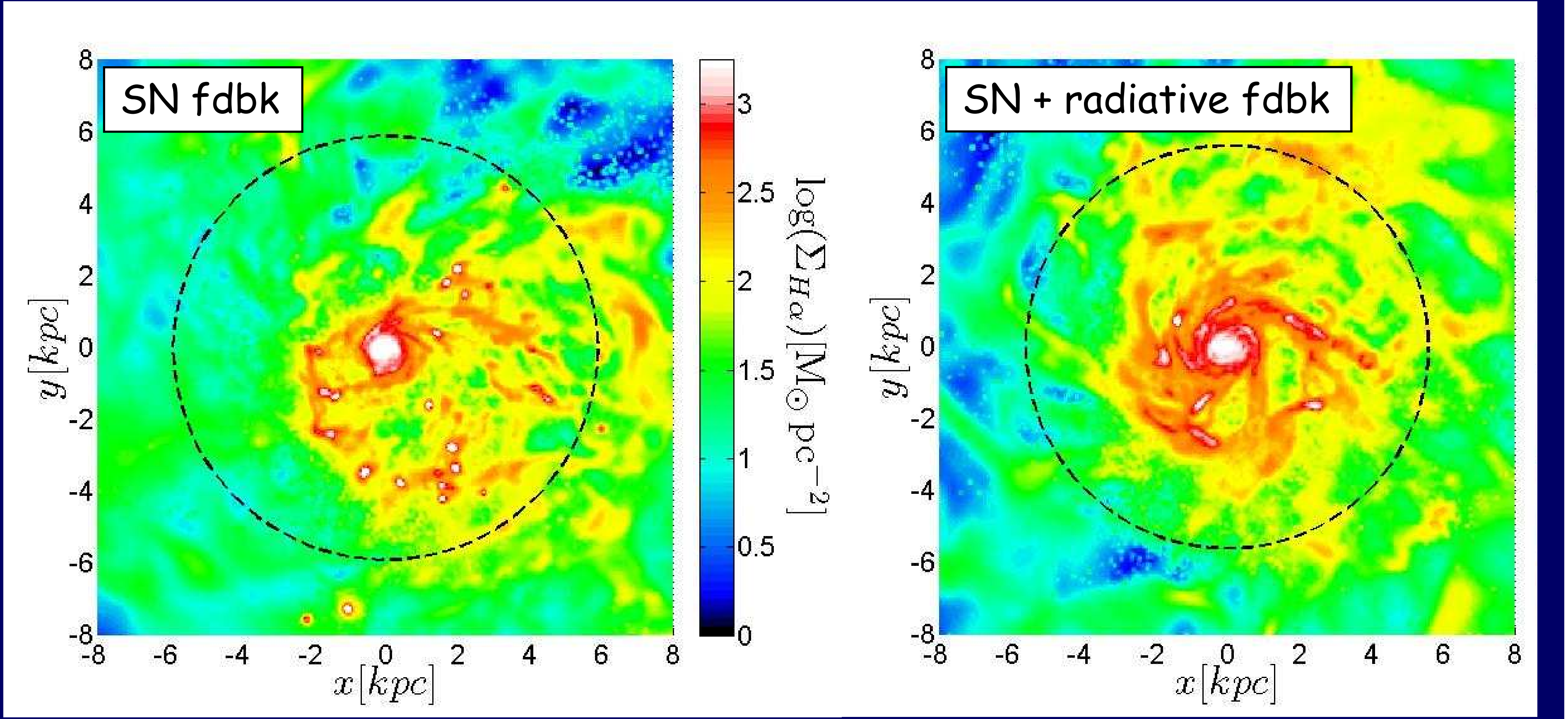
VELA 15 a=0.18



The Effect of Radiative Fdbk on Clumps

gas disk expands, bulge may lose gas
giant clumps survive, small clumps disrupt

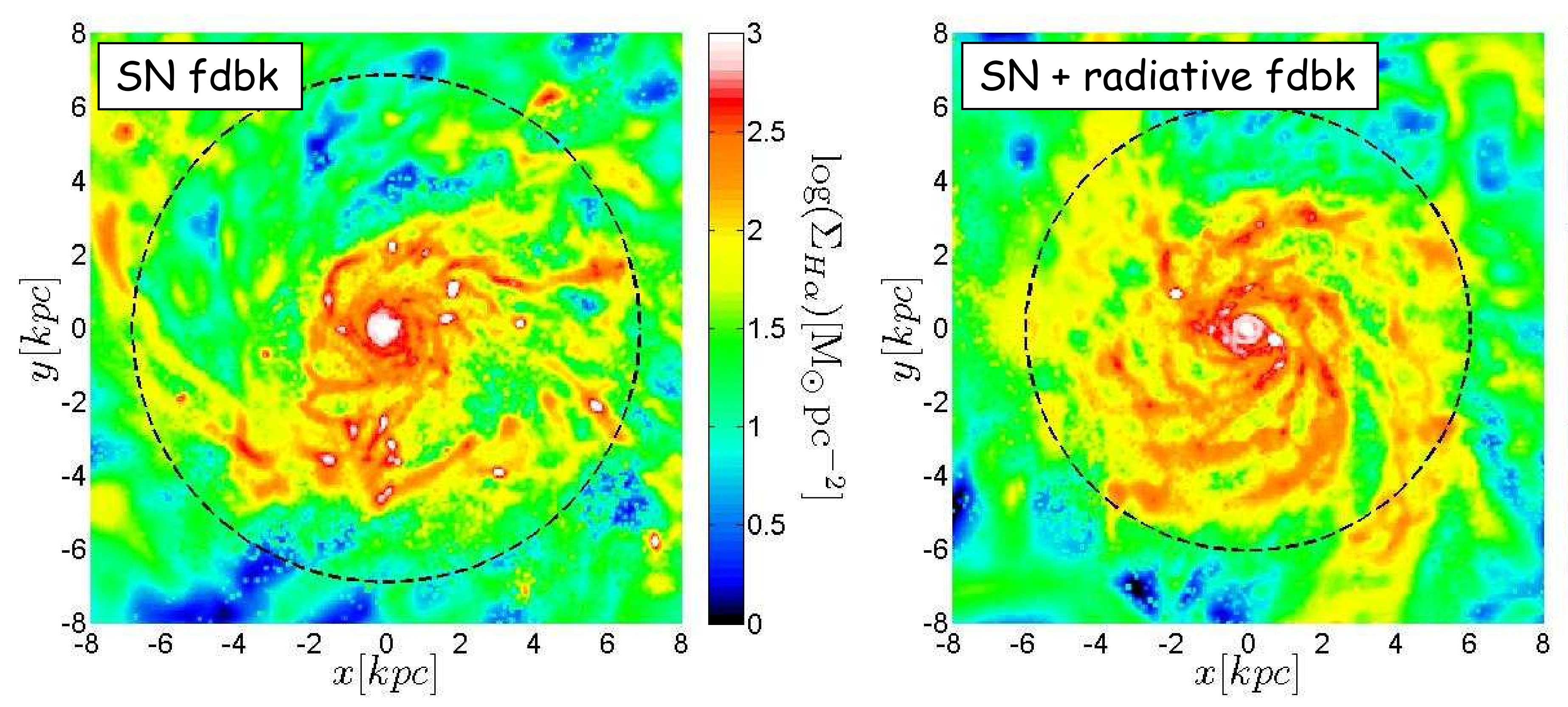
VELA 07   a=0.25



The Effect of Radiative Fdbk on Clumps

gas disk expands, bulge may lose gas
giant clumps survive, small clumps disrupt

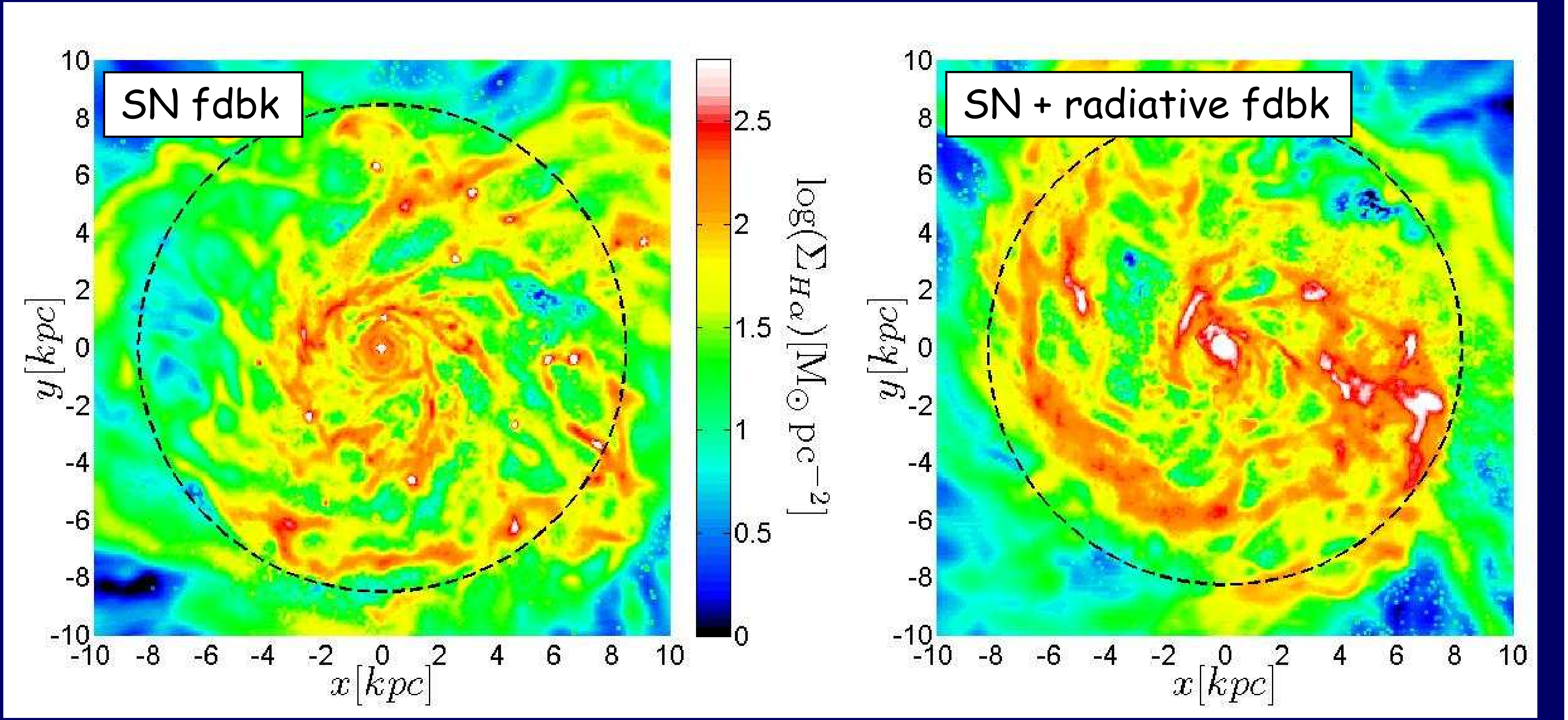
VELA 07 a=0.26



The Effect of Radiative Fdbk on Clumps

gas disk expands, bulge may lose gas
giant clumps survive, small clumps disrupt

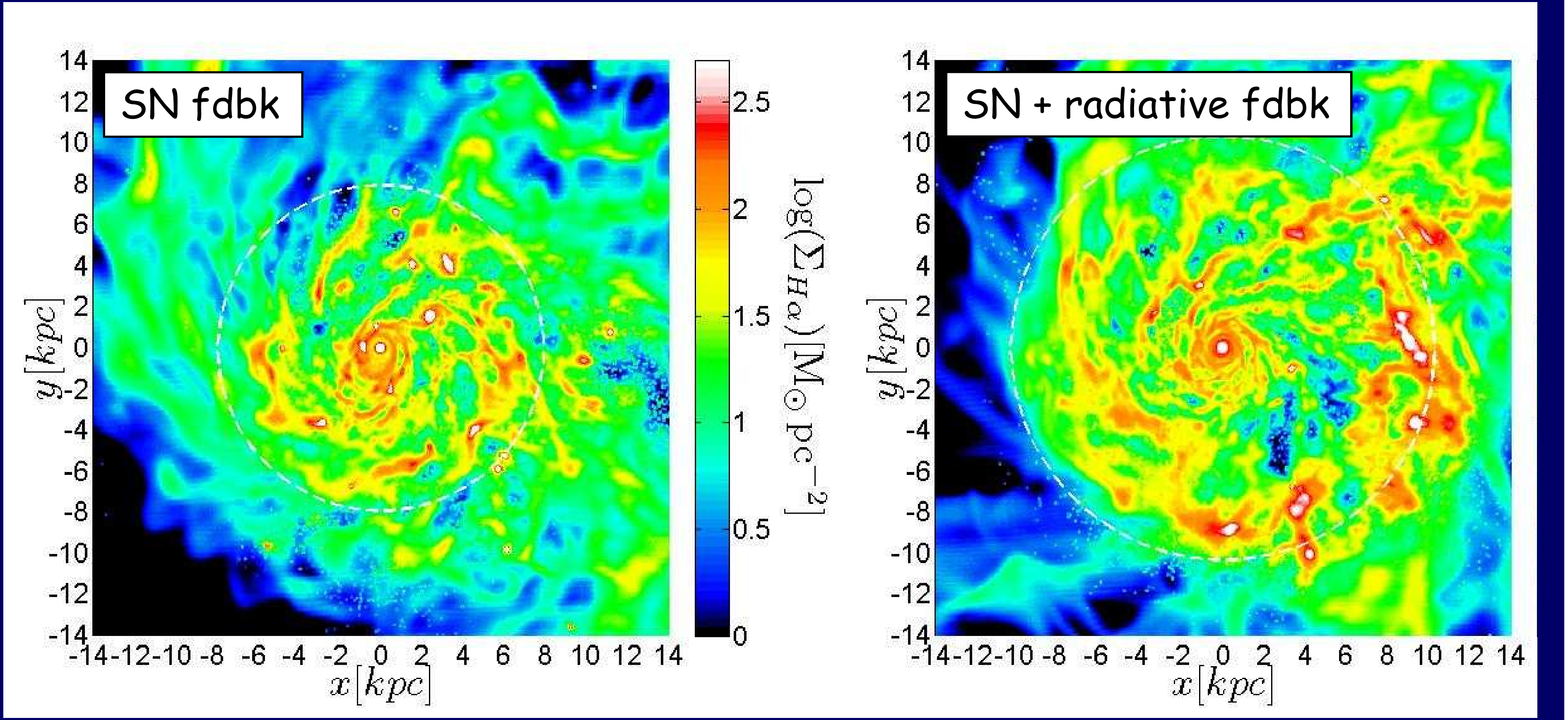
VELA 07 a=0.27



The Effect of Radiative Fdbk on Clumps

gas disk expands, bulge may lose gas
giant clumps survive, small clumps disrupt

VELA 07 a=0.29



Clump Evolution during Migration: Summary

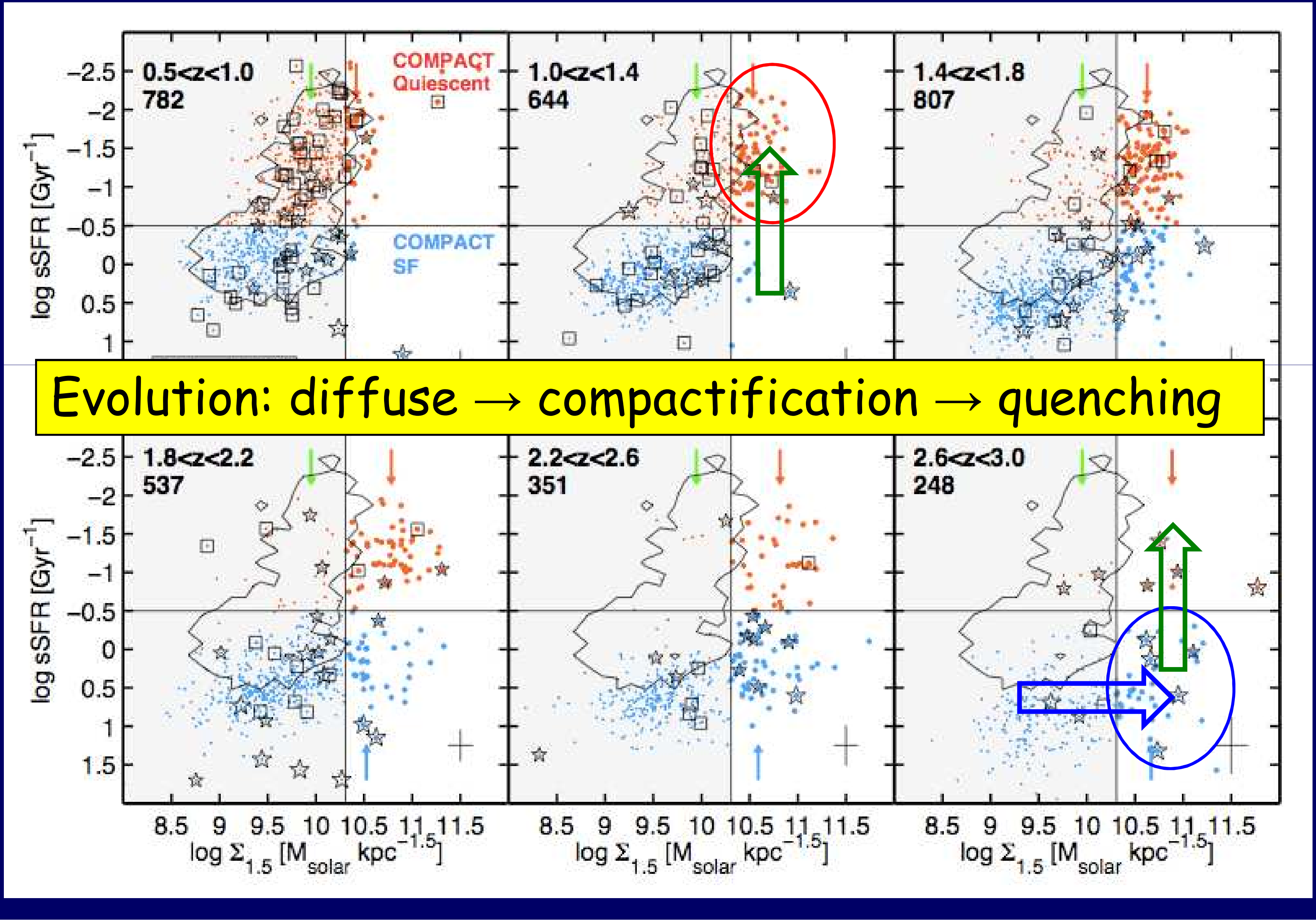
- SFR in giant clumps drives η~1-2 steady winds
- Gas gain by accretion
- Stellar loss by tidal stripping
- The massive clumps keep ~constant mass
- They live for t_{mig}~ 300 Myr
- They feed gas & stars to the bulge
- Less massive clumps disrupt

Expect a weak gradient of clump mass in disks
Certain gradient in age/color

3. Compactification and Quenching

Observations: Blue Nuggets -> Red Nuggets

Barro+ 13 CANDELS z=1-3



Evolution: diffuse → compactification → quenching

Self-Regulated VDI <-> Inflow to Center

Self-regulated Toomre instability $Q \approx \frac{\sigma\Omega}{\Sigma} \approx \delta^{-1}\frac{\sigma}{V} \approx 1$ $\longrightarrow$ $\frac{M_{\rm cold}}{M_{\rm tot}} \equiv \delta \approx \frac{\sigma}{V}$

1. Torques between perturbations drive AM out & mass in (e.g. migration)

Gammie 01; Dekel, Sari, Ceverino 09

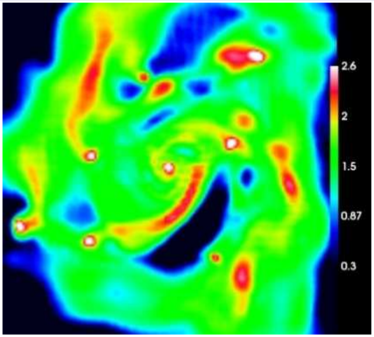
2. Inflow down potential gradient provides the energy for driving σ to Q~1, compensating for the turbulence decay

Krumholz, Burkert 10; Bournaud et al. 11; Cacciato et al. 12; Forbes et al. 13; Dekel et al. 13

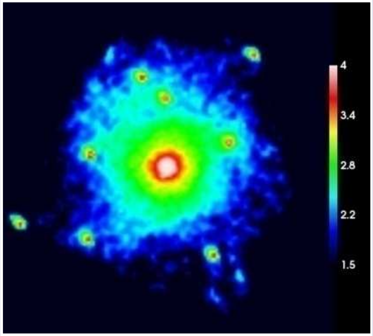
$\dot{M}_{\rm inflow} V^2 \approx \frac{M\sigma^2}{t_{\rm dyn}}$ $\longrightarrow$ $\boxed{t_{\rm inflow} \approx t_{\rm dyn}\,\delta^{-2}}$

$$\dot{M}_{\rm inflow} \approx 25\, M_{\Theta}\,{\rm yr}^{-1}\, M_{\rm cold,10.5}\,(1+z)_3^{3/2}\,\delta_{0.2}^2$$

gas inflow and clump migration



clumpy gas disk



compact stellar bulge

Red Nuggets and Blue Nuggets

Dekel & Burkert 2013; Zolotov et al. 2014

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

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

Self-regulated instability $Q \sim 1$

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

$$\delta \approx \frac{\Sigma_{\rm g}}{\Sigma_{\rm g} + \Sigma_{*} + \Sigma_{\rm dm}}$$

Wetness parameter

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

$$\varepsilon_{\rm sfr} \leq 0.02 \quad \delta \geq 0.2$$

Bi-modality in Σ: either compact or extended
(wet inflow → $\Sigma \Uparrow$ (DM dominated) → $w \Uparrow$ → wetter inflow)

Blue nuggets are dispersion dominated: $\sigma/V \sim \delta$

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

Red Nuggets and Blue Nuggets

Dekel & Burkert 2013; Zolotov et al. 2014

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

Inflow is "wet" if $t_{inflow} << t_{sfr}$

Self-regulated instability Q ~ 1

$$\frac{M_{\text{cold}}}{M_{\text{tot}}} \equiv \delta \approx \frac{\sigma}{V}$$

$$\delta \approx \frac{\Sigma_{\text{g}}}{\Sigma_{\text{g}} + \Sigma_{*} + \Sigma_{\text{dm}}}$$

Wetness parameter

$$\boxed{w \equiv \frac{t_{\text{sfr}}}{t_{\text{inflow}}} \approx \varepsilon_{\text{sfr}}^{-1} \delta^{2} > 1}$$

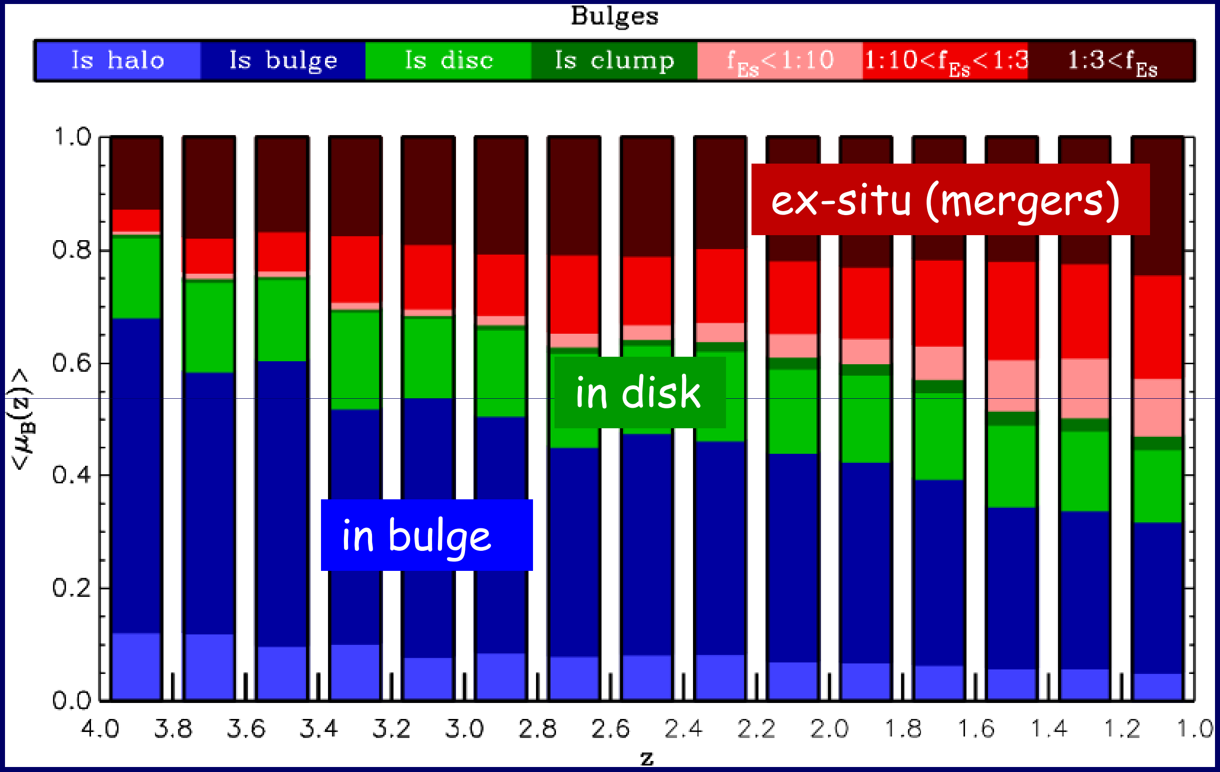
$$\varepsilon_{\text{sfr}} \le 0.02 \qquad \delta \ge 0.2$$

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

Wet Origin of Bulge: Stellar Birthplace

Simulations: Tweed, Zolotov, Dekel, Ceverino, Primack 2013

Fraction of bulge stars born in



ex-situ (mergers)

in disk

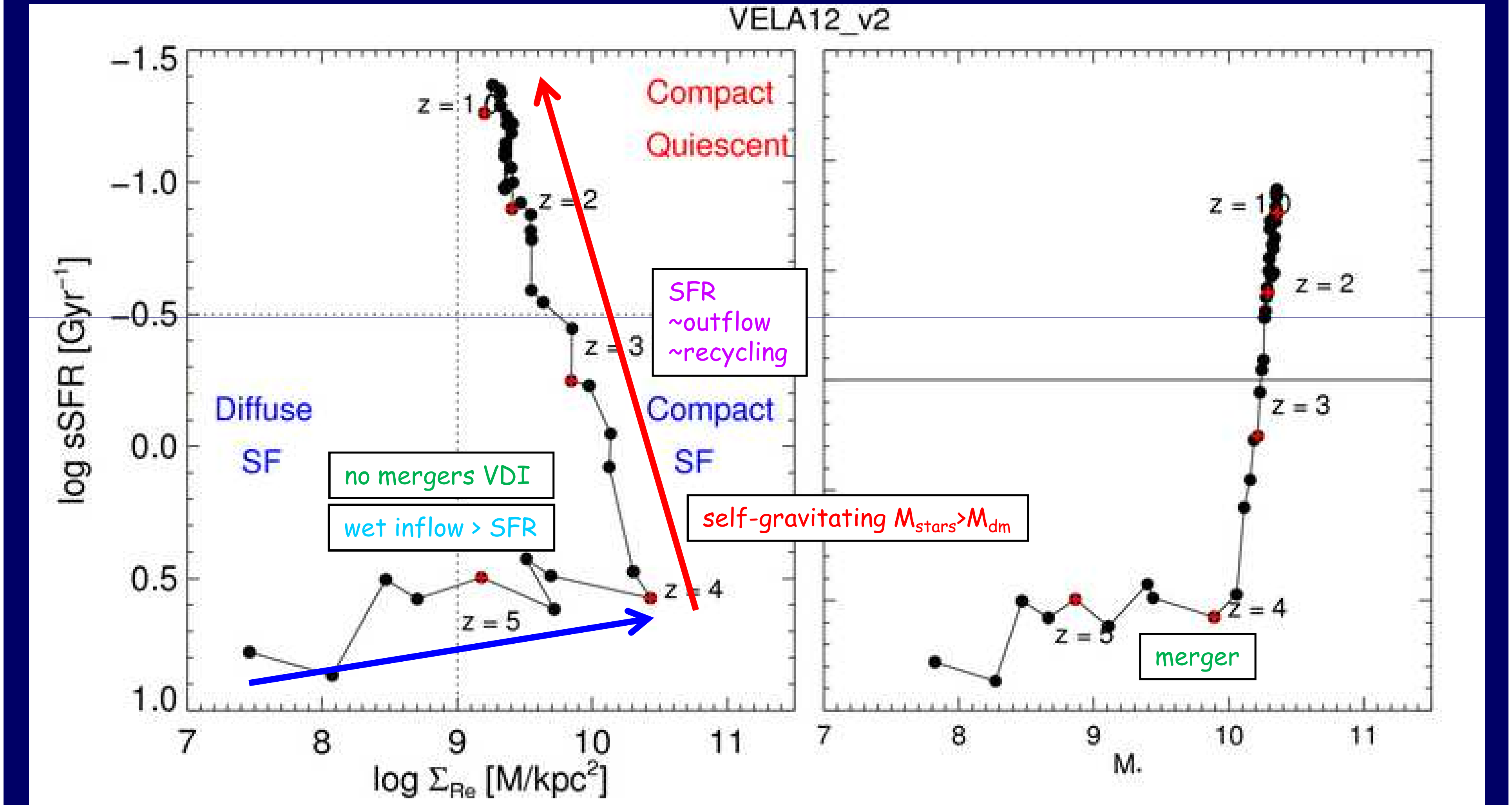
in bulge

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

Driven by wet VDI or wet mergers

Compactification and quenching

Zolotov+ 2014 ART cosmological simulations, res. 25pc, with radiative fdbk



SFR
~outflow
~recycling

no mergers VDI

wet inflow > SFR

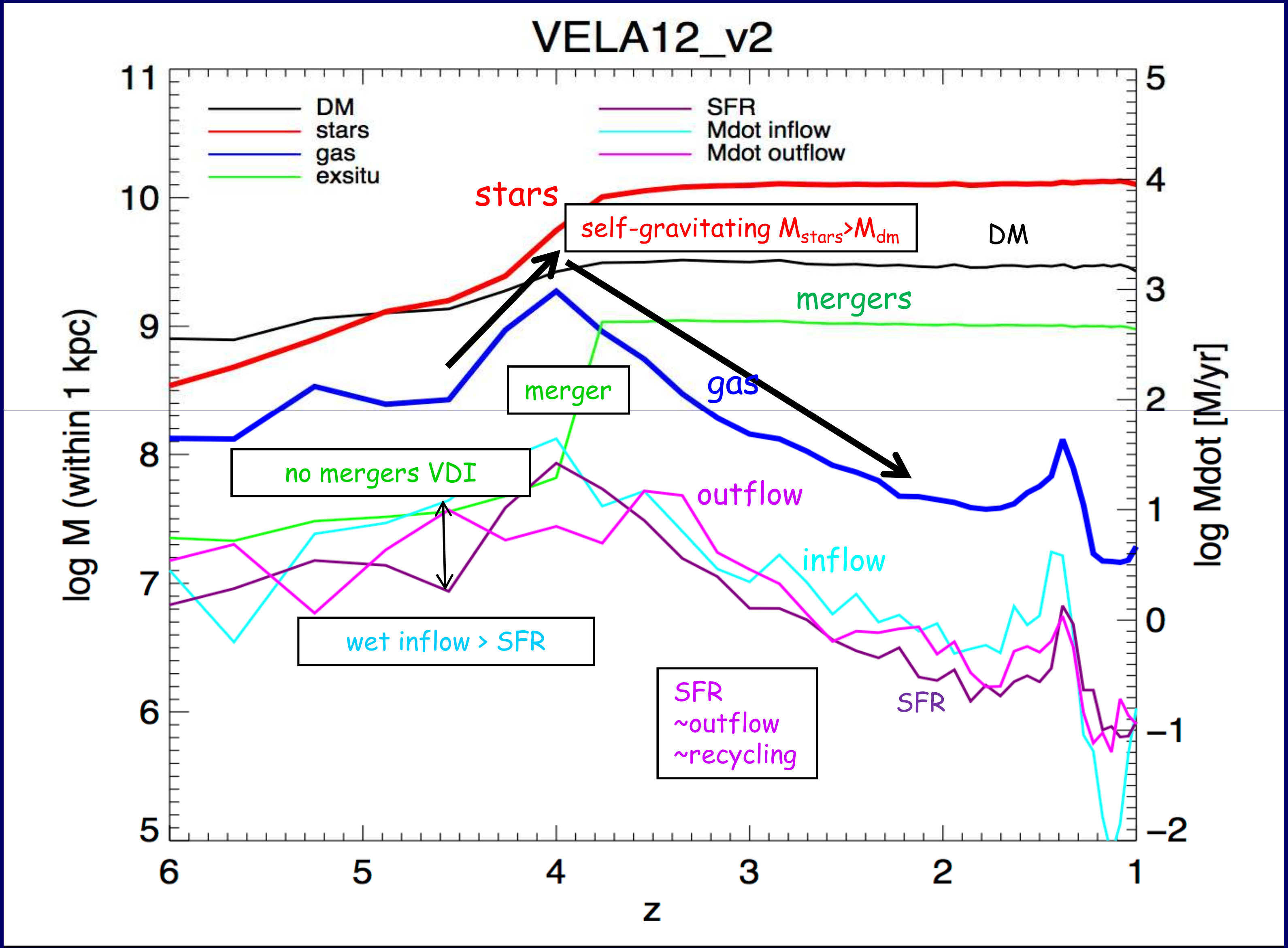
self-gravitating M_{stars}>M_{dm}

merger

effective stellar surface density

stellar mass

Compactification and quenching



From dark-matter dominance to self-gravity

In VDI wet compactification (Dekel & Burkert 14)

- If dominated by dark-matter:
  compactification → $\delta \Uparrow$ → w $\Uparrow$ → compact. continues

- If the baryons are self-gravitating:
  compact. → $\delta \Downarrow$ → w $\Downarrow$ → compact. stops, SFR wins → quenching

A bathtub model for inside 1 kpc

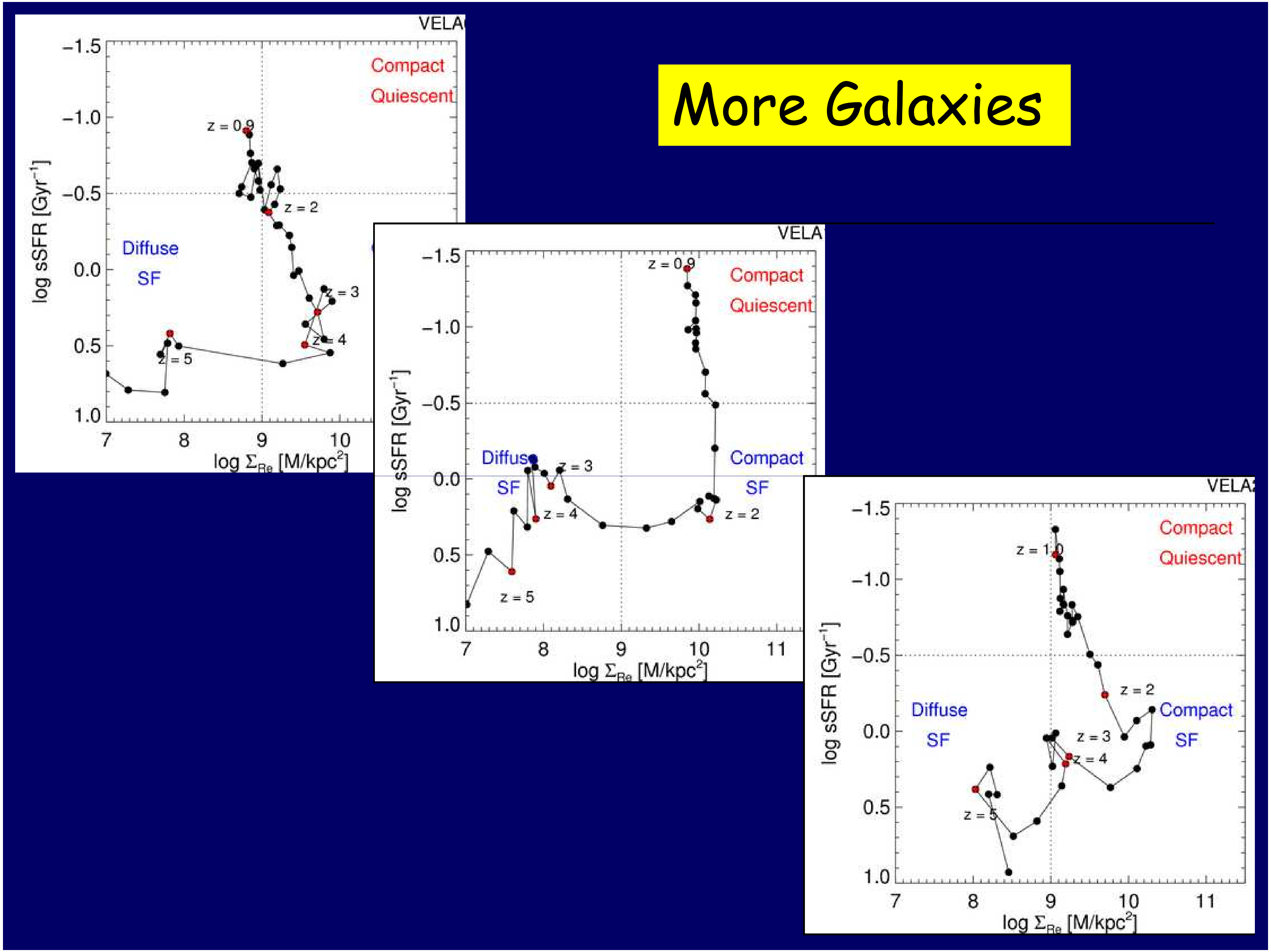
$$\dot{M}_{\rm gas} \approx \dot{M}_{\rm in} - (1+\eta_{\rm out}) \overset{M_{\rm g}^{3/2}}{\boxed{M_{\rm gas} / \tau_{\rm sfr}}}$$

In a merger: a boost in inflow

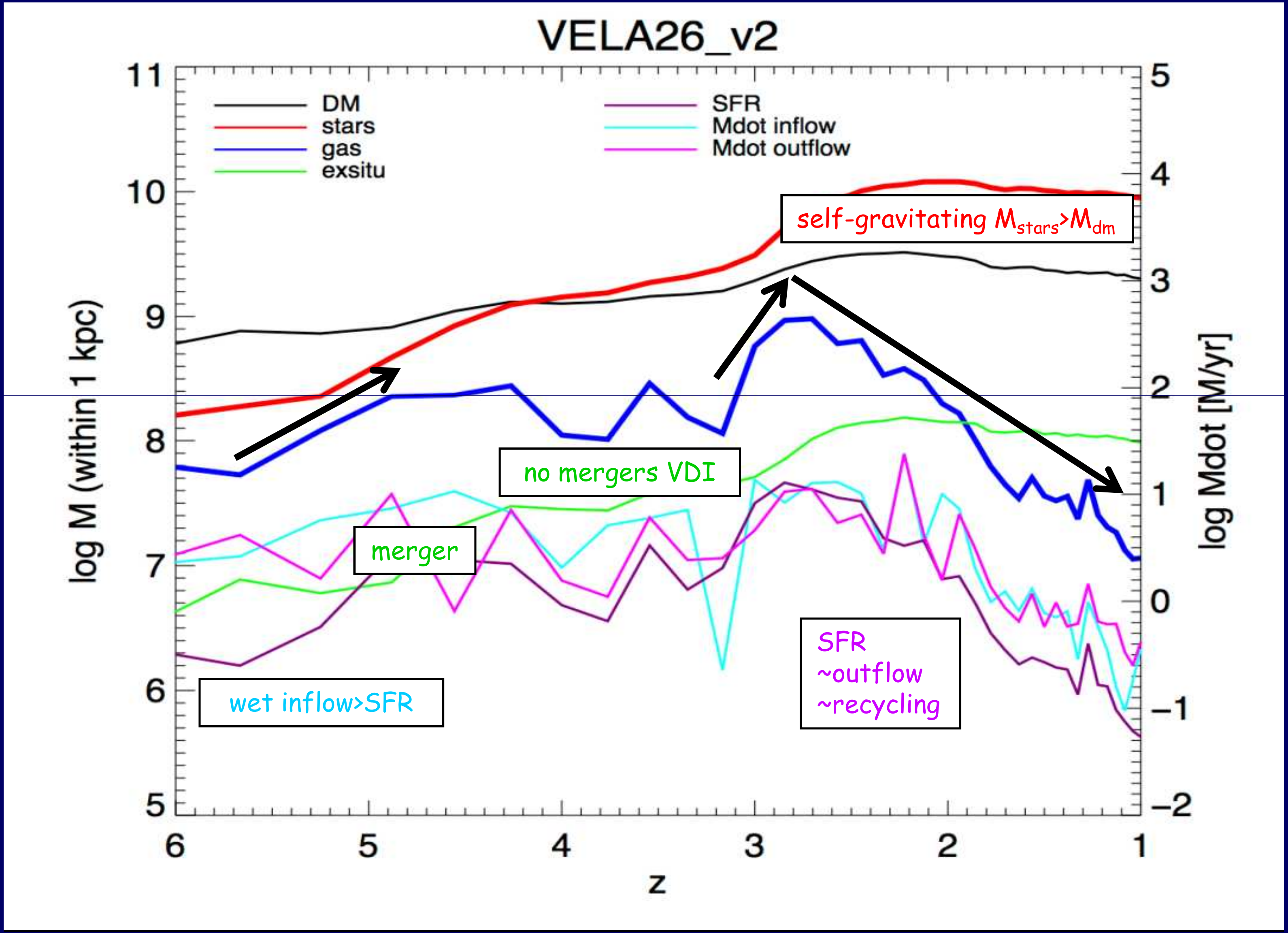
- If dark-matter dominated: $\tau_{\rm sfr} \approx const.$ $\quad M_{\rm g} \approx \dot{M}_{\rm in} \tau (1 - e^{-t/\tau}) \Uparrow$

- If baryons self-gravitate: $\tau_{\rm sfr} \approx M_{\rm gas}^{-1/2}$ $\quad M_{\rm g} \Downarrow$

More Galaxies



Compactification and quenching



self-gravitating M_{stars}>M_{dm}

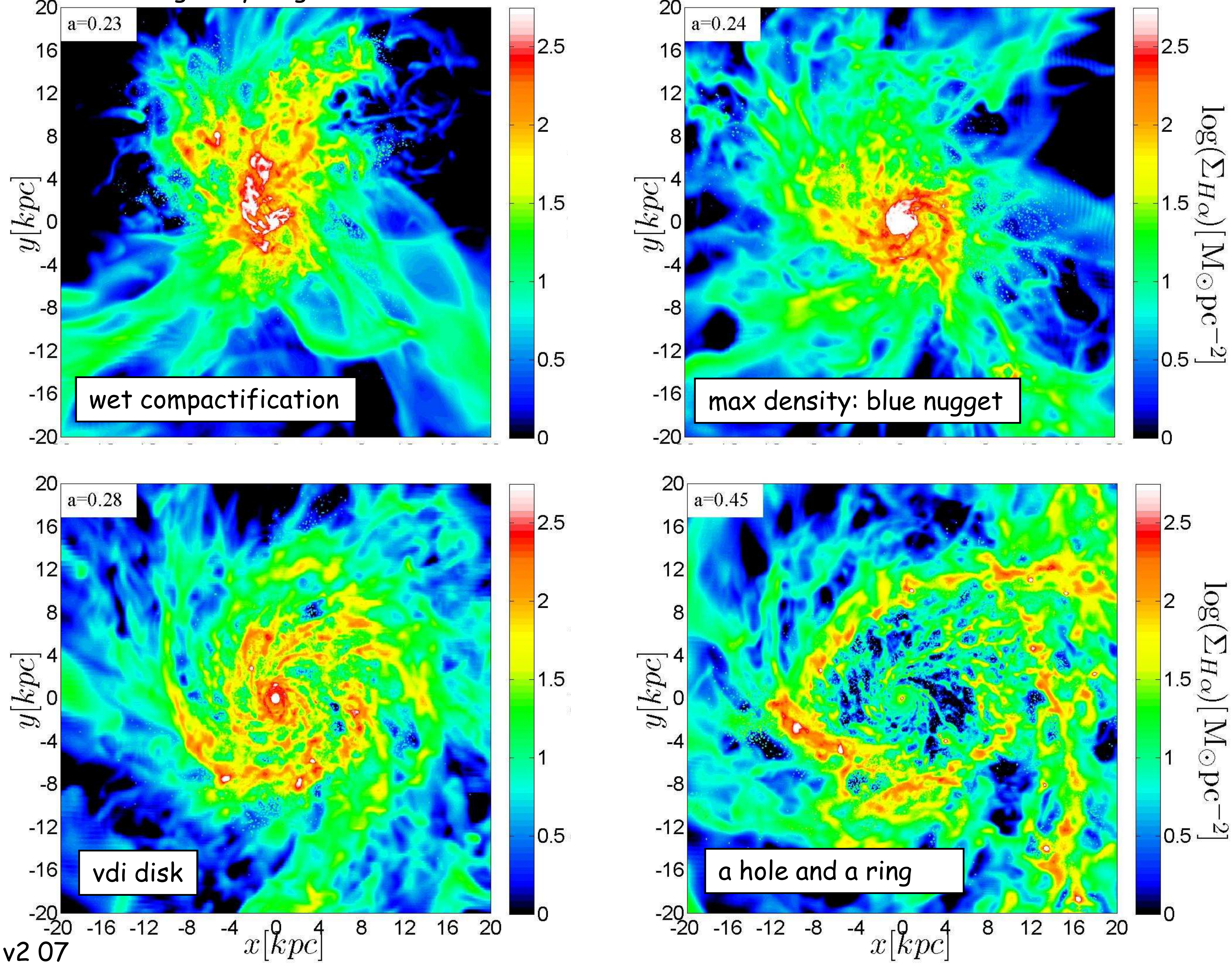
no mergers VDI

merger

wet inflow>SFR

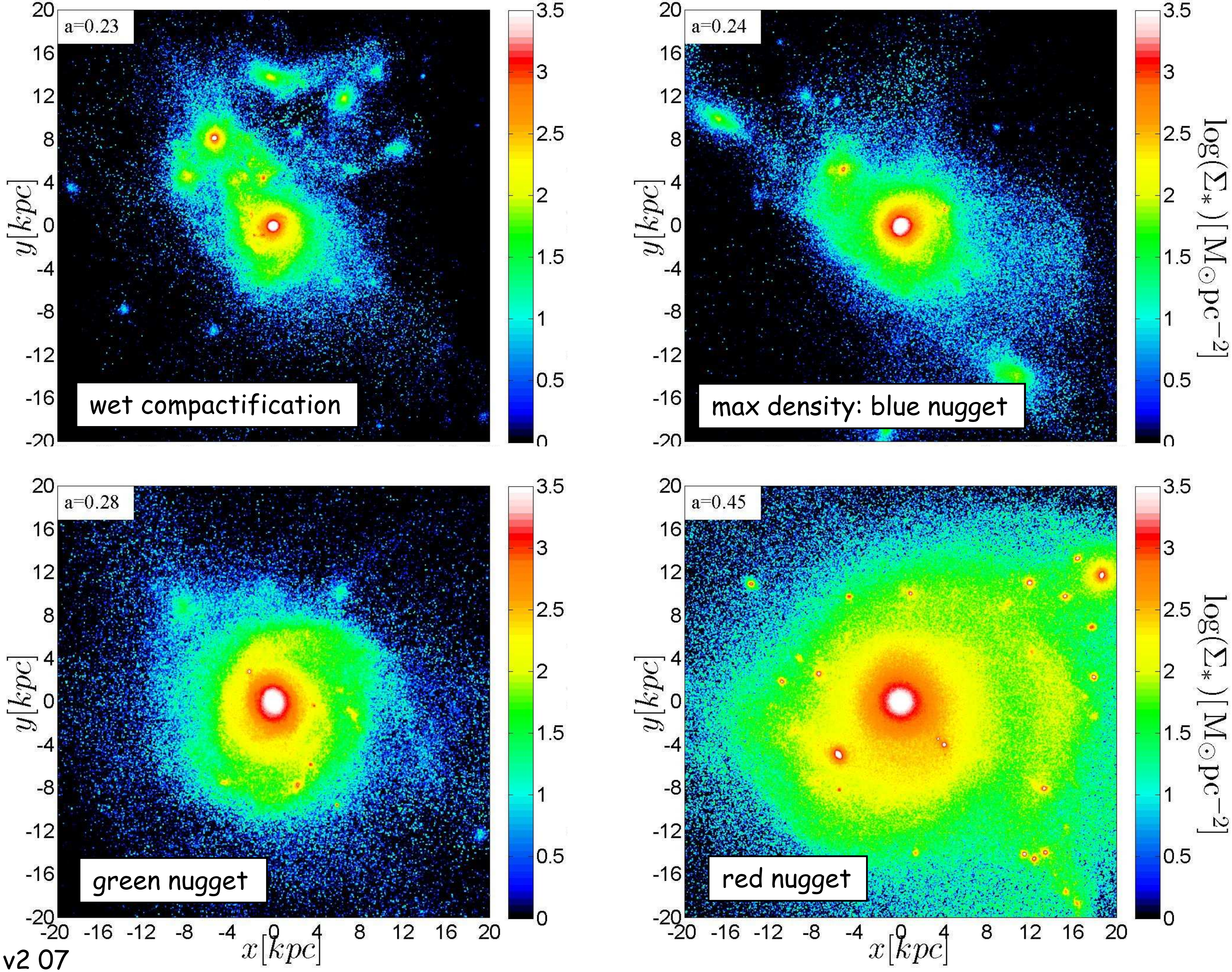
SFR
~outflow
~recycling

gas + young stars

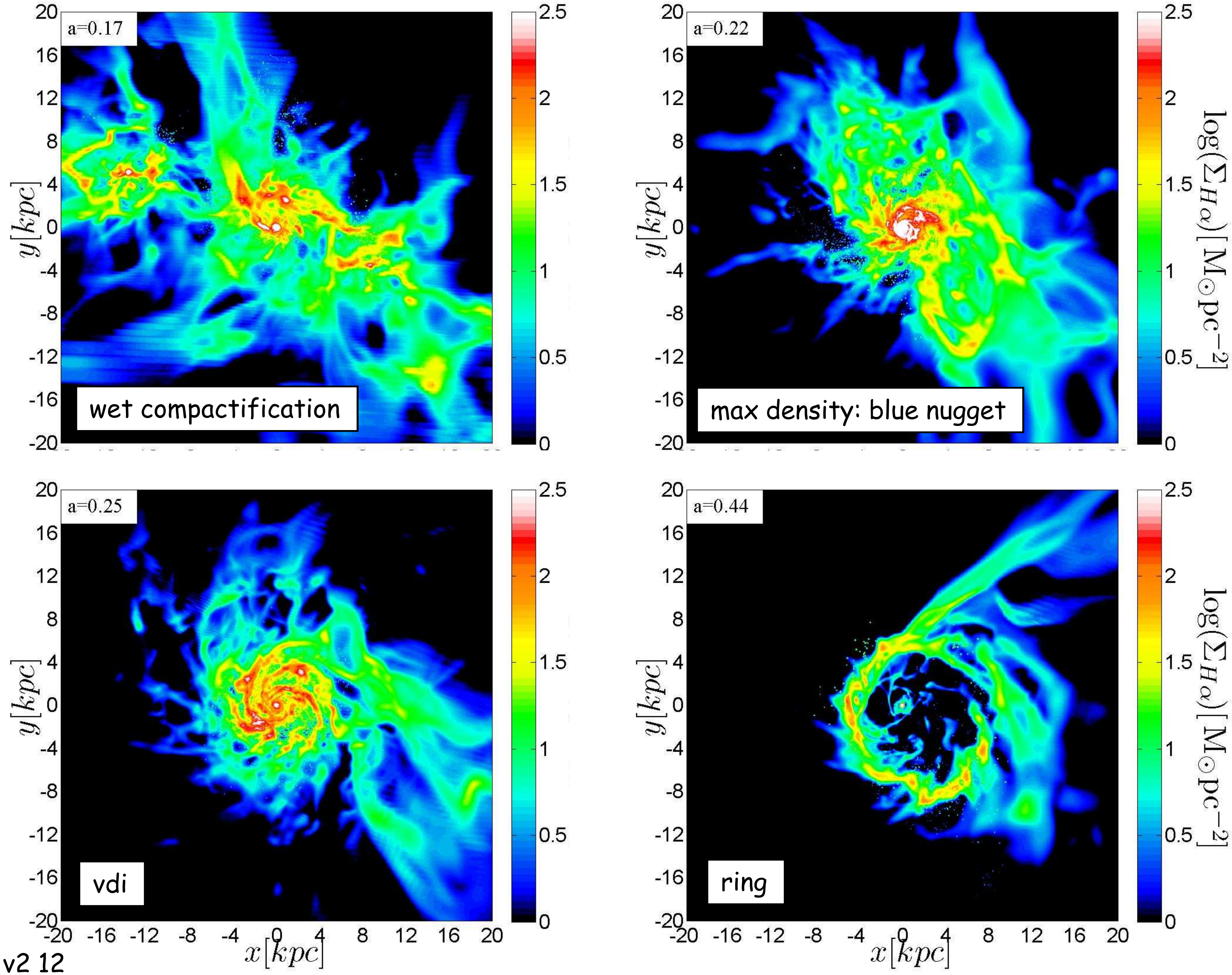


vela v2 07

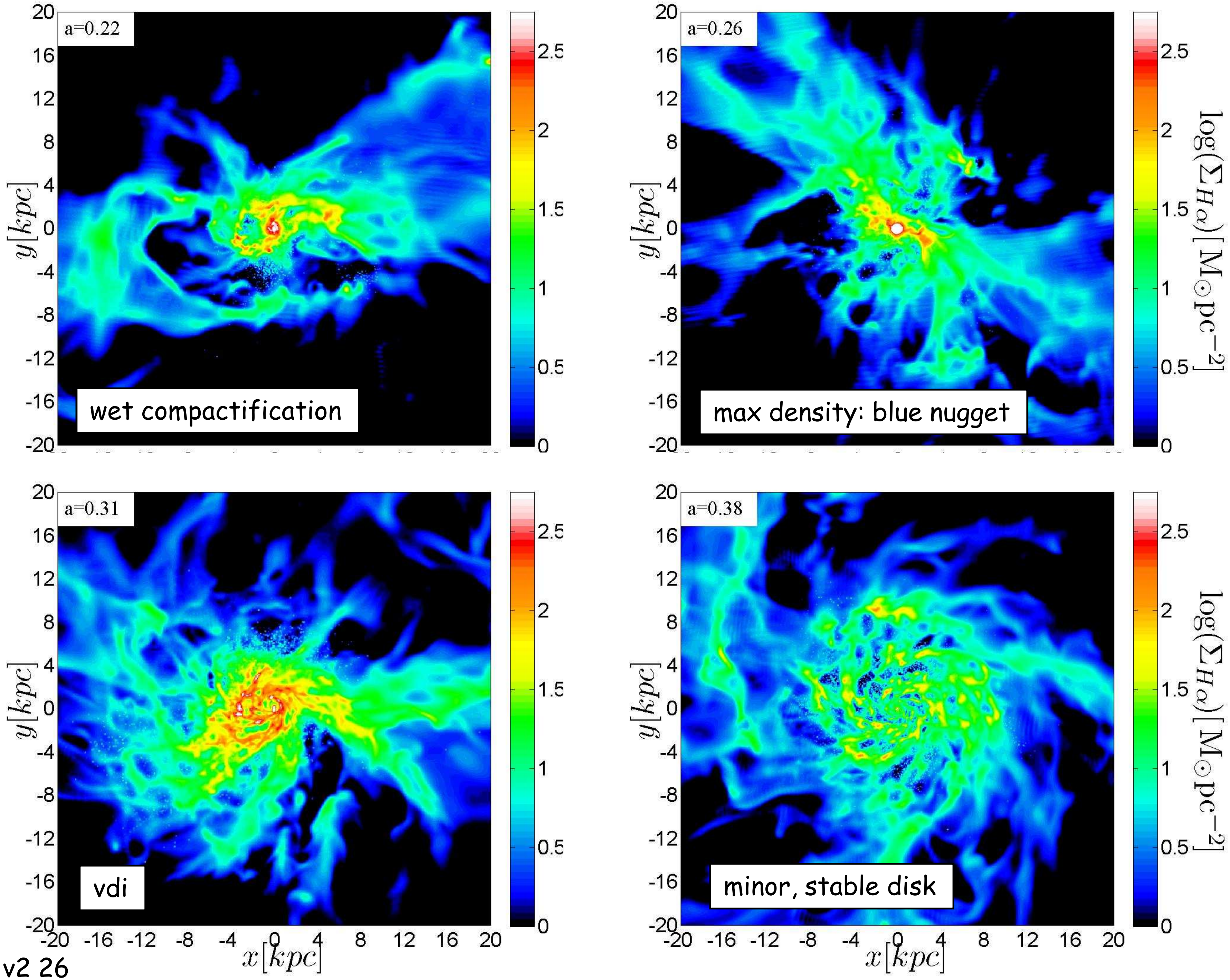
stars



vela v2 07

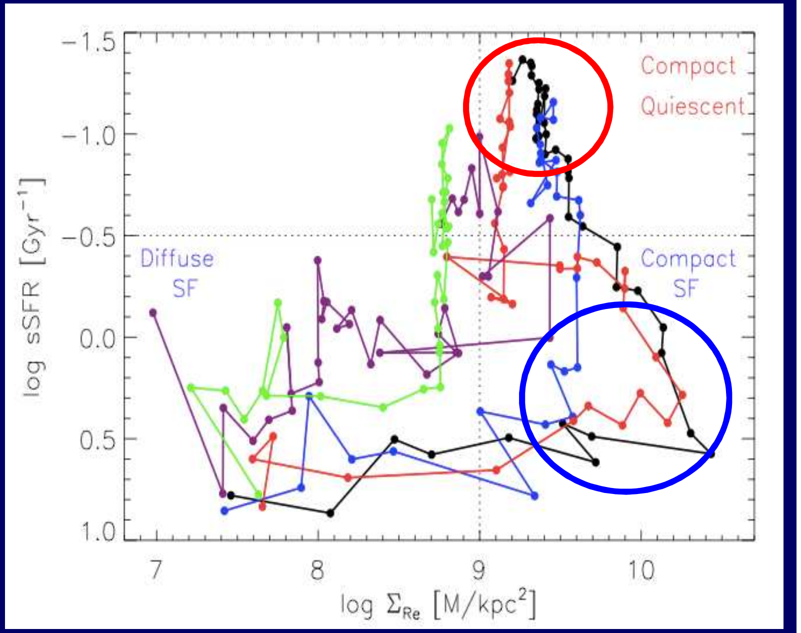

a=0.17
wet compactification
a=0.22
max density: blue nugget
a=0.25
vdi
a=0.44
ring
$y[kpc]$
$x[kpc]$
-20 -16 -12 -8 -4 0 4 8 12 16 20
$\log(\Sigma_{H\alpha})[\mathrm{M}_\odot \mathrm{pc}^{-2}]$
0 0.5 1 1.5 2 2.5

vela v2 12

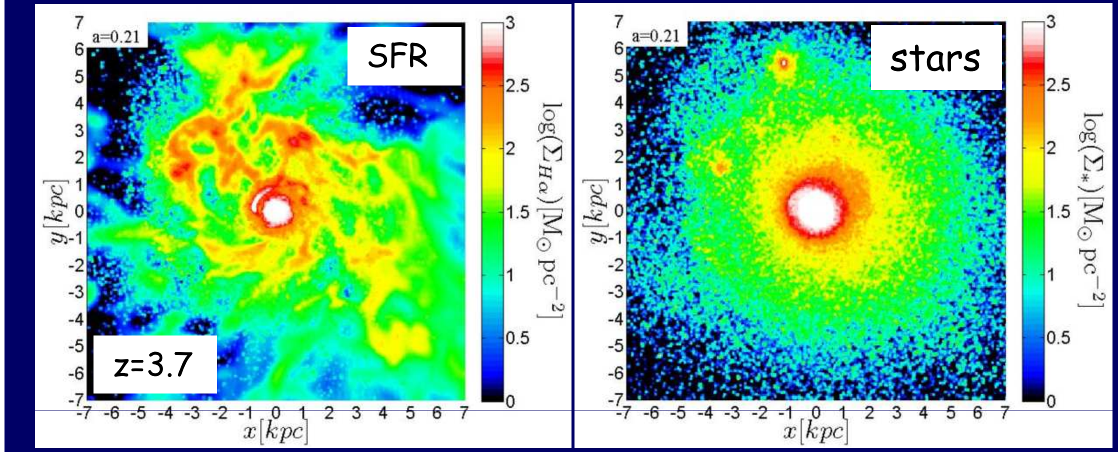

a=0.22
wet compactification
a=0.26
max density: blue nugget
a=0.31
vdi
a=0.38
minor, stable disk
y[kpc]
x[kpc]
20
16
12
8
4
0
-4
-8
-12
-16
-20
0
0.5
1
1.5
2
2.5
log(Σ_Hα)[M⊙pc^-2]

vela v2 26

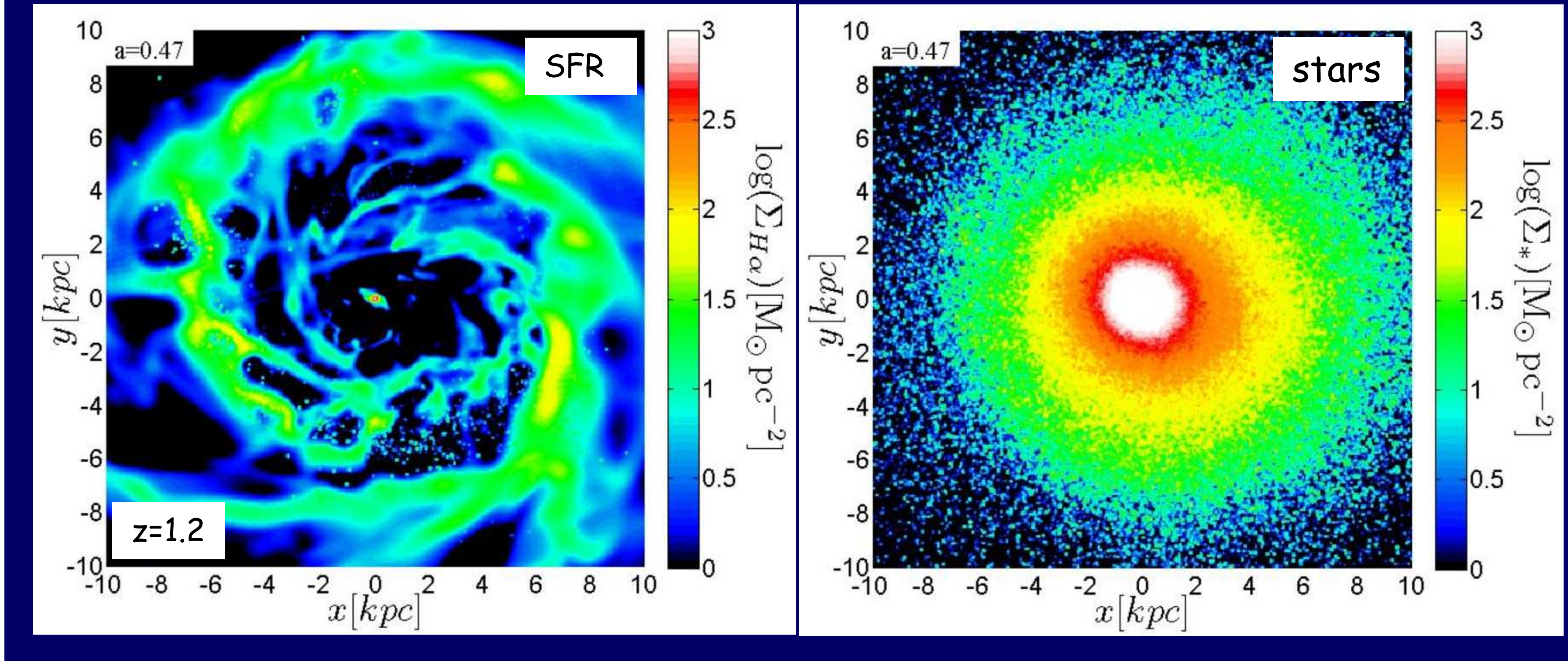
Blue -> Red Nuggets



blue nugget



red nugget

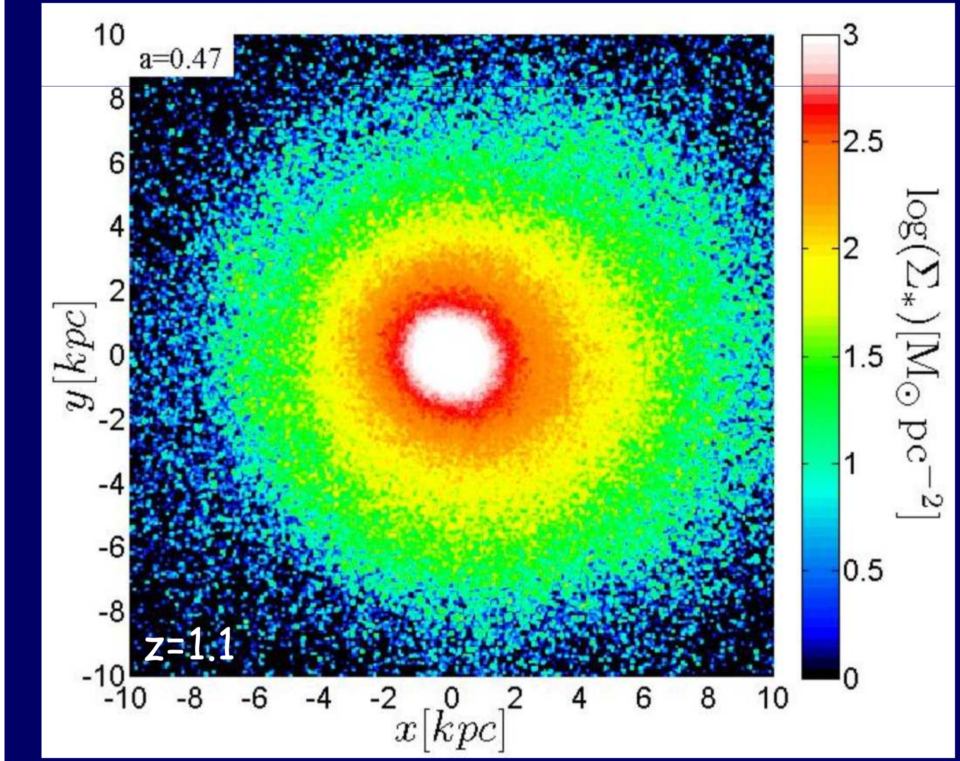


Termination of VDI: Q-quenching

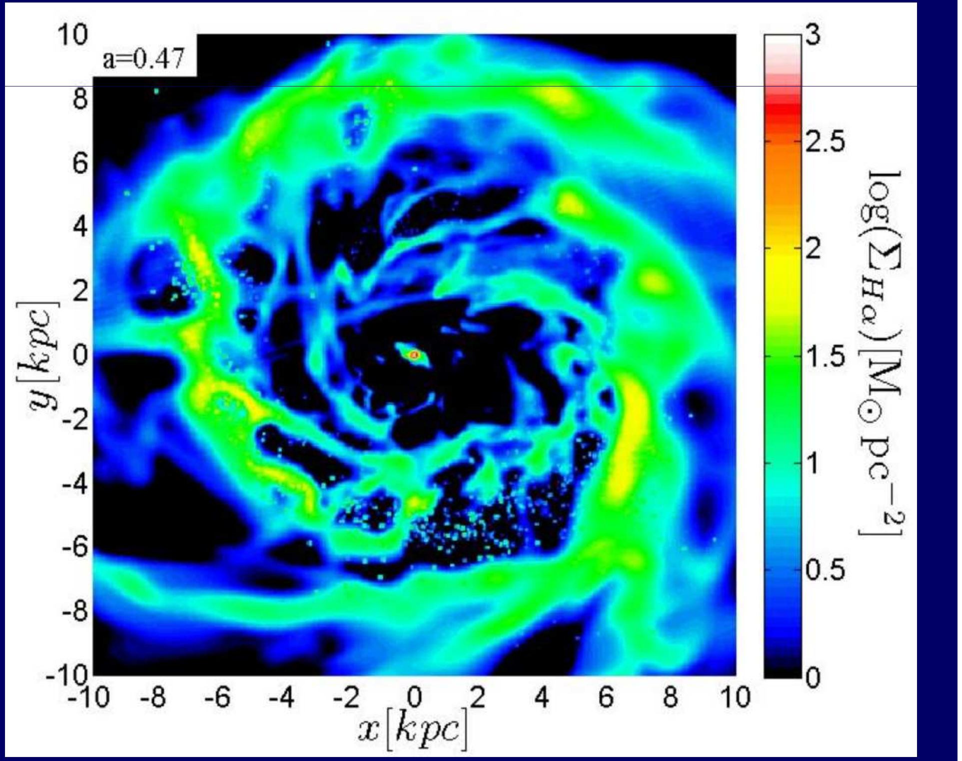
$$Q \approx \frac{\Omega \sigma_{\mathrm{gas}}}{\Sigma_{\mathrm{gas}}}$$

Ω up by massive compact bulge (morphological q)
σ_{gas} up by contraction & by feedback
Σ_{gas} down by SFR + outflows & by end of VDI inflow

Massive compact bulge



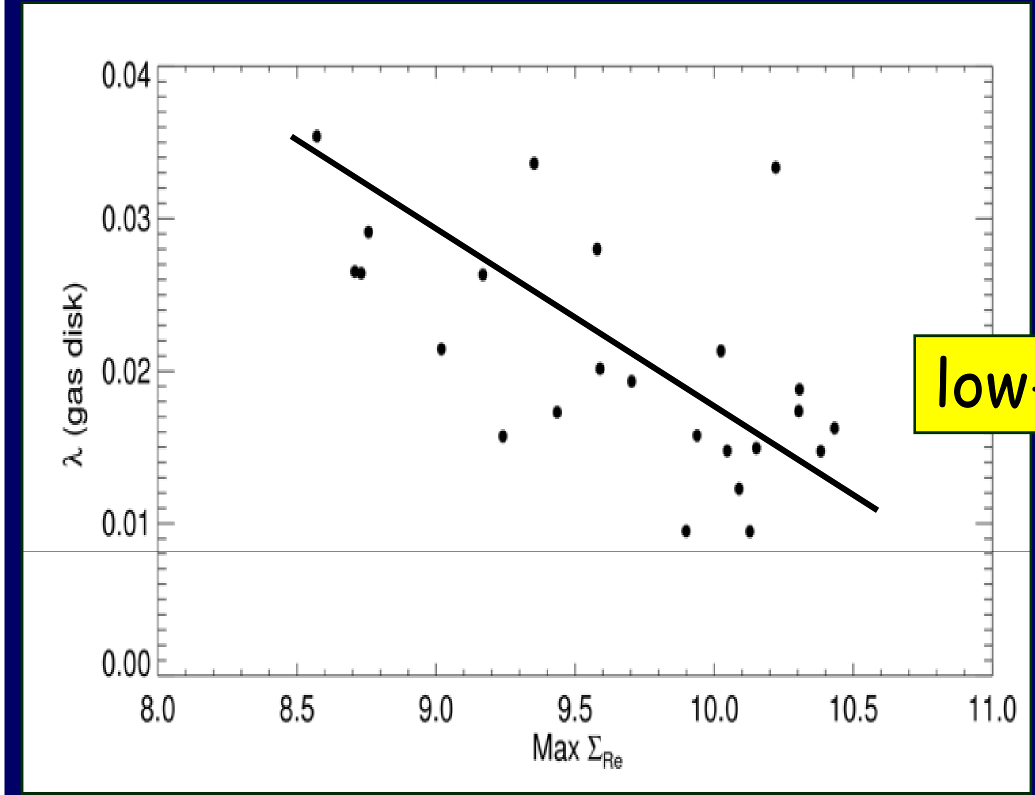
Ring of star formation



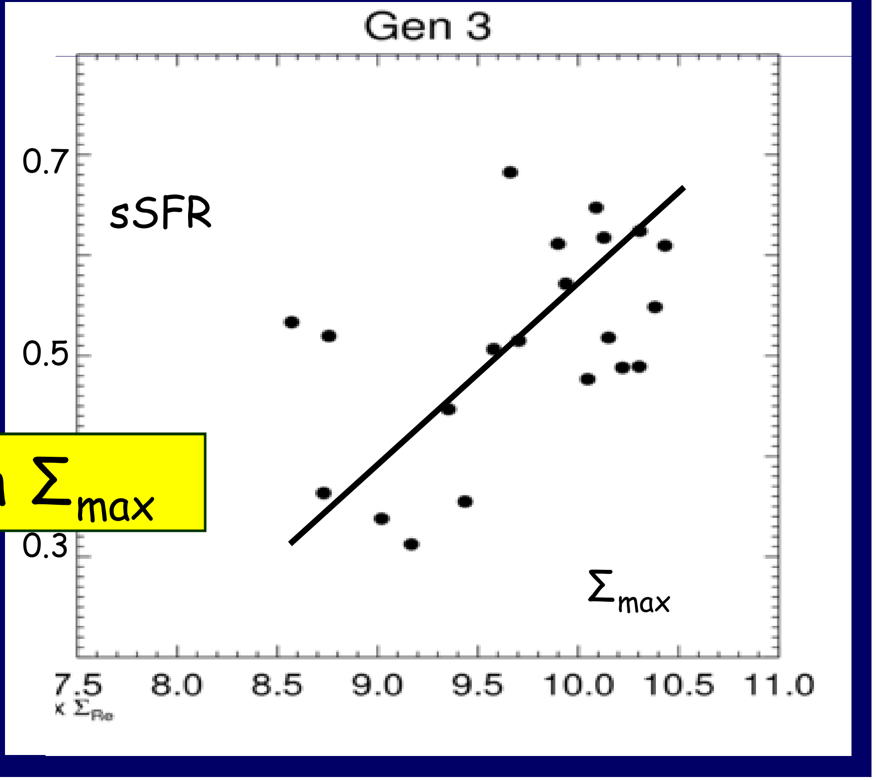
Blue Nuggets by Wet Inflow: Spin and sSFR

Simulations confirm model predictions

Dekel, Burkert 14; Zolotov+ 14



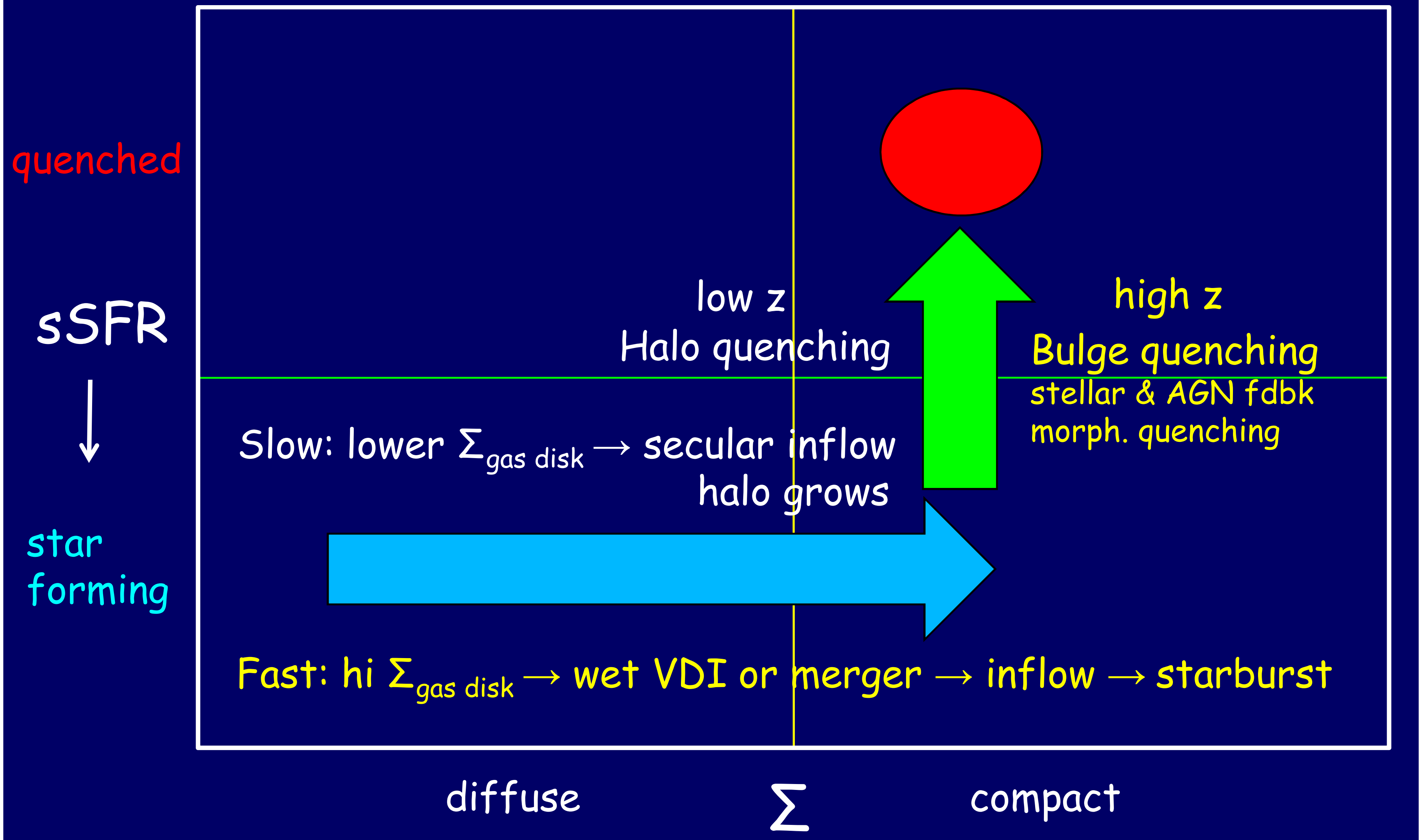
low-spin disk -> high Σ_{max}



high-sSFR disk -> high Σ_{max}

Two Modes of Evolution: Fast and Slow

Barro, Fang, Yesuf, Woo …



quenched

sSFR

↓

star forming

low z

Halo quenching

high z

Bulge quenching

stellar & AGN fdbk

morph. quenching

Slow: lower $\Sigma_{gas\ disk}$ → secular inflow

halo grows

Fast: hi $\Sigma_{gas\ disk}$ → wet VDI or merger → inflow → starburst

diffuse Σ compact

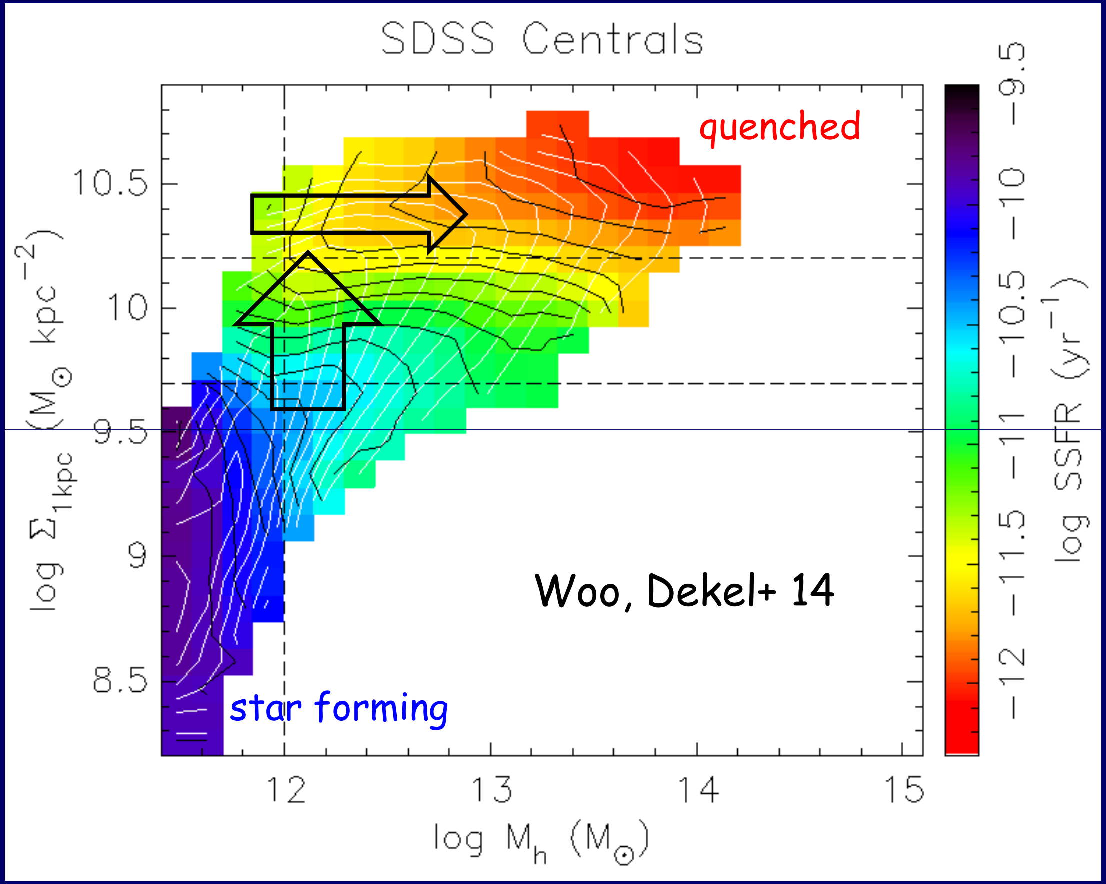
Two Quenching Mechanisms: Bulge & Halo

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



Need both bulge and halo quenching

Conclusions

Inflows live in harmony with outflows: penetration~0.5

- Streams join the disk through an outer, tilted, rotating ring
- Strong recycling. The high sSFR at z~2 is a challenge.

With realistic trapping, η~2, giant clumps survive radiative feedback

- Giant clumps keep ~constant mass during migration
- Small clumps disrupt

Typical evolution of high-z galaxies:

- Wet compactification (mergers & VDI) to compact SFGs (blue nuggets)
- High SFR, outflows, massive self-gravitating bulge → fast quenching compact ellipticals (red nuggets), gas rings
- Long-term halo quenching