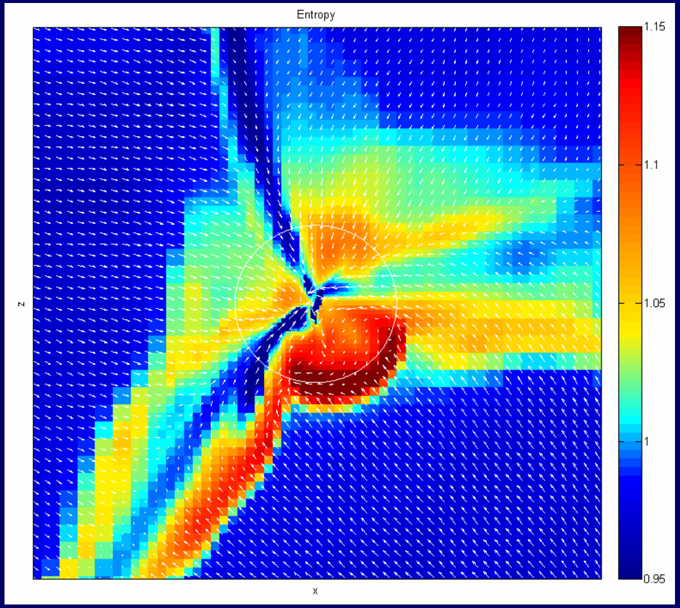
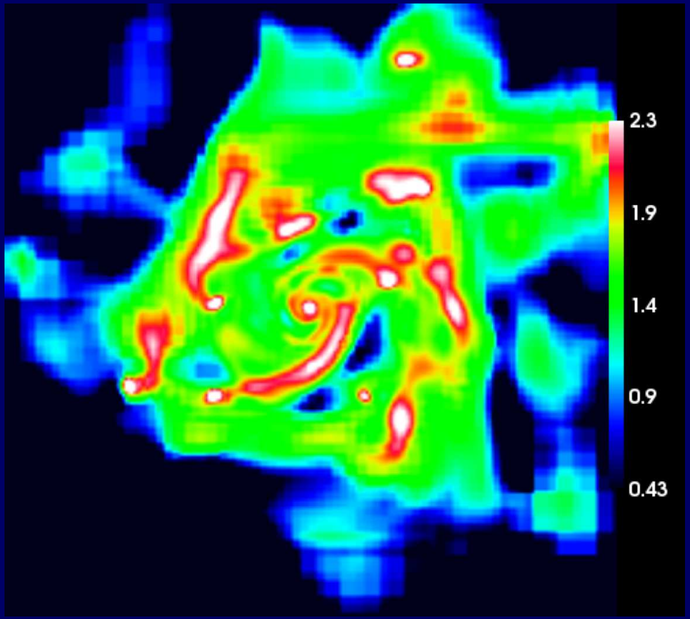
Galaxies from the Cosmic Web:

Cold Streams, Clumpy Disks & Compact Spheroids

Avishai Dekel, HU Jerusalem

Toledo, December 2009





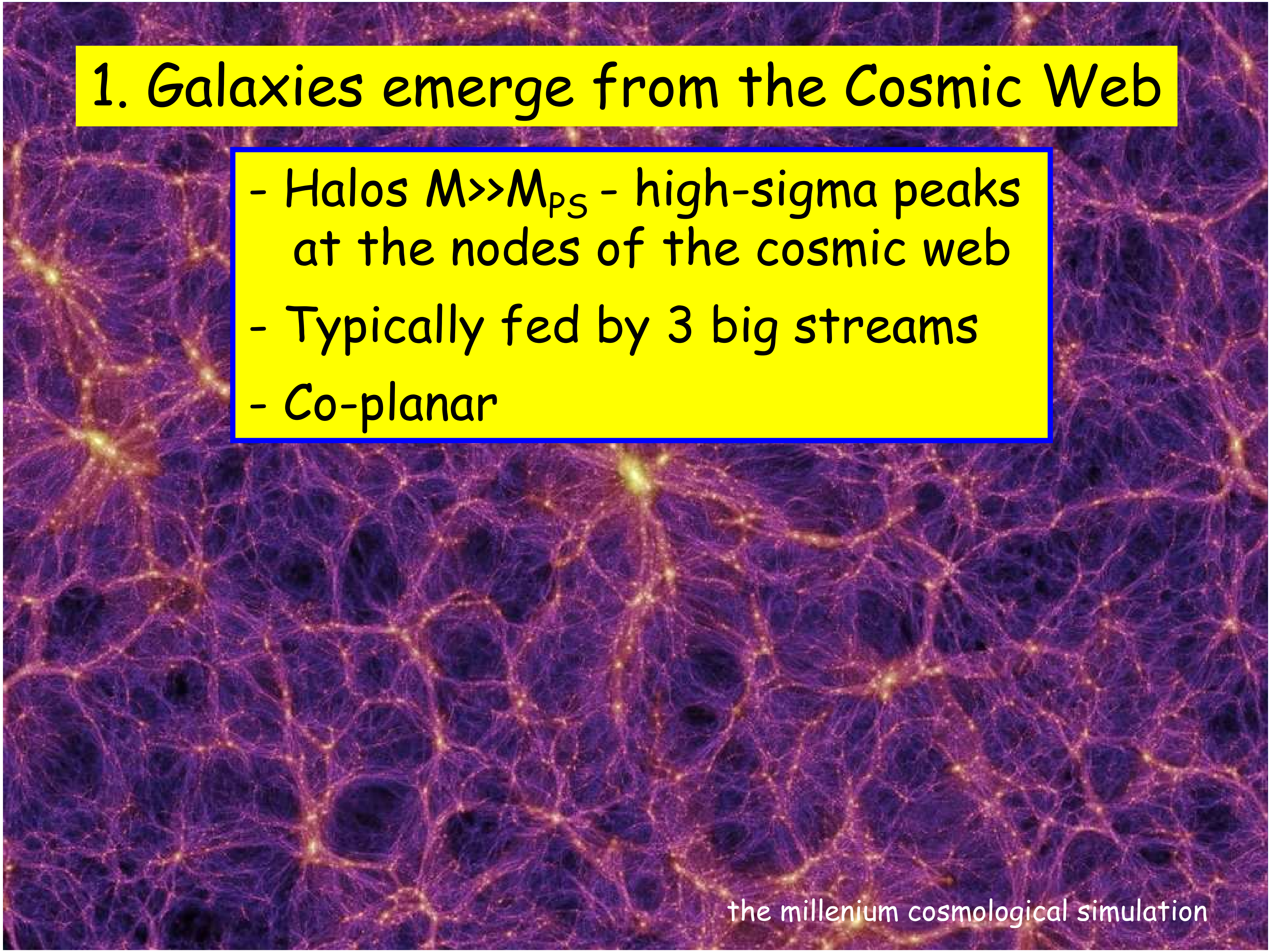
LCDM makes robust theoretical predictions for massive galaxy formation at high z

Theory seems consistent with observations

Combined, they introduce a coherent picture

1. Galaxies emerge from the Cosmic Web

- Halos $M \gg M_{PS}$ - high-sigma peaks at the nodes of the cosmic web
- Typically fed by 3 big streams
- Co-planar



the millenium cosmological simulation

2. Accretion Rate into a Halo

Neistein, van den Bosch, Dekel 06; Neistein & Dekel 07, 08; Genel et al 08

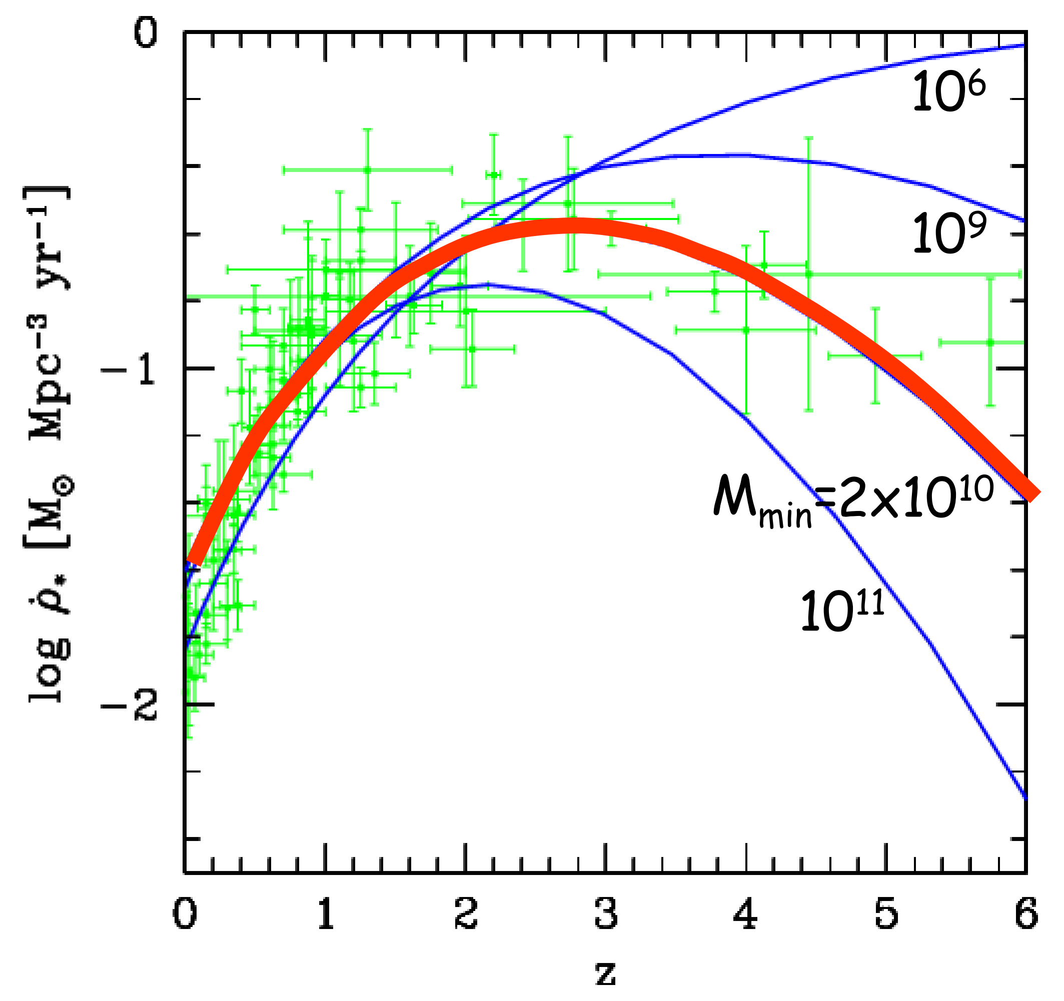
From N-body simulations/EPS, Approximate for LCDM:

$$\left\langle \dot{M}_{baryon} \right\rangle \approx 100\, M_{\otimes}\, yr^{-1}\; M_{12}^{1.15}\, (1+z)_{3.5}^{2.25}\, f_{0.16}$$

The accretion rate is the primary driver of halo/galaxy growth & SFR - can serve for successful simple modeling

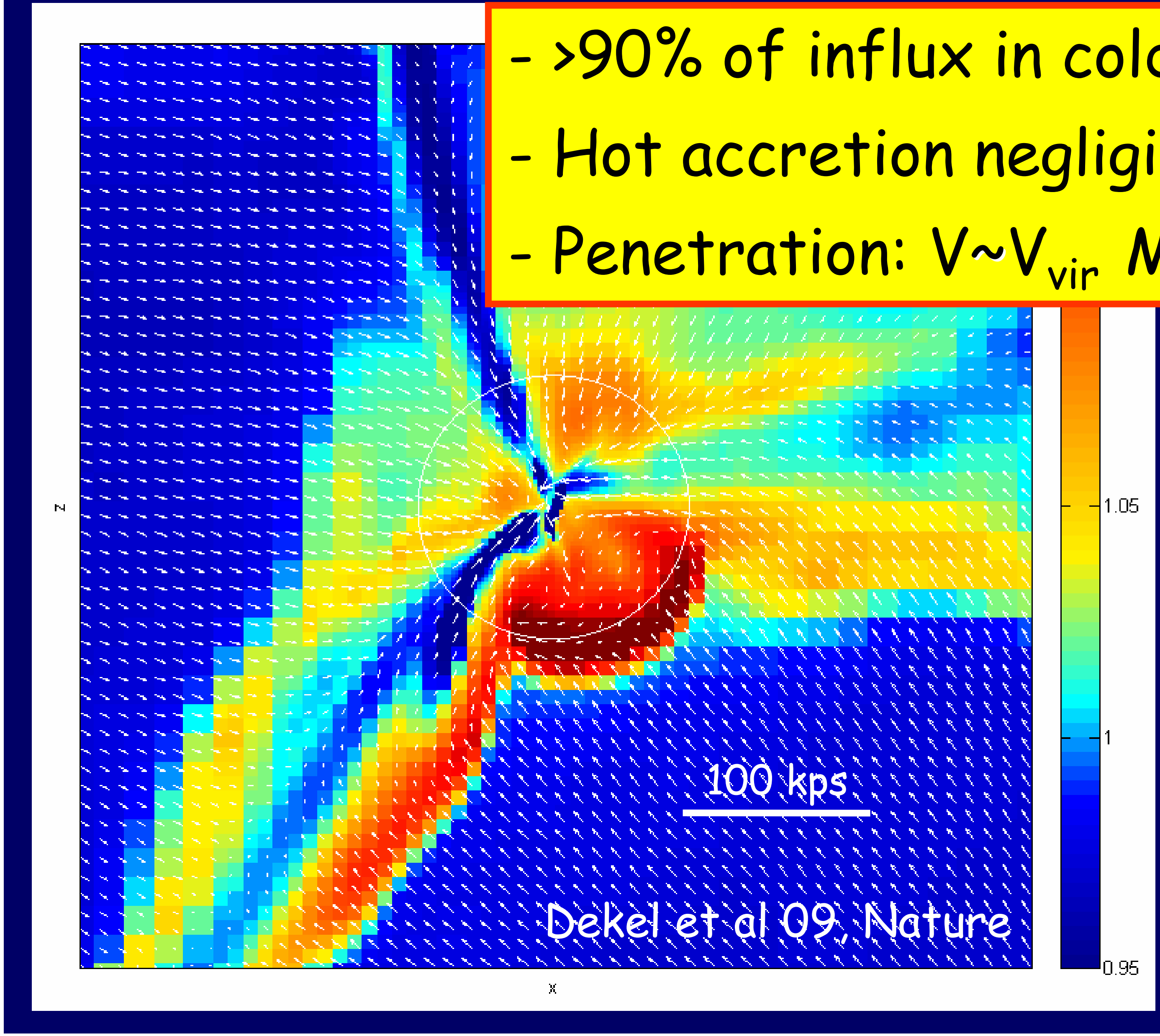
Star-formation history:

$$SFR = f_b \left\langle \dot{M}_{halo} \right\rangle$$



Bouche et al. 09
Dutton et al. 09

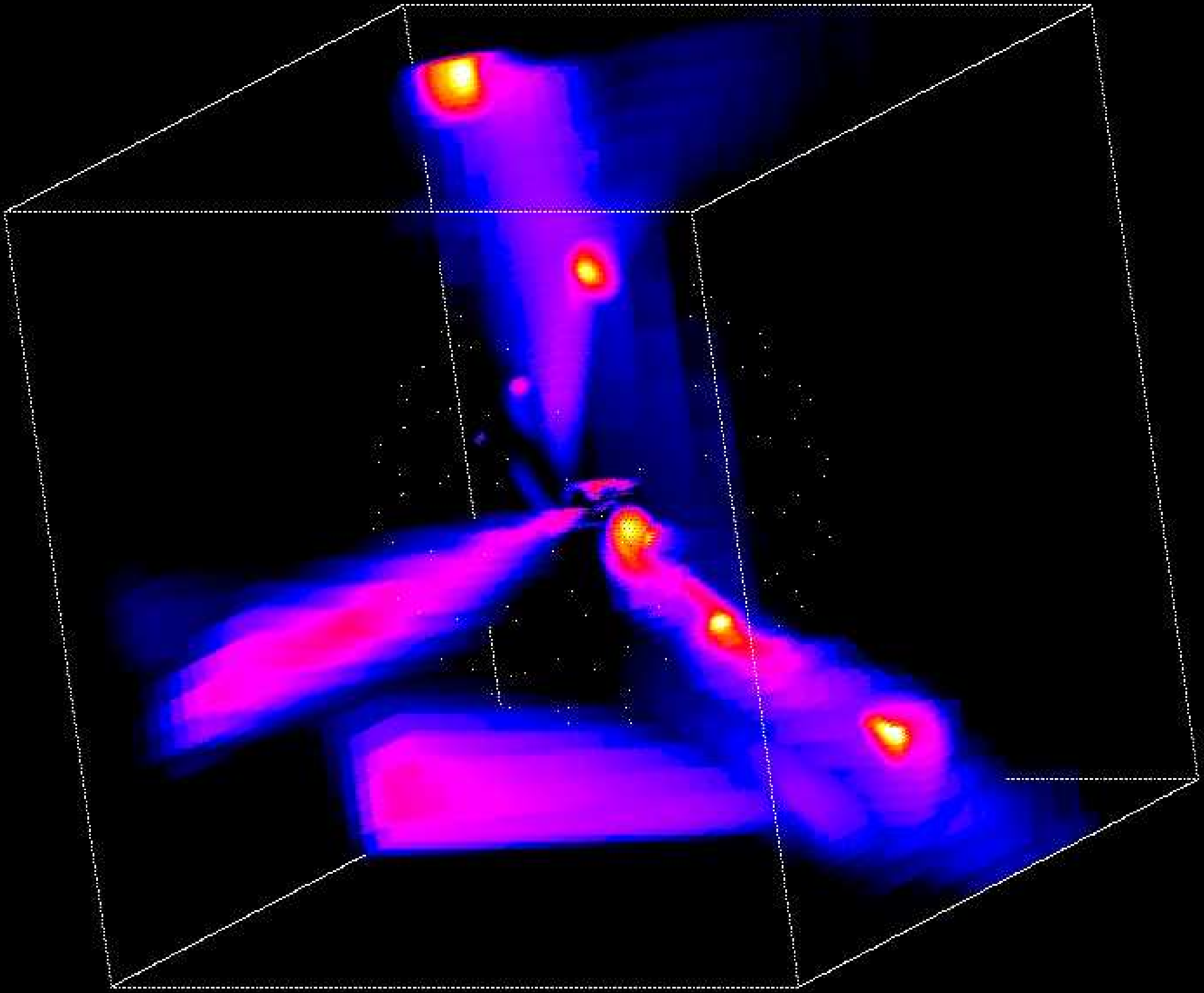
4. Cold Sterams



- >90% of influx in cold streams
- Hot accretion negligible
- Penetration: $V \sim V_{vir}$ $Mdot(r) \sim const$

Dekel et al 09, Nature

Flux
per
solid
angle



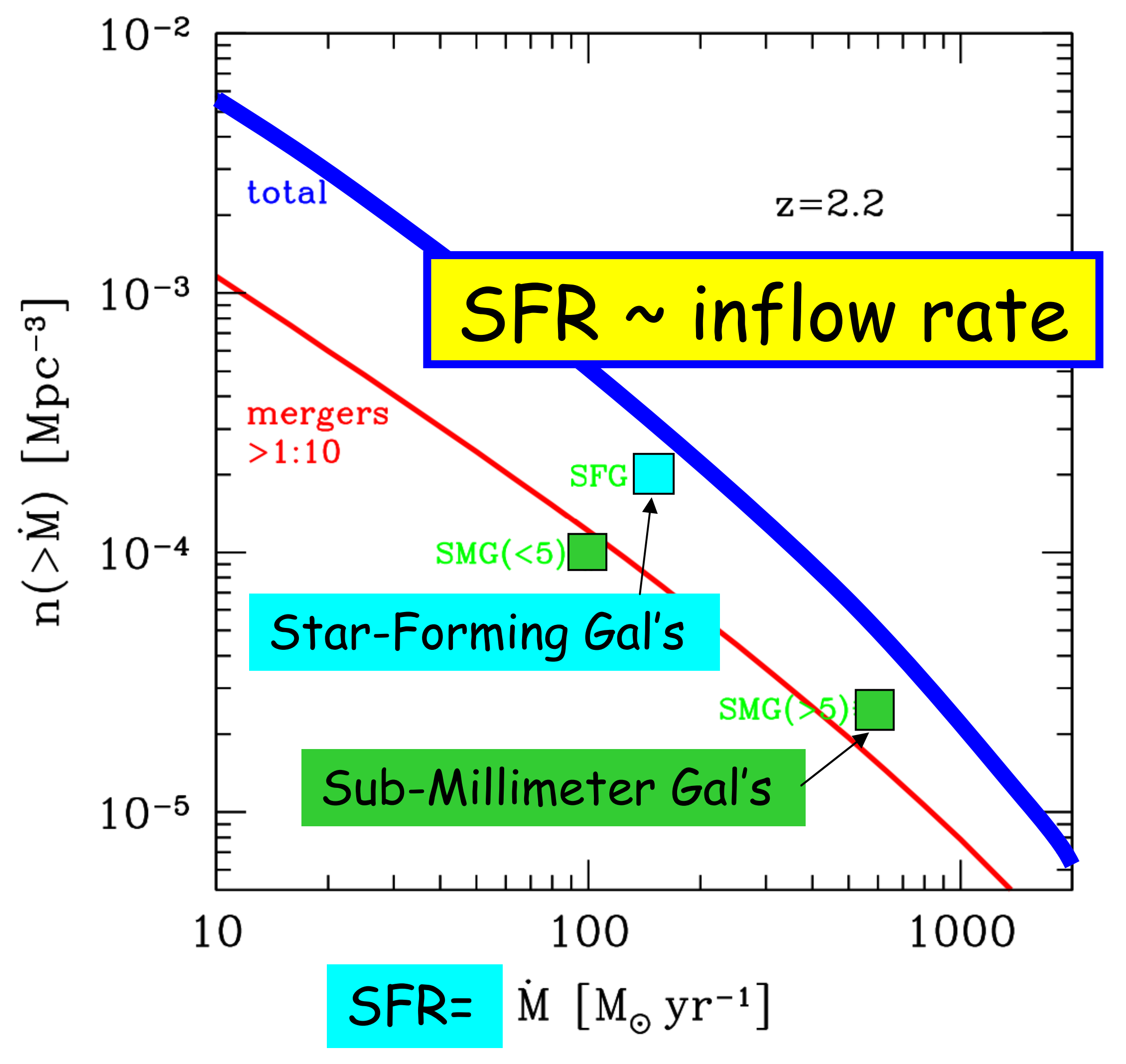
Dekel
et al 09

Galaxy density at a given gas inflow rate

$$n(\dot{M}) = \int_0^\infty P(\dot{M}\,|\,M)\, n(M)\, dM$$

P(Mdot|M) from cosmological hydro simulations (MareNostrum)

n(M) by Sheth-Tormen



Dekel et al 09, Nature

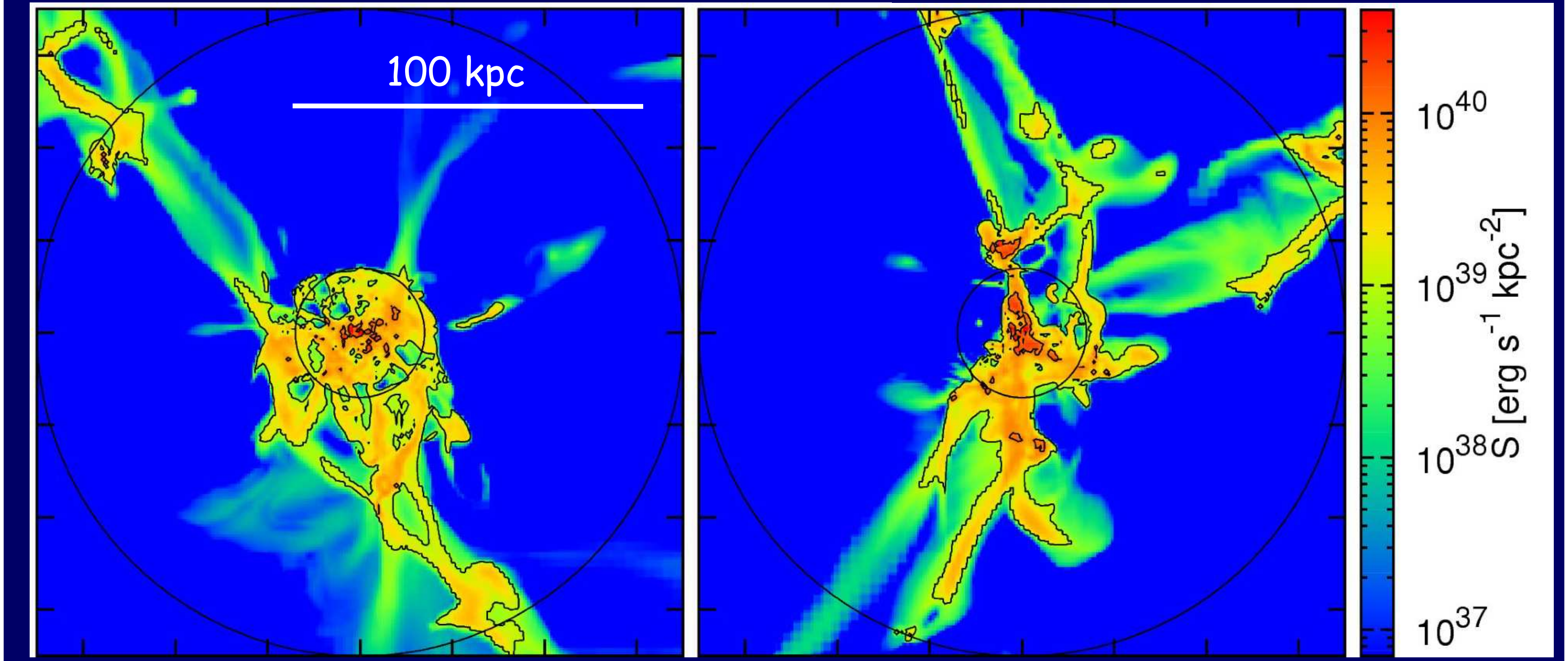
5. Lyman-alpha from Cold streams

Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 09

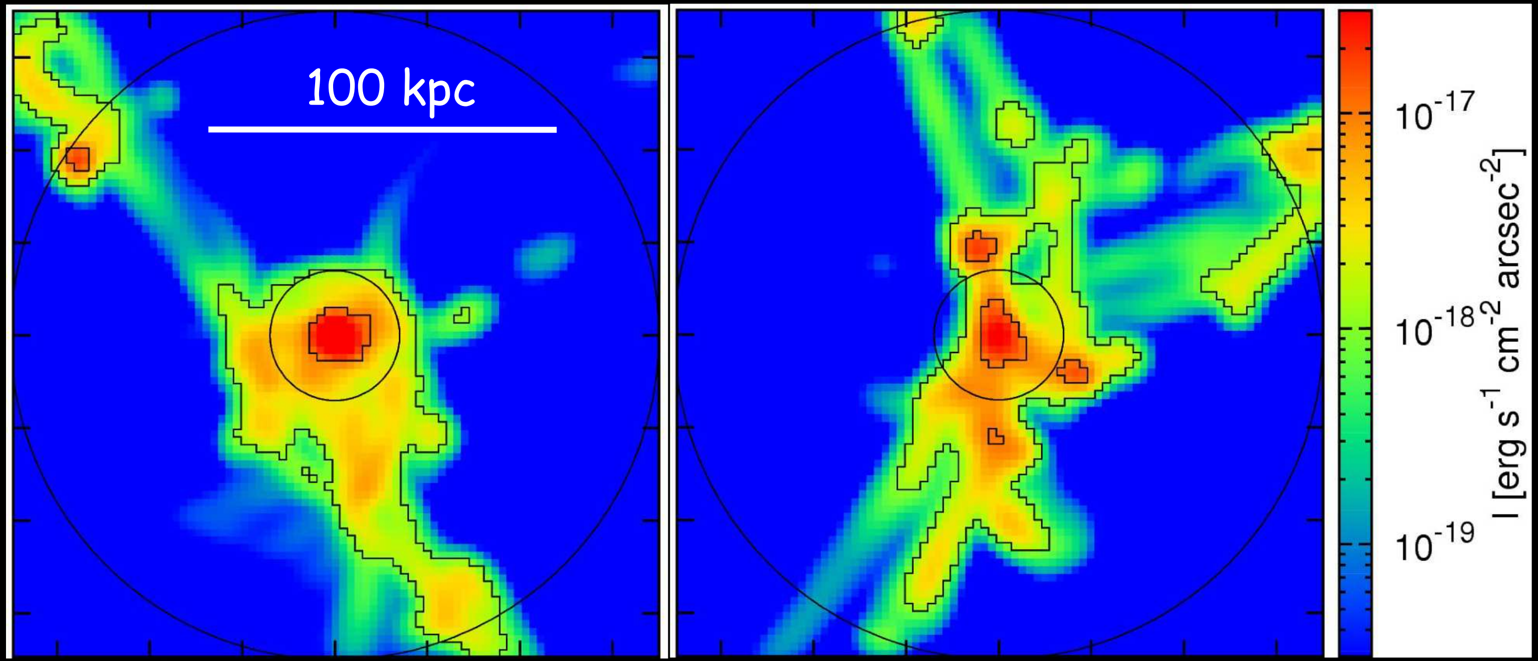
$T=(1\text{-}5)\times10^4$ K $n=0.01\text{-}0.1$ cm^{-3} $N_{HI}\sim10^{20}$ cm^{-2} pressure equilib.

$L \sim 10^{43\text{-}44}$ erg s^{-1}

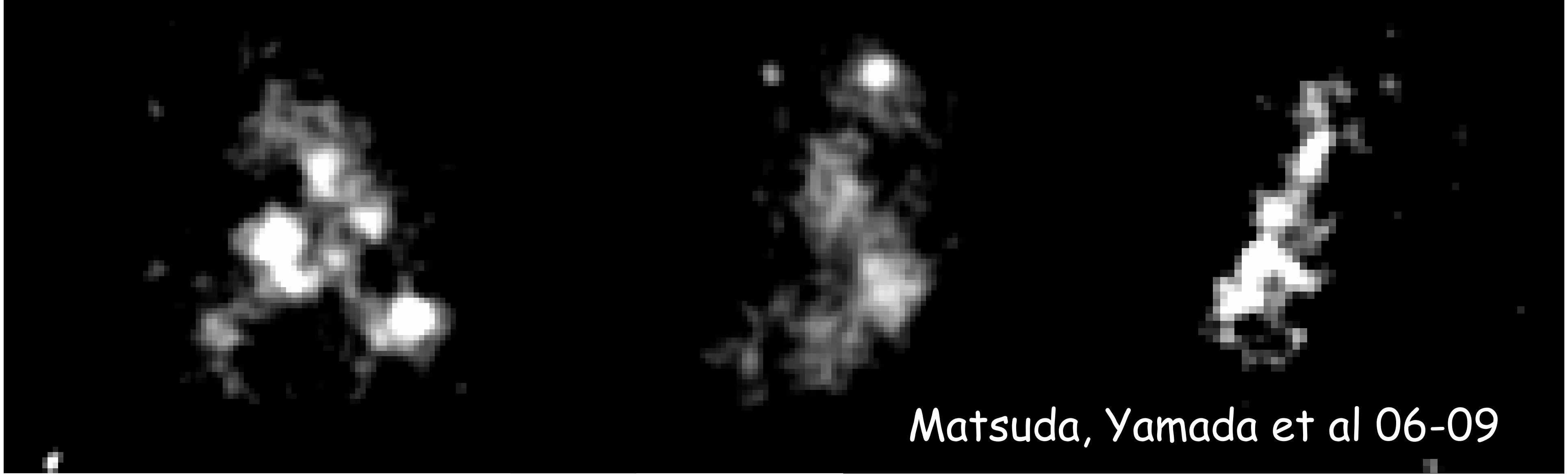
Surface brightness



Cold streams as Lyman-alpha Blobs

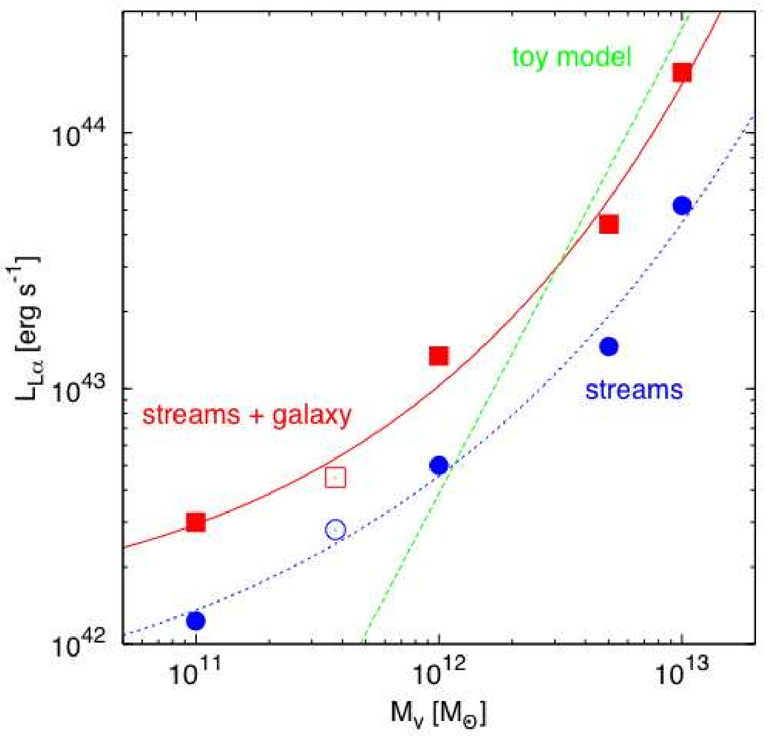


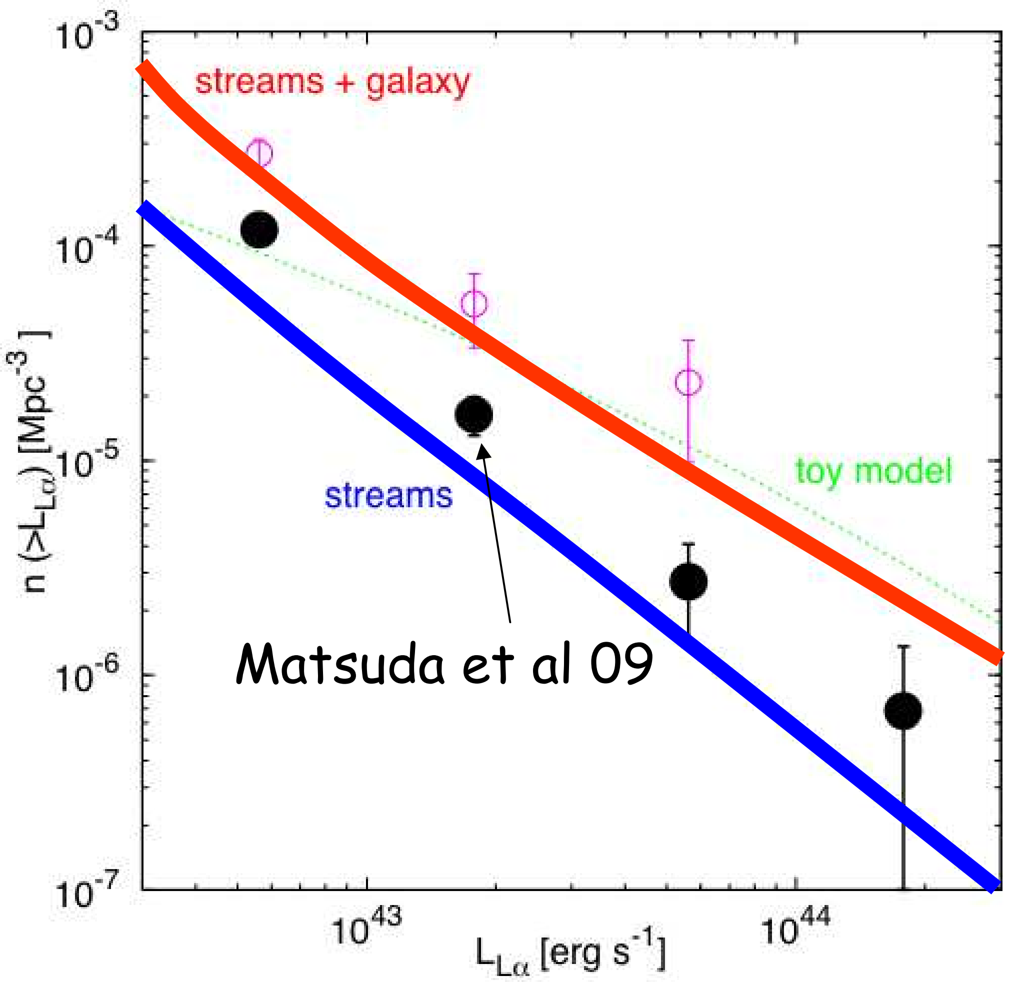
Goerdt,
Dekel,
Sternberg,
Ceverino,
Teyssier,
Primack 09



Matsuda, Yamada et al 06-09

Lyman-alpha Luminosity Function





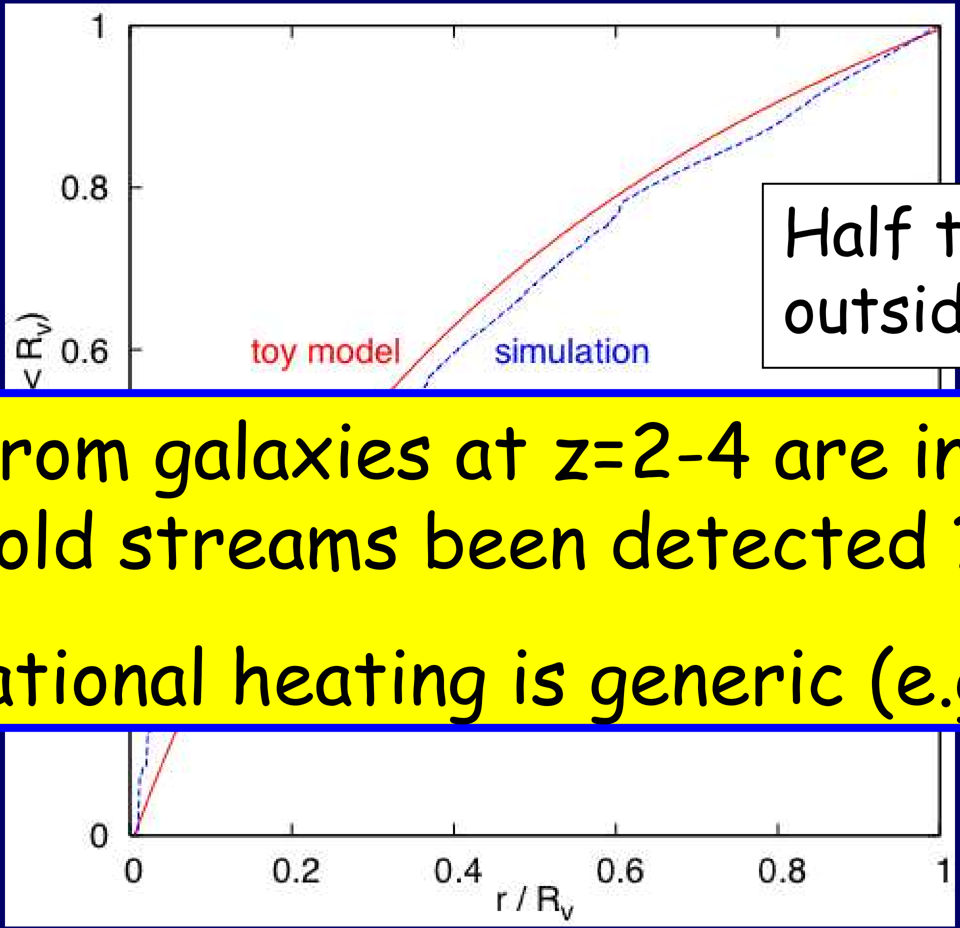
Matsuda et al 09

Isophotal area and kinematics also consistent with data

Gravity Powers Lyman-alpha Emission

$$E_{heat}(r) = f_c\,\dot{M}_c \left|\frac{\partial\varphi}{\partial r}\right|$$

$$E_{heat} \approx 1.2\times10^{43}\,erg\,s^{-1}\; f_c\,M_{12}^{1.82}\,(1+z)_4^{3.25}$$



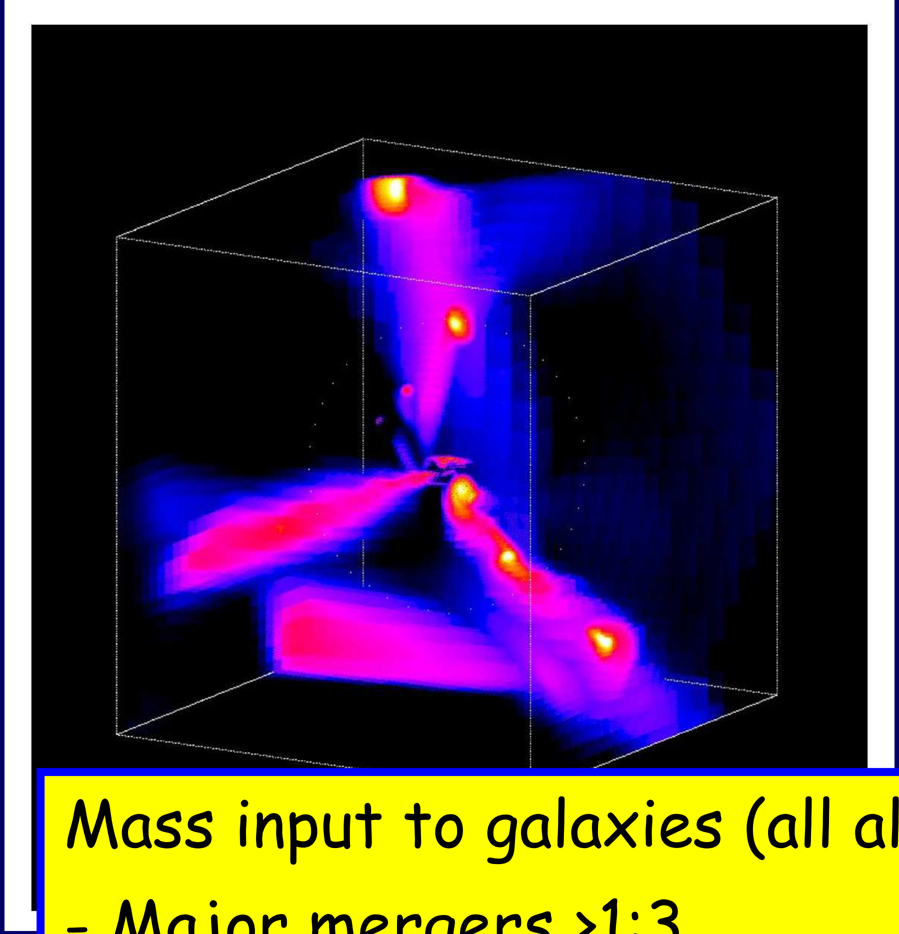
Half the luminosity outside 0.3R$_v$

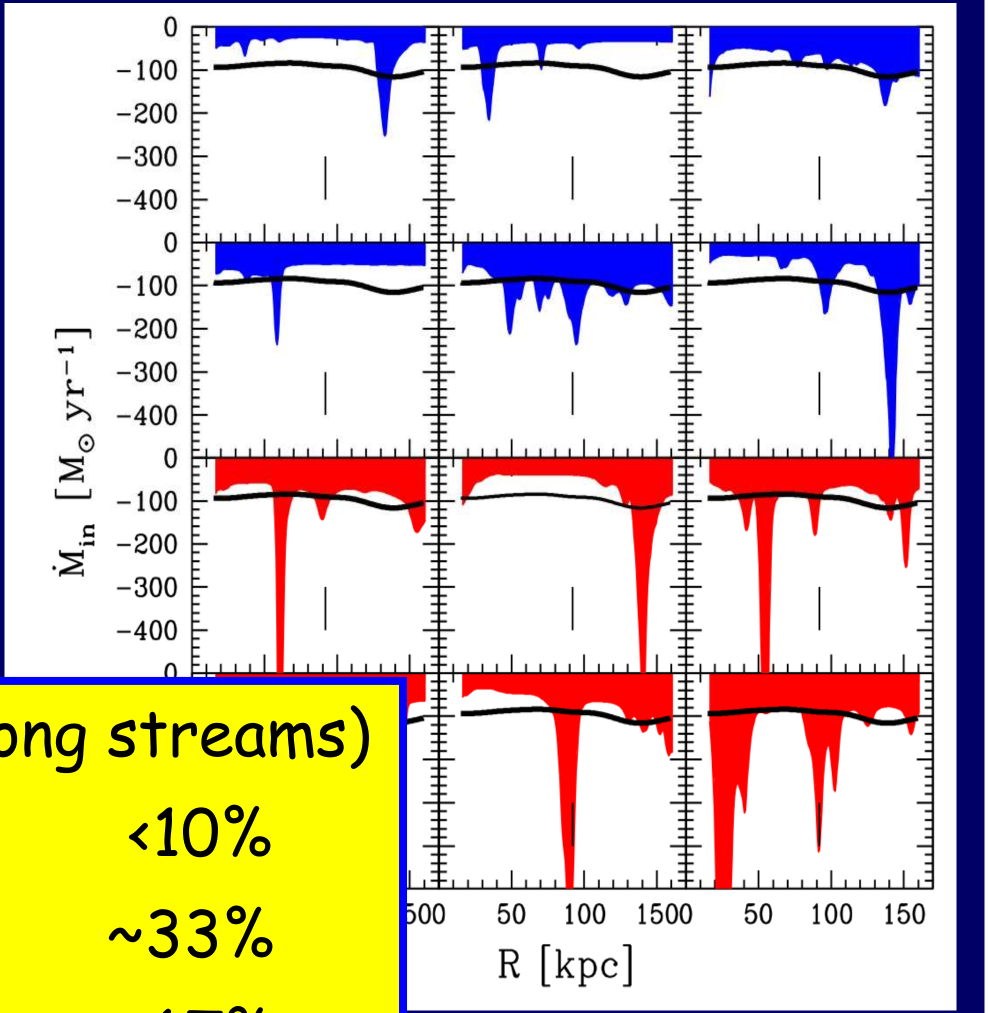
LABs from galaxies at z=2-4 are inevitable
Have cold streams been detected ?

Gravitational heating is generic (e.g. clusters)

6. Stream clumpiness - mergers

Dekel et al 09, Nature



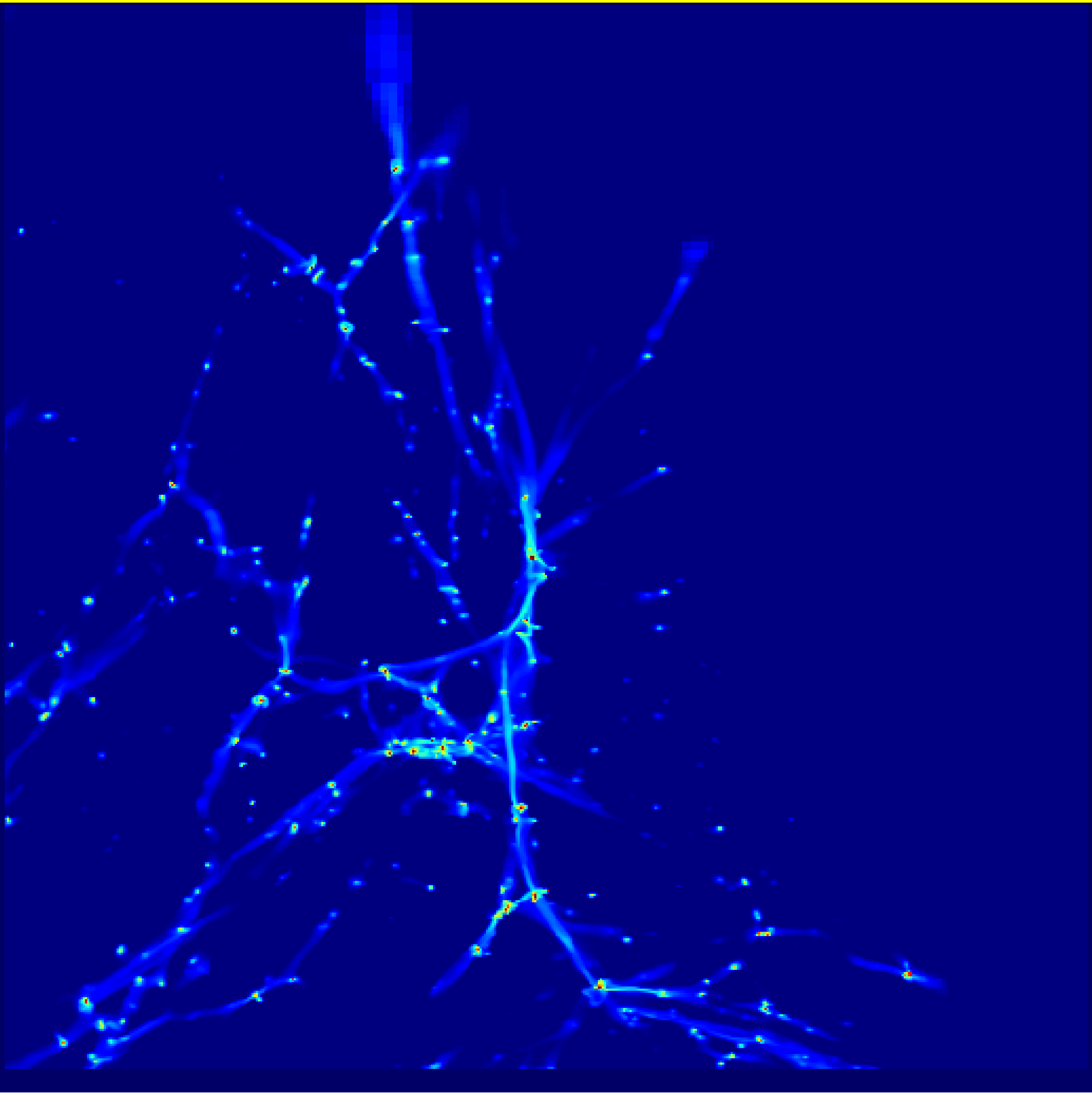


Mass input to galaxies (all along streams)

- Major mergers >1:3	<10%
- Major+minor mergers >1:10	~33%
- Miniminors and smooth flows	~67%

$M=10^{12}M_\odot$ $z=2.5$

All hi-z mergers are along cold streams



AMR RAMSES
Teyssier, Dekel

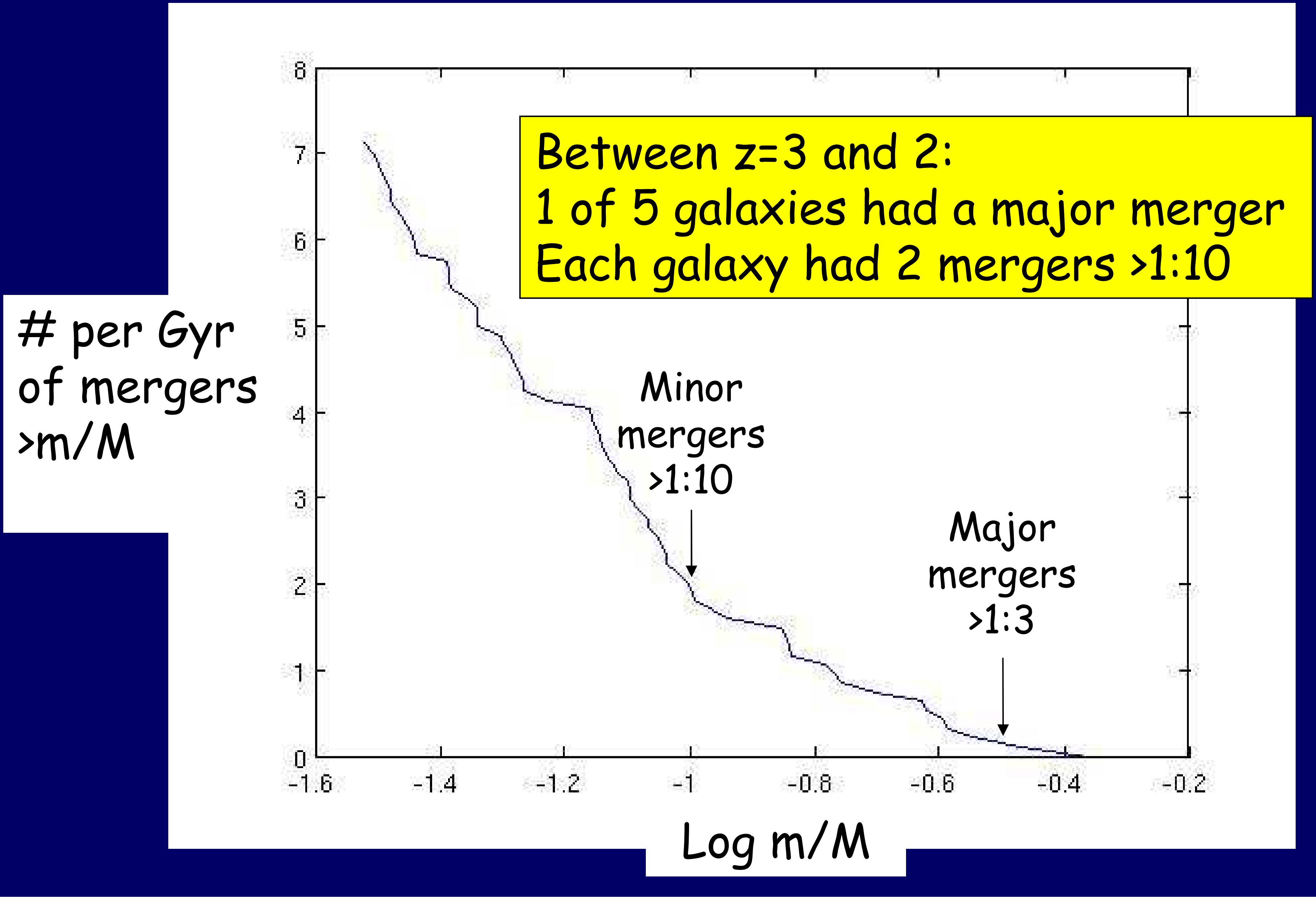
box 300 kpc

res 30 pc

z = 5.0 to 2.5

Merger Rate

Romero et al. 2010



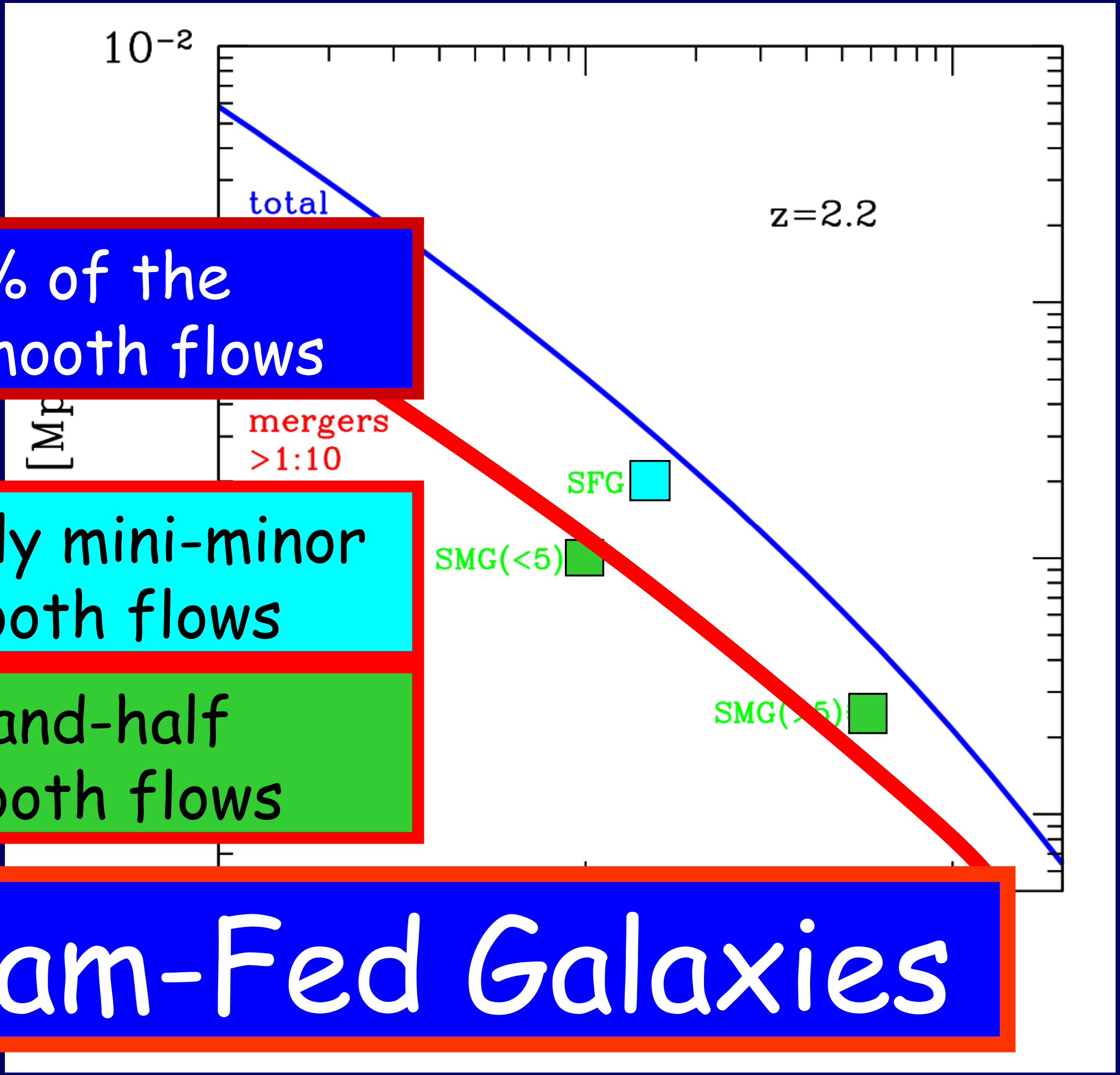
Between z=3 and 2:
1 of 5 galaxies had a major merger
Each galaxy had 2 mergers >1:10

per Gyr of mergers >m/M

Log m/M

Fraction of Mergers

$$n(\dot{M}) = \int_0^\infty P(\dot{M}\,|\,M)\, n(M)\, dM$$



At a given dM/dt, 75% of the galaxies are fed by smooth flows

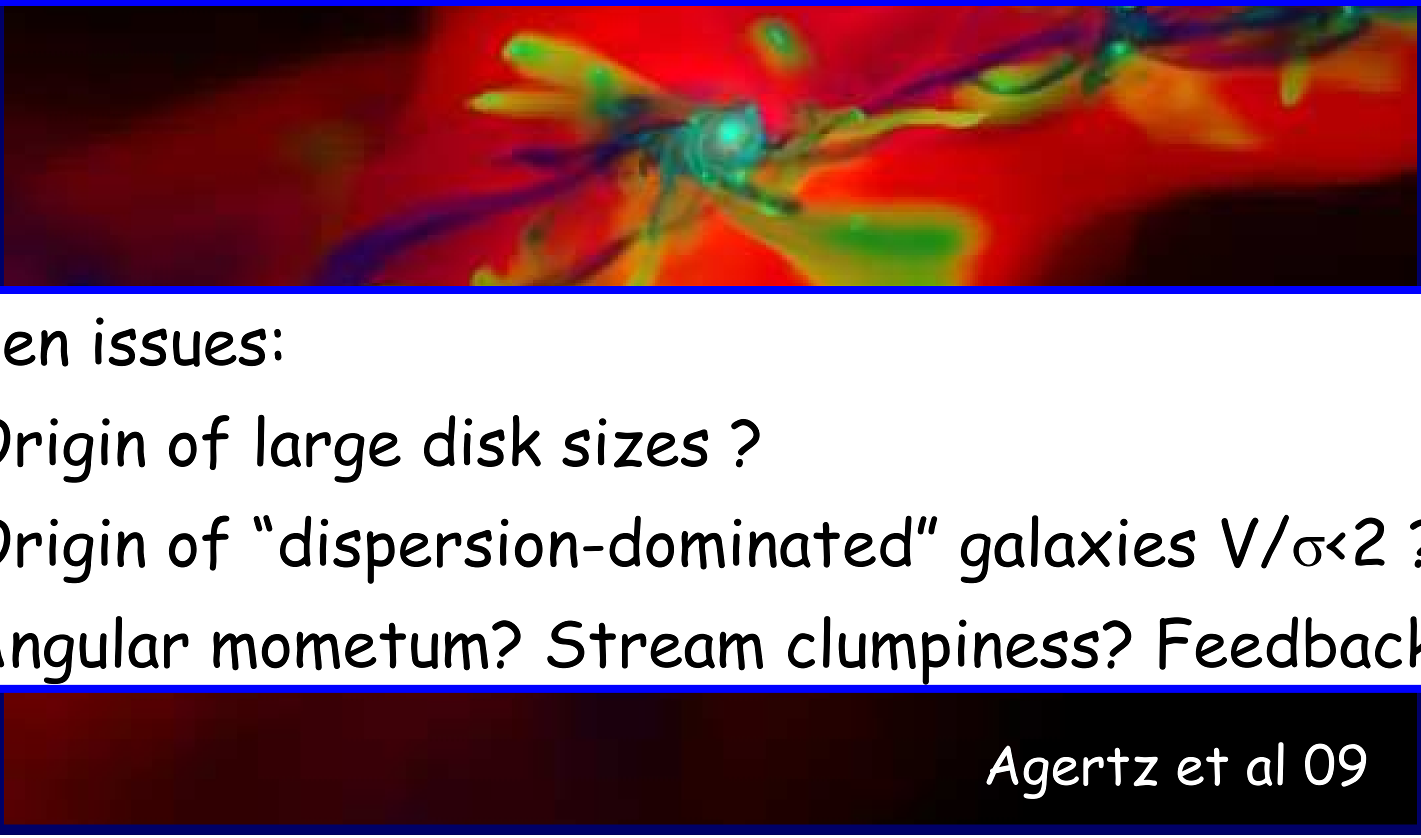
BzK/BX/BM are mostly mini-minor mergers <1:10, i.e. smooth flows

Bright SMG are half-and-half mergers >1:10 and smooth flows

SFG: Stream-Fed Galaxies

7. Extended Rotating Disks

- Streams bring in the angular momentum
- Extended disks must form (in many cases)
- Disk spin & size are determined by one stream
- Clumpy streams generate turbulence

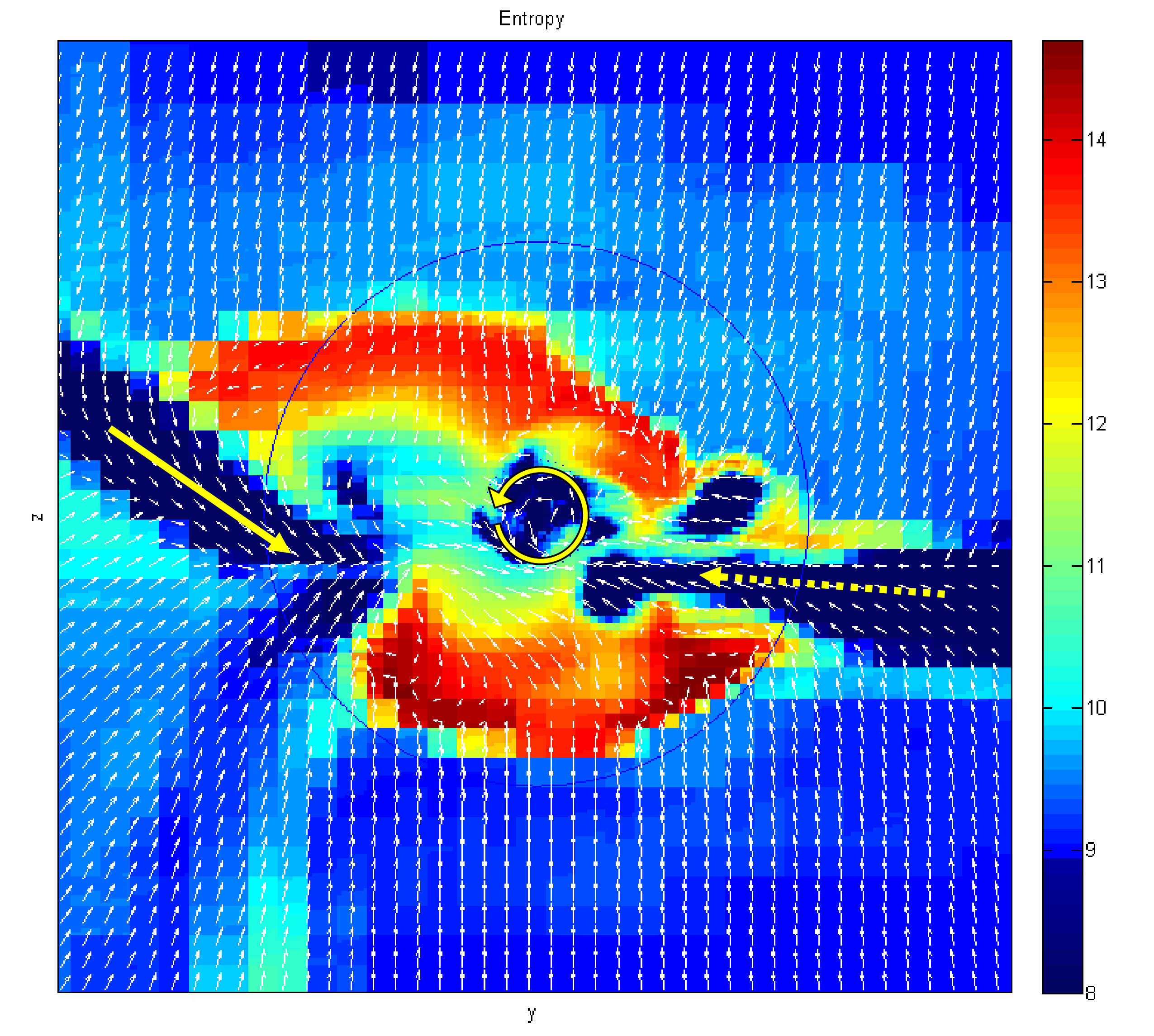


Open issues:

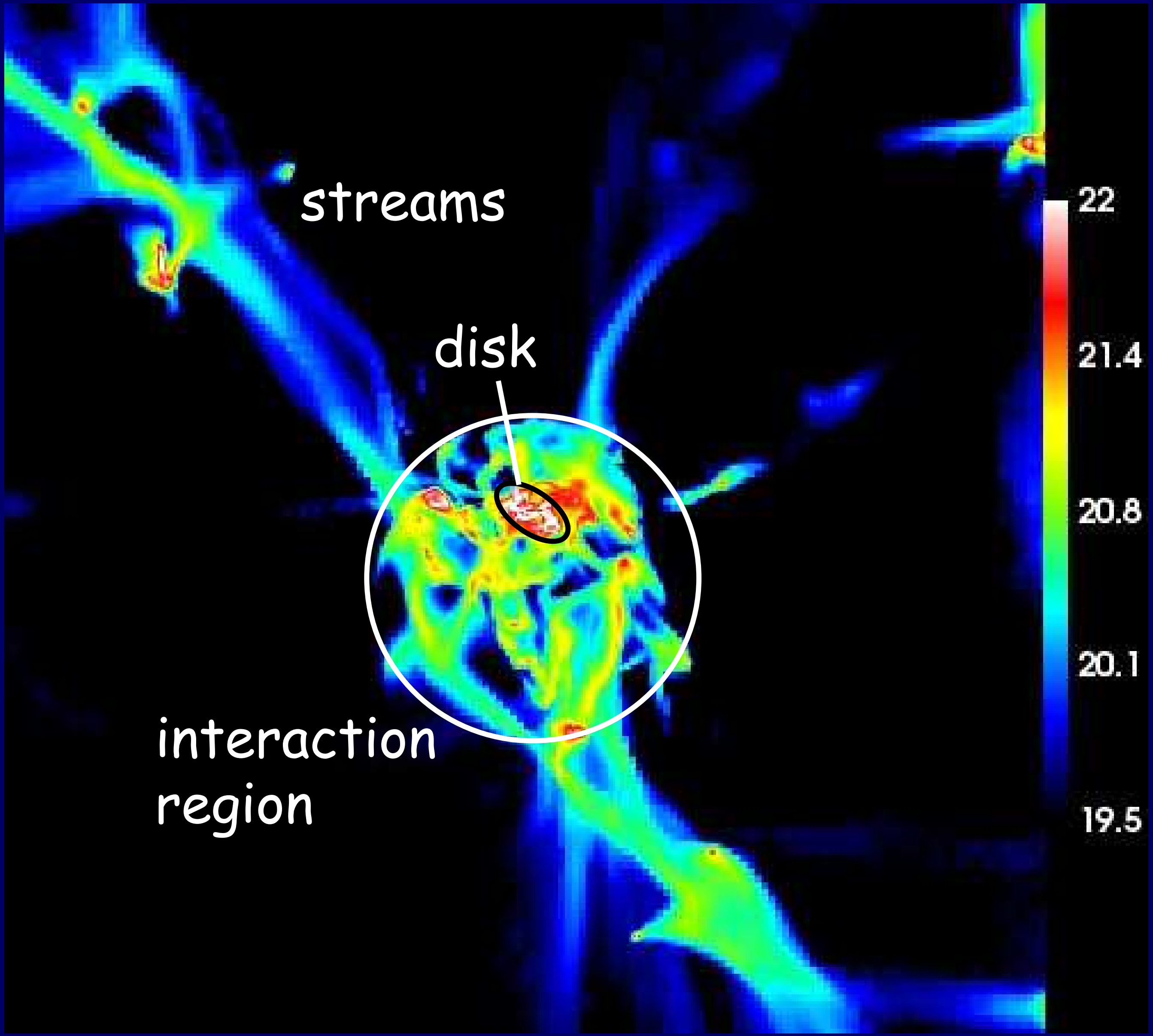
- Origin of large disk sizes ?
- Origin of “dispersion-dominated” galaxies $V/\sigma<2$?
- Angular mometum? Stream clumpiness? Feedback?

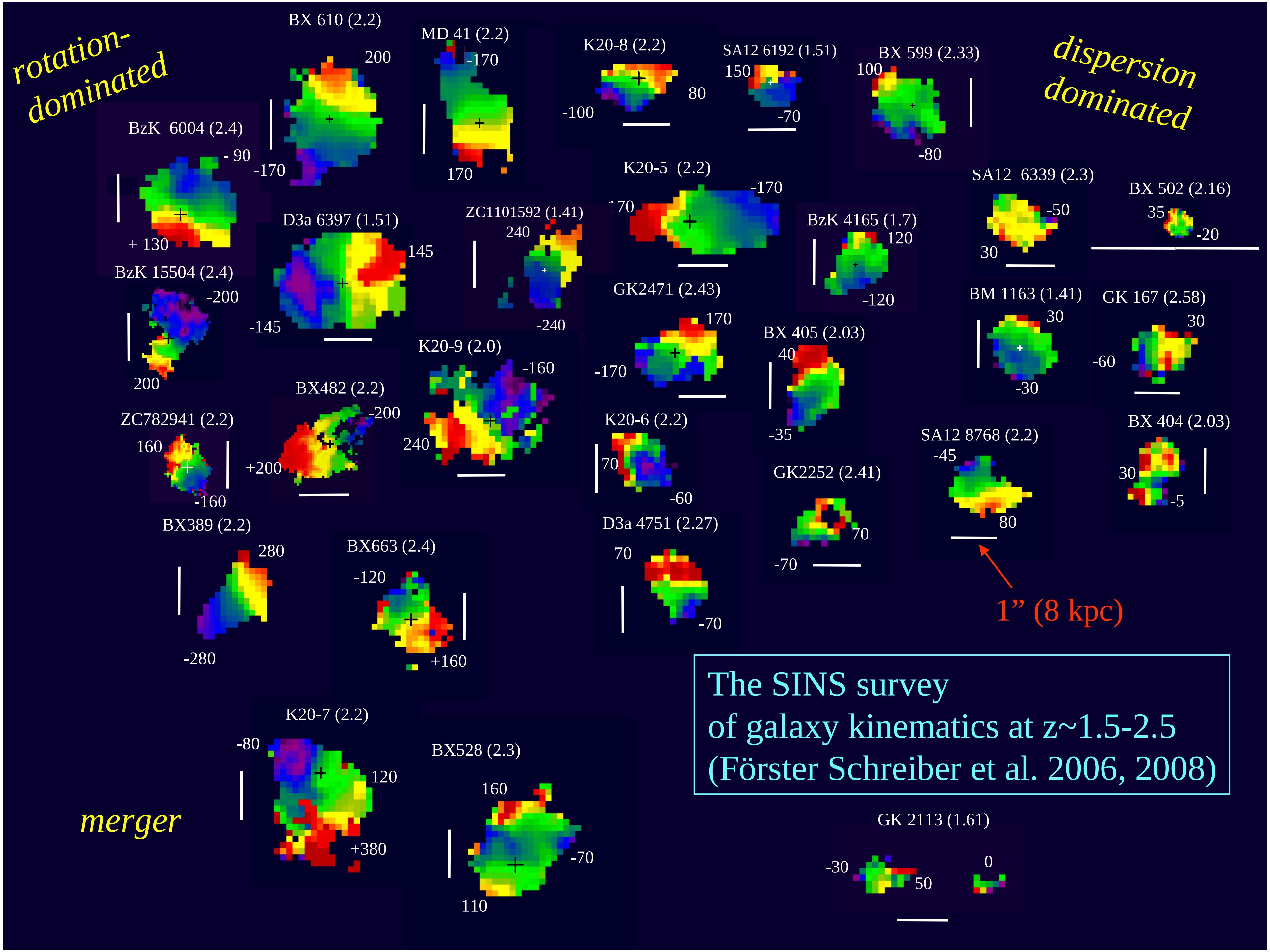
Agertz et al 09

Disk Buildup by Streams



A Disk Fed by Cold Streams





The SINS survey
of galaxy kinematics at z~1.5-2.5
(Förster Schreiber et al. 2006, 2008)

8. Wild Disk Instability

Noguchi 99
Immeli et al. 04

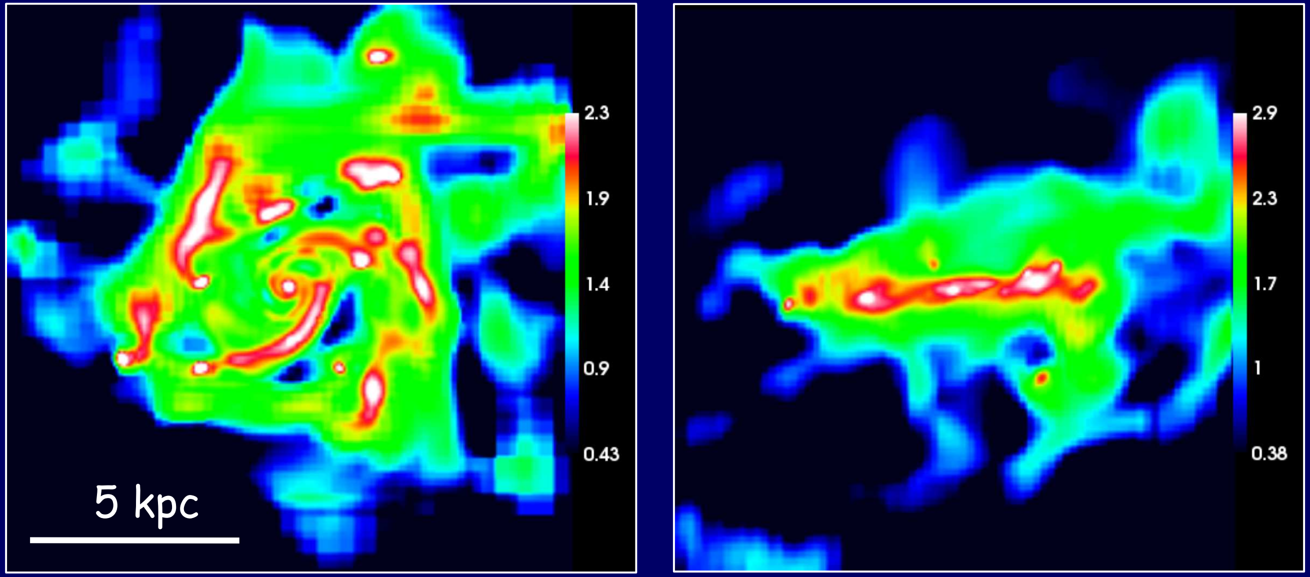
Bournaud,
Elmegreen,
Elmegreen 06, 08

High gas density → disk wildly unstable

$$Q \approx \frac{\sigma\,\Omega}{\pi\,G\,\boxed{\Sigma}} \leq 1$$

Giant clumps and transient features

$$R_{\rm clump} \approx \frac{7\,G\,\boxed{\Sigma}}{\Omega^2}$$



Dekel, Sari,
Ceverino 09

Ceverino,
Dekel,
Bournaud 09

Agertz et al. 09

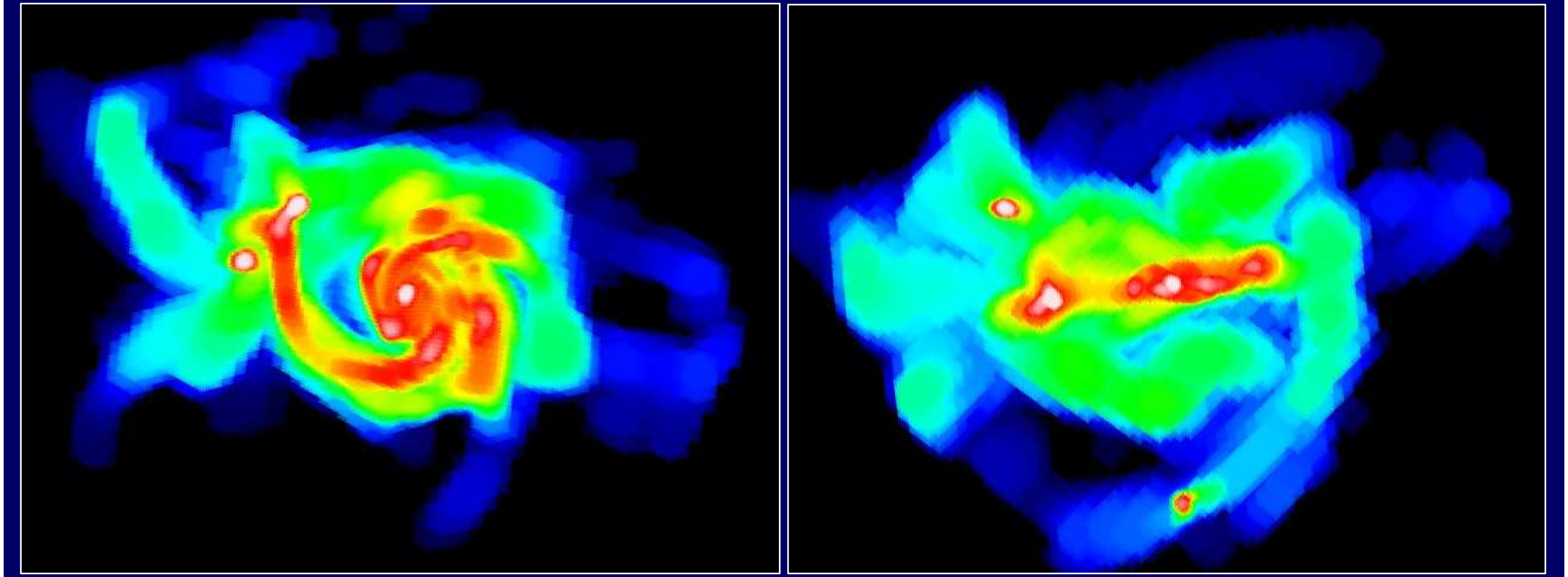
Self-regulation at Q ~ 1 by clump encounters and torques, high σ/V~1/4

Efficient star formation in the clumps (to be understood)

Rapid migration of massive clumps and angular-momentum transport
→ bulge formation

Cosmological Simulation: Stream-fed disk of giant gas clumps

Ceverino, Dekel, bournaud 2009 AMR res: 70 pc $M_v=8\times10^{11}\,M_\odot$ z=2.1



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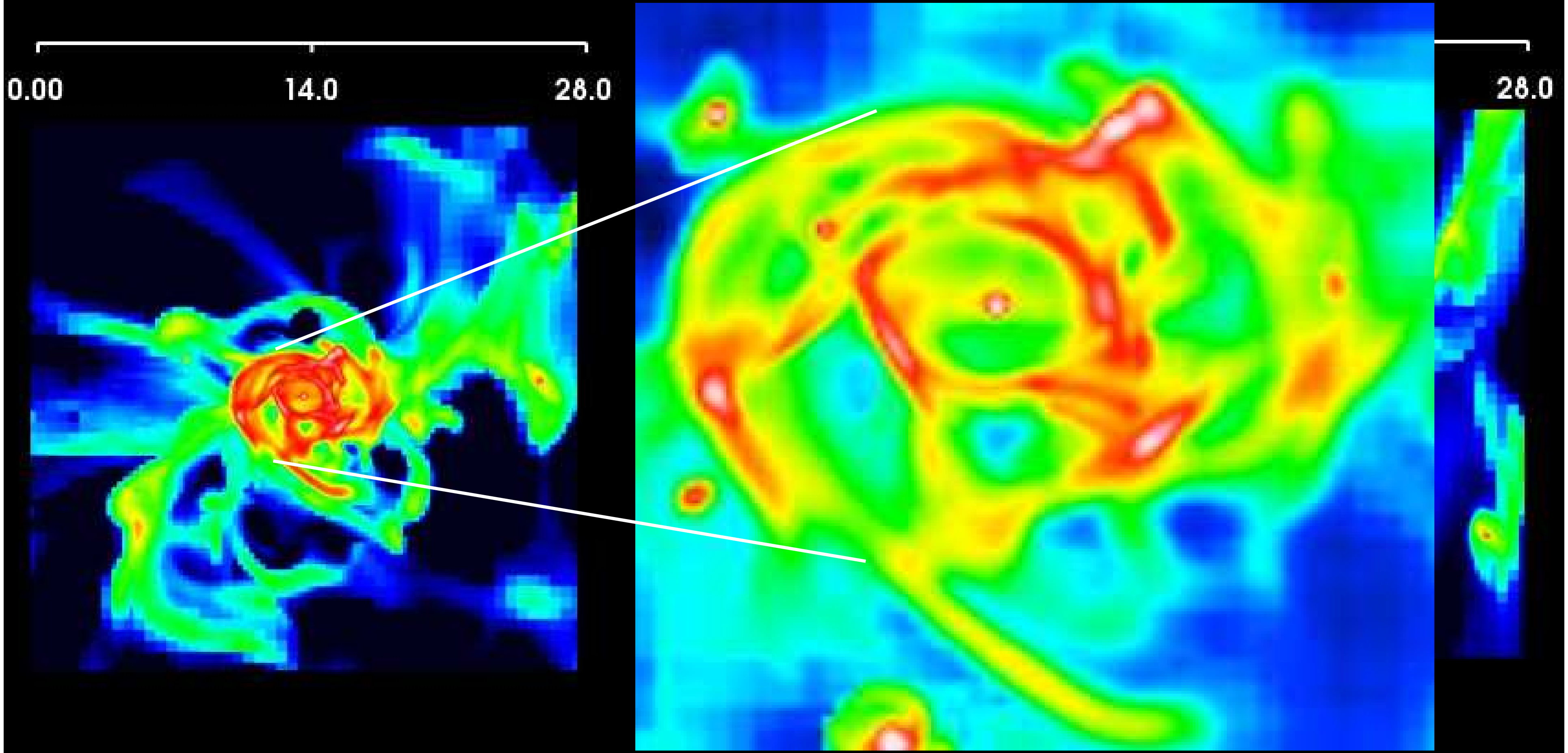
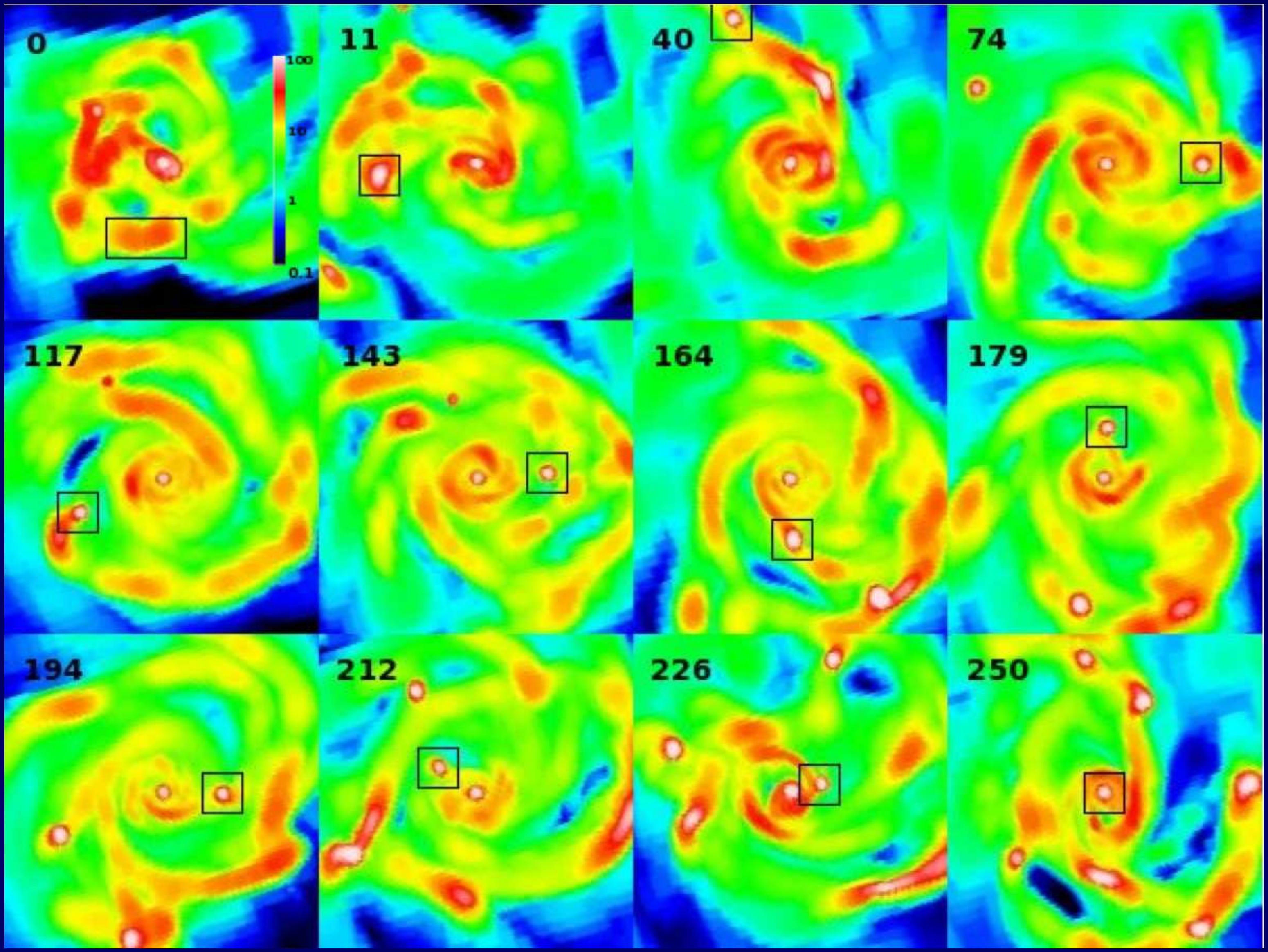
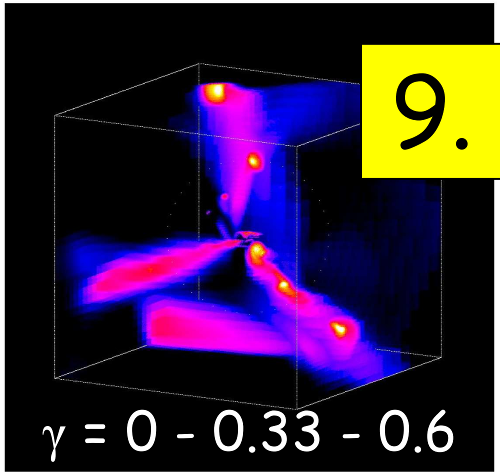


Clump Formation & Migration

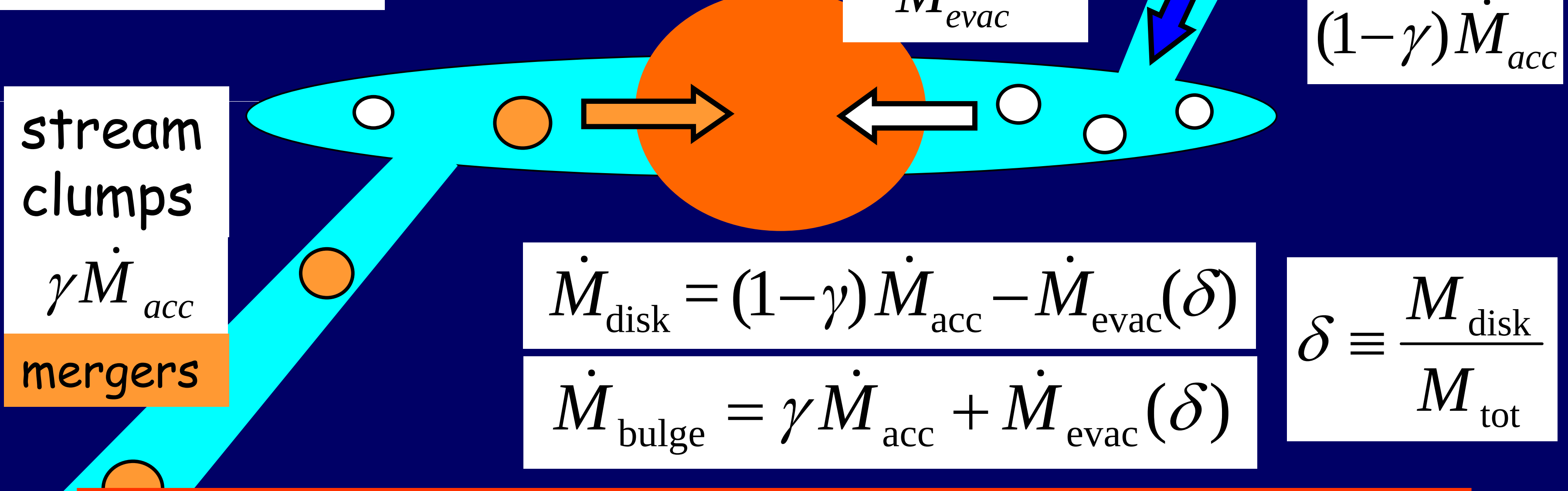


9. Cosmological Steady State

Dekel, Sari, Ceverino 09



γ = 0 - 0.33 - 0.6



migration

$\dot{M}_{evac}$

smooth streams

$(1-\gamma)\dot{M}_{acc}$

stream clumps

$\gamma \dot{M}_{acc}$

mergers

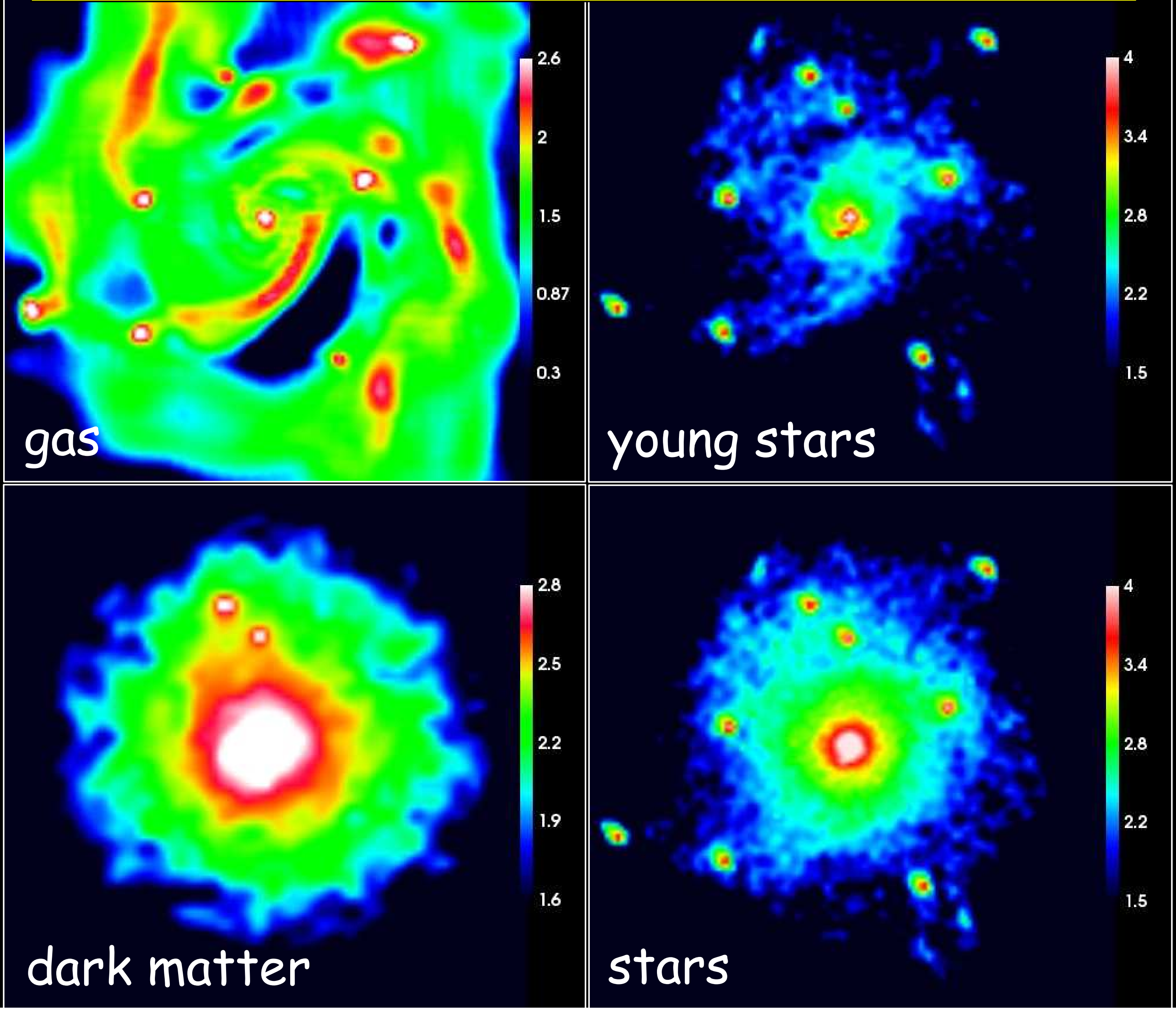
$$\dot{M}_{\rm disk} = (1-\gamma)\dot{M}_{\rm acc} - \dot{M}_{\rm evac}(\delta)$$

$$\dot{M}_{\rm bulge} = \gamma \dot{M}_{\rm acc} + \dot{M}_{\rm evac}(\delta)$$

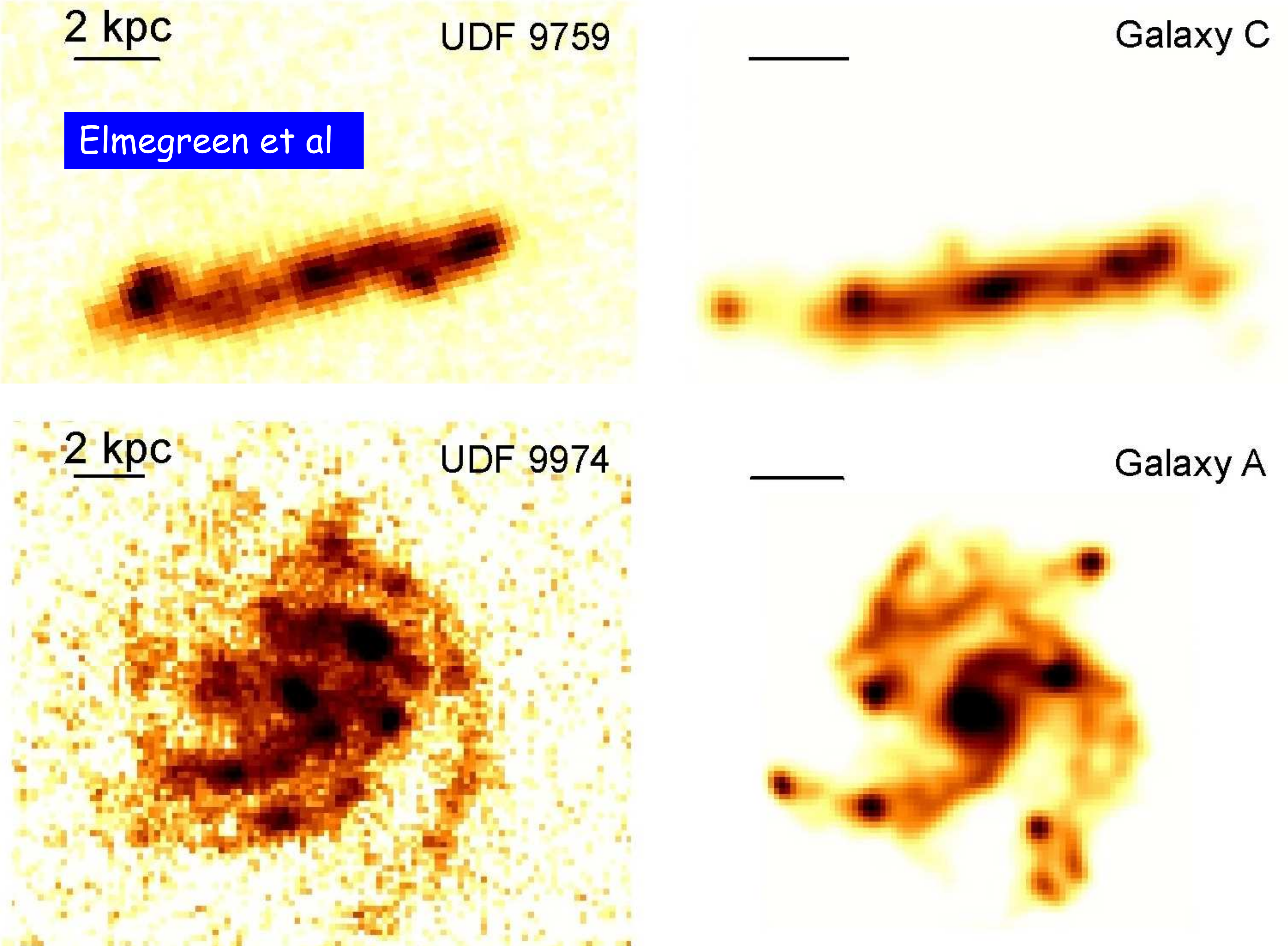
$$\delta \equiv \frac{M_{\rm disk}}{M_{\rm tot}}$$

Steady state for several Gyrs:
draining disk is replenished by cold streams,
bulge ~ disk ~ dark matter

Disk Clumps vs Stream Clumps

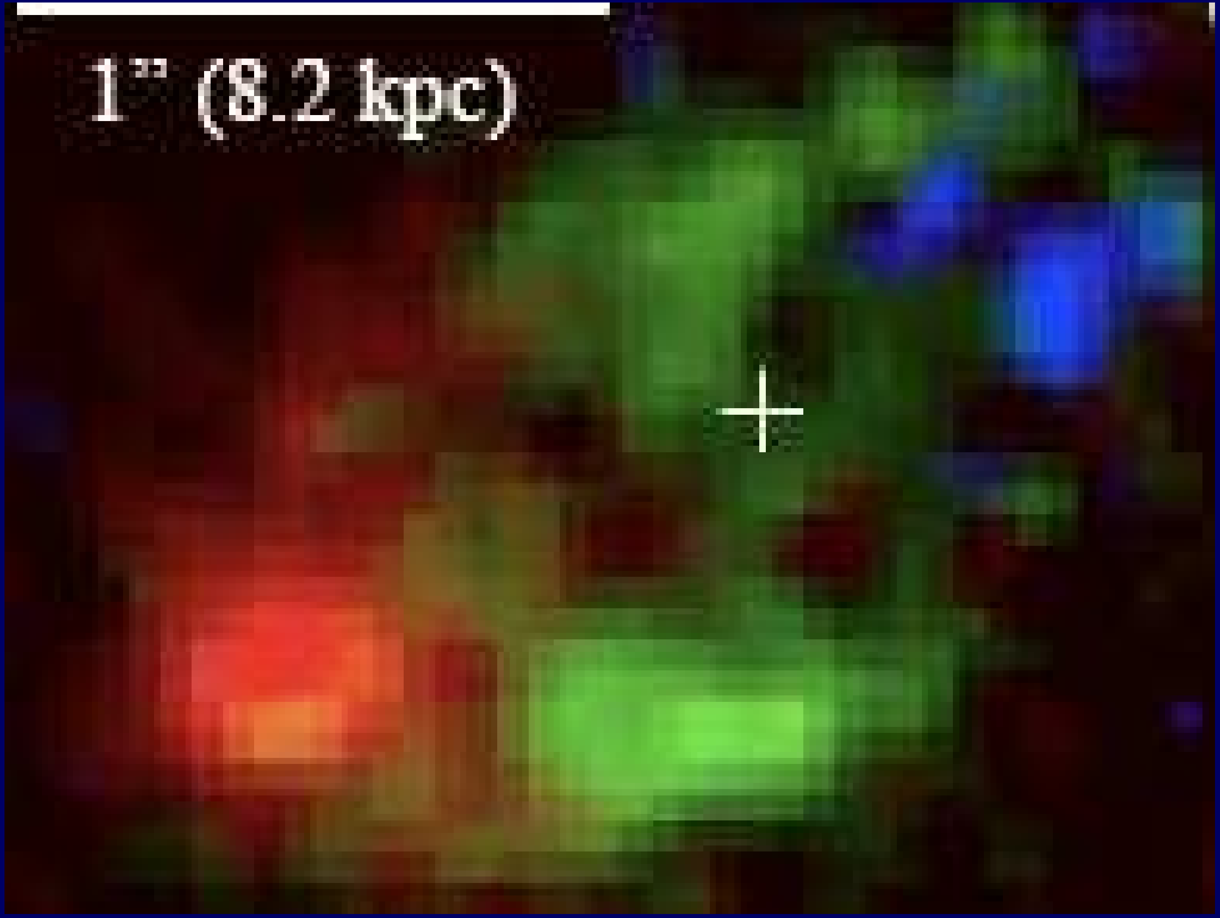


Observations vs. Simulations



Elmegreen et al

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

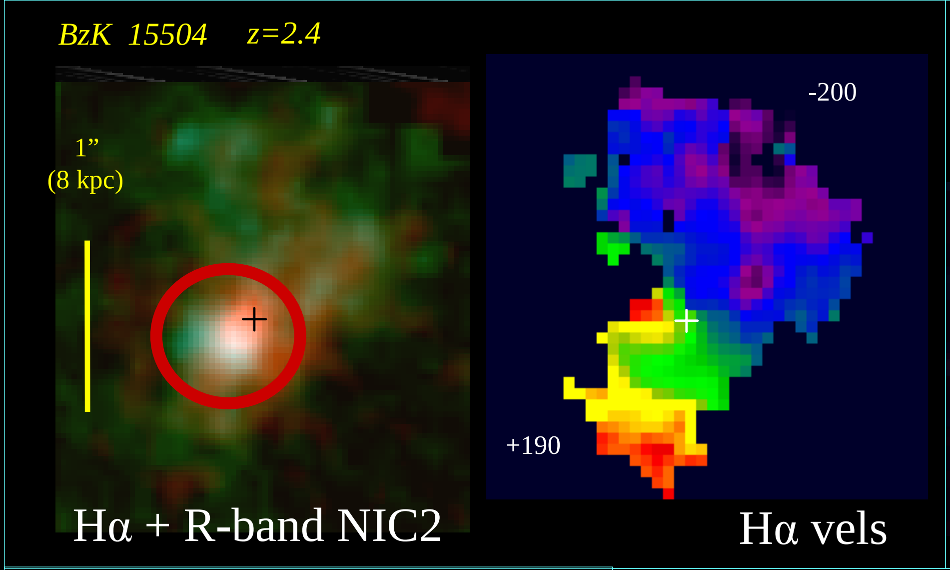


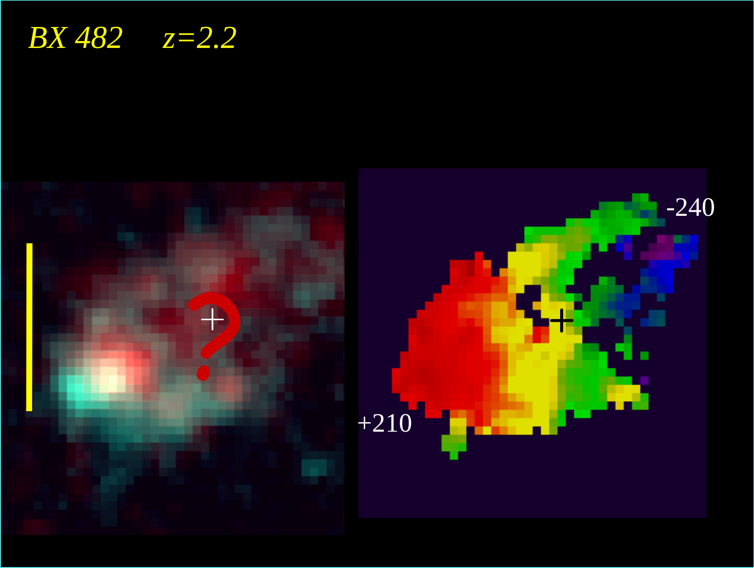
Hα star-form regions

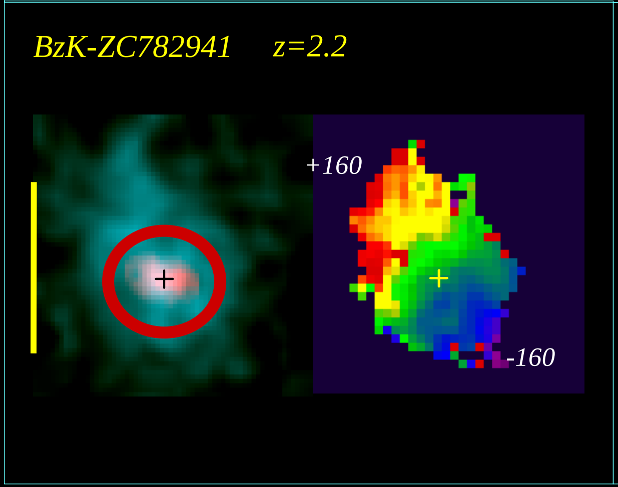
color-code velocity field

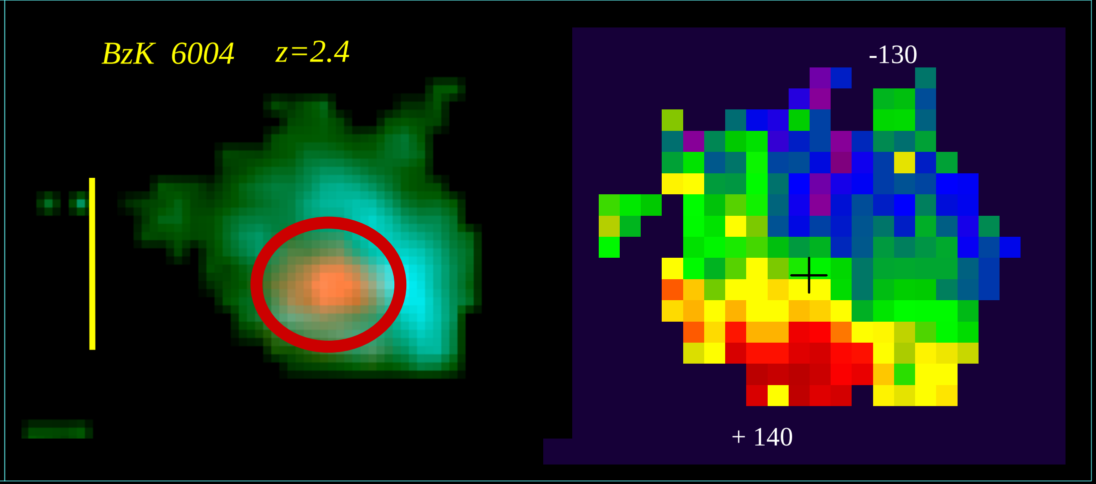
Genzel et al 08

Clumpy disks with comparable bulges







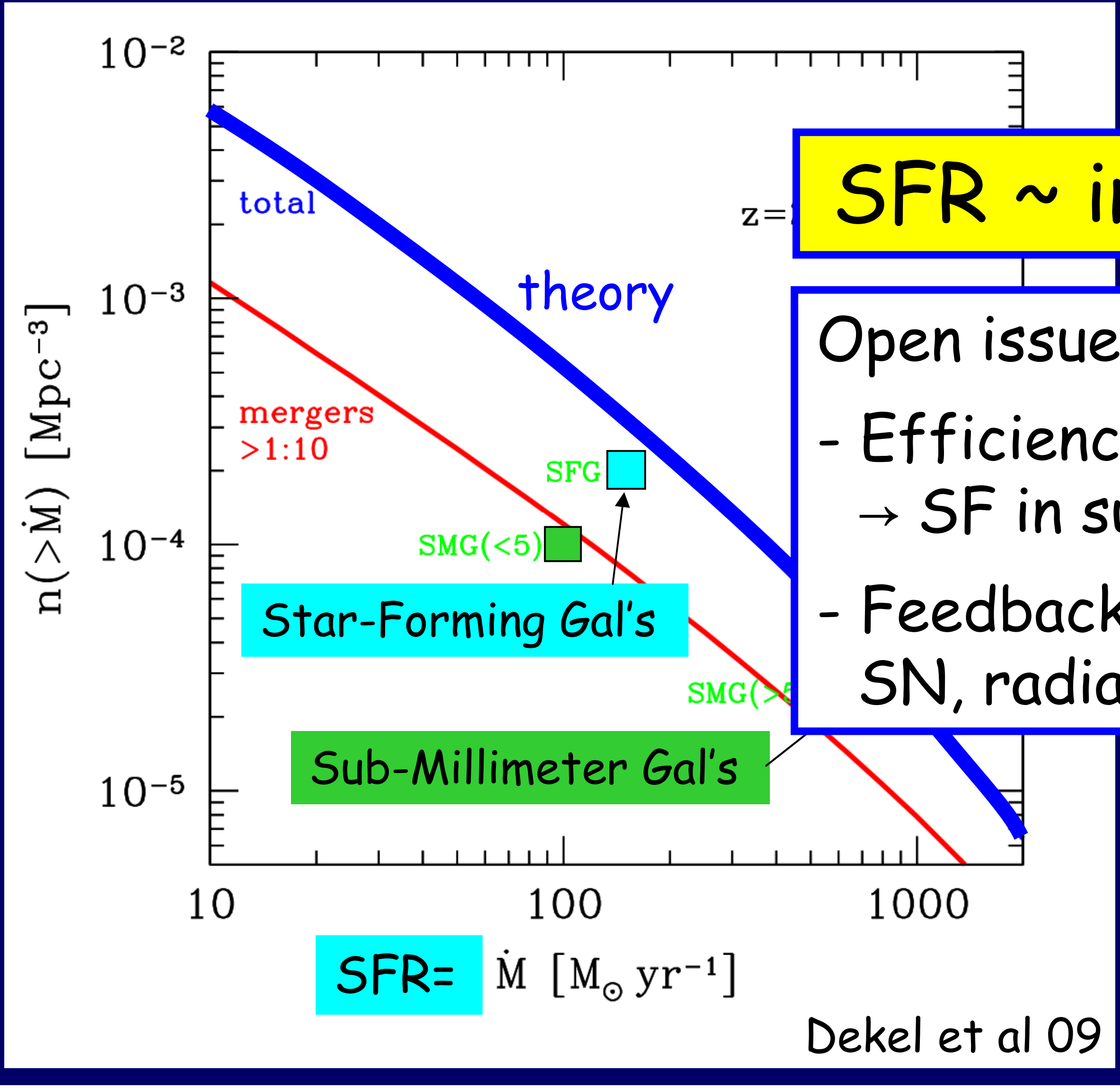


Genzel et al. 08; Förster Schreiber et al. 20

M(≤3 kpc)/M(≤15 kpc)~0.2-0.4

10. Rapid Star Formation - in Clumps

Theory versus observation



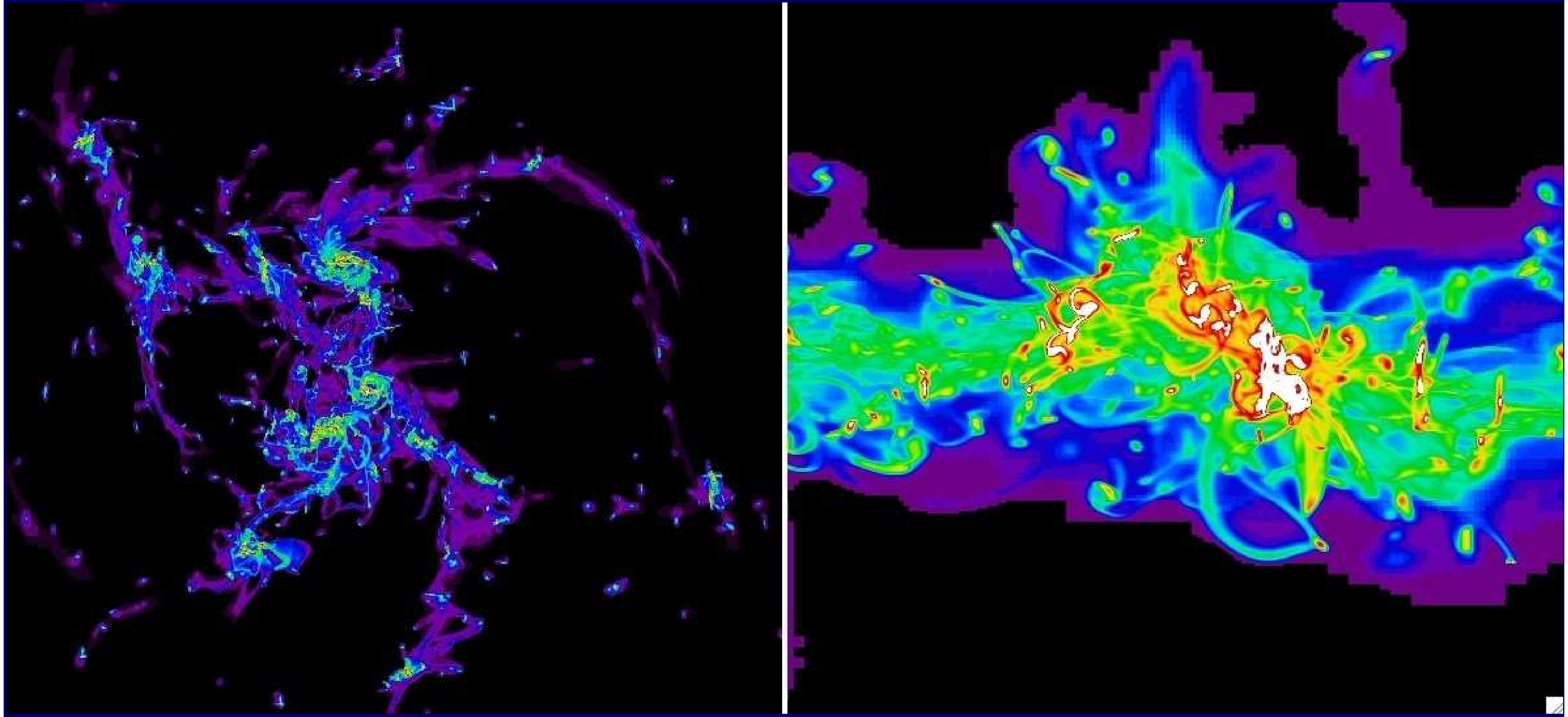
Dekel et al 09

SFR ~ inflow rate

Open issues:

- Efficiency SFR/(Mg/td) ~ 1%
  → SF in sub-clumps
- Feedback & clump survival
  SN, radiative, AGN

Sub-structure in the disk giant clumps



Bournaud 09 AMR 2 pc resolution

Survival of Giant Clumps

Murray et al. 09; Krumholz & Dekel 09

SFR efficiency $\varepsilon \equiv \frac{\dot{\Sigma}_*}{\Sigma_\mathrm{g} / t_\mathrm{ff}}$ ~ 0.01 -- Kennicutt law

$$t_\mathrm{ff} \approx 15\,\mathrm{Myr}\, M_9^{-1/2} R_1^{3/2}$$

If $t_{ff} > 3$ Myr, the mass fraction ejected is

$$f_\mathrm{eject} \approx 0.08\, \varepsilon_{-2} (\Sigma_{-1} M_9)^{-1/4}$$

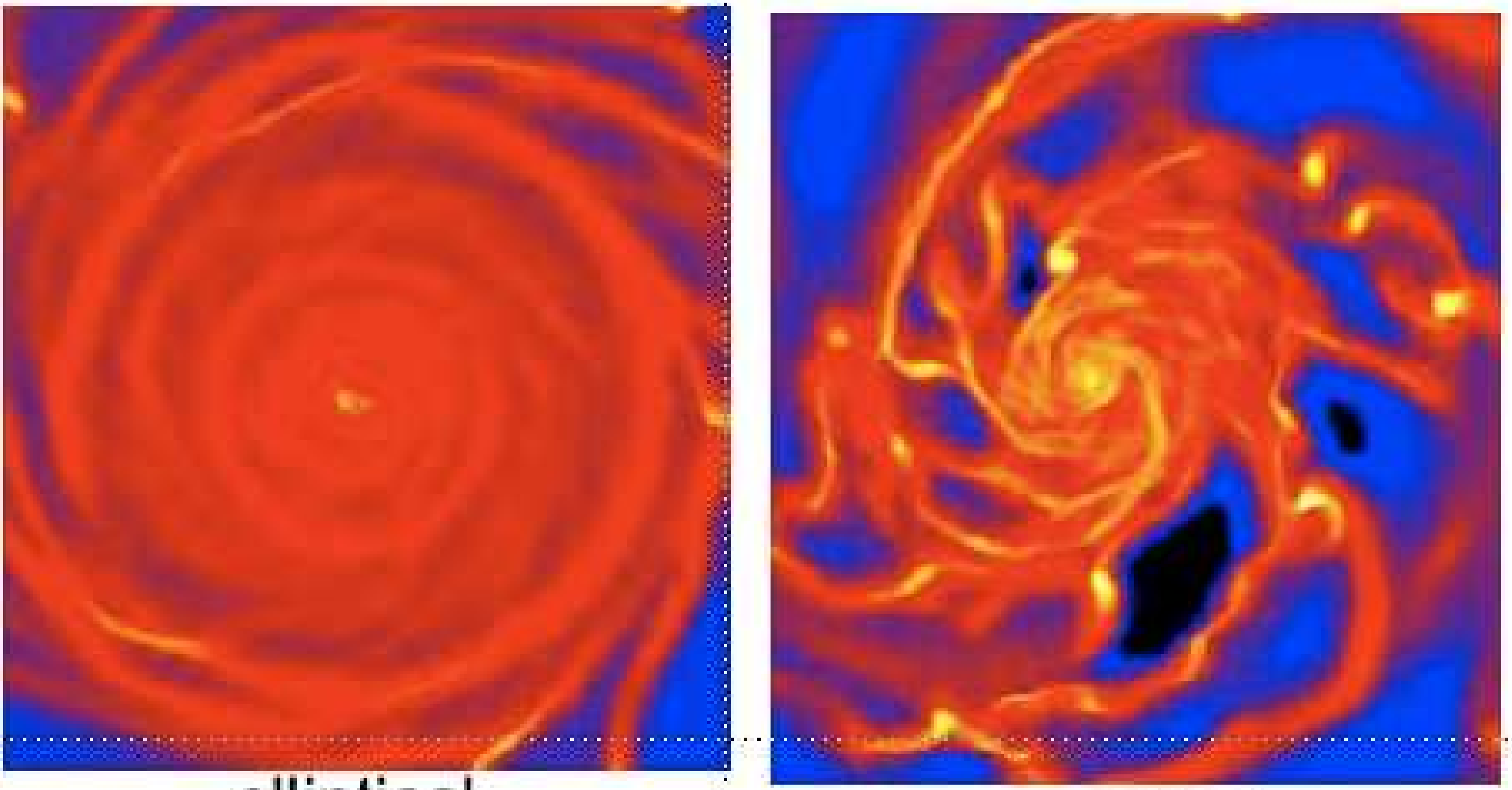
→ Giant clumps in high-z disks survive if the SFR obeys the Kennicutt law

11. Massive Compact Spheroids

- Wet Mergers (incoming stream clumps)
- Wild disk instability (in-situ disk clumps)

Bimodality blue-disk/red-spheroid at high z
driven by the degree of clumpiness in the streams

Morphological Quenching: disk stabilization by a bulge


elliptical

spiral

Bournaud, AMR

Conclusion

LCDM makes robust theoretical predictions for how massive galaxies form at high z, consistent with observations, together suggesting a coherent picture

- Galaxies are fed by cold streams from the cosmic web
  Streams include major & minor mergers and smooth flows
  Streams radiate as Lyman-alpha blobs

- Gas-rich disks form, develop wild instability, self-regulated
  Giant clumps form stars (?) and migrate to a bulge
  Cosmological steady state with bulge ~ disk
  Angular momentum versus dispersion (?)

- Spheroids form by mergers and by wild disk instability

- Disks are stabilized (SFR quenched) by bulge, external turbulence, low accretion rate, gas consumption

- Main open issues: star formation & feedback

Galaxies Emerge from the Cosmic Web