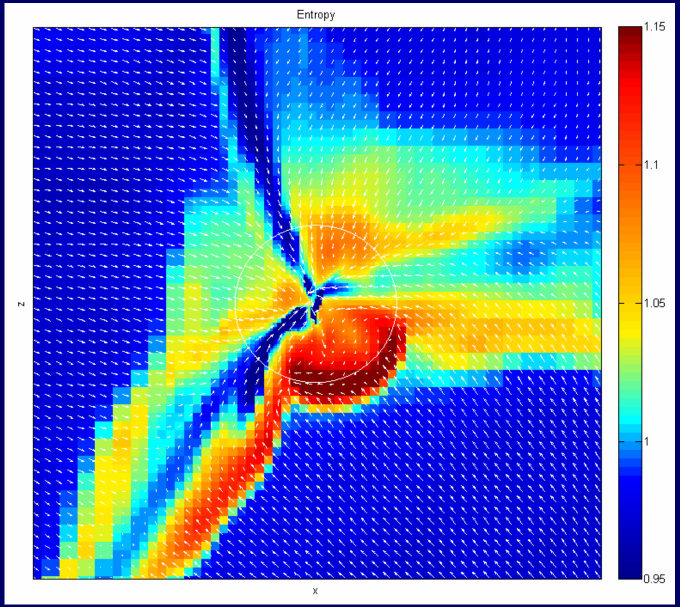
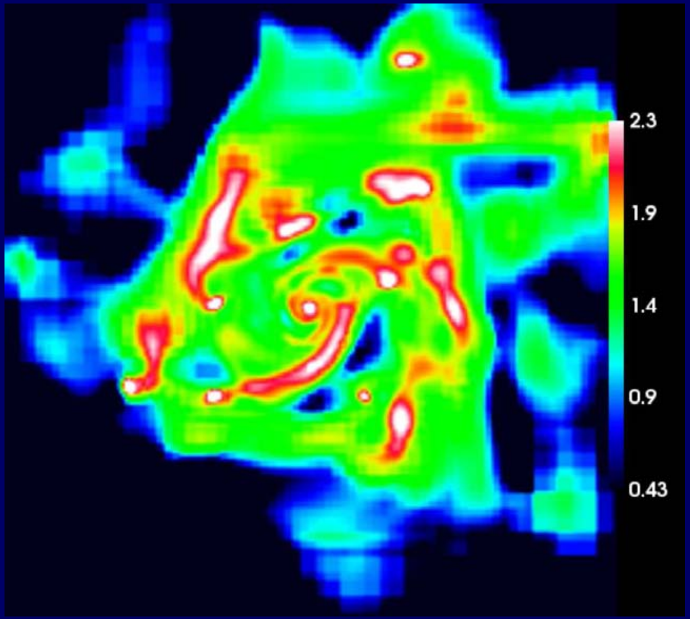
Galaxies from the Cosmic Web:

Cold Streams, Clumpy Disks & Compact Spheroids

Avishai Dekel, HU Jerusalem

IAP, December 2009



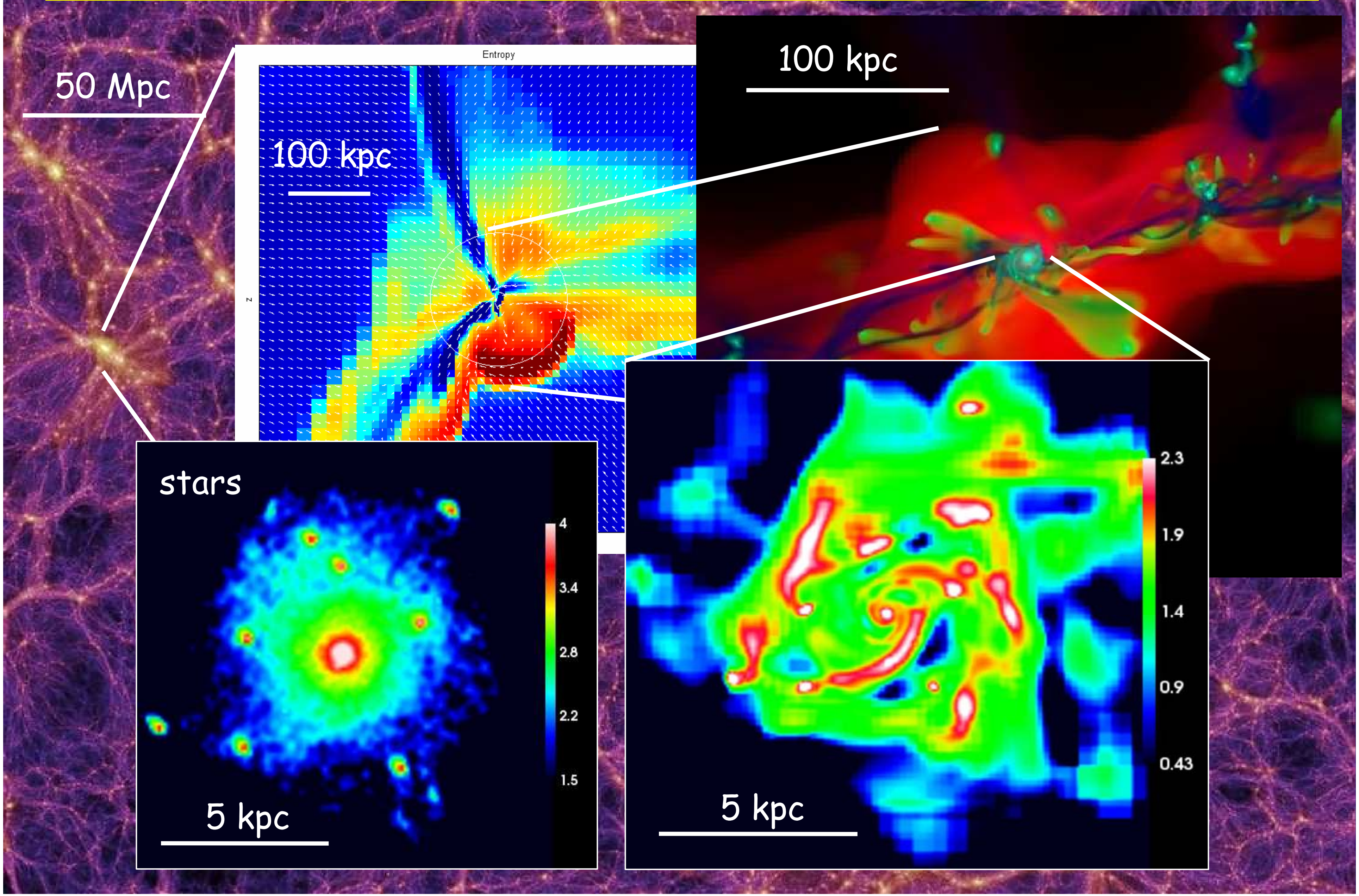


LCDM makes robust theoretical predictions for massive galaxy formation at high z

Theory seems consistent with observations

Combined, they introduce a coherent picture

Galaxies Emerge from the Cosmic Web



Collaborators

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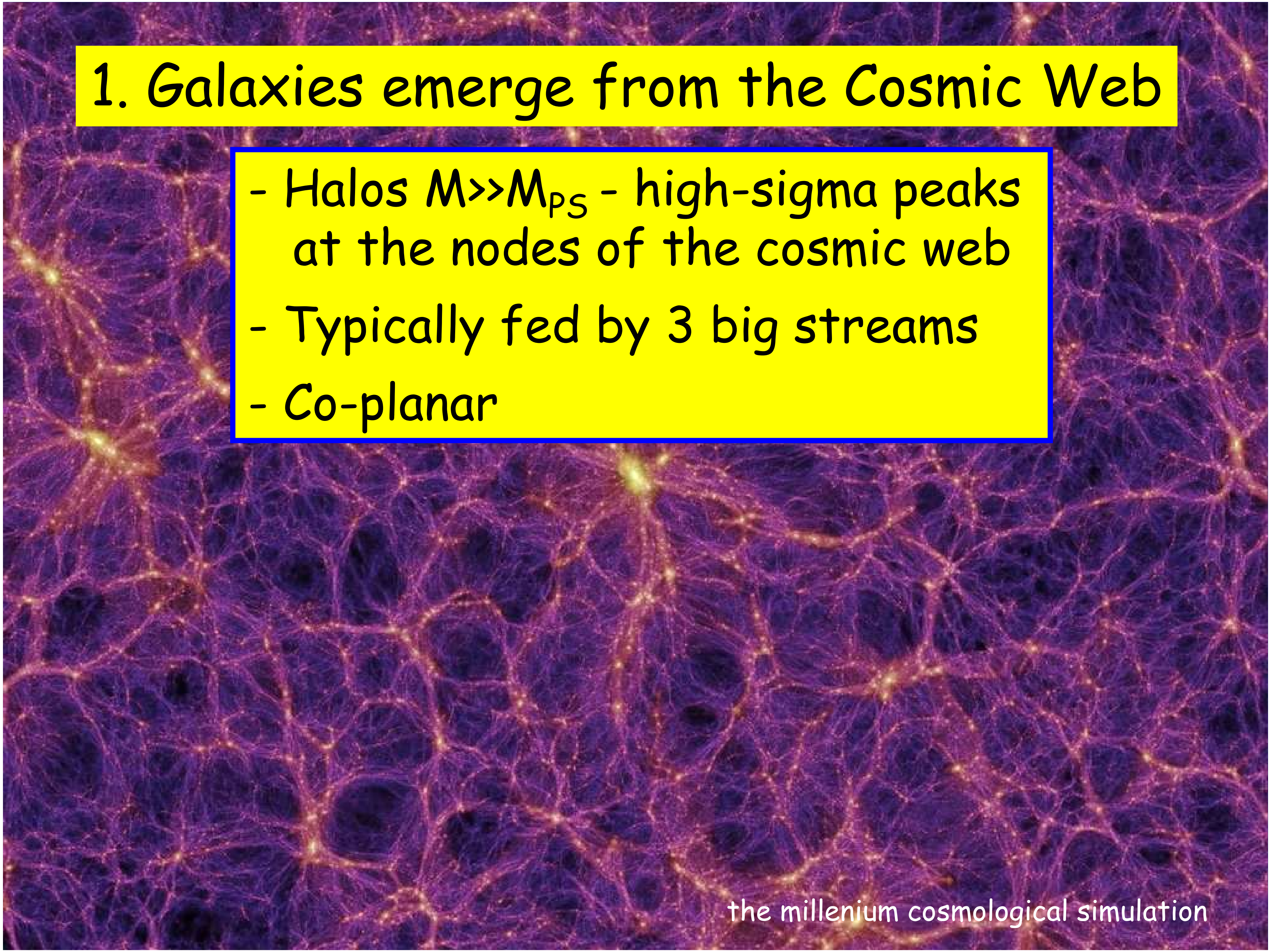
Outline

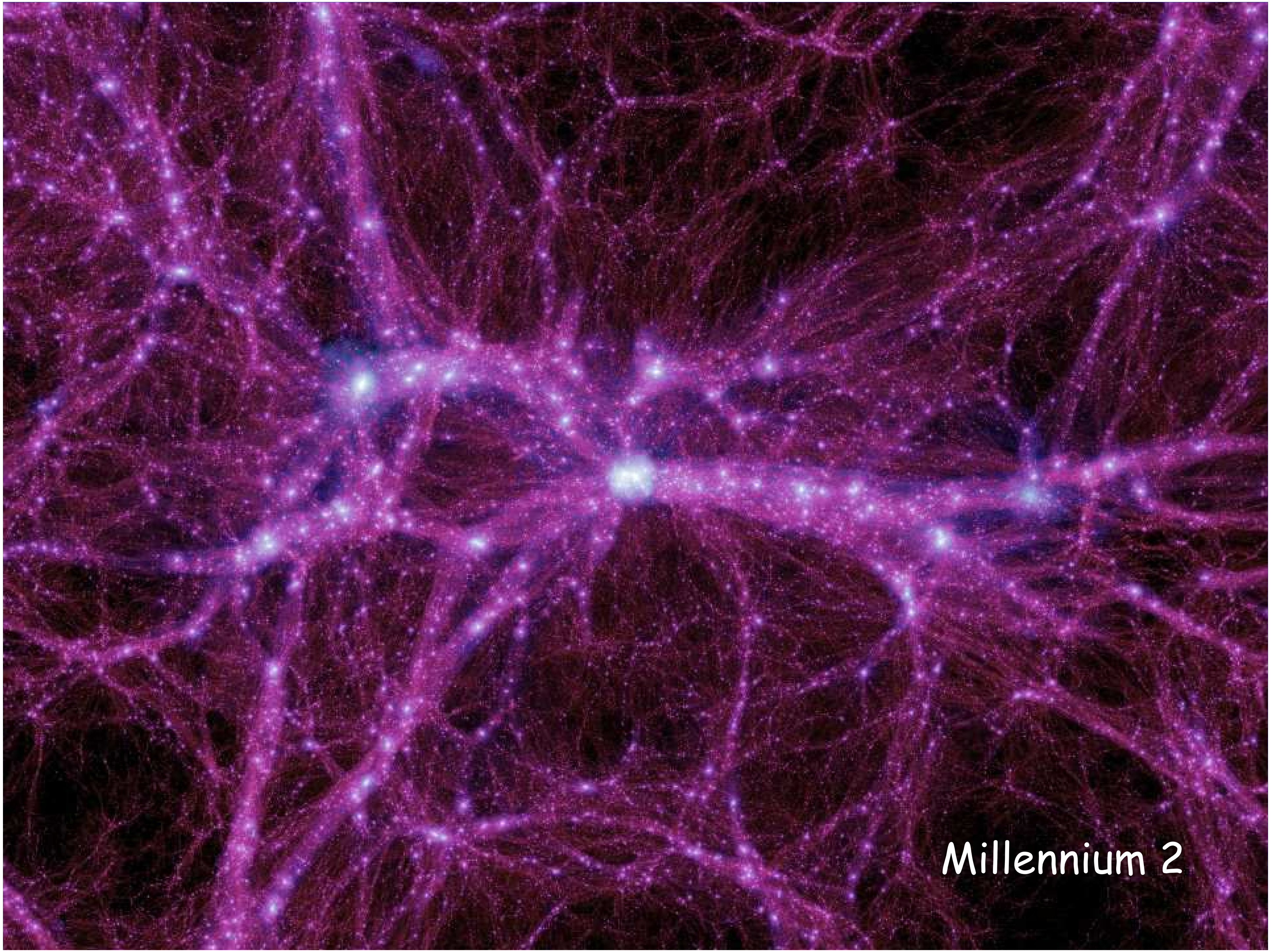
- Galaxies from the cosmic web
- Cold streams into hot massive halos
- Streams as Lyman-alpha blobs
- Stream clumpiness: mergers
- Wild disk instability: cosmological steady state
- SFR and feedback in disk clumps
- Spheroid formation: galaxy bimodality at high z



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



Millennium 2

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

Steady State

$$\dot{M}_{\mathrm{gas}} = \dot{M}_{\mathrm{in}} - \dot{M}_{*}$$

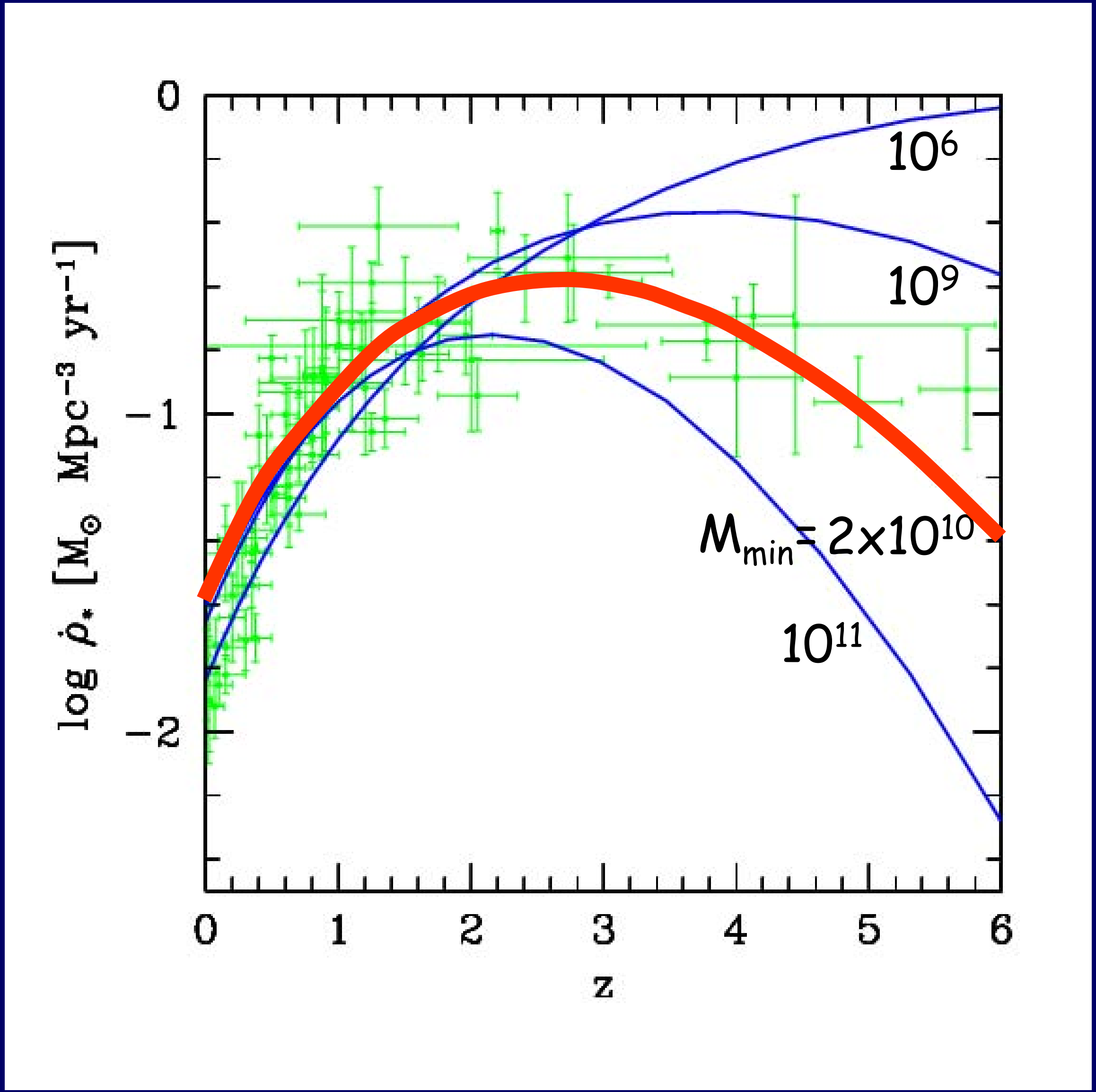
$$\dot{M}_{*} = \eta \frac{M_{\mathrm{gas}}}{t_{\mathrm{ff}}}$$

At late times, when $t_{sf} < t_{acc}$

$$\dot{M}_{\mathrm{gas}} \rightarrow 0 \quad \dot{M}_{*} \rightarrow \dot{M}_{\mathrm{in}}$$

Star-formation history:

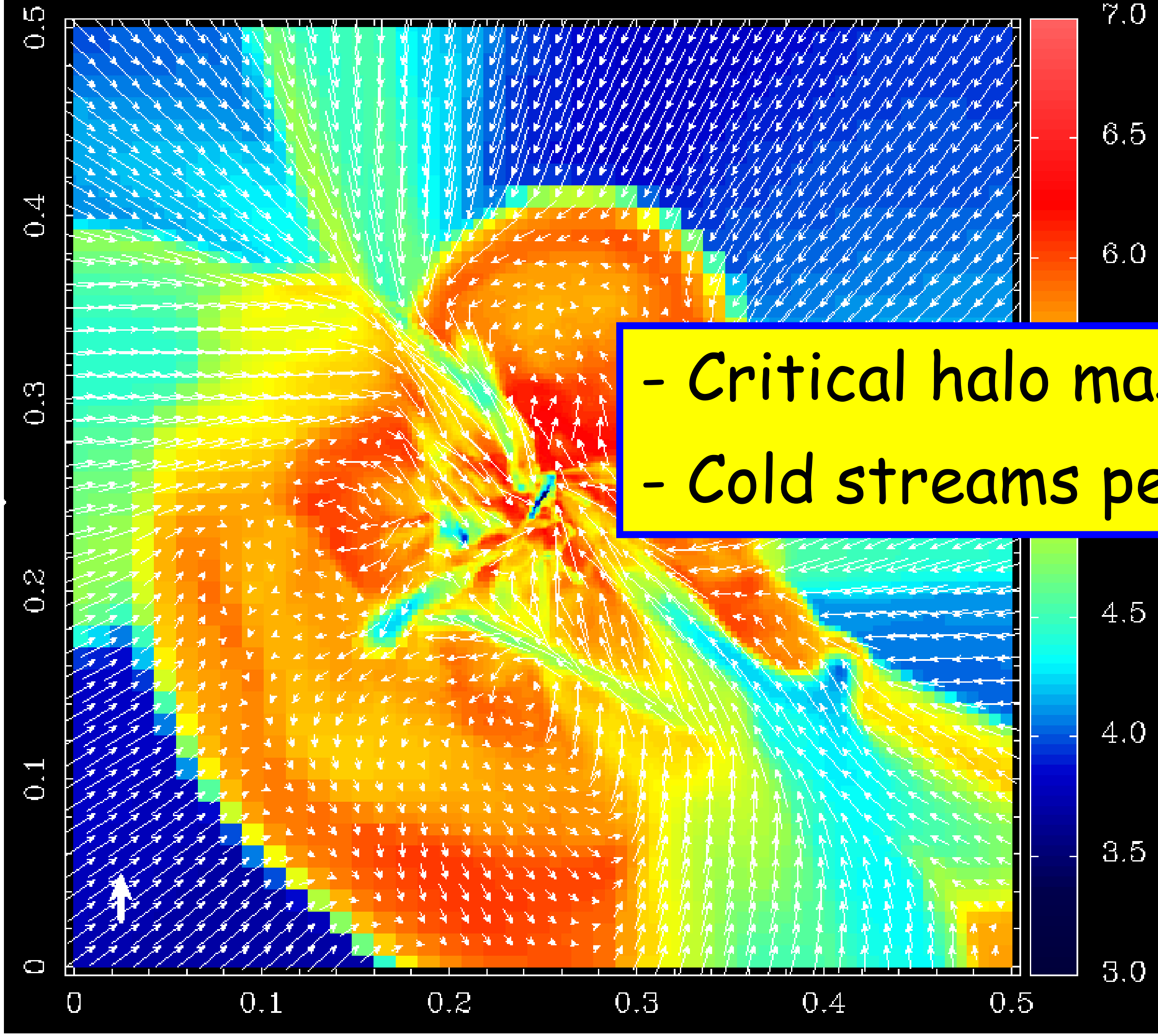
$$SFR = f_b \left\langle \dot{M}_{halo} \right\rangle$$



Bouche et al. 09

3. Virial Shock Heating

Birnboim & Dekel 03, Keres et al 05, Dekel & Birnboim 06

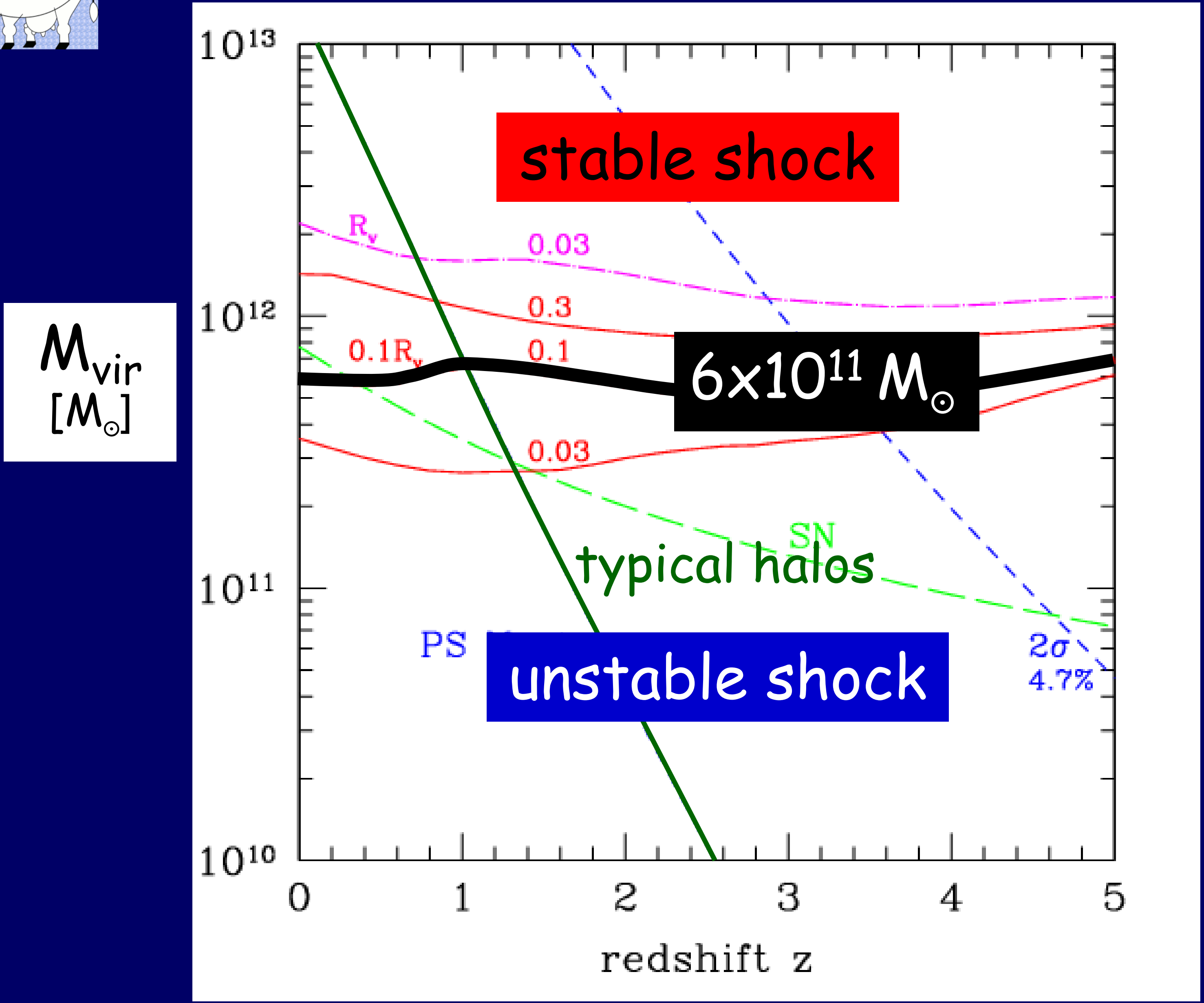


- Critical halo mass ~$10^{12}M_\odot$
- Cold streams penetrate at $z>2$

Shock-Heating Scale

Birnboim & Dekel 03
Dekel & Birnboim 06

Keres
et al 05



At High z, in Massive Halos: Cold Streams in Hot Halos

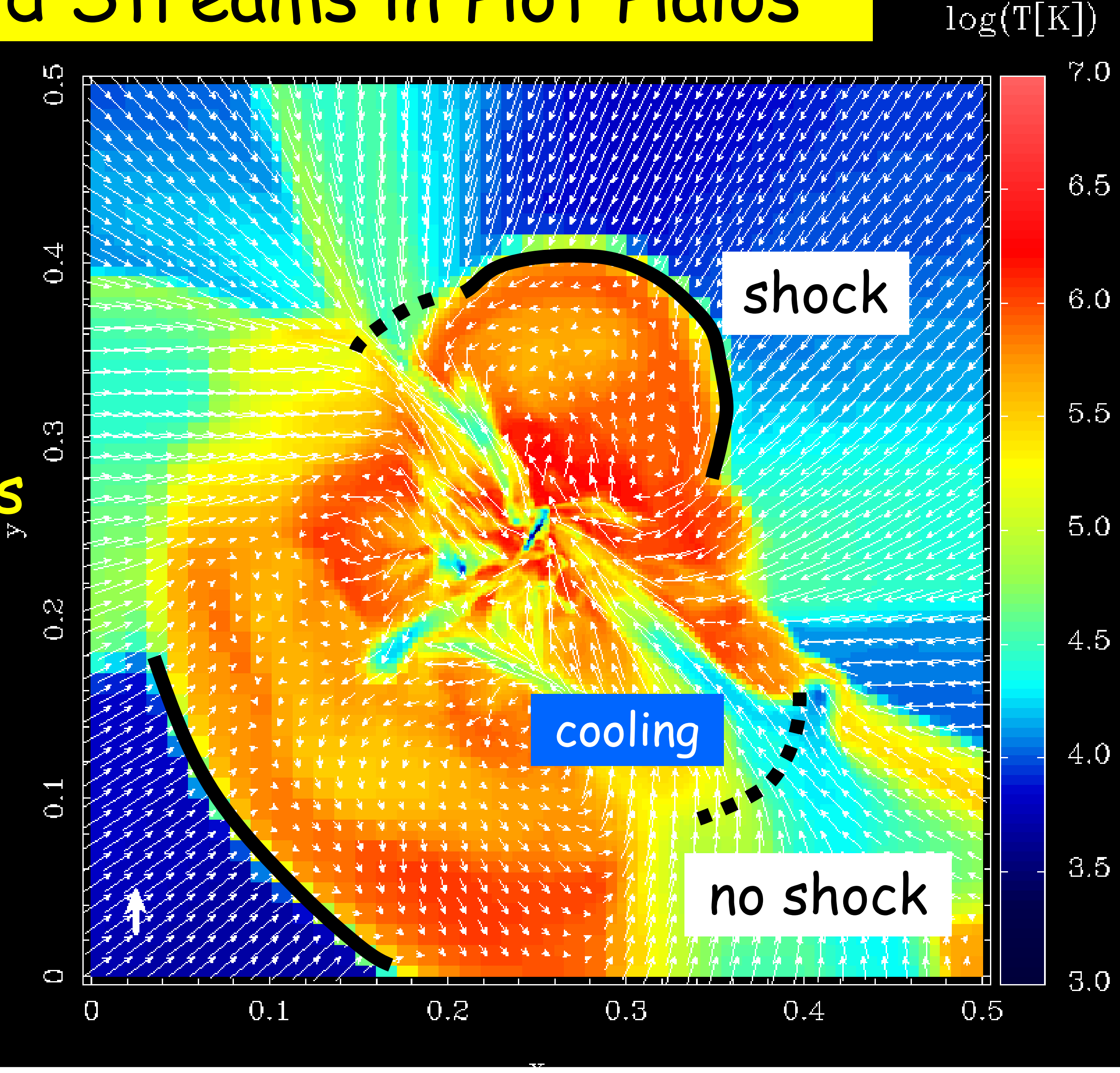
in $M > M_{shock}$

Totally hot at z<1

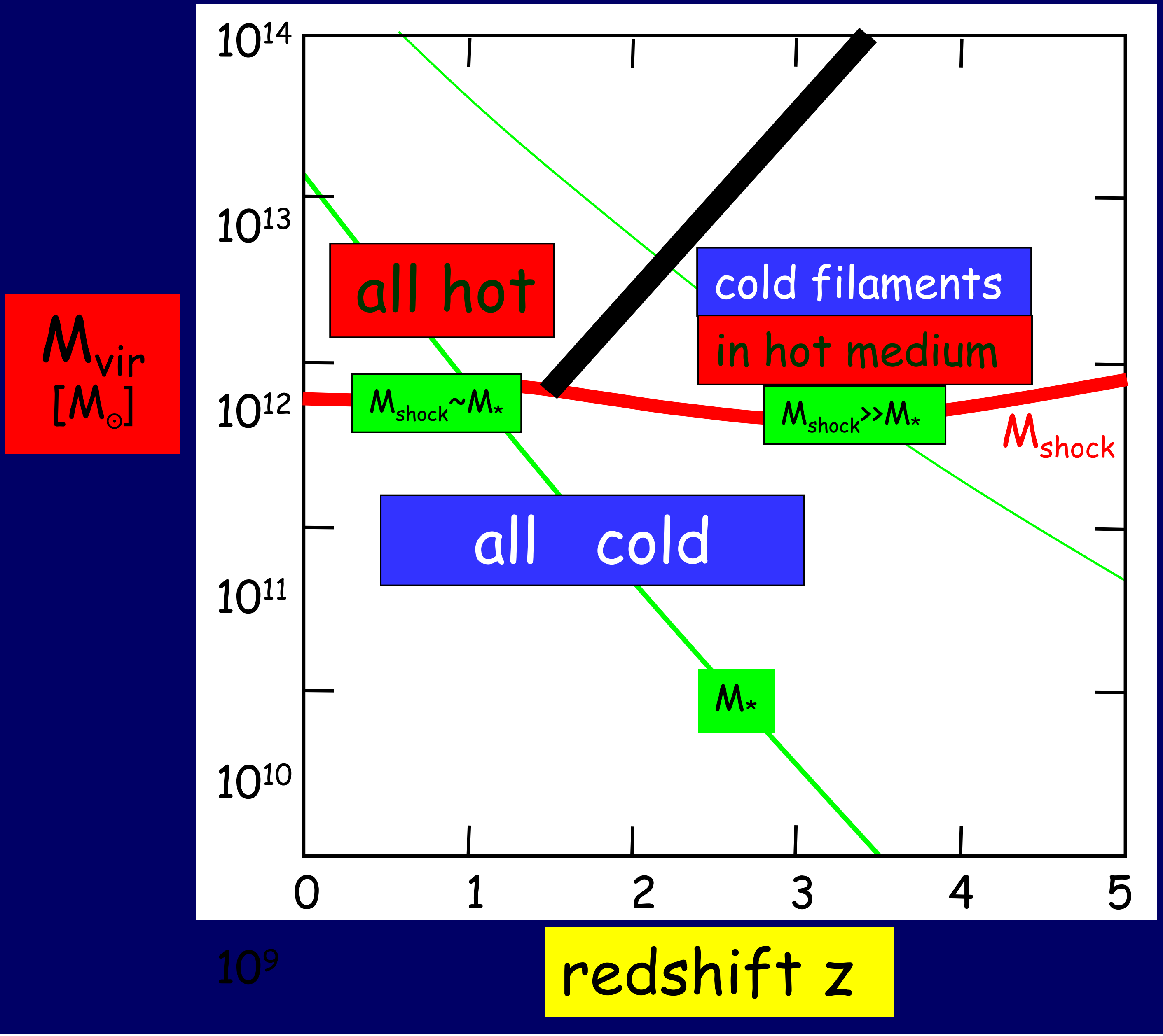
Cold streams at z>2

Dekel & Birnboim 2006

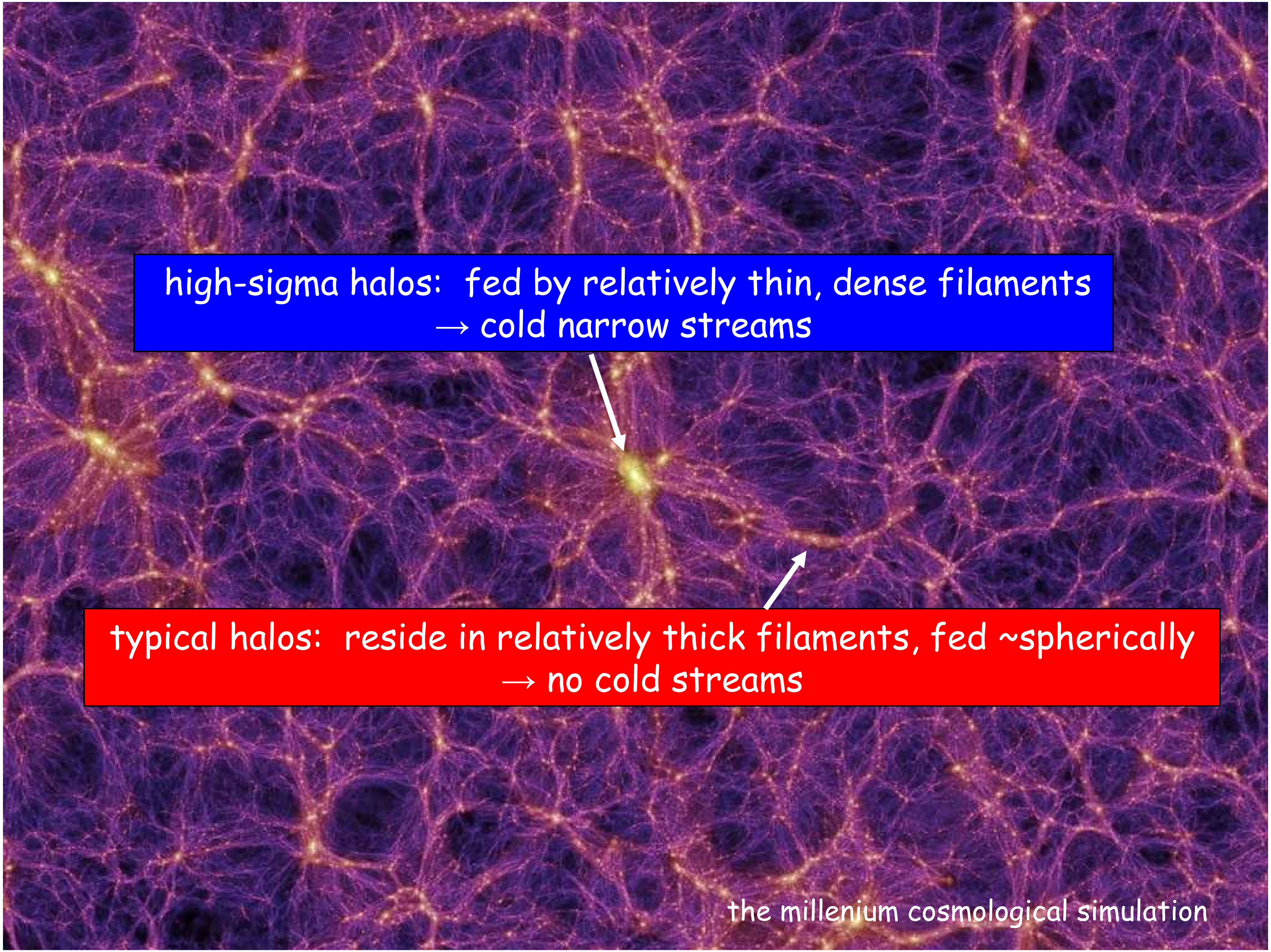
Kravtsov et al



Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06

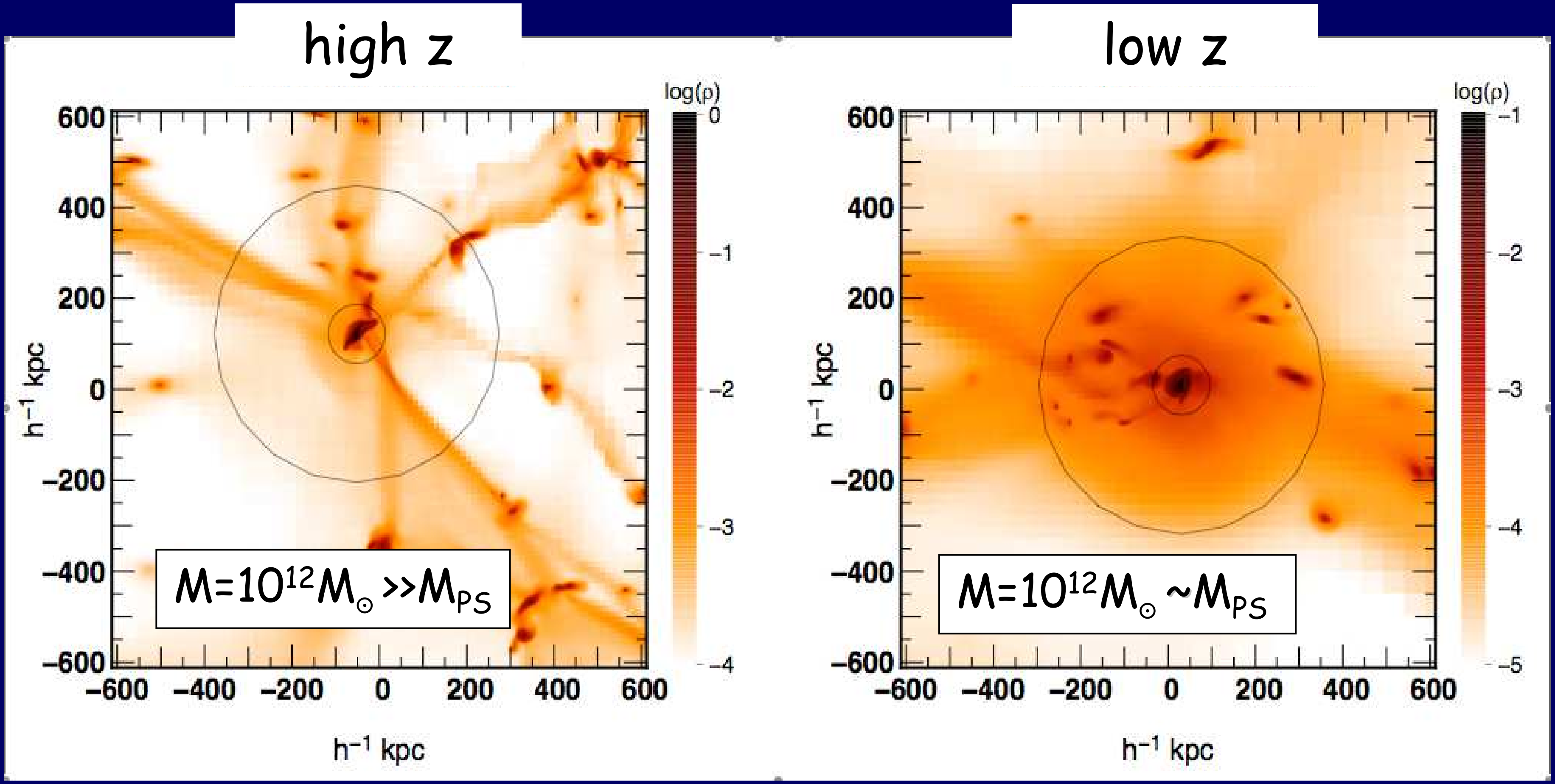


high-sigma halos: fed by relatively thin, dense filaments
→ cold narrow streams

typical halos: reside in relatively thick filaments, fed ~spherically
→ no cold streams

the millenium cosmological simulation

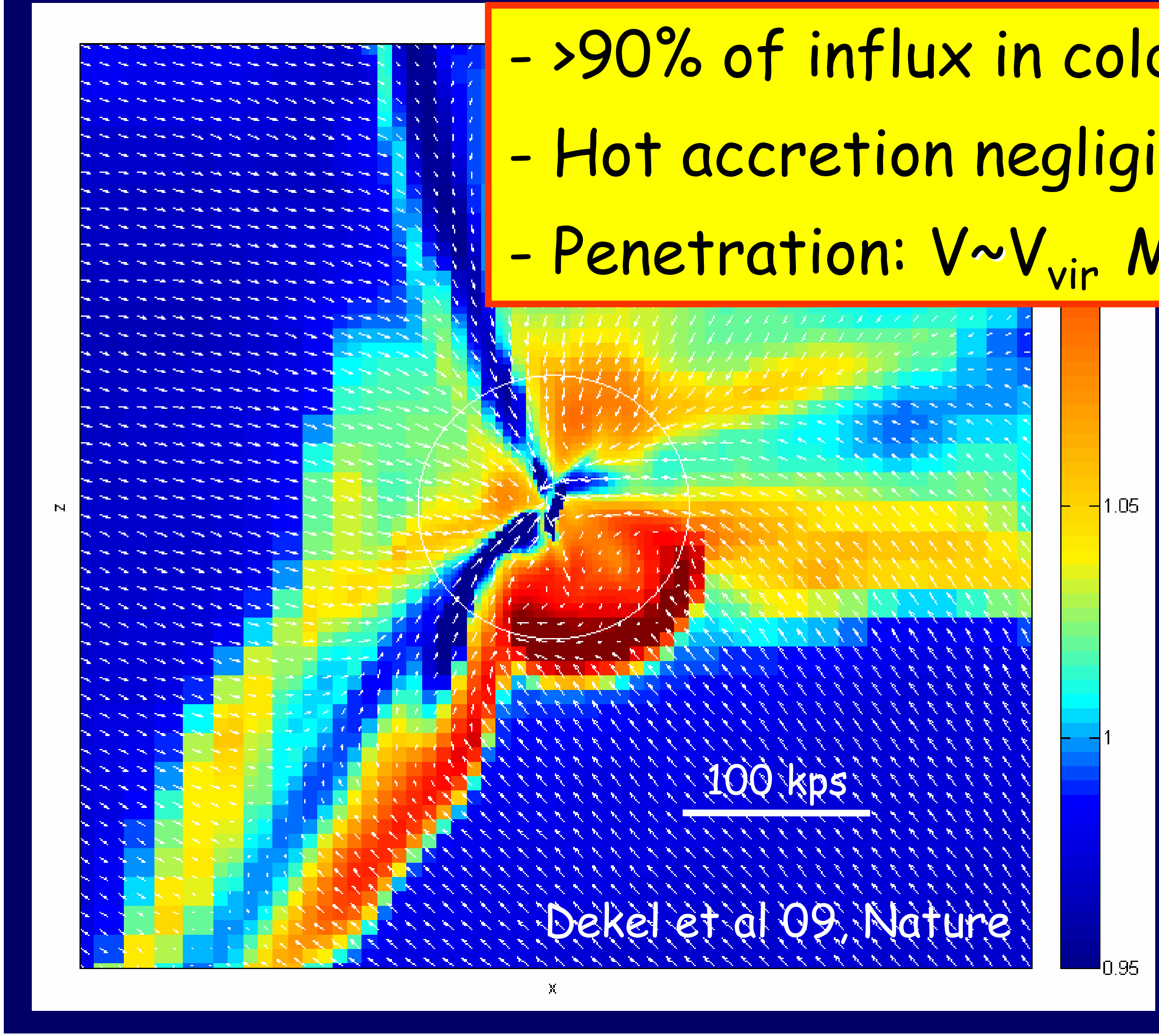
Narrow dense gas streams at high z versus spherical infall at low z



Ocvirk, Pichon, Teyssier 08

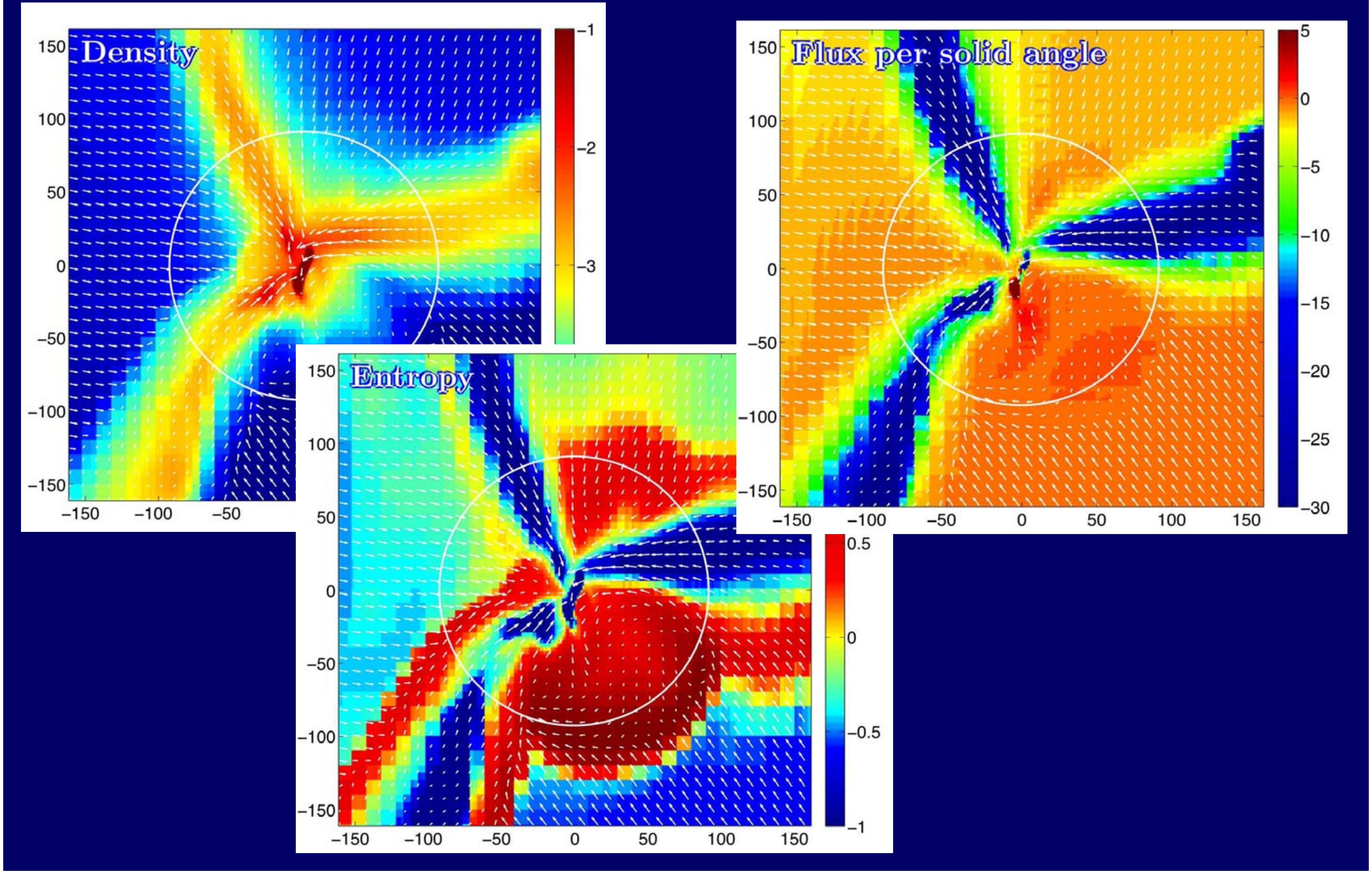
4. Cold Sterams

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

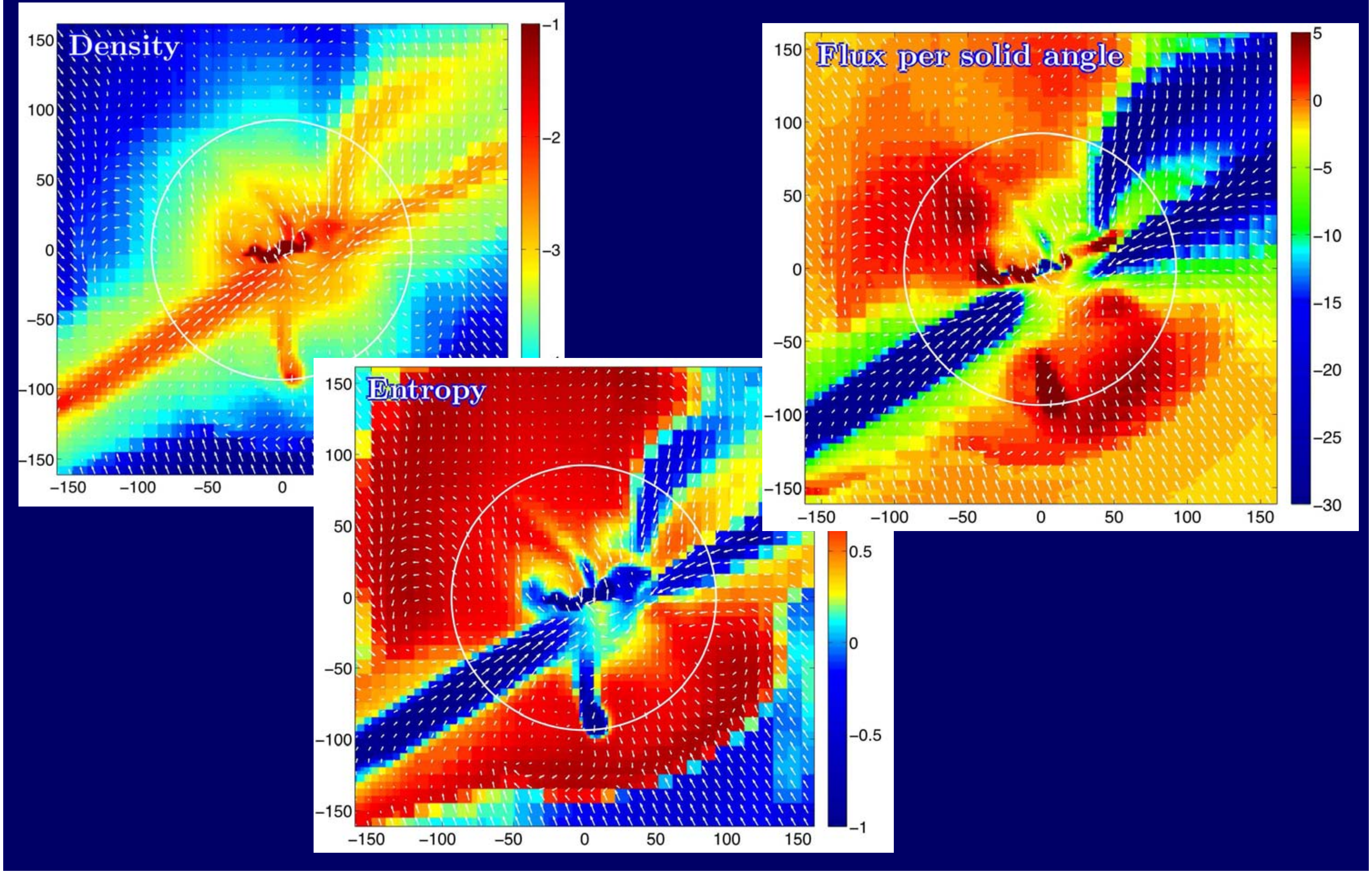


Dekel et al 09, Nature

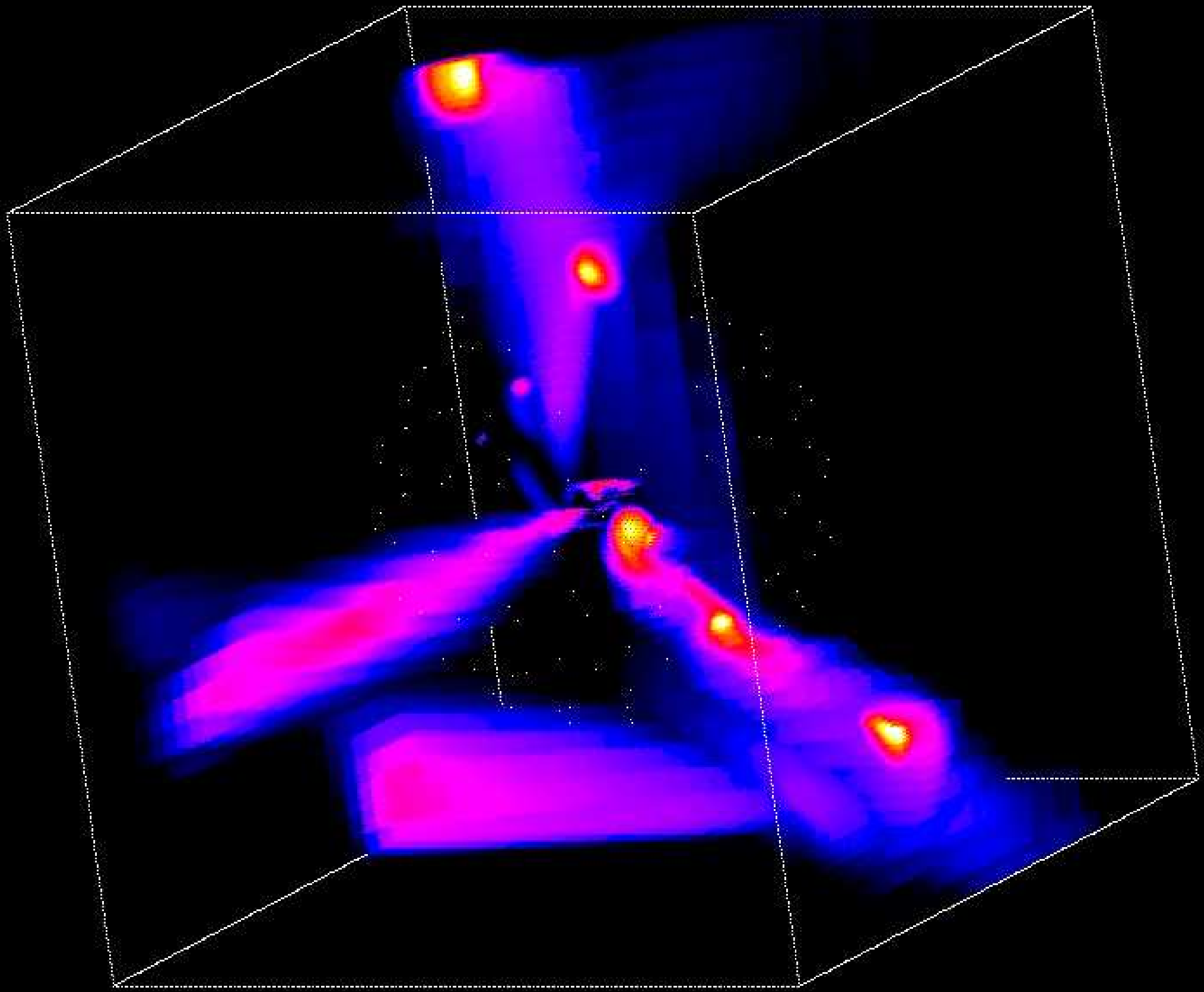
Cold streams through hot halos



Cold streams through hot halos

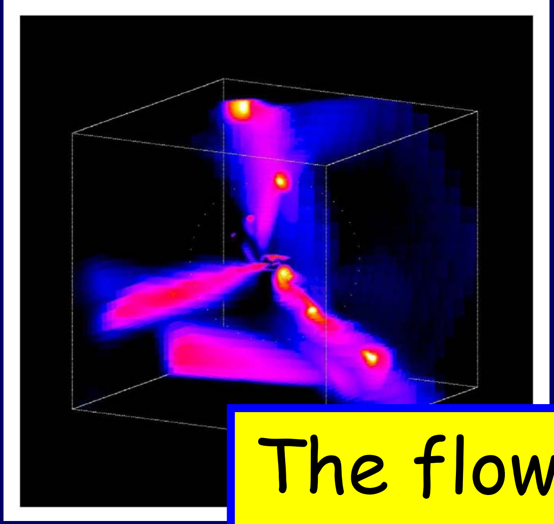


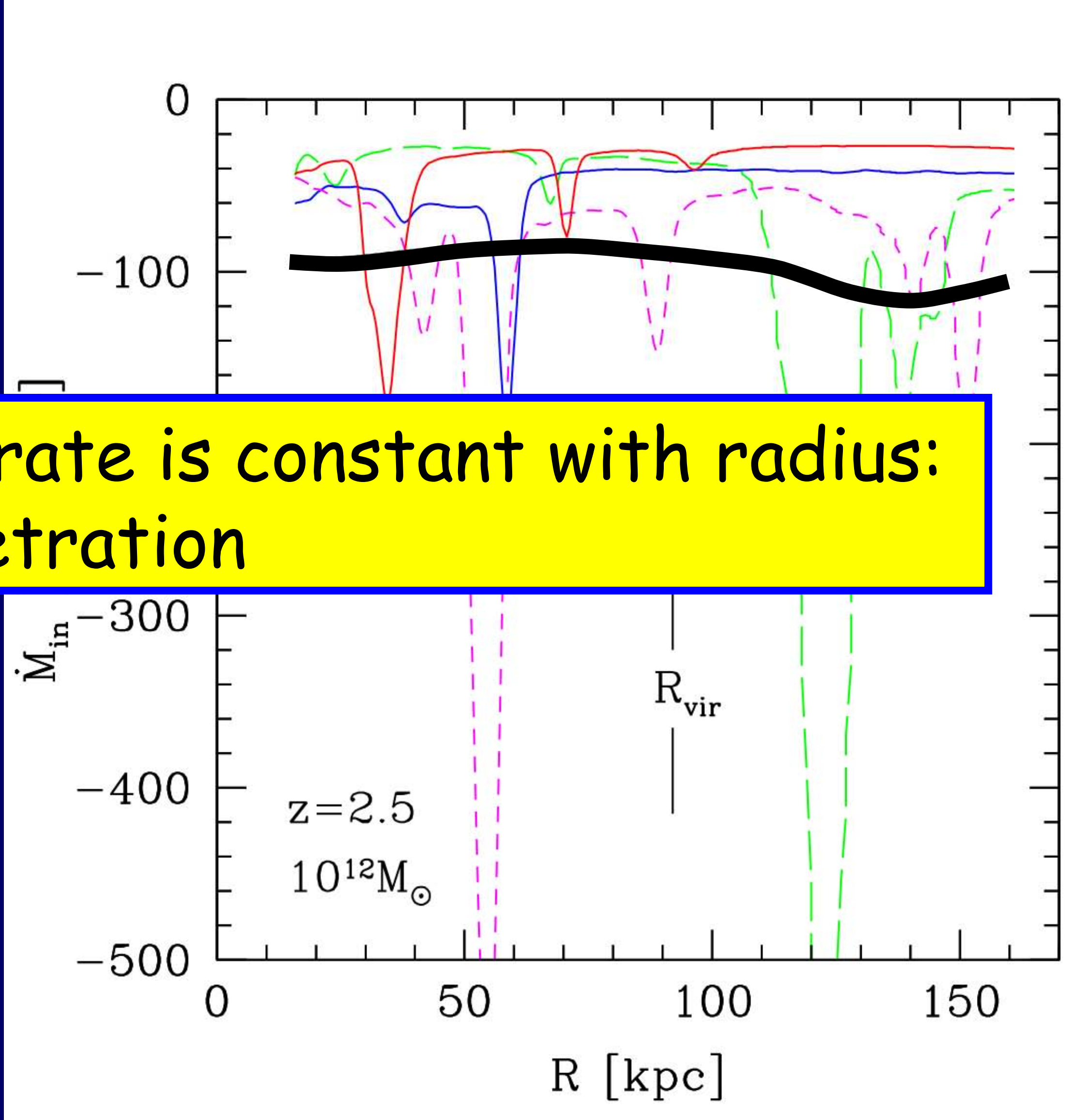
Flux
per
solid
angle



Dekel
et al 09

Inflow rate through the halo into the disk

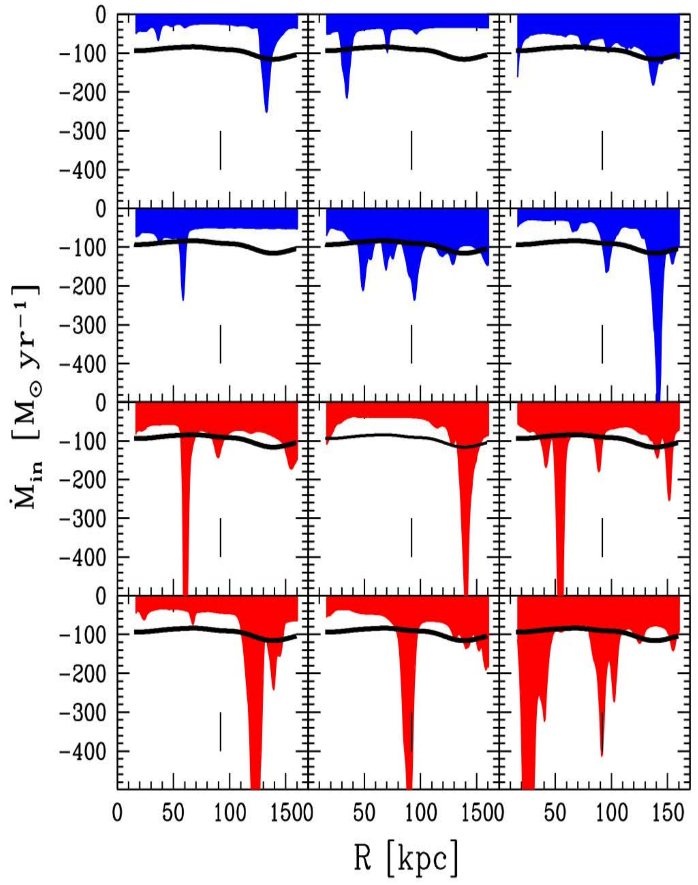


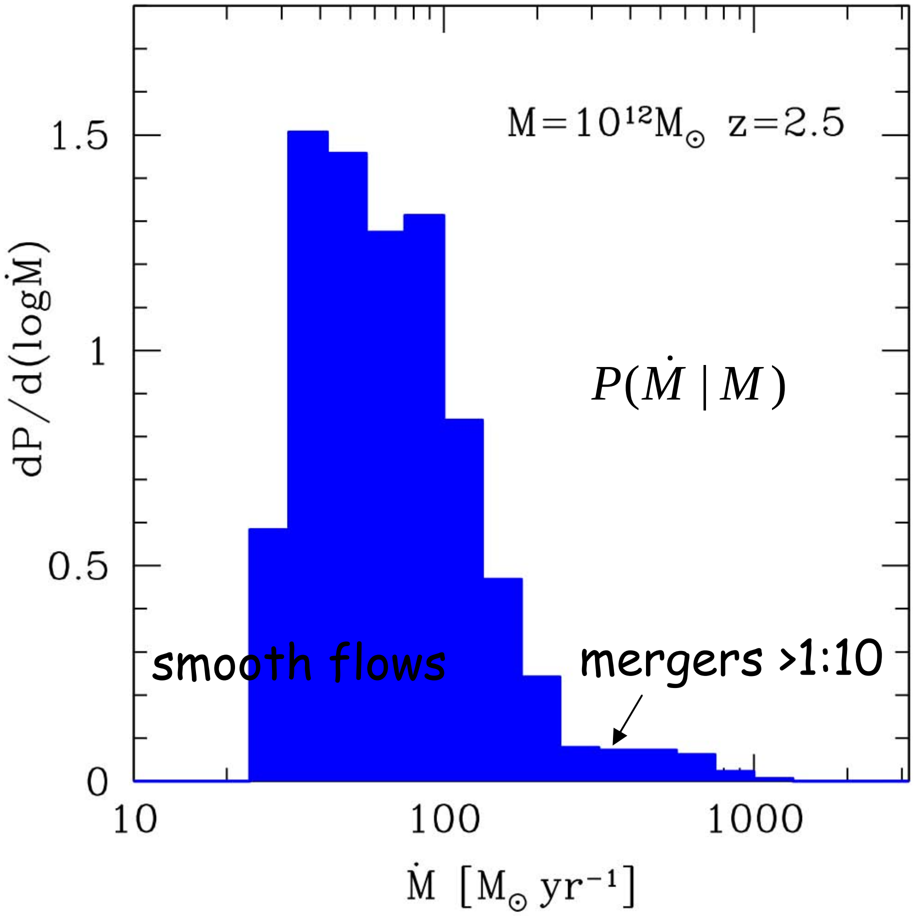


The flow rate is constant with radius:
deep penetration

Distribution of gas inflow rate

Cosmological hydro simulations (MareNostrum, Dekel et al. 09)





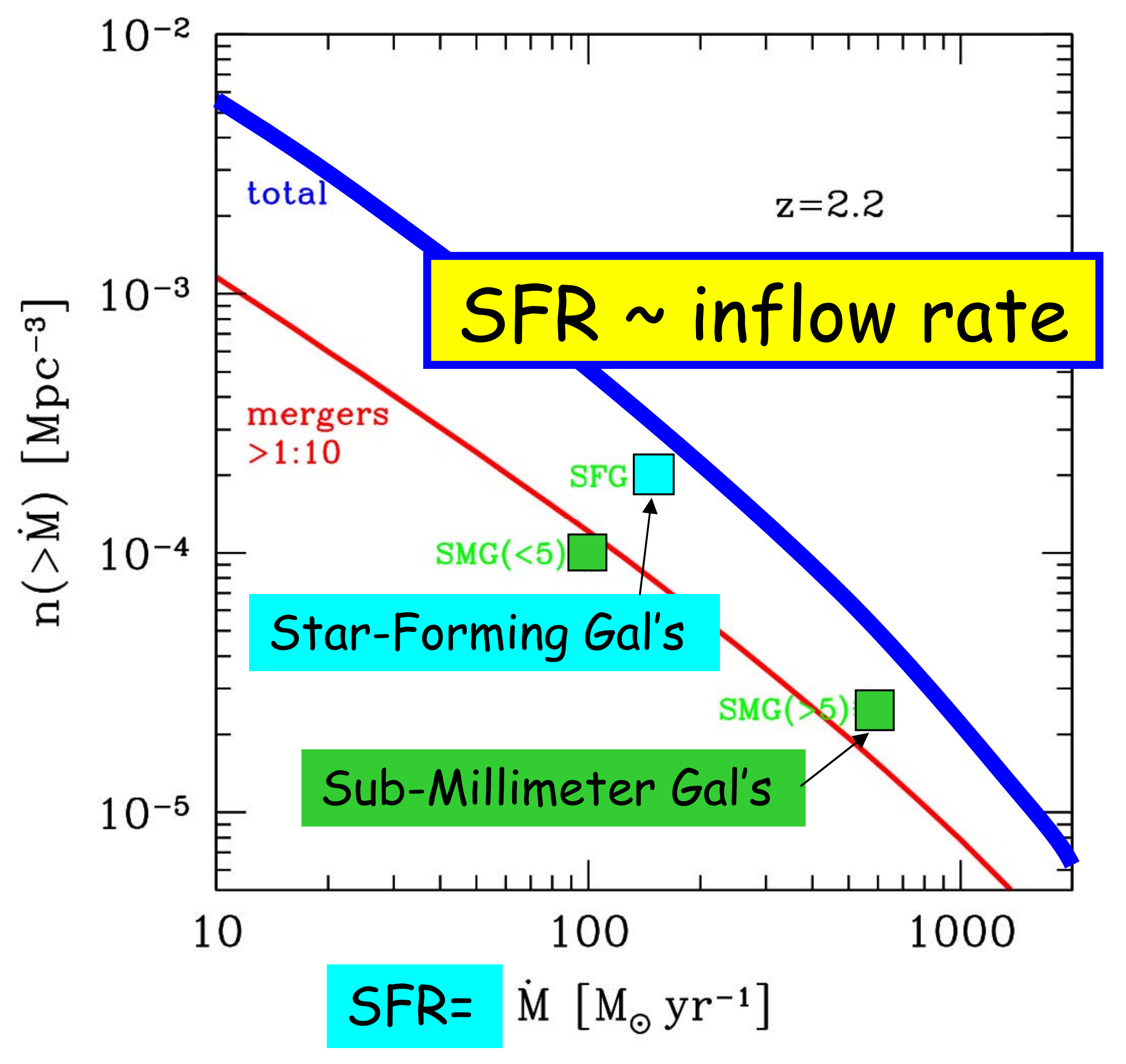
Galaxy density at a given gas inflow rate

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

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

n(M) by Sheth-Tormen

Dekel et al 09, Nature



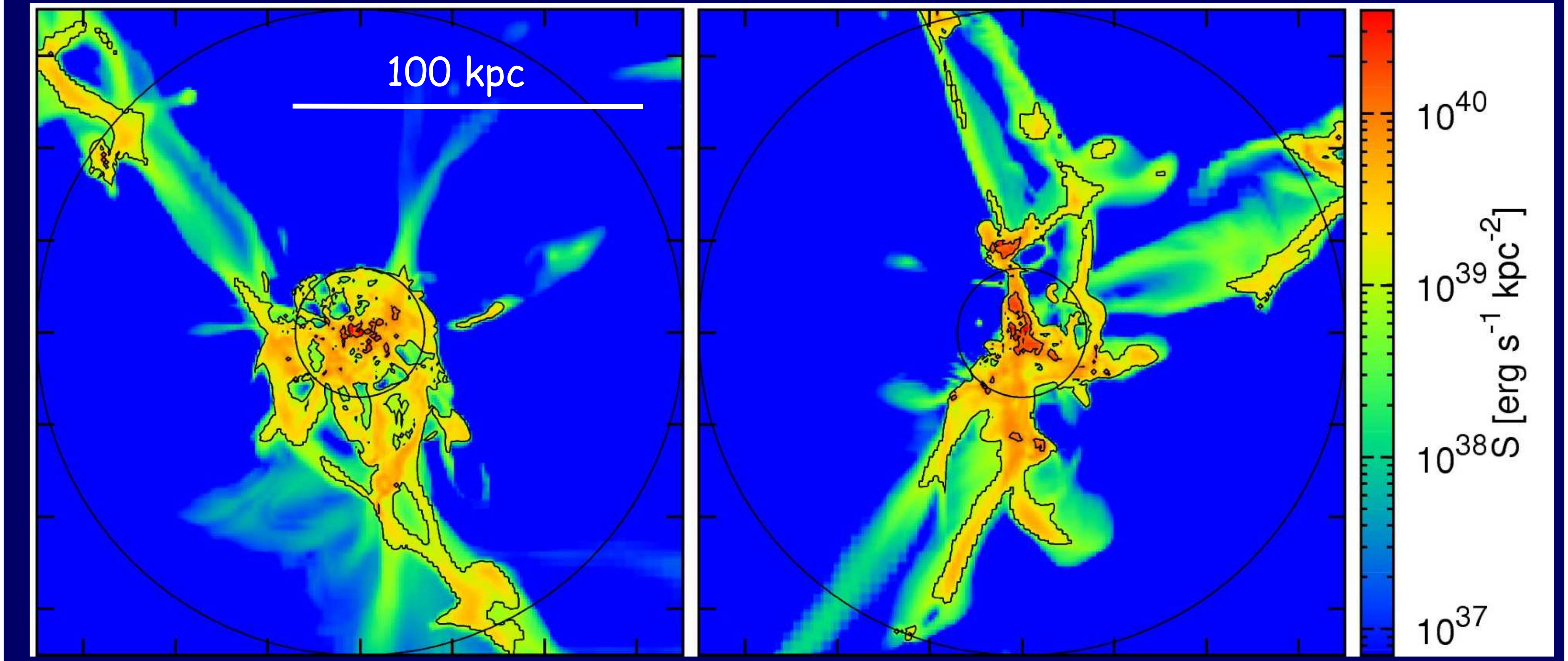
5. Lyman-alpha from Cold streams

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

T=(1-5)x10^4 K n=0.01-0.1 cm^{-3} N_{HI}~10^{20} cm^{-2} pressure equilib.

L ~10^{43-44} erg s^{-1}

Surface brightness

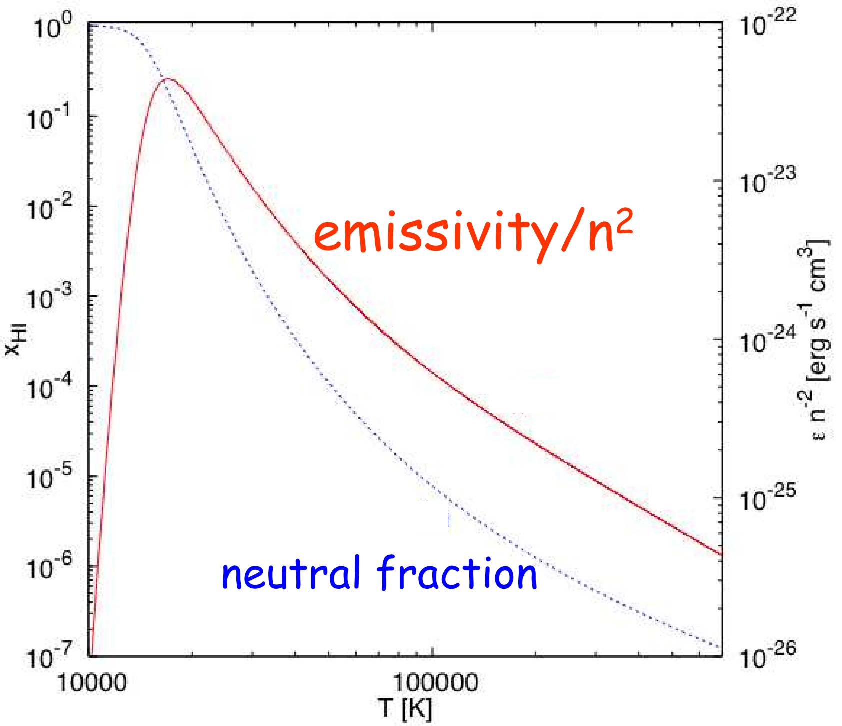


Lyman-alpha Emissivity

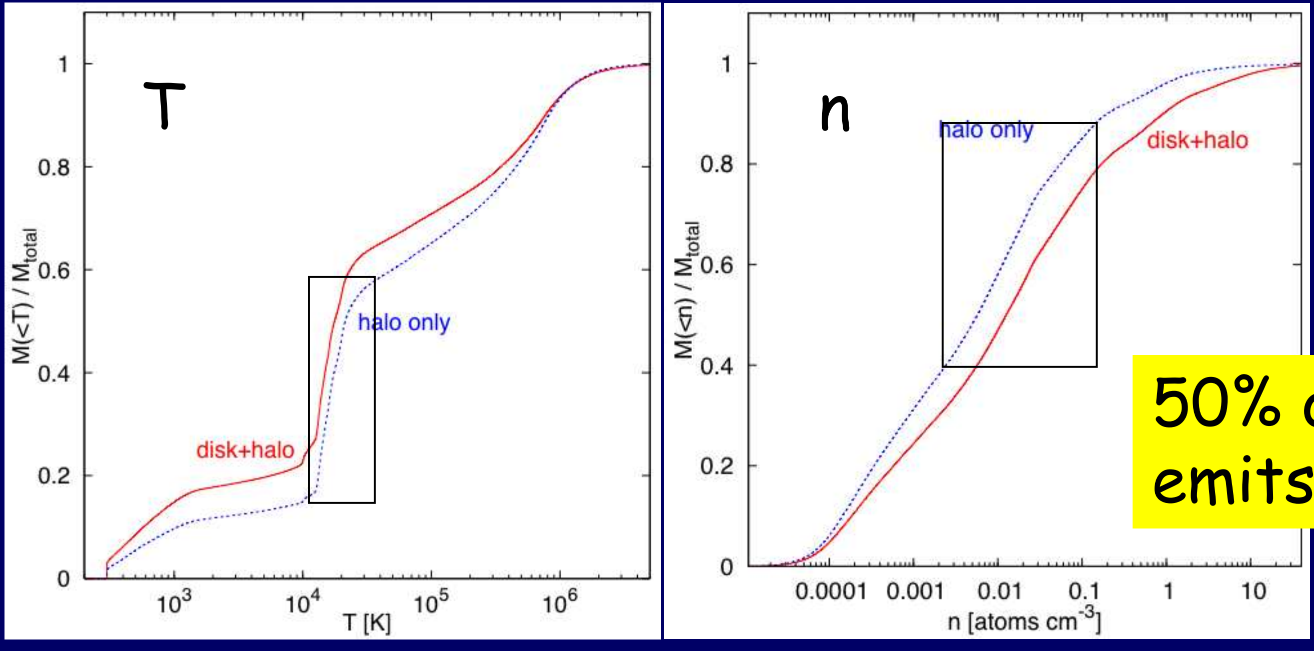
Collisional excitation:

$$\varepsilon = n_e \, n_{HI} \, q_{1s\rightarrow 1p}(T) \, h\nu_{L\alpha}$$

Streams are self-shielded from UV background.

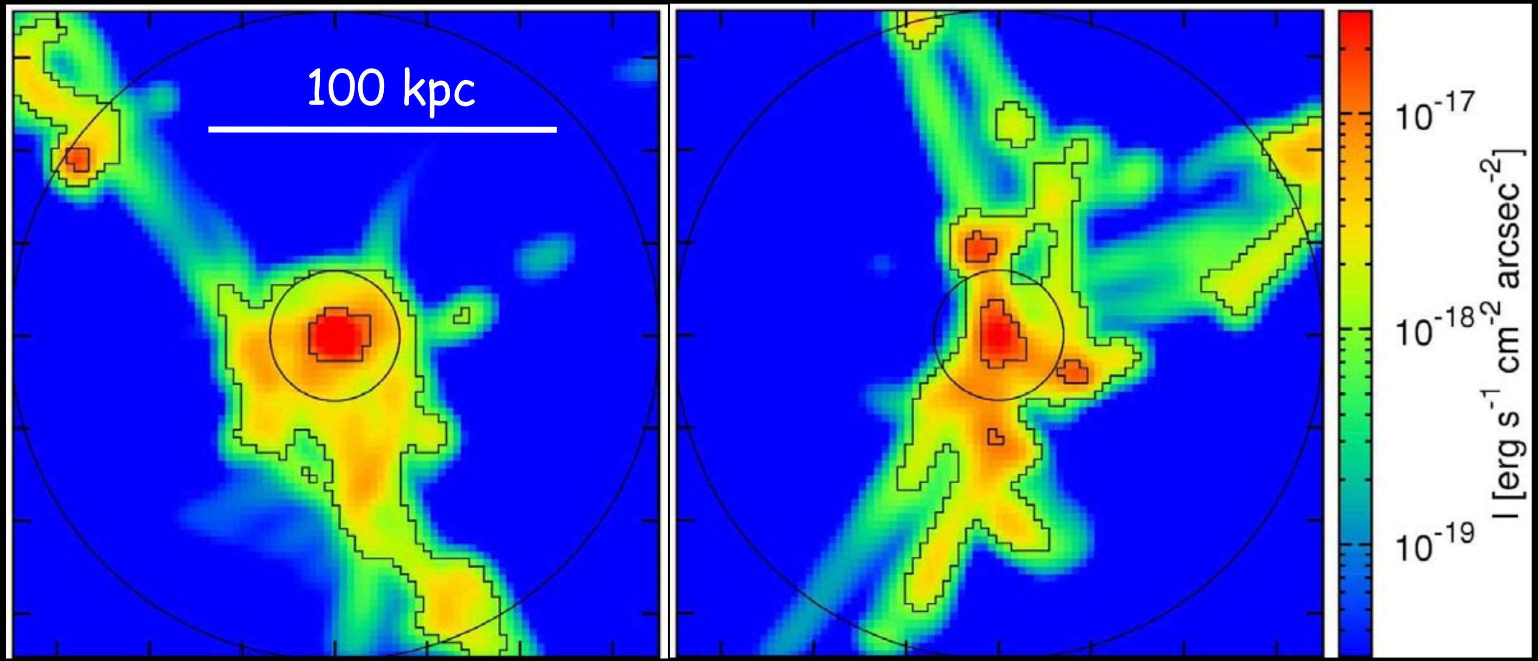


Cumulative distribution of T & n



50% of the gas emits Lα effectively

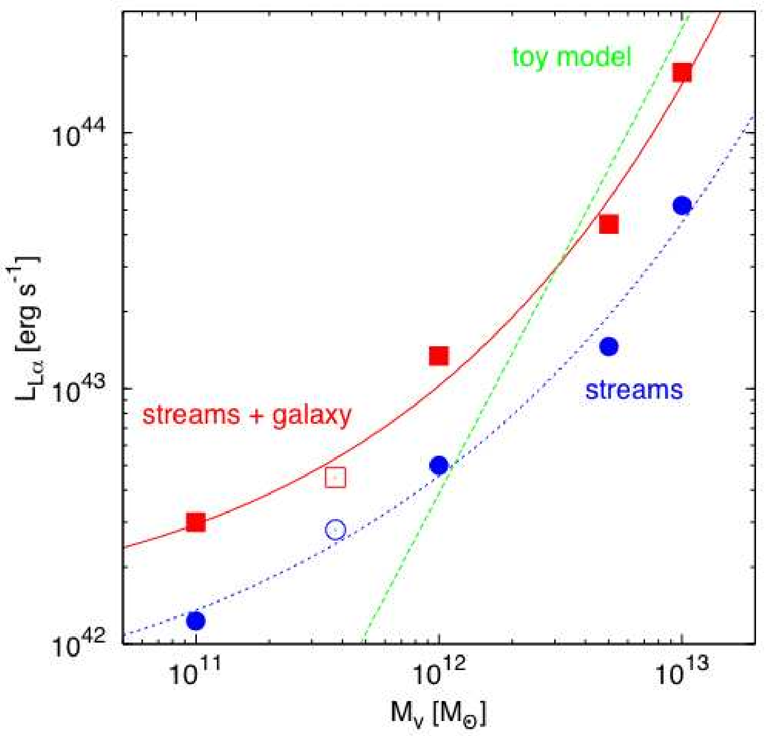
Cold streams as Lyman-alpha Blobs

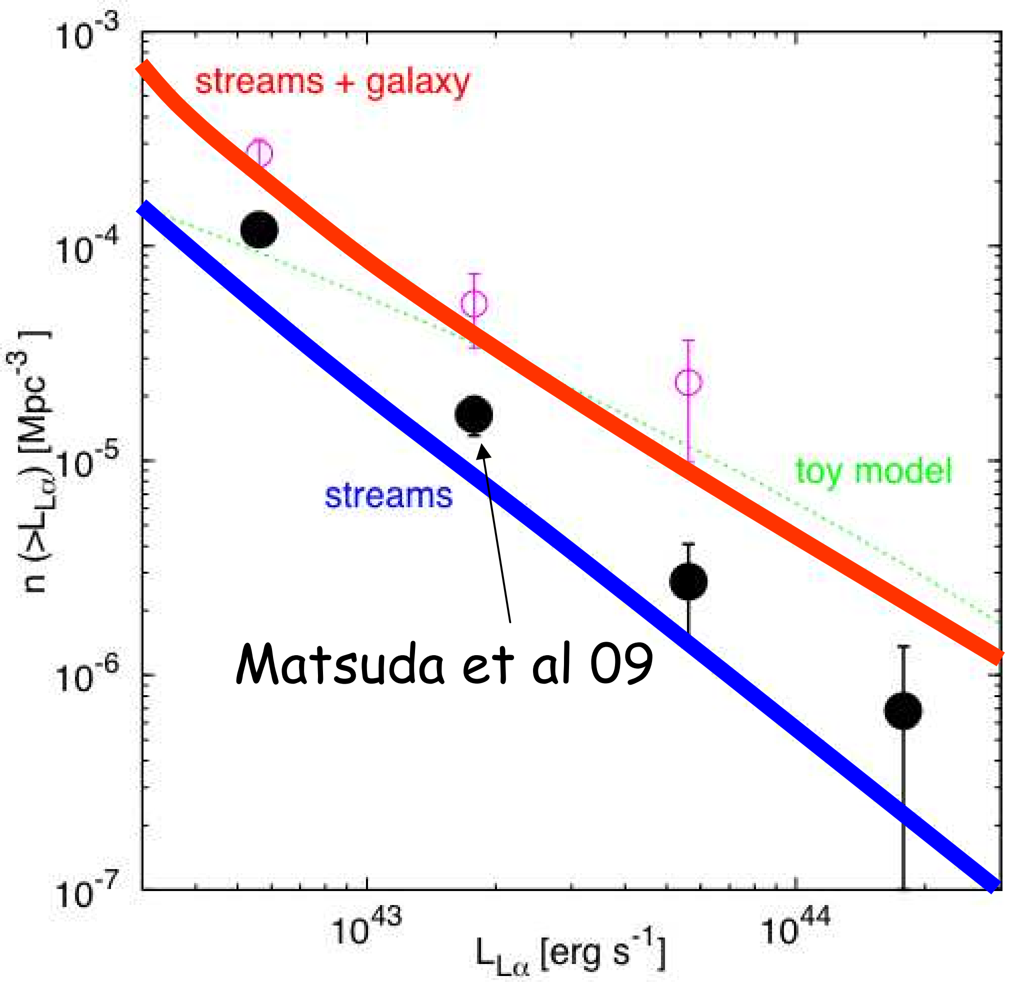


Goerdt,
Dekel,
Sternberg,
Ceverino,
Teyssier,
Primack 09

Matsuda et al 06-09

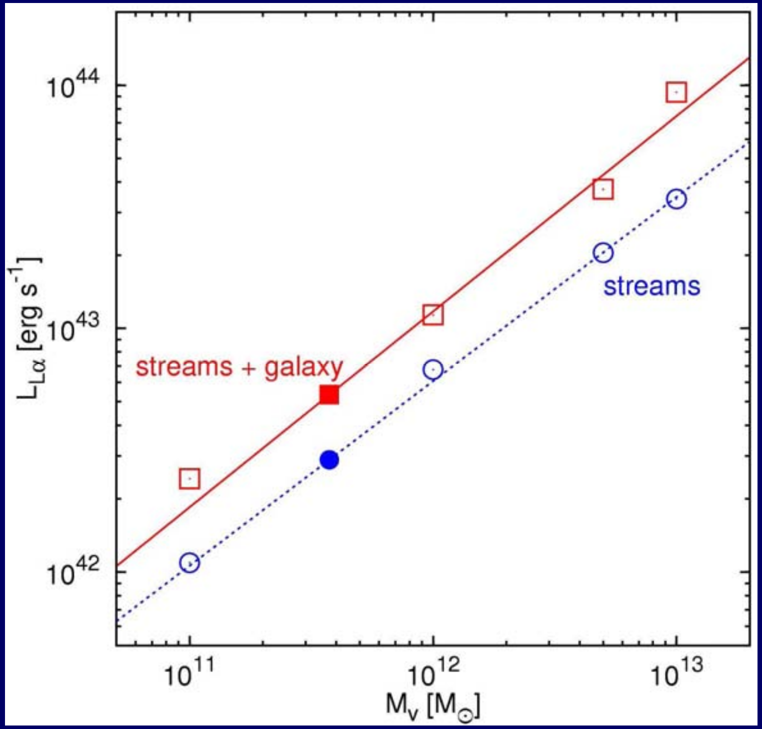
Lyman-alpha Luminosity Function

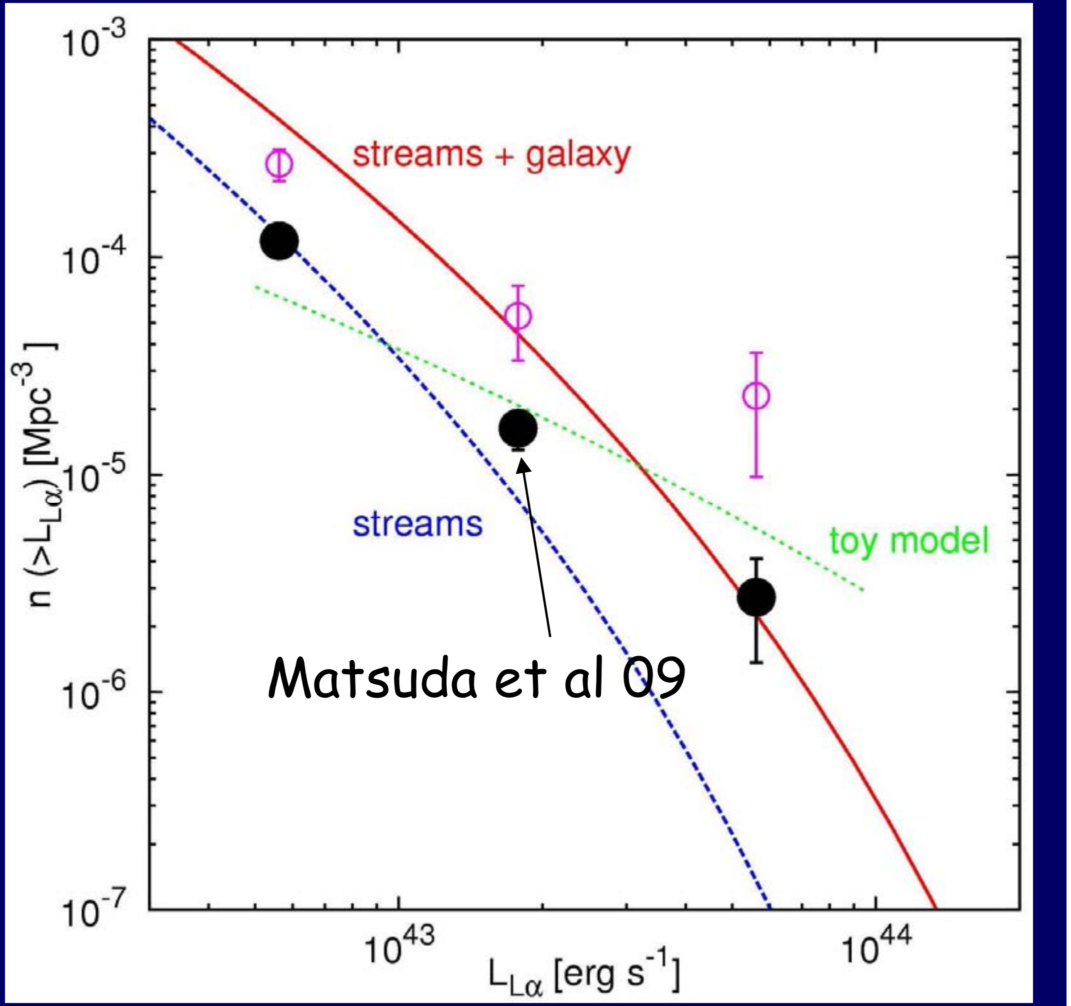



Matsuda et al 09

Isophotal area and kinematics also consistent with data

Lyman-alpha Luminosity Function

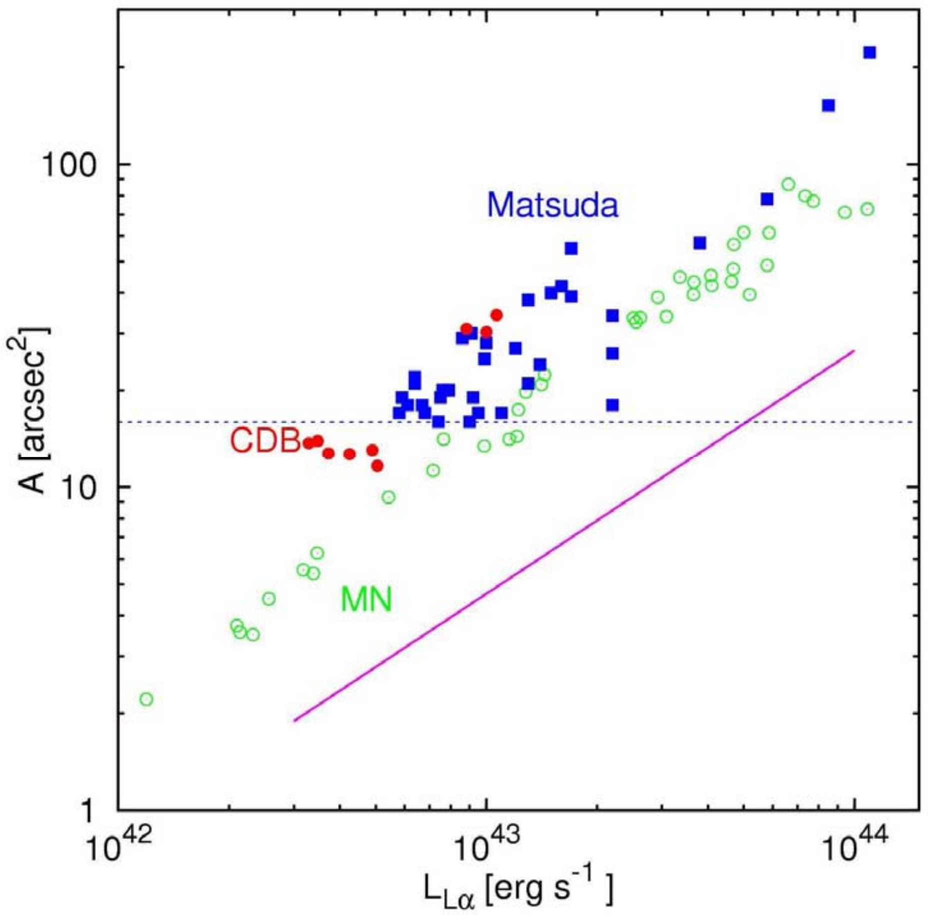


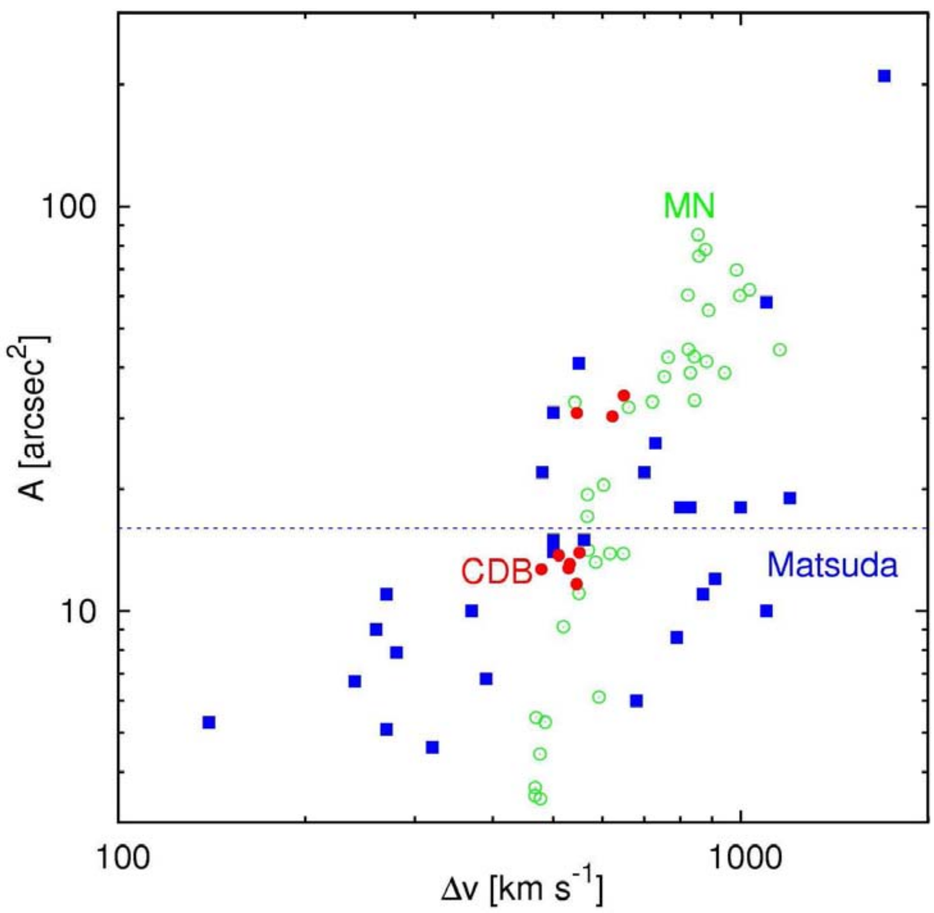


Matsuda et al 09

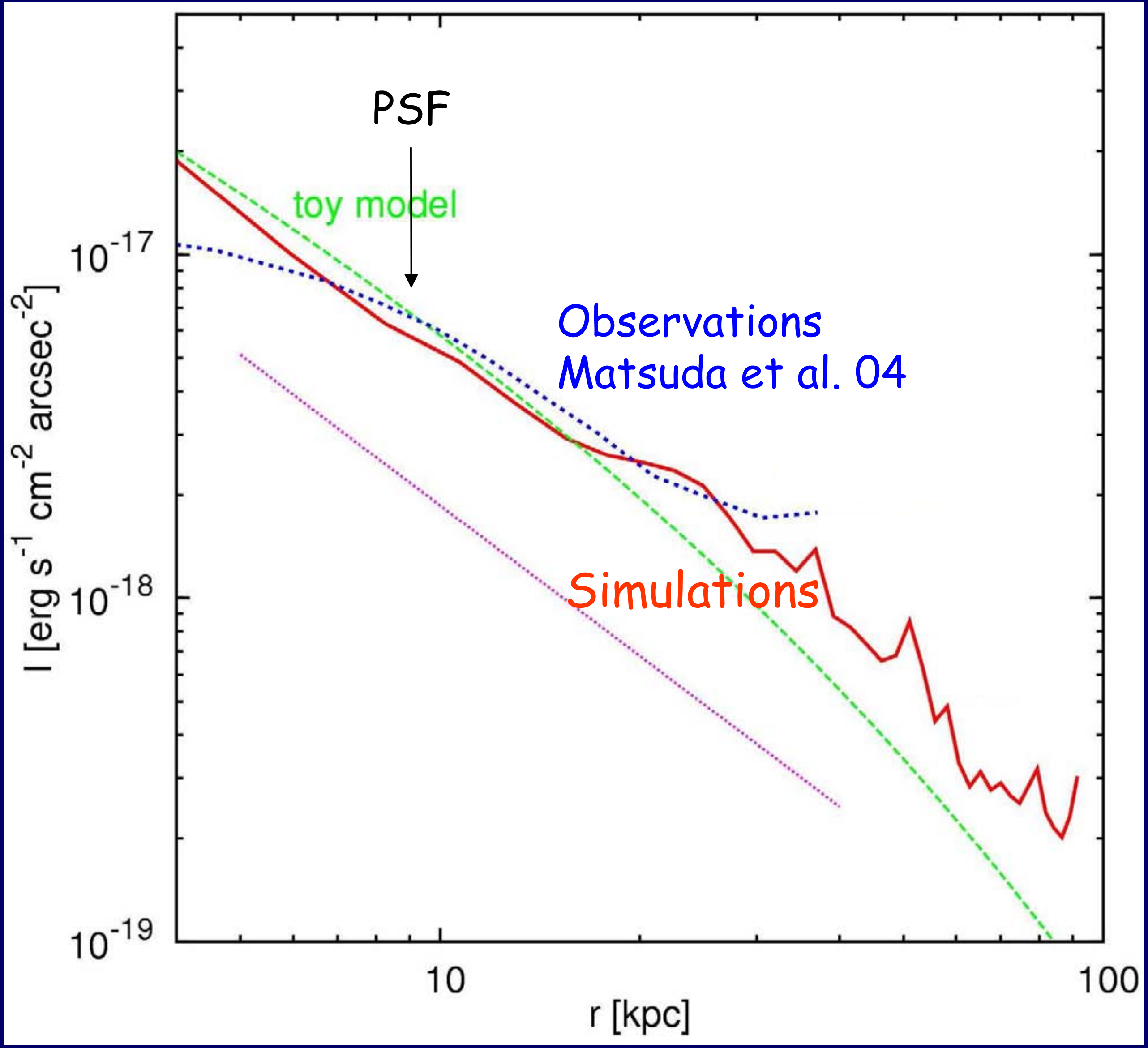
Isophotal area and kinematics also consistent with data

LAB Scaling Relations





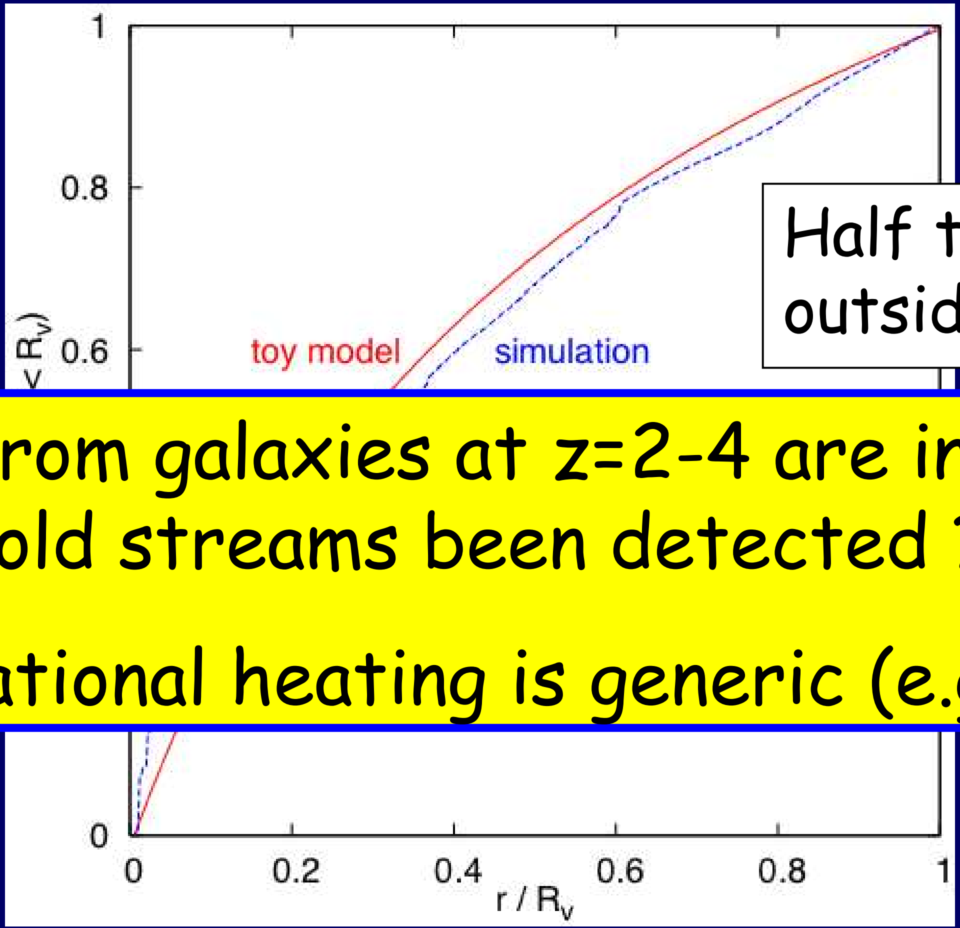
Lyman-alpha Surface Brightness Profile



Gravity Powers Lyman-alpha Emission

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

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

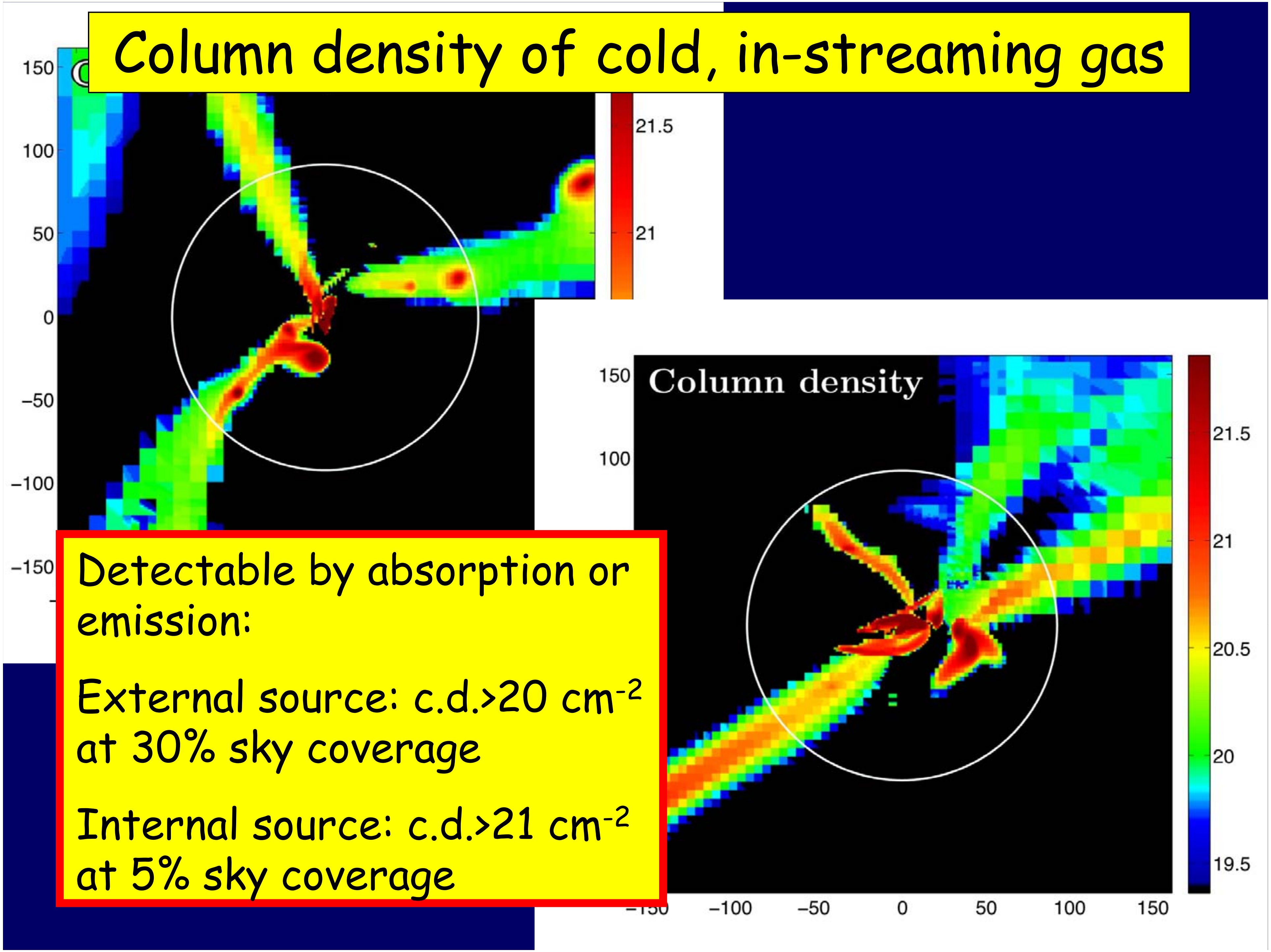


Half the luminosity outside $0.3R_v$

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

Gravitational heating is generic (e.g. clusters)

Column density of cold, in-streaming gas



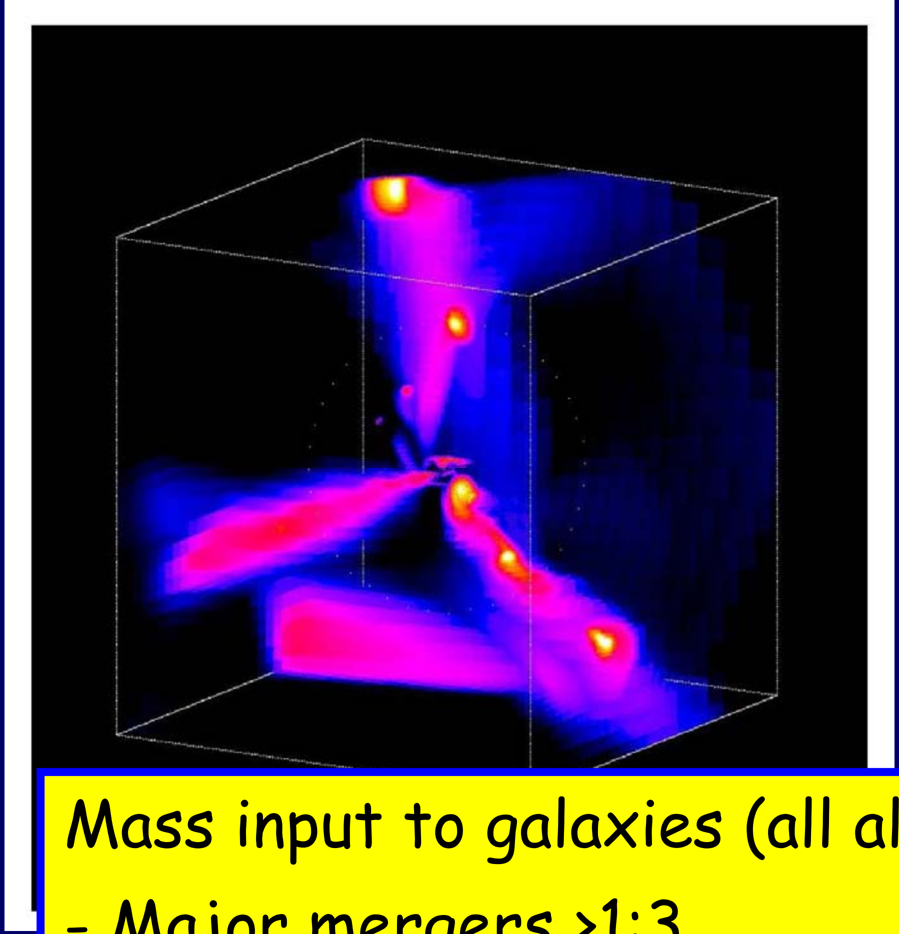
Detectable by absorption or emission:

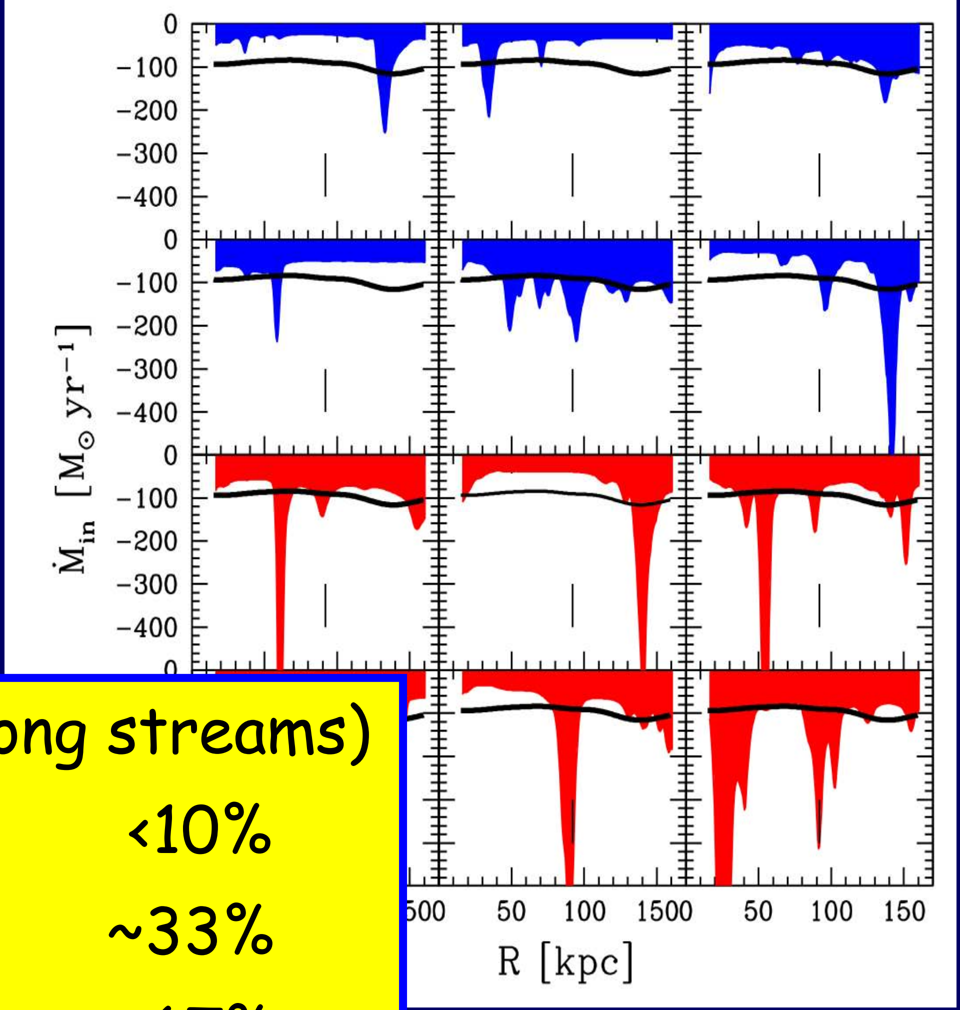
External source: c.d.>20 cm^{-2} at 30% sky coverage

Internal source: c.d.>21 cm^{-2} at 5% sky coverage

6. Stream clumpiness - mergers

Dekel et al 09, Nature



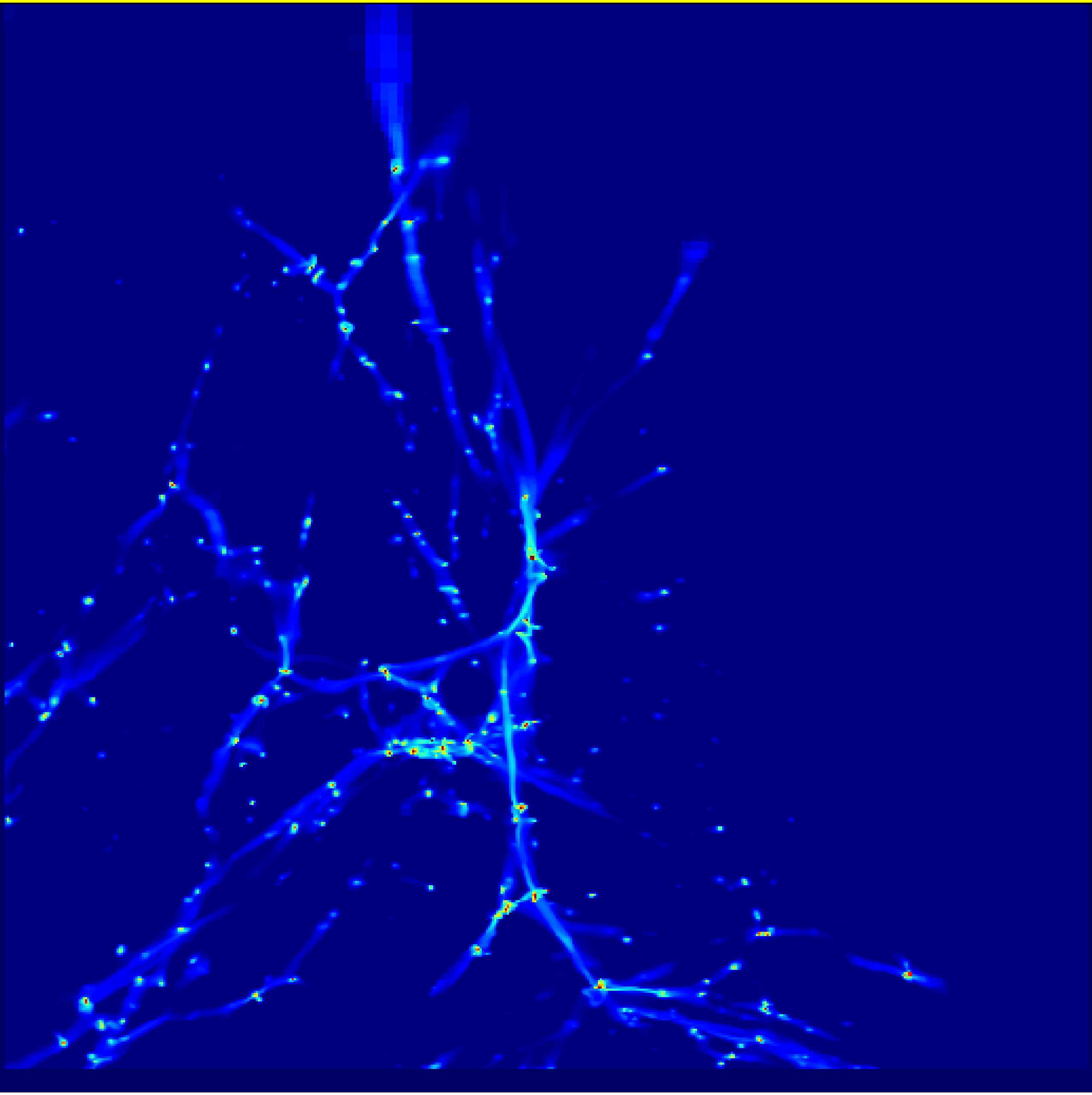


Mass input to galaxies (all along streams)

- 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

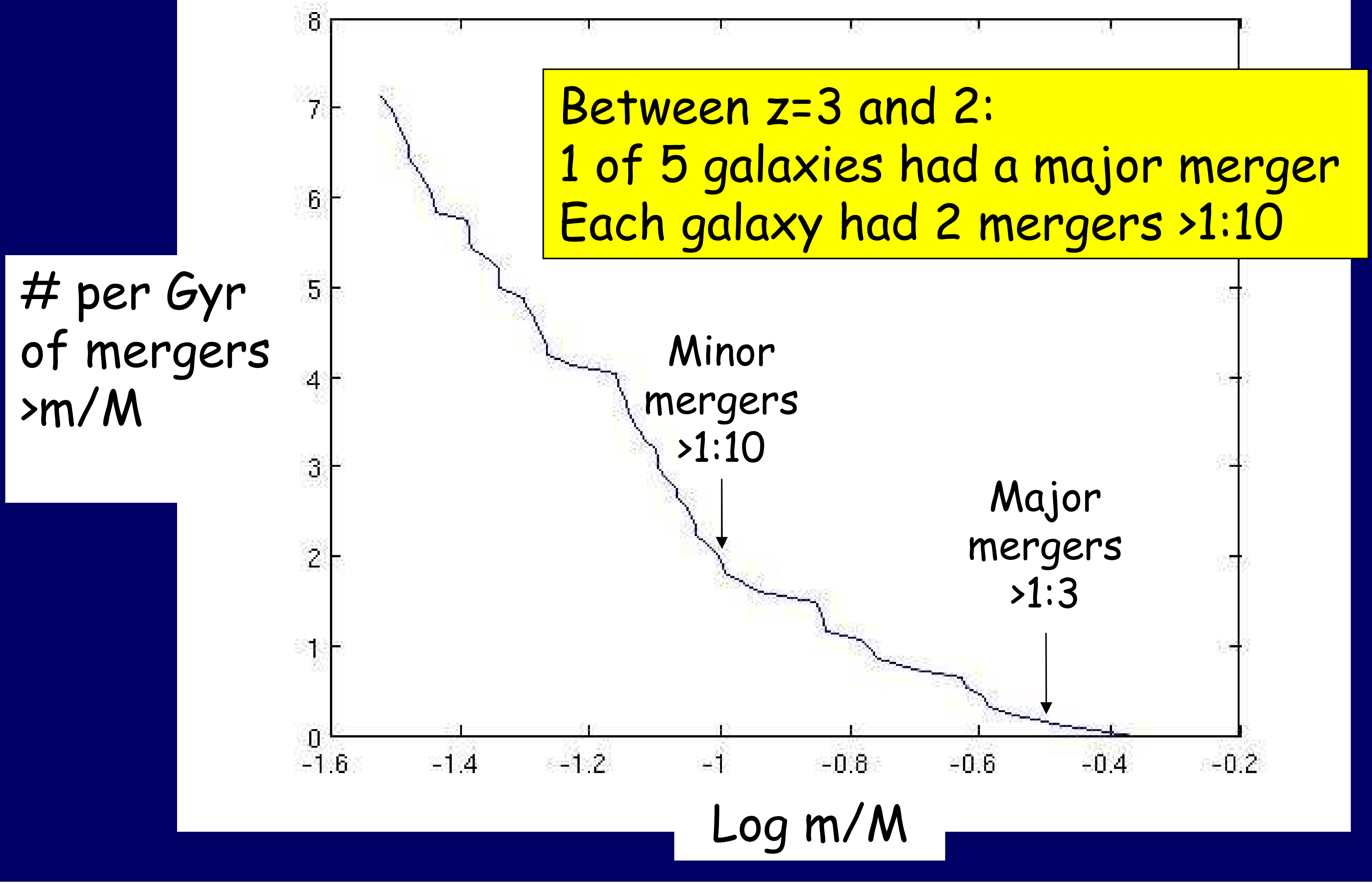
box 300 kpc

res 30 pc

$z = 5.0$ to 2.5

Merger Rate

Romero et al. 2010



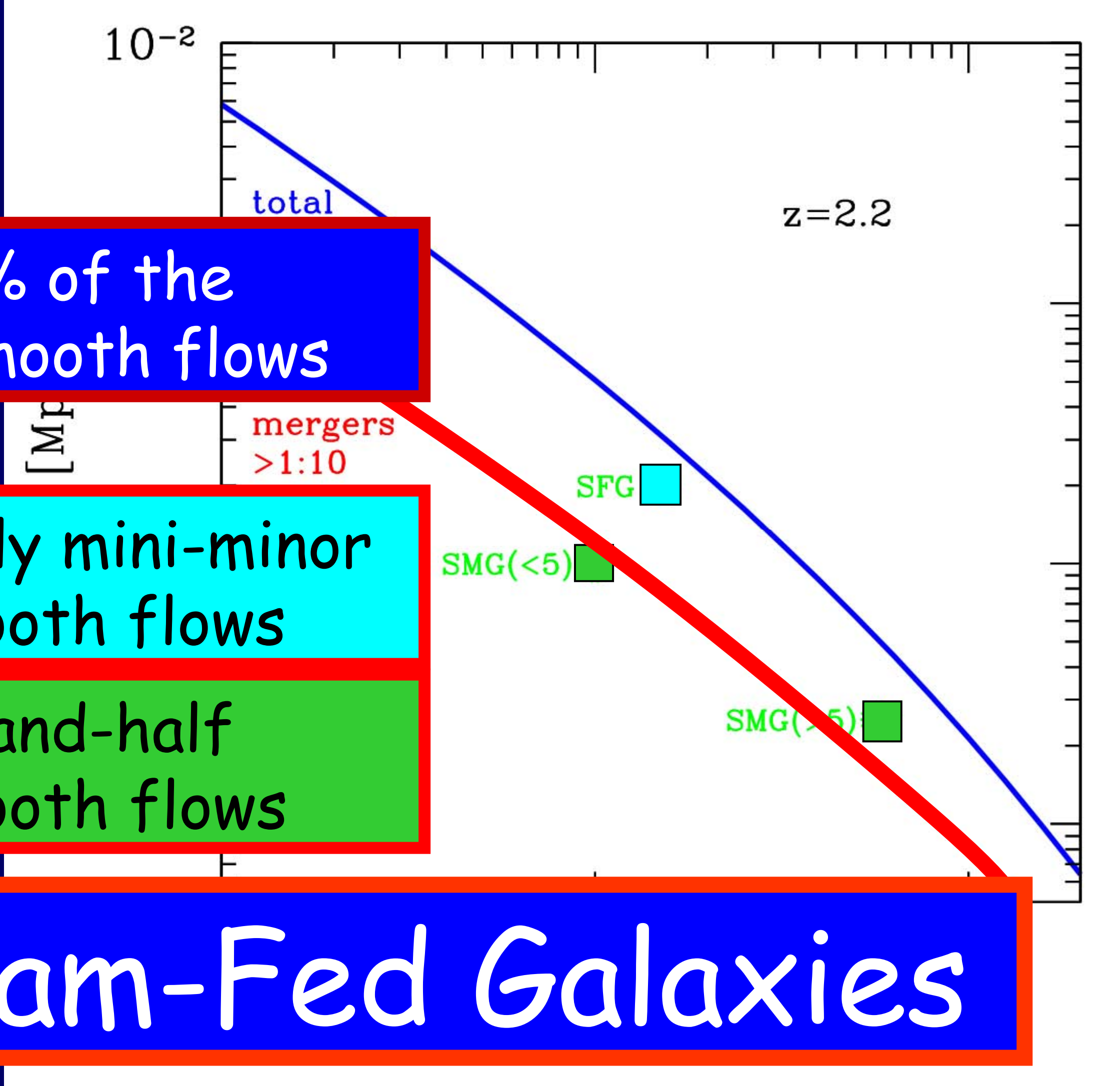
Between z=3 and 2:
1 of 5 galaxies had a major merger
Each galaxy had 2 mergers >1:10

Minor mergers >1:10

Major mergers >1:3

Fraction of Mergers

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



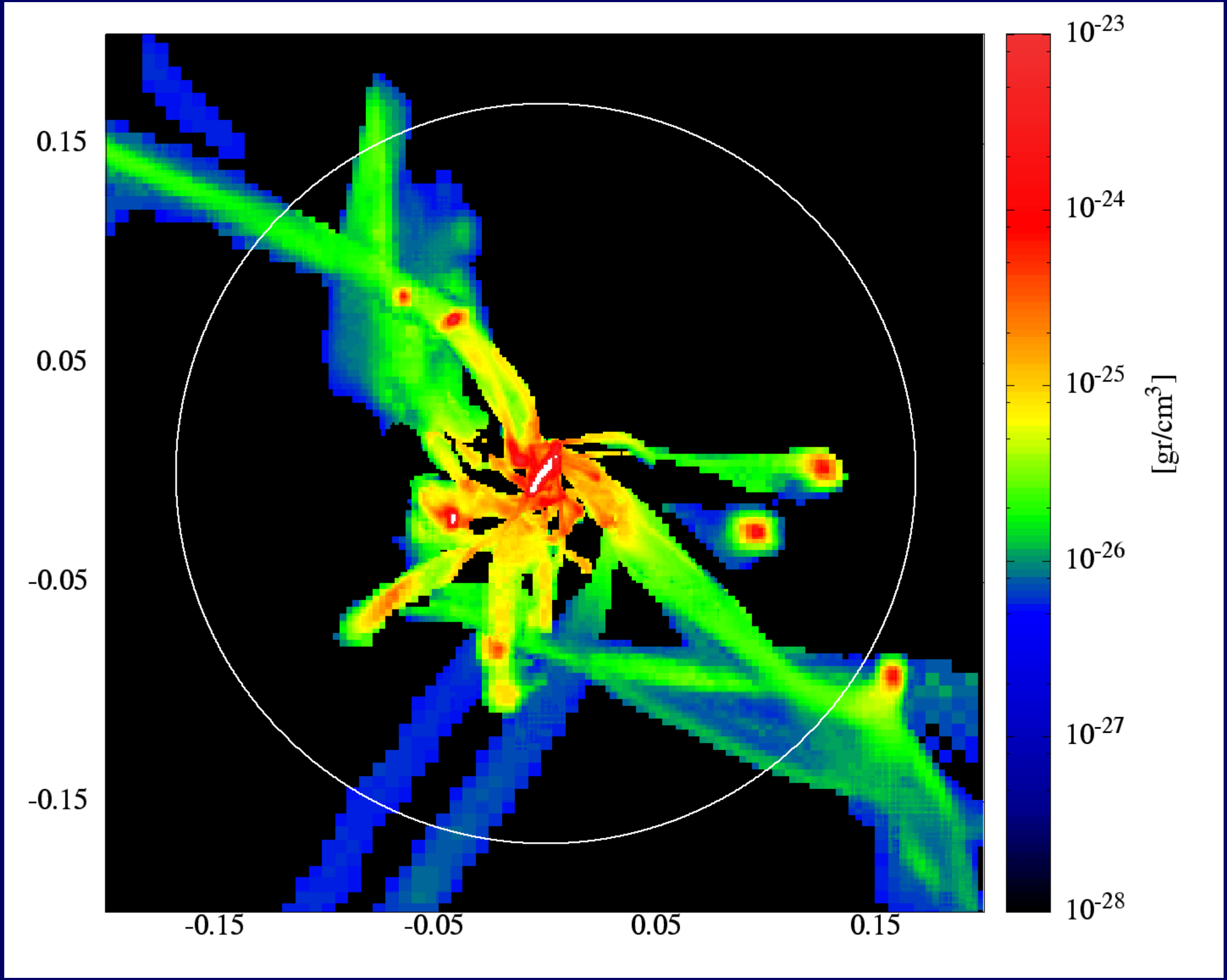
At a given dM/dt, 75% of the galaxies are fed by smooth flows

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

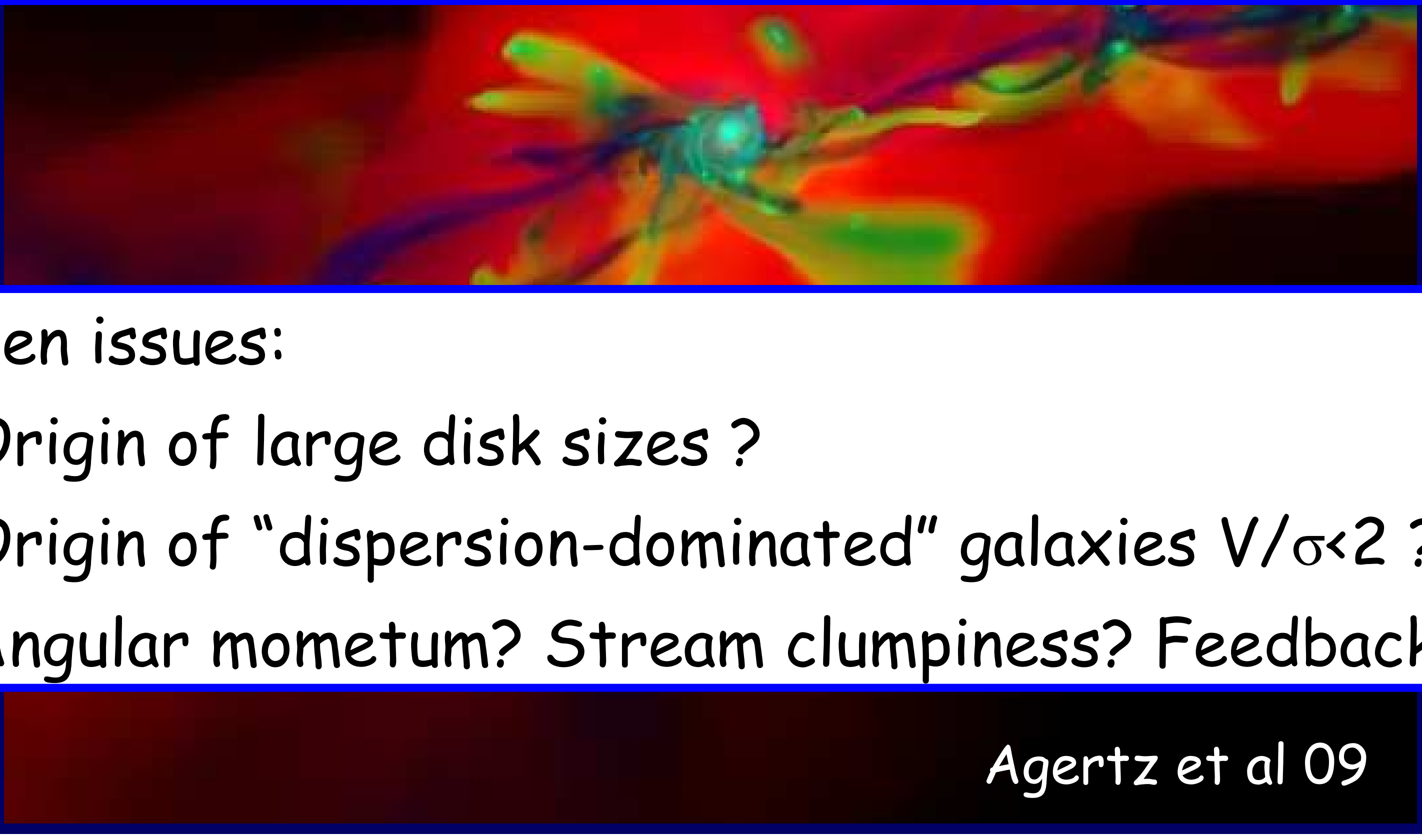
A third of the stream mass is in clump >1:10



Birnboim,
Zinger,
Dekel,
Kravtsov

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

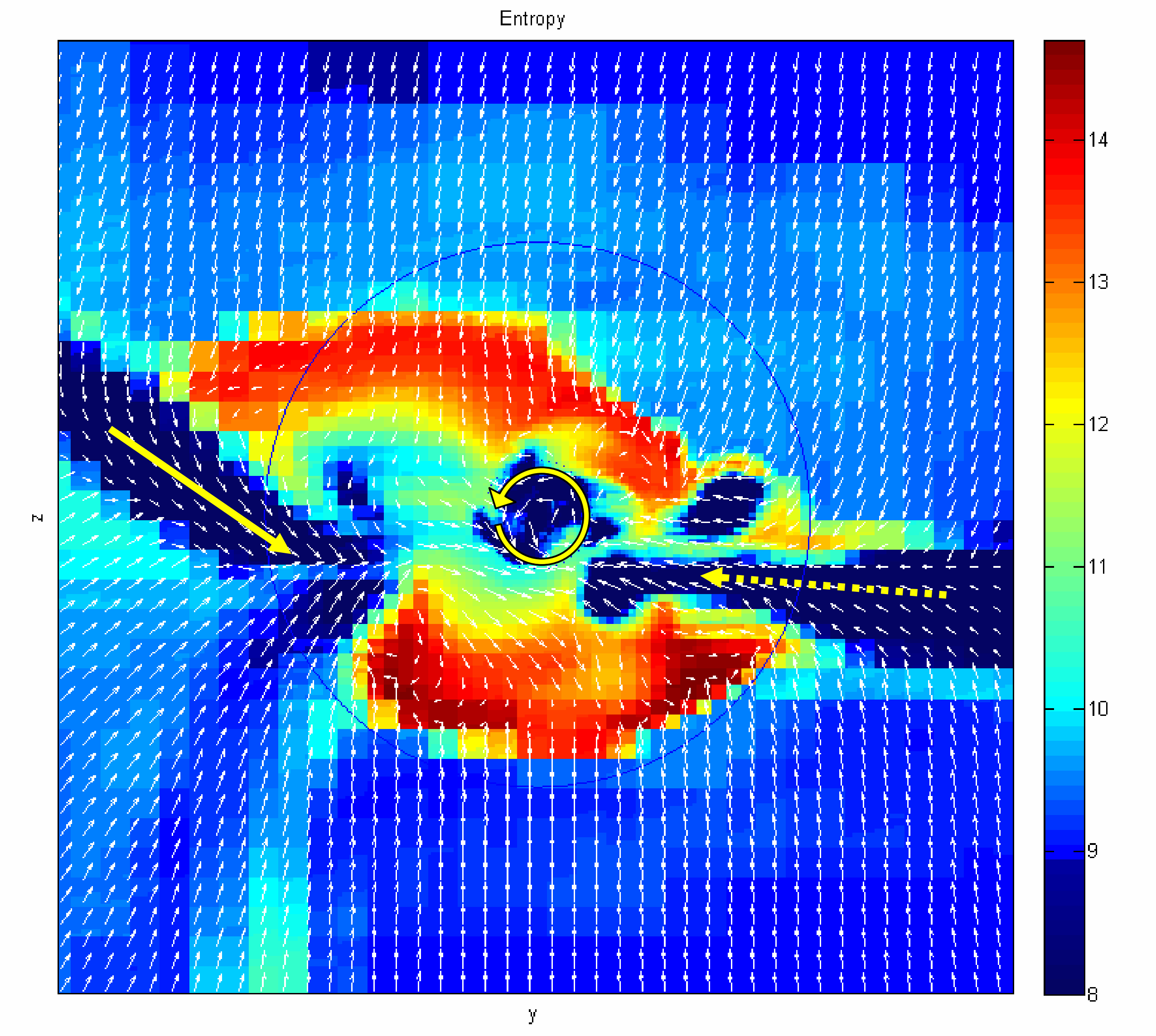


Open issues:

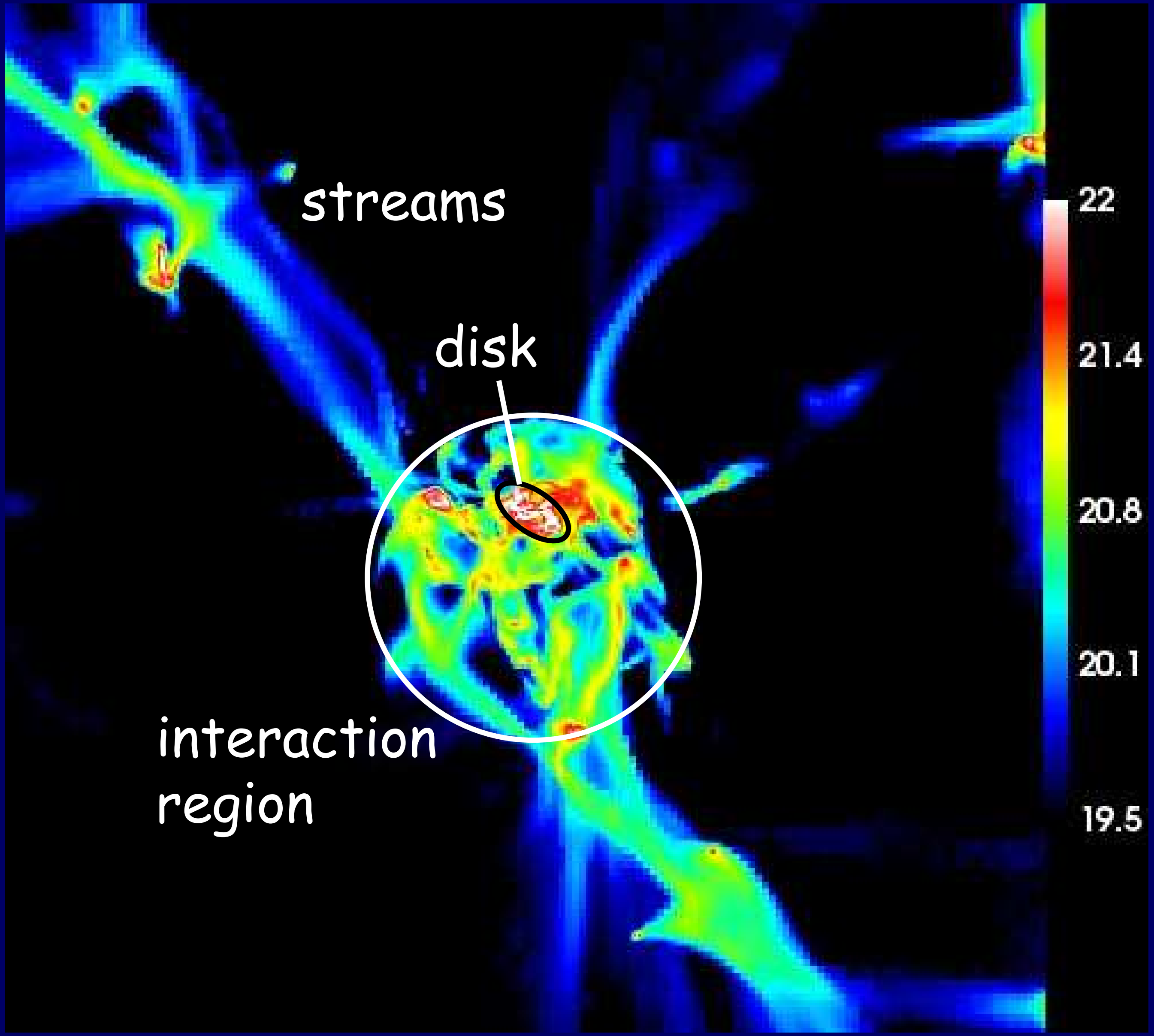
- Origin of large disk sizes ?
- Origin of "dispersion-dominated" galaxies $V/\sigma<2$?
- Angular mometum? Stream clumpiness? Feedback?

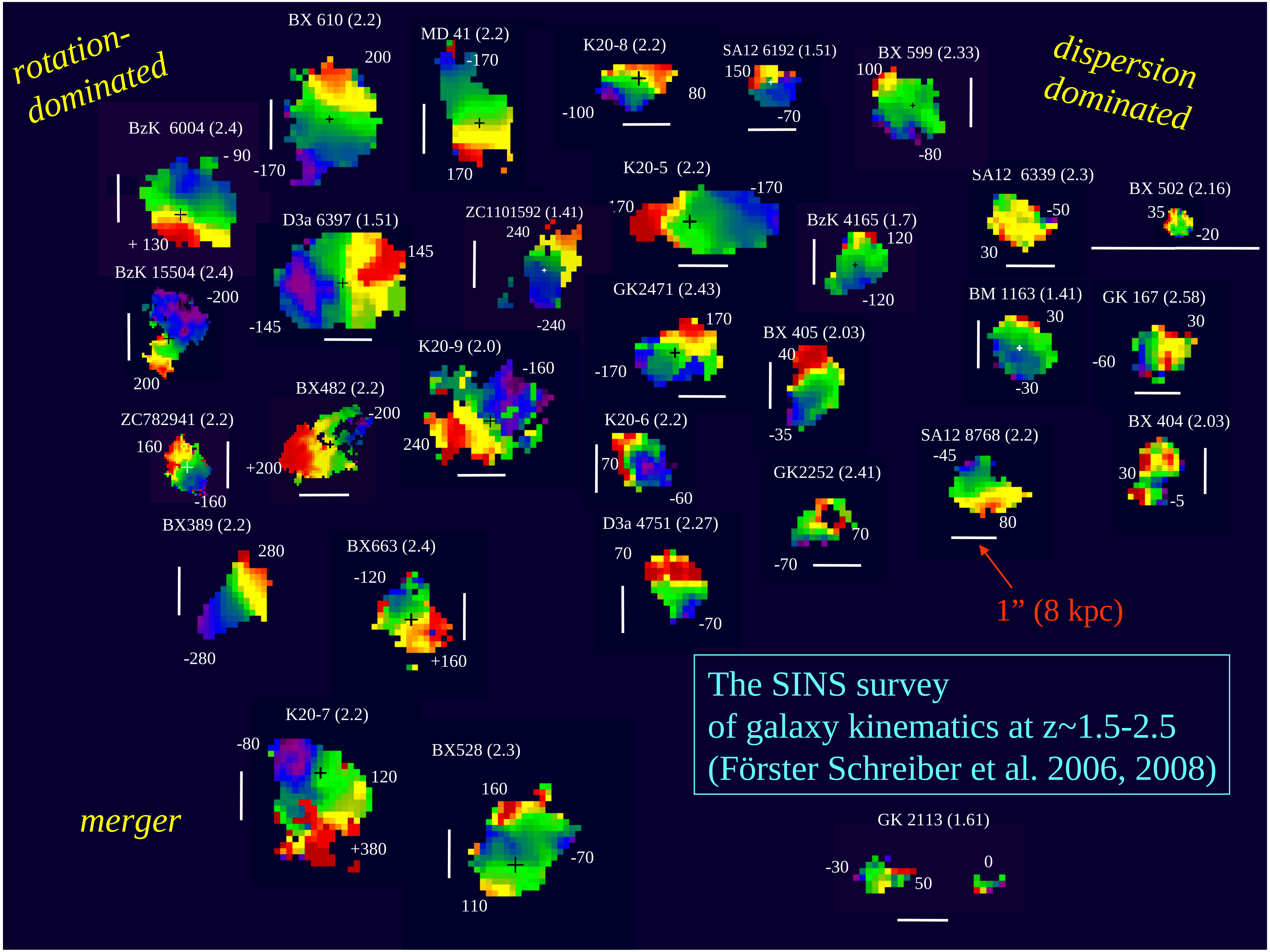
Agertz et al 09

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

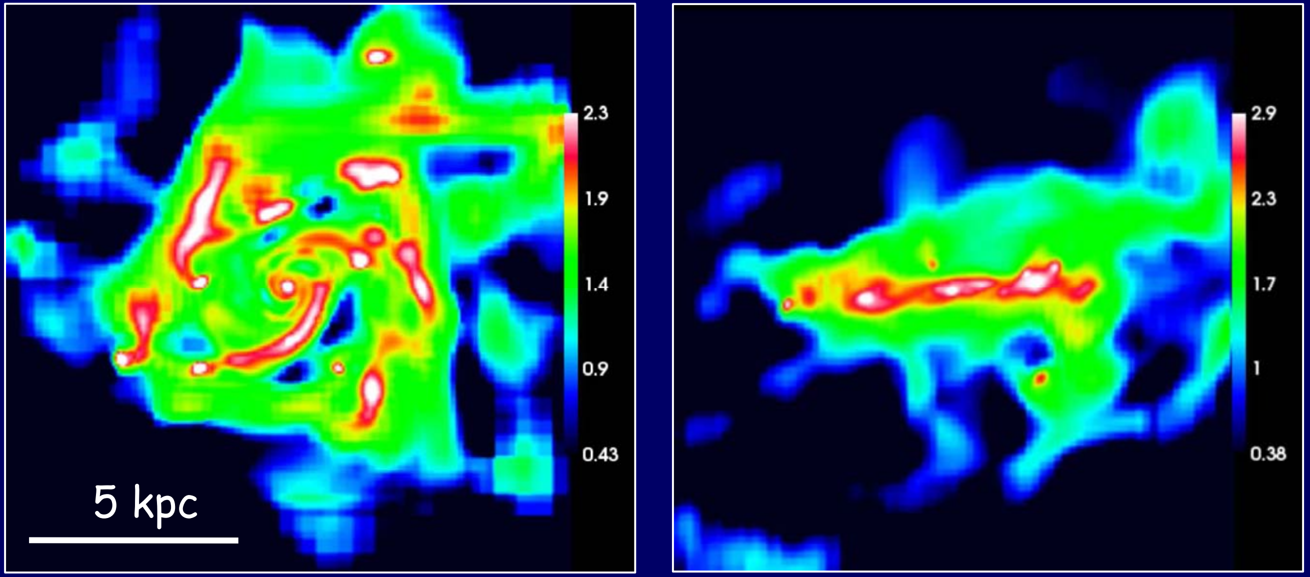
Bournaud,
Elmegreen,
Elmegreen 06, 08

High gas density → disk wildly unstable

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

Giant clumps and transient features

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



Dekel, Sari,
Ceverino 09

Ceverino,
Dekel,
Bournaud 09

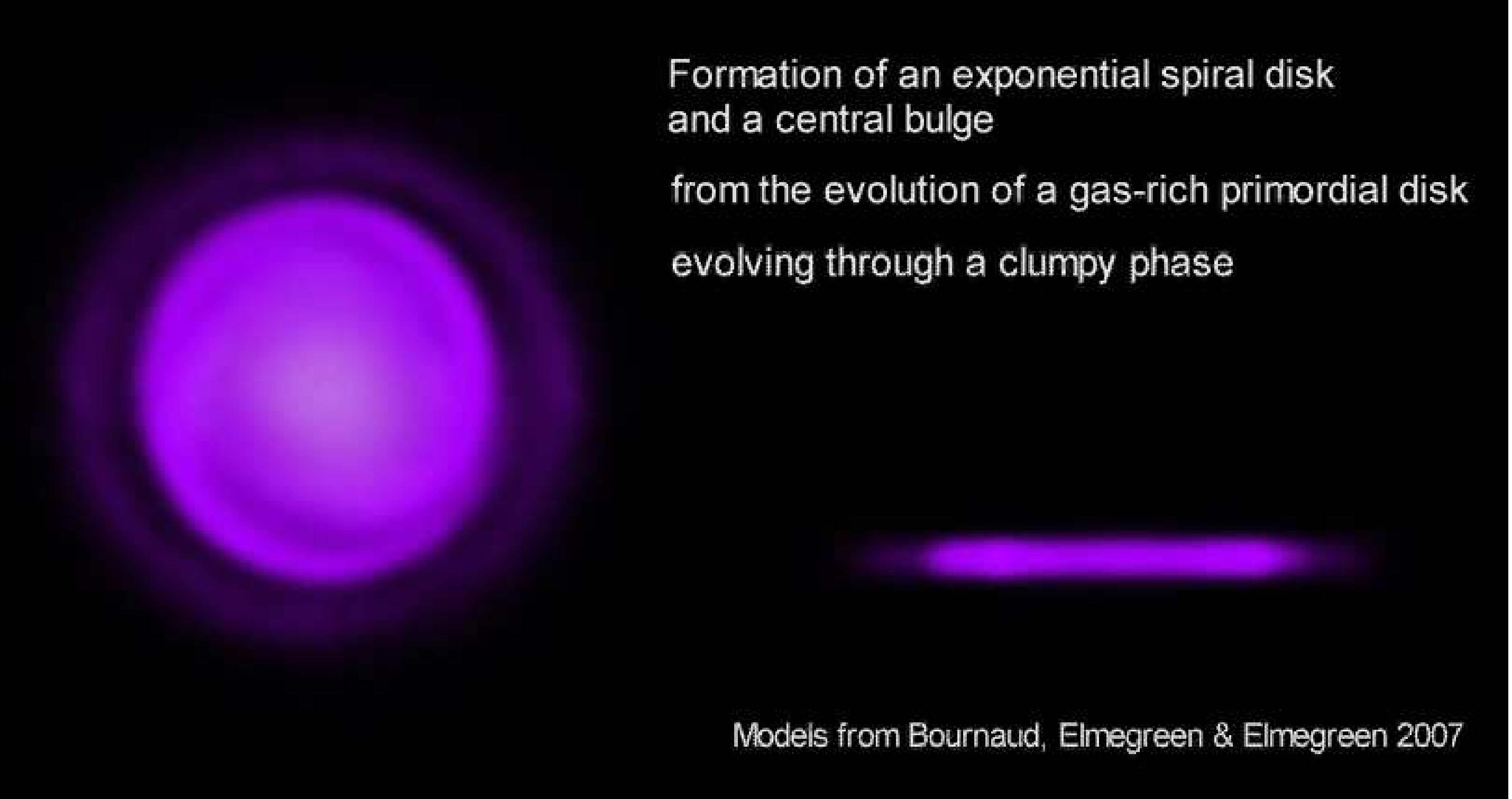
Agertz et al. 09

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

turbulent disk - giant clumps - migration -



Formation of an exponential spiral disk and a central bulge

from the evolution of a gas-rich primordial disk

evolving through a clumpy phase

Models from Bournaud, Elmegreen & Elmegreen 2007

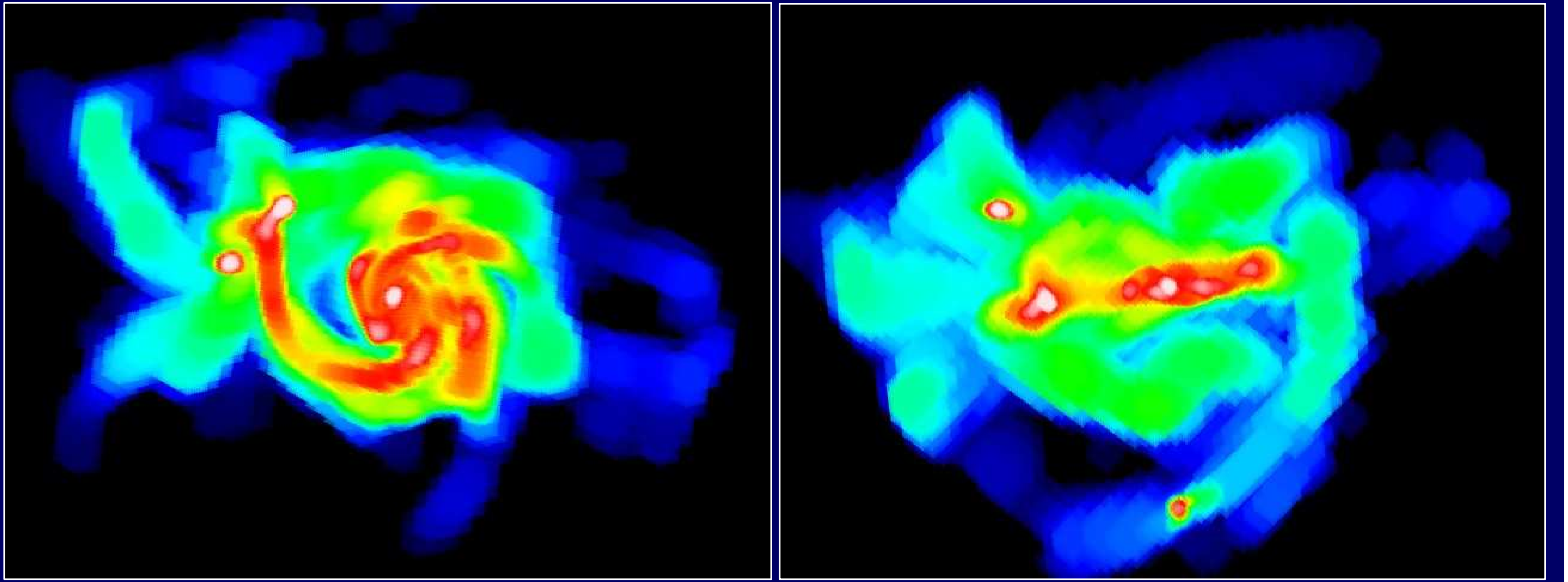
Noguchi 99;

One episode of 0.5 Gyr?

green 06, 08

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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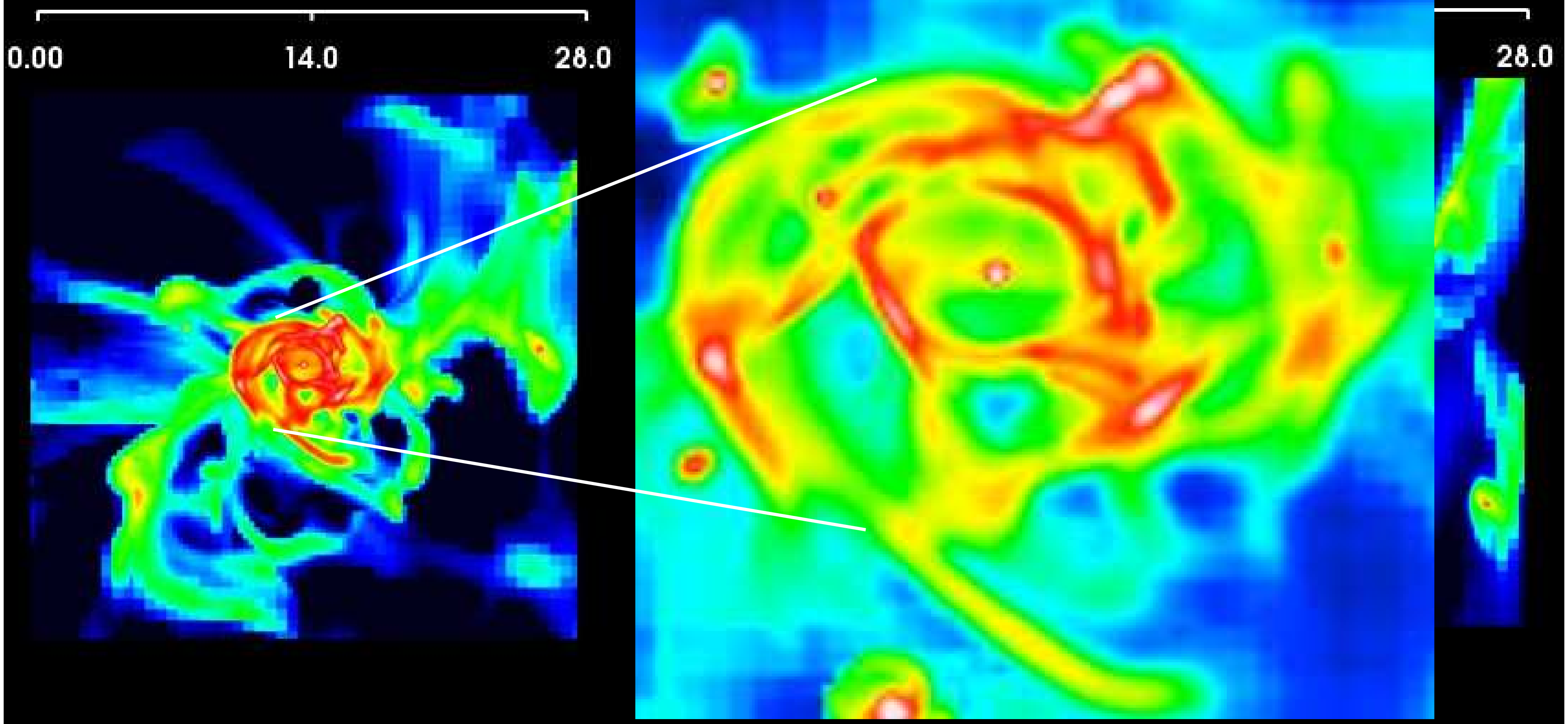
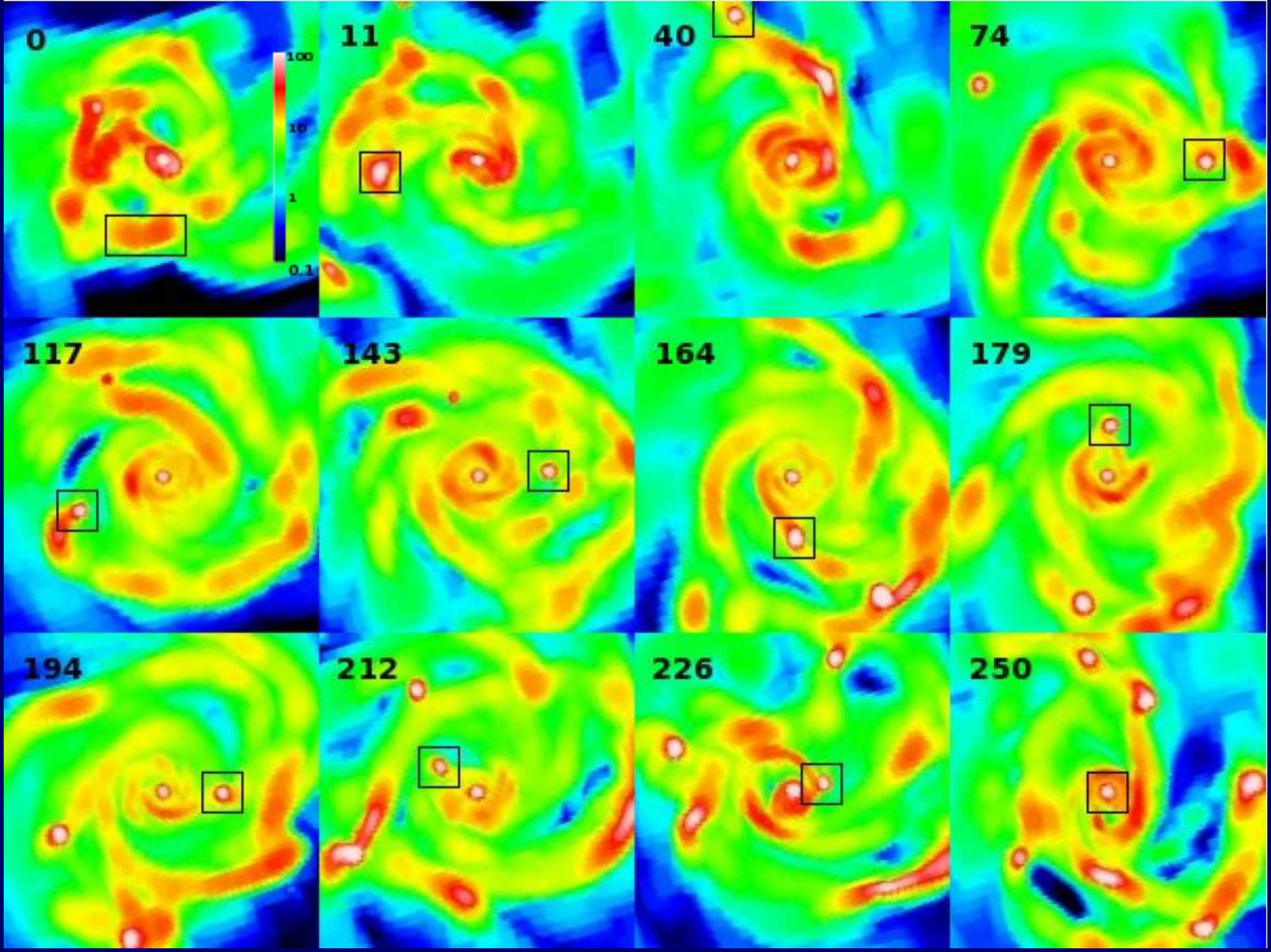
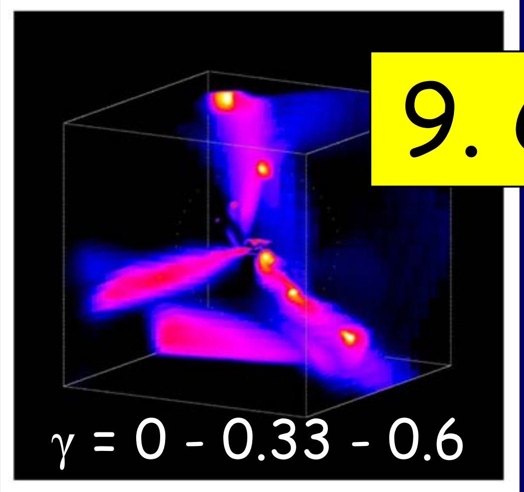


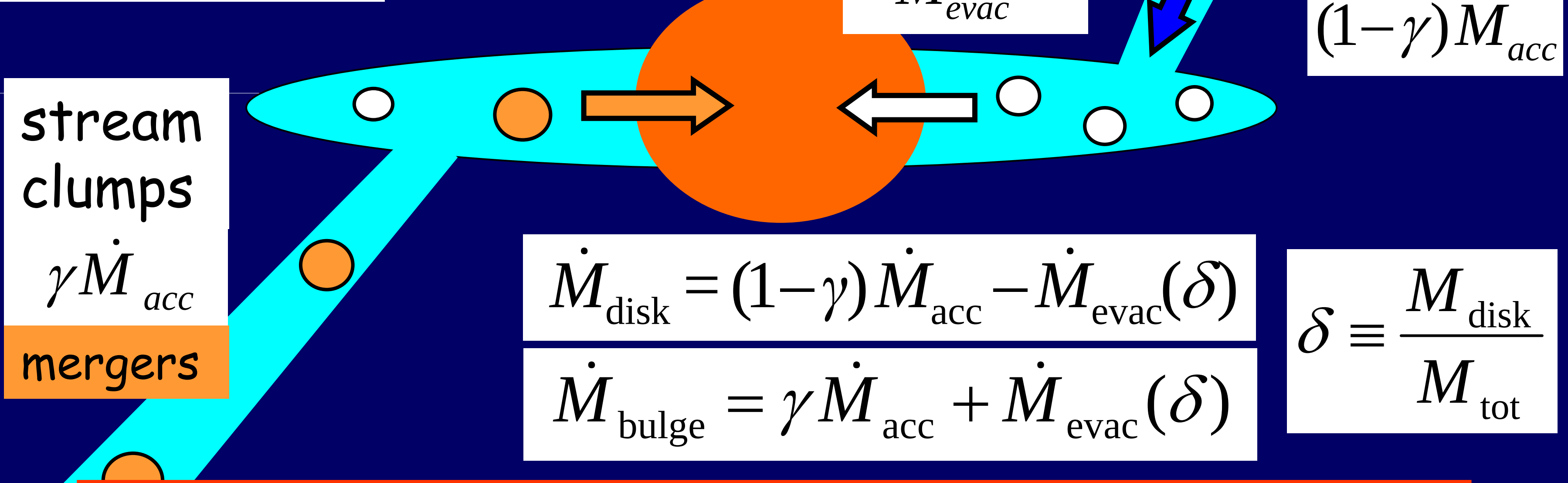
Clump Formation & Migration



9. Cosmological Steady State

Dekel, Sari, Ceverino 09





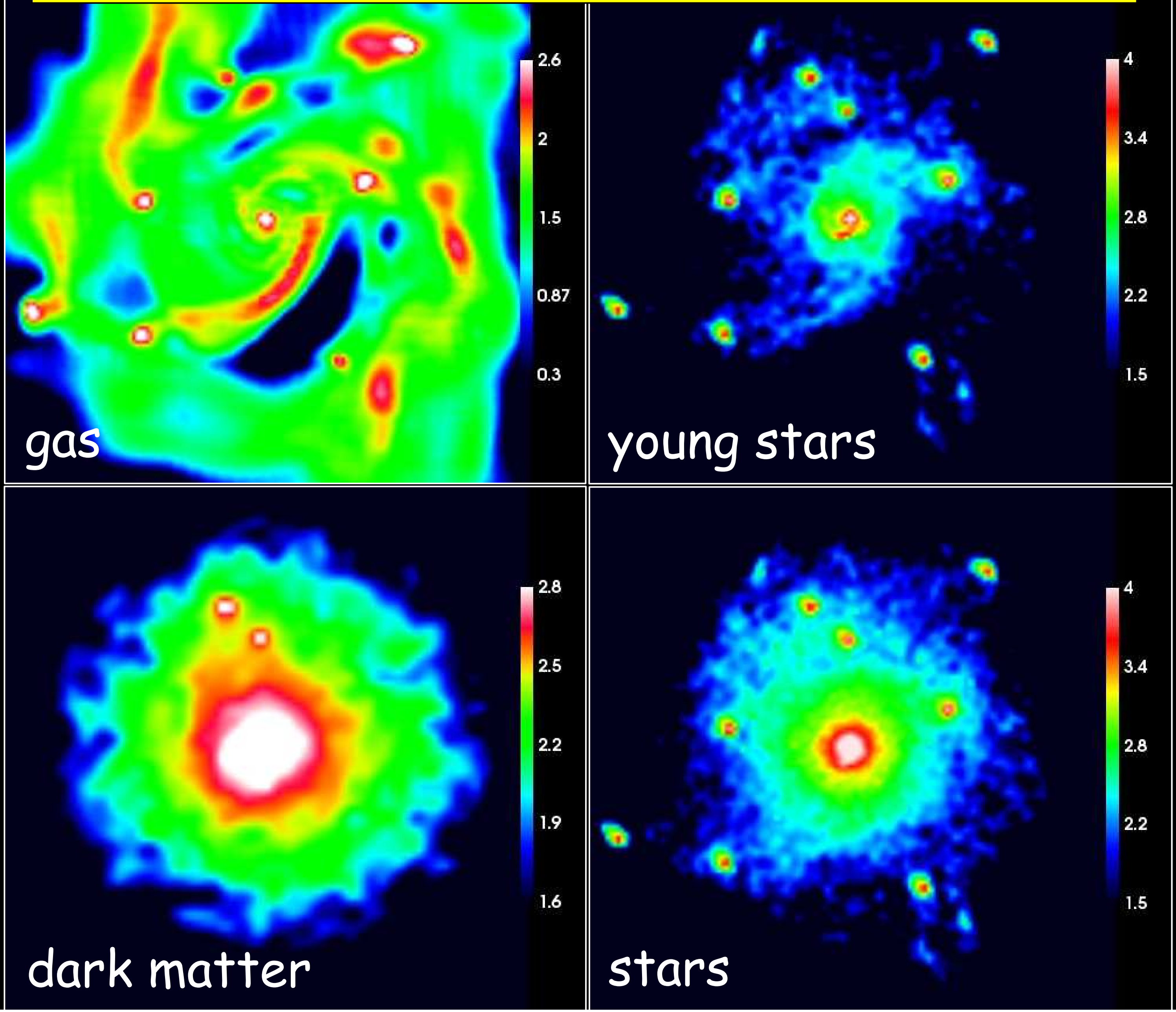
$$\dot{M}_{\rm disk} = (1-\gamma)\dot{M}_{\rm acc} - \dot{M}_{\rm evac}(\delta)$$

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

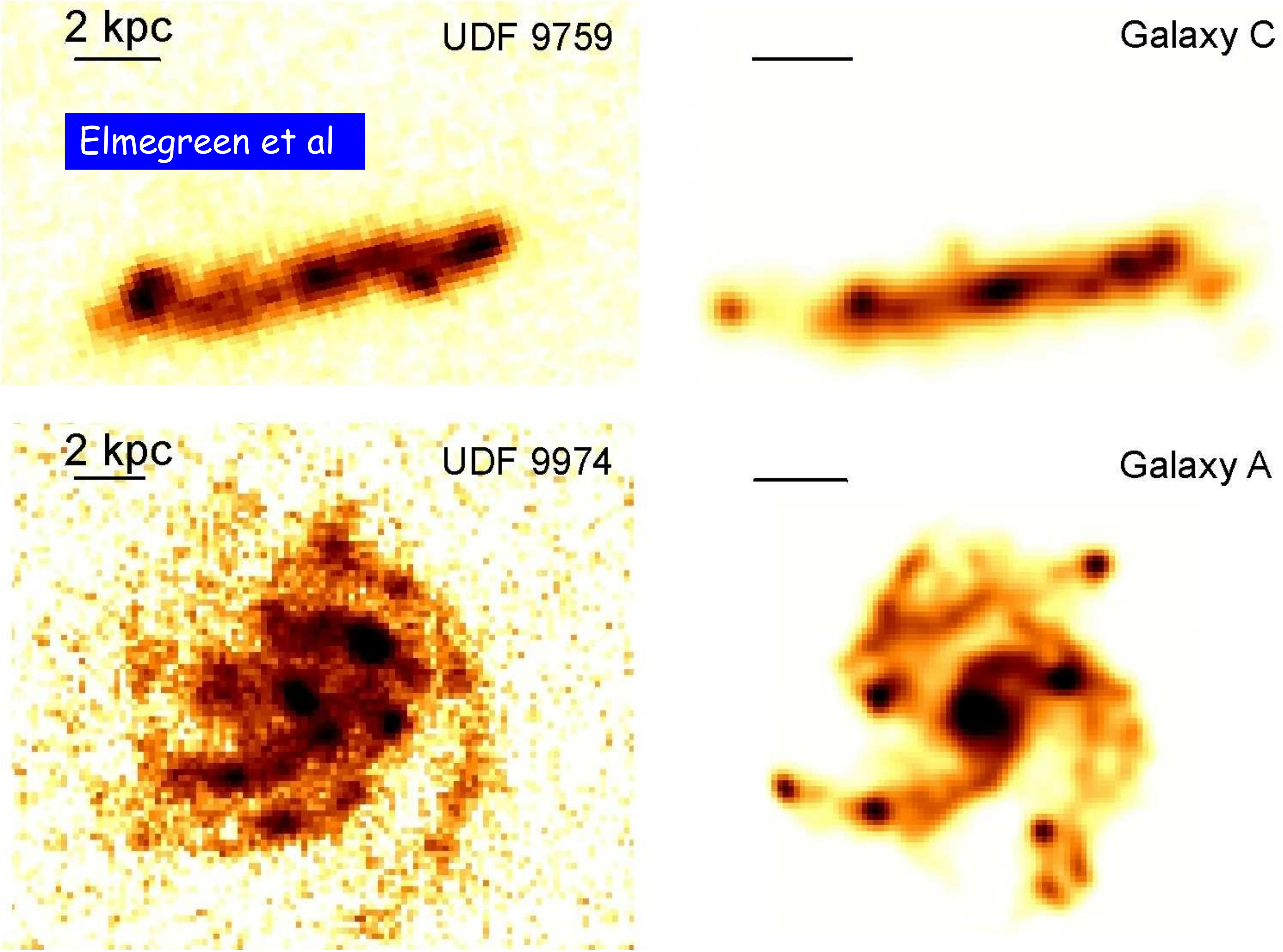
$$\delta \equiv \frac{M_{\rm disk}}{M_{\rm tot}}$$

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

Disk Clumps vs Stream Clumps

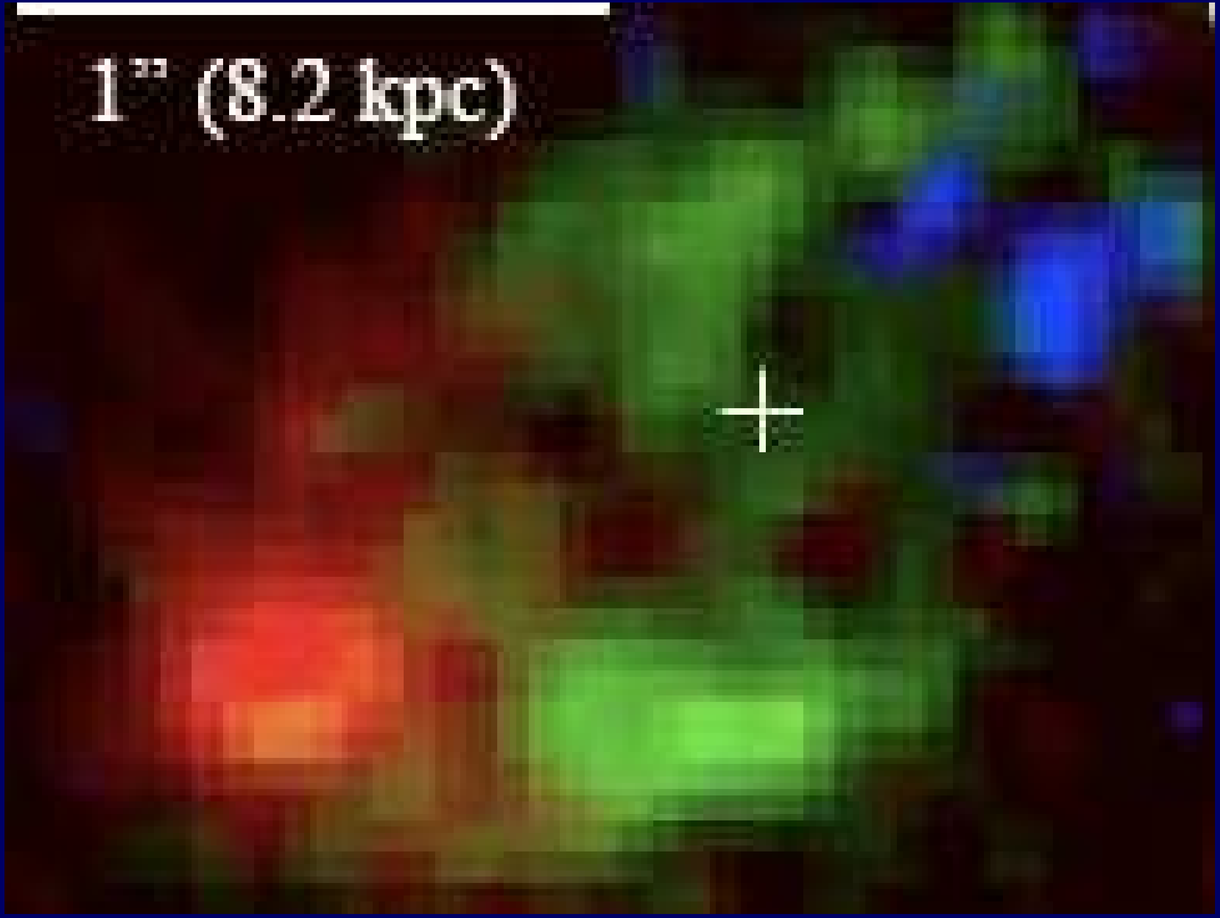


Observations vs. Simulations



Elmegreen et al

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

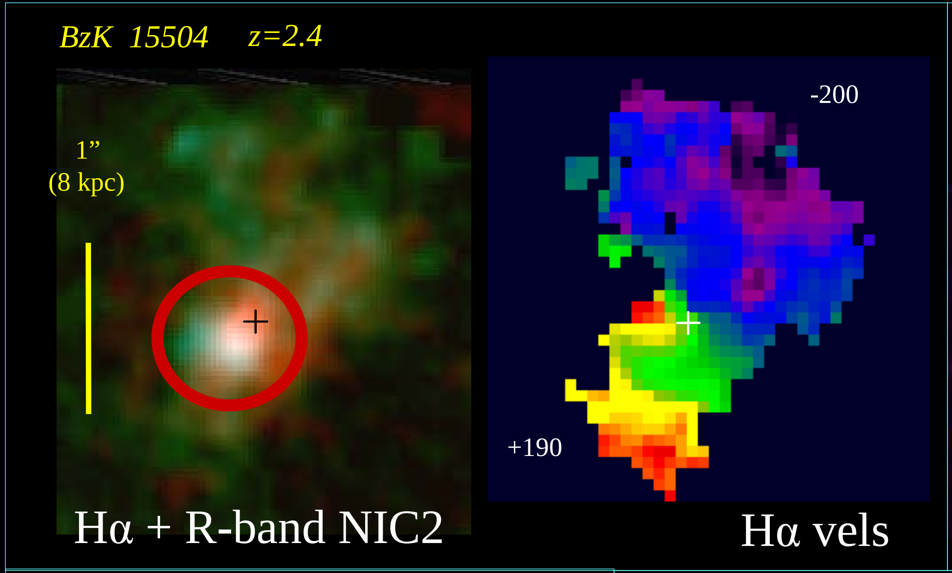


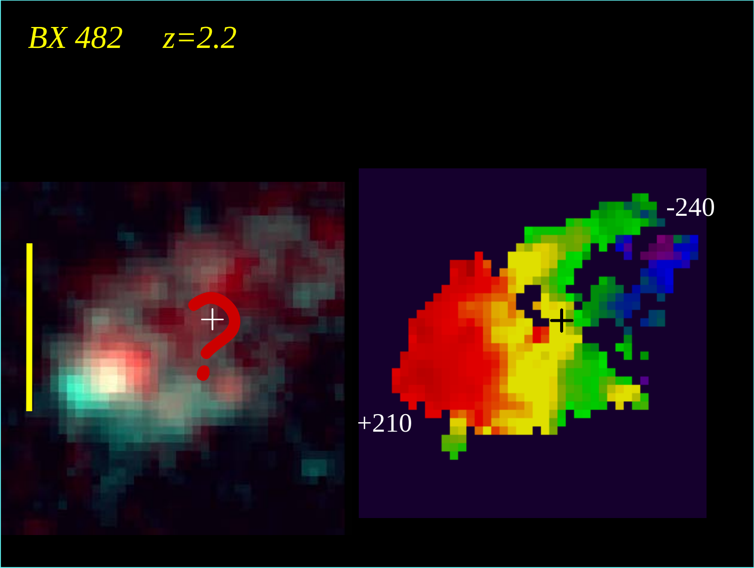
Hα star-form regions

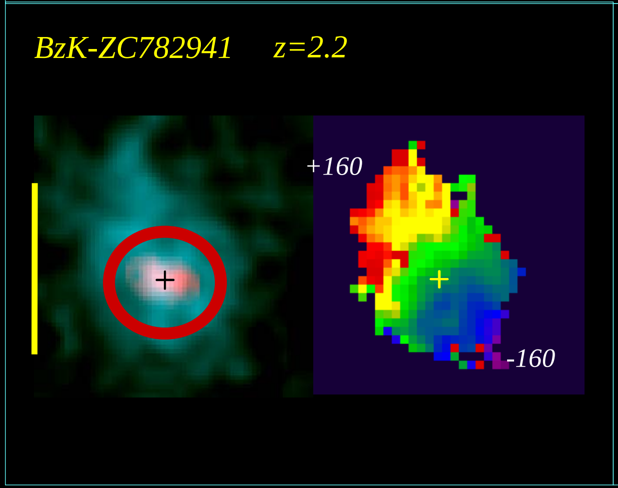
color-code velocity field

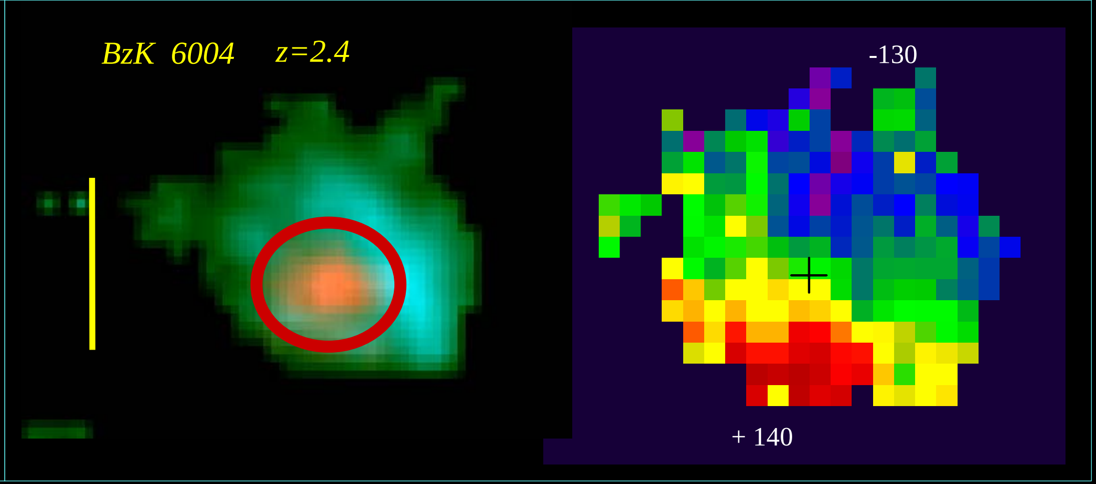
Genzel et al 08

Clumpy disks with comparable bulges





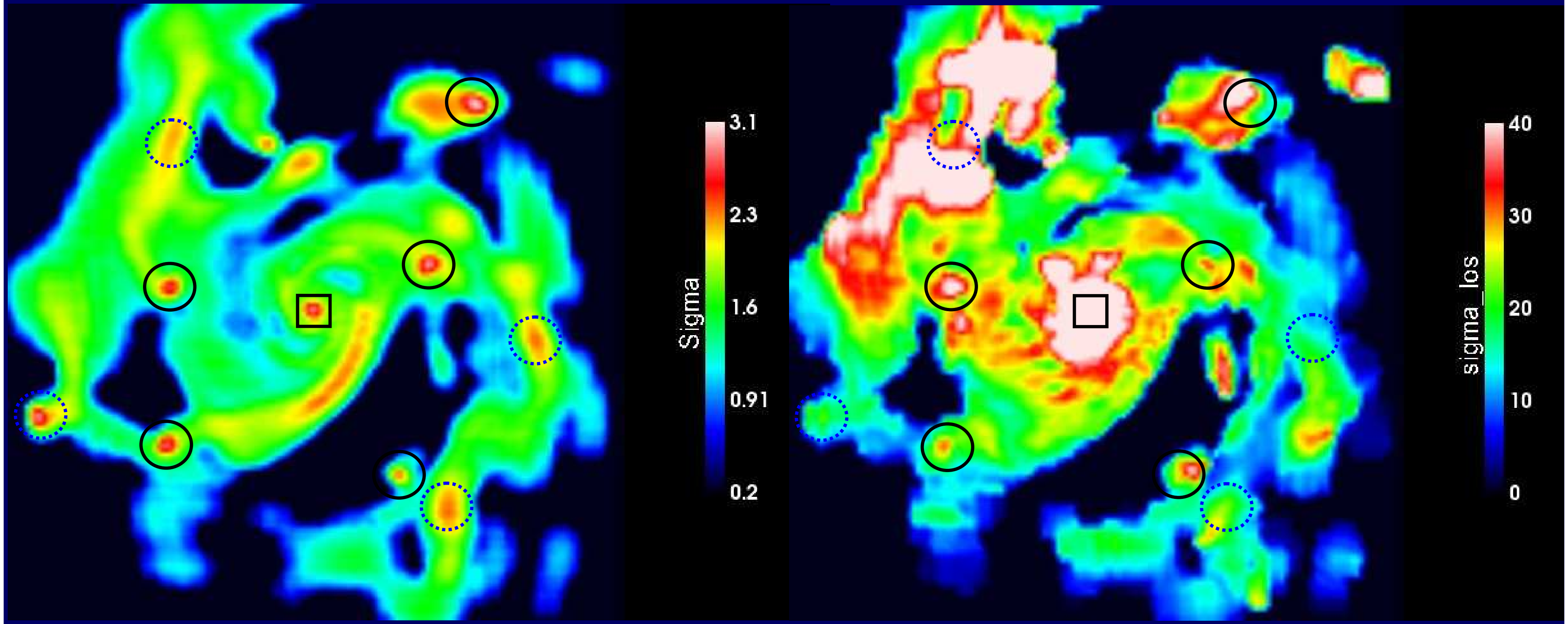




Genzel et al. 08; Förster Schreiber et al. 20

M(≤3 kpc)/M(≤15 kpc)~0.2-0.4

Kinematic detection of clumps?

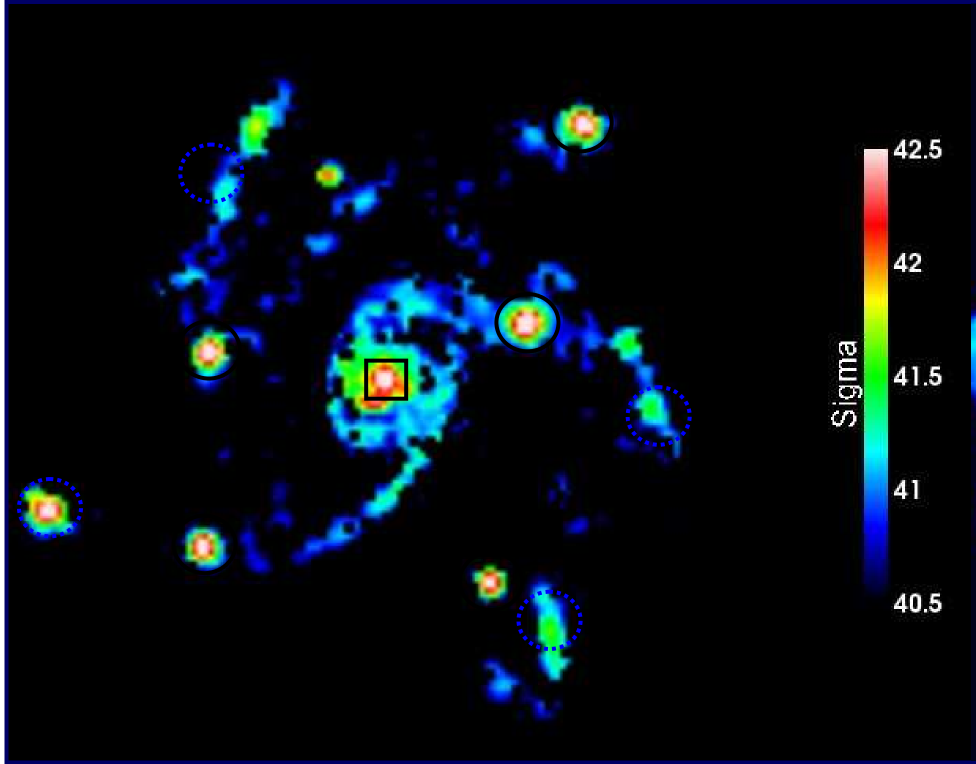


Gas density

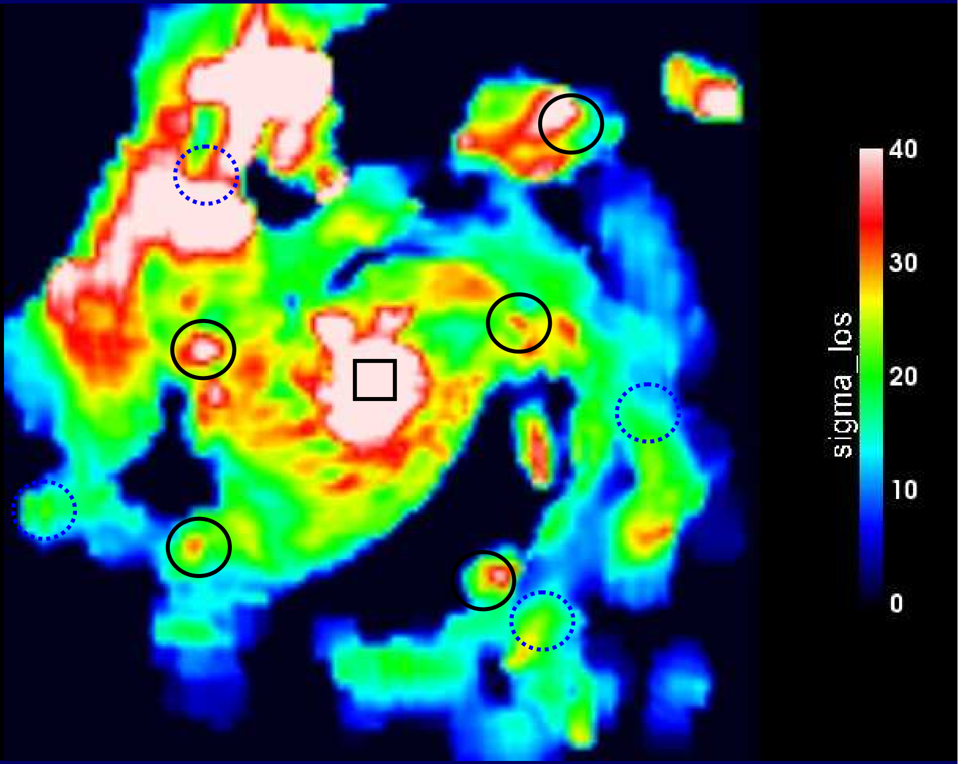
Velocity dispersion

Kinematic detection of clumps?

H-alpha density

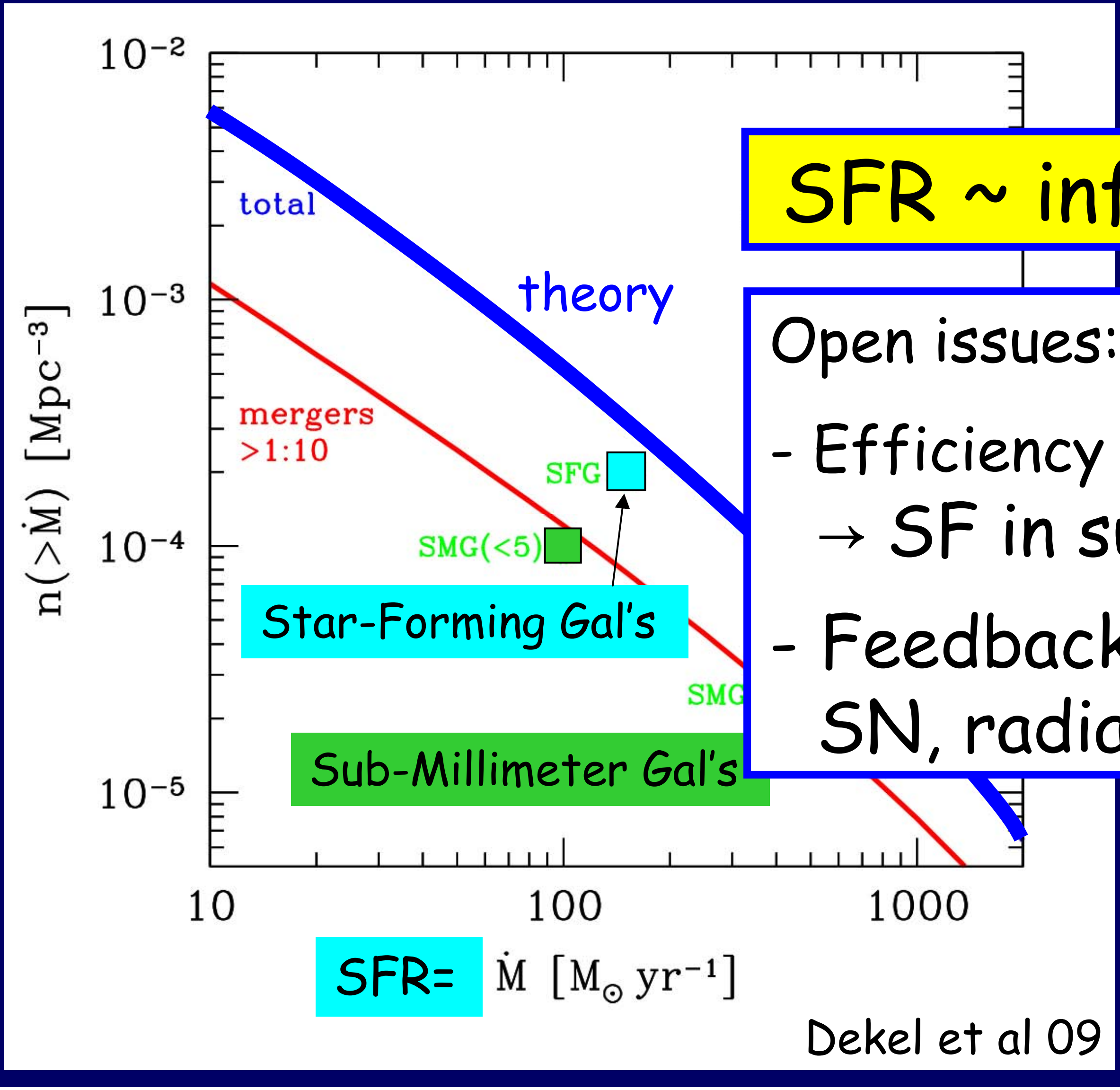


Velocity dispersion



10. Rapid Star Formation - in Clumps

Theory versus observation



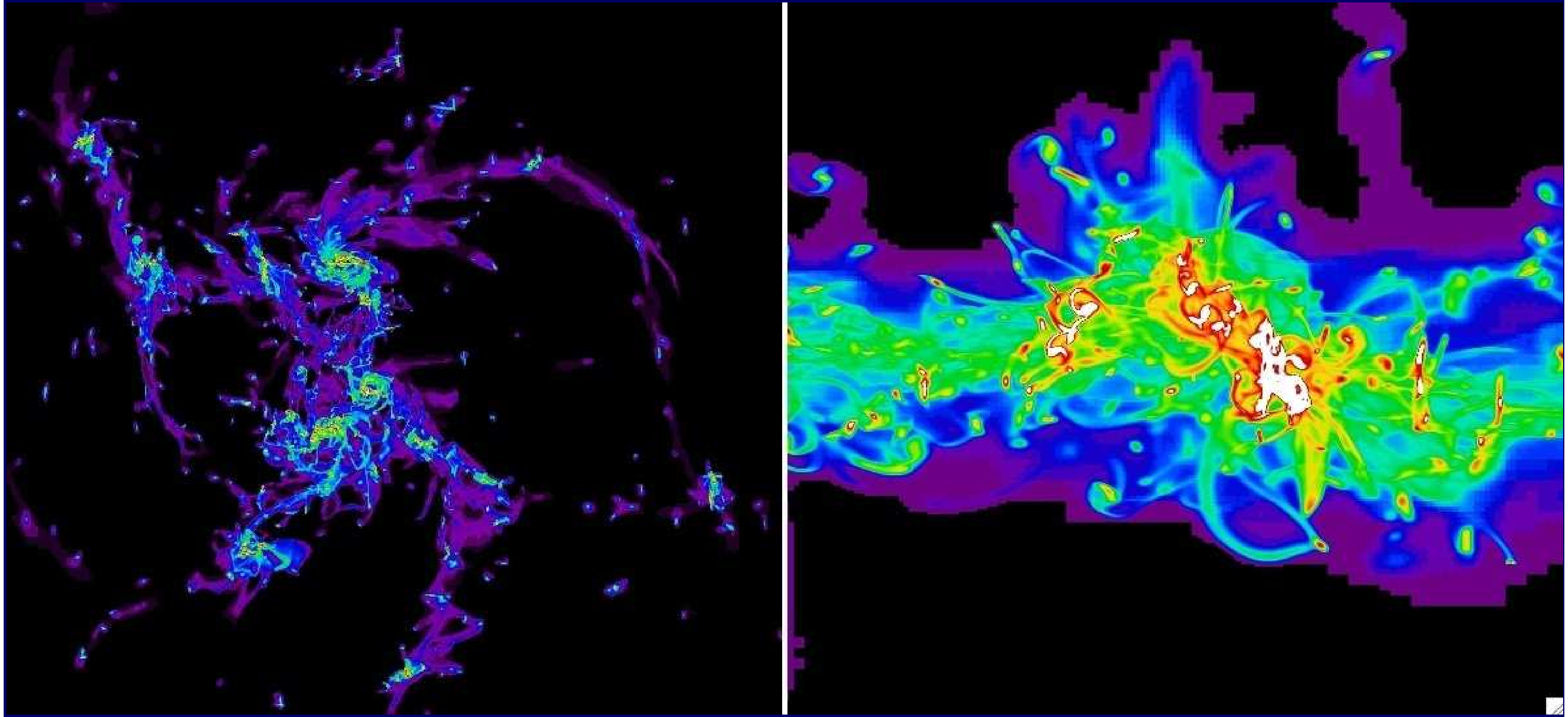
Dekel et al 09

SFR ~ inflow rate

Open issues:

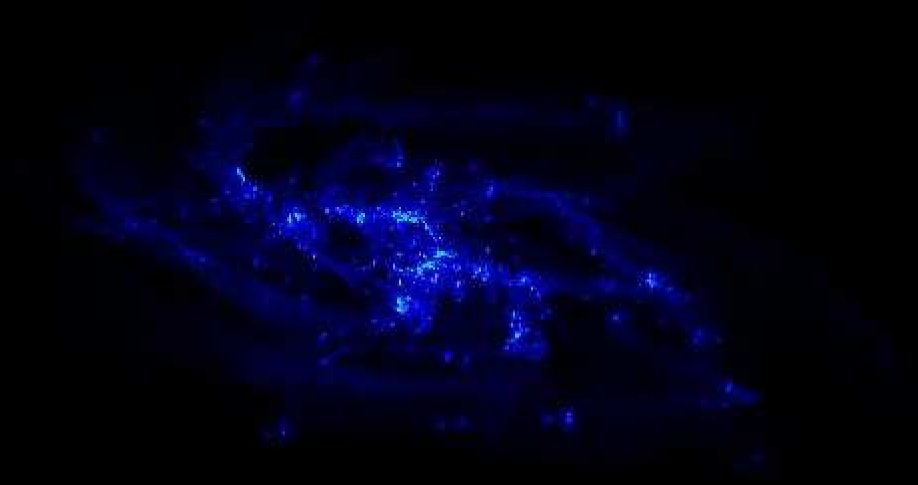
- Efficiency SFR/(Mg/td) ~ 1%
  → SF in sub-clumps
- Feedback & clump survival
  SN, radiative, AGN

Sub-structure in the disk giant clumps



Bournaud 09 AMR 2 pc resolution

Sub-structure in the disk



Bournaud 09; AMR 2 pc resolution

Survival of Giant Clumps

Murray et al. 09; Krumholz & Dekel 09

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

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

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

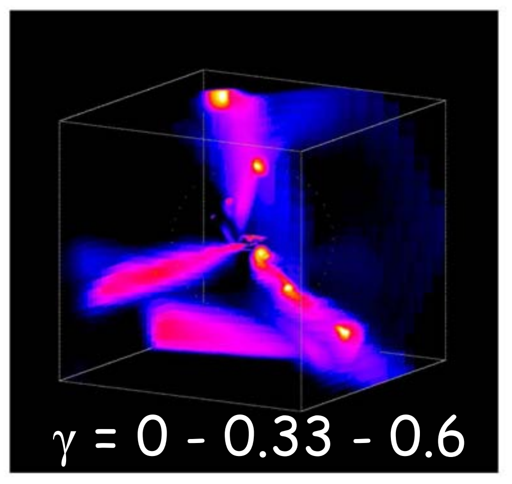
$$f_{\rm eject} \approx 0.08\, \varepsilon_{-2} (\Sigma_{-1} M_9)^{-1/4}$$

→ **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)

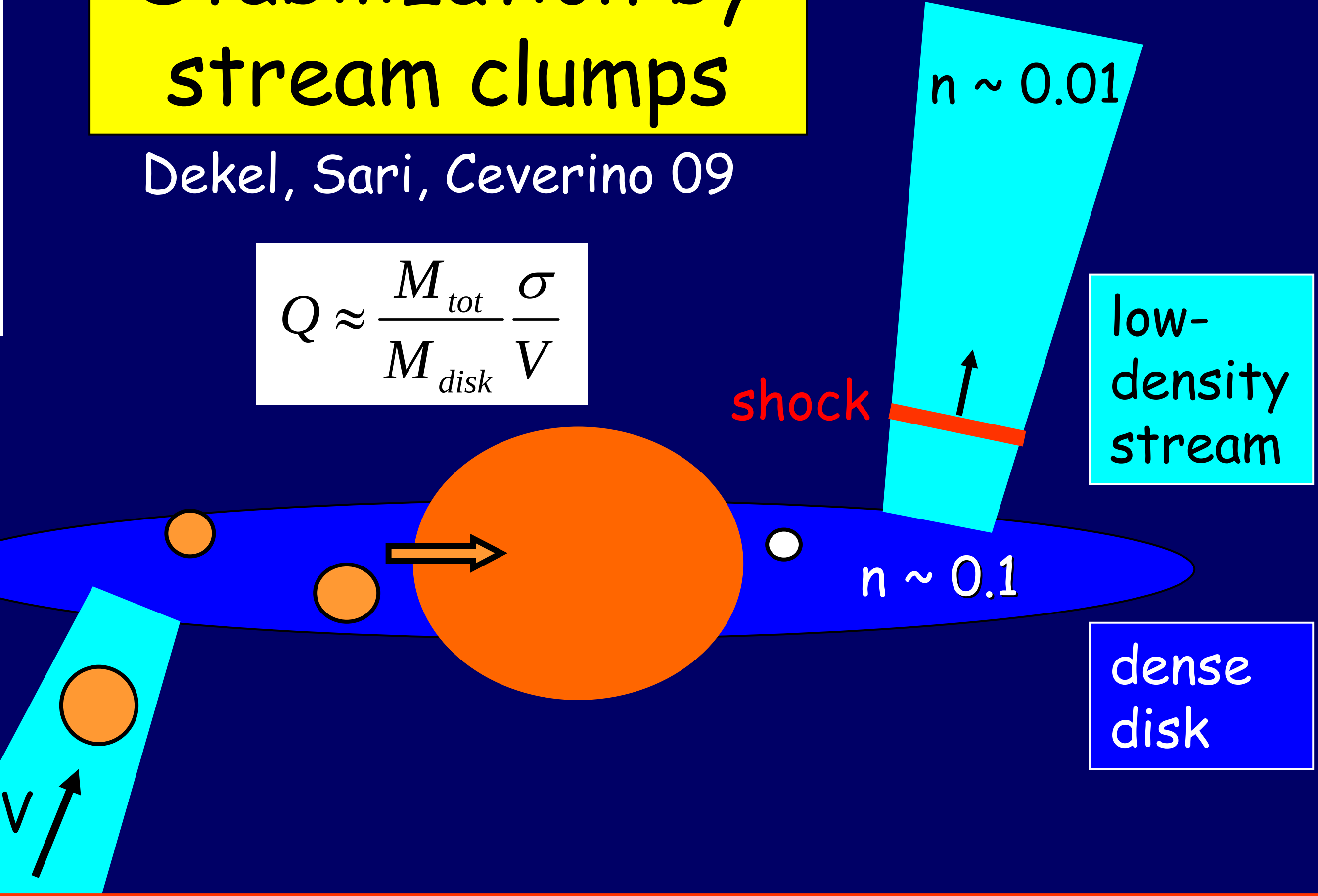
Bimodality blue-disk/red-spheroid at high z
driven by the degree of clumpiness in the streams



Stabilization by stream clumps

Dekel, Sari, Ceverino 09

$$Q \approx \frac{M_{tot}}{M_{disk}} \frac{\sigma}{V}$$



- Stabilization Q>1 due to bulge growth & turbulence ...driven by clumpy streams

- Cosmological stable steady state for $M_{disk}/M_{tot}<0.3$
  → Bimodality at high z

12. Disk Stabilization – SF Quenching

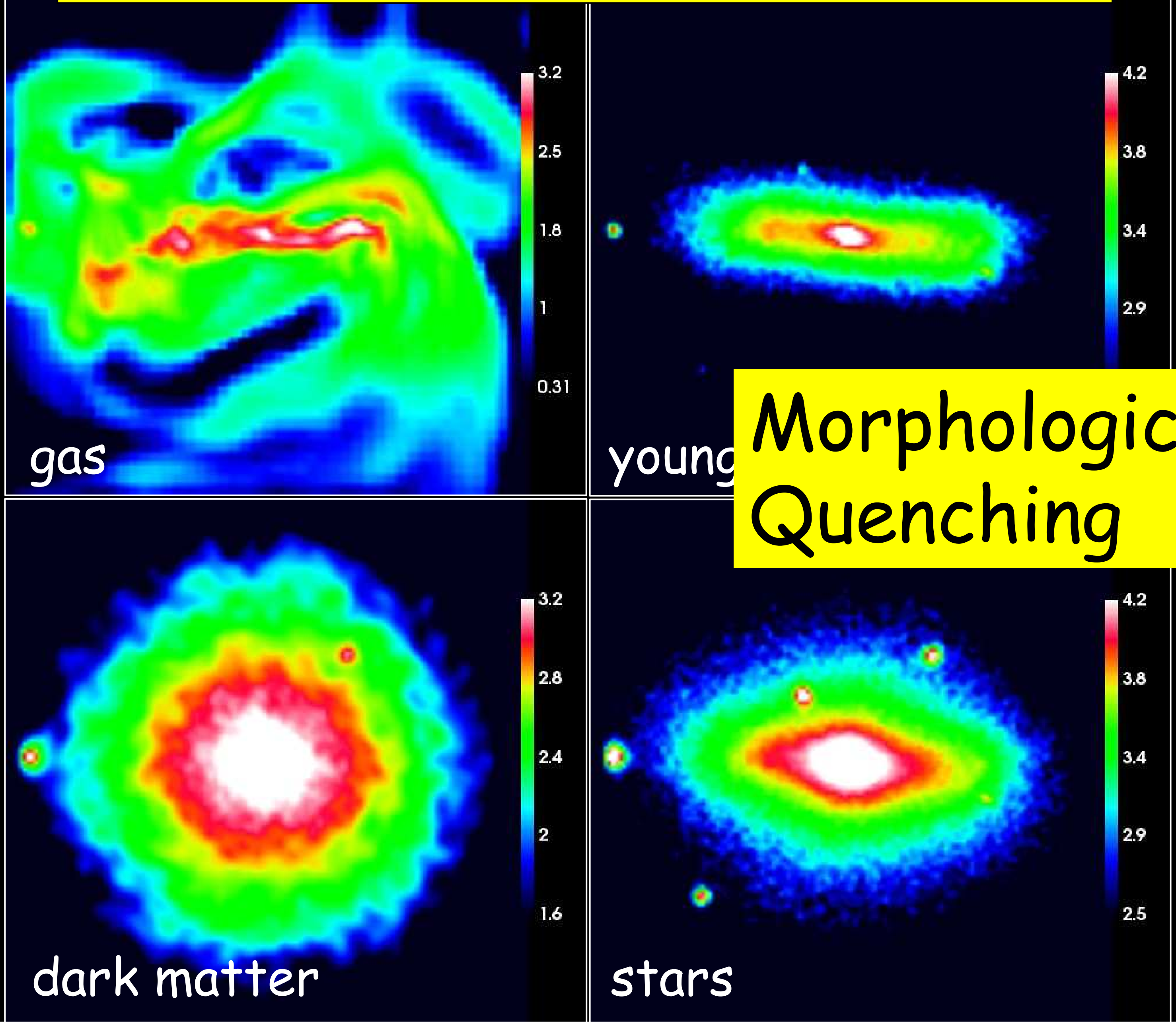
- Dominant bulge – Morpholopgical quenching
- Excessive turbulence by external sources: clumpy streams, feedback
- Low accretion rate (e.g. at late times)
- Low gas fraction (e.g. today's spirals)

Martig
et al 09

Relation to today's galaxies ?

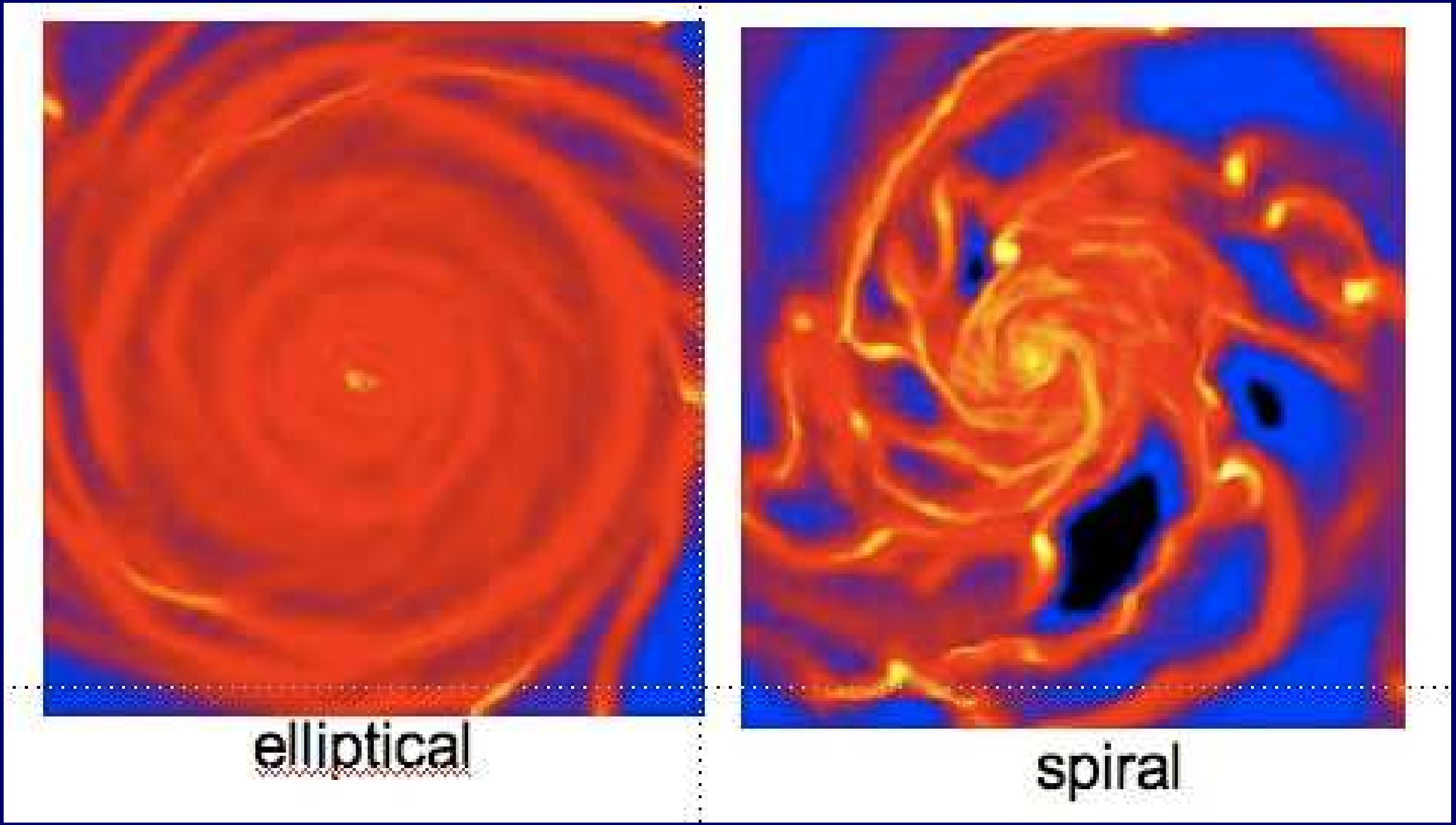
- The descendants of the high-z clumpy disks are probably S0s and rotating Es, or thick disks of spirals
- Thin disks form later by slow accretion

Massive Bulge - Stable Disk



Morphological Quenching

Morphological Quenching: disk stabilization by a bulge



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

Key Theoretical Issues

1. Cosmic web
2. Accretion rate
2. Virial shock heating
4. Cold streams
5. Lyman-alpha blobs
6. Stream clumpiness: mergers
7. Rotation vs dispersion: angular momentum & feedback
8. Disk instability
9. Cosmological steady state
10. SFR in disk clumps
11. Spheroid formation
12. Stabilization – SF quenching.
    Descendants at $z=0$