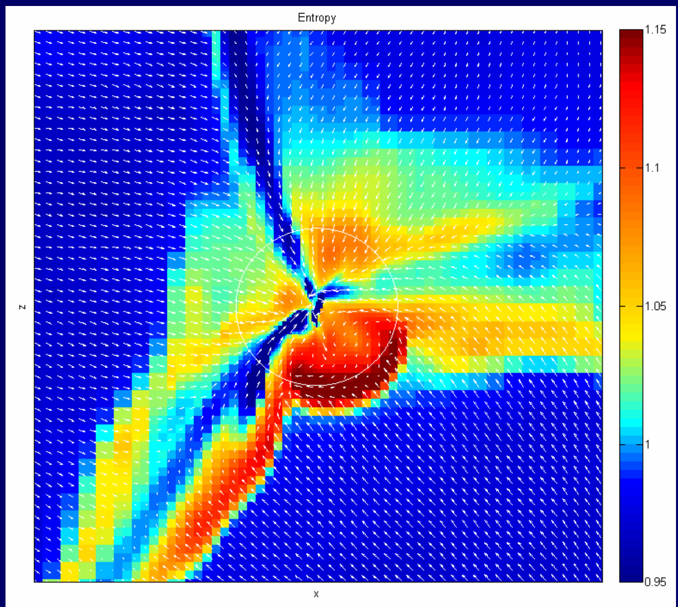
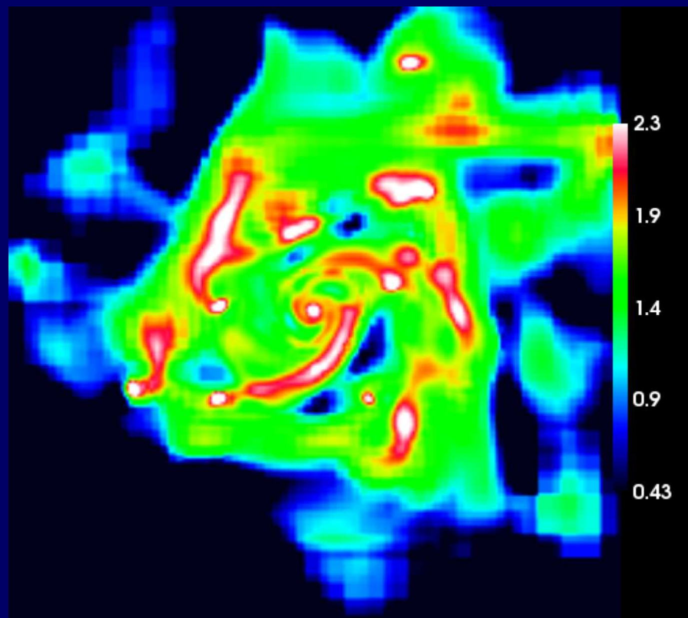
Galaxy Formation at High Redshift:

Cold Streams, Clumpy Disks & Compact Spheroids

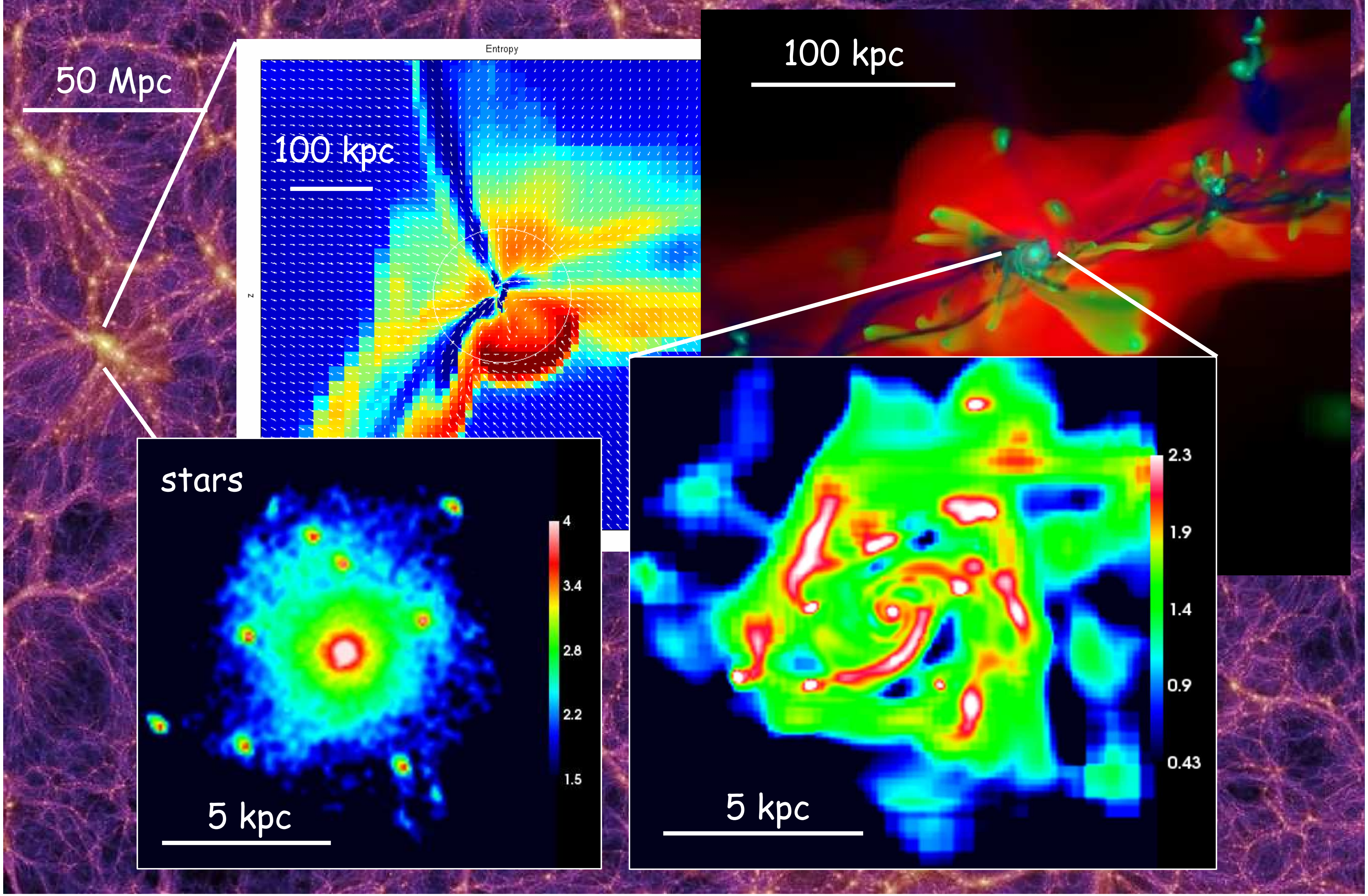
Avishai Dekel, HU Jerusalem

SFR@50, July 2009





Galaxies Emerge from the Cosmic Web



Collaborators

Simulations:
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HU Team:
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R. Sari (HU)
E. Zinger (HU)

Outline

- Star-forming disks and quenched ellipticals at high redshift. mergers?

- Feeding massive galaxies by cold streams
  inflow rate vs SFR, smooth flows vs mergers

- Disk fragmentation & bulge formation
  steady state, migration to a bulge, star formation, stabilization by clumpy streams

- Origin of bimodality at high redshift

1. Observed Bimodality at High z

in ~$10^{11}M_\odot$ galaxies at z~2-3:

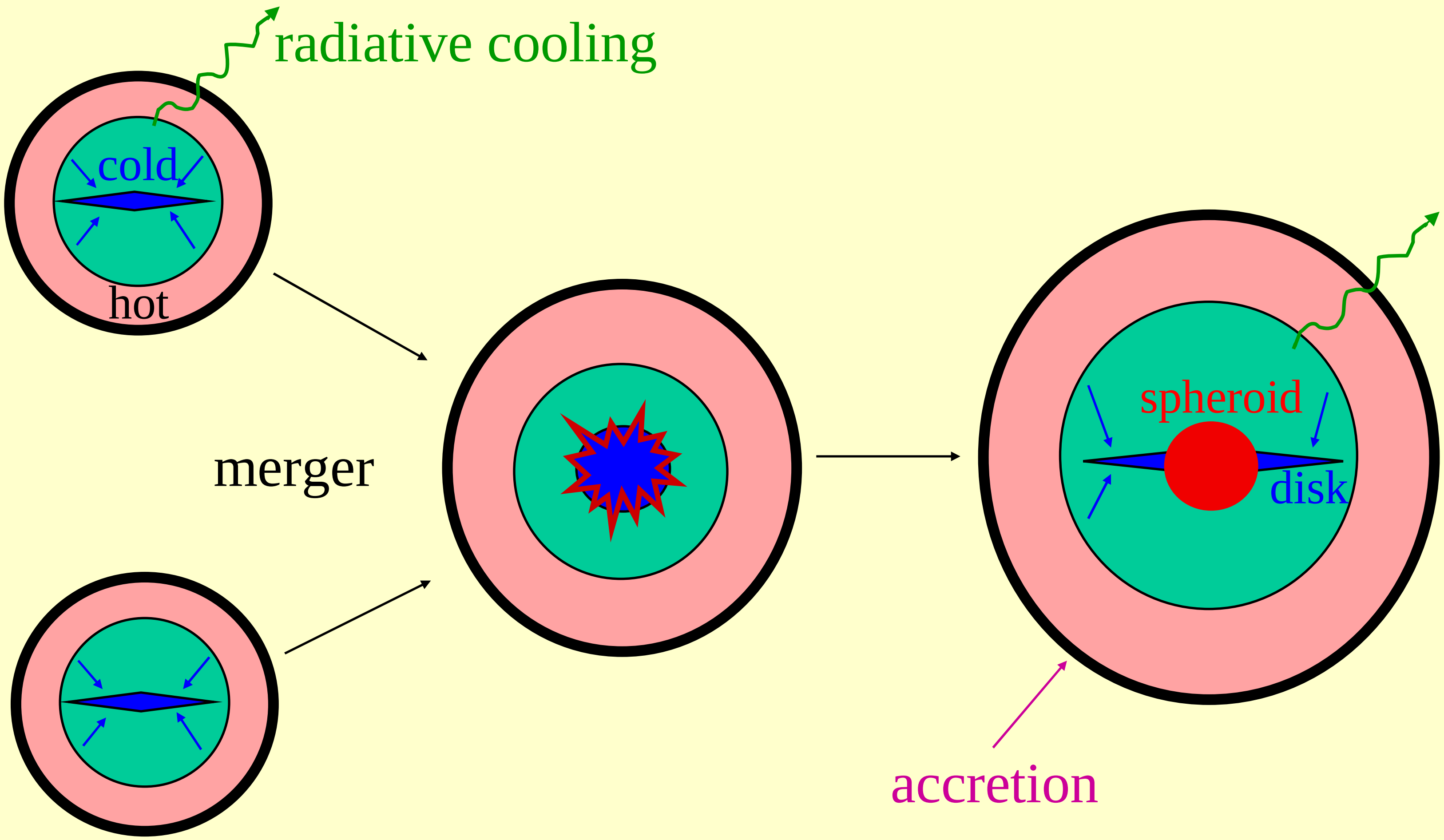
Intense star formers: SFR~150 $M_\odot yr^{-1}$
clumpy, rotating, extended, gaseous disks

Suppressed SFR in compact spheroids

Major mergers? starbursts & spheroids

TJ Cox

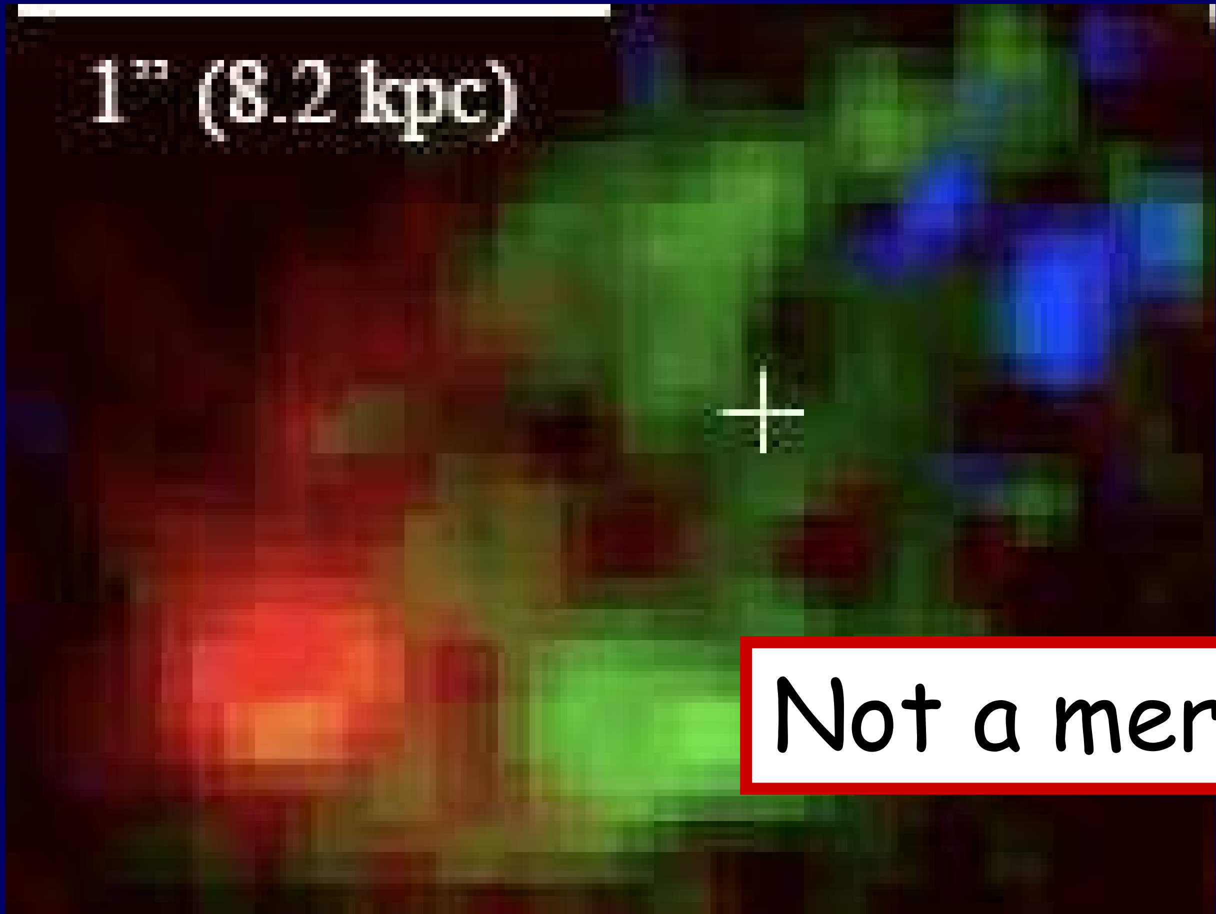
Standard Paradigm: Mergers



halos cold gas → young stars → old stars

Gas removal by QSOs leads to red-and-dead Ellipticals

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

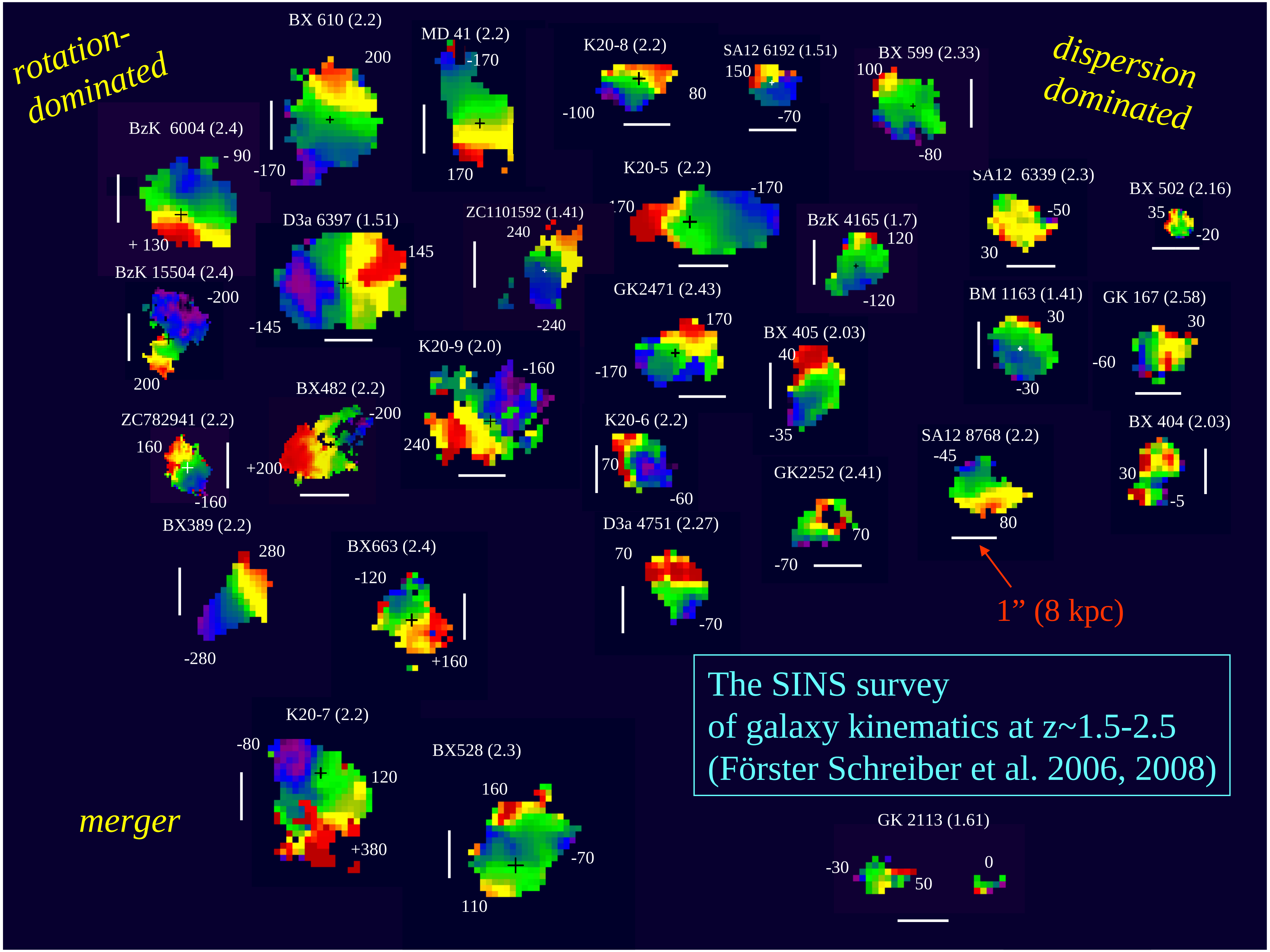


Hα star-form regions

color-code velocity field

Not a merger!

Genzel et al 08


rotation-dominated
dispersion dominated
merger
BX 610 (2.2)
200
-170
MD 41 (2.2)
-170
170
K20-8 (2.2)
80
-100
SA12 6192 (1.51)
150
-70
BX 599 (2.33)
100
-80
BzK 6004 (2.4)
- 90
+ 130
K20-5 (2.2)
-170
SA12 6339 (2.3)
-50
30
BX 502 (2.16)
35
-20
D3a 6397 (1.51)
145
-145
ZC1101592 (1.41)
240
-240
BzK 4165 (1.7)
120
-120
BzK 15504 (2.4)
-200
200
GK2471 (2.43)
170
-170
BM 1163 (1.41)
30
-30
GK 167 (2.58)
30
-60
K20-9 (2.0)
-160
240
BX 405 (2.03)
40
-35
BX482 (2.2)
-200
+200
ZC782941 (2.2)
160
-160
K20-6 (2.2)
70
-60
SA12 8768 (2.2)
-45
80
BX 404 (2.03)
30
-5
GK2252 (2.41)
70
-70
BX389 (2.2)
280
-280
BX663 (2.4)
-120
+160
D3a 4751 (2.27)
70
-70
1” (8 kpc)
The SINS survey
of galaxy kinematics at z~1.5-2.5
(Förster Schreiber et al. 2006, 2008)
K20-7 (2.2)
-80
120
+380
BX528 (2.3)
160
-70
110
GK 2113 (1.61)
-30
50
0

Open Questions

- Efficient cold gas supply to massive galaxies ?
- High SFR not through major mergers ?
- Clumpy, extended, think disks ?
- Early formation of so many spheroids ?
- Suppression of SFR ?

2. Cold Streams
in Hot Massive Halos at High z

Birnboim & Dekel 2003

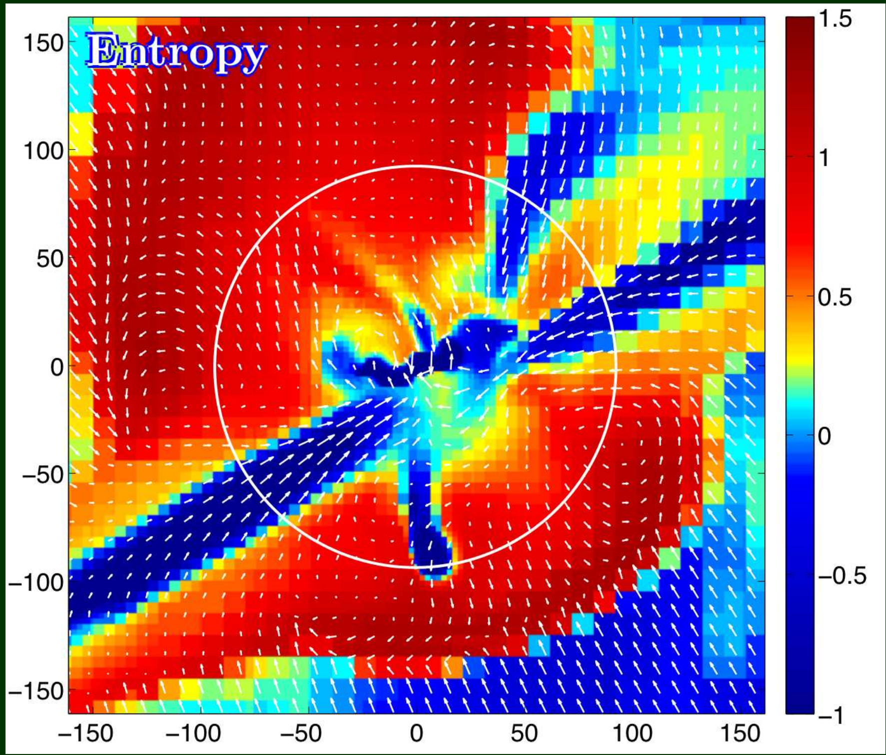
Keres et al. 2005

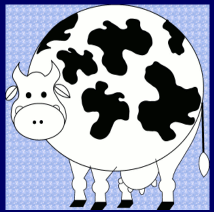
Dekel & Birnboim 2006

Keres et al. 2008

Ocvirk et al. 2008

Dekel et al. 2009, Nature



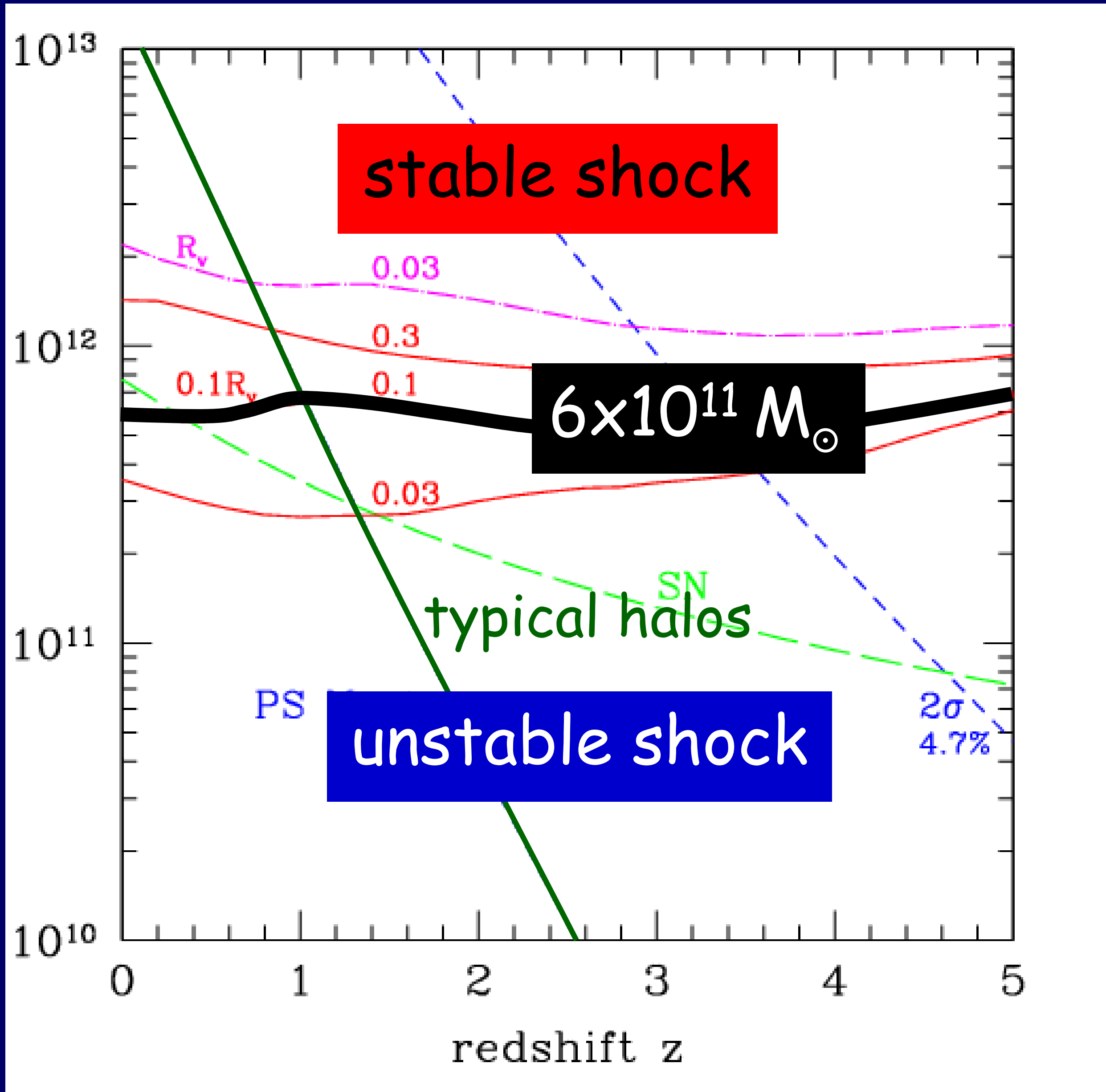


Shock-Heating Scale

Birnboim & Dekel 03
Dekel & Birnboim 06

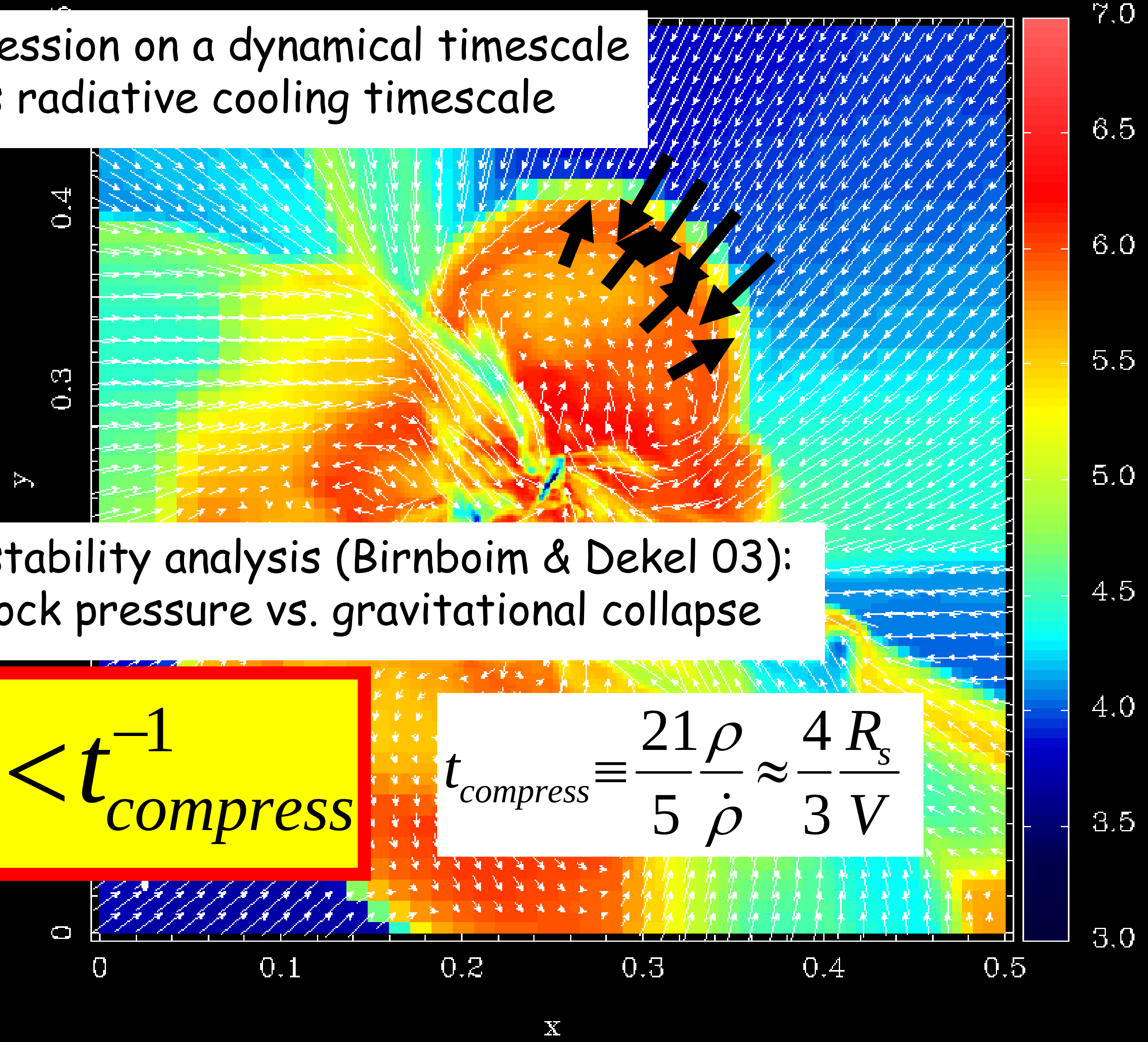
Keres
et al 05

M_{vir}
$[M_\odot]$



Gas through shock: heats to virial temperature

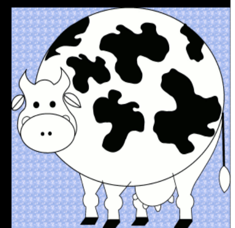
compression on a dynamical timescale
versus radiative cooling timescale



Shock-stability analysis (Birnboim & Dekel 03):
post-shock pressure vs. gravitational collapse

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

$$t_{compress} \equiv \frac{21}{5}\frac{\rho}{\dot{\rho}} \approx \frac{4}{3}\frac{R_s}{V}$$



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

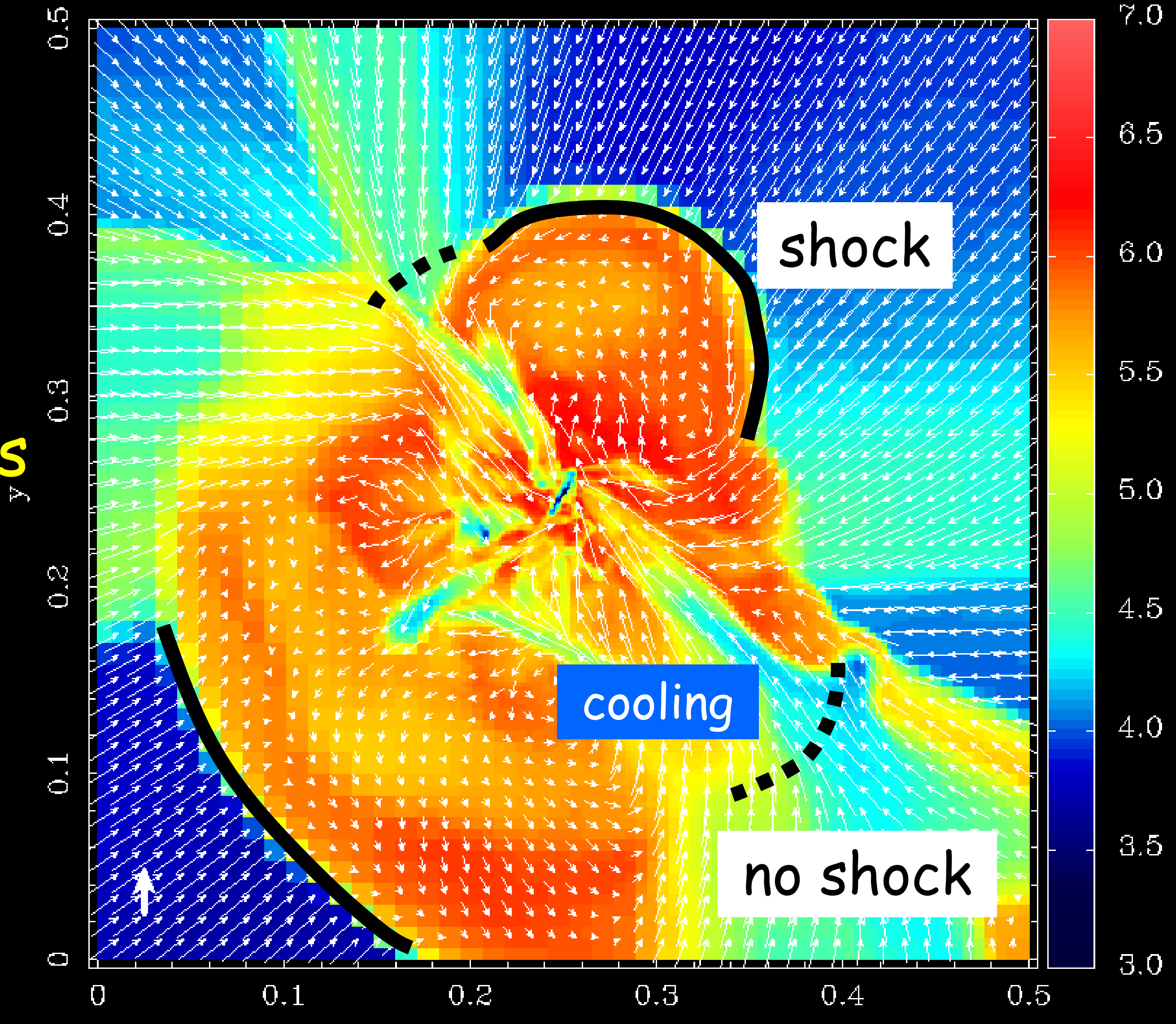
in $M > M_{shock}$

Totally hot at z<1

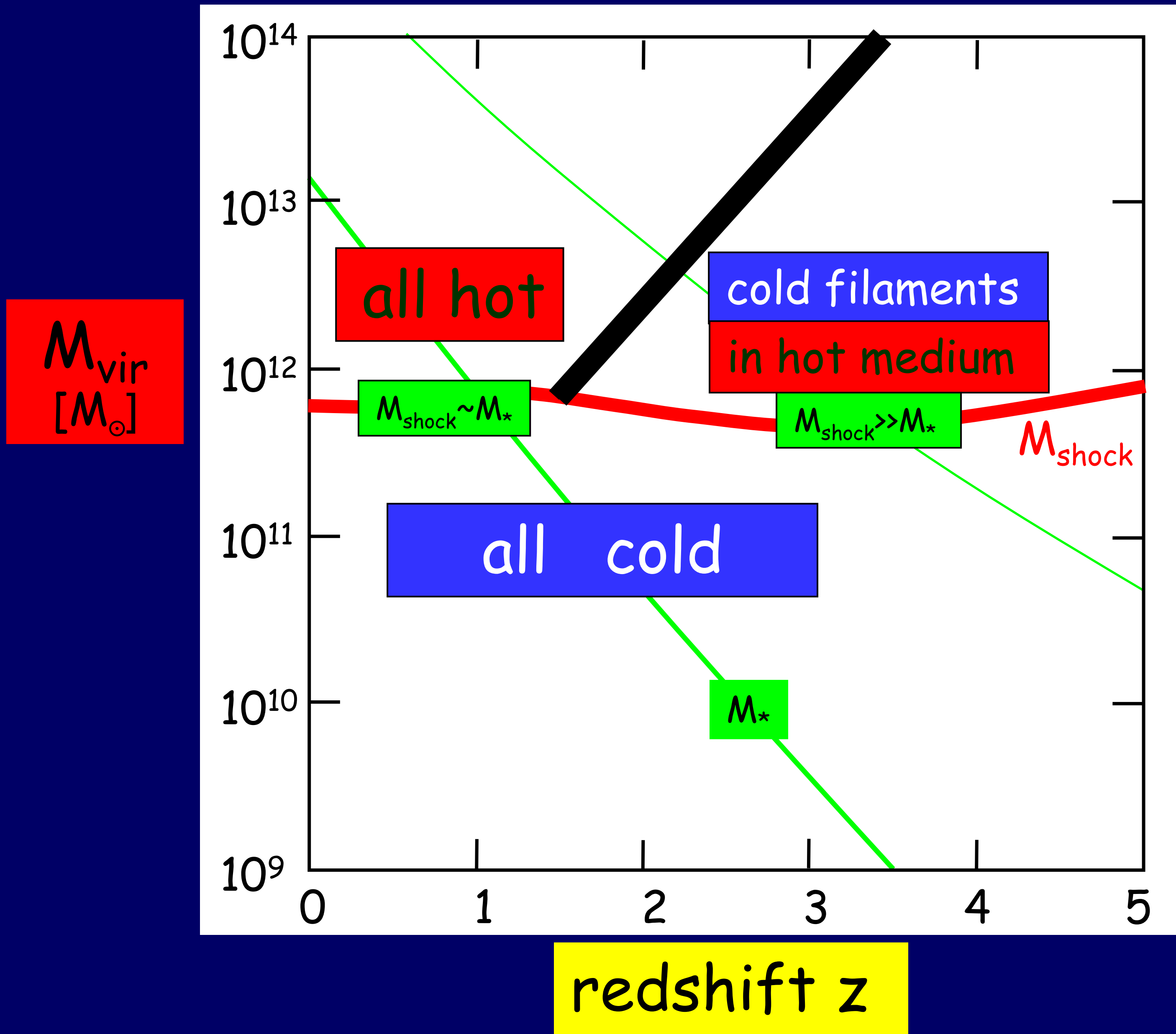
Cold streams at z>2

Dekel & Birnboim 2006

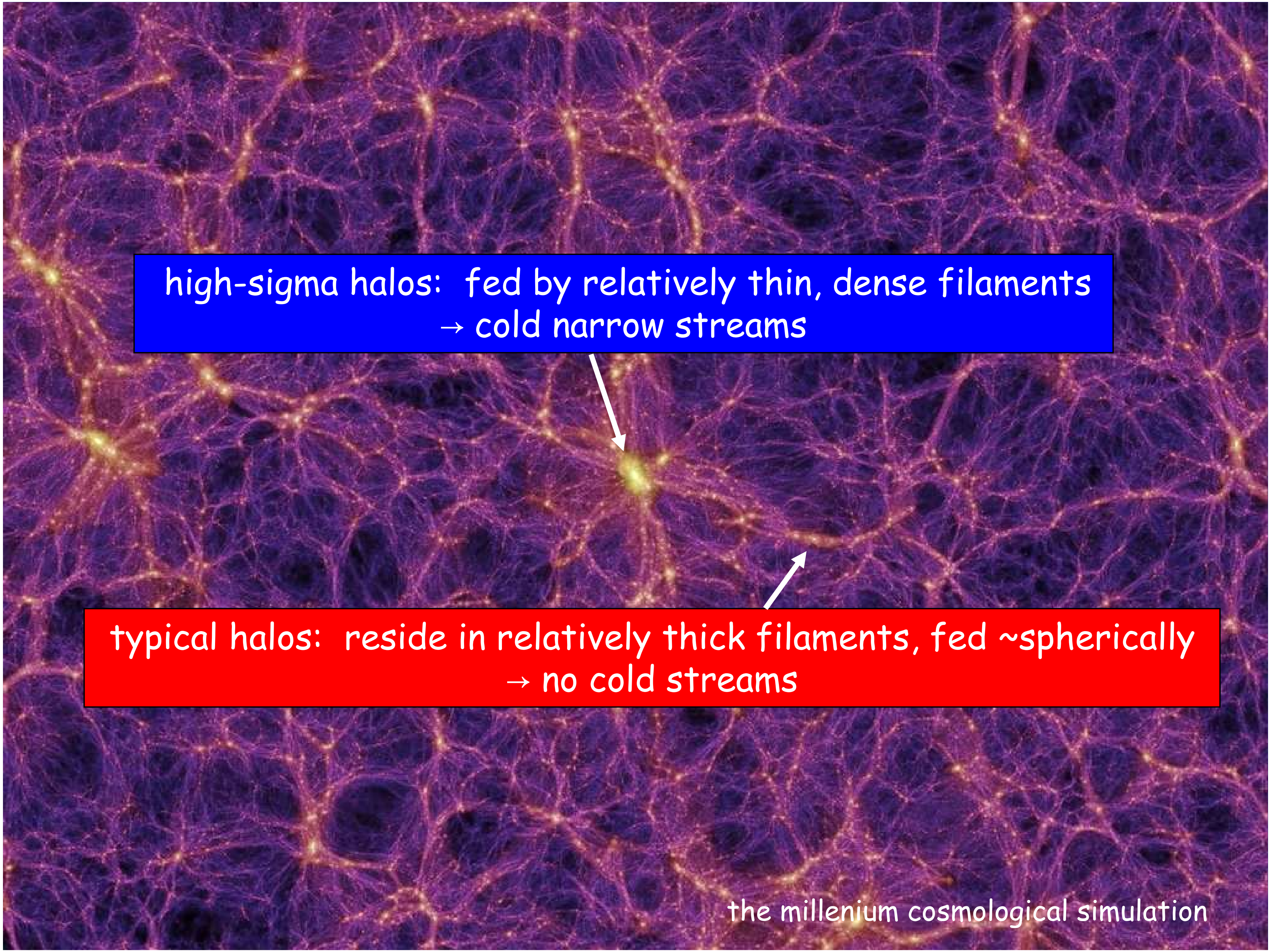
Kravtsov et al



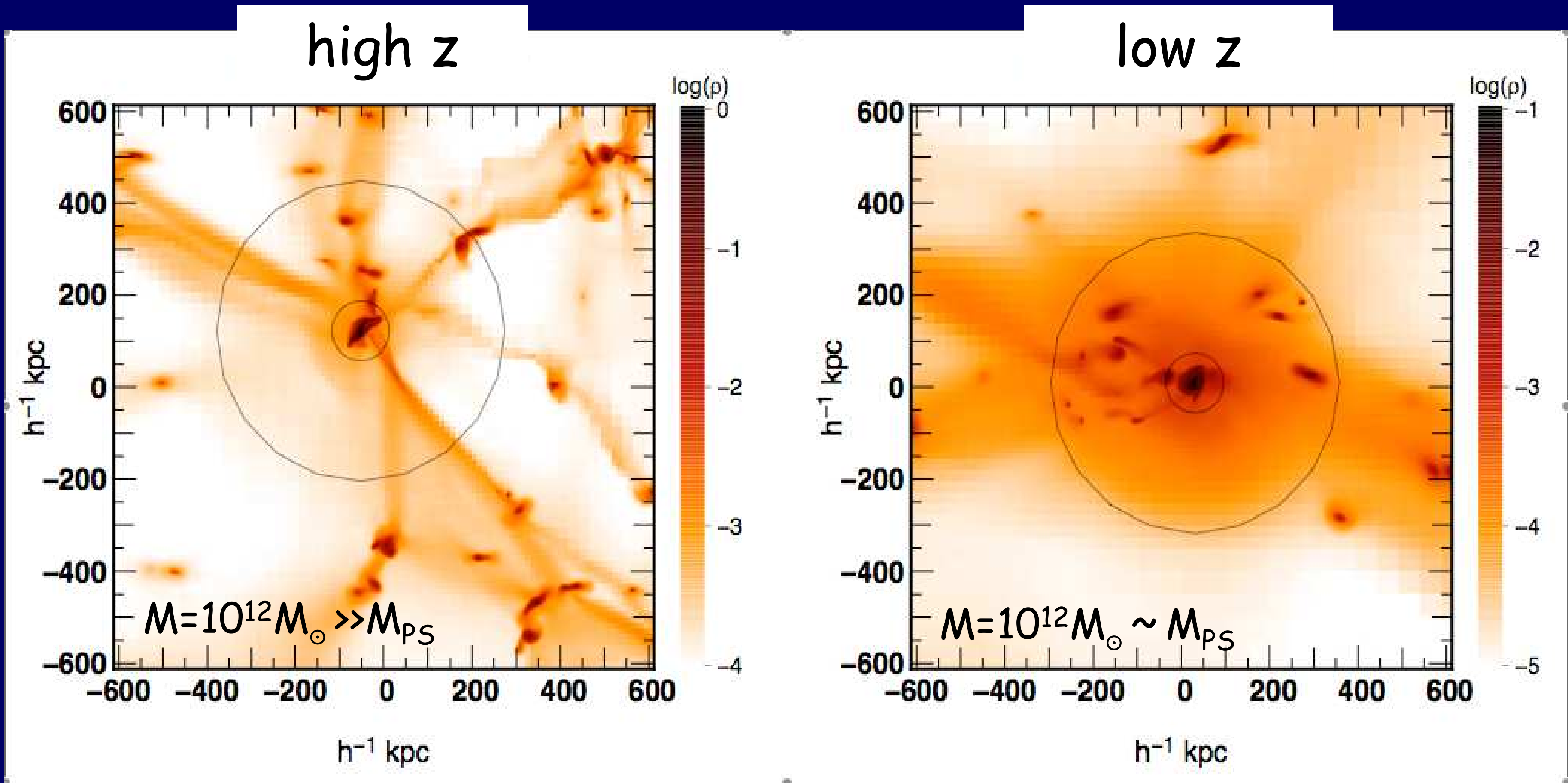
Cold Streams in Big Galaxies at High z



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

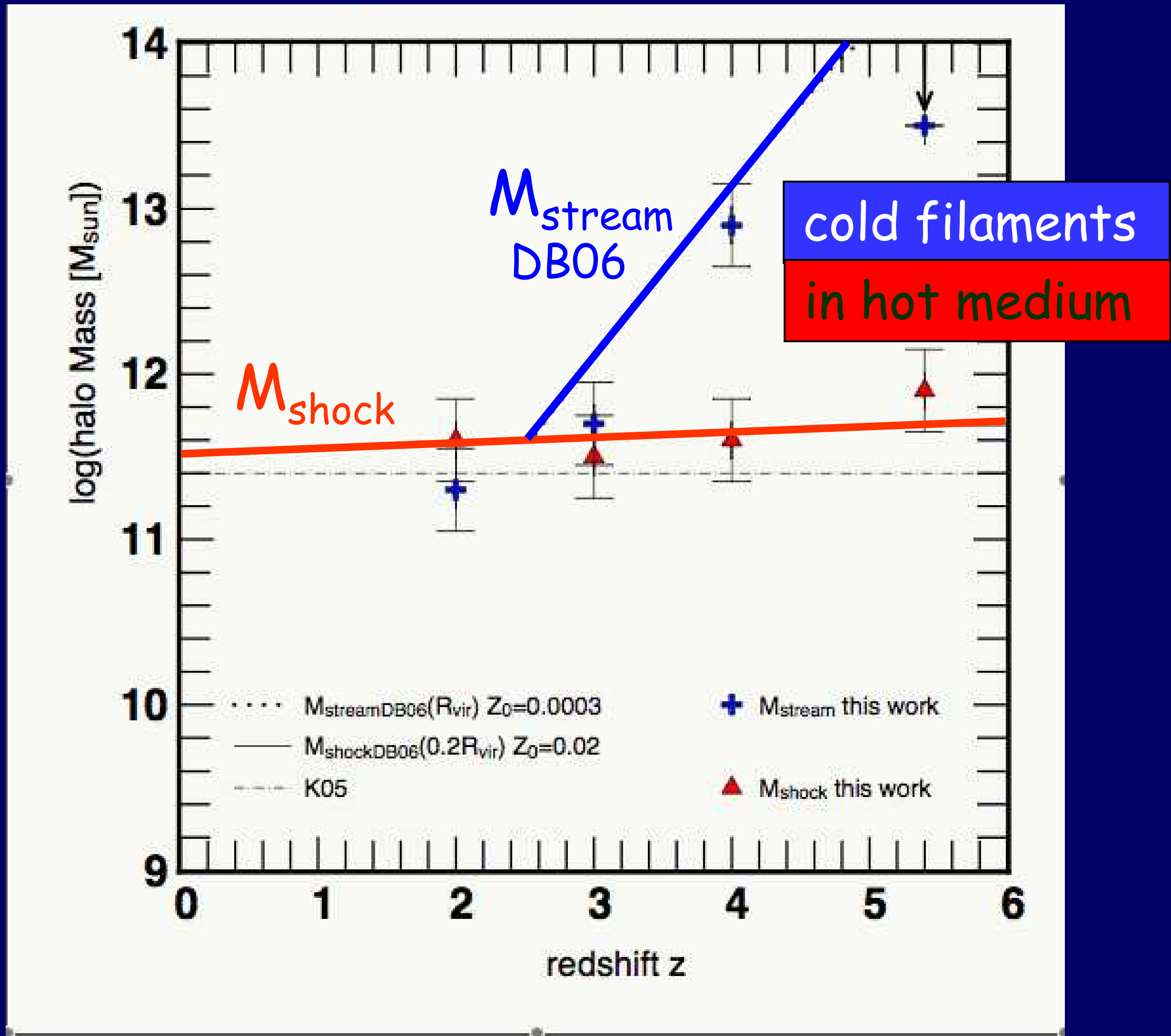
Gas Density in Massive Halos $2 \times 10^{12} M_\odot$



Ocvirk, Pichon, Teyssier 08

Critical Mass in Cosmological Simulations

Ocvirk, Pichon, Teyssier 08



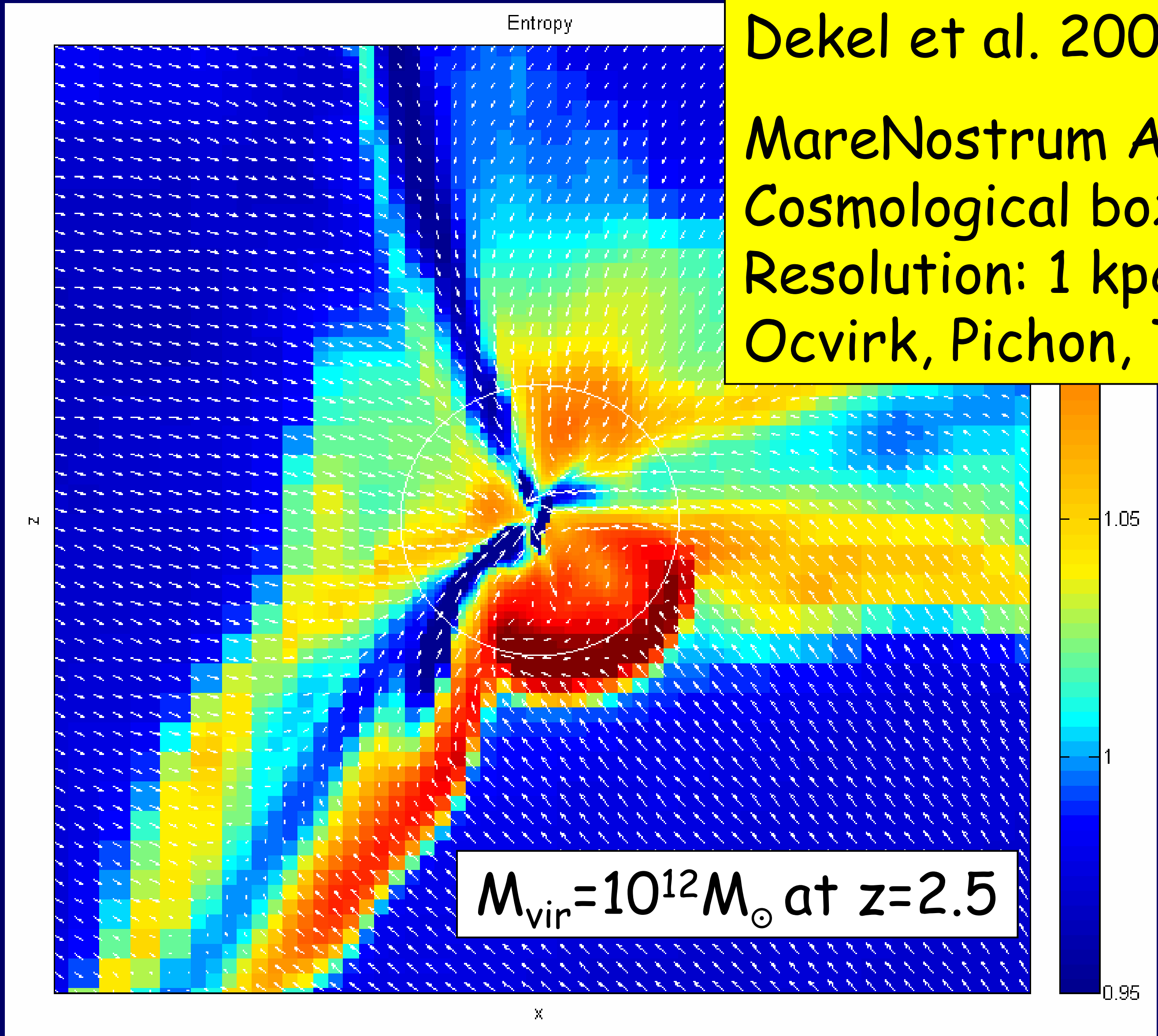
Stream Properties

Dekel et al. 2009, Nature

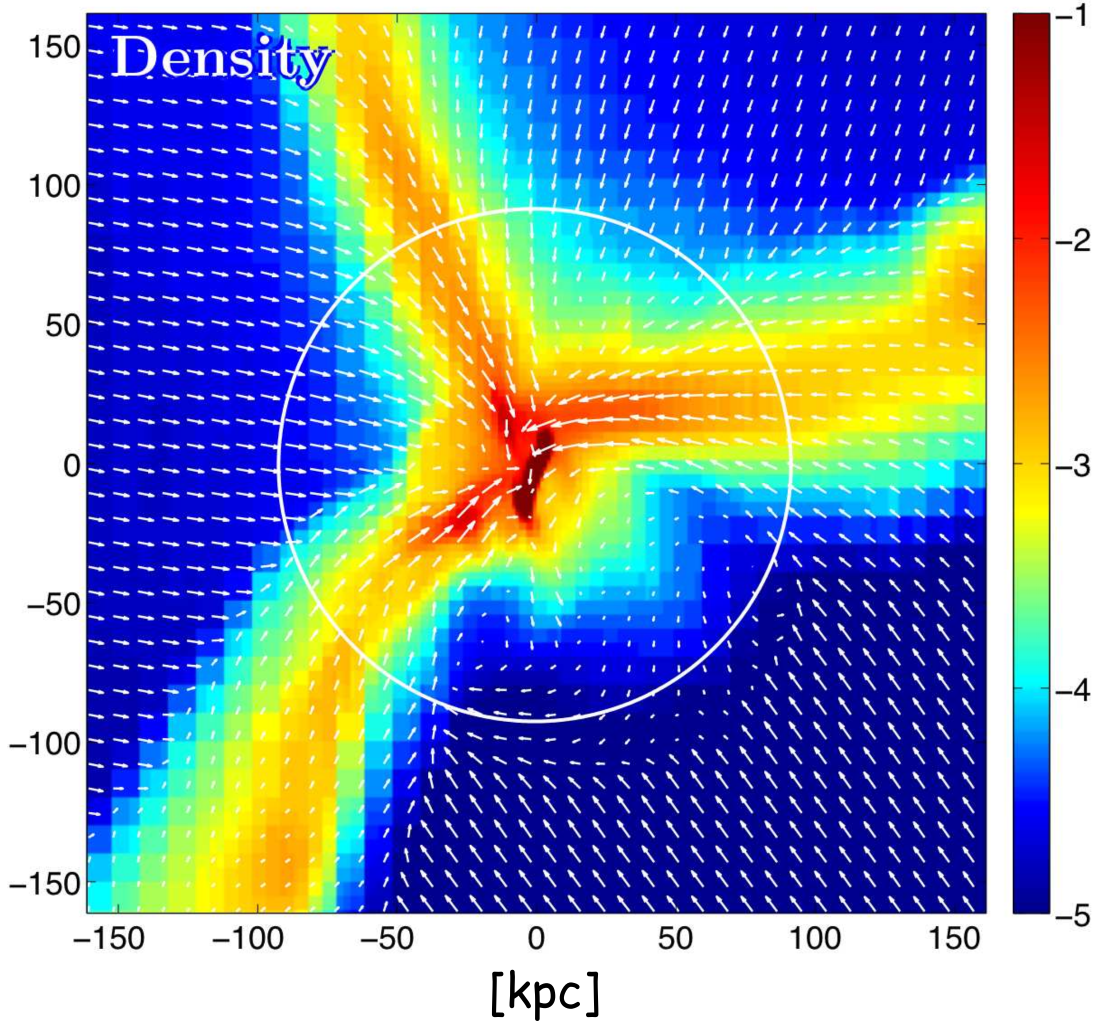
Massive high-z disks by cold narrow streams

Dekel et al. 2009, Nature

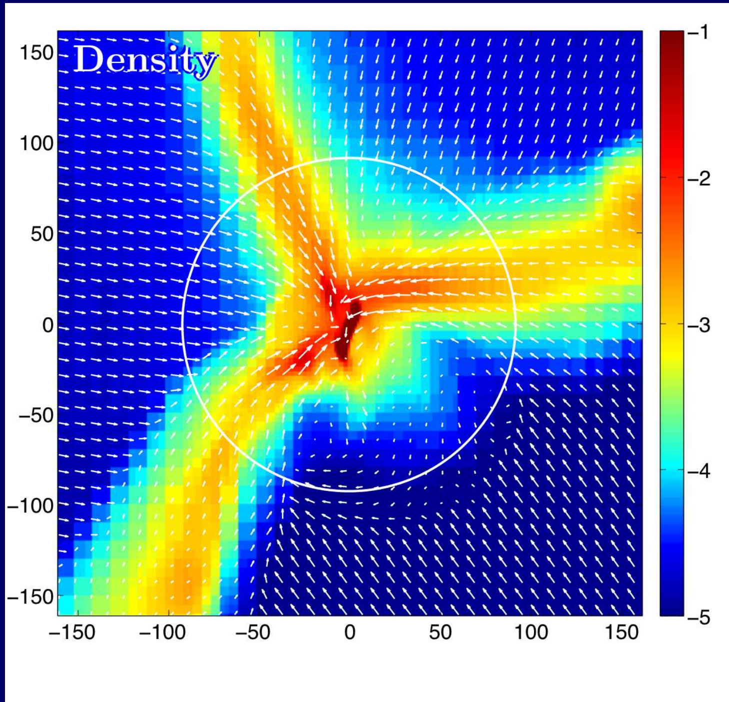
MareNostrum AMR simulation
Cosmological box: 50 Mpc
Resolution: 1 kpc
Ocvirk, Pichon, Teyssier 2008



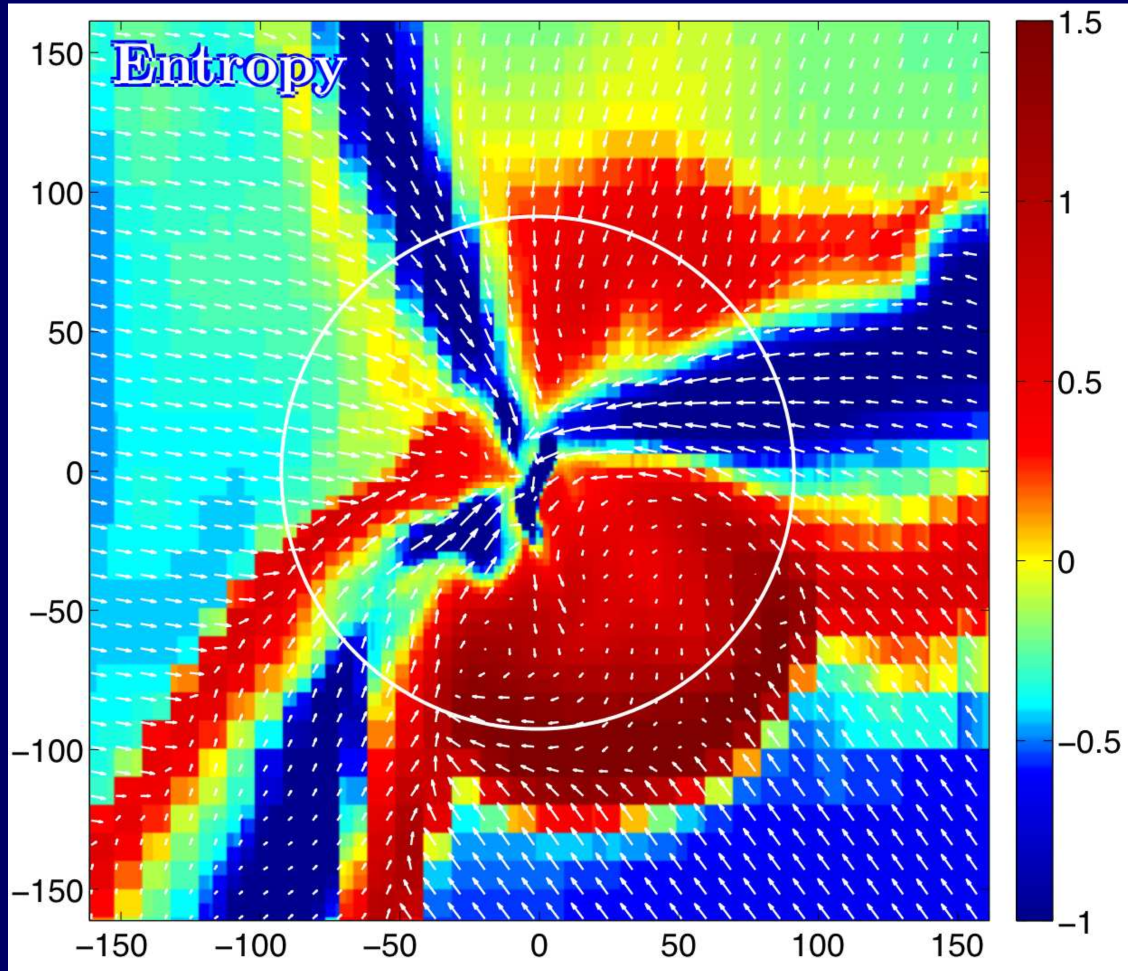
Gas density: following dark-matter filaments



Entropy: virial shock & low-entropy streams

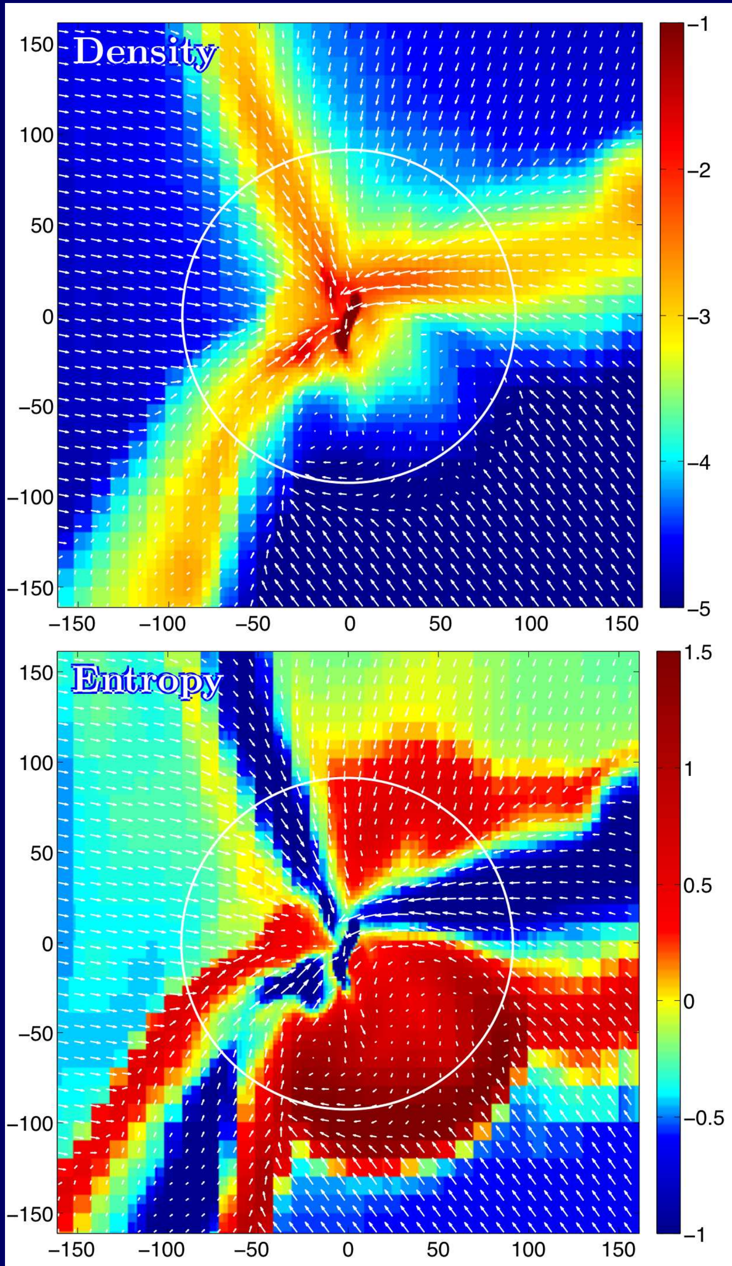


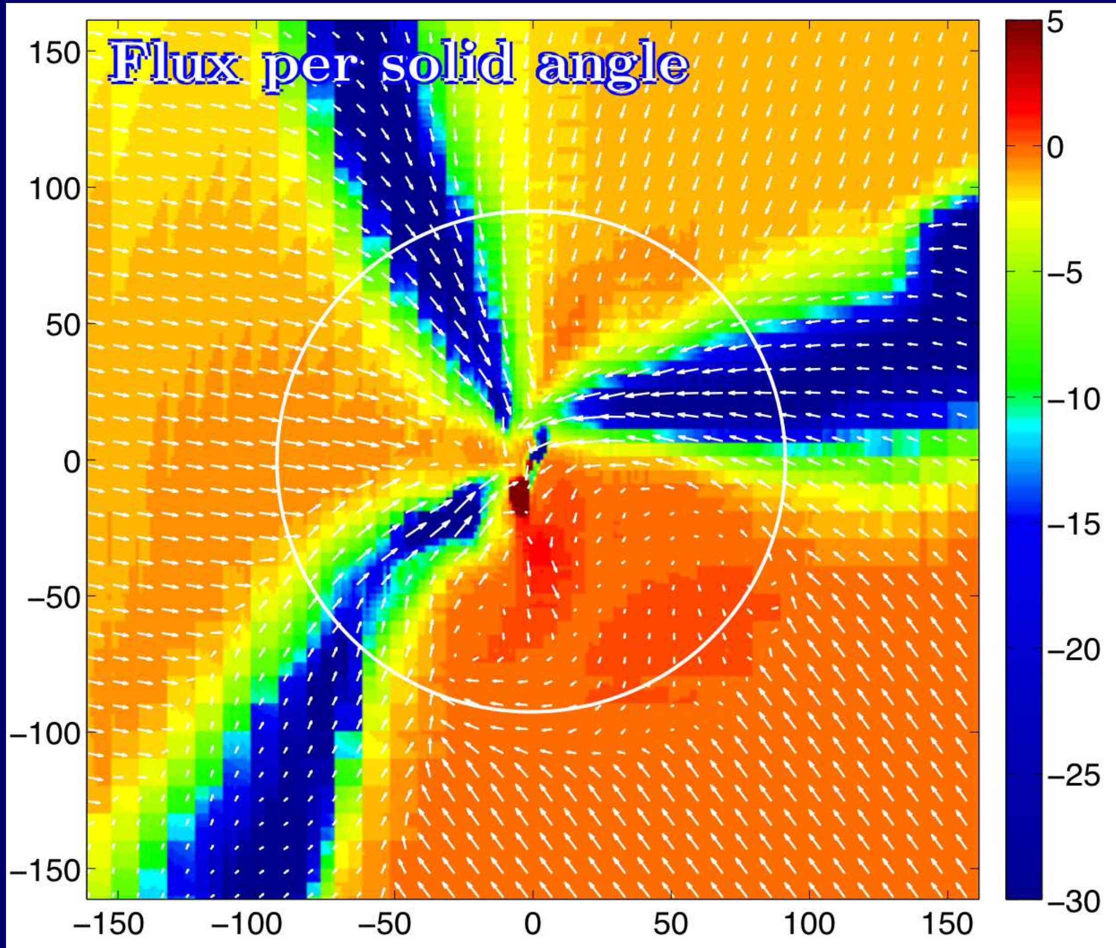
$\log(T/\rho^{2/3})$



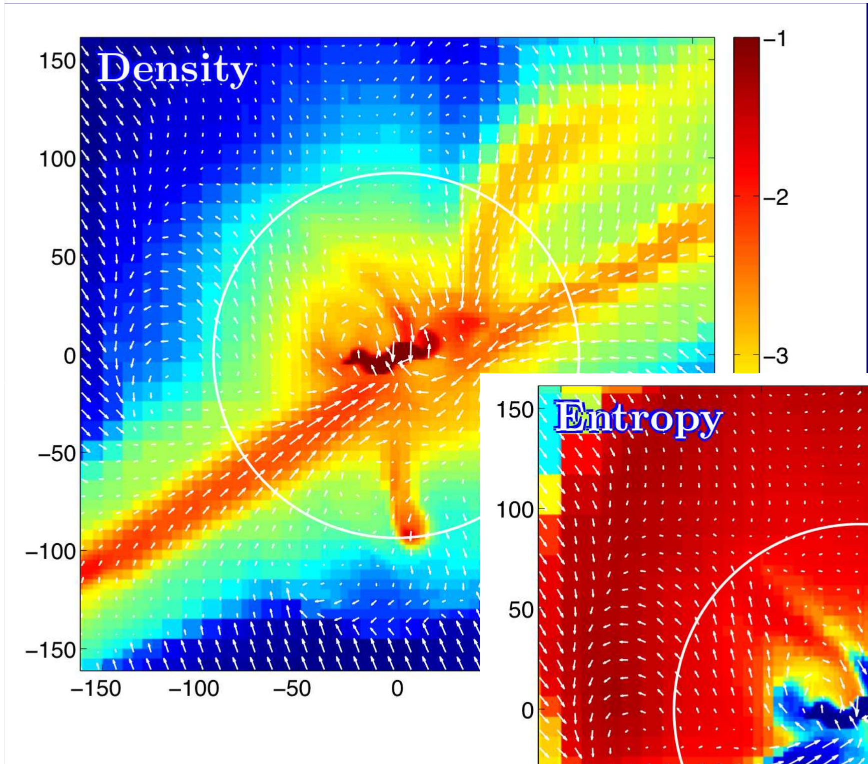
Inward gas flux: all in the streams

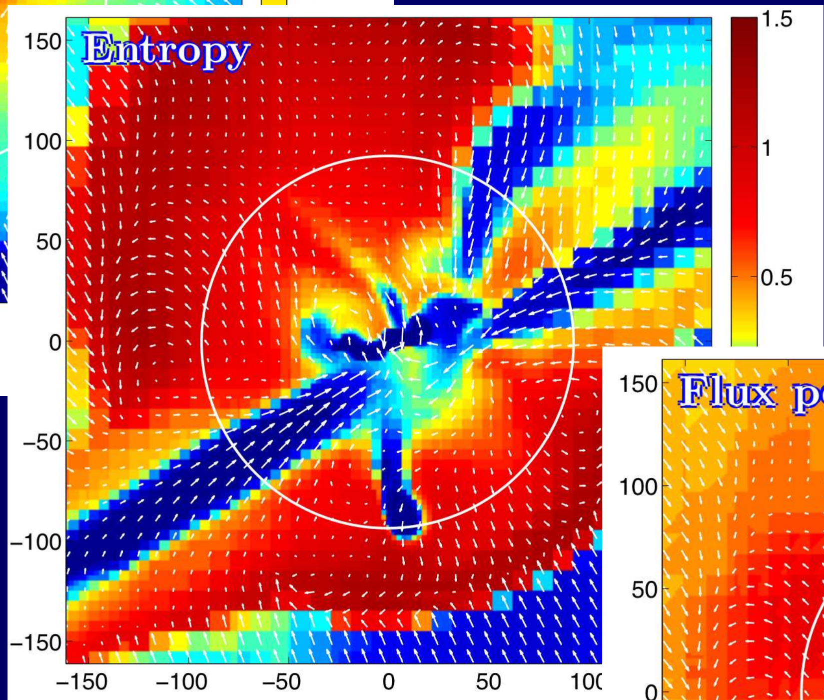
$$\dot{m} = \rho v_r r^2 [M_{\otimes}\, yr^{-1}\, rad^{-2}]$$

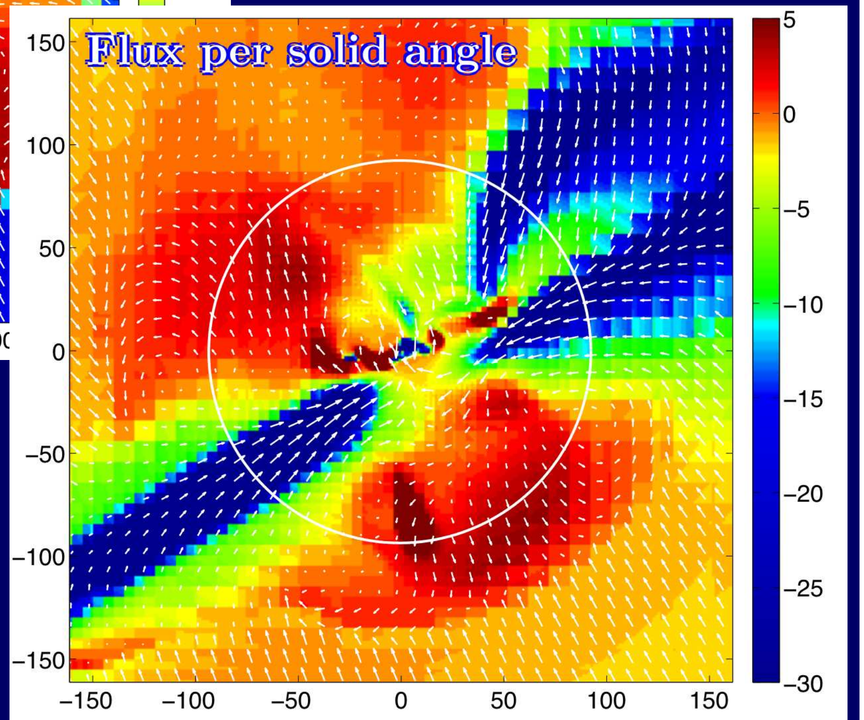




Another example

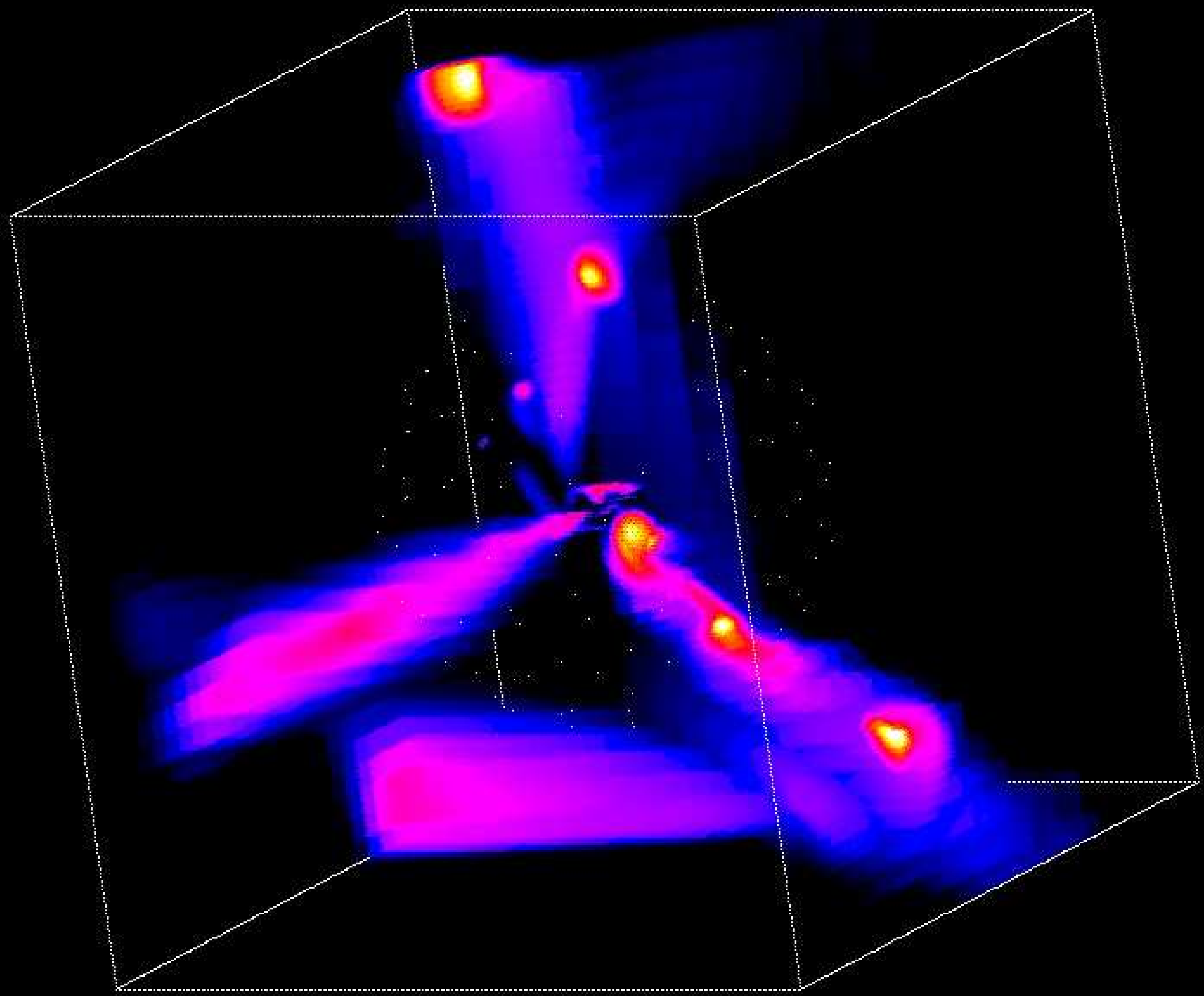




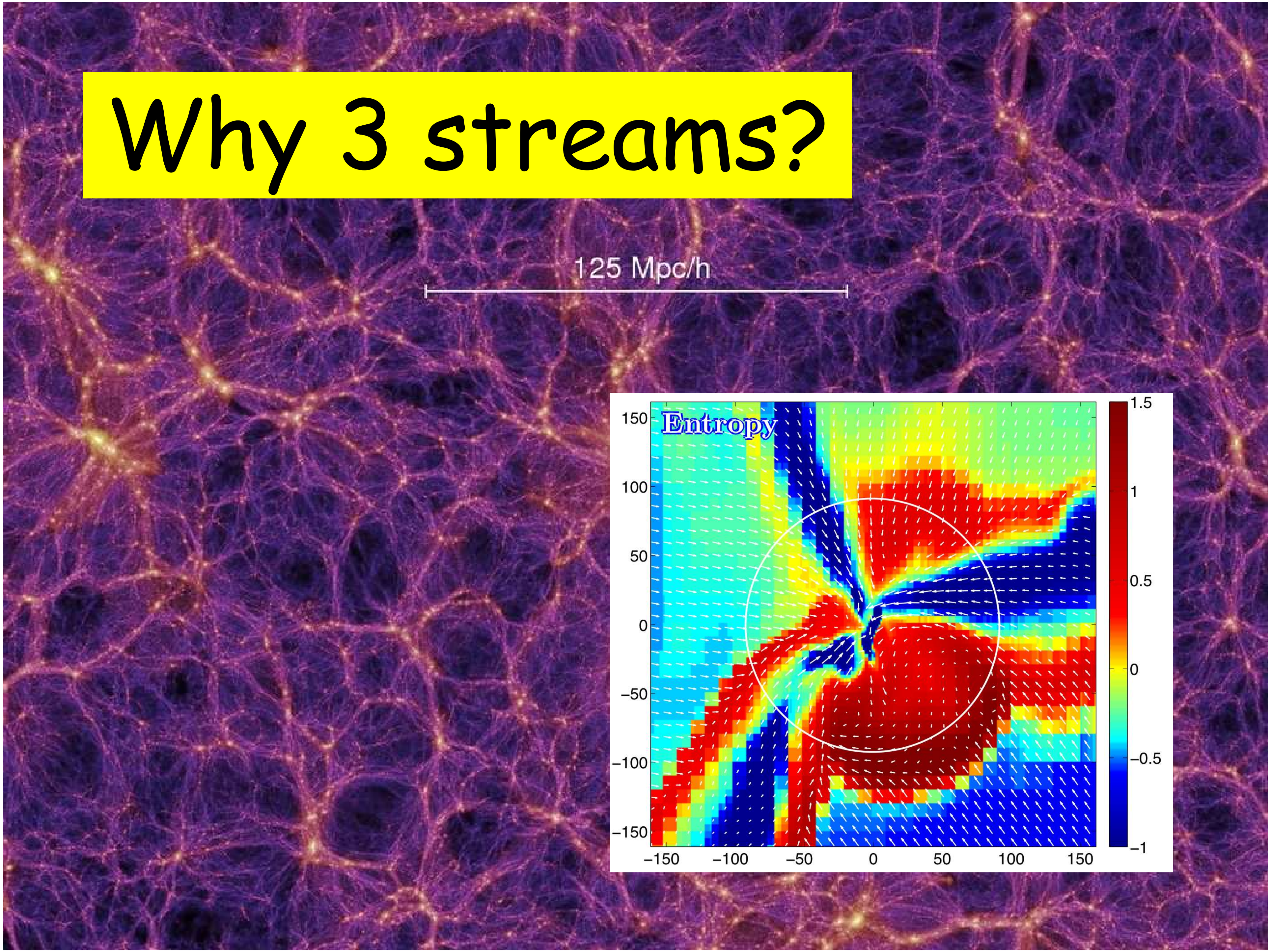


Always 3 streams?

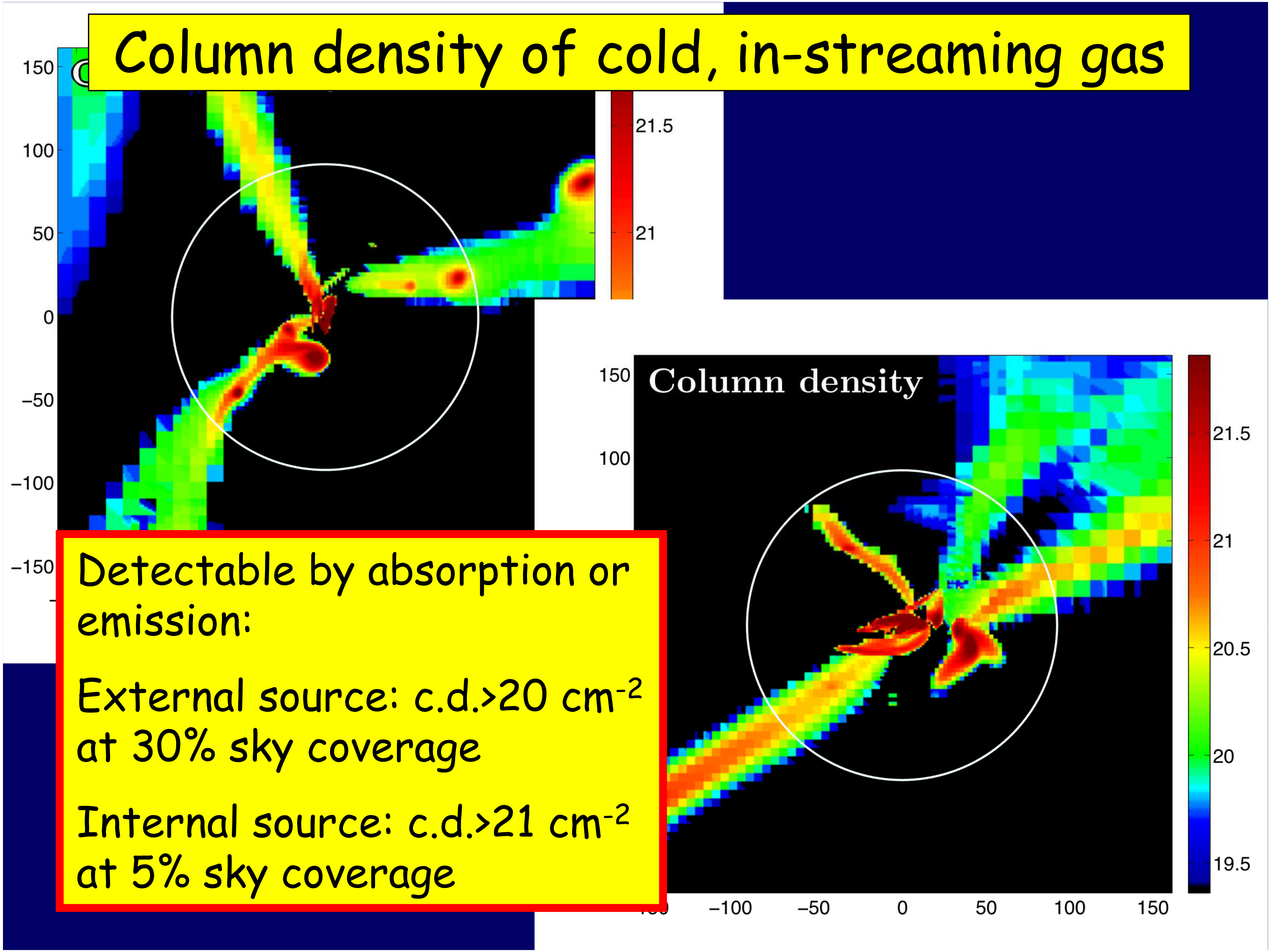
Flux per solid angle



Why 3 streams?



Column density of cold, in-streaming gas

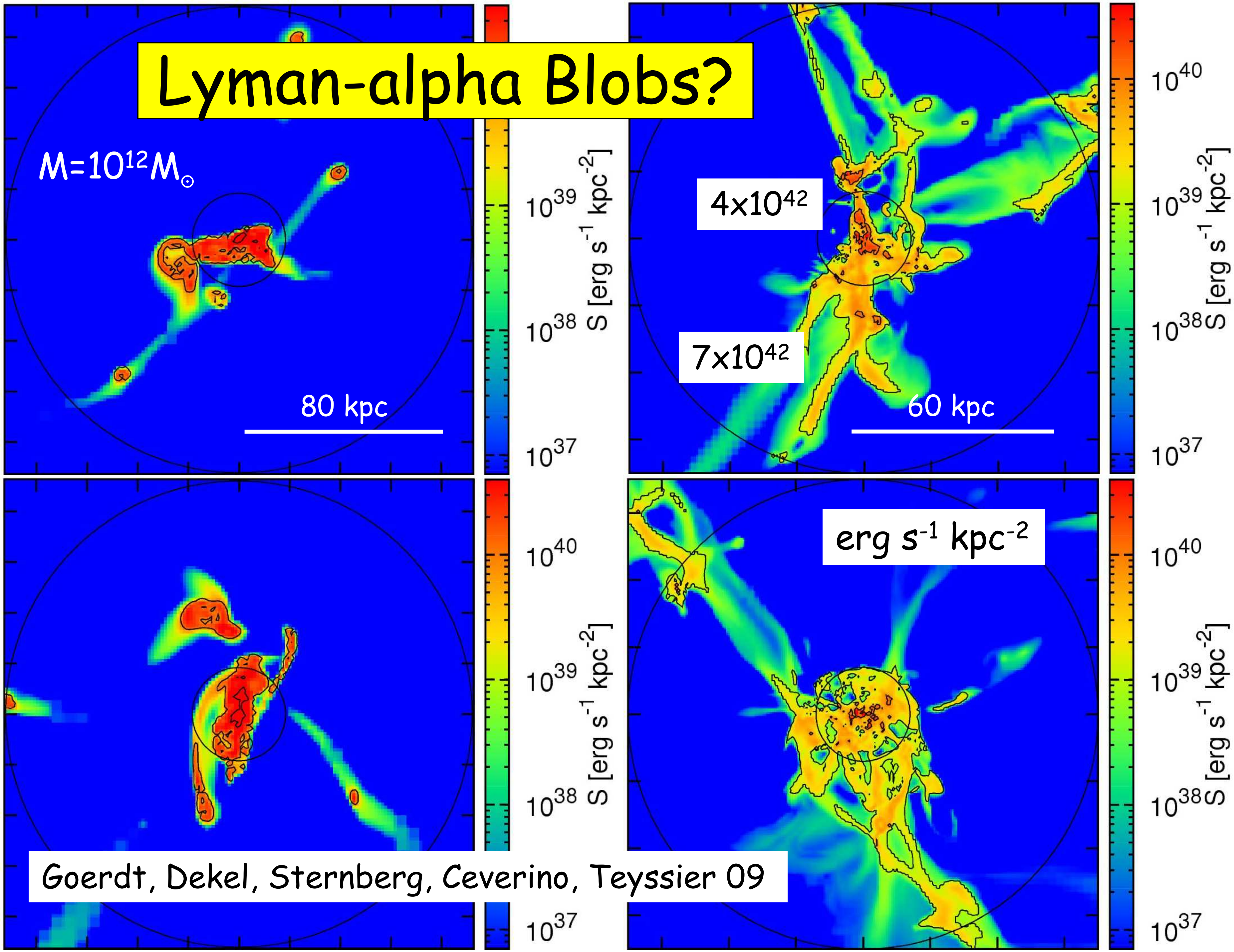


Detectable by absorption or emission:

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

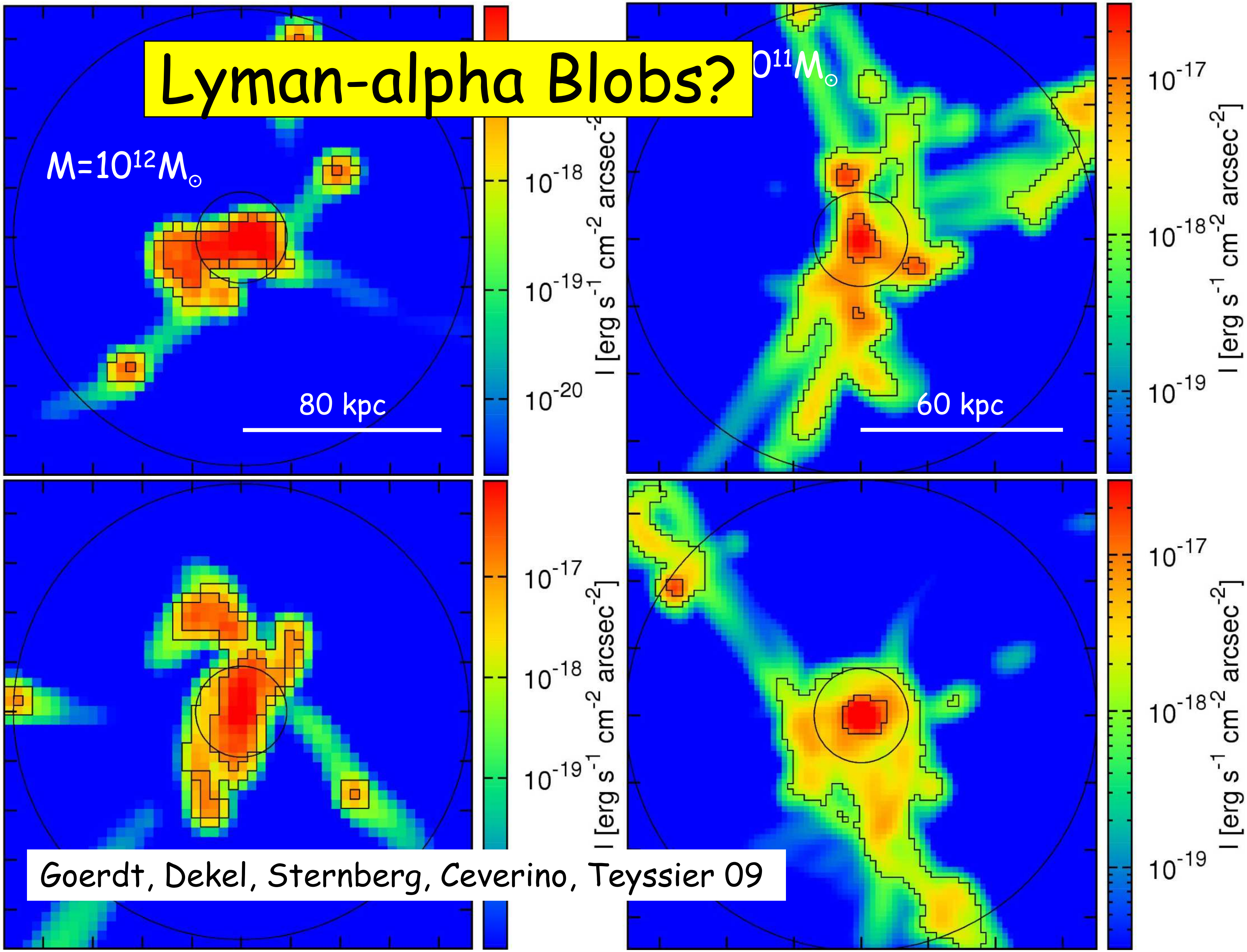
Internal source: c.d.>21 cm^{-2} at 5% sky coverage

Lyman-alpha Blobs?



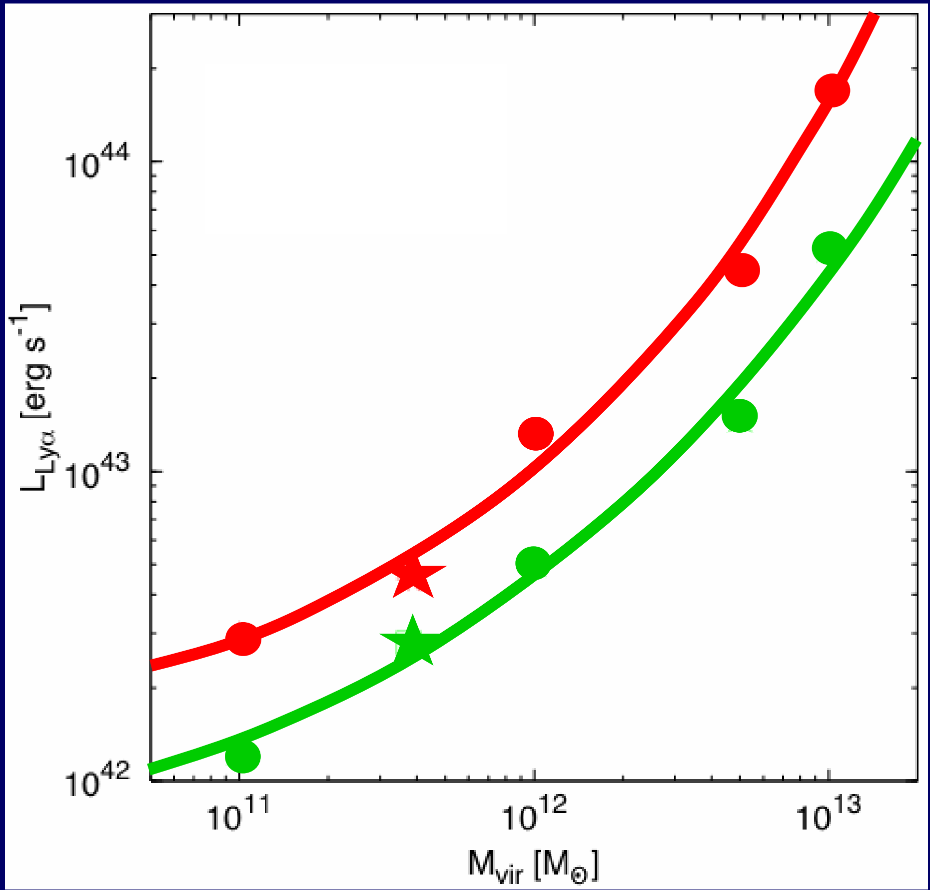
Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

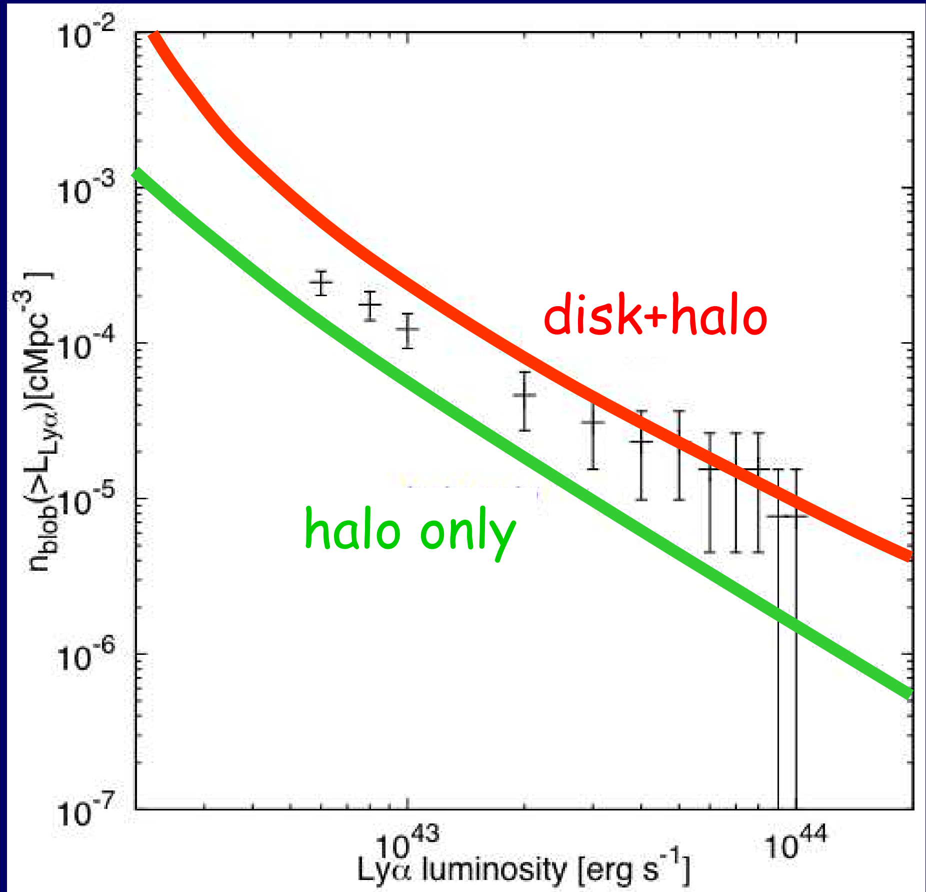
Lyman-alpha Blobs?



Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

Lyman-alpha Luminosity Function





Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

Gas inflow rate vs observed SFR

Dekel et al. 2009, Nature

Average Accretion Rate into a Halo

Neistein, van den Bosch, Dekel 06; Neistein & Dekel 07, 08

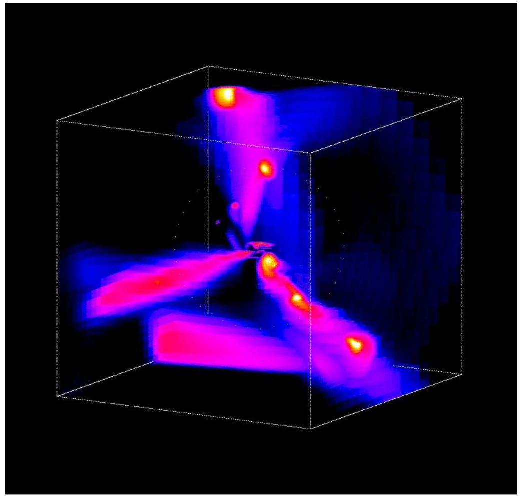
From N-body simulations or EPS, Approximate for LCDM:

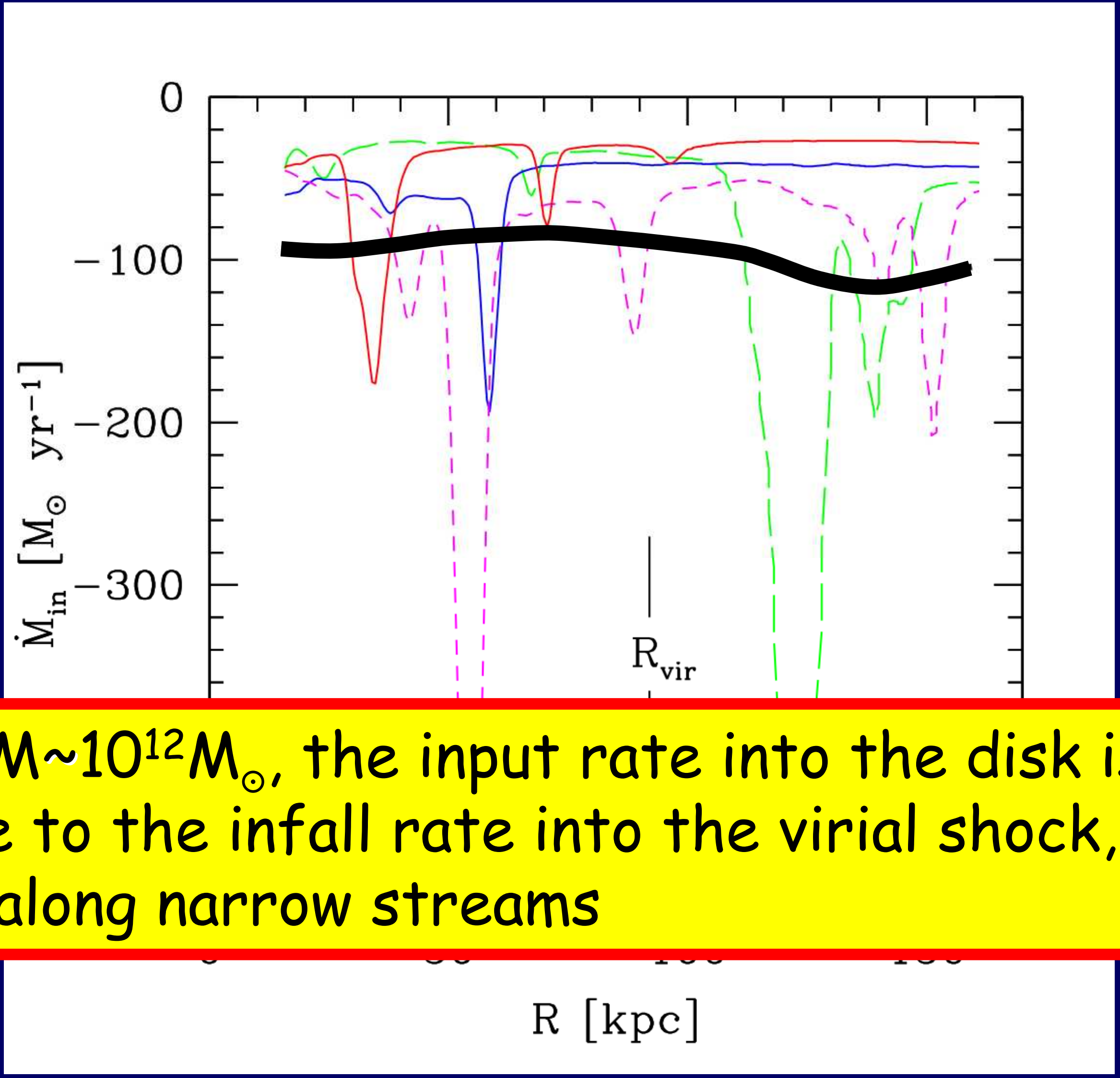
$$\left\langle \dot{M}_b \right\rangle_{vir} \approx 6.6\, M_{\Theta} yr^{-1}\, M_{12}^{1.15} (1+z)^{2.25}\, f_{0.165}$$

$M=2\times10^{12} M_\odot$ $z=2.2$ → $dM/dt \sim 200\ M_\odot yr^{-1}$

May explain the Star Forming Galaxies if
- the streams penetrate efficiently to the disk
- the streams are gas rich
- SFR follows rapidly

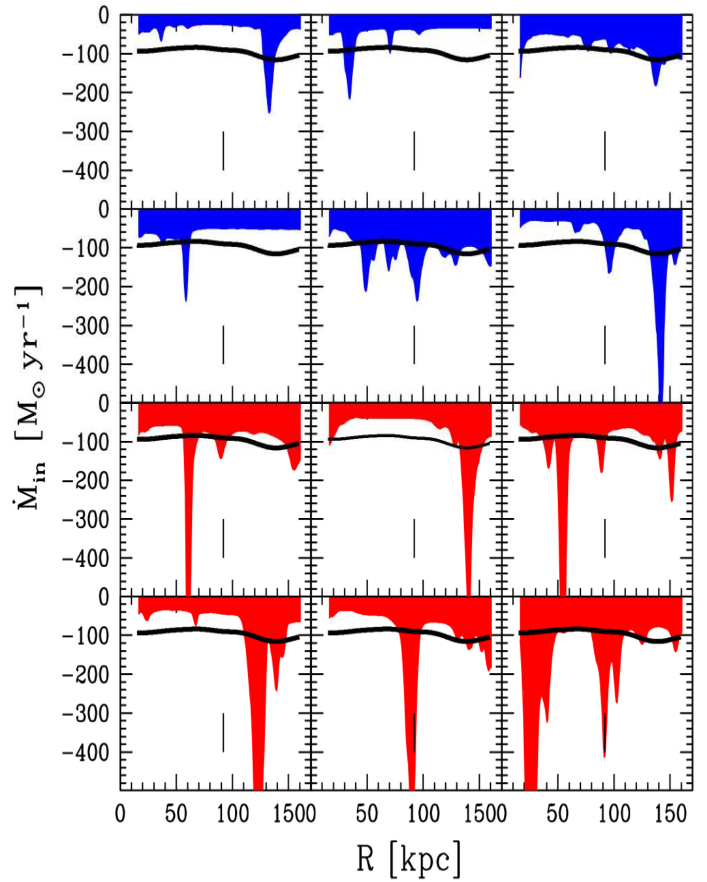
Inflow Rate into the Disk

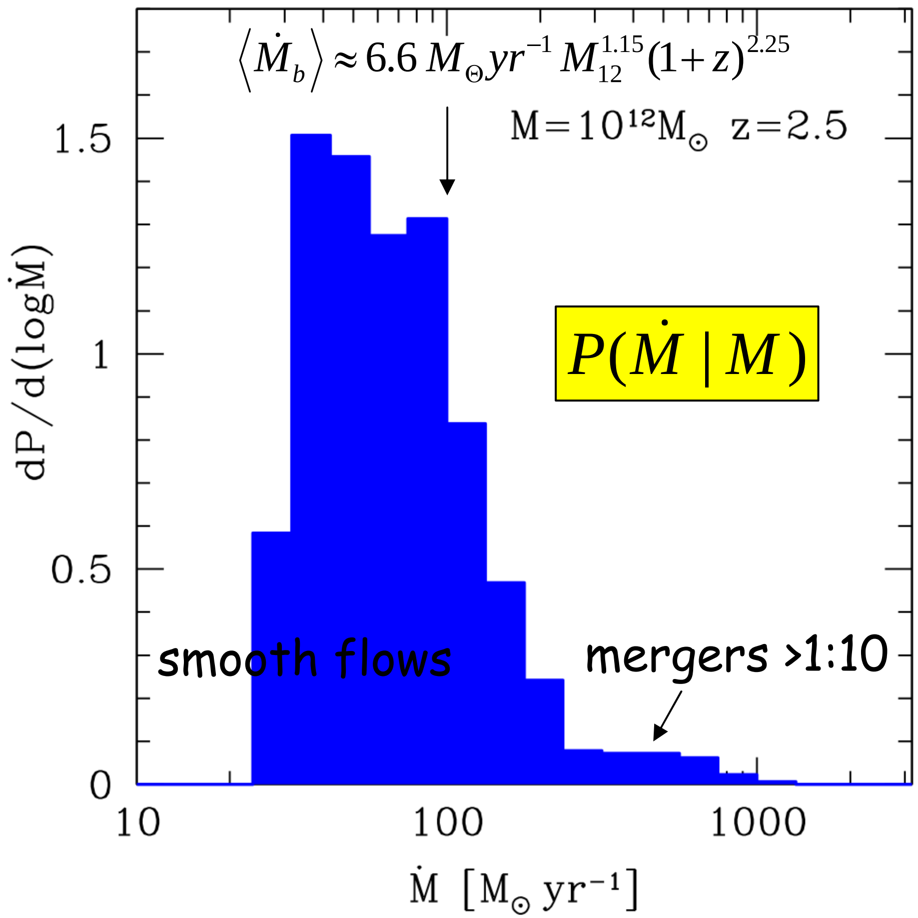




At z~2-3, $M \sim 10^{12} M_\odot$, the input rate into the disk is comparable to the infall rate into the virial shock, most of it along narrow streams

Conditional Distribution of Gas Inflow Rate





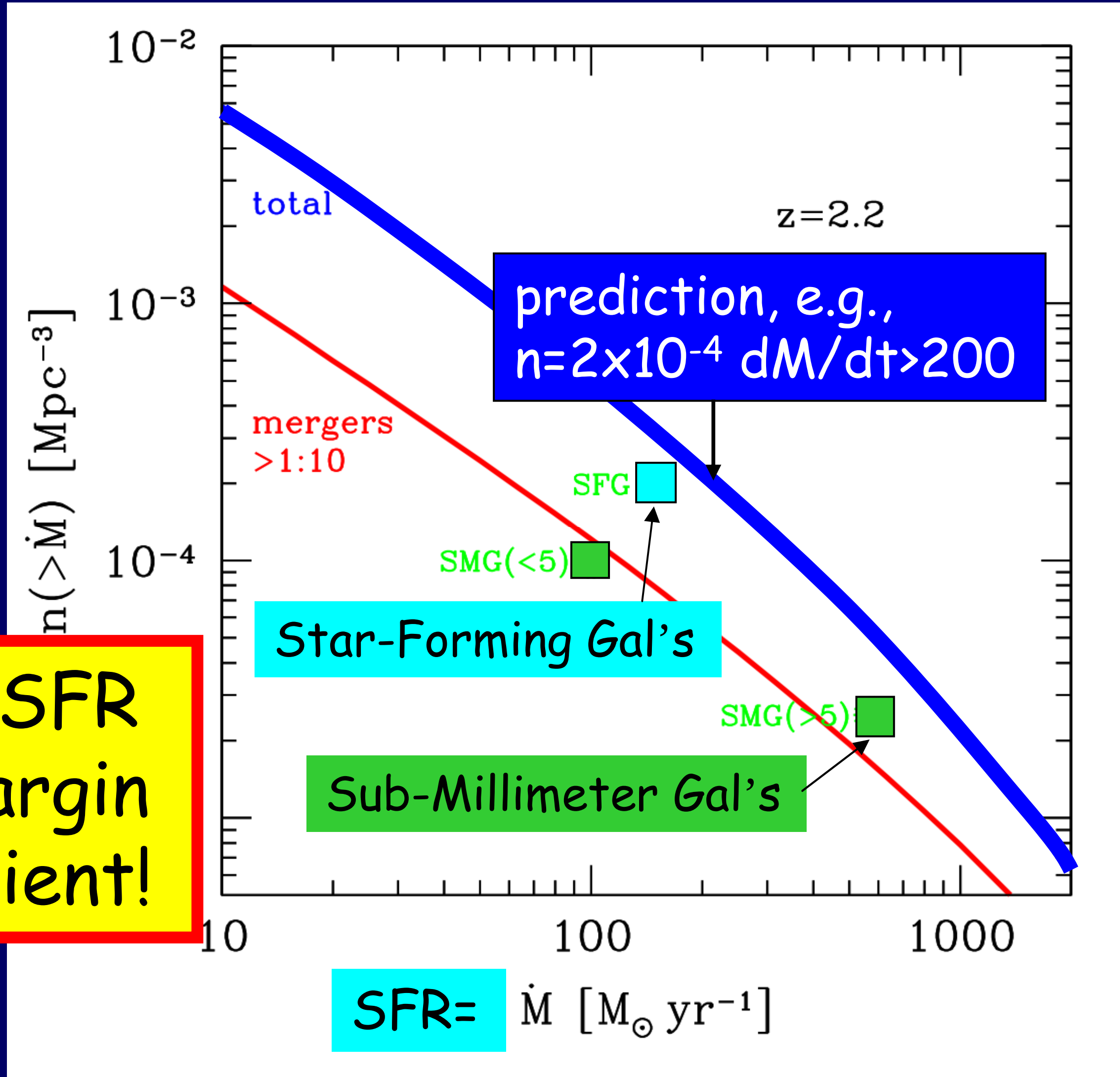
Comoving Number Density of Galaxies as a function of gas inflow rate

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

Assume scaling of P(Mdot|M)

$$\dot{M}_b \approx 6.6\, M_\Theta yr^{-1}\, M_{12}^{1.15} (1+z)^{2.25}$$

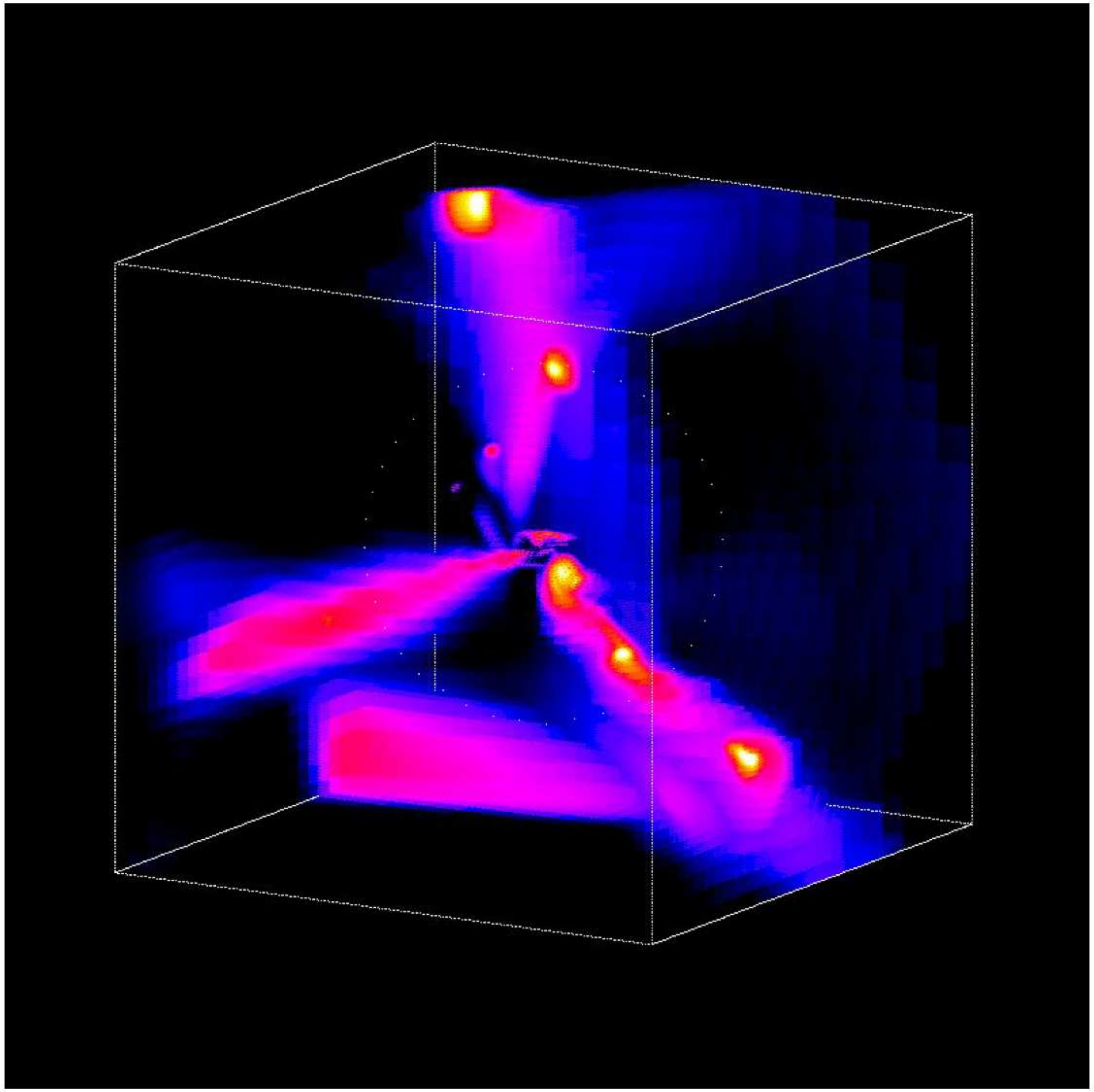
n(M) by Sheth-Tormen



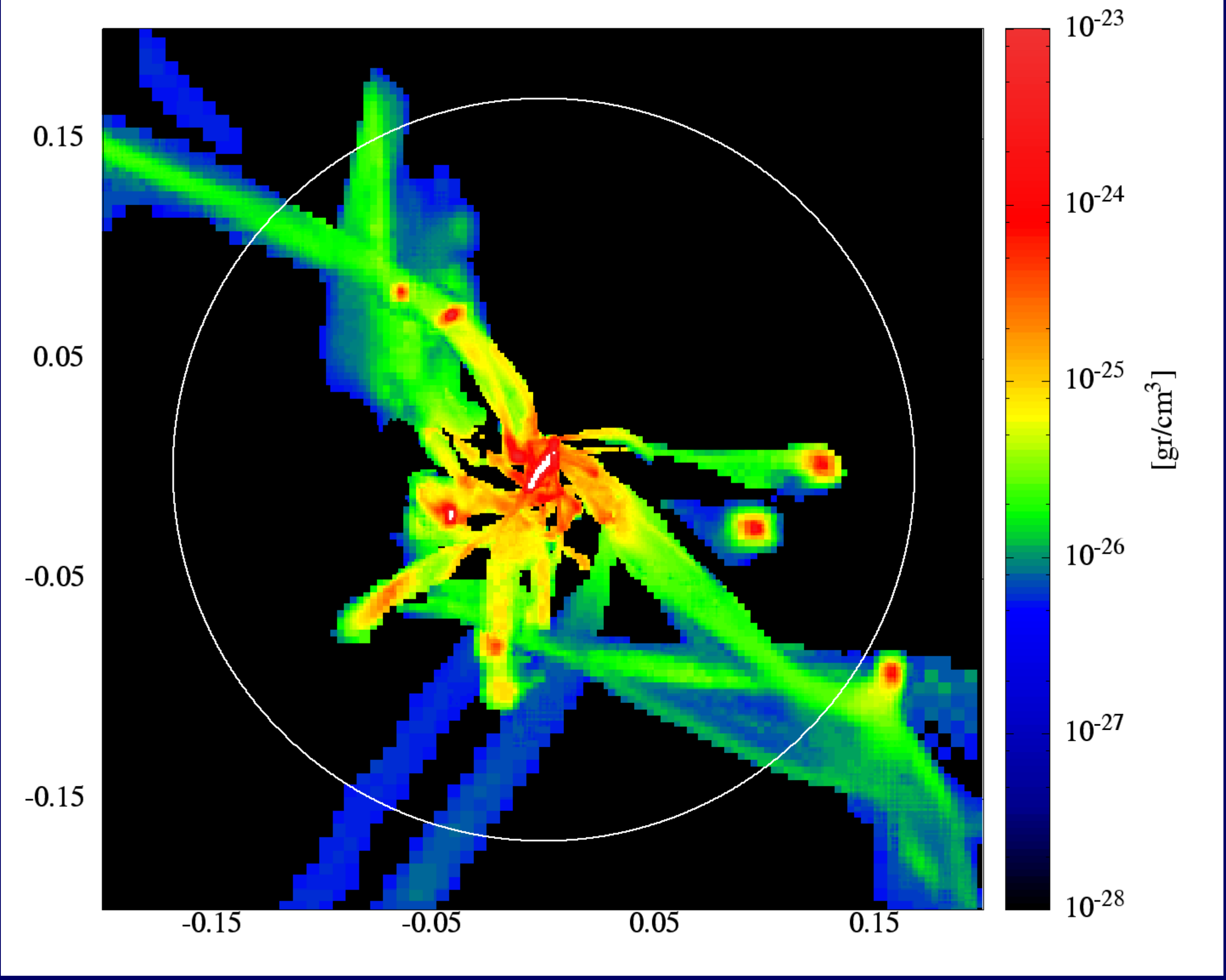
Gas inflow rate > SFR
but by a small margin
→ SFR very efficient!

Smooth Flows vs Mergers

Streams in 3D: partly clumpy

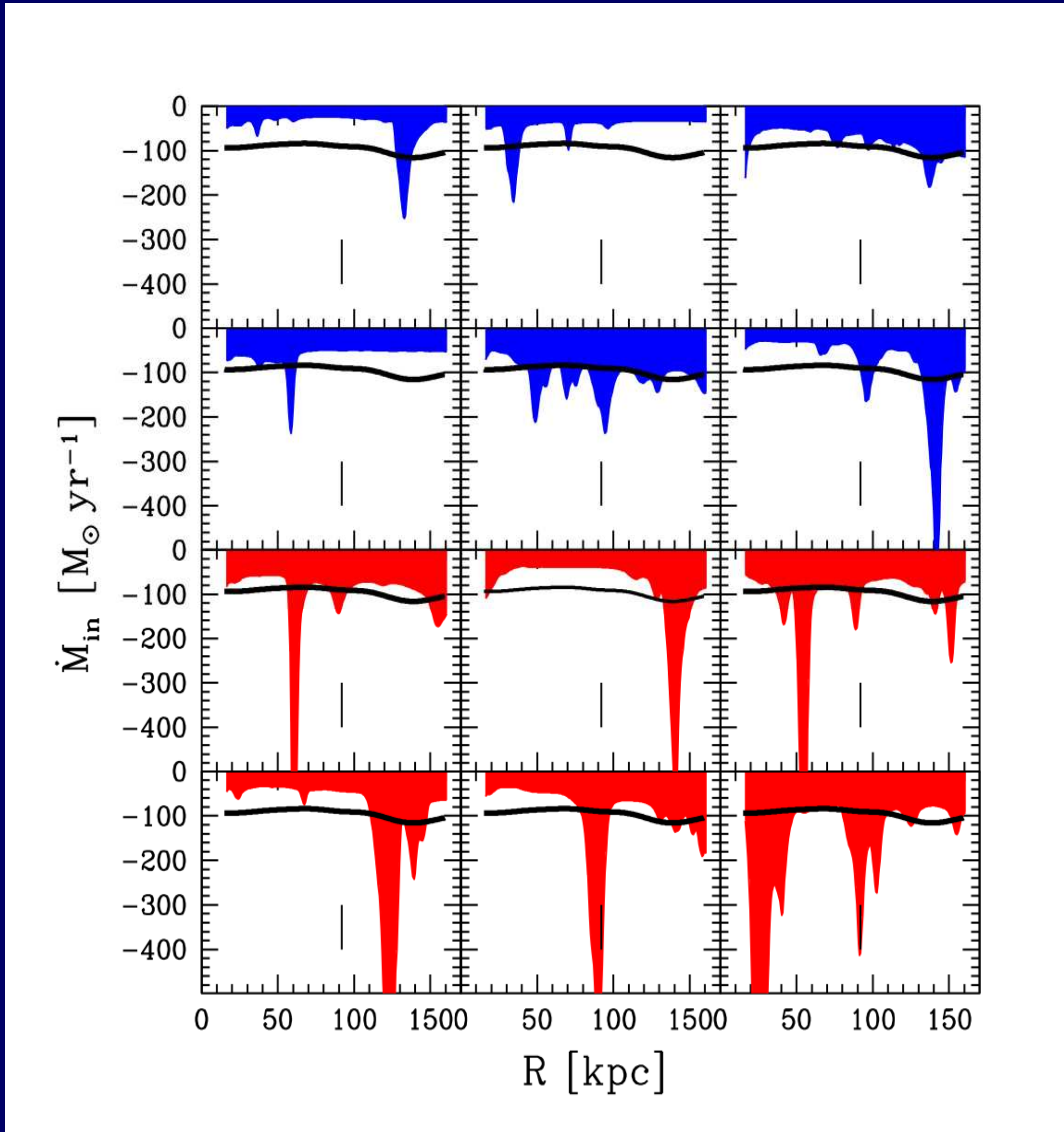


Half the stream mass is in clump >1:10



Birnboim,
Zinger,
Dekel,
Kravtsov

Inflow Rate into the Disk



on average, 33% of the flux is in mergers > 1:10

but the duty cycle is < 10%

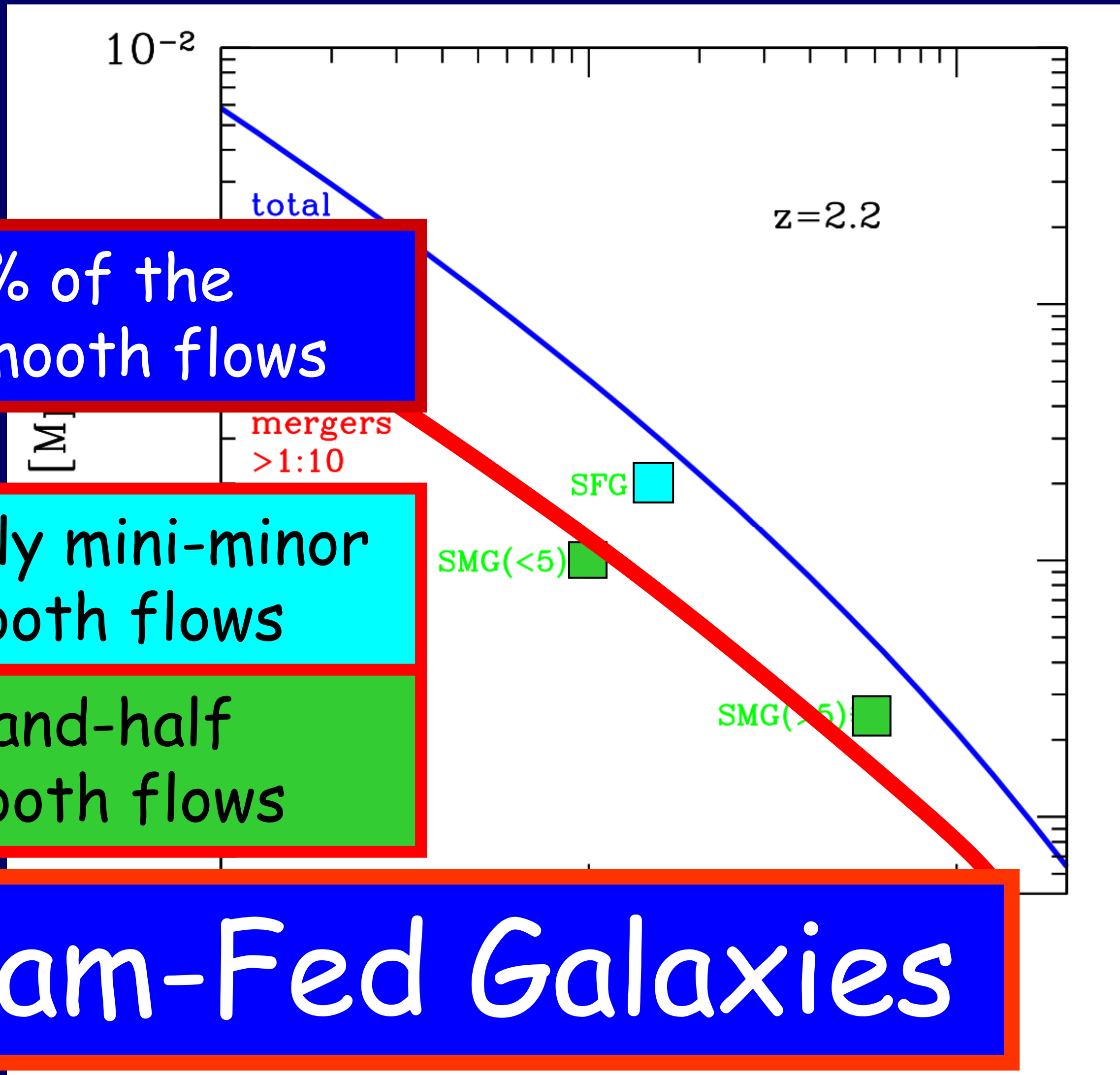
Fraction of Mergers

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

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

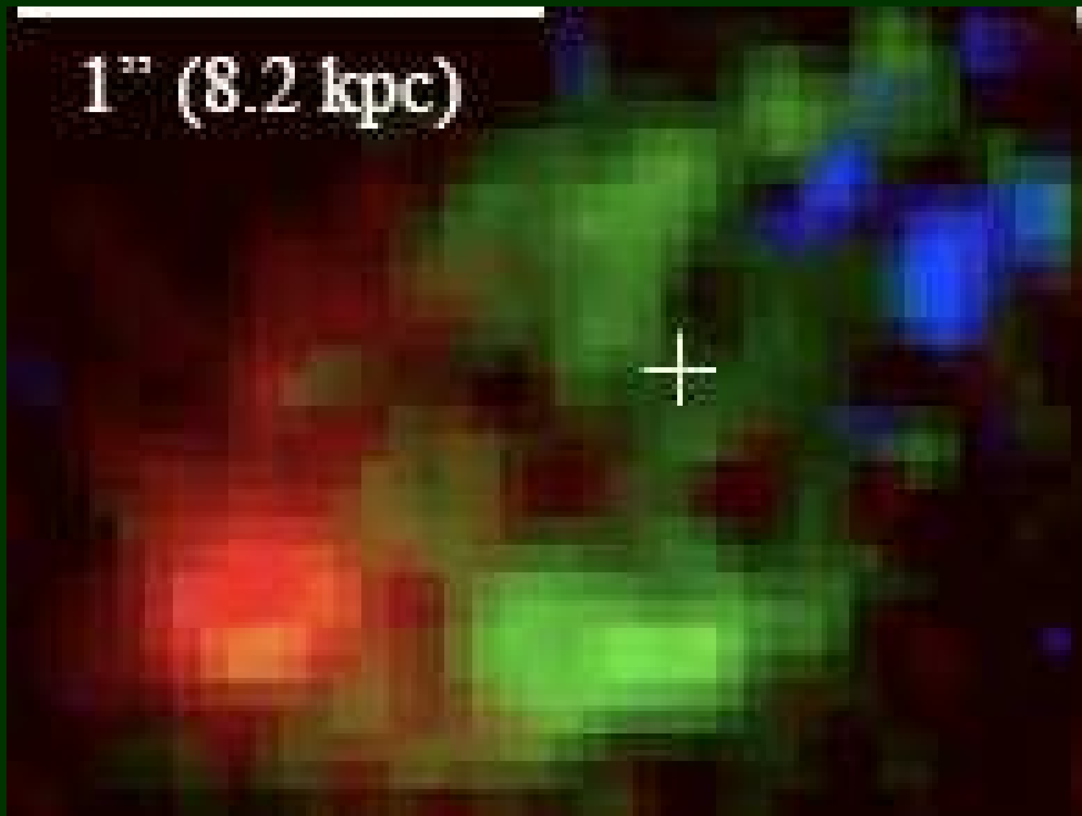
BzK/BX/BM are mostly mini-minor mergers <1:10, i.e. smooth flows

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

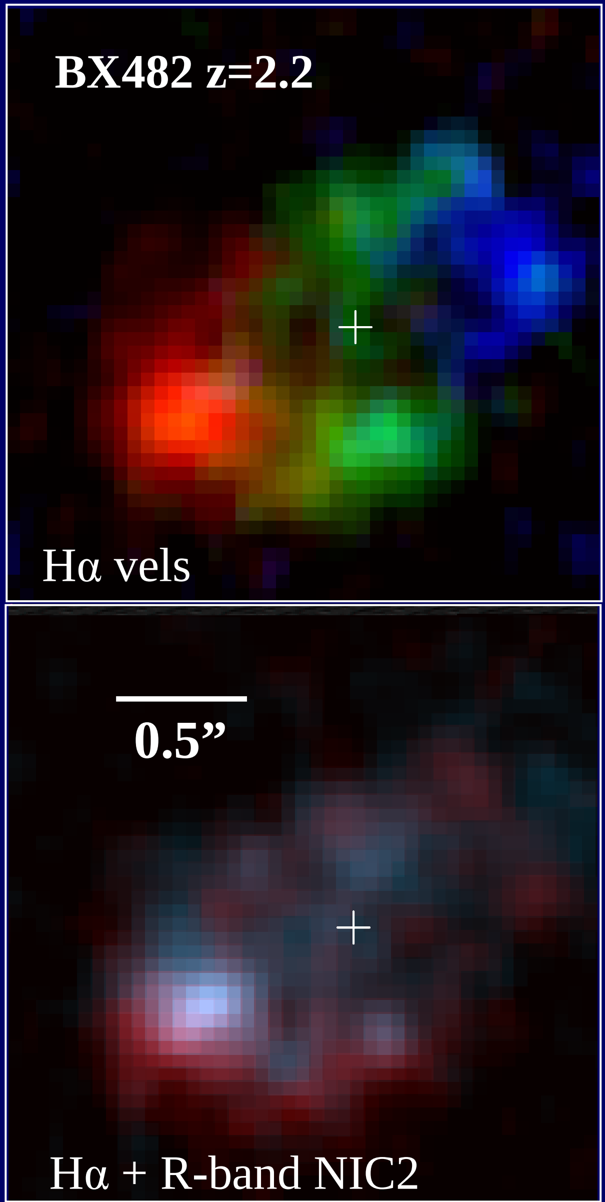


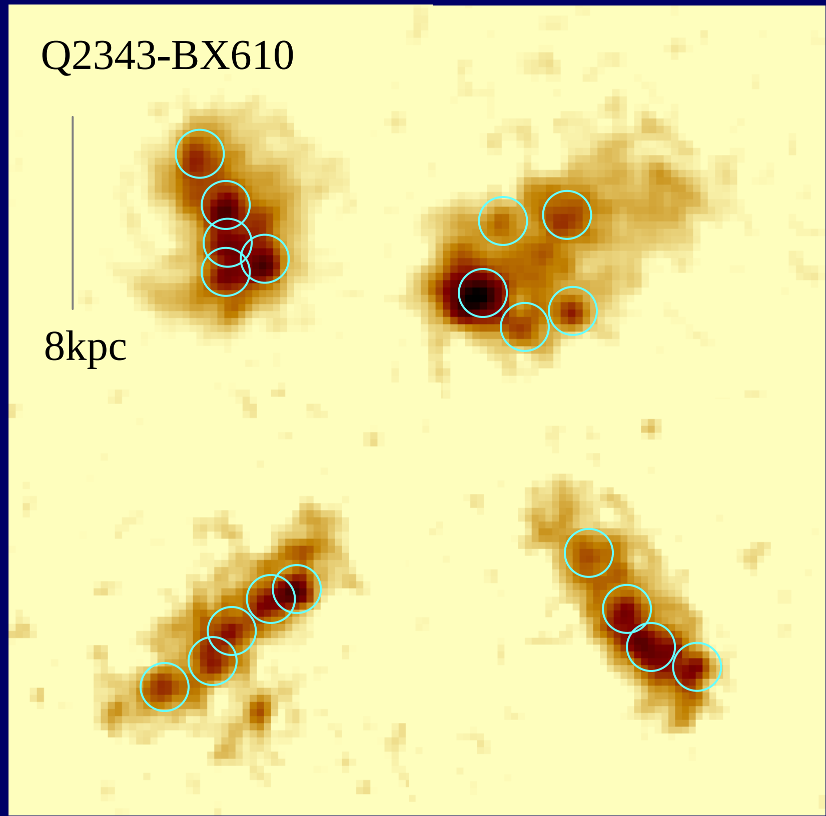
SFG: Stream-Fed Galaxies

3. Disks with Giant Clumps



Chain Galaxies – Fragmented Disks

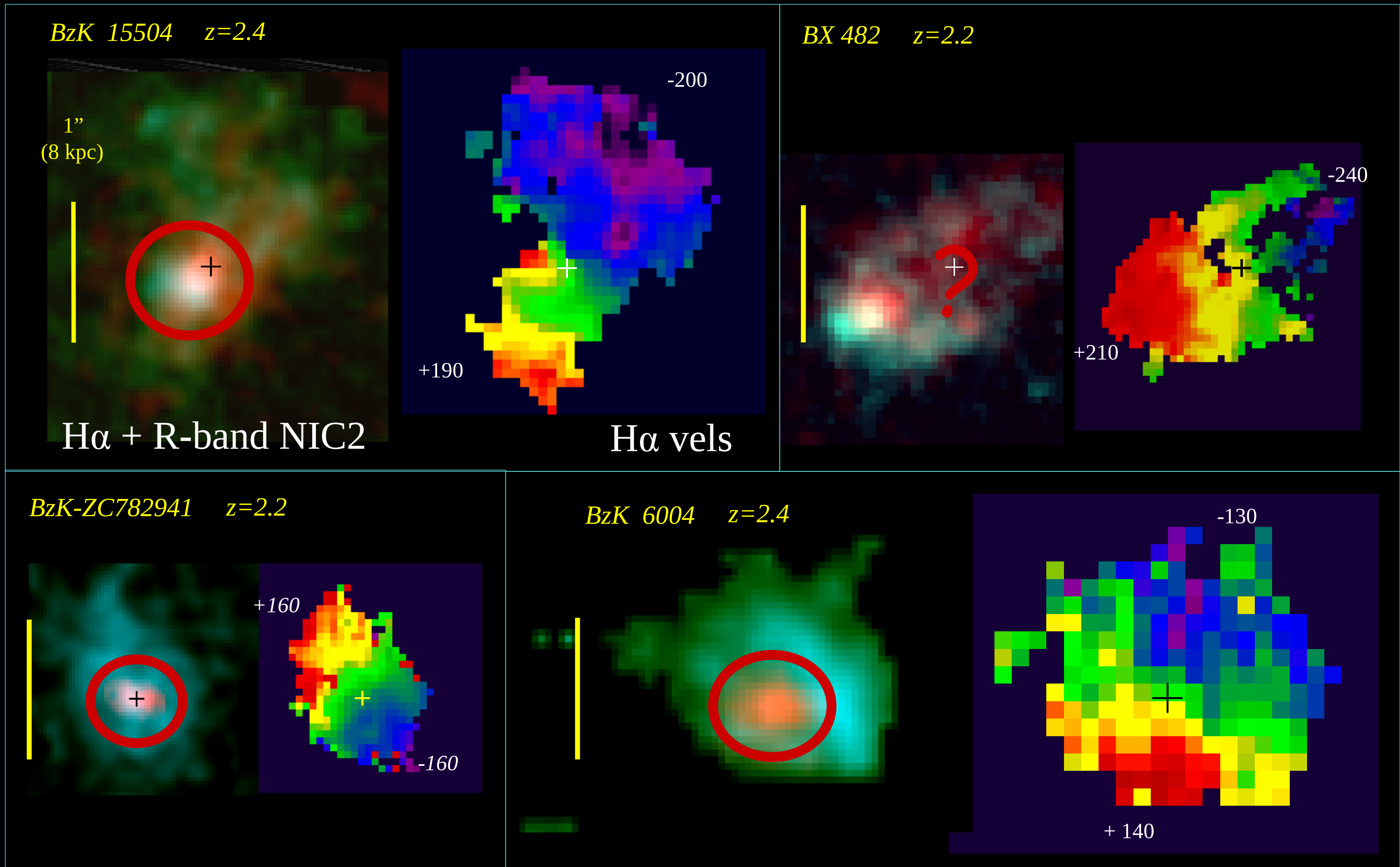




NICMOS H_{160}
Foerster Schreiber, Shapley et al. 2008

Genzel et al. 2008, Foerster Schreiber et al. 2008b,
Elmegreen & Elmegreen 2005, Elmegreen et al. 2007

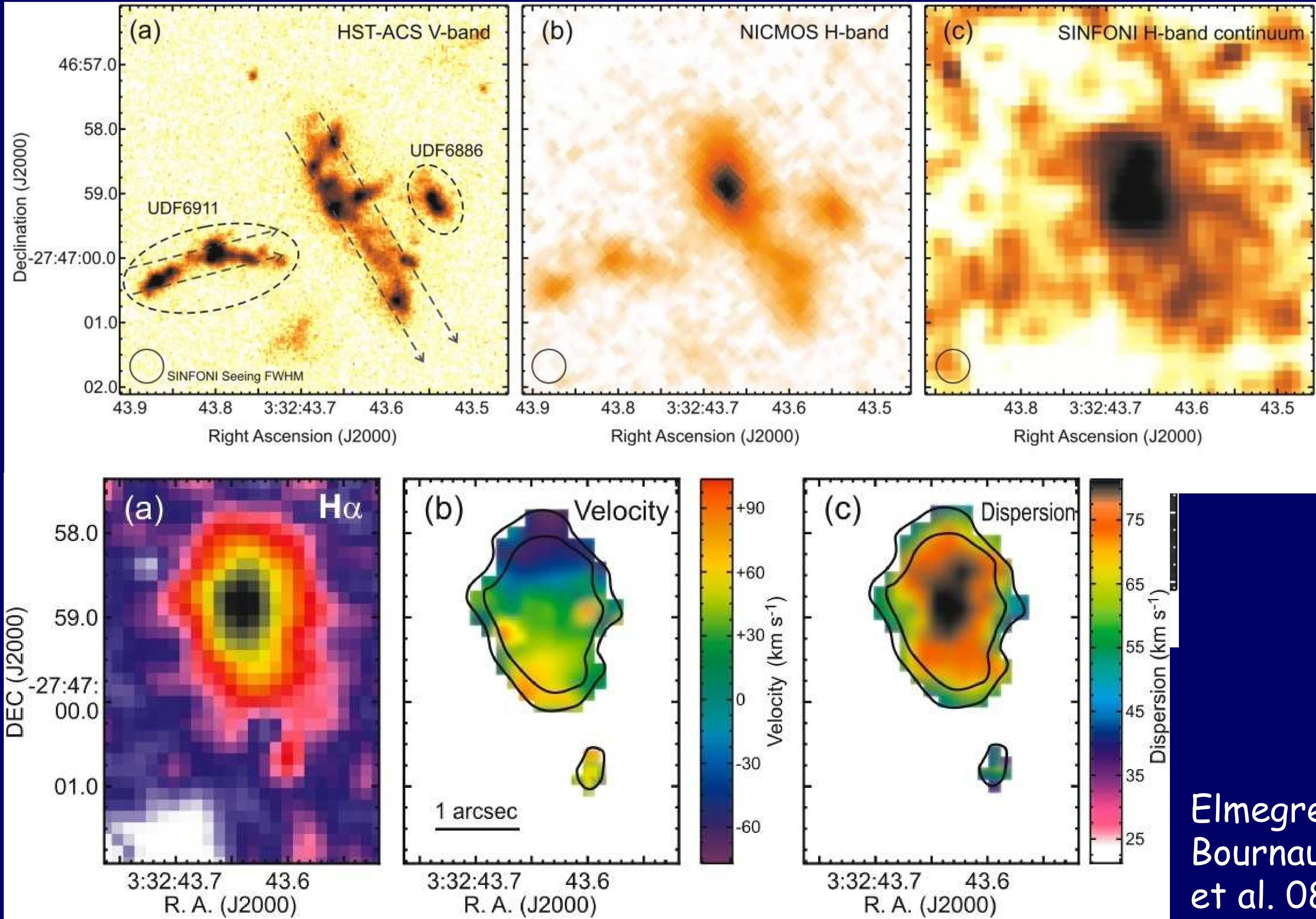
Clumpy Disks with Bulges



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

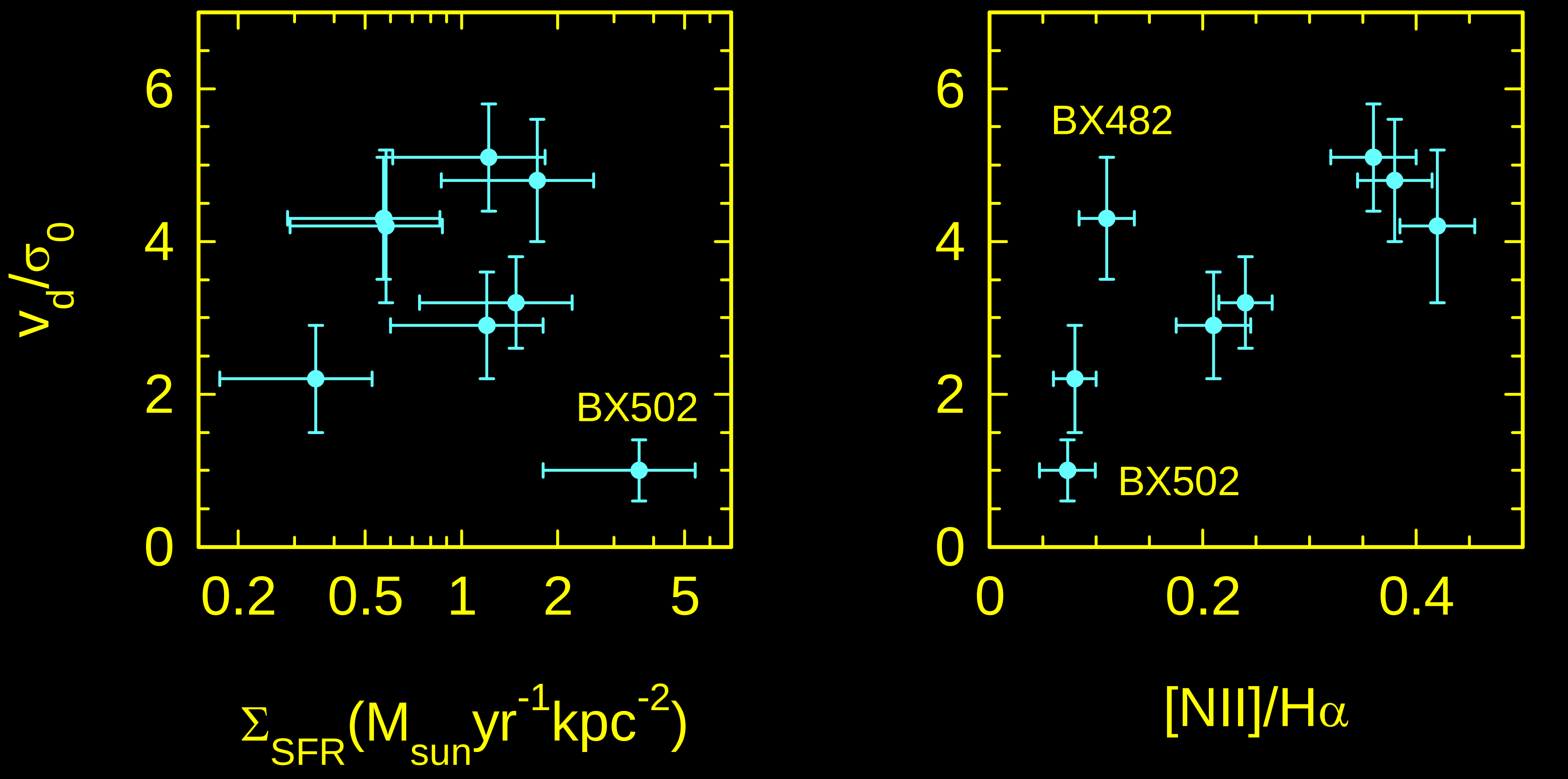
M(≤3 kpc)/M(≤15 kpc)~0.2-0.4

A rotating "chain" of clumps with a bulge



Elmegreen, Bournaud et al. 08

z~2 disks are turbulent

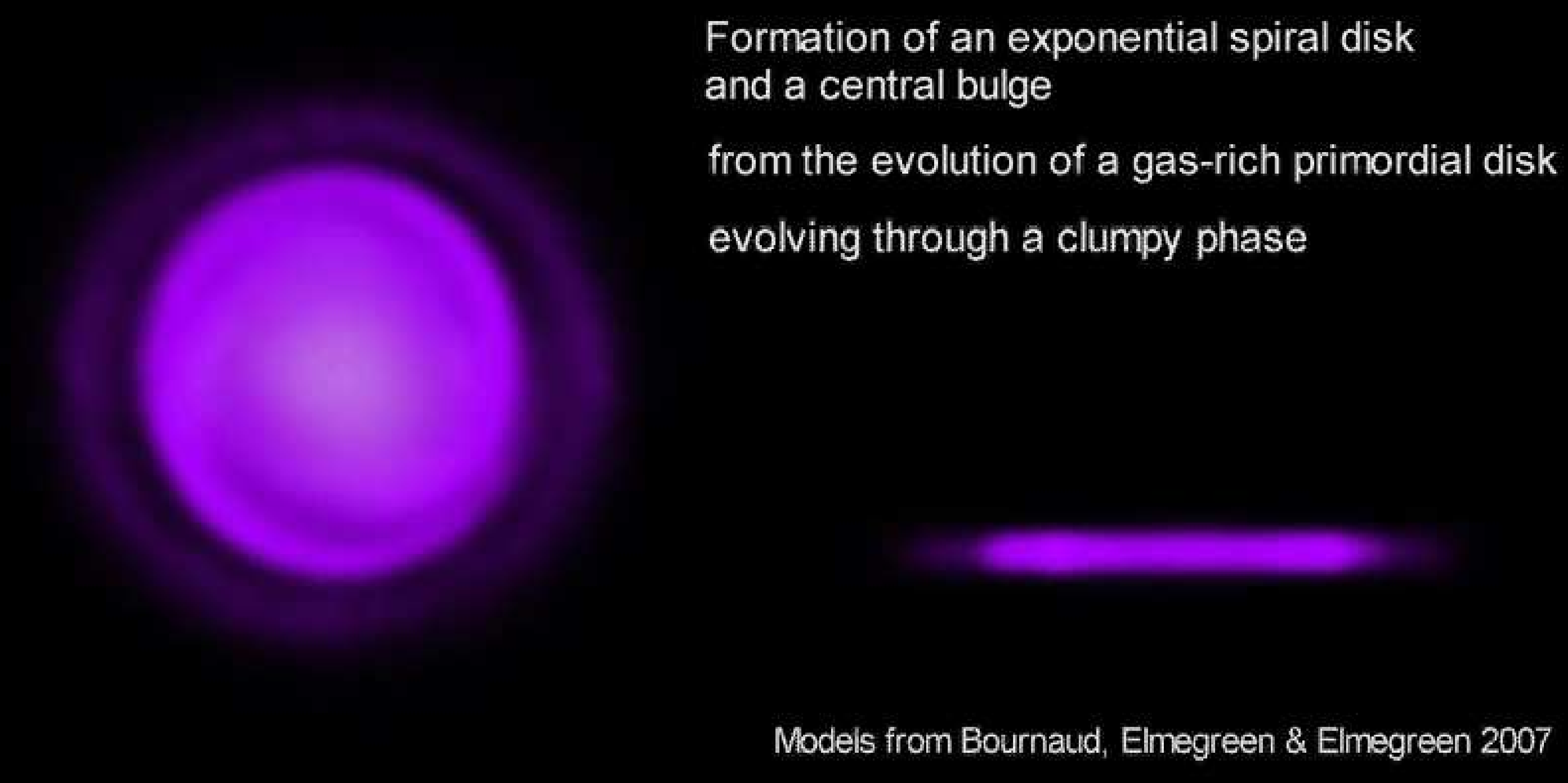


Genzel et al. 2008

Disk Breakup into Giant Clumps
Migration, Spheroid & Stabilization

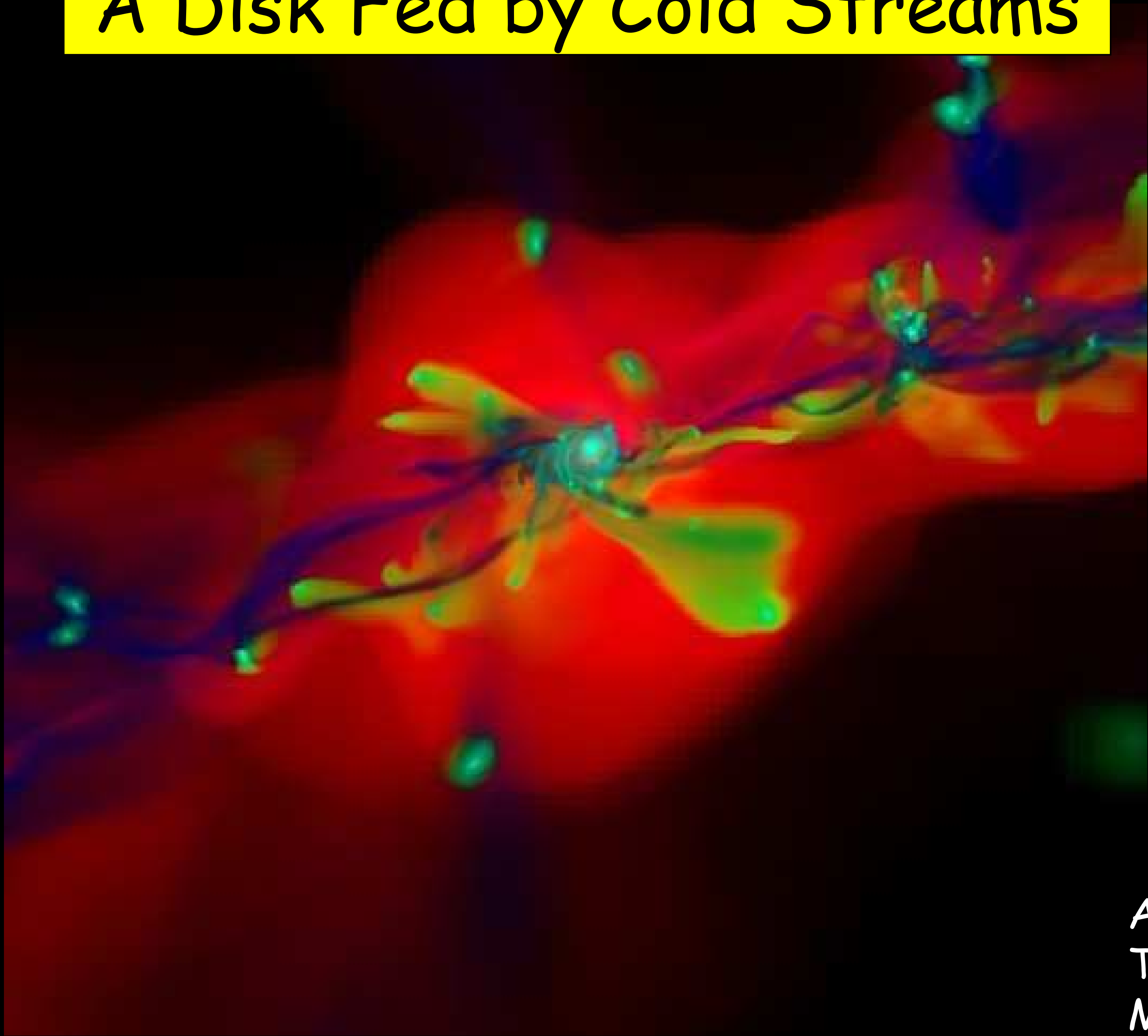
Dekel, Sari, Ceverino 2009

Isolated, gas-rich, turbulent disk - giant clumps - migration - bulge



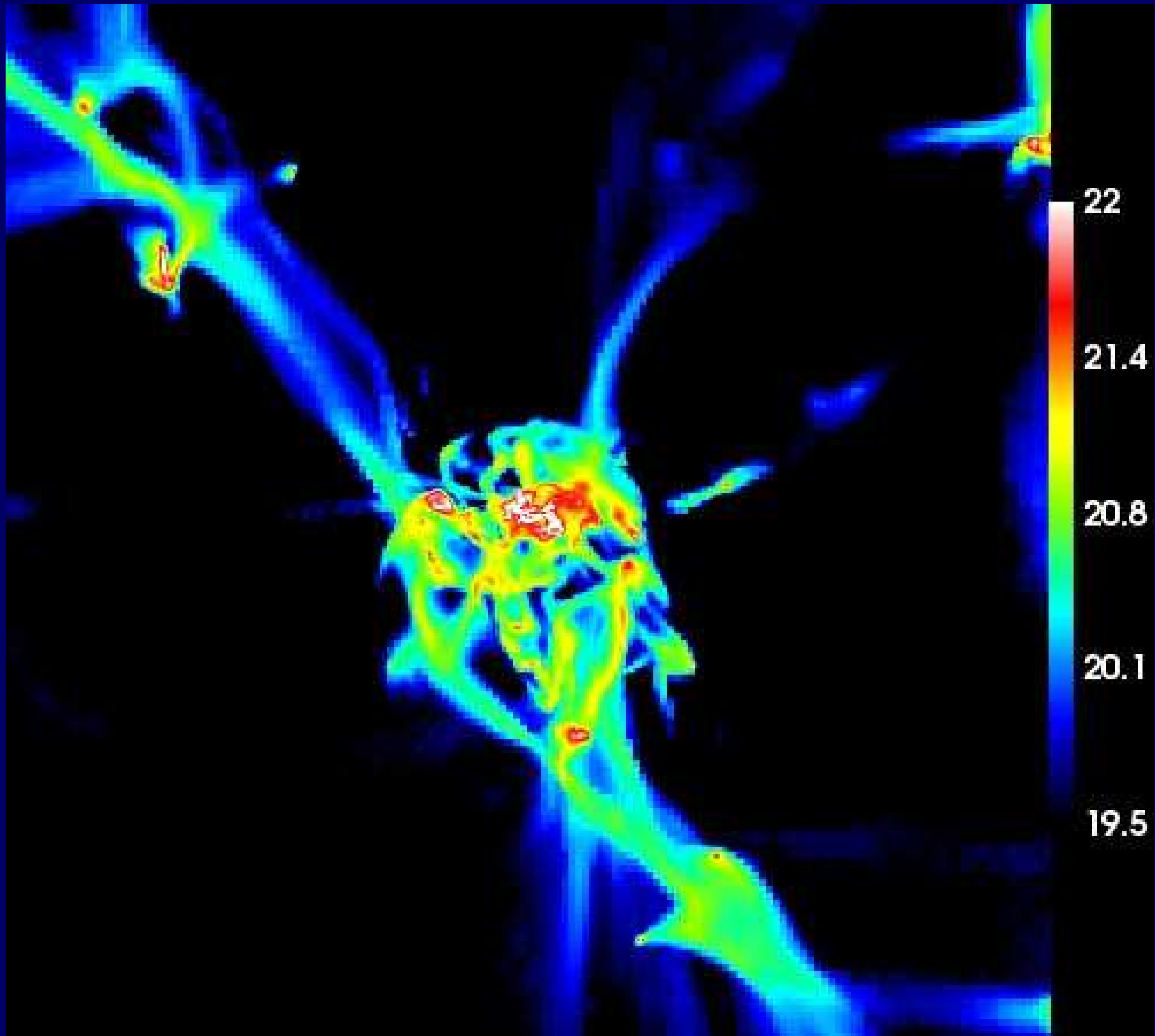
Noguchi 99; **One episode of 0.5 Gyr?** green 06, 08

A Disk Fed by Cold Streams

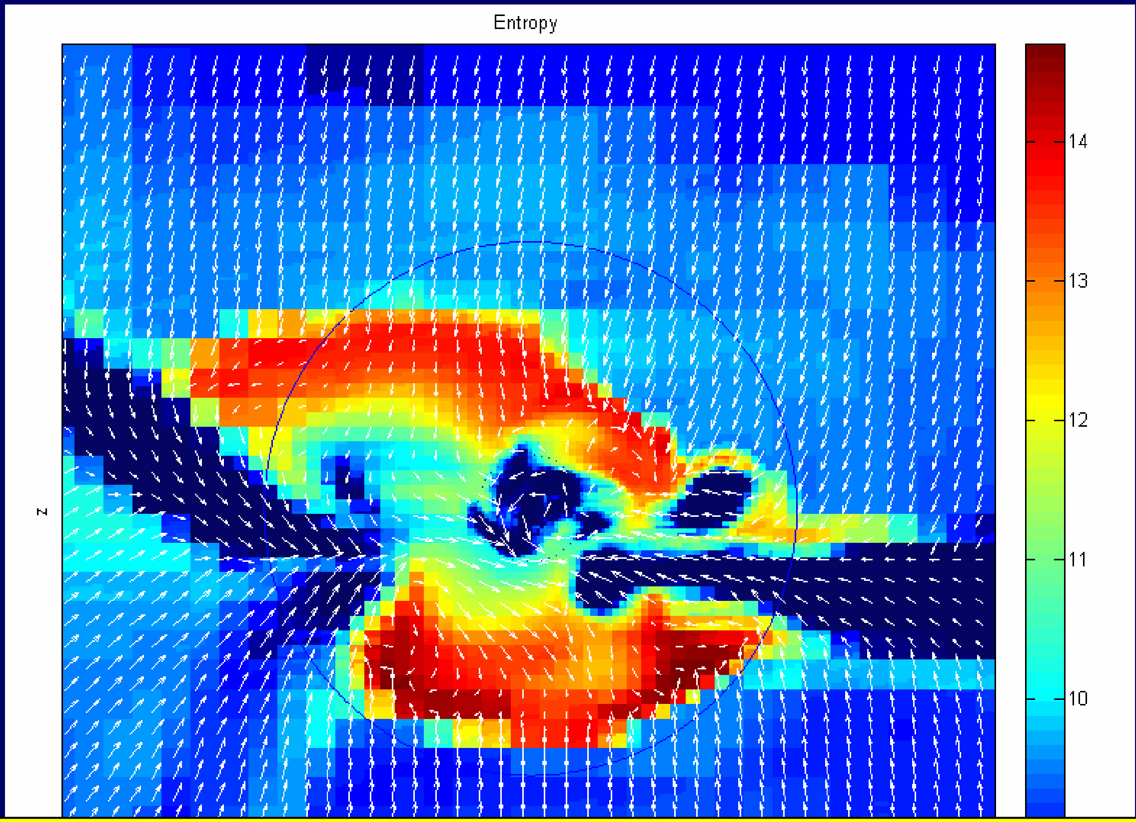


Agretz,
Teyssier,
Moore 09

A Disk Fed by Cold Streams



Disk Buildup by Streams



- Smooth streams build a gaseous disk
- A stream with a large impact parameter determines the disk spin
- Clumpy streams generate turbulence

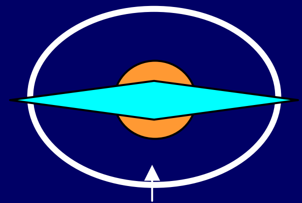
Disk – Giant Clumps - Bulge

Dekel, Sari, Ceverino 09

Toomre instablity: $Q \approx \frac{\sigma\Omega}{\pi G\Sigma} \le 0.67$

Giant clumps: $R_{\rm clump} \approx \frac{7G\Sigma}{\Omega^2}$

Disk fraction: $\delta \equiv \frac{M_{\rm disk}}{M_{\rm tot}(R_{\rm disk})}$



$\frac{M_{\rm baryon}}{M_{\rm tot}(R_{\rm disk})} \approx 0.6$

$\delta \approx \frac{\sigma}{V}$ $\approx \frac{1}{3}$ ← $1 \approx Q \approx \delta^{-1}\frac{\sigma}{V}$

$\frac{m_{\rm clump}}{M_{\rm disk}} \approx 0.02\,\delta_{0.3}^2$

Self-regulation at Q ~ 0.67:

Clump encounters vs
Dissipation of turbulence

$t_{\rm enc} \approx 2\alpha^{-1}Q^4 t_{\rm dyn}$

$t_{\rm dis} \approx 1.4Q^{-1}t_{\rm dyn}$

$\alpha \equiv \frac{\sum m_{\rm clump}}{M_{\rm disk}} \approx 0.2$

Migration to the center by
collisions and dynamical friction

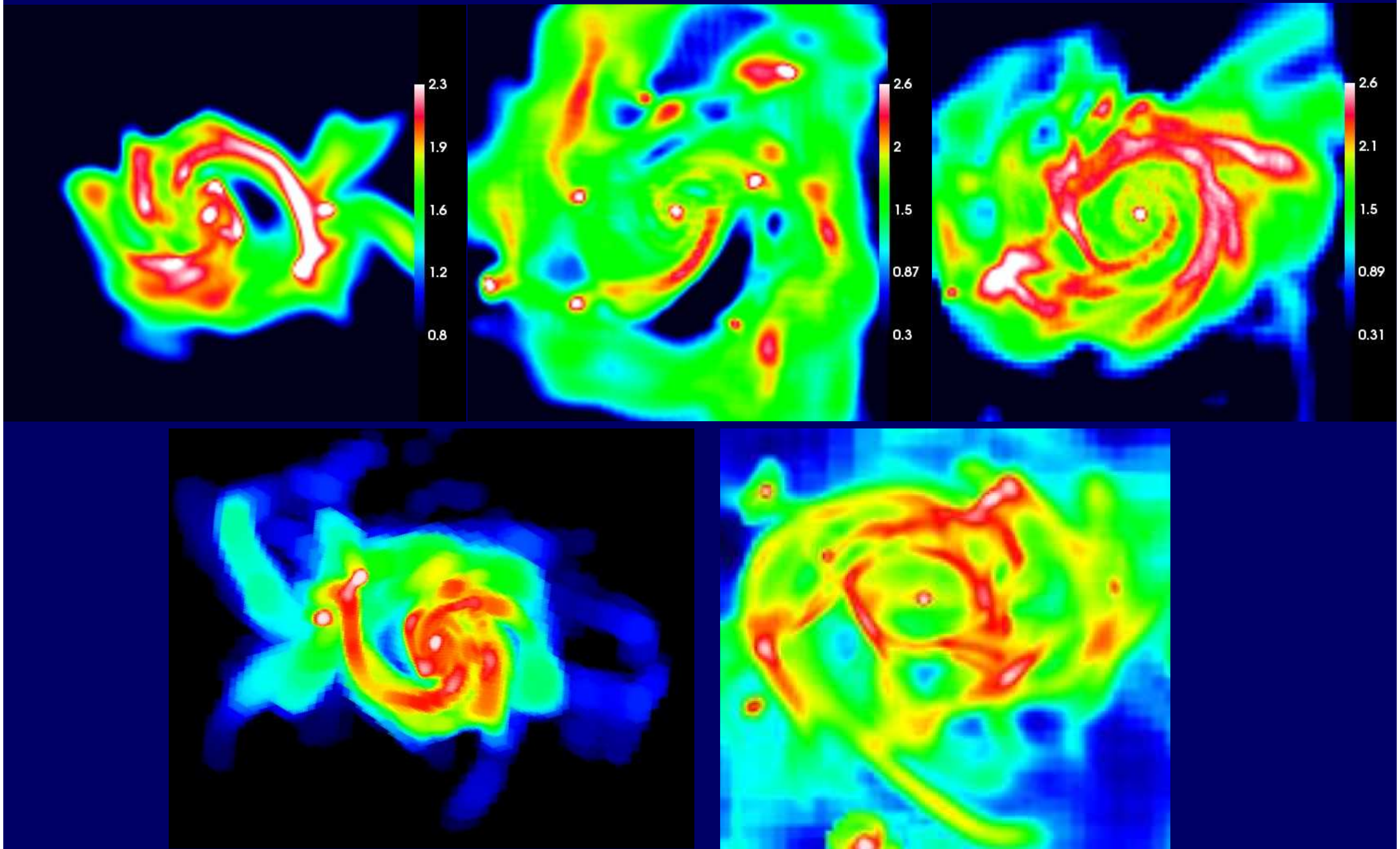
$t_{\rm mig} \approx 2Q^2\delta^{-2}t_{\rm dyn}$

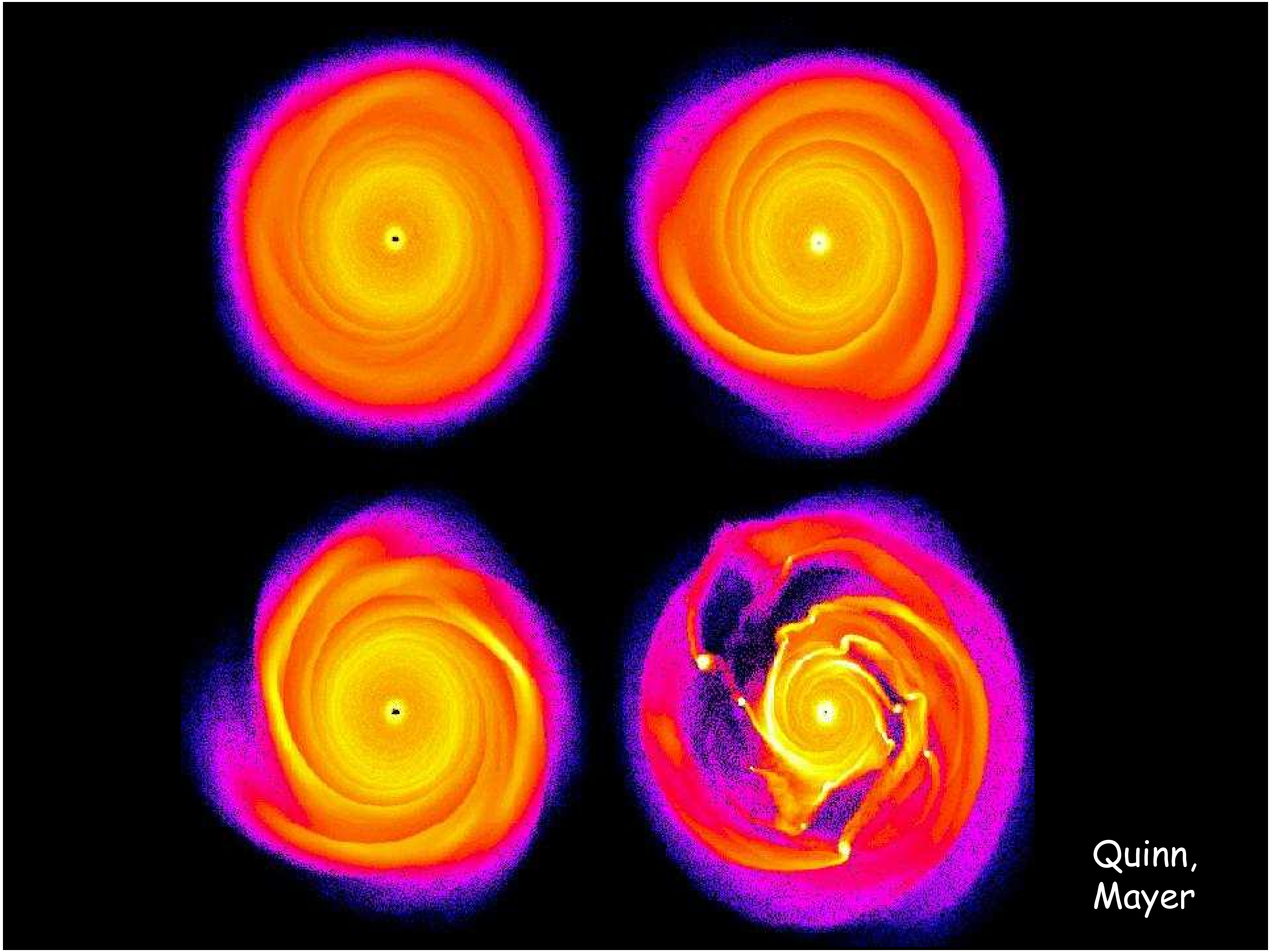
$t_{\rm evac} \approx \alpha^{-1}t_{\rm mig}$

Angular-momentum transfer + streams at outer disk → disk extended x2

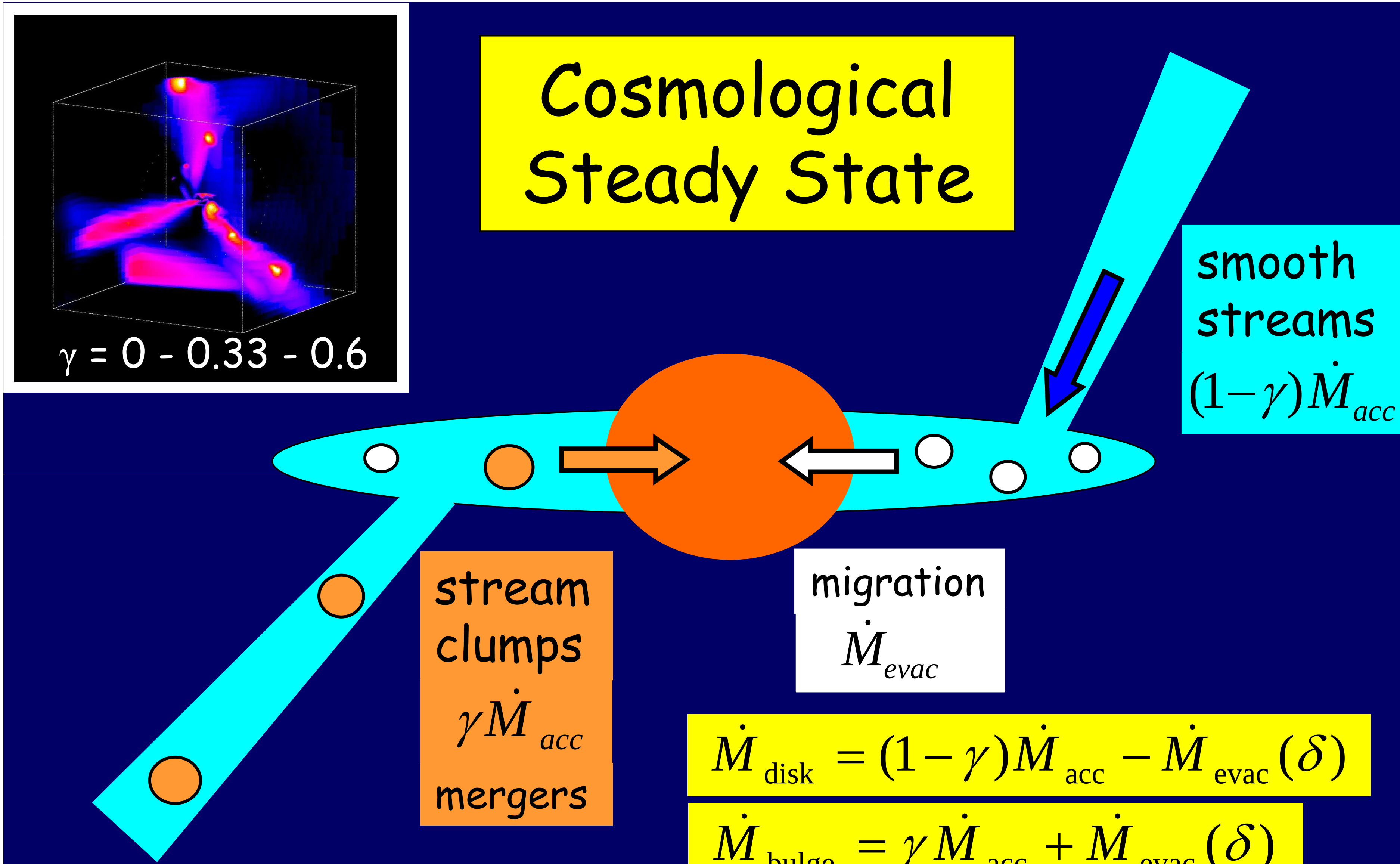
$t_{\rm SFR} \sim t_{\rm mig}$ → dissipative coalescence into a compact spheroid

Bound Clumps and Transient Features




Quinn,
Mayer

Cosmological Steady State



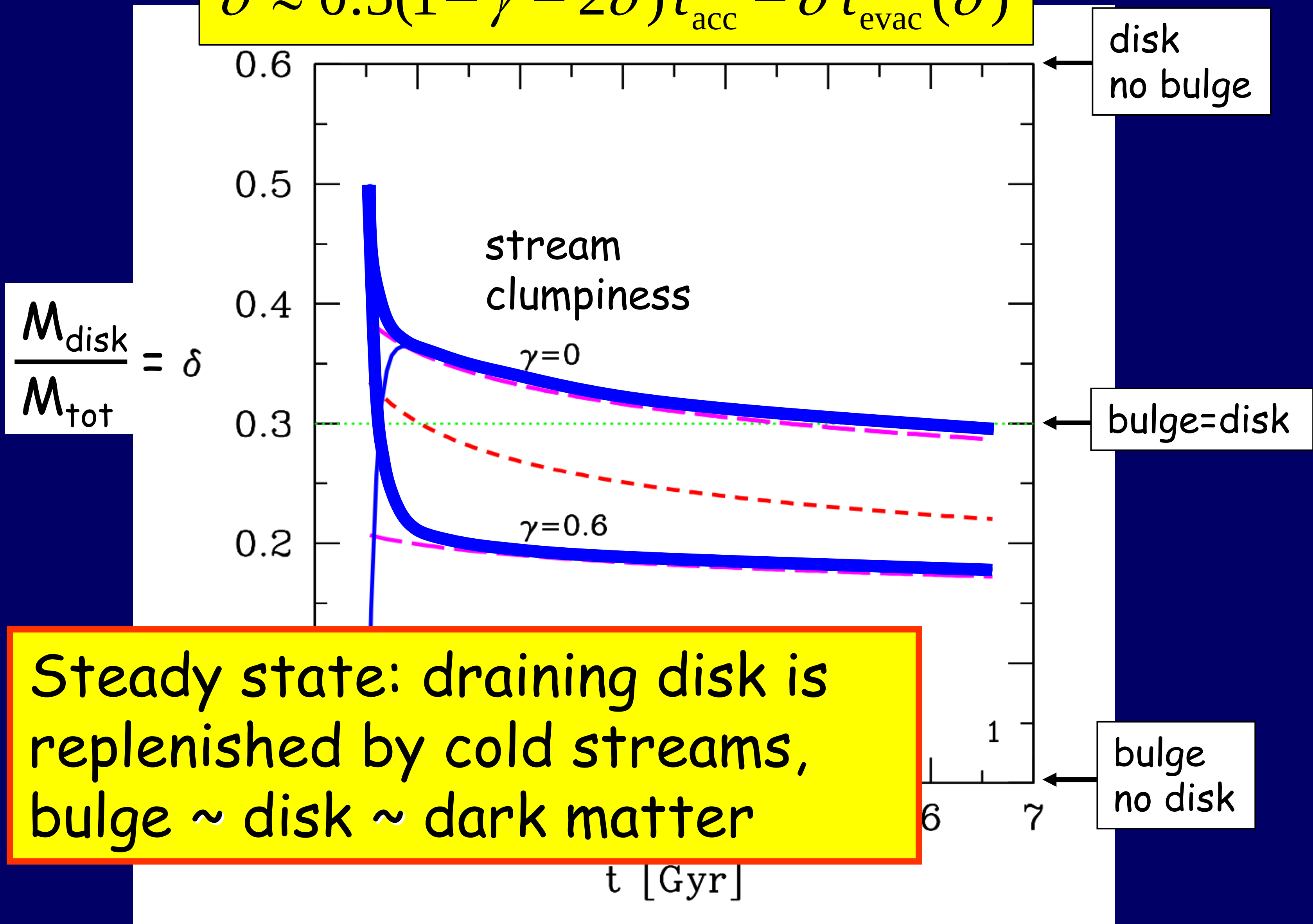
$$\dot{M}_{\rm disk} = (1-\gamma)\dot{M}_{\rm acc} - \dot{M}_{\rm evac}(\delta)$$

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

$$\dot{\delta} \approx 0.5(1-\gamma-2\delta)\, t_{\rm acc}^{-1} - \delta\, t_{\rm evac}^{-1}(\delta)$$

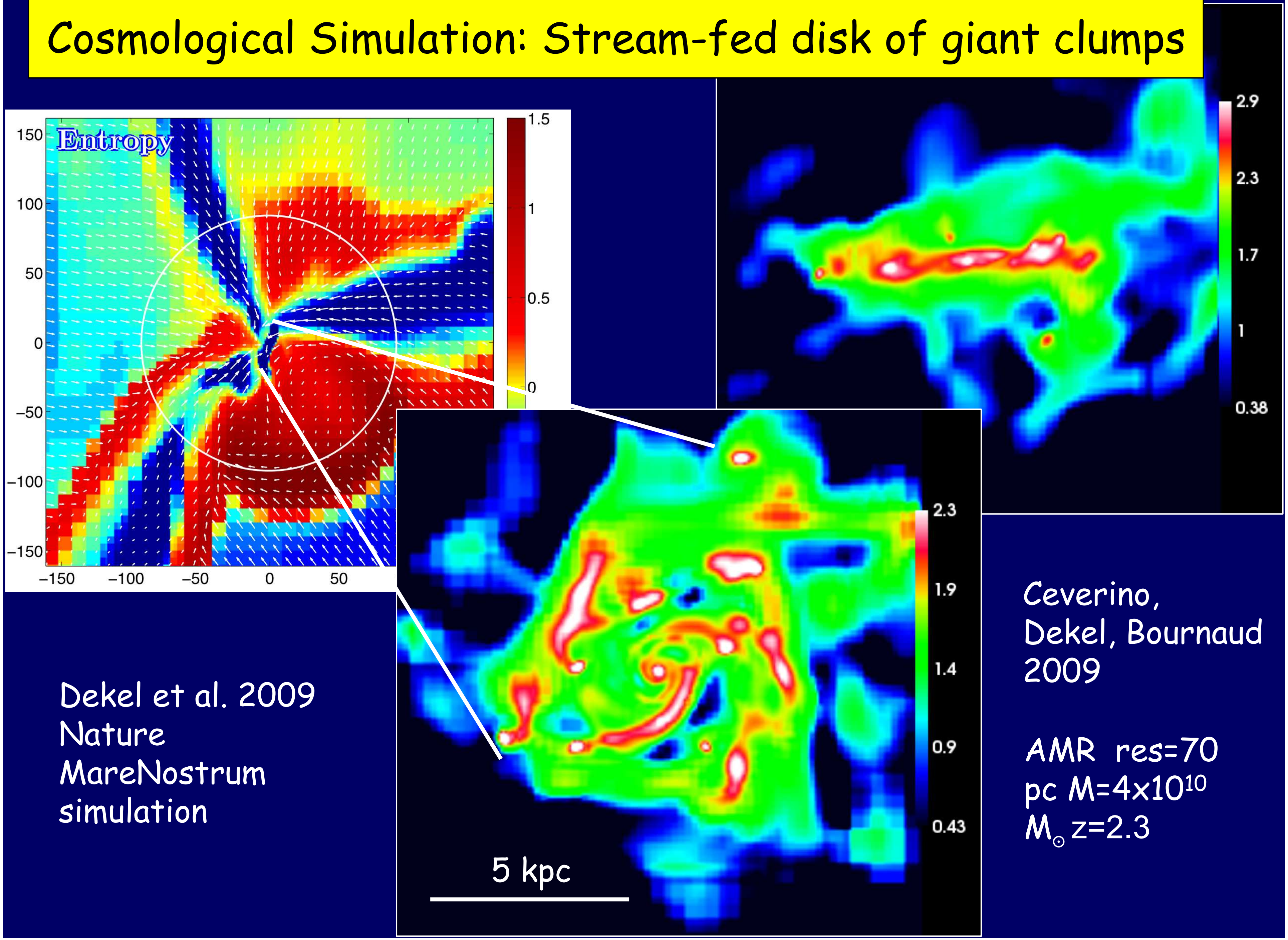
Evolution into Steady State

$$\dot{\delta} \approx 0.5(1-\gamma-2\delta)\,t_{acc}^{-1} - \delta\, t_{evac}^{-1}(\delta)$$



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

Cosmological Simulation: Stream-fed disk of giant clumps



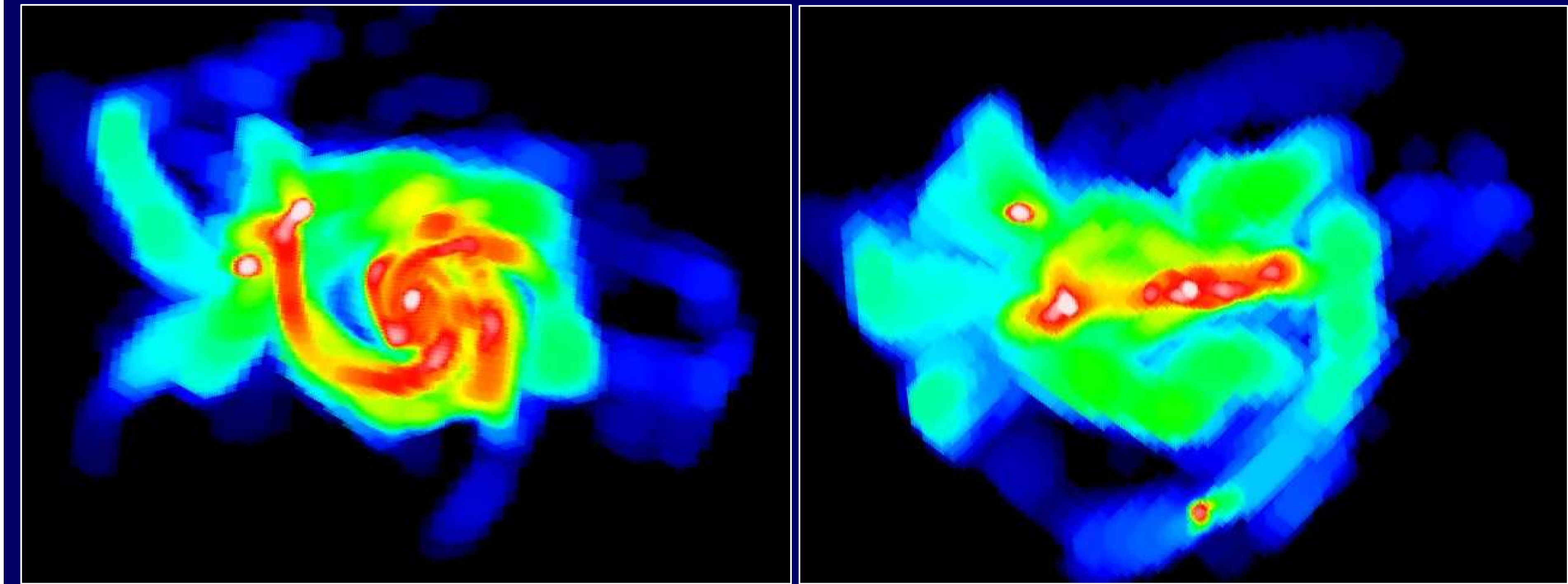
Dekel et al. 2009
Nature
MareNostrum
simulation

Ceverino,
Dekel, Bournaud
2009

AMR res=70 pc $M=4\times10^{10}$ $M_\odot$ $z=2.3$

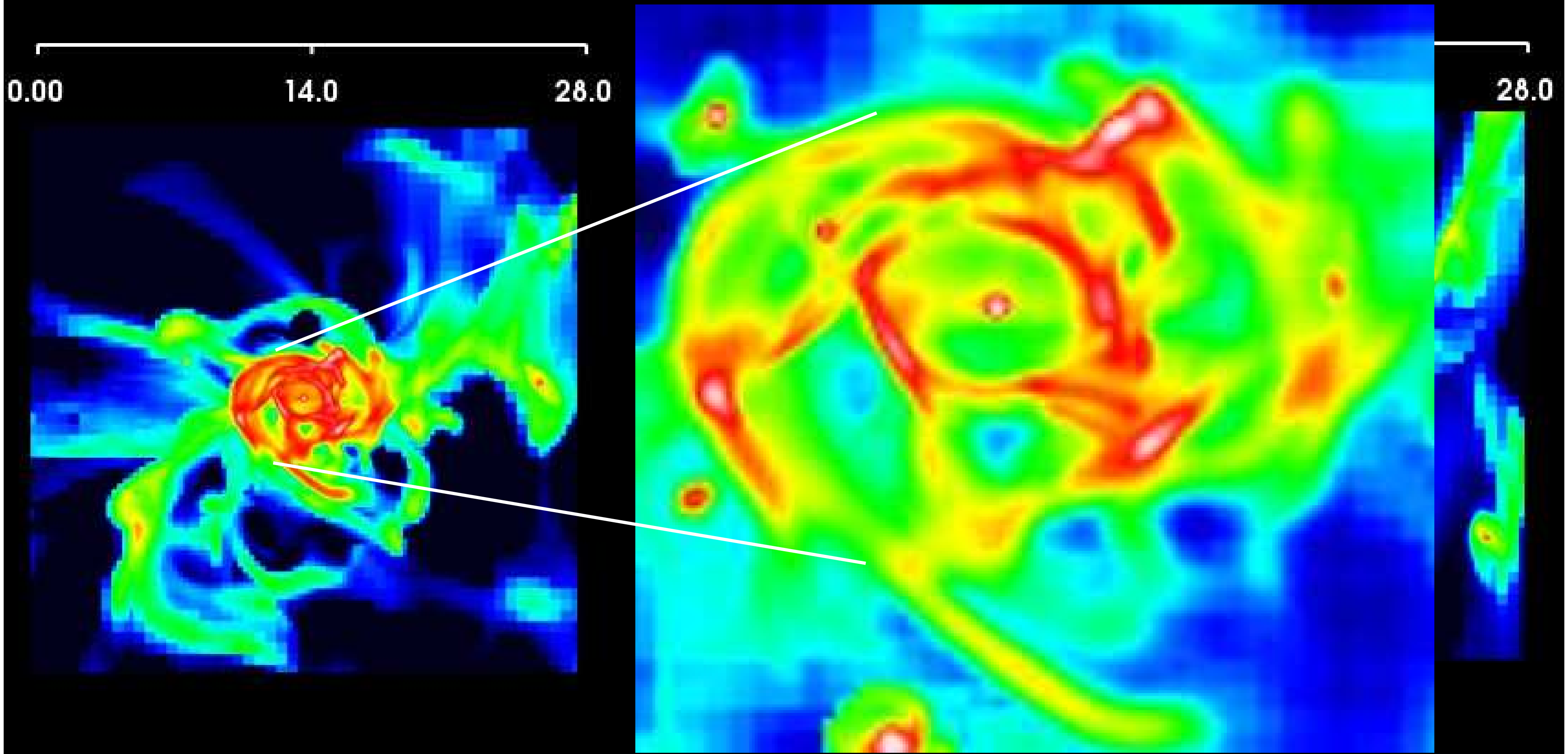
Cosmological Simulation: Stream-fed disk of giant gas clumps

Ceverino, Dekel 2009   AMR res: 70 pc M_v=8x10^{11} $M_\odot$ z=2.1

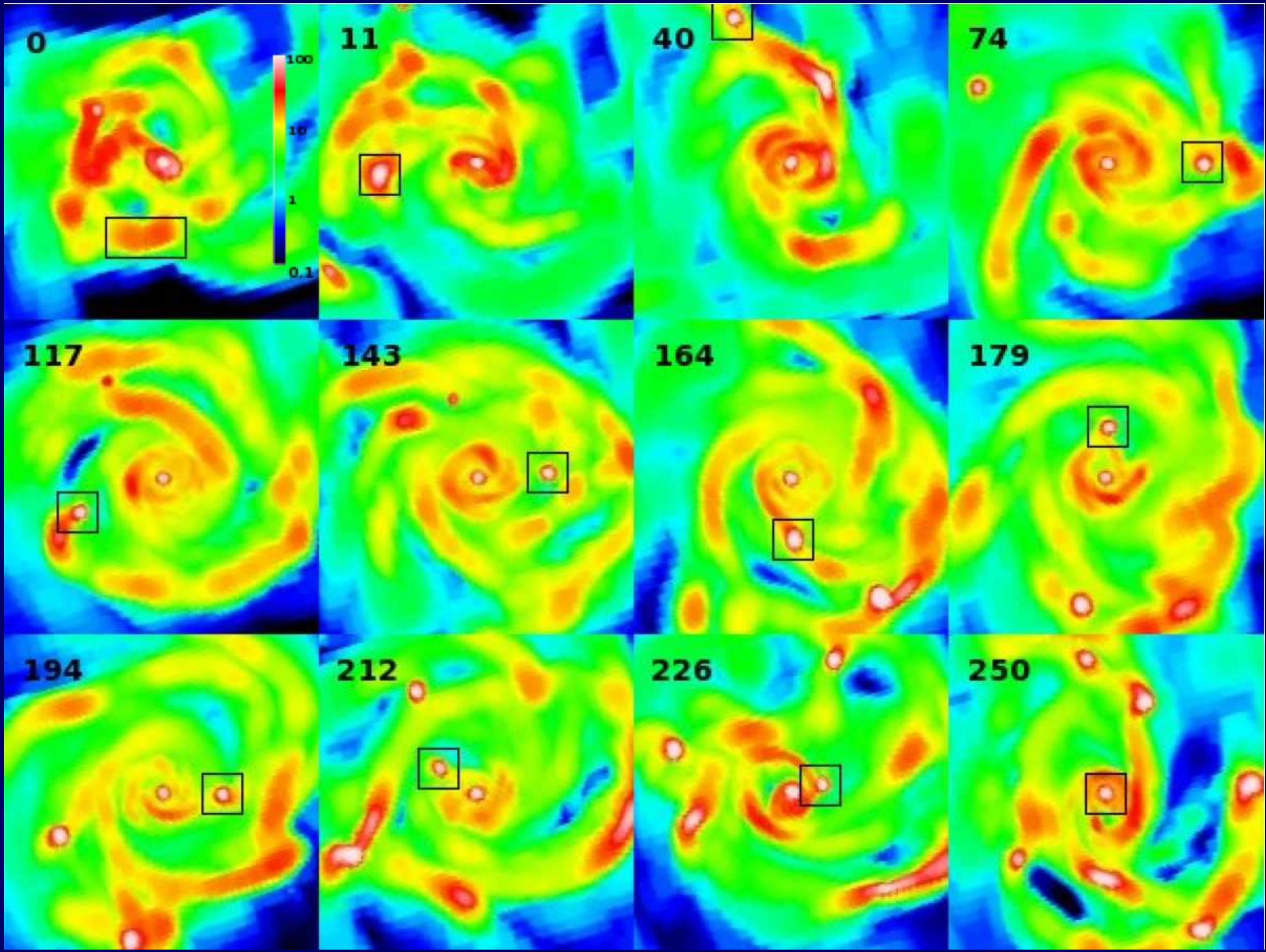


Cosmological Simulation:
Stream-fed disk of giant gas clumps

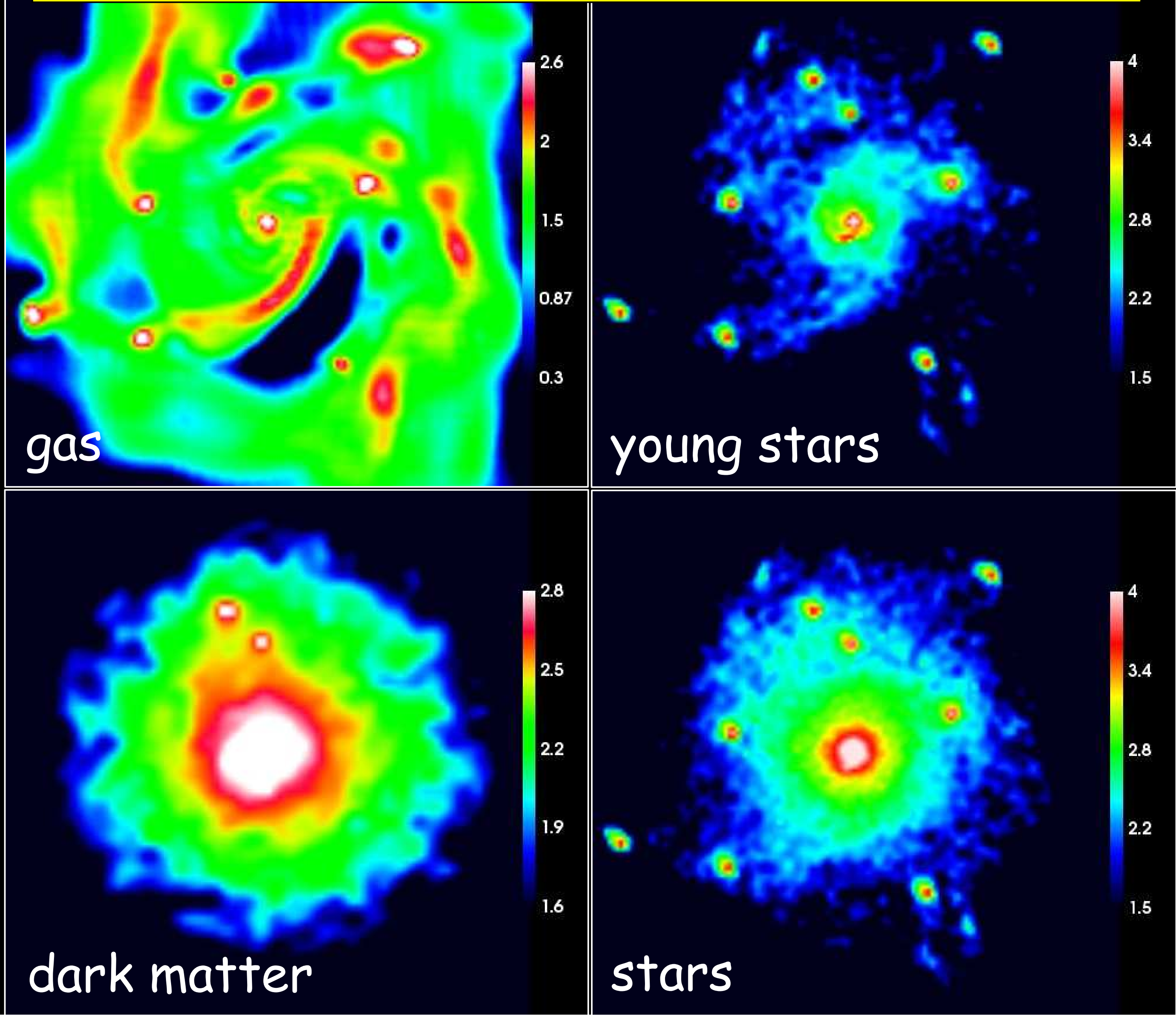
Ceverino, Dekel 2009   AMR res: 70 pc M_v=8x10^{11} $M_\odot$ z=2.1



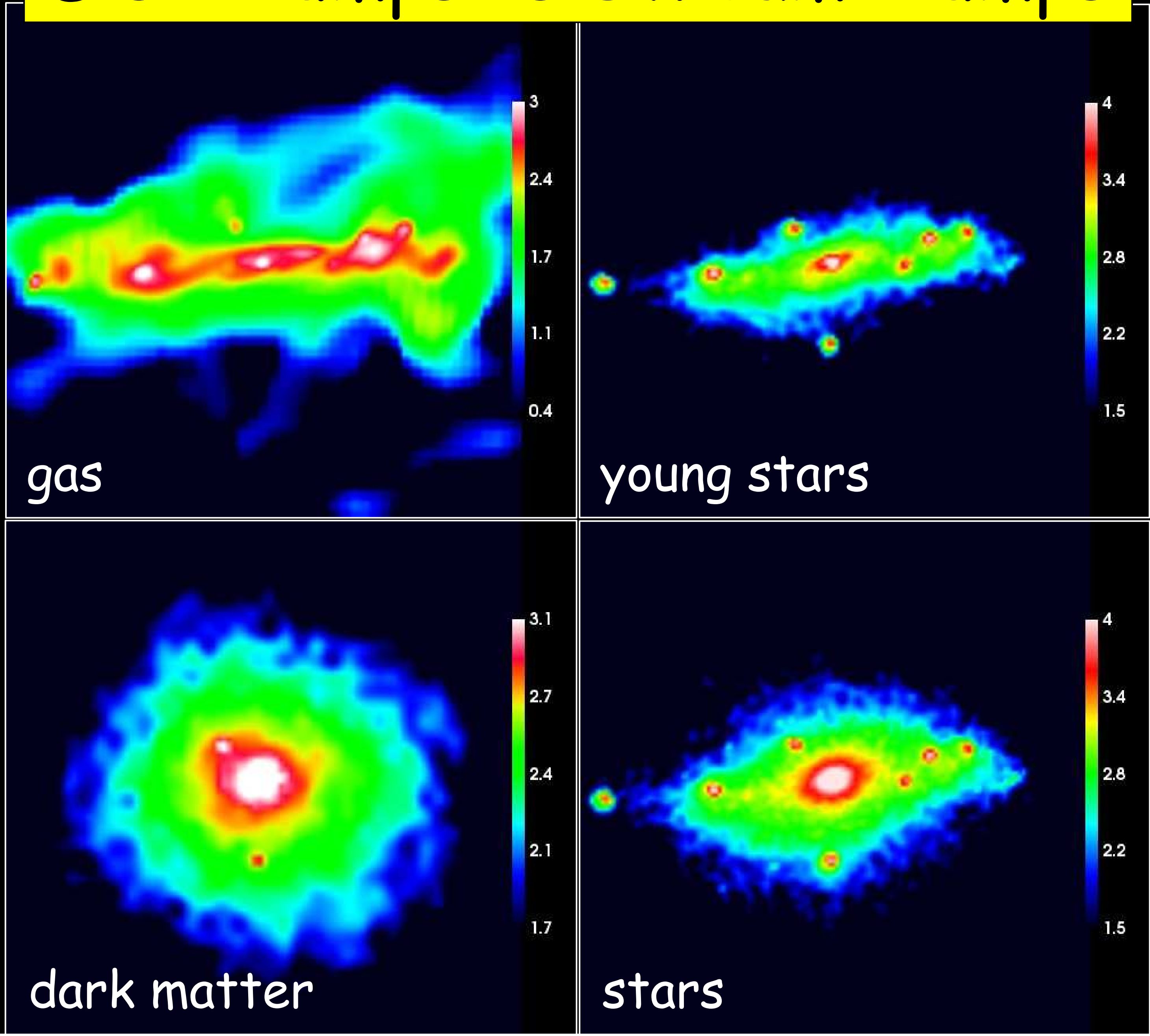
Clump Formation & Migration



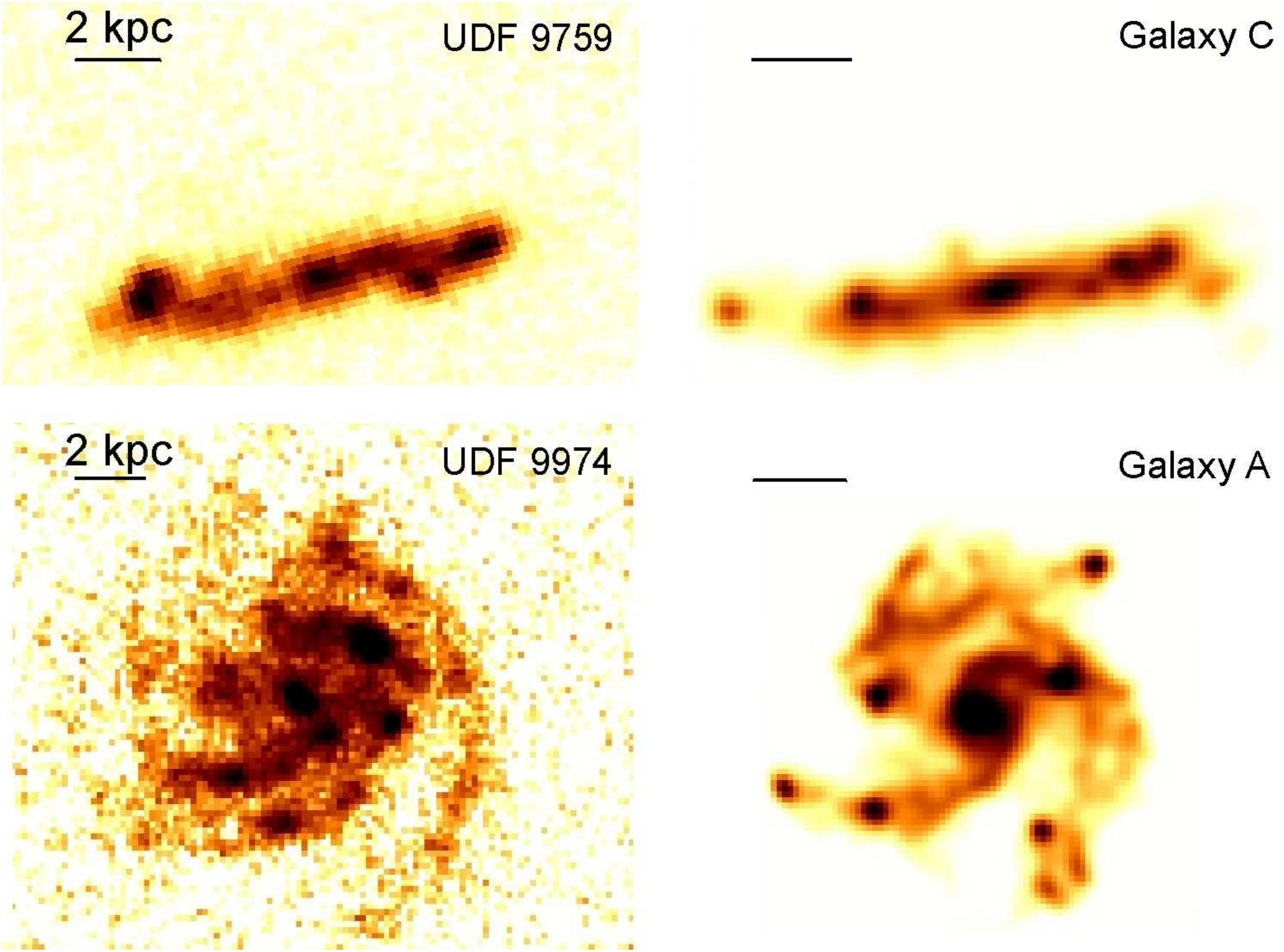
Disk Clumps vs Stream Clumps



Disk Clumps vs Stream Clumps



Observations vs. Simulations



Star Formation and Feedback

Predicted accretion rate versus observed SFR → $\dot{M}_* \approx \dot{M}_{acc}$

→ SFR efficiency per t_{dyn} in clumps: $\eta = \frac{\dot{M}_*}{(\sum m_{clump})/t_{dyn}} \approx 0.06\, \delta_{0.3}^{-1}$

if require η ~ 0.01 → star formation in denser sub-clumps

Clumps not disrupted by SN feedback $\sigma > V_{SN} \approx \eta_{0.1}^{1/2} \times 30\, \mathrm{km\, s^{-1}}$

Clump disruption by radiative stellar feedback?

Murray et al.: 20% of the clump turn into stars in 1-2 t_{dyn} while the rest 80% gas is expelled back to the disk.

Clumps become smaller star clusters – slower migration.

Steady state is valid: disrupted clumps are replaced by new clumps.

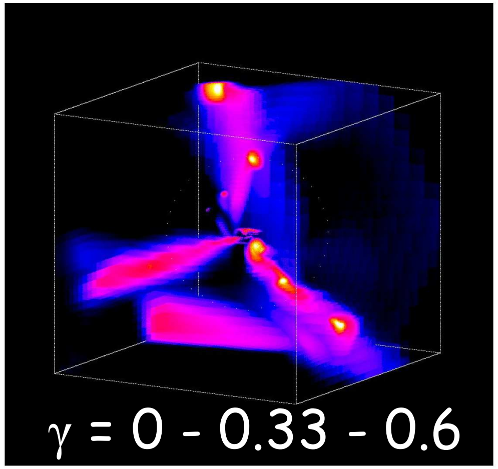
Disk evacuation into star clusters instead of migration.

$t_{SF} \approx t_{mig} \approx 10\, t_{dyn}$

But little bulge buildup by migration.

Are there enough mergers for spheroid buildup?

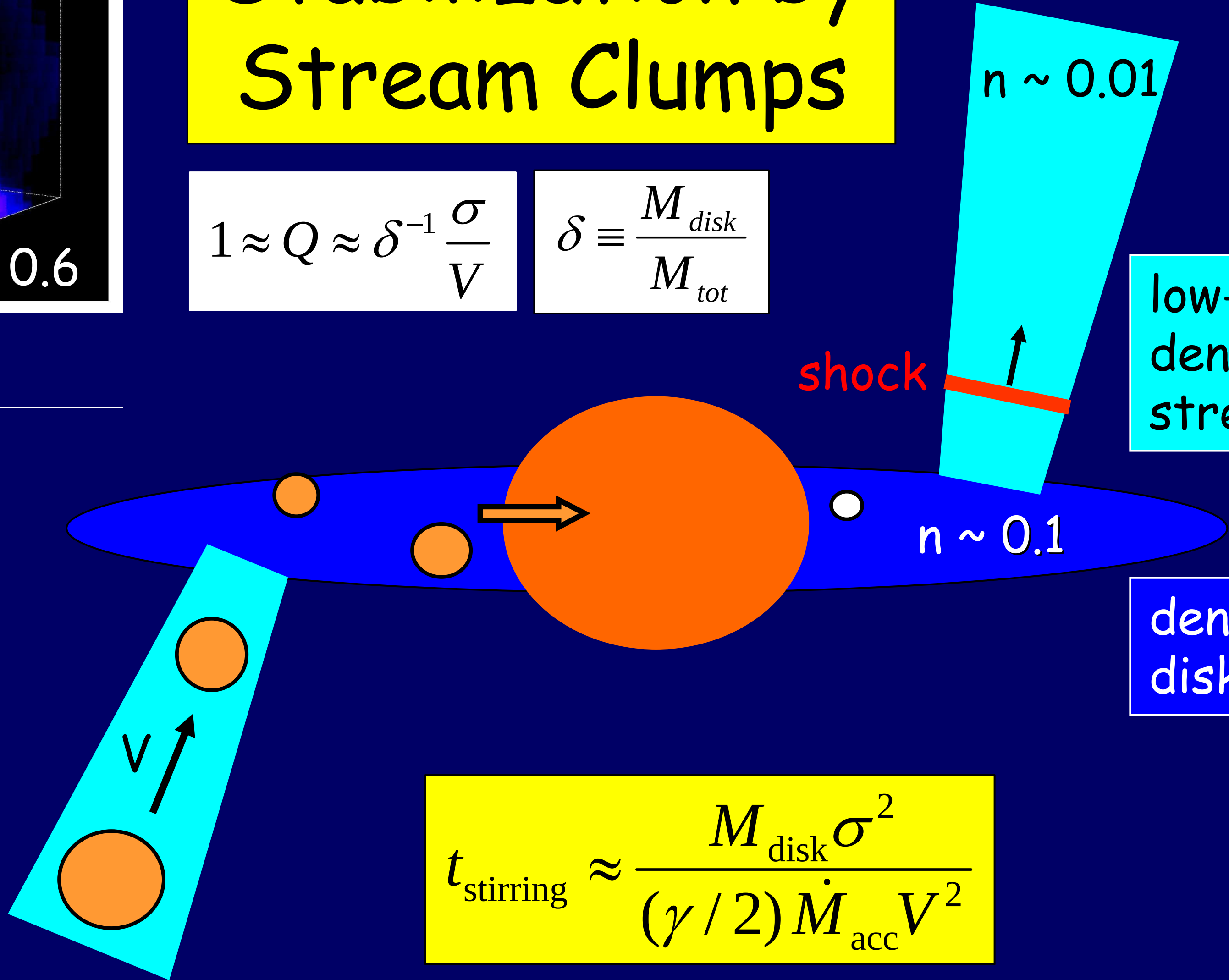
Observational test: is the age-spread in each clump <100 Myr?



Stabilization by Stream Clumps

$$1 \approx Q \approx \delta^{-1} \frac{\sigma}{V}$$

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



low-density stream

dense disk

dense stream clumps

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

$$t_{\rm stirring} \approx \frac{M_{\rm disk}\sigma^2}{(\gamma/2)\dot{M}_{\rm acc}V^2}$$

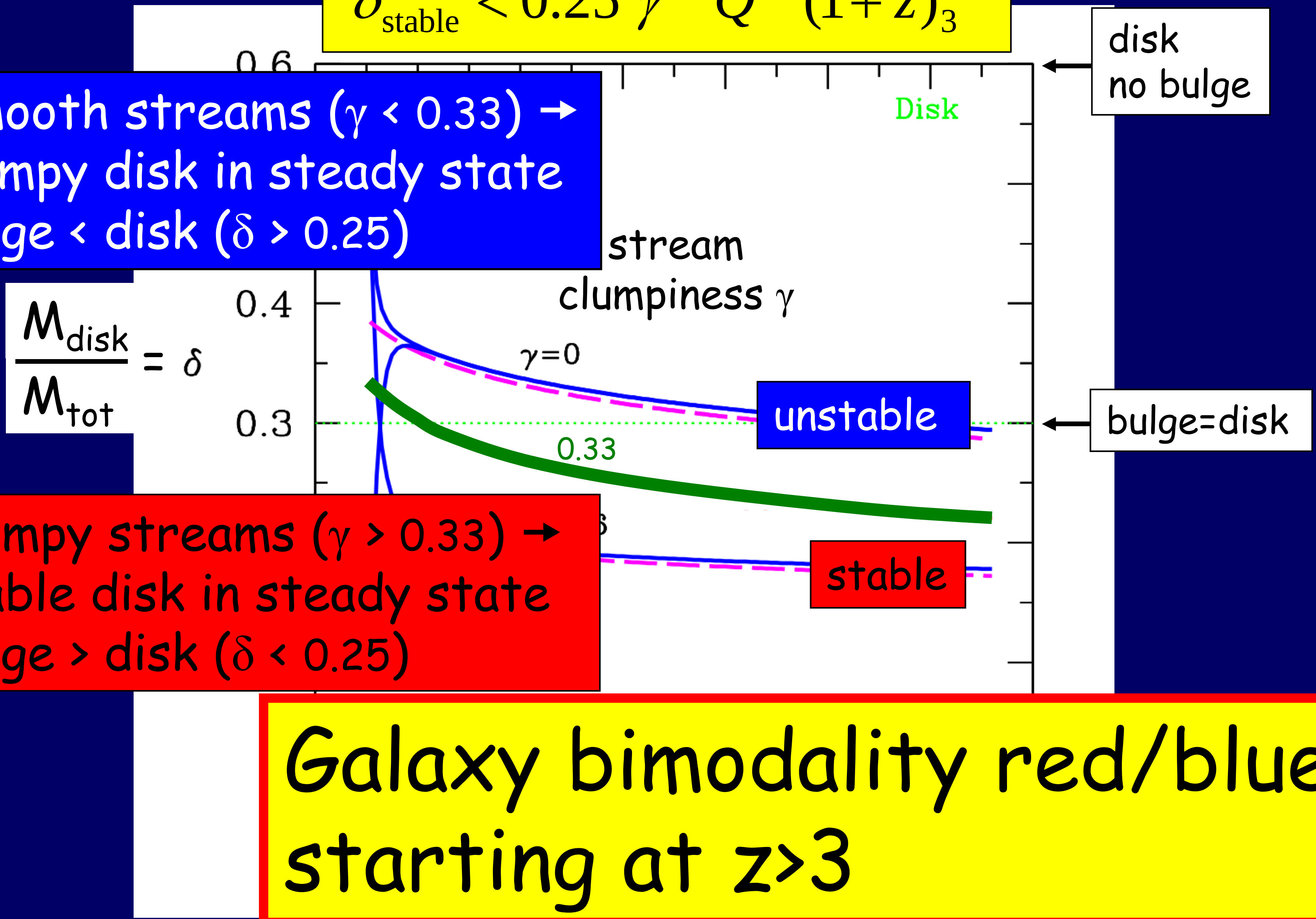
stabilization Q>1 for $\delta_{\rm stable} < 0.25\, \gamma^{1/3}\, Q^{-1} (1+z)_3^{1/3}$

Stabilization by Stream Clumps

$$\delta_{\rm stable} < 0.25\,\gamma^{1/3} Q^{-1} (1+z)_3^{1/3}$$

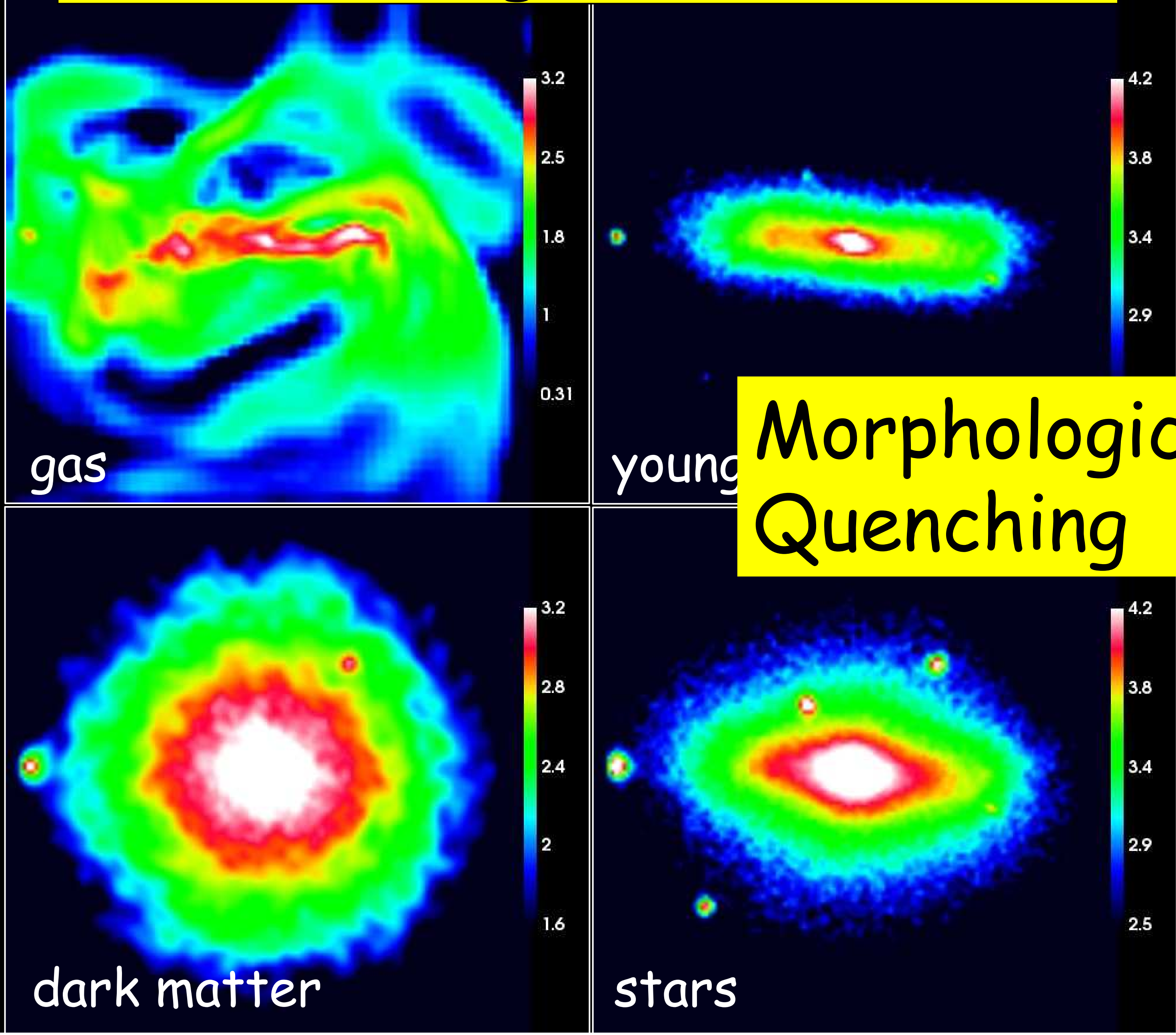
Smooth streams (γ < 0.33) → clumpy disk in steady state bulge < disk (δ > 0.25)

Clumpy streams (γ > 0.33) → stable disk in steady state bulge > disk (δ < 0.25)

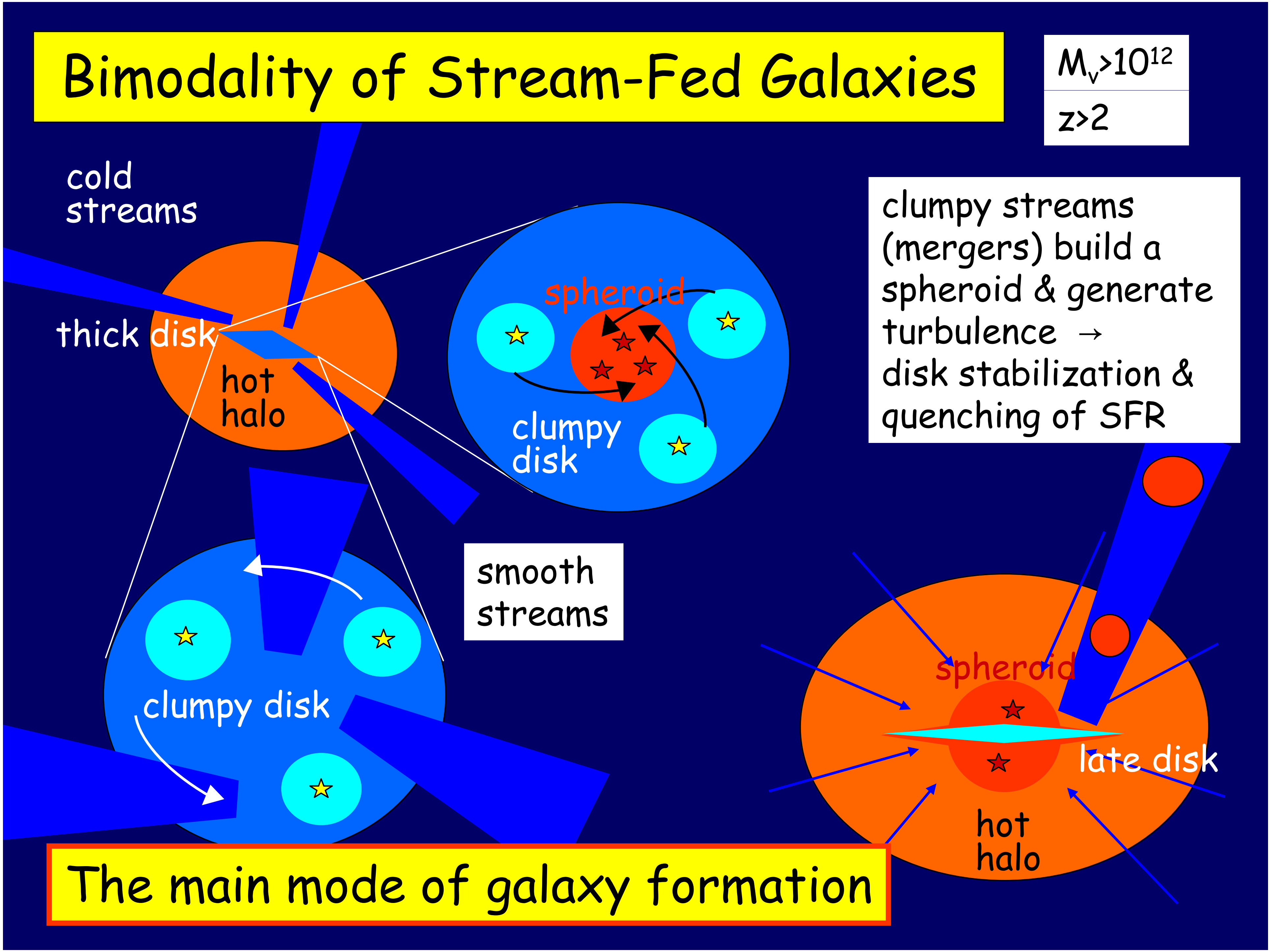


Galaxy bimodality red/blue starting at z>3

Massive Bulge – Stable Disk

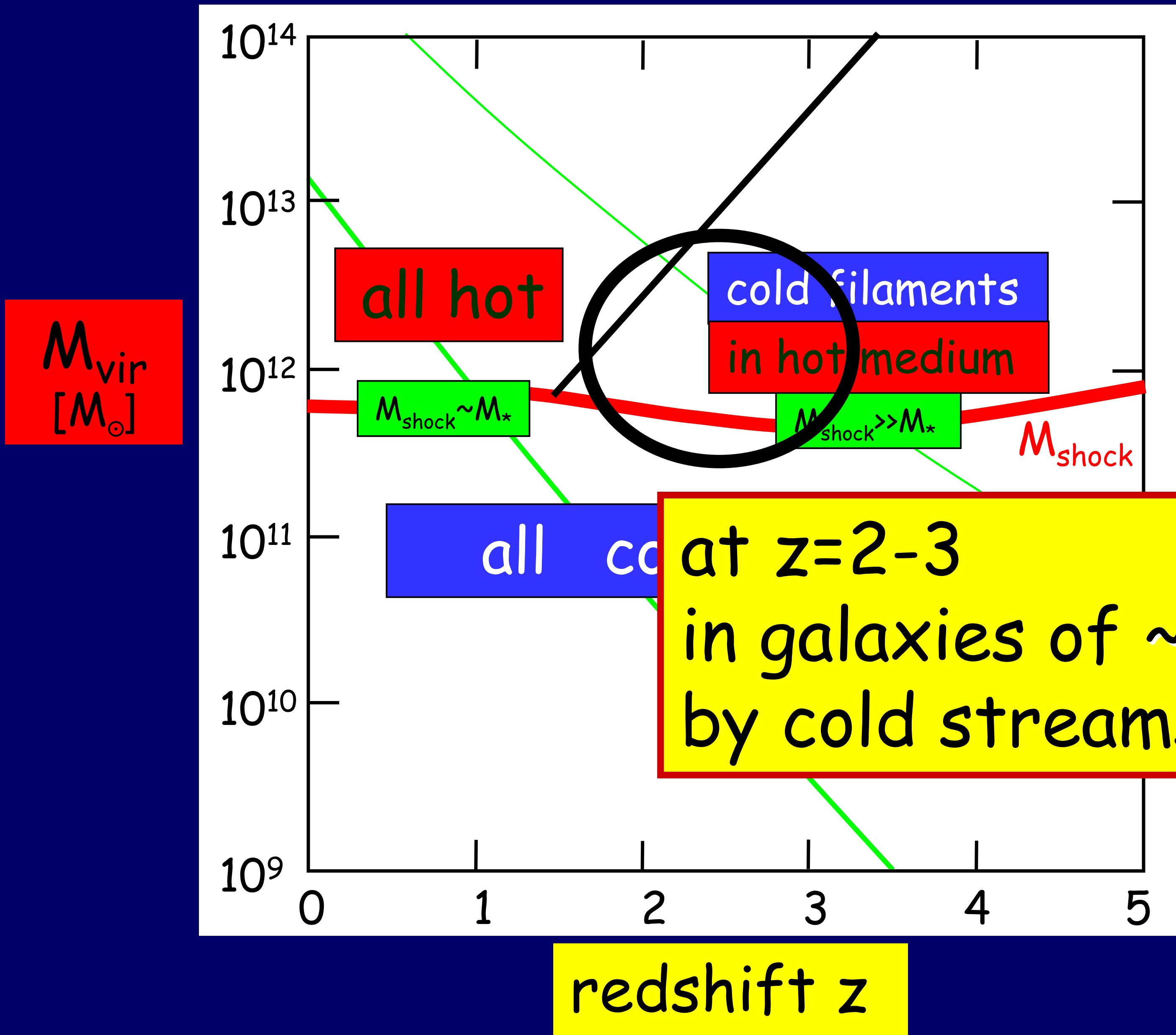


Morphological Quenching



Bimodality of Stream-Fed Galaxies
M_v>10[12]
z>2
cold streams
thick disk
hot halo
spheroid
clumpy disk
clumpy streams (mergers) build a spheroid & generate turbulence →
disk stabilization & quenching of SFR
smooth streams
clumpy disk
spheroid
late disk
hot halo
The main mode of galaxy formation

When and where did most stars form?



at z=2-3
in galaxies of ~10^{11} $M_\odot$
by cold streams

Dekel & Birnboim 06

Open Issues

- Star formation in the giant clumps

- Clump survival

- Fate of the hi-z clumpy disks at $z=0$

  thick stellar disks of spirals? Lenticulars?

- Why are $z=0$ disks not wildly unstable?
- low input rate of cold streams
- disk is dominated by stars
- dominant bulge (?)

- How did thin disks form at late z?

  by cold, spherical, slow accretion in $M_{vir} < 10^{12}\ M_\odot$

Conclusions

Stream-Fed Galaxies: High-z massive galaxies are driven by narrow cold streams penetrating shock-heated halos (>$10^{12}M_\odot$)

Bimodality: star-forming disks vs red-and-dead spheroids by stream clumpiness: on average 1/3 mergers >1:10 and 2/3 smooth

Unstable disks in steady state driven by streams ~ 3Gyr gaseous, extended, turbulent $V/\sigma \sim 4$, self-regulated by gravity, giant clumps $10^{8\text{-}9}M_\odot$ & transient features, bulge ~ disk

SFR in clumps ~ accretion rate ~ $100M_\odot\,yr^{-1}$. In sub-clumps

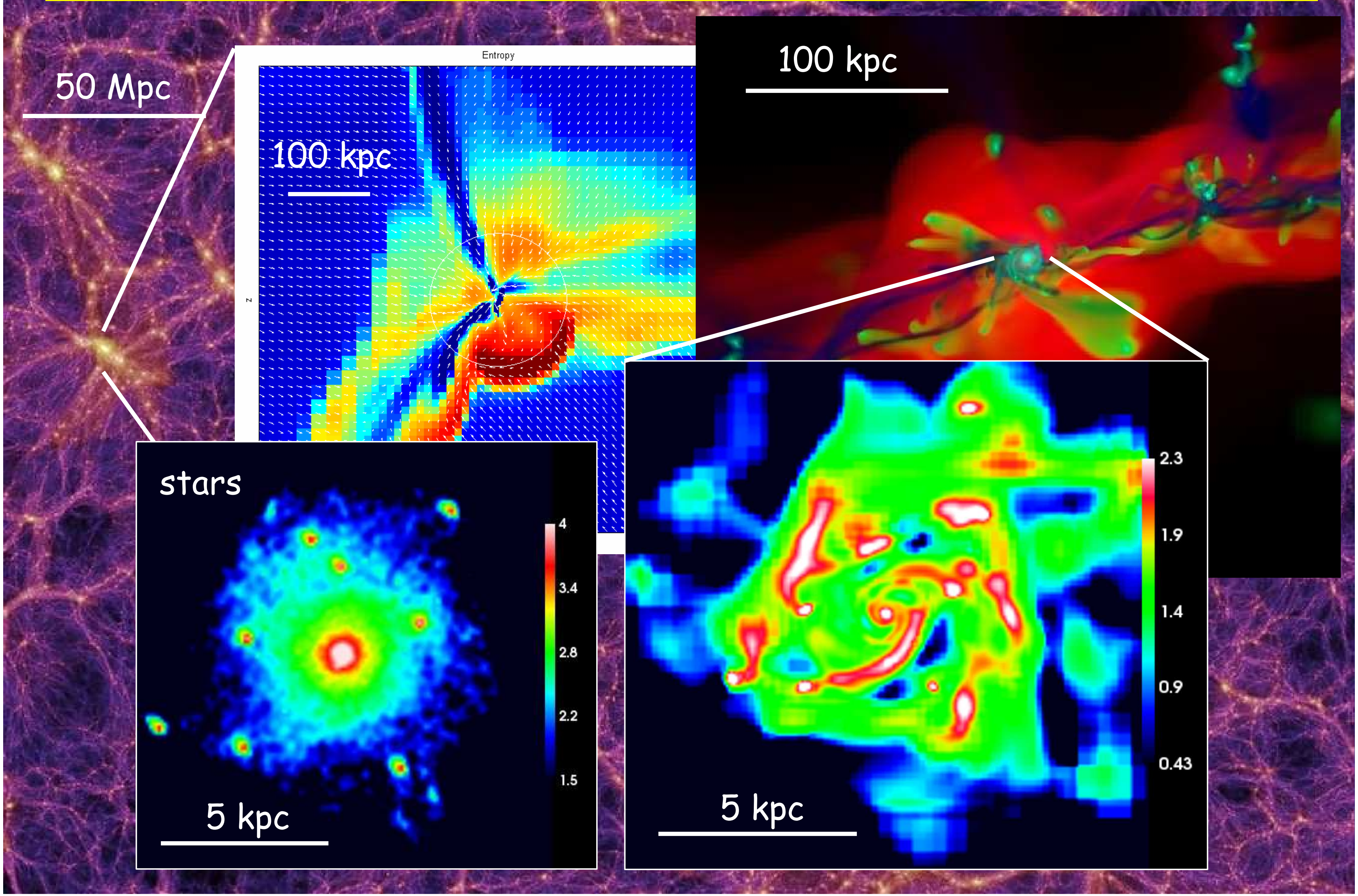
Merger starbursts are only 1/4 of the SFGs at a given SFR

Bulge buildup from the disk by clump migration and angular momentum transport. Compact spheroids in extended disks

Morphological Quenching into red galaxies: disk stabilization by bulge growth and turbulence, driven by clumpy streams (mergers)

Cold streams as **Lα Blobs**, also detectable as absorbers LLS, DLAS

Galaxies Emerge from the Cosmic Web



Thank you