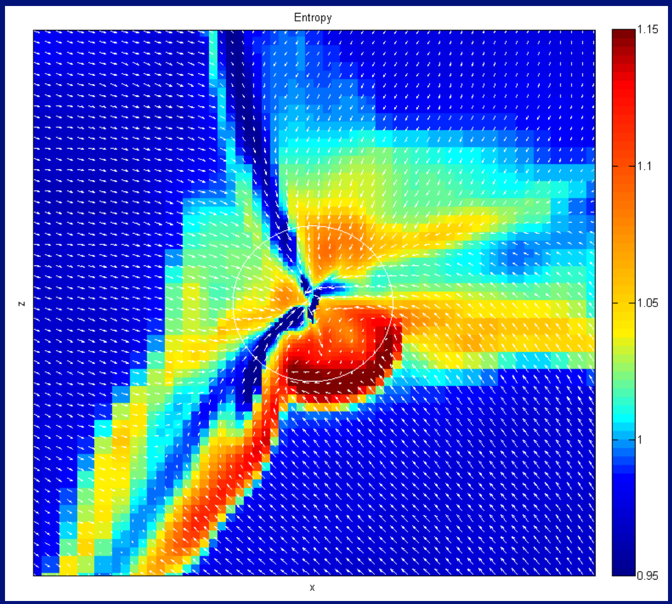
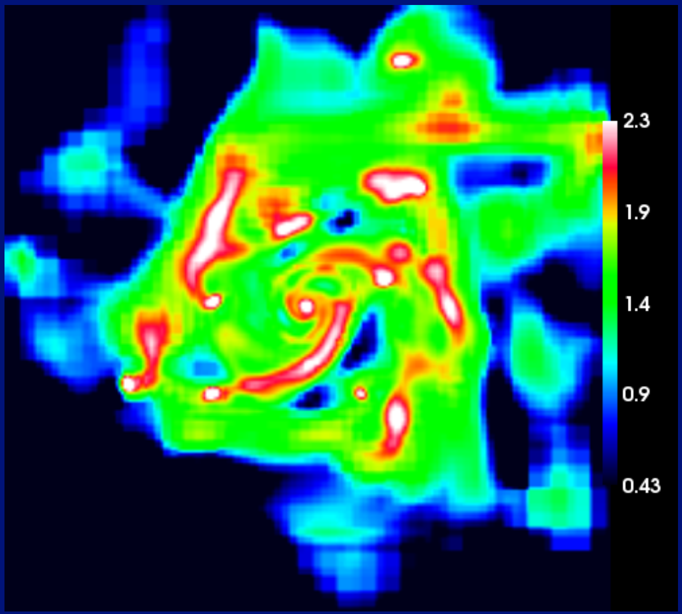
High-z Galaxy Formation in LCDM

Cosmic Web, Cold Streams, Clumpy Disks & Spheroids

Avishai Dekel, HU Jerusalem,

UCSC, July 2010





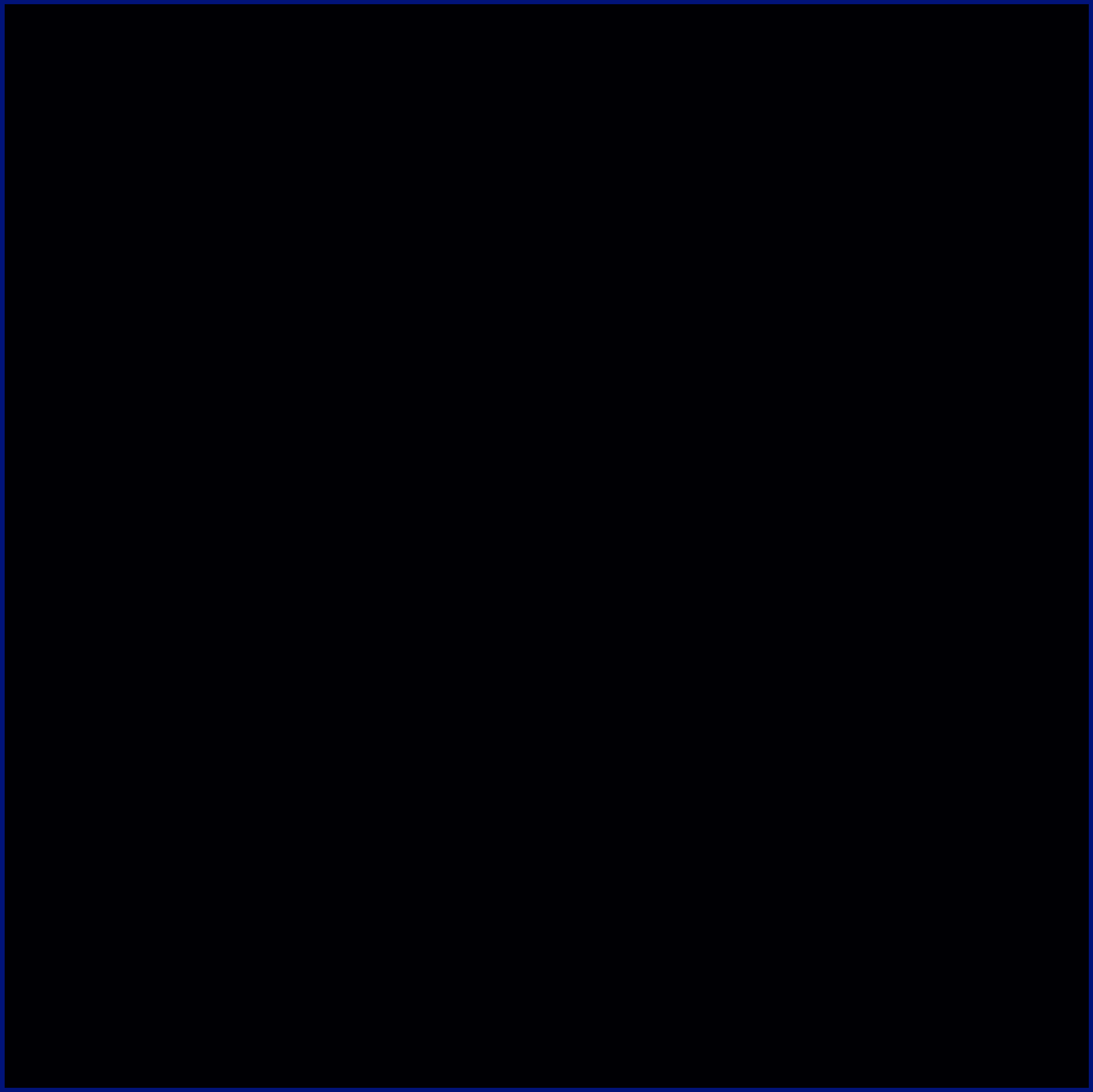
LCDM makes certain solid theoretical predictions for the most active phase of galaxy formation: massive galaxies (~$10^{11} M_{\odot}$) at high z (~2-3)

Theory seems consistent with observations, introducing a coherent picture

Open questions: SFR & feedback

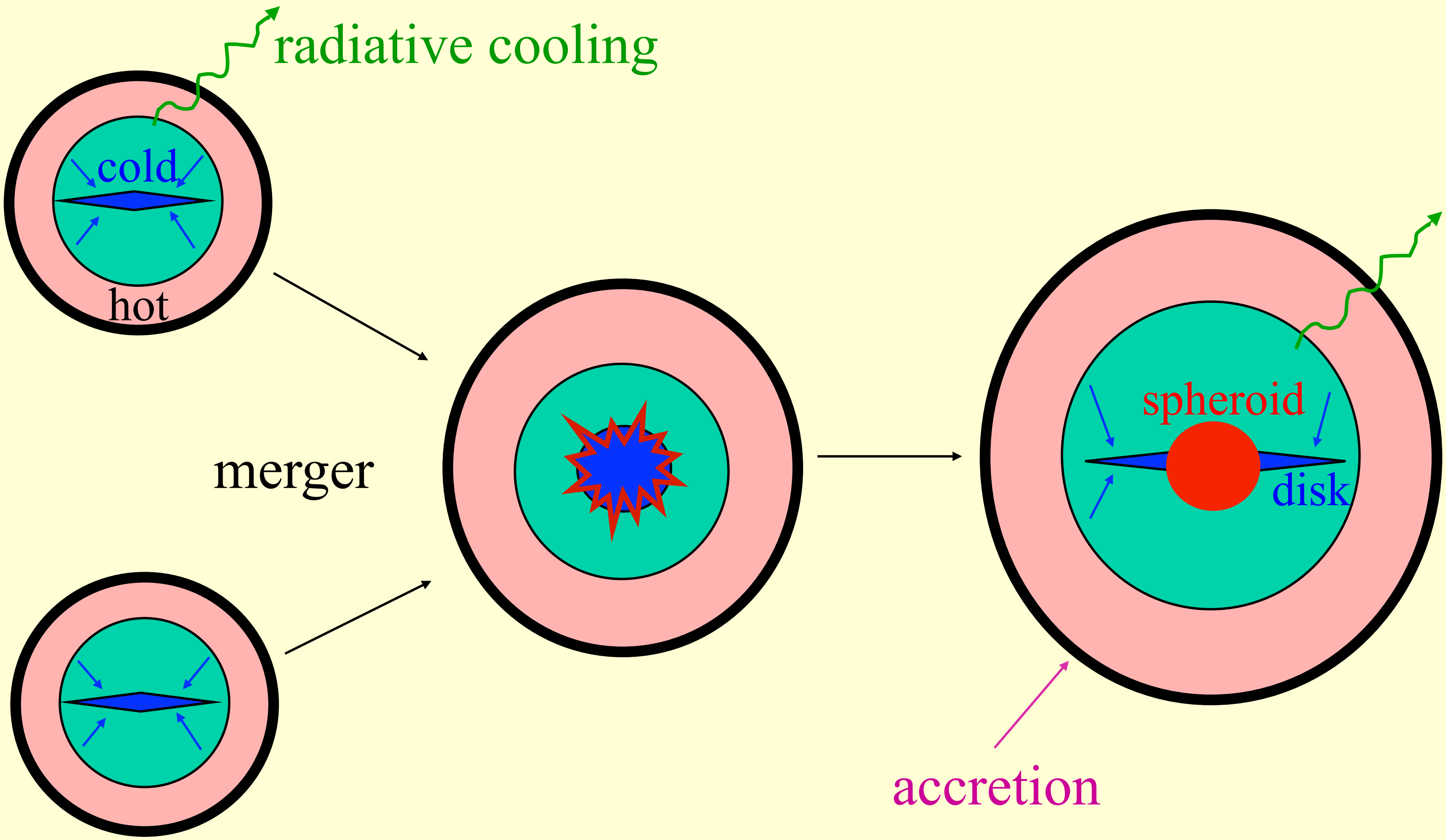
Simulations is a theorist's tool

Major mergers? starbursts & spheroids



TJ Cox

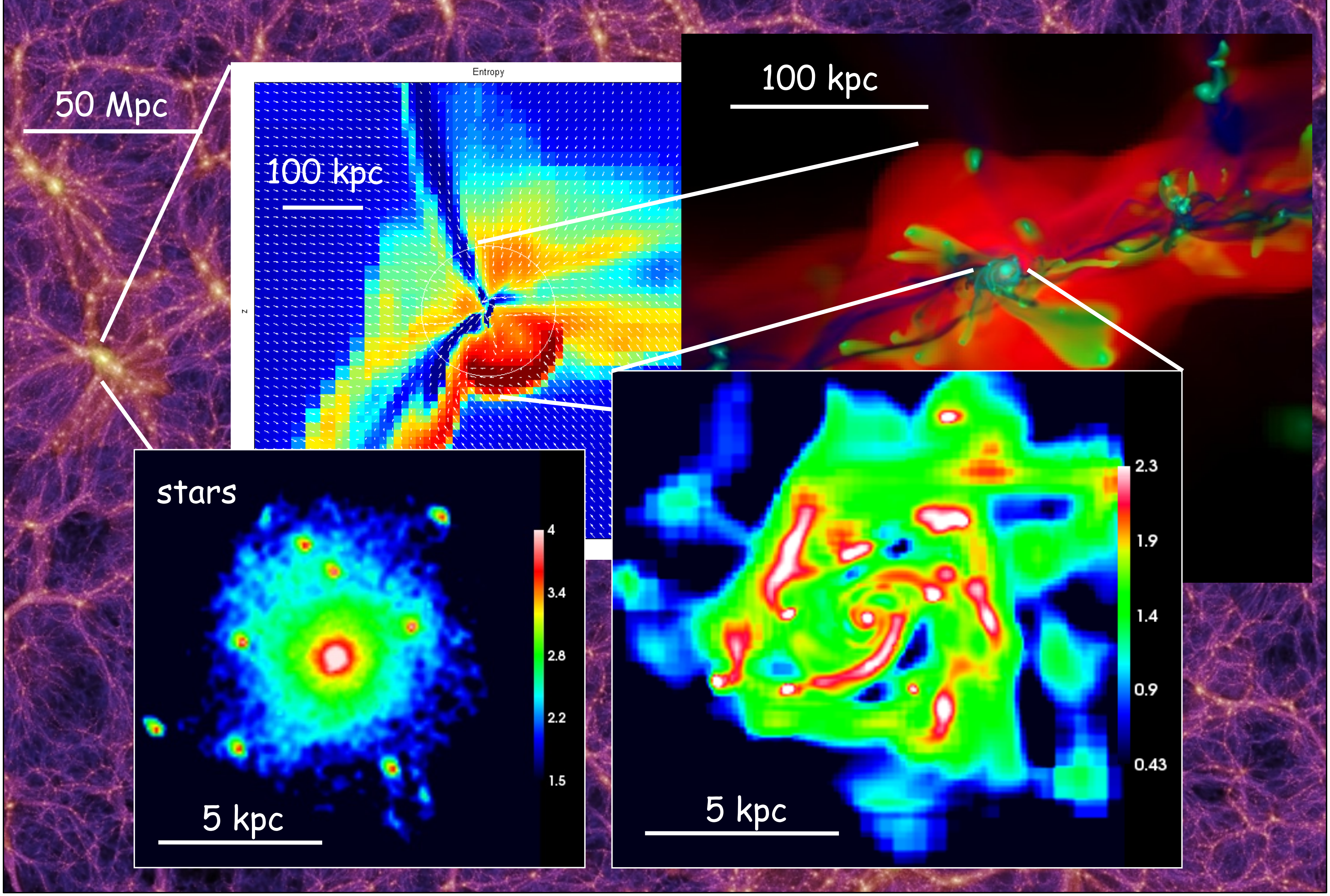
Standard Paradigm: Mergers



halos   cold gas → young stars → old stars

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

Cosmic Web, Cold Streams, Clumpy Disks & Spheroids



Collaborators

Simulations:
D. Ceverino (HU)
A. Kravtsov (Chicago)
A. Klypin (NMSU)

R. Teyssier (Zurich)
F. Bournaud (Paris)
M. Martig (Paris)
A. Burkert (Munich)
T. Naab (MPA)

DIP:
Genzel's group (MPE)
N. Bouche (UCSB)
N. Forster Schreiber
A. Sternberg (TAU)
L. Tacconi (MPE)

HU Team:
Y. Birnboim (CfA)
M. Cacciato (HU)
D. Ceverino (HU)
T. Goerdt (HU)
E. Neistein (MPA)
R. Sari (HU)
E. Zinger (HU)

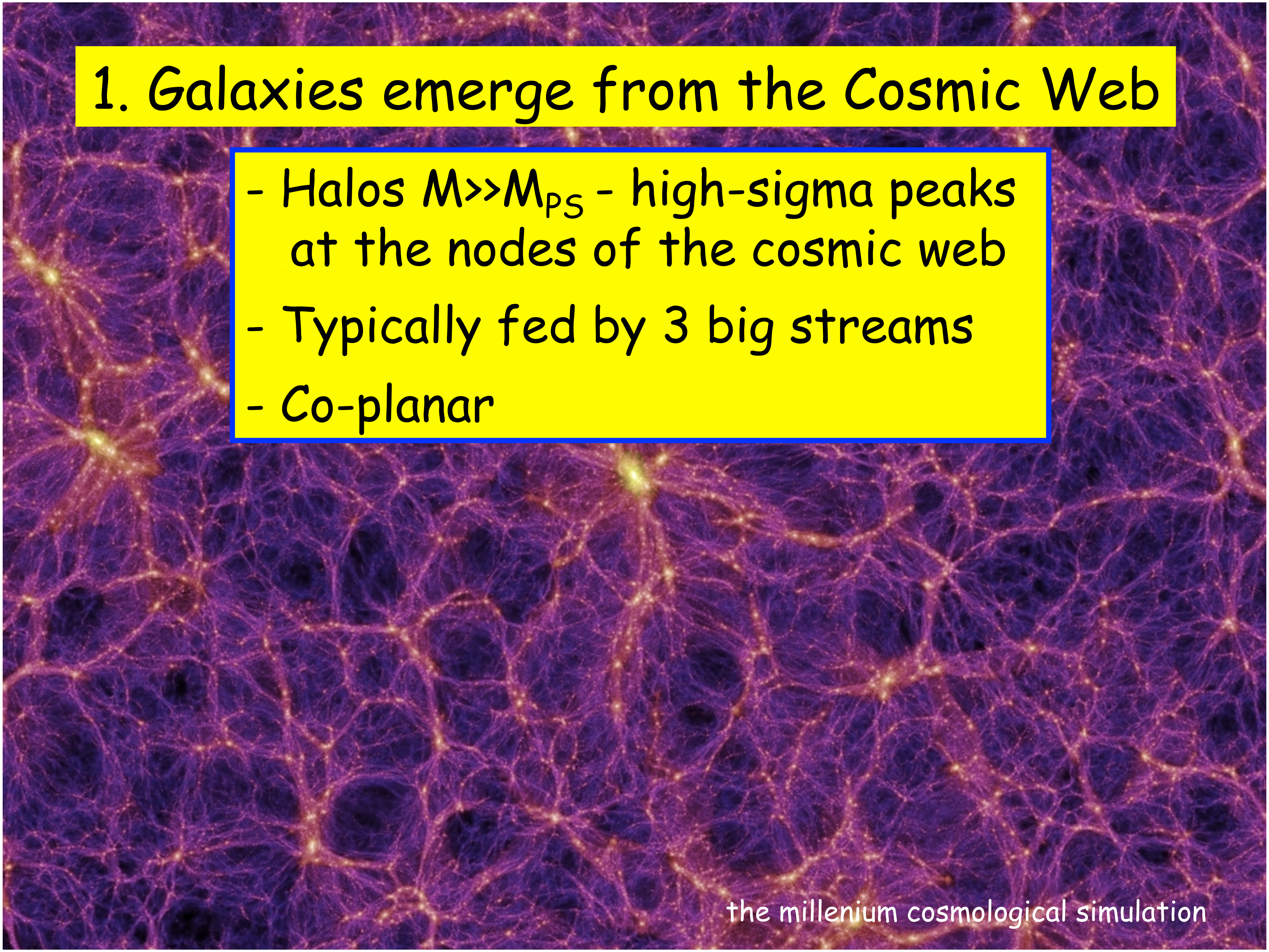
UCSC:
S. Faber's group
D. Kasen
M. Krumholz
J. Primack
J. Prochaska

Outline

- Galaxies from the cosmic web
- Cold gas streams into hot halos
- Streams in Lyman-alpha
- Mergers: stream clumpiness
- Violent disk instability in steady state
- SFR and feedback in disk clumps
- Spheroid formation: galaxy bimodality
- Quenching of star formation

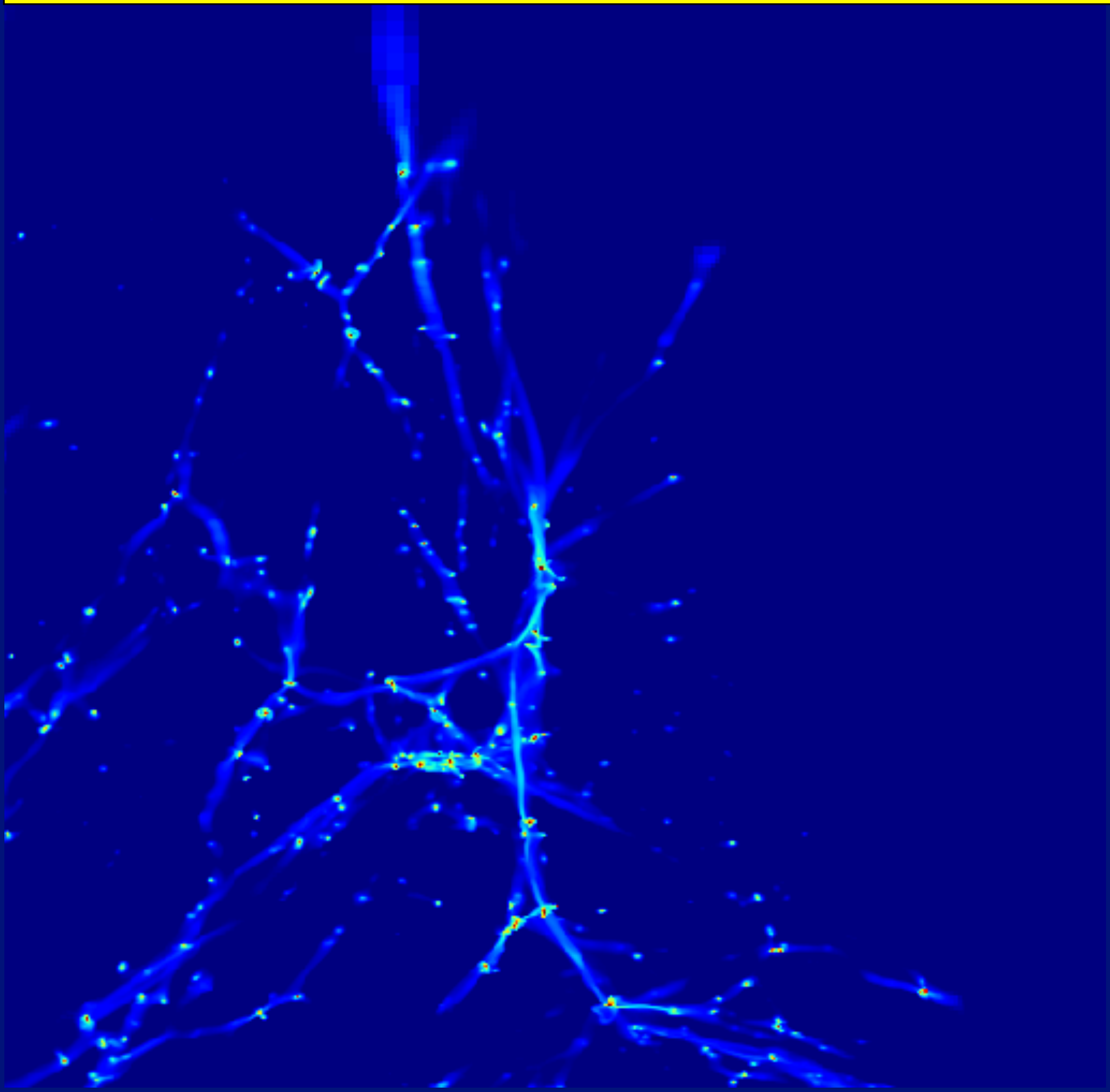
1. Galaxies emerge from the Cosmic Web

- 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

Three Streams: filament mergers



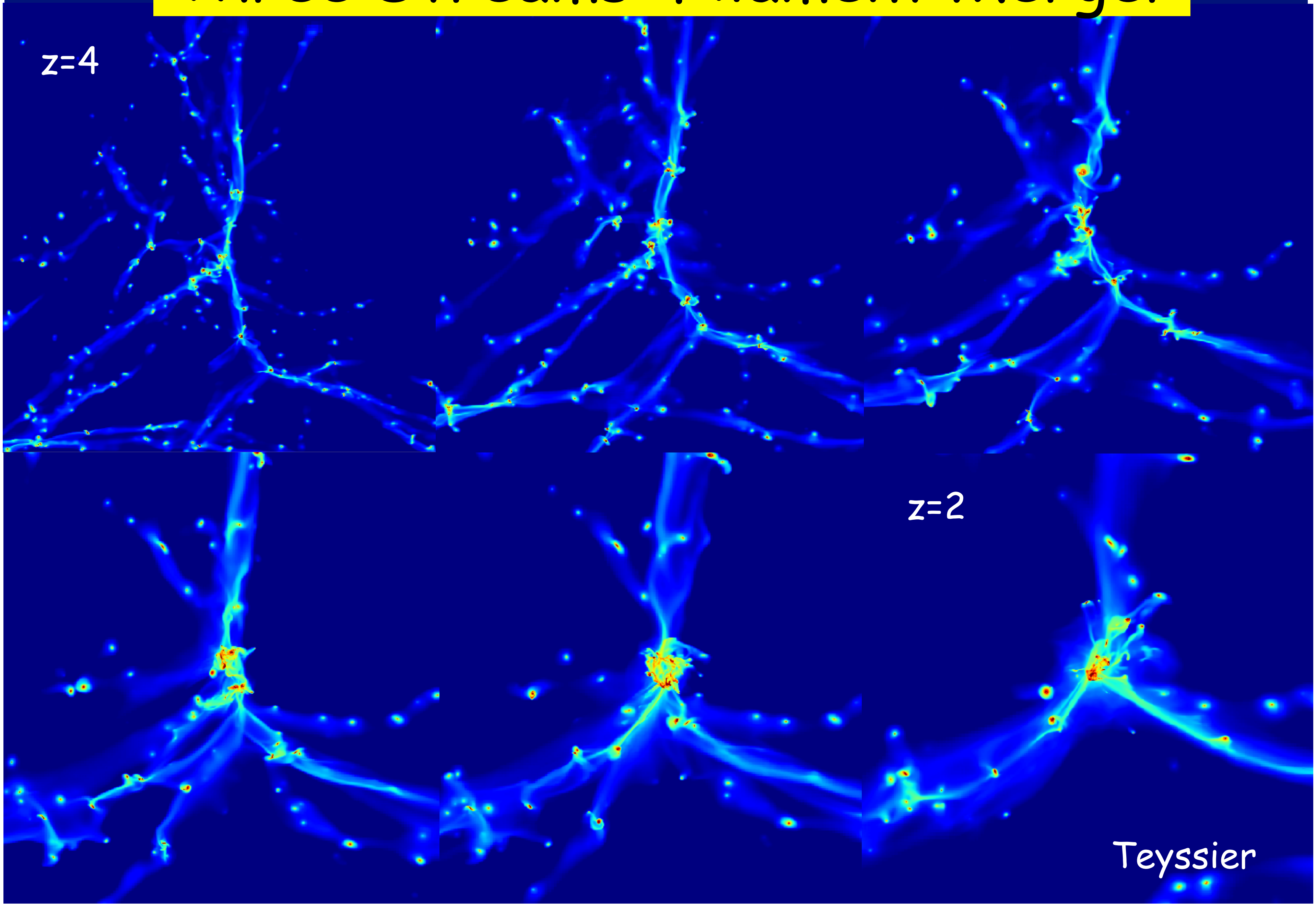
AMR RAMSES
Teyssier, Dekel

box 300 kpc

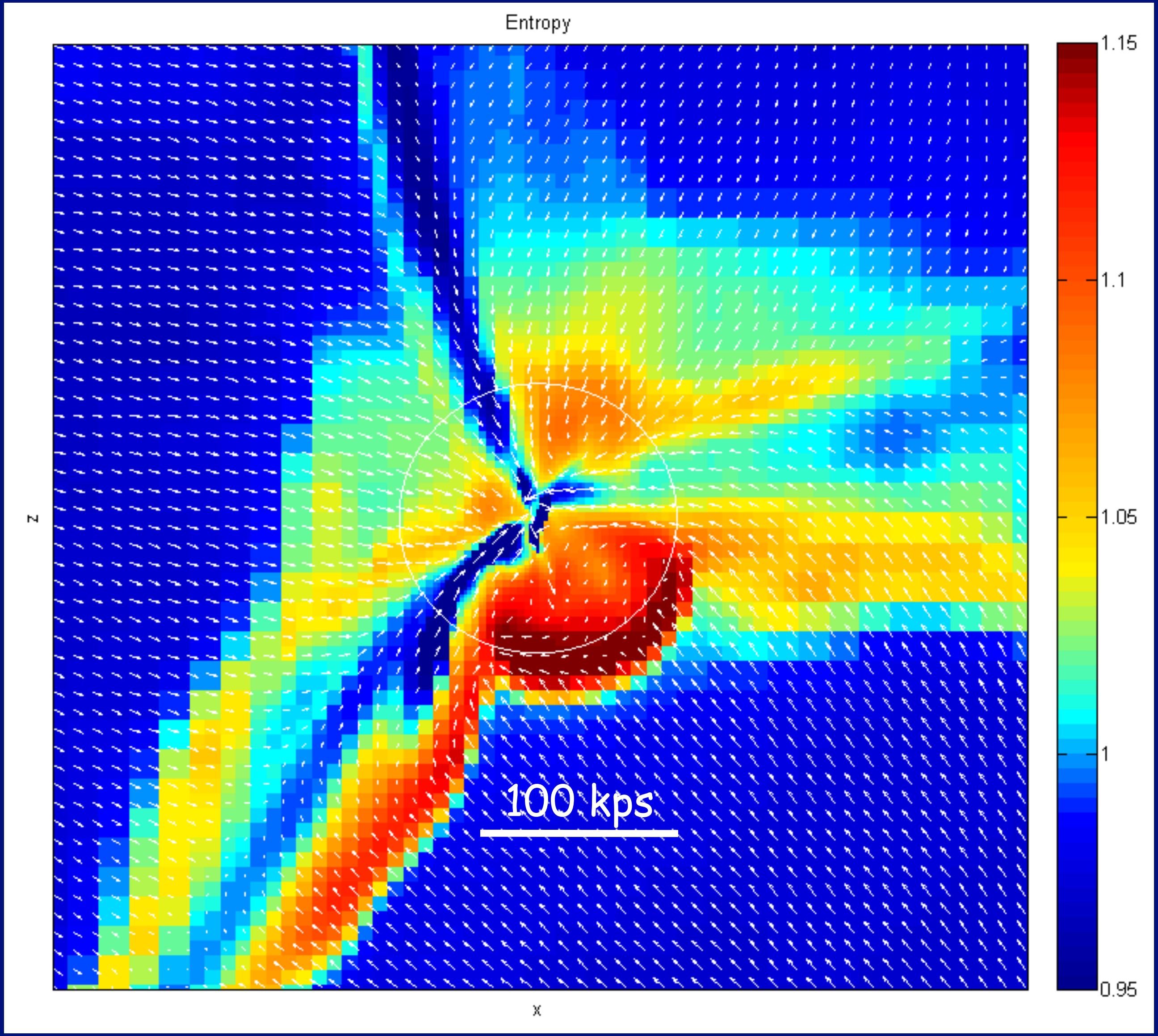
res 30 pc

z = 5.0 to 2.5

Three Streams: Filament Merger



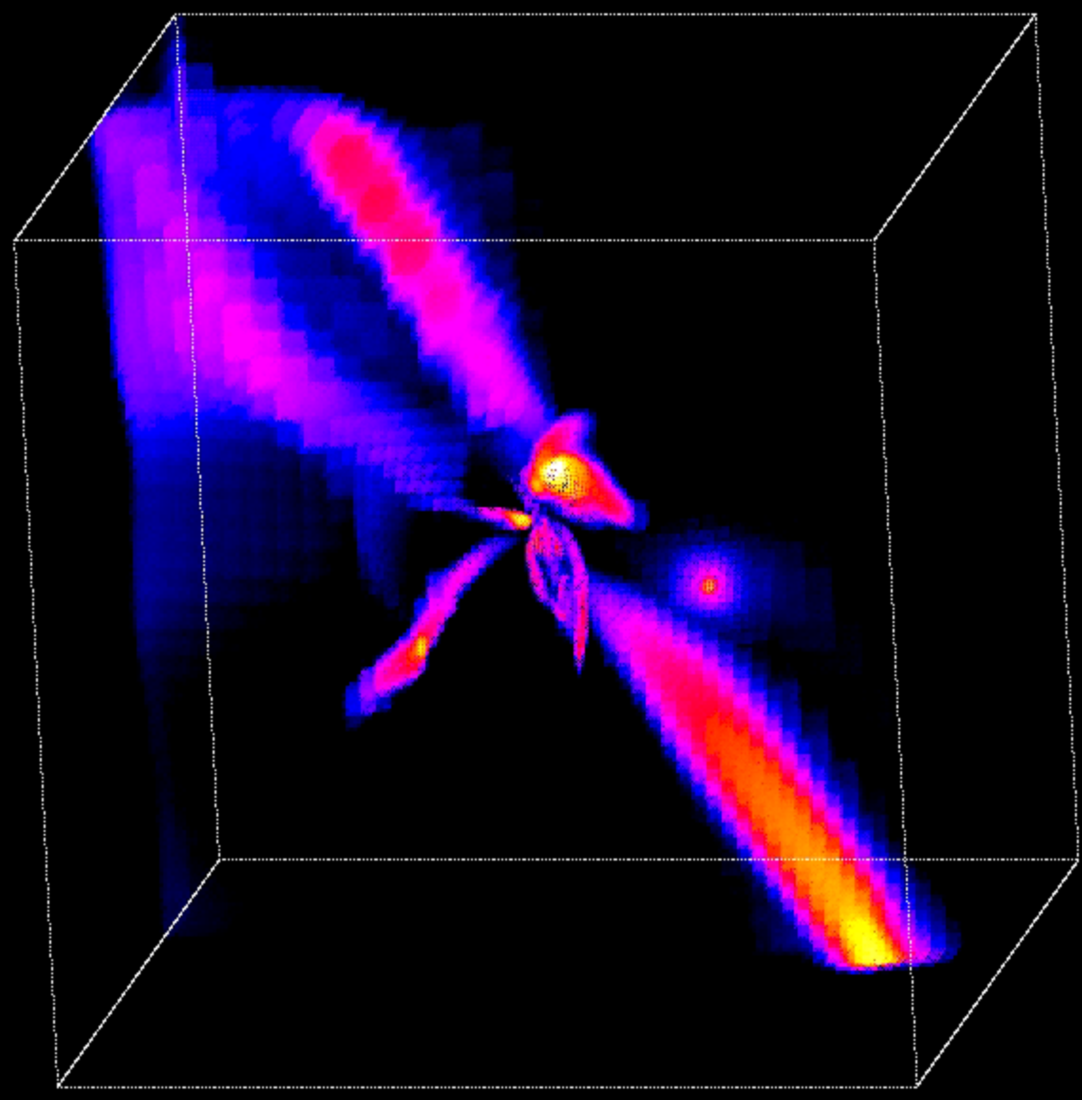
Streams are Co-planar



Dekel et al
09 Nature

Streams are Co-planar

Flux
per
solid
angle



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 in LCDM (<10% accuracy):

$$\left\langle \dot{M}_{baryon} \right\rangle = 80\, M_{\otimes} yr^{-1}\; M_{12}^{1.14}\; (1+z)_3^{2.4}\; f_{0.17}$$

Almost all penetrate to the inner halo in cold streams

The accretion rate governs galaxy growth & SFR
- can serve for successful simple modeling

SFR Driven by Accretion

Mass conservation

$$\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - \dot{M}_{*}$$

Kennicutt SFR

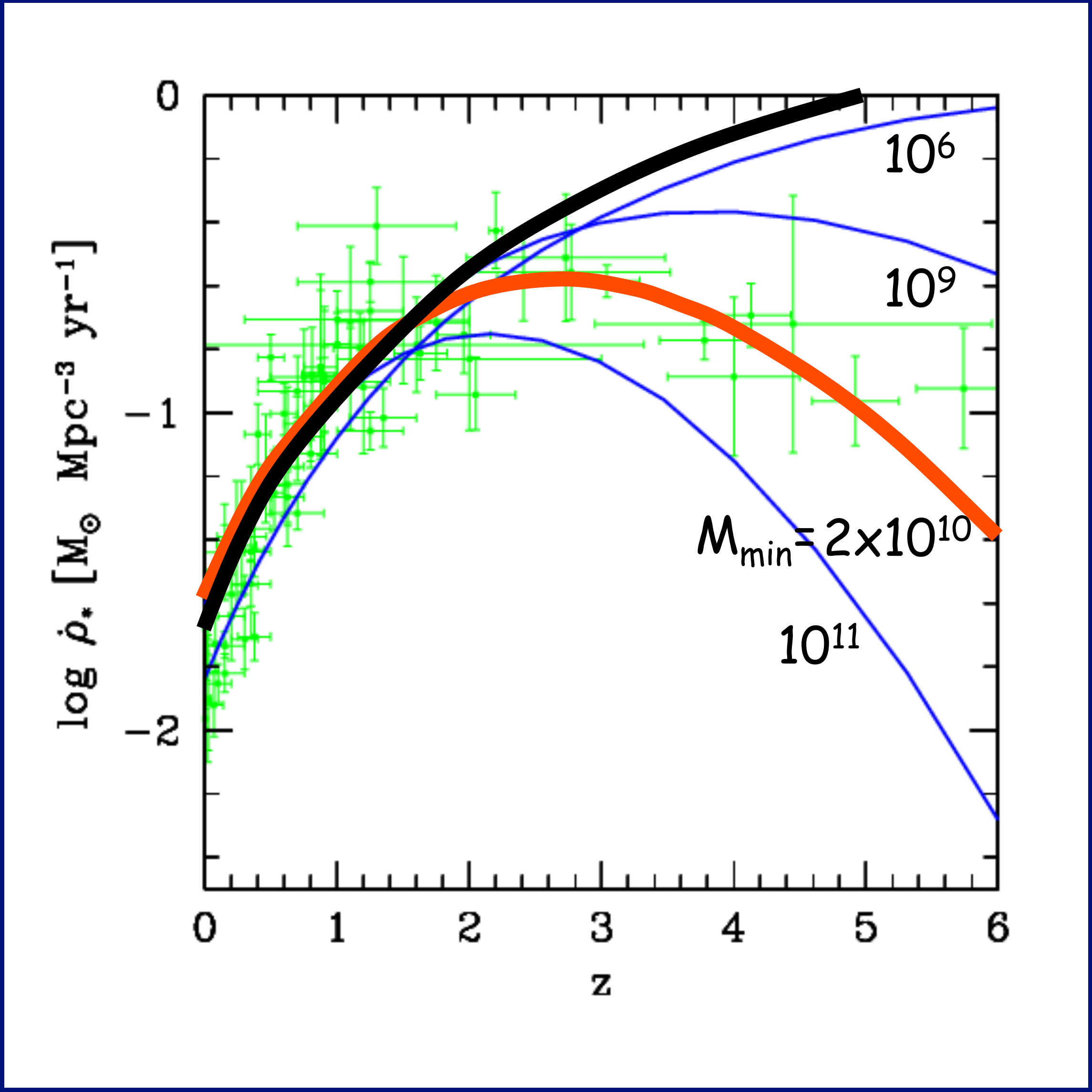
$$\dot{M}_{*} = \varepsilon \frac{M_{\rm gas}}{t_{\rm ff}}$$

Steady state

$$\dot{M}_{\rm gas} \rightarrow 0 \quad \dot{M}_{*} \rightarrow \dot{M}_{\rm acc}$$

Star-formation history:

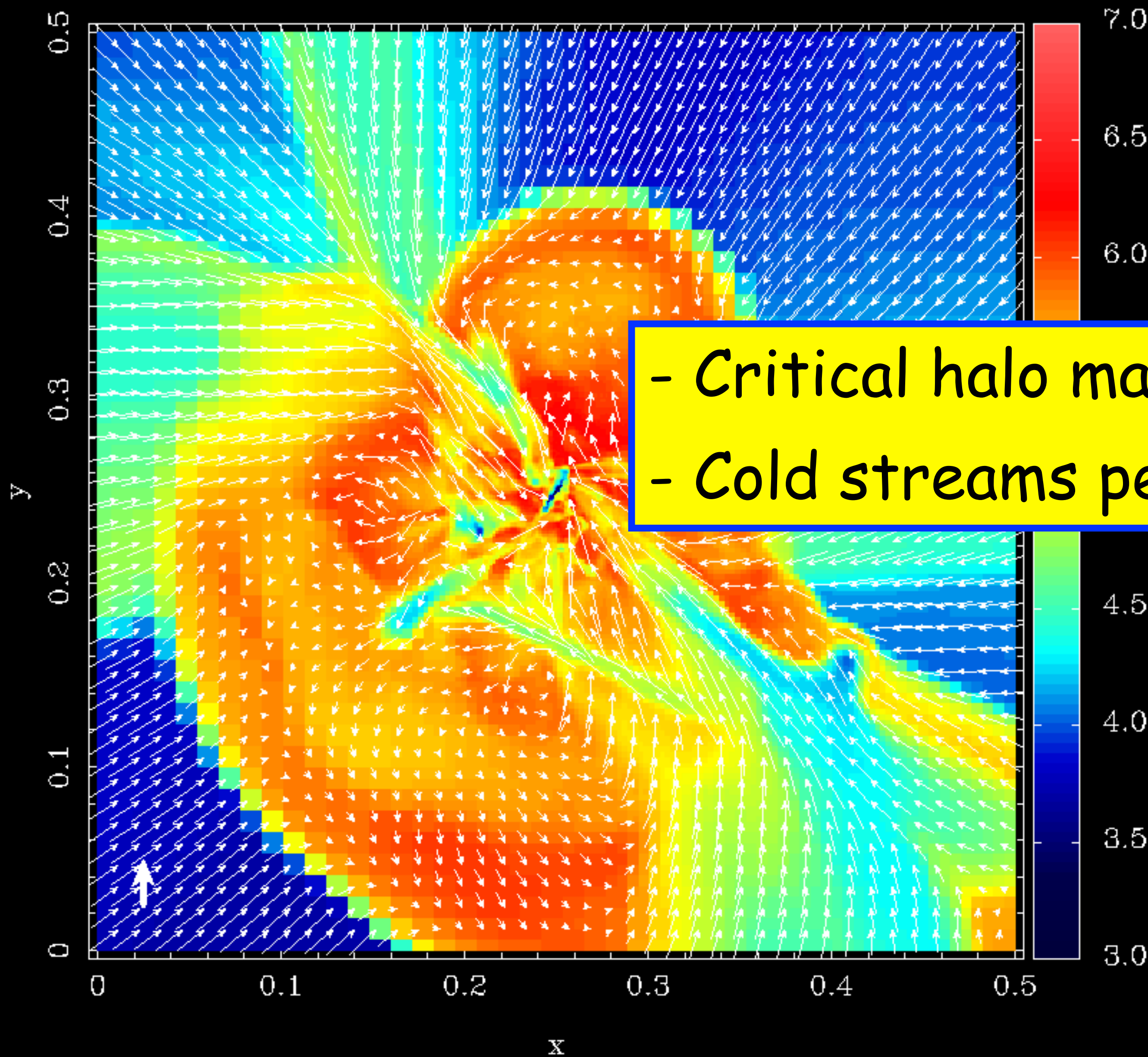
$$SFR = f_b \left\langle \dot{M}_{halo} \right\rangle$$



Bouche et al. 09

3. Virial Shock Heating

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

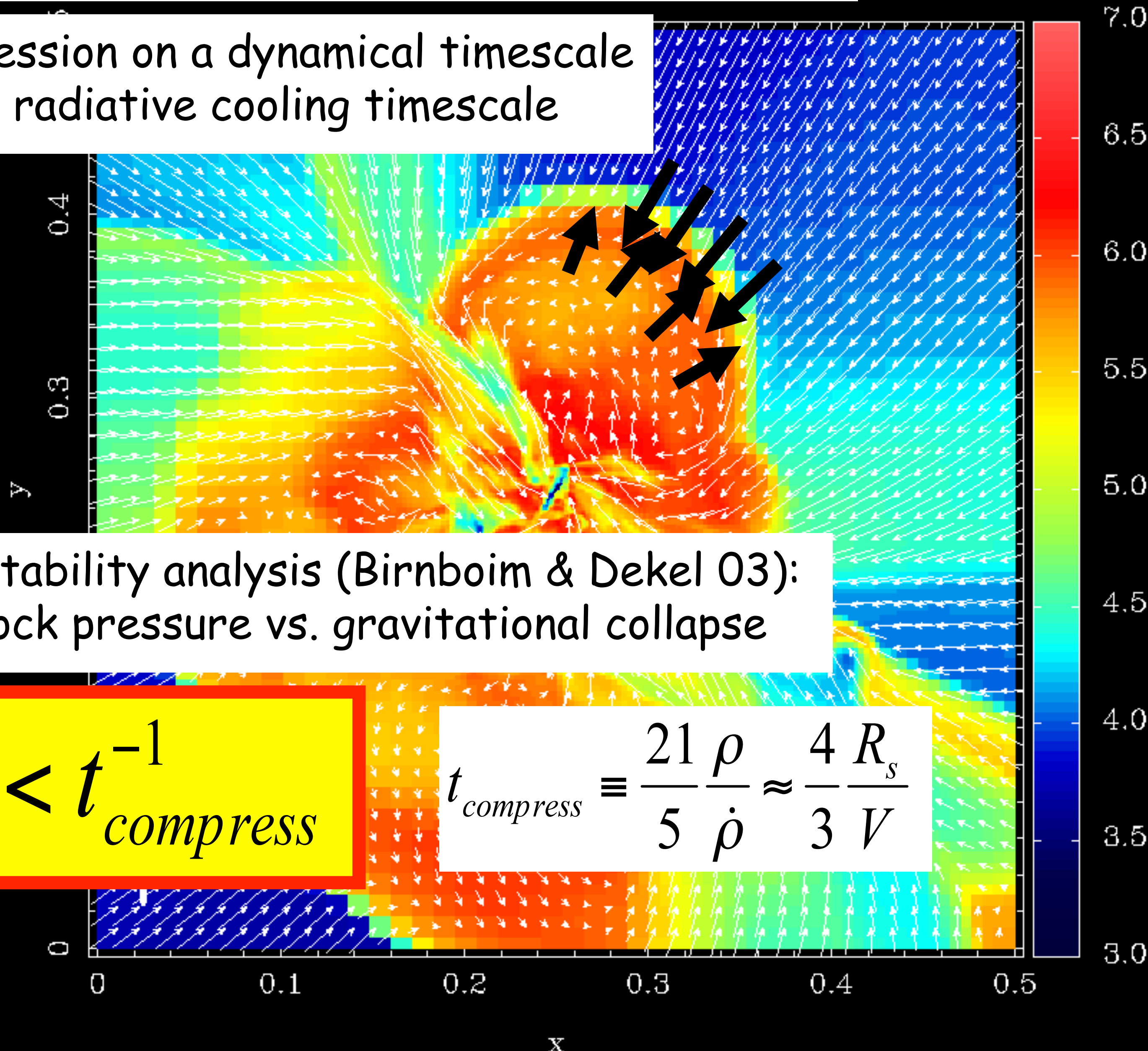


- Critical halo mass ~$10^{12} M_{\odot}$
- Cold streams penetrate at z>2

Kravtsov

Gas through shock: heats to virial temperature

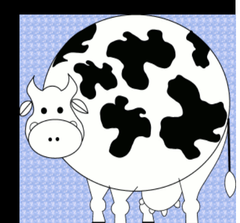
compression on a dynamical timescale
versus radiative cooling timescale

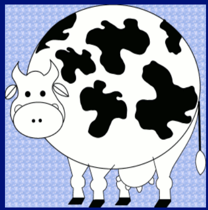


Shock-stability analysis (Birnboim & Dekel 03):
post-shock pressure vs. gravitational collapse

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

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

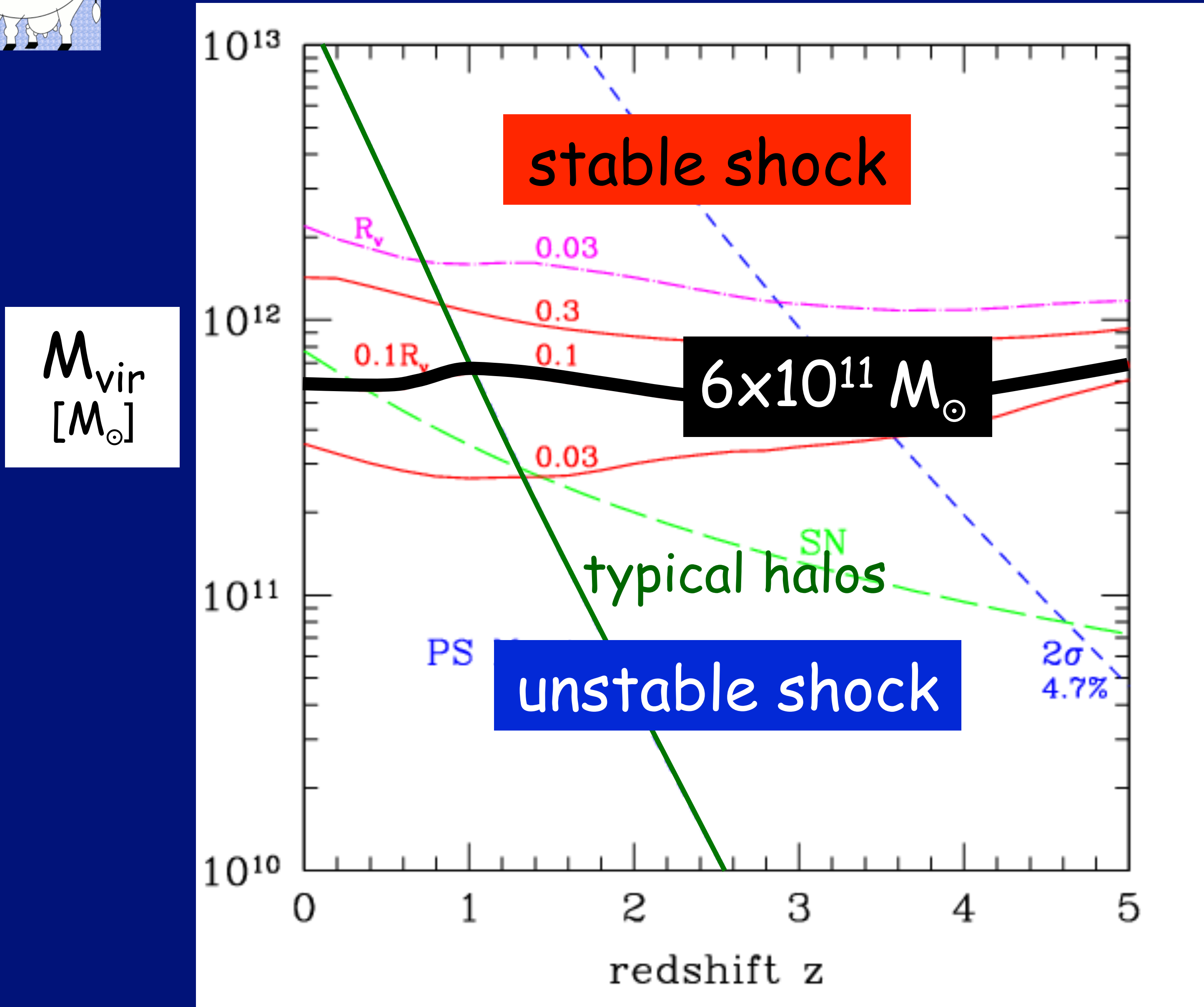




Shock-Heating Scale

Birnboim & Dekel 03
Dekel & Birnboim 06

Keres et al 05



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

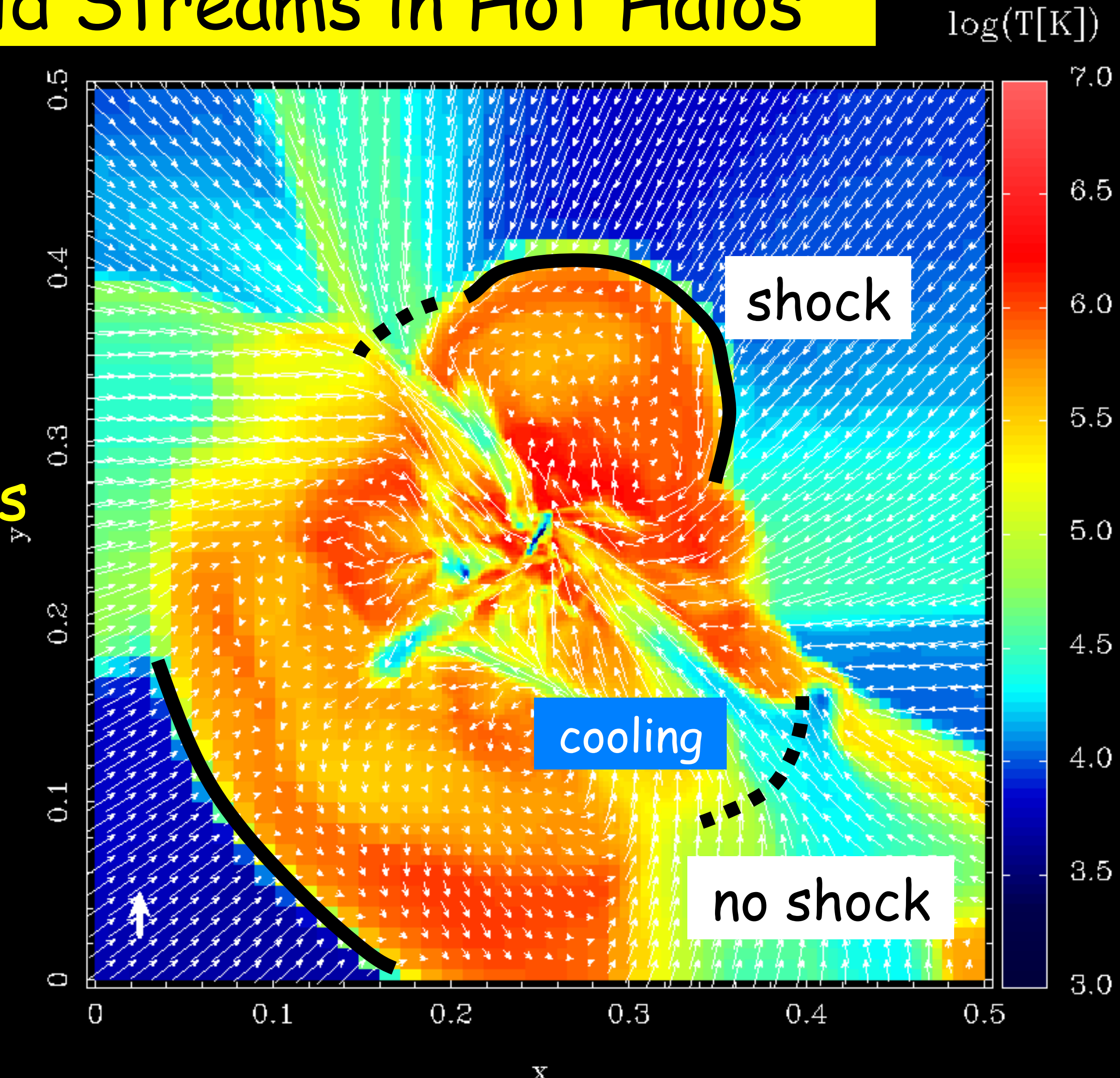
in $M > M_{shock}$

Totally hot at z<1

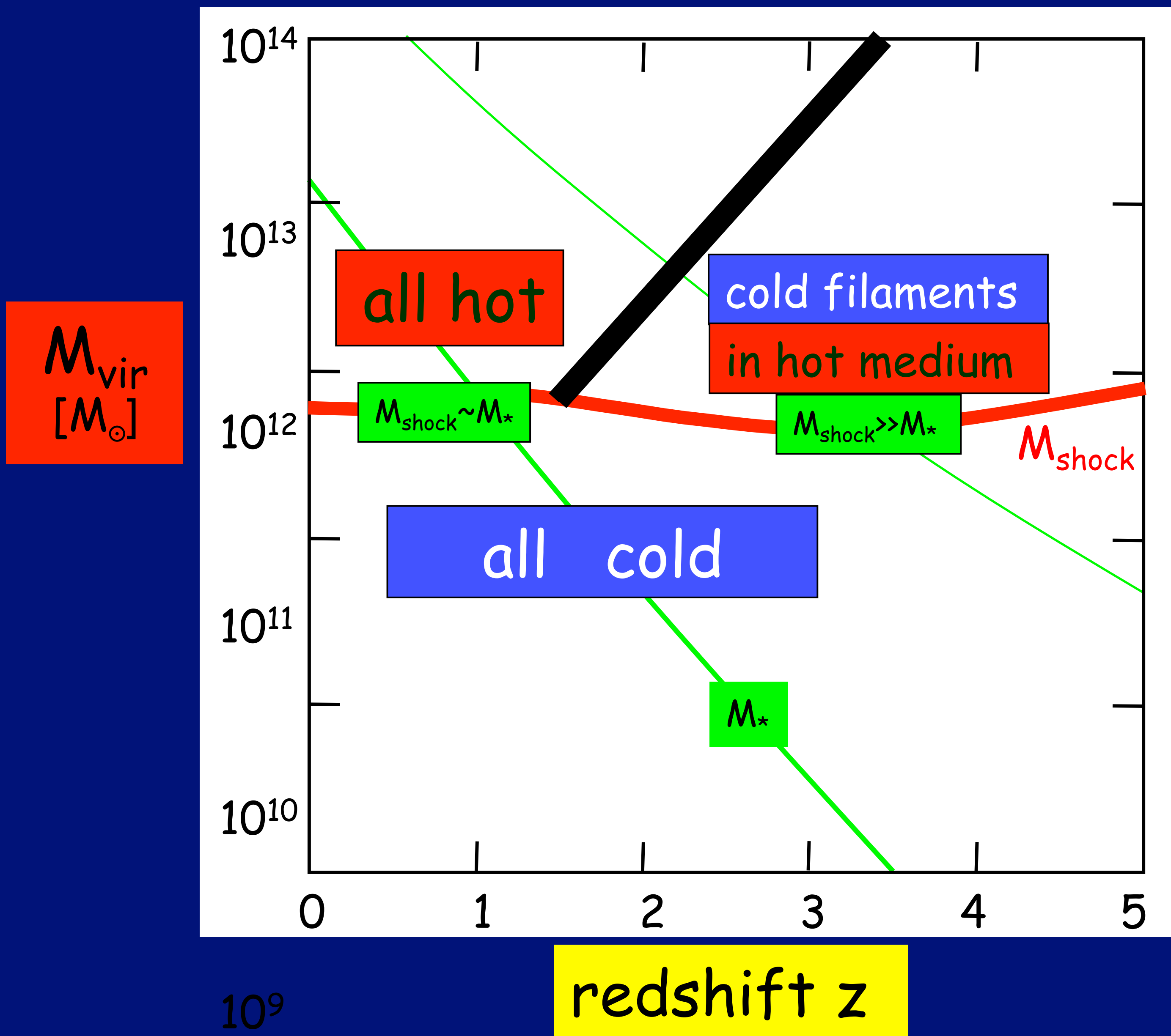
Cold streams at z>2

Dekel & Birnboim 2006

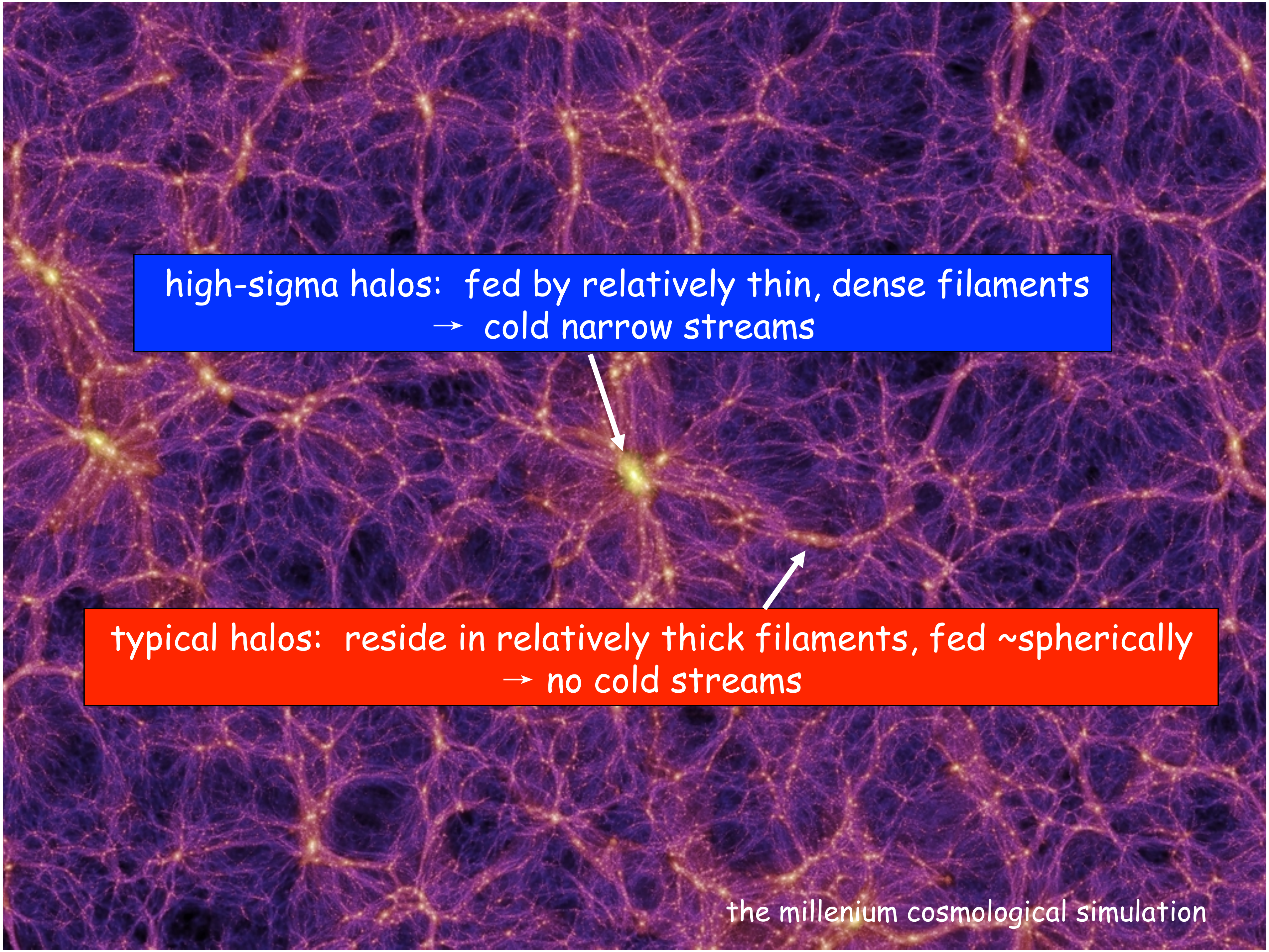
Kravtsov et al



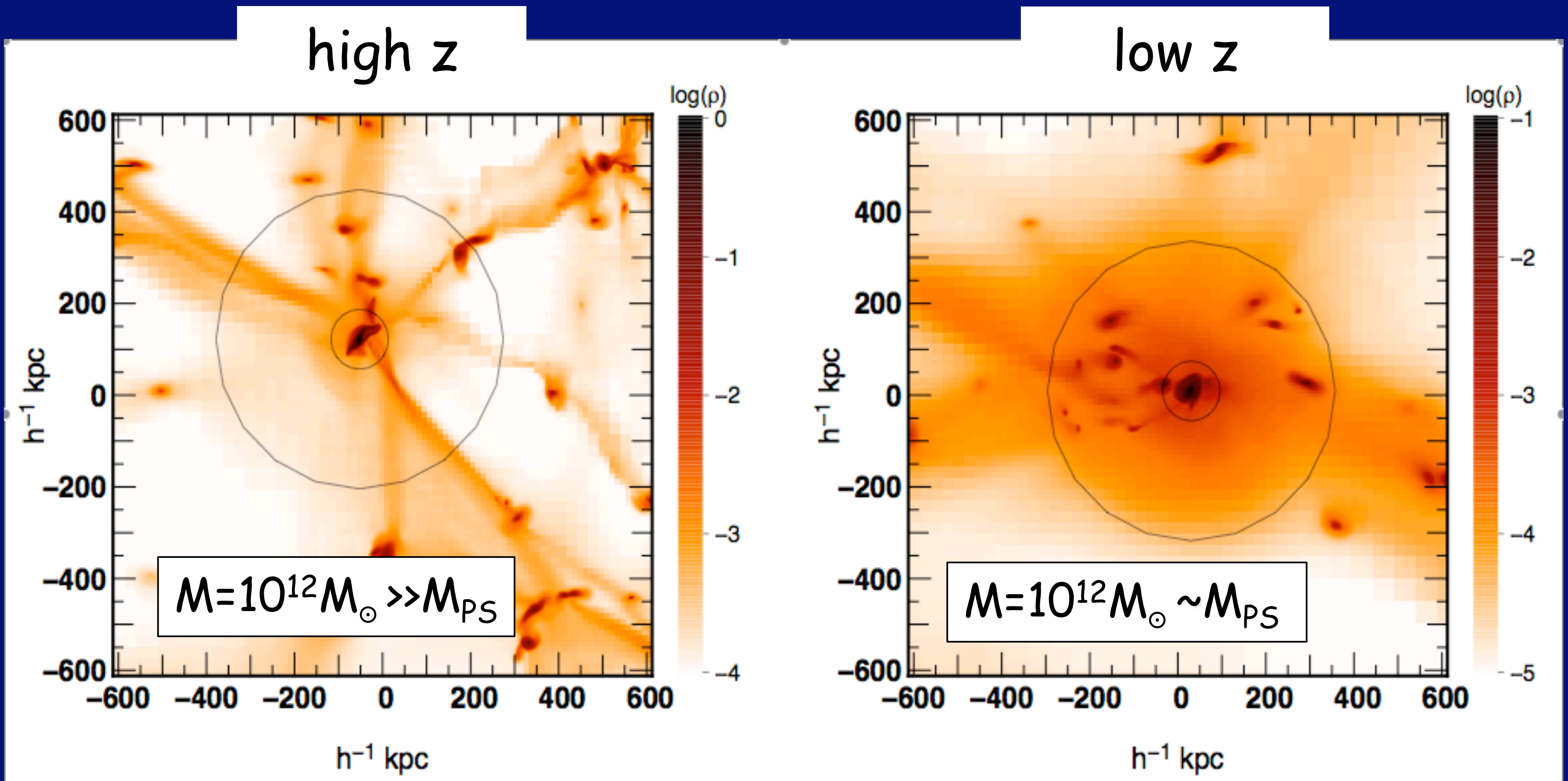
Cold Streams in Big Galaxies at High z



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

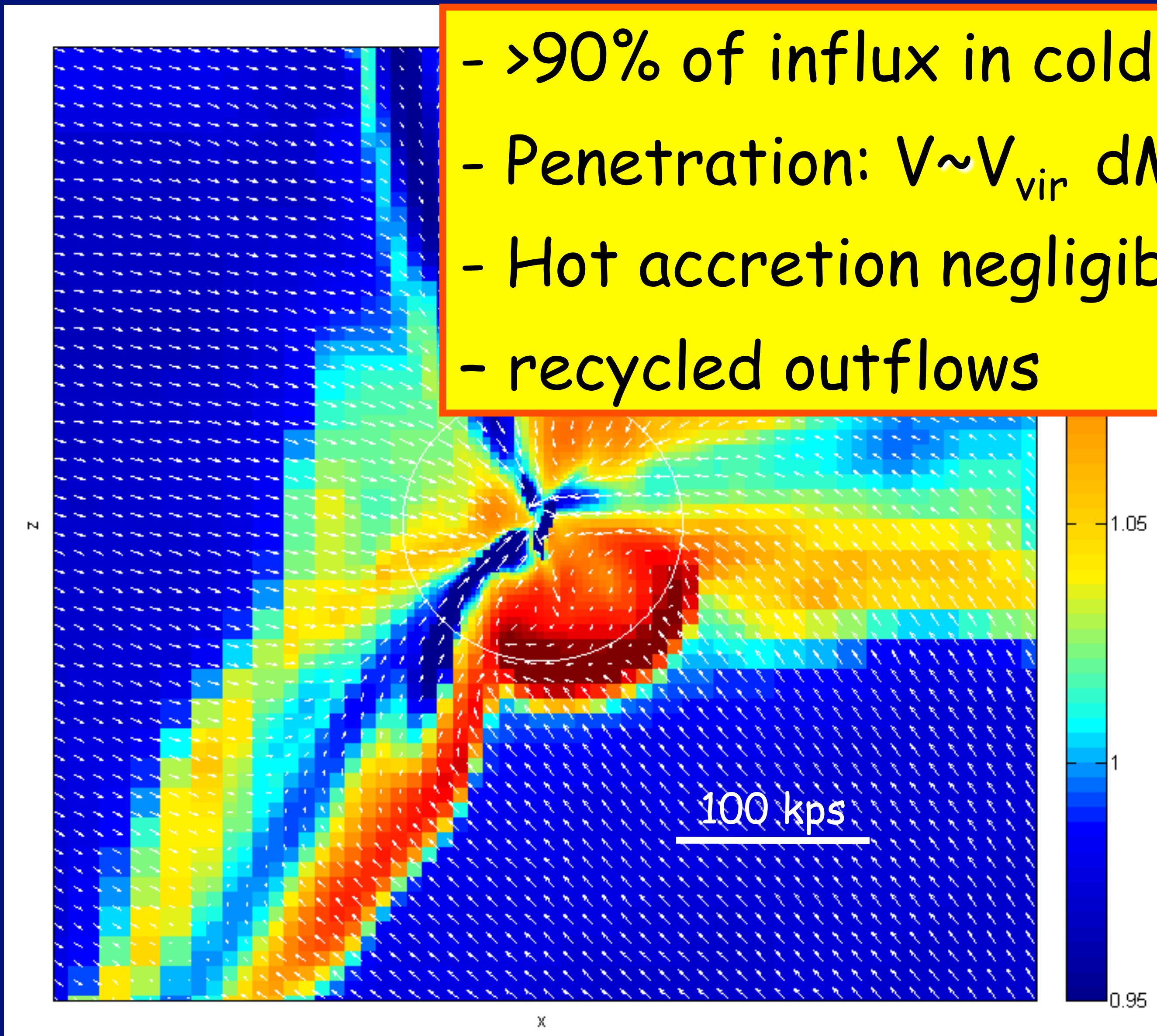
Narrow dense gas streams at high z versus spherical infall at low z



Ocvirk, Pichon, Teyssier 08

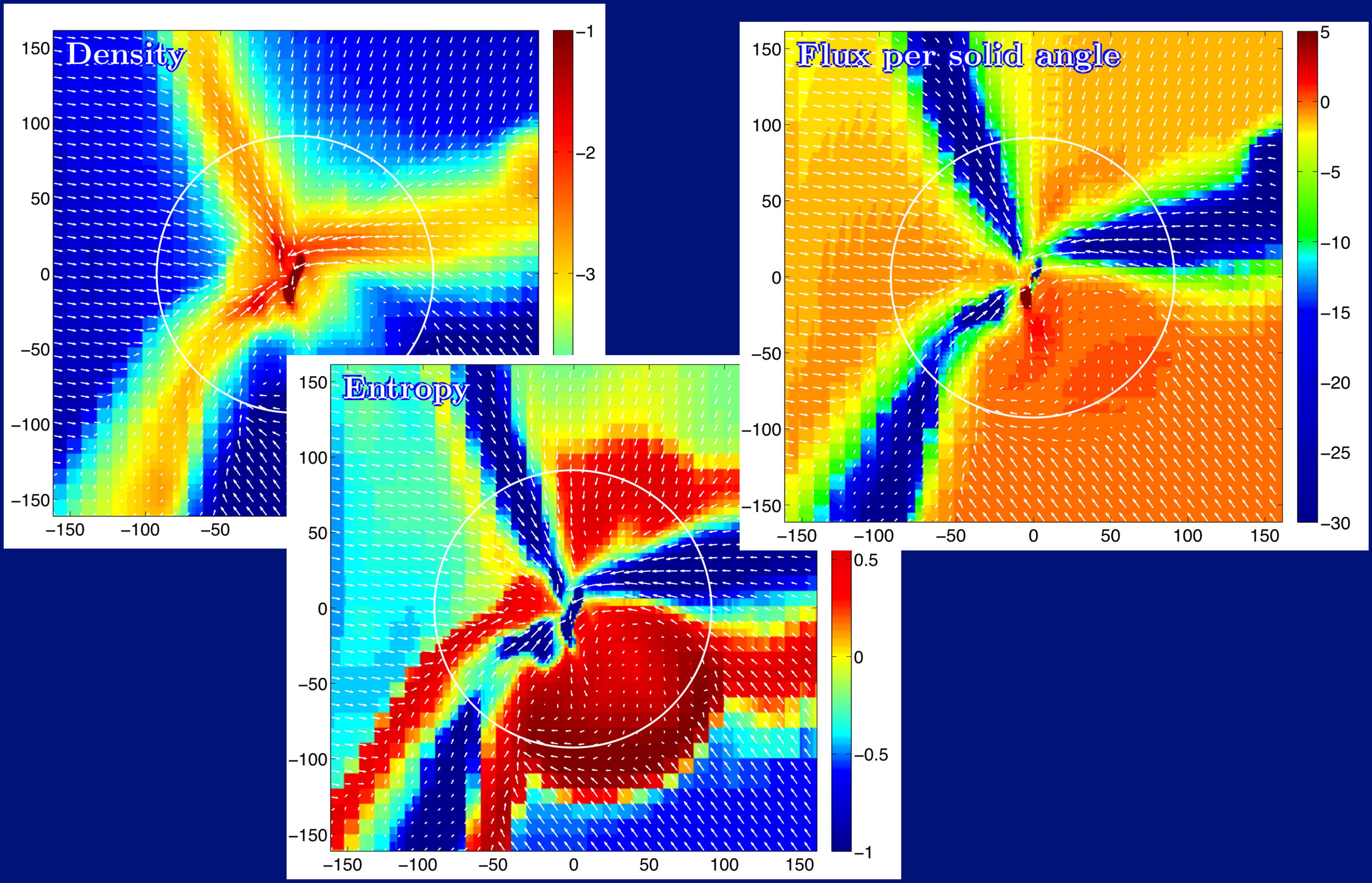
4. Cold Sterams

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

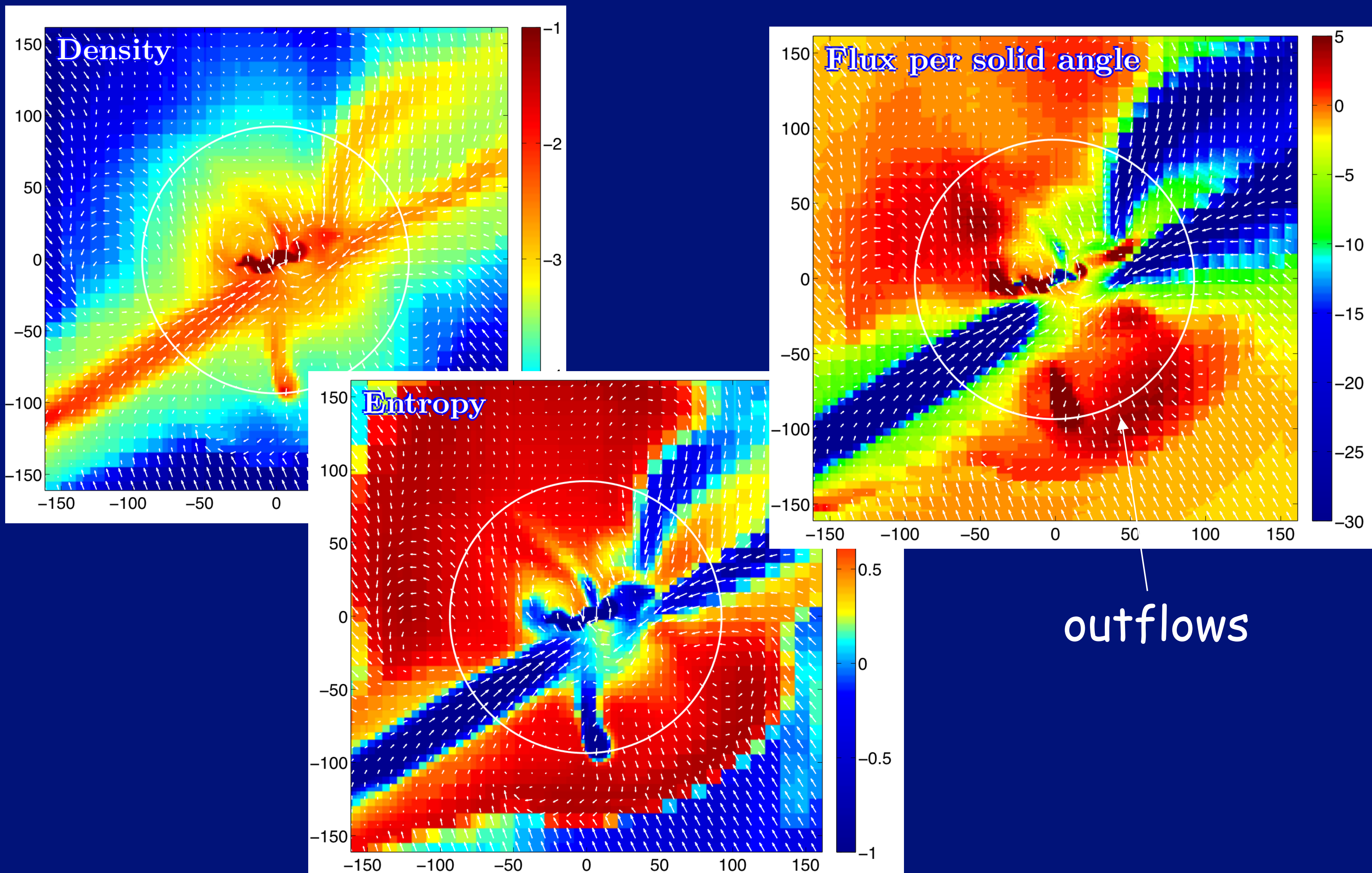


Dekel et al 09
Nature

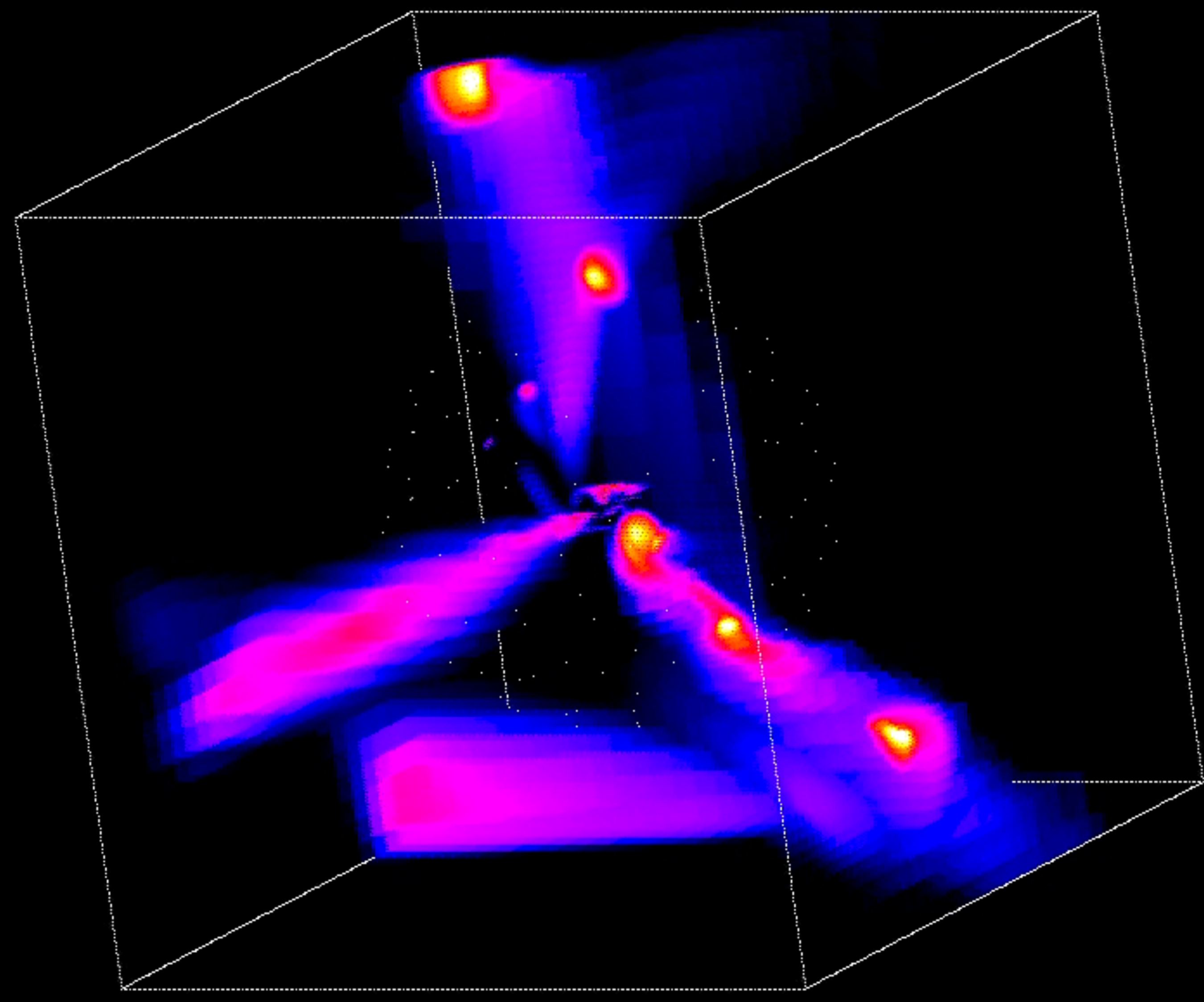
Cold streams through hot halos



Cold streams through hot halos



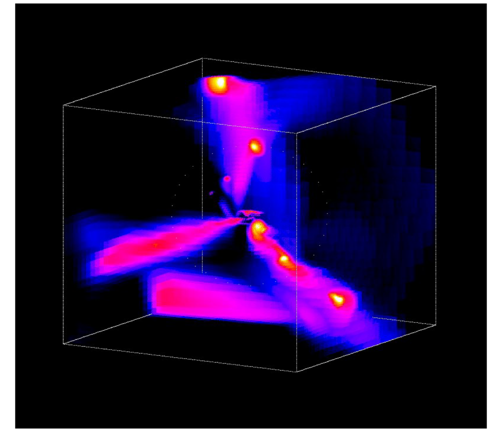
Flux per solid angle

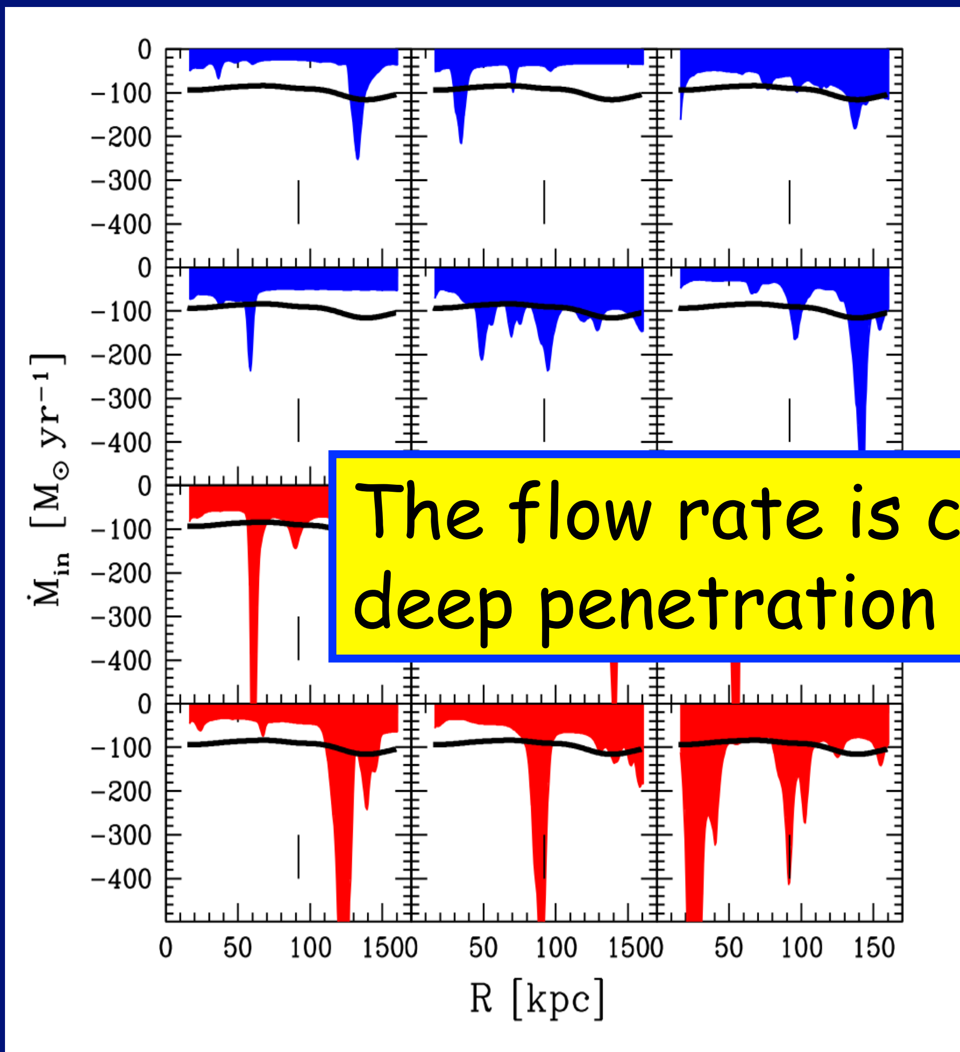


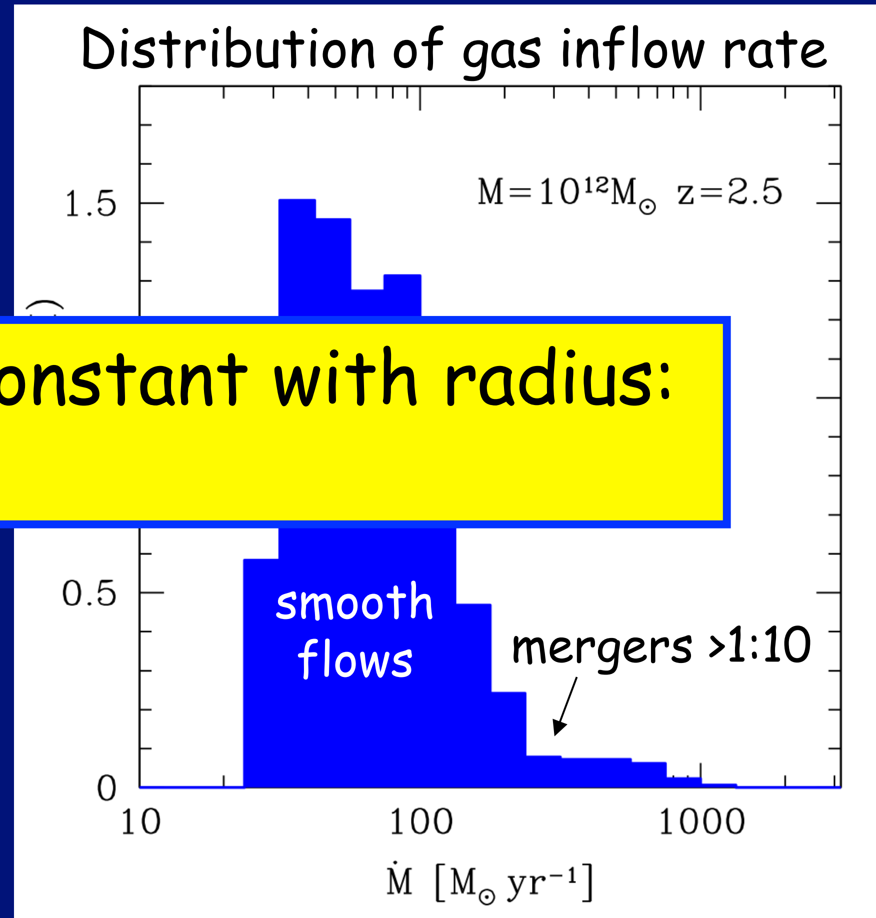
Dekel et al 09

Inflow rate through the halo into the disk

Cosmological hydro simulations MareNostrum, Dekel et al. 09







The flow rate is constant with radius: deep penetration

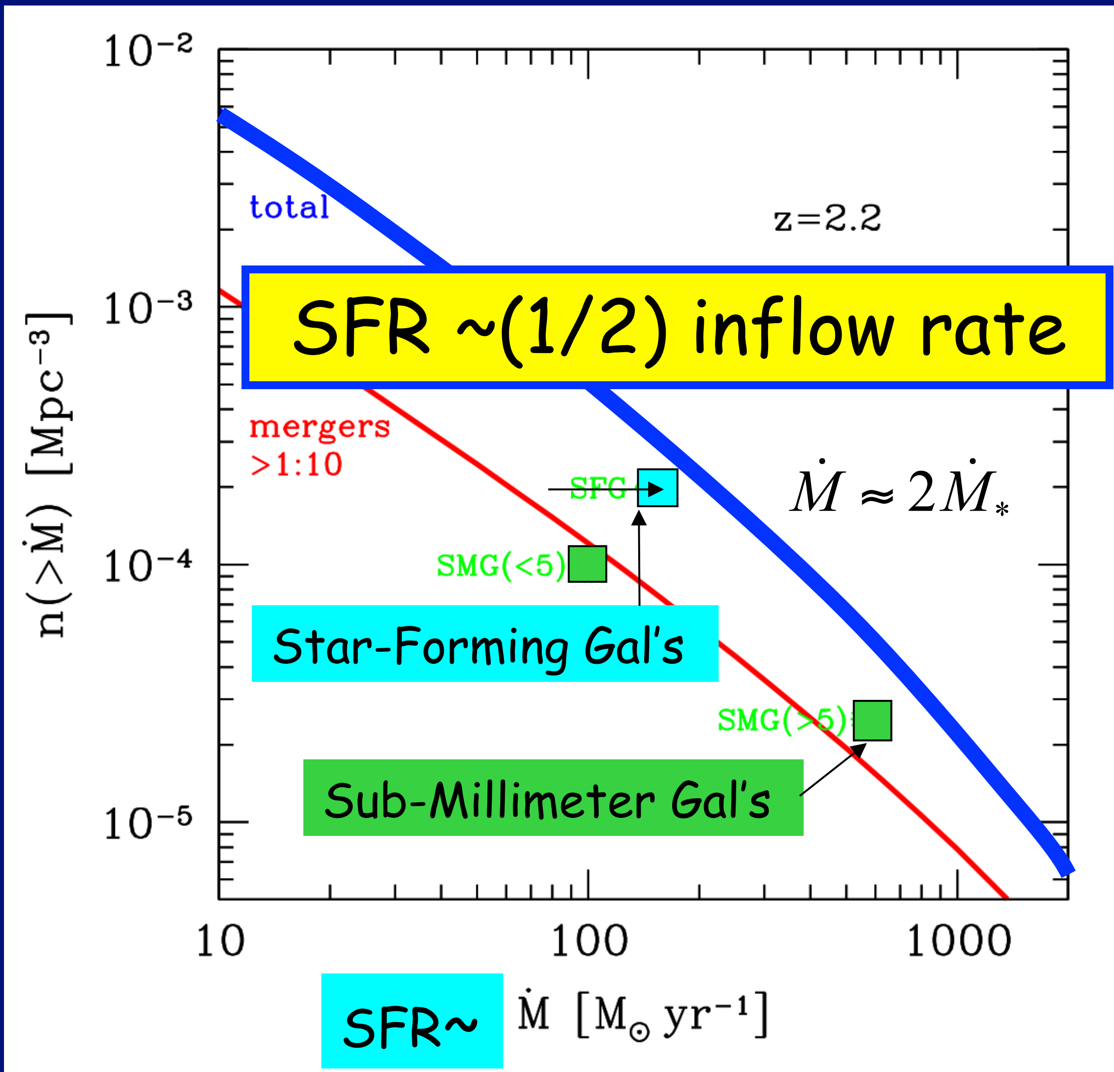
Galaxy density at a given gas inflow rate

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

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

n(M) by Sheth-Tormen

Dekel et al 09, Nature



5. Lyman-alpha from Cold streams

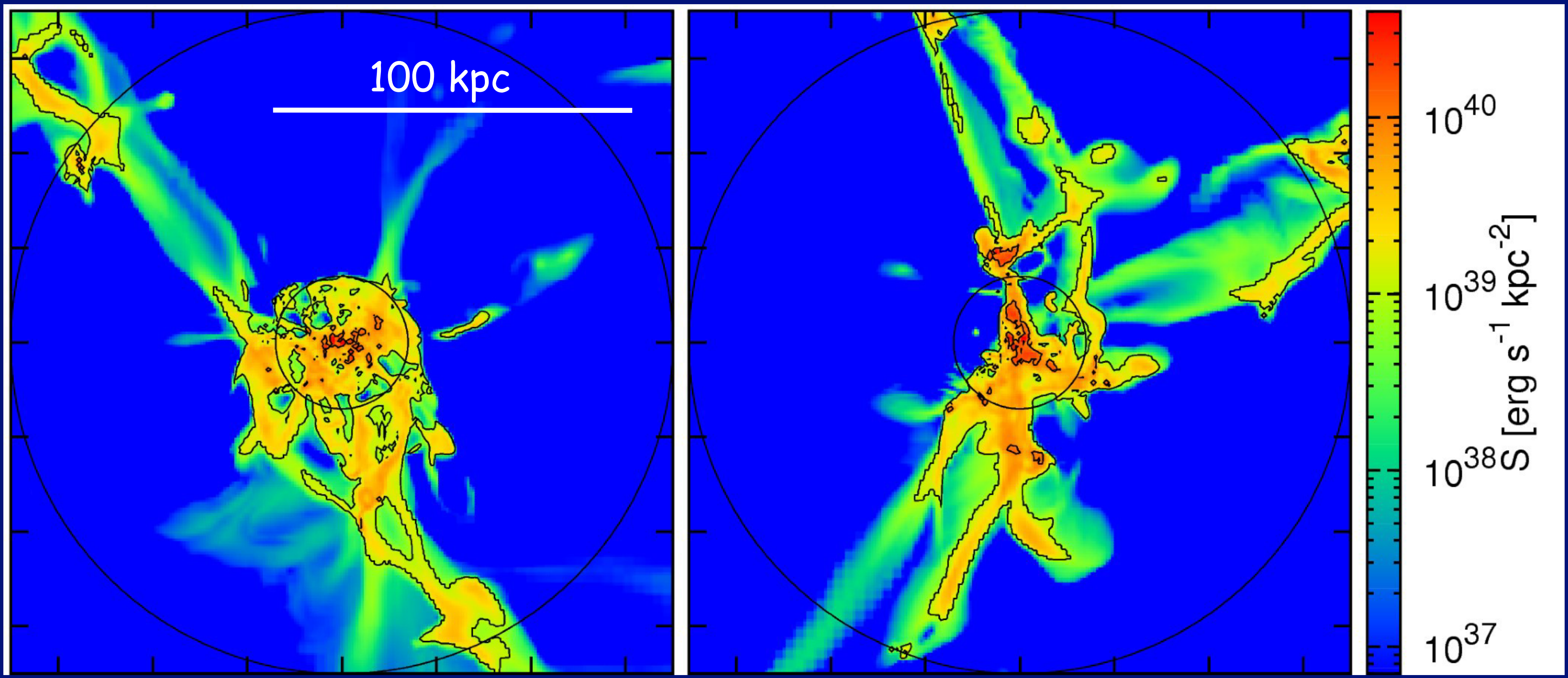
Fardal et al 01; Furlanetto et al 05; Dijkstra & Loeb 09

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

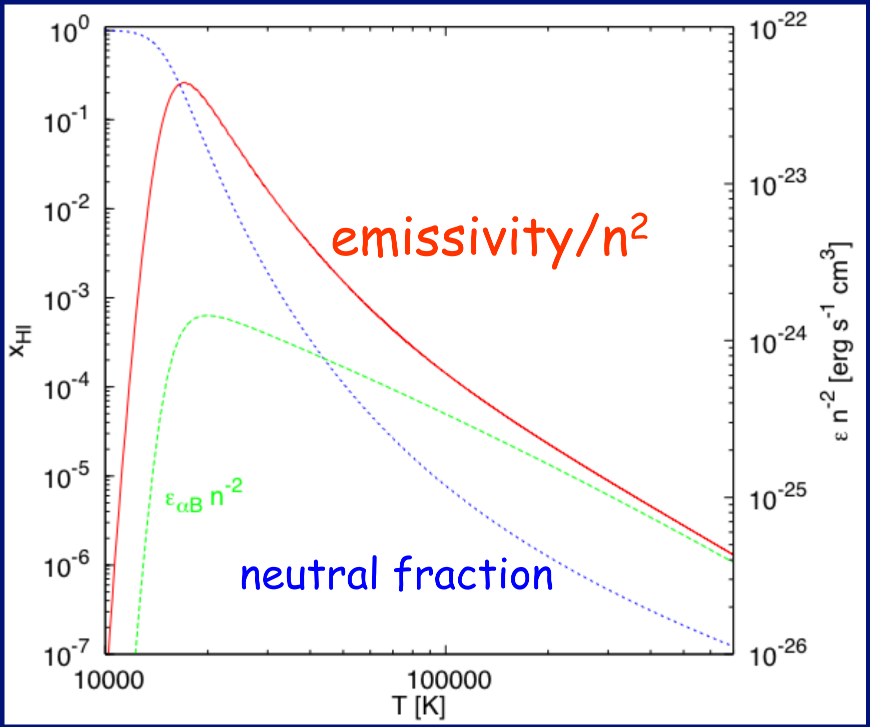
$T=(1\text{-}5)\times10^4$ K $n=0.01\text{-}0.1$ cm^{-3} $N_{HI}\sim10^{20}$ cm^{-2} pressure equilib.

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

Surface brightness



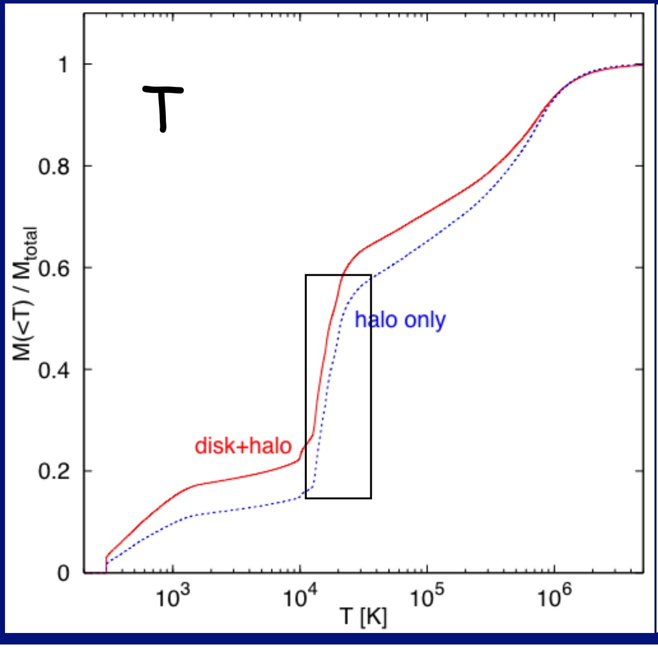
Lyman-alpha Emissivity

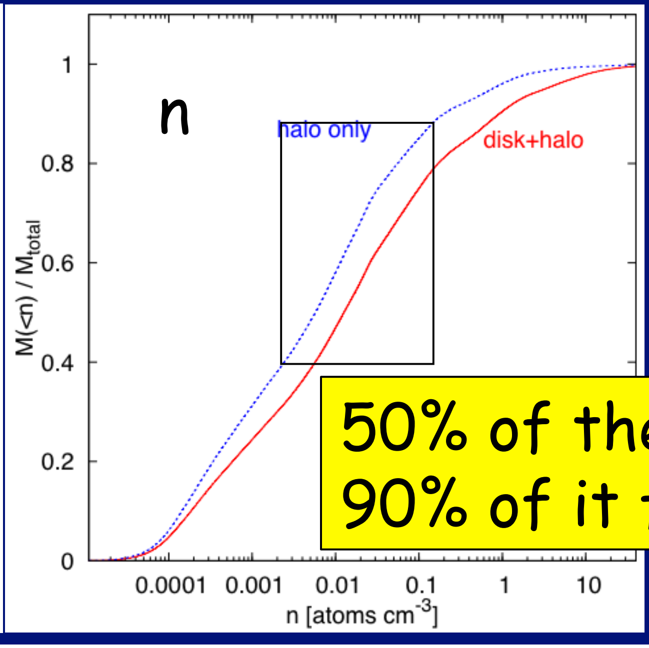


Collisional excitation:

Streams are self-shielded from UV background.

Cumulative distribution of T & n



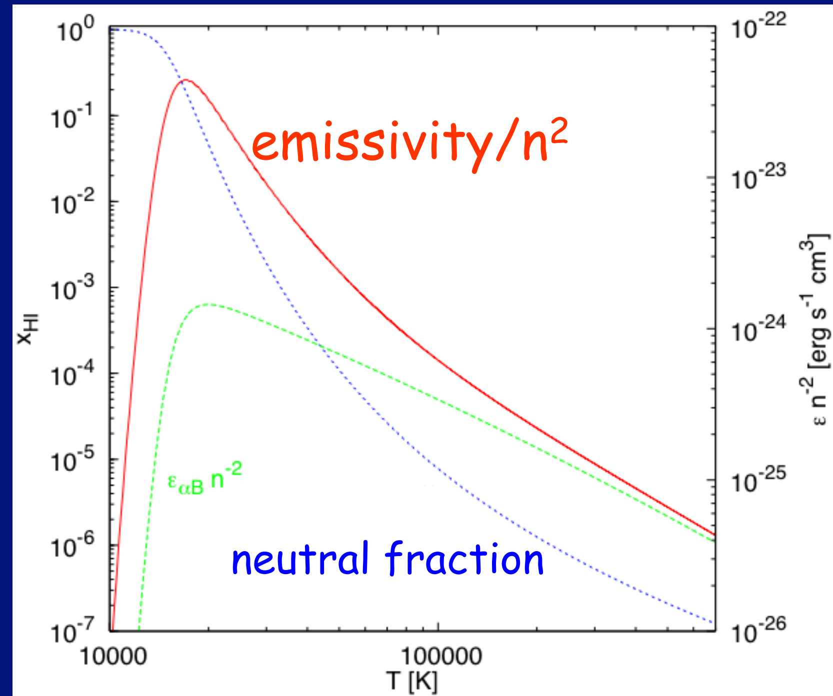


50% of the gas emits La
90% of it from 0.01<n<0.3

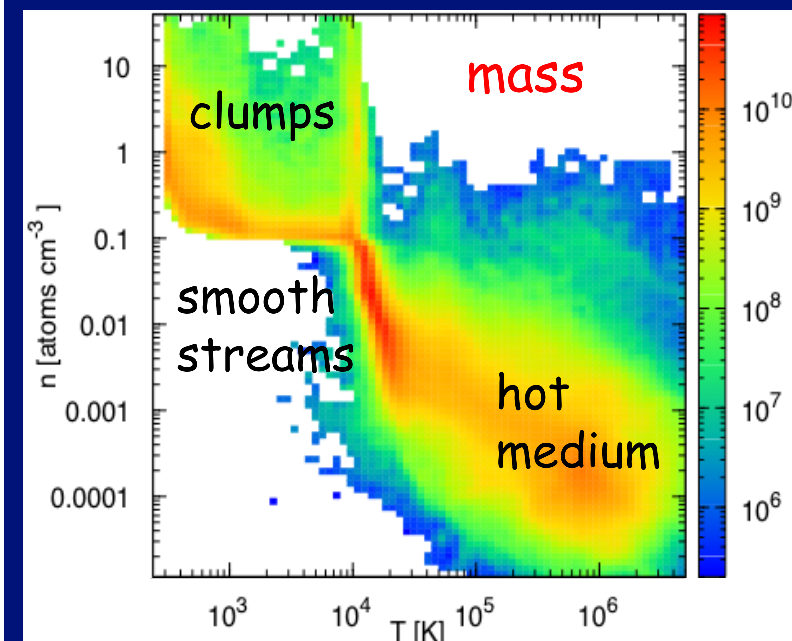
Lyman-alpha Emissivity

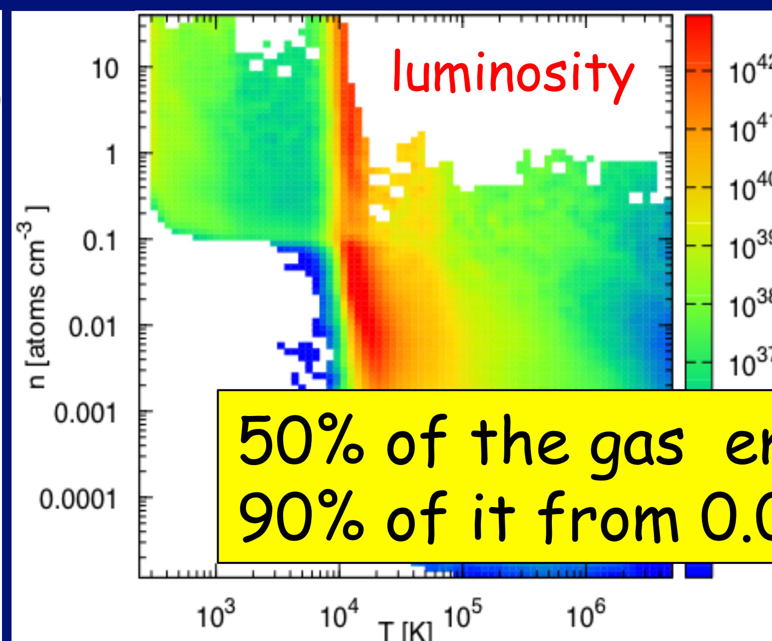
Collisional excitation:

Streams are self-shielded from UV background



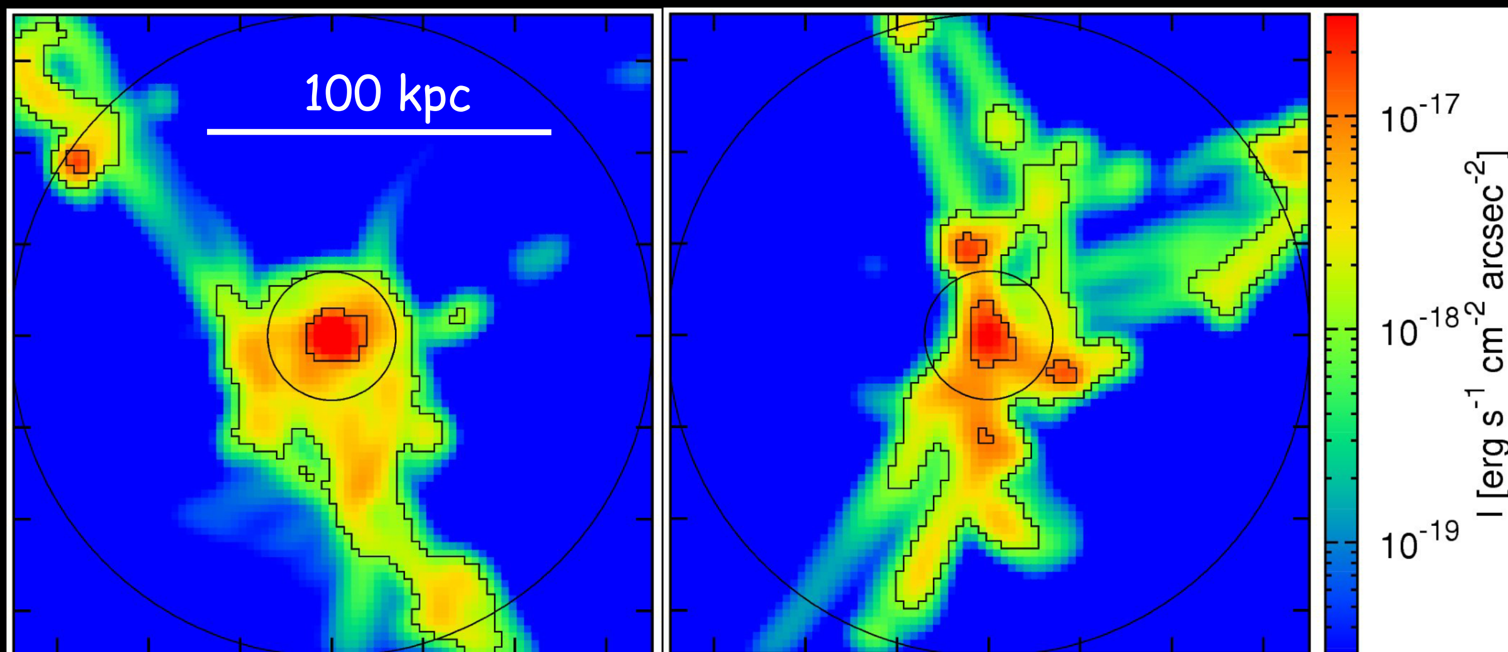
Distribution of n & T in streams



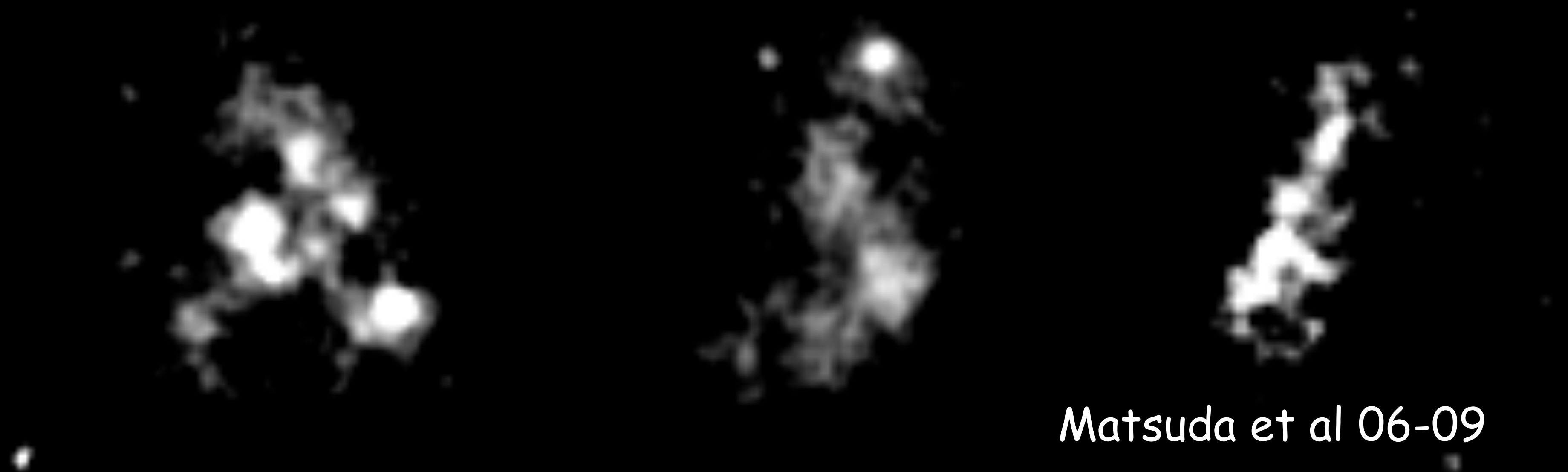


50% of the gas emits La
90% of it from 0.01<n<0.3

Cold streams as Lyman-alpha Blobs

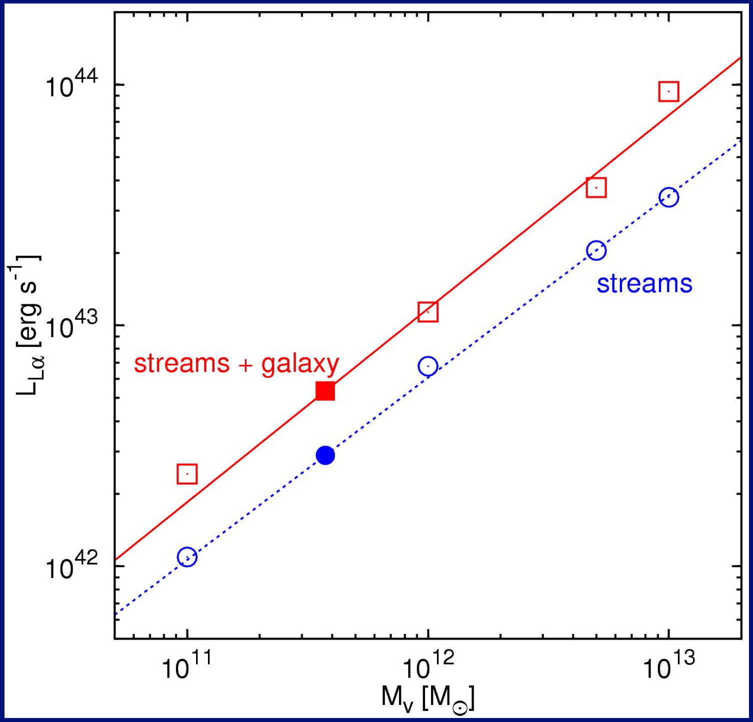


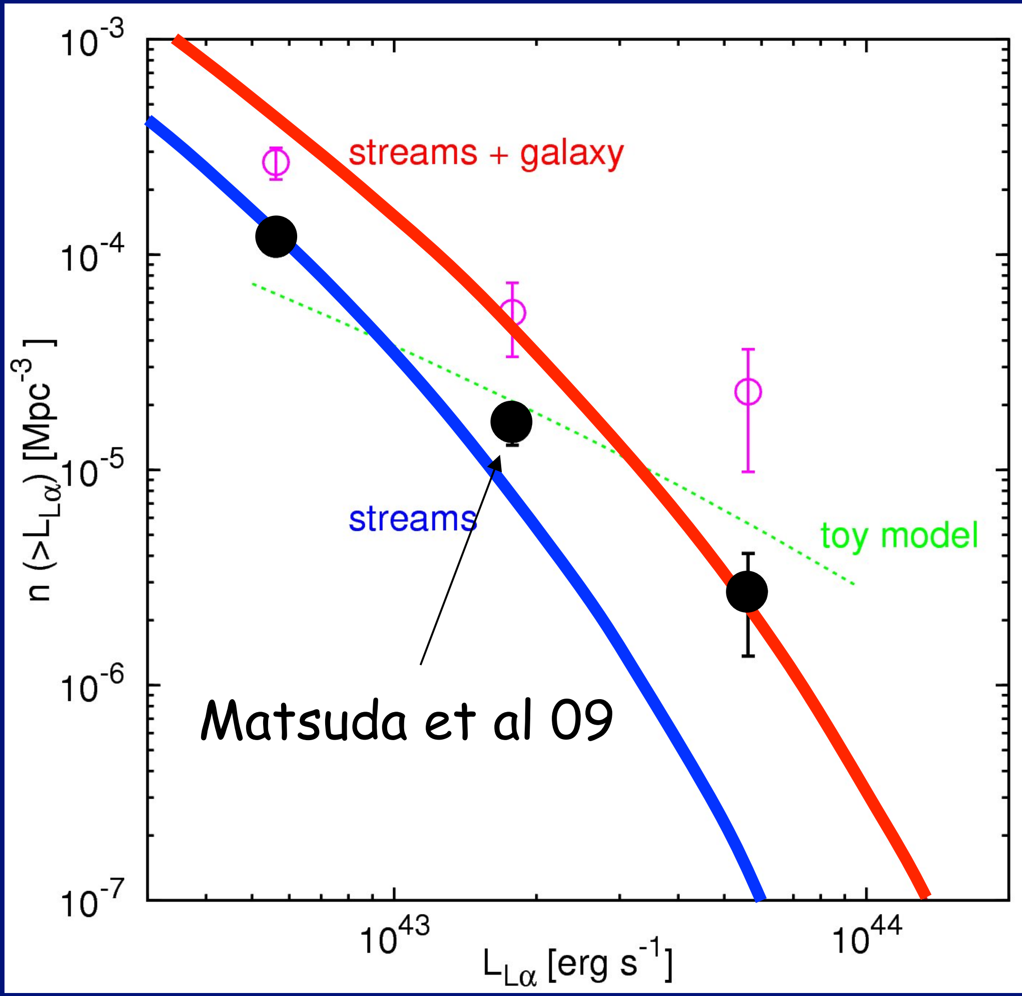
Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 09



Matsuda et al 06-09

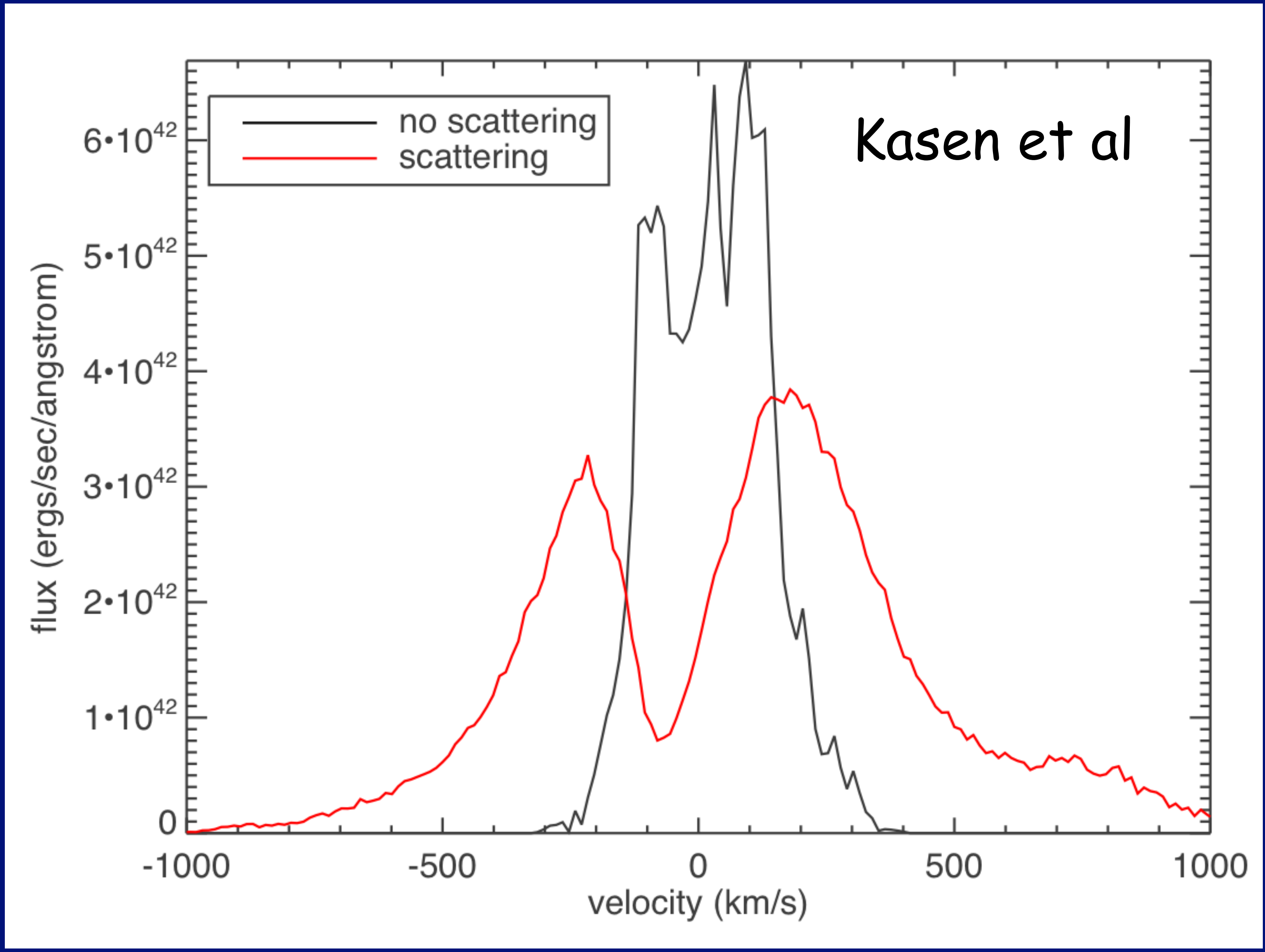
Lyman-alpha Luminosity Function





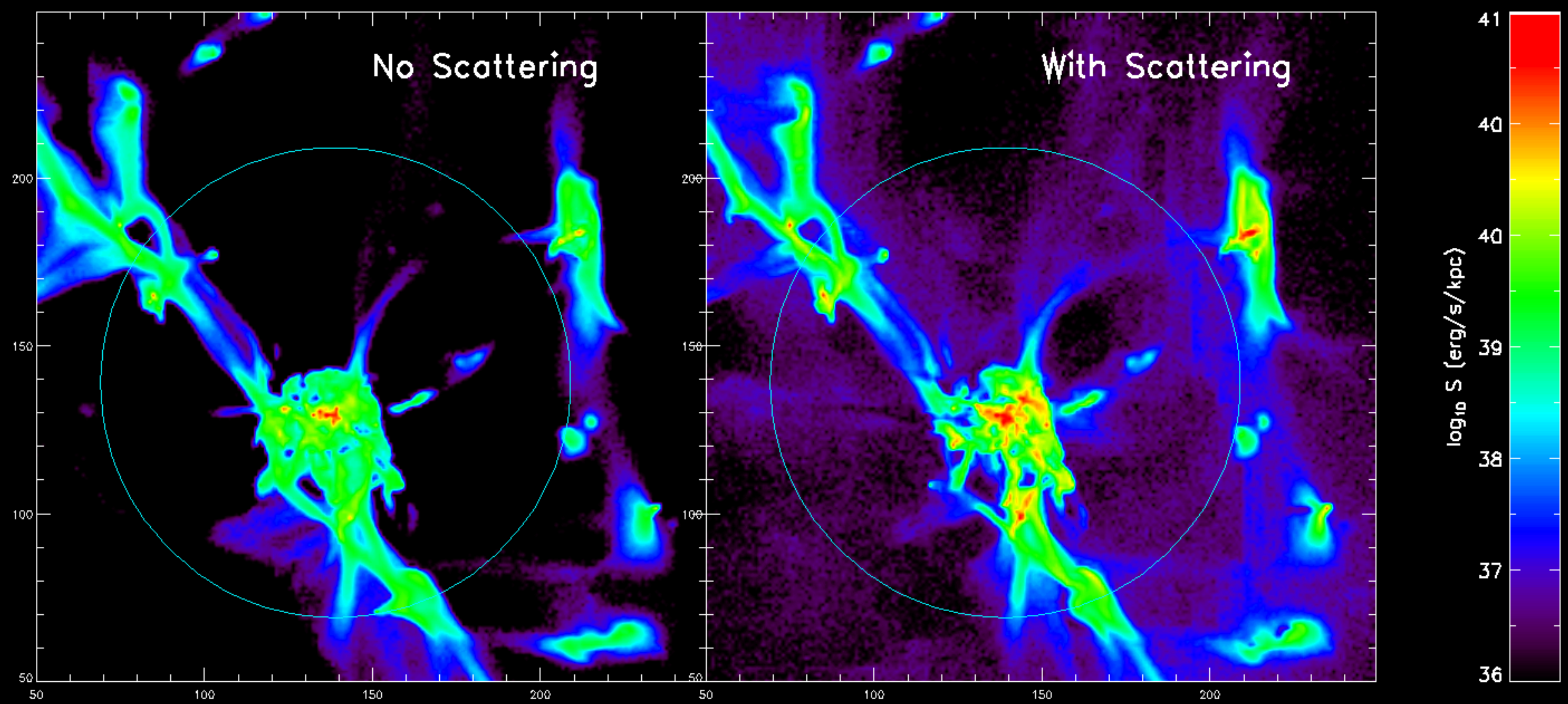
Isophotal area and kinematics also consistent with data

Lya Line Profile - radiative transfer

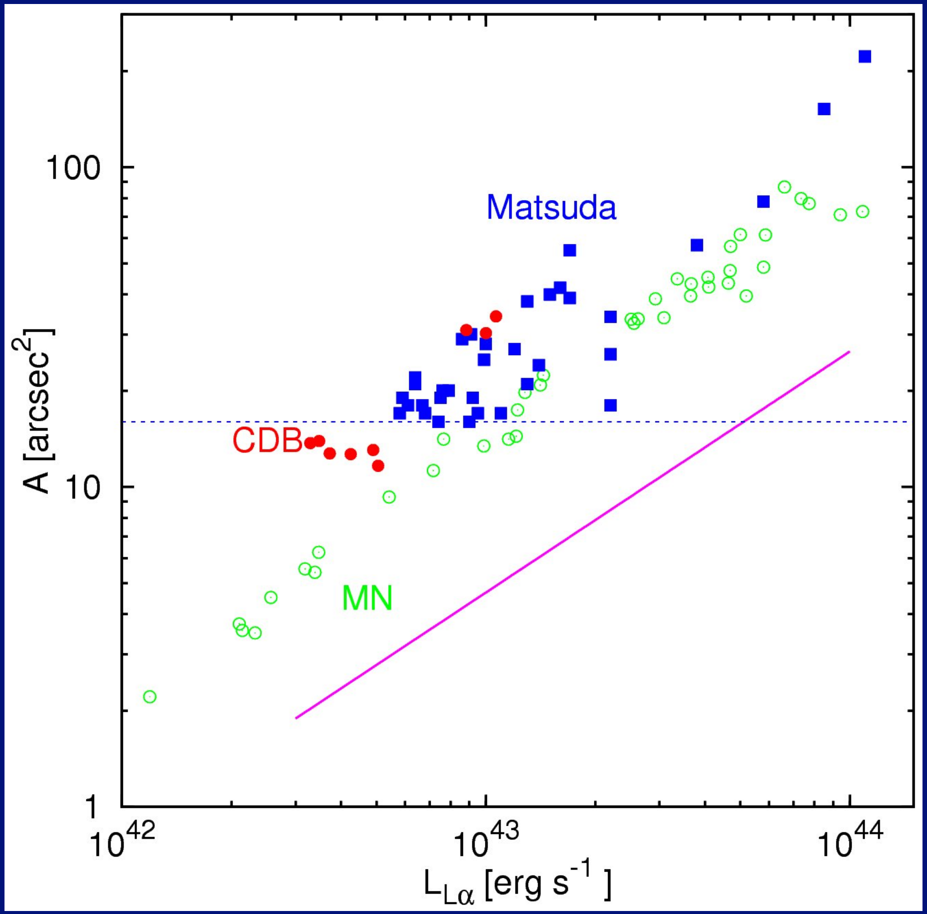


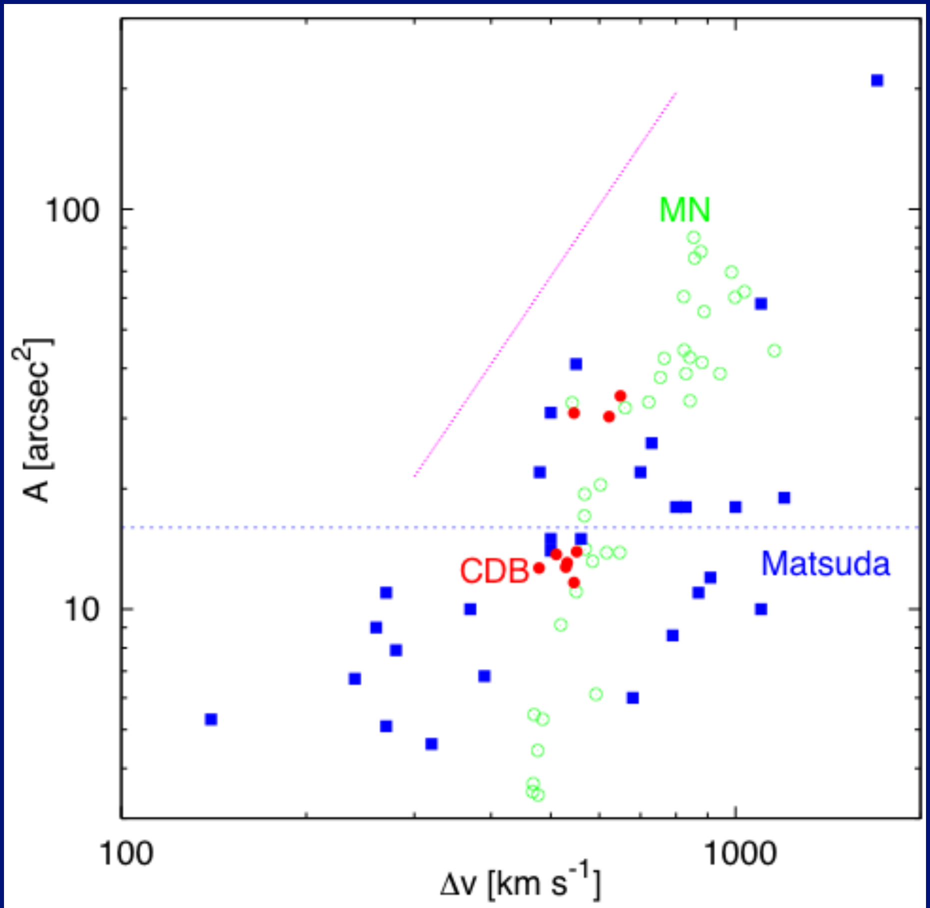
Lya Image - radiative transfer

Kasen et al

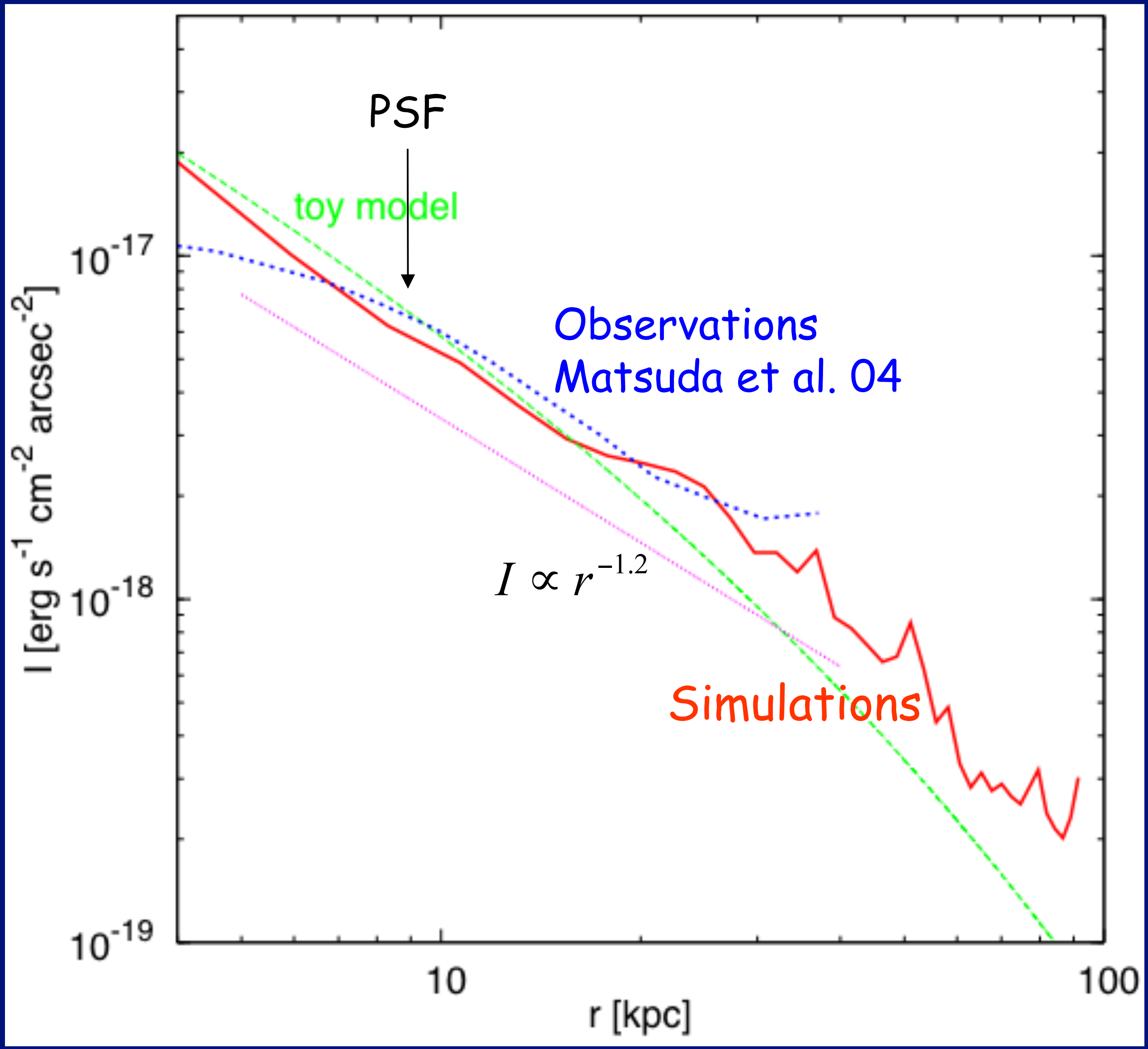


LAB Scaling Relations



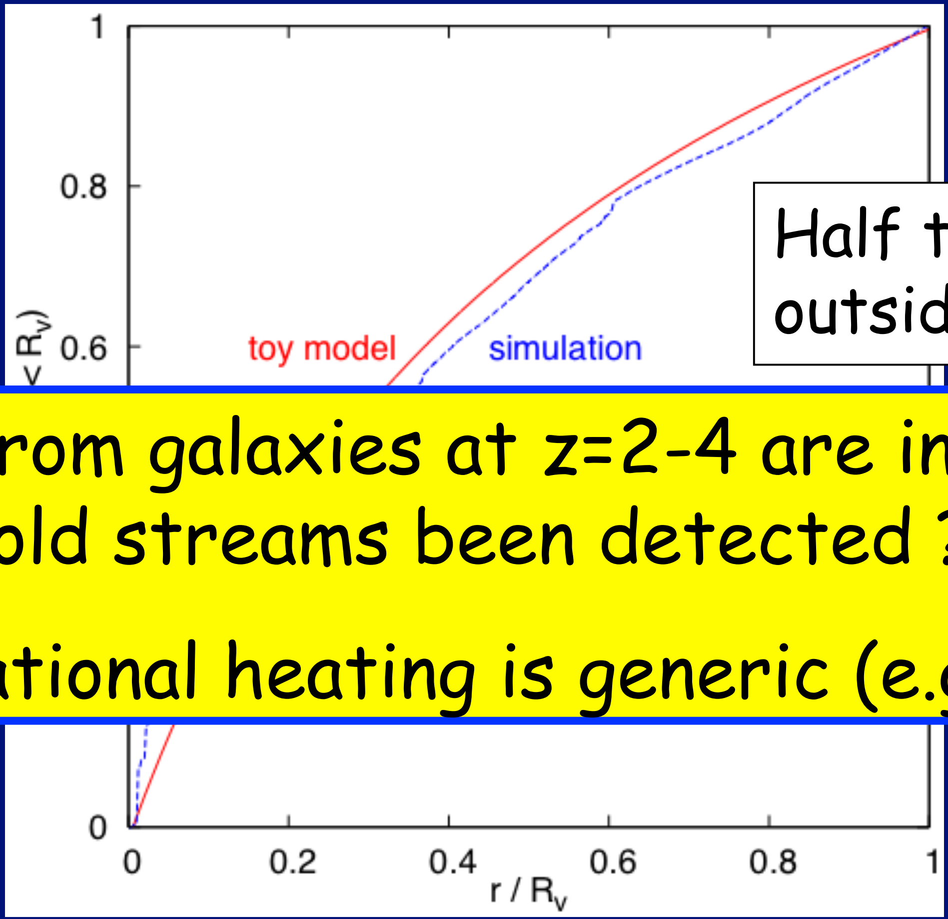


Lyman-alpha Surface Brightness Profile



Gravity Powers Lyman-alpha Emission

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



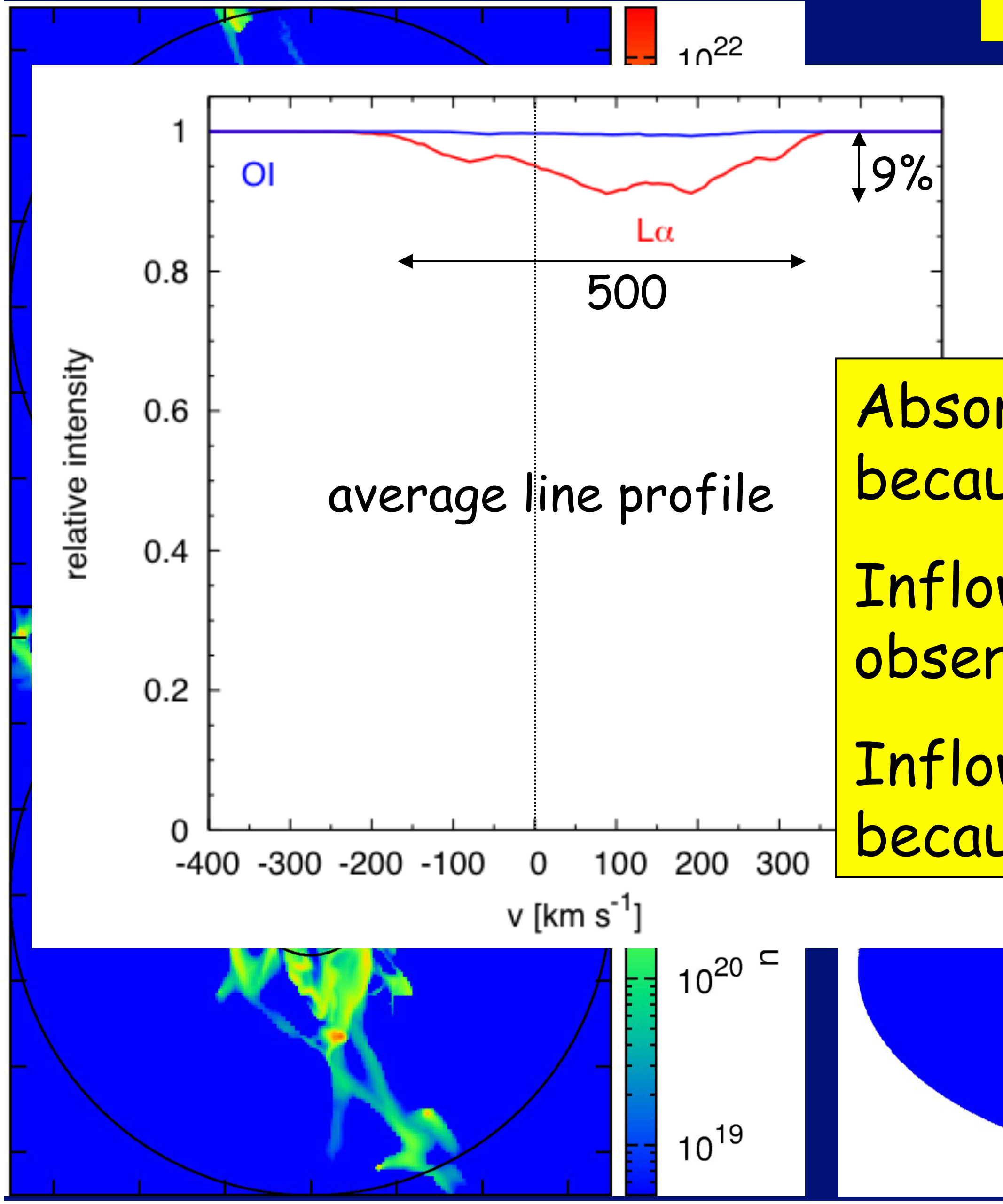
Half the luminosity outside $0.3R_v$

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

Gravitational heating is generic (e.g. clusters)

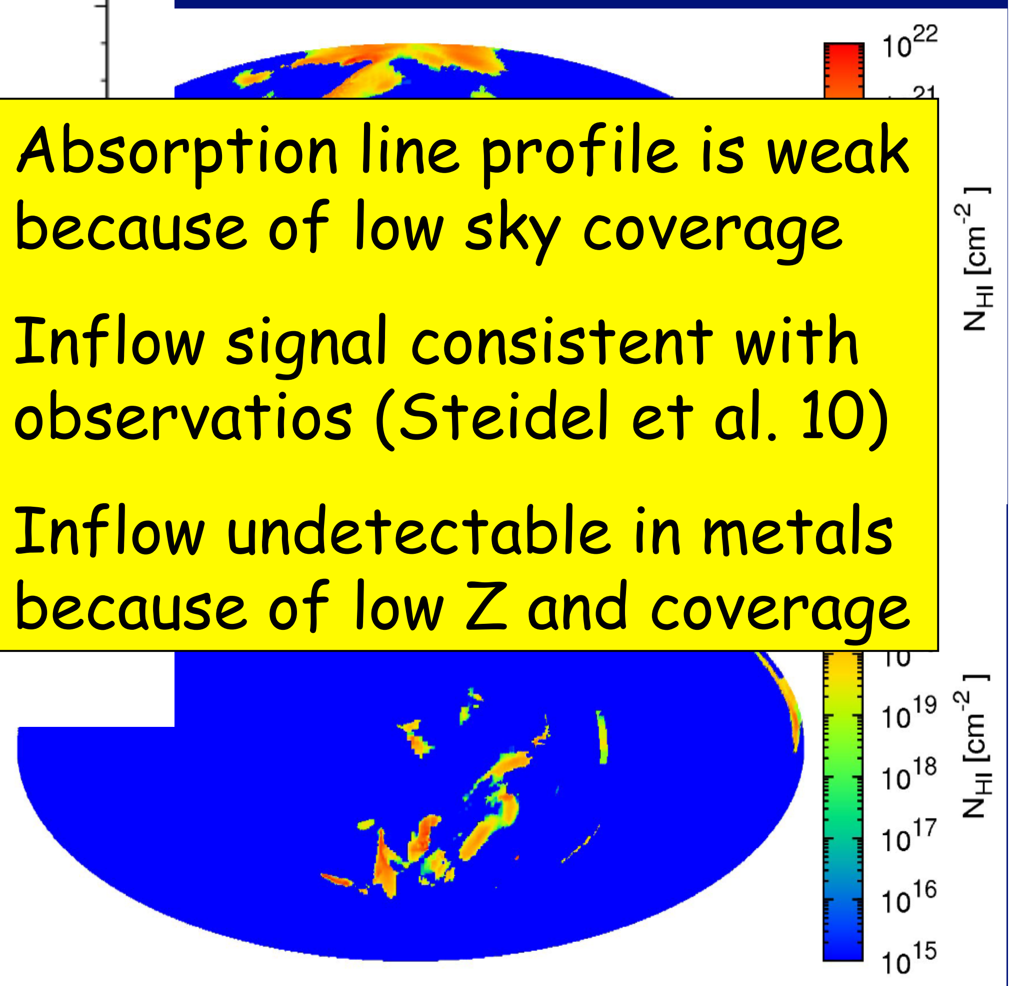
Lya Absorption

background source



HI column density

central source



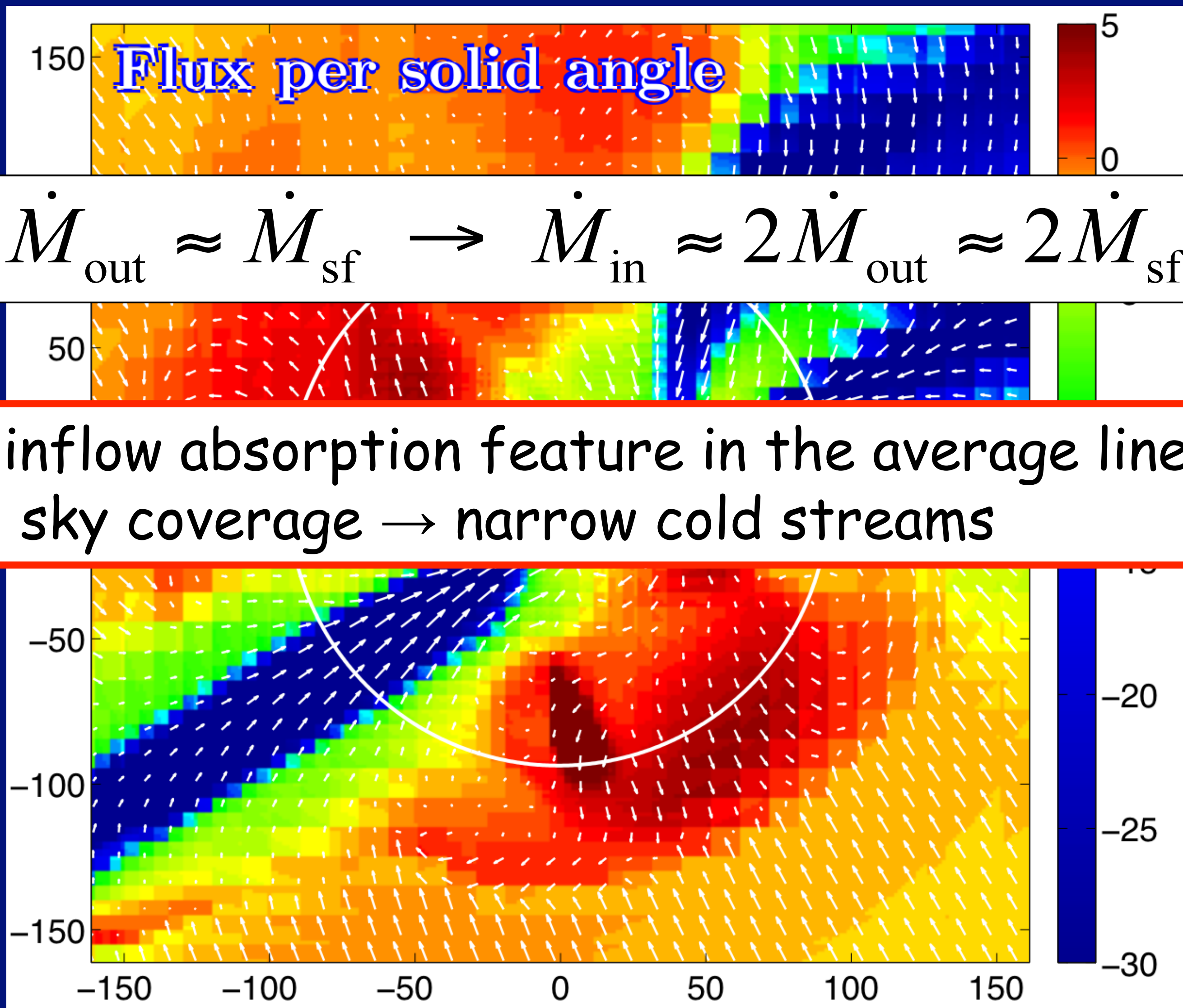
Absorption line profile is weak because of low sky coverage

Inflow signal consistent with observatios (Steidel et al. 10)

Inflow undetectable in metals because of low Z and coverage

Inflow and Outflow

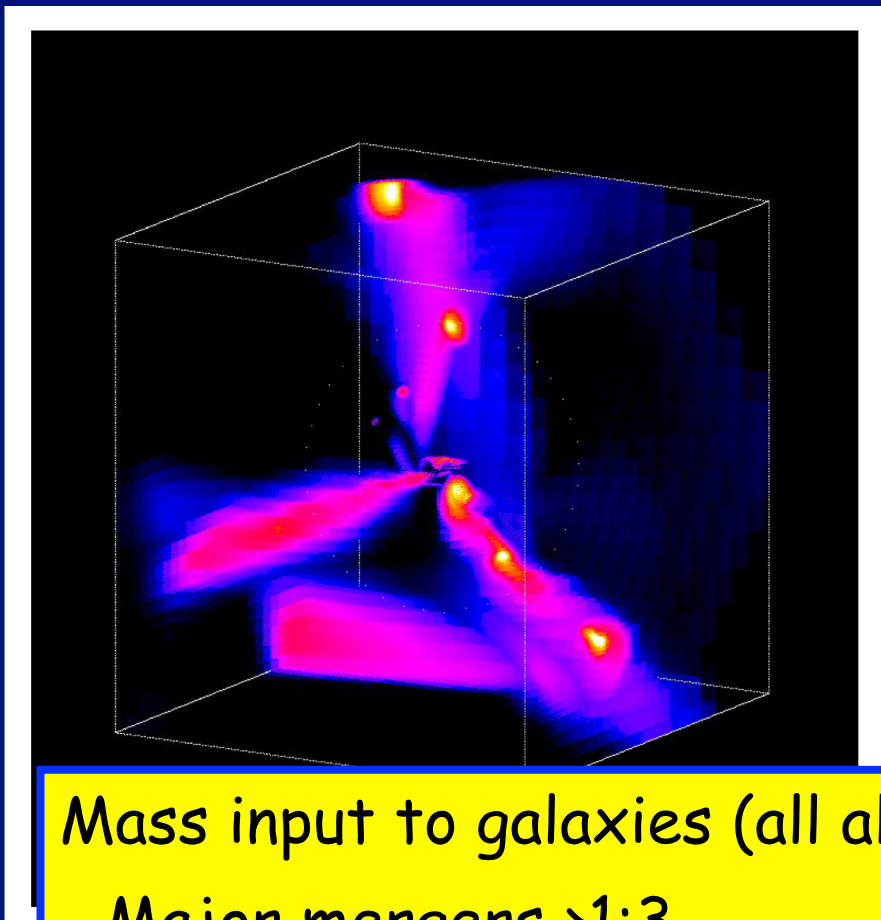
$$\dot{M}_{\rm out} \approx \dot{M}_{\rm sf} \;\rightarrow\; \dot{M}_{\rm in} \approx 2\dot{M}_{\rm out} \approx 2\dot{M}_{\rm sf}$$

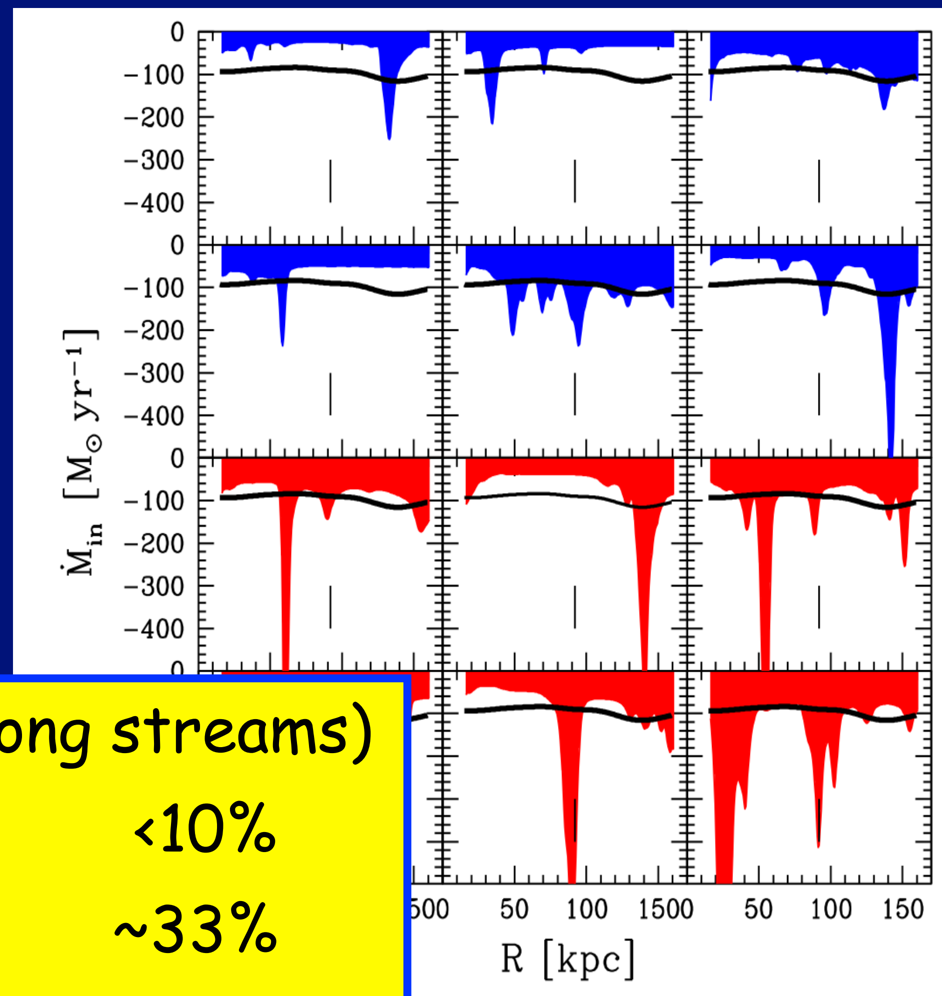


A weak inflow absorption feature in the average line profile
→ small sky coverage → narrow cold streams

6. Stream Clumpiness - Mergers

Dekel et al 09, Nature



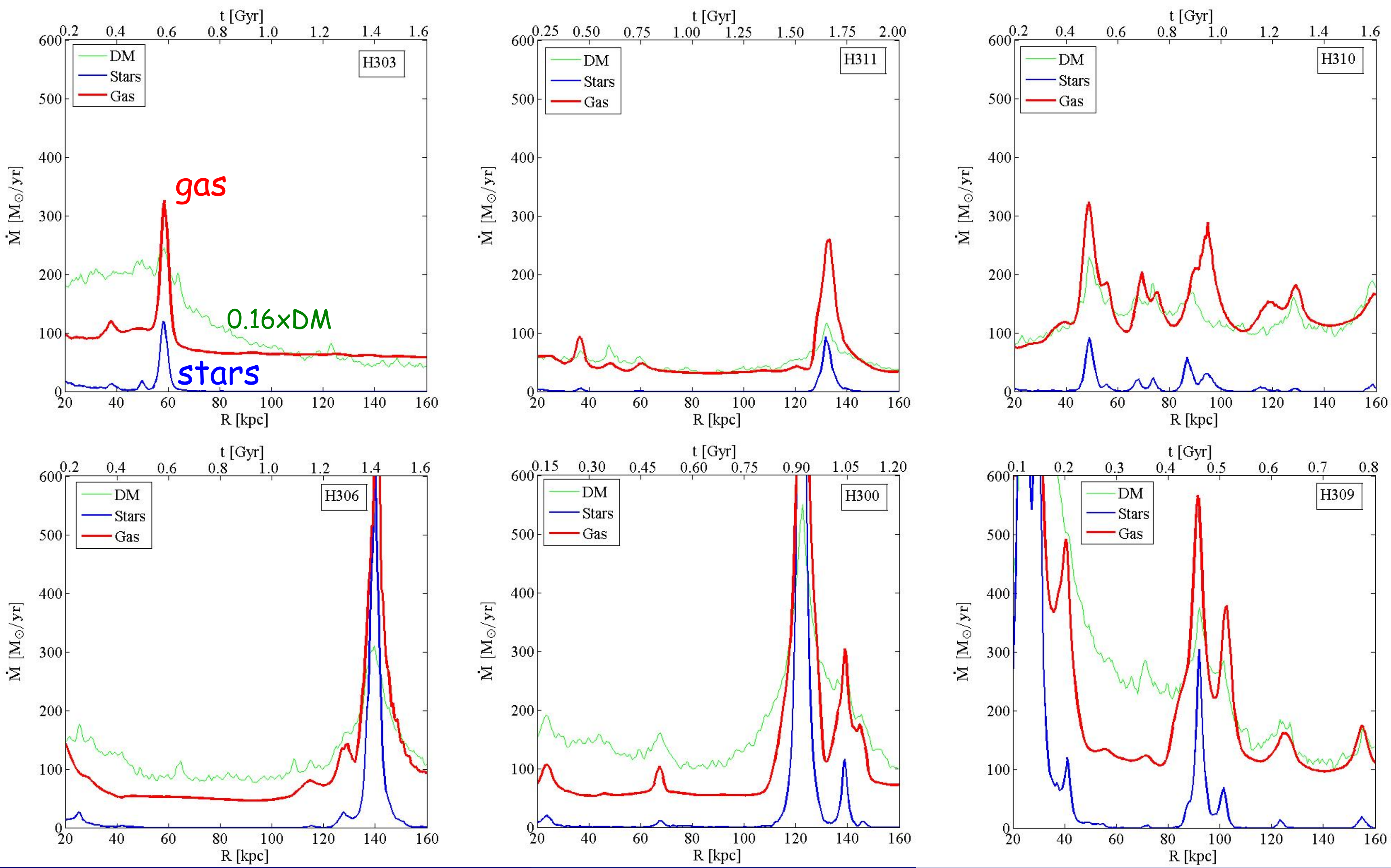


Mass input to galaxies (all along streams)

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

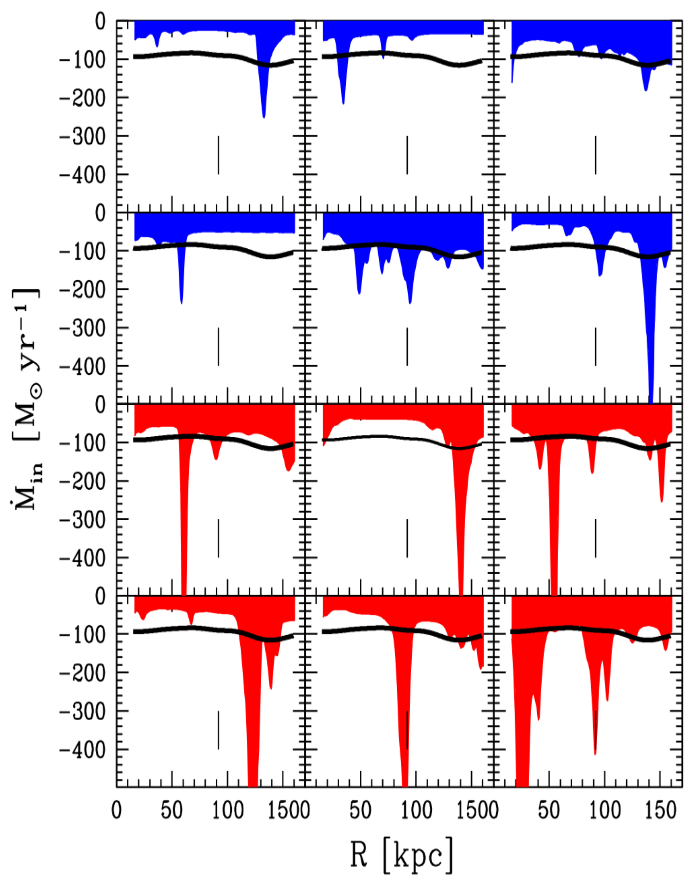
$M=10^{12}M_{\odot}$ $z=2.5$

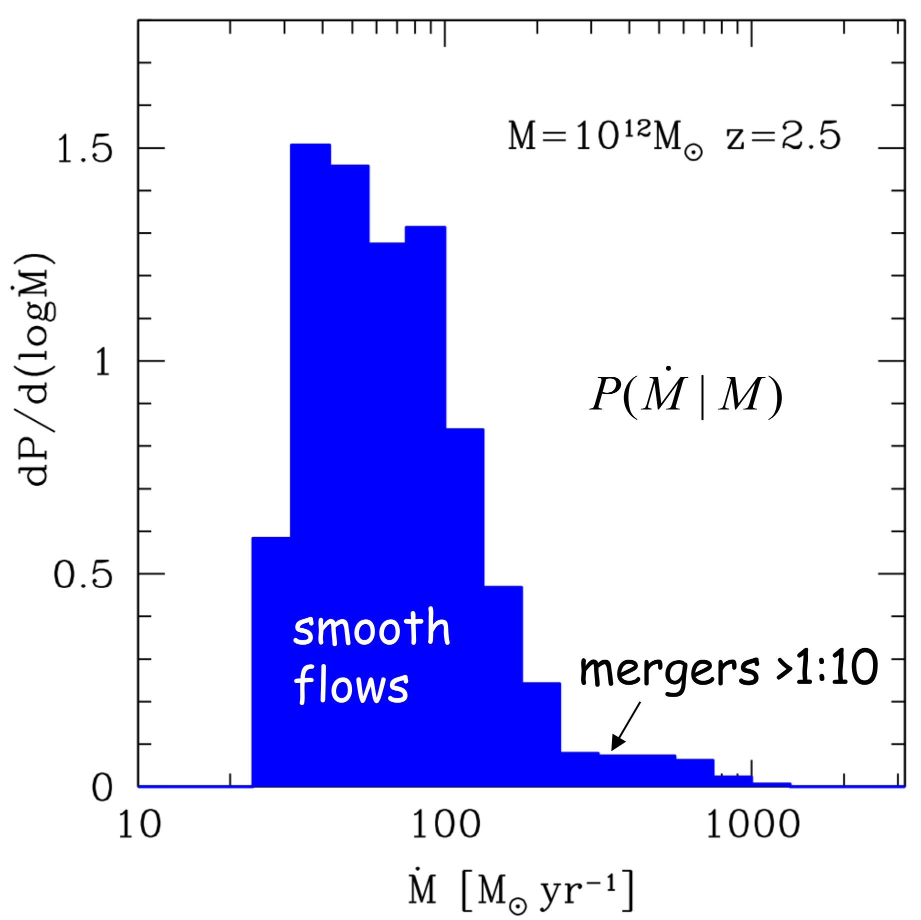
Accretion Rate in Streams: smooth and clumpy



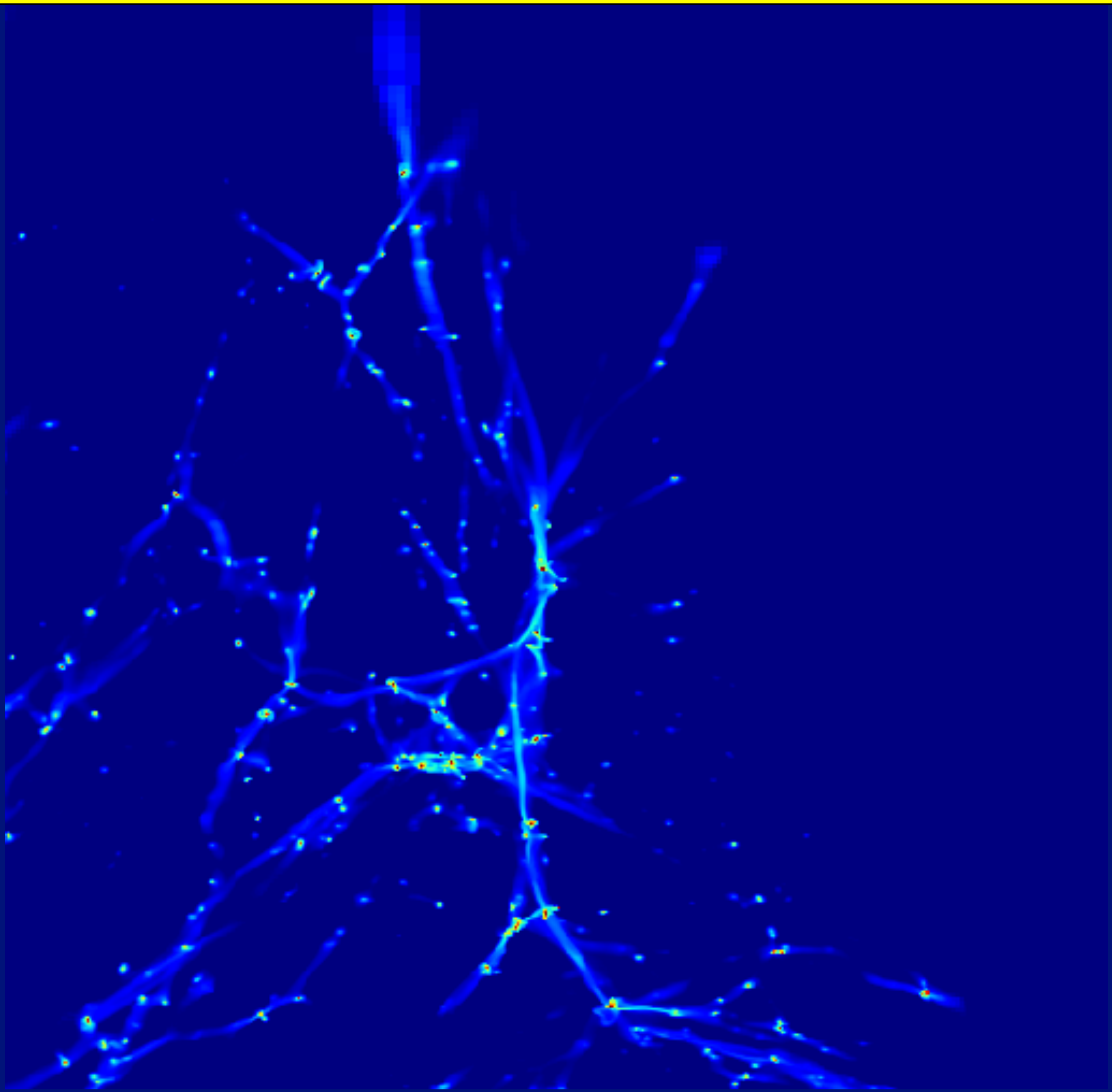
Distribution of gas inflow rate

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





All hi-z mergers are along cold streams



AMR RAMSES
Teyssier, Dekel

box 300 kpc

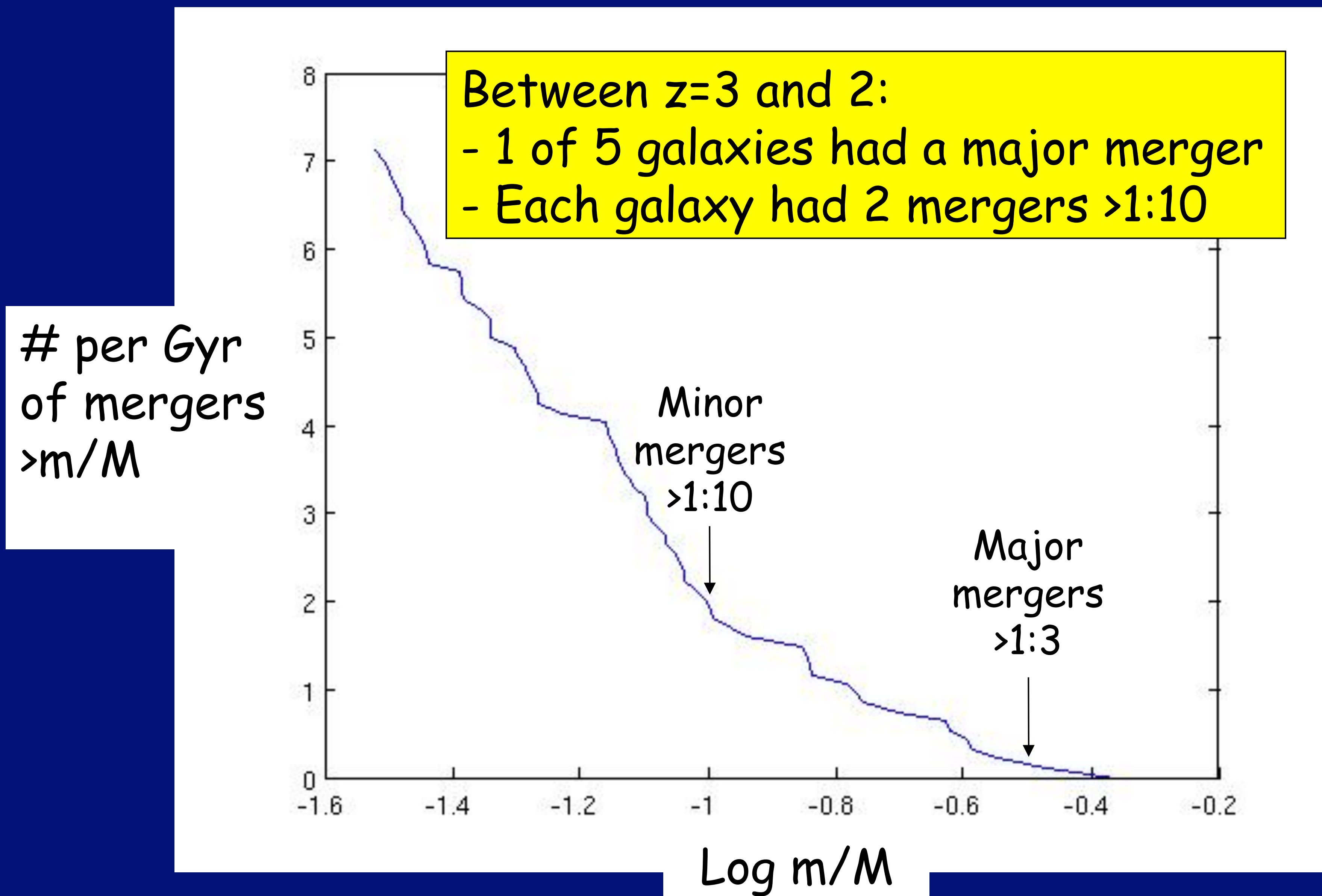
res 30 pc

$z = 5.0$ to 2.5

Merger Rate

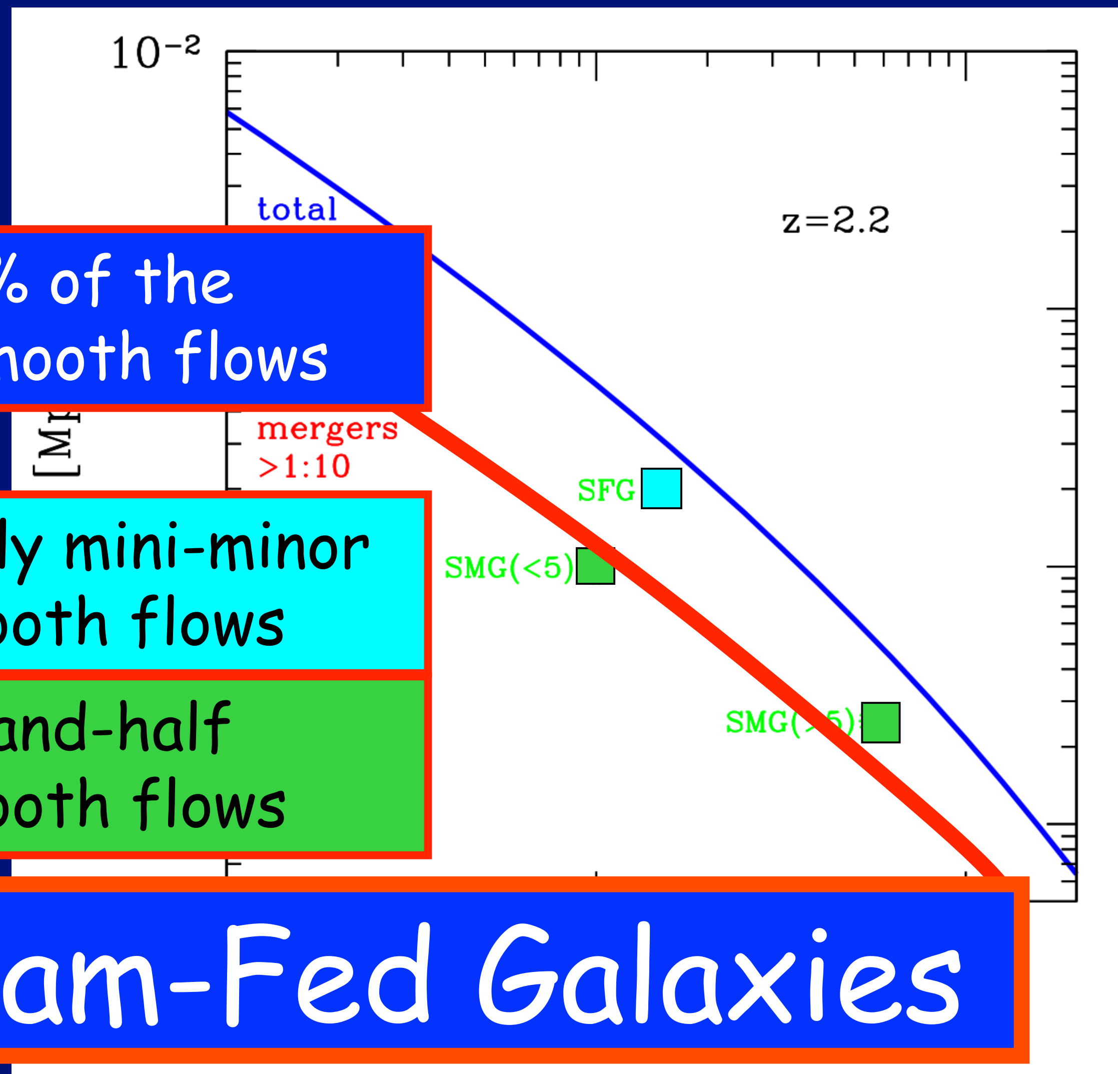
Romero et al. 2010

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



Mergers have a Limited Contribution to SFR

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



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

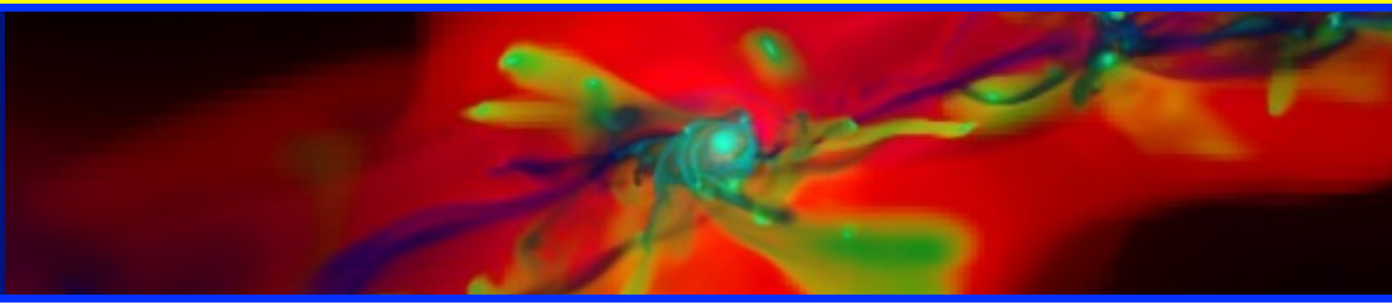
BzK/BX/BM are mostly mini-minor mergers <1:10, i.e. smooth flows

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

SFG: Stream-Fed Galaxies

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

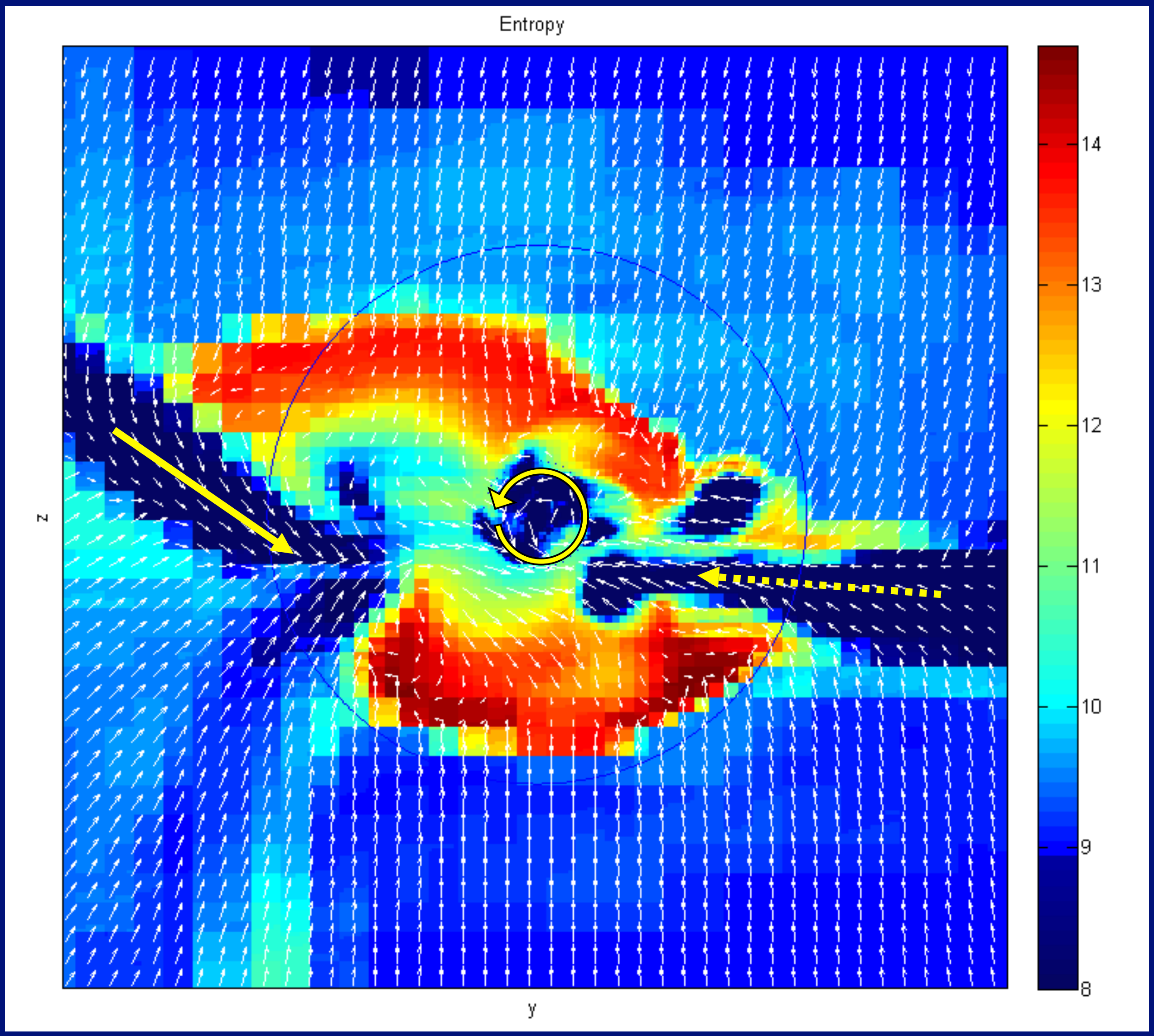


Open issues:

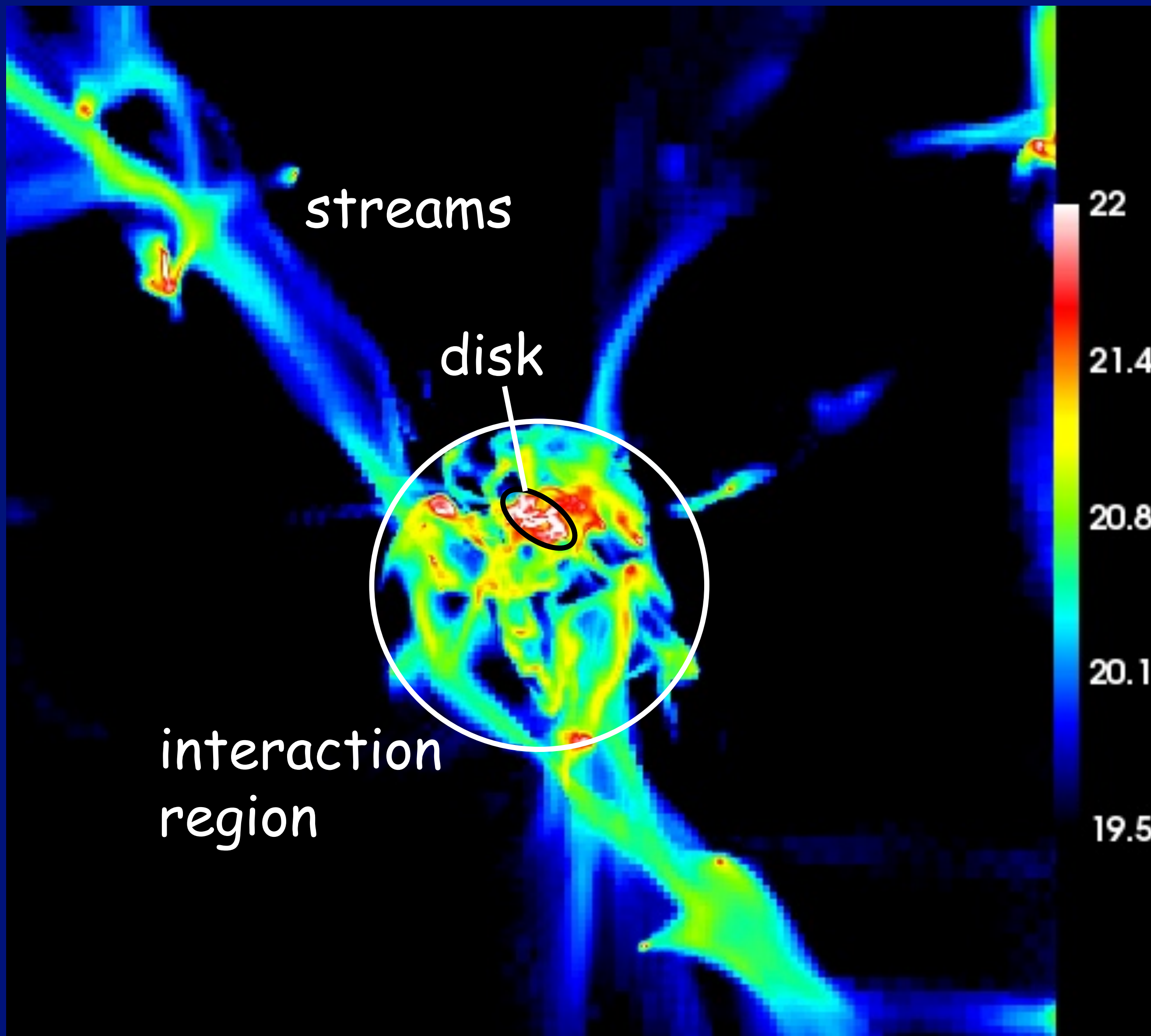
- Origin of large disk sizes ?
- Origin of “dispersion-dominated” galaxies $V/\sigma<2$?
- Angular mometum? Stream clumpiness? Feedback?

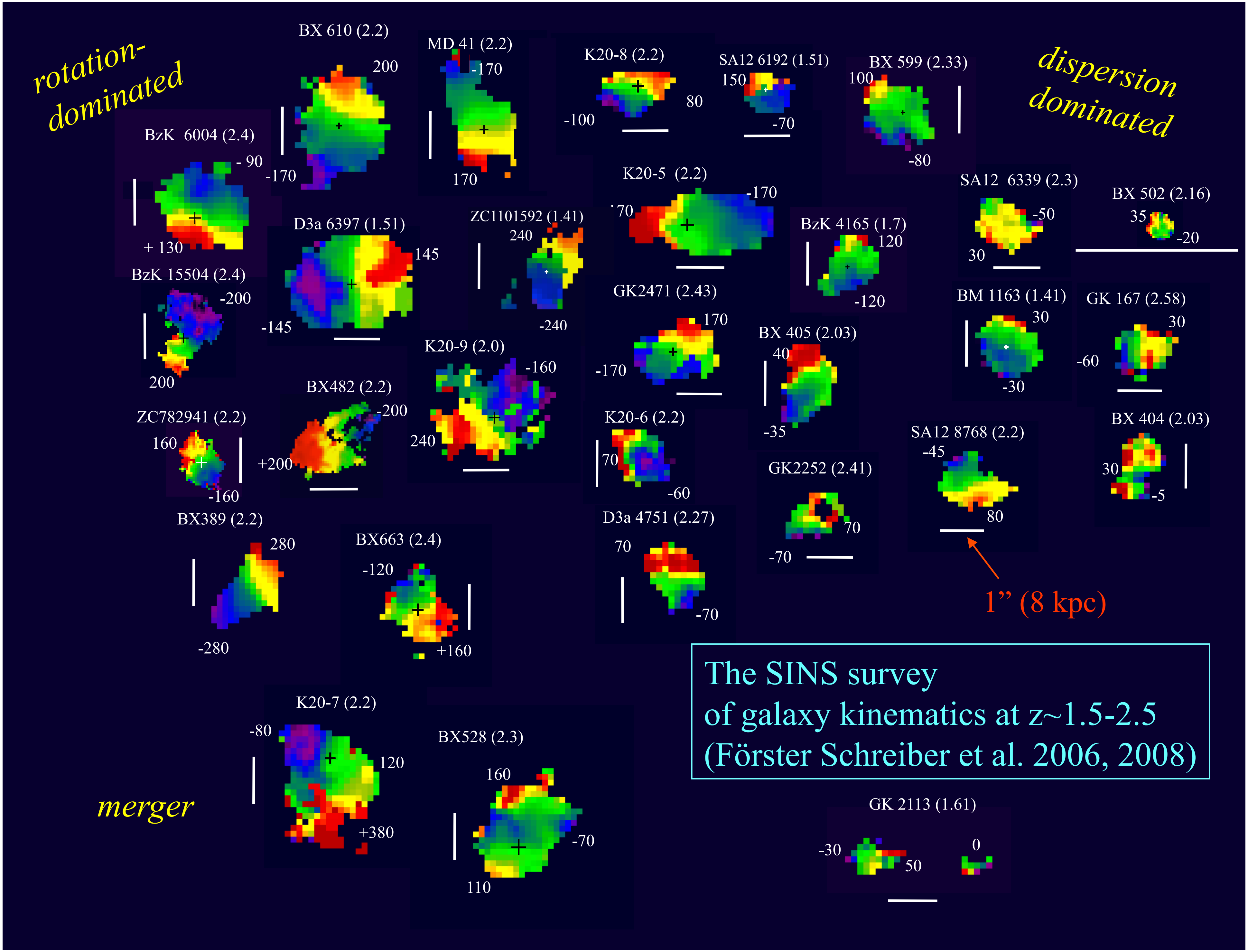
Agertz et al 09

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. Violent Disk Instability

Noguchi 99
Immeli et al. 04

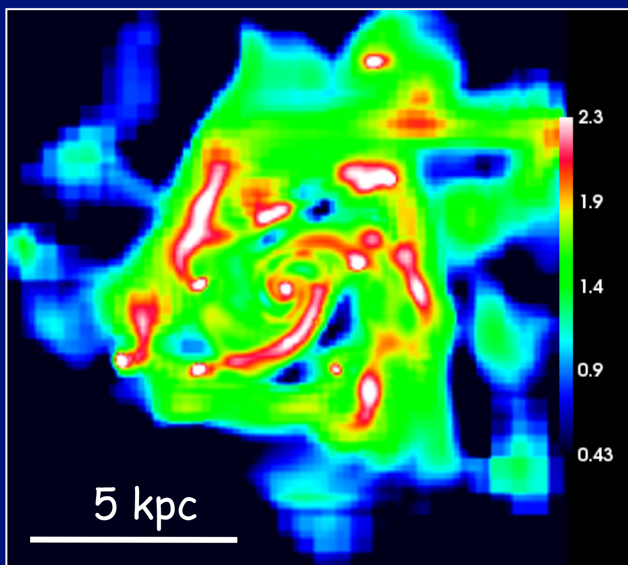
Bournaud, Elmegreen, Elmegreen 06, 08

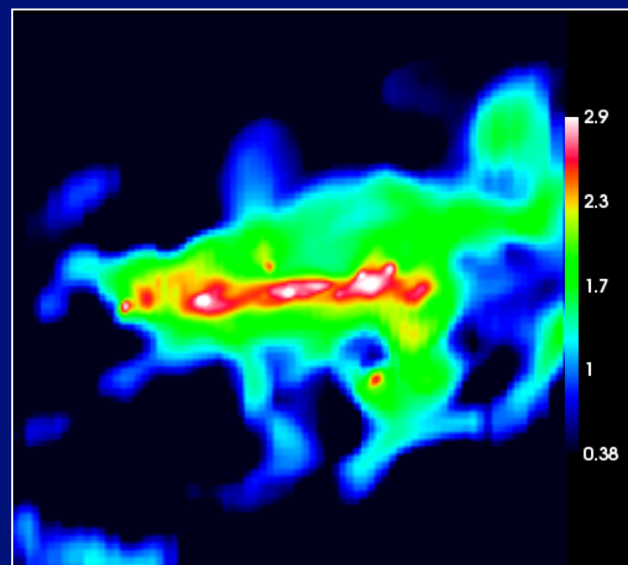
High gas density → disk wildly unstable

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

Giant clumps and transient features

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





Dekel, Sari, Ceverino 09

Ceverino, Dekel, Bournaud 09

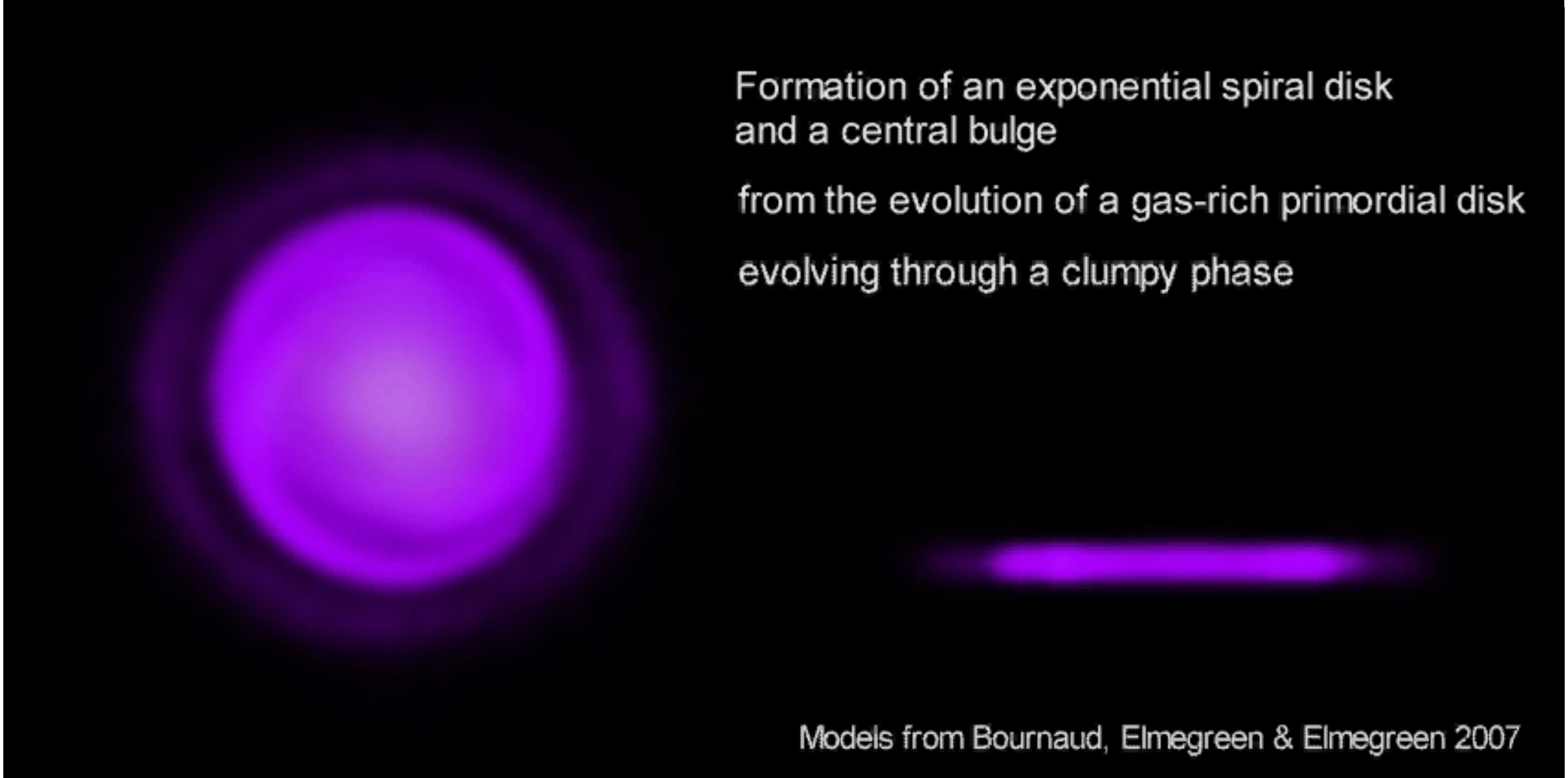
Agertz et al. 09

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

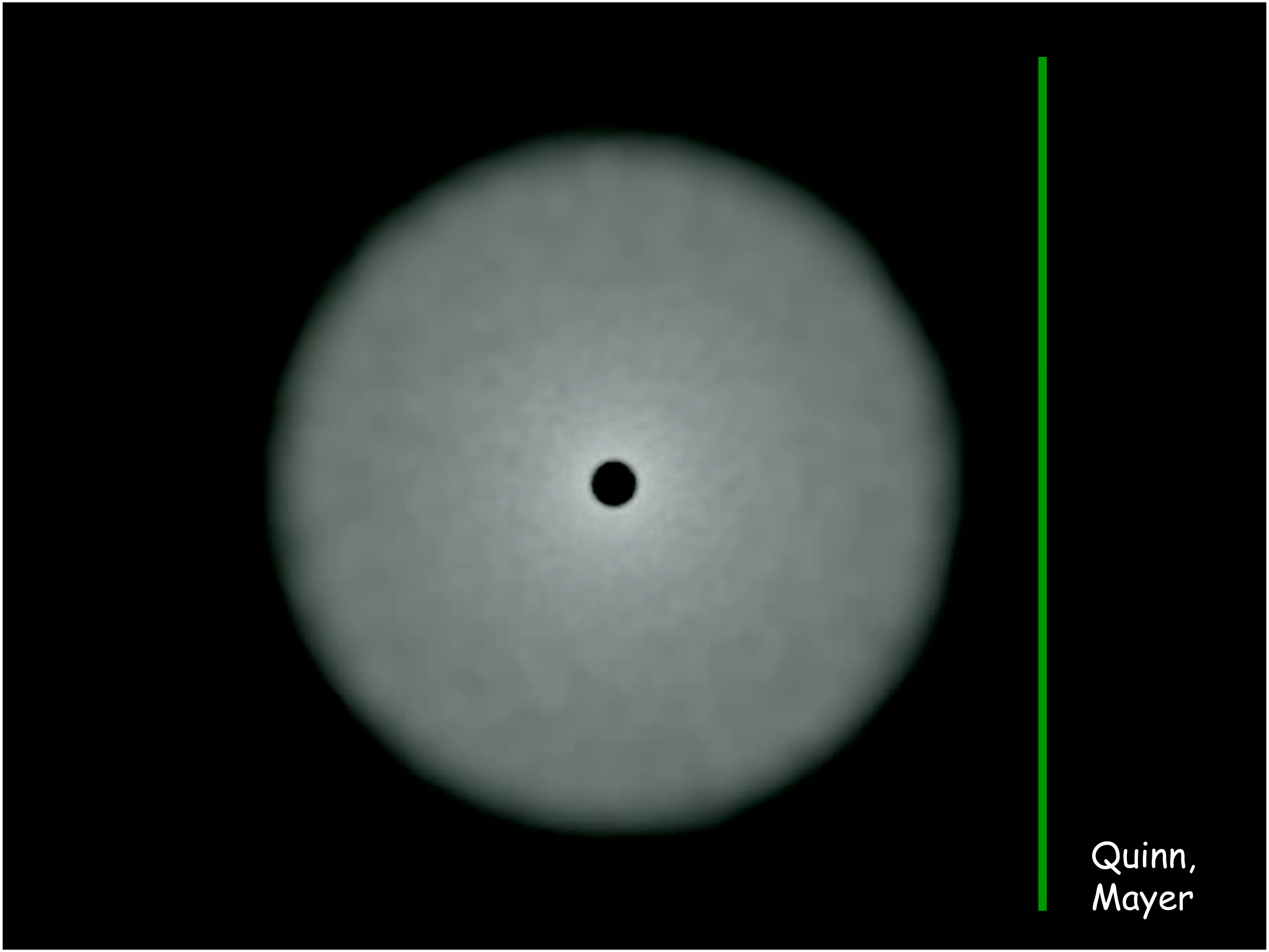
Efficient star formation in the clumps (to be understood)

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

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

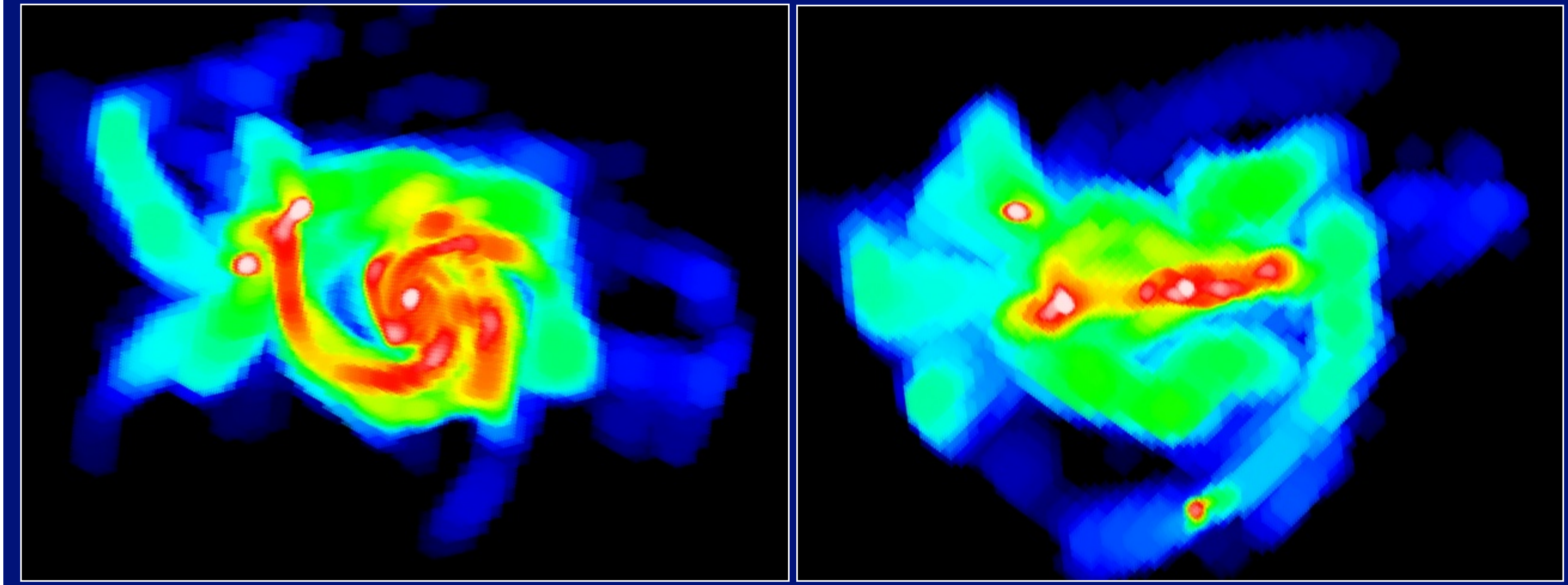


Noguchi 99; **One episode of 0.5 Gyr?** green 06, 08


Quinn,
Mayer

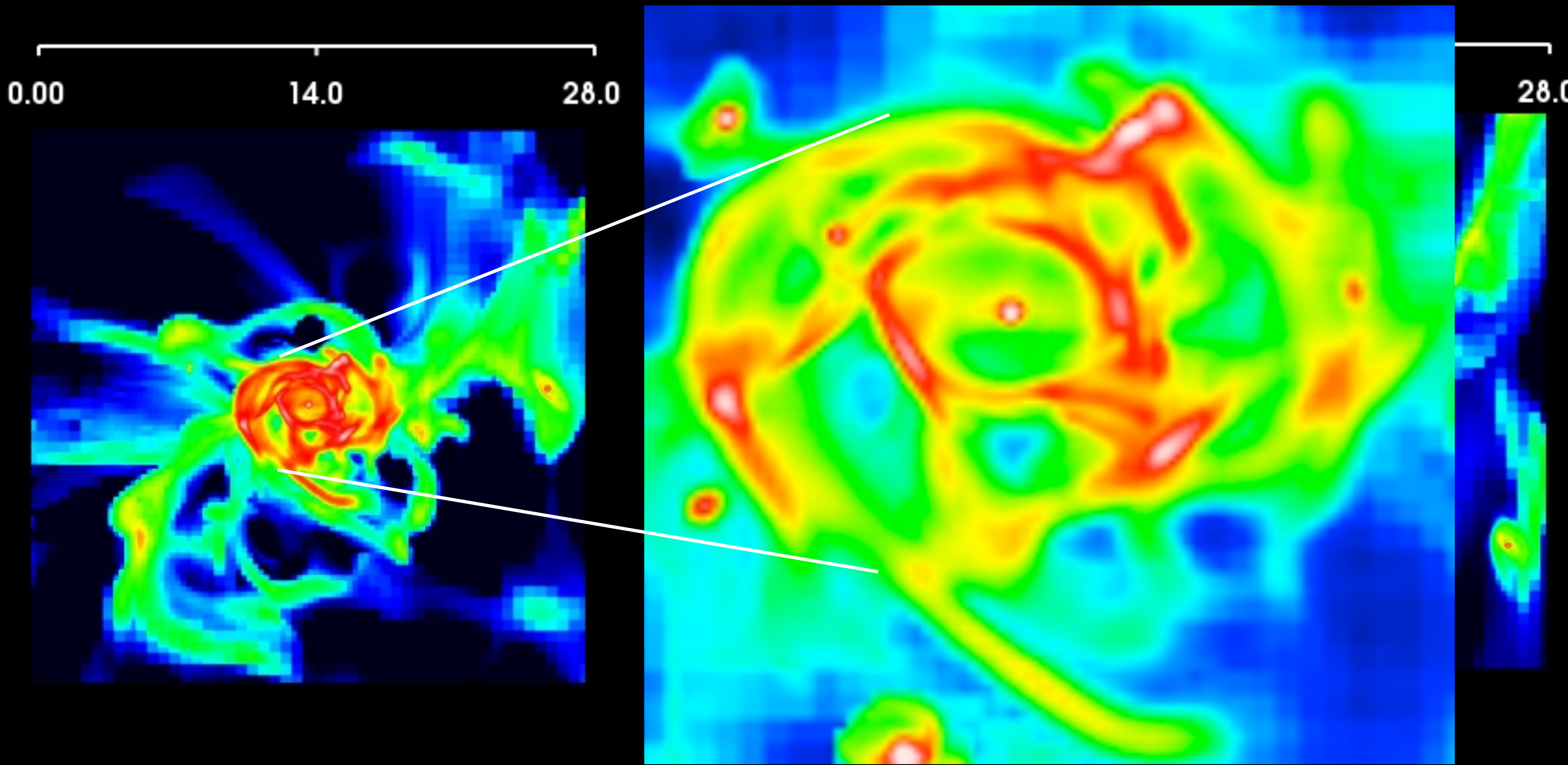
Cosmological Simulation: Stream-fed disk of giant gas clumps

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

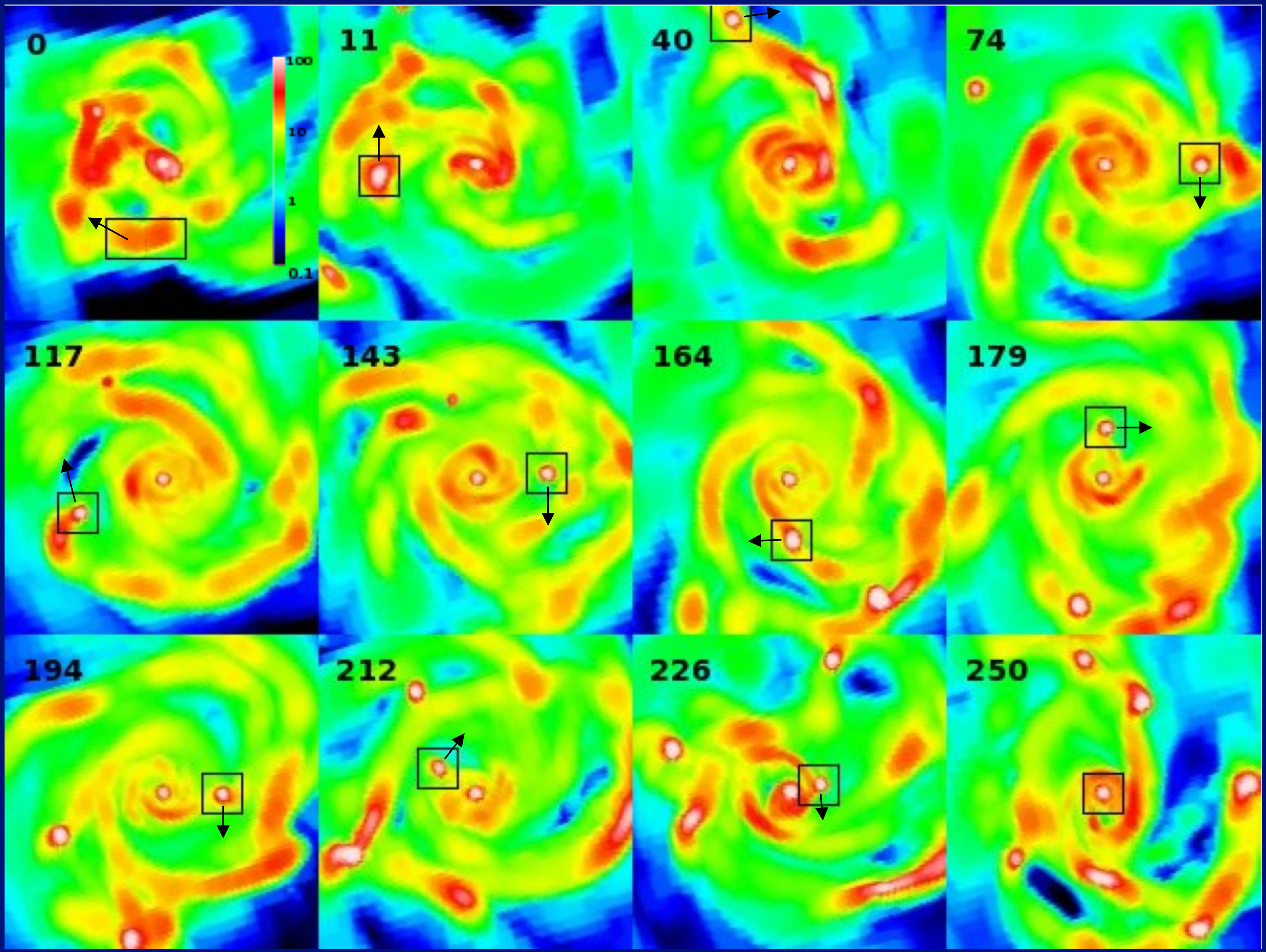


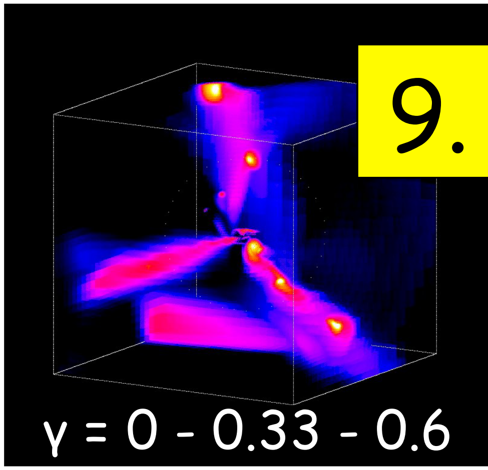
Cosmological Simulation:
Stream-fed disk of giant gas clumps

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



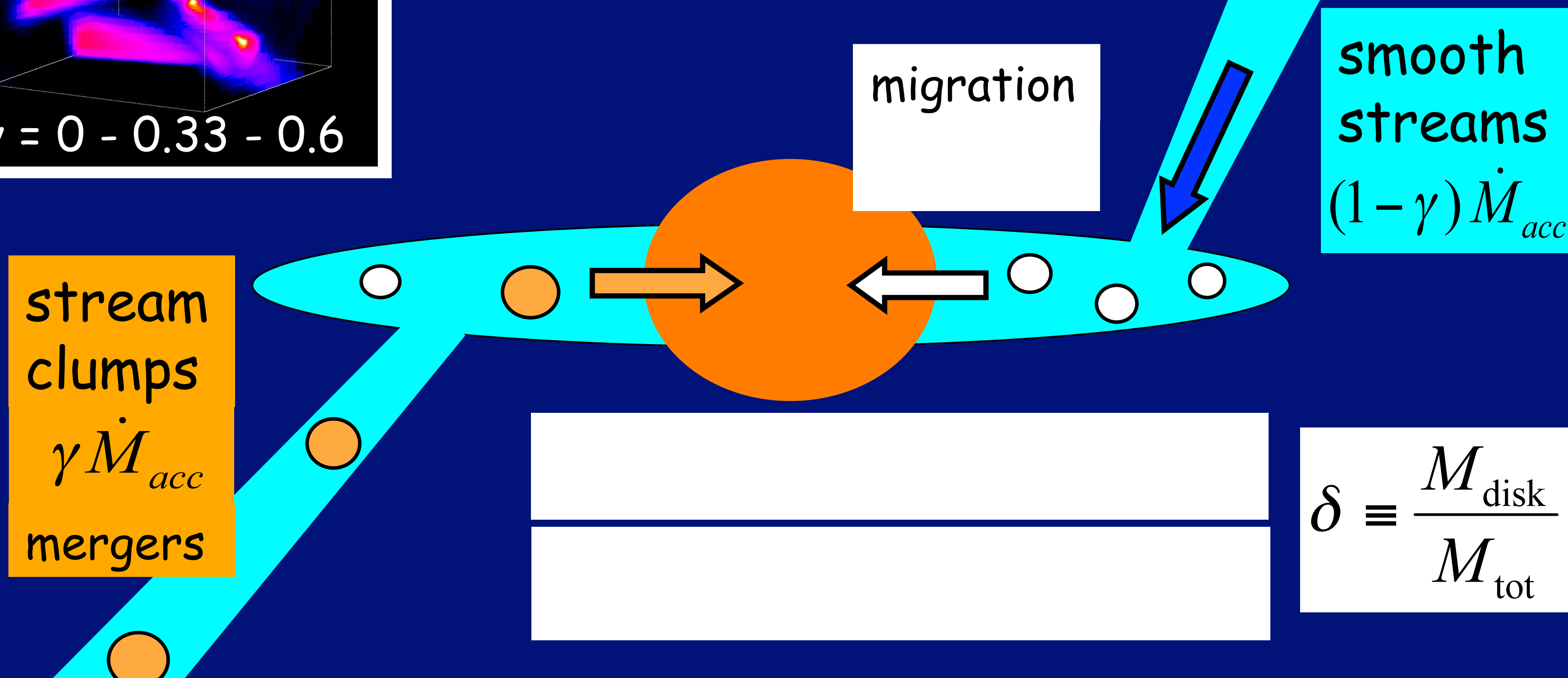
Clump Formation & Migration





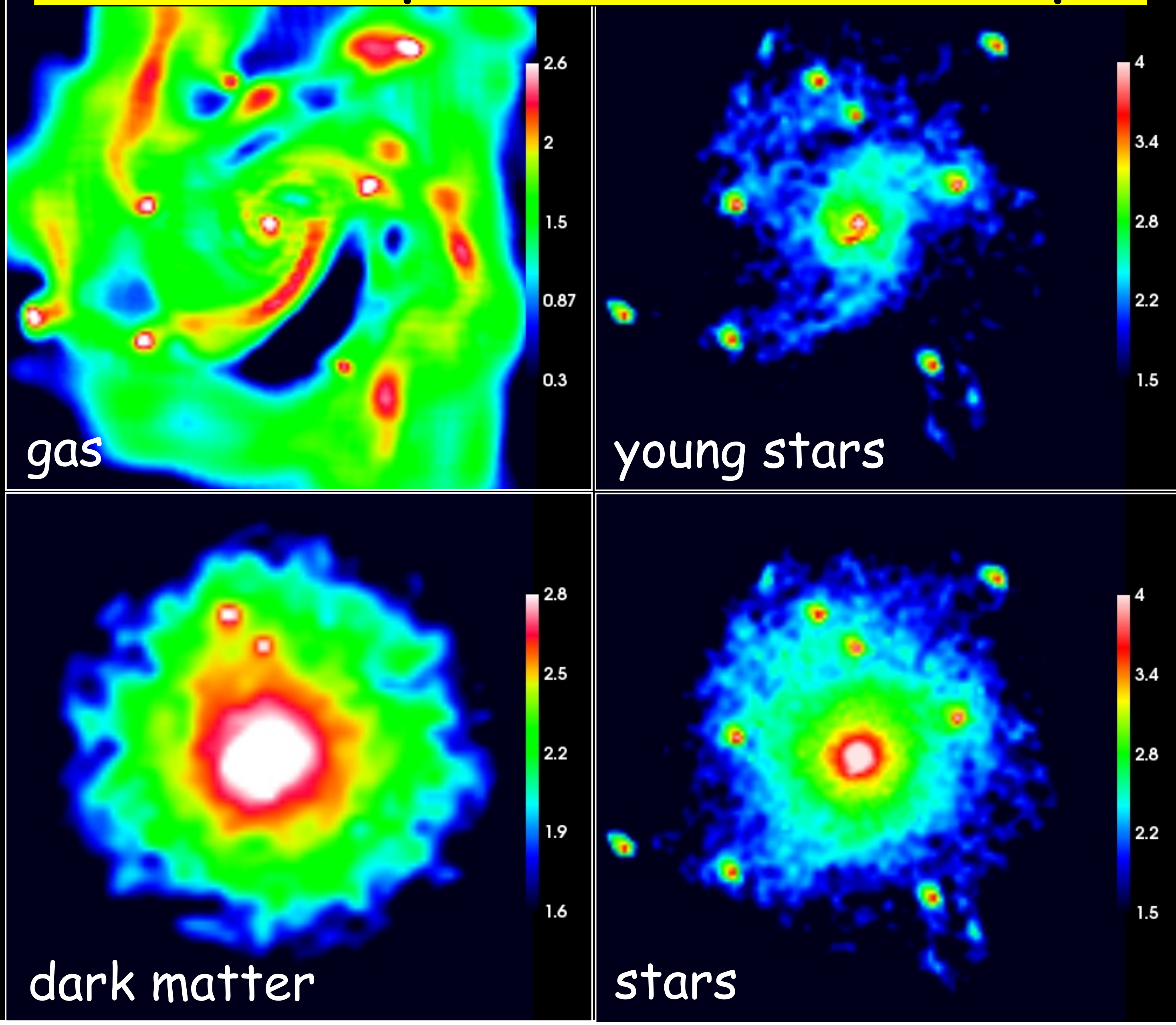
9. Cosmological Steady State

Dekel, Sari, Ceverino 09

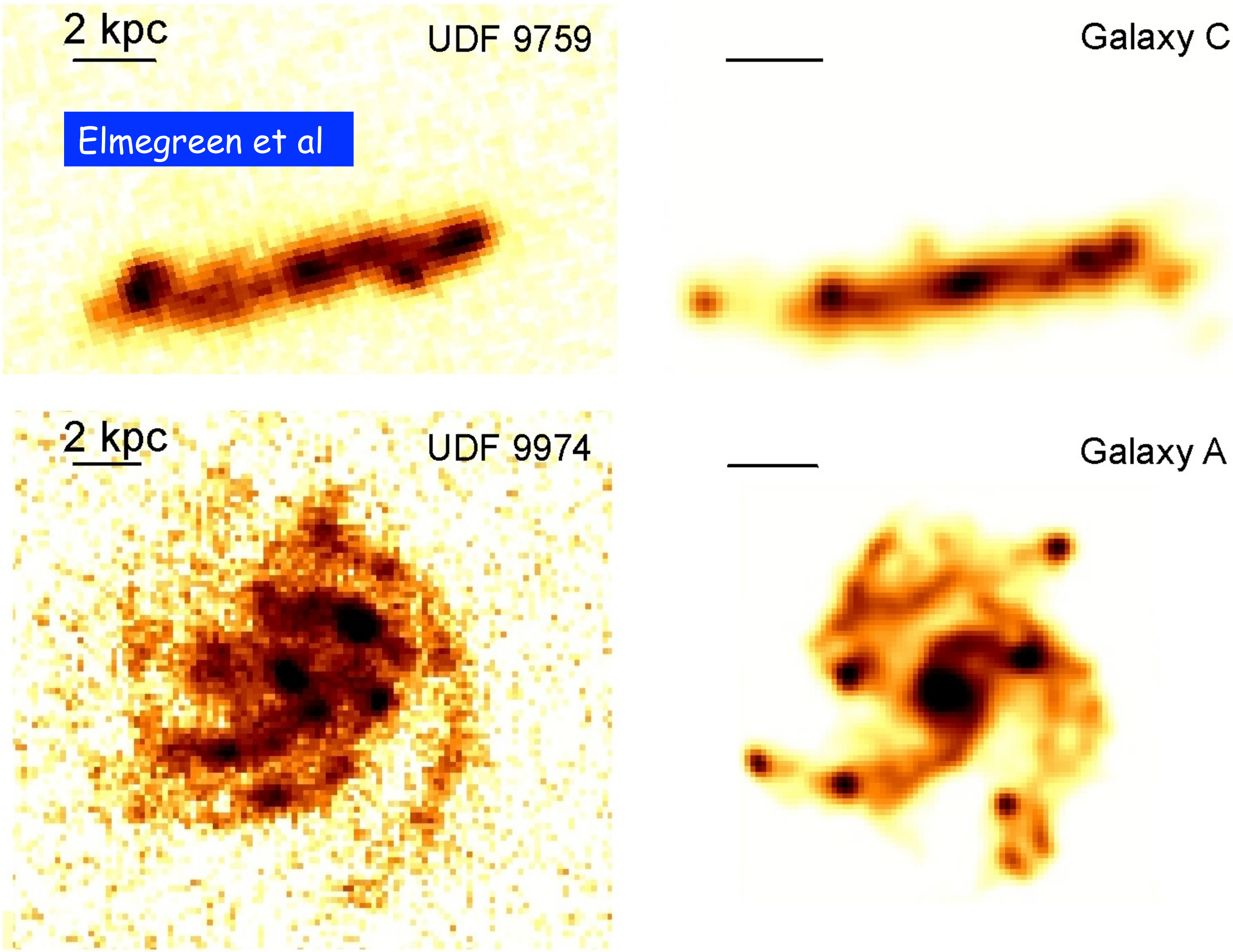


Steady state for several Gyrs:
draining disk is replenished by cold streams,
bulge ~ disk ~ dark matter

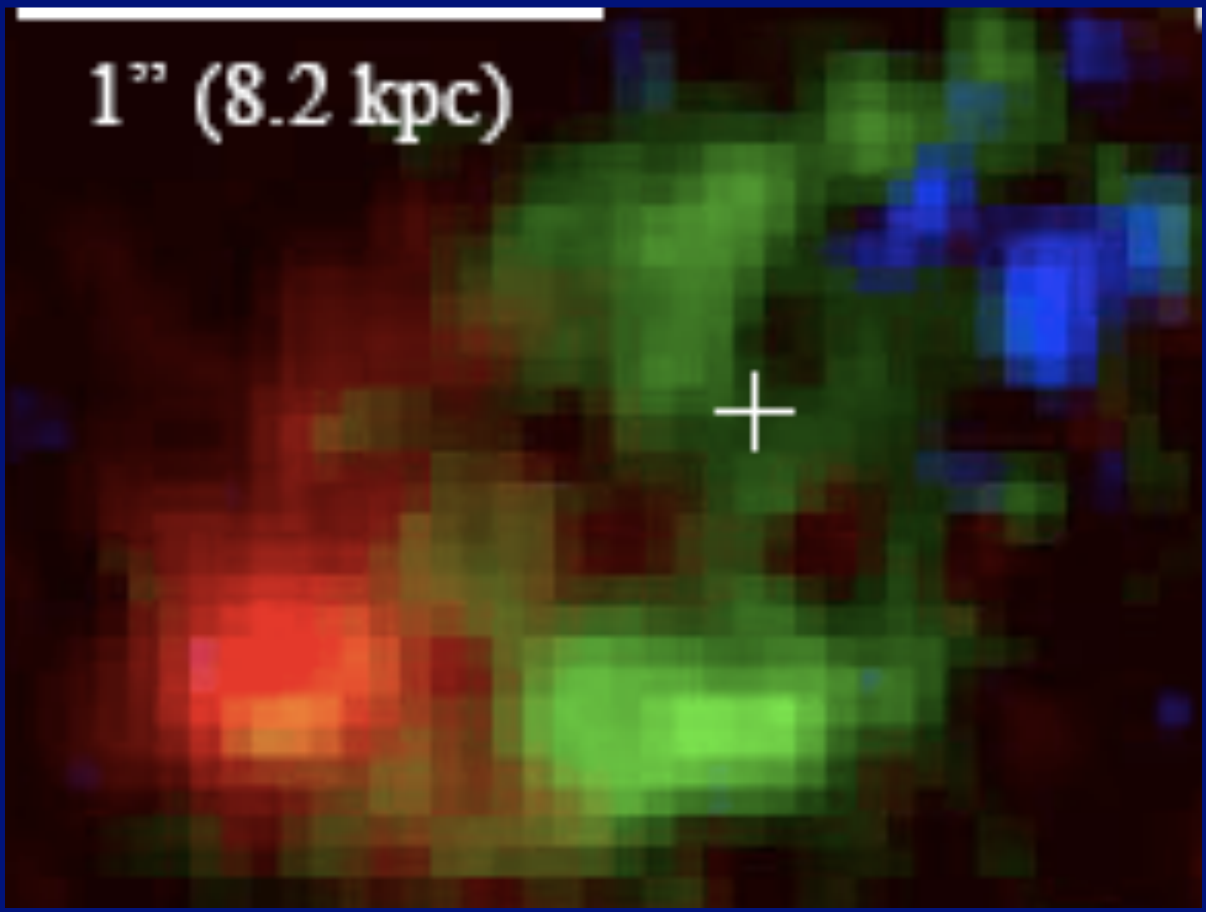
Disk Clumps vs Stream Clumps



Observations vs. Simulations



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

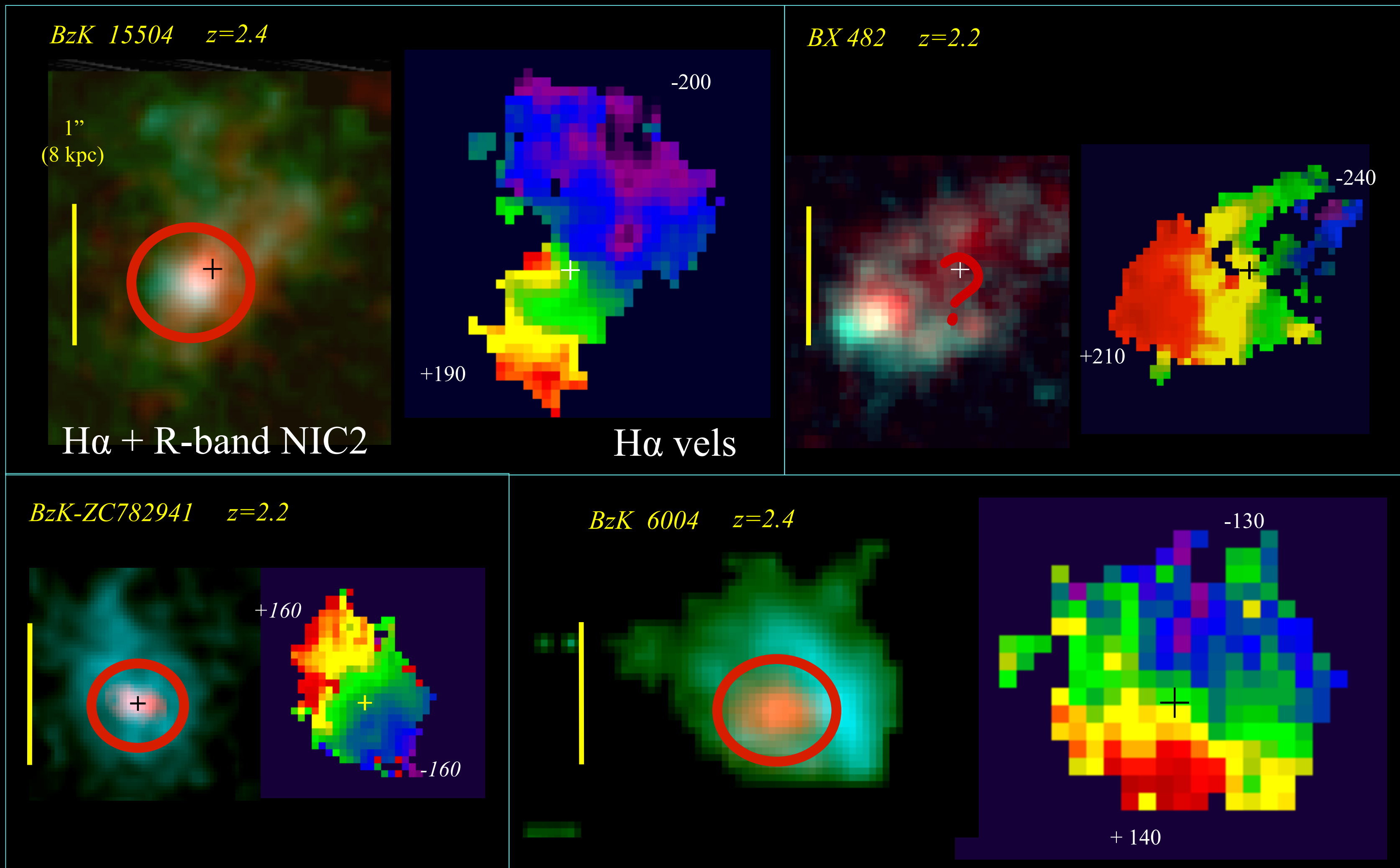


Ha star-form regions

color-code velocity field

Genzel et al 08

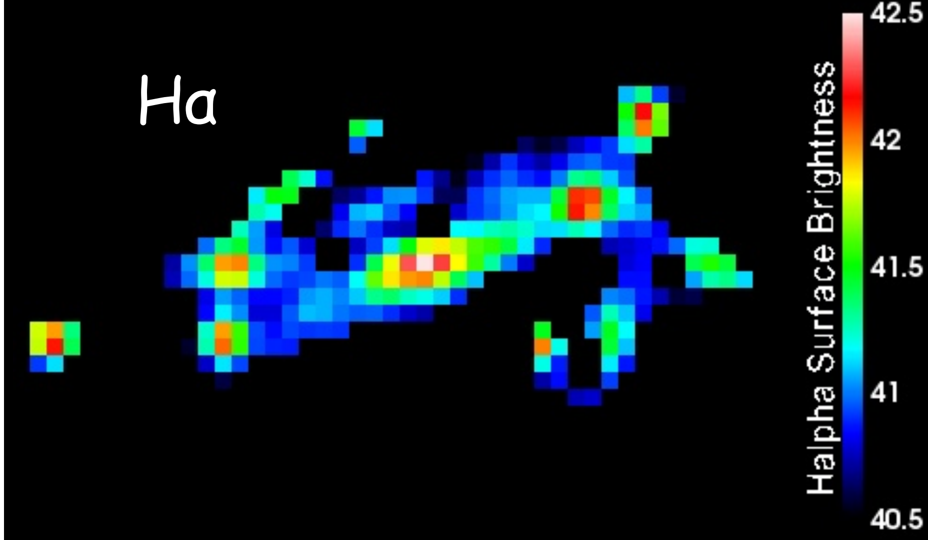
Clumpy disks with comparable bulges

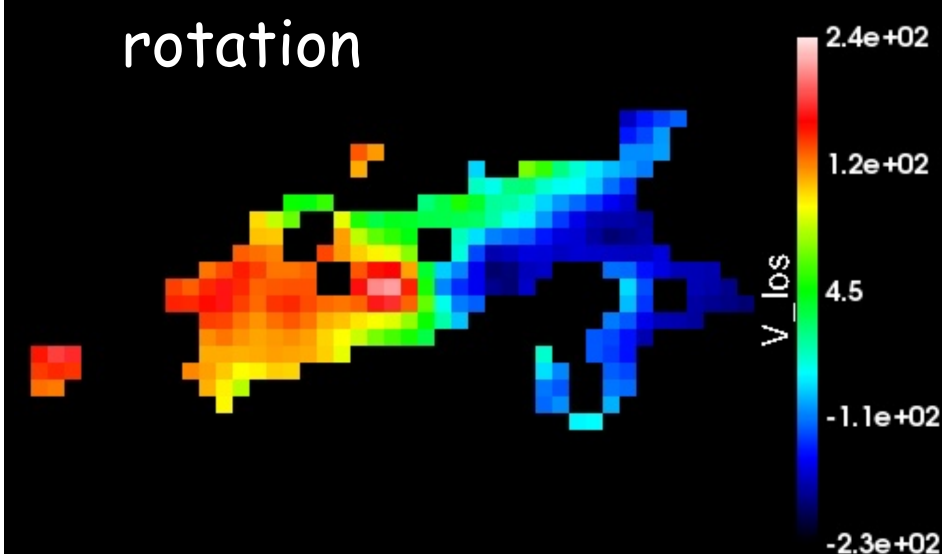


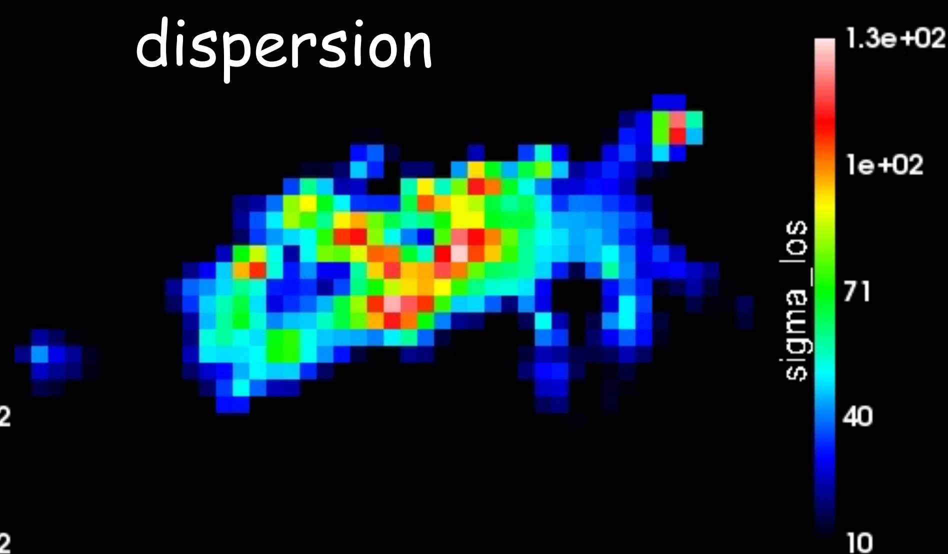
Genzel et al. 08; Förster Schreiber et al. 20

M(≤3 kpc)/M(≤15 kpc)~0.2-0.4

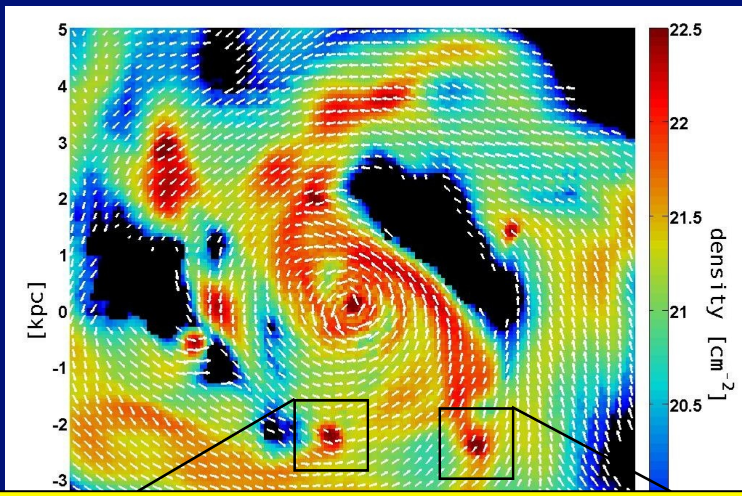
Kinematics of Simulated Clumpy Disk

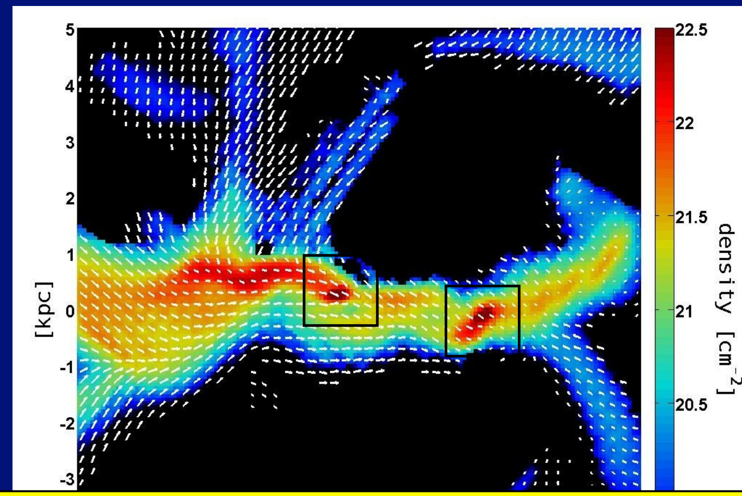






The Clumps are Spinning



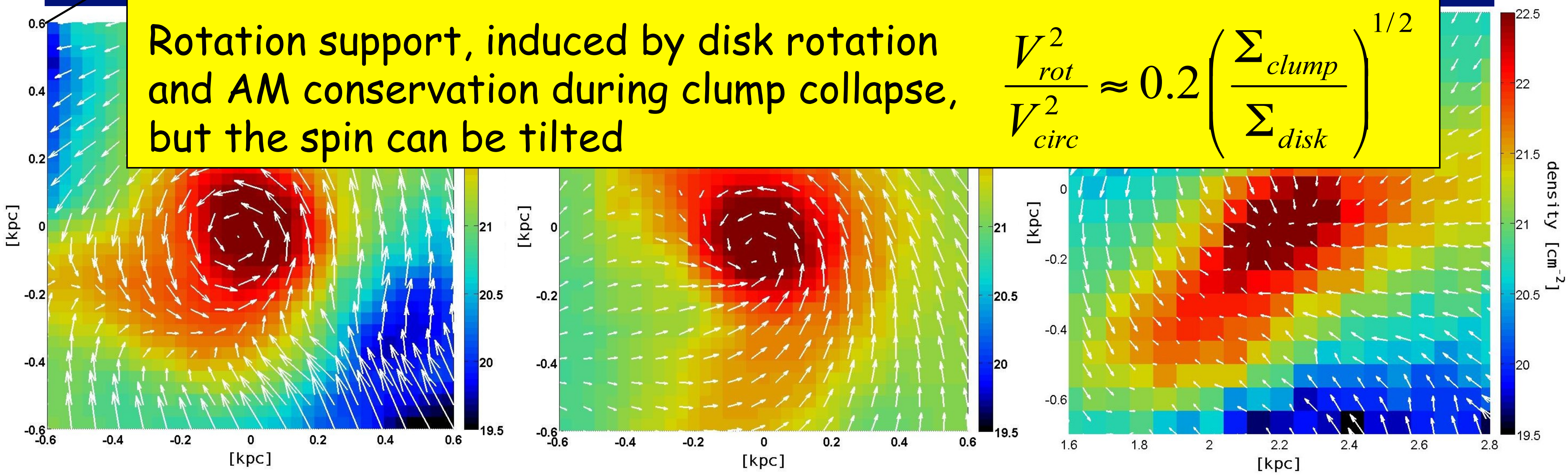


Jeans equation for an isotropic rotator

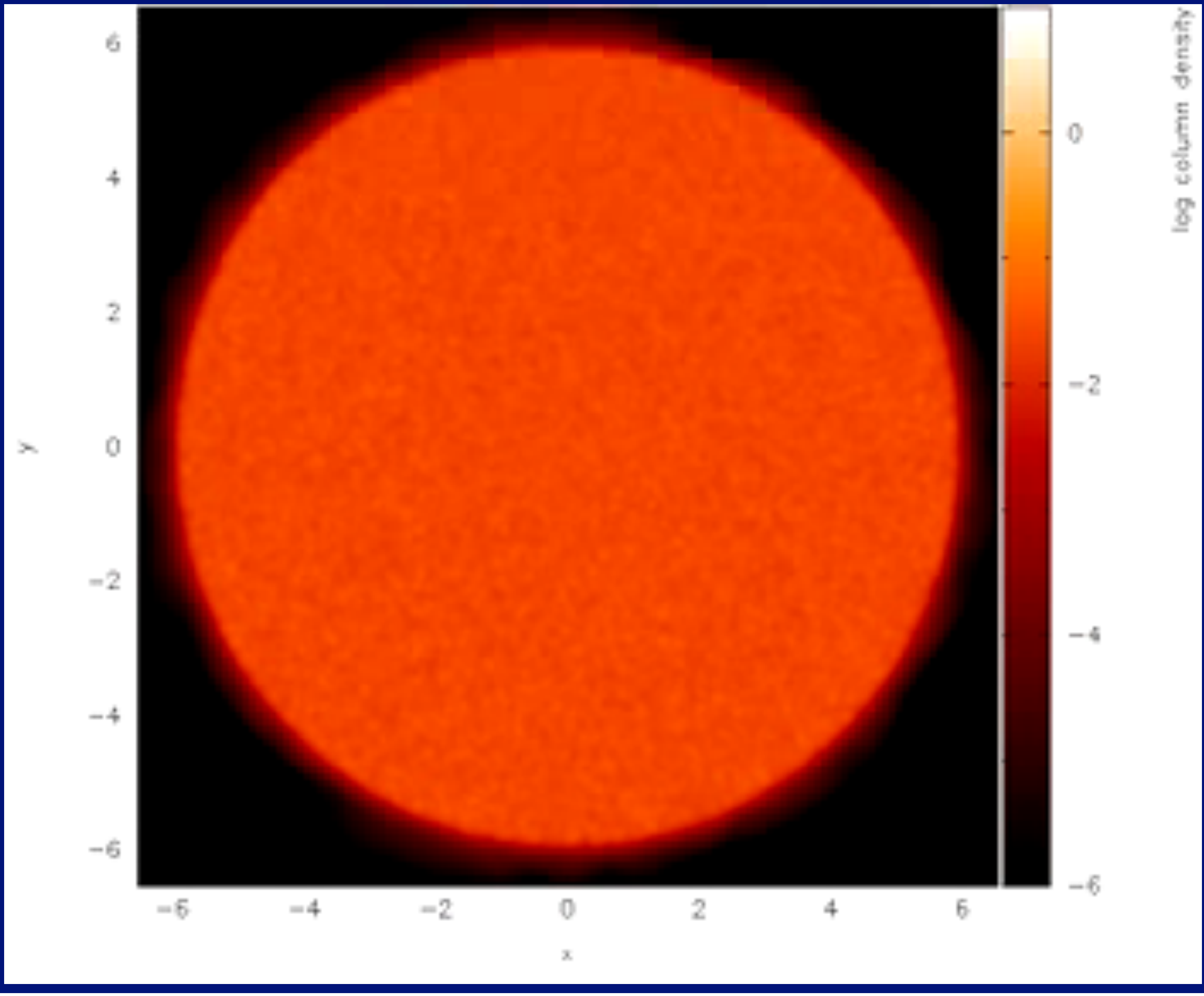
$$V_{circ}^2 = \frac{GM}{R} = V_{rot}^2 + 2\sigma^2$$

Rotation support, induced by disk rotation and AM conservation during clump collapse, but the spin can be tilted

$$\frac{V_{rot}^2}{V_{circ}^2} \approx 0.2 \left(\frac{\Sigma_{clump}}{\Sigma_{disk}} \right)^{1/2}$$

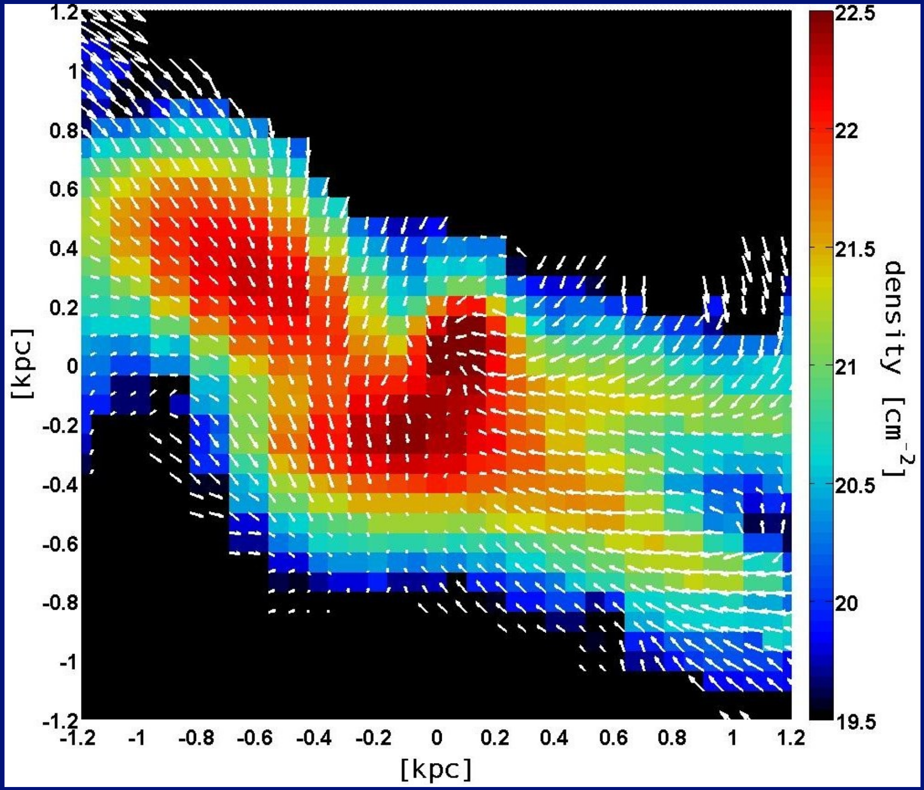


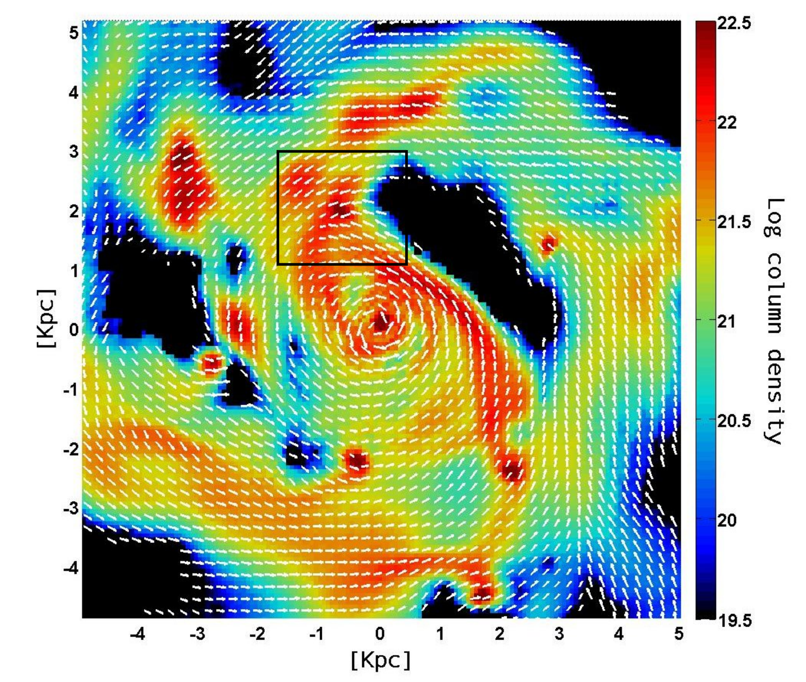
Rotating Clumps in a Wildly Unstable Disk

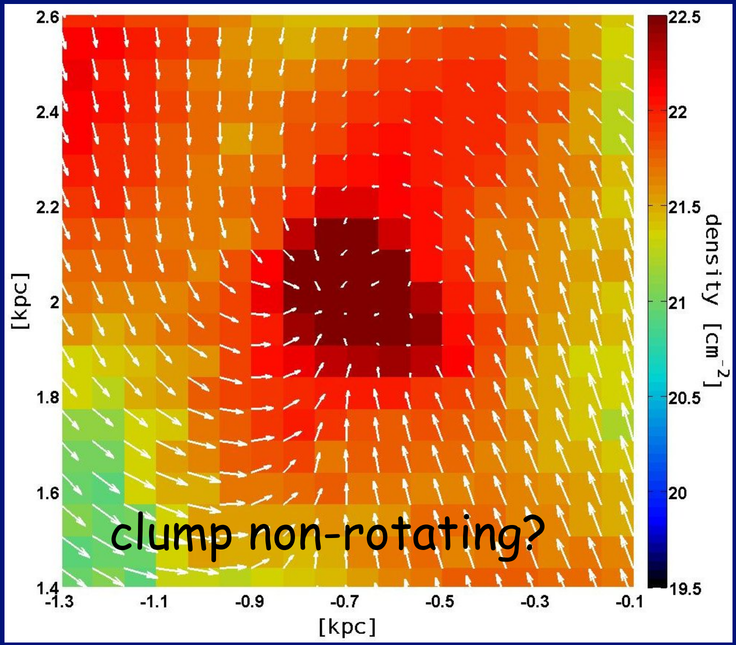


Naab

Interacting Clumps

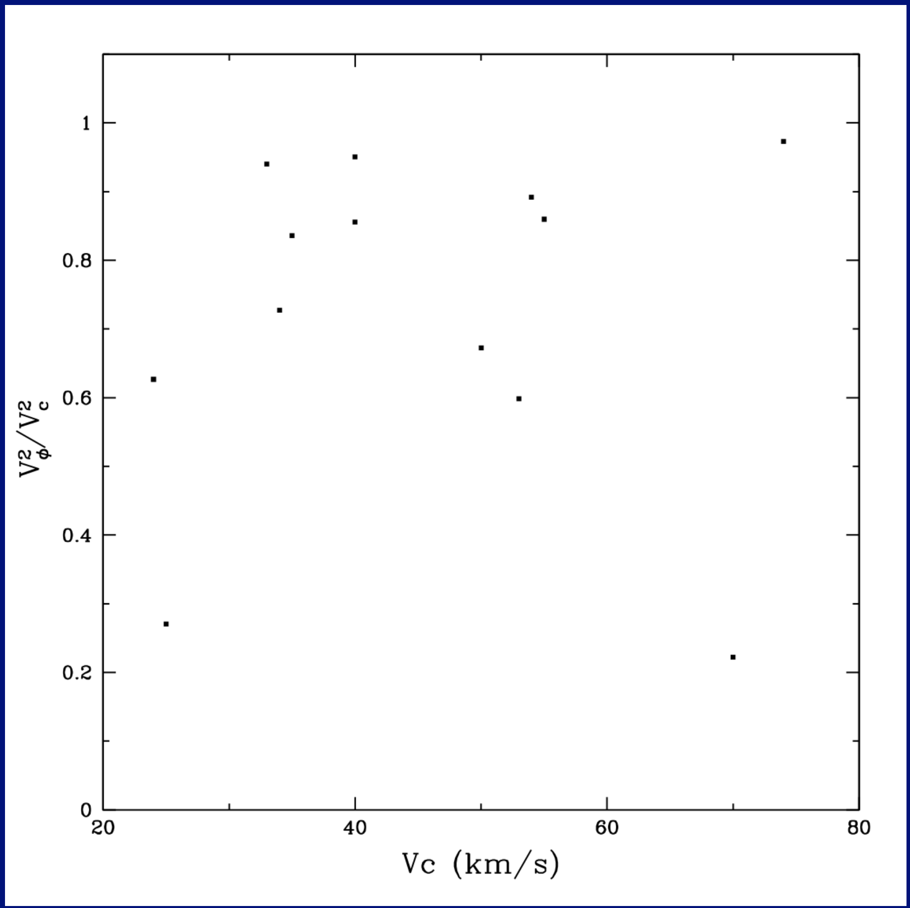




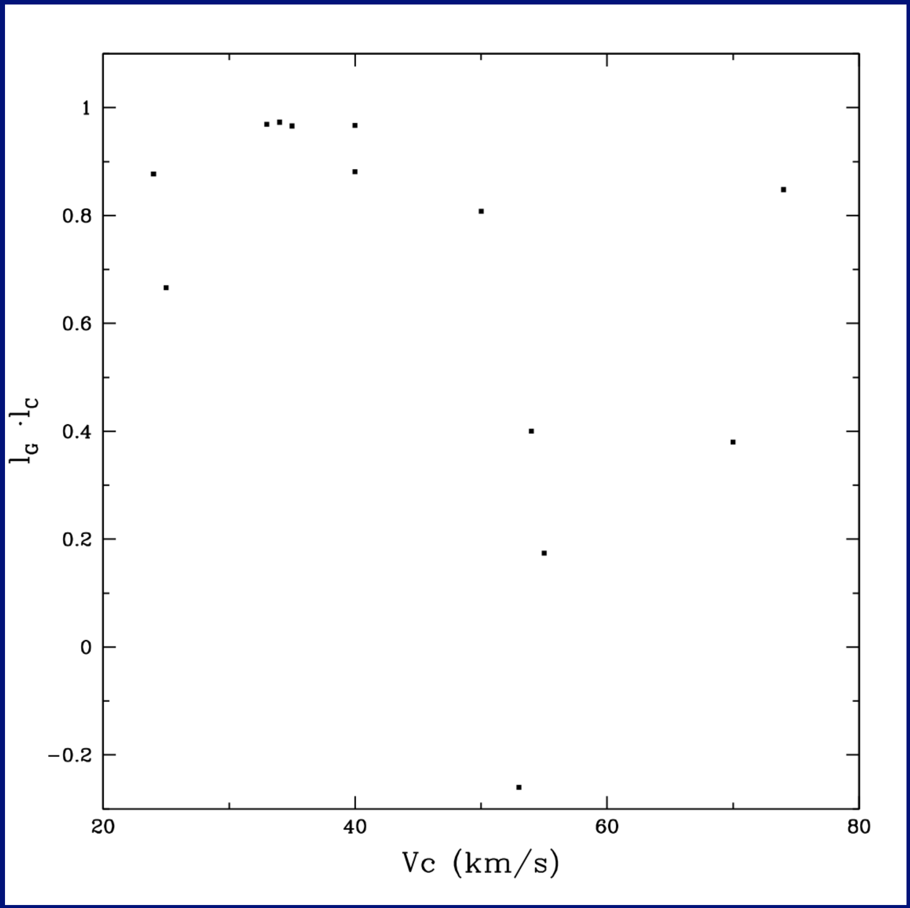


Clump Rotational Support

Rotational Support

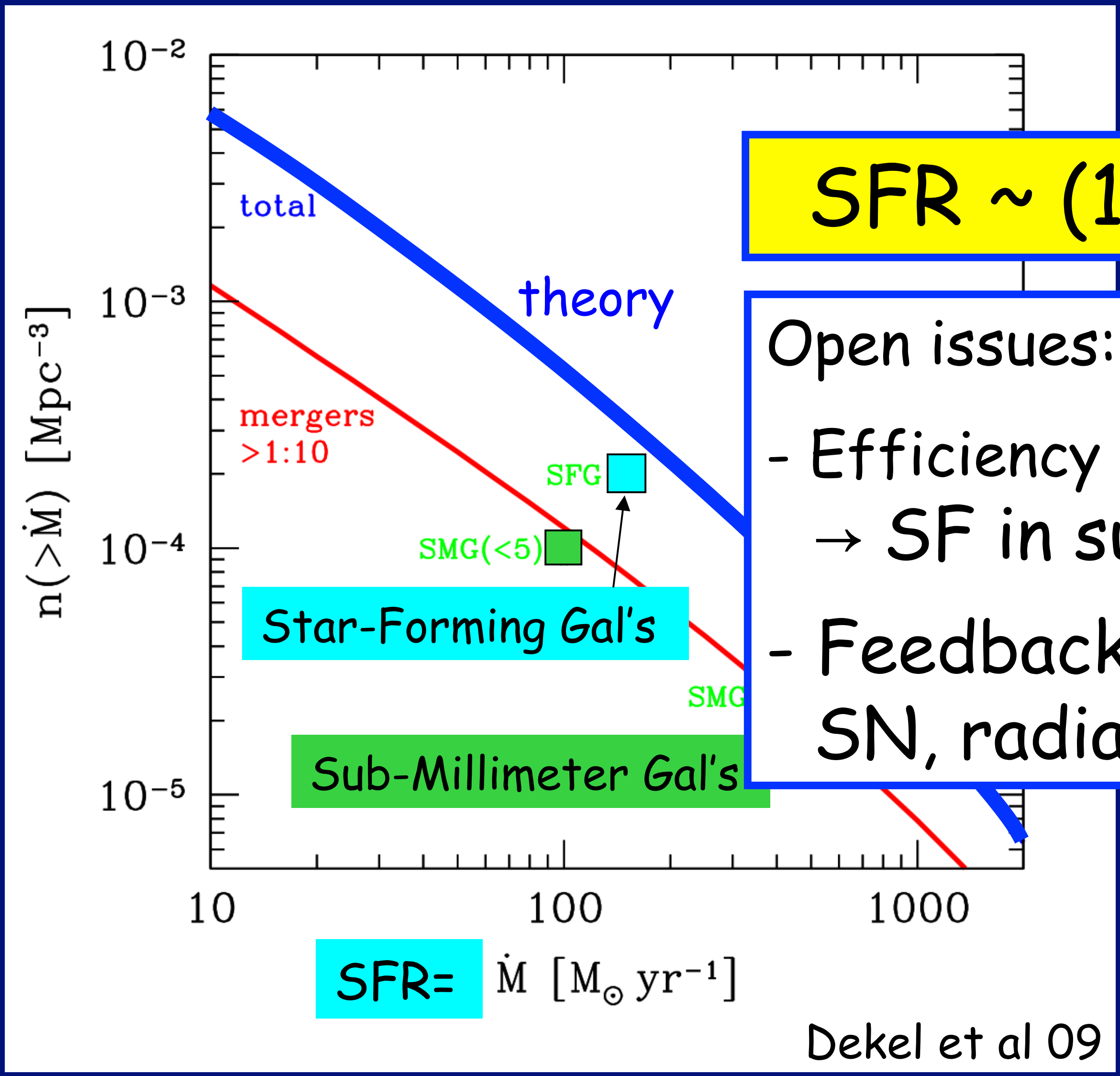


Clump-Disk Spin Alignment



10. Rapid Star Formation - in Clumps

Theory versus observation

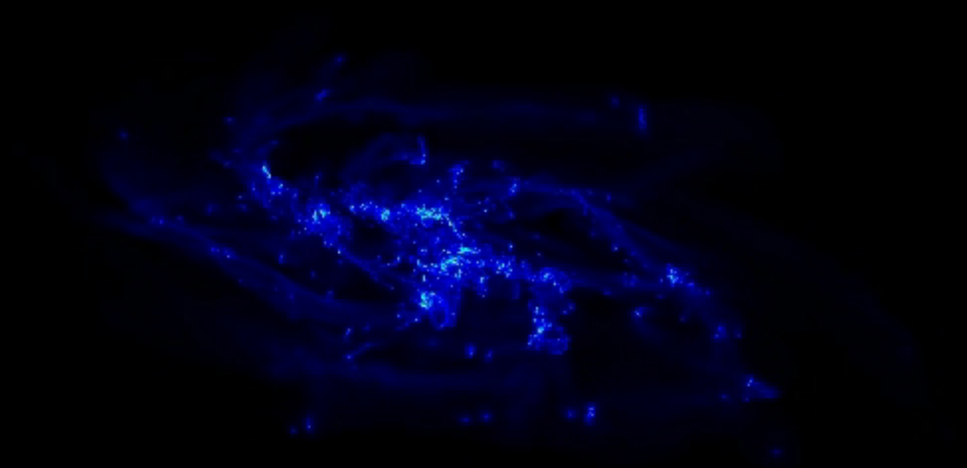


SFR ~ (1/2) inflow rate

Open issues:

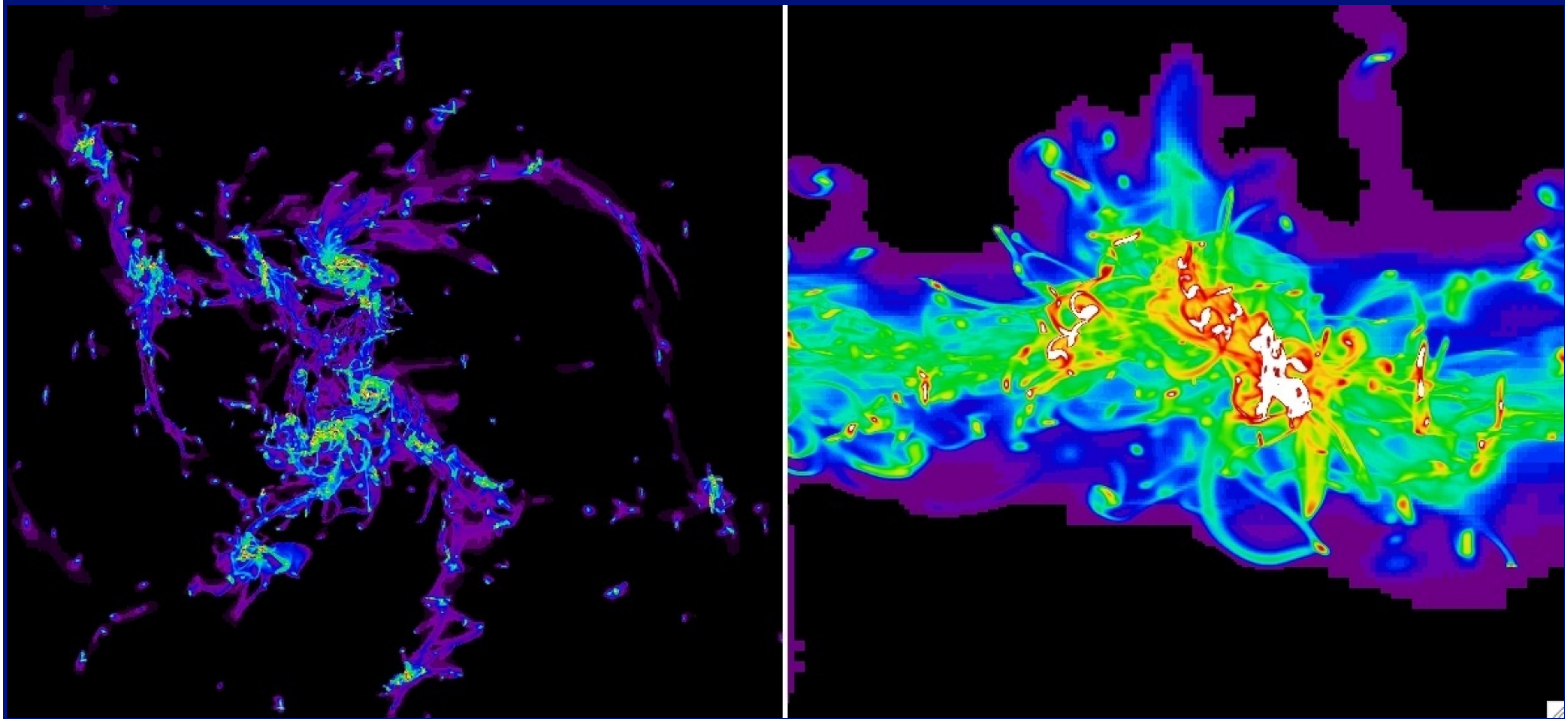
- Efficiency SFR/(M_{gas}/t_{ff}) ~ 1%
  → SF in sub-clumps
- Feedback & clump survival
  SN, radiative, AGN

Sub-structure in the disk giant clumps



Bournaud 09; AMR 2 pc resolution

Sub-structure in the disk giant clumps



Bournaud 09 AMR 2 pc resolution

Survival of Giant Clumps

Murray et al. 09;   Krumholz & Dekel 09

SFR efficiency $\varepsilon \equiv \dfrac{\dot{\Sigma}_*}{\Sigma_g / t_{ff}}$ ~ 0.01 -- Kennicutt law

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

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

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

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

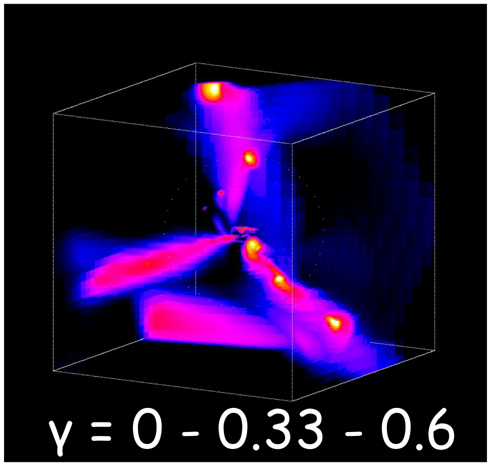
11. Massive Compact Spheroids

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

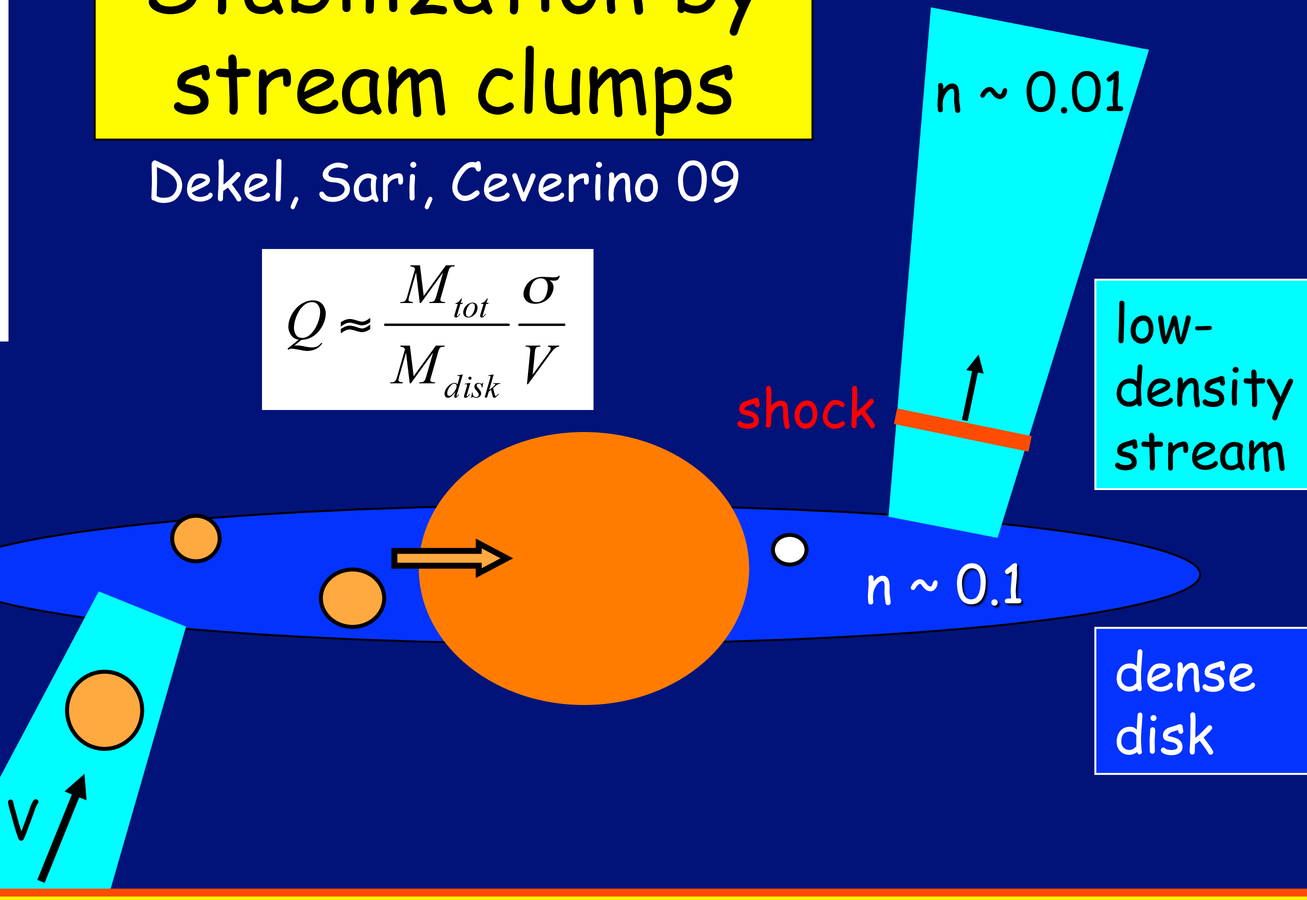
Bimodality blue-disk/red-spheroid at high z
driven by the degree of clumpiness in the streams

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

- Stable disk in steady state for M_{disk}/M_{tot}<0.3
→ Bimodality at high z: blue disks and red spheroids

12. Disk Stabilization – SF Quenching

- Dominant bulge – Morpholopgical quenching

Martig et al 09

- Excessive turbulence by external sources: ...clumpy streams, feedback

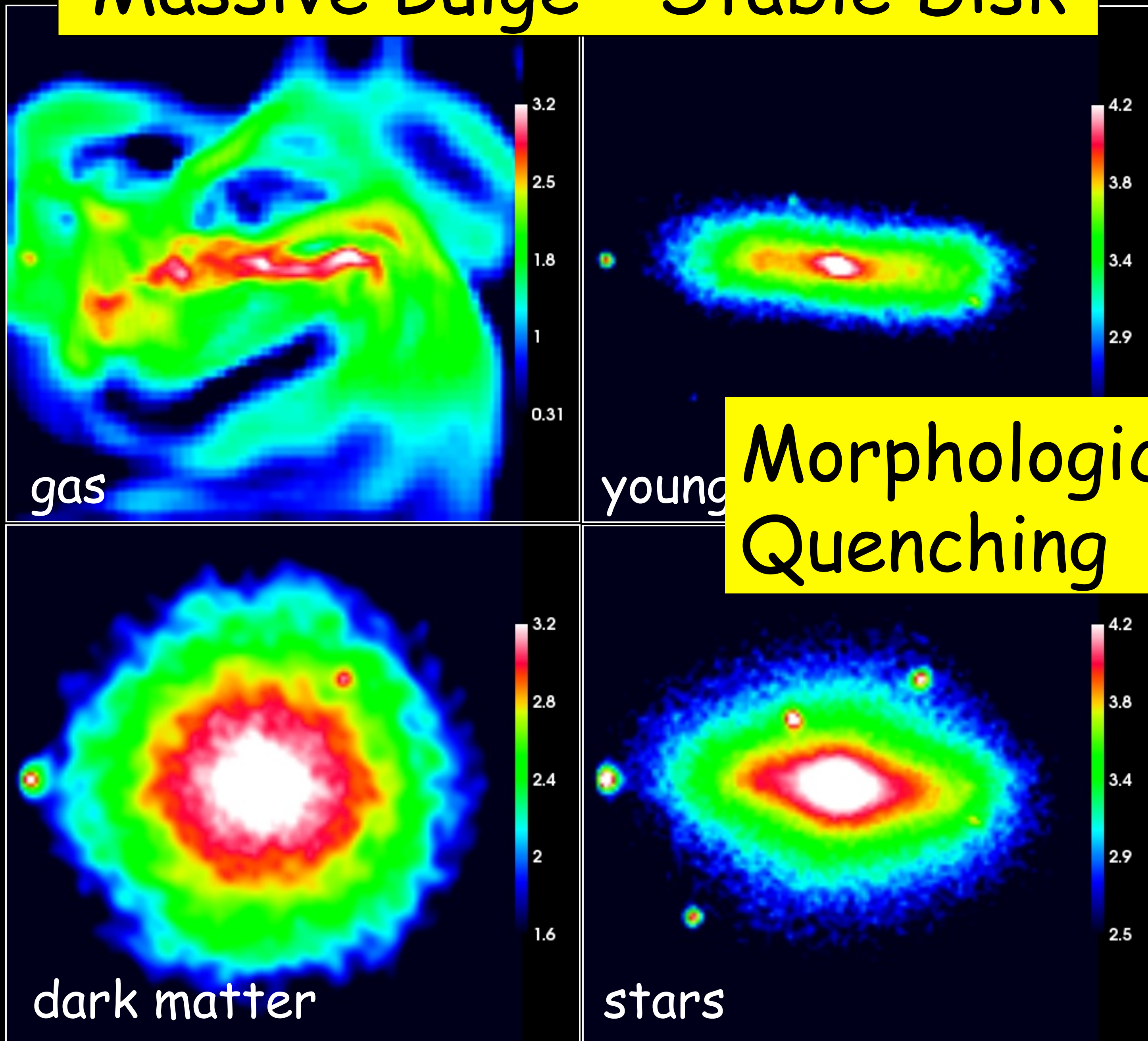
$$Q \approx \frac{M_{tot}}{M_{disk}} \frac{\sigma}{V}$$

- Low accretion rate (e.g. at late times)
- Low gas fraction (e.g. today's spirals)

Relation to today's galaxies ?

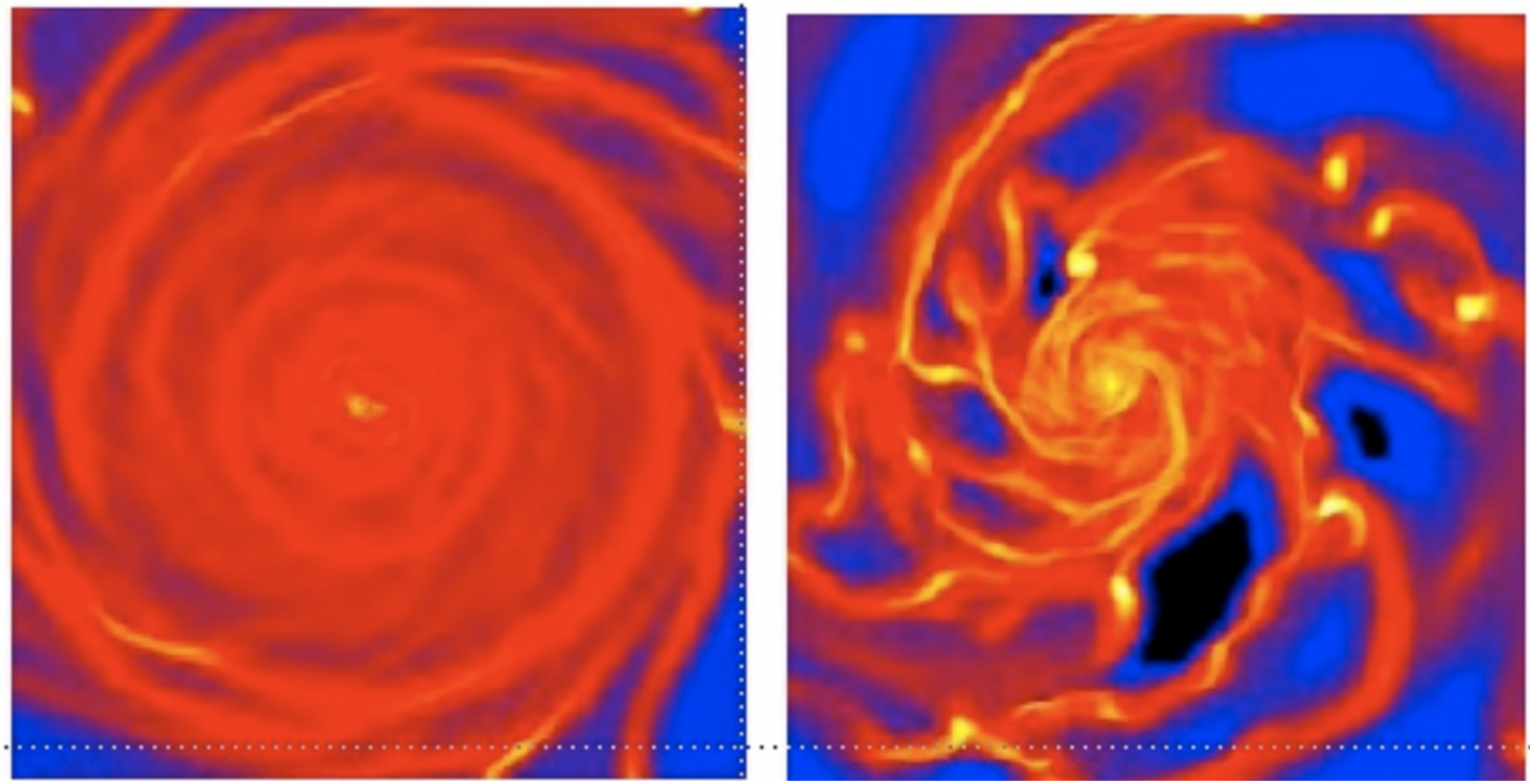
- The descendants of the high-z clumpy disks are probably ... S0s and rotating Es, or thick disks of spirals
- Thin disks form later by slow accretion

Massive Bulge - Stable Disk



Morphological Quenching

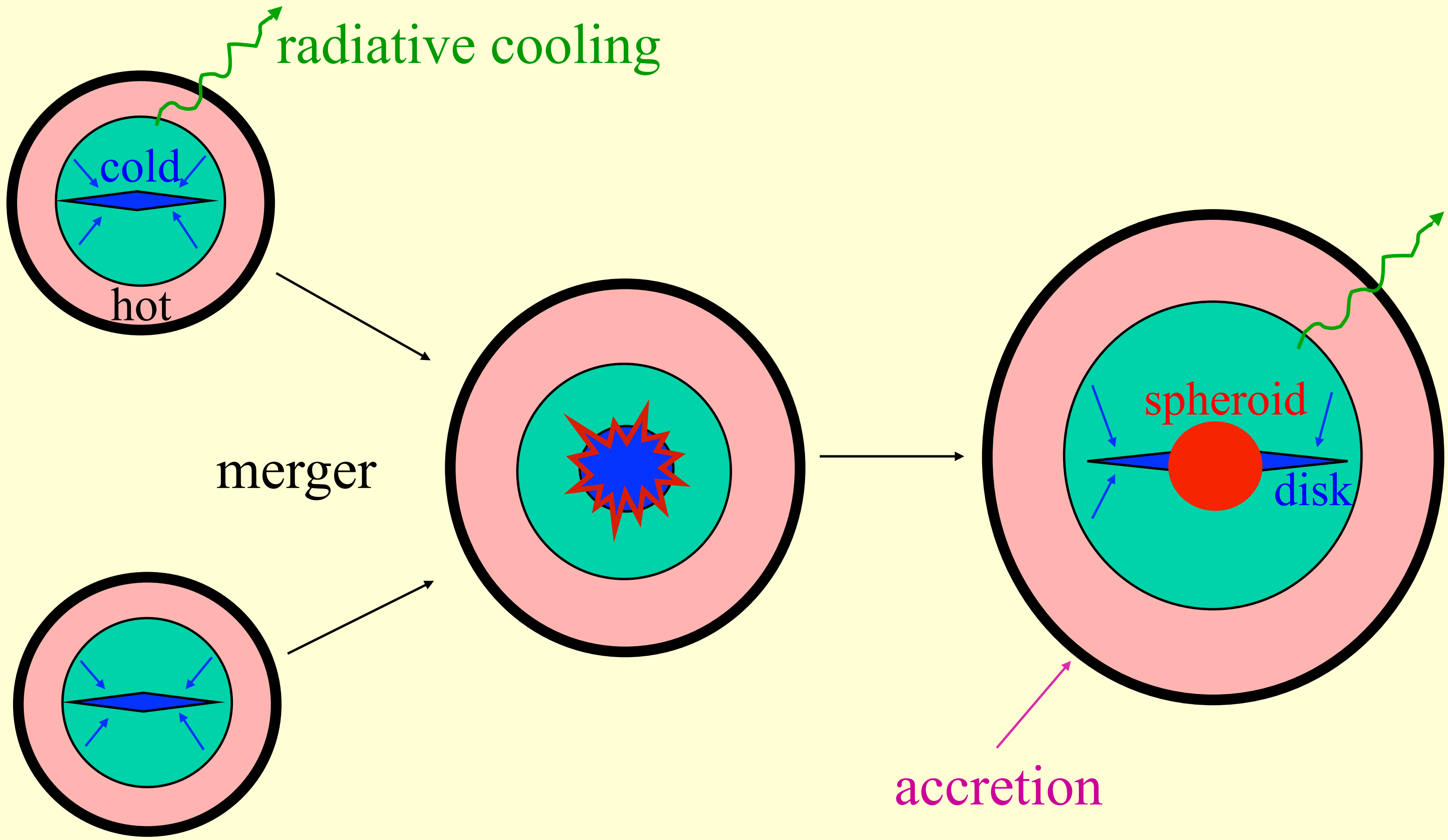
Morphological Quenching: disk stabilization by a bulge



Big Bulge   Small Bulge

Bournaud, AMR

Standard Paradigm: Mergers

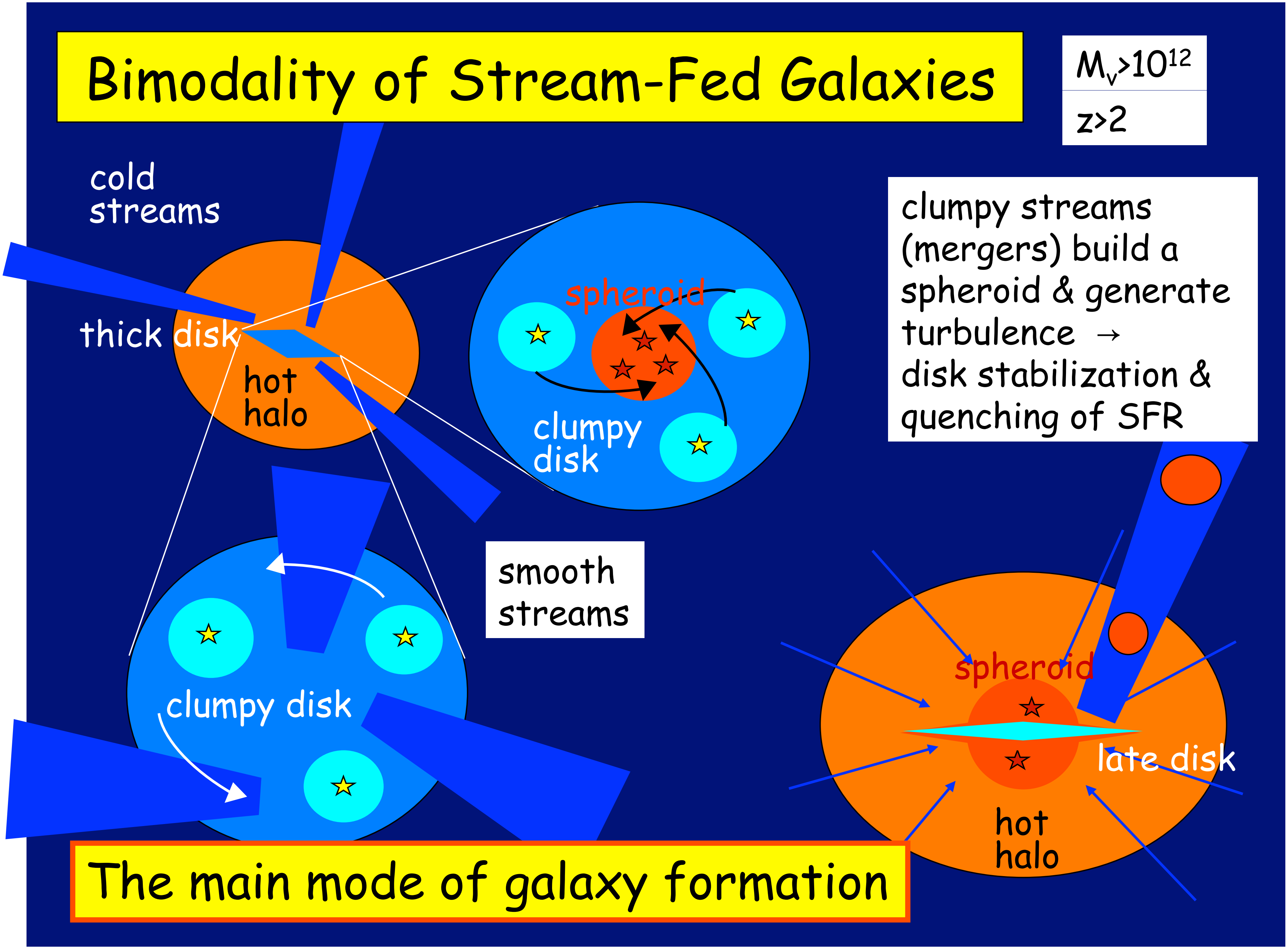


halos cold gas → young stars → old stars

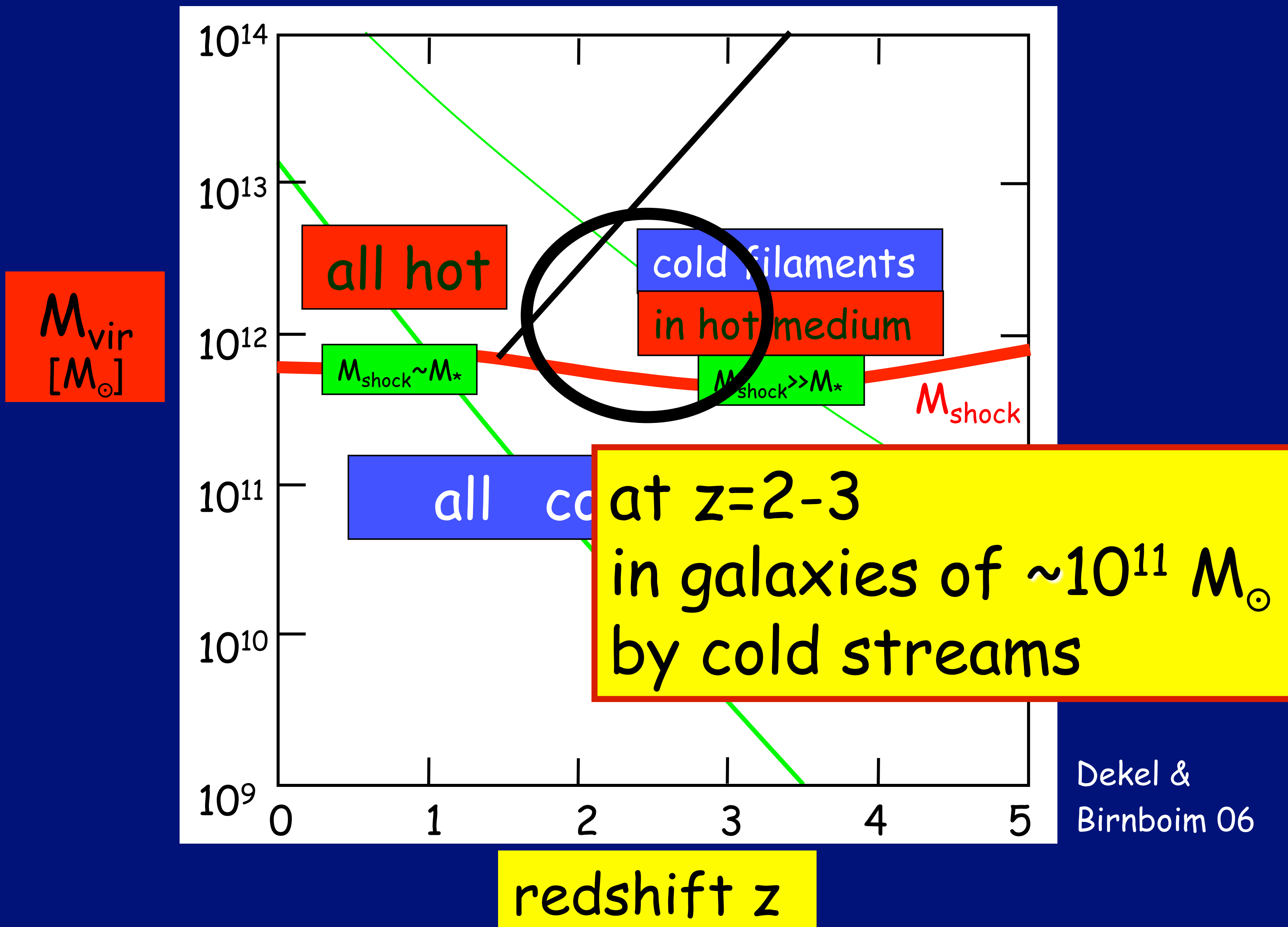
Gas removal by QSOs leads to red-and-dead Ellipticals

Major mergers? starbursts & spheroids

TJ Cox


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?



Dekel & Birnboim 06

Conclusion

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

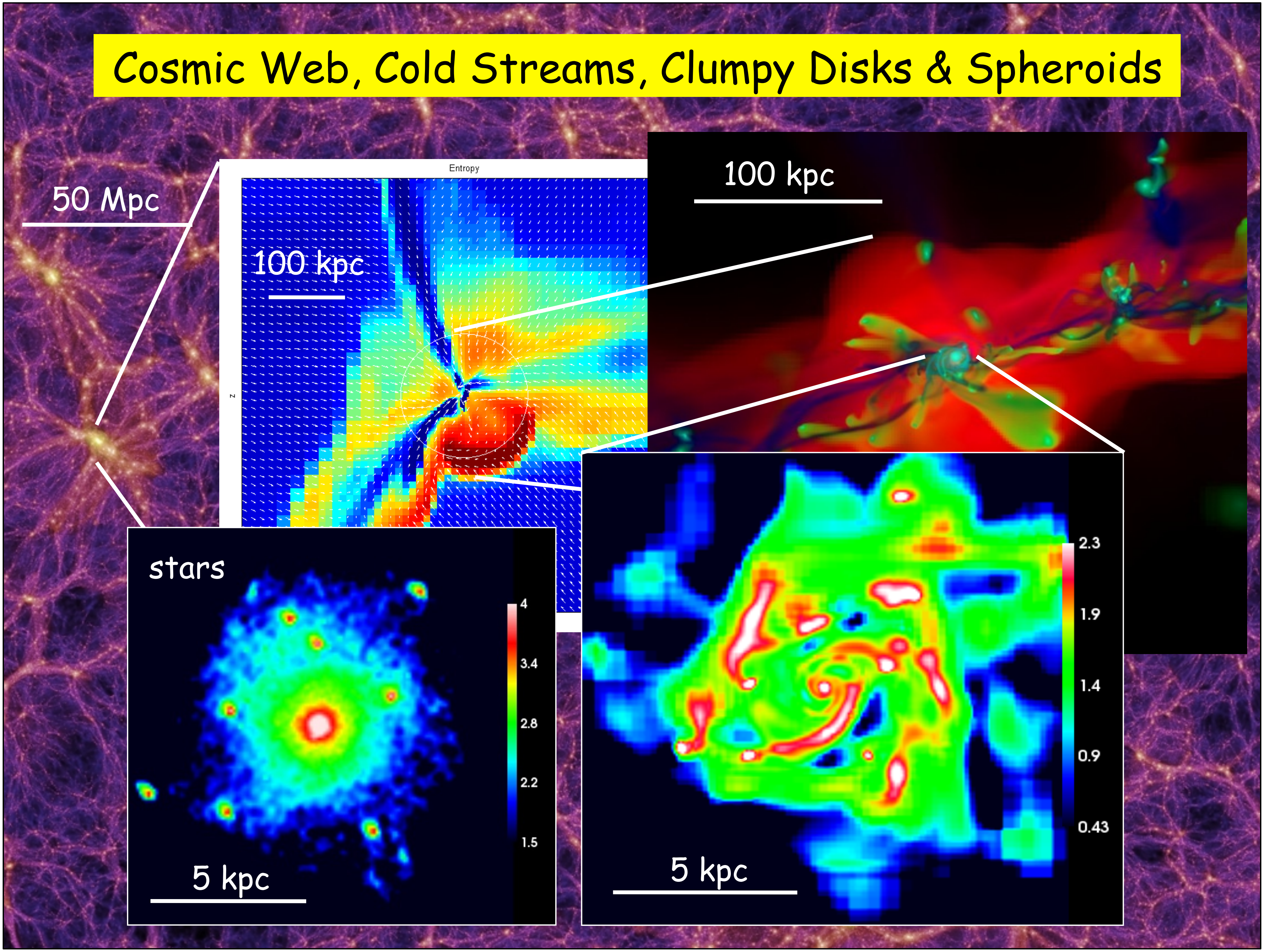
- Galaxies are fed by cold streams from the cosmic web
Streams include major & minor mergers and smooth flows
Streams radiate as Lyman-alpha blobs

- Gas-rich disks form, develop violent 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 violent disk instability

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

- Main open issues: star formation & feedback



Cosmic Web, Cold Streams, Clumpy Disks & Spheroids
50 Mpc
Entropy
100 kpc
100 kpc
stars
4
3.4
2.8
2.2
1.5
5 kpc
2.3
1.9
1.4
0.9
0.43
5 kpc

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

Key Theoretical Issues

1. Galaxies in the cosmic web
2. Accretion rate
3. Virial shock heating
4. Cold streams into hot halos
5. Streams as Lyman-alpha blobs
6. Stream clumpiness: mergers
7. Rotation vs dispersion: angular momentum & feedback
8. Violent Disk instability in steady state
9. SFR in disk clumps
10. Spheroid formation
11. Quenching of star formation