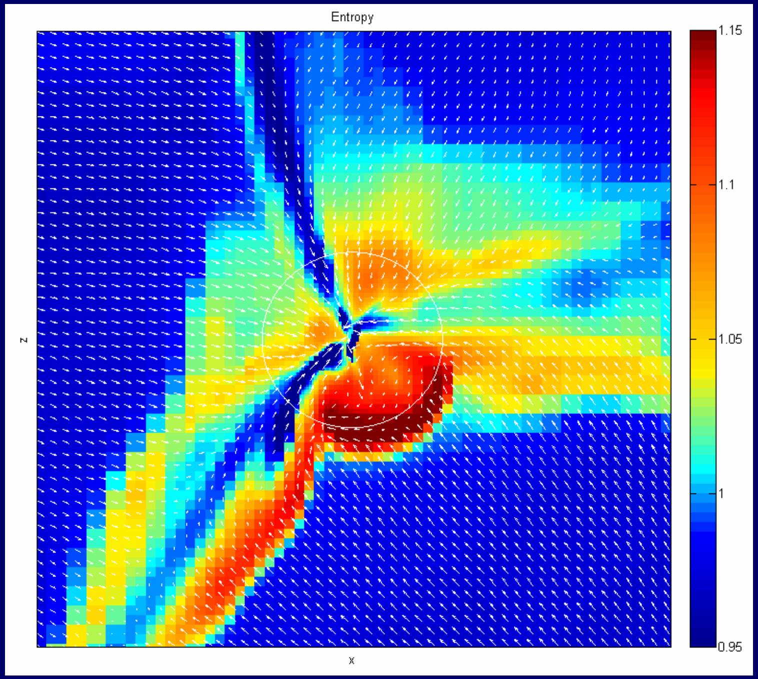
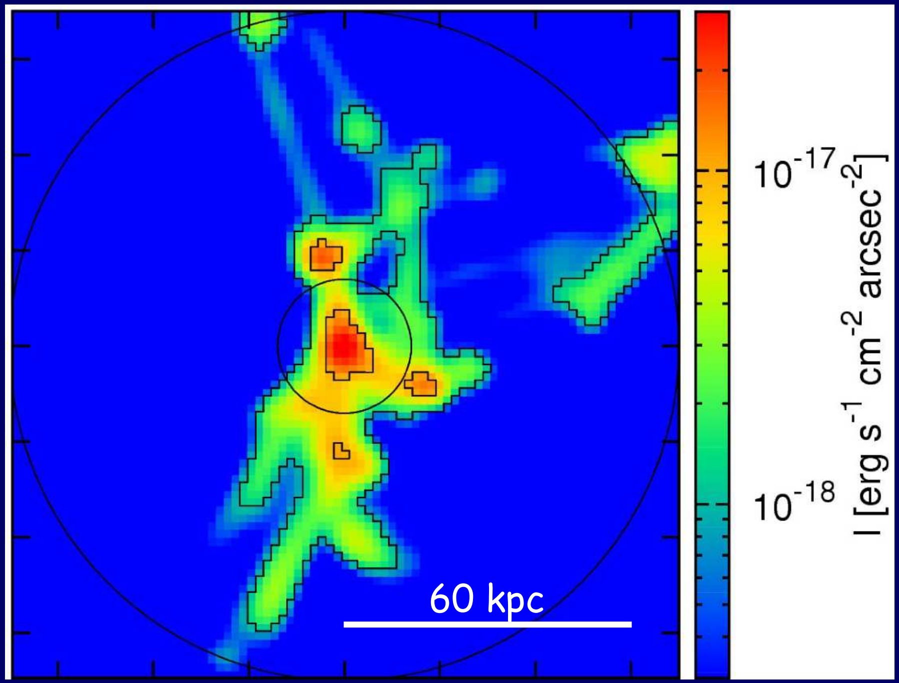
Cold Streams as Lyman Alpha Blobs

Avishai Dekel, HU Jerusalem

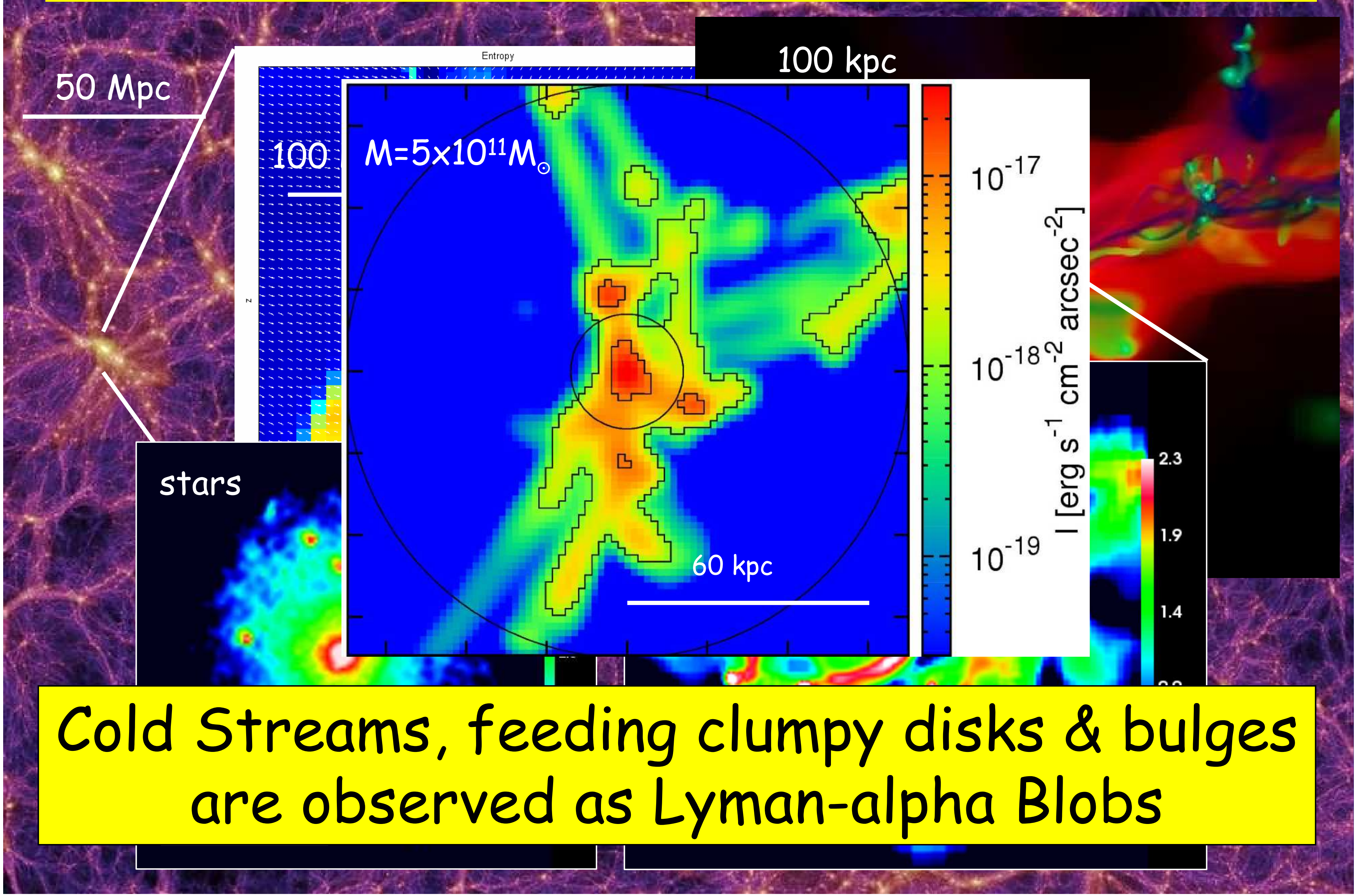
Paris, July 2009

T. Goerdt, D. Ceverino, R. Teyssier, A. Sternberg





Galaxies Emerge from the Cosmic Web



Cold Streams, feeding clumpy disks & bulges are observed as Lyman-alpha Blobs

Collaborators

Simulations:
R. Teyssier (Paris)
A. Kravtsov (Chicago)
D. Ceverino (HU)
F. Bournaud (Paris)

HU Team:
Y. Birnboim (CfA)
D. Ceverino (HU)
J. Freundlich (Paris)
T. Goerdt (HU)
E. Neistein (MPA)
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

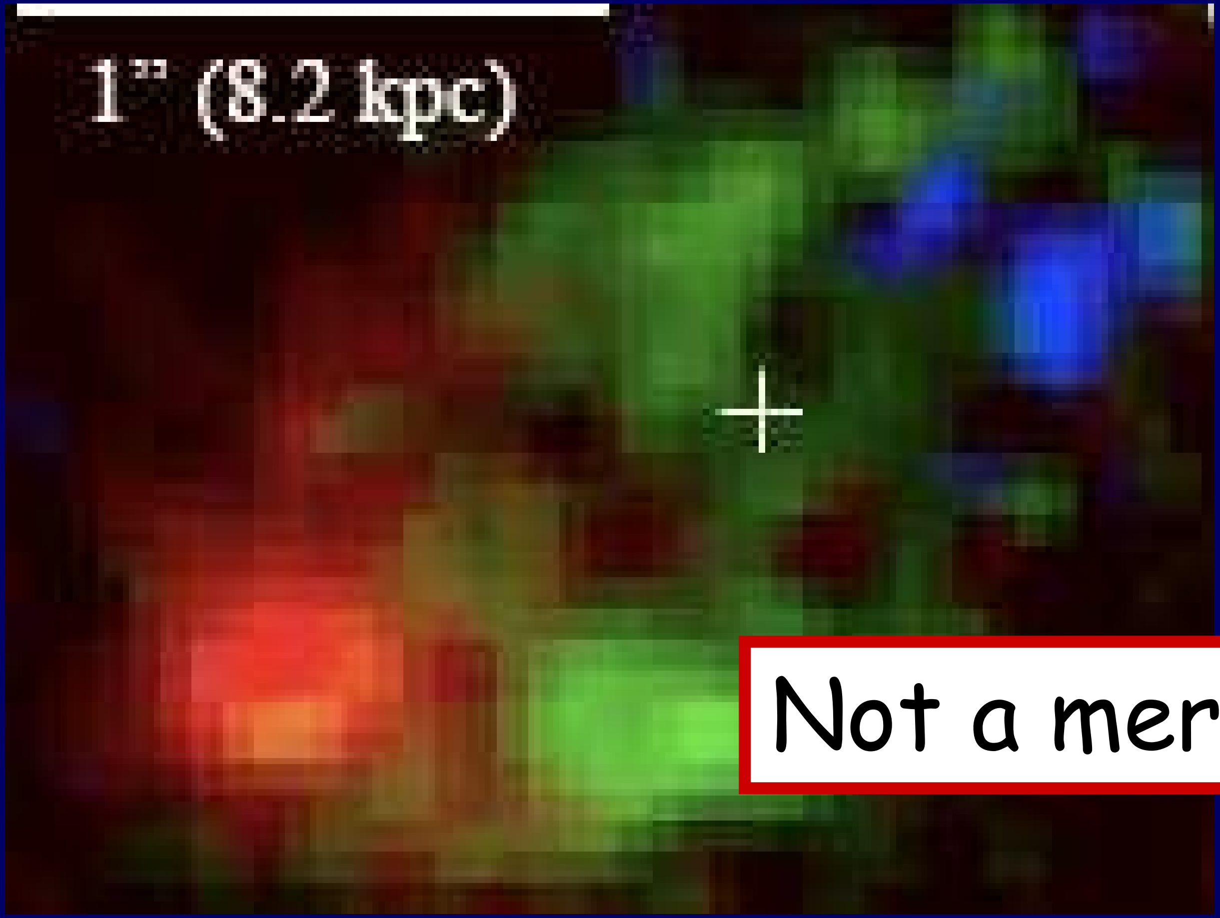
1. Observed Bimodality at High z

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

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

Suppressed SFR in compact spheroids

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

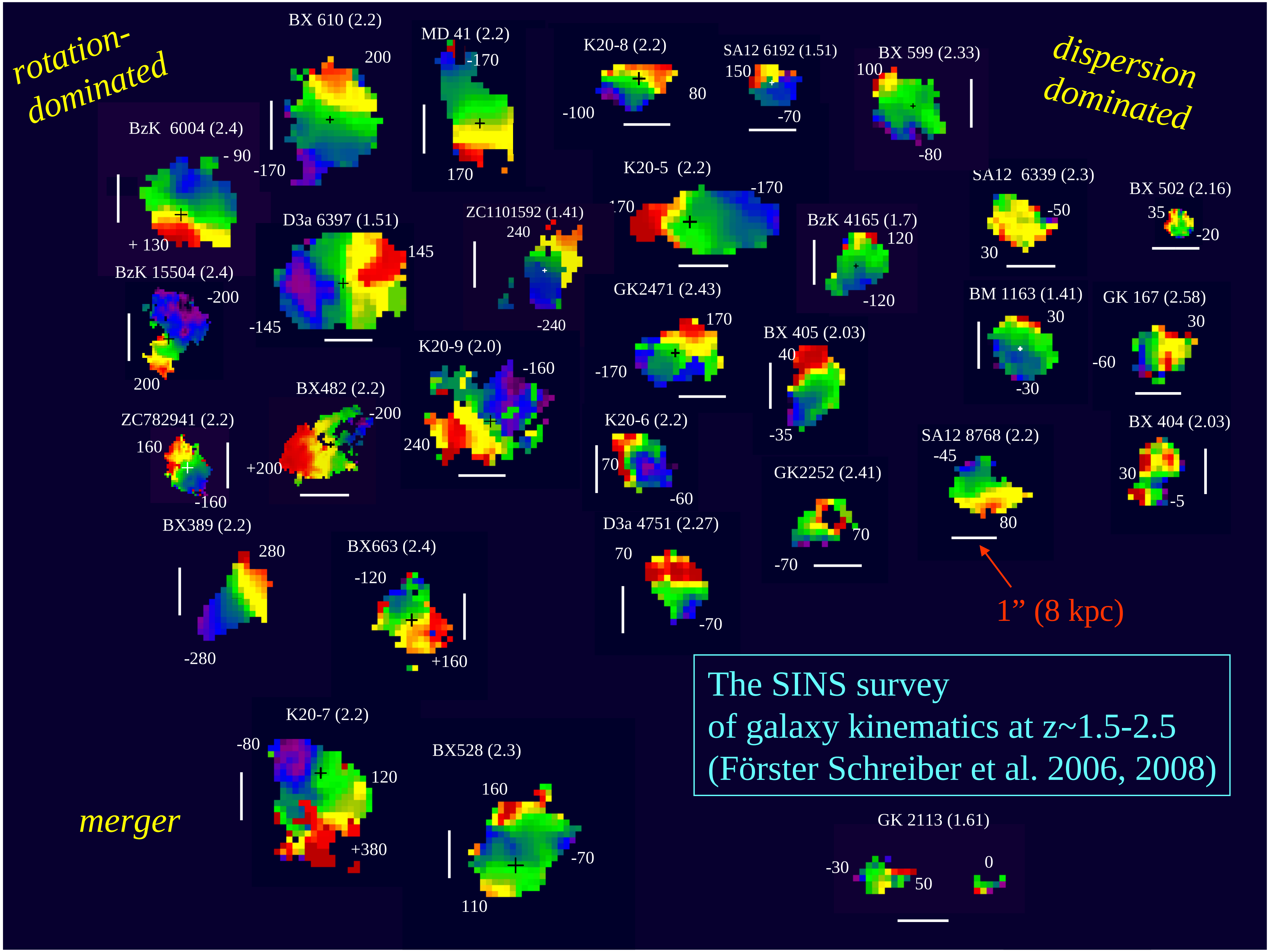


Hα star-form regions

color-code velocity field

Not a merger!

Genzel et al 08



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

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

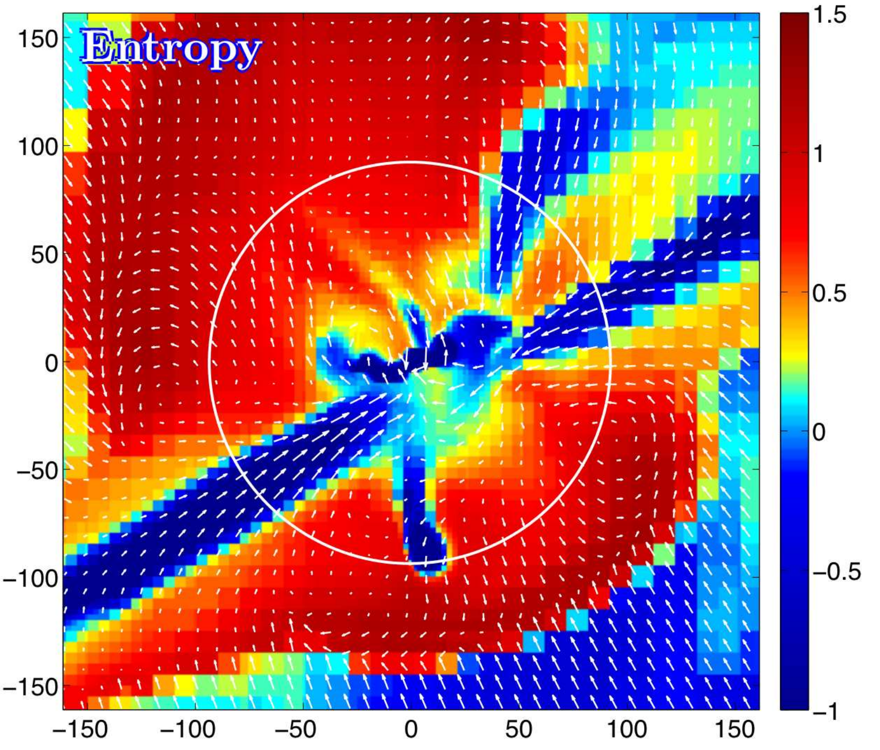
Keres et al. 2005

Dekel & Birnboim 2006

Keres et al. 2008

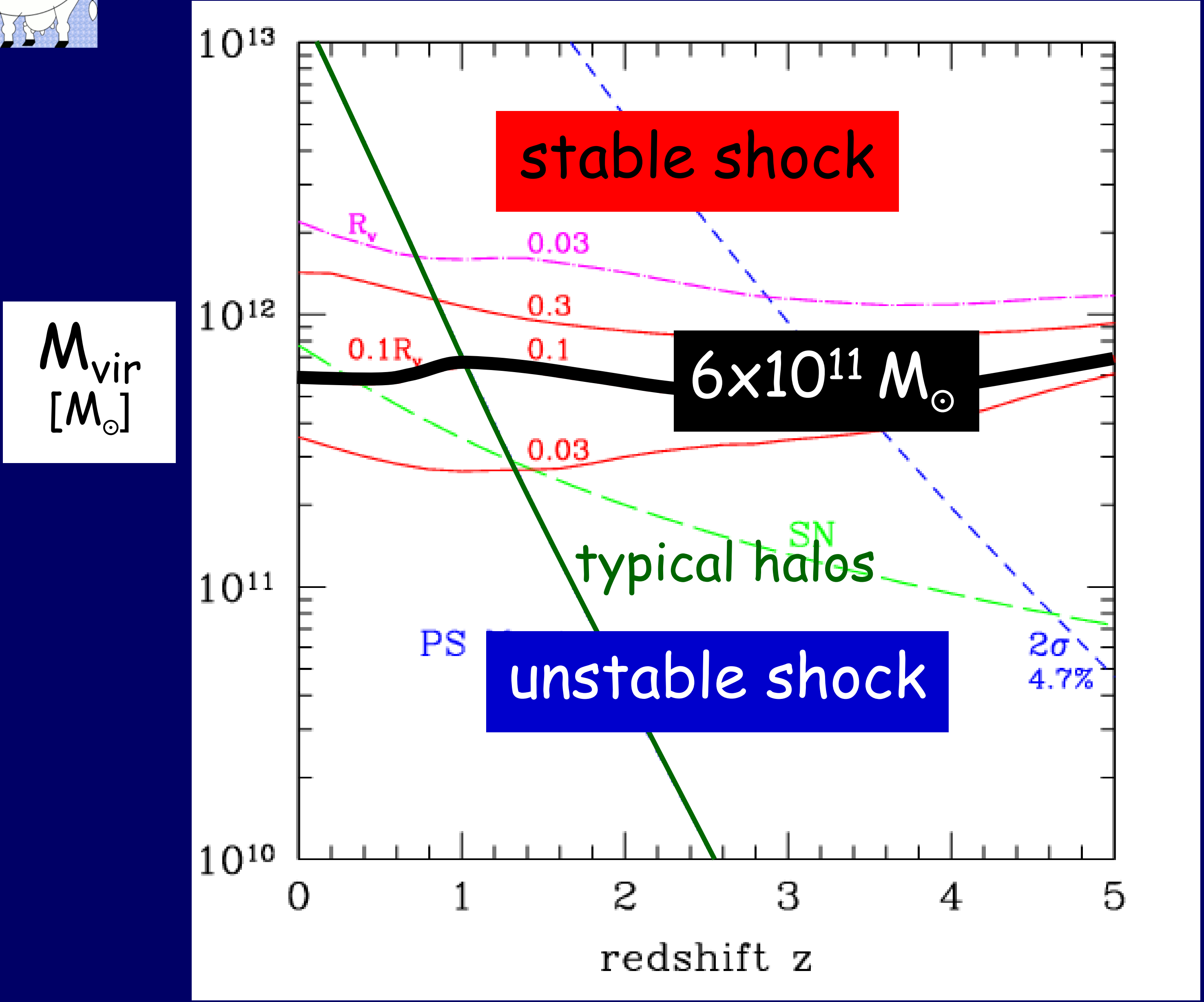
Ocvirk et al. 2008

Dekel et al. 2009, Nature



Shock-Heating Scale

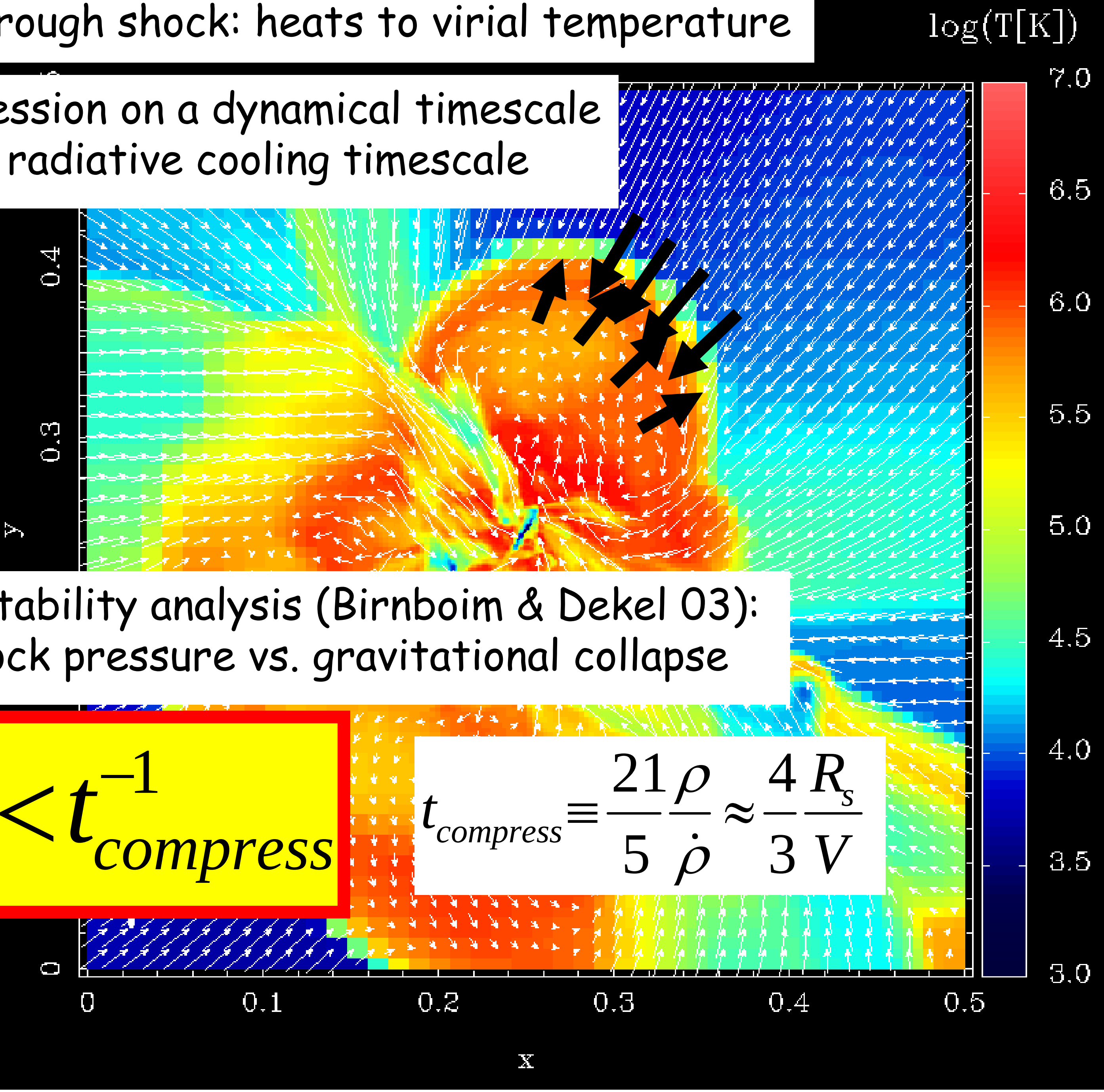
Birnboim & Dekel 03
Dekel & Birnboim 06



Keres
et al 05

Gas through shock: heats to virial temperature

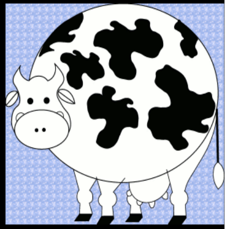
compression on a dynamical timescale
versus radiative cooling timescale



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

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

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

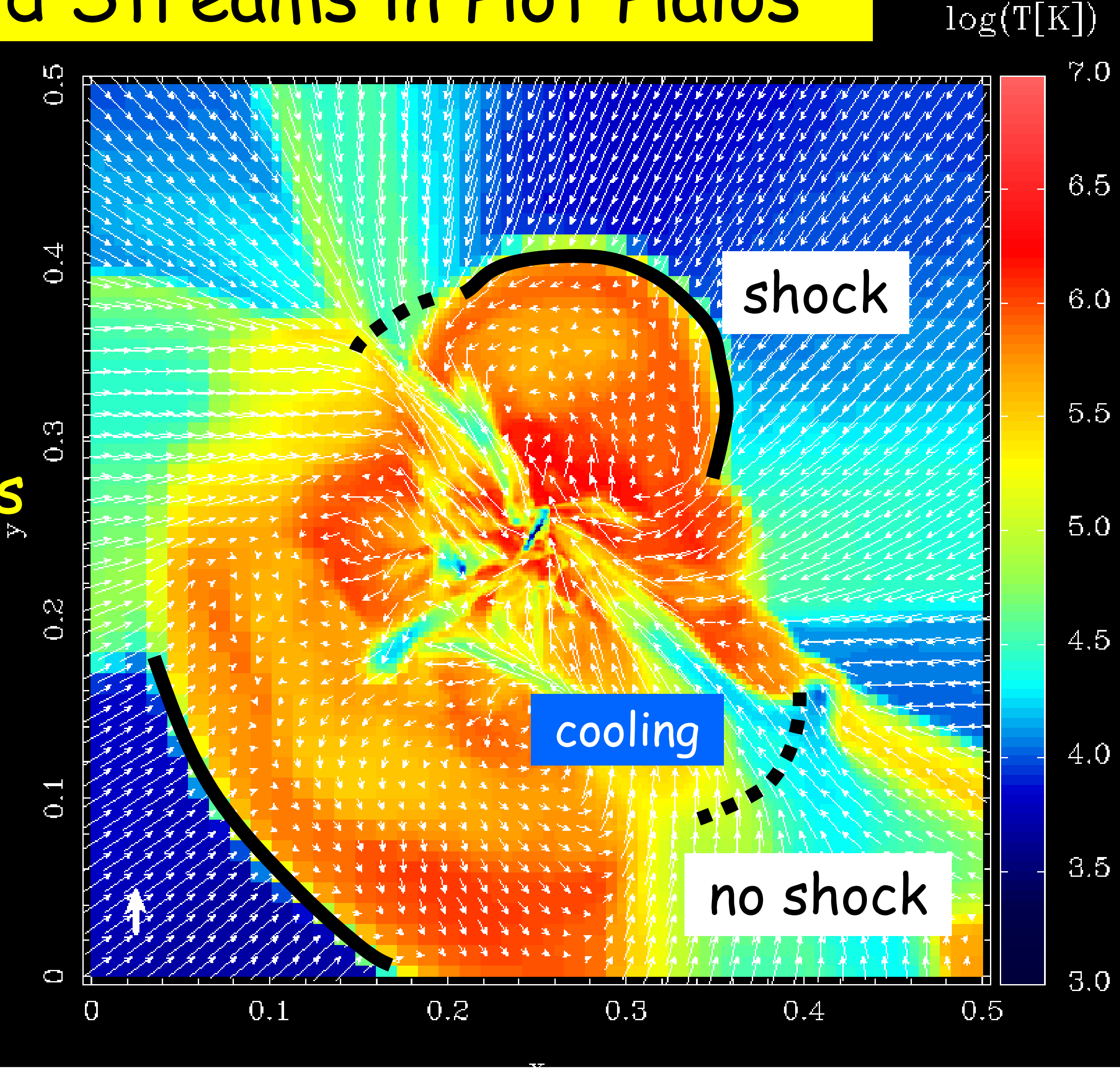


At High z, in Massive Halos: Cold Streams in Hot Halos

in $M>M_{shock}$

Totally hot at z<1

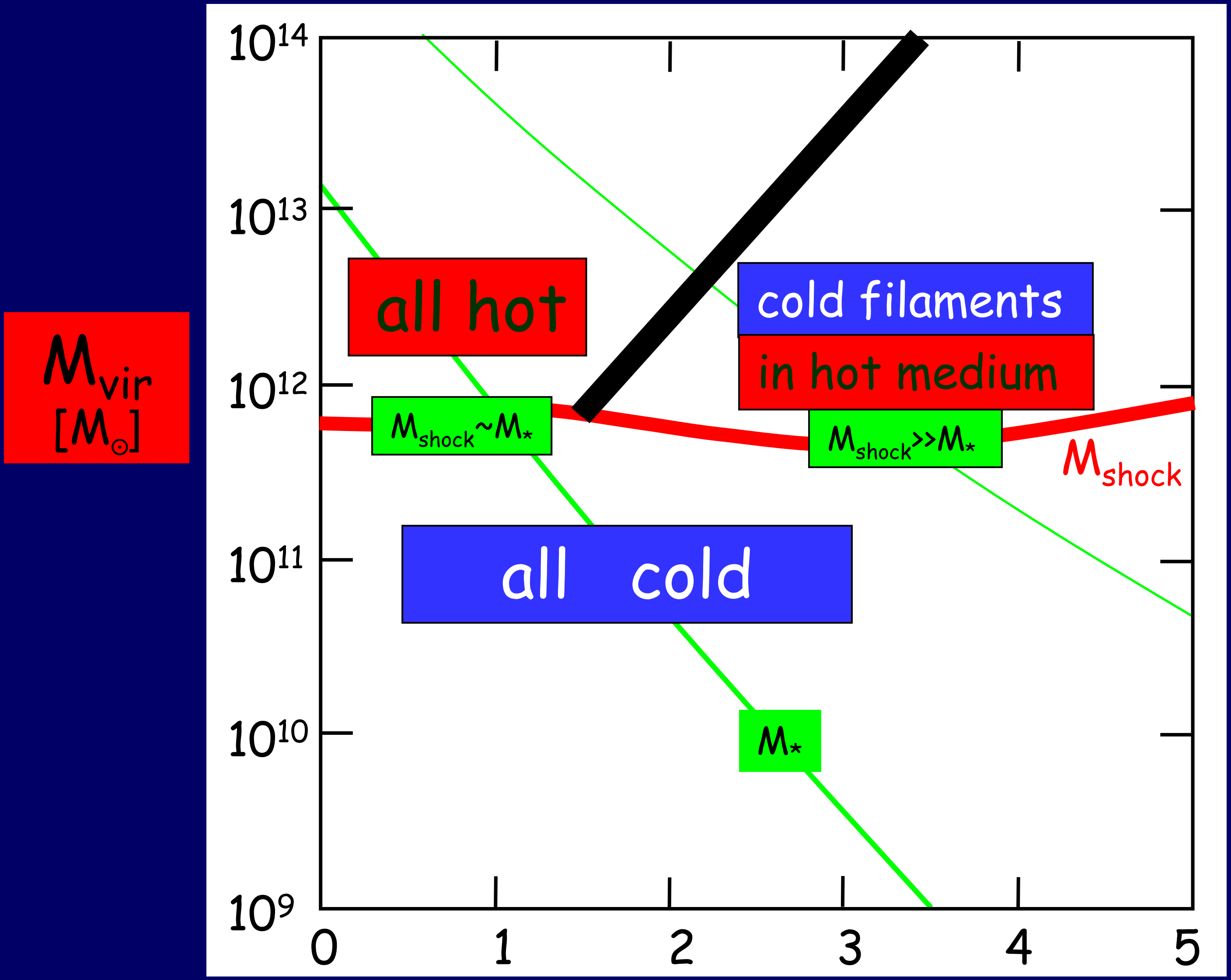
Cold streams at z>2



Dekel & Birnboim 2006

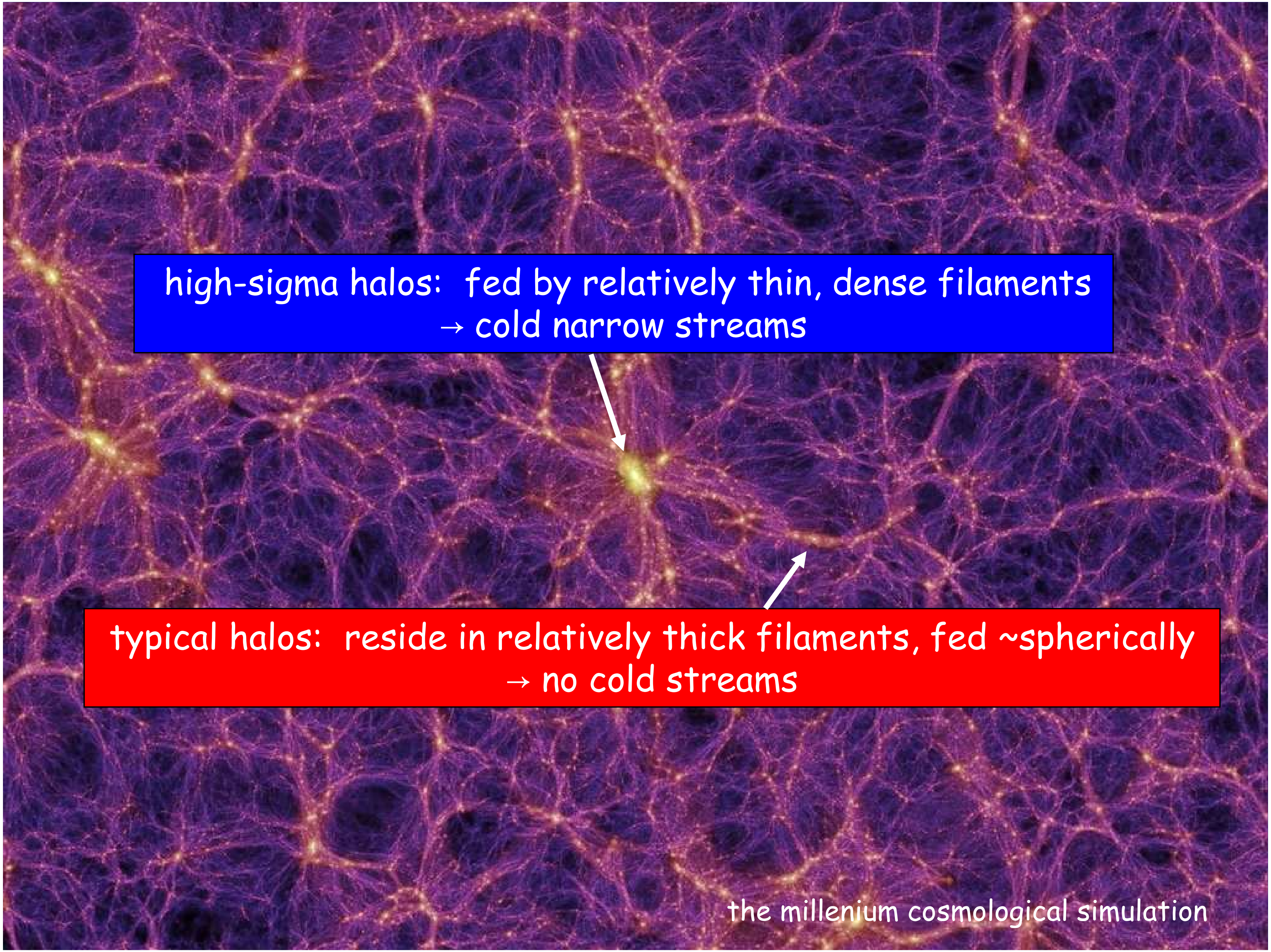
Kravtsov et al

Cold Streams in Big Galaxies at High z



redshift z

Dekel &
Birnboim 06

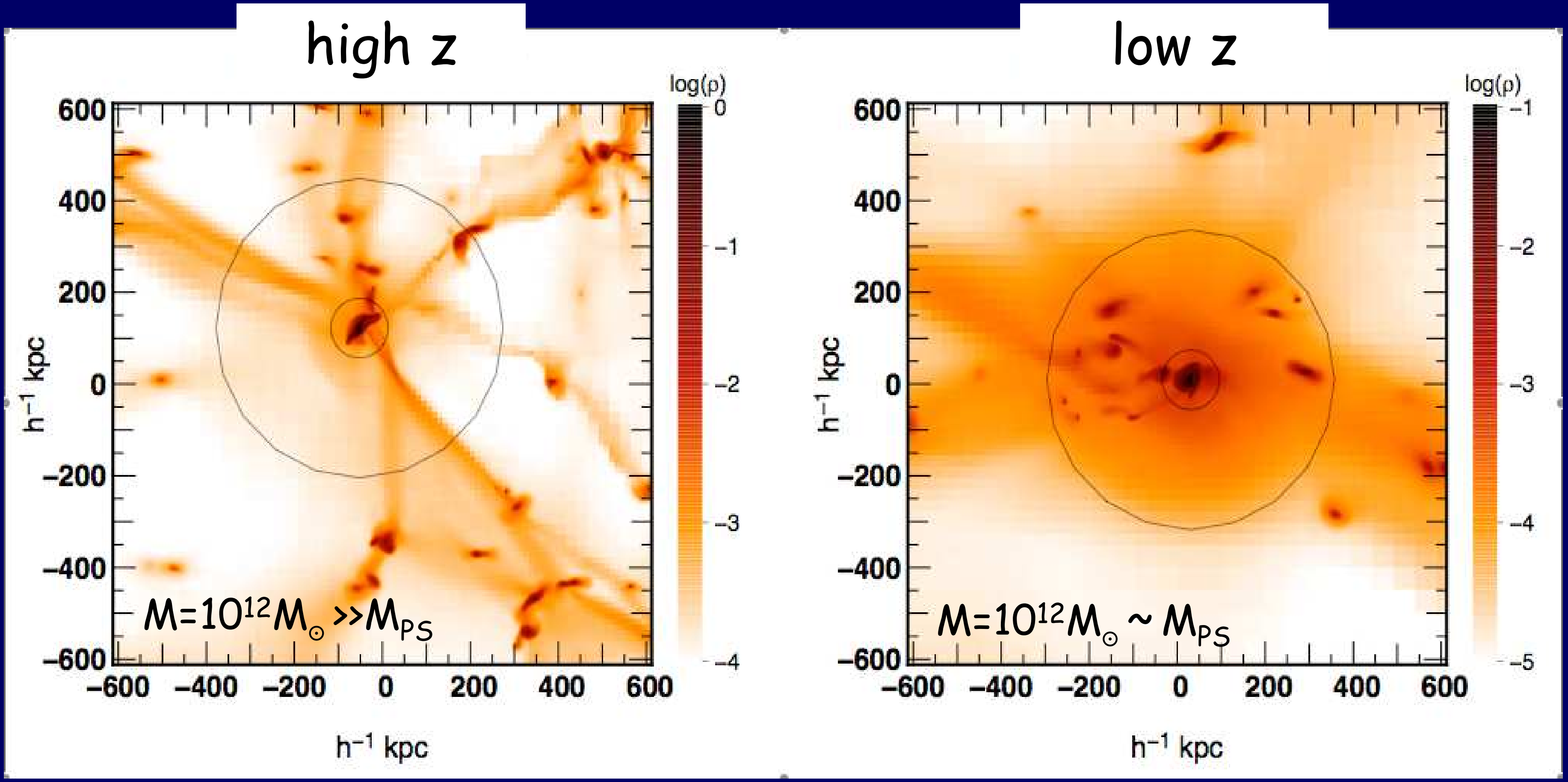


high-sigma halos: fed by relatively thin, dense filaments
→ cold narrow streams

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

the millenium cosmological simulation

Gas Density in Massive Halos $2\times10^{12}M_\odot$



high z

low z

$M=10^{12}M_\odot \gg M_{PS}$

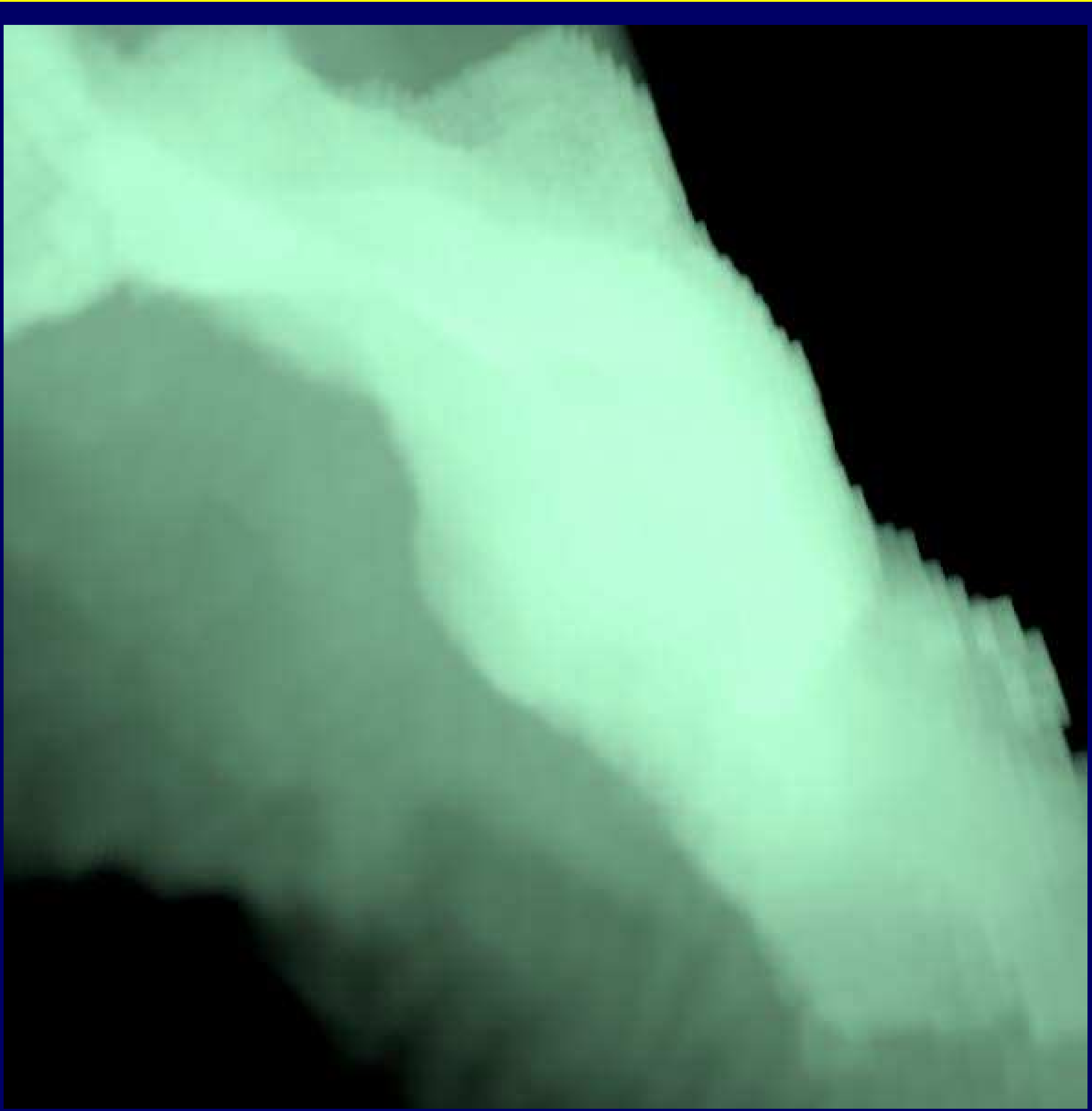
$M=10^{12}M_\odot \sim M_{PS}$

Ocvirk, Pichon, Teyssier 08

Stream Properties

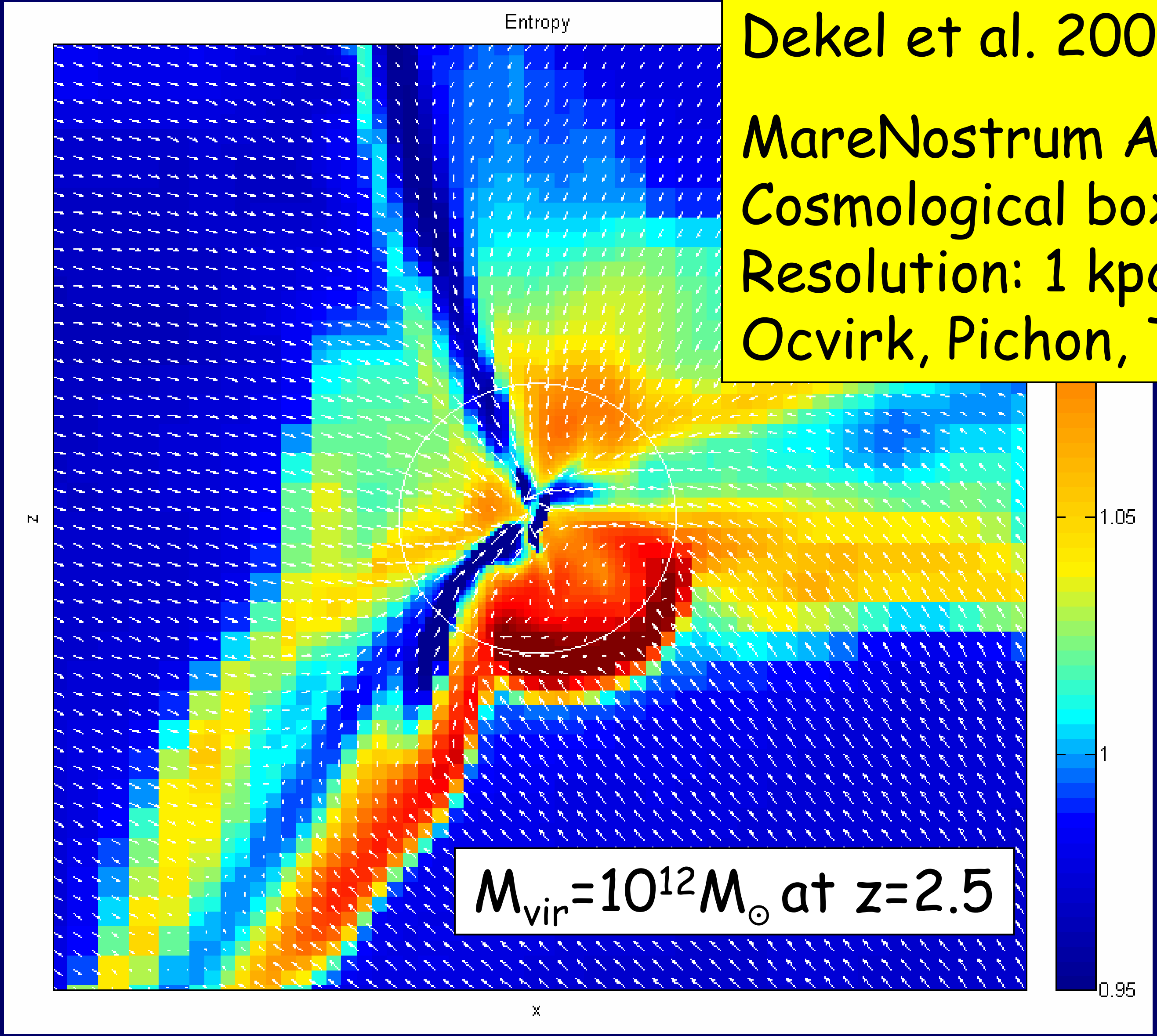
Dekel et al. 2009, Nature

A disk fed by streams at high z



Governato,
Quinn,
Brooks
et al.

Massive high-z disks by cold narrow streams

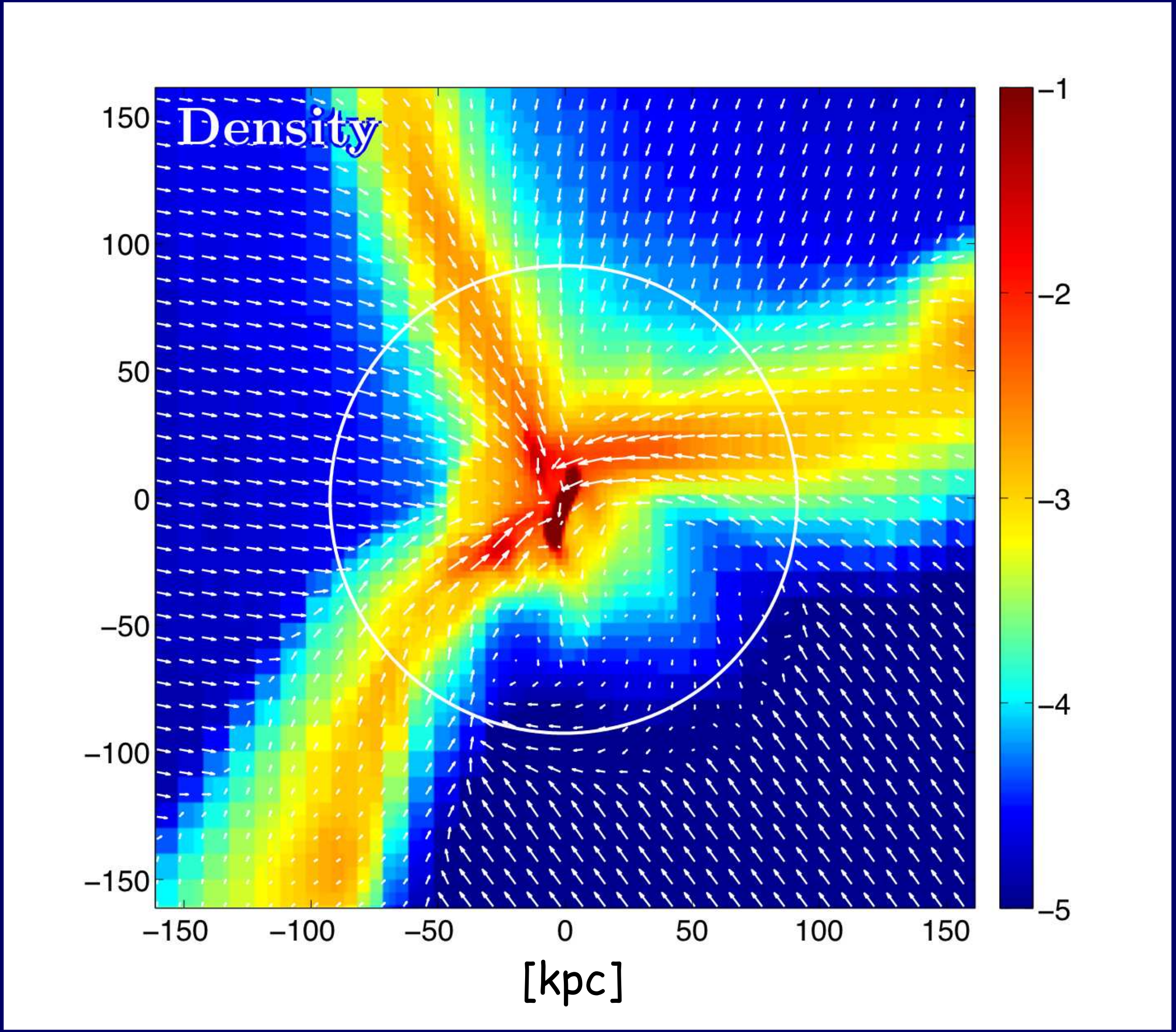


$M_{vir}=10^{12}M_{\odot}$ at $z=2.5$

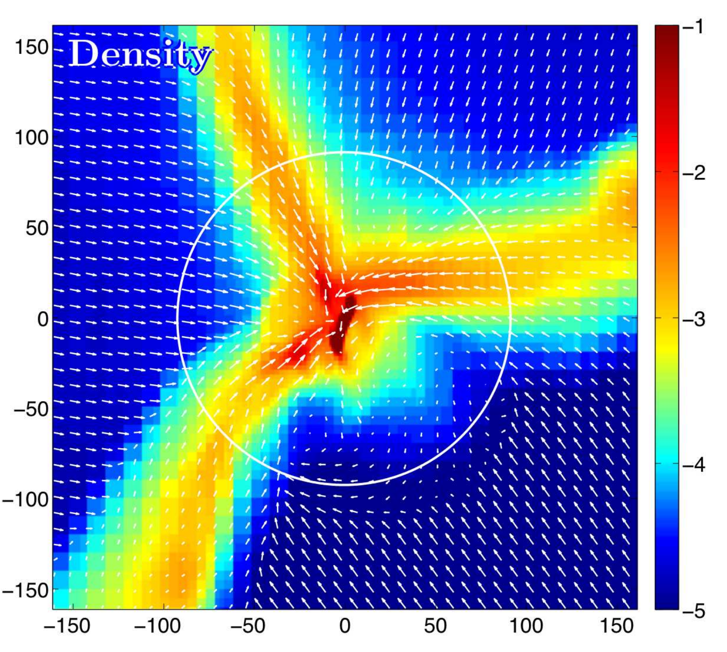
Dekel et al. 2009, Nature

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

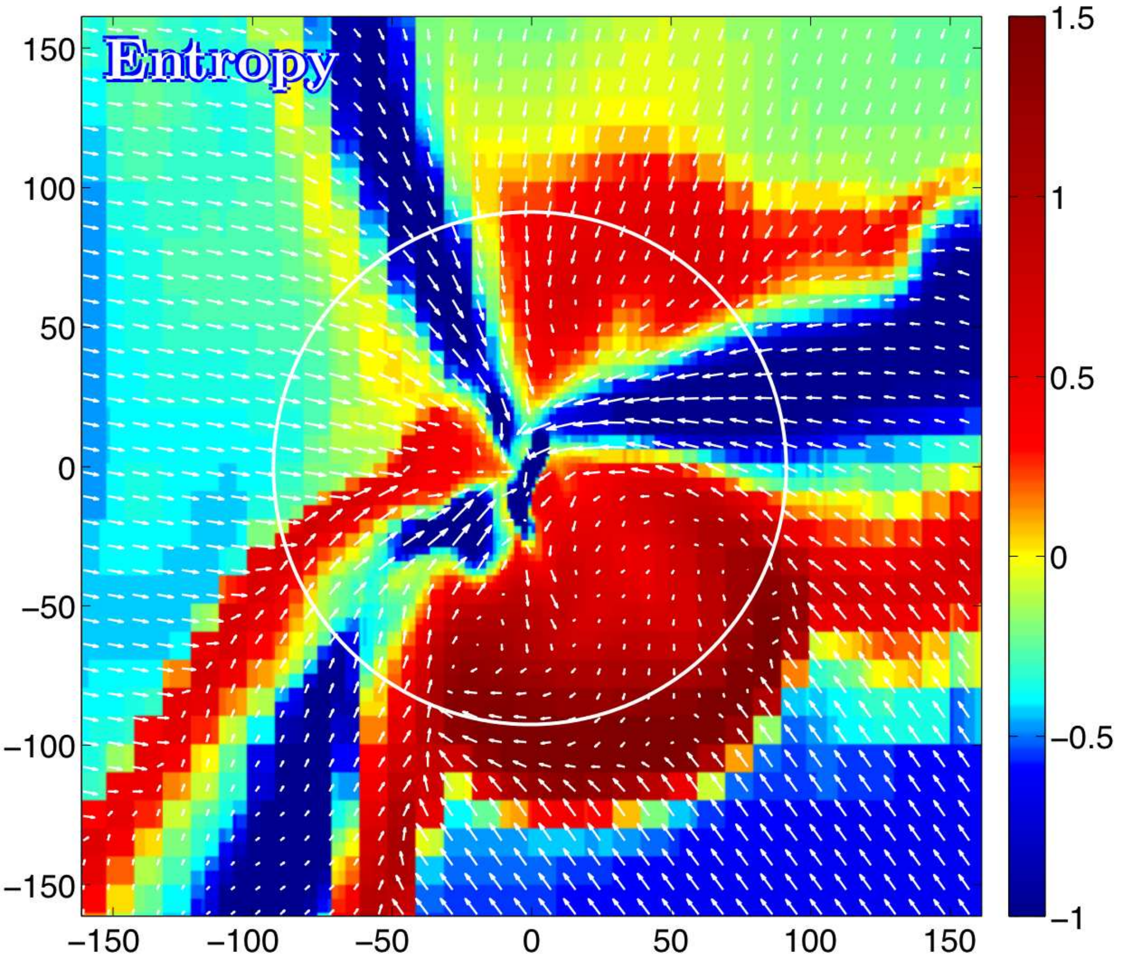
Gas density: following dark-matter filaments



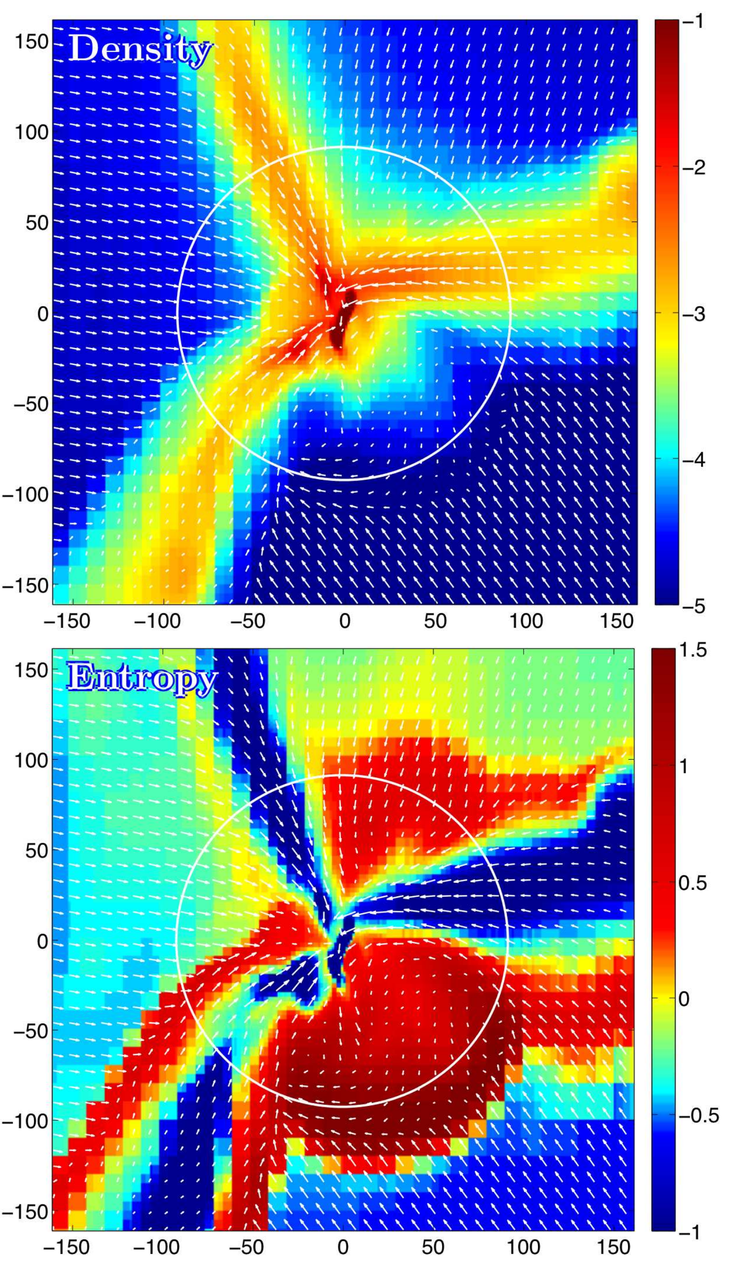
Entropy: virial shock & low-entropy streams



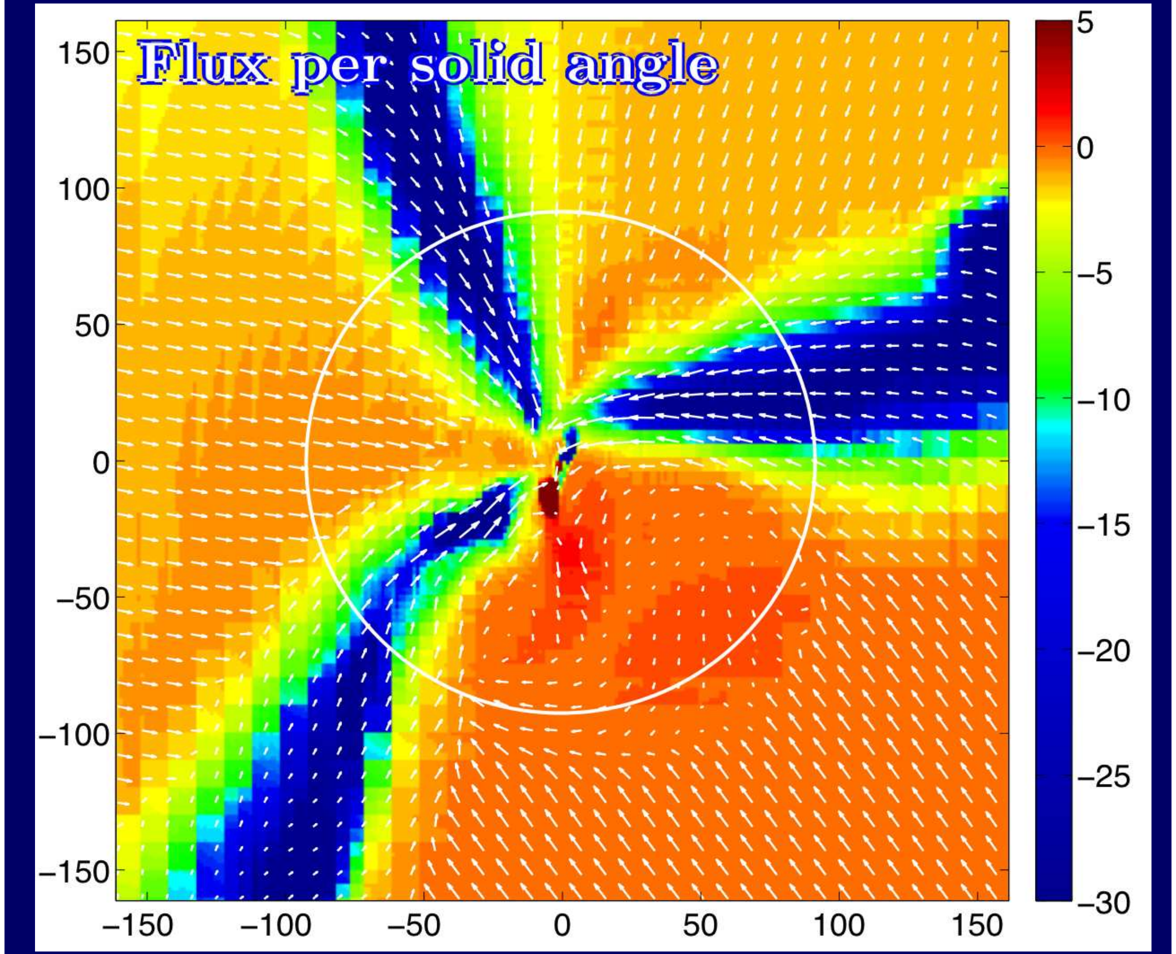
$\log(T/\rho^{2/3})$



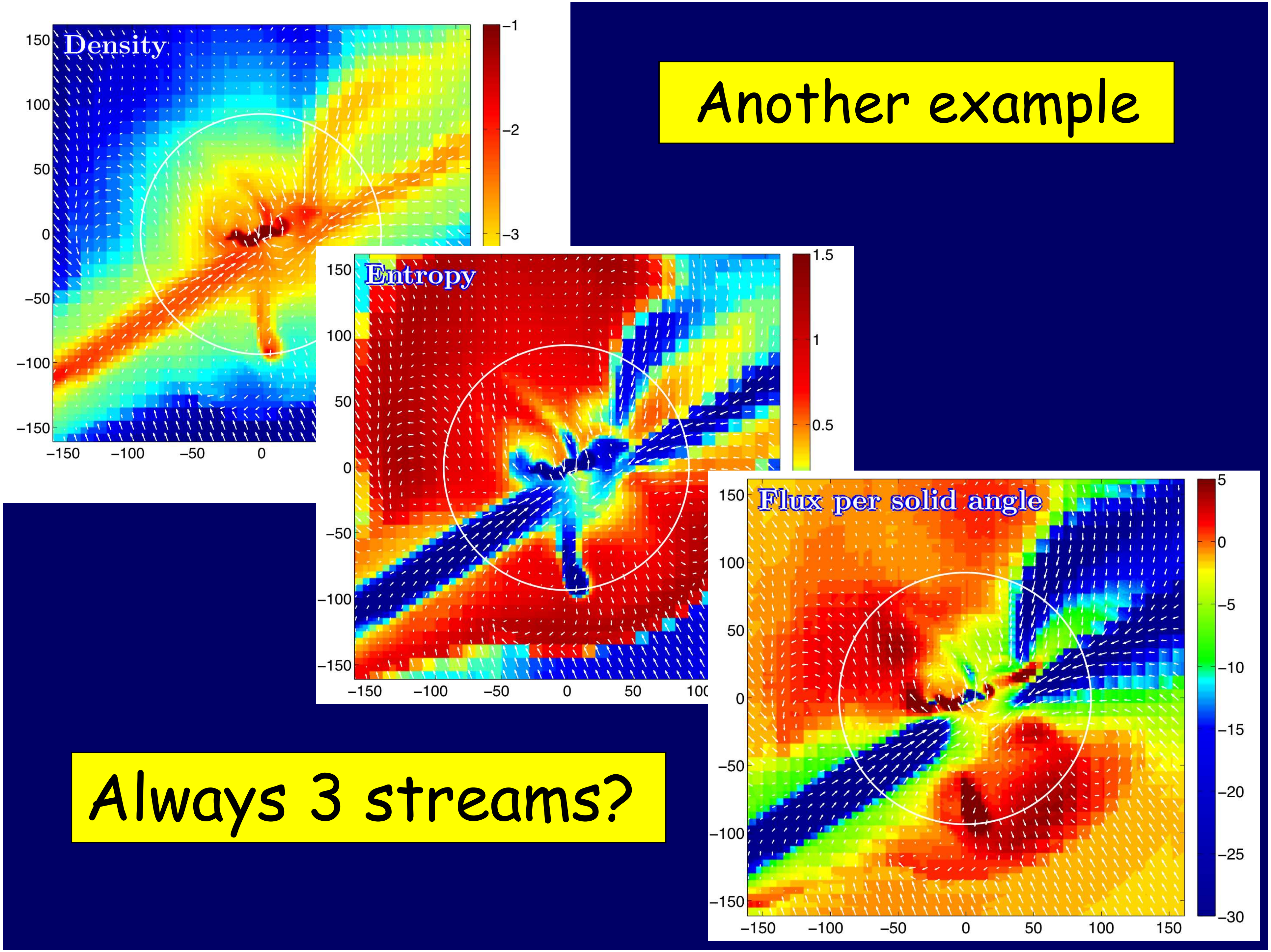
Inward gas flux: all in the streams



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

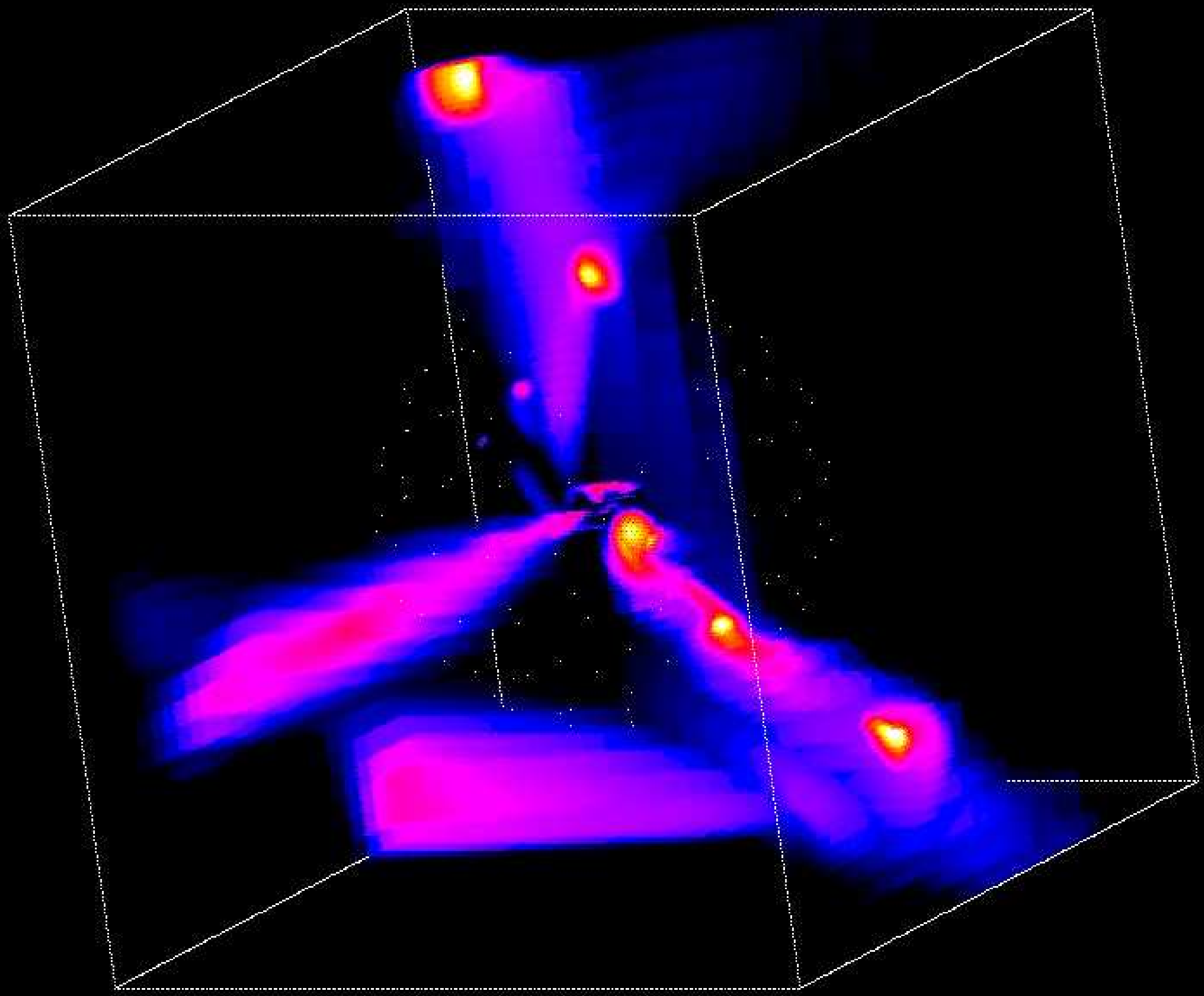


Another example

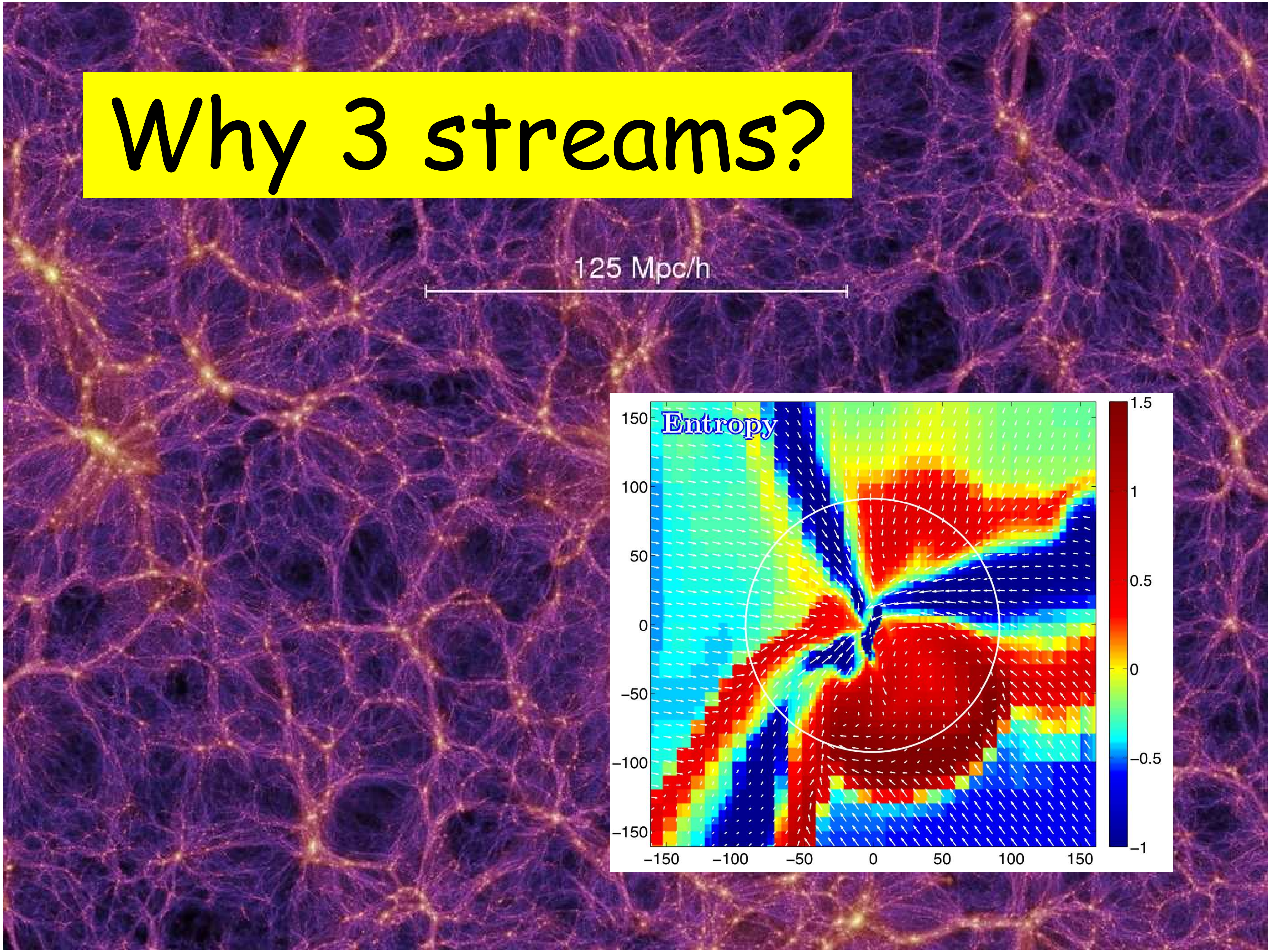


Always 3 streams?

Flux
per
solid
angle



Why 3 streams?



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

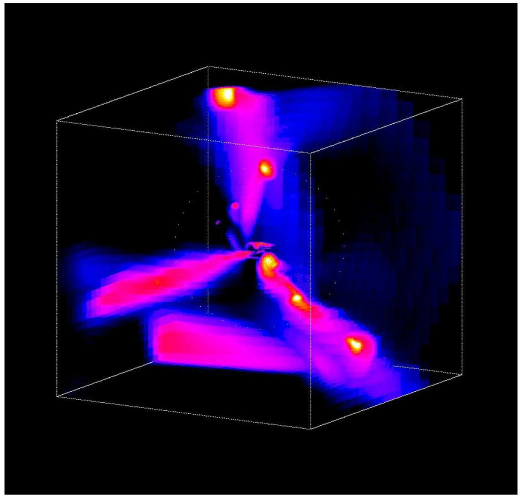
From N-body simulations or EPS, Approximate for LCDM:

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

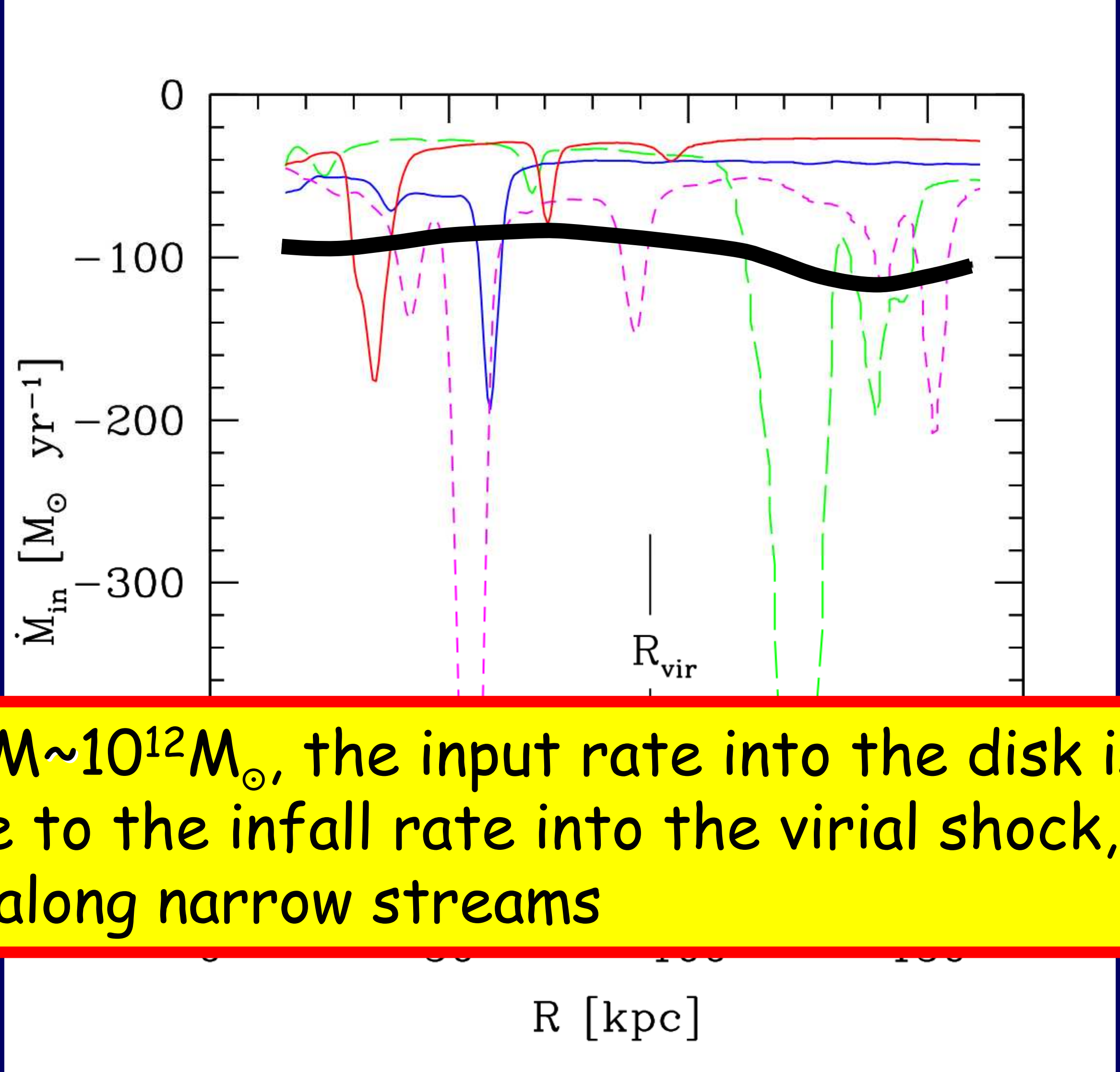
$M=2\times10^{12}M_{\odot}$ $z=2.2$ → $dM/dt \sim 200\ M_{\odot}yr^{-1}$

May explain the Star Forming Galaxies if

- the streams penetrate efficiently to the disk
- the streams are gas rich
- SFR follows rapidly

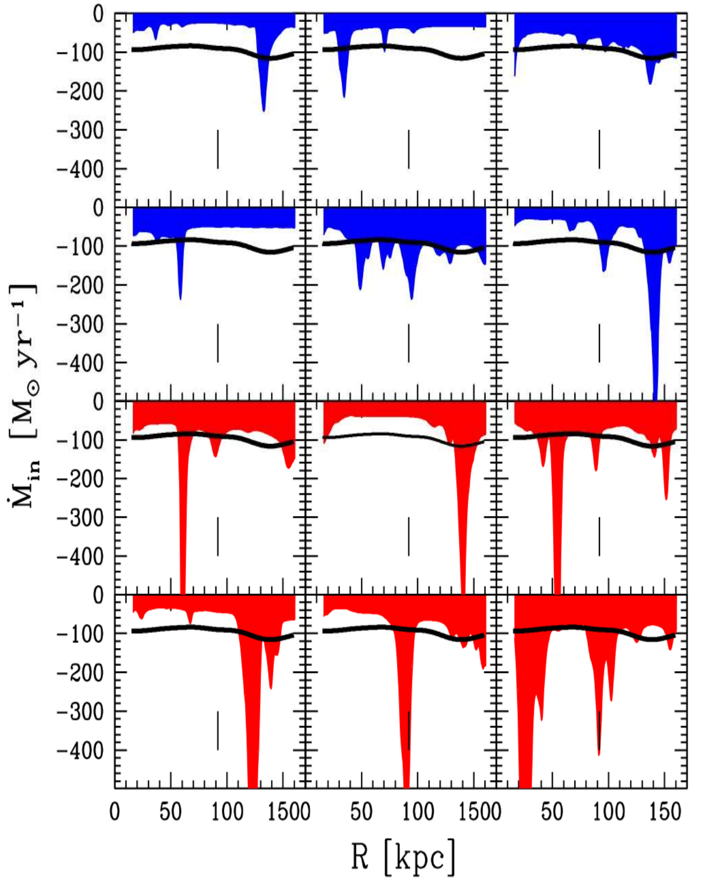


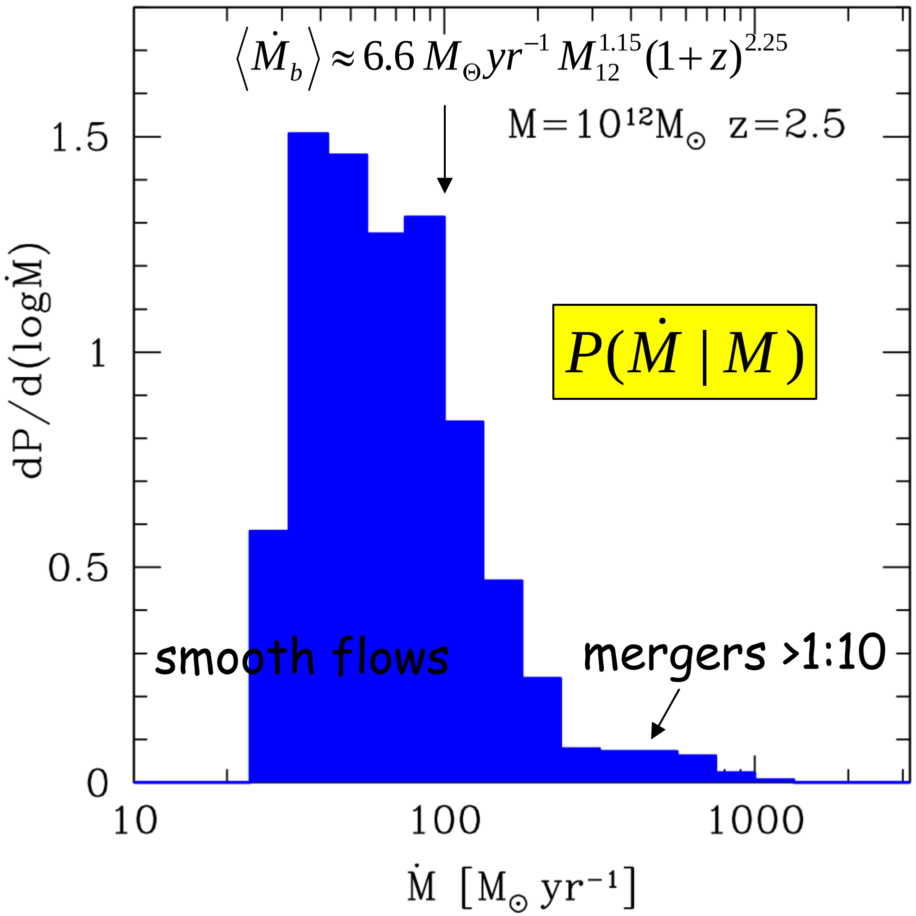
Inflow Rate into the Disk



At z~2-3, M~$10^{12}M_\odot$, 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





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

$P(\dot{M} \mid M)$

smooth flows

mergers >1:10

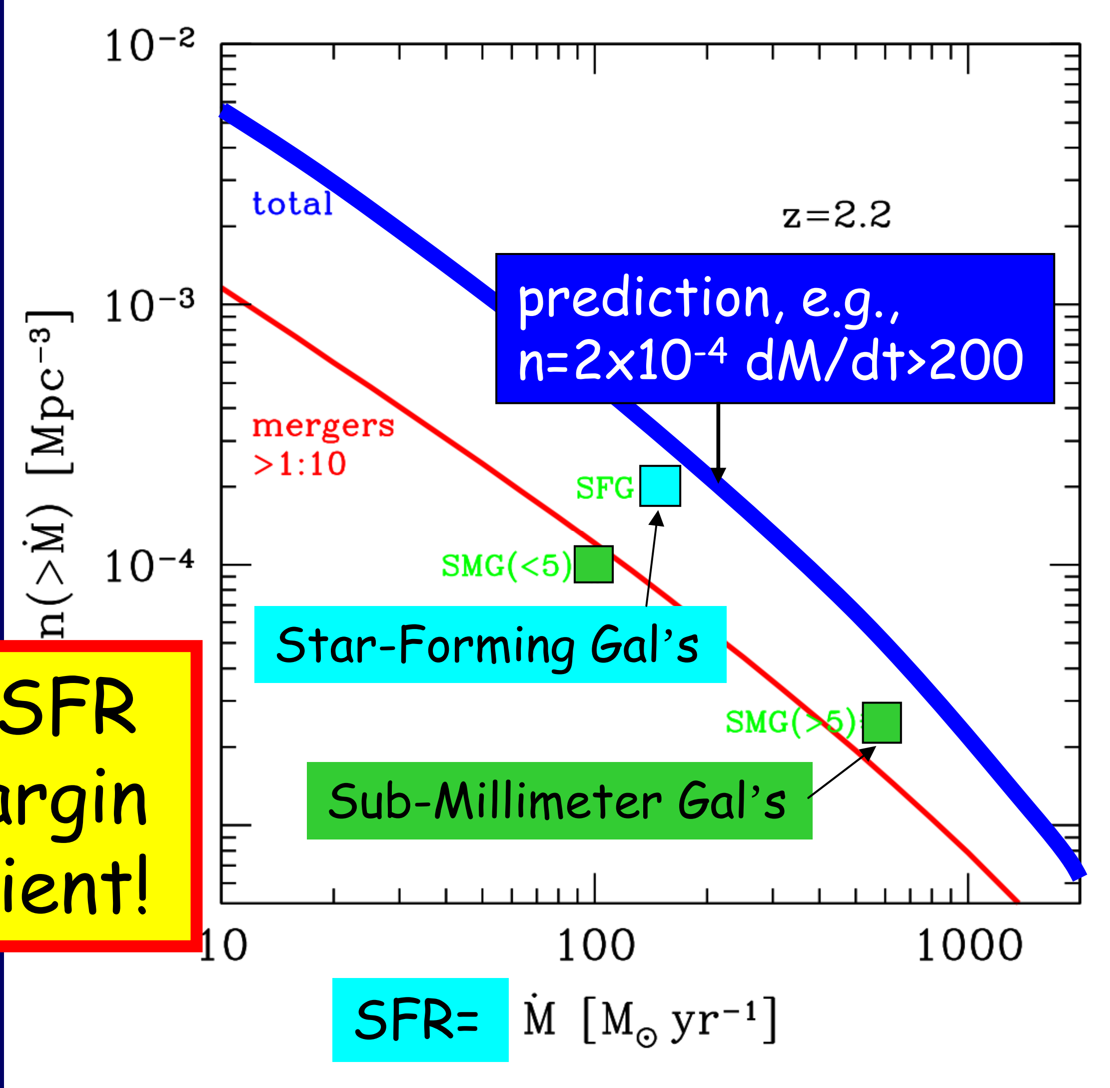
Comoving Number Density of Galaxies as a function of gas inflow rate

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

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



prediction, e.g., n=2x10^{-4} dM/dt>200

Star-Forming Gal's

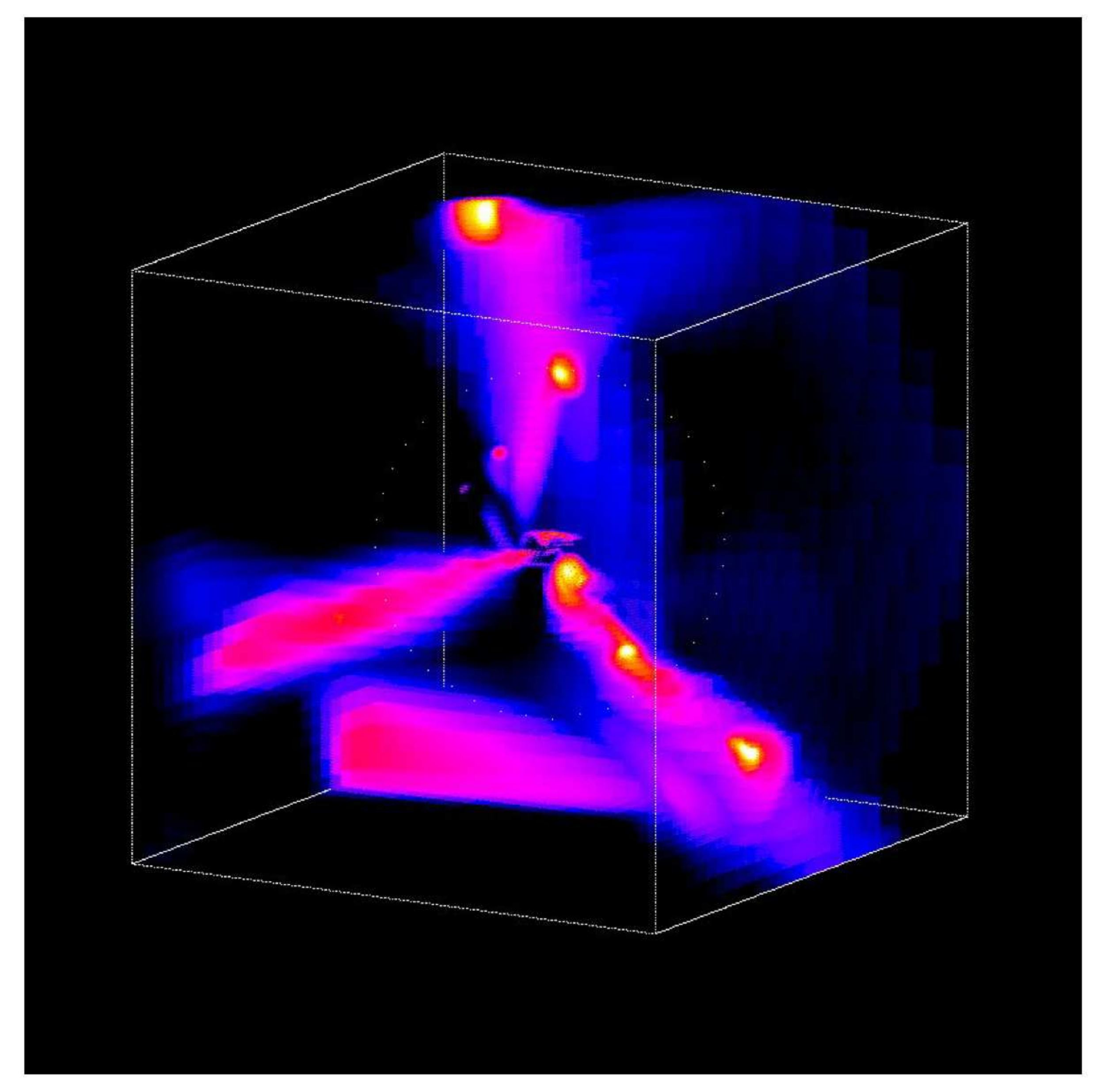
Sub-Millimeter Gal's

SFR=

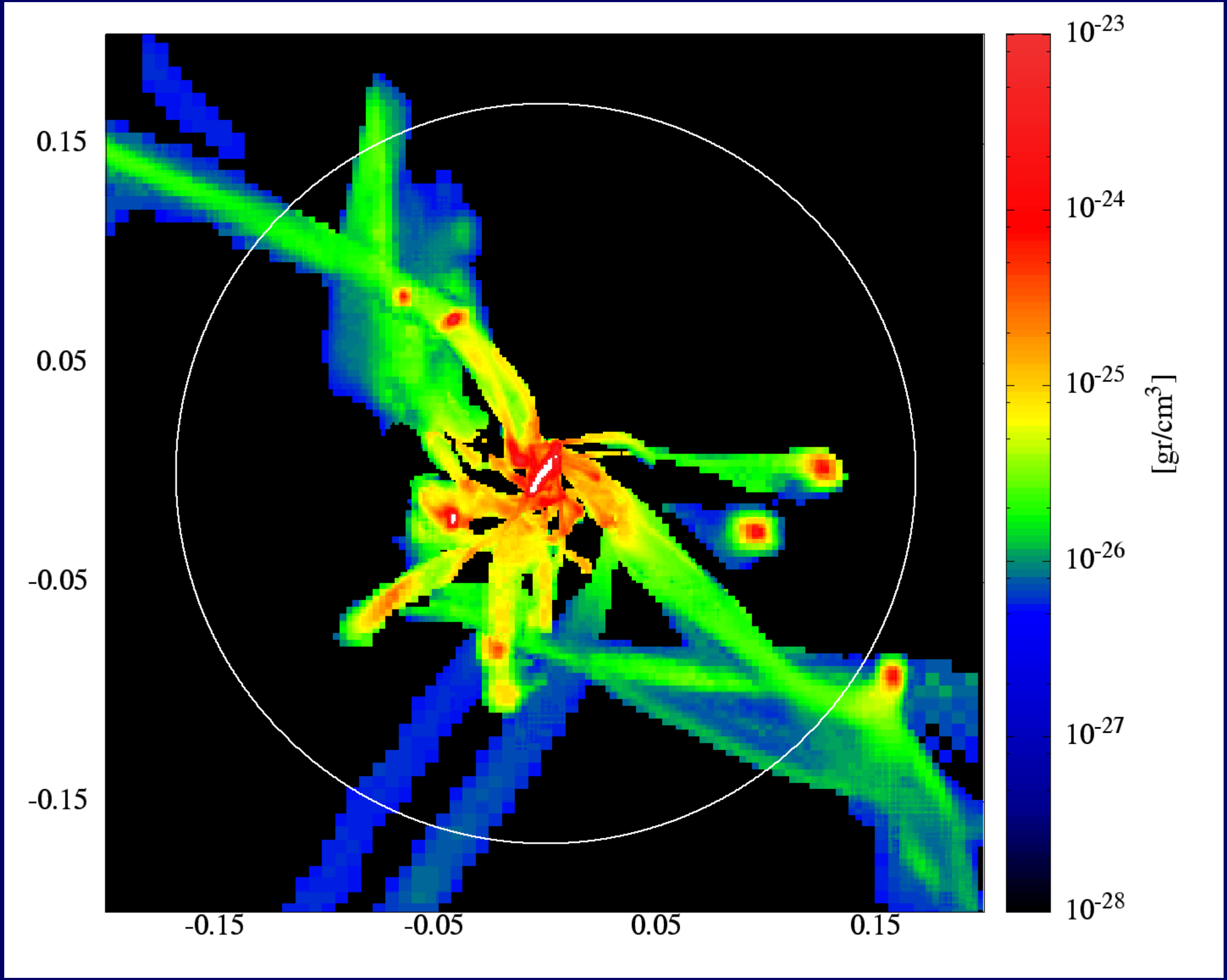
Gas inflow rate > SFR but by a small margin → SFR very efficient!

Smooth Flows vs Mergers

Streams in 3D: partly clumpy

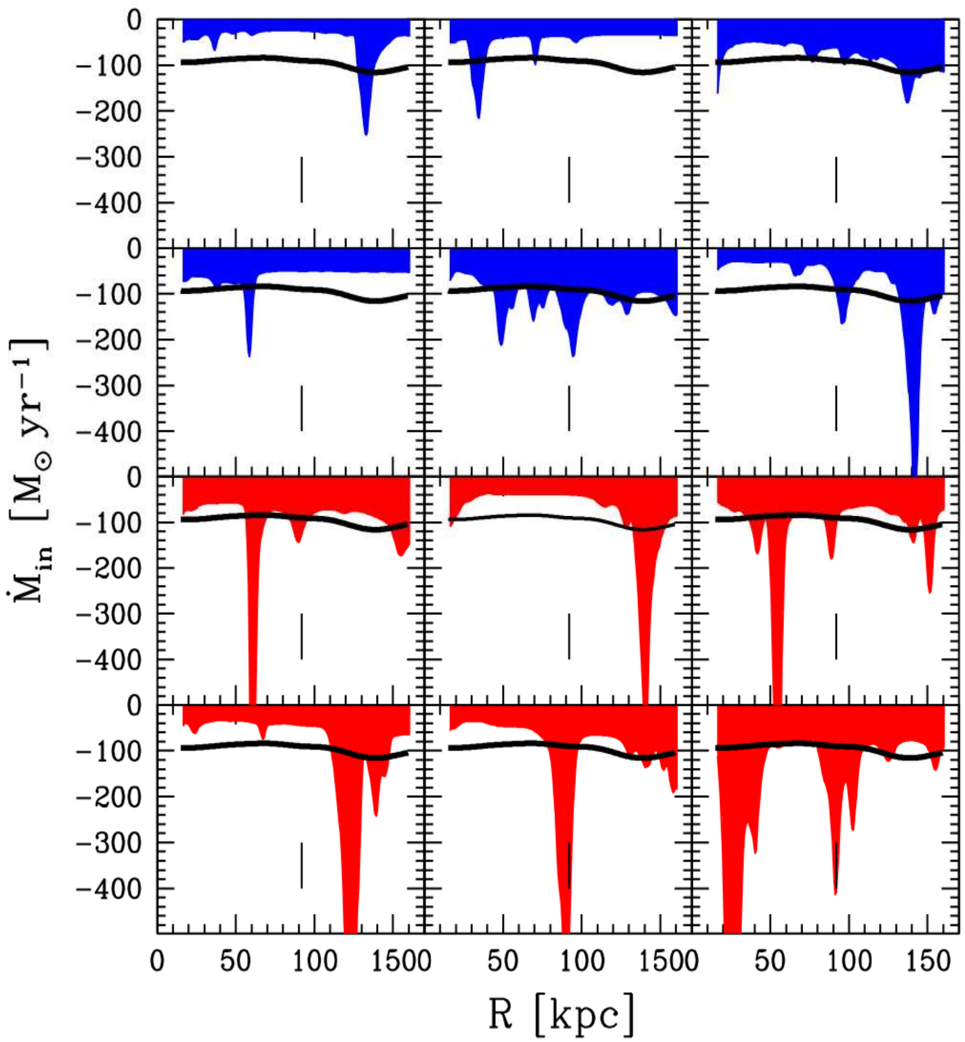


Half the stream mass is in clump >1:10



Birnboim,
Zinger,
Dekel,
Kravtsov

Inflow Rate into the Disk

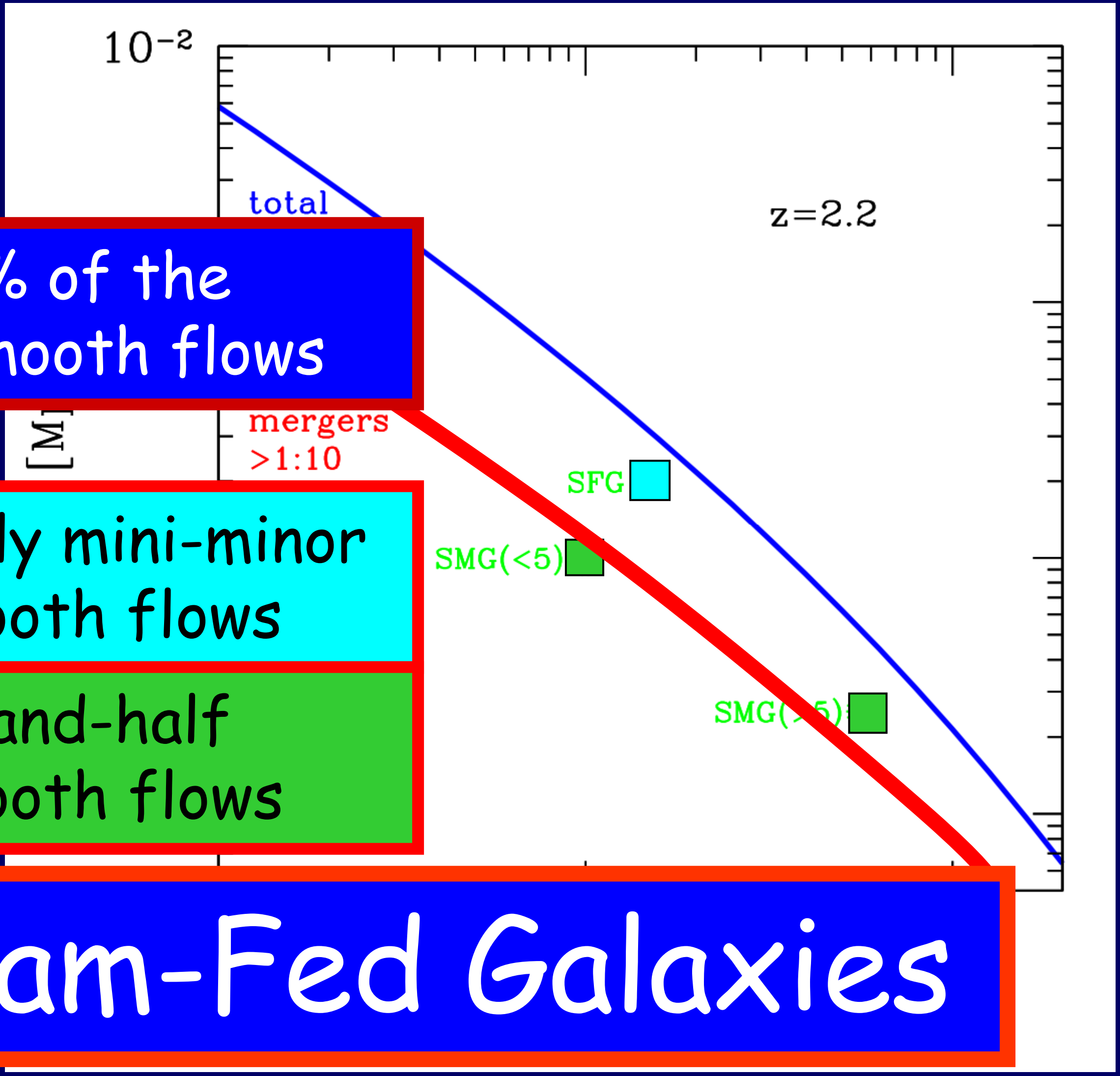


on average, 33% of the flux is in mergers > 1:10

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

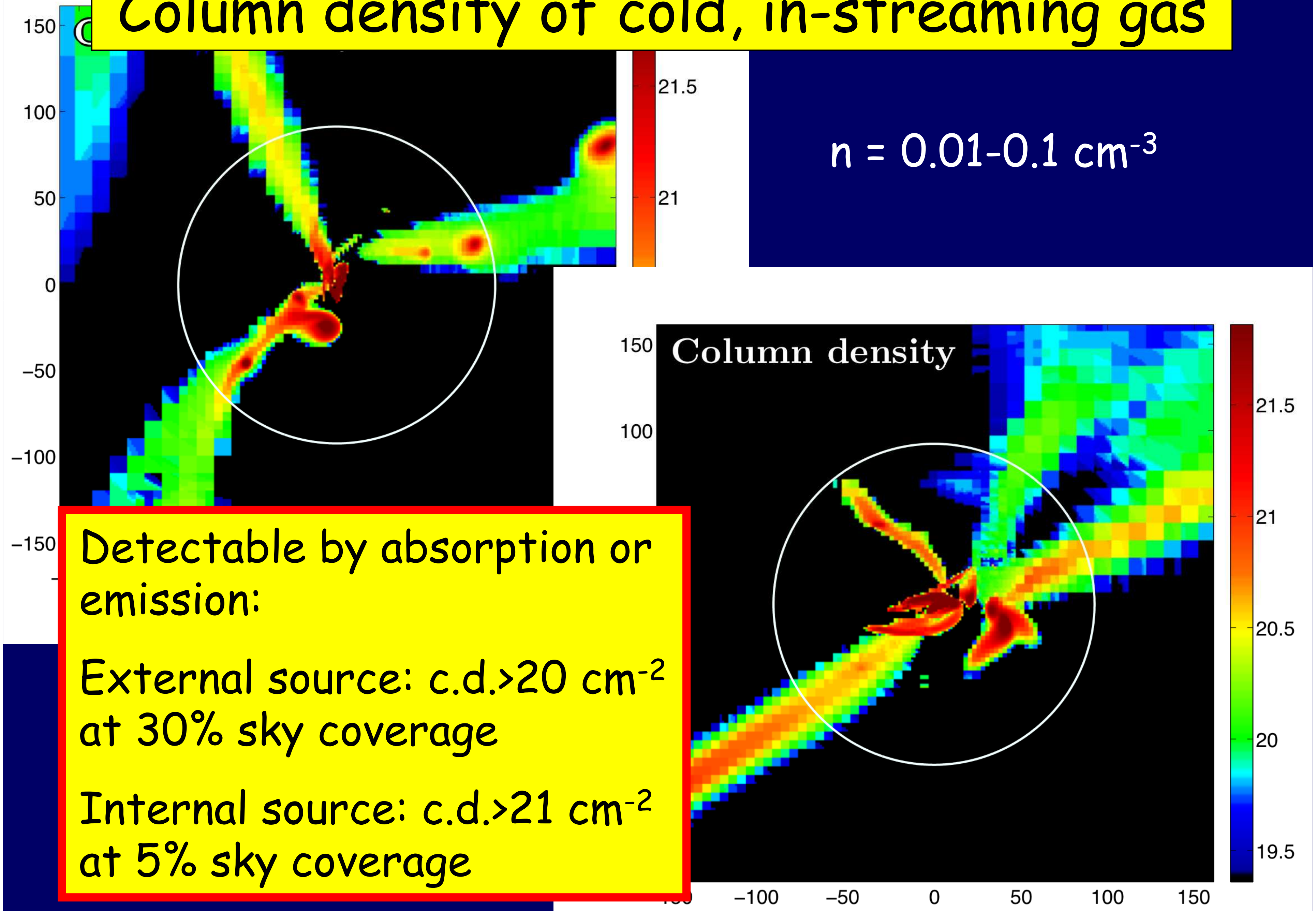
3. Lyman Alpha

Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

Earlier work:

- Haiman et al. 2000
- Fardal et al. 2001 (SPH)
- Furlanetto et al. 2005 (AMR)
- Dijkstra & Loeb 2009 (toy model)

Column density of cold, in-streaming gas



$n = 0.01\text{-}0.1\ \mathrm{cm}^{-3}$

Detectable by absorption or emission:

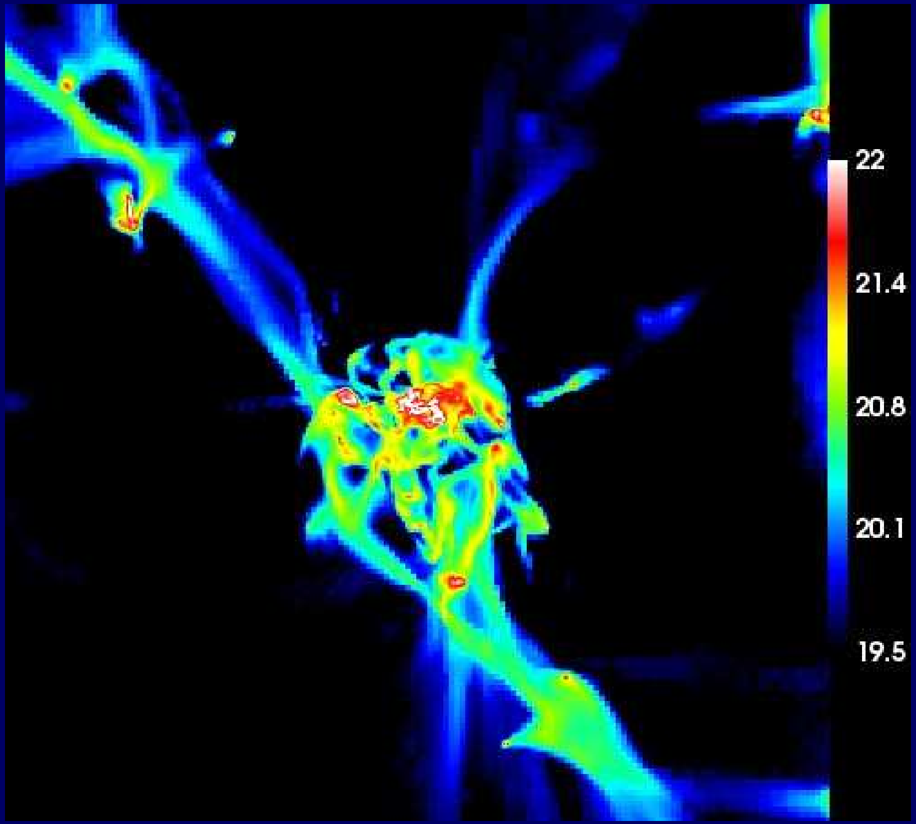
External source: c.d.>20 cm^{-2} at 30% sky coverage

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

High Resolution Simulations

Ceverino, Dekel, Bournaud 2009

- AMR 35-70 pc resolution
- ΛCDM cosmology
- $M_{vir}=5\times10^{11}\,M_{\odot}$ at $z=2.3$
- cooling to 300K
- UV background, shielding if n>0.1
- star formation
- feedback, metals



Streams are Largely Self-Shielded

Neutral column density perpendicular to stream

$N_I \approx 10^{20}\, cm^{-2}$ $n_H \approx 0.03$

UV background Lyman continuum intensity at z=3

$$4\pi J^* \approx 2.2\times 10^5\ photons\ s^{-1}\, cm^{-2}$$

Photoionized column

$$N_{II}^{photo} = \frac{2\pi J^*}{n_H \underbrace{\alpha_B}_{\text{recombination}}} = \frac{4.2\times 10^{17}}{n_H} cm^{-2}$$

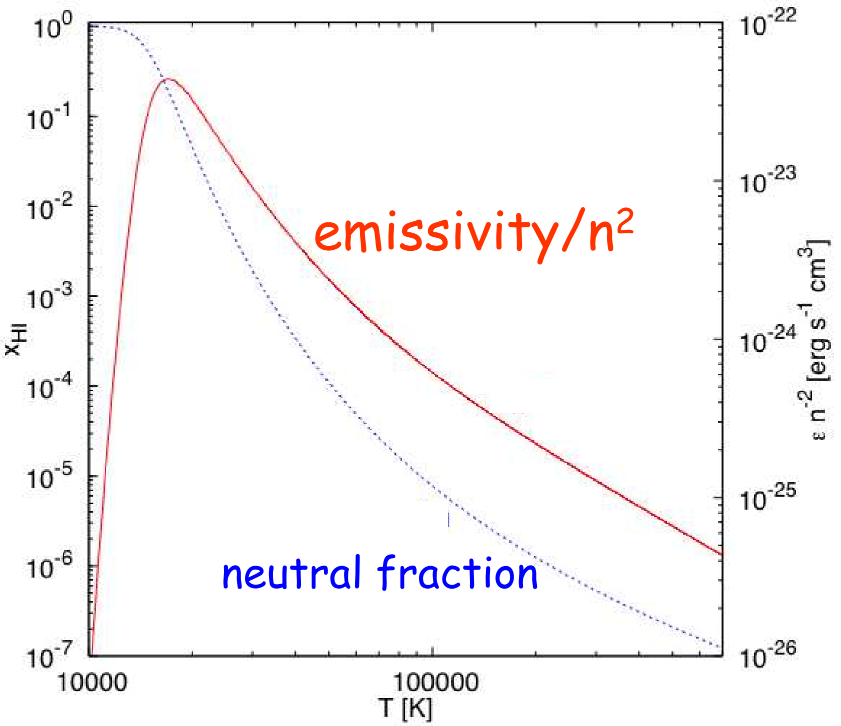
→ $N_I >> N_{II}^{photo}$

Lyman-alpha Emissivity

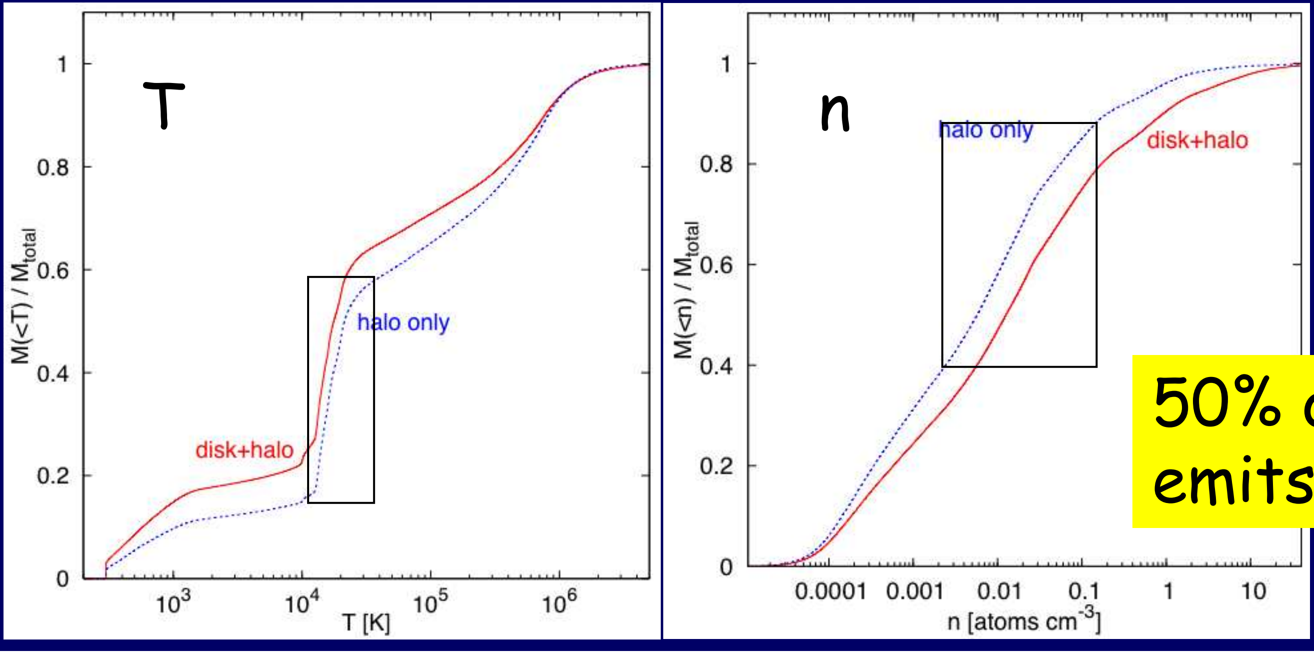
Collisional excitation:

$$\varepsilon = n_e \, n_{HI} \, q_{1s\to 2p}(T) \, h\nu_{L\alpha}$$

$$q_{1s\to 2p} = \frac{2.41\times 10^{-8}}{T_4^{0.5}} T_4^{0.22} \exp\left(-\frac{h\nu_{L\alpha}}{kT}\right) cm^3 s^{-1}$$



Cumulative distribution of T & n
in the halo



Gnat & Sternberg 07,
collisional ionization
equilibrium, case-B
H recombination

50% of the gas
emits Lα effectively

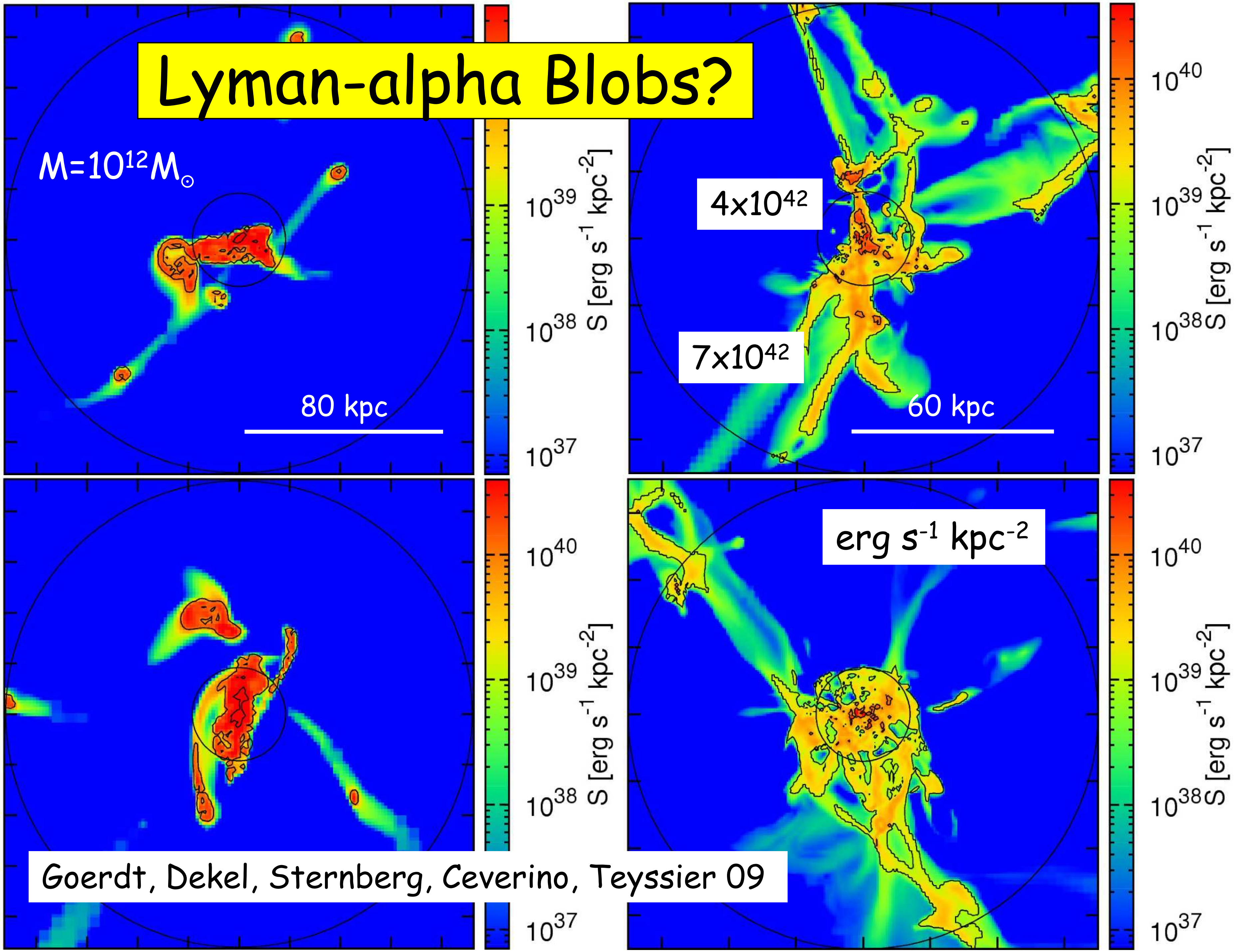
Lyman Alpha Luminosity

$$L_{L\alpha} = f_\alpha \sum \varepsilon_i(T,n) V_i$$

radiative transfer

- f_α=0.5
- Ignore dust

Lyman-alpha Blobs?



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

80 kpc

4×10^{42}

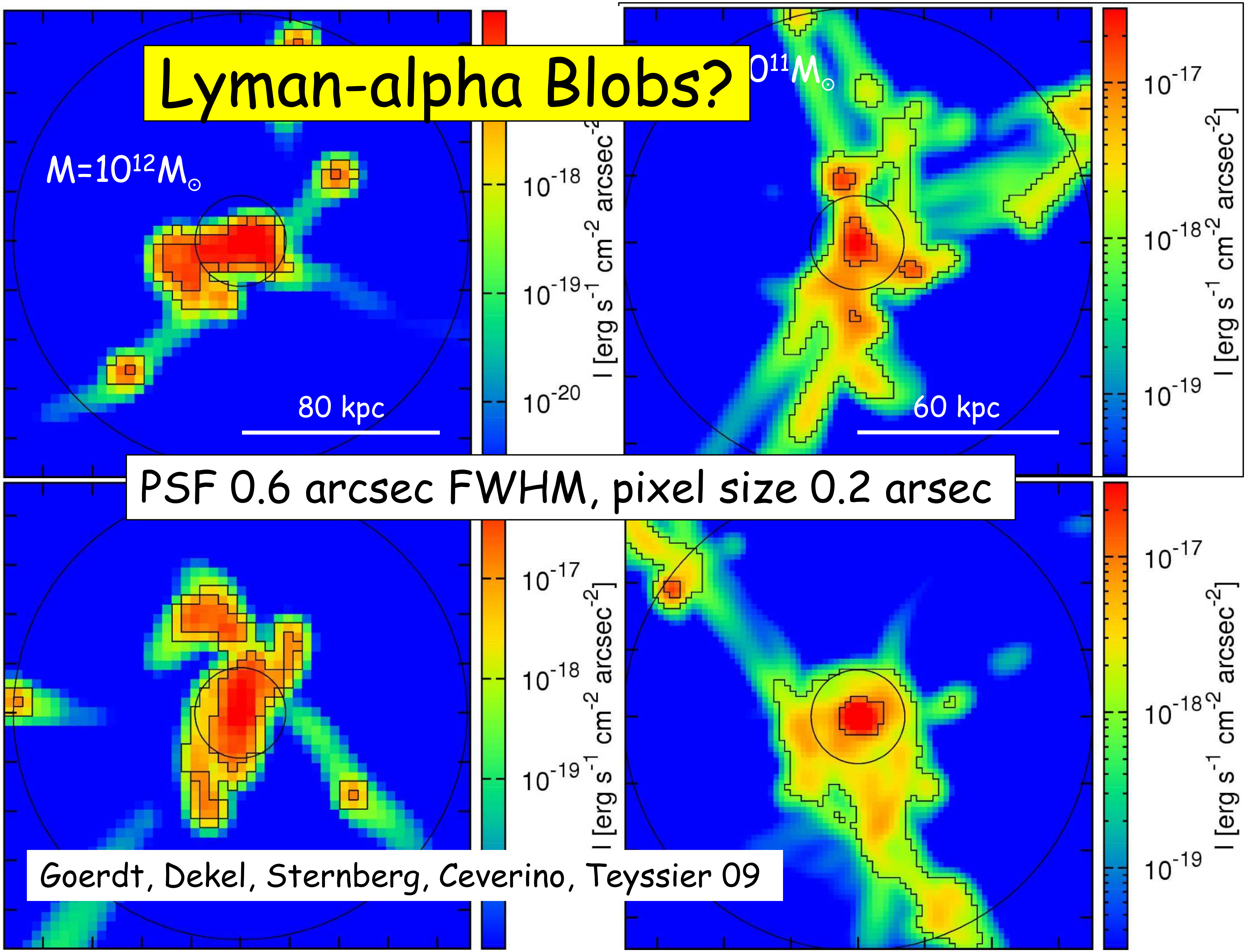
7×10^{42}

60 kpc

erg s^{-1} kpc^{-2}

Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

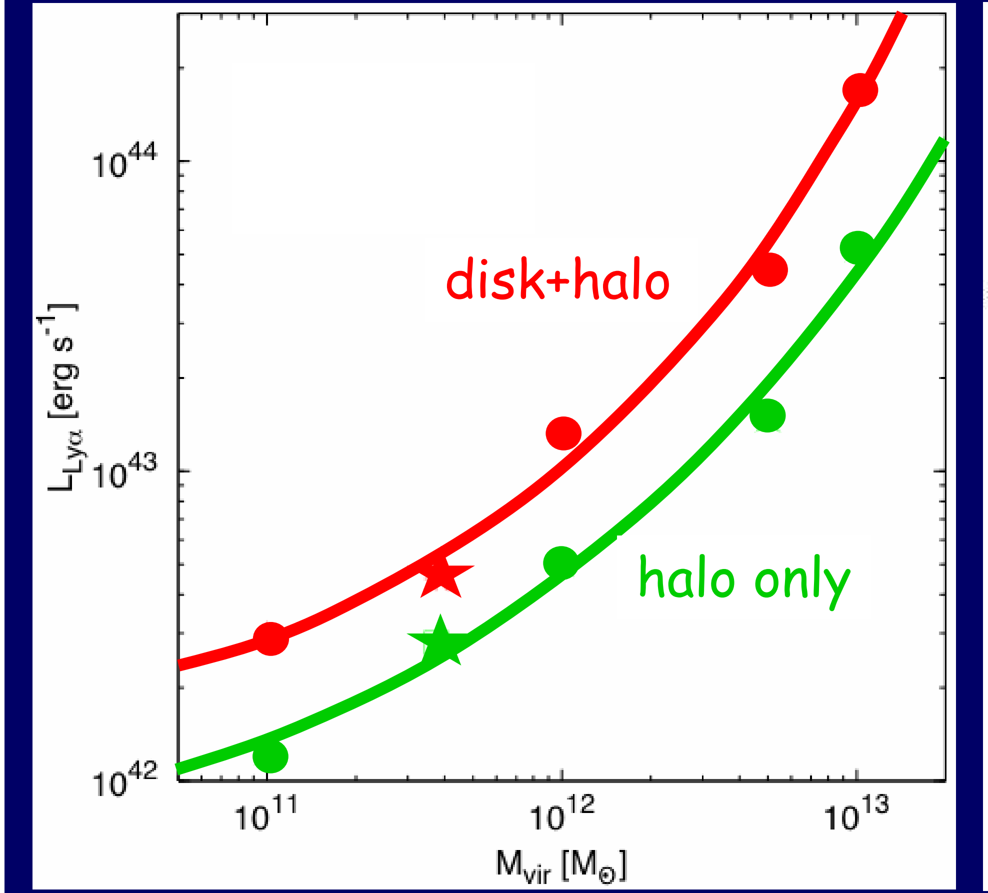
Lyman-alpha Blobs?

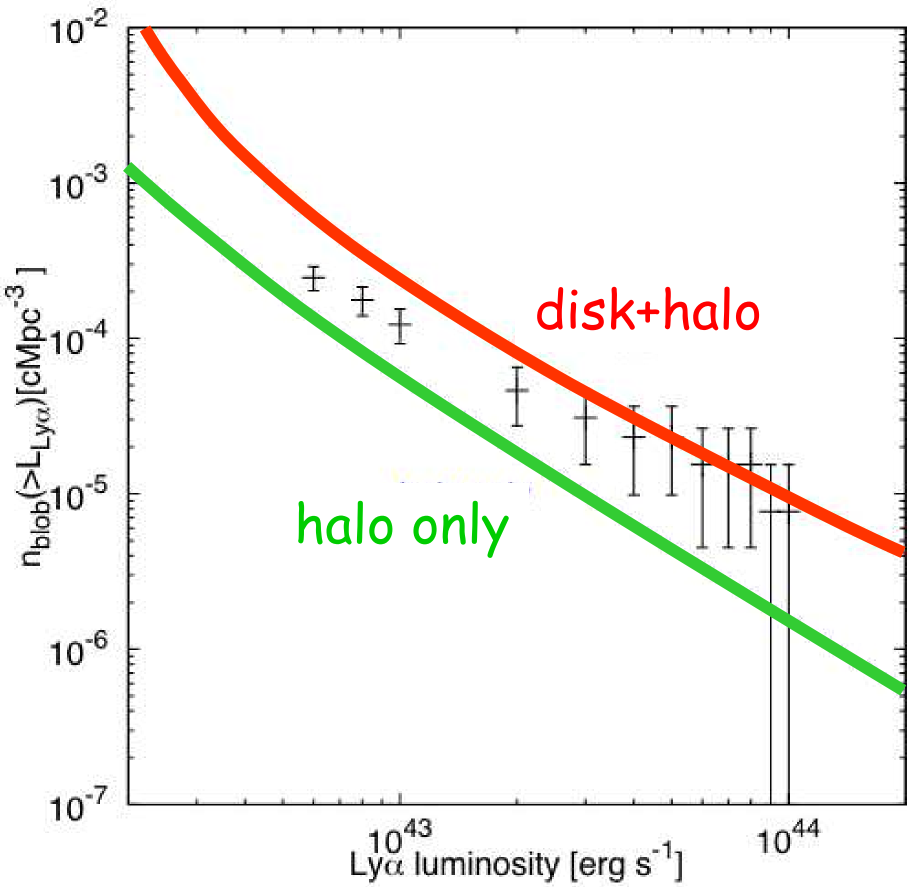


PSF 0.6 arcsec FWHM, pixel size 0.2 arsec

Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

Lyman-alpha Luminosity Function





Goerdt, Dekel, Sternberg, Ceverino, Teyssier 09

Power Lyman-alpha Emission by Gravity

Gravitational heating

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

Average inflow through halo (EPS, simulations, Neistein, Dekel 06, 07, 08)

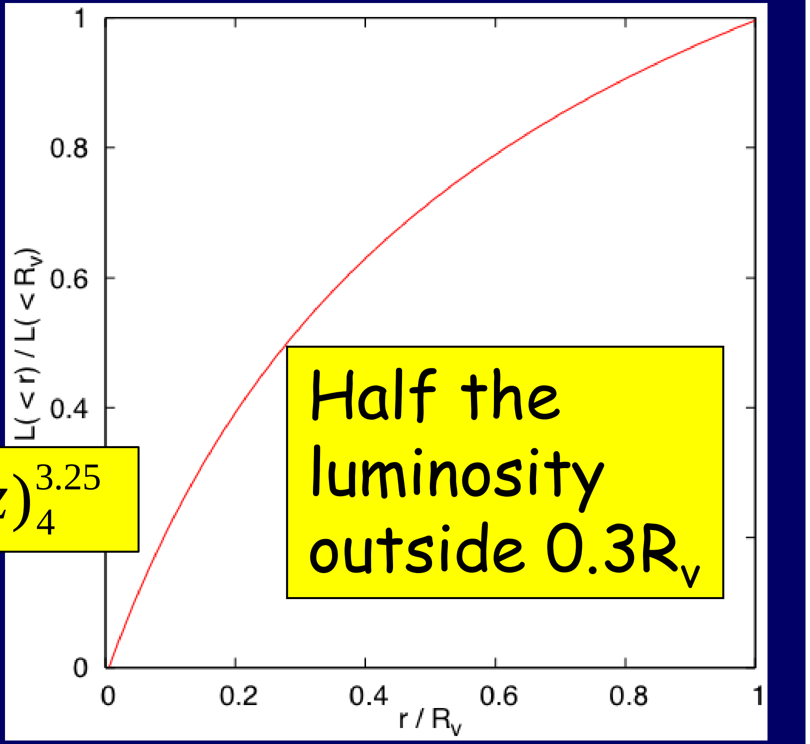
$$\dot{M}_c \approx 140 \, M_\otimes yr^{-1} \, M_{12}^{1.15} \, (1+z)_4^{2.25}$$

Potential well

$$\Delta\phi \approx 3V_{vir}^2$$

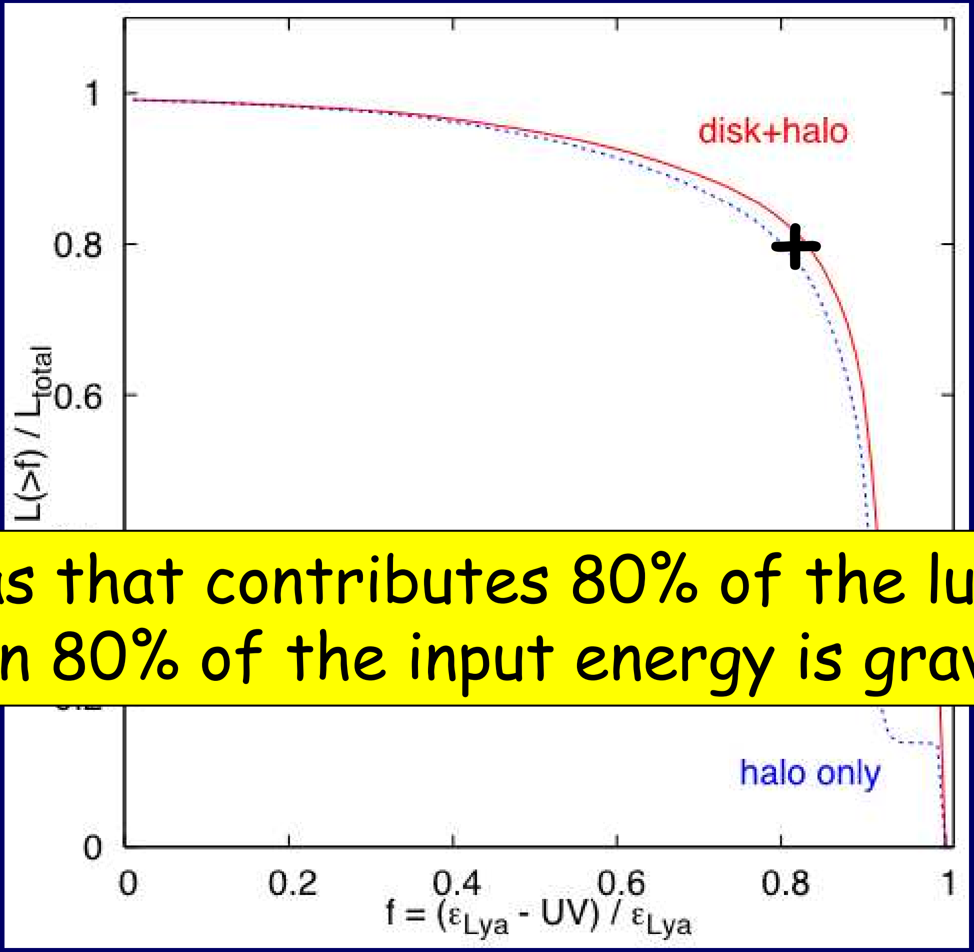
$$V_{vir} \approx 240 \, km \, s^{-1} \, M_{12}^{1/3} \, (1+z)_4^{1/2}$$

→ $$E_{heat} \approx 1.2\times 10^{43} erg \, s^{-1} \; f_c \, M_{12}^{1.82} \, (1+z)_4^{3.25}$$



Half the luminosity outside 0.3R$_v$

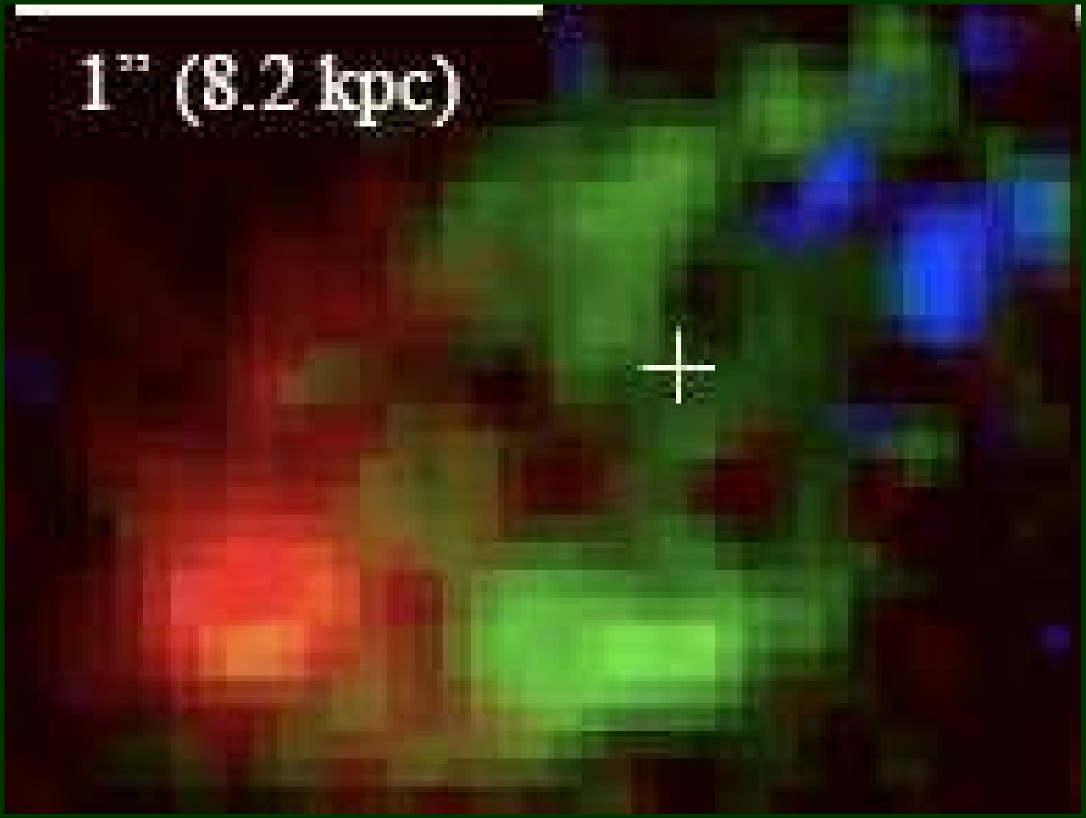
The Energy Source: Gravitational Heating vs. UV Background



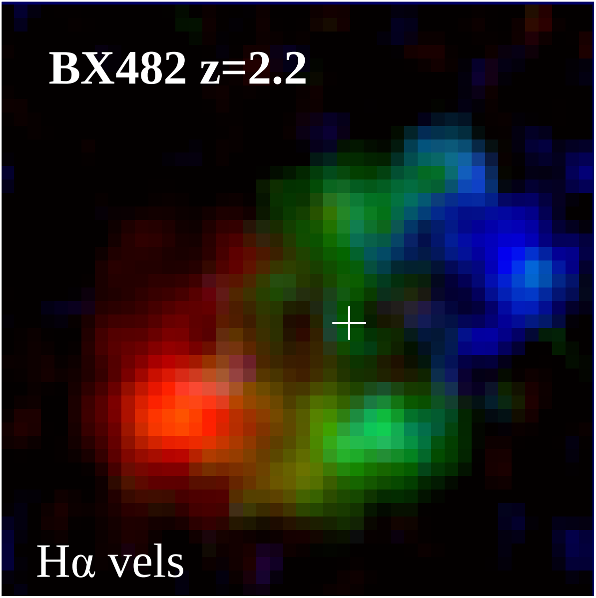
In the gas that contributes 80% of the luminosity more than 80% of the input energy is gravitational

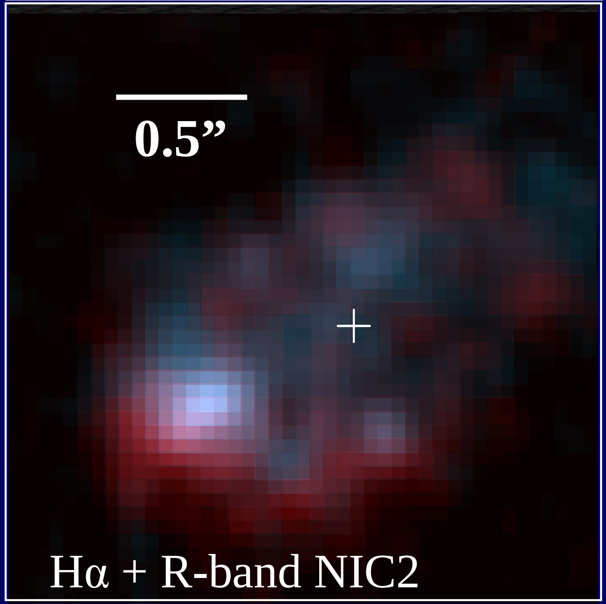
fractional contribution of gravitational heating

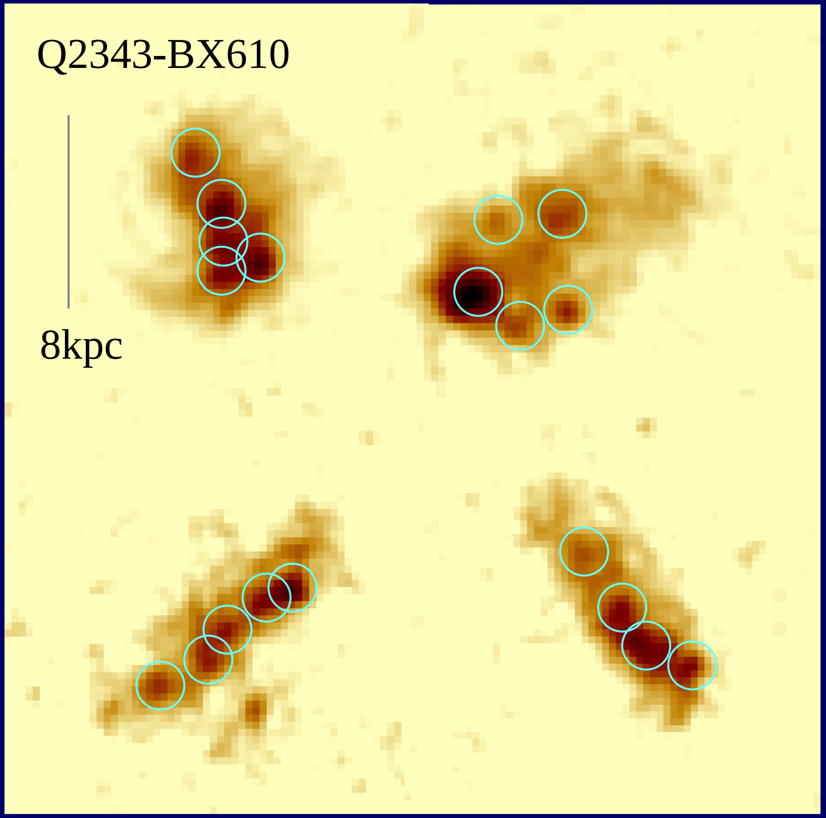
4. Disks with Giant Clumps



Chain Galaxies – Fragmented Disks





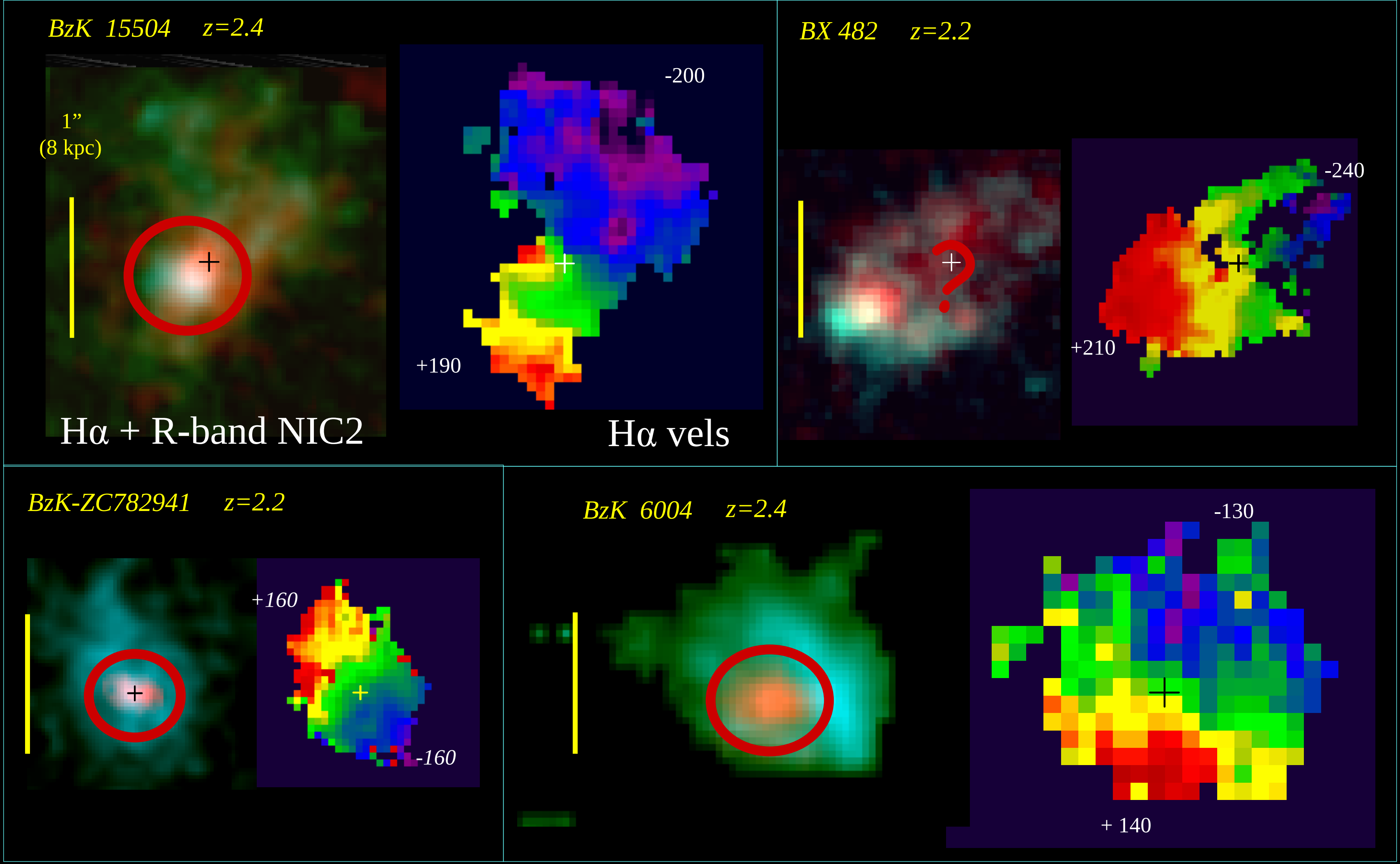


NICMOS H_{160}

Foerster Schreiber, Shapley et al. 2008

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

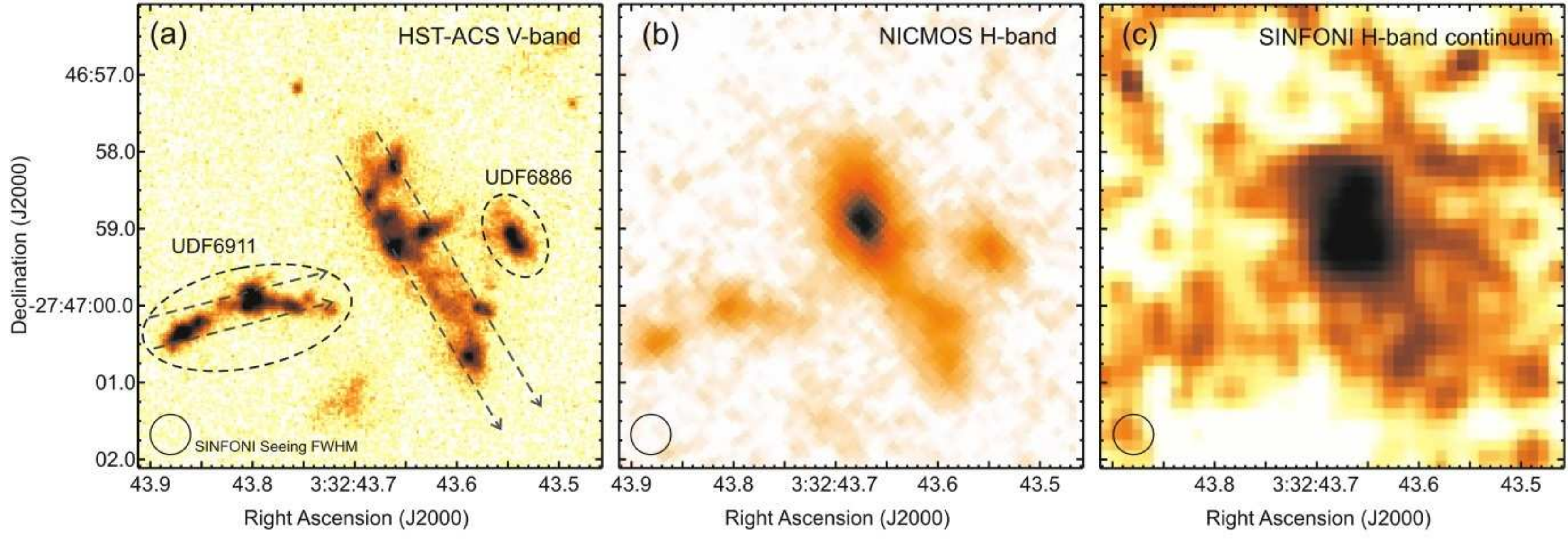
Clumpy Disks with Bulges

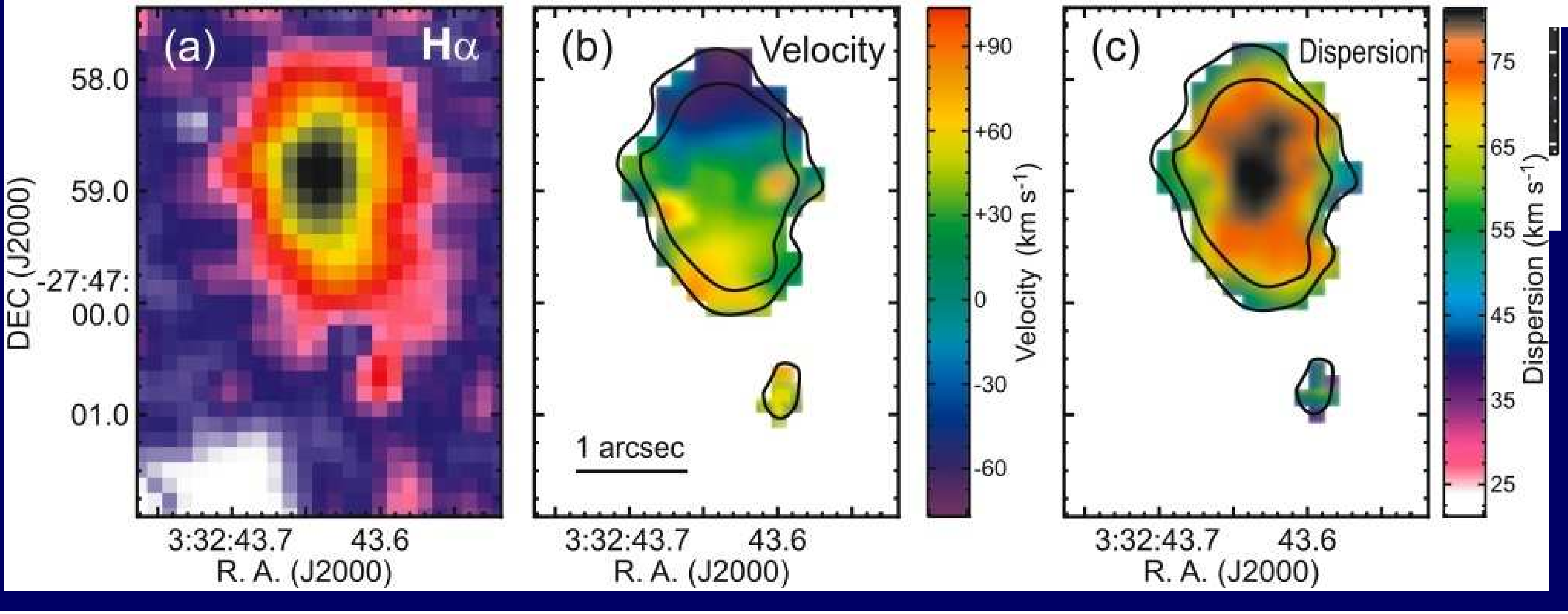


Genzel et al. 08; Förster Schreiber et al. 20

$M(\leq 3\ \mathrm{kpc})/M(\leq 15\ \mathrm{kpc}) \sim 0.2-0.4$

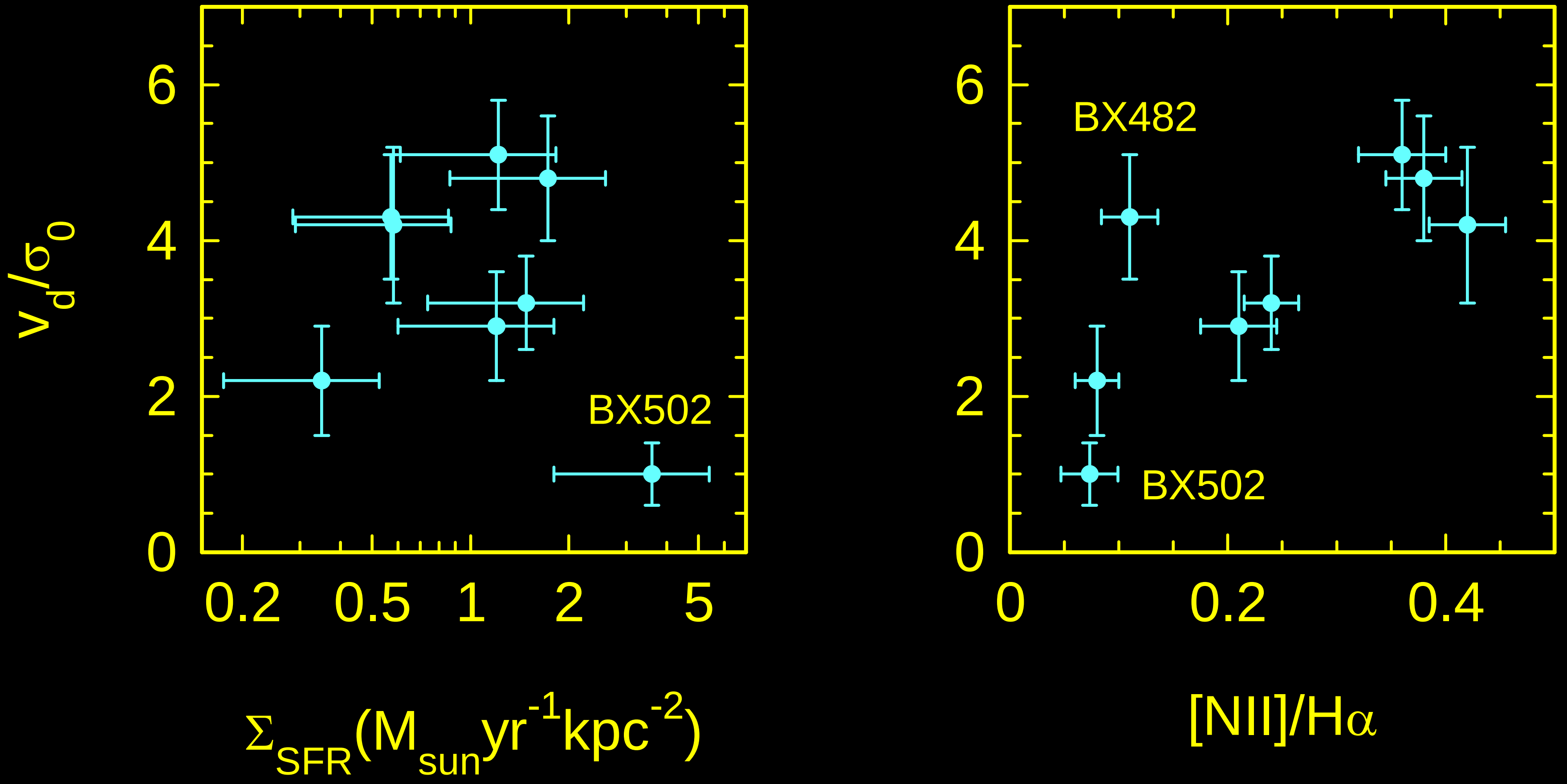
A rotating “chain” of clumps with a bulge





Elmegreen,
Bournaud
et al. 08

z~2 disks are turbulent



Genzel et al. 2008

Disk Breakup into Giant Clumps Star Formation, Migration to a Bulge, Stabilization

Dekel, Sari, Ceverino 2009

Ceverino, Dekel, Bournaud 2009

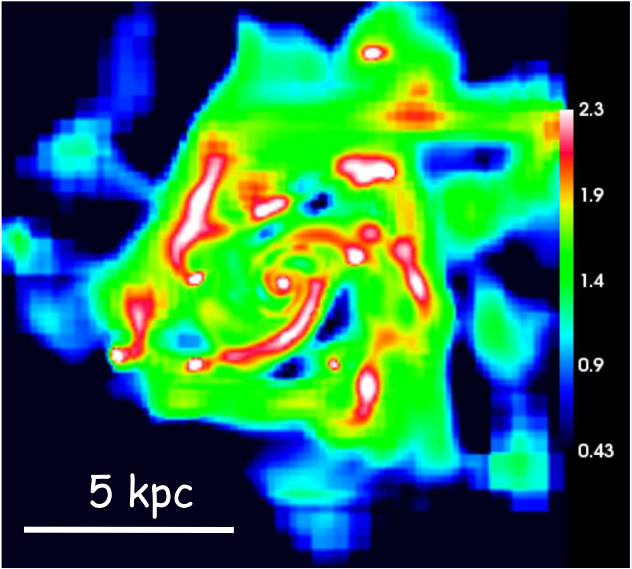
Disk – Giant Clumps - Bulge

High gas density → disk wildly unstable

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

Giant clumps and transient features

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

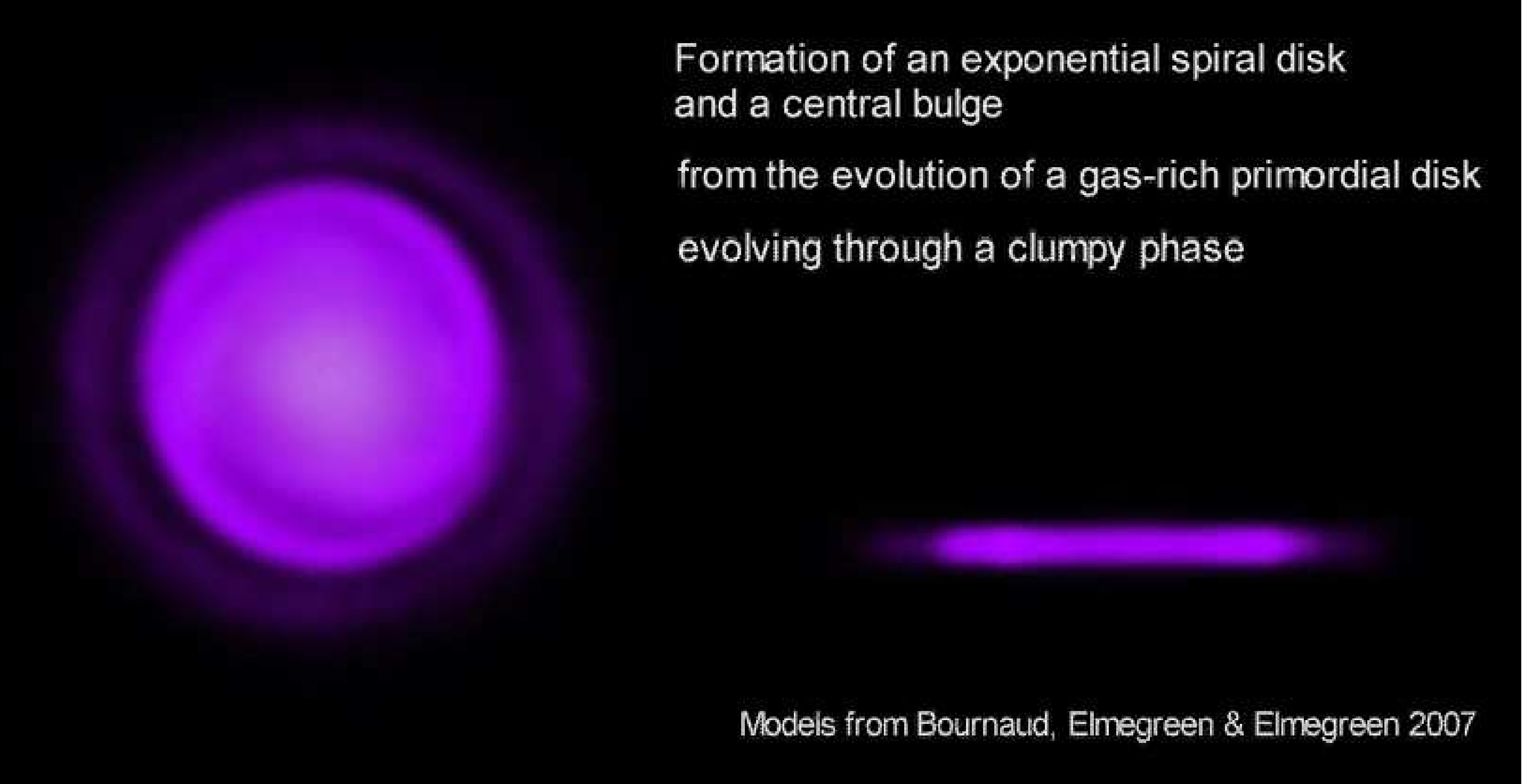


Self-regulation at Q ~ 1 by clump encounters and torques, high σ/V~1/4

Efficient star formation in the clumps

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

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



Formation of an exponential spiral disk
and a central bulge

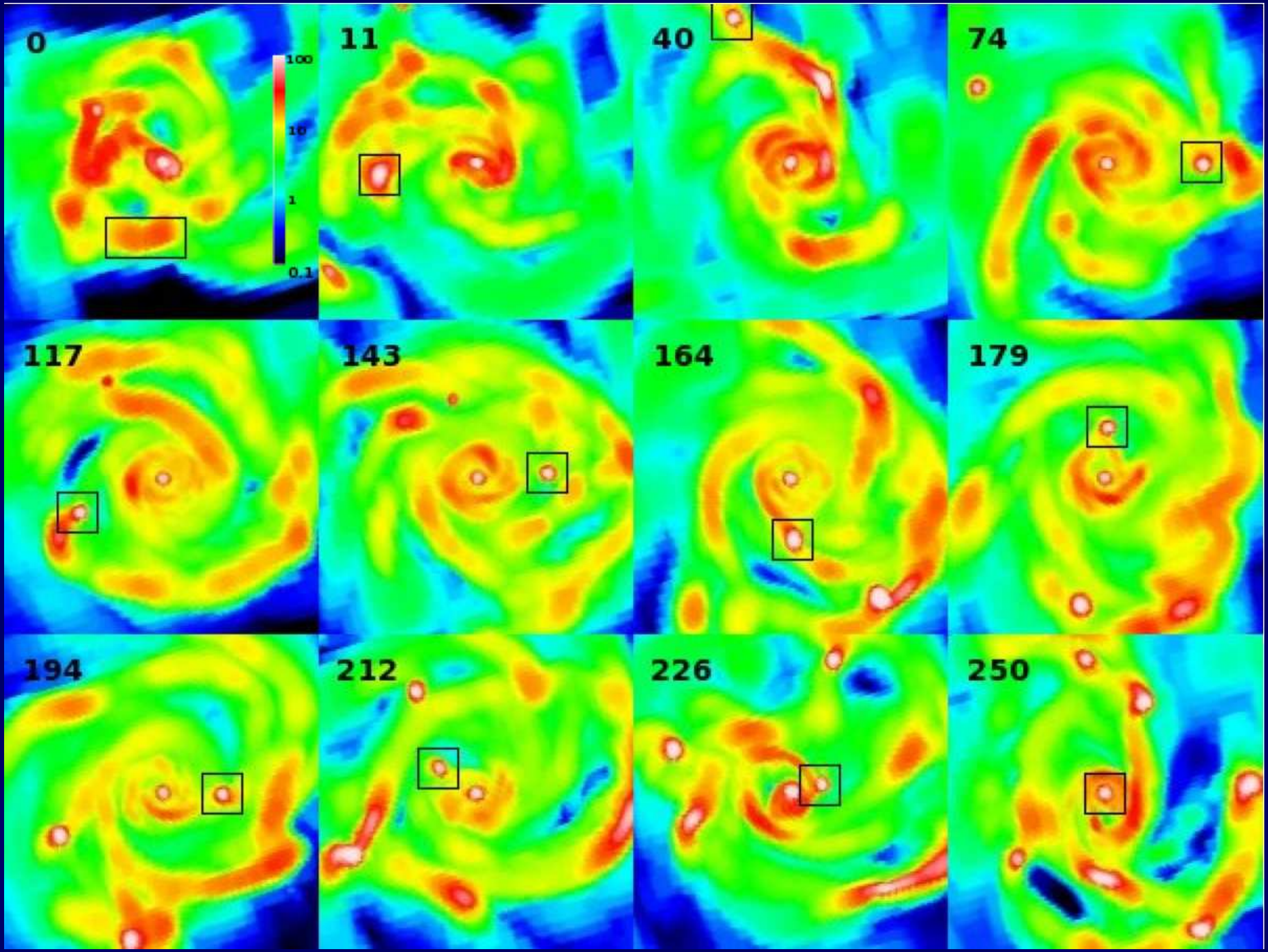
from the evolution of a gas-rich primordial disk

evolving through a clumpy phase

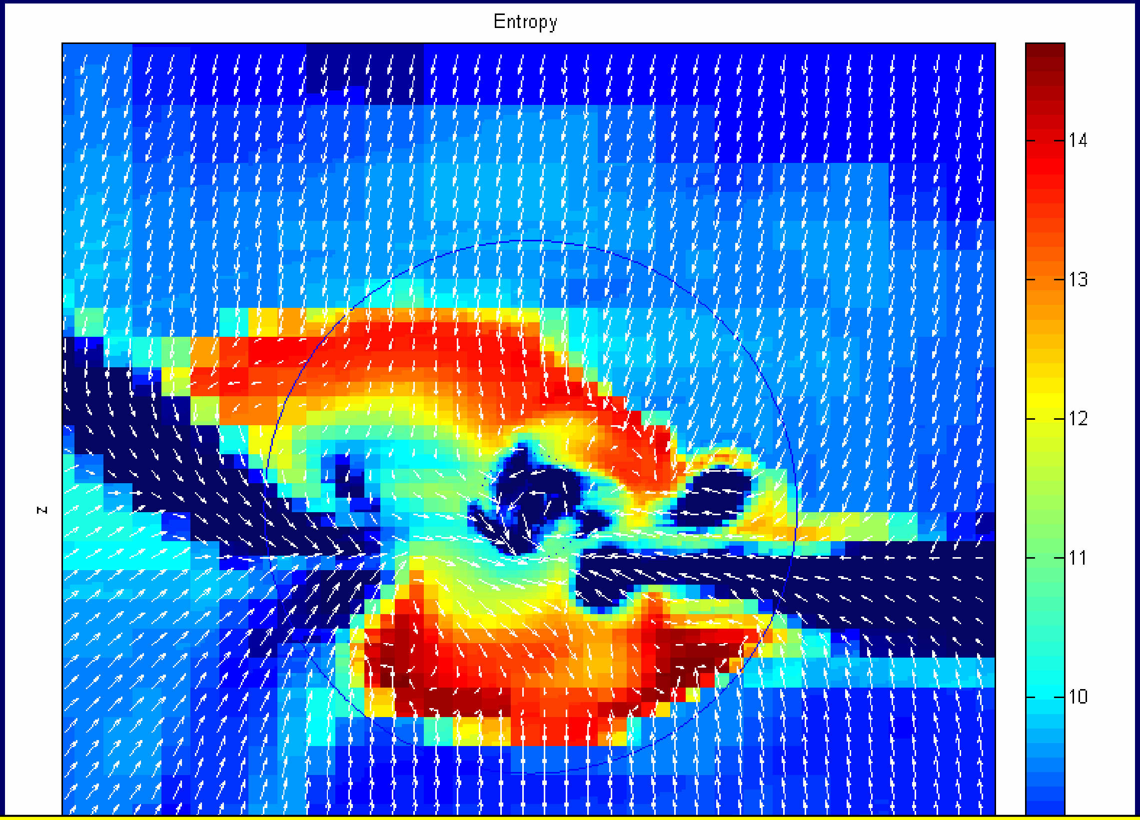
Models from Bournaud, Elmegreen & Elmegreen 2007

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

Clump Formation & Migration in a Cosmological Steady State

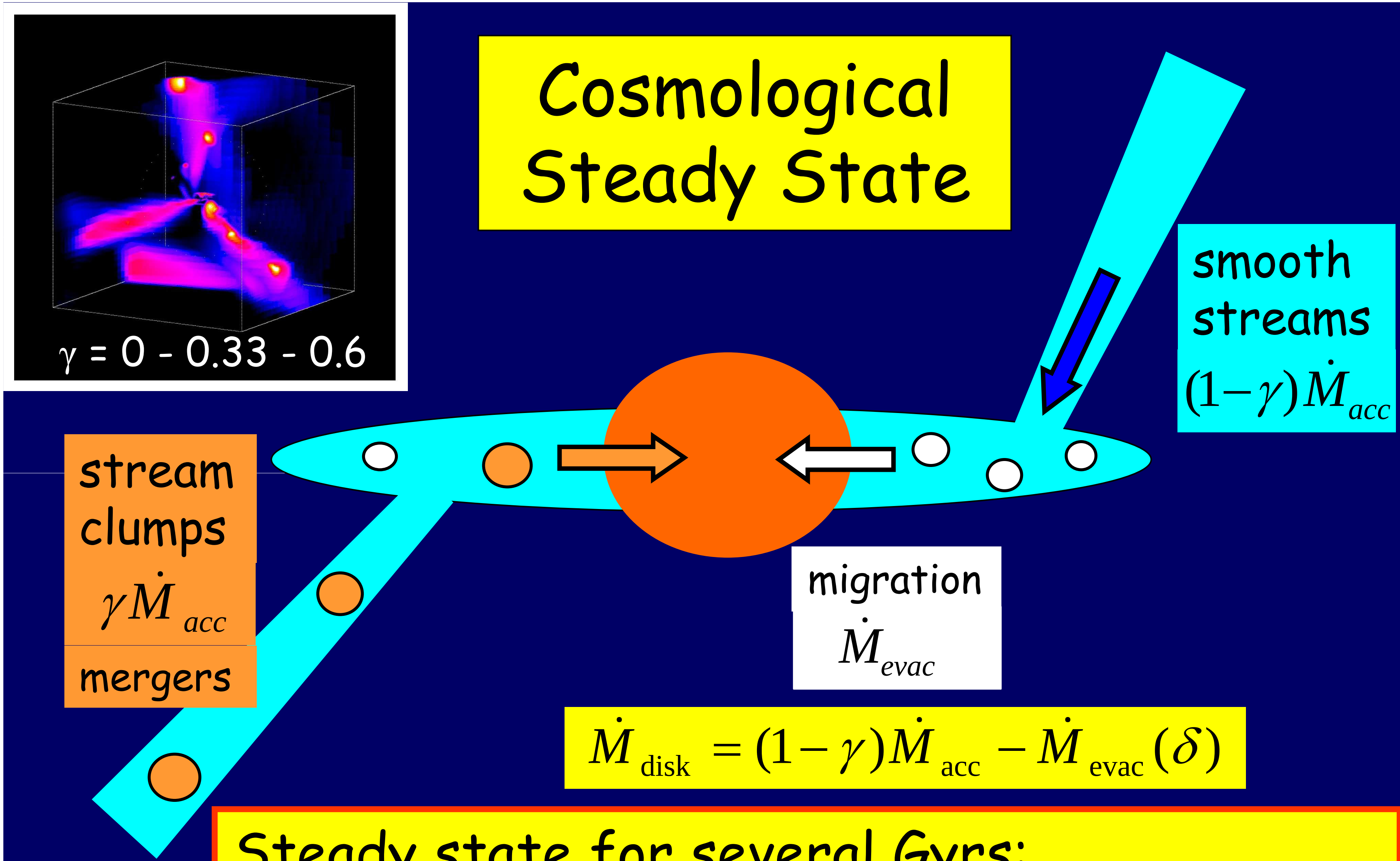


Disk Buildup by Streams



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

Cosmological Steady State



γ = 0 - 0.33 - 0.6

smooth streams

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

stream clumps

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

mergers

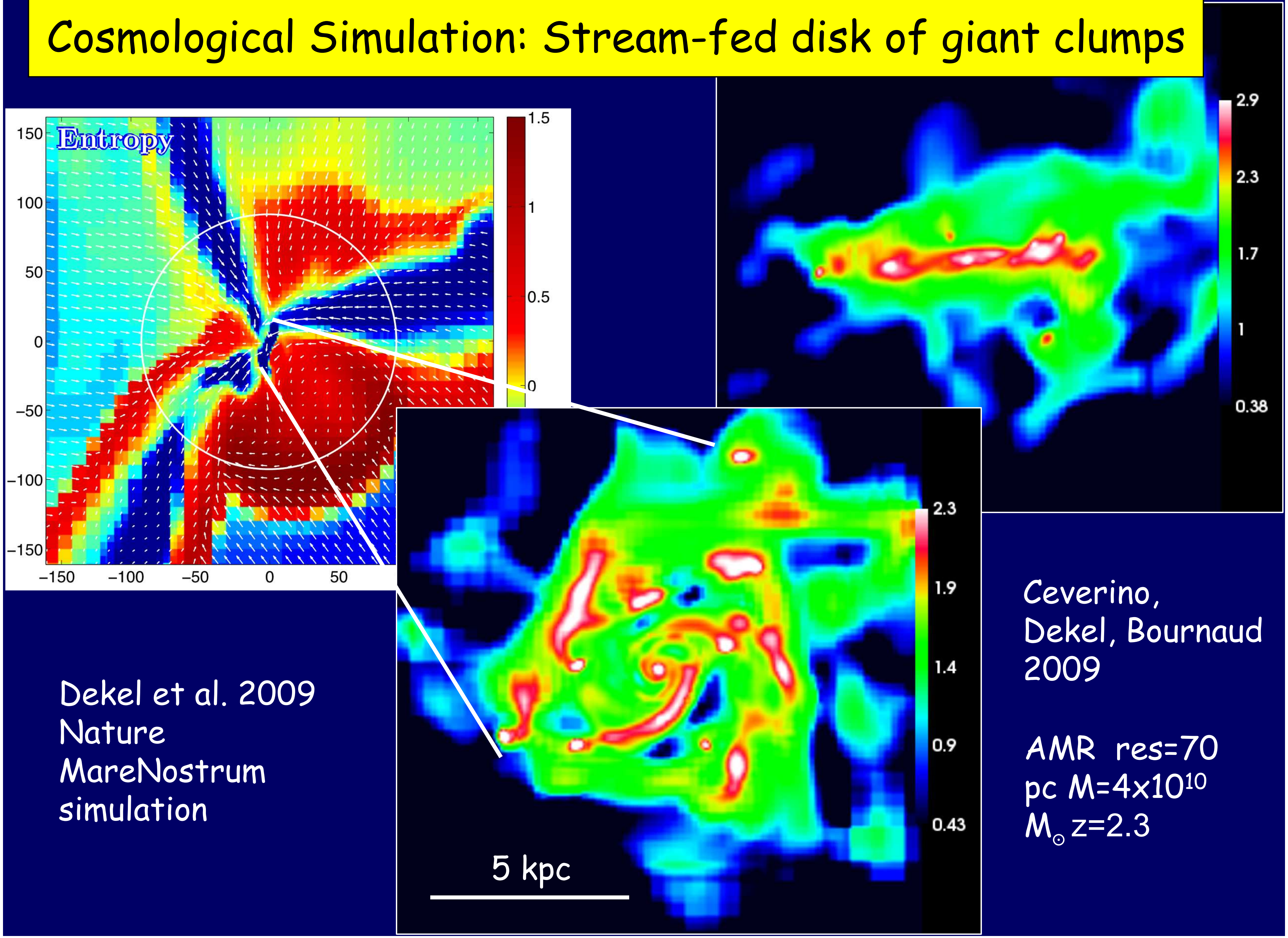
migration

$\dot{M}_{evac}$

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

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

Cosmological Simulation: Stream-fed disk of giant clumps



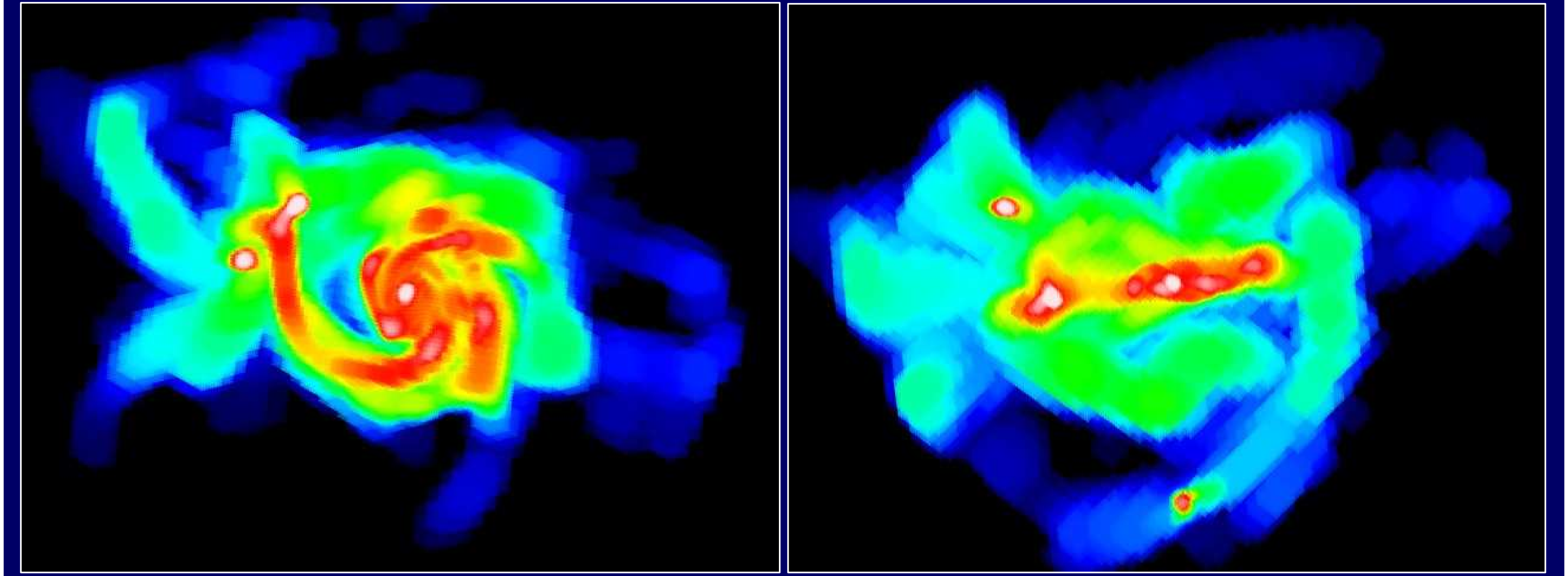
Dekel et al. 2009
Nature
MareNostrum
simulation

Ceverino,
Dekel, Bournaud
2009

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

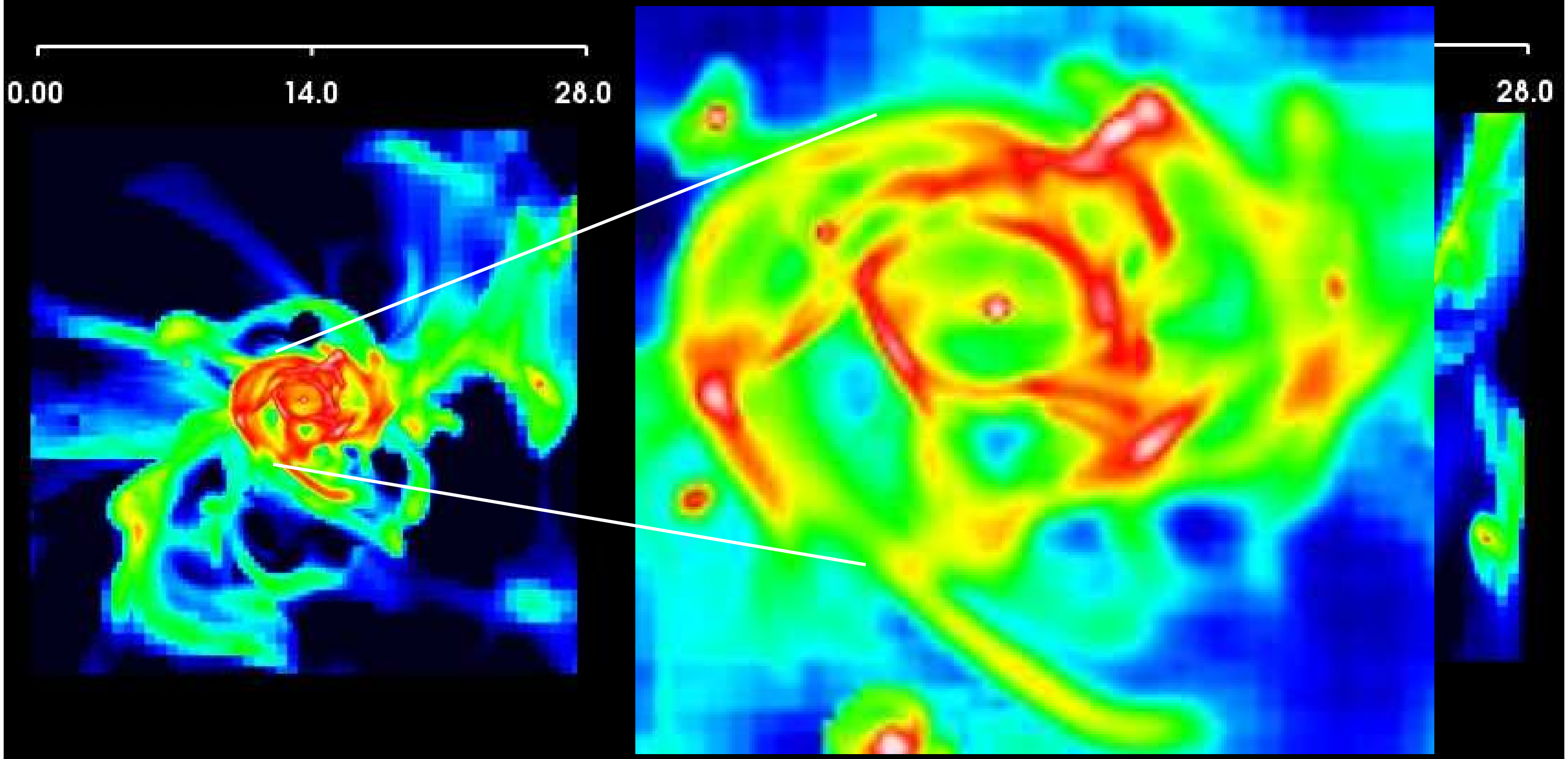
Cosmological Simulation: Stream-fed disk of giant gas clumps

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

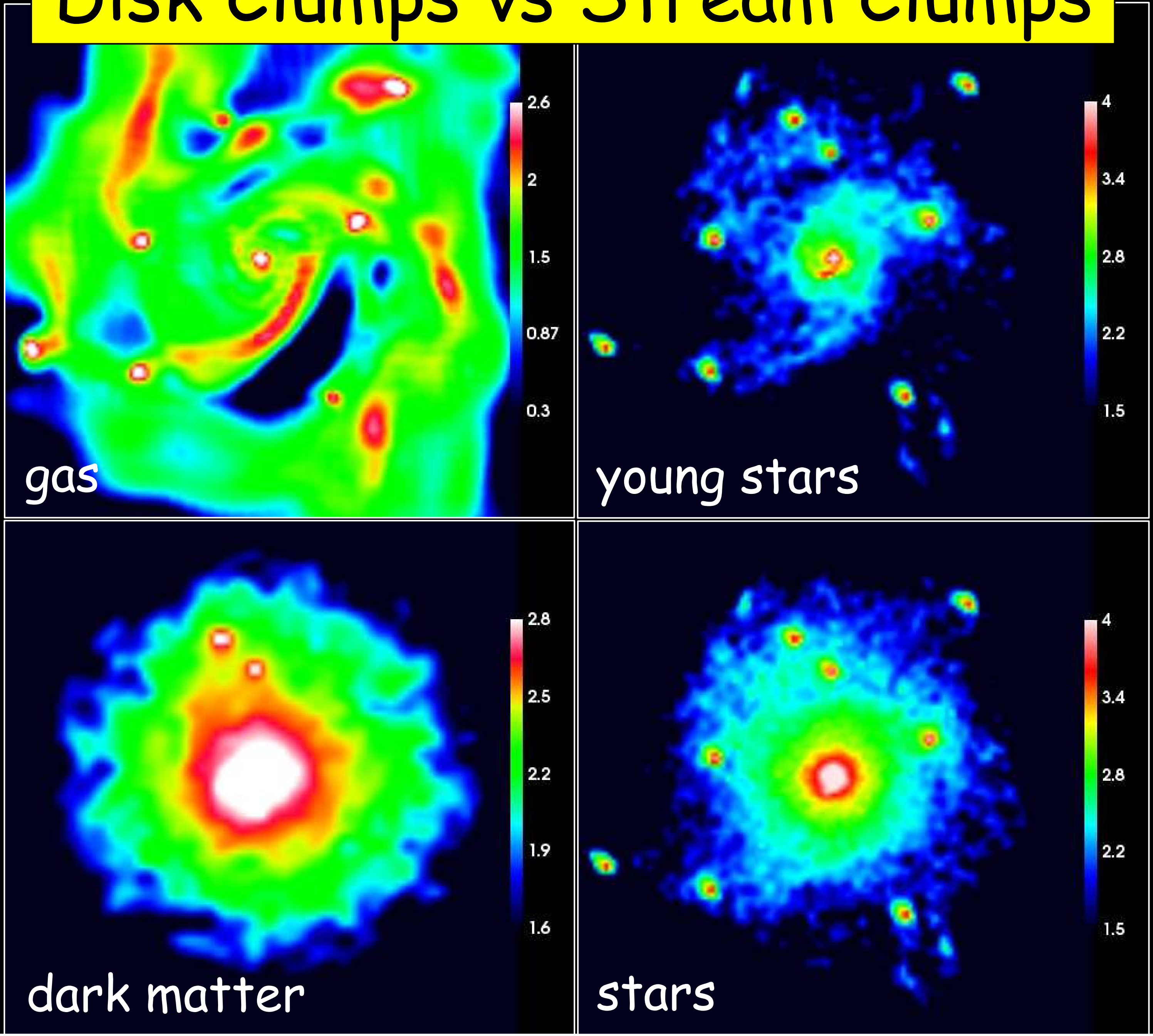


Cosmological Simulation: Stream-fed disk of giant gas clumps

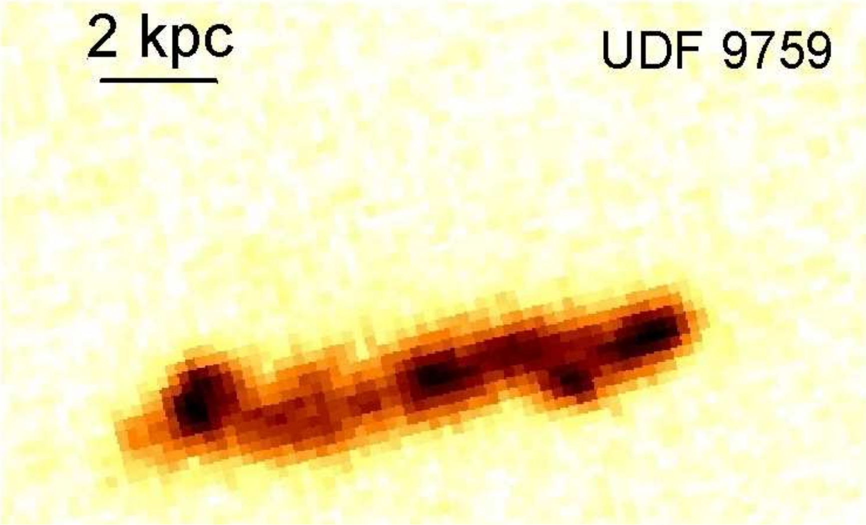
Ceverino, Dekel, Bournaud 2009 AMR res: 70 pc $M_v = 8 \times 10^{11} M_\odot$ z=2.1

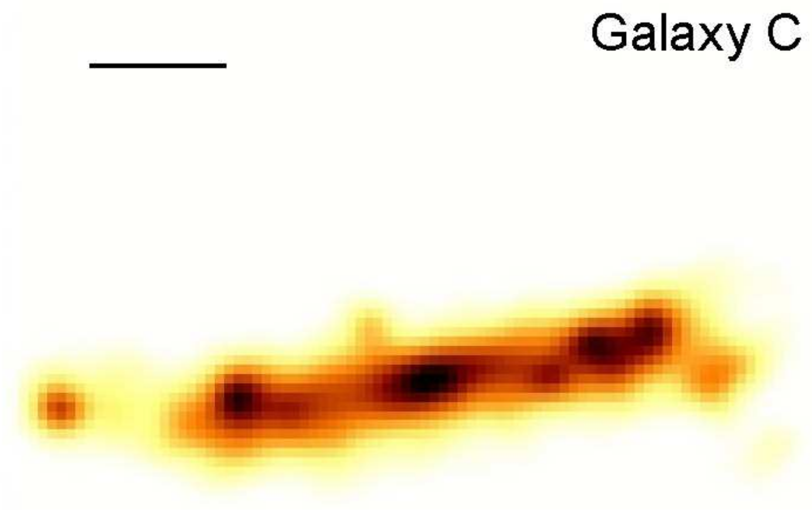


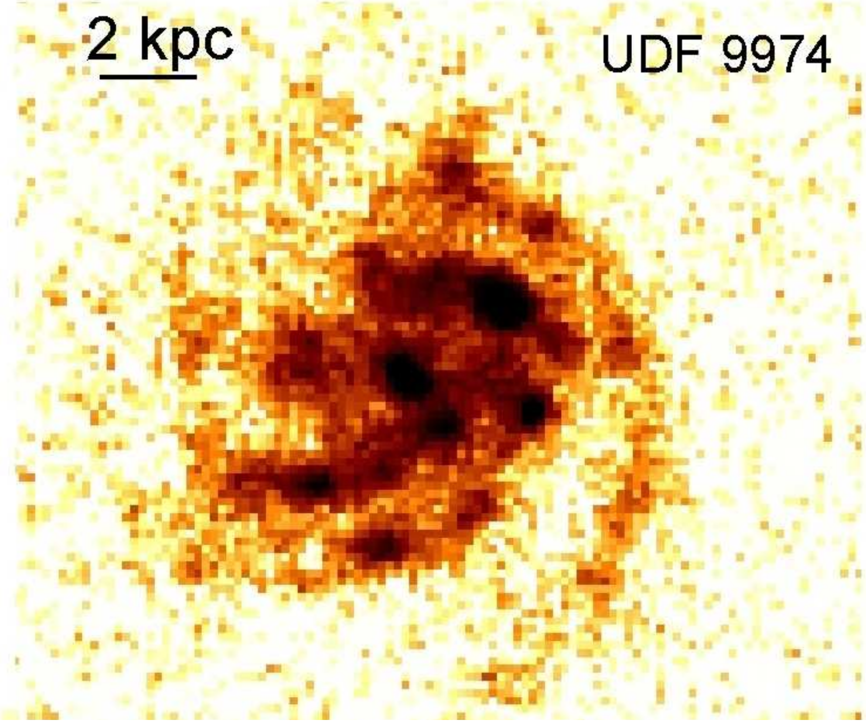
Disk Clumps vs Stream Clumps

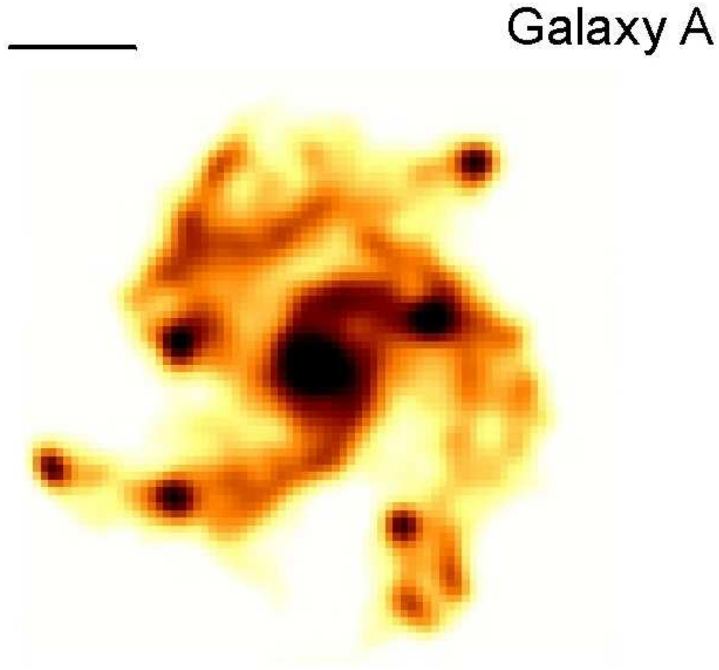


Observations vs. Simulations





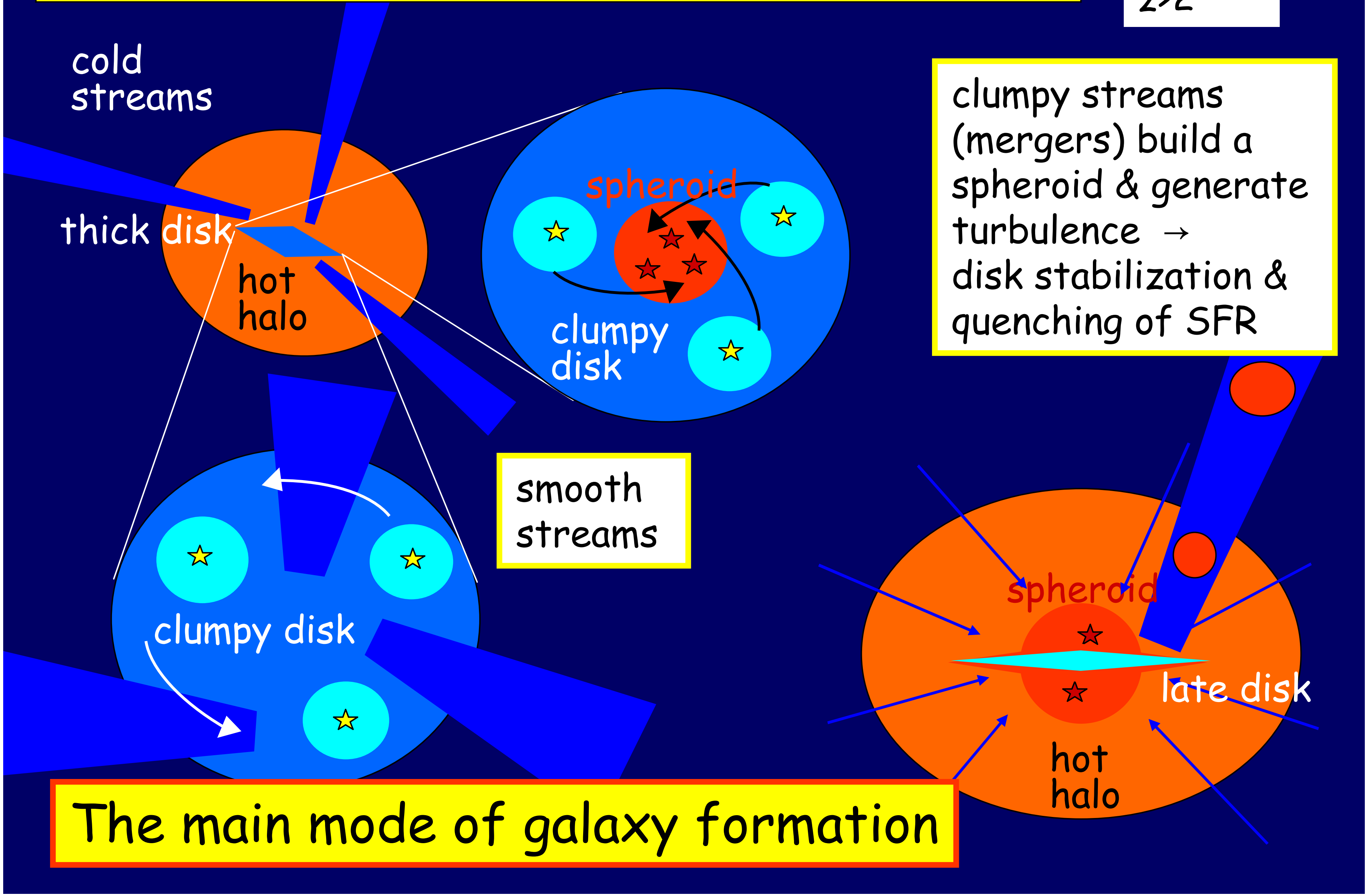




Bimodality of Stream-Fed Galaxies

$M_v > 10^{12}$

$z > 2$

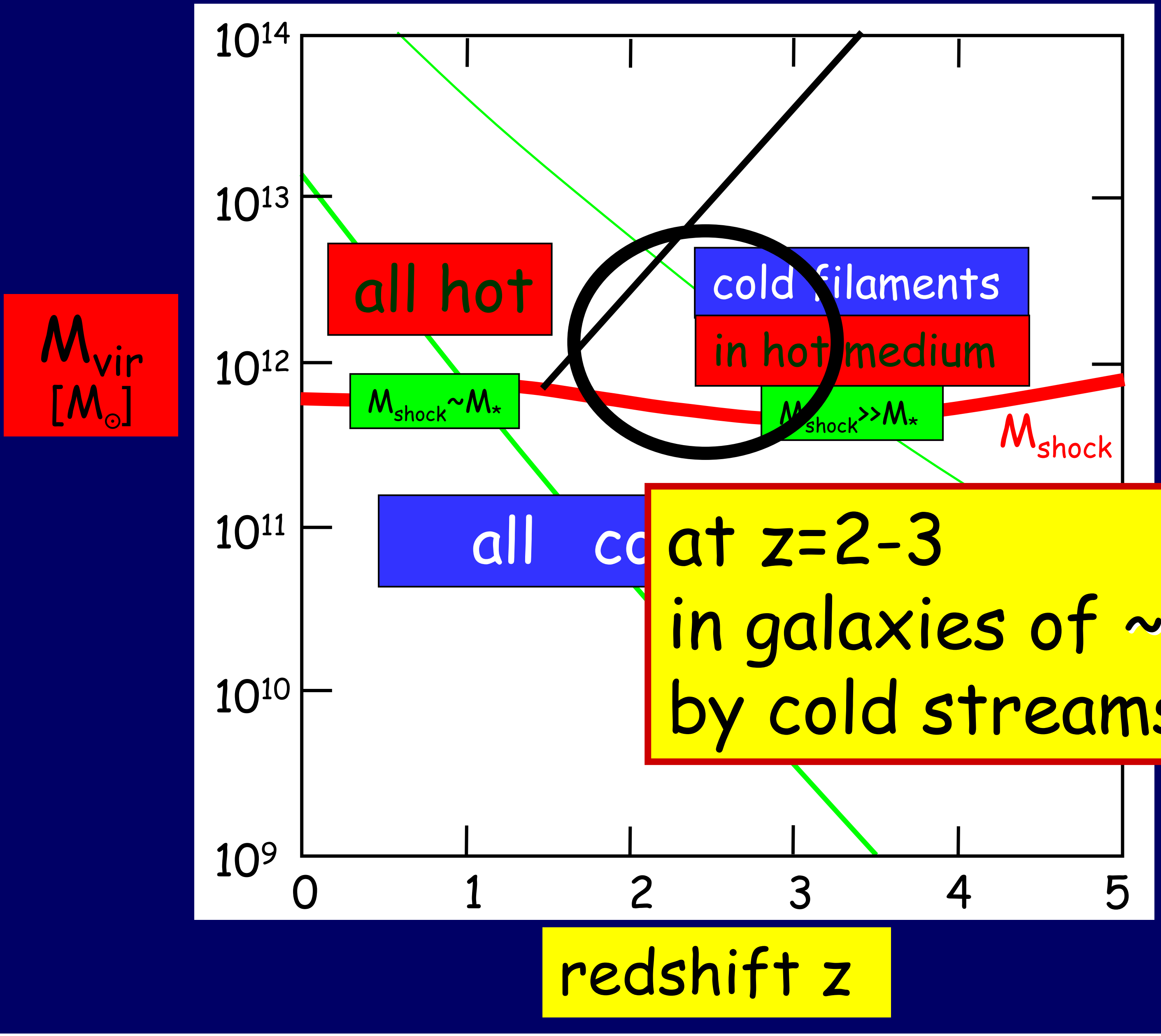


clumpy streams (mergers) build a spheroid & generate turbulence →
disk stabilization & quenching of SFR

smooth streams

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 & clumps survival
- Fate of the hi-z clumpy disks at z=0

  thick stellar disks of spirals? Lenticulars?
- How did thin disks form at late z?

  by cold, spherical, slow accretion in $M_{vir} < 10^{12}\ M_\odot$
- Why are z=0 disks not wildly unstable?
- low input rate of cold streams
- disk is dominated by stars
- dominant bulge (?)

- More detailed modeling of radiation transfer
- Lyman alpha absorbers

Conclusions

Stream-Fed Galaxies: High-z massive galaxies are driven by narrow cold streams of the cosmic web, penetrating hot halos (>$10^{12}M_\odot$). 33% clumps >1:10 (mergers), the rest is smoother.

Cold streams → Lα Blobs powered by gravitational infall

Streams are detectable as absorbers: LLS?, DLAS?

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

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

Bulge buildup: from the disk and by mergers

Bimodality: star-forming disks vs red-and-dead spheroids by stream clumpiness. Morphological quenching: disk stabilized by bulge

Cold Streams as Lyman alpha Blobs Powered by Gravitational Heating