High-z Galaxy Formation in LCDM

Theory Challenges

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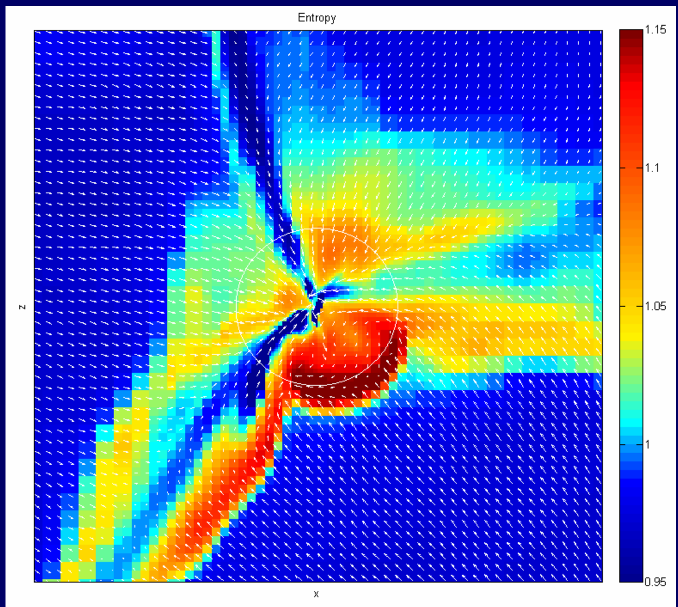
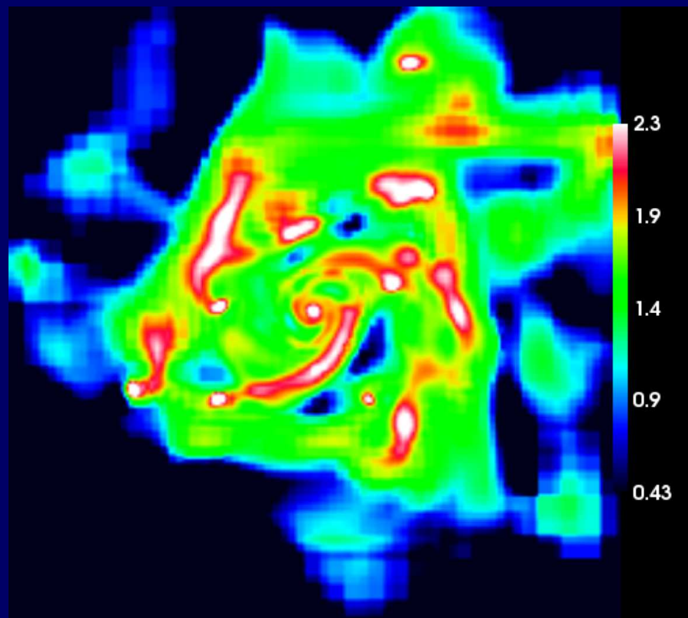
Santa Cruz, August 2010



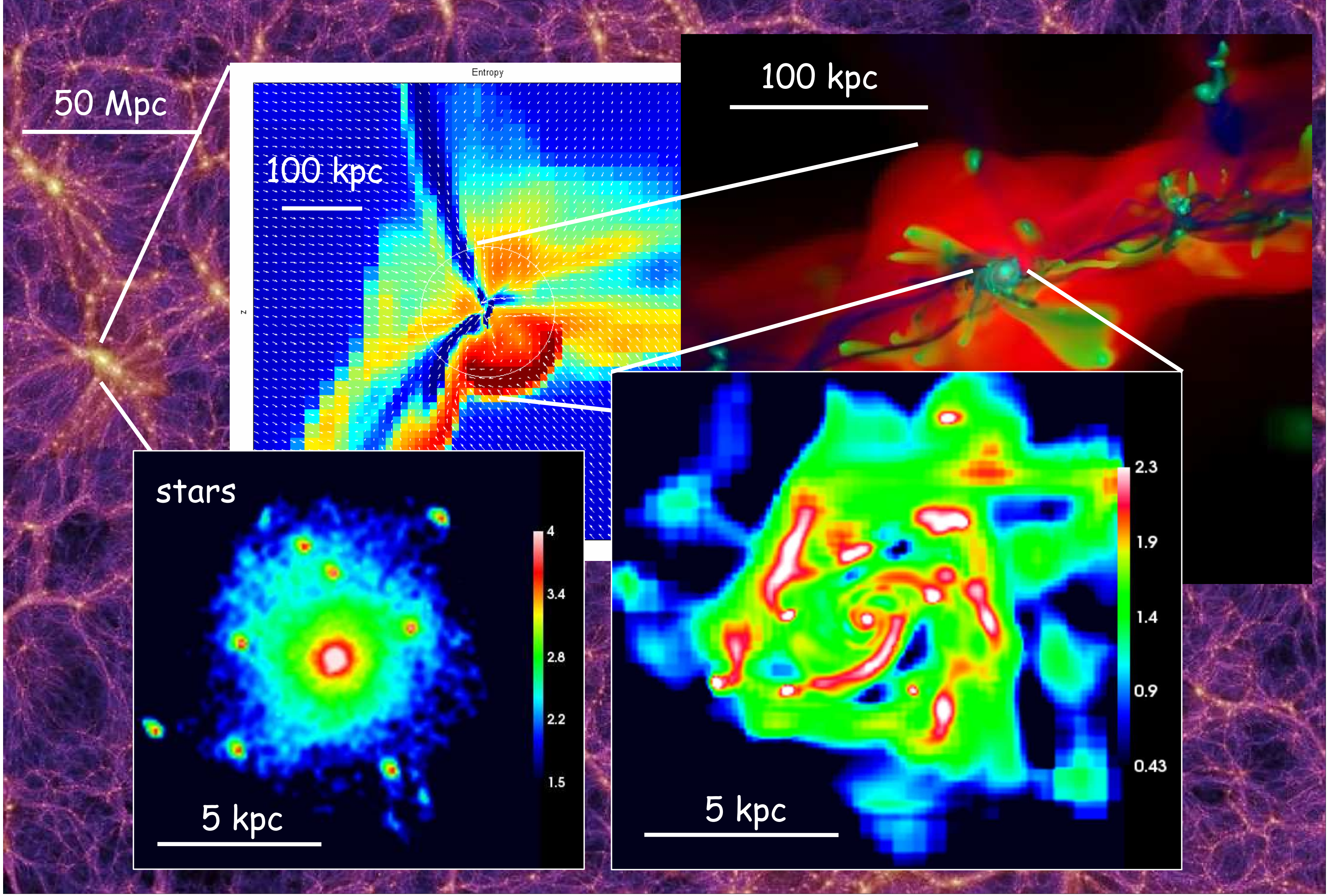


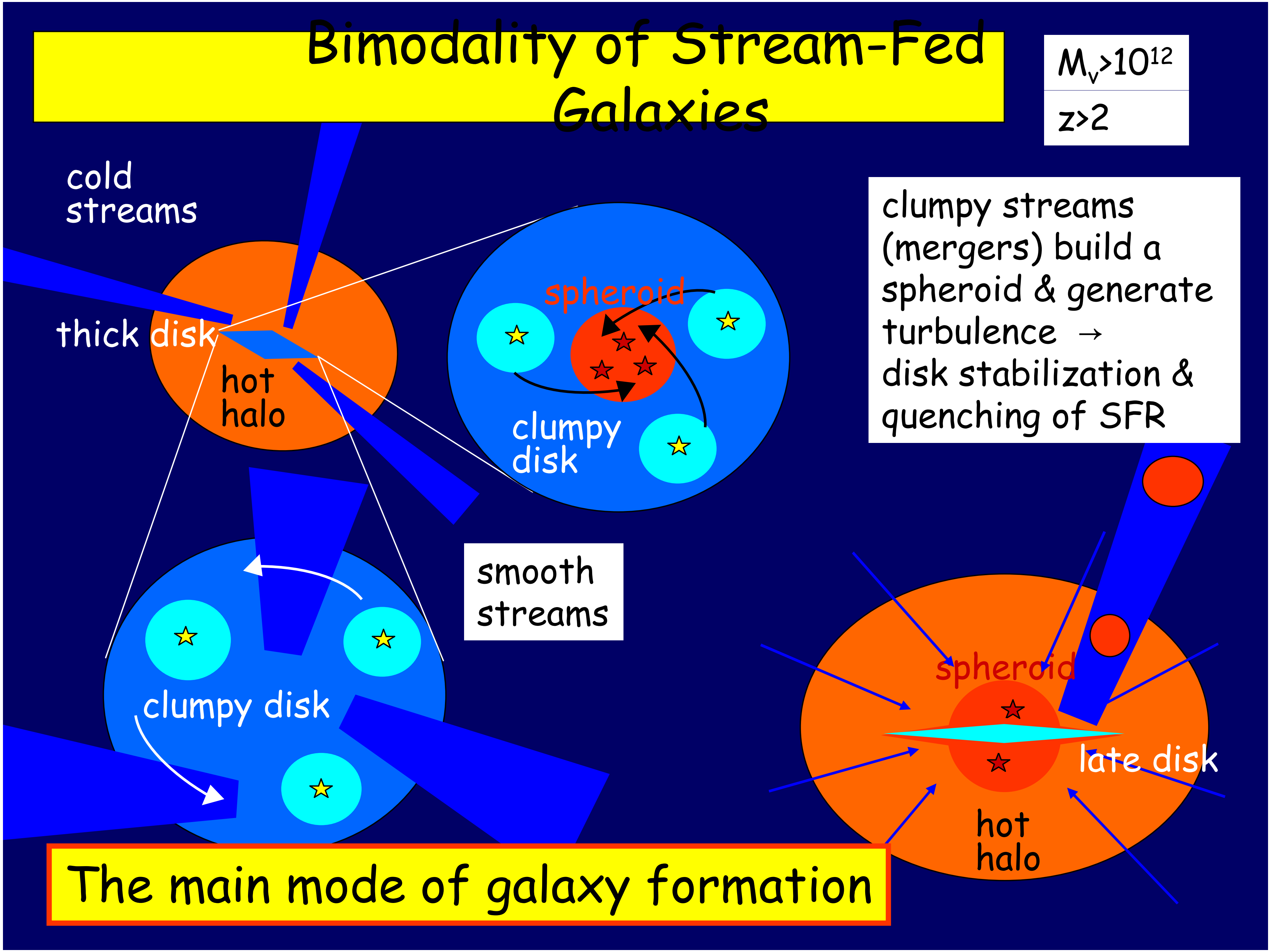
LCDM makes certain solid theoretical predictions for the most active phase of galaxy formation: massive galaxies (~$10^{11}M_{\odot}$) at high z (~2-3)

Theory seems consistent with observations, introducing a coherent picture

Open questions: SFR & feedback

Cosmic Web, Cold Streams, Clumpy Disks & Spheroids



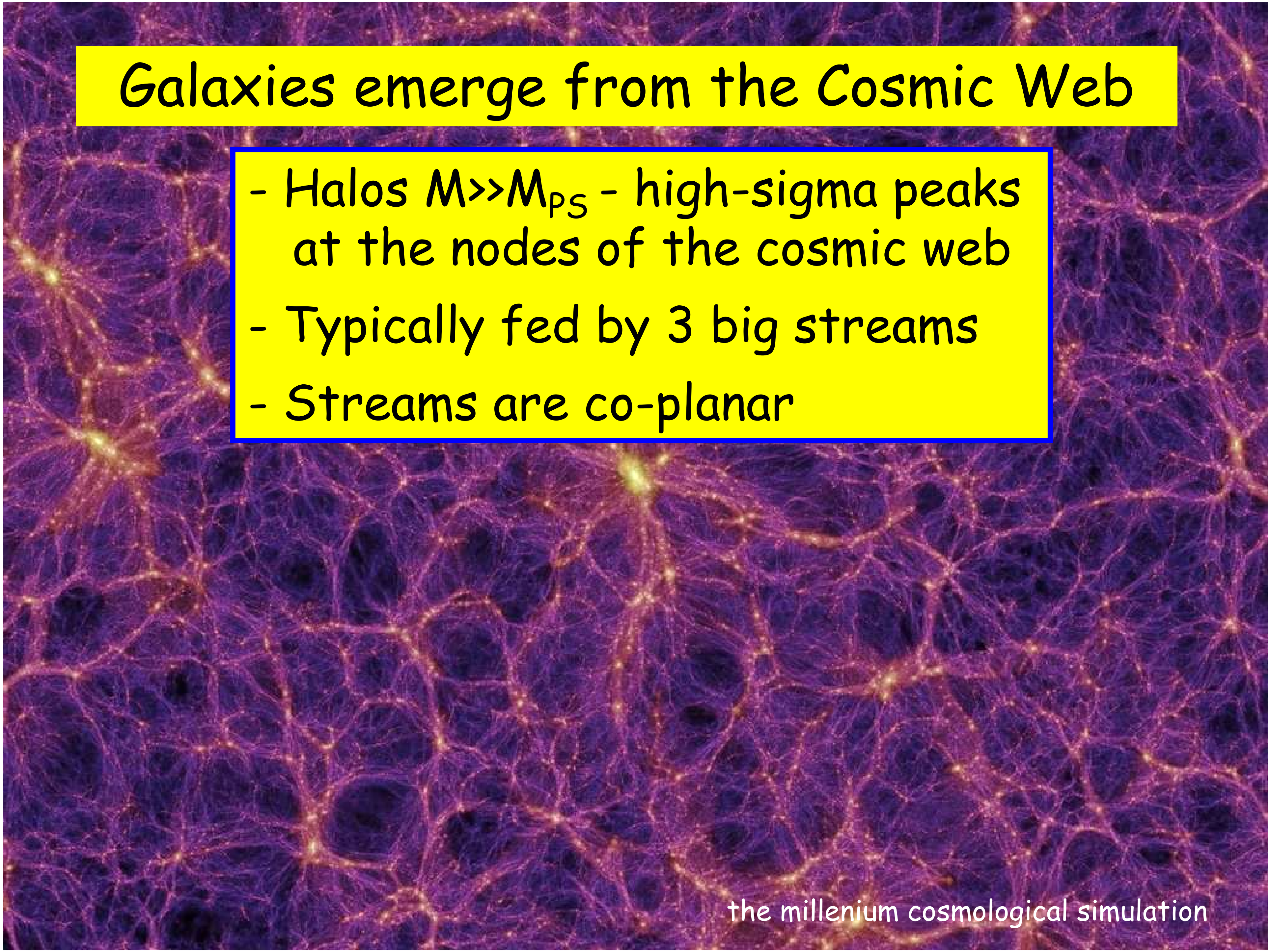

Bimodality of Stream-Fed Galaxies
$M_v > 10^{12}$
$z > 2$
cold streams
thick disk
hot halo
spheroid
clumpy disk
clumpy streams (mergers) build a spheroid & generate turbulence →
disk stabilization & quenching of SFR
smooth streams
clumpy disk
spheroid
late disk
hot halo
The main mode of galaxy formation

Theory Challenges

- Galaxies from the cosmic web
- Cold streams in Lyman alpha
- Outflows
- Stream-disk interaction
- Wild clumpy disks
  - angular momentum
  - driving the turbulence
  - clump support
  - clump disruption
- Bulge-less disks
- Fate of wild disks - stabilization

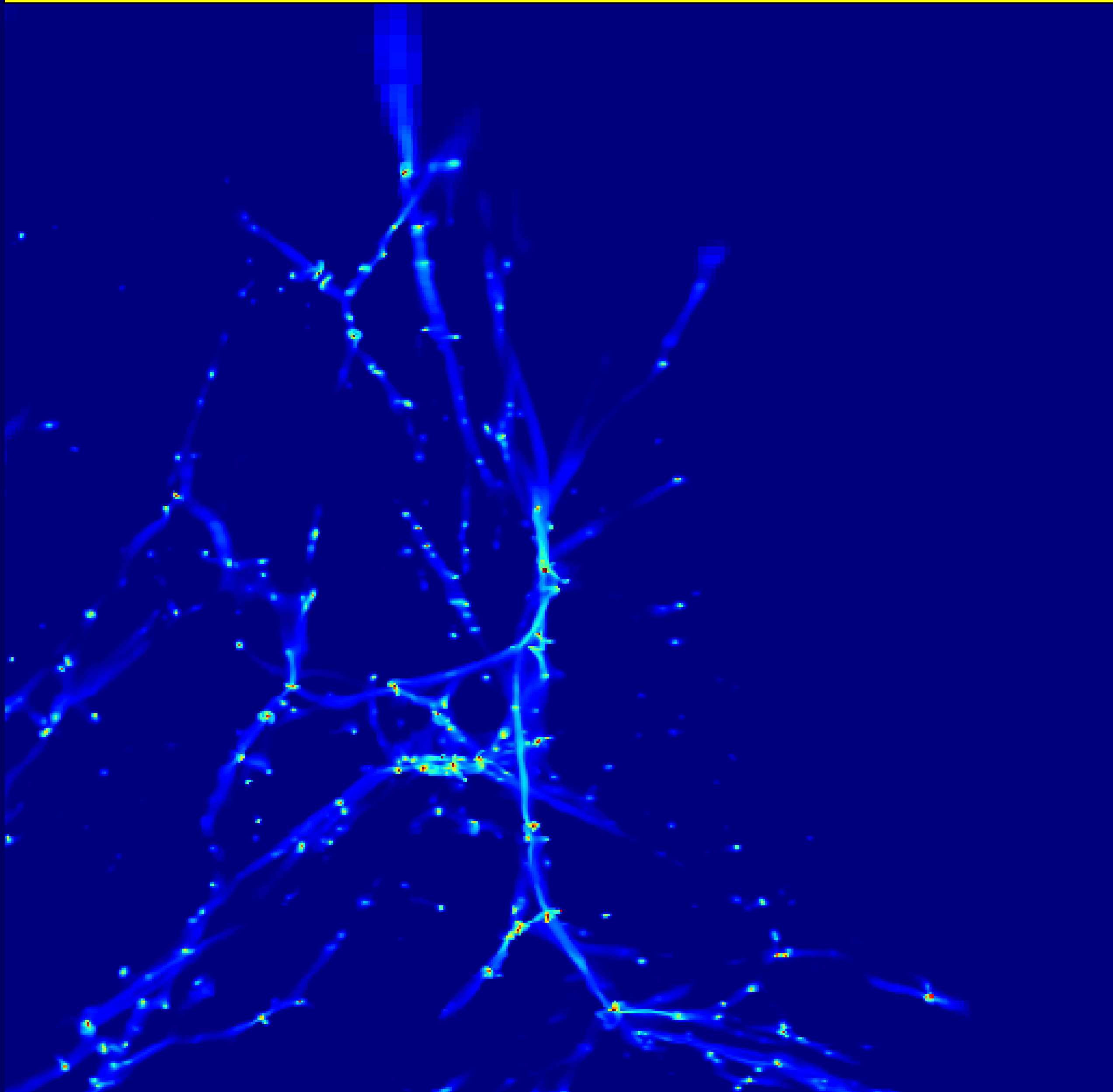
Galaxies emerge from the Cosmic Web

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

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):

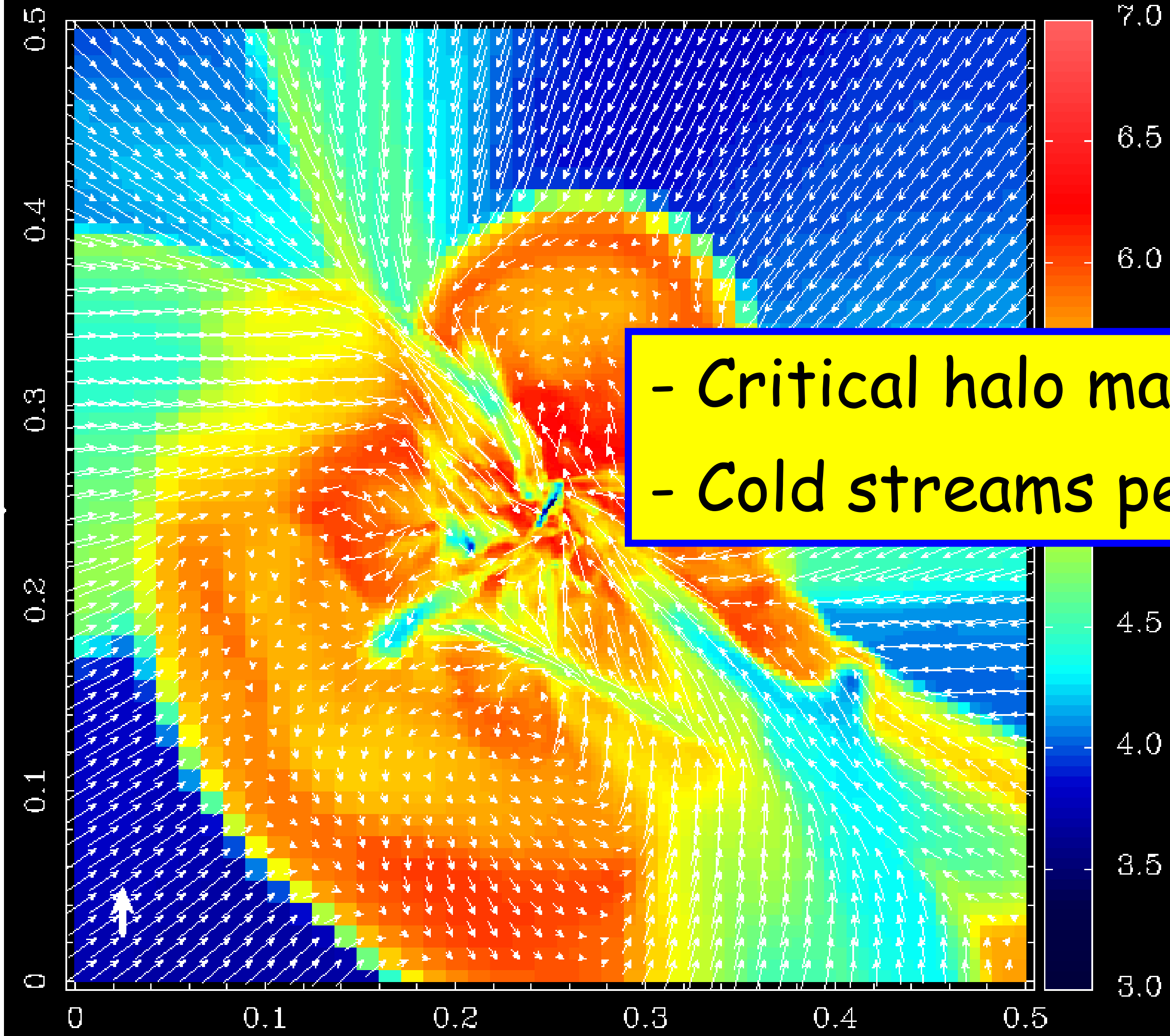
$$\left\langle \dot{M}_{baryon} \right\rangle = 80\, M_{\otimes} yr^{-1}\; M_{12}^{1.14}\; (1+z)_3^{2.4}\;\; f_{0.17}$$

Almost all penetrate to the inner halo in cold streams

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

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

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

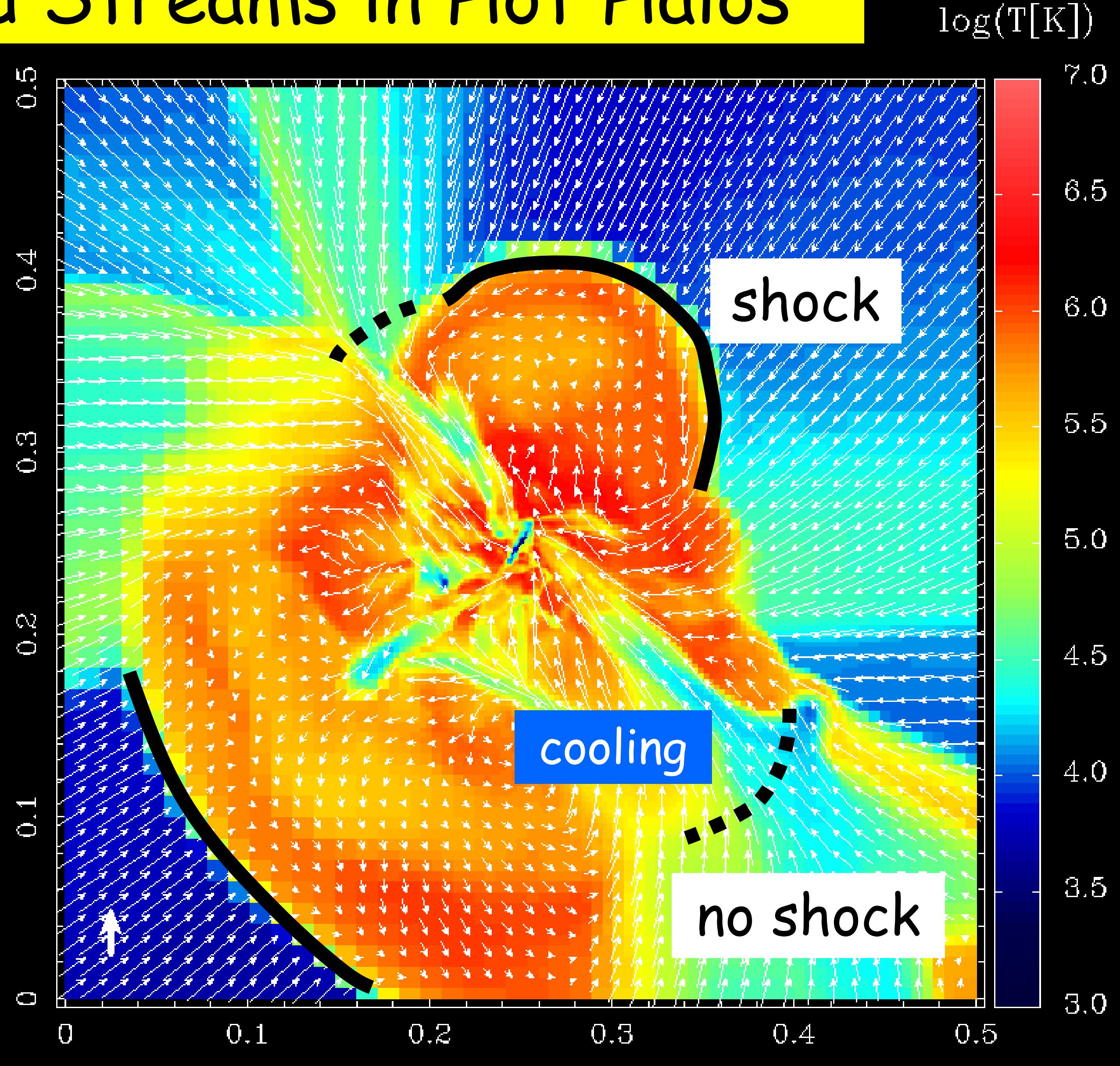
in $M>M_{shock}$

Totally hot at z<1

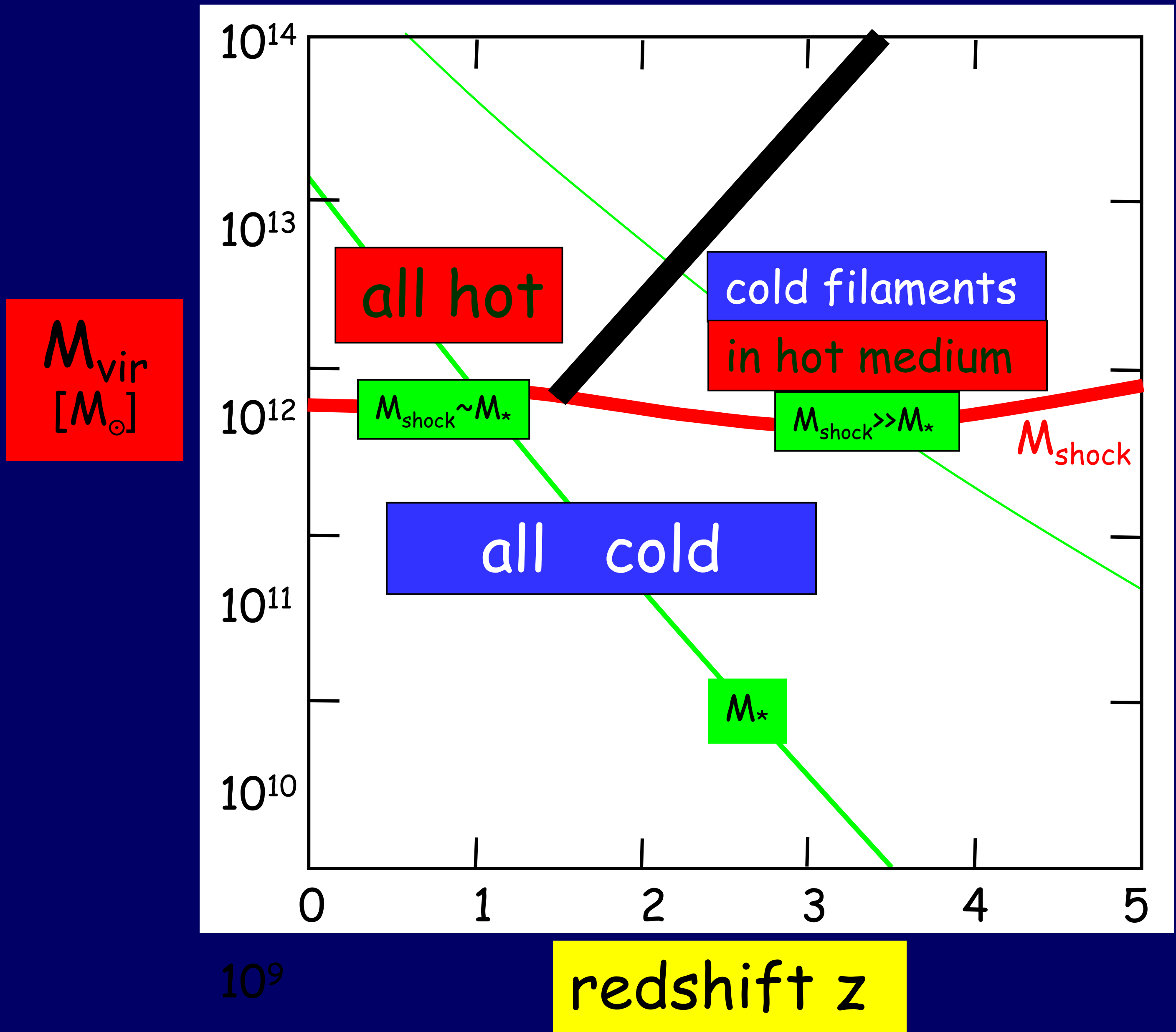
Cold streams at z>2

Dekel & Birnboim 2006

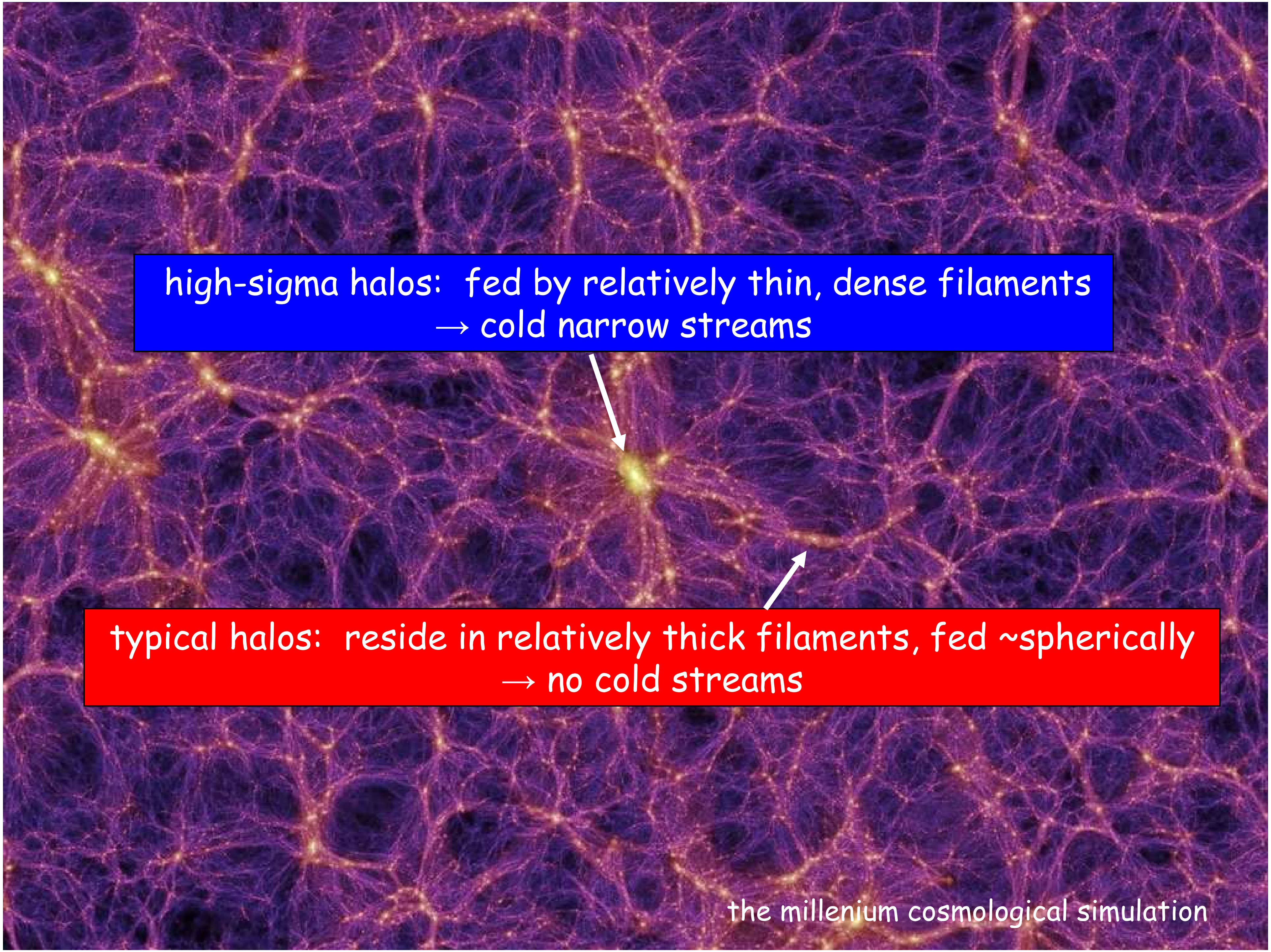
Kravtsov et al



Cold Streams in Big Galaxies at High z

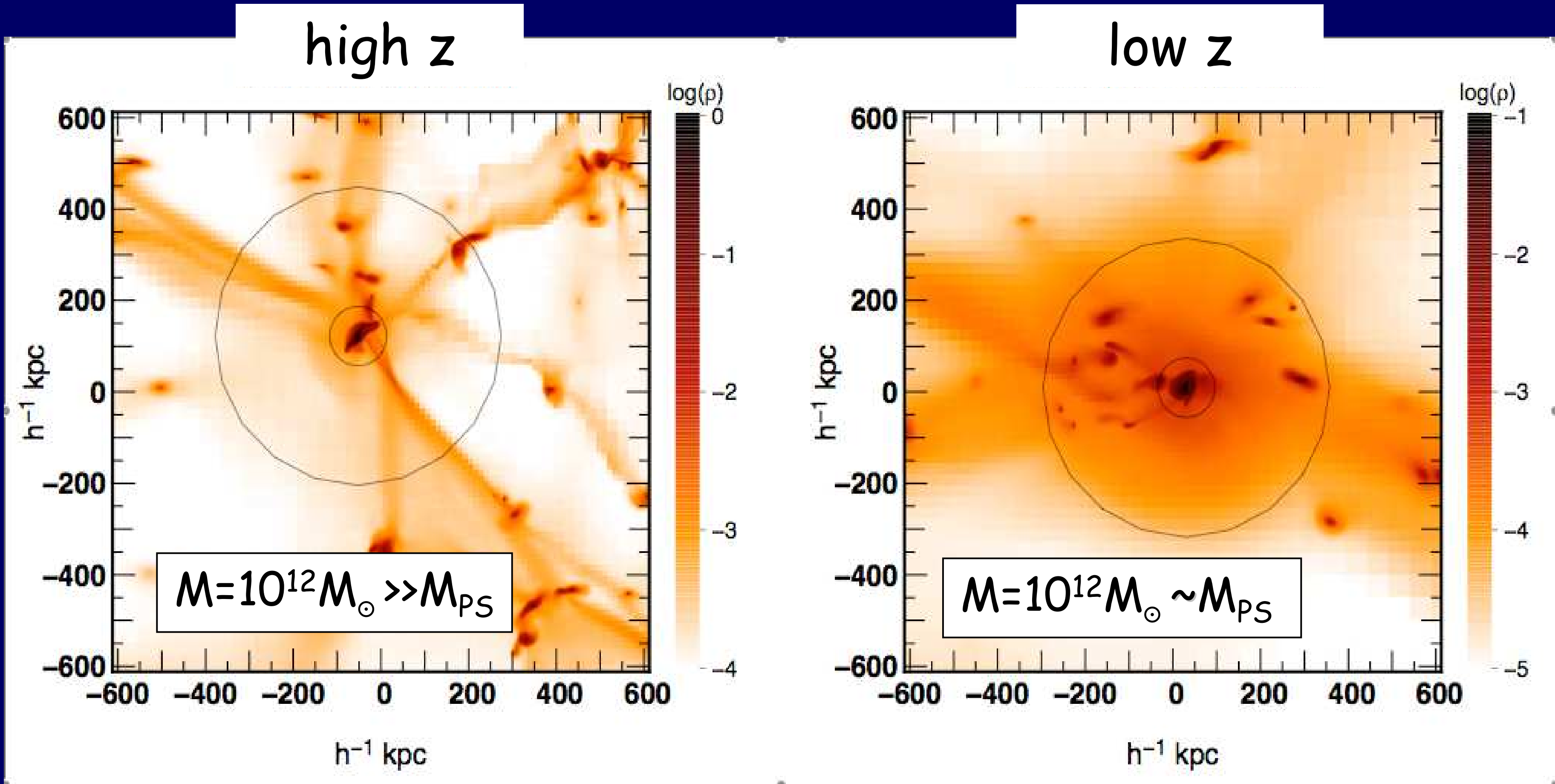


Dekel & Birnboim 06



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

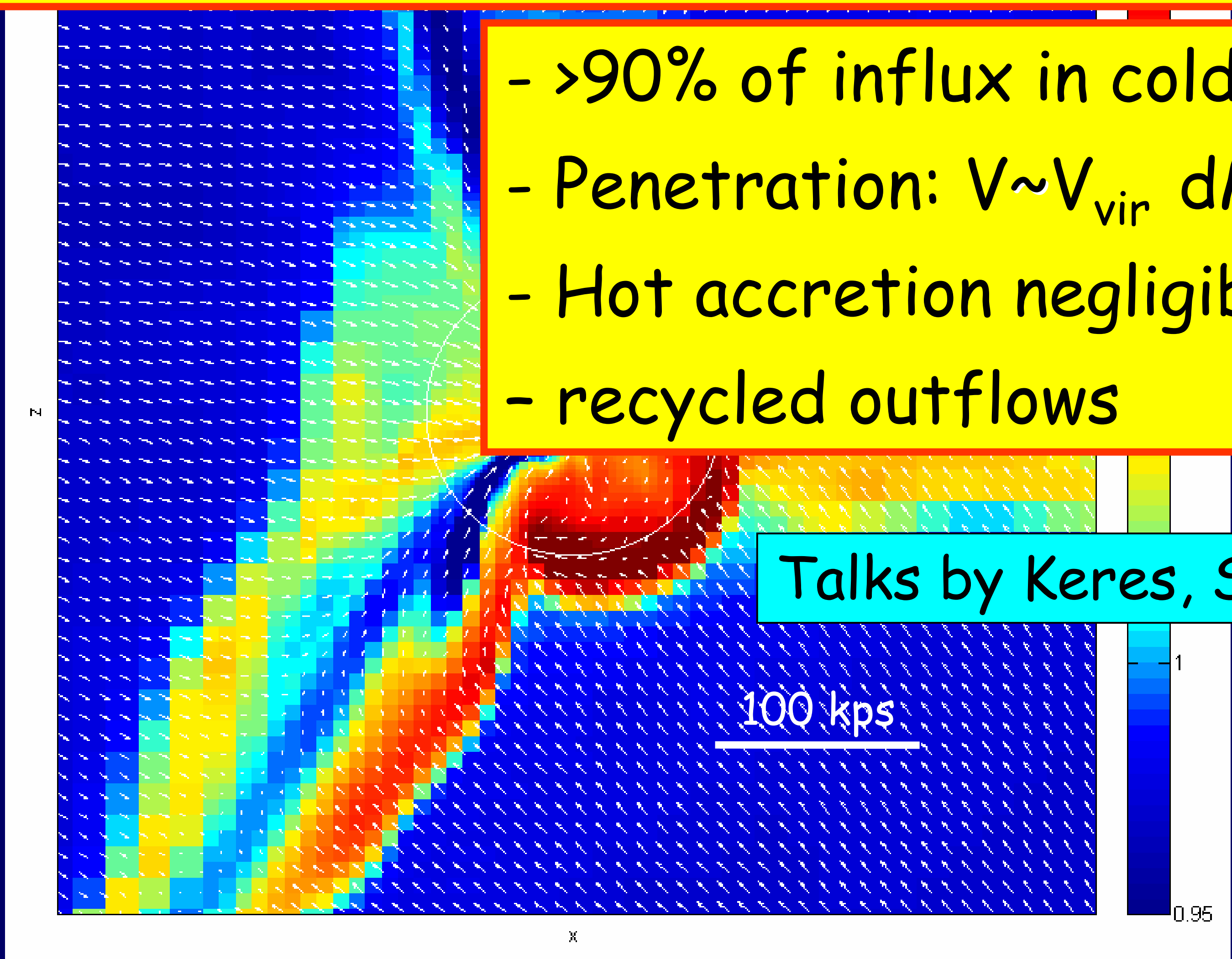
Cold Sterams

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

Neistein et al 06, 07, 08; Genel et al 08

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

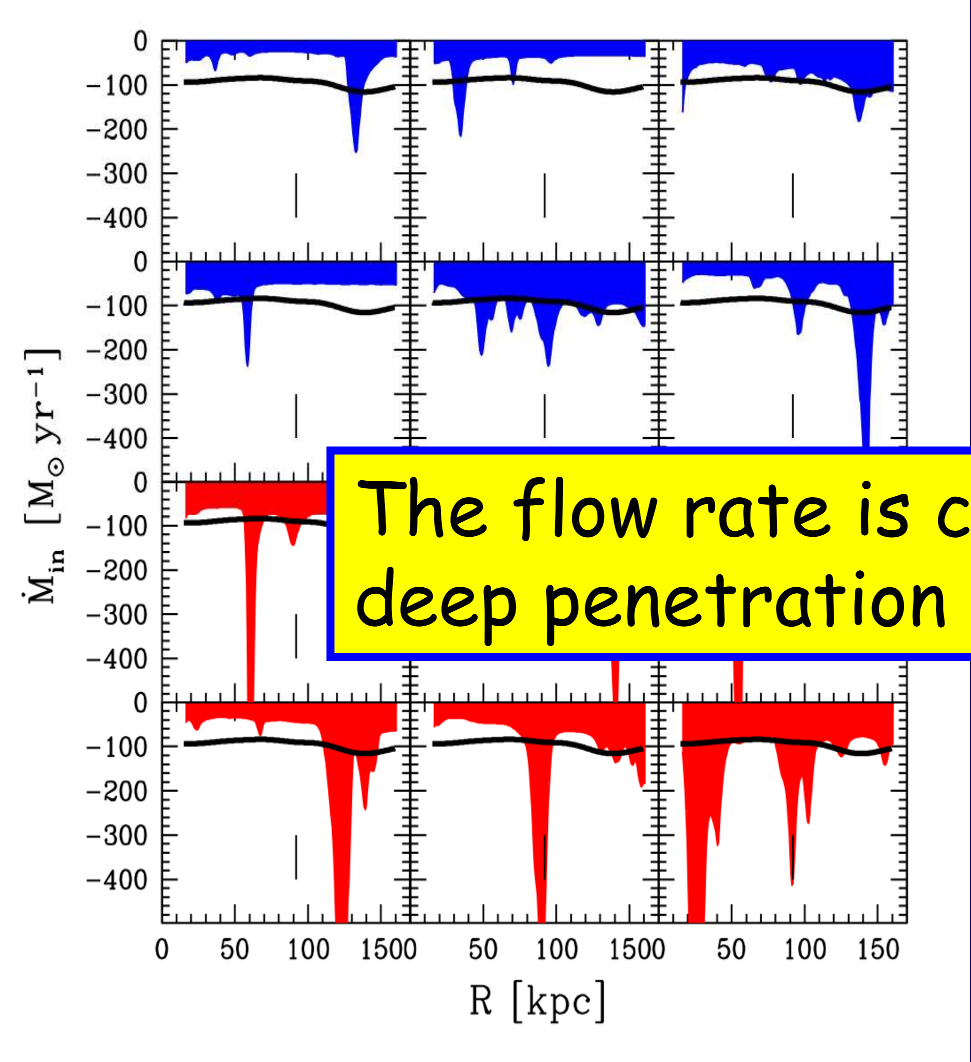
Talks by Keres, Stewart, Leitner

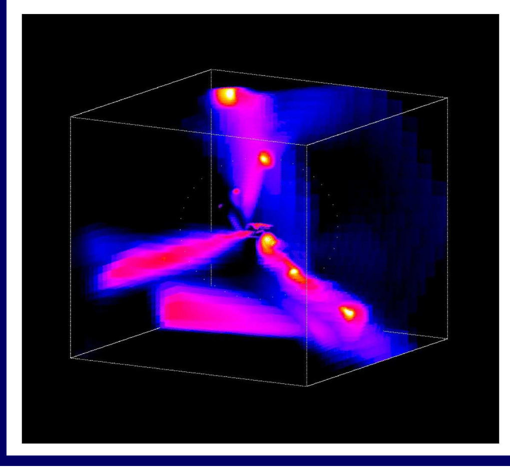


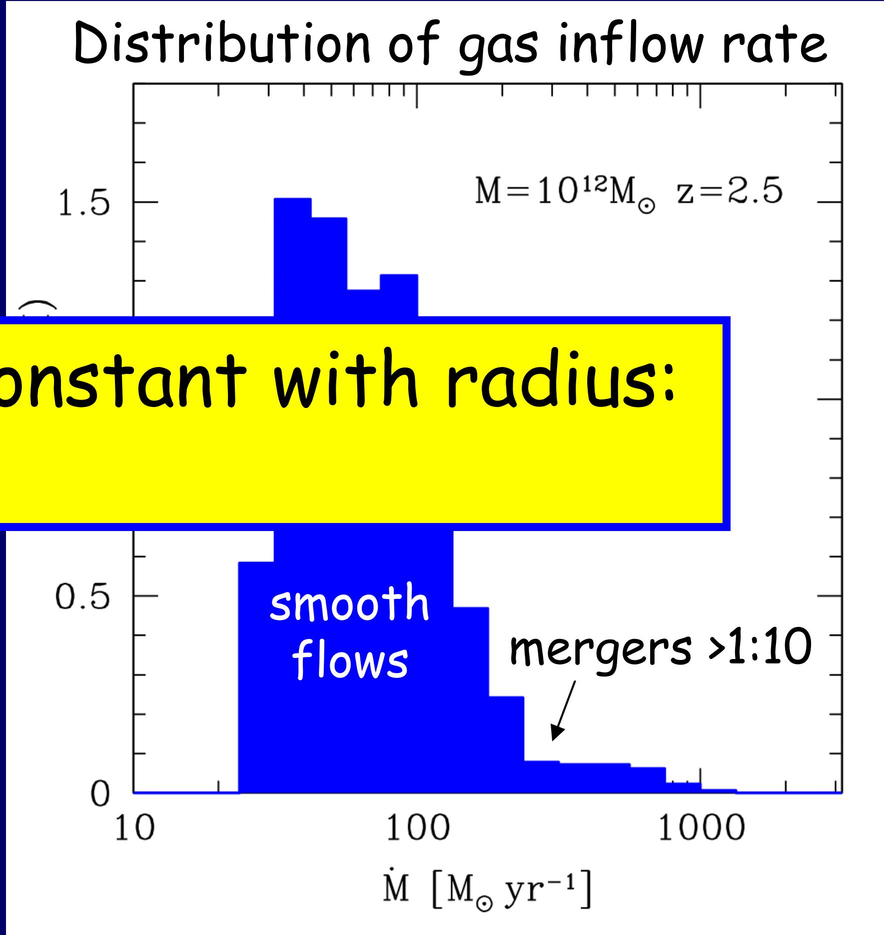
Dekel et al 09 Nature

Inflow rate through the halo into the disk

Cosmological hydro simulations MareNostrum, Dekel et al. 09







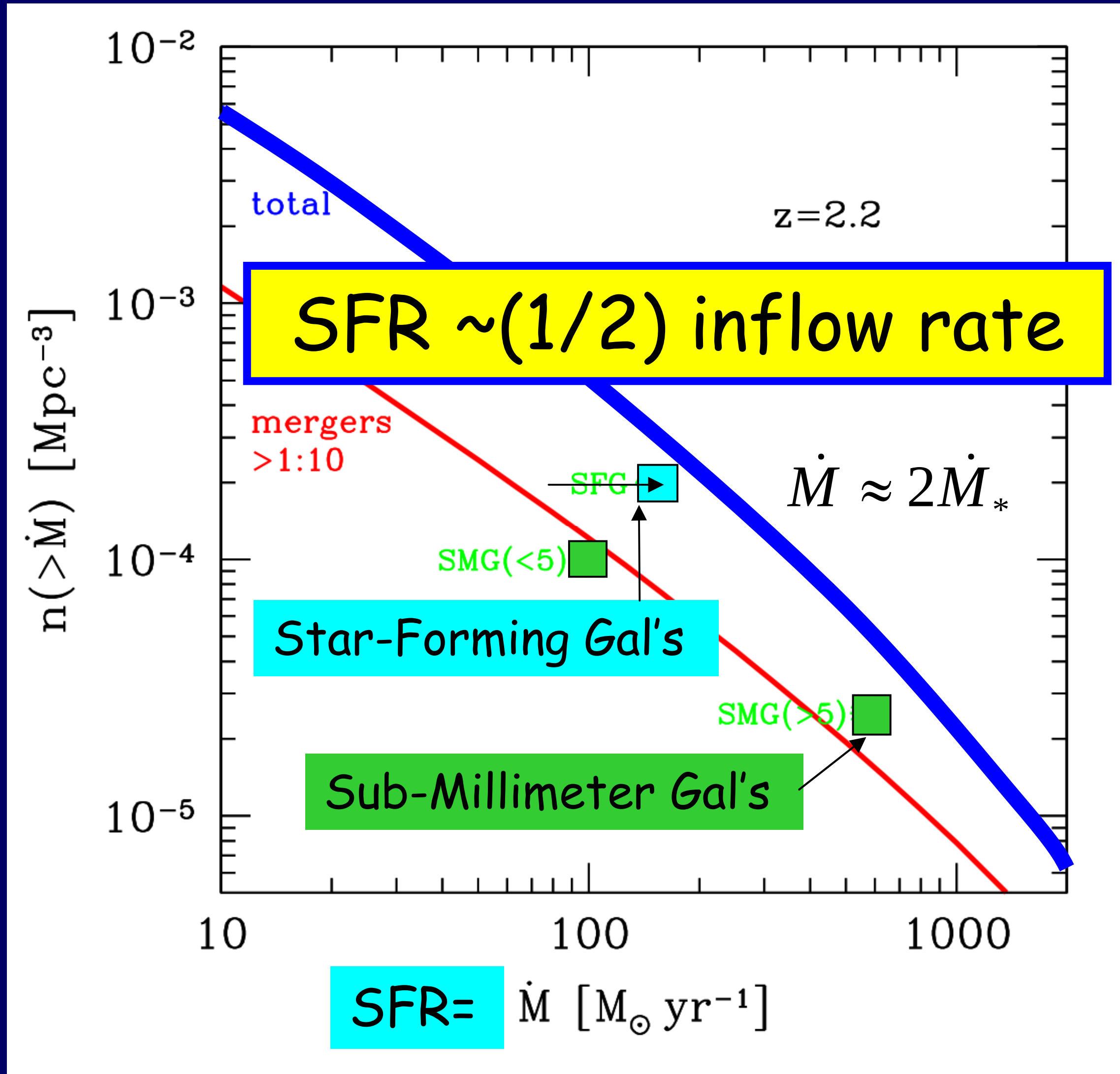
The flow rate is constant with radius: deep penetration

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

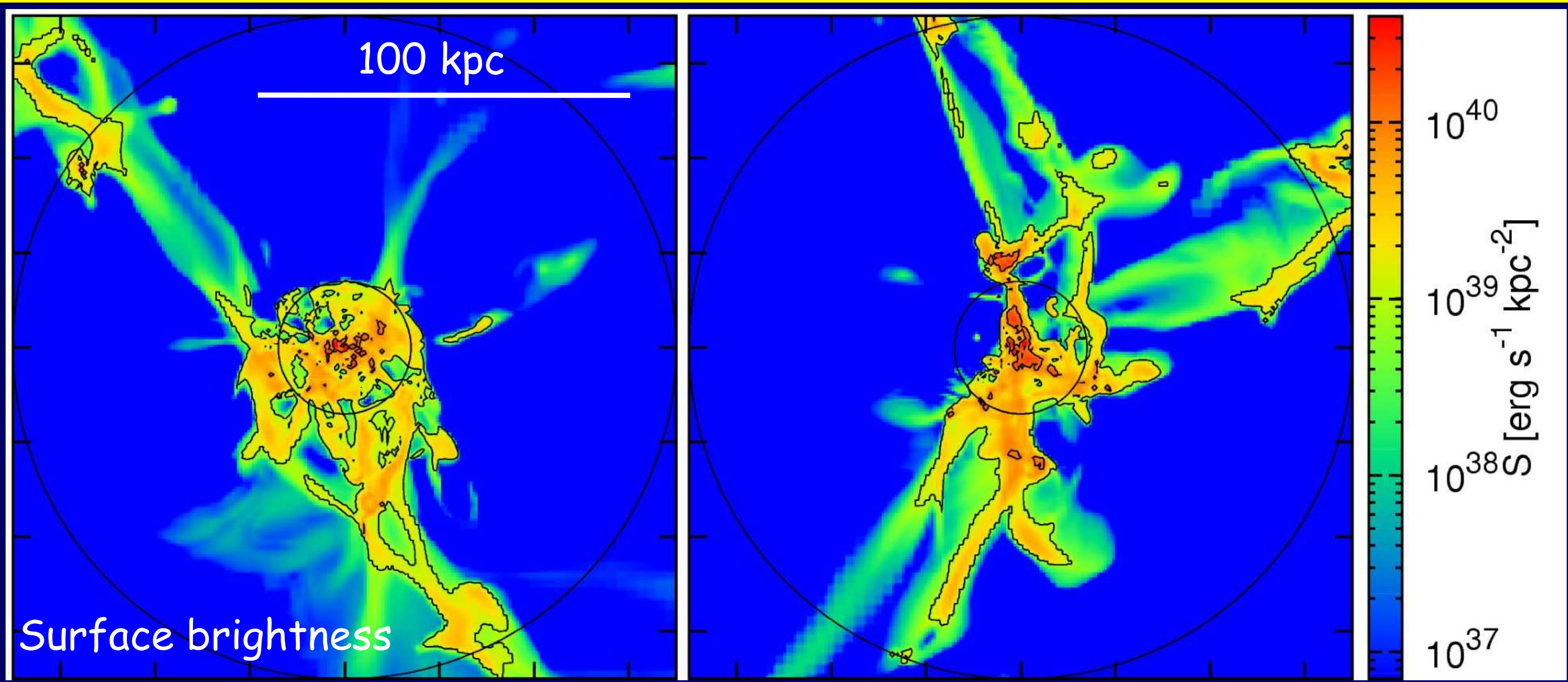
Lyman-alpha from Cold streams

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

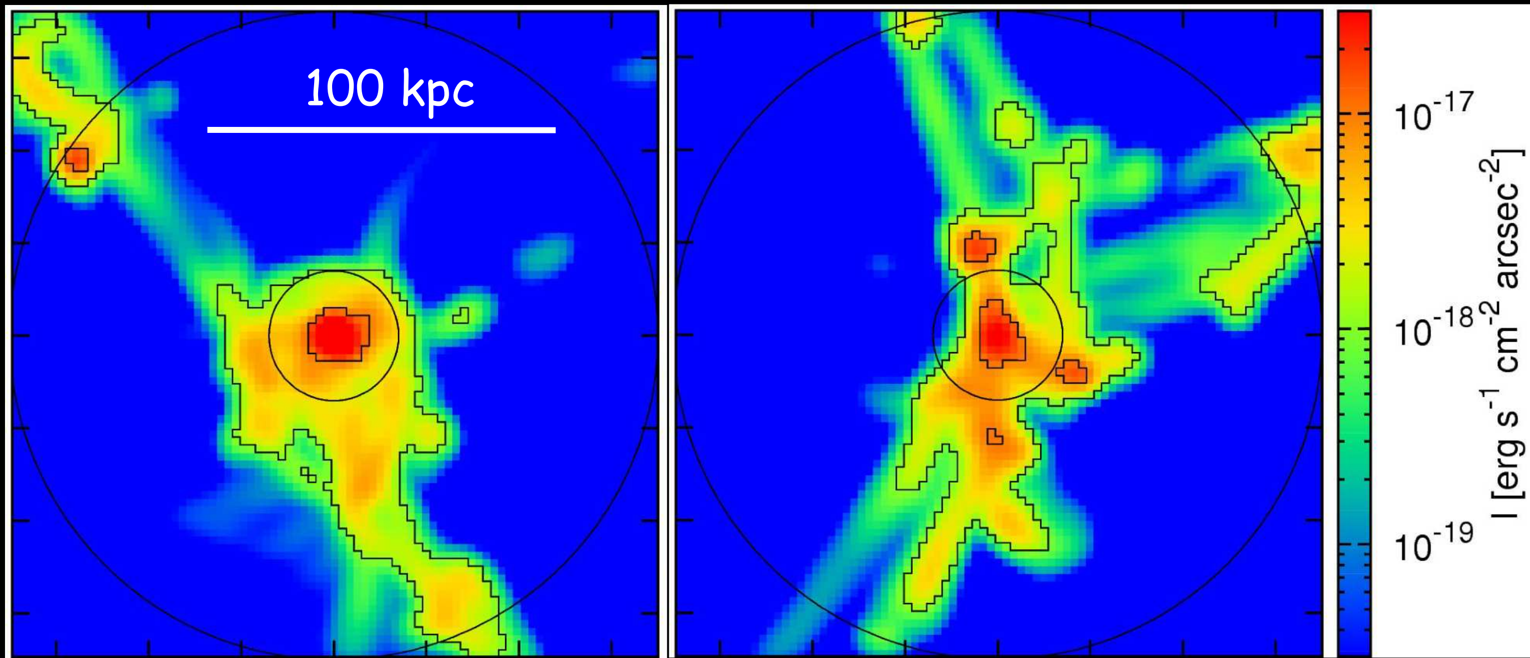
Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 10

$T=(1\text{-}5)\times10^{4}$ K $n=0.01\text{-}0.1$ cm^{-3} $N_{HI}\sim10^{20}$ cm^{-2} $L \sim10^{43\text{-}44}$ erg s^{-1}

- Extended cold gas is provided by the incoming streams
- Lya is powered by gravitational infall into halo potential well



Cold streams as Lyman-alpha Blobs



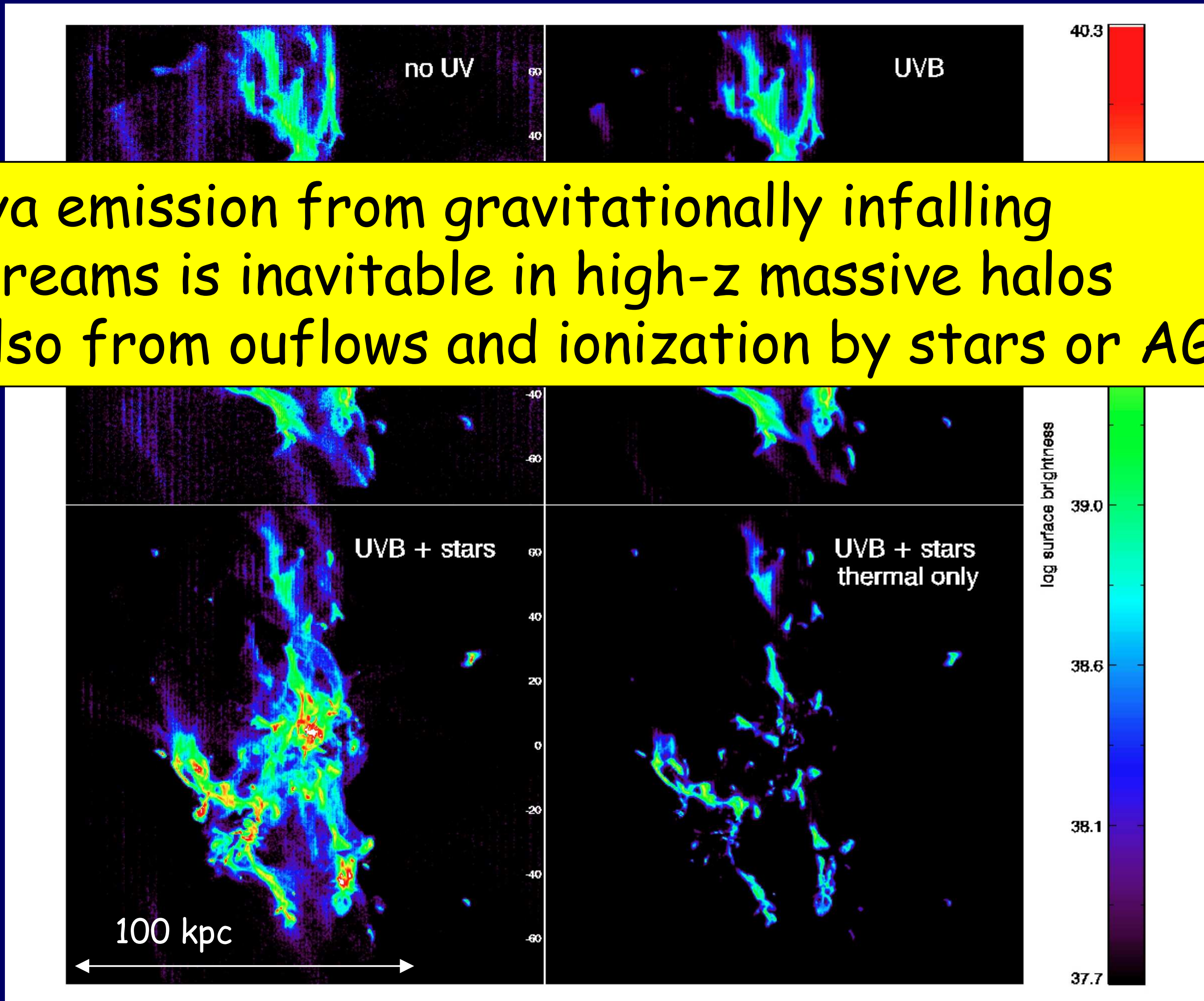
Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 10

Matsuda et al 06-09

Lyman Alpha Emission (LABs)

Radiative transfer, ionization from stars, dust

Kasen, Fumagalli, Ceverino, Dekel, Prochaska, Primack



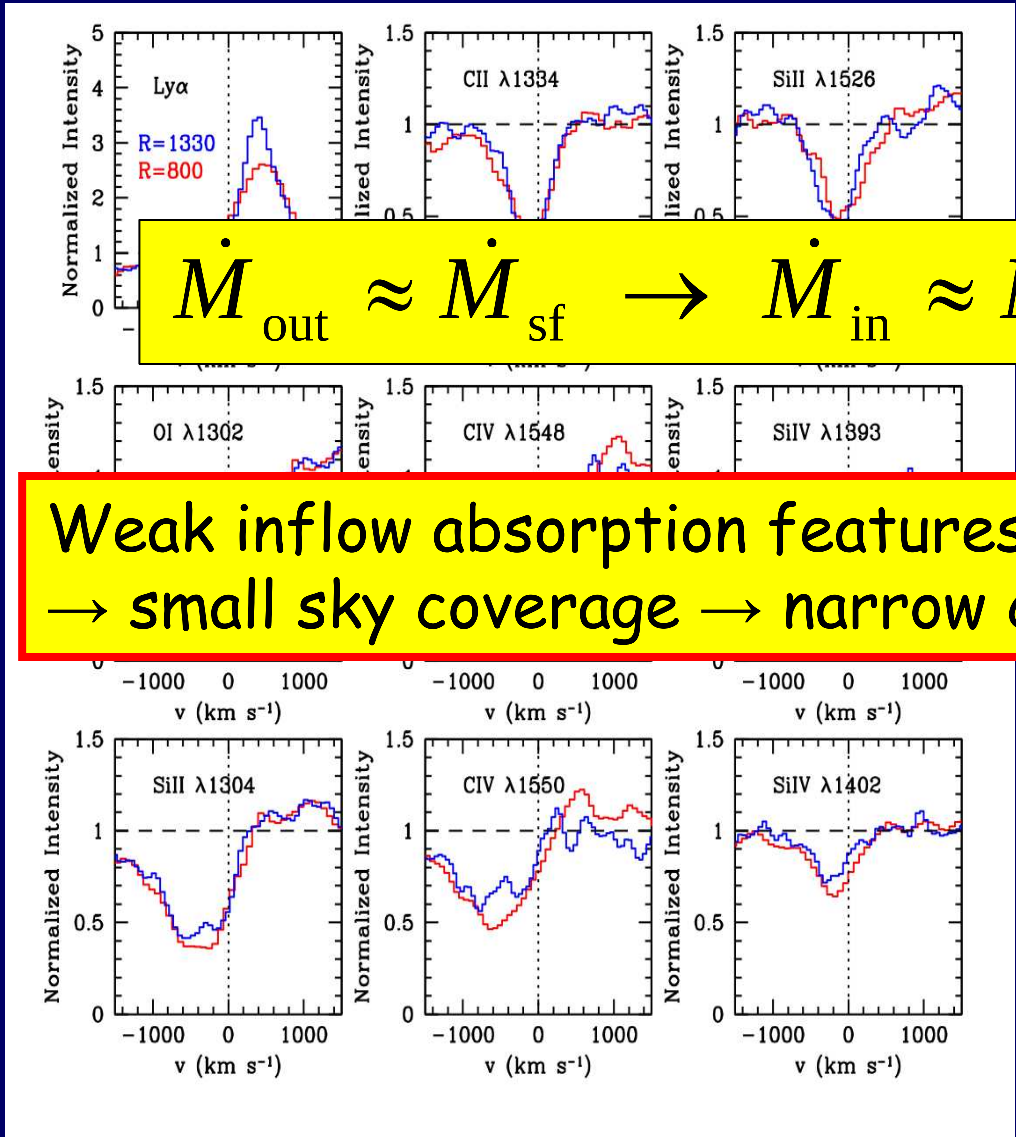
- Lya emission from gravitationally infalling streams is inavitable in high-z massive halos
- Also from ouflows and ionization by stars or AGN

Massive Outflows Observed

Steidel et al. 2010

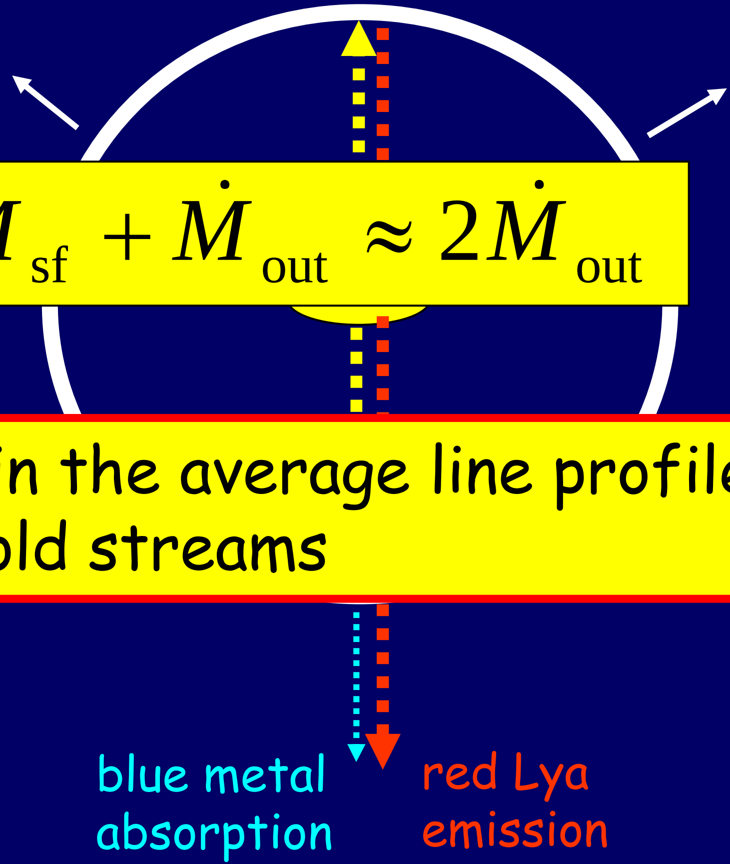
No inflow?

Stacked line profiles of Lya and metal absorption



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

Weak inflow absorption features in the average line profile → small sky coverage → narrow cold streams

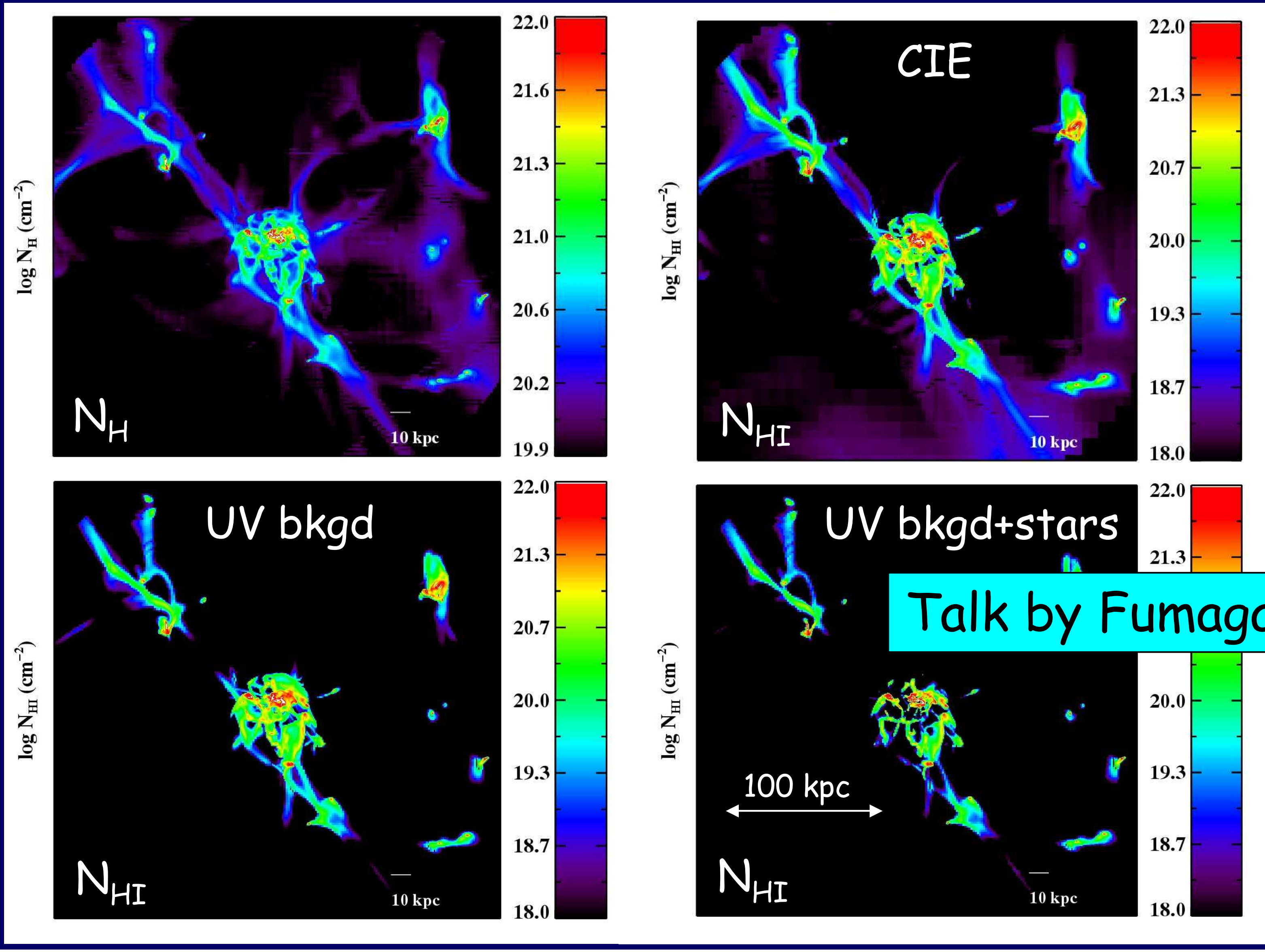


Talks by Koo, Prochaska

Neutral Hydrogen Column Density

Radiative transfer, ionization from stars, dust

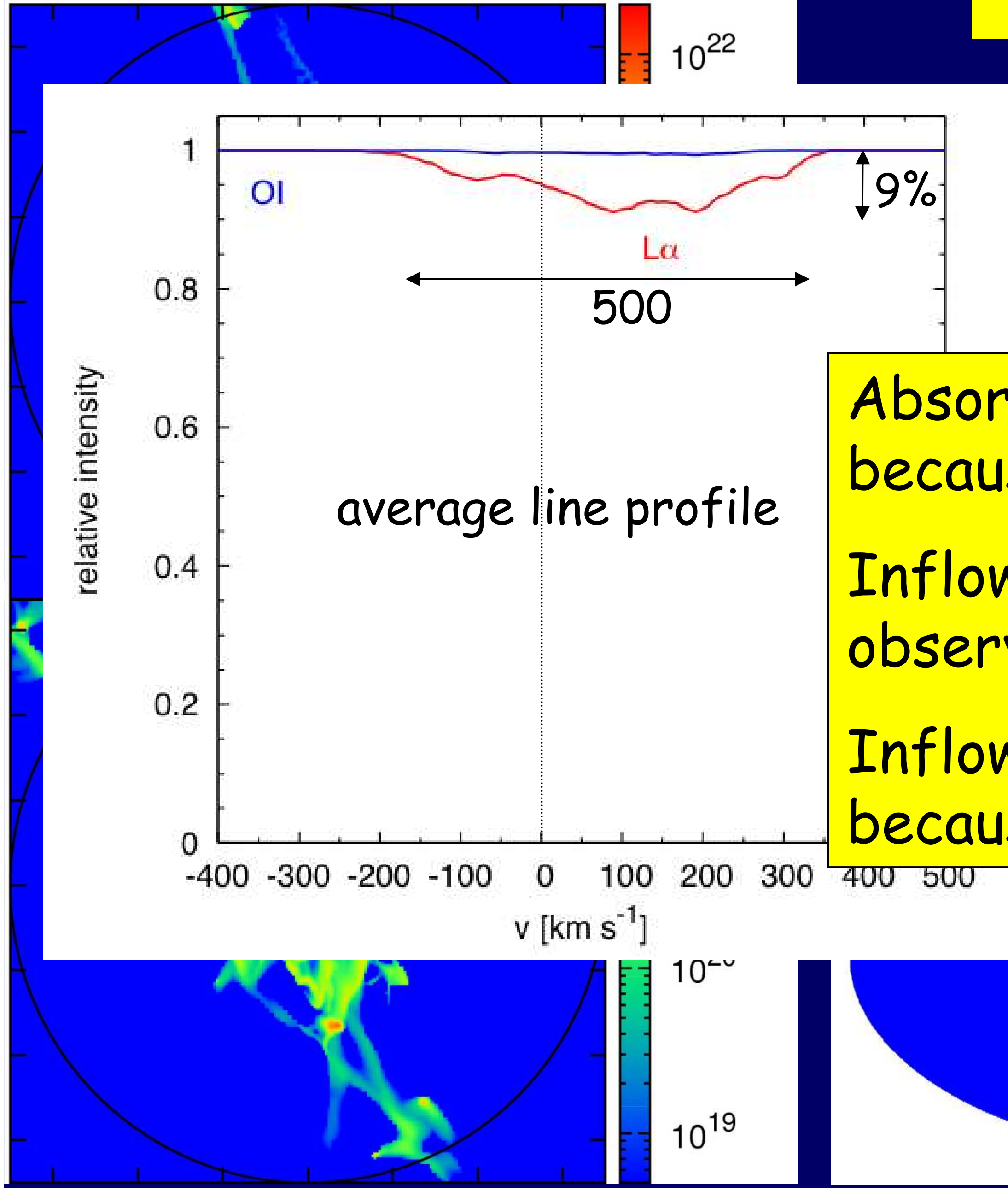
Kasen, Fumagalli, Ceverino, Dekel, Prochaska, Primack



Talk by Fumagalli

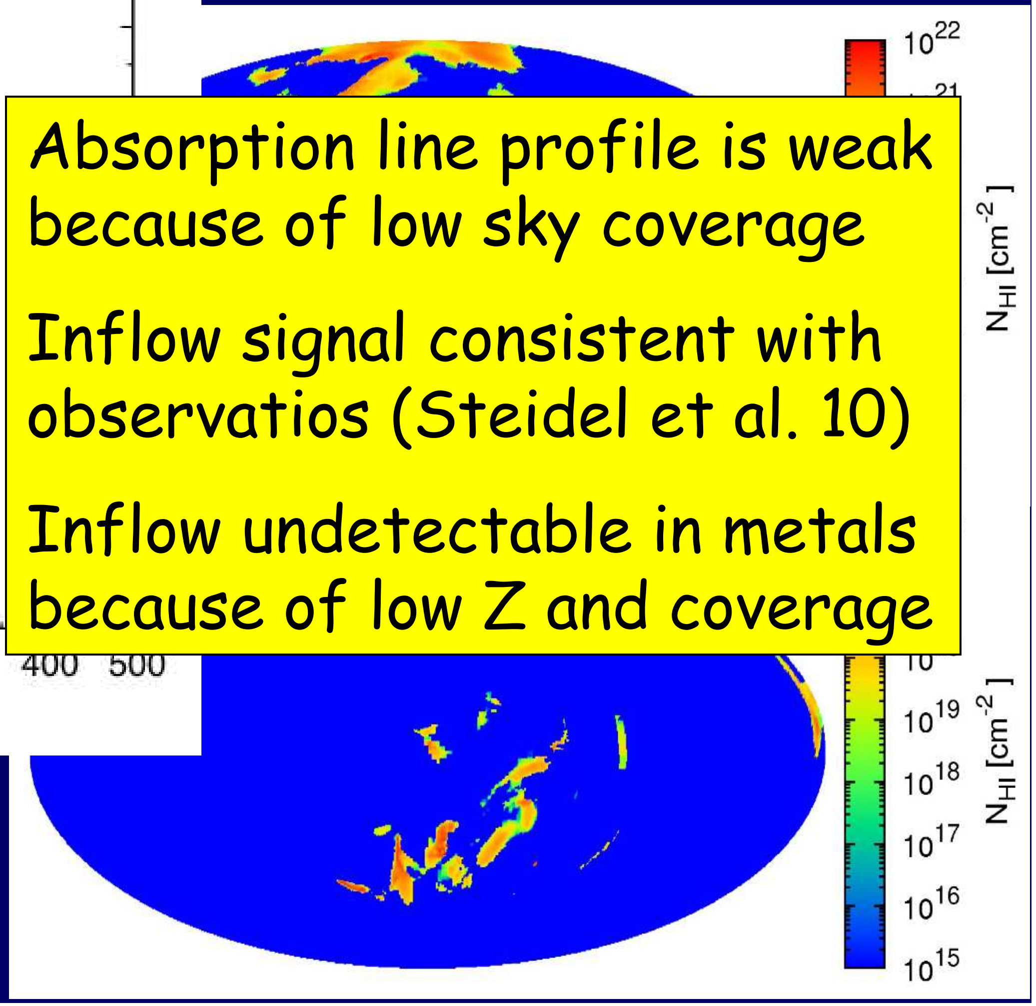
Lyα Absorption

background source



HI column density

central source

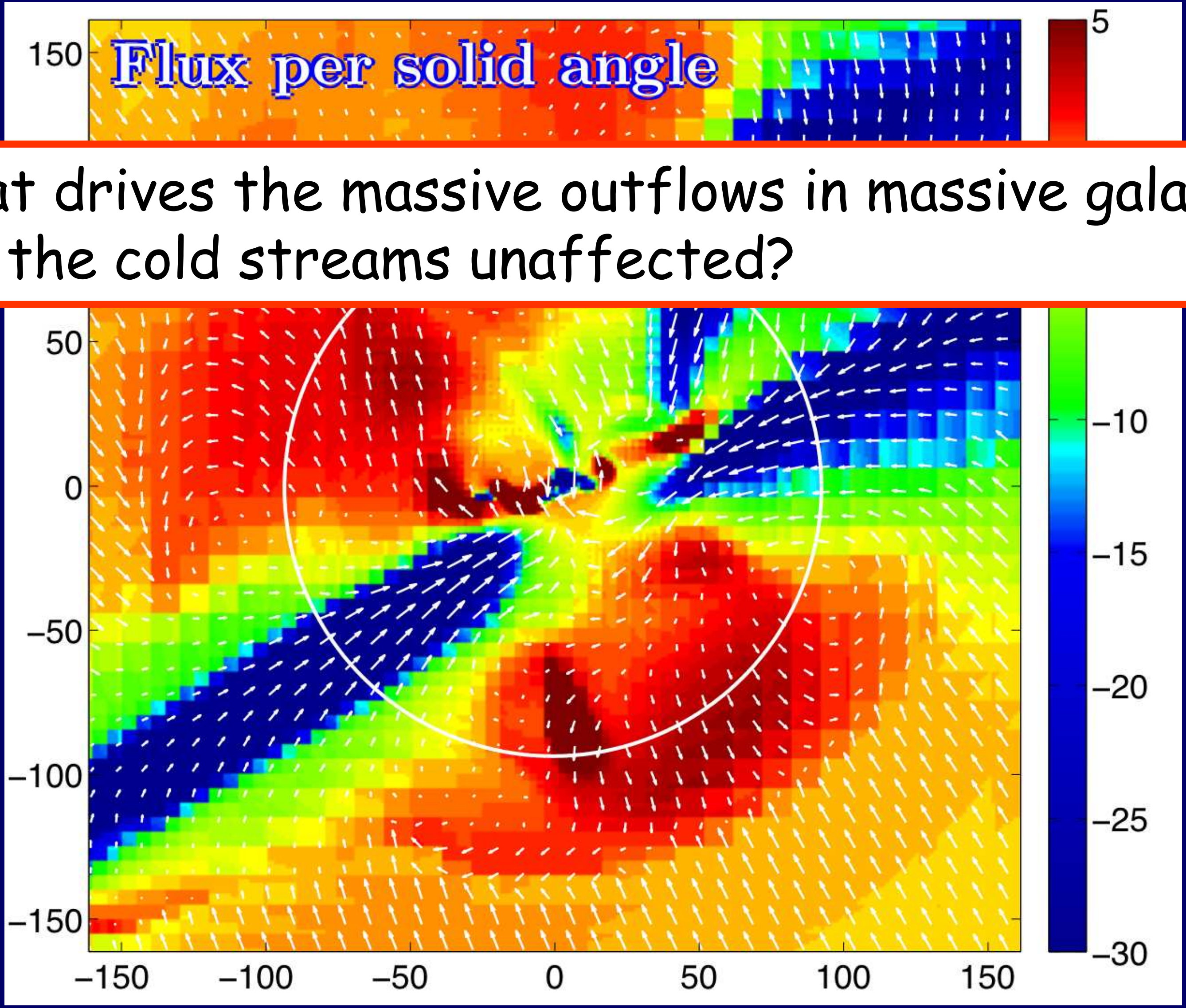


Absorption line profile is weak because of low sky coverage

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

Inflow undetectable in metals because of low Z and coverage

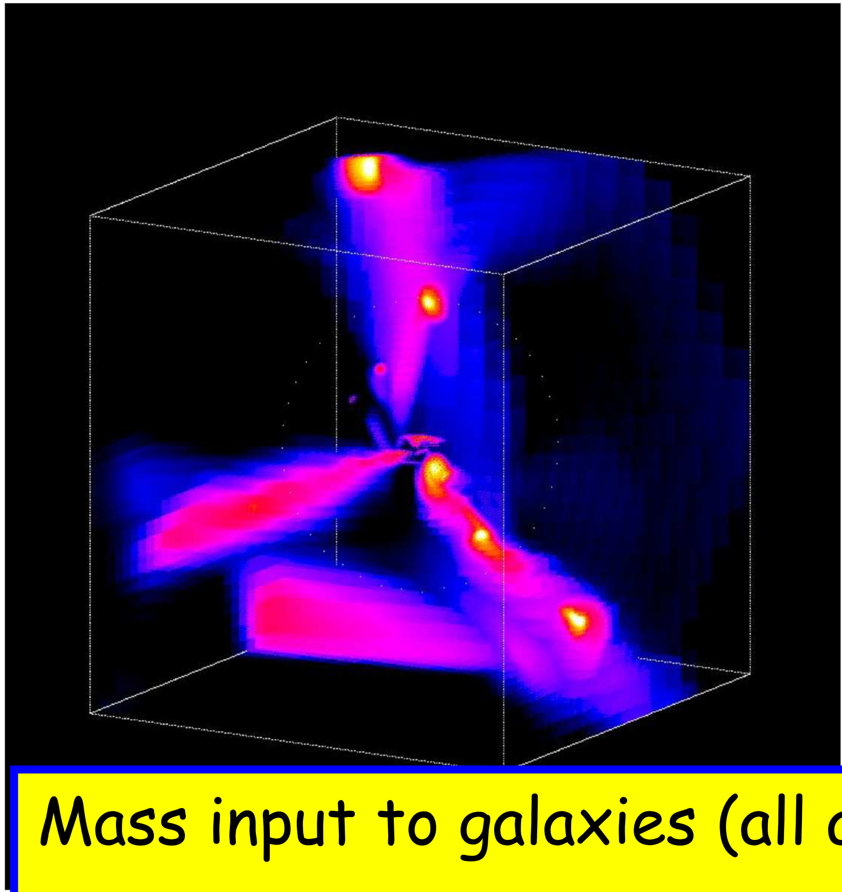
Inflow and Outflow

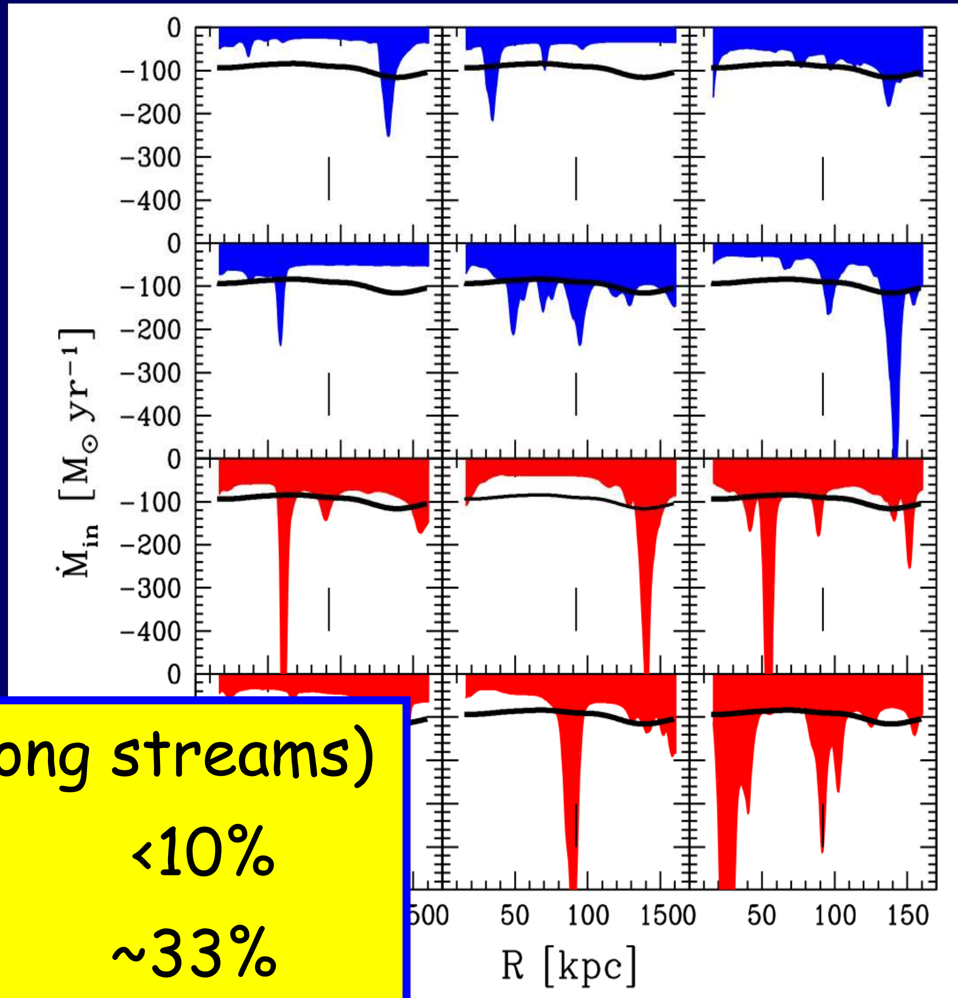


- What drives the massive outflows in massive galaxies?
- Are the cold streams unaffected?

Stream Clumpiness - Mergers

Dekel et al 09, Nature





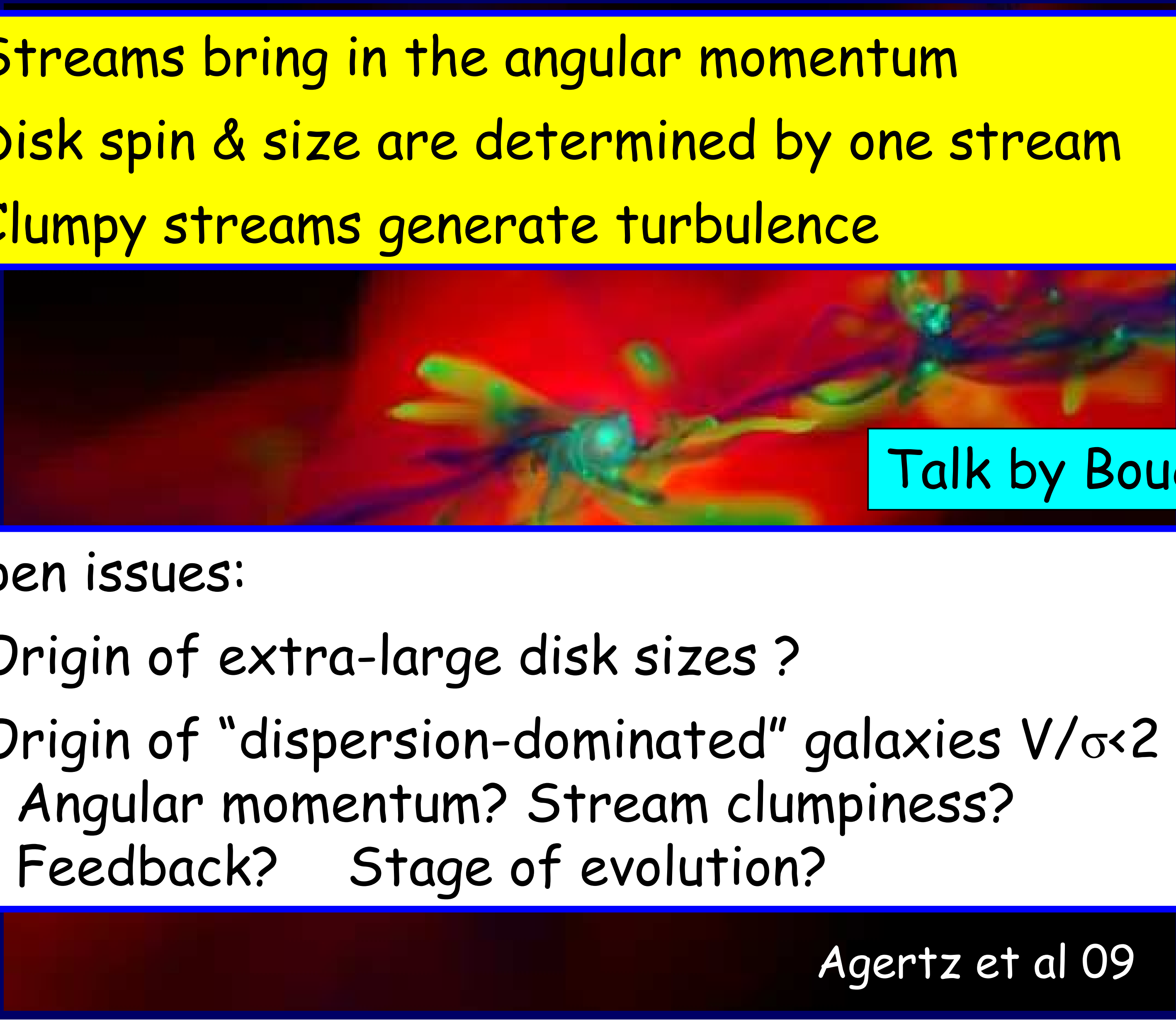
Mass input to galaxies (all along streams)

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

Talk by Teyssier

Angular Momentum

- Streams bring in the angular momentum
- Disk spin & size are determined by one stream
- Clumpy streams generate turbulence



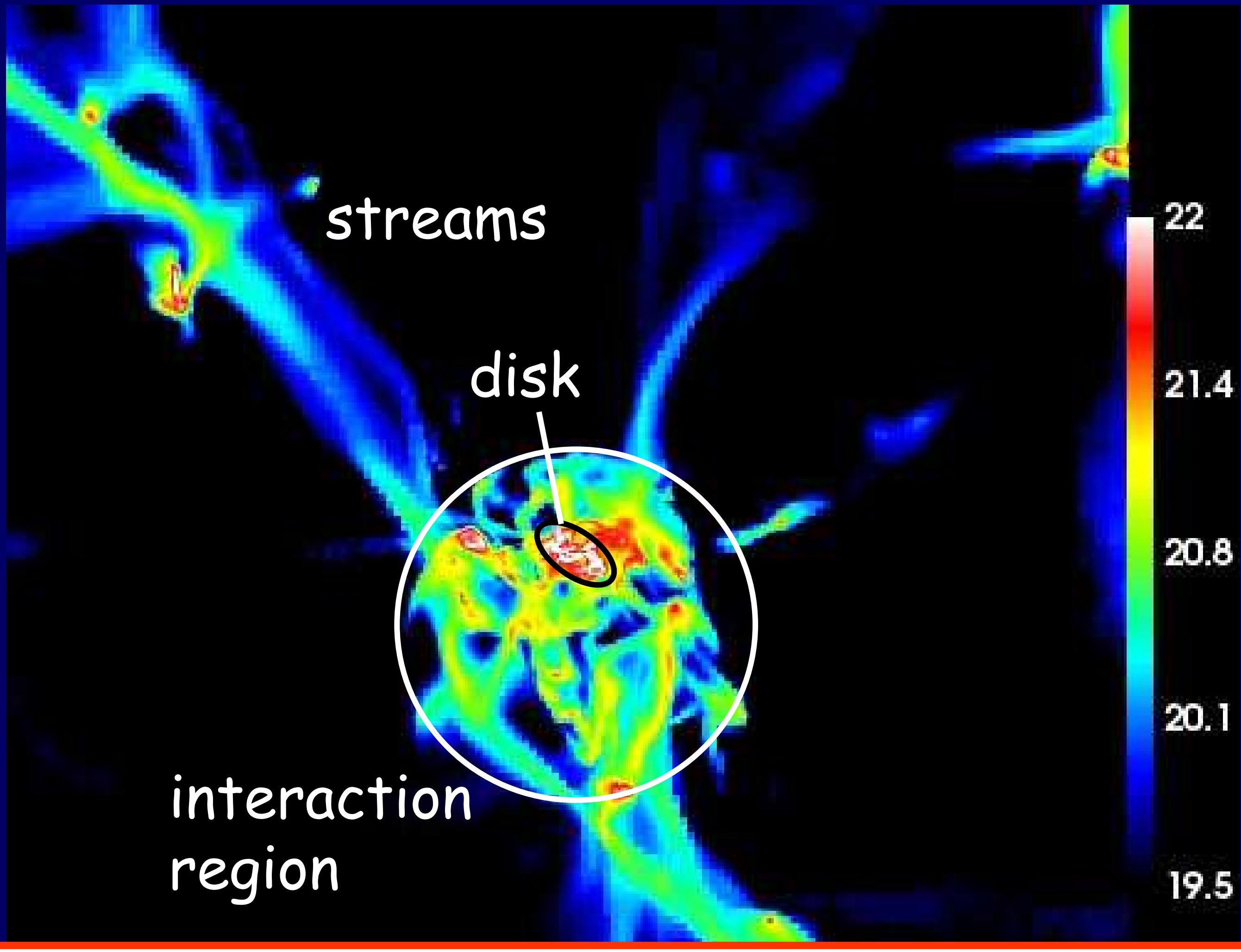
Talk by Bouche

Open issues:

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

Agertz et al 09

A Disk Fed by Cold Streams



Stream-disk interaction? Stream collisions? Stream instability – hydrodynamical? thermal? gravitational?

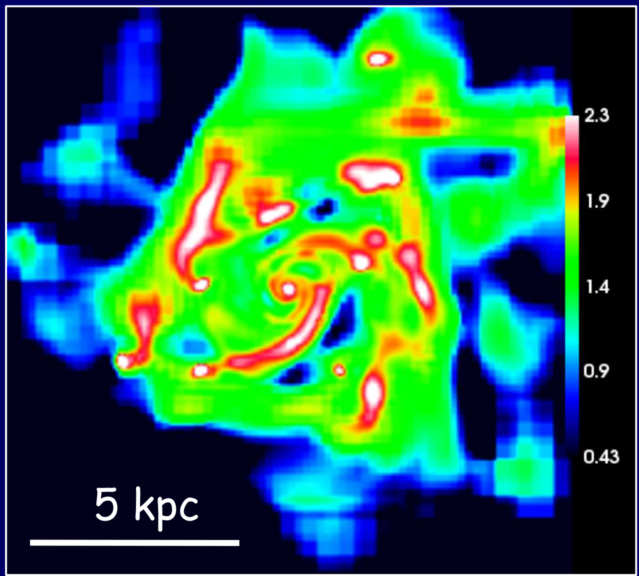
Violent Disk Instability

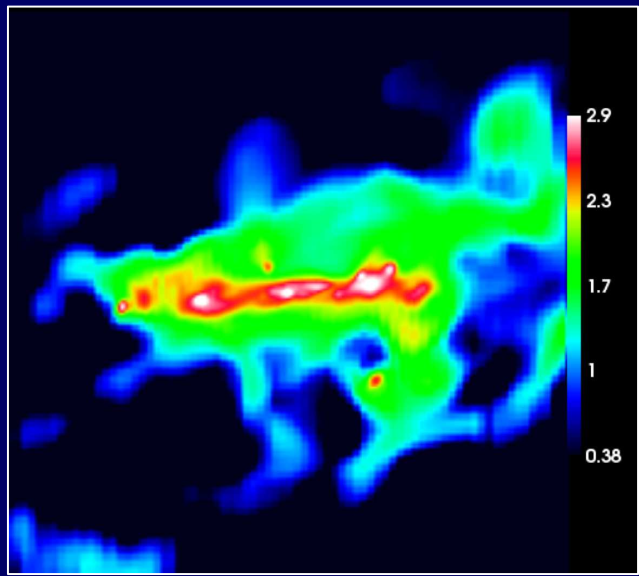
High gas density → disk wildly unstable

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

Giant clumps and transient features

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





Self-regulation at Q ~ 1 with high σ/V~1/4

Star formation and feedback in the clumps

Rapid migration of massive clumps and mass inflow → bulge formation

Noguchi 99
Immeli et al. 04

Bournaud,
Elmegreen,
Elmegreen 06, 08

Dekel, Sari,
Ceverino 09

Ceverino, Dekel,
Bournaud 09

Agertz et al. 09

Talks by
Cacciato,
Ceverino,
Teyssier,
Genel

What Drives the Turbulence?

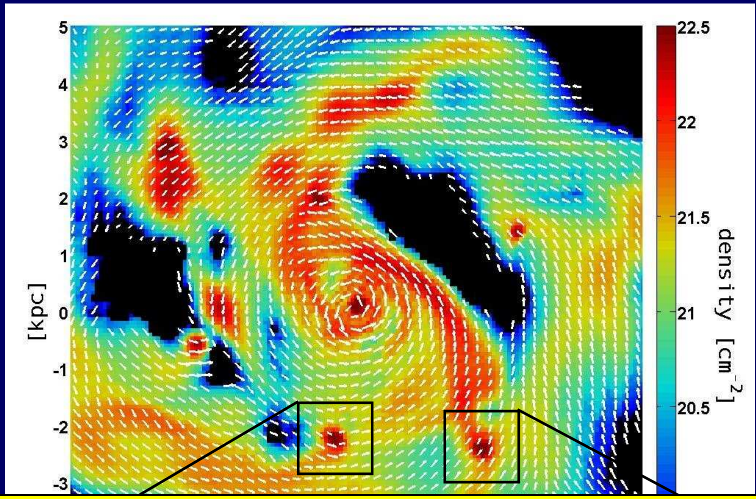
- Gravity: accretion, migration

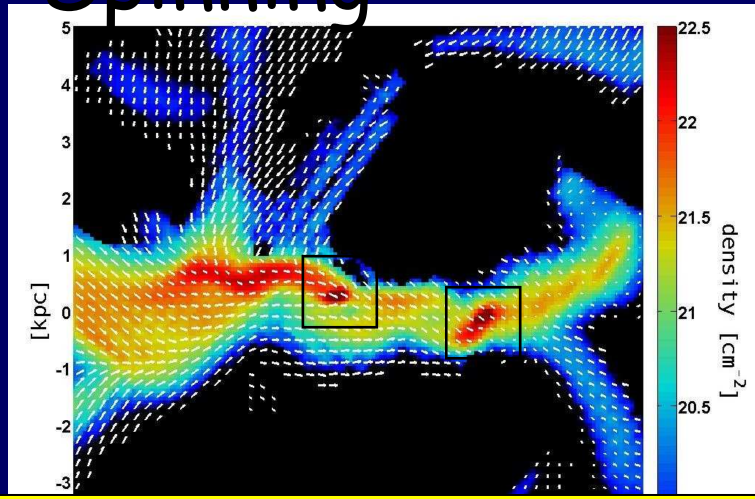
$$\dot{E} \approx \frac{GM}{R}\dot{M}$$

- Feedback: SN, radiative, AGN

Talks by Genel, Cacciato

Clump Support: The Clumps are Spinning



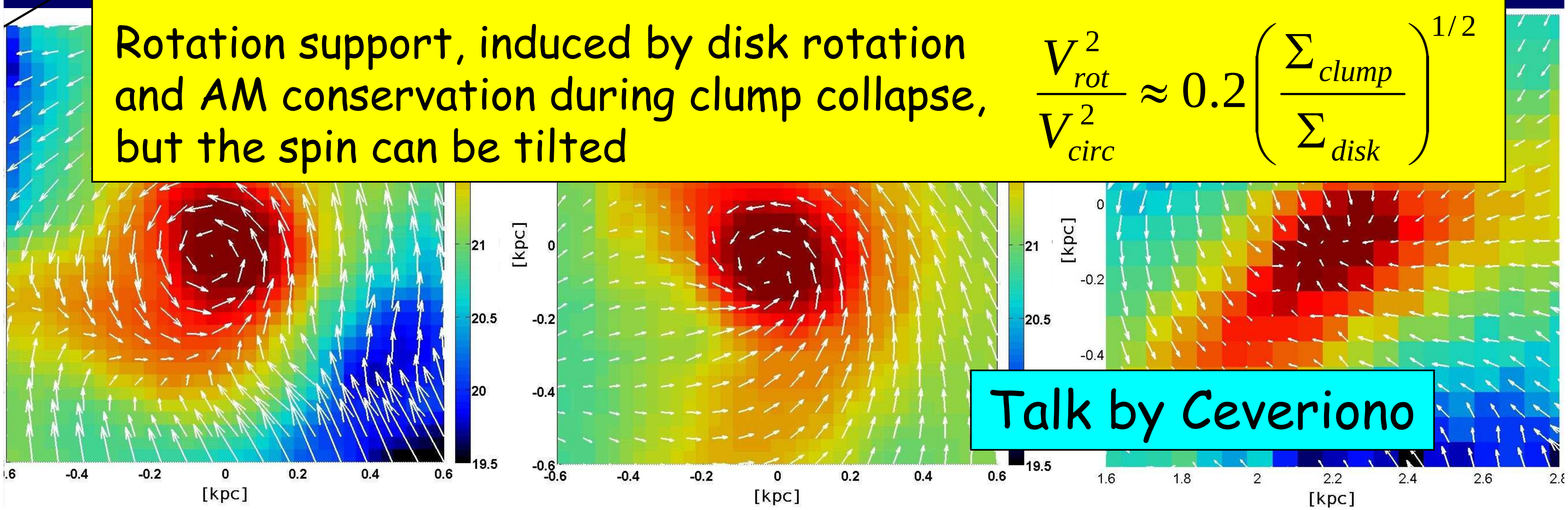


Jeans equation for an isotropic rotator

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

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

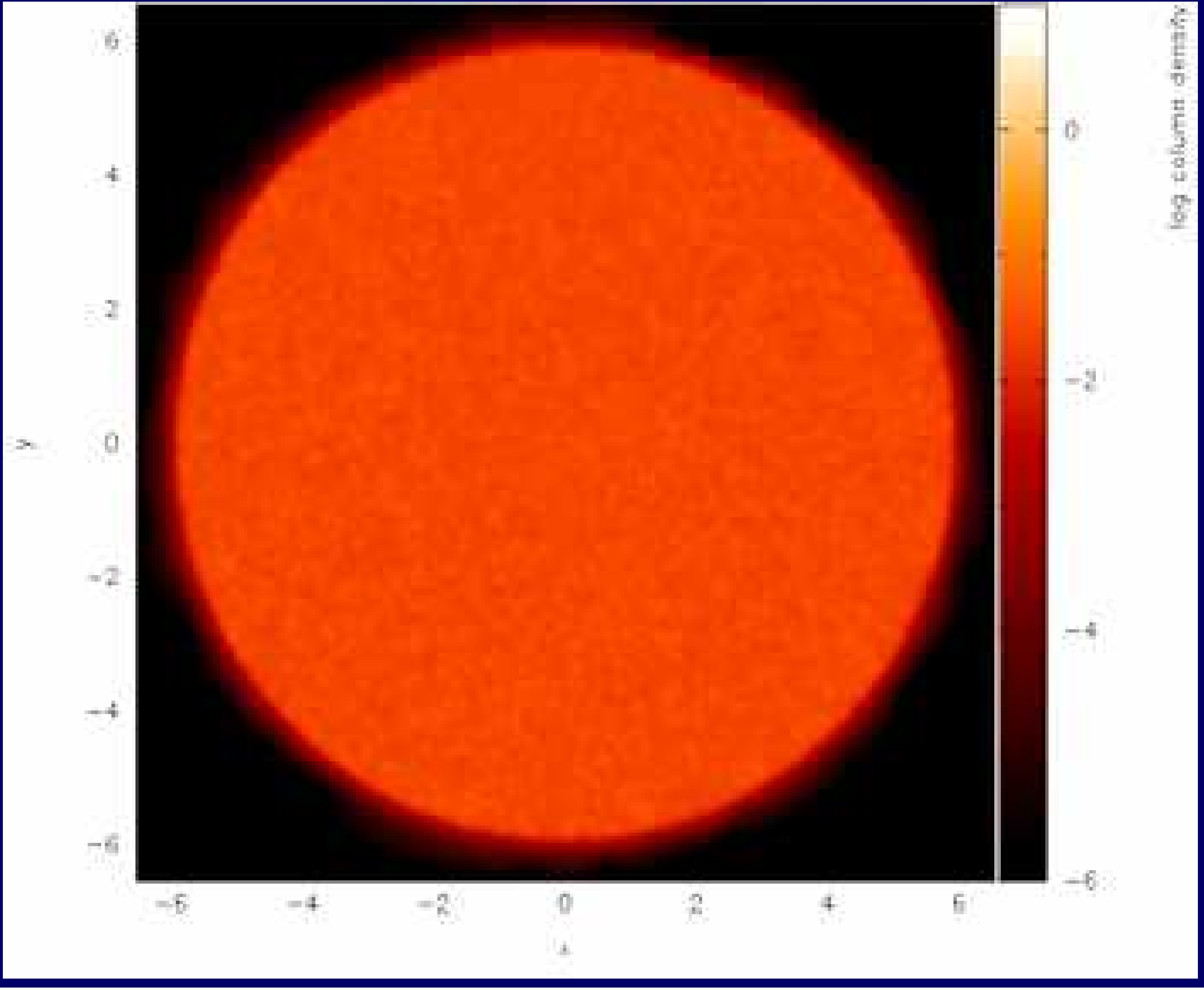
$$\frac{V_{rot}^2}{V_{circ}^2} \approx 0.2 \left(\frac{\Sigma_{clump}}{\Sigma_{disk}} \right)^{1/2}$$



Talk by Ceveriono

Rotating Clumps in a Wildly Unstable Disk

Naab



Clump Disruption by Stellar Radiation Pressure

Murray et al. 10;   Krumholz & Dekel 10

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

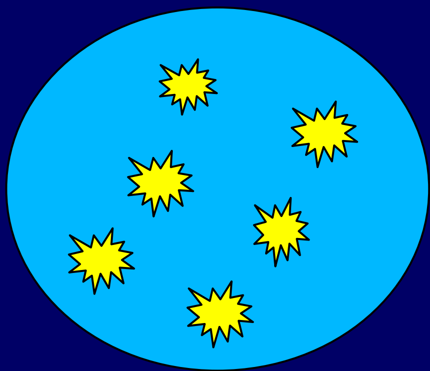
$t_{ff} \approx 15\,\mathrm{Myr}\, M_9^{-1/2} R_1^{3/2}$

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**

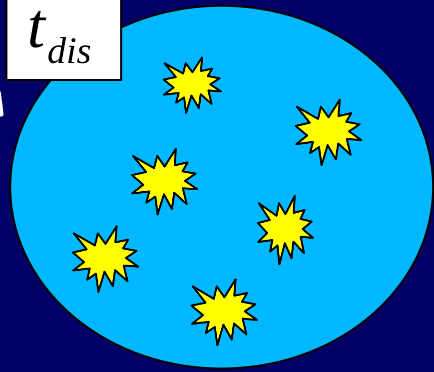
If ε~0.1, "fireworks": clumpy disk in steady state: the clumps are disrupted before they migrate to the center as new clumps form



A Fireworks Model of Clumpy Disks

Clumpy disk in steady state: the clumps are disrupted before they migrate to the center as new clumps form

t_{dis}



SFR efficiencies $\eta = \frac{M_{c*}}{M_c} \approx 0.1$ $\varepsilon = \frac{\dot{M}_{c*}}{M_c / t_{ff}}$ $\rightarrow$ $\eta = \varepsilon \frac{t_{dis}}{t_{ff}}$

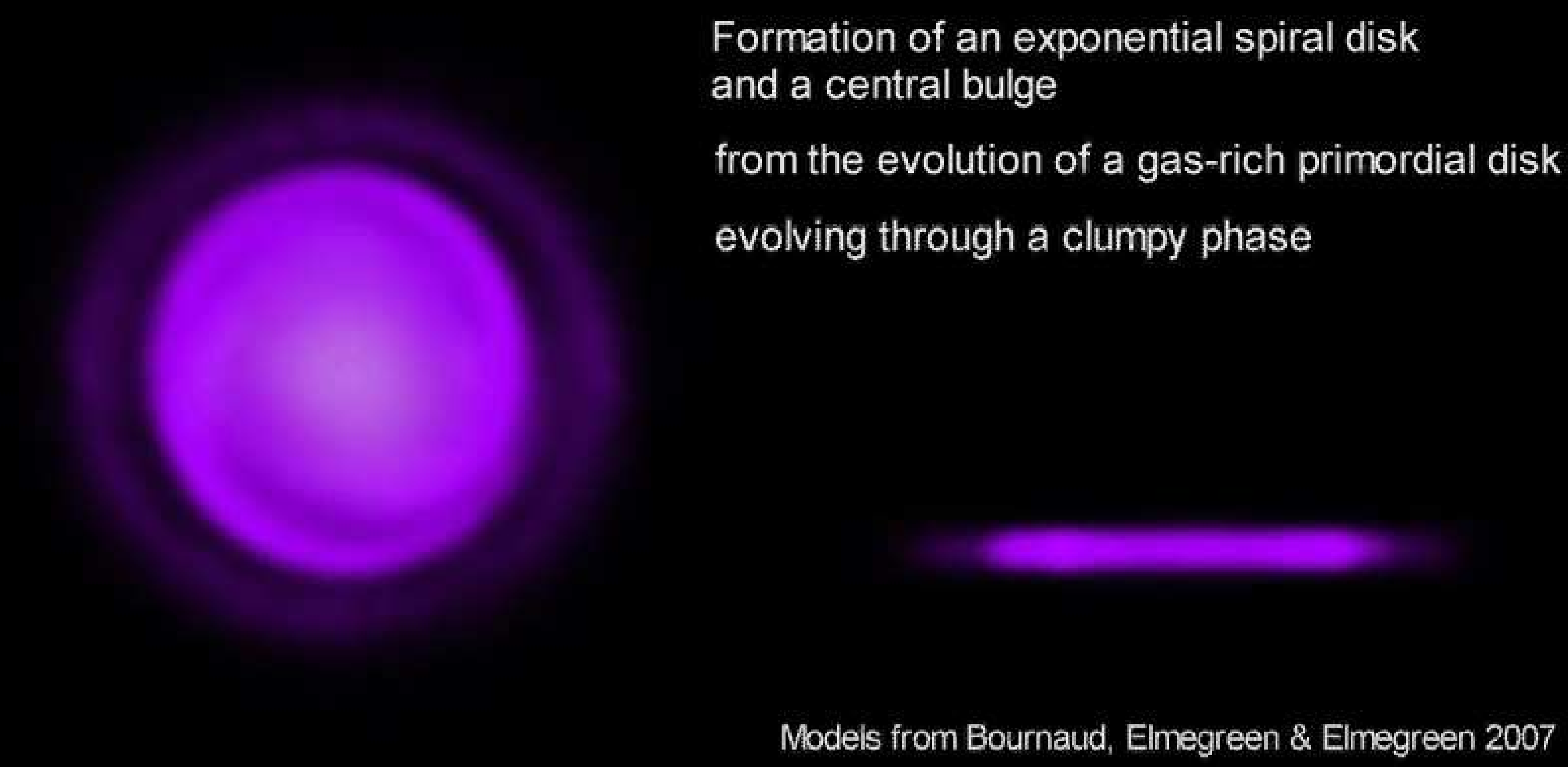
Simulations: $\alpha = \frac{\sum M_c}{M_{disk}} \approx 0.2$ $\beta = \frac{\sum \dot{M}_{c*}}{\dot{M}_*} \approx 0.5$ $\rightarrow$ $\eta = \frac{\beta}{\alpha} \frac{\dot{M}_* t_{dis}}{M_{disk}}$

$\rightarrow$ $\varepsilon = 0.1 \beta \alpha_{0.2}^{-1} (\dot{M}_* / M_d)_{Gyr^{-1}} t_{ff,20} \approx 0.1$ $\rightarrow$ $t_{dis} \approx t_{ff}$

Simulation steady state: $t_{form} \approx t_{mig} \approx 16 t_{ff}$

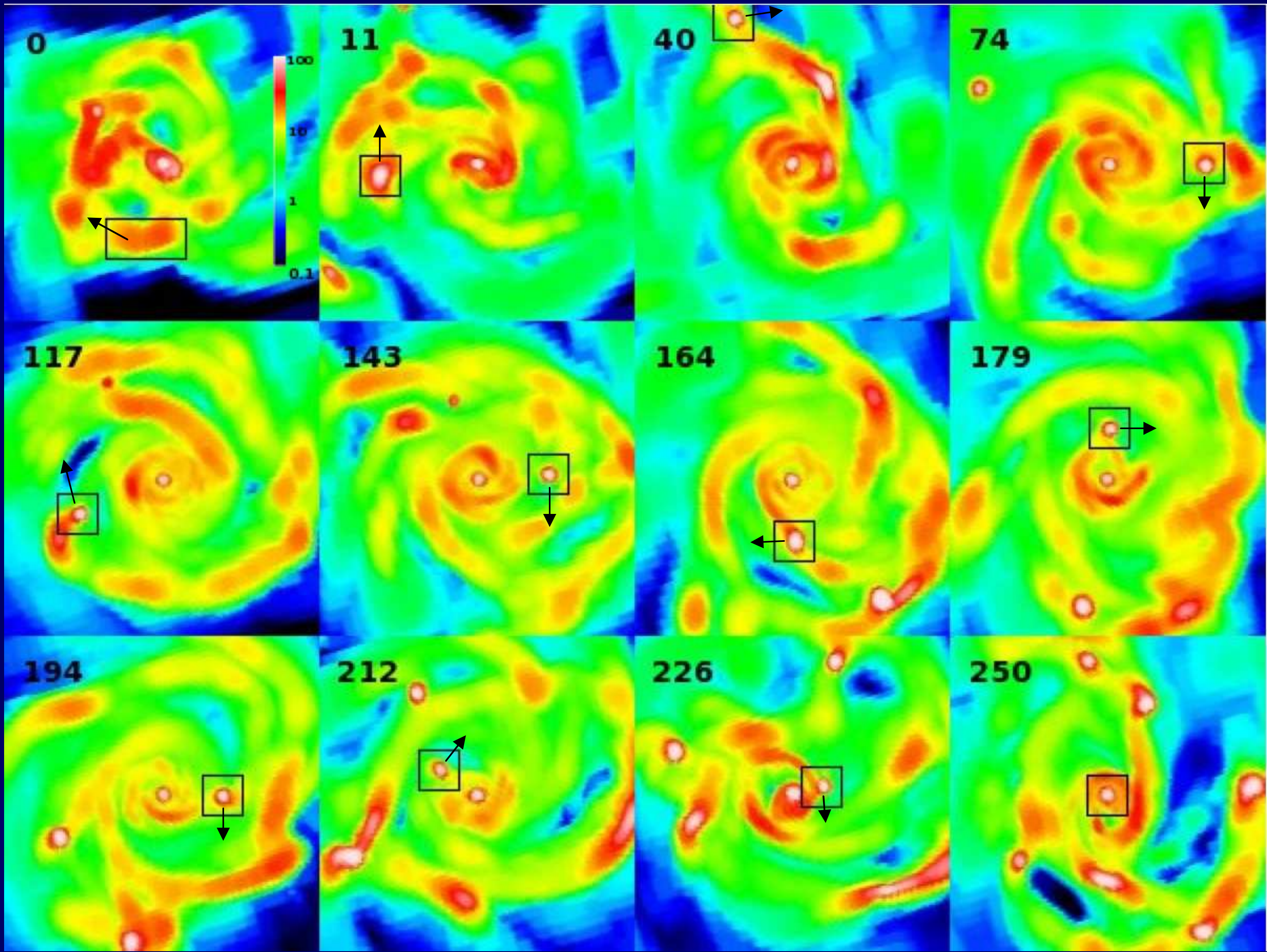
Duty cycle $\mu = \frac{t_{dis}}{t_{mig}} \approx 0.06 \frac{t_{dis}}{t_{ff}}$ but should be ~1

Wildly Unstable Disk: Migration into a Bulge



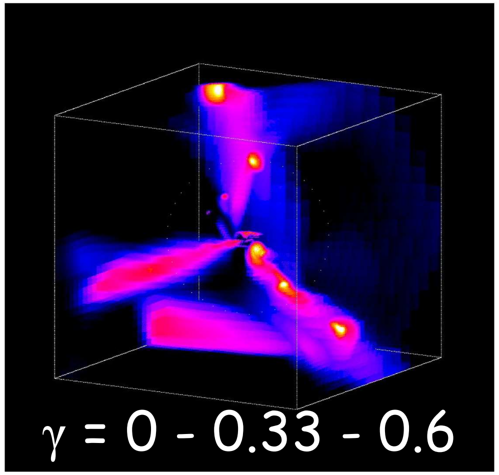
Noguchi 99; Immeli et al. 04; Bournaud, Elmegreen, Elmegreen 06, 08

Clump Formation & Migration to a Bulge



Cosmological Steady State

Dekel, Sari, Ceverino 09



migration
$\dot{M}_{evac}$

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

stream clumps
$\gamma \dot{M}_{acc}$
mergers

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

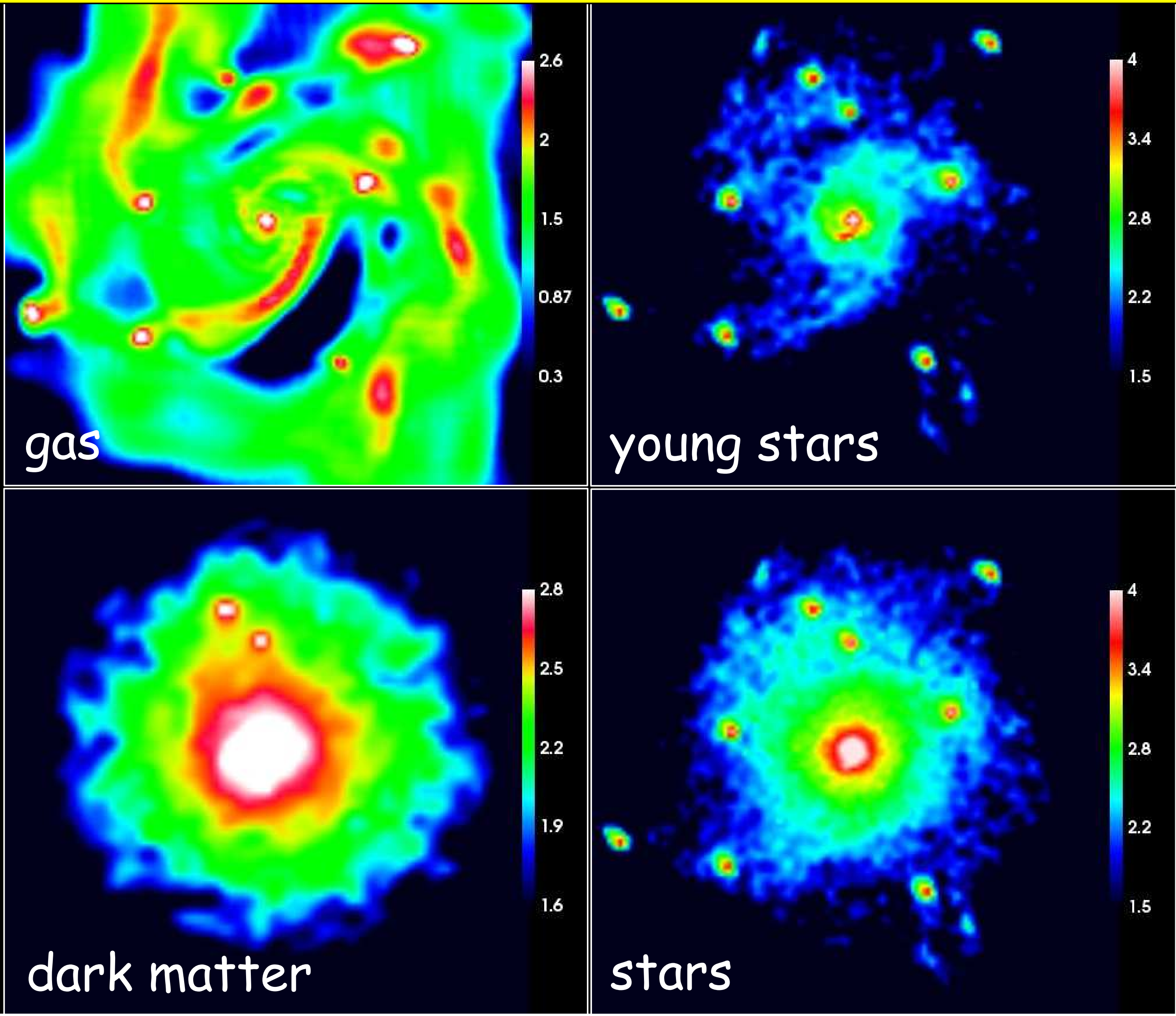
$$\dot{M}_{\rm bulge} = \gamma \dot{M}_{\rm acc} + \dot{M}_{\rm evac}(\delta)$$

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

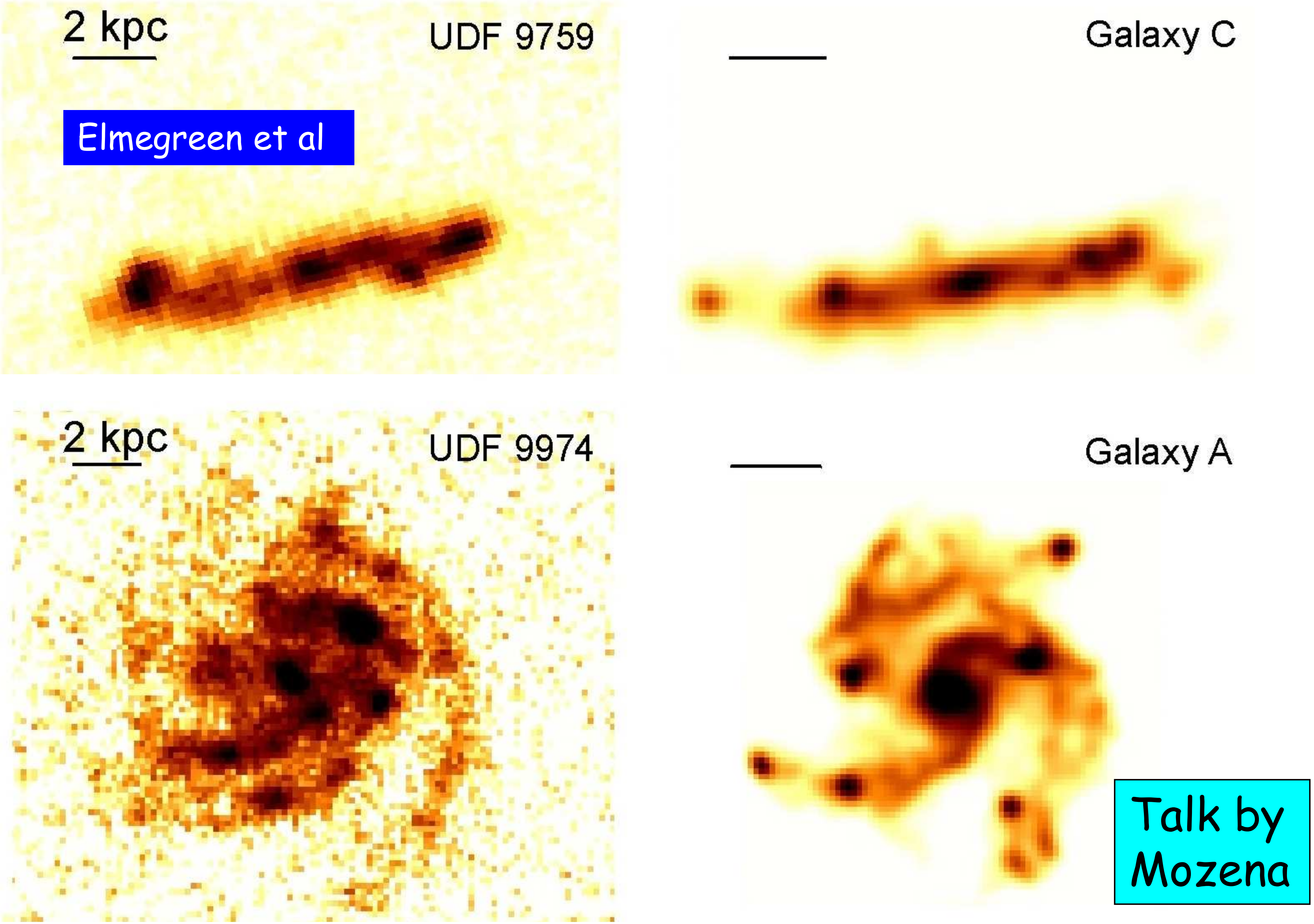
Steady state for a few Gyr:
draining disk is replenished by cold streams,
bulge ~ disk ~ dark matter

Talks by Cacciato, Genel

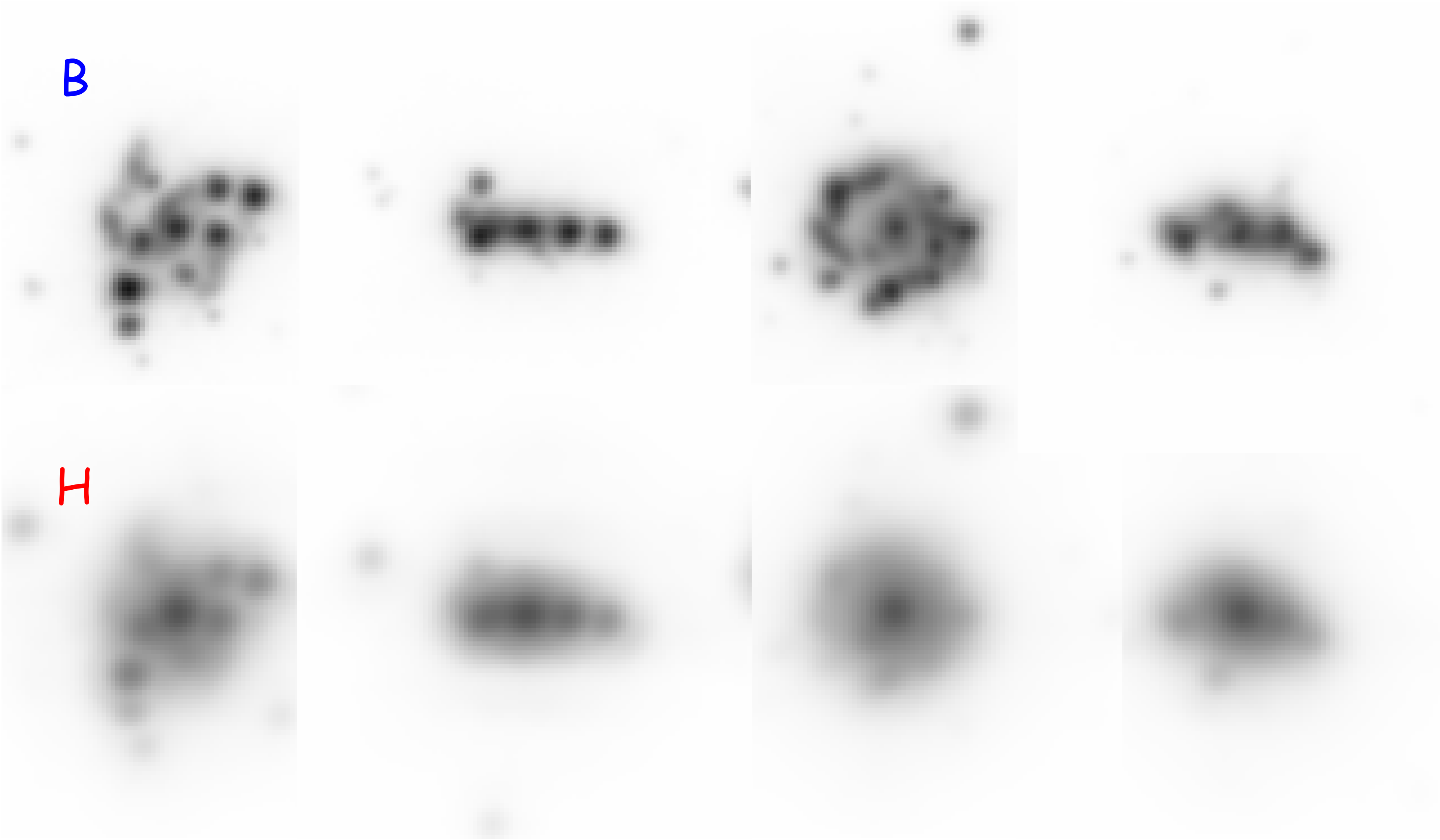
Wild Disk Instability → Bulge



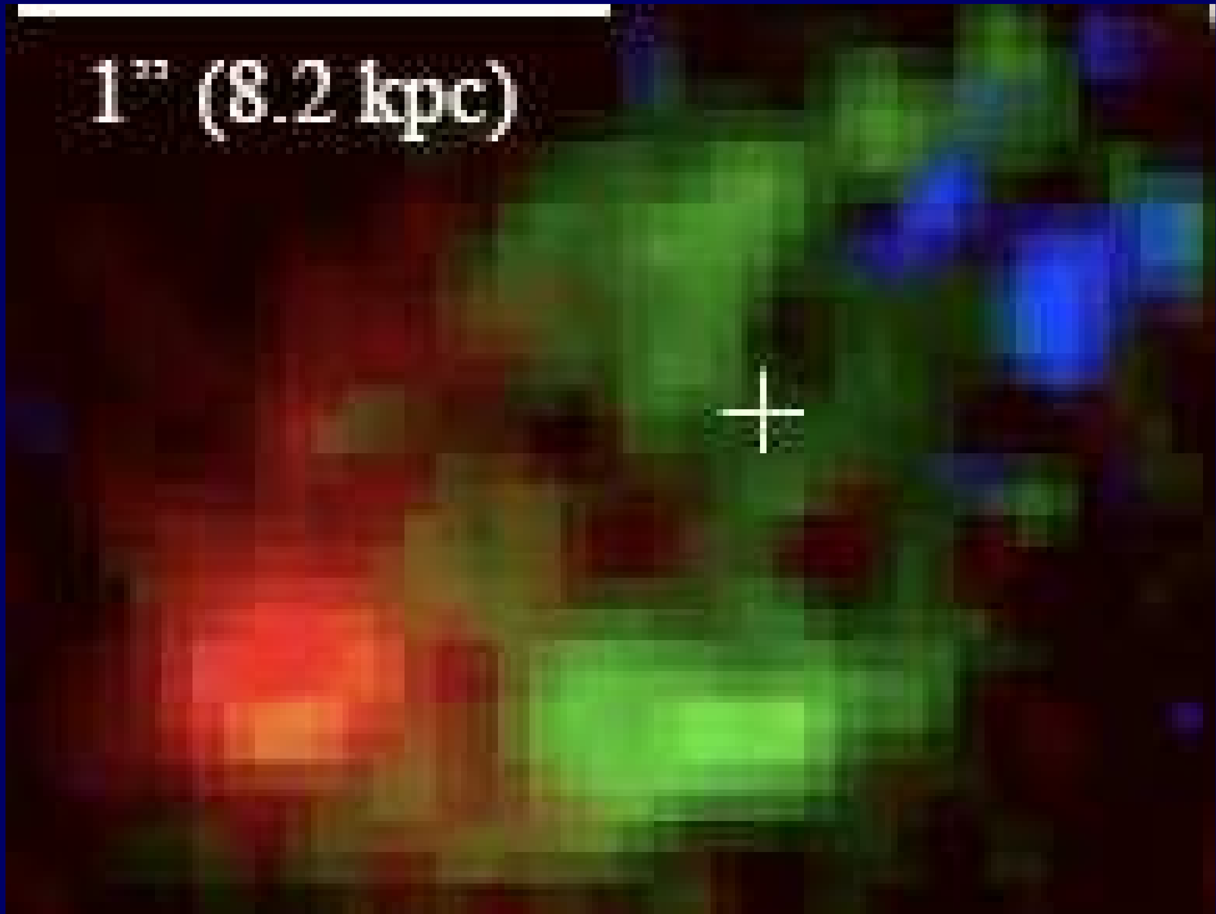
Observations vs. Simulations



Stellar Images of Clumpy Disks z=2



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



Hα star-form regions

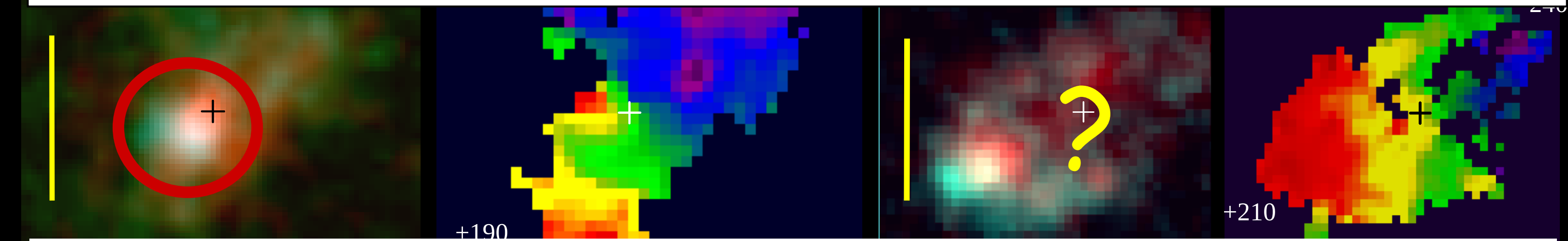
color-code velocity field

Genzel et al 08

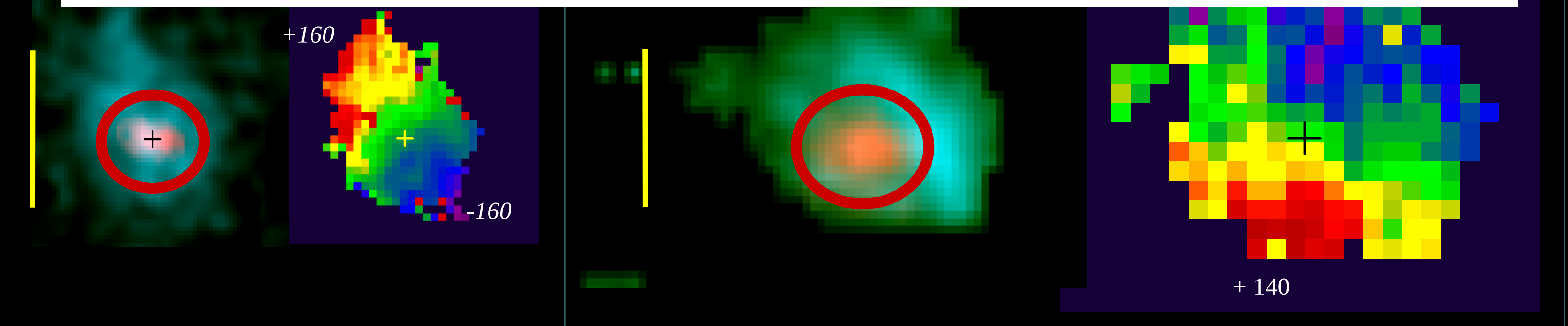
Clumpy Disks with Massive Bulges?

A bulge-less disk ???

- A young clumpy disk that will soon form a bulge?
- Bulge removed by feedback (SN, radiative, AGN)?

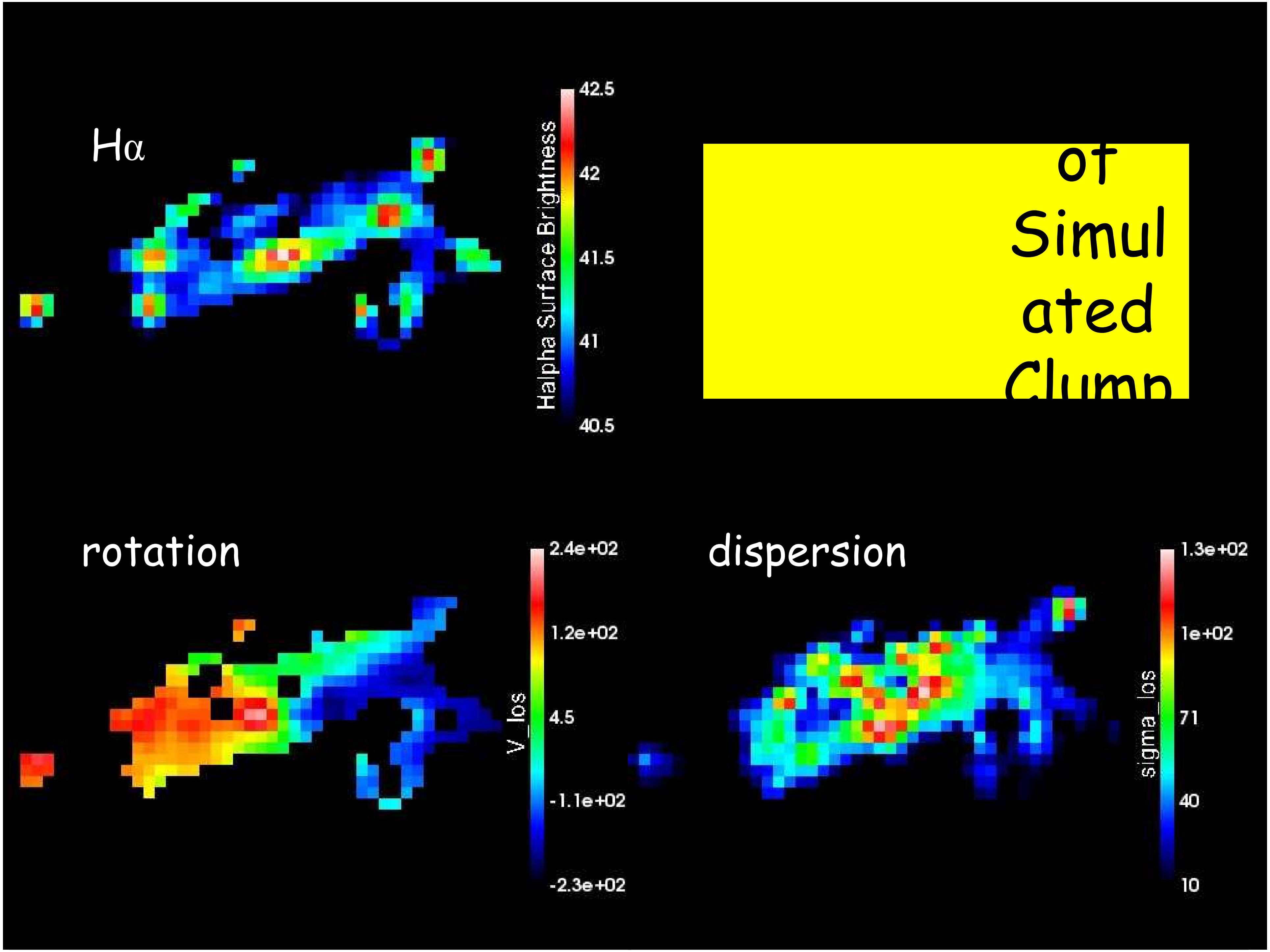


Clump coalescence into the bulge = wet mergers.
If SFR efficiency in mergers is 10xKennicutt then stellar radiative feedback could disrupt the bulge

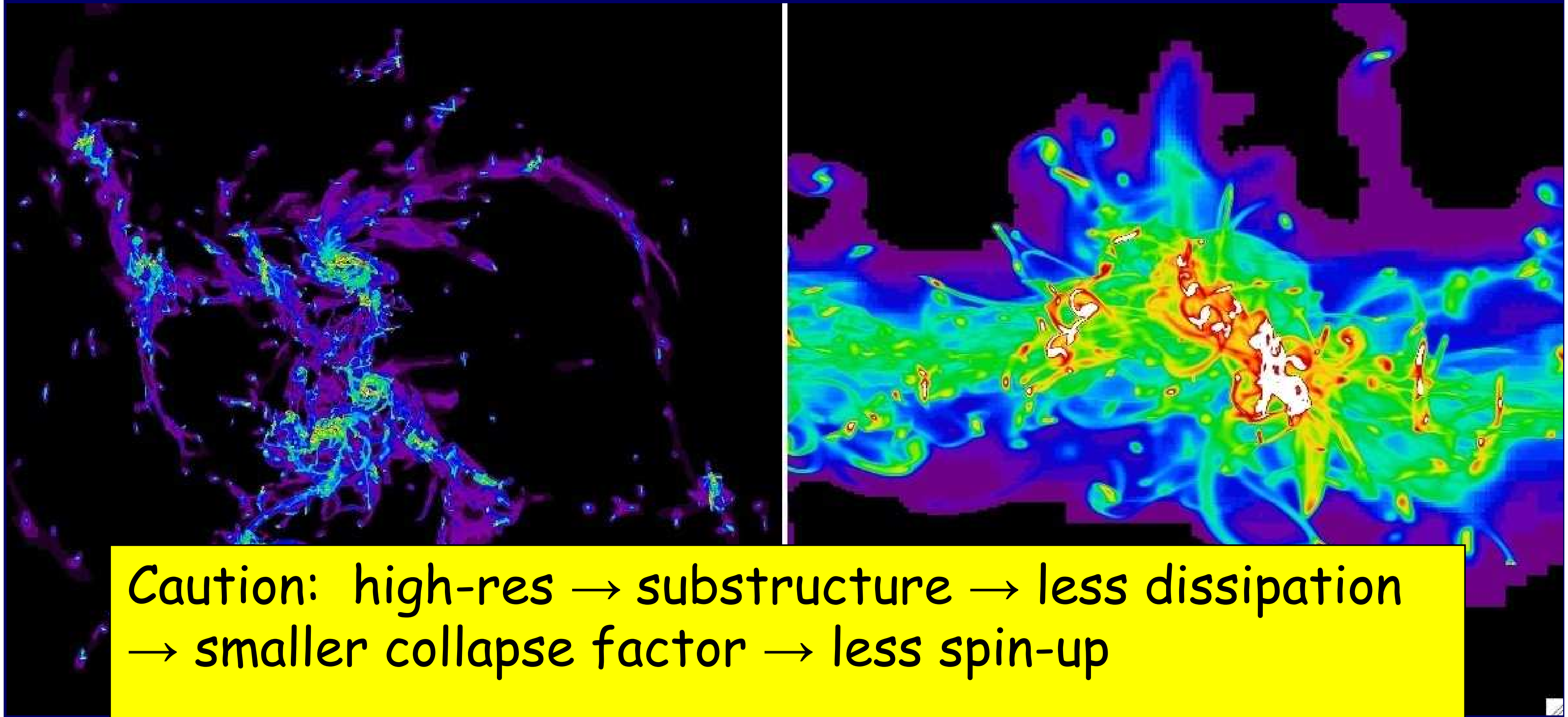


Genzel et al. 08; Förster Schreiber et al. 10

M(≤3 kpc)/M(≤15 kpc)~0.2-0.4


Hα
Halpha Surface Brightness
42.5
42
41.5
41
40.5
of
Simul
ated
Clump
rotation
V_los
2.4e+02
1.2e+02
4.5
-1.1e+02
-2.3e+02
dispersion
sigma_los
1.3e+02
1e+02
71
40
10

Sub-structure in the disk giant clumps



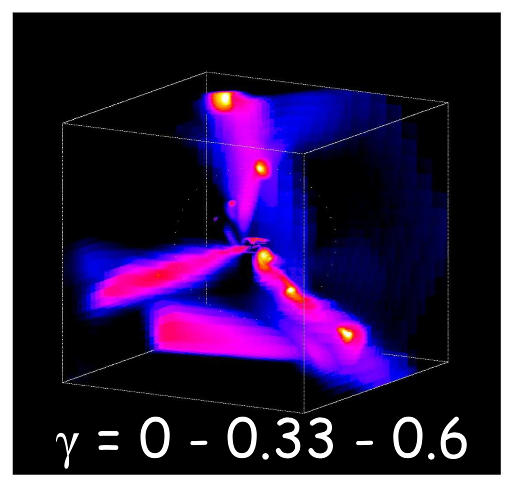
Caution: high-res → substructure → less dissipation → smaller collapse factor → less spin-up

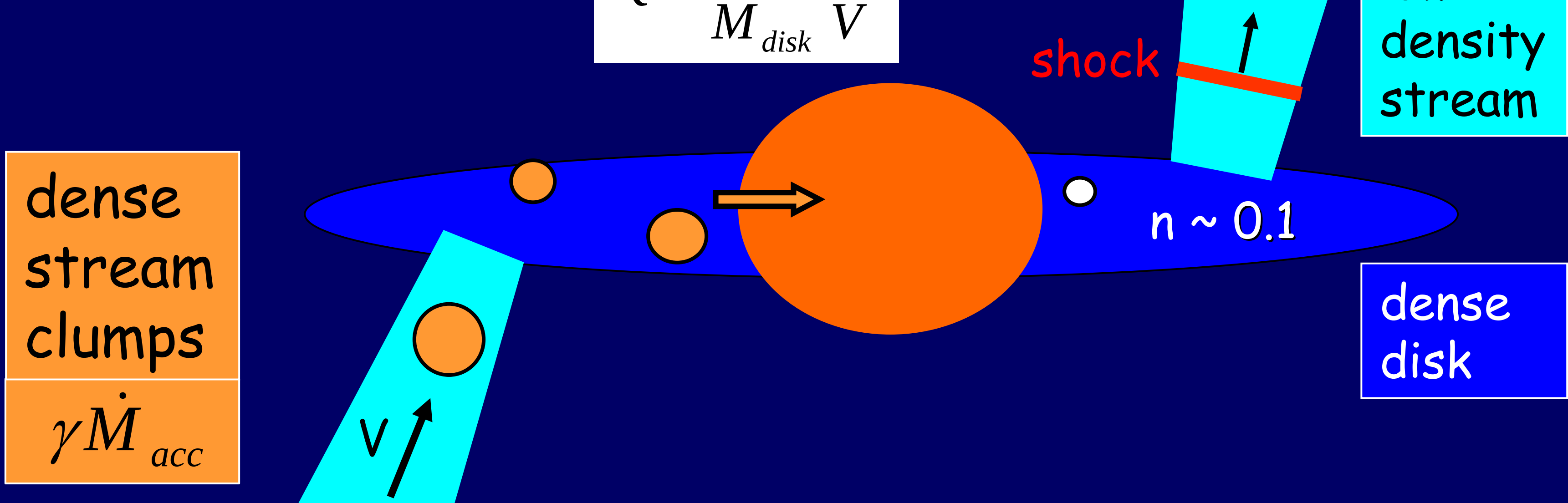
Caution: MW molecular clouds are not spin-supported

Bournaud, Teyssier 10 AMR 2 pc resolution

Stabilization by stream clumps

Dekel, Sari, Ceverino 09





- 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 – Morphologopical 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

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. Disruption (?)
  Cosmological steady state with bulge ~ disk. Bulge disruption (?)
  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