Introduction to Inflowing Streams: Solid Predictions and Open Issues

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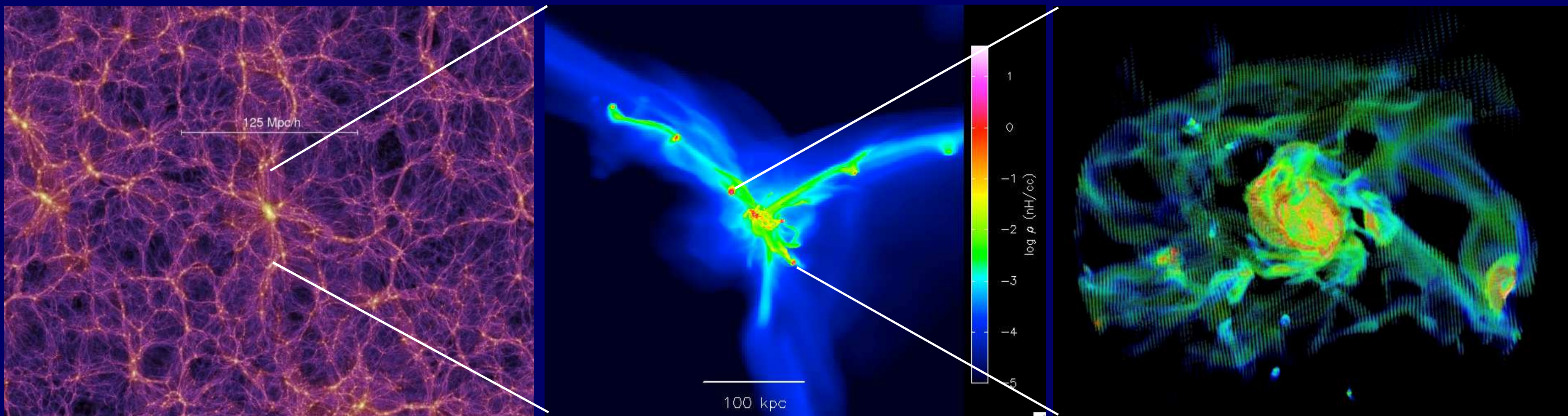
IGM@50 Spineto, June 2015



Average Accretion Rate into Halos

EPS + simulations, Dekel+13

Self-invariant time variable $\omega \equiv \delta_c / D(t)$ $\longrightarrow$ $dM / d\omega = \text{const.} \rightarrow \dot{M} \propto \dot{\omega}$

In EdS regime (z>1) $D(t) \propto (1+z)^{-1} \propto t^{2/3} \rightarrow \dot{M} \propto (1+z)^{5/2}$

In ΛCDM - weak M dependence $\dot{M} / M \propto M^{\alpha}, \ \alpha = (n+3)/6 \approx 0.14$

Specific accretion rate $\dot{M} / M \approx s\,(1+z)^{5/2} \quad s \approx 0.03\ \text{Gyr}^{-1}$

Mass growth $M \approx M_0 e^{-\alpha z}$

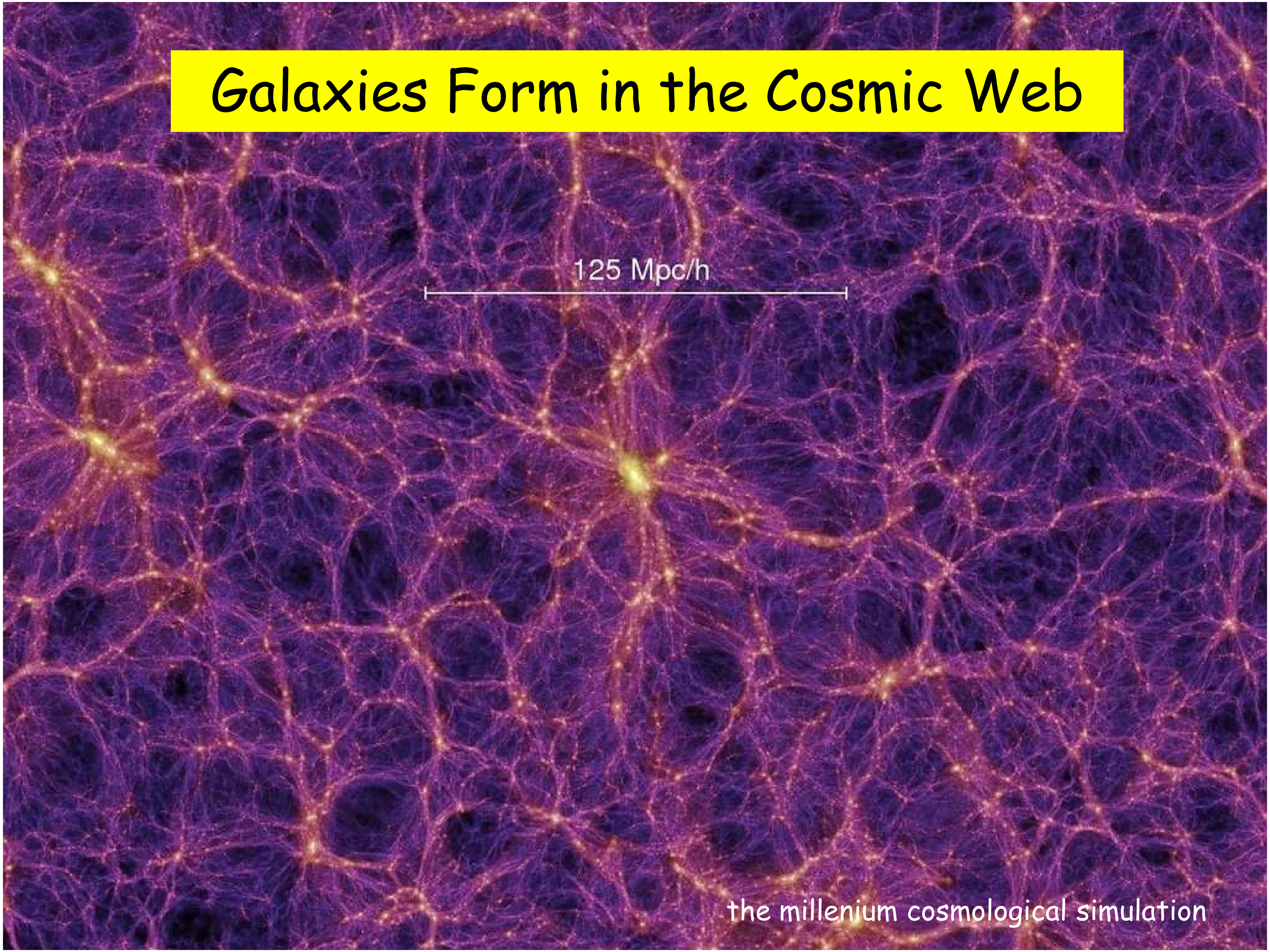
$\alpha = (3/2)\,s\,t_1 \approx 1 \quad (1+z)^{-1} \approx (t/t_1)^{2/3} \quad t_1 \approx 17.5\,\text{Gyr}$

Baryons and star formation
(simulations and bathtub model)

$\text{sSFR} \approx (\dot{M}/M)_{0.1R\text{vir}} \approx (\dot{M}/M)_{R\text{vir}}$

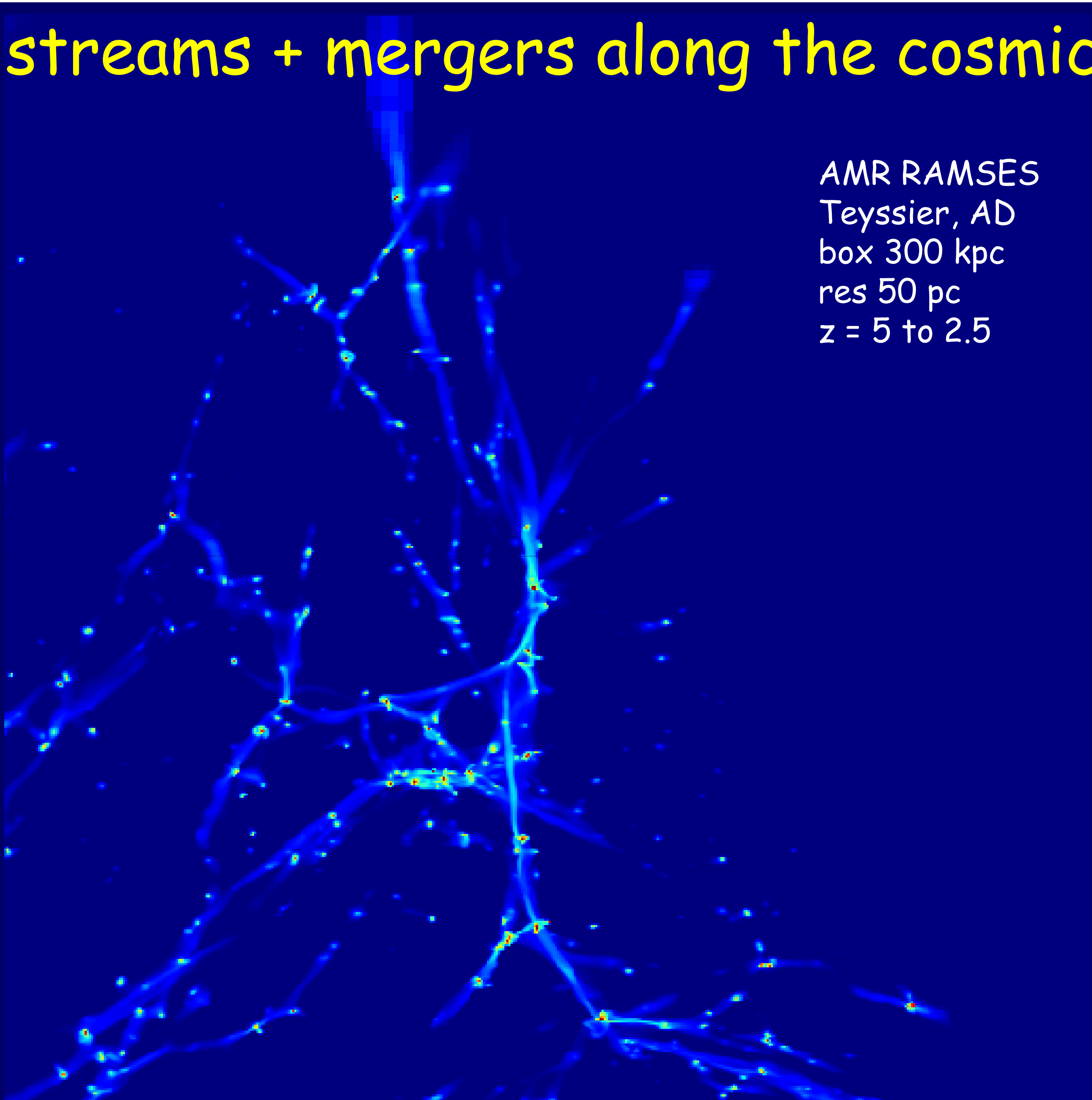
$\text{sSFR} \approx 0.046\ \text{Gyr}^{-1}\, M_{*,10}^{0.14}\,(1+z)^{5/2}$

Galaxies Form in the Cosmic Web



the millenium cosmological simulation

Gas streams + mergers along the cosmic web



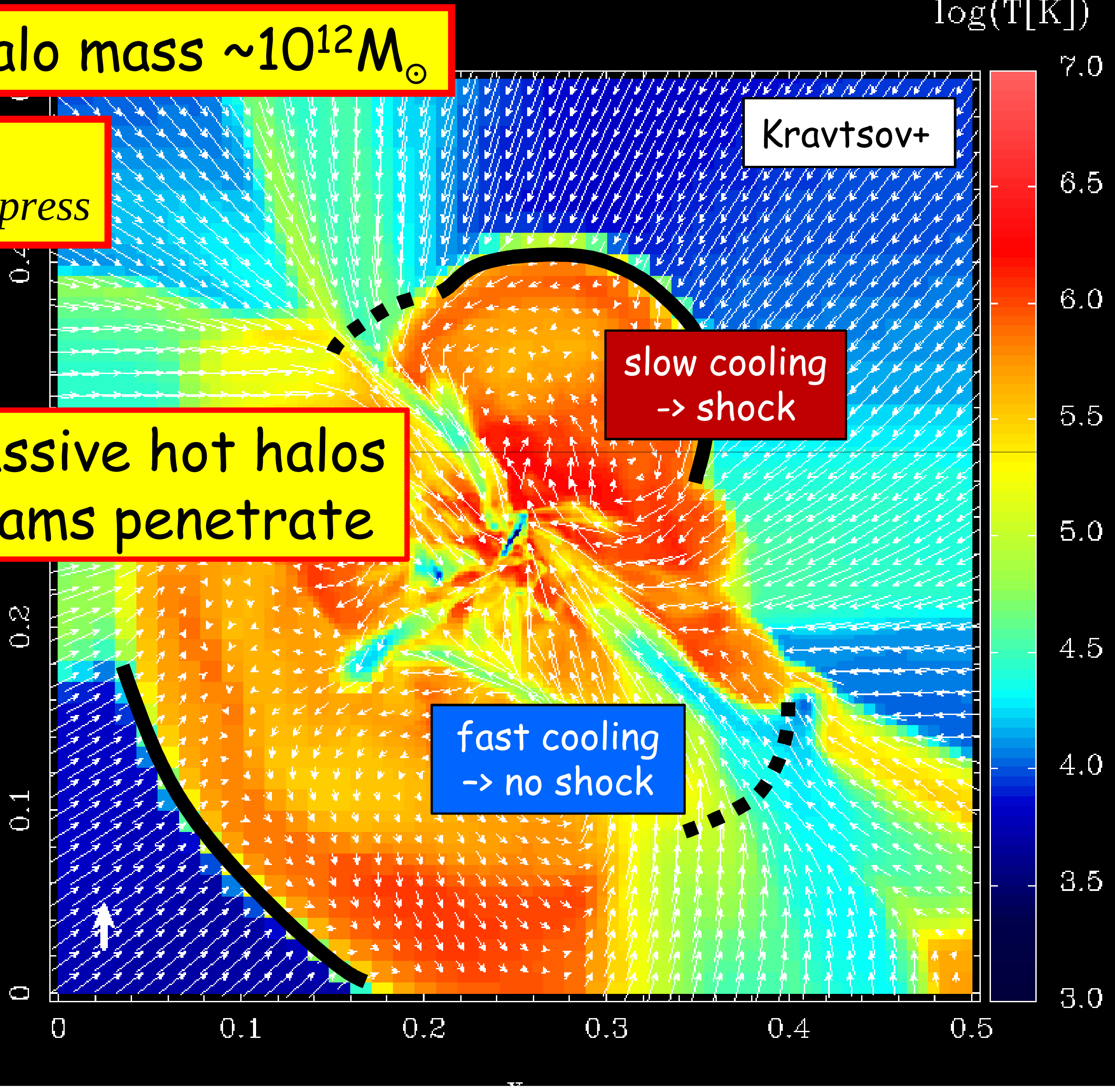
Virial Shock Heating

Birnboim & AD 03; AD & Birnboim 06; Keres+ 05, 09

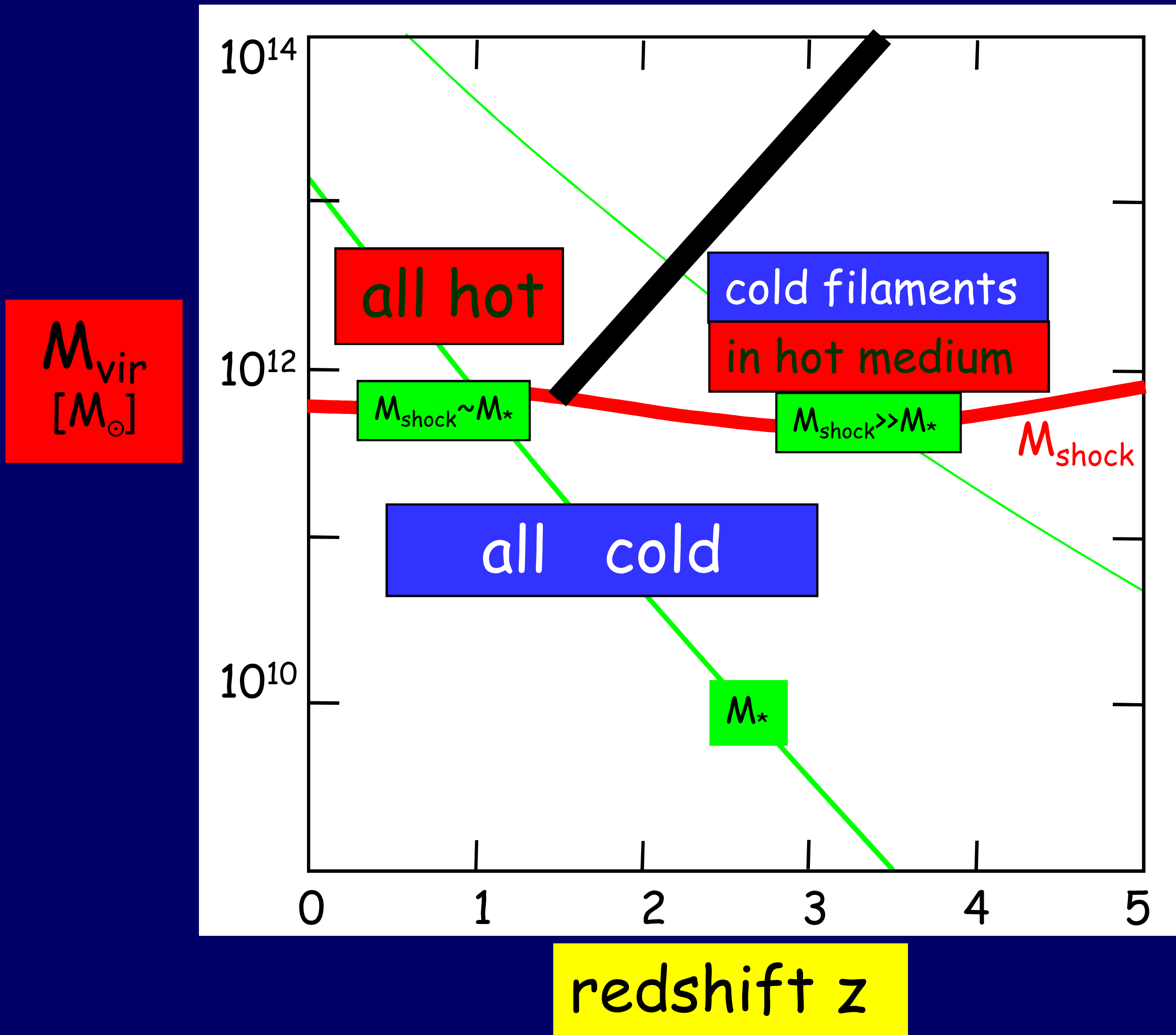
critical halo mass ~$10^{12} M_\odot$

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

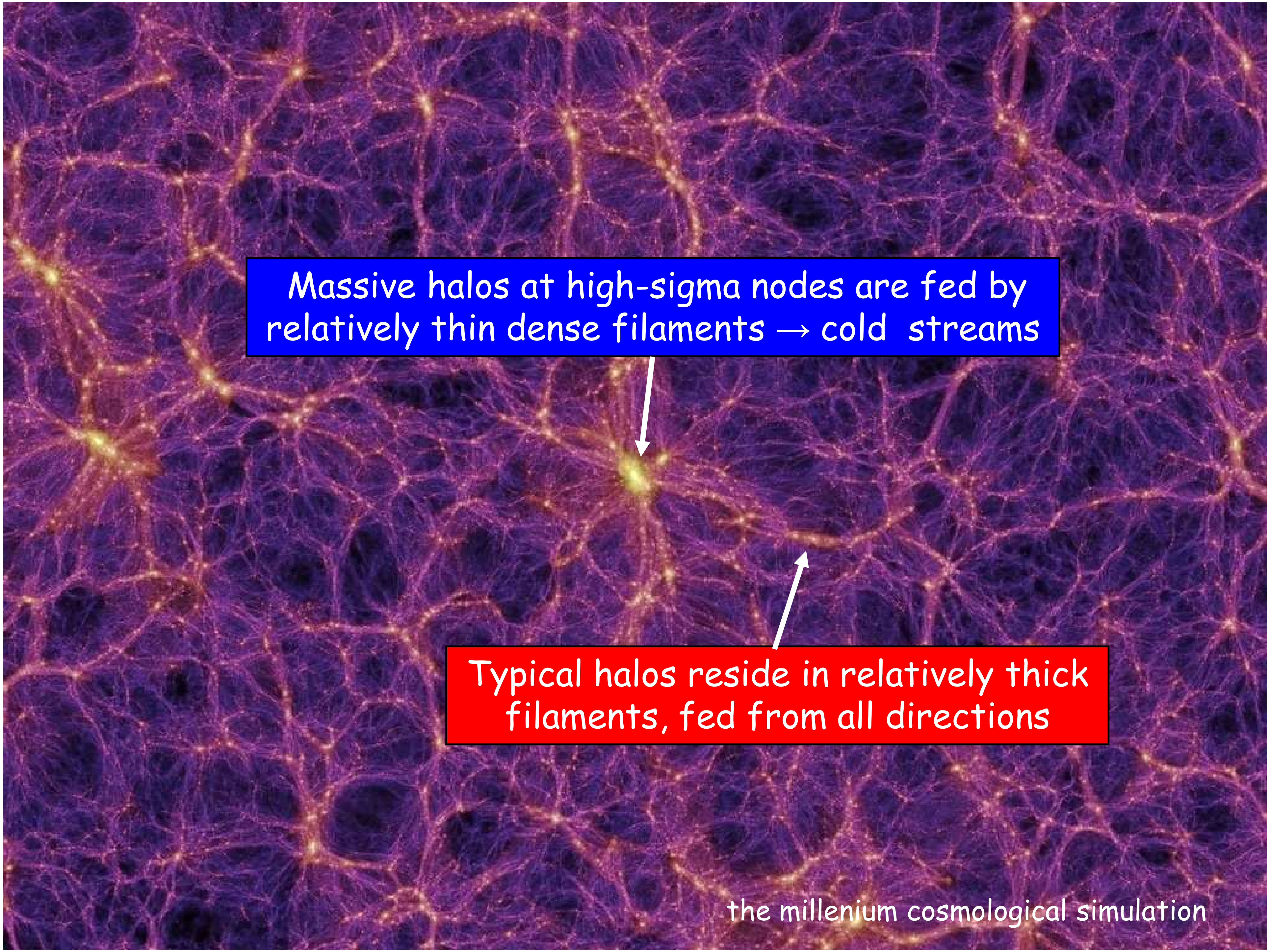
in hi-z massive hot halos cold streams penetrate



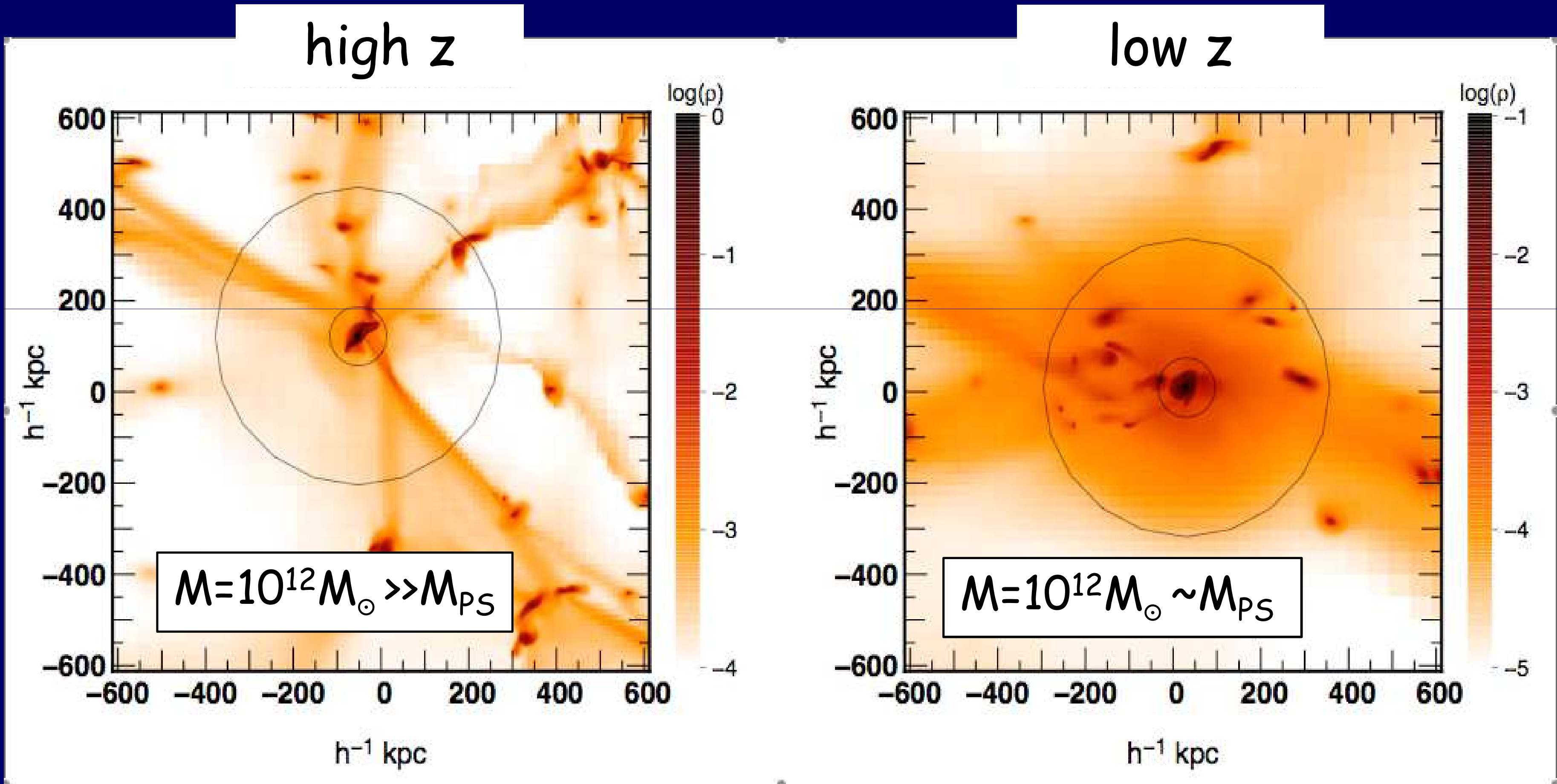
Cold Streams in Big Galaxies at High z



AD & Birnboim 06
Ocvirk+ 08
Keres+ 05,09

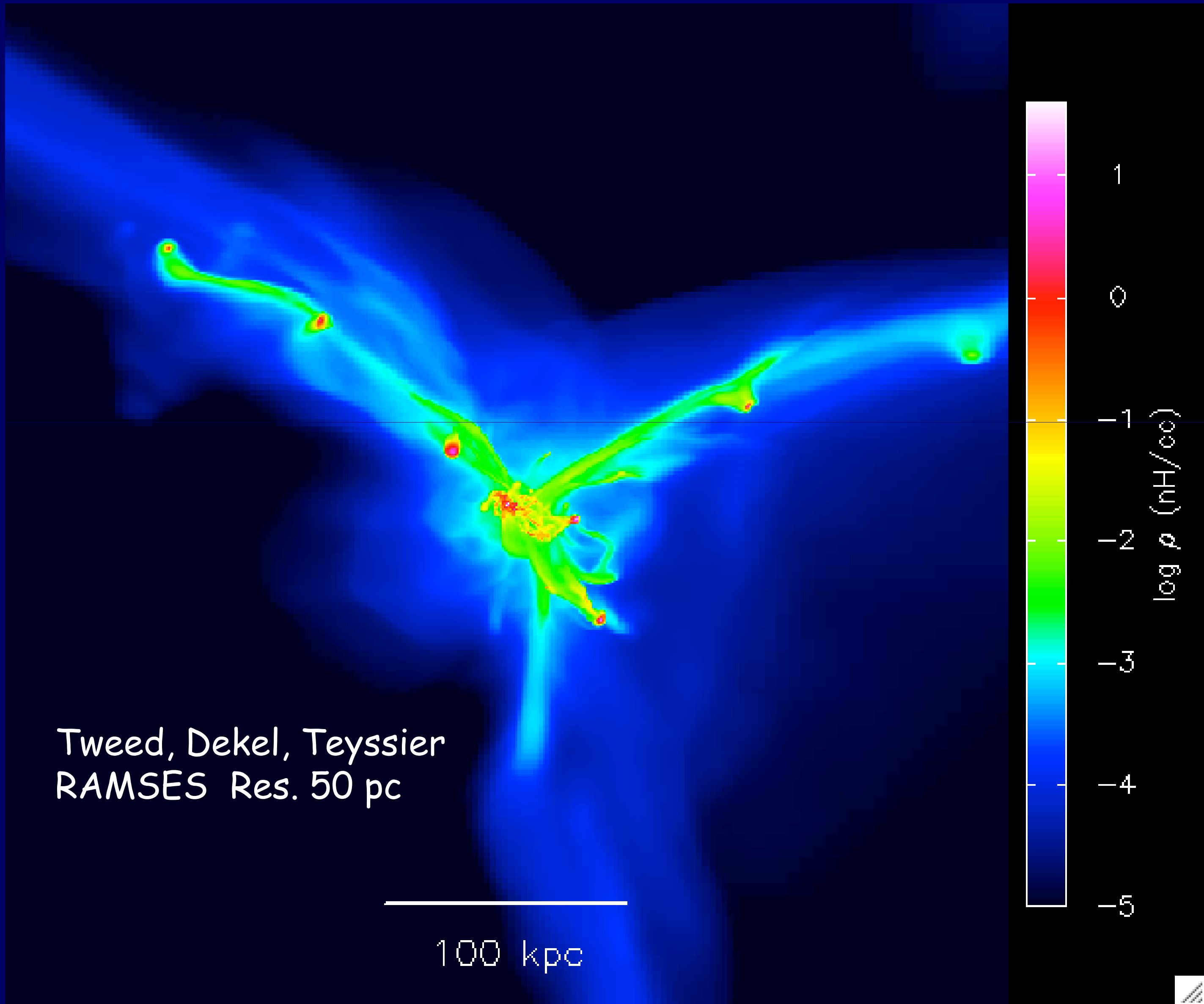

Massive halos at high-sigma nodes are fed by relatively thin dense filaments → cold streams
Typical halos reside in relatively thick filaments, fed from all directions
the millenium cosmological simulation

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



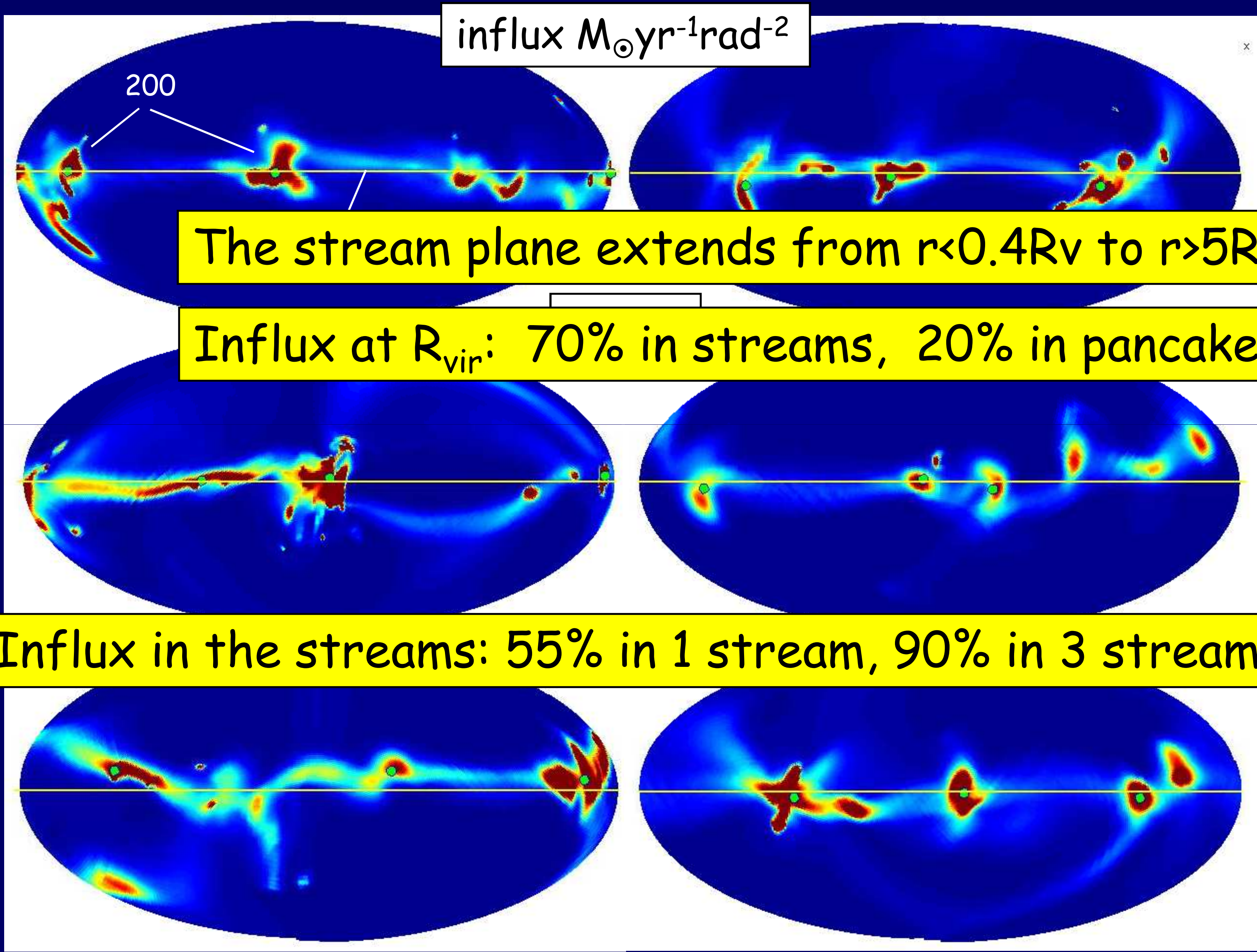
Ocvirk, Pichon, Teyssier 08

Streams Feeding a Hi-z Galaxy



Co-planar Streams and Pancakes

Danovich+12



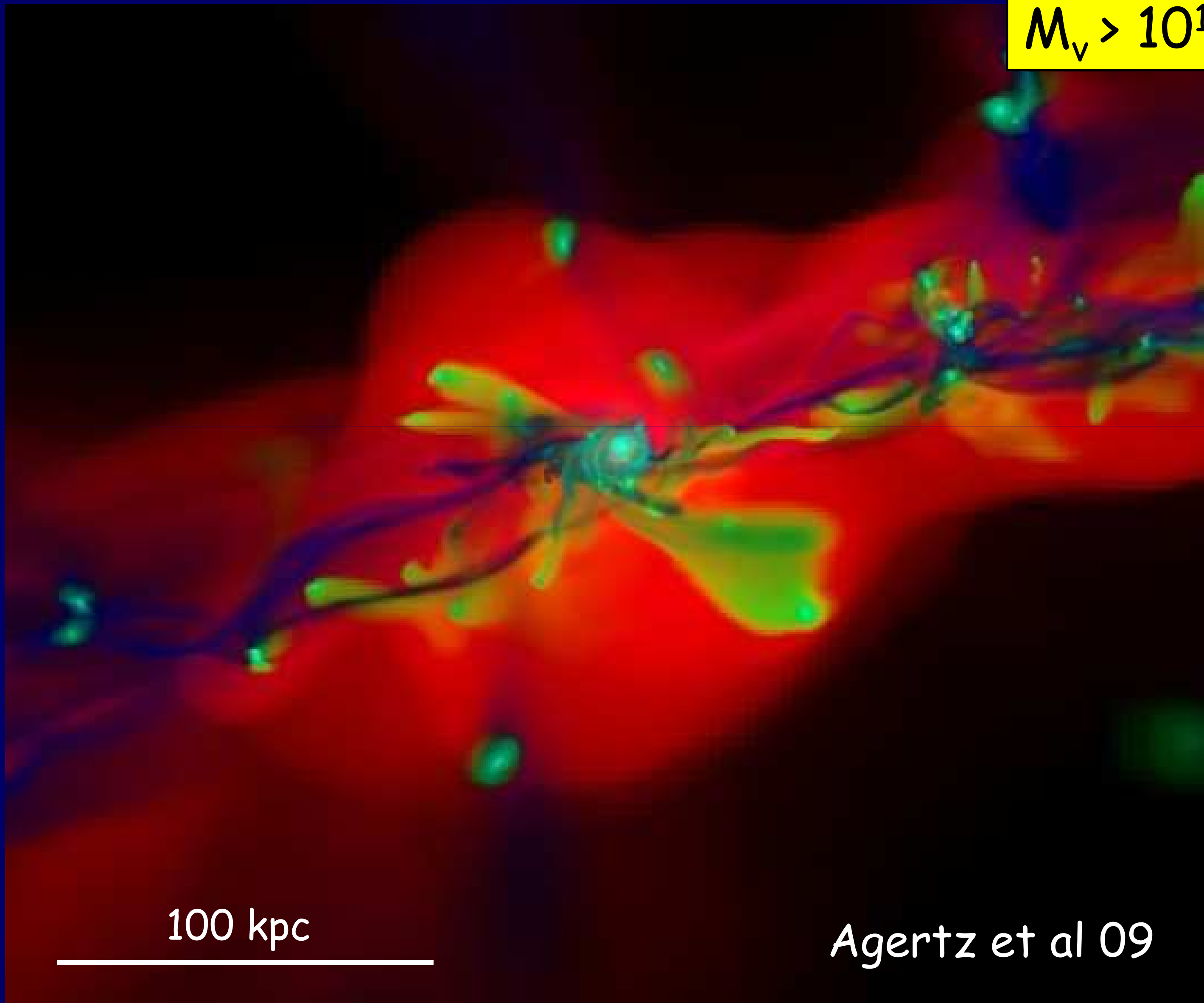
The stream plane extends from r<0.4Rv to r>5Rv

Influx at R_{vir}: 70% in streams, 20% in pancakes

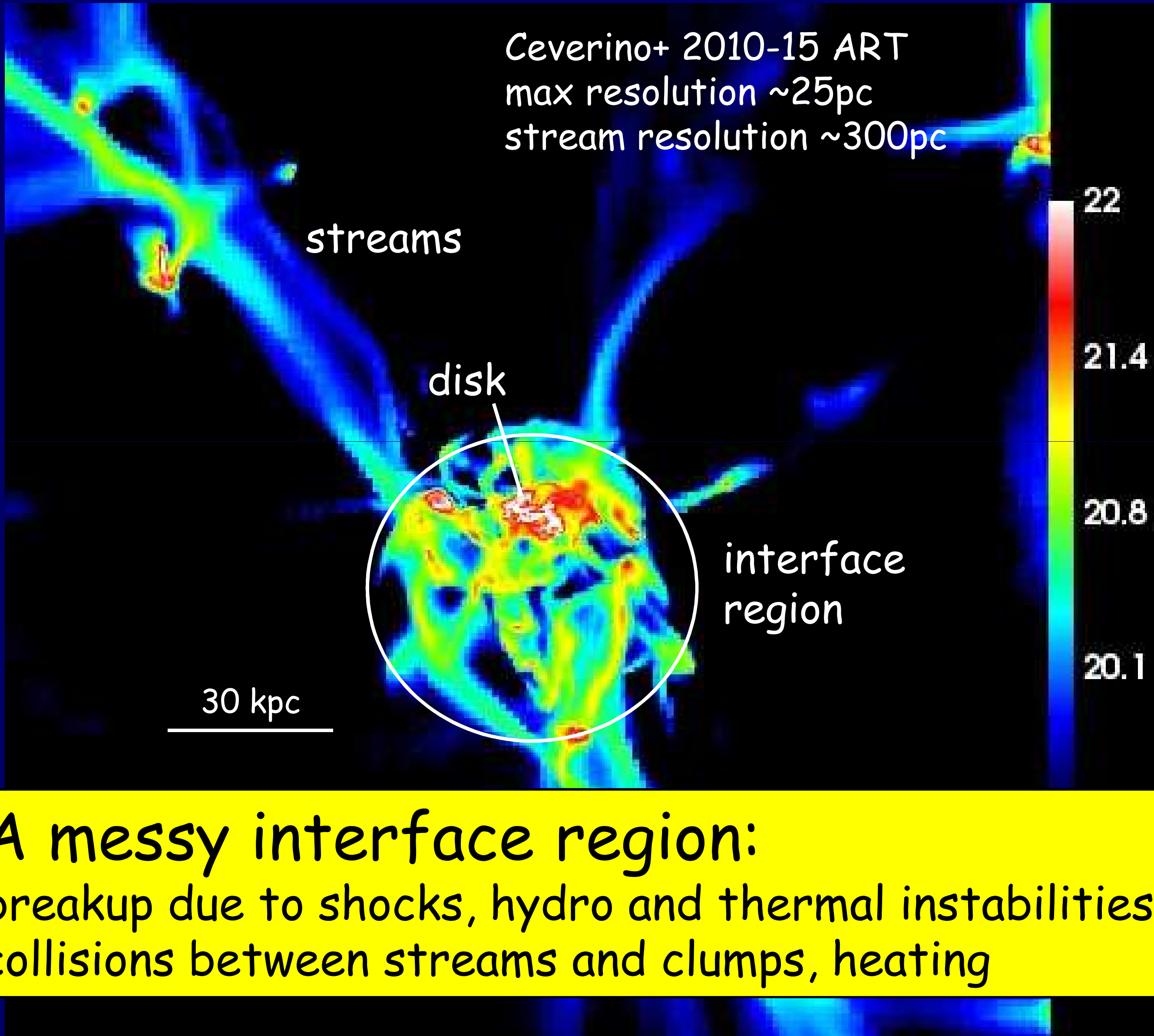
Influx in the streams: 55% in 1 stream, 90% in 3 streams

Cold Streams Penetrate through Hot Halos

$M_v > 10^{12}\ M_\odot$



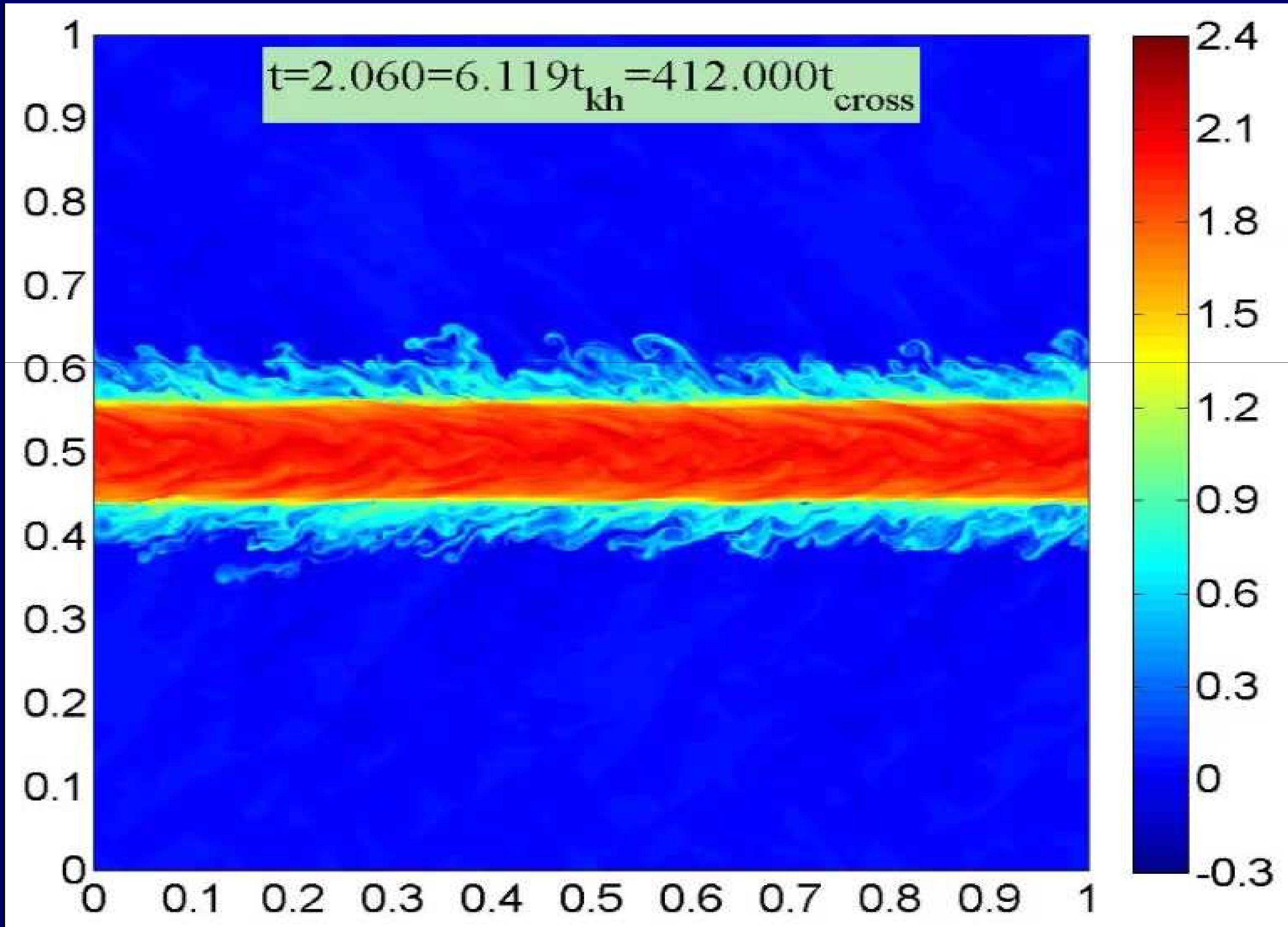
How do the streams join the disk?



A messy interface region:
breakup due to shocks, hydro and thermal instabilities, collisions between streams and clumps, heating

KH Instability of a Cold Supersonic Stream

Mandelker, Padnos+ 15 A cold dense stream in a hot dilute medium (2D adiabatic)



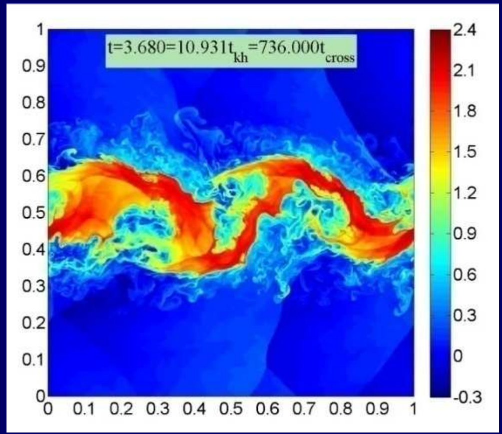
KH Instability of a Cold Supersonic Stream

Mandelker, Padnos, Birnboim, Burkert, Forbes, Krumholz, Ntormousi, AD 2015
A cold dense stream in a hot dilute medium (2D adiabatic)

Under what conditions (Mach, contrast, perturbation) the streams
- dissipate their kinetic energy and/or heat up?
- fragment and/or break up?

Linear perturbations may become nonlinear on a virial timescale
e.g. for Mach~1 and $\delta\rho/\rho \sim \delta T/T \sim 50$

Expect a boost by thermal and gravitational instabilities when cooling and self-gravity are incorporated



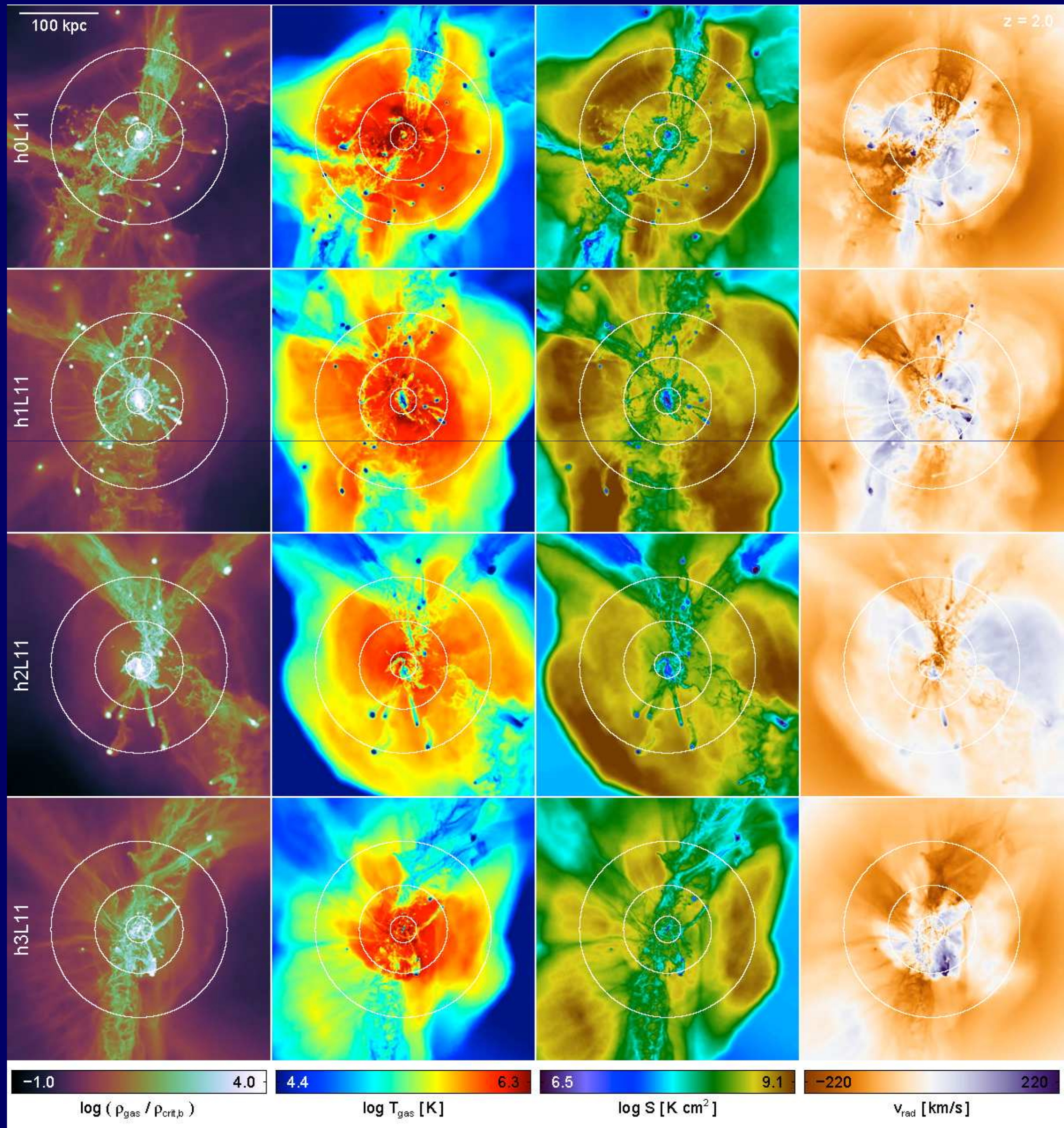
Cold Streams Heat Up in the Inner Halo?

Nelson+15 AREPO with effective resolution ~0.5 kpc in the streams

Streams penetrate all the way in, with low entropy and high influx, but heat up in the inner halo

Observational constraint: the SFR is ~ the inflow rate into the halo (within x2, same in simulations)

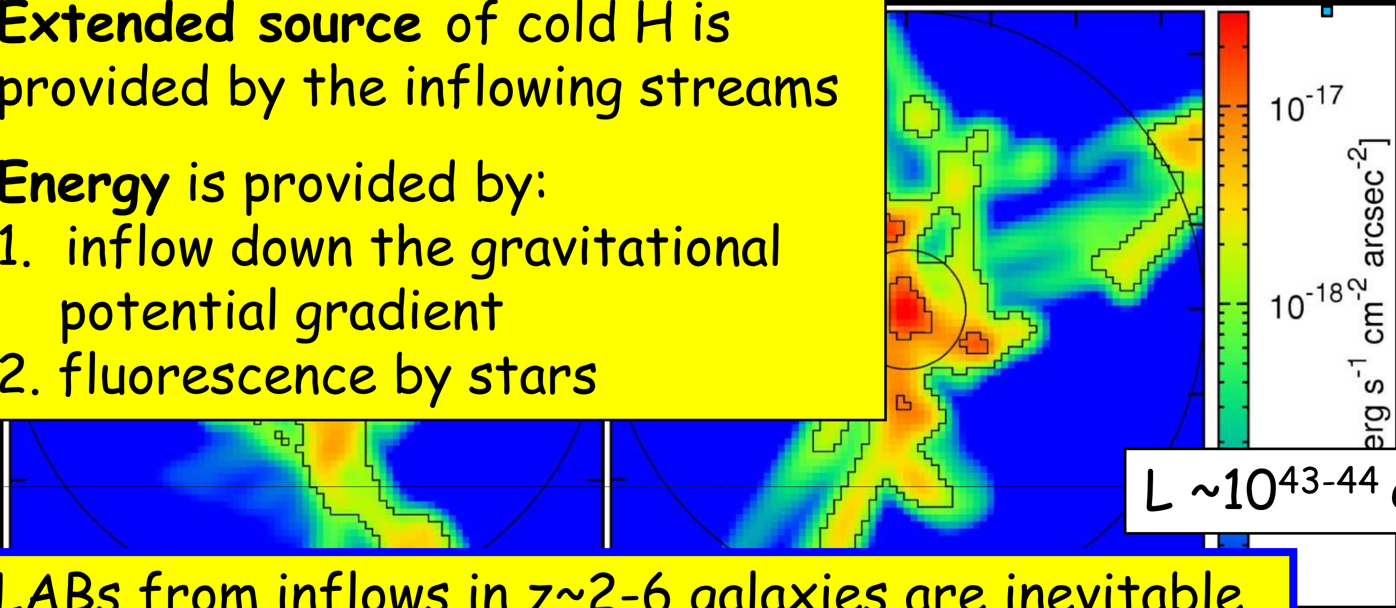
Heating and rapid cooling in the dense streams near the galaxy?



Cold streams as Lyman-alpha Blobs

Extended source of cold H is provided by the inflowing streams

Energy is provided by:
1. inflow down the gravitational potential gradient
2. fluorescence by stars

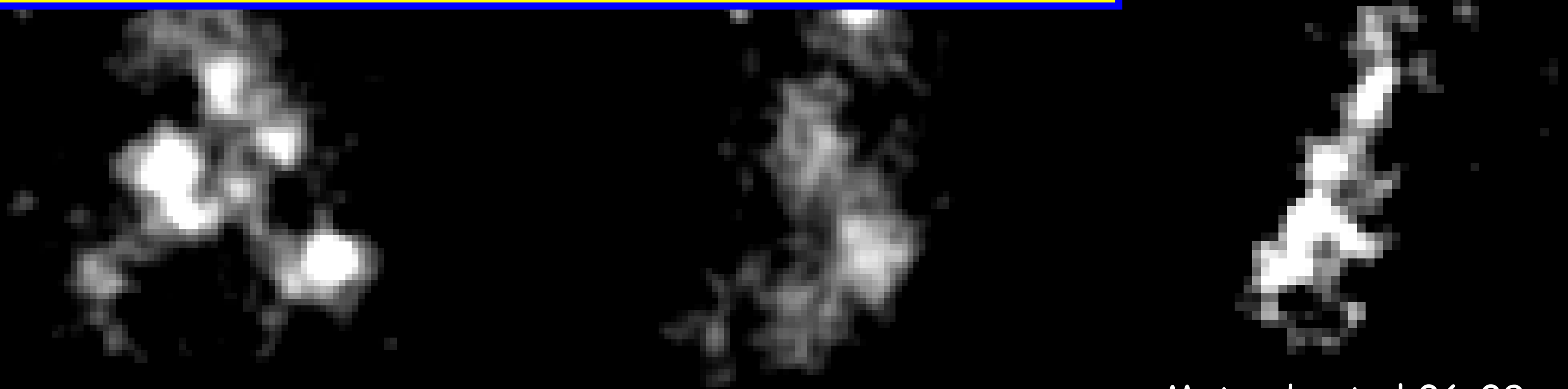


Goerdt+ 10

Faucher-Giguere, Keres+10

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

LABs from inflows in z~2-6 galaxies are inevitable.
Have cold streams been detected ?



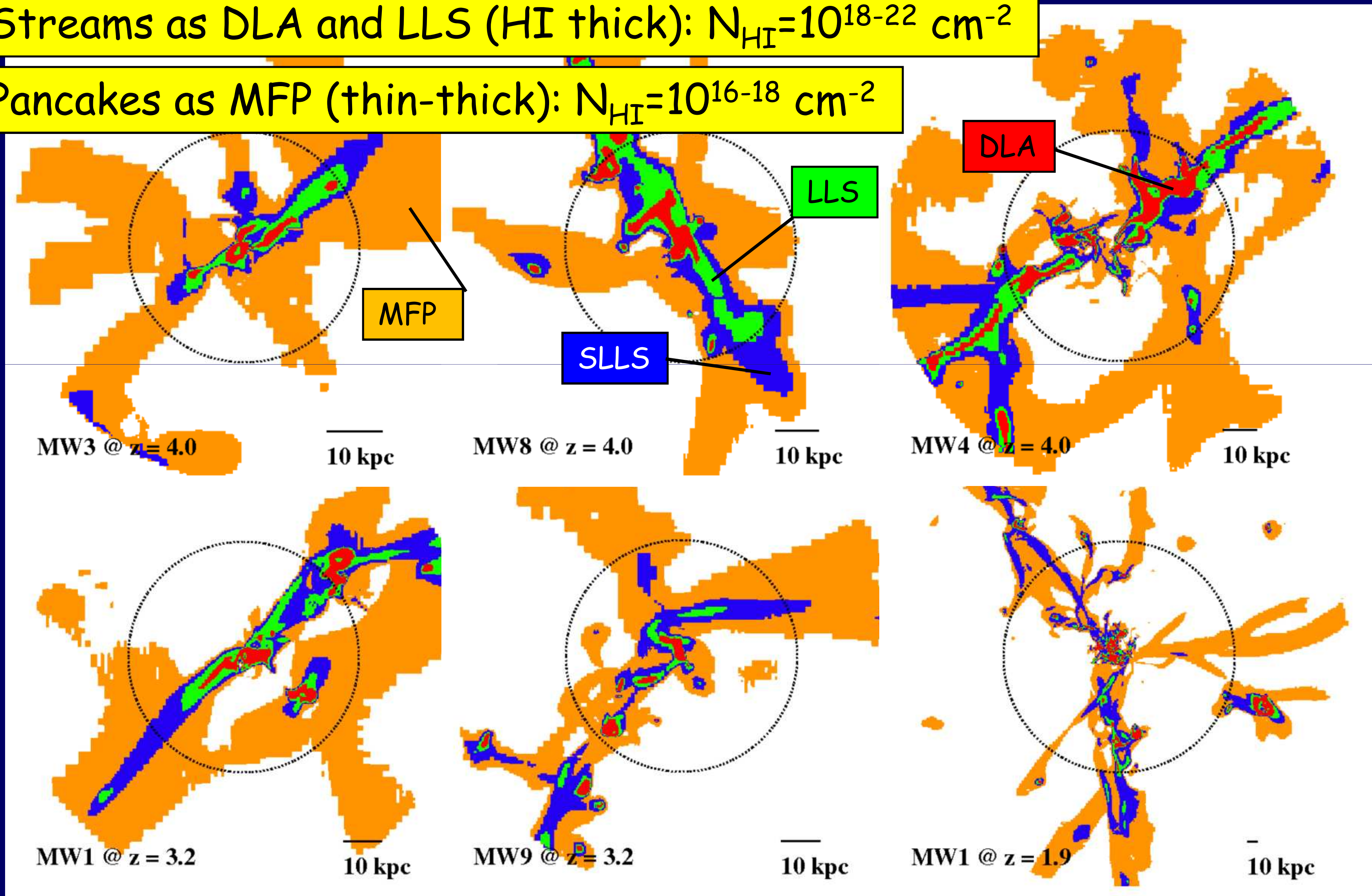
Matsuda et al 06-09

Cold Streams & Pancakes in Ly-a Absorption

Fumagalli+11 Goerdt+ 12

Streams as DLA and LLS (HI thick): $N_{HI}=10^{18-22}$ cm^{-2}

Pancakes as MFP (thin-thick): $N_{HI}=10^{16-18}$ cm^{-2}



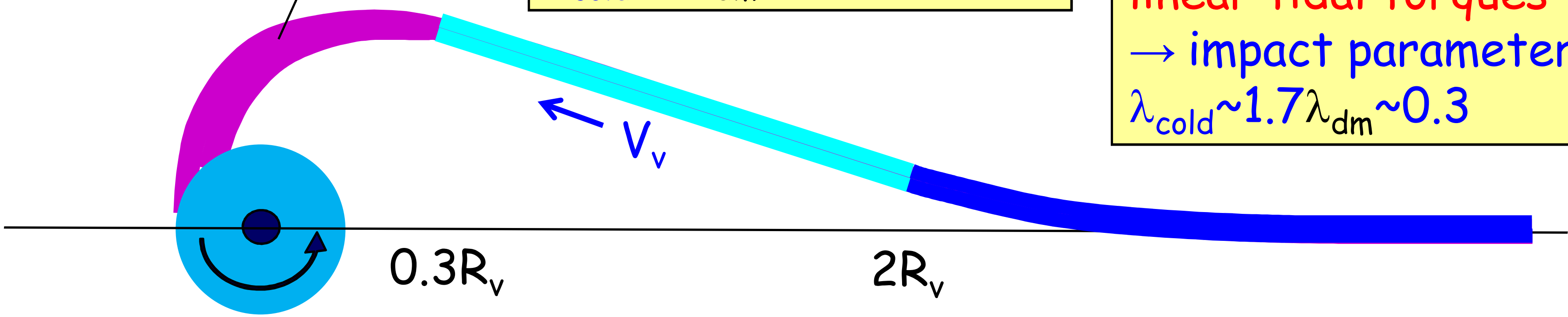
AM Buildup by Cold Gas in 4 Phases

Danovich+ 15

III. inner halo – extended tilted ring
non-linear torques, dissipation
AM loss $\lambda_{cold} \rightarrow 0.04$ & alignment

II. outer halo
AM transport, j~const.
$\lambda_{cold} \sim 3\lambda_{dm} \sim 0.1$ DM mix

I. cosmic web
linear tidal torques
$\rightarrow$ impact parameter
$\lambda_{cold} \sim 1.7\lambda_{dm} \sim 0.3$

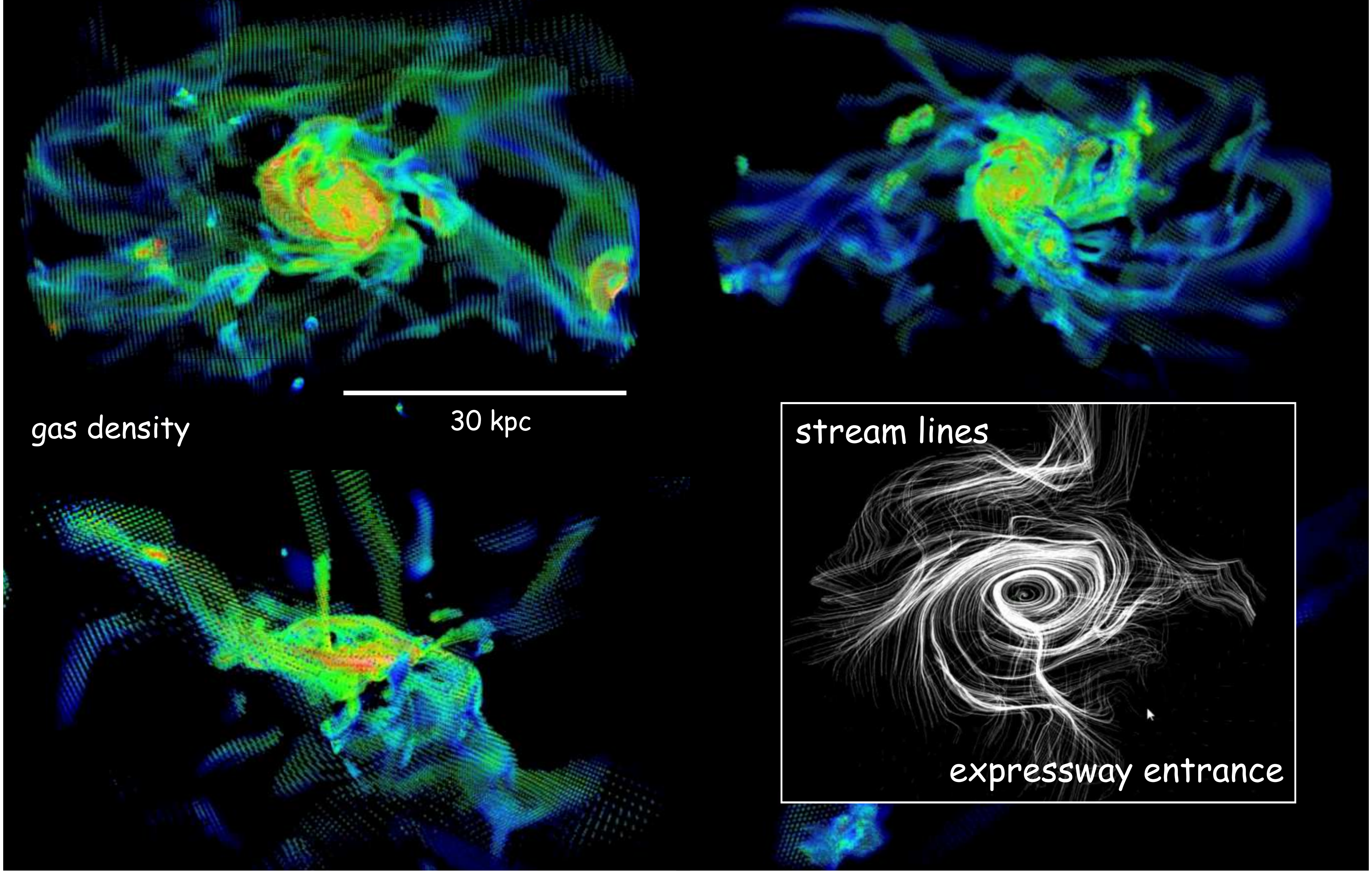


IV. inner disc (+ bulge)
disk instability, outflows
$\lambda_{baryons} \sim 0.03$

spin parameter $\lambda \sim \frac{J/M}{\sqrt{2}R_V V_V}$

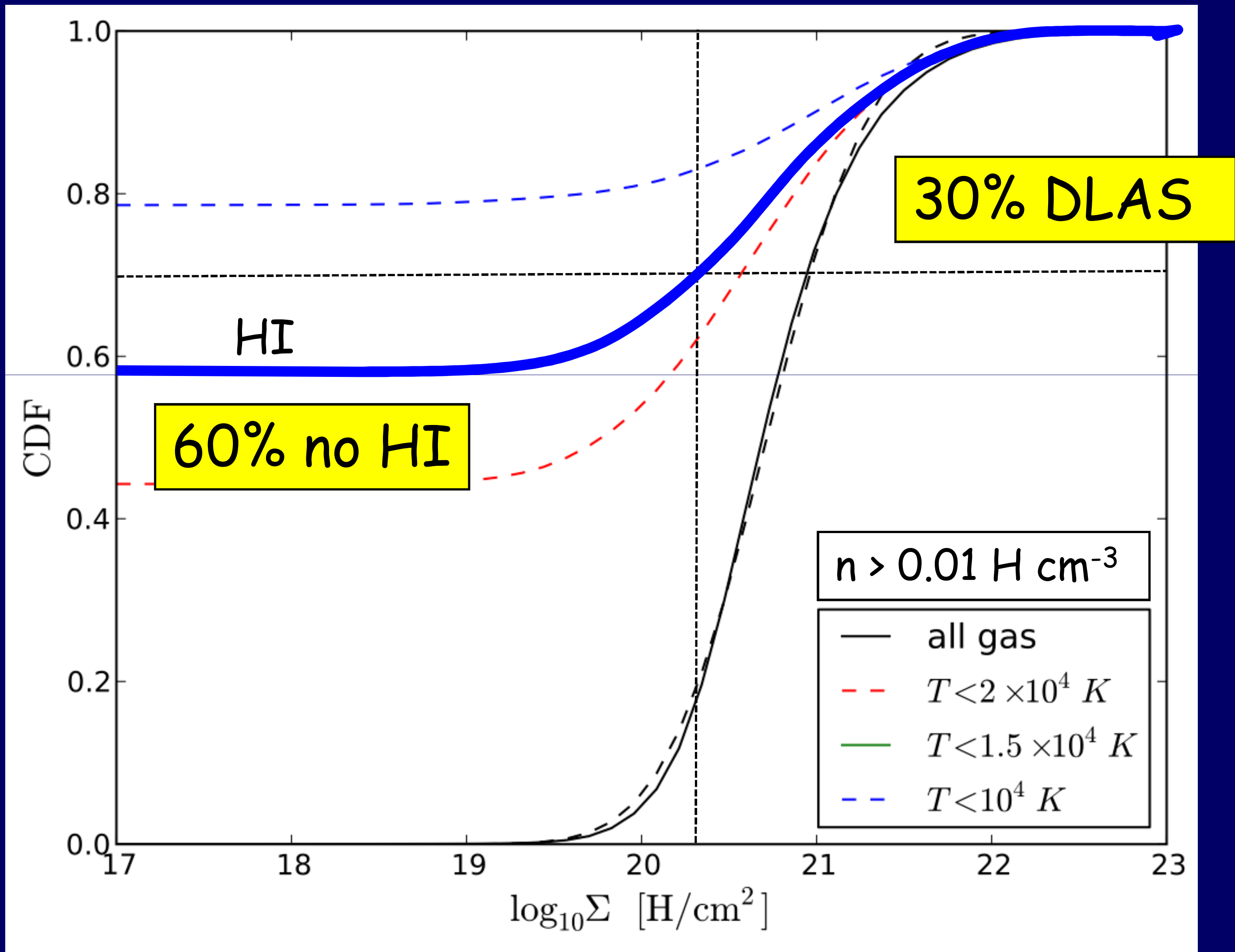
Streams Join the Disk via an Extended Ring

Stewart+ 11-15   Pichon+ 11-15   Danovich+ 12-15



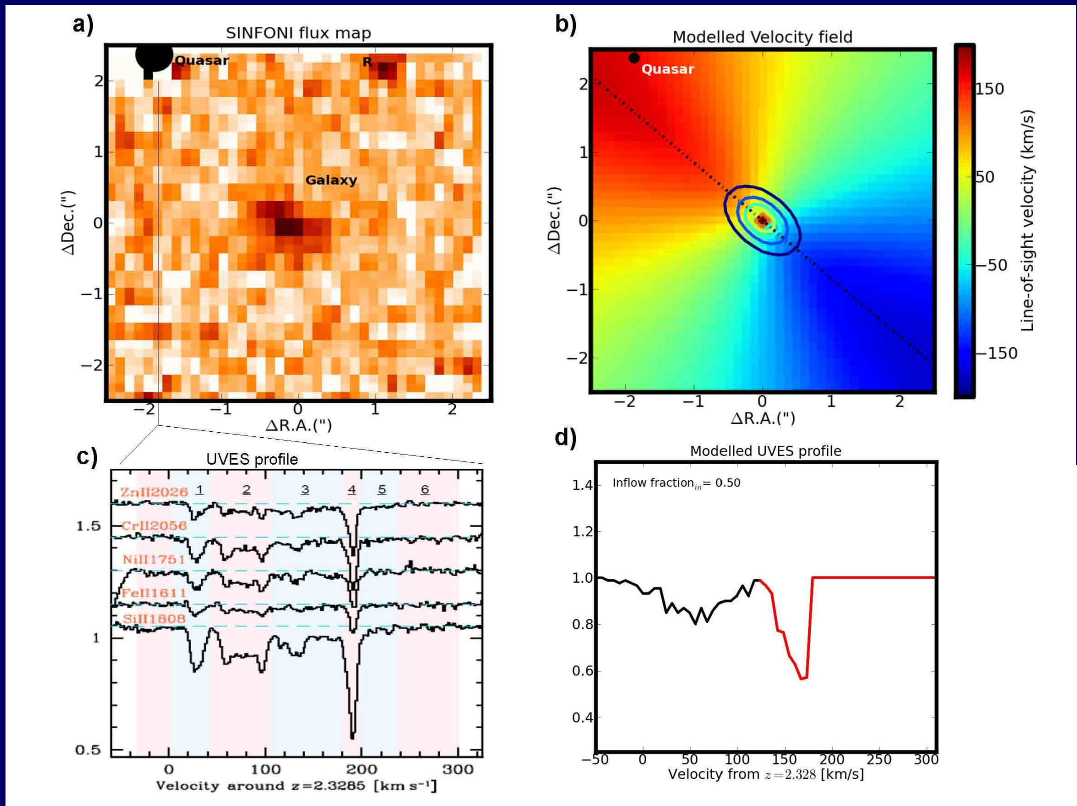
Extended Ring: HI Column Density

Random lines of sight through (0.1-0.3)R_v

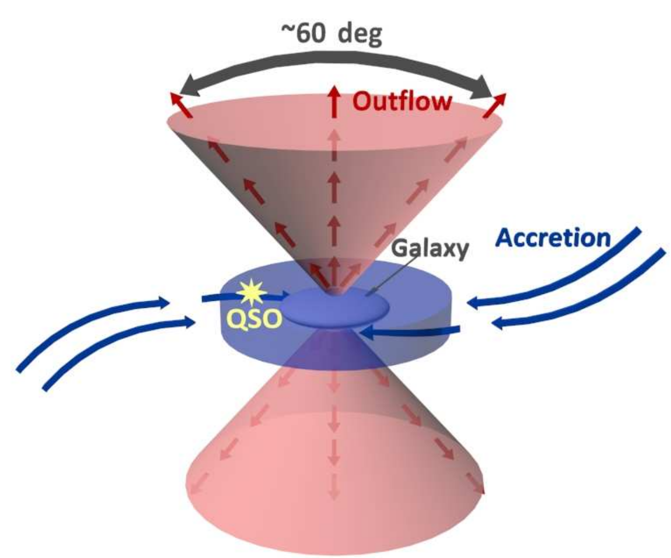


Detection of an Extended Ring?

Bouche+ 2013



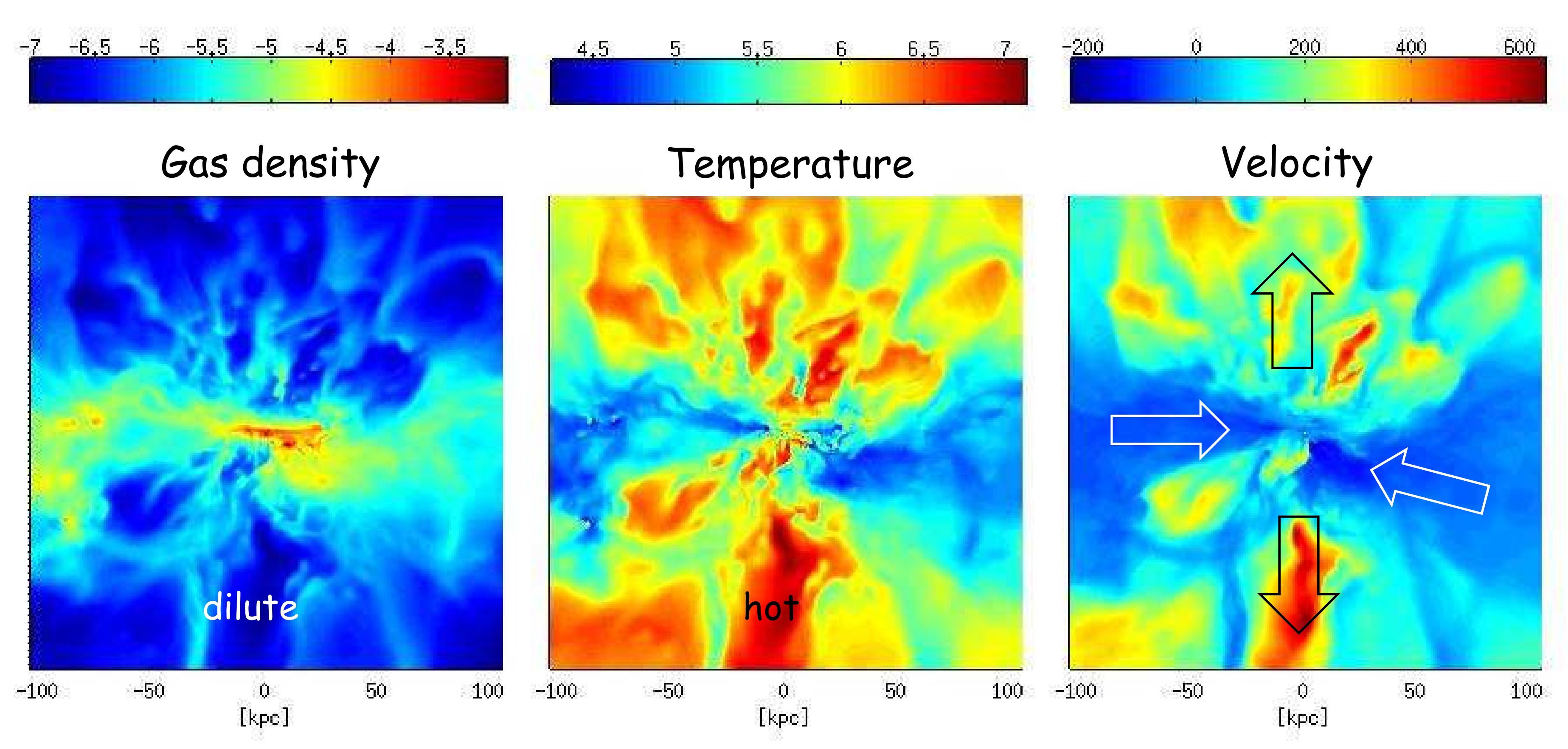
z=2.3
Low-Z gas
26 kpc from center
V=180 km/s



Crighton+ 2013 z=2.4, 54 kpc

Steidel+ 2002, Kacprzak+ 2010

Inflows and Outflows



DeGraf, Ceverino + 15
Nelson+ 15

cosmological simulations 25pc

z=2.6 M_v=7x10^{11}
radiative fdbk η~3

- Do outflows find their way out through the dilute medium?
- How do they affect the inflowing streams (smooth, mergers)?
- Recycling?

Minimal Bathtub Toy Model

Dekel, Mandelker 14
Dave+ Lilly+

Continuity gas: $\dot{M}_{\rm g} = f_{\rm ga}\dot{M}_{\rm acc} - (\mu+\eta)\dot{M}_{\rm sf}$

$\eta = \dot{M}_{\rm loss}/\dot{M}_{\rm sf} = \eta_{\rm out} - \eta_{\rm rec}$

stars: $\dot{M}_{\rm s} = f_{\rm sa}\dot{M}_{\rm acc} + \mu\dot{M}_{\rm sf}$

$\mu \approx 0.5$ fraction left in stars

Accretion rate $\dot{M}_{\rm acc}/M_{\rm acc} = 0.03\,Gyr^{-1}(1+z)^{5/2}$

$M_{\rm a} = M_{\rm ai}e^{-0.8(z-z_i)}$

SFR $\dot{M}_{\rm sf} = M_{\rm g}/t_{\rm sf} \quad t_{\rm sf} = \varepsilon^{-1}t_{\rm d} \propto t$

-> Simple equation $\dot{M}_{\rm g} = A - \tau^{-1}M_{\rm g}$

Quasi-steady-state solution

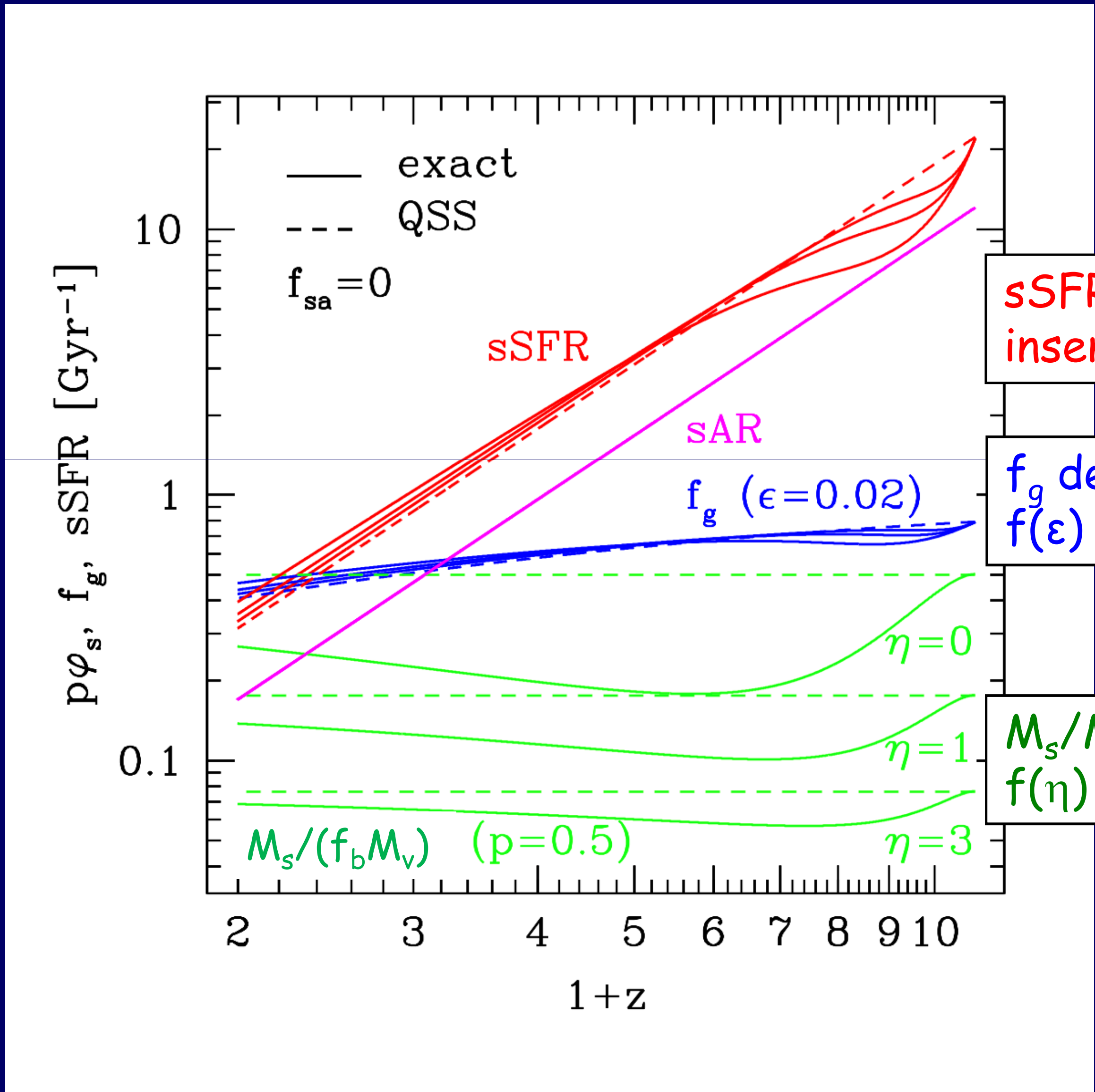
$\dot{M}_{\rm g} \approx 0$

$M_{\rm g} \approx A\tau$

$$\mathrm{SFR} \approx \frac{f_{\rm ga}}{\mu+\eta}\dot{M}_{\rm acc}$$

$$\mathrm{sSFR} = \frac{f_{\rm ga}}{\mu+f_{\rm sa}\eta}\,\mathrm{sAR}$$

Bathtub Toy Model: Solution



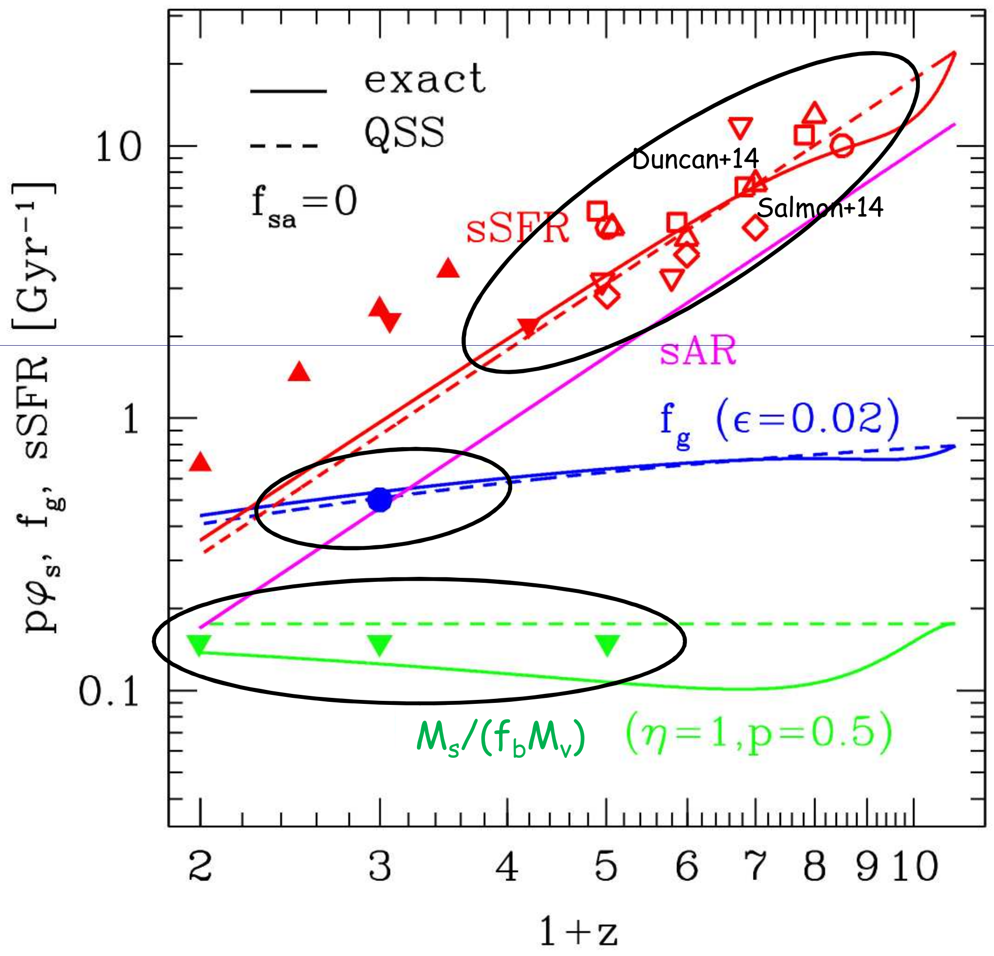
sSFR > sAR
insensitive to ε,η

f_g declines slowly
f(ε)

M_s/M_v ~const.
f(η)

Bathtub Toy Model vs Observations

If *gaseous accretion* (high z): a good fit at z>3



sSFR > sAR

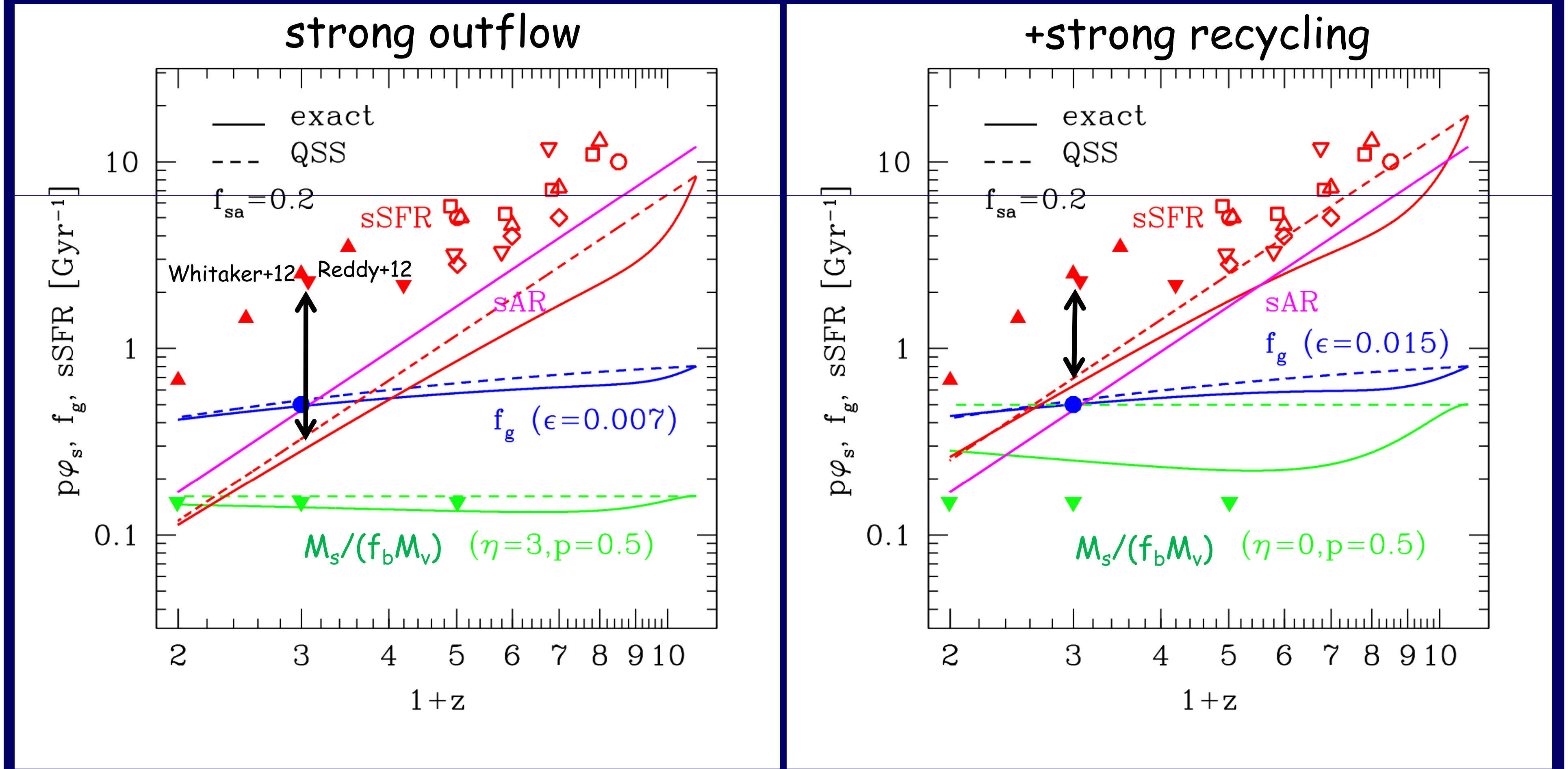
$f_g \rightarrow \varepsilon$~0.02

$M_s/M_v \rightarrow \eta$~1

Bathtub Toy Model vs Observations

If some stellar accretion: can't match the high sSFR at z~2

Modeling recycling? Observational bias? Toy model invalid?



Robust Predictions in LCDM Cosmology

Massive high-z galaxies are fed intensely by cosmic-web streams (and pancakes) involving smooth flows and merging galaxies,
$sAR \sim 0.04\ Gyr^{-1}\ (1+z)^{5/2}$

The streams tend to be co-planar out to a few R_{vir}
Inflow is 70% in streams (95% in 3 streams), 20% in pancakes

Gas streams penetrate to the inner halo ~constant inflow rate and V
Gas supply to the galaxy has to permit SFR ~ AR over long periods

Gas streams bring in AM (TTT), and lose some AM in an extended ring in the inner halo

Streams and outer ring are observable
in Ly-alpha (emission, absorption) and soft X-ray

Massive low-z galaxies are fed slowly by a hot mode from a wide angle

Open Issues and Challenges

Linear & Non-linear evolution of gas streams in the cosmic web
(e.g. mergers of streams, why 3 co-planar streams?,TTT)

Supersonic stream instabilities with ~10pc resolution:
dissipative slow-down & heating, fragmentation & break-up

Interplay between inflows and outflows, for a range of feedbacks

Recycling

Interplay between streams & galaxy: dissipation and AM exchange in the outer ring, stimulating disk instability, triggering compaction

Observed sSFR is ~ a few x predicted sAR at z=1-3

Observe the streams, e.g. the rotating tilted outer ring,
in Ly-alpha (emission, absorption) and X-ray