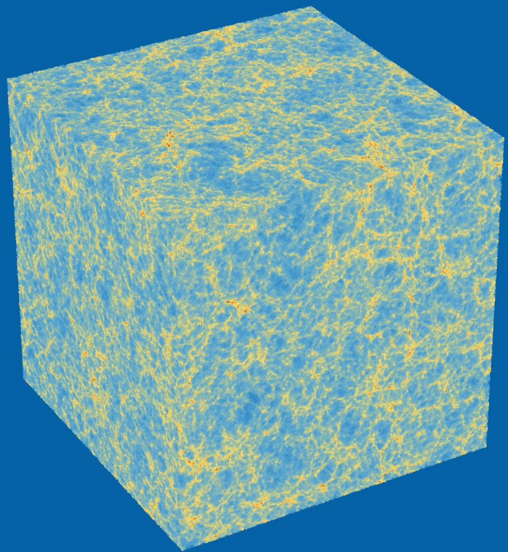
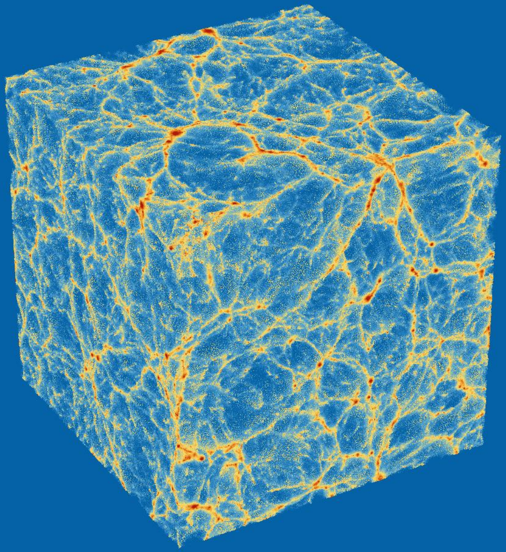
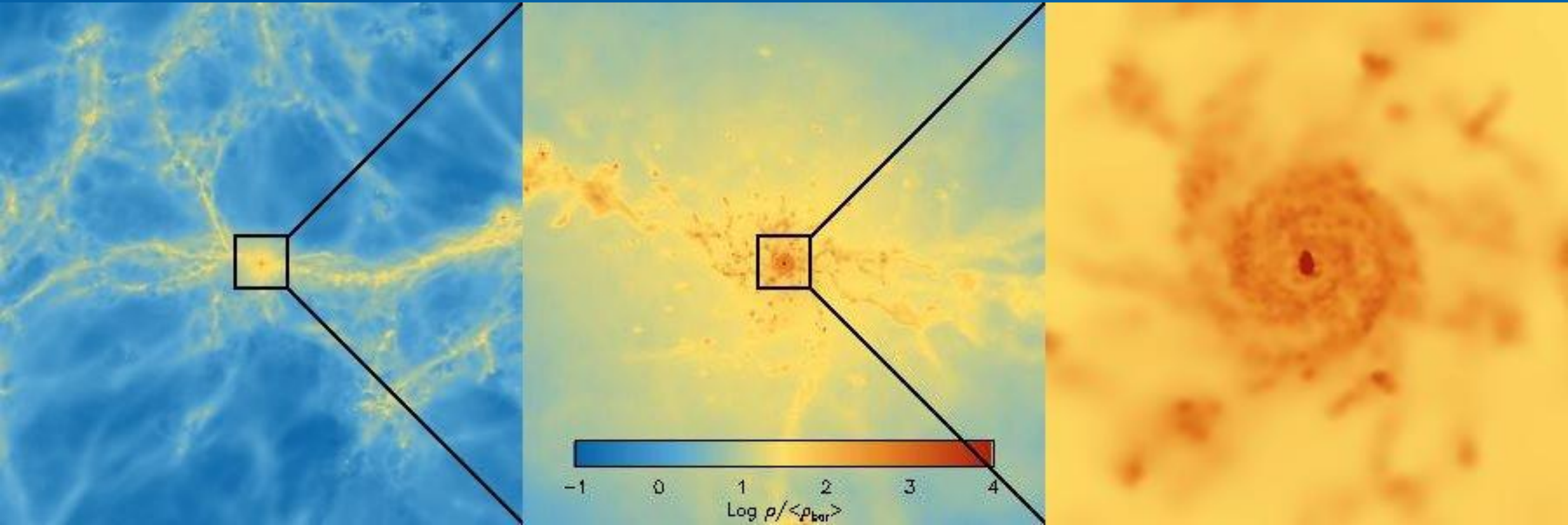
Gas around galaxies

Joop Schaye (Leiden)
(Yope Shea)







Galaxies and the IGM: Two sides of the same coin

- Central questions in galaxy formation:
  - How do galaxies get their gas?
  - How do galaxies regulate their rates of star formation and black hole growth?
  - What is the effect of the environment on galaxies?
  - How was the IGM reionized and enriched?
- All these questions involve the interaction between galaxies and the IGM. E.g.:
  - Galaxies are fueled by intergalactic gas
  - Feedback drives galactic winds into IG space
  - The IGM can strip/strangulate satellites

But one side is usually ignored…

- Semi-analytic models usually ignore the gas around galaxies in their comparison to observations
- Simulations of the ICM usually ignore observations of galaxies and BHs

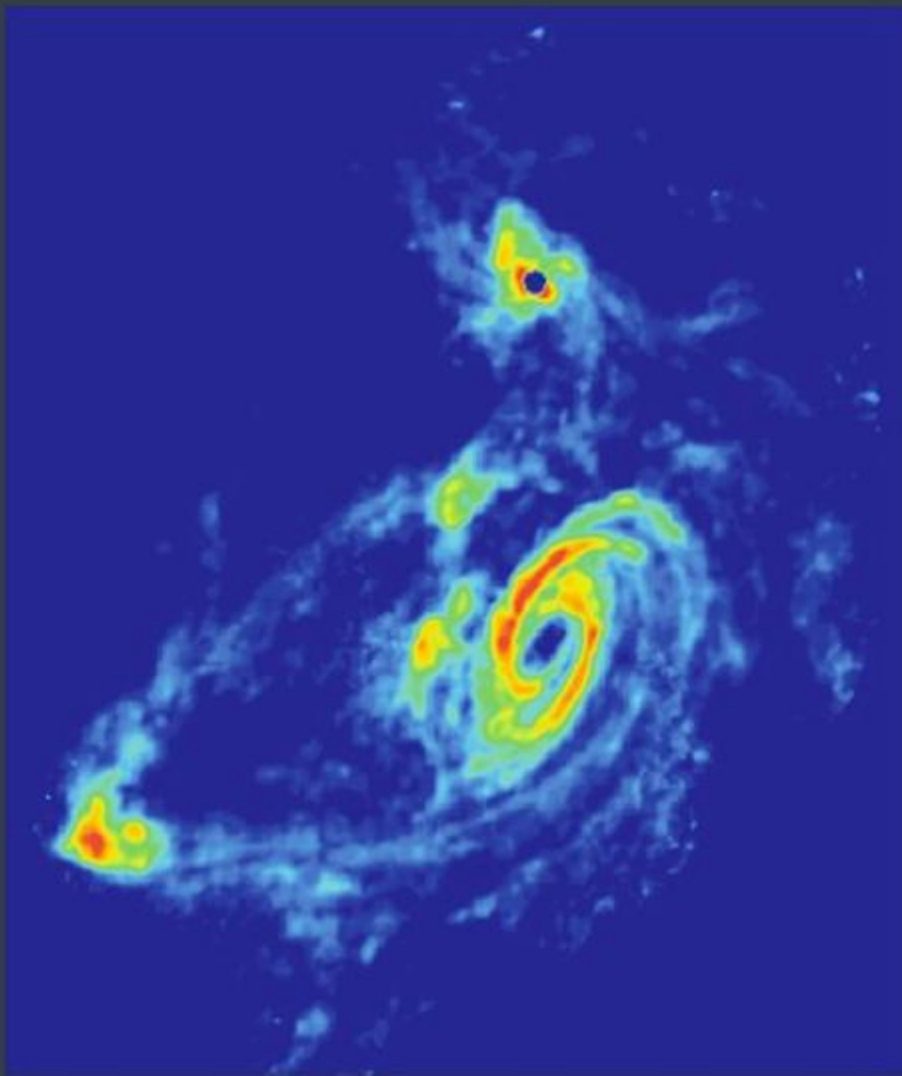
What can we learn from a model that reproduces selected observations but whose key ingredients (sources and sinks of gas and energy) are wrong?

Gas completes the picture

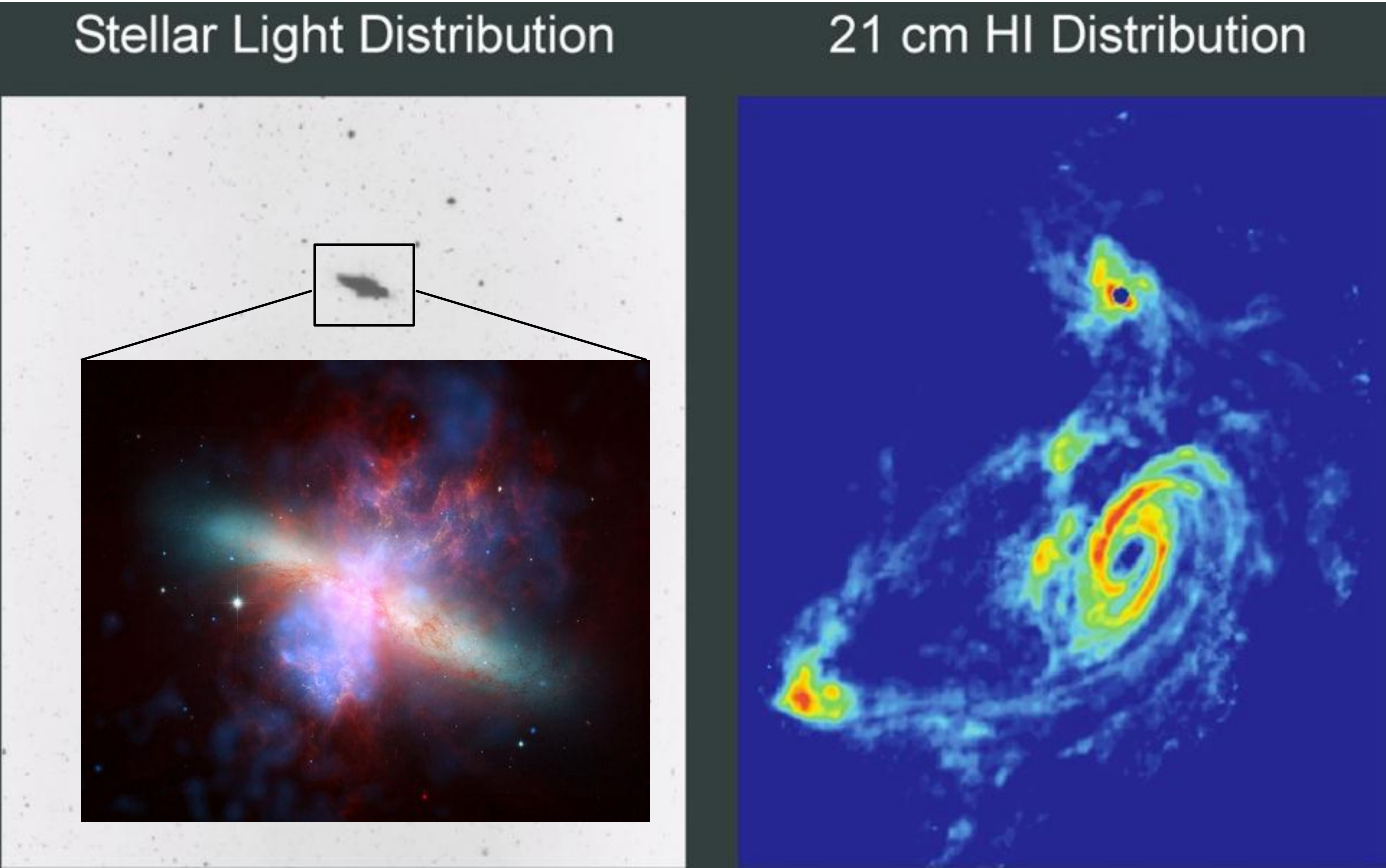
Gas completes the picture

Stellar Light Distribution

21 cm HI Distribution



Gas completes the picture



Cosmological hydro simulations

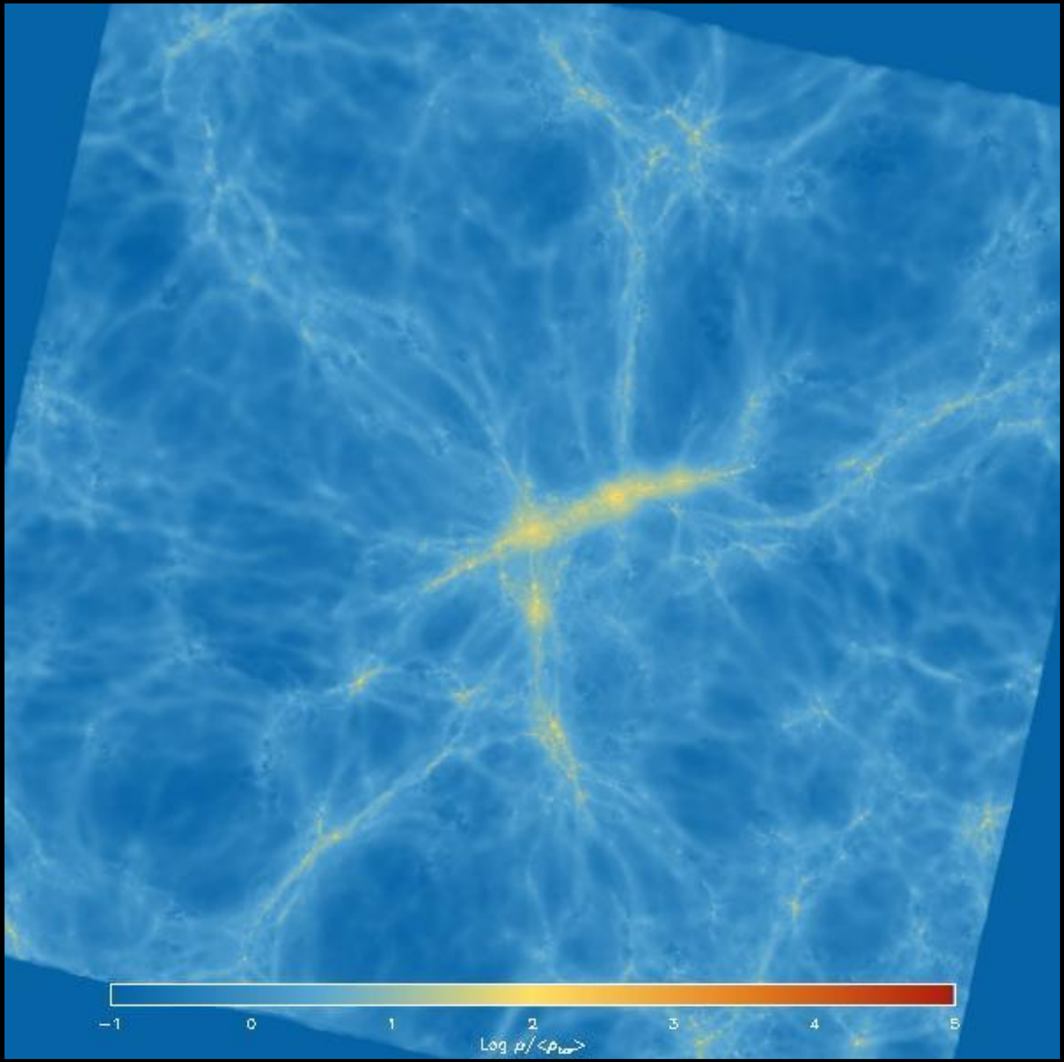
- Evolution from z>~100 to z ~< 10 of a representative part of the universe
- Expansion solved analytically and scaled out
- Initial conditions from the CMB & LSS
- Boundary conditions: periodic
- Components: cold dark matter, gas, stars, radiation (optically thin)
- Discretizaton: time, mass (SPH) or length (AMR)
- Gravity and hydro solvers (and MHD, RT, …)
- Scales ~< 10^3 pc to ~ 10^2 Mpc
- Sub-grid modules are a crucial part of the game

OverWhelmingly Large Simulations (OWLS)

- Cosmological (WMAP1/3/5), hydro (SPH,gadget 3; Springel 2005)
- New baryonic physics modules:
  - star formation (JS & Dalla Vecchia 2008)
  - SN feedback (Dalla Vecchia & JS 2008, 2010)
  - chemodynamics (Wiersma, JS, et al. 2009b)
  - radiative cooling (Wiersma, JS & Smith 2009a)
  - AGN (Booth & JS 2009; Springel et al. 2005)
- Two sets:
  - L = 25 Mpc/h to z=2 $m_{\mathrm{b}} = 1\times10^{6}\ h^{-1}\,\mathrm{M}_{\odot},\quad \varepsilon \leq 0.5\,h^{-1}\,\mathrm{kpc}$
  - L = 100 Mpc/h to z=0 $m_{\mathrm{b}} = 9\times10^{7}\ h^{-1}\,\mathrm{M}_{\odot},\quad \varepsilon \leq 2\,h^{-1}\,\mathrm{kpc}$
- Runs repeated many times with varying physics/numerics

JS, Dalla Vecchia, Booth, Wiersma, Theuns, et al. (2010)

Zooming into a massive galaxy at z=2: Gas density



Depth: 2 Mpc/h

Log M = 12.6
Log M* = 11.5

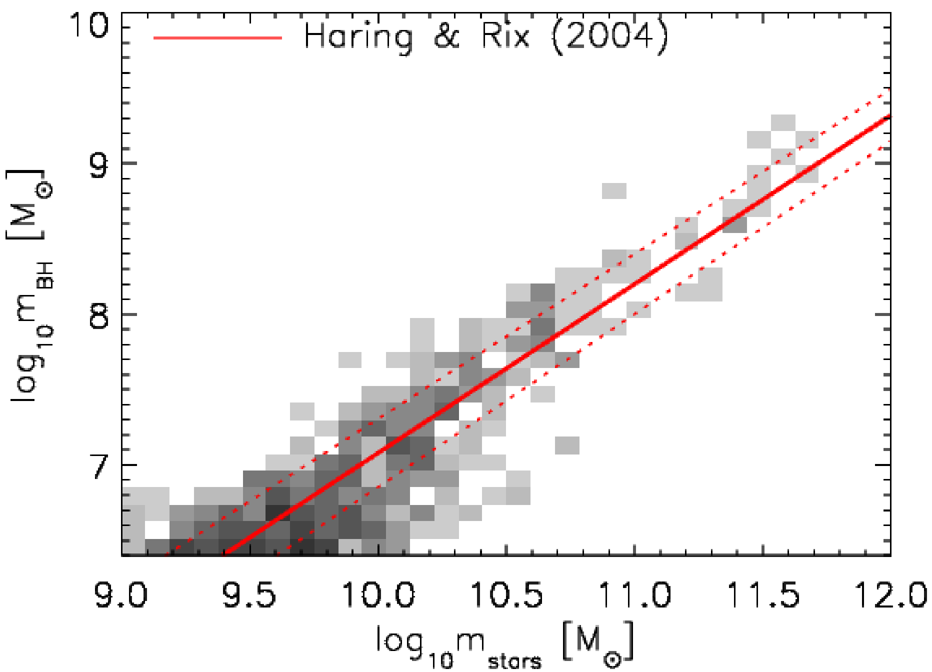
Simulation:
REF
L025
N512

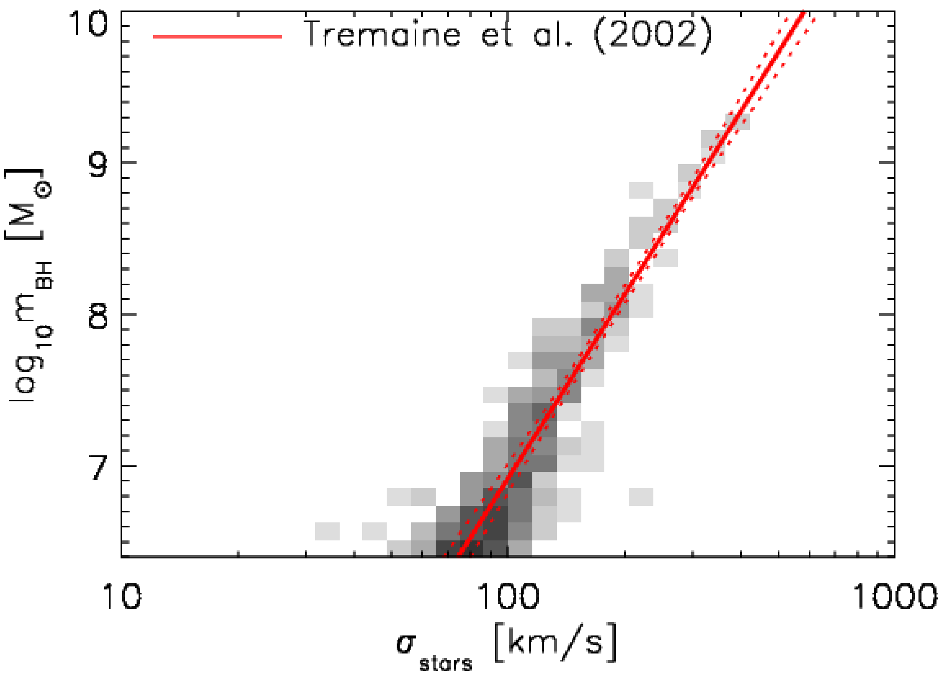
25 Mpc/h

Why study groups of galaxies

- Nearly all stars are formed in groups
- Most stars are still in groups
- Clusters form from groups
- **Can observe both the stars and the gas (in emission)**
- Both feedback from SF and AGN could be important (on energetic grounds)

BH scaling relations



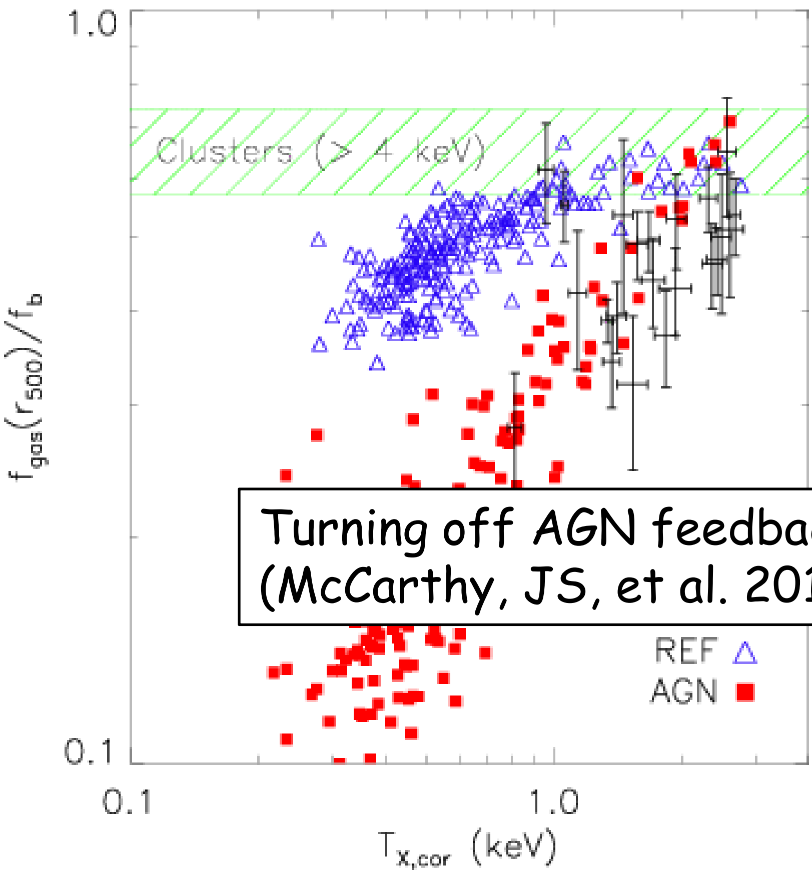


Feedback efficiency: 1.5%

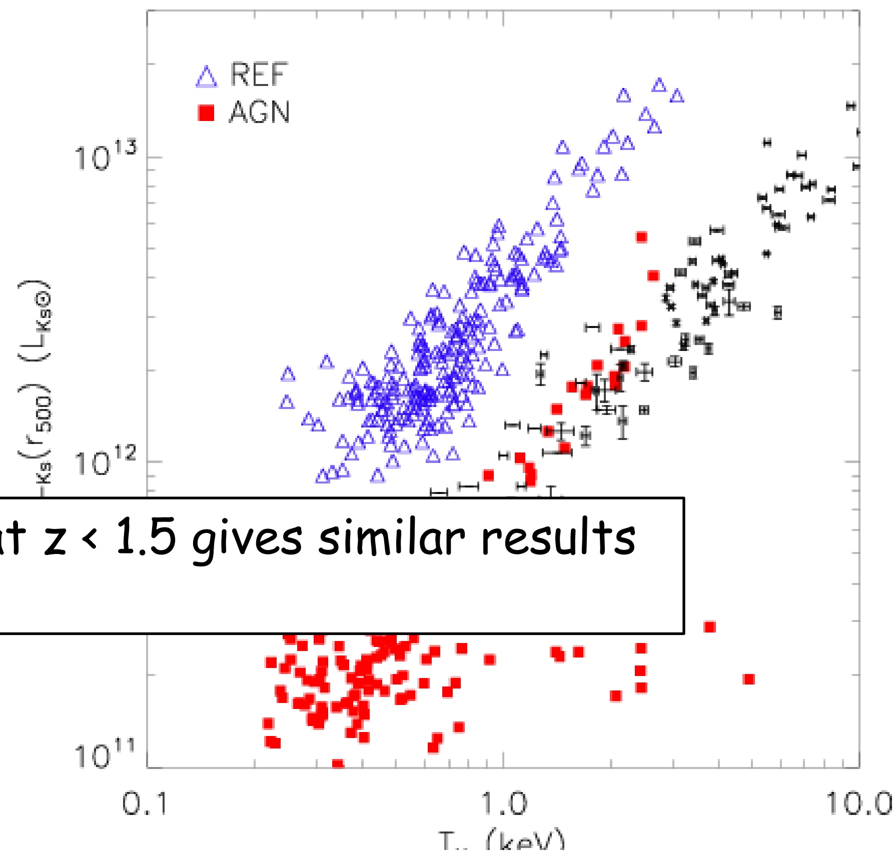
Booth & JS (2009, 2010)

Group gas and stellar contents

Gas fraction



K-band luminosity



Turning off AGN feedback at z < 1.5 gives similar results (McCarthy, JS, et al. 2011)

McCarthy, JS, et al. (2010)

Observations: Lin & Mohr 2004, Horner 2001, Rasmussen & Ponman (2009)

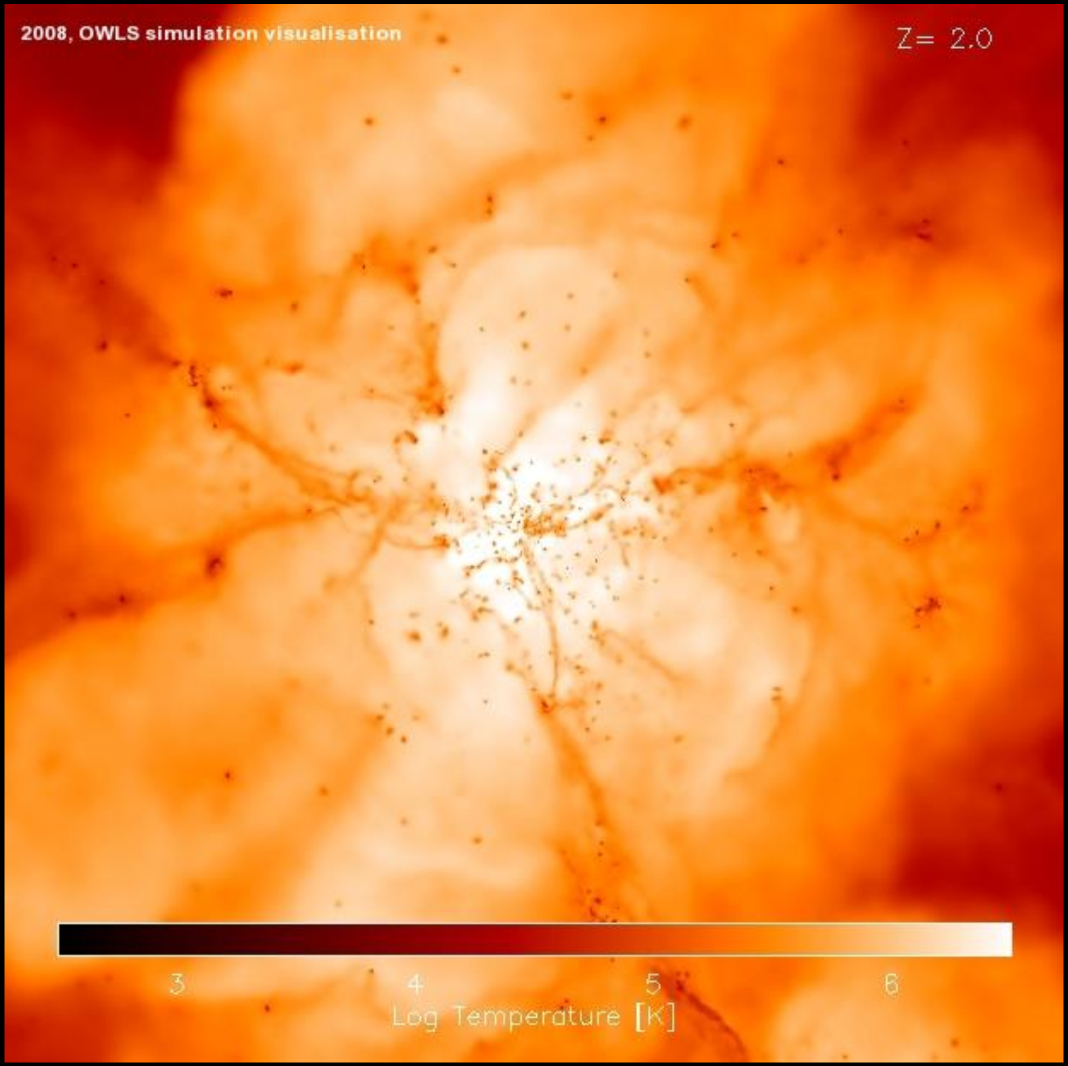
Groups of galaxies

- AGN feedback enables hydro simulations to simultaneously match the stellar *and* gas properties (McCarthy, JS+ 2010; Puchwein+ 2010; Fabjan+ 2010)
- AGN eject low-entropy gas at high redshift ($z > 1.5$; quasar mode) (McCarthy, JS+ 2011)
  - Low gas fractions at low z
  - High entropy gas replaces ejected material (but entropy not directly raised by AGN!)
- Low gas fractions imply that BH (and bulge) growth is regulated on the scale of dark haloes (Booth & JS '09, '10, '11)

Gas accretion

- Semi-analytic models assume spherical symmetry
- Simulations show importance of cold inflowing streams (e.g. Keres+ 2005, Ocvirk+ 2008; Dekel+ 2009) and the disruptive effect of outflows (e.g. van de Voort 2011a,b,c; Crain+ 2010; McCarthy+ 2011)

Evolution of a massive galaxy down to z=2

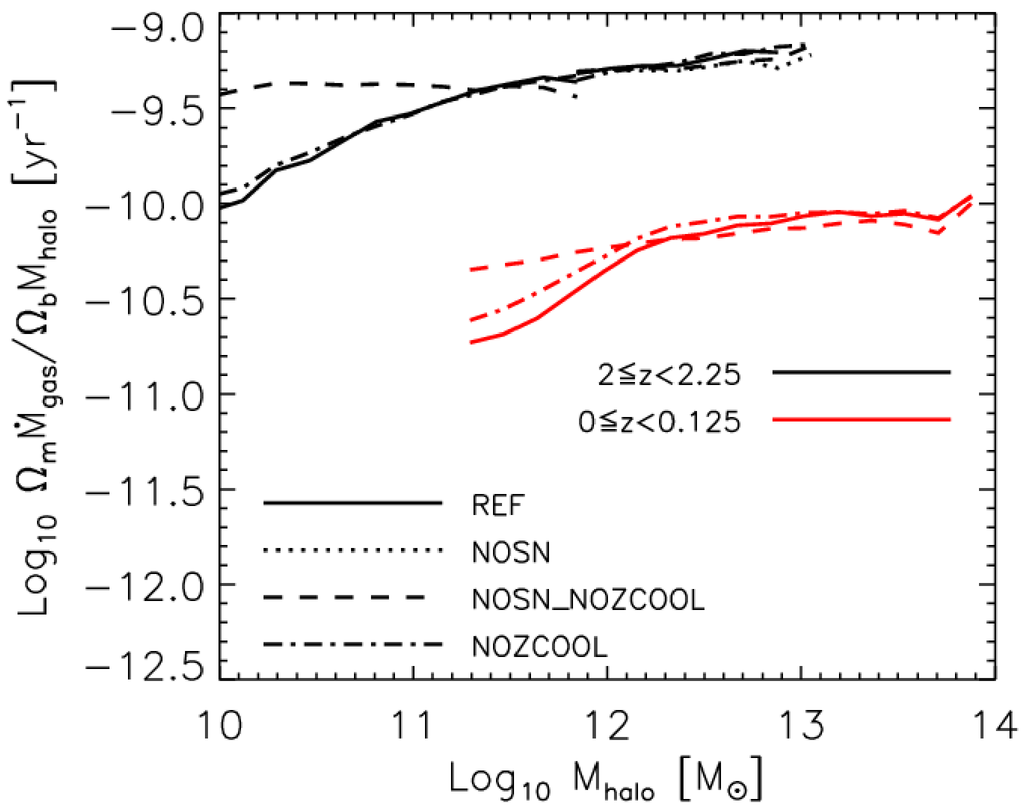


3 Mpc/h

At z = 2:
Log M = 12.3
Log M* = 10.6

Simulation:
WVCIRC
L025
N512

Specific accretion rates onto haloes

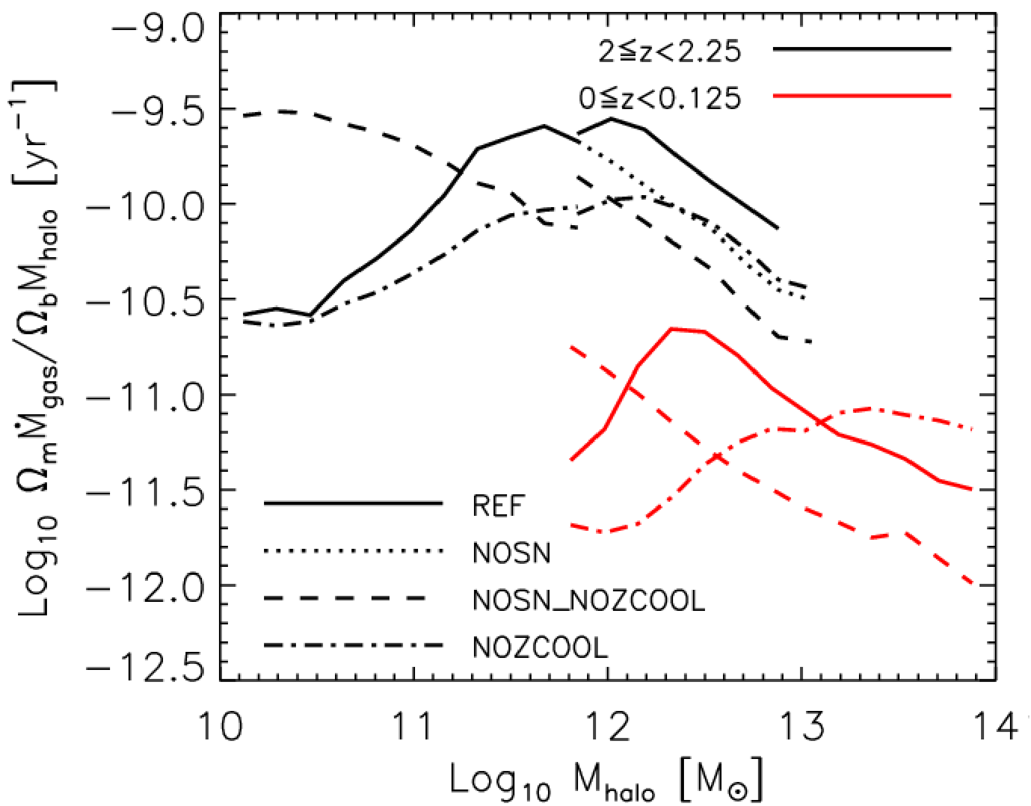


Specific accretion rates onto haloes:

- Nearly independent of mass
- Increase with z
- Fairly insensitive to feedback

Van de Voort, JS et al. (2011a)

Specific accretion rates onto galaxies

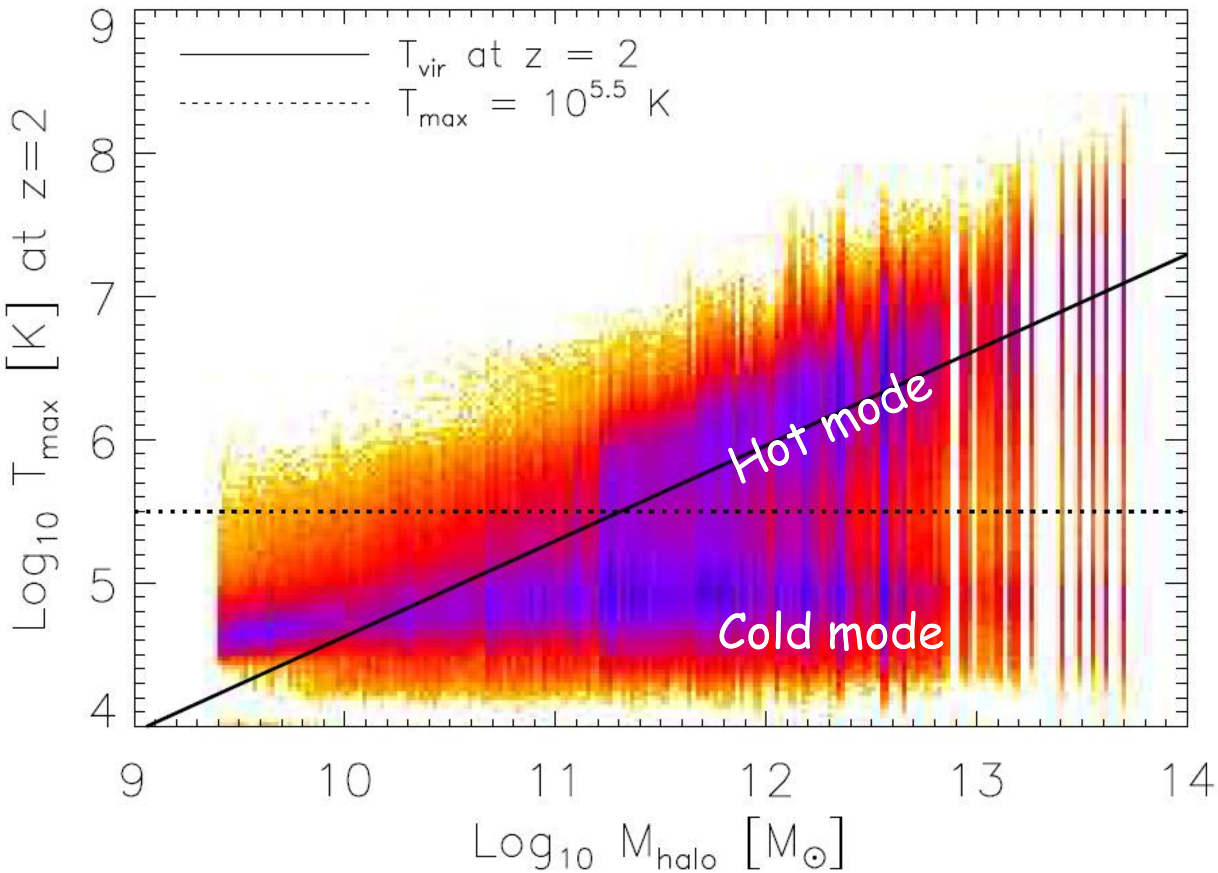


Specific accretion rates onto galaxies:

- Peak at $M_{halo} \sim 10^{12}\ M_{\odot}$
- Increase with z
- Sensitive to feedback
- Much smaller than halo accretion rates

Van de Voort, JS et al. (2011a)

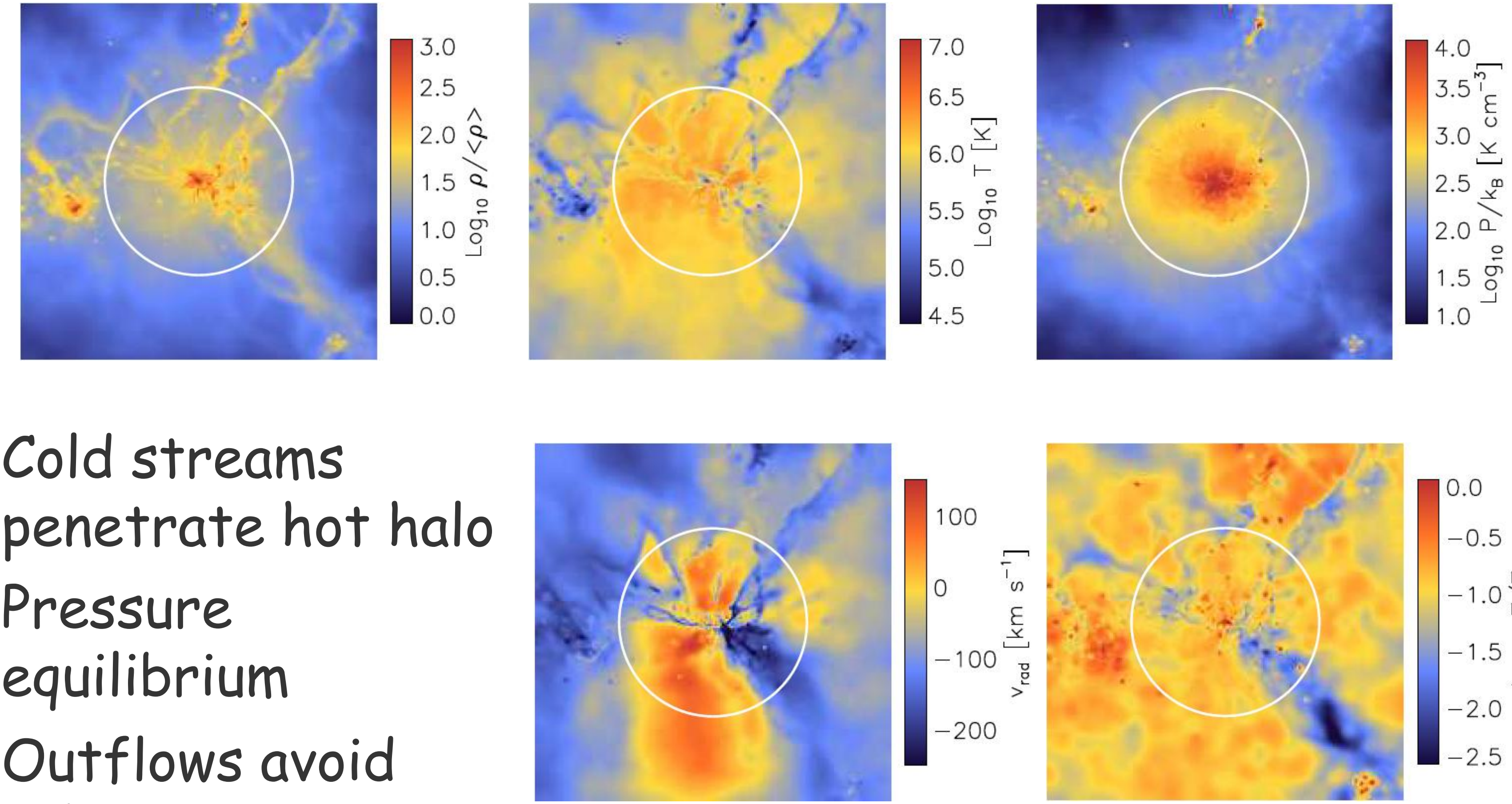
Two modes of gas accretion



- Bimodal temperature distribution
- Hot accretion more important in massive haloes (> $10^{12}\ M_\odot$)

Van de Voort, JS et al. (2011a)

A 10^{12} $M_{\odot}$ at z = 2

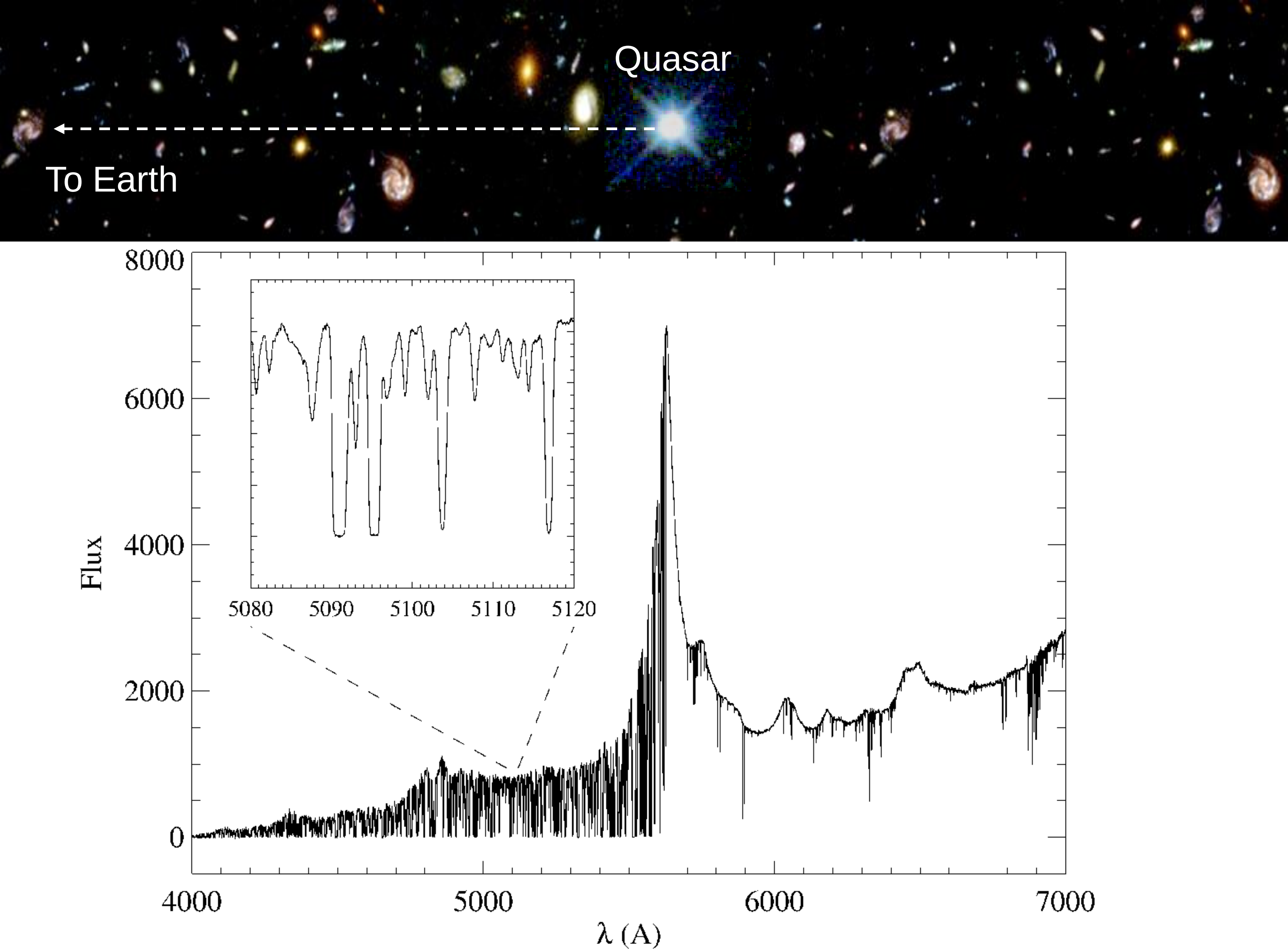


- Cold streams penetrate hot halo
- Pressure equilibrium
- Outflows avoid cold streams
- Streams have low metallicity

Van de Voort & JS (2011d)

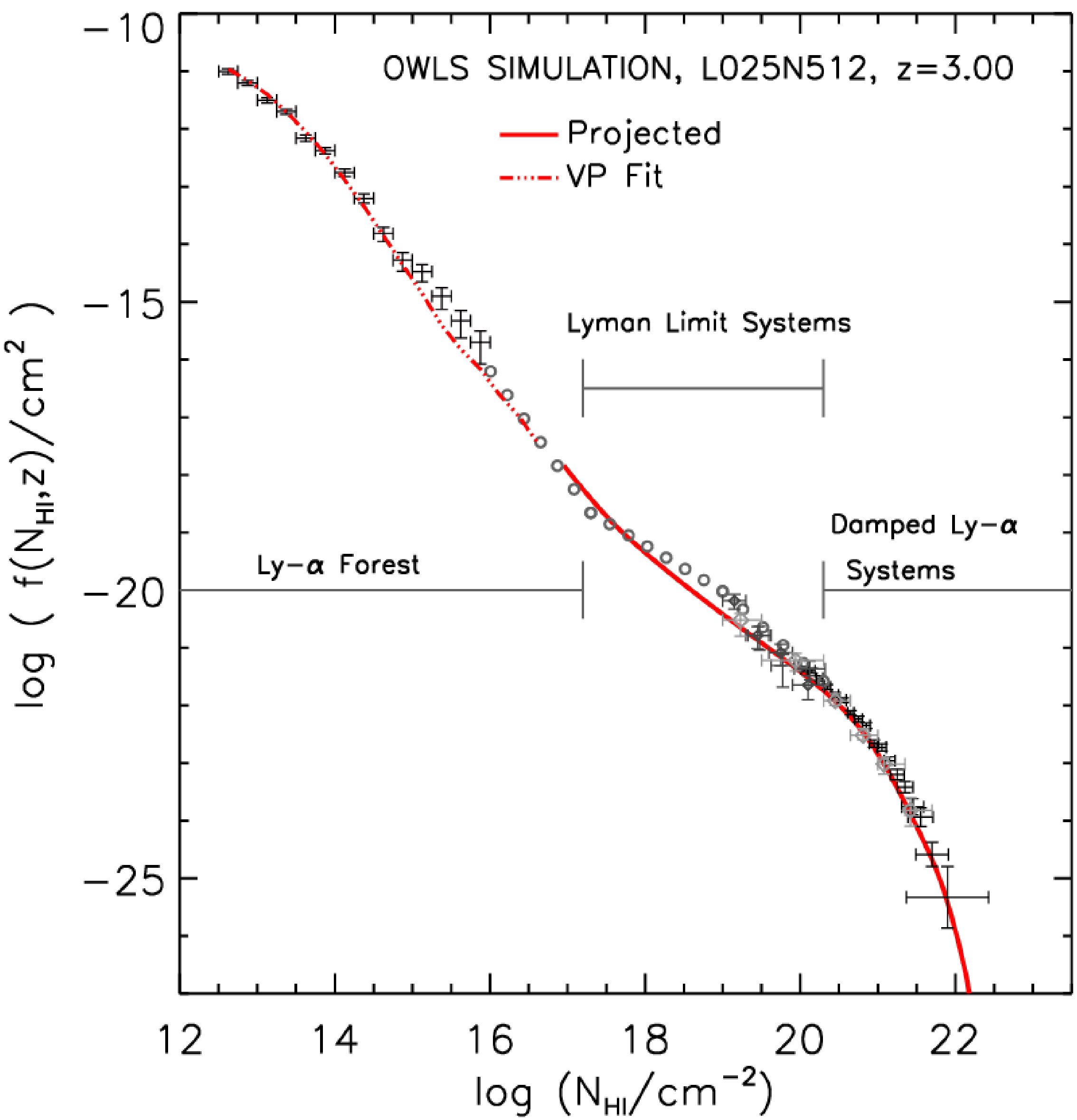
Studying gas in absorption at $z \sim 3$

Does cold accretion exist?



Quasar
To Earth
8000
6000
4000
2000
0
Flux
5080
5090
5100
5110
5120
4000
5000
6000
7000
λ (A)

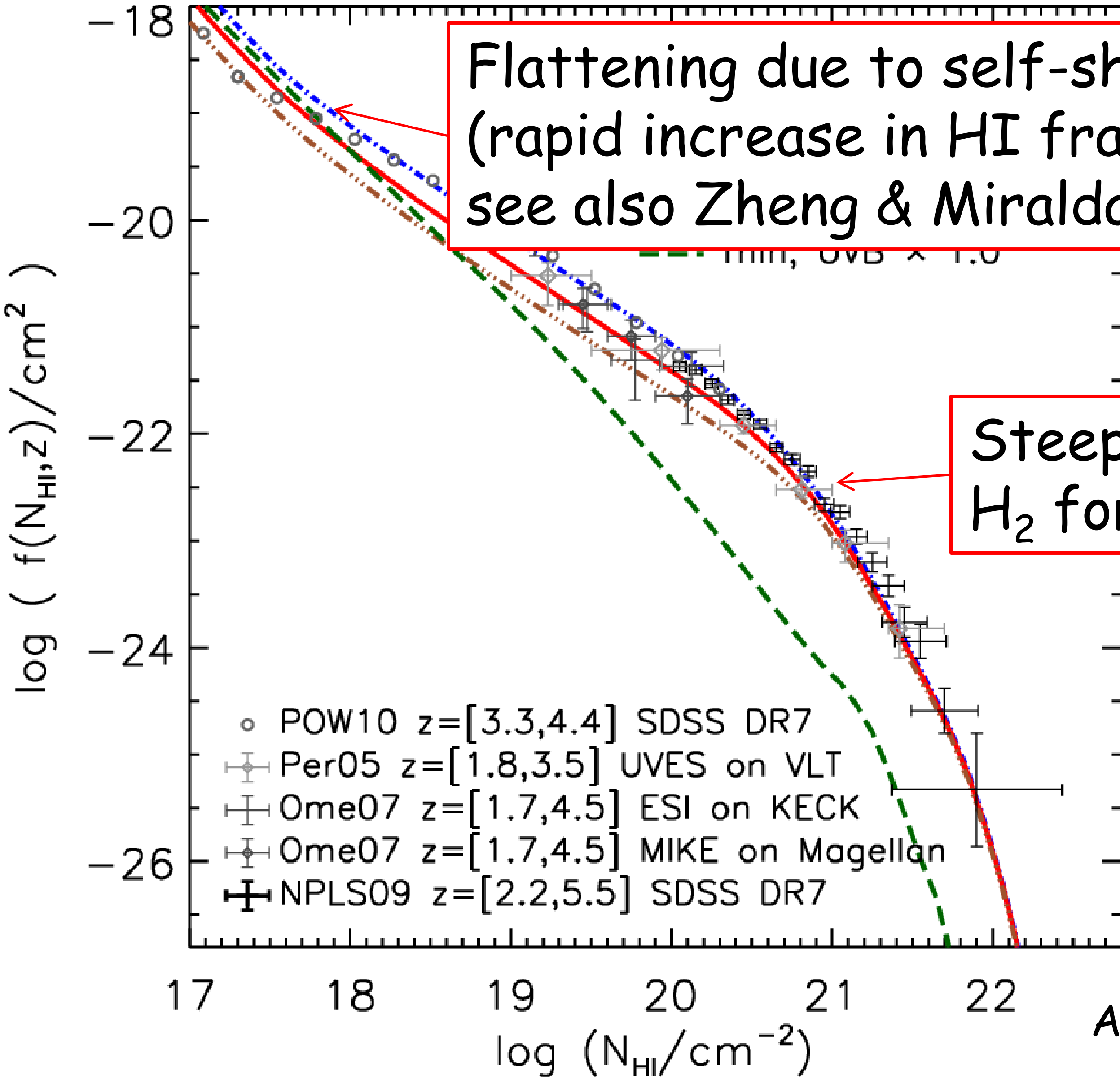
HI column density distribution at z=3



Amazing agreement!

Altay, Theuns, JS, Crighton, Dalla Vecchia (2011)

Effect of self-shielding

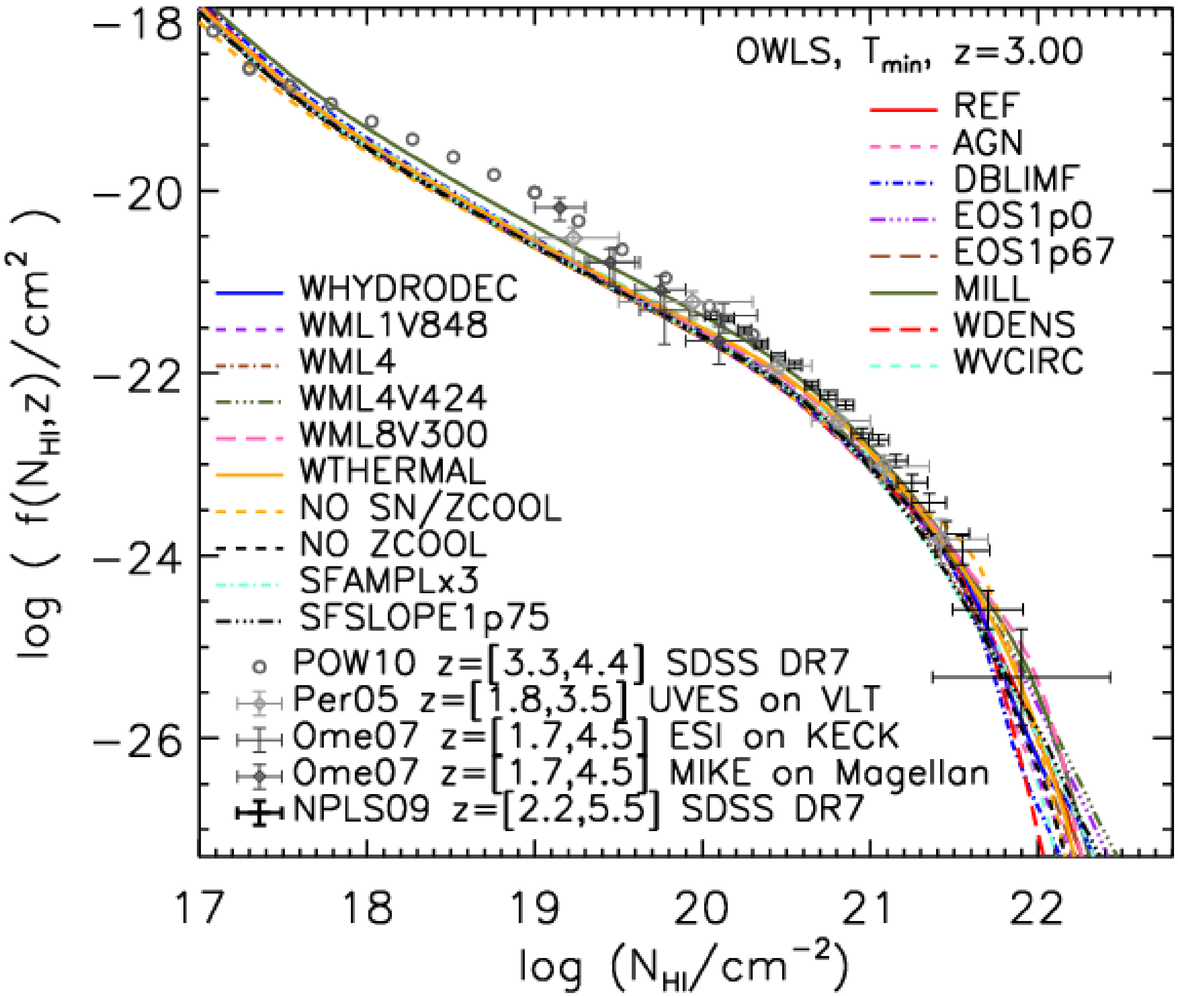


Flattening due to self-shielding (rapid increase in HI fraction; see also Zheng & Miralda-Escude 2002)

Steepening due to H_2 formation (JS 2001b)

Altay, Theuns, JS, Crighton, Dalla Vecchia (2011)

Effect of subgrid physics



Very robust!

Altay et al. (in prep)

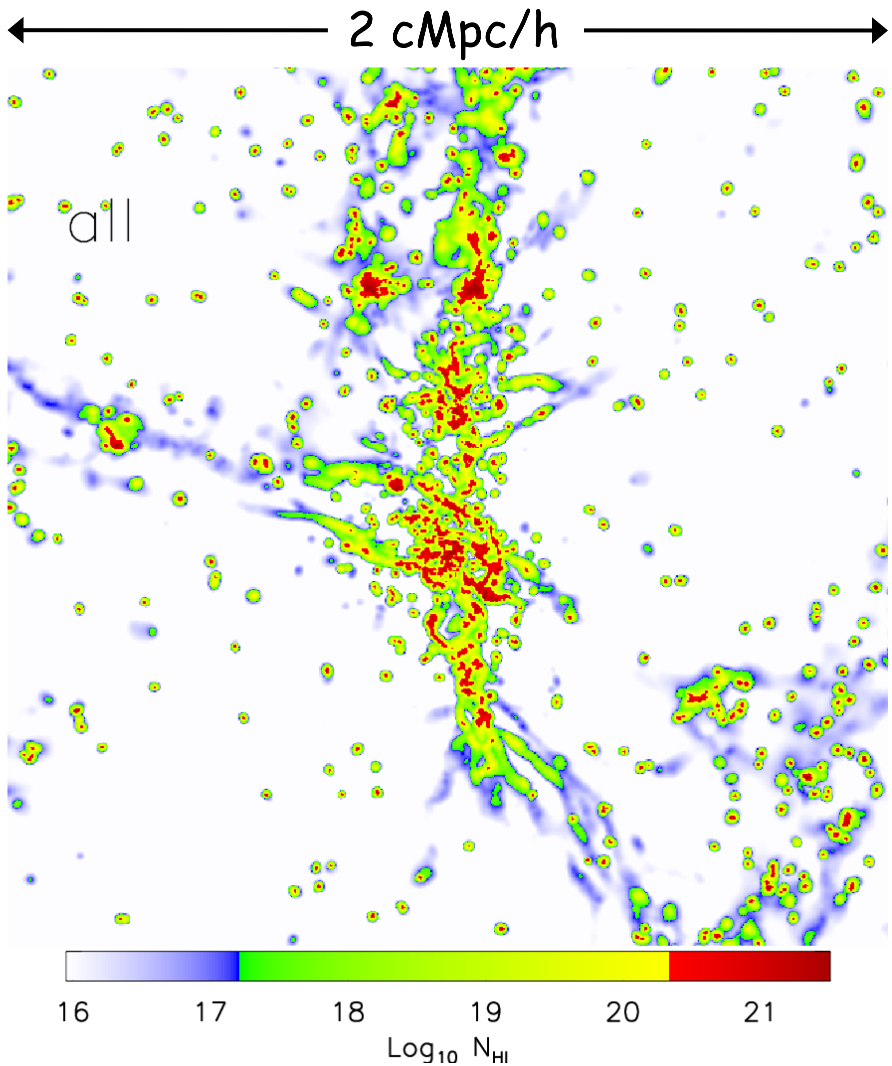
The HI column density distribution

- Reproduced by hydro simulations over 10 orders of magnitude!
- Reflects the mass distribution as a function of volume density, modulated by self-shielding and molecule formation

What does this tell us about cold accretion?

HI column density map

All gas

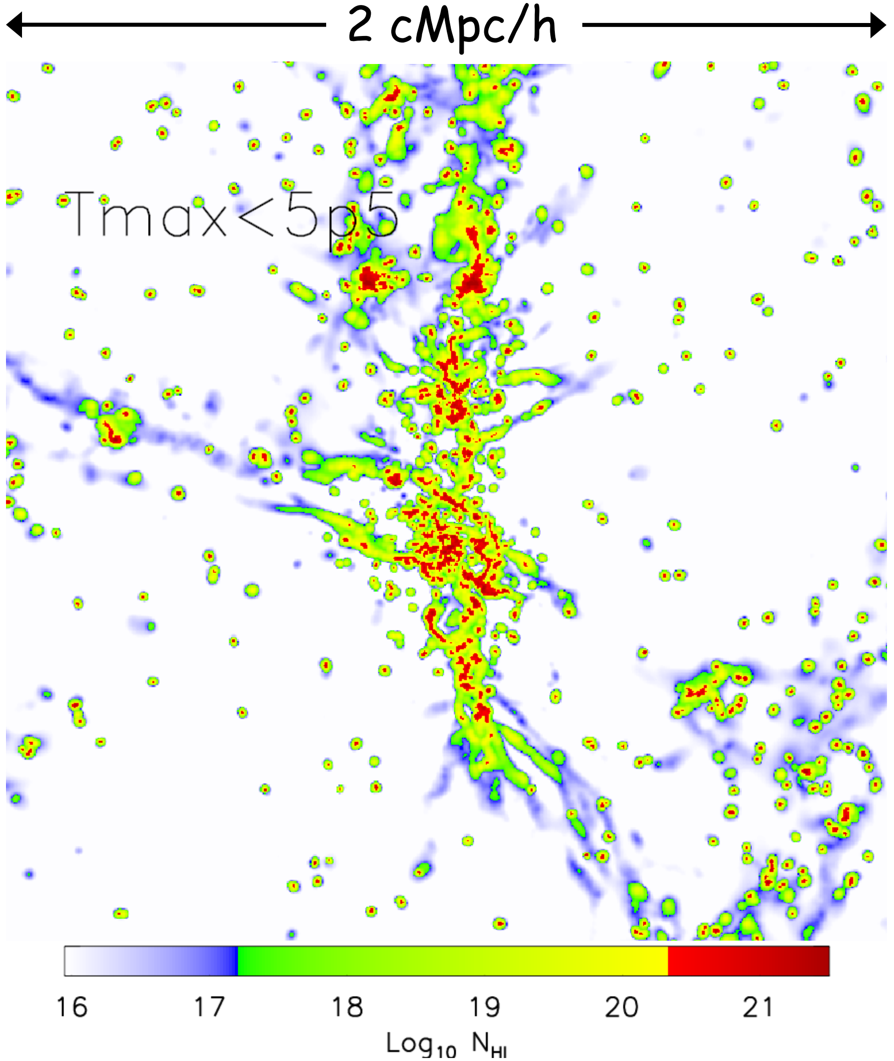


$z = 3$
$10^{12.4}\ M_{\odot}$ halo

Van de Voort, JS et al. (2011c)

HI column density map

Cold-mode:
$T_{max} < 10^{5.5}$ K

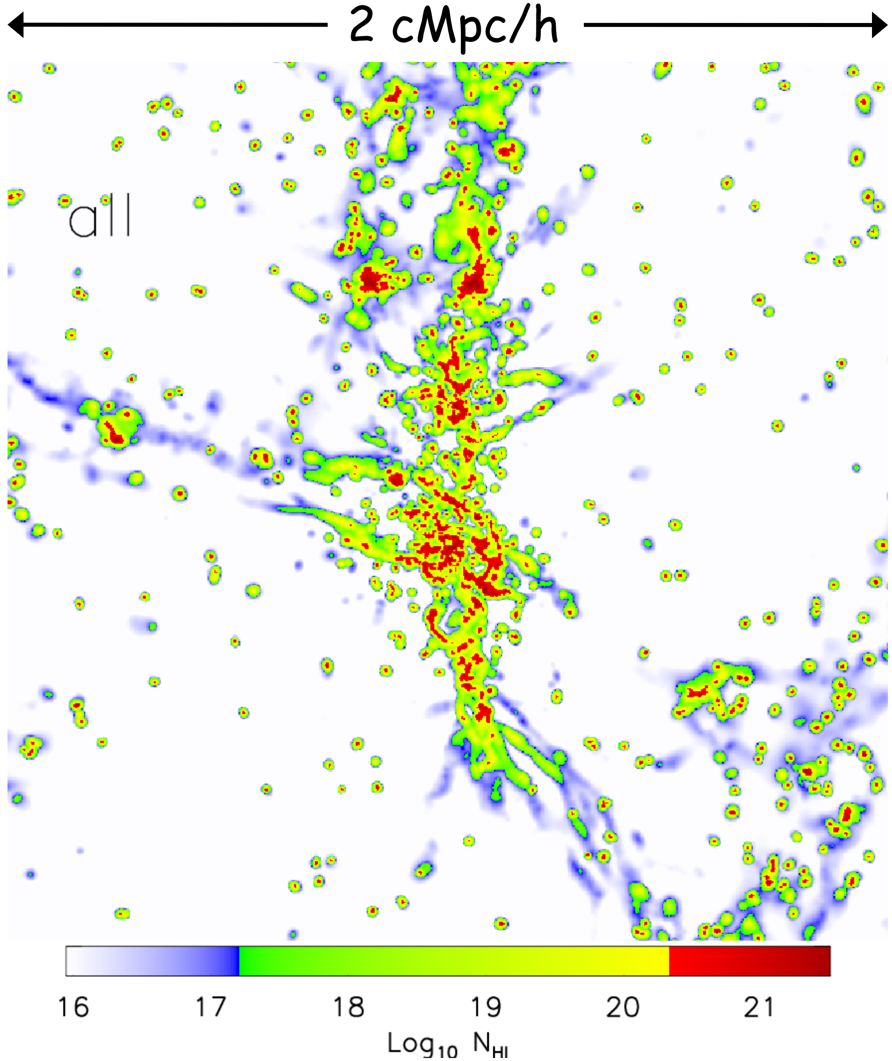


z = 3
$10^{12.4}$ $M_\odot$ halo

Van de Voort, JS et al. (2011c)

HI column density map

All gas

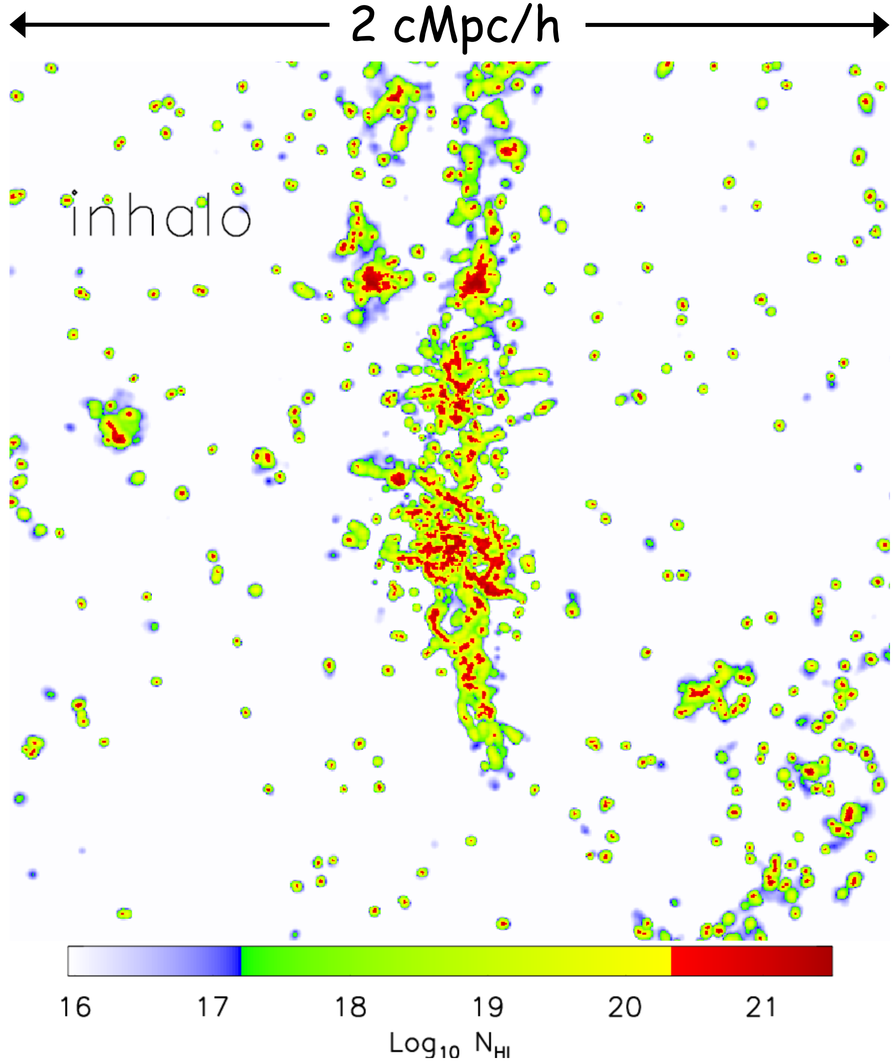


$z = 3$
$10^{12.4}\ M_{\odot}$ halo

Van de Voort, JS et al. (2011c)

HI column density map

In haloes

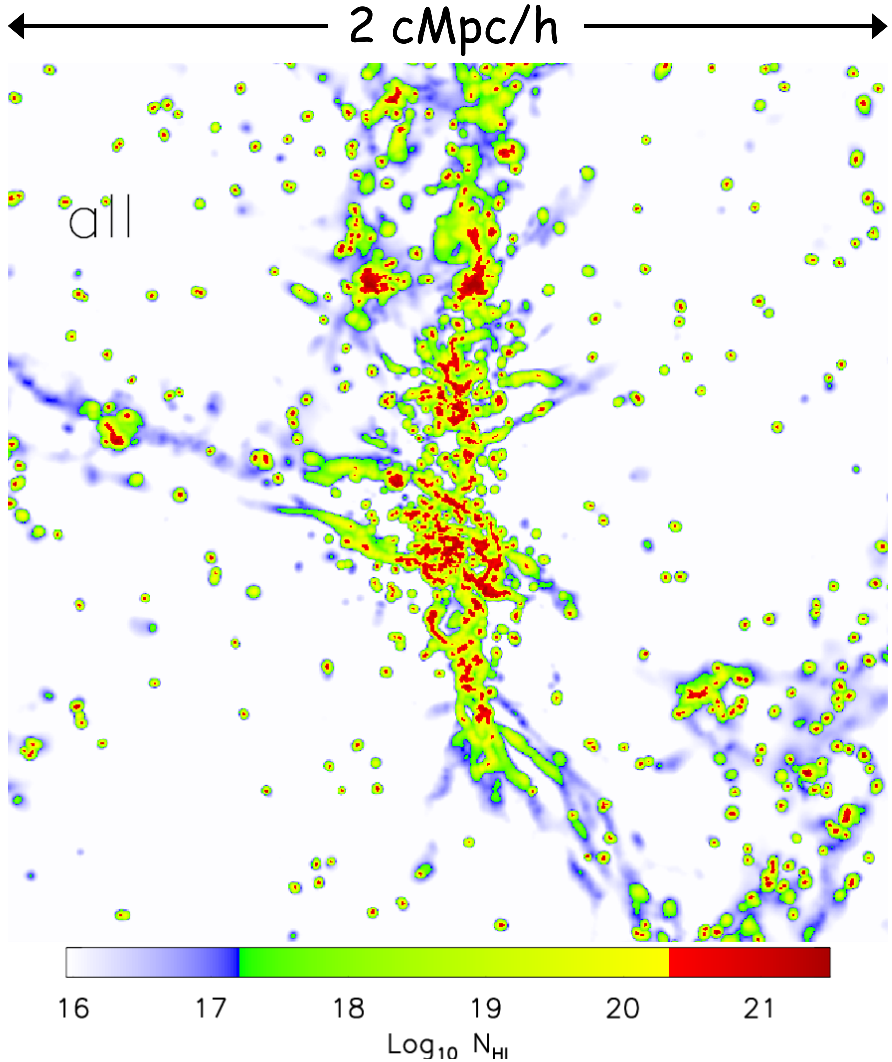


$z = 3$
$10^{12.4}\ M_{\odot}$ halo

Van de Voort, JS et al. (2011c)

HI column density map

All gas

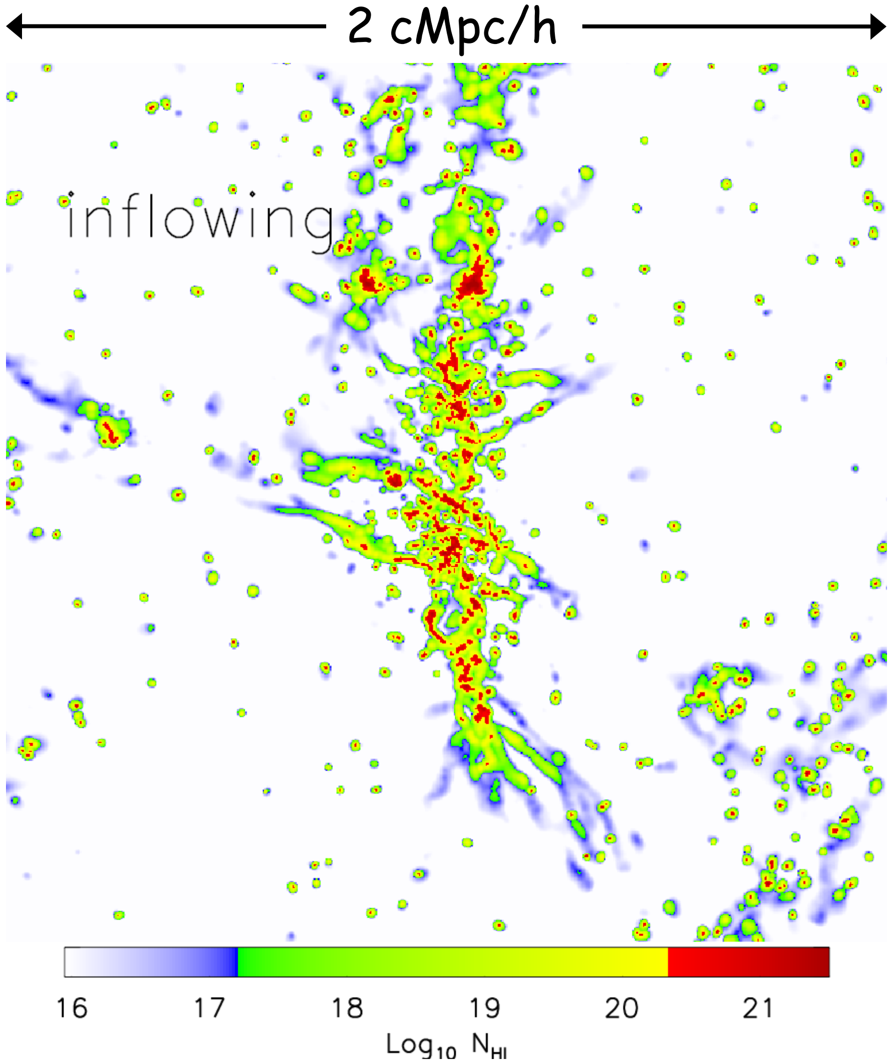


$z = 3$
$10^{12.4}\ M_{\odot}$ halo

Van de Voort, JS et al. (2011c)

HI column density map

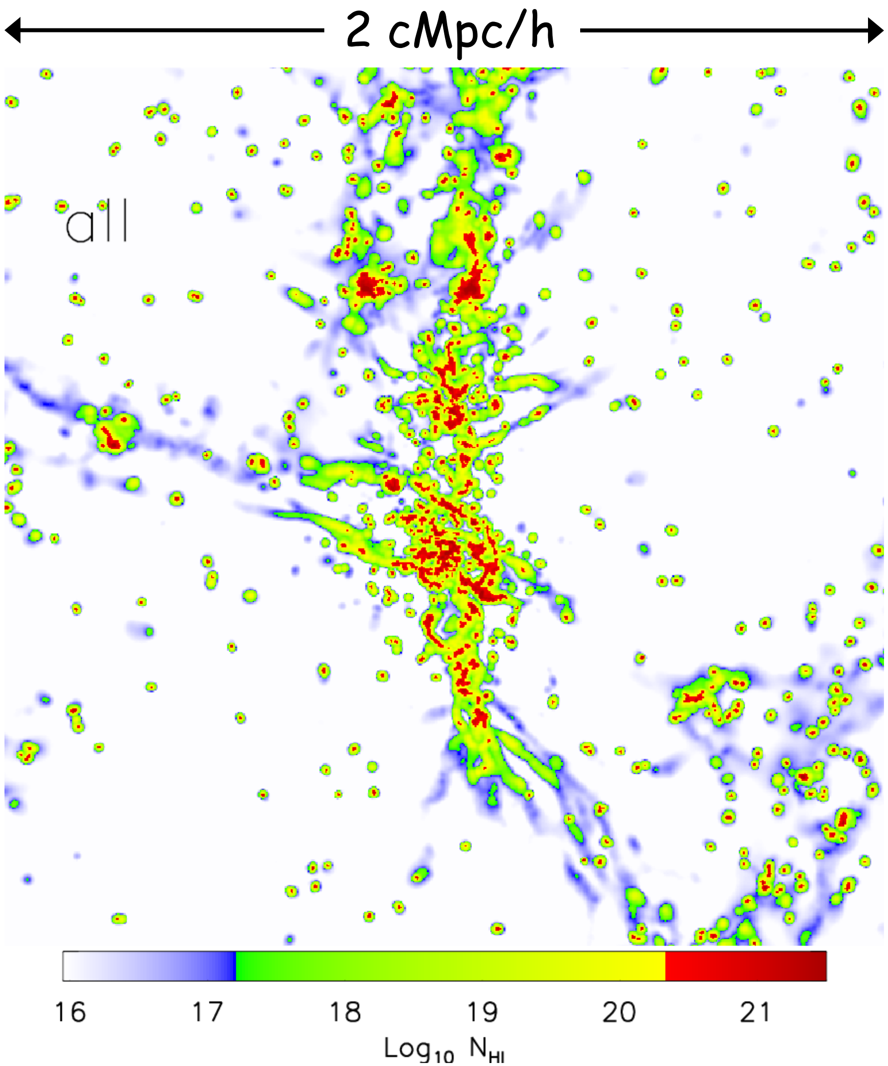
Inflowing faster than $v_{circ/4}$ of nearest halo



$z = 3$
$10^{12.4}\ M_{\odot}$ halo

Van de Voort, JS et al. (2011c)

HI column density map

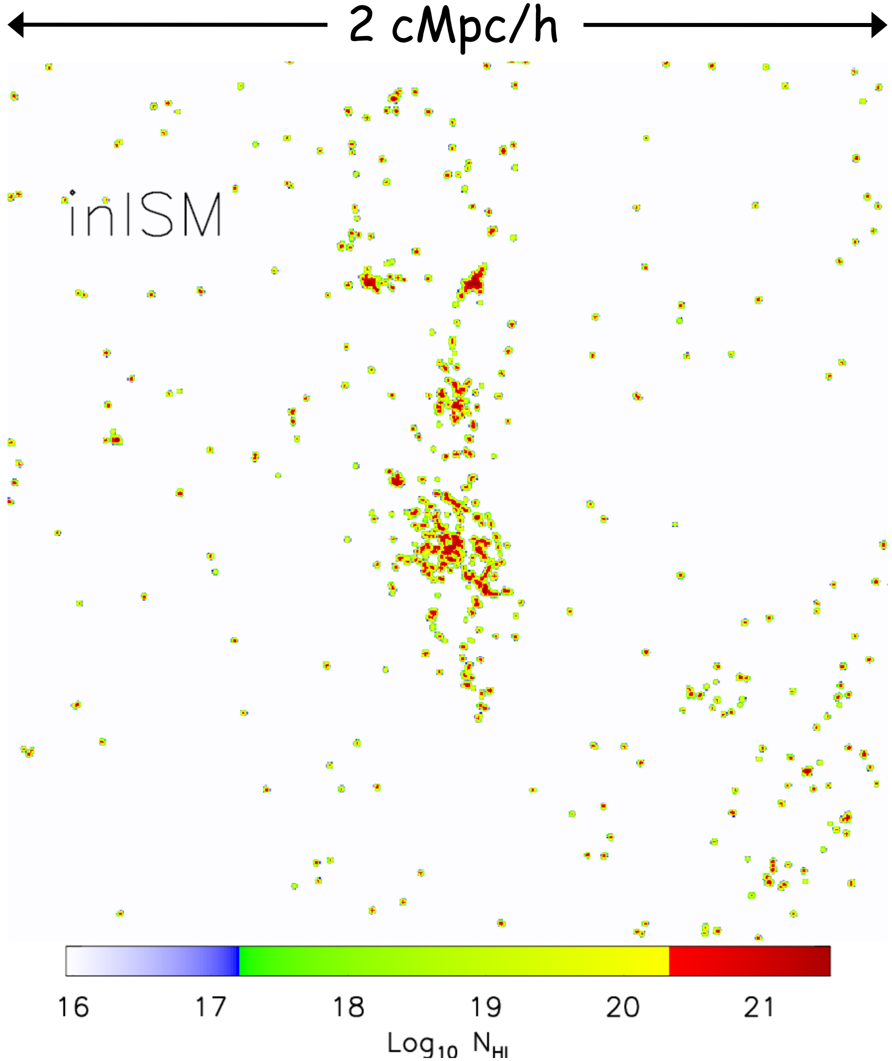


All gas

$z = 3$
$10^{12.4}\ M_{\odot}$ halo

Van de Voort, JS et al. (2011c)

HI column density map



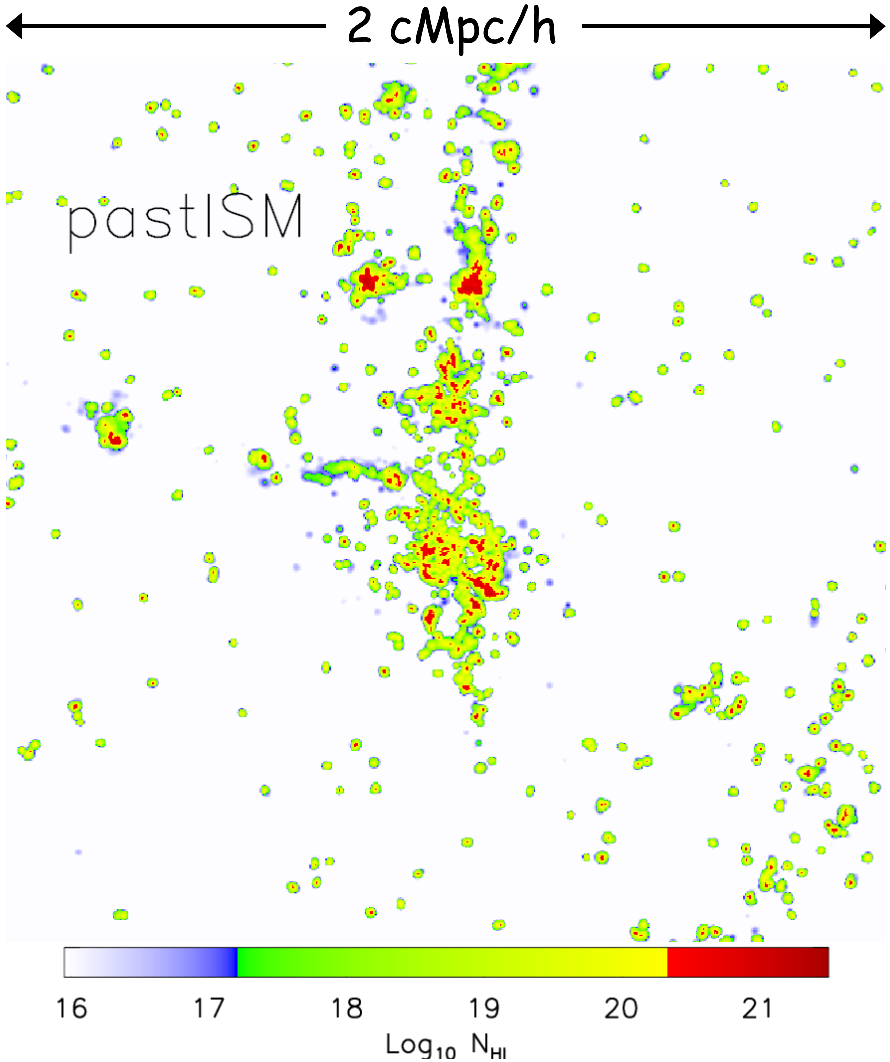
ISM

$z = 3$
$10^{12.4}\ M_\odot$ halo

Van de Voort, JS et al. (2011c)

HI column density map

Has been part of the ISM

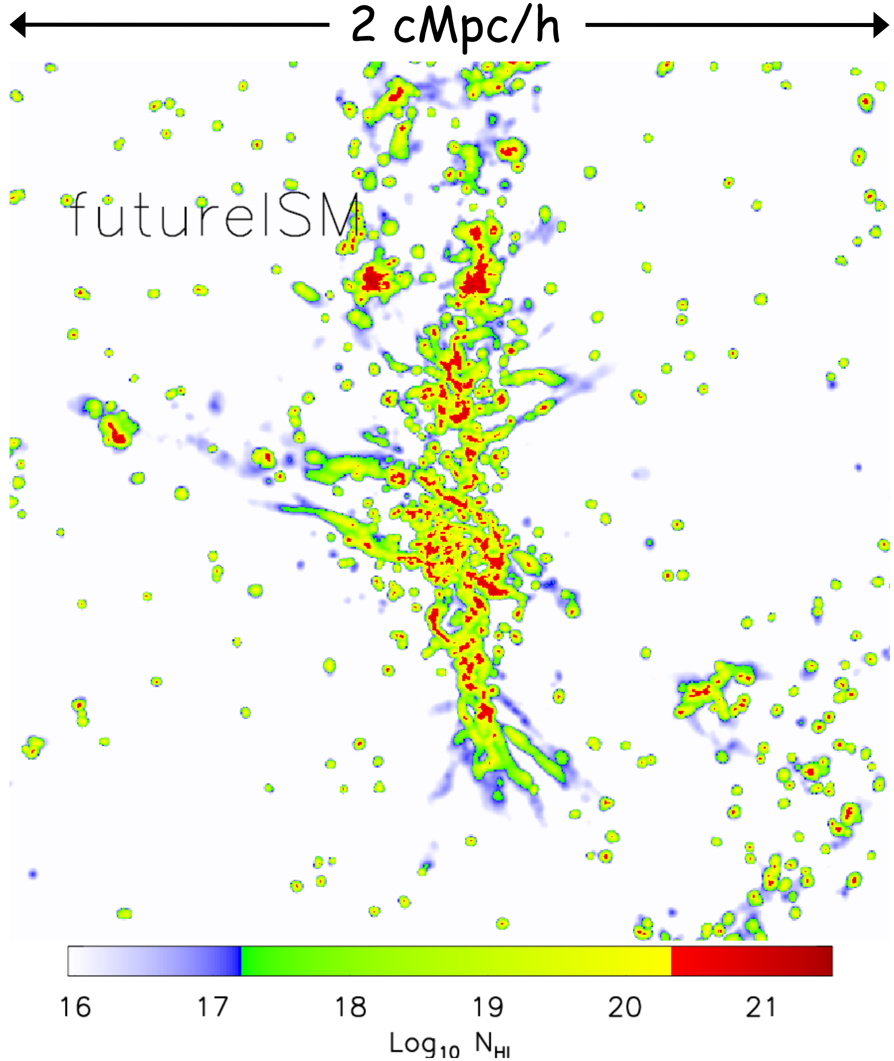


$z = 3$
$10^{12.4}$ $M_\odot$ halo

Van de Voort, JS et al. (2011c)

HI column density map

Will become ISM before z = 2



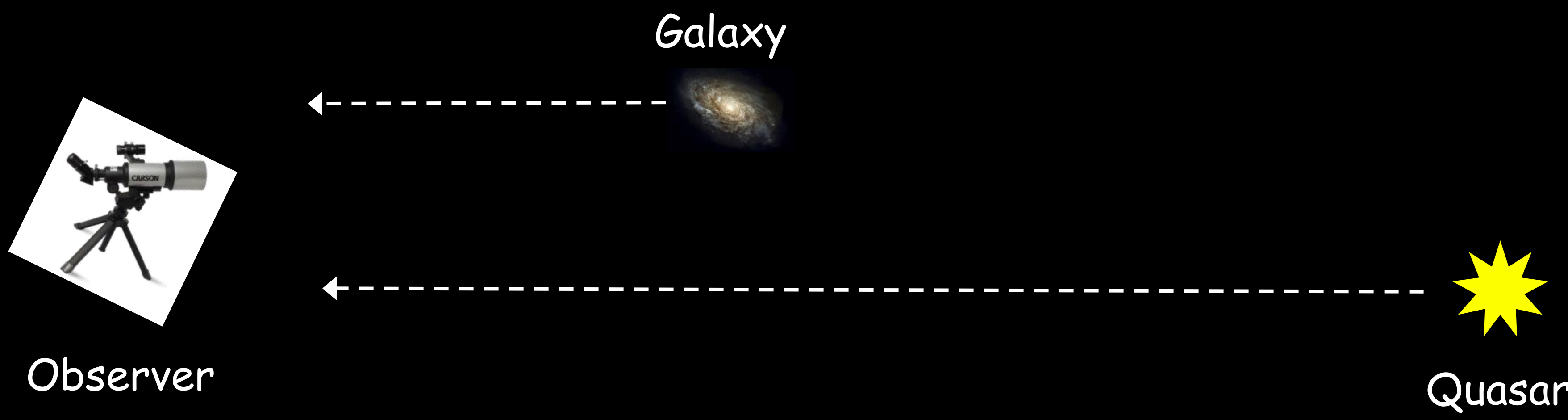
z = 3
$10^{12.4}\ M_{\odot}$ halo

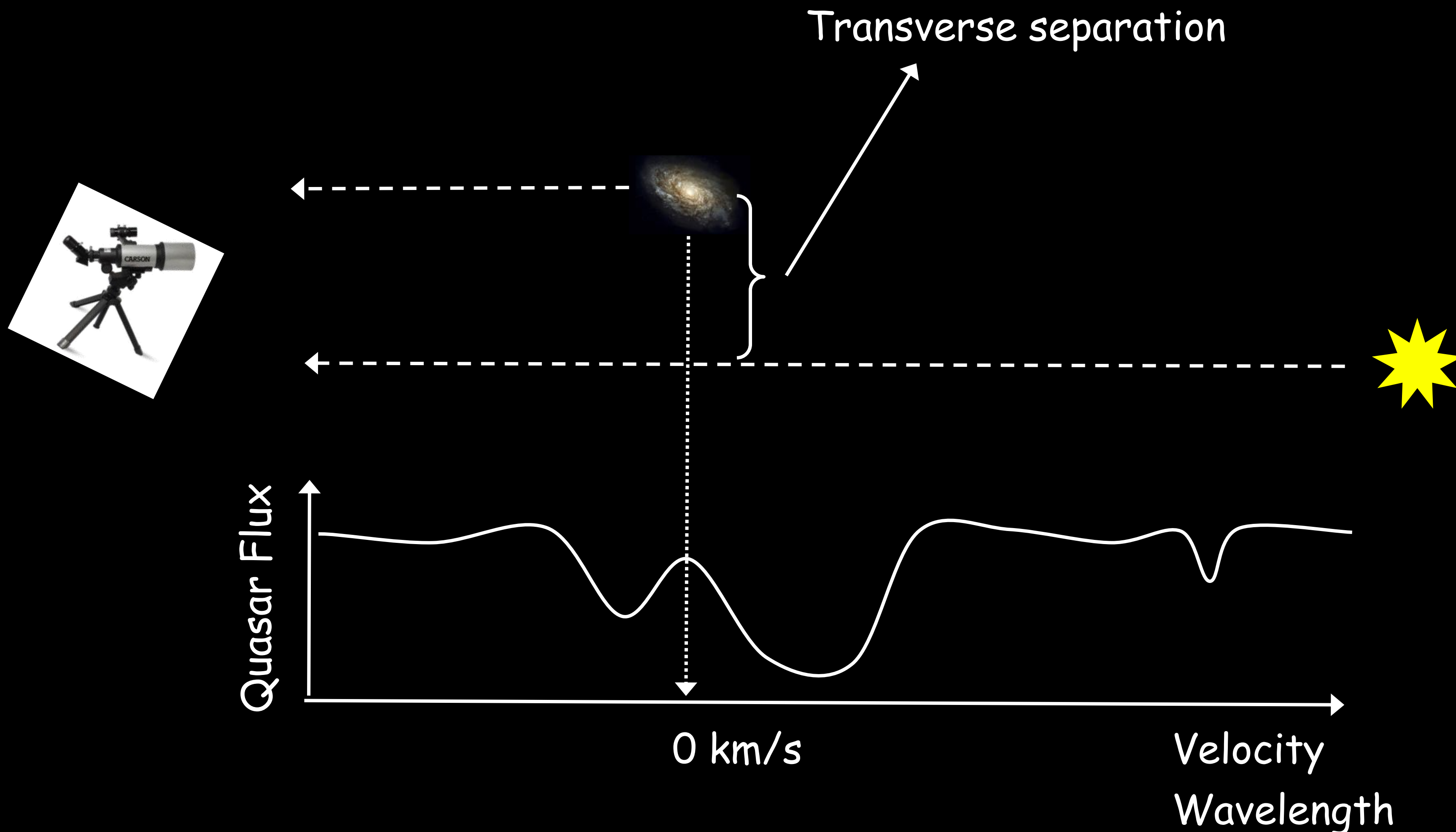
Van de Voort, JS et al. (2011c)

Cold accretion flows and the nature of high column density HI absorption

- Cold accretion flows have already been observed in the form of high column density HI absorbers, particularly Lyman limit systems
- Lyman limit systems trace accreting gas in and around low-mass ($< 10^{11}\ M_\odot$) haloes
- DLAs trace gas within low-mass ($< 10^{11}\ M_\odot$) haloes that is accreting onto galaxies
- Ultra strong DLAs trace the ISM of relatively massive ($> 10^{11}\ M_\odot$) galaxies

Observing the connection between the IGM and galaxies at $z \sim 2.4$


Galaxy
Observer
Quasar

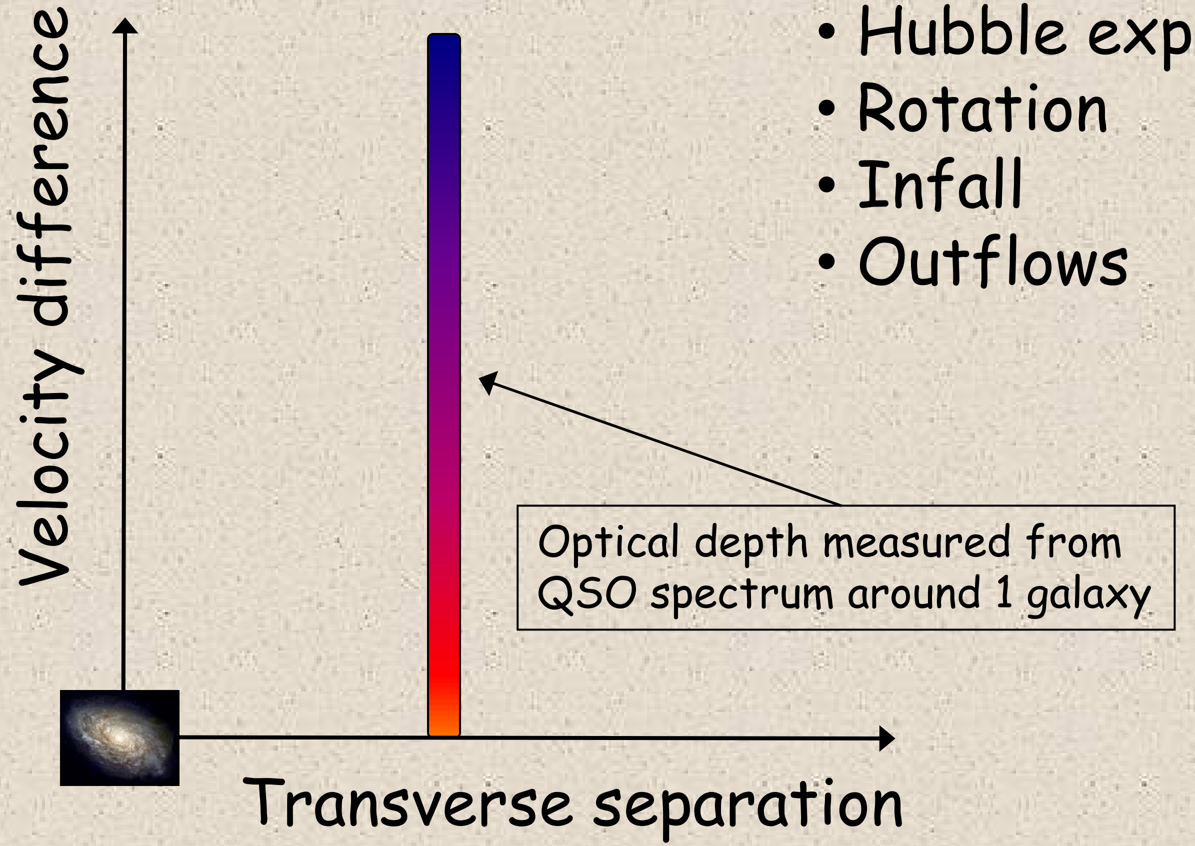


For each transition we measure optical depth as a function of

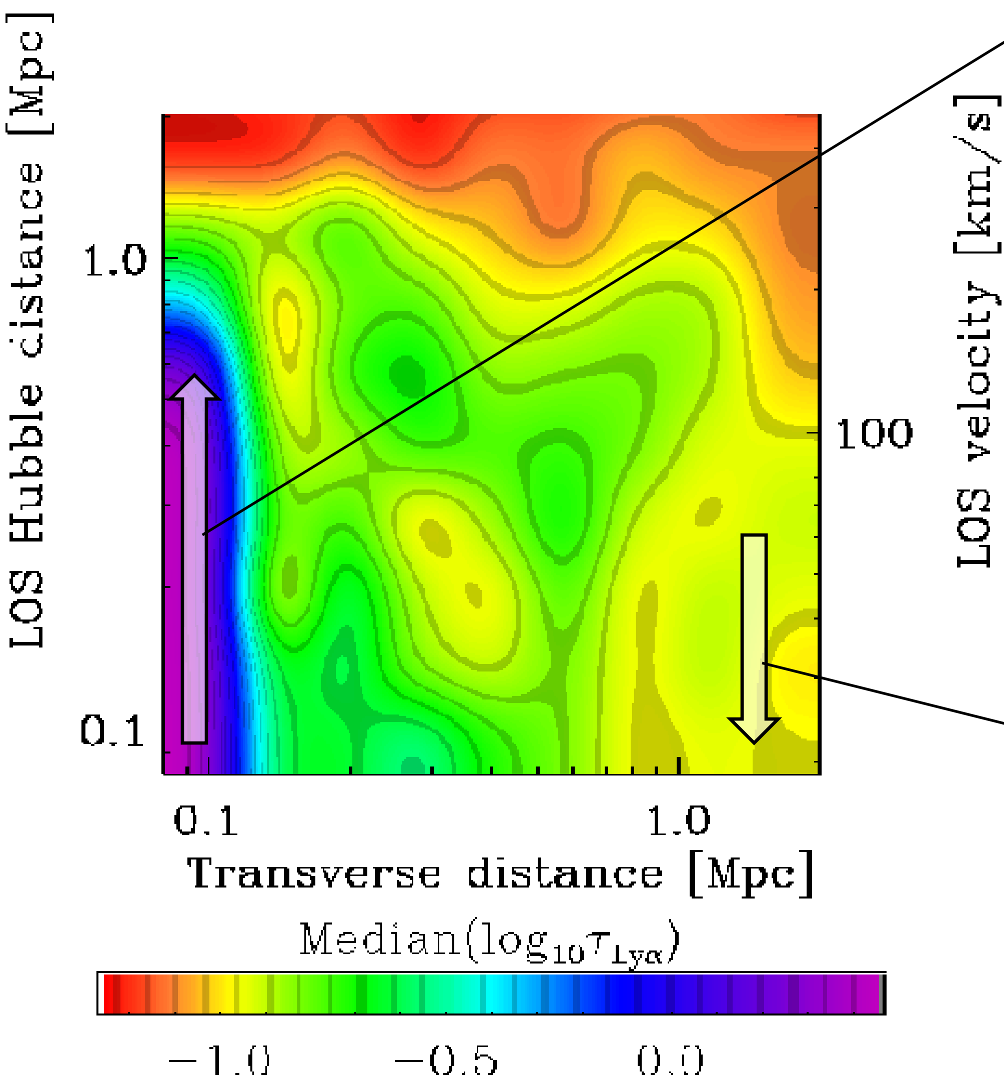
- velocity difference from galaxy ($v = H^*d + v_{pec}$)
- galaxy impact parameter

Velocity differences due to

- Hubble expansion: $v = H * d$
- Rotation
- Infall
- Outflows



Neutral hydrogen around z ~ 2 galaxies



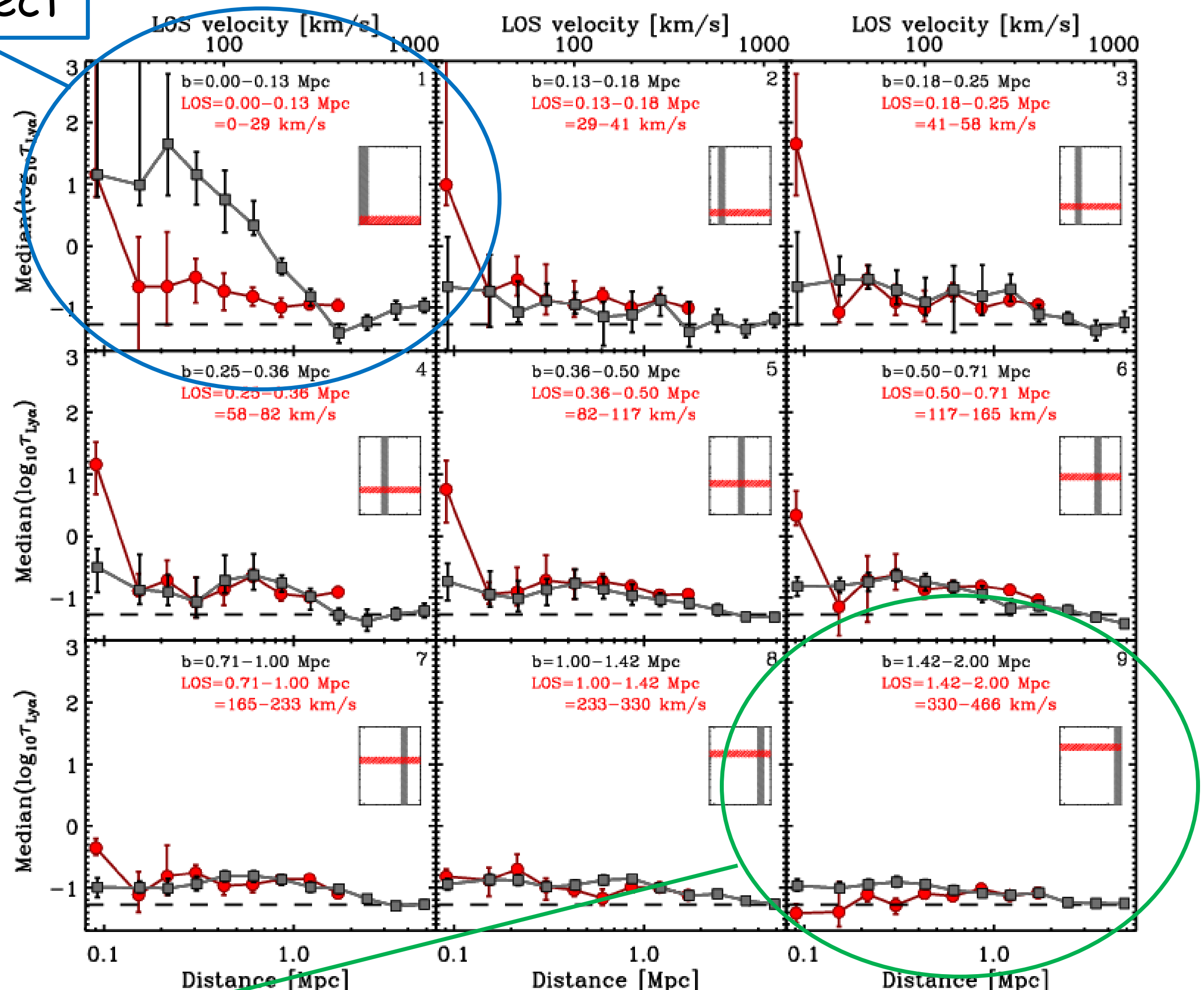
Elongation due to redshift errors and motions in and around haloes ("Finger of God effect")

Compression due to infall ("Kaiser effect")

Rakic, JS, Steidel, Rudie (2011b)

Redshift space distortions

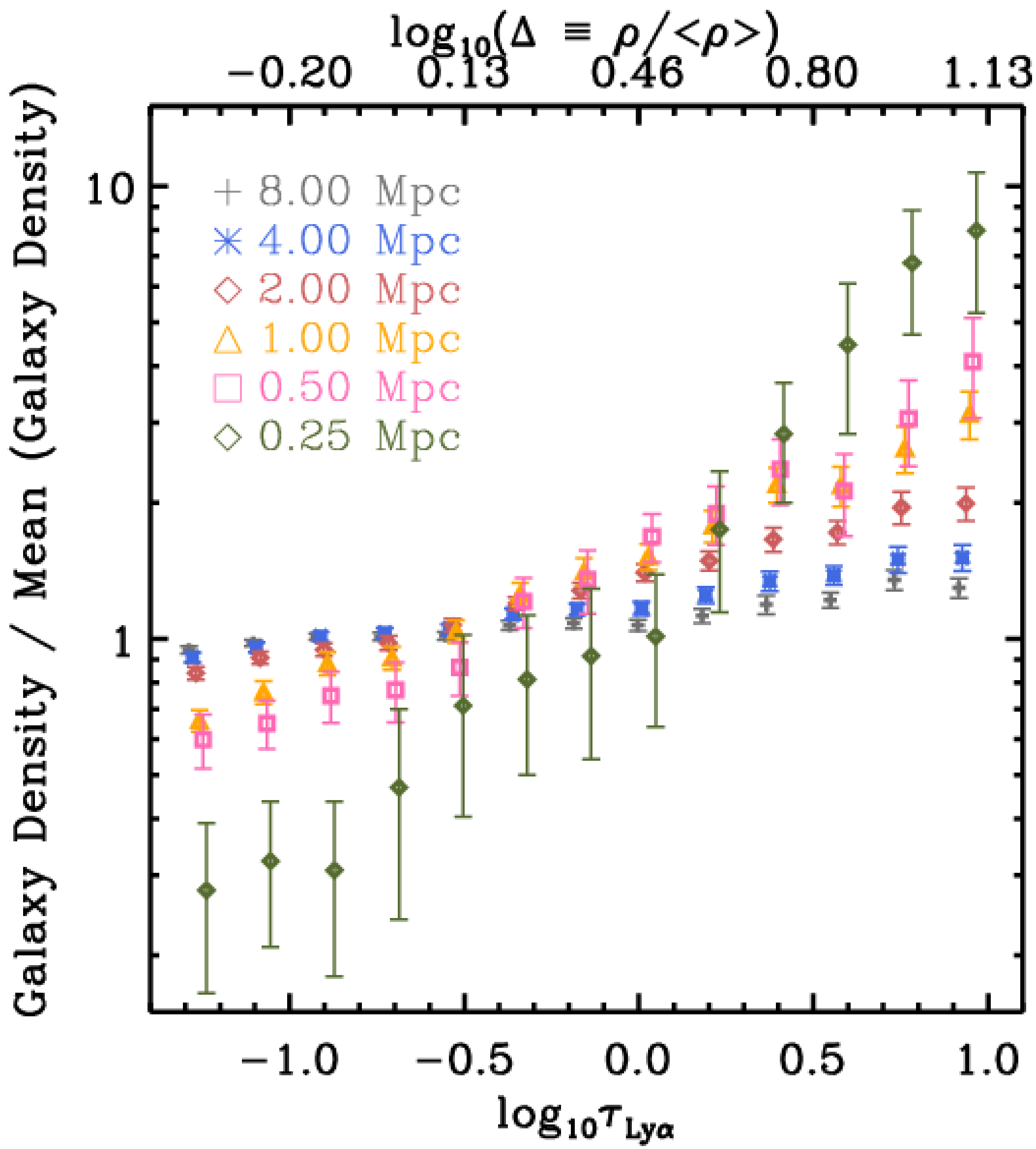
Finger of God effect



Kaiser effect

Rakic, JS, Steidel, Rudie (2011b)

Absorber centered view

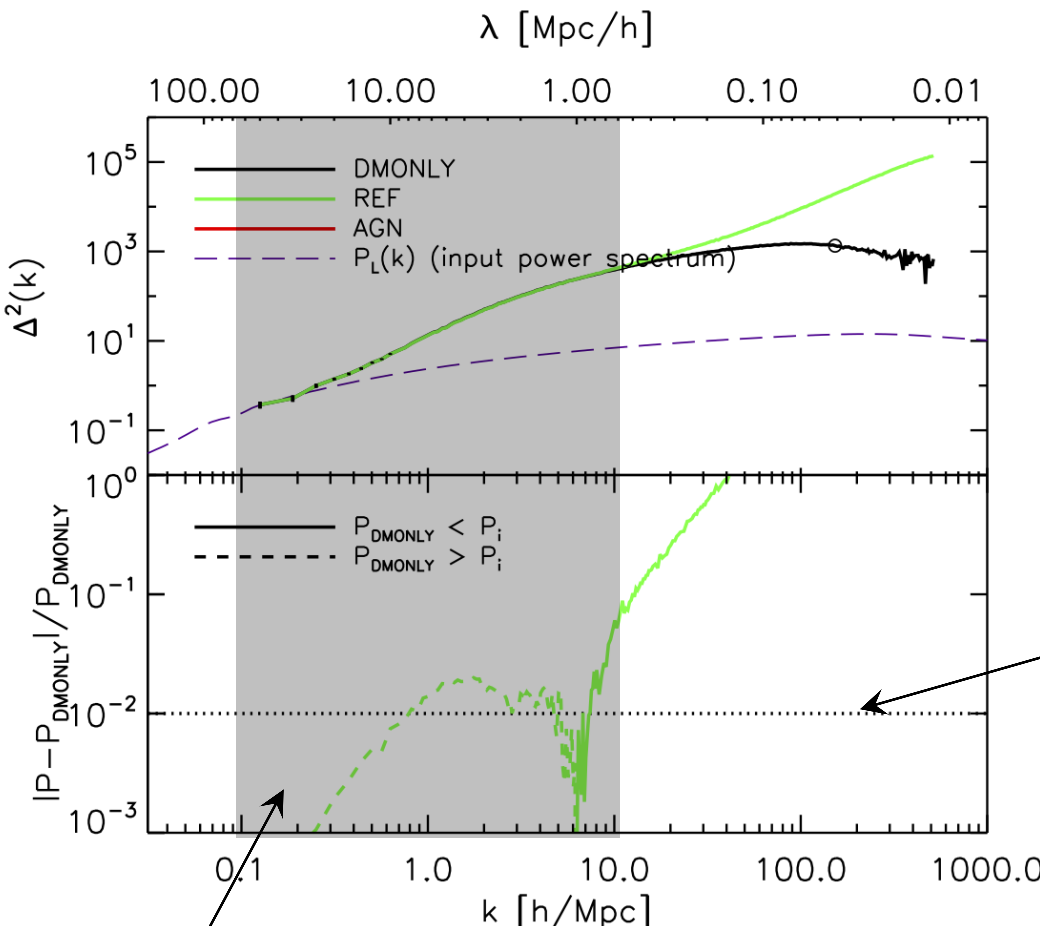


Rakic, JS, Steidel, Rudie (2011b)

Why cosmologists should care about gas around galaxies

- Baryons change the large-scale distribution of matter.
- Cosmic shear is the driver for WFIRST and EUCLID (recently selected by ESA!).
- Previous work (e.g. Jing et al. 2006; Rudd et al. 2008; Guillet et al. 2009; Cassarini et al. 2010) suffered from overcooling, as is the case for the OWLS reference model.
- Overcooling was thought to be conservative: effect of baryons too strong.

Baryons and the matter power spectrum

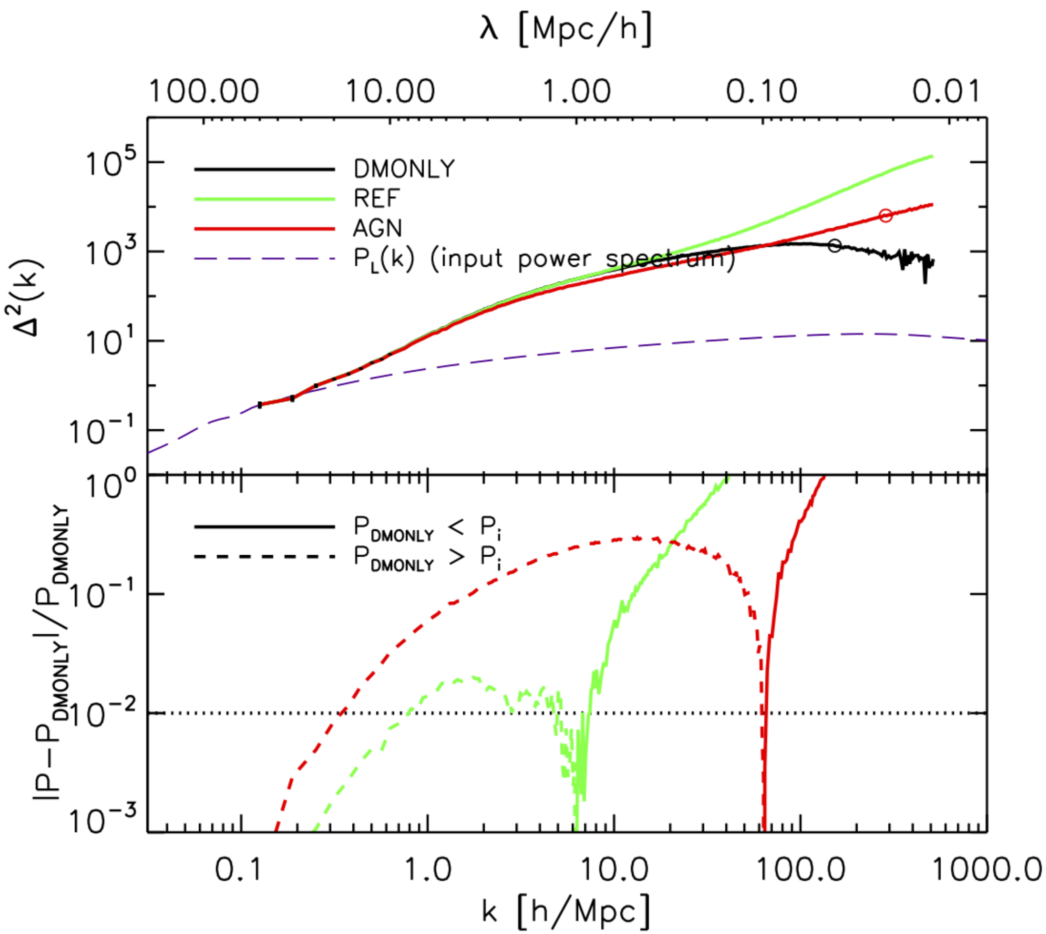


1% difference wrt dark matter only

Range of interest for cosmic shear

Van Daalen, JS+ (2011)

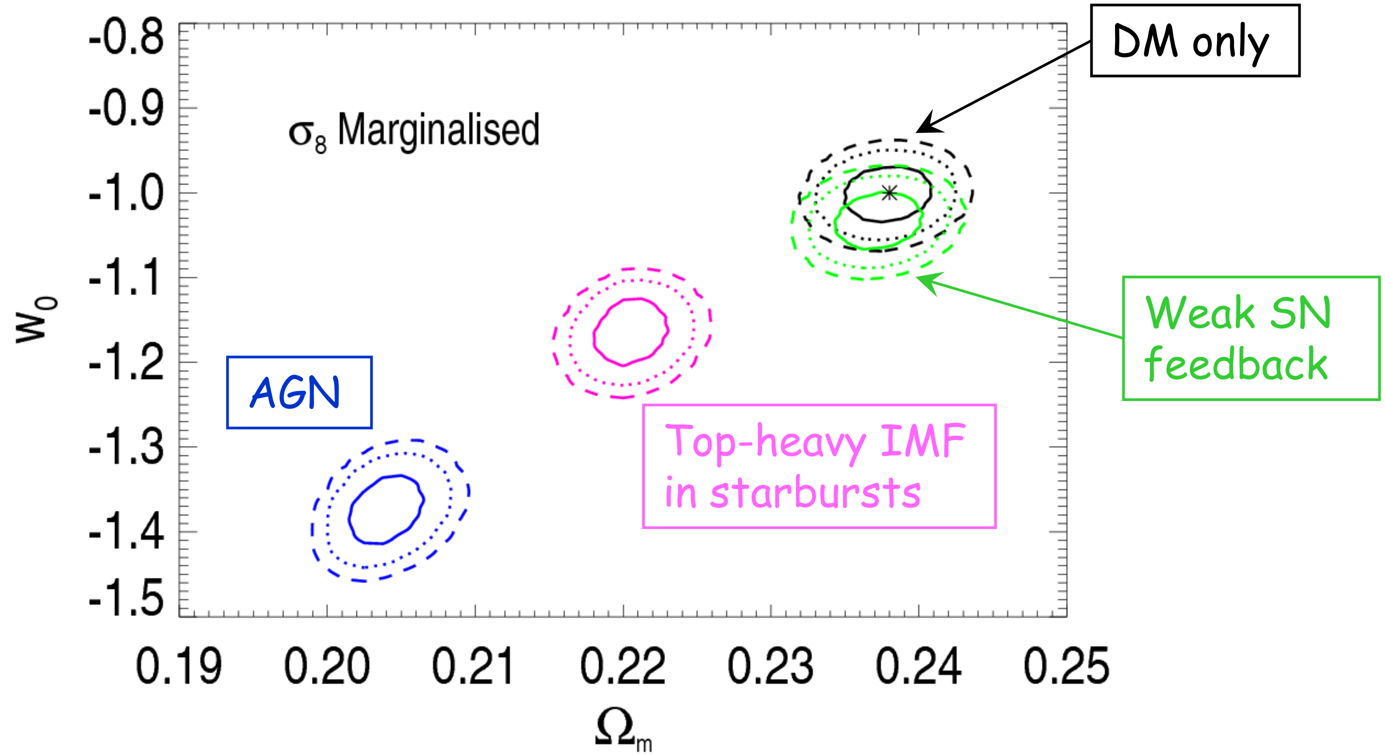
Baryons and the matter power spectrum



The feedback required to solve the overcooling problem suppresses power on large scales

Van Daalen, JS+ (2011)

Biases due to galaxy formation for a Euclid-like weak lensing survey



Galaxy formation provides a challenge (target?) for weak lensing

Semboloni, Hoekstra, JS, van Daalen, McCarthy (2011)

Galaxy formation and cosmology

- Feedback processes change the distribution of matter both on small and (shockingly) large scales
- Baryonic effects are large compared to the subtle effects numerical cosmologists are worrying about
- Dark matter simulations are only adequate on scales >>> 10 Mpc