Super-high resolution simulations of high redshift galaxies©

J. Devriendt (Oxford)

with T. Kimm, H. Tillson, S. Geen, A. Slyz, Y. Dubois (Oxford)
L. Powell (CEA Saclay / MPE)
C. Pichon (IAP)
R. Teyssier (Zurich/CEA Saclay)
J. Blaizot, J. Rosdahl, A. Verhamme (Lyon)
D. Pogosyan (Alberta)
S. Kassin (NASA Goddard)

Outlook

- What is (arguably) ***THE*** biggest problem with galaxy formation as we currently understand it?

- Lessons from the Mare Nostrum cosmological simulation

- The re-simulation way: more physics @ high resolution with the  (NUT) suite

- Where are we going next?

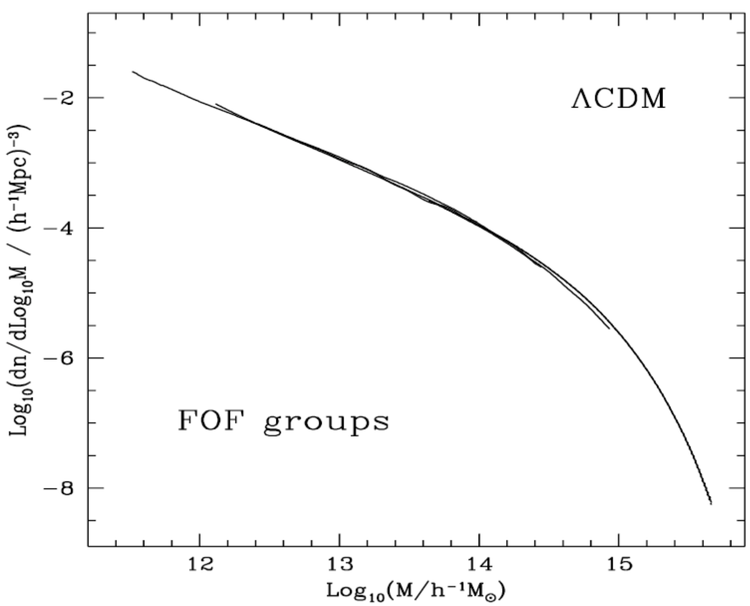
- What observations do we need?

The biggest problem (part I) : Luminosity Functions @ z=0

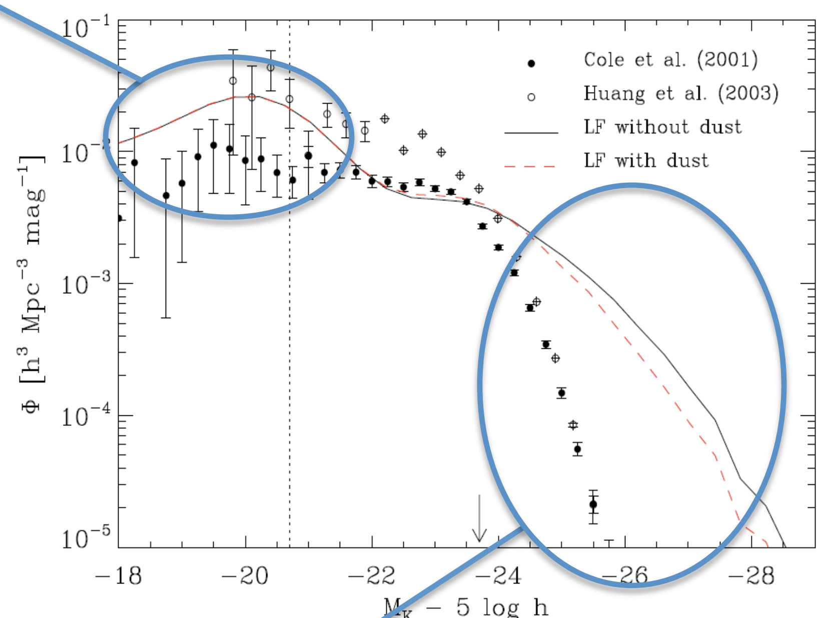
Supernovae, re-ionisation?

DM halo mass function

Galaxy luminosity function hydro simulations with SN fb but w/o AGN fb.



Jenkins et al 2010



Nuza et al 2010

AGN feedback?

c.f. Yohan's talk on wednesday

The biggest problem (part II) : Numerical Implementation

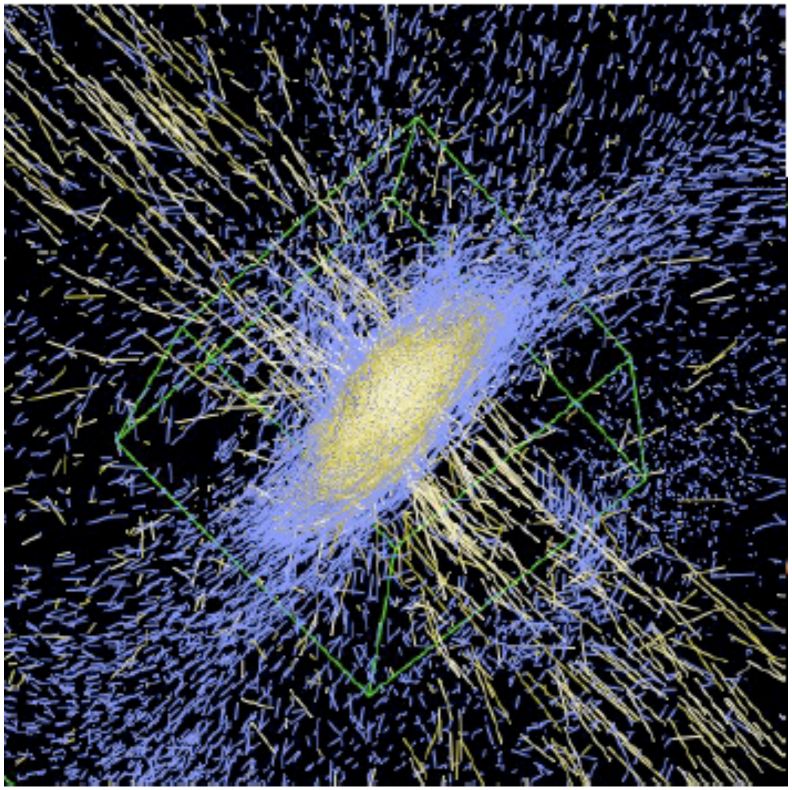
Example of galactic winds in numerical simulation by Springel & Hernquist 2003 but see also Dave et al 2008, Governato et al 2010 etc …

Pick a particle at random according to an 'arbitrary ' probability distribution law & modify its velocity:

$$\boldsymbol{v}' = \boldsymbol{v} + v_{\mathrm{w}}\, \boldsymbol{n}$$

where n is either random direction on unit sphere (isotropic wind) or is along the rotation axis of a spinning object & v_w is the 'wind velocity'.

DECOUPLE spawned wind particle for a brief time (max 50 Myr) from hydrodynamic Interactions



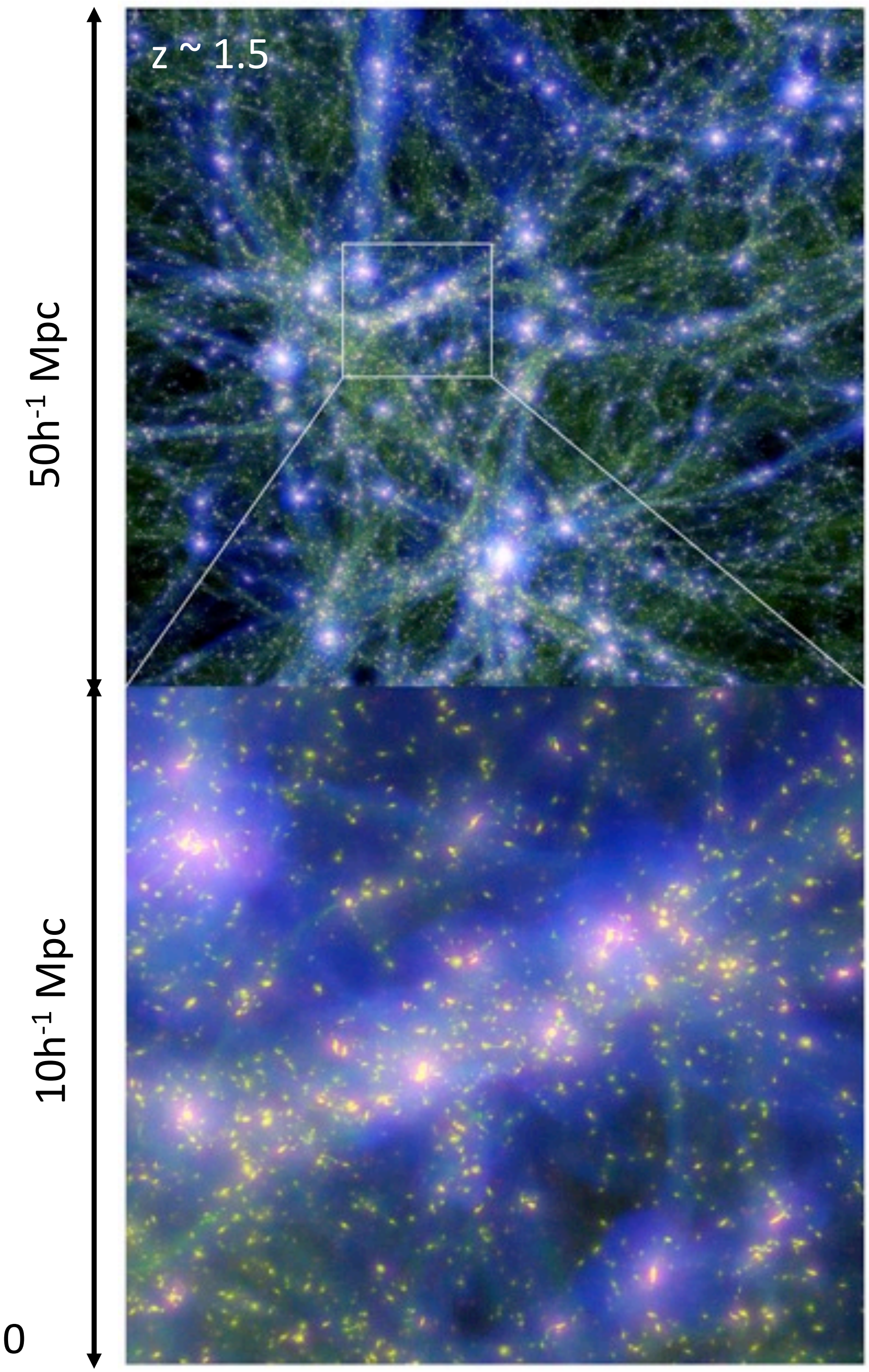
HORIZON
Mare Nostrum Simulation

(still the most resolved cosmological hydro simulation to date!)

~ 1 billion
DM particles
~1 billion cell
root grid
(3 -6 AMR levels)

Resolution:
~ $10^7\ M_\odot$ (DM part)
~ 1.5 kpc (physical)

Ocvirk et al 2008
Dekel et al 2009
Devriendt et al 2010



blue: gas temperature
green: gas density
red: dark matter density

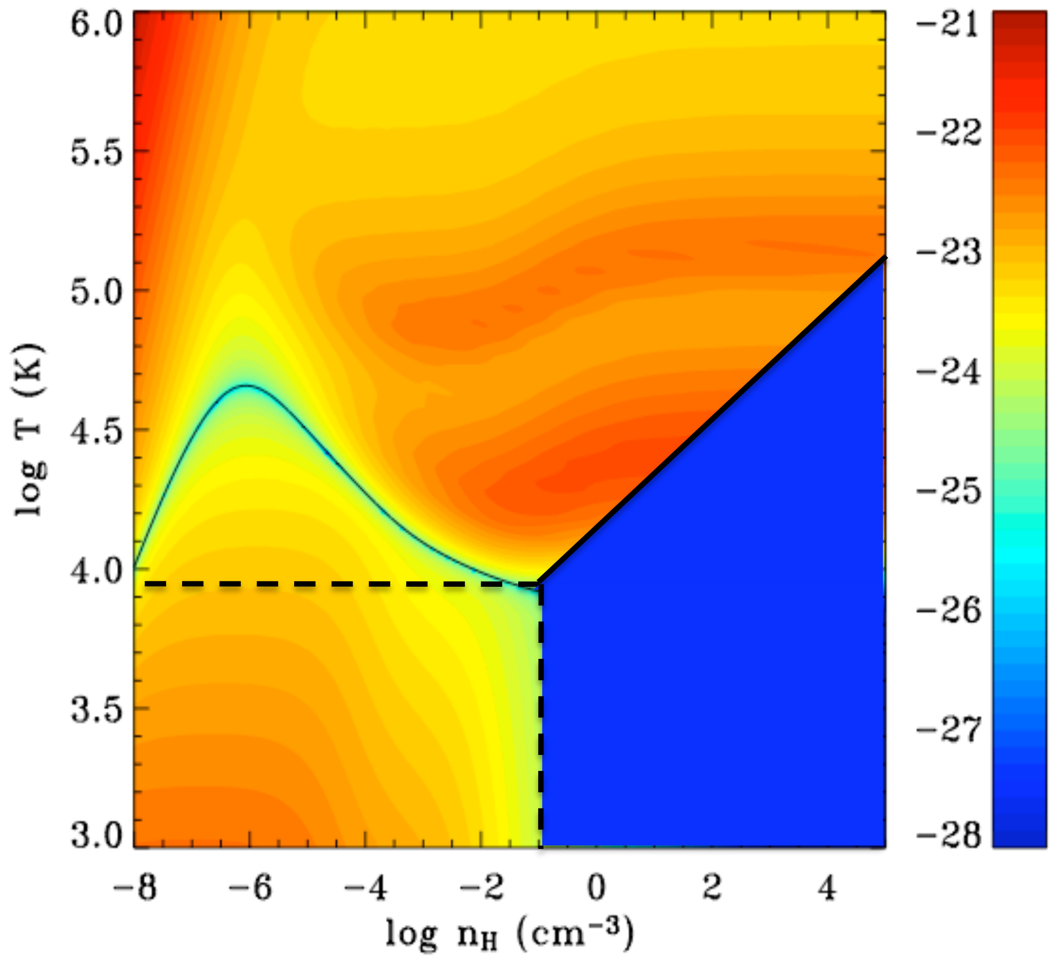
<u>CPU time:</u>
~ 4 weeks on ~ 2000 procs to reach z=1.5 in 2007. Estimated time to finish is 8 (time remaining between z=1.5 and z=0) x 2 (resolution increase) = 16 weeks
Today procs ~ 3 times faster → 7 weeks, i.e. 2.4 million CPU hours

<u>Volume of data:</u>
~ 150-200 Gb per snapshot, i.e.
~ 15-20 Tb for a 140 Myr time resolution

Radiative Cooling

Metal dependent Cooling + Heating Rate (in the presence of UV radiation once reionization turned on)

Switch to polytropic EOS to ensure no numerical fragmentation at finest refinement level



Model for Star Formation

if $\rho_{\rm g} > \rho_0$ ⟹ $\dot{\rho}_* = \frac{\rho_{\rm g}}{t_*(\rho_{\rm g})}$

ρ_0 = 0.1 atoms/cm^3

$$t_* = t_0 (\frac{\rho_{\rm g}}{\rho_0})^{-1/2}$$

Choose t_0 so that have ~ 1% star formation efficiency per free fall time

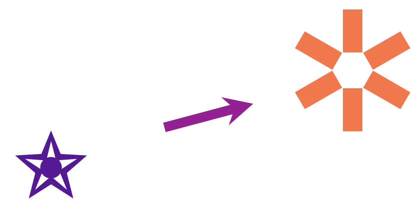
(Krumholtz & Tan 2005)

$m_* \sim 10^7\ M_{sun}$

Model for supernovae feedback

Dubois & Teyssier 2008

Impose single Sedov
solution with
10 Myr delay

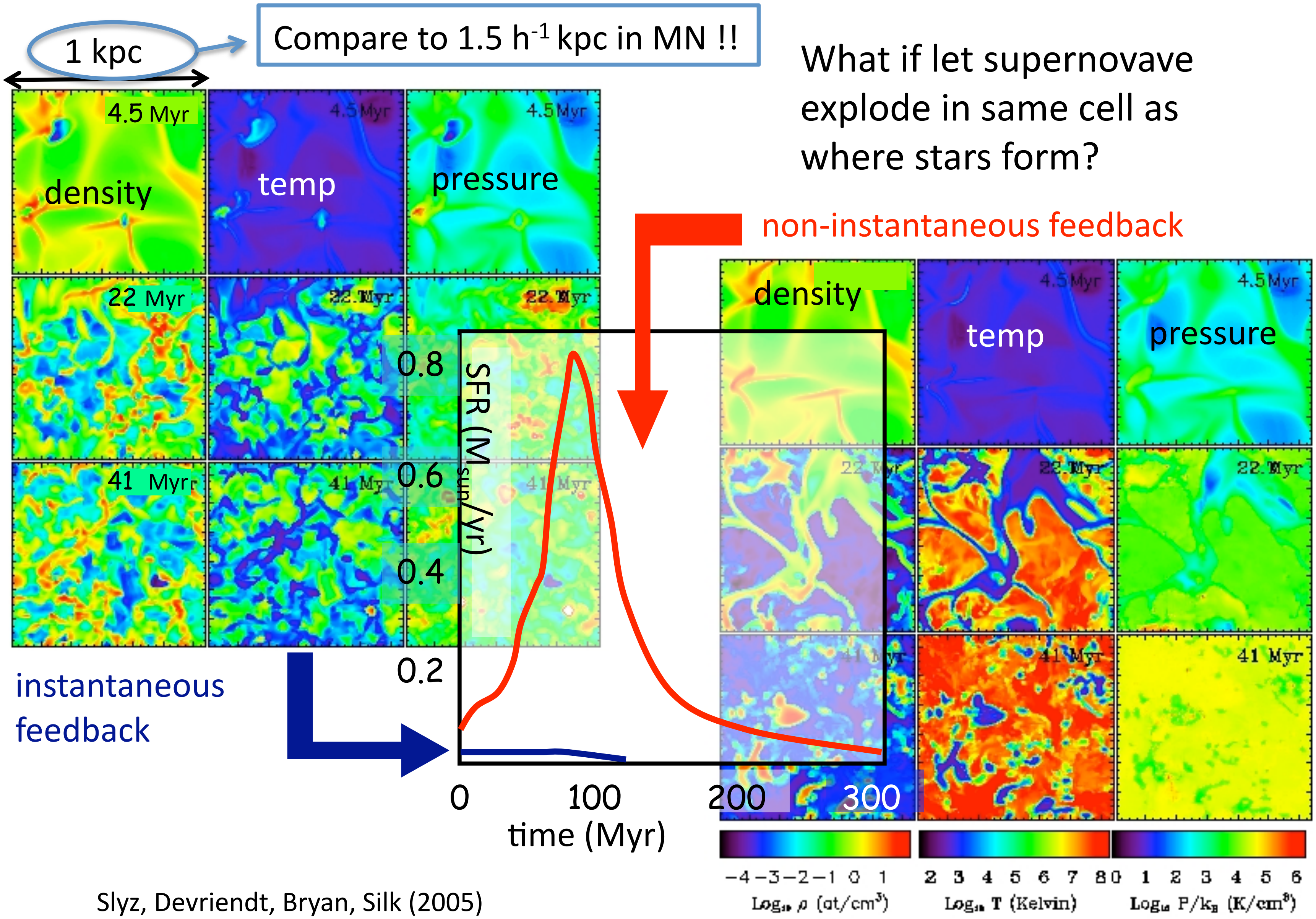


→ ~ 10^5 supernovae/star particle
for Salpeter IMF

Produce metals that are advected as a passive scalar &
incorporated into cooling and heating routine

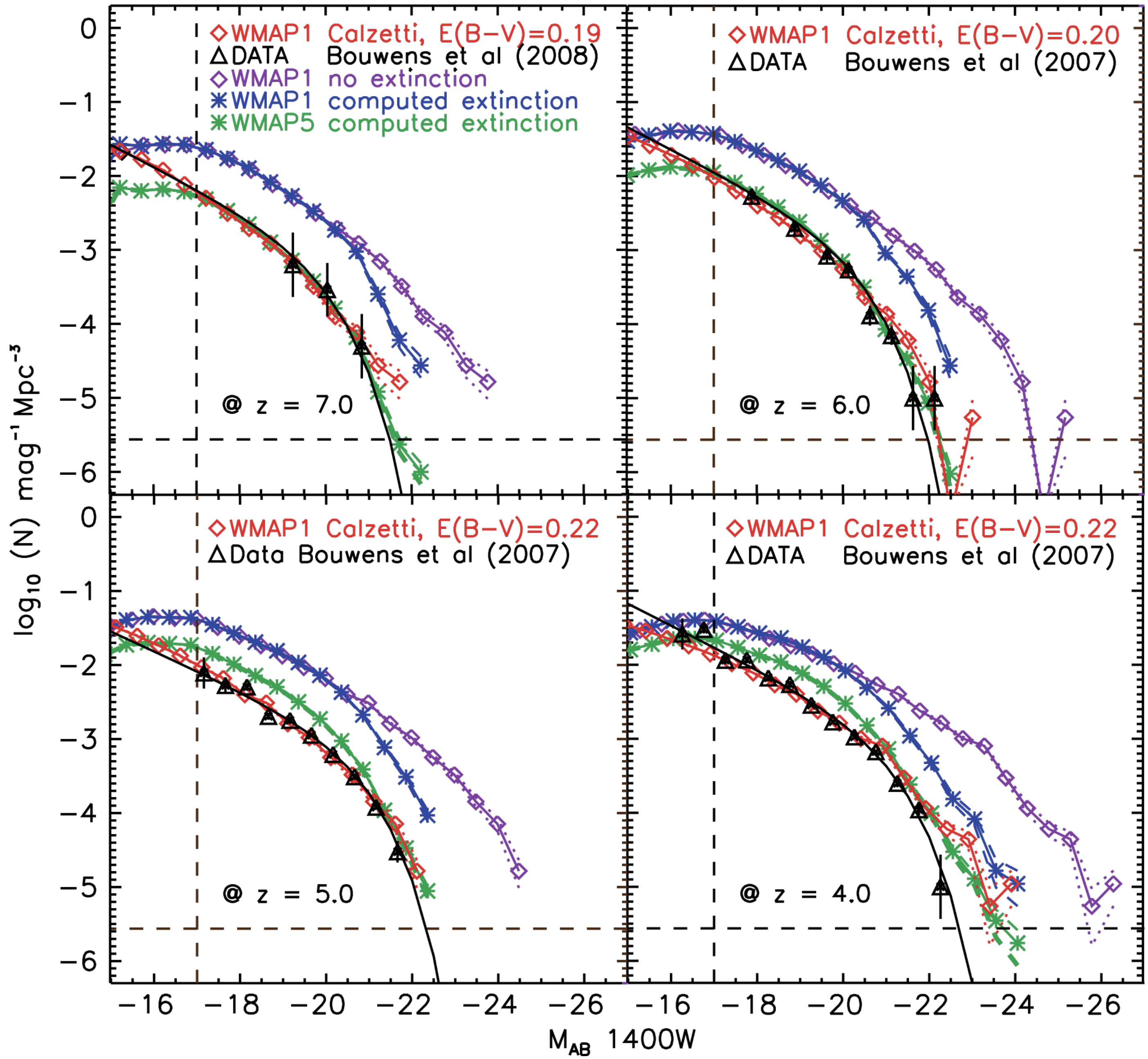
Why is feedback so difficult to model?

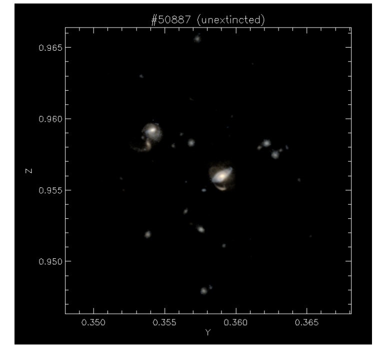
What if let supernovave explode in same cell as where stars form?

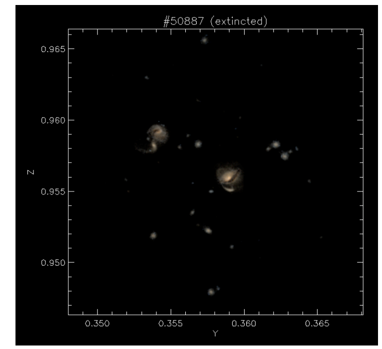


Slyz, Devriendt, Bryan, Silk (2005)

Lessons from MN: LF evolution @ high z





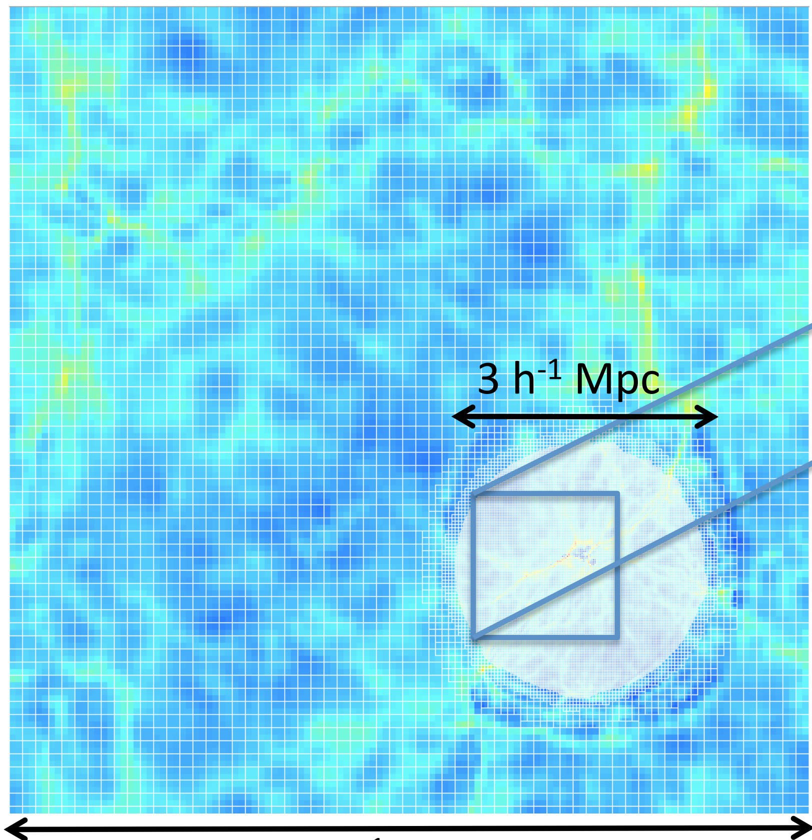


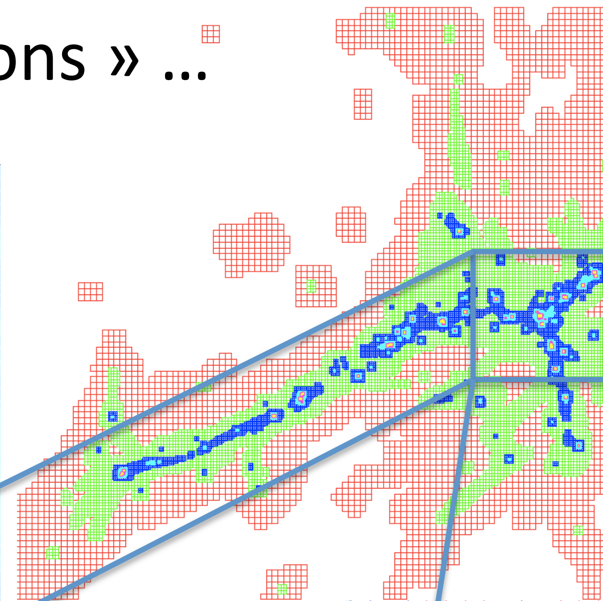
Luminosity functions of MN galaxies in the rest-frame UV measured in the simulation volume at different z & with different prescriptions for extinction (calculated vs averaged Calzetti law). Also shown is an attempt to rescale to WMAP5 cosmology. Note the degeneracy between extinction, cosmology and AGN fb.

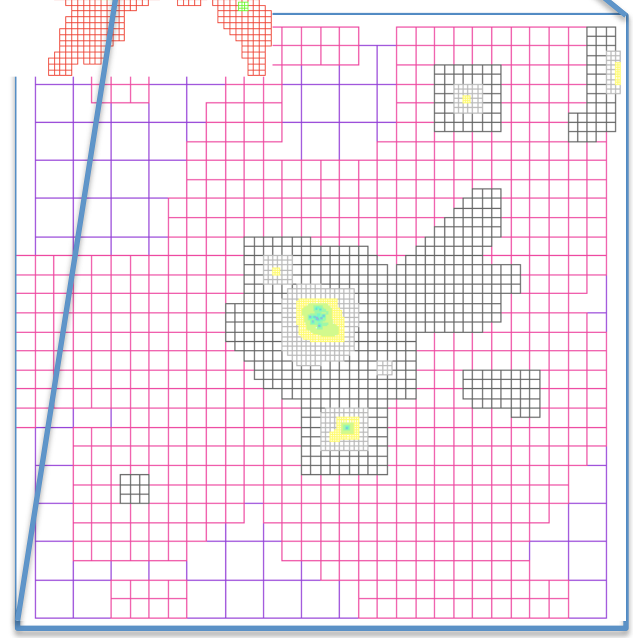
Devriendt et al, 2010

AMR NUT « re-simulations » …

with RAMSES (Teyssier 2002)







CPU time:

From 0.5 to several million hours on ~ 200 procs

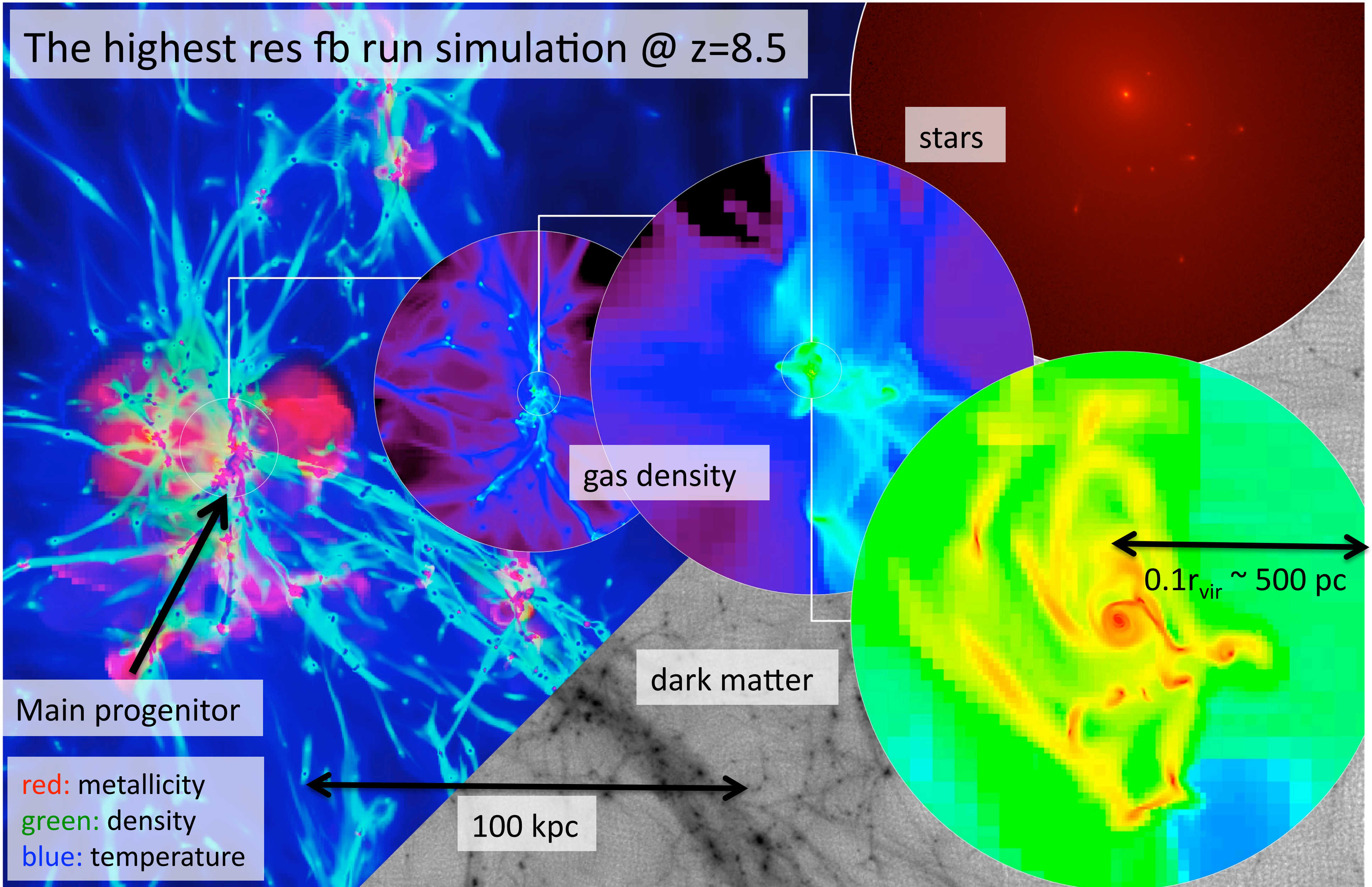
Data:

~ 2 Tb per simu @ 100 Myr time resolution

spatial resolution ~ 0.5-48 pc (physical) on finest level

128 root grid,
3 nested grids
8-15 AMR refinement levels
Identical simulations (IC / DM particle mass res → 5 x 10^4 $M_\odot$) with different physics implemented (adiabatic, cooling, star formation, SN feedback (this talk), RT (see Joki's talk for more), stellar winds, MHD …)

The highest res fb run simulation @ z=8.5



• ~ 0.5 parsec resolution, M_{DM} ~ $5 \times 10^4 M_\odot$, M_* ~ 150 $M_\odot$
• Metal cooling, UV background, supernovae feedback
• WMAP5 (σ_8: 0.796, H_0: , Ω_b: 0.0441, Ω_M: 0.258, Ω_Λ: 0.742, n: 0.963)

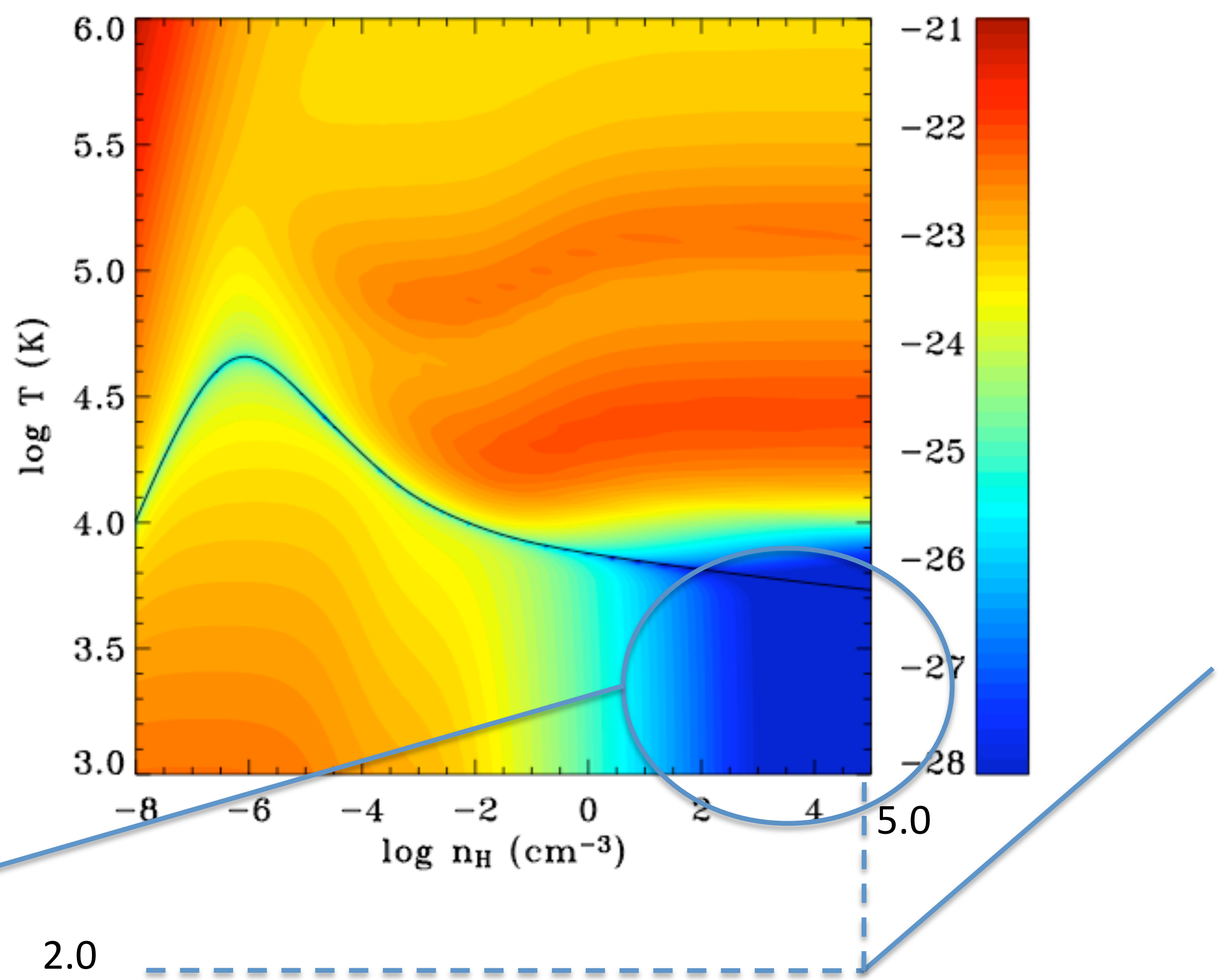
Code: RAMSES (Teyssier, 2002)
N-body + AMR

Radiative Cooling

Metal dependent Cooling + Heating Rate (in the presence of UV radiation once reionization turned on)

Switch to polytropic EOS to ensure no numerical fragmentation at finest refinement level

Modified to include metal line cooling (no molecular cooling yet)



Model for Star Formation

if $\rho_g > \rho_0$ ⟹ $\dot{\rho}_* = \frac{\rho_g}{t_*(\rho_g)}$

ρ_0 = 10^5 atoms/cm^3

$$t_* = t_0(\frac{\rho_g}{\rho_0})^{-1/2}$$

Choose t_0 so that have ~ 1% star formation efficiency per free fall time

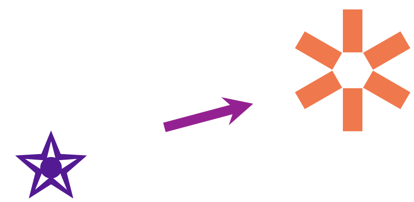
(Krumholtz & Tan 2005)

$m_* = 167\ M_{sun}$

Model for supernovae feedback

Impose:

(i) same single 10 Myr delay Sedov solution
(but now SN travel distance is resolved!)



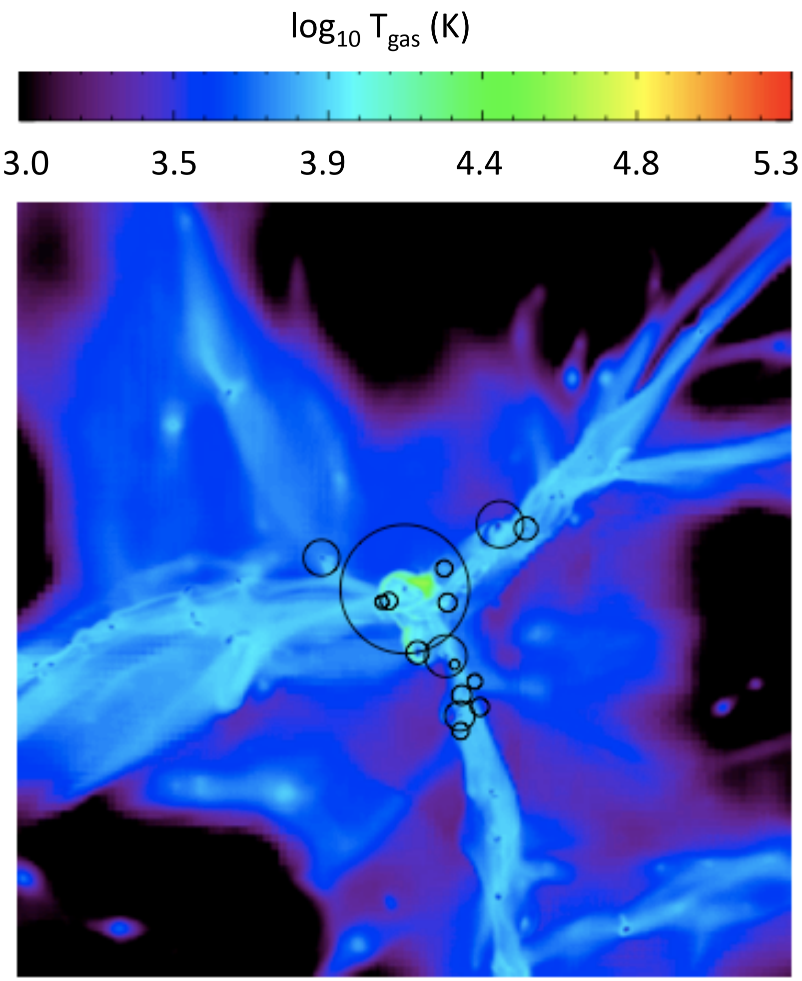
(i) multiple delay Sedov solutions for SN II
& SN Ia (with or w/o stellar winds)

~ 1-10^2 supernovae/star particle
for Salpeter IMF

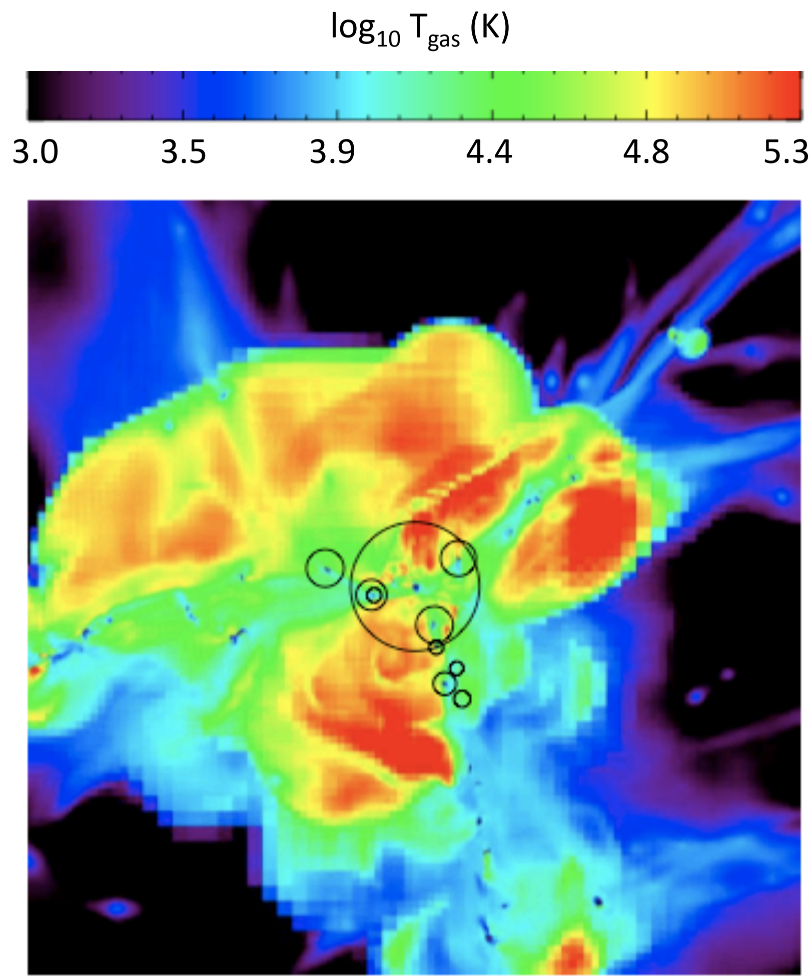
Produce metals that are advected as a passive scalar & incorporated into cooling and heating routine (note that in case (ii) more metals are produced)

Resolving individual SNR: a (collective) wind?

Cooling +star formation



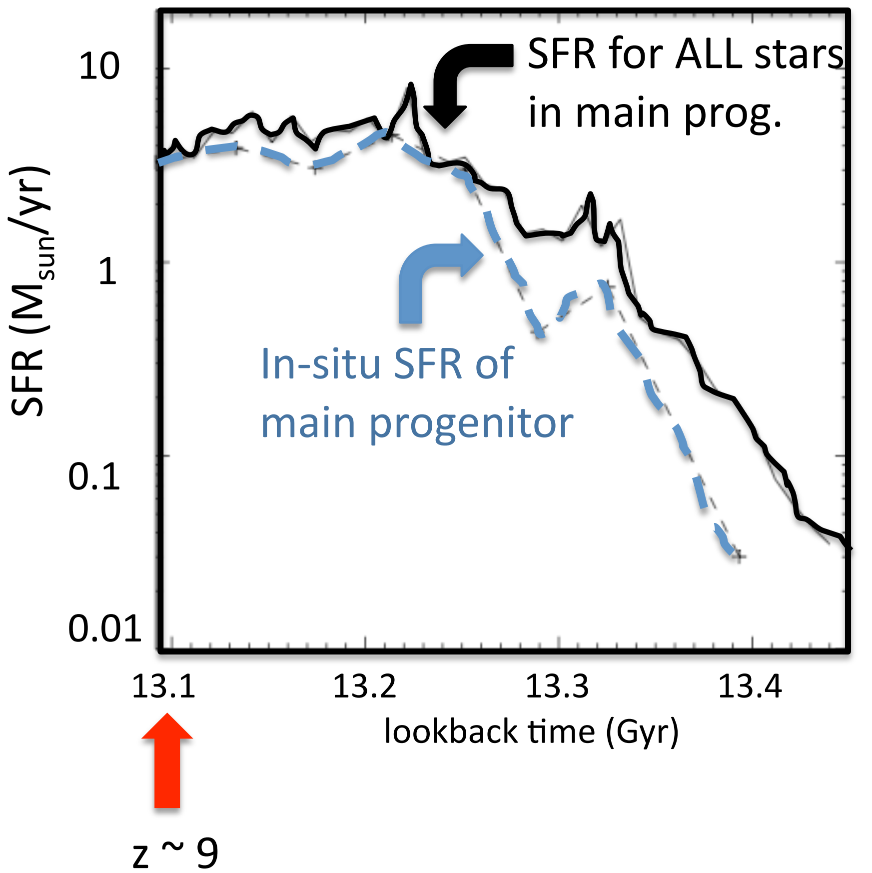
Cooling + star formation + supernovae fbk



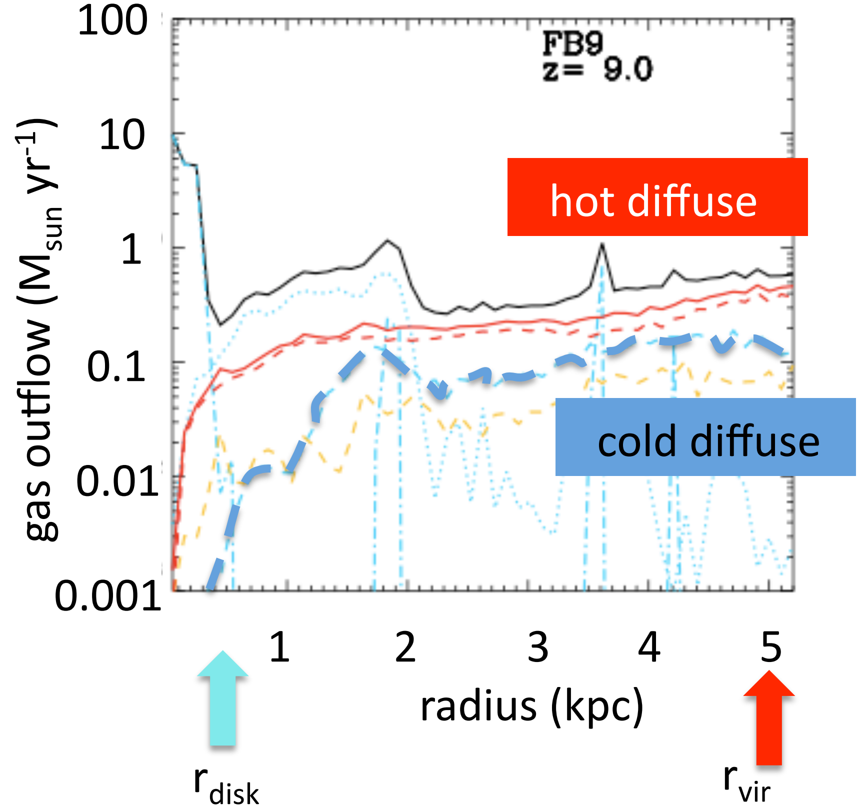
Powell et al 2011

Outflow vs SFR @ z = 9 within r_{vir}

Cooling + star formation + supernovae fbk

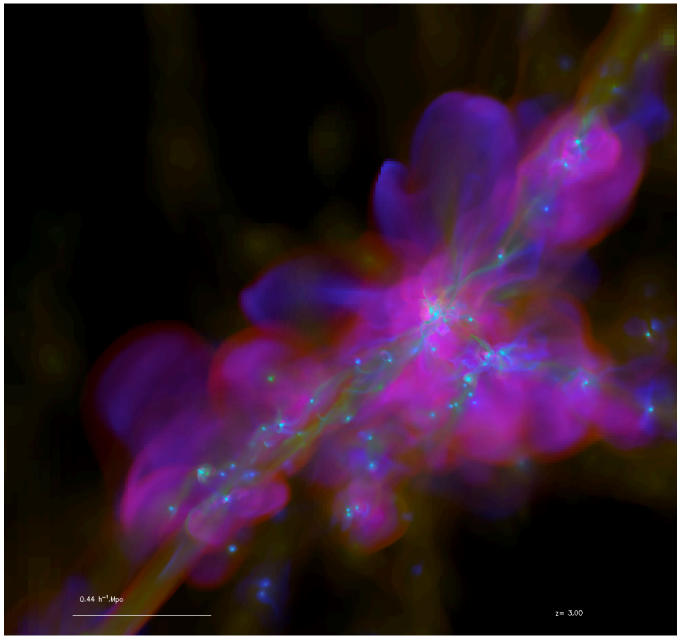


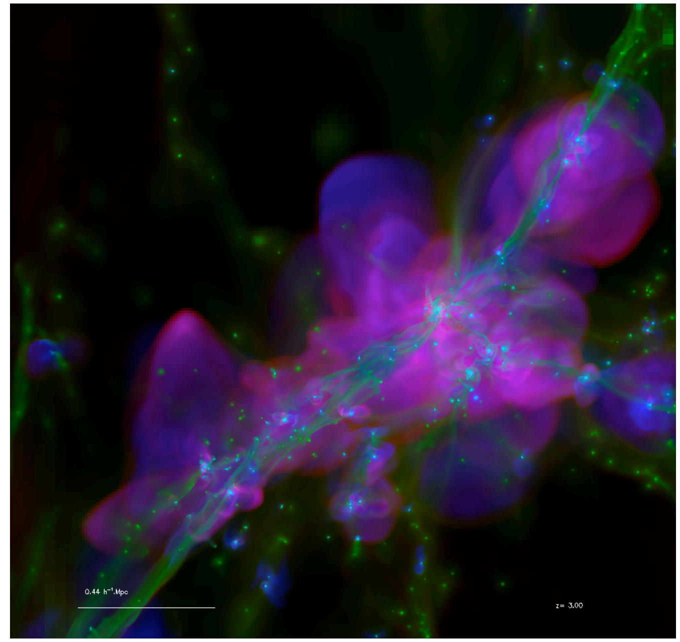
feedback run

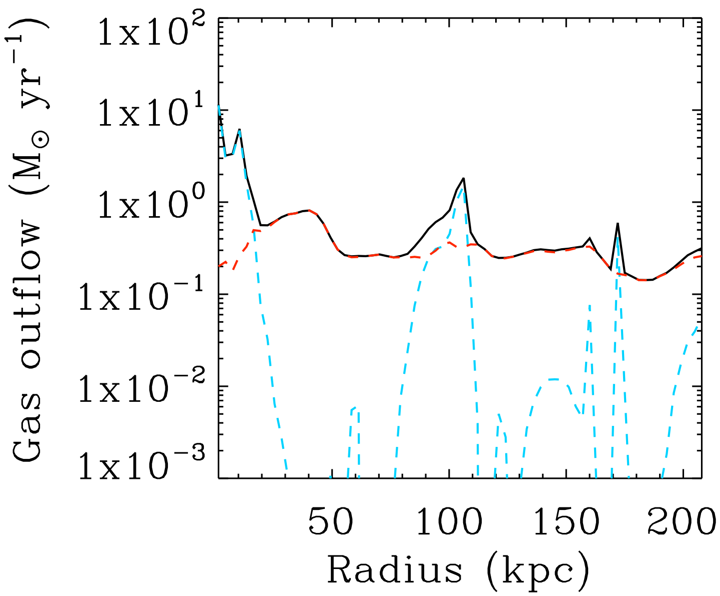


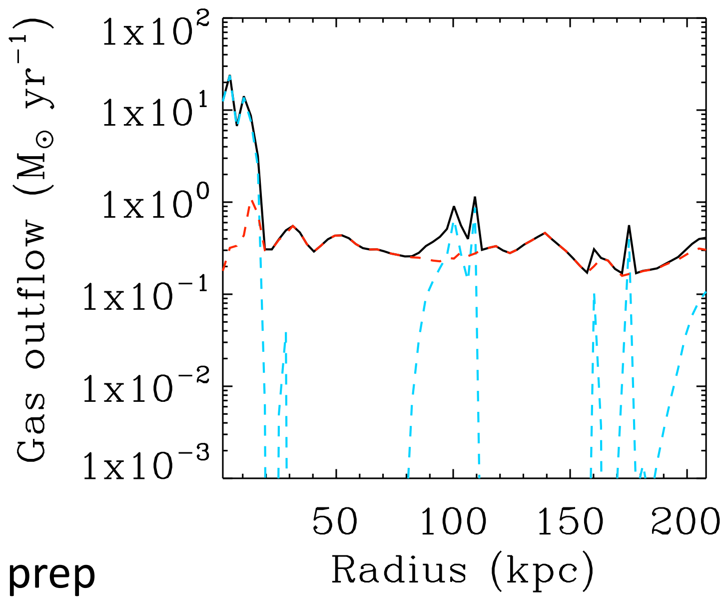
Verdict: SFR ~ 10 x outflow – Fast, metal rich, collective wind (v_w = 100-250 km/s ; Z = 0.1-0.5 $Z_\odot$ @ z=9 in a halo 5×10^9 $M_\odot$) but low mass loading (Powell et al 2011)

Convergence @ 10 pc and RT negligible effect



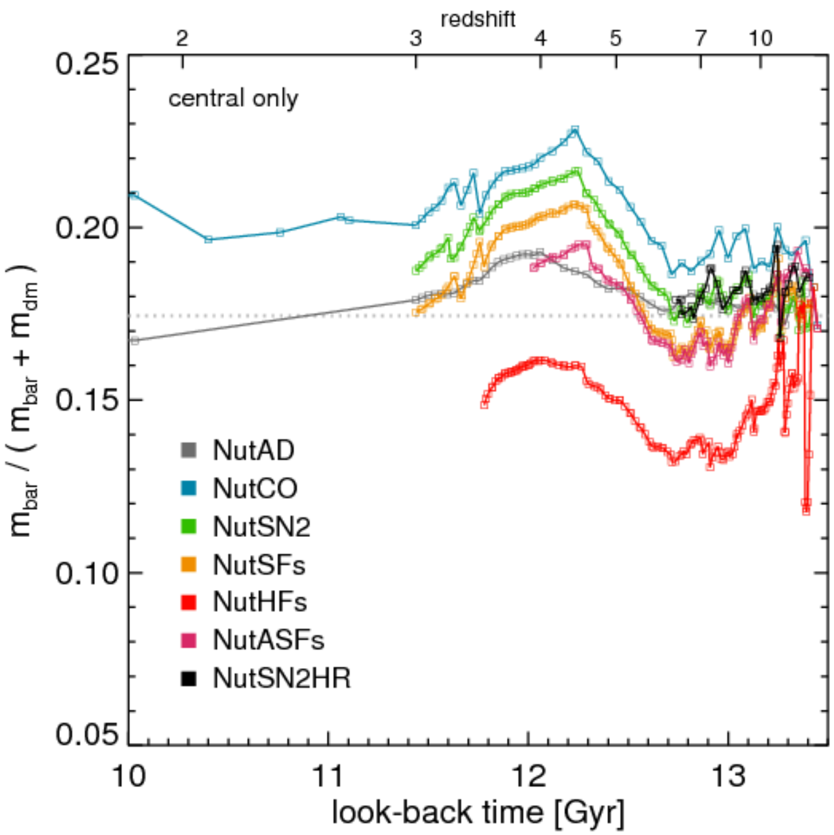


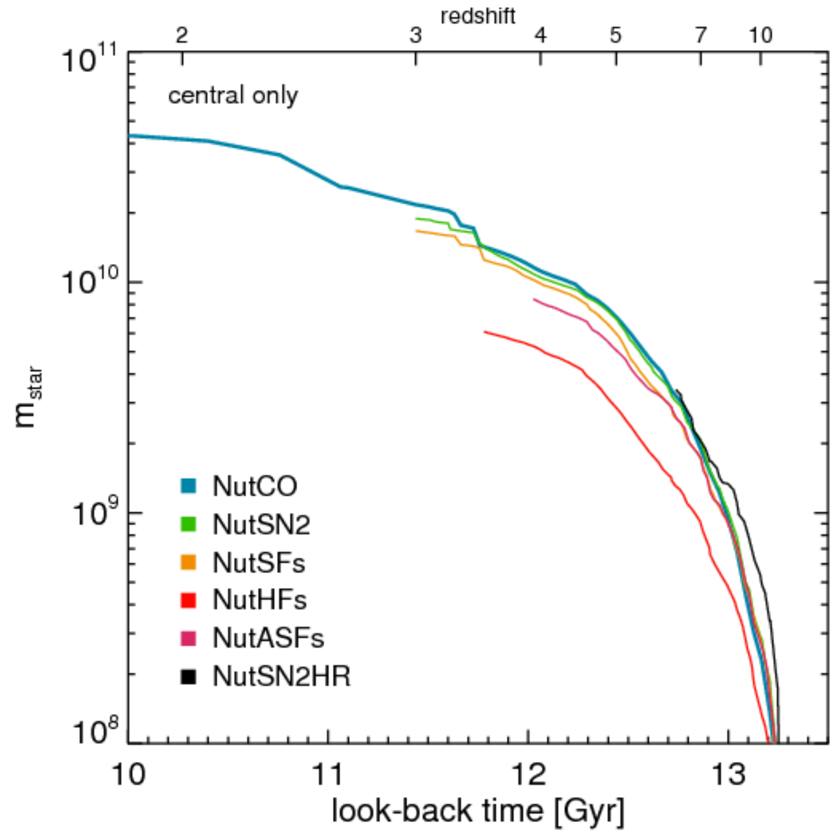




Powell et al, in prep

More physics: Stellar winds? Type Ia SNs? Hypernovae? small AGN? RT? All these?





Kimm et al, in prep

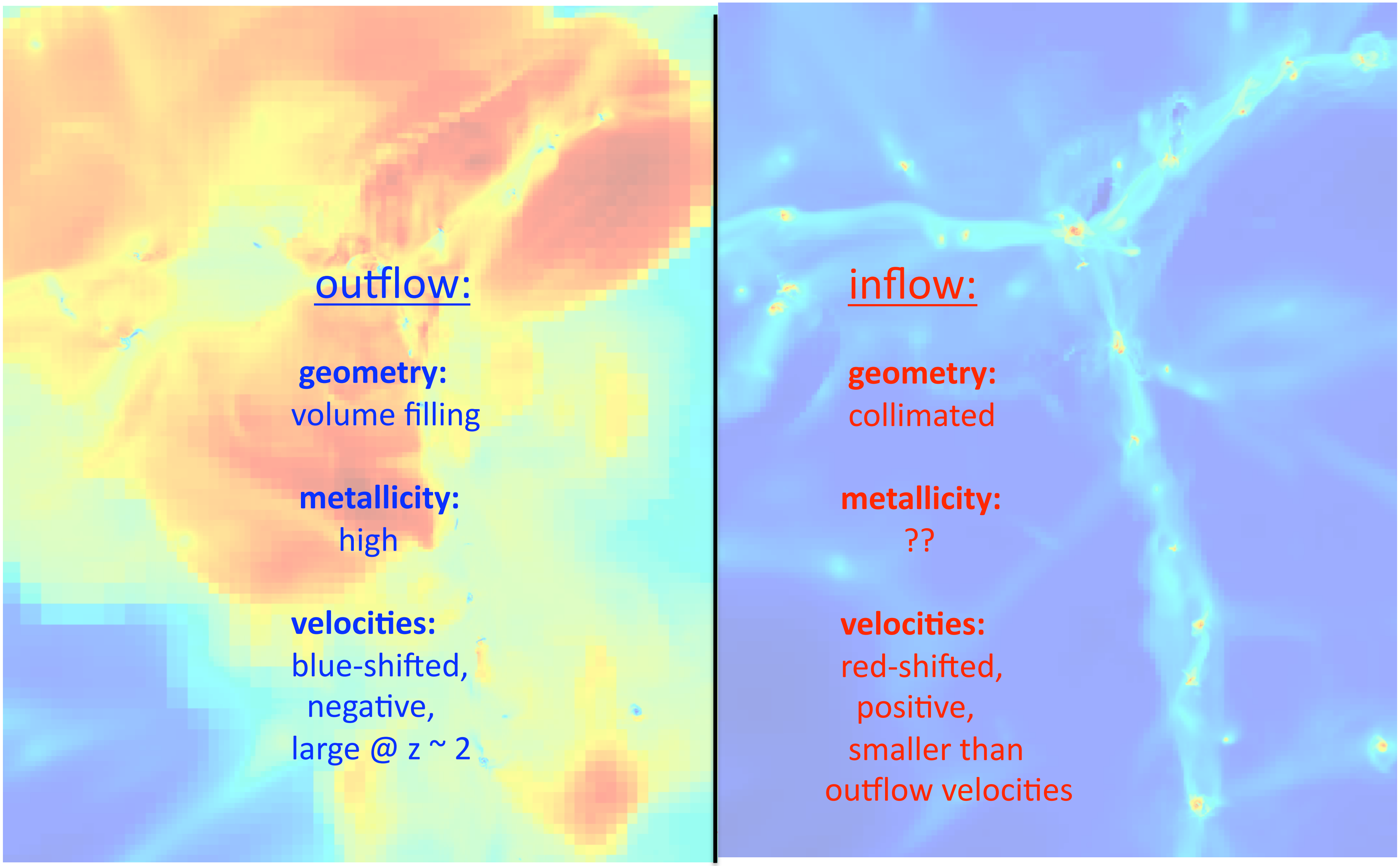
Where next?

Still more physics:
MHD missing: tension confined bubbles become buoyant (Pontzen et al, in prep)?
Role of Molecules? Better cooling with RT? Dust? Cosmic Rays?

Resolution min ~ 10 pc but do we need more as we add more
physics?

Progressive inclusion in lower res cosmo sims for statistics
MN with SW, SN Ia, Hypernovae, AGNs? But what subgrid model?

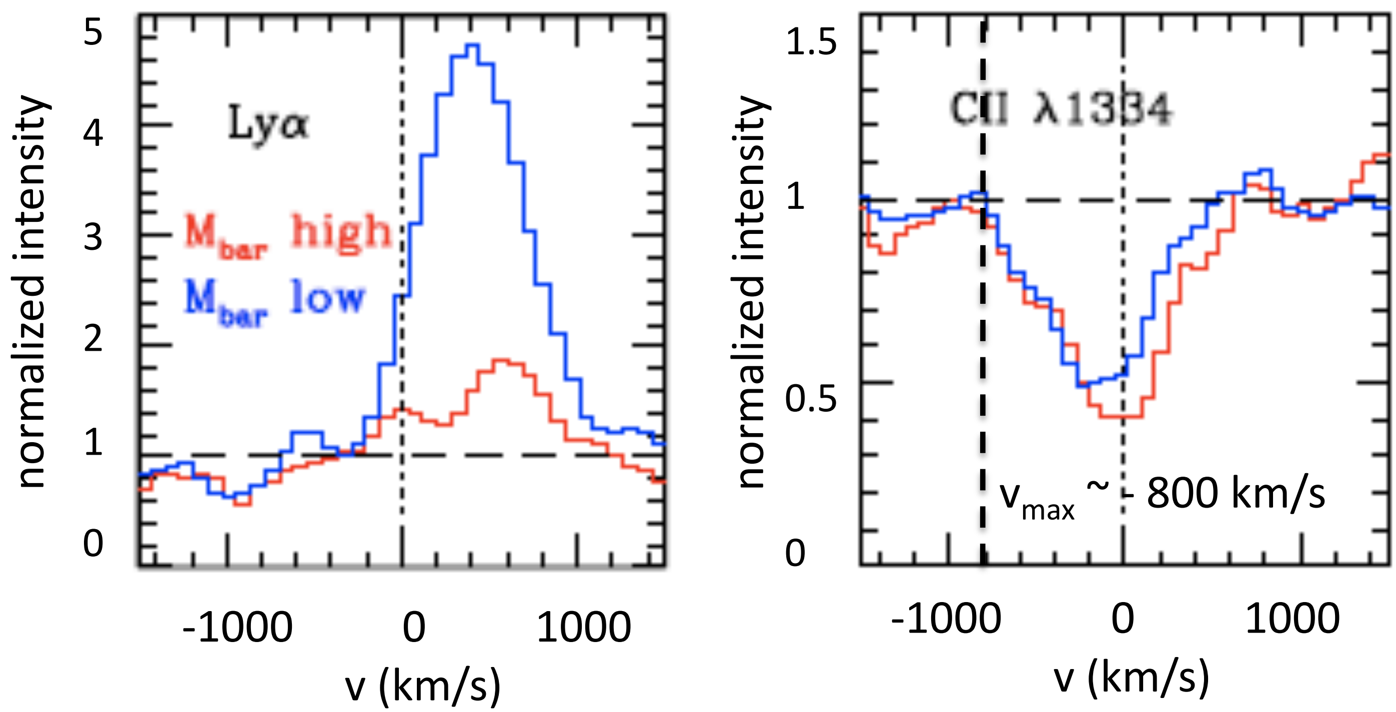
What observations (part I) ?



Evidence for infall in higher mass sub-sample?

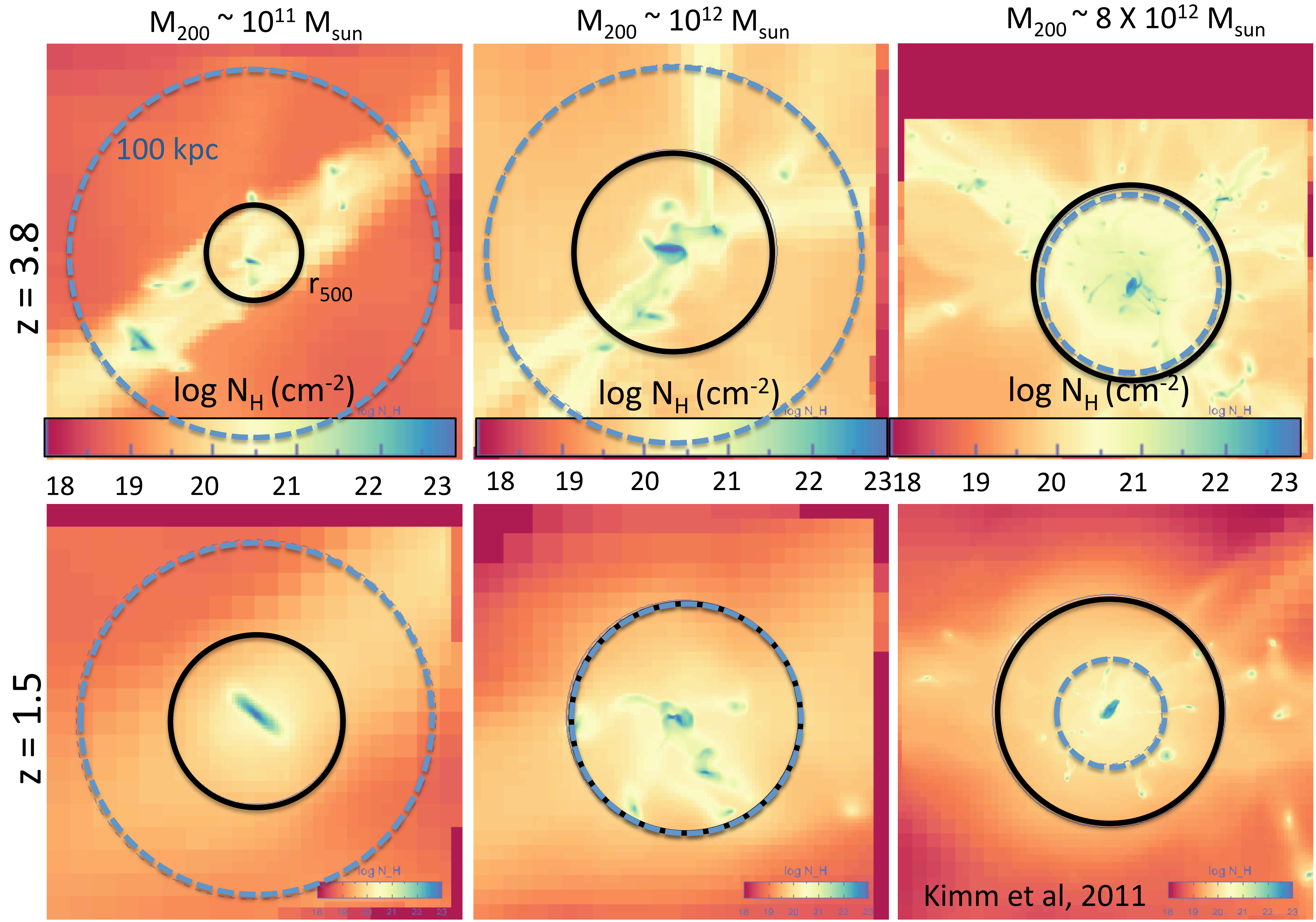
Blue: $M_{baryon} < 5 \times 10^{10} M_{sun}$

Red: $M_{baryon} > 5 \times 10^{10} M_{sun}$



Steidel et al 2010

Column Density Maps



Can we find the cold filaments with metal absorption lines?

e.g. CII (1334.5) absorption line profile

optical depth

$$I_{rel}(v) = I(v)/I_0 = \exp\left[-\int \sigma_{\rm CII} n_{\rm CII}(v) dl\right]$$

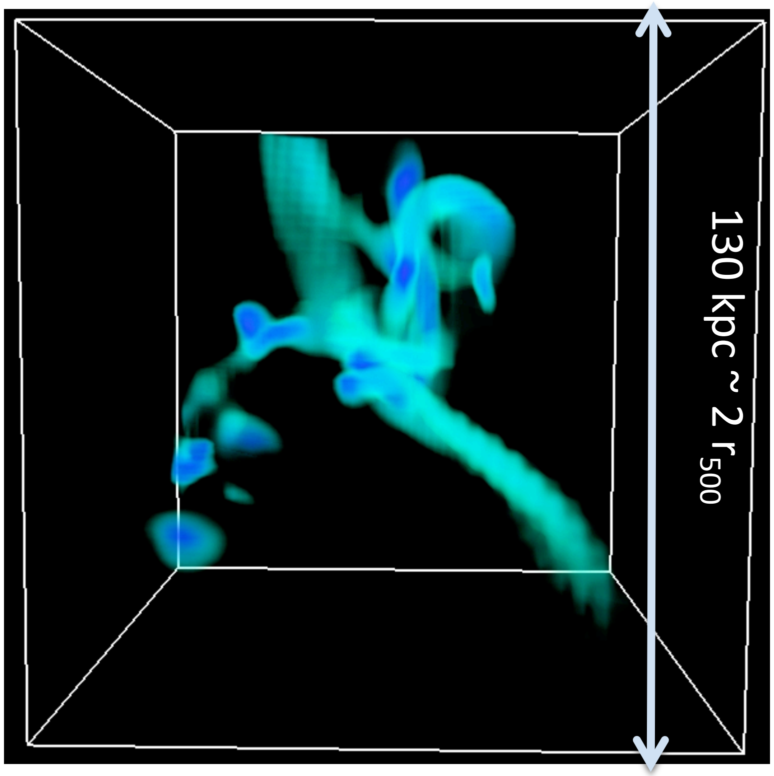
collision cross-section : $\sigma_{\rm CII} = (3\pi\sigma_T/8)^{1/2} f \lambda_0 \backsimeq 1.5 \times 10^{-18} {\rm cm}^2$

Assume: 1) abundance ratio is solar: $[C/Z]_{sun} \cong 0.178$ (Grevesse et al. 2010)

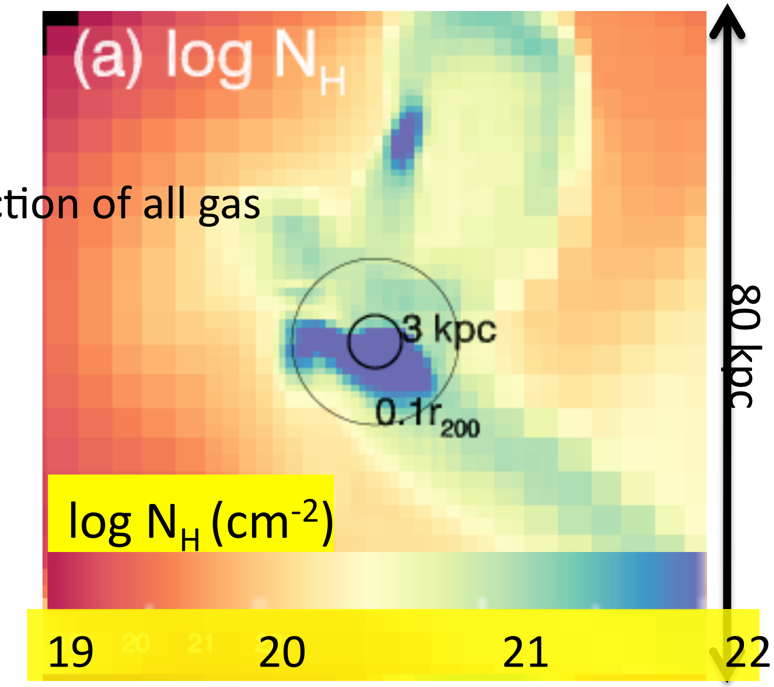
2) all carbon atoms are eligible for the transition: $n_C = n_{CII}$

$$n_{\rm CII} = n_{\rm C} = \frac{0.178 Z \rho(v)}{m_C}$$

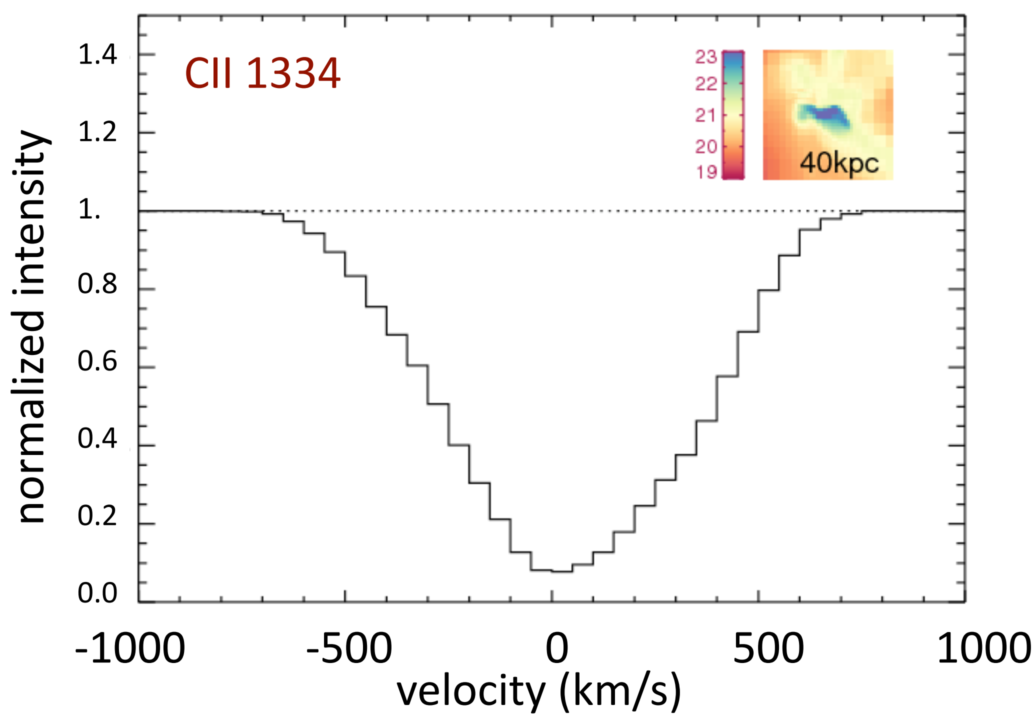
mass of Carbon



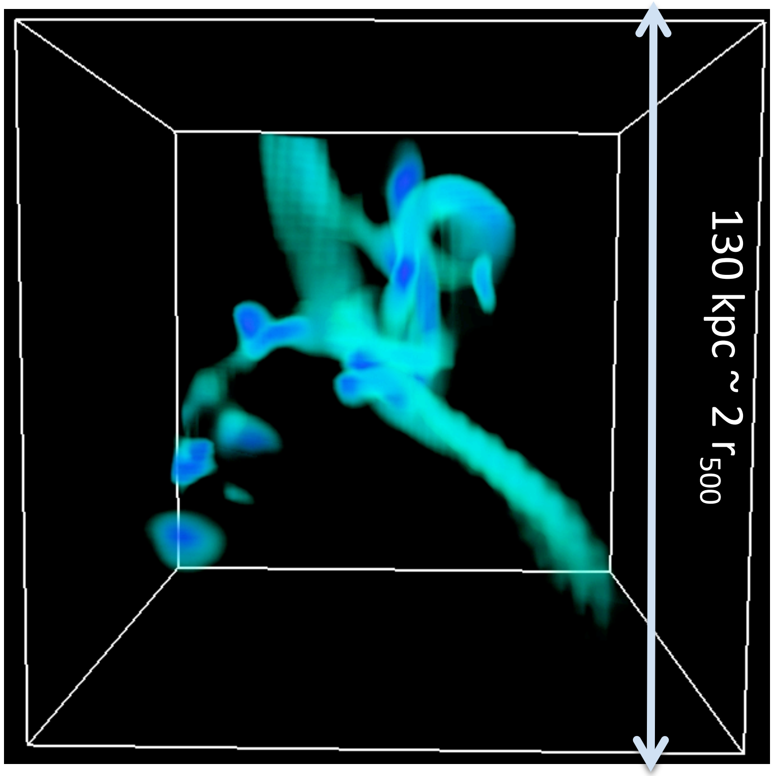
projection of all gas



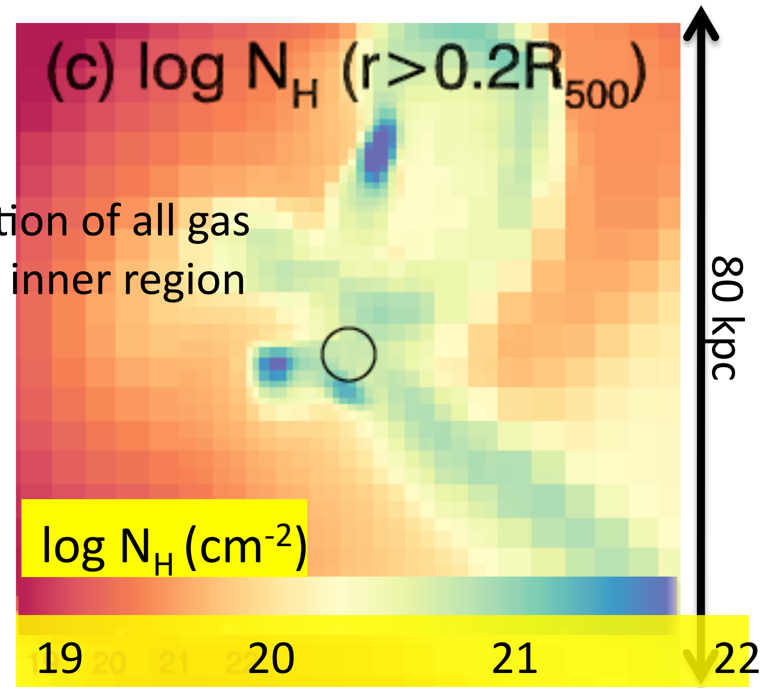
absorption profile
with inner dense region



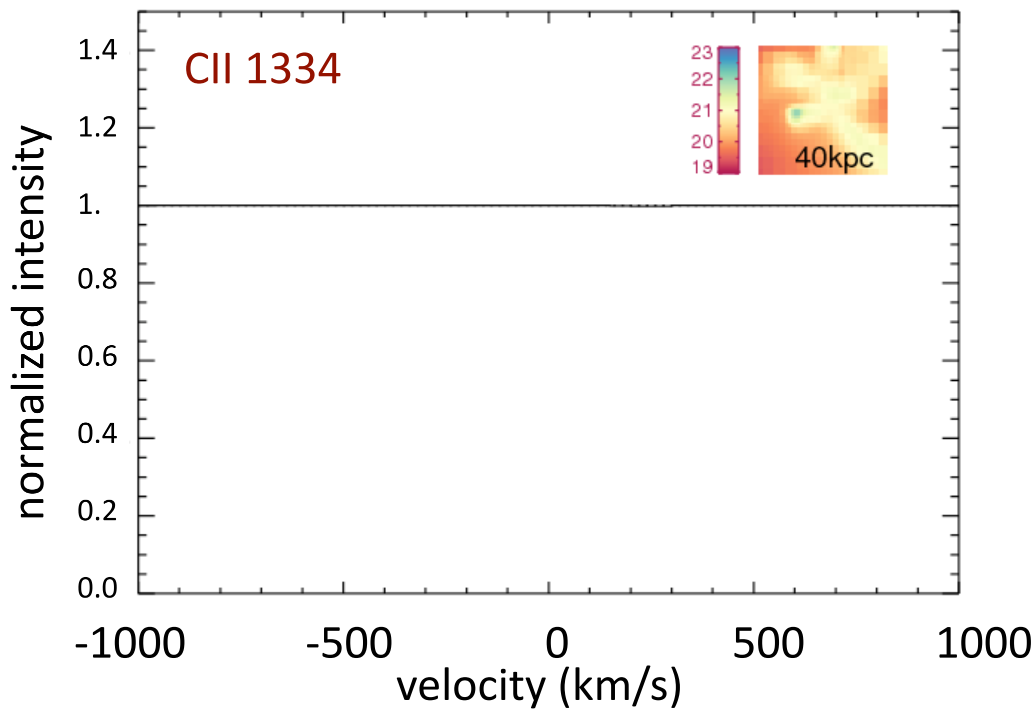
Kimm et al, 2011



projection of all gas
except inner region



absorption profile
without inner dense region

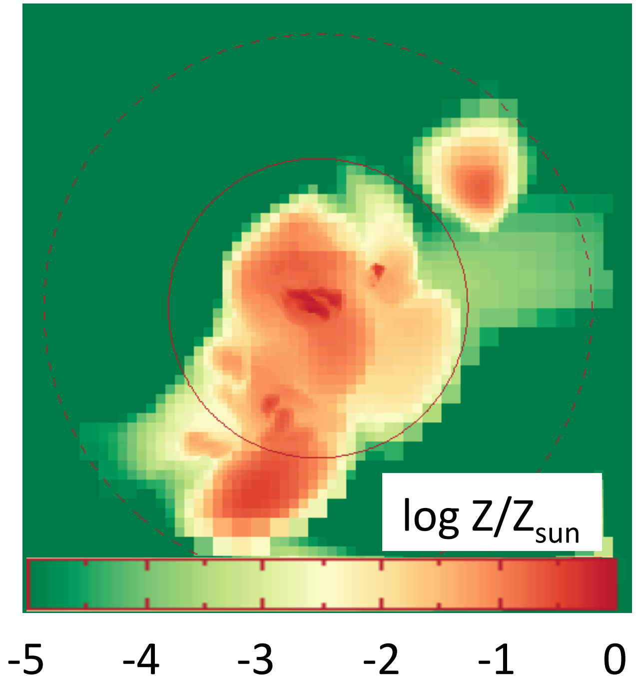


Kimm et al, 2011

Metallicity of filaments in simulation?

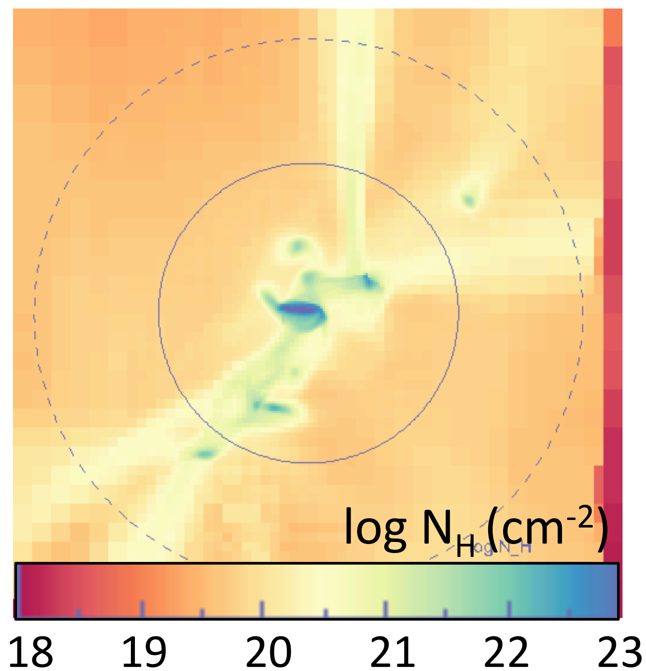
Halo @ $z = 3.8$

$M_{200} \sim 10^{12}\ M_{sun}$



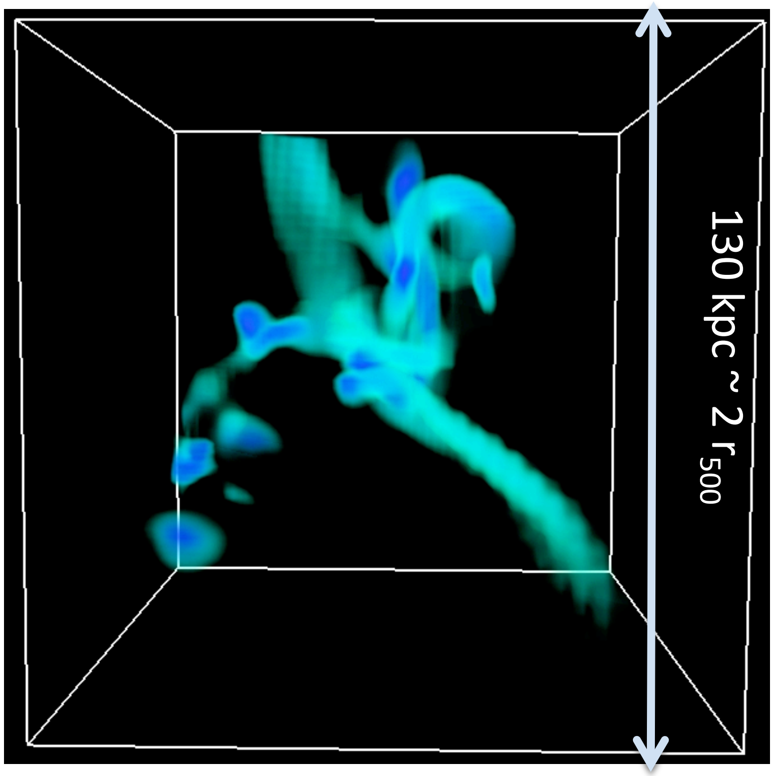
metallicity map

Metallicity of cold filaments devoid of embedded substructures ~ $10^{-5}\ Z_{sun}$!

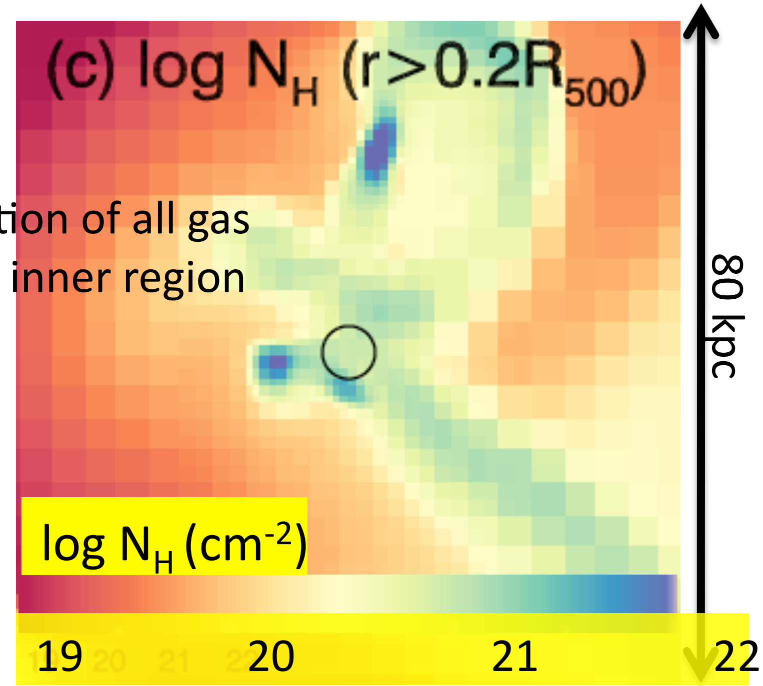


column density map

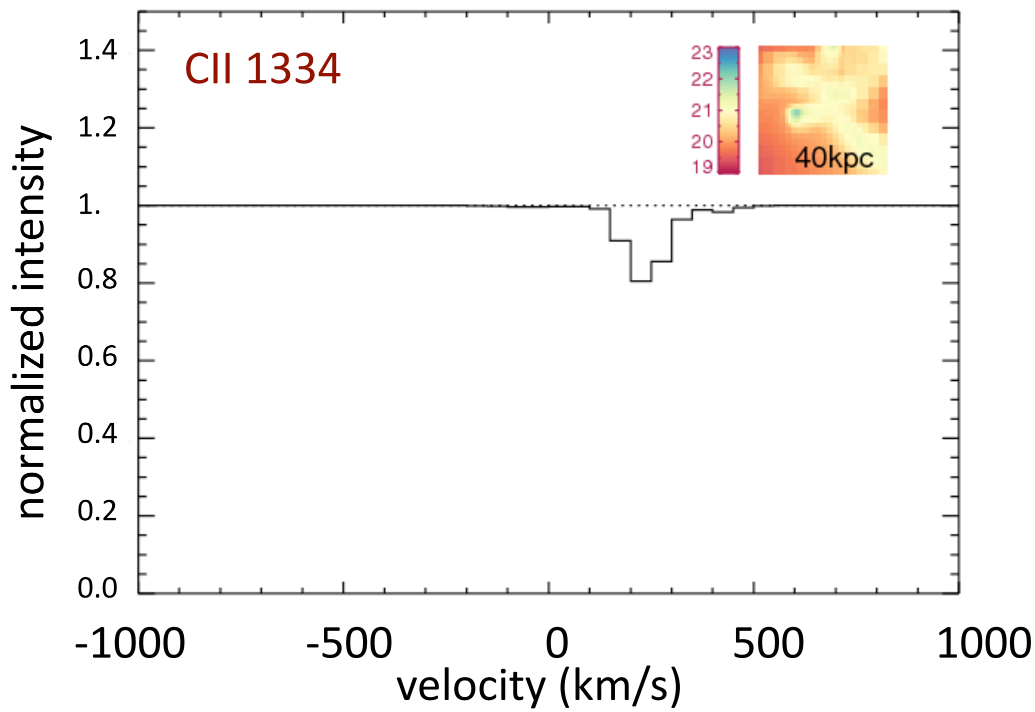
Kimm et al, 2011



projection of all gas
except inner region



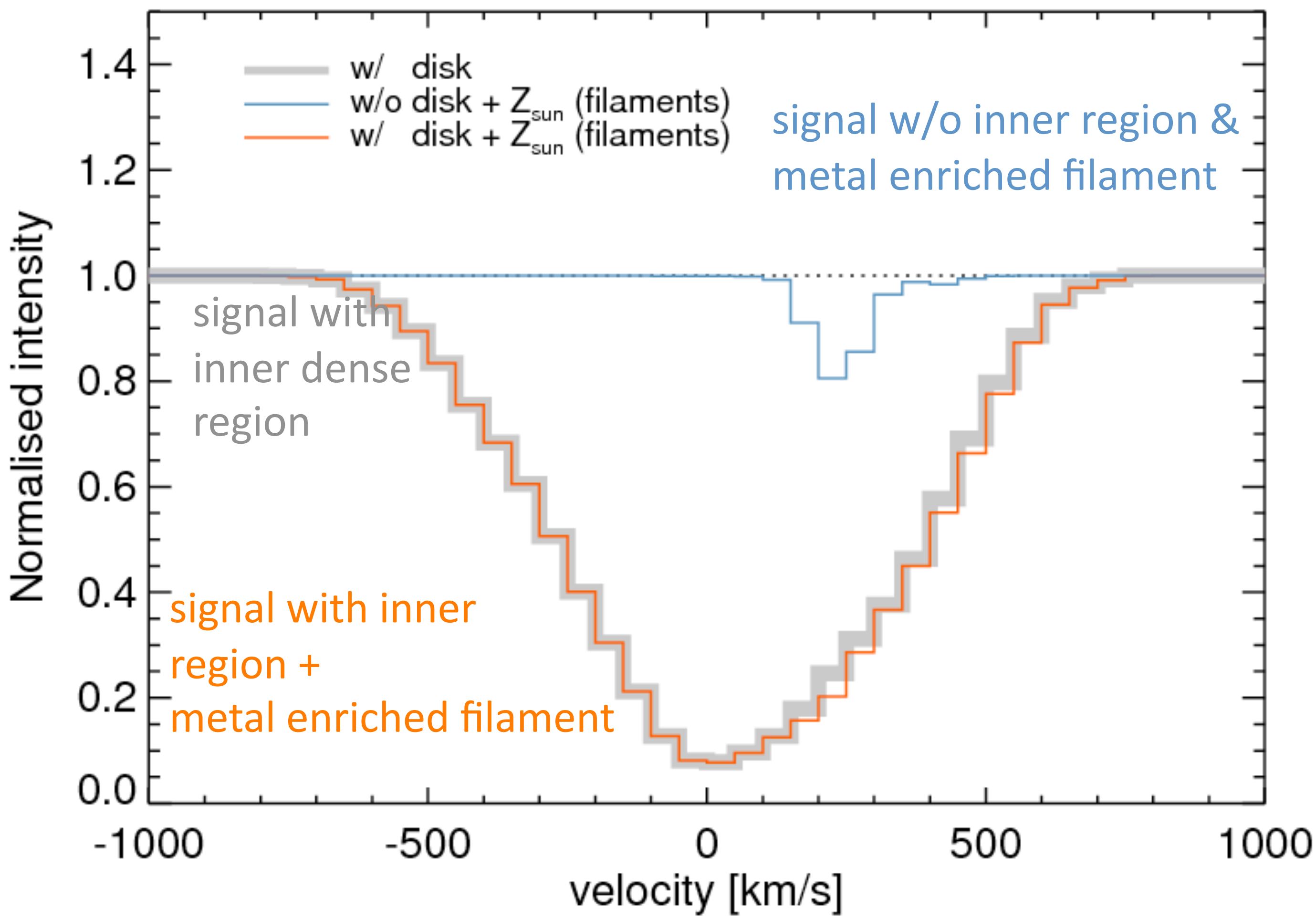
absorption profile
without inner dense region
+ Z_{solar} in filament



Conclusion: Ly-alpha is the only way to go for inflow!

with the caveat that very difficult to model (ionisation, velocity field of ISM)

for outflows need mass/velocity profiles for the hot metal rich gas (background galaxies?) like Strickland & Heckman (2009) for M82 (hard & soft X-ray?)

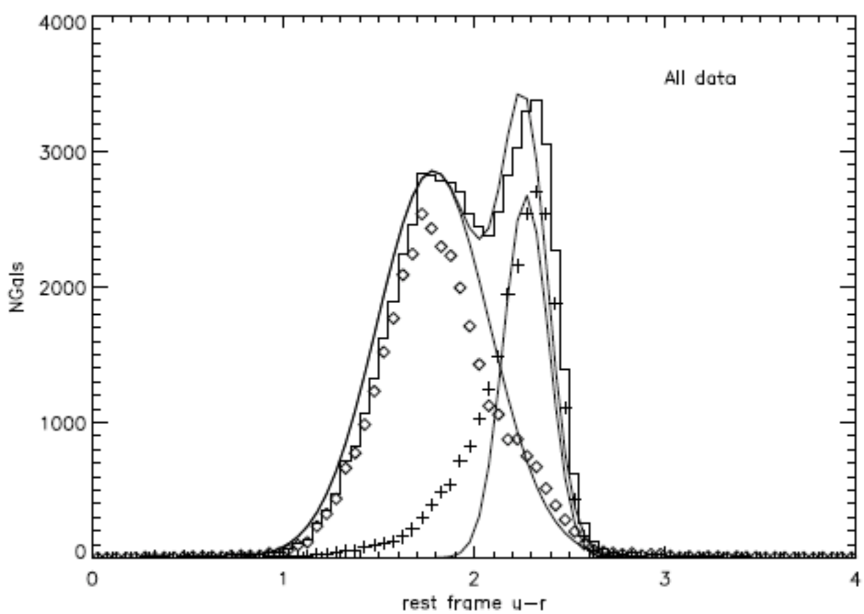


Kimm et al, 2011 see Joki & Anne's talks for Ly-alpha predictions

What observations (part II)? angular momentum

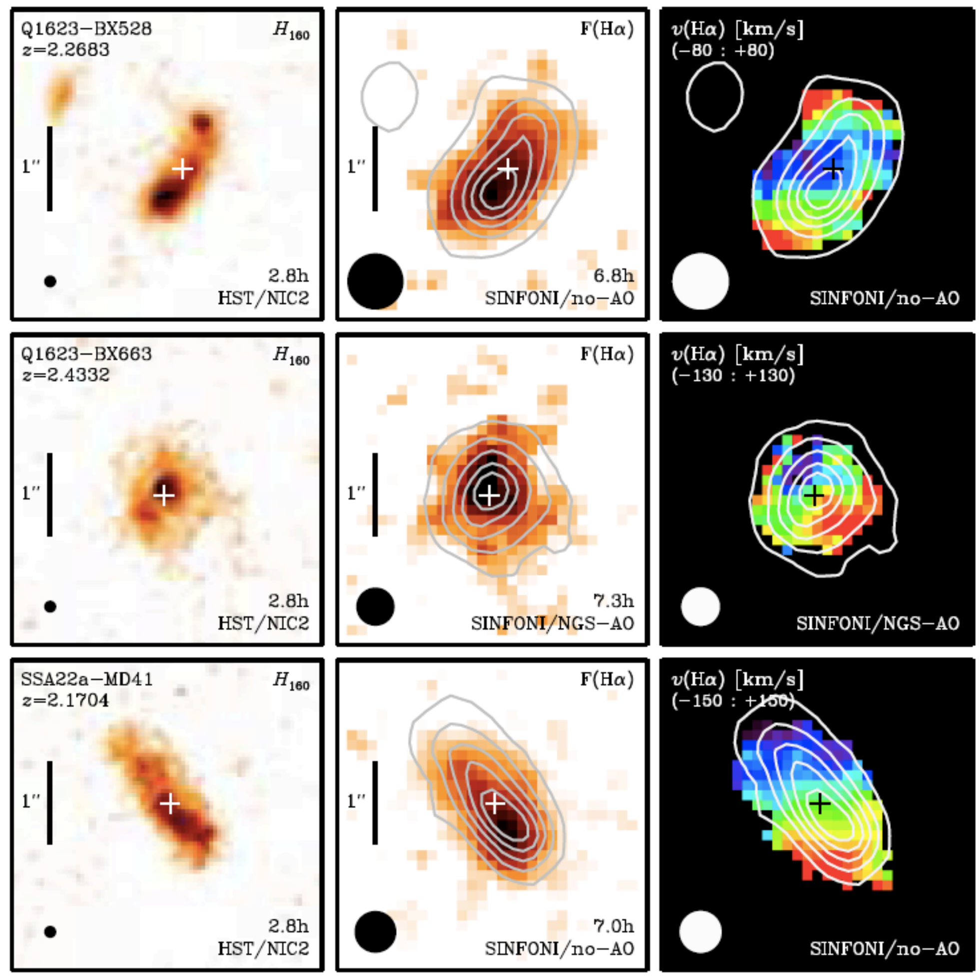
A large fraction of local galaxies have discs …

Galaxy zoo: Lintott et al 2008



… and so do a lot of higher redshift (z>1) objects

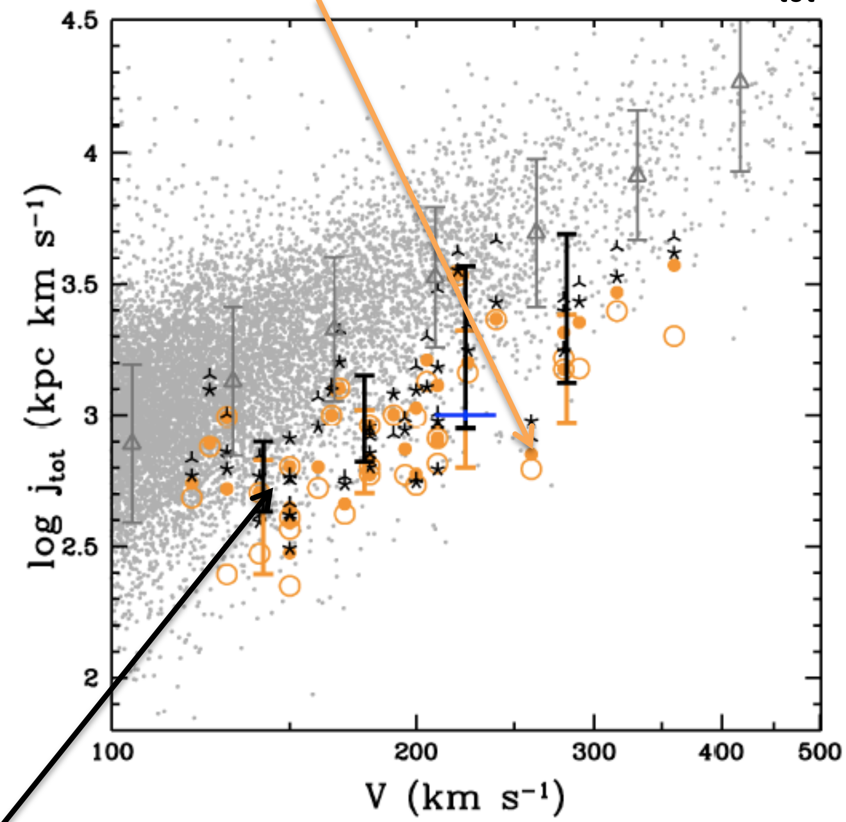
Sinfoni: Forster-Schreiber et al 2010



bc @ z=0 not matched by standard theory

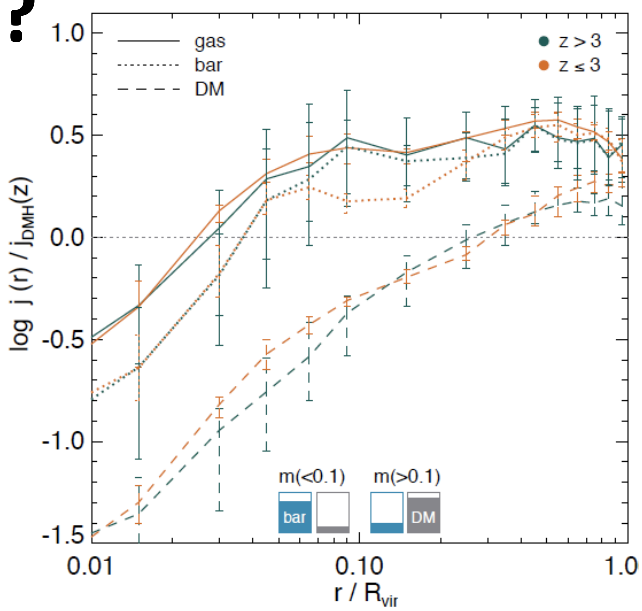
Upper (solid) and lower (empty) j_{tot}

Kassin et al, in prep

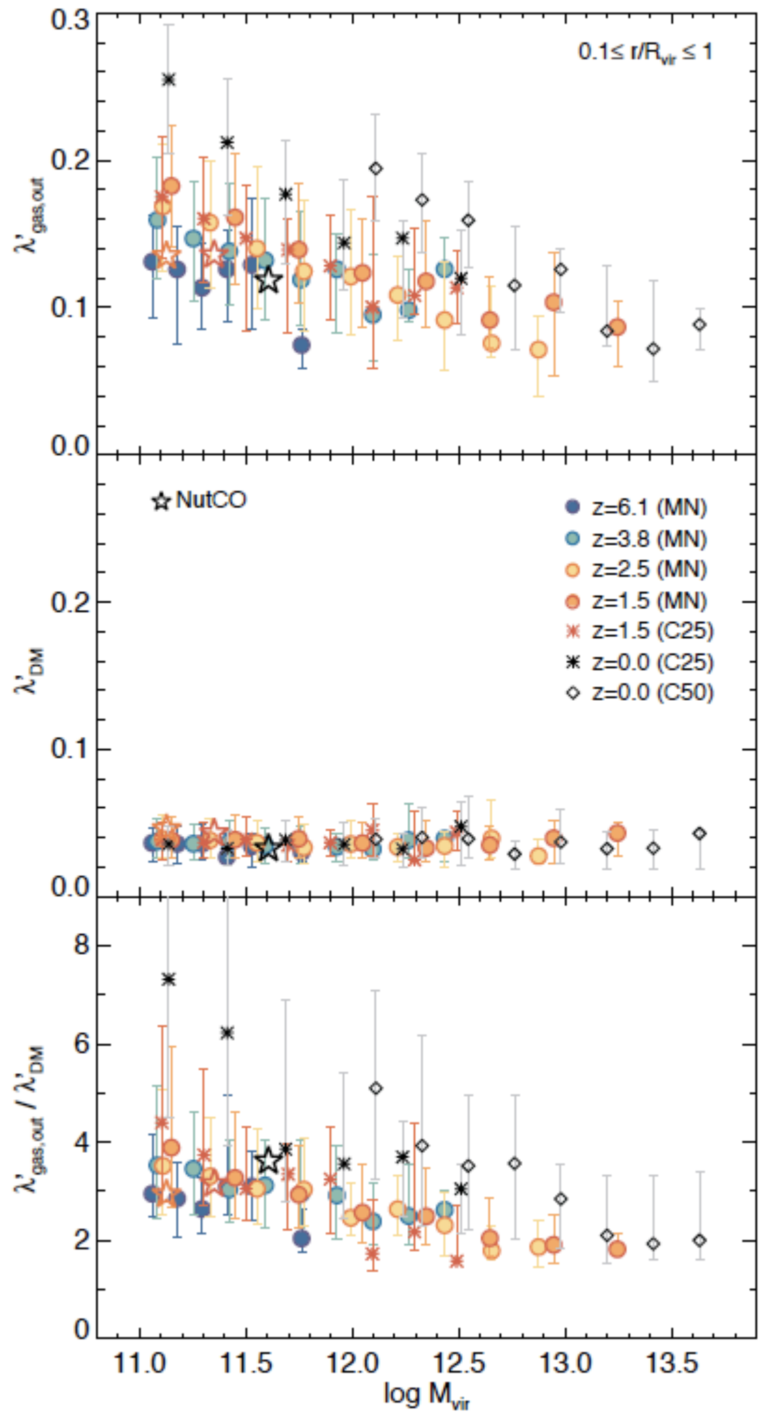


Estimates $j_{tot} \sim 2V_{flat} r_d$ (black symbols) differ from measure by factor ~ 1.5 (higher)
bc no account for rising inner part with lower V (r_d stands for disk scale length in band R or K)
<u>Note</u>: this is significantly less than difference between galaxies and DM halos.

AM linked to gas inflow but outflow ?



Strong link to inflow:
Kimm et al, 2011



Reduced spin parameter:
$\lambda' = j \,/\, (\sqrt{2}\, R_{vir}\, V_c)$
(Bullock et al 2001)
No trend for DM vs 2 trends for gas:

1 / decreases when halo mass increases
→ Shock heating vs cooling/cold flows

2/ increases with redshift @ fixed mass
→ cosmic origin of angular mom
(Pichon et al 2011)

Conclusions

Feedback (preventative and negative) is ***the*** current issue in galaxy formation:

1- Key is at high redshift: by z=2-3 if SF has not been drastically reduced, galaxies already contain **too many stars**!

2- 'Normal' SNs capable of driving fast winds with velocities similar to observed ones but mass loading is small (NUT series)

3- Does problem arise from missing physics/resolution (instabilities not captured, subtle RT effects, dust driven winds)? Or simply more energy (Hypernovae,AGNs), even in small galaxies?

4- More work needed on simu side to sort out point 3, and multi-lambda observations (surveys) to pin down the 'epoch of feedback' (metal absorption lines for CGM outflows, ly-alpha measurements of inflows, stellar mass function and SFR evolution with z for typical galaxies, internal velocity field for angular momentum: disk/bulge build up …)