DLAS @ Z~5

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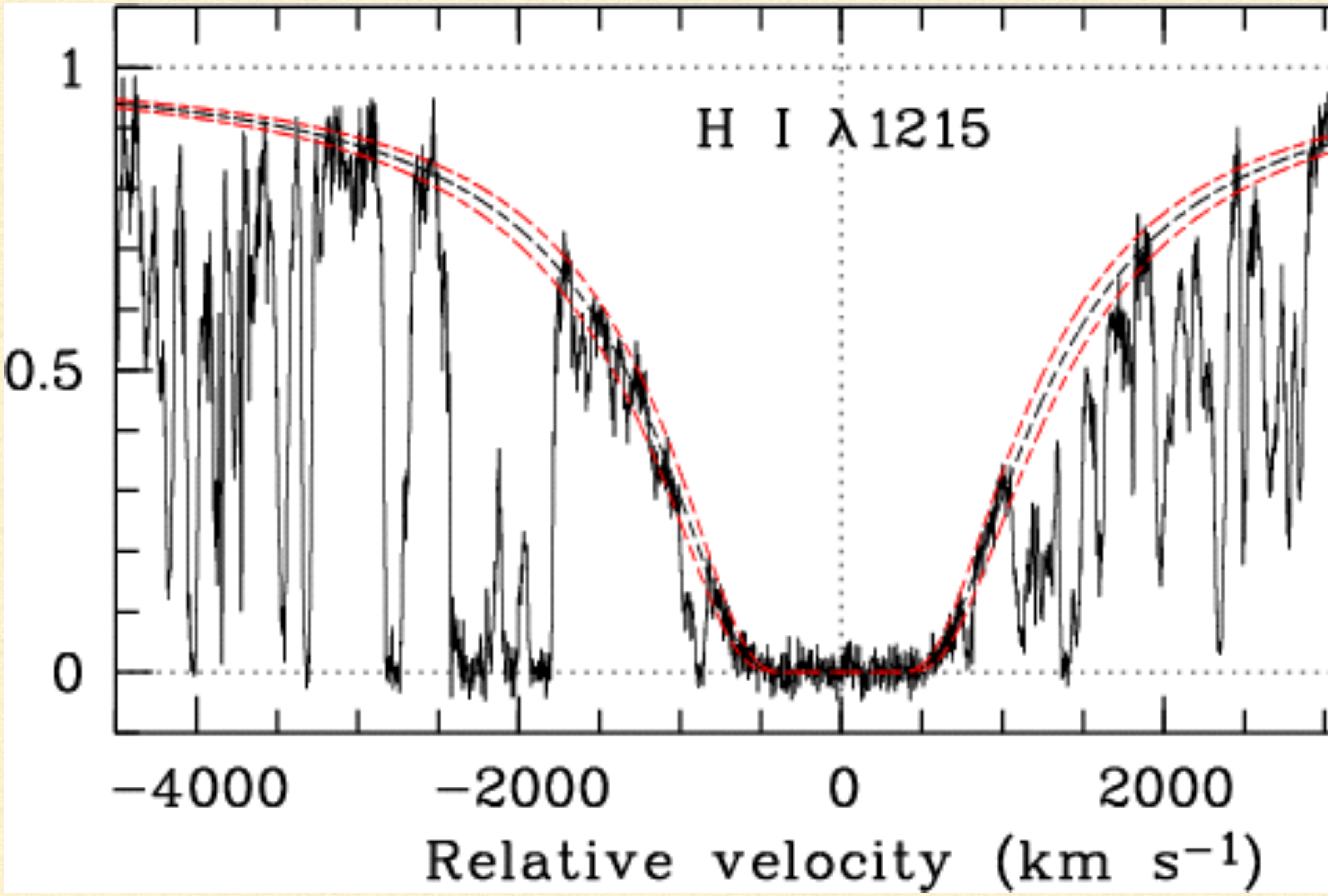
DAMPED LYMAN ALPHA SYSTEMS

- Damped Lyman Alpha Systems (DLAS) are the highest column density hydrogen absorption systems, $N_{HI} > 2\times10^{20}$ cm^{-2}.
- These are column densities that locally are associated with the cold gas disks of galaxies. (Wolfe et al. 1986)



COLD GAS IN GALAXIES

- Damped Lyman Alpha Systems give us a direct measure of cold gas in dark matter halos that can used to high redshift. For this reason they have presented challenges to cosmology and galaxy formation for many years.

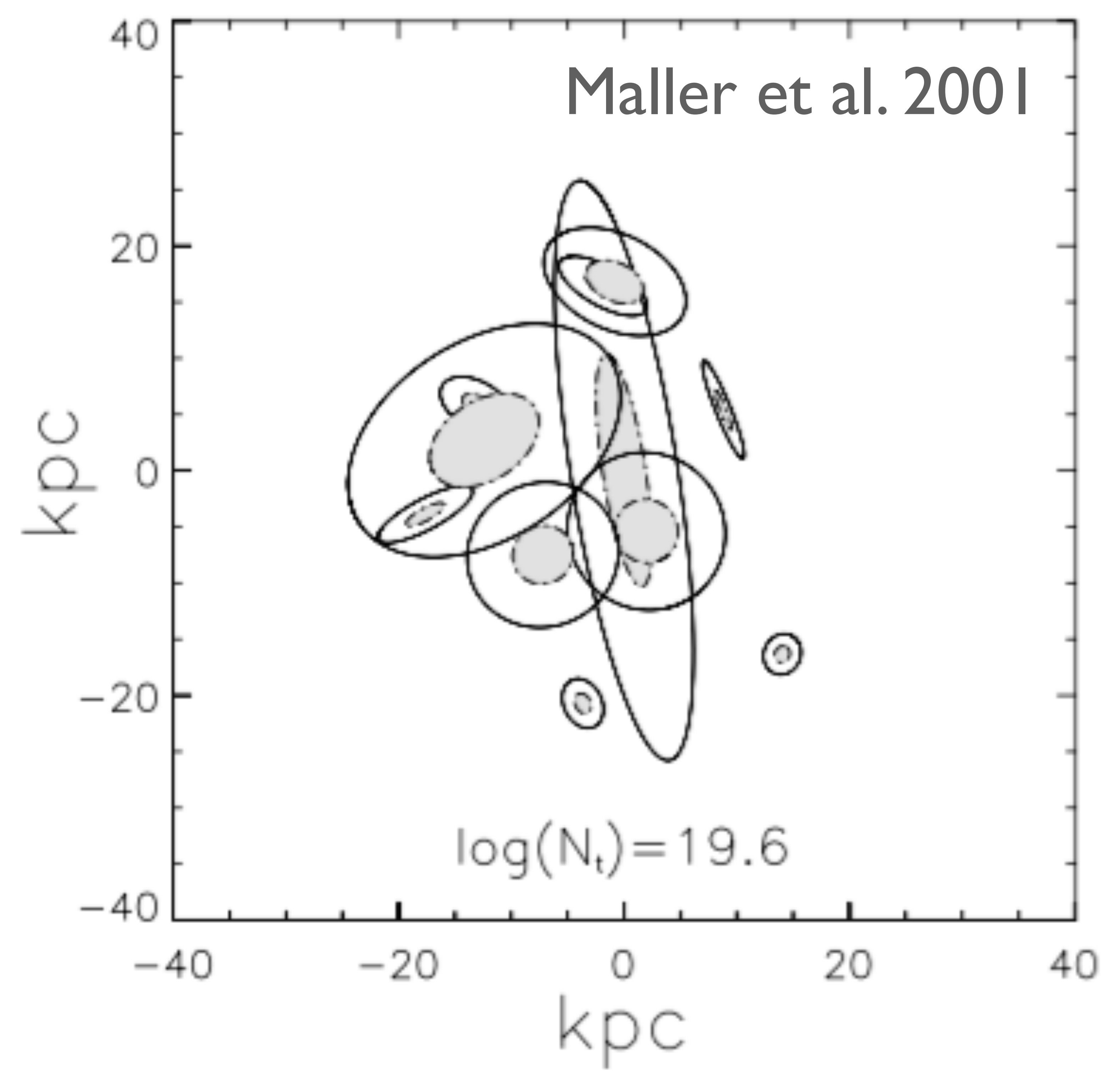
- H+CDM was ruled out because there are not enough halos at higher redshift to account for the observed number of DLAS (Ma et al. 1997) .

- Early cosmological hydrodynamical simulations also did not produce the observed number of DLAS and required a large number of DLAS to come from unresolved halos, as low as v_{vir} = 30 km/s. (Gardner et al. 1997, 2001)

DLAS KINEMATICS

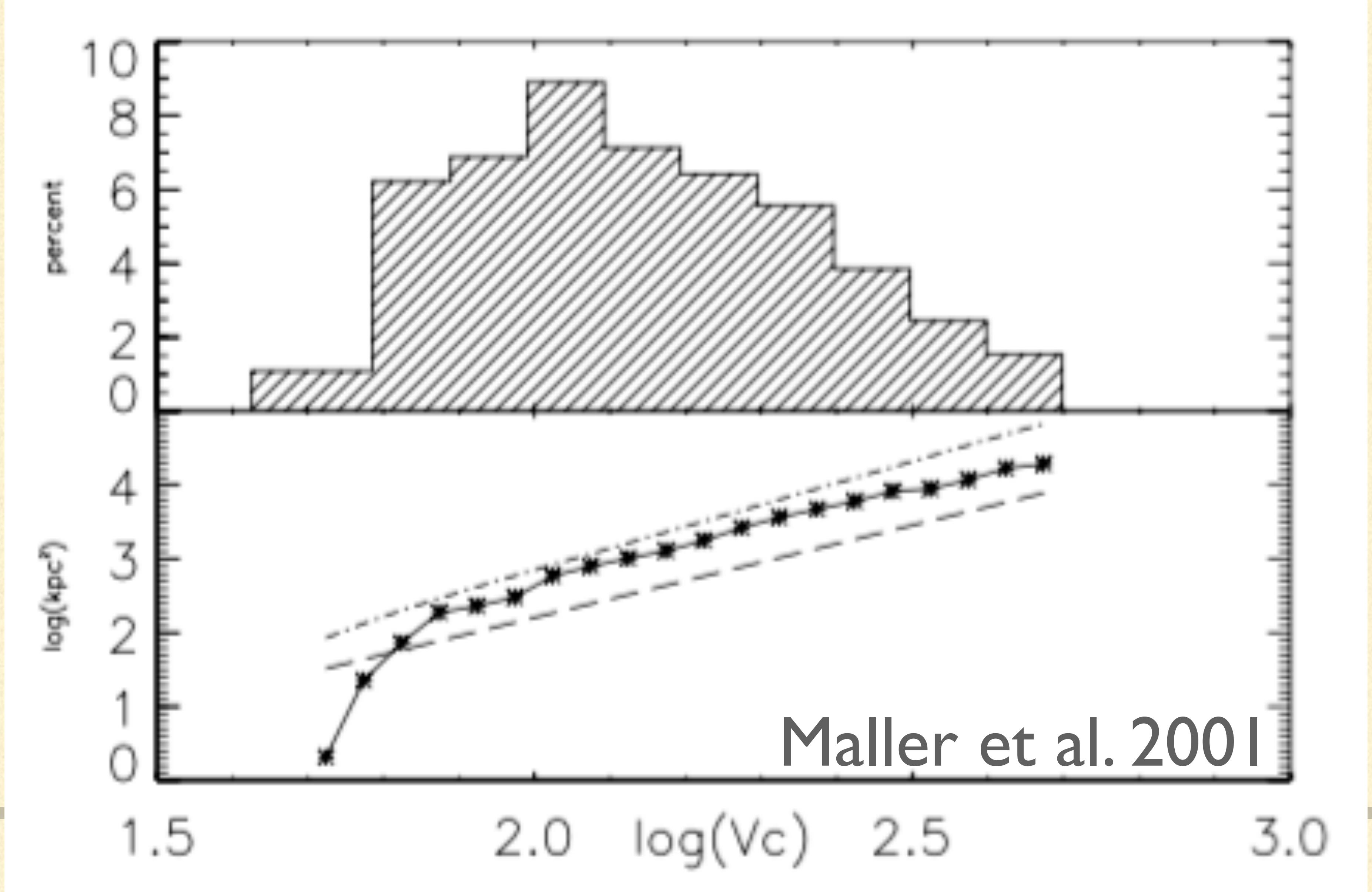
- In a series of papers Wolfe and Prochaska (1997, 1999, 2001) studied the kinematics of DLAS. They found that these systems had large velocity widths (~100 km/s) and evidence for multiple components. They proposed a model of large, thick disks as the source of DLAS.
- This proposal is hard to reconcile with CDM in which halos should be smaller at high redshift. As an alternative it was suggested that DLAS were often made multiple systems instead of single gas disks. (Haehnelt et al. 1998, Maller et al. 2001, 2003)

We used the semi-analytic model of Somerville and Primack 1999, Somerville et al. 2001 to model DLAS. We found that we could match the observed kinematics, but only if the gas disks where much larger than commonly assumed. Then intersecting multiple galaxies in a halo become common giving the larger velocity widths.



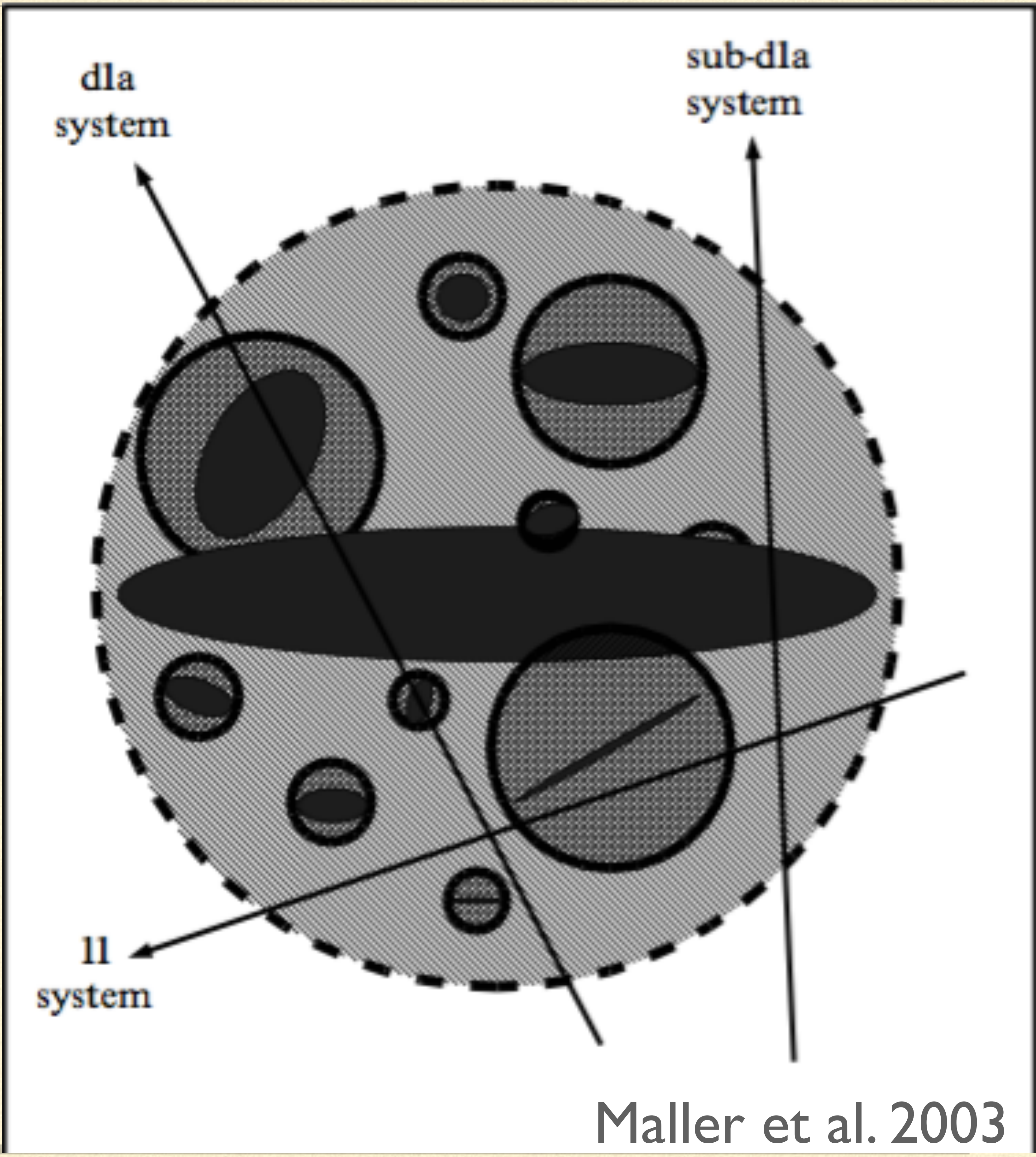
Maller et al. 2001

One important aspect of making this work is that DLAS come from moderate to large mass systems. In our model mostly from halos with velocities between 80 km/s and 300 km/s. Low mass halos much contribute very little to the DLAS cross section in order to get velocities as big as observed.



Maller et al. 2001

In our follow up paper we explored the ability of our model to match the high ionization state gas kinematics, by modeling that gas as the hot gas in the SAM. (Maller et al. 2003) Our model produced reasonable results. I mention this because it hasn't really been looked at since and to point out that DLAS tell us not only about cold gas, but also how cold gas and hot gas relate to one another.



Maller et al. 2003

THE LAST 15 YEARS

- Over the last 15 years improvements to cosmological hydrodynamical simulations have been able to produce DLAS that are larger in agreement with the observations at z=2 - 4.

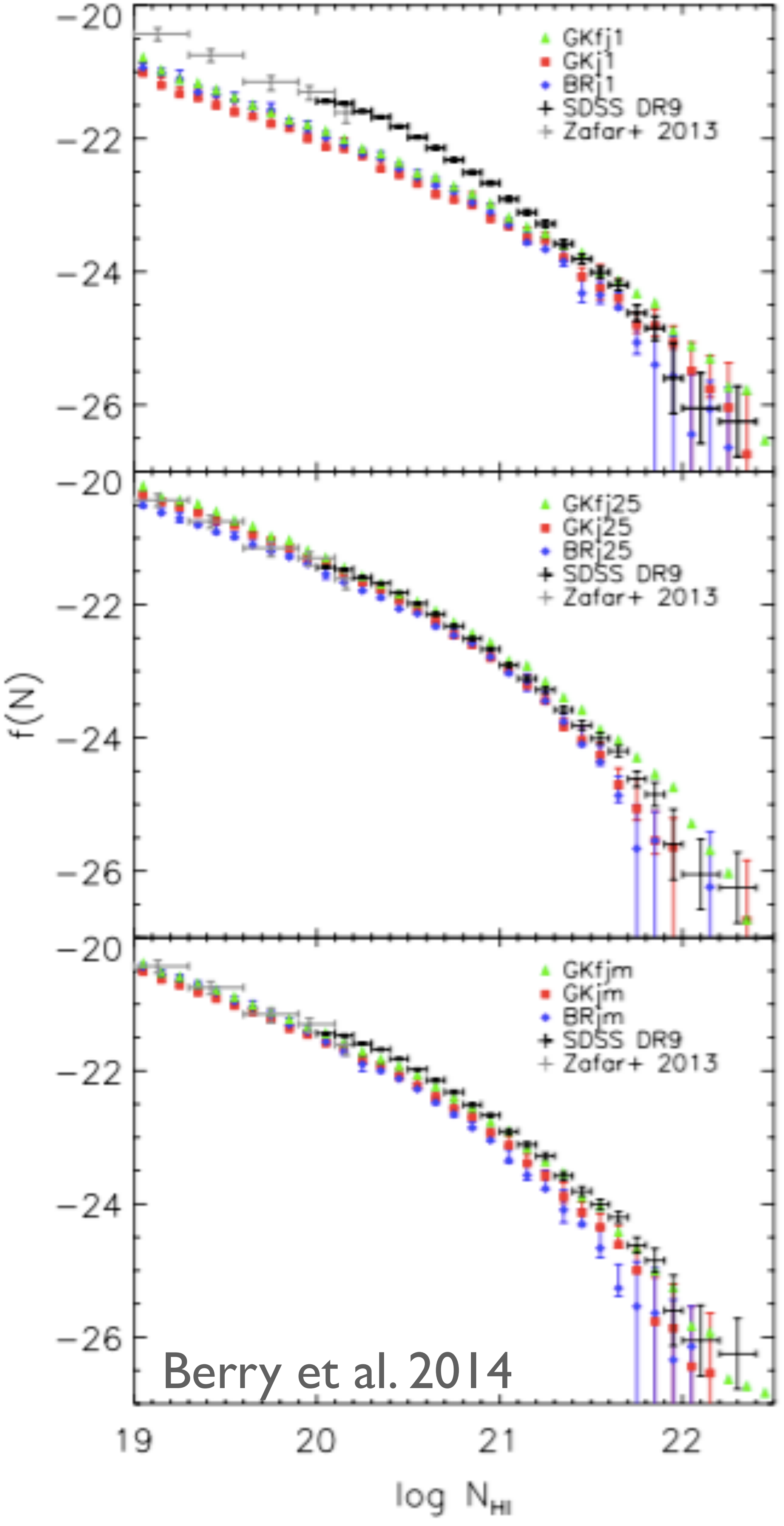
- This success combines moving to the ΛCDM model with producing larger gas disks in simulations, both from better resolution and improvements in the implementation of feedback. (Pontzen et al. 2008, Tescari et al. 2009, Fumagalli et al. 2011, Cen 2012, Dave et al 2013, Bird et al. 2013, 2015)

- We have also revisited this issue with more up to date semi-analytic model. (Berry et al. 2014, 2016)

NEW MODELS

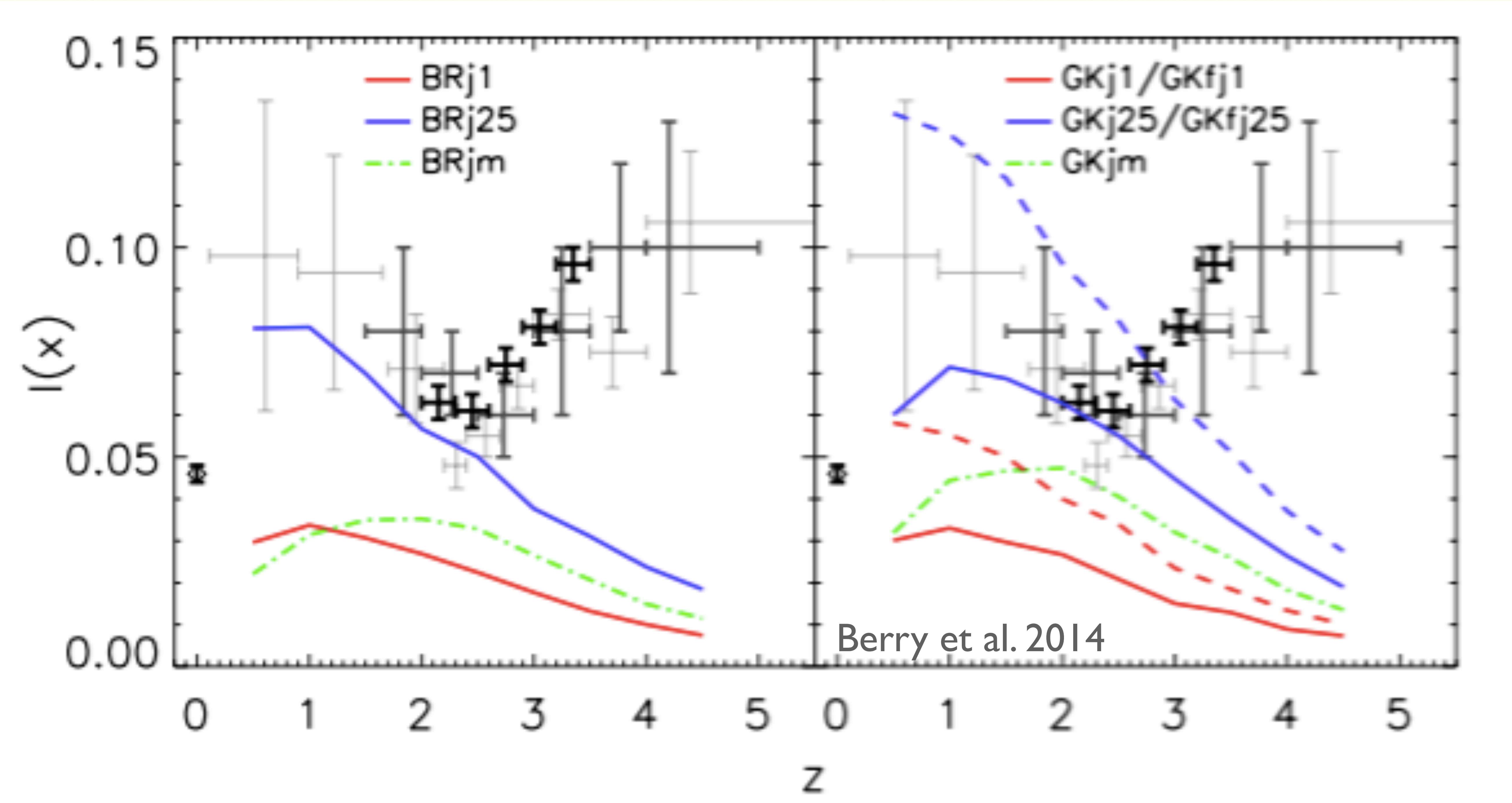
- Our new models use the updated SAM of Somerville et al. 2012 with the addition of gas partitioning used in Popping et al. 2104 and Somerville et al. 2015.
- Gas partitioning refers to a model for diving hydrogen into atomic, ionized and molecular states. This is particular relevant for DLAS since we believe that at very high column density hydrogen is mostly converted into molecular gas and this explains why these systems are not seen as DLAS.

f(N) is the distribution of column densities found in absorption systems. As you can see in the plot, the models with gas partitioning (colors) shows good agreement with the data (black). This agreement had been hard to reach before with models producing too many very high column density systems. Converting those high density systems into molecular hydrogen solves that.



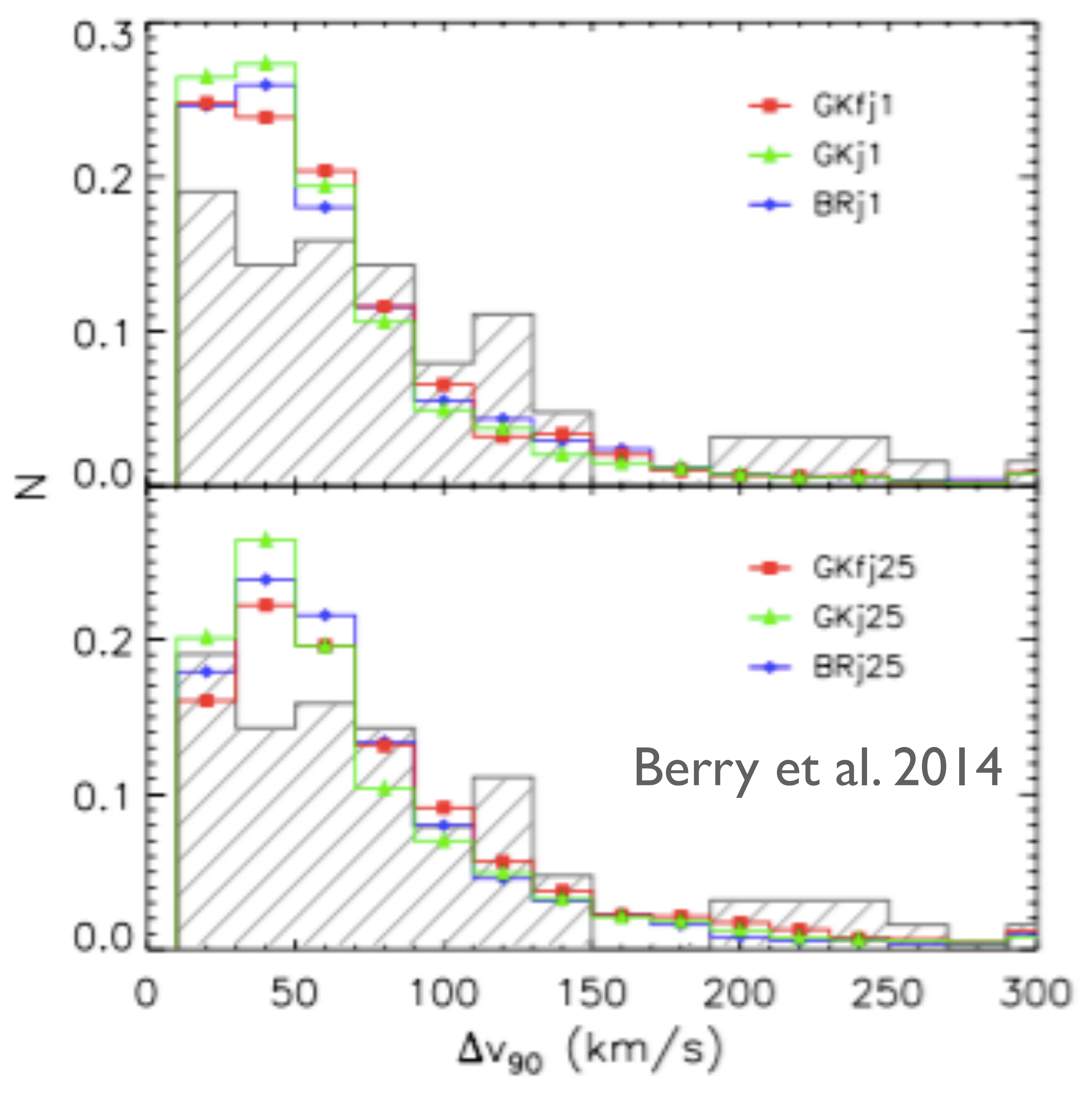
Berry et al. 2014

If we look at the number of systems per absorption distance we find a familiar problem. Models with the gas disk having the normal size in the SAM produce too few systems. We need to increase the size of gas disks by 2.5 times to get models that work for z < 3. None of our models work for z > 3.



Berry et al. 2014

With this change our semi-analytic model produces excellent agreement with the number, column density distribution, velocity width distribution and metallicities of DLAS.



Berry et al. 2014

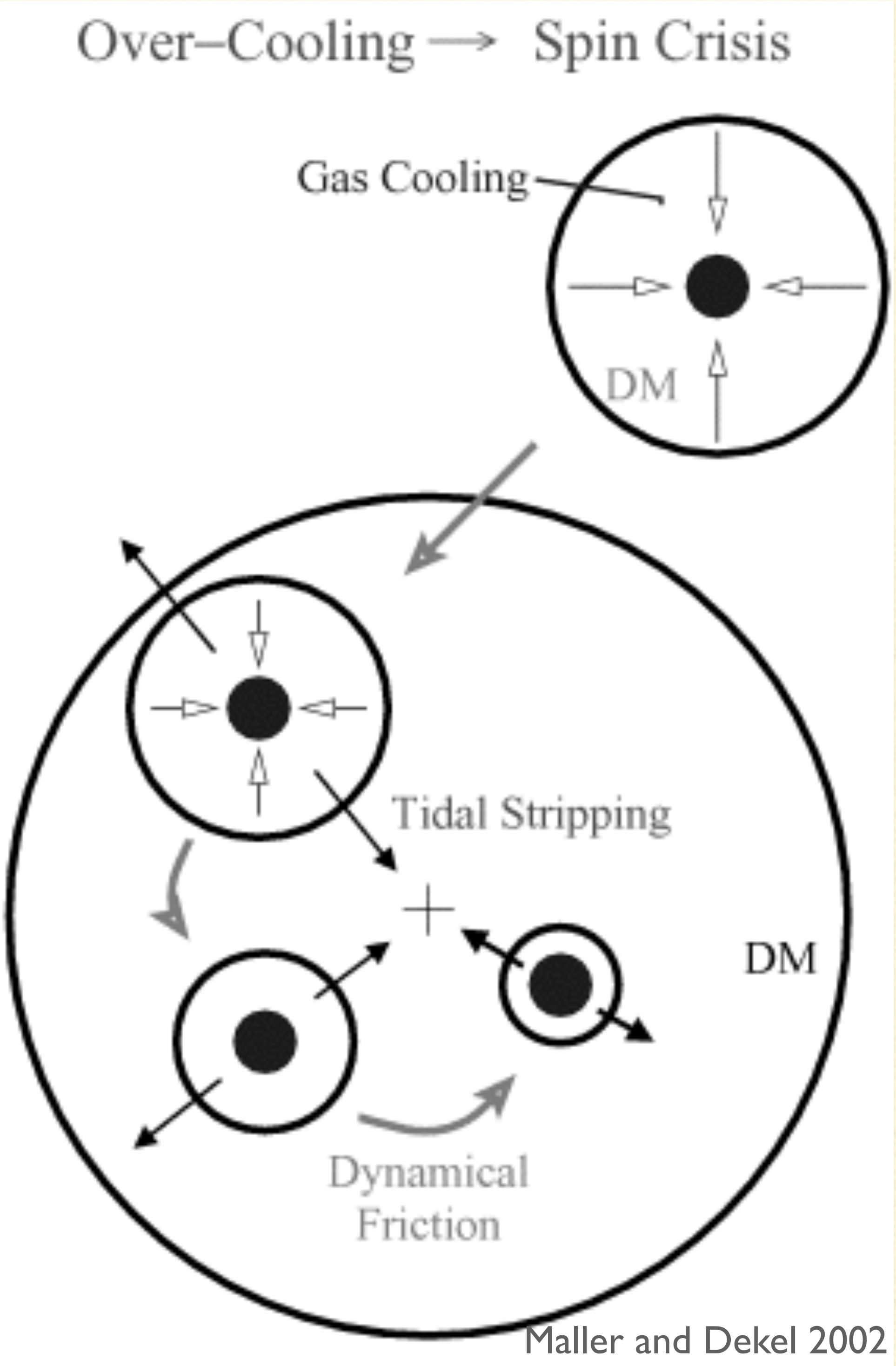
Of course this is only below z of 3, at higher redshift we fall far short of producing the observed number of systems. I'll return to this issue later, but for now lets look at the theory of galaxy disk sizes.

ANGULAR MOMENTUM CONSERVATION

- The standard model of disk sizes was presented by Fall and Efstathiou (1982) and says that the specific angular momentum of gas is originally the same as the halo and that when gas cools it keeps its angular momentum stopping its collapse when it becomes angular momentum supported. (Mestel 1963)
- This model has been updated to account for more realistic halos (Dalcanton et al. 1997, Mo et al. 1999), but the basic idea is still used today in all semi-analytic models because it results in a good match to observed disk sizes.

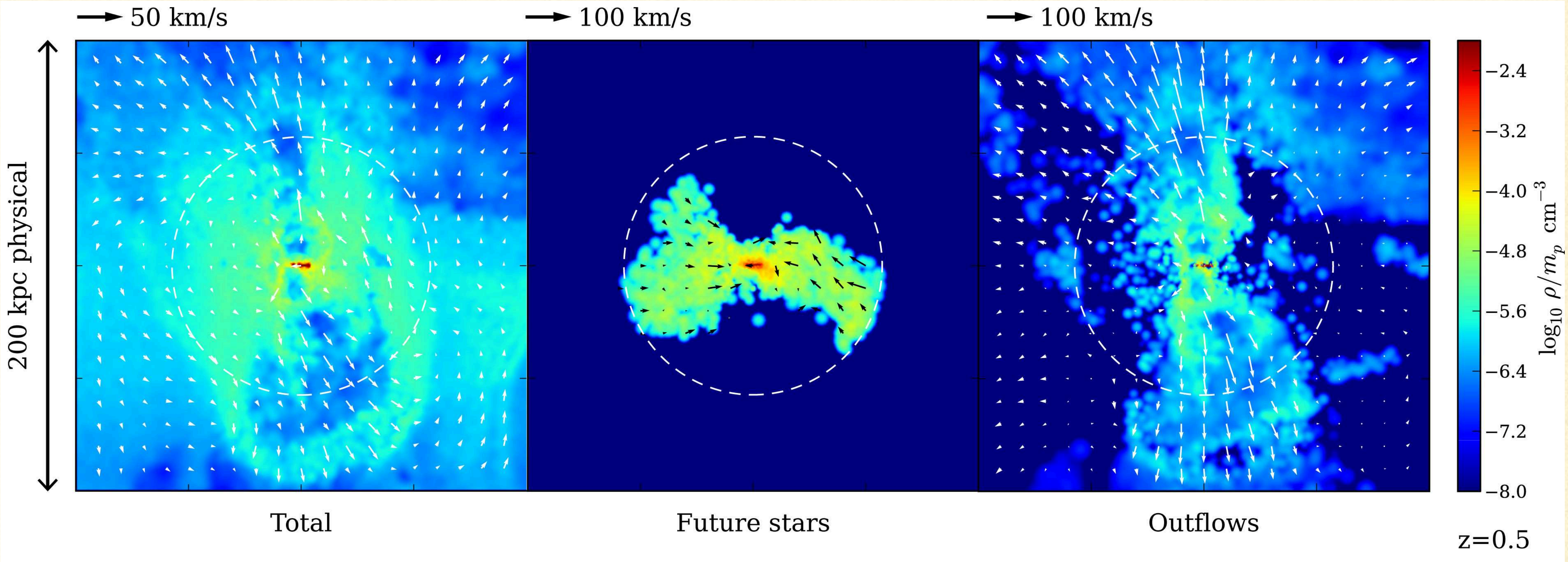
BUT WHAT ABOUT FEEDBACK?

- We now know most of the available gas does end up in a galaxy, only 1/3 or less does. Is it reasonable to assume the gas that does make the galaxy samples the angular momentum in an unbiased fashion?
- We proposed a simple toy model which suggest that it doesn't (Maller and Dekel 2002). If small mass halos are more likely to have their gas removed by feedback, then larger mergers contribute most of the gas to a galaxy. Large mergers contribute more angular momentum, so gas will actually have higher angular momentum than dark matter.

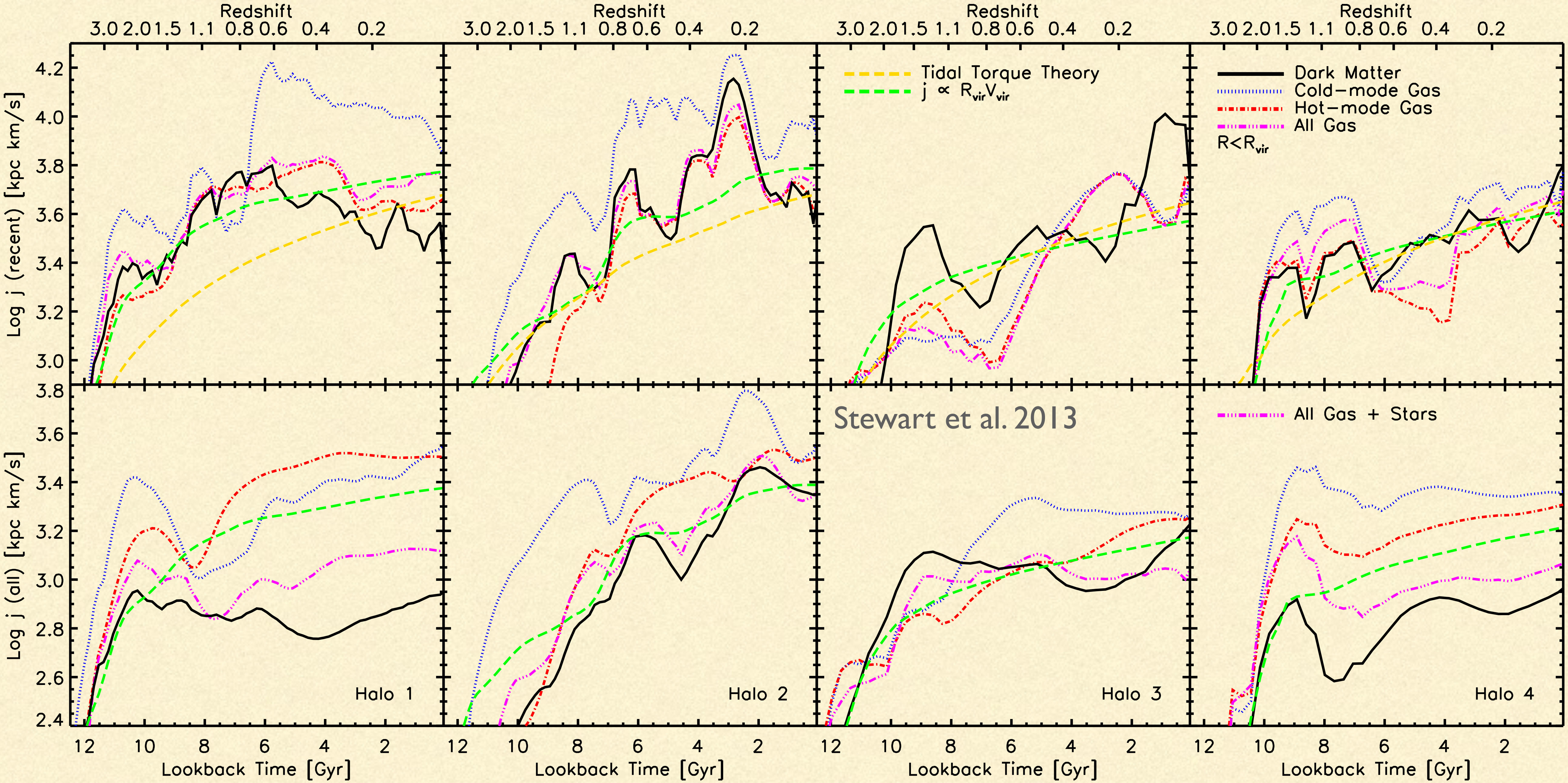


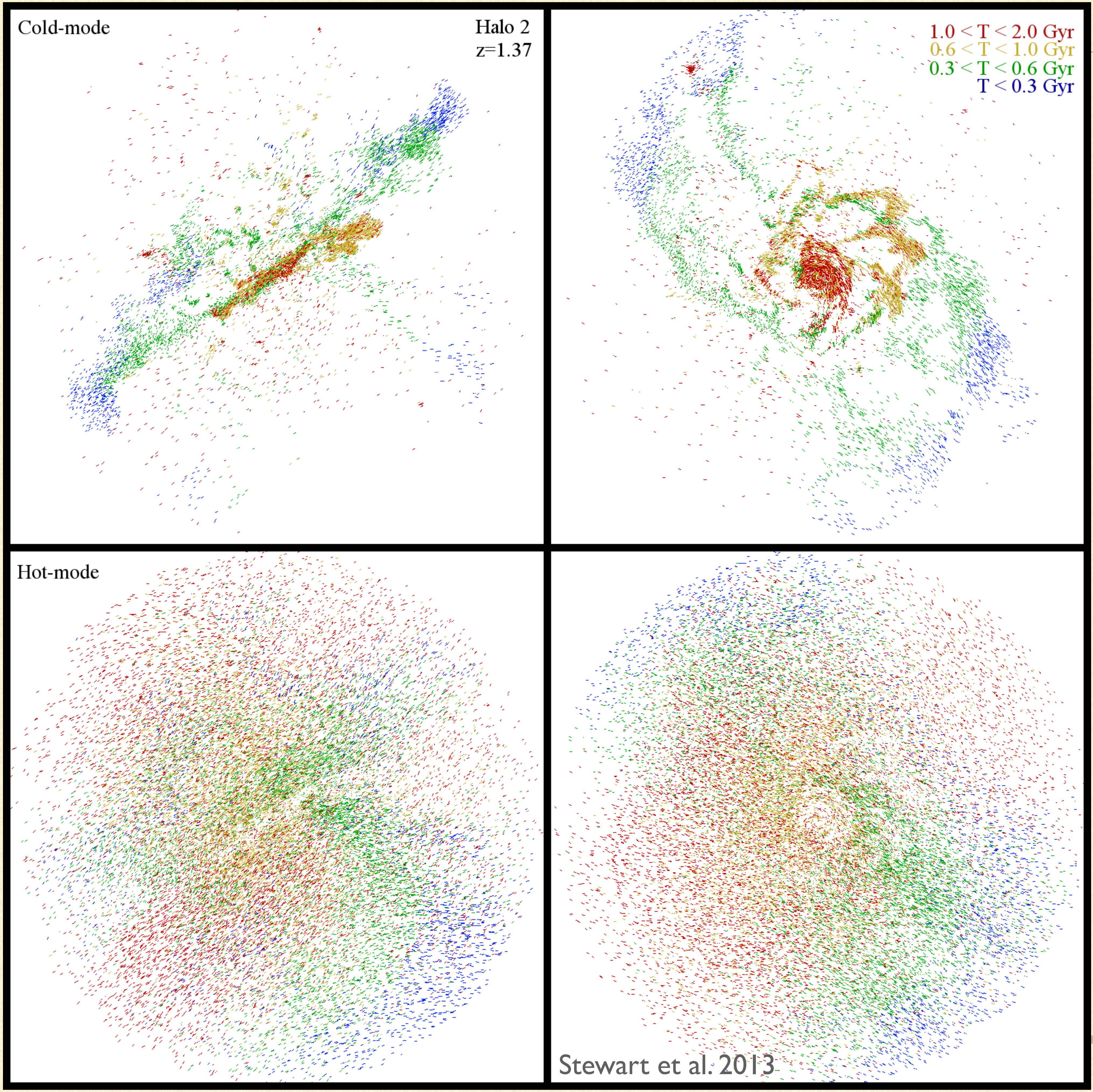
Maller and Dekel 2002

In hydrodynamical simulations with effective feedback the gas that eventually makes a galaxy is not uniformly in the halo, but preferentially aligned with the disk and has higher angular momentum. Gas aligned with the poles is preferentially expelled and has lower angular momentum. (Brook et al 2011)



More recently we looked at how angular momentum grows in a halo (Stewart et al. 2013, see also Pichon et al. 2011) and what we found is that gas does not come in with the same angular momentum as dark matter.



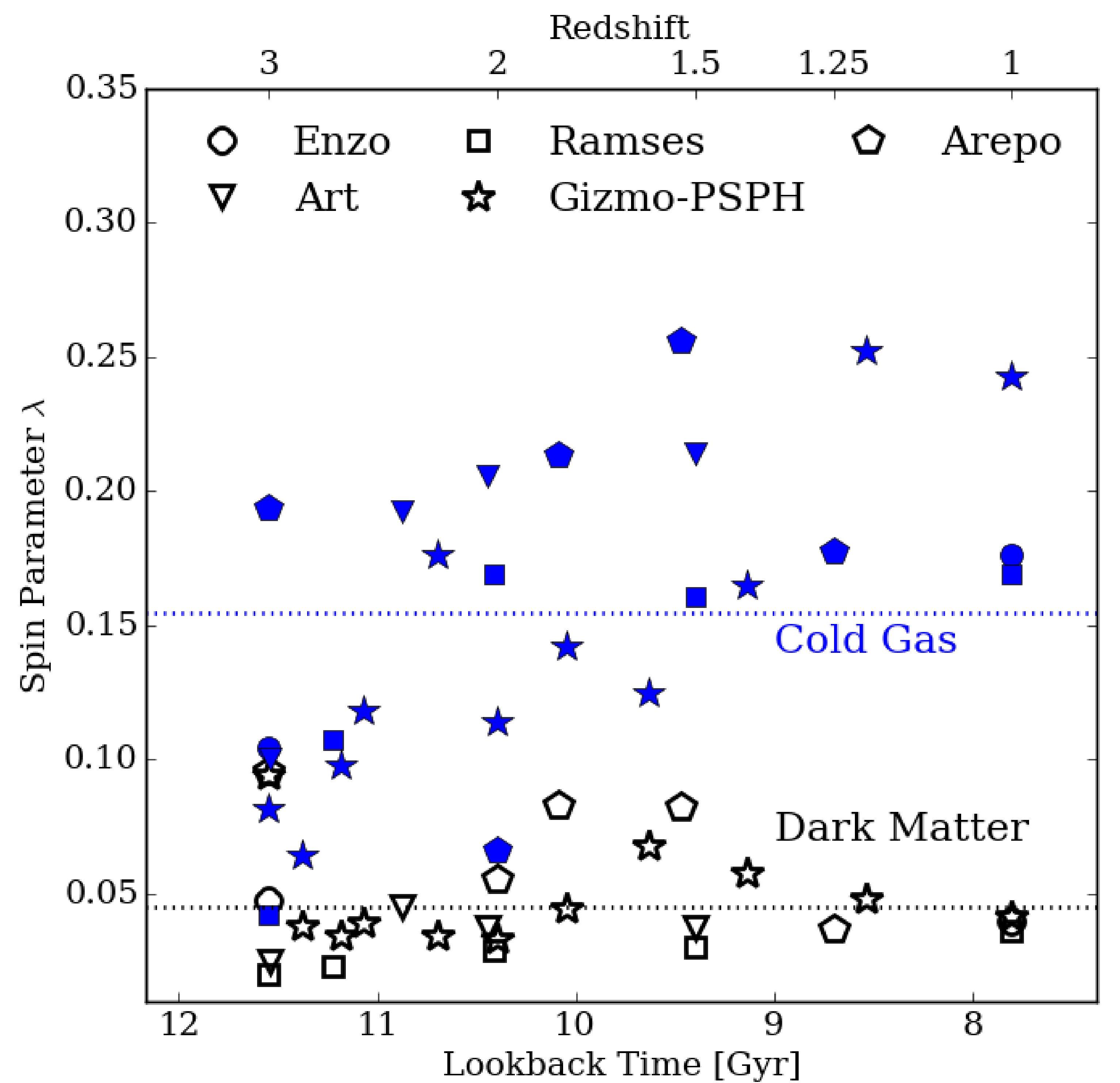


This occurs because gas that comes in without shock heating preferentially comes in along filaments. Hot gas and dark matter comes in from every direction. So the warm gas that forms the galaxy has higher specific angular momentum then the dark matter

SCYLLA MULTI-CODE COMPARISON

- One might worry that these results depend on the type of cosmological hydrodynamical code used.
- In order to address this we have been running a simulation comparison project running five codes using the same initial conditions.
- Our five codes are Enzo (AMR), Ramses (AMR), ART (AMR), AREPO (moving mesh), Gizmo-PSPH (SPH)

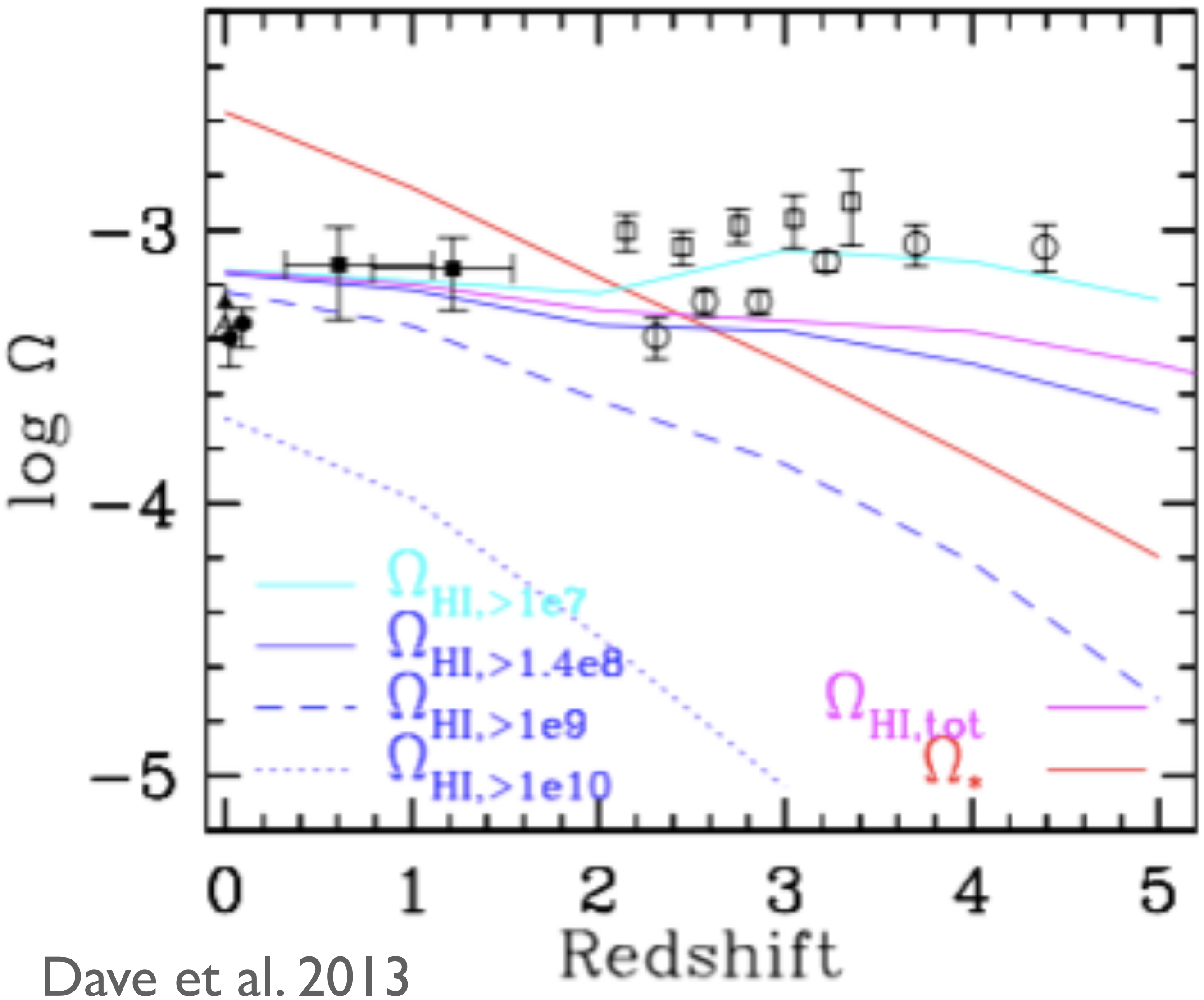
All 5 of our codes show the same results for angular momentum. The angular momentum of warm gas is 3 to 5 times higher than the angular momentum of dark matter. This naturally will result in larger gas disks than assumed using angular momentum conservation in agreement with what we need to explain DLAS.



Stewart et al. in prep

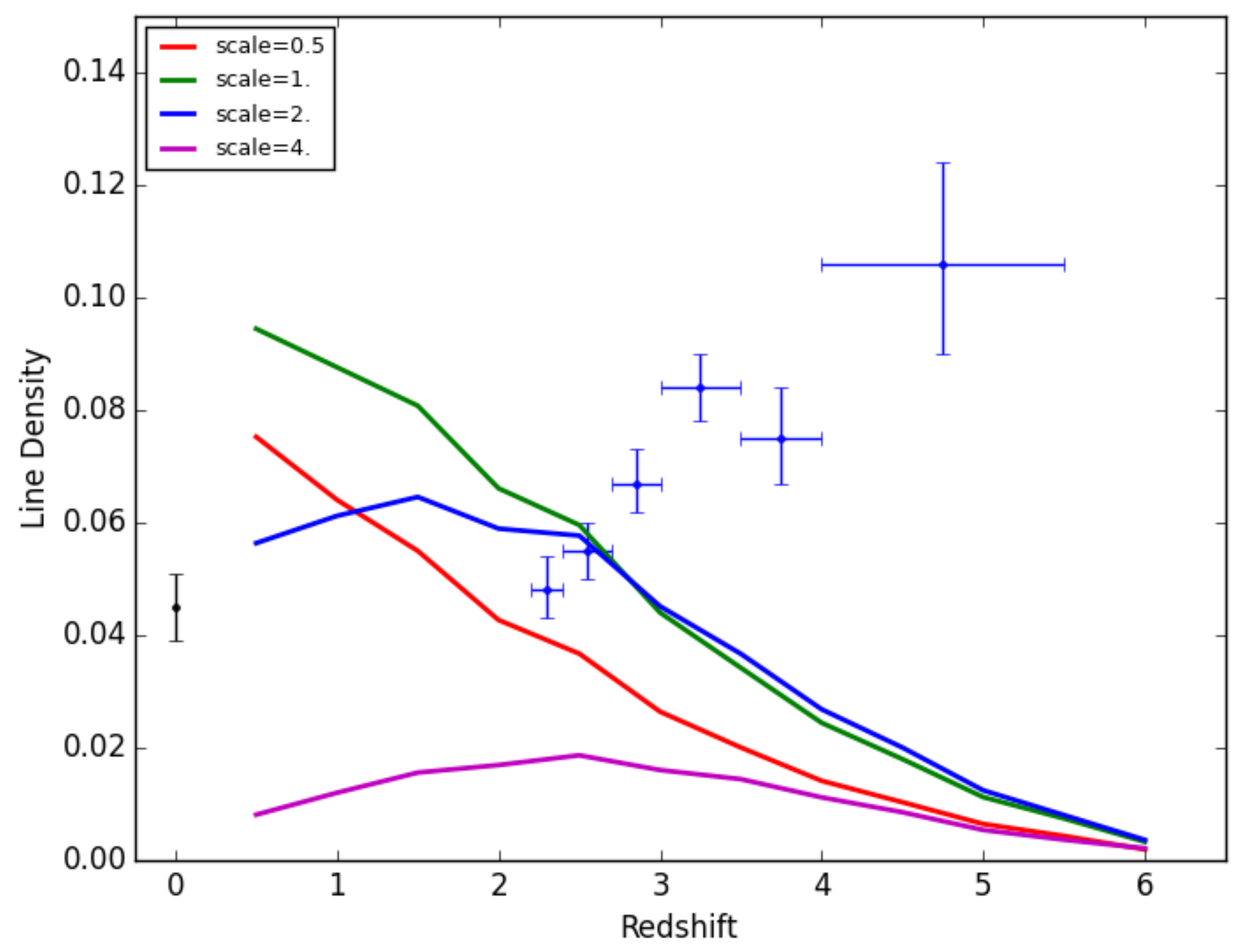
DLAS AT Z=5

- Previously we saw that our semi-analytic model produced too few DLAS at high z.
- This is also the case in hydrodynamical simulations. The plot shows the mass density of HI in the simulation (purple line) and the data (circles). The simulations is far below the observations.
- One must extrapolate below the simulations resolution to try and get the same amount of HI gas as observed.

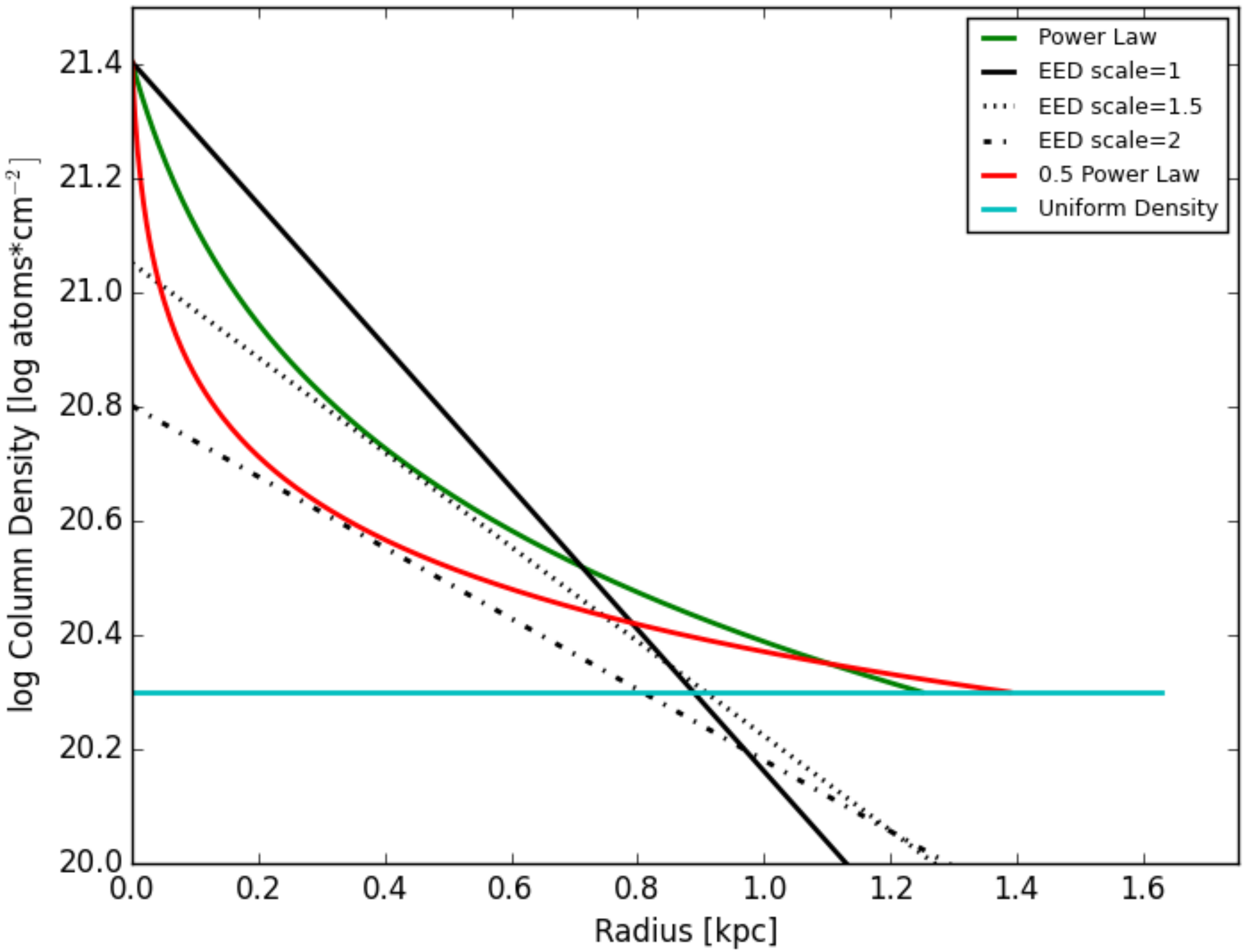


Dave et al. 2013

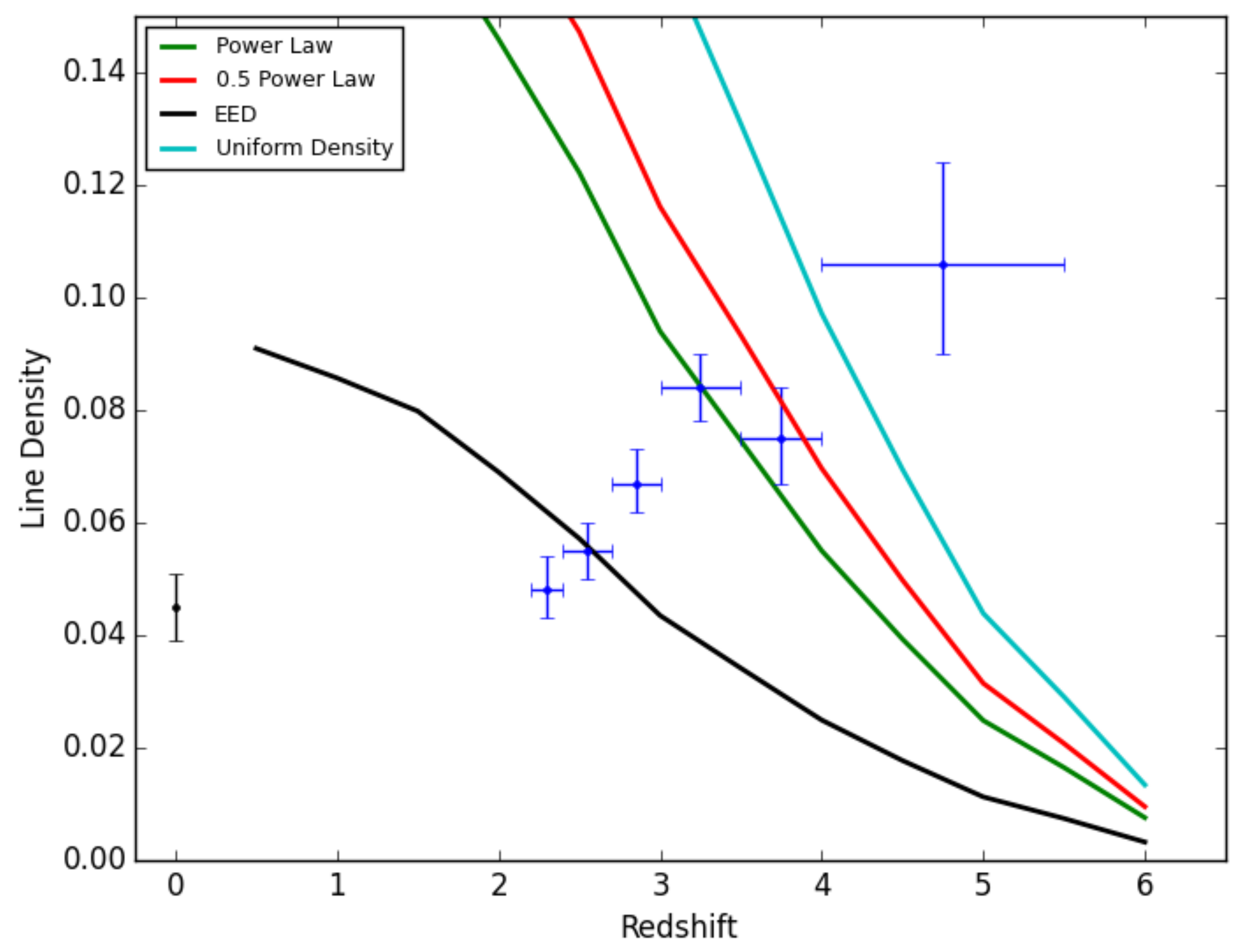
We can try our usual plan of increasing the size of the gas disks. But doing so doesn't increase the number of DLAS and increasing the size enough actually lowers it number.



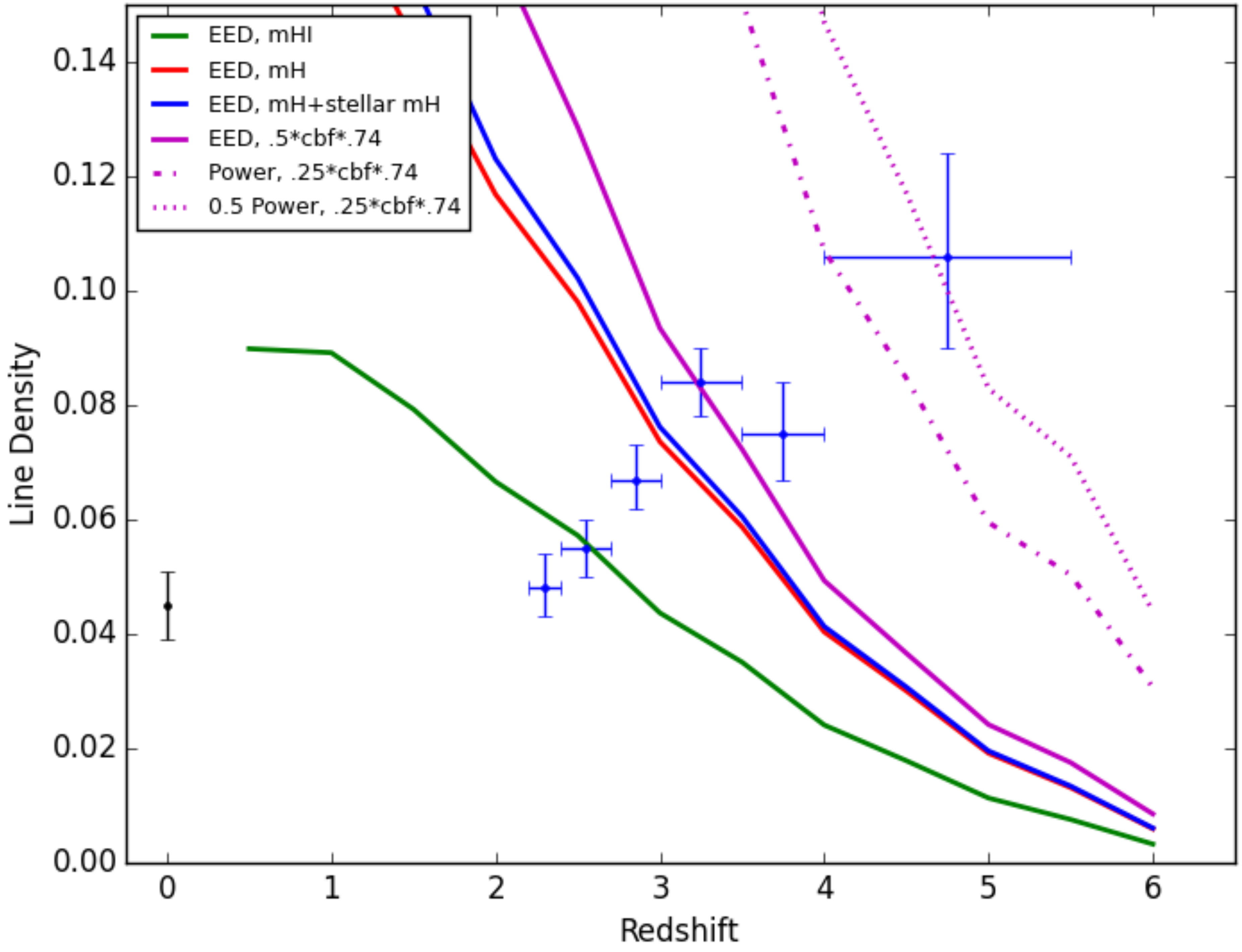
The reason for this it that the gas disks have central surface densities far above the DLAS threshold. Increasing their size lowers the central surface density so that the DLAS cross section remains almost the same size. To increase the cross section one has to change the profile.



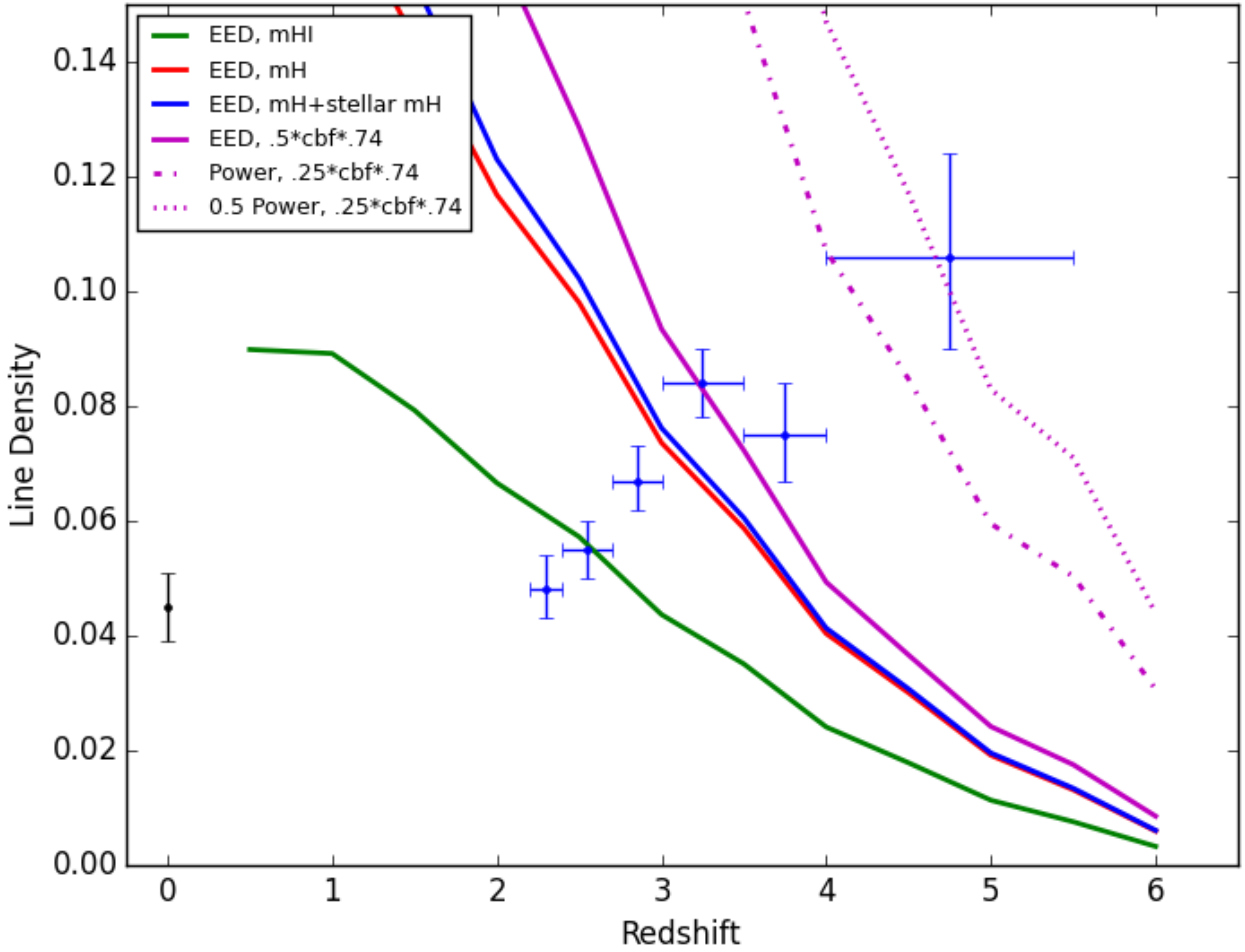
Changing the profile produces more DLAS, but not enough to match the z=5 observations. The only way to match observations is if there is more neutral hydrogen in these systems.



If we convert the ionized and molecular hydrogen back to atomic hydrogen that raises the number of DLAS by about 50%. If we convert all stars into hydrogen gas, that has almost no effect since there has been little star formation at these high redshifts.



If we assume that feedback is much less efficient and half the baryons stay in the halo as atomic gas that only doubles the number of DLAS if we keep the same profile. We have to use half the possible baryons and change the profile to match the z=5 observations, but keeping things that way over vastly over produces the number of systems at z=4.



CONCLUSIONS

- It is possible to match the number of DLAS seen at z=5, but doing so requires radically changing the amount of HI in galaxy formation models. There are a number of possible ways this could happen, but all of them can't continue to z=3.
- Feedback could be much less efficient at z=5 and gas disks more extended.
- Lower mass halos could contribute a large fraction of the DLAS cross section at z=5, but then that gas must disappear at lower redshift.
- Either scenario suggests large changes to galaxy formation physics at these high redshifts. Both can also be tested with future observations of the column density distribution and velocity width distribution at these redshifts.