Studying the CGM of Galaxies

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Galaxies in a cosmological context & the case for Feedback

Virgo Cluster - (DeepSkyColors.com)

- Clusters show galaxies of a range of ages, suggesting a bottom-up formation history.

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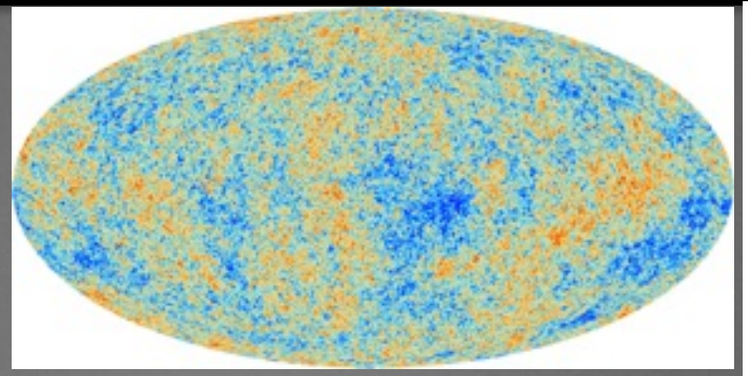
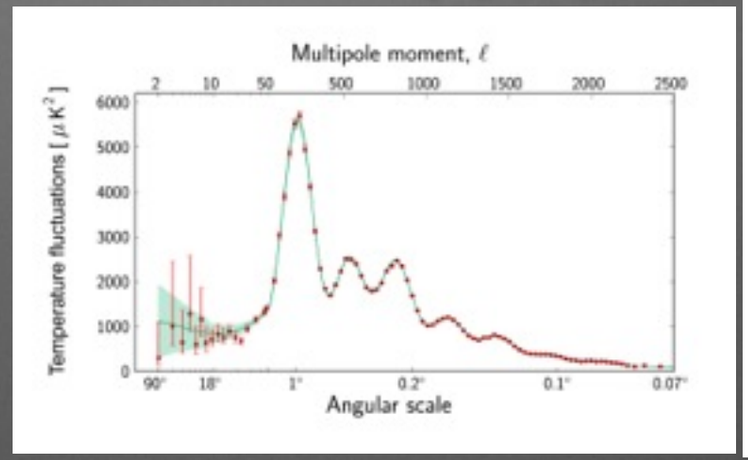
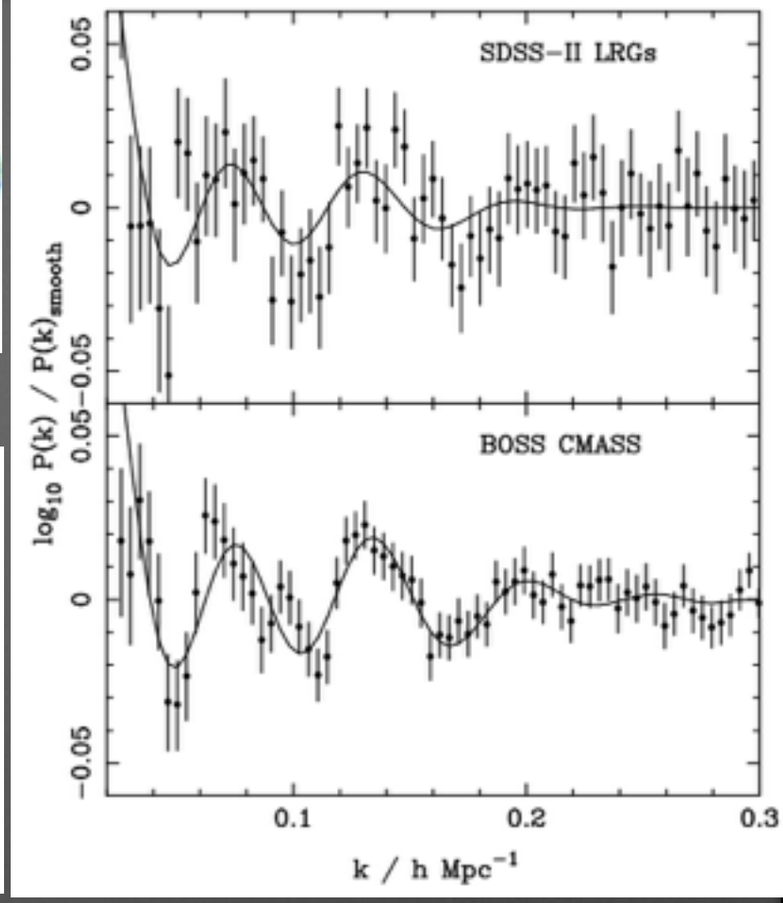


Planck Map (ESA)



Planck Power spectrum (ESA)



BOSS BAO DR9 - Anderson+12

- Such a model is predicted by ΛCDM, and matches well with observations of fluctuation scales in the CMB and in galaxy surveys

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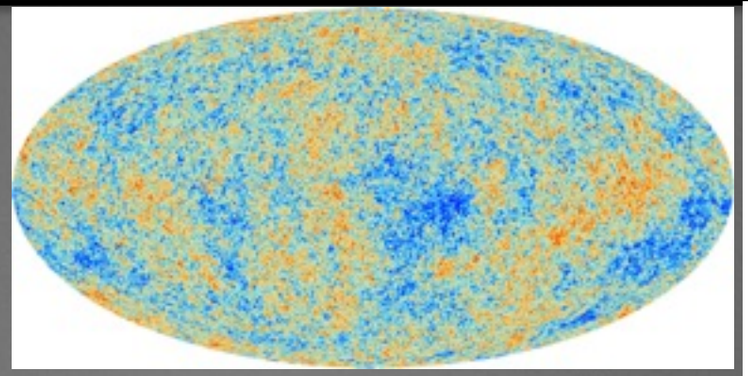
Virgo Cluster - (DeepSkyColors.com)

- But this model over-predicts the number of small and medium-sized galaxies, seen by comparing the predictions of ΛCDM simulations and luminosity functions of galaxies. Feedback is a natural extension that can account for this discrepancy.



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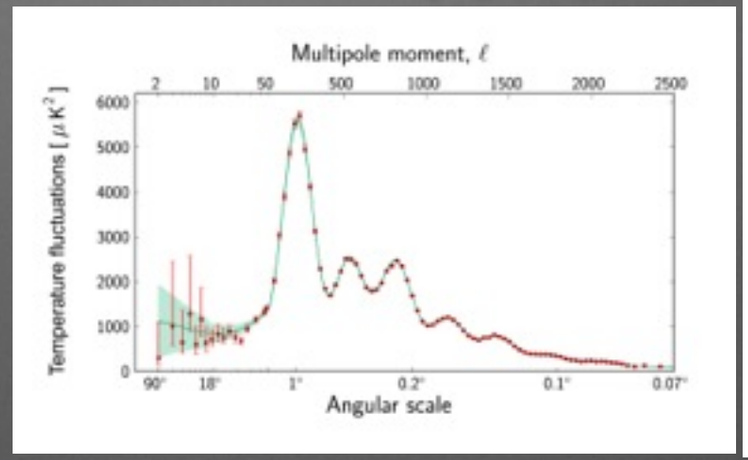

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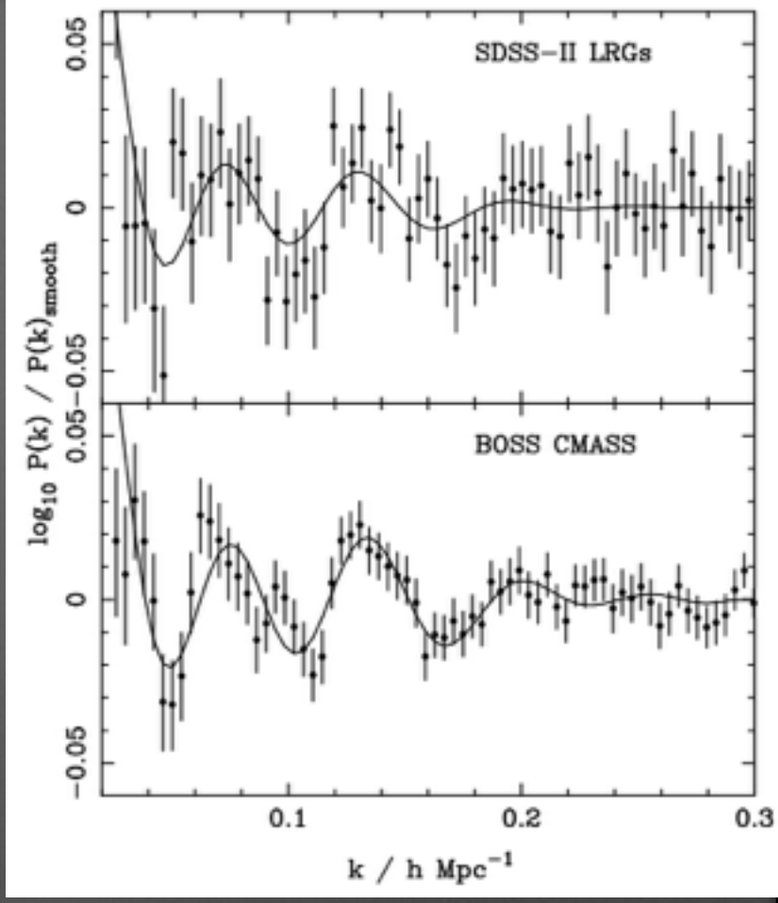
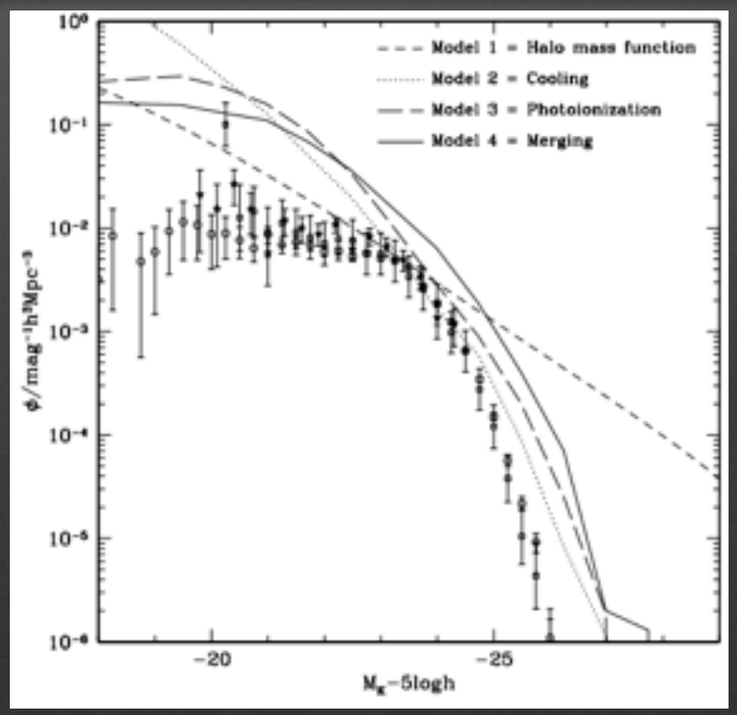


BOSS BAO DR9 - Anderson+12

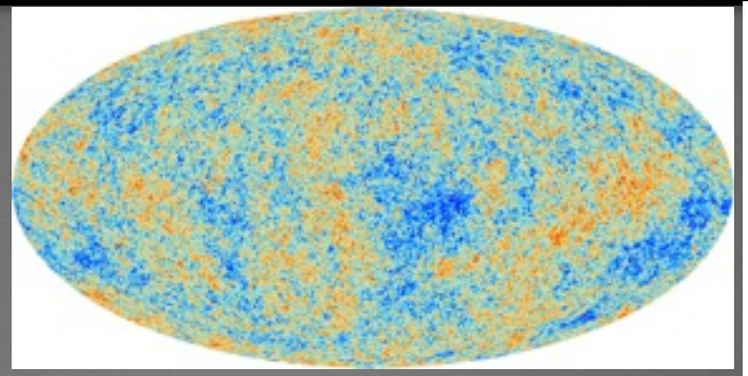


Halo Mass Function - Benson+2003

Galaxies in a cosmological context & the case for Feedback

Virgo Cluster - (DeepSkyColors.com)

- But feedback impacts other things. For example, Eagle tunes its feedback to ensure reasonably sized galaxies.



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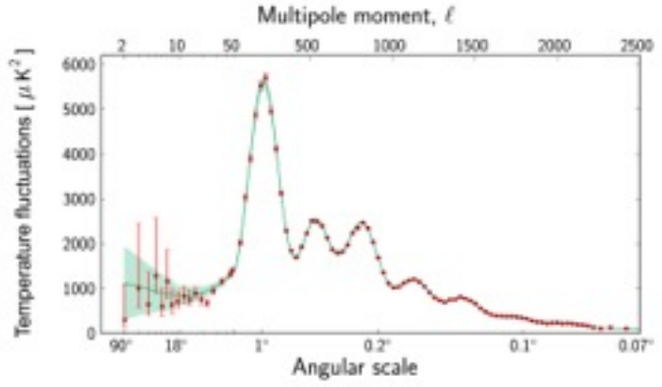

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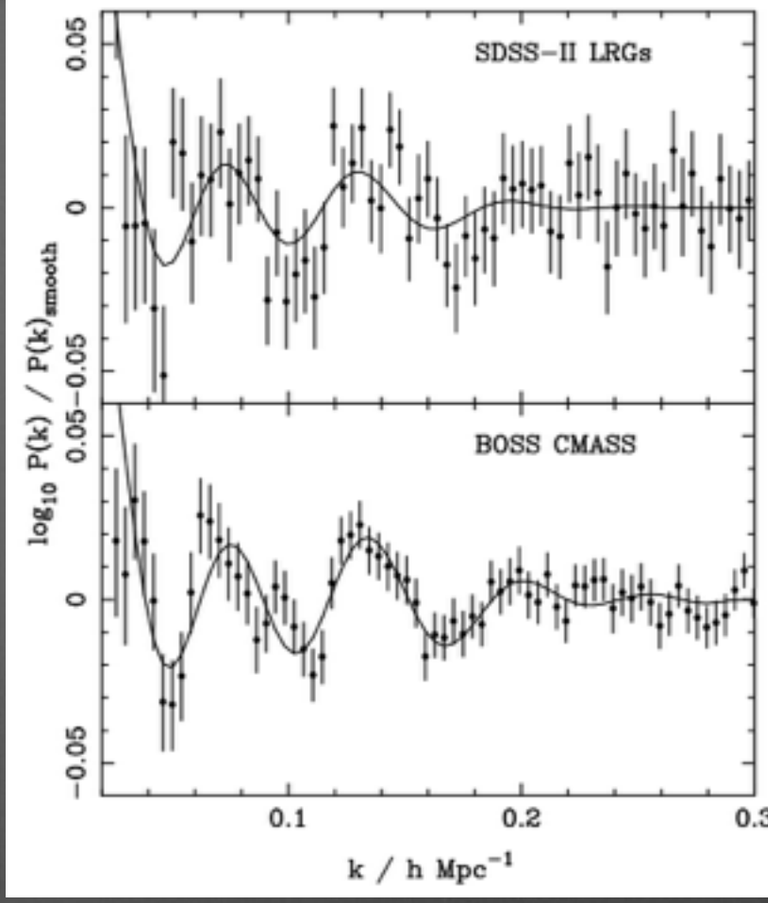

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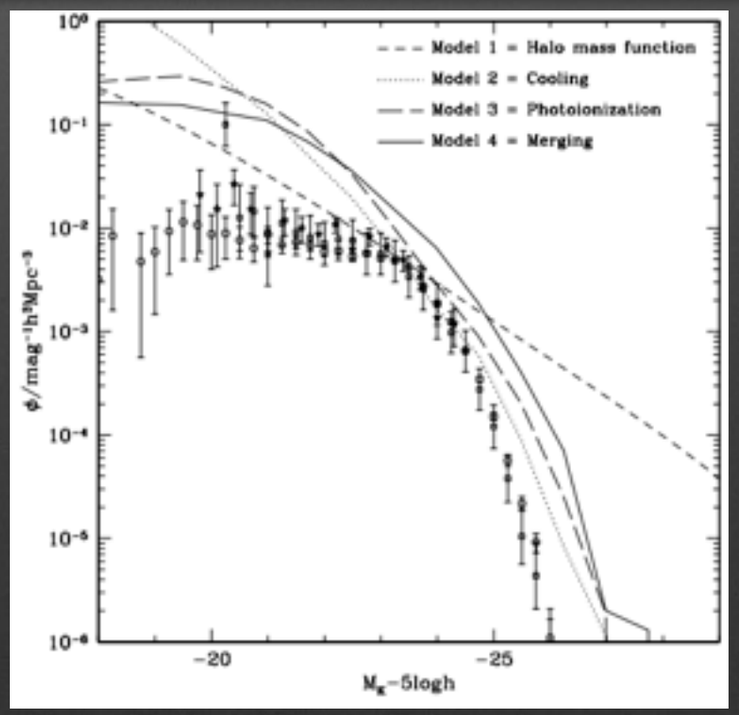

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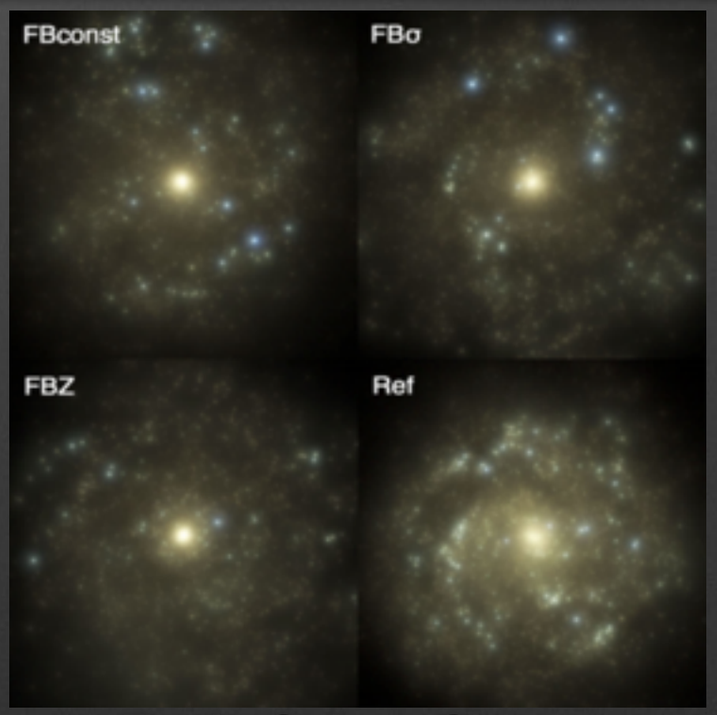
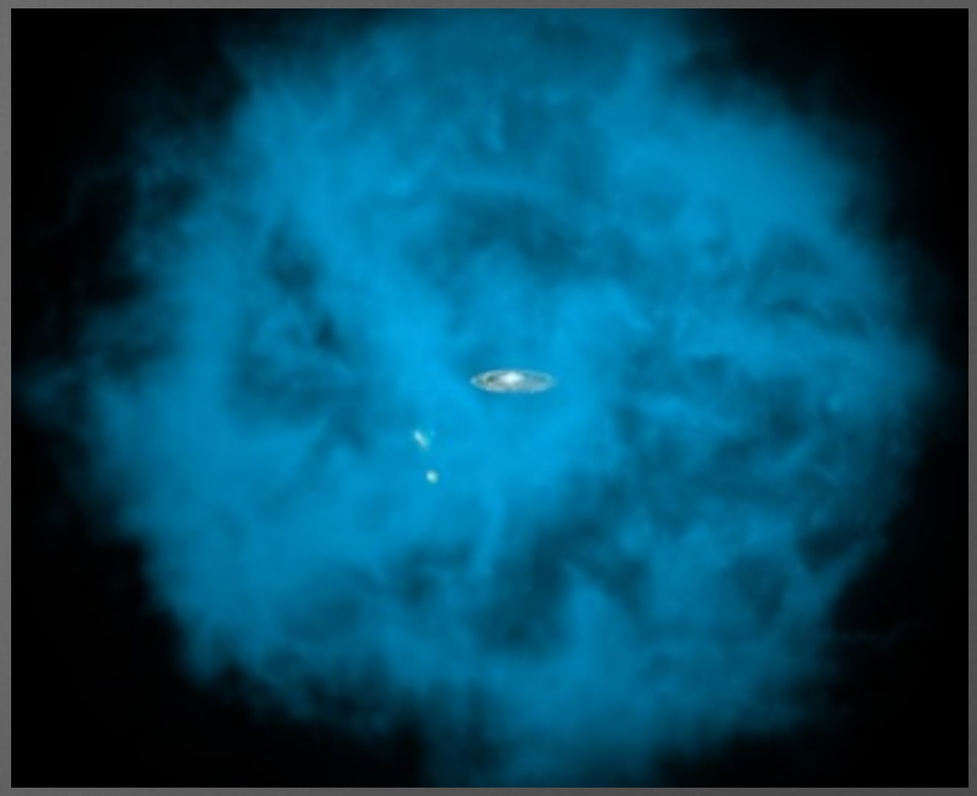


Eagle Galaxy Sizes - Crain+2015

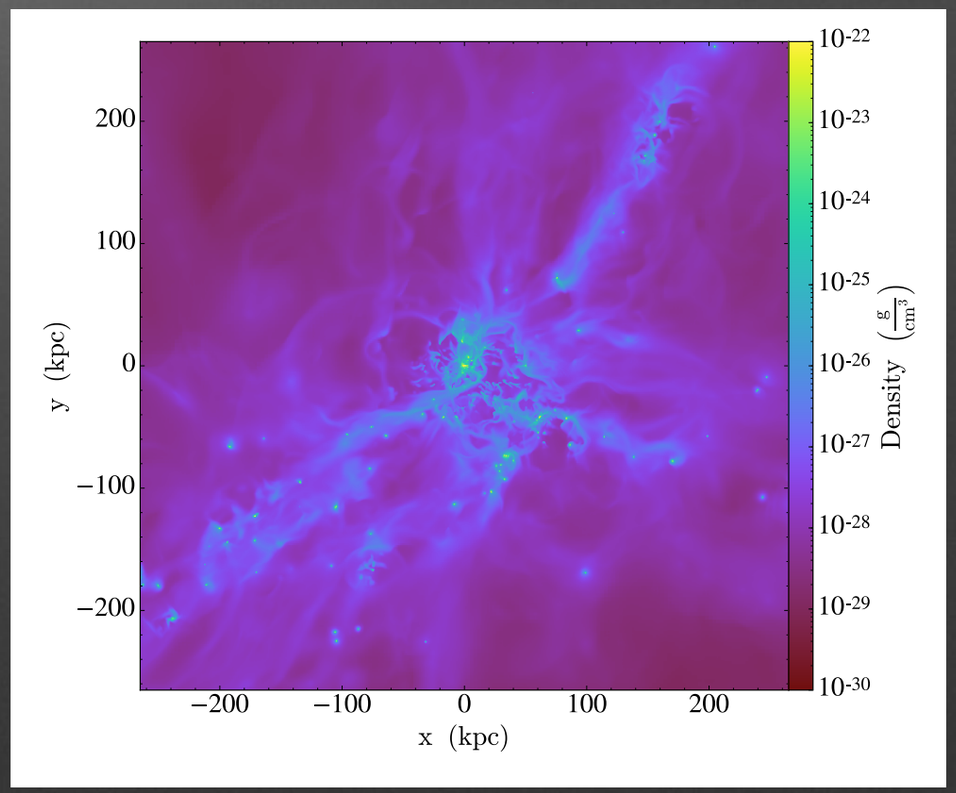
The Circum-Galactic Medium (CGM)

- The circum-galactic medium (CGM) is the environment extending from the outer edge of a galaxy out to its virial radius.

- It mediates both the accretion of material from the rest of the Universe, and any material and radiation expelled by the galaxy.



NASA/CXC/M.Weiss; NASA/CXC/Ohio State/A.Gupta et al.



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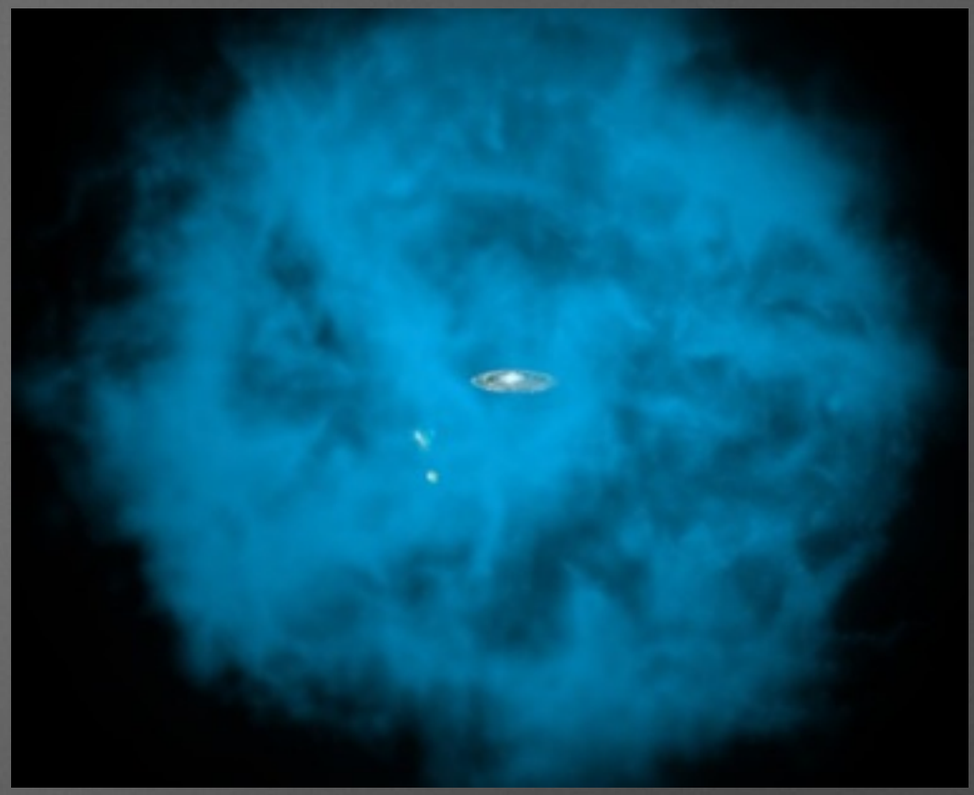
- Gas is enriched by metals that are formed within stars and ejected during feedback events. Thus enriched gas is intimately tied to the feedback.

- Metals in the disk mix on small time-scales, but those ejected into the CGM change on much longer time-scales



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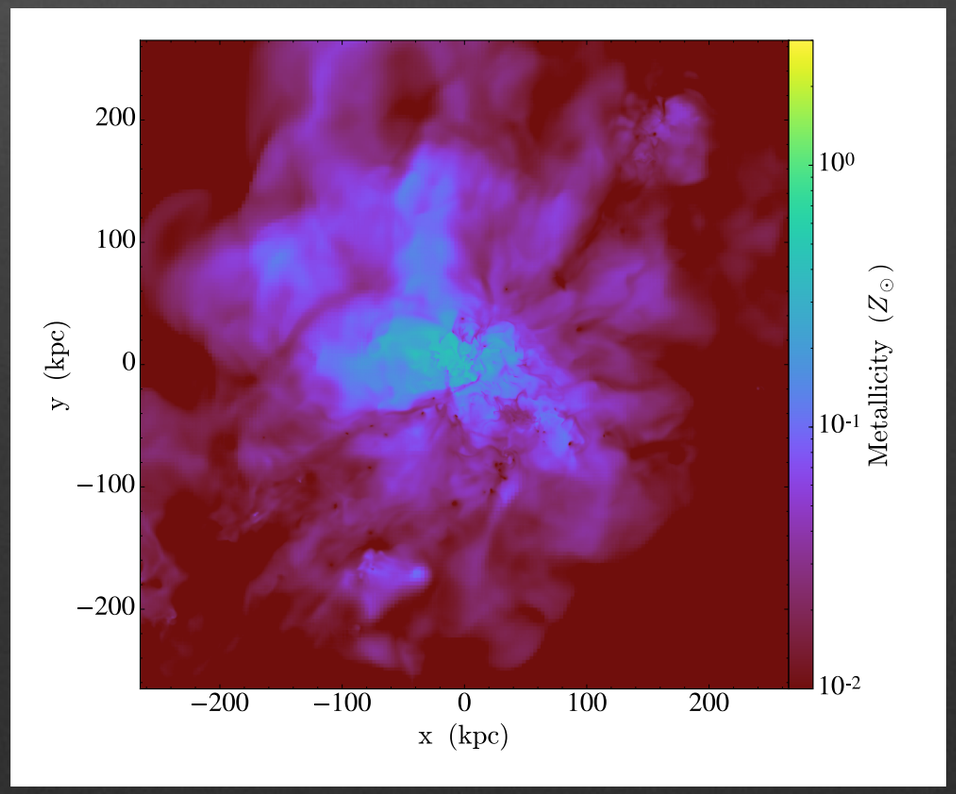
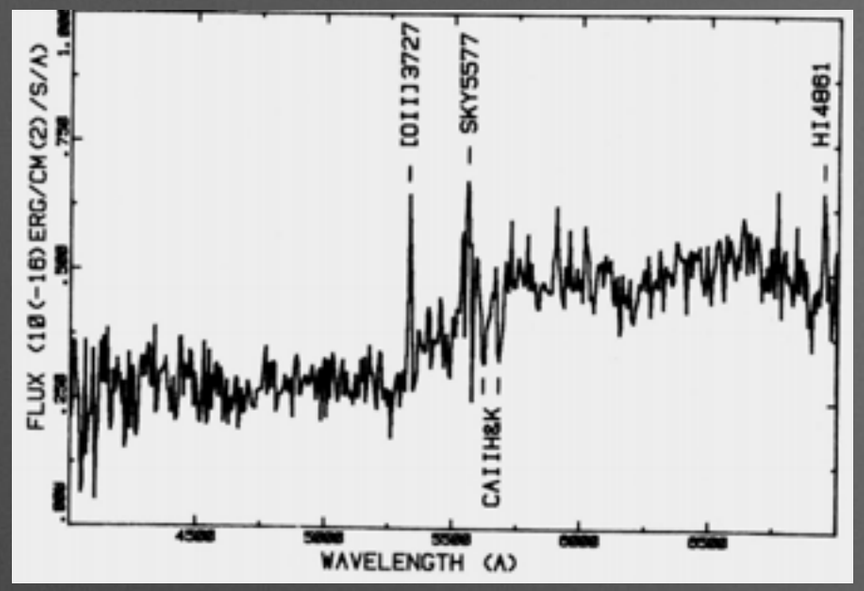
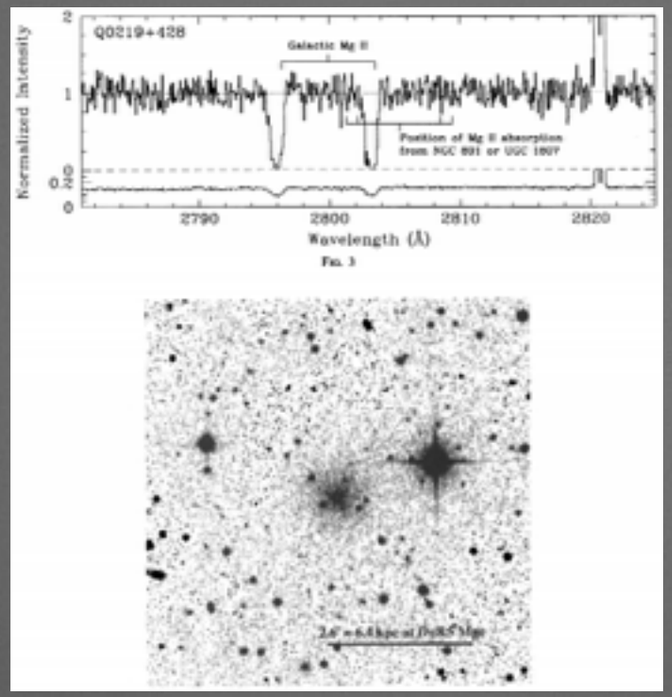


Observations of the CGM

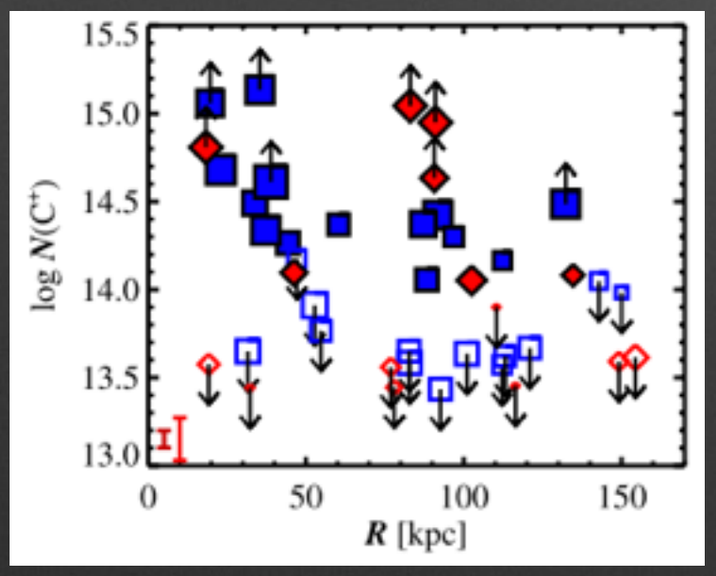


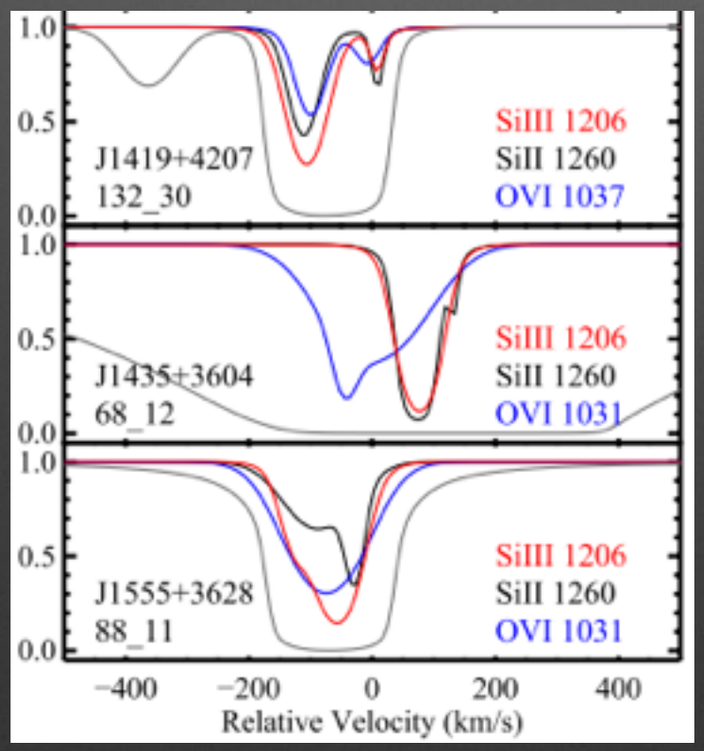
z=0.5 QSO - Bergeron 1986



z=0.44 QSO - Bowen+1995

The CGM is typically too diffuse to see in optical emission lines, and too cool (for small galaxies) to see in x-rays.





Werk+2013

- Serendipitous distant quasars whose sight lines pass near foreground can reveal the structure of the foreground CGM via absorption.
- The best survey of the structure of the CGM comes from the COS Halos survey (Tumlinson+2011;Werk +2013).
- This reveals a structure to the expelled metals, both in density and velocity space

Comparing with Simulations

- So do simulations give predictive power in the CGM that could invalidate feedback models? Recall: Cosmological simulations require a huge span in length scales, and necessarily implement feedback (and star formation) with sub-grid physics.

- AMR is essential for resolving the CGM structure (compare with SPH).

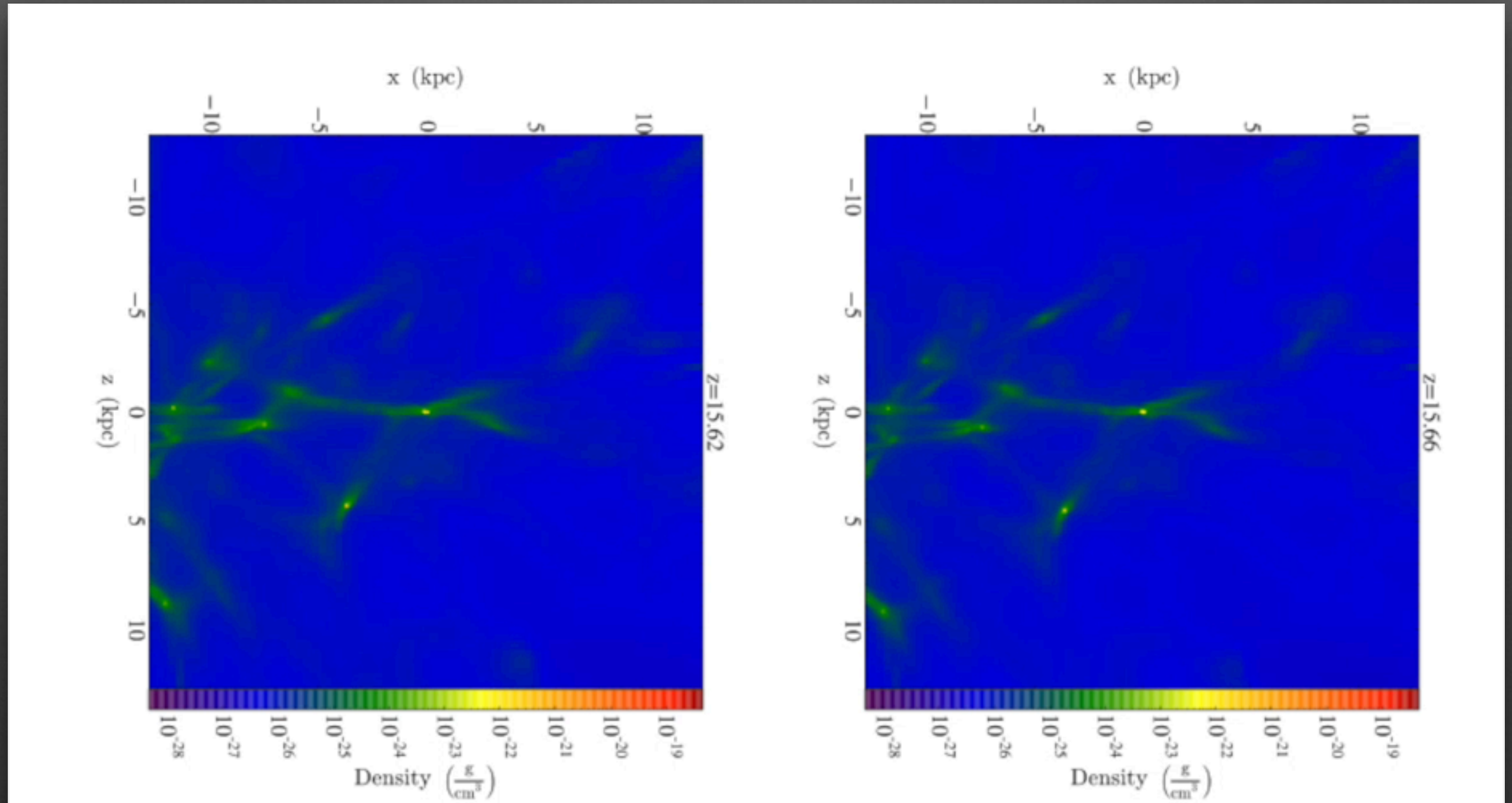
- Previous groups have looked at this (e.g., Hummels+2013), although their resolution was quite poor (>~100pc) and used only the cosmic UV background to determine the ionic state of the CGM gas.

Part I: The NUT Runs

- The NUT suite (Powell+11) explored the effect of changing the star formation (SF) and feedback (FB) prescriptions in a galaxy with ~10 pc resolution. Julien has already introduced this suite.

- Recall the SF replicates the Kennicutt-Schmidt law ($\dot{M}_{SFR} \sim \rho_H^{1.5}$), but we have two different SF models:
  - SF1 = stars form with constant efficiency, ~0.01, wherever $\rho_H > 400$ cm^{-3}
  - SF2 = stars form where grav. unstable, with efficiency = f(M,n_H) (recall Taysun, Valentin, and Julien's talk yesterday)

- Feedback follows the sedov-blast wave solution. We implement this in three different models:
  - FB0 = Feedback turned off as a comparison set.
  - FB1 = Dubois & Teyssier 2008 - Salpeter IMF injecting energy consistent with Sedov
  - FB2 = Kimm & Cen 2015 - Chabrier IMF injecting momentum or energy consistent with Sedov depending on resolution (recall Taysun and Maxime's talk from yesterday).



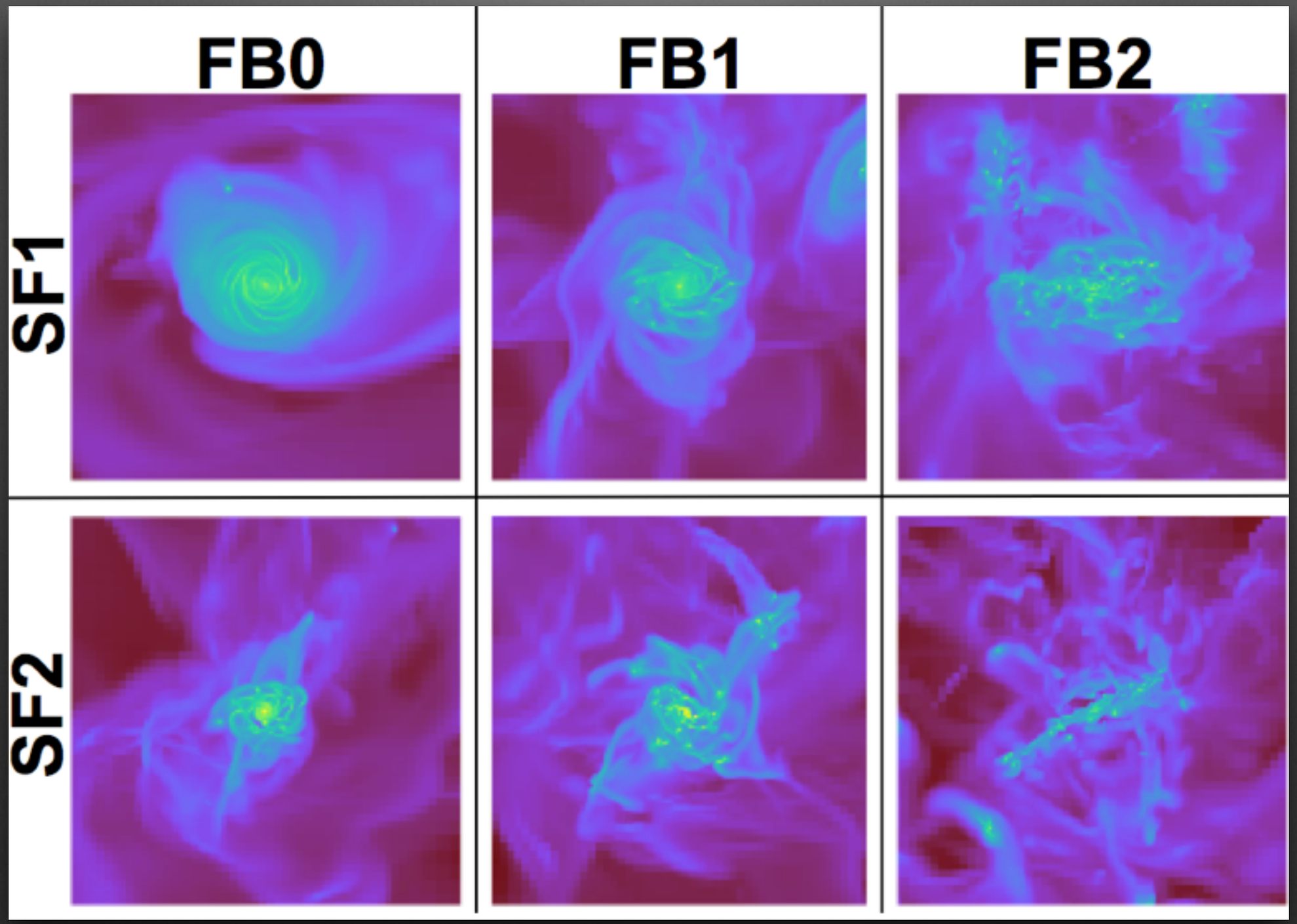
SF: Density Threshold (SF1)

SF: Gravitational Unstable (SF2)

Evolution of the Nut Galaxy

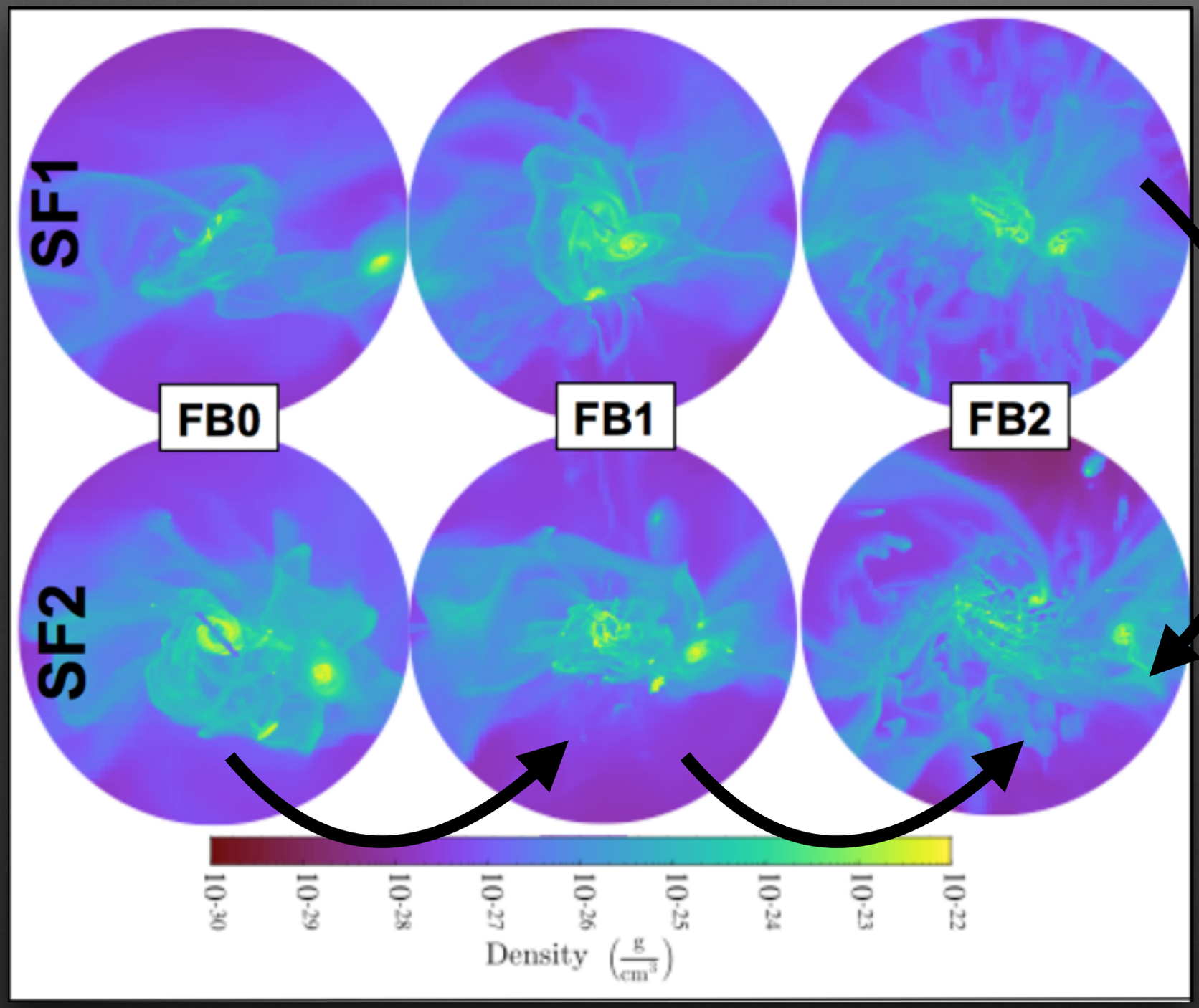
*Made with yt toolkit

NUT Galaxy at z=3



Images are 10 kpc across

Nut CGM at z=3



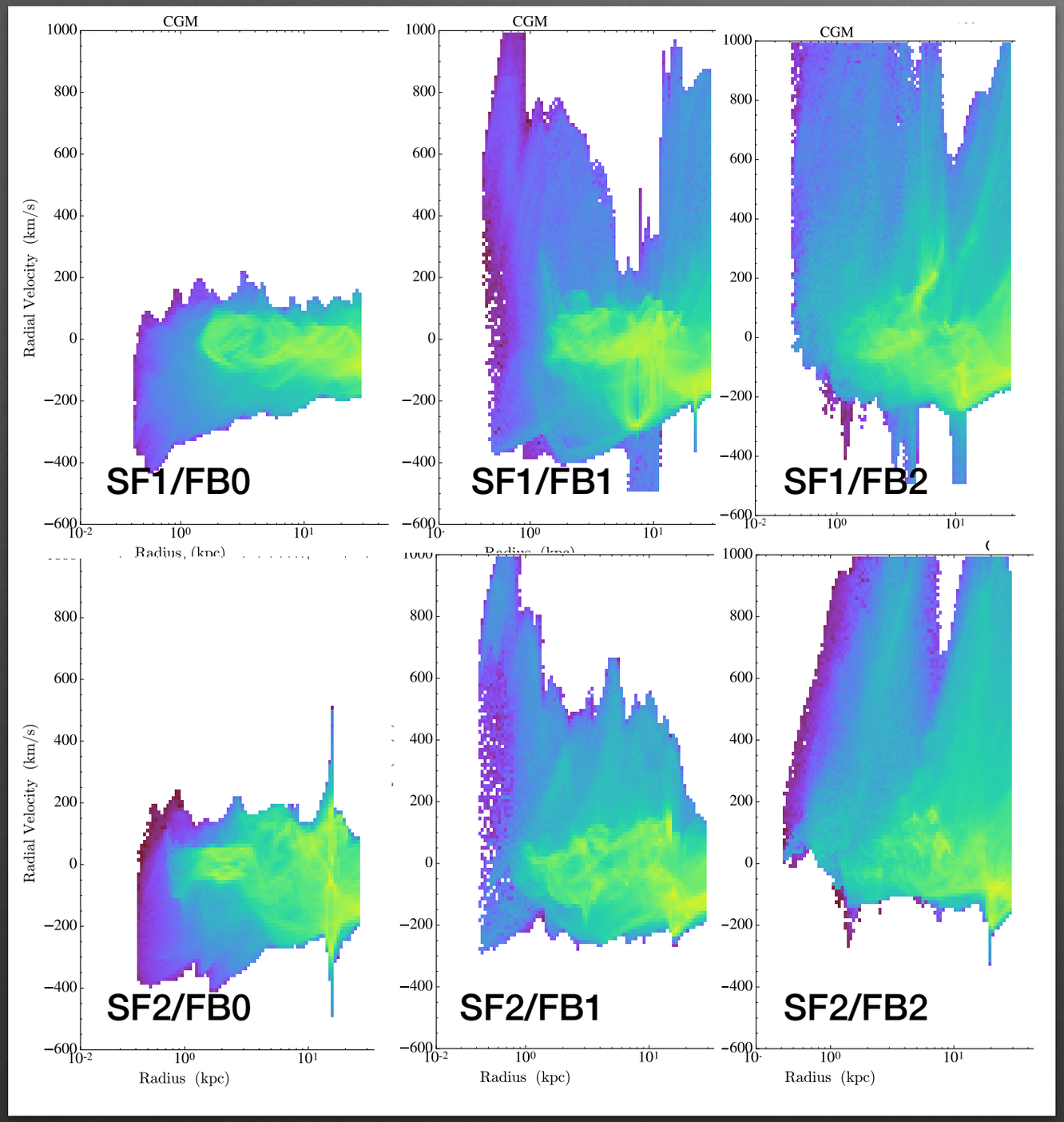
SF2 increases the gas/star ratio by 50-70%

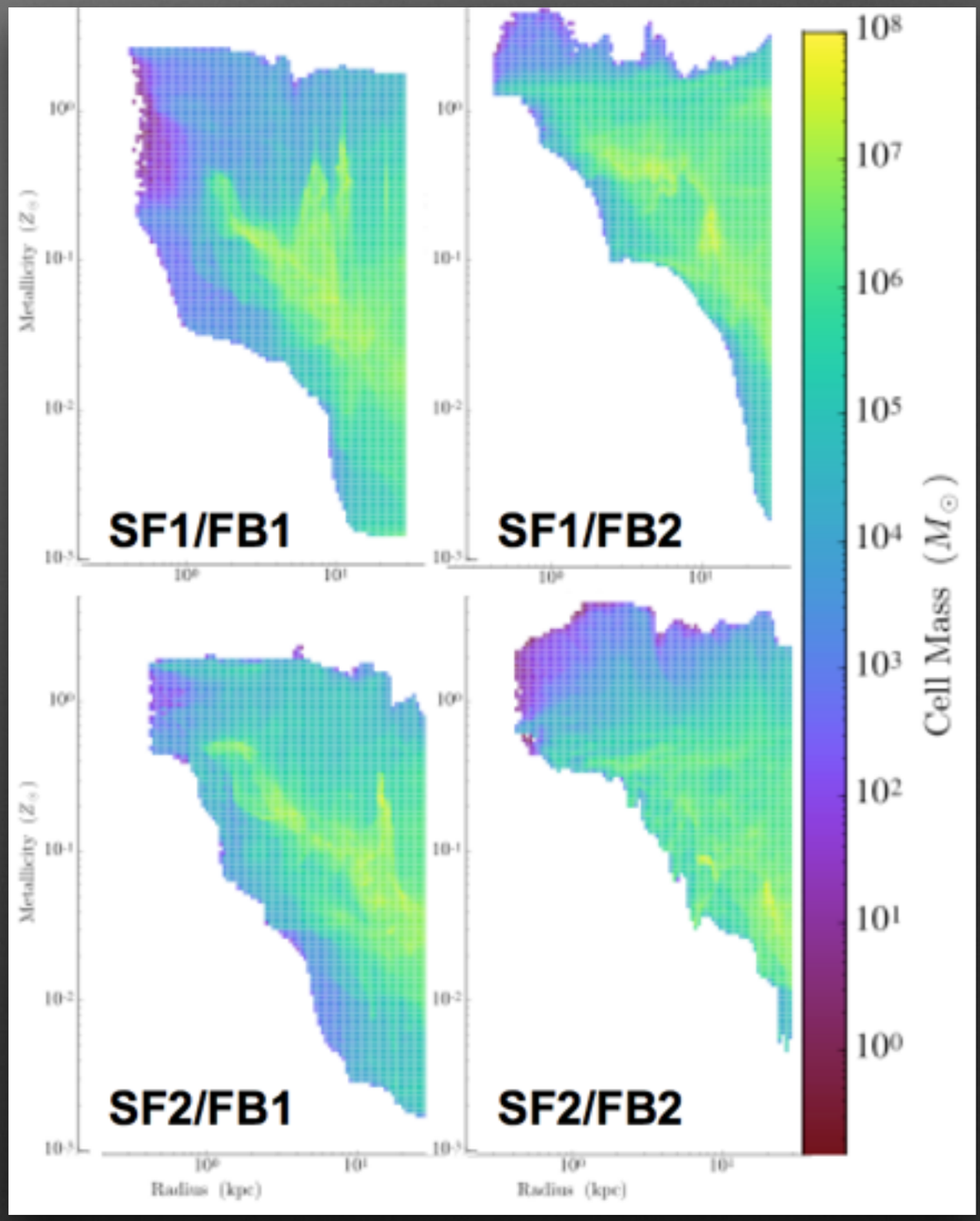
FB2 doubles the gas/star ratio again

FB1 doubles the gas/star ratio

Images are 60 kpc across

How does FB affect the CGM





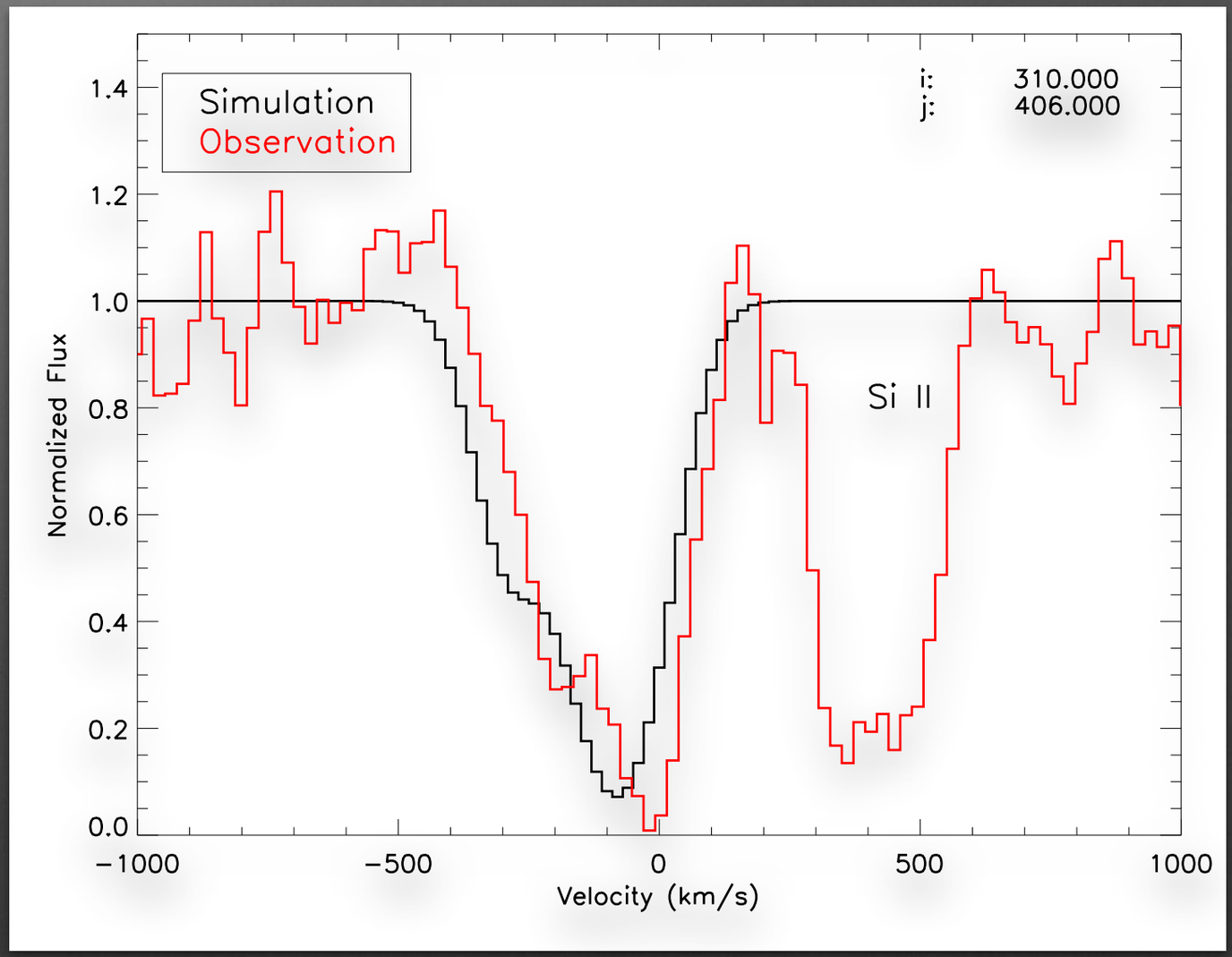
Radial Velocity Profiles

Metallicity Profiles

FB: Outflows @ v ~1000km/s ; FB1: $Z \sim 0.1 Z_{sun}$, FB2: $Z = 0.15\text{-}0.33 Z_{sun}$

Mock Observations

- So the dataset can tell us some of the structure of the CGM, but what would be observed.
- For some of our runs we have included Joki's radiative transfer and thus model the ionisation state of Hydrogen.
- Working with John Chisholm we can construct data cubes that can be combined into mock images as viewed by an integral field unit.
- This allows for more direct comparisons with observations to be made, and is ongoing.



Part II : Nephthys 

- We have recently begun a new simulation suite to explore a range of galaxy masses (halo masses from $10^{10.5 - 12.3}$) with a key focus on the CGM.

- We are now enforcing a resolution of 100pc in the CGM (still up to 10pc in dense regions), roughly resolving the cooling length scale ($c_s * \tau_{cool}$). We achieve this by using an additional refinement criteria in rho_fine, refining on gas more dense than 100 times the average baryon density.

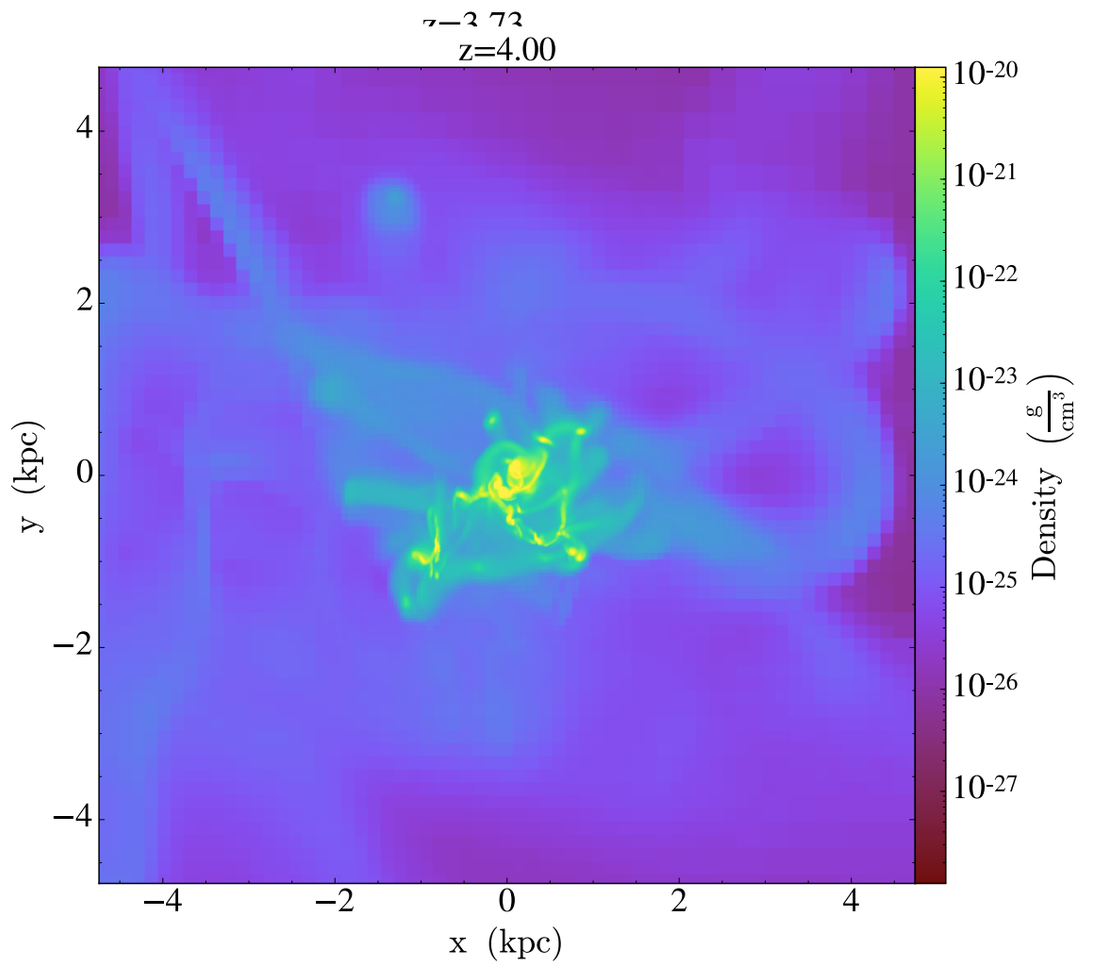
- This increases the number of octs at this level by a factor of 45 and the number of octs overall by a factor of 16, leading to a slowdown of ~ 3.

- For each galaxy we (will) simulate with no FB, FB (SNIa and SNII) with no RT, and with RT, down to z=0.75.

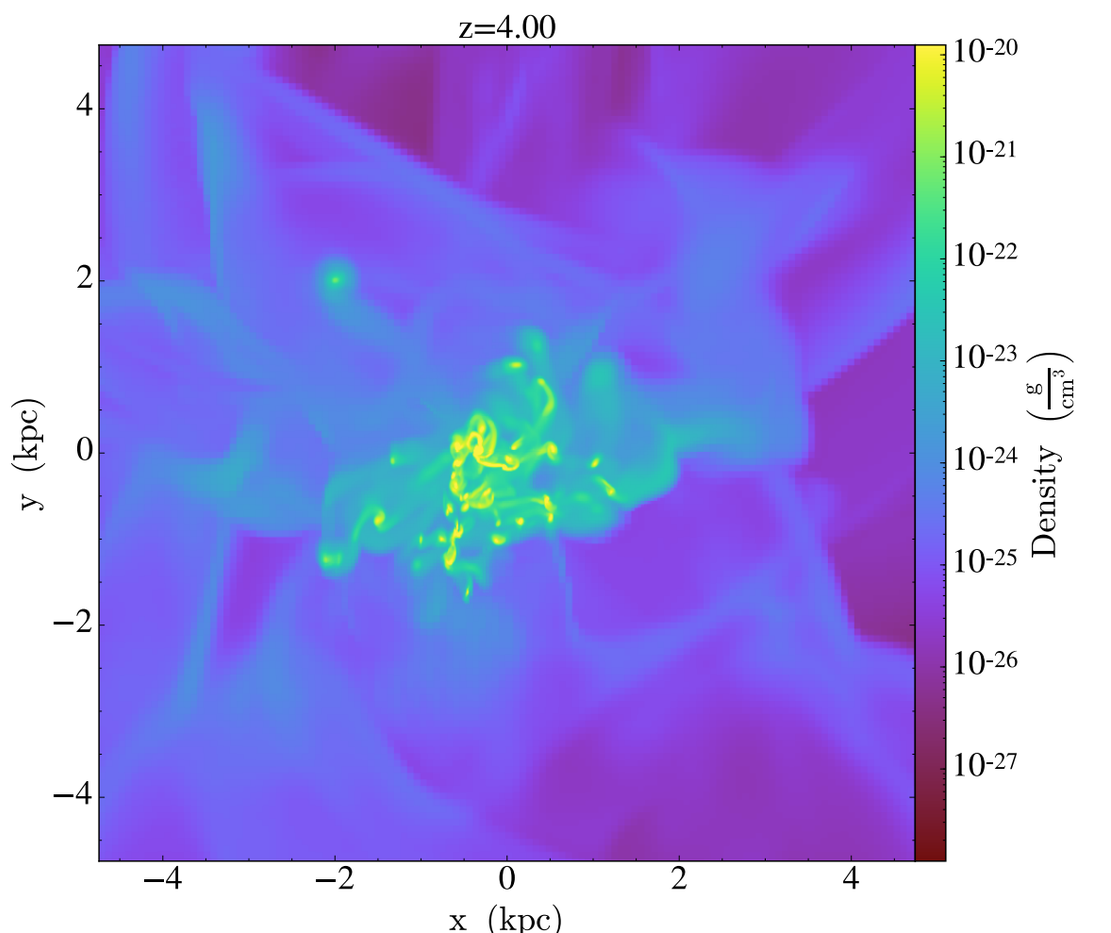
What does the extra refinement get us?

- ** (~4Myr differ between images) **
- The extra refinement ensures crisp edges to infalling structure.
- With outflows, this amount of resolution will be essential to be able to compare with observations.
- Added resolution leads to clumpier disk —> more resolved sheets lead to greater instabilities (but surprisingly not more star formation)?

Refinement = Lagrangian

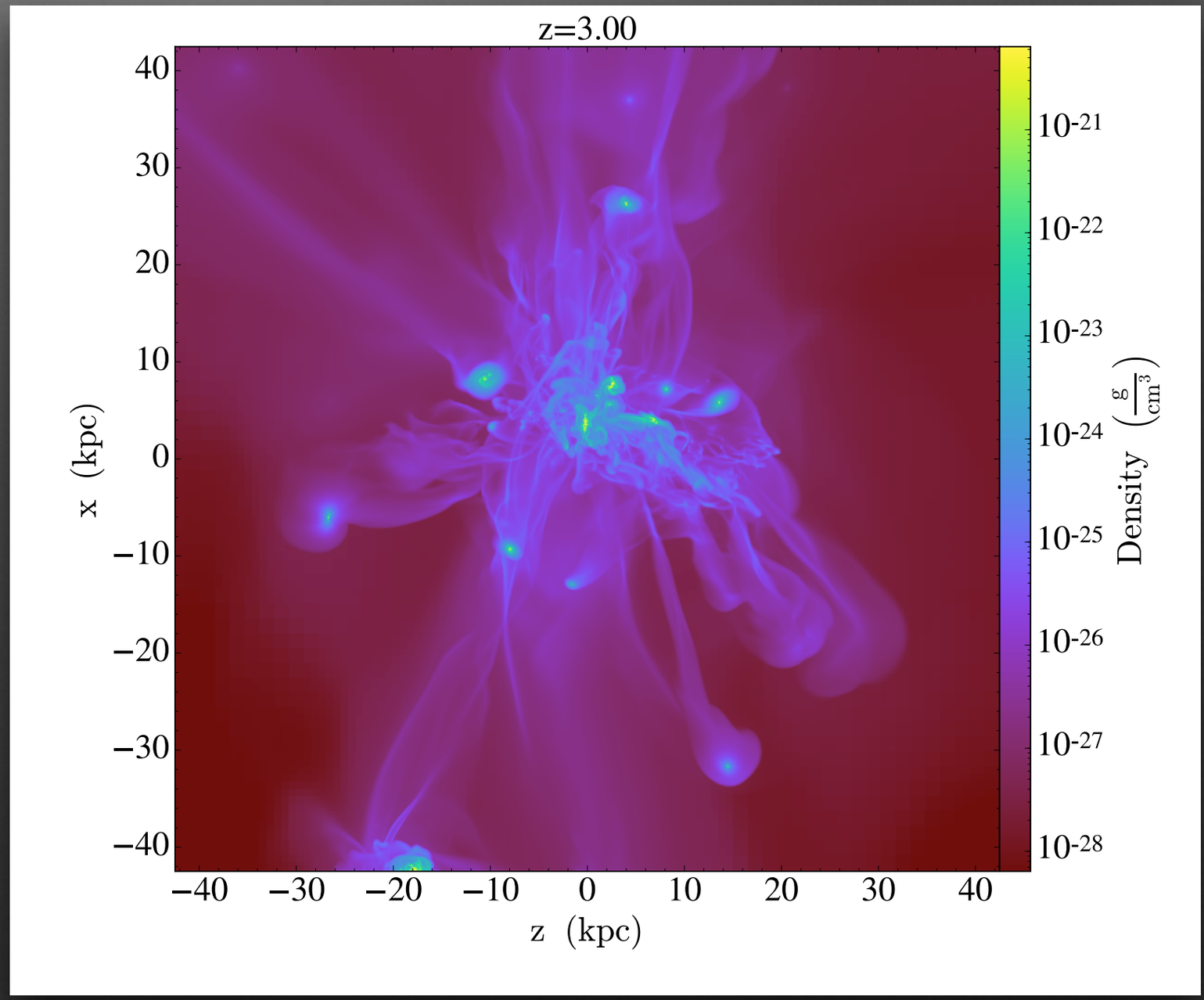


Refinement += CGM Ref 100pc



Early Results

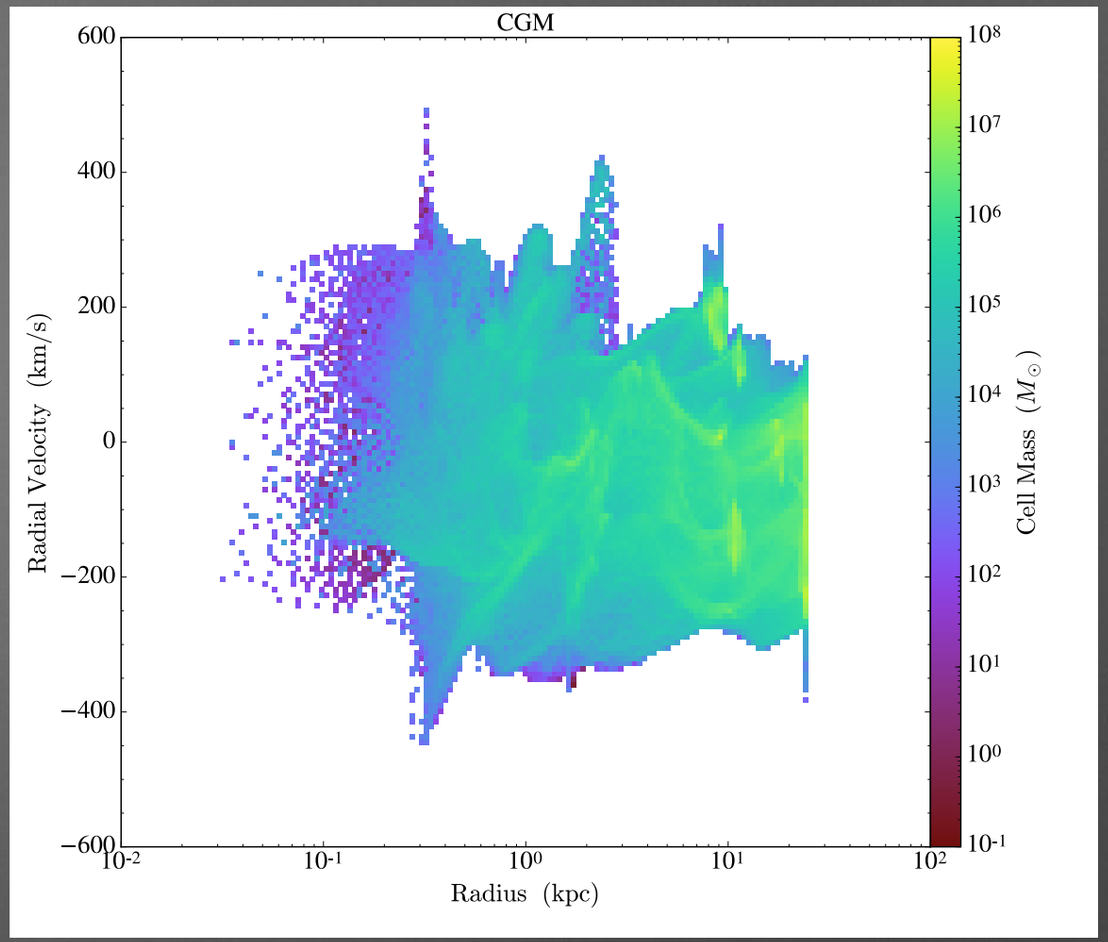
- This galaxy is an analog to the NUT galaxy.
- We are able to resolve with amazing detail the structure in the CGM.



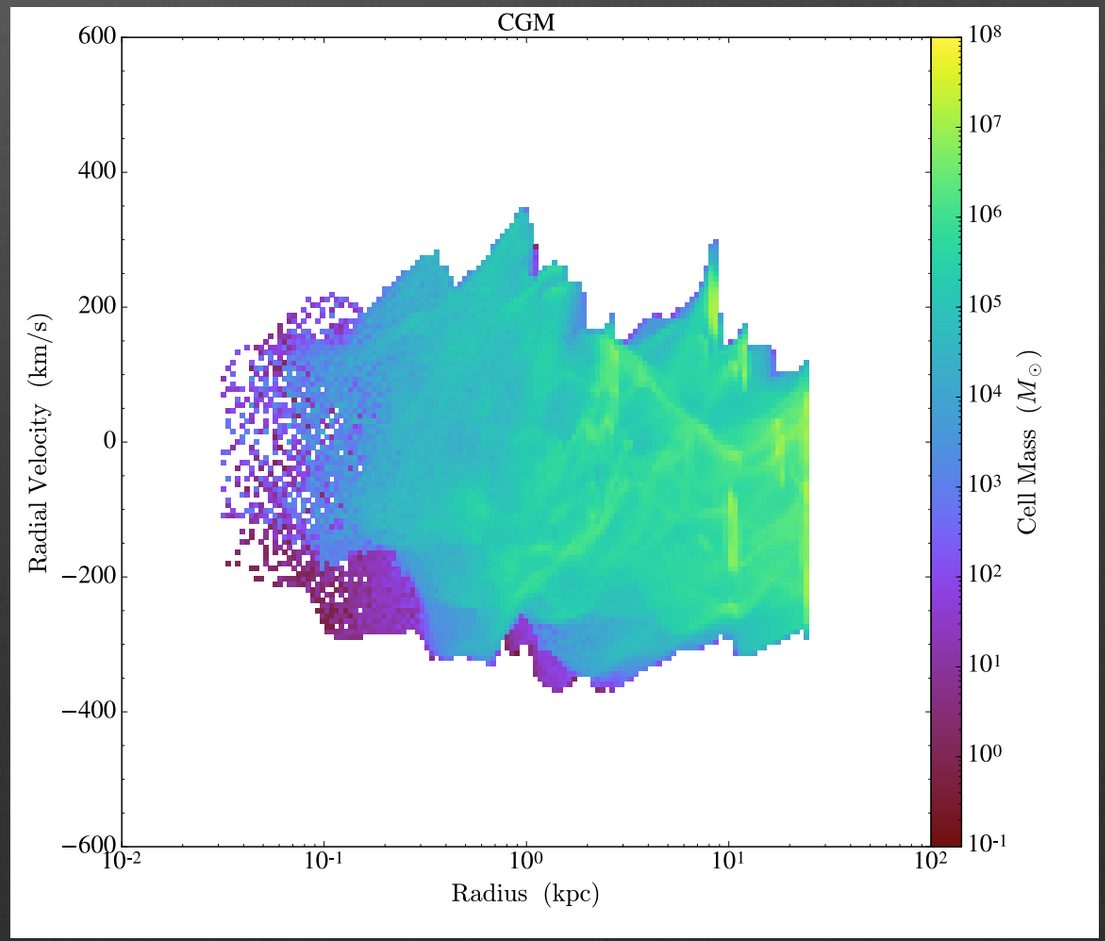
CGM

- Extremely new simulations, so I haven't been able to analyse them in detail.
- Also, no runs with FB at comparable redshifts.
- So breifly, we see that without refining the CGM @ 100 pc, you get more very high velocity flows —> Could be that this material is inflows, so higher density in the CGM @ 100 pc run, and is thus flagged as part of the disk.

Refinement = Lagrangian



Refinement += CGM Ref 100pc



Summary

- The particulars of the star-formation model can lead to variations in CGM gas/stellar mass ratios (50-70%)

- The feedback model can lead to 100-300% increase in this ratio as well.

- These effects appear to act roughly linearly!

- The metallicity of the CGM is the same in both FB1 sims, but higher in SF1/FB2 than SF2/FB2. Not clear why.

- We have begun a suite of 9 simulations looking at >~10 galaxies spanning masses $\log M_{DM}$ ~ 10.5 - 12.3, within a range of environments.

- These simulations include extra refinement in the CGM to resolve the cooling lengthscales.

But wait … there's more!
Ramses Dev

- Computer clusters are becoming more and more oversubscribed, so it's useful to be able to get you job in the queue early. But with Ramses this means knowing the last output that will be generated.

- However, now read_params will check if nrestart corresponds to an existing file, and if it is not, it will decrement it down to 1 until finding an existing output. (see pull request #201 on ramses bitbucket repository).

- yt (the analysis toolkit: yt-project.org) now has full support for the time units for cosmological Ramses simulations. This includes star particles ages (which in yt is their age, not their t_birth as in Ramses).

Ramses Wish List

- Ramses works best at a set number of octs/core, yet at high redshifts the number of octs is much less than at low redshift, making communication overhead very poor early in our simulations. Ideal, we should start with less processors and increase this number at subsequent restarts.

- Rerunning jobs on other clusters means sometimes changing the #cores/node, possibly benefiting from changing the number of cores.

- Sometimes we run out of memory, and we just cannot afford more octs/core. Yet our simulation requires it. Choices: To restart from scratch, or find a new machine. Or…

    - We need an effective conversion tool to translate an output to a different number of processors. The DICE and Restart patches do this, but the memory constraints make this (apparently) unfeasible.

Ramses User Meetings
Wish List

- Future meetings should include a Hack day!

Thank you!