Impact of Stellar Feedback in Dwarf Galaxy formation and the CGM

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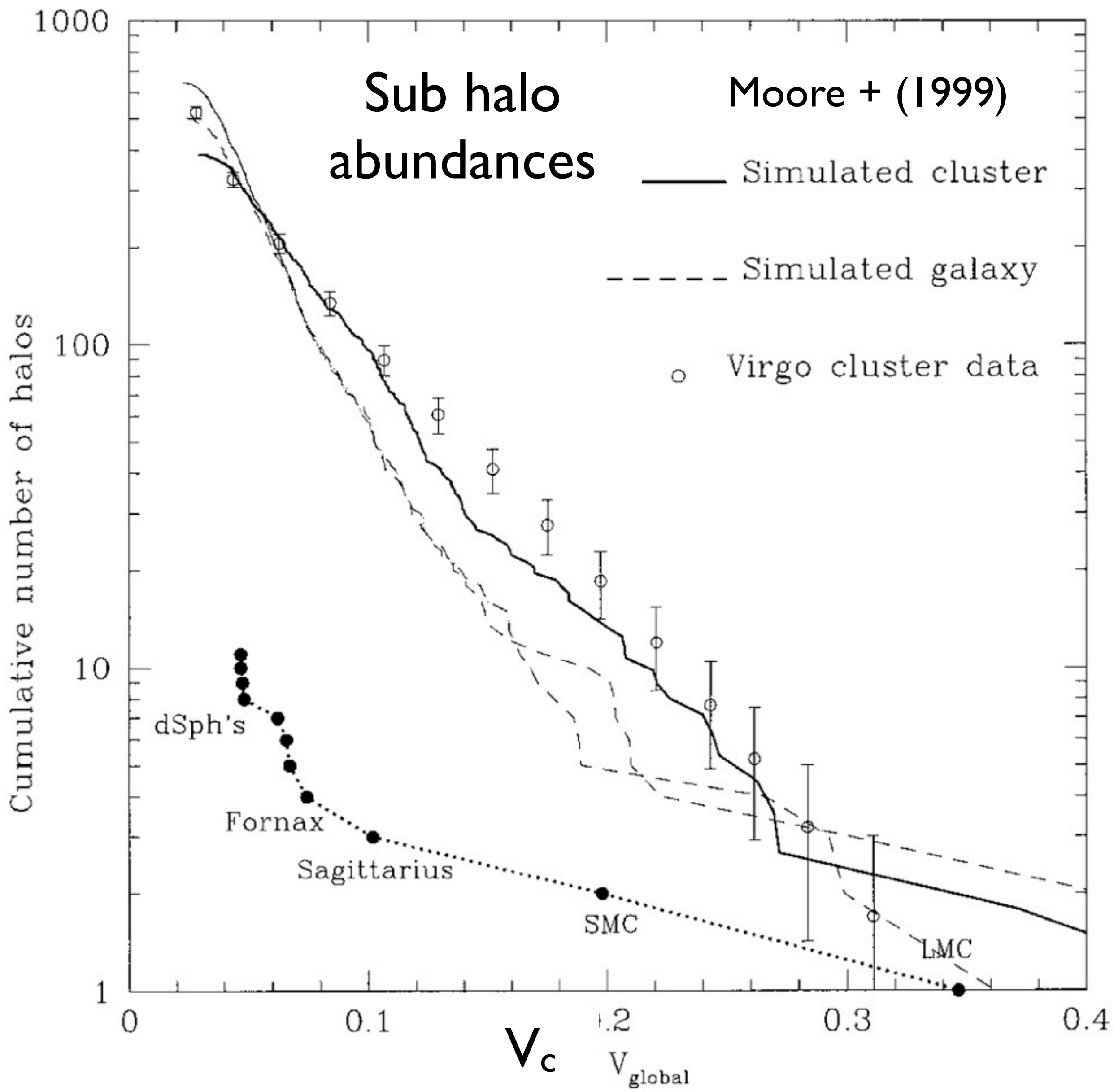
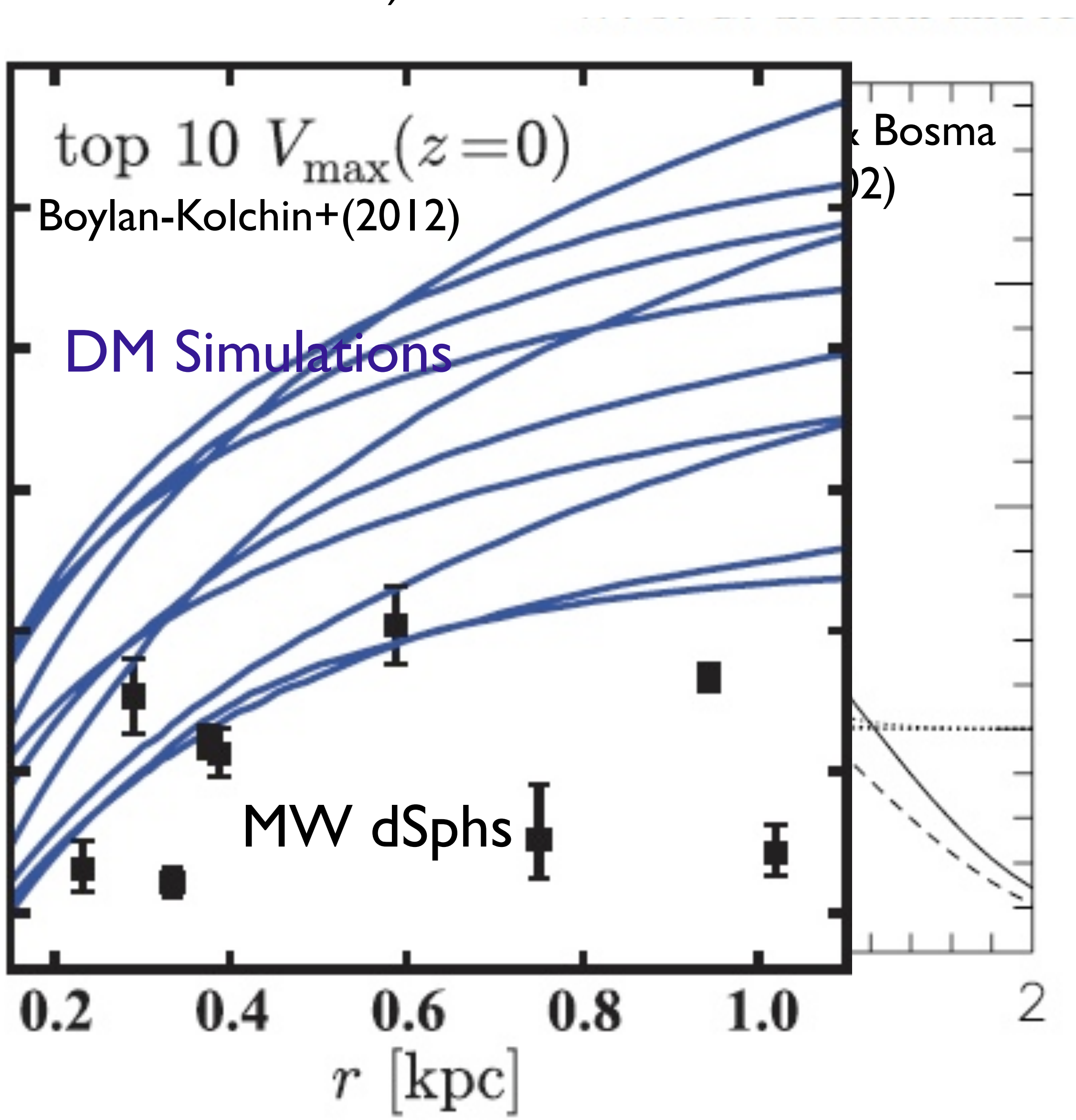
Part I: Formation of Dwarf Galaxies and the Impact of Stellar Feedback

- Baryonic processes, especially feedback that drives outflows are crucial for dwarf galaxy formation
- Main approach: using existing observations to constrain (subgrid) feedback models
- *Checklist:*
  - *Stellar mass-halo mass relation*
  - *Stellar age distribution*
  - *Bursty SF and high sSFR*
  - *Stellar distribution, kinematics* $V/\sigma \sim 1$
  - *H I kinematics*
  - *Gas and stellar metallicities*
  - *H I gas content*
  - *DM-profile, cusp-core transformation*
  - *...*

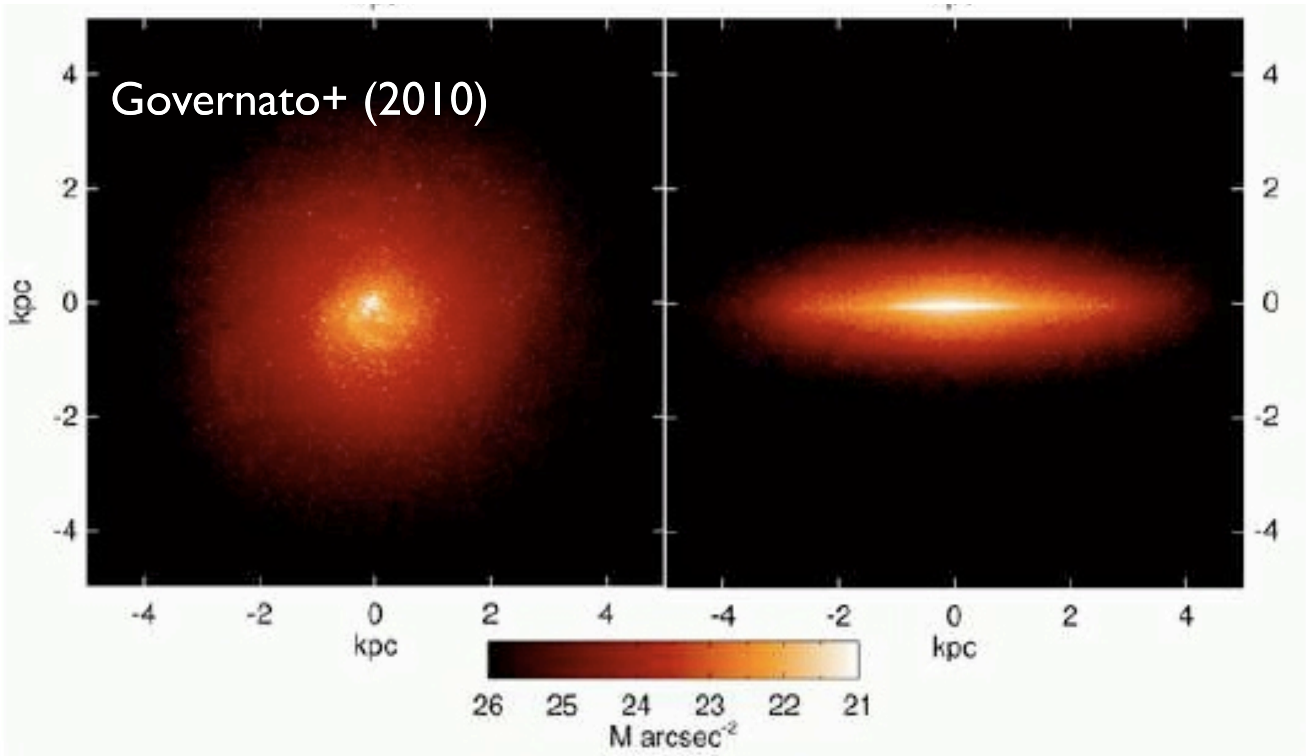
Challenges in ΛCDM Dwarf Galaxy Formation

- Very inefficient star formation at z = 0, M_*/M_h is much lower than more massive halos (e.g., Behroozi+2013, Moster+2013)
- The "missing satellite" problem (e.g. Moore +1999, Klypin+1999, Diemand+08;)
- The "cusp-core" problem (Moore 94, Flores & Primack 94; de Blok & Bosma 02)
- The "too big to fail" problem (Boylan-Kolchin+2012)

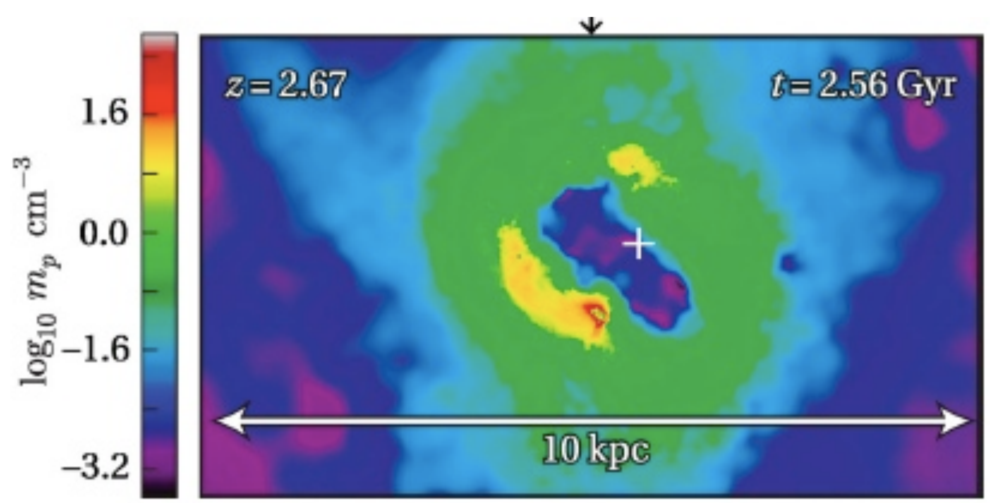




The Effect of Baryonic Processes in Dwarfs

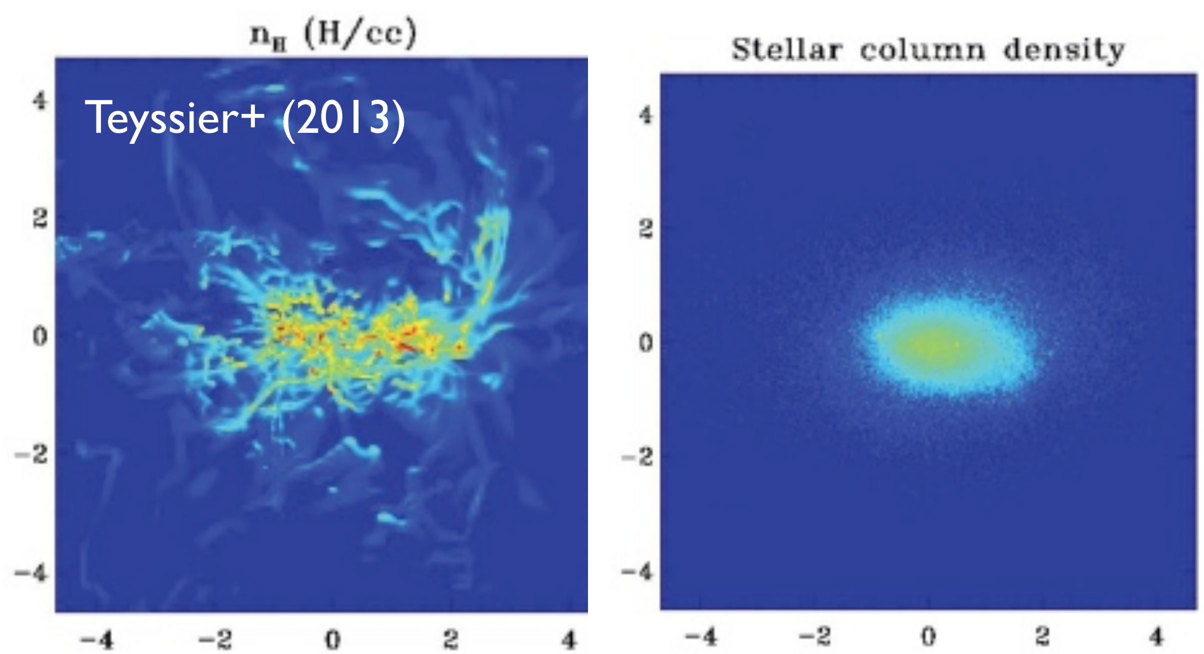


Governato+ (2010, 2012): Bulgeless dwarf galaxies with "cored" dark matter profile



Pontzen & Governato (2012): Rapid change of the central potential transform cusp into cores

- Due to the shallow potential wells, gas accretion, star formation and outflows proceed differently in dwarf galaxies than more massive galaxies. Baryons are crucial:
- UVB heating suppress SF (e.g. Efstathiou +92; Bullock+00; Dijkstra+04; Kravtsov+04; Madau +08)
- Feedback and outflows also regulate SF and are important for DM cores (Mashchenko+08; Governato+10; 12, Zolotov+12; Teyssier+13; Di Cintio+14)



Teyssier+(2013): feedback create dark matter cores, and makes the stellar distribution dynamically hot v/σ ~ 1

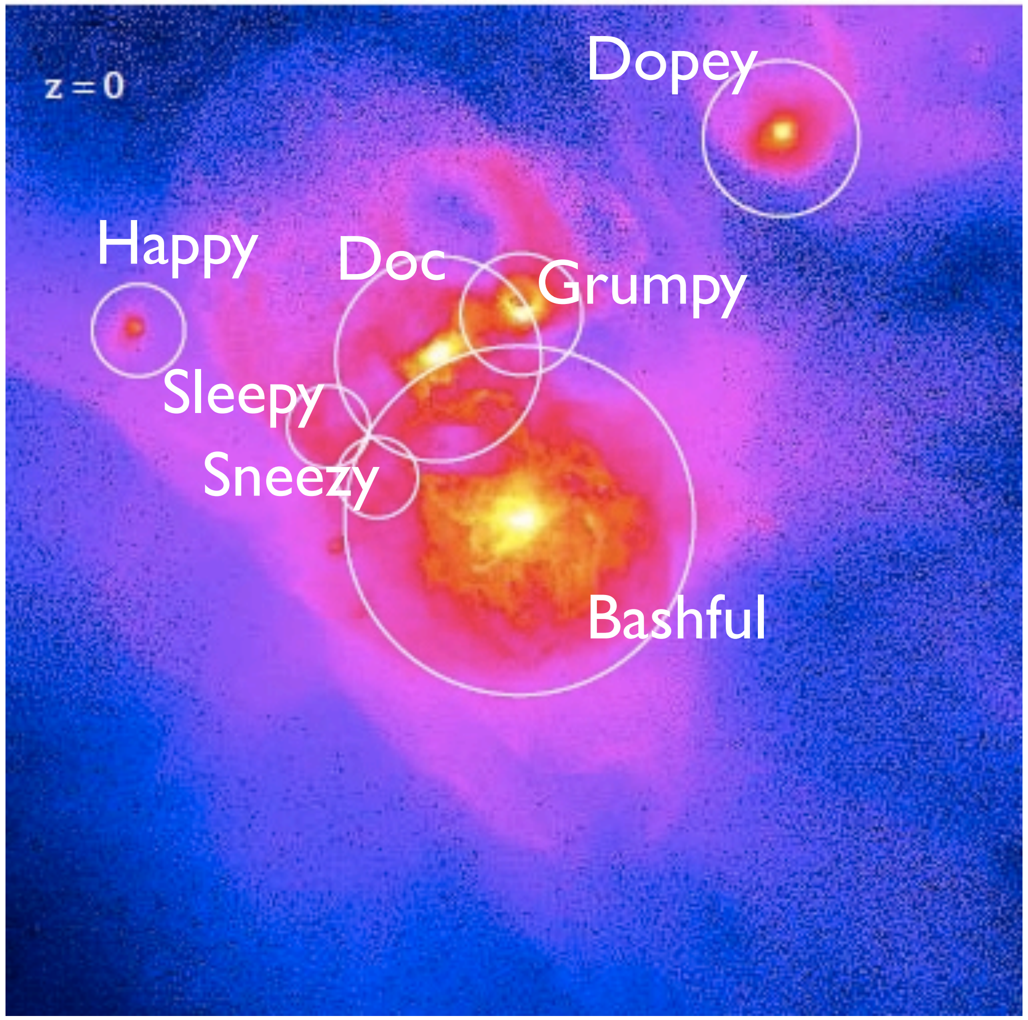
The Simulation

- TreeSPH code Gasoline (Wadsley+ 2004) Gasoline
- SF simple K-S relation: $d\rho_*/dt = \epsilon_{SF}\, \rho_{gas}/t_{dyn} \propto \rho_{gas}^{1.5}$ when gas has $n_H > n_{th} = 100\ cm^{-3}$
- Each star particle represent a simple stellar population following a Kroupa+(2001) initial mass function
- Blastwave feedback model for SN II (Stinson+ 2006). After each SNe inject 10^{51} ergs into the ISM, radiative cooling is delayed according to analytical solution from McKee & Ostriker (1977), depending on local ISM properties.
- Same initial condition and feedback parameters as the DG1 in Governato et al. (2010).
- Non-equilibrium primordial cooling + equilibrium metal-line cooling from Cloudy (Ferland+ 1998), under uniform UVB (Haardt & Madau 2012)
- Smagorinsky turbulent diffusion model (Wadsley+ 2008; Shen+2010) to capture mixing of metal due to turbulence. Diffusion coefficient proportional to velocity shear.
- Resolution: $M_{DM} = 1.6 \times 10^4\ M_{sun}$, $M_{SPH} = 3300\ M_{sun}$, $M_* = 1000\ M_{sun}$, softening length 86 pc, smoothing length 8.6 pc

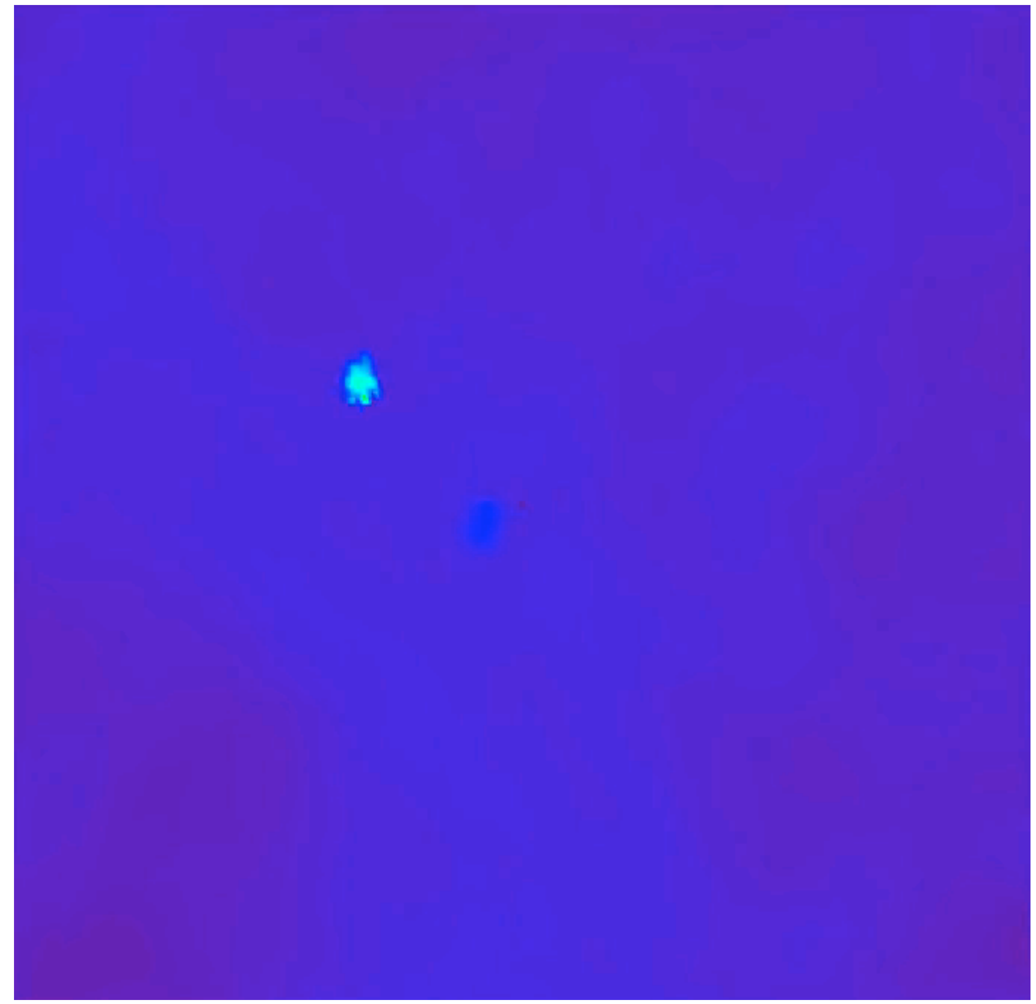
Evolution of gas density and temperature

Shen et al. (2014)

Gas column density



Column-weighted Temperature

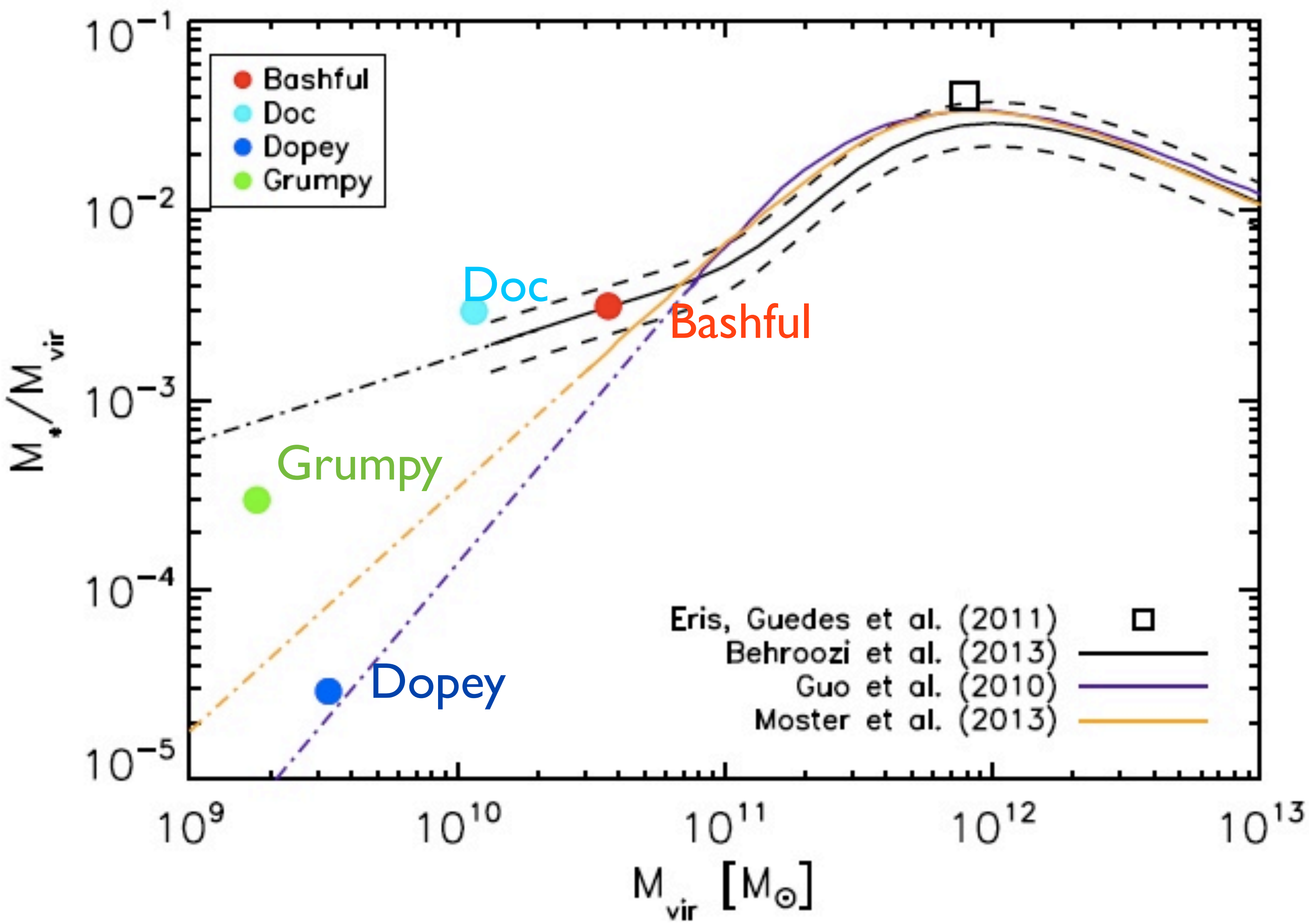


1 Mpc x 1 Mpc comoving box, 12 times Rvir of the most massive halo

- Gas is heated by the ionizing background, accretion is "smooth";
- Feedback destroys the ISM and generate large scale galactic winds;
- z = 0, group of 7 dwarf galaxies contains gas in the high resolution region; 4 luminous, 3 dark, the galaxies are merging at z = 0;
- Field dwarfs: the closest massive system > 3 Mpc away;

Stellar Mass and the Star formation Efficiency

Name	M_{vir} [$M_\odot$]	R_{vir} [kpc]	V_{max} [$km\,s^{-1}$]	$V_{1/2}$ [$km\,s^{-1}$]	M_* [$M_\odot$]	M_{gas} [$M_\odot$]	M_{HI} [$M_\odot$]	f_b	$\langle[Fe/H]\rangle$	M_V	$B-V$
Bashful	3.59×10^{10}	85.23	50.7	18.3	1.15×10^8	8.14×10^8	2.34×10^7	0.026	-0.96 ± 0.51	−15.5	0.3
Doc	1.16×10^{10}	50.52	38.2	21.6	3.40×10^7	1.74×10^8	1.98×10^7	0.018	-1.14 ± 0.44	−14.0	0.4
Dopey	3.30×10^9	38.45	22.9	4.44	9.60×10^4	4.47×10^7	1.96×10^6	0.014	-1.97 ± 0.44	−8.61	0.2
Grumpy	1.78×10^9	29.36	22.2	3.76	5.30×10^5	3.00×10^7	5.40×10^5	0.017	-1.52 ± 0.54	−11.0	0.0
Happy	6.60×10^8	22.49	15.6	—	—	2.54×10^6	—	0.004	—	—	—
Sleepy	4.45×10^8	19.71	14.8	—	—	—	—	—	—	—	—
Sneezy	4.38×10^8	19.62	13.2	—	—	1.64×10^5	—	0.0004	—	—	—



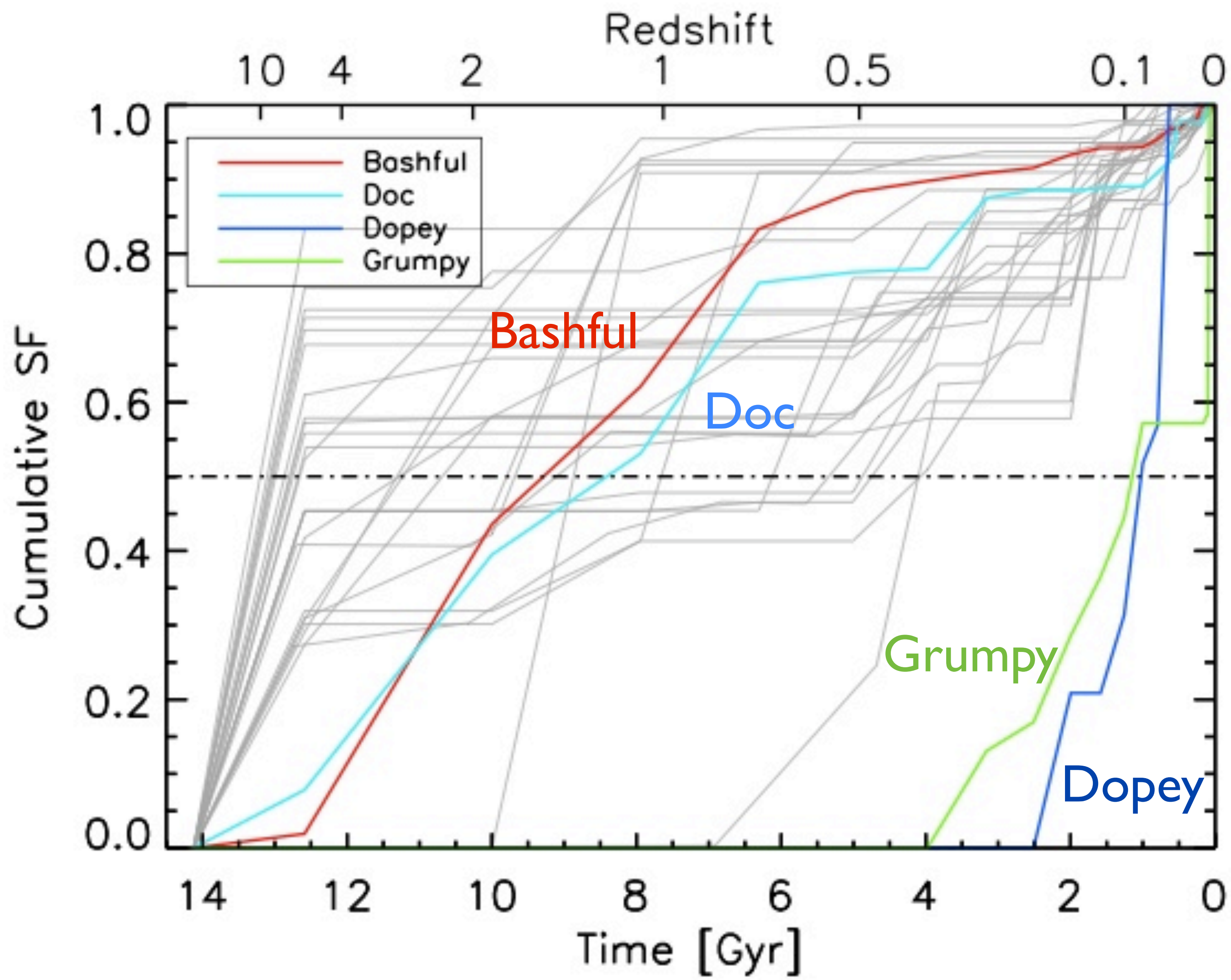
- All luminous dwarfs have halo mass > 10^9 M_{sun}. M_* ranges from 10^5 M_{sun} to 10^8 M_{sun}
- Two luminous dwarfs: Bashful and Doc: $M_*/M_h \sim 0.003$, are consistent with abundance matching results Behroozi + (2013)
- Two faint dwarfs: Dopey & Grumpy: very inefficient star formation, M_*/M_h = 2e-5 and 3e-4.

Star Formation History

- Observed SFH in dIrrs are diverse. Most galaxies formed the majority of of stars at z > 1, but there are ongoing SF activities today. On average, ~ 8% of stars over the last 1 Gyr;

- Bashful and Doc have a close to linear SFH, about half at 10 Gyr ago, 75%-85% 6 Gyr ago, ~10% at last 1 Gyr.

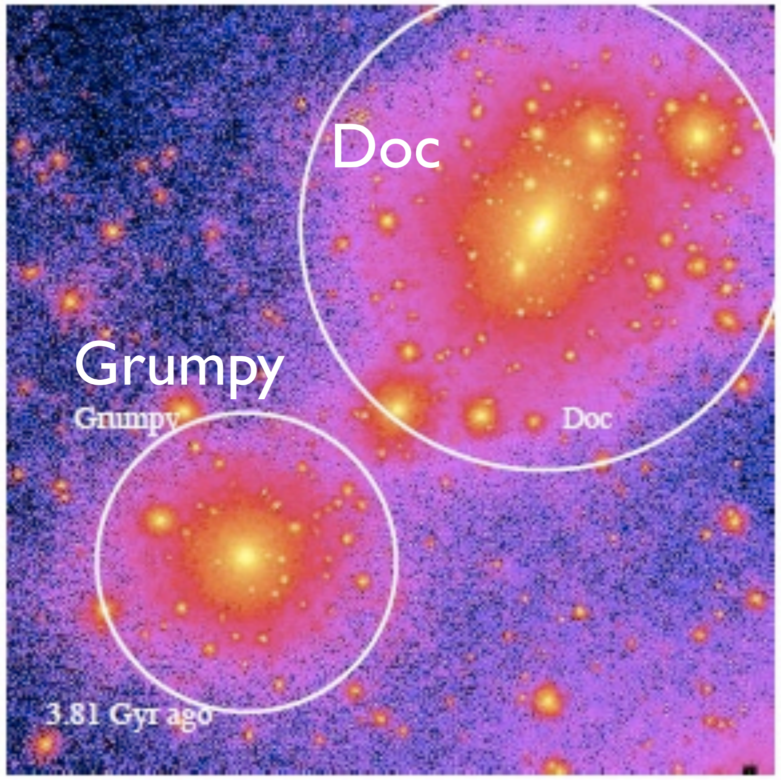
- All four dwarfs can be characterized as star forming, but only Bashful have SF today

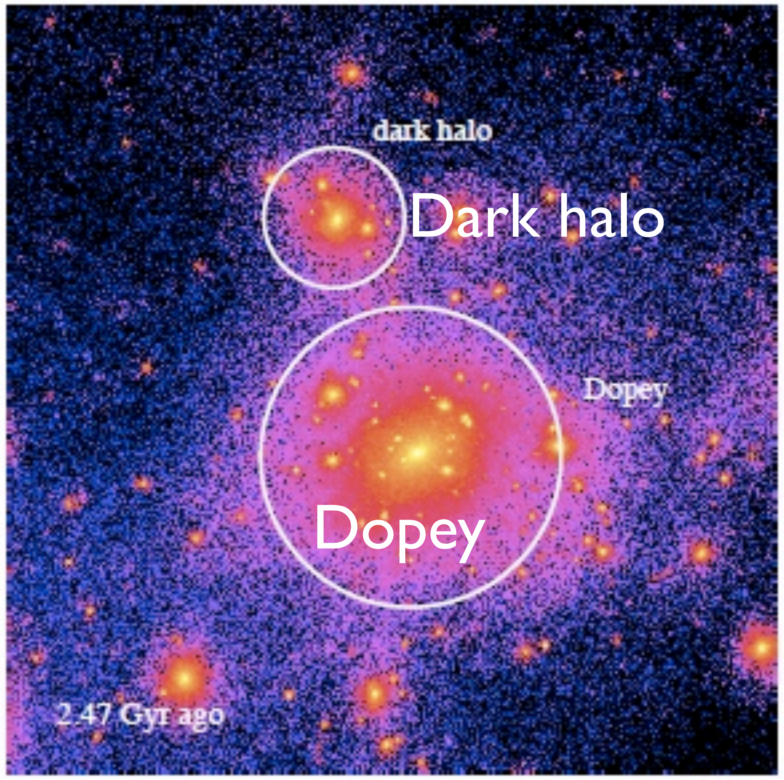


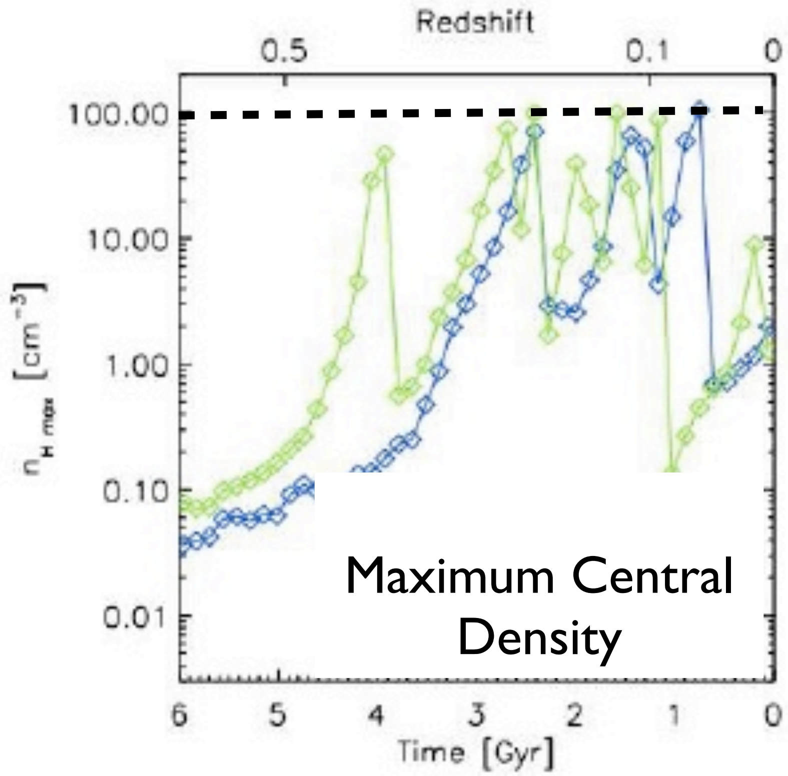
Observation: star formation histories of dIrr galaxies in the ANGST sample, derived using the CMD of resolved stellar population (Weisz et al. 2011)

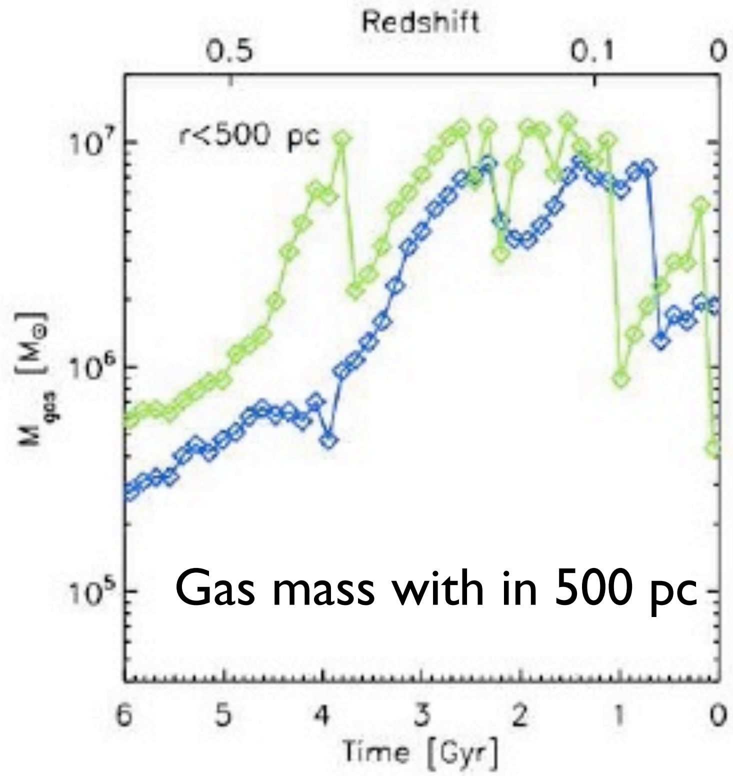
- The two faint dwarfs do not contain very ancient populations. The median stellar age is 1.1 Gyr, comparing to 9.7 Gyr and 9.1 of Bashful and Doc.

Origins of the Two Faint Dwarfs





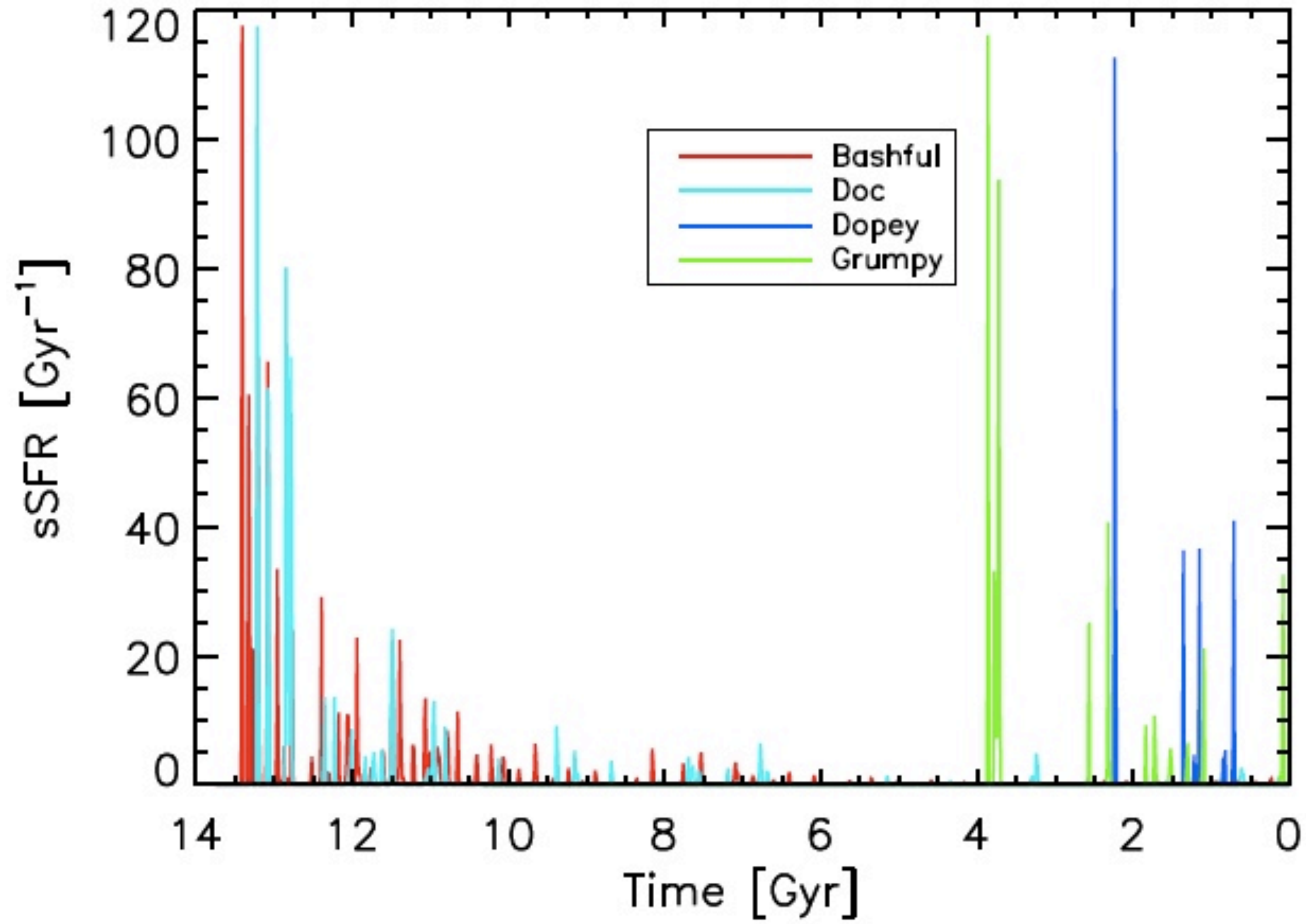




- Due to the UV heating, gas in Dopey and Grumpy cannot condense. Typical gas density n~ 0.001-0.01 cm^{-3} for majority of time (z > 0.5).
- The two faint dwarf galaxies are "lit up" from interactions, in which rapid gas inflow allow gas density at the central region to be above than the threshold.
- The young stellar disk is very compact ($r_{1/2}$ = 80-90 pc), blue (B-V = 0.2 for Dopey and 0.0 for Grumpy)
- Similar to extremely metal-poor blue compact dwarfs (XBCD, e.g., Papaderos+2008), although Dopey and Grumpy are much fainter in generals

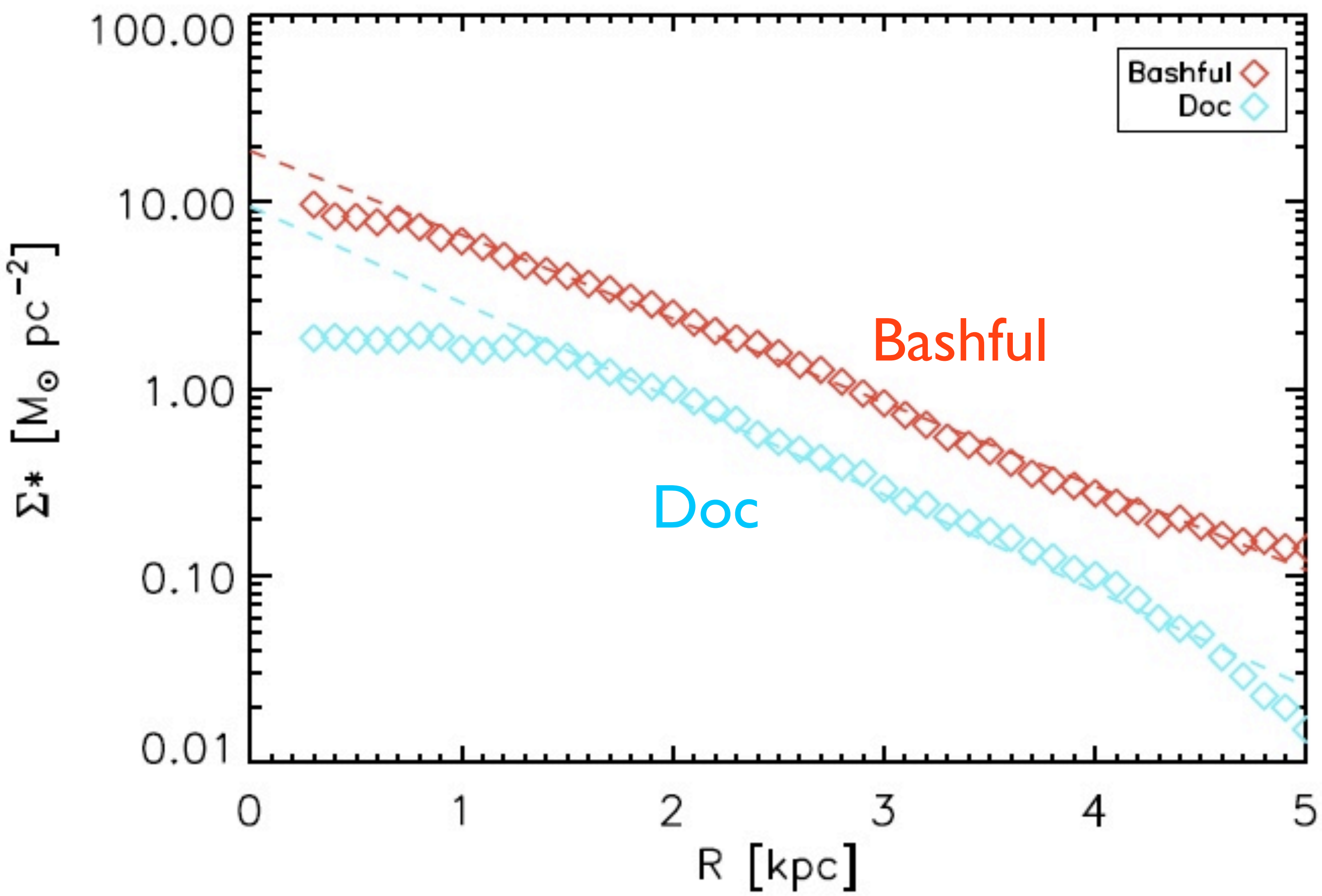
Extremely Bursty SFR

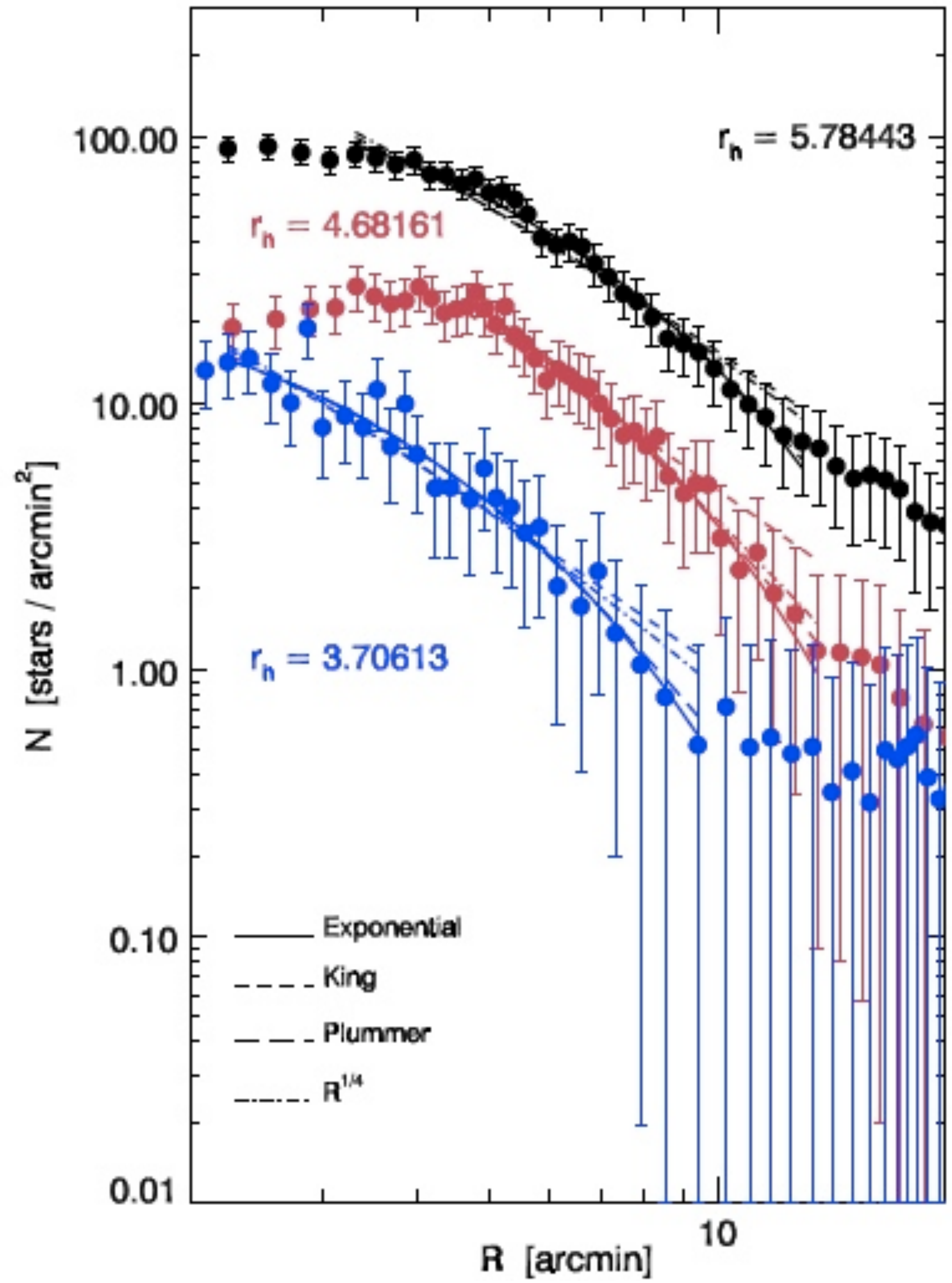
- Resolved stellar population of nearby dwarfs: temporal separation of bursts 10-100 Myr (Tolstoy +2009)
- Discrepancies between FUV and Hα estimated SFR in local dwarfs (Lee+2009), also between FUV and the SED fitting in the AIFALFA dwarf sample (Huang+2012)
- All four dwarfs show peak sSFR = SFR/M* 50-100 Gyr^{-1}, far beyond normal massive galaxies



- Extreme emission-line galaxies in CANDELS: "...*We conclude that these objects are galaxies with ~10^8 Msun in stellar mass", undergoing an enormous starburst phase with M_*/M_{*dot} of only ~15 Myr...*" (van der Wel+ 2011)
- For $M_* = 10^8$ M_{sun}, ~ 85% of total SFR in bursts (Kauffmann 2014)

Stellar Distribution and Cores

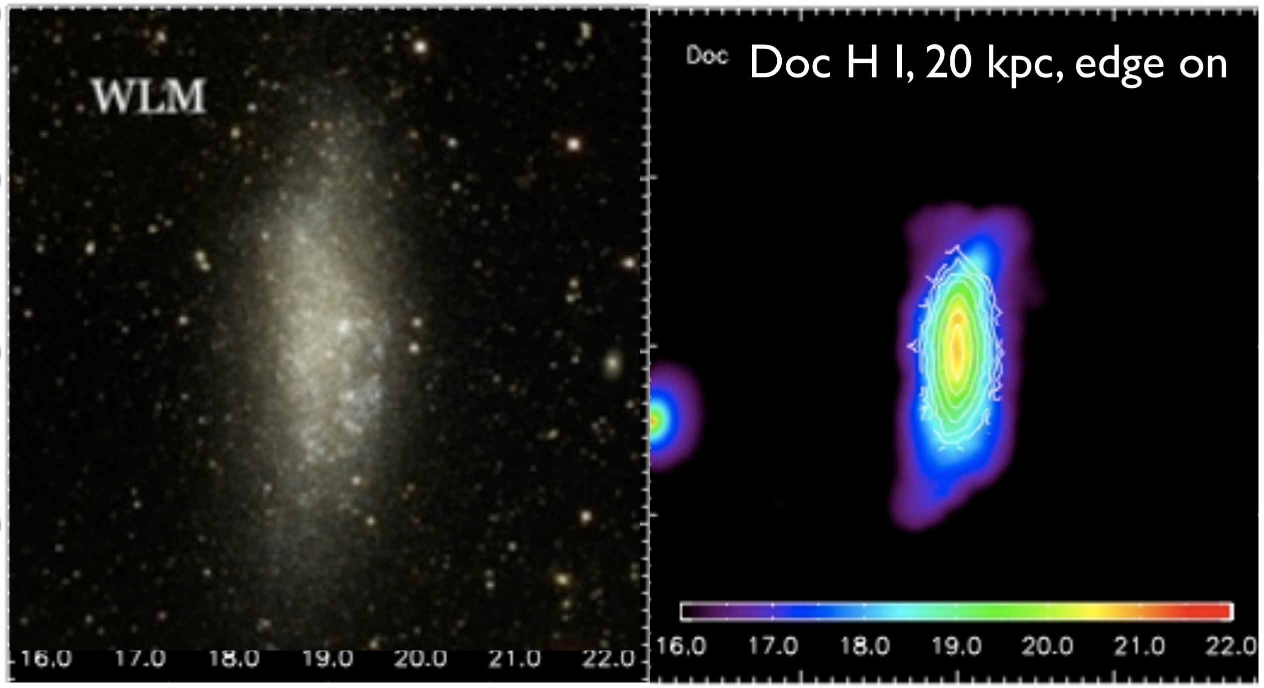




- At z = 0, both Bashful and Doc has an exponential profile with R_d=0.97 and 0.84 kpc, respectively. Both are bulge-less as also seen in Governato et al. (2010)
- Doc appear to have a stellar "core" in the center 1 kpc, probably caused by the same mechanism that generate DM cores

The RGB stars in the isolated dwarf galaxy WLM also shows signature of a stellar core (Leaman+2012) of size ~ 1 kpc. Doc has similar dynamical (~10^{10} M_{sun}) and stellar mass (~10^7 M_{sun})

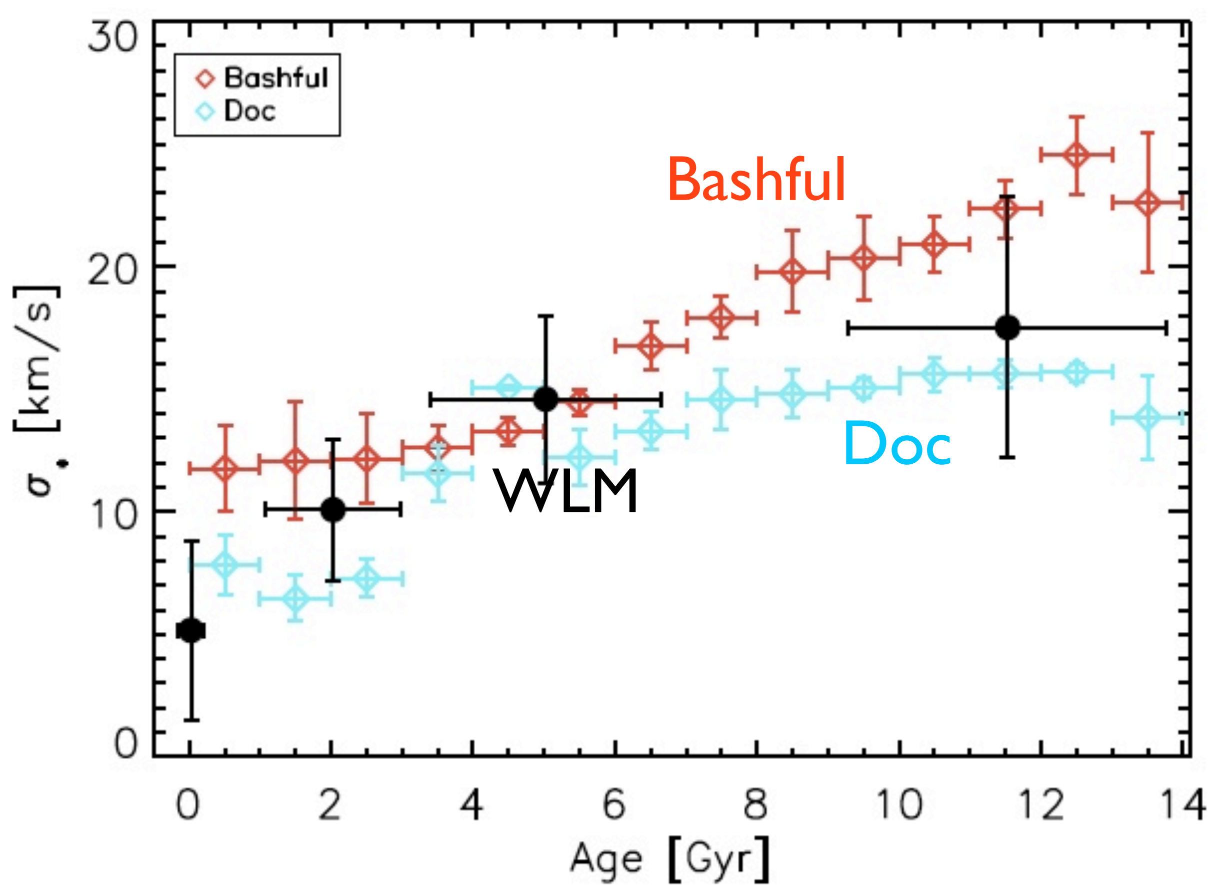
Gaseous and Stellar Disk Morphologies and Kinematics



H I kinematics:

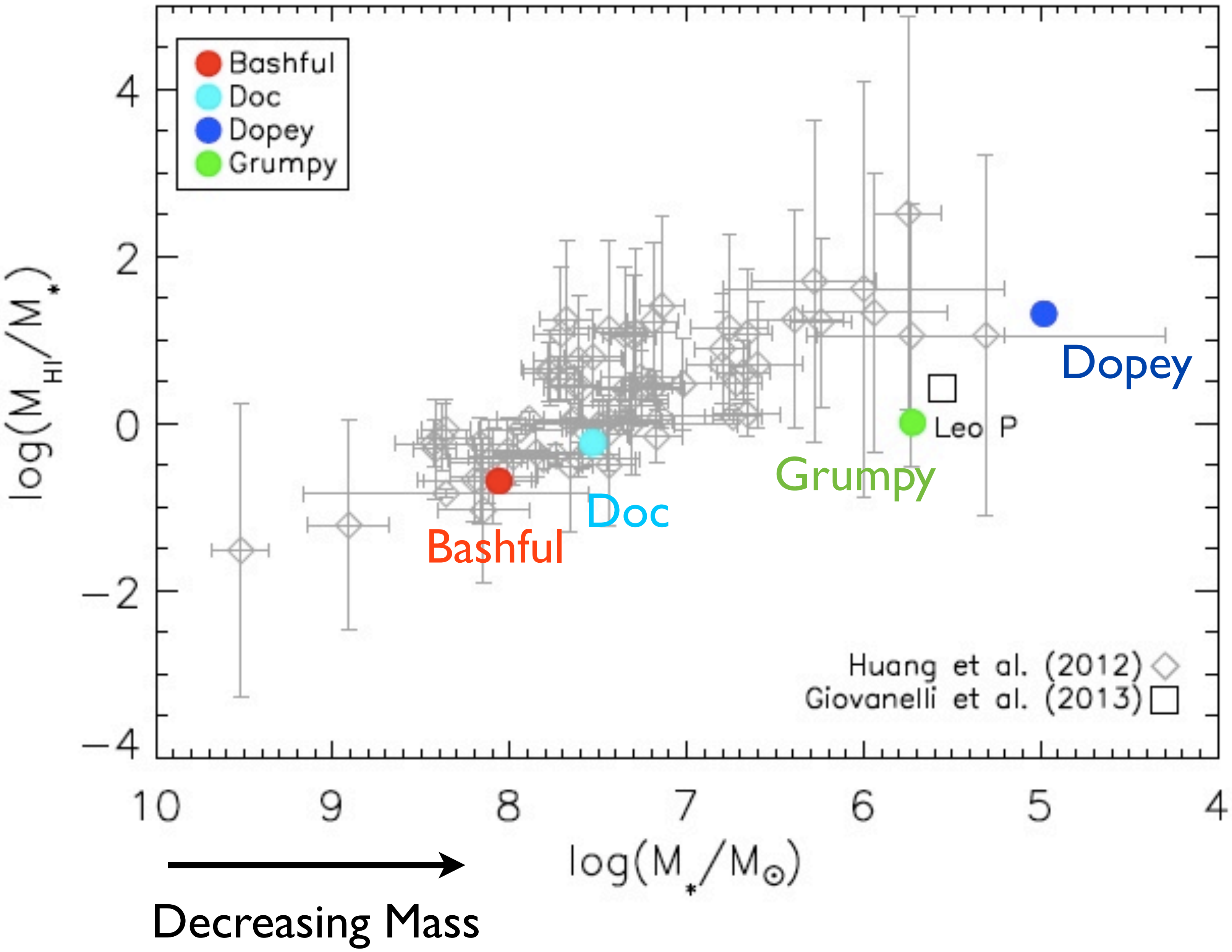
	V_{HI} [km/s]	σ_{HI} [km/s]	V/σ (HI)
Bashful	32.5	8.24	3.9
Doc	15.0	5.6	2.7
Dopey	3.0	1.5	2.0
Grumpy	6.8	11.5	0.6

1 D line-of-sight stellar velocity dispersion as function of stellar age within 2 kpc



- At z =0, both Bashful and Doc's stellar disks have kinematically hot configurations, with low V/σ (~ 1 or a few). Large galaxies are generally more rotationally supported (e.g., Mateo+ 1998)
- Strong feedback and outflows prevent the H I disk settle into a thin configuration, star formation occur in a rather "thick" disk with high velocity dispersion. Also seen in idealized dwarf simulation from Teyssier+ (2013)

Cold Gas Content



- Low star formation efficiencies are not always result of gas ejection. In the case of Dopey and Grumpy, the combination of UVB heating and high SF threshold makes SF very inefficient

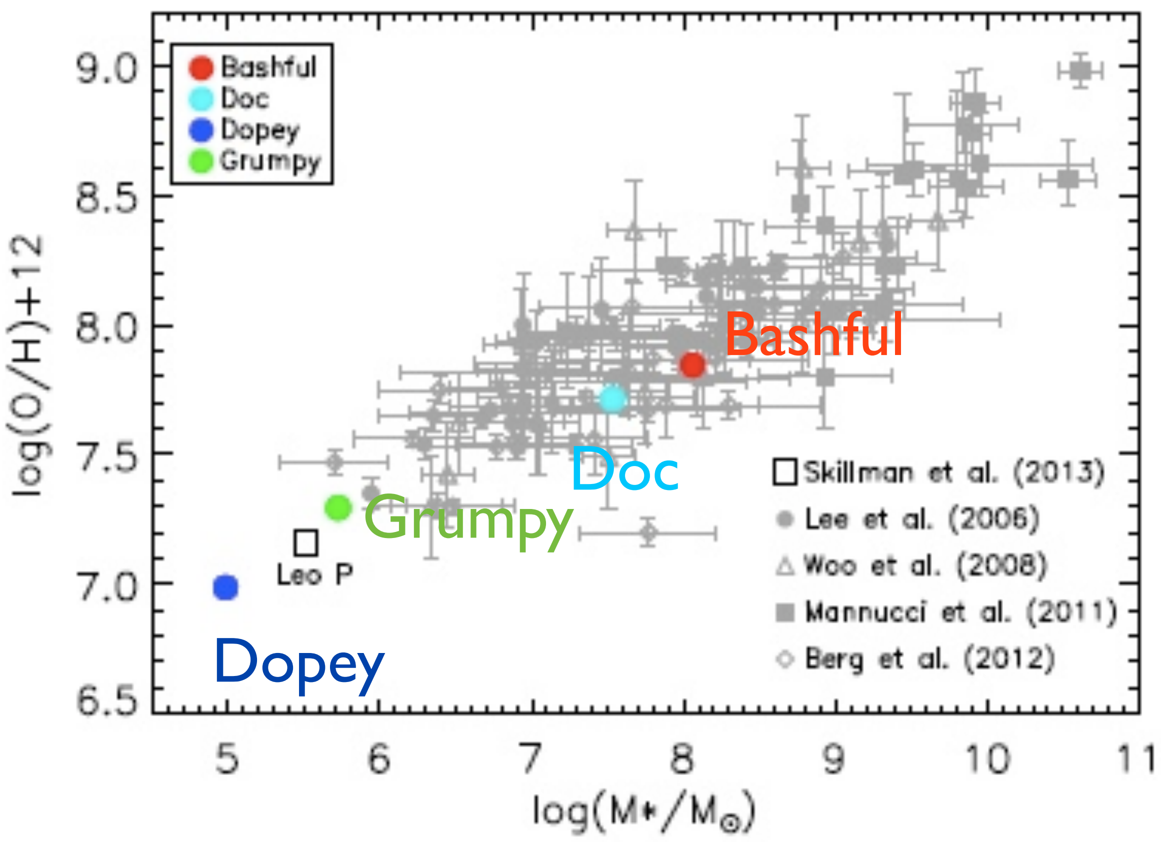
- Data: 74 low-mass galaxies discovered by ALFALFA H I survey with reliable UV/optical images (Huang et al. 2012). About half are dominated by atomic gas. ($M_{HI}/M_* > 1$)

- In Simulation, the baryon fractions all the luminous dwarfs are similar, from 1.5-2.6%. But the gas to stars ratio increase for smaller system.

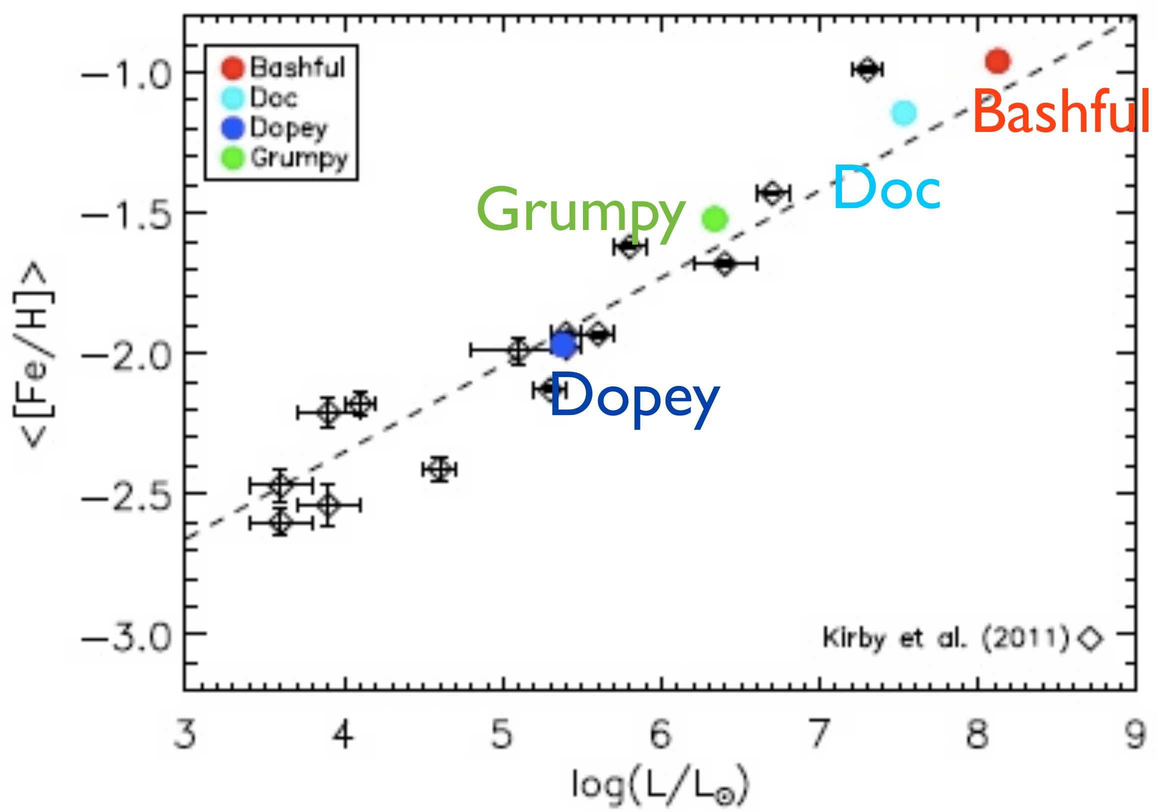
- Dopey has 20 times more H I than stars (!) Grumpy has $M_{HI}/M_* \sim 1$, close to that of Leo P (Giovanelli+2013)

Gas and Stellar Metallicities

Gaseous mass-metallicity relation



Stellar luminosity metallicity relation



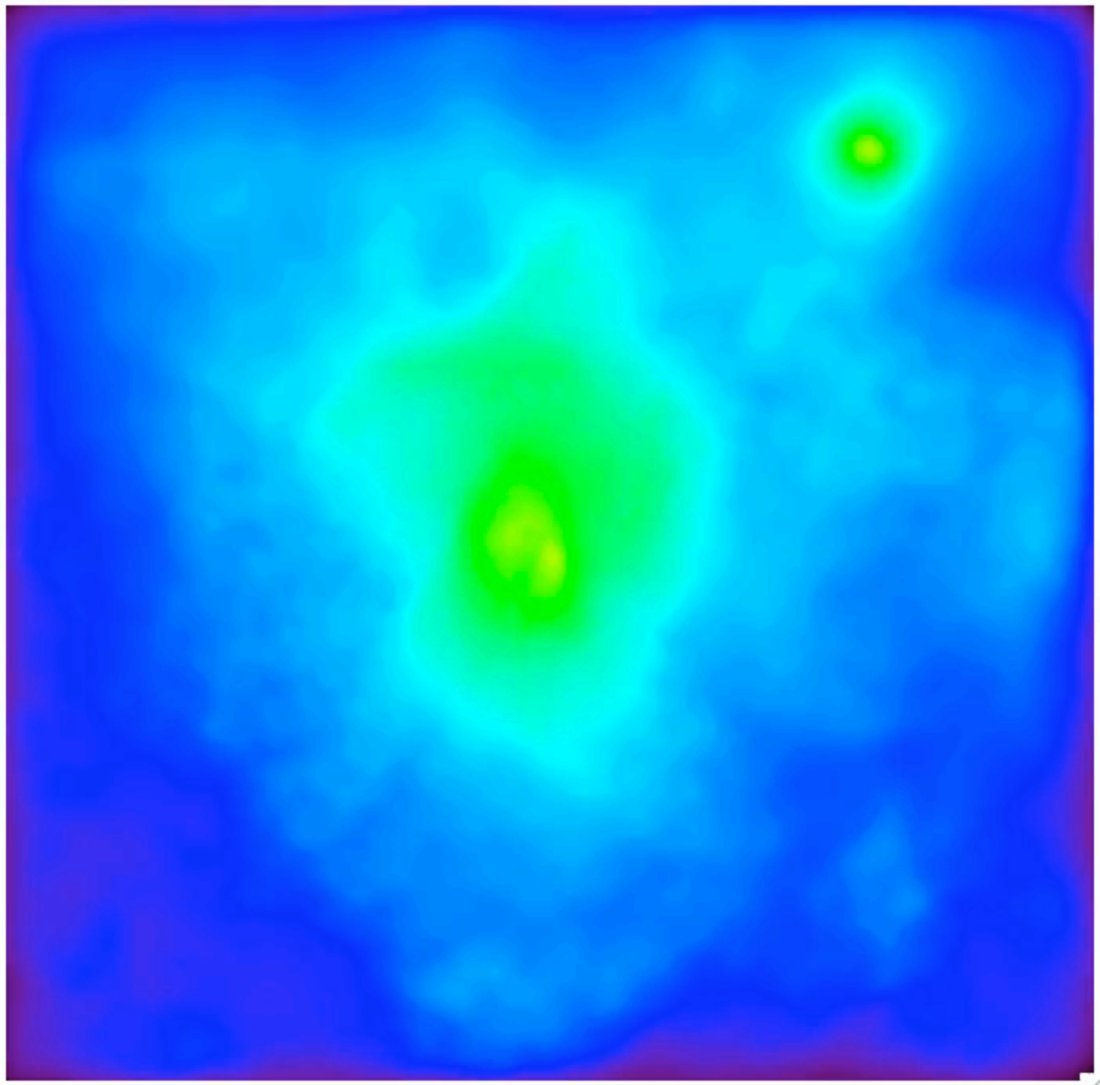
•Gaseous oxygen abundances for the 4 dwarfs lie on the mass-metallicity relationship that spans 5 decades in stellar mass. Dopey and Grumpy have metallicity similar to Leo P (Skillman+2013). These are relatively quiescent extreme metal deficient (XMD) dwarfs classified in Skillman+(2013)

• Fraction of metal ejected metals *decreaes(!)* with decreasing stellar mass, 90% Bashful, 89% Doc, 54% Grumpy, 8% Dopey. Small dwarfs have not enough energy to power large scale outflows. *Low metal abundance result from inefficient SF, not outflows*

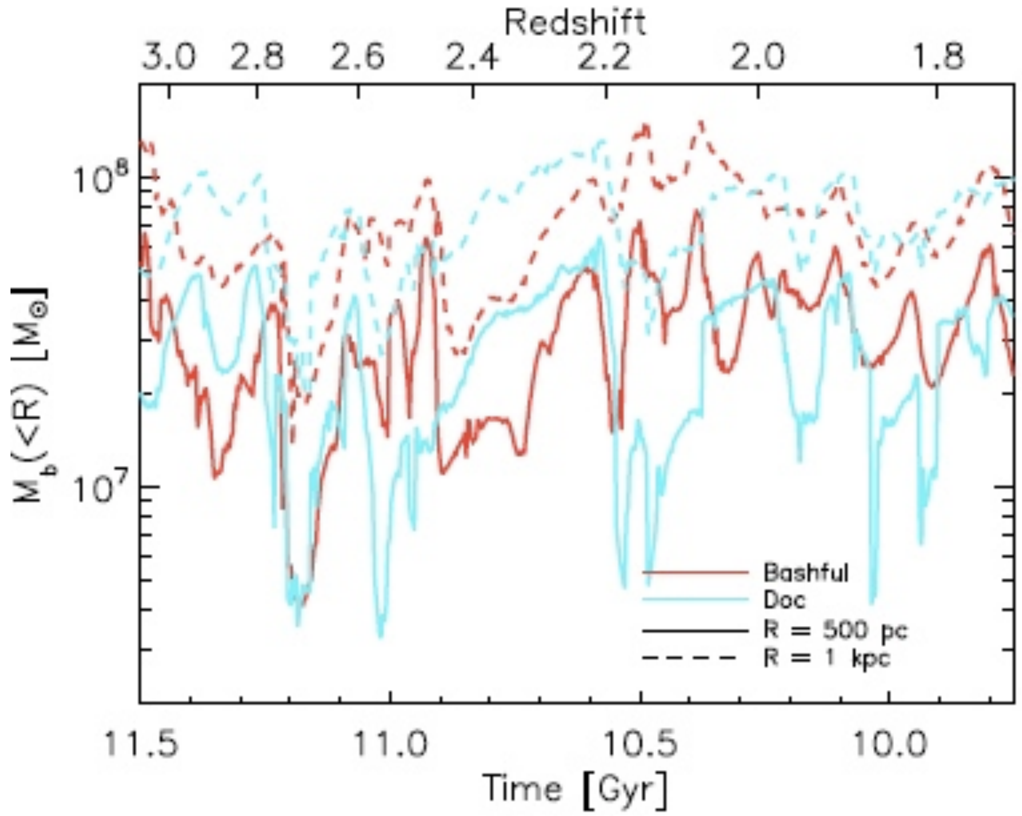
•Stellar metallicity- luminosity relation consistent with the Milky Way's dSphs from Kirby+(2011), suggesting that the stellar metallicity does depend on the environment (see also Kirby+2013)

Gas flows in the central region: cusp-core transformation

Madau, Shen & Governato (2014)



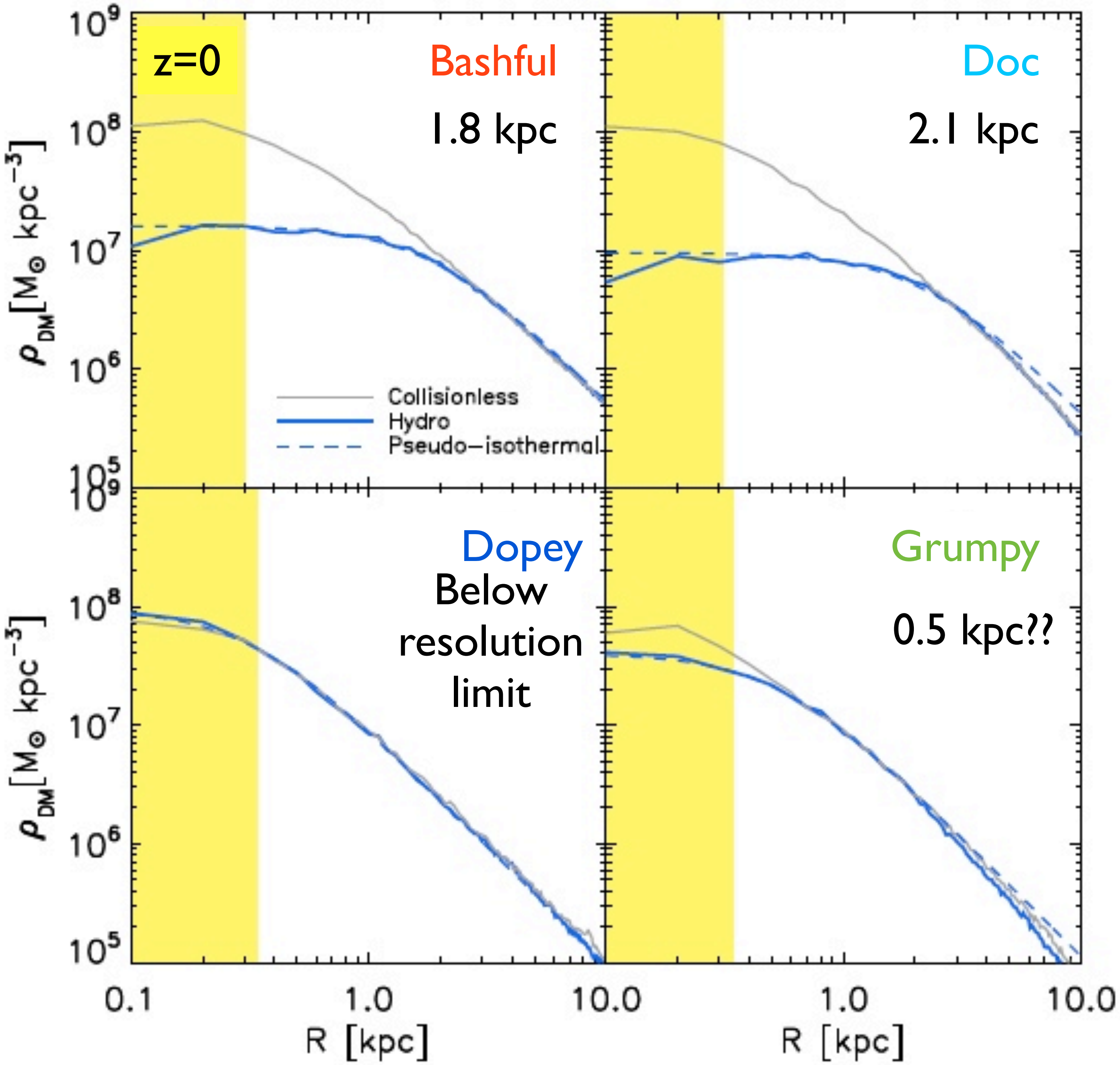
Gas density within 5 kpc of the center of Bashful from z =3.0 to 1.5

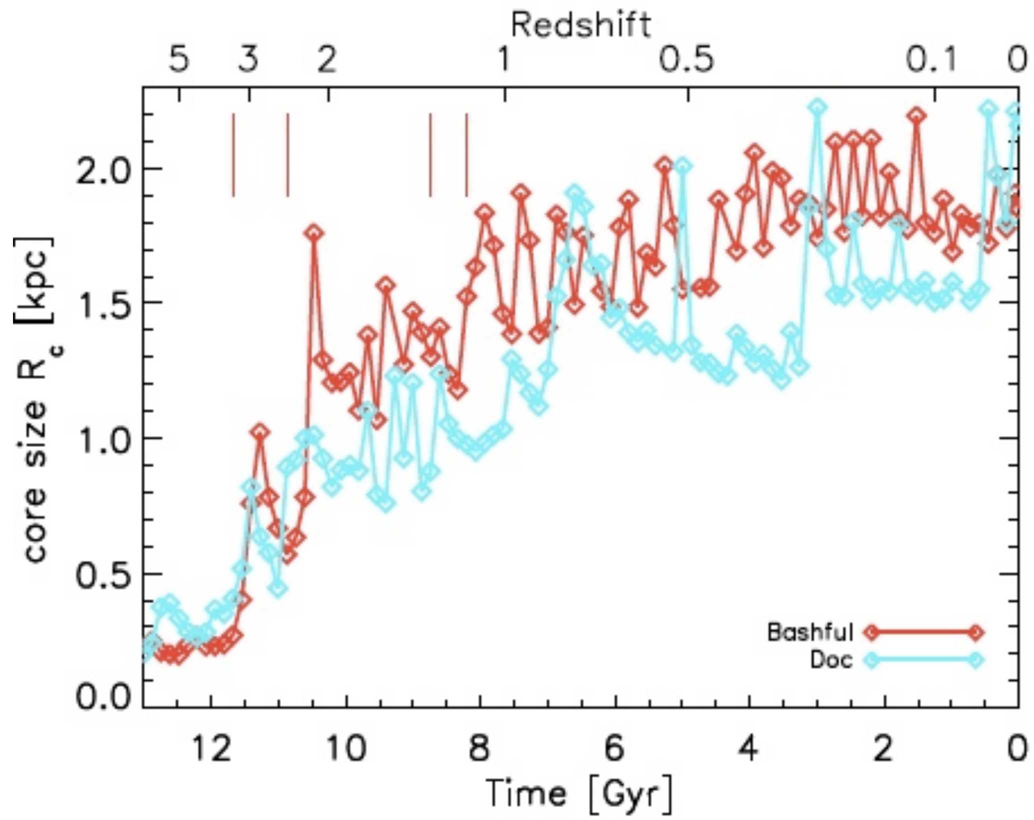


- SF burst followed by rapid decrease in M_b and M_{gas}

- Rapid ($t < t_{dyn}$) change of central potential, transfer energy into DM and generate cores, confirm results from previous studies (Governato+2010, 2012; Pontzen & Governato 2012, Tayssier+ 2013)

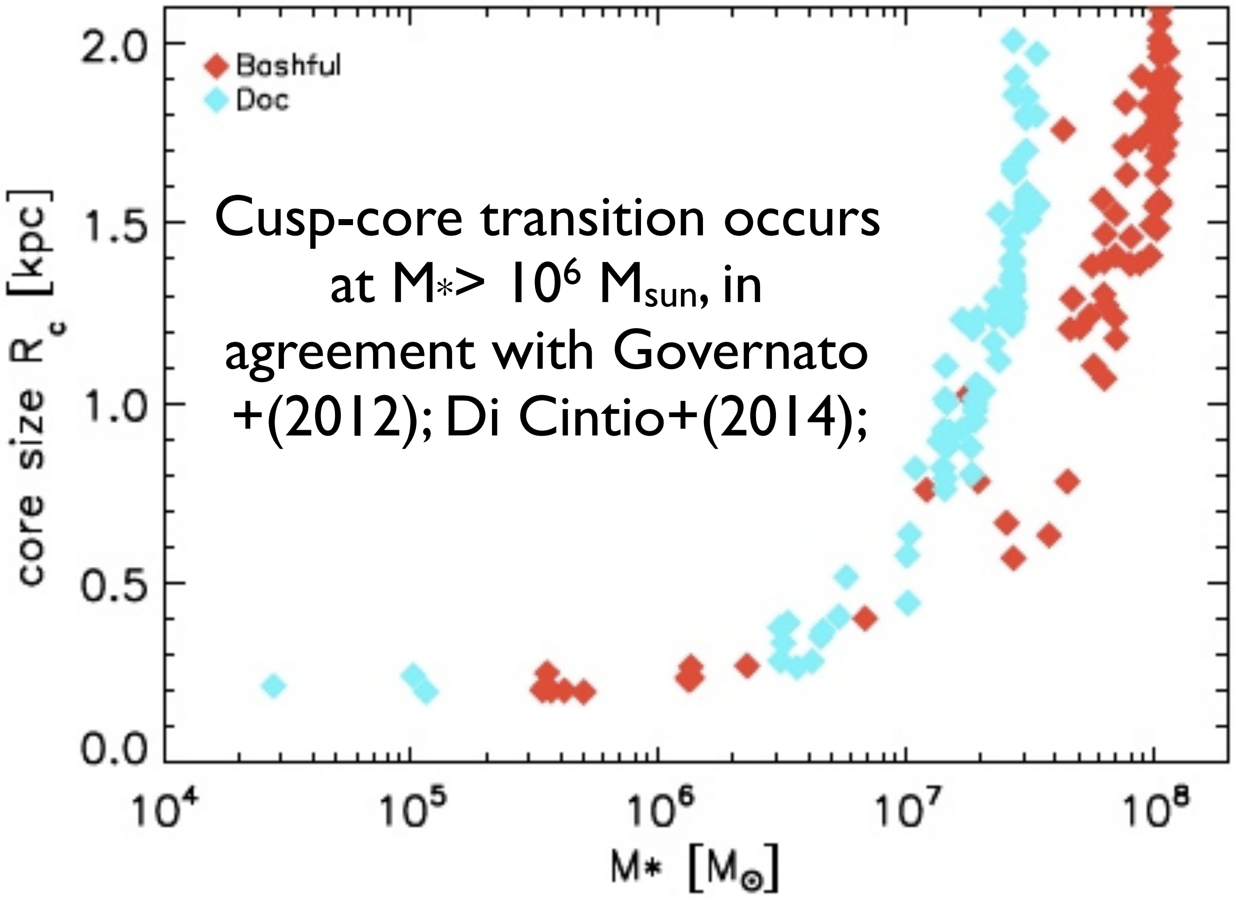
DM Distribution of Four Luminous Dwarf Galaxies

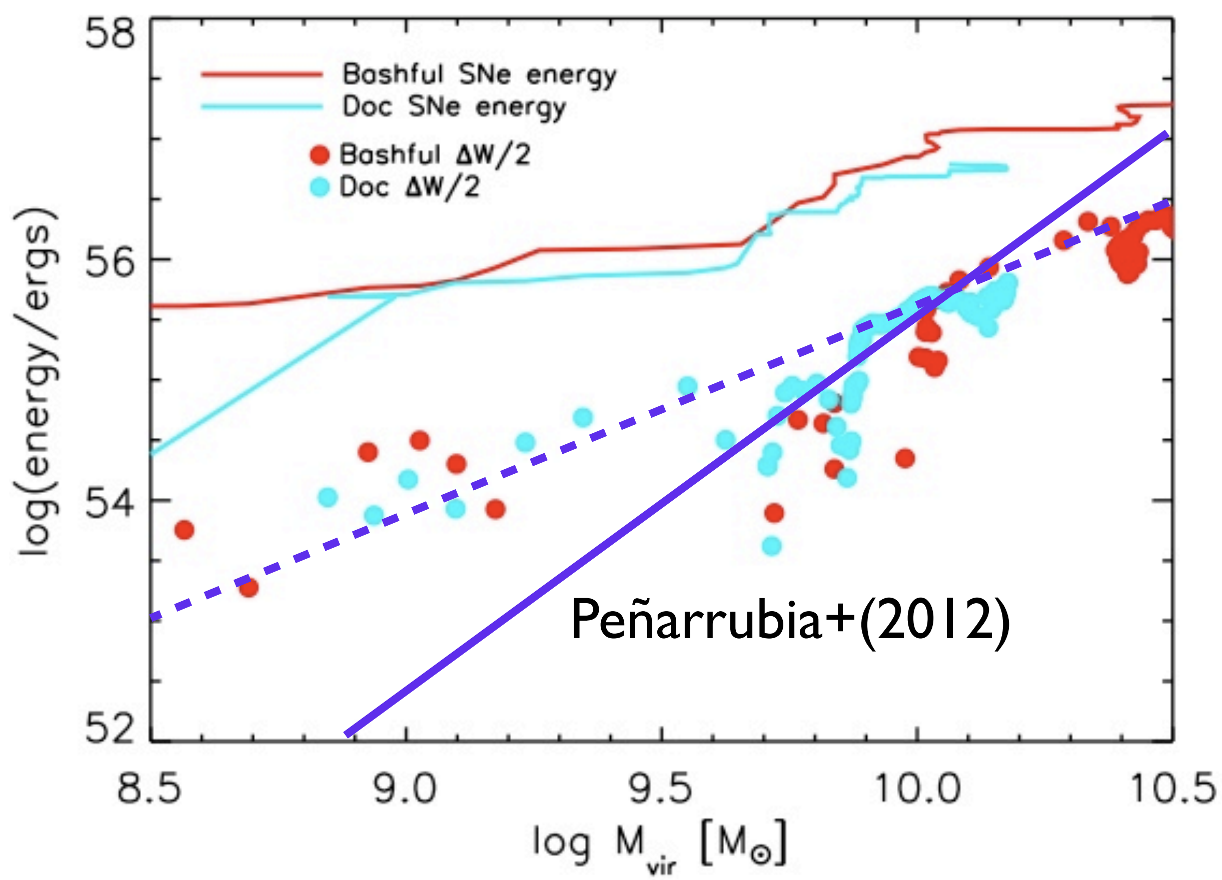




- Cores are already in place at high redshift (z >~ 2) and are resilient to galaxy mergers
- *Early cores can be quite generic in dwarf galaxies because large percentage of SF formed at high z*

Cusp-core Transformation: Is there enough energy?





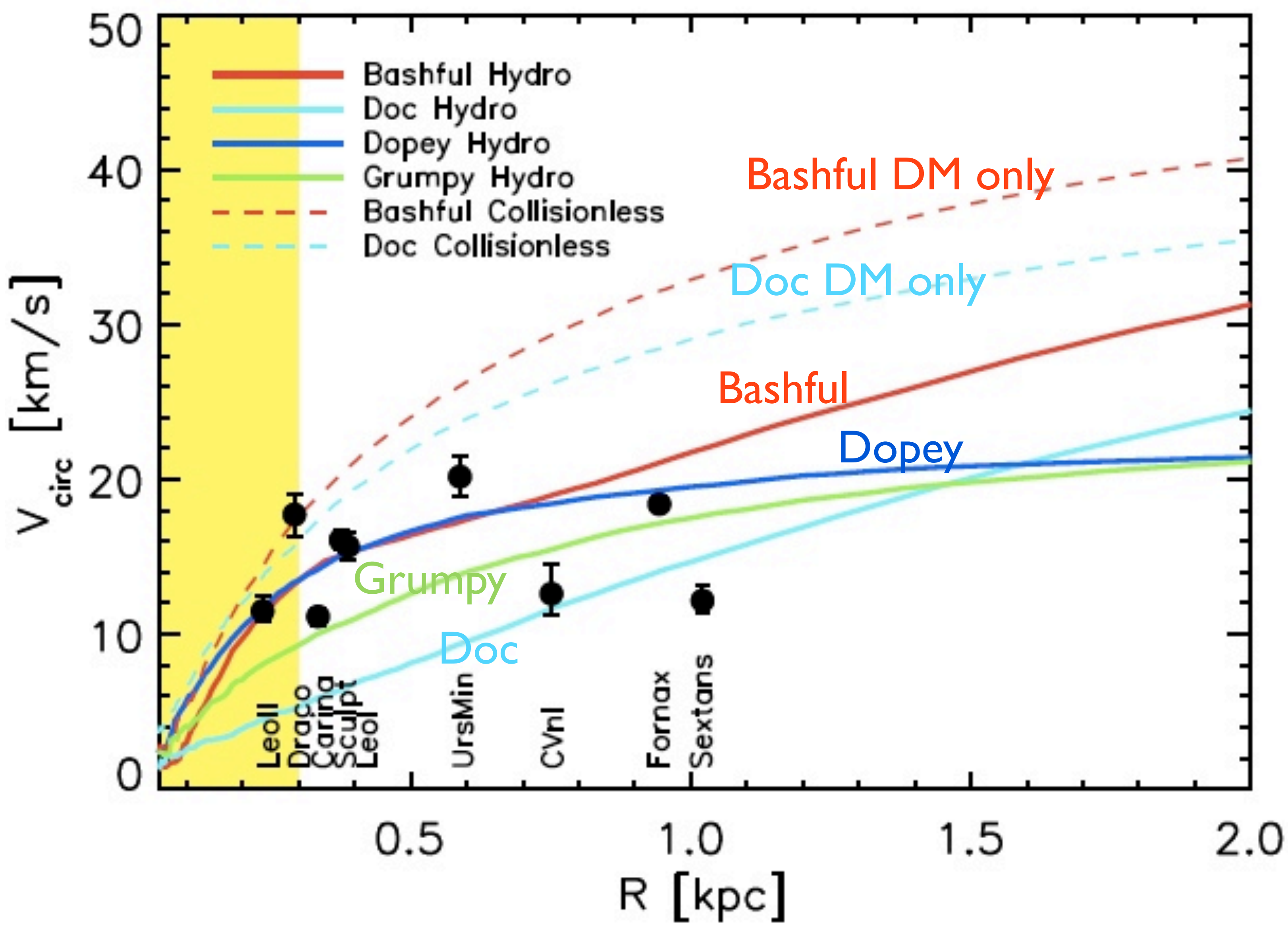
Analytical energy estimation using the Virial Theorem: $E = (W_{core}-W_{cusp})/2$, where

$$W = -4\pi G \int_0^{R_{\rm vir}} \rho_{\rm DM} M(<R) R dR.$$

- For core formation: $E_{SN} > E$
- Peñarrubia+(2012): to generate cores the coupling of SN energy to the ISM needs to be close to unity.

- The simulation appear to have enough energy to generate cores at all time. Only 2% of coupling is sufficient.
- *High SF efficiency at high z is the key*: from SFH observations dwarfs form majority of the stars at z > 1.

The "Too Big to Fail" Problem



The circular velocity at the center does not reflect halo mass: Doc has smaller V_{circ} than Dopey, although being 3 times larger in viral mass.

Also seen in observation: e.g. M(Leo I) > M(Draco), yet Draco's V_{circ} is higher

- The "Too-big-to-fail" problem: most massive halos around MW size halos in DM-only simulation have to high central densities comparing to MW's satellites (Boylan-Kolchin+2011)
- With core formation, the rotation curve is slow rising. Although V_{max} = 51 km/s for Bashful and 38 km/s for Doc, neither exceeds 20 km/s at the center.

Summary

Checking against observations:

- *Stellar mass-halo mass relation*
- *Star formation history*
- *Bursty SF and high sSFR*
- *Stellar distribution, kinematics V/σ ~1*
- *H I kinematics*
- *Gas and stellar metallicities*
- *H I gas content*
- *CGM enrichment*
- *DM-profile, cusp-core transformation*

Simple adiabatic feedback, together with high SF threshold and UV heating, does remarkably well in matching observations.

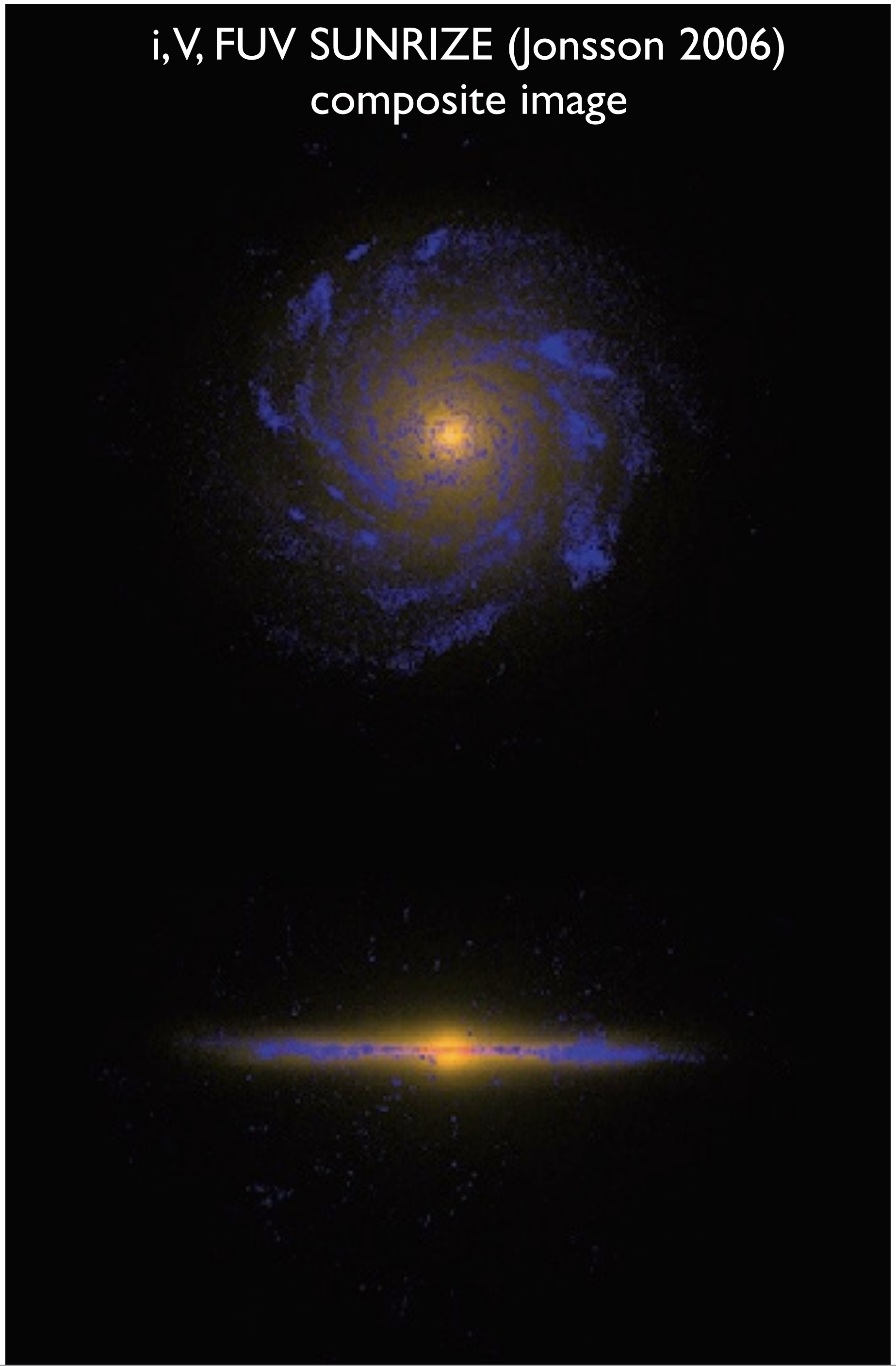
- Baryonic processes are crucial in dwarf galaxies formation. The properties of the galaxies are strong function of the potential.
- The dwarfs are very inefficient forming stars, but this is not simply result of ejecting the gas. Combination of UVB heating and high SF threshold can results in gas rich, faint dwarfs.
- Dwarfs are more efficient in forming stars at higher redshift, sSFR can reach 50 - 100 Gyr^{-1} -- extreme emission line star burst dwarfs (van de Wel+ 2011). Profound impact on the energetics of DM core formation, and the TBTF problem.
- Majority (87%) of metals ejected into the IGM. Mass loading is a few tens, much higher than MW-size galaxies, although below certain mass SNe do not have enough power to create winds and DM cores (Dopey)

Part II: Feedback, Outflows and the Circumgalactic Medium

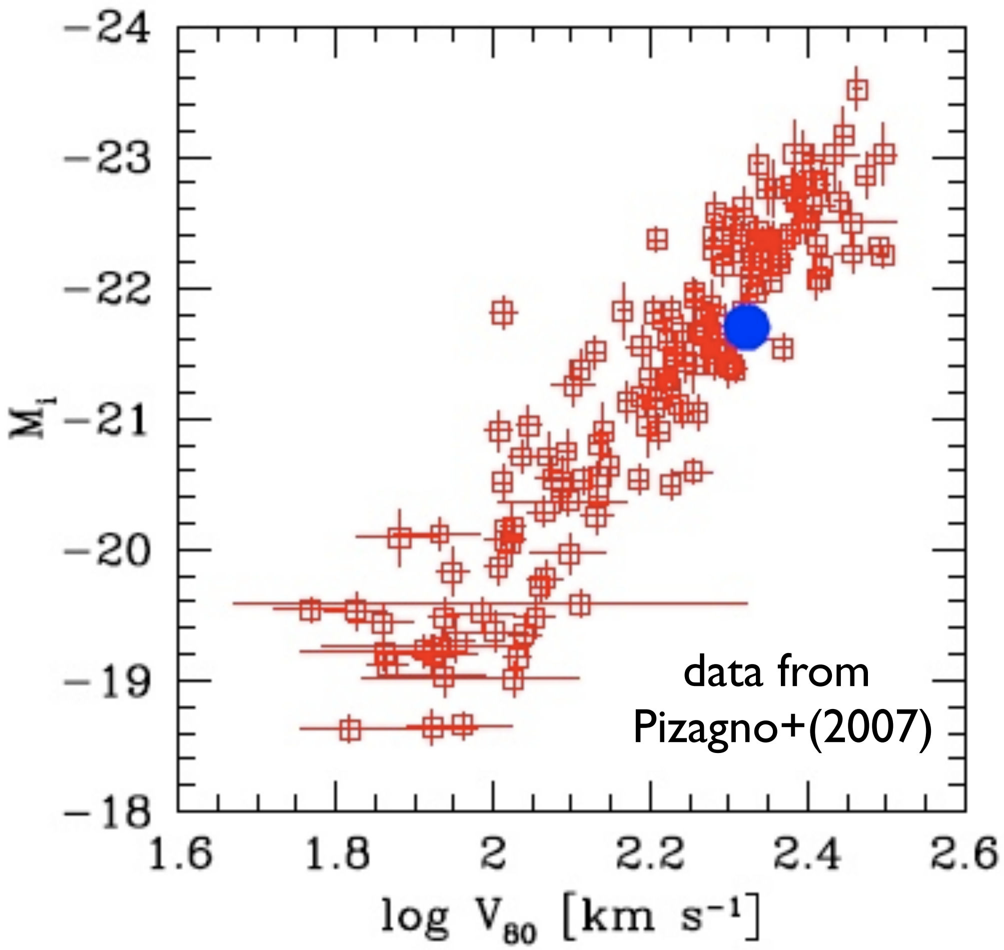
- The circumgalactic medium around 1) massive (few times 10^{11} M_{sun}) star forming galaxies at high z; 2) field dwarf galaxies of mass 10^{10} M_{sun} at $z = 0$;
    - The origins metals and general properties;
    - Column density distribution and kinematics;
    - Equivalent width distribution: confronting to observations (LBGs and DLAs)
    - Gas accretion and Lyman limit system metallicities;

The Eris Suite of Simulations

Guedes et al. (2011);



- Eris has structural properties, mass budget and scaling relations all consistent with observations.

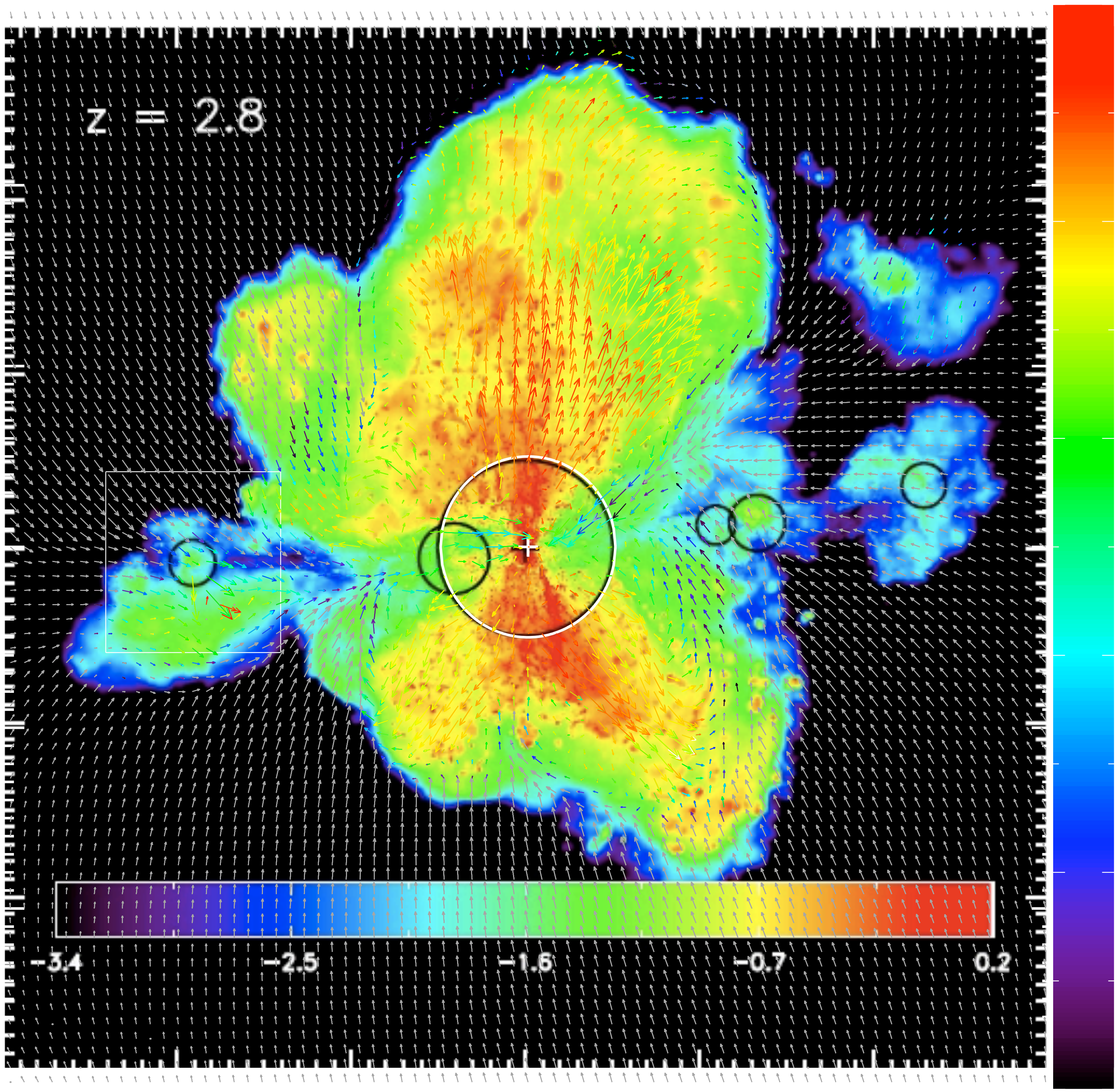


	M_{vir} [$10^{12}M_{sun}$]	V_{sun} [km/s]	M* [$10^{10}M_{sun}$]	f_b	B/D	R_d [kpc]	M_i	SFR [M_{sun} yr^{-1}]
Eris	0.79	206	3.9	0.12	0.35	2.5	-21.7	1.1
MW	1±0.2	221±18	4.9-5.5	?	0.33	2.3±0.6	?	0.68-1.45

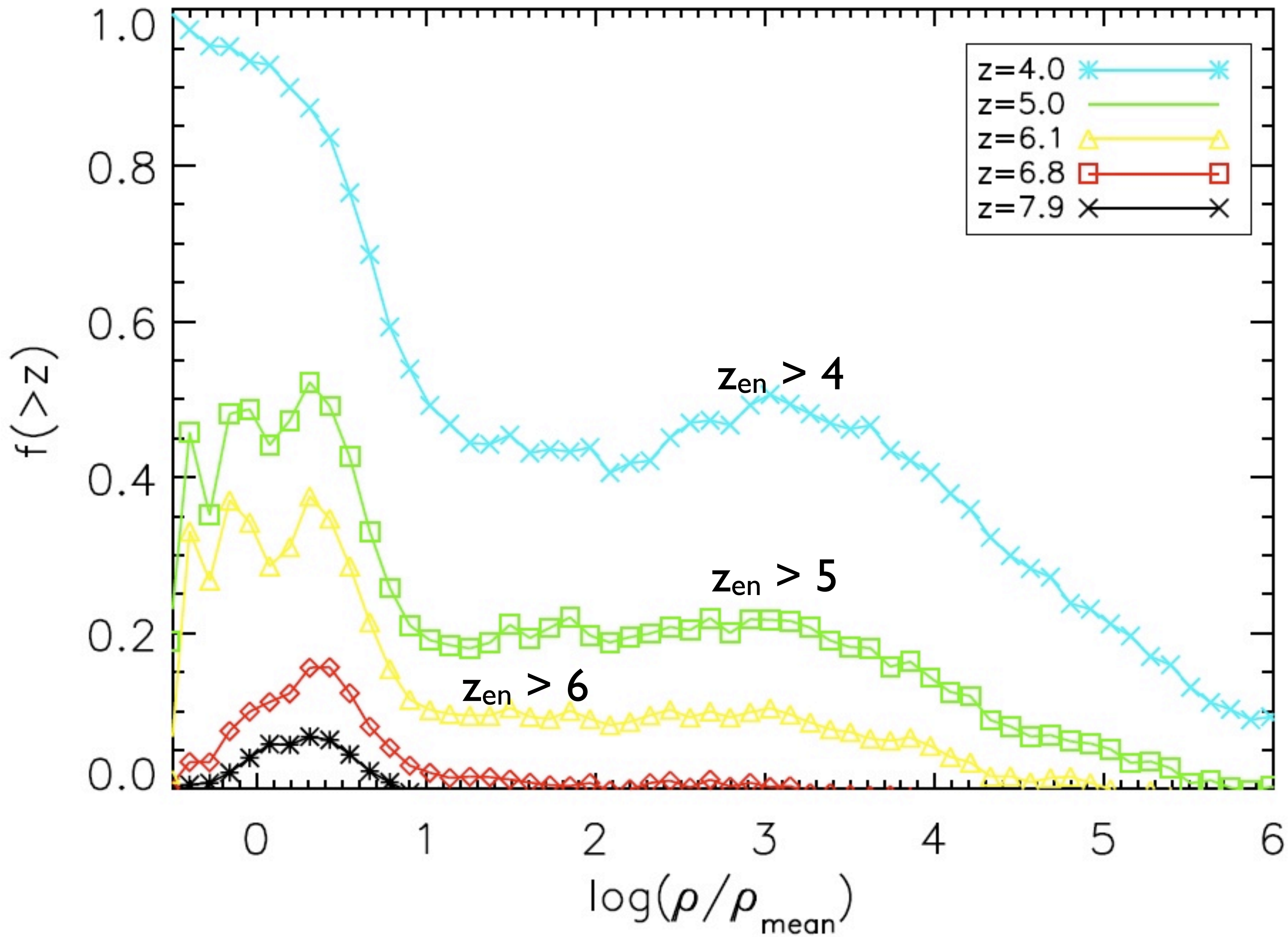
The Circumgalactic Medium of massive SF galaxies at high z

Shen et al. (2012,2013);

- Eris2: improved cooling and chemical mixing from original Eris simulation (Guedes +2011)
- At z=2.8, Eris2 has M_{vir} and M_* close to an LBG but lower than typical observed Lyman Break Galaxies (e.g, Steidel+ 2010)
- More than half of metals locked in the warm-hot (T > 10^5) phase
- Cold, SF gas has 12+log(O/H)=8.5, within the M_*-Z relationship (Erb+2006)
- The metal "bubble" extends up to 200-250 kpc, 4-5 R_{vir}



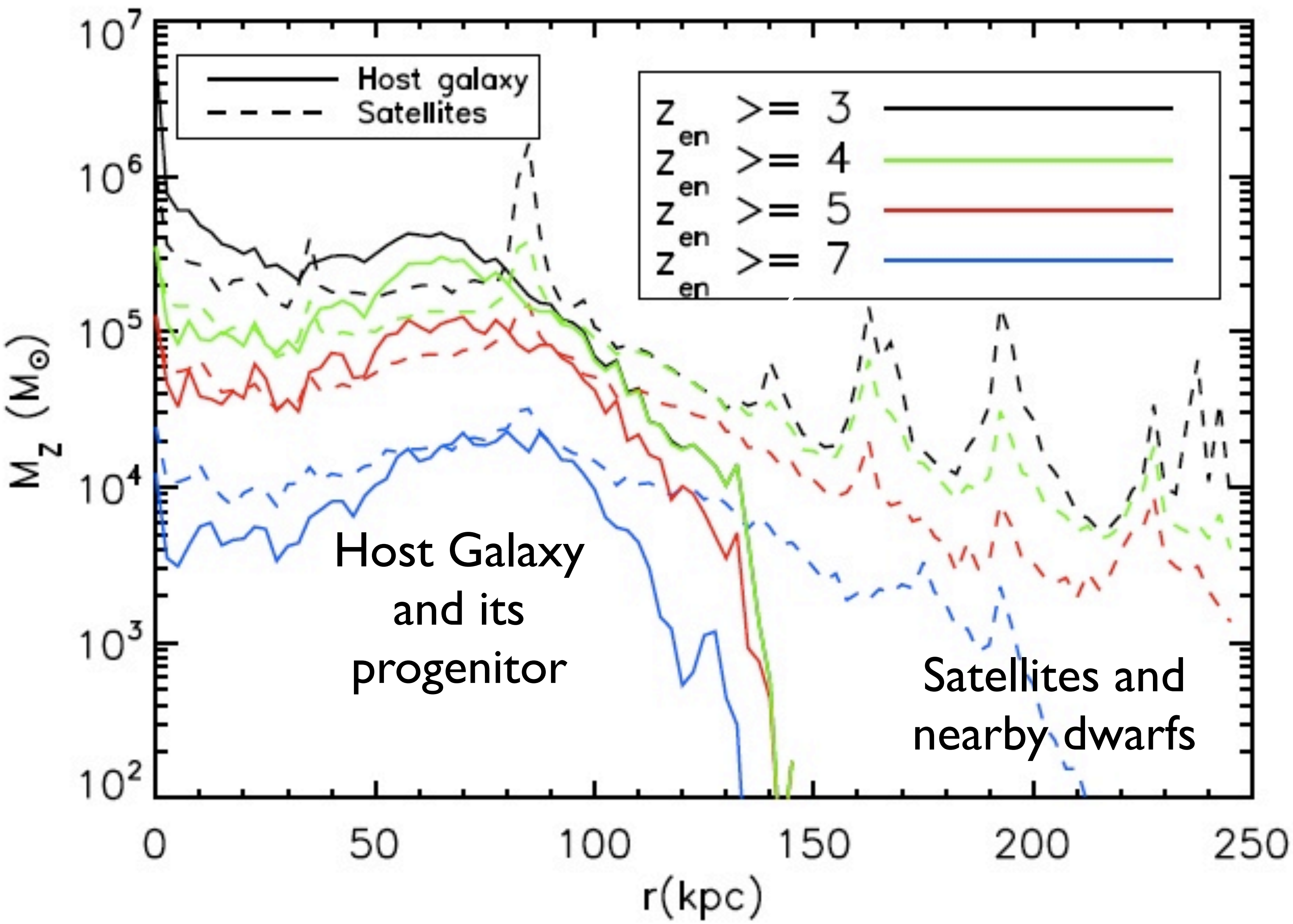
When are the CGM metals produced?



- Metals in lower density region were ejected at higher z. 50 % of metals at δ =1 at z = 3 were produced at z > 5

- Beyond 2 Rvir (100 kpc), only 9% of all the metals are enriched at z < 5, the bulk of metals was released at redshifts 5<z<8 by early star formation and outflows

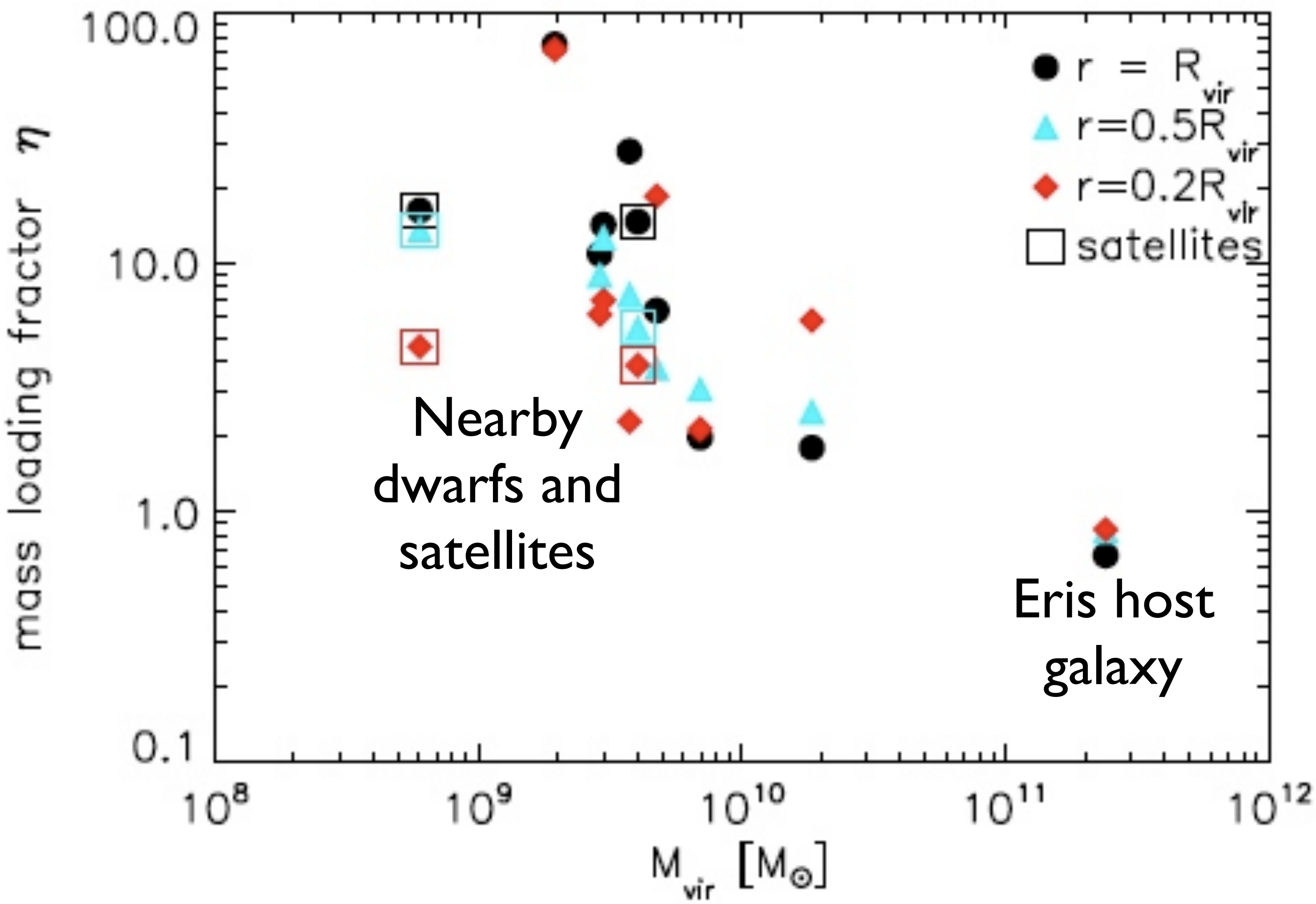
Contribution of Host, Satellites Progenitors and Companions



- Define mean enrichment redshift: $\langle z_{en} \rangle = \sum \Delta m_z^i z_{en}^i / \sum \Delta m_z^i$
- Comparable contributions from host galaxies and substructure, in particular at high z
- Contribution from the host extend to ~ 2 R_{vir} and drops quickly

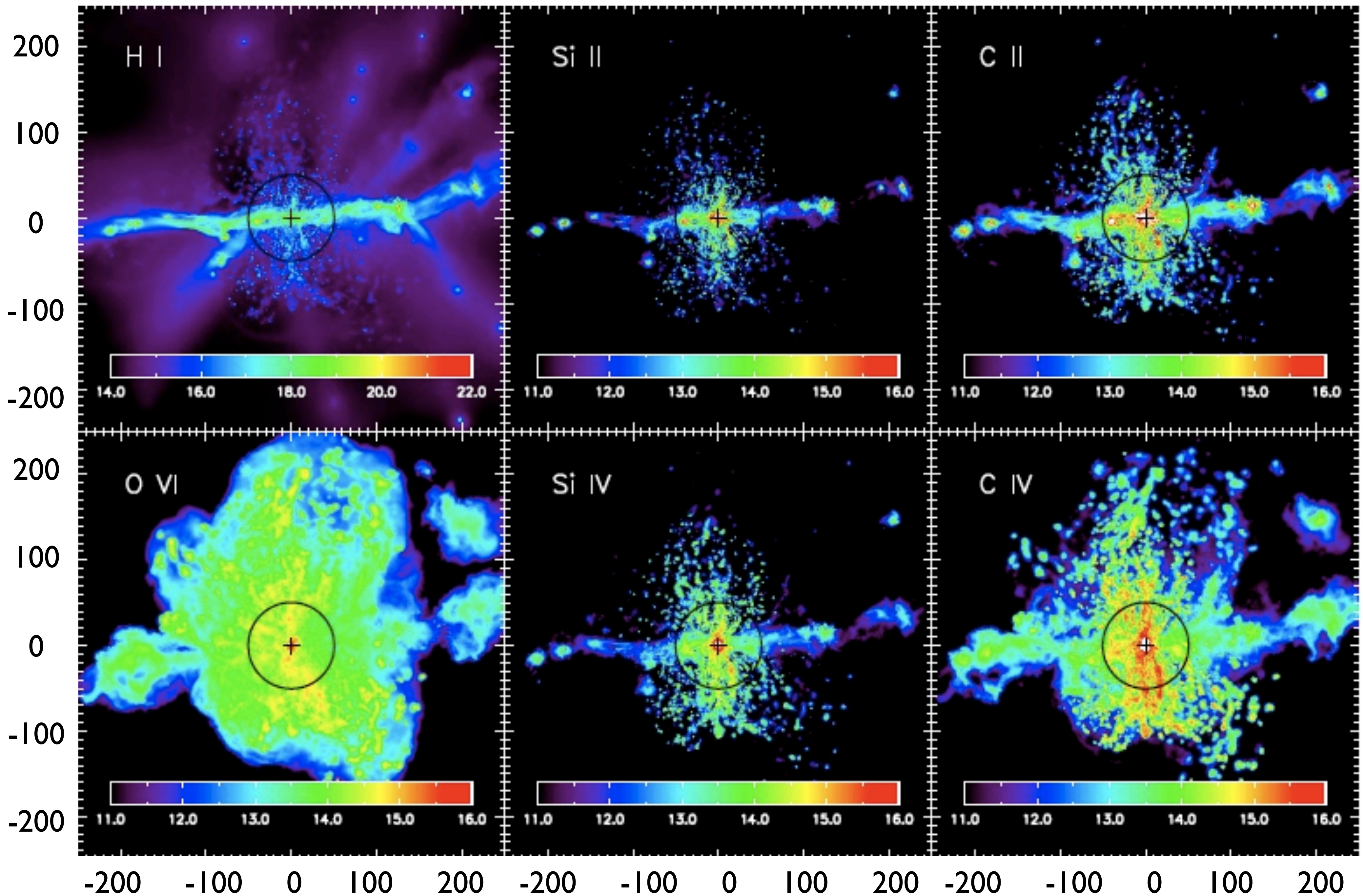
	r ≤ 3 Rvir	r > 3 Rvir
Host	60%	0
Sat. Progenitors	28%	5%
Nearby Dwarfs	12%	95%

The Mass-loading Factor of Eris2 and its Satellites



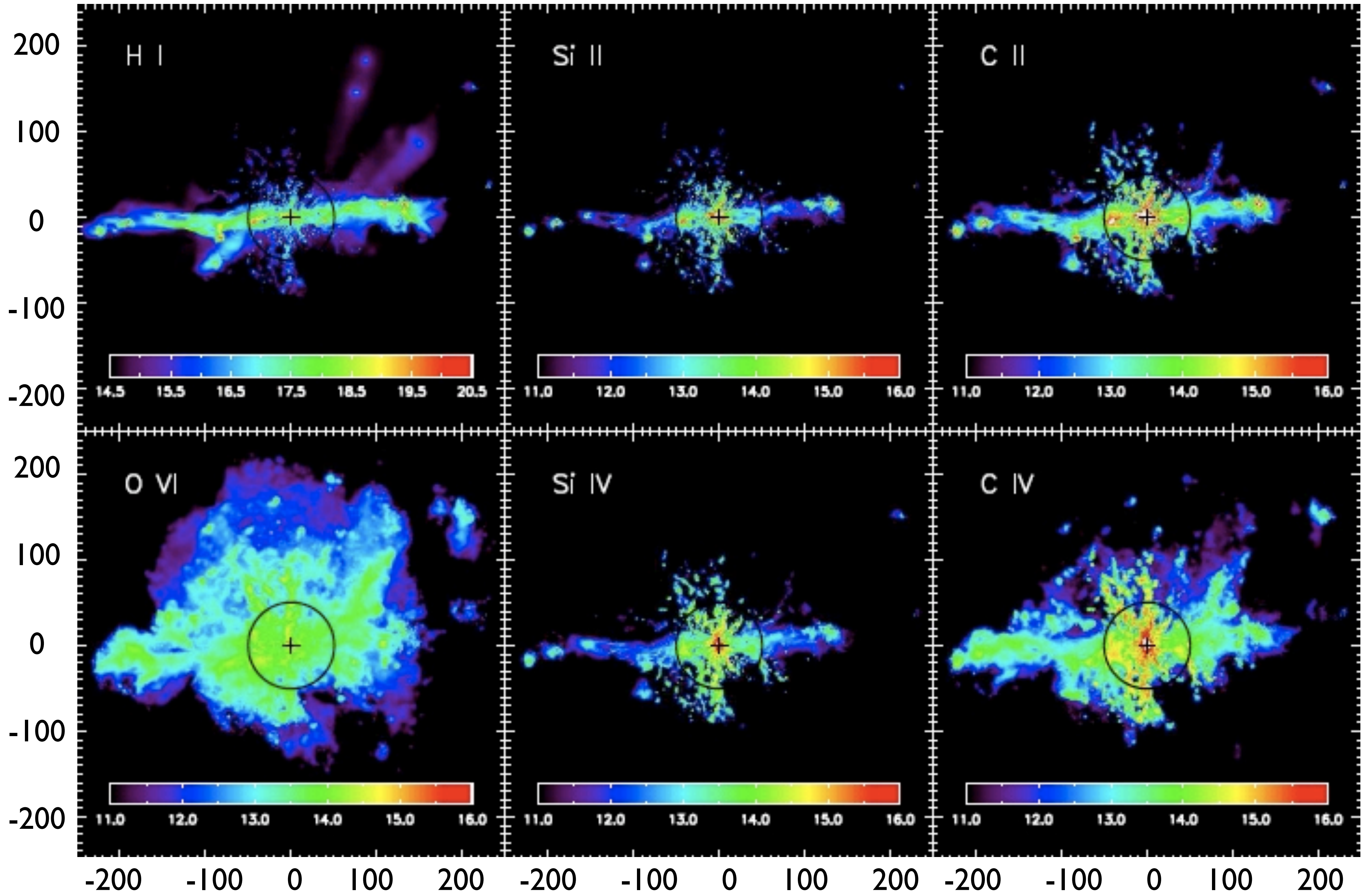
- Mass loading $\eta \equiv (dM_w/dt)/SFR$; dM_w/dt calculated at each distance using mass flux
- η ~ 1 for the main host, similar to other zoom-in simulations of L* galaxies (e.g. Hopkins+ 2014)
- Mass loading factor follows a general trend of increasing mass loading with decreasing halo mass (see also Charlotte Christensen's Talk)

CGM Metals Traced by Different Ions



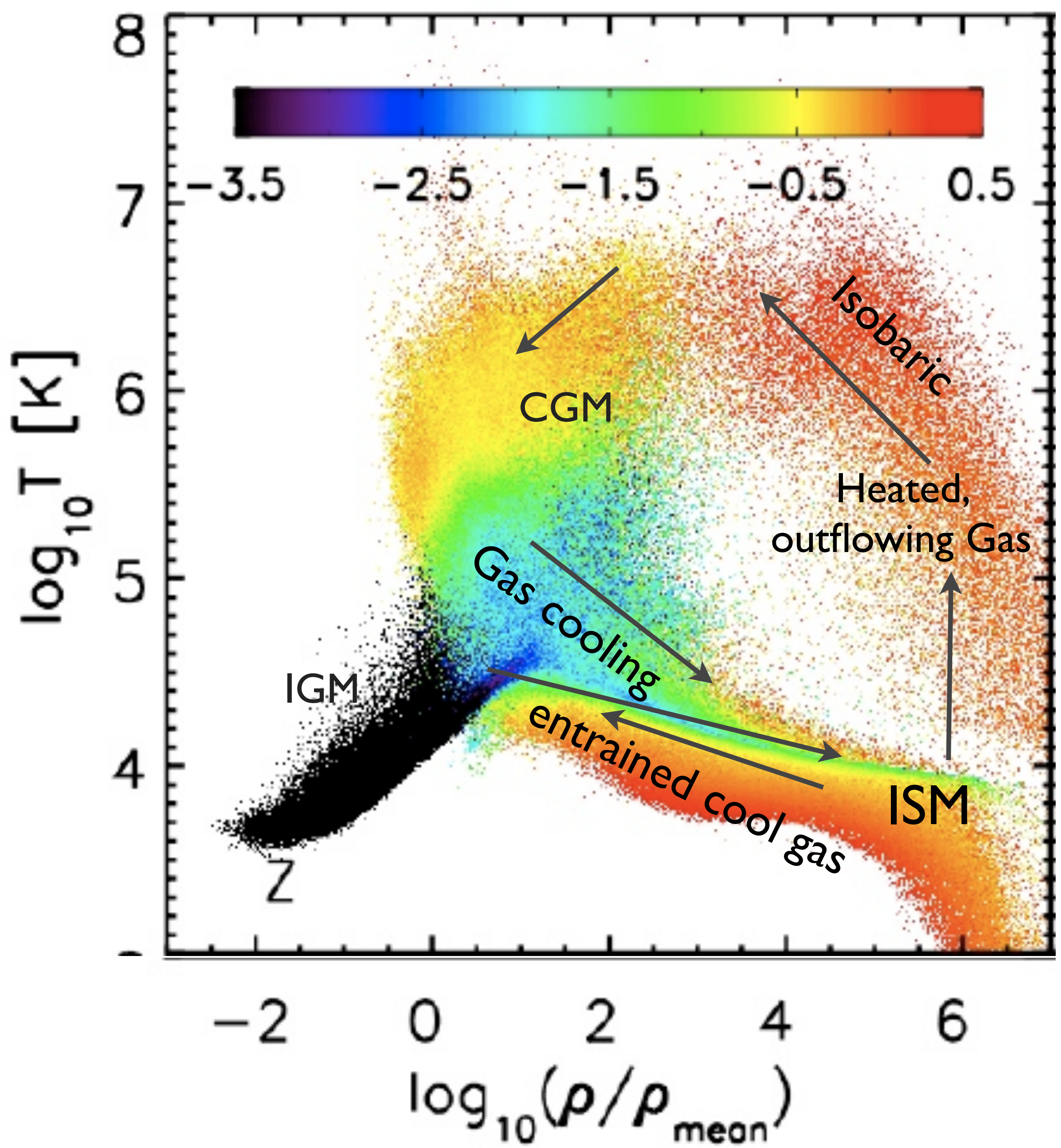
- Covering factors of low ions (C II, Si II) decrease more rapidly (b > R_{vir}) than high ions
- O VI has large covering factor up to 3 R_{vir}, M_O(CGM) ~5x 10^7 M_{sun}> M_O(ISM)

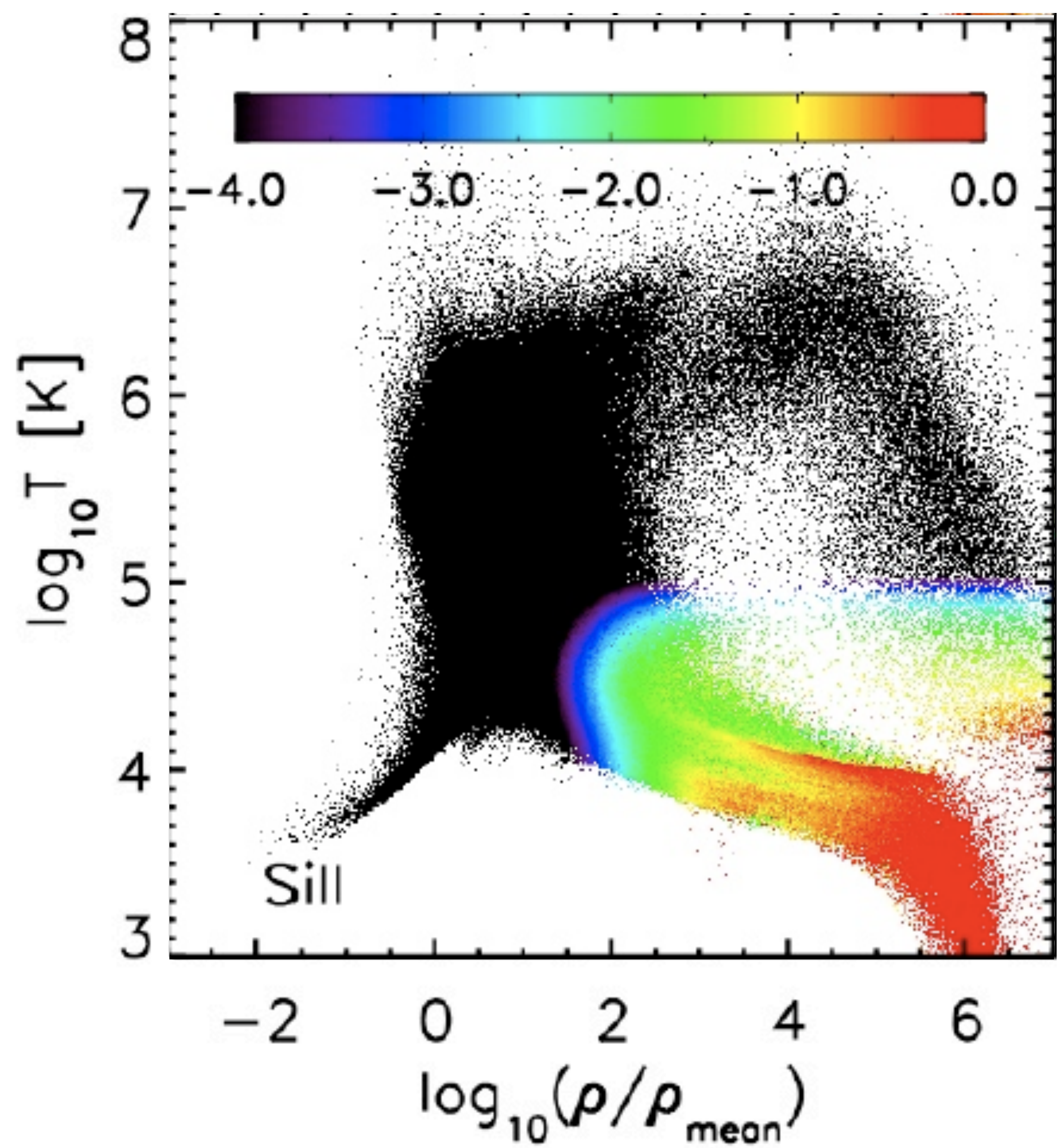
CGM Kinematics



- Inflows and outflows have clearly different orientations at large distances (in this particular projection and time), but more mixed closer to the disk
- Optically thick H I mostly accretion flows with certain enrichment (i.e. not pristine gas). By mass, most low ions track accretion flows, while O VI tracks outflows.

Distribution Ions in ρ-T plane: Cycle of Metals at z =2-3

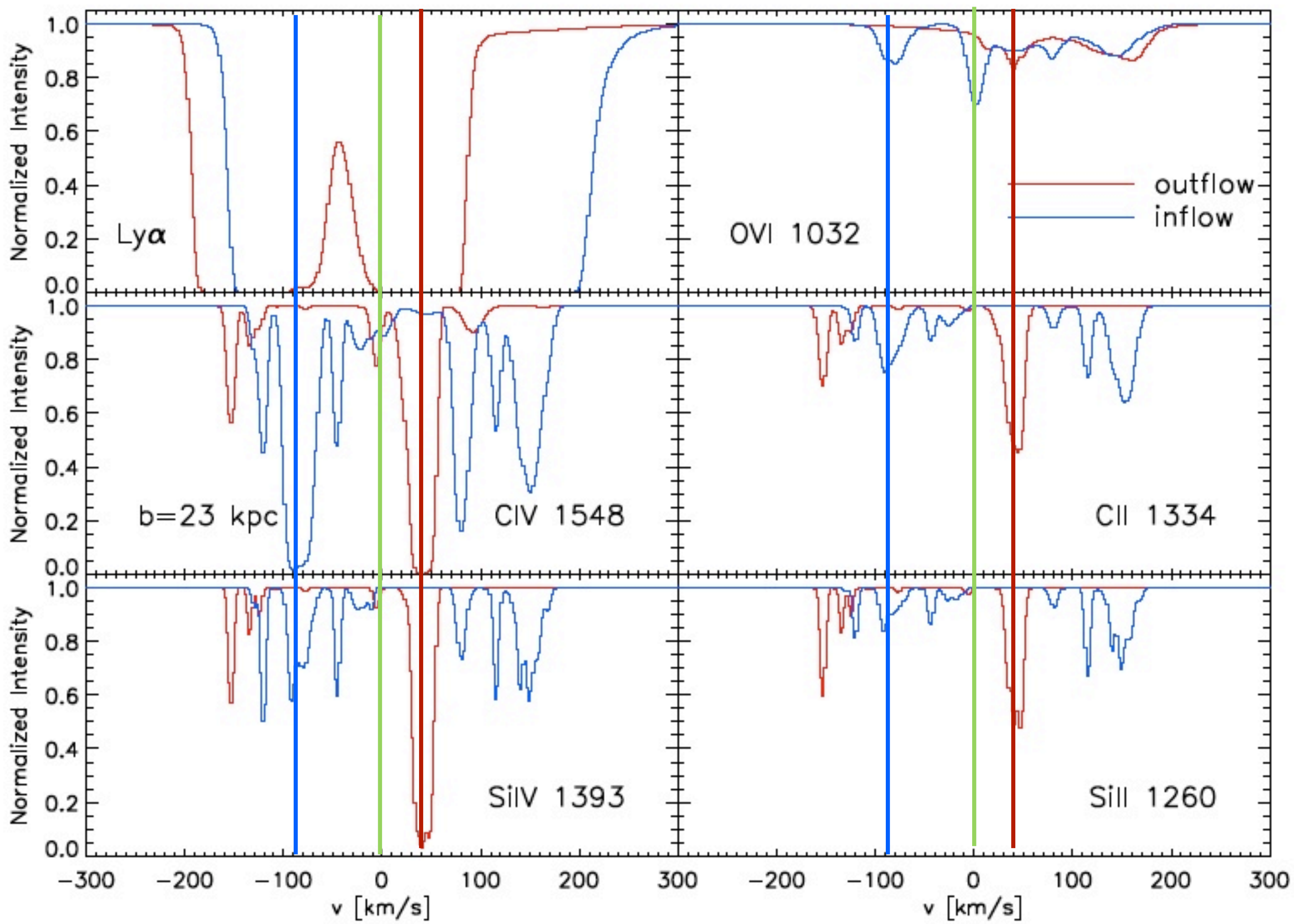




High ions (e.g., O VI): tracking mostly outflows and "ancient" CGM (see also Ford+2013)

Low ions (e.g., Mg II, Si II and C II): outflows, accretion flows (including recycled metals)

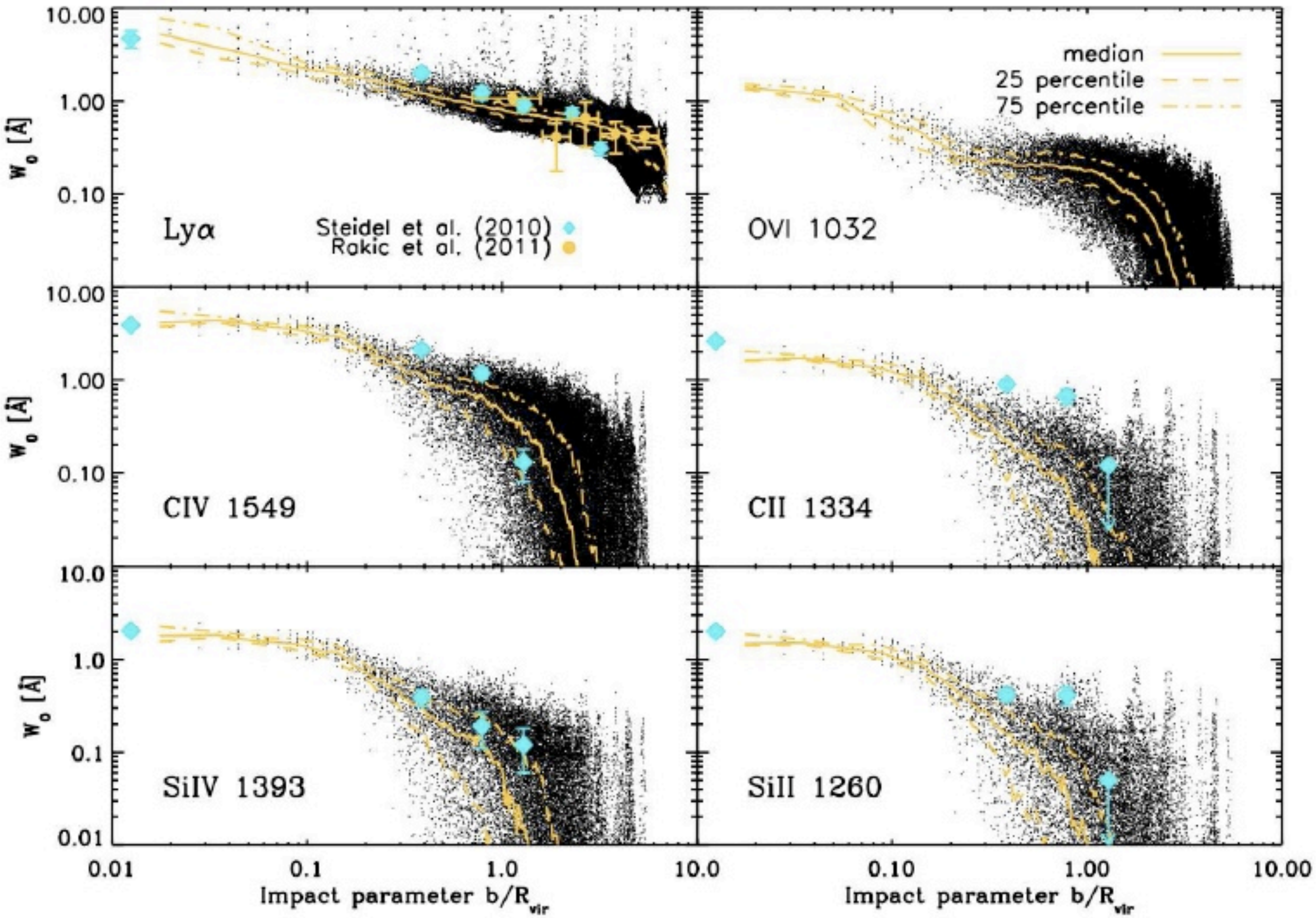
Synthetic Absorption Spectra



- Coexistence of high and low ions -- multi-phase nature of absorbers
- The low ions exhibit narrower lines
- O VI absorbers do not always track the same gas as the lower ionization absorbers -- mostly collisionally ionized

- Optical depth $\tau(\nu) = \sum_j (m_j Z_j/m) W_{2D}(r_{jl}, h_j)\sigma_j(\nu)$; $\sigma_j(\nu)$ - cross section (Voigt function), $W_{2D}(r_{jl}, h_j)$ - 2D SPH kernel
- Rest frame equivalent width: $W_0 = c/\nu_0^2 \int [1-e^{-\tau(\nu)}]d\nu$

W_0-b Relation and Comparison with Observations of LBGs

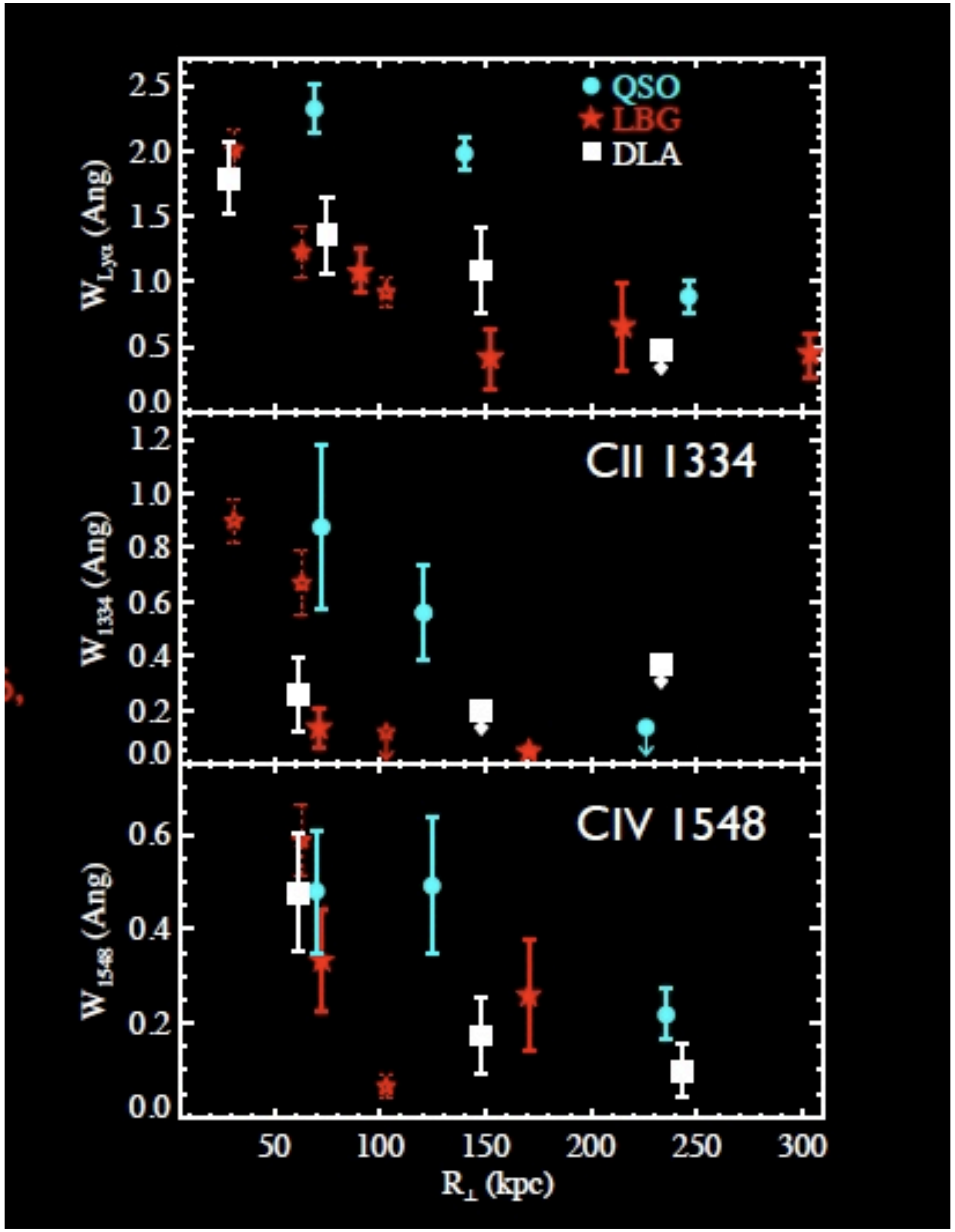


- Line strength declines slower for C IV and OVI compared to C II and Si II
- Ly α: remains strong to >~ 5 R_{vir}
- Broadly consistent with observations from Steidel+ (2010) and Rakic+ (2011)
- W_0 for metal ions: Higher than simulations without strong outflows (e.g., Fumagalli+ 2011; Goerdt+ 2012)
- At small b, lines are mostly saturated -- W_0 determined by velocity

- 3 orthogonal projections, each has 500 x 500 evenly-spaced slightlines within b = 250 kpc region centered at the main host

Comparison with the CGM of DLA Host Galaxies

Rubin et al. , in prep

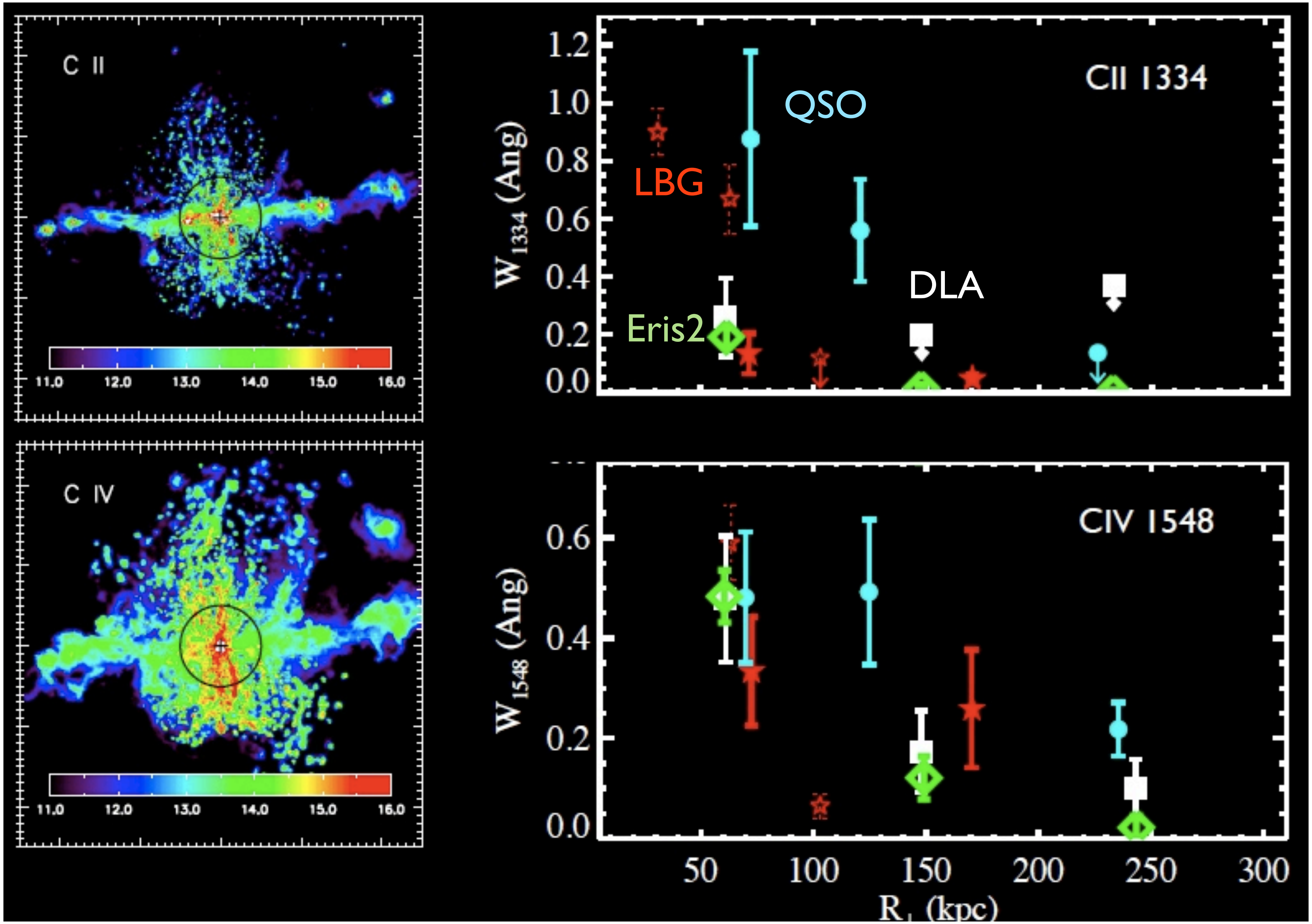


- Damped-Lya Absorbers (DLAs): N $_{HI}$ > $10^{20.3}$ cm^{-2}, mostly neutral gas
- DLA bias suggest they rise in halos with mass up to 10^{12} Msun (Font-Riberta+2012)
- The "average" CGM of DLA galaxies are very similar to LBGs

QSO: Prochaska+ 2013

LBGs: Adelberger+05, Simcoe+06, Steidel+10, Rakic+11, Rudie +12,Crighton+14

And how about Eris2?



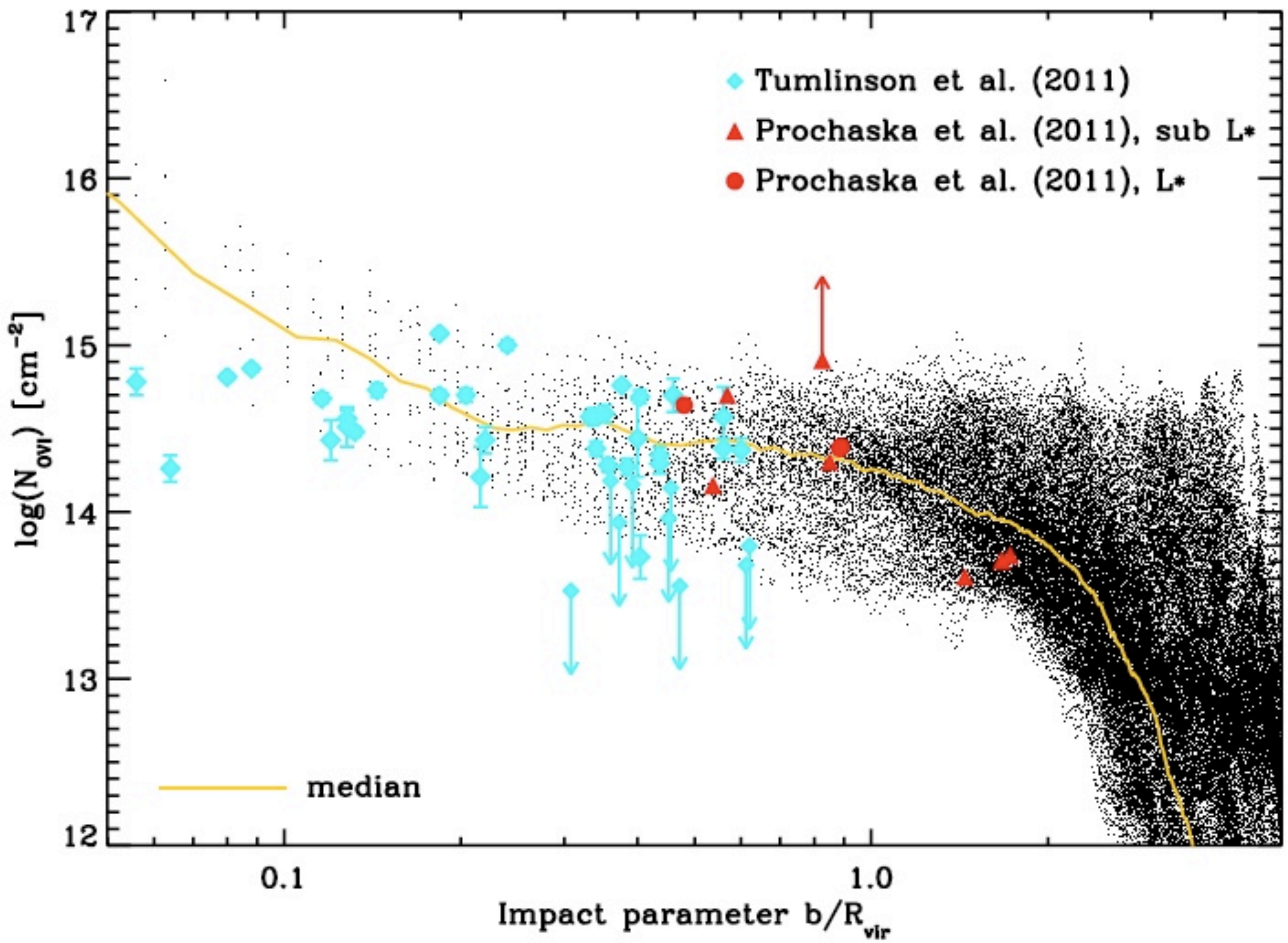
The N_{OVI}-b Relation in Eris2: Comparison with Low z Starburst Galaxies

- At z~2-3, Eris2 has sSFR ~ 10^{-9} yr^{-1}, close to the local star burst galaxies in Tumlinson + (2011) and Prochaska+ (2011)

- N_{OVI}-b relation agreement with observations; but higher at b< 0.1 R_{vir}

- Typical N_{OVI} >~10^{13-14} cm^{-2} up to 3 R_{vir}

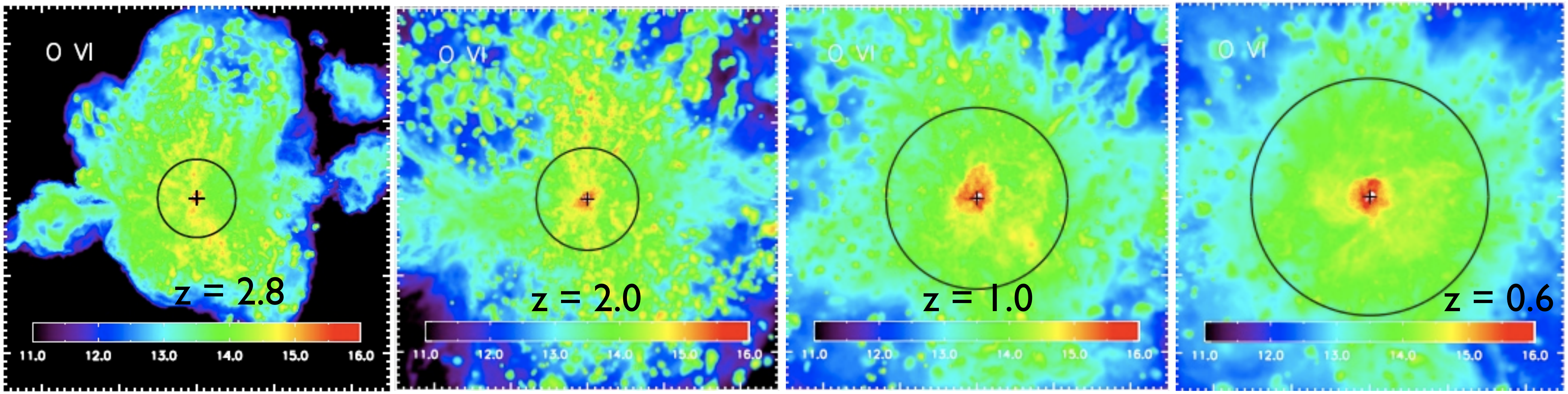
- N_{OVI} -b mostly determined by SFR?

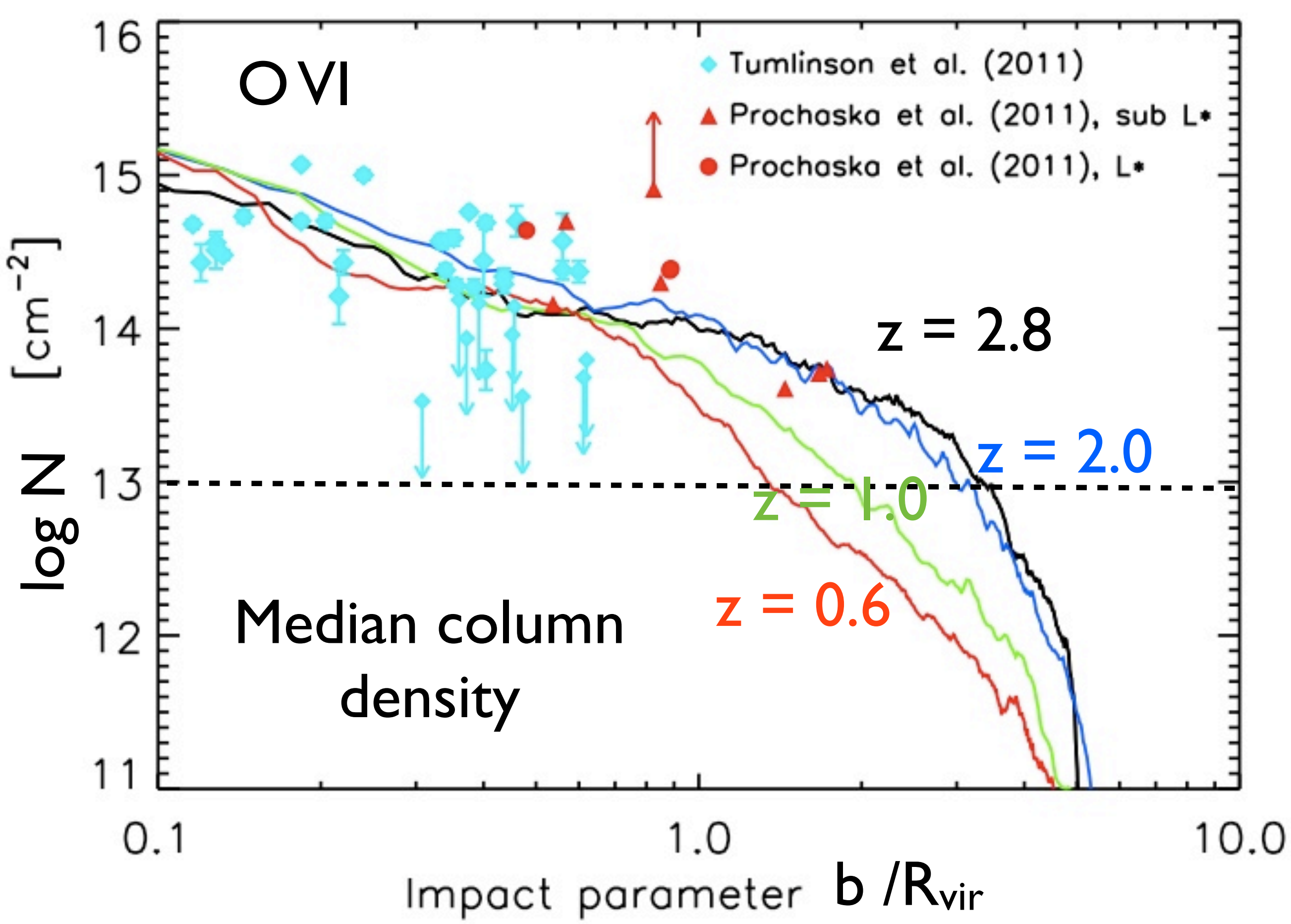


- R_{vir} ~ 160 kpc for sub-L* galaxies (Prochaska+ 2011)
- R_{vir} ~ 200-300 kpc for L* galaxies (Tumlinson+2011)

Evolution of the O VI in the CGM

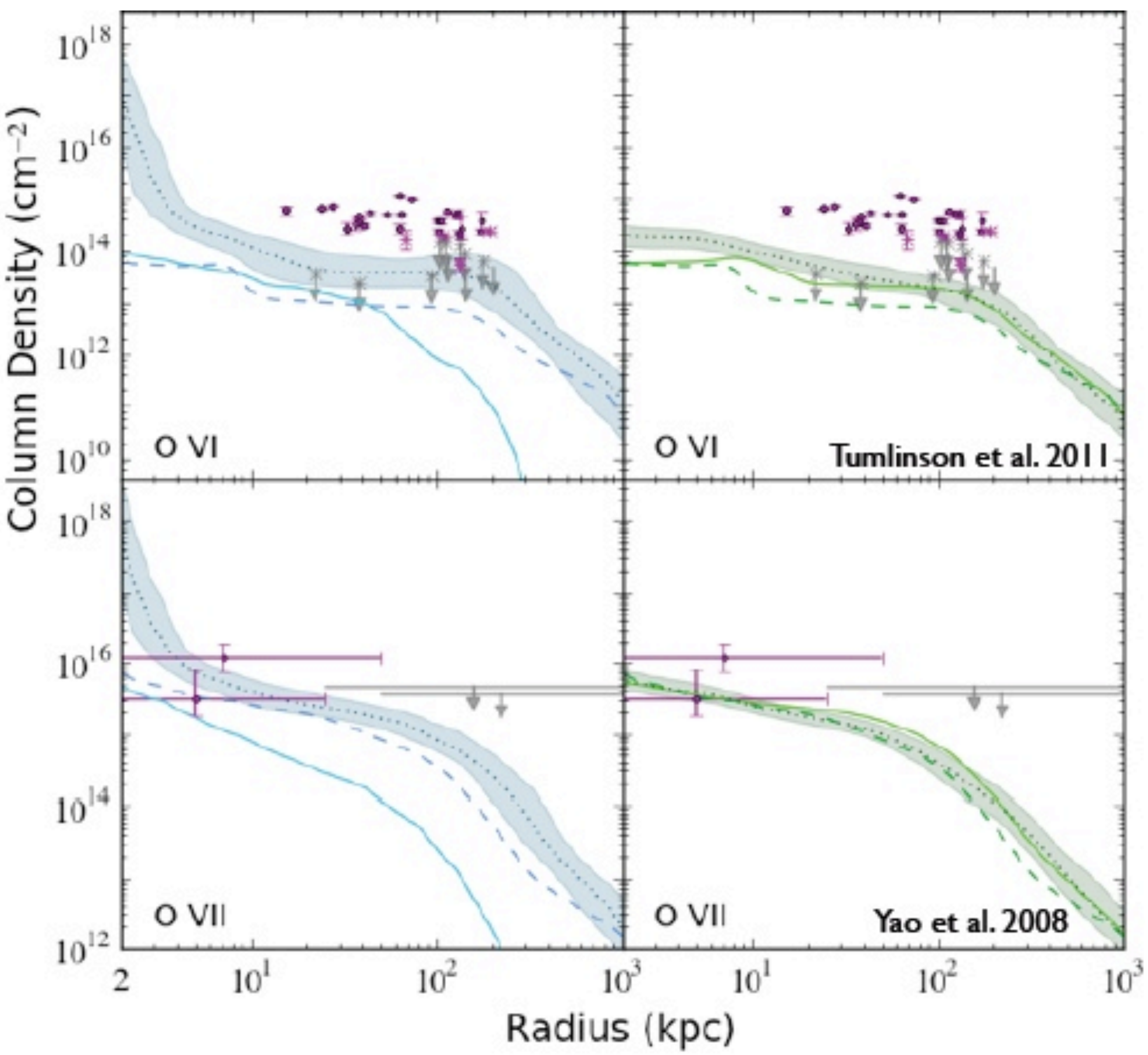
box size: 500 physical kpc

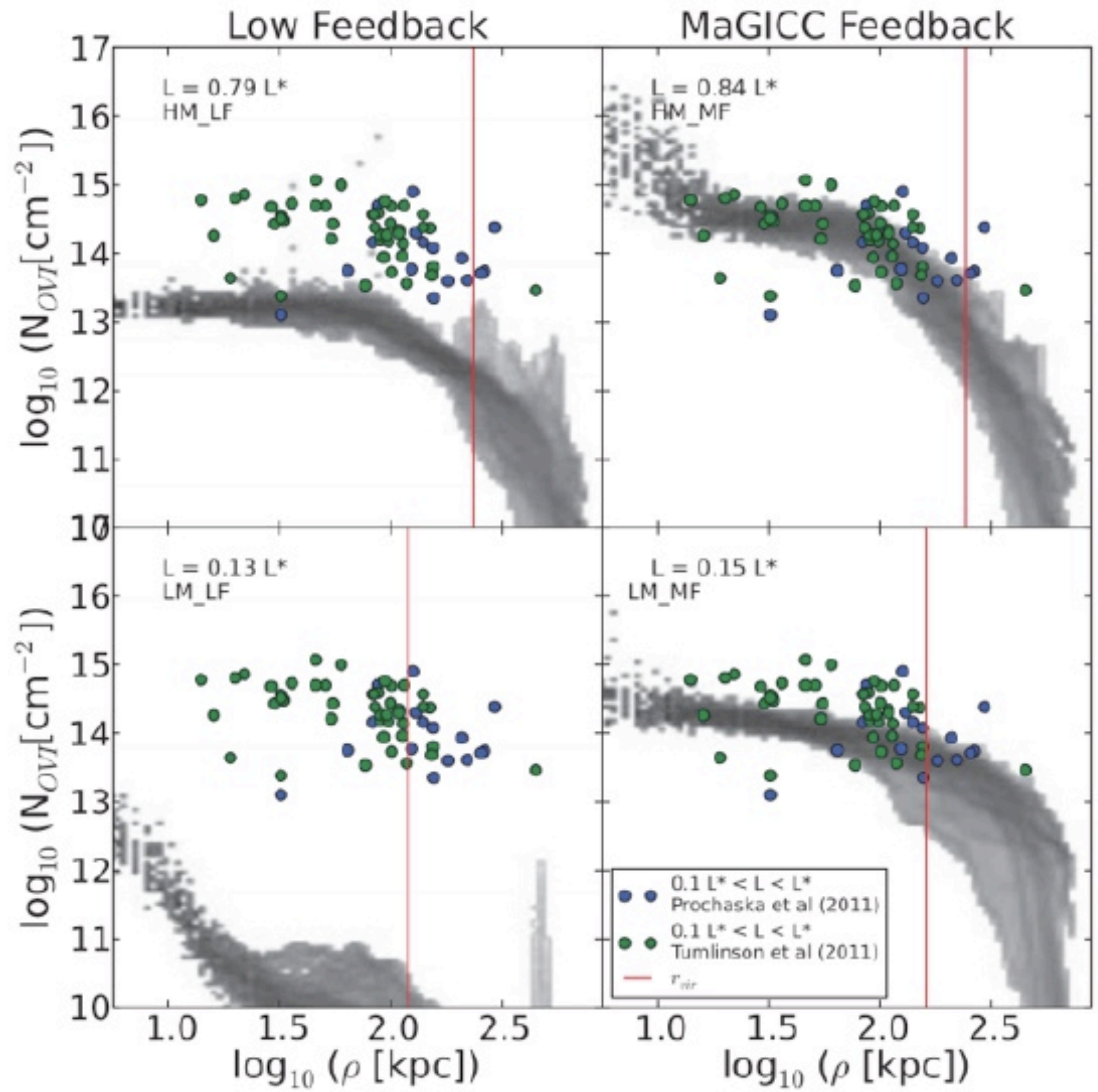




- From z ~3 to 0.6, the O VI halo grows with R_{vir}. Large column density within R_{vir}.
- Cf of $N_{OVI} > 10^{13}$ cm^{-2} remains ~ unity for all redshift within R_{vir}
- All redshift consistent with the observations of star-forming galaxies (Tumlinson+2011; Prochaska +2011).

CGM metals are sensitive probes of feedback and the thermodynamics of the halo gas

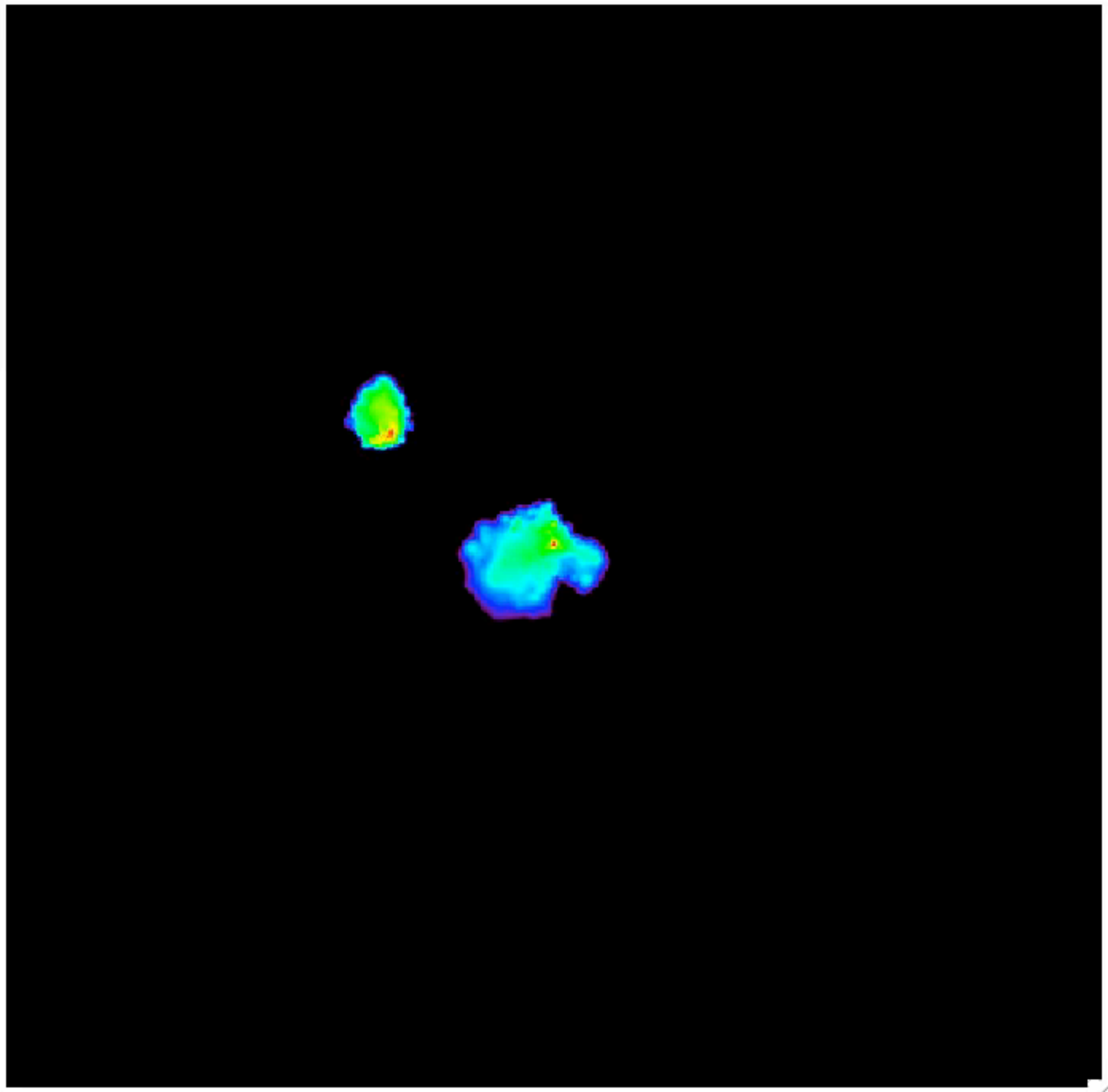




Hummels+ (2013): 1) different feedback schemes produce different column density distribution; 2) Gas is too hot to get right amount of O VI

Stinson+ (2012): strong feedback is necessary to reproduce extended O VI halos

The CGM of Low-Mass (0.01 L*) Dwarfs



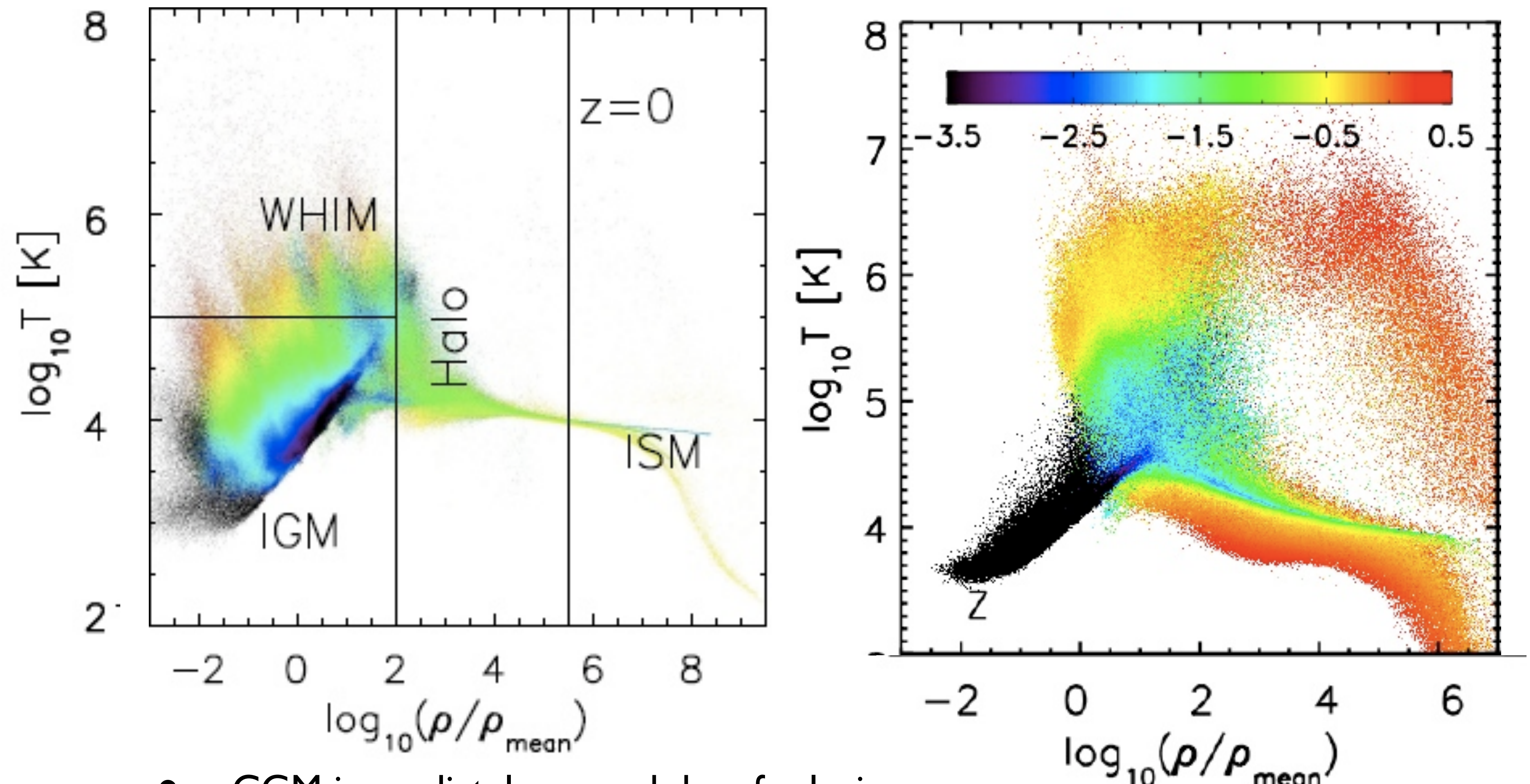
1 Mpc x 1 Mpc comoving box

- Although majority of stars formed at $z > 1$, the metal enriched gas continue to grow with the expansion of the Universe; reaches ~ 3 Mpc at $z = 0$. 87% of metals are outside of the viral radii, very low recycling.

- At $z=0$, the mass loading factors at R_{vir} are 17 for Bashful and 12 for Doc, 10-15 times higher than MW size galaxies. Reaches 30-50 at high z.

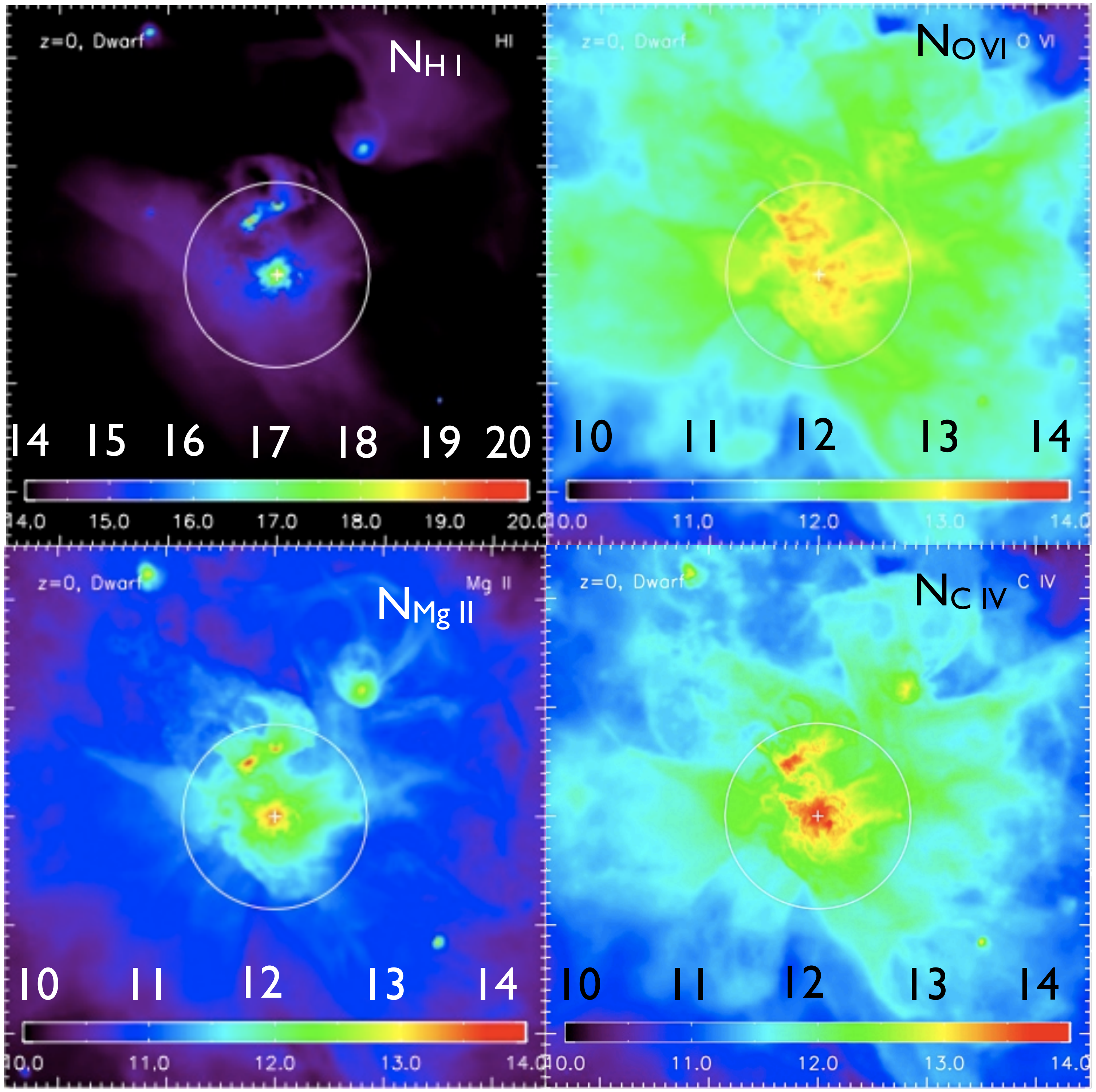
- Majority of metals are cool, 80% < 10^5 K, 57% < 3×10^4 K.

ρ-T Diagram Comparison



- CGM immediately around dwarf galaxie
- Winds from dwarf galaxies are able to enrich the IGM
- Lack of hot (> 1e6 K) halo due to the shallow potentials

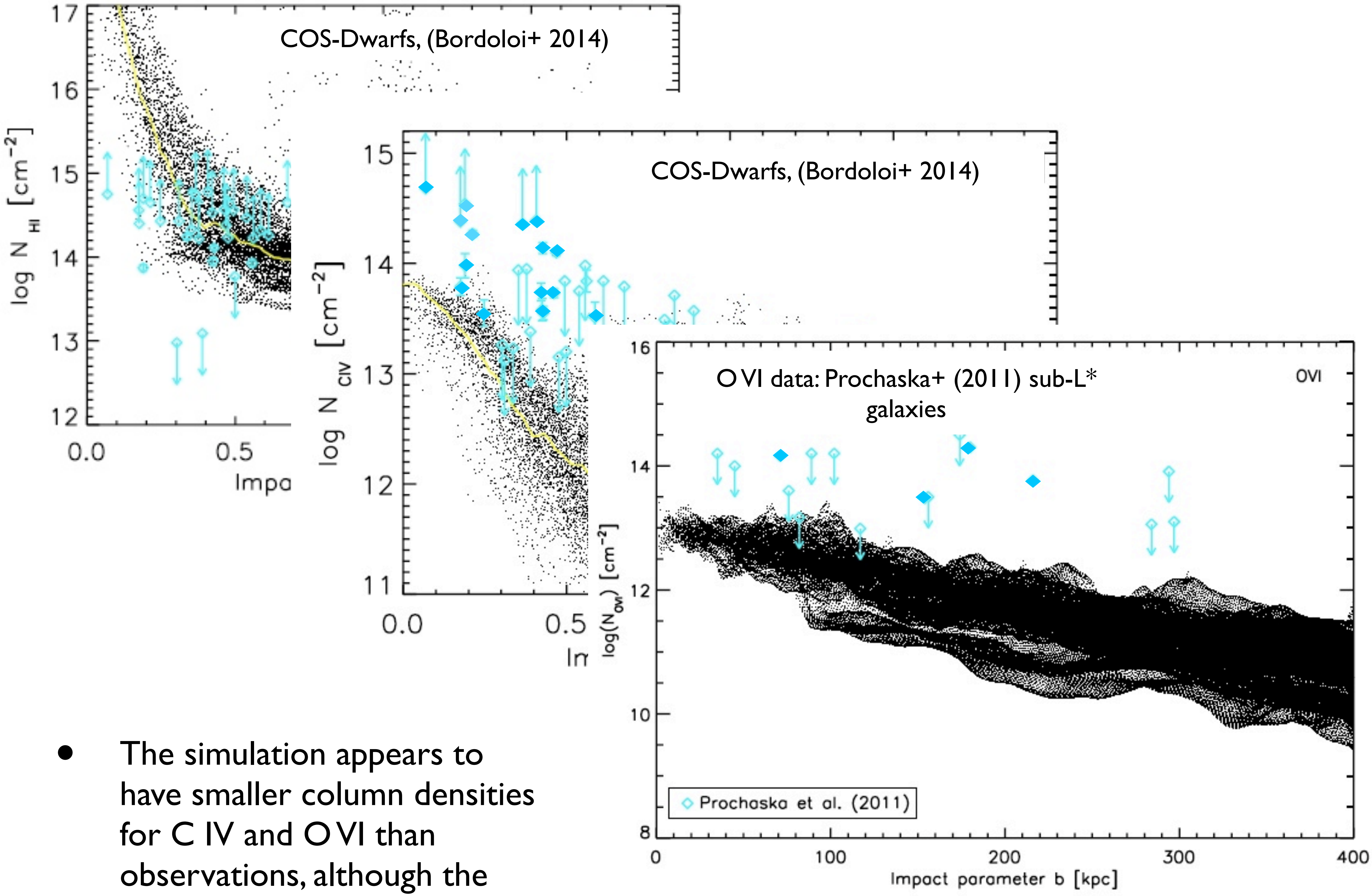
Column Density of Ions at z = 0



Box Size 500 kpc on a side

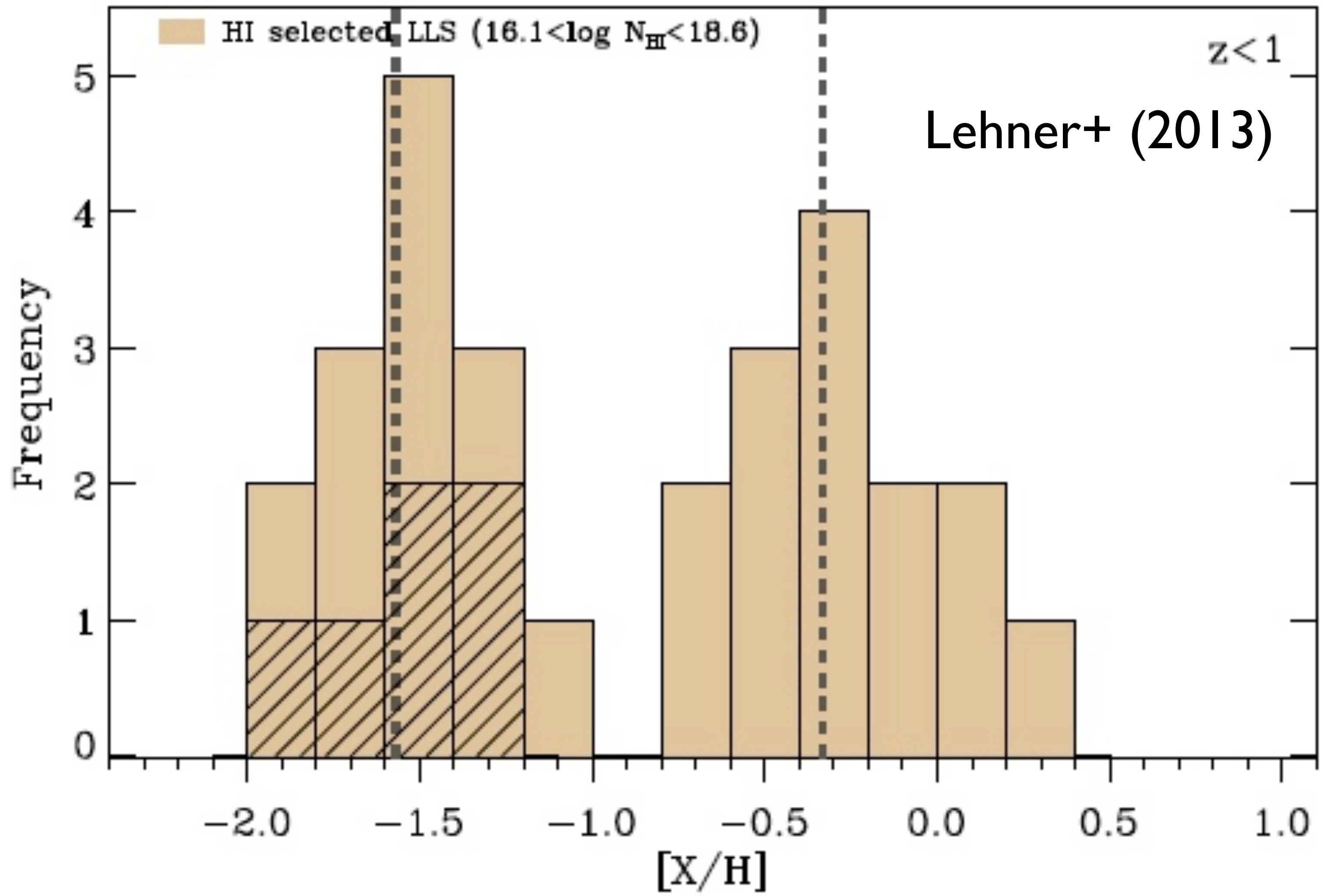
- The distributions of high ionization species (e.g. OVI) is more extended than those of low ions.
- O VI column within Rvir is around 10^{13}-10^{14} cm^{-2}, an order of magnitude lower than more massive halos in Tumlinson+(2011) and Prochaska+ (2011)
- Low ions such as Mg II or C II drop below 10^{13} rapidly with impact parameter due to photoionization

Comparison with observations at z = 0



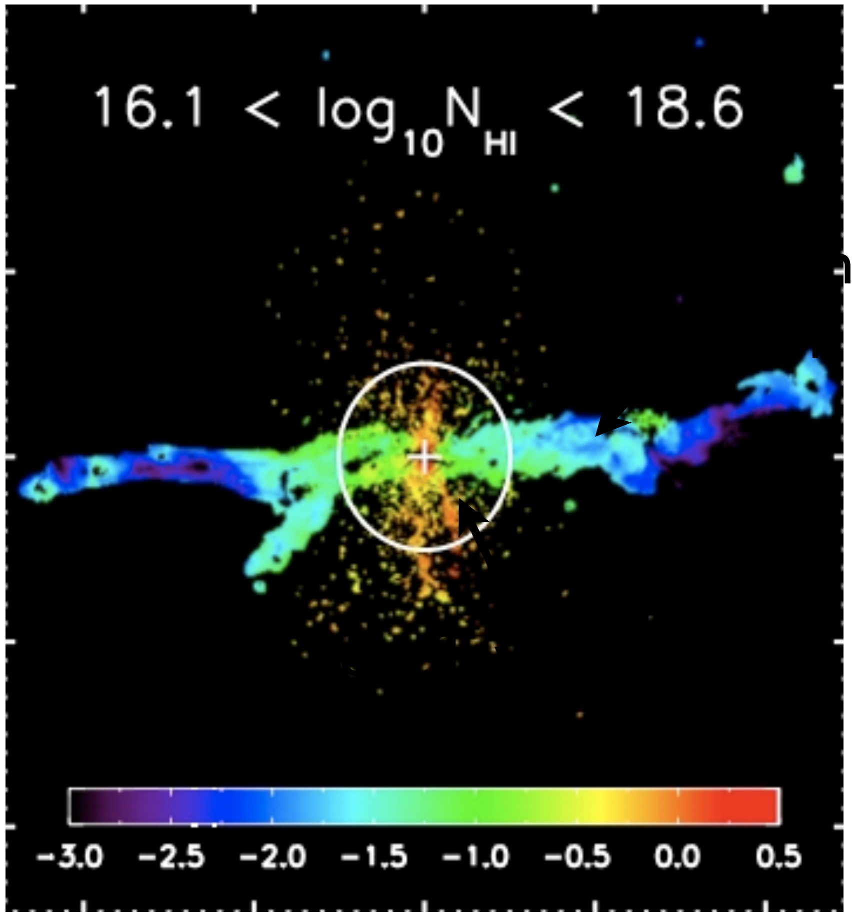
- The simulation appears to have smaller column densities for C IV and O VI than observations, although the mass loading is very high

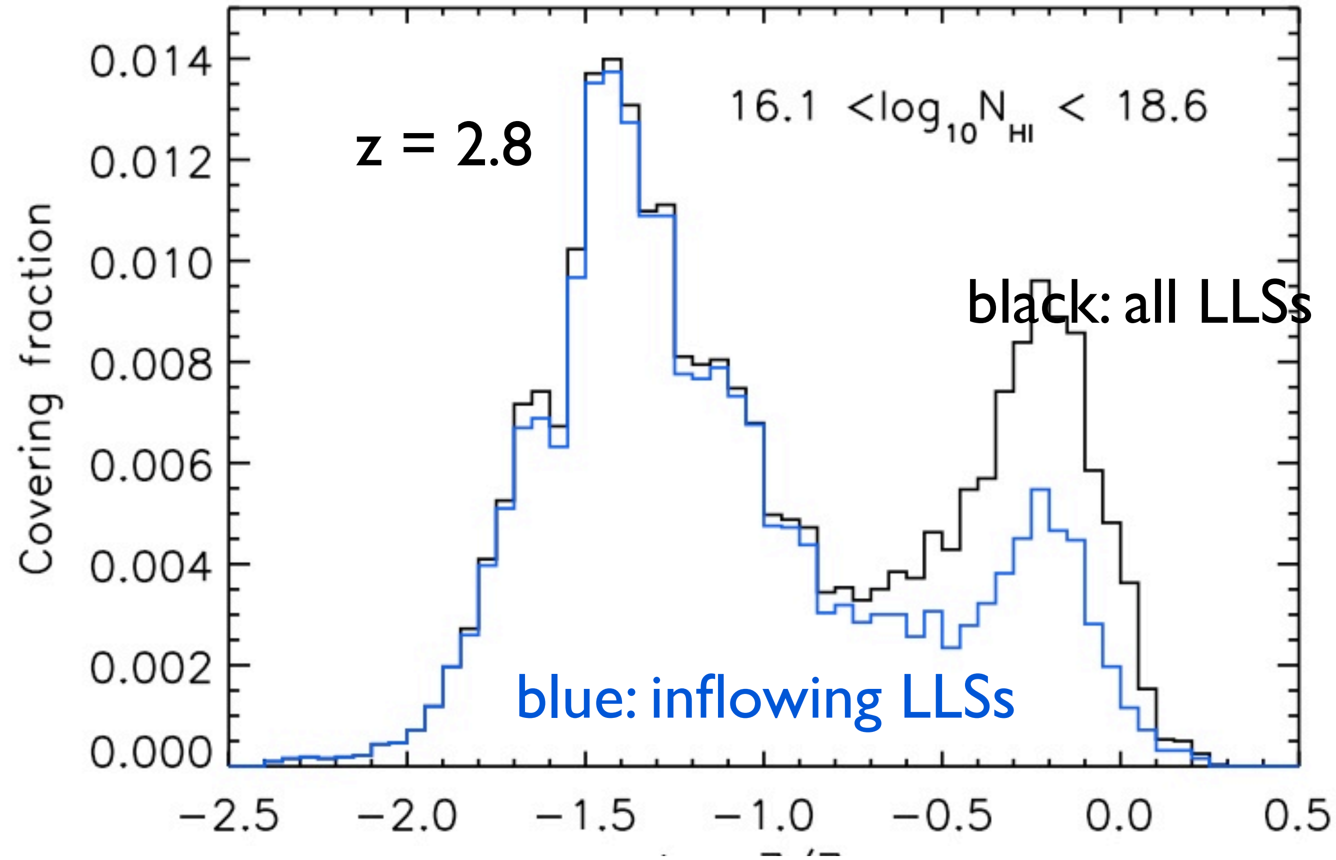
Gas accretion, Lyman-limit Systems and metallicities (z~1)

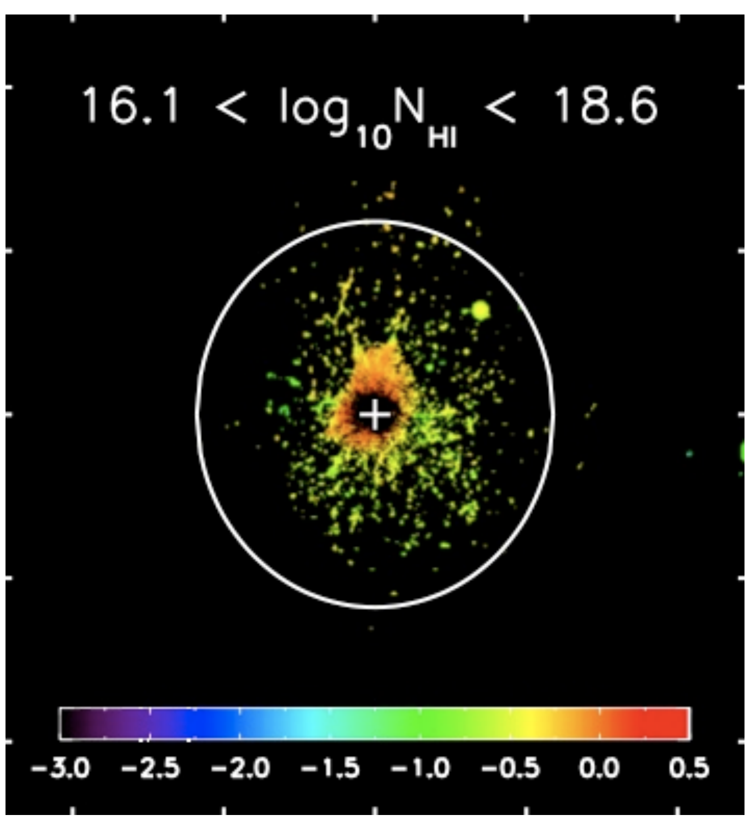


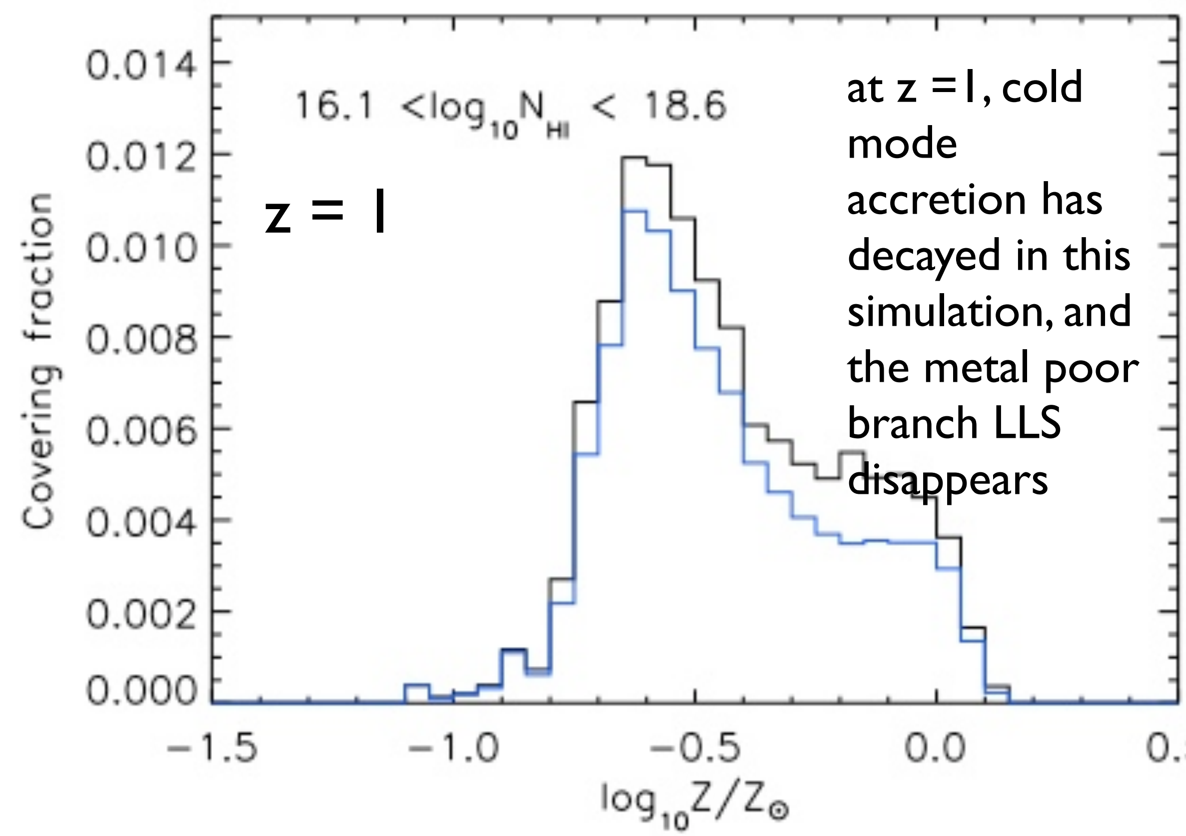
- Lyman limit systems at z~1 (16.1 < log N_{HI} < 18.6) shows bimodal metallicity distribution
- metal-poor: accretion flows that is enriched by dwarf satellites
- metal-rich: outflows or recycled wind materials
- Mixing between inflow and outflows maybe not very effective

Bimodal Metallicity Distribution in Simulations

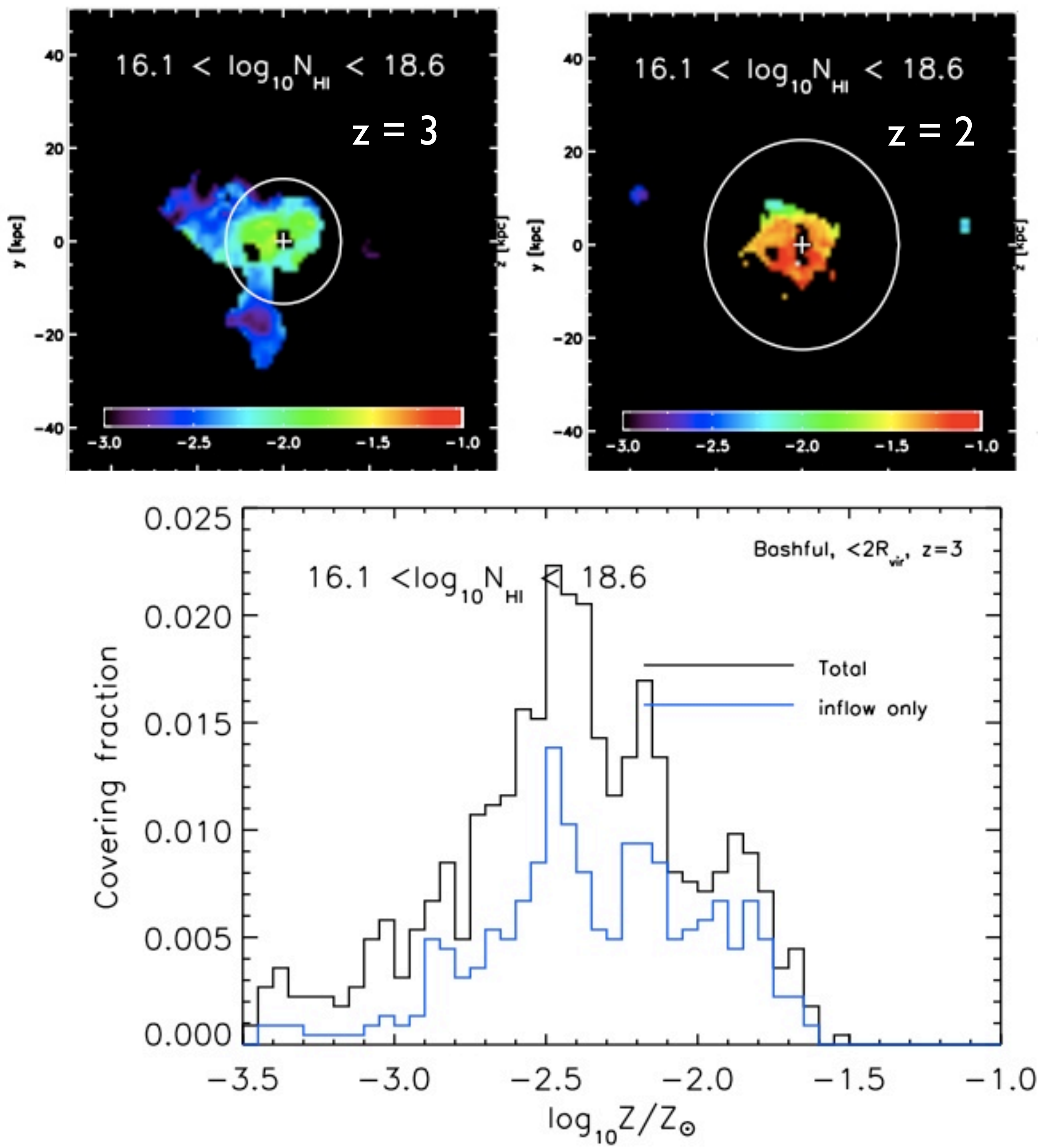








LLS around Dwarf Galaxies



- Accretion onto dwarf galaxies is generally not along filaments
- Outflows are more disruptive
- LLS metallicity distribution consistent with a single peak

Summary: The CGM as a test of feedback

- Zoom-in simulation provides a laboratory to study in detail on the distribution, kinematics and evolution of the CGM, useful tool to interpret observations
- The CGM shows multi-phase structure with coexistence of high and low ionization species. However, O VI absorbers are NOT always in the same phase
- Majority of low ionization species track the inflowing material, and O VI mostly track the outflows and the ambient CGM.
- The spacial distribution of H I and metals in agreement with observations of LBGs (Steidel +2010; Rudie+2012) and DLAs (Rubin+ in prep). Feedback & outflows are crucial.
- The column density of O VI remains high within R_{vir} at all redshift, N-b/R_{vir} relations consistent with the observations of massive local star forming galaxies (Tumlinson+2010; Prochaska+2011), and without strong evolution with redshift.
- The cold inflows are substantially enriched to $Z > 0.01\ Z_{sun}$. The metallicities of the LLSs at high z have a bimodal distribution as observed in Lehner et al. (2013). The metal poor branch tracks inflows and the metal rich predominantly tracks outflows. However, the bimodal distribution evolve with time and disappears at z <1. Dwarf galaxies have smoother accretion and the LLSs do not show bimodality.