Symposium
«The Periodic Table through Space and Time»

How the Periodic Table Travels from Galaxies to Voids

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United Nations Educational, Scientific and Cultural Organization
2019 IYPT International Year of the Periodic Table of Chemical Elements

IAU 100 Years: Under One Sky
International Astronomical Union 1919 - 2019

Metals in the distant IGM (examples)

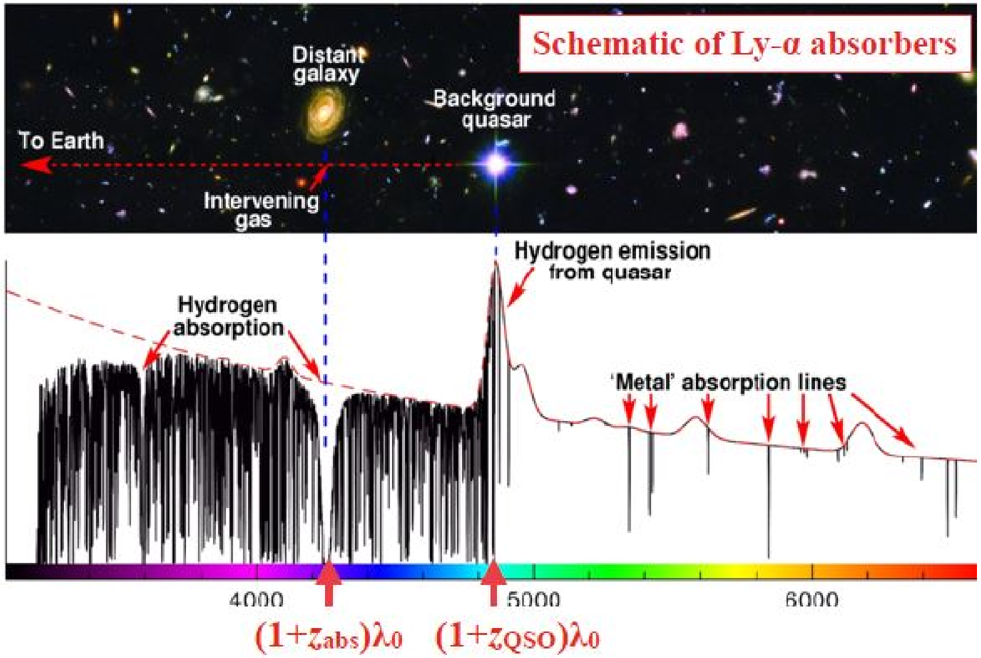
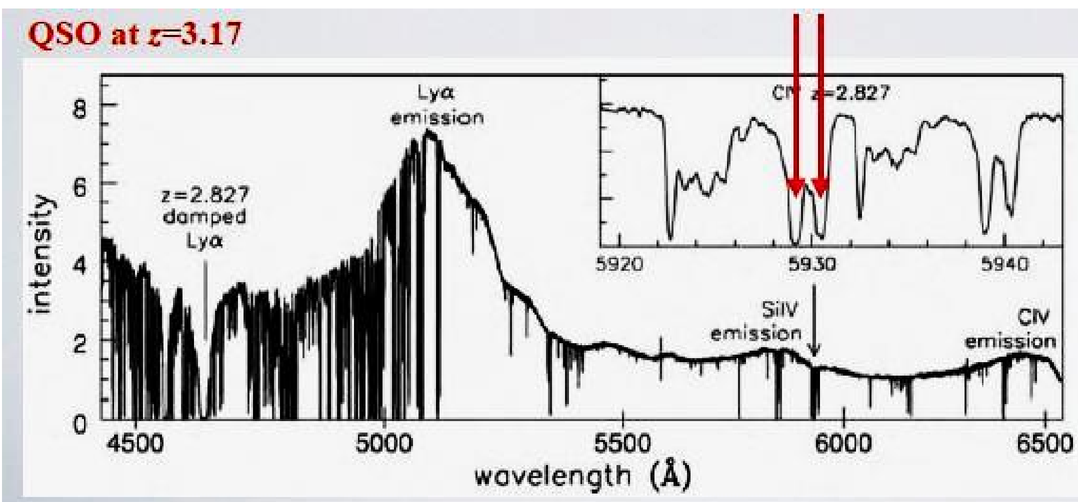


Table 1. A few strong atomic transitions

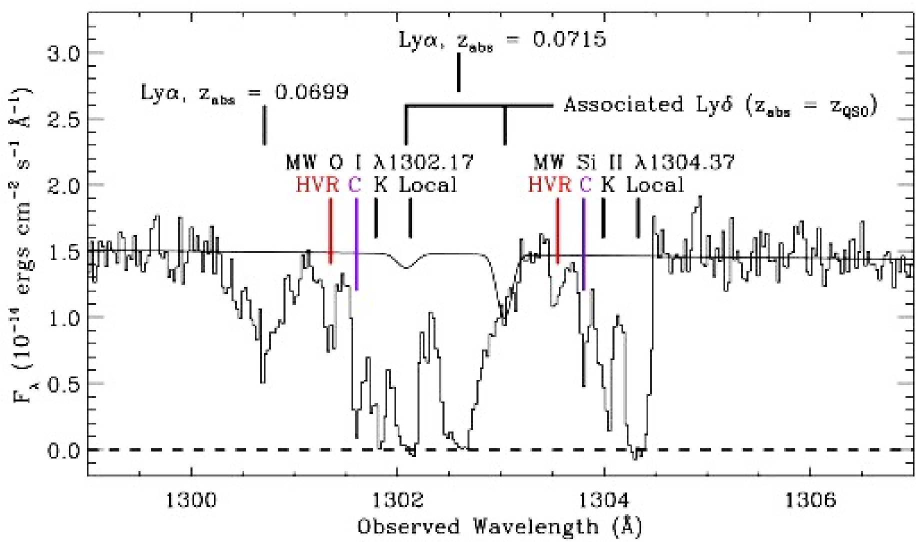
Ion	λ_o (Å)	f	$\log(\lambda_o f)$	$\log(\lambda_o^2 f)$
O VI	1031.927	0.130	2.128	5.141
O VI	1037.616	0.0648	1.828	4.844
H I	1215.670	0.4162	2.704	5.789
O I	1302.169	0.0486	1.801	4.916
C II	1334.532	0.118	2.197	5.323
Si IV	1393.755	0.528	2.867	6.011
Si IV	1402.770	0.262	2.565	5.712
C IV	1548.202	0.194	2.448	5.667
C IV	1550.774	0.097	2.177	5.368
Mg II	2796.352	0.592	3.219	6.666
Mg II	2803.531	0.295	2.918	6.365



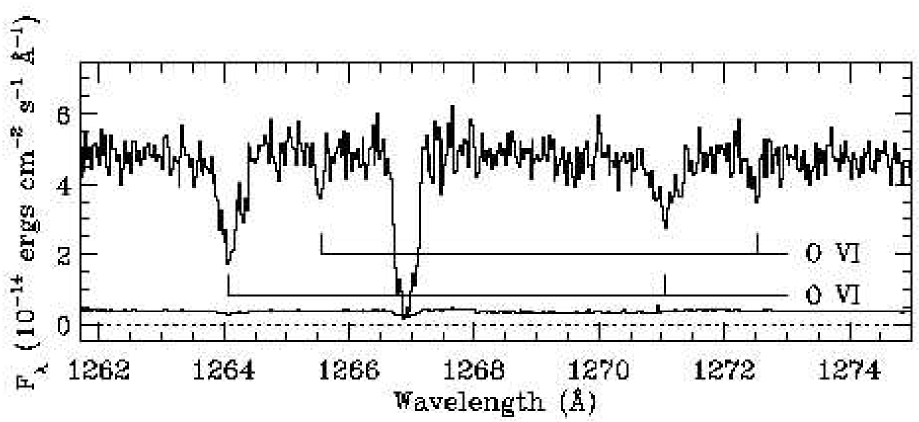
Absorption lines (doublet) by C IV, rest wavelength = 1548.2 Å and 1550.8 Å

http://www.astro.caltech.edu/~pparihar/ay127/lectures/lecture14.pdf

Metals in the CGM and local (z < 2) IGM (examples)



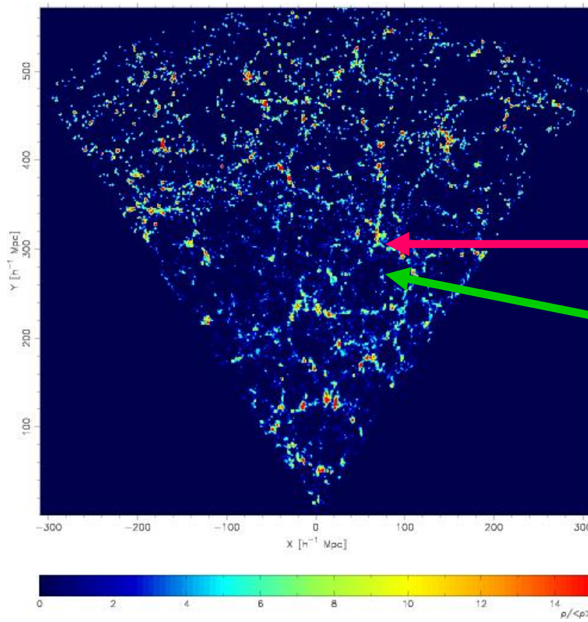
STIS spectrum of 3C 351. The absorption profiles of the O I 1302.2 and Si II 1304.4 lines due to the ISM of the MW, as well as several extragalactic absorption lines are seen. Four main components are readily apparent in the Galactic O I and Si II profiles: the high-velocity absorption lines associated with complex C and the high-velocity ridge; absorption arising in IVC complex C/K (*Tripp+2003)*.

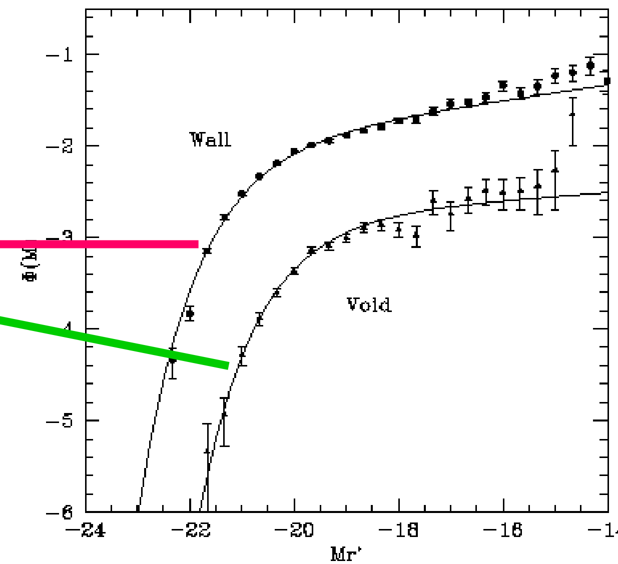


STIS spectrum of quasar H1821+643 showing the strong OVI absorption lines at z = 0.22497 and the weaker absorber at z = 0.22637. The calibrated flux is plotted vs. observed heliocentric wavelength, and the solid line near zero is the 1σ flux uncertainty (*Tripp+2000*)

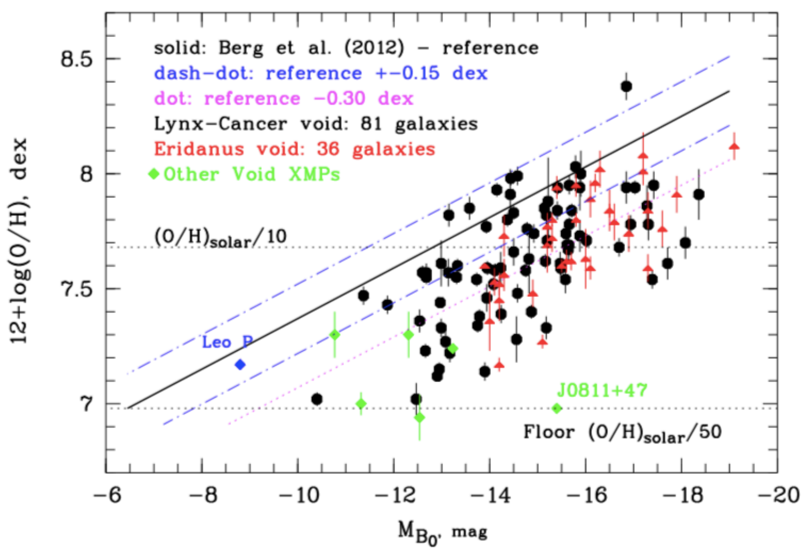
Metals in in voids: Galaxies

Void galaxies are fainter than galaxies at higher densities (*Hoyle+2005*).





About 50 known XMP galaxies with $Z < Z_{\odot}/20$ (or $12 + \log(O/H) < 7.38$. The best local proxies for forming galaxies in the early Universe? *(Guseva+2017, Pustilnik+2018)*

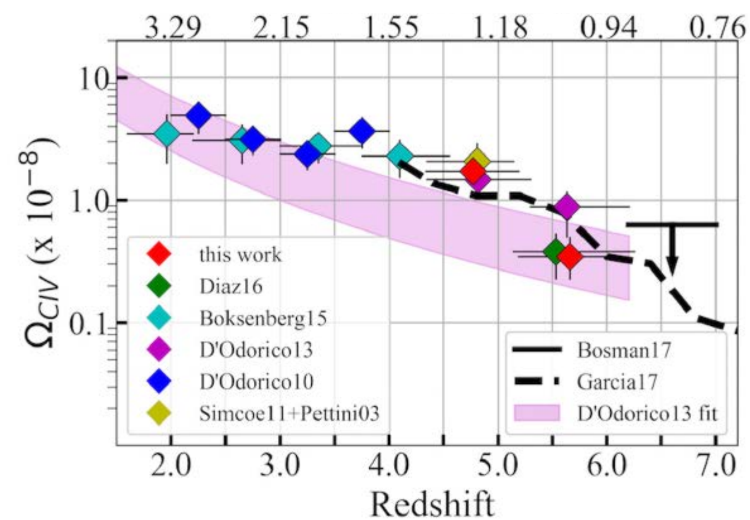


Metals in in voids: Lyα absorbers

Stocke+2007 have used the Hubble/STIS and FUSE archives of UV spectra of bright AGN and identified 61 Lyα absorbers in nearby ($z \leq 0.1$) voids. located > $1.4h^{-1}$ Mpc from the nearest galaxy. No metal lines in any individual absorber, or in any group of absorbers were detected. This implies yields metallicity limits $Z < 10^{-1.8\pm0.4} Z_{\odot}$.

Although the void Lyα absorbers could be pristine material, considerably deeper spectra are required to rule out a "universal metallicity floor" produced by bursts of early star formation, with no subsequent star formation in the voids. The most consistent conclusion derived from these low-z results, and similar searches at $z = 3 - 5$, is that galaxy filaments have increased their mean IGM metallicity by factors of 30–100 since $z \sim 3$.

Recent measuremens (*Codorianu+2018*) confirm the initial conlcusion by *Songaila 2001* on very weak evolution of metallicity during the entire post-dark ages epochs 2<z<5; ii) metallicity is of ~0.001 solar.



NB. *Campana+2015* - Missing cosmic metals can be revealed by X–ray absorption towards distant sources.

Census of metals in the Universe

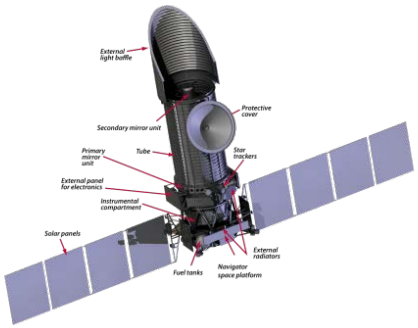
At z = 0 the fraction of metals produced by star-forming galaxies and retained within them is ~ 20 − 25%. These metals, which can be traced up to galactocentric distances of ~ 150 − 500 kpc, add ~ 20 − 30% to the total metal census, still leaving about 50% of the total metal budget undetected. This is known as the missing metals problem. (*Peeples et al. 2014; Shull, Smith & Danforth 2012, Campana+2015*).

A keen demand for powerful UV insruments

Burchett+2019 – “UV spectroscopy provides unique insights into the cold-warm gas in and around most massive structures in the Universe, providing highly complementary views of the baryonic contents of the universe provided by X-ray and microwave observations. With a substantial UV un- dertaking beyond the Hubble Space Telescope, all of the above would be achievable *over the entire epoch of galaxy cluster formation*.”

Tumlinson+2019 “Spatially-resolved UV spectroscopy can dissect the baryon cycle at unprece- dented scales, complementing information from other wavelengths with unique constraints on mass, metallicity, ionization, and kinematics“.

To LUVOIR via WSO-UV! *Shustov+2018*

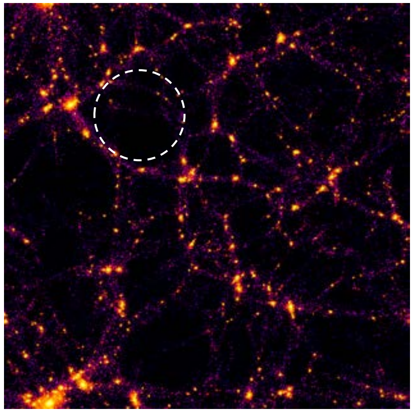


Problems

- Missing metals problem
- Mixing problem
- How metals are transported into the IGM

$\sim 10^0$ pc

$\sim 10^4$ pc



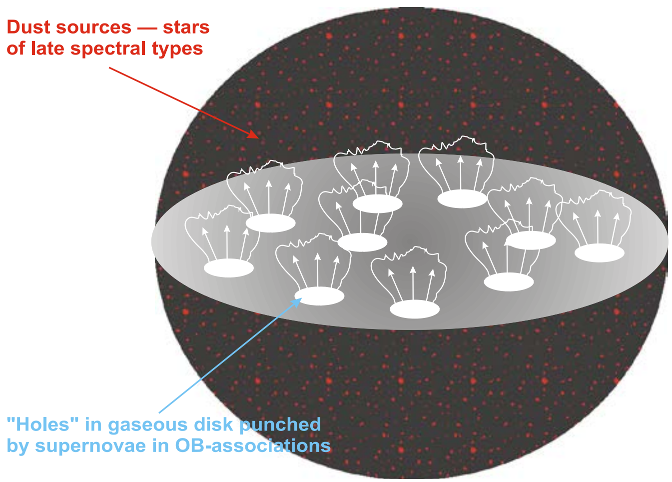
$\sim 10^7$ pc

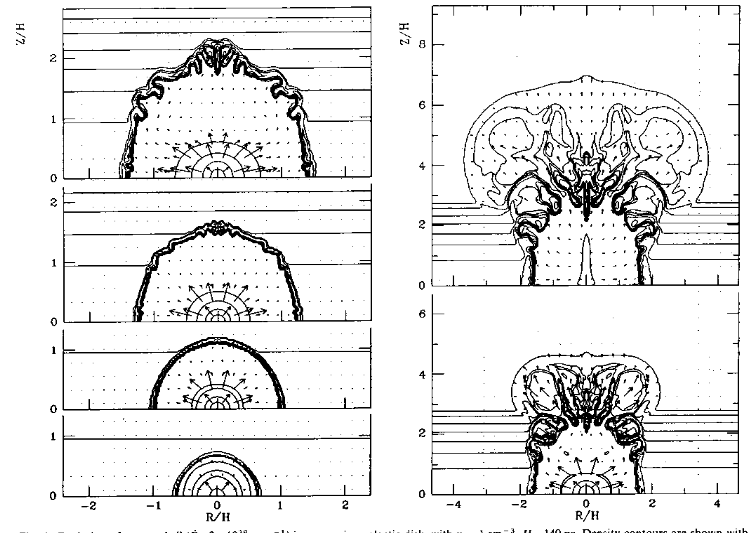
How metals go from galaxies into the IGM

Major mechanisms:

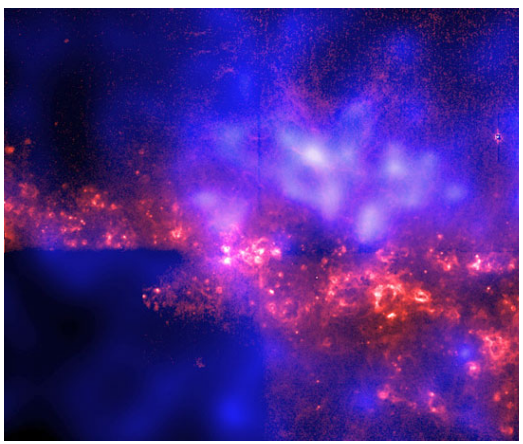
- Merging of protogalaxies
- Galactic wind (on the next slides)
- Outflows from AGN (AGNs)
- Tidal stripping (ram pressure stripping)
- Dust loss (on the next slides)

Galactic wind: metals abandon galaxy





Shustov 1989



Chandra observations of NGC 4631 (it is similar to the MW). X-ray image – in blue HST - in red. (*Wang et al., 2002*)

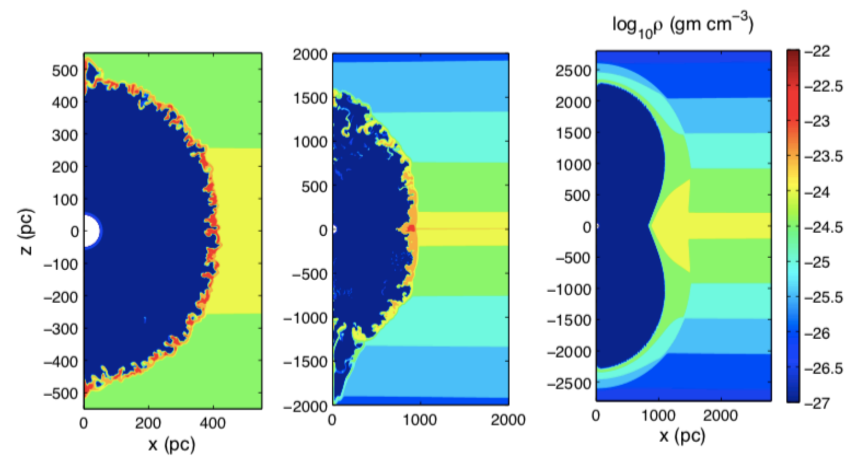
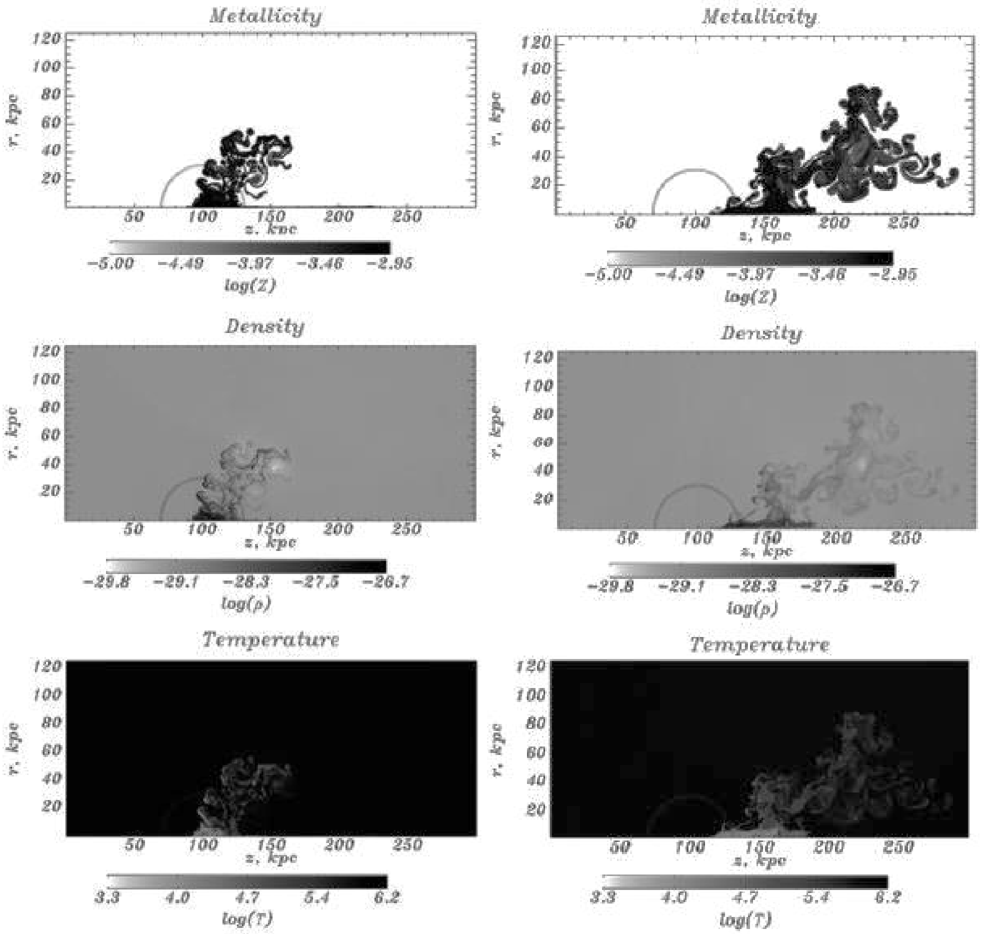


Figure 8. Density contours for the same cases as in Fig 7. Here, fragmentation of the shell is clearly seen in the run with cooling.

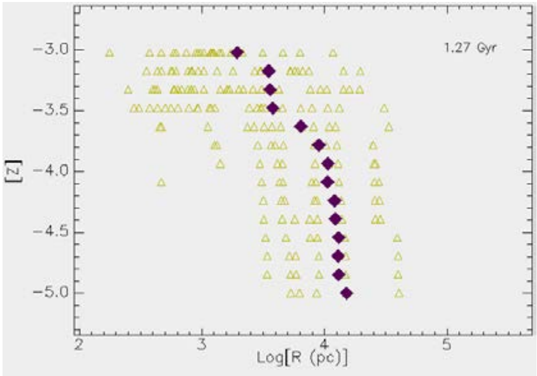
Roy+2013

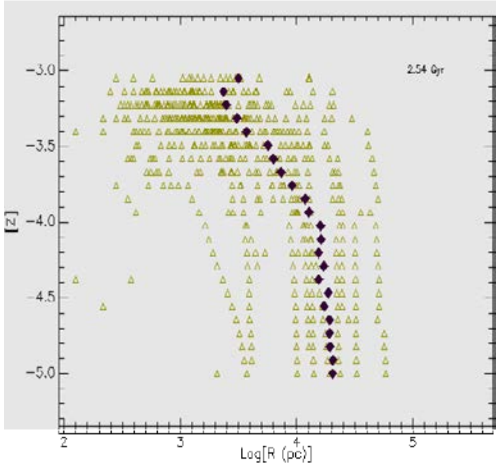
From CGM to IGM (theory)

t = 1.27 Gyr t = 2.54 Gyr.



Size – metallicity relation





Metals become confined in fragments of smaller size – the smaller the fragment the higher is its metallicity. *Dedikov+2004,2008, Vasiliev+2009.*
See either most recent paper *Vasiliev+2019 (*and his talk at this symposium). *Eugeny)*

Distribution of metallicity in the CGM (theory)

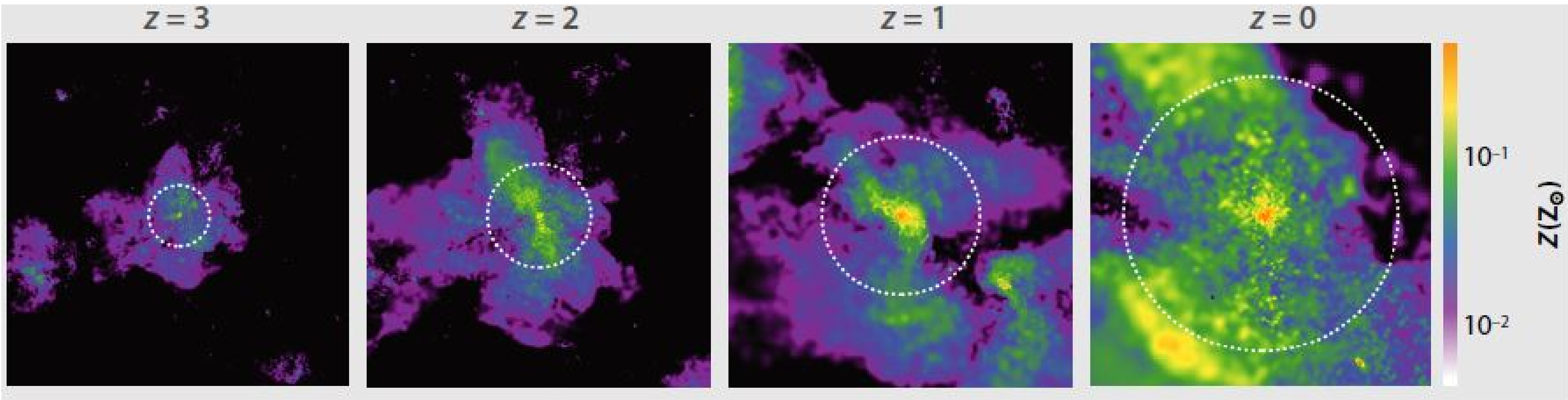
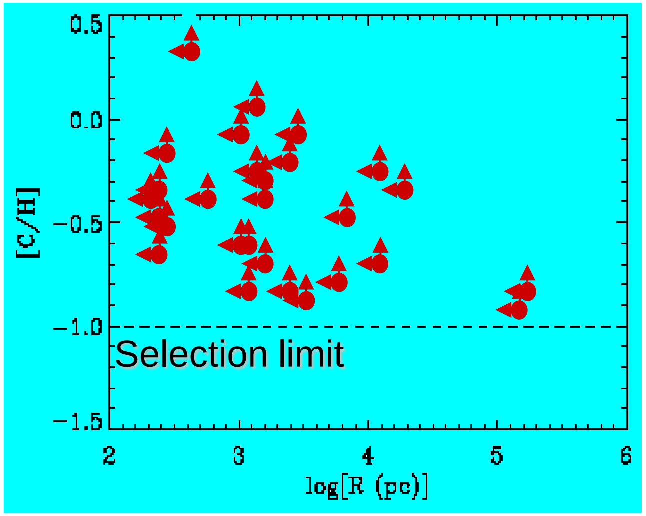


Figure 1: Distribution of the metallicity in the CGM of a galaxy at 4 different epochs in the EAGLE simulations (Schaye et al., 2015; Oppenheimer et al., 2016). The dotted white circle encloses the virial radius of that galaxy at each epoch (each panel is 1 Mpc physical, adapted from Fig. 3 in Tumlinson, Peeples, & Werk 2017). At any redshift, the CGM is filled with low and high metallicity gas, but only at $z \gtrsim 1$ does the IGM start to have metal-enriched gas. These findings can be directly confronted with empirical results.

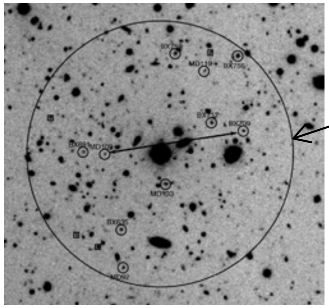
Lehner+2019

Nonuniformity of metal distribution (observ.)

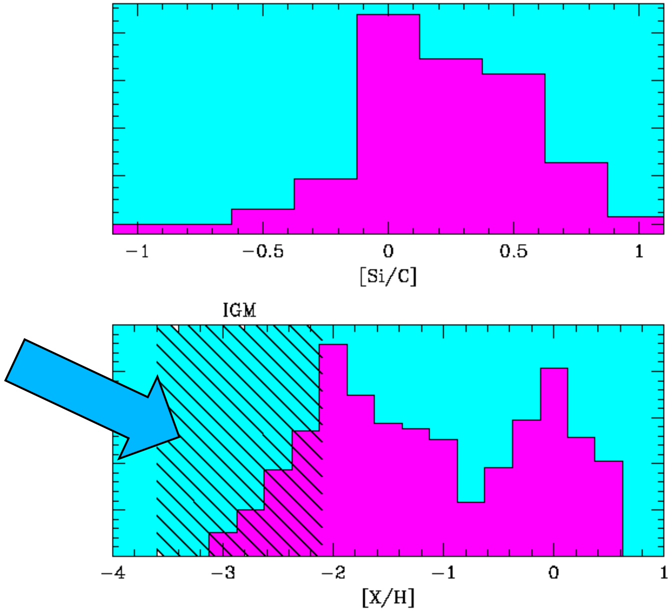
Schaye +2007
carried out a survey for high-metallicity CIV absorbers at redshift z ≈ 2.3 in 9 high-quality quasar spectra.

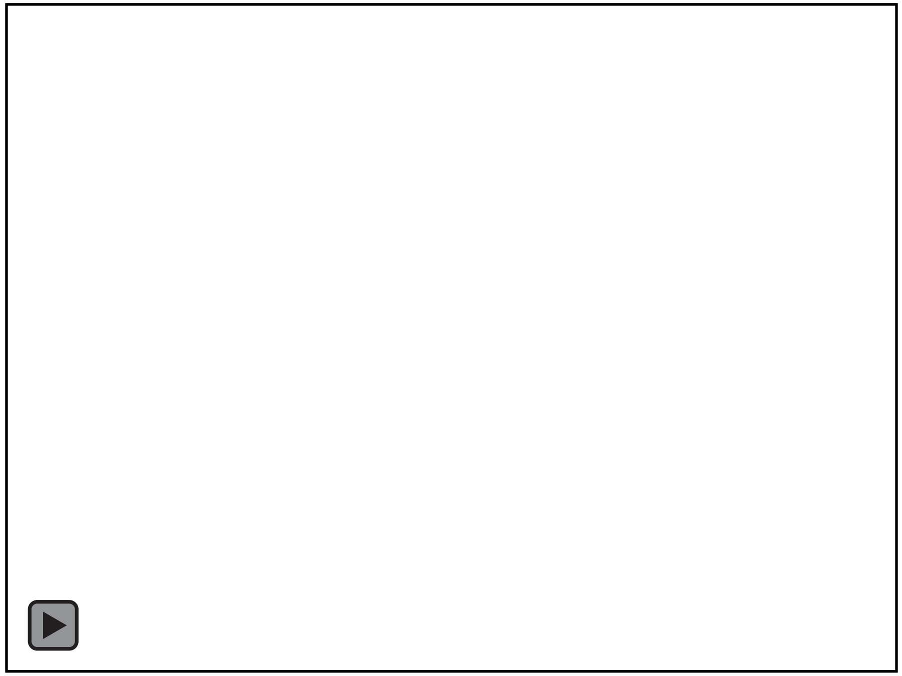


Simcoe+2006 presented a comparative study of galaxies and intergalactic gas toward the z = 2:73 quasar HS 1700+6416



Radius around QSO LoS = 0.5 Mpc physical.



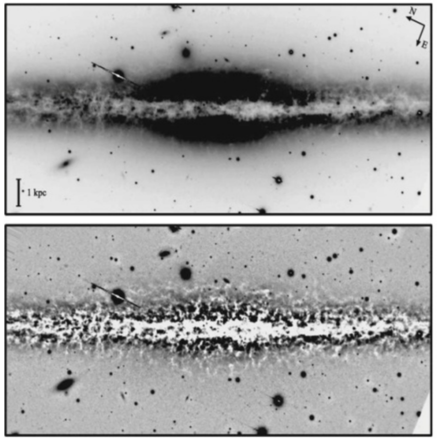


Evolution of gas metallicity in the vicinity (10 x 5.625 comoving Mpc) of massive simulated galaxy. The colour scale ranges from [O/H]=-5 (black / dark blue) to [O/H]=-1 (red / white). Metals are injected into the gas when stars die in supernova explosions. At late times, accretion onto the supermassive black hole in the galaxy powers outflows of enriched gas into the intergalactic medium (IGM). *https://www.youtube.com/watch?v=jk5bLrVI8Tw*

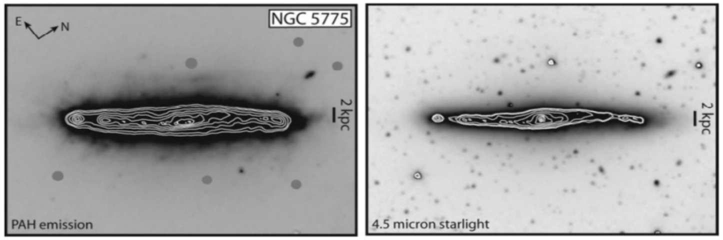
Observation of dust dust in the CGM

Evidences:

Dust is observed in the vicinity (up to heights z ~ 2 kpc) of disk gala-xies and in the IGM. Estimates of typical size and volume density of extraplanar dust component are rather different. E.g. *Hirashita&Lin 2018* found that a grain radius in the IGM is in a range of a ~ 0.01–0.03 μm. Observations (*Jones+2013*) demonstrate that most of dust exists as very small grains (e.g.PAHs).



V-band image of the edge-on galaxy NGC 891 from *Howk & Savage (2000)*. The top panel shows the direct V-band image. The bottom panel shows an unsharp-masked version of the V-band image. The clouds seen here each have masses in excess of ~ 10^5 $M_\odot$.



Spitzer observations of NGC 5775 showing PAH emission (left) in the 8 μm band and the distribution of stellar light (right) in the 4.5 μm band.. Filamentary PAH emission is seen in this galaxy up to z ~ 5 kpc (*Howk 2009).*

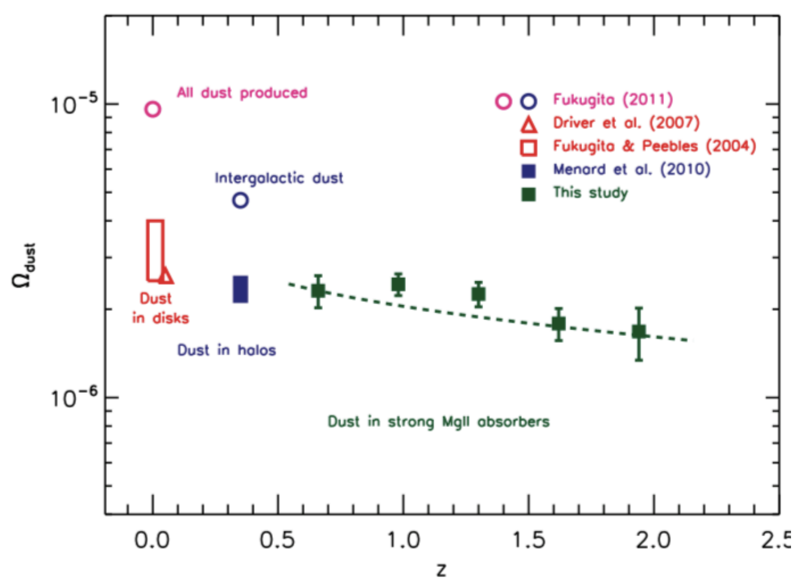
Observation of dust in the IGM (some examples)

FIR observations: *Wszolek&Rudnicki 1990; Stickel+(1997.*

Malhotra+1997 reported the detection of the 2175 °A feature (signature of the Milky Way type of dust)) in the composite spectra of 92 QSO (SS92 sample is a large, uniform survey with absorbers at a wide range of redshifts ($0.2 < z < 2.2$).

Dust has long been suspected to be a constituent of QSO absorbers. The presence of dust in DLAs is suggested by the differential depletion of the refractory elements like Cr and Fe with respect to the volatile elements like Zn. [Cr/Zn] has been found to be correlated with E(B-V) in a sample of a few Sloan Digital Sky Survey (SDSS) QSOs (*Khare+2004*).

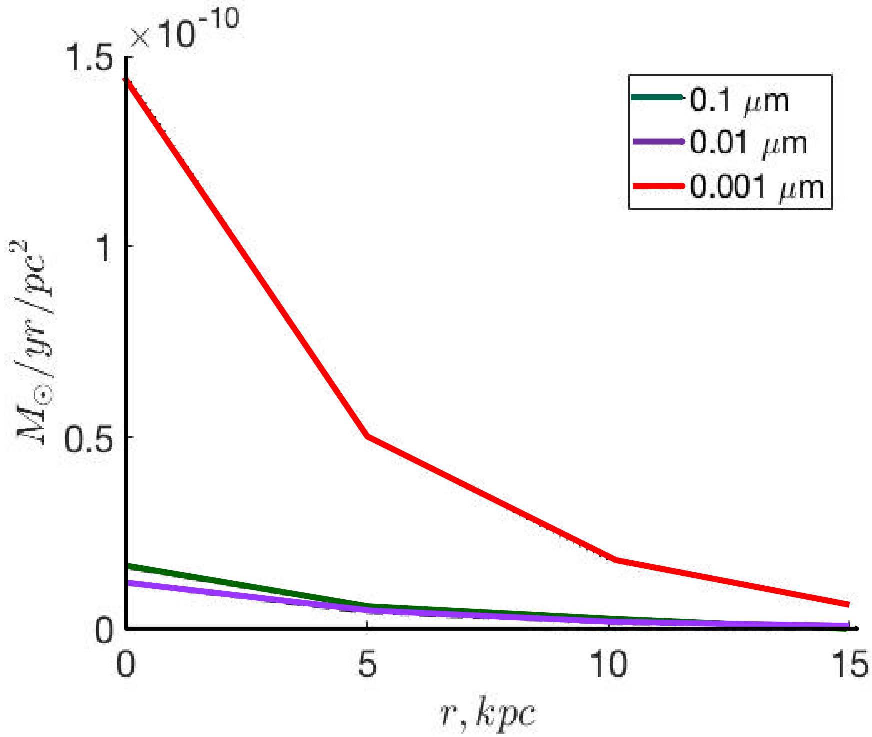
MgII absorbers induce reddening on background quasars. *Menard+2012* measured this effect and infer the cosmic density of dust residing in these systems to be $\Omega \approx 2 \times 10^{-6}$, in units of the critical density of the universe, <u>which is comparable to the amount of dust found in galactic disks or about half the amount inferred to exist outside galaxies</u>



Mechanisms of expelling:

- Galactic wind
- Radiation pressure (models to mention few):

Pecker 1970, Chiao&Wickramasinghe 1972, Smidt (1974) – an idea
Ferrara+1991, Shustov&Wiebe 1995 – numerical models
Bianchi & Ferrara 2005, Khoperskov&Shchekinov 2014 …



Dust loss rate at various distances fron center of t Galaxy *Sivkova+2019*

Our estimates of metal loss rate for the MW

via wind - **0.02 - 0.03 $M_\odot yr^{-1}$**

by dust expelling ~ **0.01 $M_\odot yr^{-1}$**

Total accretion rate of metals **< 0.01 $M_\odot yr^{-1}$**

Conclusions

1. The enrichment of the intergalactic medium with heavy elements is a process that lies at the nexus of poorly-understood aspects of physical cosmology. (*Aguirre+2008*)

2. Dust should be included in compehensive models of chemical evolution of the Universe (first steps – *Callura&Mateucci2004, 2006*)

3. UV + X-ray + IR missions are very promising

Thanks for your attention!