Jason Tumlinson, Molly Peeples
& Jessica Werk

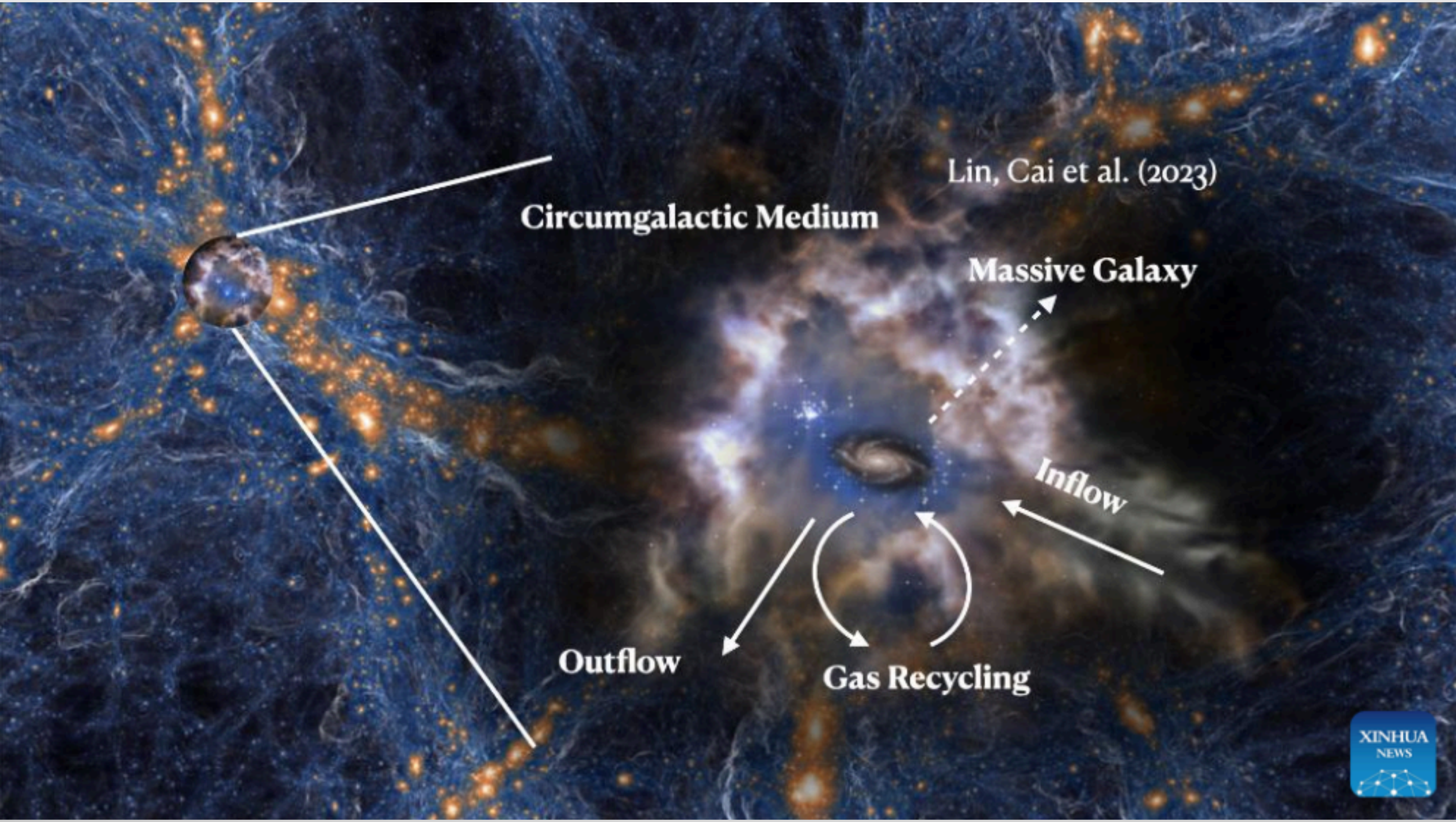
2017, ARA&A, 55, 389

The circumgalactic medium (CGM)

Related reviews/resources

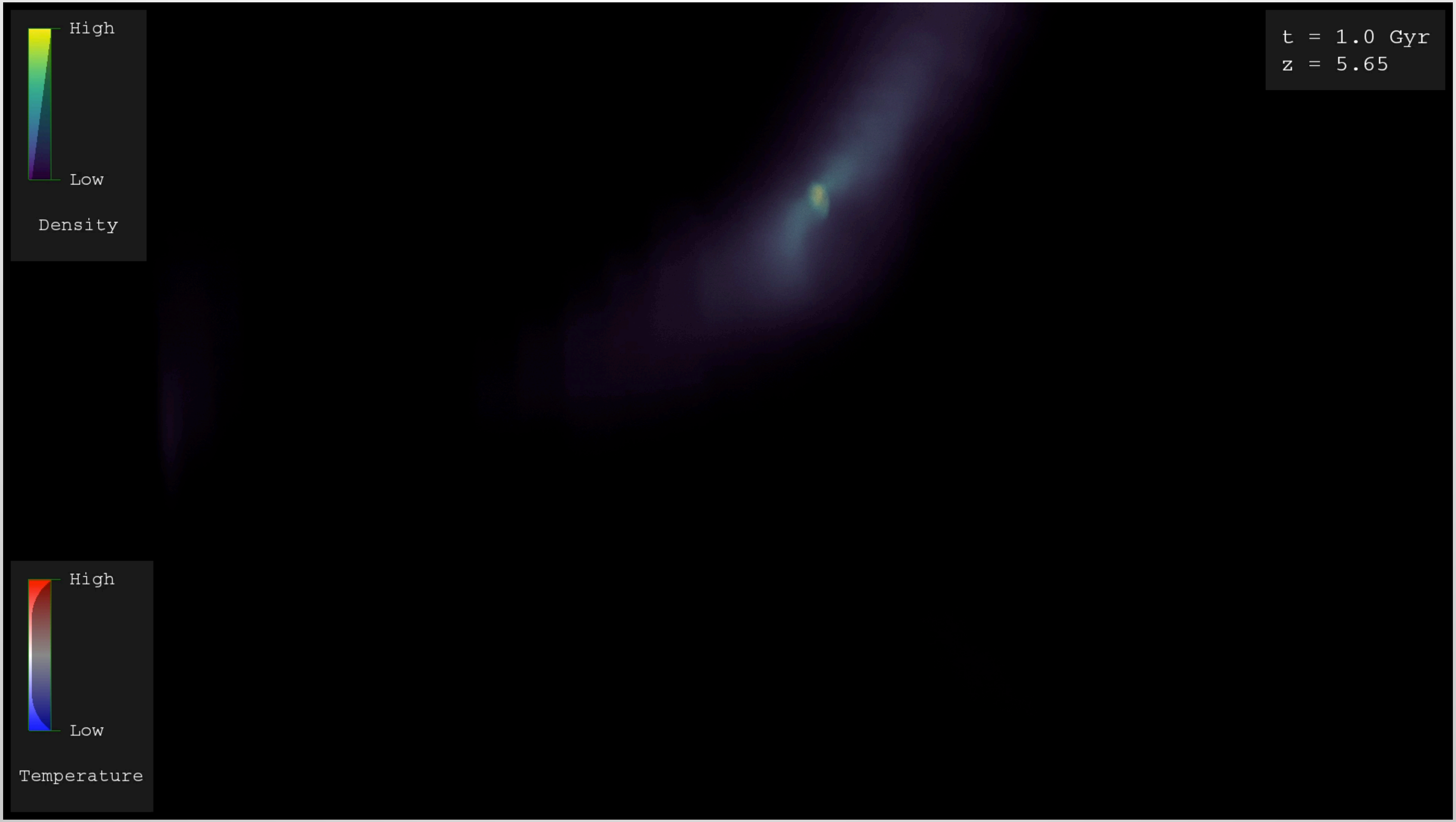
- Peroux & Howk 2020, ARA&A
- Wolfe et al. 2005 ARA&A

What is the CGM?



The extended gas reservoir over hundreds of kpc

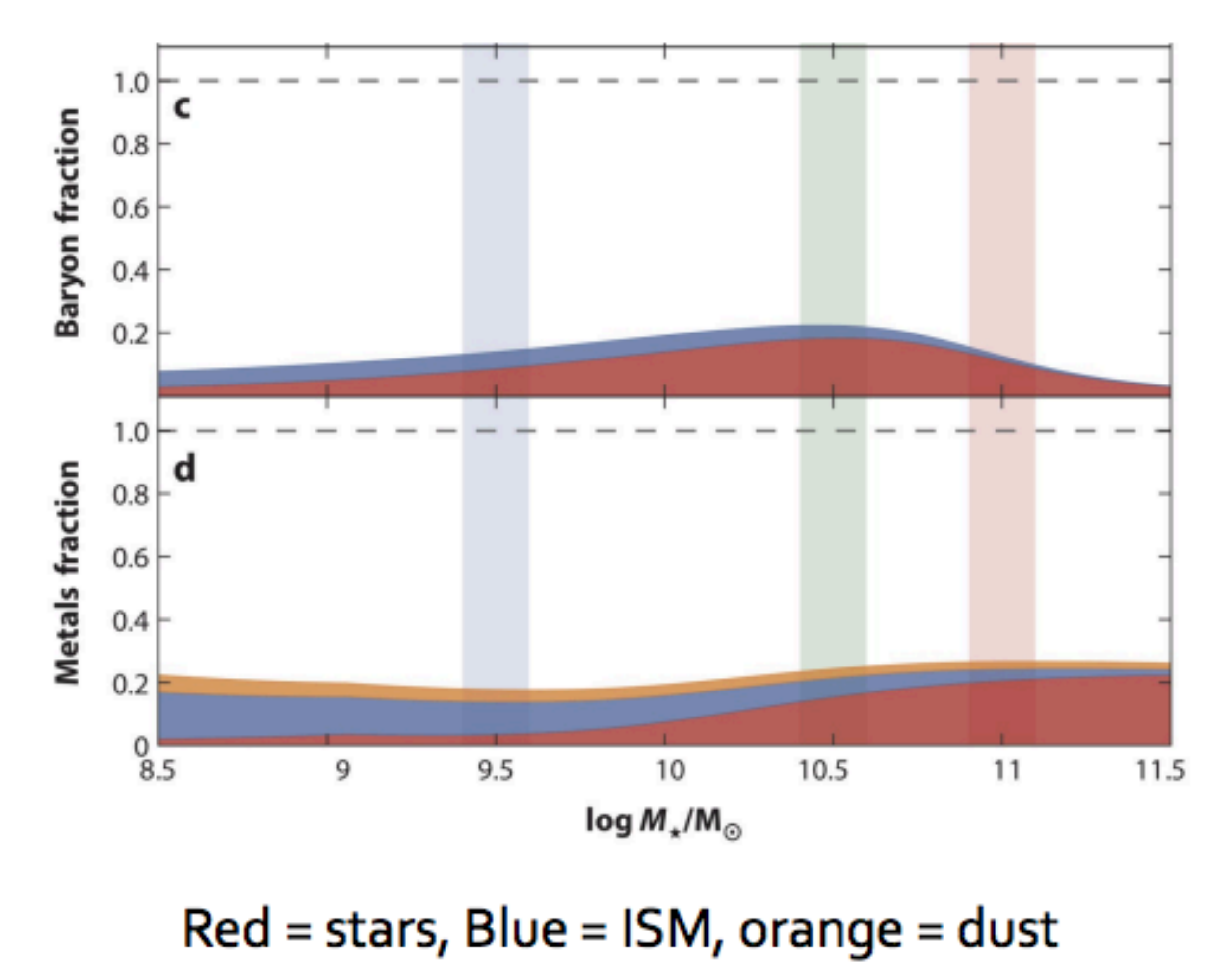
Why do we care?



The CGM captures complex processes.

Simulation from the FOGGIE collaboration

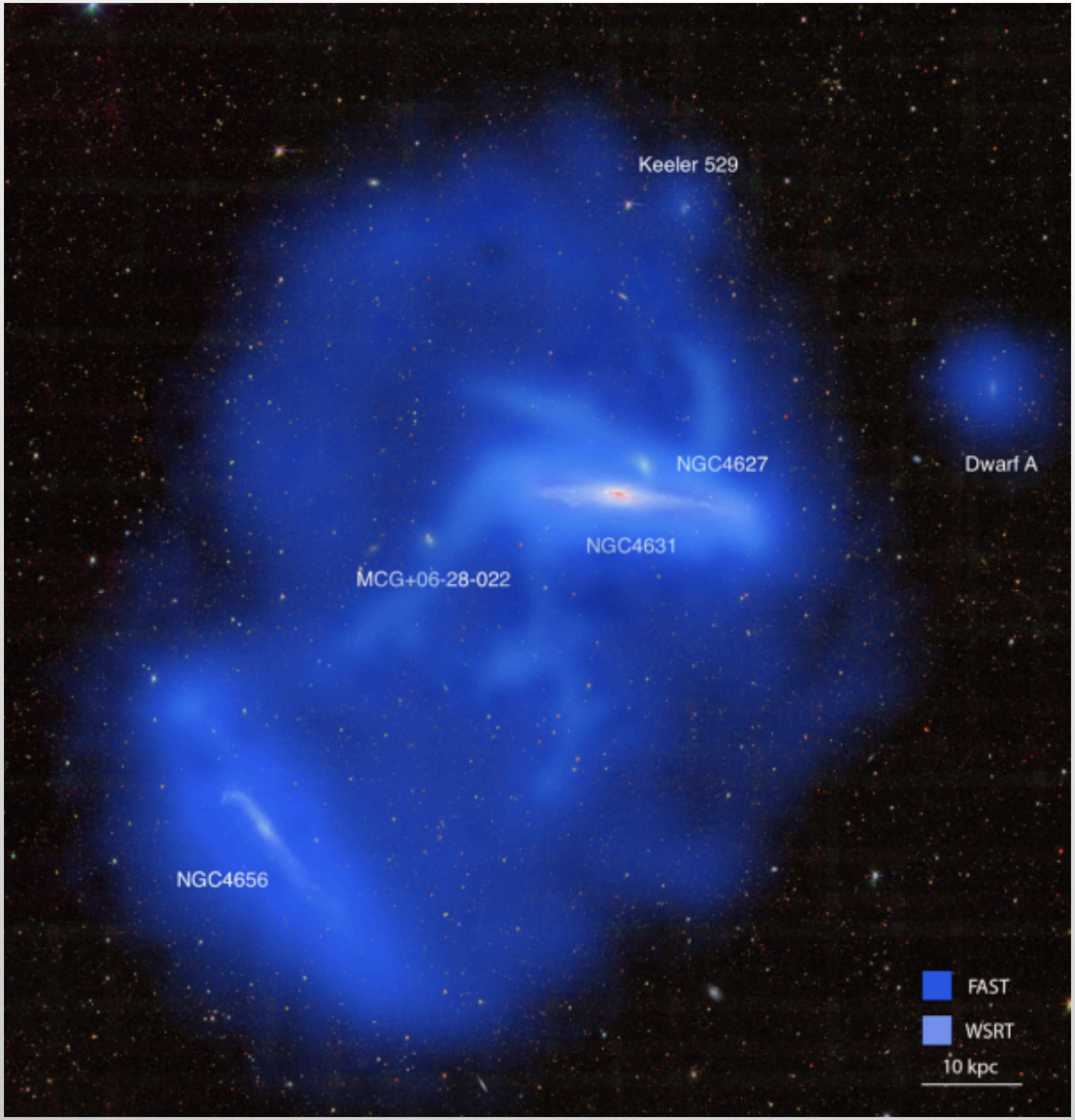
Why do we care?



The CGM may contain the bulk of galactic baryons.

Adapted from Tumlinson et al. (2017)

How do we trace the CGM?



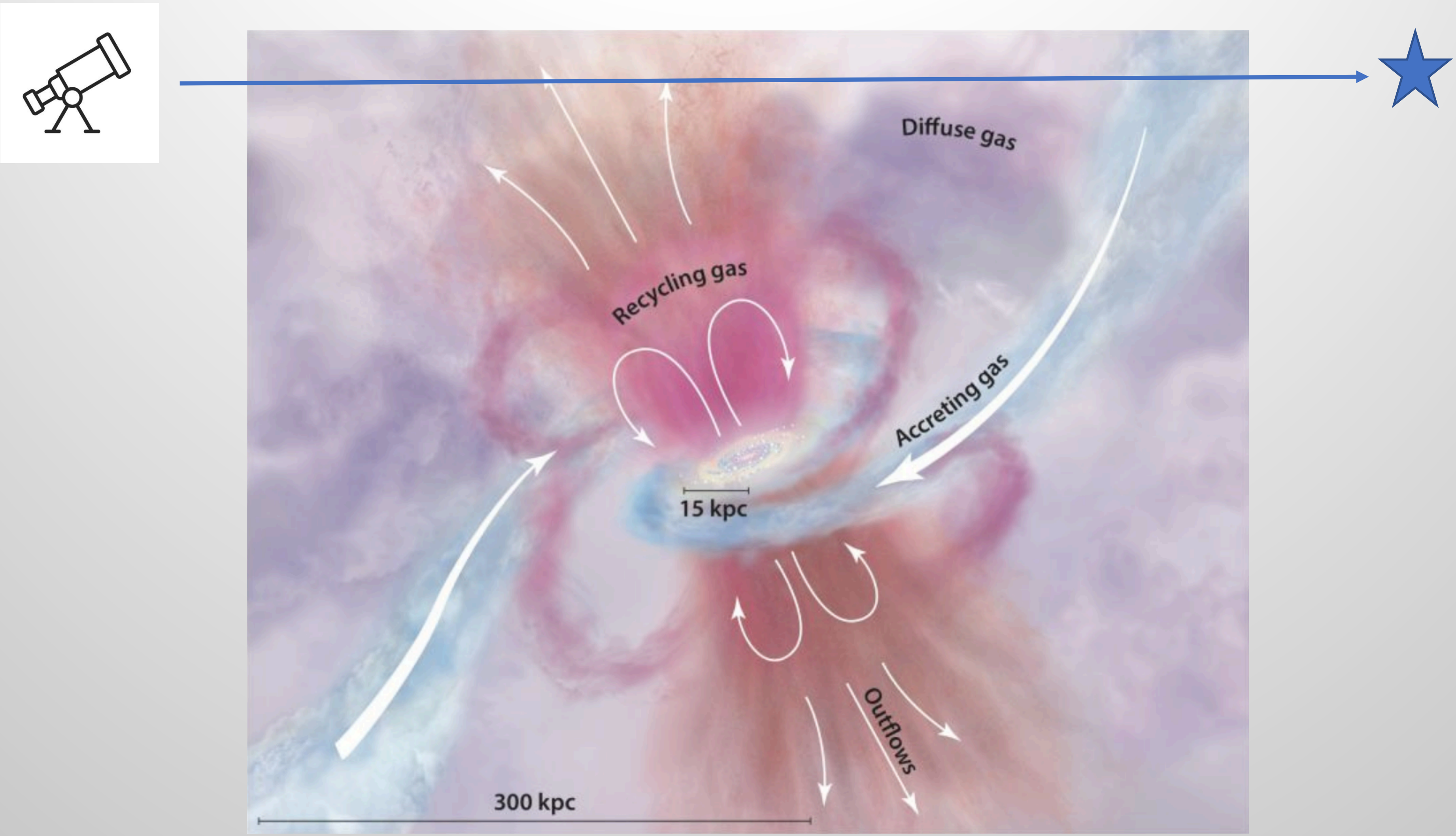
Currently, extremely challenging to detect extended diffuse gas in emission.

Deep map by FAST gets down to column densities N(HI) ~ 10^{18} cm^{-2}. CGM is expected to extended orders of magnitude below this.

Jargon alert: column density is an integrated line of sight measurement in atoms per sq. cm.

Wang et al. (2023)

Tracing gas and metals with QSO absorption lines



Tumlinson, Peeples & Werk (2017)

Tracing gas and metals with QSO absorption lines

Peroux & Howk (2020)

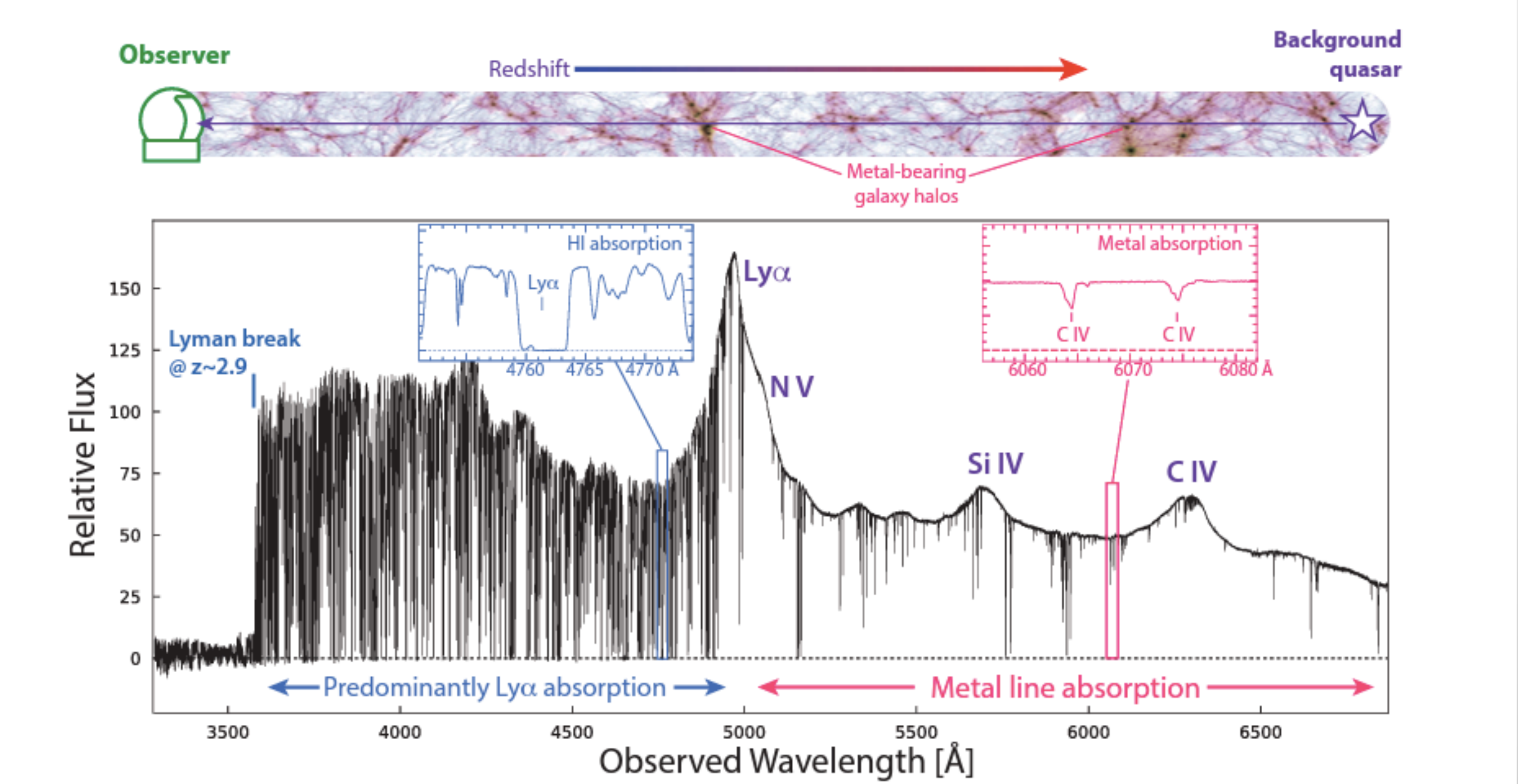


Figure 2

Absorption lines superimposed on the QSO's spectrum due to intervening *gas* in the intergalactic medium (IGM), circumgalactic medium (CGM) and interstellar medium (ISM). Jargon alert: Lyman break; Lyα forest.

A little bit of (ancient) history

No. 1, 1966 LETTERS TO THE EDITOR 369

ON THE ABSORPTION SPECTRUM OF 1116+12

We have analyzed two spectrograms of the quasi-stellar radio source 1116+12. Schmidt (1966) has derived a redshift of 2.118 from emission lines at 3795 and 4827 Å which were identified as Ly-α λ 1216 and C IV λ 1549, respectively. We have found on both plates wide absorption features at 3585 and 4570 Å. These absorption features are tentatively identified as Ly-α and C IV, respectively, with a redshift of 1.949. In this Letter we describe briefly the techniques and results of our analysis and, following Bahcall and Salpeter (1965, 1966), some implications of our tentative identifications.

Bahcall, Peterson & Schmidt (1966)

Intervening or ejected? Evidence from Lyα forest:

1. If ejected, redshifts correspond to ejection velocities

$$\beta = \frac{v_{ej}}{c} = \frac{(1+z_e)^2 - (1+z_a)^2}{(1+z_e)^2 + (1+z_a)^2}$$

2. Same line density from QSO to QSO and not a strong function of redshift

3. Closely separated projected pairs showed common absorption.

What makes an absorption spectrum?

Jargon alerts!

The flux (F) observed is a function of the intrinsic flux of the background object (F_0) and the line of sight optical depth (**τ**):

$$F(\nu) = F_0(\nu)e^{-\tau(\nu)}.$$

The optical depth (**τ**) is related to the column density (N) of intervening material and its absorption cross section (**σ**):

$$\tau(\nu) = \int_0^{+\infty} n\sigma(\nu)\, ds = N\sigma(\nu),$$

The cross section (**σ**) is in turn driven by the f-value (oscillator strength), which measures the fundamental strength of a given transition. The line shape (**ϕ**) describes the shape of the line.

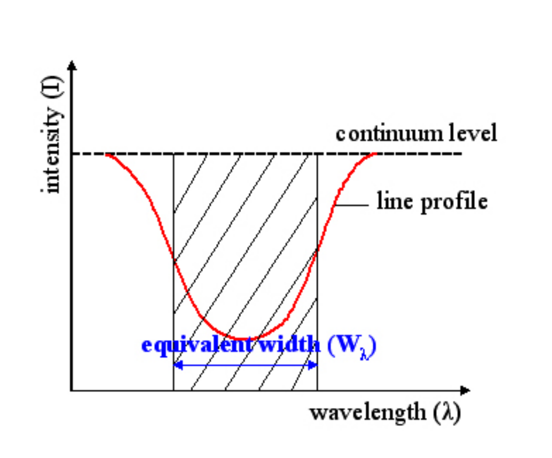
$$\sigma(\nu) = \frac{\pi e^2}{m_e c} f\phi(\nu).$$

Defining a line profile: Equivalent width

The observed wavelength of a line is $\lambda_{obs} = (1+z) x \lambda_{rest}$

Equivalent width:

$$W_{\rm rest} = \int \frac{F_0(\lambda) - F(\lambda)}{F_0(\lambda)}\, d\lambda_{rest} = \int \left(1 - e^{-\tau(\lambda)}\right) d\lambda_{rest},$$



measured in Angstroms.

$W_{obs} = W_{rest} \times (1+z)$

EWs are usually used when the spectral line is *unresolved. EWs* have positive values for absorption lines and negative values for emission lines.

Defining a line profile: Column density

Column density:

$$N = 1.13 \times 10^{20} \frac{W(\lambda)}{\lambda_0^2 f}$$

Where W is the EW. This conversion between EW and N is only applicable when the line is unsaturated. Measured in atoms cm^{-2}.

Doppler parameter:

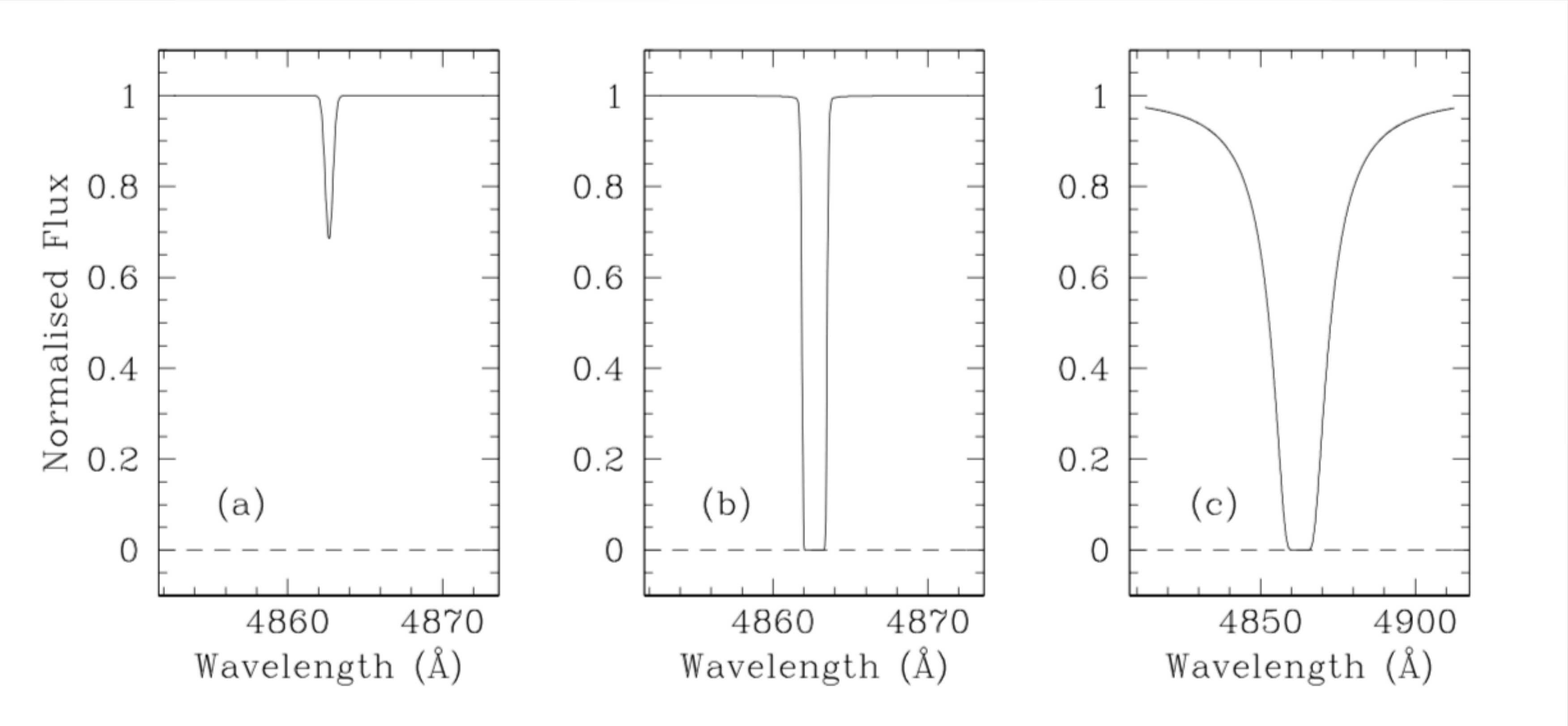
$$b = \sqrt{\frac{2kT}{m} + b_{turbulent}^2}$$

Measured in km/s.

Since Doppler parameter (or b-value) is a measure of line width it can also be expressed in terms of FWHM or σ

$$b = \sqrt{2}\sigma = \frac{FWHM}{2\sqrt{ln2}}$$

Defining a line profile: the three regimes



Unsaturated (weak/linear) Saturated Damped

Defining a line profile: the curve of growth

The curve of growth shows the connection between EW and N. Three regimes, of which only two have unique conversions between EW and N.

1) Unsaturated (linear) regime

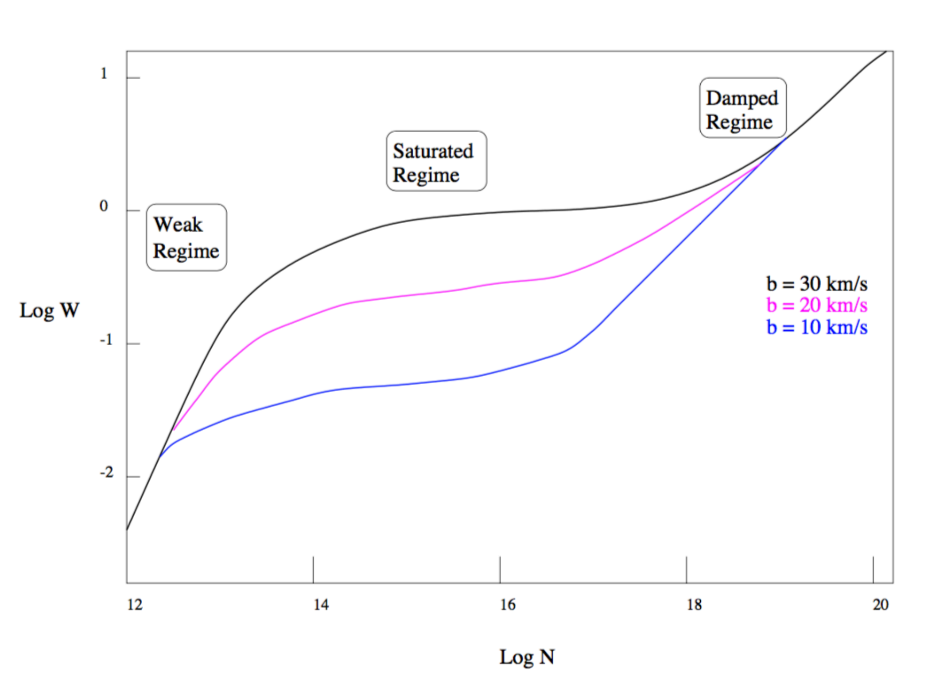
$$W(\lambda) = \frac{\pi e^2 \lambda_0}{m_e c^2} N \lambda_0 f$$

2) Saturated regime

$$W(\lambda) \sim \frac{2b\lambda_0}{c} \sqrt{\ln\left(\frac{\pi^{0.5} e^2 N \lambda_0 f}{m_e c b}\right)}$$

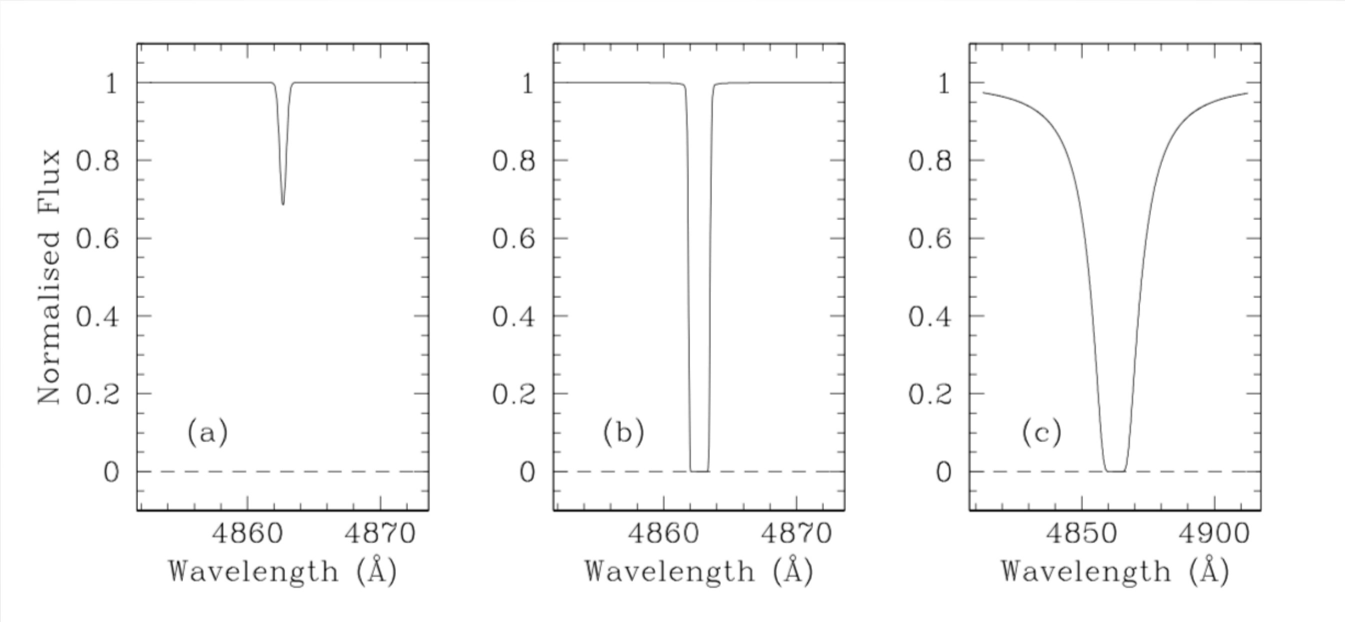
3) Damped regime

$$W(\lambda) \sim \frac{\lambda_0^{1.5}}{c} \sqrt{\frac{e^2}{m_e c} N \lambda_0 f \Gamma}$$



The connection between EW and N in the saturated regime is dependent on b value (Doppler parameter). I.e. can't convert from EW to N in a non-degenerate way.

Defining a line profile: the Voigt profile

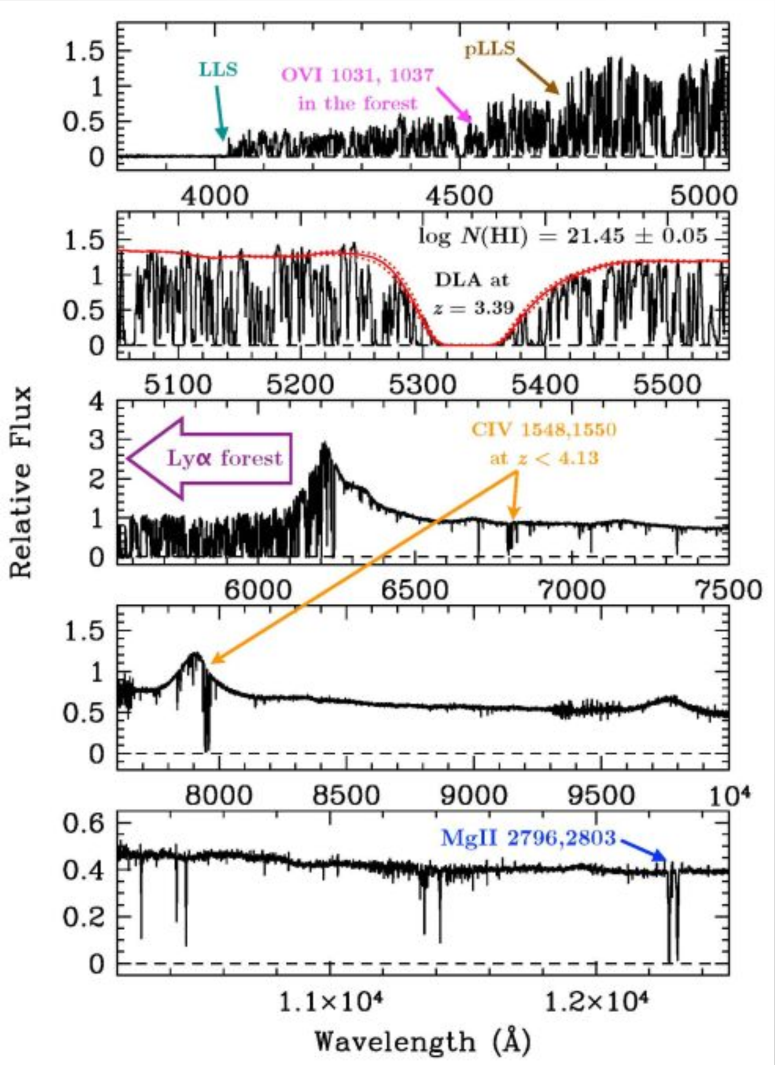


Unsaturated Saturated Damped

The line profile is overall described as a ‘Voigt’ profile, which is the combination of a Gaussian (describing the internal motions of the gas, turbulent and thermal) and a Lorentz component (QM uncertainties in lambda) which become important at high column density and lead to damping wings.

More details on line formation in lecture 1 of ISM course: www.astro.uvic.ca/~sara/A503.html

The QSO absorption line zoo



The different types of absorbers are named for the features through which they are identified. E.g.

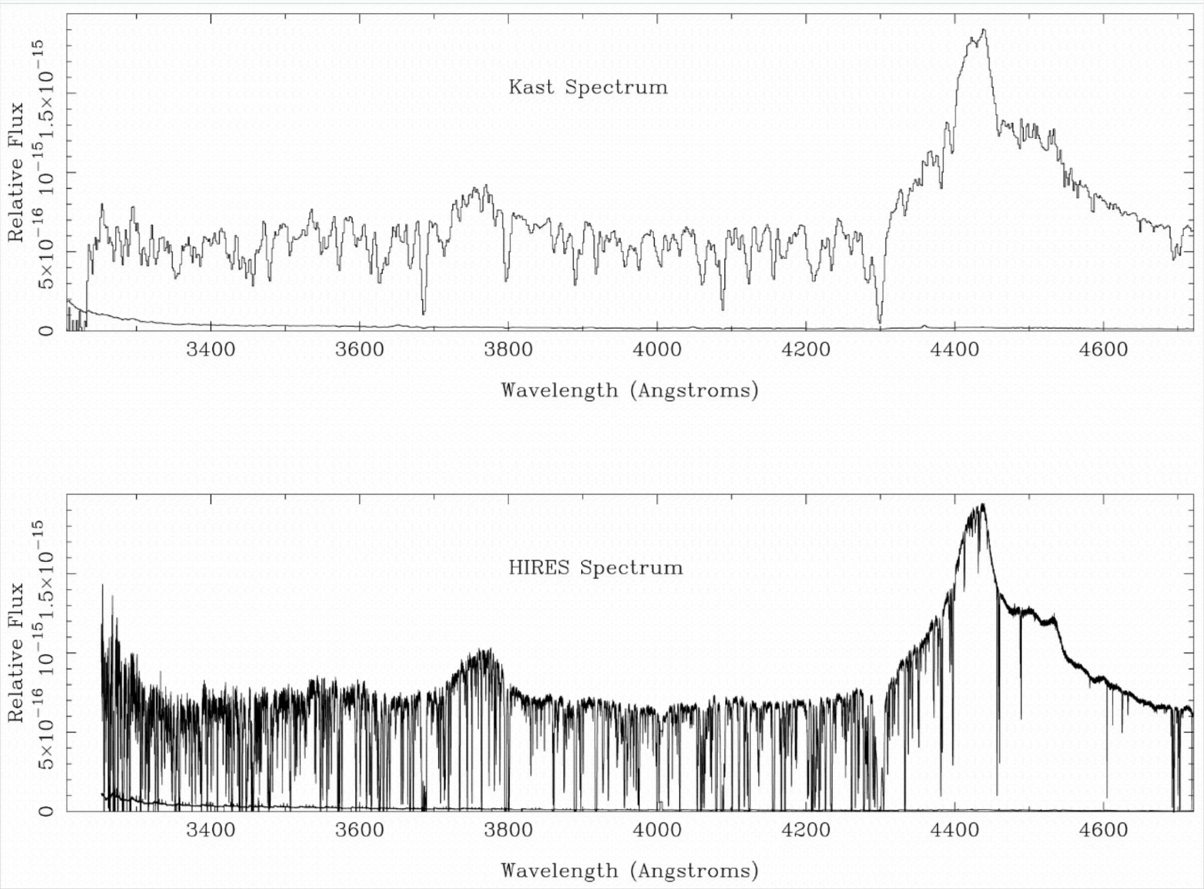
- CIV, MgII, CaII absorbers identified by their metal lines.
- Damped Lyman alpha systems(DLAs), sub-DLAs and Lyman limit systems identified by their HI properties.

Absorber	Log N(HI)	Signature	What is it?
Lyα forest	11 - 17.5 cm^{-2}	Lyα 1216 A	IGM/CGM
CIV system	> 14 cm^{-2} ?	CIV 1548 A	IGM/ISM/CGM
MgII system	> 17 cm^{-2}	Mg II 2796 A	ISM/CGM
Lyman limit systems	> 17.5 cm^{-2}	Lyman limit at 912 A	ISM/CGM
Sub-DLA	19 - 20.3 cm^{-2}	Weak Lyα damping wings	CGM? Massive (gas-poor) galaxy ISM?
DLA	> 20.3 cm^{-2}	Lyα damping wings	Galaxy ISM
CaII system	> 19 cm^{-2} ?	CaII 3935 A	High density gas?

Instrumentation: echelle spectroscopy

The field of QSO absorption line spectroscopy benefits from high resolution for two reasons.

1). The Lyα forest is very dense – high resolution needed to deblend the lines.



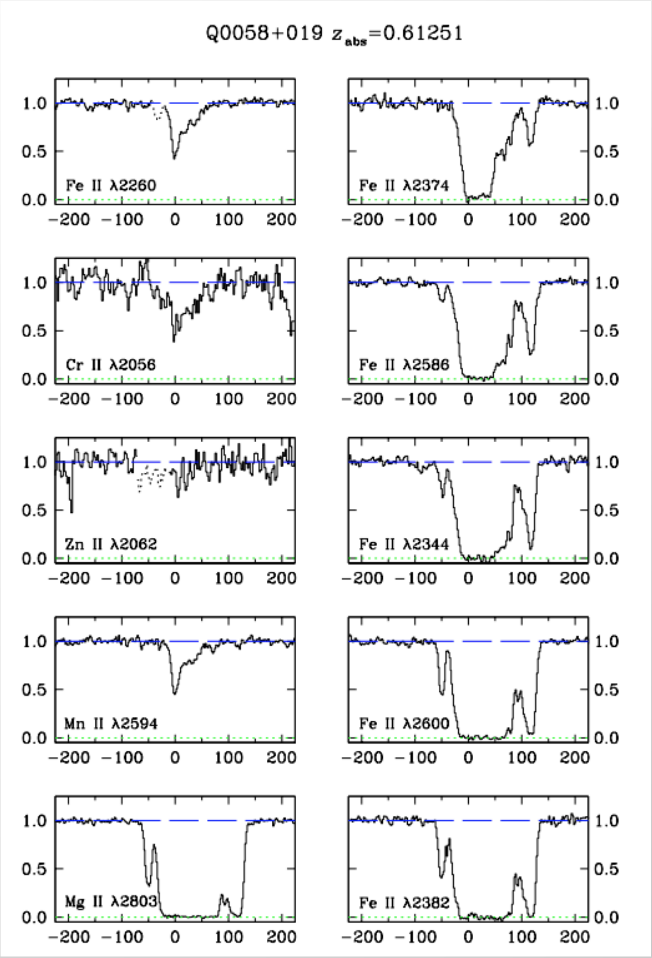
O'Meara et al. (2001)

Instrumentation: echelle spectroscopy

The field of QSO absorption line spectroscopy benefits from high resolution for two reasons.

1). The Lyα forest is very dense – high resolution needed to deblend the lines.

2). Metal lines are kinematically complex; although we could still get a total N(X) as long as they are unsaturated (why?).

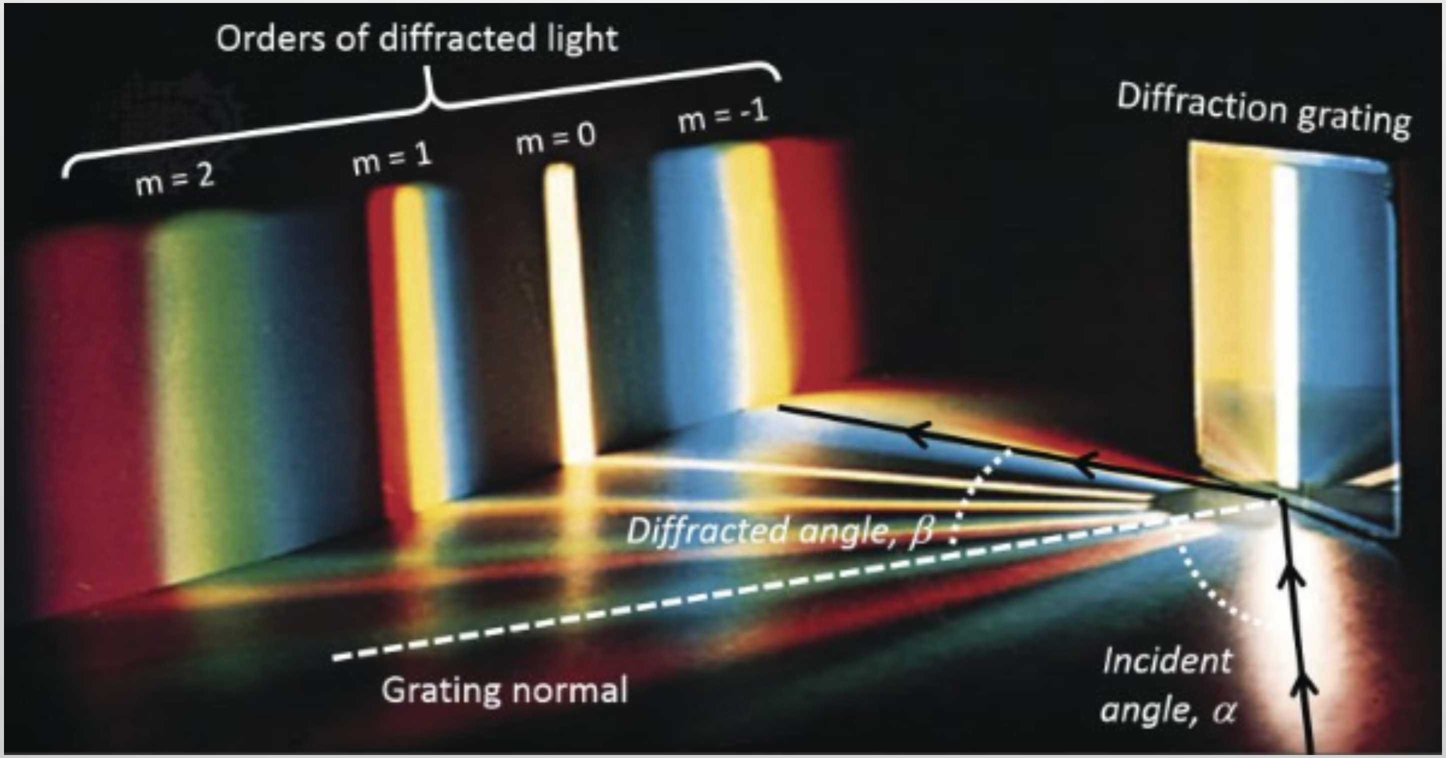


Pettini et al. (2000)

Instrumentation: echelle spectroscopy

Working at high orders or high grating rulings have their challenges (what?). An alternative is cross dispersed AKA echelle spectroscopy.

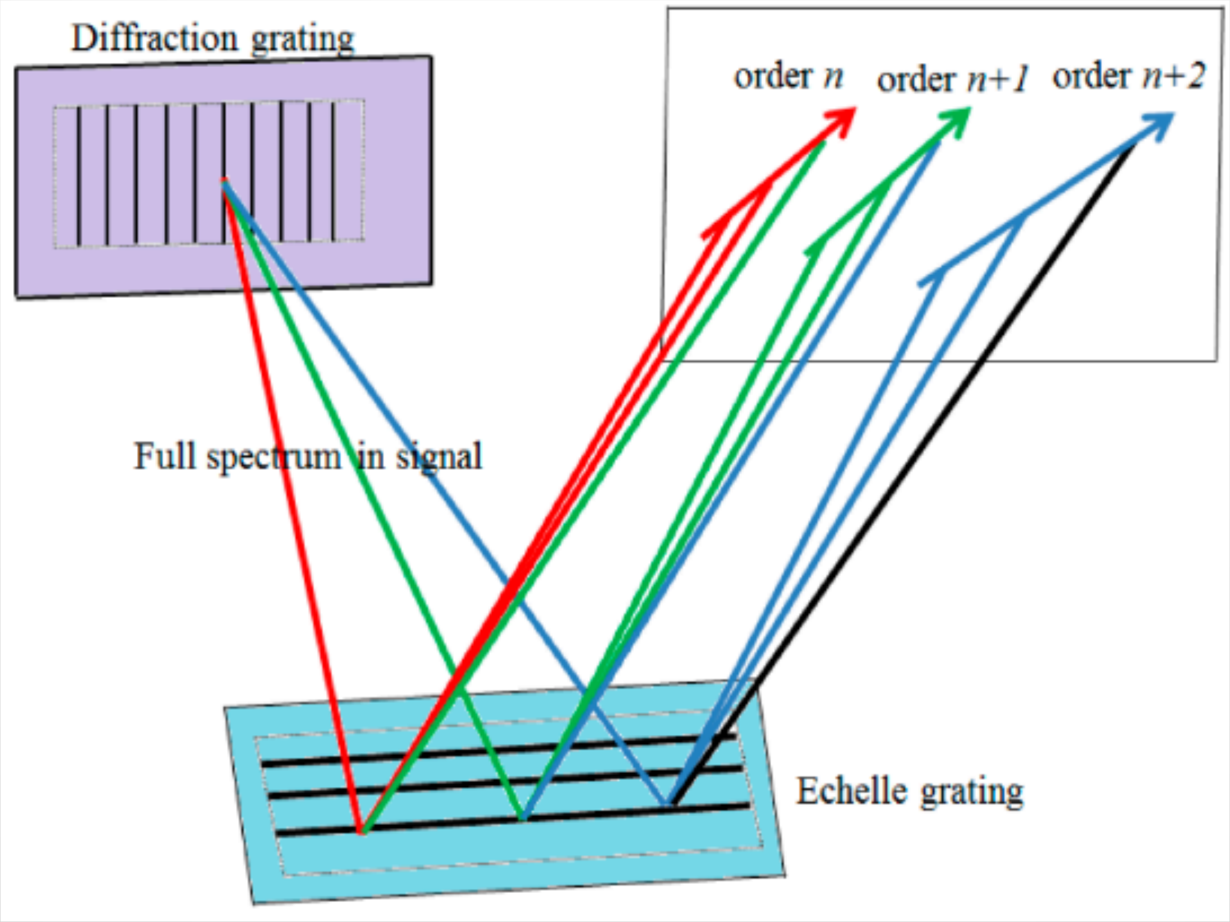
Recall from an earlier lecture that a grating produces different spectral orders. In most spectrographs we work with n=1 to avoid overlapping orders.



$$n\lambda = d \sin\theta$$

Instrumentation: echelle spectroscopy

Also recall that the grating equation tells us that each point on the spectrum is the superposition of many orders: $n\lambda = d \sin\theta$. These orders can be separated by placing a second grating perpendicular to the first.



Instrumentation: echelle spectroscopy

Echelle spectrographs on 8-10 metre class telescopes (e.g. HIRES on Keck and UVES on the VLT) generated a revolution for the field of QSO absorption line spectroscopy.

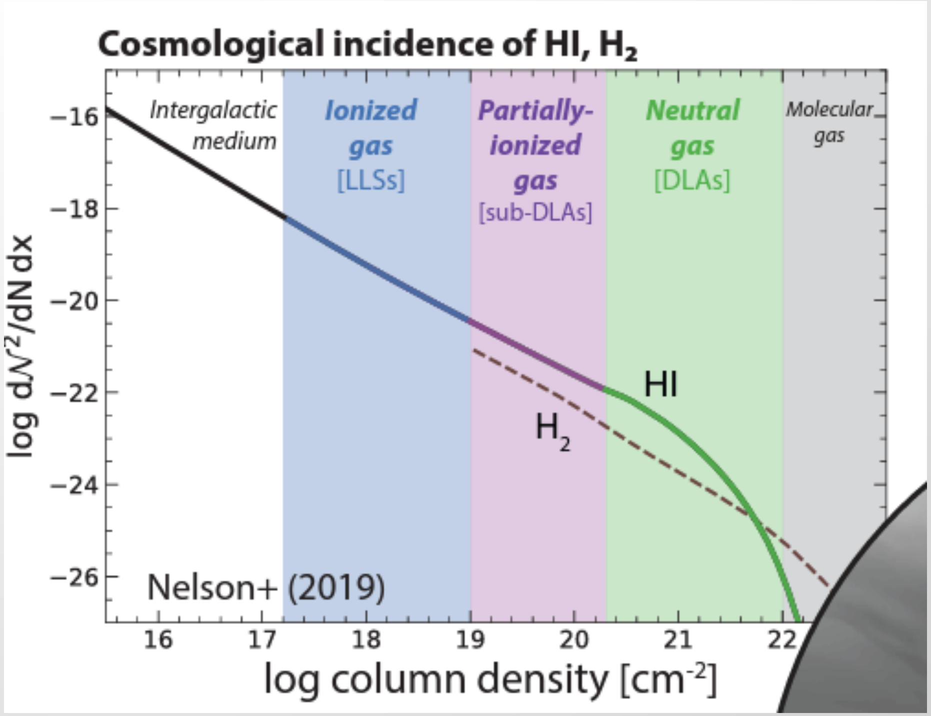
(Also for the field of studying metal poor stars).

A cosmic census of (neutral) gasc

The column density distribution function describes how many absorbers exist per unit column density per unit redshift path.

$$f(N,z)dNdX = \frac{\mathcal{N}}{\Delta N \sum_{i=1}^{m} \Delta X_i} dNdX,$$

The redshift path (dX) is related to a redshift interval (dz) but is a comoving unit that depends on cosmology:



Peroux & Howk (2020)

$$X(z) = \int_0^z (1+z)^2 \left[\frac{H_0}{H(z)}\right] dz = \int_0^z (1+z)^2 \left[\Omega_\Lambda + \Omega_m (1+z)^3\right]^{-1/2} dz,$$

A cosmic census of (neutral) gas

Integrating f(N) gives the total amount of neutral gas.

$$\rho_{\rm neutral\ gas}(z) = \frac{H_o \mu m_{\rm H}}{c} \int_{N_{min}}^{N_{max}} N f(N,z) dN,$$

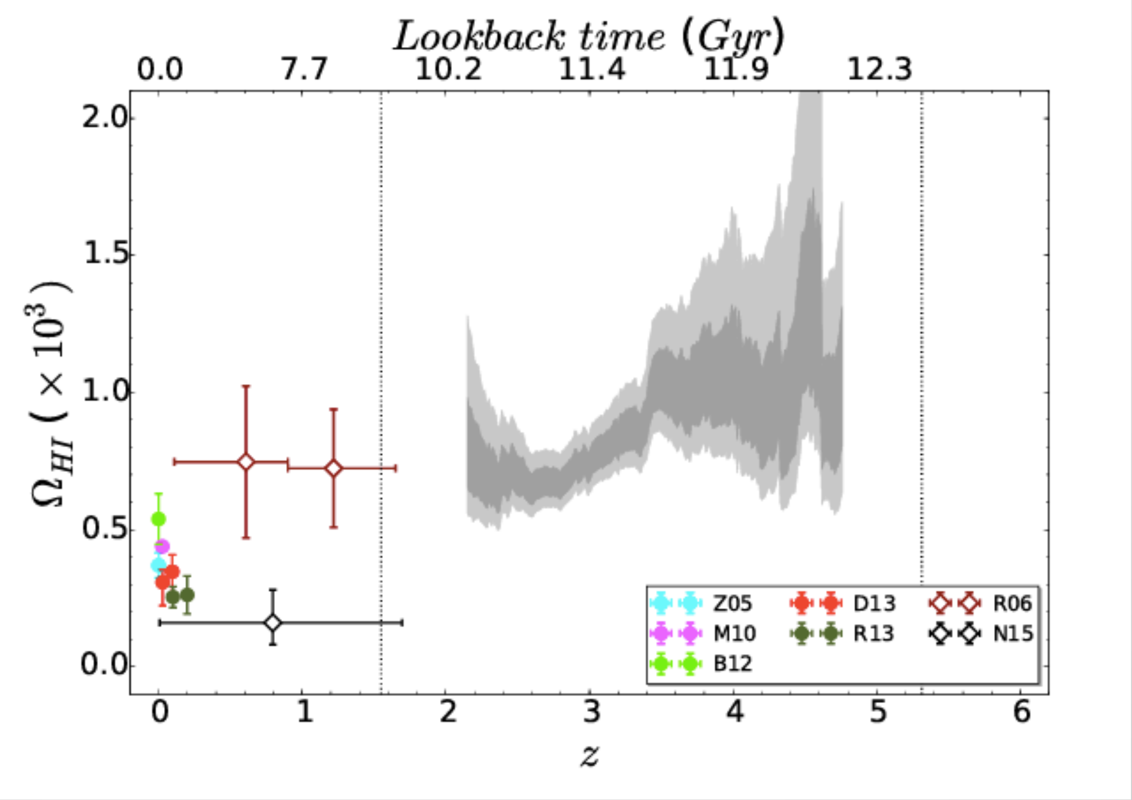
This integral is dominated by DLAs (because f(N) is a power law with index ~ -1.5) – useful as DLA N(HI) is easily measured in low resolution spectra which exist in large numbers thanks to QSO surveys such as SDSS.

Neutral gas density often expressed in units of the universe's critical density:

$$\Omega(z) = \rho(z)/\rho_{\rm crit,0} = \rho(z)/(3\,H_0^2/8\pi G).$$

A cosmic census of (neutral) gas

- Ω_{HI} is very flat with redshift: neutral gas must be replenished. CGM is the reservoir?
- Problems at low z where optical surveys can't trace DLAs (SKA will save us!).



Sanchez Ramirez et al. (2016)

Measuring metal abundances

Jargon/nomenclature alert

We have previously encountered the use of 12 + log (O/H) for gas phase metallicities. For generally we can define the abundance of element X as

$$A(X) = \log (n(x)/n(H)) + 12$$

Where A(H) is arbitrarily set to 12. I.e. A(X) measures the abundance of element X per 10^{12} atoms of H.

Alternatively use [X/H] "square bracket" notation which measures the abundance relative to H reletive to a log solar scale.

$$[X/H] = log(N(X)/N(H)) - log(N(X)_{\odot}/N(H)_{\odot})$$

Measuring metal abundances

The definition:

$$[X/H] = log(N(X)/N(H)) - log(N(X)_{\odot}/N(H)_{\odot})$$

I.e. we use abundances relative to solar on a log scale.

Challenge #1: ionization states

We also assume that N(XII) = N(X) and N(HI)=N(H). This (nominally) works because the ionization potential of XII is usually >13.6 eV and these photons are shielded by HI. However, debates about ionization corrections continue to crop up.

Complete Ionization Potentials for the First 10 Elements (eV)

Z	element	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	H	13.6									
2	He	24.6	54.4								
3	Li	5.4	75.6	122							
4	Be	9.3	18.2	154	218						
5	B	8.3	25.2	37.9	259	340					
6	C	11.3	24.4	47.9	64.5	392	490				
7	N	14.5	29.6	47.5	77.5	97.9	552	667			
8	O	13.6	35.1	54.9	77.4	114	138	739	871		
9	F	17.4	35.0	62.7	87.1	114	157	185	953	1103	
10	Ne	21.6	41.0	63.5	97.1	126	158	207	239	1196	1362

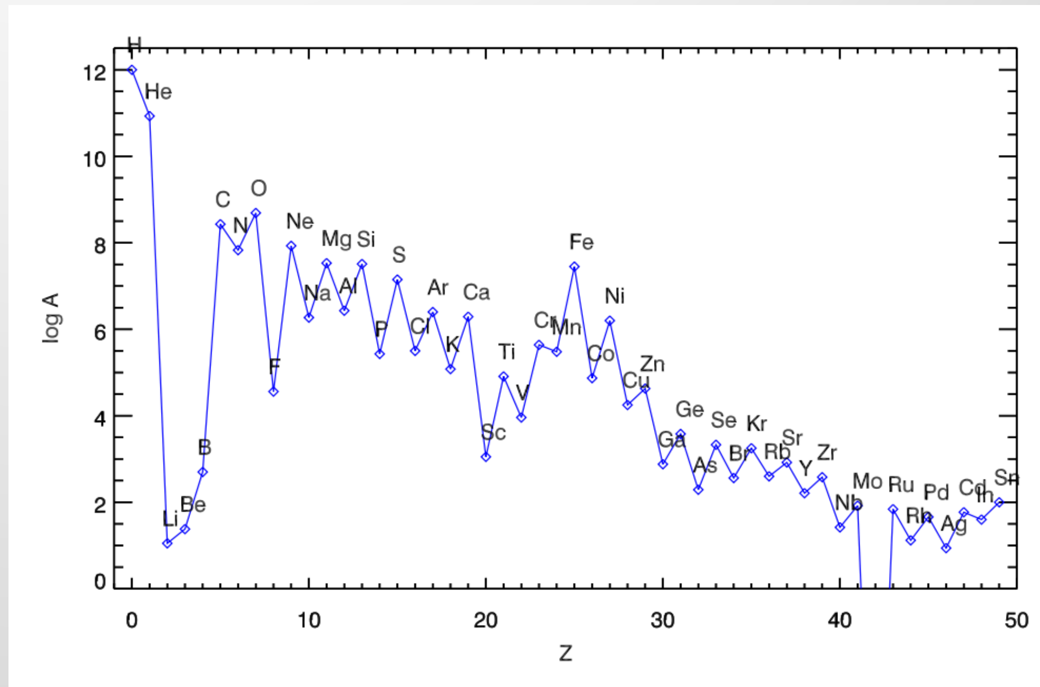
First 5 Ionization Potentials (eV) only, for other "A" group elements

Z	element	1st	2nd	3rd	4th	5th	Z	element	1st	2nd	3rd	4th	5th
11	Na	5.1	47.3	71.6	98.9	138	38	Sr	5.7	11.0	43.6	57	71.6
12	Mg	7.6	15.0	80.1	109	141	49	In	5.8	18.9	28.0	54	?
13	Al	6.0	18.8	28.4	120	154	50	Sn	7.3	14.6	30.5	40.7	72.3
14	Si	8.2	16.3	33.5	45.1	167	51	Sb	8.6	16.5	25.3	44.2	56
15	P	10.5	19.7	30.2	51.4	65.0	52	Te	9.0	18.6	28.0	37.4	58.8
16	S	10.4	23.3	34.8	47.3	72.7	53	I	10.5	19.1	33	?	?
17	Cl	13.0	23.8	39.6	53.5	67.8	54	Xe	12.1	21.2	32.1	?	?
18	Ar	15.8	27.6	40.7	59.8	75.0	55	Cs	3.9	25.1	?	?	?
19	K	4.3	31.6	45.7	60.9	82.7	56	Ba	5.2	10.0	?	?	?
20	Ca	6.1	11.9	50.9	67.1	84.4	81	Tl	6.1	20.4	29.8	?	?
31	Ga	6.0	20.5	30.7	64	?	82	Pb	7.4	15.0	31.9	42.3	68.8
32	Ge	7.9	15.9	34.2	45.7	93.5	83	Bi	7.3	16.7	25.6	45.3	56.0
33	As	9.8	18.6	28.4	50.1	62.6	84	Po	8.4	?	?	?	?
34	Se	9.8	21.2	30.8	42.9	68.3	85	At	9.5	?	?	?	?
35	Br	11.8	21.8	36	47.3	59.7	86	Rn	10.7	?	?	?	?
36	Kr	14.0	24.4	37.0	52.5	64.7	87	Fr	4	?	?	?	?
37	Rb	4.2	27.3	40	52.6	71.0	88	Ra	5.3	10.1	?	?	?

Measuring metal abundances

Solar abundances measured in solar photosphere and in meteorites

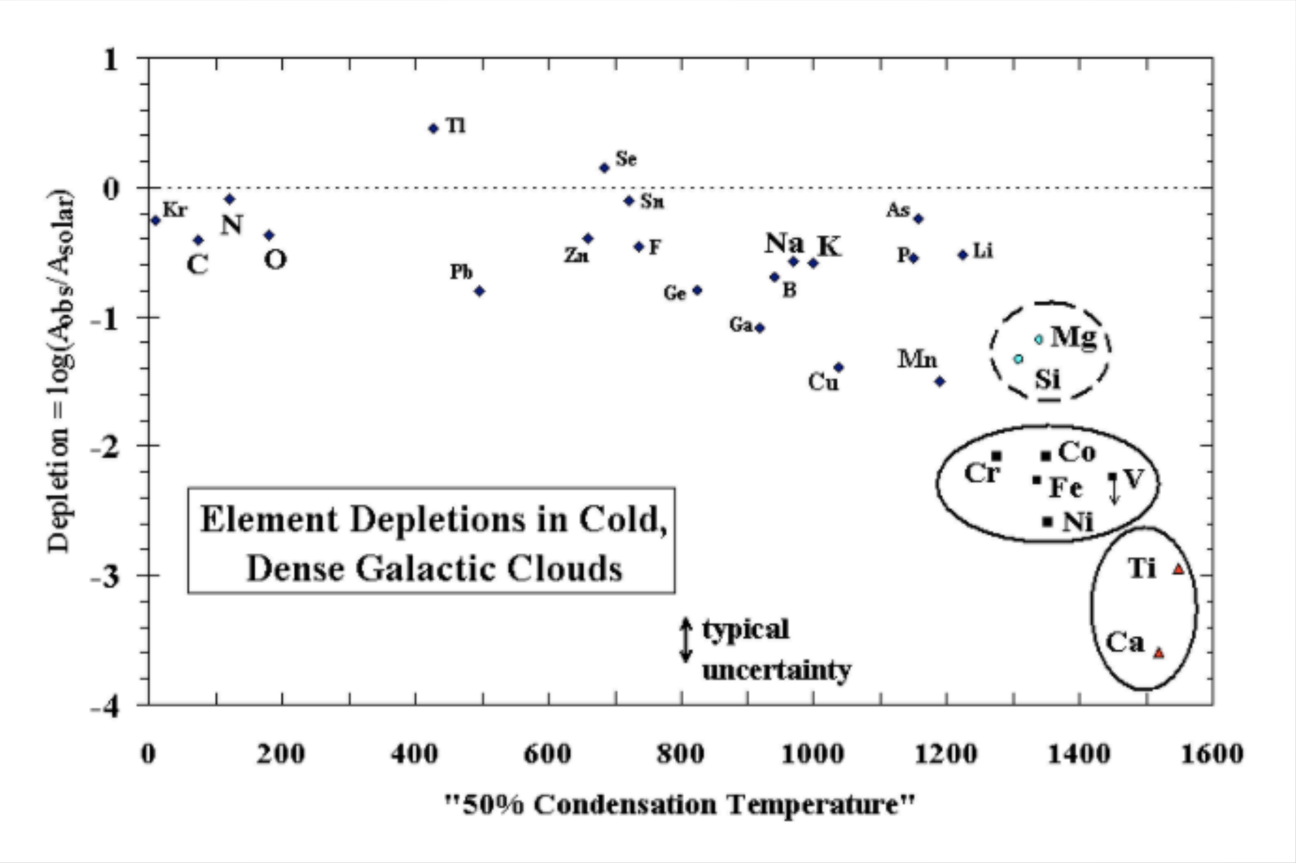
	Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04
2	He	$[10.93 \pm 0.01]$	1.29
3	Li	1.05 ± 0.10	3.26 ± 0.05
4	Be	1.38 ± 0.09	1.30 ± 0.03
5	B	2.70 ± 0.20	2.79 ± 0.04
6	C	8.43 ± 0.05	7.39 ± 0.04
7	N	7.83 ± 0.05	6.26 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04
9	F	4.56 ± 0.30	4.42 ± 0.06
10	Ne	$[7.93 \pm 0.10]$	-1.12
11	Na	6.24 ± 0.04	6.27 ± 0.02
12	Mg	7.60 ± 0.04	7.53 ± 0.01
13	Al	6.45 ± 0.03	6.43 ± 0.01
14	Si	7.51 ± 0.03	7.51 ± 0.01
15	P	5.41 ± 0.03	5.43 ± 0.04
16	S	7.12 ± 0.03	7.15 ± 0.02



Solar abundances from Asplund et al. (2009).

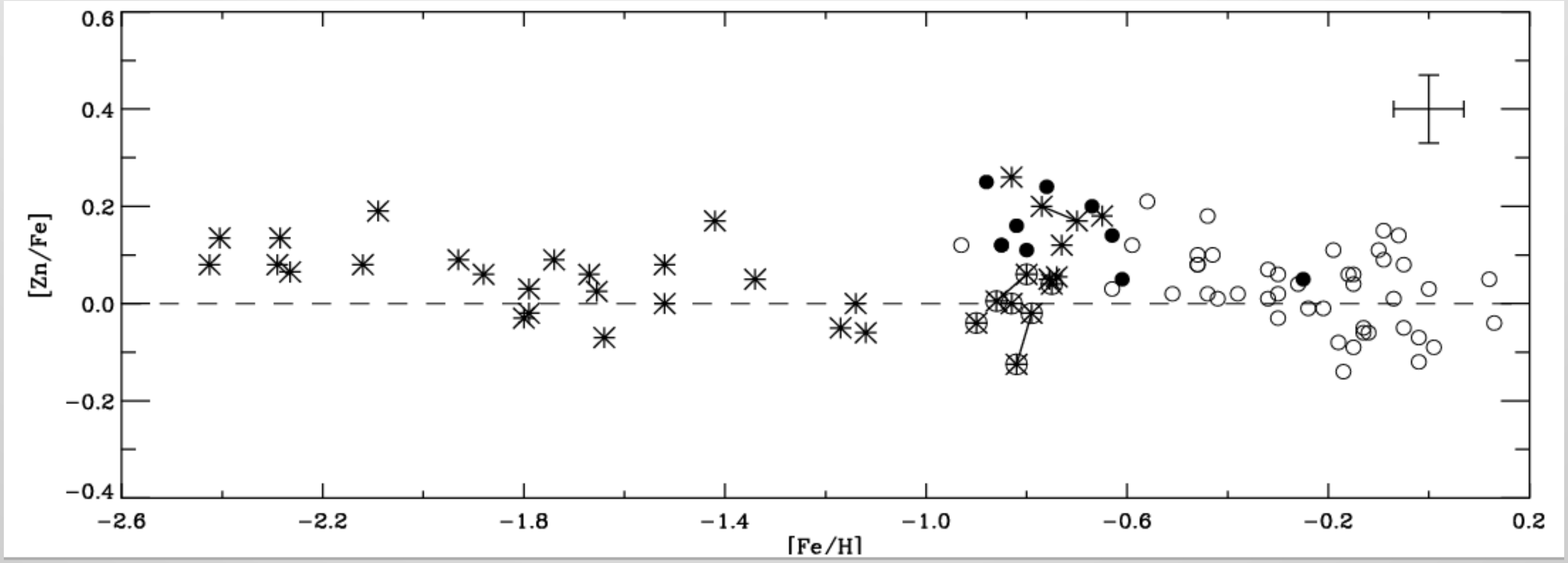
Measuring metal abundances

Challenge #2: Which element? For HII regions we use O/H; in stars we usually use Fe/H. We can't use O or Fe (easily) for DLAS: O lines usually saturated and Fe is depleted onto dust.



Measuring metal abundances

One common solution is to use Zn to measure 'metallicity' in DLAs: Zn traces Fe in stars (i.e. a good proxy), lines are not saturated and little affected by dust. Alternatively, try to estimate a dust depletion correction factor.



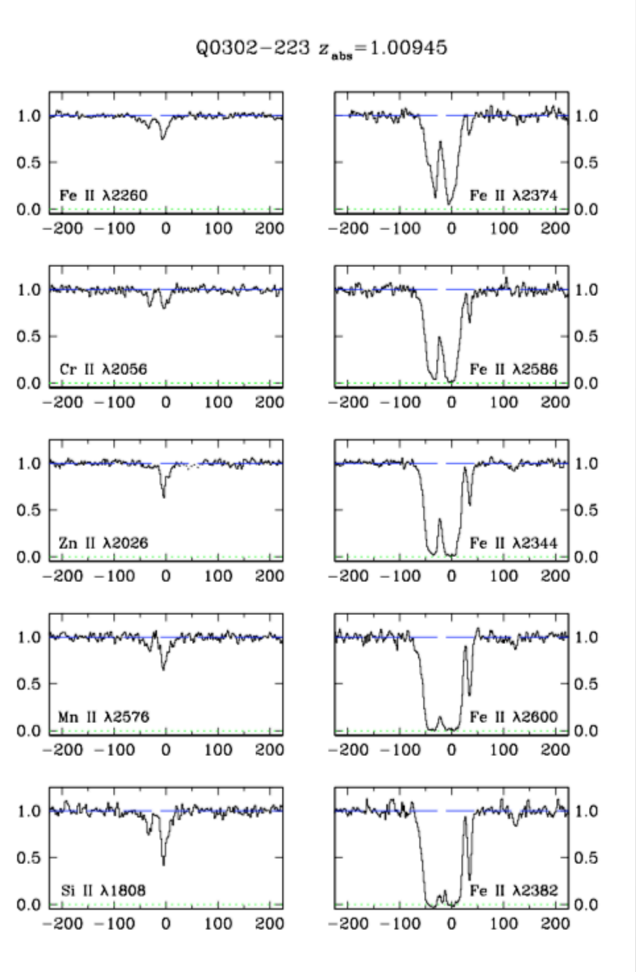
Measuring metal abundances

Challenge #3: The need for high resolution spectroscopy on large telescopes.

High resolution is required to 1) check the lines aren't saturated, 2) study velocity structure and 3) fit individual lines.

The field underwent a revolution in the late 90s/early 2000s when echelle spectrographs became available on Keck and VLT.

Even so, observations are expensive. In contrast to many thousands of DLA HI measurements, abundance measurements of DLAs count in the few hundred.



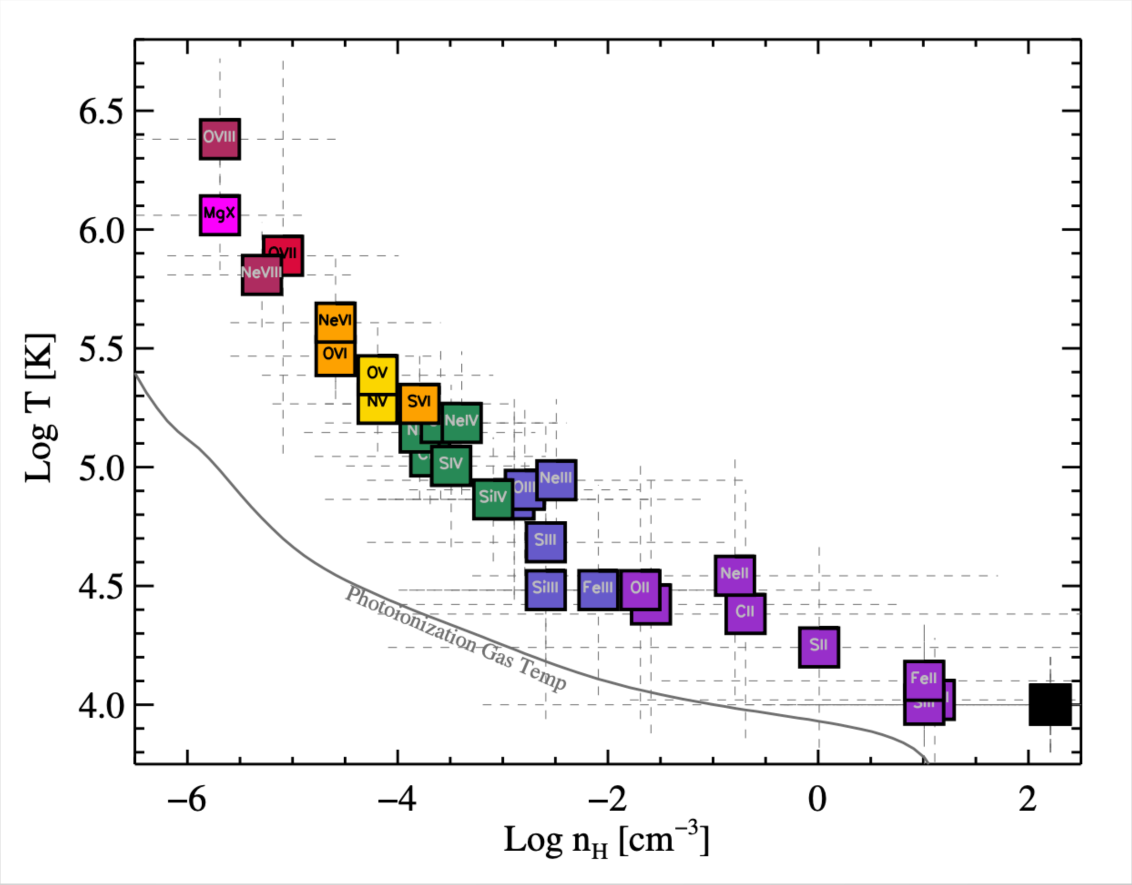
Ellison (2000)

Measuring metal abundances

Challenge #4: The multiphase ISM/CGM best studied in the rest frame UV

Space telescopes required (unless very high z).

- **HI:** 1215, 1025… Å
- **MgII:** 2803, 2796, Å
- **SiII:** 1526, 1260…Å
- **SiIII:** 1206 Å
- **SiIV:** 1402, 1393 Å
- **CIV:** 1550, 1548 Å
- **OVI:** 1031, 1037 Å
- **NeVIII:** 770, 780 Å



Tumlinson, Peeples & Werk (2017)

Measuring metal abundances

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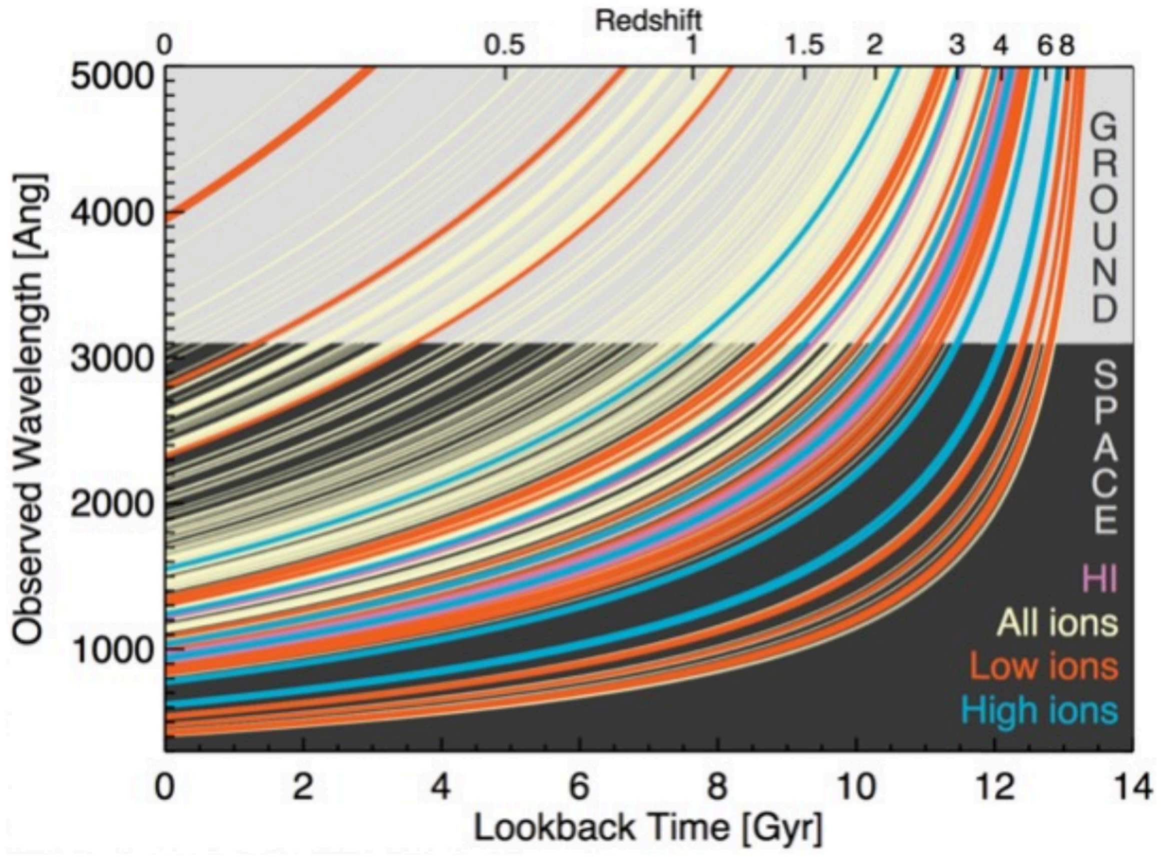

Tumlinson, Peeples & Werk (2017)

Measuring metal abundances

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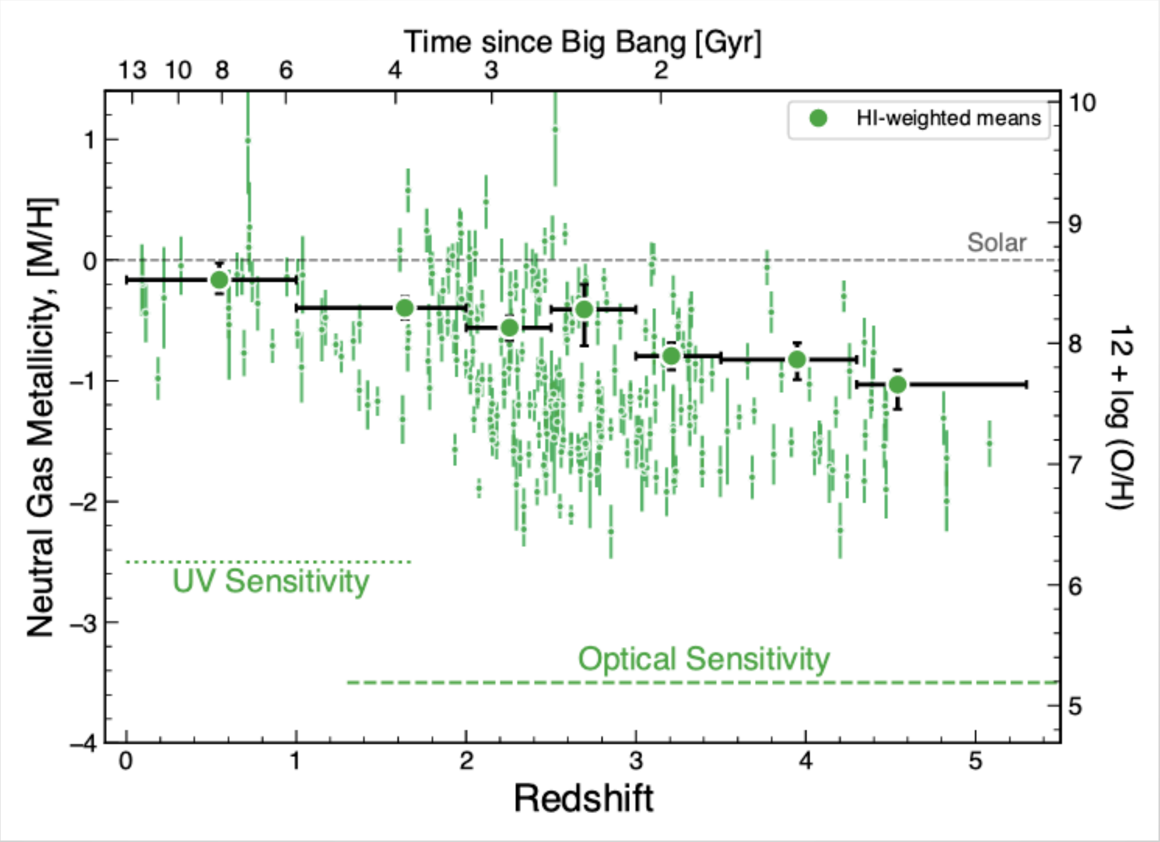


Peroux & Howk (2020)

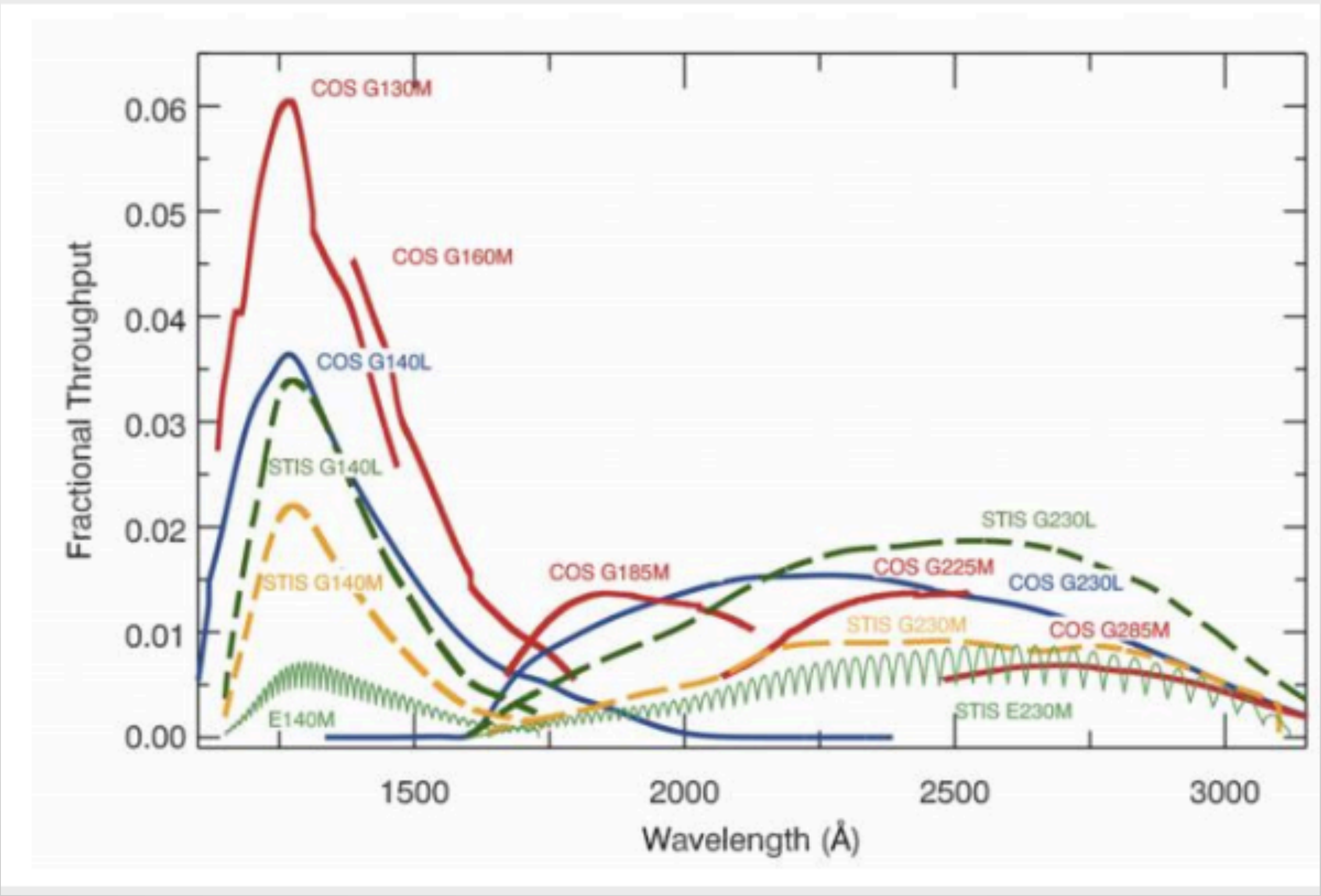
Instrumentation: working in the UV

HST remains the primary option for UV spectroscopy (JWST is visible/IR only). For many years the Space Telescope Imaging Spectrograph (STIS) had been the workhorse. The Cosmic Origins Spectrograph (COS) was installed in 2009.

		COS/FUV	COS/NUV	STIS/FUV	STIS/NUV
Spectral coverage (Å)		900 - 1775 (M) 900 - 2050 (L)	1700 - 3200 (M) 1650 - 3200 (L)	1150 - 1700 (M, L) ---	1650–3100 (M) 1570–3180 (L)
Effective area (cm2) 950 Å (FUV) 1300 Å (FUV) 2500 Å (NUV)		 20 (G130M) 3000 (M) 1800 (L)	 --- 600 (M) 750 (L)	 --- 400 (M) 1700 (L)	 --- 350 (M) 900 (L)
Resolving power R = λ/dλ	H	---	---	114,000	114,000
	M	16,000 - 17,000	16,000 - 24,000	11,500 - 45,800	9100 - 30,000
	M (λ < 1150)	13,000 & 1000 - 3000	---	---	---
	L	1500 - 4000	2100 - 3200	1000	500 - 1005
Number of pixels along dispersion		16,3841(32,768)[1]	1024	1024 (2048)	1024 (2048)
Background[2] (counts/sec/resel)		1.00 x 10-4 (FUVA) 9.54 x 10-5 (FUVB)	7.89 x 10-3	1.5 x 10-3	9.0x10-3
Background Equivalent Flux (ergs/cm2/sec/Å)		7.6 x 10-17 G130M at 1264 Å	4.8 x 10-15 G225M at 2160 Å	9.0 x 10-15 E140M at 1297.5 Å	8.0 x10-15 E230M at 2581 Å

Instrumentation: working in the UV

Although it covers a similar wavelength range to STIS (and doesn't have an echelle) COS provided a big improvement over STIS in terms of FUV performance.

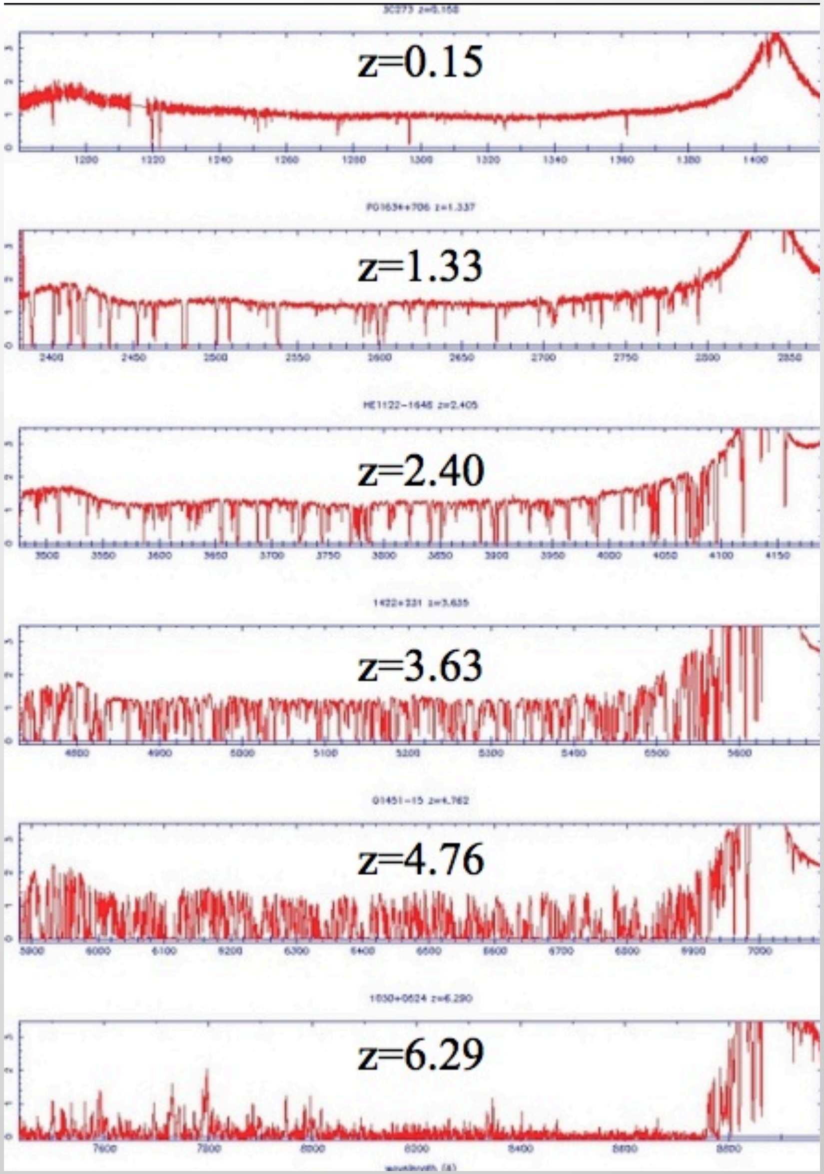


Aside: The Lyα forest is not as dense at low z

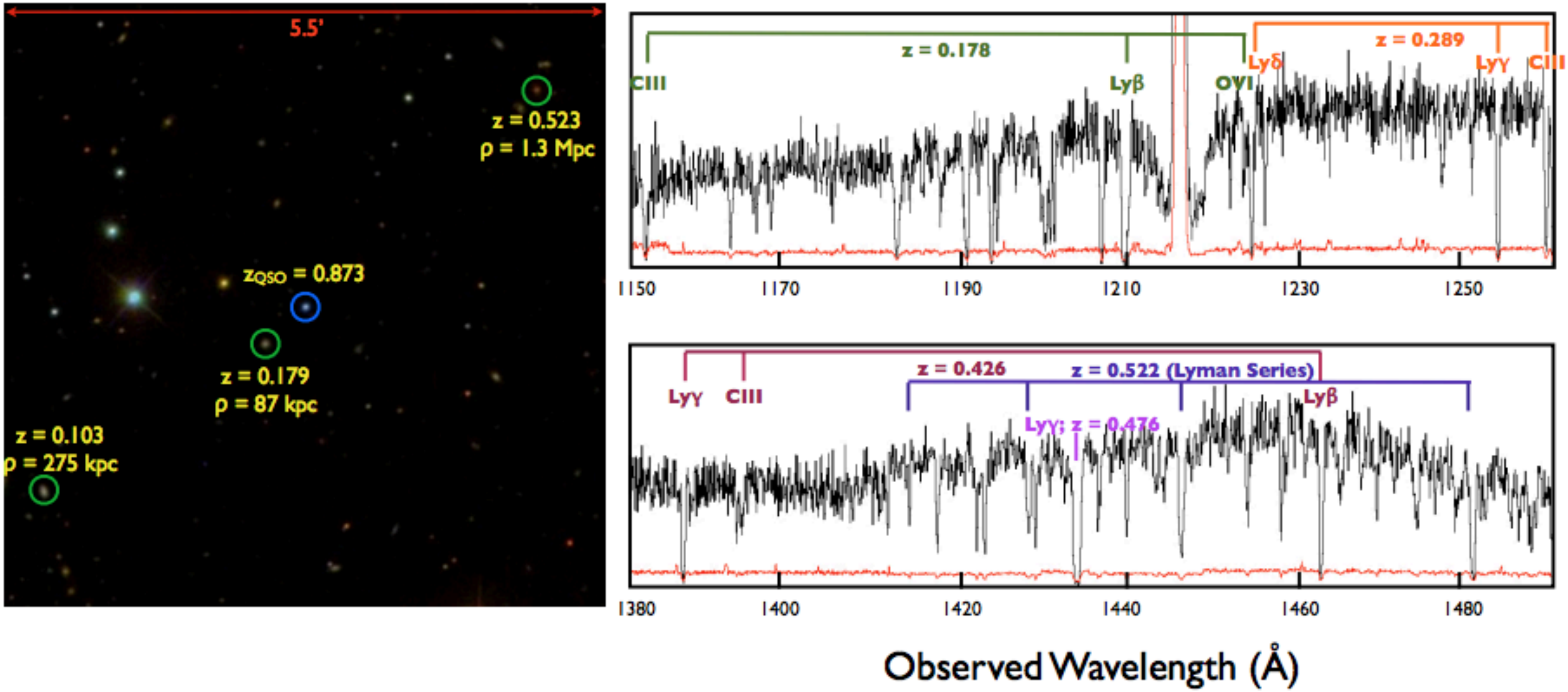
The evolution of the cosmic web is reflected in the line density of the Lya forest. Structure becomes more sparse at low z. Means that lower resolution can be used.

At very high z the IGM is completely opaque because the universe transitions to being mostly neutral (absorption everywhere, not just in filamentary structures).

Jargon alert: Gunn-Peterson trough.



Linking absorption properties to galaxies



Complementing QSO spectroscopy with complete redshifts of neighbouring galaxies is essential for connecting galaxy properties with CGM properties. Often there are multiple absorbers at different redshifts that need to be untangled.

Jargon alert: impact parameter

Summary

- The CGM is the extended (hundreds of kpc) reservoir of gas around galaxies. It traces the galactic gas ecosystem and contains most of a galaxy's baryons
- QSO absorption lines allow us to make a "complete" census of gas in a way that is independent of emission sensitivities.
- Main observational limitation is lines are mostly located in rest-frame UV.
- Many species observed (HI and metals) across many ionization states.
- Column densities easily derived from equivalent widths unless the line is saturated.
- We can determine abundances, but must be cautious of dust depletion and ionization effects.
- The study of QSO absorption lines becomes most meaningful when we can connect to galaxy properties.