Quasar absorption lines

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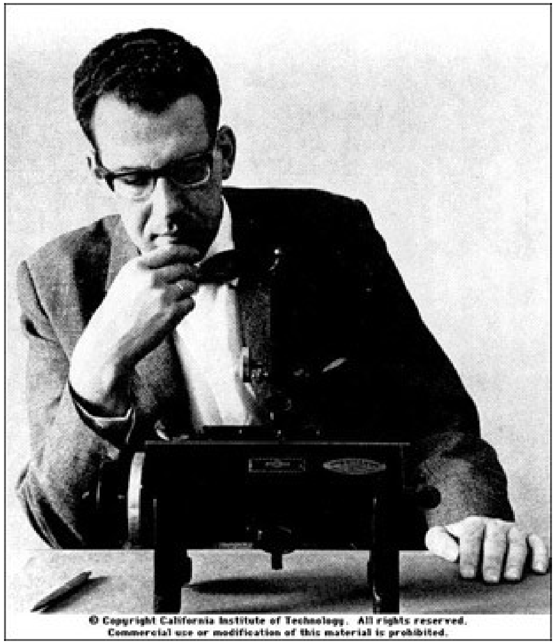
A bit of history

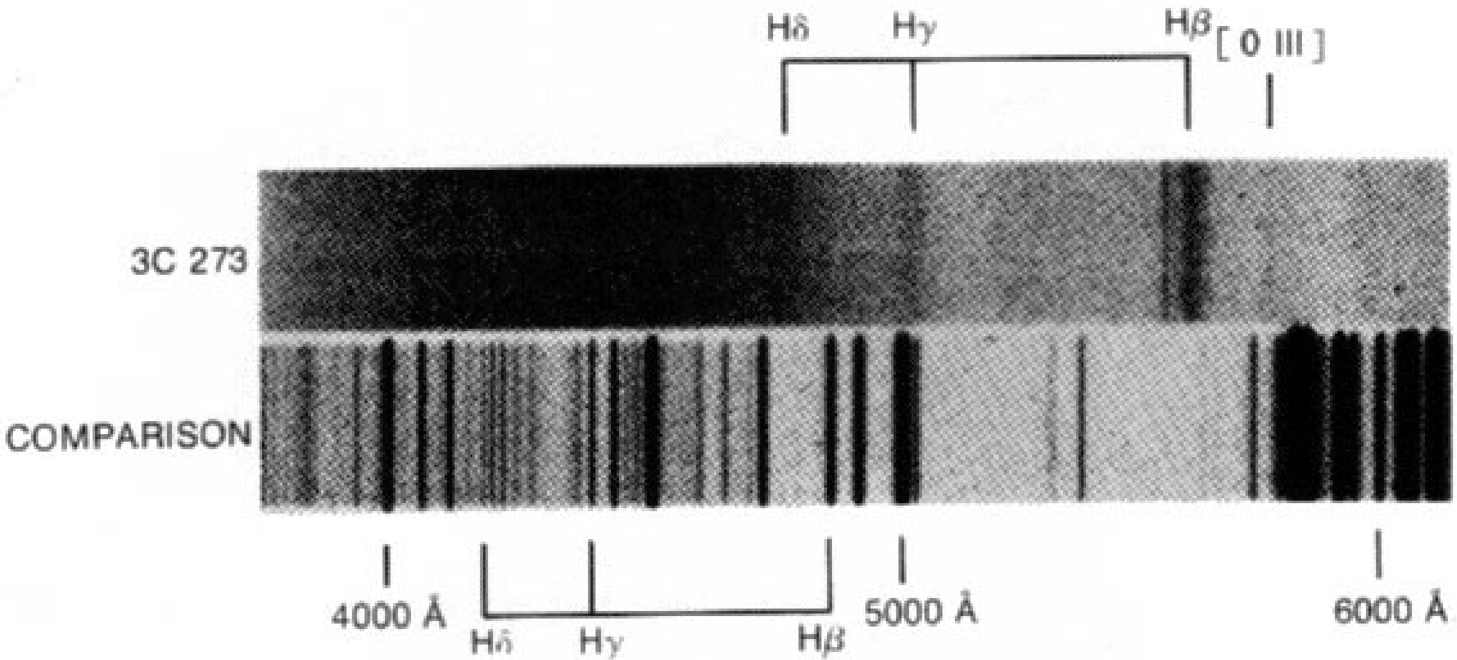
3C48

- 1960: Matthews & Sandage: Discovery of radio source with point-source, blue optical counterpart (looks like a star)

  → quasi-stellar radio source → "quasar"
  very peculiar star???

- 1963: Schmidt realises the emission lines of 3C273 are Balmer shifted by 16%
  Same conclusion for 3C48 (z=0.37) by Greenstein & Matthews

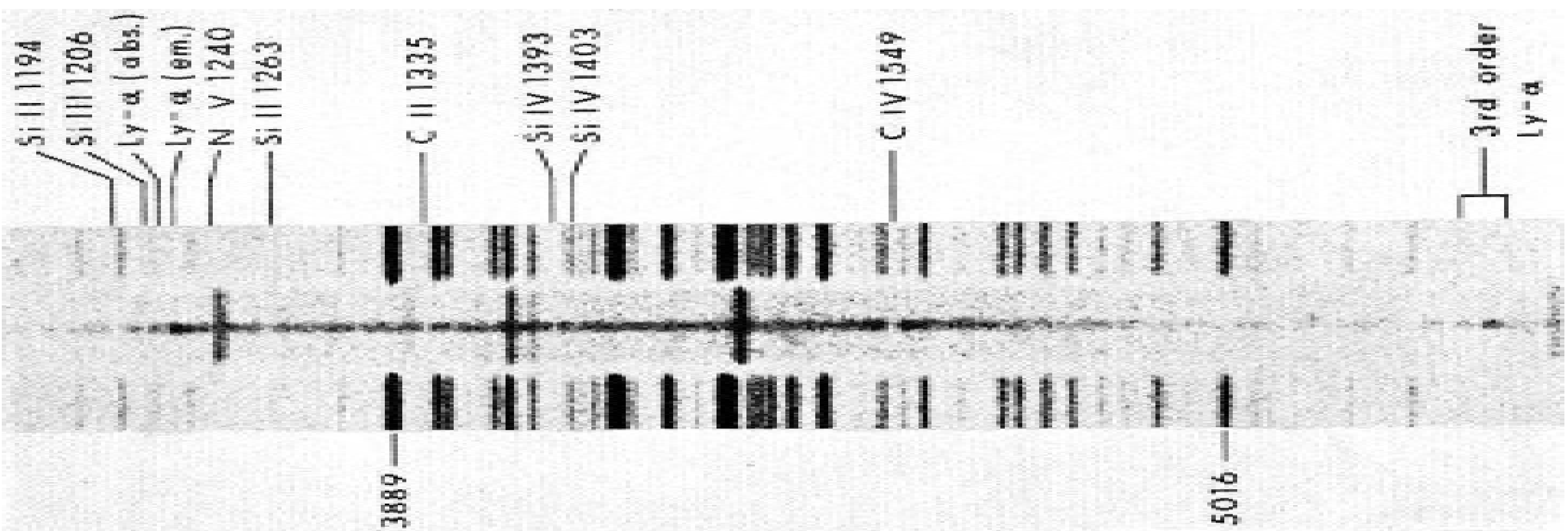




A bit of history

- So quasars are very very bright objects at cosmological distances
  (For quasar **absorption lines**, it is almost all what we need to know)

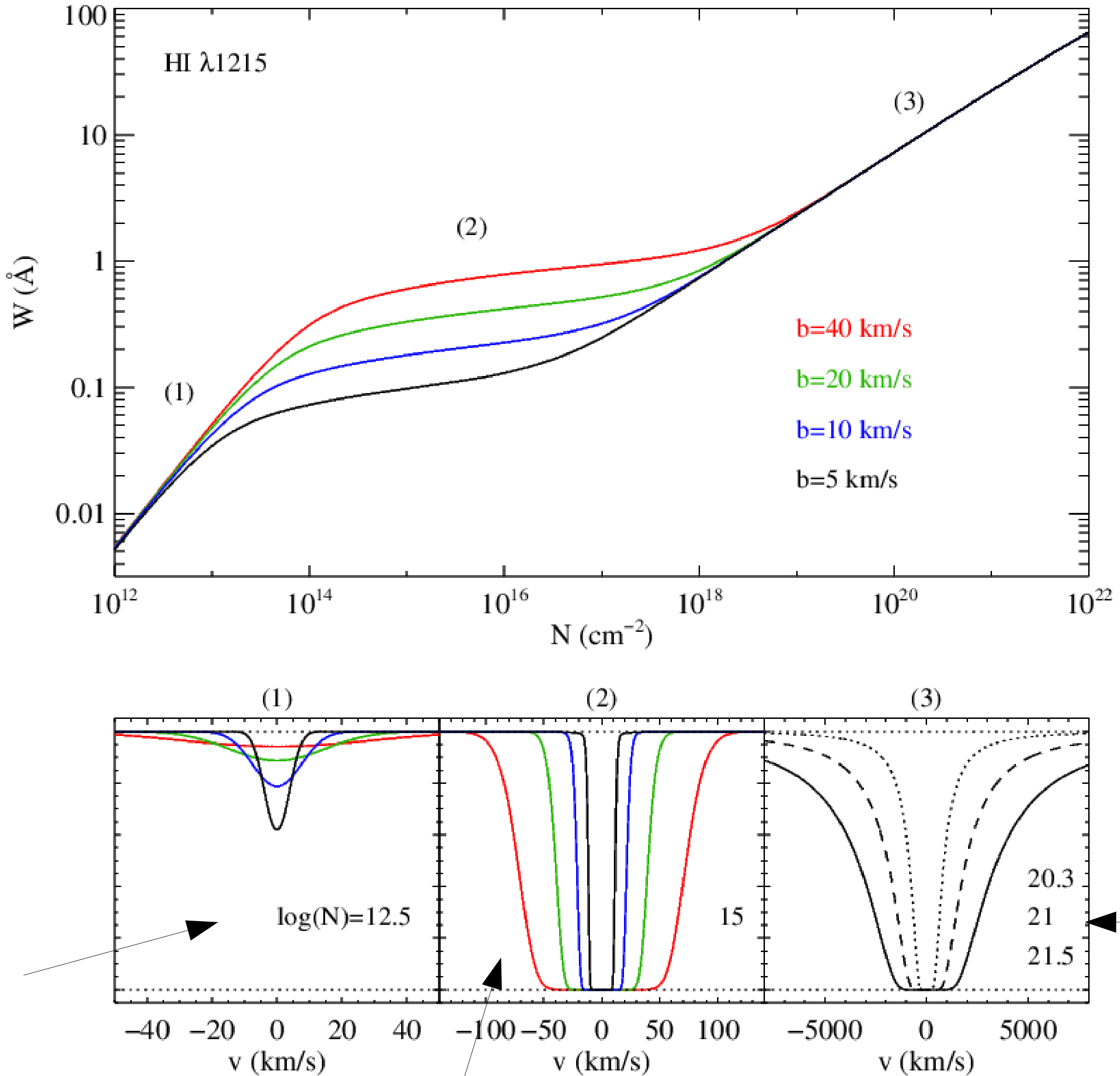
- 1966: Burbidge: first detection of absorption lines in a quasar spectrum



The basics of quasar absorption lines

→ whiteboard

The basics of quasar absorption lines



The width depends on b and depth on N, but the total surface of the line (EW) does not

The shape and EW depend only on N

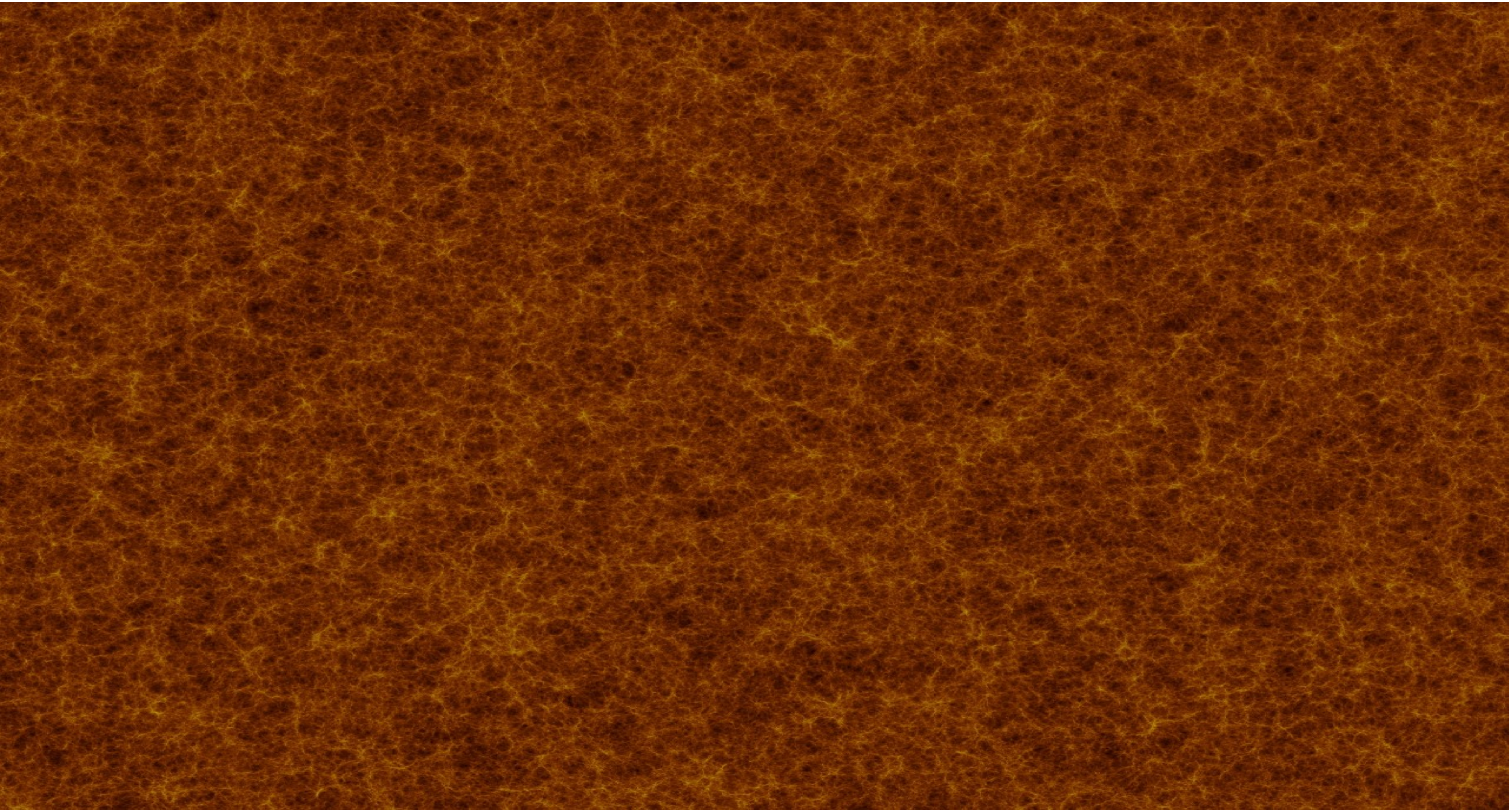
The shape depends on b & N, as well as the EW → big mess

The Ly-alpha forest: gas in the IGM

The most numerous lines in quasar absorption spectra are Ly-alpha from the **I**nter**G**alactic **M**edium → Ly-alpha forest

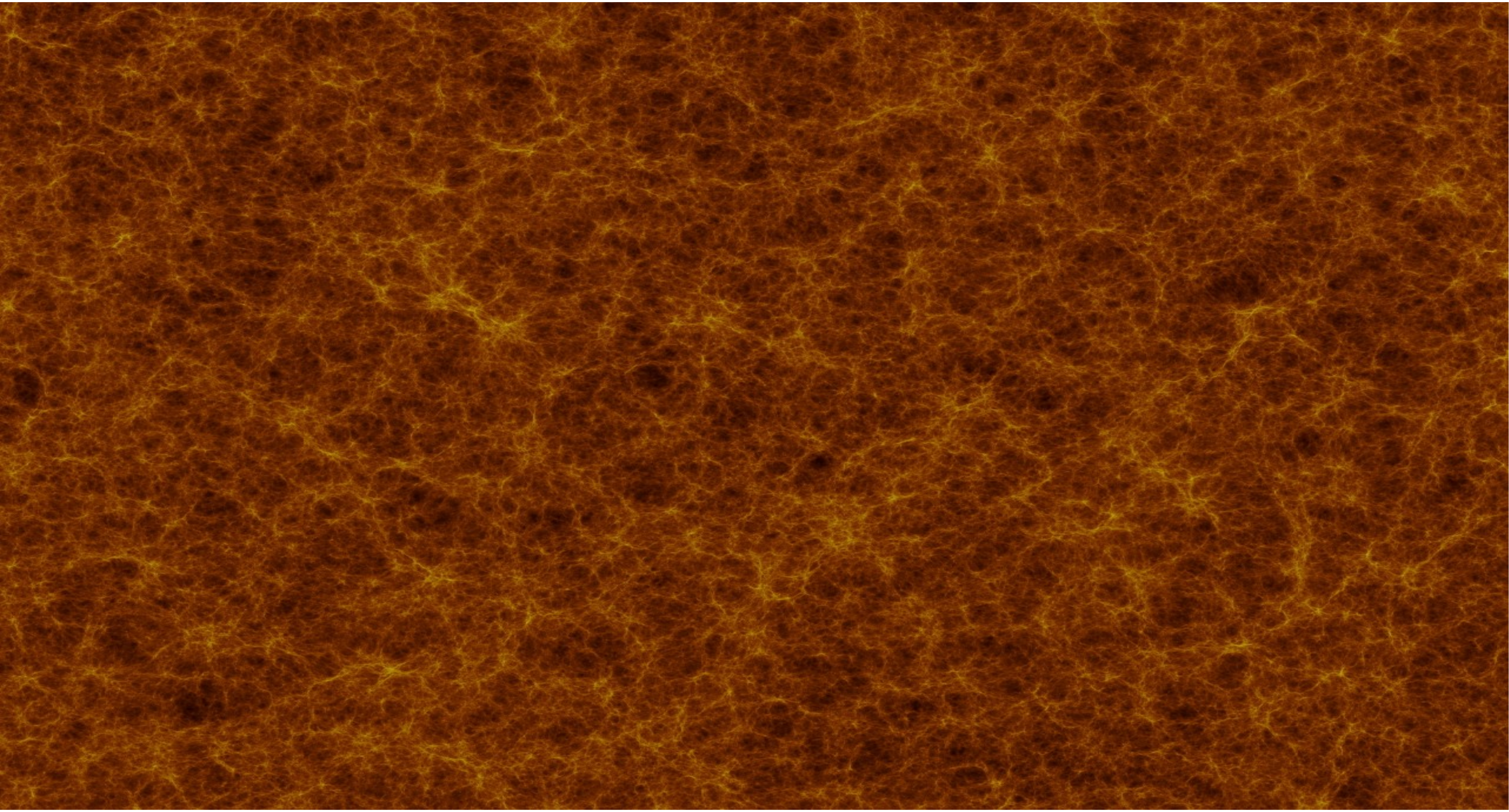
→ Gas everywhere?

The Ly-alpha forest: gas in the IGM



http://gigapan.com/gigapans/76215/

The Ly-alpha forest: gas in the IGM



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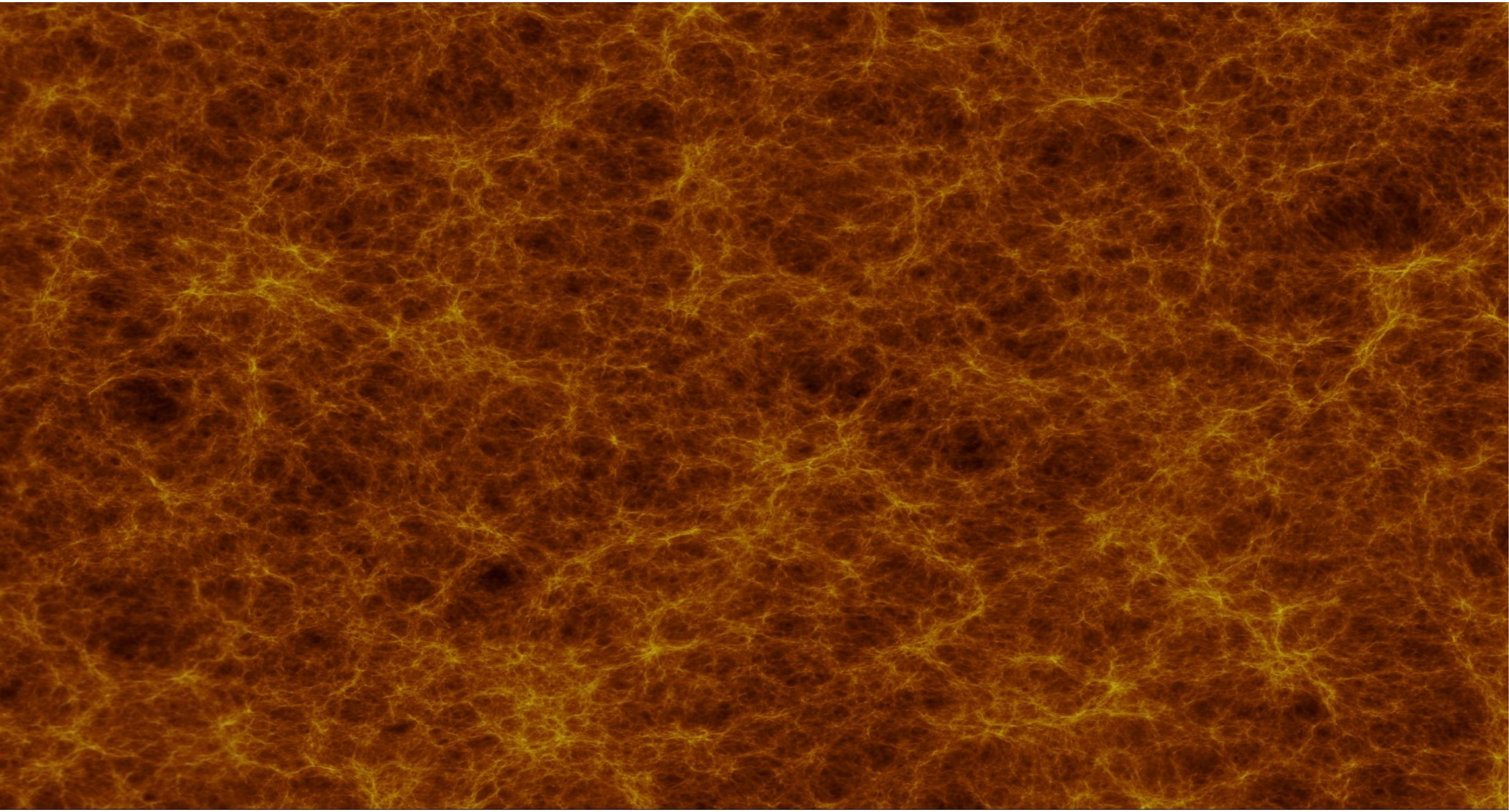
The Ly-alpha forest: gas in the IGM



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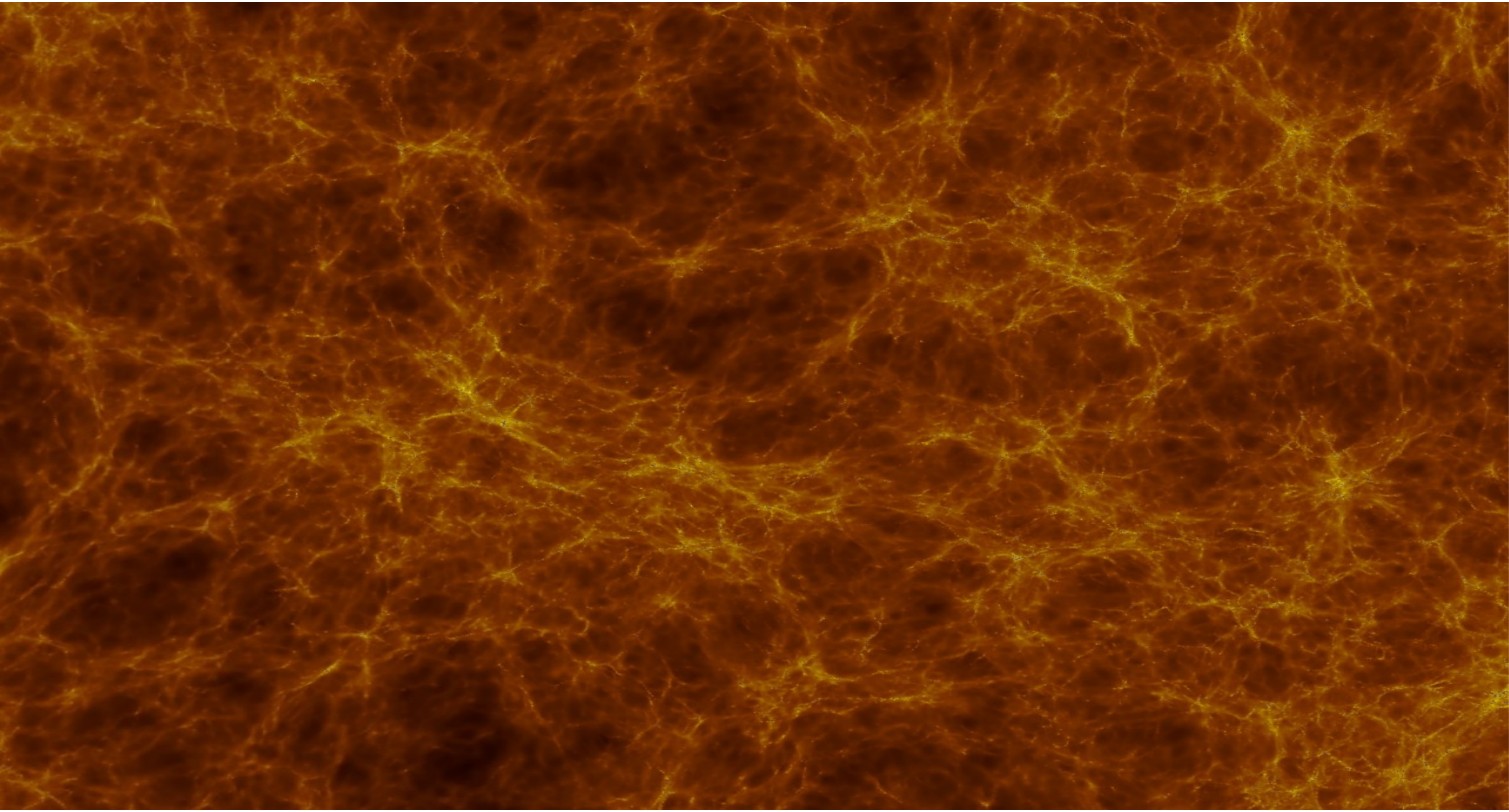
The Ly-alpha forest: gas in the IGM



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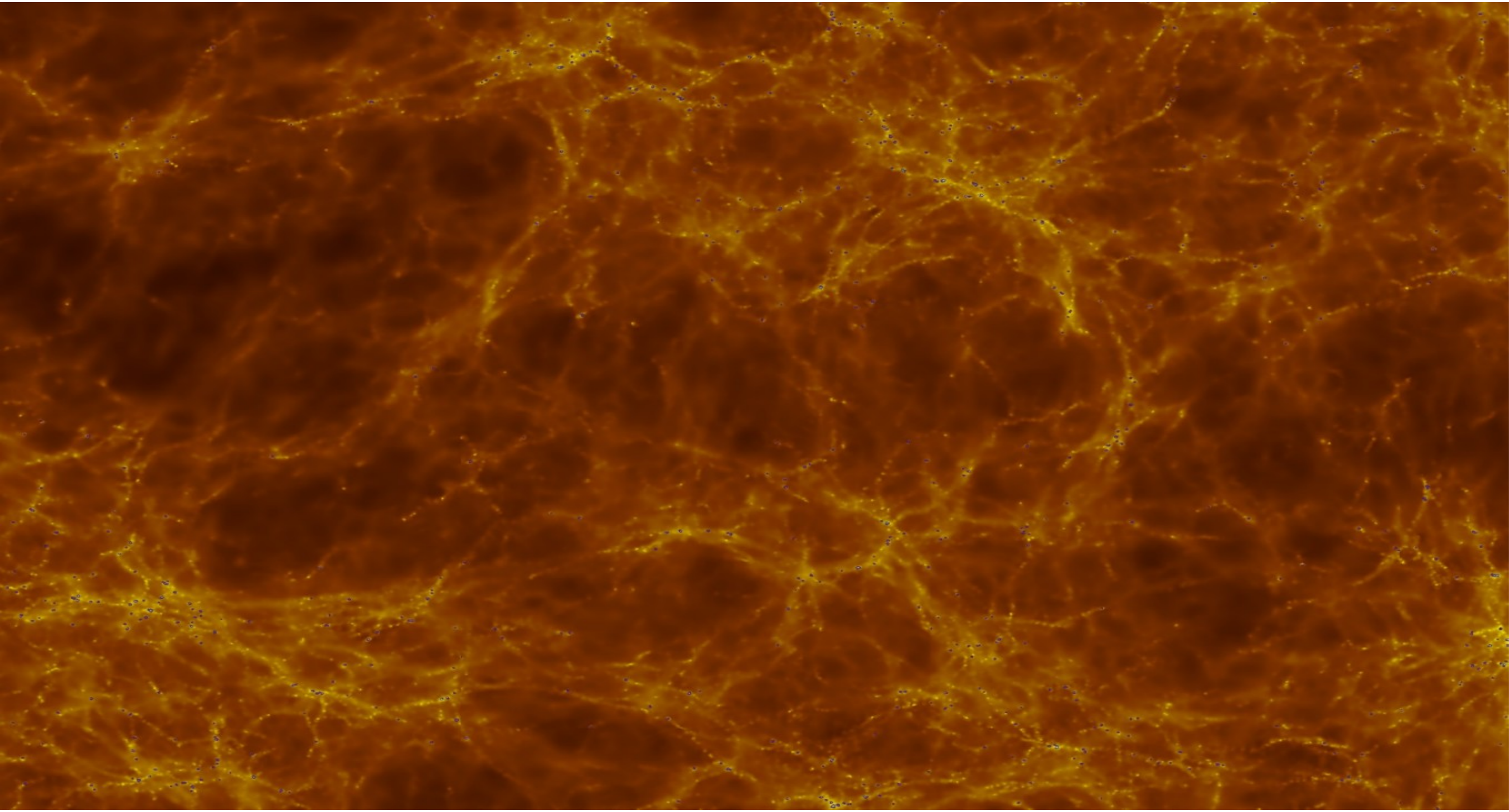
The Ly-alpha forest: gas in the IGM



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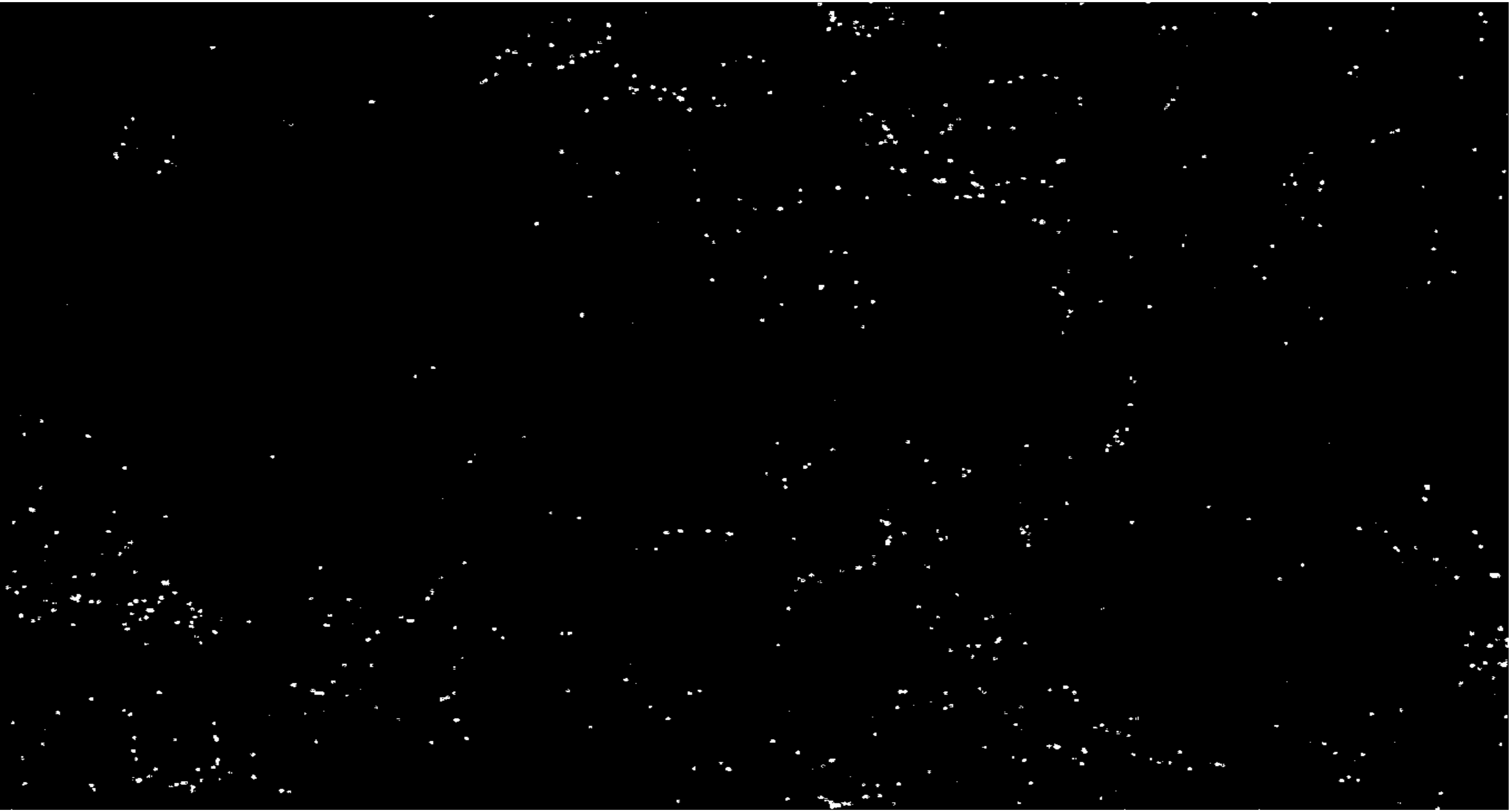
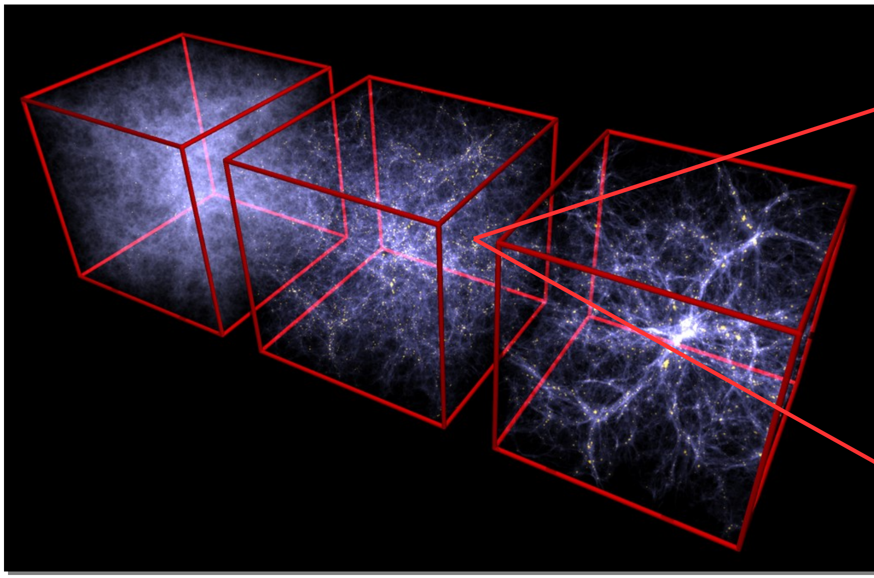
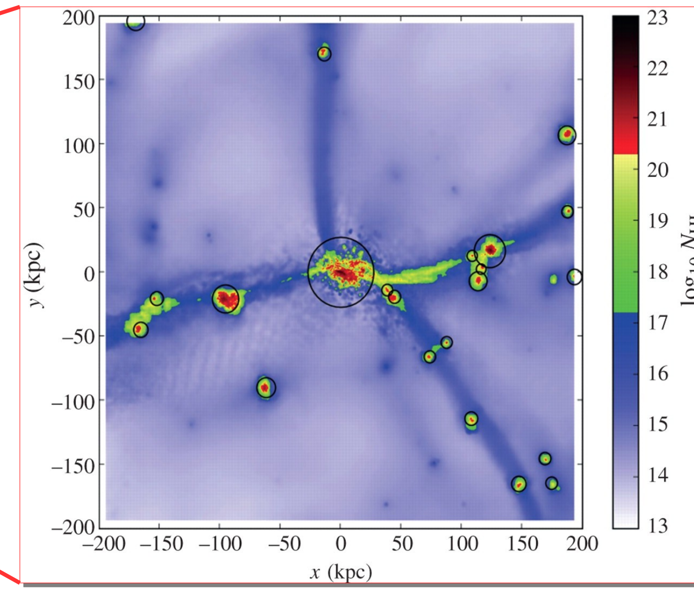
The Ly-alpha forest: gas in the IGM



http://gigapan.com/gigapans/76215/

There are also galaxies

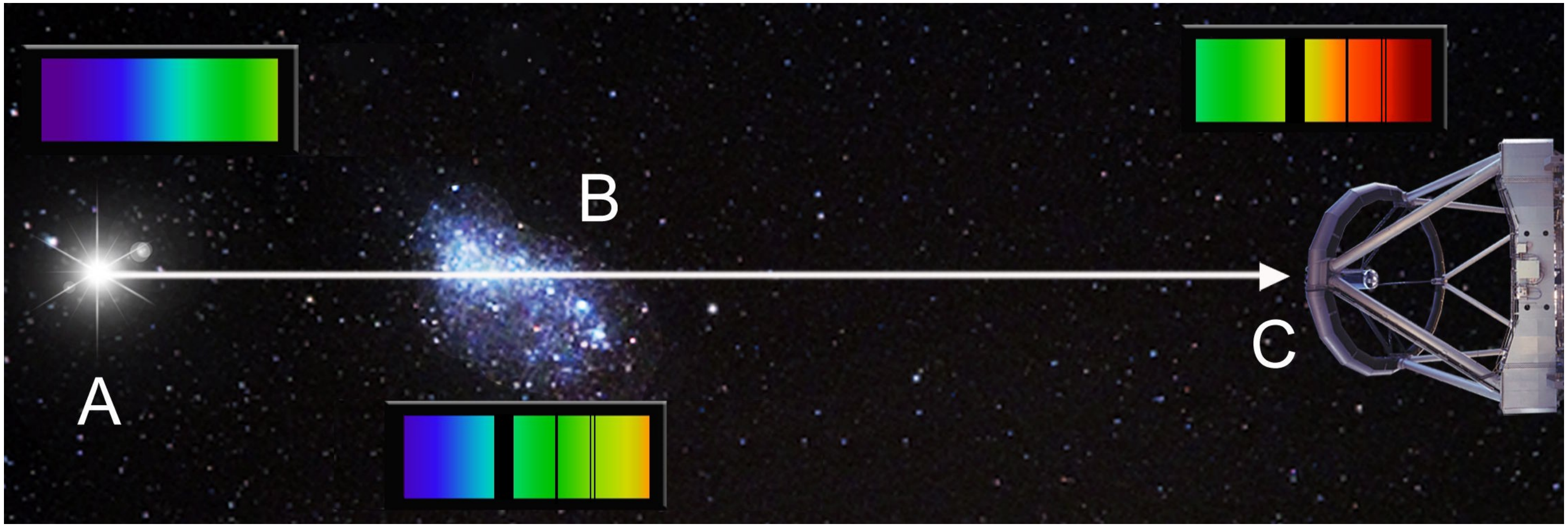


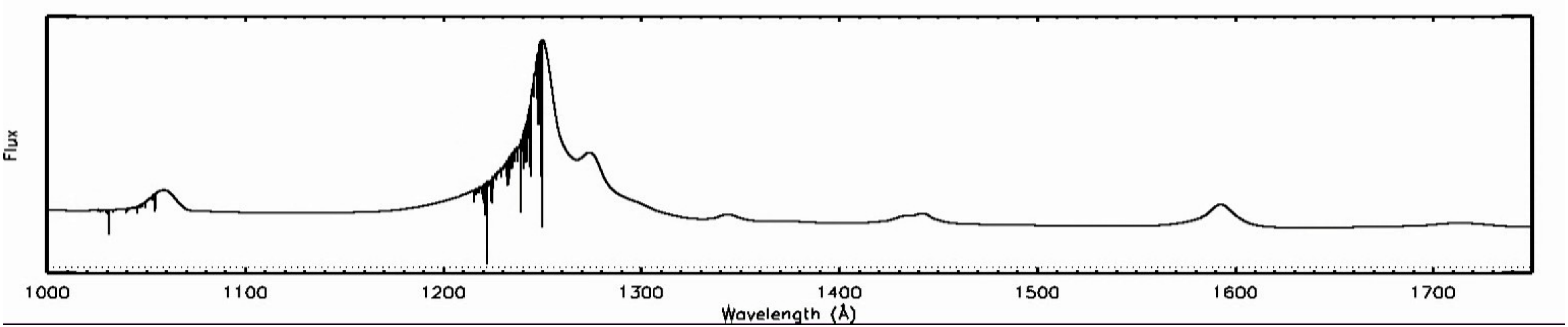


Sometimes, the quasar line of sight hits neutral gas → Damped Ly-alpha system (DLA)

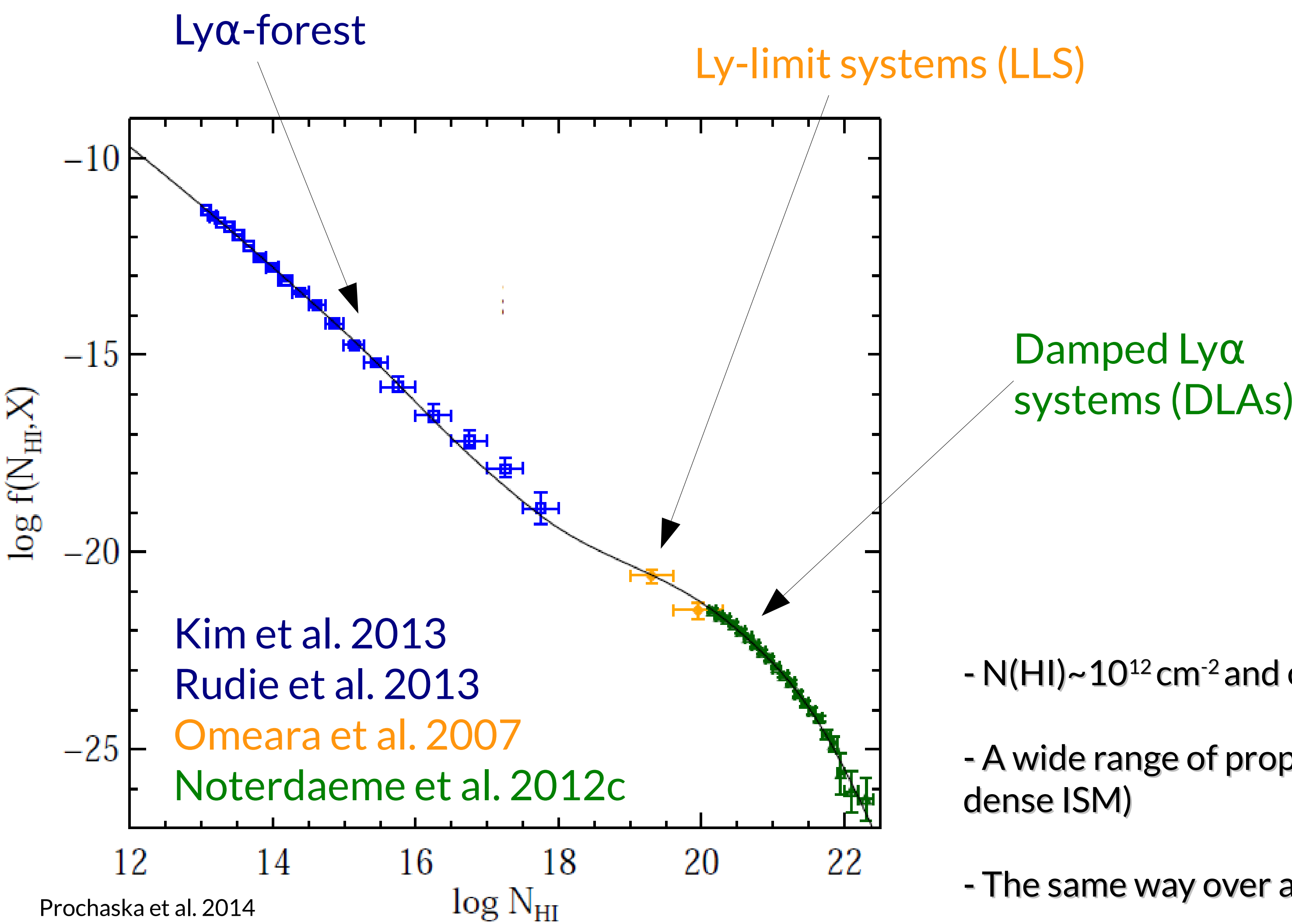
DLAs are thought to arise within/next to galaxies (we'll talk about this later)

A quasar spectrum





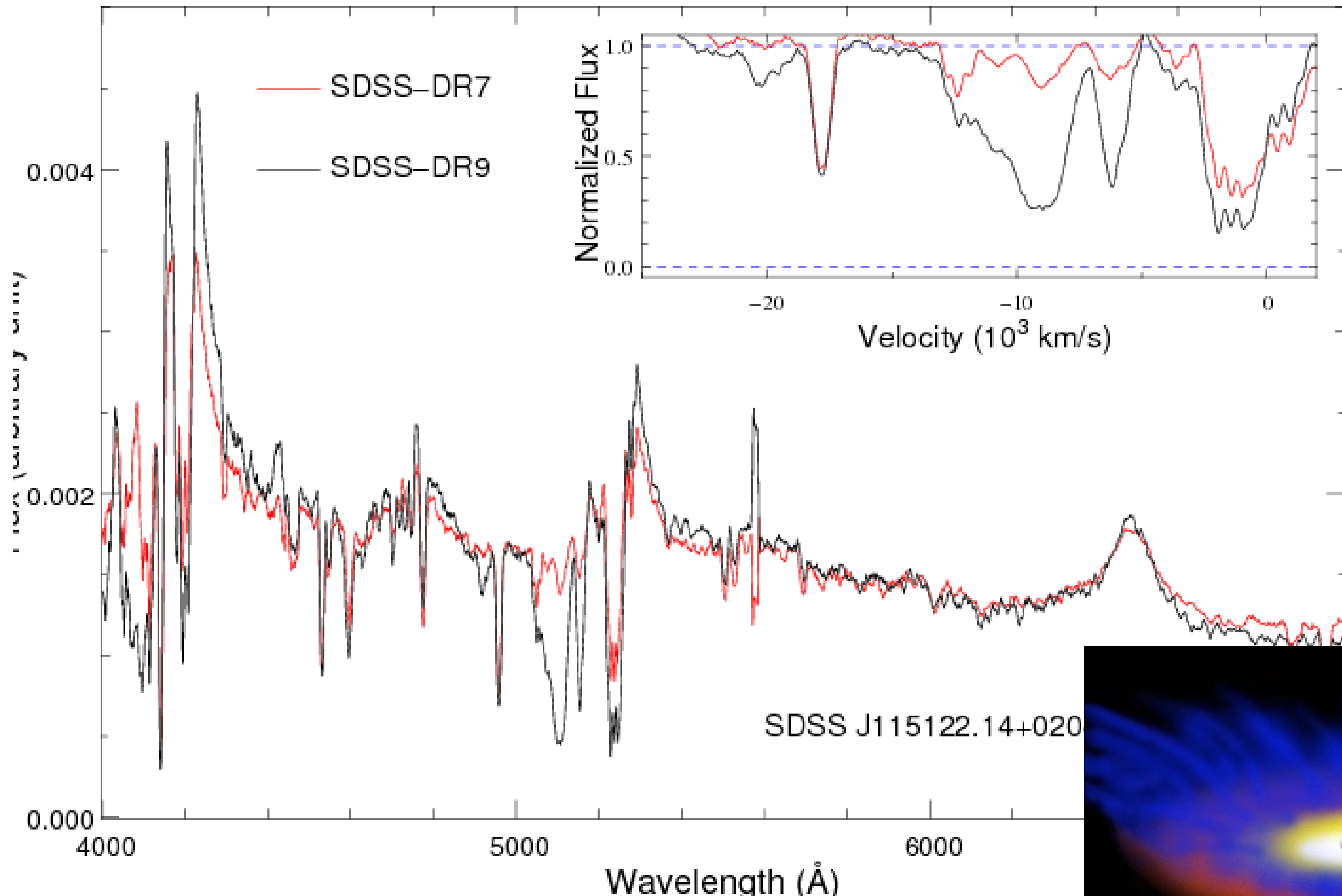
Intervening systems: classify systems by N(HI)

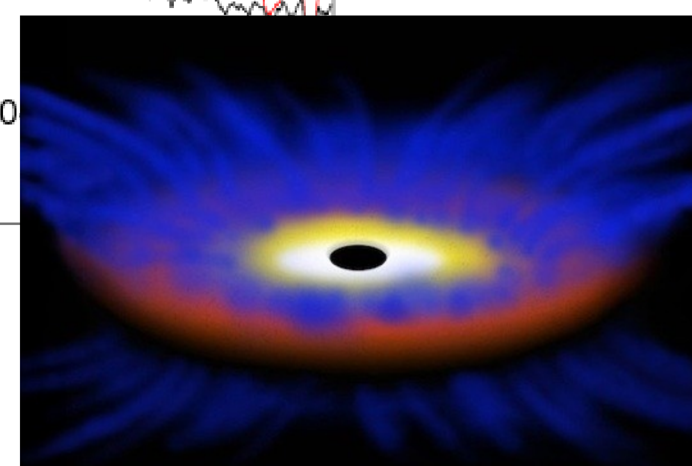


Prochaska et al. 2014

- $N(HI) \sim 10^{12}\ cm^{-2}$ and over ten orders of magnitude
- A wide range of properties (very tenuous IGM to dense ISM)
- The same way over a wide redshift range
- Detection independent of the luminosity of the associated object

e.g. Broad Absorption Lines



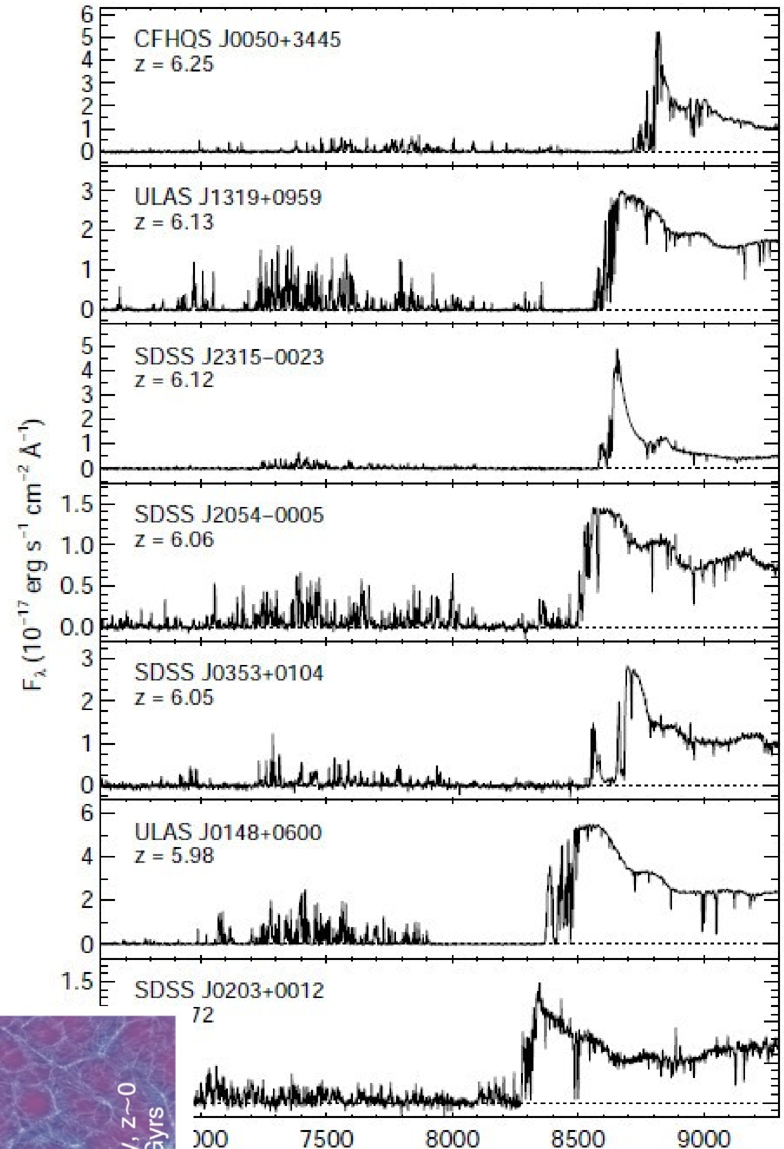


Reionisation and Gunn-Peterson effect

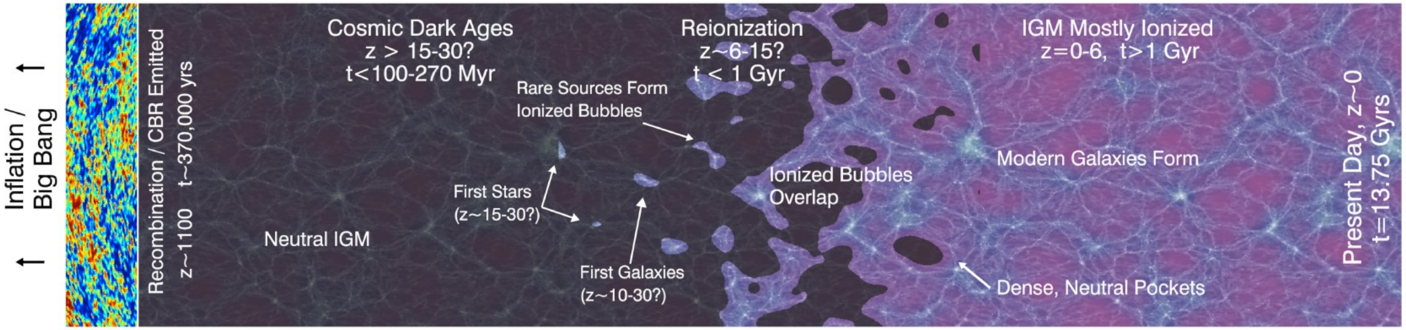
Gunn-Peterson effect: Neutral hydrogen regions overlap and cause complete ($\tau >> 1$) Ly-α absorption blueward of the Ly-α emission line

No GP effect up to z=6
→ The Universe is mostly ionised

GP trough appears at z~6.3 but varies strongly from one line of sight to the other
→ The reionisation is patchy



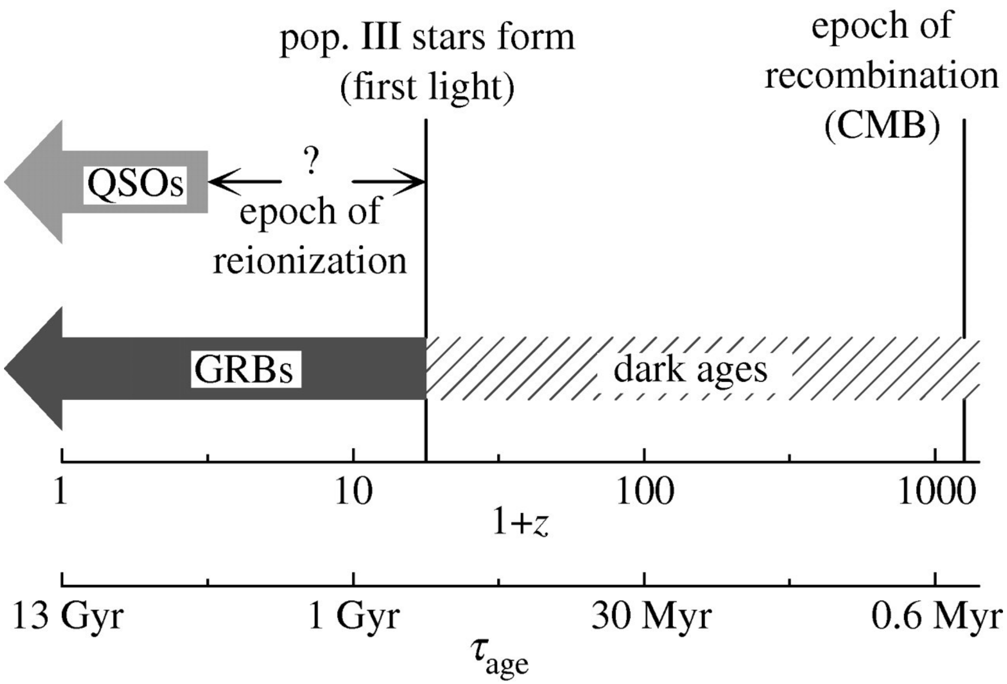
Becker et al. 2014



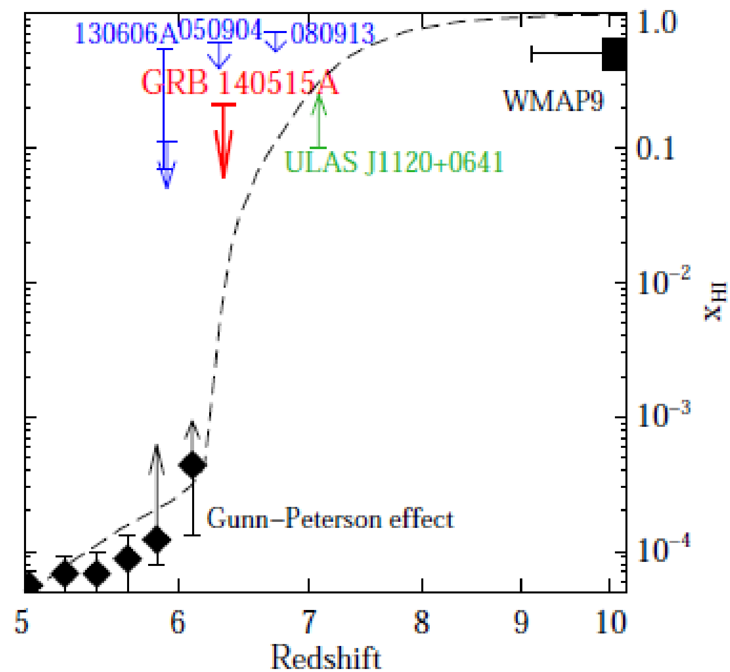
Robertson et al. 2010

(Gamma-ray bursts can be used as well)

- The very high-z: GRBs

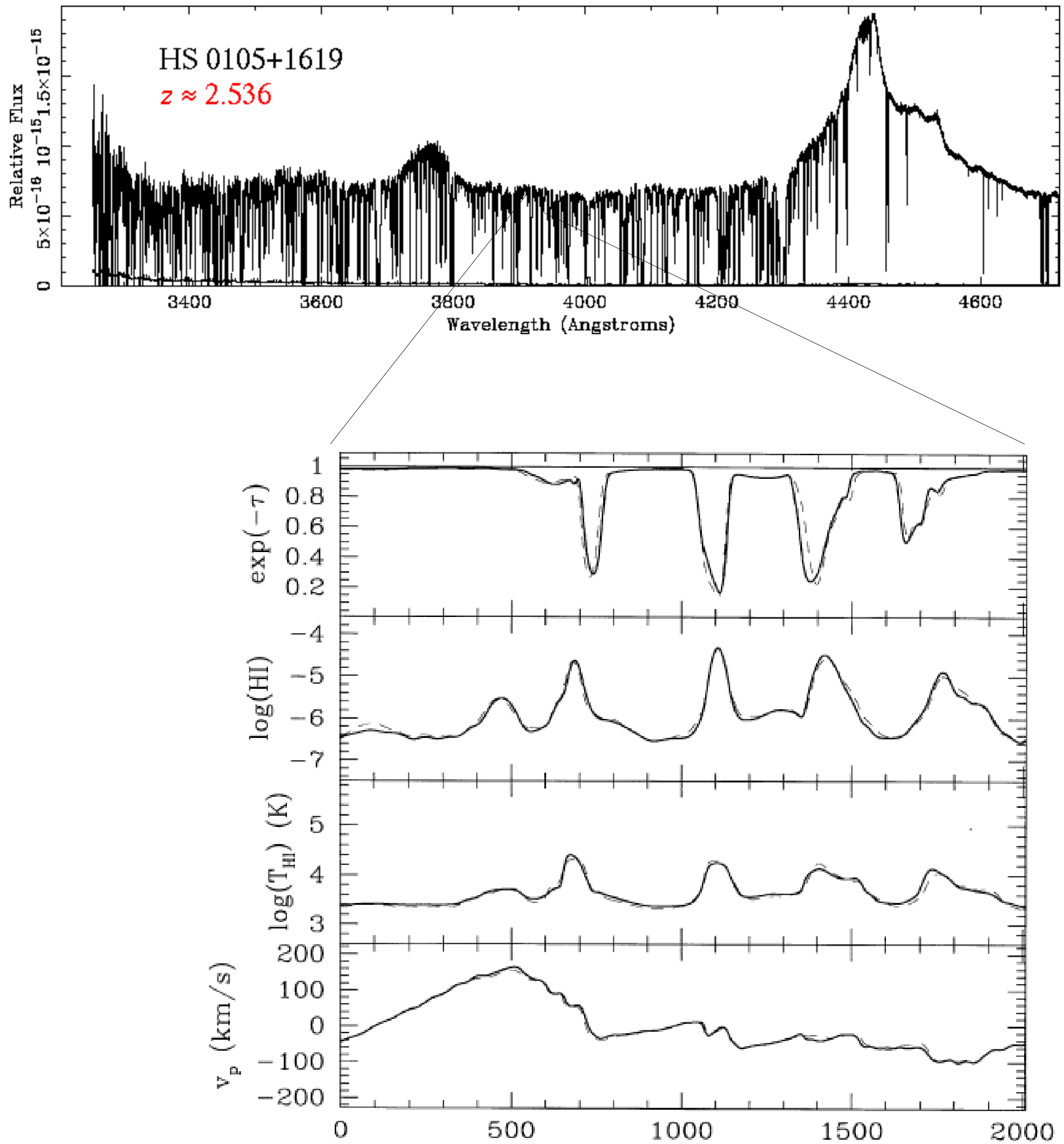


Lamb 2002



Chornock et al. 2014

Physical conditions in the IGM



Theuns et al. 1998

What we observe is
$I = I_0 \exp(-\tau(\lambda))$

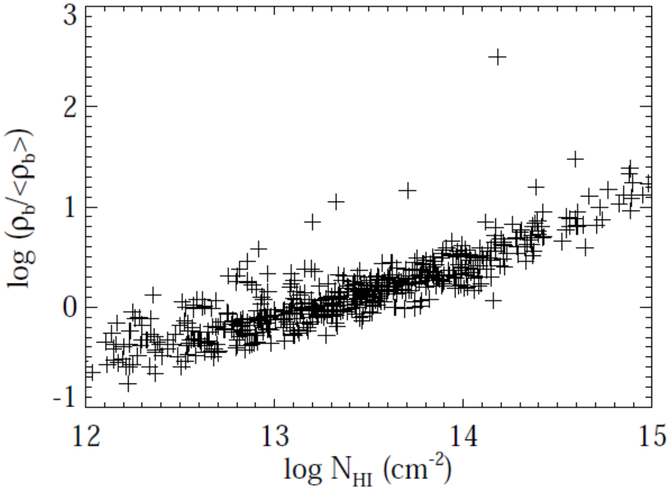
In principle, we know how to decompose each line into N,b,z

In practice: not easy to apply to Ly-alpha forest

What we want are the physical properties. → Compare with models.

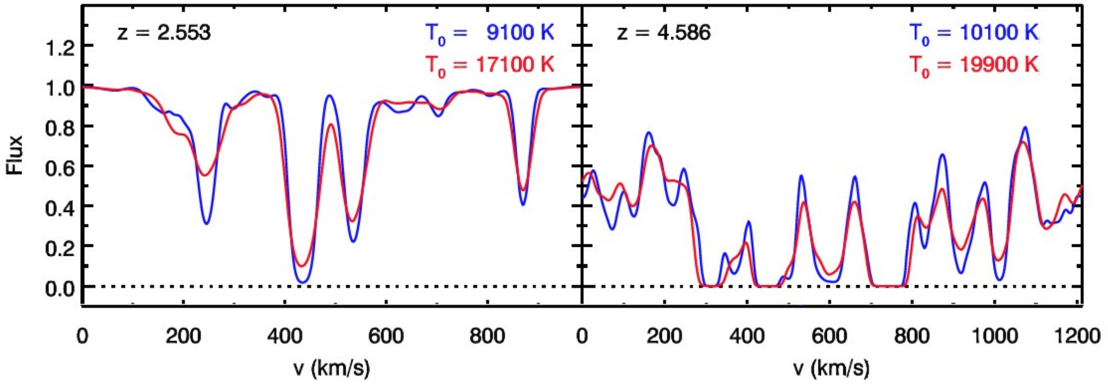
Physical conditions in the IGM

- Density



Schaye 2000: The observed column density is a fairly good tracer of the overdensities

- Temperature

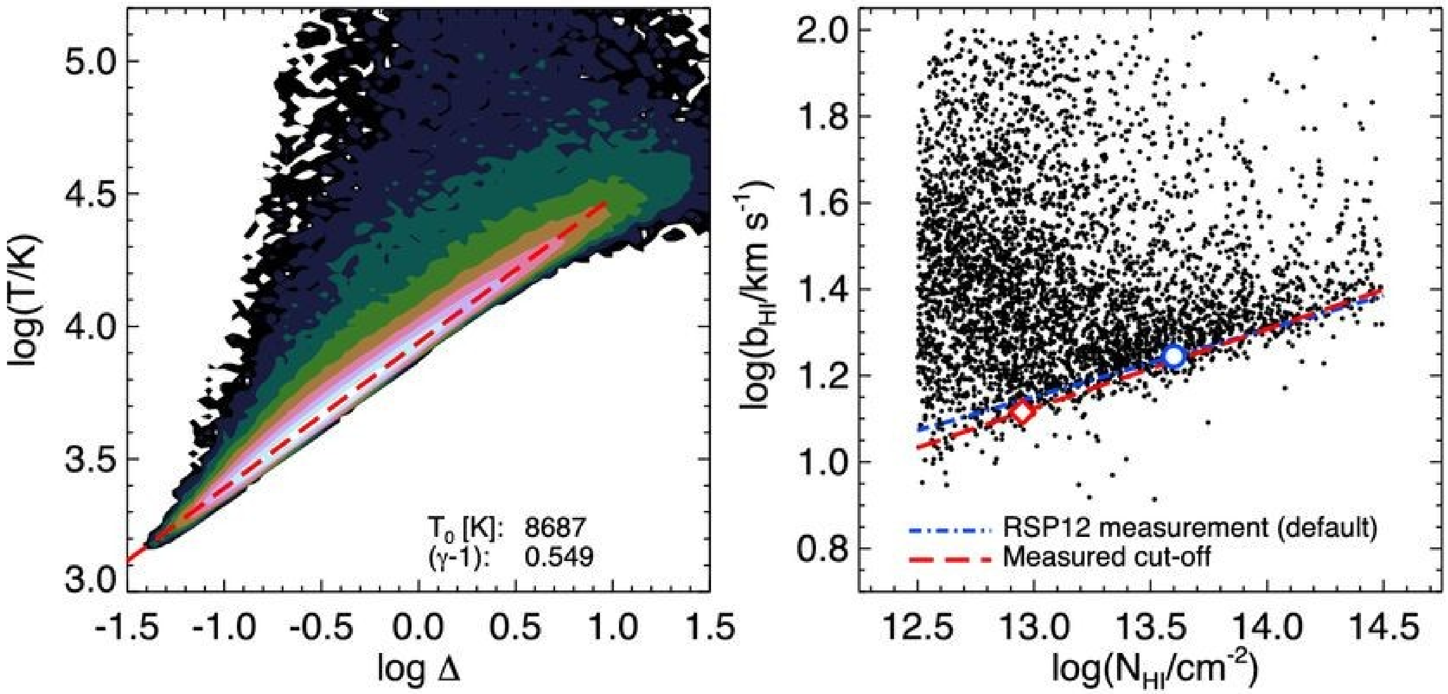


Becker et al. 2011: The smoothness of the lines is a fairly good indicator of the temperature

Physical conditions in the IGM

Physics → we expect a relation between temperature and density
→ relation between width and column density of the Ly-alpha forest lines?

- The temperature – density relation T = To $^{\gamma}$
  Competition between photoelectric heating and adiabatic cooling

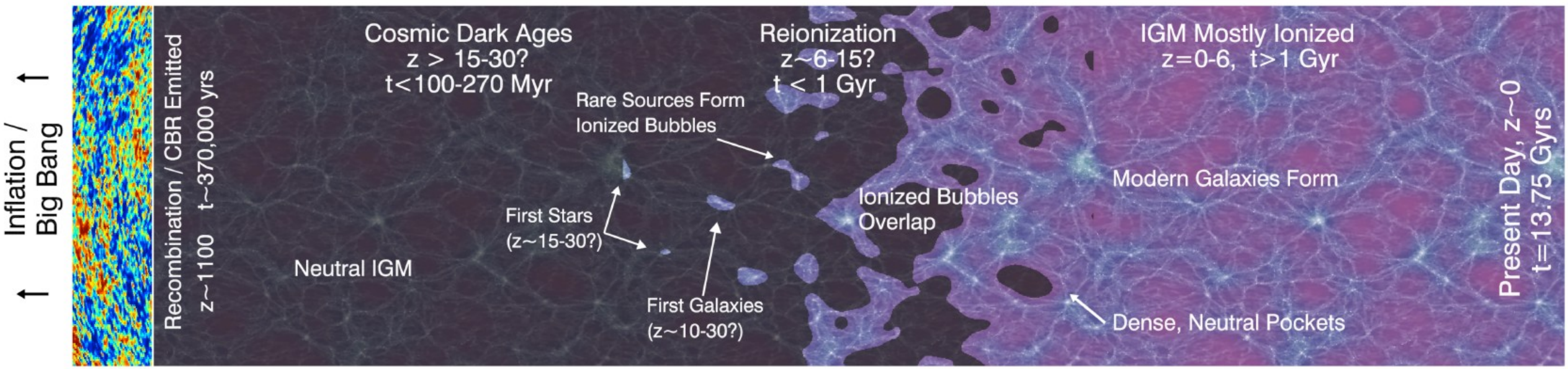


Bolton et al. 2014

Cooling is very slow, so IGM keeps trace of thermal history

Physical conditions in the IGM: evolution

- Reionisation



Robertson et al. 2010

Production of ionising photons:

SFR density (Msun/yr/Mpc3)

$$dn_{ion}/dt = f_{esc}\,\zeta_Q\,\rho_{SFR}$$

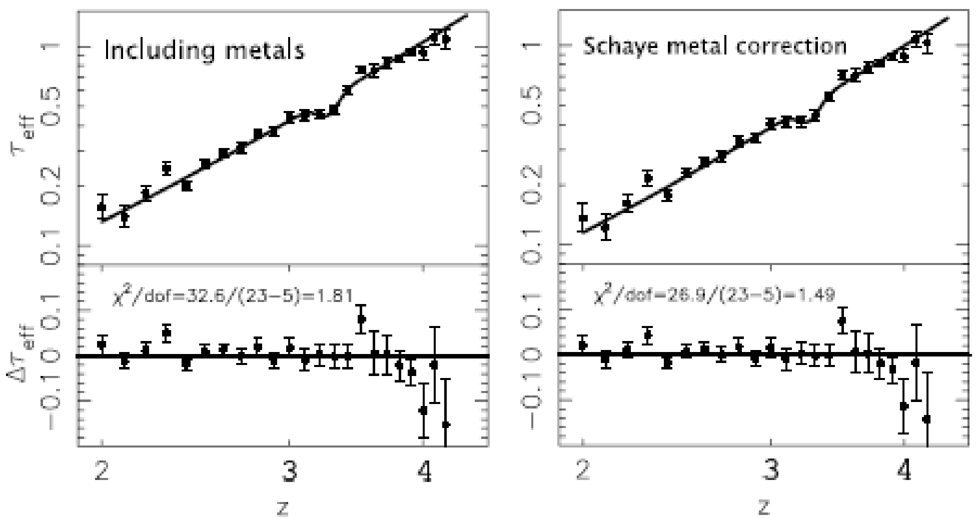
fraction of ionising photons escaping a galaxy

H-ionising photon per unit SFR density

Recombination rate: depends on IGM temperature and density
enhanced in overdensities

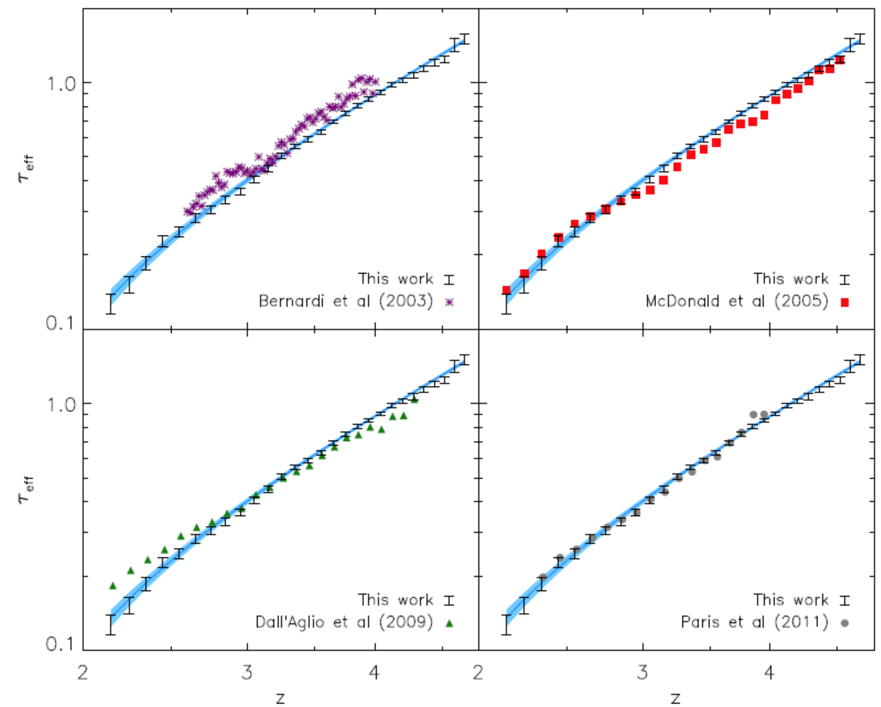
Physical conditions in the IGM: evolution

- Evolution (**opacity**/temperature)



Faucher-Giguère et al. 2008

High-resolution spectroscopy



Becker et al. 2013

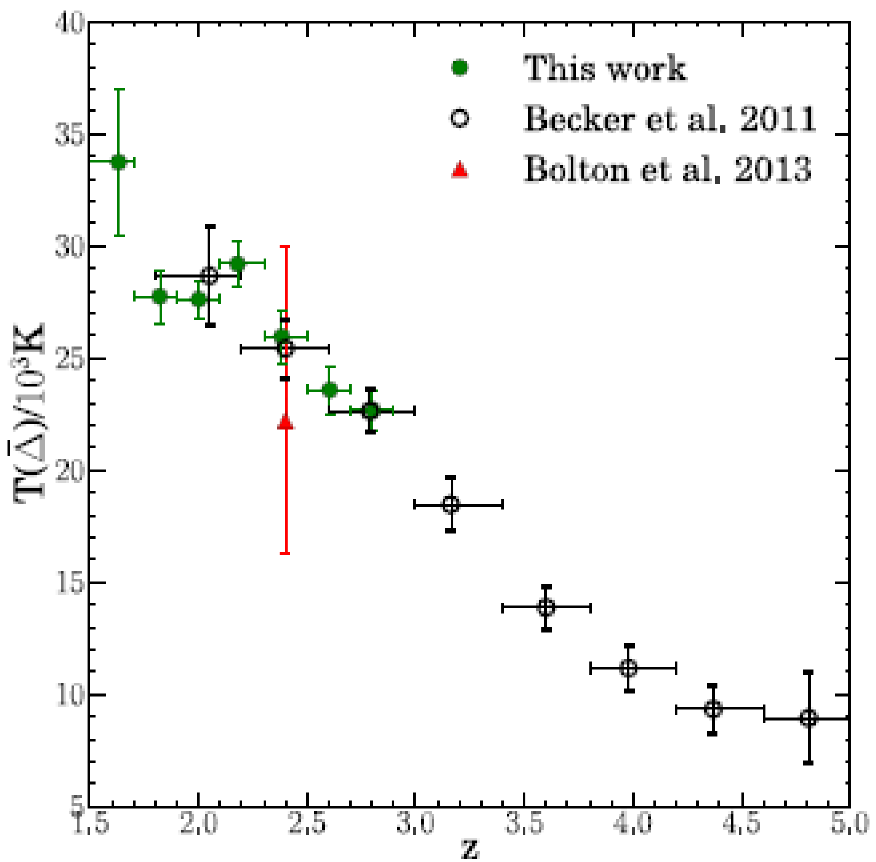
Compositing of low-R spectra

HI ionisation by galaxies
HeII ionisation requires harder UV (300Å, quasars?), and the recombination rate is fast

Physical conditions in the IGM: evolution

- Evolution (opacity/**temperature**)

T increases with decreasing redshift because it then traces higher over-densities:
- bounded against cooling by expansion
- higher recombination rate so more atoms for photo-electric heating

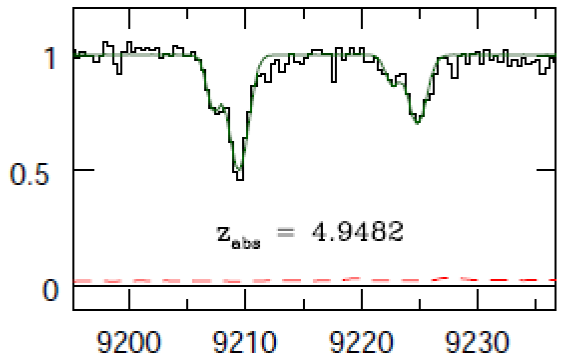


Temperature in over-densities

Boera et al. 2014

Metals in the IGM

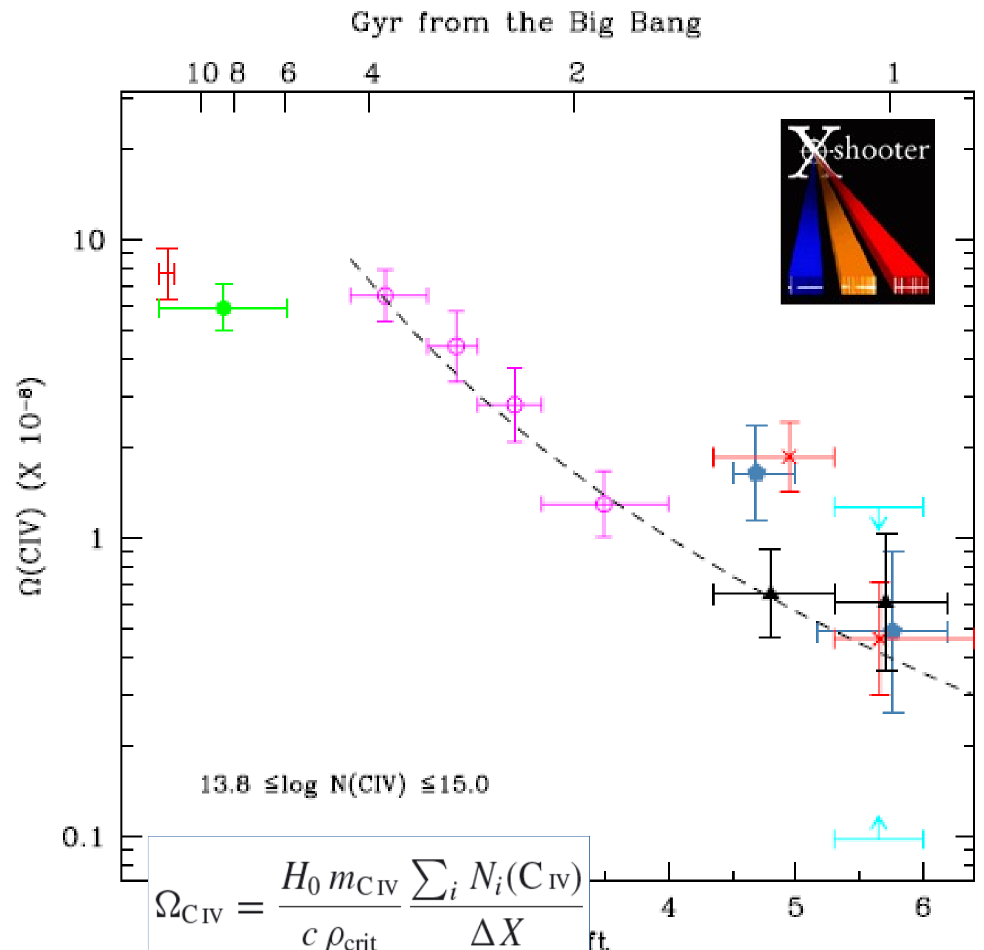
- Heavy elements are produced by stars in galaxies



- CIV always found for log NHI>15
- CIV in ~50% at log NHI = 14.5

- Metallicity ~ 0.001-0.01 solar at z~2-3

- At z>>6, information on IGM will come mostly from metals



$$\Omega_{\mathrm{C\,IV}} = \frac{H_0\, m_{\mathrm{C\,IV}}}{c\,\rho_{\mathrm{crit}}} \frac{\sum_i N_i(\mathrm{C\,IV})}{\Delta X}$$

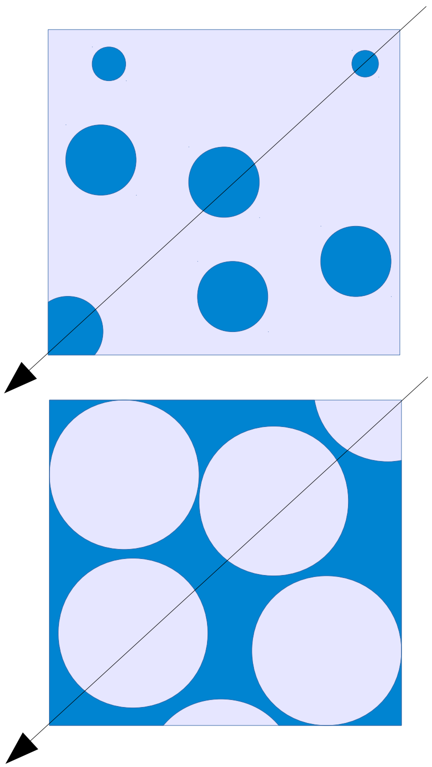
D'Odorico et al. 2013

- How did they get into the IGM?

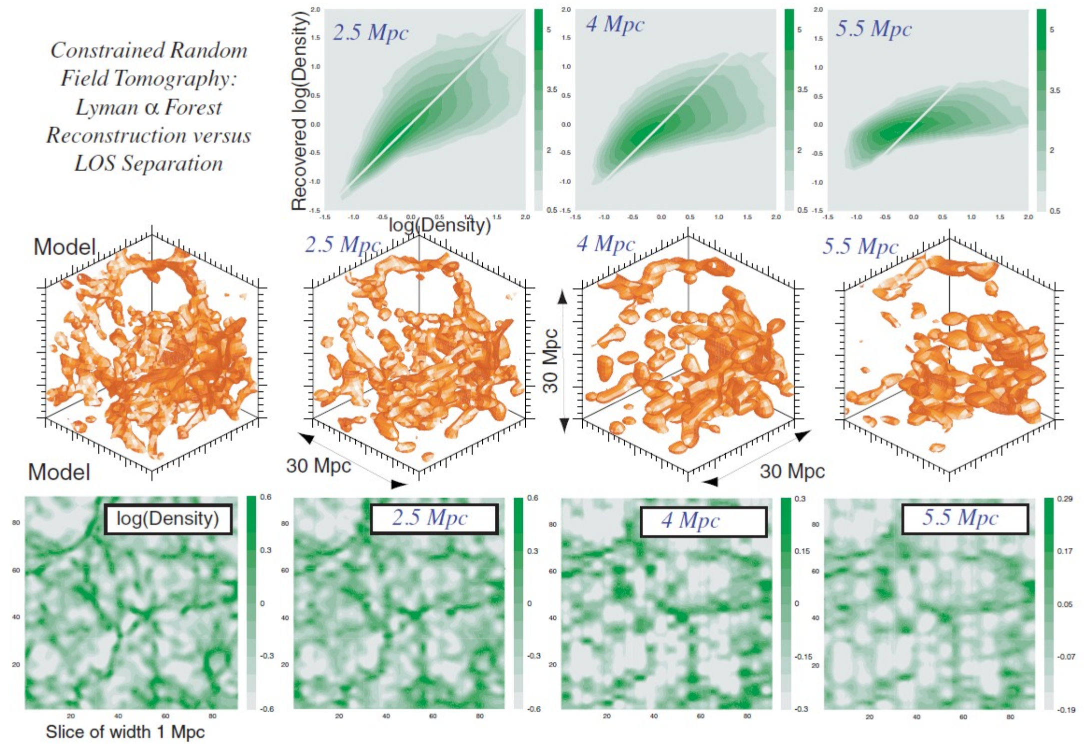
→ Constraints on outflow mechanisms and star-formation history

The Ly-alpha forest: tomography of the IGM

Tomography



Pichon et al. 2001, Cauci et al. 2008

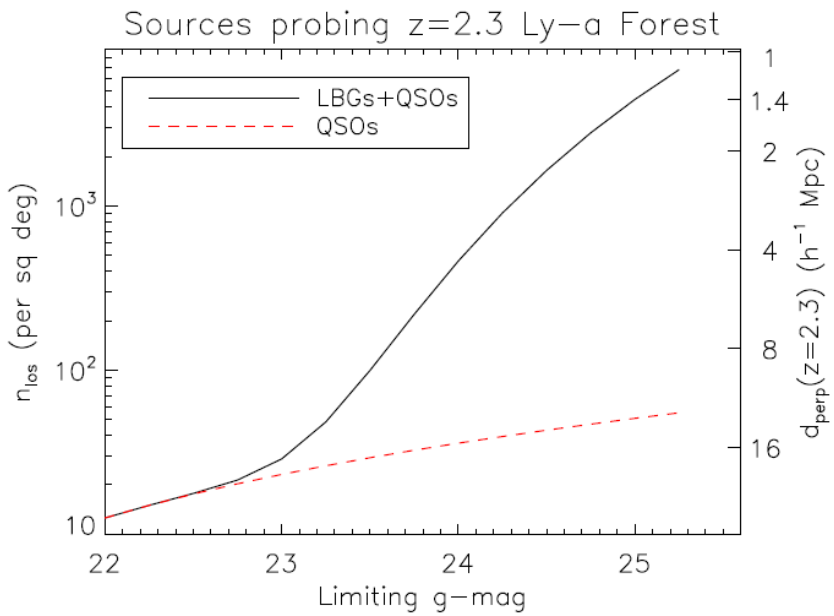


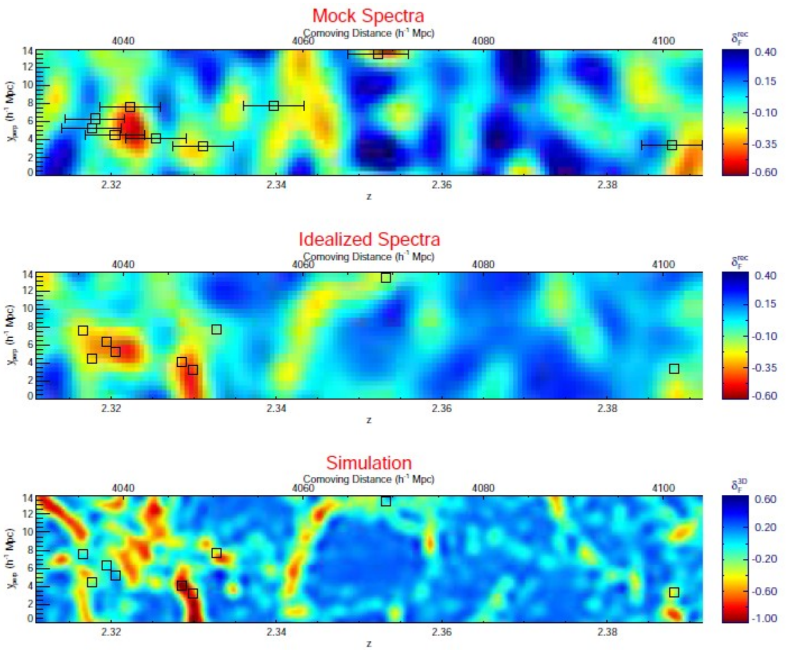
900 400 150 /deg^2

~Mpc resolution: We will need 1000 LoS/deg^2 (SDSS-III/BOSS: 17)

The Ly-alpha forest: tomography of the IGM

Quasar are not enough → use LBGs!





Steidel et al. 2009: S/N=30 per pixel @ R=5000 for r=24.5

Evans et al. 2012: S/N>8 per resolution element @ R=5000 for r=24.8

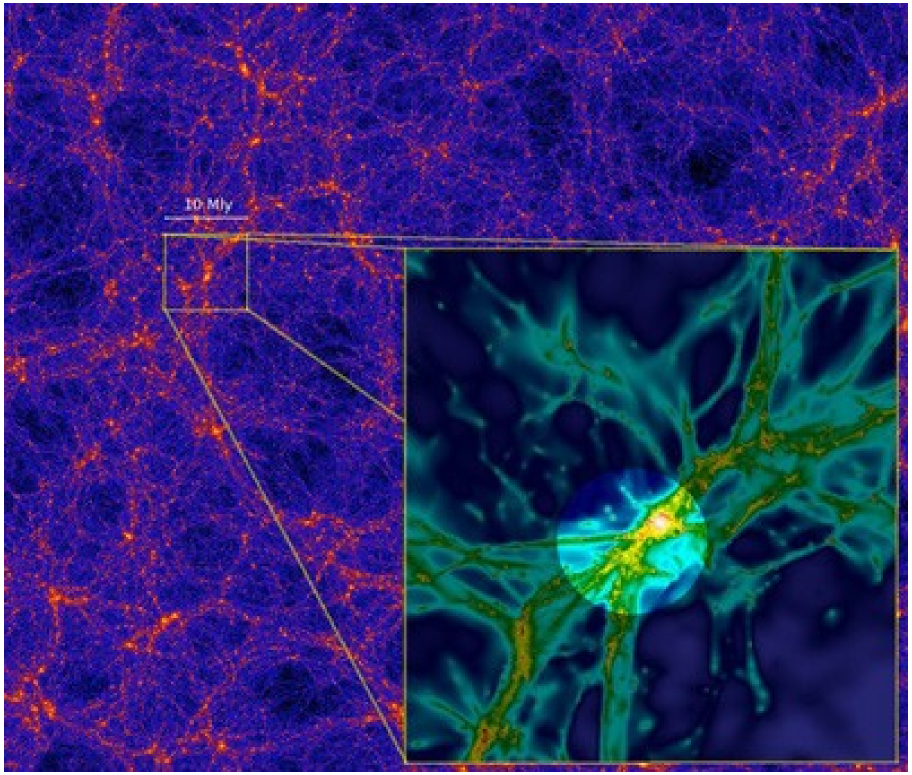
→ MOS@ELT

Lee et al. 2014: you don't need to resolve forest. S/N~4 @ R~1000 is enough to g~24

→ VLT is ~ok (?)

Shining of an IGM filament

- Filament in the cosmic web: Ly-alpha in emission



Cantalupo et al. 2014

The knots of a filament in absorption

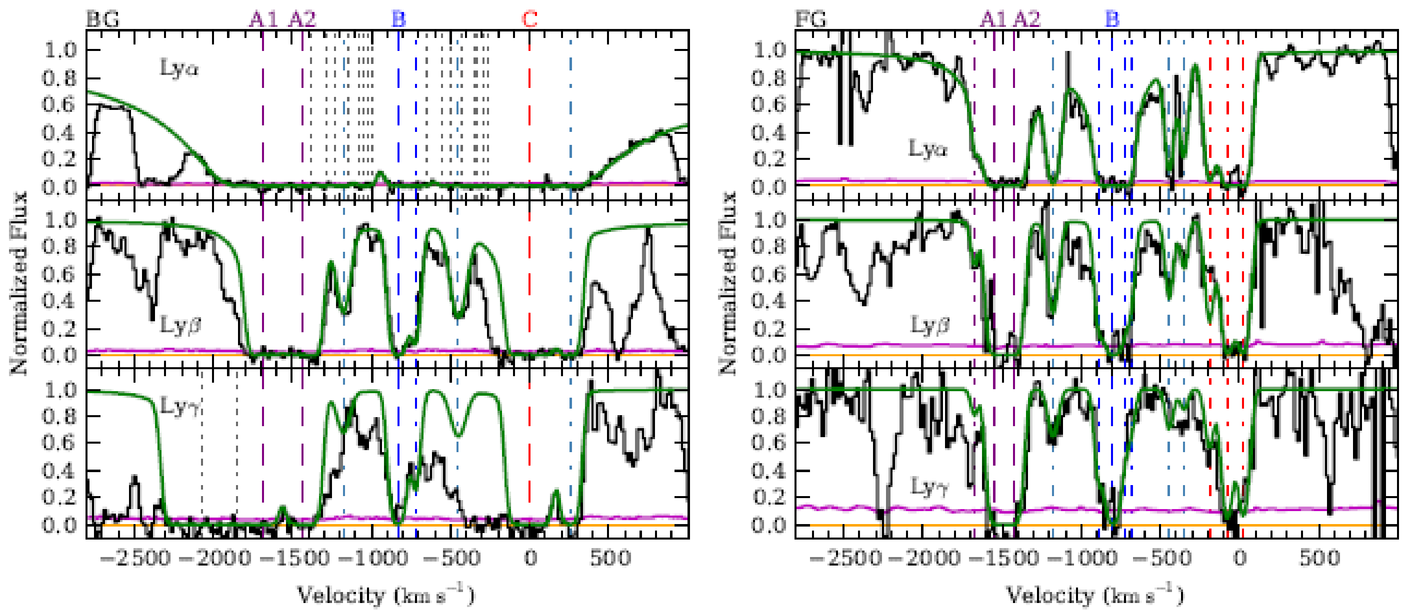
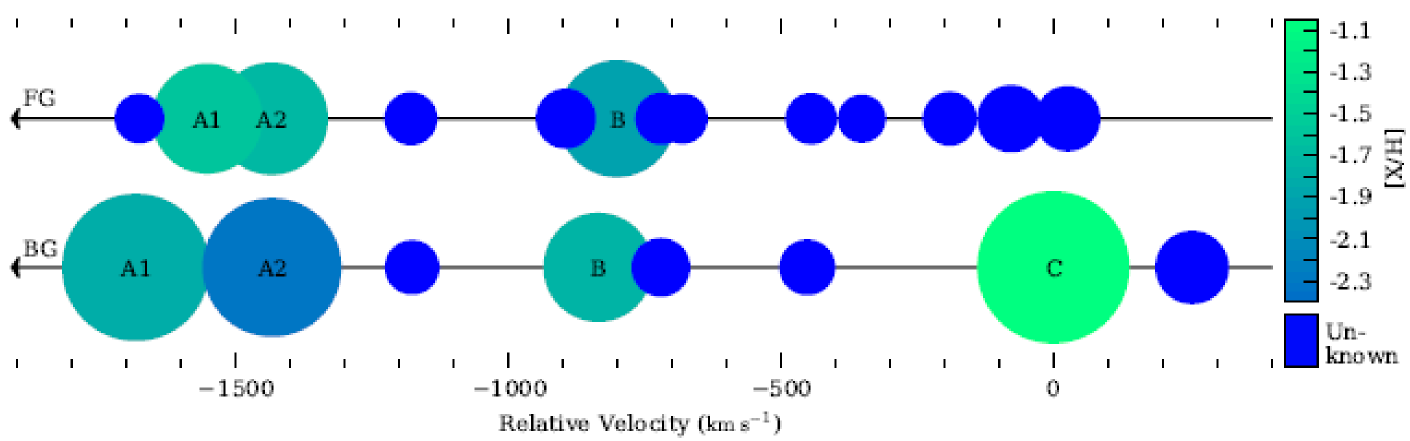
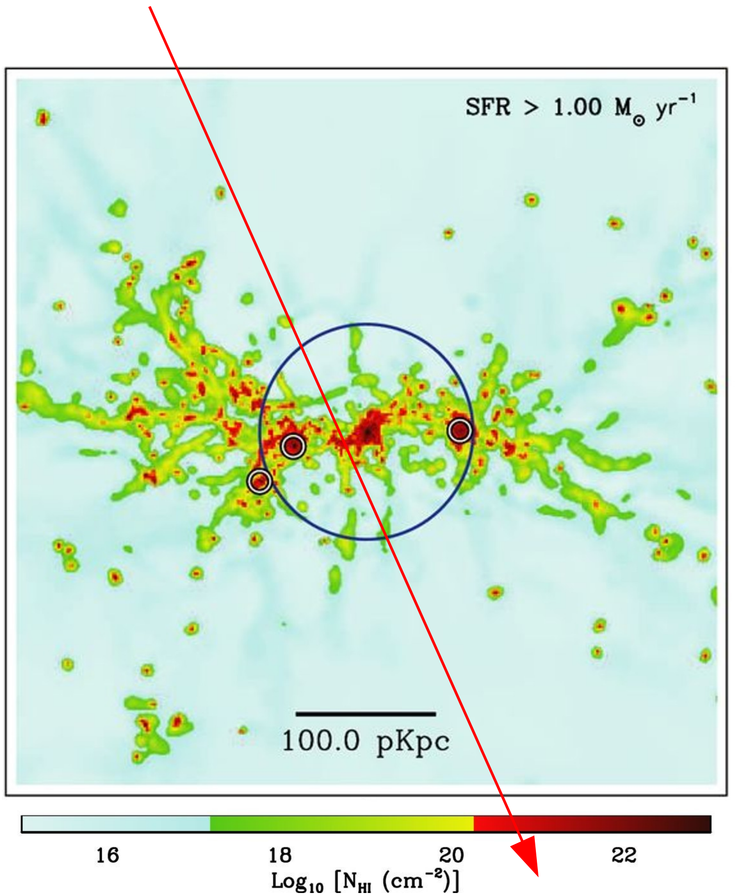


Fig. 2. Fits to Lyα (top), Lyβ (middle), and Lyγ (bottom) H I absorptions in the BG (left) and FG (right) spectra. Dashed purple, blue, and red lines mark the log N(H I) > 18.0 components in regions A, B, and C, while dash-dotted purple, blue, and red lines indicate the weaker components within the respective regions. Dash-dotted blue-gray lines signal low column density components between the three main regions that are also part of the absorption structure. Dotted gray lines in the BG-Lyα panel indicate blended components from Si II λ1190 and 1193 absorptions associated with a $z \simeq 2.75$ DLA.



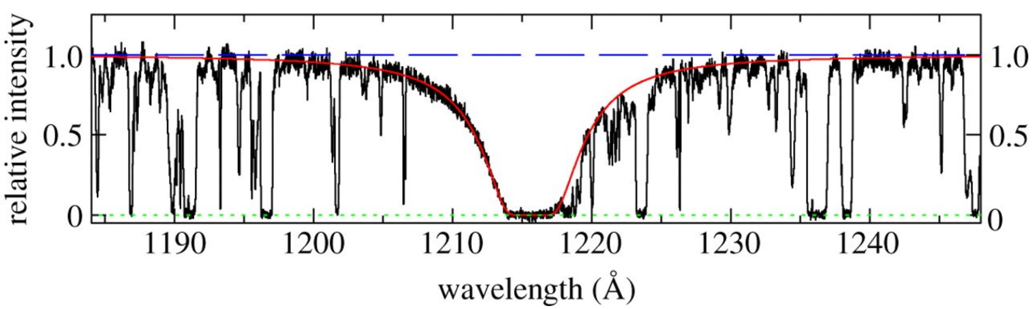
Finley et al. 2014

Gas in galaxies: Damped Lyman-alpha systems

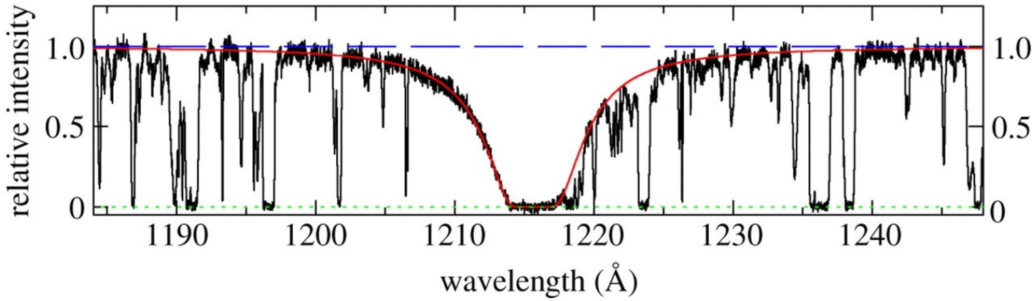


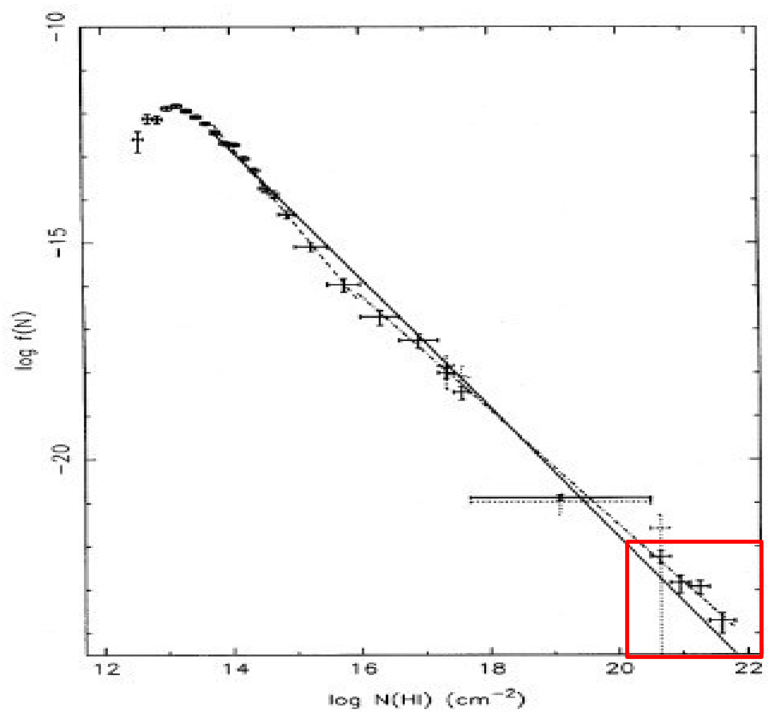
At log(NHI)>20, all ionising photons are absorbed in the external layers

→ **DLAs correspond to <u>neutral gas</u>**

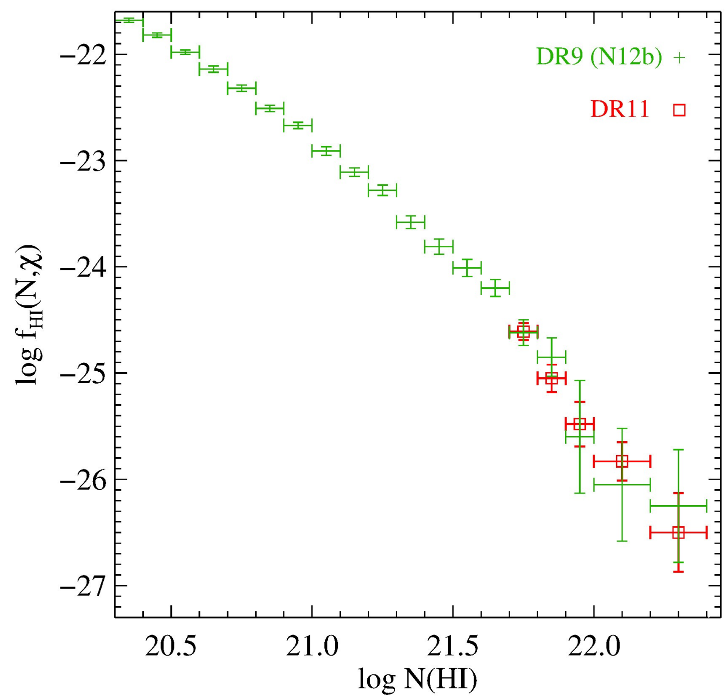


counting DLAs





Petitjean et al. 1993



Noterdaeme et al. 2012c,2014

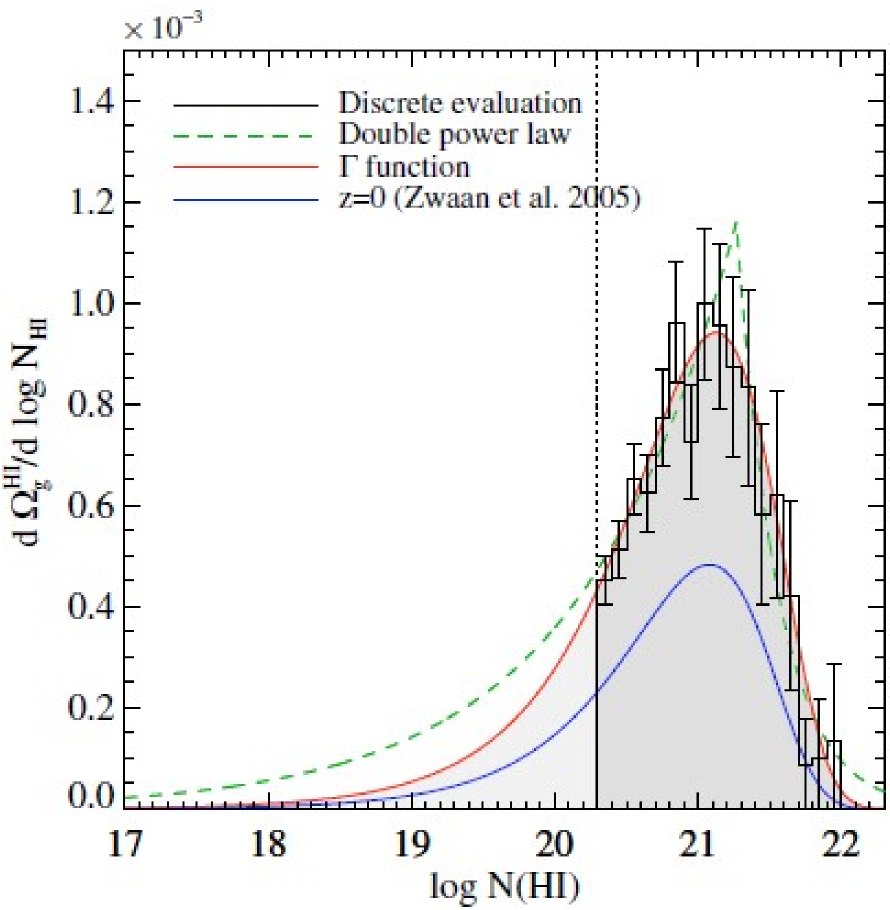
Huge increase of statistics mainly thanks to **SDSS** ~100 to several 10^4

How much gas in DLAs?

→ whiteboard

DLAs contain the bulk of neutral gas in the Universe

- **HI**



Noterdaeme et al. 2009b

DLAs contain the bulk of the neutral gas at high-z

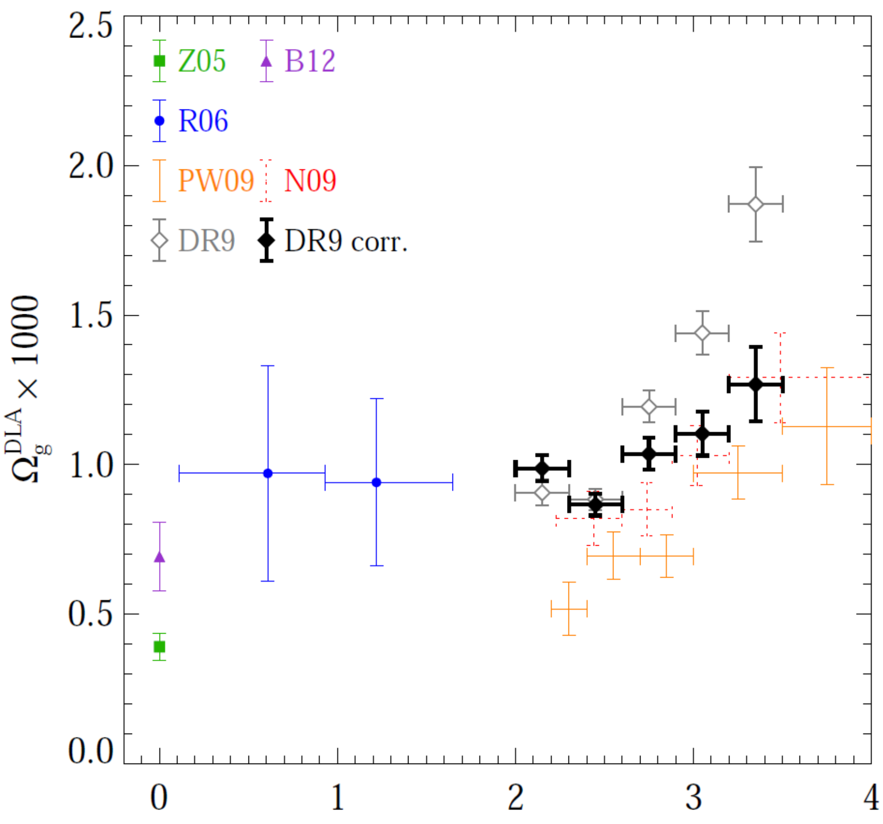
They probe a wide range of redshift **free from Malmquist bias**.

- ground-based telescopes: z>1.6

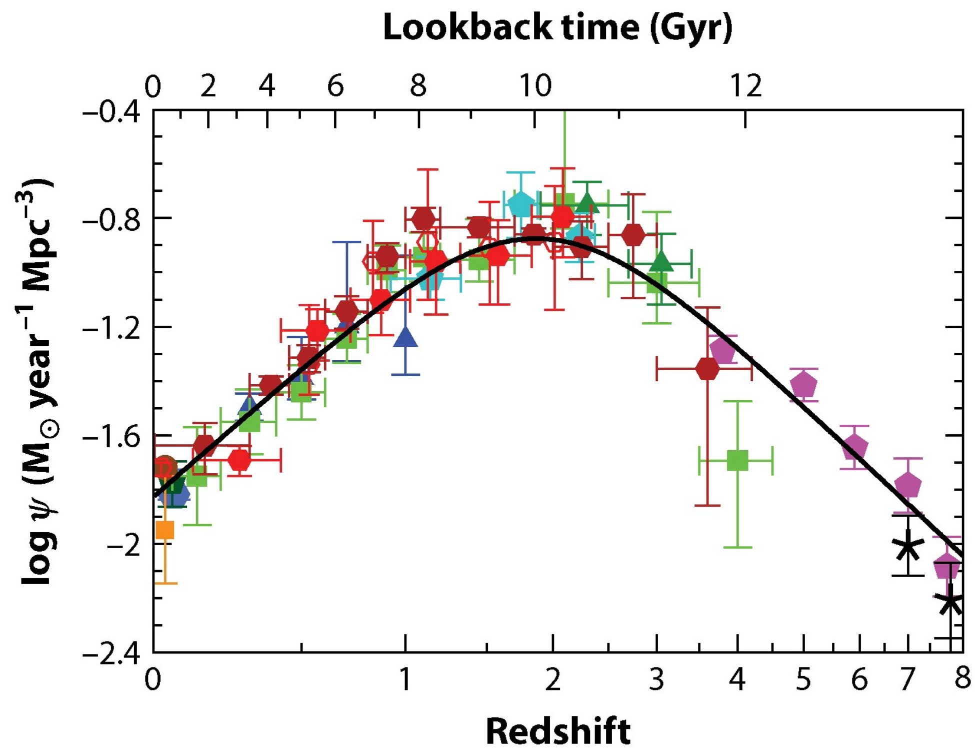
- blending with Lyman-alpha forest becomes severe at z>3.5

Does the neutral gas behave like star-formation?

Cosmological density



Noterdaeme et al. 2012c



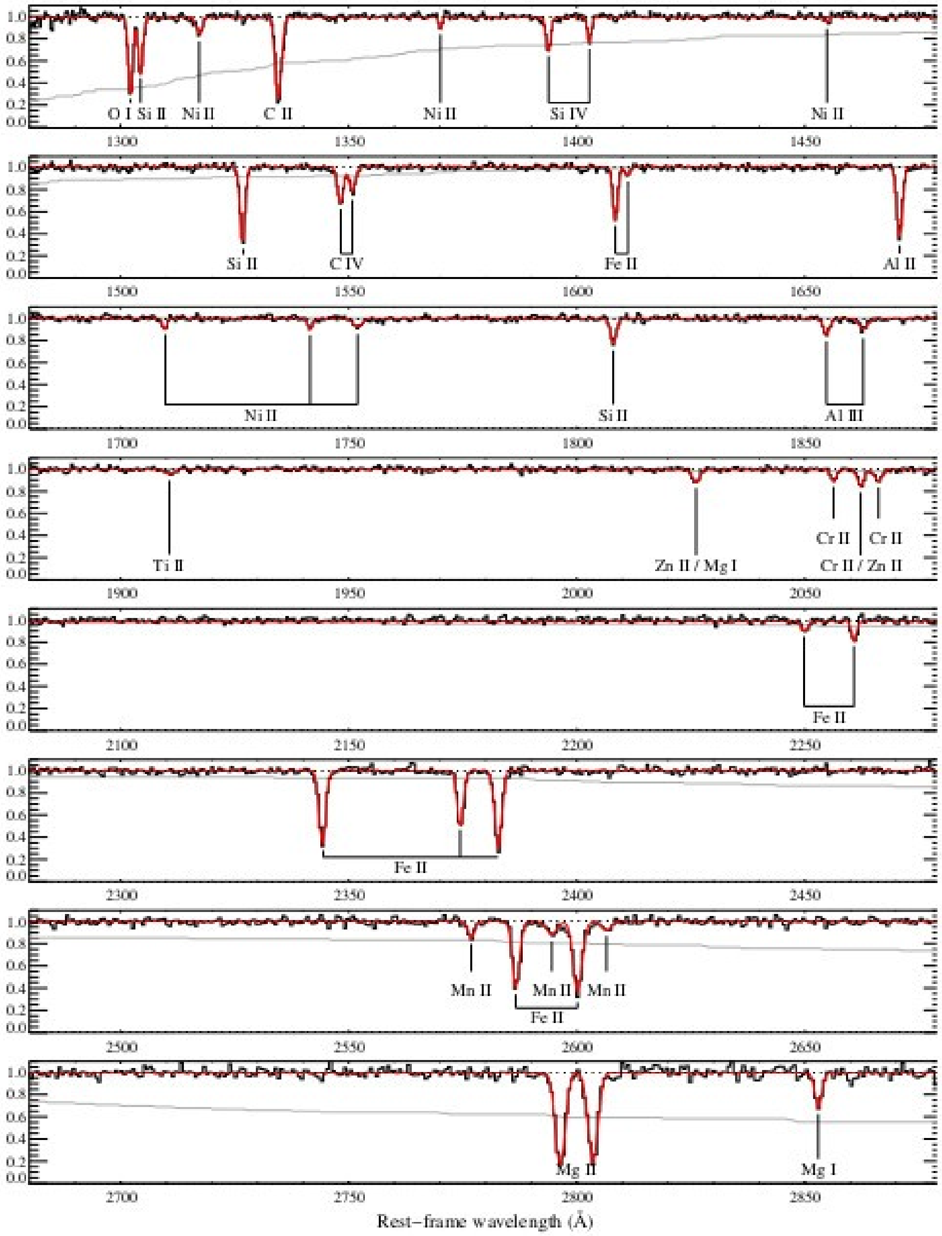
Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

- Systematics dominate
- z>3.5 not well constrained: blending with Ly-alpha forest, need higher resolution (medium is ok)

Hummmm....

Metals in DLAs

- about 20 different elements detected in DLAs → smoking gun of star formation



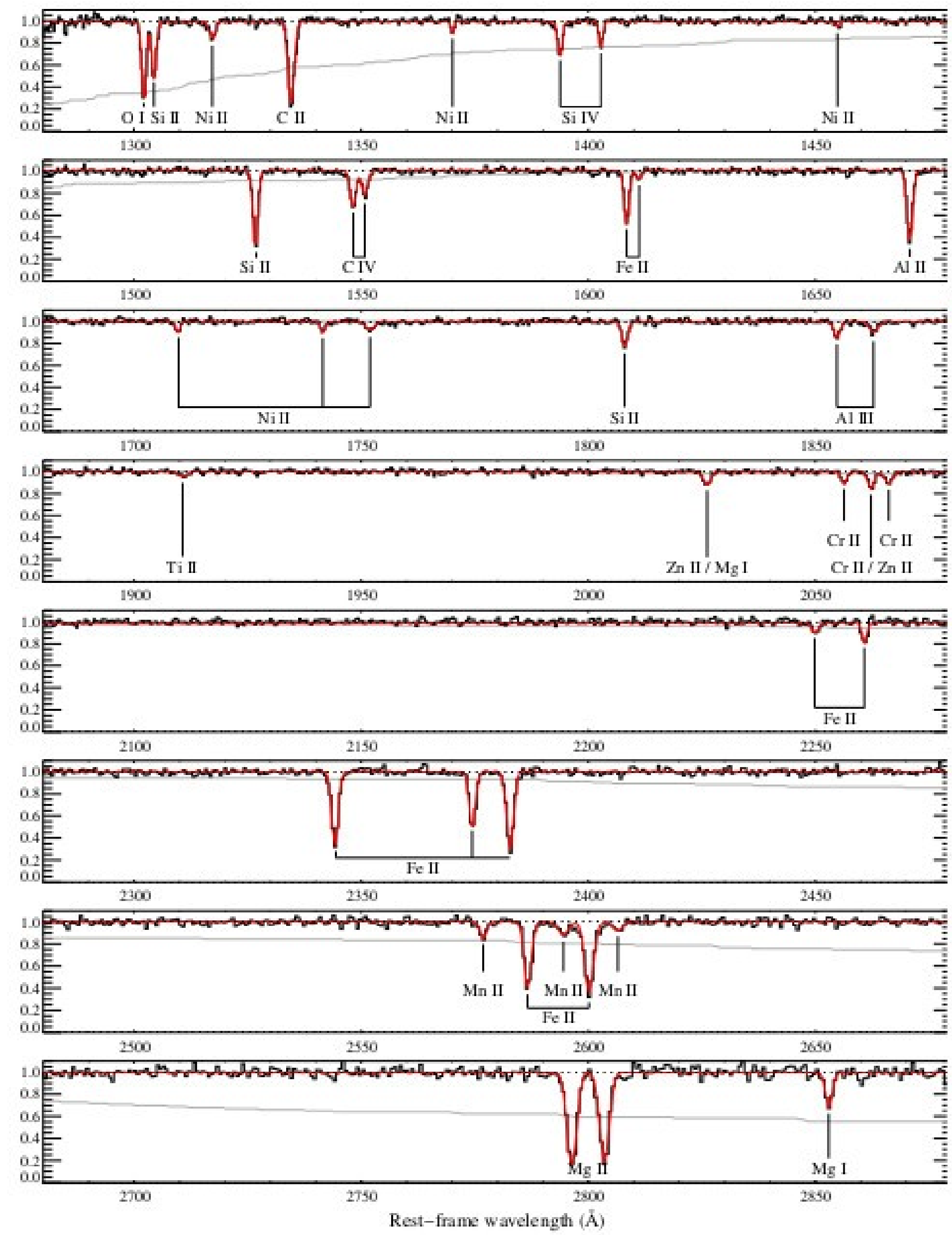
Metals in DLAs

- about 20 different elements detected in DLAs → smoking gun of star formation

- Column density measurements are robust in DLAs: independent of physical parameters like temperature or density

- hν < 13.6 eV → Metals mostly in a single ionisation stage (FeII, SiII, ZnII, OI, NI...)
  → N(ZnII) ~ N(Zn)
  → ZnII/HI = Zn/H
  → no ionisation correction

Abundances measurements in DLAs are accurate (typically 0.1 dex)

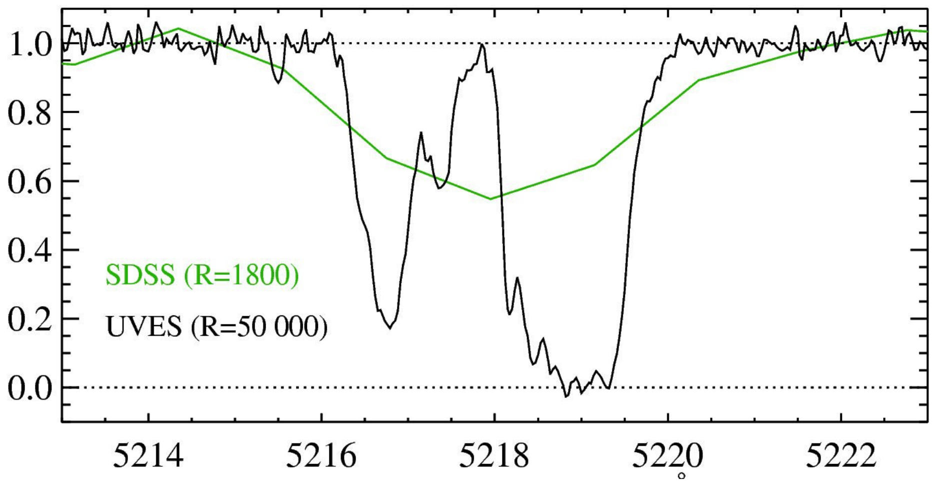


Measuring metallicities

- **In practice: high vs low spectral resolution**

  - high R: Voigt-profile fitting
    Apparent Optical Depth

  - low R: only Equivalent Widths
    → Assuming optically thin is very dangerous!



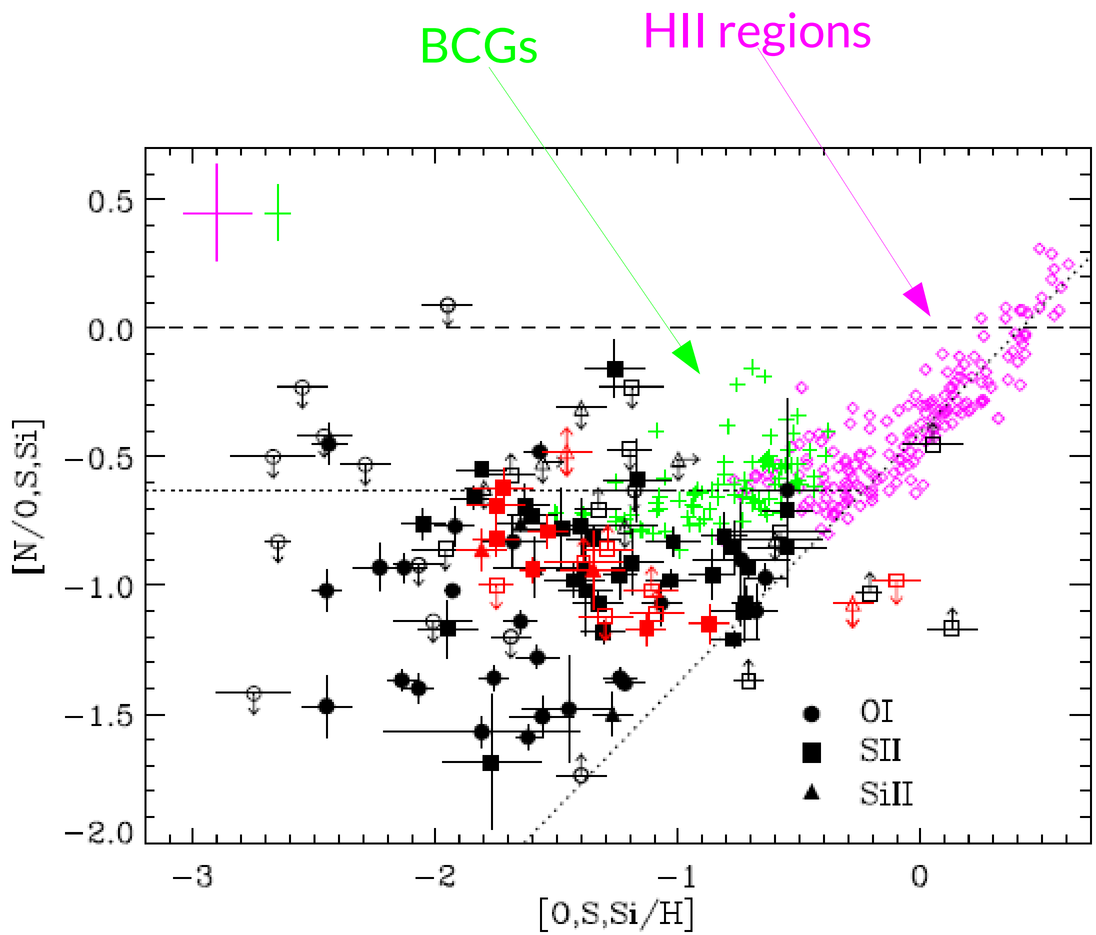
Metallicities have to be measured at "high" spectral resolution.

Nucleosynthesis

→ Zinc as proxy for iron?
Barbuy et al. 2015 (Galactic buldge stars): [Zn/Fe] decreases with increasing metallicity.

SN type II enrichment:
overabundance of O compared to N
overabundance of alpha elements compared to iron-peak

→ **An example**, [N/O] vs [O/H]
Petitjean et al. 2008, Pettini et al. 2008, Zafar et al. 2014



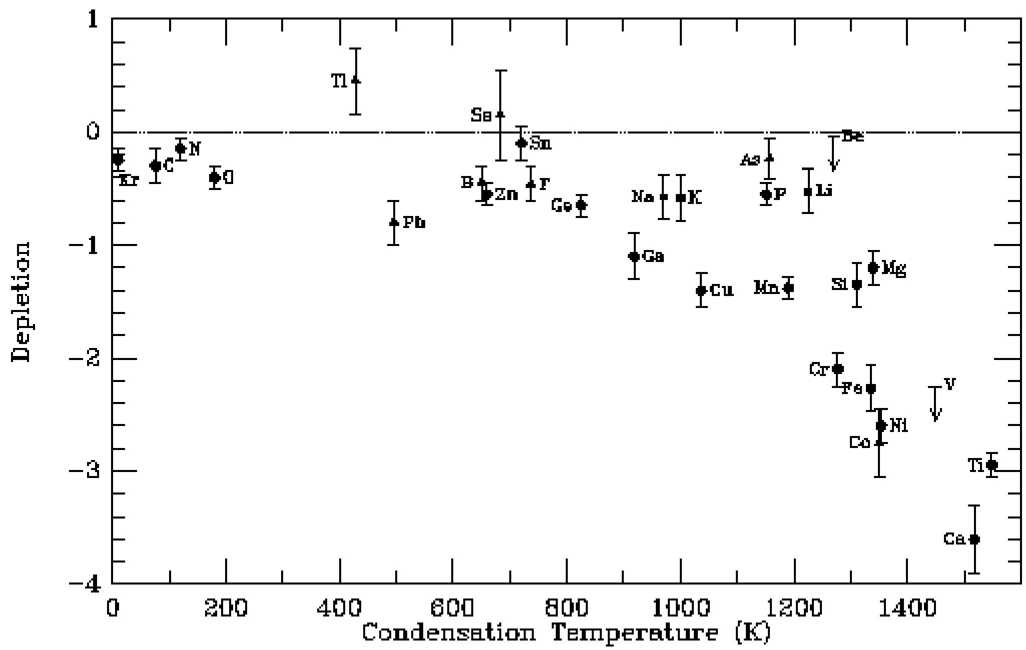
Zafar et al. 2014

Do we see all the metals?

- **Depletion**

  Does the gas-phase abundance represent the true abundance?

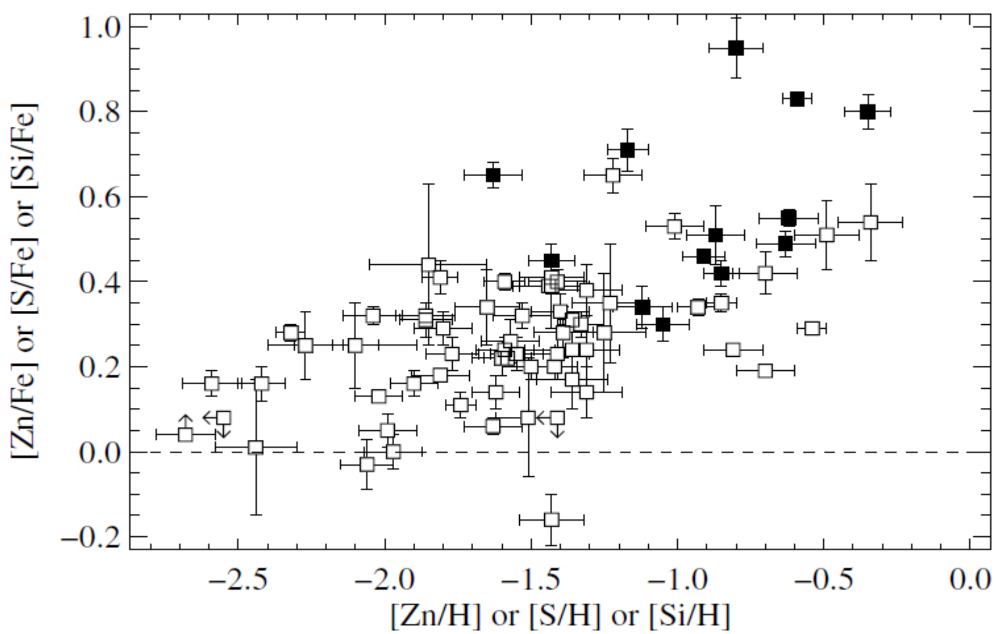
  → Several species tend to easily deplete onto dust grains (e.g. Fe, Ni, Cr), while other are more volatile (Zn, S)



- **Depletion**

  Does the gas-phase abundance represent the overall abundance?

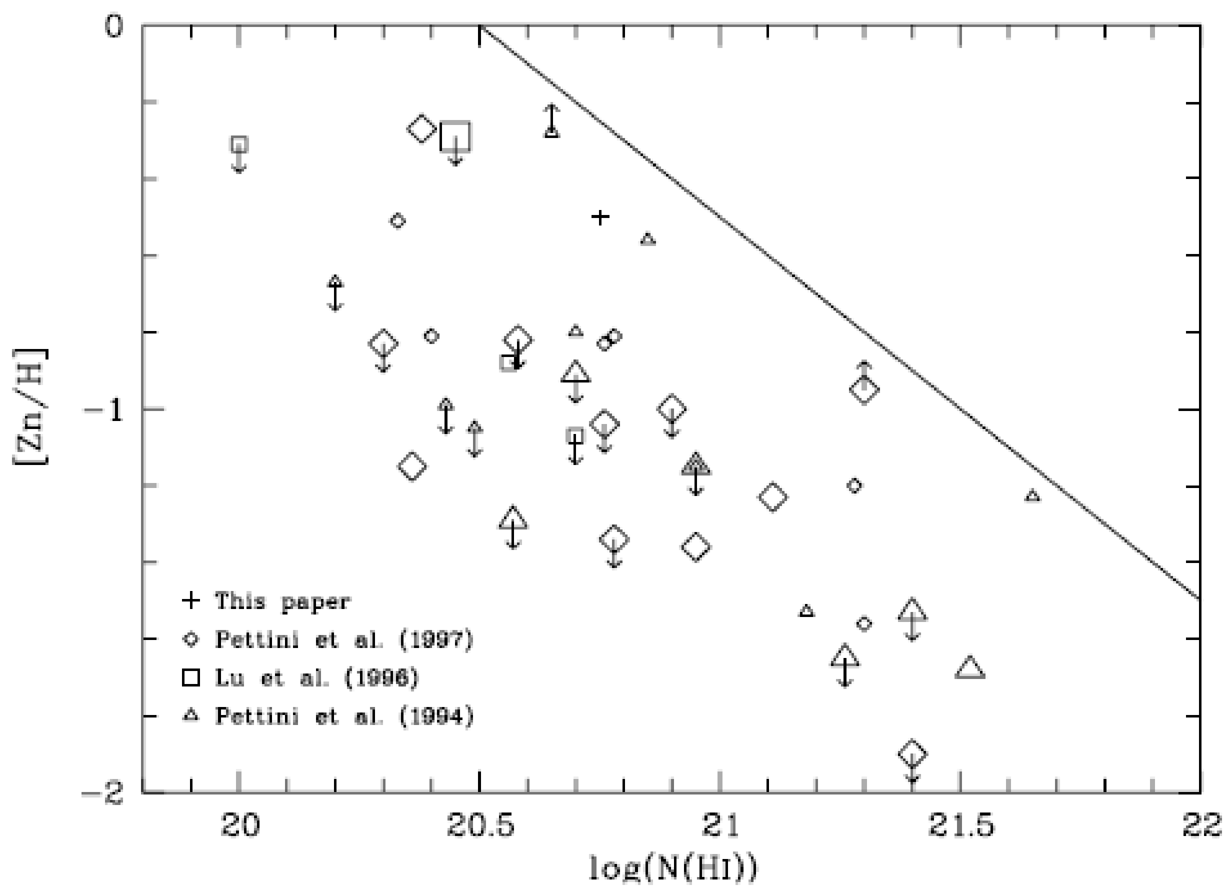
  → Several species tend to easily deplete onto dust grains (e.g. Fe, Ni, Cr), while other are more volatile (Zn, S)



Noterdaeme et al. 2008a

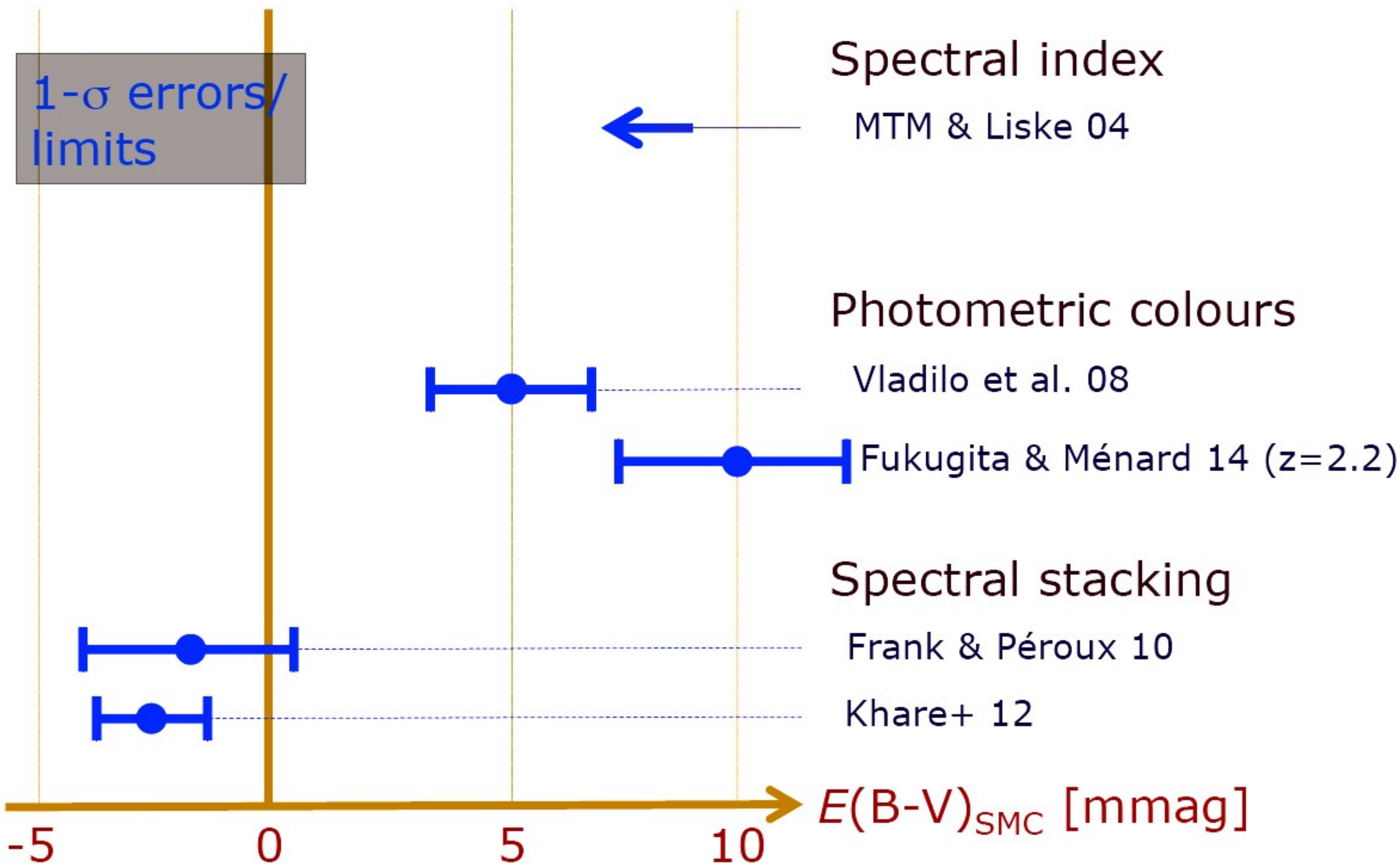
→ [Zn/Fe] increases with [Zn/H]
→ Higher detection rate of H_2 when both are high.

Do we miss high-Z, high-NHI systems?



Boisse et al. 1998

Is there any direct evidence for dust in DLAs?



Slide from M. Murphy

dust bias?

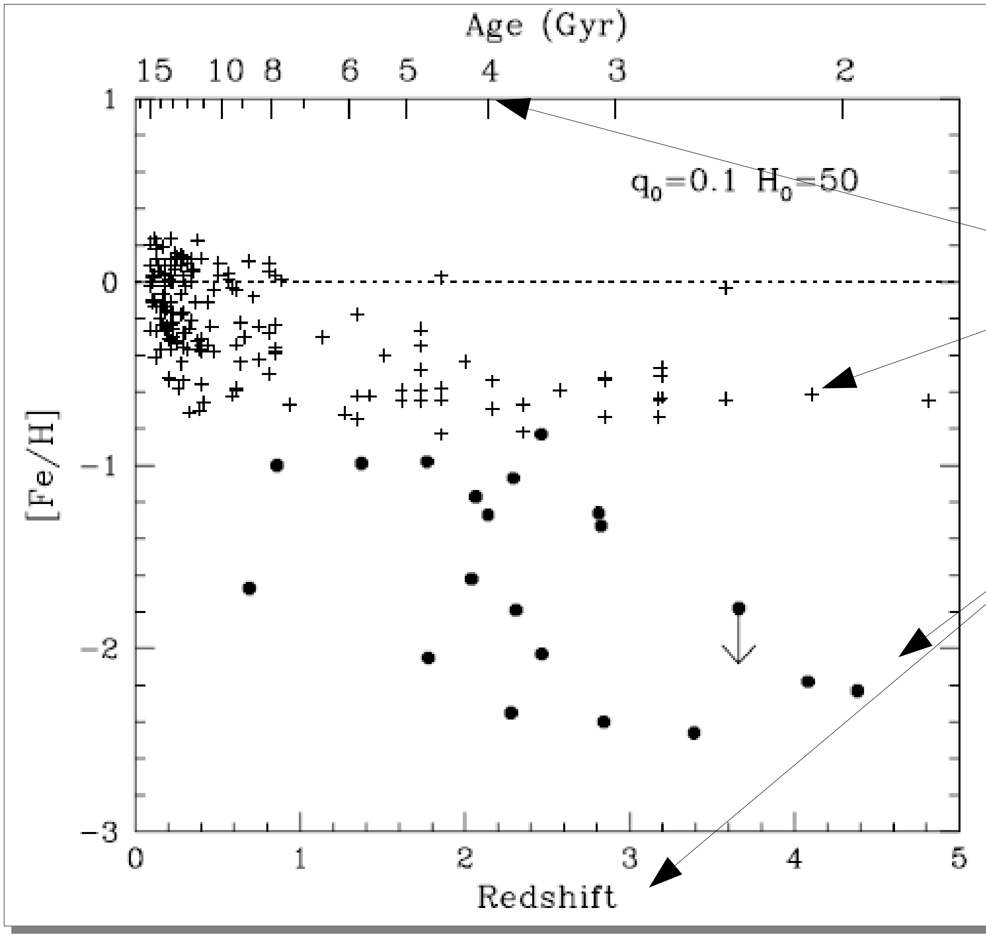
CORALS (Ellison et al. 2005)

- 66 radio-selected QSOs
- Incidence of DLAs consistent with optically-selected quasars
- Total HI also consistent (within x2) with optical surveys

→ <u>No bias</u>....of what?

→ The bulk of neutral gas is not affected by dust-biasing

The age-metallicity relation: a long story

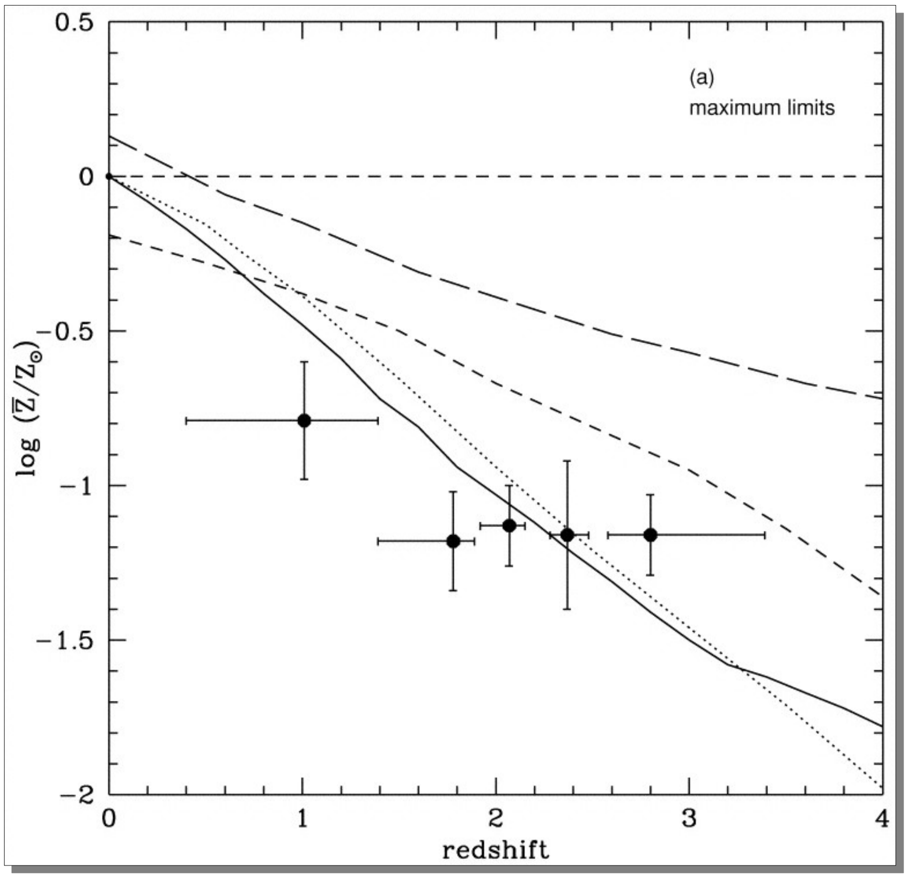


Lu et al. 1996

Galactic stars

DLAs

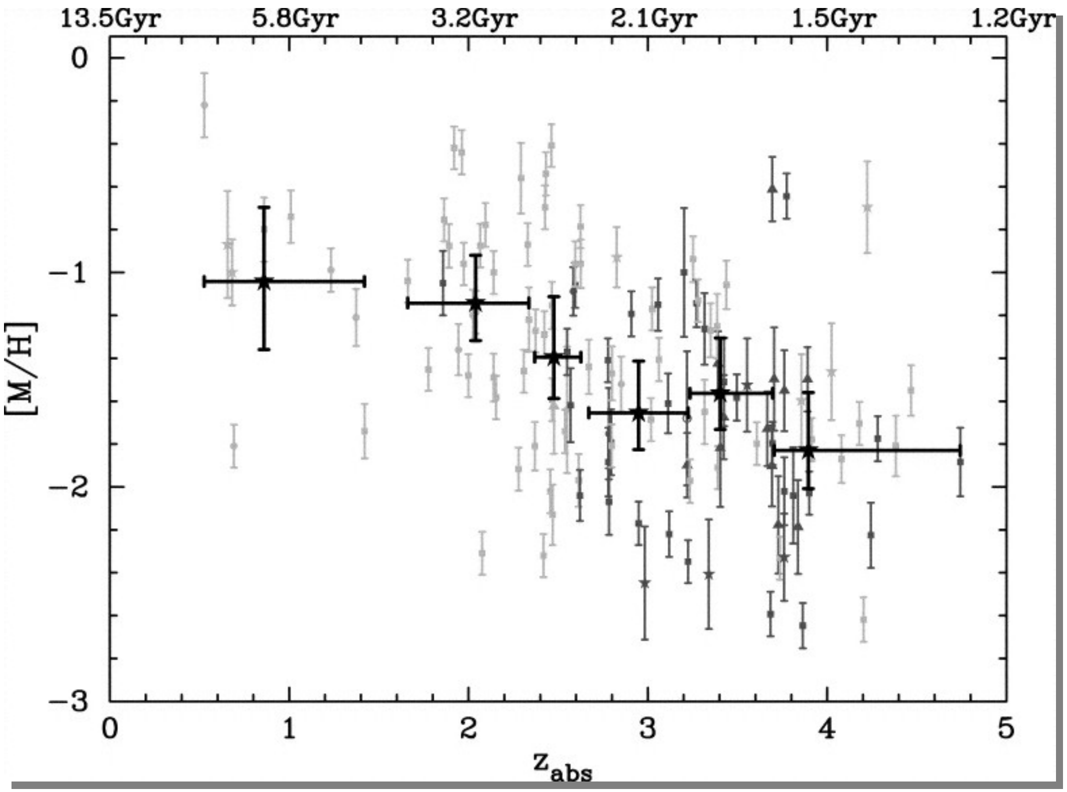
The age-metallicity relation: a long story



Lu et al. 1996

Kulkarni et al. 2002

The age-metallicity relation: a long story

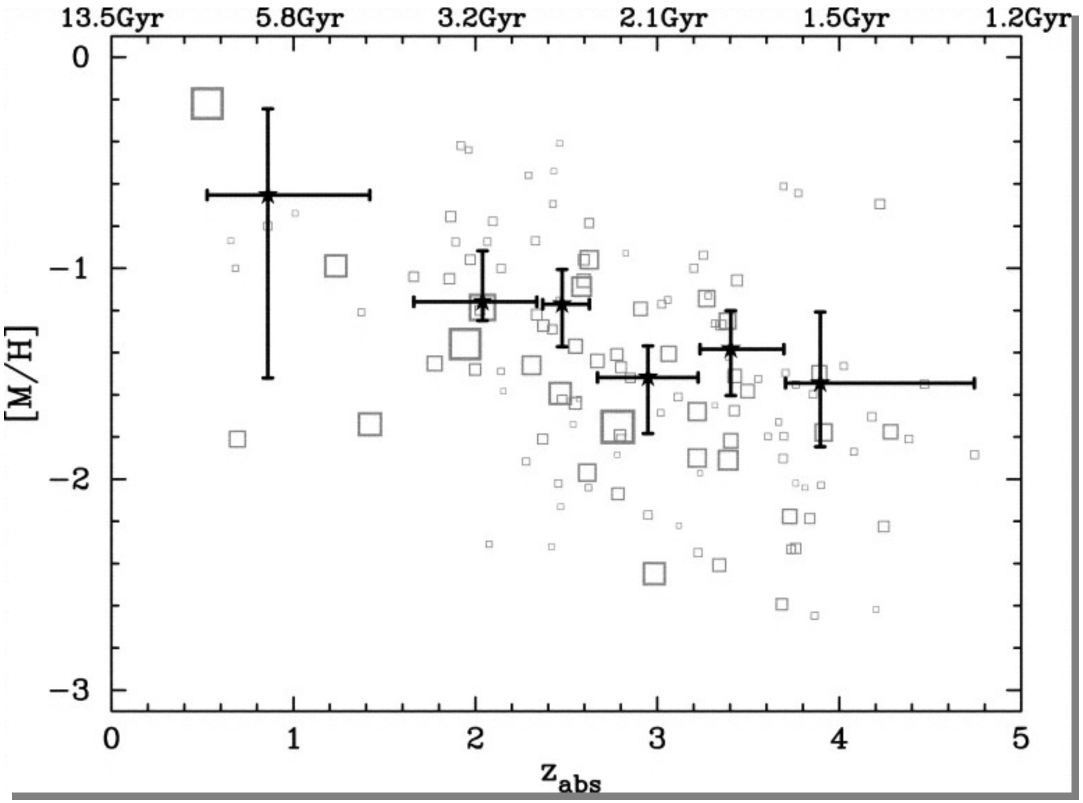


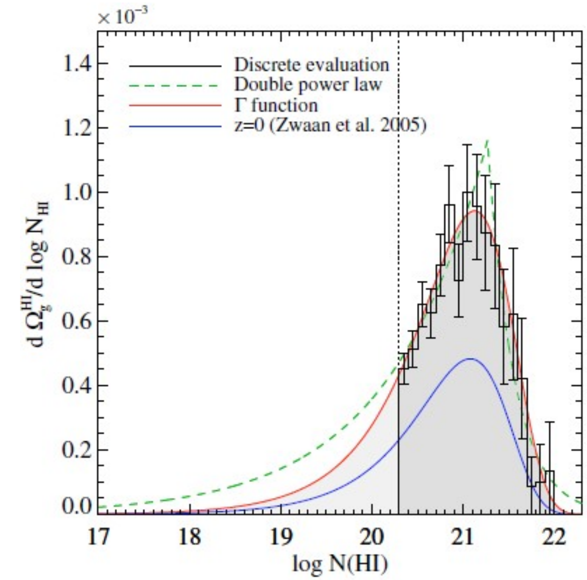
Lu et al. 1996

Kulkarni et al. 2002

Prochaska et al. 2003

The age-metallicity relation: a long story

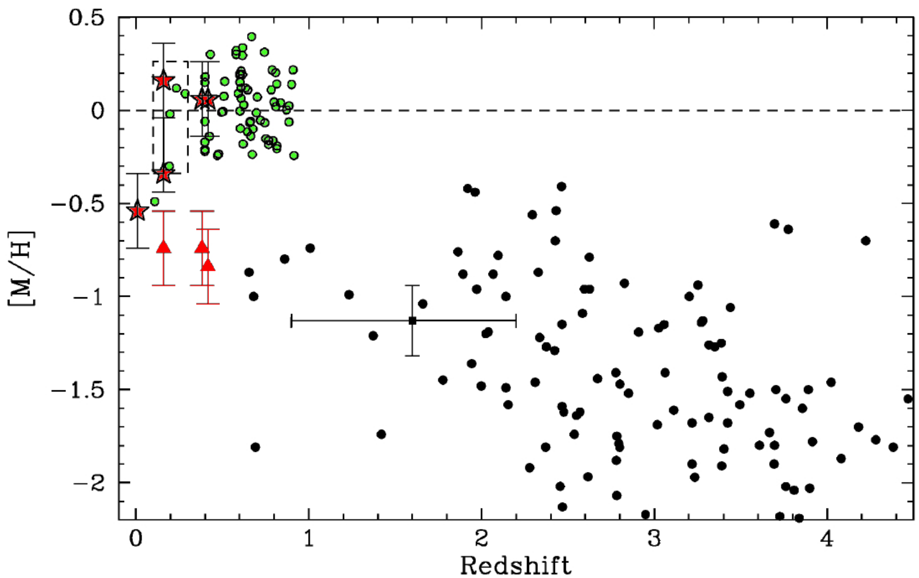




Noterdaeme et al. 2009,2012

Wolfe et al. 2005, ARA&A: *"This result is robust owing to the large value of $\sum_i^m N_i$. This is important since the shape of f(N, X) indicates that <Z> is sensitive to the metallicity of systems with the largest values of N(H I). Because $\sum_i^m N_i \geq 1 \times 10^{22}$ cm^{-2} in each of the high-redshift bins, only unusual, very metal-rich systems with N(H I) > 10^{22} cm^{-2} could increase <Z> significantly, i.e., only systems which depart significantly from the current N(H I) versus [M/H] relation could cause a marked increase in <Z>. "*

The age-metallicity relation: a long story

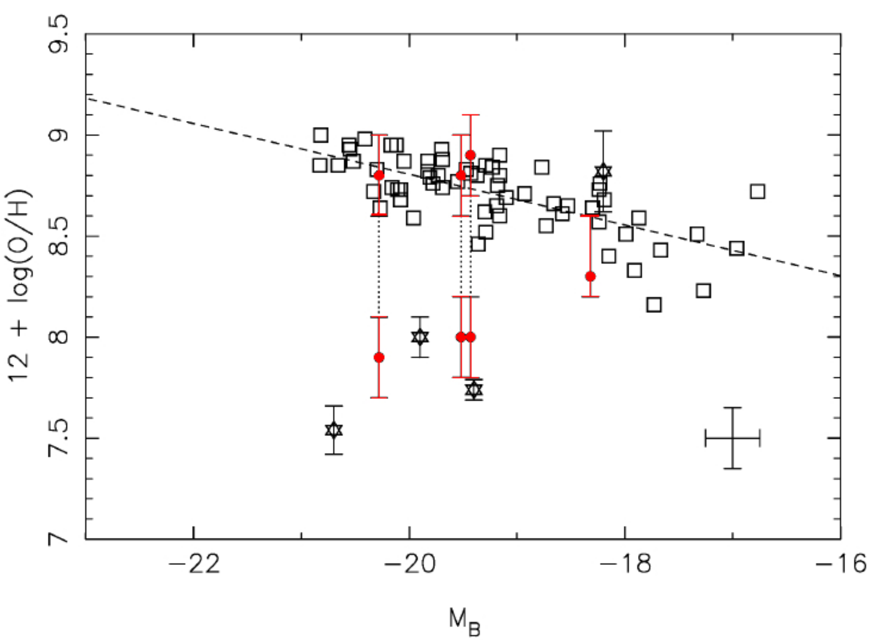


Lu et al. 1996

Kulkarni et al. 2002

Prochaska et al. 2003

Ellison et al. 2005

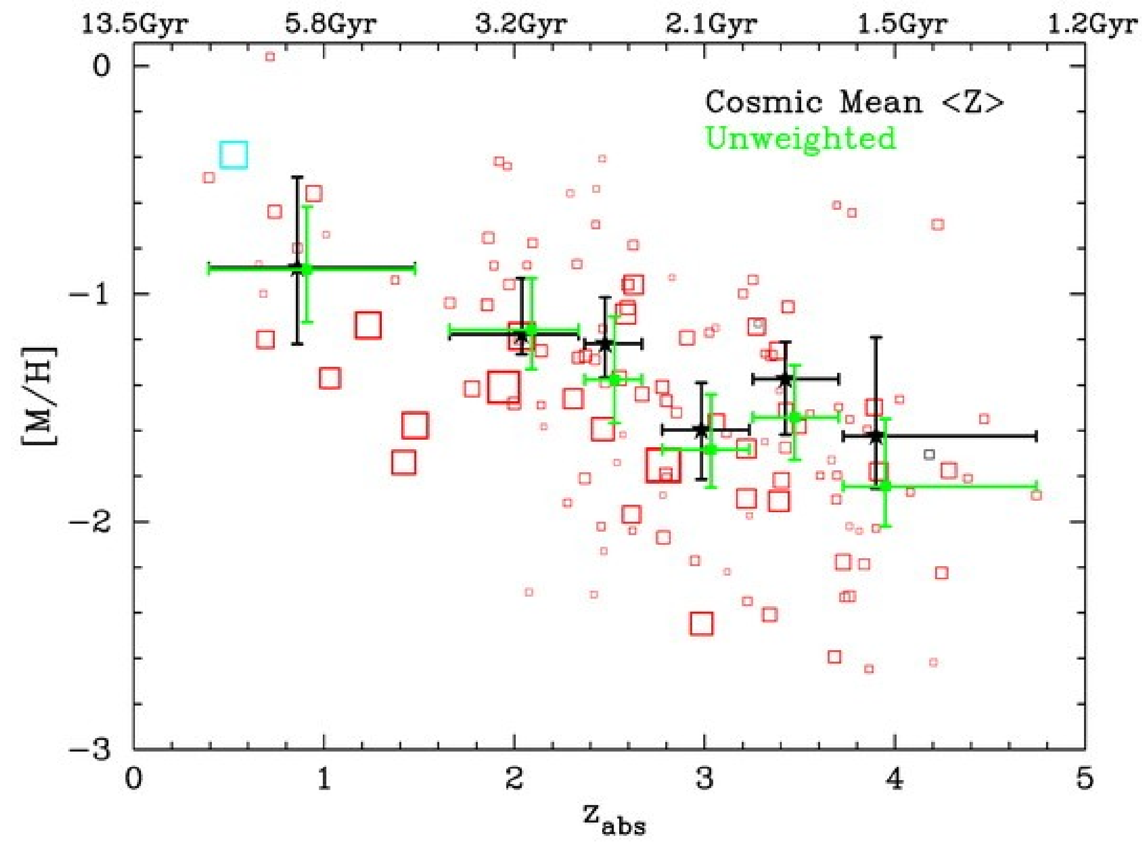


Emission-line metallicity
of absorption-selected galaxies

Upper branch: follows
the Metallicity-Luminosity but
inconsistent with DLA metallicities

Lower-branch: ok with DLA metallicities
but out of Z-L relation.

The age-metallicity relation: a long story



Lu et al. 1996

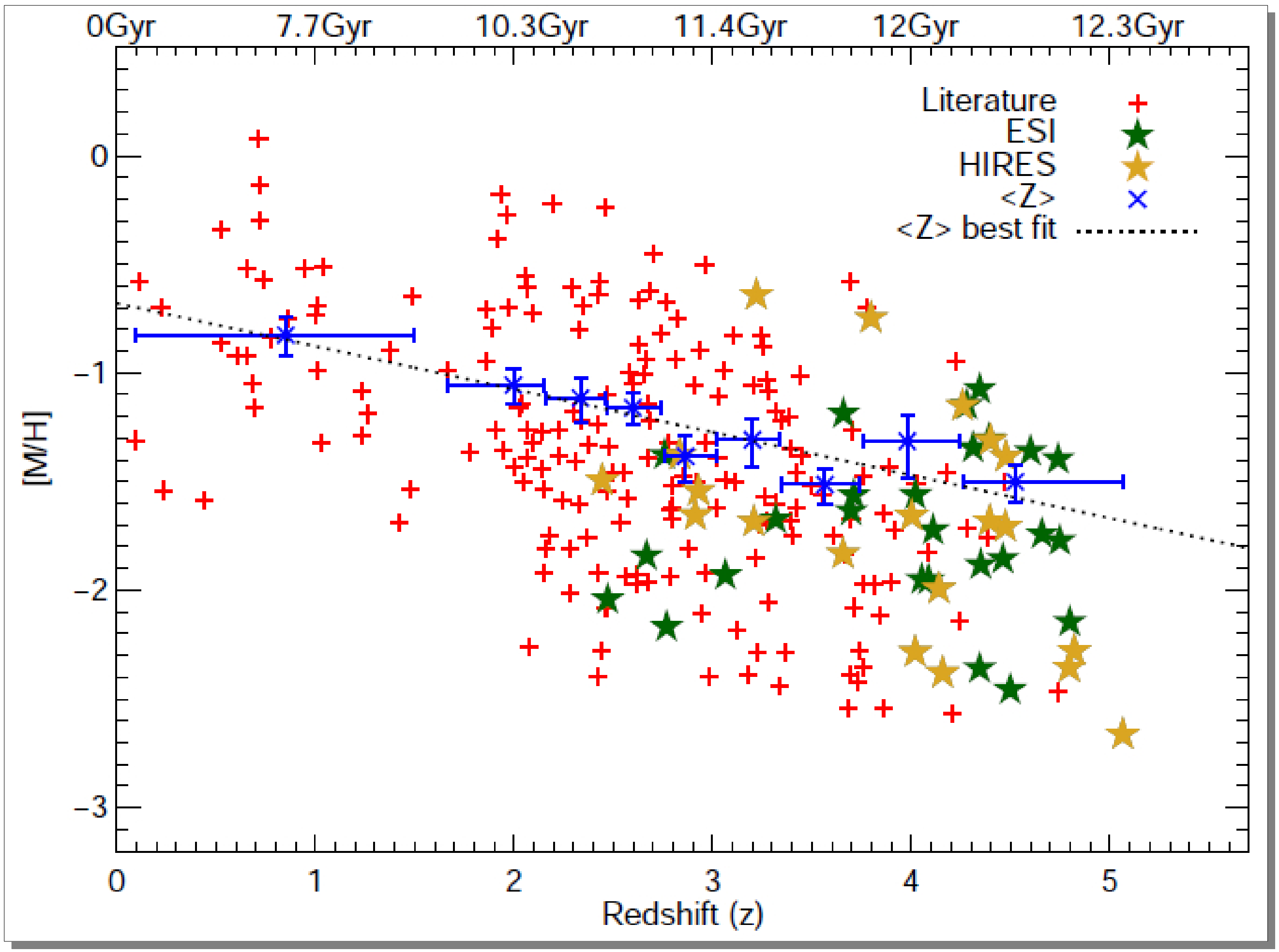
Kulkarni et al. 2002

Prochaska et al. 2003

Ellison et al. 2005

Rao et al. 2006

The age-metallicity relation: a long story



Lu et al. 1996

Kulkarni et al. 2002

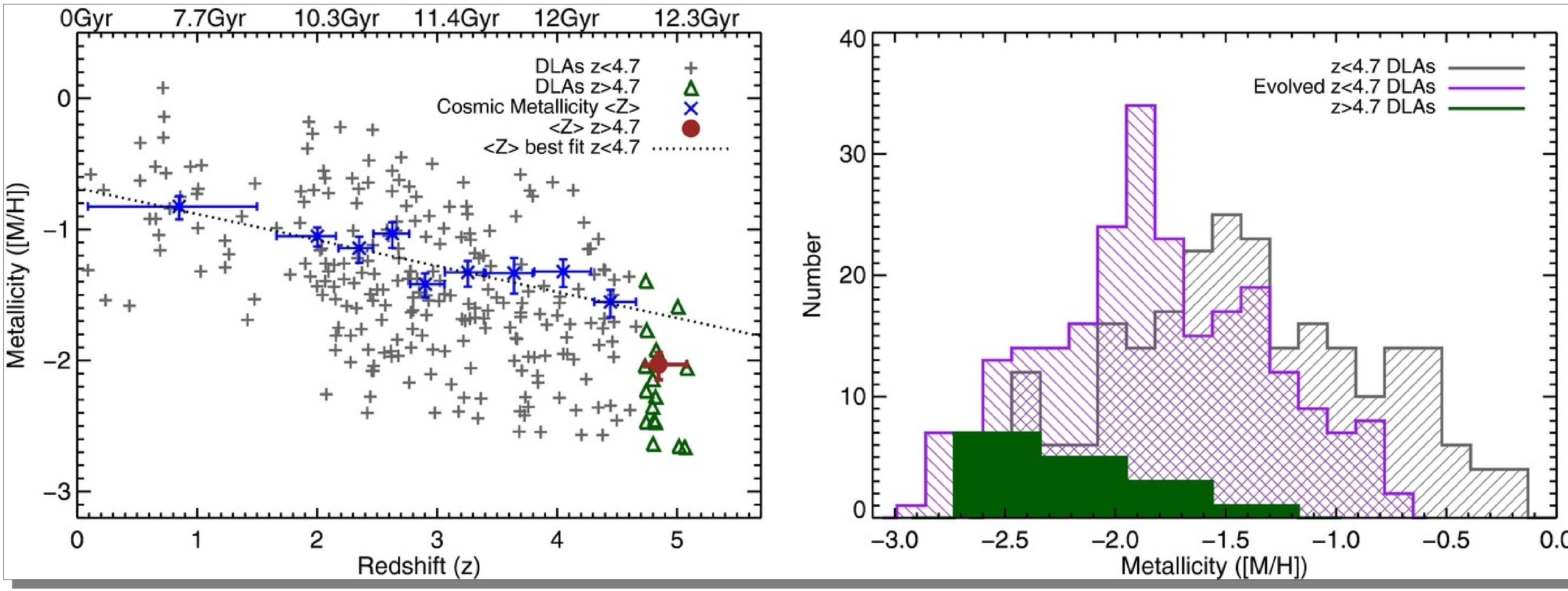
Prochaska et al. 2003

Ellison et al. 2005

Rao et al. 2006

Rafelski et al. 2012

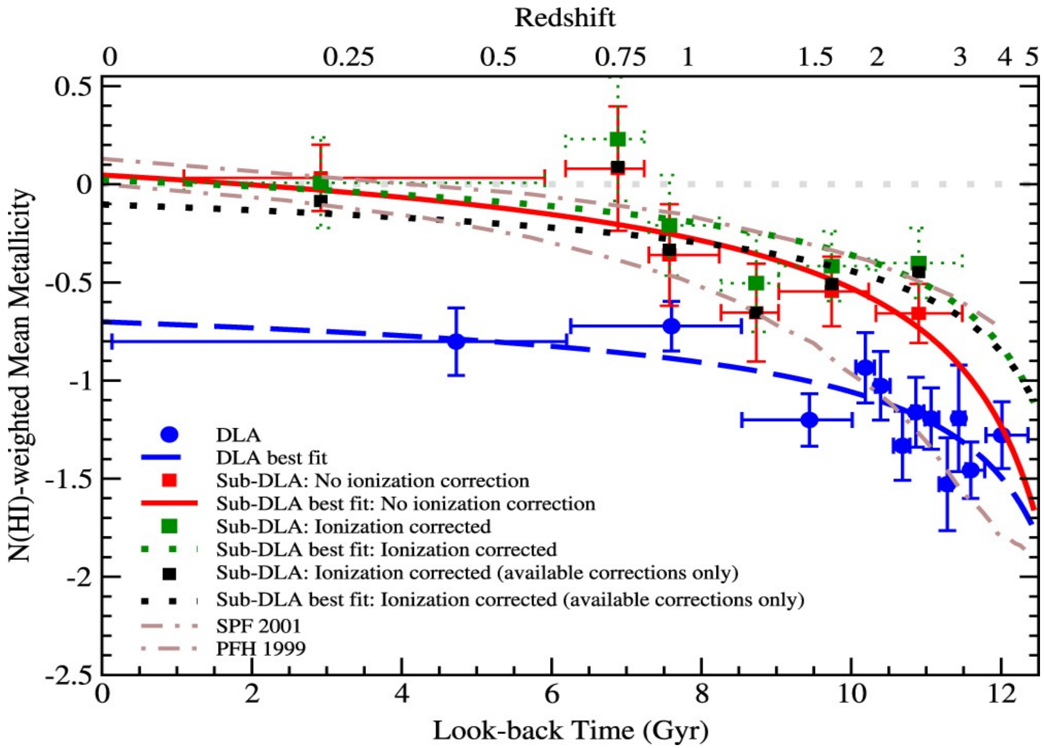
The age-metallicity relation: a long story



Rafelski et al. 2014

A fast change in metallicity at z>4.7?

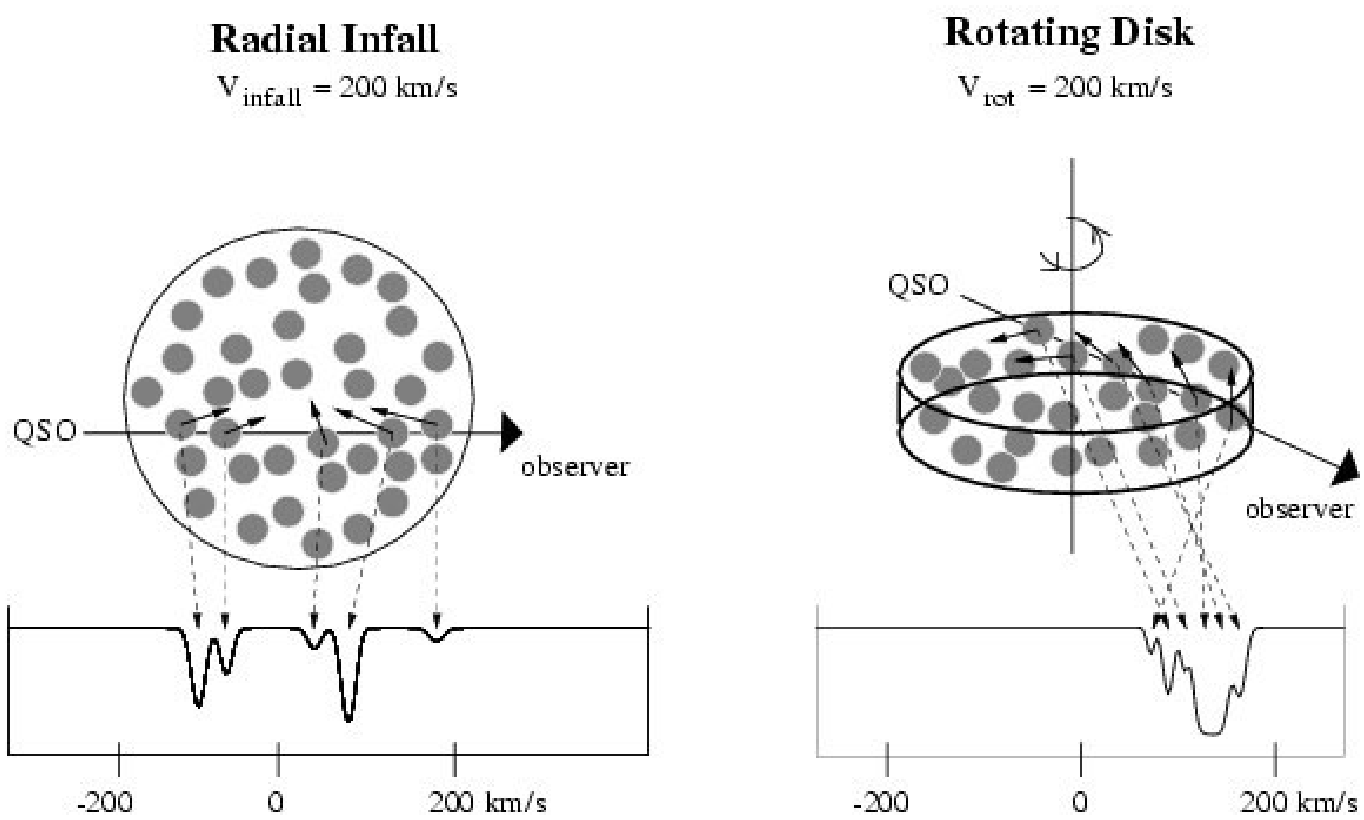
Kulkarni and co-workers: sub-DLAs tend to be more metal-rich



Som et al. 2015

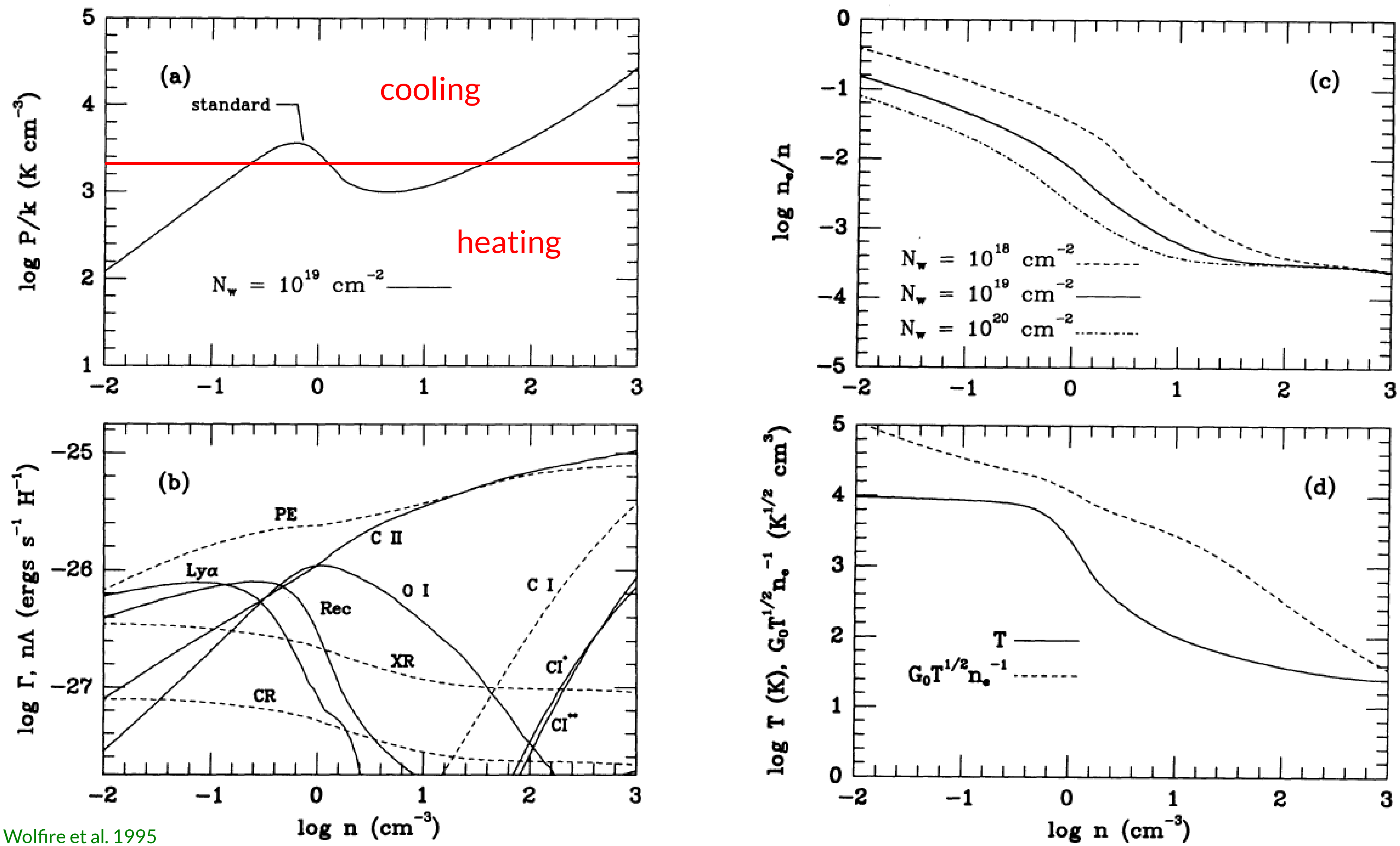
→ does this mean more massive galaxies?

Basic principle



Physical conditions in the neutral gas

Under pressure equilibrium: a simple two phase model



Wolfire et al. 1995

Are DLAs **w**arm **n**eutral **m**edium or **c**old **n**eutral **m**edium?

Physical conditions in the neutral gas

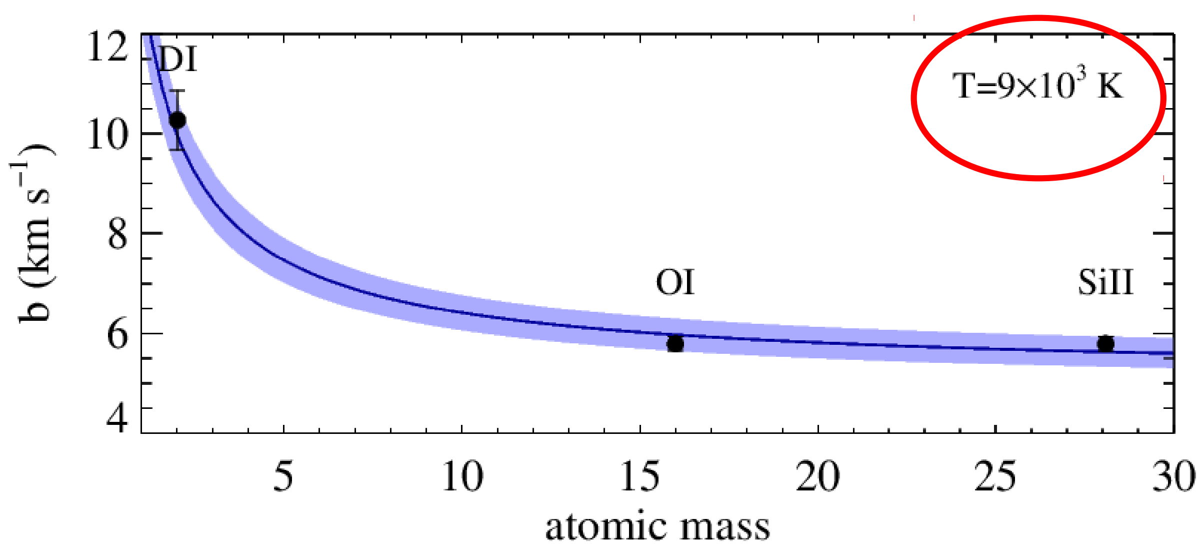
Look for the difference between “Warm Neutral Medium” and “Cold Neutral Medium”

Idea: Temperature → Broadening of the lines

Doppler parameter: $b^2 = 2k_BT/m + b_{turb}^2$

So, if we use two species (different masses), we may solve the degeneracy.
Problems: m>>1 ==> $2k_bT/m$ negligible compared to b_{turb}^2
HI (m=1) but damped regime → no constraint on b

Solution: look for much less abundant “type” of hydrogen, so that the line is not saturated



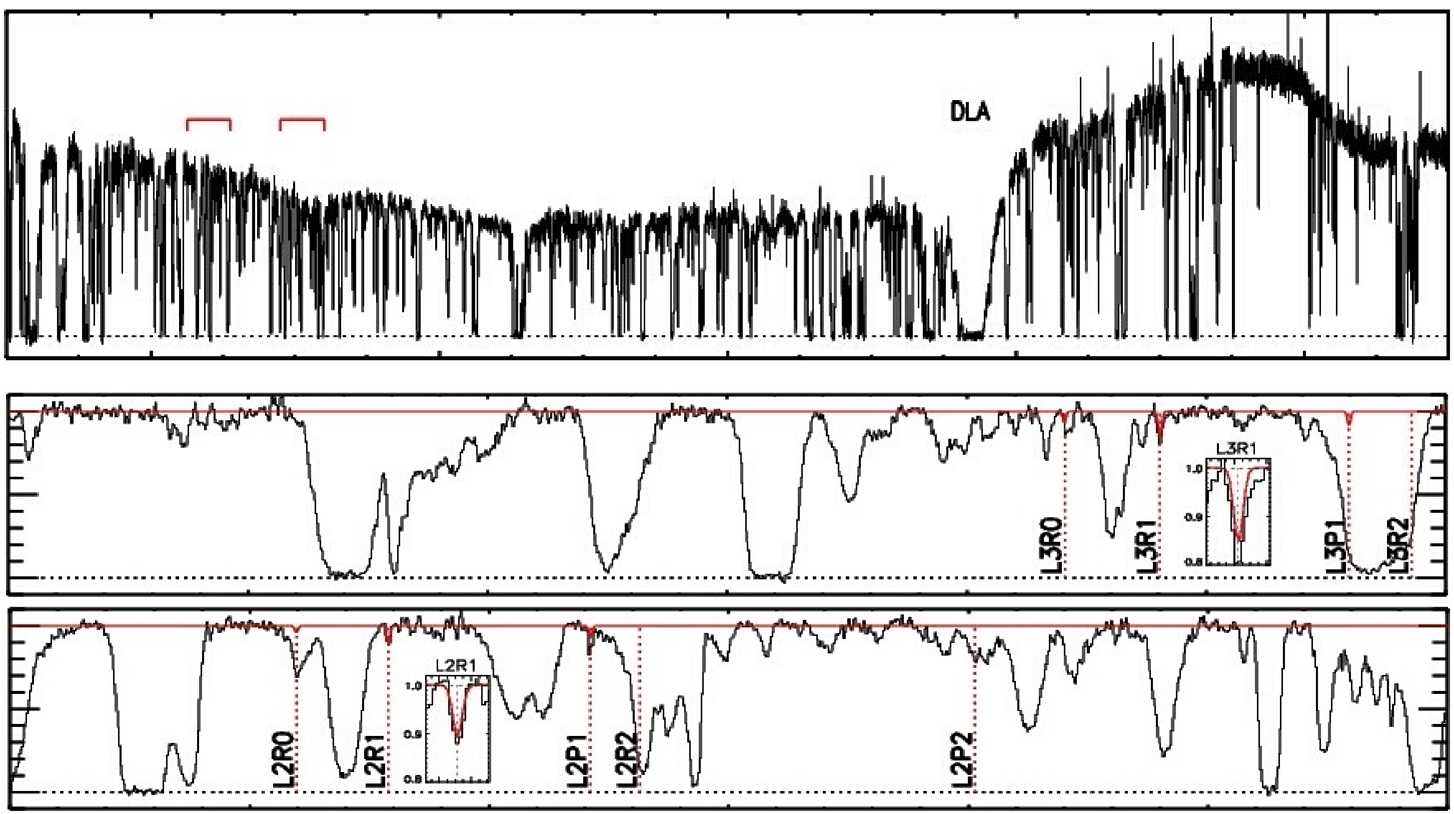
Noterdaeme et al. 2012b

Physical conditions in the neutral gas

Idea: H_2 forms better in cold dense environments

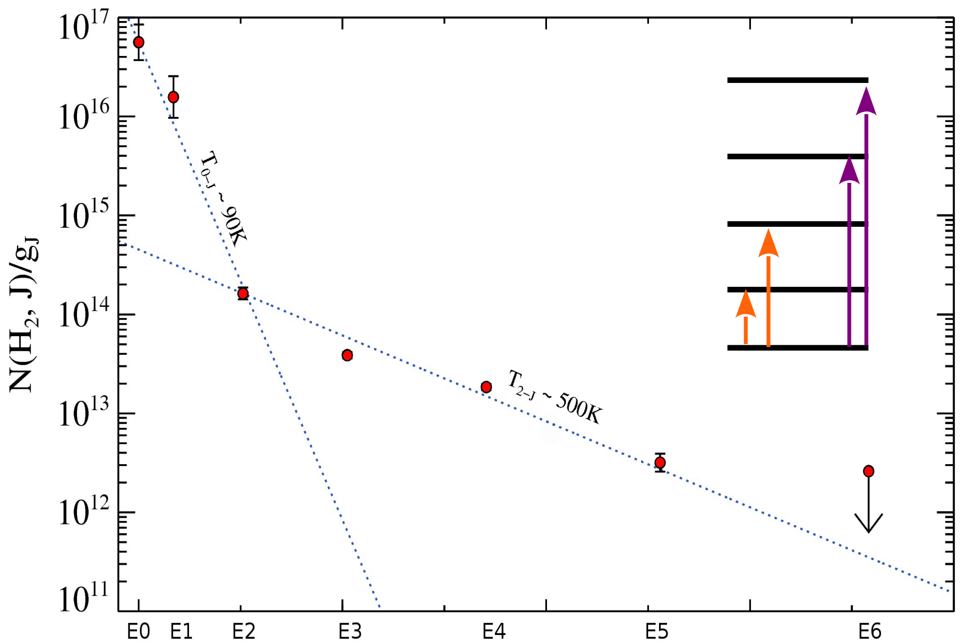
Problem: H_2 lines are weak and in the Lya-forest

Solution: high-resolution in the blue → **UVES @ VLT**



Possibility to detect one H2 molecule for a million Hydrogen atoms
→ little H_2 in most DLAs (Ledoux+03, Noterdaeme+08) → mostly WNM

H_2 a nice probe of the local physical conditions



-3

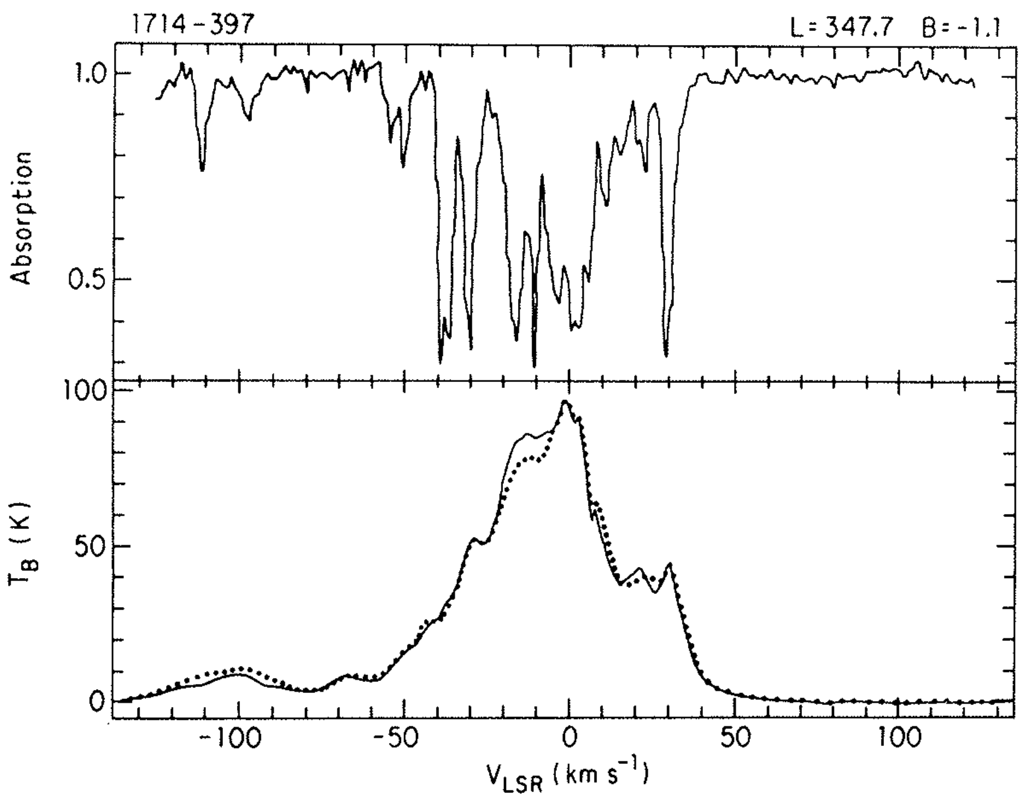
- Rotational levels of H2: collisions, radiative excitations, shielding effects
- CI fine-structure levels: pressure,density

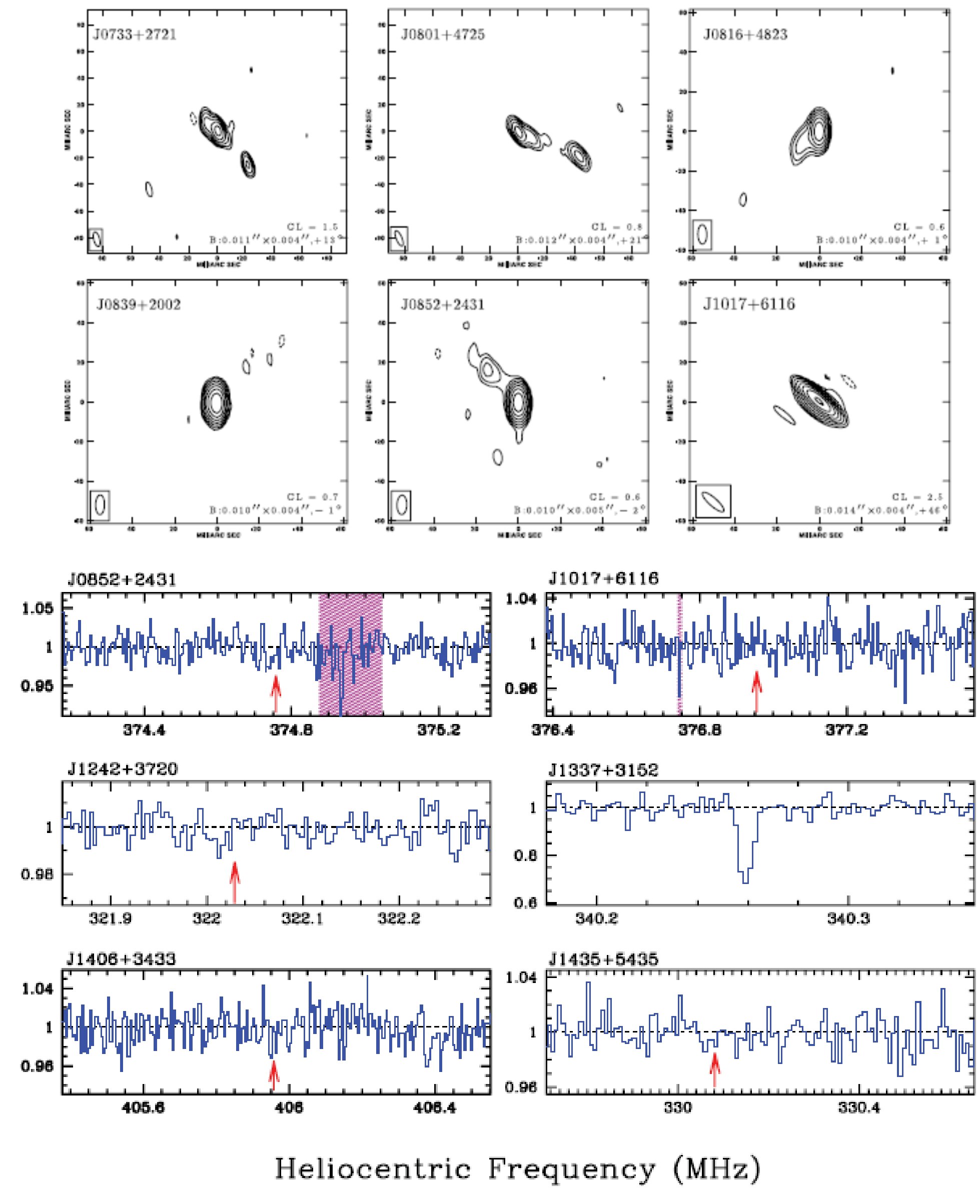
- T ~ 100K
- UV field
- n ~ 1 - 100 cm
- D ~ pc

We can also use the **radio** domain: 21-cm

- emission (CNM+WNM): not possible yet at high-z
- <u>absorption</u> (CNM):

$$\rightarrow \quad N(\mathrm{H\,I}) = 1.835 \times 10^{18}\, \frac{T_s}{f_c} \int \tau(v)\, dv$$

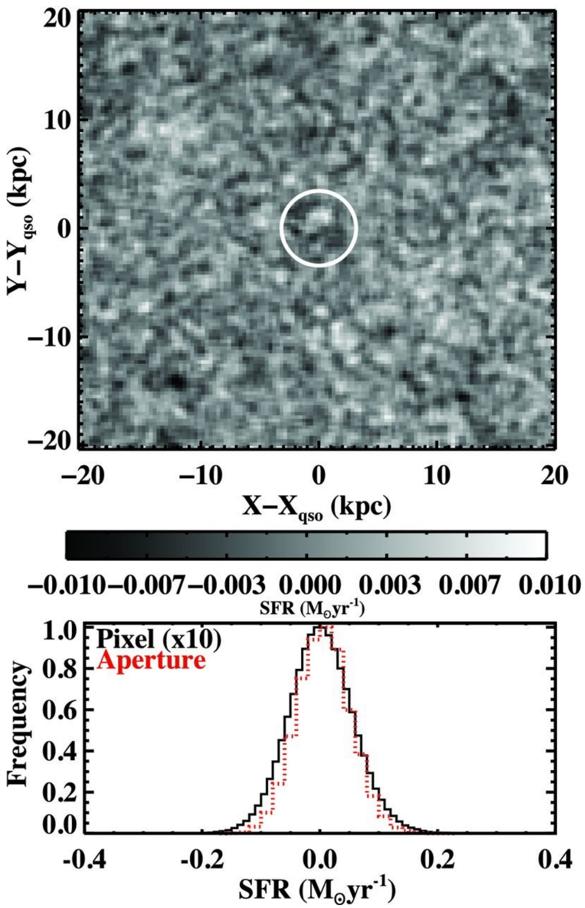




Srianand et al. 2012

Star-formation in the overall DLA population?

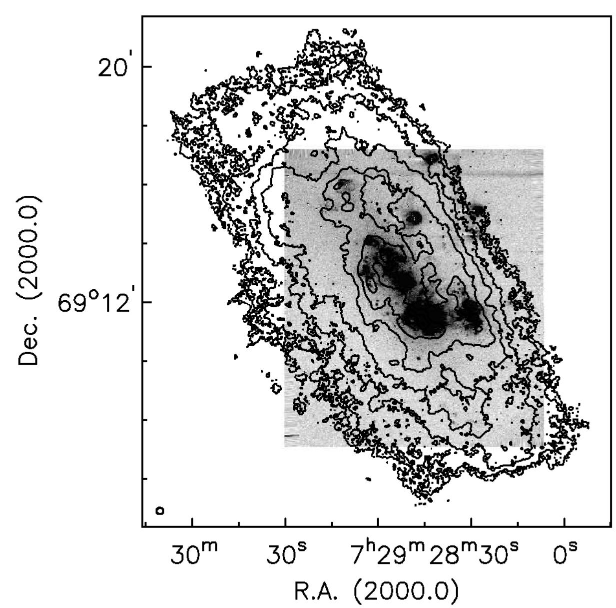
Star-formation



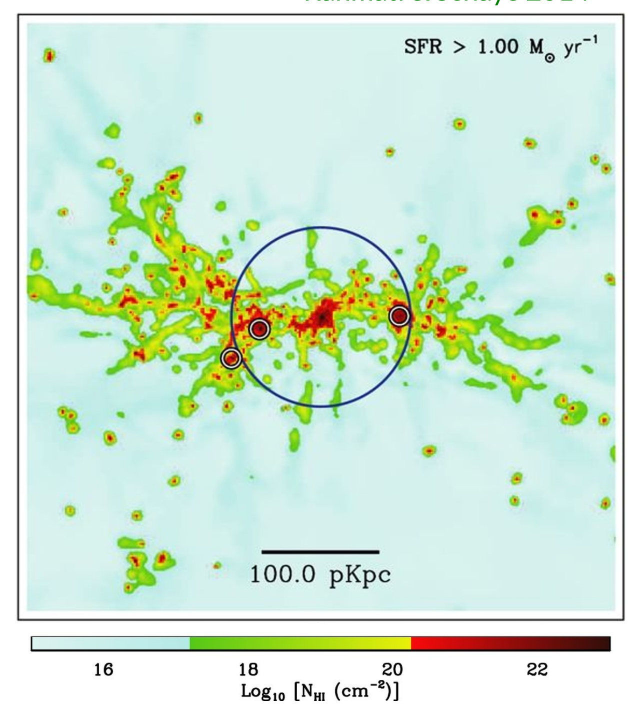
Fumagalli et al. 2015:

20 DLAs fields imaged with HST
no detection, even from stack

Very little in-situ star formation: is this surprising?



Rahmati & Schaye 2014



DLAs

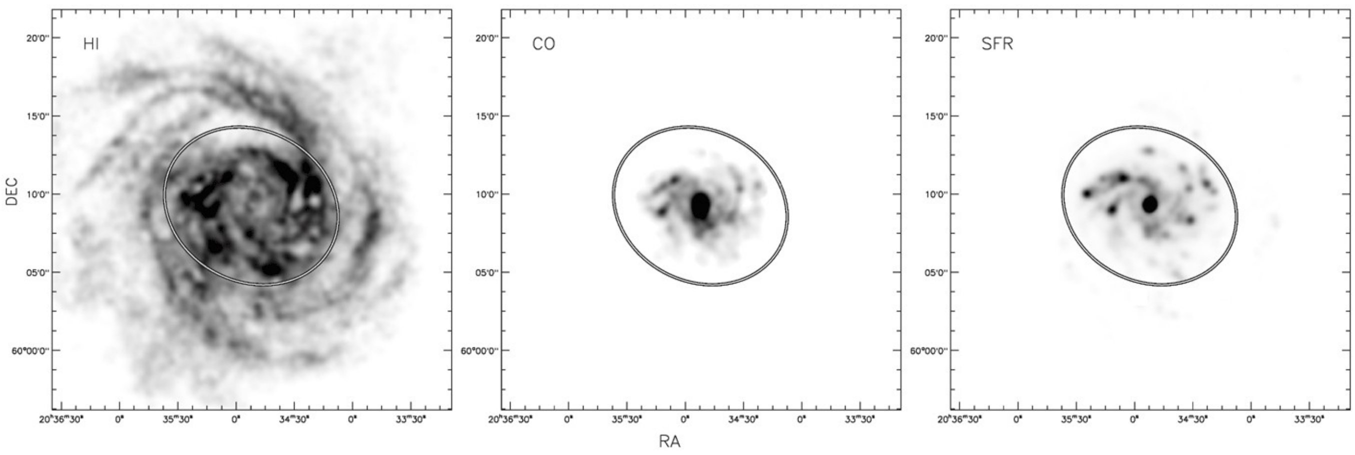
DLAs contain most of the neutral gas in the Universe

DLAs present significant amount of metal enrichment, increasing with time

DLAs contain generally little dust

DLAs are mostly WNM

Hot questions: Where is the CNM?   Where is the star-formation (i.e. where are the supposed DLA galaxies) ?

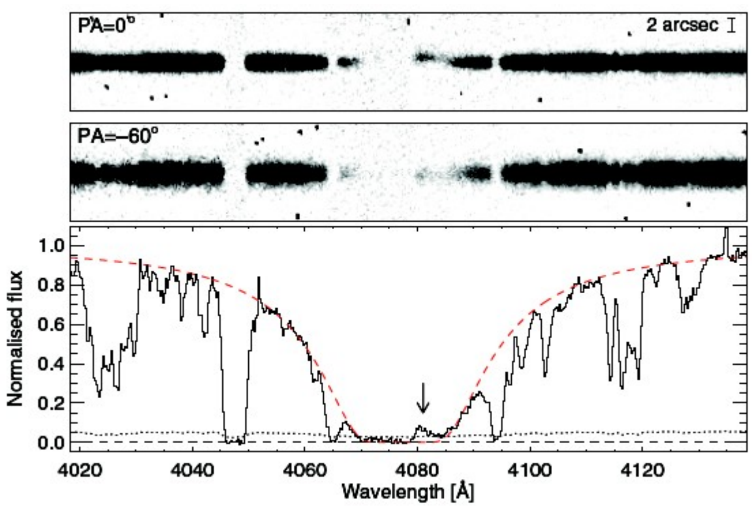


Idea 1: Look for metal-rich systems

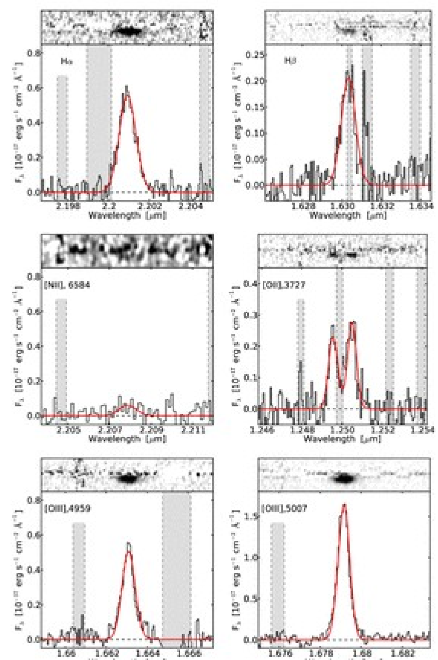
More metals → More star-formation?

It works!

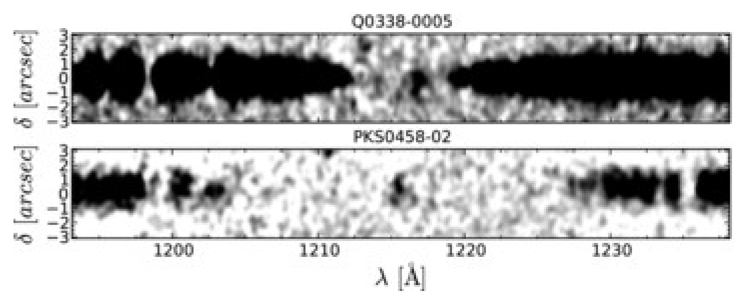
But we can be far from the galaxy:
- metals are spread far away, and
- probability of interception by quasar line of sight goes as d^2



Fynbo et al. 2010,2013



Fynbo et al. 2011
Krogager et al. 2013

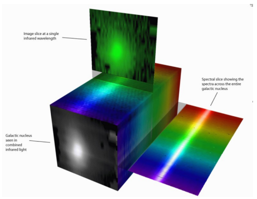


Krogager et al. 2012

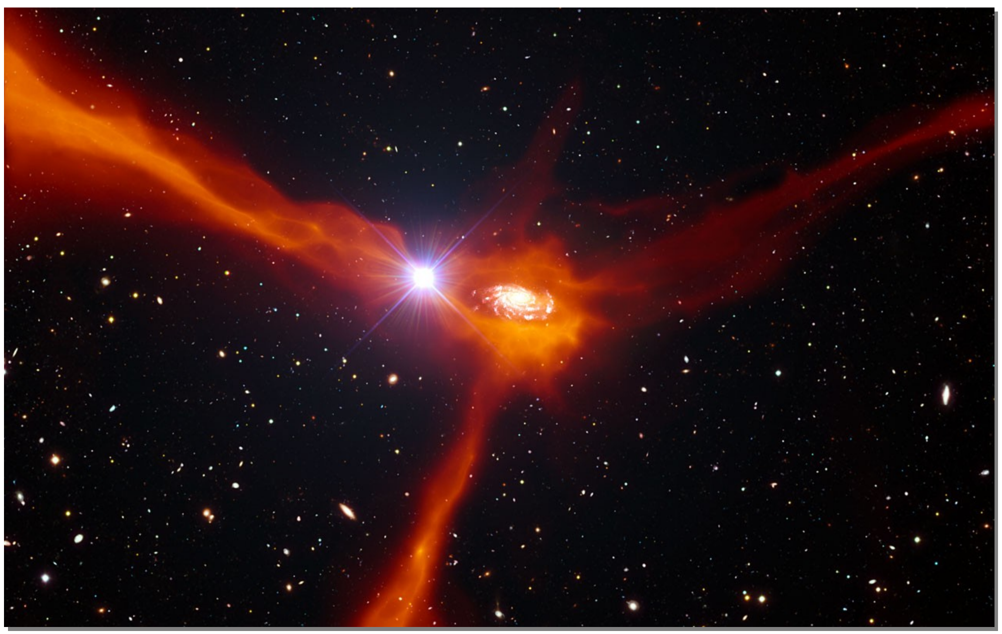
Idea 2-: Look all around the quasar line of sight

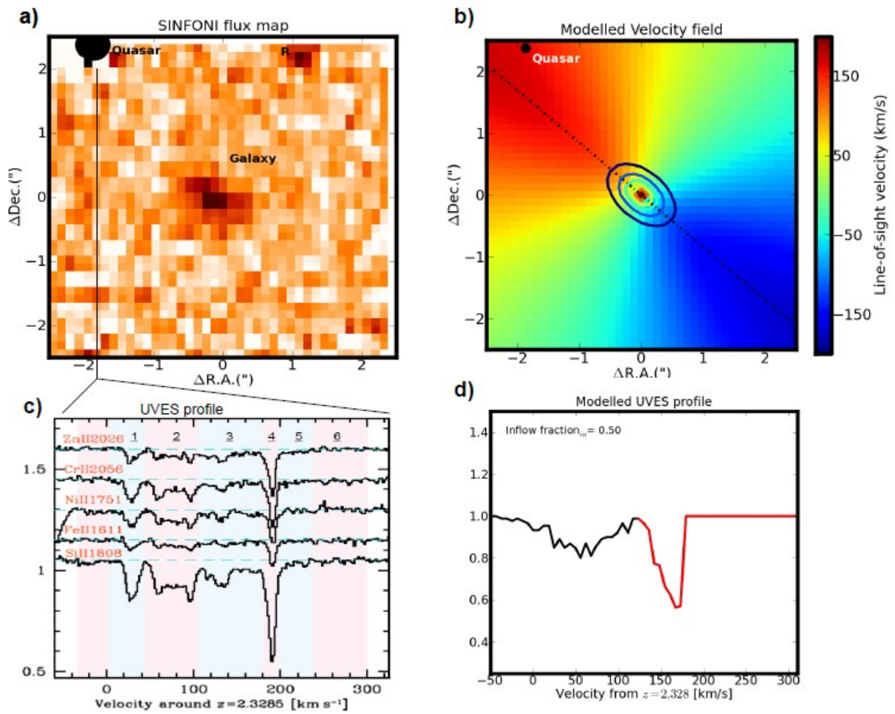
→ Very time consuming
→ But when it works, you get very nice results!

SINFONI



Cool inflow onto massive galaxy





Bouché et al. 2013

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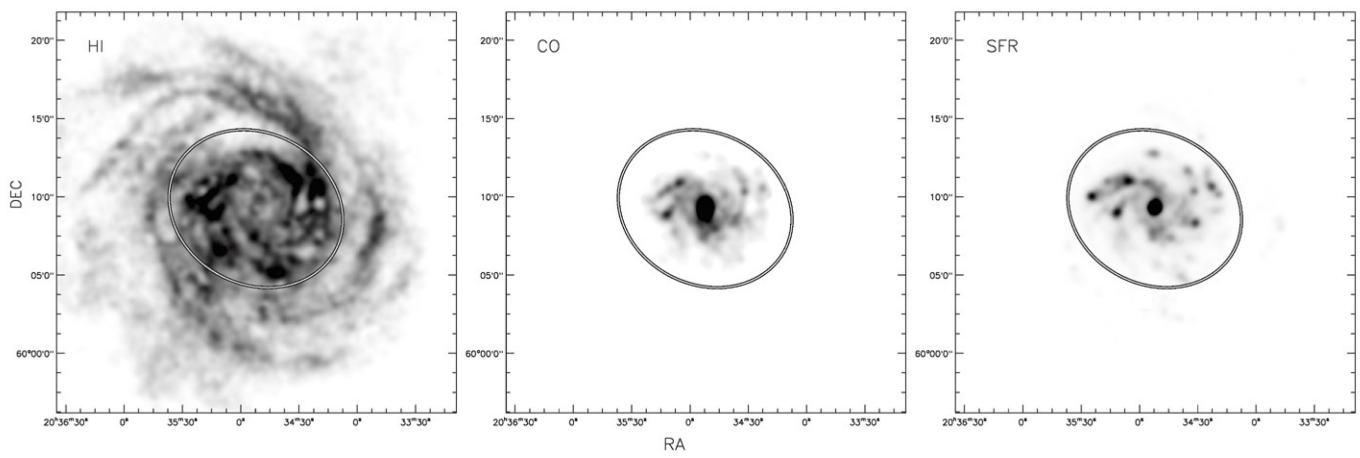
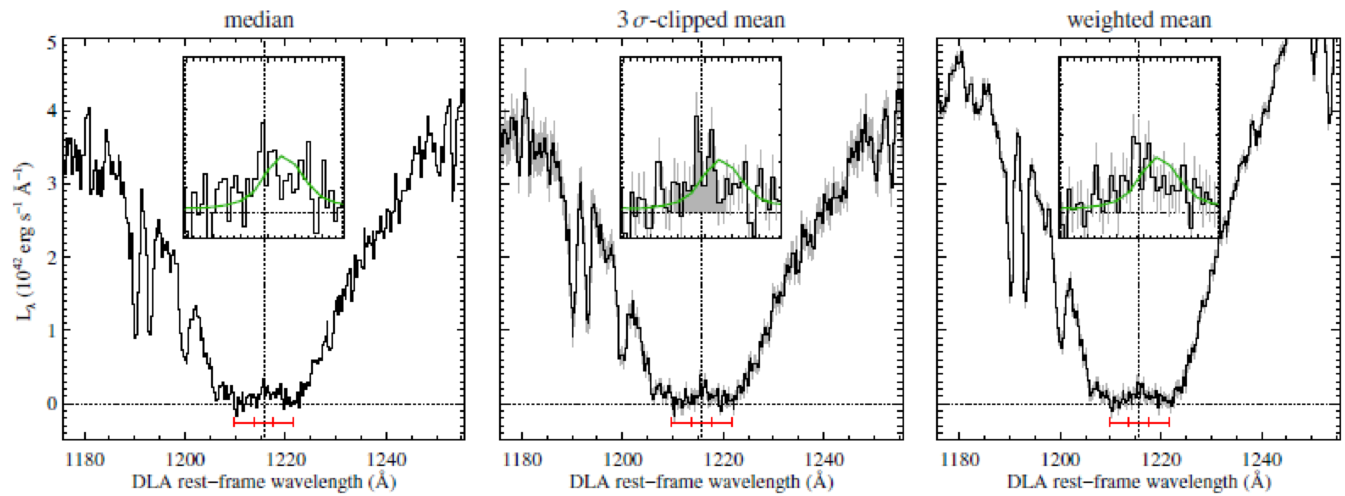


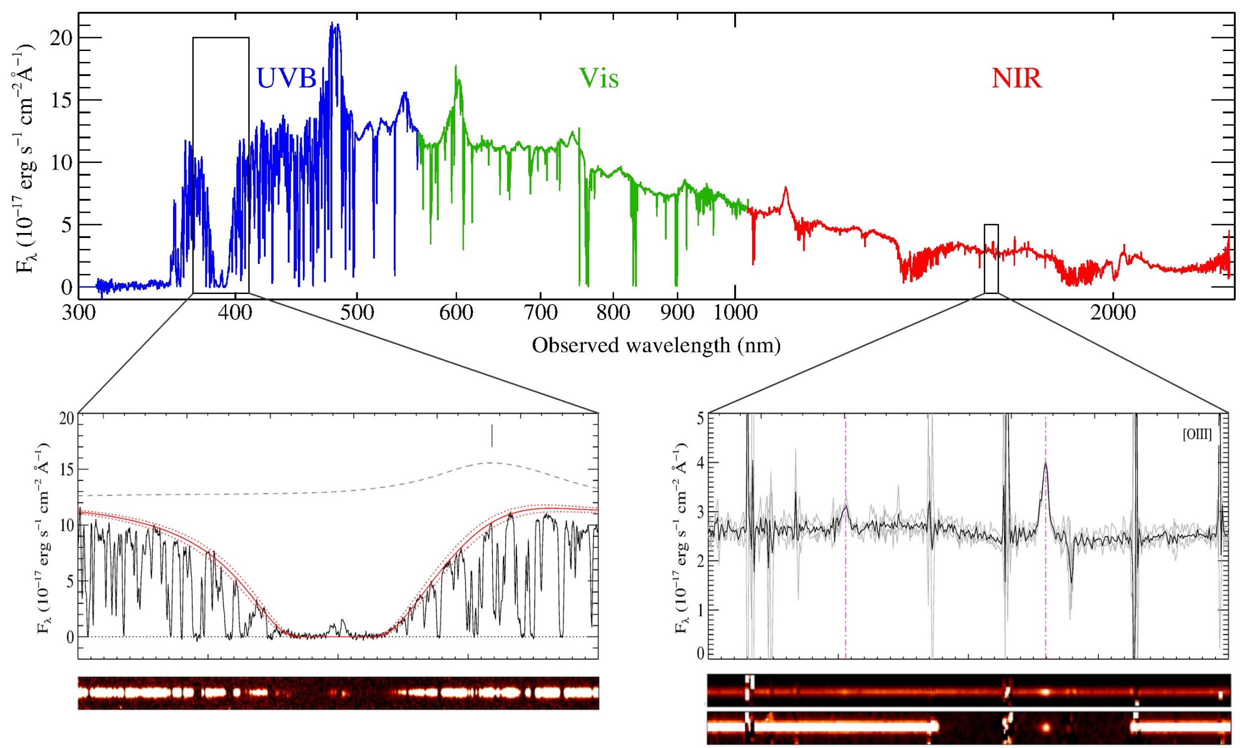
Idea 3: Look for very high column densities

Statistically, using SDSS



Noterdaeme et al. 2014

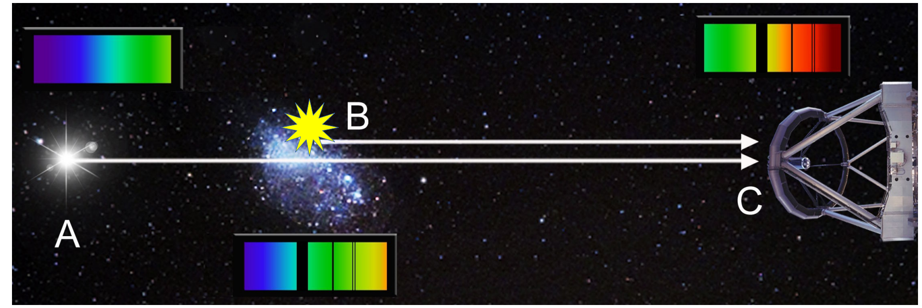
In individual systems, using X-shooter

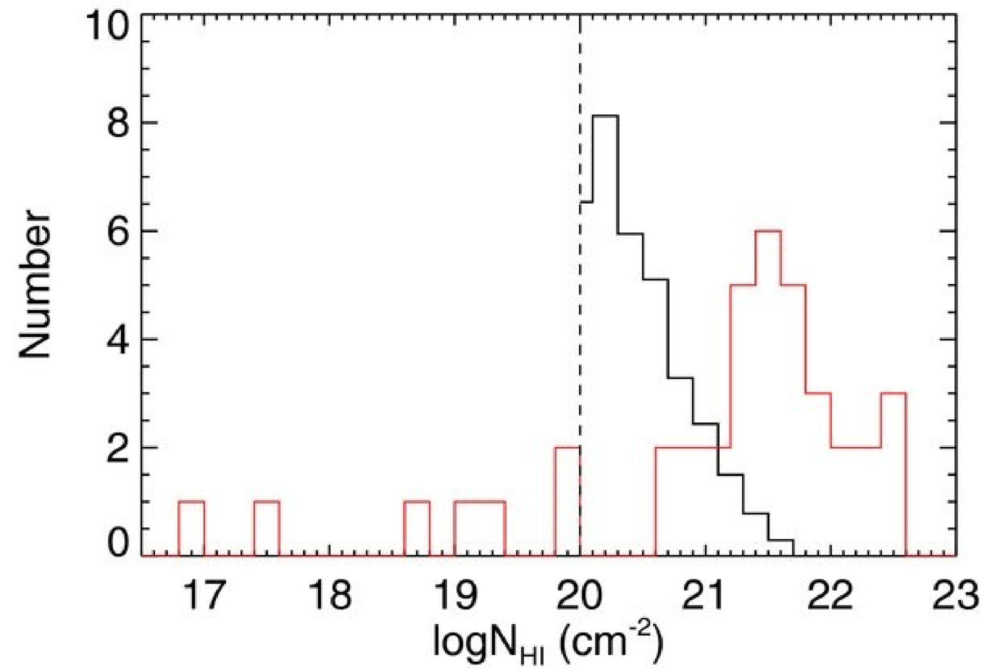


Noterdaeme et al. 2012a

Idea 3: Look for very high column densities

we can also use GRBs...

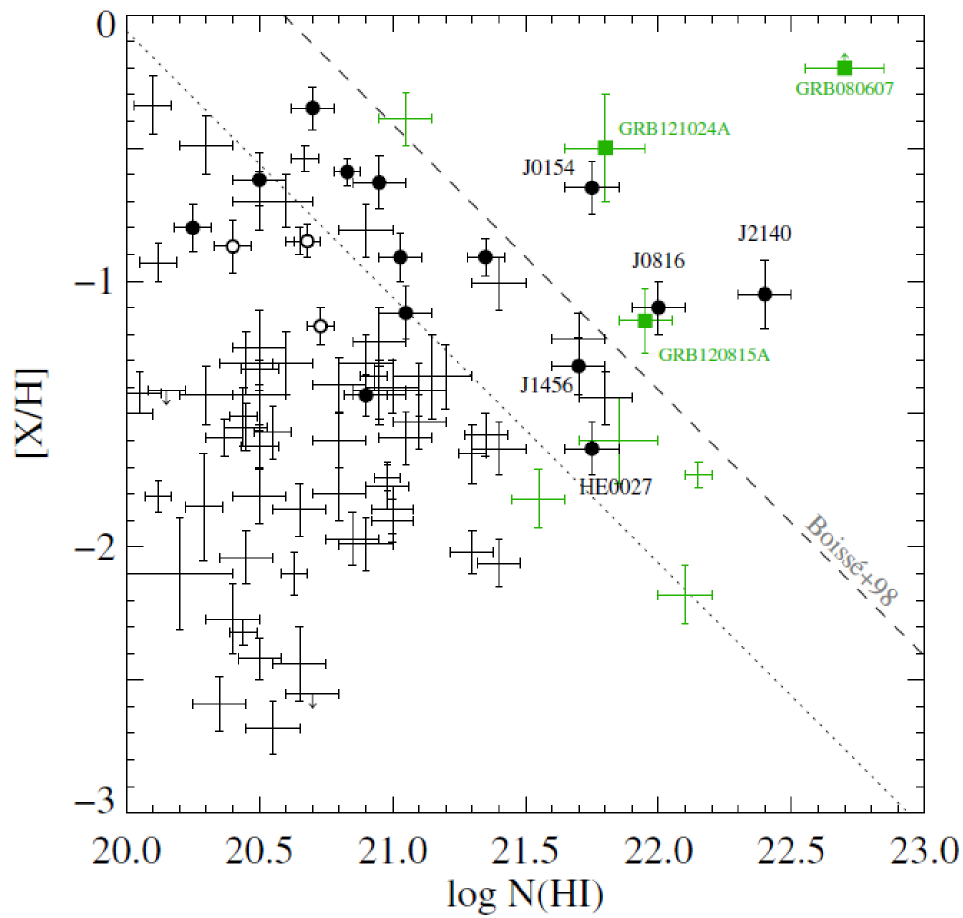




Fynbo et al. 2008

… but you have to be fast (RRM on VLT)

Idea 3: Look for very high column densities



Noterdaeme et al. 2015b

...and we now also see systems beyond the “old” limit
...and guess what? They have H_2!

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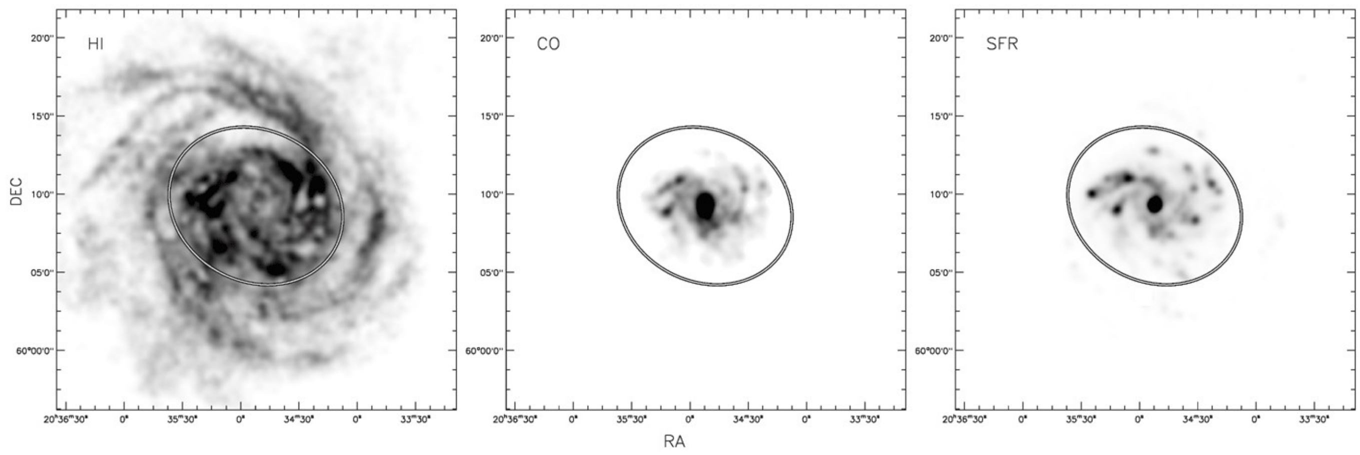
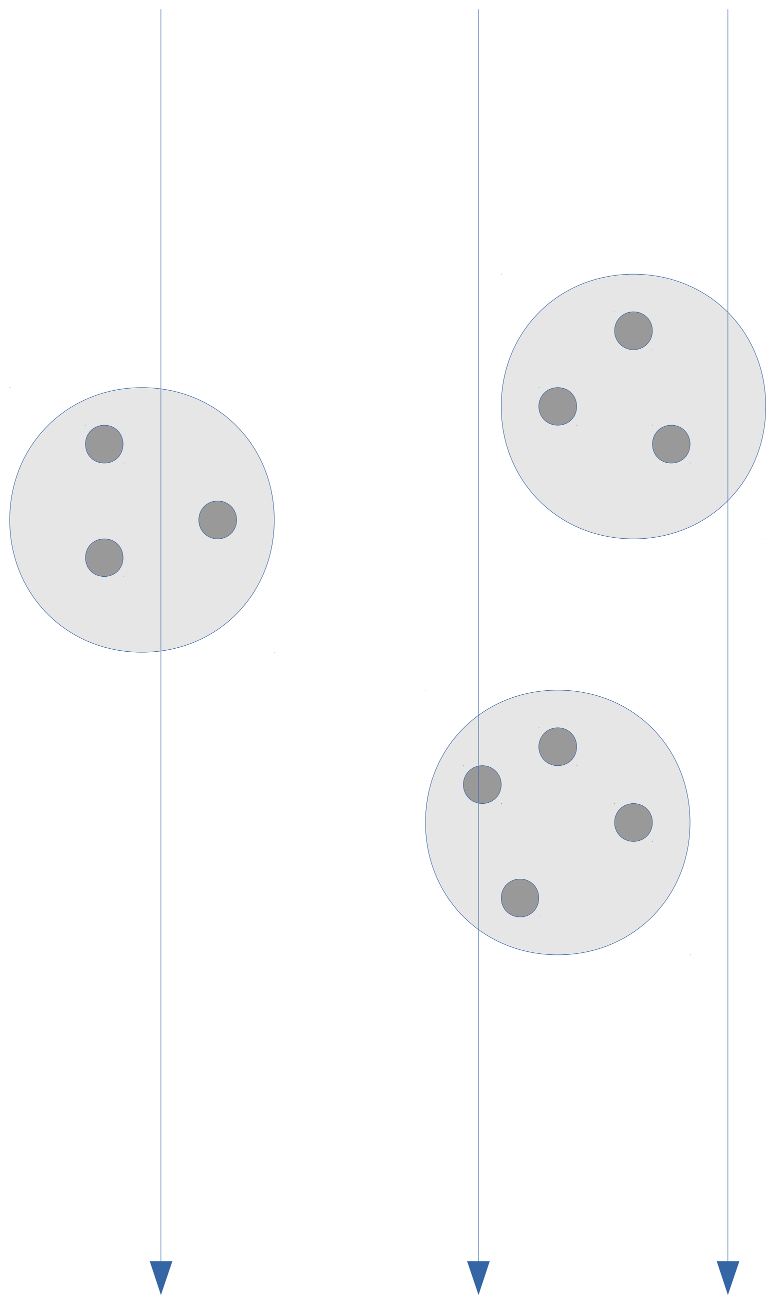
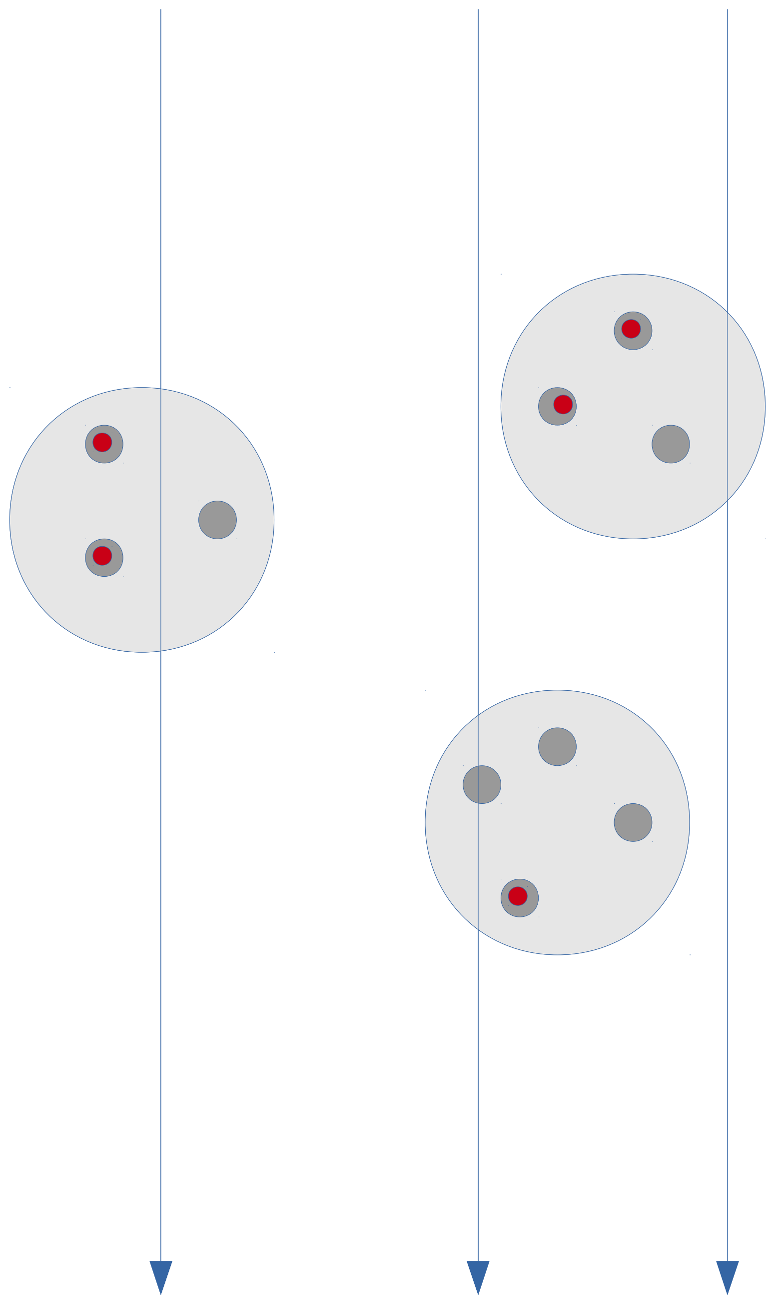


Idea 4: Look directly for the cold gas



Idea 4: Look directly for the cold gas



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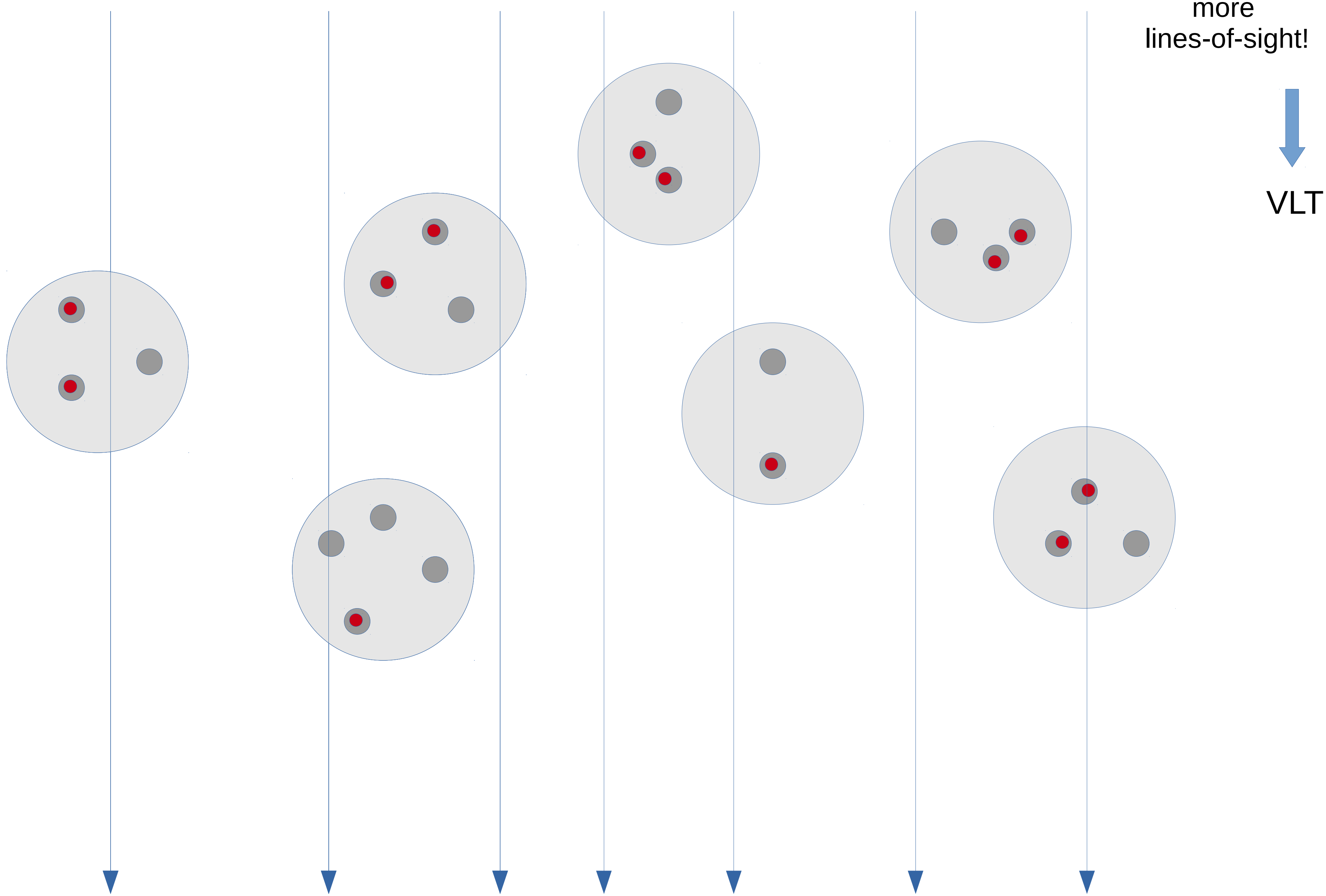

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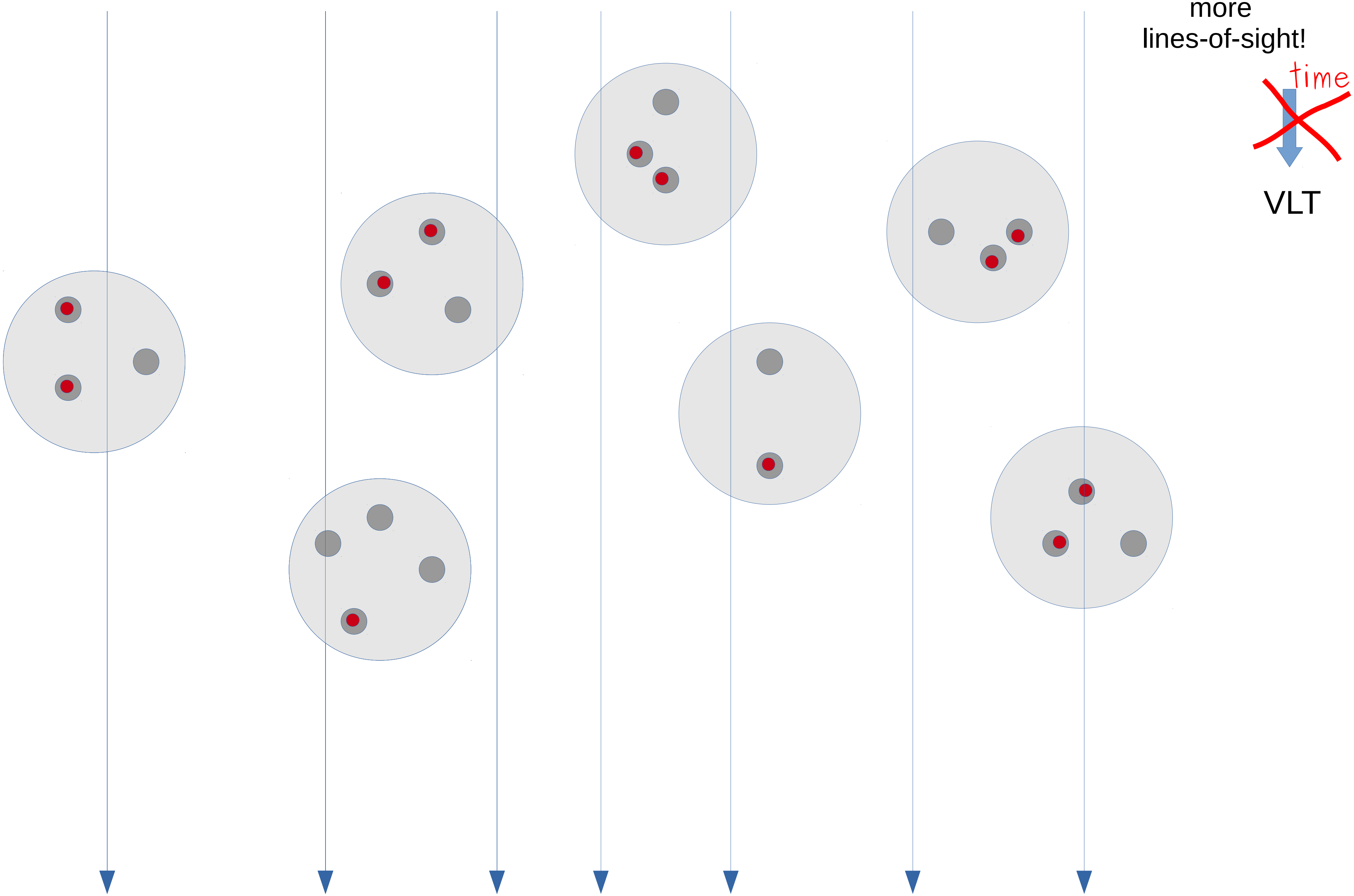

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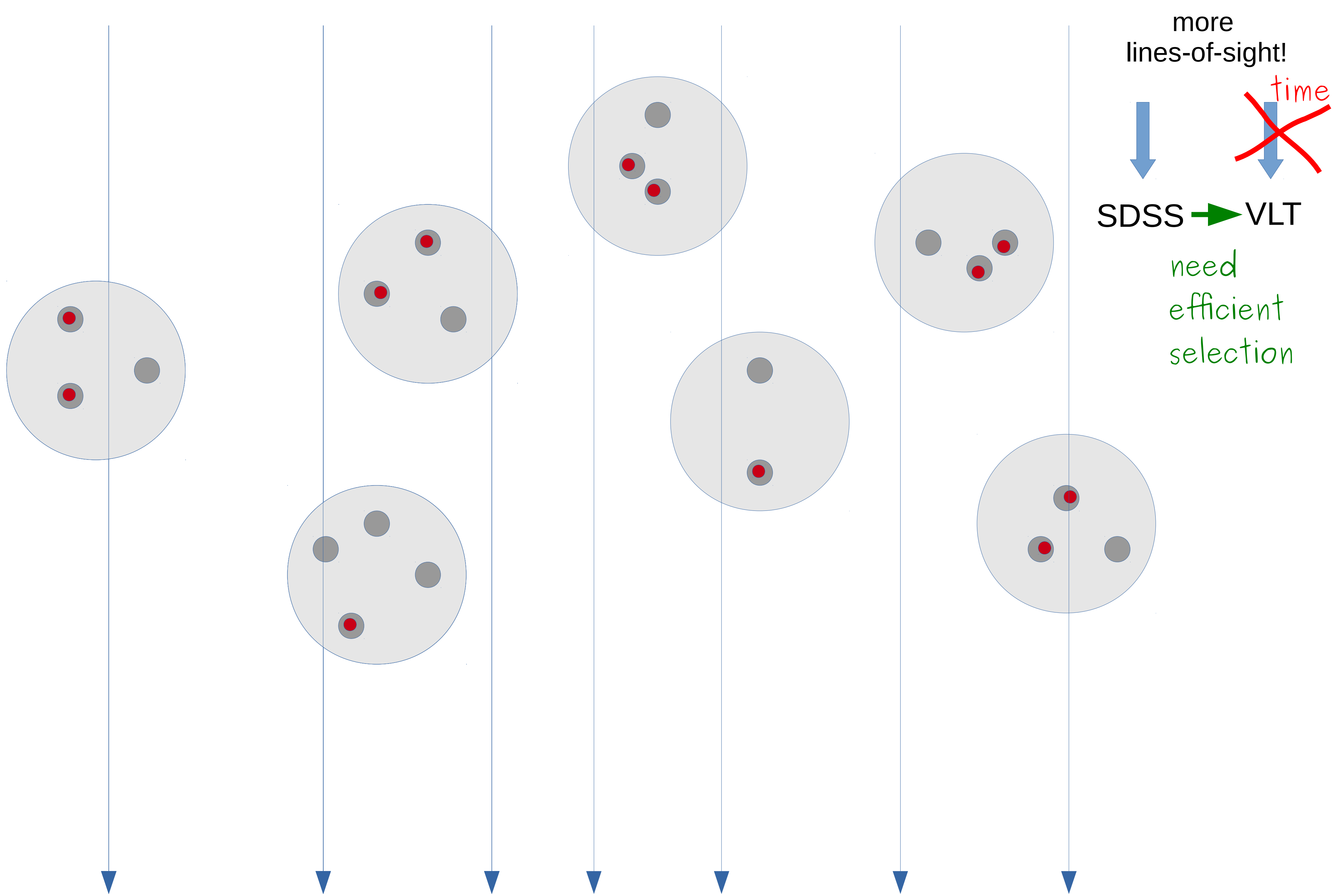

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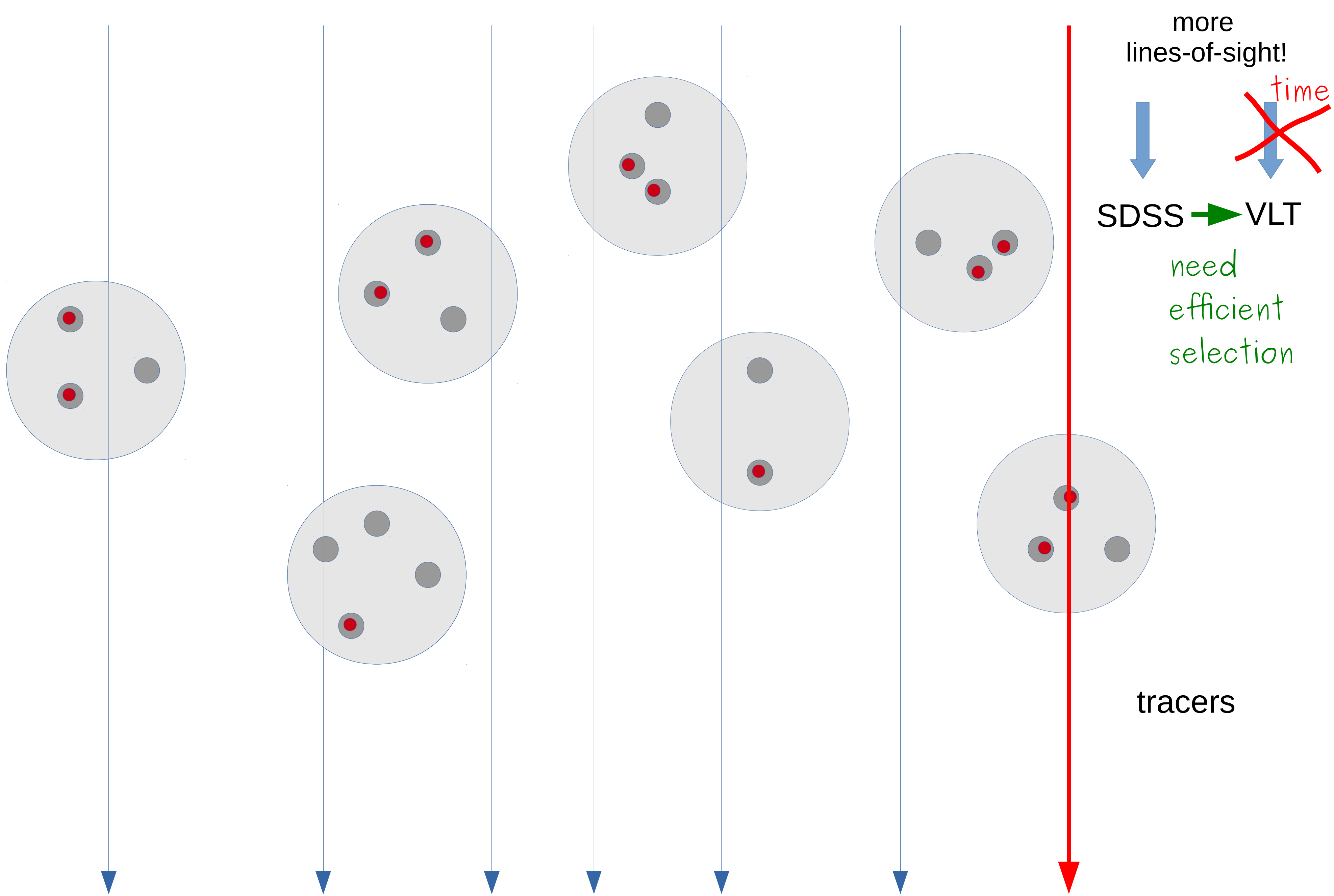

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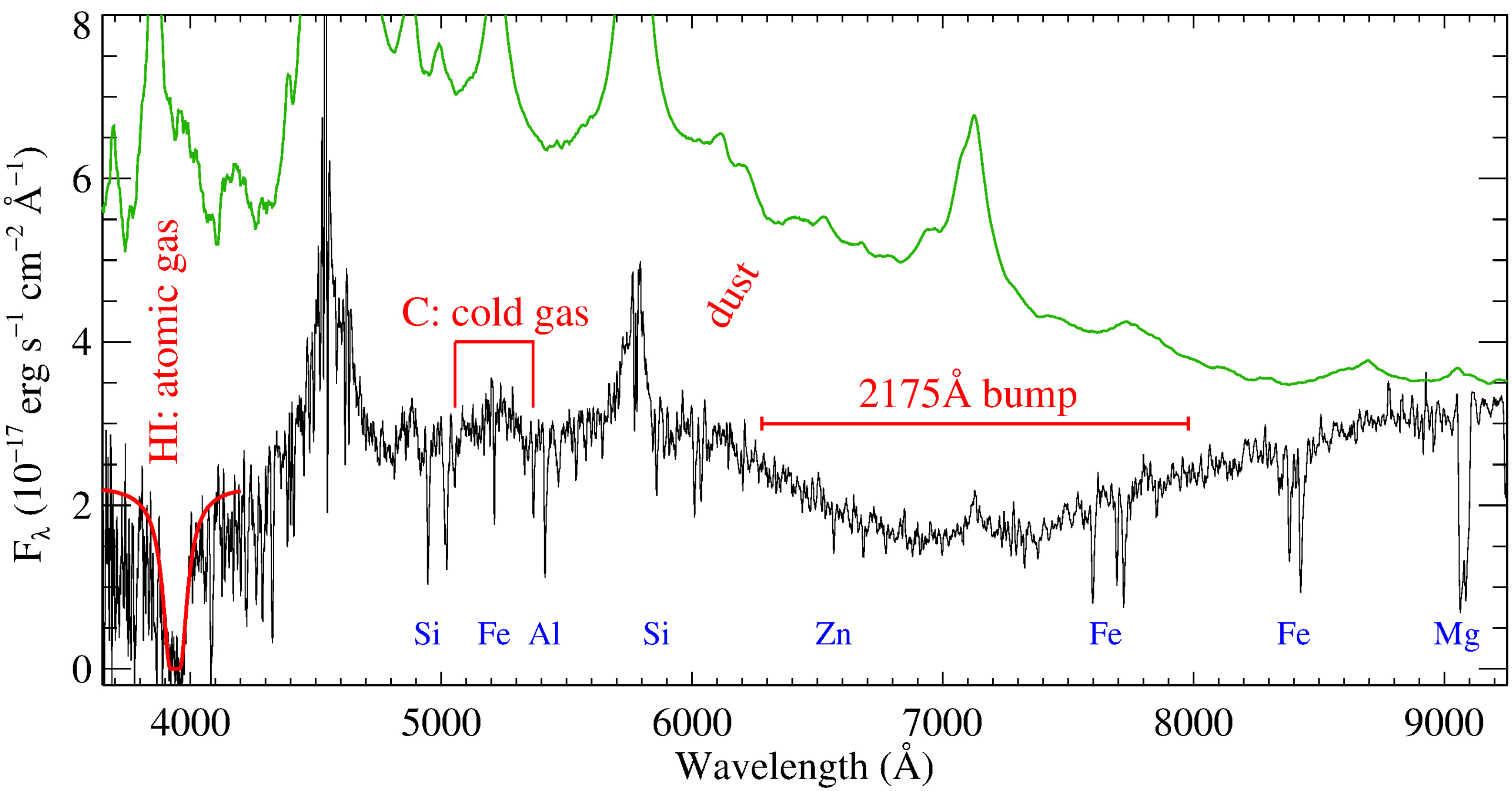
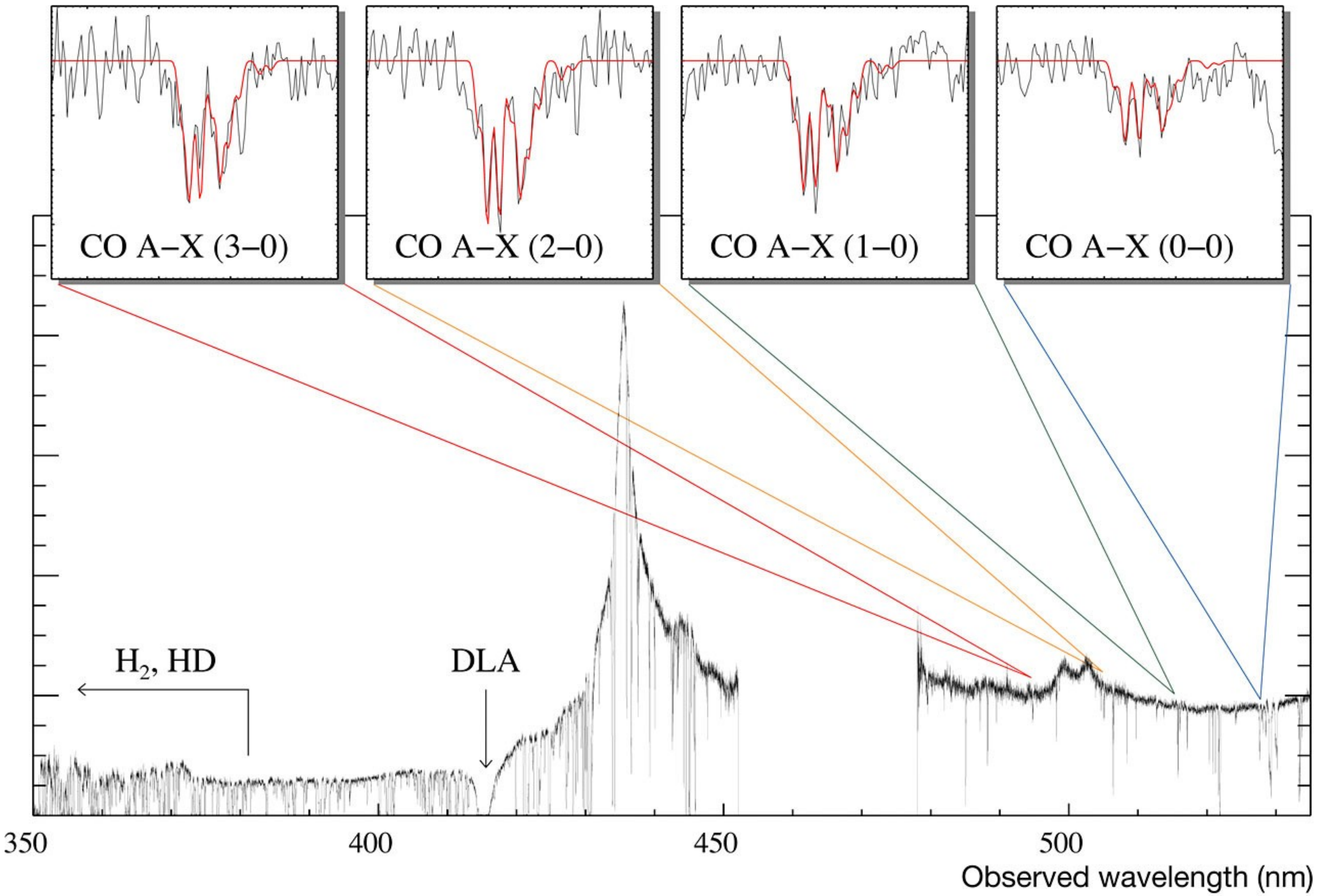


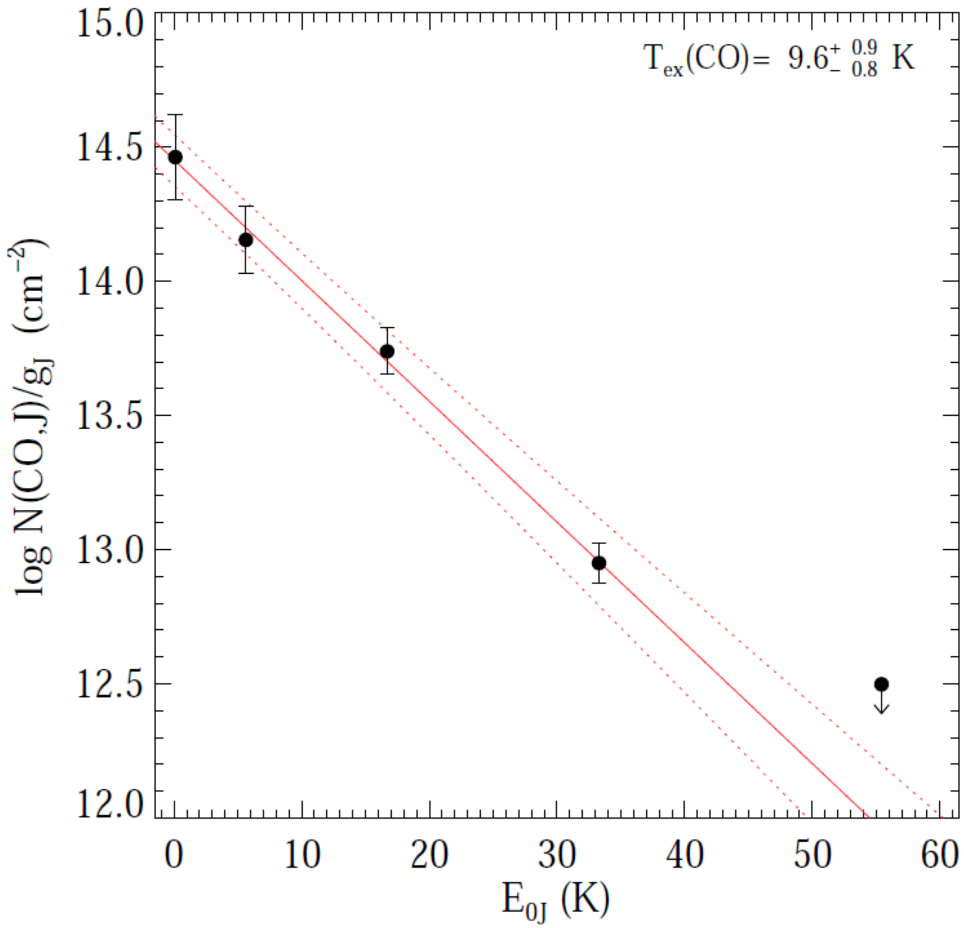
Idea 4: Look directly for the cold gas

We do detect cold gas, with new molecules!

1st, 2nd, 3rd, … detections of CO in absorption all done at VLT



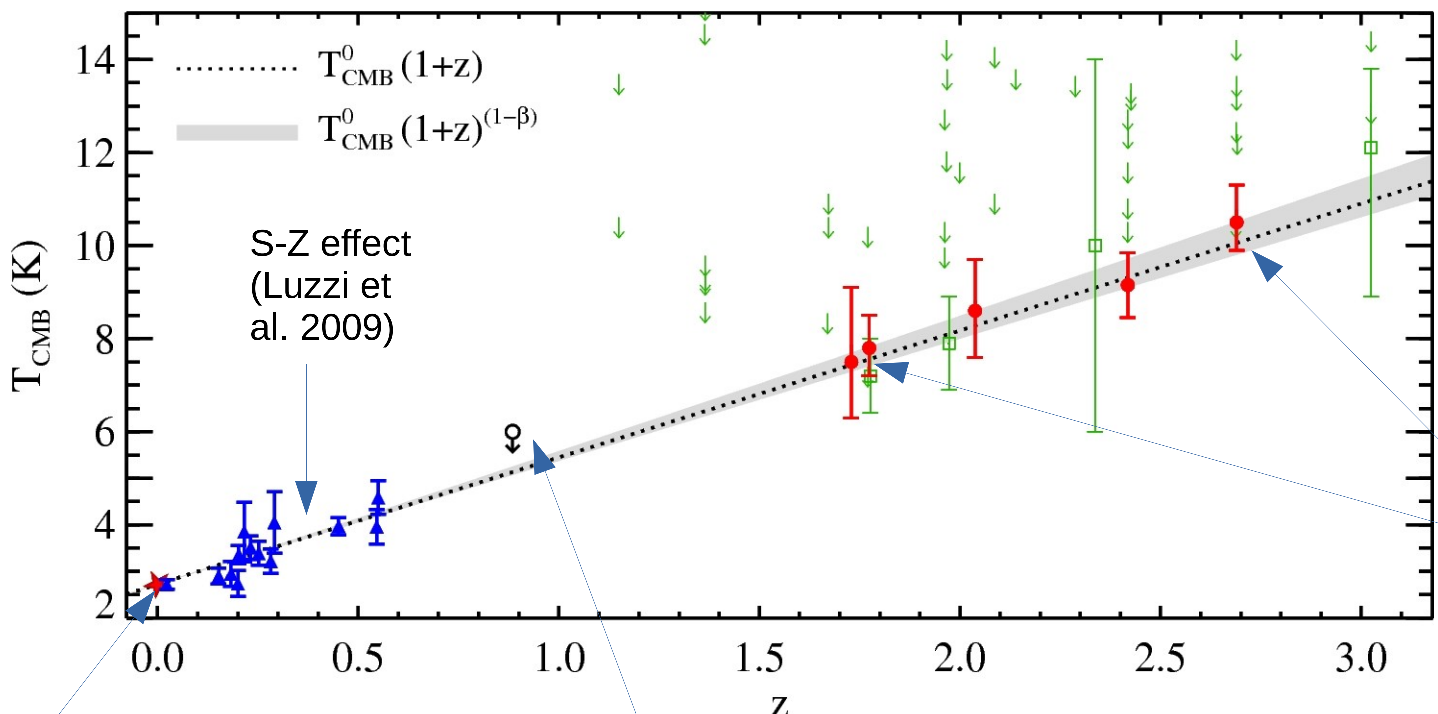
and CO is great because its excitation is dominated by CMB



$$\frac{N_1}{N_0} = \frac{g_1}{g_0} e^{-E_{01}/kT_{01}}$$

Fundamental physics

Strongly supports the adiabatic cooling of the Universe (β=-0.007+/-0.027)



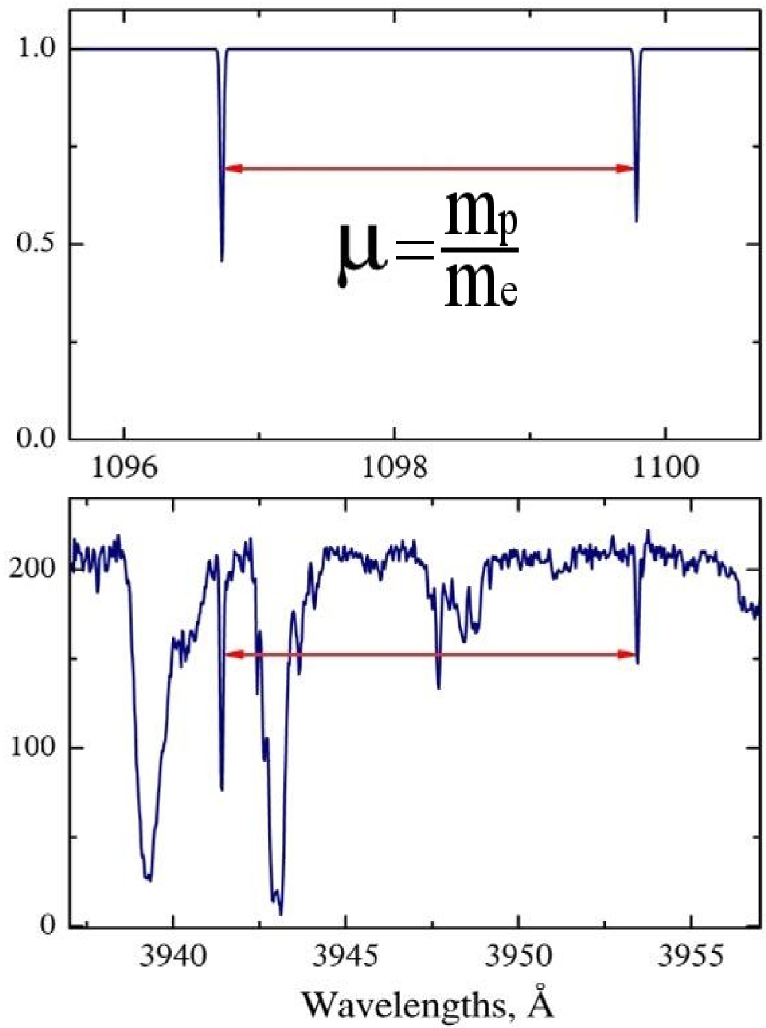
CO

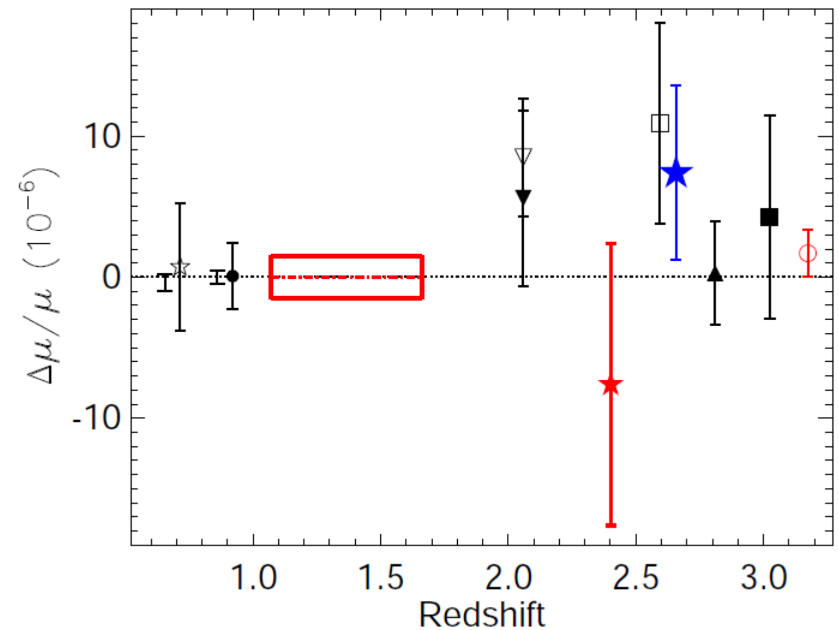
Molecules (sub-mm, CEST): Wiklind & Combes 1996

COBE (Mather et al. 1999)
T=2.725+/-0.002 K

CN at z=0 (Herzberg 1950): "From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3 K follows, which has of course only a very restricted meaning."

We can also constrain the variation of fundamental constants...





$$\lambda_i = \lambda_i^0 (1 + z_{abs}) \left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

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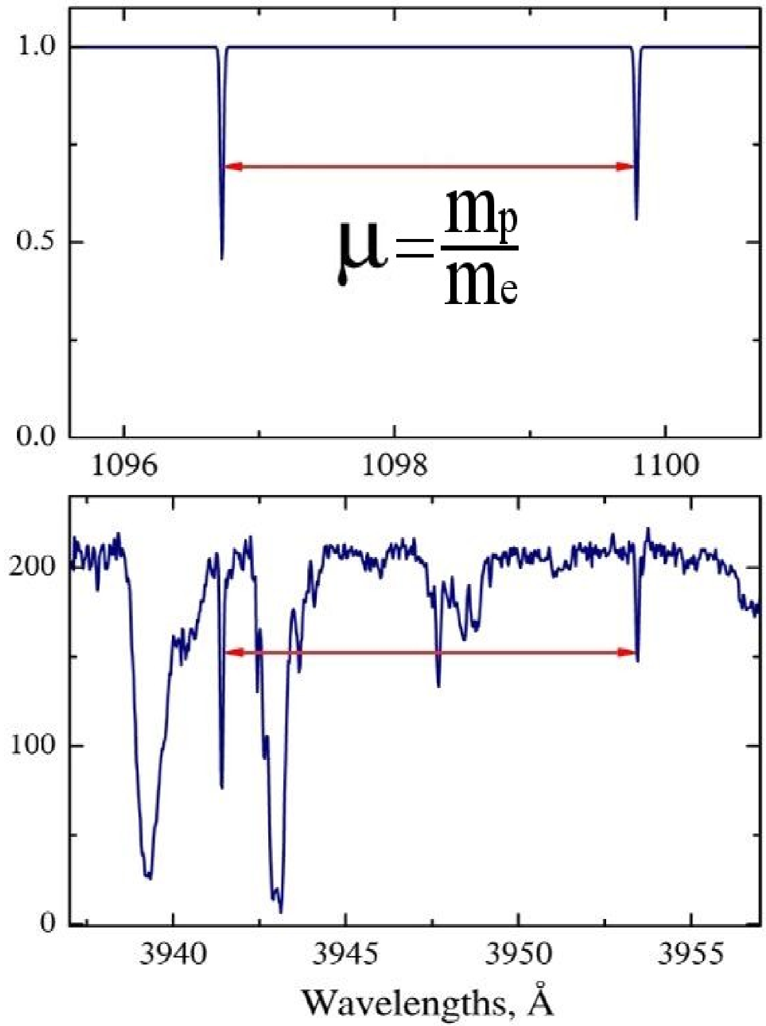
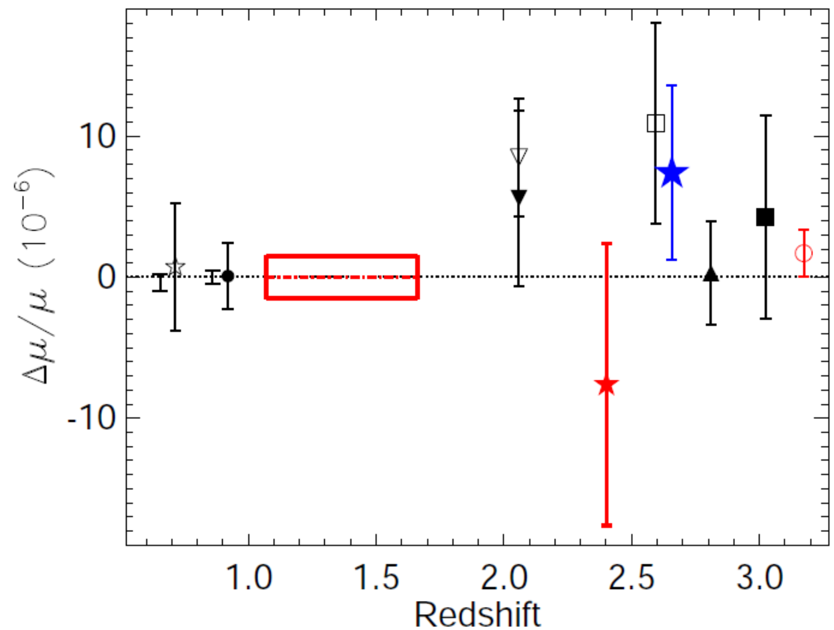


$$\lambda_i = \lambda_i^0 (1 + z_{abs}) \left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

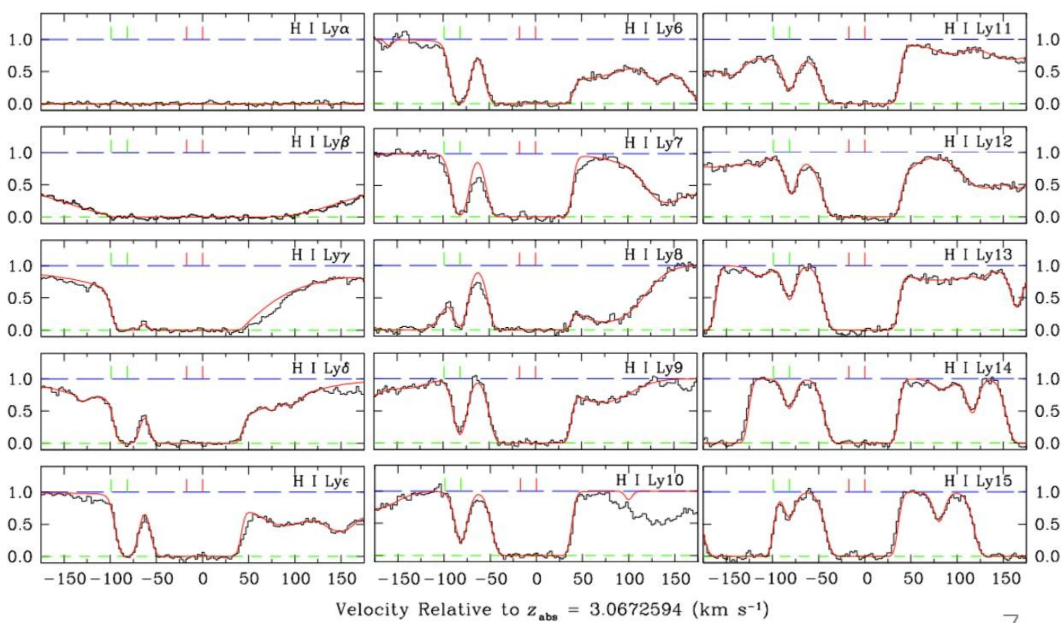
Rahmani et al. 2013

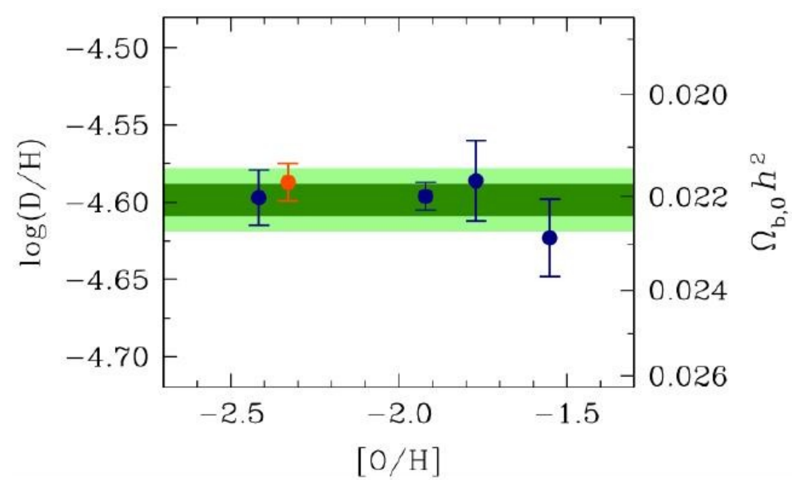


For (very) technical details, talk to

Ω_b

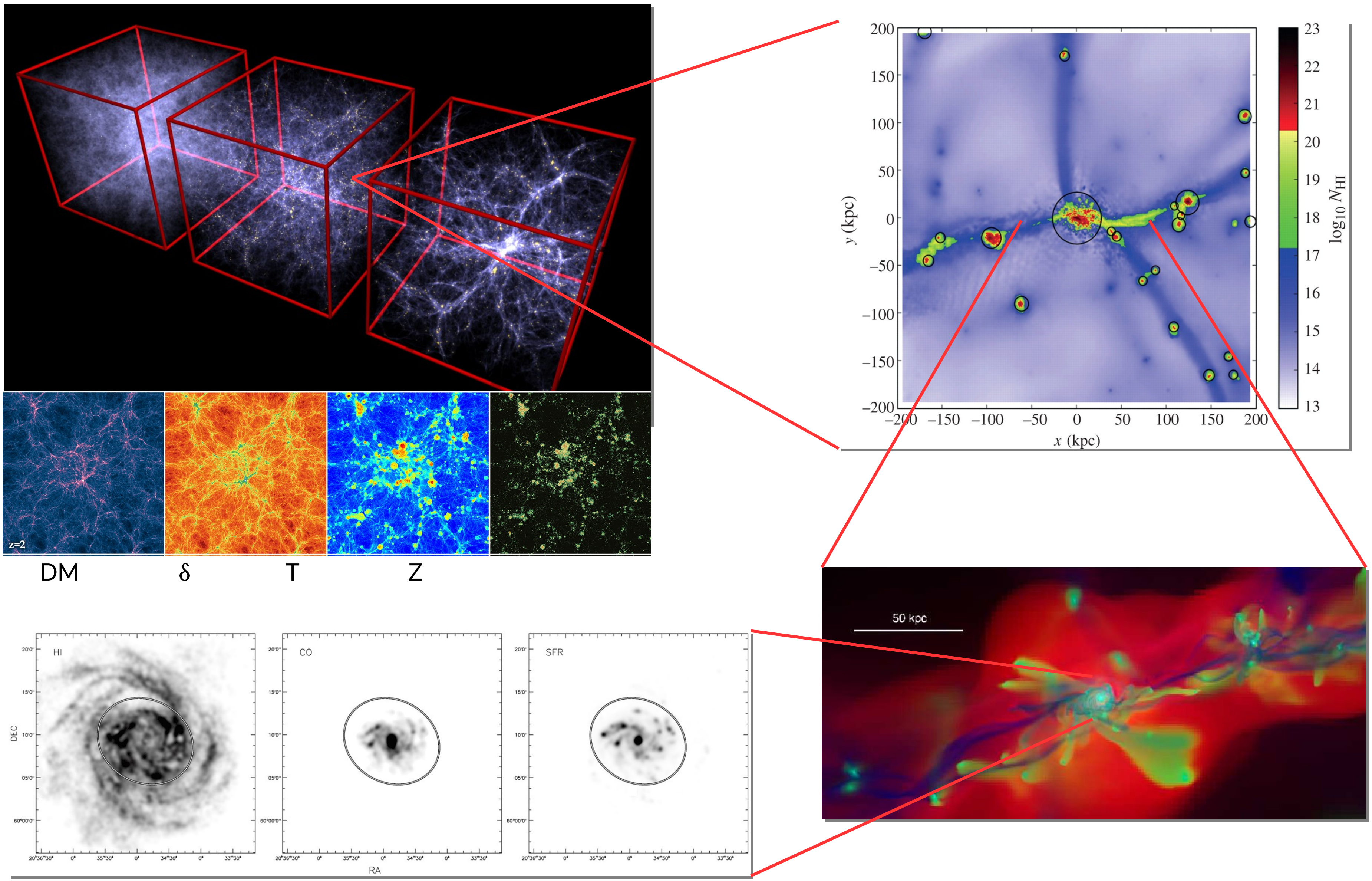
D/H ~ 10^{-5}
DI and HI very close in velocity space





Cooke et al. 2014

Quasar absorption lines can be used to probe gas with very different properties over very different scales as well as studying fundamental physics & cosmology

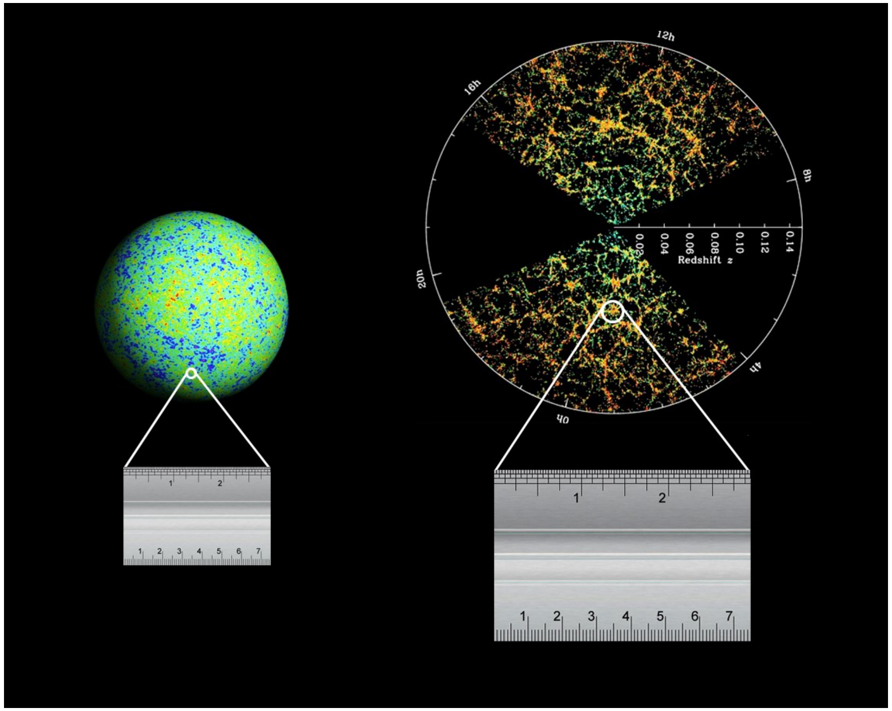


Many, many lines of sight

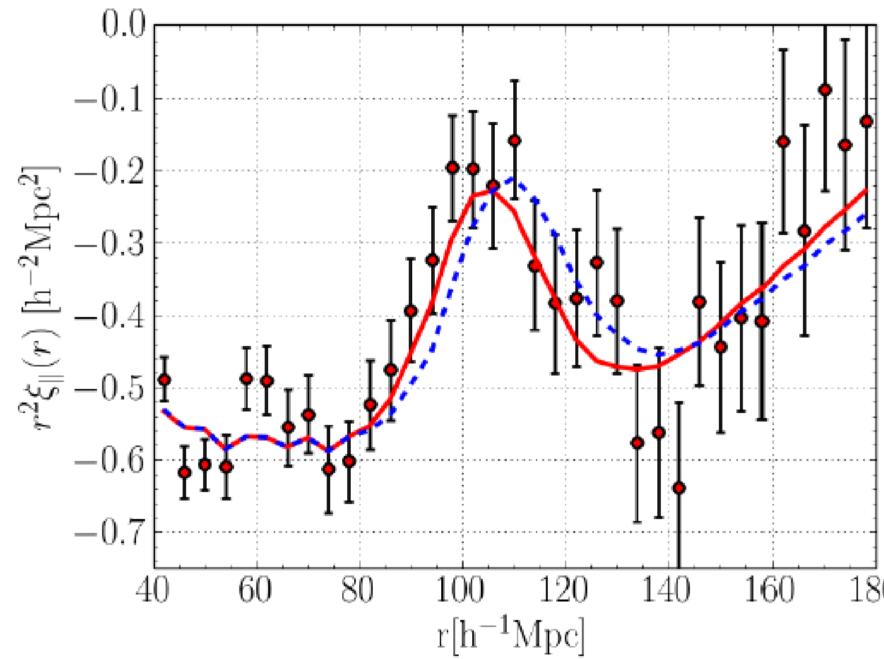
x10

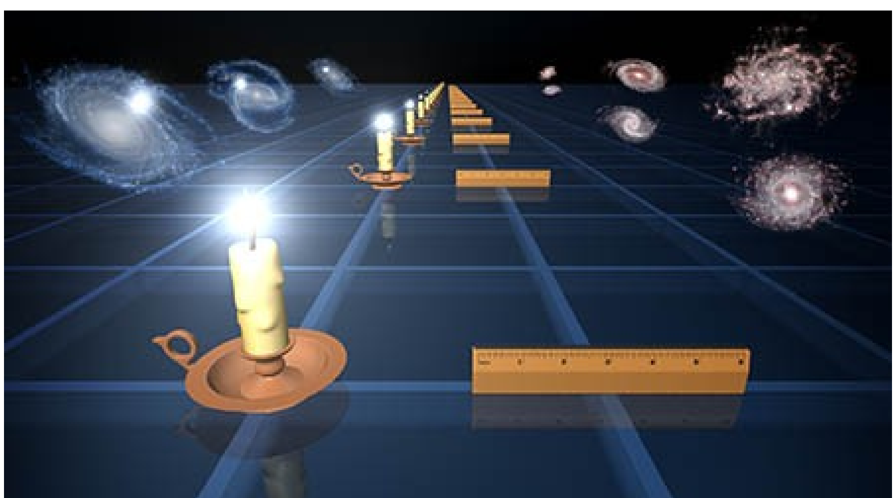
	BOSS (2009-2014)	e-BOSS (2014-2020)	DESI
Telescope	2.5m	2.5m	**4m @KPNO**
Imaging survey	SDSS	SDSS, DES	ZTF, DEcam, CFHT?
Redshift	$0.2<z<0.7$	$0.6<z<3.5$	$0.2<z<3.5$
Number density	150 deg^{-2}	180 deg^{-2}	**2800 deg^{-2}**
Exposure time	80 minutes	80 minutes	**10-15 minutes**
Sky coverage	10000 deg^2	7500 deg^2	**14000 deg^2**
Field-of-view	6.7 deg^2	6.7 deg^2	6.7 deg^2
Number of fibers	1000	1000	**5000**
Wavelength range	360-1000nm	360-1000nm	360-1000nm
Spectral resolution	1600-2600	1600-2600	**2300-5000**
Target galaxies	LRGs+Lya QSOs	LRGs+ELGs+QSOs	LRGs+ELGs+QSOs
FOM BAO gal.+Lya QSOs	21	~45	~140

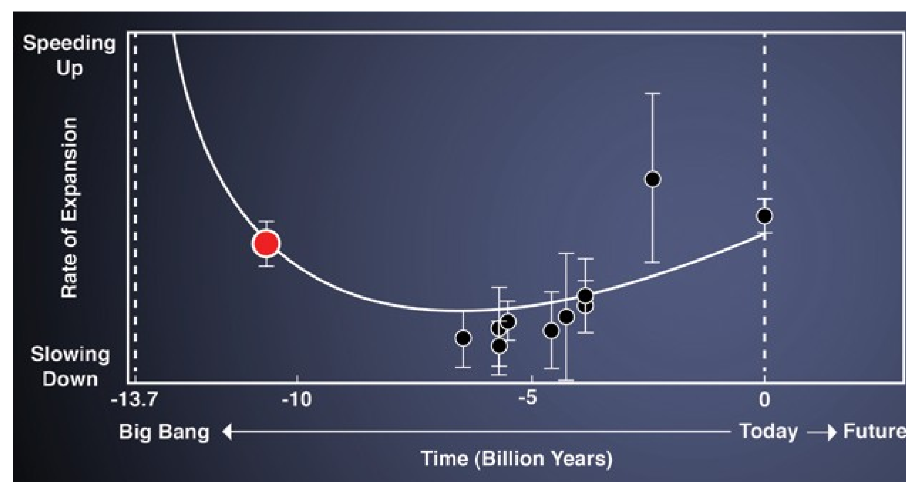
(non-ESO, non-OPTICON) Baryonic Acoustic Oscillations



Busca et al. 2012, Delubac et al. 2014







! This is large survey science