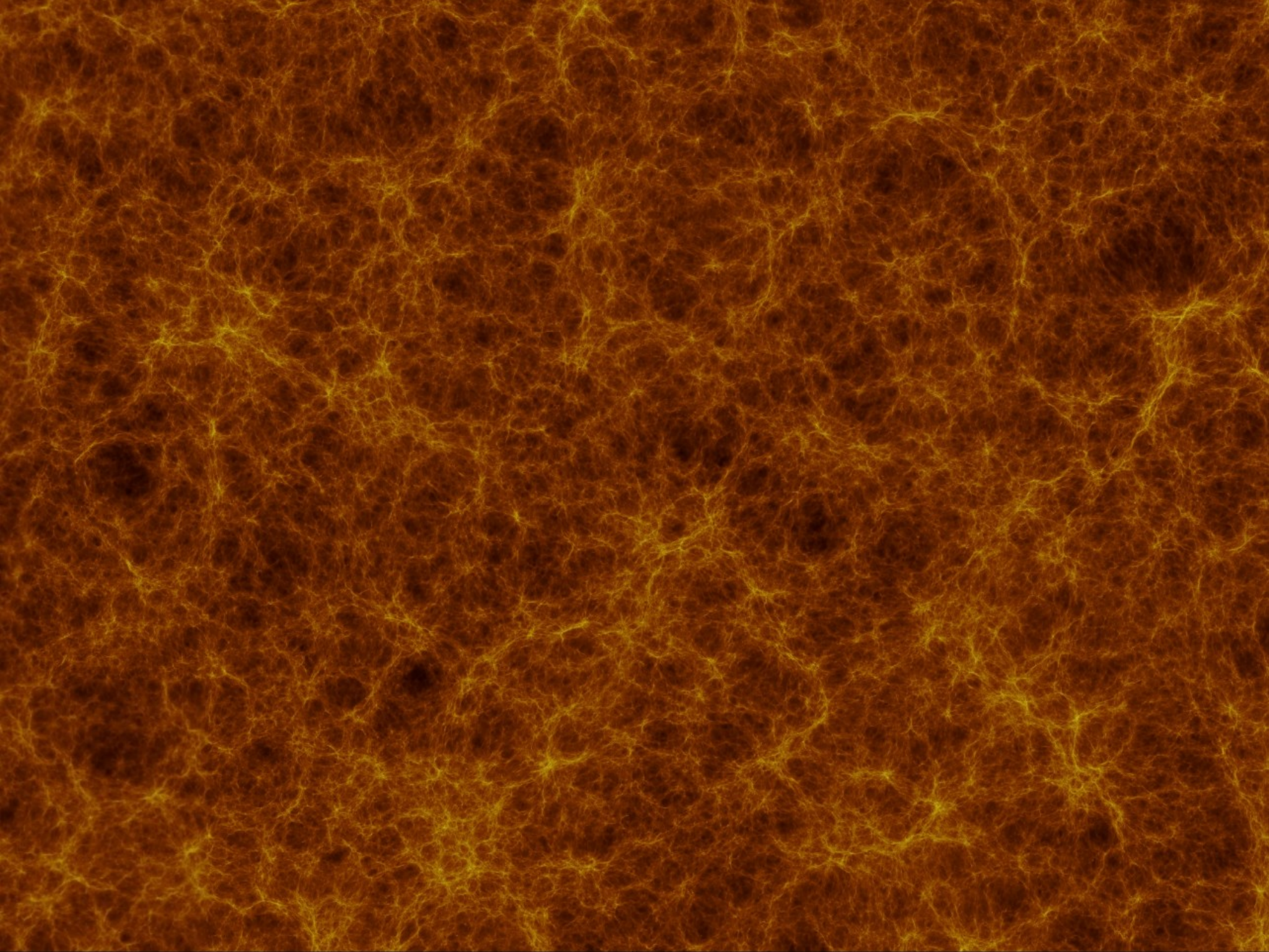
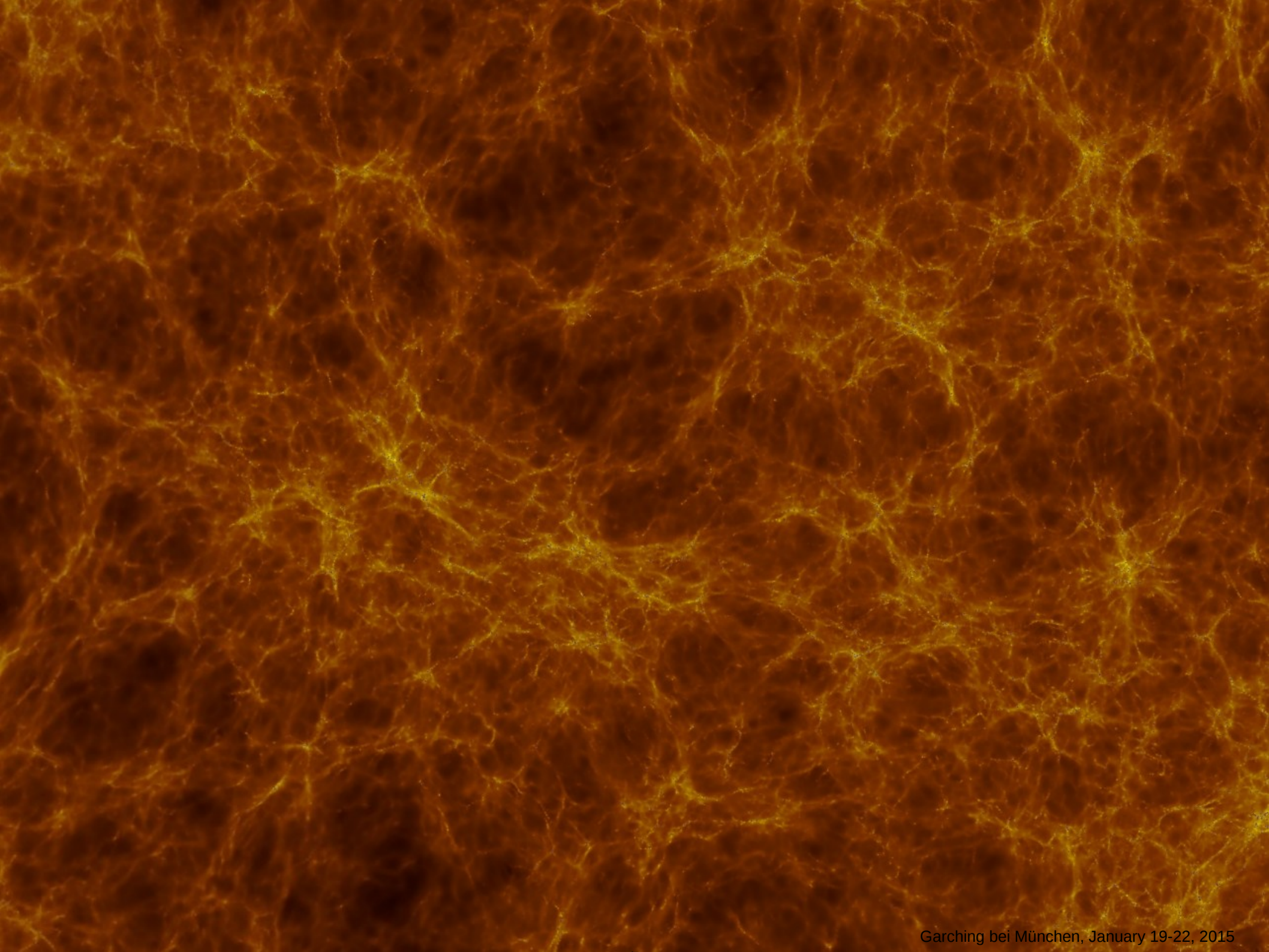
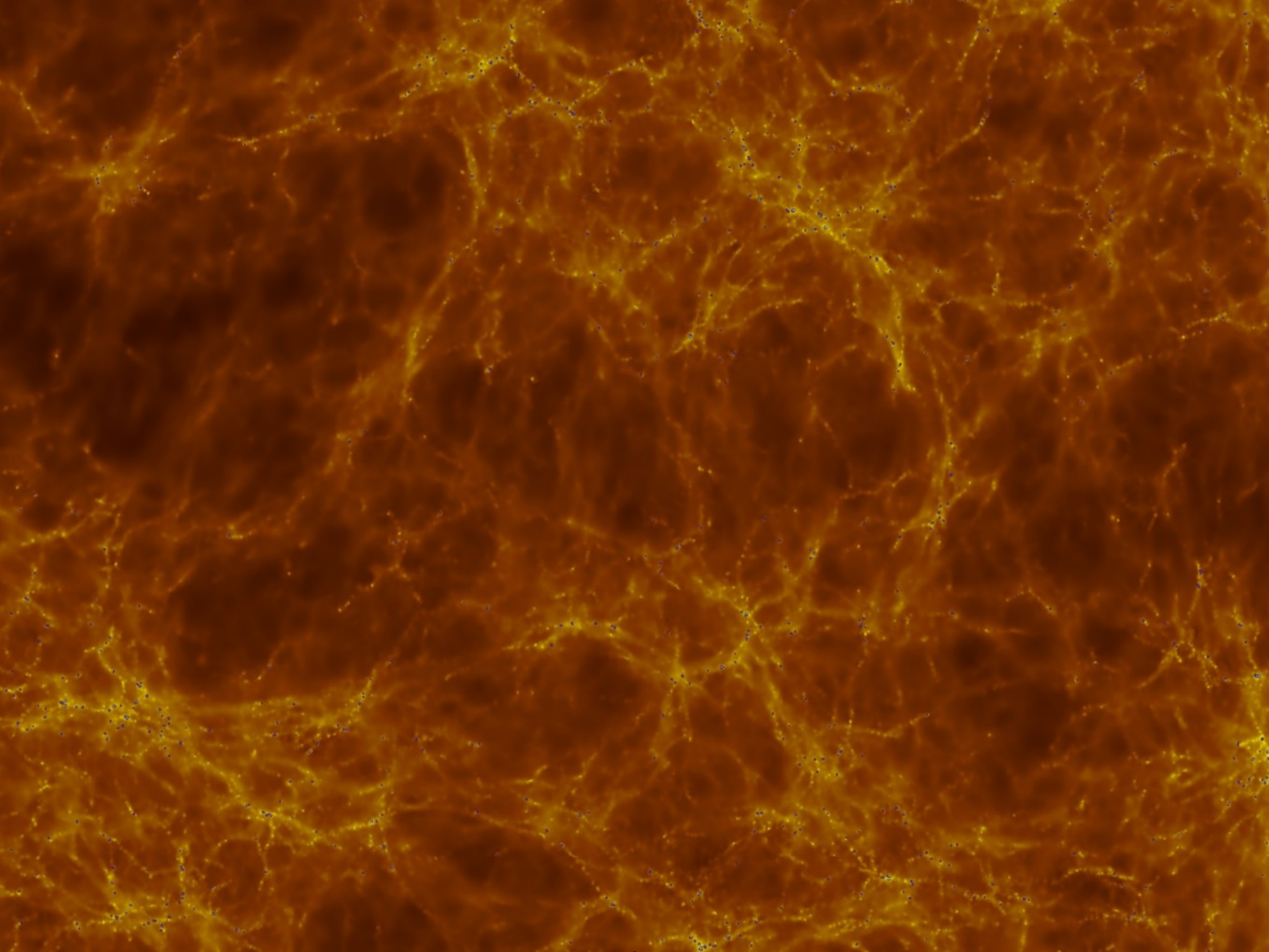
Gas at high-z

+ a bit about fundamental cosmology/physics

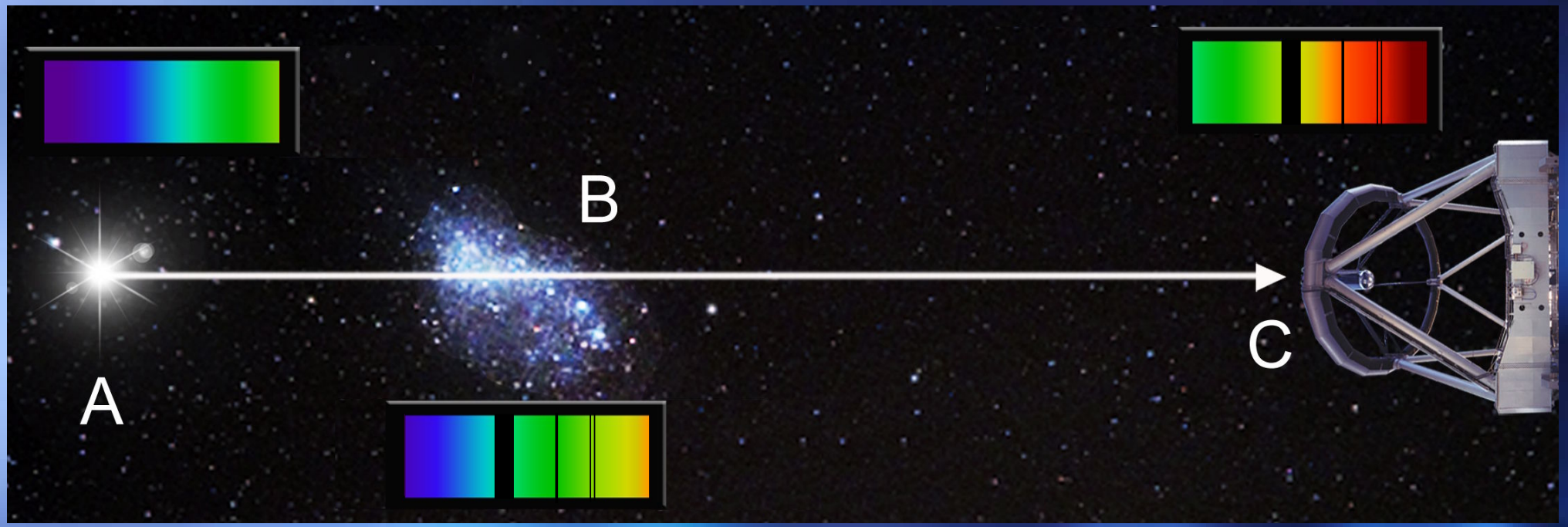
Pasquier Noterdaeme

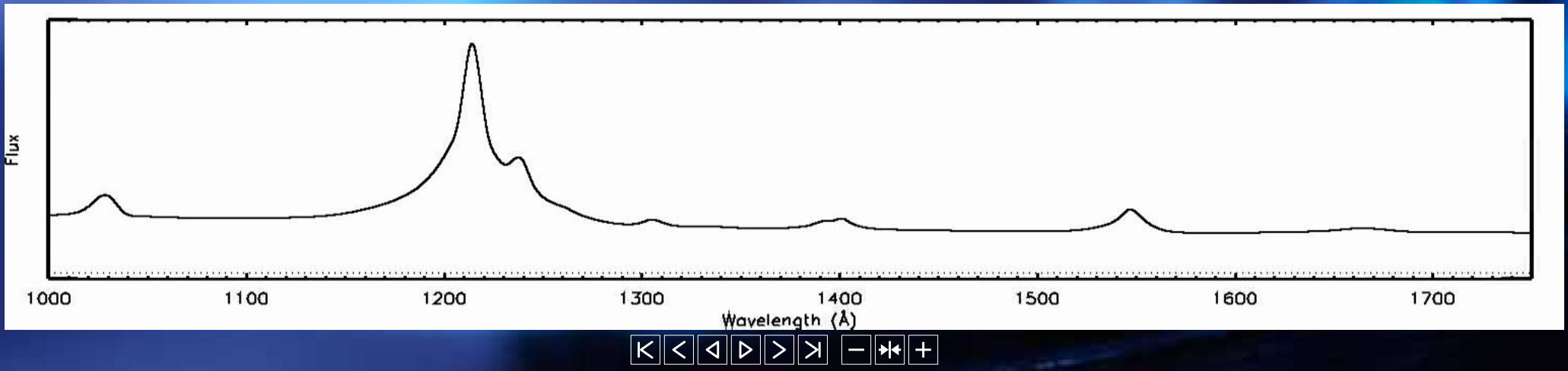



Garching bei München, January 19-22, 2015



Quasar absorption lines





Outline

I – How do we detect high-z gas?

II – The Intergalactic medium

III - Gas in high-z galaxies

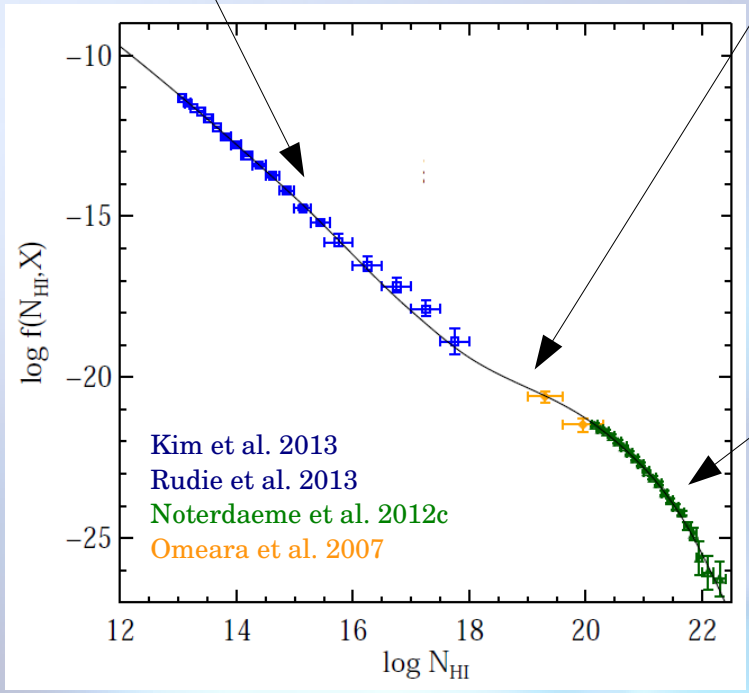
IV – Cosmology / Fundamental physics

Absorption systems classified by N(HI)

Lyα-forest

Ly-limit systems (LLS)

Damped Lyα systems (DLAs)



Prochaska et al. 2014

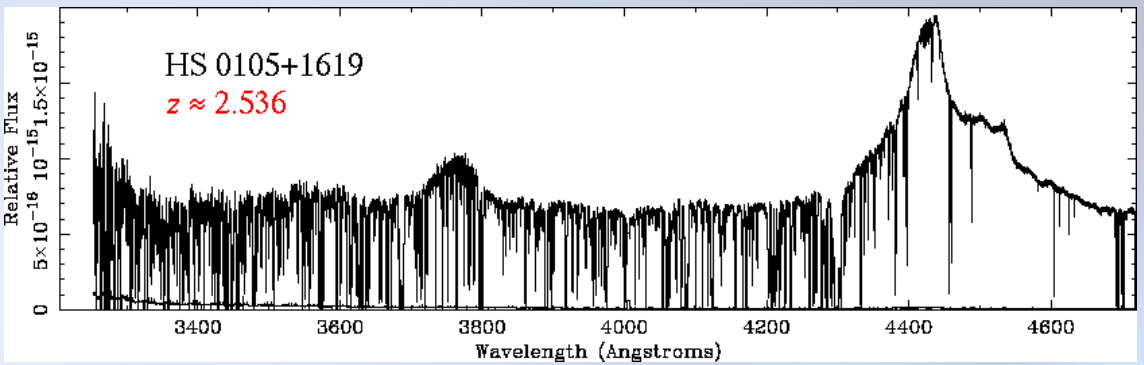
- N(HI)~10^{12} cm^{-2} and over ten orders of magnitude

- A wide range of properties (very tenuous IGM to dense ISM)

- The same way over a wide redshift range

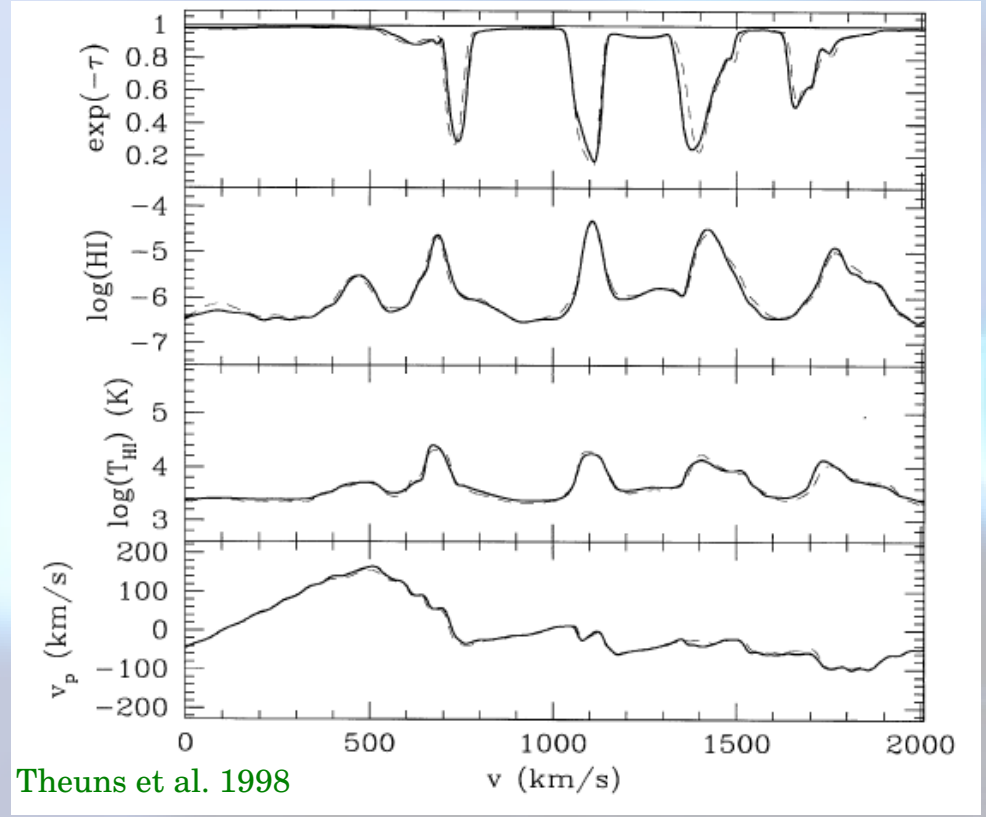
- Detection independent of the luminosity of the associated object

The Inter-Galactic Medium



Observable: $I = I_0 \exp(-\tau(\lambda))$

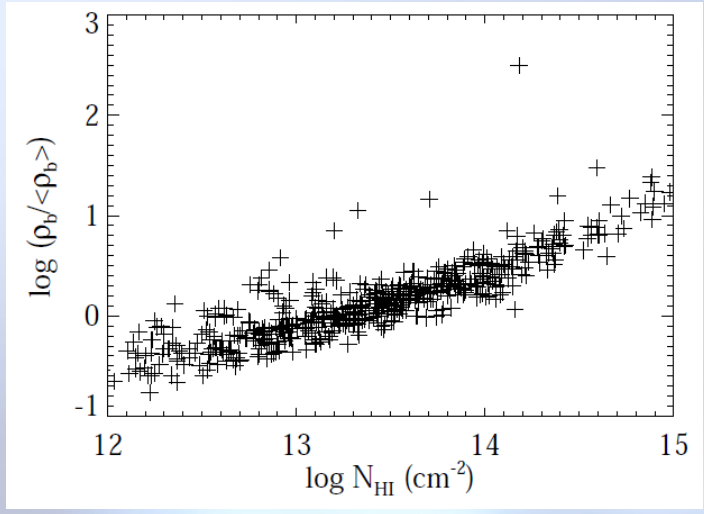
- line decomposition: N, b, z
- Physical properties of the gas?



Theuns et al. 1998

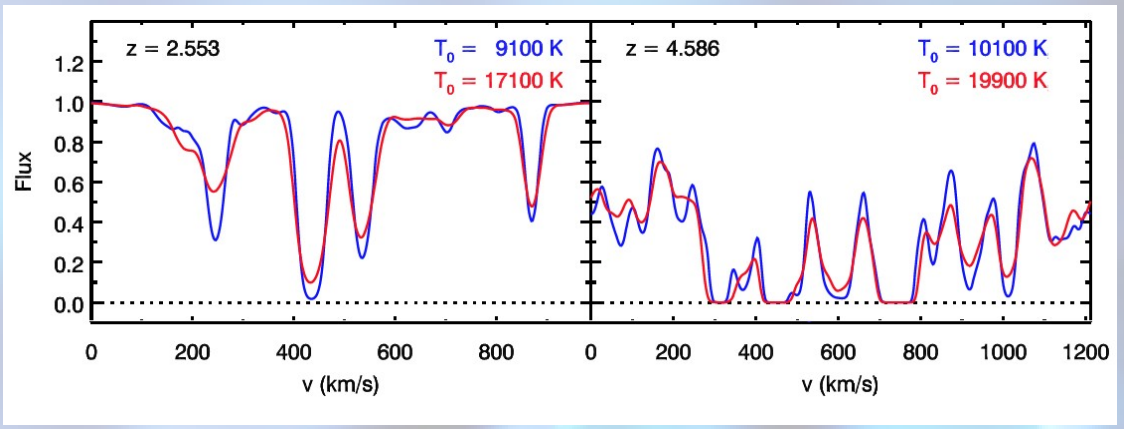
The Inter-Galactic Medium

- Density



Schaye 2000

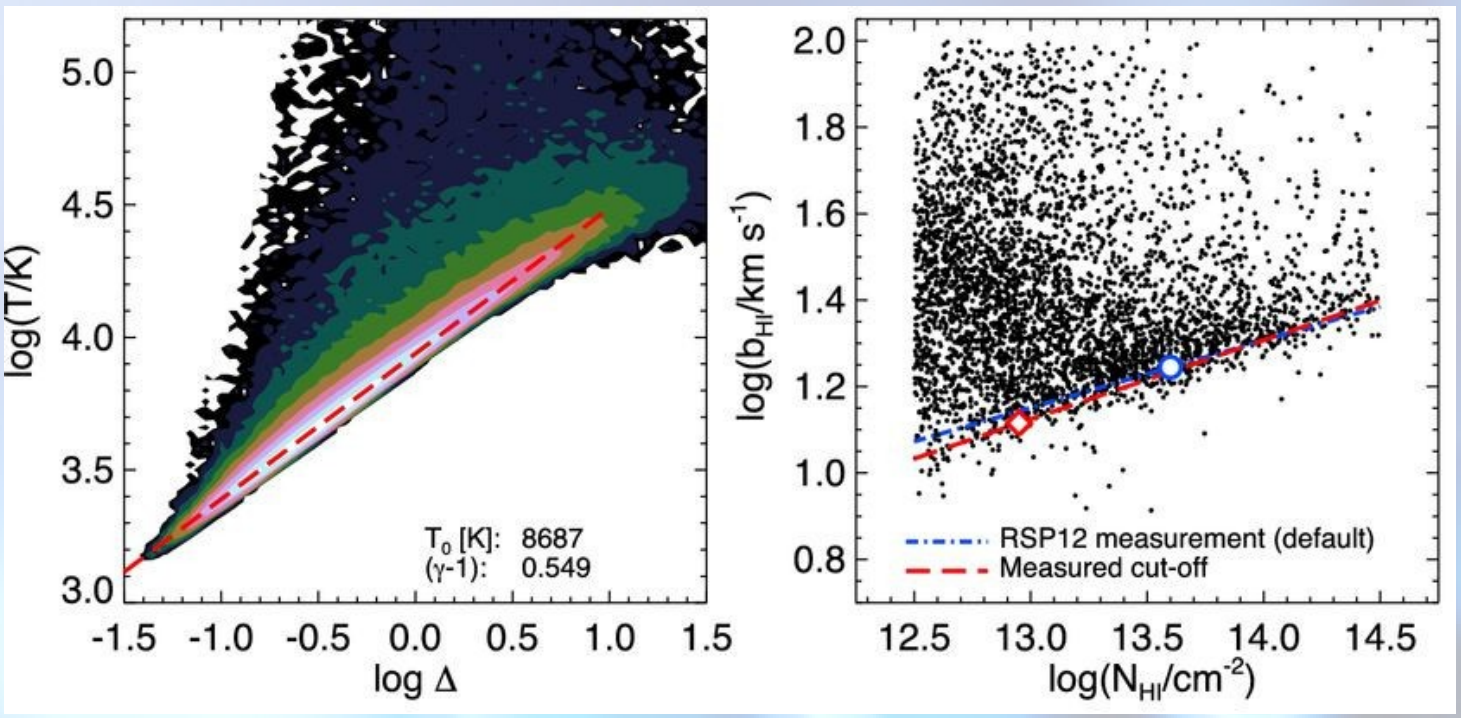
- Temperature



Becker et al. 2011

The Inter-Galactic Medium

- The temperature – density relation $T = T_0 \Delta^{\gamma}$
  Competition between photoelectric heating and adiabatic cooling

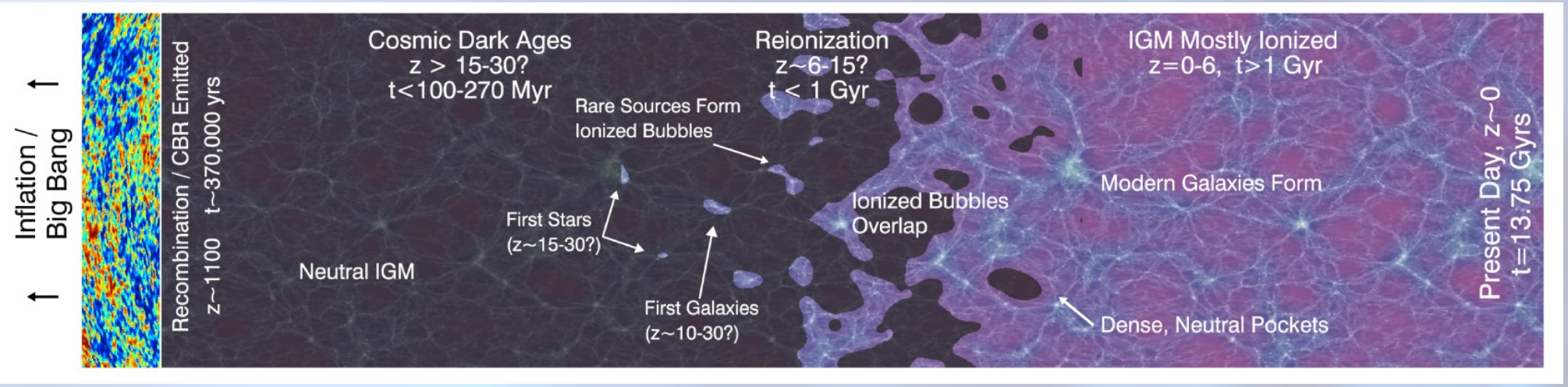


Bolton et al. 2014

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

The Inter-Galactic Medium

- Reionisation



Robertson et al. 2010

Production of ionising photons:

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

SFR density (Msun/yr/Mpc3)

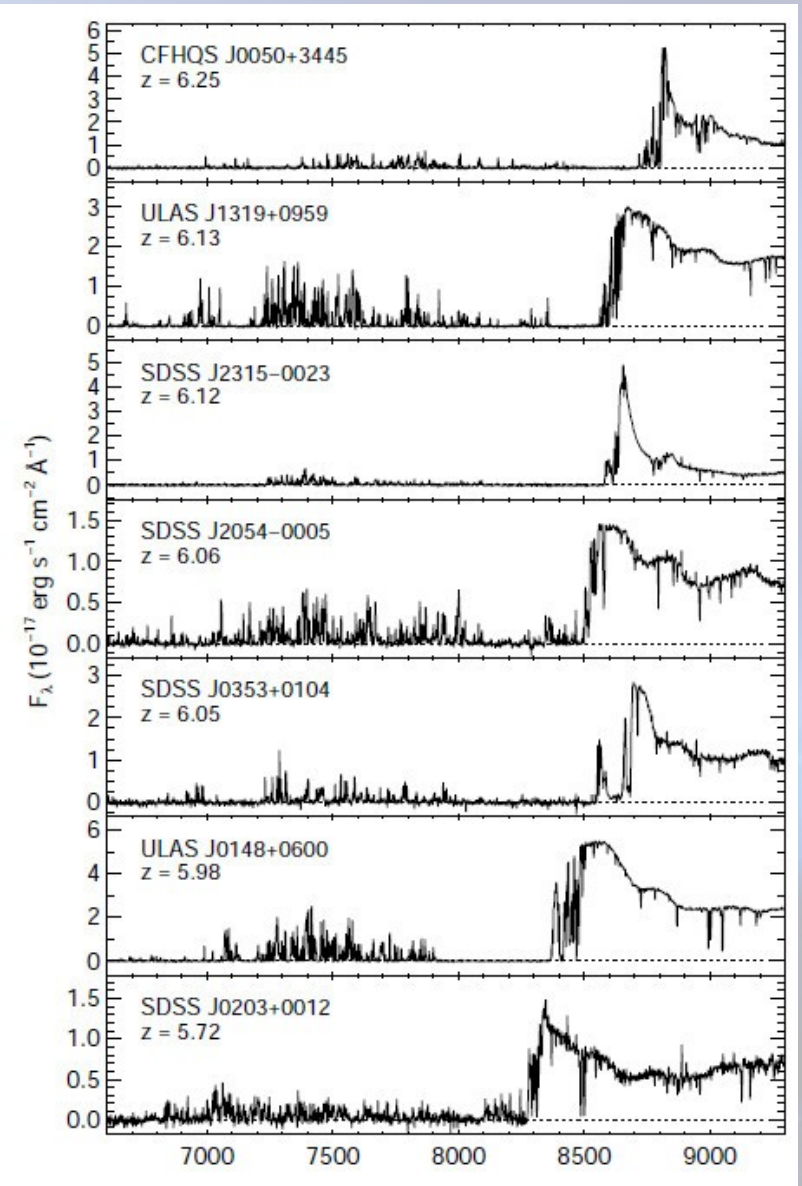
fraction of ionising photons escaping a galaxy

H-ionising photon per unit SFR density

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

The Inter-Galactic Medium

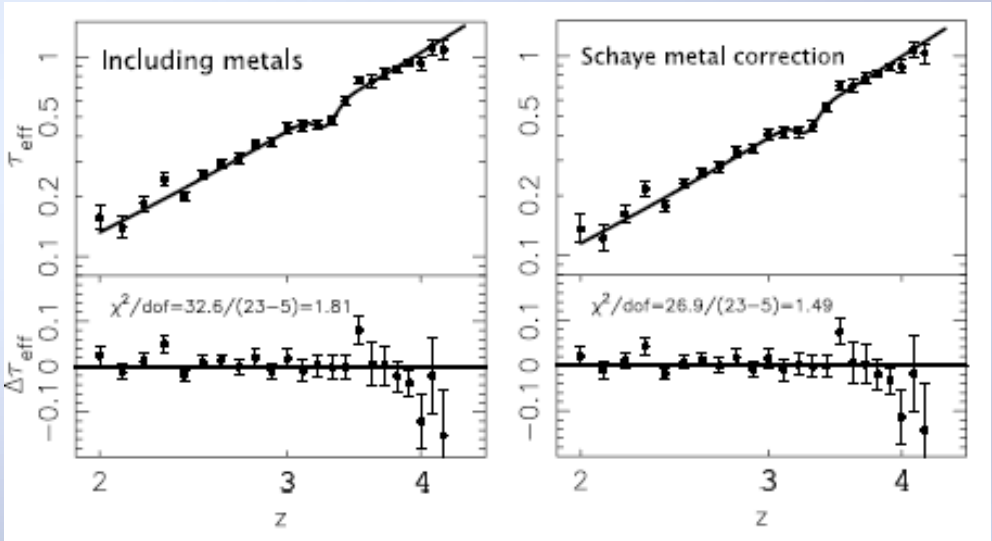
- HI Reionisation



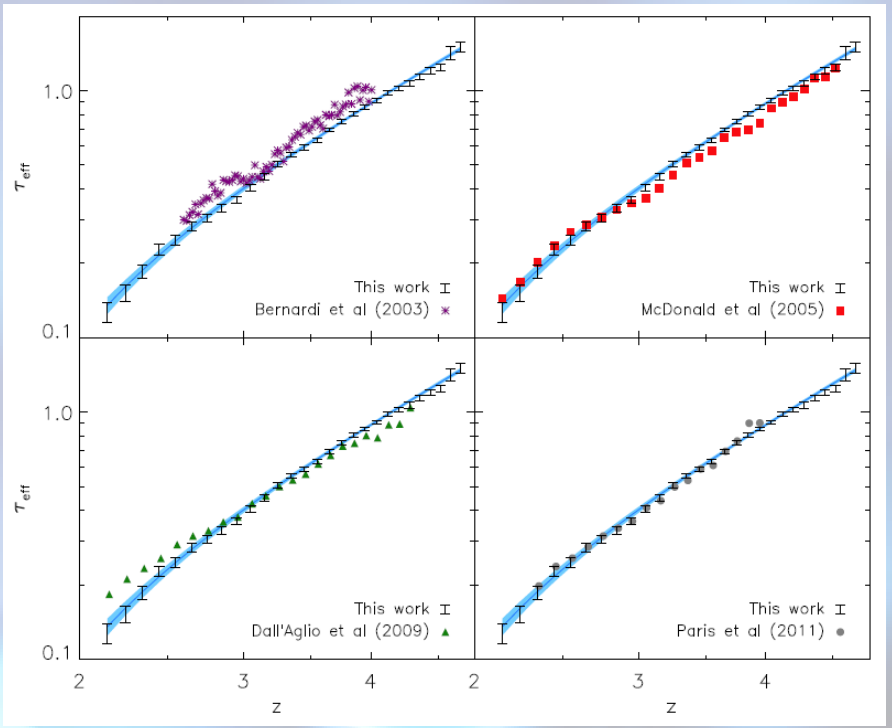
Becker et al. 2014

The Inter-Galactic Medium

- Evolution (**opacity**/temperature/metals)



Faucher-Giguère et al. 2008



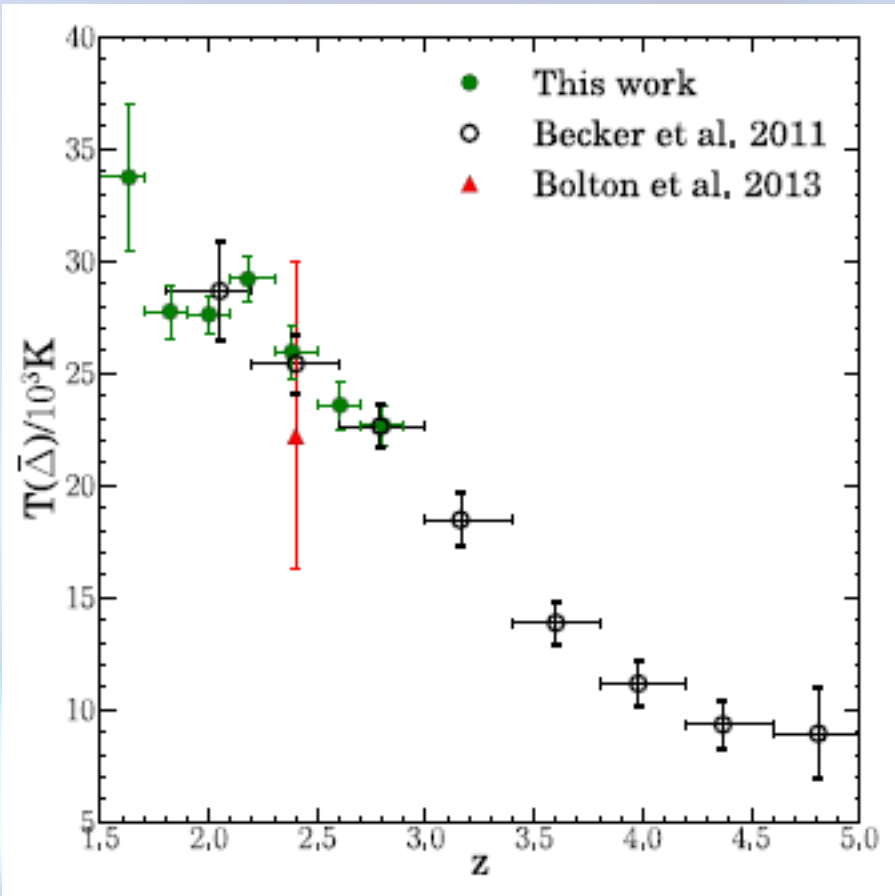
Becker et al. 2013

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

The Inter-Galactic Medium

- Evolution (opacity/**temperature**/metals)

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

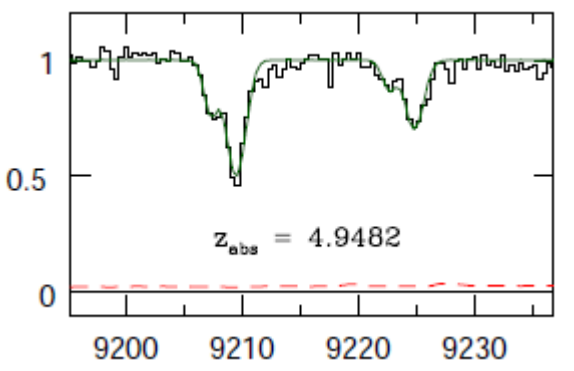


Temperature in over-densities

Boera et al. 2014

The Inter-Galactic Medium

- Evolution (opacity/temperature/**metals**)

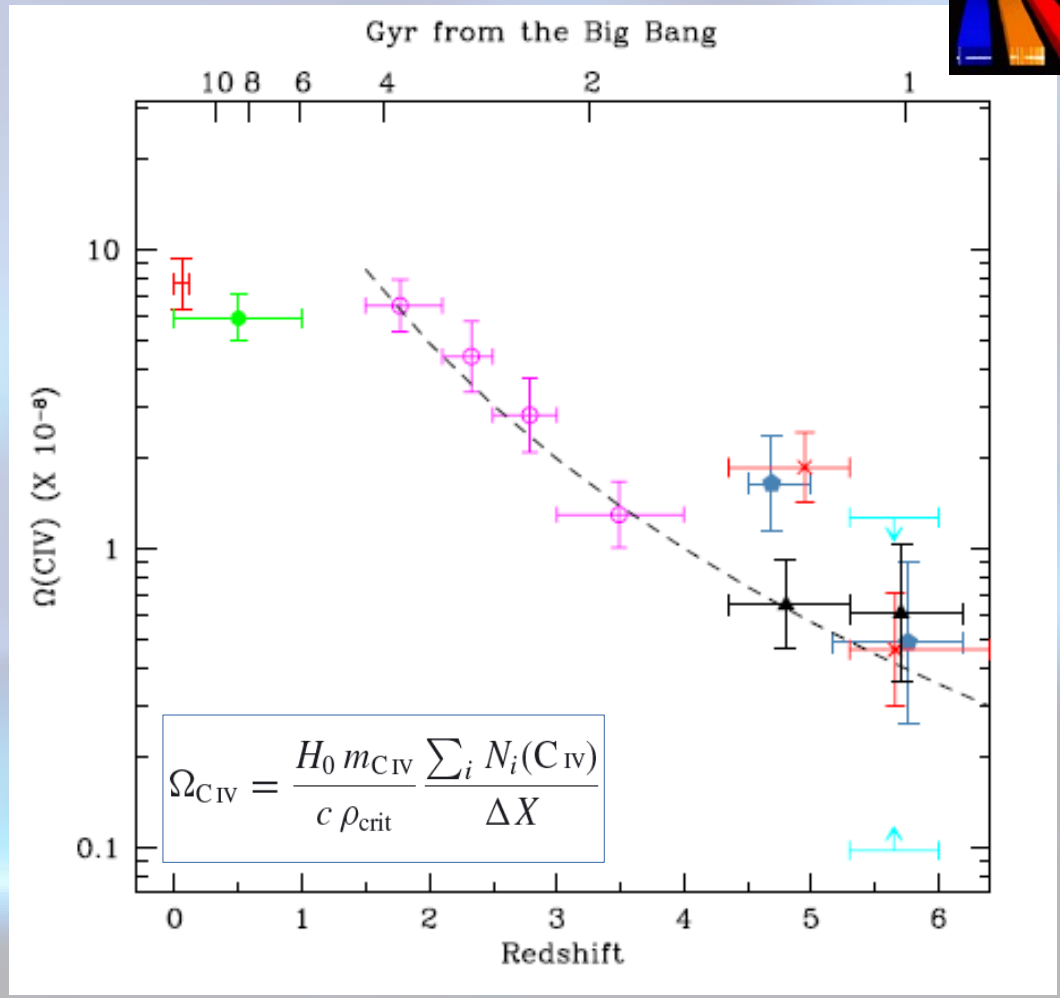


- CIV always found for log NHI>15
- CIV in ~50% at log NHI = 14.5

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

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

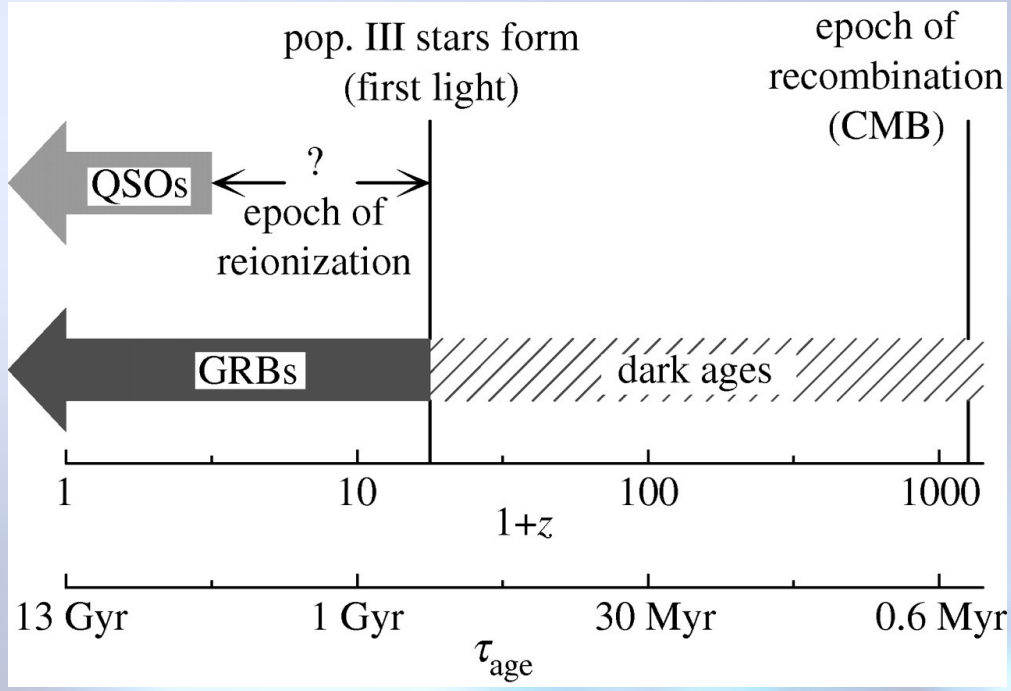
Q: How far from galaxies is the IGM enriched? ==> extreme sensitivity at high resolution



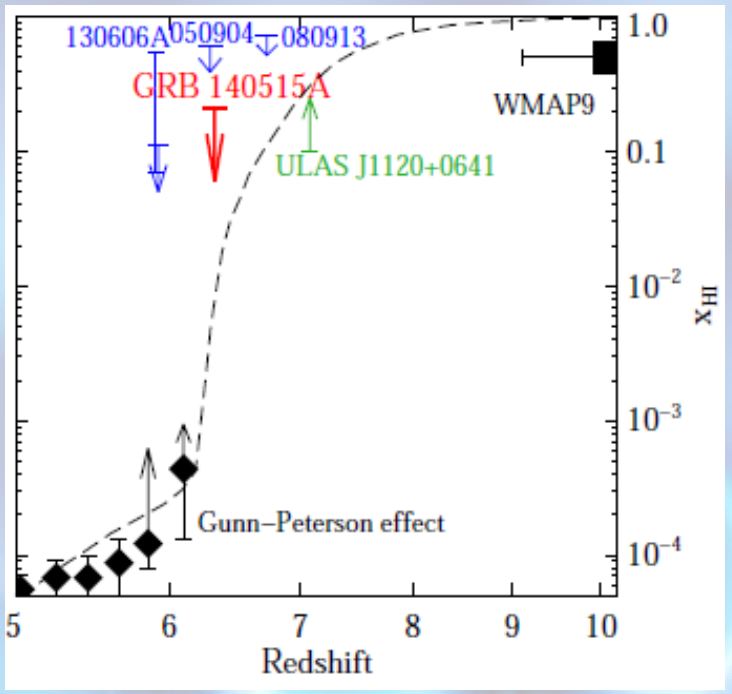
D'Odorico et al. 2013

The Inter-Galactic Medium

- The very high-z: GRBs



Lamb 2002



Chornock et al. 2014

The Inter-Galactic Medium

Ly-alpha opacity ~δ

Temperature T(δ)

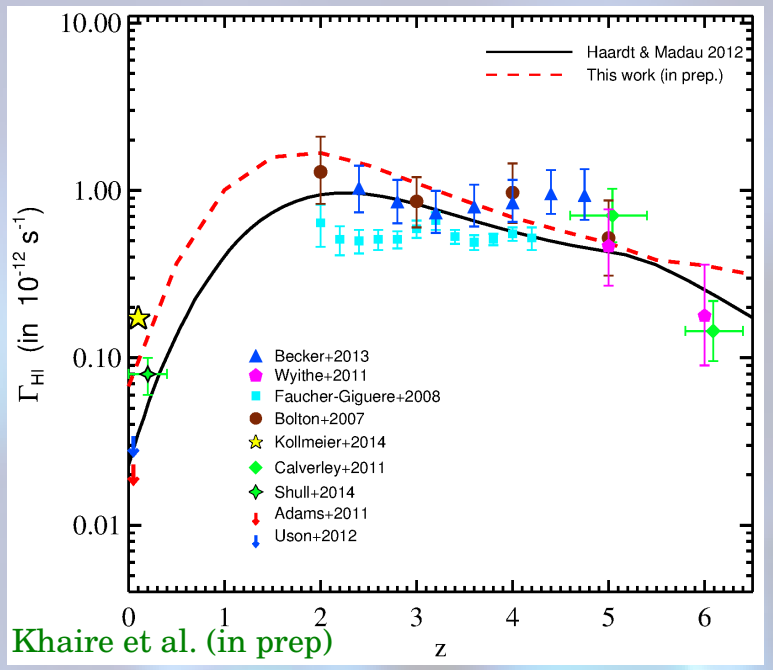
Ionisation rate of HI

Opacity to >13.6 photons (IGM+CGM)

ionising emissivity

non-ionising emissivity (SFR)

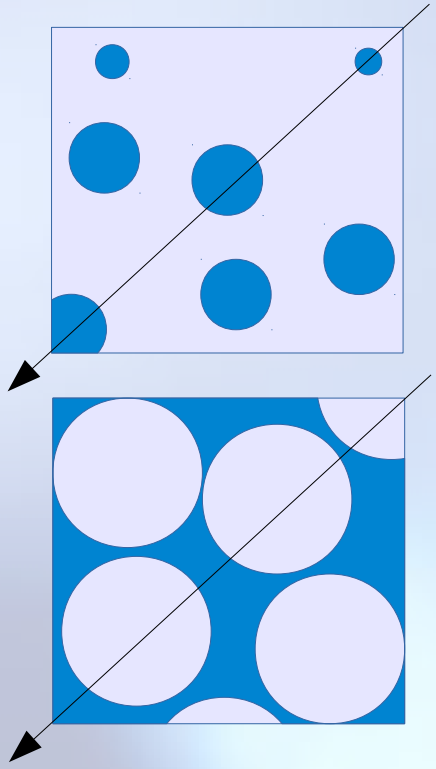
f_{esc} (galaxies)



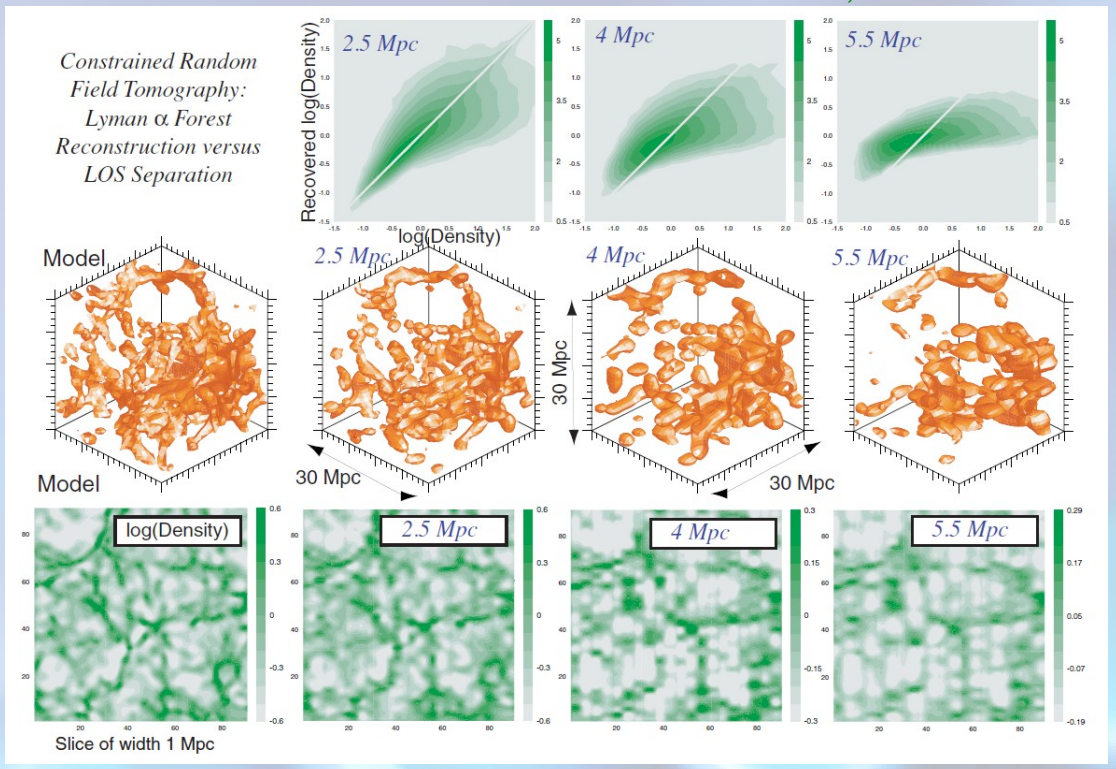
Khaire et al. (in prep)

The Inter-Galactic Medium

Tomography



Pichon et al. 2001, Cauci et al. 2008

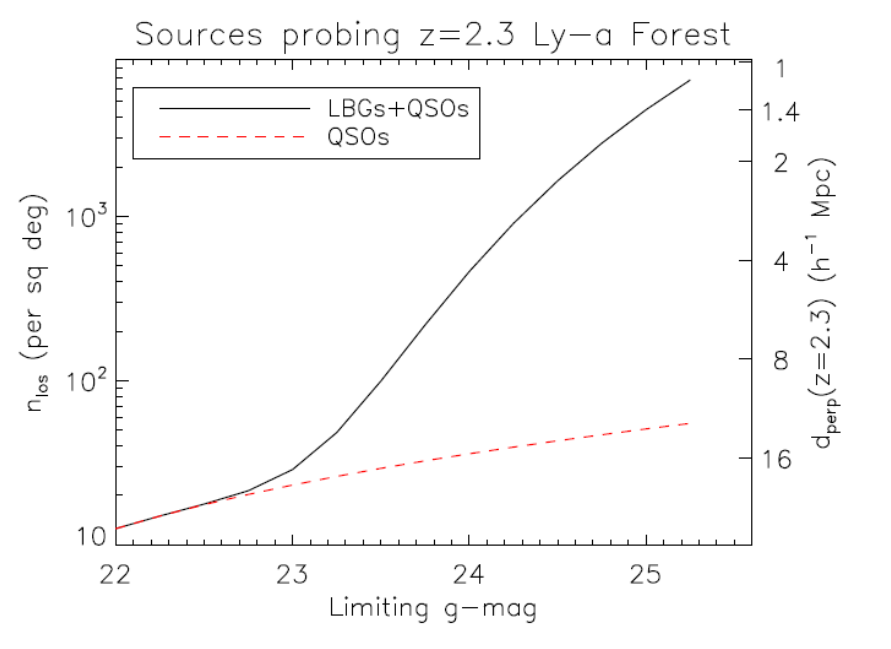


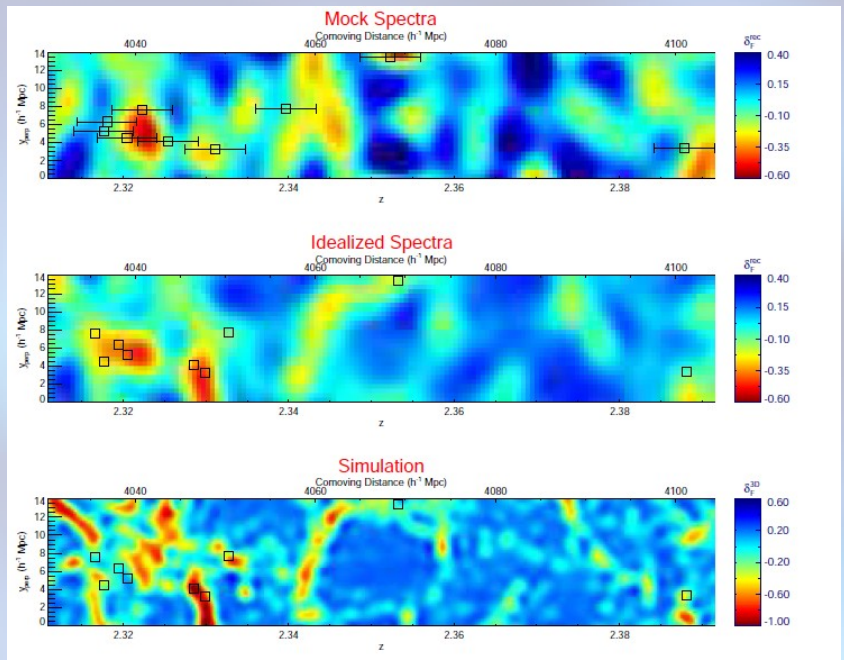
900 400 150 /deg^2

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

The Inter-Galactic Medium

Tomography: go faint and 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

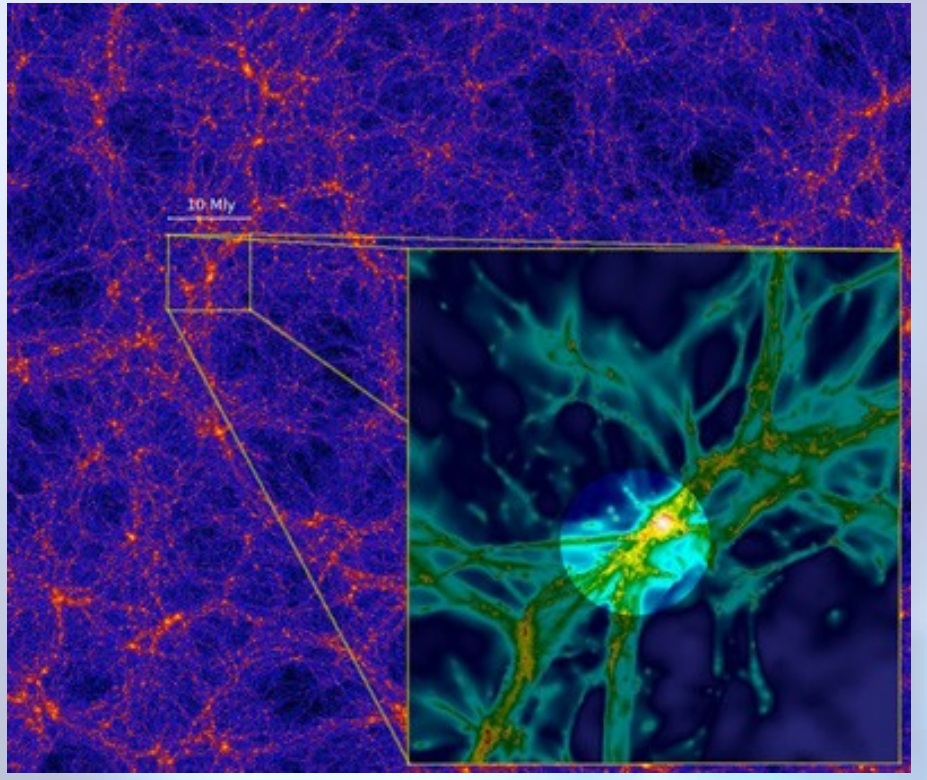
MOS@ELT

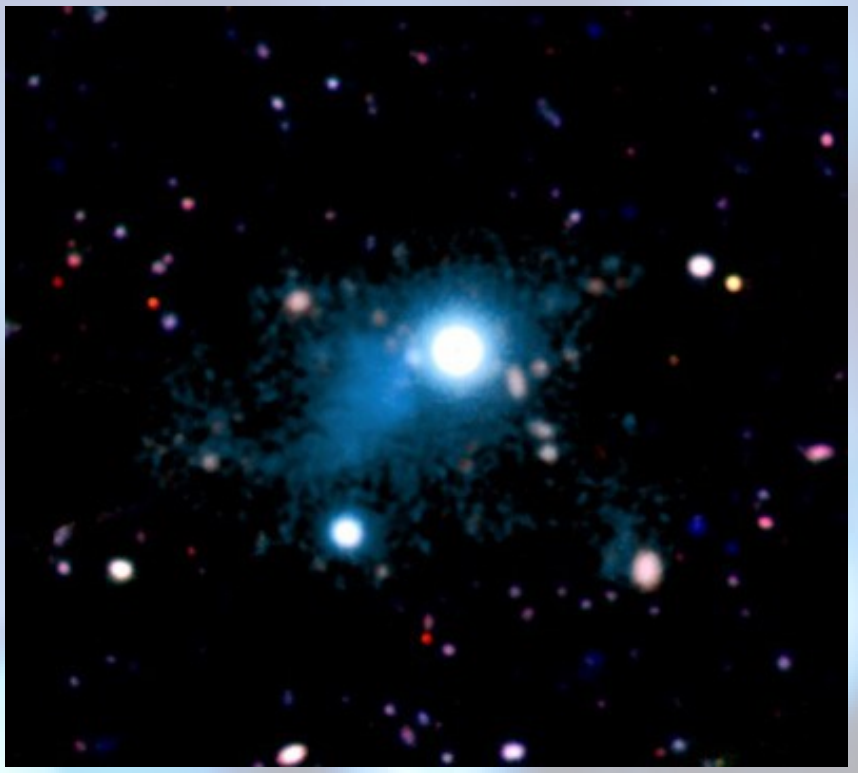
Lee et al. 2014: you don't need to resolve forest. S/N~4 @ R~1000 is enough to g~24

VLT is ~ok (?)

The Inter-Galactic Medium

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

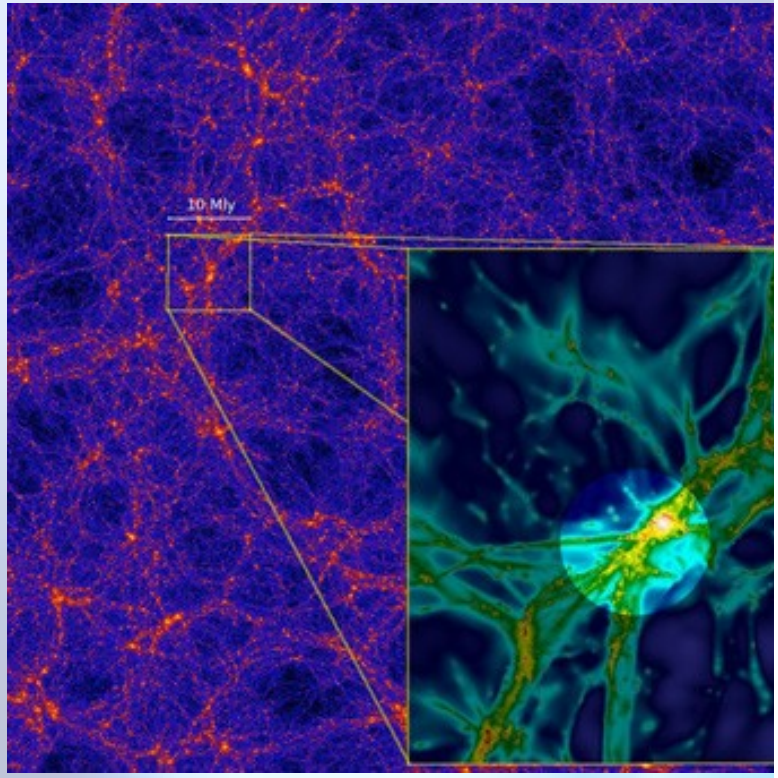




Cantalupo et al. 2014

The Inter-Galactic Medium

- Filament in the cosmic web: Ly-alpha in ~~emission~~ absorption: the knots



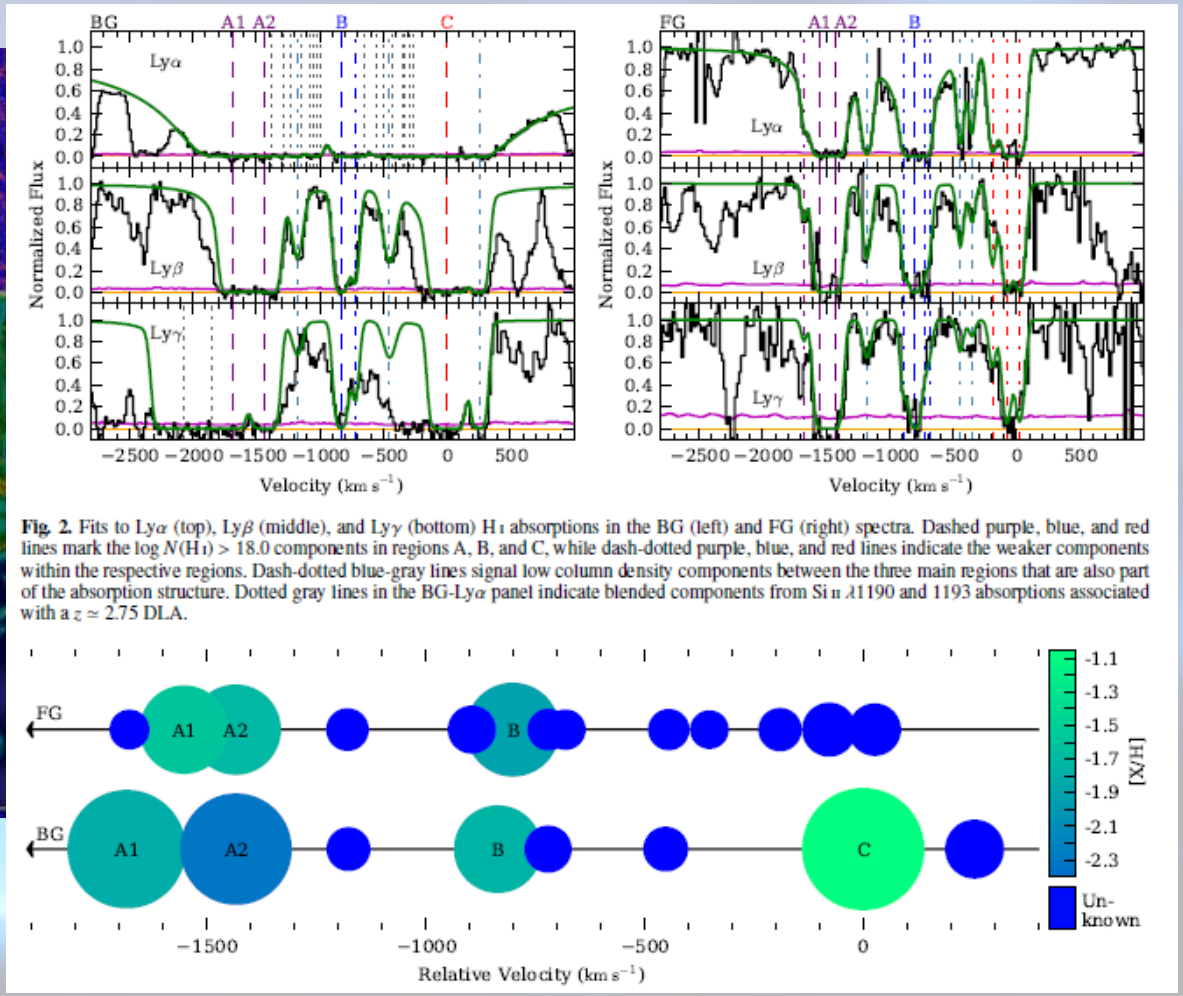
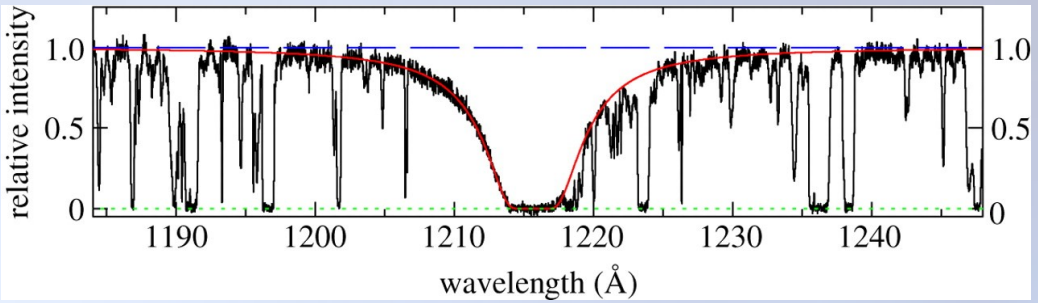
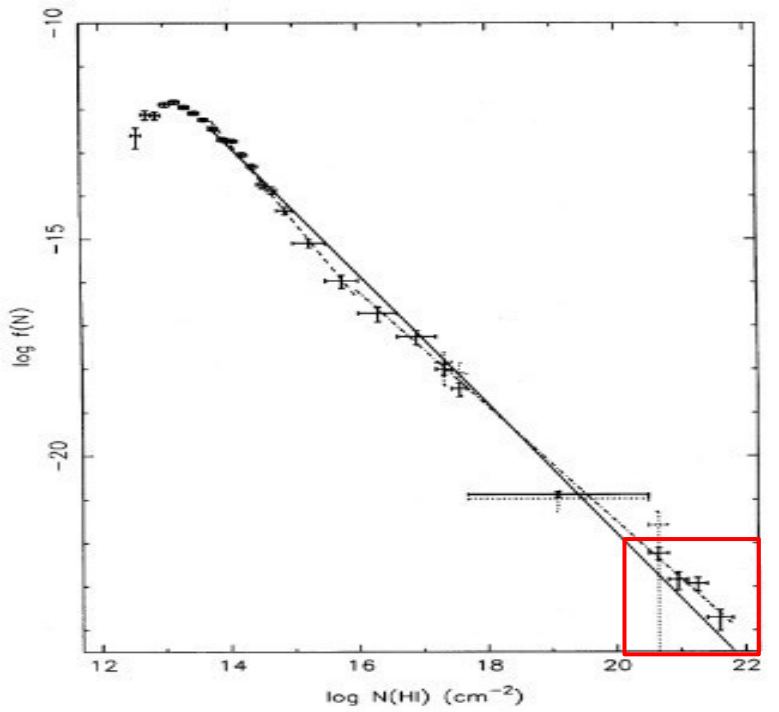


Fig. 2. Fits to Lyα (top), Lyβ (middle), and Lyγ (bottom) H I absorptions in the BG (left) and FG (right) spectra. Dashed purple, blue, and red lines mark the log N(H I) > 18.0 components in regions A, B, and C, while dash-dotted purple, blue, and red lines indicate the weaker components within the respective 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.

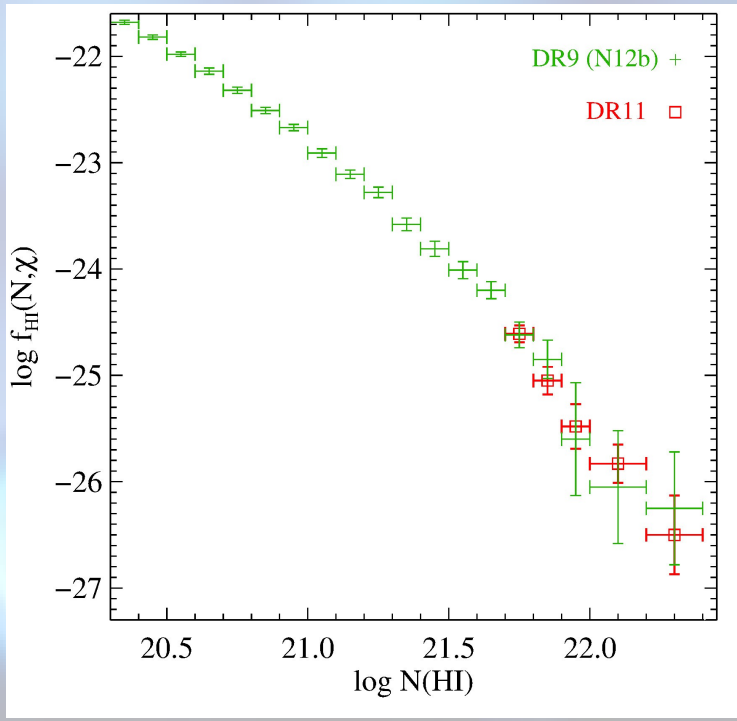
Finley et al. 2014

Neutral gas (DLAs)





Petitjean et al. 1993

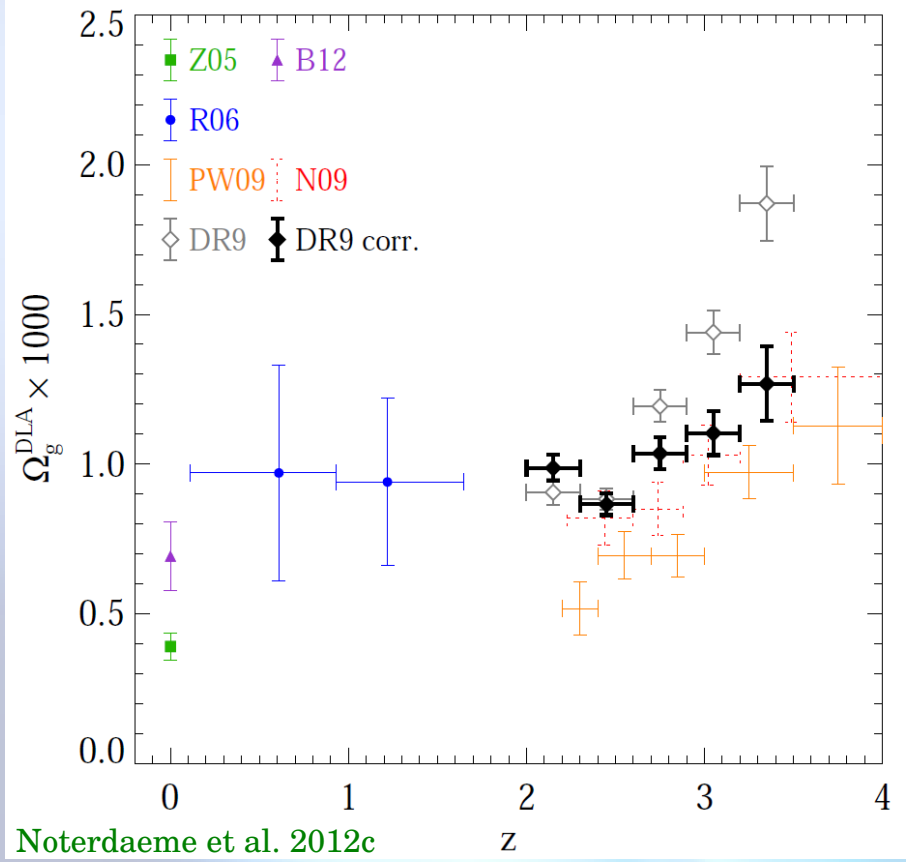


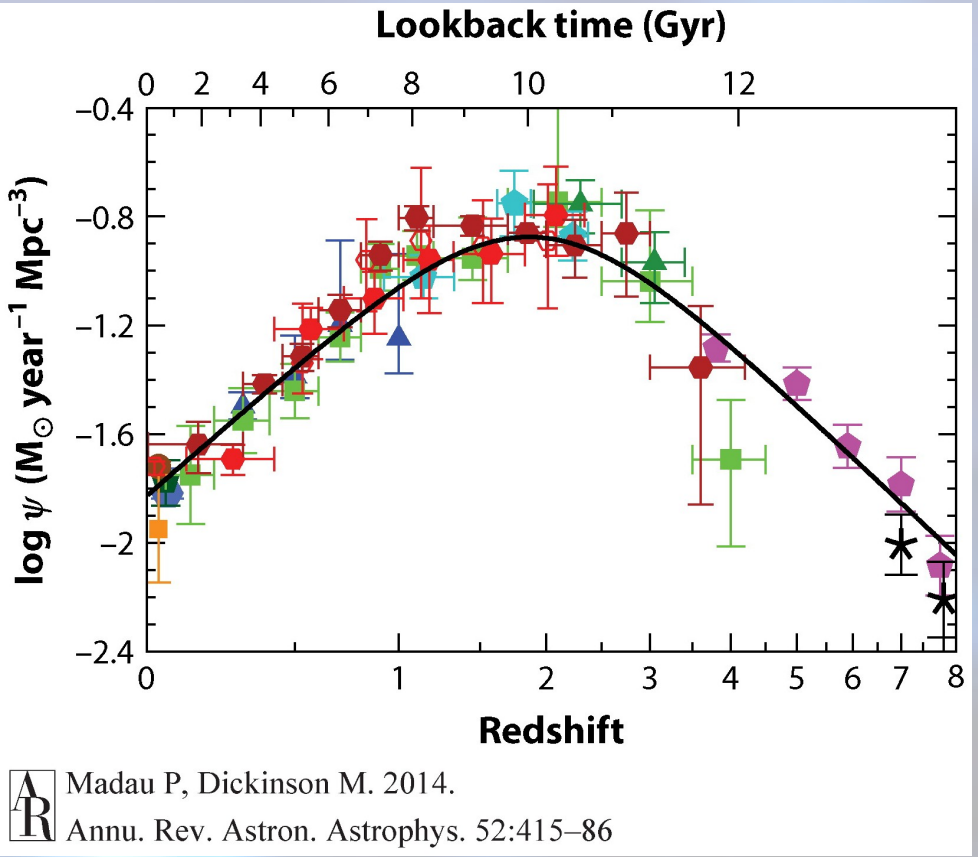
Noterdaeme et al. 2012c,2014

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

Neutral gas (DLAs)

Cosmological density

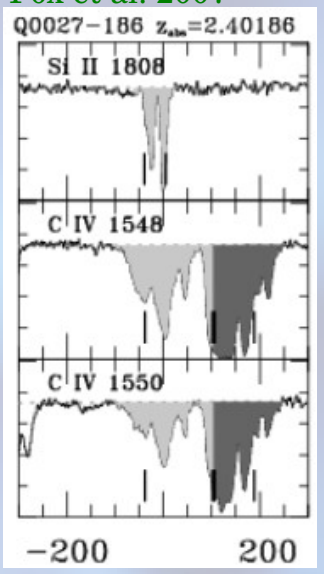


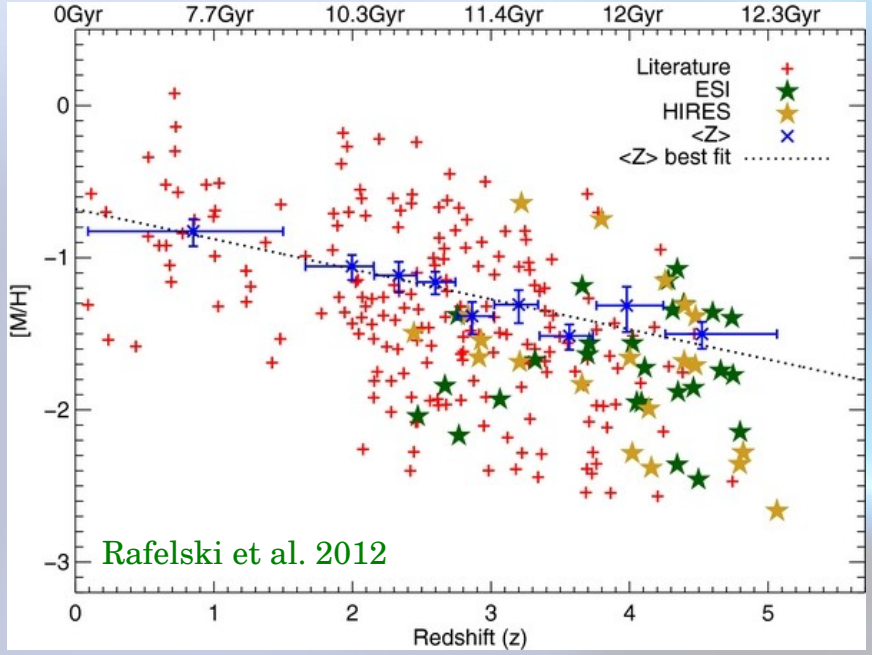


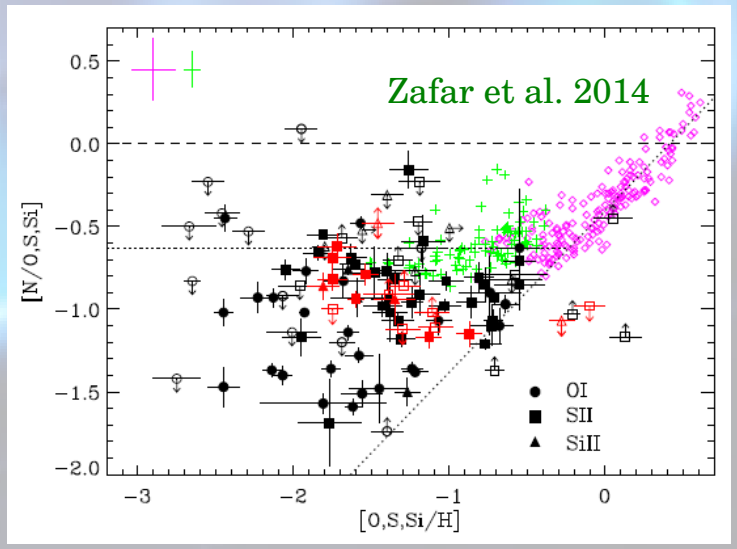
- Systematics dominate
- z>3.5 not well constrained: blending with Ly-alpha forest, need higher resolution (medium is ok)

Neutral gas (DLAs)

Fox et al. 2007



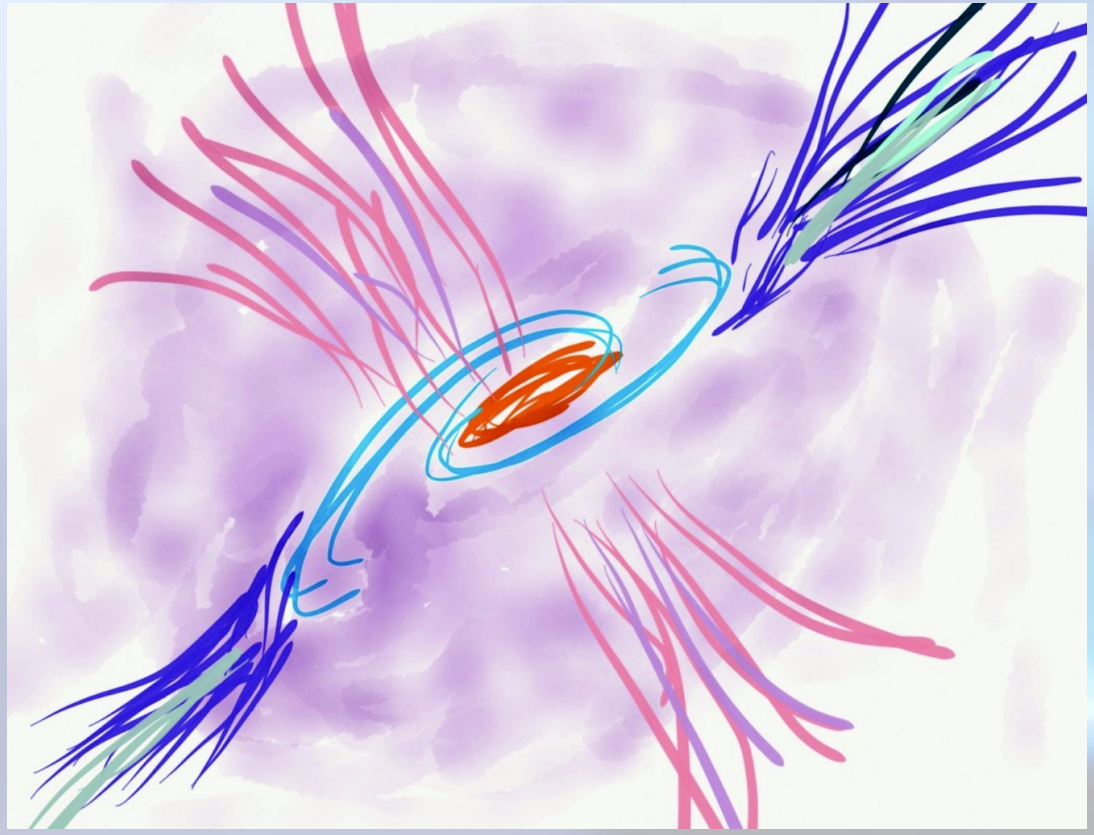




Neutral gas (DLAs)

DLAs are linked to the process of star-formation but not enough gas to sustain SFR

Simulations (C. Howk)



Questions:

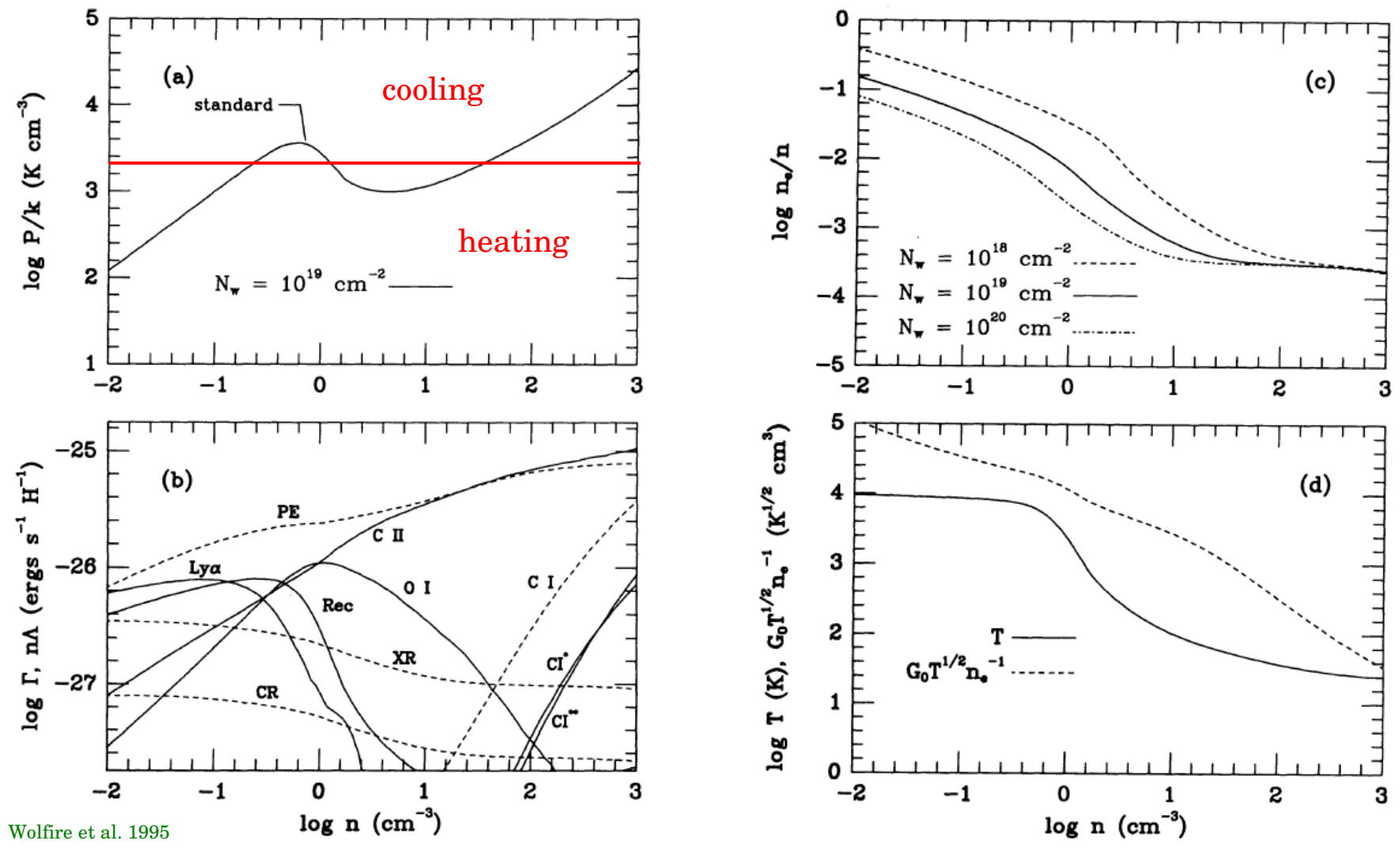
- Physical state of the gas?

- Which gas?

- Where are the galaxies?

Neutral gas (DLAs)

Physical conditions - a simplified picture for the ISM: WNM + CNM



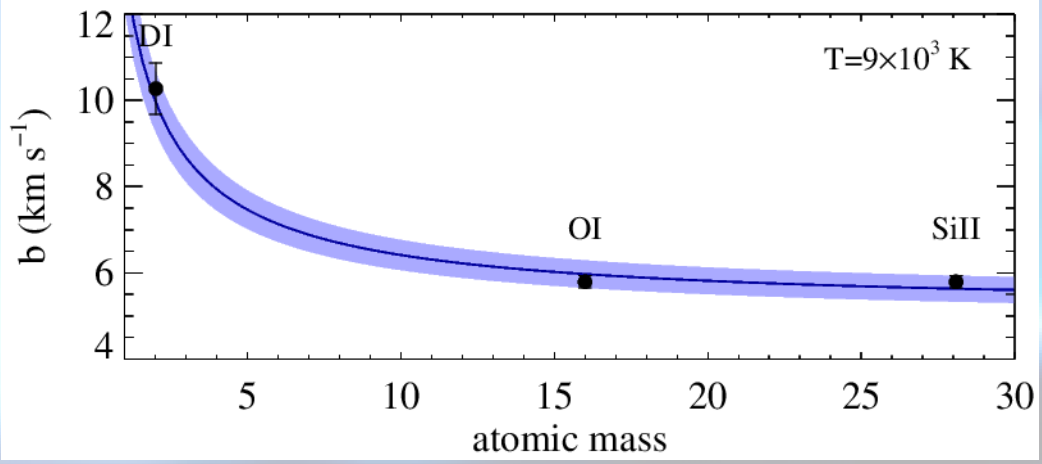
Wolfire et al. 1995

Neutral gas (DLAs)

Physical conditions – temperature from line broadening

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

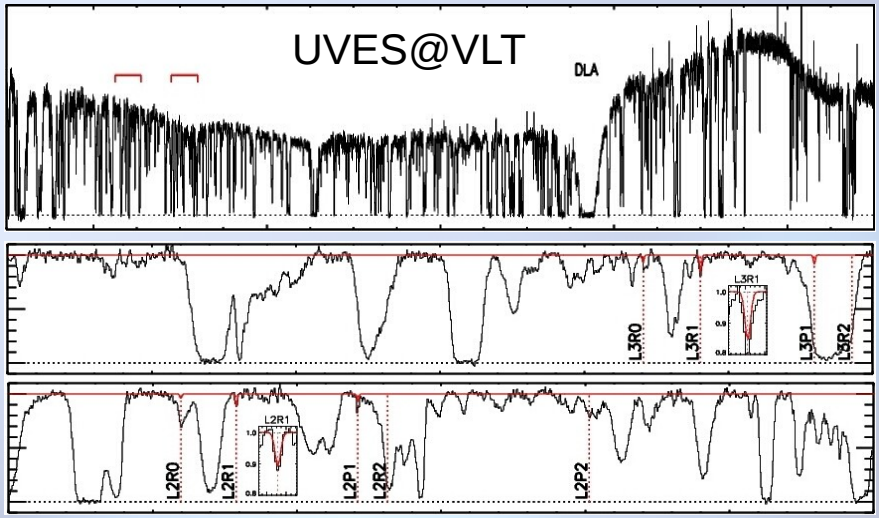
- HI Ly-α depends only on N(HI)
- metals (but m>>1: need very good data) Carswell et al. 2012
- DI helps (10^{-5} times HI) Noterdaeme et al. 2012a

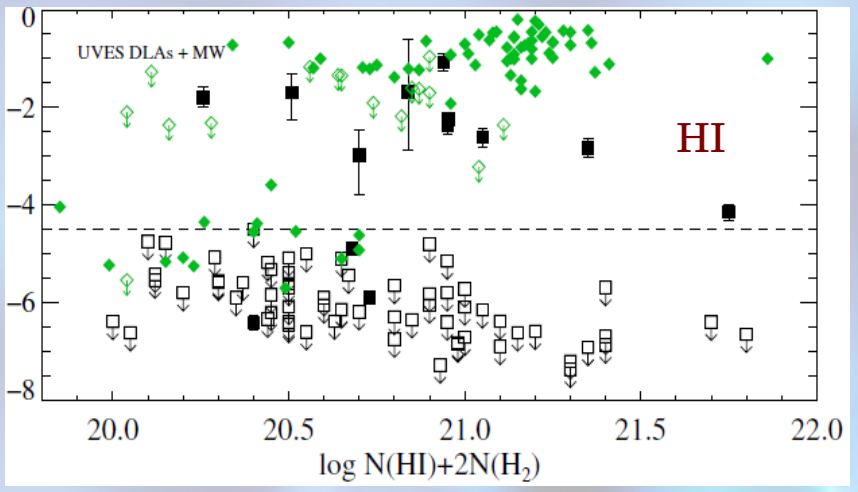


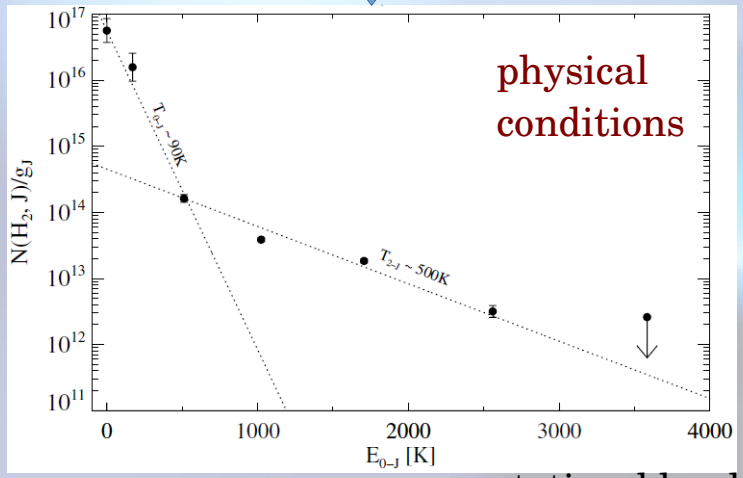
Neutral gas (DLAs)

Physical conditions - using H_2 UV lines and fine-structure of different species

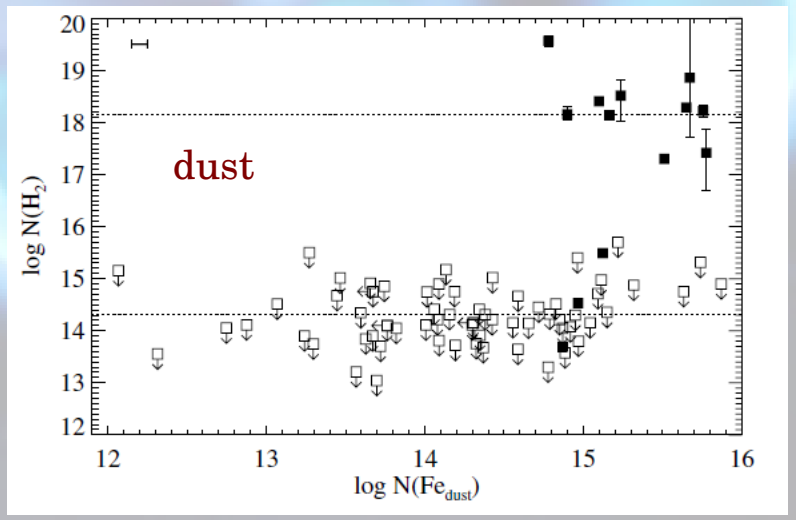
- H_2 is located in the Lyman-alpha forest: high-resolution spectroscopy in the blue







rotational levels



Neutral gas (DLAs)

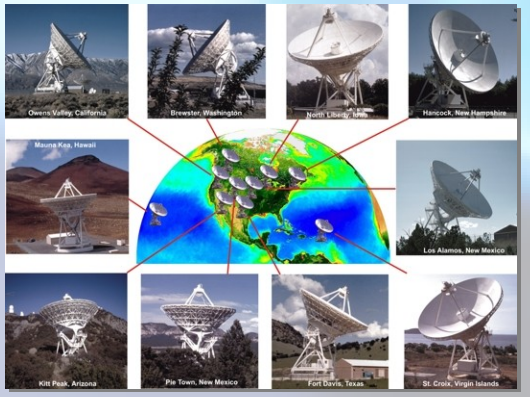
Physical conditions - using 21-cm

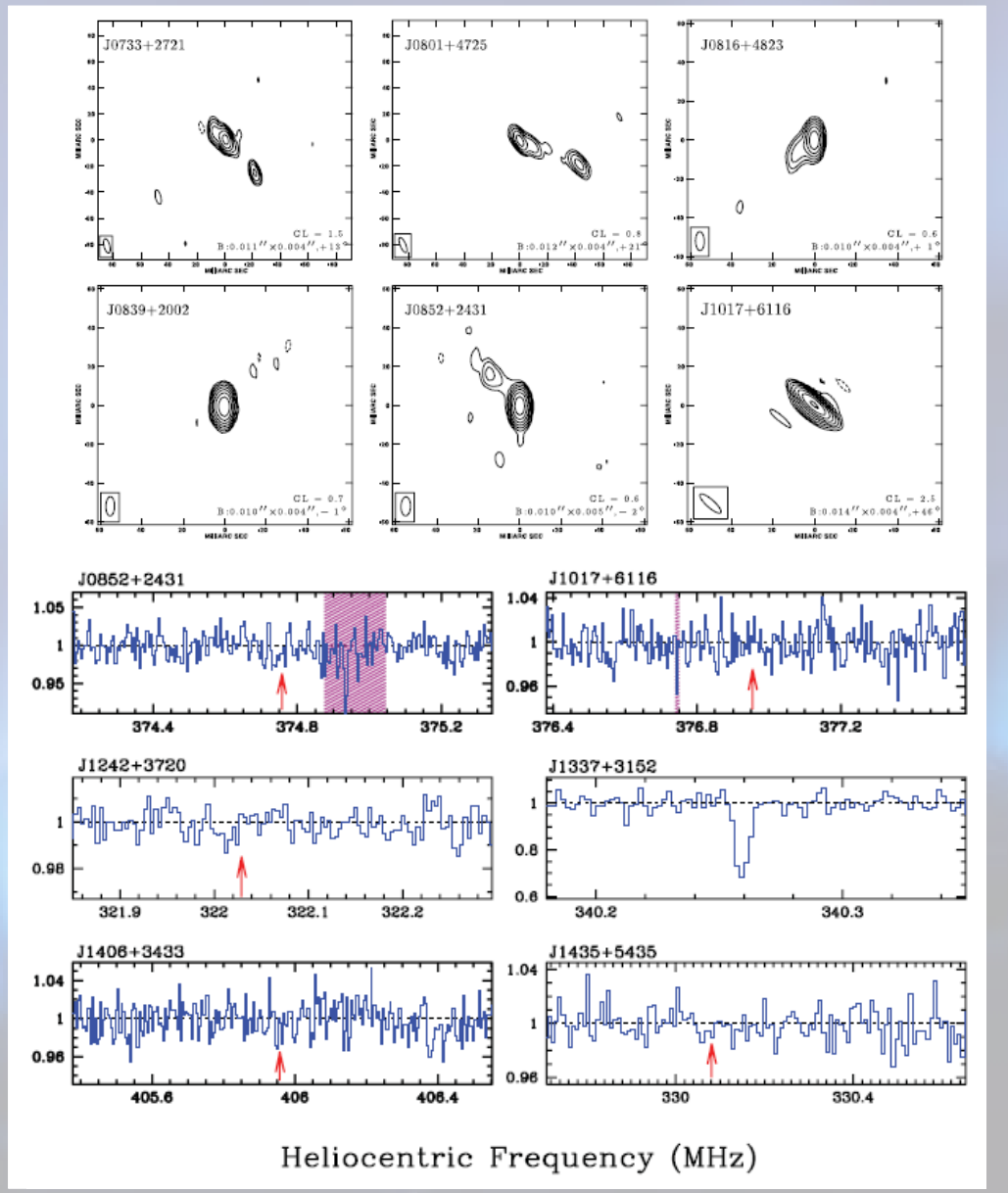
- emission (CNM+WNM): not possible yet at high-z
- absorption (CNM):

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

currently possible for F>100mJy

Several surveys using GMRT, GBT...





Srianand et al. 2012

Neutral gas (DLAs)

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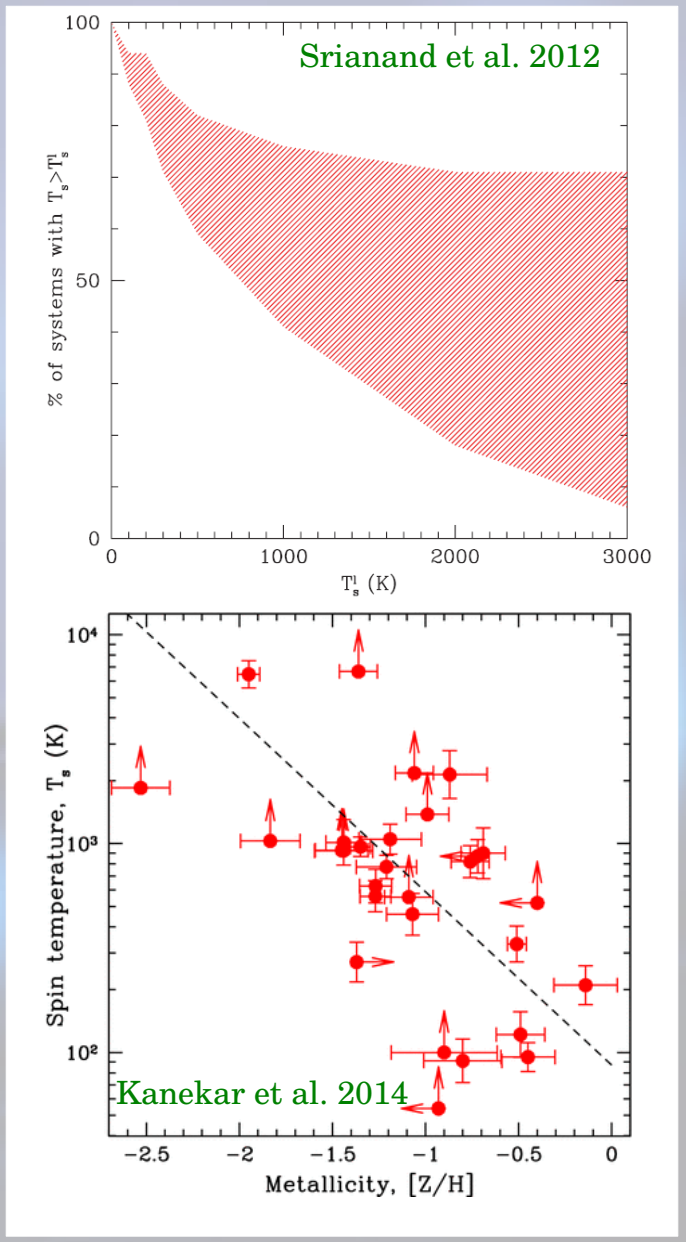


Neutral gas (DLAs)

Physical conditions

- Mostly WNM — $n \sim 0.1 cm^{-3}$, $T \sim 10^4$ K — kpc scales
- 21cm/H_2: CNM in <10% of DLAs — (those with highest metallicity/dust content)
- H_2 fractions remain low
- T~100-150K in H_2-clouds
- $n \sim 10\text{-}50\ cm^{-3}$ — pc scales (background sources not points, even in optical!)
- UV pumping

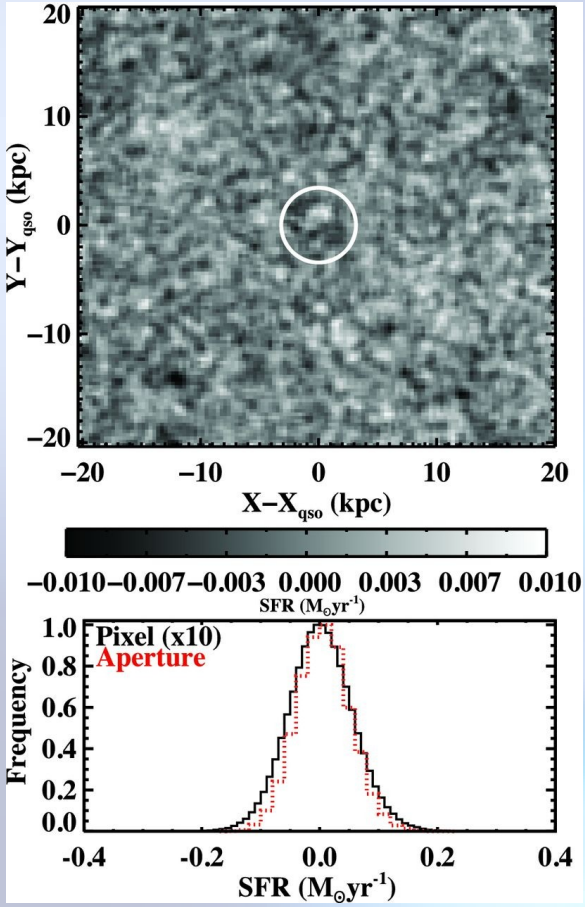
- Each species behave differently to external conditions (CI*, CII*, SiII*, OI*, HD)

Questions:

- Are we missing something (cold dense dusty gas)?
- What about HI ==> H_2?
- Star-formation?

Neutral gas (DLAs)

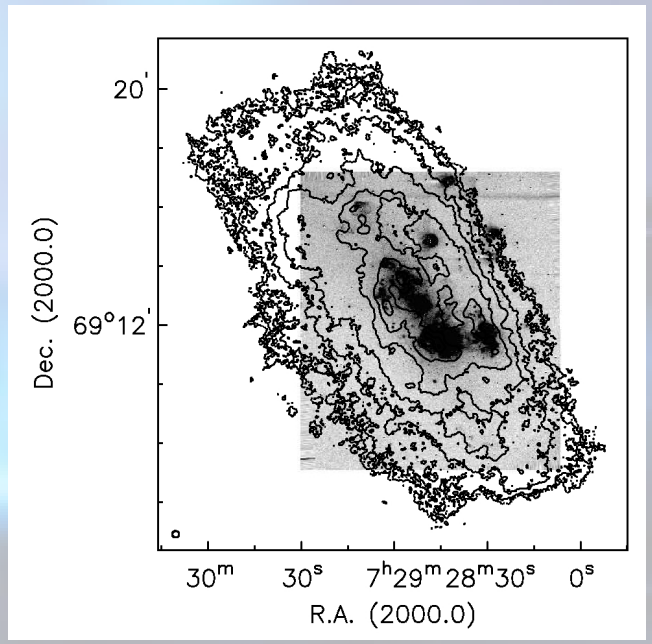
Star-formation



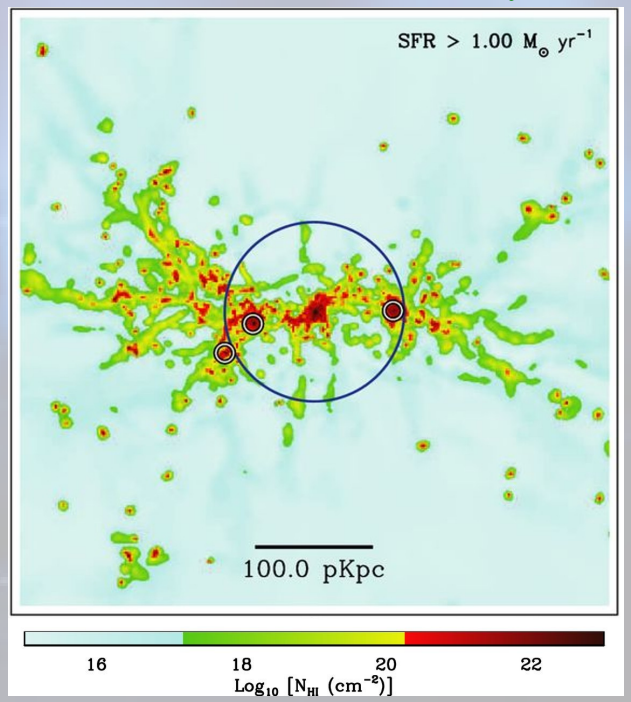
Fumagalli et al. 2015:

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

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



Rahmati & Schaye 2014



Neutral gas (DLAs)

Star-formation

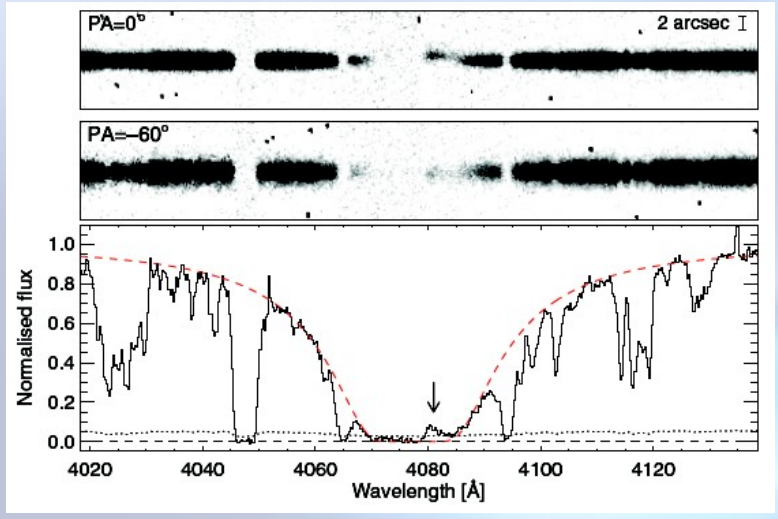
Metallicity/ Kinematics — Ledoux+06

→ Kinematics / Mass — discussed

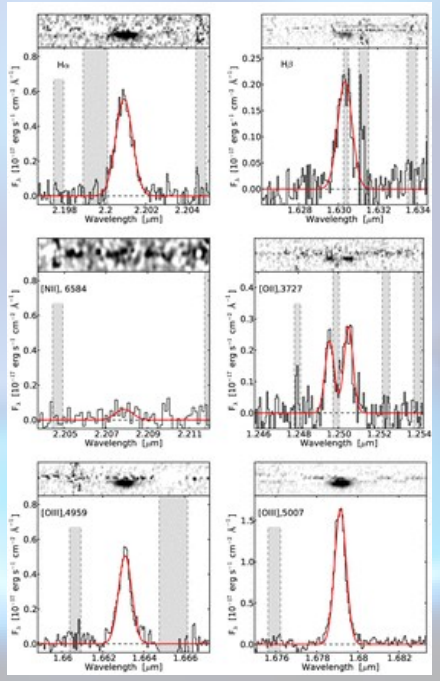
→ Mass/ Metallicity — Moller et al.

→ Metallicity/ Luminosity — Fynbo et al.

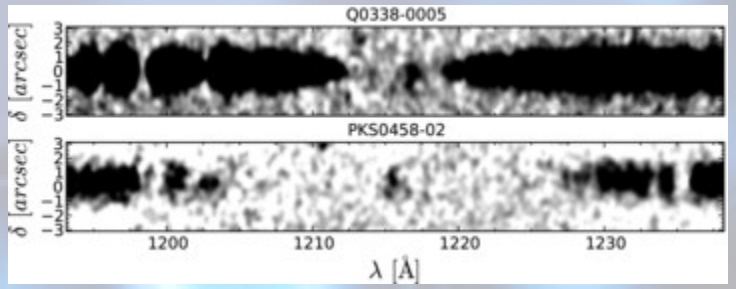
Mass/ Luminosity → Metallicity/ Luminosity



Fynbo et al. 2010,2013



Fynbo et al. 2011
Krogager et al. 2013



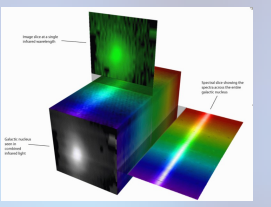
Krogager et al. 2012

(a) it works
(b) getting absorption and emission simultaneously is great! (SFR, Masses, kinematics, chemical enrichment,age, transfer, etc.)

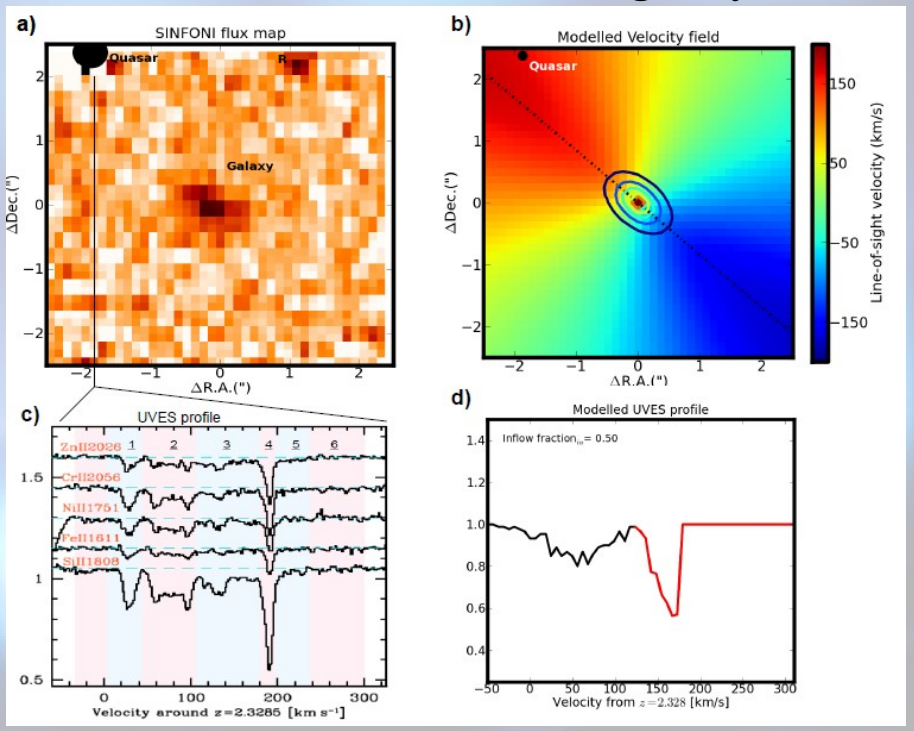
Neutral gas (DLAs)

Star-formation

SINFONI



Cool inflow onto massive galaxy

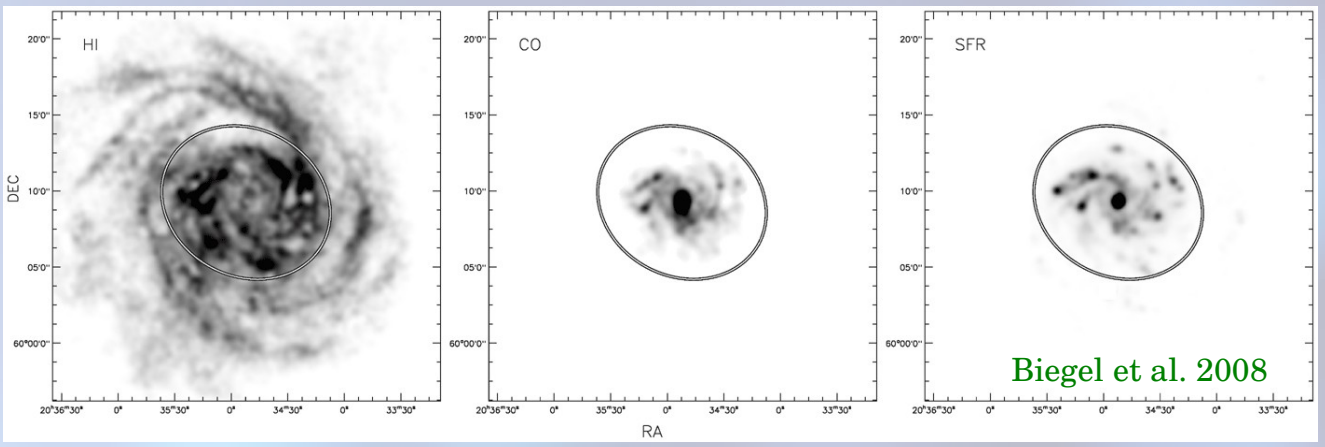


Bouché et al. 2013

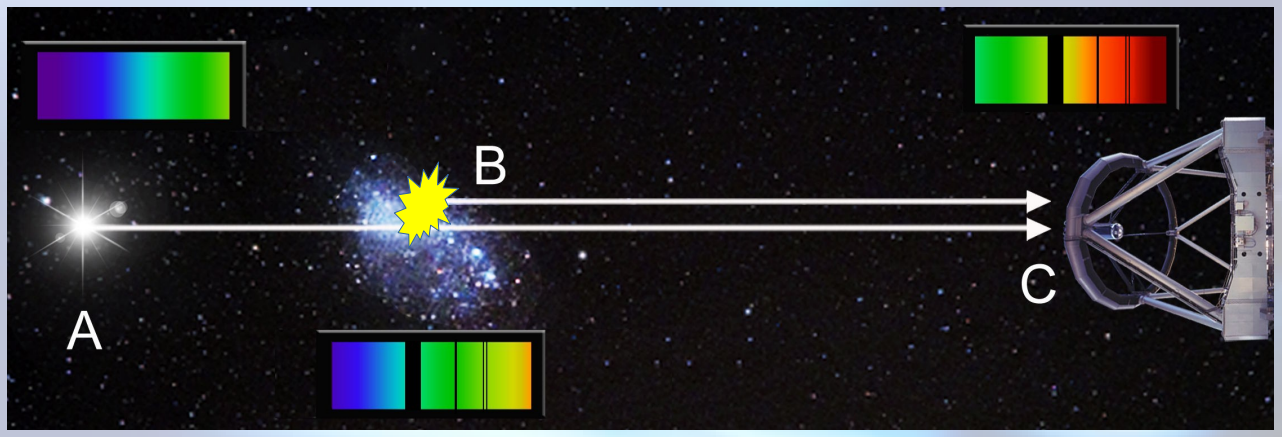
Neutral gas (DLAs)

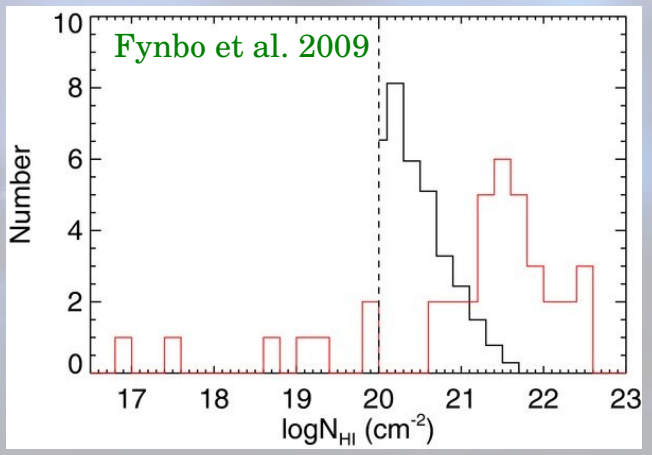
Star-formation

Get *inside* galaxies



GRBs

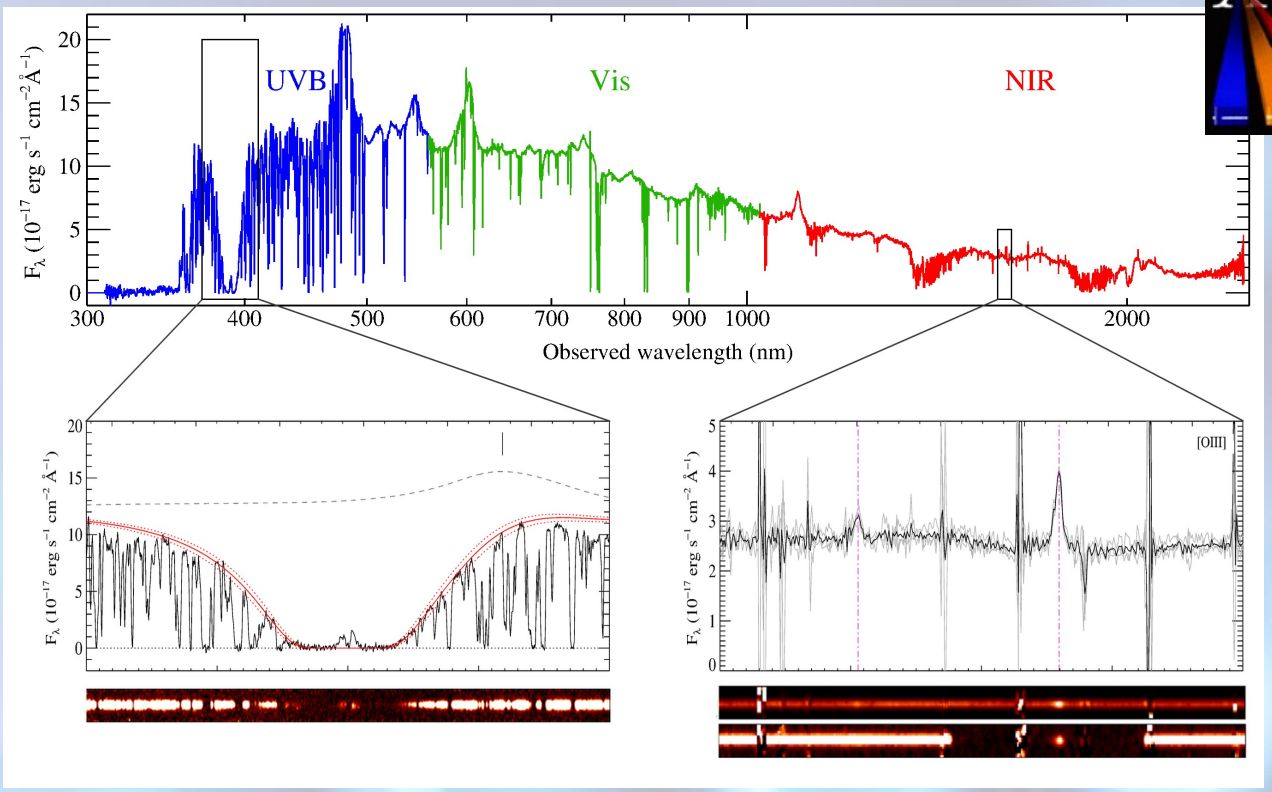




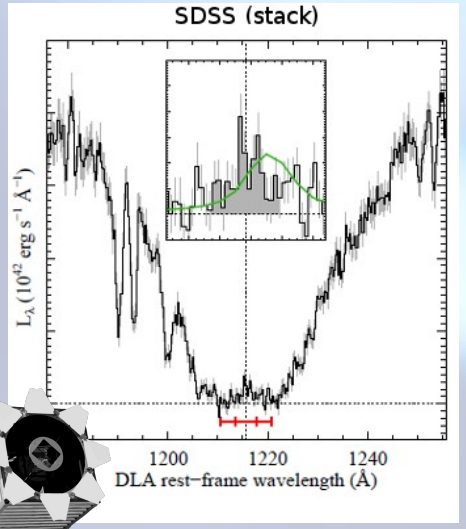
Neutral gas (DLAs)

Star-formation

Get *inside* galaxies
- S-K relation?
- HI H_2?



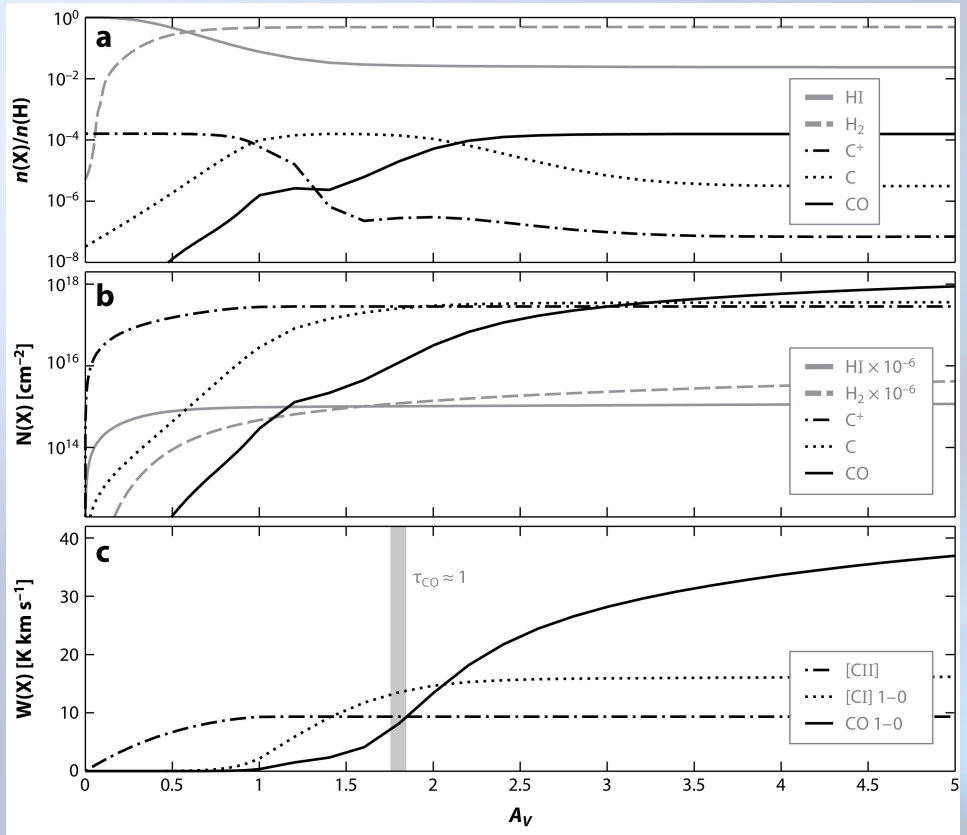
b~0.9kpc!
SFR, masses, age, gas flows, metallicity, etc.



b<2.5kpc

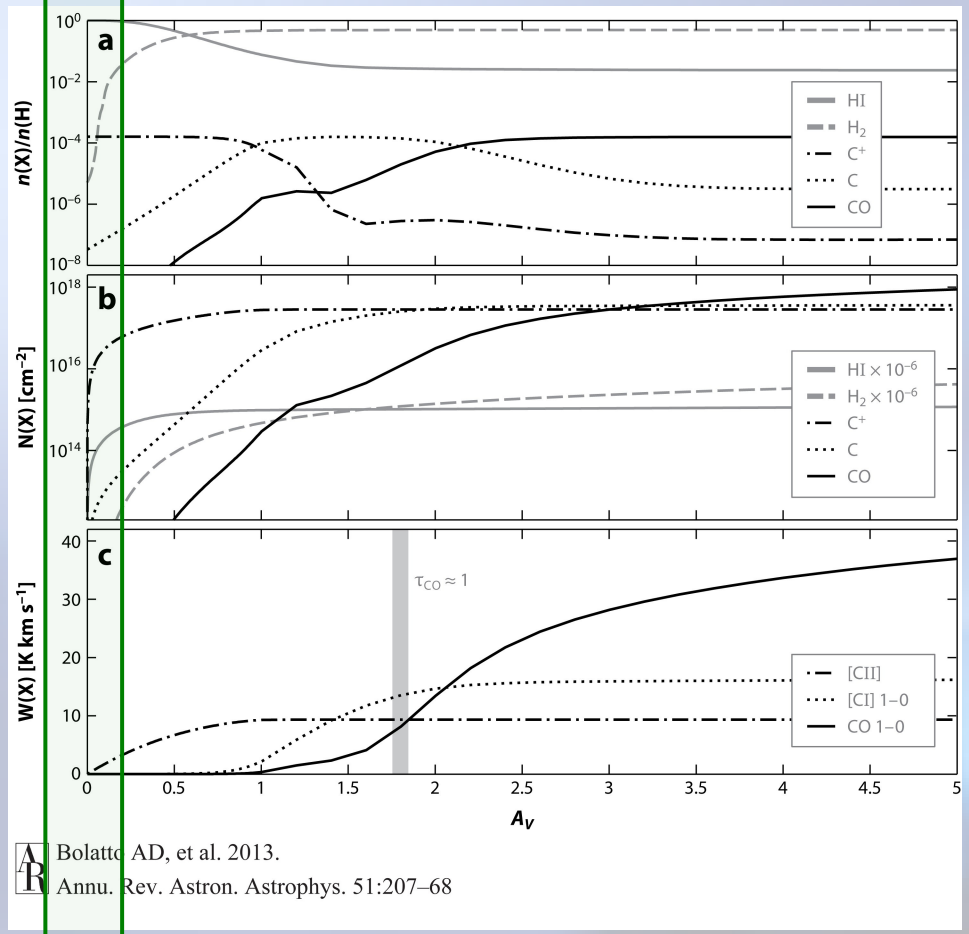
Noterdaeme et al. 2012a, 2014

Where is cold gas?



Bolatto AD, et al. 2013.
Annu. Rev. Astron. Astrophys. 51:207–68

Where is cold gas?



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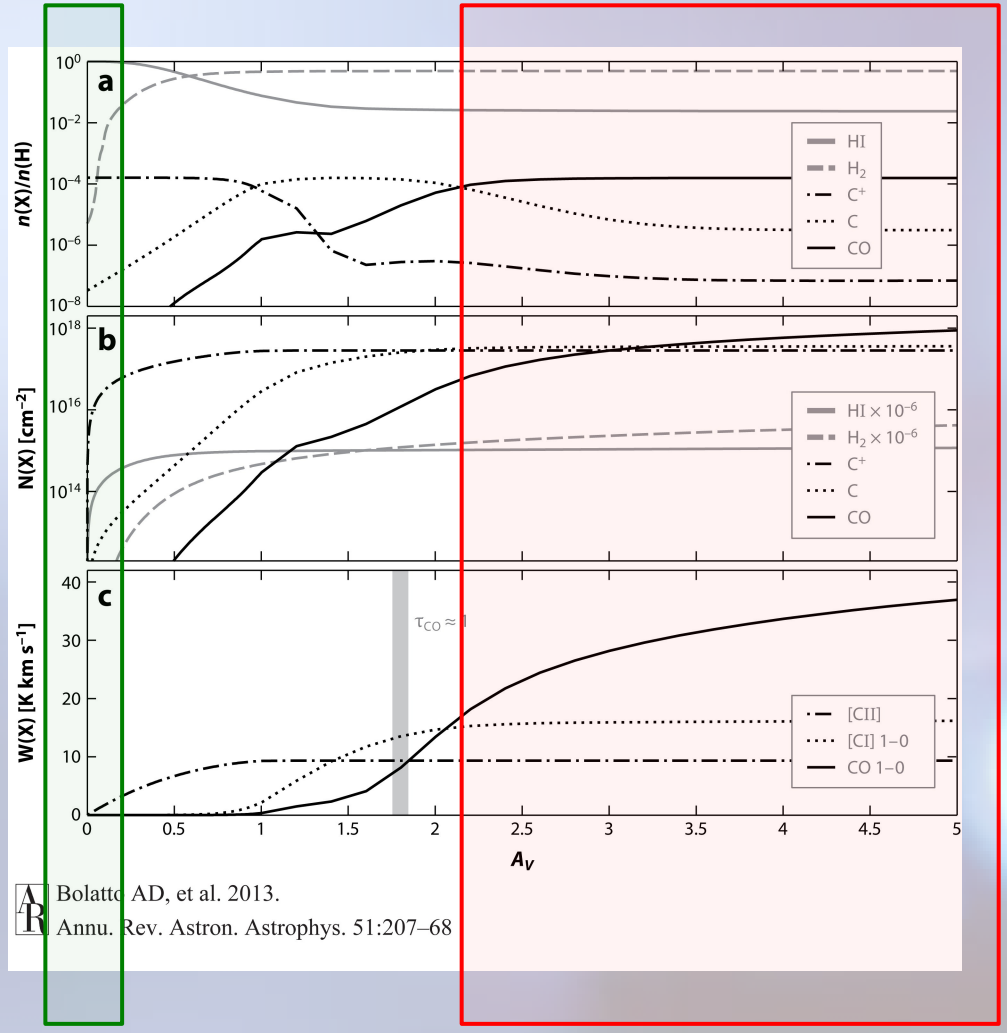
DLAs

Where is cold gas?



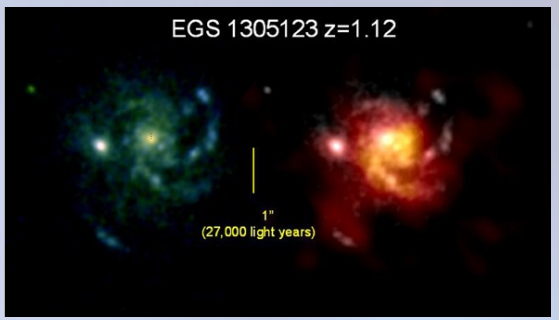
Bolatto AD, et al. 2013.
Annu. Rev. Astron. Astrophys. 51:207–68

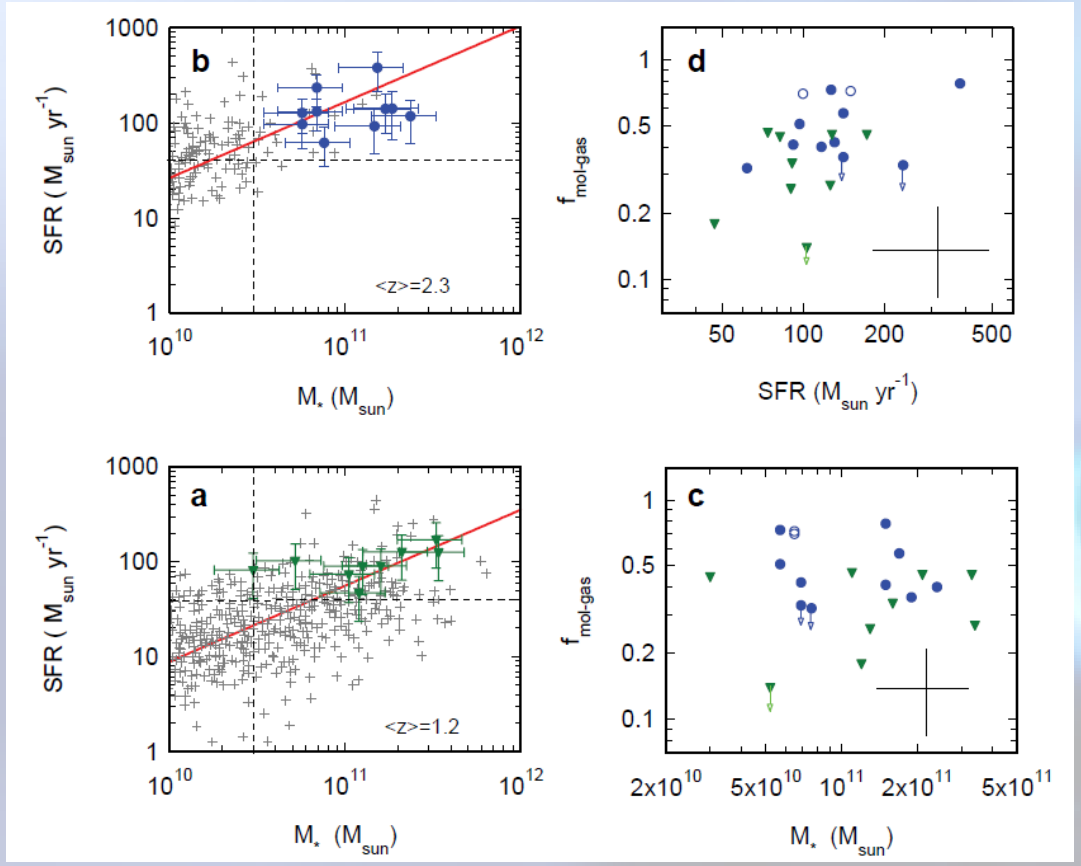
DLAs

Dense molecular gas

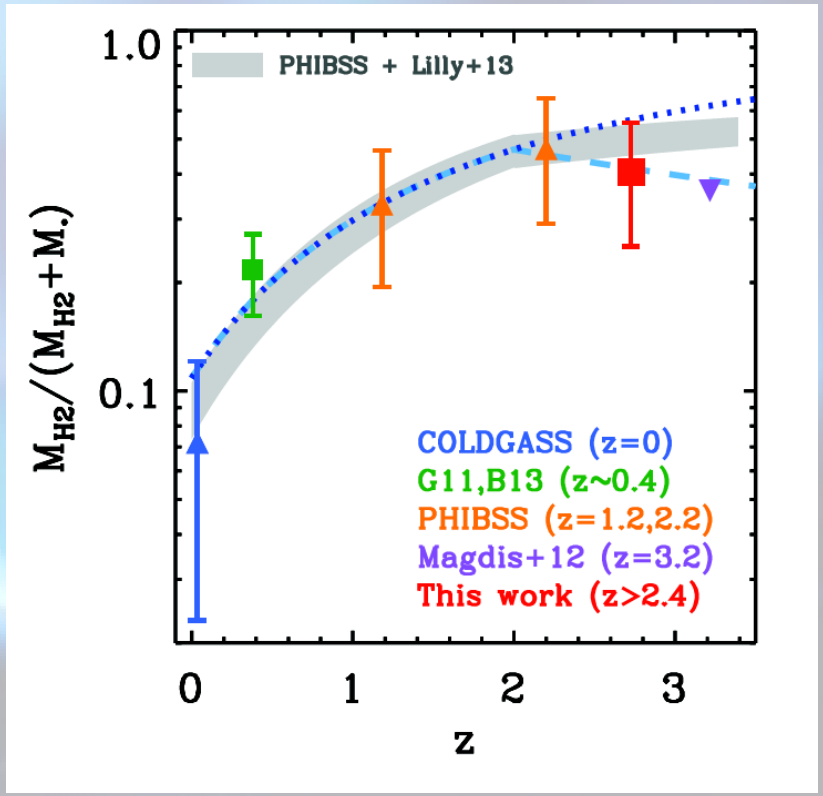
Where is cold gas?

Dense molecular gas in emission





Tacconi et al. 2010



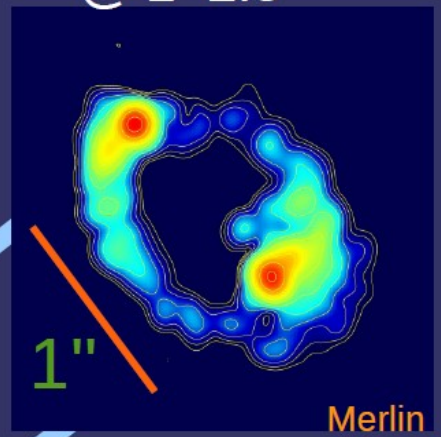
Saintonge et al. 2013

Where is cold gas?

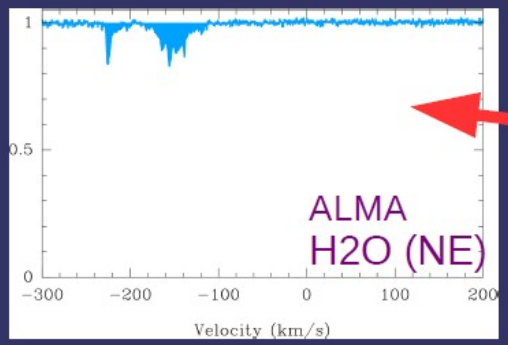
Dense molecular gas in absorption

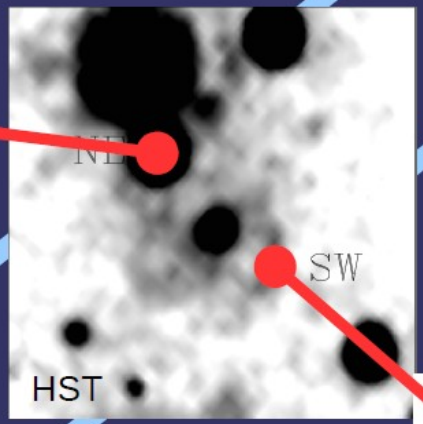
The line(s) of sight to PKS1830-211

Lensed blazar @ z=2.5

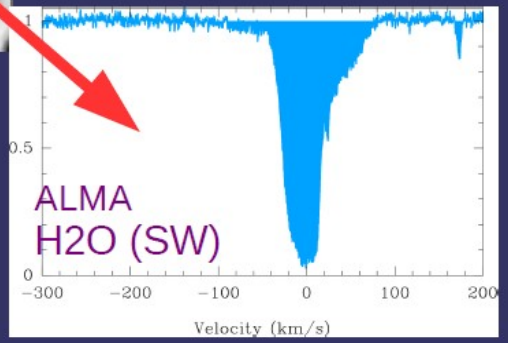


Absorber = nearly face-on spiral galaxy @ z=0.89





~pc at submm



S. Muller

Where is cold gas?

Dense molecular gas in absorption

Chemical inventory toward the SW los

1 atom	2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms
H	CH	NH_2	NH_3	CH_2NH	CH_3OH	CH_3NH_2
C	OH	H_2O	H_2CO	c-C_3H_2	CH_3CN	CH_3CCH
	CO	C_2H	l-C_3H	l-C_3H_2	NH_2CHO	CH_3CHO
	CS	HCN	HNCO	H_2CCN		
	SiO	HNC	HOCO+	H_2CCO		
	NS	N_2H+	H_2CS	C_4H		
	SO	HCO+		HC_3N		
	SO+	HCO				
	CN	HOC+				
	SH+	H_2S				
	HCl	H_2Cl+				
		HCS+				
		C_2S				
		H_2O+				

@ z=0.89 !

46 species detected
+ isotopic variants

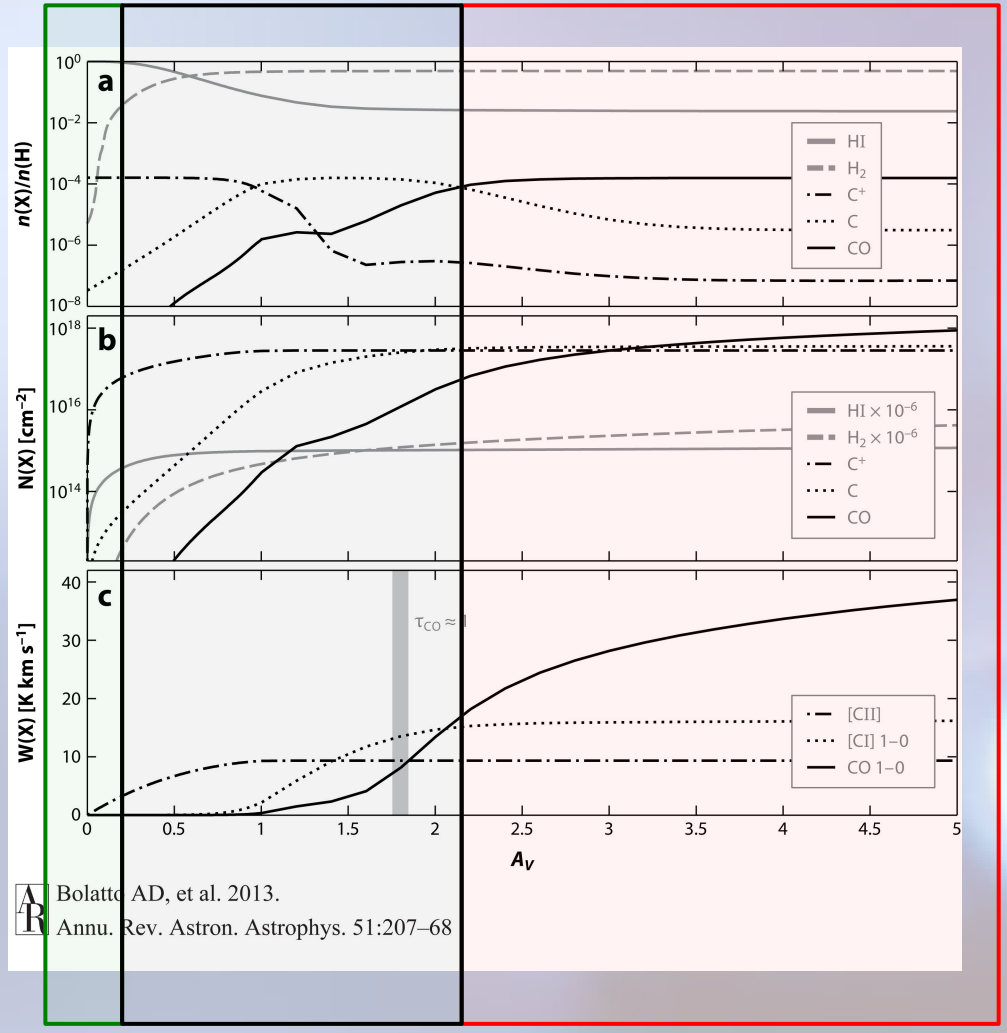
All (exc. H and OH) observed at mm/submm
Muller et al 2006, 2011, 2013, 2014
PdBI, ATCA, ALMA cycle 0
+ ALMA cycle 1 and 2

??? CH+, OH+, CF+, HF, H2F+, O_2

S. Muller

Where is cold gas?

Where is cold gas?



Bolatto AD, et al. 2013.
Annu. Rev. Astron. Astrophys. 51:207–68

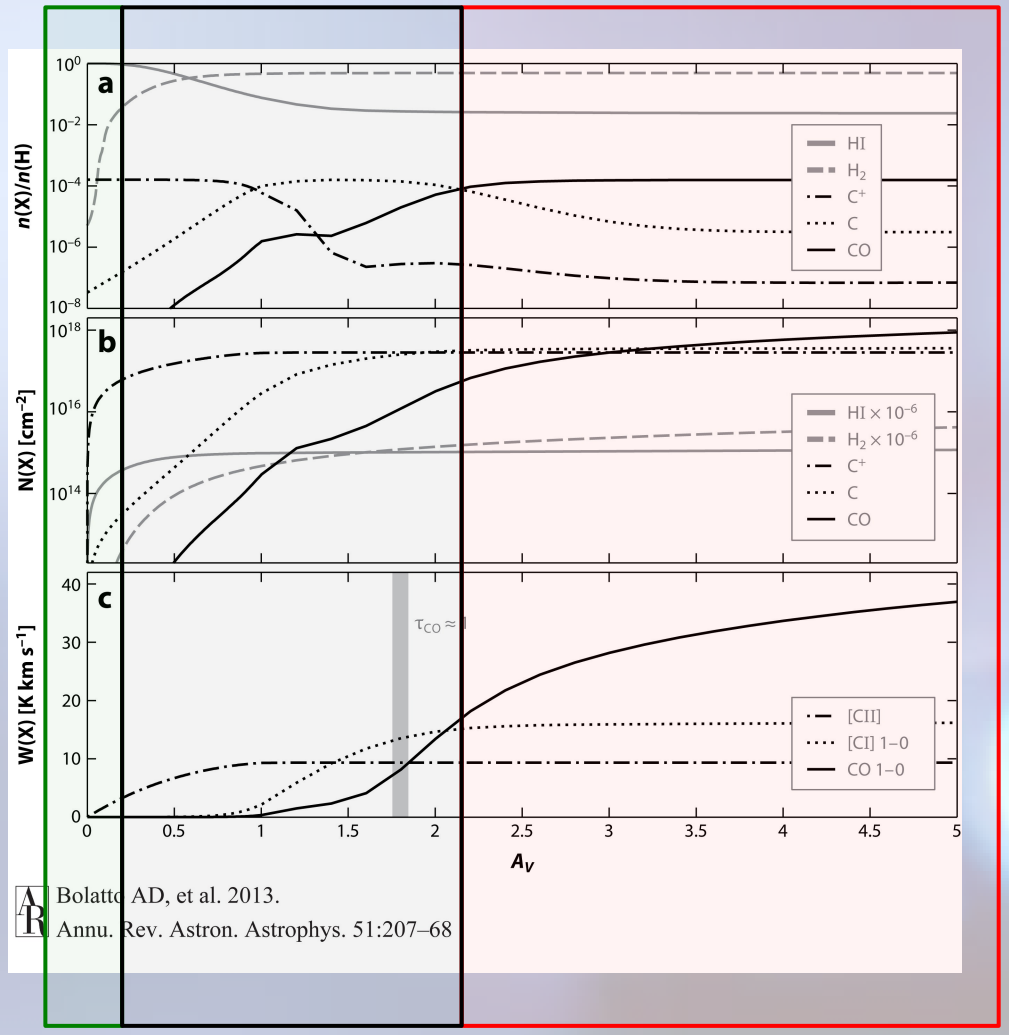
DLAs

Dense molecular gas

DARK gas

Where is cold gas?

Where is cold gas?



DLAs

Dense molecular gas

DARK gas

Why “dark” ?

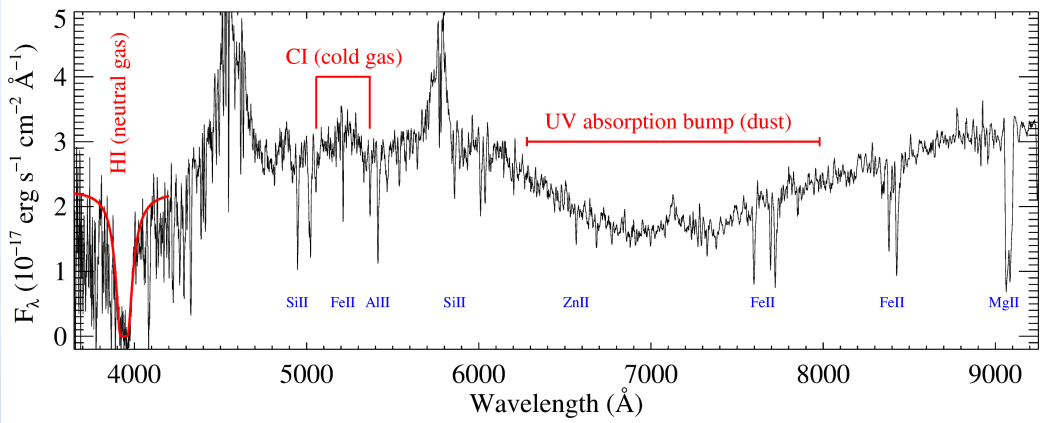
- Dark is fashionable (matter, energy)
- “No” emission line
- not seen (yet) in absorption
  - very small cross section
  - significant dust extinction

Is it important?

- Quick reply: we don't know, so...yes
- Could contain very significant fraction of total gas mass
- Only probe of cold gas in low-mass galaxies
- Sensitive to external conditions (e.g. UV flux, pressure)
- Rich chemistry

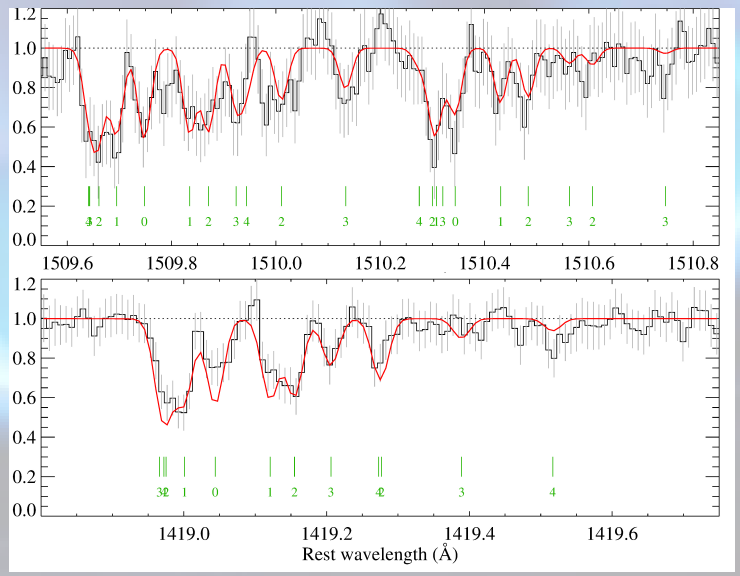
Cold gas

Can we detect it?



faint, red

CO



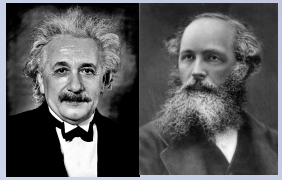
- Compensate very small cross-section by very large number of lines of sight

- Use of IR/radio QSO selection to minimize/avoid dust-biasing

Cosmology / Fundamental physics

T_{CMB}

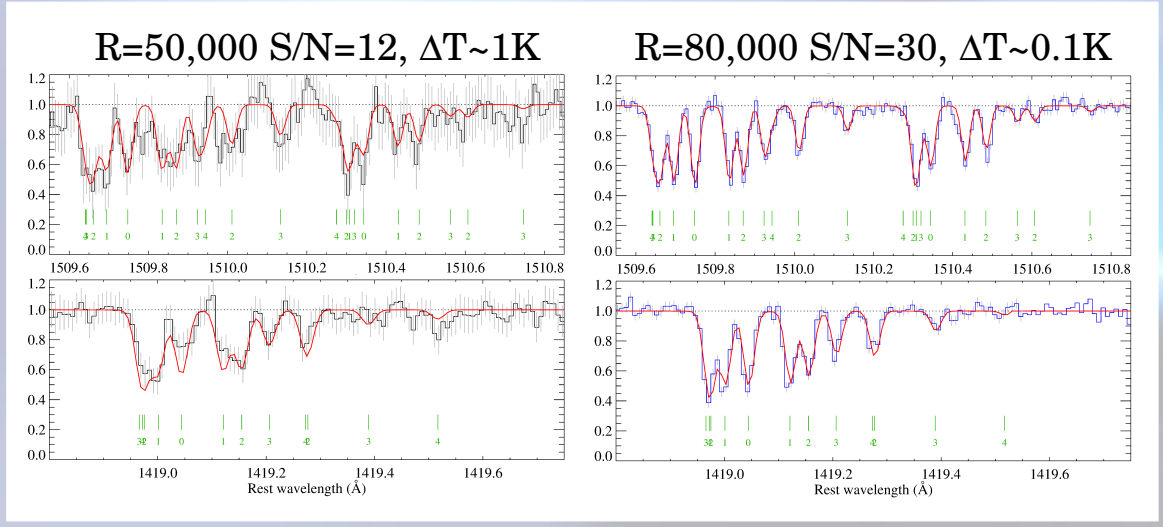
adiabatic expansion: $T_{CMB} = T^0_{CMB}\,(1+z)$

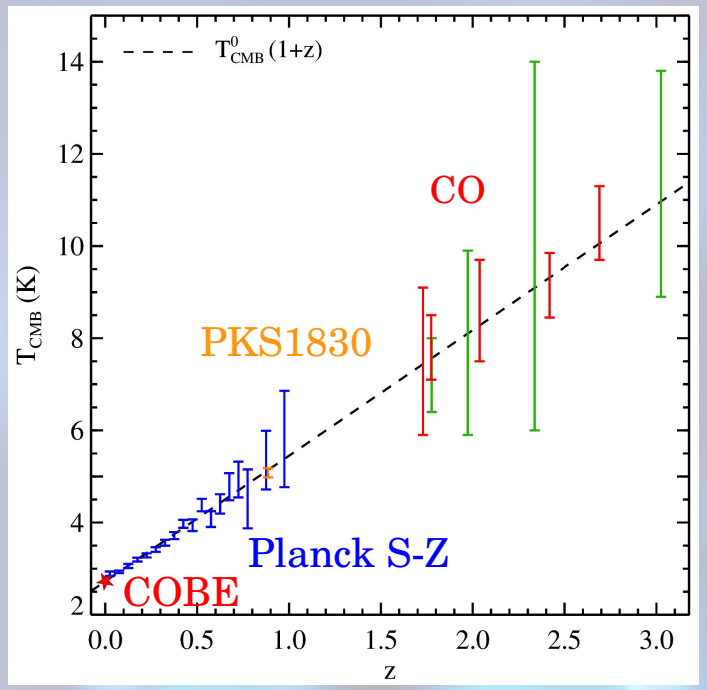


Needs to be verified by measurements:
any departure would mean
(i) violation of equivalence principle
variation of constants
(ii) the number of photons is not conserved
e.g. decaying dark energy
(iii) both

use of interstellar species

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





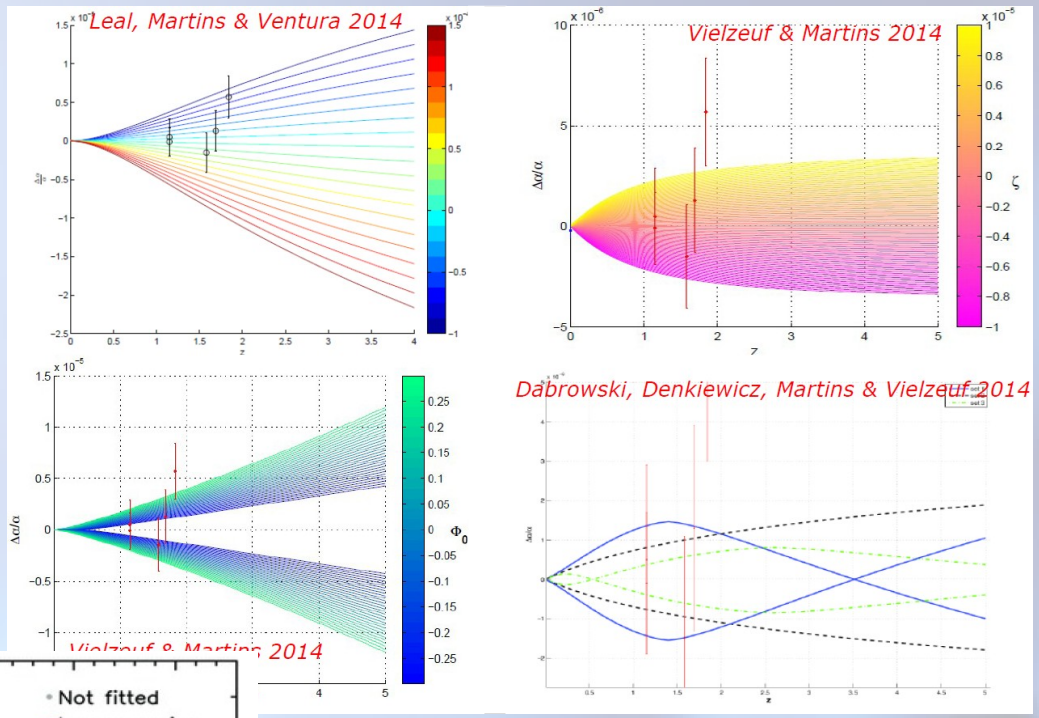
~60 CI in SDSS-II
~20 with UVES
7 CO

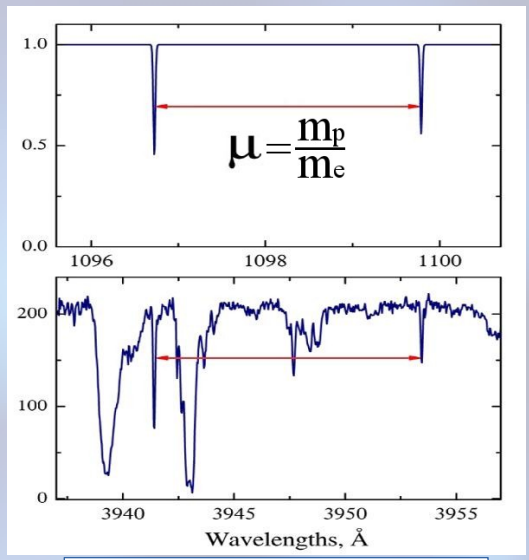
Cosmology / Fundamental physics

α, μ

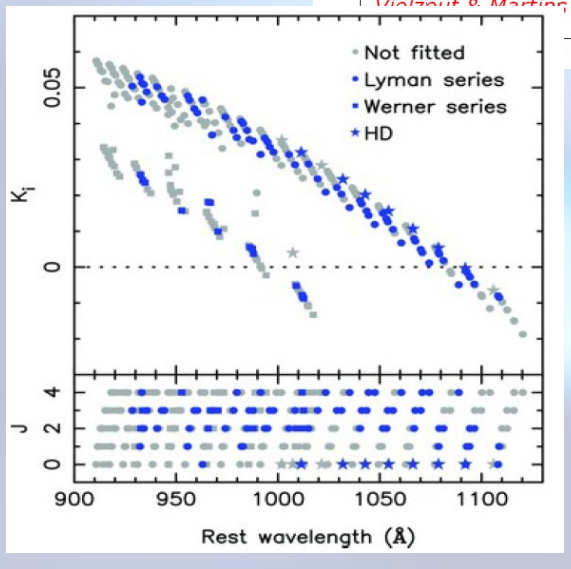
10^{-6}

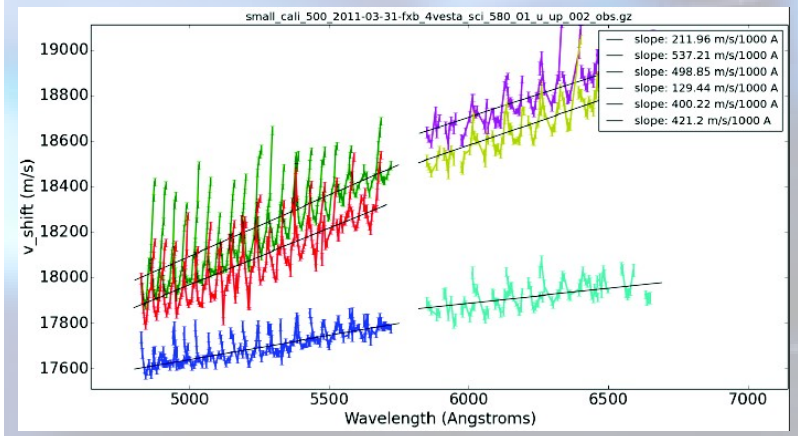
20m/s

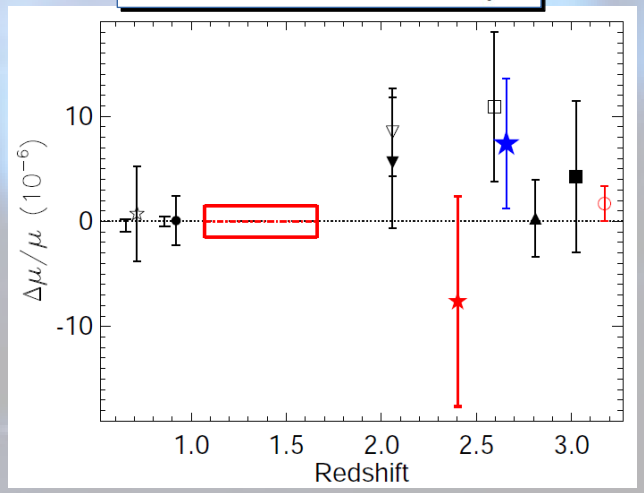




$$\lambda_i = \lambda_i^0 (1 + z_{abs}) \left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$





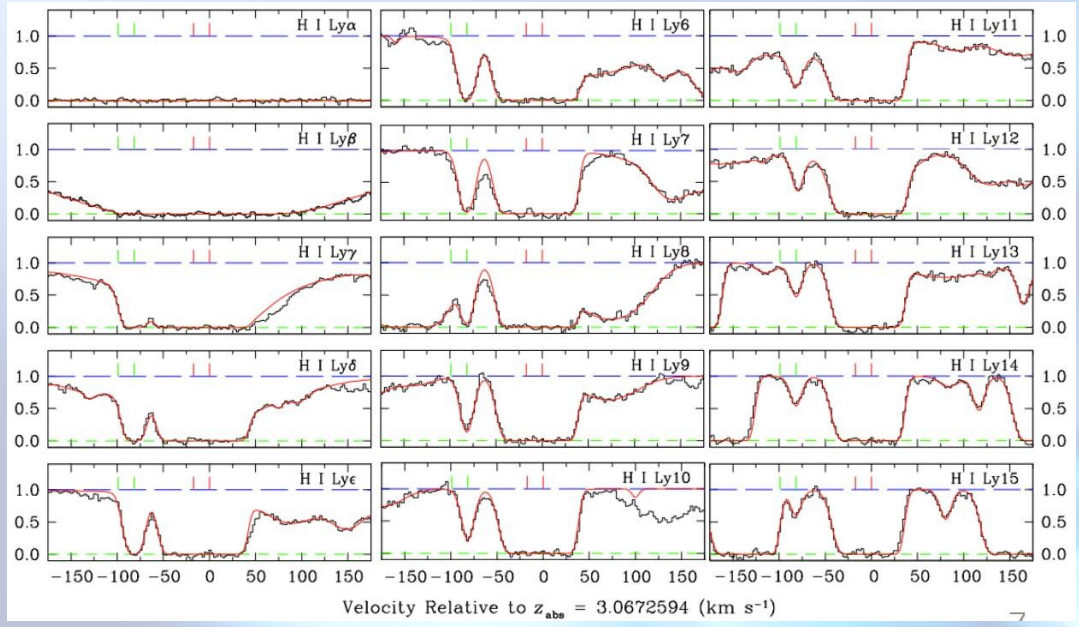


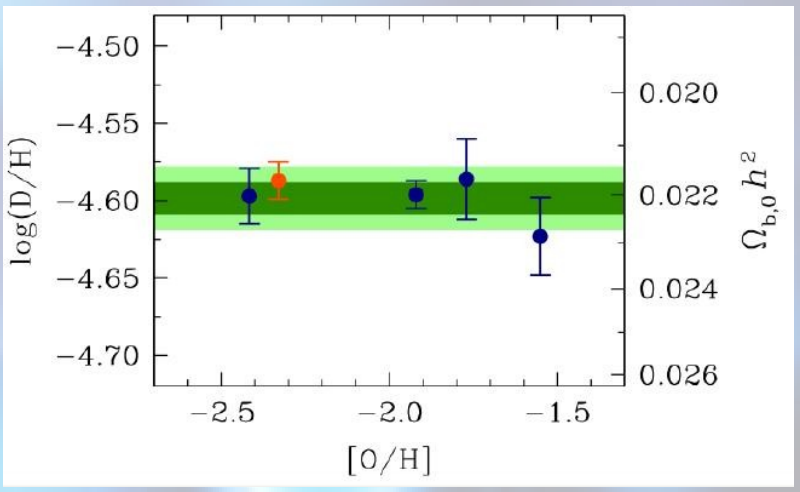
Rahmani et al. 2013

Cosmology / Fundamental physics

Ω_b

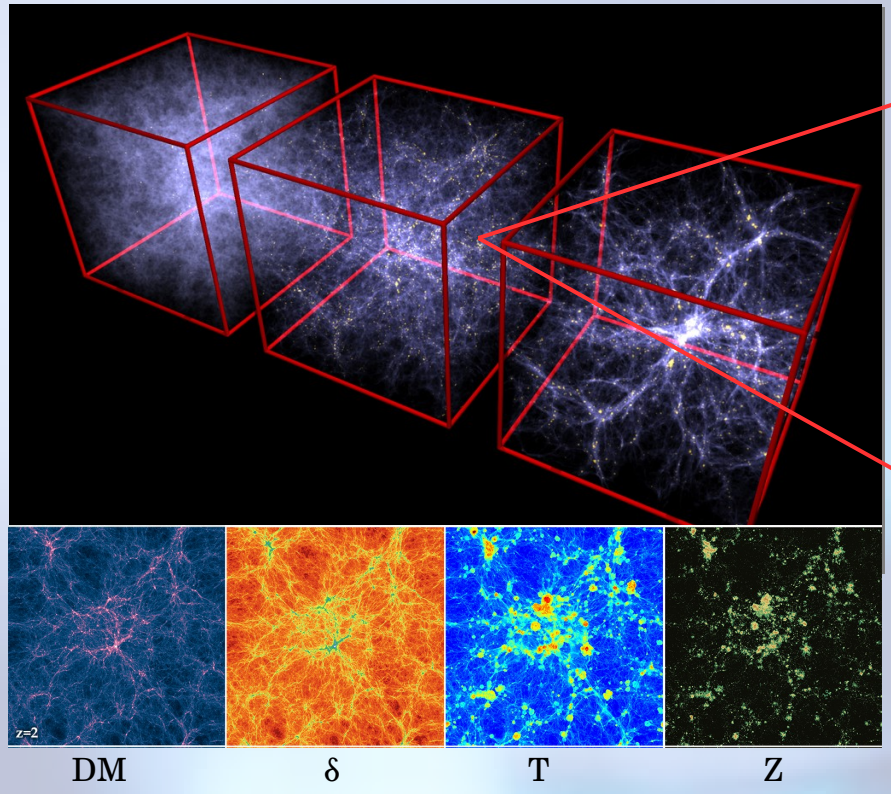
D/H ~ 10^{-5}
DI and HI very close in velocity space

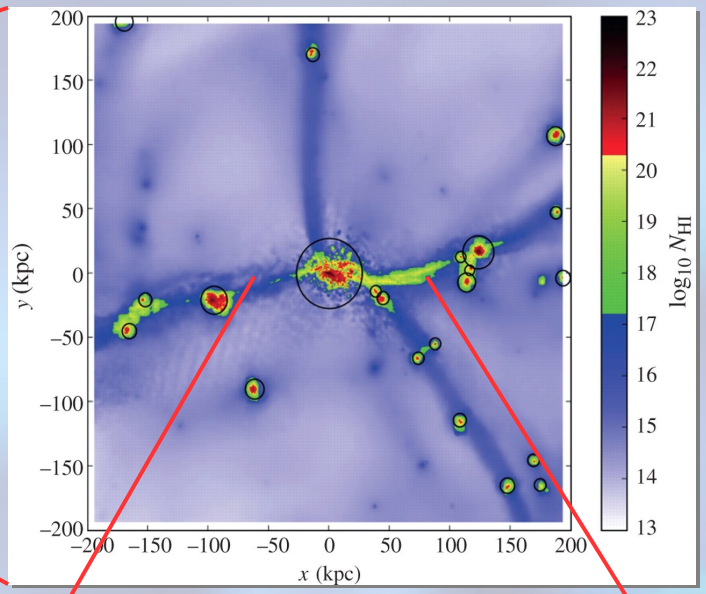


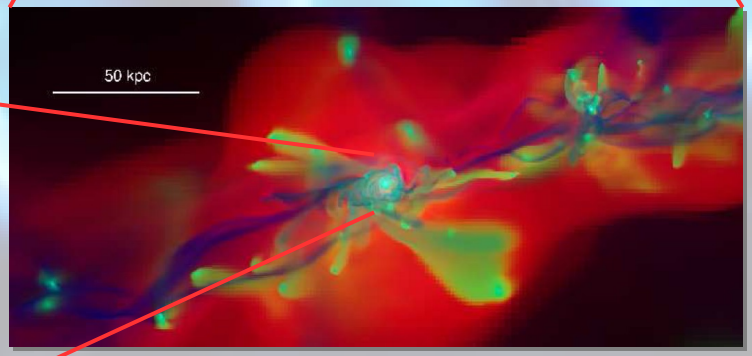


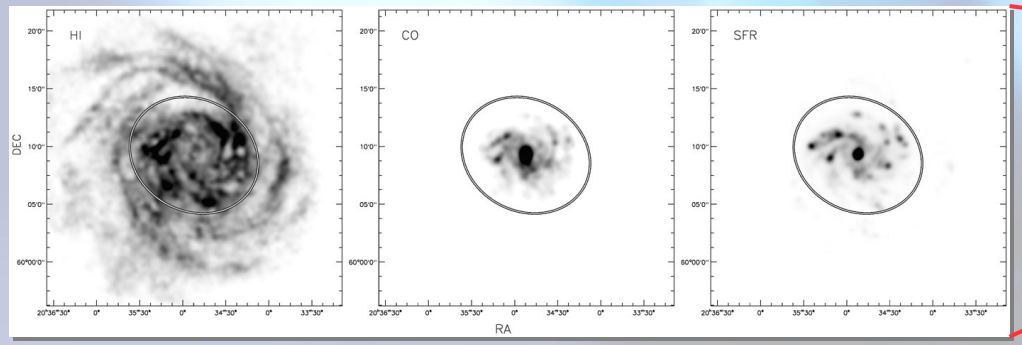
Cooke et al. 2014

Summary

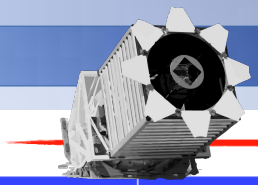






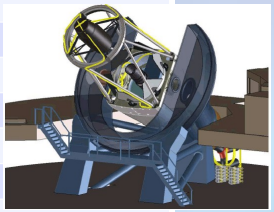


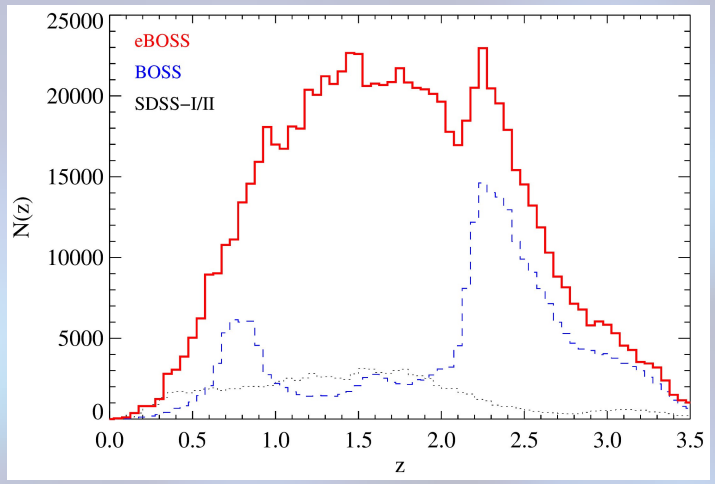
Many, many lines of sight



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





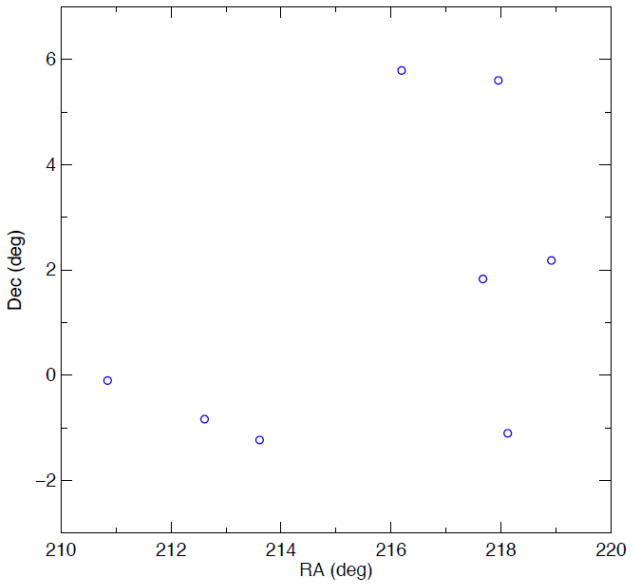
DESI: 10^6 QSOs @ z>2.2
2.5×10^6 @ 0.5<z<2.2

All science limited by small numbers:
e.g. eBOSS 200 CO
MeerKAT 600 21-cm

ELT: HIRES
MOS
IFS

blue!

8 QSOs at z>2 with $m_r < 18$



~1000 QSOs at z>2 with $m_r < 21$