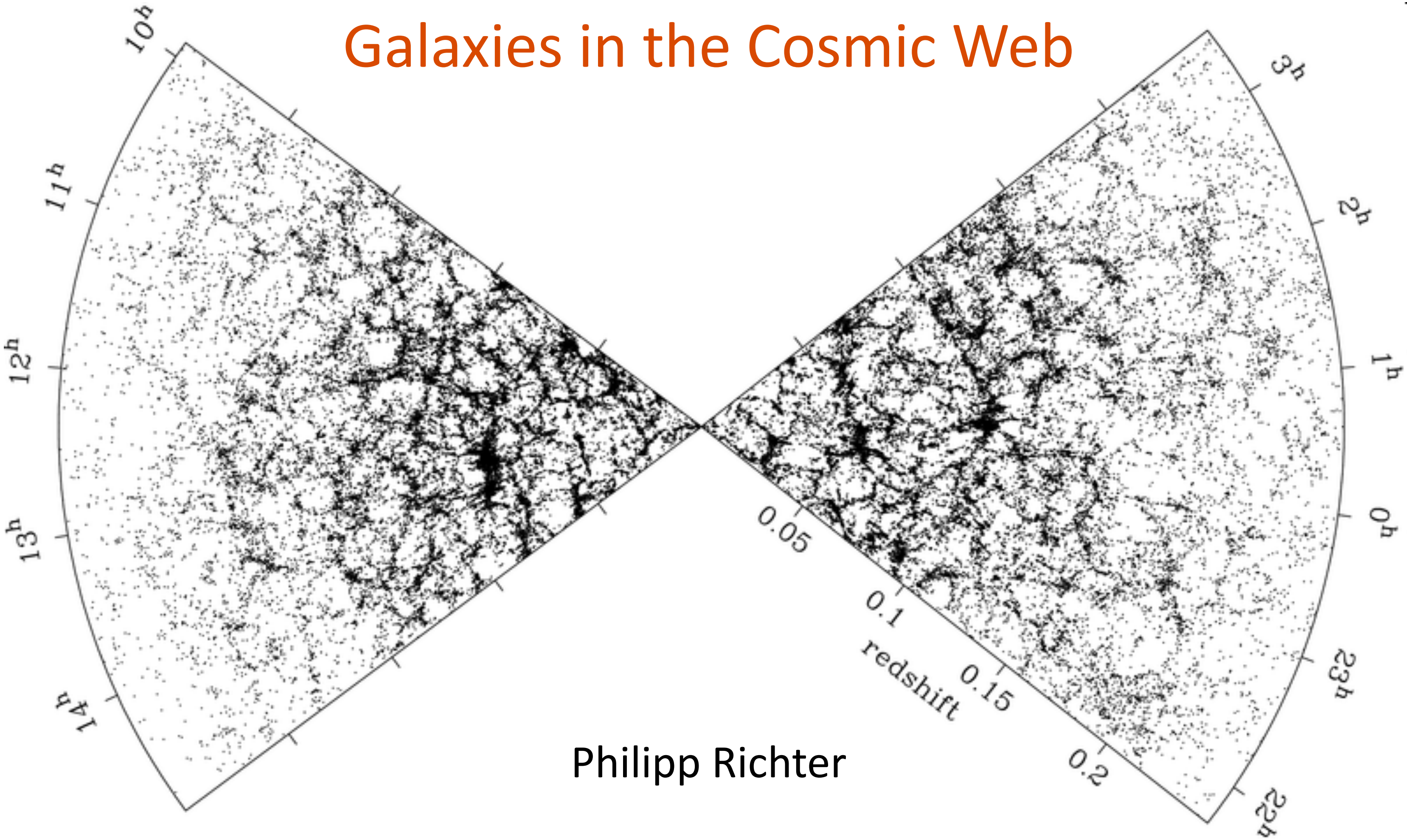
Talk DESY Zeuthen, January 2009

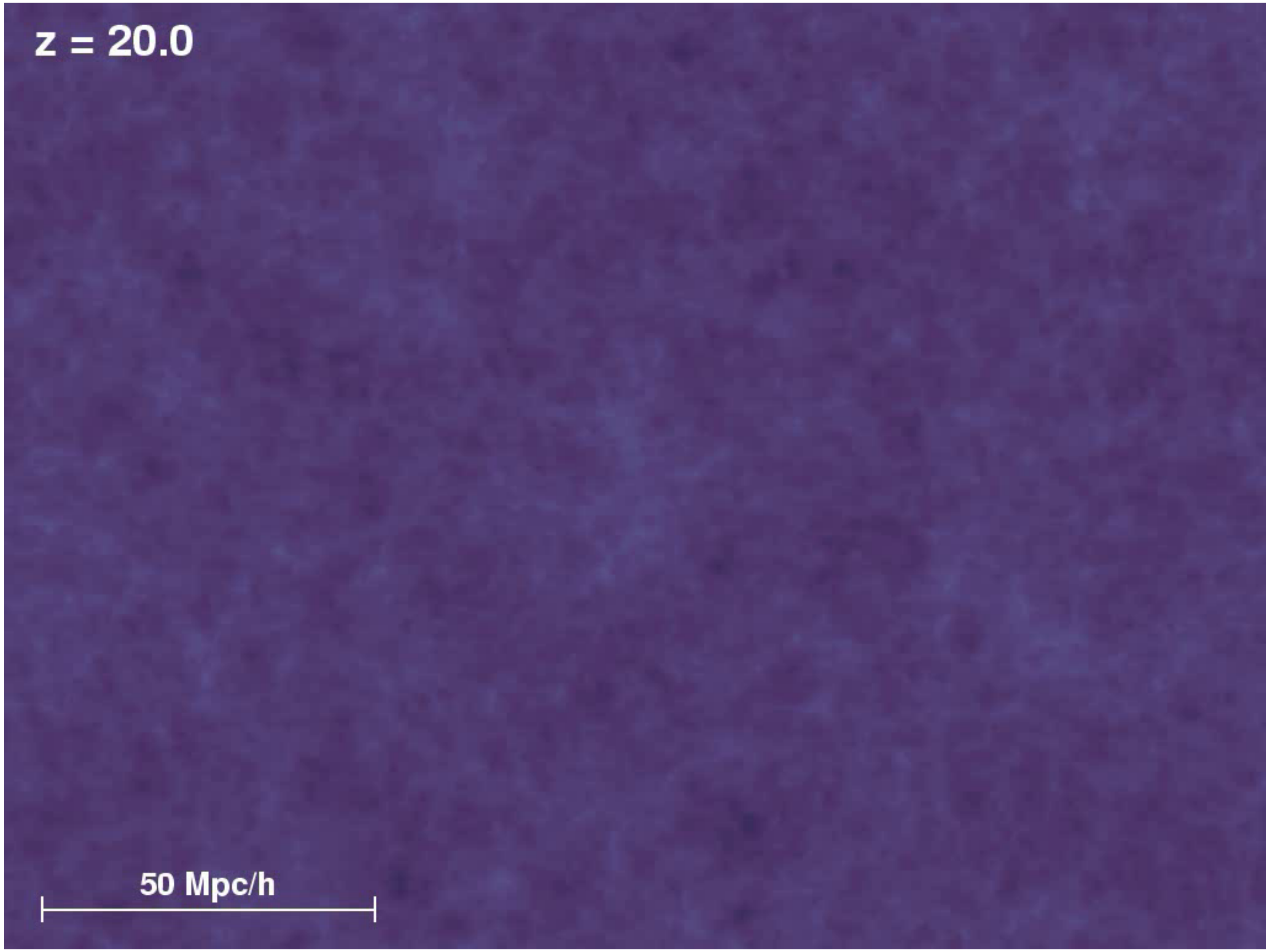
Galaxies in the Cosmic Web



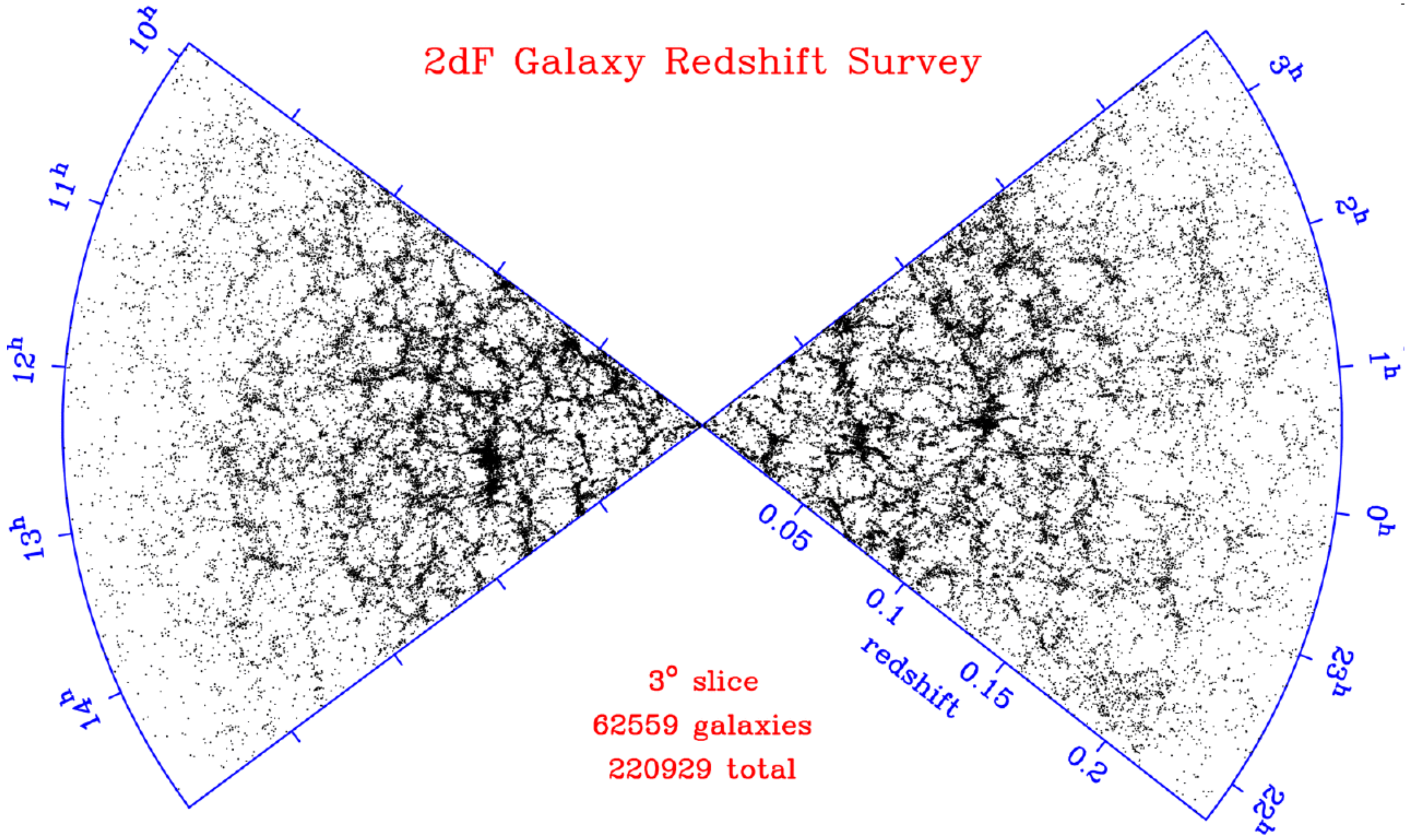
Philipp Richter

Institut für Physik und Astronomie, Universität Potsdam

Structure evolution at large scales

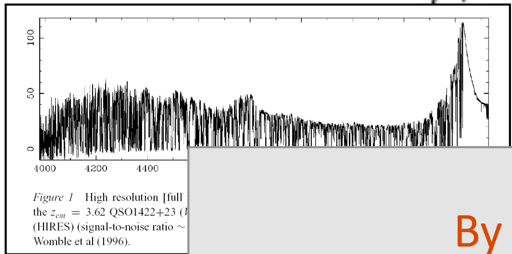


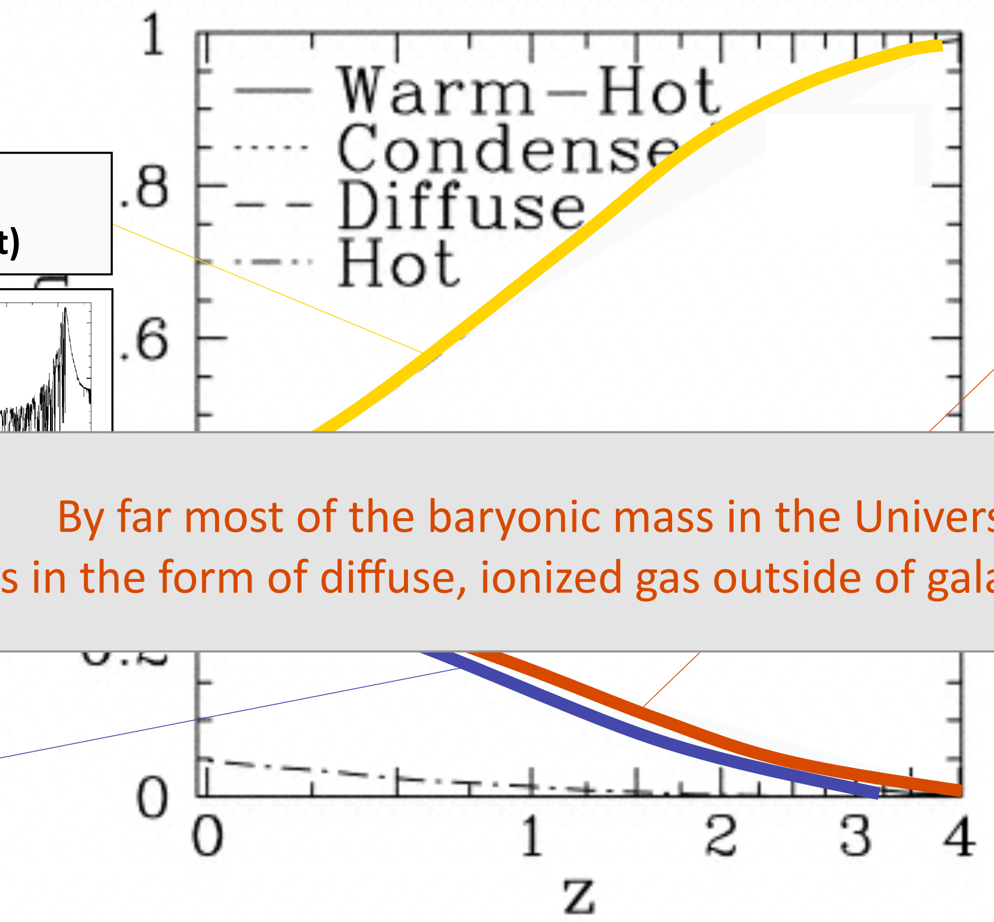
Distribution of galaxies in the Universe



Distribution of baryonic matter in the Universe

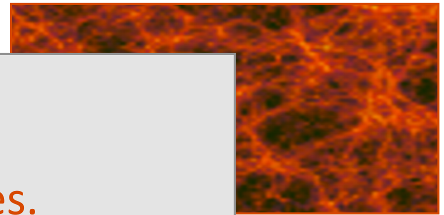
Diffuse ionized inter-galactic gas (Lya forest)





(Dave et al. 2001)

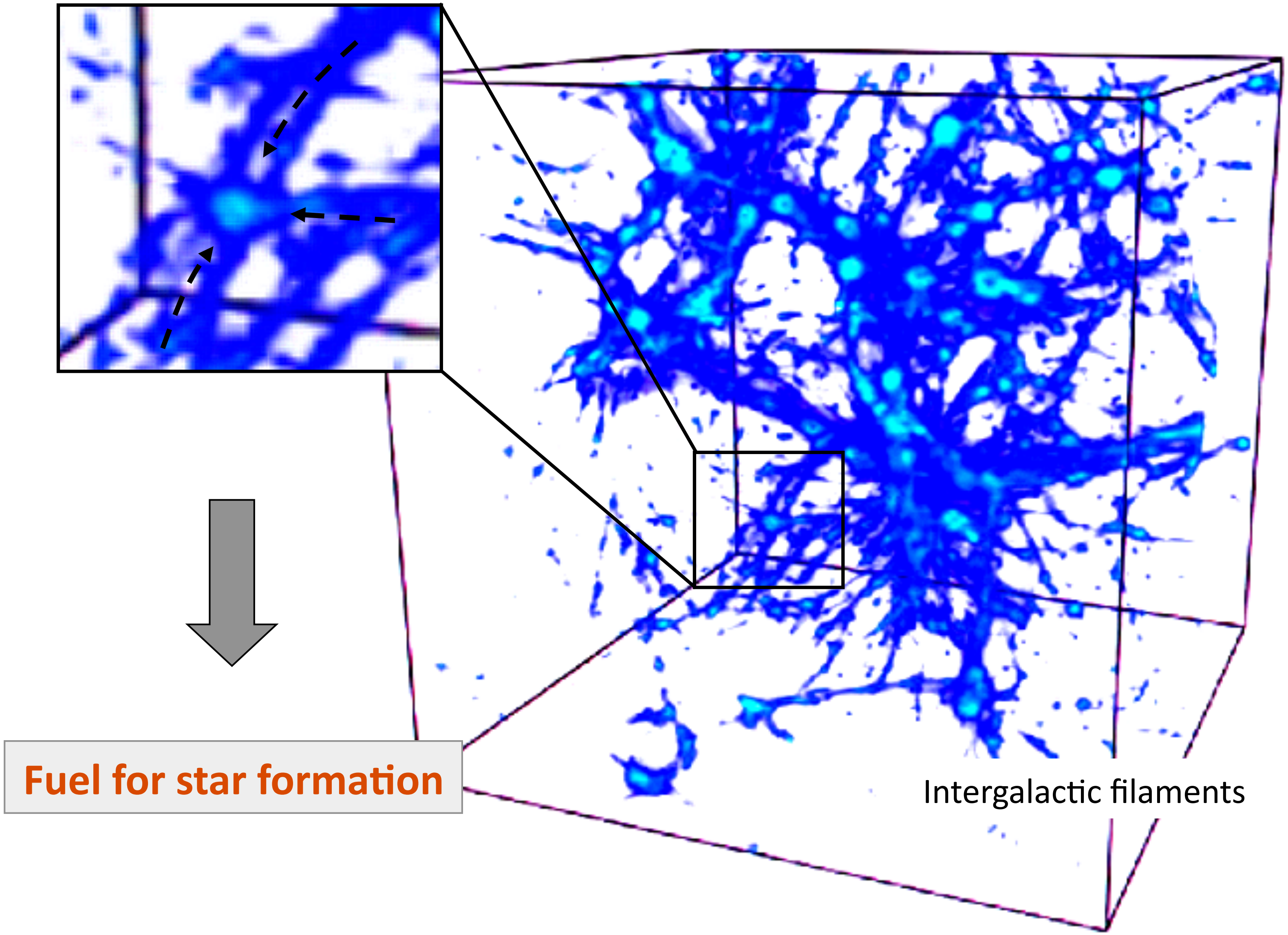
Warm-hot inter-galactic gas (WHIM)



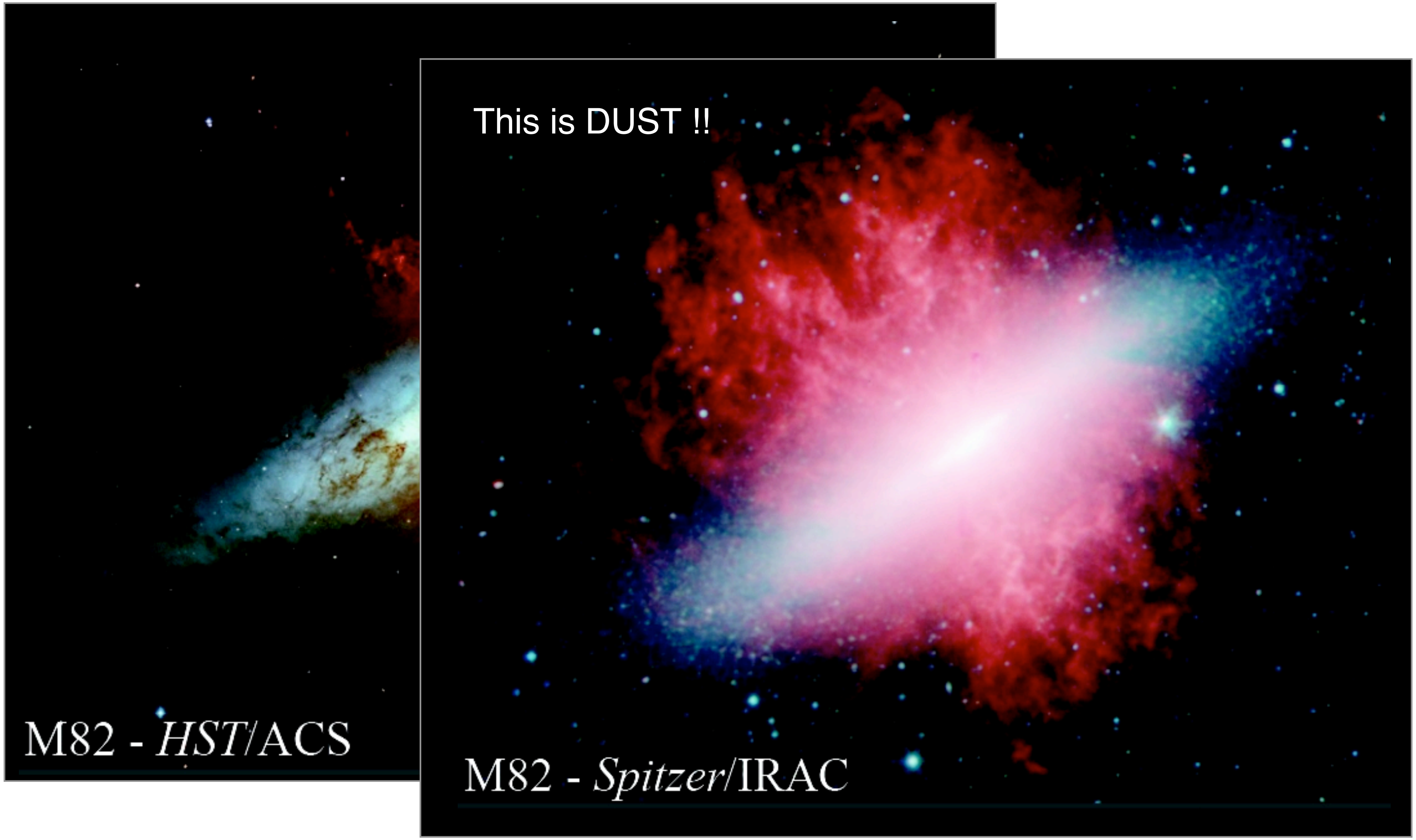
By far most of the baryonic mass in the Universe
is in the form of diffuse, ionized gas outside of galaxies.

Stars and gas in galaxies

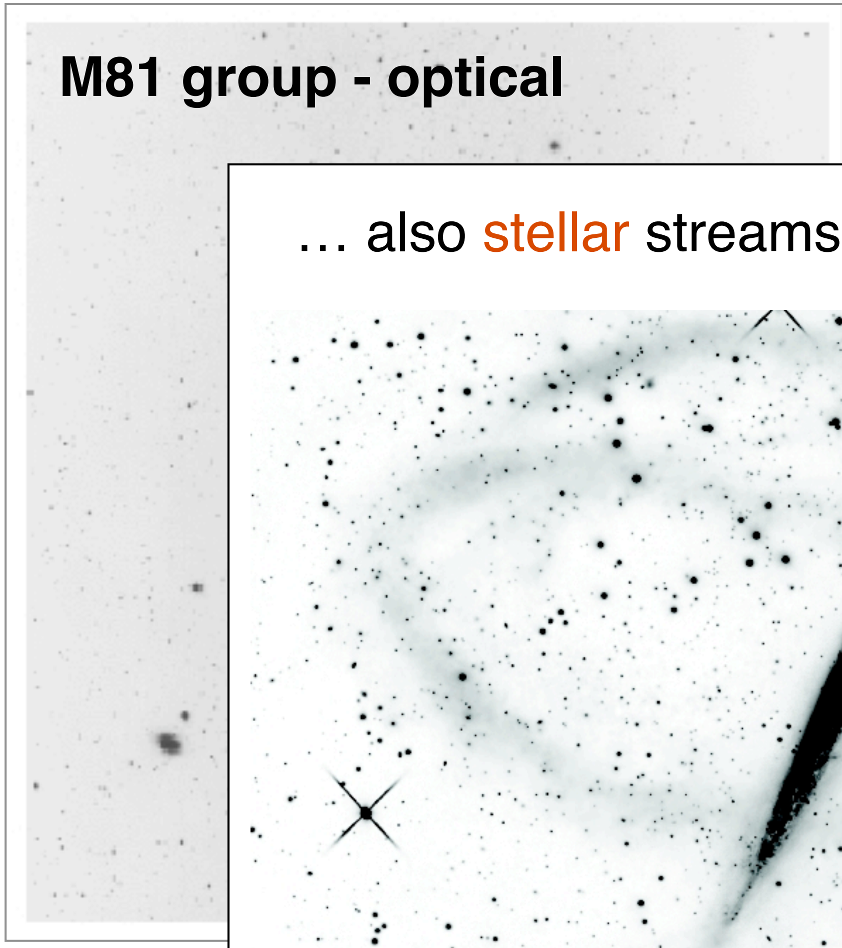
Circumgalactic gas – gas accretion from the intergalactic medium

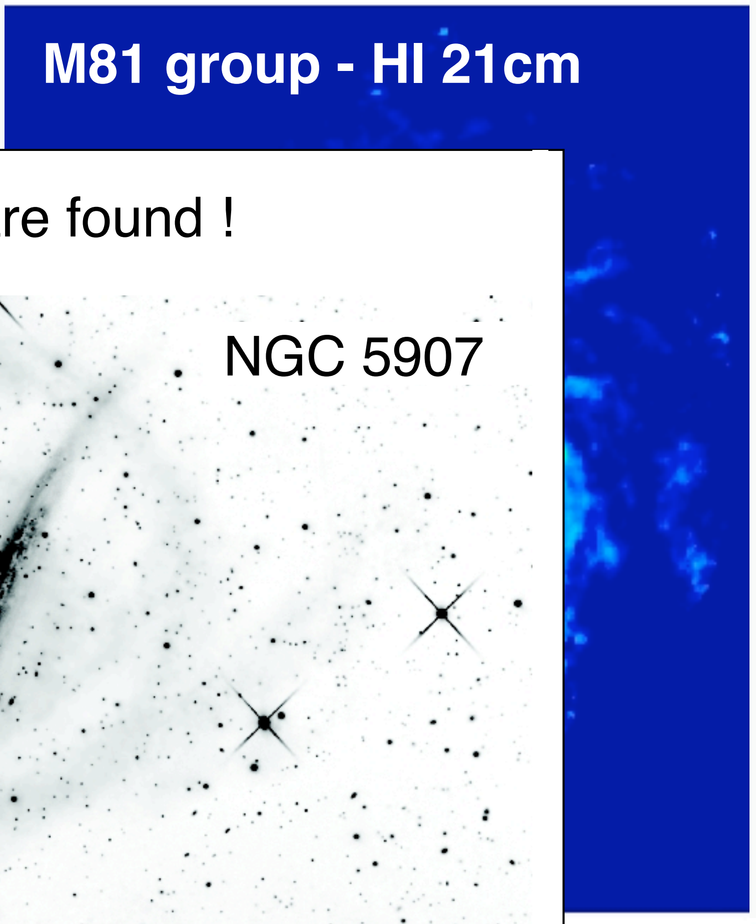


Circumgalactic gas – outflows and galactic winds



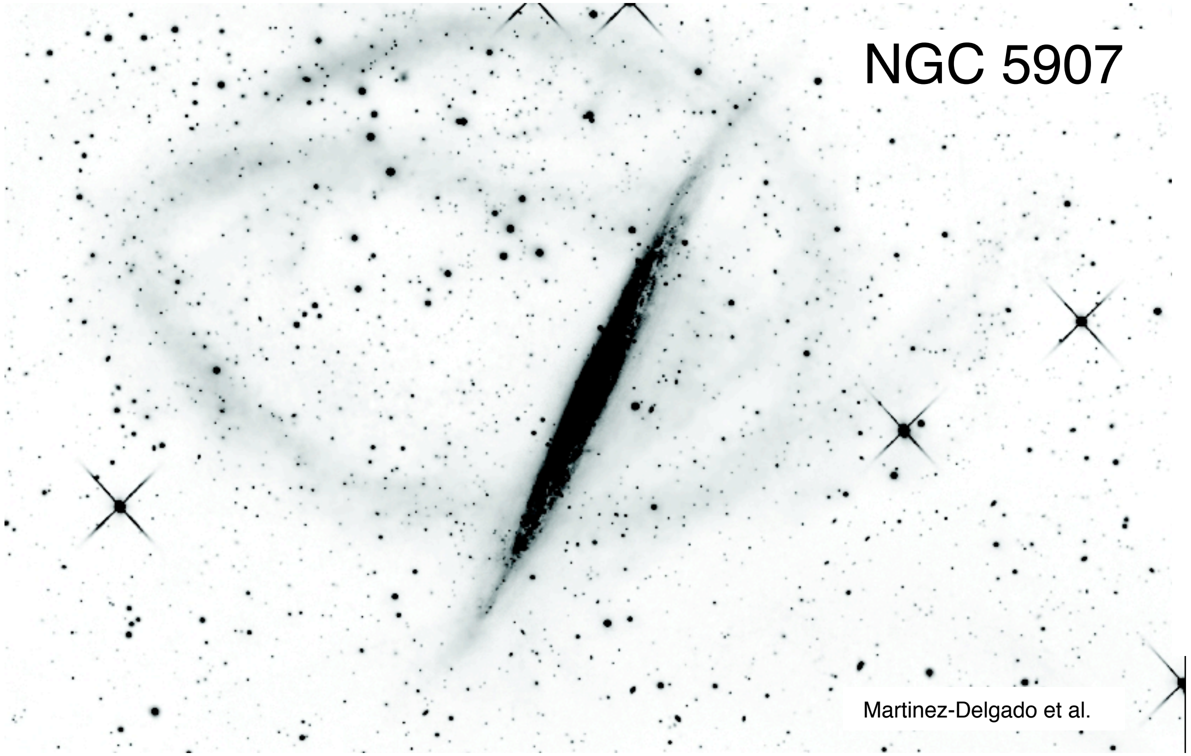
Circumgalactic gas – galaxy interactions





(M. Yun)

… also stellar streams are found !



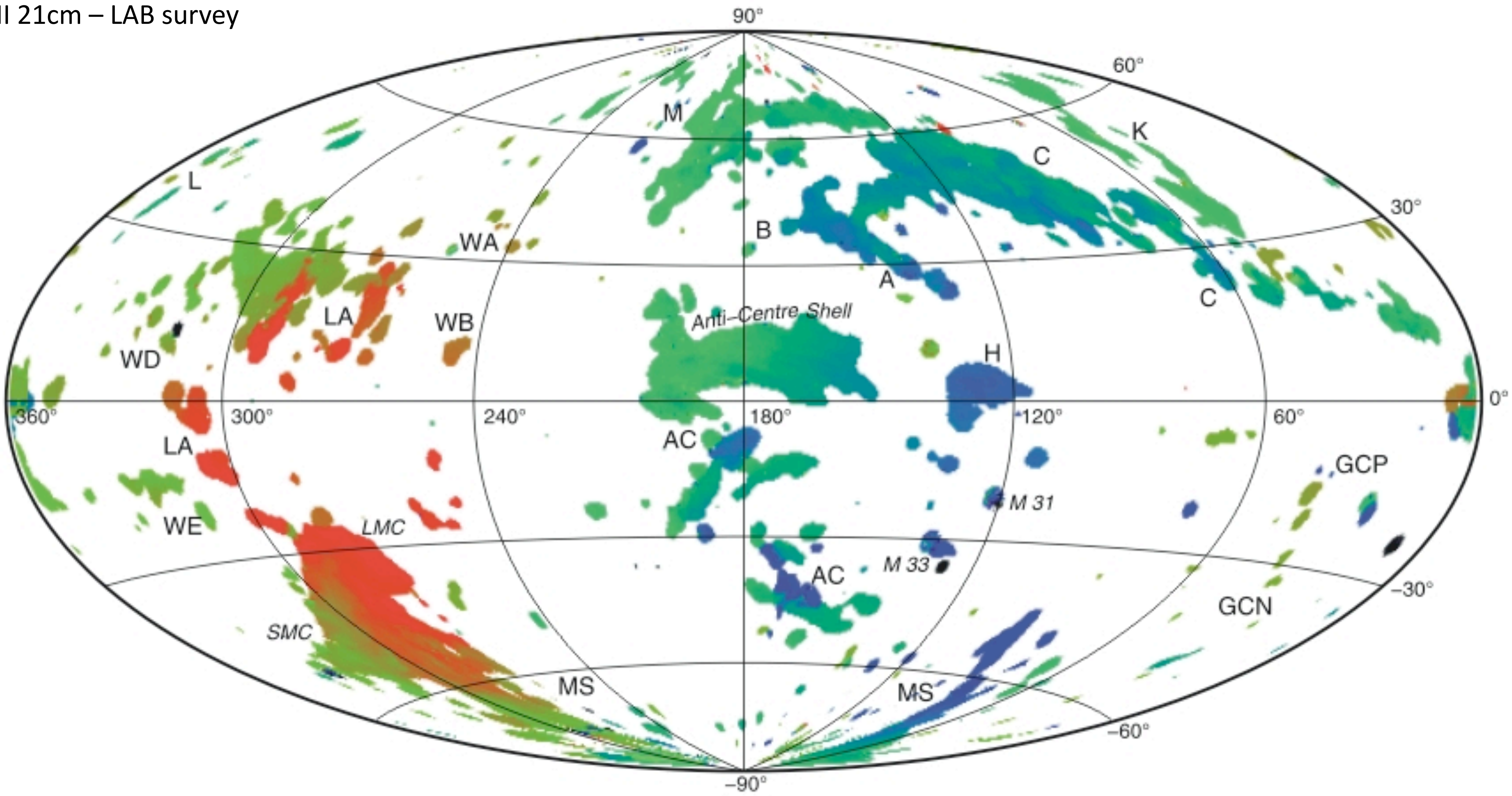
Motivation

Studies of the gaseous intergalactic environment of galaxies provide crucial information about

- the internal evolution of galaxies
- the hierarchical formation of galaxies
- structure evolution in the Universe
- distribution of (baryonic) matter
- physical processes in the intergalactic medium
- cosmological parameters

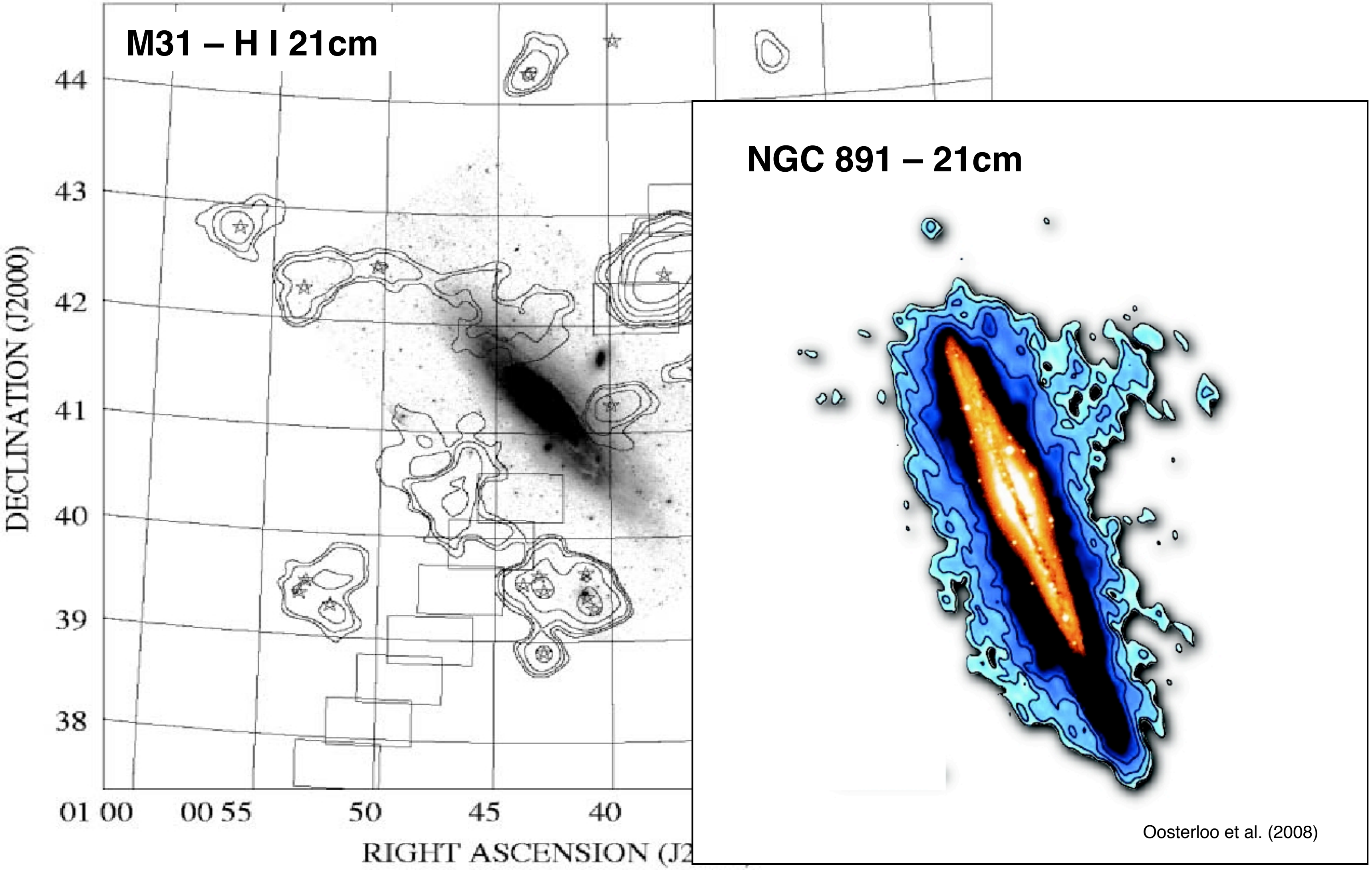
Galactic high-velocity clouds (HVCs)

HI 21cm – LAB survey

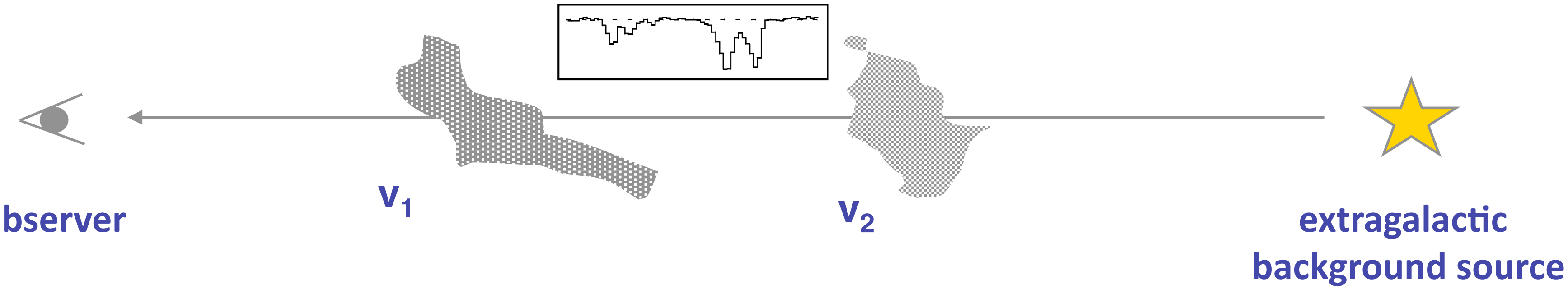


The Milky Way is surrounded by large amounts of neutral gas.

HVC analogs in other galaxies

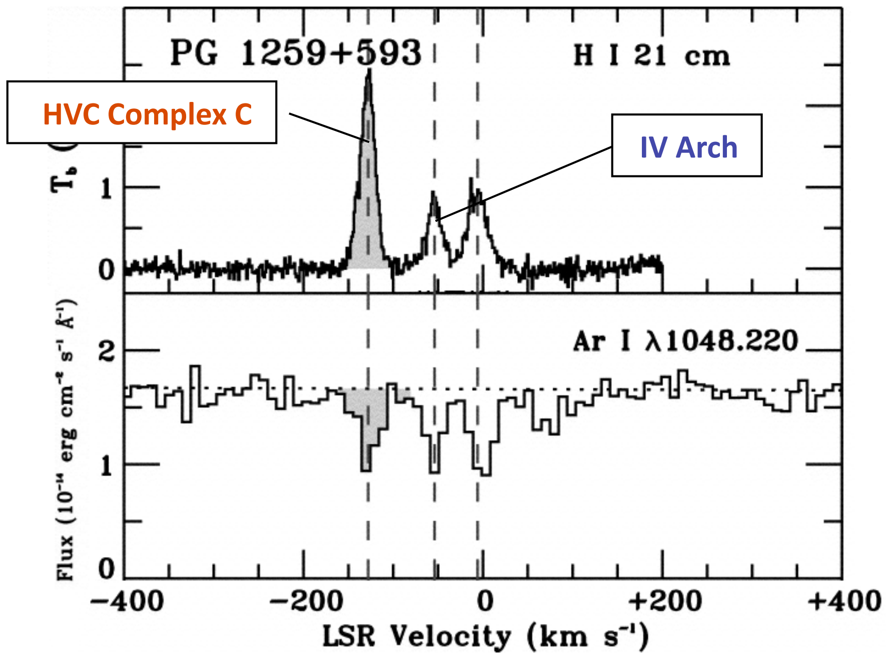


Absorption spectroscopy of IVCs and HVCs

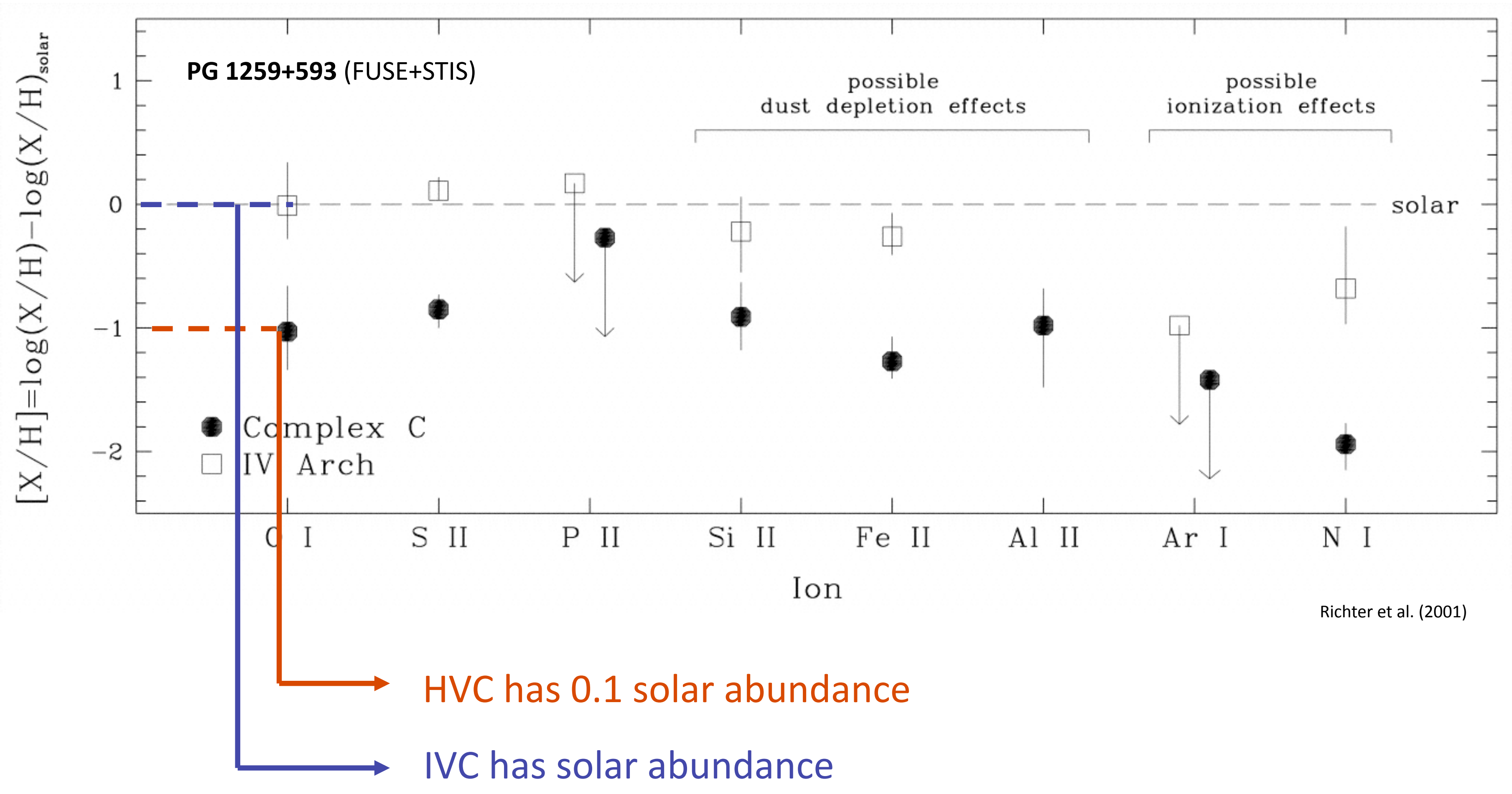


Major Absorption Lines

Species	λ_0 [Å]	Species	λ_0 [Å]
H	1215.7	Al III	1862.8
N V	1238.8	Fe II	2344.2
N V	1242.8	Fe II	2374.5
Si II	1260.4	Fe II	2382.8
Si II	1304.4	Fe II	2586.6
O I	1304.9	Fe II	2600.2
C II	1334.5	Mg II	2796.3
Si IV	1393.8	Mg II	2803.5
Si IV	1402.8	Mg I	2853.0
Si II	1526.7	Ca II	3934.8
C IV	1548.2	Ca II	3969.6
C IV	1550.8	Na I	5891.6
Al II	1670.8	Na I	5897.6
Al III	1854.7		



Metal abundances in IVCs and HVCs from absorption studies

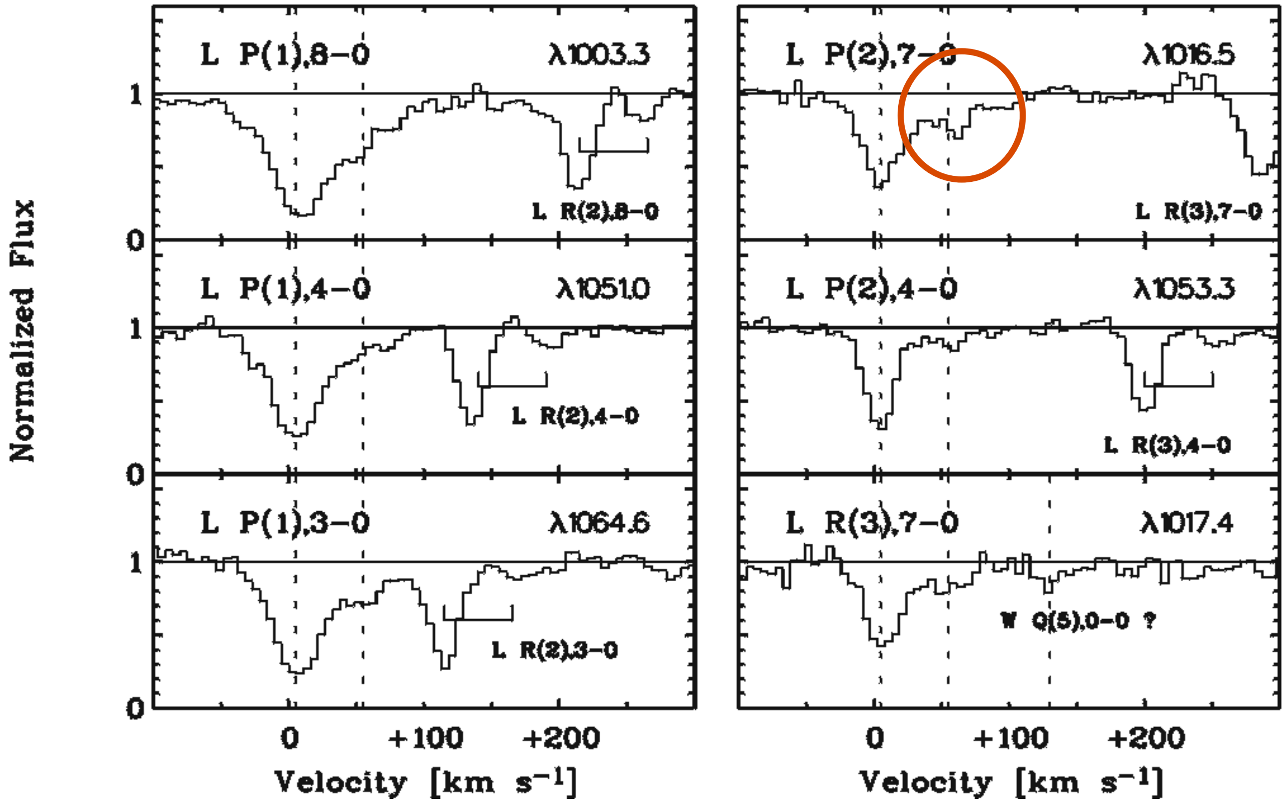


Richter et al. (2001)

Physical conditions in IVCs and HVCs from absorption studies

LMC SK - 68 80 (FUSE)

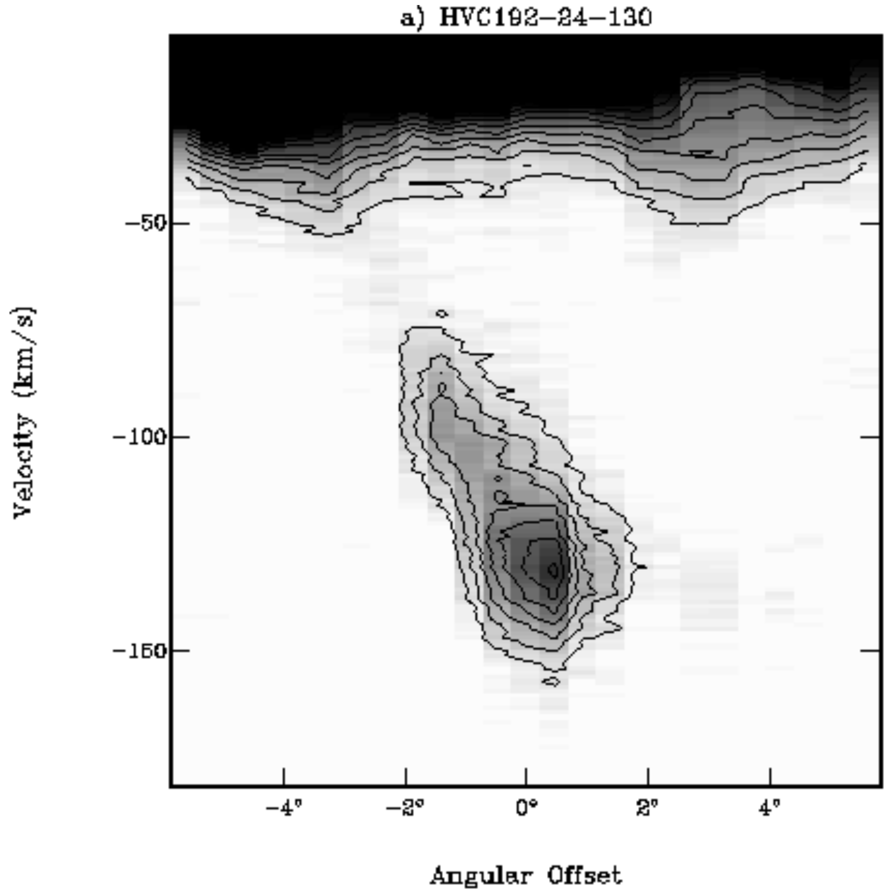
Molecular hydrogen absorption in extraplanar IV gas

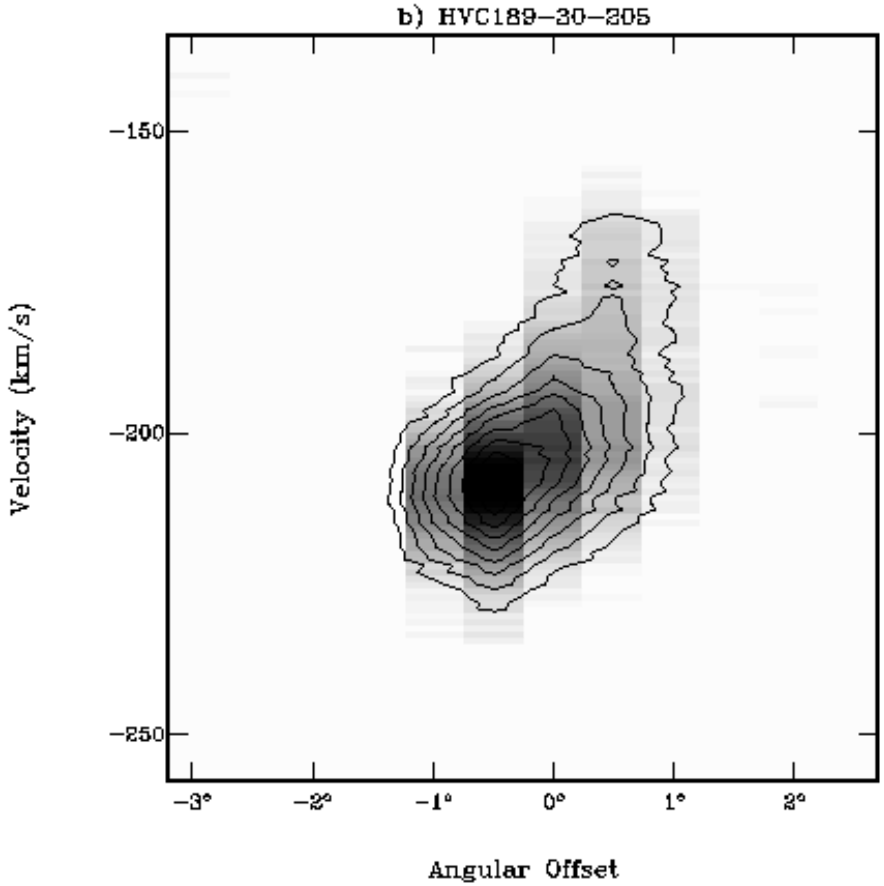


Richter, Sembach & Howk (2003)

Extreme small-scale structure: $n > 500$ cm^{-3}, $L < 100$ AU (!)

Head-tail structures of HVCs and hot coronal gas



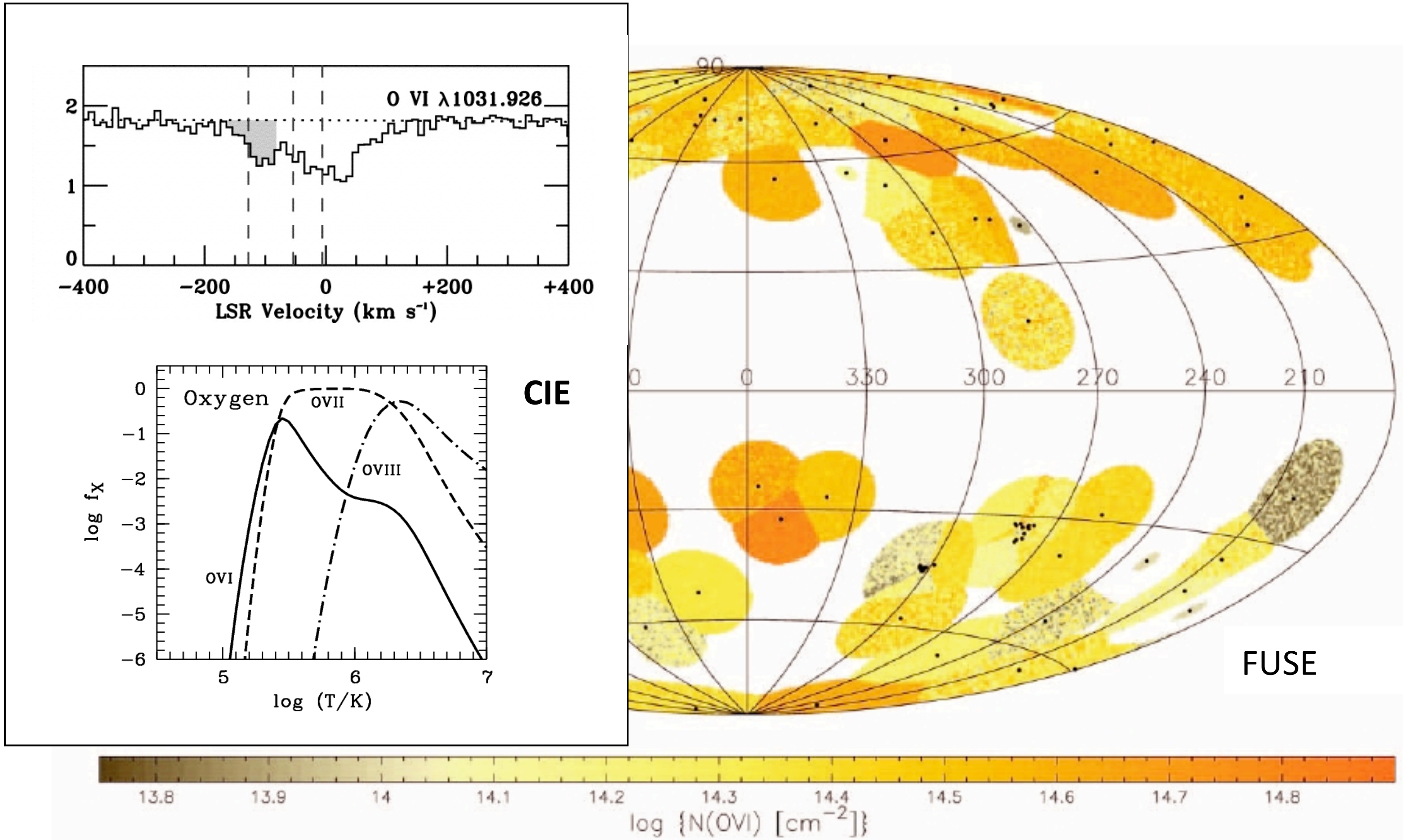


(Brüns et al. 2003)

HVCs interact with the hot Corona

Hot coronal gas in other spiral galaxies

Distribution of OVI in the Milky Way halo

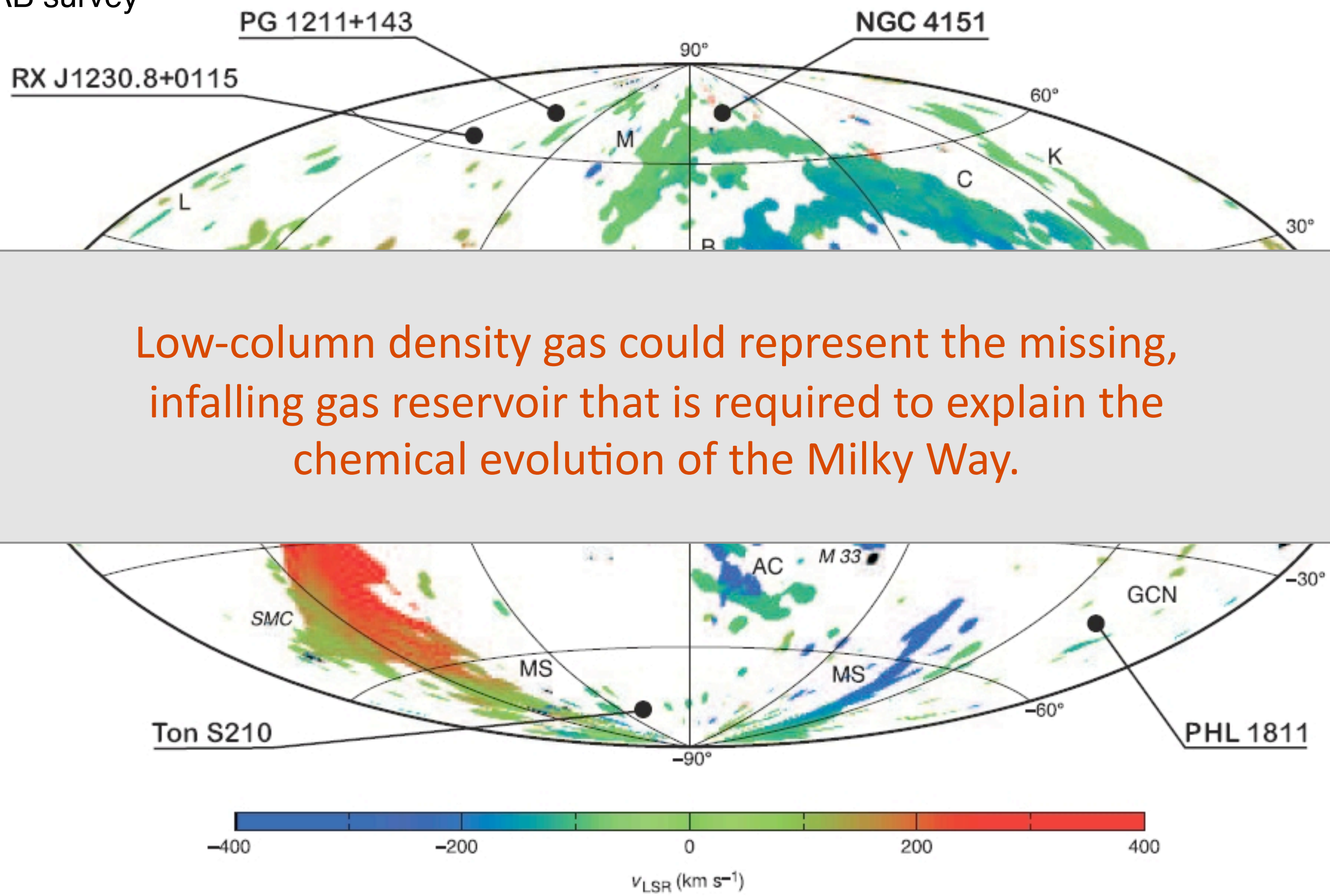


(Savage et al. 2004; Sembach et al. 2004; Wakker et al. 2004)

Low-column density gas in the Milky Way halo

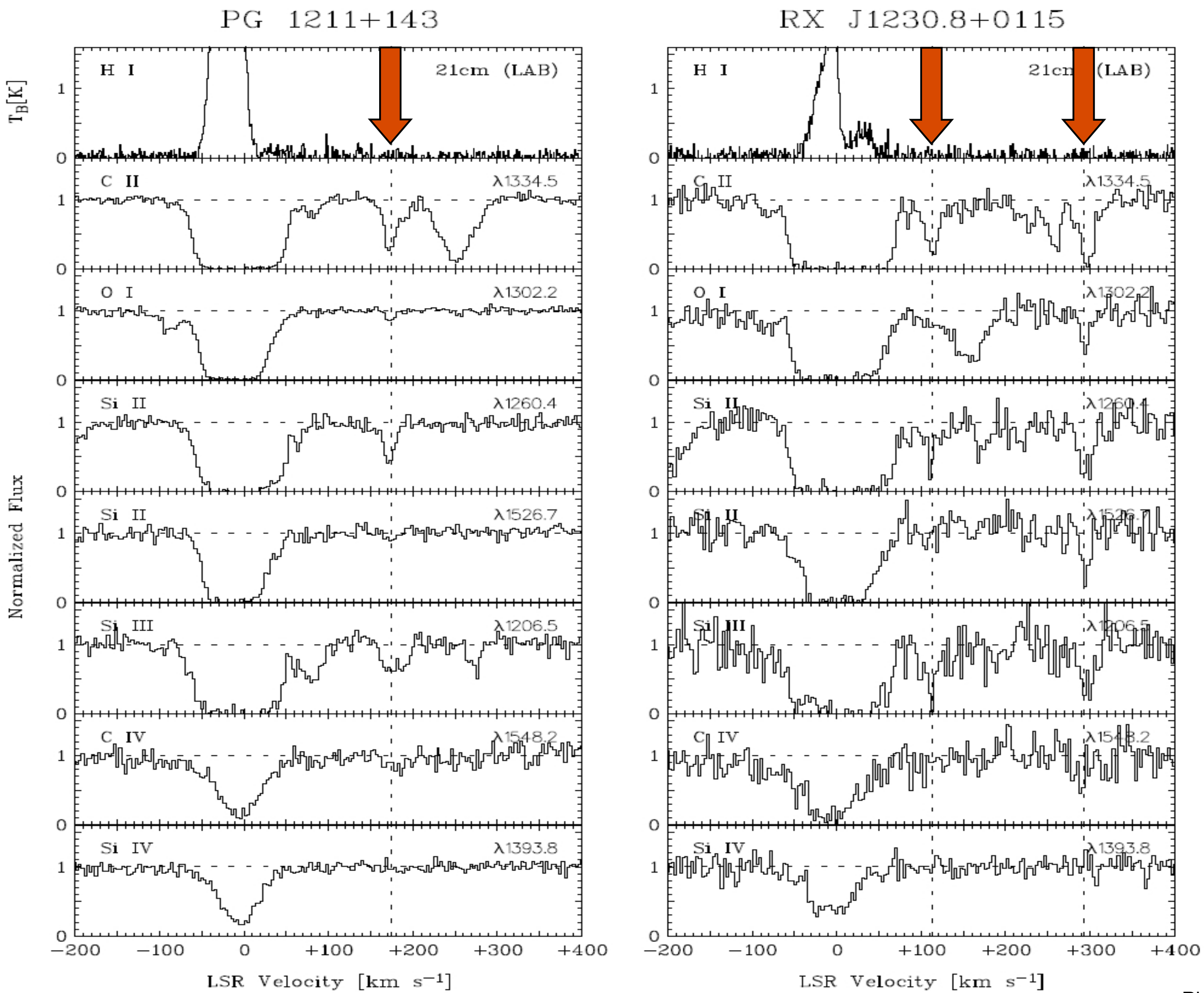
Search for unsaturated OI l1302 high-velocity absorption in HST/STIS data

HI 21cm – LAB survey



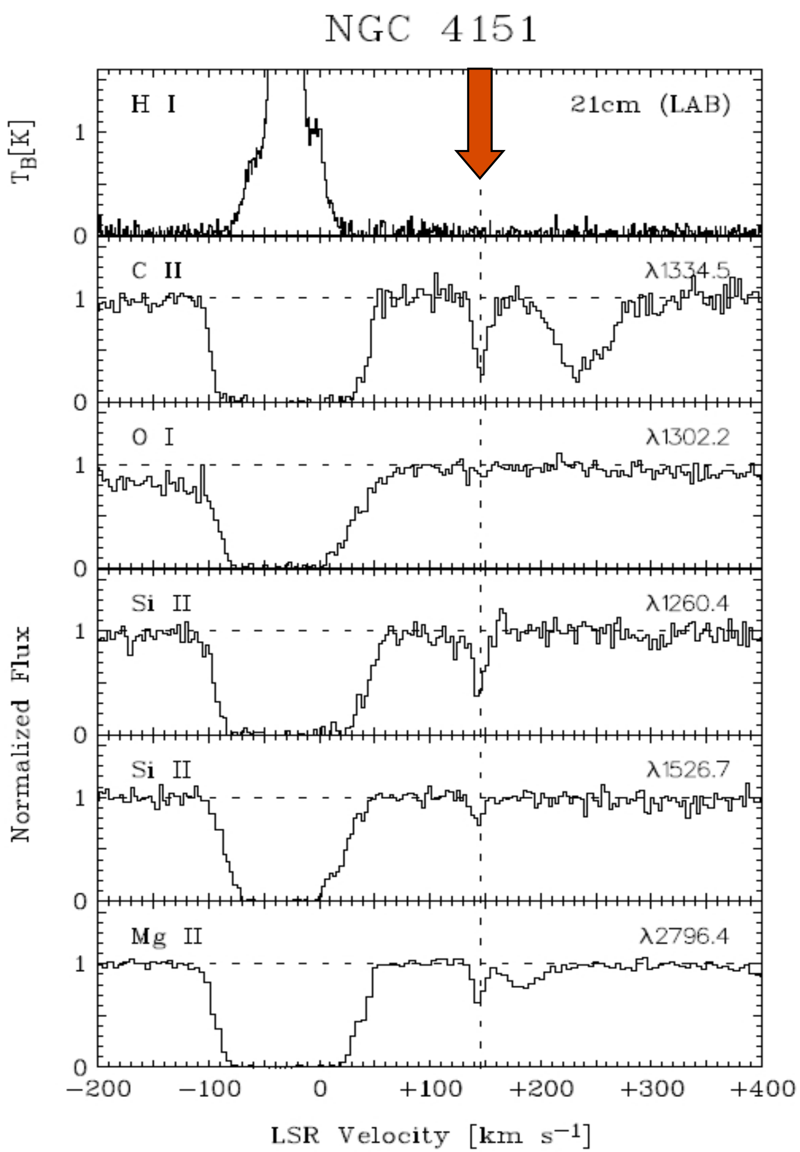
Low-column density gas could represent the missing, infalling gas reservoir that is required to explain the chemical evolution of the Milky Way.

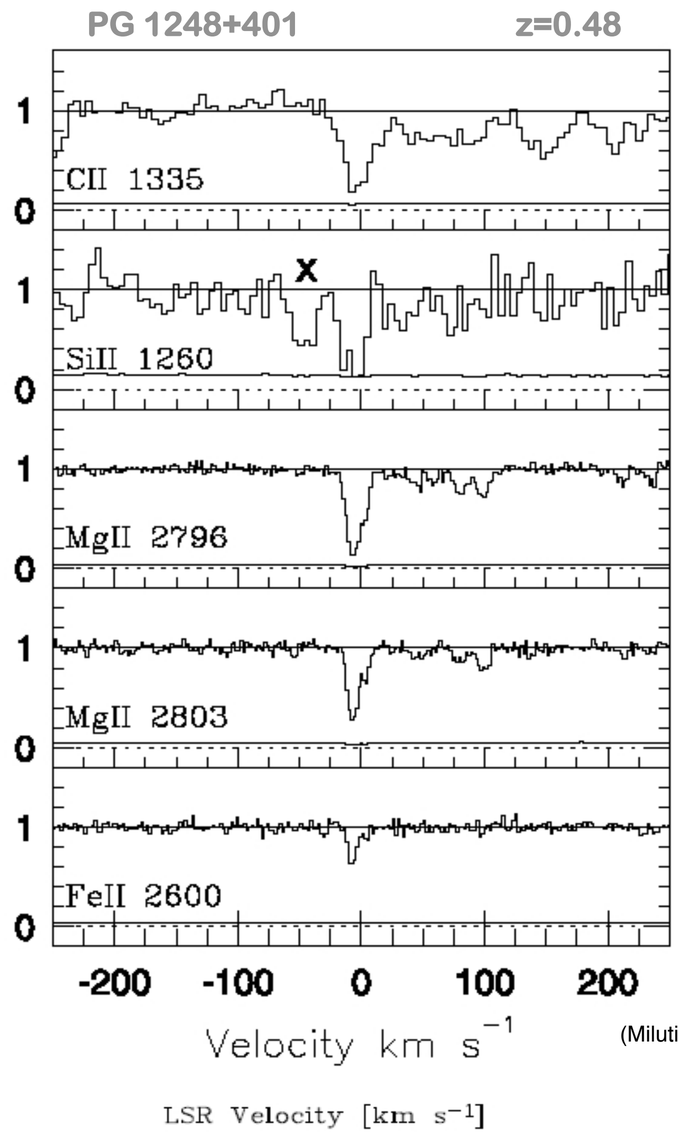
Detection of low-column density gas in the Milky Way halo with HST



Richter et al. (2008)

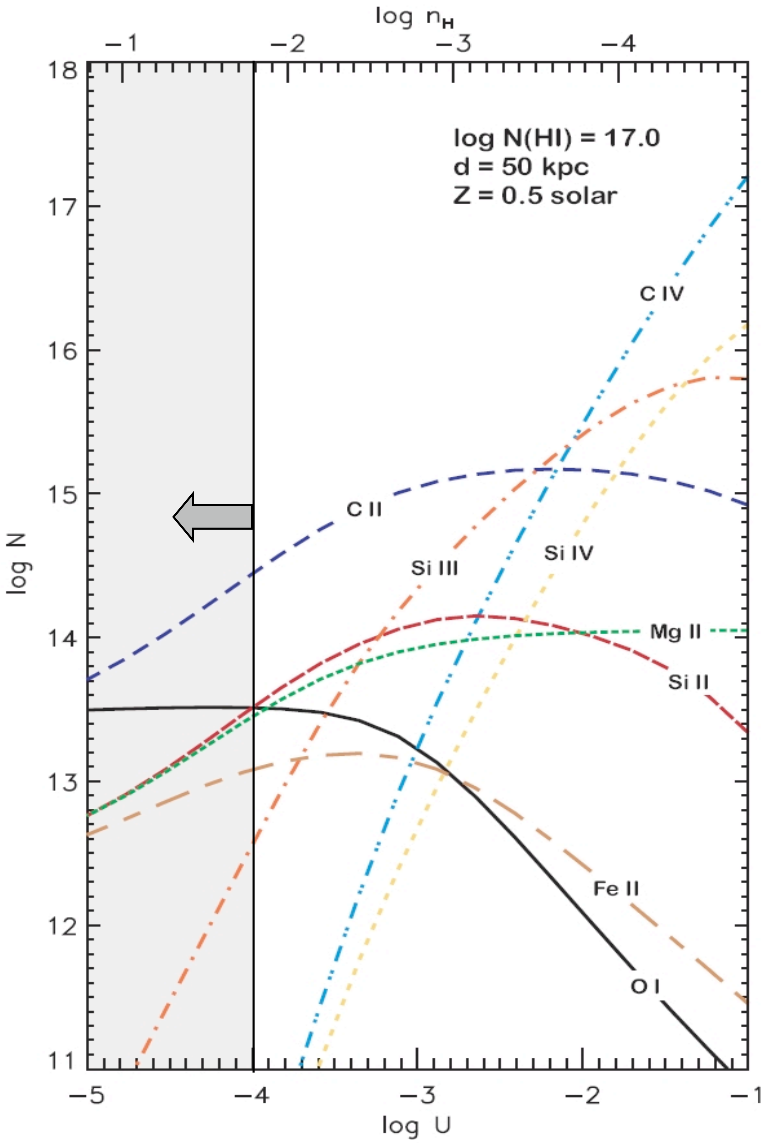
Detection of low-column density gas in the Milky Way halo with HST





(Milutinovic et al. 2006)

Ionization modeling of the halo gas structures



Ionization parameter derived from N(OI) and N(SiII):

$$\log U \approx 1.67\,[\log N(\mathrm{Si\,II}) - \log N(\mathrm{O\,I}) + A_{\mathrm{Si}}] + B_U$$

Density derived from distance-dependend radiation field X(*d*), adopting MW model from Fox et al. (2006):

$$\log n_{\mathrm{H}} \approx \log X_{\gamma}(d) - \log U - 6.4$$

Ionization fraction assuming optically thin absorption:

$$\log f_{\mathrm{H}} \approx 0.88 \log U + 4.9$$

Absorber thickness from N(H) and n_H:

$$L = \frac{N(\mathrm{HI}) + N(\mathrm{HII})}{n_{\mathrm{H}}}$$

Are these absorbers important in any way ?

- They have a considerable absorption cross section (f ~ 0.2)
- Like weak MgII systems, some of the systems have super-solar iron abundances
- If they are at large distances (d=100 kpc), their total mass is:

$$M_{\rm LLS} \approx 10^7\, M_\odot\, f\, \mu \left(\frac{d}{10\,{\rm kpc}}\right)^2 \left(\frac{N}{10^{18}\,{\rm cm}^2}\right) \sim 3 \times 10^8 M_\odot$$

➡ mass-circulation rate: $\dot{M} \approx 0.3 M_\odot\ {\rm yr}^{-1}$

- absorbers are small (pc-scale), have low-masses (a few solar masses), but must extremely numerous (if spherical, $N>10^6$ for d>10 kpc)
- need new UV data from COS (HST) to further study their nature

Overview: properties of gas surrounding the Milky Way

- Milky Way halo gas is an extreme multi-phase medium (from H_2 to OVI)

  (e.g. Richter et al. 1999, 2003; Savage et al. 2003; Sembach et al. 1999, 2003; Wakker et al. 2001, 2003; Fox et al. 2004, 2005 …)

- Metal abundances in IVCs and HVCs span a large range (~0.1-1.0 solar)

  (e.g., Wakker et al. 1999, 2001; Richter et al. 1999, 2001; Sembach et al. 2002; Tripp et al. 2003; Collins et al. 2003)

- Distances of 21cm IVCs and HVCs are between 0.5 and 20 kpc

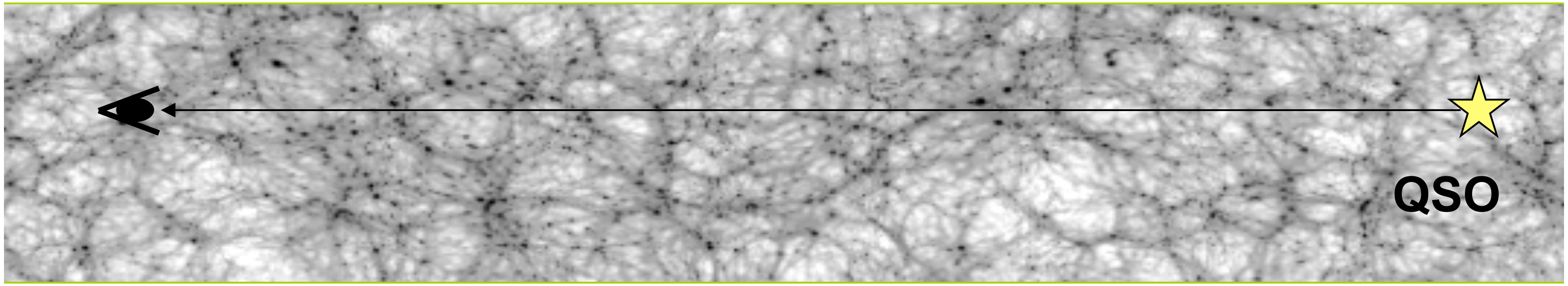
  (e.g., Wakker et al. 2007, 2008; Thom et al. 2007)

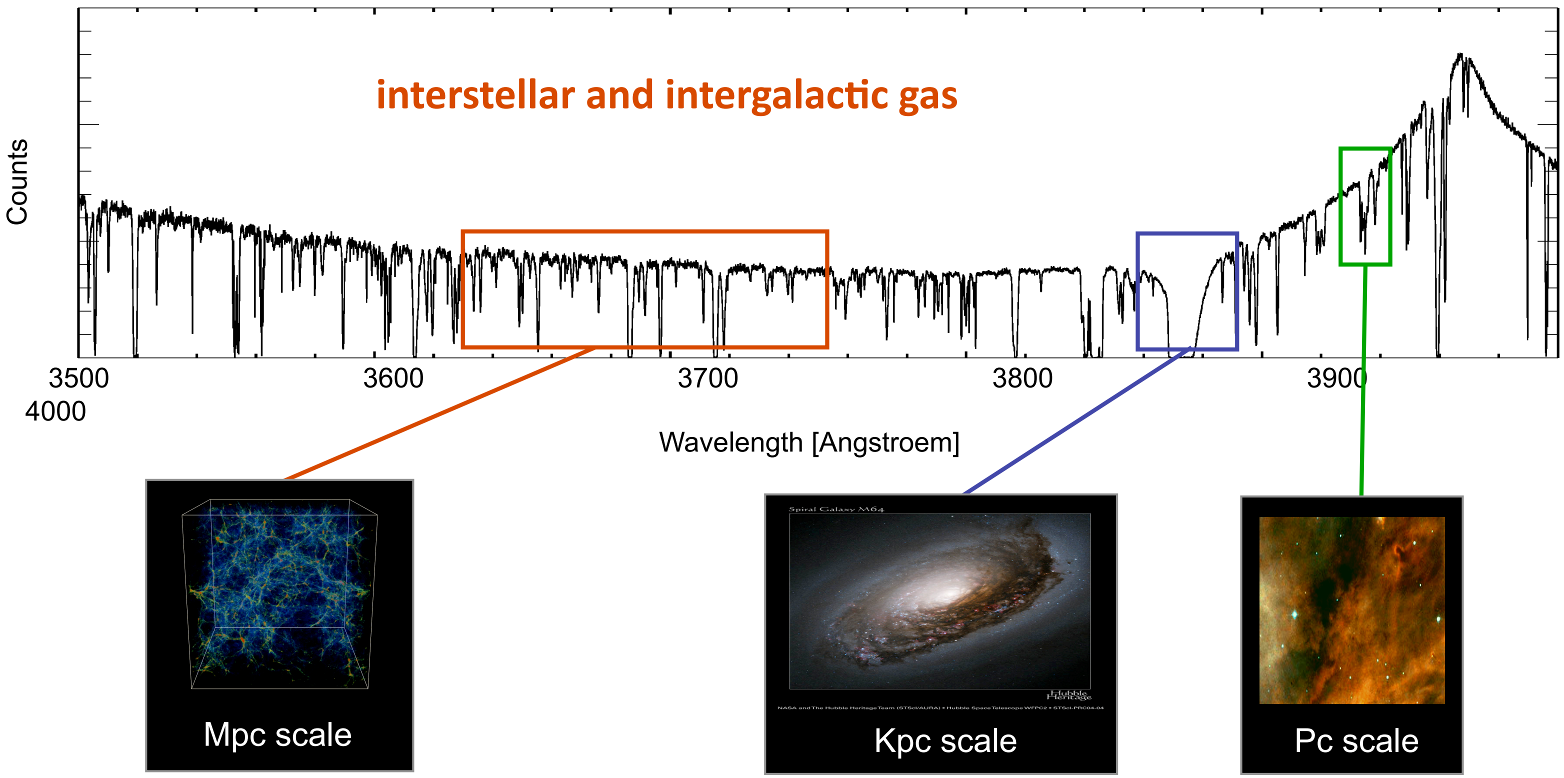
- Various processes lead to the circulation of gas in the Milky Way halo

- Milky Way is accreting gas from the IGM and from satellite galaxies

- Gas physics on vastly different scales (AU - Mpc) has to be considered

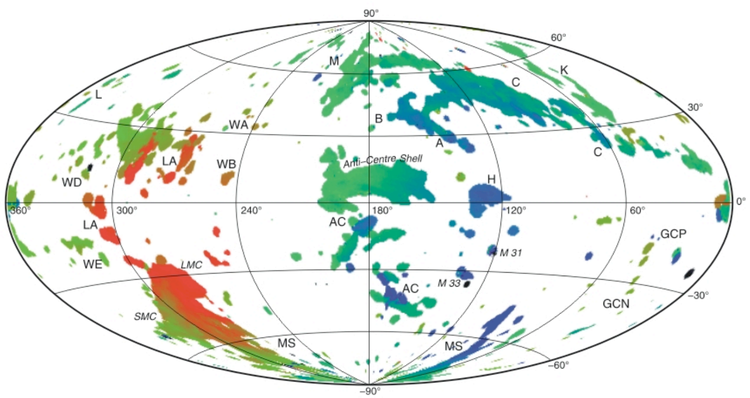
Quasar absorption line systems – tracers of galaxy halos far away ?

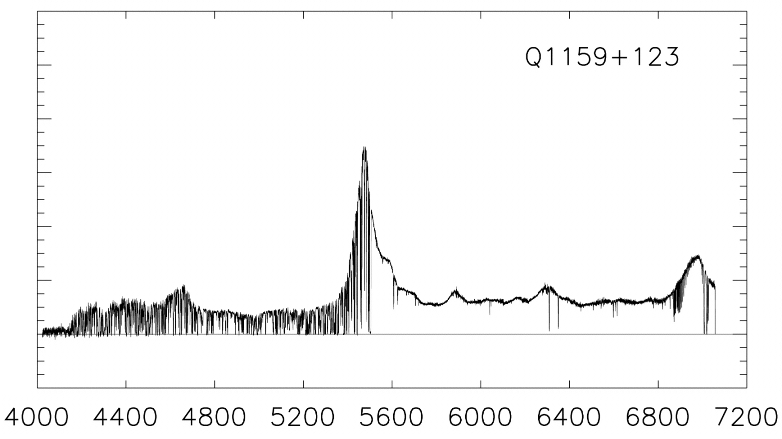




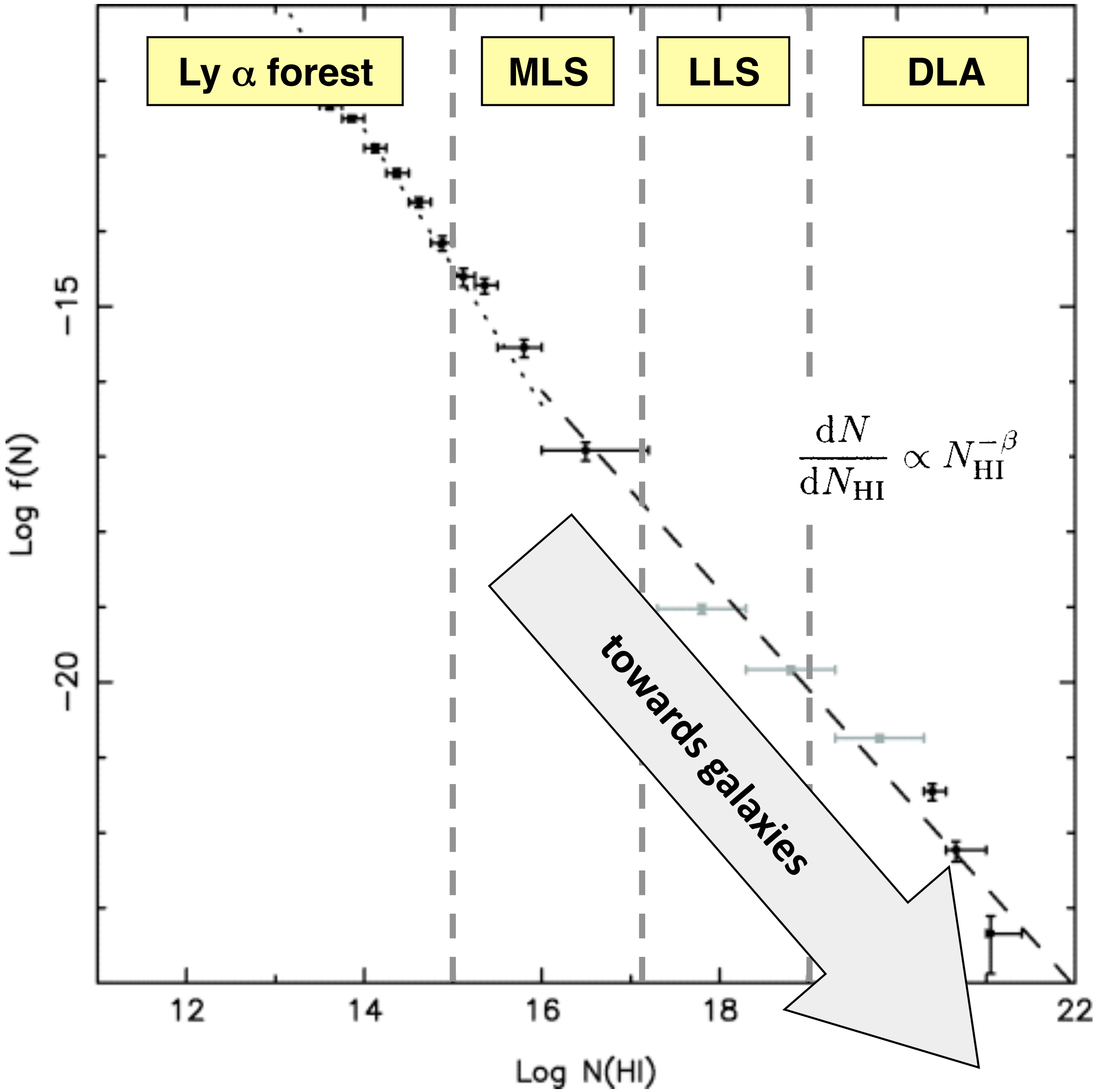
Circumgalactic gas in a more cosmological context

- Absorption measurements in the Milky Way halo
- QSO absorption-line systems and their relation to galaxy halos
- How do we bring these things together ?

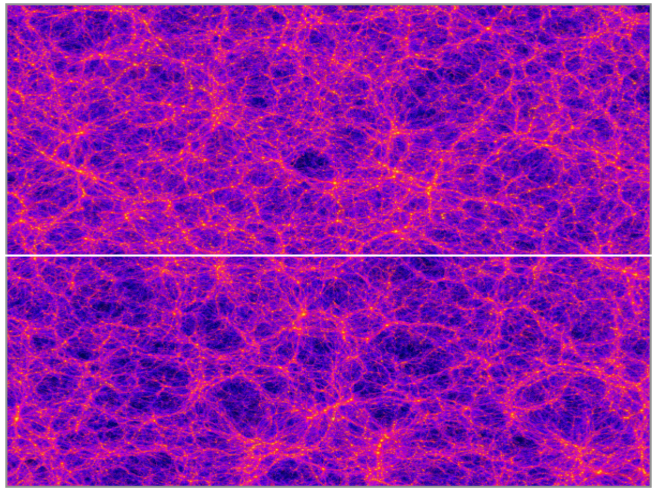




HI column density distribution – from the IGM to galaxies

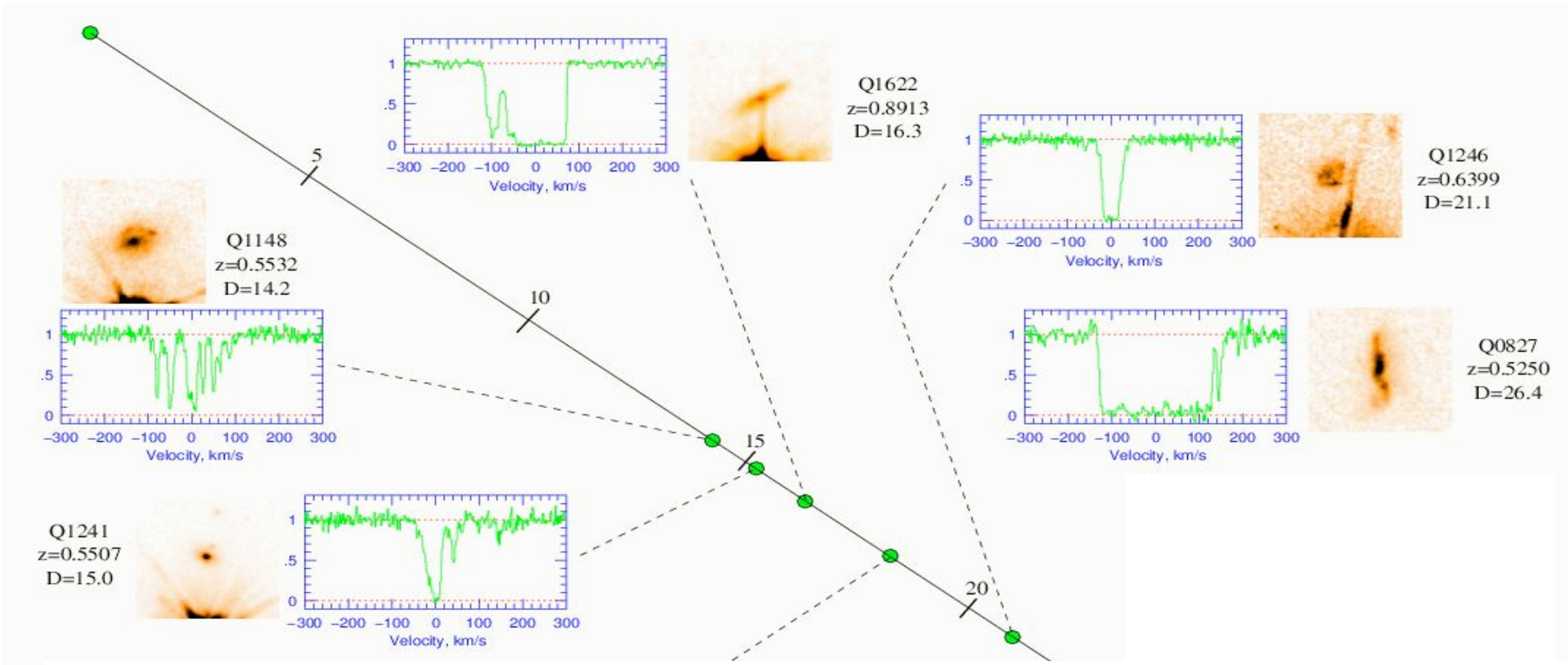


large-scale structure



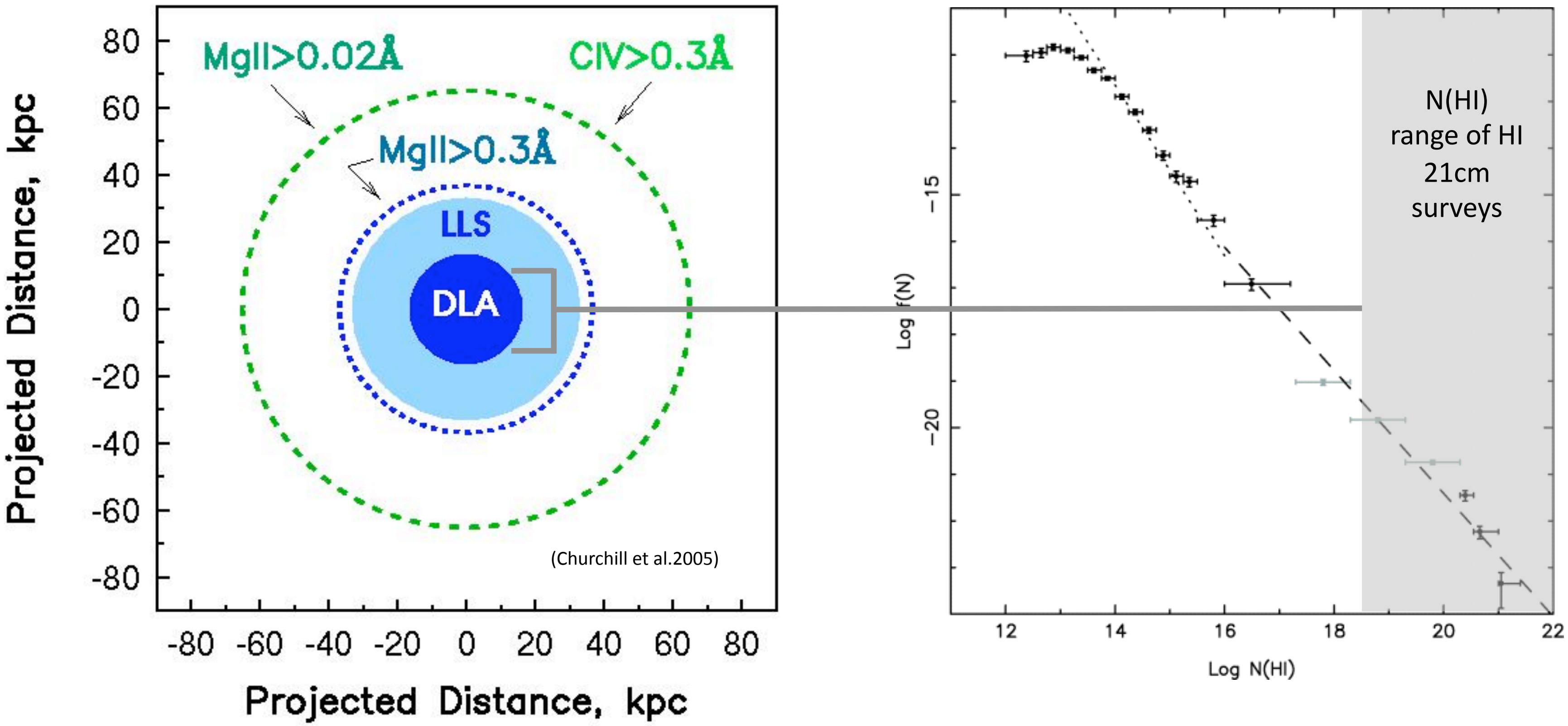
… as well as galaxies and their gaseous environment

Strong MgII absorbers and their relation to galaxies



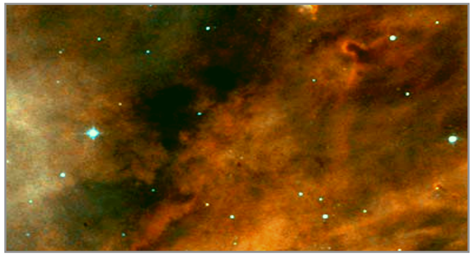
- strong MgII systems have EW > 0.3 A
- they are found typically within 35 h^{-1} kpc of bright galaxies
- they probably trace disks and 21cm HVC analogs

Absorption cross sections of galaxy halos

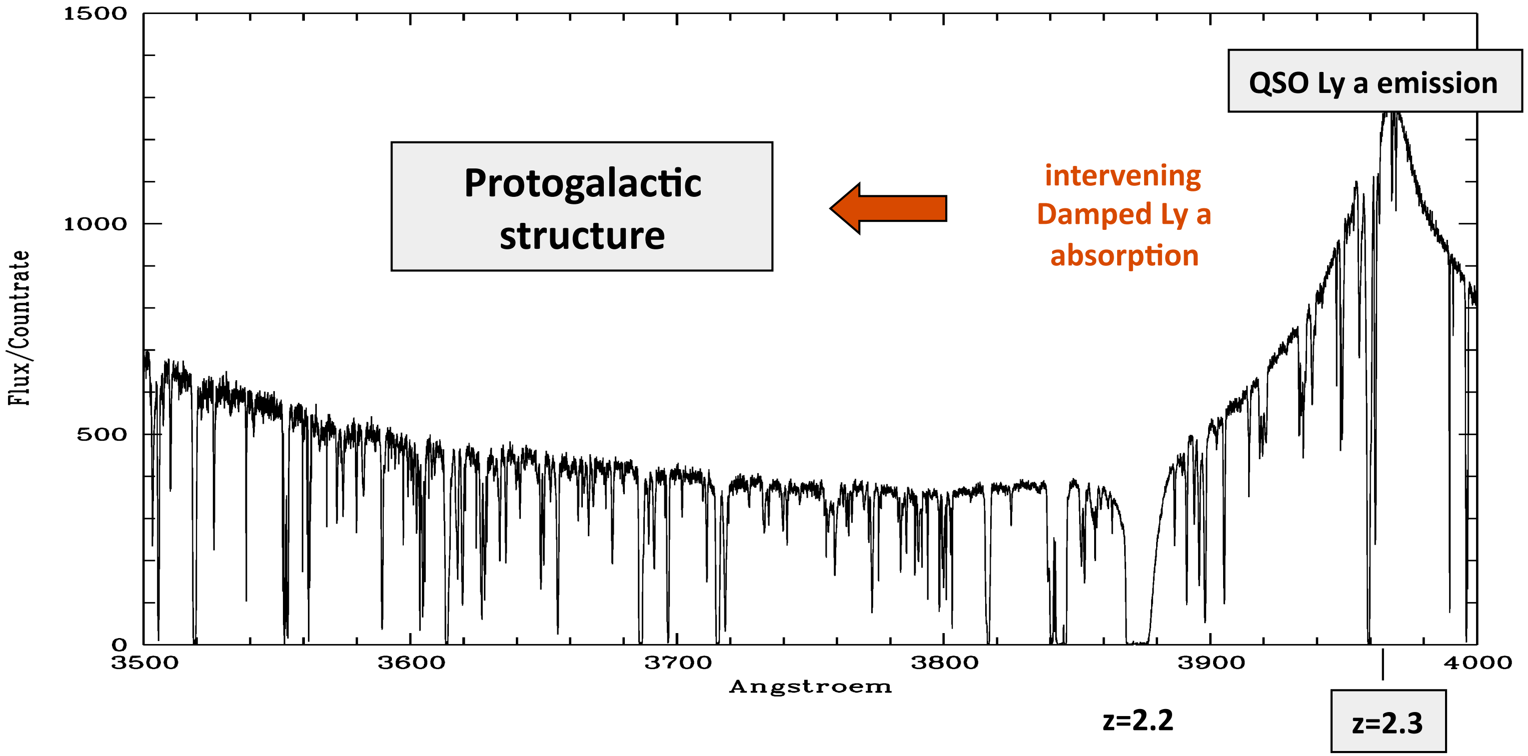


Scenario is consistent with observed gas distribution around the Milky Way.

DLAs and the formation of galaxies

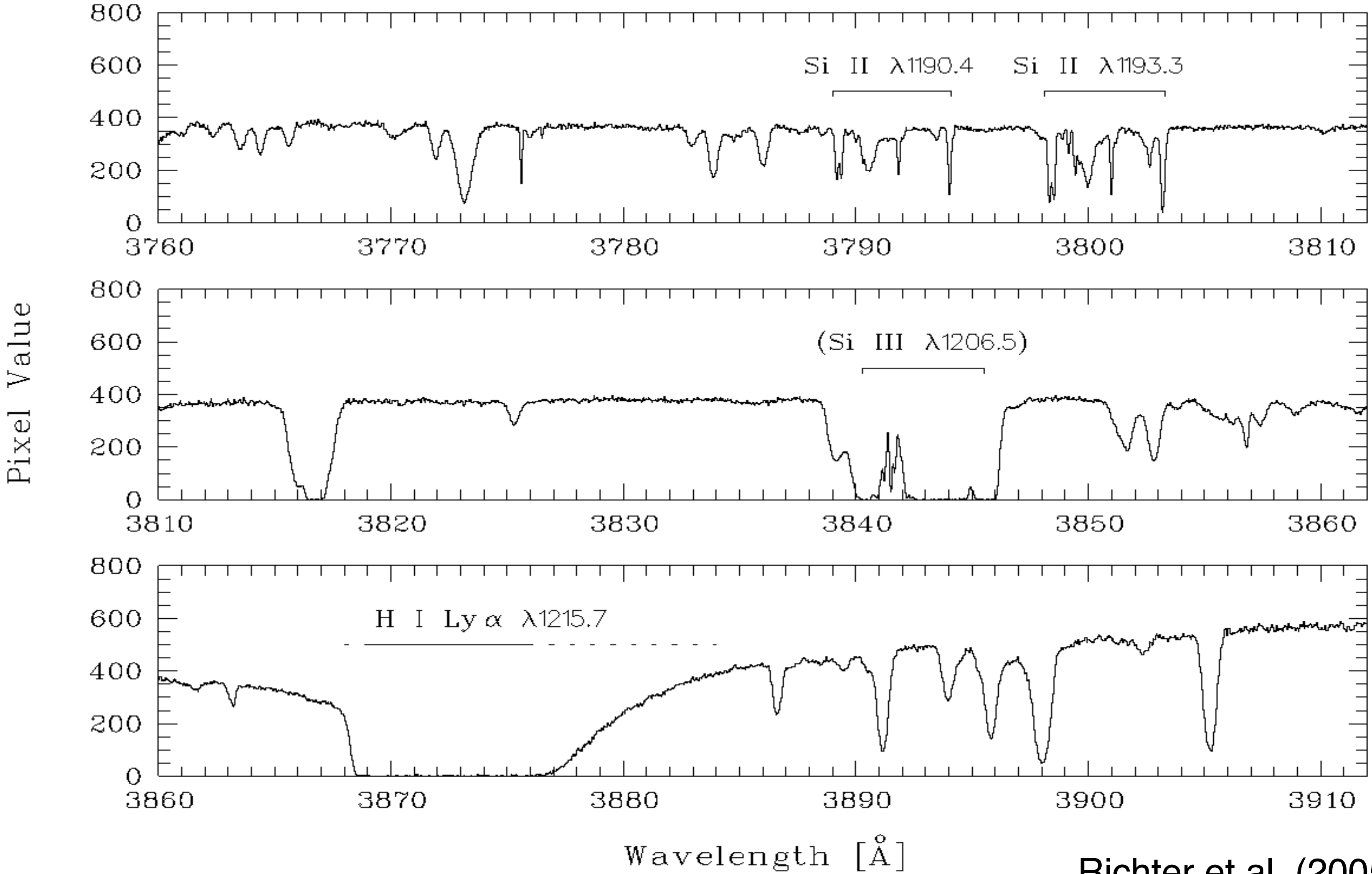


?



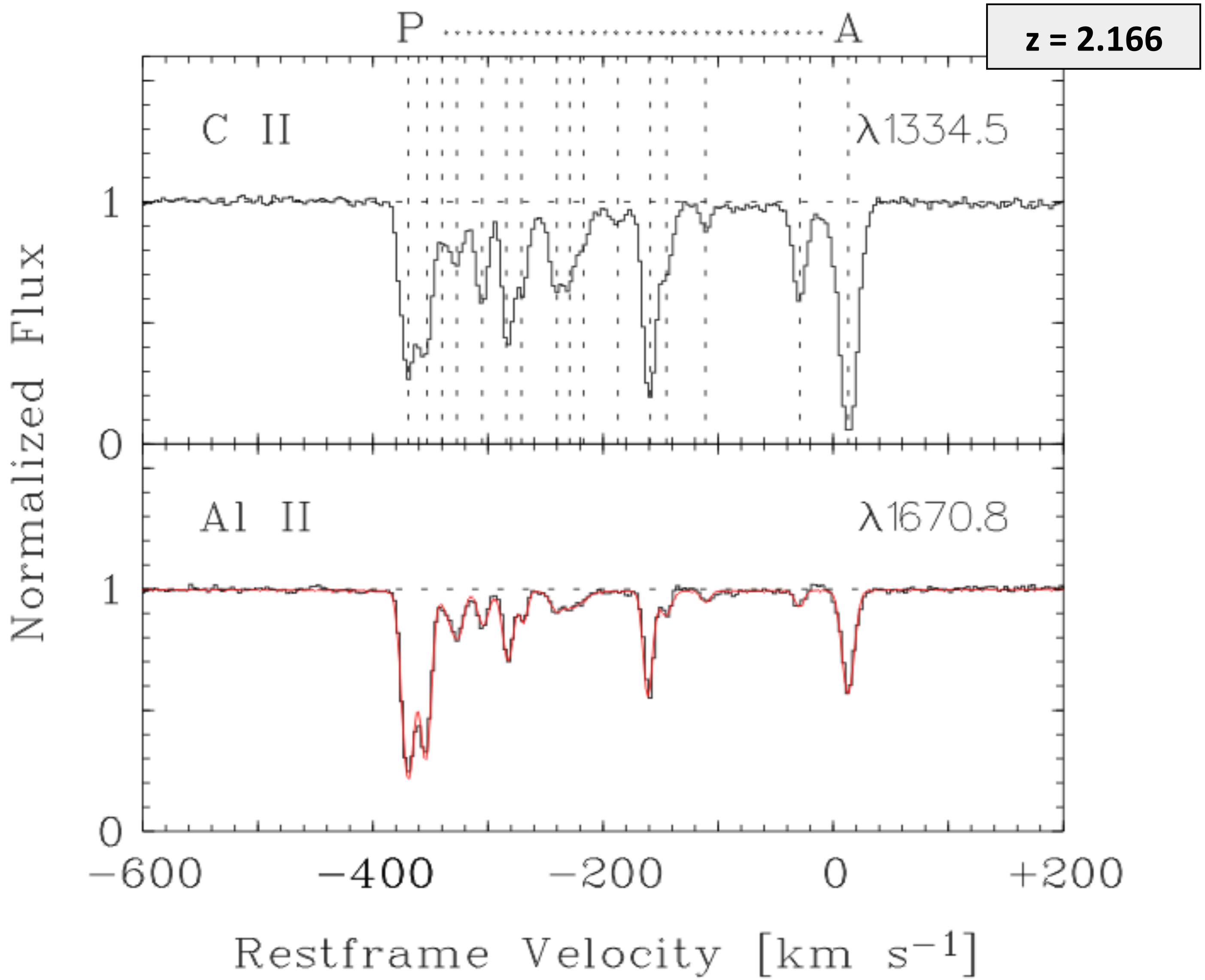
Observations of DLAs with the ESO Very Large Telescope

HE 0001-2340

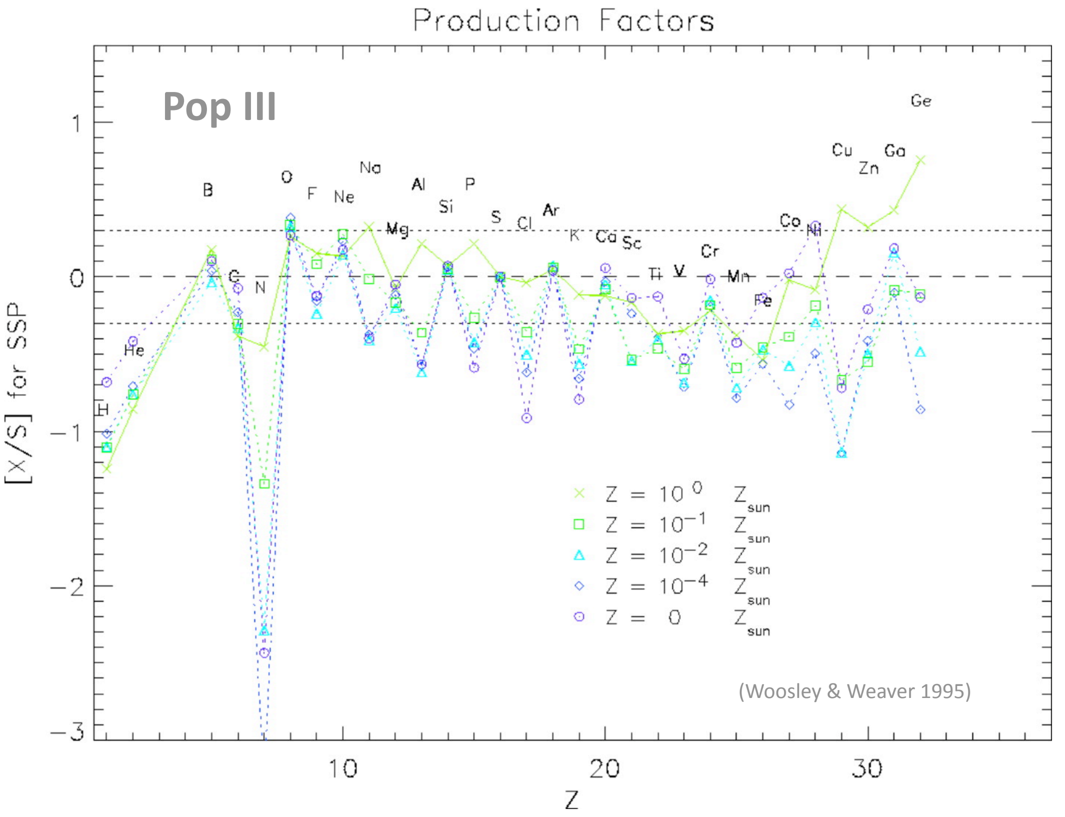


Richter et al. (2005)

Example: DLA systems at z=2 towards the quasar HE 0001-2340



Chemical composition and enrichment history



[M/H] ~ 1/65 solar

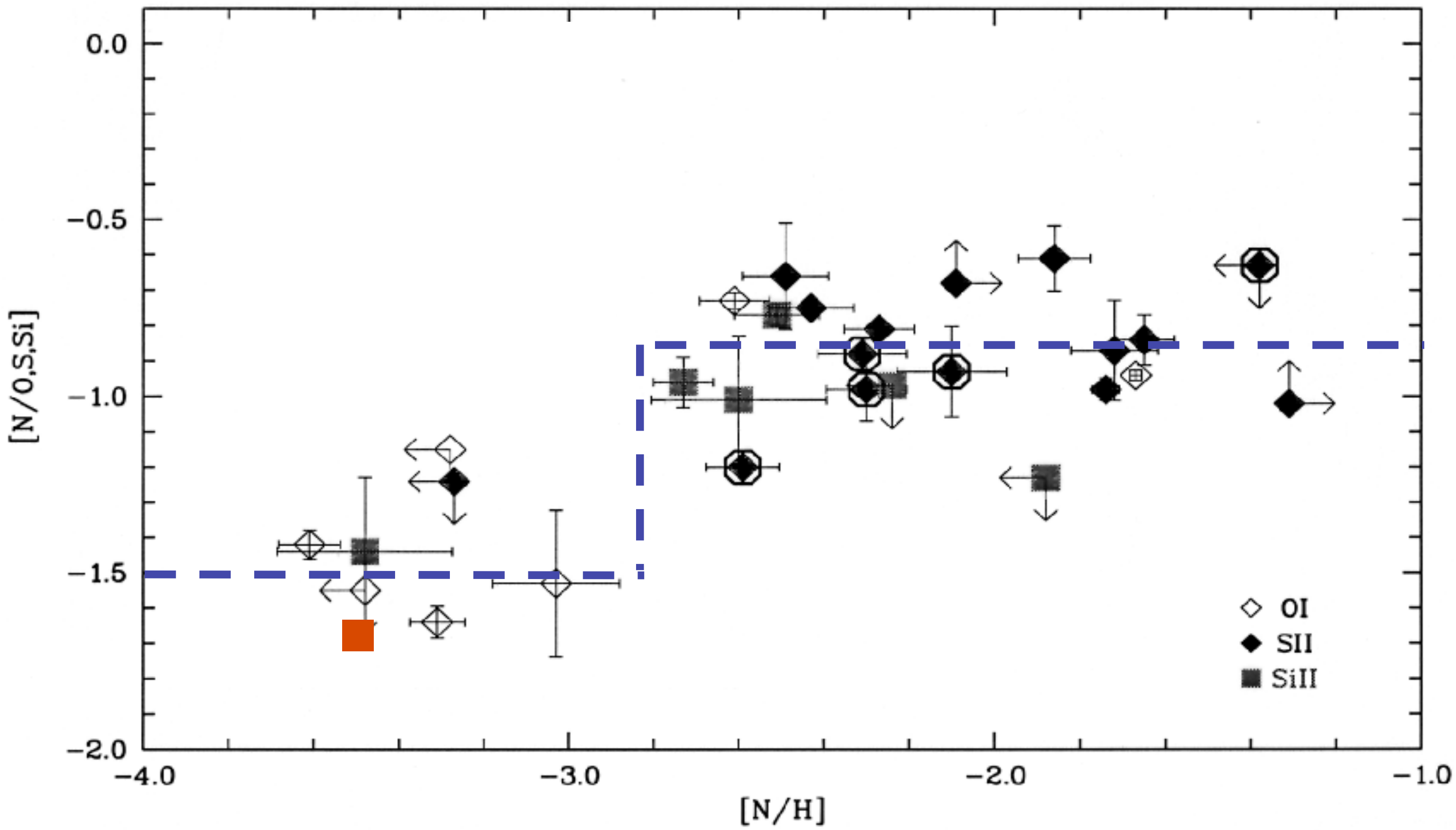
[N/O] ~ 1/50 solar

[α/Fe] ~ 2 x solar

no dust

Signatures from the first stars in the Universe !

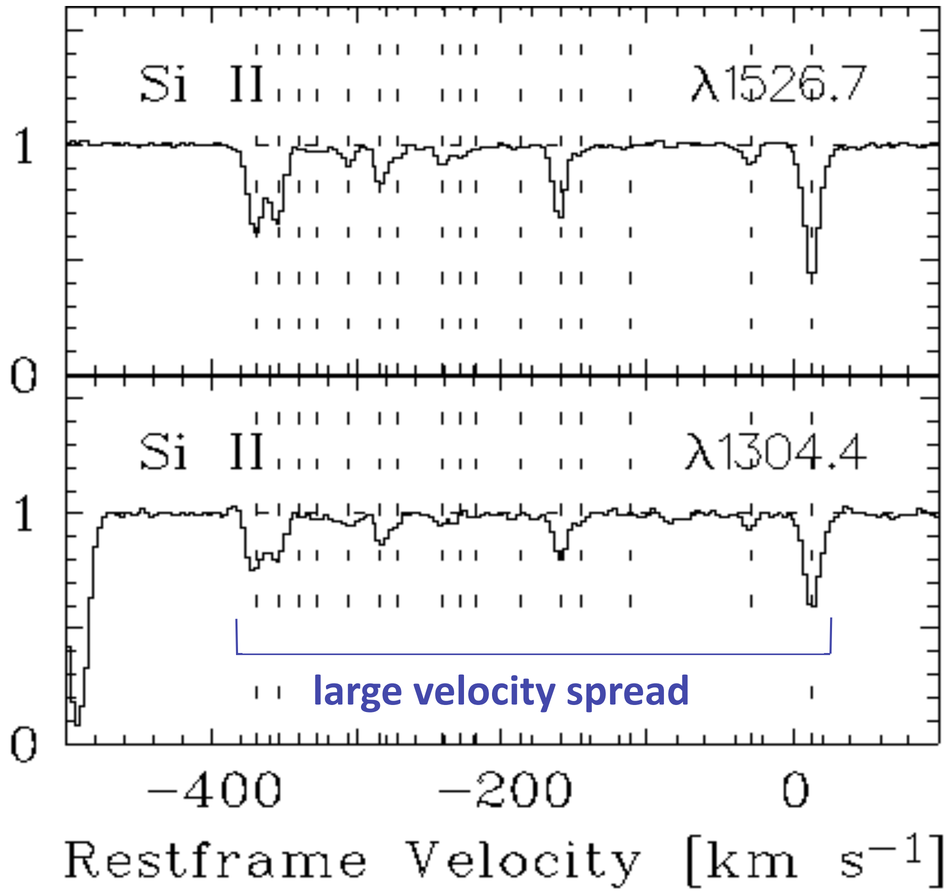
Nitrogen abundance pattern

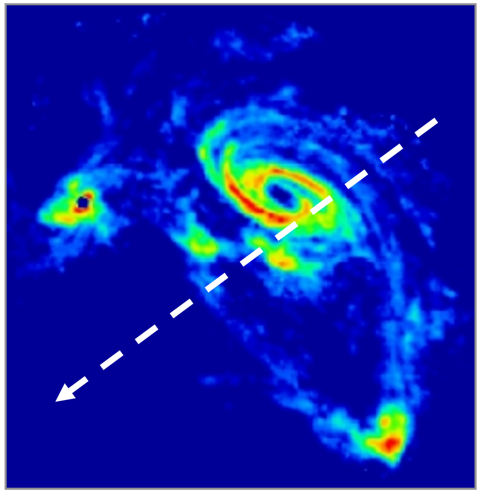


... most nitrogen-deficient galaxy detected so far.

HE 0001-2340: galaxy formation at high redshift

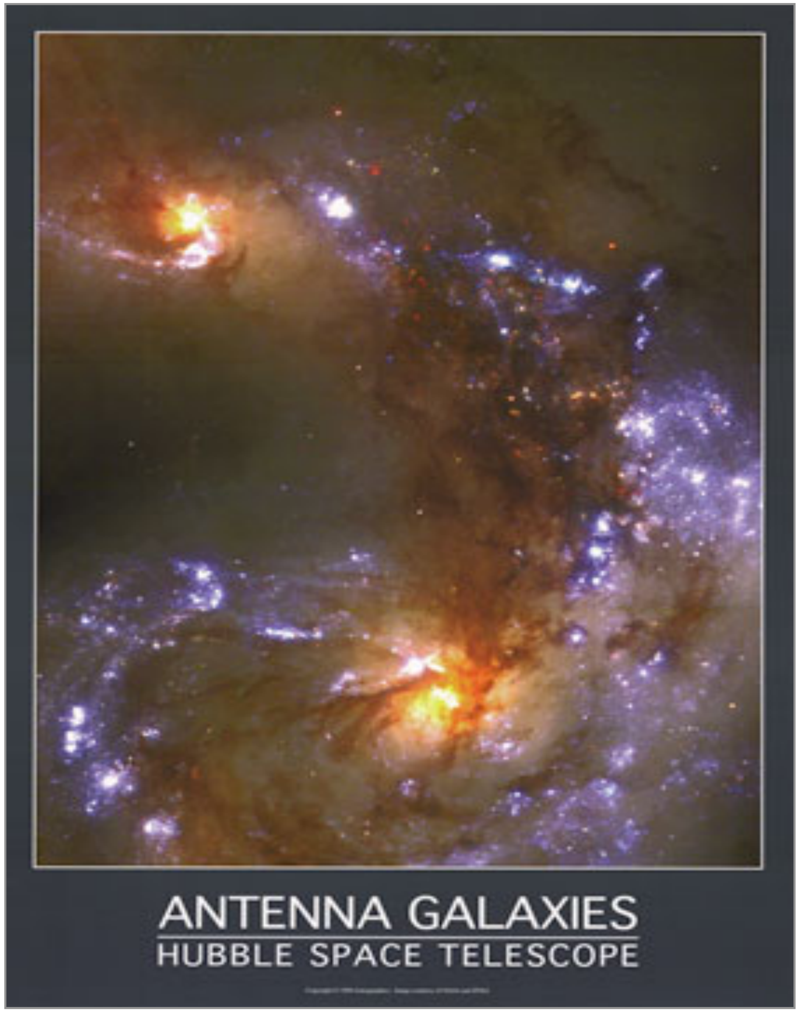
strong abundance anomalies !





Merger event ?

Abundance anomalies – evidence for SNe explosions from massive stars



[O/C] . –0.1

[Al/C] .+0.5

[Si/C] .+0.6

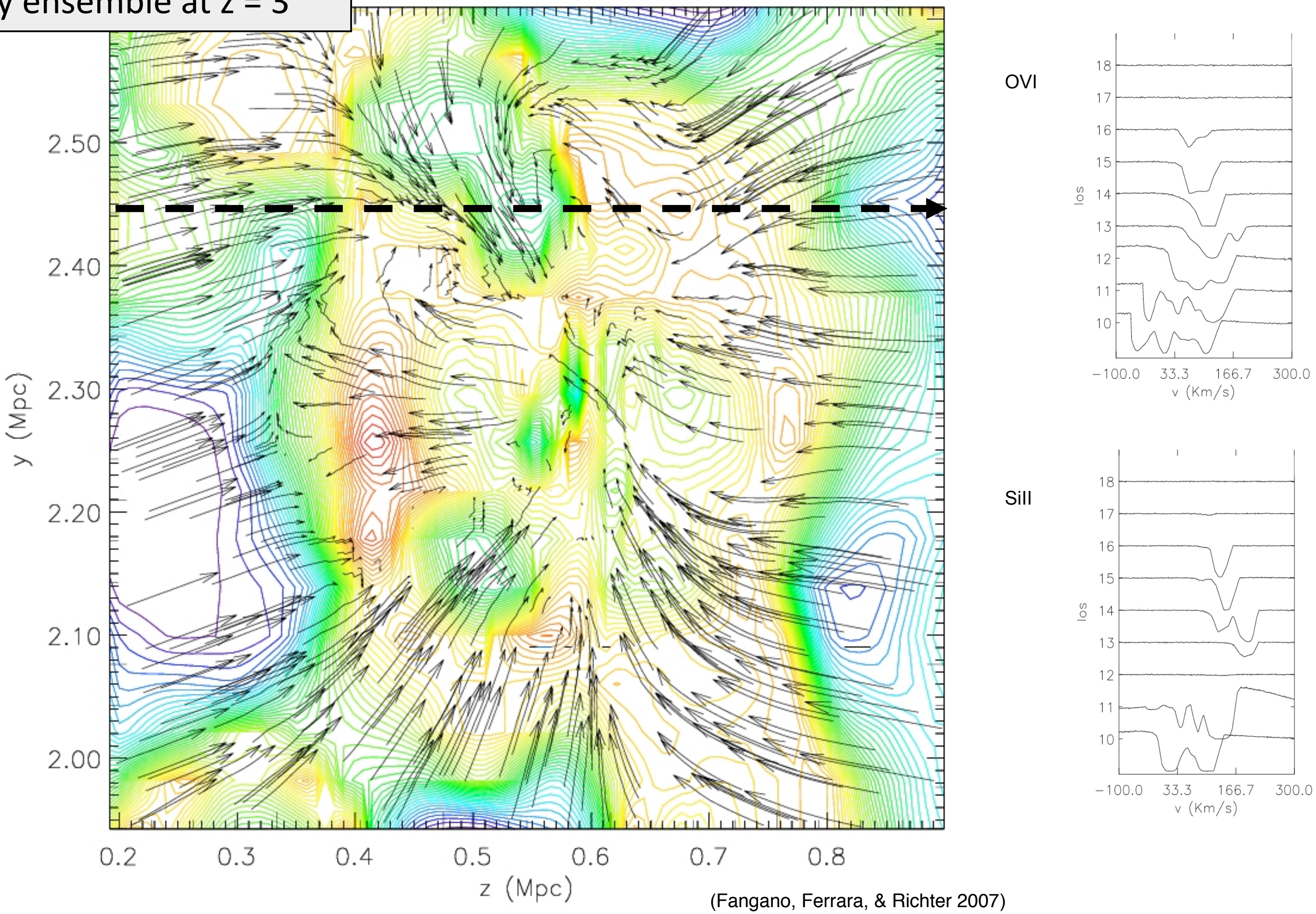
[P/C] .+1.5

(D/H) . 3 x 10^{-4} ??

Richter et al. (2005)

Numerical simulations of circumgalactic gas at low and high z

galaxy ensemble at z = 3



(Fangano, Ferrara, & Richter 2007)

Conclusions

- The evolution of galaxies in the cosmic web can be studied in great detail by investigating their circumgalactic gaseous environment
- Galaxies (also the Milky Way !) accrete large amounts of gaseous matter from the intergalactic medium to fuel star formation
- QSO absorption spectra can be used to study the chemical enrichment of early galactic structures and to learn about the first stars in the Universe.