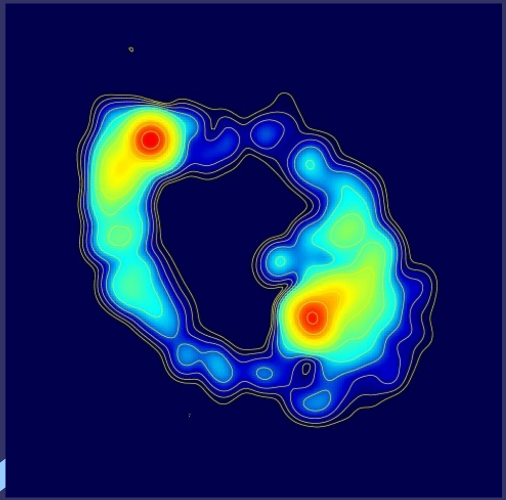
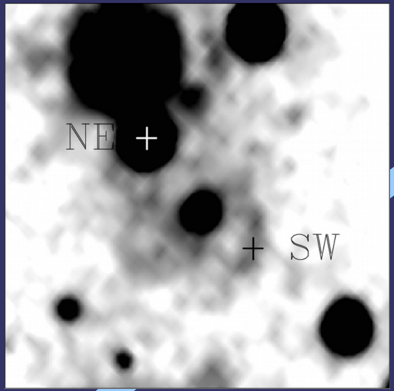
Molecules in absorption at intermediate redshifts





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The Cosmic Cycle of Dust and Gas in the Galaxy
Quy Nhon, Vietnam, 2018 July 11th

CHALMERS

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Molecules in absorption

- Very sensitive … provided there is a background continuum

- No signal dilution by distance (as sensitive at high-z than local)

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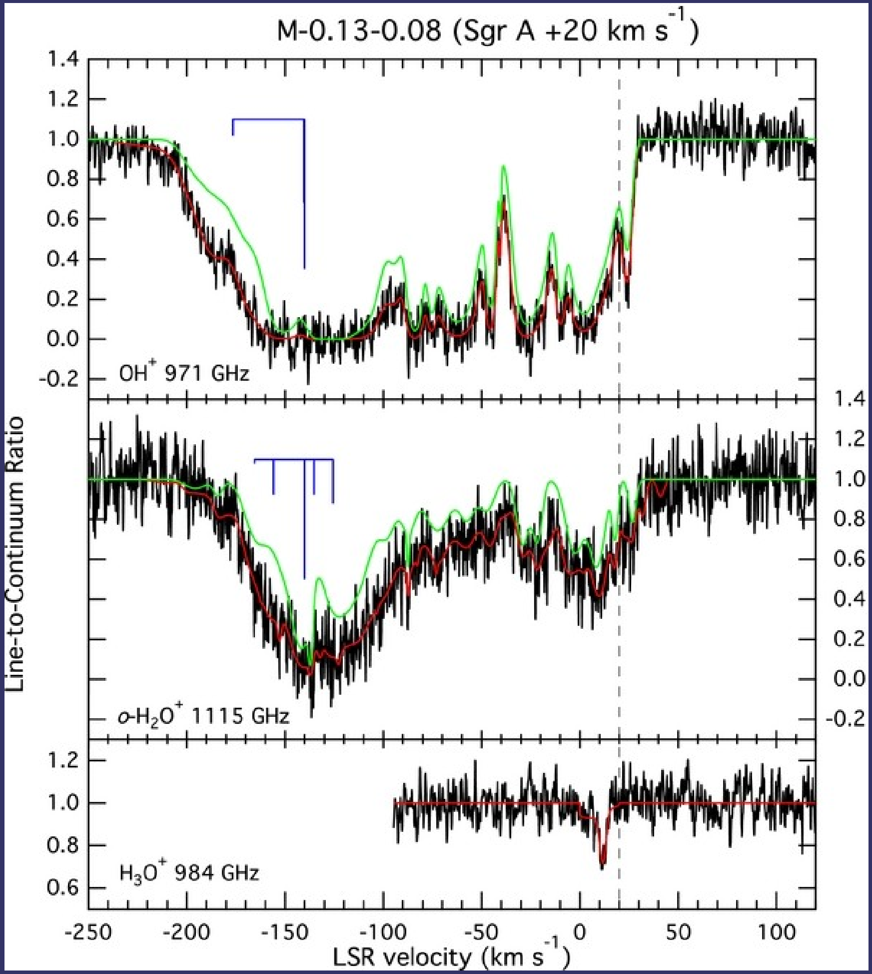
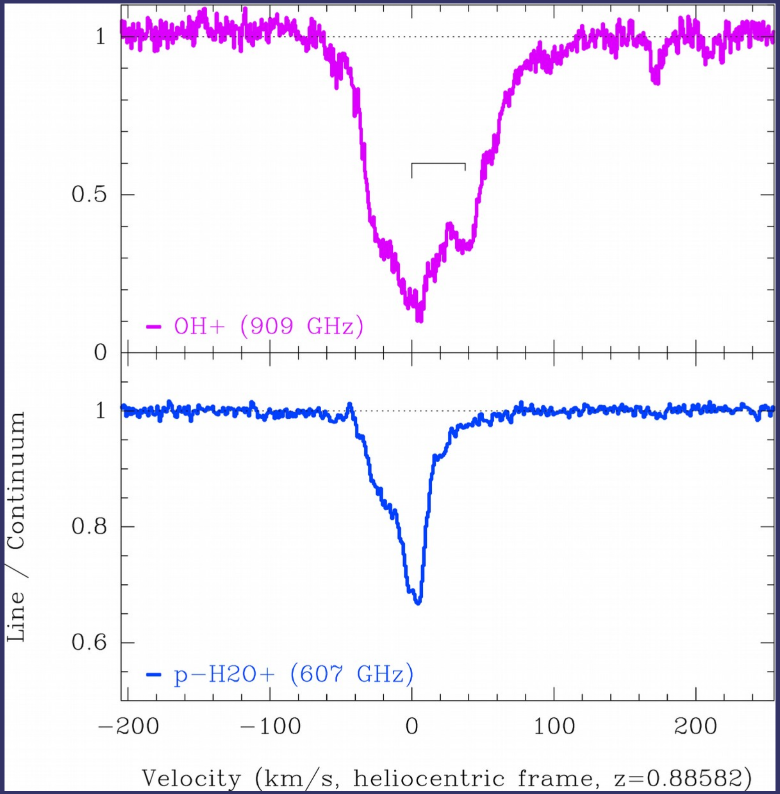
Indriolo+15



OH+, H2O+, H3O+ toward the Galactic center



Muller+16

OH+, H2O+ @z=0.89 toward PKS1830-211

Molecules in absorption

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- Outstanding angular resolution = size of the continuum illumination
  Quasars have emission size of ~few mas
  1 mas = 8 pc @z=0.89
  But … along a line of sight = cylinder of absorption

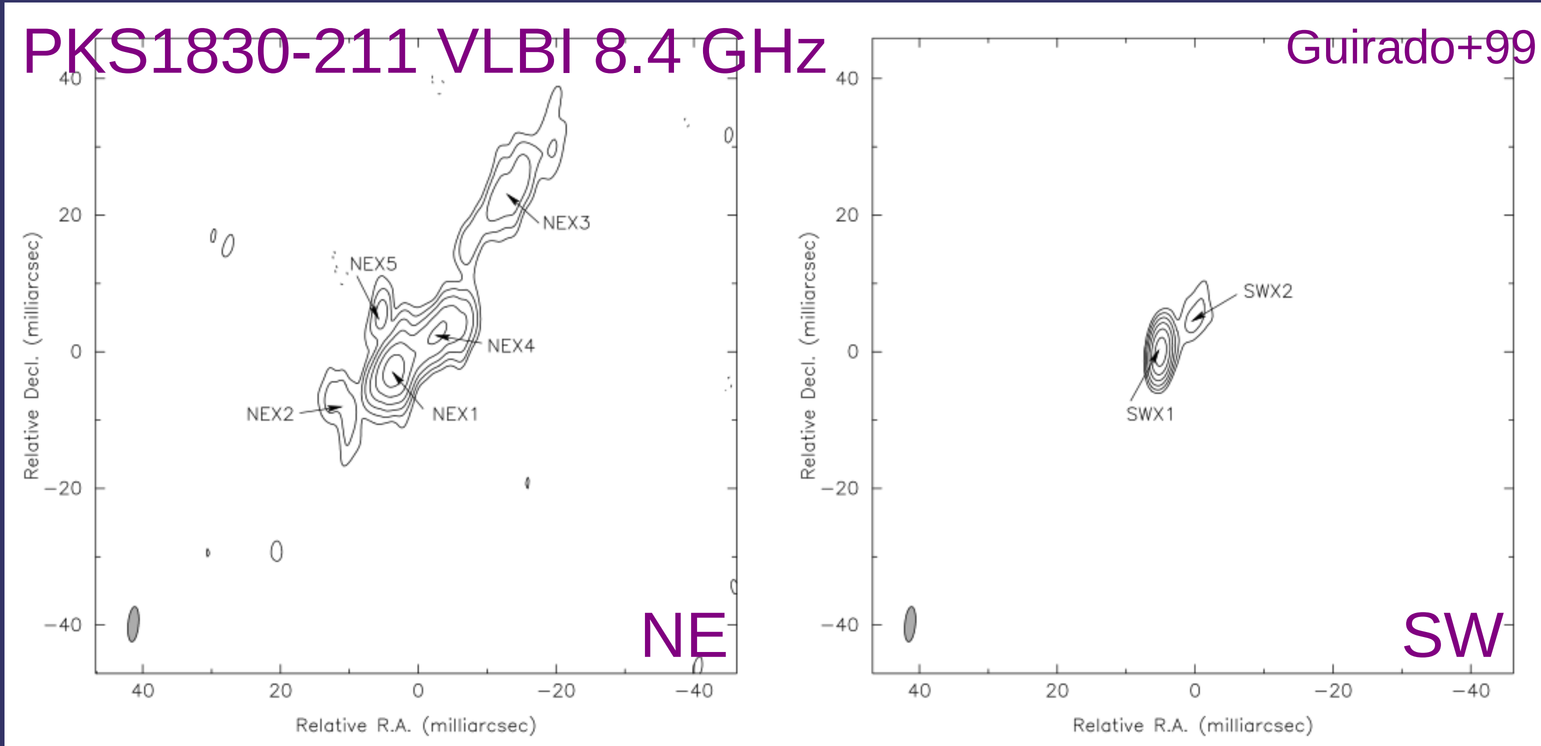

Fig. 1. Maps of the NE image (*left*) and SW image (*right*) of PKS 1830–211 at 8.4 GHz. Contours are -1,1,2,4,8,1

Molecules in absorption

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- In diffuse gas, the excitation of polar molecules is simple
  (low-collision regime, coupling with CMB photons)

- Line-to-continuum ratio can be converted directly into opacity
  Get (robust) column densities and chemical abundances

- Easy line identification (only low-energy levels populated, no confusion)

Extragalactic radio-mm molecular absorbers

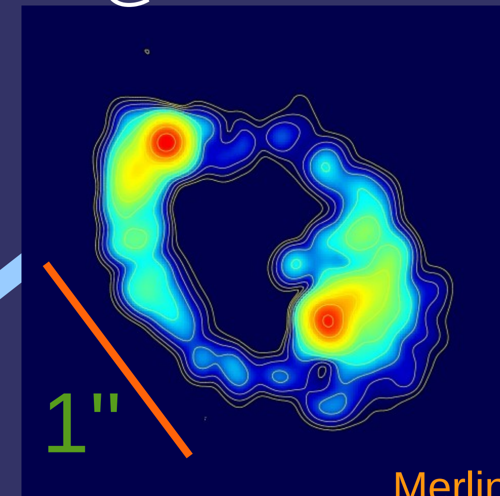
Source	z(abs)	Background continuum flux (Jy @3mm)	$N(H_2)$ (cm^{-2})	Molecules detected
Cen A	0.002	6	2×10^{20}	CO, OH, NH_3, CN, HCO^+, HCN, N_2H^+, C_2H, CS, H_2CO, C_3H_2
3C293	0.045		2×10^{19}	CO, HCO^+, HCN
4C31.04	0.060		1×10^{19}	CO, HCO^+, HCN
PKS 1413+135	0.247	0.5	5×10^{20}	CO, CN, HCO^+, HCN, HNC
B 1504+377	0.673	0.4	5×10^{20}	CO, HCO^+, HCN, HNC
B 0218+357	0.685	0.5 lensed	4×10^{21}	CO, NH_3, H_20, HCO^+, HCN, HNC, C_2H, CS, H_2S, H_2CO
PKS 0132-097	0.765	0.4 lensed		OH, CO, HCO+
PKS 1830-211	0.886	2-3 lensed	2×10^{22}	**> 50 species** (not incl. isotopic variants)

@z>0.1

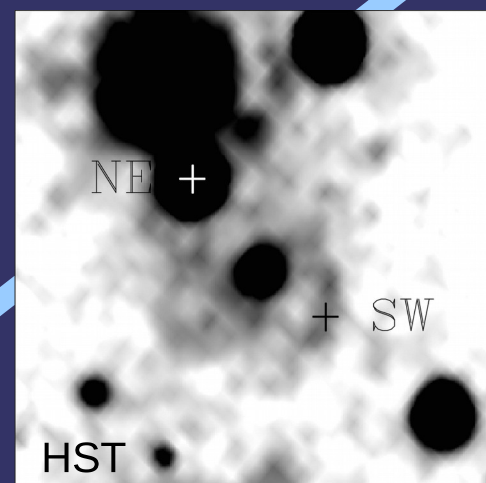
See Combes 2008, Wiklind et al 2018

The line(s) of sight to PKS1830-211

Lensed blazar
@ z=2.5

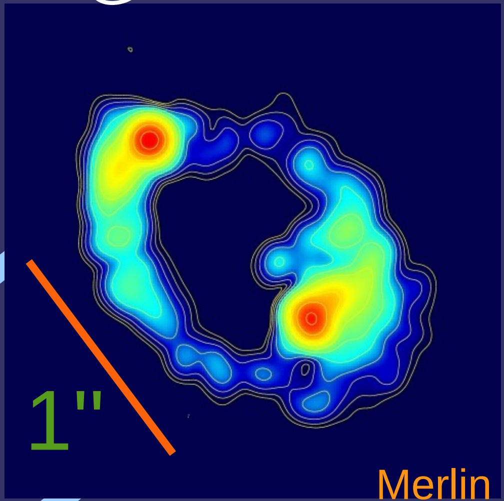


Foreground
nearly face-on spiral galaxy
@ z=0.89

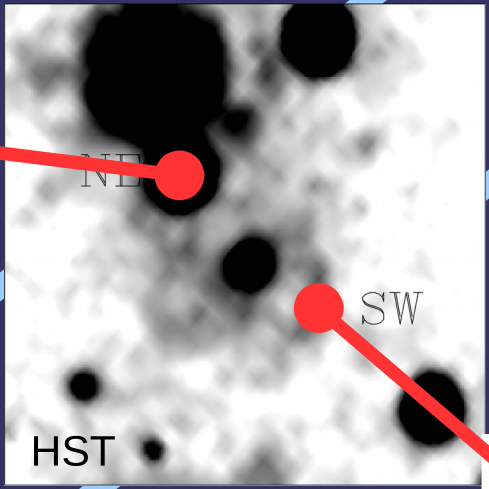


The line(s) of sight to PKS1830-211

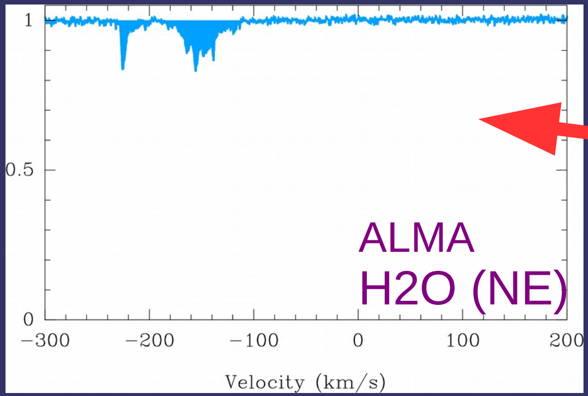
Lensed blazar @ z=2.5



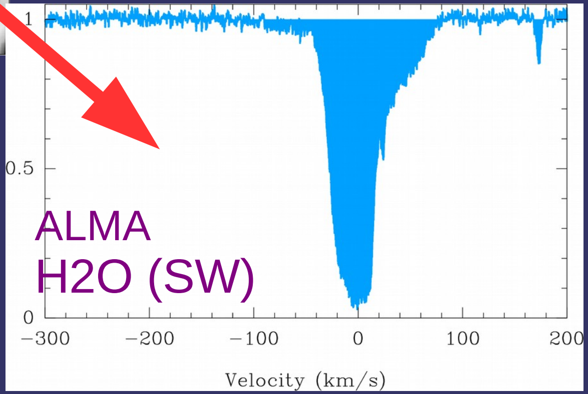
Absorber = nearly face-on spiral galaxy @ z=0.89



~ mas / pc scale



$N(H_2) \sim 1 \times 10^{21}$ cm^{-2}



$N(H_2) \sim 2 \times 10^{22}$ cm^{-2}

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	CH+ (*)	H_2O (**)	H_2CO (**)	c-C_3H_2	CH_3CN	CH_3CCH
	OH	H_2O^+	l-C_3H	l-C_3H_2	NH_2CHO	CH_3CHO
	OH+	C_2H	HNCO	H_2CCN		
	HF	HCN (**)	HOCO+	H_2CCO		
	CN	HNC (**)	H_2CS	C_4H		
	CO (**)	N_2H^+		HC_3N		
	CF+	HCO+ (***)				
	SH+ (*)	HCO				
	HCl (*)	HOC+				
	ArH+ (*)	H_2S (**)				
	SiO (**)	H_2Cl^+ (*)				
	CS (*)	HCS+				
	NS	C_2S				
	SO					
	SO+					

51 species detected

+ 24 isotopic variants (*)

Including 14 hydrides

All (exc. H and OH) observed at mm/submm
e.g., Muller et al. 06, 11, 13, 14, 16, 17
PdBI, ATCA, ALMA cycle 0,1,2

Upper limits on D-species, H_2F^+, O_2, ...

@ z=0.89 !

Chemical inventory toward the **NE** los

1 atom	2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms
H	CH		NH_3			
C	CH+ (*)	H_2O	H_2CO	c-C_3H_2		
	OH	H_2O^+				
	OH+	C_2H				
	HF	HCN				
		HNC				
	CO					
		HCO+				
	ArH+ (*)					
		H_2Cl^+ (*)				

19 species detected

+ 3 isotopic variants (*)

Including 10 hydrides

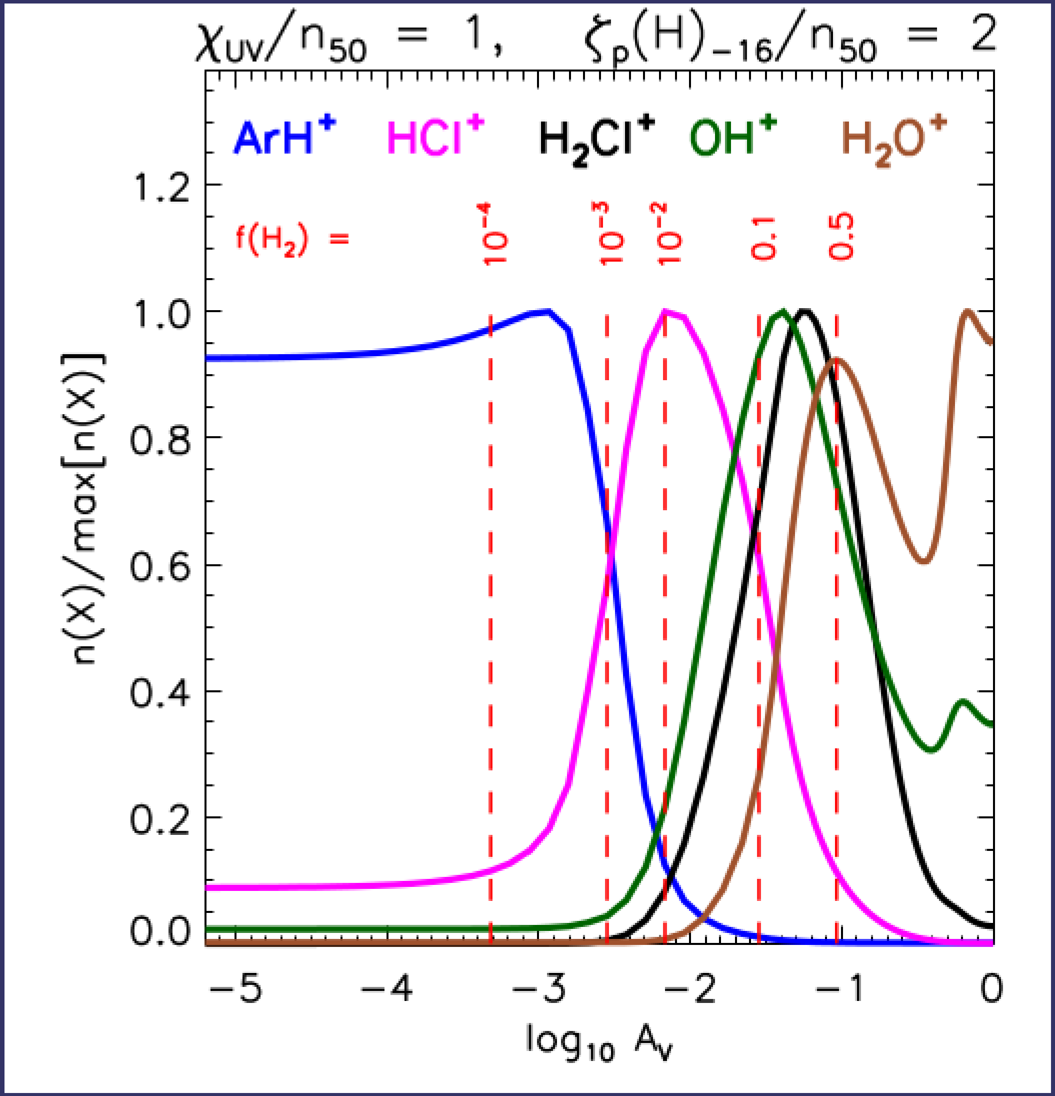
All (exc. H and OH) observed at mm/submm
e.g., Muller et al. 06, 11, 13, 14, 16, 17

PdBI, ATCA, ALMA cycle 0,1,2,3

@ z=0.89 !

Hydrides as critical diagnostics of the physics and chemistry of the ISM

Chemical predictions
Physics and chemistry of diffuse clouds



e.g. Neufeld & Wolfire 2016:

Ingredients:

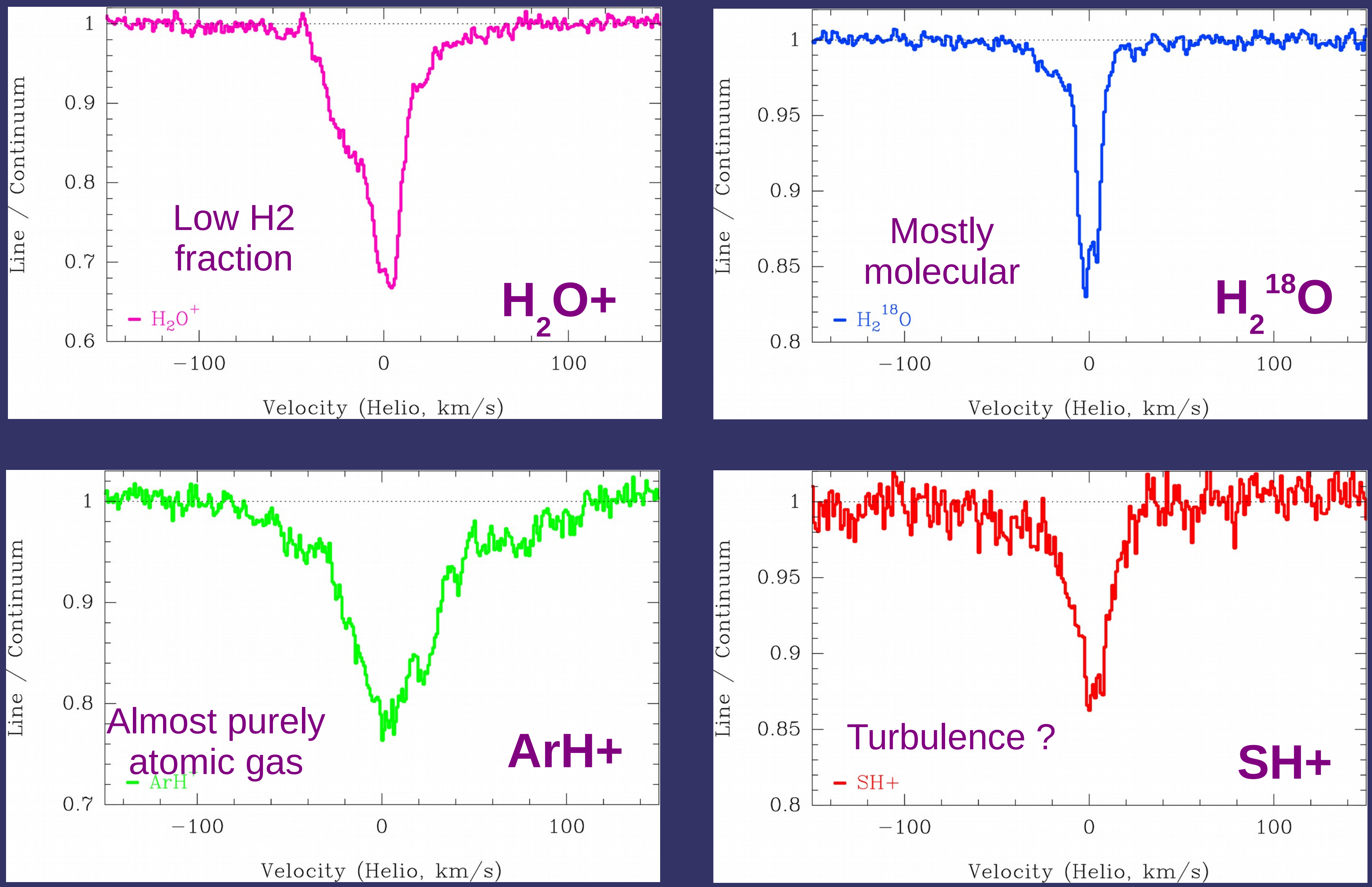
UV radiation field
Cosmic-ray ionization
Cloud extinction
Chemistry

Sequence:

ArH+ - HCl+ - H2Cl+ - OH+ - H2O+

Reaching peak abundance
At increasing molecular fraction

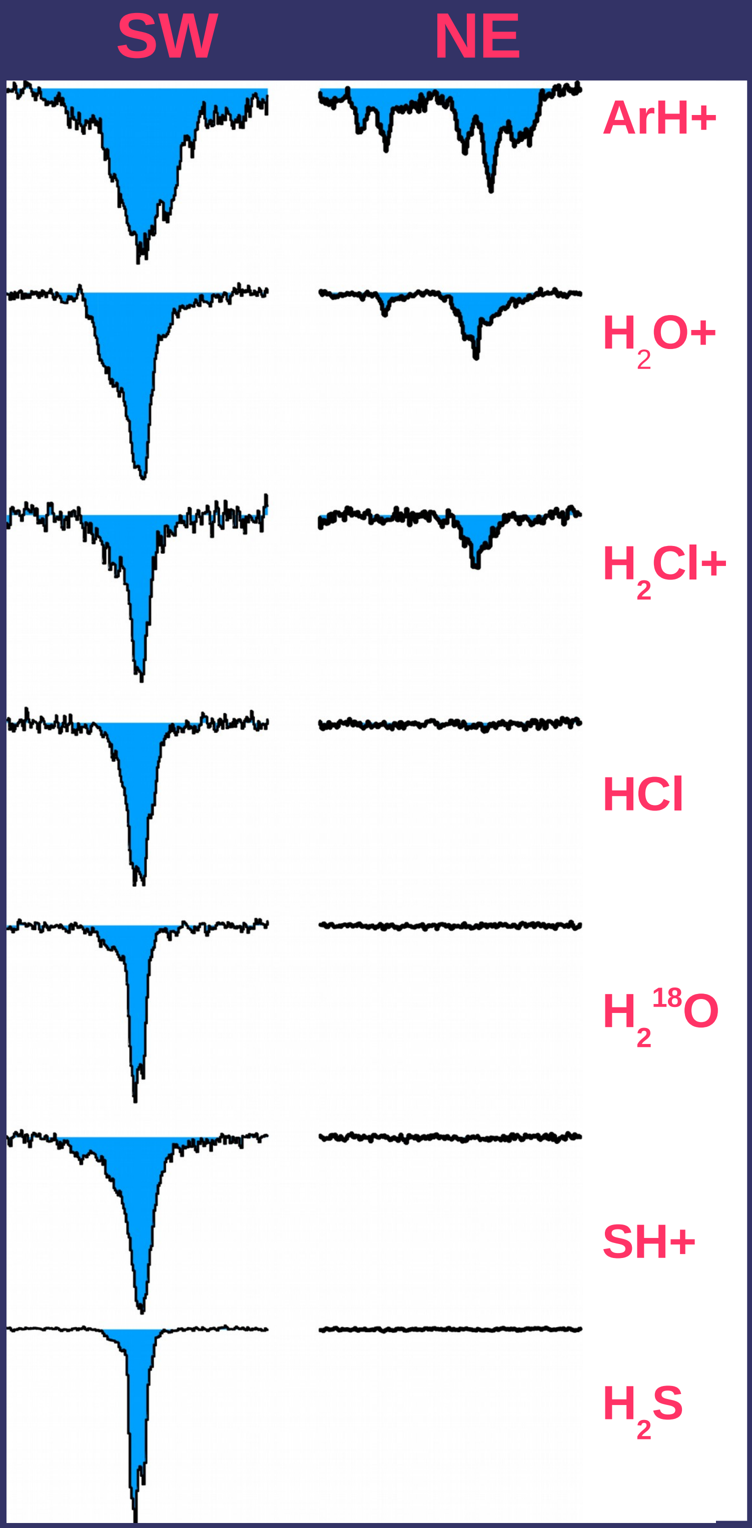
Comparison of SW line profiles



>> different gas components along the line of sight

ALMA cycle 2

Comparison of the two los toward PKS1830-211



Enhanced NE / SW ratio

Diffuse gas tracers
Low molecular fraction

No detection toward NE

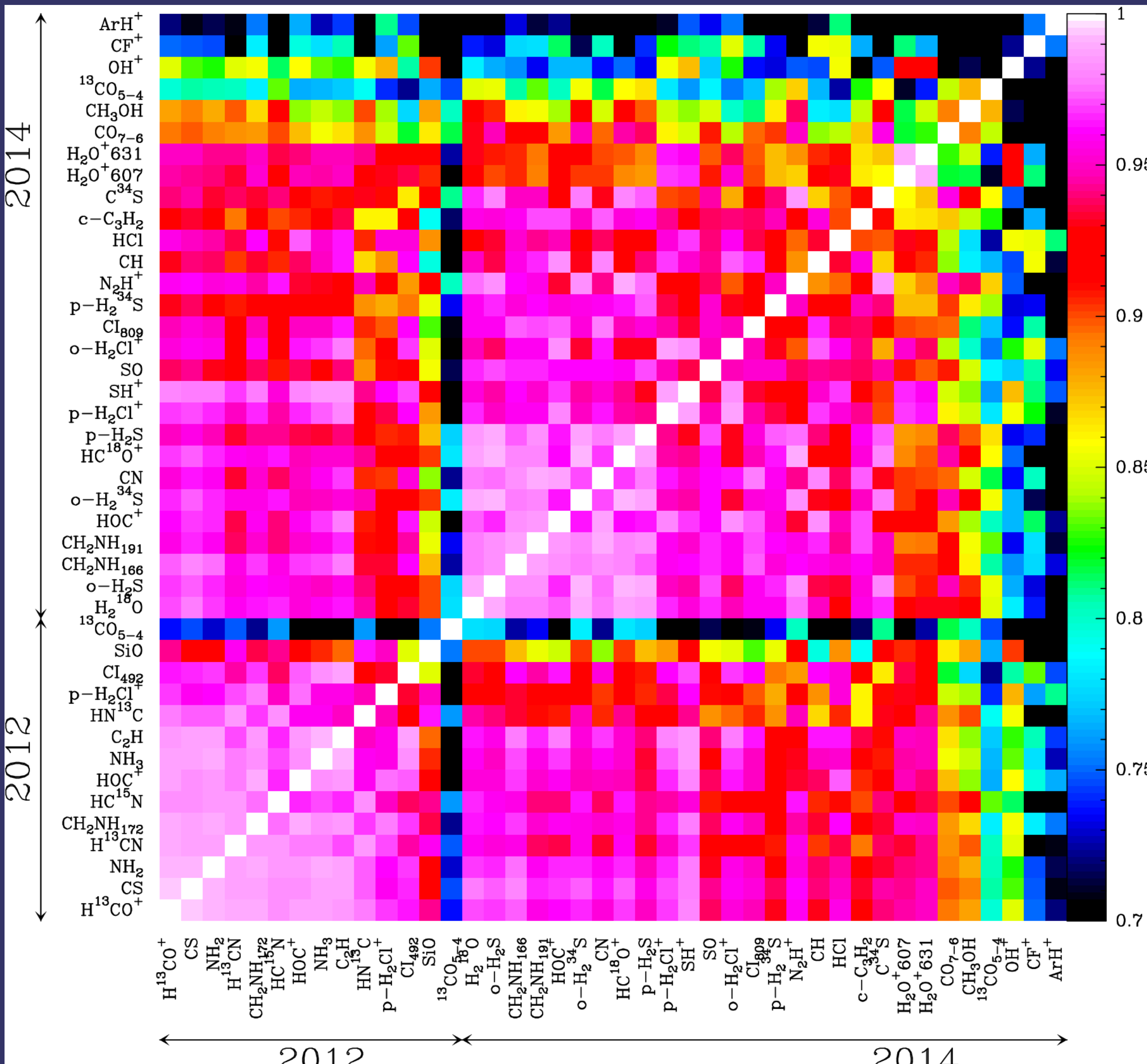
High molecular fraction tracers

Species	Column densities (cm^{-2}) SW	NE	Ratio SW/NE
HI	1.3×10^{21}	2.5×10^{21}	0.5
ArH^+	2.7×10^{13}	1.3×10^{13}	2.1
OH^+	1.6×10^{15}	7.6×10^{14}	2.2
H_2Cl^+	1.4×10^{13}	3.7×10^{12}	3.8
H_2O^+	2.7×10^{14}	7.0×10^{13}	3.9
CH^+	9.7×10^{14}	1.9×10^{14}	5.1
CH	7.7×10^{14}	3.5×10^{13}	22
HF	$>3.4 \times 10^{14}$	0.18×10^{14}	>19
SH^+	3.9×10^{13}	$<3.2 \times 10^{11}$	> 120

Tracers of increasing molecular fraction

→ multi-phase composition of the absorbing gas

Chemical correlation – ALMA spectra – SW los



ArH+ is the weird guy (tracing almost purely atomic)

CF+, 13CO, CH3OH, OH+

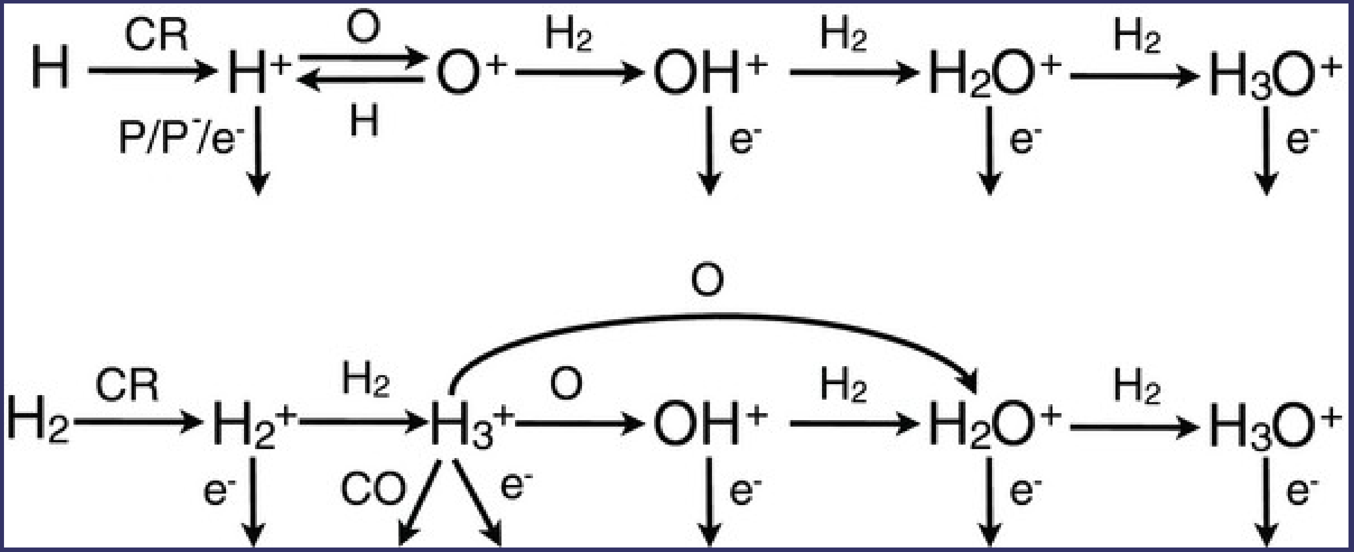
Also different from the bulk of Standard molecules:

HCO+, HCN, CS, HOC+, CH2NH, NH3, ...

in prep

Fraction of molecular hydrogen
Cosmic-ray ionization rate of atomic hydrogen

OH+ and H2O+ chemistry network:



Hollenbach et al 2012

The relative abundances of OH+ / H2O+ provide estimates of:

- the molecular fraction f(H2)

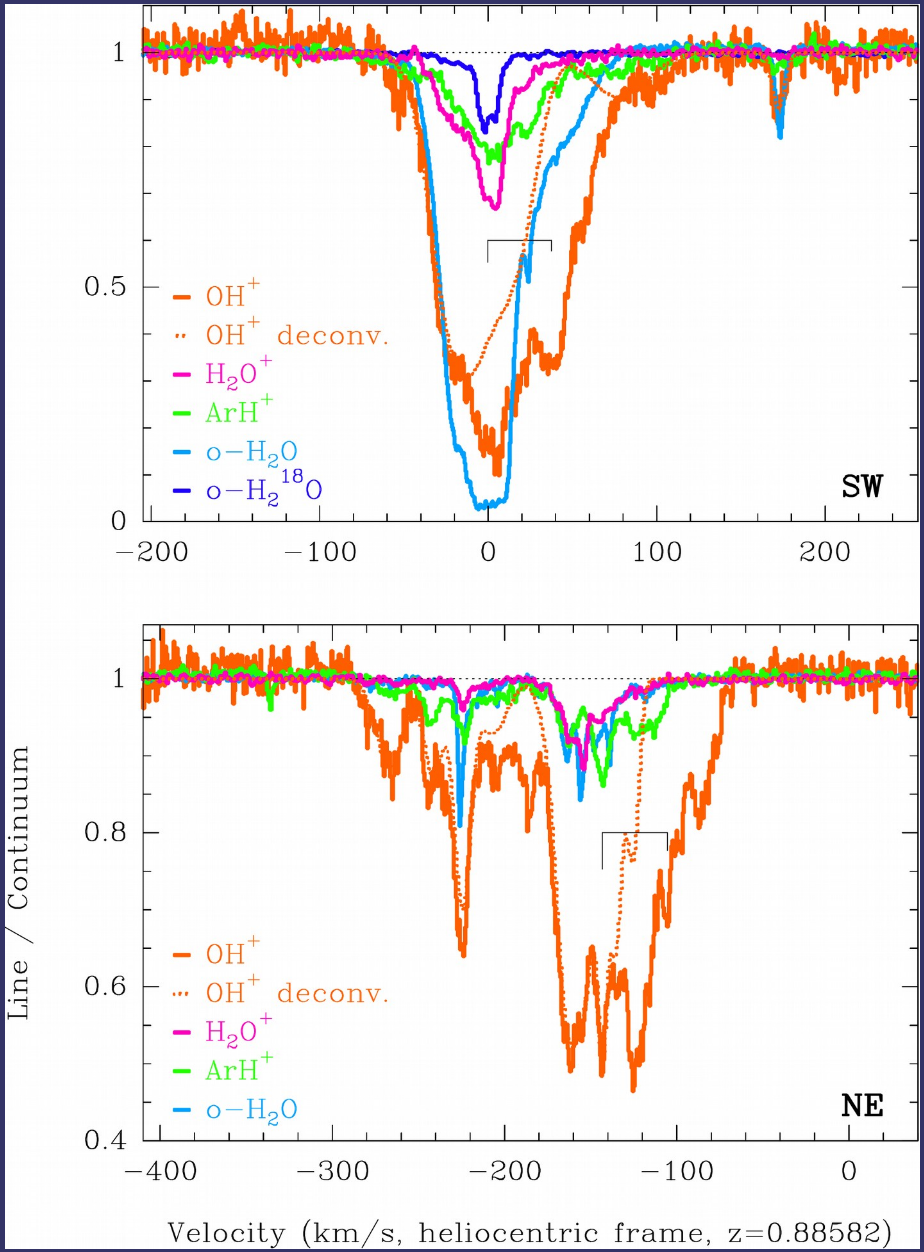
$$f_{\mathrm{H_2}} = \frac{2 x_e k_7 / k_4}{N(\mathrm{OH^+})/N(\mathrm{H_2O^+}) - k_6/k_4}.$$

- the cosmic-ray ionization rate of atomic hydrogen

Indriolo et al 2015

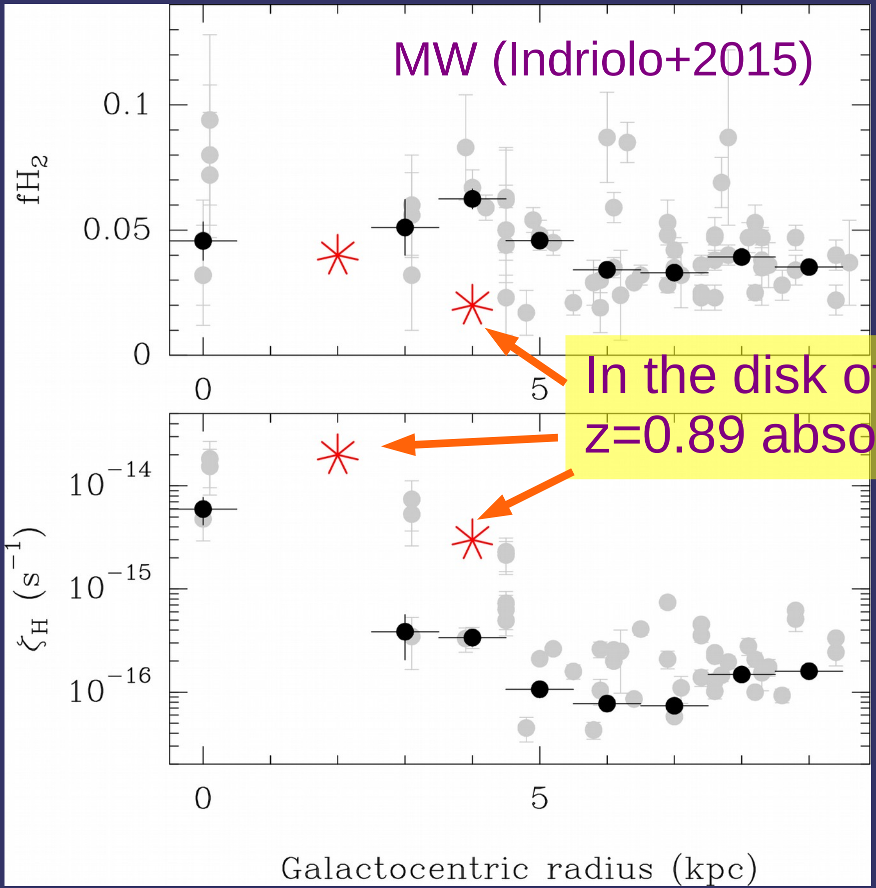
$$\epsilon \zeta_{\mathrm{H}} = \frac{N(\mathrm{OH^+})}{N(\mathrm{H})} n_{\mathrm{H}} x_e \left[\frac{k_7}{N(\mathrm{OH^+})/N(\mathrm{H_2O^+}) - k_6/k_4} + k_5 \right]$$

Fraction of molecular hydrogen
Cosmic-ray ionization rate of atomic hydrogen



Use OH+ and H2O+ relative abundances
See e.g. Hollenbach+2012, Indriolo+2015

(Caveat: fractional abundance of electrons)



Muller et al 2016

Summary “Chemistry in PKS1830”

- Chemistry typical of diffuse/translucent clouds in the MW

- Hydrides reveals the multi-phase composition of the absorbing gas

- Observations of species difficult to observe from the ground at *z*=0
  e.g. H2O, OH+, ...

- Herschel in the MW (PRISMAS) <=> ALMA at z=0.89
  e.g., CH+, OH+, H2O+, HF, ArH+, …
  with high-quality spectral baseline and no contamination by emission

- Search for new interstellar molecules (or get deep upper limits)

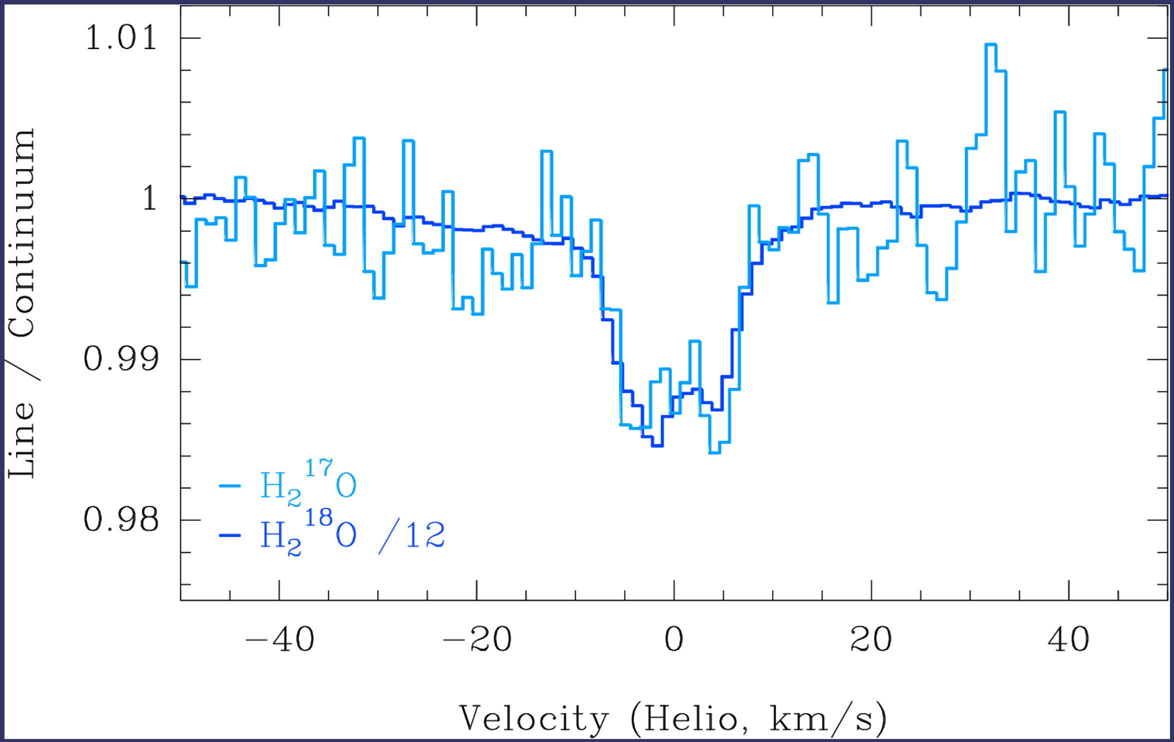
Isotopic ratios and constraints on nucleosynthesis

For molecular absorbers at intermediate redshift z=0.68 – 0.89:

- Look-back time of about half the current age of the Universe
- Possible to measure isotopic ratios of C, N, O, S, Si, Cl, Ar
- Evolution effects already visible
- Low mass stars (< ~1.5 Mo) have no time to contribute

>> Signature from massive star nucleosynthesis

Oxygen



ALMA Cycle 1 & 2

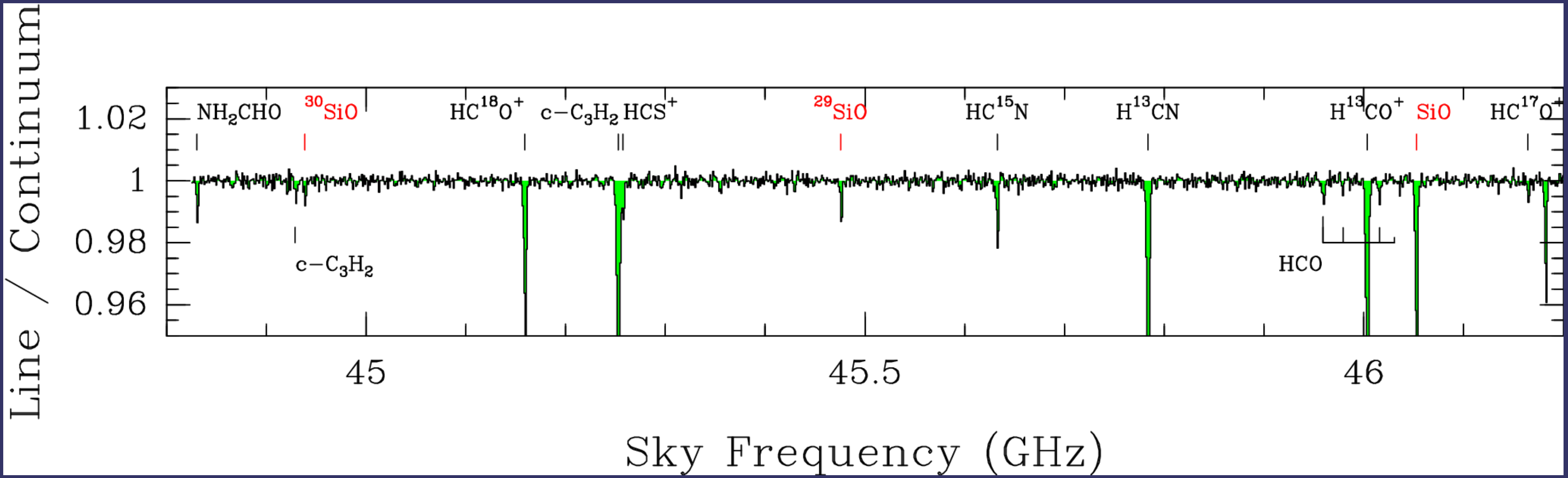
$^{18}O/^{17}O$ = 12 +- 2 @ z=0.89

Solar = 5.5

ISM = 3.5 +- 0.2

AGB IRC+10216 = 0.7 +- 0.2

Silicon



ATCA, Muller et al 2011, 2013

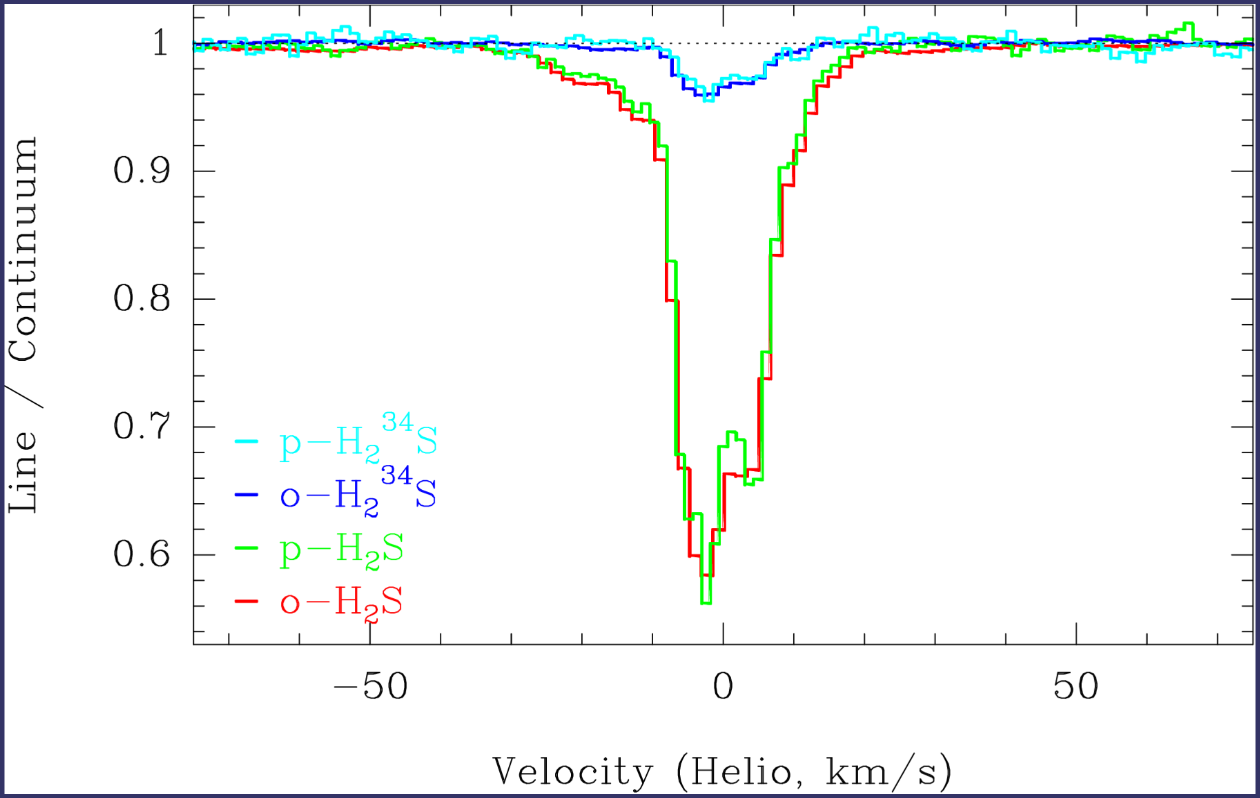
ATCA 2011 -> $^{28}Si/^{29}Si = 6.5 \pm 0.5$ @ z=0.89

-> $^{29}Si/^{30}Si = 1.8 \pm 0.3$

Earth and local ISM: $^{28}Si/^{29}Si = 20$

$^{29}Si/^{30}Si = 1.5$

Sulfur



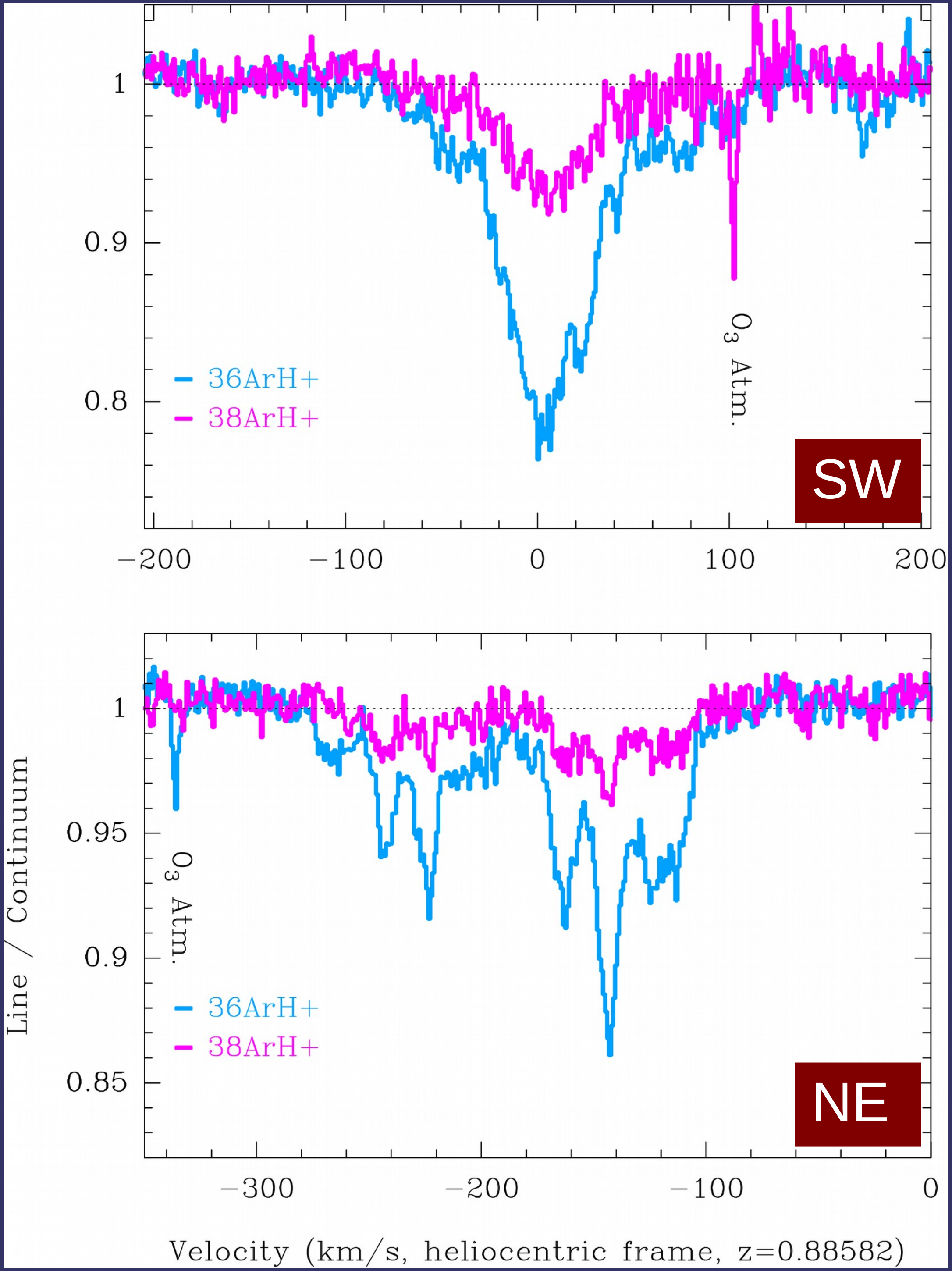
$^{32}S/^{34}S \sim 12$ @ z=0.89

ALMA Cycle 2

Solar = 22

ISM = 19 +- 8 (Lucas & Liszt 1998)

AGB IRC+10216 = 21.8 +- 2.6 (Cernicharo et al 2000)



Argon

Detection of argonium in SW & SW los:

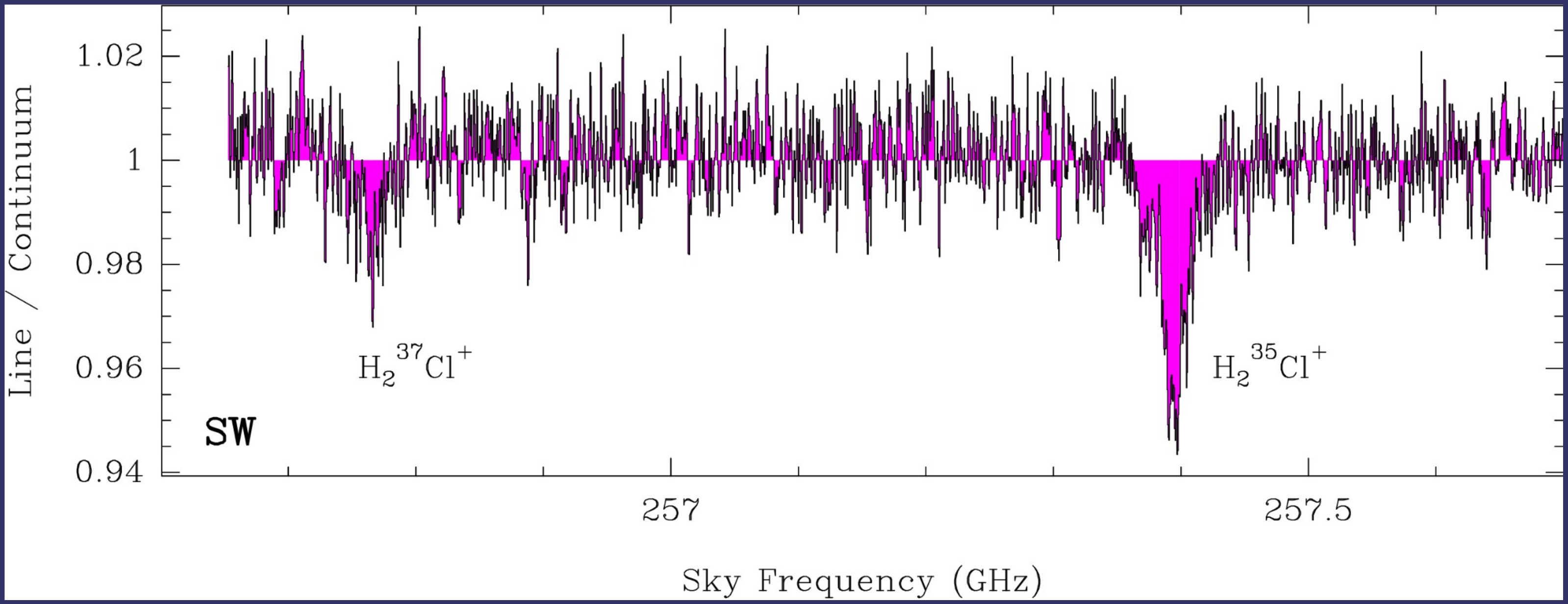
$^{36}Ar/^{38}Ar$ = 3.46 +/- 0.16 (SW)
= 4.5 +/- 0.3 (NE)
@z=0.89

Müller H., Muller S., et al 2015

Solar value: 5.5

Alpha-elements Si, S, Ar all have different ratios than solar ...

Chlorine



Detection of chloronium $H_2{}^{35}Cl^+$ and $H_2{}^{37}Cl^+$ toward PKS1830-211

ALMA Cycle 0 – Muller et al 2014b

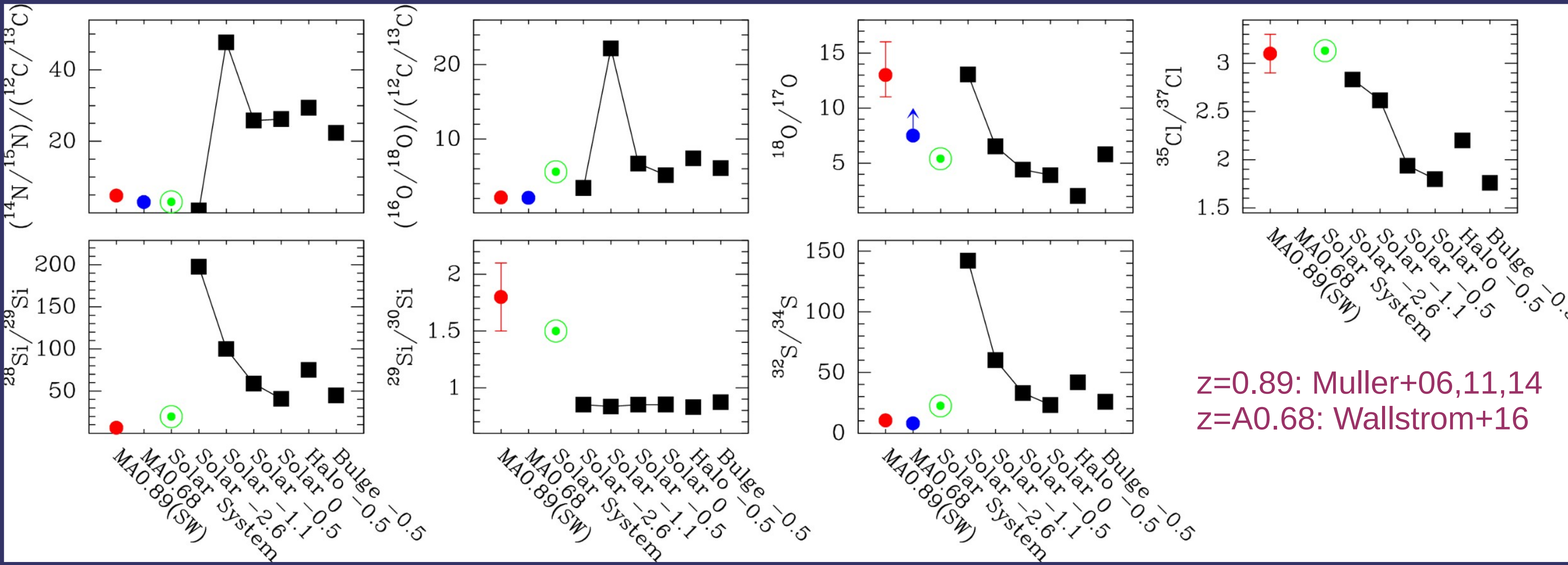
-> $^{35}Cl/^{37}Cl = 3.1^{+0.3}_{-0.2}$ @z=0.89

$^{35}Cl/^{37}Cl$ = 3.1 Earth

= 3.1 +- 0.6 AGB IRC+10216 (Cernicharo et al 2000)

= 1 – 5 in various Galactic sources (Cernicharo et al 2010, Peng et al 2010)

Comparison with time / metallicity evolution models



Models from Kobayashi et al 2011

Solar neighbourhood at [Fe/H] = -2.6 (metal-poor SNe II)
-1.1 (SNe II + AGB)
-0.5 (SNe II + AGB + SNe Ia)

Halo and Bulge components

But, what is the metallicity, IMF, SFR in the molecular absorbers ?

Summary

Molecular absorbers at intermediate redshift:

- Probe the interstellar chemistry and physical conditions in the disk of distant galaxies

Molecules as cosmological probes:

- Evolution of the CMB temperature with redshift
- Test of invariance of fundamental constants
- Isotopic ratios and constraints on nucleosynthesis

Strong interests to find more absorbers, hopefully at z>1 !