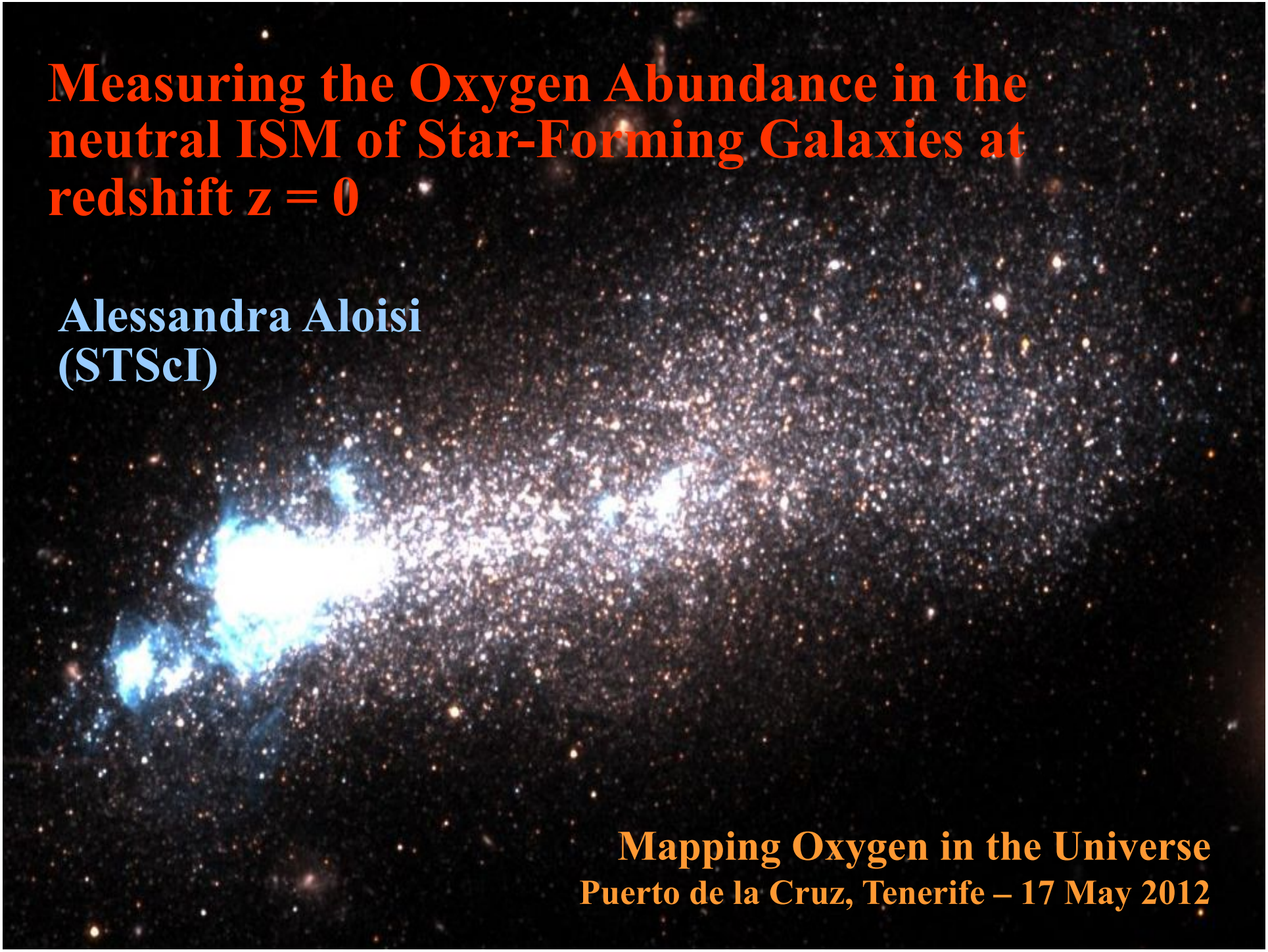
Measuring the Oxygen Abundance in the neutral ISM of Star-Forming Galaxies at redshift z = 0

Alessandra Aloisi
(STScI)



Mapping Oxygen in the Universe
Puerto de la Cruz, Tenerife – 17 May 2012

Measuring the Oxygen Abundance in the neutral ISM of Star-Forming Galaxies at redshift z = 0

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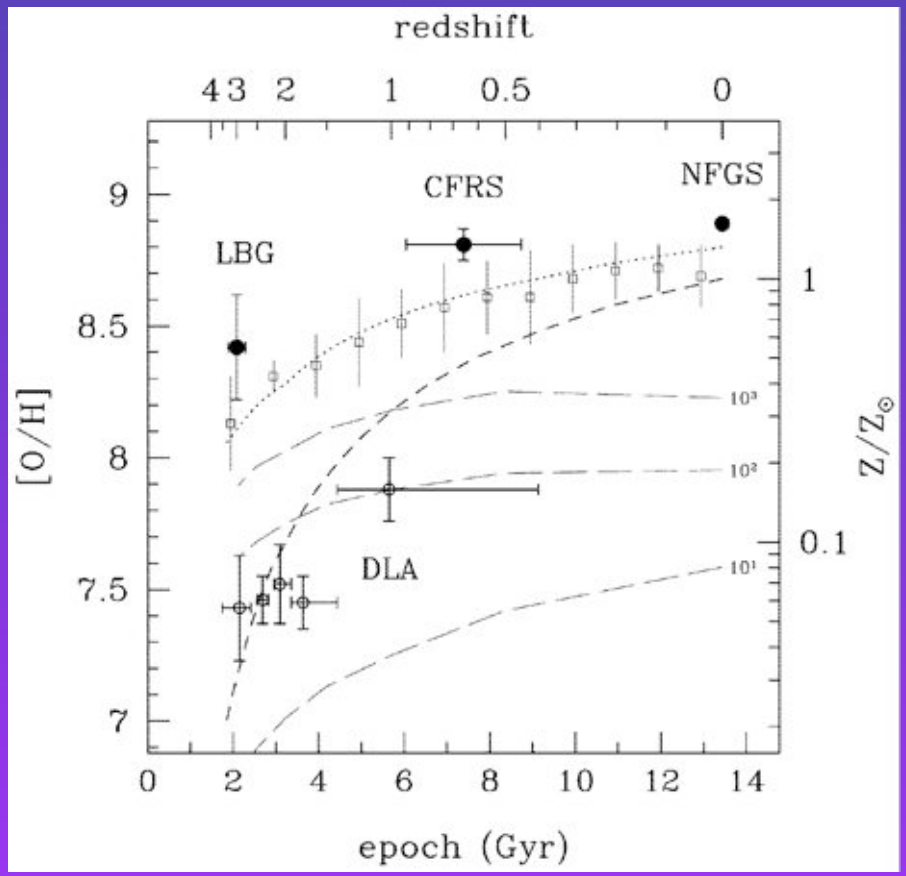
Why measuring Abundances in the Neutral ISM of SFGs ?

Abundances in SFGs inferred from O in nebular (emission-line) spectra of HII regions. However:

- ✓ **HII regions may suffer from self-enrichment** *(Kunth & Sargent 1986)*
- ✓ **Bulk of metals in SFGs may be in neutral gas (up to 90-95% for BCDs)**

Need to infer abundances in neutral ISM through UV absorption-line spectra !

Importance of this Kind of Studies



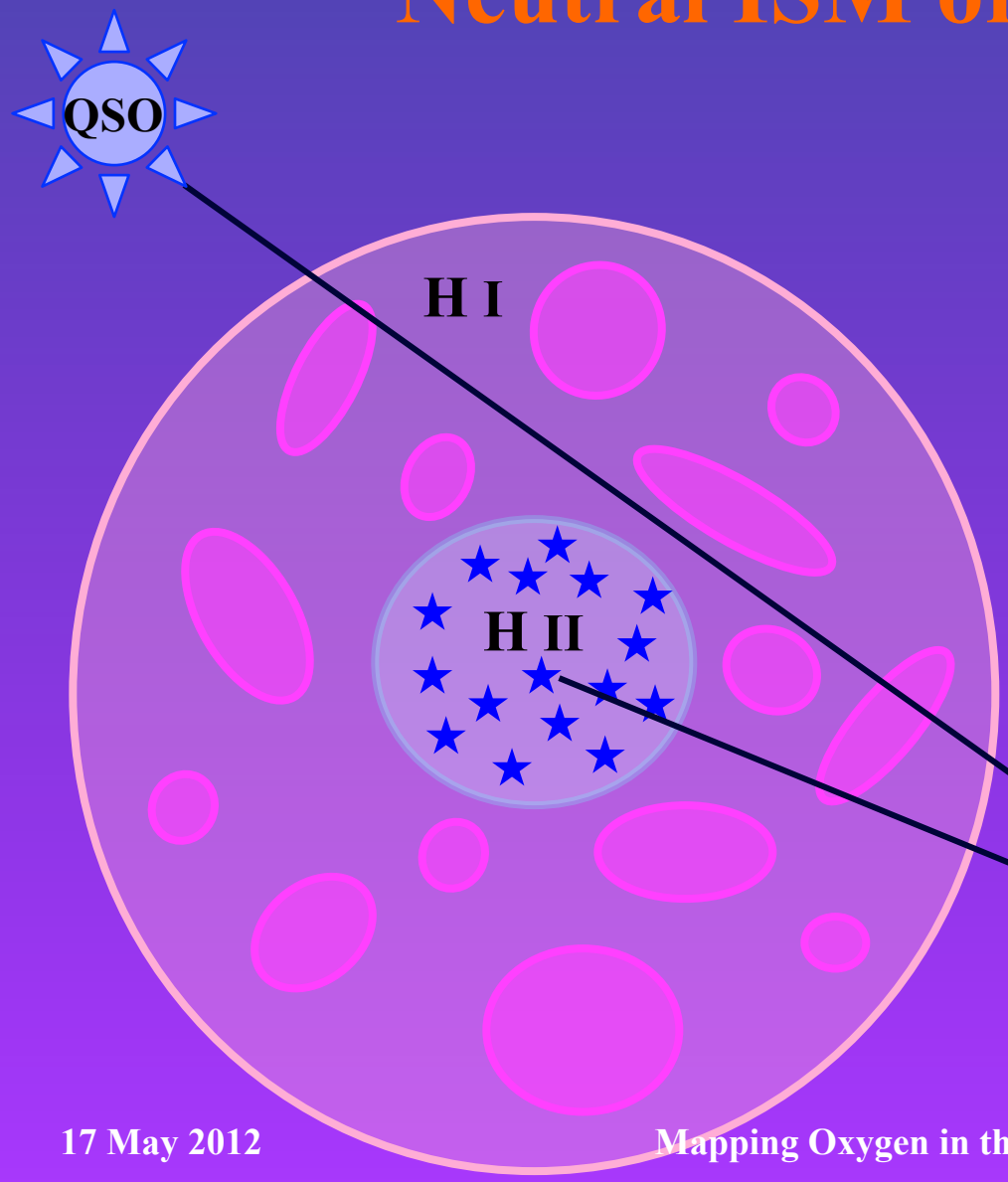
Lilly et al. (2003)

- Solid circles: [O/H] from em lines
- Open circles: [Fe/H] from abs lines
- Lines: various theoretical models

Z offset of ~ 1 dex at high z between LBGs and DLAs

- High-z difference due to:
  - ✓ techniques (absorption vs emission)?
  - ✓ element considered (O vs Fe) ?
  - ✓ selection of samples ?
- Similar offset at z = 0 ?

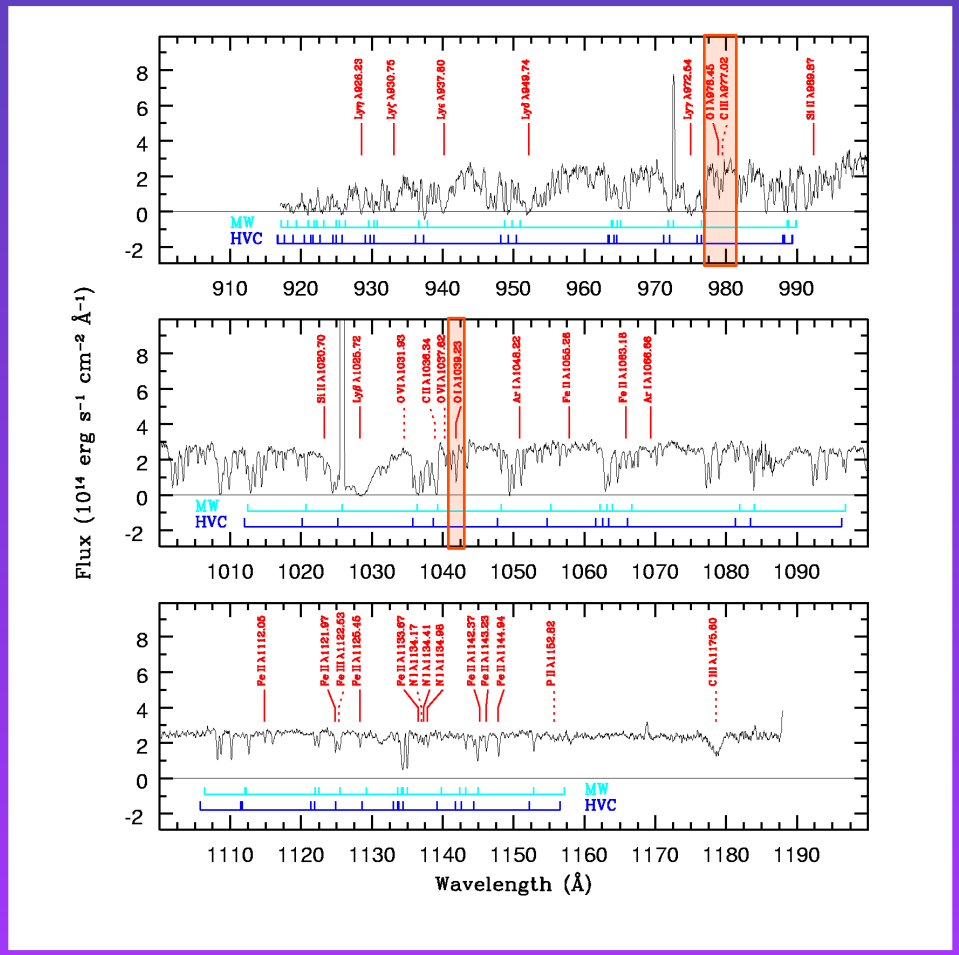
How to measure Abundances in the Neutral ISM of Galaxies



- QSOs as background UV sources
  - ✓ galaxy halos at z > 0.35
  - ✓ large impact parameters (10-150 kpc)
  - ✓ bright QSOs are rare
- HII regions/young clusters within galaxy as background UV sources
  - ✓ galaxy cores at z < 0.1 (D < 50 Mpc)
  - ✓ small impact parameters (1-5 kpc)
  - ✓ HII regions/young clusters abundant in SFGs

Example of Neutral Gas Abundances with FUSE: I Zw 18

Aloisi et al. (2003)



FUSE (900-1200 Å) suitable for most abundant species (v ~ 30 km/sec):

H I O I Ar I Si II
P II C II N I Fe II

Better constrained abundances are for Fe II (a lot of transitions with different strengths)

Several OI line available below 1040 Å, including the most used (and strongest) 976 and 1039 (in red)

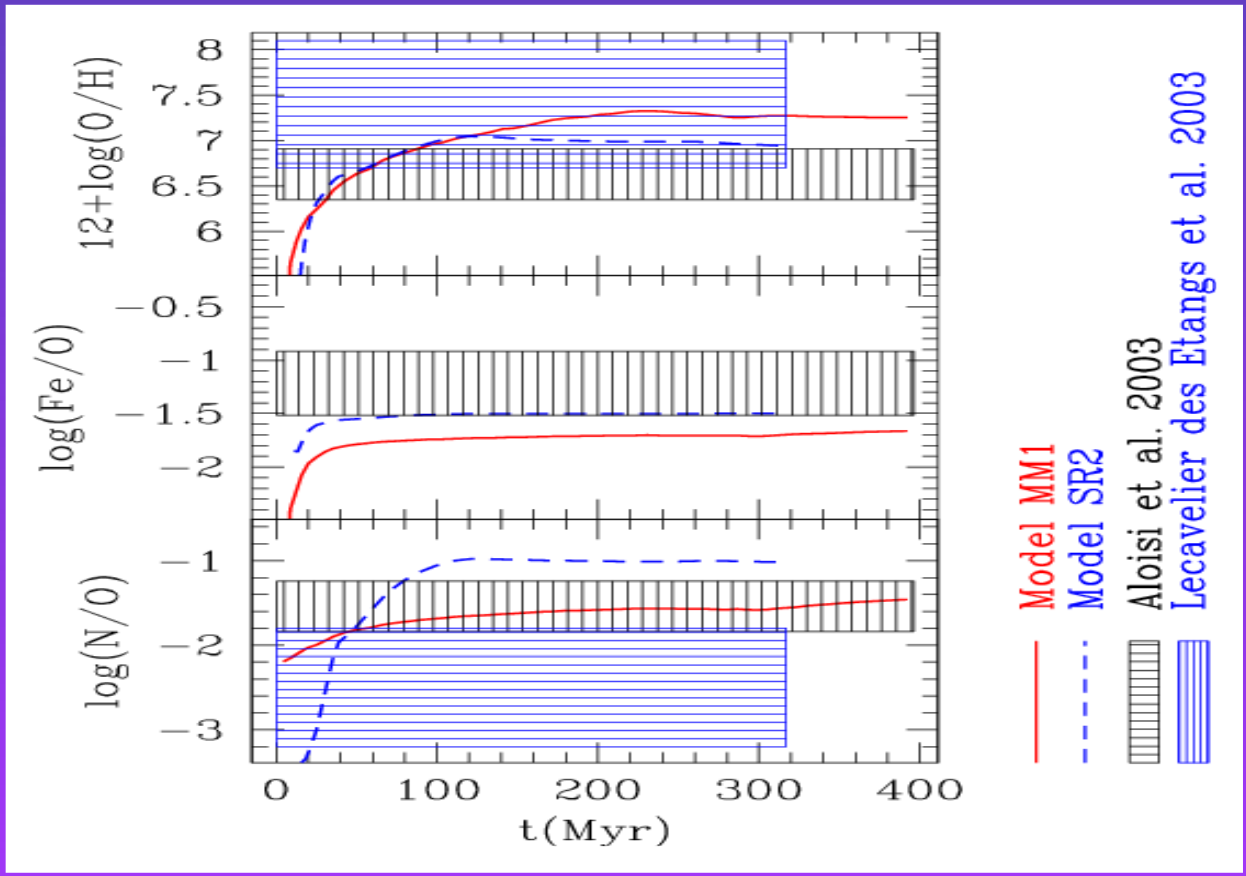
HI already enriched in heavy elements, i.e. not primordial

Existence of a Z offset between neutral & ionized gas, except for Fe

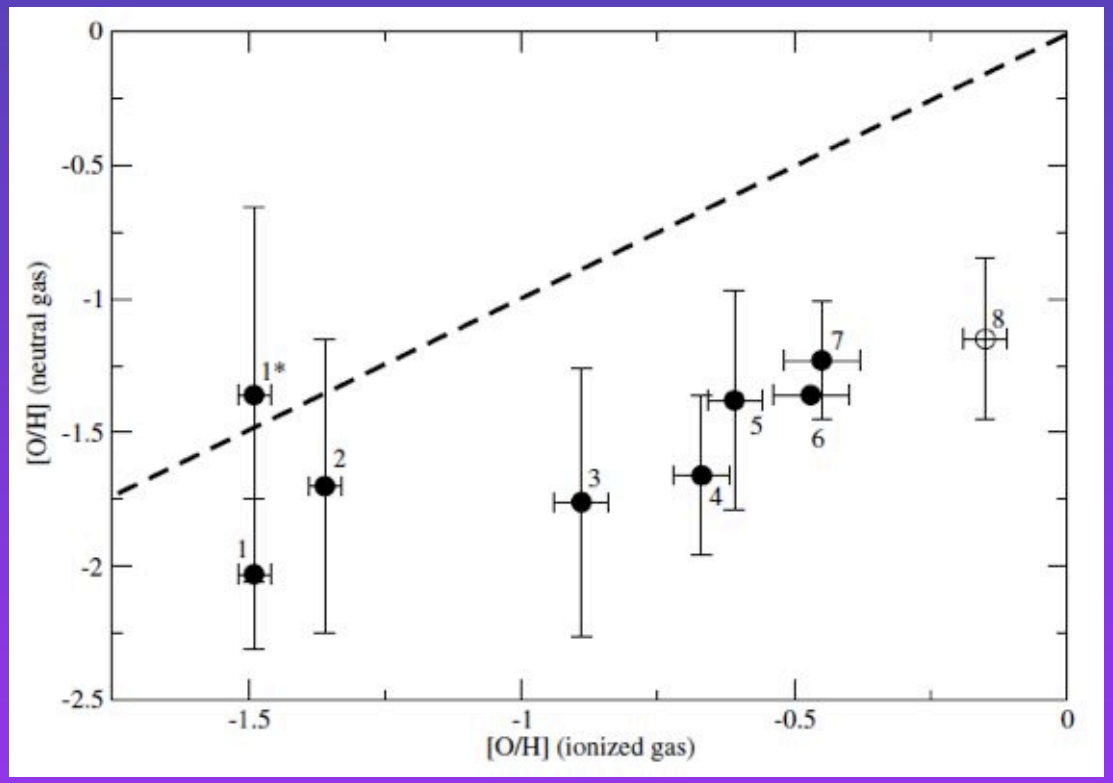
SF at least ~ 1 Gyr old required to explain Fe in ISM

Abundances in the Neutral ISM to constrain Chemical Evolution Models: I Zw 18

Recchi et al. (2004)



FUSE Results on Oxygen Abundances in the Neutral ISM of Local SFGs



1 I Zw 18 *Aloisi et al. (2003)*

1* I Zw 18 *Lecavelier des Etangs et al. (2004)*

2 SBS 0335-052 *Thuan et al. (2005)*

3 I Zw 36 *Lebouteiller et al. (2004)*

4 Mrk 59 *Thuan et al. (2002)*

5 Pox 36 *Lebouteiller et al. (2009)*

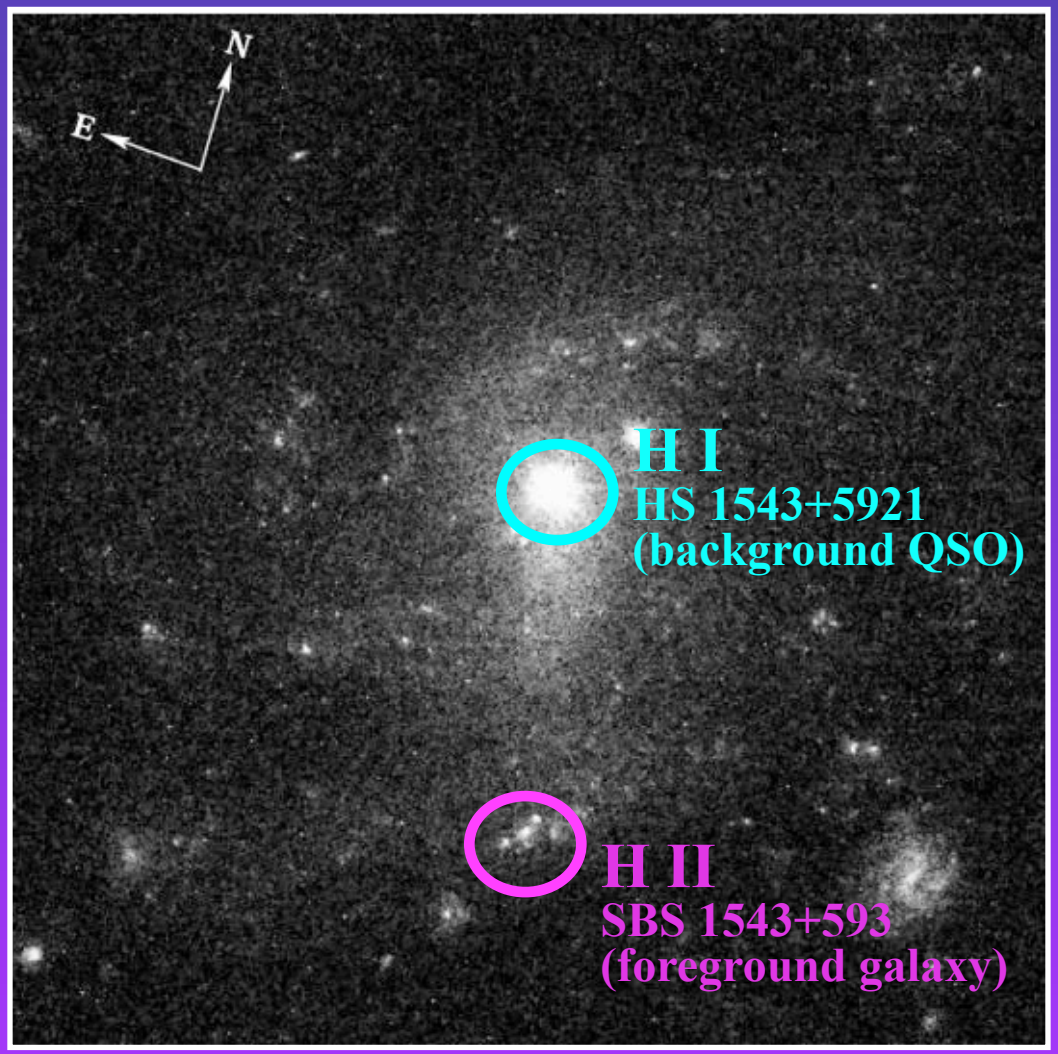
12 NGC 625 *Cannon et al. (2005)*

13 NGC 1705 *Heckman et al. (2001)*

16 NGC 604 (M33) *Lebouteiller et al. (2006)*

→ **H I more metal-poor than H II ?**
Are we looking at a large halo of HI in SFG galaxies?
H II regions not fair tracer of the ISM metallicity ?

A Counterexample: SBS 1543+593/HS 1543+5921



Schulte-Ladbeck et al. (2004, 2005)

- STIS abundances of the damped Lyα system toward QSO HS 1543+5921 (z=0.807)
- Emission-line abundances of the HII region in SBS 1543+593 (LSBG at D ~ 40 Mpc)

→

Neutral & ionized gas abundances agree

However, measurements where not along same sightline !

Caveats on Neutral Gas Abundances from FUSE Studies

Saturation/Hidden Saturation

- strong lines (e.g., O)
- unresolved multiple components due to large FUSE aperture used

Ionization

- ionization corrections (only some ions may be present)
- intervening ionized gas (S, Si, Mg, P, C, Fe, Al)
- partially ionized gas (N & Ar)

Depletion

- alpha-elements Si & Mg more than O, Ar & S
- Fe-peak element Fe (Cr, Co, Ni) more than Zn or Mn

Need to move to COS wavelengths to sample additional lines with different strength and additional ions!

COS Survey of Local SFGs

34 HST orbits in Cycle 17 to target 9 galaxies (program 11579, PI: Aloisi)

- **8 orbits of ACS/SBC pre-imaging** (archival data for SBS0335-052)
  - ✓ F125LP filter used (longwards of Lyα)
  - ✓ Data taken Jan-Mar 2009 (before SM4)
  - ✓ ACS/WFC, ACS/HRC, WFPC2 archival data used for ACS/SBC red leak
- **26 orbits of COS/FUV spectroscopy**
  - ✓ one sightline in each galaxy of the sample
  - ✓ second sightline in M83 and NGC5253
  - ✓ spectra acquired in Nov 2009 – May 2011
  - ✓ spectral range covered ~ 1150 − 1450 Å
  - ✓ spectral resolution v ~ 18 km/sec
  - ✓ S/N ~ 10-30 per resolution element (~ 6 pixels)

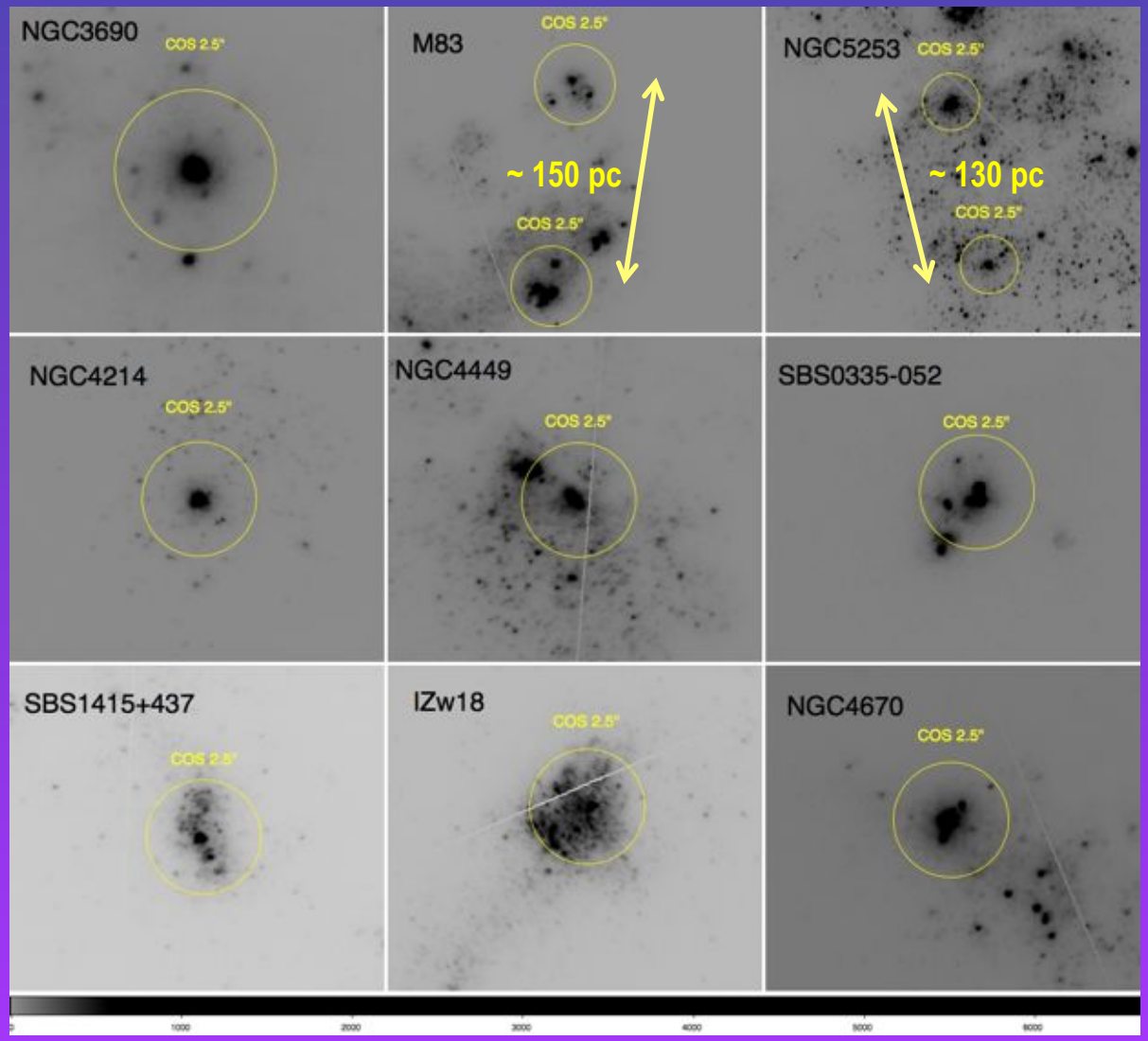
A couple of papers ready to be submitted !

Properties of the COS SFG Sample

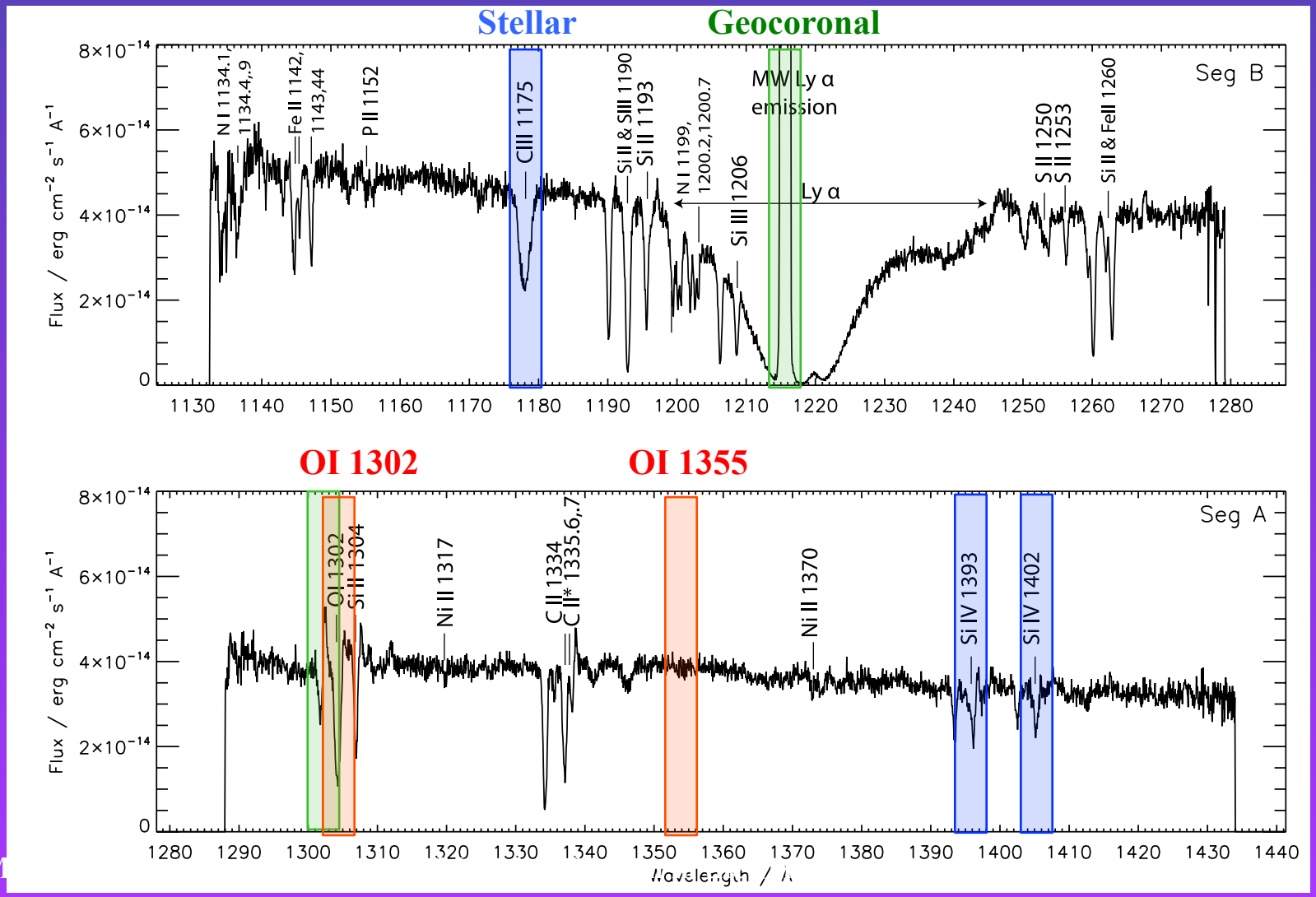
COS Sample of SFGs spans a wide range in Z, SFR, and type of galaxy, allowing to investigate the metallicity behavior of the neutral ISM as a function of the galaxy properties at z = 0

Name	Type	V (mag)	vel (km/s)	E(B-V) (mag)	12+log(O/H)	log(L_{UV}+L_{FIR}) (ergs/s)
M83	SBc	7.5	513	0.066	9.3	43.06
NGC 3690	Merger	12.0	3,119	0.017	8.8	45.06
NGC 4214	Irr	9.8	291	0.022	8.2	41.84
NGC 4449 NUC	Irr	9.6	203	0.019	8.4	42.38
NGC 4670	BCD	13.1	1,069	0.015	8.3	42.95
NGC 5253	Irr	10.4	403	0.056	8.2	41.77
SBS 0335-052	BCD	17.7	4,043	0.047	7.3	...
SBS 1415+437	BCD	15.6	609	0.009	7.6	41.83
I Zw 18	BCD	15.6	753	0.032	7.2	<41.82

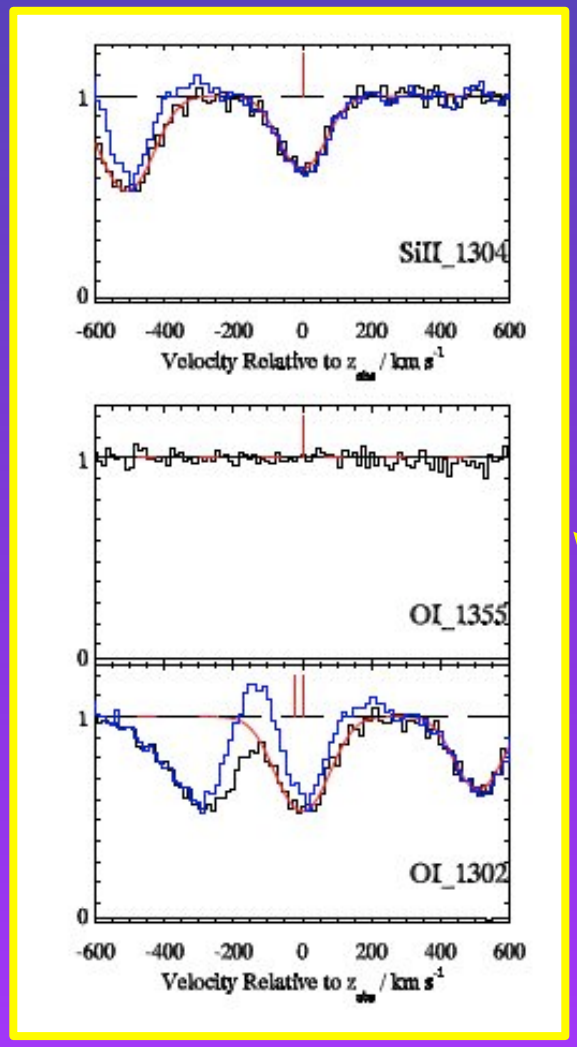
ACS/SBC Pre-Imaging of COS SFG Sample

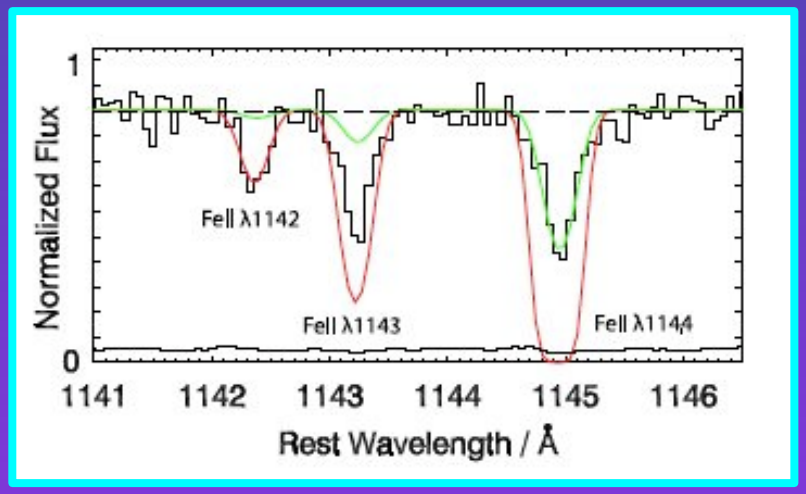


Example of Neutral Gas Abundances with COS/FUV: SBS 1415+437



Some Obstacles to Overcome in the ISM Abundance Determinations with COS

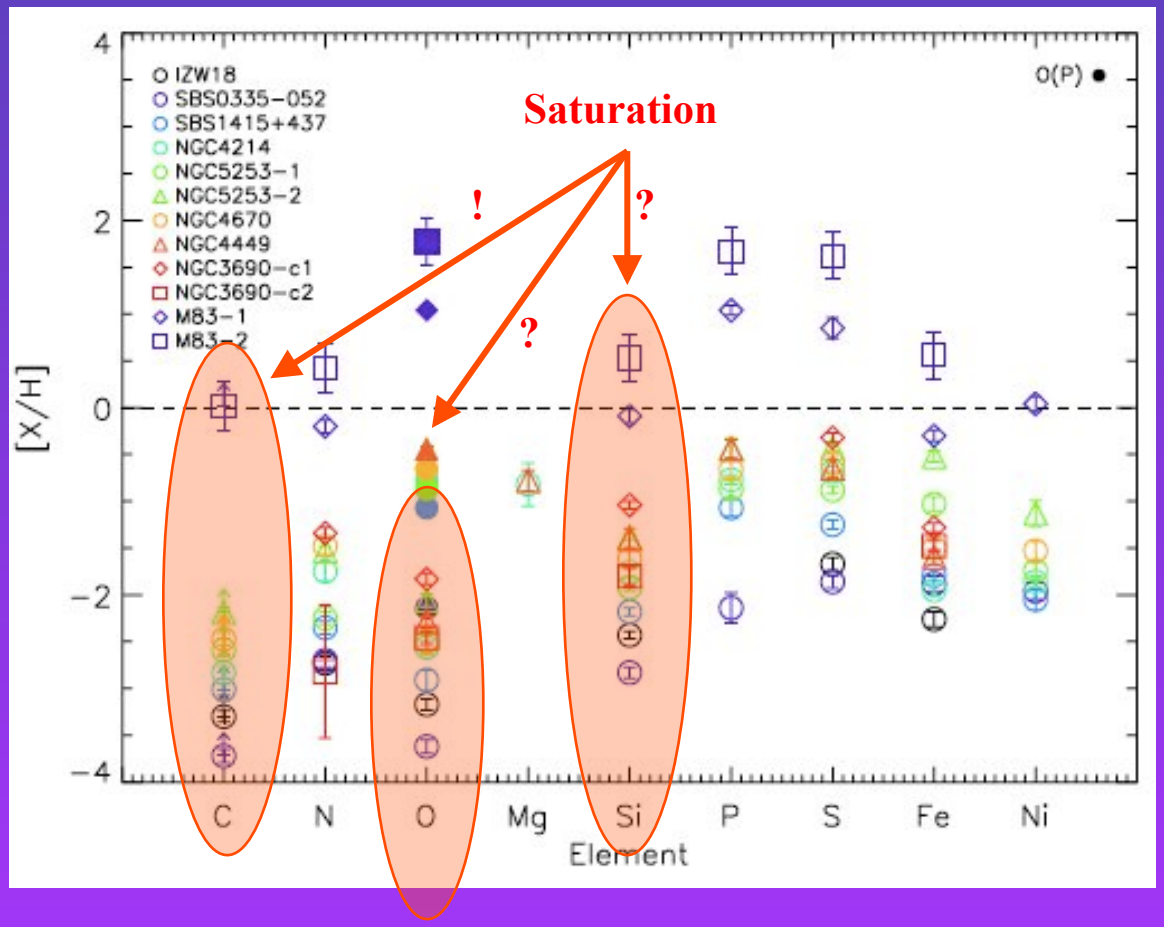




Effects of Hidden Saturation:
Despite the strongest line does not appear saturated, its fit (green) does not properly reproduce the weakest lines, thus uncovering hidden saturation. The abundance is better estimated in this case by fitting the weakest line (red)

Removal of Geocoronal Contamination:
notice that after the removal, the shape of the OI λ1302 line in velocity space is similar to SiII λ1304

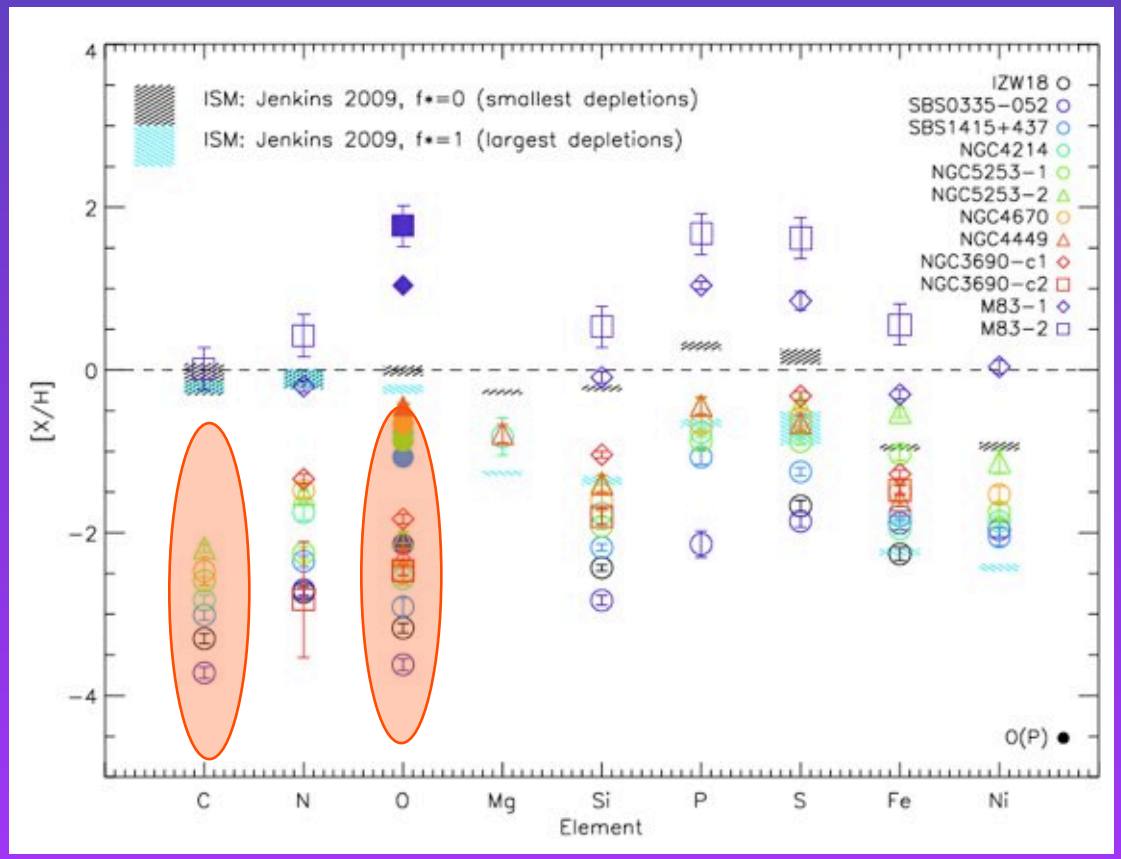
Neutral ISM Abundances in the COS Sample of SFGs



- Solar photospheric abundances from *Asplund (2009)*
- Saturation affecting C, and likely O and Si
- Solid symbols: O as traced by P according to *Lebouteiller et al. 2005* (but see also *Jenkins 2009*)
- α elements O (as traced by P), S, and Mg consistent with each other as expected (all produced in the ejecta of SNe II from massive stars)
- Si not in agreement with other α elements: likely due to hidden saturation of the weakest line or depletion
- Fe-peak elements Fe & Ni in agreement with each other

Comparison with Local ISM in Milky Way

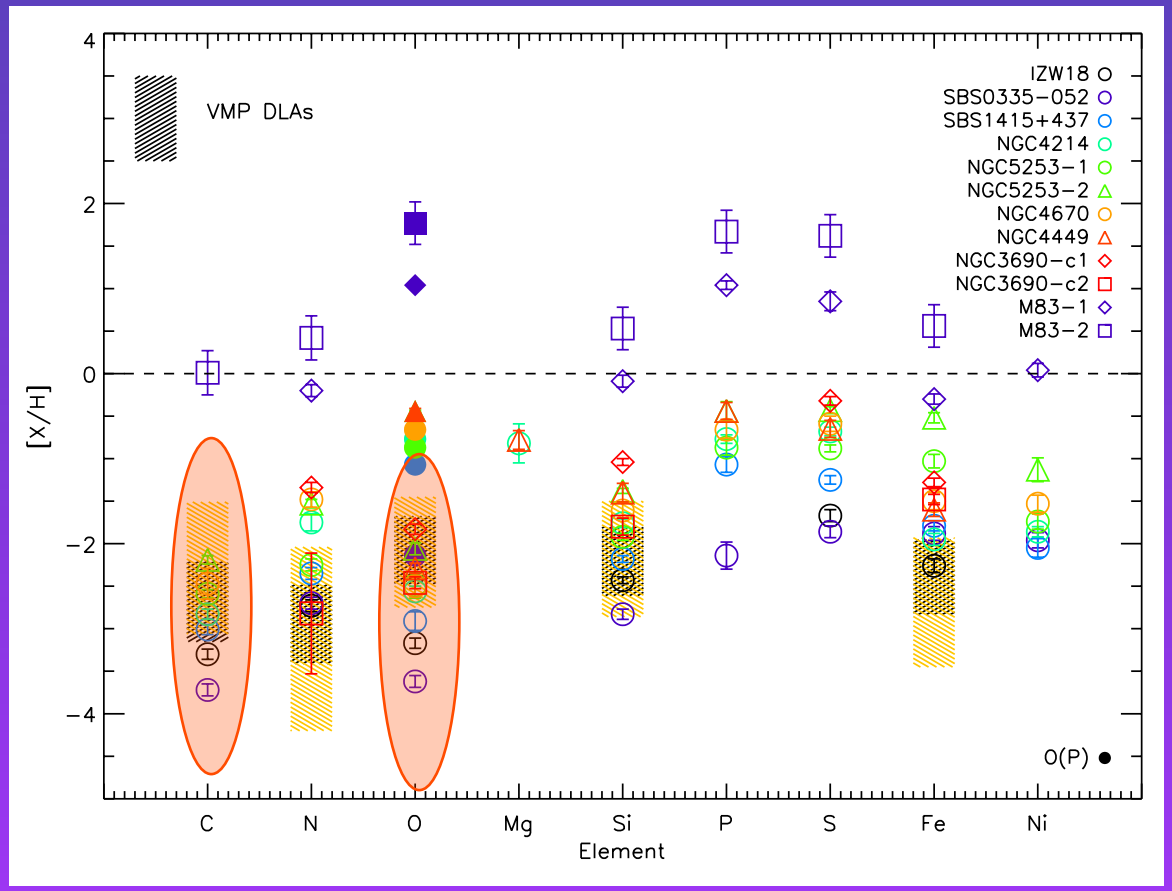
Jenkins et al. (2009)



- Fe-peak elements less depleted compared to α elements in SFGs than local IMS
  - ✓ Only upper end of Mg, P, and S values in SFGs included in local ISM range (except for M83)
  - ✓ All values of Fe and Ni included in Local ISM range (except for M83)
- Saturated elements, as expected, much more depleted in SFGs than local ISM, except for Si that behaves more like other α elements
  - ✓ Is Si only marginally affected by saturation after all?
  - ✓ Is Si more depleted than Mg and S because of condensation into dust grains ?
- N more depleted in SFGs compared to Local ISM

Comparison with Very Metal-Poor DLAs

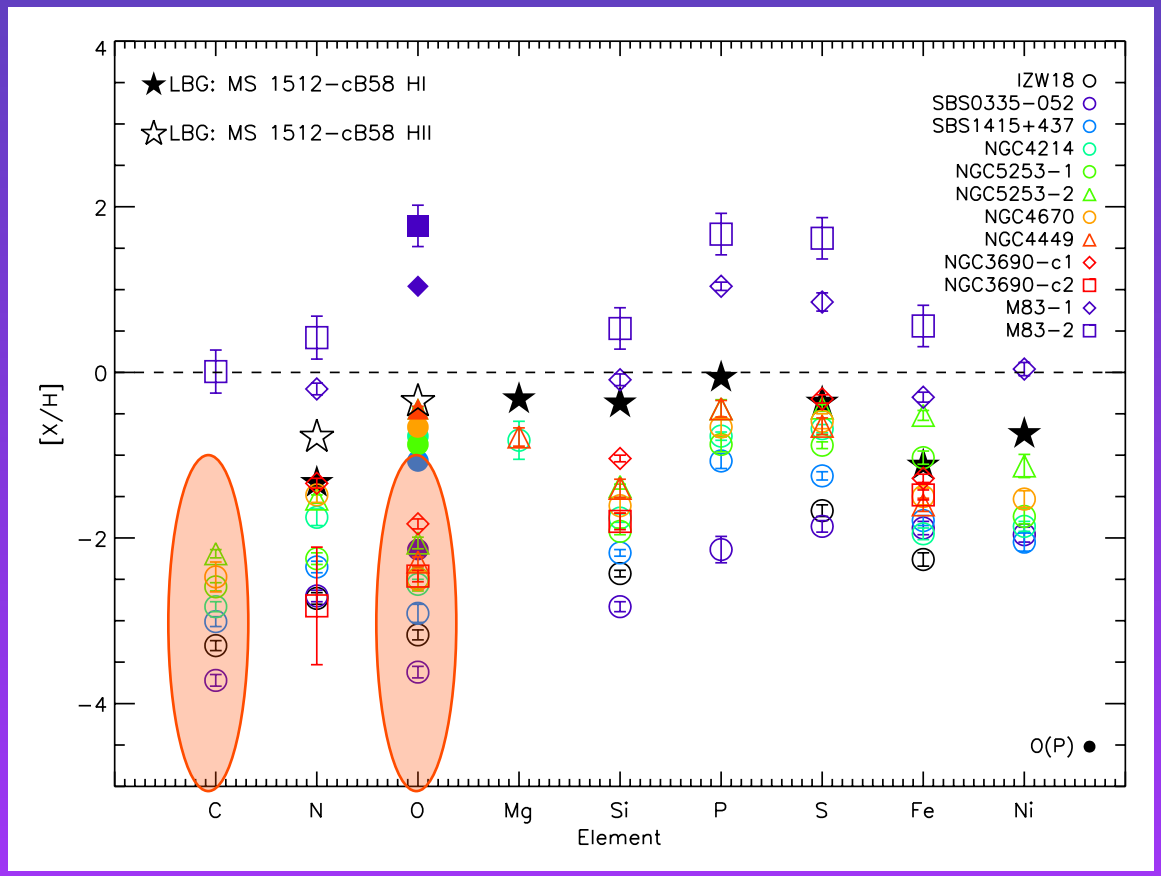
Cooke et al. (2011)



- C and O in SFGs lower than in DLAs due to saturation
- O as inferred from P in SFGs not in agreement with DLA values
- N, Fe, and at lower level Si in DLAs at low end of values in SFGs

Comparison with LBG MS 1512−cB58

Teplitz et al. (2000), Pettini et al. (2002)



- α elements (Mg, Si, S) in ISM in agreement with α element O in nebular gas of LBG
  - ✓ Is this LBG chemically homogeneous ?
- ISM values in LBG in upper part of ISM values in SFGs (excluding M83) with similar abundance pattern
  - ✓ Are more metal-rich local SFGs similar to LBGs in this sense?

Abundances in HII Regions of the COS Sample of SFGs

Compilation of HII region Abundances in SFGs of the COS sample from the literature (all 1D spectra, except for N and O in SBS 0335-052 which are from IFU data)

Galaxy	log(C/H)	log(N/H)	log(O/H)	log(Si/H)	log(S/H)	log(Fe/H)	References
IZW18	-5.70 ± 0.13	-6.39 ± 0.04	-4.83 ± 0.08	-6.39 ± 0.15	-6.26 ± 0.05	-6.46 ± 0.05	C, Si: 1 (NW region); N, Fe: 2 (SE region); O, S: 2 (NW regi
SBS0335-052	-5.51 ± 0.10	-6.19 ± 0.05	-4.71 ± 0.02	-6.28 ± 0.13	-6.37 ± 0.41	-6.10 ± 0.02	C, Si: 1 ; N, O: 3 (clusters 4,5); S, Fe: 4 (clusters 1, 2)
SBS1415+437	-5.18 ± 0.13	-5.95 ± 0.01	-4.39 ± 0.01	-5.86 ± 0.14	-5.89 ± 0.01	-6.14 ± 0.01	C, Si: 1; N, O, S, Fe: 5 (region e1)
NGC4214	—	-5.05 ± 0.12	-3.80 ± 0.08	—	-5.39 ± 0.04	—	N, O, S: 6 (region C20/Knot 1)
NGC5253-1	-4.44 ± 0.45	-5.16 ± 0.13	-3.69 ± 0.07	-5.35 ± 0.32	-5.43 ± 0.07	-5.94 ± 0.15	C, Si: 1; N, O, S, Fe: 7 (Knot D/UV-2)
NGC5253-2	-4.44 ± 0.45	-5.35 ± 0.04	-4.04 ± 0.07	-5.35 ± 0.32	-5.43 ± 0.07	-5.94 ± 0.15	C, Si: 1; N, O: 8 (region 7); S, Fe: 7 (Knot D/UV-2)
NGC4670	—	-5.01 ± 0.05	-3.73 ± 0.02	—	-5.29 ± 0.05	—	N, O, S: 9 (calculated from nuclear region fluxes, see text for
NGC4449	—	—	-4.16 ± 0.07	—	-5.67 ± 0.03	—	O, S: 10 (calculated from Region 11 line fluxes, see text for d
NGC3690-c1	—	-5.49 ± 0.00	-3.62 ± 0.00	—	-4.85 ± 0.00	—	N, O, S: 11 (errors not available)
NGC3690-c2	—	-5.49 ± 0.00	-3.62 ± 0.00	—	—	—	N, O: 11 (errors not available)
M83-1	—	-3.66 ± 0.05	-3.25 ± 0.03	—	-5.25 ± 0.01	—	N, O, S: 12 (calculated from Region A line fluxes, see text for
M83-2	—	-3.57 ± 0.05	-3.02 ± 0.02	—	-4.75 ± 0.06	—	N, O, S: 12 (calculated from Region B line fluxes, see text for

Table 2: References: (1)=Izotov & Thuan (1999), (2)=Izotov et al. (1999), (3)=Izotov et al. (2006a), (4)=Izotov et al. (2009),(5)=Guseva et al. (2003),(6)=Kobulnicky & Skillman (1996),(7)=López-Sánchez et al. (2007), (8)=Walsh & Roy (1989), (9)=Moustakas & Kennicutt (2006), (10)=Buckalew et al. (2005),(11)=French (1980),(12)=Bresolin & Kennicutt (2002)

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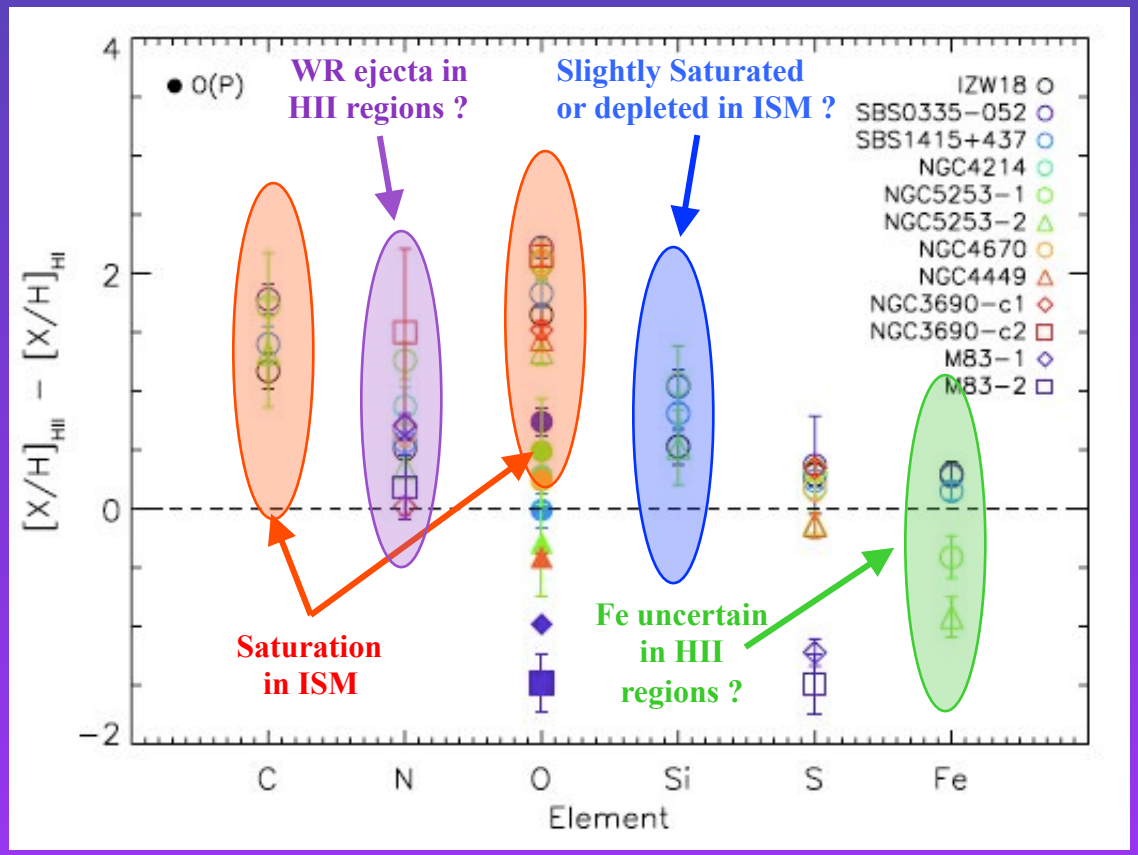
Comparison with Abundances in HII Regions

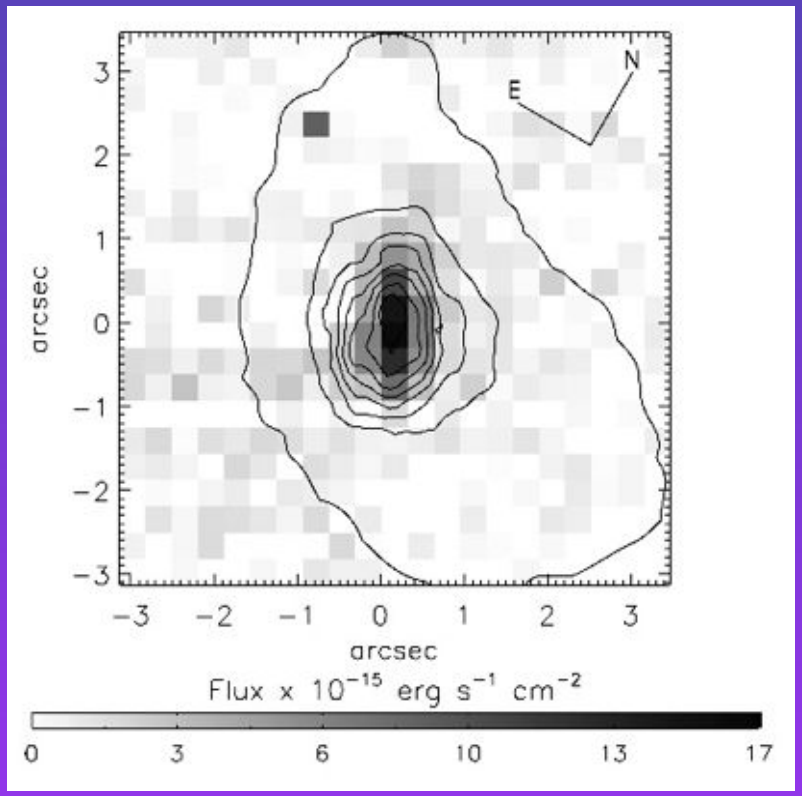


- C and O underabundant in ISM compared to HII region due to saturation
- Si slightly underabundant in ISM compared to HII regions due to saturation or condensation into dust grains
- Fe similar or higher in ISM
  - ✓ uncertainties in Fe determination from emission lines due to large ionization corrections?
- N also underabundant in ISM compared to HII regions
  - ✓ N enrichment of HII regions by WR ejecta ?

➡ S only reliable element in both ISM and HII region abundance determinations !
Is S indicating chemical homogeneity of different gas phases in SFGs ?

N Enrichment in HII Regions with IFU

James et al. 2009

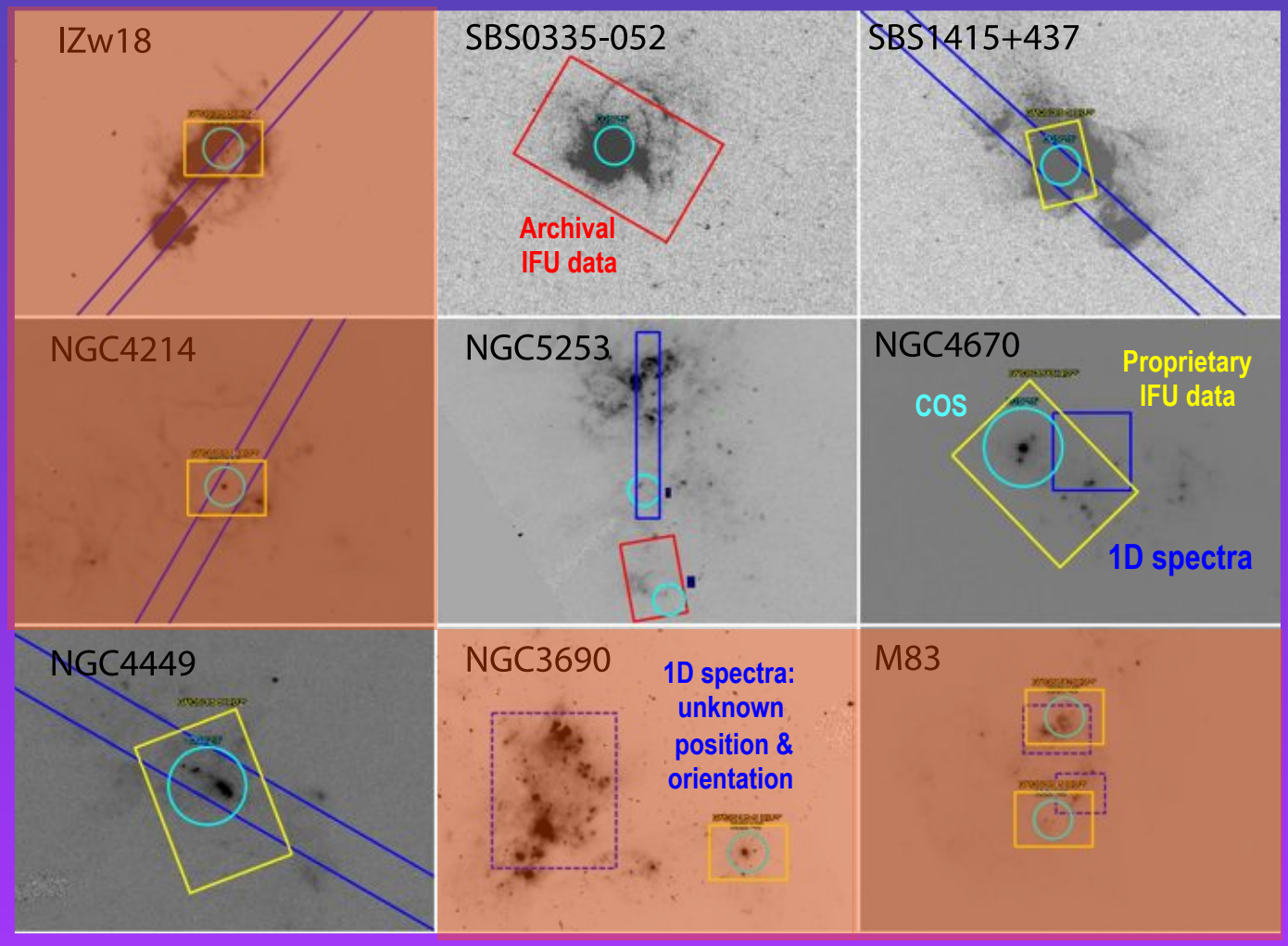


- Mkr 966 is BCD with anomalously high N/O
- IFU data show evidence of broad & narrow components
  - ✓ Broad component associated with elevated N/O in inner core region
  - ✓ Broad component associated with high N_e (10^7 cm^{-3})
  - ✓ Emission map of WR feature at λ 4658 correlates with broad component
- See also *Lopez-Sanches (2007)* for similar findings from 1D nebular spectra of NGC 5253

➡ Caution in using 1D spectra to infer properties of nebular gas because of local variations of physical properties !

Gemini/GMOS proposal to obtain IFU data of COS SFG sample submitted and accepted in Dec 2011 for ½ of the requested time!

Gemini/GMOS Observations of SFGs in COS Sample



Gemini GN-2012A-Q-33 (PI: James)

NGC 4449 Apr 2012
NGC 4670 Apr 2012
SBS 1415+437 Apr 2012

Archival IFU data

NFC 5253 Feb-Jul 2008
SBS 0335-052 Nov 2003

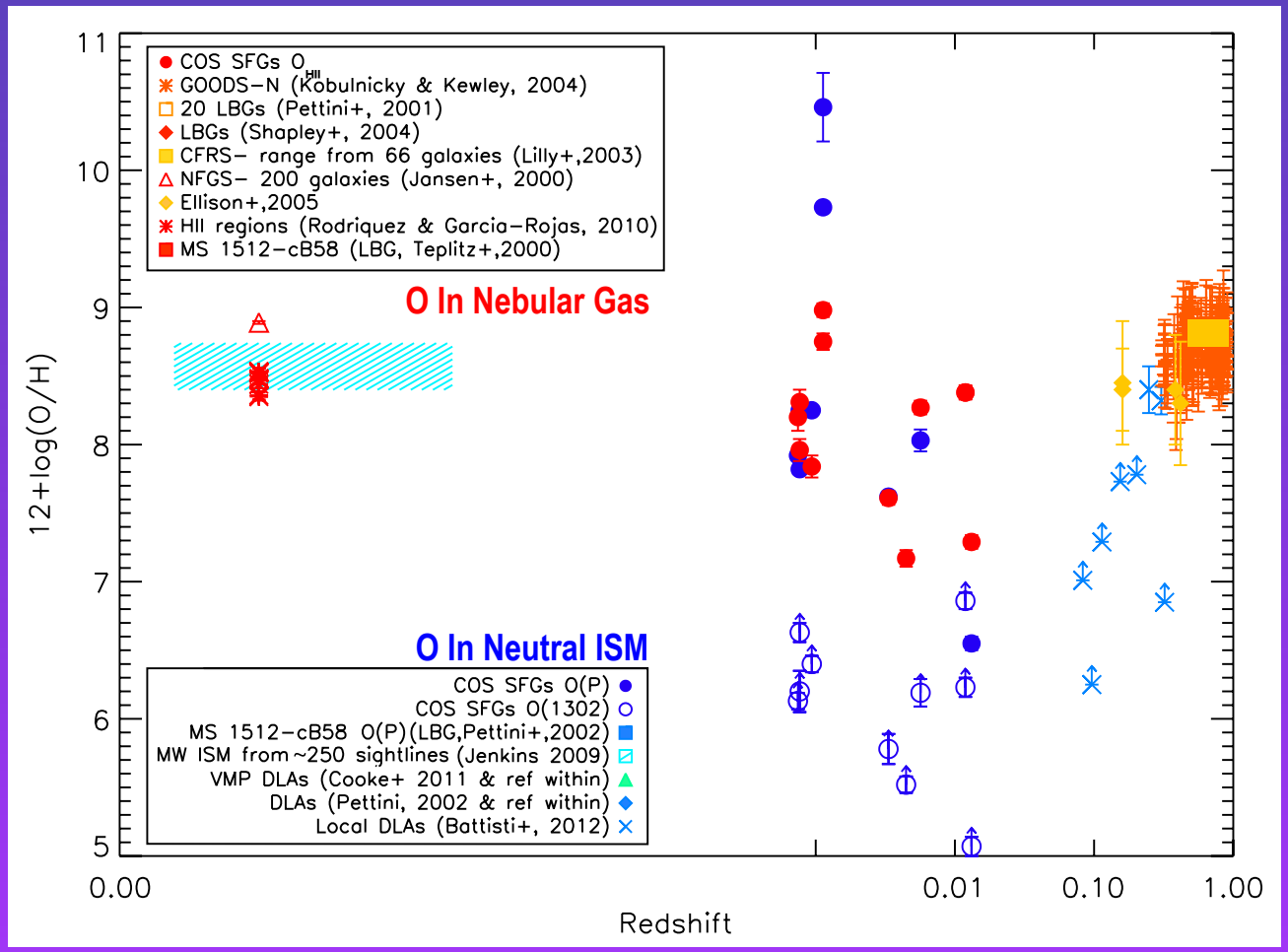
IFU time still to be allocated

I Zw 18
NGC 4241
NGC 3690
M83

Direct method will be used to determine O abundances !

Z vs Cosmic Time: 0 < z < 1

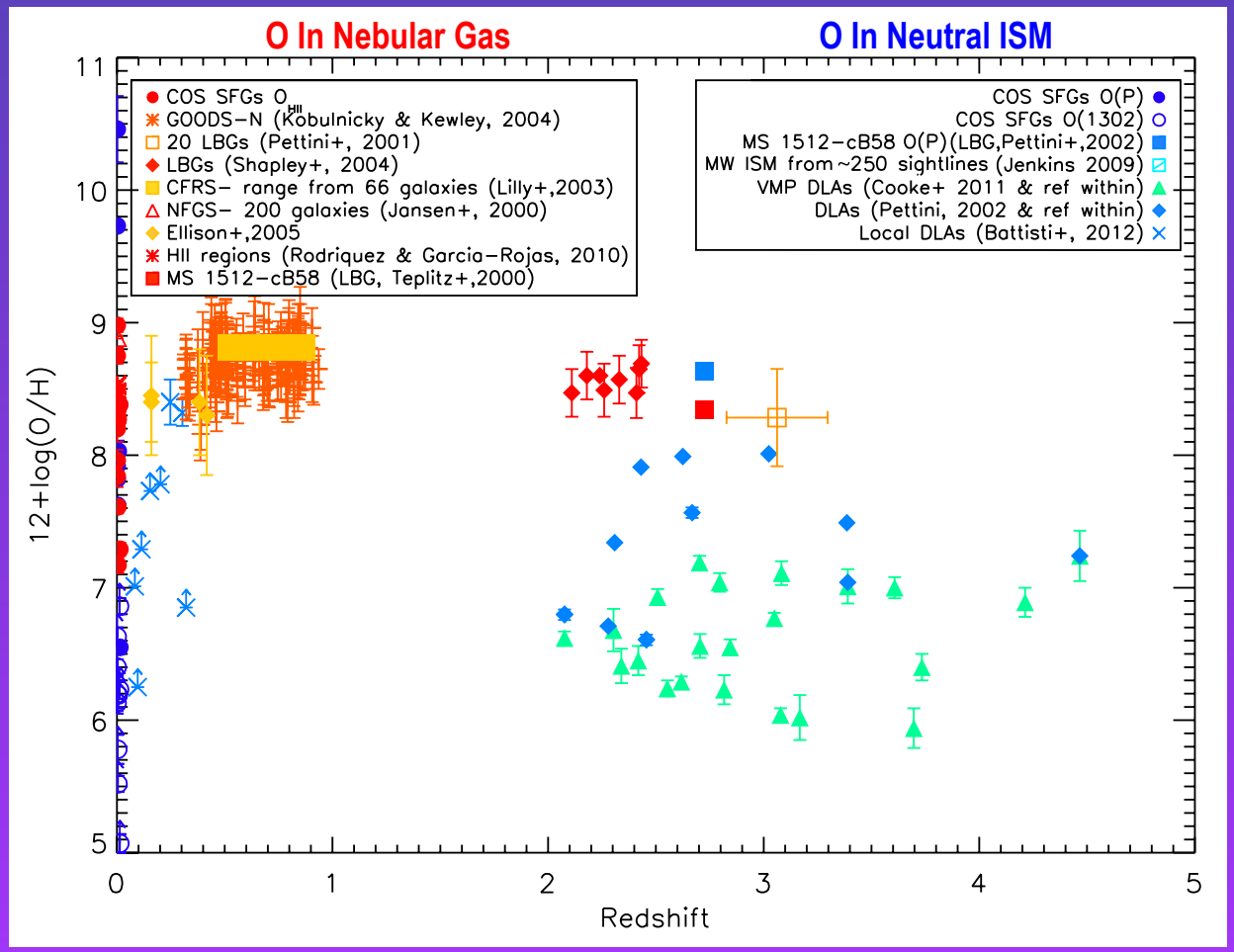
Only O considered in our plot



- Our lower limits on O abundances in the ISM of SFGs (open blue circles) are consistent with lower limits in DLAs at z ~ 0.01-1
- Assuming chemical homogeneity, O in neutral ISM of our SFGs should be as high as O in nebular gas (solid red circles)
- Lower O in nebular gas of our SFG sample compared to same in Local ISM or samples of field galaxies likely due to selection effects (sample is dwarf/merging galaxies at z ~ 0 with lower Z due to lower M)

Z vs Cosmic Time: 0 < z < 5

Only O considered in our plot



- **Our lower limits on O abundances in the ISM of SFGs (open blue circles) are also consistent with measurements in DLAs at z ~ 2-4**
- **LBG MS 1512-cB58 at z=2.7 also chemically homogeneous between neutral ISM and nebular gas (solid red and blue squares)**

Are DLAs different from LBGs in terms of Z (thus M) with DLAs being the more common lower-mass galaxies in the high-z Universe and LBGs the MW-type galaxies selected based on their increased SFRs?

Summary and Conclusions

1. Sample of local SFGs observed with COS addresses biases of FUSE observations (multiple sightlines, availability of ions, etc.)
2. α element S (in addition to P used as tracer of O ?) key to perform direct comparison of α-element abundances in neutral ISM and nebular gas (see also Pettini et al. 2002 for S as proxy of O in ISM)
3. HI abundances similar to what found in HII regions associated with COS absorption-line spectra, except for N:
   - ✓ N enrichment in HII regions by WNL stars ?
   - ✓ Same O metallicity in HI and HII ?
     - O offset identified by FUSE due to observational biases ?
4. Both our SFG sample at z ~ 0 and the lensed LBG MS 1512-cB58 at z ~ 2.7 are chemically homogeneous in their neutral/ionized gas phases
5. Difference between DLAs and LBGs in the high-z Universe (z ~ 2-3) easily explained in terms of metallicity, thus mass
   - ✓ DLAs likely the most common lower-mass galaxies selected based on their high gas content
   - ✓ LBGs likely typical L* galaxies selected based on their increased SFRs