Gas-Phase Metallicities of Ultraluminous Infrared Galaxies with Far-Infrared Emission Lines

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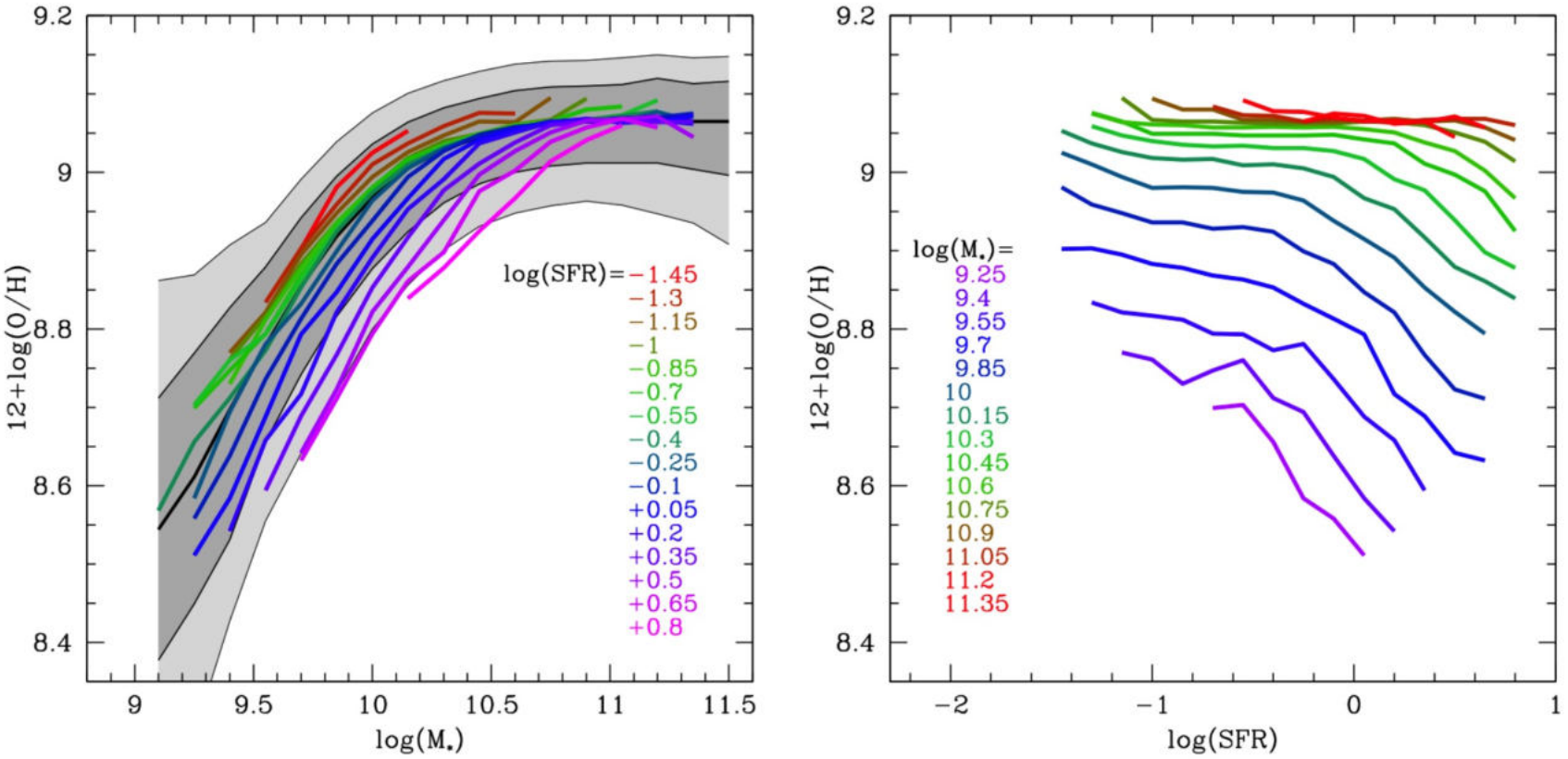
SOFIA Community Tele-Talk, April 20, 2022

Outline

- Fundamental Metallicity Relation (FMR)
- What are ULIRGs?
- Far-infrared metallicity diagnostics
- SOFIA FIFI-LS observations of ULIRGs
- Where do ULIRGs locate on MZR?
- Conclusion

Fundamental Metallicity Relation (FMR)

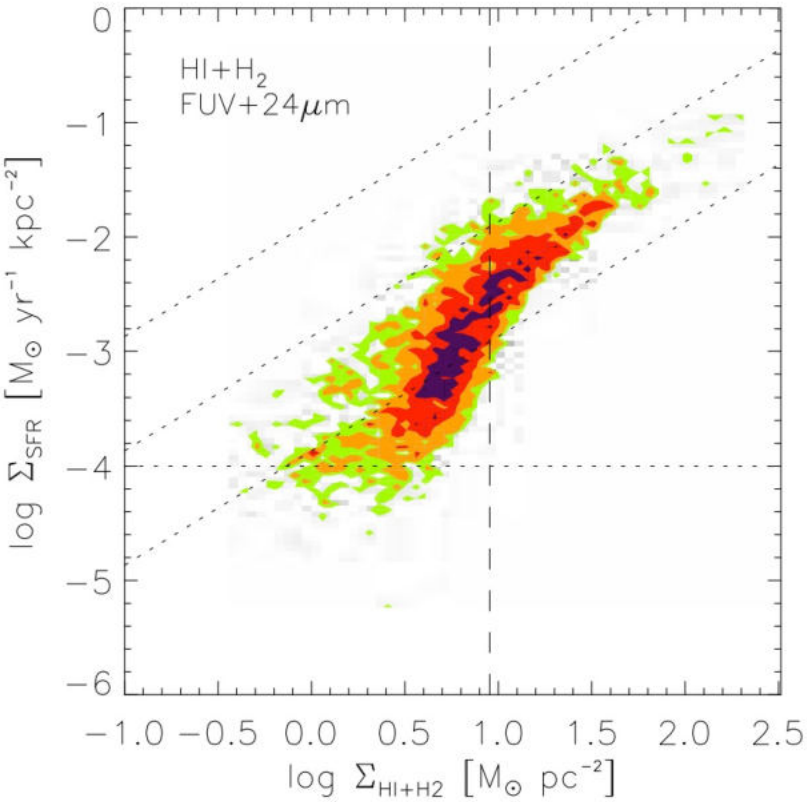
- ❑ At fixed stellar mass, gas-phase metallicity decreases with increasing star formation rate.
- ❑ The correlation between metallicity and SFR is mostly significant for low-mass galaxies.



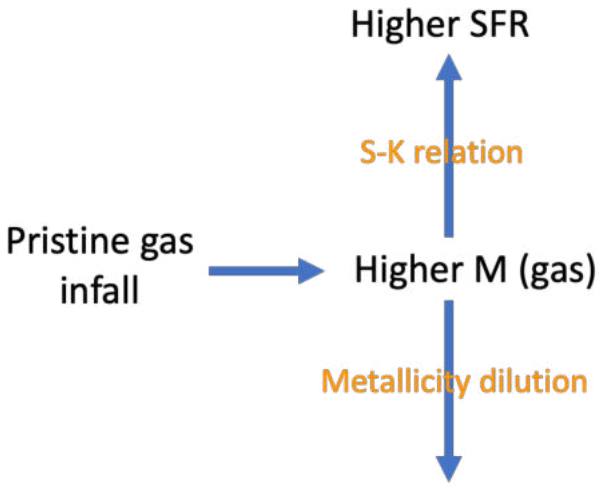
Mannucci et al. 2010

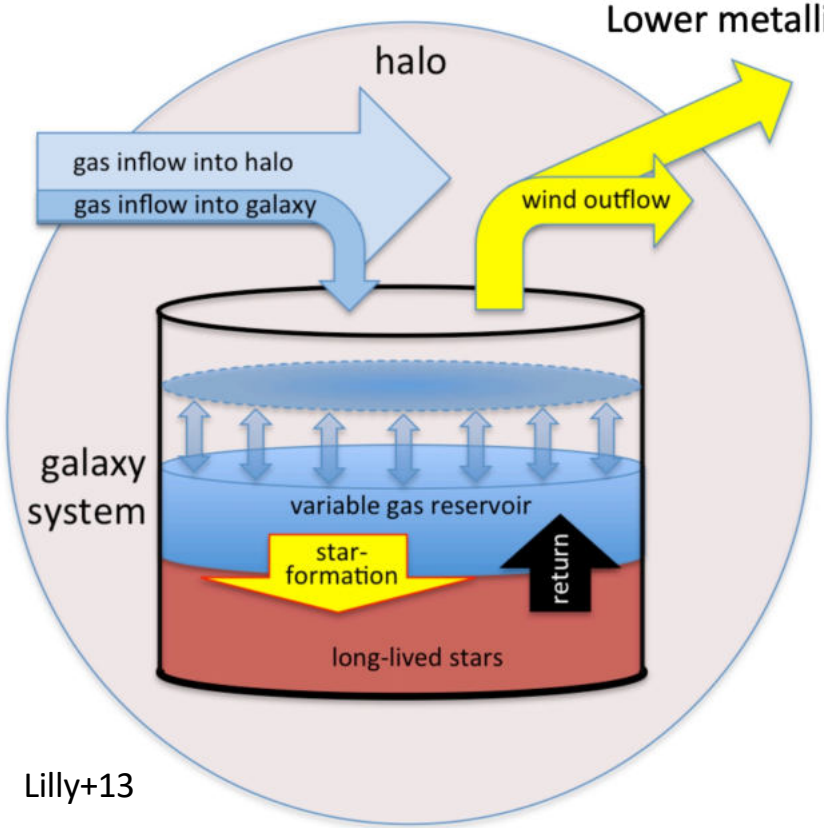
Why do we expect FMR?

- SFR is a proxy of the gas content.



Bigiel+08

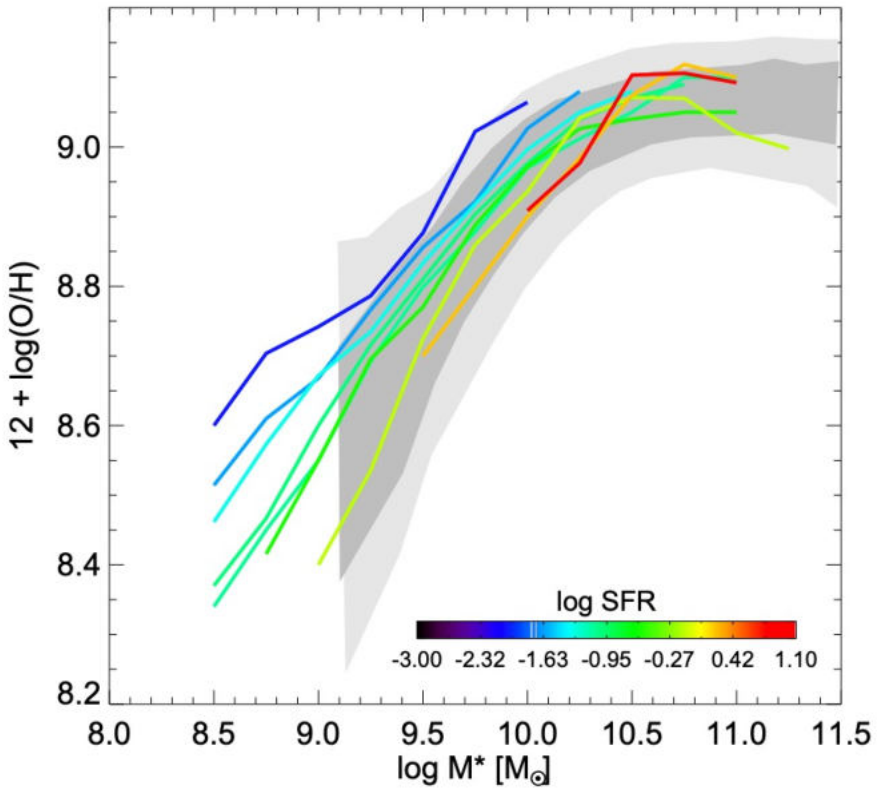


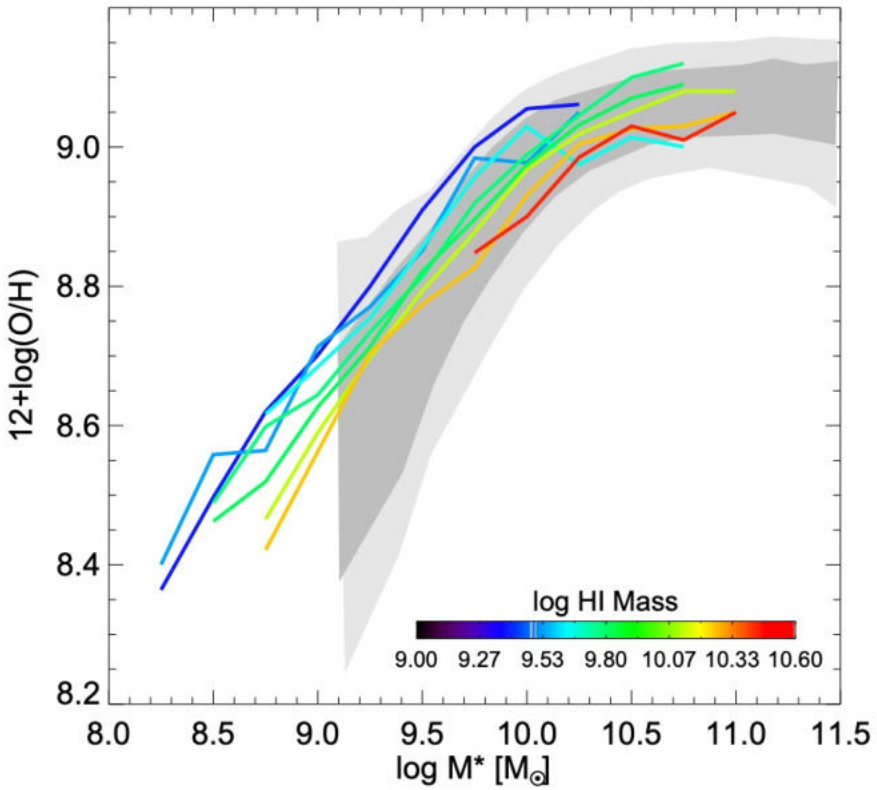


Lilly+13

Gas Fundamental Metallicity Relation

- Since SFR is determined by the amount of gas, the gas fundamental metallicity should be the fundamental relation.

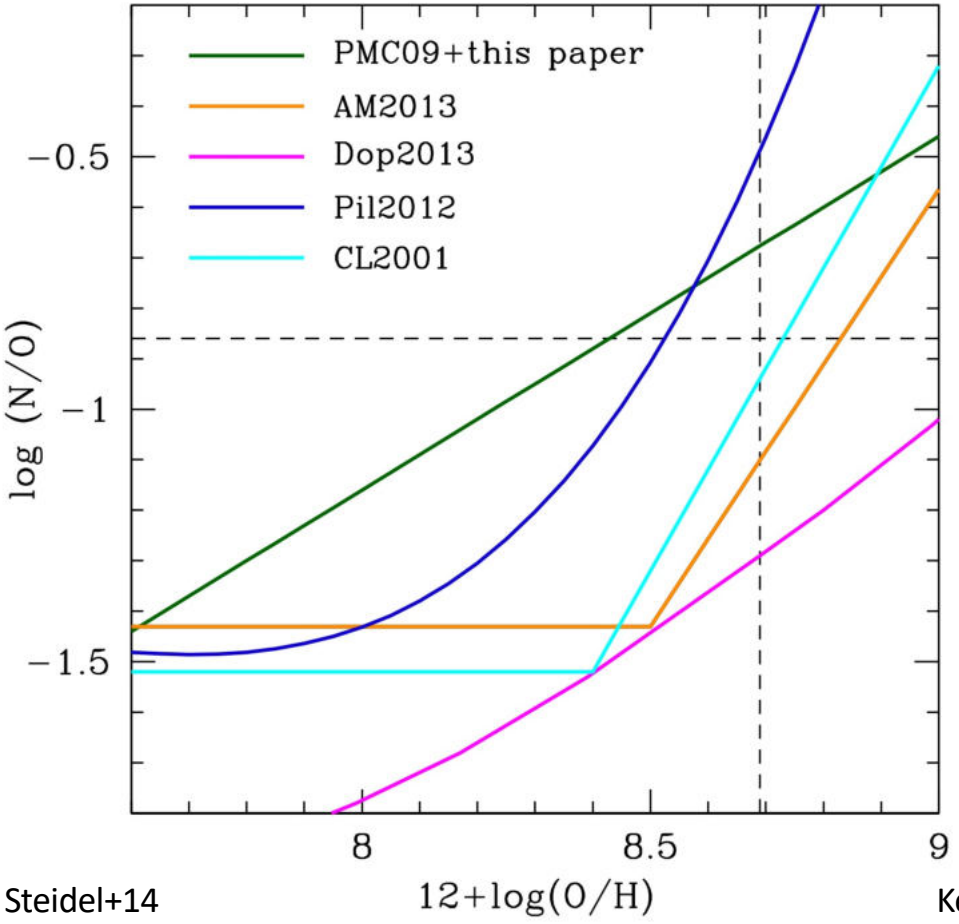




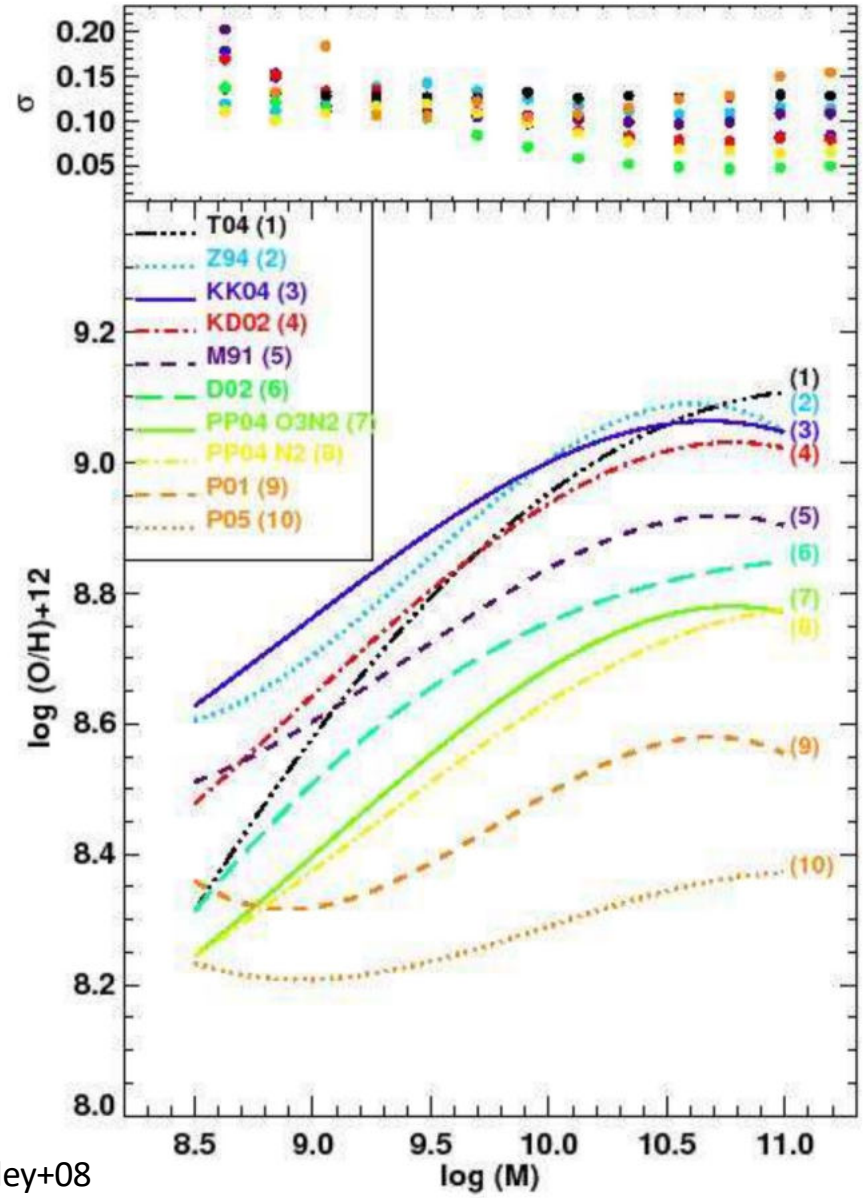
Bothwell et al. 2013

N/O versus O/H trends in literature

- There are different observed relations, spanning almost one order of magnitude of N/O for a given O/H.



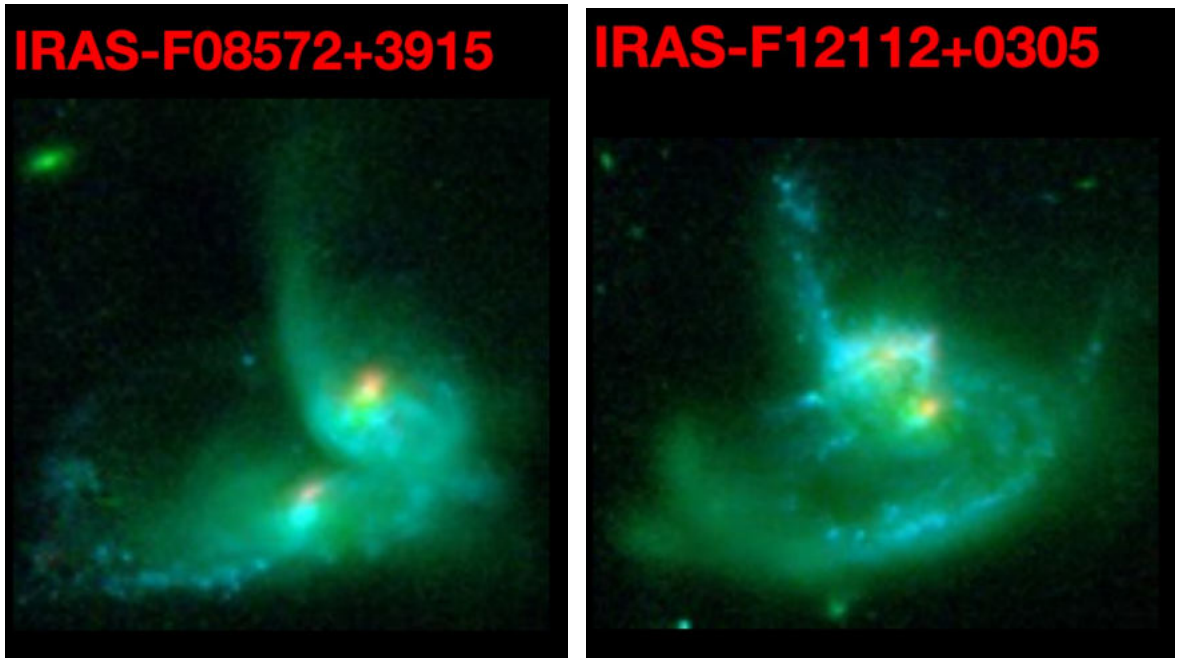
Steidel+14



Kewley+08

What are ULIRGs?

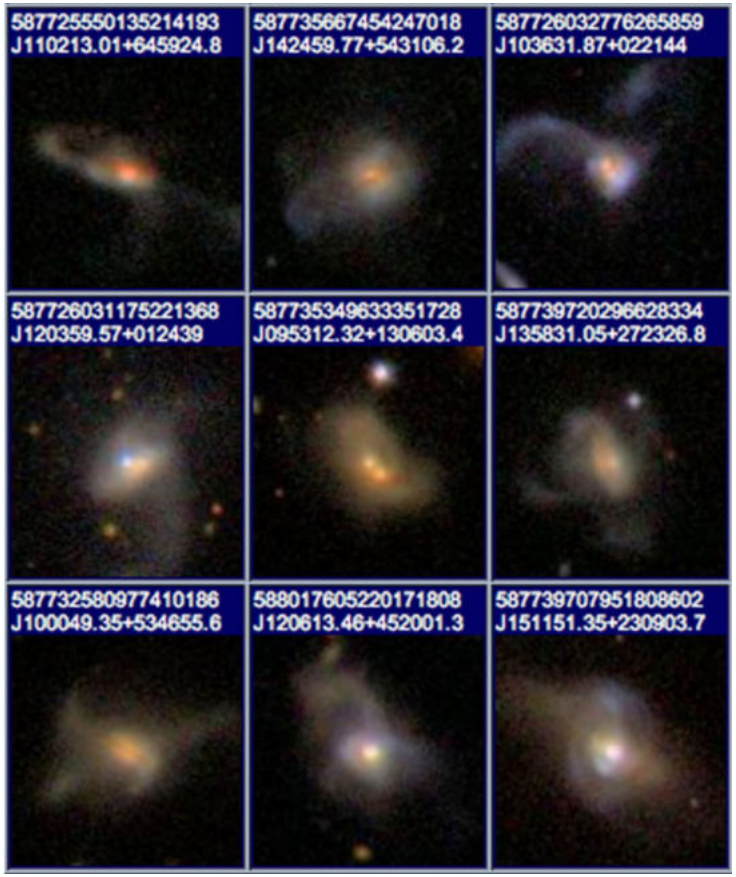
- $L_{IR}(8-1000\ \mu m) \geq 10^{12}\ L_{\odot}$
- Local ULIRGs are remnants of major mergers either at an advanced merger stage or in a post-merger stage with an enhanced star formation rate.
- At low redshifts (z<0.3), ULIRGs are rare, with less than one per hundred square degrees, and are mostly mergers between approximately equal-mass galaxies. However, the number density of ULIRGs increases rapidly with redshift, reaching a density of several hundred per square degree at z ≥ 1.

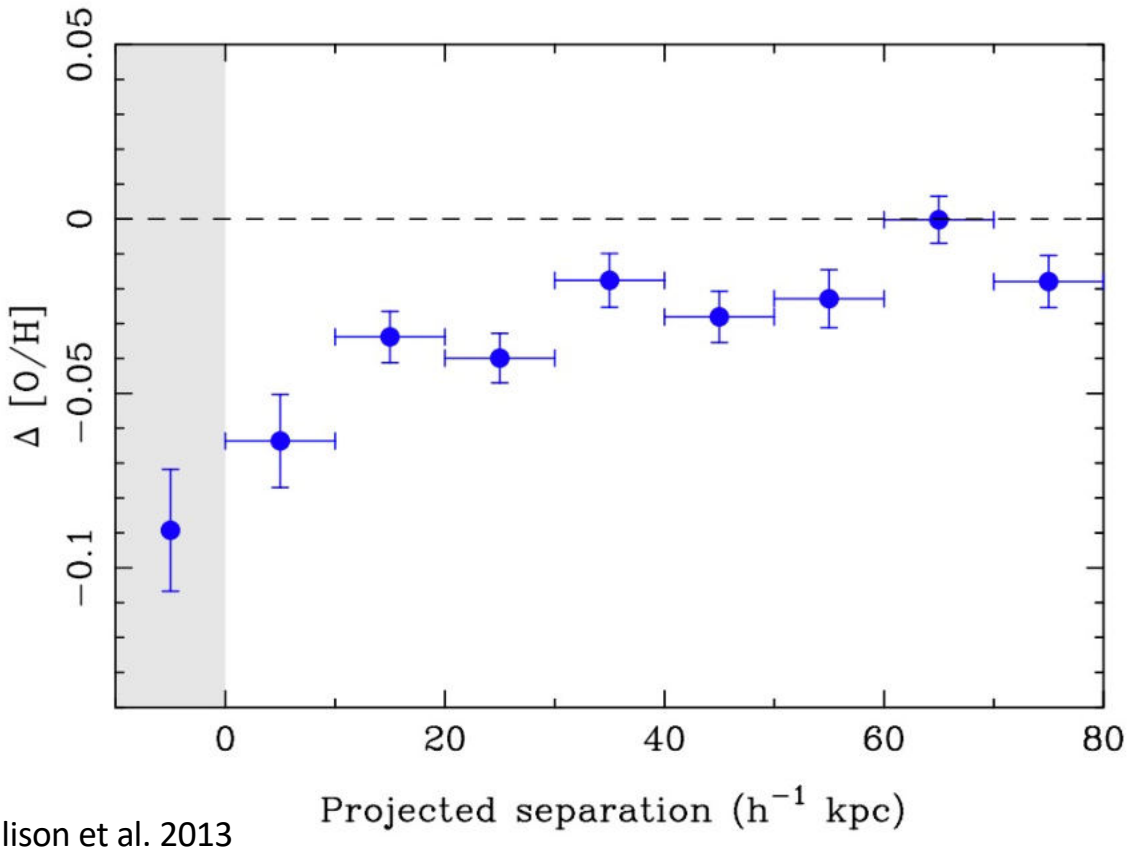


HST ACS/WFC I-band (814 nm)

Metallicity of optically-selected post-merger galaxies

- Optically-selected post-merger galaxies in the local Universe are found to be ~0.09 dex metal-poor compared to control sample with similar stellar mass and environment density.

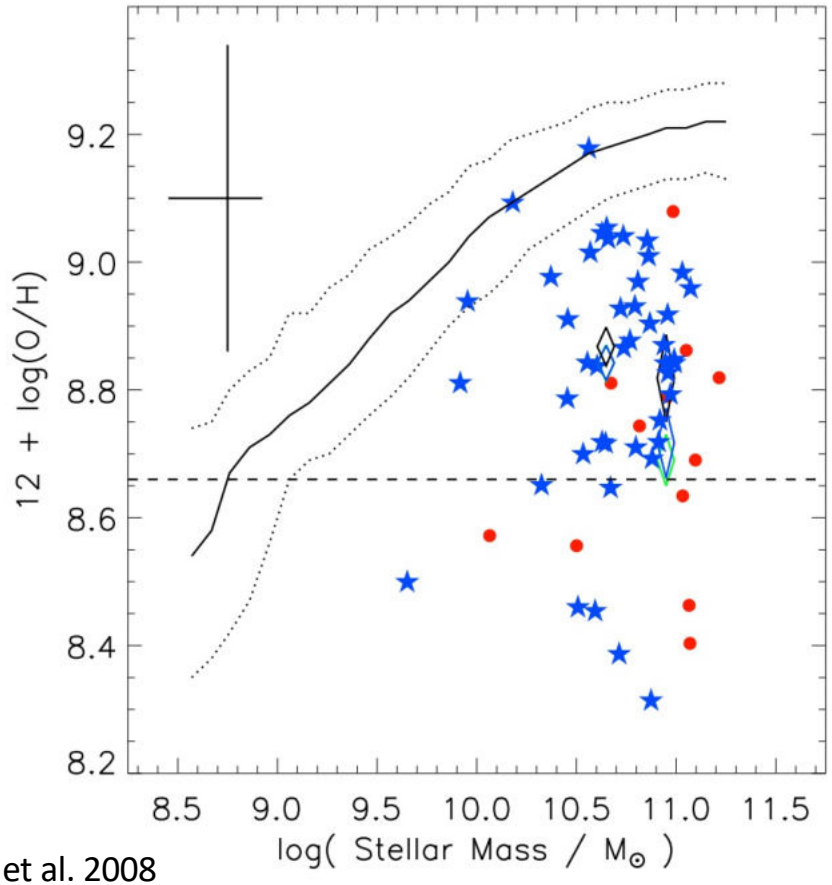


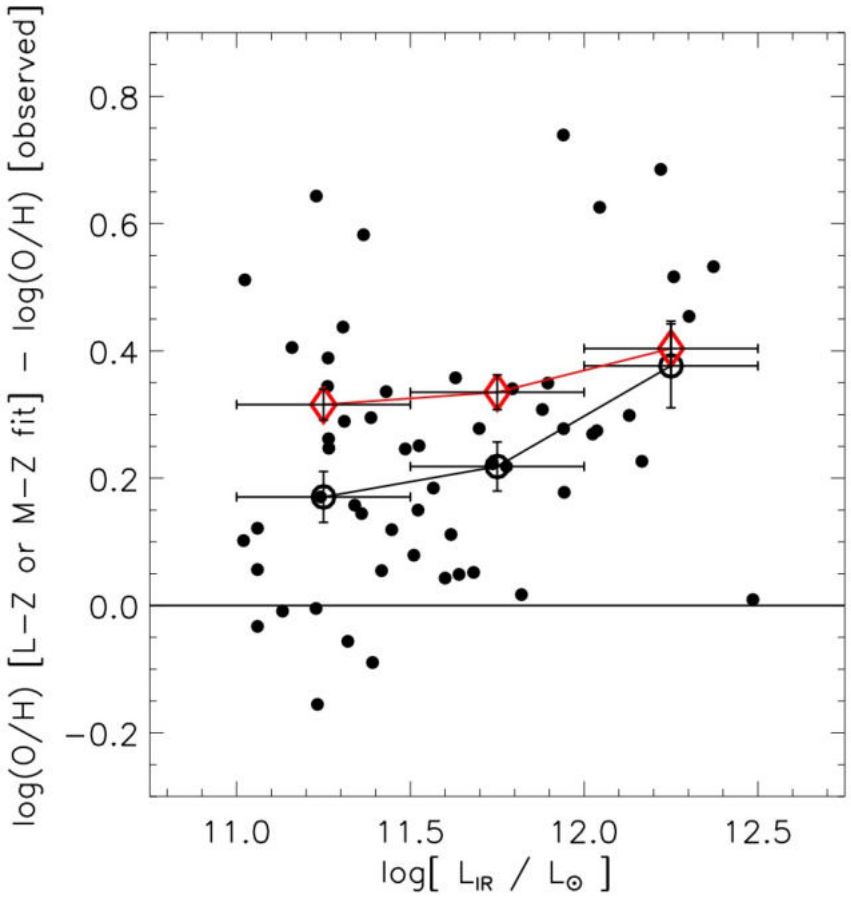


Ellison et al. 2013

Optical metallicity of ULIRGs

- The gas-phase metal abundances of local ULIRGs, with oxygen abundance used as a proxy for metallicity, inferred from optical emission lines appear to lie ~0.4 dex below the now well-established stellar mass-metallicity relation for star forming galaxies, when the two populations are compared at the same stellar mass.

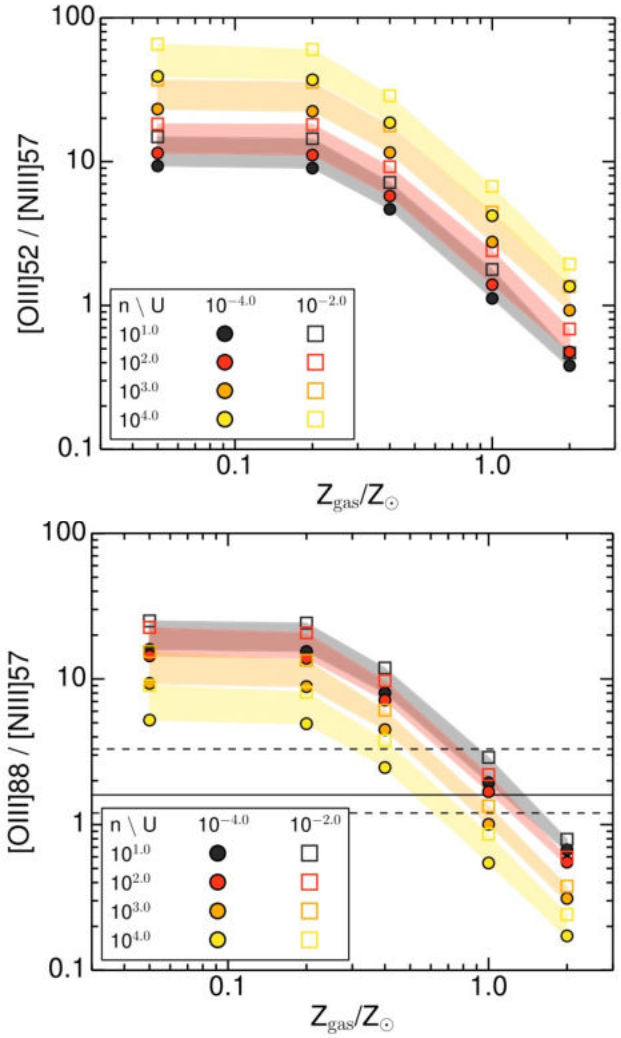


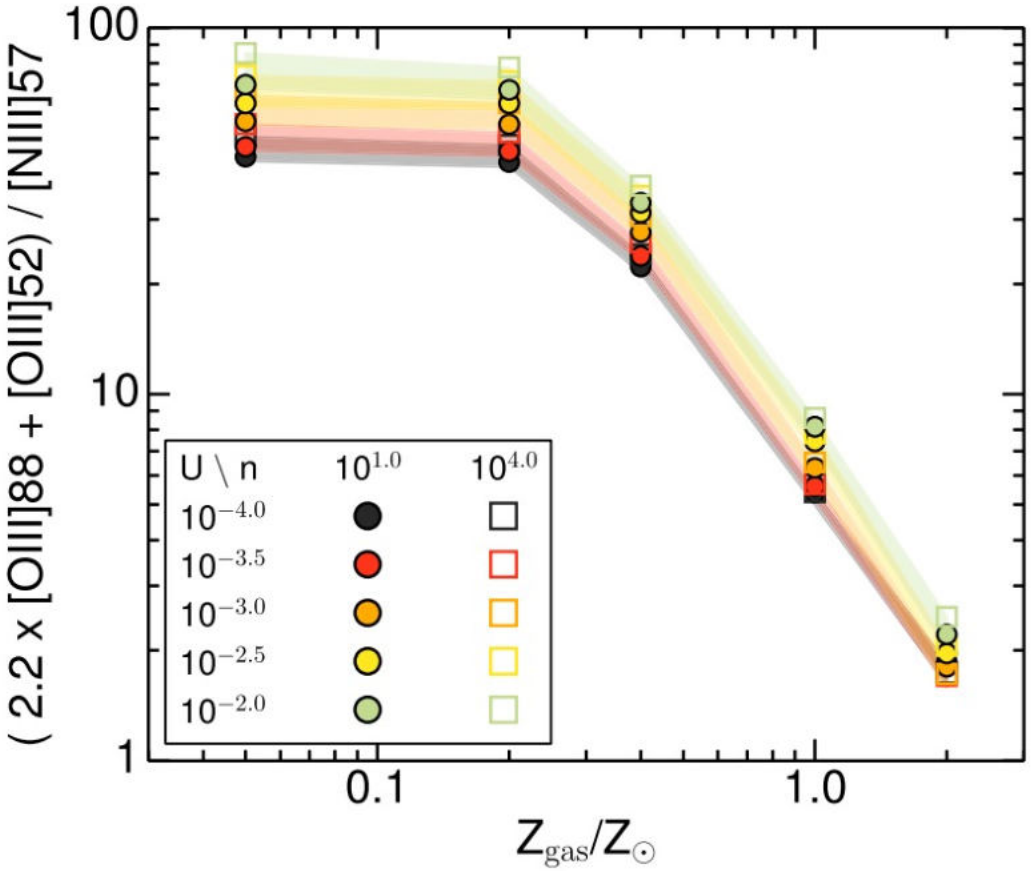


Rupke et al. 2008

Far-infrared metallicity diagnostics

- For a fixed metallicity, the density dependence of the [O III]52 µm/[N III]57 µm ratio is the opposite of that of the [O III]88 µm/[N III]57 µm ratio.





Pereira-Santaella et al. 2017

Cycle 8 SOFIA FIFI-LS proposal to observe key FIR lines

Are local ULIRGs low in metals? Testing a new metallicity diagnostic with FIFI-LS.

Abstract

A comprehensive study of the physical properties of low-z ultra luminous infrared galaxies (ULIRGs), specifically their interstellar medium (ISM), is critical to understanding the evolution of >L* galaxies and active galactic nuclei across cosmic time. ULIRGs at low redshifts are central to this endeavor, as they establish a baseline from which to measure evolution with redshift in the ULIRG population. We propose FIFI-LS observations of the far-IR (FIR) fine structure lines of 11 ULIRGs selected by IRAS at $0.01 < z < 0.13$, primarily targeting the [OIII]52 and [NIII]57 um lines, which are currently only accessible by FIFI-LS. The proposed observations will provide comprehensive diagnostics of the physical conditions of the ISM such as the gas density, radiation field intensity, and metallicity that is much less susceptible to extinction than traditionally used UV/optical transitions. We will be able to apply the excellent FIR metallicity diagnostic, ([OIII]52+[OIII]88)/[NIII]57, for the first time, which breaks the density degeneracy and reduces the scatter in the correlation to within 0.2 dex. The unprecedentedly reliable metallicity measurements will address whether ULIRGs lie below the mass-metallicity relation of star-forming galaxies as previously thought based on optical metallicity diagnostics. Along with archival Herschel/PACS+SPIRE observations, we will be able to test all the line-ratio diagnostics by comparing to models (e.g. Cloudy) and identify the best pairs to optimize future observations with ALMA for high-z analogs. This pilot SOFIA program will open up the opportunity to increasing the sample of low-redshift ($0.1 < z < 0.3$) ULIRGs with the full set of FIR line observations by a factor of 2-3. This program will also demonstrate a key science program for the Origins Space Telescope that focusses on metallicity measurements out to z of 6 with results from Cycle 7 potentially making an impact in Astro2020 Discussions.

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Dr. Hooshang Nayyeri	University of California, Irvine
Dr. Julie Wardlow	Lancaster University
Mr. Derek Wilson	University of California, Irvine

Our main target line was [OIII]52 μm line as it is not covered by Herschel/PACS data for any of our local sources.

Cycle 8 SOFIA FIFI-LS proposal to observe key FIR lines

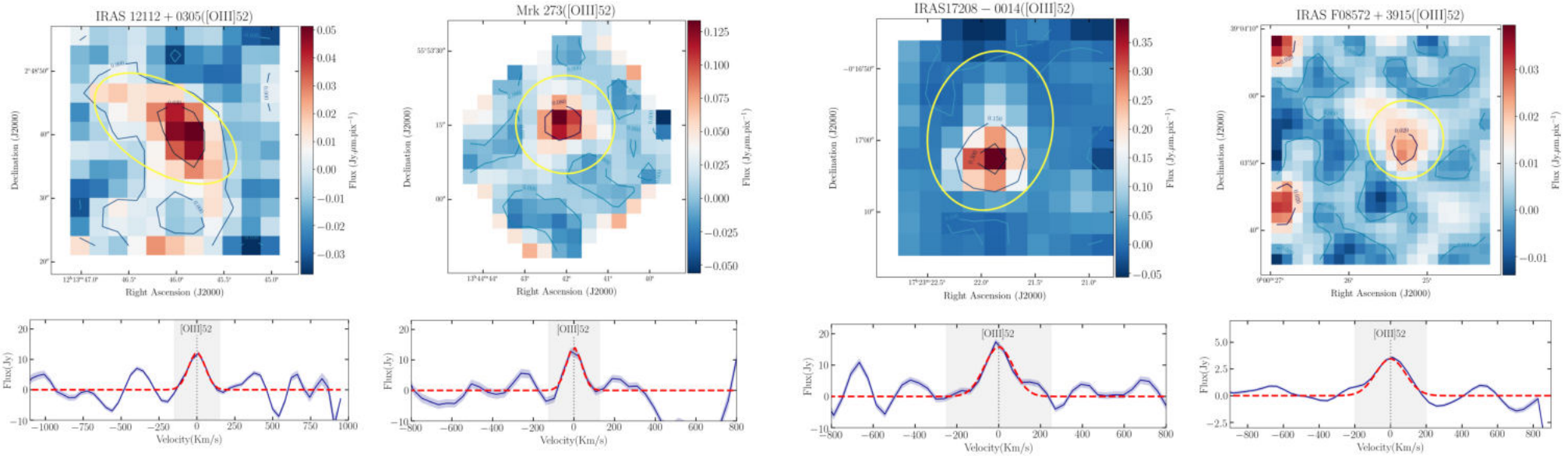
Targeted Sources: 11 (U)LIRGS

Source ID	z	$S_{60\mu m}$ (Jy)	$log(L_{IR})$ $log(L_{\odot})$
IRAS F08572+3915	0.0584	7.30	12.04
IRAS F09111-1007	0.0541	6.75	12.00
IRAS F09320+6134	0.0394	11.68	12.00
IRAS 10565+2448	0.0430	12.10	12.28
IRAS 12112+0305	0.0730	8.18	12.48
Mrk 273	0.0378	22.51	12.10
IRAS 14348-1447	0.0830	6.82	12.60
IRAS 15206+3342	0.1244	1.52	12.07
IRAS 15250+3609	0.0552	7.10	12.00
Arp 220	0.0181	104.09	12.20
IRAS 17208-0014	0.0430	34.79	12.68

SOFIA FIFI-LS observations of key FIR lines

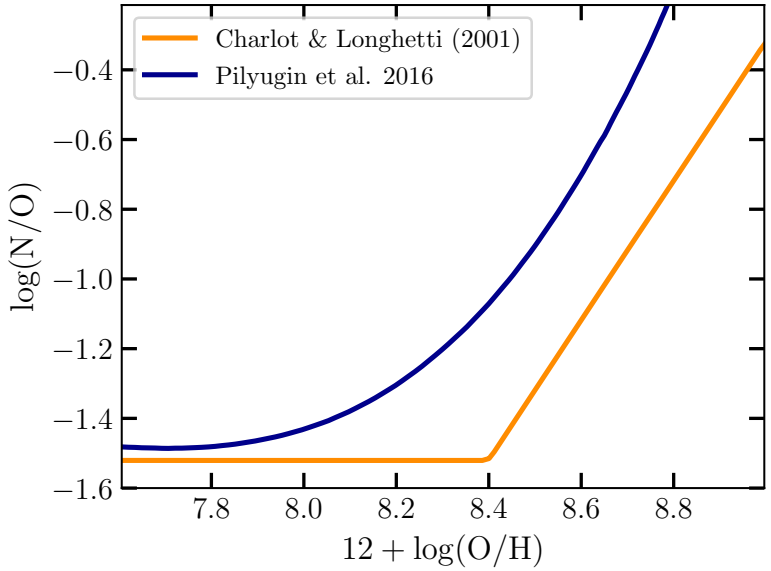
5 ULIRGS with all key lines detected

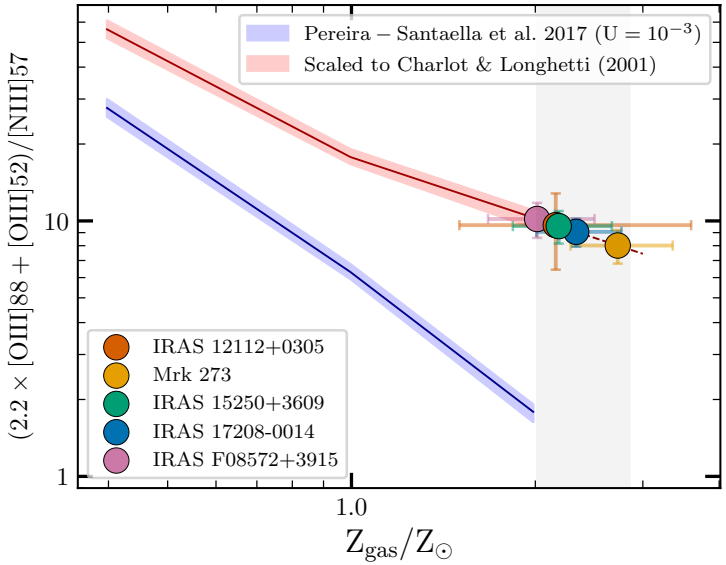
Source ID	[O III]52μm $\times 10^{-16}$W.m^{-2}	[N III]57μm $\times 10^{-16}$W.m^{-2}	[O III]88μm $\times 10^{-16}$W.m^{-2}
IRAS 12112+0305	3.06 ± 0.69	0.56 ± 0.17	1.06 ± 0.14
Mrk 273	2.49 ± 0.42	1.50 ± 0.20	4.33 ± 0.33
IRAS 15250+3609	6.99 ± 0.72	0.83 ± 0.09	0.41 ± 0.04
IRAS 17208-0014	5.06 ± 0.47	1.18 ± 0.13	2.56 ± 0.20
IRAS F08572+3915	1.31 ± 0.01	0.24 ± 0.04	0.51 ± 0.03



FIR metallicity measurements

- In order to maintain comparable results on the oxygen abundance that can be directly compared to existing results from optical measurements on the mass-metallicity relation of star-forming galaxies, we recalibrate the FIR oxygen abundances to the same N/O − O/H relation as optical measurement.

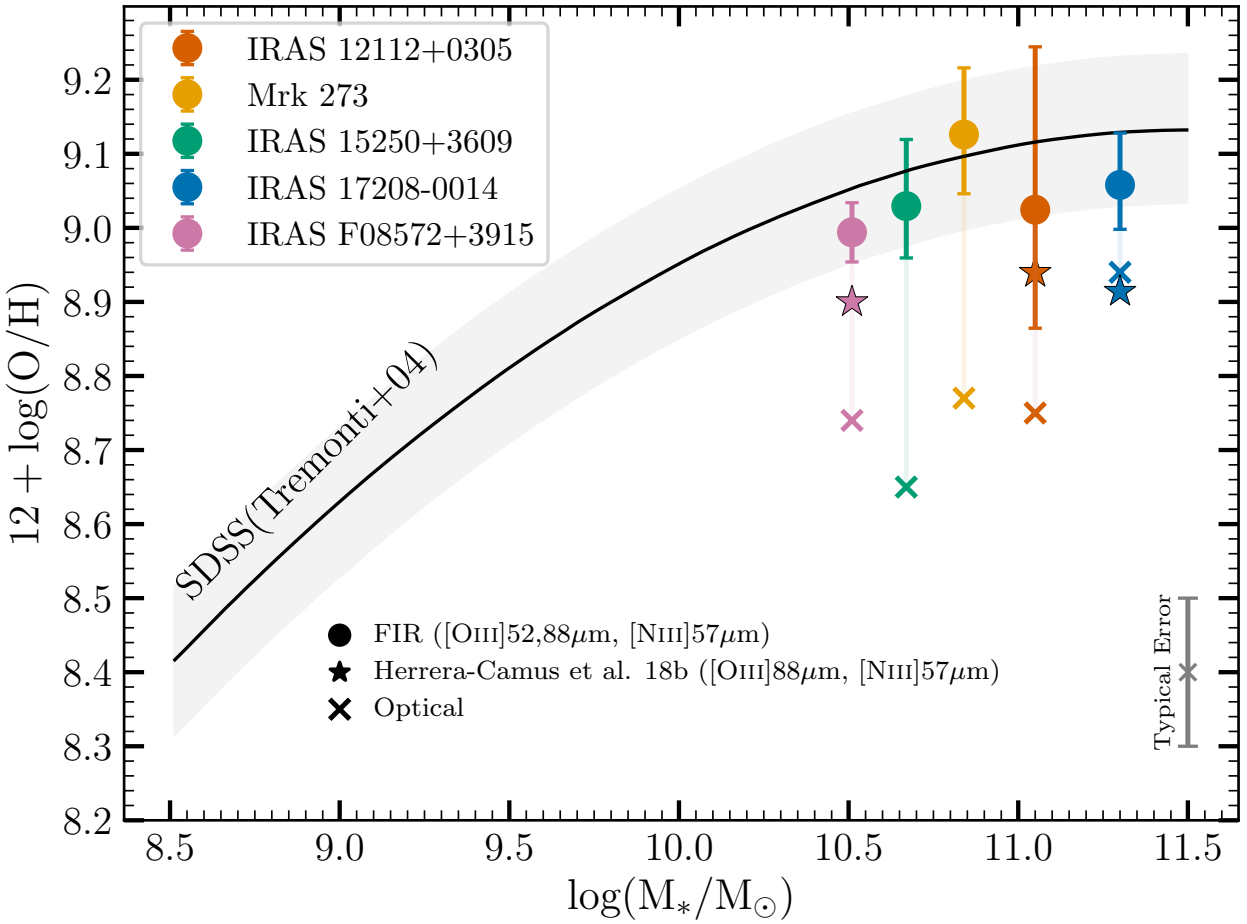




Source ID	z	$S_{60\mu m}$ (Jy)	$\log(L_{IR}/L_\odot)$	$\log M_*/M_\odot$	$12+\log(\mathrm{O/H})_{\mathrm{FIR}}$	$12+\log(\mathrm{O/H})_{\mathrm{Optical}}$
IRAS 12112+0305	0.0730	8.18	12.48	11.05	$9.02^{+0.22}_{-0.16}$	8.75
Mrk 273	0.0378	22.51	12.10	10.84	$9.13^{+0.09}_{-0.08}$	8.77
IRAS 15250+3609	0.0552	7.10	12.00	10.67	$9.03^{+0.09}_{-0.07}$	8.65
IRAS 17208-0014	0.0430	34.79	12.68	11.30	$9.06^{+0.07}_{-0.06}$	8.94
IRAS F08572+3915	0.0584	7.30	12.04	10.51	$8.99^{+0.09}_{-0.08}$	8.74

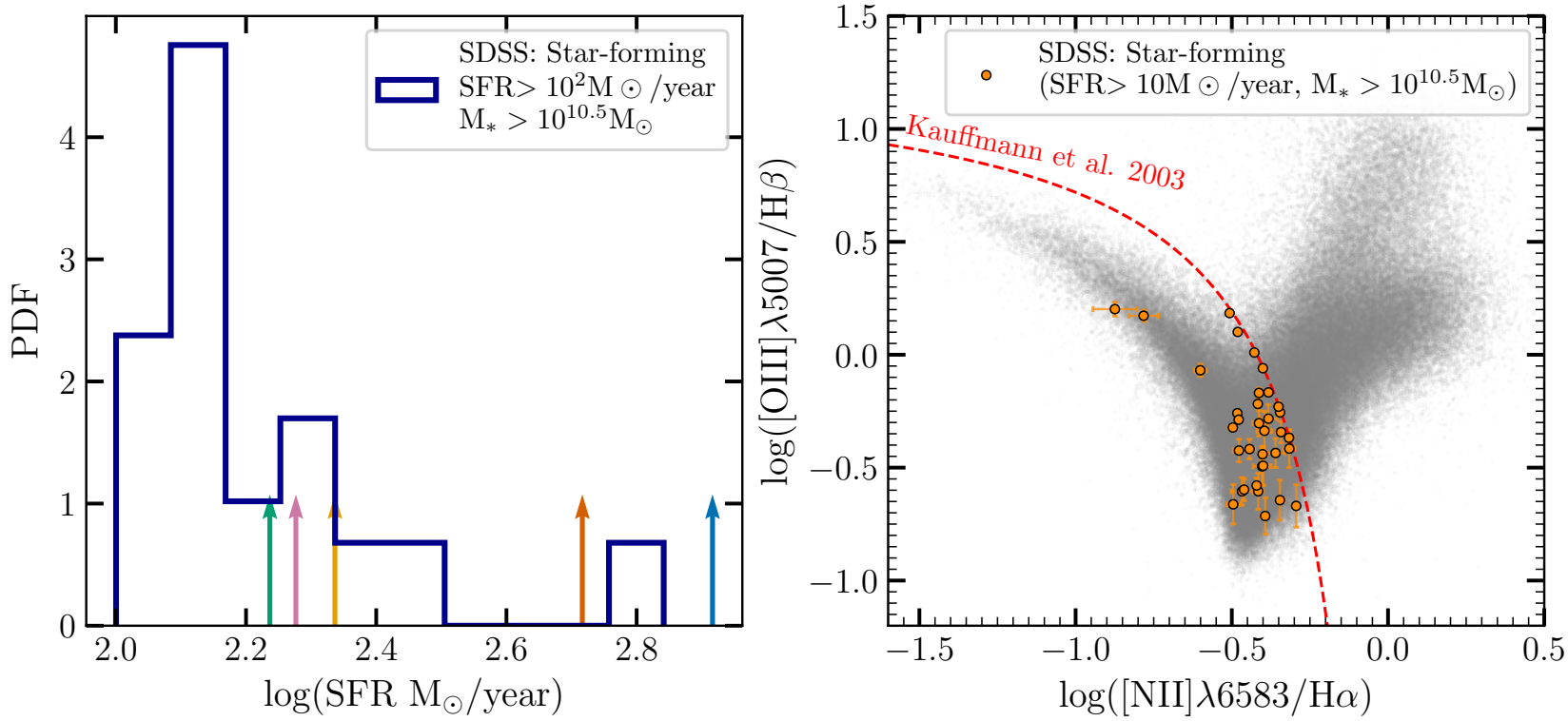
Where do ULIRGs locate on MZR?

- These FIR-based, extinction-insensitive metallicity measurements indicate that ULIRGs lie on the mass-metallicity relation of star-forming galaxies. They do not indicate unusual metal deficiencies in ULIRGs, as one would conclude with optical line ratios alone.

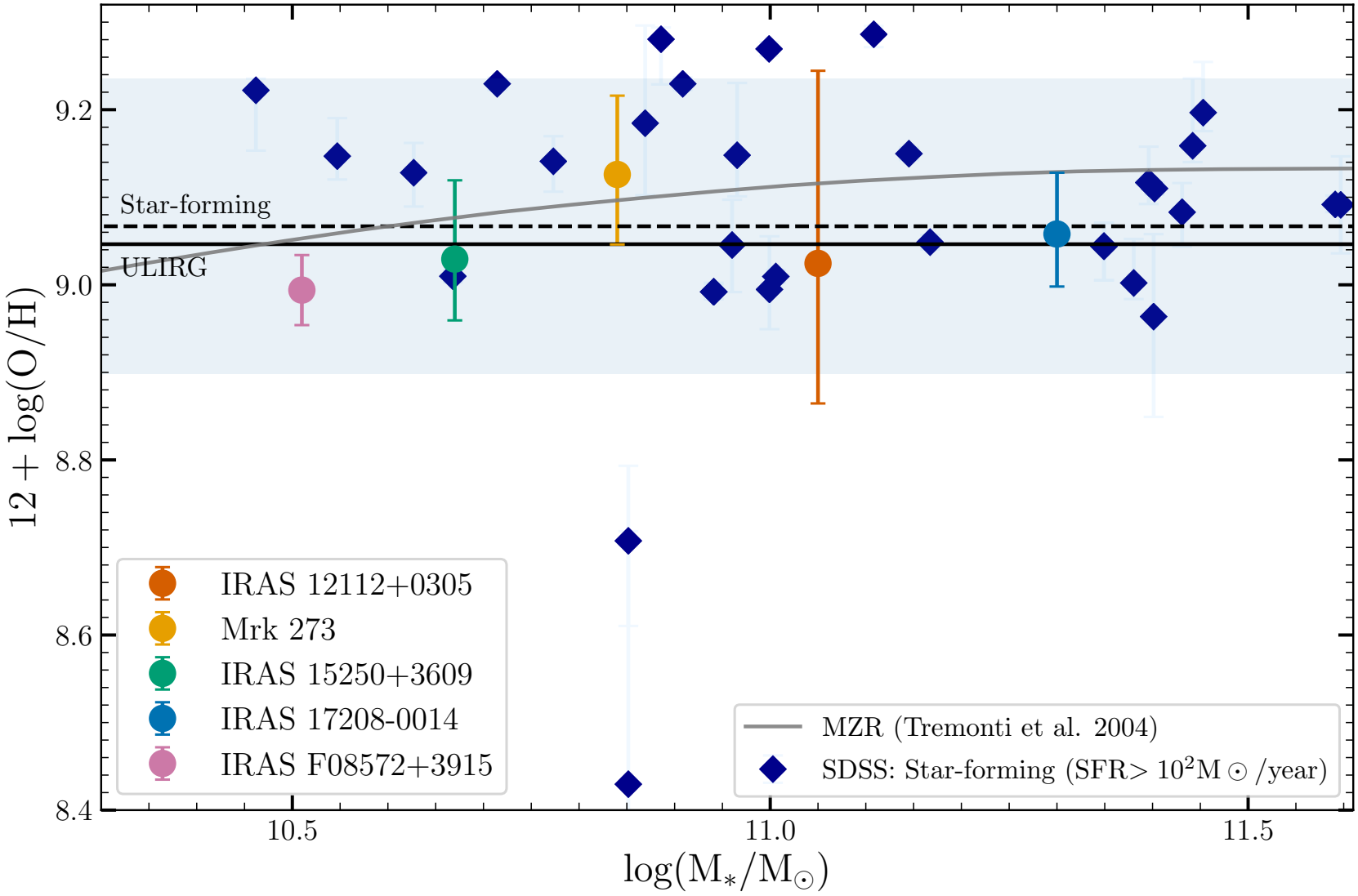


Control sample of less-dusty galaxies from SDSS

- We select galaxies at 0.07 < z < 0.3 with SFR > 100 $M_\odot$/year and A_V< 2.4. We further exclude AGNs from the sample using BPT diagram, as it is known that optical-based metallicities can be contaminated by the ionizing spectrum of an AGN, while FIR metallicity indicator used in this work is robust even in the presence of an AGN.



ULIRGs lie on the local FMR



Conclusion

- ULIRGs are metal-rich or at least have oxygen abundances comparable to normal star-forming galaxies but remain heavily dust-obscured.
- ULIRG sample follows the fundamental metallicity relation and optical lines are not representative of the metallicity of heavily dust-obscured galaxies.
- As dust-obscured, IR-bright galaxies dominate the star-formation rate density of the universe during the peak epoch of star formation, we caution the use of rest-frame optical measurements alone to study the metal abundances of galaxies at redshifts of 2-3.

Thank you!