Unveiling chemical enrichment in galaxies through infrared emission lines

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February 5th
2024

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Index

1 Introduction

2 Methodology

3 Oxygen and nitrogen abundances from infrared emission lines

4 Sulphur abundances from infrared emission lines

5 Observing the “deep-diving” phase

6 Conclusions

Index

1 **Introduction**

2

3

4

5

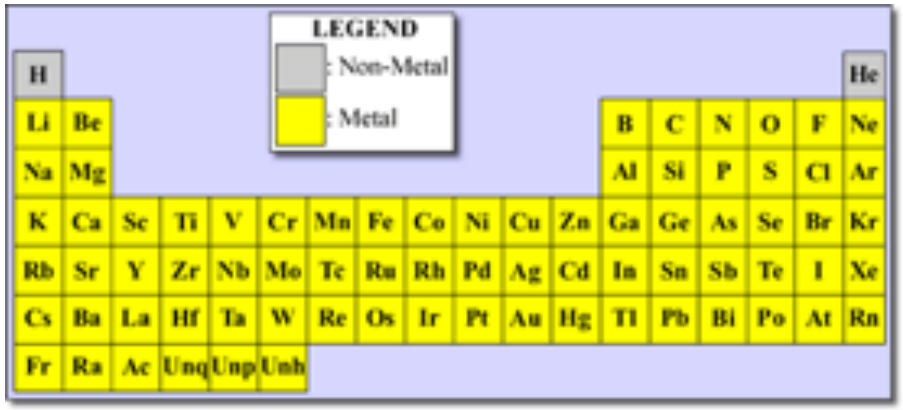
6

Metallicity

The evolution of galaxies is related to the metallicity in their regions.

The metallicity is usually analysed by estimating two chemical abundances ratios:

$$12 + \log(O/H) \quad \text{and} \quad \log(N/O)$$



(Metals in astrophysics)

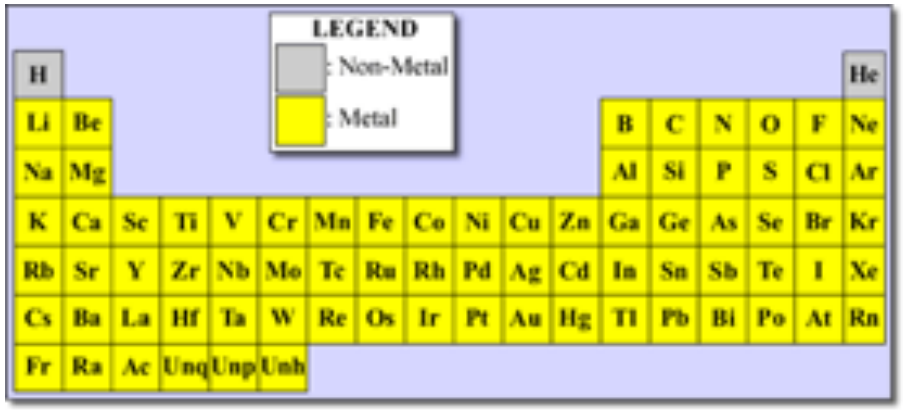
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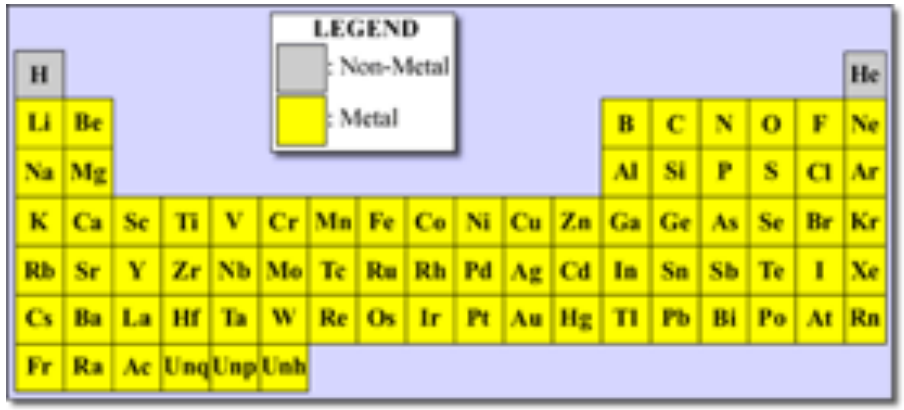
...and 12+log(S/H)??



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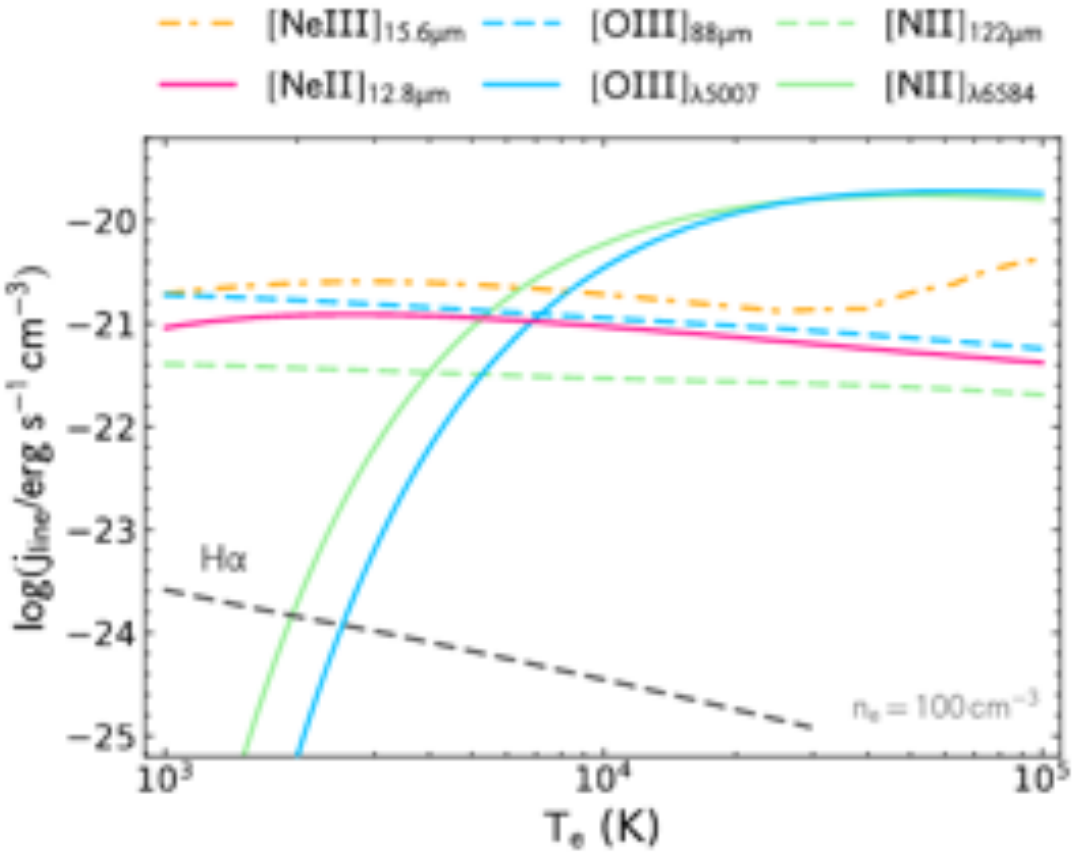
To estimate this quantities in the optical range, we have:

Star-forming galaxies
and
Seyferts 2

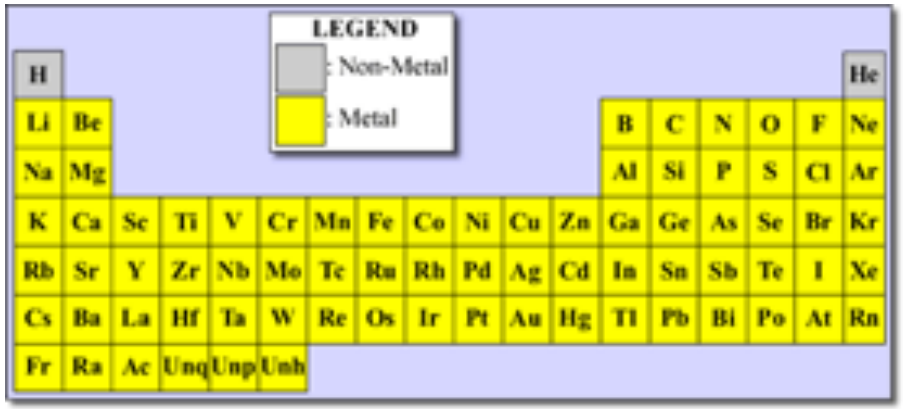
- Direct or T_e-method

Metallicity

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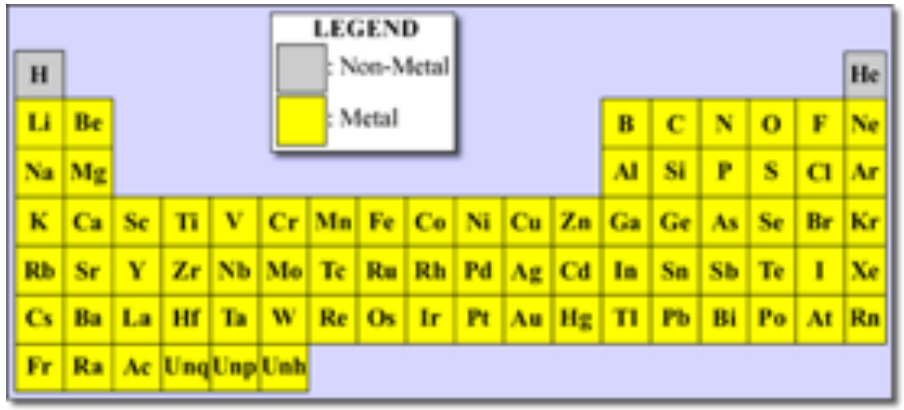
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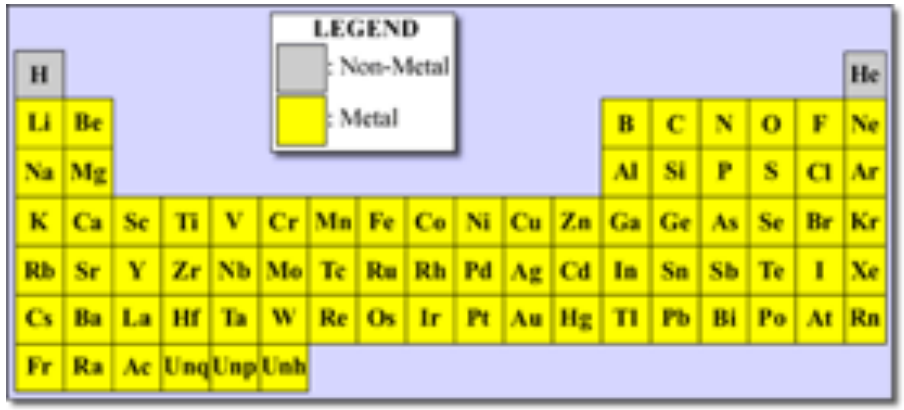
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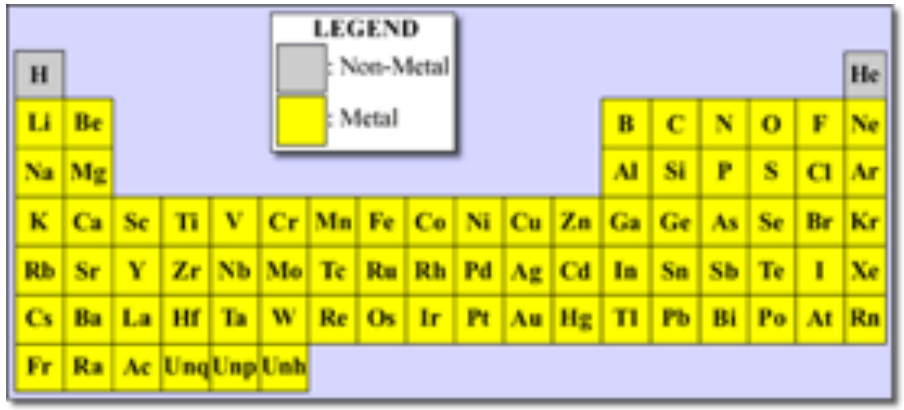
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- Direct or T_e-method
- Photoionization models to match emission line ratios

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(Metals in astrophysics)

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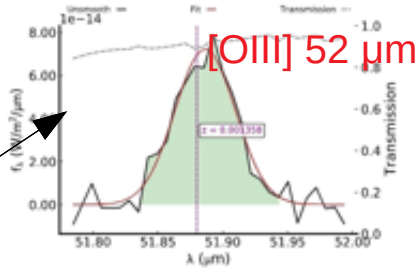
Star-forming galaxies
and
Seyferts 2

- Direct or T_e-method
- Photoionization models to match emission line ratios
- Calibrations based on strong emission lines

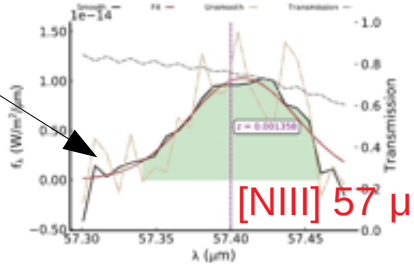
Archival data from...



SOFIA: 50 – 205 μm



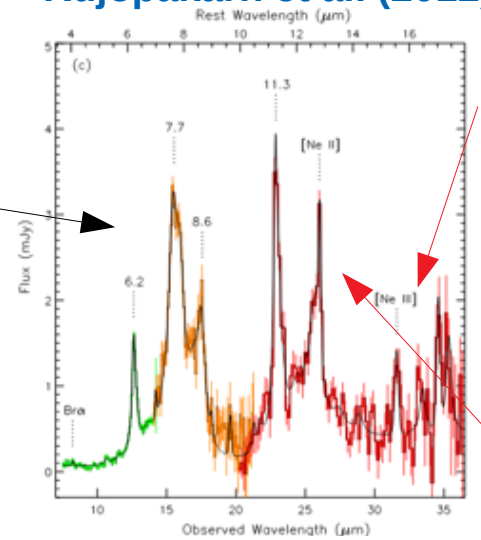
Spinoglio et al. (2022)





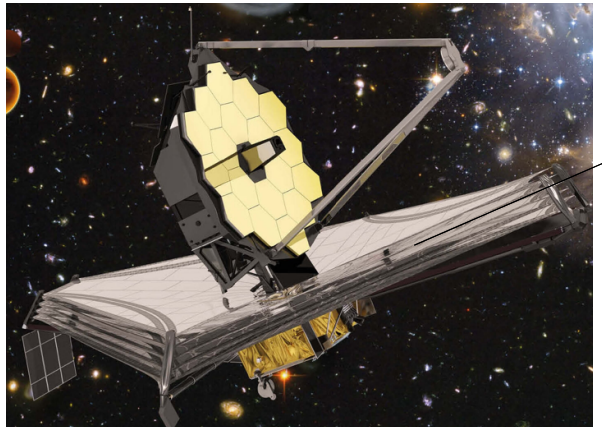
Spitzer: 5 – 39 μm

Rujopakarn et al. (2012)



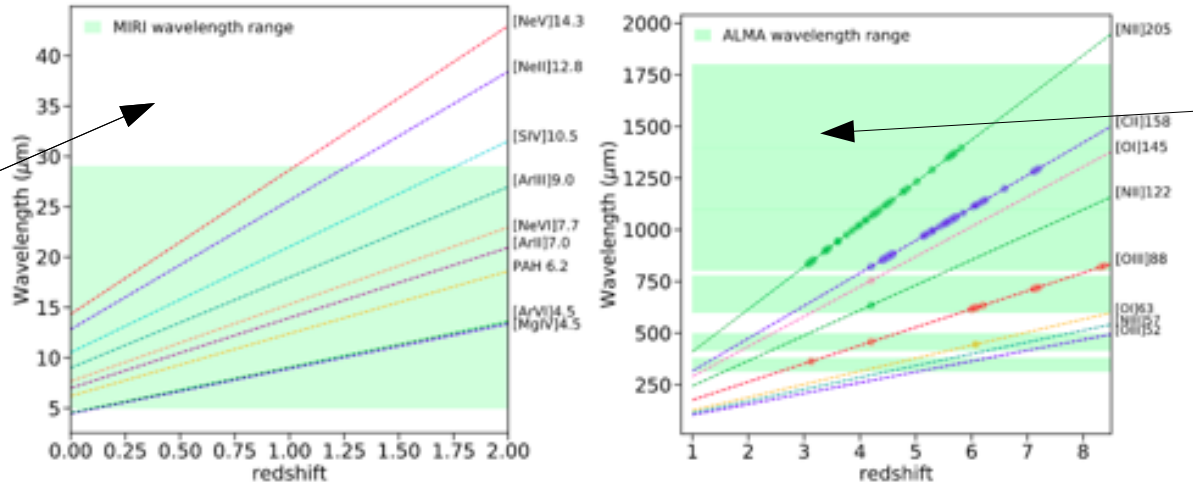
+ other facilities: ISO, HST

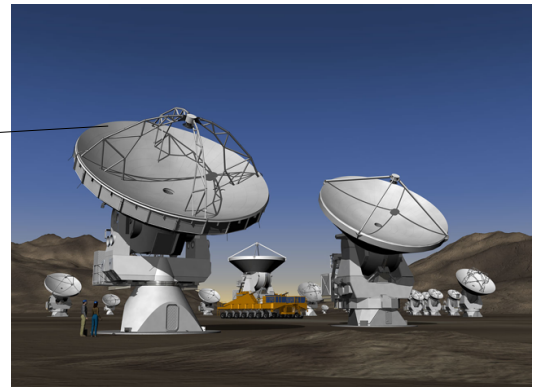
And newcoming data from...



JWST: 4.9 – 28.9 μm

Mordini et al. (2022)





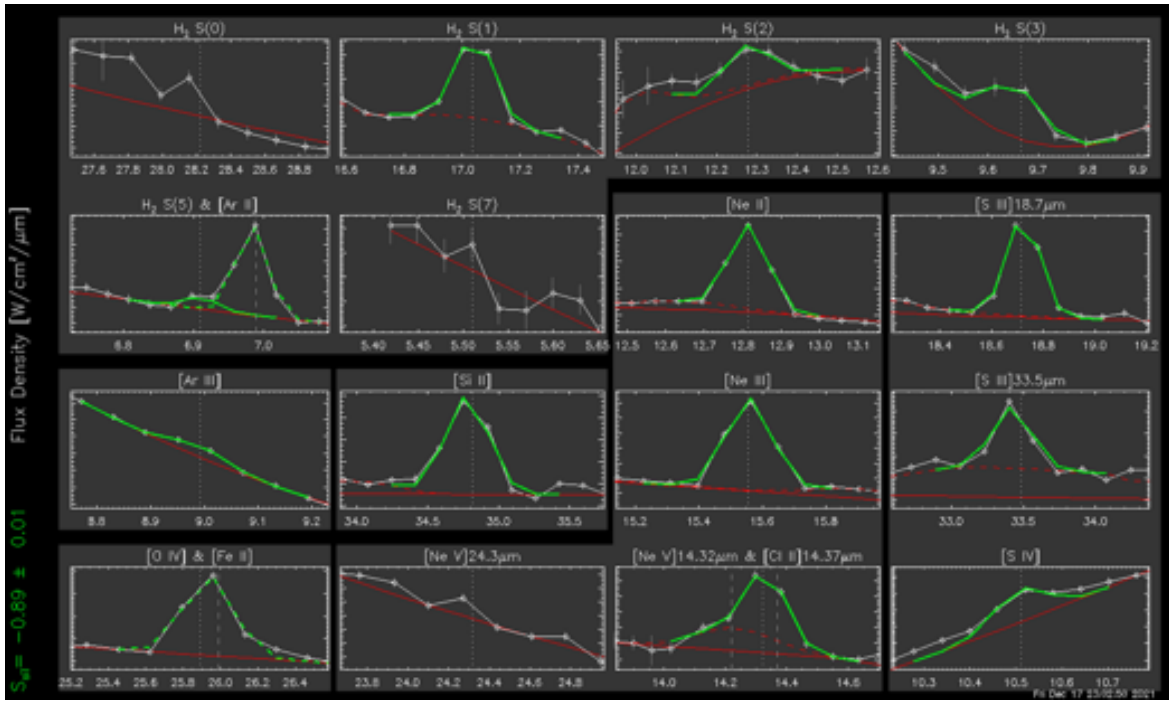
ALMA: 0.3 – 3 mm

+ other facilities: METIS

Why IR emission lines?

Compared to optical emission lines, infrared emission lines provide benefits with their use on the estimation of chemical abundances:

1- Higher ionic species are traced in the IR (i.e. [NeV], [NeVI], [OIV], [ArV], [ArVI],...)



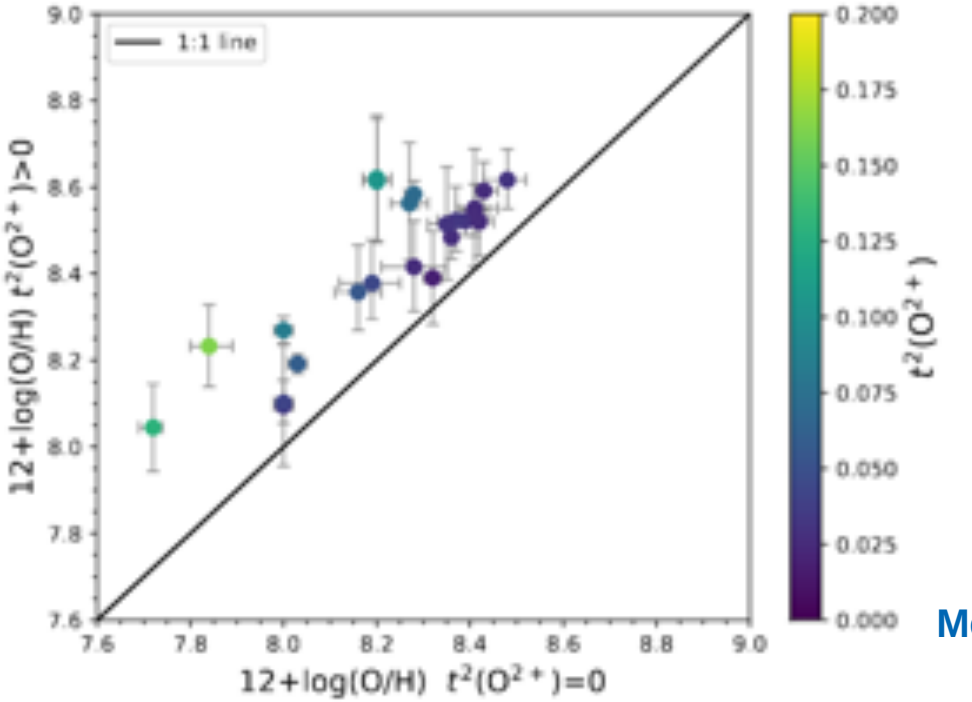
IR spectroscopic information for NGC 5128 (IDEOS)

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2- IR emission lines are almost unaffected by possible temperature fluctuations



Méndez-Delgado et al. (2023)

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3- IR regime allows us to peer through dusty environments (e.g. ULIRGs)



IRAS 20551−4250 as seen by HST

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But… all that glitters is not gold!

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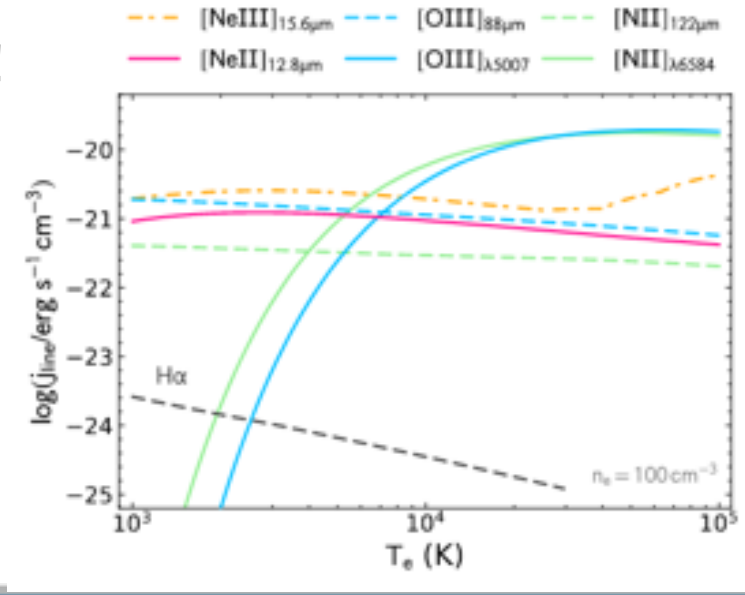
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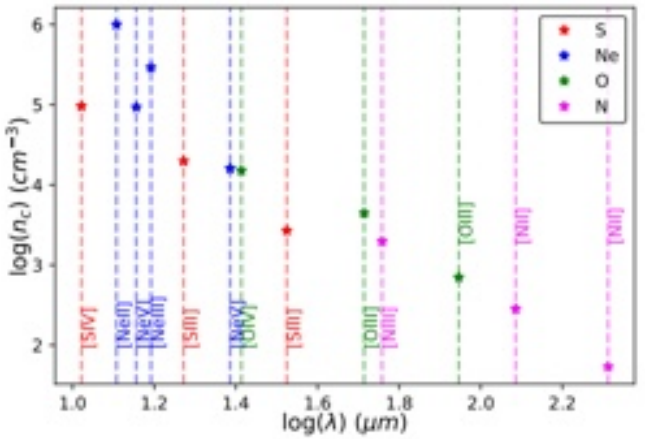
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Index

1 Introduction

2 Methodology

3

4

5

6

HII-CHI-MISTRY

We adapt the HII-CHI-MISTRY (**Pérez-Montero 2014, 2015, 2019**) code to estimate the abundance ratios O/H and N/O from IR and optical emission lines. This program also provides the ionization parameter U.



HII-CHI-MISTRY

HII-CHI-Mistry uses photoionization models to create the grid of models. But you can choose the photoionization code that you want!!!

Spectral type	SED	Grids		
		$12+\log_{10}(O/H)$	$\log_{10}(N/O)$	$\log_{10}(U)$
Star-forming galaxies	POPSTAR Burst of 10^6 yr Ratio Dust/Gas $7.5 \cdot 10^{-3}$	[6.9, 9.1] N° Values: 23	[-2.0, 0.0] N° Values: 17	[-4.0, -1.5] N° Values: 11
Seyferts	BBB max. at 13.6 eV $\alpha_X = -1$ $\alpha_{OX} = -0.8$ or -1.2	[6.9, 9.1] N° Values: 23	[-2.0, 0.0] N° Values: 17	[-4.0, -0.5] N° Values: 15
LINERs	BBB max. at 13.6 eV $\alpha_X = -1$ $\alpha_{OX} = -0.8$ or -1.2	[6.9, 9.1] N° Values: 23	[-2.0, 0.0] N° Values: 17	[-4.0, -2.5] N° Values: 6
Steps	-	0.1 dex	0.125 dex	0.25 dex
N° Models	-	4301 Star-forming	5865 Seyferts	2346 LINERs

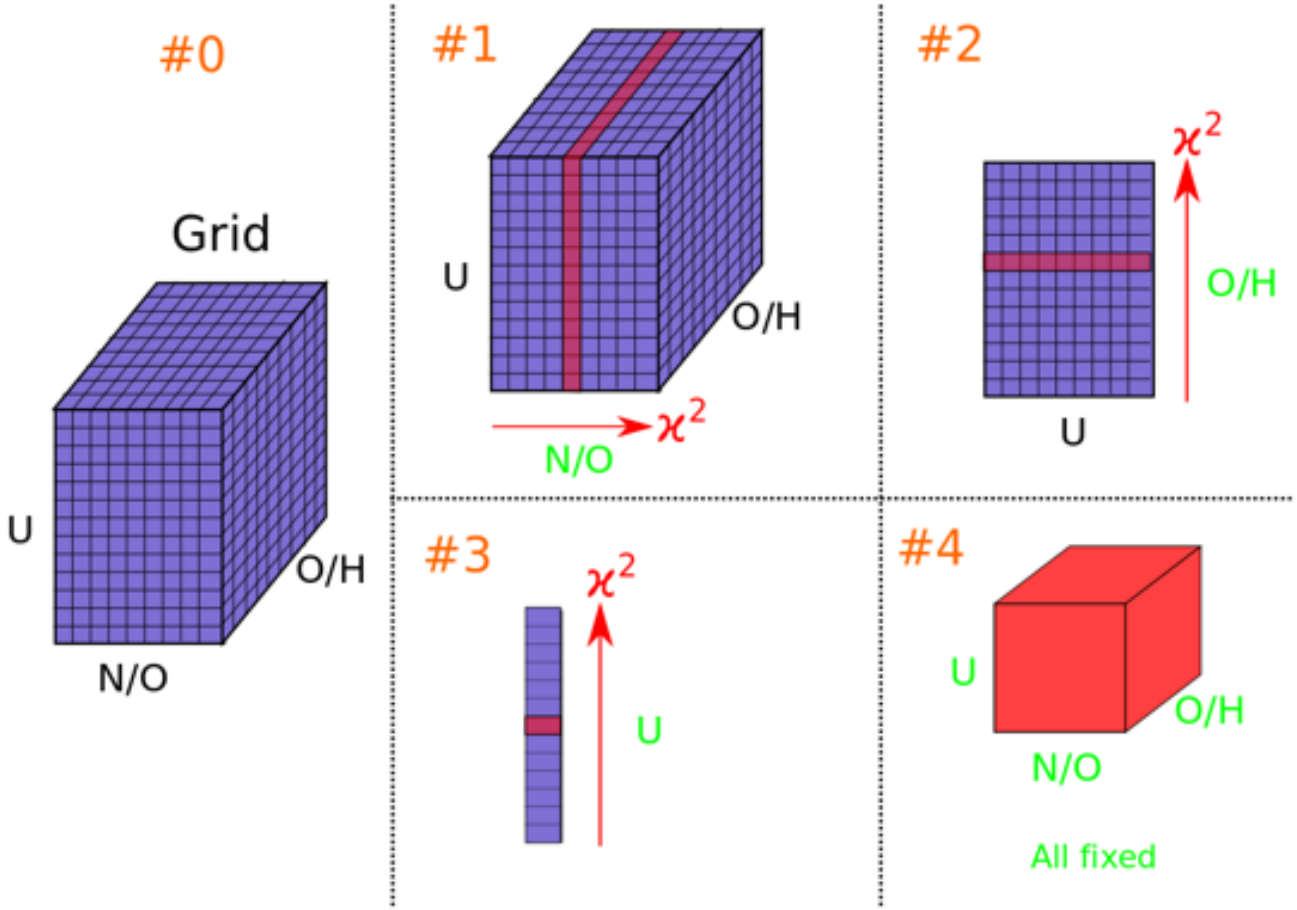
How does HII-CHI-MISTRY work?

Input: Optical emission lines

[OII] 3727, [NeIII] 3868, [OIII] 4363, [OIII] 5007, [NII] 6584, [SII] 6717,6731, Hβ

Input: IR emission lines

HI 4μm, HI 7μm, [SIV] 10μm, HI 12μm, [NeII] 12μm, [NeV] 14μm, [NeIII] 15μm, [SIII] 18μm, [NeV] 24μm, [OIV] 26μm, [SIII] 33μm, [OIII] 52μm, [NIII] 57μm, [OIII] 88μm, [NII] 122μm, [NII] 205μm



Index

1 Introduction

2 Methodology

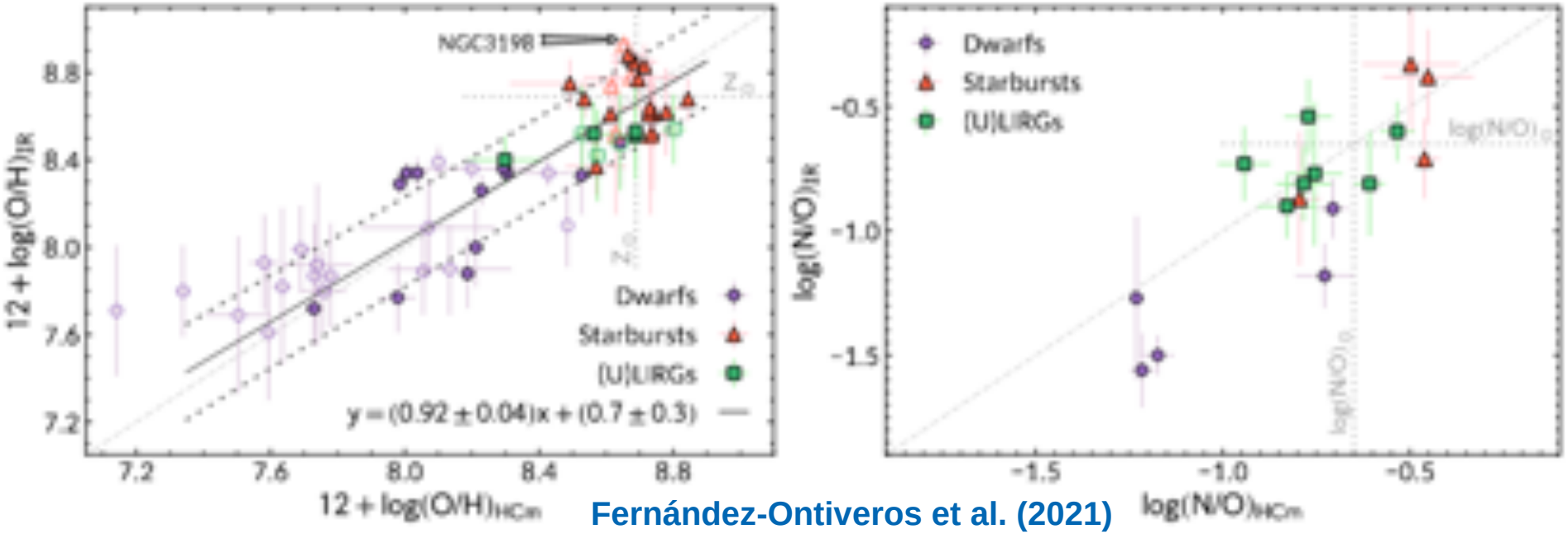
3 Oxygen and nitrogen abundances from infrared emission lines

4

5

6

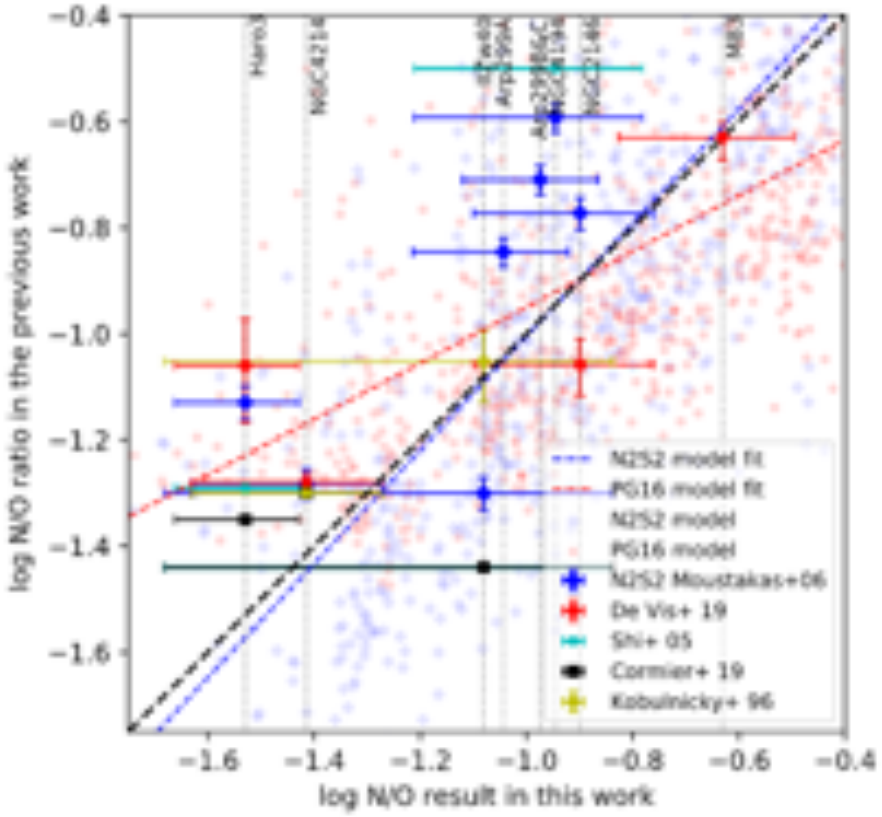
Results for SFGs



Fernández-Ontiveros et al. (2021)

Fernandéz-Ontiveros et al. (2021) presented the first upgrade for HII-CHI-Mistry to derive chemical abundnaces from IR emission lines. When compared IR and optical abundances, they observed some slight discrepancies for O/H, but in the case of N/O, these discrepancies are higher.

Results for SFGs

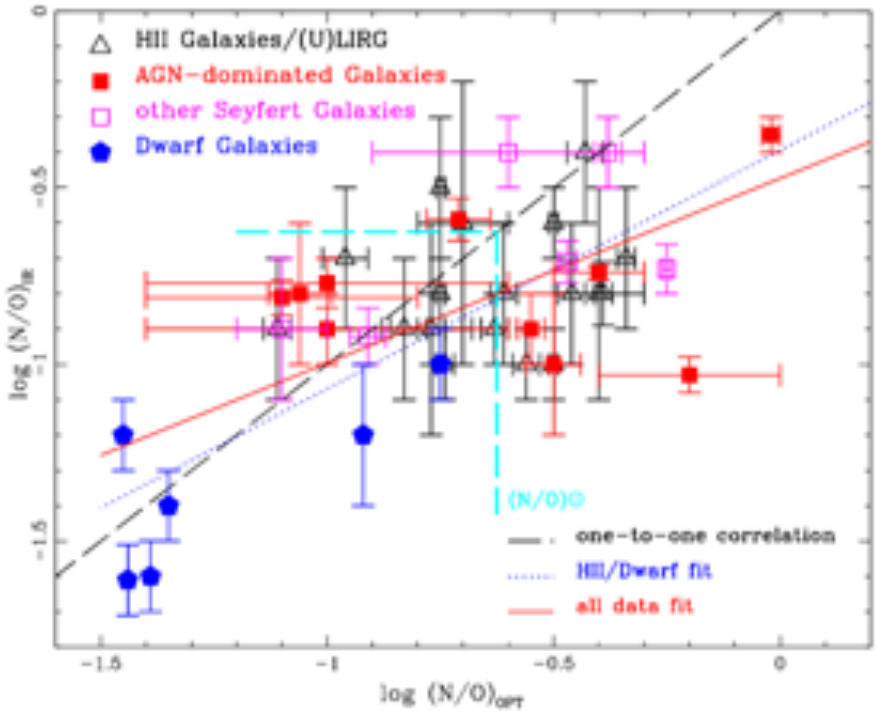


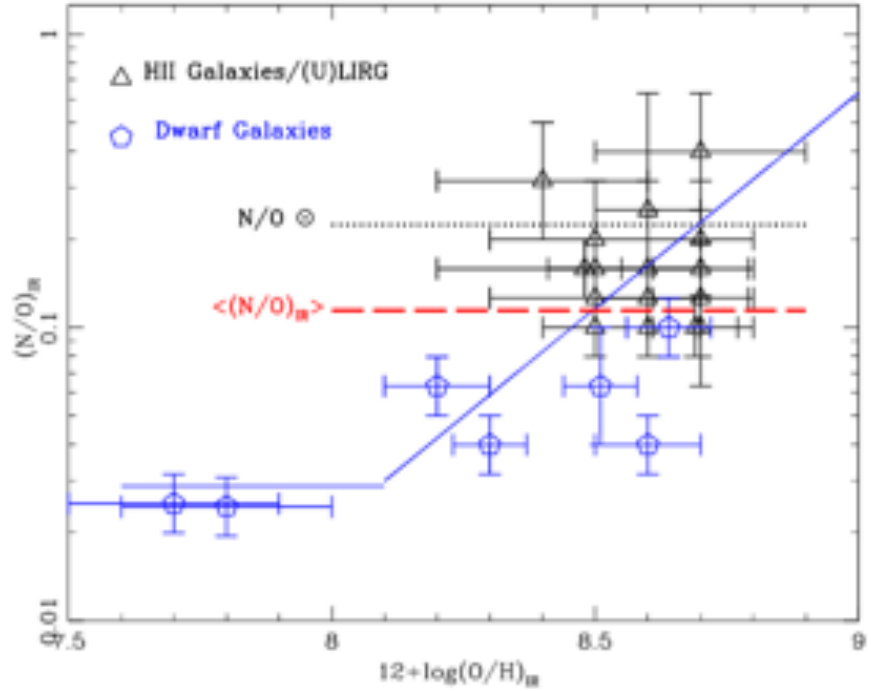
Galaxy	Optical log N/O	Far-IR log N/O
Arp 299 A	$-0.85^{+0.02}_{-0.02}$ [a]	$-1.04^{+0.12}_{-0.11}$
Arp 299 B&C	$-0.71^{+0.02}_{-0.02}$ [a]	$-0.97^{+0.09}_{-0.14}$
Haro 3	$-1.13^{+0.01}_{-0.01}$ [a], $-1.06^{+0.08}_{-0.07}$ [b], -1.29 [c], -1.35 [d],	$-1.53^{+0.10}_{-0.13}$
II Zw 40	$-1.30^{+0.02}_{-0.01}$ [a], -1.44 [c], -1.44 [d], $-1.052^{+0.05}_{-0.07}$ [e]	$-1.08^{+0.24}_{-0.08}$
M83	$-0.63^{+0.02}_{-0.04}$ [b]	$-0.63^{+0.13}_{-0.19}$
NGC 2146	$-0.77^{+0.02}_{-0.01}$ [a], $-1.06^{+0.04}_{-0.05}$ [b]	$-0.90^{+0.13}_{-0.20}$
NGC 4194	$-0.59^{+0.02}_{-0.02}$ [a], -0.5 [c]	$-0.95^{+0.18}_{-0.26}$
NGC 4214 region I	$-1.30^{+0.02}_{-0.01}$ [a], $-1.28^{+0.01}_{-0.01}$ [b], -1.30 [d,e],	$-1.41^{+0.14}_{-0.21}$

Peng et al. (2021)

Peng et al. (2021) also found discrepancies in the N/O ratio when compared optical and infrared estimations

Results for AGNs





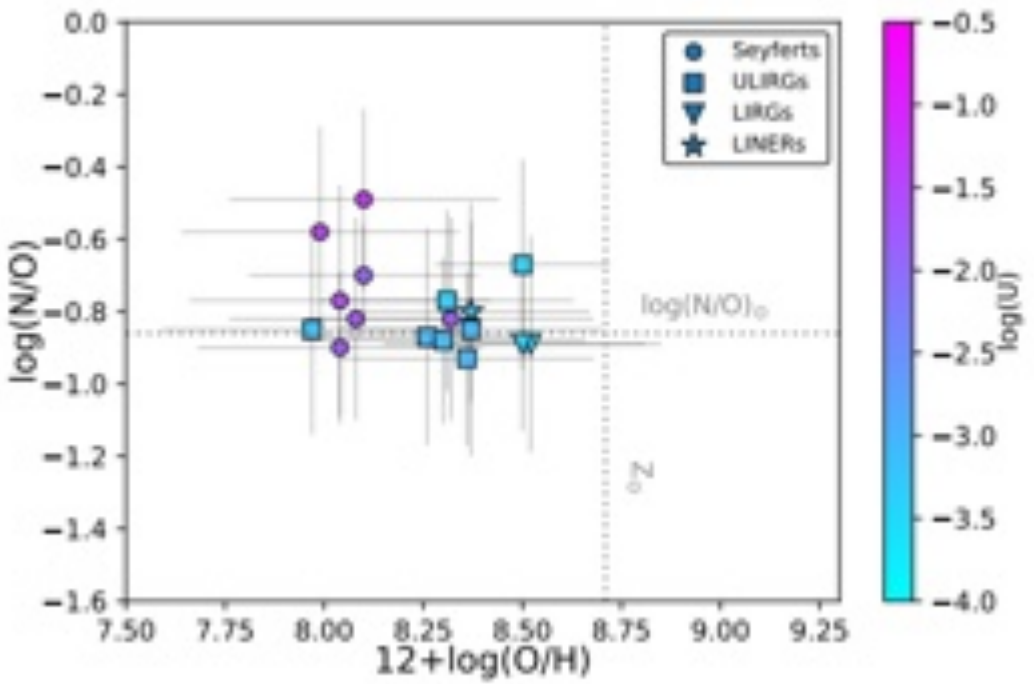
Spinoglio et al. (2022)

Also in AGNs some discrepancies are found when estimating N/O through emission line calibrations (N3O3 based on FIR emission lines)

Abundances in the NLR of AGN

Pérez-Díaz et al. (2022)

		$\log_{10}(N/O)$		
Sample	**N°$_{tot}$**	**N°**	**Median**	**Std. Dev.**
All galaxies	58	35	-0.83	0.17
Seyferts	43	22	-0.81	0.20
ULIRGs	8	8	-0.86	0.07
LIRGs	4	4	-0.885	0.019
LINERs	3	1	-0.80	-

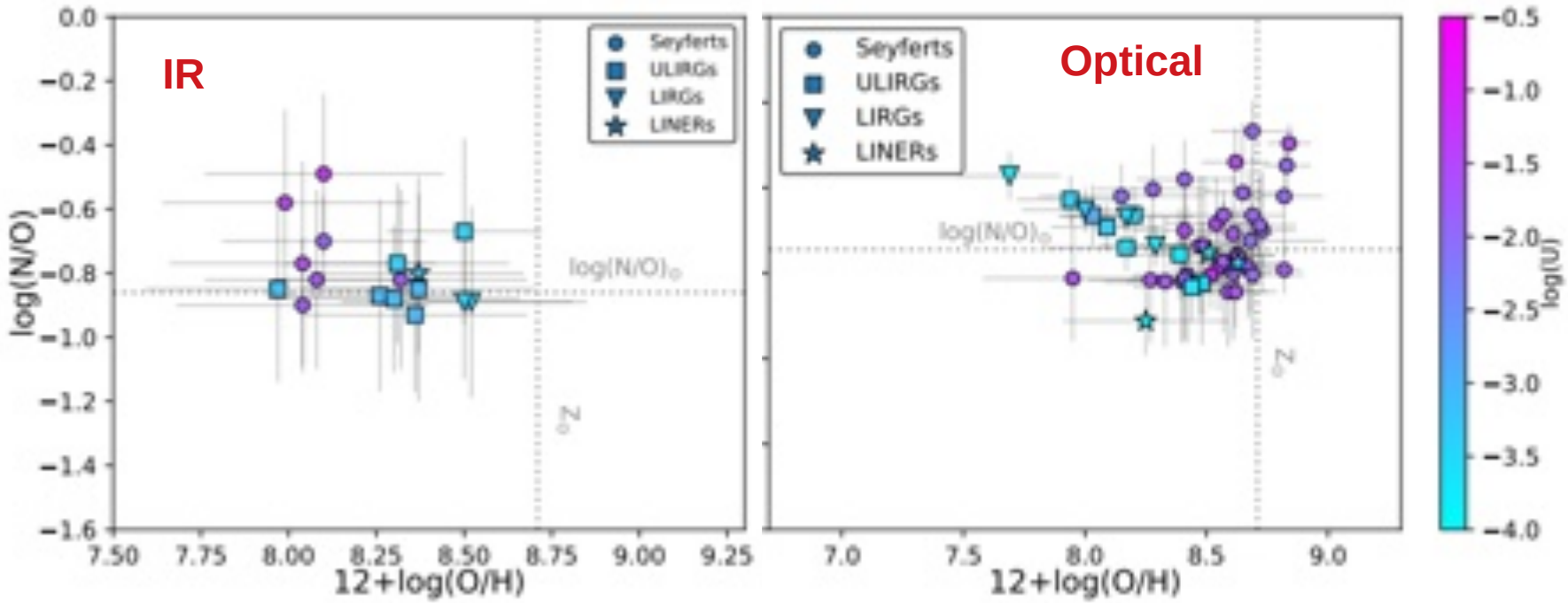


		$\log_{10}(U)$		
Sample	**N°$_{tot}$**	**N°**	**Median**	**Std. Dev.**
All galaxies	58	52	-1.73	0.80
Seyferts	43	39	-1.67	0.33
ULIRGs	8	7	-3.08	0.15
LIRGs	4	4	-3.58	0.14
LINERs	3	2	-3.24	0.10

		$12 + \log_{10}(O/H)$		
Sample	**N°$_{tot}$**	**N°**	**Median**	**Std. Dev.**
All galaxies	58	26	8.05	0.24
Seyferts	43	15	7.99	0.16
ULIRGs	8	7	8.32	0.20
LIRGs	4	2	8.495	0.005
LINERs	3	2	8.17	0.18

Abundances in the NLR of AGN

Pérez-Díaz et al. (2022, A&A)



Index

1 Introduction

2 Methodology

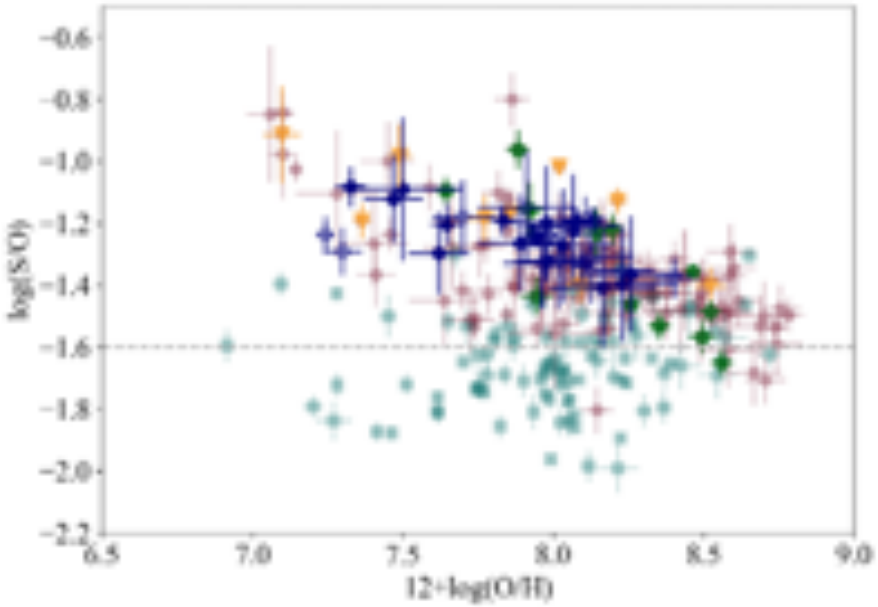
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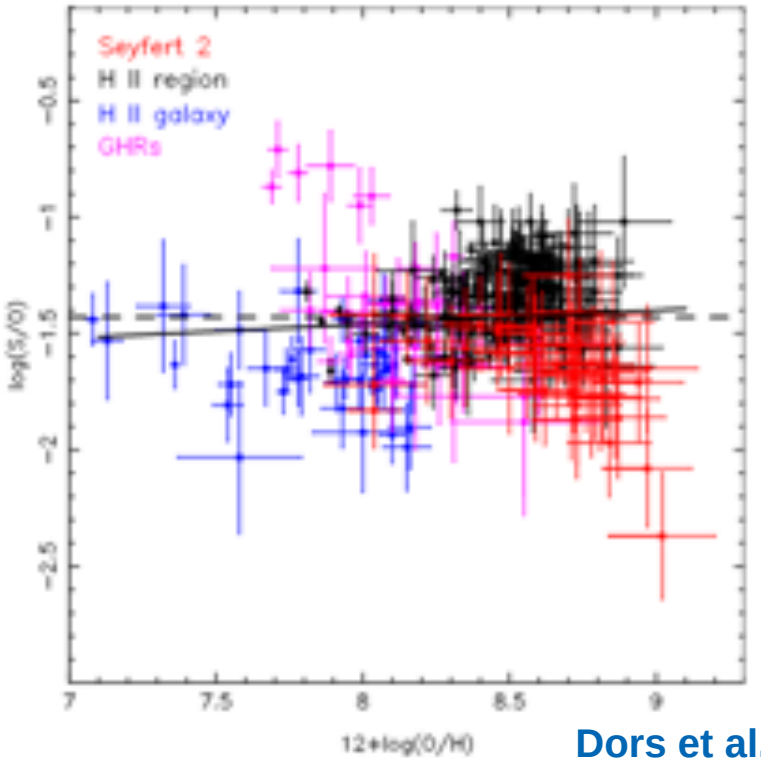
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Overview on sulphur studies



Díaz et al. (2022)

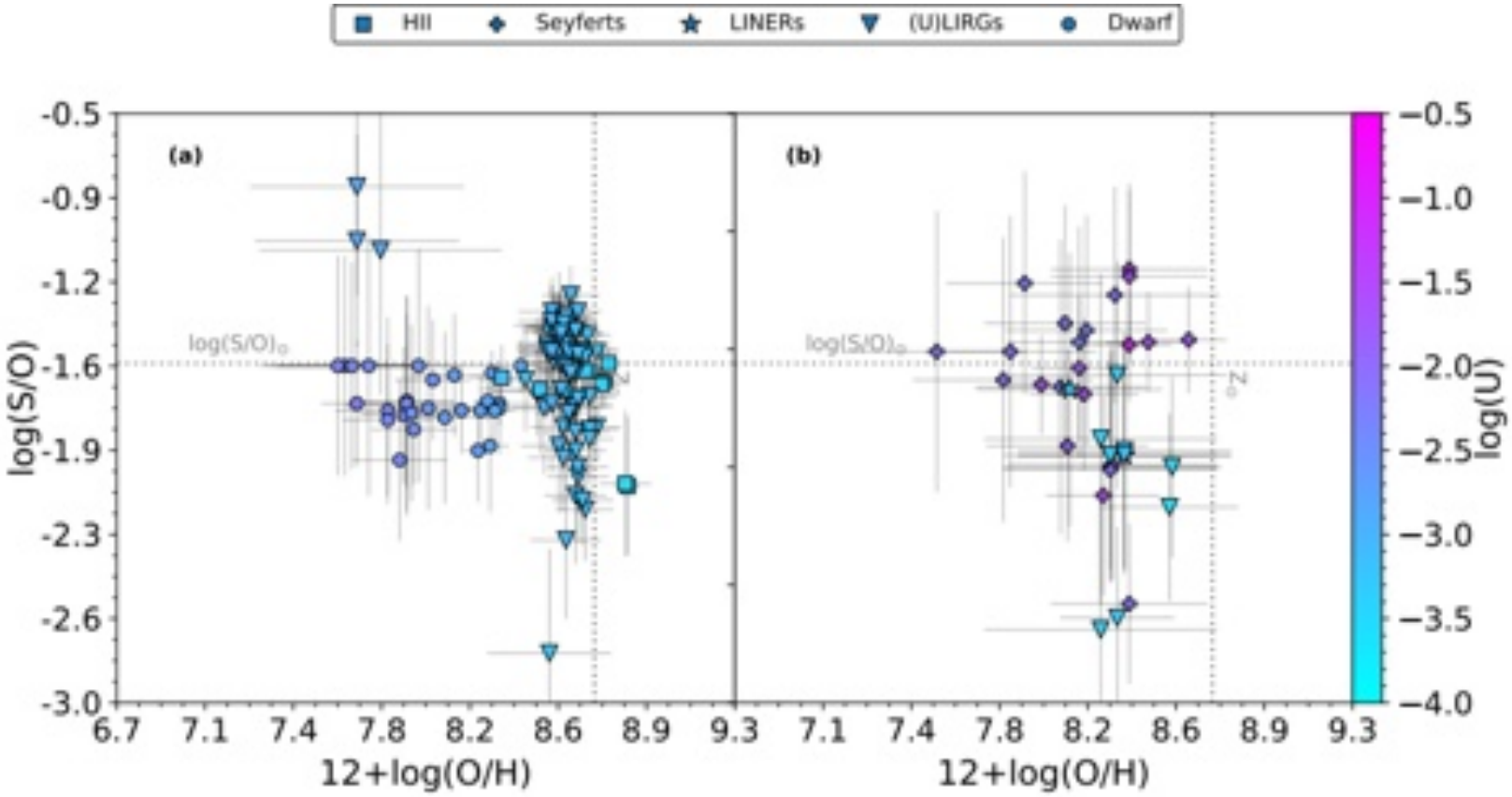


Dors et al. (2023)

Some galaxies (either SF- or AGN-dominated) present log(S/O) ratios which deviate from the solar ratio.

Sulphur study from IR emission

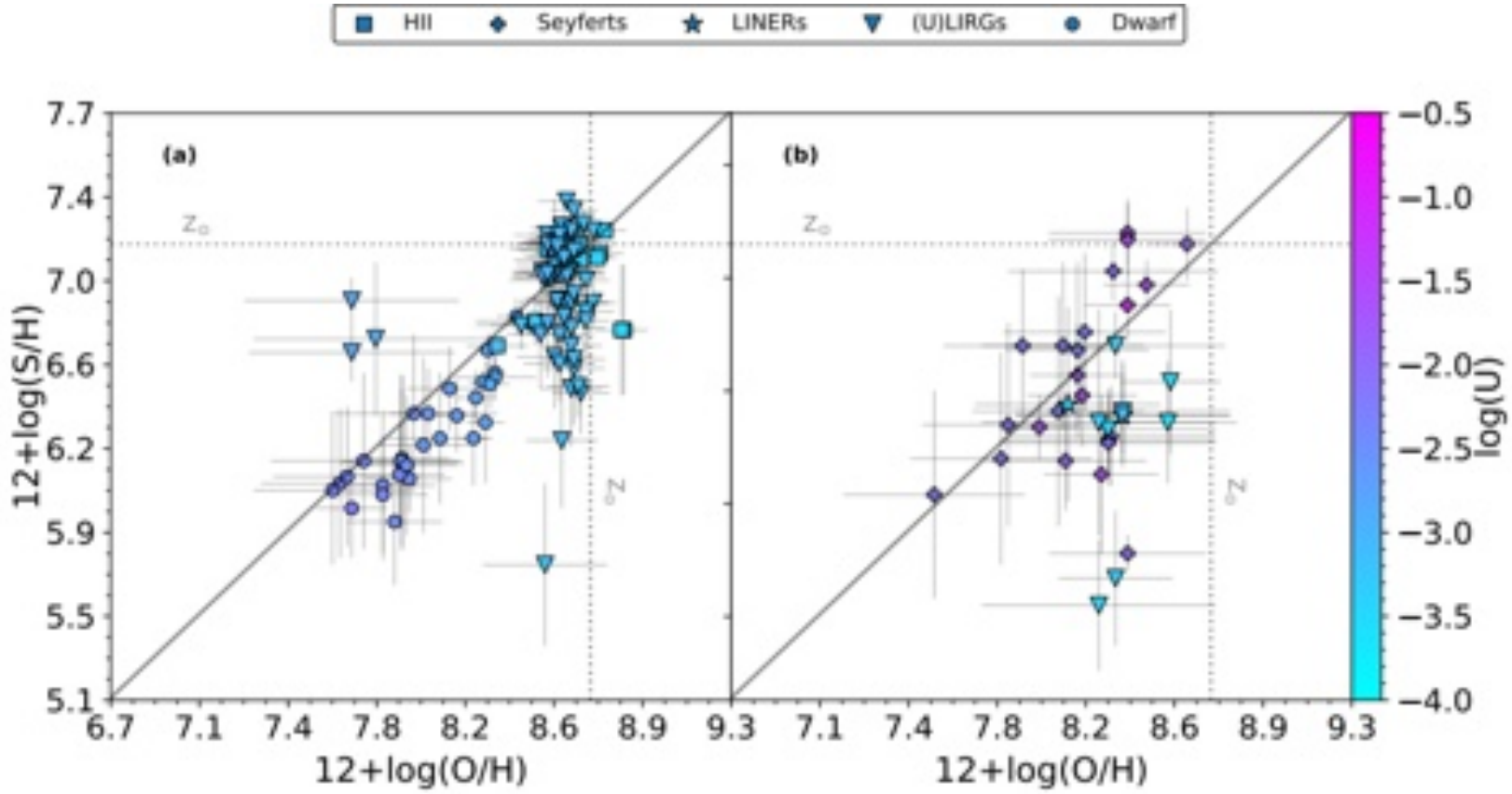
We take advantage on the extremely low dependence of IR emission lines on temperature and the availability of [SIII] and [SIV] emission lines.



Pérez-Díaz et al. (submitted)

Sulphur study from IR emission

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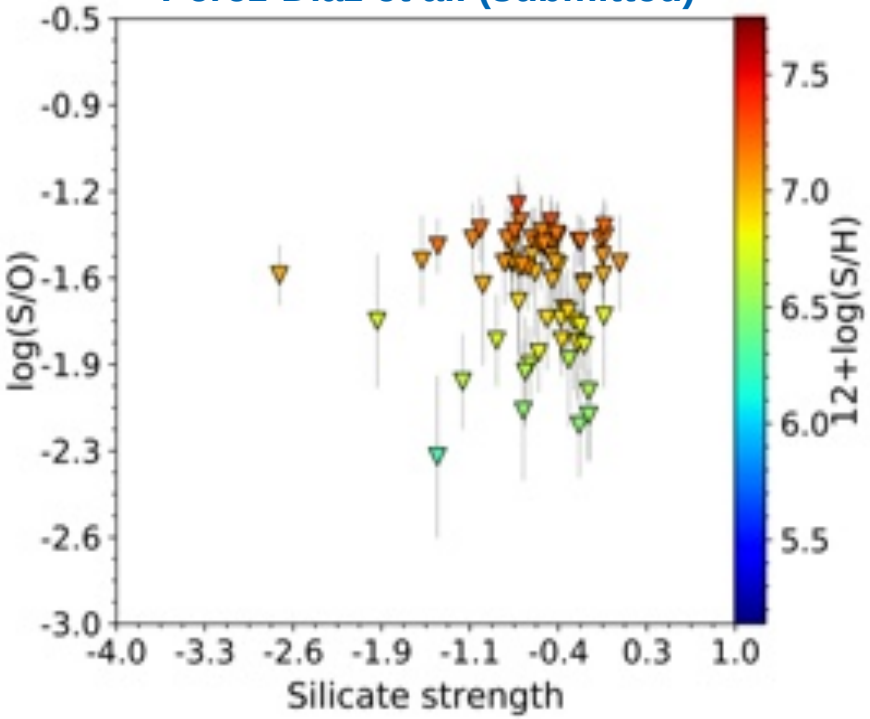


Pérez-Díaz et al. (submitted)

Sulphur study from IR emission

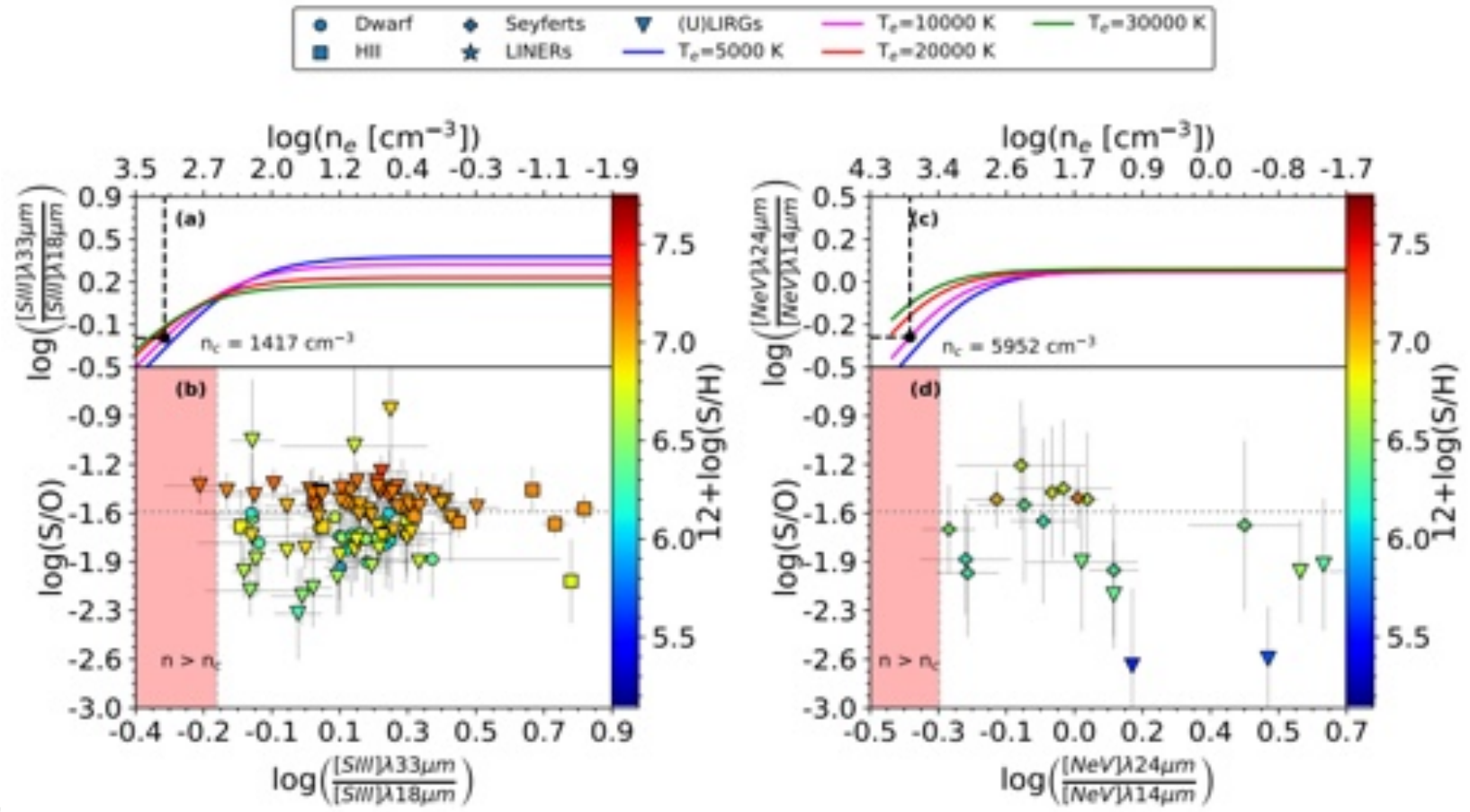
We discard possible observational effects, for instance, in the detection of [SIV] due to the strength of the silicate emission in the [10, 12] μm regime.

Pérez-Díaz et al. (submitted)



Sulphur study from IR emission

We explore whether these deviations are explained by the physical conditions of the gas-phase ISM



Pérez-Díaz et al. (submitted)

Index

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2 Methodology

3 Oxygen and nitrogen abundances from infrared emission lines

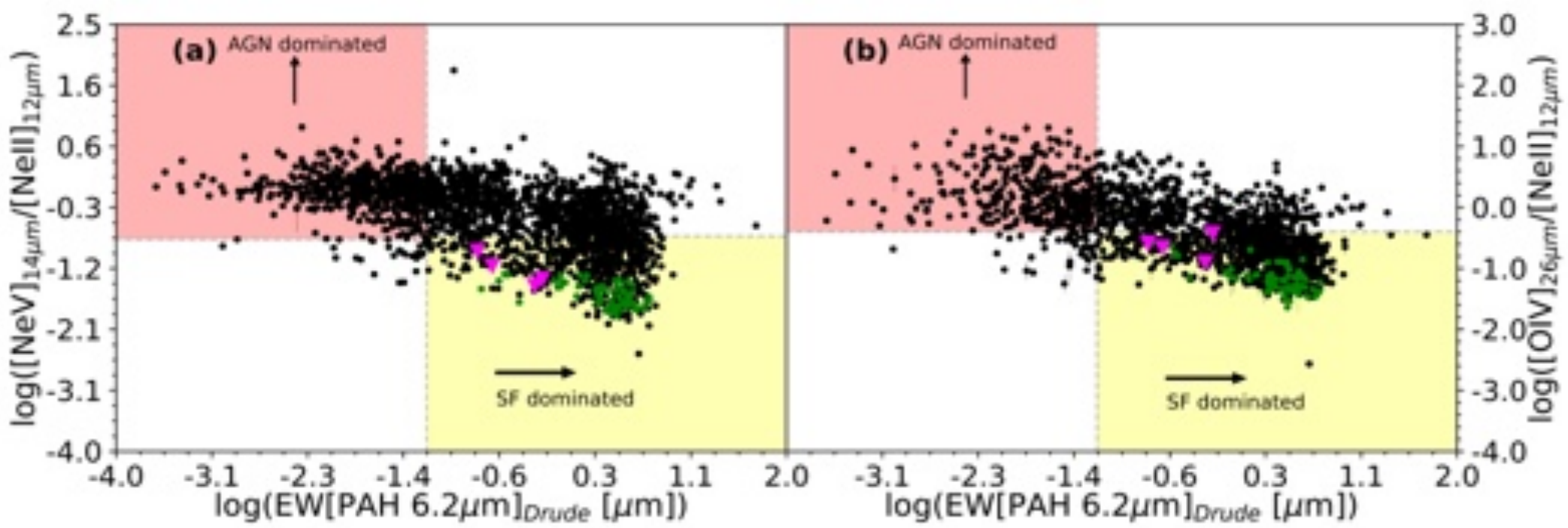
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5 Observing the “deep-diving” phase

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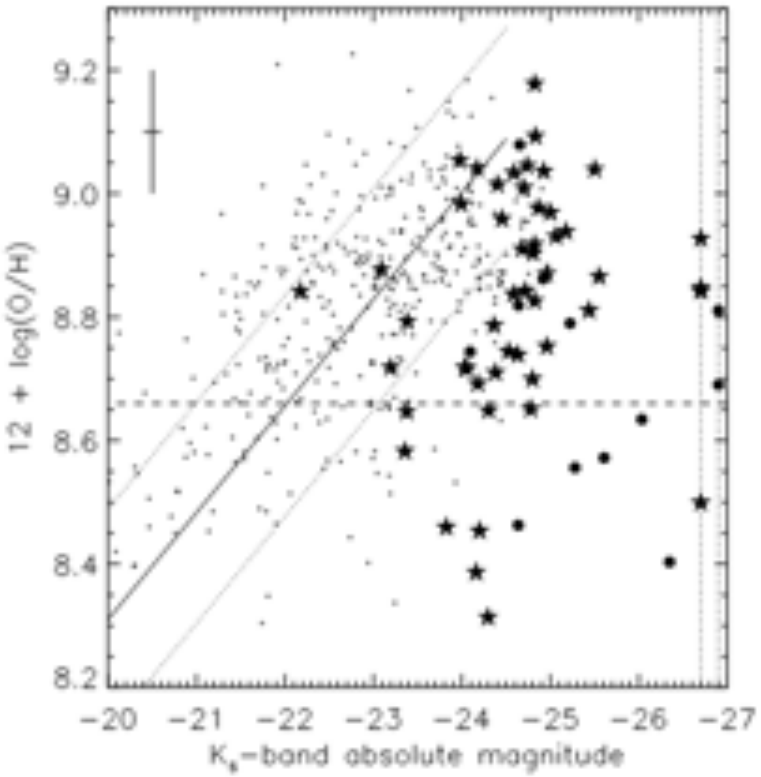
Analysing the chemical content of (U)LIRGs

Pérez-Díaz et al. (2024, NatAs)



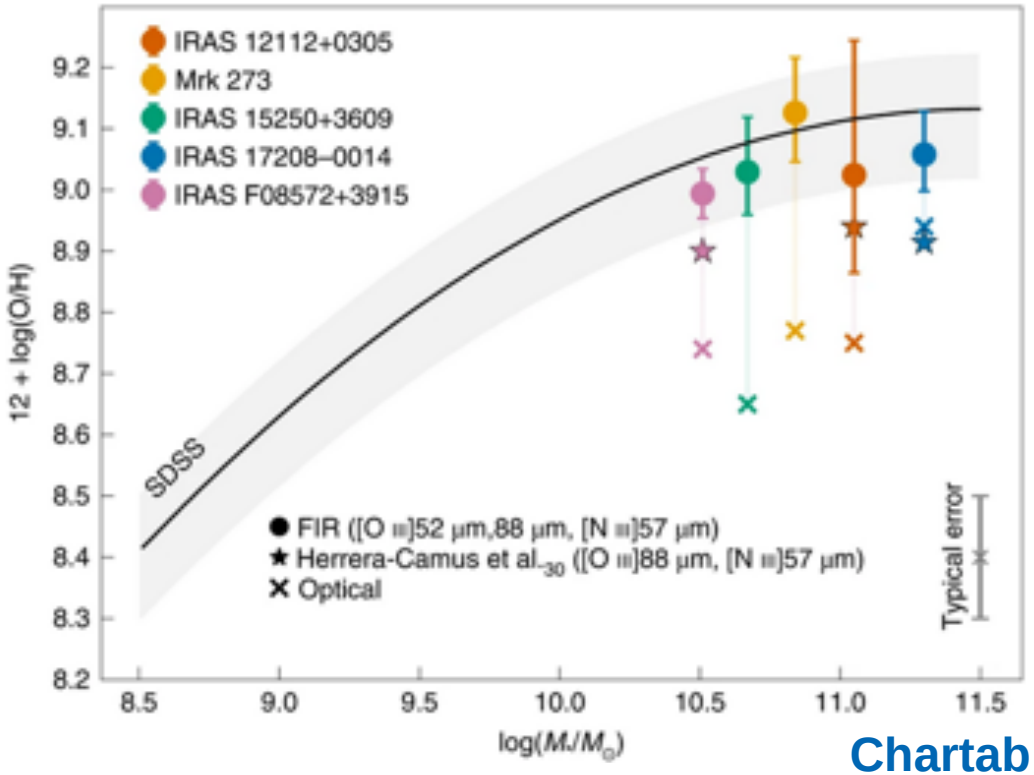
Complementary to the samples of SFGs from **Fernández-Ontíveros et al. (2021)** and AGNs from **Pérez-Díaz et al. (2022)**, we also analyzed the IR spectroscopic database from IDEOS (**Hernán-Caballero et al. 2016, Spoon et al. 2022**).

Previous results on the chemical content in (U)LIRGs



Rupke et al. 2008

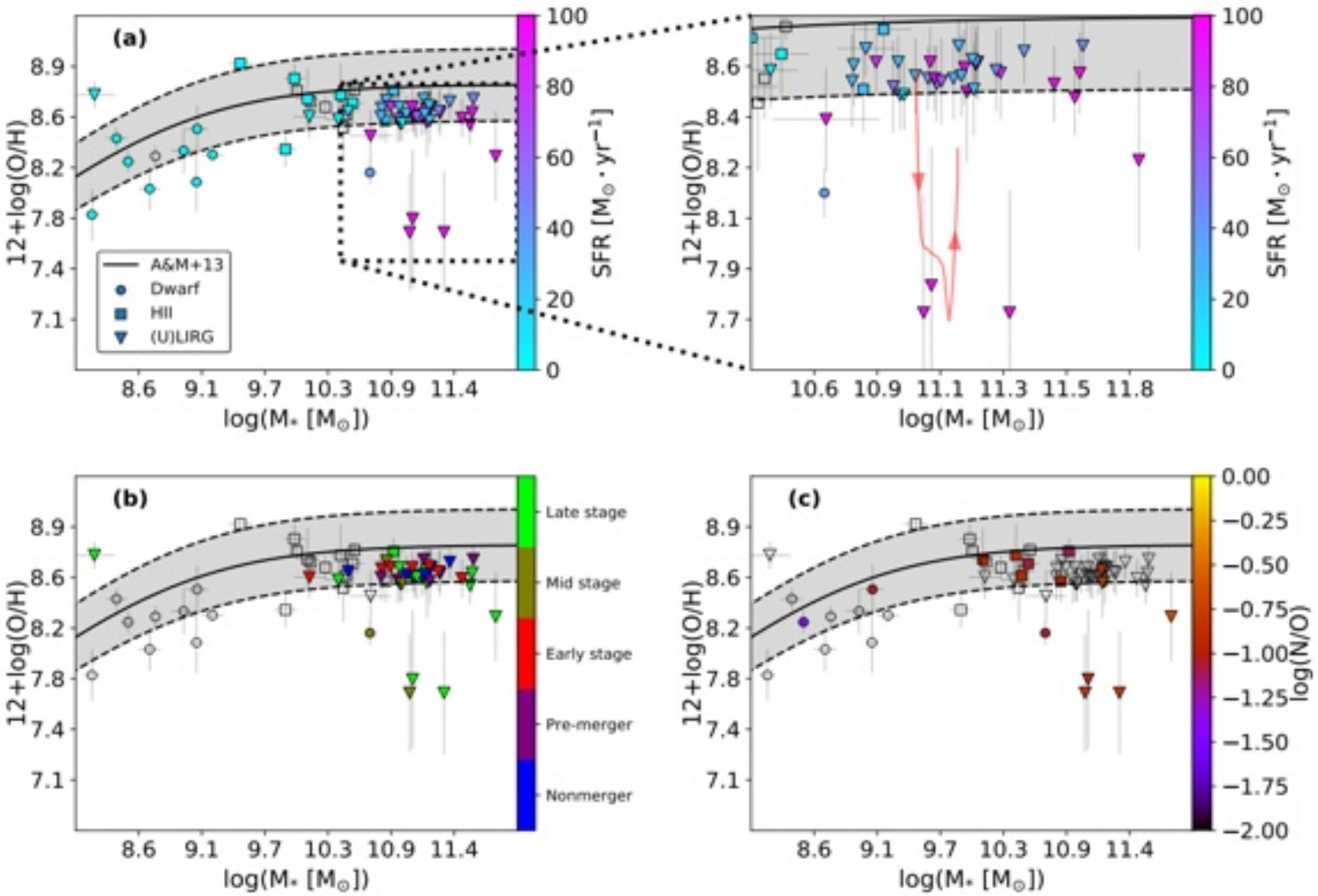
Optical studies pointed to lower chemical abundances in (U)LIRGs than in SFGs.



Chartab et al. 2022

A recent study on the chemical content based on IR emission lines pointed that (U)LIRGs, on the contrary to optical studies, follow the MZR.

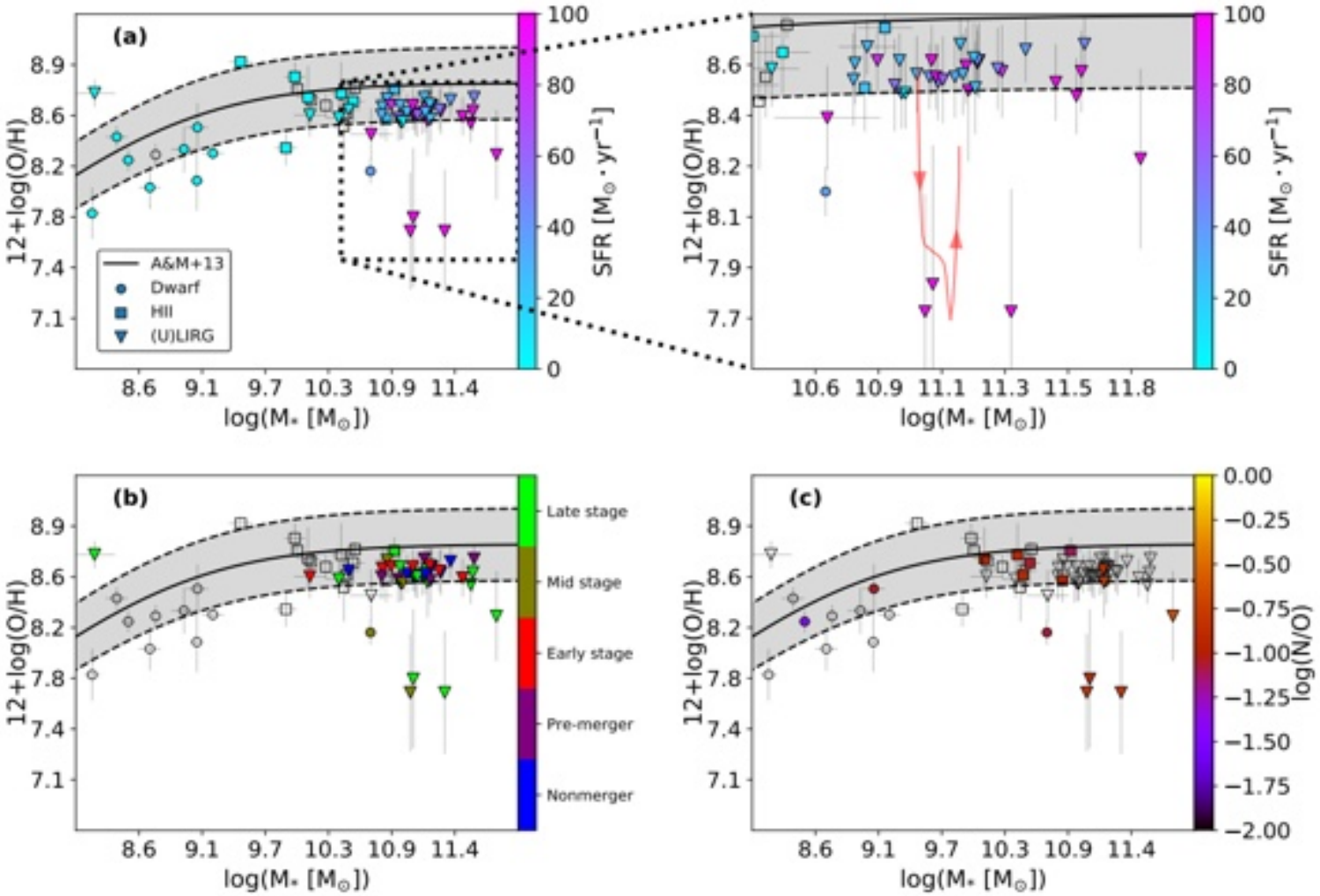
Analysing the chemical content of (U)LIRGs



(Ultra)-Luminous Infrared Galaxies do follow the MZR, although we detect some (U)LIRGs clearly deviate from that behaviour:

Pérez-Díaz et al. (2024, NatAs)

Analysing the chemical content of (U)LIRGs

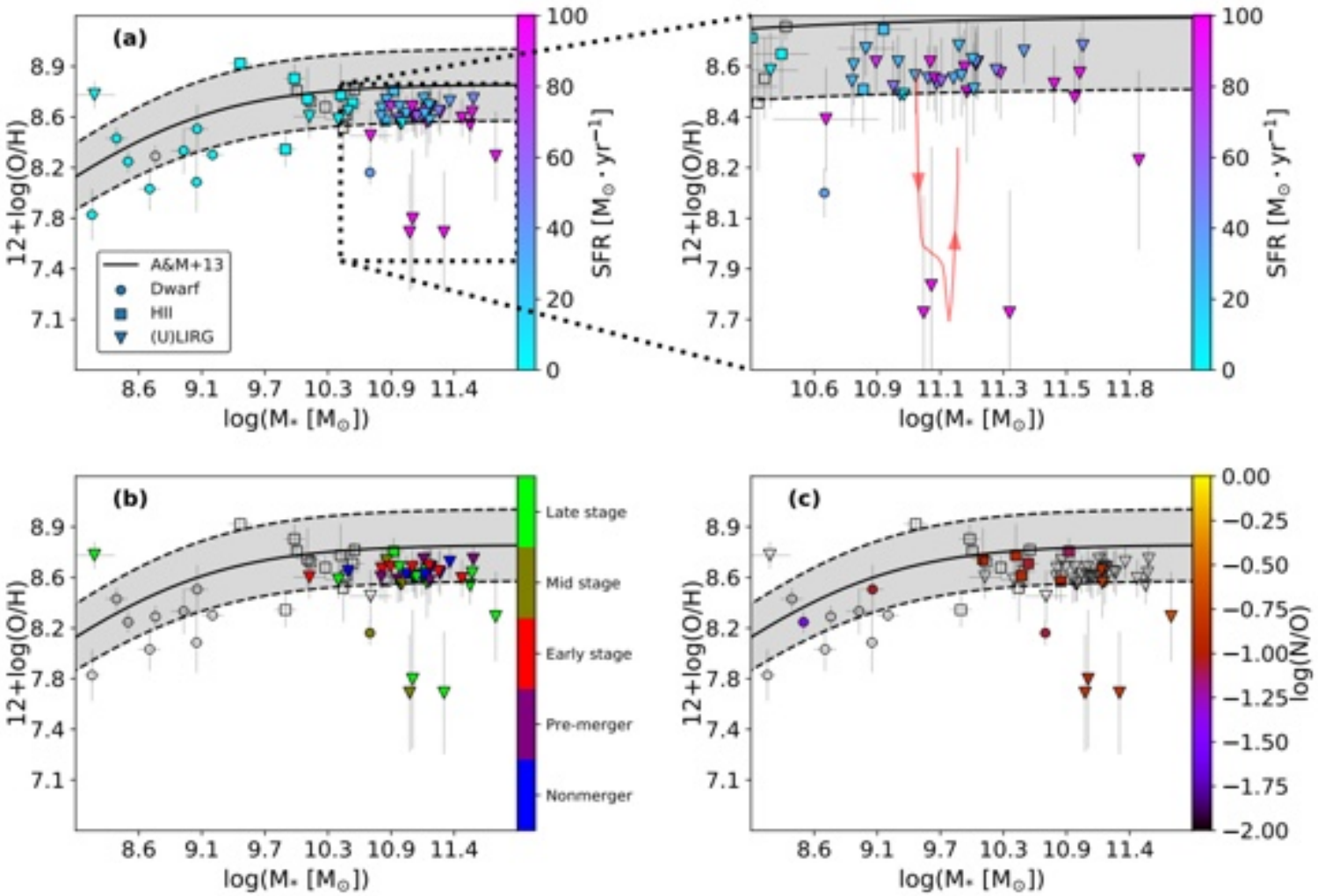


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Analysing the chemical content of (U)LIRGs



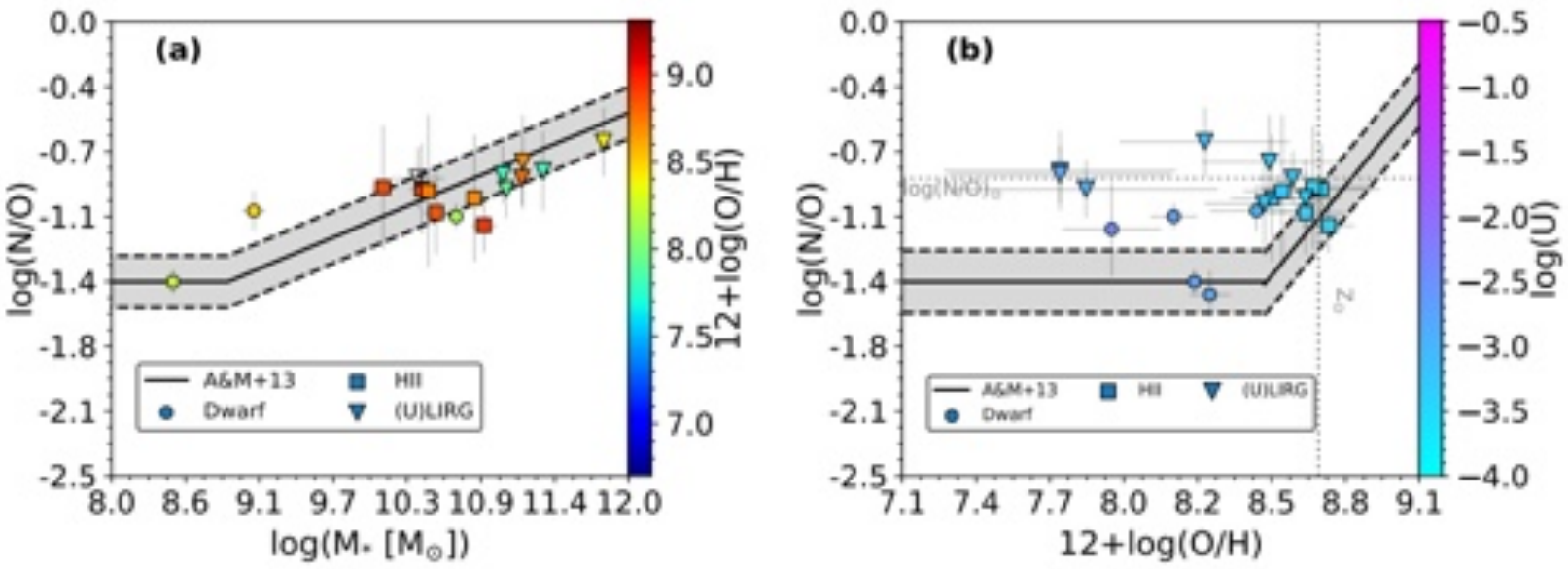
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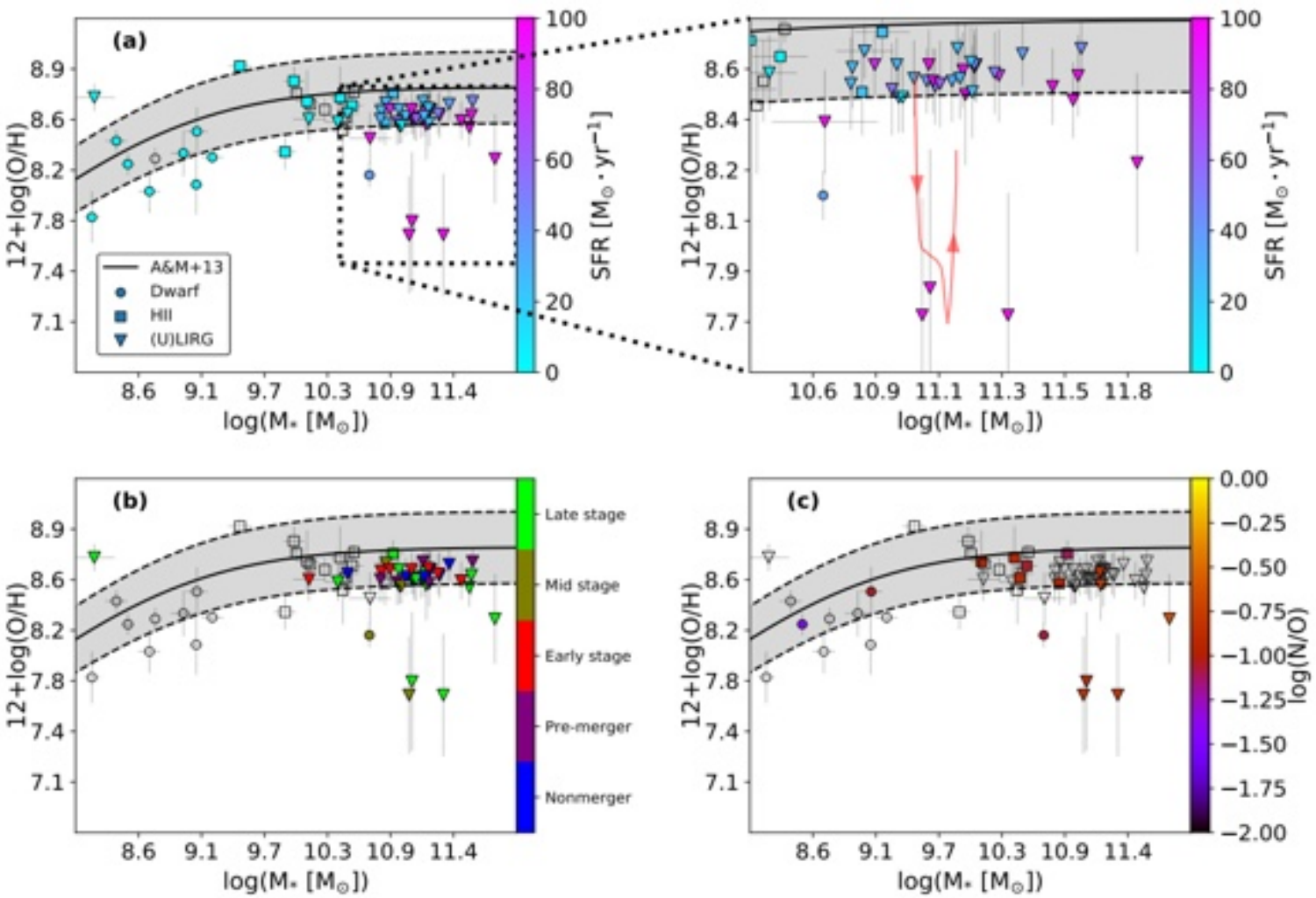
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Pérez-Díaz et al. (2024, NatAs)

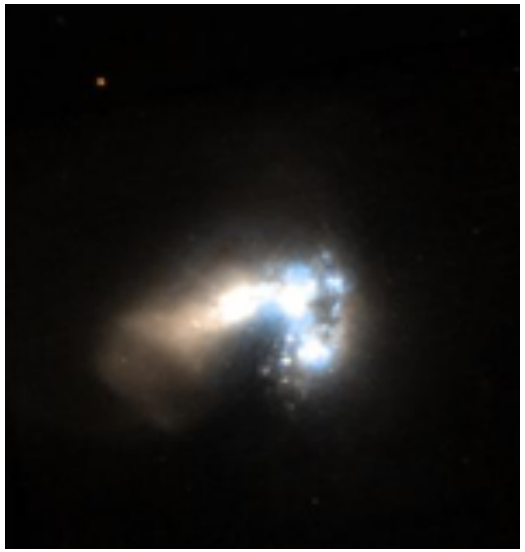
Deep-diving (U)LIRGs

HST F814W/F435W



IRAS 20551−4250

HST F814W/F606W



Haro 11

HST F814W/F435W



IRAS 12112+0305

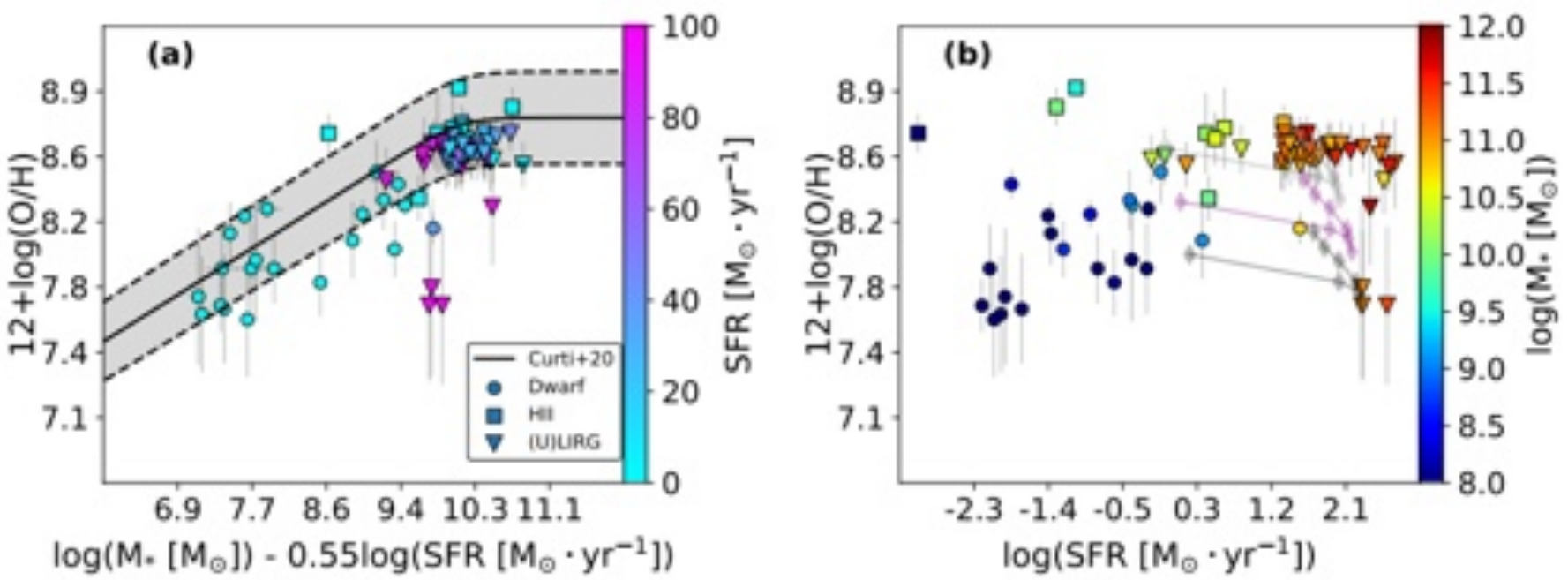
HST F814W/F435W



IRAS 23128-5919

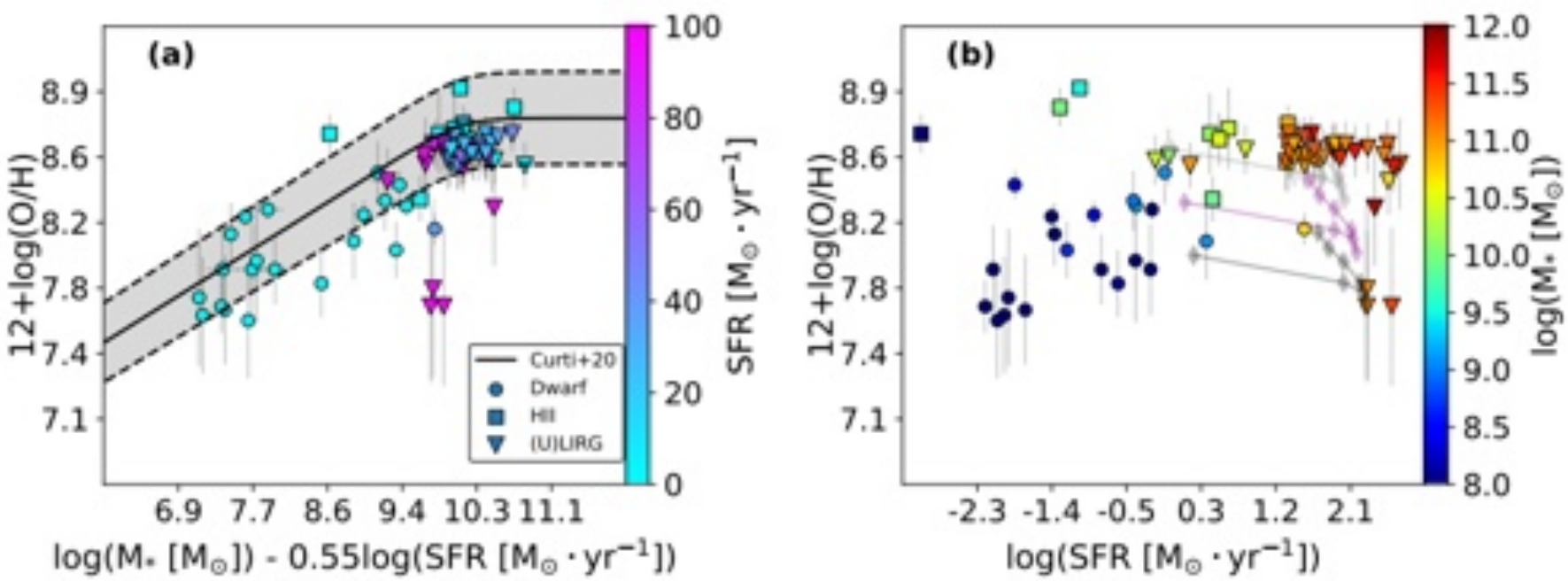
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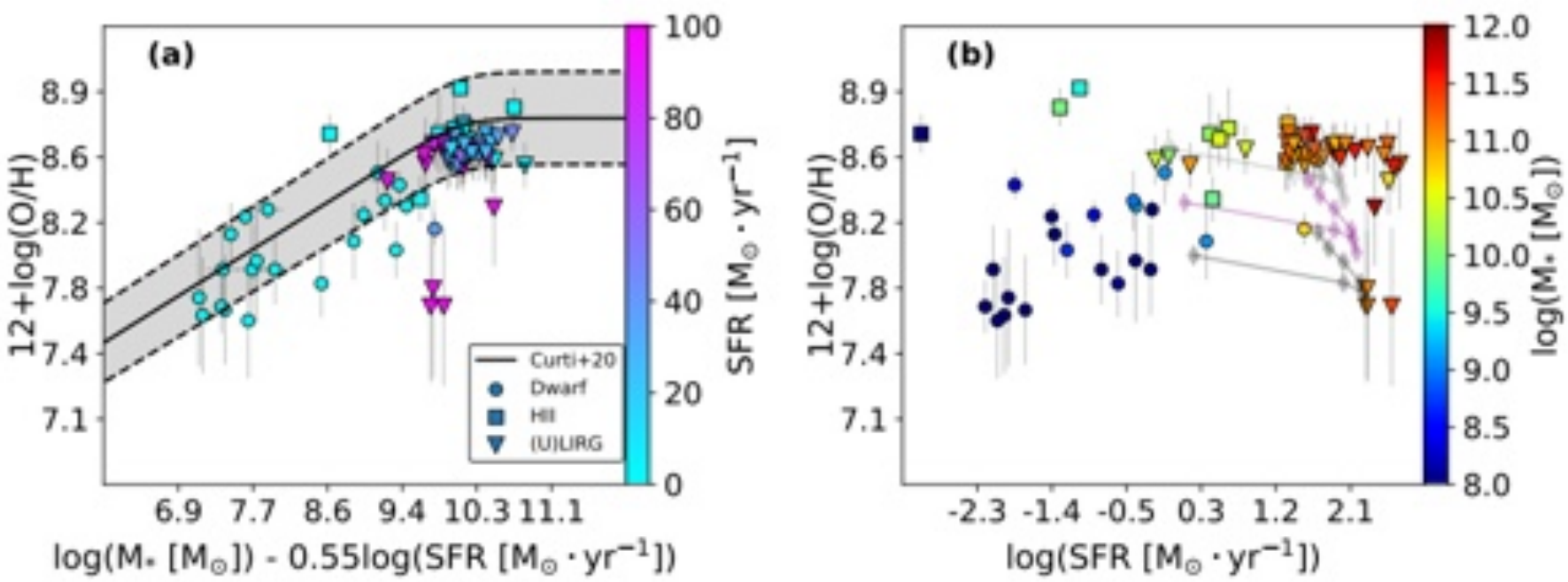
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"Deep-diving (U)LIRGs"

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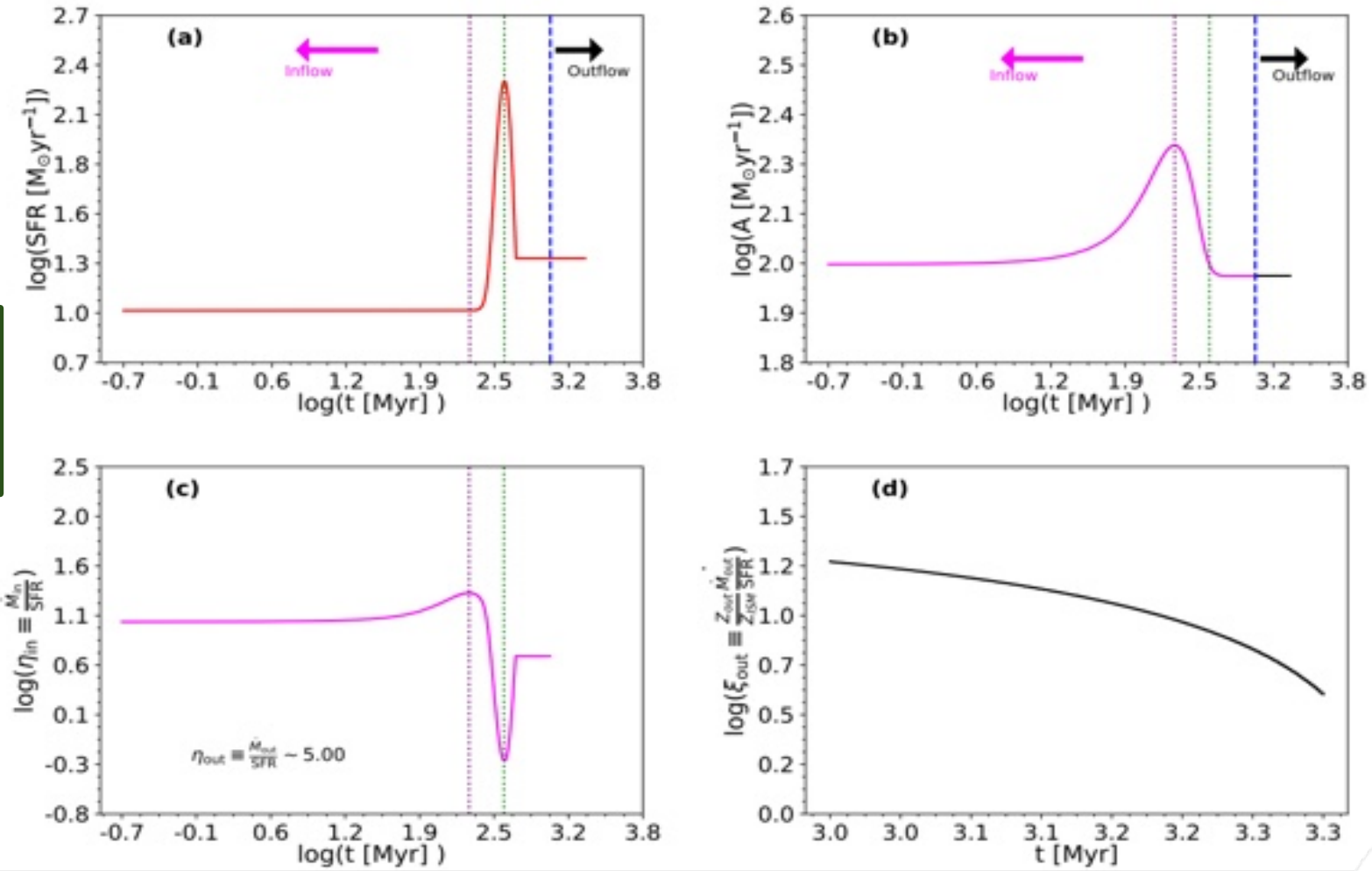
"Deep-diving (U)LIRGs"

Merger-driven infall of metal-poor gas depressed the metal content of the ISM during a short phase (< 700 Myr) of (U)LIRGs, eventually, star formation and outflows pollute again the ISM = **Deep Dive**

Analysing the chemical content of (U)LIRGs

Merger-driven infall of metal-poor gas depressed the metal content of the ISM during a short phase (< 700 Myr) of (U)LIRGs, eventually, star formation and outflows pollute again the ISM = **Deep Dive**

"Deep-diving (U)LIRGs"



Index

1 Introduction

2 Methodology

3 Oxygen and nitrogen abundances from infrared emission lines

4 Sulphur abundances from infrared emission lines

5 Observing the “deep-diving” phase

6 Conclusions

Takeaway messages

1- **HII-CHI-Mistry (and HII-CHI-Mistry-IR)** allows us the estimation of **12+log(O/H), 12+log(S/H) log(N/O) and log(U)** based only on optical (or IR) emission lines and without assuming any relation.

2- Our methodology can be applied for both, **AGN and SFG**, accounting for their differences. HII-CHI-Mistry is a versatile tool that can be **used in large sample** of galaxies.

3- We obtained that sulphur-to-oxygen abundances **do not follow the solar ratio** in many (U)LIRGs, finding a similar result in AGNs. This is in agreement with optical studies.

4- IR emission lines are key in order to properly estimate the chemical content of the gas-phase ISM in dusty objects such as (U)LIRGs, finding that they can be an indirect **proof of metal-poor gas enrichment (deep-diving)**.

5- The d**eep-diving phase** is relatively **short** in timescales, explaining the low statistics in our findings.

Thank you for your attention!

"Basically all models are wrong, but some of them are useful"

George Box (1919-2013)

This research has been funded by grants
PID2022-136598NB-C31, C32, and C33

The wokshop has been funded by grant
PID2019-107408GB-C41

all grants are funded by
MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe"