Spectral evidences of density variations in HII regions. Effects on metallicity determinations

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Good things, like wine, take time

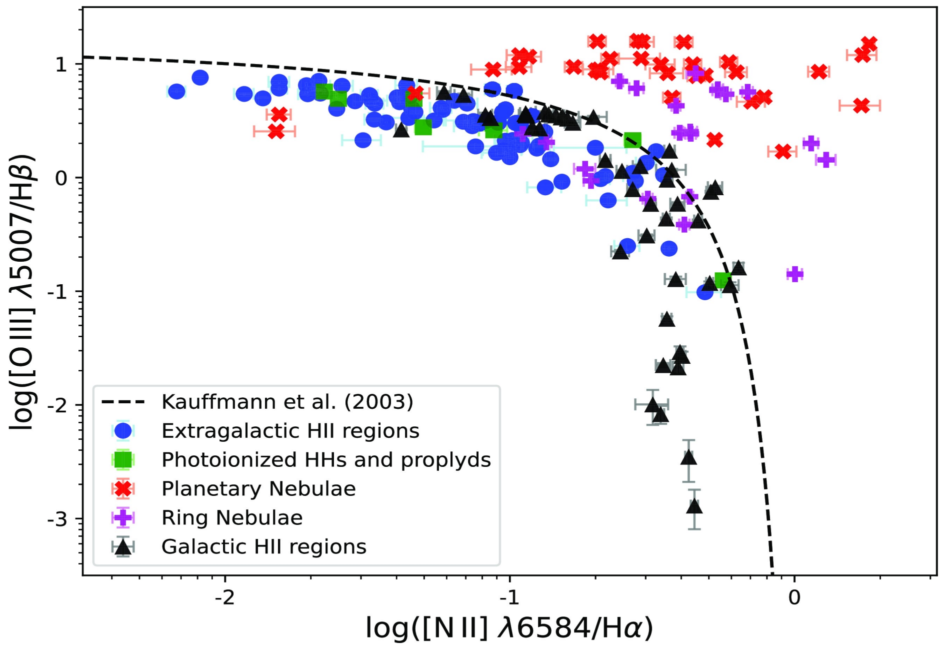
During the last 20 years, our group at IAC:

Have obtained **very deep spectra** of Galactic and extragalactic ionized nebulae to detect very faint emission lines, as O^{++} **recombination lines** (RLs), $I(\lambda) \sim 10^{-4} \times I(\mathrm{H}\beta)$, for studying the **Abundance Discrepancy** problem (**Méndez-Delgado's talk**)

Abundances of O^{++} (and other ions) determined from RLs are systematically 2-3 times higher than those derived from **collisionally excited lines** (CELs)

- Most spectra taken with **8-10m telescopes** (VLT, GTC, Keck…)
- Each spectrum contains **tens or hundreds of emission lines**
- All spectra with **direct determination of electron temperature, T_e**
- Electron density, n_e, determined with **several line ratios**

DESIRED: DEep Spectra of Ionized REgions Database



BPT diagram for DESIRED objects

- **DESIRED data: 190 echelle or long-slit spectra** of:
    - 68 extragalactic HII regions
    - 41 Galactic HII regions
    - 34 Galactic PNe
    - 7 Galactic ring nebulae around massive WR stars
    - 5 Herbig-Haro objects in the Orion nebula

Homogeneous re-analysis of all the spectra with updated atomic data and methodologies

First Result: Temperature fluctuations produce systematic bias in T_e([OIII]) that undererestimate O^{++} abundances determined from optical CELs (**Méndez-Delgado+23a**)

Article

Temperature inhomogeneities cause the abundance discrepancy in H II regions

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H II regions are ionized nebulae surrounding massive stars. They exhibit a wealth of

Méndez-Delgado's talk

In this talk we will focus on **electron density structure of HII regions and its effect on abundance determinations**

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Density biases and temperature relations for DESIRED H II regions

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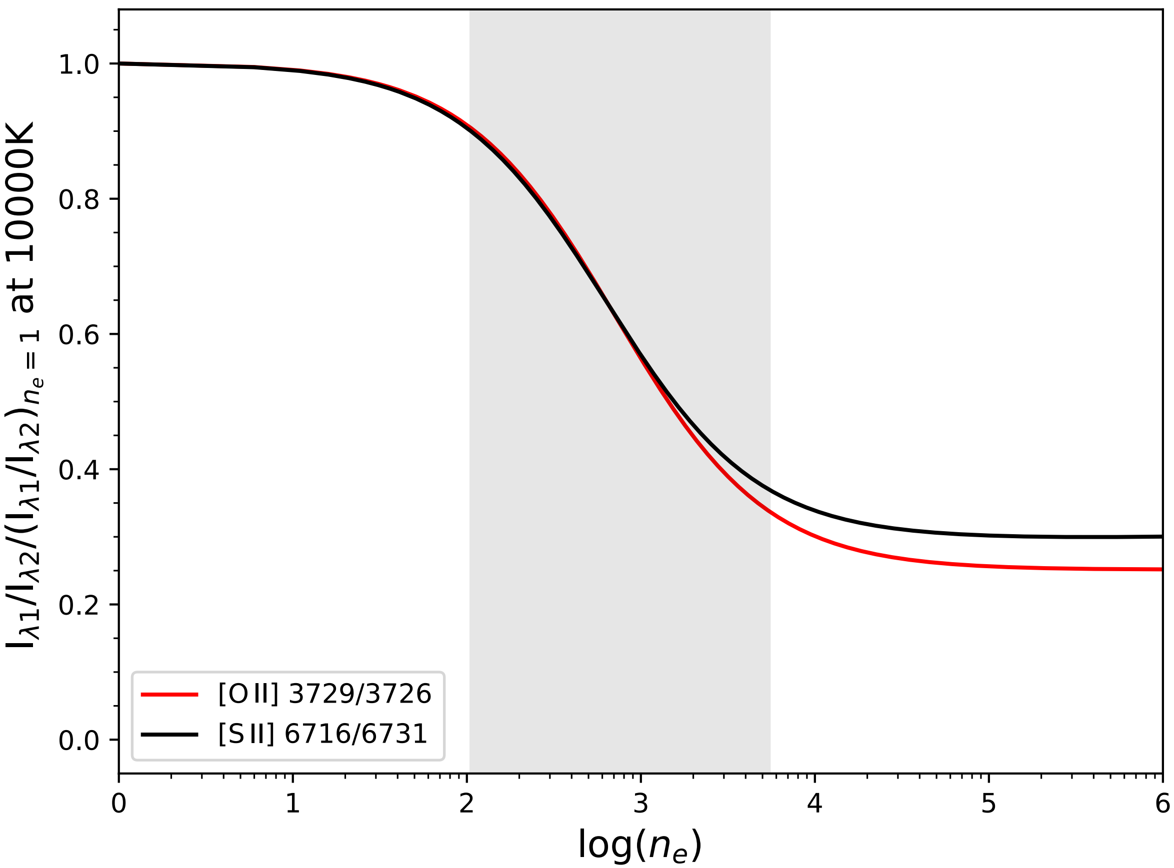
Results published in **Méndez-Delgado+23b**

[SII] 6717/6731 and [OII] 3729/3726



Ratios normalized with the value at n_e = 1 cm^{-3}

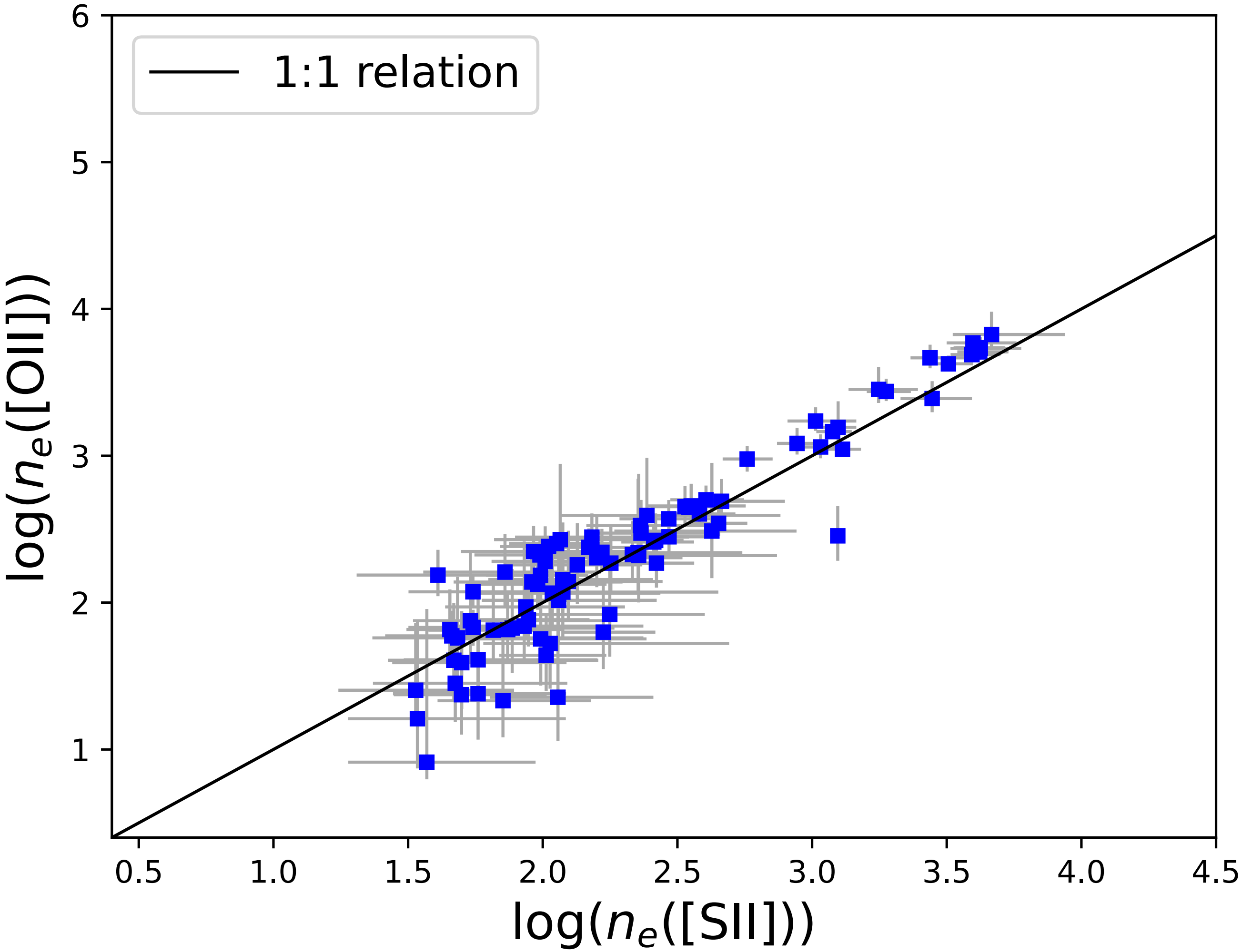
The most common density indicators

Very similar dependency

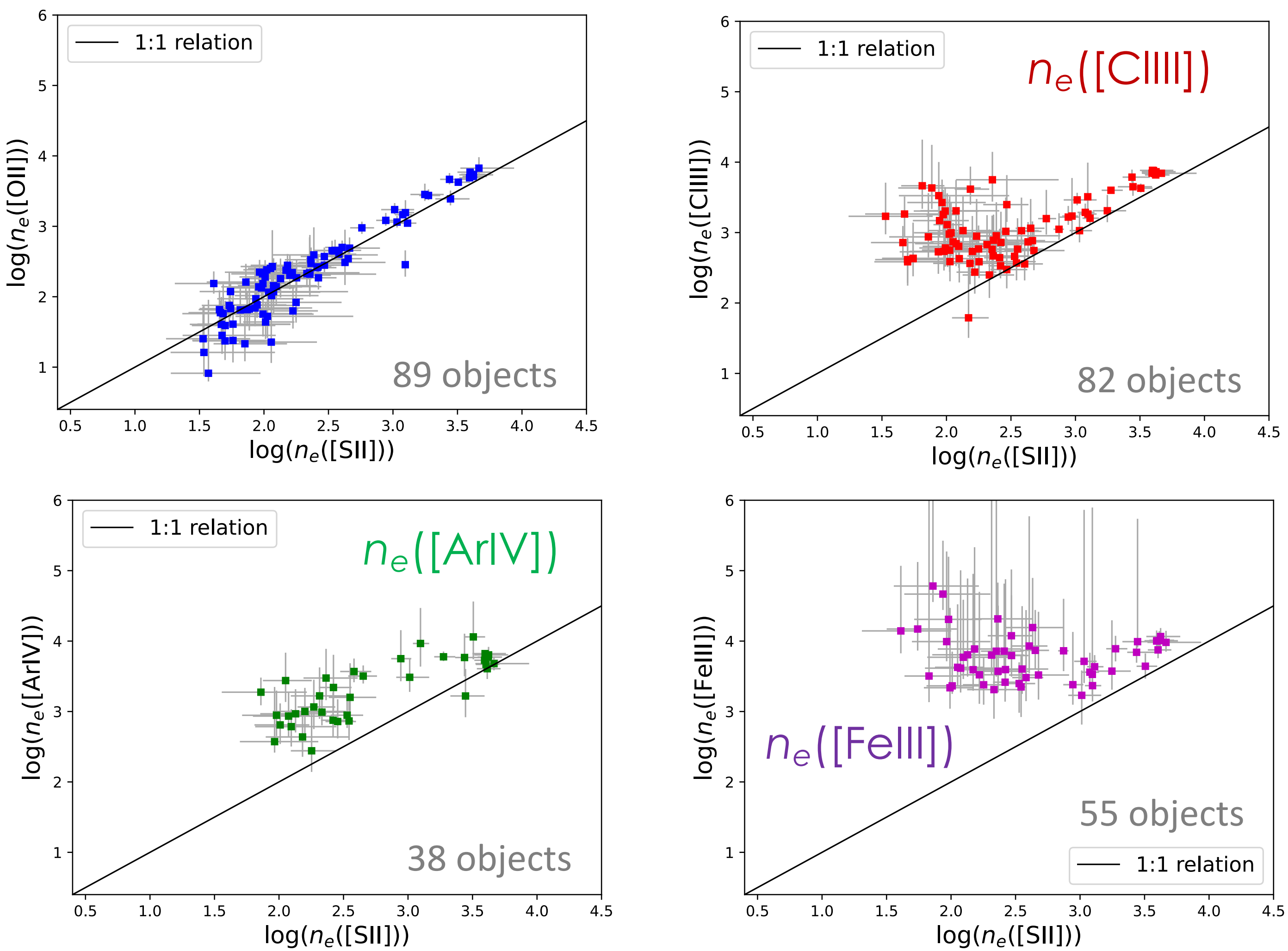
10^2 – few×10^3 cm^{-3}

The vast majority of HII regions observed so far only have n_e values determined from [SII] 6717/6731

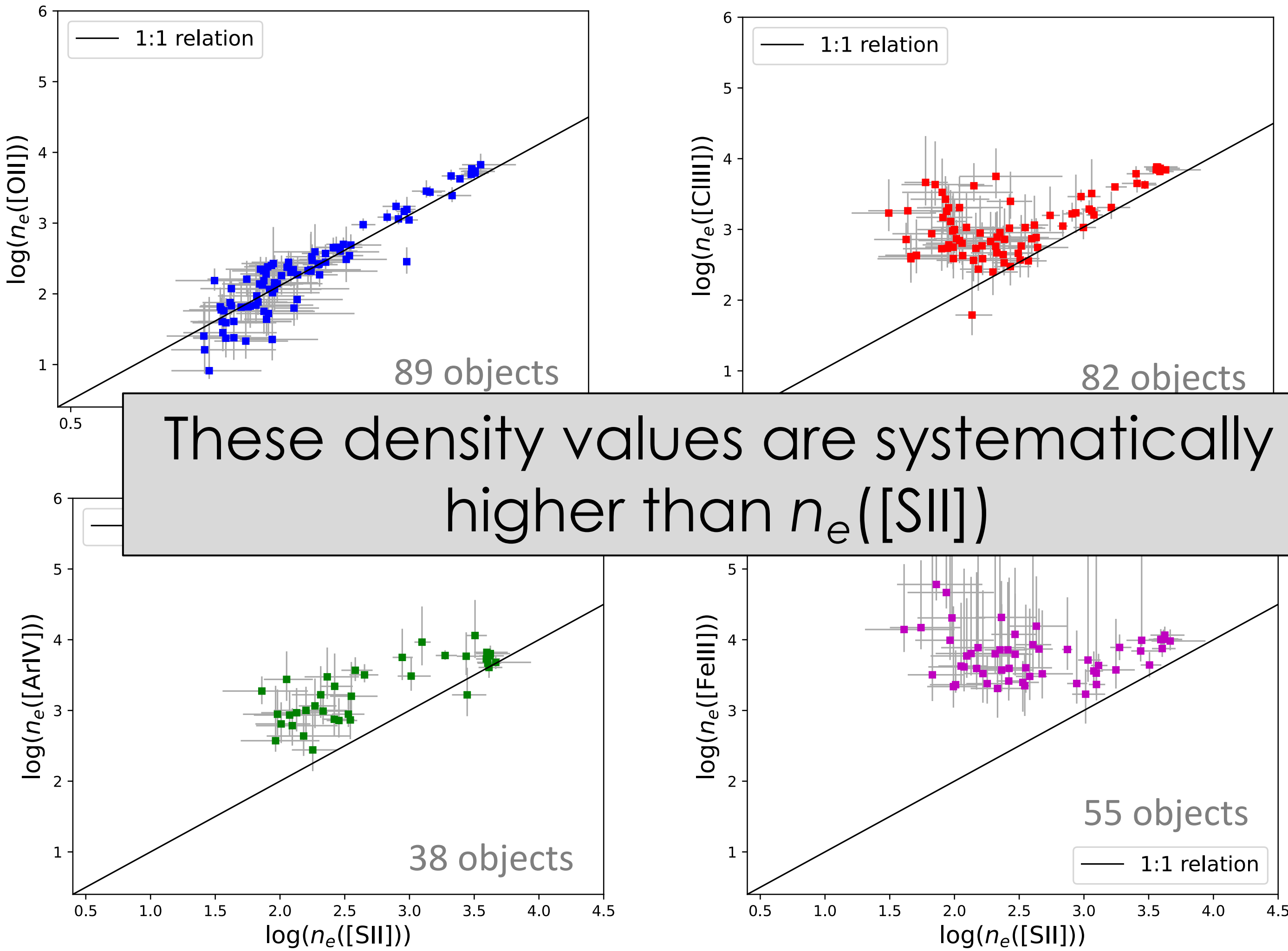
n_e([SII]) vs. n_e([OII]) for DESIRED HII regions



n_e([SII]) vs. n_e([ClIII]), n_e([ArIV]) and n_e([FeIII]) for DESIRED HII regions

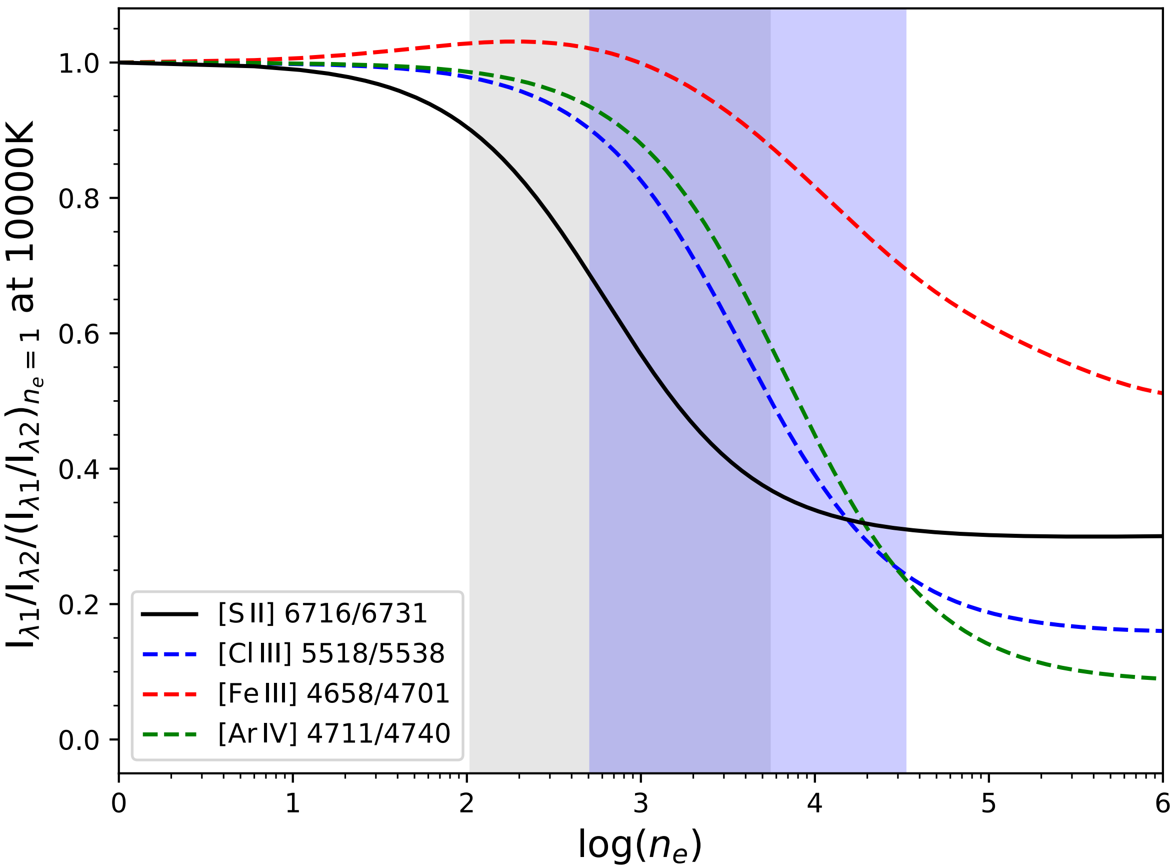


n_e([SII]) vs. n_e([ClIII]), n_e([ArIV]) and n_e([FeIII]) for DESIRED HII regions



These density values are systematically higher than n_e([SII])

[ClIII] 5518/5538, [ArIV] 4711/4740 and [FeIII] 4658/4701

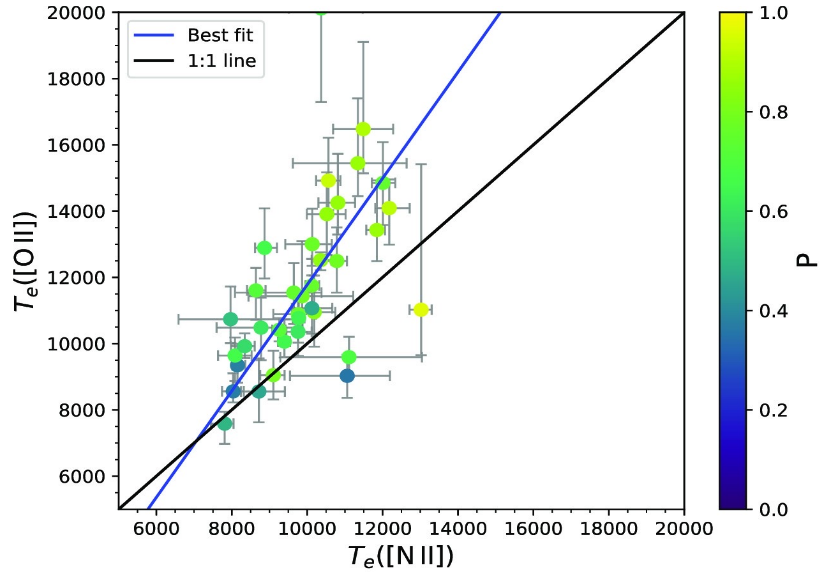


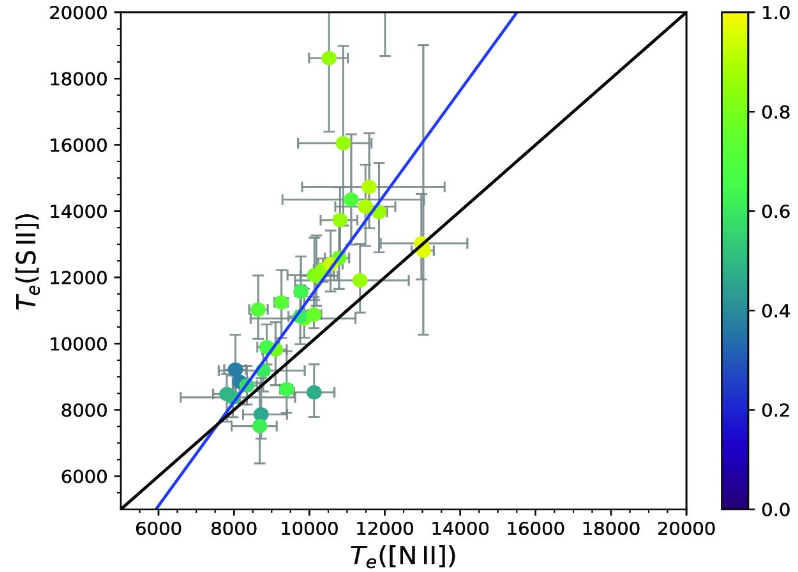
Indicators for higher densities

few×10^3 – few×10^4 cm^{-3}

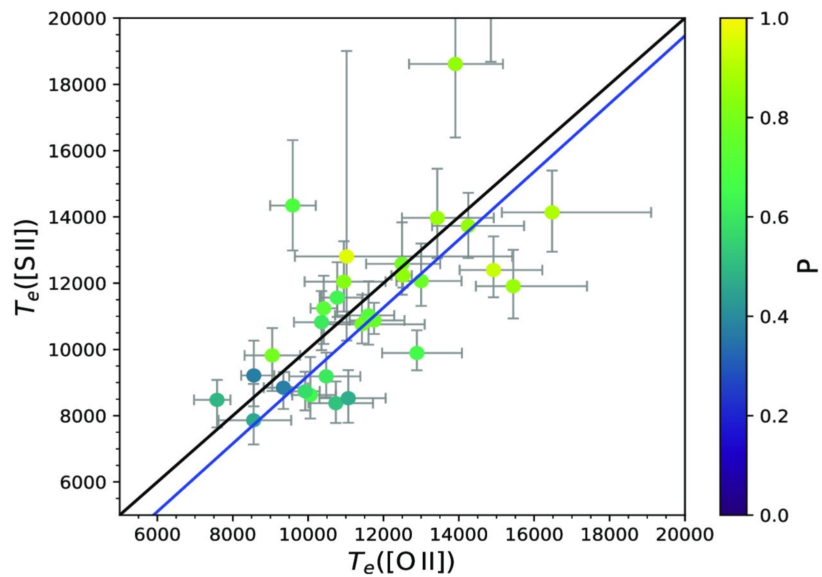
Ratios normalized with the value at n_e = 1 cm^{-3}

The dependence of T_e([OII]), T_e([SII]) and T_e([NII]) on n_e





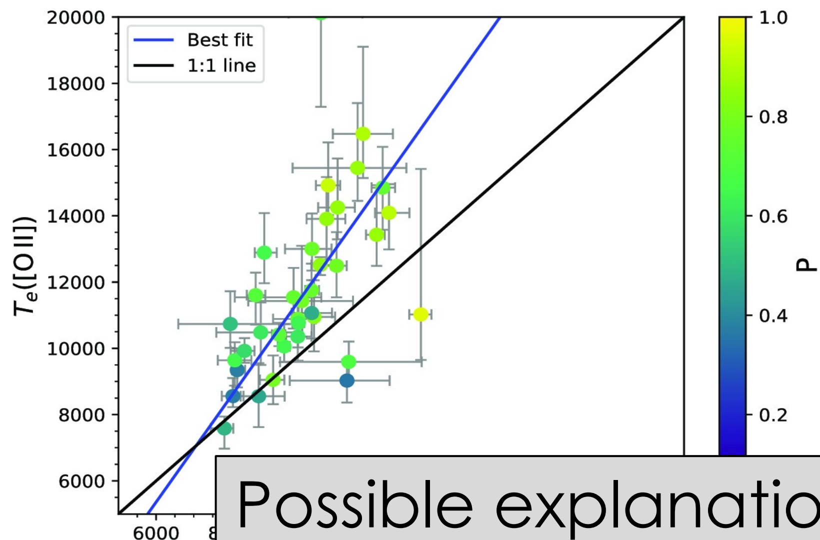
DESIRED data

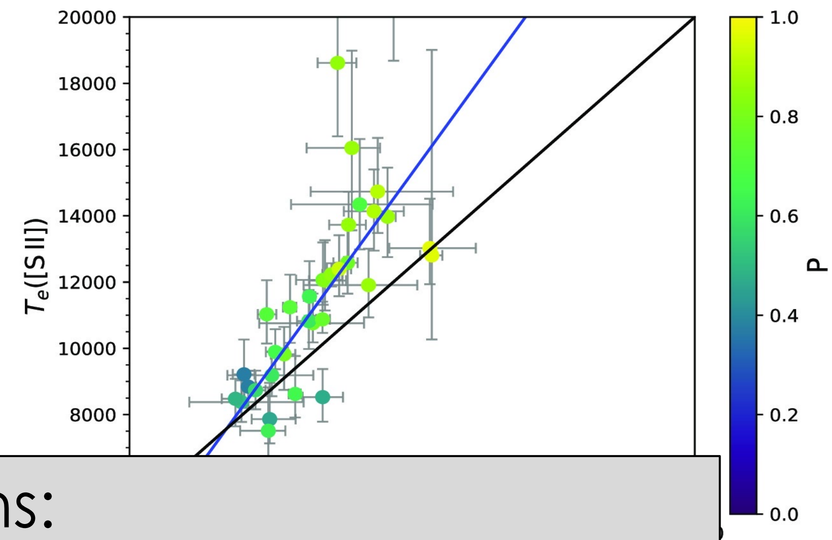


P : indicator of ionization degree

Behaviour also detected by Rickards Vaught+23 Rickards Vaught's talk

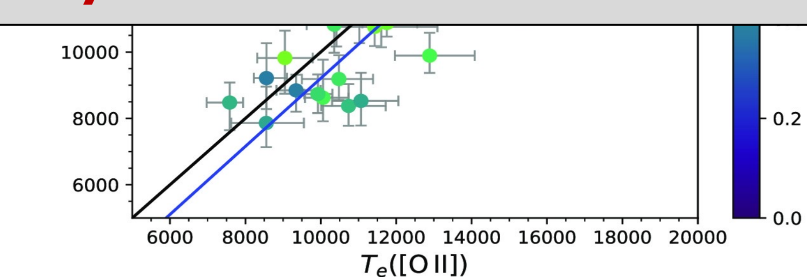
The dependence of T_e([OII]), T_e([SII]) and T_e([NII]) on n_e





Possible explanations:

- Different T_e in the S+, O+ and N+ zones
- Recombination contribution
- Temperature fluctuations
- **Density variations ✓**

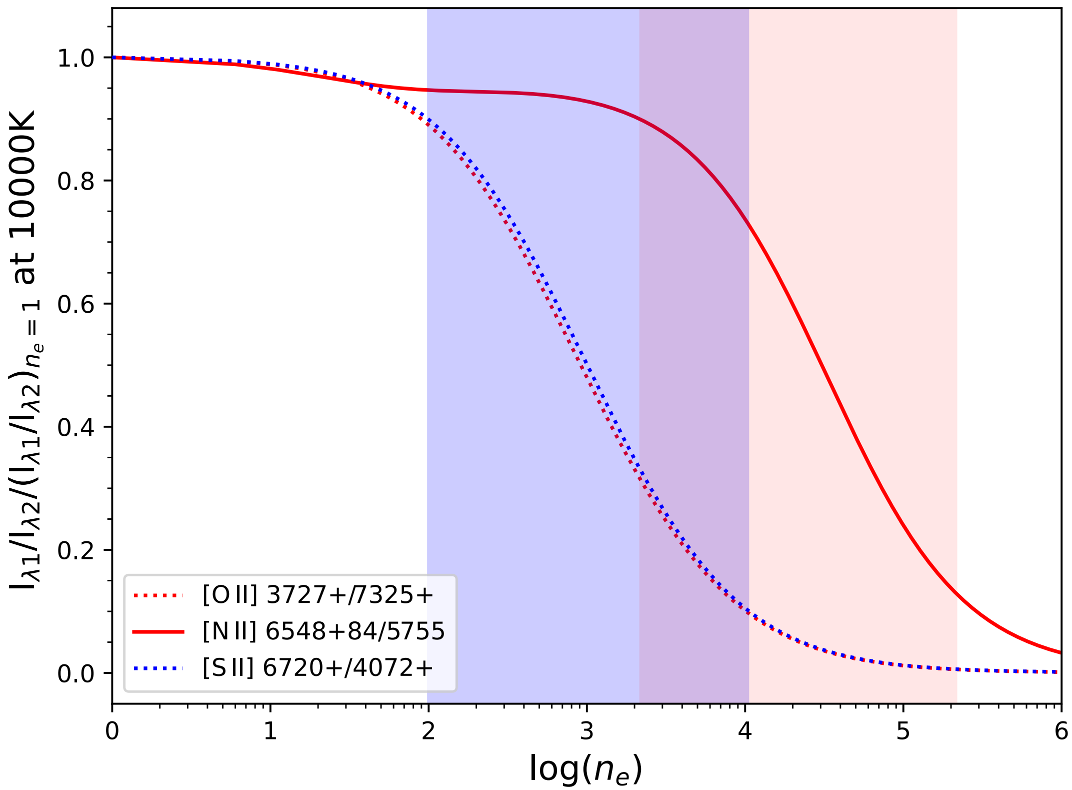


The dependence of T_e([OII]), T_e([SII]) and T_e([NII]) on n_e

Once T_e is fixed, n_e can also be calculated from the ratio of **auroral/nebular** lines:

[OII] 7319+20+30+31/3726+29
[SII] 4069+76/6716+31
} Sensitive to low densities

[NII] 6548+84/5755 → Sensitive to high densities



Density dependence of the line ratios used to determine T_e([OII]), T_e([SII]) and T_e([NII]) assuming T_e=10,000K

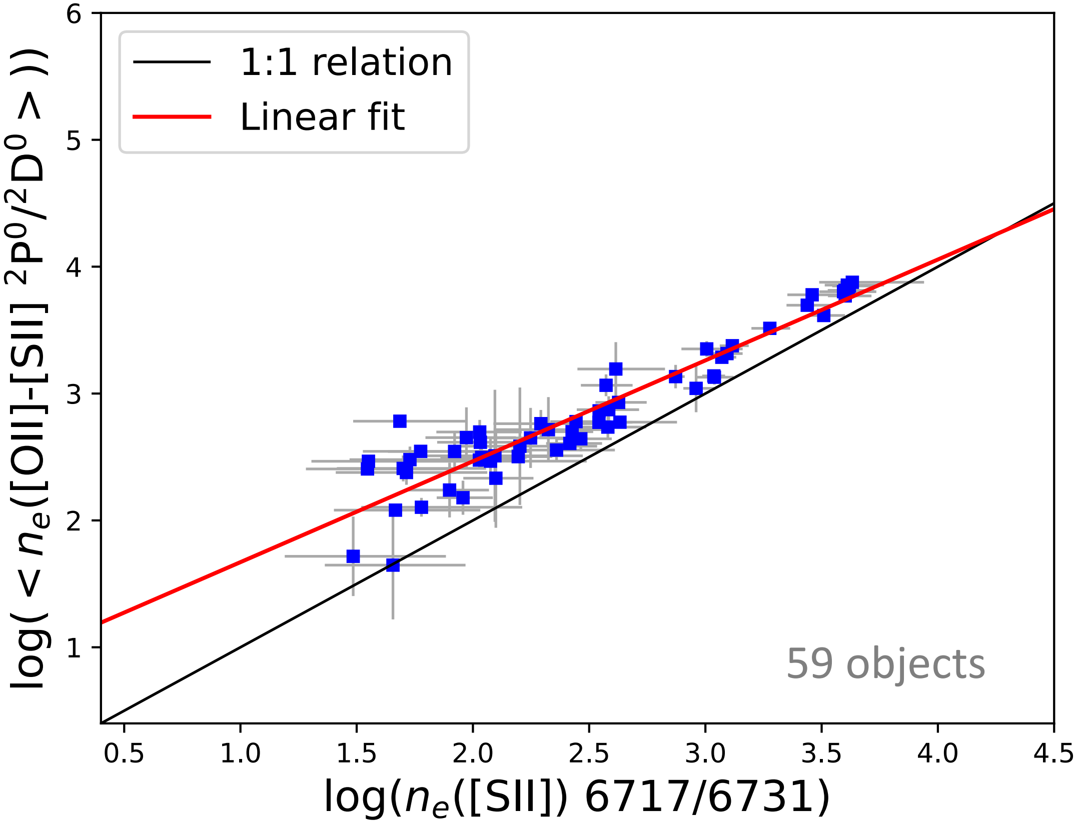
n_e([SII] aur/neb) and n_e([OII] aur/neb) vs. n_e([SII])

n_e determined from the [OII] and [SII] auroral/nebular line ratios are higher than the values obtained from the common [SII] nebular indicator

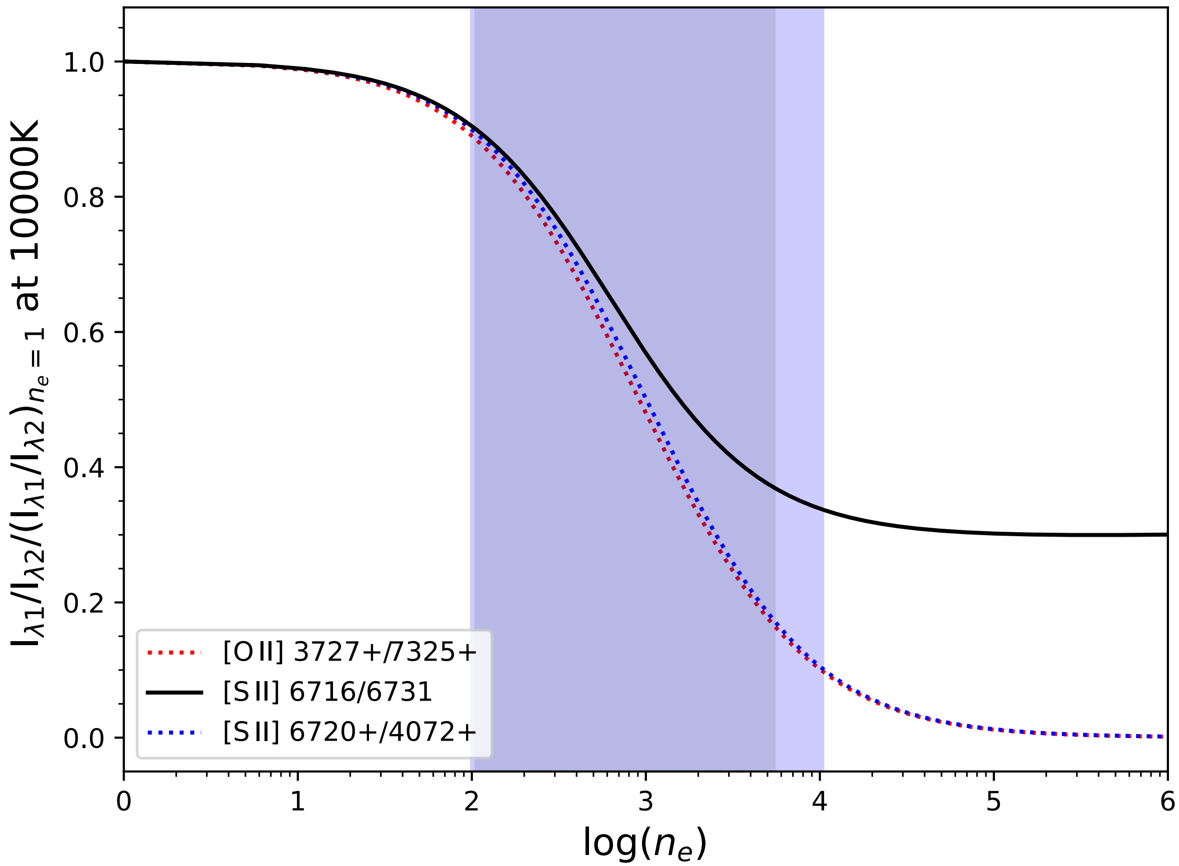
Ordinate:

Weighted mean of n_e determined from [SII] and [OII] auroral/nebular assuming T_e([NII])

~300 cm^{-3} higher than n_e([SII]) on average

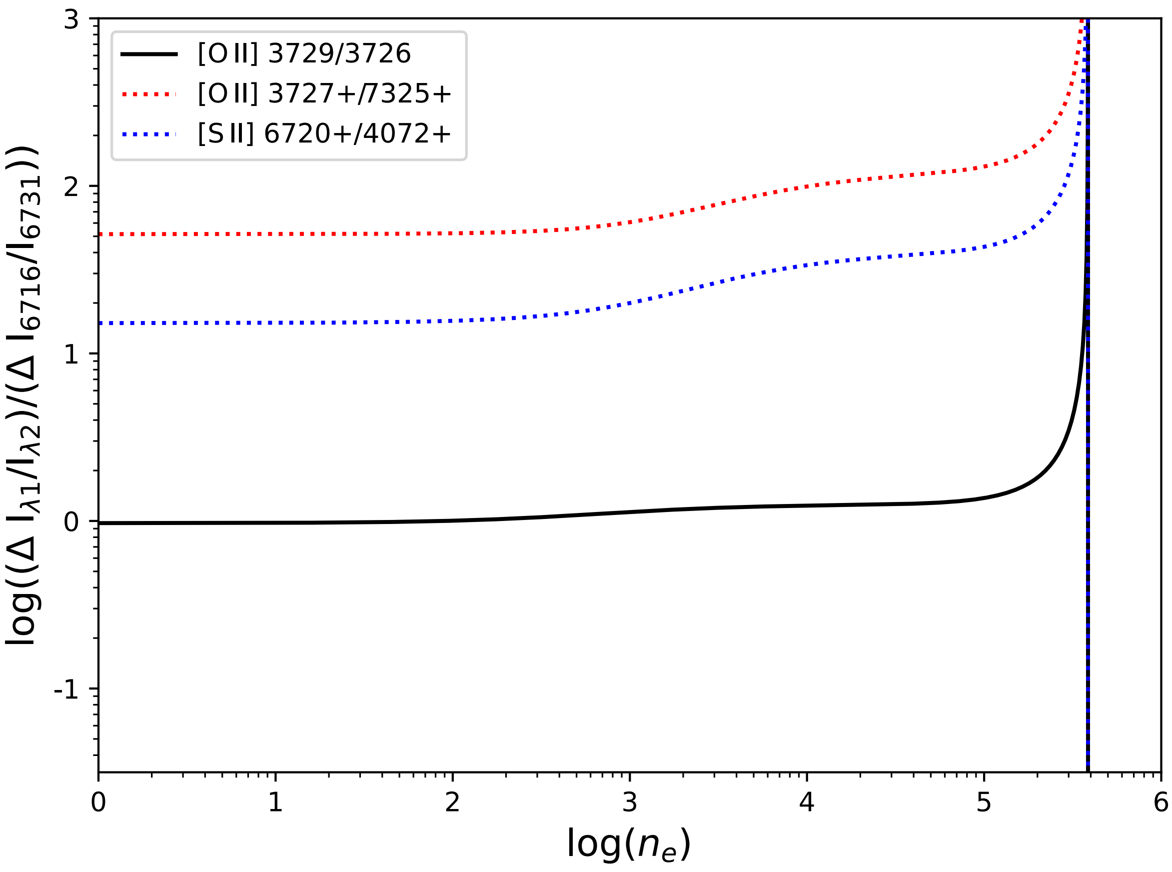


Range of validity of [OII] and [SII] auroral/nebular and the common [SII] nebular line ratios



Ratios normalized with the value at n_e = 1 cm^{-3}

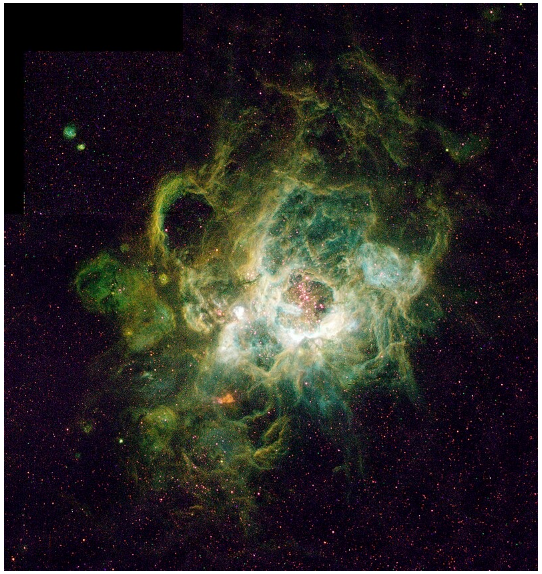
The auroral/nebular ones are more sensitive to n_e



Density sensitivity, defined as $\frac{\Delta(I_{\lambda_1}/I_{\lambda_2})}{\Delta n_e}$ with respect to that of [SII] nebular

Effects of density inhomogeneities in metallicity of HII regions

The presence of **density inhomogeneities** in the gas of HII regions should not be neglected



In the presence of high density inclusions, the different indicators give different values of the mean n_e representative of the nebula

This may **affect metallicities** determined from CELs differently for optical or FIR lines

Using optical CELs:

<u>O^{++}/H^{+} is not affected</u> (but greatly affected by temperature fluctuations)

<u>O^{+}/H^{+} may be lower</u> if the true n_e is ~300 cm^{-3} higher

- ≤ 0.1 dex using T_e([NII]) + n_e([SII] nebular)
- up to **0.3-0.4 dex** using T_e([OII]) + n_e([SII] nebular)

➔ Larger effects at lower metallicities
➔ Affecting the O^{++}/O^{+} ratio

Using FIR CELs:

Bright [OIII] fine structure lines at 52 and 88 μm

Abundances from **FIR CELs almost independent on T_e**

Chen+23 and Lamarche+22 obtain O^{++}/H^{+} for extragalactic HII regions from FIR [OIII] lines assuming T_e([OIII]) and n_e([SII] nebular) or other indicators valid in the low density domain

Object	Authors	O^{++}/H^{+} (optical CELs)	O^{++}/H^{+} (FIR CELs)	O^{++}/H^{+} (optical RLs)
Mrk71	Chen+23	–	**7.68 ± 0.09**	–
	DESIRED			
NGC5455	Lamarche+22	–	**8.17 ± 0.38**	–
	DESIRED			
NGC5461	Lamarche+22	–	**8.46 ± 0.34**	–
	DESIRED			

Using FIR CELs:

Bright [OIII] fine structure lines at 52 and 88 μm

Using n_e([SII] nebular) and T_e([OIII])

Object	Authors	O^{++}/H^{+} (optical CELs)	O^{++}/H^{+} (FIR CELs)	O^{++}/H^{+} (optical RLs)
Mrk71	Chen+23	–	**7.68 ± 0.09**	–
	DESIRED	**7.73 ± 0.03**		
NGC5455	Lamarche+22	–	**8.17 ± 0.38**	–
	DESIRED	**8.19 ± 0.02**		
NGC5461	Lamarche+22	–	**8.46 ± 0.34**	–
	DESIRED	**8.29 ± 0.04**		

Using FIR CELs:

Bright [OIII] fine structure lines at 52 and 88 μm

O^{++}/H^{+} (optical CELs) ≈ O^{++}/H^{+} (FIR CELs)
Conclusion:
No temperature fluctuations!!!

Object	Authors	O^{++}/H^{+} (optical CELs)	O^{++}/H^{+} (FIR CELs)	O^{++}/H^{+} (optical RLs)
Mrk71	Chen+23	–	**7.68 ± 0.09**	–
	DESIRED	**7.73 ± 0.03**		
NGC5455	Lamarche+22	–	**8.17 ± 0.38**	–
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Using FIR CELs:

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Mrk71	Chen+23	–	**7.68 ± 0.09**	–
	DESIRED	**7.73 ± 0.03**		**8.02 ± 0.10**
NGC5455	Lamarche+22	–	**8.17 ± 0.38**	–
	DESIRED	**8.19 ± 0.02**		**8.28 ± 0.14**
NGC5461	Lamarche+22	–	**8.46 ± 0.34**	–
	DESIRED	**8.29 ± 0.04**		**8.68 ± 0.12**

Using FIR CELs:

Bright [OIII] fine structure lines at 52 and 88 μm

Using n_e(aur/neb)

Object	Authors	O^{++}/H^+ (optical CELs)	O^{++}/H^+ (FIR CELs)	O^{++}/H^+ (optical RLs)
Mrk71	Chen+23	–	7.68 ± 0.09	–
	DESIRED	7.73 ± 0.03	8.04 ± 0.10	8.02 ± 0.10
NGC5455	Lamarche+22	–	8.17 ± 0.38	–
	DESIRED	8.19 ± 0.02	8.32 ± 0.17	8.28 ± 0.14
NGC5461	Lamarche+22	–	8.46 ± 0.34	–
	DESIRED	8.29 ± 0.04	8.66 ± 0.26	8.68 ± 0.12

Using FIR CELs:

Bright [OIII] fine structure lines at 52 and 88 μm

O^{++}/H^{+} (FIR CELs) ≈ O^{++}/H^{+} (optical RLs)
Density inhomogeneities!!!
Temperature fluctuations!!!

Object	Authors	O^{++}/H^{+} (optical CELs)	O^{++}/H^{+} (FIR CELs)	O^{++}/H^{+} (optical RLs)
Mrk71	Chen+23	–	7.68 ± 0.09	–
	DESIRED	7.73 ± 0.03	8.04 ± 0.10	8.02 ± 0.10
NGC5455	Lamarche+22	–	8.17 ± 0.38	–
	DESIRED	8.19 ± 0.02	8.32 ± 0.17	8.28 ± 0.14
NGC5461	Lamarche+22	–	8.46 ± 0.34	–
	DESIRED	8.29 ± 0.04	8.66 ± 0.26	8.68 ± 0.12

Sorry guys, bad news for the direct method…

- There are observational evidences of the **presence of density variations inside HII regions**
- **True densities may be ~300 cm^{-3} higher** than those obtained from the common standard n_e([SII]) indicator
- **O^{+}/H^{+} determined from optical CELs may be underestimated**
- **O^{++}/H^{+} determined from FIR CELs may be underestimated** in a "conspiratorial" way, mimicking the effect of temperature fluctuations
- **There should be temperature and density variations in HII regions affecting their metallicity calculations**

REFERENCES

- Chen, Y., *et a*l. (2023) *Nature Astronomy*, *7*, *771*
- Lamarche, C., *et al*. (2022) *ApJ*, *925*, 194
- Méndez-Delgado, J.E, Esteban, C., García-Rojas, J., Kreckel, K., Peimbert, *M*. (2023a) *Nature*, 618, *249*
- *M*éndez-Delgado, J.E., *et al.* (2023b) *MNRAS*, *523*, *2952*
- Rickards Vaught, Ryan J., *et al*. (2023) eprint arXiv:2309.17440