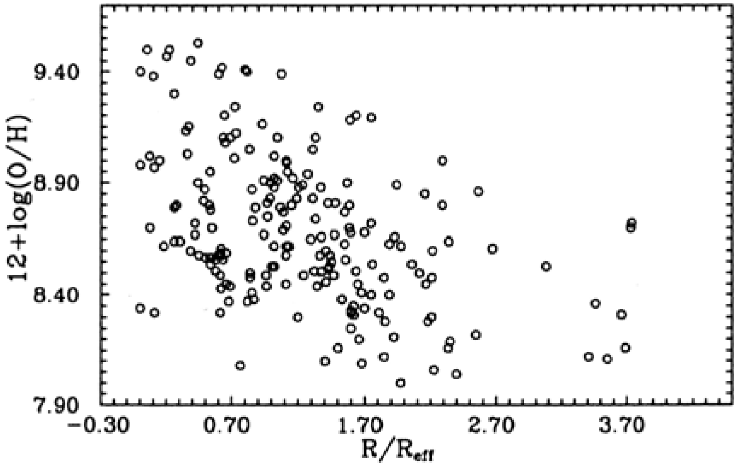
DERIVING ABUNDANCE GRADIENTS ACROSS GALAXY DISCS

M 101

Introduction

- Elemental abundance gradients in galactic discs are important constraints for models of how spiral galaxies form and evolve.
- Some current chemo-dynamical models developed in a cosmological framework (see, e.g. Gibson et al. 2013, consider the shape of the radial metallicity gradient and its time evolution as a major observational constraint.
- The use of Integral Field Spectrographs (IFS) can allow the analysis of abundance gradients in external galaxies exploring an often-complex scenario… provided we can derive them accurately over the full extension of galaxy discs.

Analysing abundance gradients



Evolutionary phenomena in galaxies
Sta. Cruz de Tenerife, 1988

ABUNDANCE GRADIENTS IN DISC GALAXIES AND CHEMICAL EVOLUTION MODELS

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Abundance gradient as a differencial effect

Astron. Astrophys. 197, 33–46 (1988)

ASTRONOMY AND ASTROPHYSICS

Models of galactic chemical evolution: the problem of uniqueness

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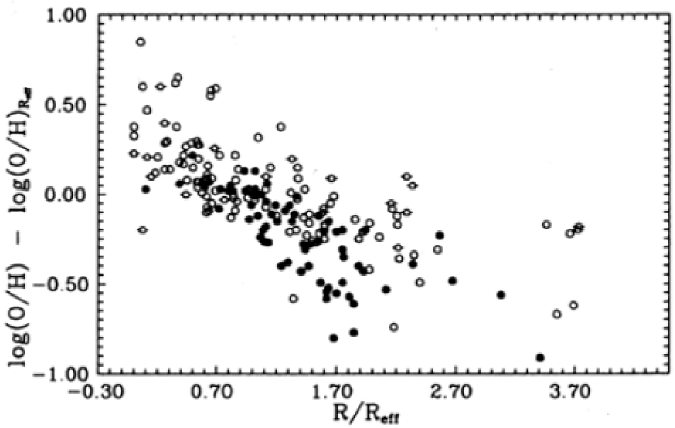
Received April 20, accepted December 1, 1987

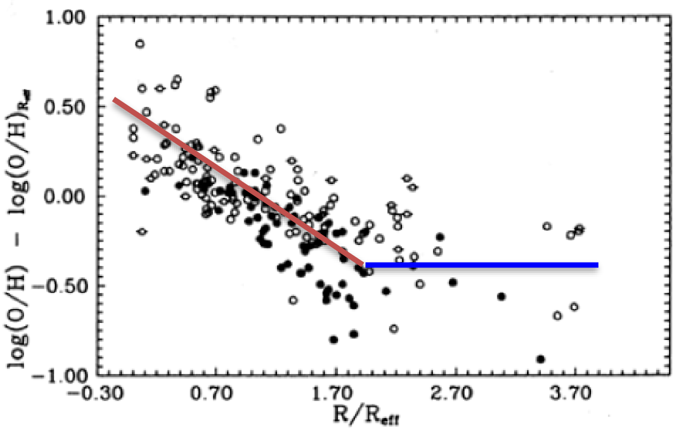
- Abundance ratios between elements depend mostly on stellar nucleosynthesis and the IMF.
- The slope of any abundance gradient is not sensitive at all to the adopted nucleosynthesis.
- The predicted absolute abundance of any element depend on all adopted parameters hence it does not represent by itself a good test of any theory … however it should be reproduced by any selfconsistent model.

- Then … why normalizing only to galactic radius and not also to absolute abundance?



A universal abundance gradient?

18 galaxies, 200 HII regions



$$\frac{D\log\left(O/H\right)}{DR} = -a/R_{eff}$$

- O/H abundances in galaxy discs are between 1/10 and 10 times its value at the effective radius of a given disc!

$$(O/H)_R = (O/H)_{R_{eff}} \times 10^{-a\left(\frac{R}{R_{Reff}}-1\right)}$$

where a is the slope of the gradient and

$a \approx 0.40$, $R/R_{eff} < 1.75$

$a \approx 0.00$, $R/R_{eff} > 1.75$

- Galaxies with large R_{eff} have flatter gradients tan galaxies with small R_{eff}

CALIFA SURVEY

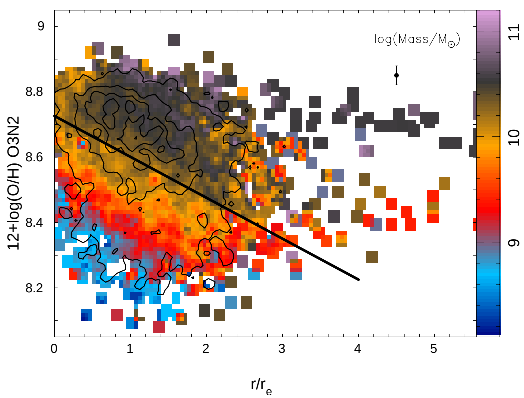
A&A 563, A49 (2014)
DOI: 10.1051/0004-6361/201322343

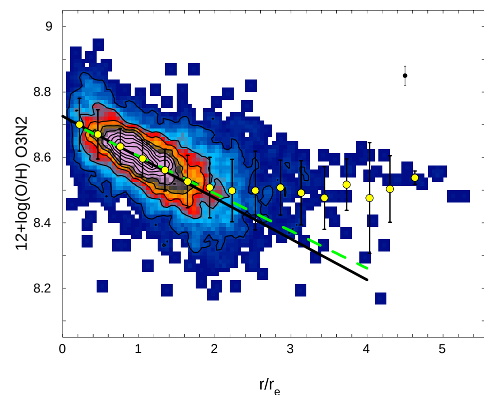
Astronomy & Astrophysics

A characteristic oxygen abundance gradient in galaxy disks unveiled with CALIFA⋆,⋆⋆

S. F. Sánchez[1,2,3], F. F. Rosales-Ortega[4], J. Iglesias-Páramo[1,2], M. Mollá[5], J. Barrera-Ballesteros[6], R. A. Marino[7], E. Pérez[1], P. Sánchez-Blazquez[8], R. González Delgado[1], R. Cid Fernandes[9], A. de Lorenzo-Cáceres[10,11], J. Mendez-Abreu[6,10,11], L. Galbany[12], J. Falcon-Barroso[6], D. Miralles-Caballero[8], B. Husemann[13], R. García-Benito[1], D. Mast[2,1], C. J. Walcher[13], A. Gil de Paz[7], B. García-Lorenzo[6], B. Jungwiert[14], J. M. Vílchez[1], Lucie Jílková[15], M. Lyubenova[16], C. Cortijo-Ferrero[1], A. I. Díaz[8], L. Wisotzki[13], I. Márquez[1], J. Bland-Hawthorn[17], S. Ellis[17,18], G. van de Ven[16], K. Jahnke[16], P. Papaderos[19], J. M. Gomes[19], M. A. Mendoza[1], Á. R. López-Sánchez[17,18], and The CALIFA collaboration

We found that all galaxies without clear evidence of an interaction present a common gradient in the oxygen abundance, with a characteristic slope of $\alpha(O/H) = -0.1$ dex/R_e between 0.3 and 2 disk effective radii (R_e), and a scatter compatible with random fluctuations around this value, when the gradient is normalized to the disk effective radius. The slope is independent of morphology, the incidence of bars, absolute magnitude, or mass.

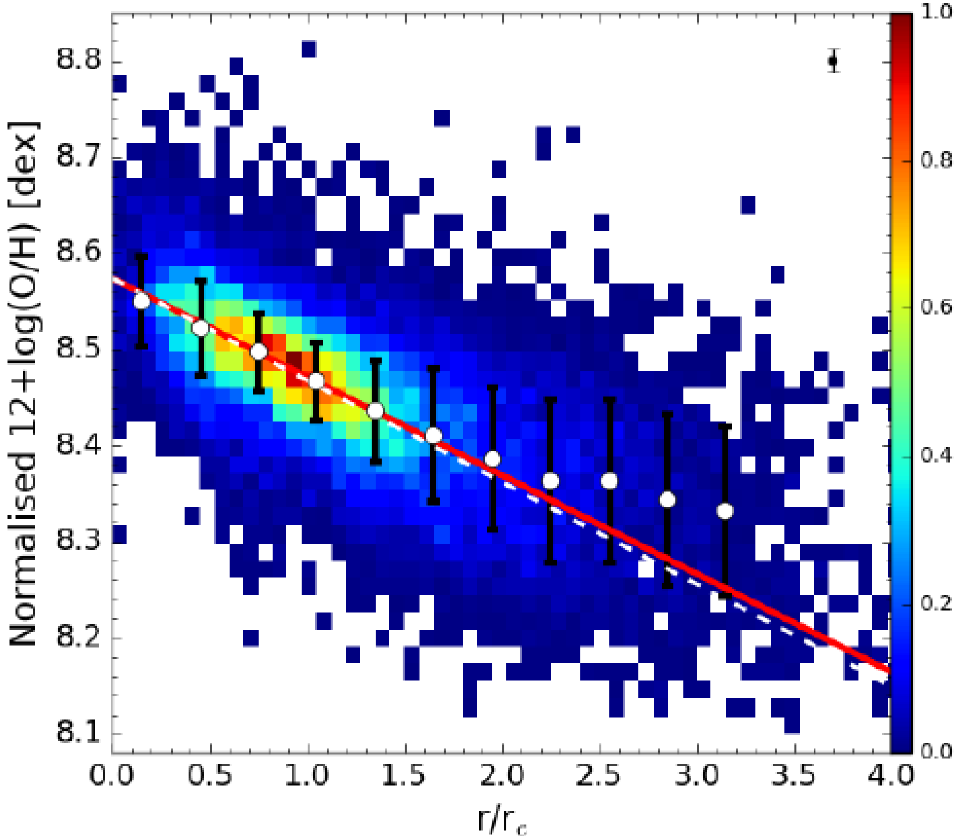




≈ 4500 HII regions in 200 galaxies

From CALIFA to MUSE

Sánchez-Menguiano et al 2018



120 galaxias
14345 HII regions

Model predictions MULCHEM

Mollá & Díaz, 2005, MNRAS, 358,521

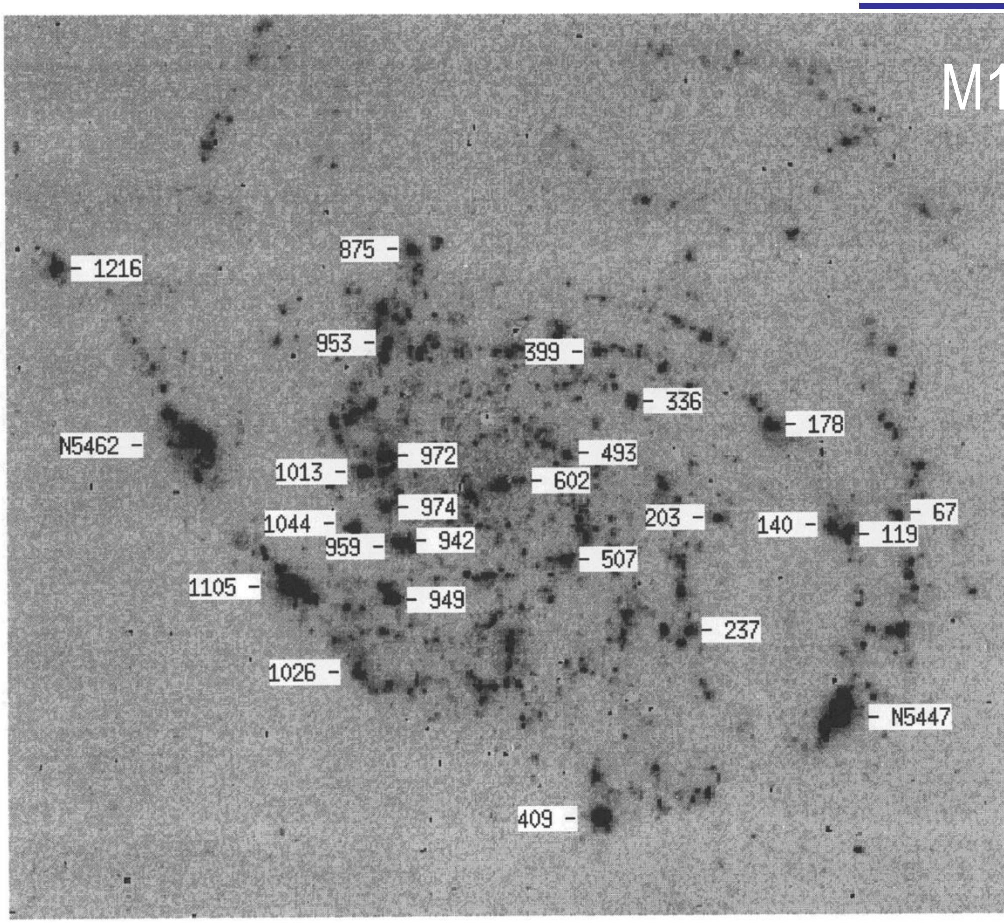
- Predict how the radial gradients were in the past for galaxies of different sizes and masses considering the growth of the disks.
- For the present time, the radial gradient ∇, measured as dex kpc−1, shows a clear dependence on R_{eff} in agreement with data.
- The normalised radial gradient is $\nabla_{Reff} \sim -0.10$ dex R_{eff}^{-1} for all galaxies with differences depending on the efficiency to form stars .
- The correlations at z = 0 may change at other redshifts:
  - In the SFR–∇ correlation, points move at higher sSFR showing steeper gradients at z = 1 than at z = 0.
  - Correlations ∇ – M_* or R_{eff} appear at all redshifts.
  - The evolution of ∇(z) is smooth, except when the disk begins form, when a very steep radial gradient appears. This occurs at any time depending on the dynamical mass; thus, these models explain all negative ∇ for isolated spiral galaxies.

Deriving present day abundance gradients from HII region observations

- **Direct method**:
  - Requires the kowledge of the physical conditions of the gas**: electron density and temperature and the adoption of an appropriate ionisation structure.**
  - Then, from the available emission lines, the corresponding ionic abundances are calculated.These abundances have to be corrected for the contribution of unseen ionisation states (ICF).
- **Empirical method:**
  - Uses the cooling properties of the ionised gas to produce empirical calibrations that relate emission-line intensity ratios of strong lines with the abundance of a given element.
  - This has been done traditionally for **oxygen**, but it can also be done using other strong emission lines or a combination of several.

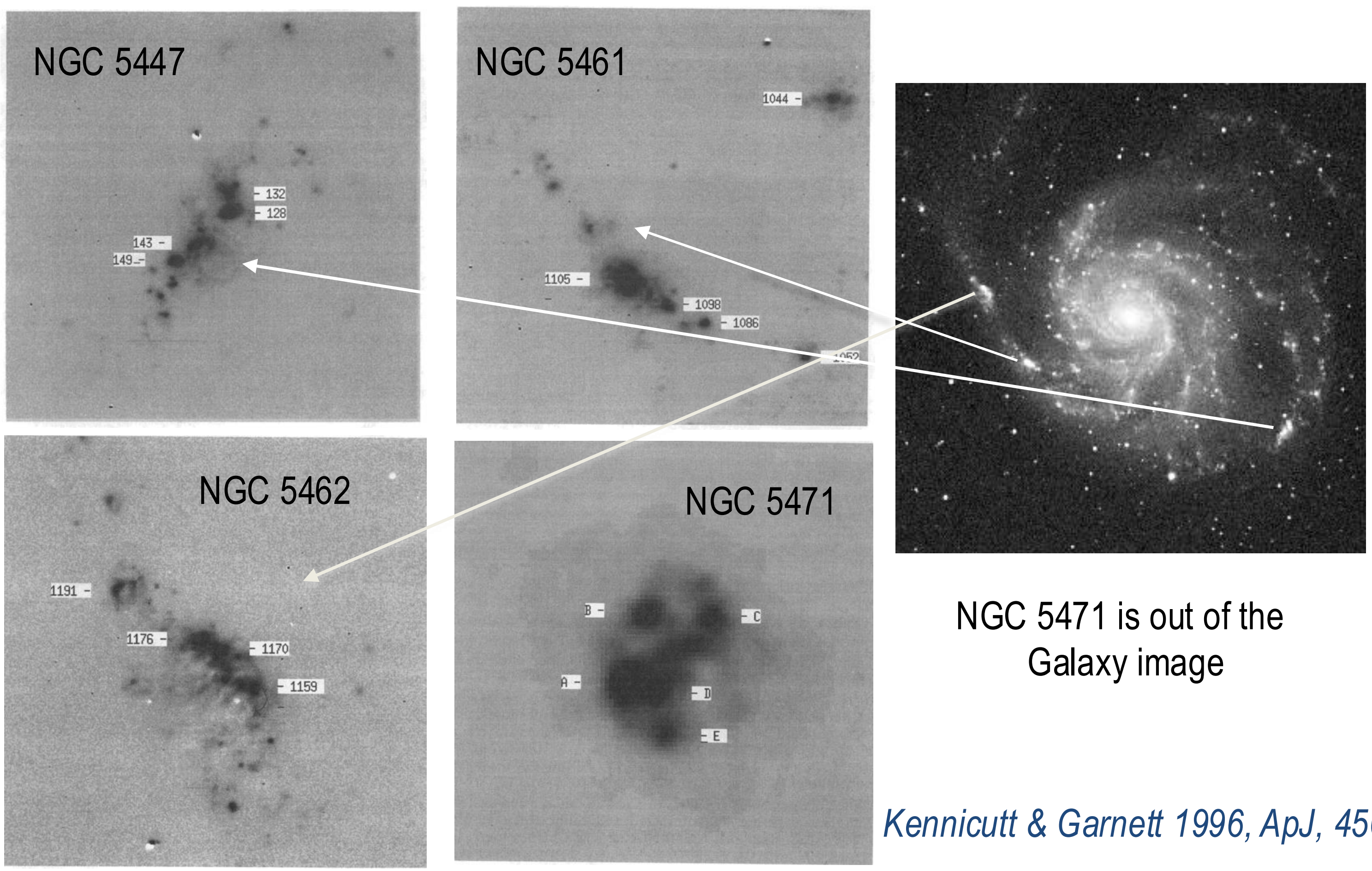
A case of study: M101

How abundance gradients are derived



Kennicutt & Garnett 1996, ApJ, 456,504

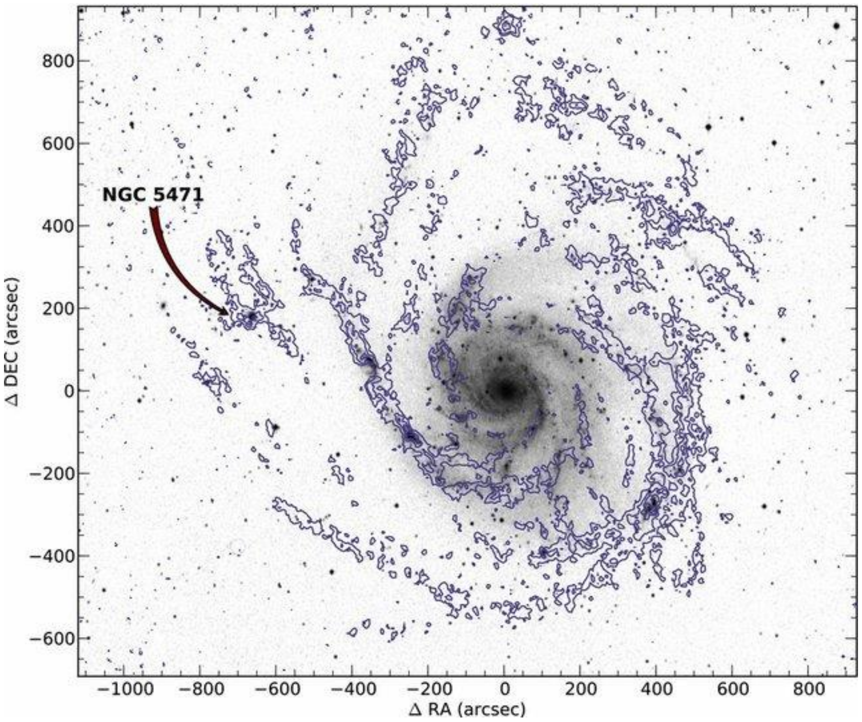
Resolved HII regions in M101

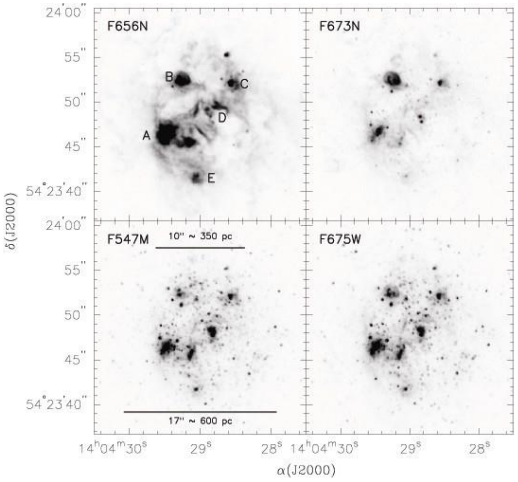


NGC 5471 is out of the Galaxy image

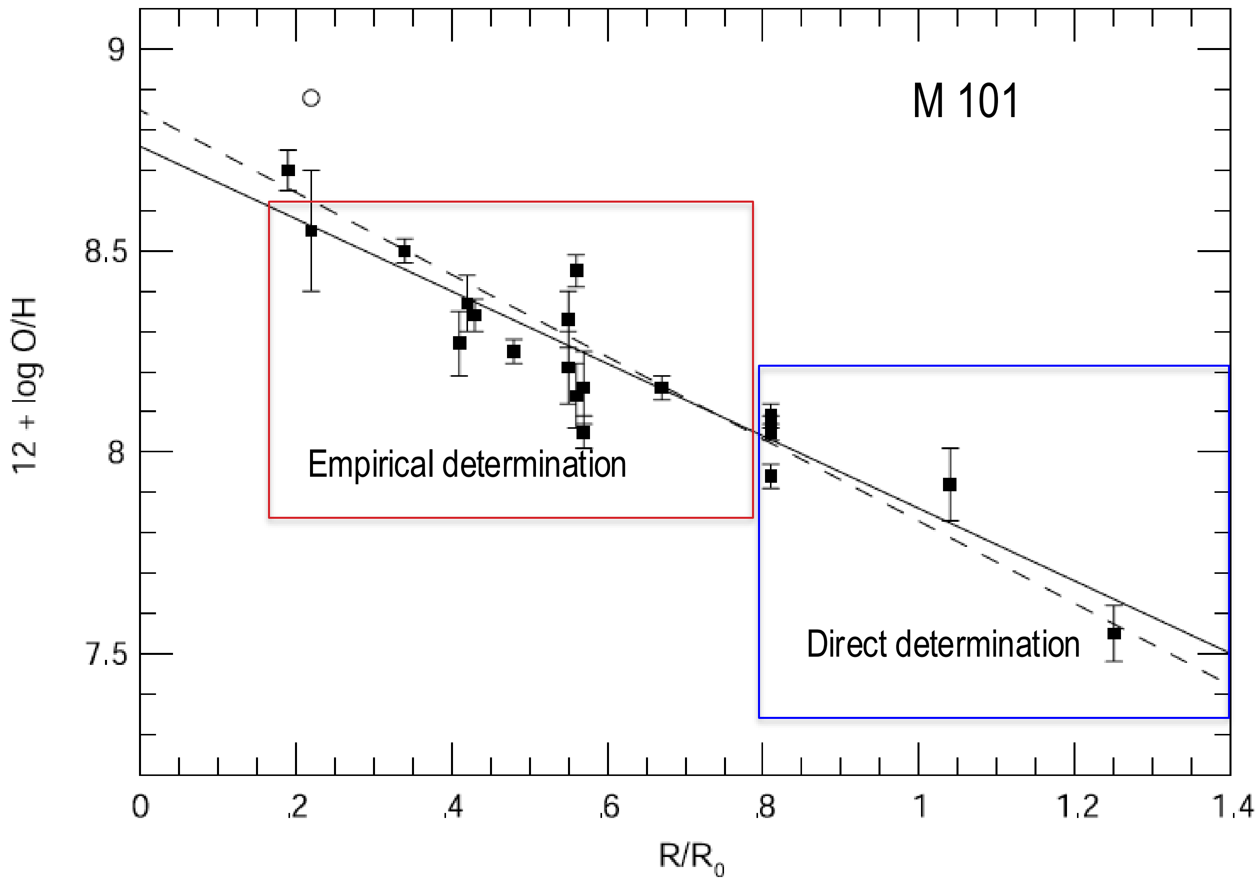
Kennicutt & Garnett 1996, ApJ, 456,504

NGC 5471 in M101

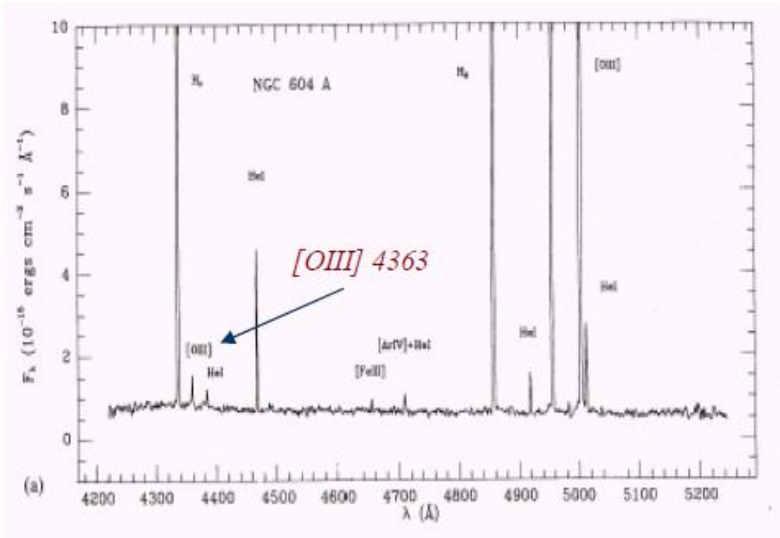




How gas oxygen abundance gradients are derived



The weakness of *auroral* lines



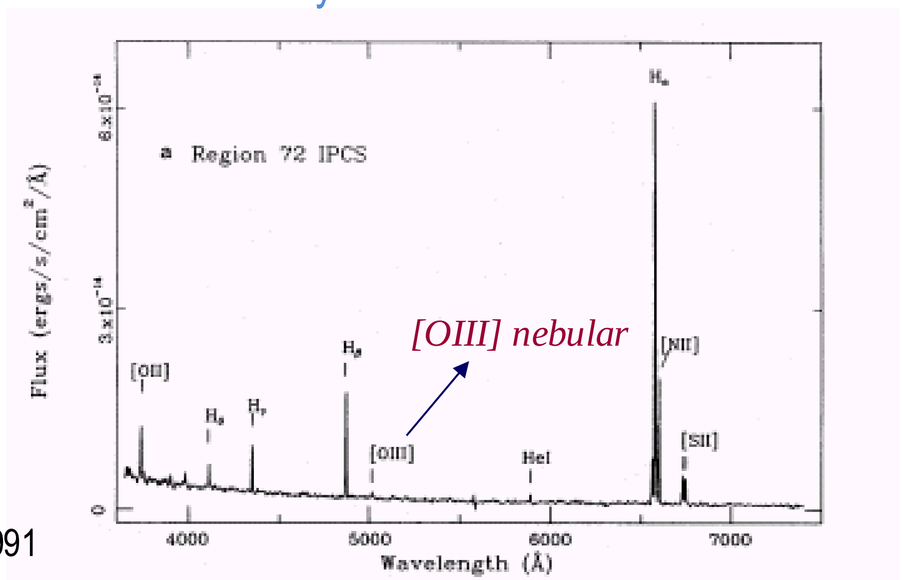
Díaz et al.1987

The auroral lines are intrinsically weak and difficult to detect and the difficulty increases with metallicity.

Low metallicity case

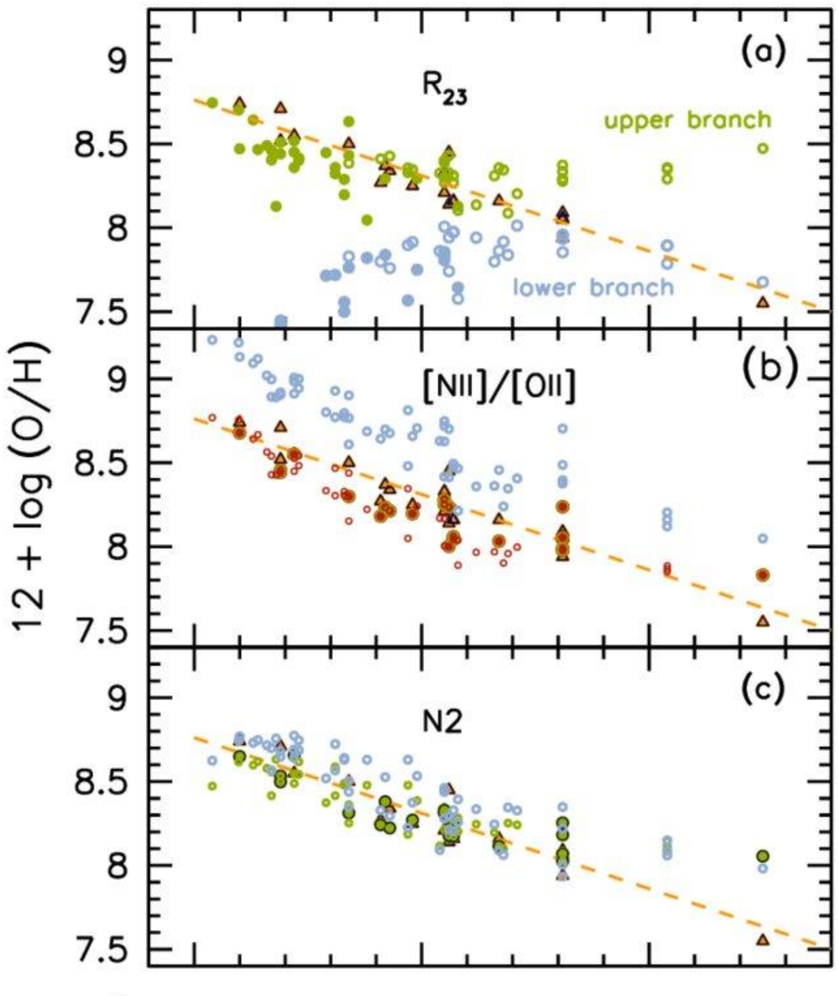
High metallicity case

At high metallicity, T_e is too low to produce any significant auroral line.



Díaz et al.1991

The M101 empirical O/H gradient



Bresolin et al. 2009, ApJ, 695, 580

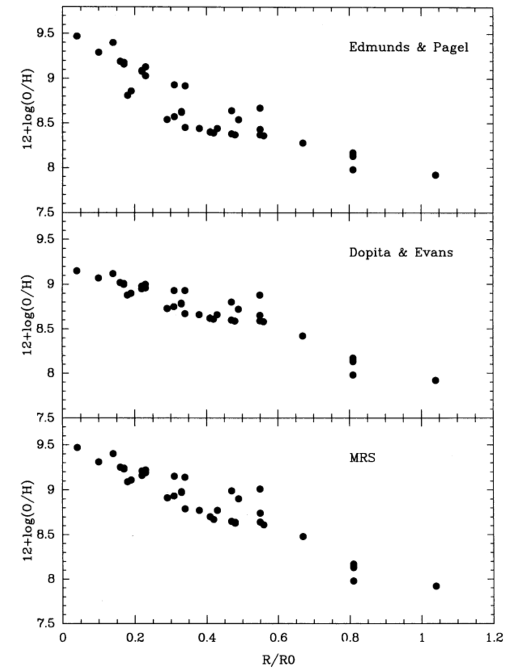
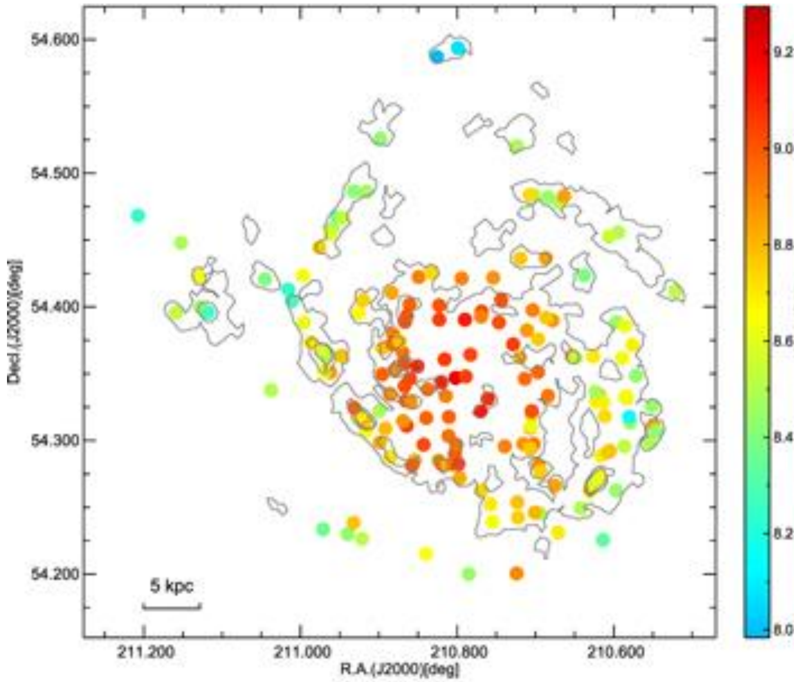
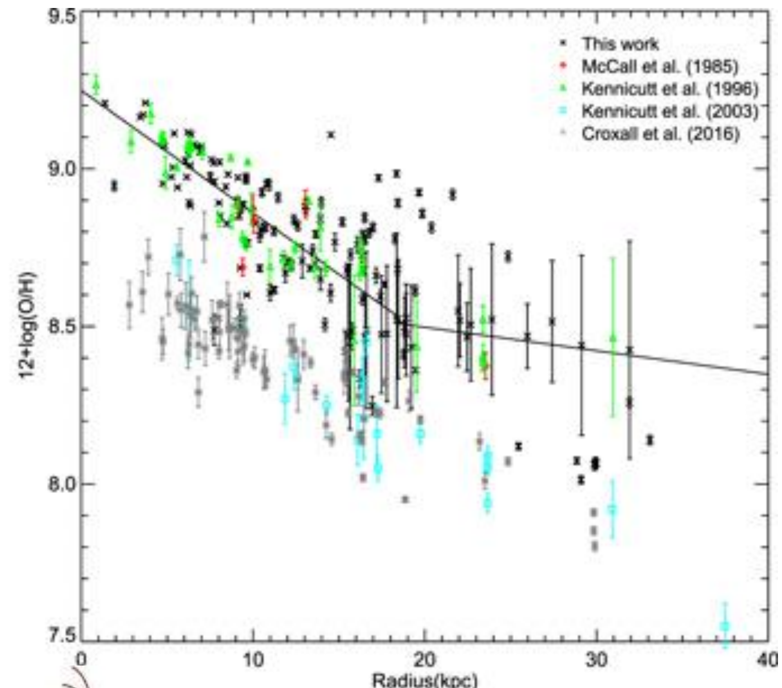


FIG. 11.—Radial variation in oxygen abundances in M101 determined from three "empirical" calibrations of the R_{23} excitation parameter.

Kennicutt & Garnett 1996, ApJ, 456, 504

Putting it all together



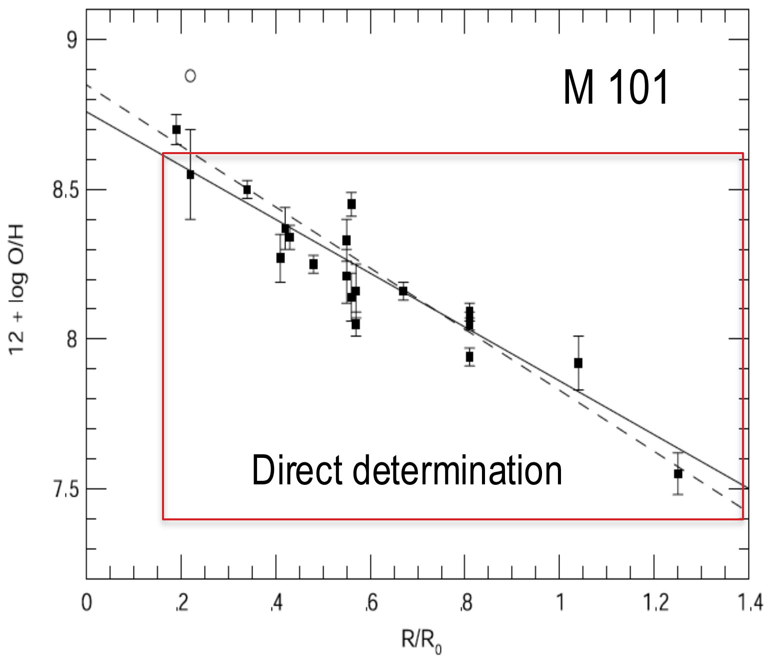


Hu et al. 2018, ApJ 854,68

Putting it all together

MOVING TO THE RED

Using Sulphur as abundance tracer



Why using sulphur?
It's all about

$$h\nu \approx kT$$

Sulphur as abundance tracer?

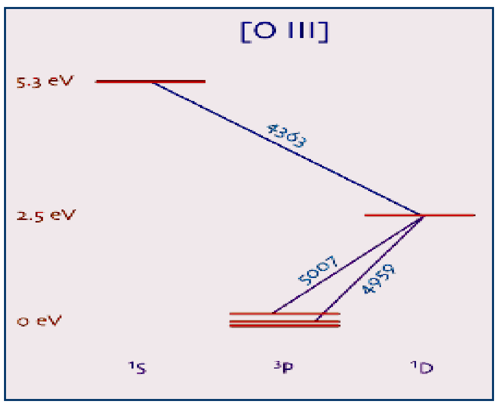
- As in the case of oxygen, sulphur is also produced in massive stars.
- Its yield is supposed to follow that of Oxygen $\Rightarrow$

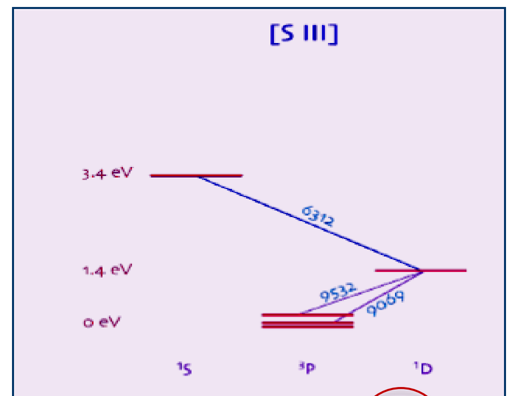
  S/O ratio seems to remain constant at

  $\log(S/O)_{\odot} \cong -1.56$.
- Although sulphur is less abundant than oxygen, in principle, ***it can also be used as abundance tracer*** providing similar information while presenting several **interesting** advantages.

Advantages of the use of Sulphur as abundance tracer

- The far-red lines of [SIII] at $\lambda\lambda$ 6312, 9069, 9532 Å are analogous to those of [OIII] at $\lambda\lambda$ 4363, 4959, 5007 Å, but their emissivities are less dependent on T_e .



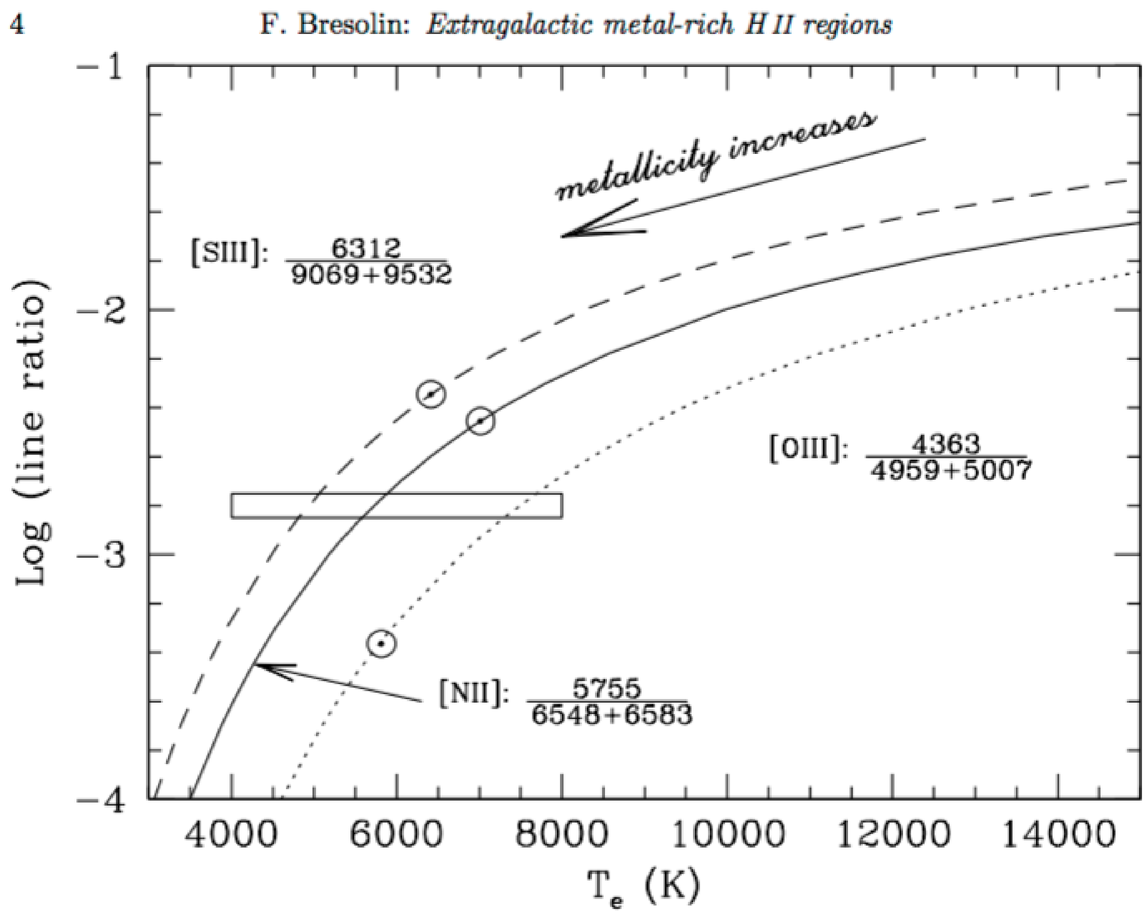


$$I_l \propto N(X^{+i})\varepsilon_l \quad \text{with} \quad \varepsilon_l \propto \Omega(T)T_e^{-0.5}e^{-\frac{\chi_i}{kT_e}}$$

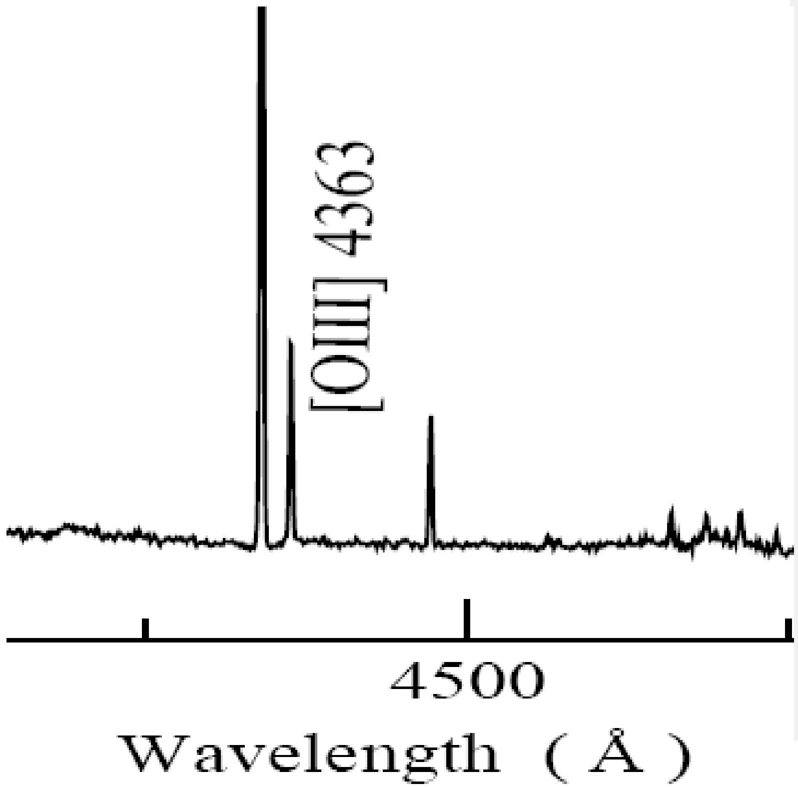
and $\chi(S^{2+}) < \chi(O^{2+})$

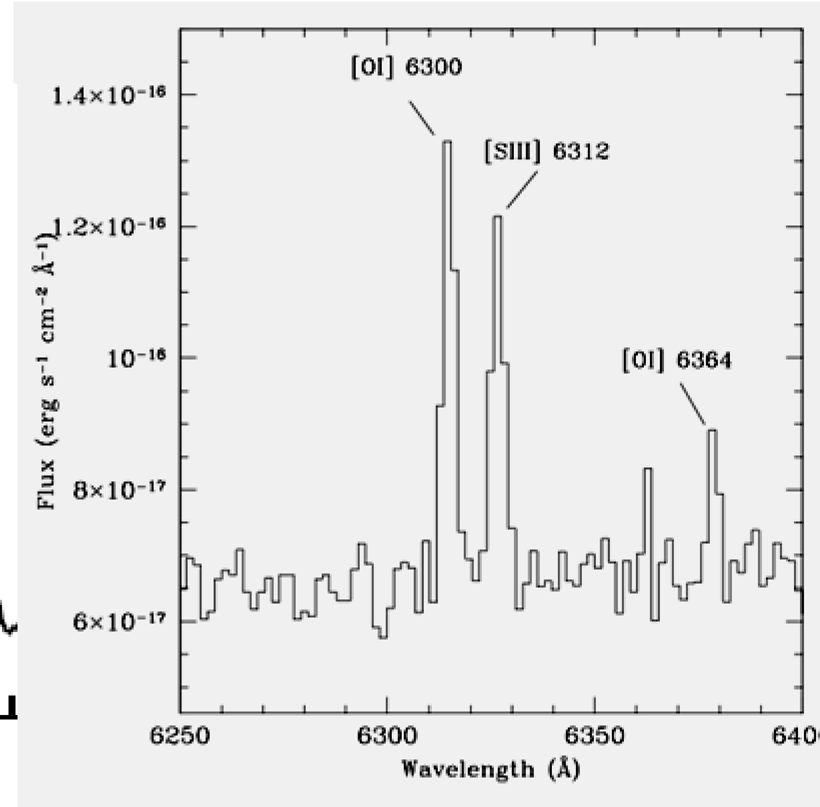
Telescope limits

Bresolin (2008) in "The metal rich universe"



Auroral line detection





Observational advantages of S

- Less contamination from stellar absorption lines from metals (there are many more lines in the blue).
- Less contribution to recombination H lines from stellar absorption.
- Less importance of reddening.
- [SII] and [SIII] lines can be measured relative to nearby H lines, minimizing the effects of reddening.
- Almost no depletion in the diffuse ISM.
- **[SIII] lines clearly detected at high abundances where "strong" [OIII] lines are very weak.**

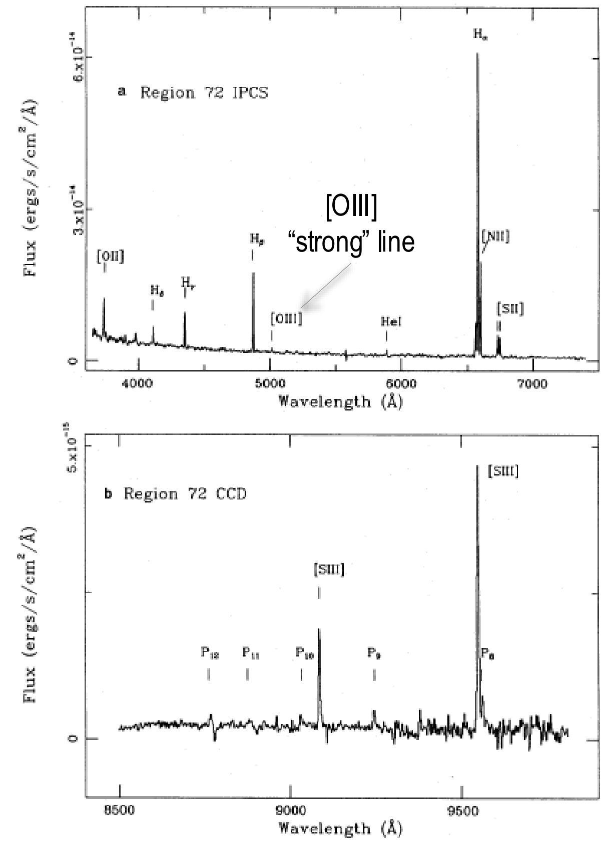


Figure 4. (a) IPCS spectrum and (b) CCD far red spectrum of region CCM72. The relevant emission lines are marked.

Direct determination of abundances

Knowledge of line electron temperatures is required

Oxygen

- T_e([OIII] is derived from the ratio of auroral to nebular lines at λλ 4363 and 4959, 5007 Å
- Most of the O is in the form of O^+ and O^{2+}. Their relative contribution depends on the degree of ionization of the nebula.
- Only for exceptionally high excitation objects, those showing HeII emission at λ 4686 Å, there is a small contribution by O^{3+}.

Sulphur

- T_e([SIII]) is derived from the ratio of auroral to nebular lines at λλ 6312 and 9069, 9532 Å.
- Most of the S is also in the form of S^+ and S^{2+}, but in most cases S^{2+} is dominant.
- A certain contribution by S^{3+} is expected in **high excitation** objects for which ICF have to be derived.

Ionisation structure

Different ions are formed in regions with different T_e.
A certain ionisation structure has to be assumed for the nebula.

Oxygen

- Three-zone approximation

Zone	Ions	Temperature
high ionisation zone	O^{2+}	Te([OIII]
mid ionisation zone	S^{3+}, Ar^{3+}	Te([SIII]
low ionisation zone	O^{+}, S^{+}	Te([OII]

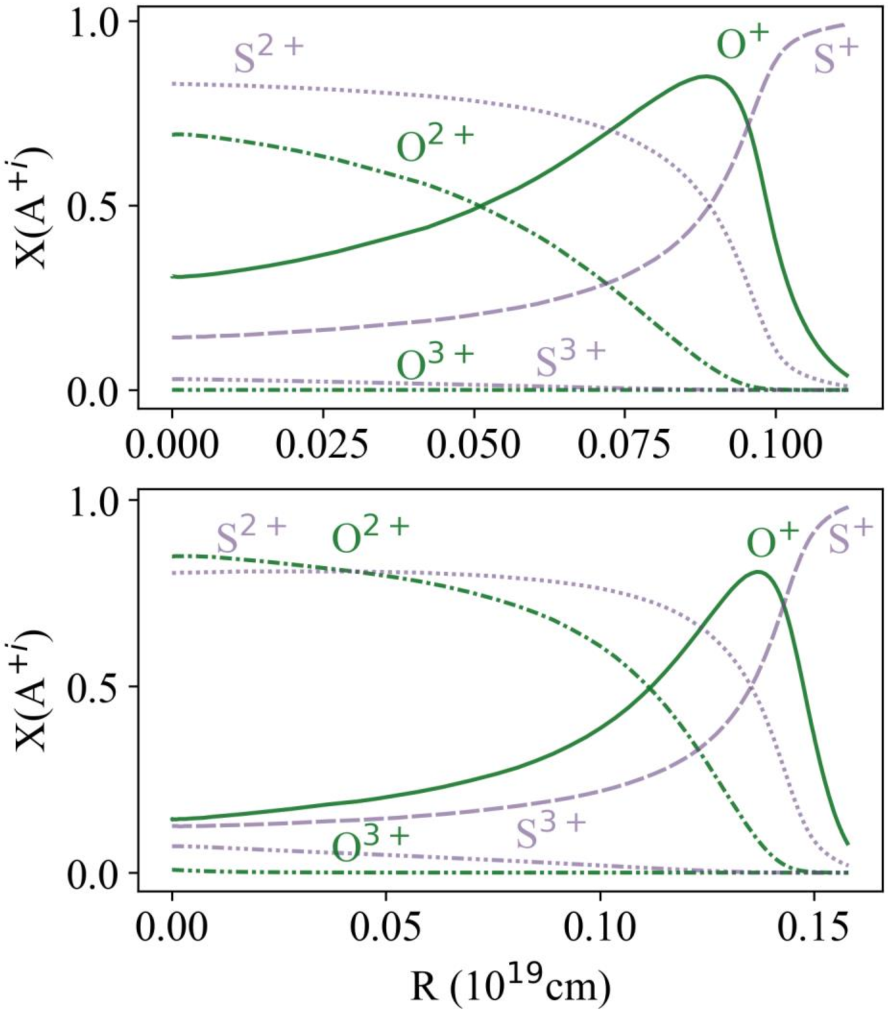
Sulphur

- Two-zone approximation

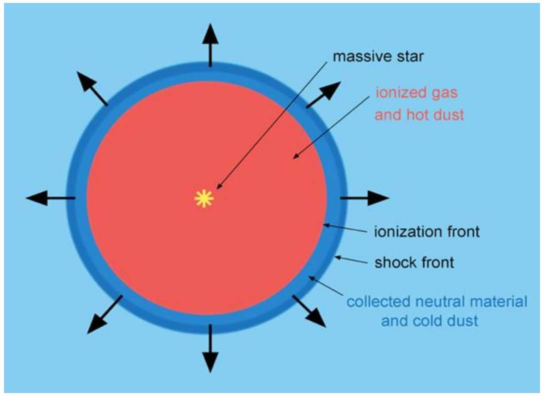
Zone	Ions	Temperature
high ionisation zone	S^{3+}, Ar^{3+}	Te([OIII]
mid-low ionisation zone	S^{+}, S^{++}, Ar^{++}	Te([SIII]

Ionisation structure

S^{2+} seems to originate in an intermediate excitation zone.



HII Regions



Deharveng et al. 2010

HII Galaxies

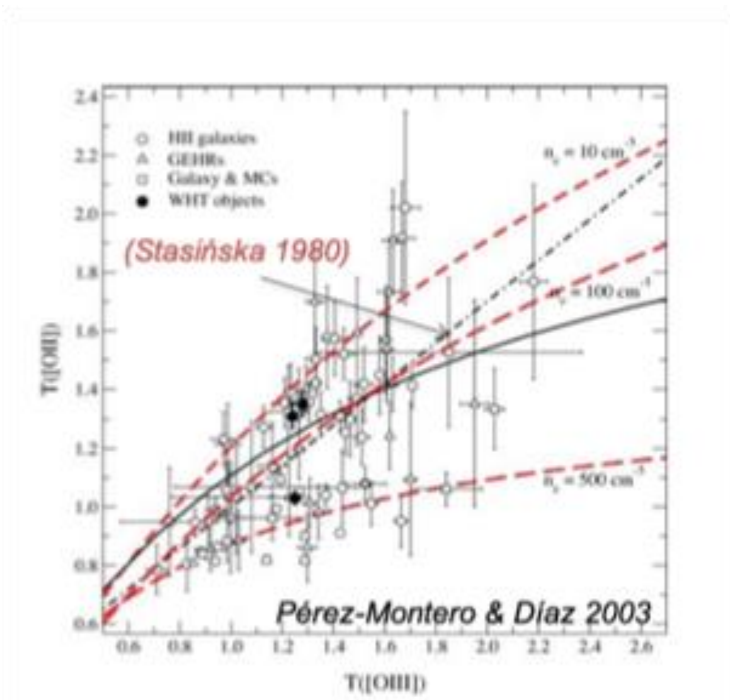
Relation between ion temperatures

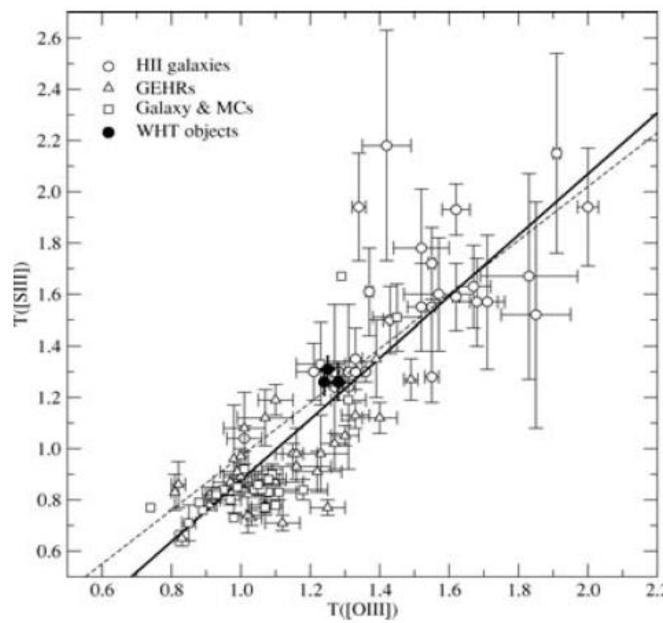
$$T_e([OII]) = 0.70 T_e([OIII]) + 3000K$$

(Stasinska 1980)

$$\boxed{T_e([SIII]) = 0.83 T_e([OIII]) + 1700K}$$

(Garnett 1992)





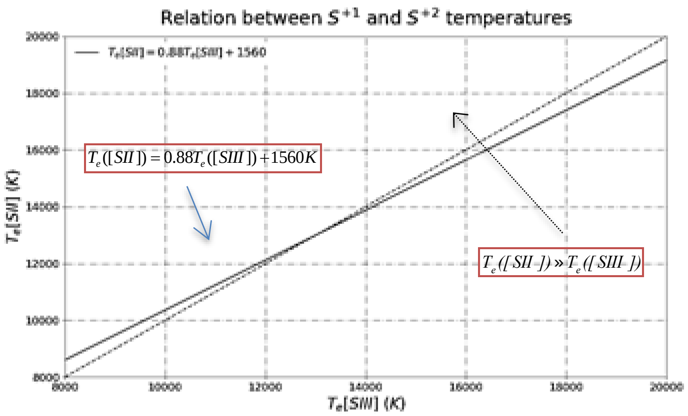
Relation between ion temperatures

- Assuming T_e([SII]) ≅ T_e([OII]) provides a relation between T_e([SII]) and T_e[SIII] as:

$$T_e([SII]) = 0.88T_e([SIII]) + 1560K$$

- Which is not very different, within measurement errors, from the one-to-one relation for the temperatures of interest … so, we can assume:

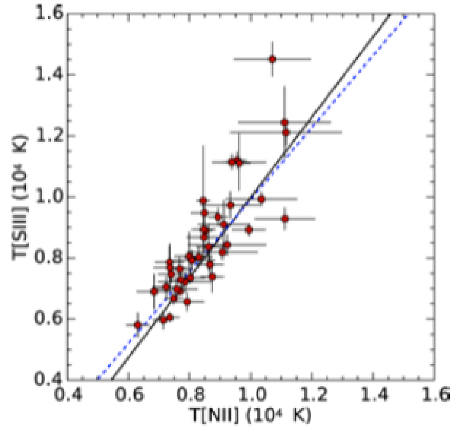
$$\boxed{T_e([SII]) \approx T_e([SIII])}$$



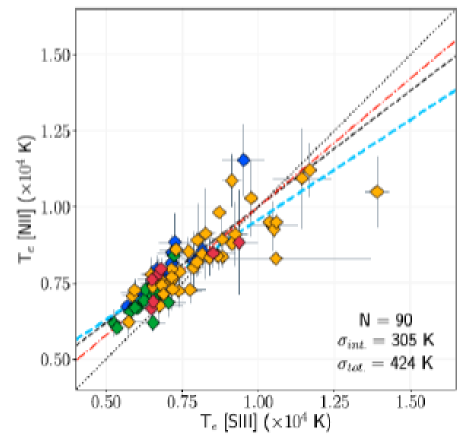
The T_e [SIII] – T_e [NII] relation

$T_e($

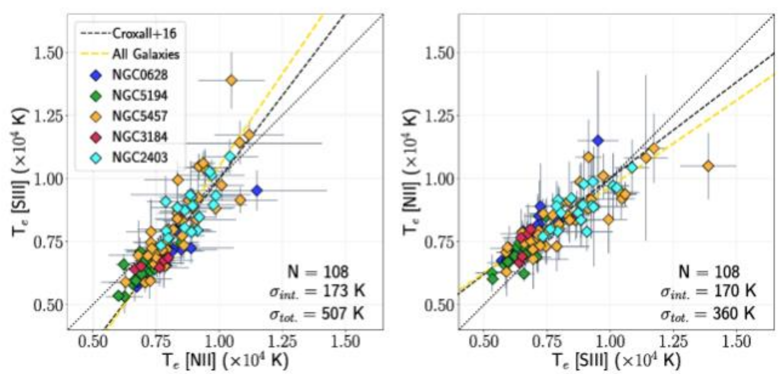
Croxall, K. et al. 2016



Berg, D. et al. 2020

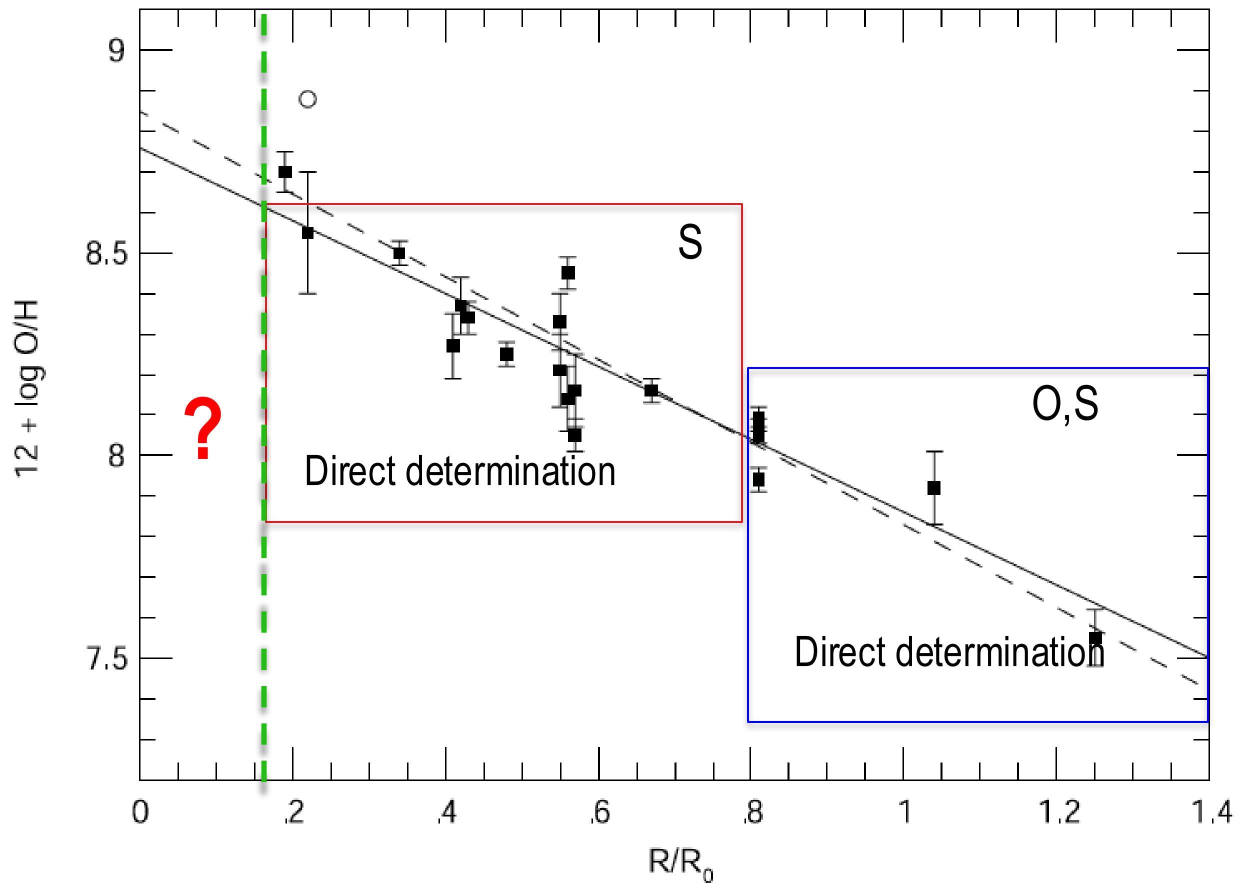


The Astrophysical Journal, 915:21 (33pp), 2021 July 1



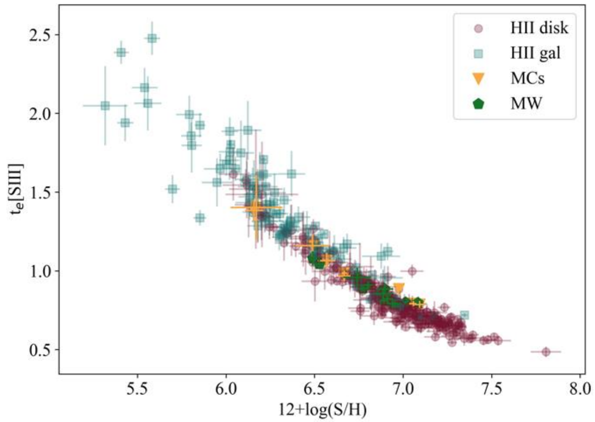
Rogers et al. 2021 (CHAOS)

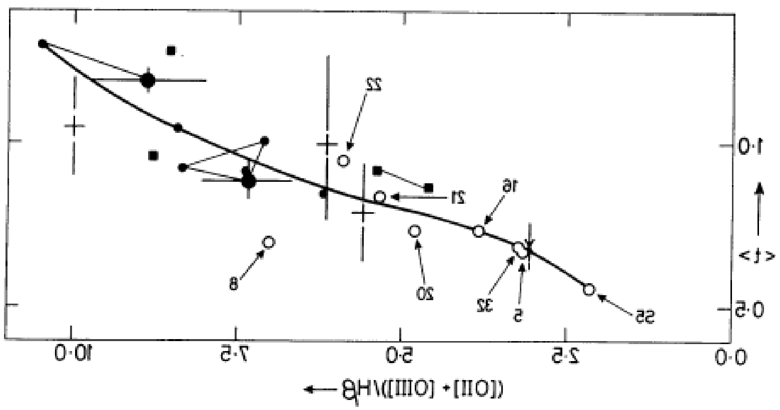
The high metallicity regime



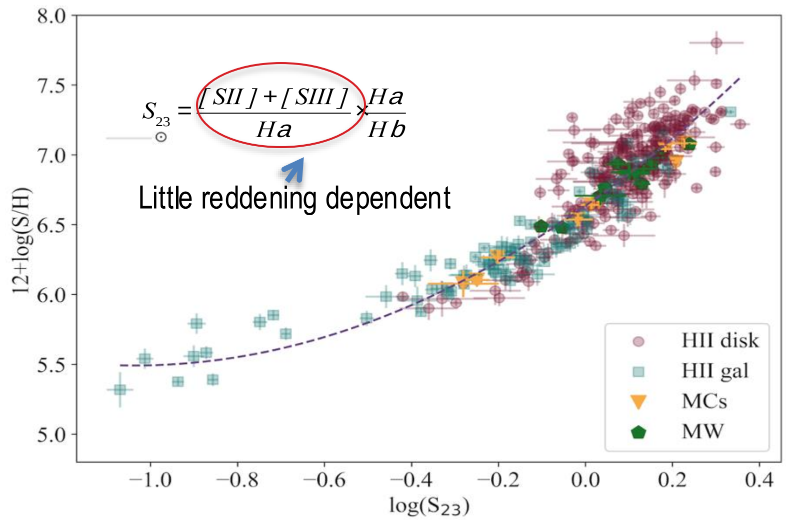
And … what about the empirical calibration?

- The effect of sulphur ions as cooling agents is evident by the good correlation shown between S/H and the respective T_e ([SIII]) and **this relation is the base of the empirical calibration.**





Pagel et al. 1979

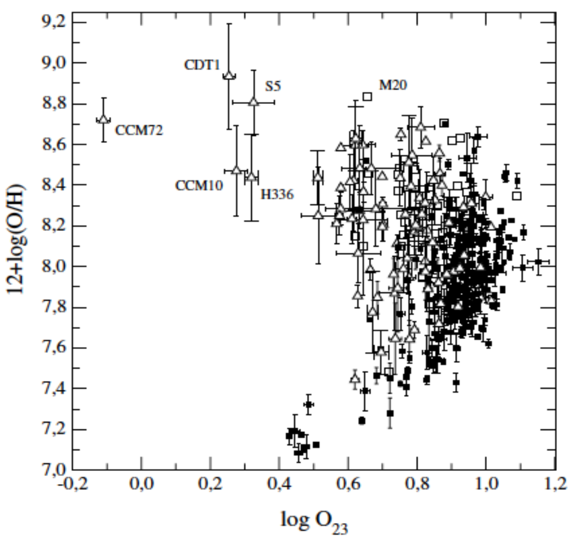


Single valued up to, at least, solar metallicity

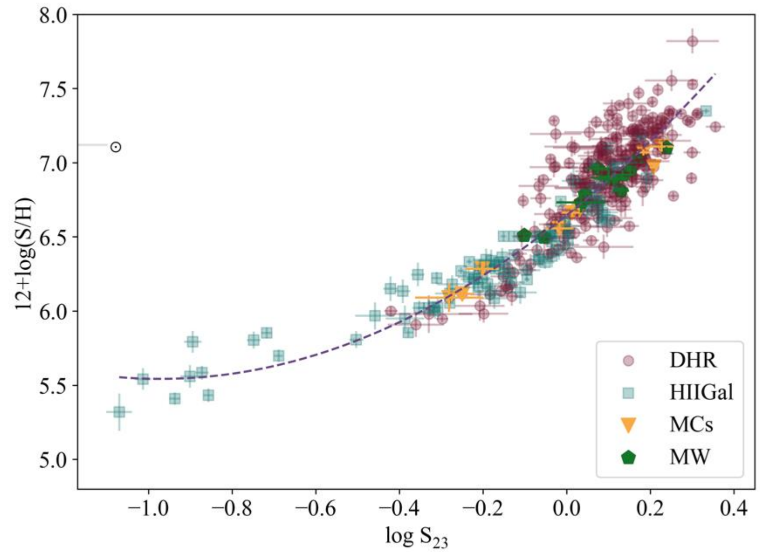
Sulphur Empirical calibration: S_{23}

- Similar to R_{23} but for Sulphur.

$$S_{23} = \frac{[SII] + [SIII]}{H\alpha} \times \frac{H\alpha}{H\beta}$$

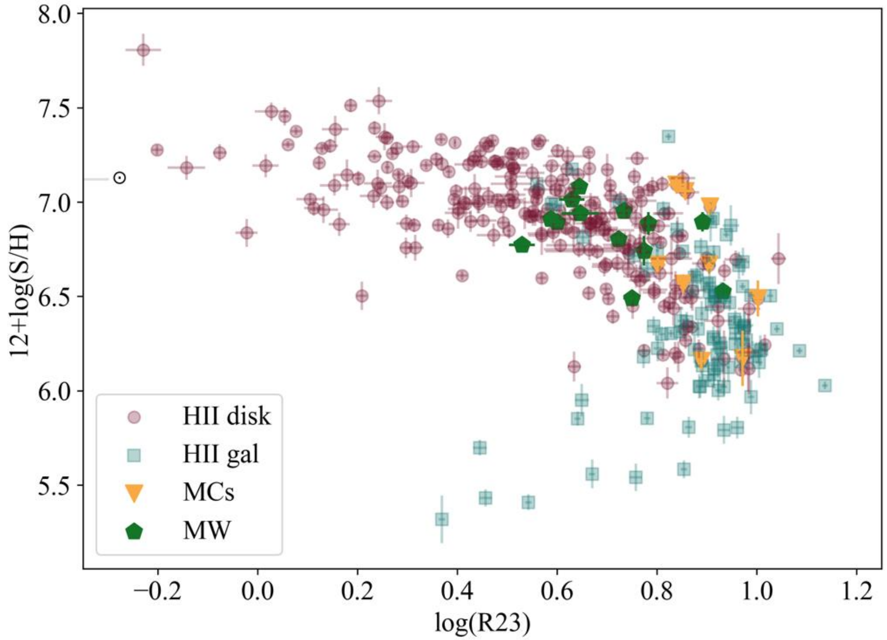


Díaz & Zamora, 2022, MNRAS

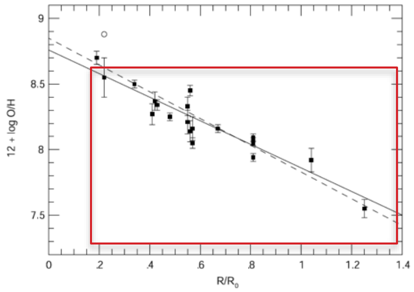


Single valued up to, at least, solar metallicity

The R_{23} parameter calibrated in terms of S/H abundances



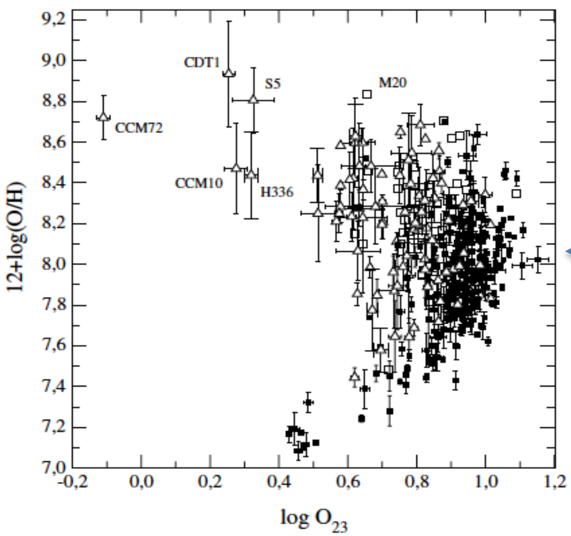
All abundances **directly** derived



Sulphur Empirical calibration: S_{23}

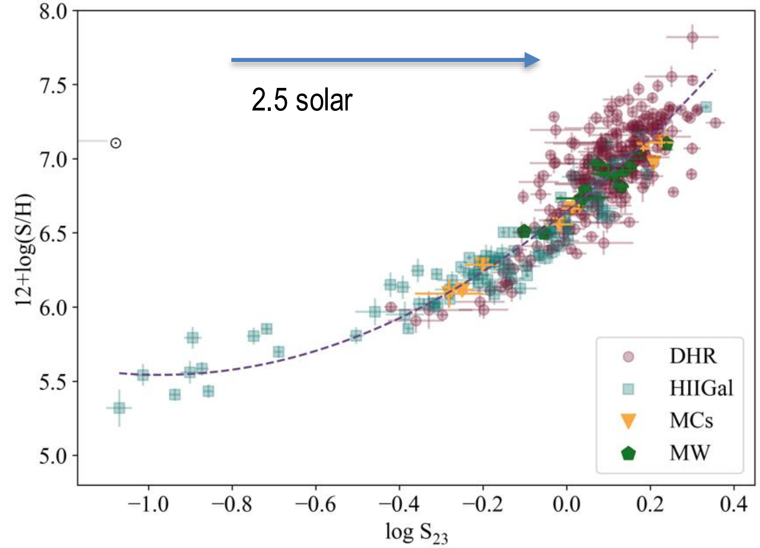
- Similar to R_{23} but for Sulphur.

$$S_{23} = \frac{[SII] + [SIII]}{Ha} \times \frac{Ha}{Hb}$$



¼ solar

Díaz & Zamora, 2022, MNRAS



Single valued up to solar metallicity

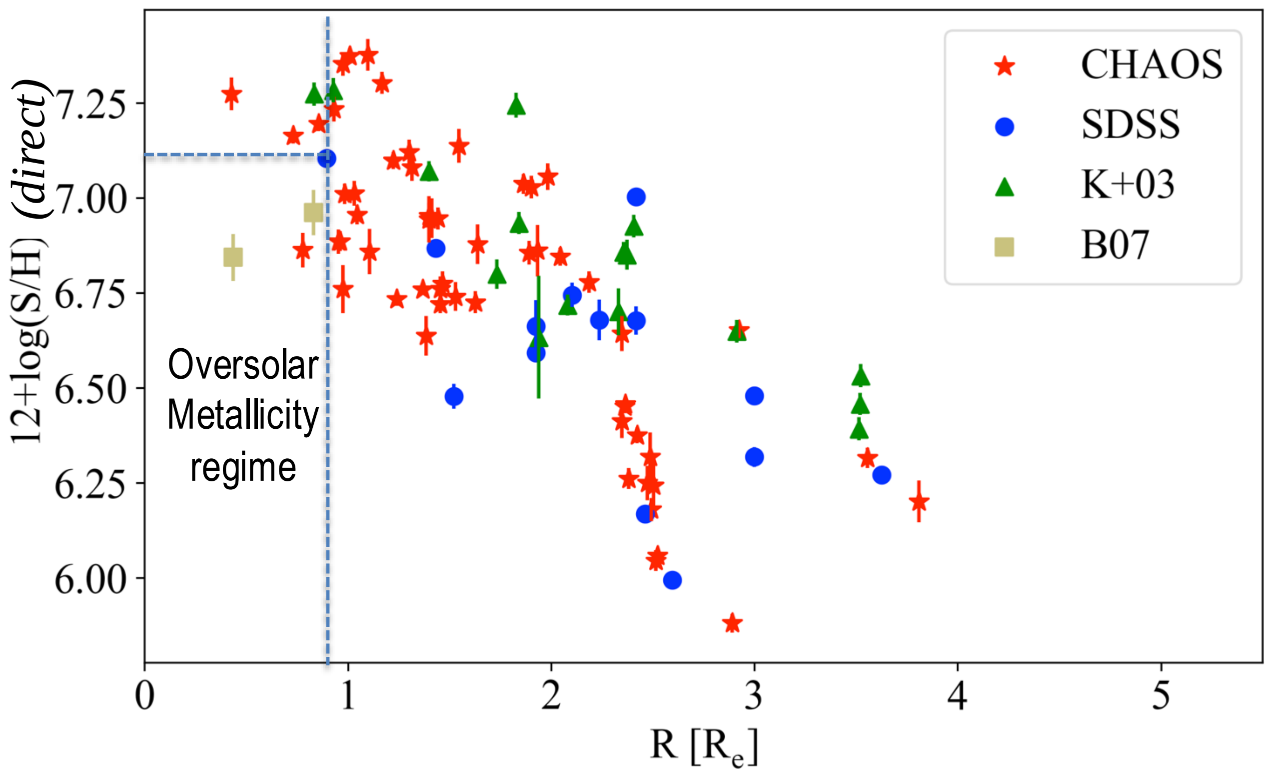
But … is this enough?

Deriving the sulphur gradient for M101

- Compiling data including emission lines of [OII] (3737,29), [OIII] (4363), [OIII] (4959,5007), [NII] (6548,84), [SIII] (6312), [SII] (6717,31), and[SIII] (9069).
- Sources:
  - *Kennicutt, Bresolin & Garnett, 2003, ApJ, 591, 801*
  - *Bresolin, 2007, ApJ, 656,186*
  - *Croxall et al. 2016 (CHAOS), ApJ, 830, 4*
  - *Piliyugin et al. 2007 (SDSS-DR5), ApJ, 669, 299*

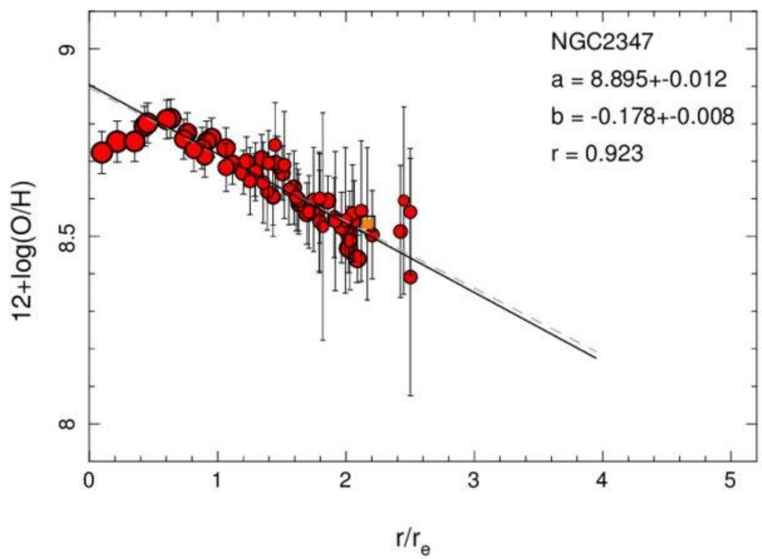
    (private analysis of the sulphur lines)

Direct abundance gradient (traced by S)



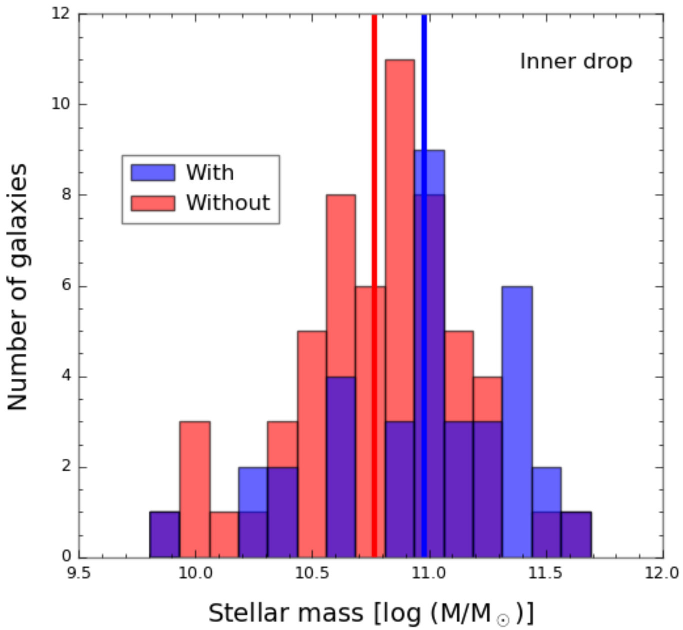
Central abundance drops

Sanchez-Mengiano et al 2018



Inner disc abundance drop

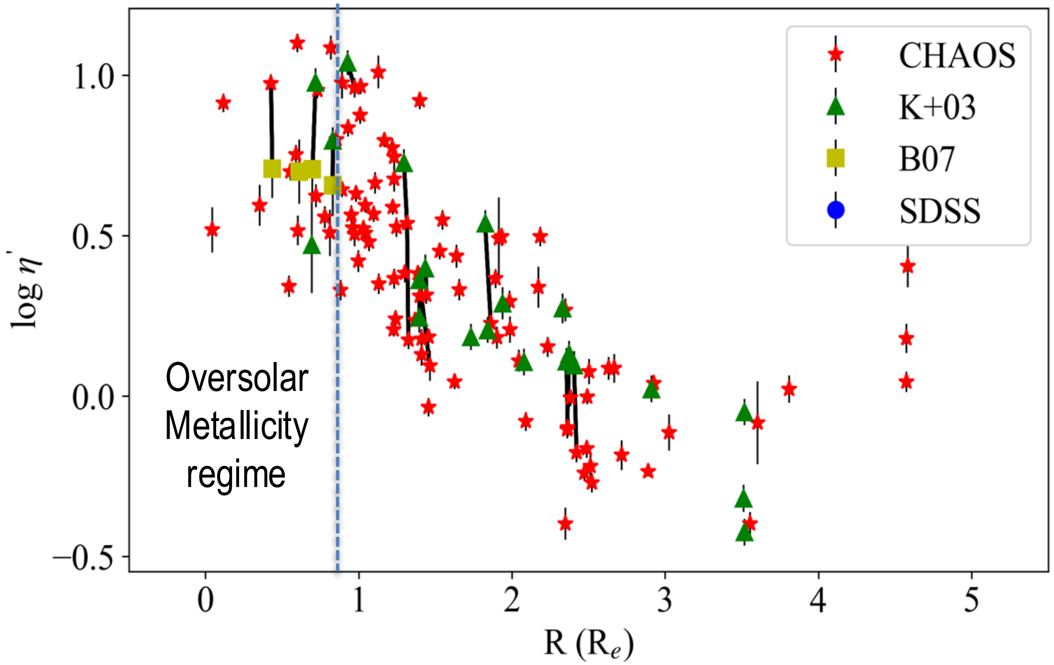
Central abundance drops



Central drops preferentially found in the most massive galaxies

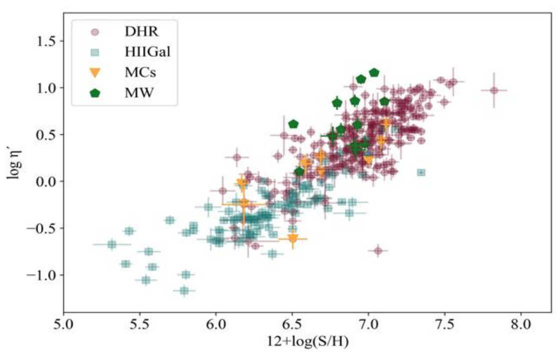
Functional parameter's gradients: the "eta" parameter

Defined in Díaz et al. 1987 and named inversion excitation parameter, it can be considered a proxy for the hardness of the ionising radiation.



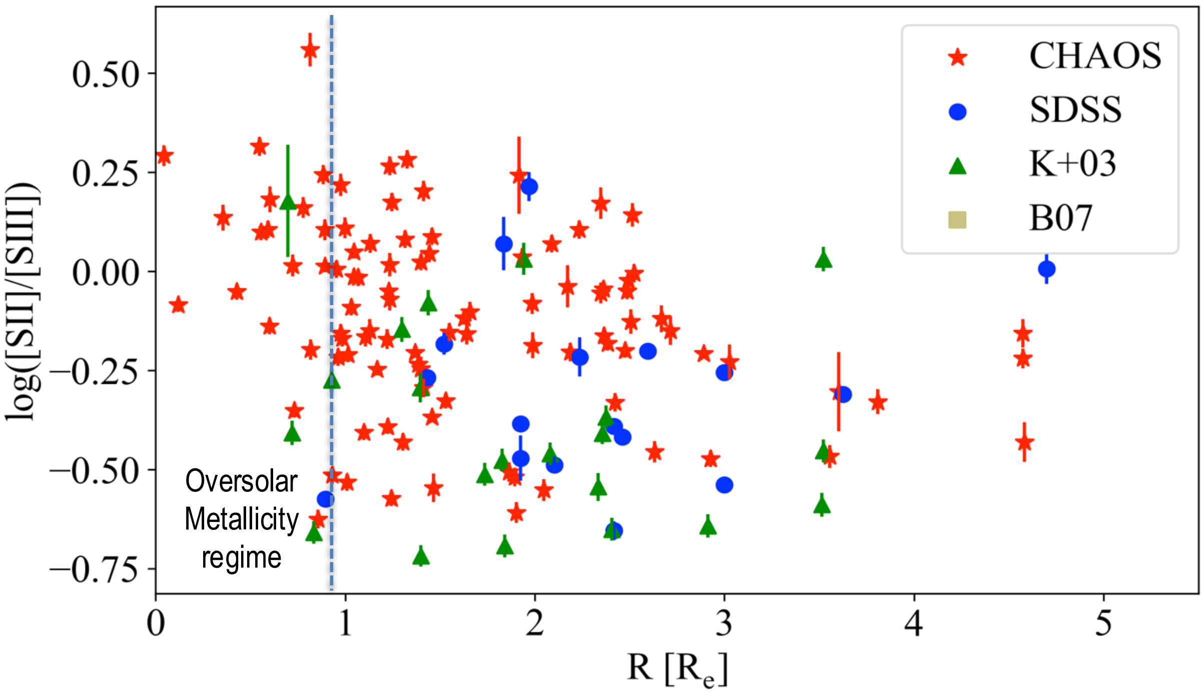
Increasing
T_{ion}

Díaz & Zamora, 2022

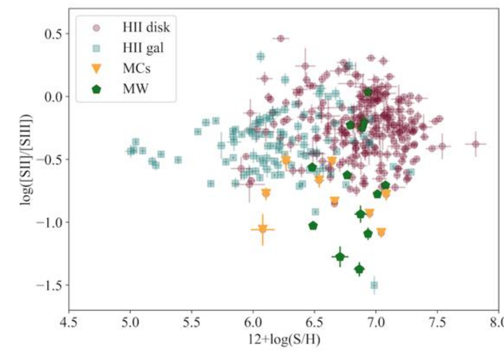


Functional parameter's gradients: the [SII]/[SIII] ratio

Calibrated in Díaz et al. 1991, can be considered as a proxy for the ionisation parameter, u, for up to solar metallicity.

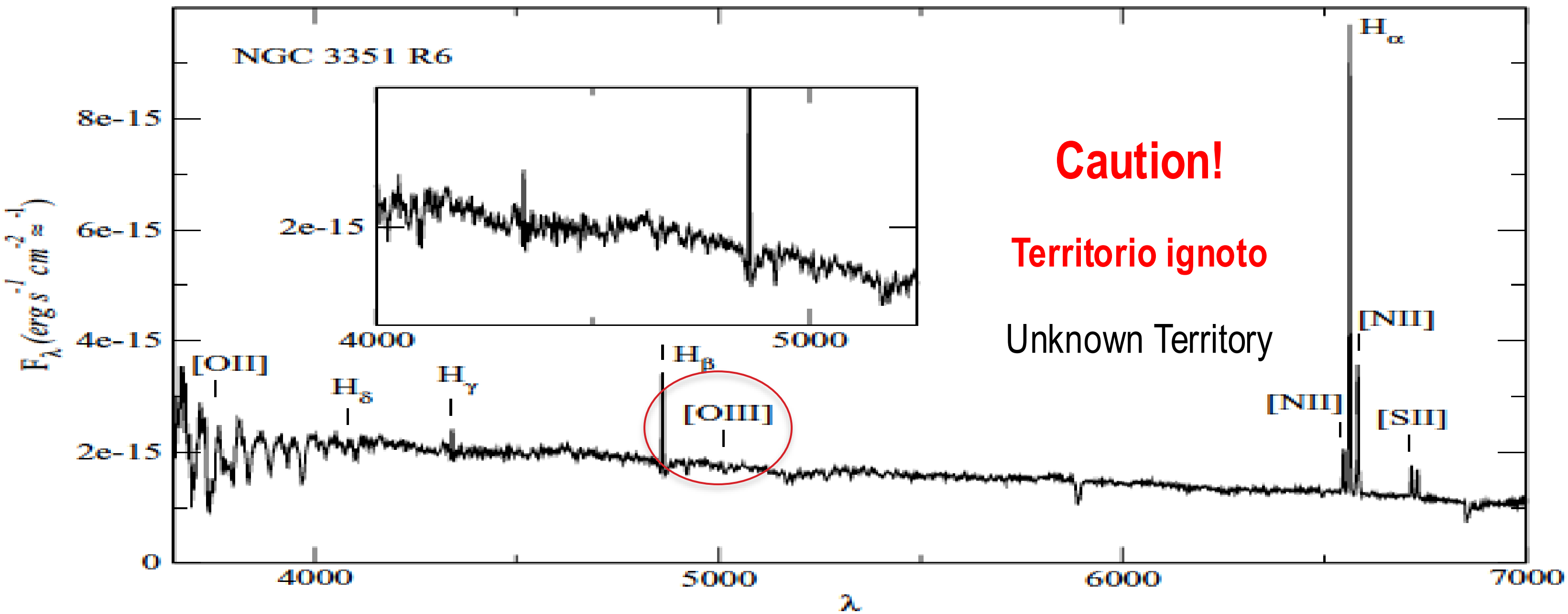


Díaz & Zamora, 2022



The over-solar metallicity regime

Díaz, A.I. et al. 2007

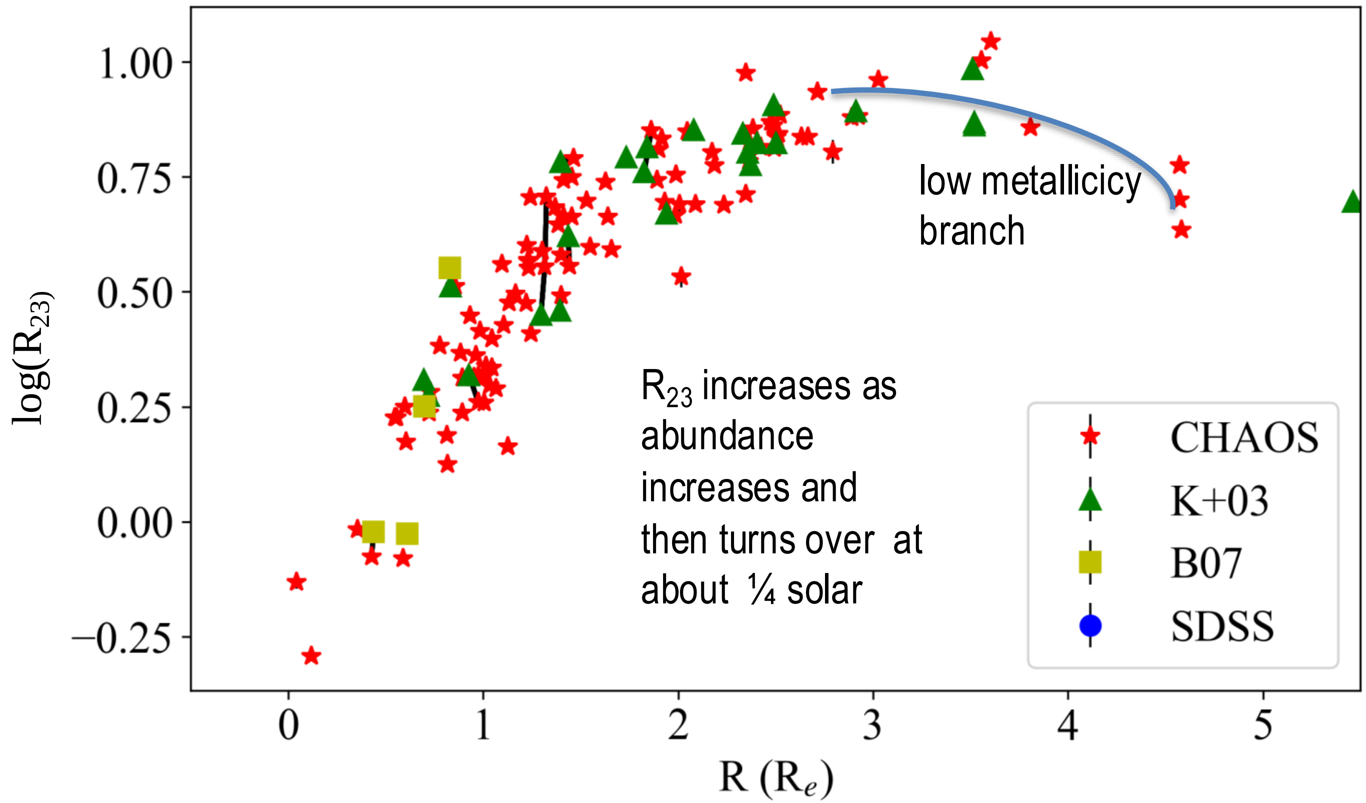


Caution!

Territorio ignoto

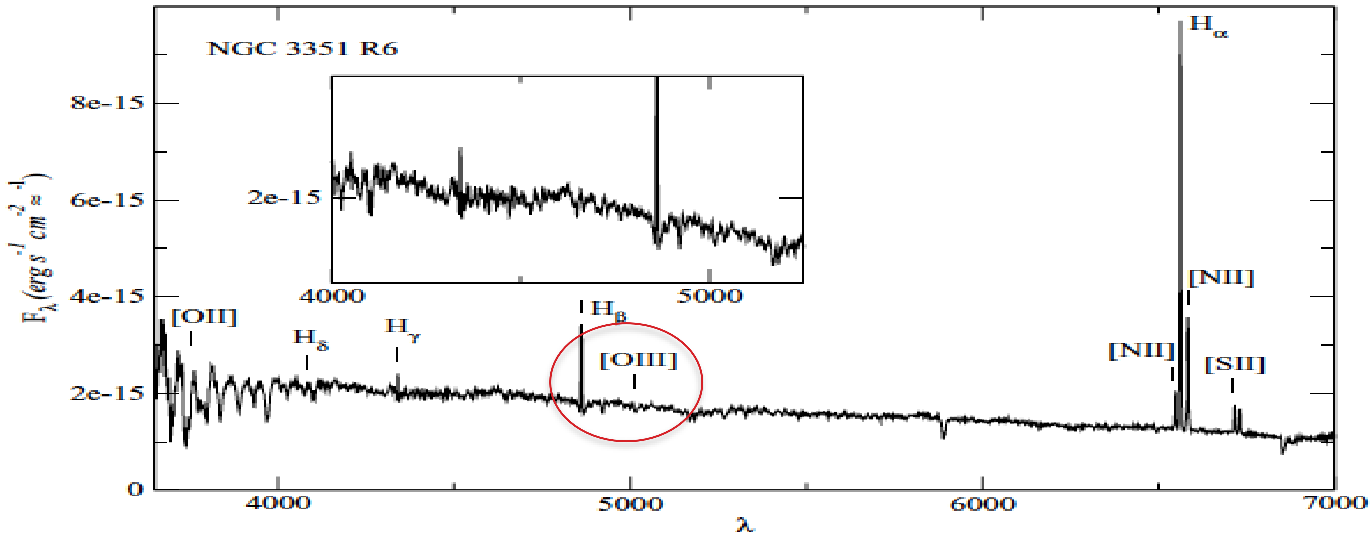
Unknown Territory

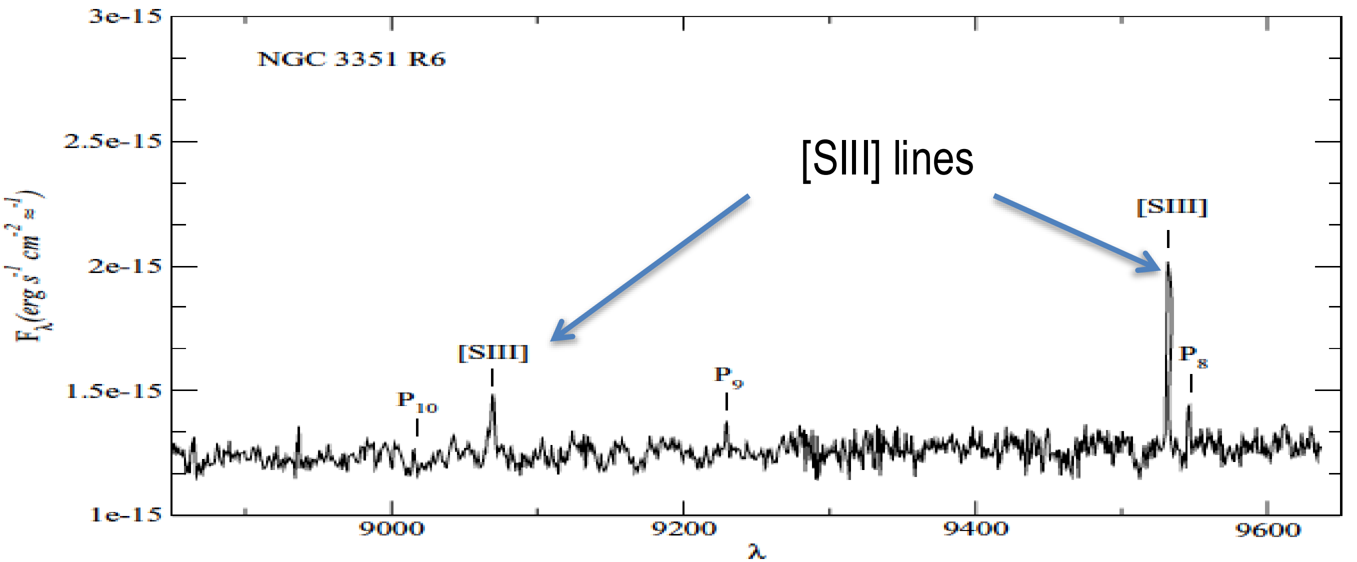
R_{23} gradient



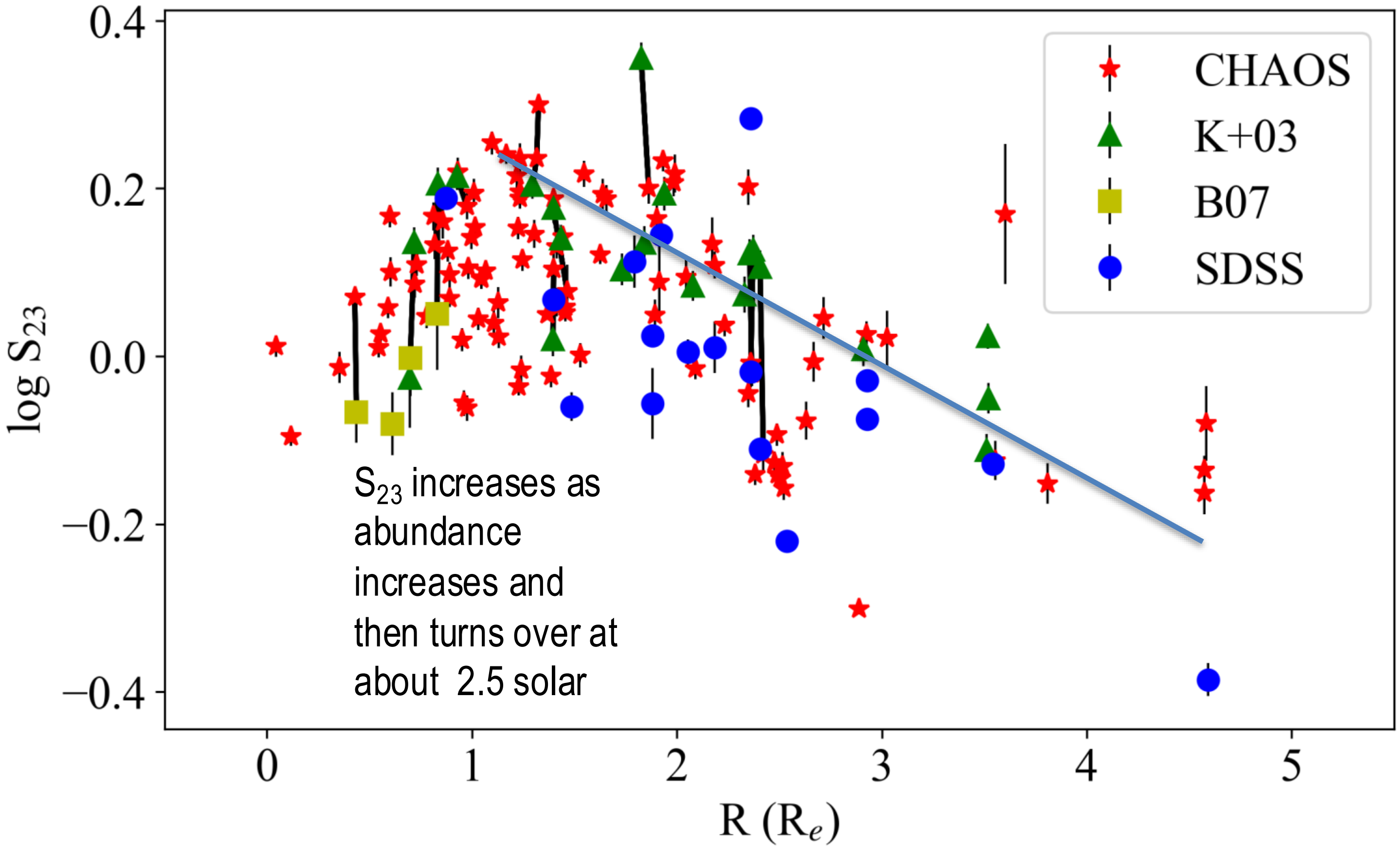
Detectability of [SIII] lines at high metallicity

Díaz, A.I. et al. 2007

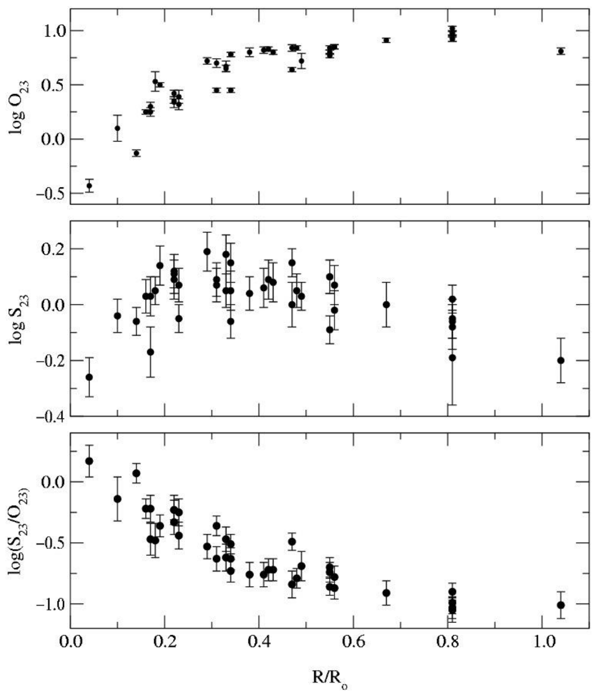


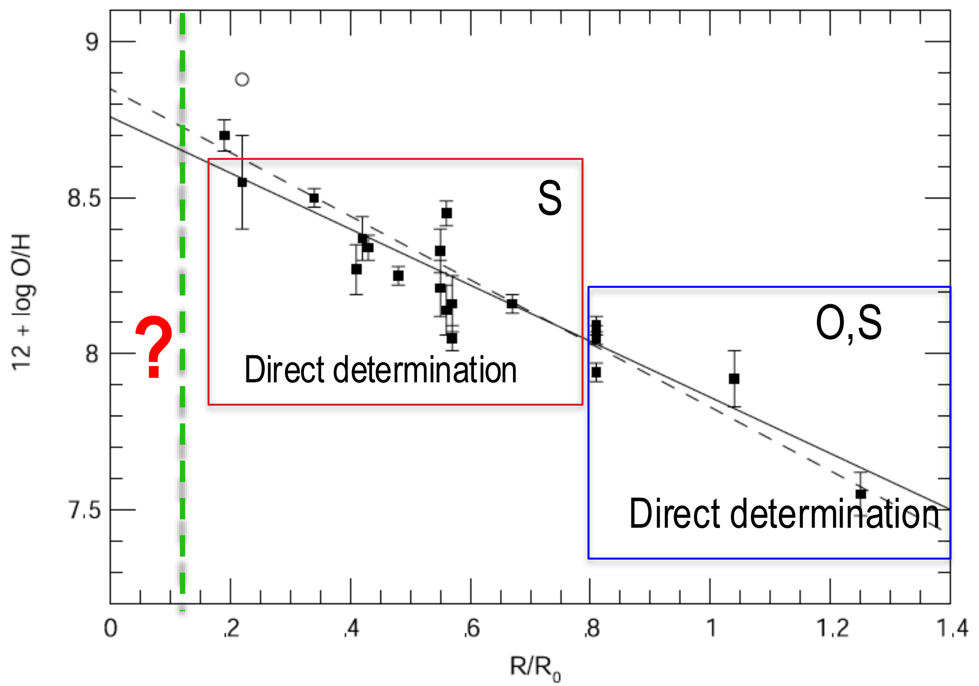


S_{23} gradient



The high metallicity regime

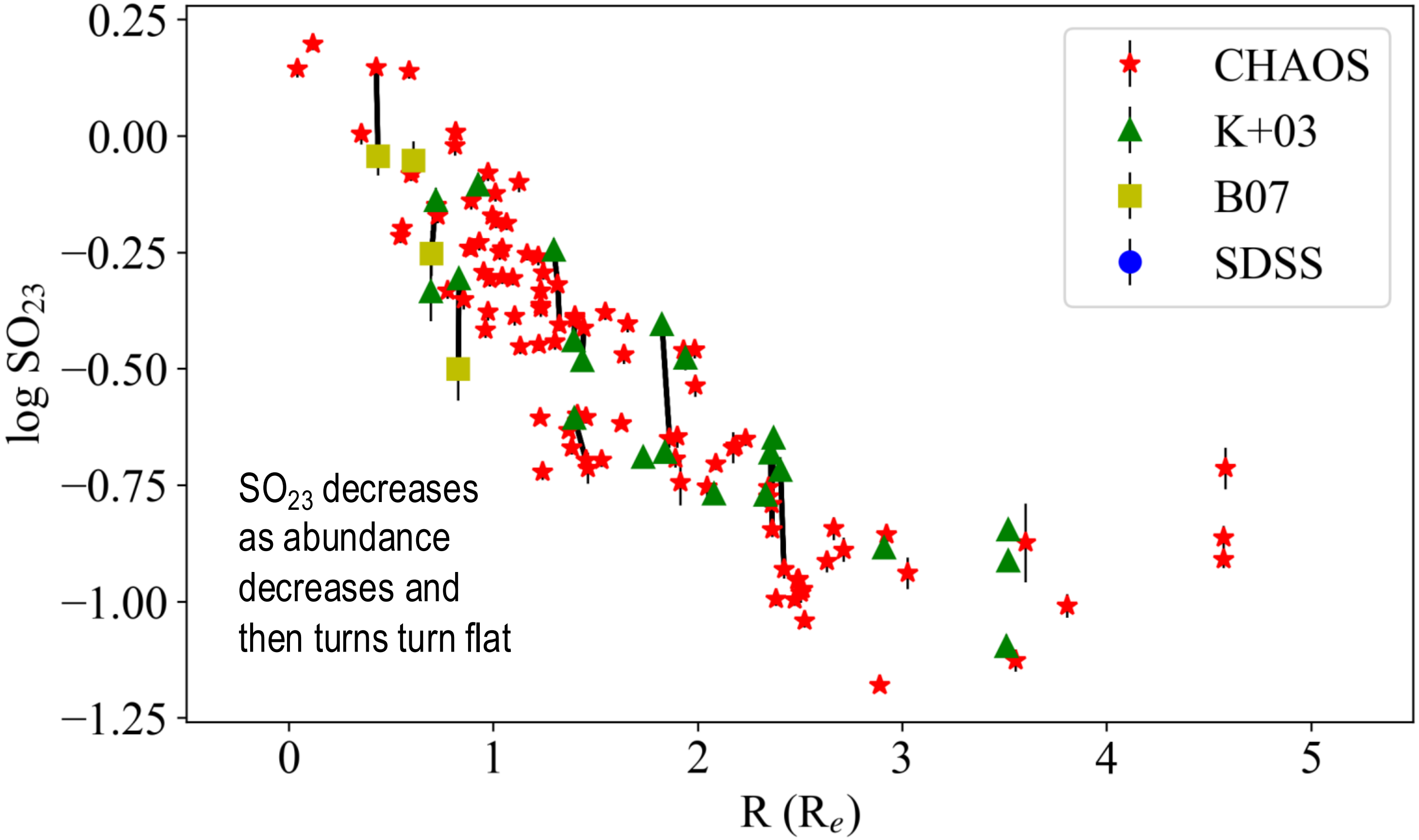




Pérez-Montero & Díaz 2005

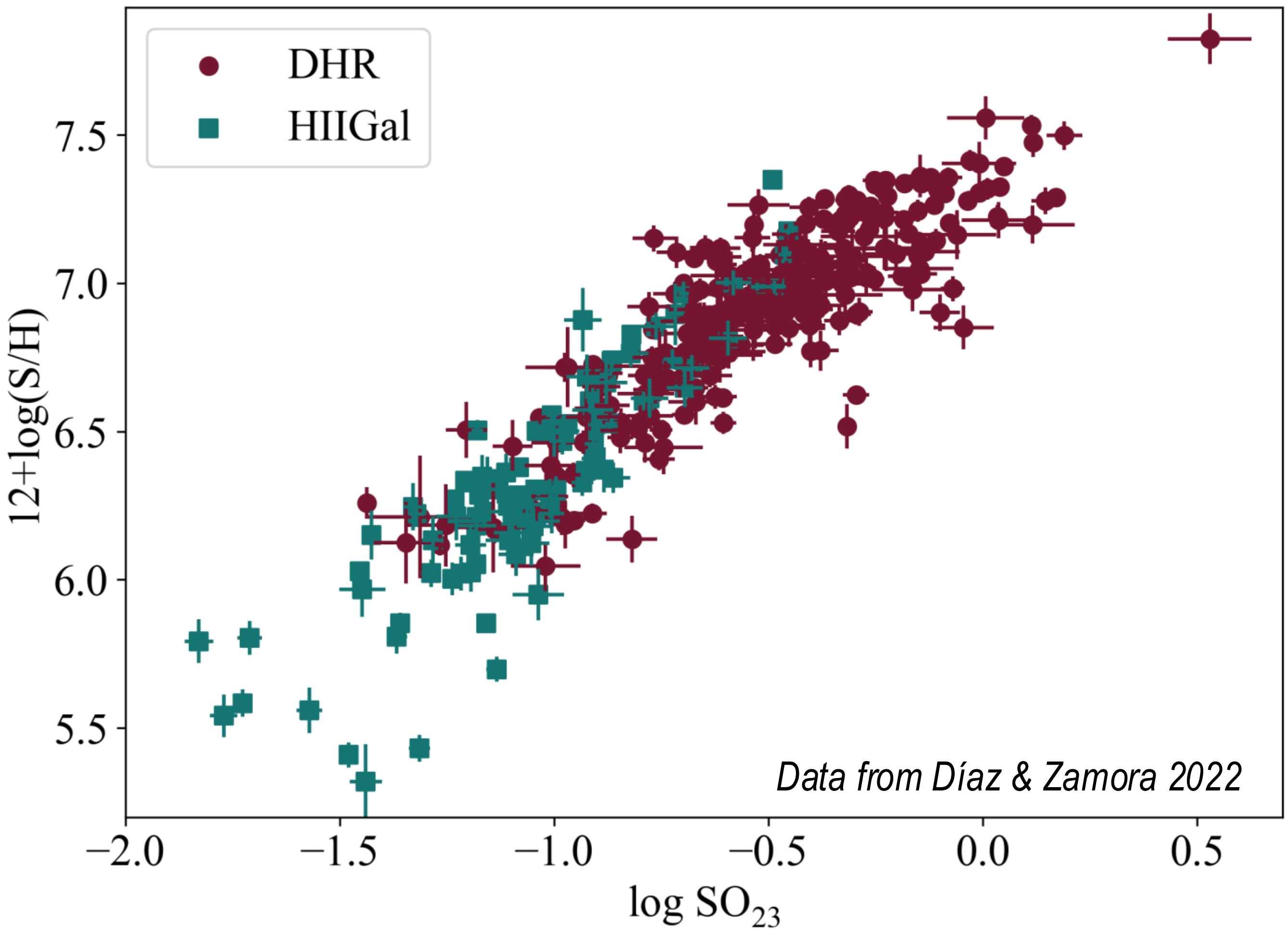
$$SO_{23} = \frac{S_{23}}{O_{23}}$$ where $O_{23} \equiv R_{23}$

SO_{23} gradient



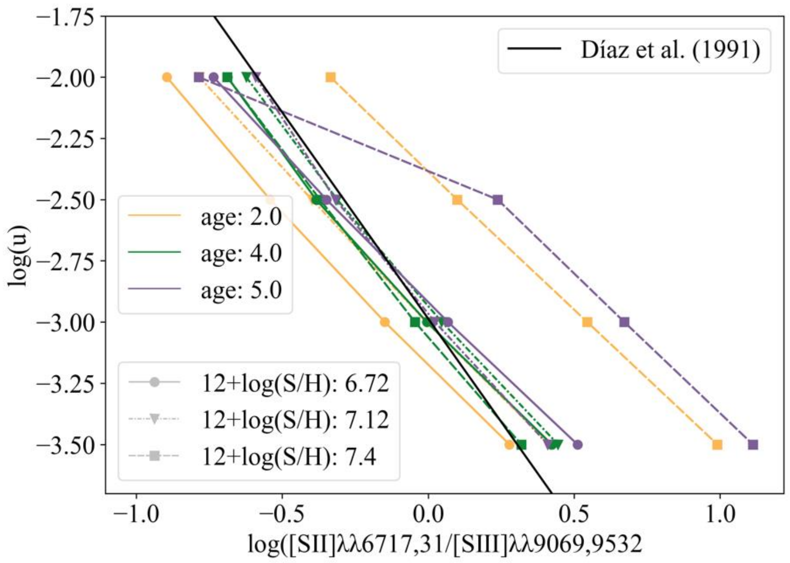
SO_{23} decreases as abundance decreases and then turns turn flat

SO_{23} calibration

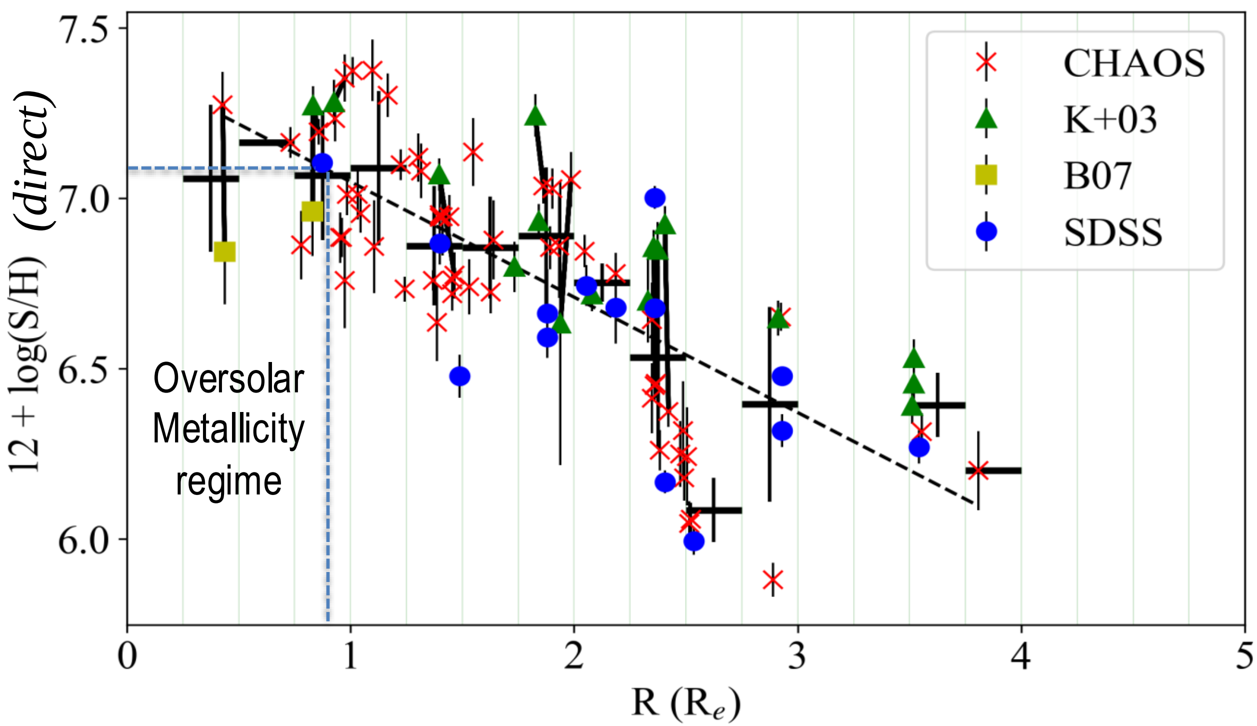


But still some caveats …

- Massive metal rich stars have lower effective temperatures than low metallicity ones which may increase the [OII]/[OIII] ratio.
- The relation between [SII]/[SIII] with ionisation parameter may also change at high sulphur abundance.



Photoionization models



to be continued ….