

UAM
Universidad Autónoma
de Madrid

DERIVING ABUNDANCE GRADIENTS ACROSS GALAXY DISCS



Ángeles I. Díaz

Theoretical Physics Department,

Universidad Autónoma de Madrid

With the collaboration of:

Sandra Zamora (UAM)

Joaquín Reyes (UAM)



Grant PID2022-136598NB-C33 funded by



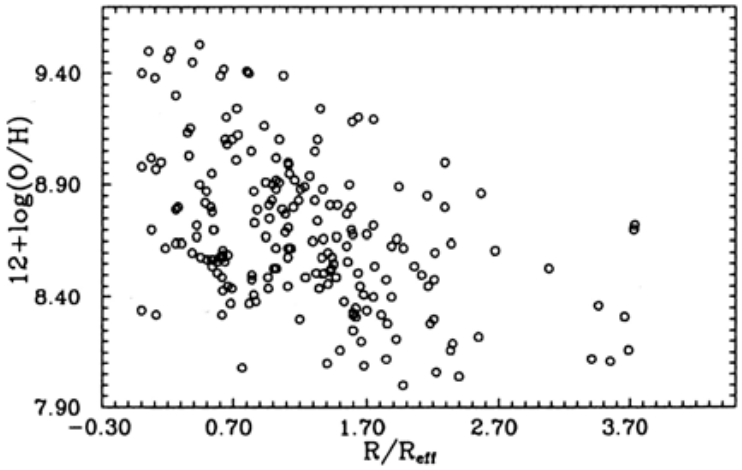


UAM
Universidad Autónoma
de Madrid

Introduction

- Elemental abundance gradients in galactic disks 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

A.I. Díaz
Dpto. de Física Te6rica, C-XI, Universidad Autónoma de Madrid, Cantoblanco, 28049-Madrid, Spain

Abundance gradient as a differencial effect

Astron. Astrophys. 197, 33–46 (1988)

ASTRONOMY AND ASTROPHYSICS

Models of galactic chemical evolution: the problem of uniqueness

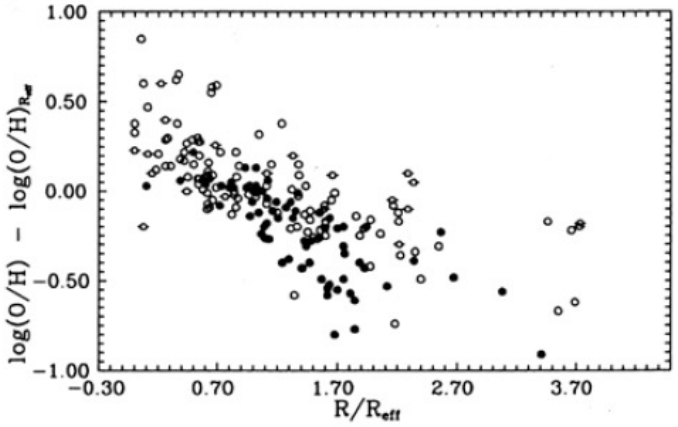
M. Tosi[1,2]

[1] Osservatorio Astronomico, C.P. 596, I-40100 Bologna, Italy
[2] Space Telescope Science Institute, Homewood Campus, Baltimore, USA

Received April 20, accepted December 1, 1987

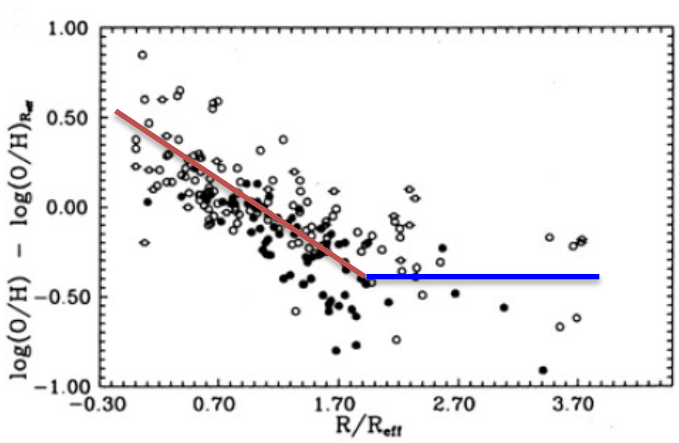
- Abundance ratios between elements depend mostly on stellar nucleosynthesis and the IMF.
- The slope of any abundance gradient is not sensitive at all to the adopted nucleosynthesis.
- The predicted absolute abundance of any element depend on all adopted parameters hence it does not represent by itself 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



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

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

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

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

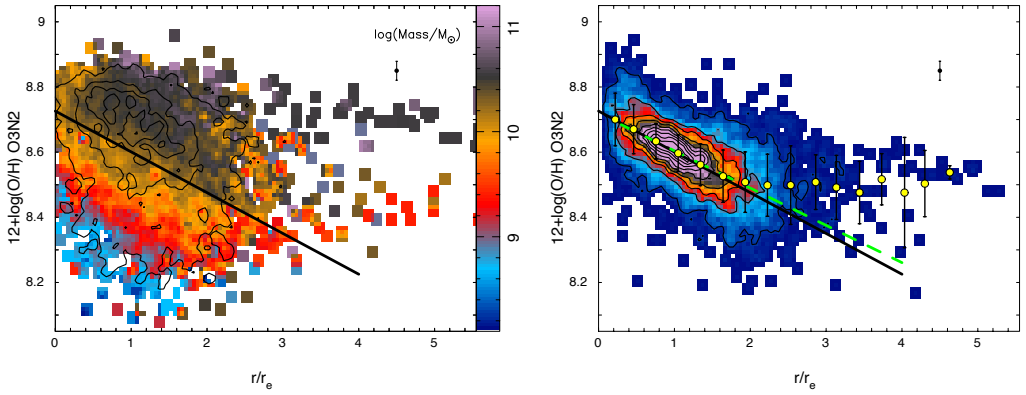
A&A 563, A49 (2014)
DOI: 10.1051/0004-6361/201322343
© ESO 2014

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

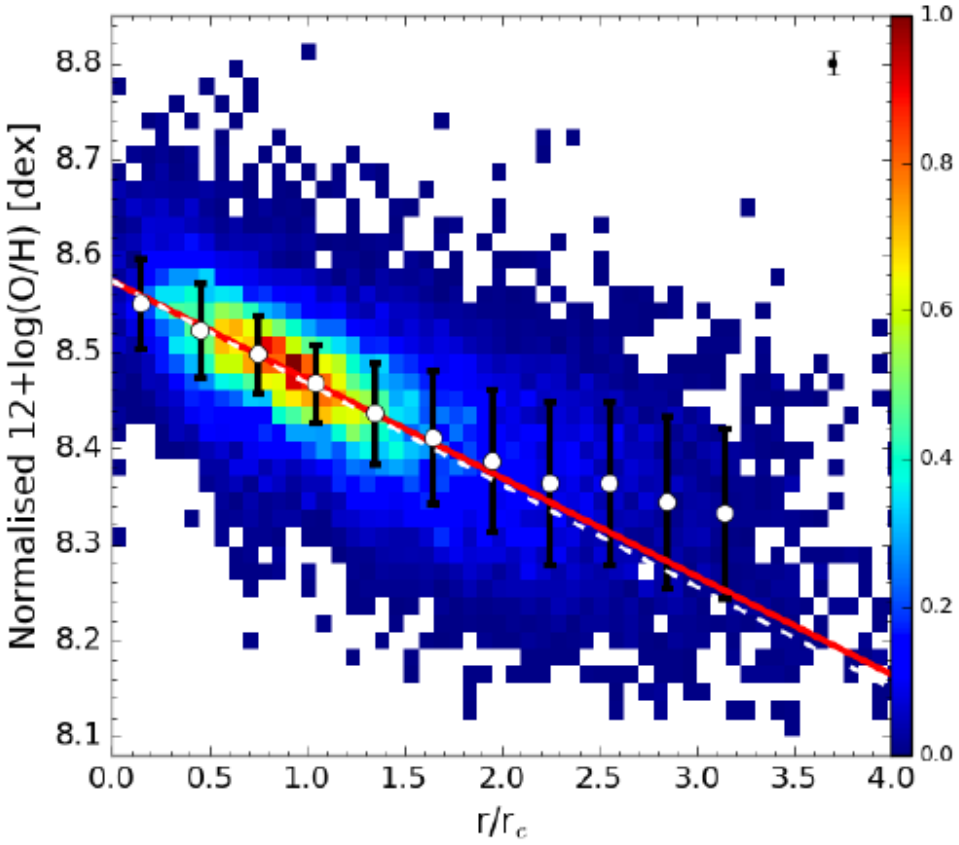
We found that all galaxies without clear evidence of an interaction present a common gradient in the oxygen abundance, with a characteristic slope of $\alpha(O/H) = -0.1$ dex/R_e between 0.3 and 2 disk effective radii (R_e), and a scatter compatible with random fluctuations around this value, when the 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



UAM
Universidad Autónoma
de Madrid

Model predictions MULCHEM

- 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.



UAM
Universidad Autónoma
de Madrid

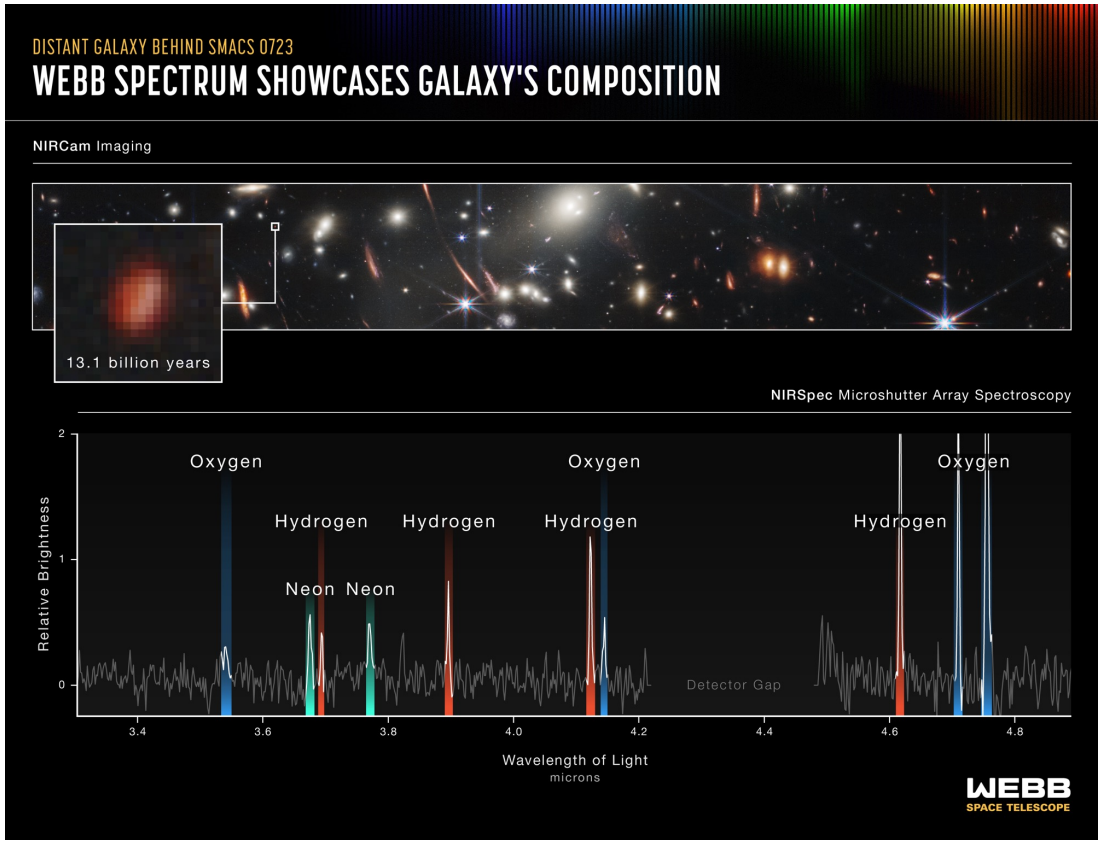
Deriving present day abundance gradients from HII region observations

- **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 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.



UAM
Universidad Autónoma
de Madrid

Coming soon …





UAM
Universidad Autónoma
de Madrid

A case of study: M101

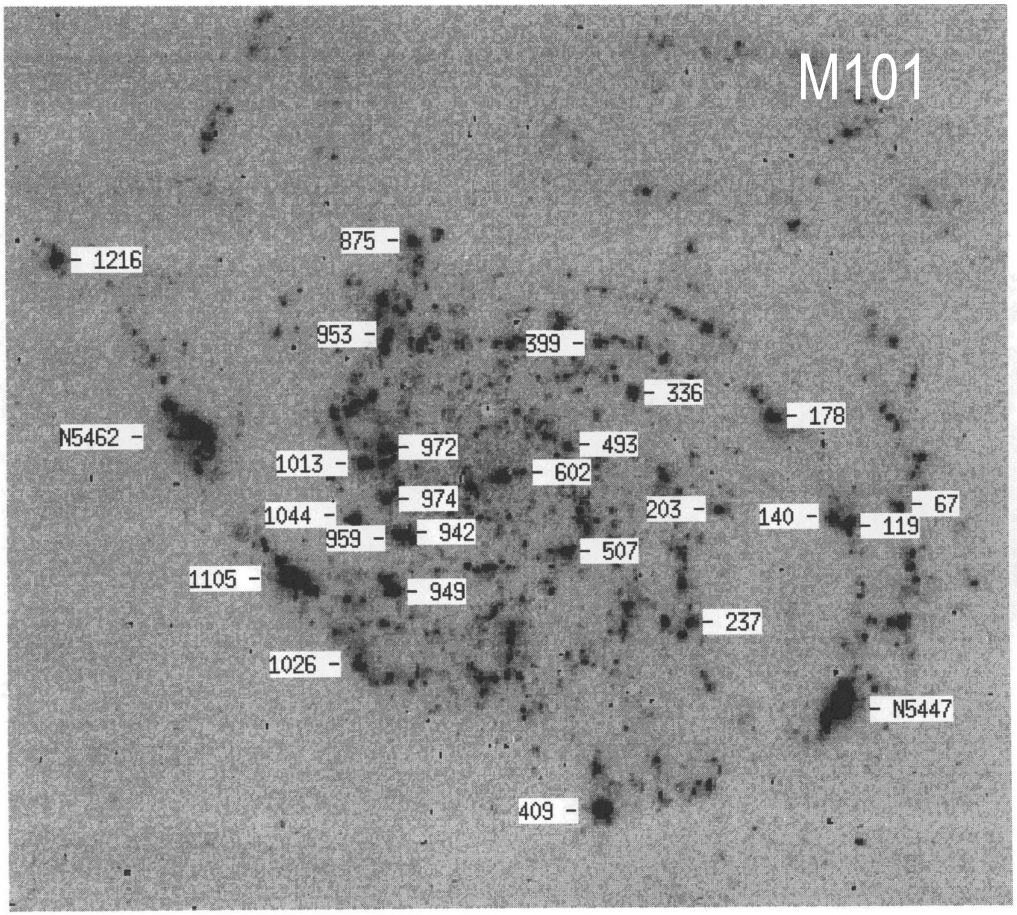






UAM
Universidad Autónoma
de Madrid

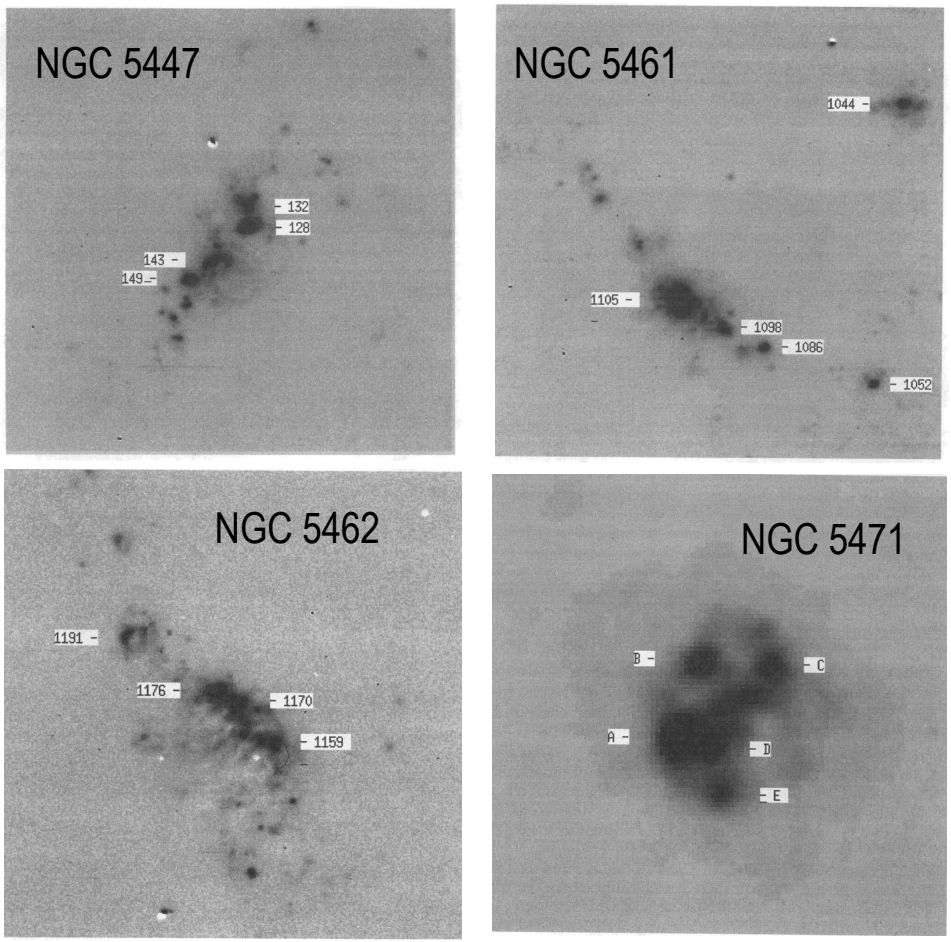
How abundance gradients are derived





UAM
Universidad Autónoma
de Madrid

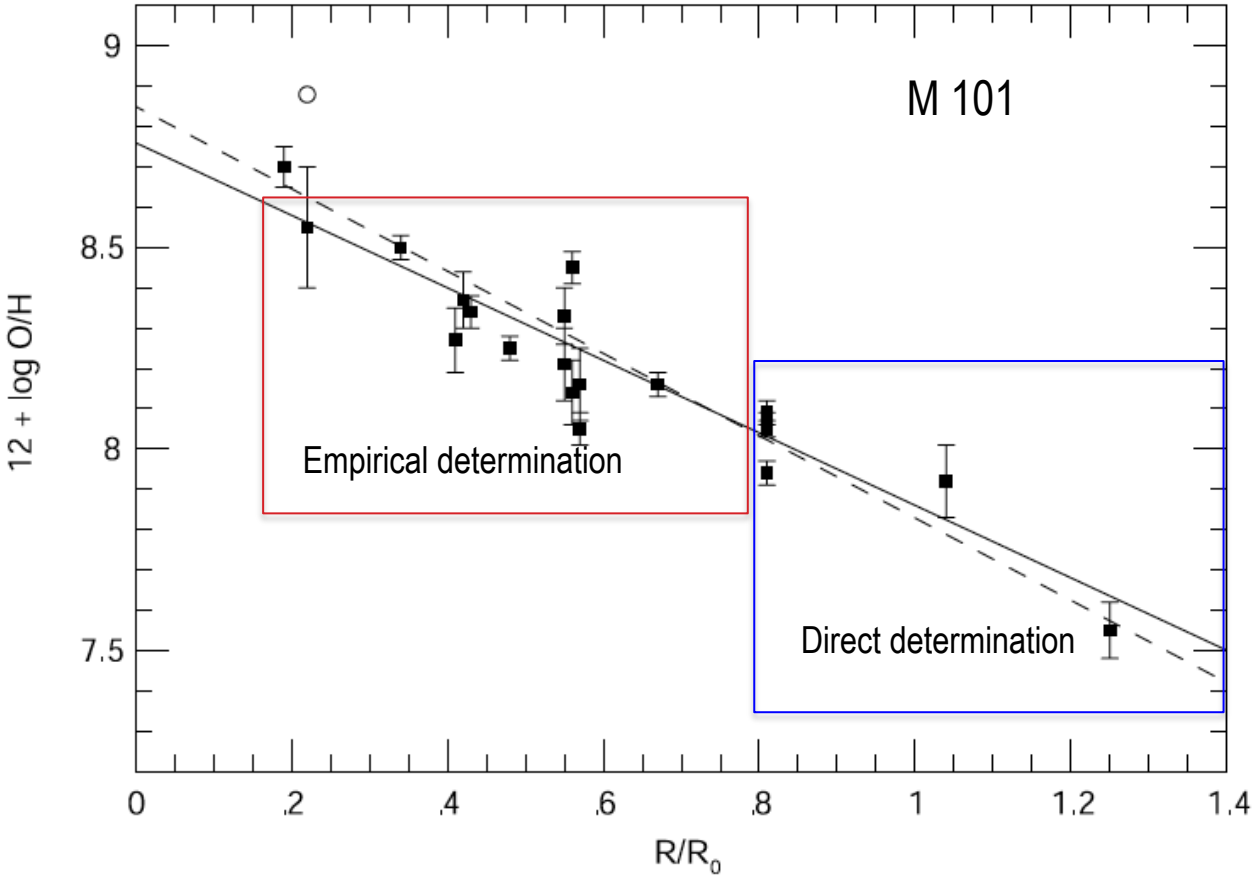
Resolved HII regions in M101



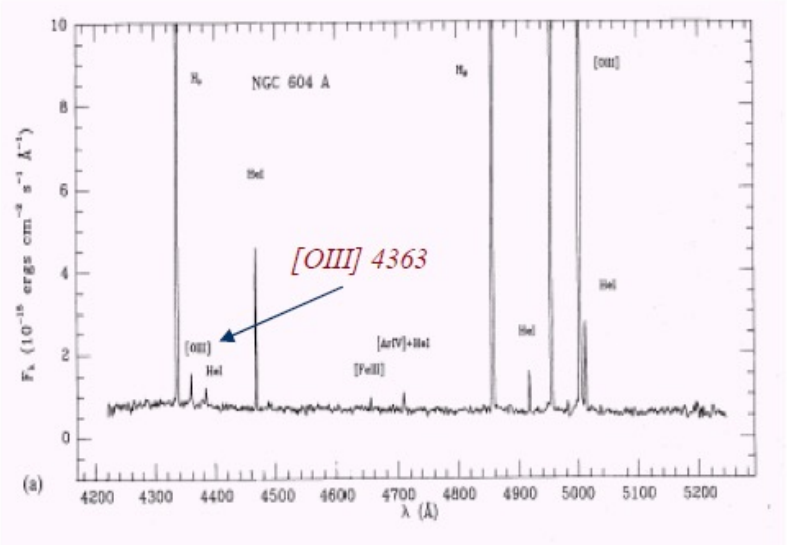


UAM
Universidad Autónoma
de Madrid

How gas oxygen abundance gradients are derived



The weakness of *auroral* lines



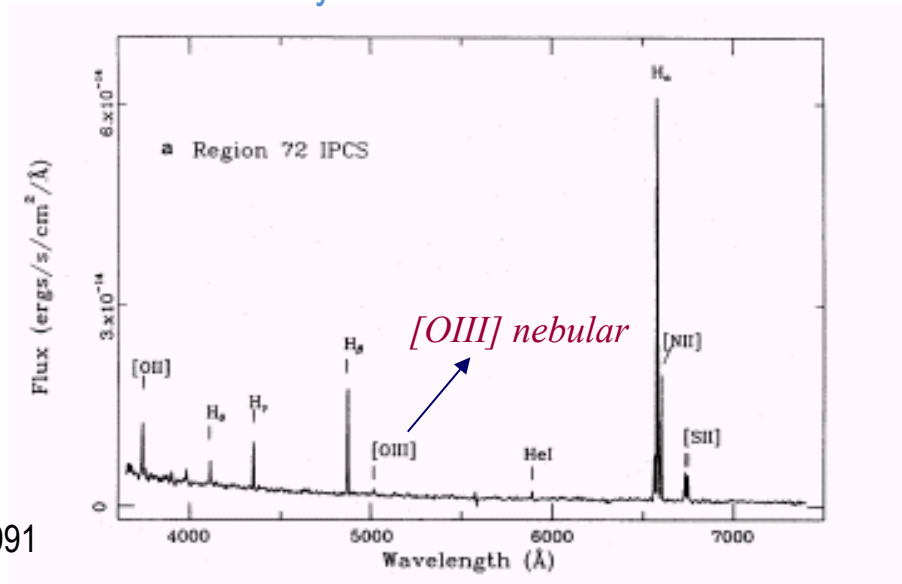
Díaz et al.1987

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

Low metallicity case

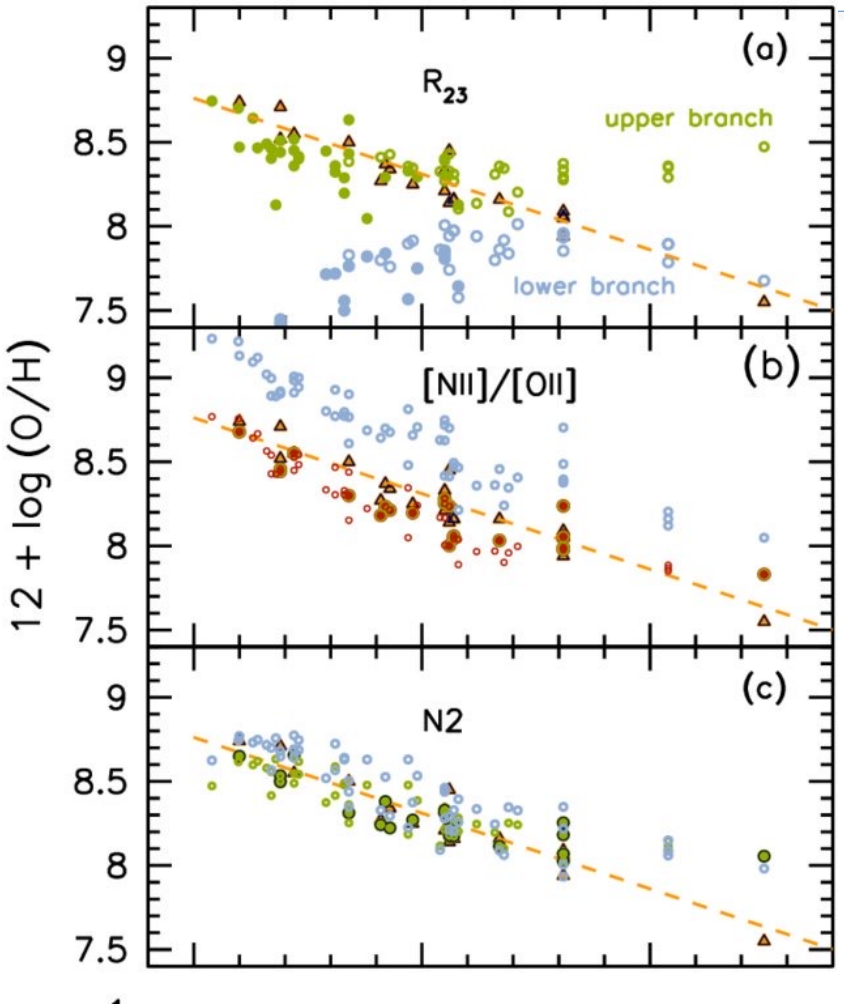
High metallicity case

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



Díaz et al.1991

The M101 empirical O/H gradient



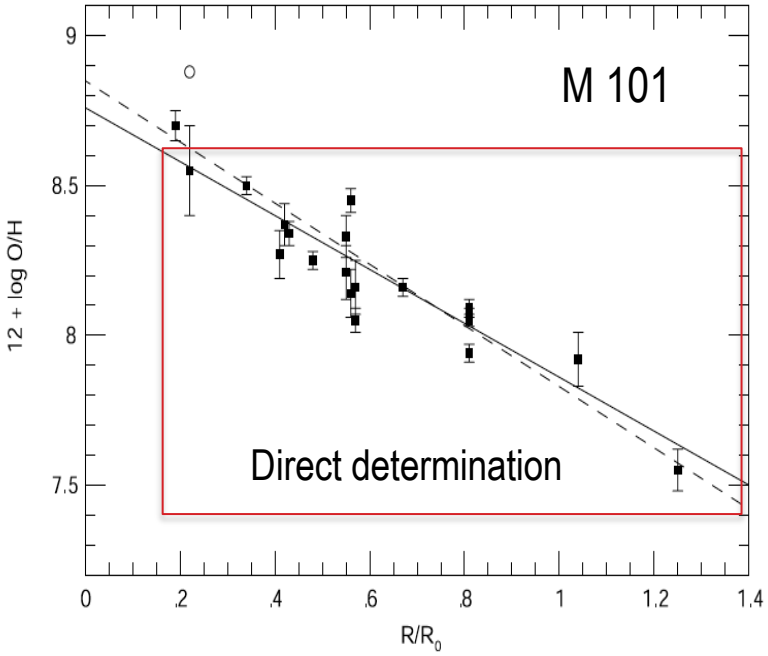
Bresolin et al. 2009, ApJ, 695, 580



UAM
Universidad Autónoma
de Madrid

Putting it all together

MOVING TO THE RED
Using Sulphur as abundance tracer



Why using sulphur?
It's all about

$$h\nu \approx kT$$



UAM
Universidad Autónoma de Madrid

Why not using Sulphur?

- 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.



UAM
Universidad Autónoma de Madrid

Why not using Sulphur?

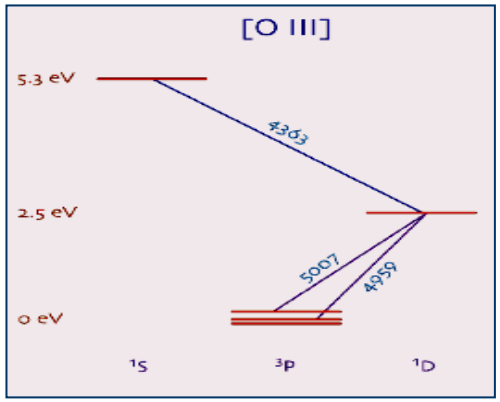
- As in the case of oxygen, sulphur is also produced in massive stars.
- Its yield is supposed to follow that of Oxygen $\Rightarrow$

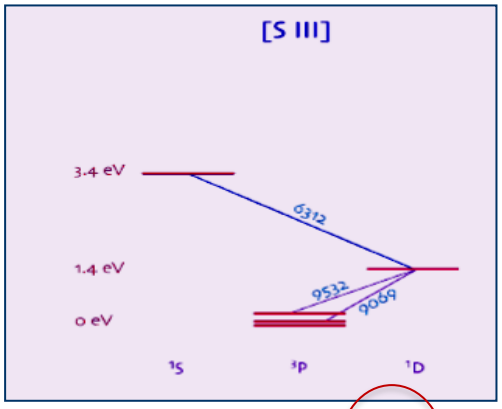
  S/O ratio seems to remain constant at

  $\log(S/O)_{\odot} \cong -1.56$.
- 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 λλ 6312, 9069, 9532 Å are analogous to those of [OIII] at λλ 4363, 4959, 5007 Å, but their emissivities are less dependent on T_e .





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

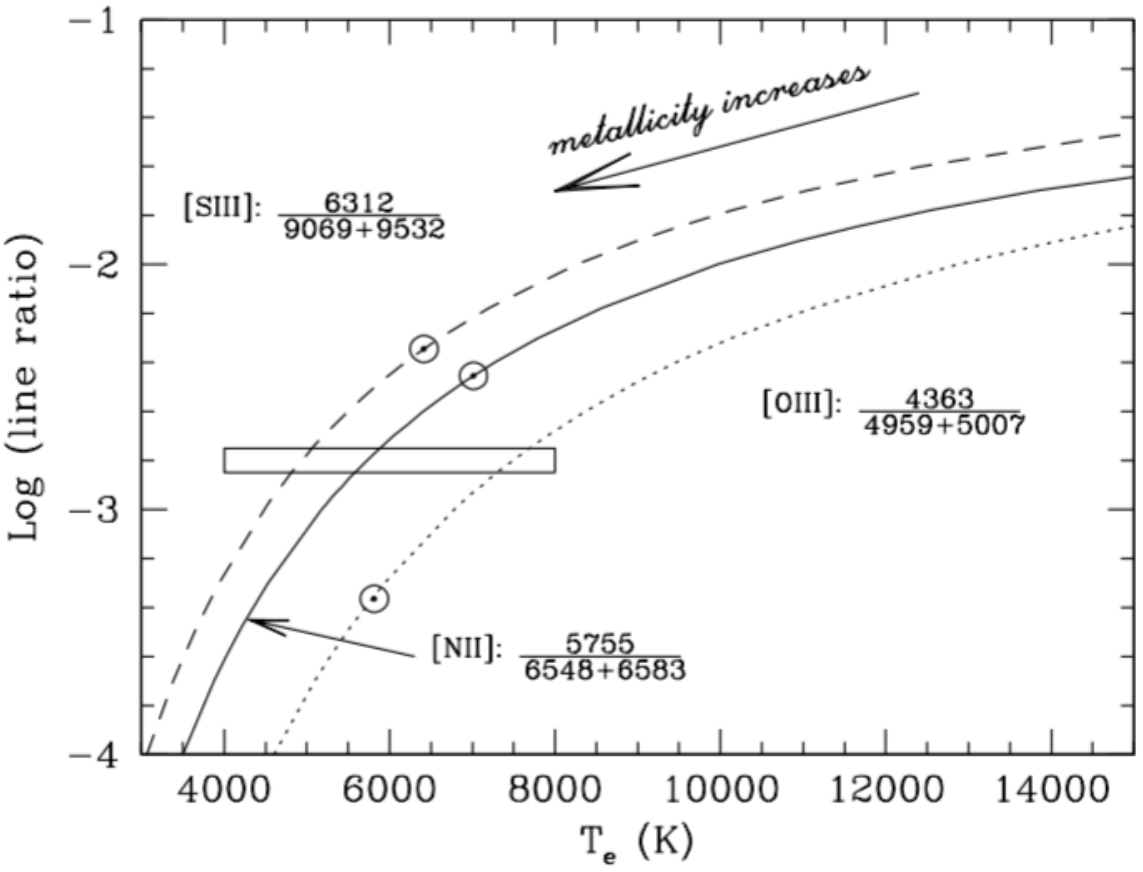
and $\chi(S^{2+}) < \chi(O^{2+})$



UAM
Universidad Autónoma
de Madrid

Telescope limits

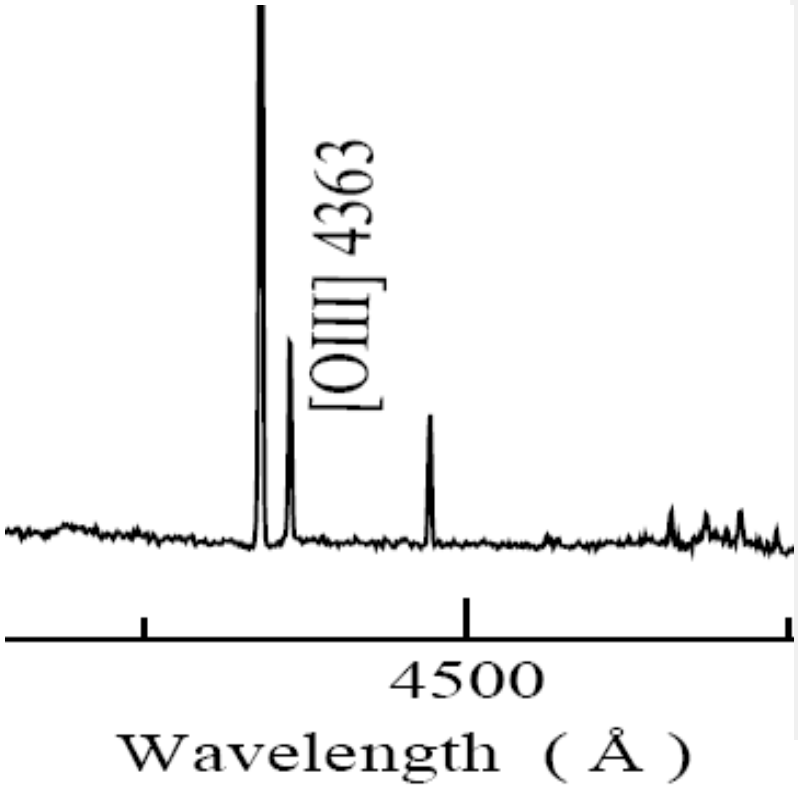
Bresolin (2008) in "The metal rich universe"

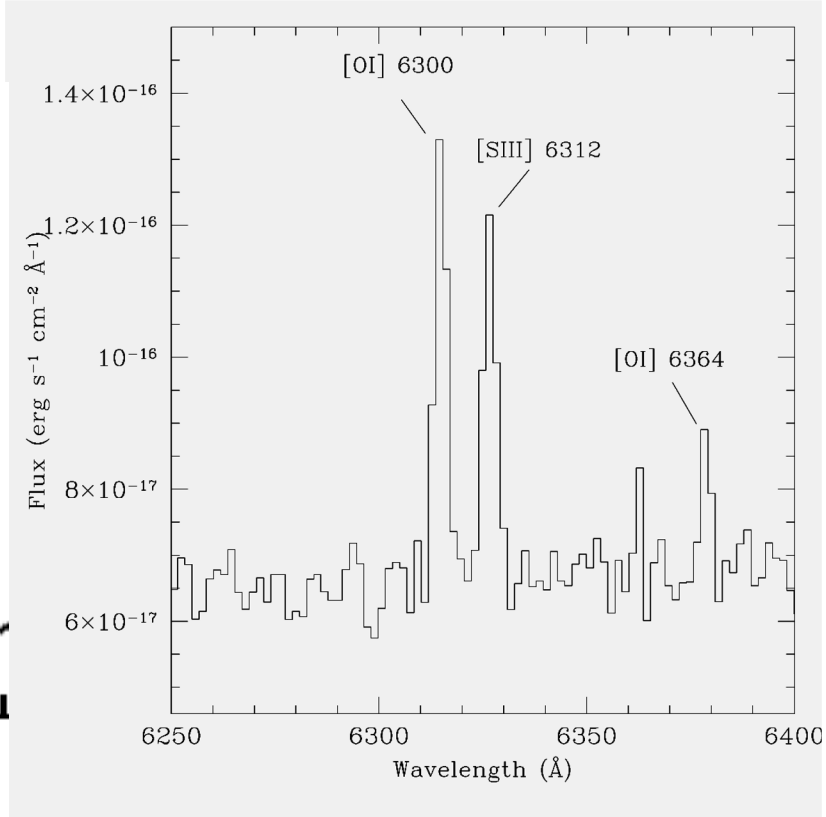




UAM
Universidad Autónoma
de Madrid

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.**

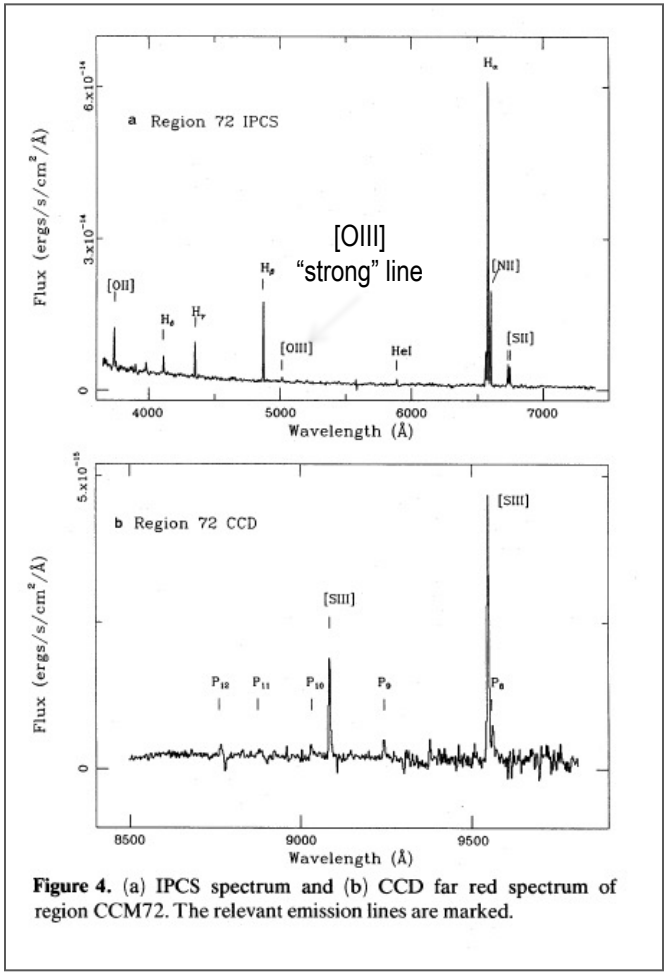
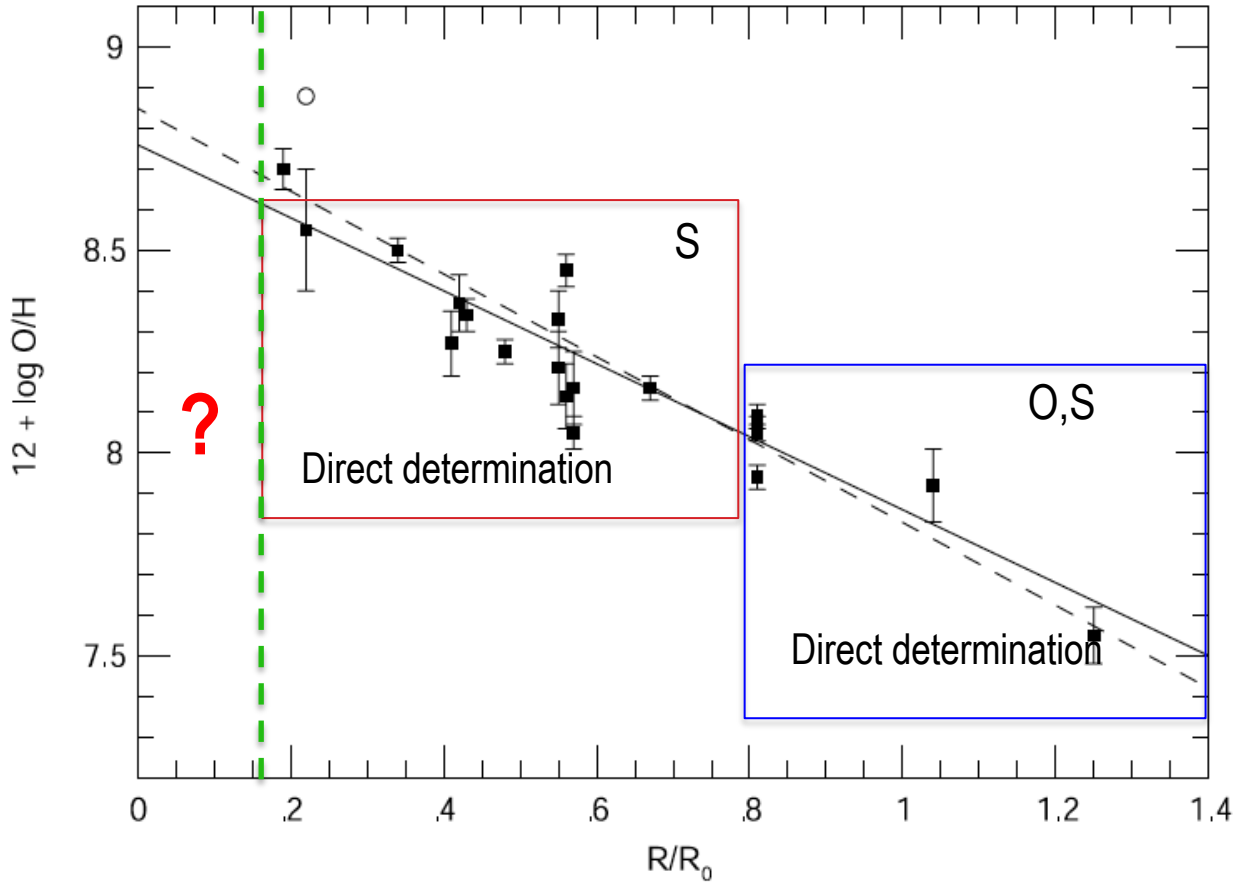


Figure 4. (a) IPCS spectrum and (b) CCD far red spectrum of region CCM72. The relevant emission lines are marked.



UAM
Universidad Autónoma
de Madrid

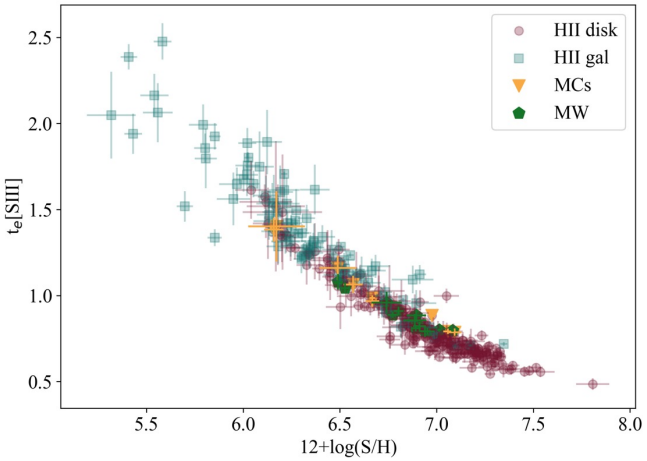
The high metallicity regime



Total S abundance and electron temperature

- The effect of sulphur as a cooling agent is evident by the good correlation shown between S/H and O/H and their respective T_e and this relation is the base of the empirical calibrations.

Díaz & Zamora, 2022, MNRAS

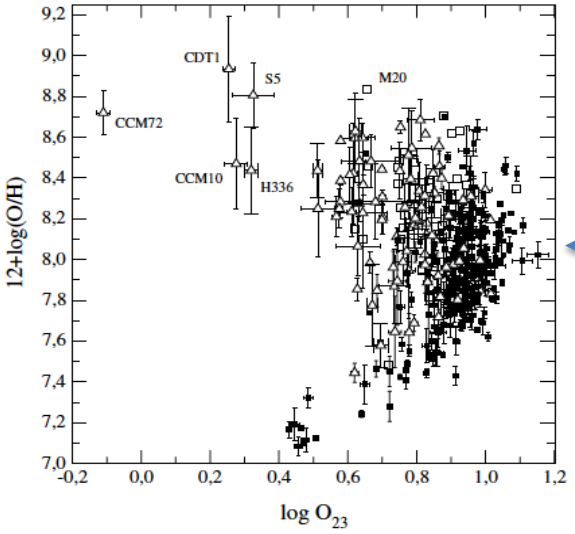


Pagel et al. 1979

Sulphur Empirical calibration: S_{23}

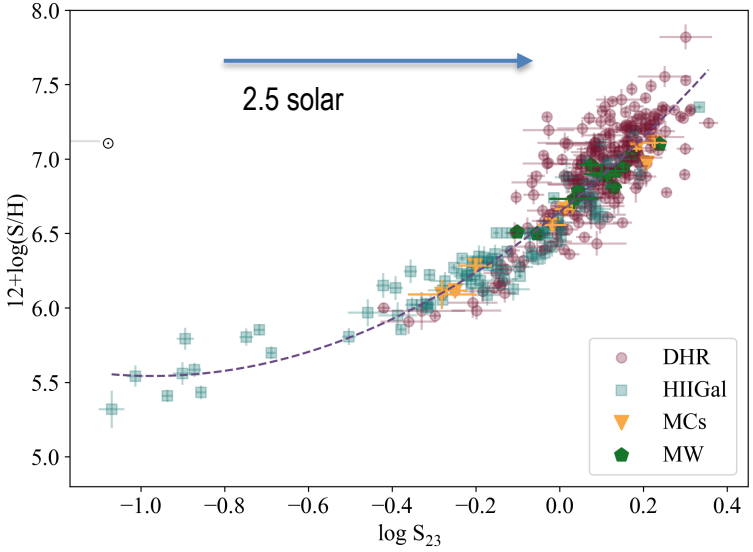
- Similar to R_{23} but for Sulphur.

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



¼ solar

Díaz & Zamora, 2022, MNRAS



Single valued up to solar metallicity



But … is this enough?

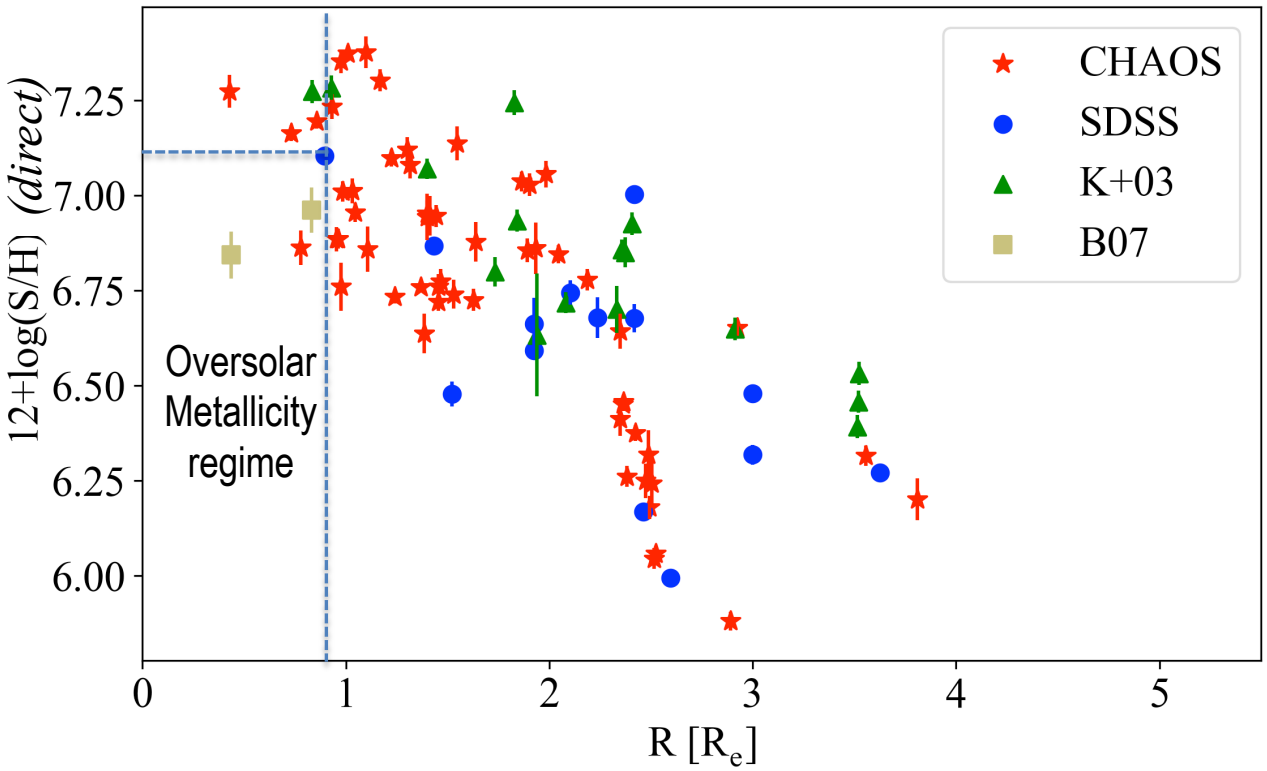


UAM
Universidad Autónoma
de Madrid

Deriving the sulphur gradient for M101

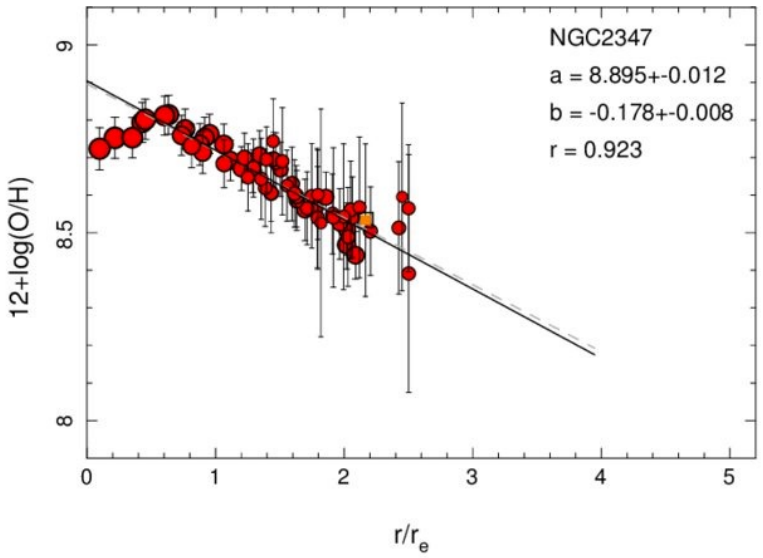
- Compiling data including emission lines of [OII] (3737,29), [OIII] (4363), [OIII] (4959,5007), [NII] (6548,84), [SIII] (6312), [SII] (6717,31), and[SIII] (9069).
- Sources:
  - Kennicutt, Bresolin & Garnett, 2003
  - Bresolin, 2007
  - Croxall et al. 2016 (CHAOS)
  - Piliyugin et al. 2007 (SDSS)

Direct abundance gradient (traced by S)



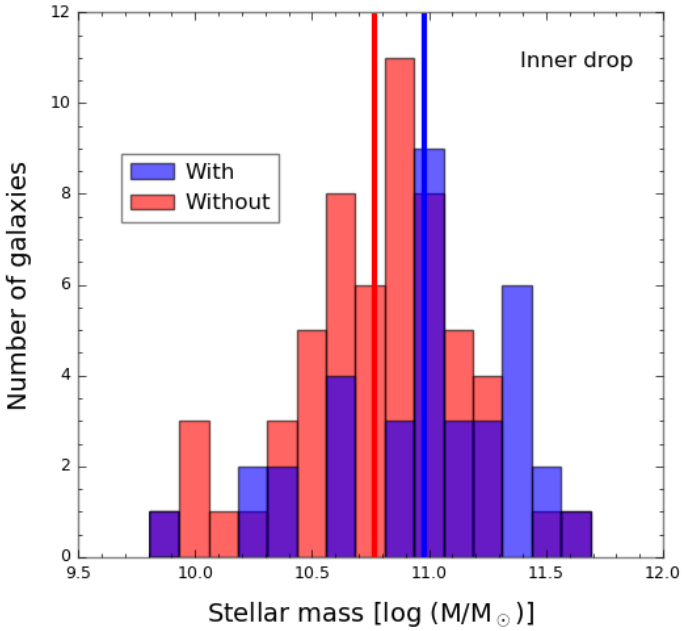
Central abundance drops

Sanchez-Mengiano et al 2018



Inner disc abundance drop

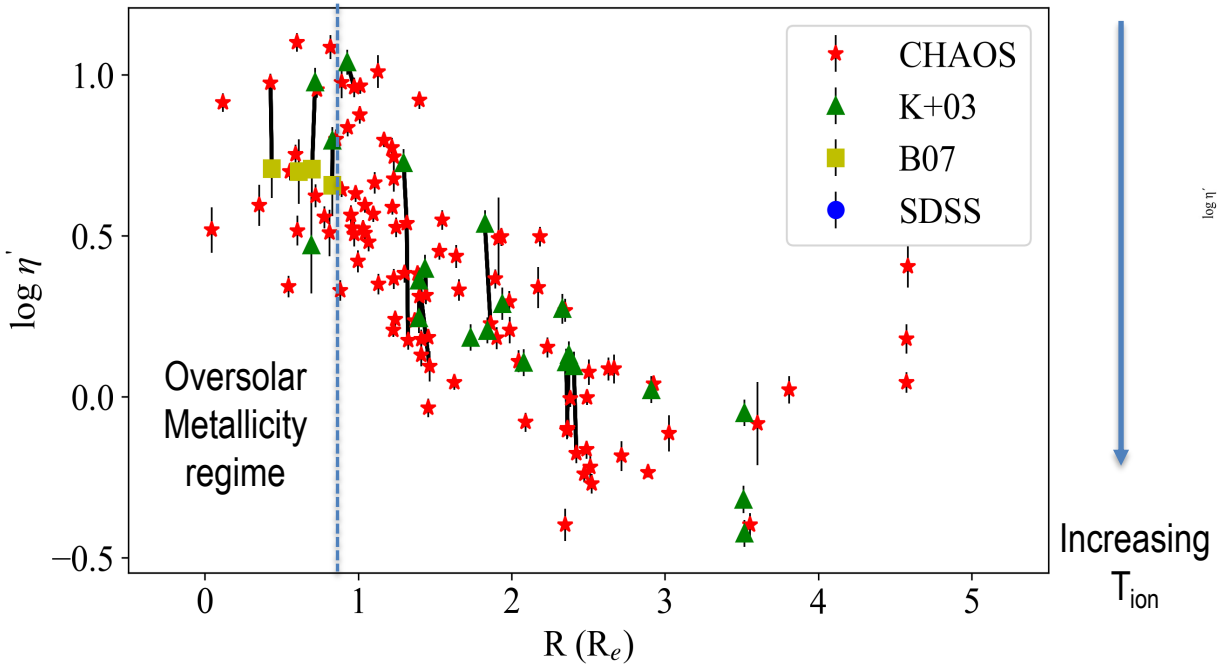
Central abundance drops



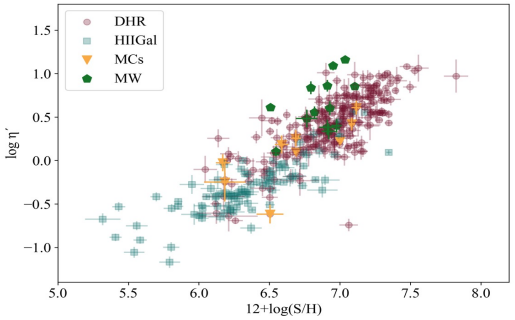
Central drops preferentially found in the most massive galaxies

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.

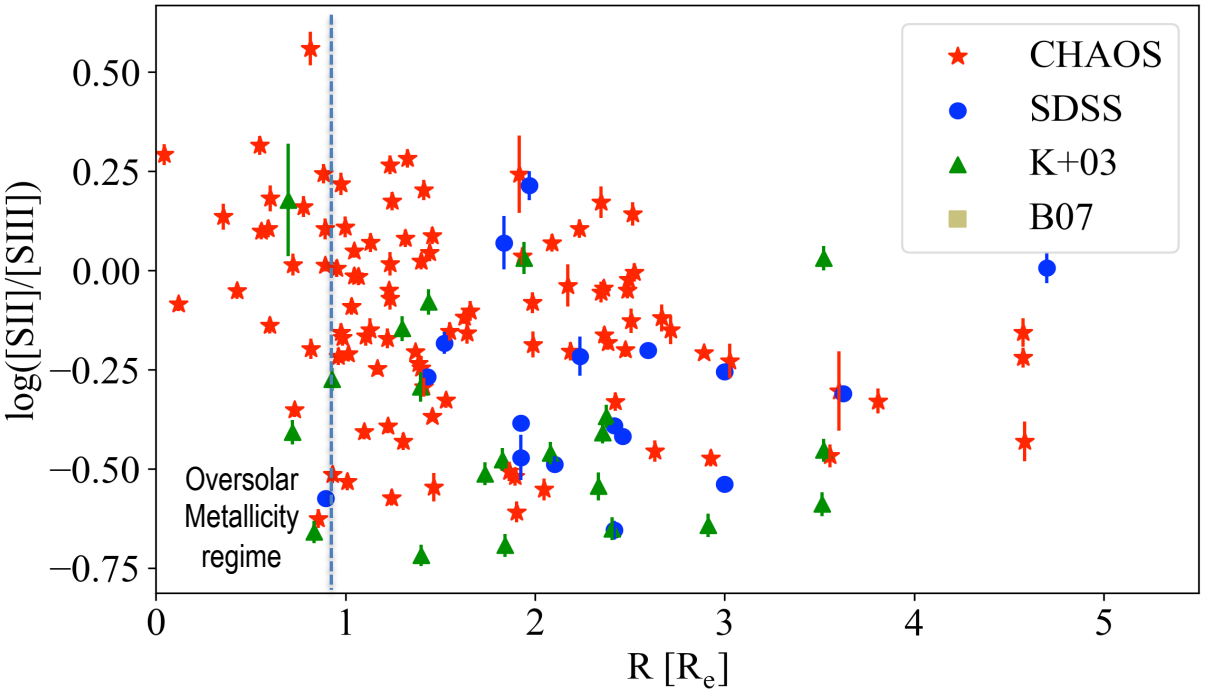


Díaz & Zamora, 2022

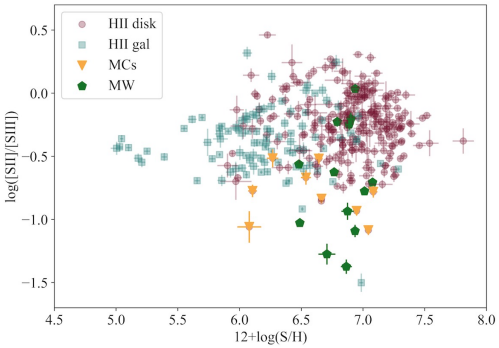


Functional parameter's gradients: the [SII]/[SIII] ratio

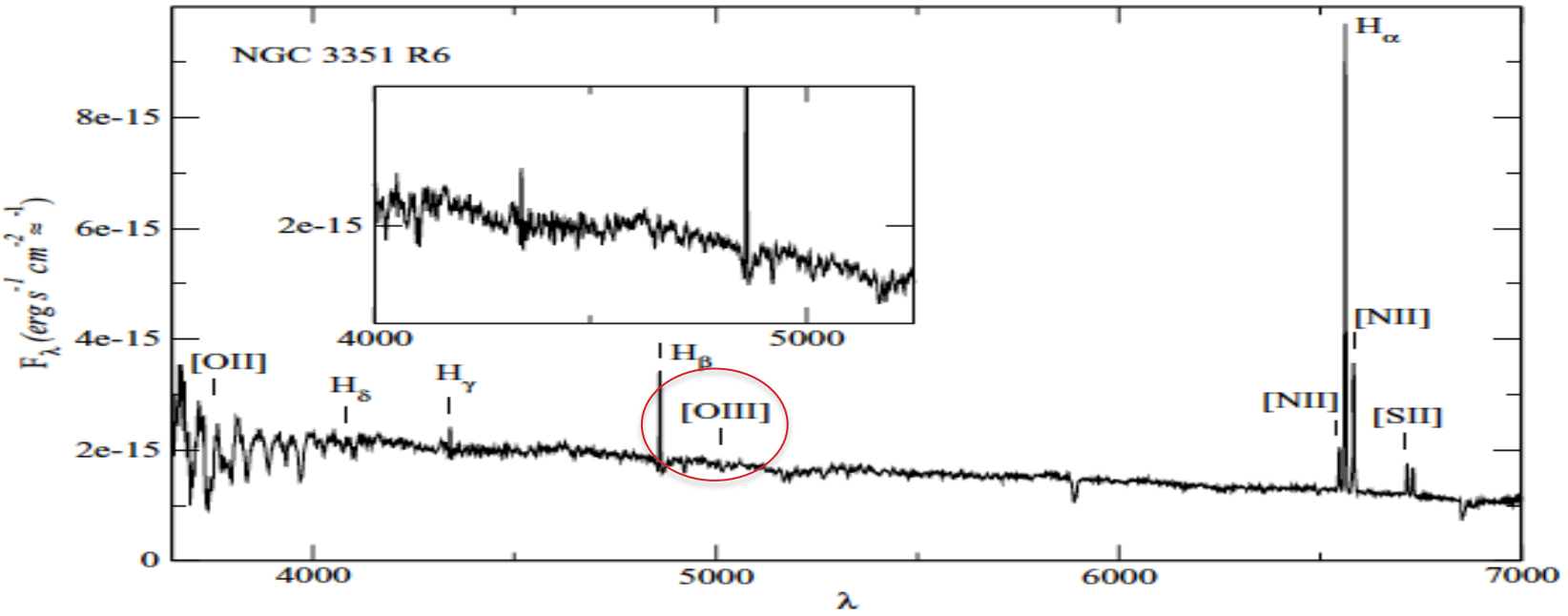
Calibrated in Díaz et al. 1991, can be considered as a proxy for the ionisation parameter, u, for up to solar metallicity.



Díaz & Zamora, 2022



Díaz, A.I. et al. 2007

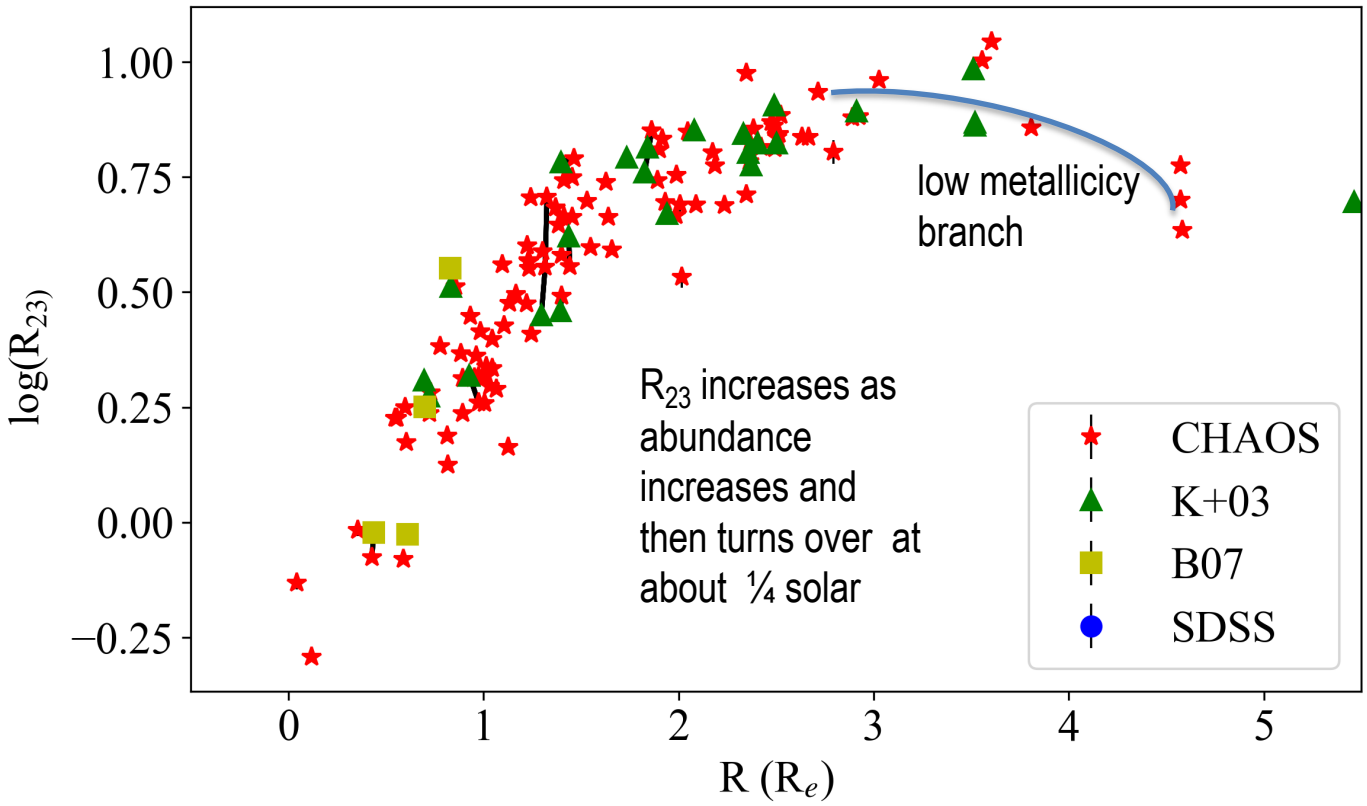


Caution!

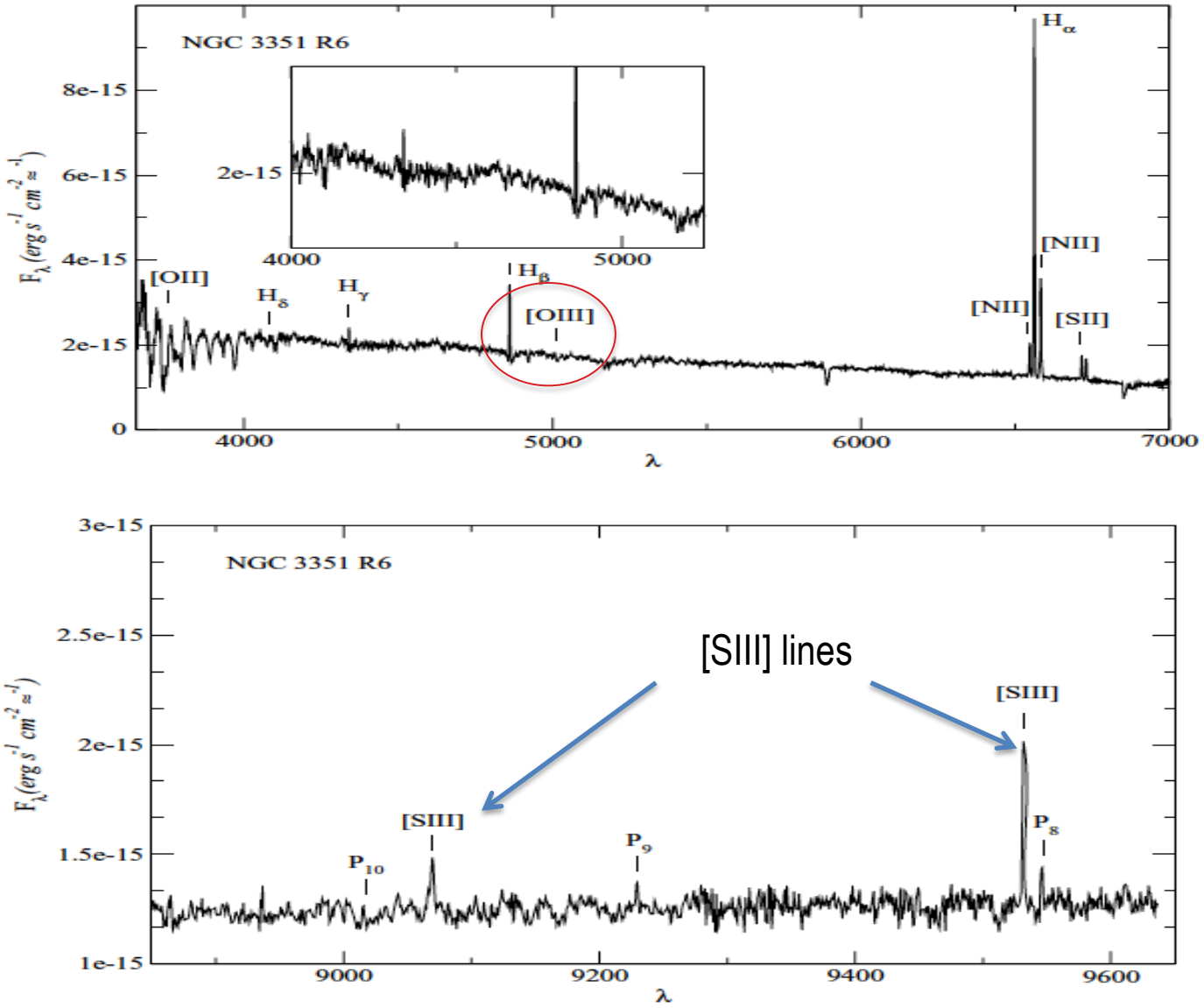
Territorio ignoto

Unknown Territory

R_{23} gradient



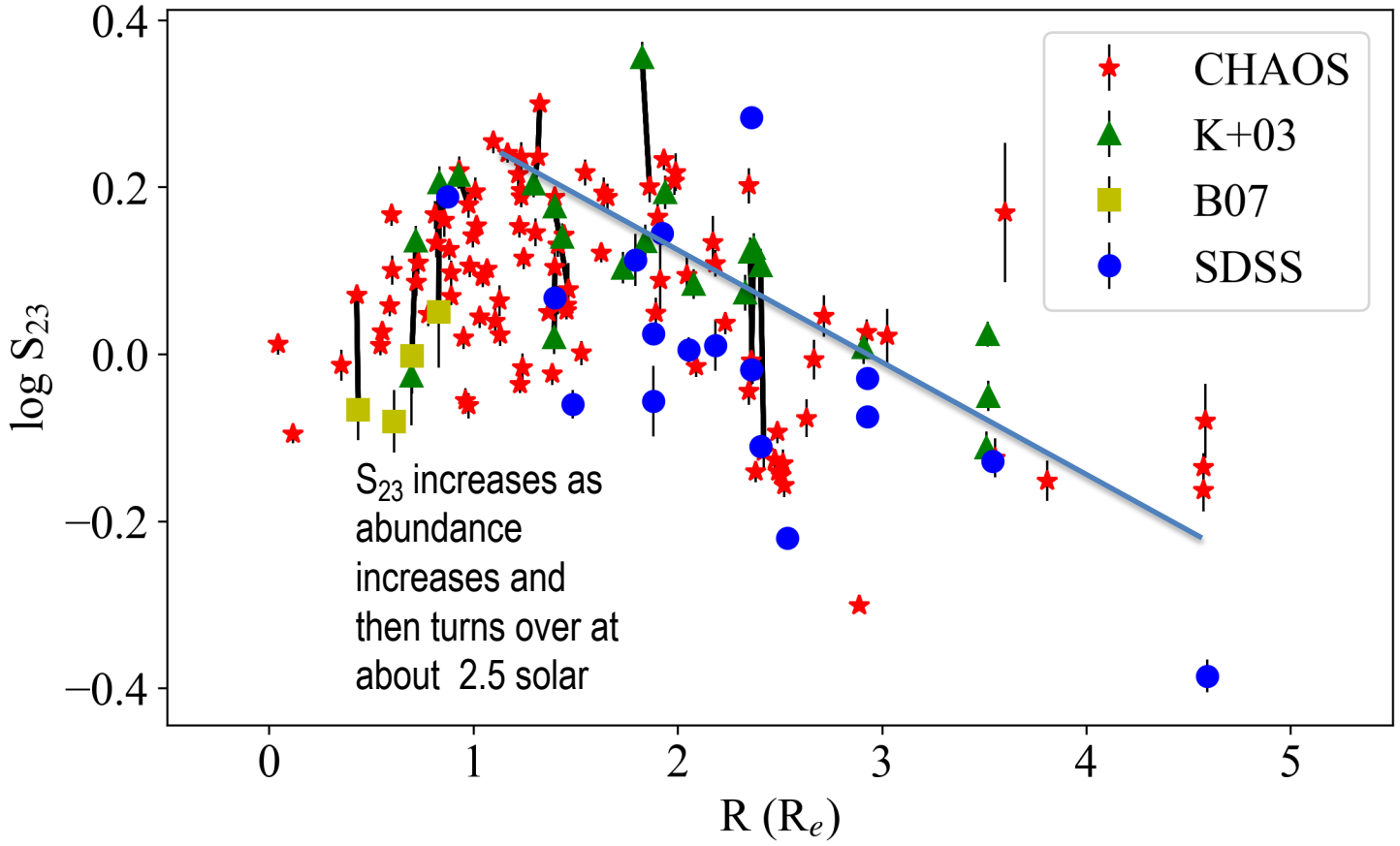
Díaz, A.I. et al. 2007



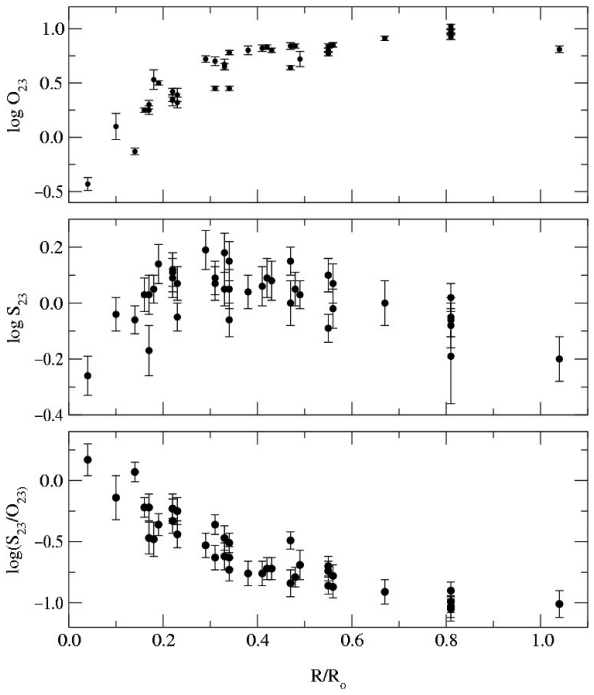


UAM
Universidad Autónoma
de Madrid

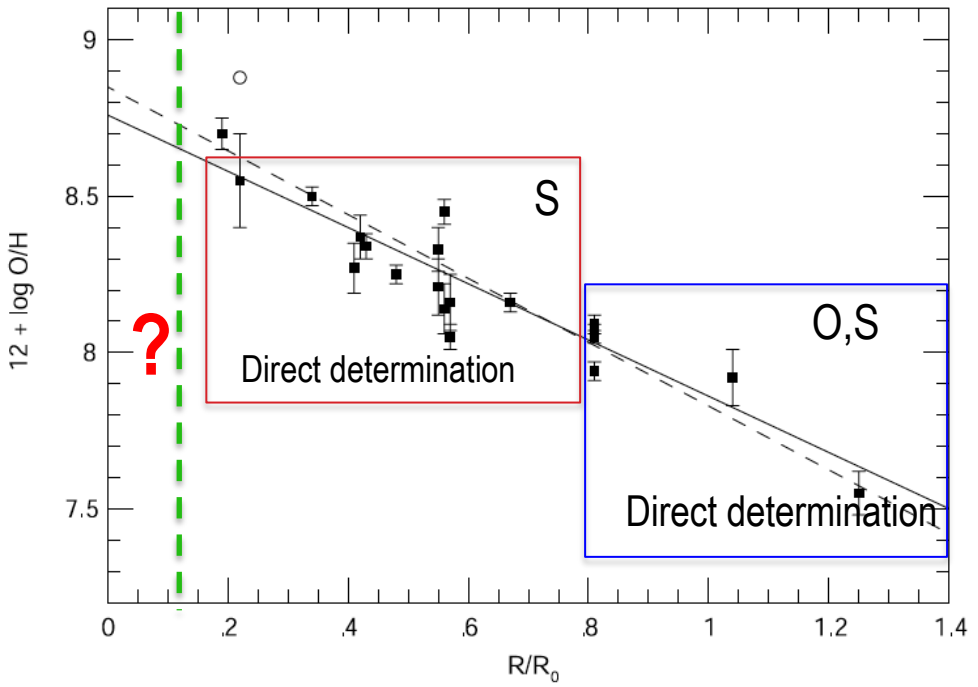
S_{23} gradient



The high metallicity regime



Pérez-Montero & Díaz 2005



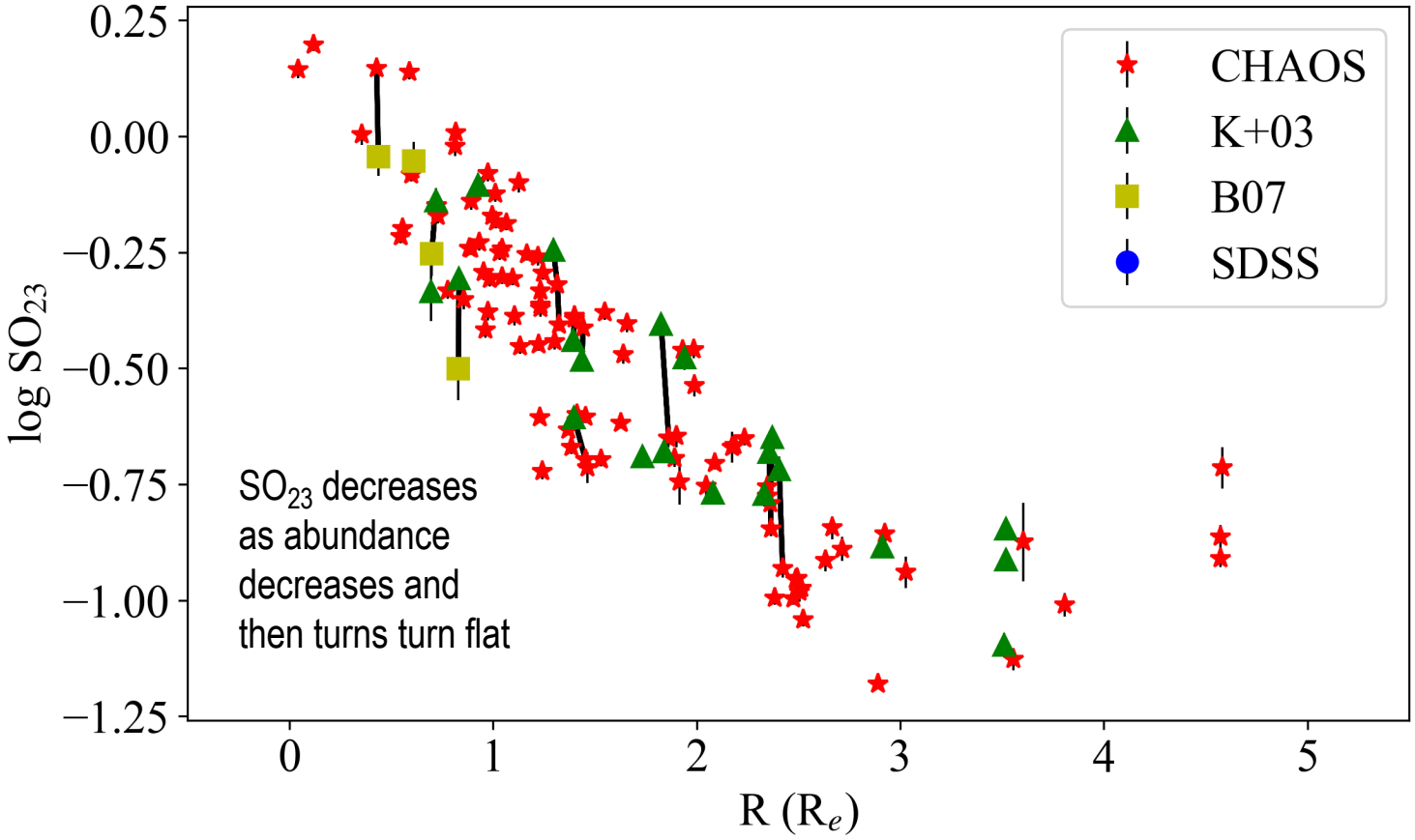
$$SO_{23} = \frac{S_{23}}{O_{23}}$$

where $O_{23} \equiv R_{23}$



UAM
Universidad Autónoma
de Madrid

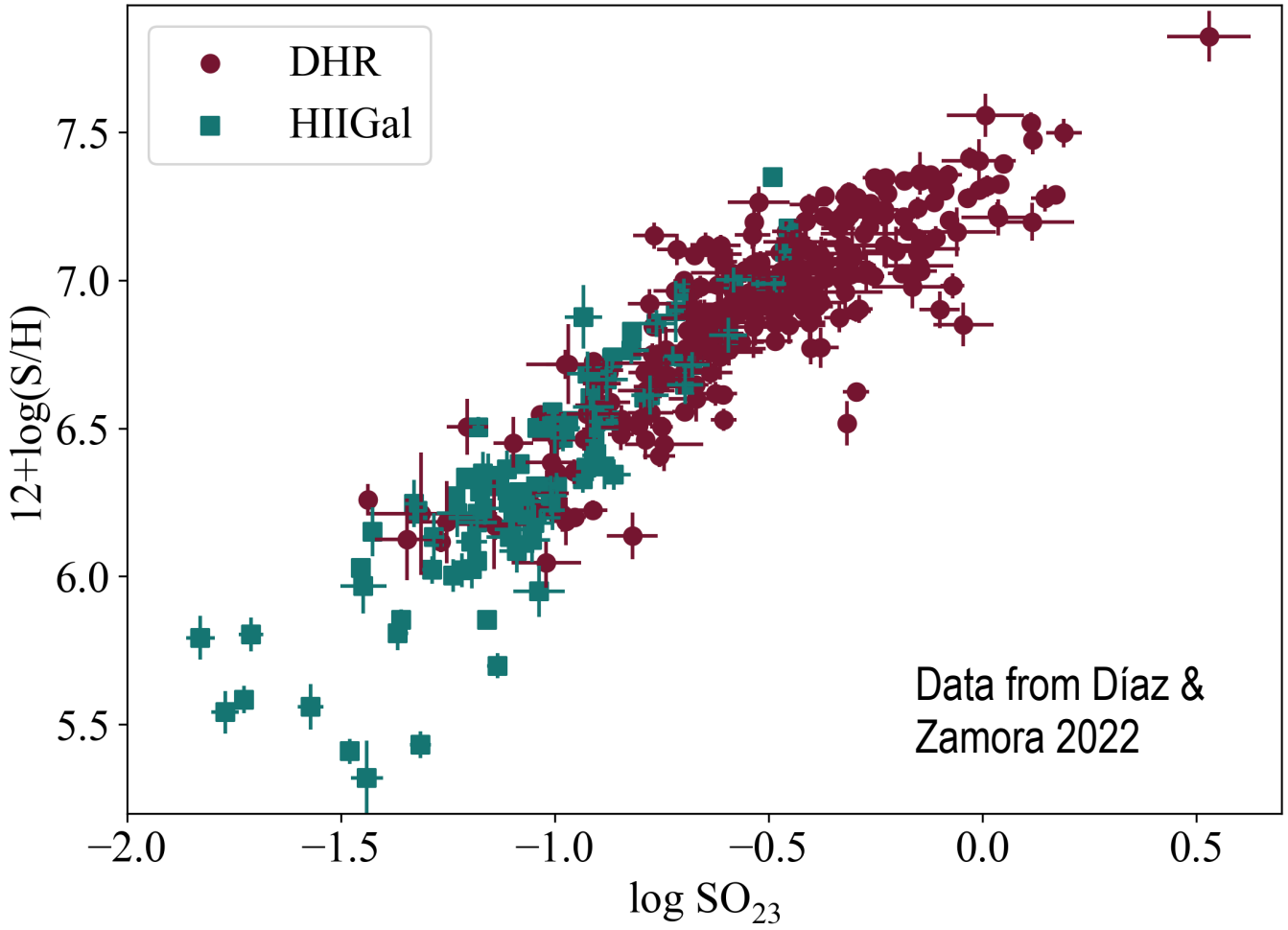
SO_{23} gradient





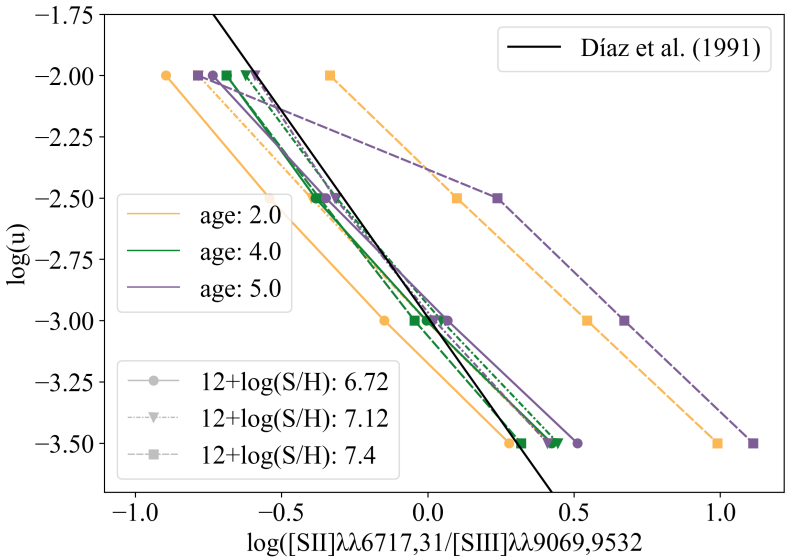
UAM
Universidad Autónoma
de Madrid

SO_{23} calibration



But still some caveats …

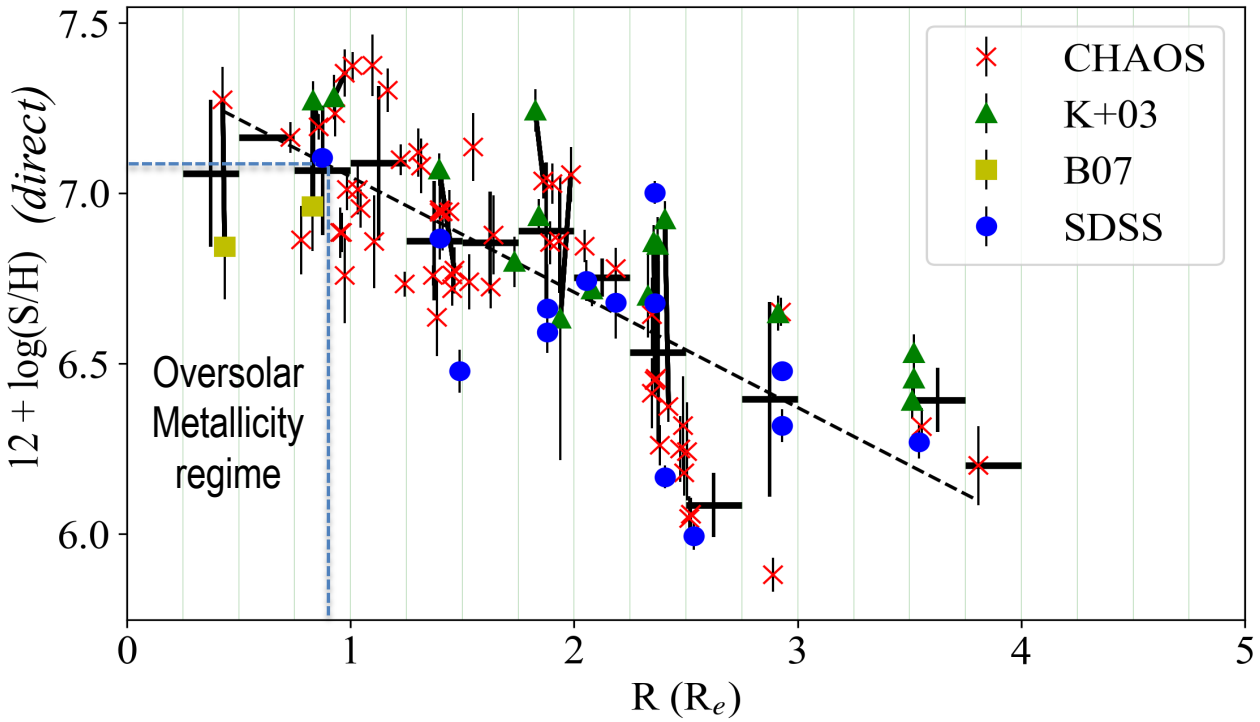
- Massive metal rich stars have lower effective temperatures than low metallicity ones which may increase the [OII]/[OIII] ratio.
- The relation between [SII]/[SIII] with ionisation parameter may also change at high sulphur abundance.





UAM
Universidad Autónoma
de Madrid

Photoionization models



to be continued ….



UAM
Universidad Autónoma
de Madrid

Thank you !
¡Gracias!



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"

