ABUNDANCE DETERMINATIONS IN GASEOUS NEBULAE

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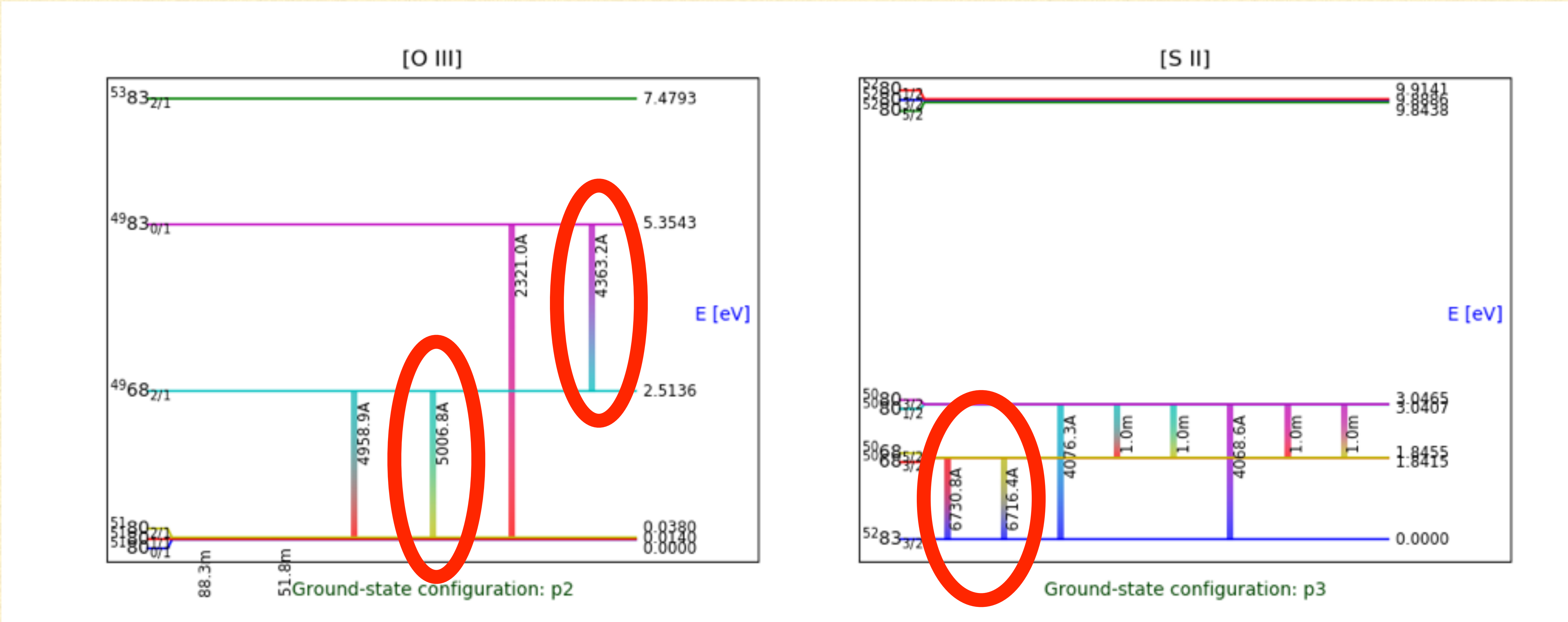
(with a little help from my friends Natalia Vale-Asari and Grazyna Stasinska)

SUMMARY

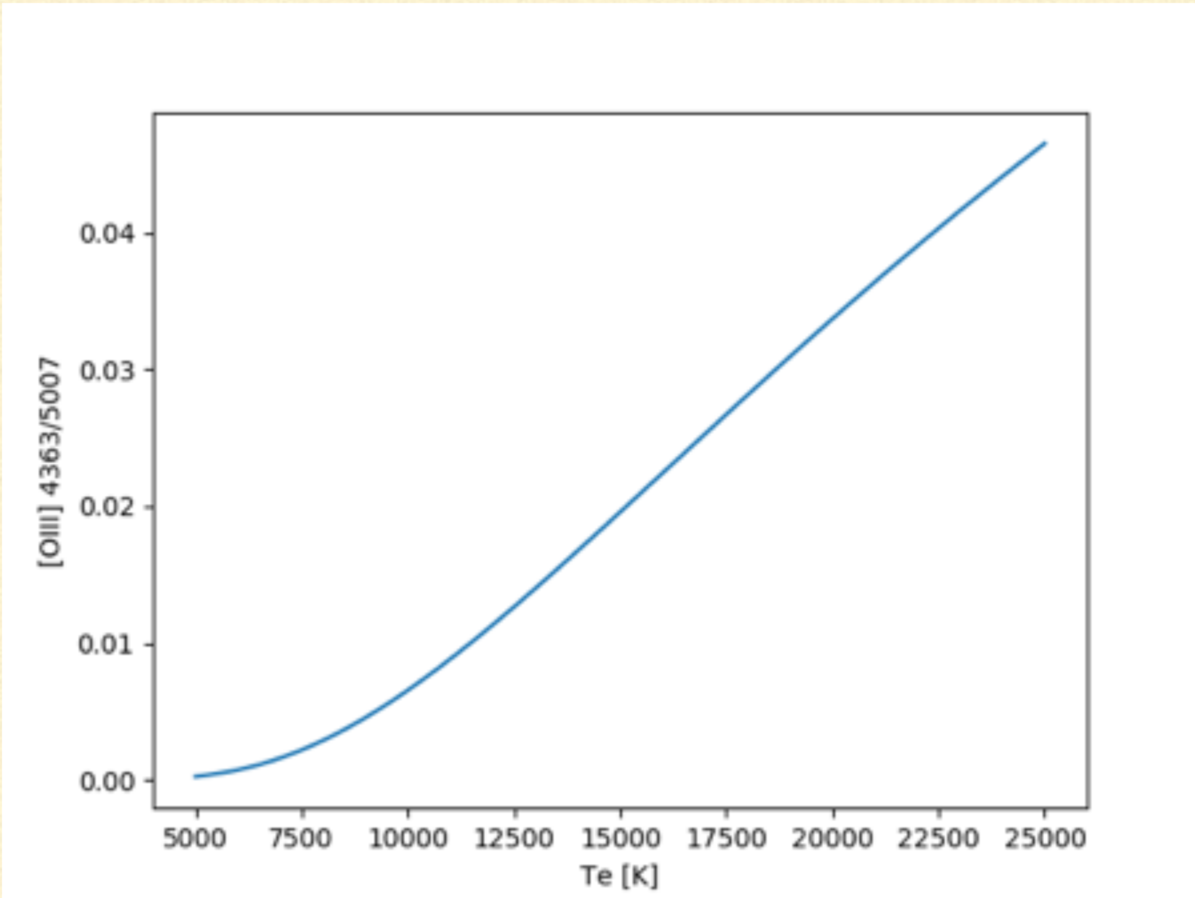
- Direct method
- Strong lines methods
  - Calibrated estimators based on
    - observations
    - models
  - Lookup tables, closest model, BOND (semi-strong lines)
  - Deep learning

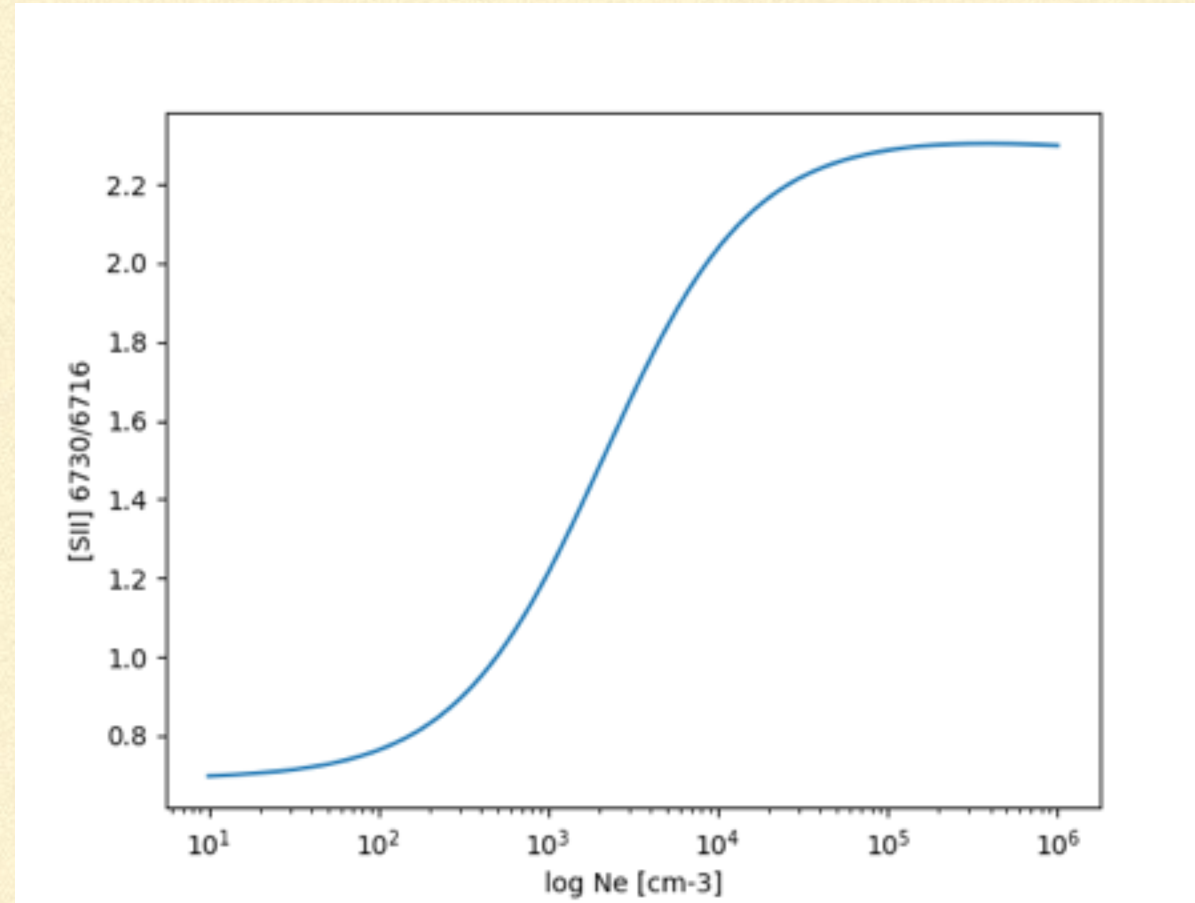
DIRECT METHOD

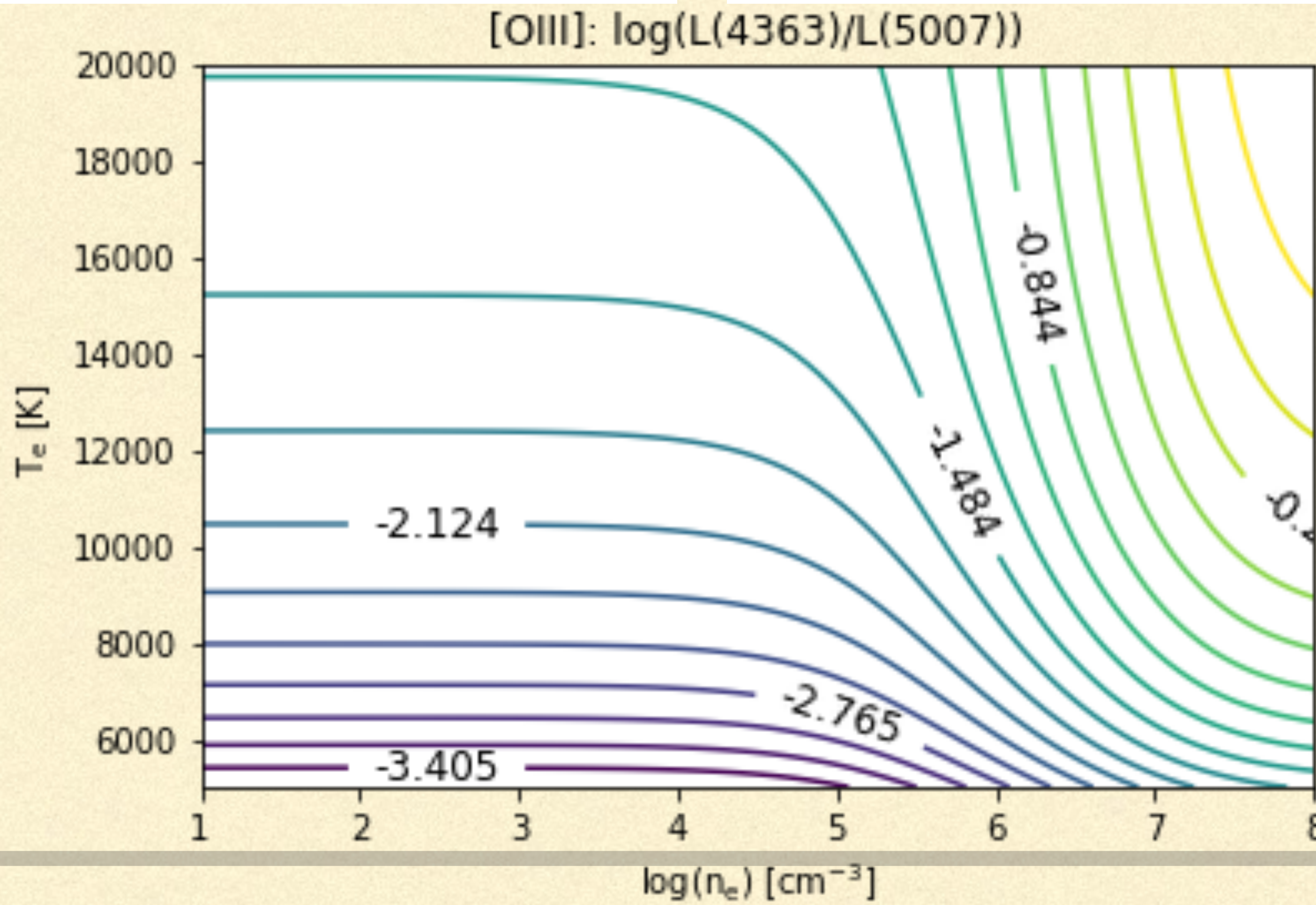
- Needs for some strong and faint lines: Ha, Hb, [OIII]4363/5007, [NII]5755/6584, [OII] 3729+, 7320+, [SII] 6716/6730
- Obtain the physical properties of the region:
  - Electron density from e.g. [SII] and/or [ClIII] line ratios.
  - Electron temperature from [NII] and/or [OIII] line ratios (take care of blends and recombination contribution).



Energy levels diagrams from PyNeb (Luridiana et al. 2015)


[OIII] 4363/5007
0.04
0.03
0.02
0.01
0.00
5000
7500
10000
12500
15000
17500
20000
22500
25000
Te [K]


[SII] 6730/6716
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
10^1
10^2
10^3
10^4
10^5
10^6
log Ne [cm-3]


[OIII]: log(L(4363)/L(5007))
T_e [K]
20000
18000
16000
14000
12000
10000
8000
6000
-0.844
-1.484
-2.124
-2.765
-3.405
1
2
3
4
5
6
7
8
$\log(n_e)$ [cm^{-3}]

DIRECT METHOD (2)

Using Te and Ne (one may consider low/high ionization regions) one obtains the ionic abundances:

$$I(\lambda) = \int j_\lambda ds = \int n(X^{+i}) n_e \epsilon_\lambda(T_e) ds,$$

$$I(\mathrm{H}\beta) = \int n(\mathrm{H}^+) n_e \epsilon(\mathrm{H}\beta, T_e) ds,$$

$$I([\mathrm{O\,III}]) = \int n(\mathrm{O}^{++}) n_e \epsilon(\lambda 5007, T_e) ds.$$

$$\frac{X^{+i}}{\mathrm{H}^+} = \frac{I(\lambda)}{I(\mathrm{H}\beta)} \frac{\epsilon_{\mathrm{H}\beta}}{\epsilon_\lambda},$$

More details in Peimbert, M., Peimbert, A., & Delgado-Inglada, G. 2017

DIRECT METHOD (3)

The total elemental abundances are obtained by summing the ionic abundances, e.g. $O^{+} + O^{++}$.

$$\frac{X}{\mathrm{H}} = \Sigma_i \frac{X^{+i}}{\mathrm{H}^{+}}.$$

If some ions are not observed, one need to correct for them using ICFs, e.g. N^{+}:

$$\frac{X}{\mathrm{H}} = \Sigma_{\mathrm{obs}} \frac{X^{+i}}{\mathrm{H}^{+}} \times ICF.$$

ICFS

- Classical ICFs from Peimbert & Costero (1969) and Kingsburgh & Barlow (1994).

- New ICFs **for PNe** from Delgado-Inglada et al. (2014).

- ICFs depends on **photoionization codes** that compute the ionization structure of nebulae. Mainly depends on U (ionization parameter) and the hardness of the ionizing SED.

- ICFs are for full objects. **NOT to be used for individual spaxels of resolved objects.**

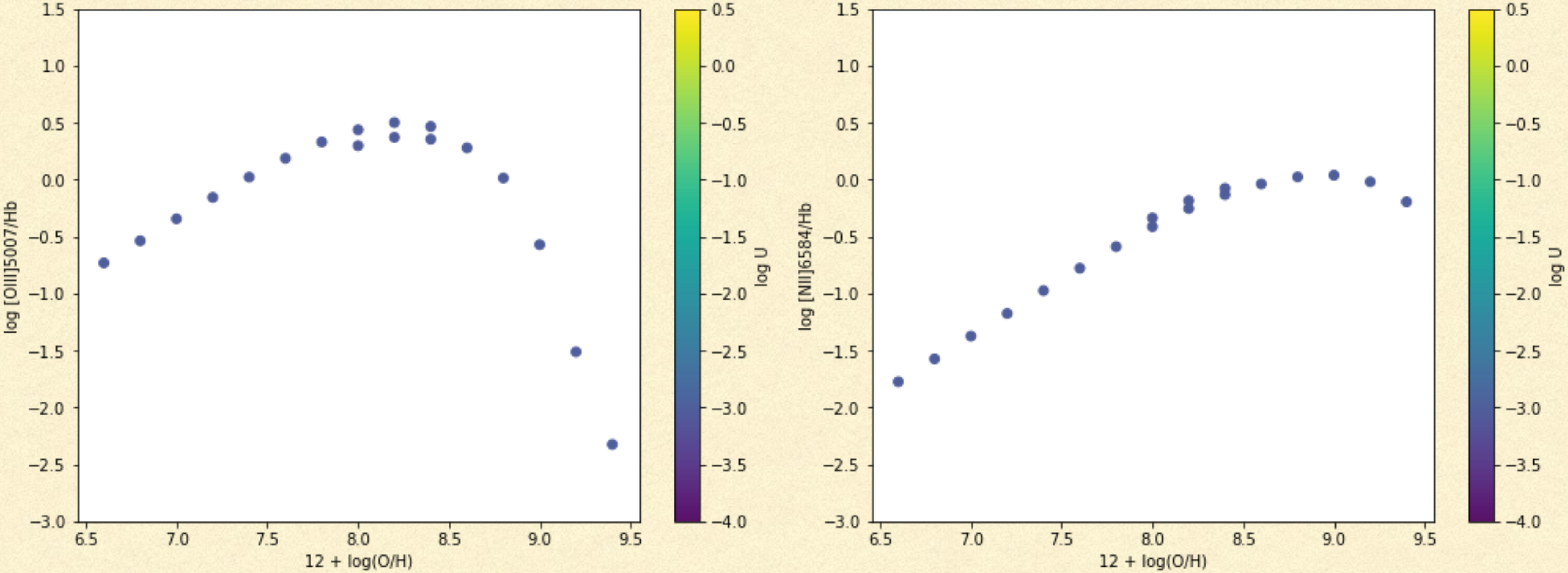
ABUNDANCES **WITHOUT** TEMPERATURE

- If one do not have access to the electron temperature(s) of the nebula (e.g. no [OIII] 4363), there is no way to determine abundances with the direct method.
- One needs to rely on **strong line methods**, that are calibrated estimation of abundances using some (few) strong lines, e.g. [OII], [OIII], [NII] and [SII].
- The calibration is made using objects for which the metallicity is known. They are:
  - real observed objects (e.g. Pilyugin papers)
  - models (e.g. Kewley)

DOUBLE-VALUED PROBLEM

- At low Z the cooling is manly due to H^+ recombination. [OIII] 5007/Hbeta increases with O/H.
- At high Z, the gas is cold and the cooling is mainly due to IR CELs. [OIII]/Hbeta is strongly decreasing with O/H as T decreases.
- Impossible to determine O/H from strong lines « from scratch ».

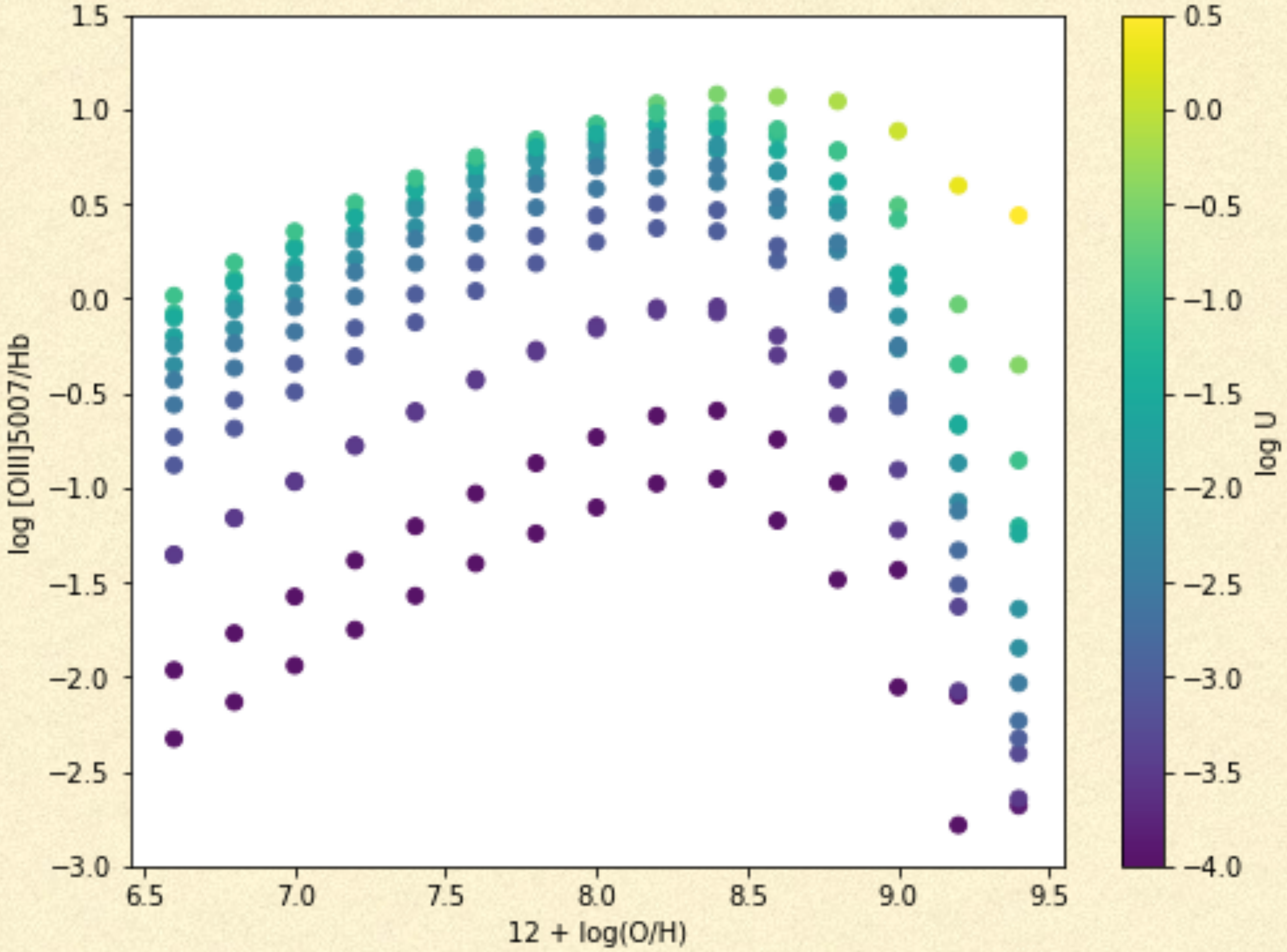
NOT ONLY DOUBLED-VALUED

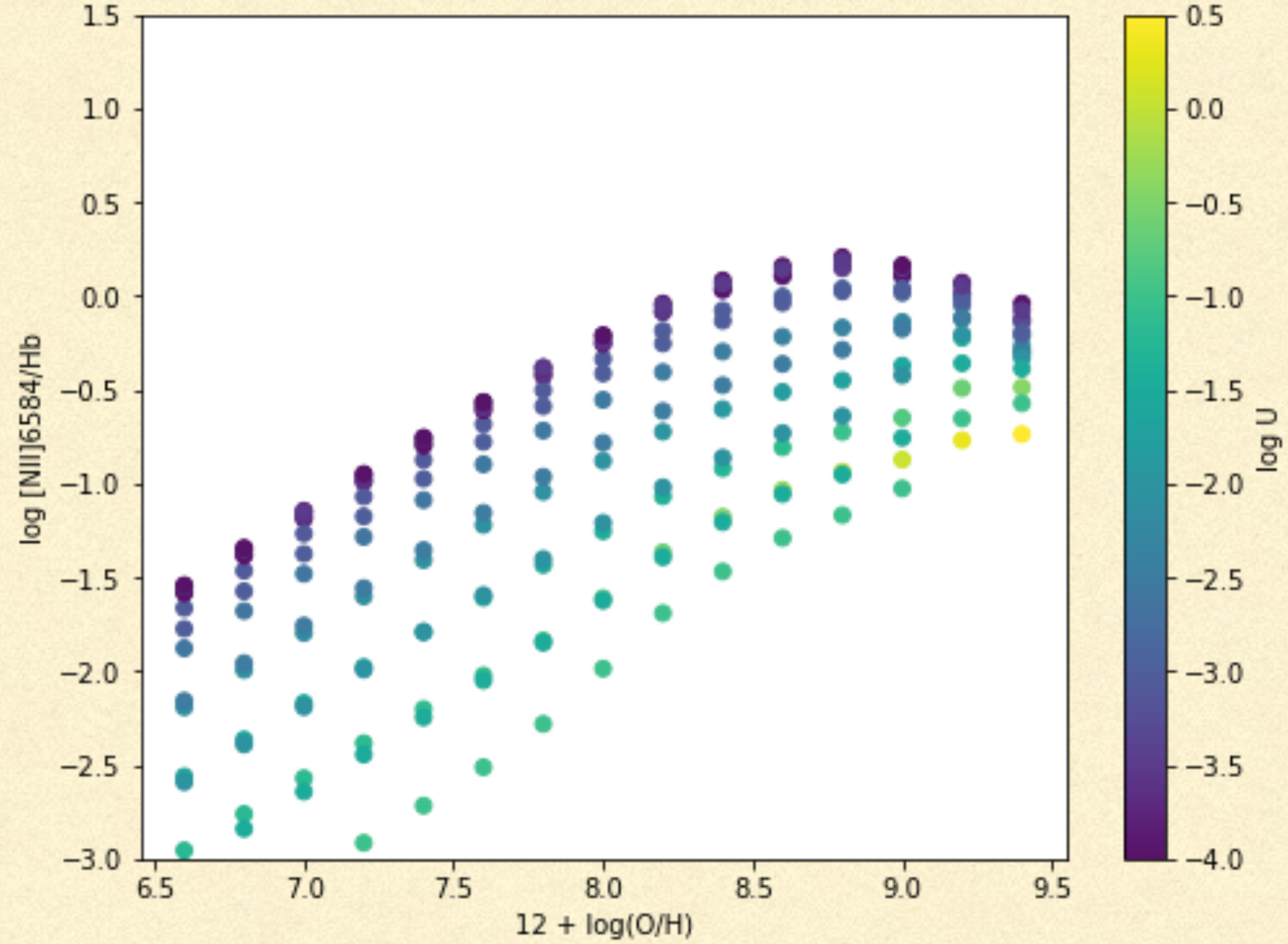


The strong lines intensities are doubled-valued with O/H…

results from 3MdB using BOND grid

IONIZATION PARAMETER





The strong lines intensities are doubled-valued with O/H, but also strongly depend on the ionization parameter.

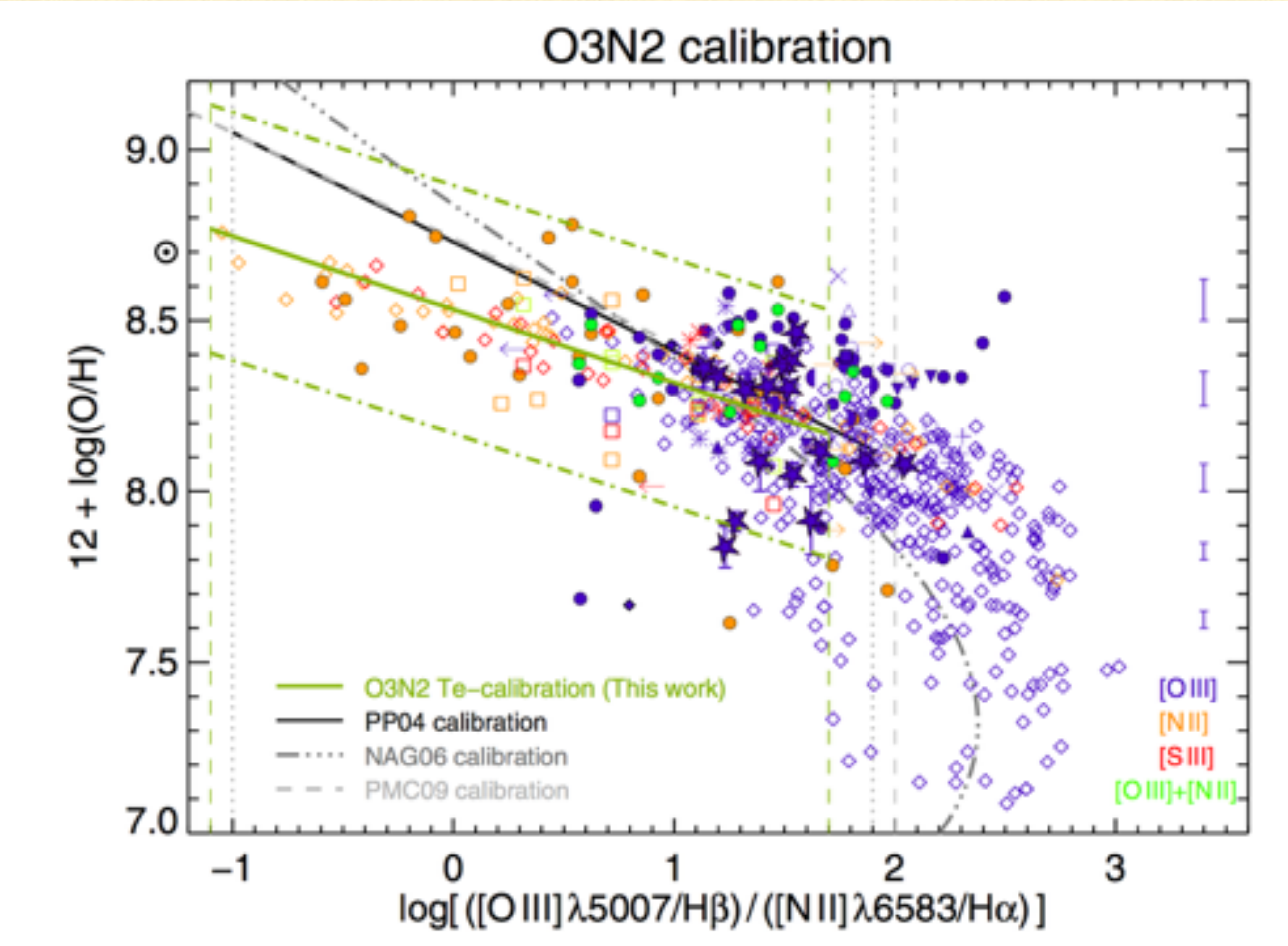
results from 3MdB using BOND grid

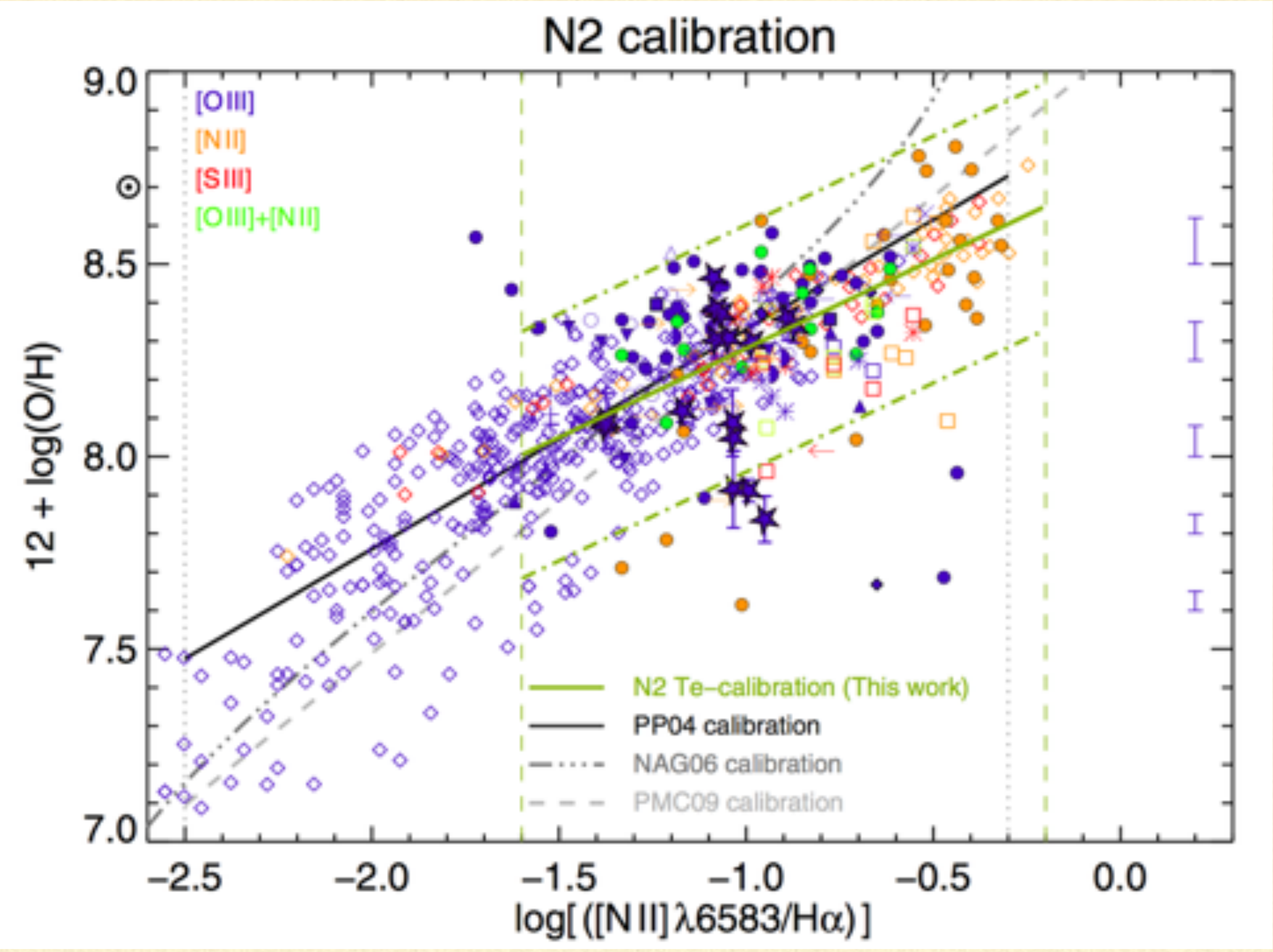
GIANT HII REGIONS EMISSION

- The main parameters defining the emission line intensities of Giant HII regions are: **O/H, U, SED hardness (age), N/O**.
- Some correlation exists:
  - SED hardness (age) is correlated with O/H due to opacity effects in stellar photospheres,
  - N/O is correlated with O/H due to primary and secondary production of N,
  - U is correlated with O/H due to effects of stellar winds on region sizes.

EMPIRICAL CALIBRATORS

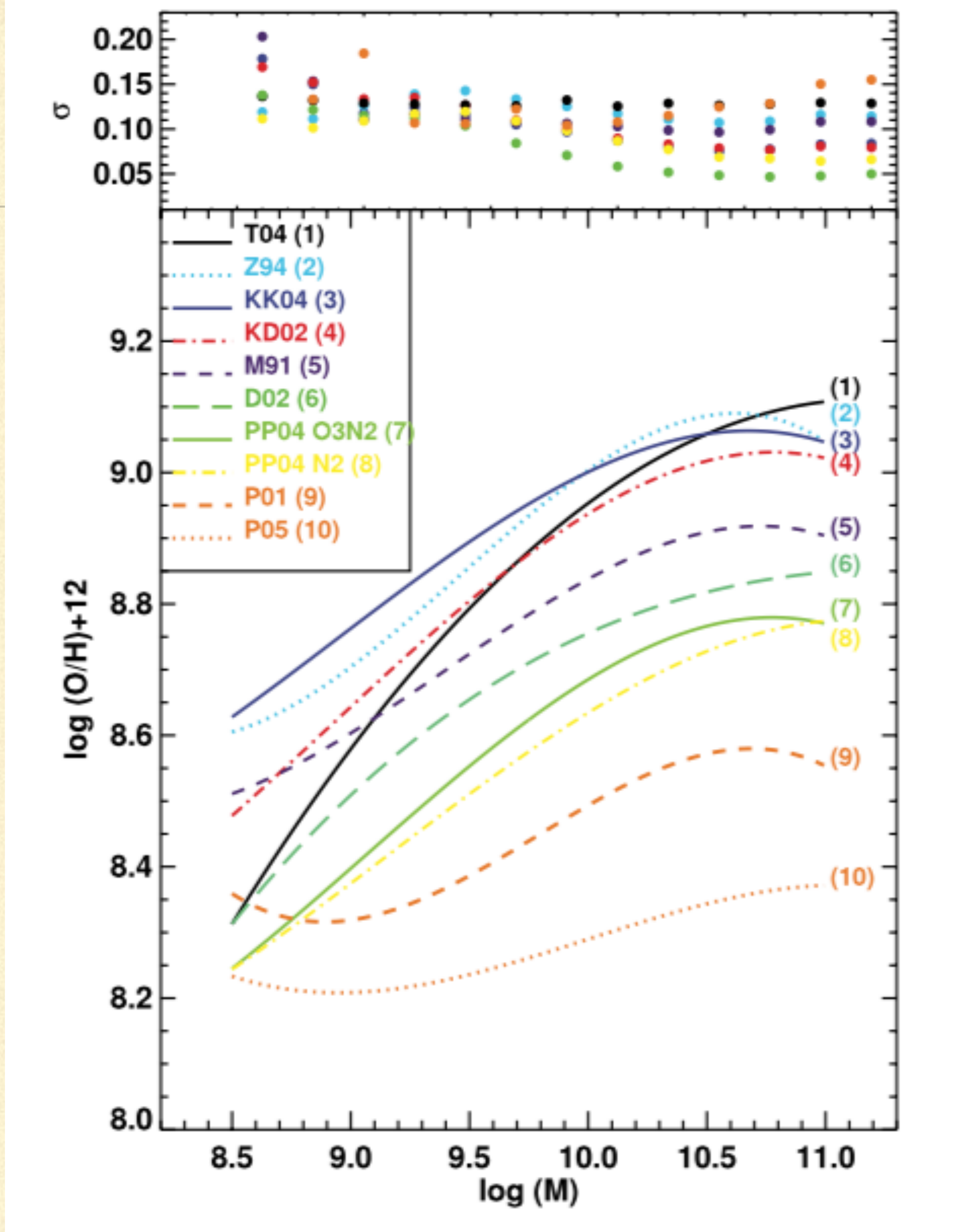
Alloin, Pettini, Pilyugin, Marino and others: a long list of calibrators, based on strong line ratios and direct method.





DIFFERENT CALIBRATORS

- Depending on the calibrator, O/H may vary by 0.7 dex!
- **Theoretical** calibrations seem to provide systematically **higher** values for O/H.



Kewley & Ellison, 2008

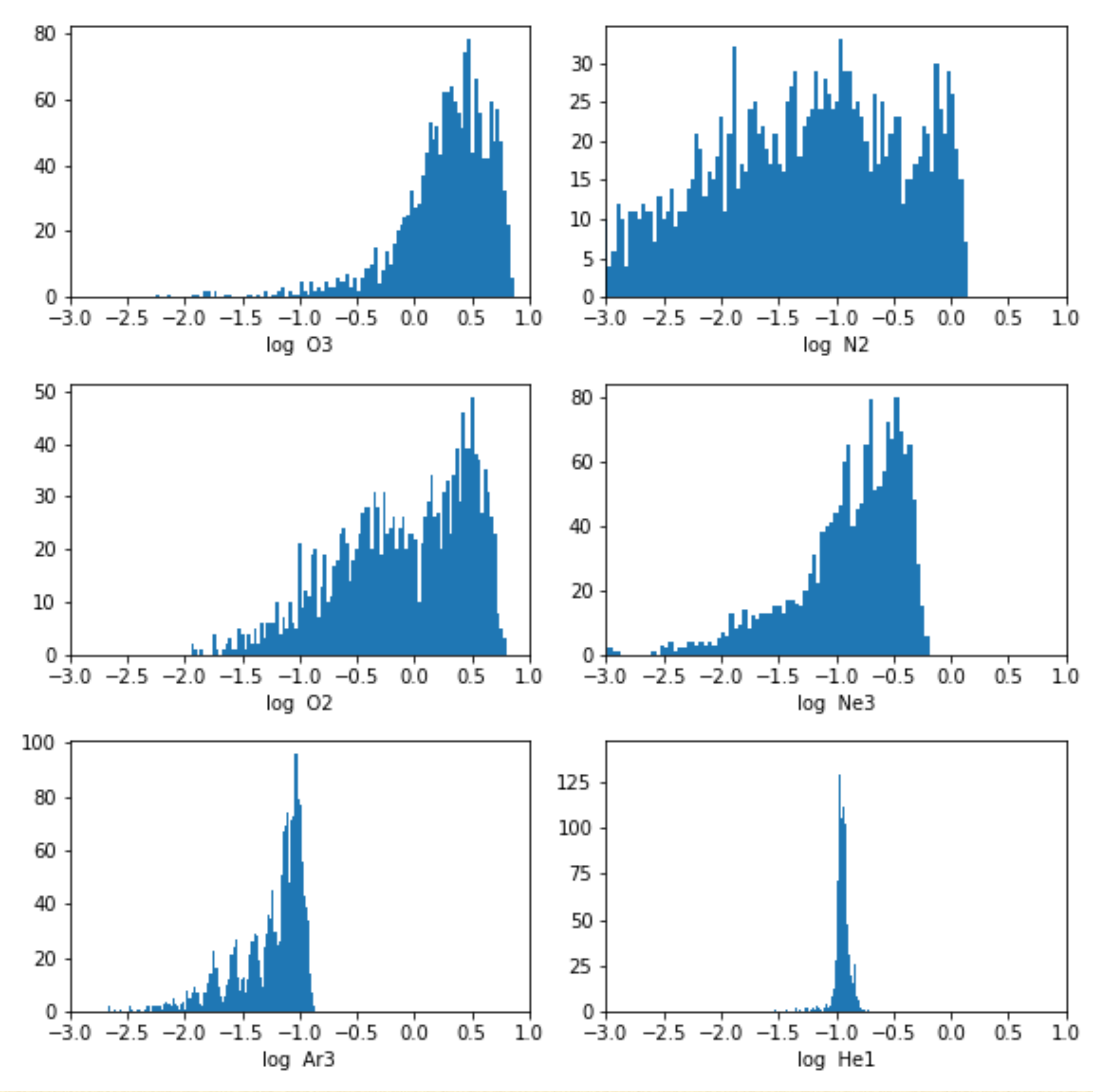
MODEL BASED METHODS

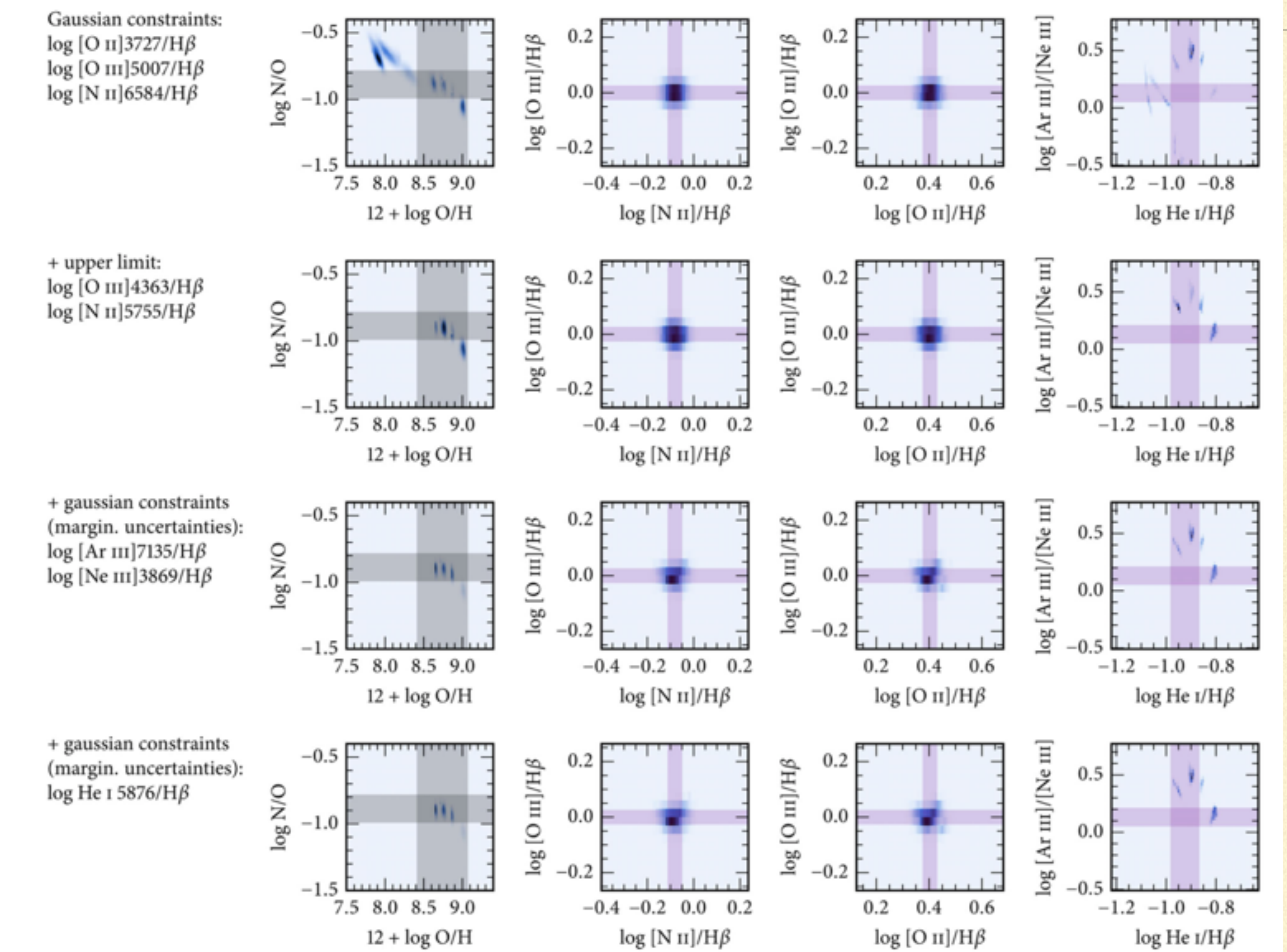
- Perez-Montero : **HII-CHI-mistry**, based on look-up table in Cloudy models of 1My starburst regions. N/O vs. O/H and log U vs. O/H relations assumed.
- Blanc: **IZI** is an IDL function that uses Bayesian inference to derive the metallicity (Z) and ionization parameter (q) of an ionized nebula given a set of observed emission line fluxes and an input photo-ionization model grid. Assumes N/O vs. O/H relation.
- Vogt: **pyqz** is a python library to interpolate a MAPPINGS grid to find Q and Metallicity. Assumes N/O vs. O/H relation.
- Thomas: **NebuBayes**. N/O vs. O/H and log U vs. O/H relations assumed. Only Constant Star Formation of 10 Myr.
- Vale-Asari: **BOND**

BOND

- No *a priori* relation between N/O and O/H.
- Free parameters for the grid: **O/H, N/O, log U, age, geometry** (different optical depths are also included in the 3MdB version of the model grid)
- Semi-strong lines are also used: [ArIII]λ7135/[NeIII]λ3869 (solves the duality) and HeI to constrain the SED hardness.
- Bayesian

SEMI-STRONG LINES





Example of the BOND solution for an H II region in NGC 1232: the panels from left to right show the joint posterior PDFs. The grey bands delimit ±1σ of the temperature-based values for O/H and N/O, and the purple bands ±1σ of the observed line ratios. Each row shows the effect of *cumulatively* adding another set of observational constraints. Note that the N/O versus O/H PDF is multipeaked, which means that there is a family of acceptable solutions in our grid (affecting mainly O/H). Those islands of solutions are a consequence of the discreteness of the starburst ages and nebular geometries in our grid.

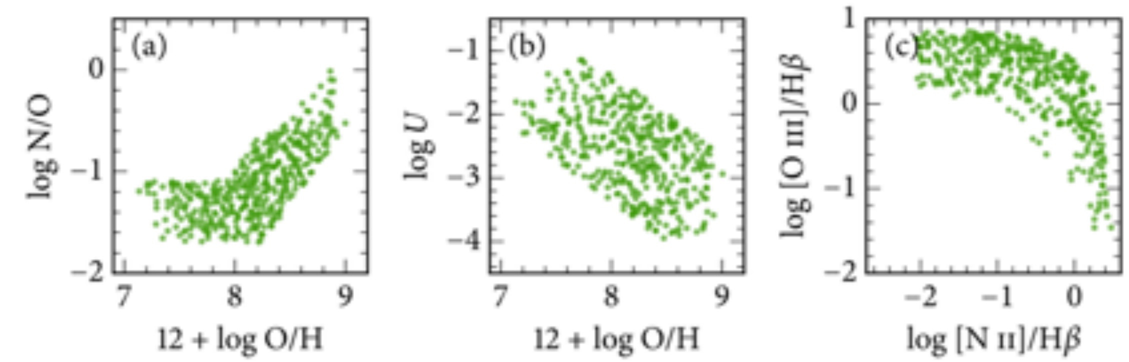


Figure A1. Fake sources chosen from the grid with age 2 Myr and filled sphere. The grid is finer than our original grid, but not as fine as the interpolated one we use as our initial octree grid. The panels show our selection of grid models on the N/O versus O/H, U versus O/H and BPT planes.

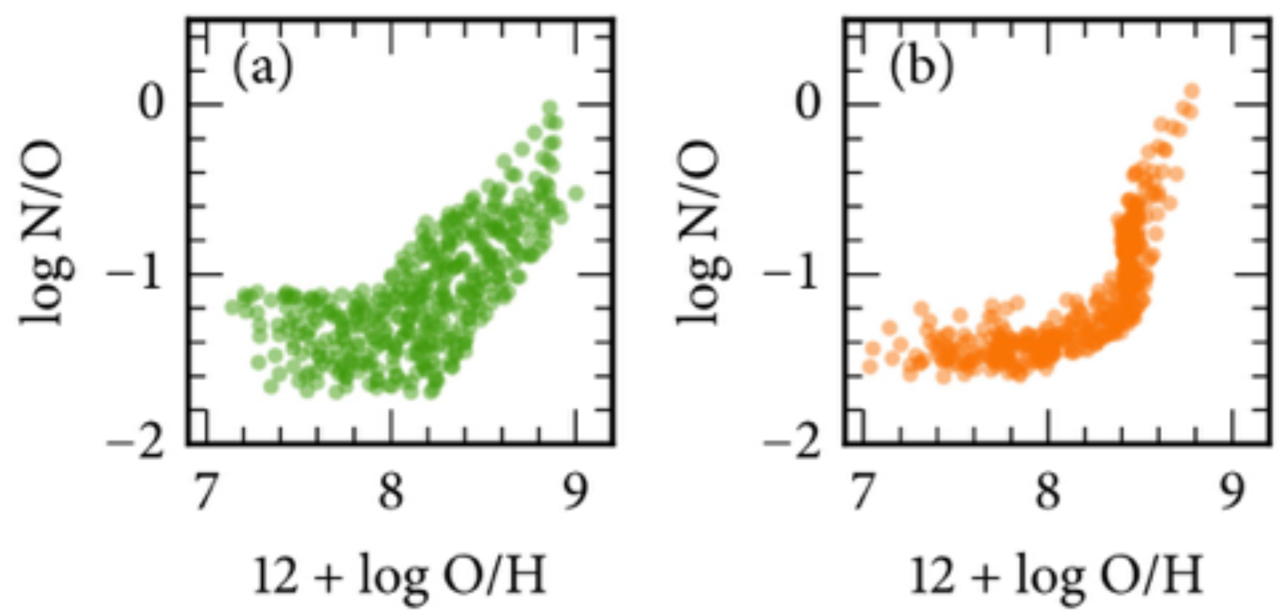


Figure C5. (a) The original N/O versus O/H diagram for our fake sources, and (b) the N/O versus O/H diagram for our fake sources as calculated by the ON calibration from Pilyugin et al. (2010).

Results obtained using Pilyugin (2010) on a sample of fake sources. The scatter strongly decreases…

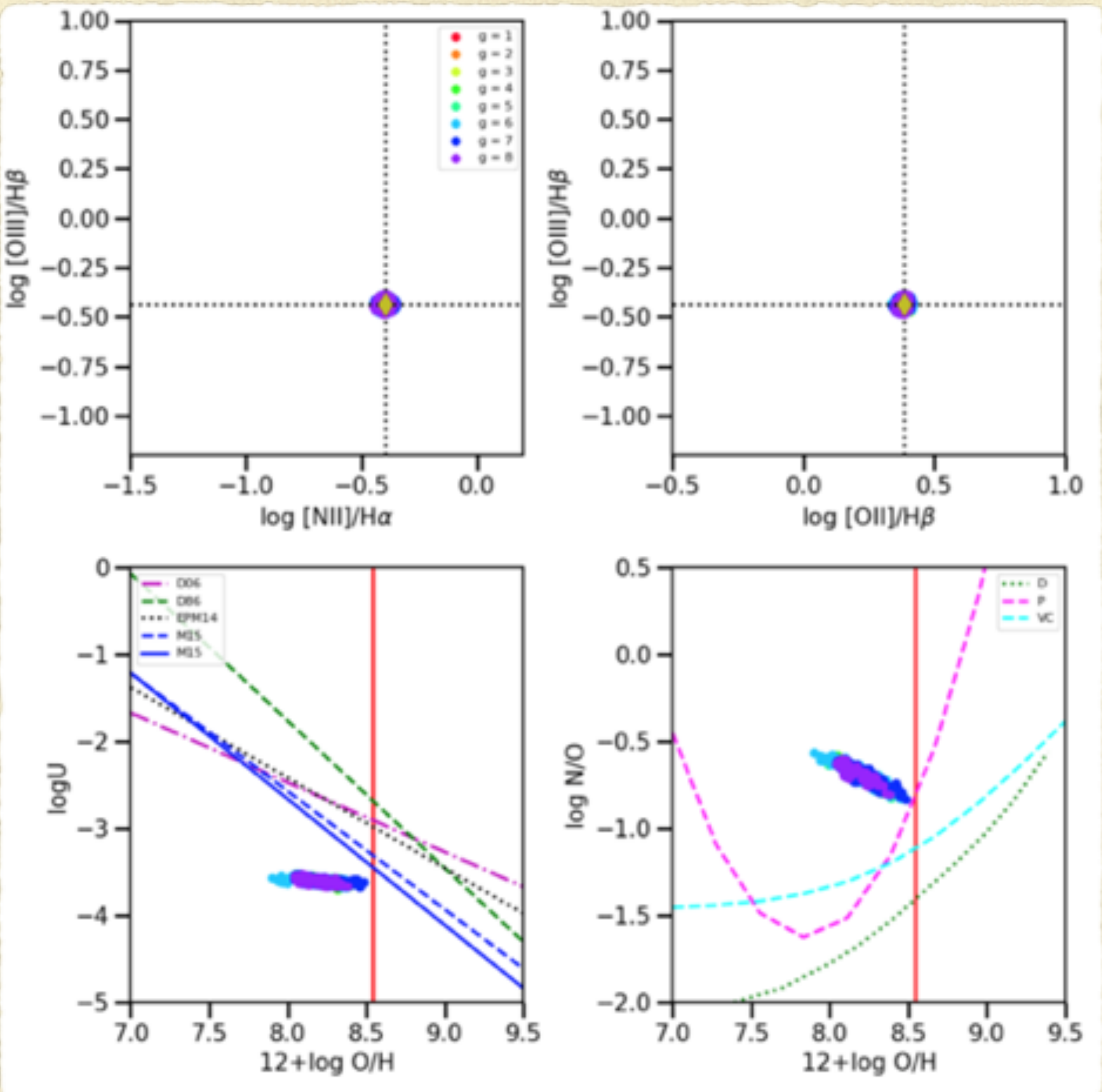
GENETIC ALGORITHM

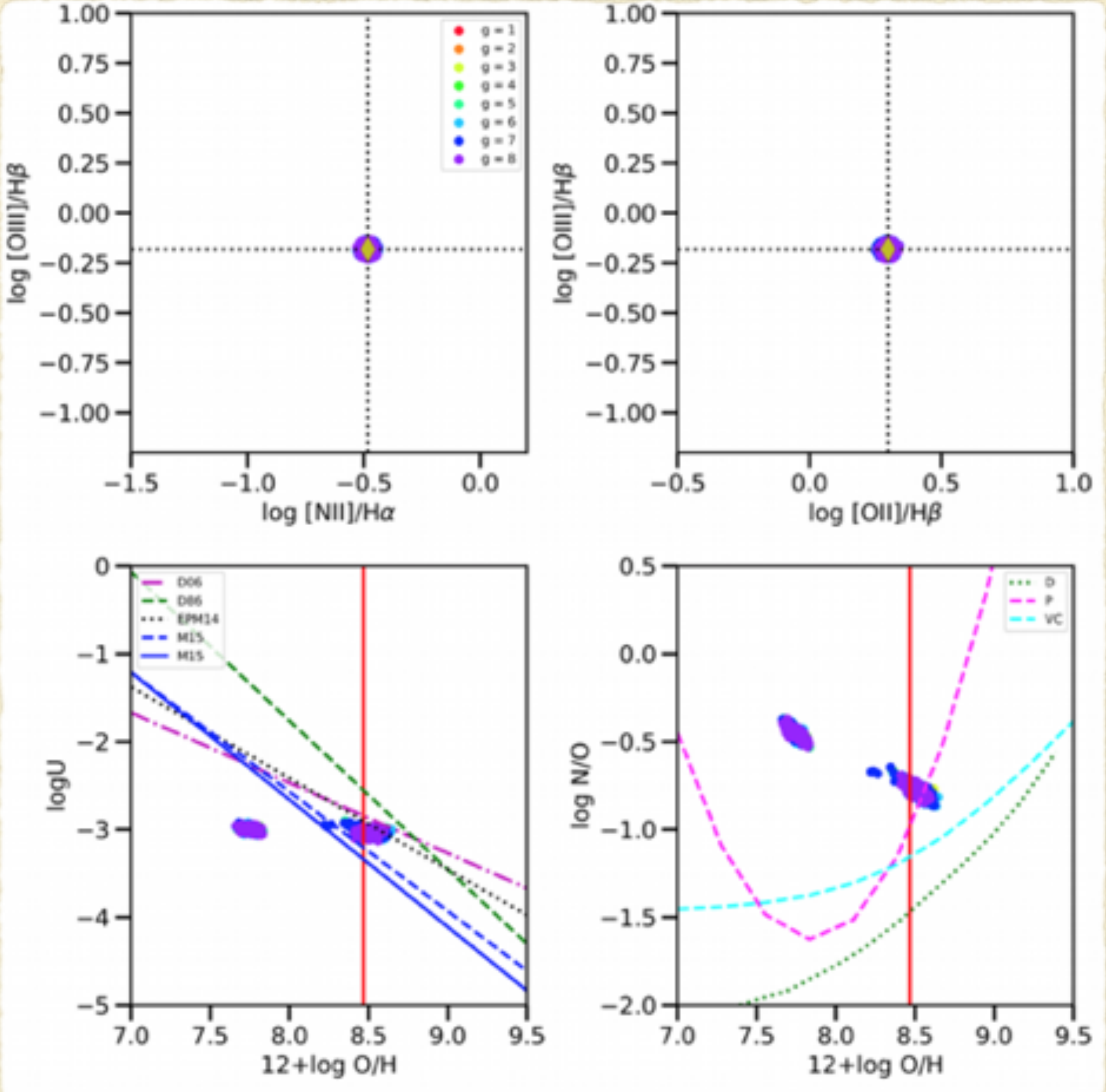
Genetic algorithm is an **iterative** process based on 2 phases looping until a convergence criterion is reached:

- **Selection** by minimizing a distance in the O-space.
- Genetic operators: **Crossover** and **Mutation** to obtain new parameters. New points in the P-space are produced.

Each iteration implies running new models with the new parameters.

As an example, we (Carlos Espinosa and Ch. Morisset) look for ALL the points in the O/H, N/O and logU space that project to the same point in the [NII]/Ha, [OII]/Hb, [OIII]/Hb space.





2 examples of find ALL the models that project on the same observable point.

!! Be very careful when using a "converging" method like the one included in Cloudy !!

If the solution is not unique, you can not know if you found the correct one...

BRAND NEW METHODS

Using convolutional neural networks to predict galaxy metallicity from three-color images

John F. Wu[1★] and Steven Boada[1]

GAME: GAlaxy Machine learning for Emission lines

G. Ucci,[1★], A. Ferrara,[1,2], A. Pallottini[1,3,4,5], S. Gallerani[1]

2018, *Monthly Notices of the Royal Astronomical Society*, **477**, 1484-1494

MNRAS **000**, i–xii (????) Preprint 6 March 2019 Compiled using MNRAS LaTeX style file v3.0

A Machine Learning Artificial Neural Network Calibration of the Strong-Line Oxygen Abundance

I-Ting Ho (何宜庭),[1★]
[1] *Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany*

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- Very interesting pioneer work on the use of neural network to determine abundances.
- ANN trained with Pilyugin set of 950 observed HII regions with O/H determined using direct method.
- Not only line intensities, also line ratios:

Table 1. Input features ($N = 16$)

Type	Line ratio
Single line	[O II], [O III], [N II], [S II]
Ratio of line pairs	[O III]/[O II], [N II]/[O II], [S II]/[O II], [N II]/[O III], [S II]/[O III], [S II]/[N II]
Sum of line pairs	([O II]+[O III]), ([O II]+[N II]), ([O II]+ [S II]), ([O III]+[N II]), ([O III]+[S II]), ([N II]+[S II])

1. All lines are normalized to $H\beta = 1$
2. The input features are the *logarithmic* of the line ratios

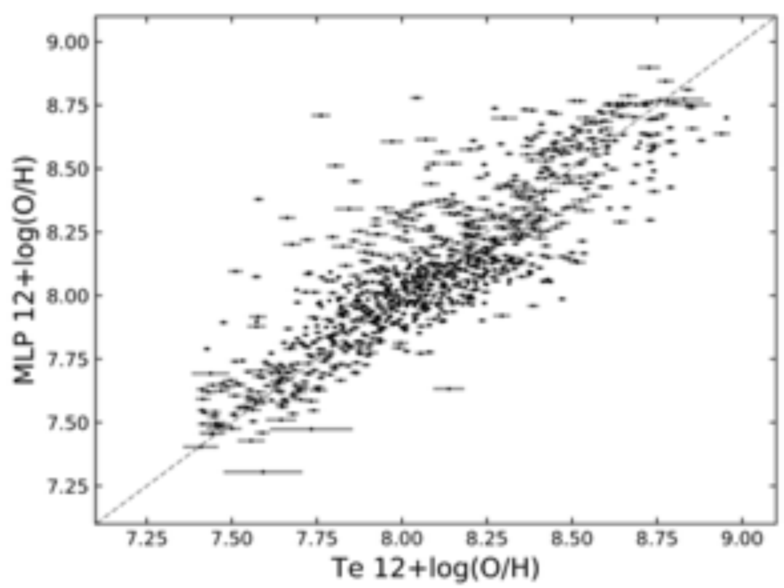

Figure 7. Comparison between oxygen abundances from the best MLP model (Section 2.3.4) and the T_e method. The data points are the working sample described in Section 2.1. The error bars are the standard deviations of the 100 predictions from the 100 model realizations. The dashed line is the one-to-one line.

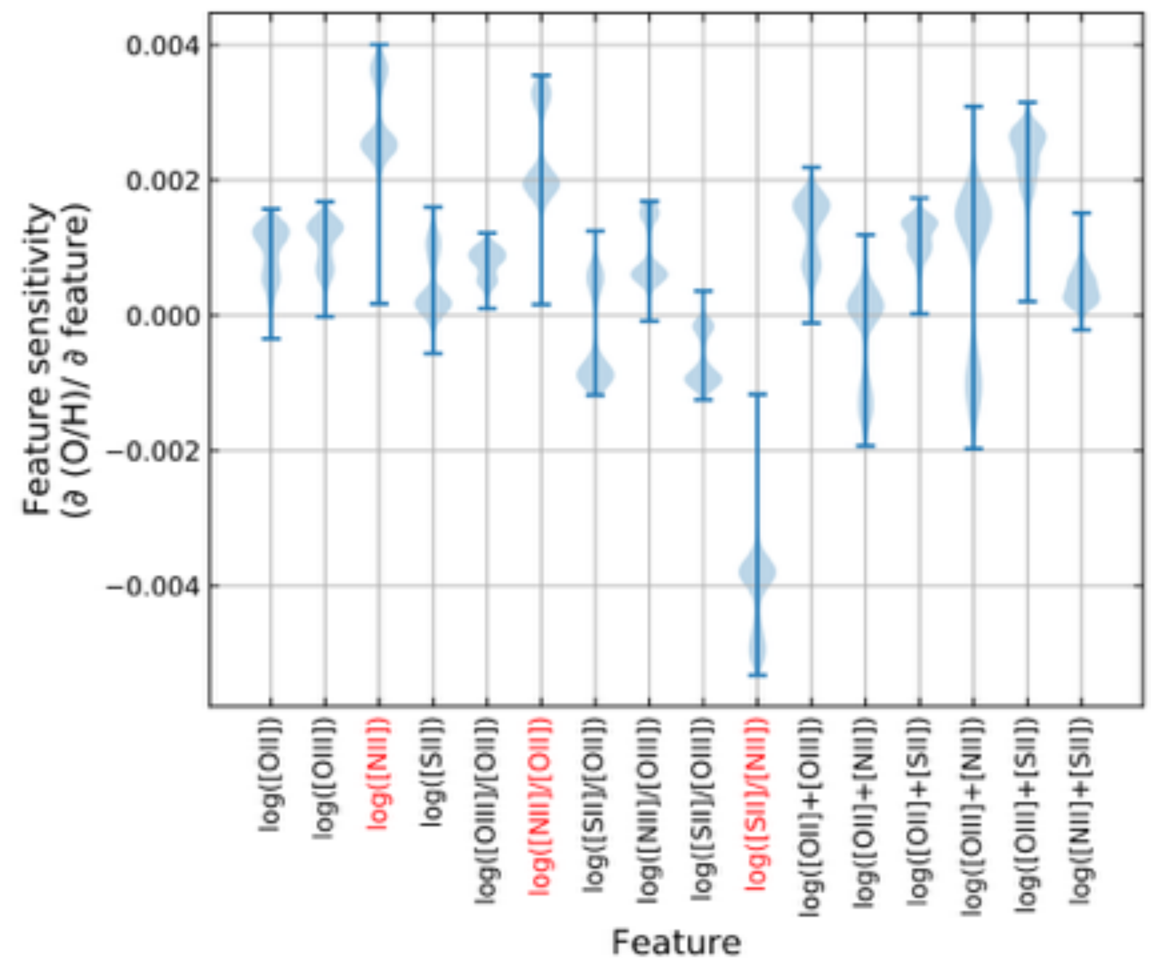

Figure 8. Feature sensitivity of the best MLP model, as measured by perturbing one feature at a time and recording the response of the output oxygen abundance. The response of the working sample to different feature perturbations is shown as the shaded vertical histograms. The top three important features are labeled in red (i.e. deviate most from zero).

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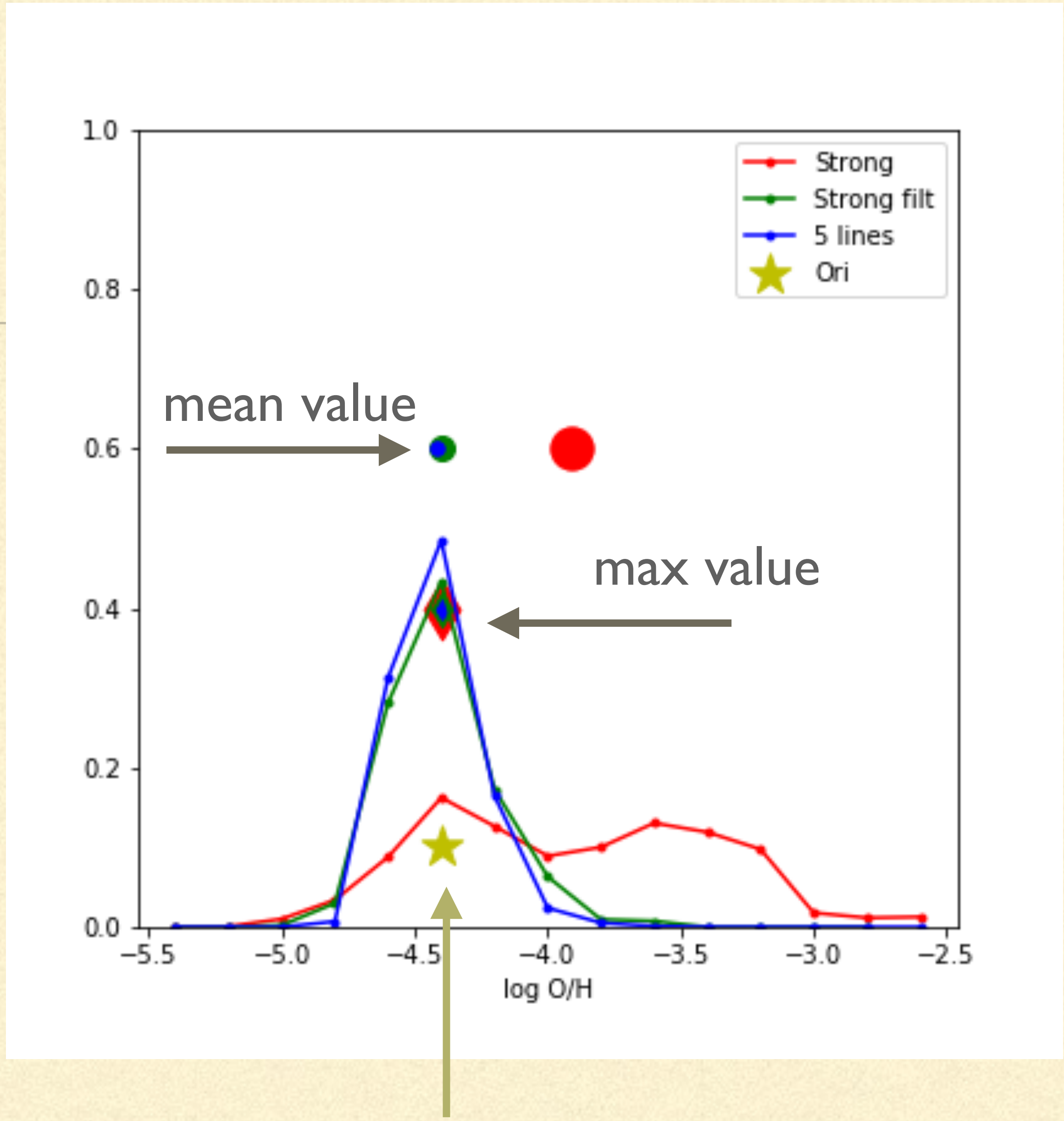
[NII], [OII], [OIII] and [SII] are the most important emission lines.

NEURAL NETWORKS

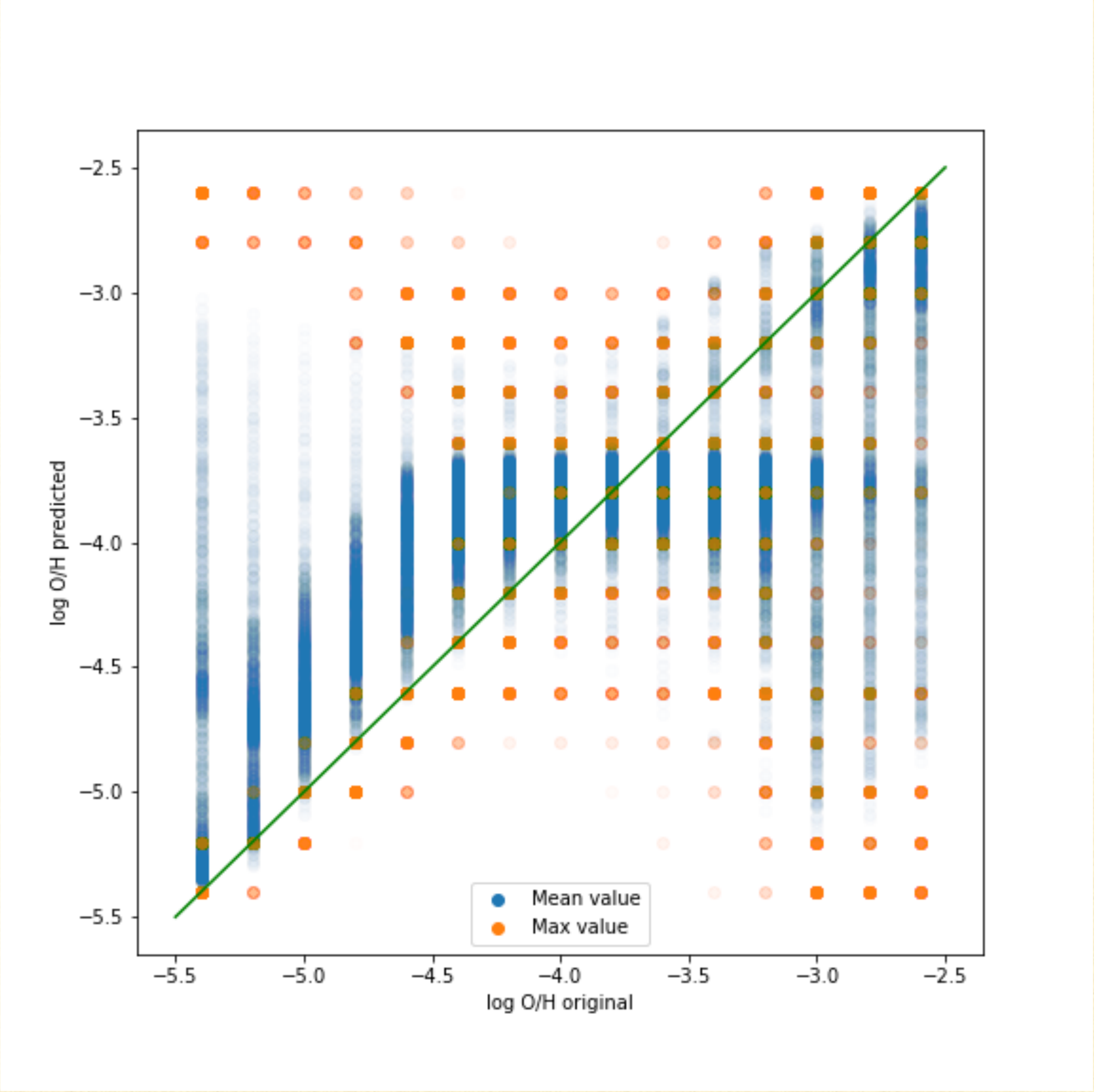
- Part of PyNeb next version: ANN (and other) regressors to determine abundances.
- Trained/tested with models or observations.
- Allows to compare sets of models (Cloudy vs. Mappings), sets of lines (Strong, semi-strong), etc.

EXAMPLE

- ANN trained using Keras front-end on Tensorflow library.
- Trained with BOND Cloudy models (from 3MdB).
- input: emission lines : 3 strong lines [NII], [OII] and [OIII], 3 strong lines with **selected regions** (N/O vs. O/H, log U vs. O/H) and 5 lines (3 strong + [NeIII] & [ArIII])
- output: O/H.

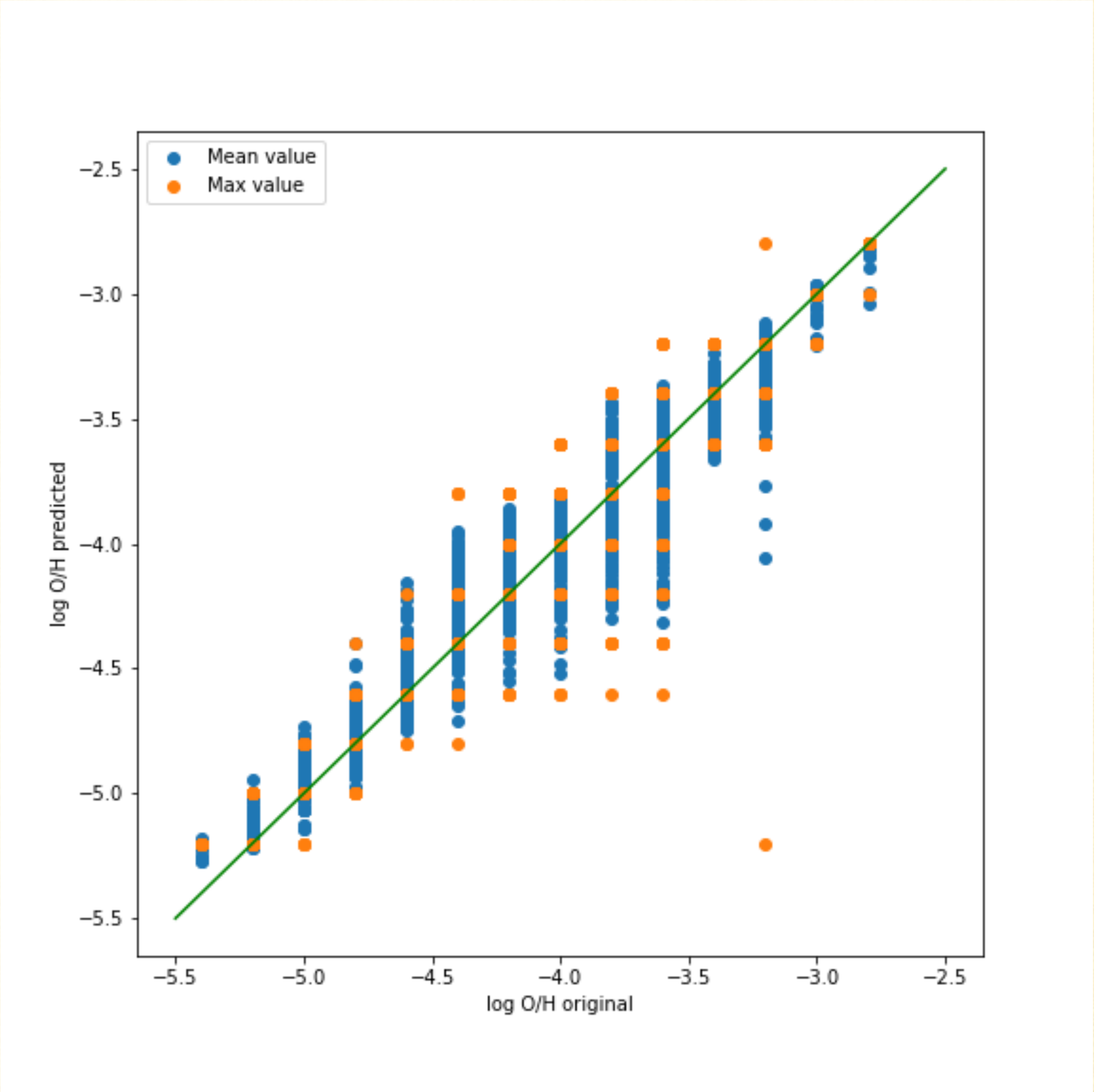


Original value

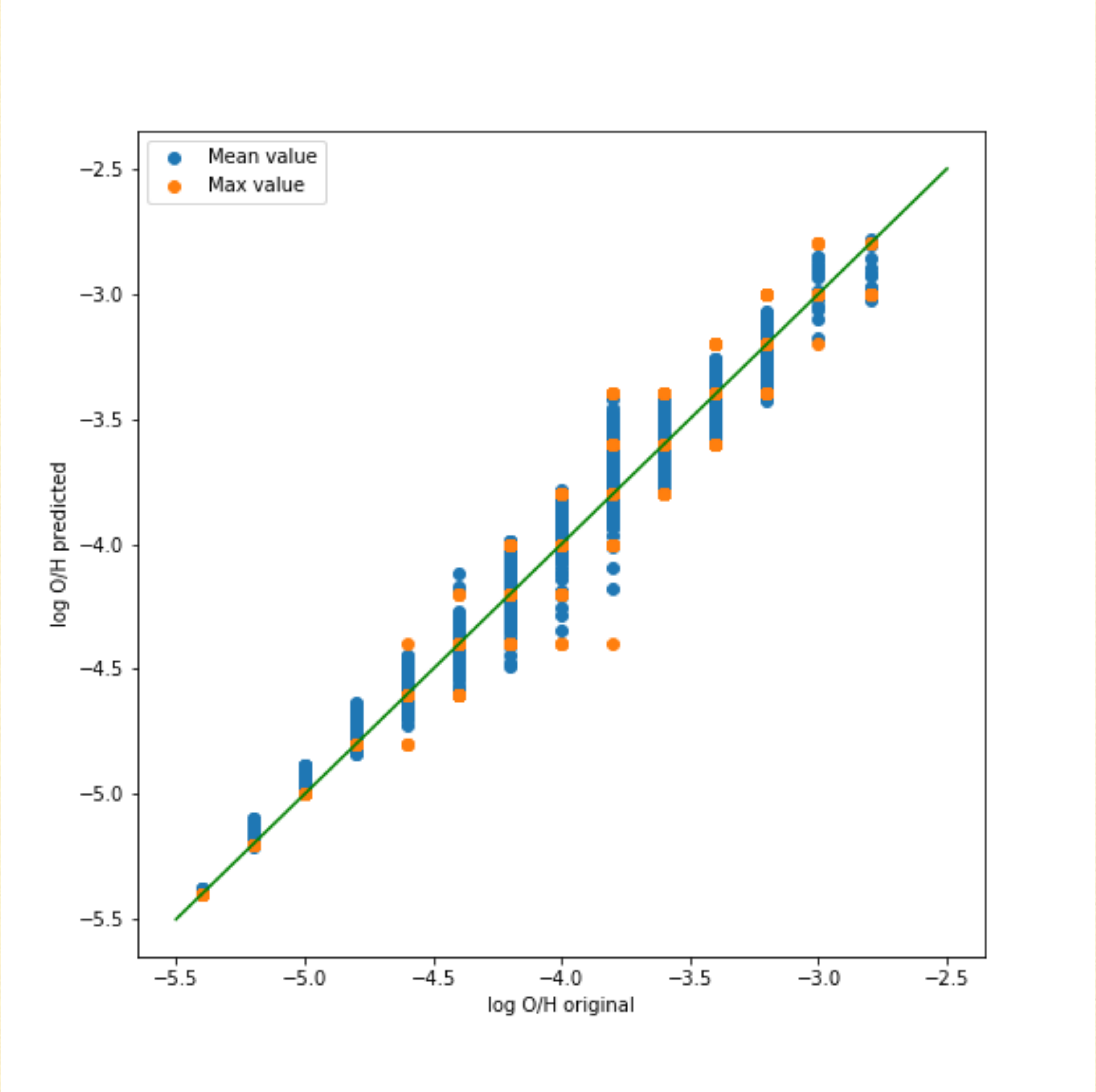


3 strong lines [NII], [OI] and [OIII] only.

Mean and Max methods to determine O/H.



3 strong lines [NII], [OI] and [OIII], selected models based on O/H, N/O and logU.
Mean and Max methods to determine O/H.



Strong and semi-strong [ArIII] and [NeIII] lines. No model selection. Mean and Max methods to determine O/H.

TAKE HOME QUESTIONS

- We will have only strong lines. C**ould we have [ArIII]λ7135 and [NeIII]λ3869** ???)
- Strong lines method needs to be calibrated:
  - Empirical: which calibrator?
  - Models: which ones? 3MdB with Cloudy, mappings? Selected models, how?
  - Shocks from 3MdBs?
- Neural network to explore complex relations and compare methods?