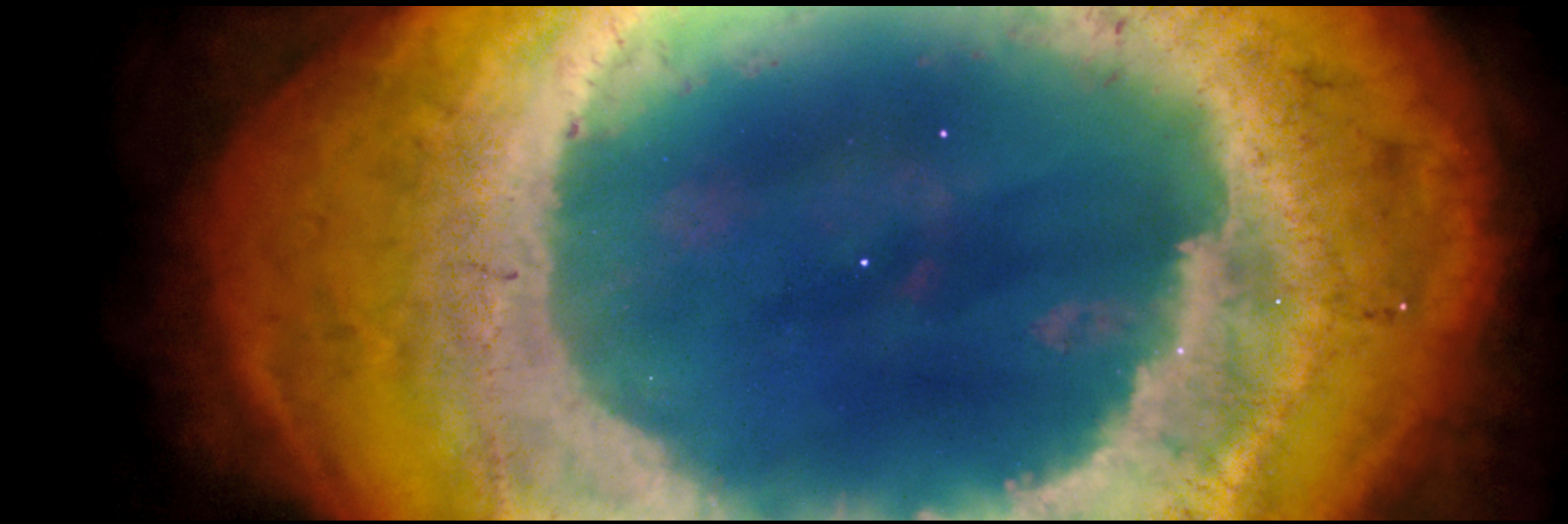
Estimating uncertainties in analyses of ionised nebulae

Roger Wesson (University College London), D. J. Stock, B. Ercolano, M. J. Barlow, P. J. Storey, M. Mohan



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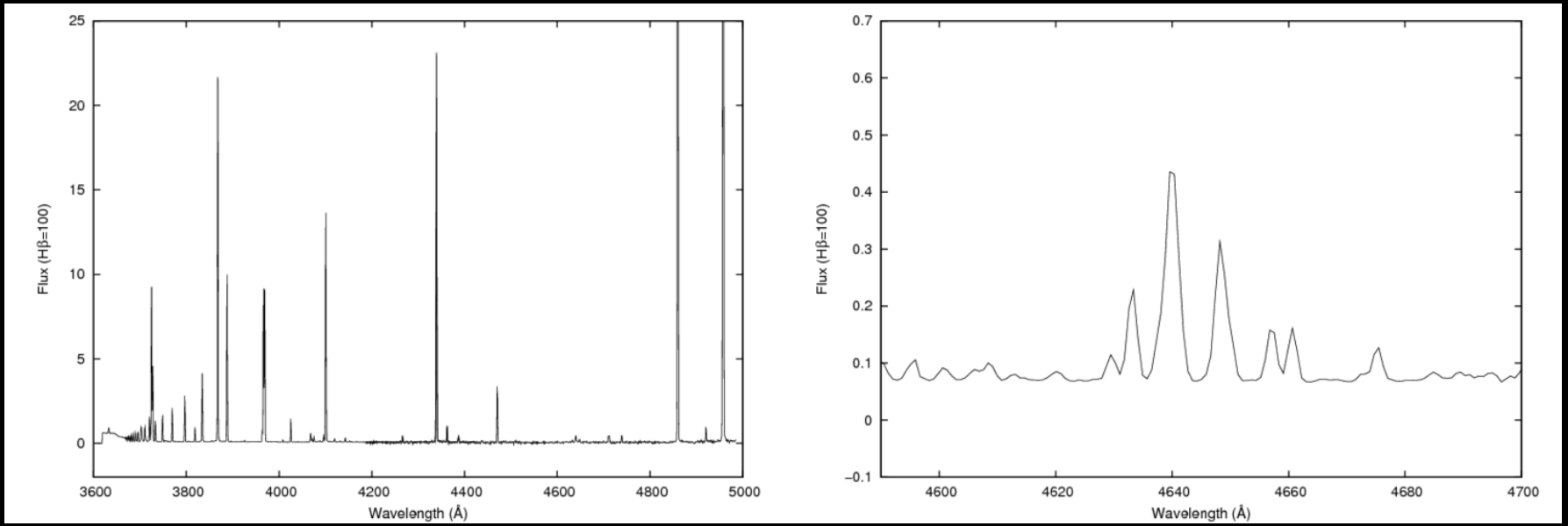
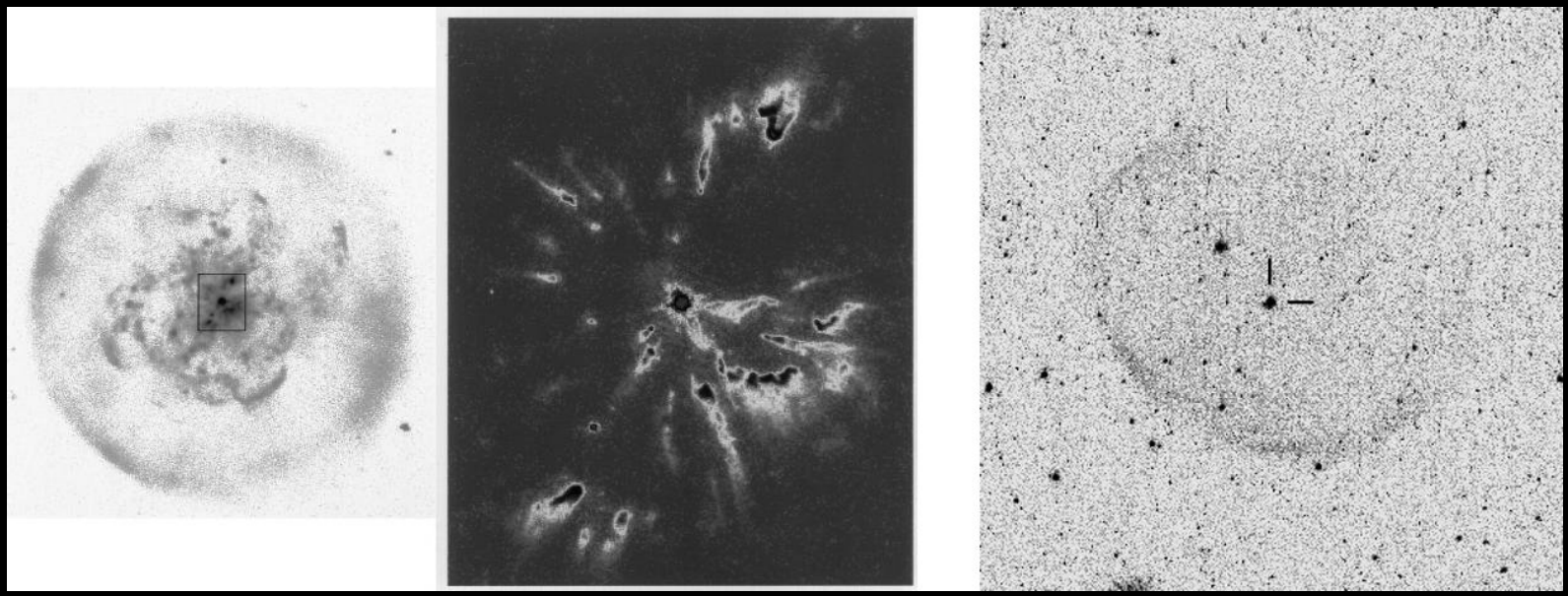
The importance of nebular abundances

- Emission line spectra of planetary nebulae and H II regions are dominated by bright collisionally excited lines (CELs) of heavy elements, and recombination lines (RLs) of H and He.
- Also present are much fainter recombination lines of heavy elements



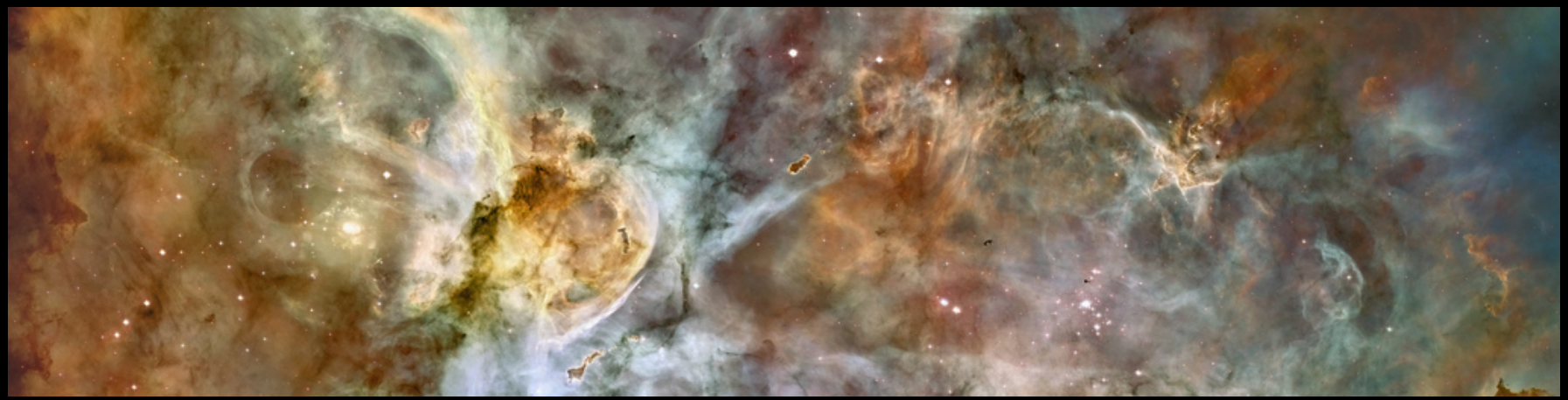
The importance of nebular abundances

- Abundances derived from ratio of CEL to RL (eg [O III] 4959/Hβ) are extremely sensitive to assumed physical conditions
- Abundances derived from ratio of RL to RL (eg O II 4075/Hβ) should be much less unreliable. But..
  a. The lines are much weaker and more difficult to measure
  b. RL abundances are always too high - by factors from a few to $\sim$2 orders of magnitude (eg Wesson et al. 2003, 2005, 2008)



The importance of nebular abundances

- Possible causes of this discrepancy include:
  - Temperature fluctuations (Peimbert 1967)
  - Density inhomogeneities (Viegas & Clegg 1994)
  - H-deficient clumps (Liu et al. 2000)
  - X-ray irradiated quasi-neutral clumps (Ercolano 2009)
- Discrepancy is also seen in H II regions, but seems to have different origin to PN abundance discrepancy



The importance of nebular abundances

- Not certain whether CELs or RLs (or neither) better reflect true abundances
- Consequent uncertainties in understanding of chemical evolution of galaxies, stellar evolution, atomic physics...
- Against this backdrop, it is important to understand the sources of uncertainties in chemical abundance determinations

Typical empirical analysis

1. Determine interstellar extinction from Hα/Hβ
2. Estimate temperatures and densities from diagnostics such as [O II] λ3727/λ3729
3. Calculate ionic abundances based on the diagnostics
4. Estimate total elemental abundances using ionisation correction schemes to account for unseen ionisation stages

A nebular abundance analysis code

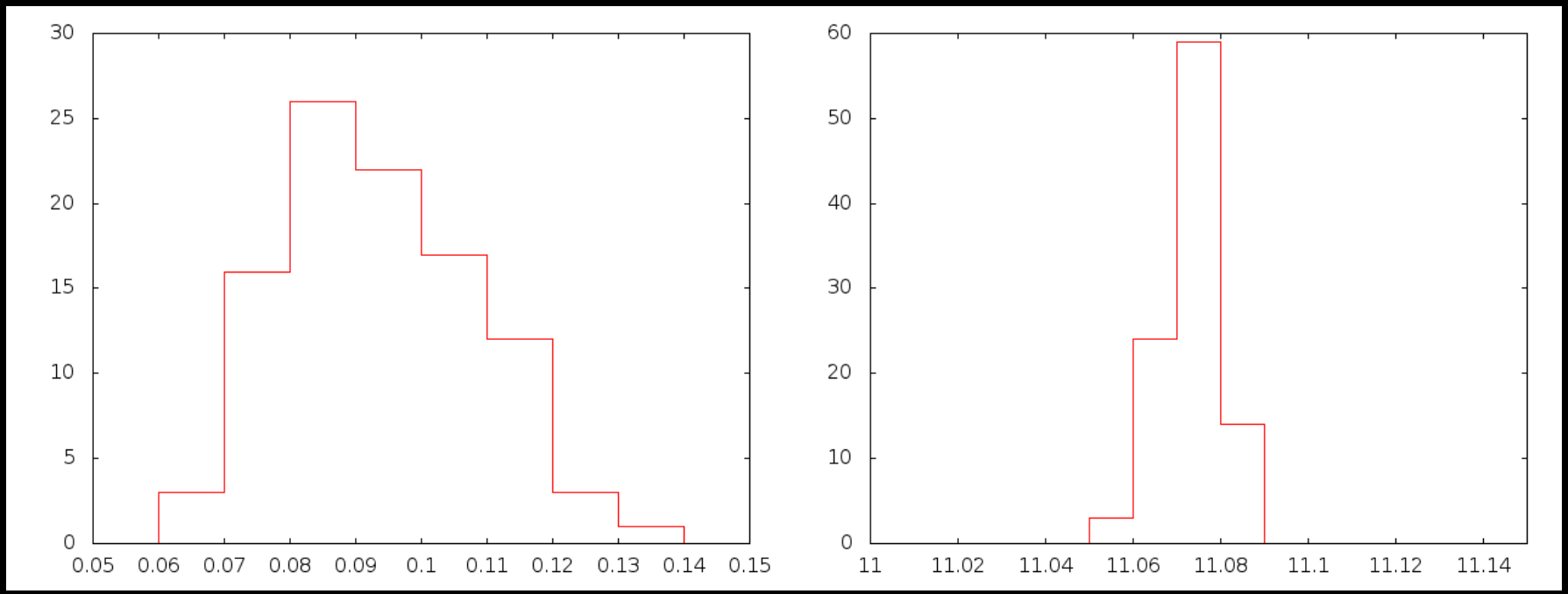
- Writing a code to automatically carry out this process is easy
- Others exist: I've made my own
- It incorporates older codes such as INTRAT and EQUIB
- It also calculates recombination line abundances and the abundance discrepancy
- It propagates uncertainties using a Monte Carlo approach

A nebular abundance analysis code

- MC approach: if uncertainties are given, randomize line fluxes assuming normally distributed uncertainties
- Analyse; store results
- Repeat a few thousand times to well sample the distribution

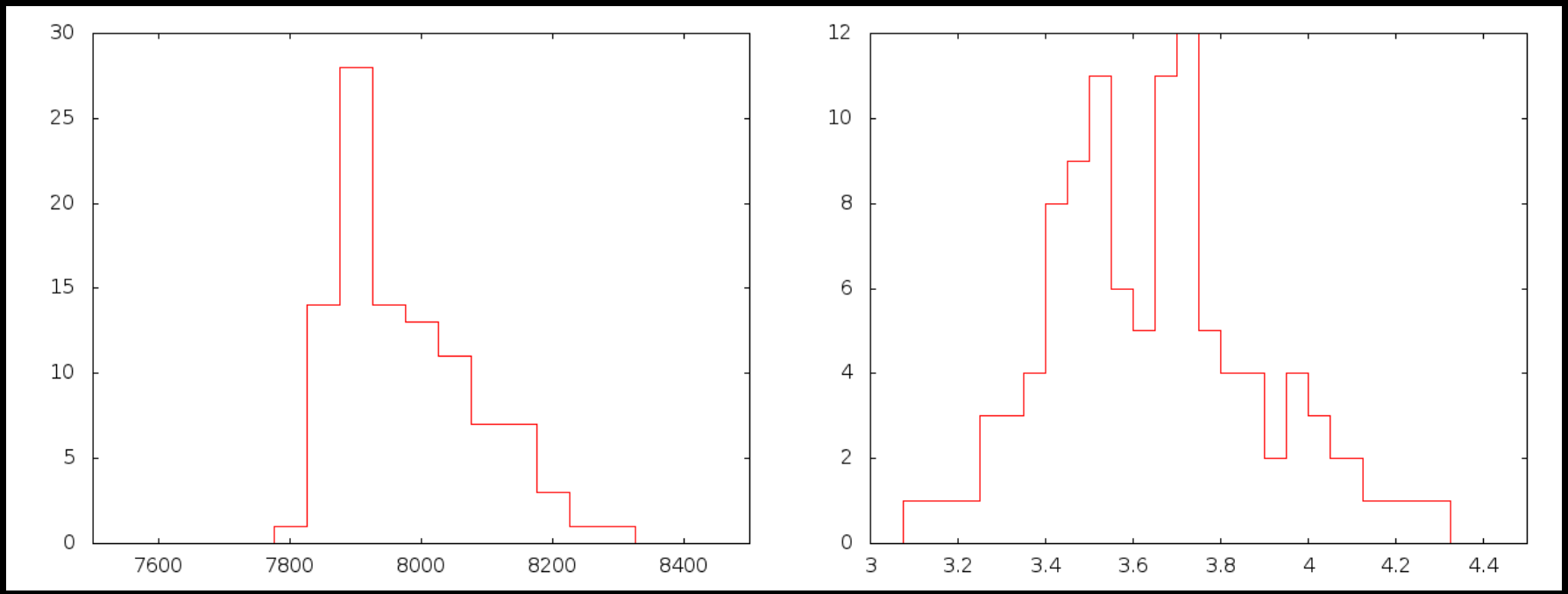
A nebular abundance analysis code

- Some example output, based on 100 realisations of integrated nebular spectrum of NGC 6543:
- Distribution of values of c(Hβ) (l) and He/H abundance (r)



A nebular abundance analysis code

- Some example output, based on 100 realisations of integrated nebular spectrum of NGC 6543:
- Distribution of values of T([O III]) (l) and adf(O) (r)



Incorporating atomic data uncertainties

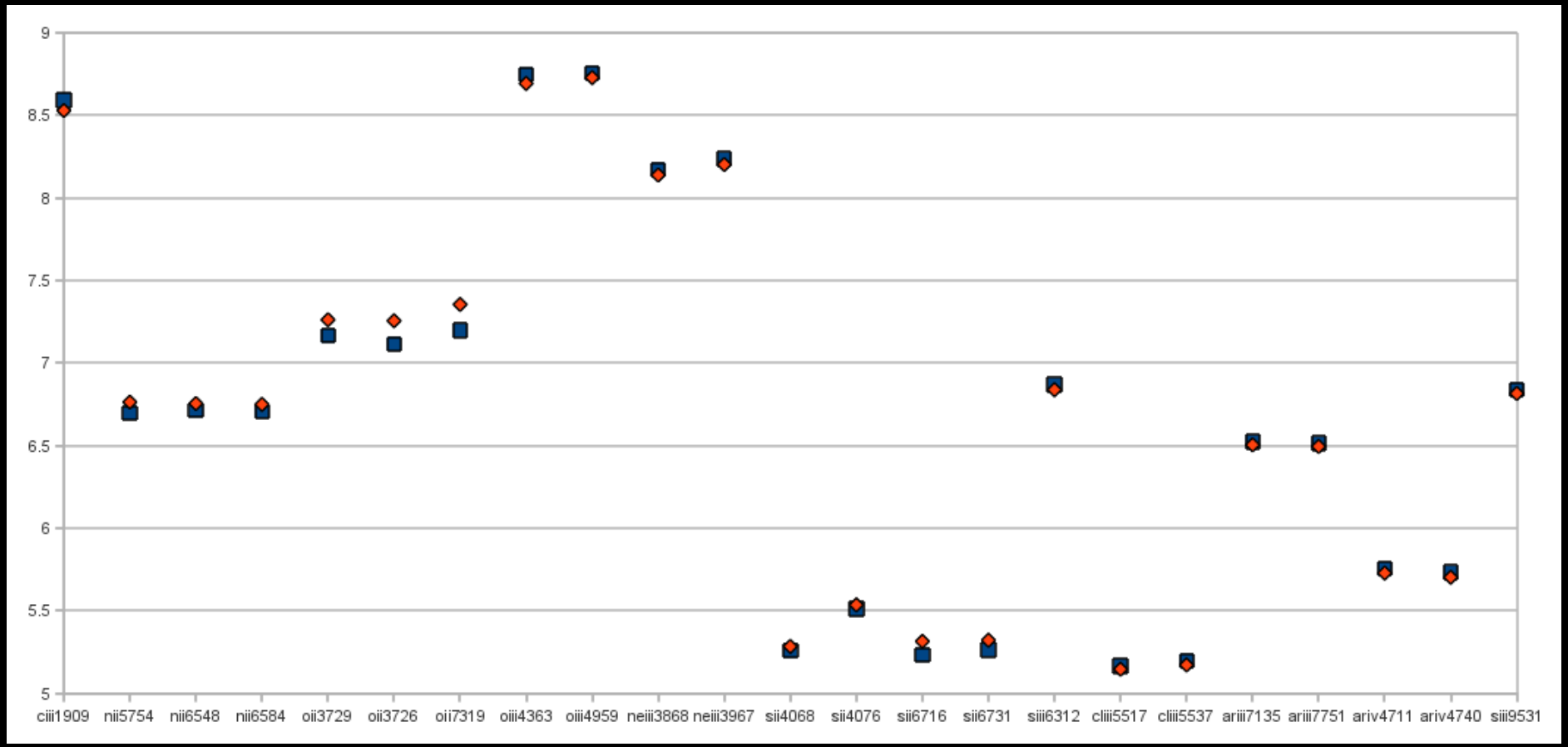
- Statistical uncertainties - how large?
- Normally distributed, or something else?
- Either way, if distribution of uncertainties is known, it is easy to incorporate into MC uncertainty propagation

Incorporating atomic data uncertainties

- Systematic uncertainties - how do they arise?
- My code uses CHIANTI database v5.2. Some errors have come to light:
  - [O II] data wrong - Kisielius et al (2009)
  - [S III] data also wrong - incorrect A-values
- Other uncertainties may exist in the database

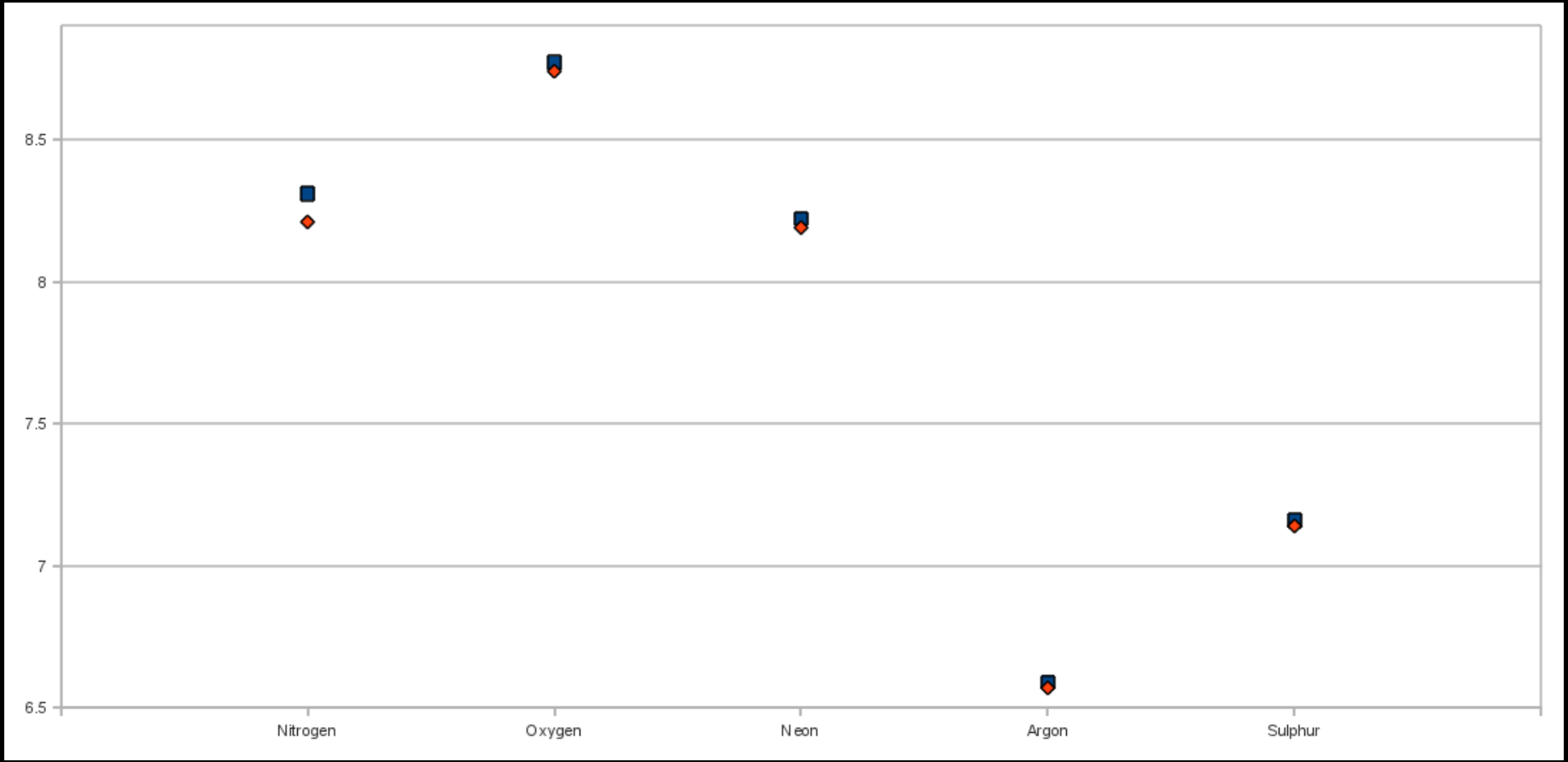
Incorporating atomic data uncertainties

- Effect on ionic abundances: analysis of NGC 6543.



Incorporating atomic data uncertainties

- Effect on total abundances: analysis of NGC 6543.



Incorporating atomic data uncertainties

- Other systematic effects can be uncovered through empirical analyses:
- e.g. O II RL abundances: V5 multiplet almost always overestimated

Investigating systematic uncertainties

- Applying empirical analysis techniques to synthetic emission line spectra (produced e.g by MOCASSIN) can demonstrate systematic uncertainties
- e.g. Ercolano, Wesson & Bastian (2010) investigated effect of spatial distribution of ionising sources on abundance determinations in H II regions
- Found that analyses in which only one temperature diagnostic is available are subject to significant biases, but if two temperatures are available, uncertainties are typically < 0.2 dex
- Current project with Denise Gonçalves at UCL is to determine ICFs for non-spherically symmetric nebulae

Summary

- Understanding chemical abundances in ionised nebulae requires an understanding of the total uncertainties
- Statistical uncertainties are easy to treat, if known
- Systematic uncertainties can be revealed by observations. If undiscovered, can lead to significant errors in abundance determinations.