EARLY STAGES IN THE CHEMICAL EVOLUTION OF GALAXIES:

Climbing the ladder of the metal production in the universe

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The importance of metals

- Metals play a very important role in star formation and stellar evolution. Amongst other things:
  - they control the cooling of the interstellar gas, thus allowing the formation of stars;
  - they affect the radiation transport, through the opacities involved in the different microscopic processes;
  - they have the most important role in the dust formation;
  - also in the mass loss from stars.

The site of metal formation

- Metals are formed inside stars →
  - We expect metal enrichment in the universe to start soon after the formation of the first massive stars.
  - After a very short life, these stars return to the ISM, in explosive events, their newly synthesised chemical elements, heavier than the primordial hydrogen and helium.
  - These ejecta, at some point, will mix with the surrounding gas, help to its cooling and propitiate the appearance of a new generation of stars.

↓

Cycle of cosmic chemical evolution

The more detailed picture

- Not all the metals are returned to the ISM within the same timescales.
  - O,S, Mg … are synthesised in the nuclei of very massive stars and return to the ISM in only a few million years.
  - C, N … are mainly made by intermediate mass stars whose lifetimes are much longer, of the order of 10^9 years.
  - Fe is produced in close binary systems.
- They do not return to the ISM in the same way.
  - Massive stars → explosive events → core colapse SNe.
  - Intermediate mass stars → envelope ejection → PNe.
  - Close binary systems → Type Ia SN.

The ways to exploit this information

- Derive chemical abundances "in situ" → in galaxies at different redshifts.
- Derive chemical abundances at the present epoch (galaxies at redshift zero) + use chemical evolution models to predict their abundances at higher redshifts.

Eventually, both approaches must converge

Then, models can be extrapolated back to even earlier times

Predictions can be made, to be confronted with planned observations

“*In situ*” abundance determinations

WE CAN NOW:

- increase the spatial resolution of spectroscopic observations using the technique of **IFS** to examine and validate the main assumptions underlying the methodologies at use in the derivation of abundances at intermediate to high redshifts:
  - **that the gas ionisation is due only to young massive stars.**
  - **that the star formation modes have the same properties as the ones observed at the present epoch.**

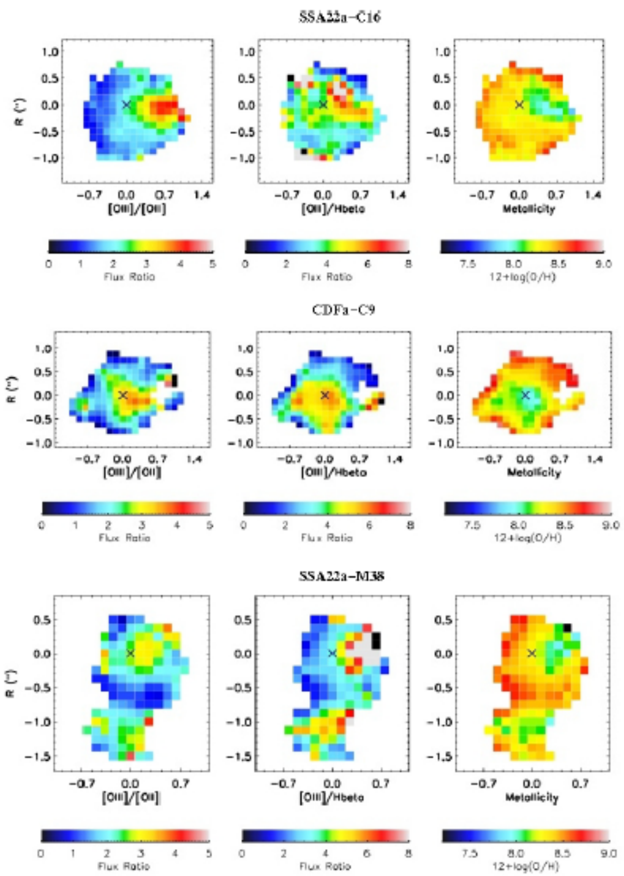
"In situ" abundance determinations

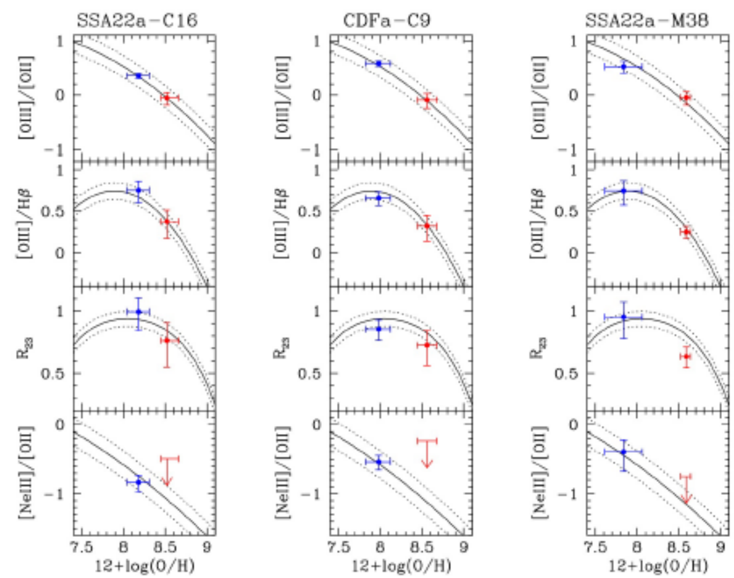
- make progress in the **determination of precise abundances for star-forming galaxies at intermediate redshifts (up to z=1.5)** making use of different leading edge instrumentation already at work or foreseen in the near future.
- **design and implement 2D-Chemical Evolution models** for spiral and irregular galaxies with a spatial resolution that can be adjusted to the existing and/or to come 2D abundance distributions and directly confronted with them.
  - Successful models will then be used to predict abundances of galaxies at different epochs that will be compared to the abundances directly obtained thus allowing the further iteration and improvement of models.

The nature and modes of star formation in the early stages of galaxy evolution

- Careful determinations of abundance distributions over galaxies could provide important pieces of information about their formation processes since gas accretion or gas ejection episodes will leave an imprint on these abundance distributions (see e.g. Cresci et al. 2010: *inverse abundance gradients*).
- In order to do this **we should verify two assumptions**:
  - the ionization of the gas in inner regions of galaxies is due only to star formation processes.
  - the star formation modes dominating at high redshifts are similar to those encountered in the local universe.

“Inverse gradients” in high redshift galaxies



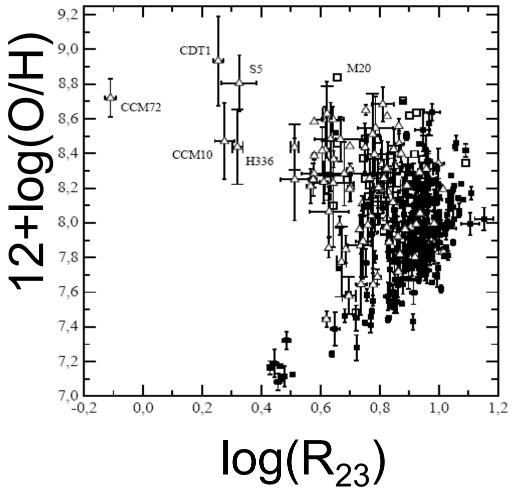


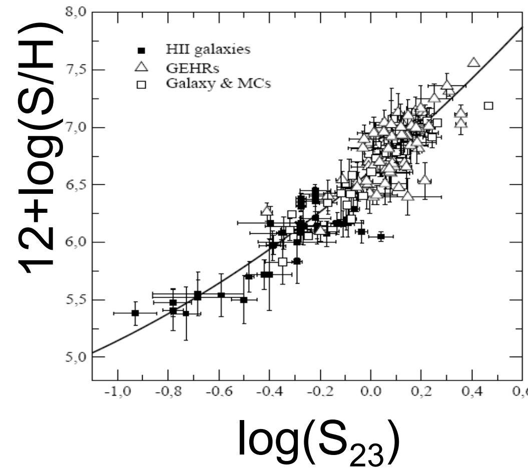
Cresci et al. 2010, Nature, 467, 811

Nebular abundance determinations

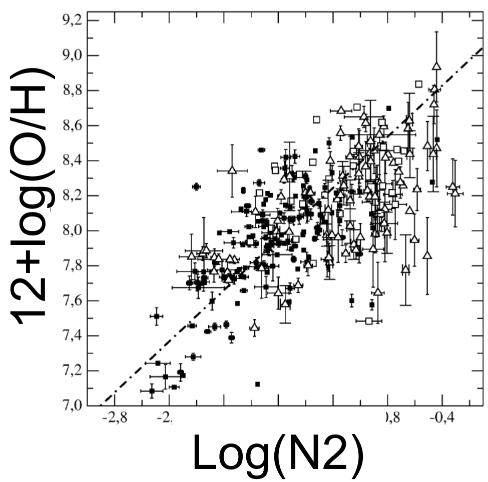
- Most of the observed emission lines in nebulae are collisional excited and their intensities depend exponentially on electron temperature which, in principle, can be derived from appropriate line ratios of auroral to nebular lines.
- The auroral lines are intrinsically weak and difficult to detect.
- It is possible to use the cooling properties of the ionised gas in order 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. One of the most popular calibrators is R_{23}.
- For intermediate-high redshift galaxies, often the N2 parameter is used (*e.g. Cresci et al. 2010; but see Morales-Luis et al. 2014, for risk evaluation).*

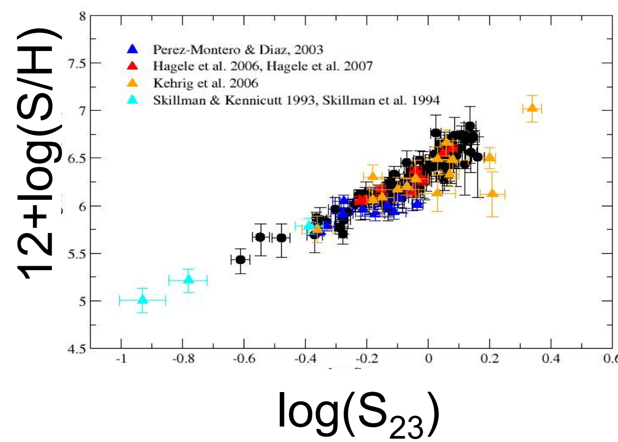
Empirical calibrations





Pérez-Montero & Diaz 2005

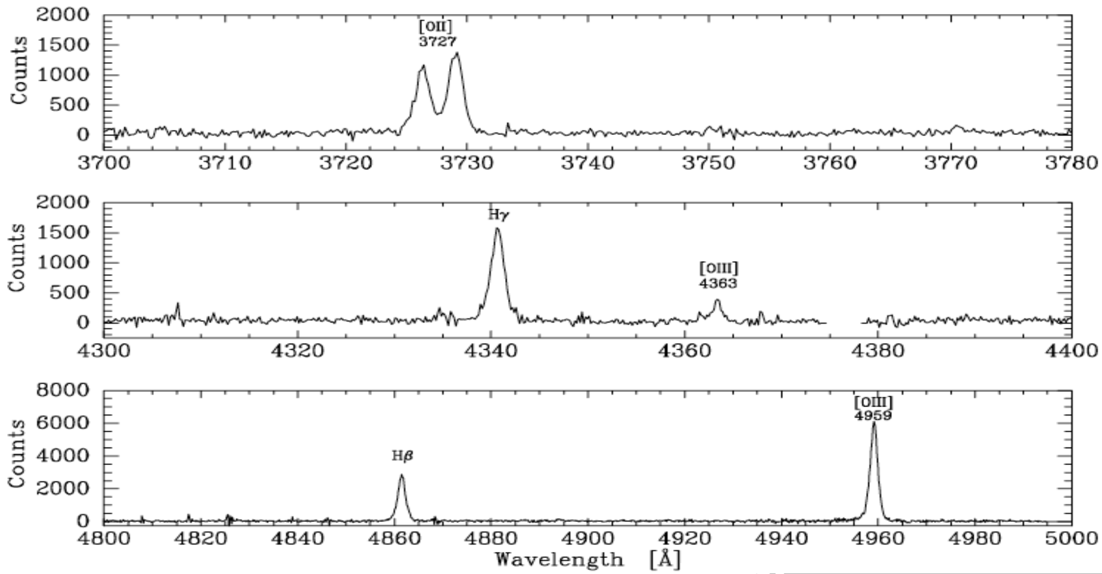




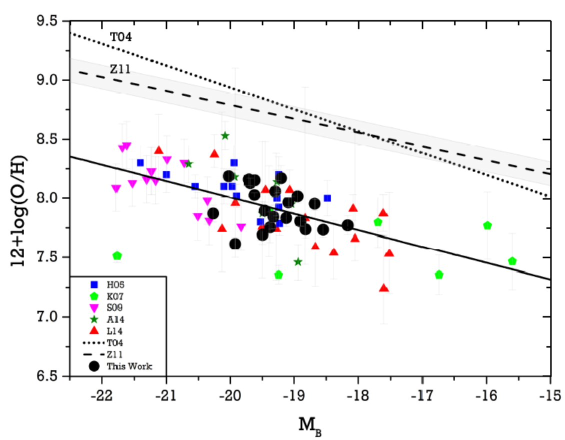
"In situ" abundance determinations

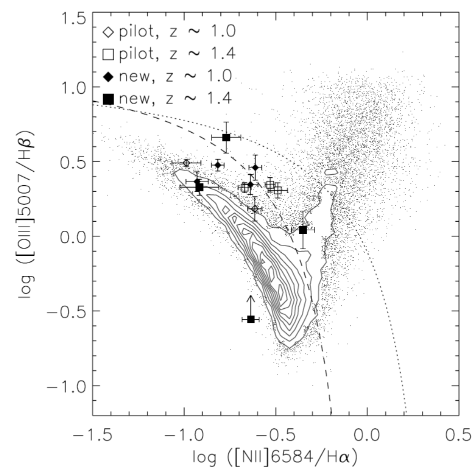
- Up to now, very few intermediate redshift galaxies have directly derived gas phase abundances.
- Only ~ 1% of the thousands of objects from the DEEP-2 Galaxy Redshift Survey (Davies et al. 2003) have been found to display the [OIII] 4363 Å temperature sensitive line.
- The objects studied have metallicities in line with those of other similarly selected objects, and are more metal poor than local systems of similar B-band luminosities and
- The reason for this discrepancy is not yet properly understood.
- **The common assumptions involved in abundances determinations from nebular emission lines might break down at higher redshifts** (Liu et al. 2008). → a sample of star-forming galaxies at $1.0 < z < 1.5$ also selected from the DEEP-2 survey have [OIII]/Hβ and [NII]/Hα emission line ratios offset from the excitation sequence observed in nearby HII regions and SDSS emission line galaxies.

Oxygen abundances of intermediate z galaxies



Pérez, J.M. et al. 2015, MNRAS, submitted





Liu, X. et al. 2008, ApJ, 678, 758

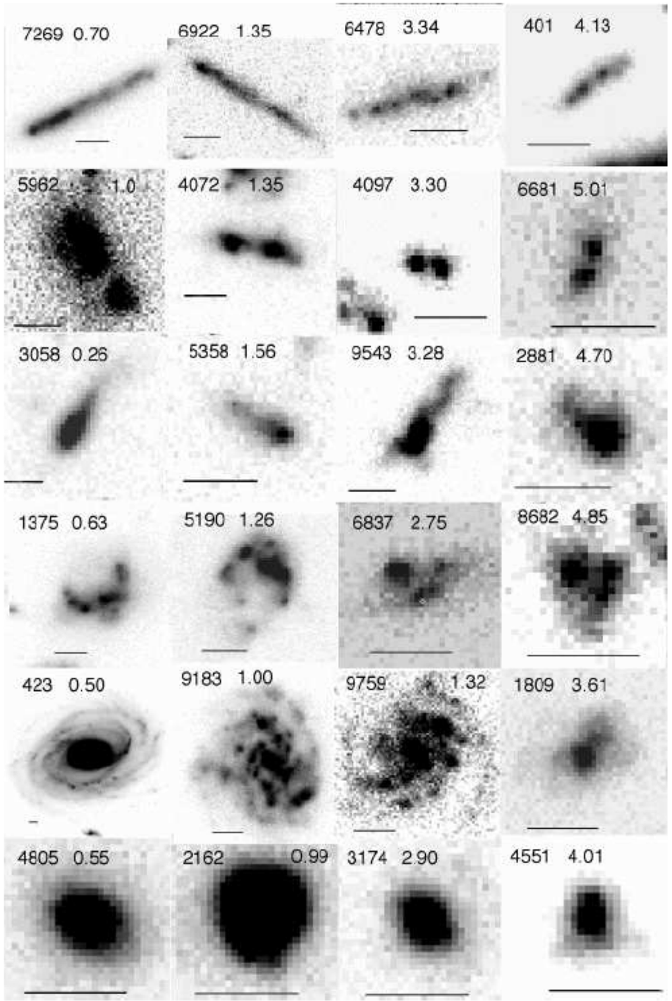
AGN-Star-Forming Connection

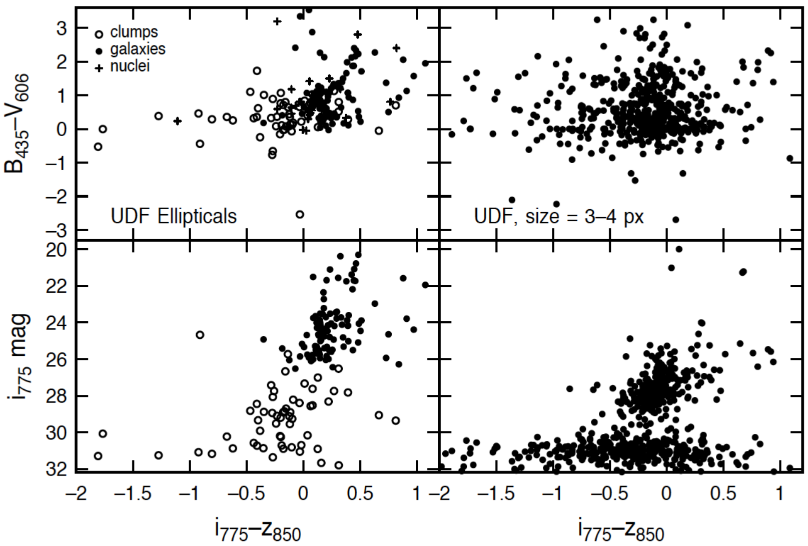
- It is widely accepted that some connection exists between star formation and activity in galactic nuclei:
  - young stars appear as one of the components of the unified model of AGN giving rise to the blue featureless continuum which is observed in Seyfert 2 galaxies;
  - galaxies with powerful AGN tend to have younger-than-average stellar populations;
  - UV light from young stars has been detected in QSO host galaxies showing that there is a physical connection between accretion onto the central massive black hole and the presence of young stars in the inner galaxy.

Star formation modes

- That the star formation modes dominating at high redshifts are similar to those encountered in the local universe might not be entirely be the case:
  - large and massive clumps of star formation have been detected in more than half of the resolved z >1 galaxies in the Hubble UDF.
  - they have sizes of about 2 kpc, estimated ages of ~10 Myr, and masses often larger than 10^8 $M_\odot$. They are so luminous that they dominate the appearance of their host galaxies.
  - massive clumps like these are found in galaxies with a variety of different morphologies, ranging from somewhat normal ellipticals, spirals, and irregulars, to types not observed locally.

Clump cluster galaxies





Elmegreen, D. et al. 2007, ApJ 658, 763

Circumnuclear star-forming regions

- In some respects, the clumps in high redshift galaxies resemble the Circumnuclear Star Forming Regions (CNSFR), a common mode of star formation found close to galactic nuclei. They
  - have sizes of about a few hundred pc;
  - show integrated Hα luminosities which overlap with those of HII galaxies;
  - seem to be ionized by luminous compact star clusters;
  - are young (age < 10^7 yr) and massive (10^6-10^8 $M_\odot$ from CaT);
  - contribute substantially, in the UV-B bands, to the emission of the entire nuclear region;
  - seem to have more than a stellar generation, with the ionising cluster having ~10% of the total dynamical mass.

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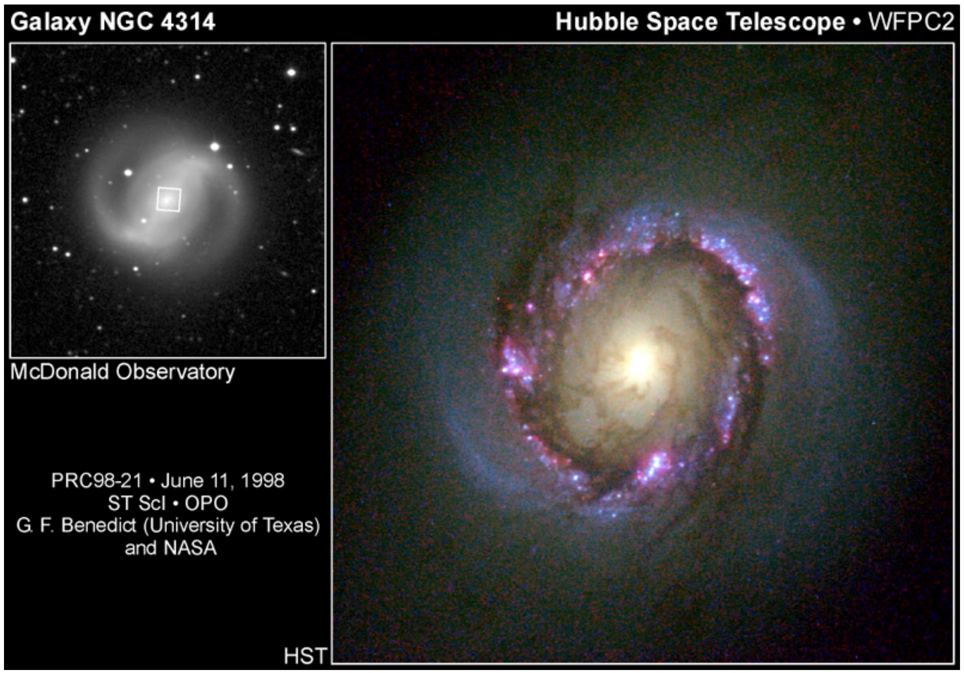
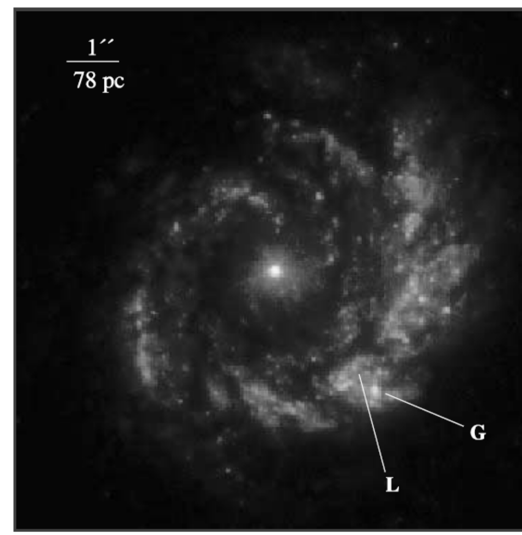
CNSFR





STIS UV image of the nuclear region of NGC 4303 (Colina el al. 2002, ApJ 579, 545)

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CNSFR

- Their ionisation structure is more similar to that of HII galaxies than to disc HII regions → relatively hard ionising sources, similar to what is found for star forming galaxies with 1.0<z<1.5 (e.g. Erb et al. 2006).
- Our study CNSFR in different galaxies show a complex kinematical behaviour with, at least two components, a narrow one dominating the hydrogen recombination lines and with a constant value of velocity dispersion, and a broader one dominating the [OIII] lines with a larger velocity dispersion that is similar to the stellar one, as measured from the Ca Triplet lines (Hägele et al. 2013).

The complex kinematical behaviour of CNSFR

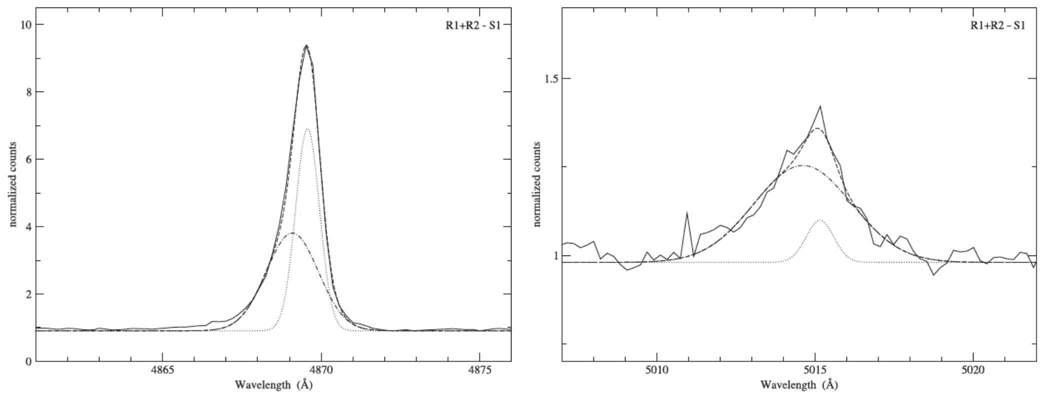

Figure 6. Sections of the normalized spectrum of R1+R2 (solid line). The left-hand panel shows from 4861 to 4876 Å containing Hβ and the right-hand panel shows from 5007 to 5022 Å containing the [O III] λ 5007 Å emission line. For both, we have superposed the fits from the NGAUSSFIT task in IRAF; the dash–dotted line is the broad component, the dotted line is the narrow component and the dashed line is the sum of both.

Hägele, G. et al. 2009, MNRAS, 396, 2295

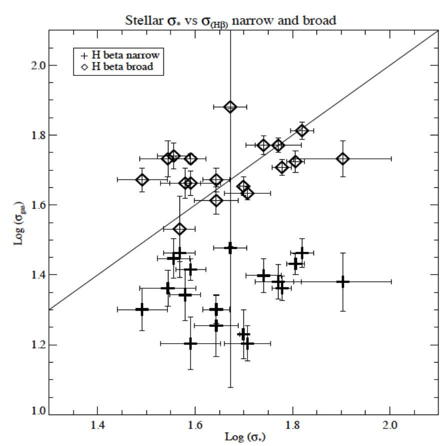

Figure 4. Gaseous (Hβ) versus stellar velocity dispersions for all the observed circumnuclear regions. The continuous line represents: $\sigma_{gas} = \sigma_{stars}$.

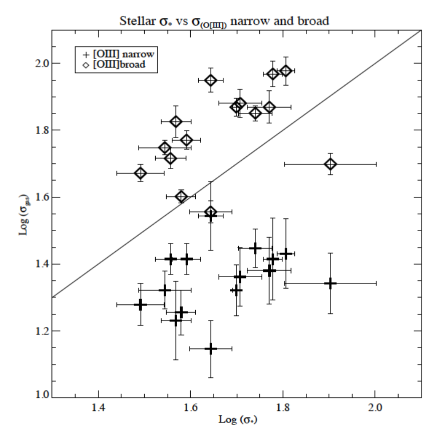

Figure 5. Gaseous (O[III]) versus stellar velocity dispersions for all the observed circumnuclear regions. The continuous line represents: $\sigma_{gas} = \sigma_{stars}$.

Hägele, G. et al. 2013, MNRAS, 432, 810

Some words of caution …

- In a galaxy like NGC 3310, ~ 30% of the total observed FUV emission is produced within a radius of 10”. At redshifts of z ~ 2–3, this structure would be confined to a region 0.2” in diameter for **Ω**=1 and would appear point-like in low-resolution observations. Consequently, in the absence of diagnostic spectroscopy, a high-redshift NGC 3310–like object could be mistaken for an active galactic nucleus (AGN) (Smith et al.1996).
- If hydrogen recombination lines and collisionally excited lines are arising from distinct kinematical components, the line intensity ratios used for any nebular analysis lose their meaning.
- In summary, **the reliable derivation of metallicities in the centers of galaxies at any redshift** requires a thorough understanding of the ionisation mechanisms at work in these places in what concerns to both thermal and non-thermal components and the spatial deconvolution of them.

Observational approach

- Modes of star formation
  - The best strategy to study the complex star forming regions in galaxies is the use of **Integral Field Spectroscopy.**
  - For CNSFR both high spatial resolution and high spectral resolution are needed. Instruments like **GMOS** (Gemini) are probably a good choice.
  - For clumps in galaxies at redshift $\lesssim$1.0 probably IFUS similar to **MUSE** will be needed.

Observational approach

- “In situ” abundance determinations
  - We do not require a complete sample but the selected sample should be representative of the population of galaxies at the redshift range explored.
  - Samples can be gathered from e.g. DEEP-2 (Keck) or VVDS (VLT).
  - X-shooter would be a good instrument that could provide abundances of He, O, Ne, N, S and Ar.
  - Maybe EMIR at GTC in the future …

"Fosil" abundance distributions

- The importance of the knowledge of abundance distributions in galaxies is widely recognised as a probe of their chemical evolution and star formation histories. This information is central to guide theoretical models of the formation and evolution of galaxies.
- What is referred to as "abundance" or "radial abundance gradient" of a galaxy represents in fact an observational limitation derived from the need to use fixed aperture and/or long-slit spectroscopy.
- The information actually required to deeply approach the issue of the formation and evolution of disc galaxies is the map of the abundance distribution of the different chemical elements.

Abundance calibrators maps

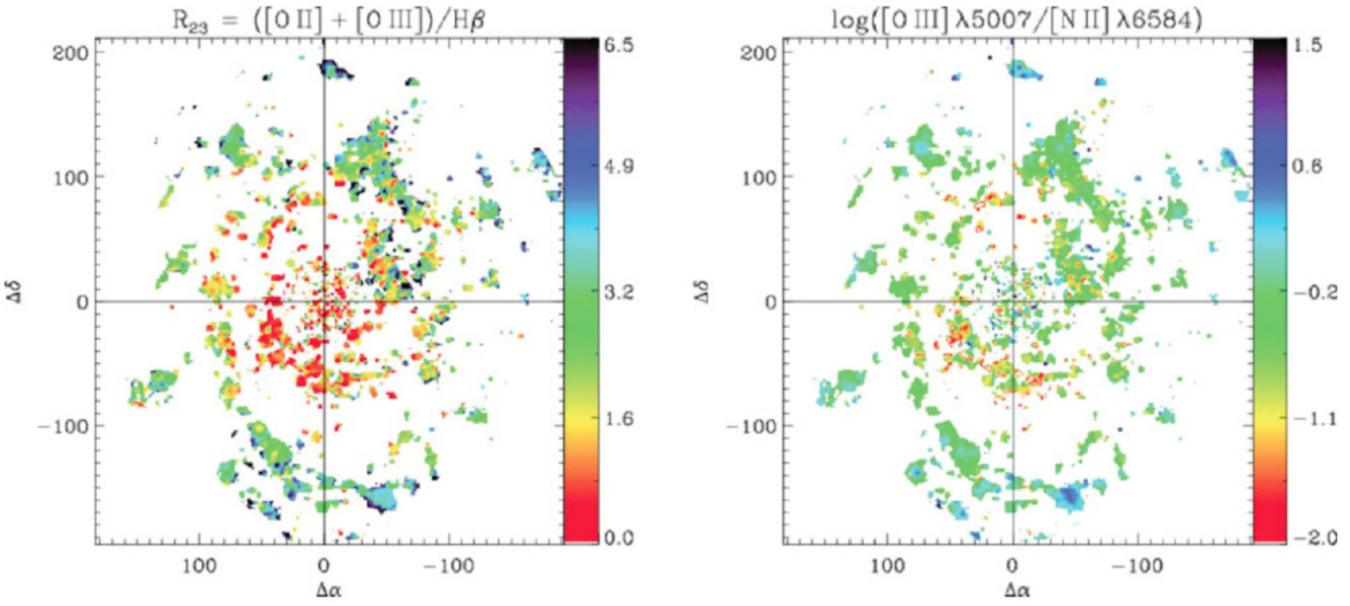

Fig. 3. *Left panel: the spatial distribution of the R_{23} parameter for NGC 268 from Rosales-Ortega et al. (2010). Right panel: same for the logarithmic [OIII]5007/[NII]6584 ratio in the same galaxy.*

Observational approach

- 2D abundance distributions
  - **IFS** or, at least, **MOS is required.**
  - CALIFA provides a useful set of data in the Northern hemispher. SAMI will do the same but for the Southern hemisphere. IFS surveys covering wavelengths up to 1 μm are under way.
  - **Reliable abundance determinations using empirical calibrators will require to widen the spectral range to encompass the [SIII] lines at 9069, 9532 Å.**
    - MaNGA → 360-1000 nm at R=2000.

muchas gracias
thank you …