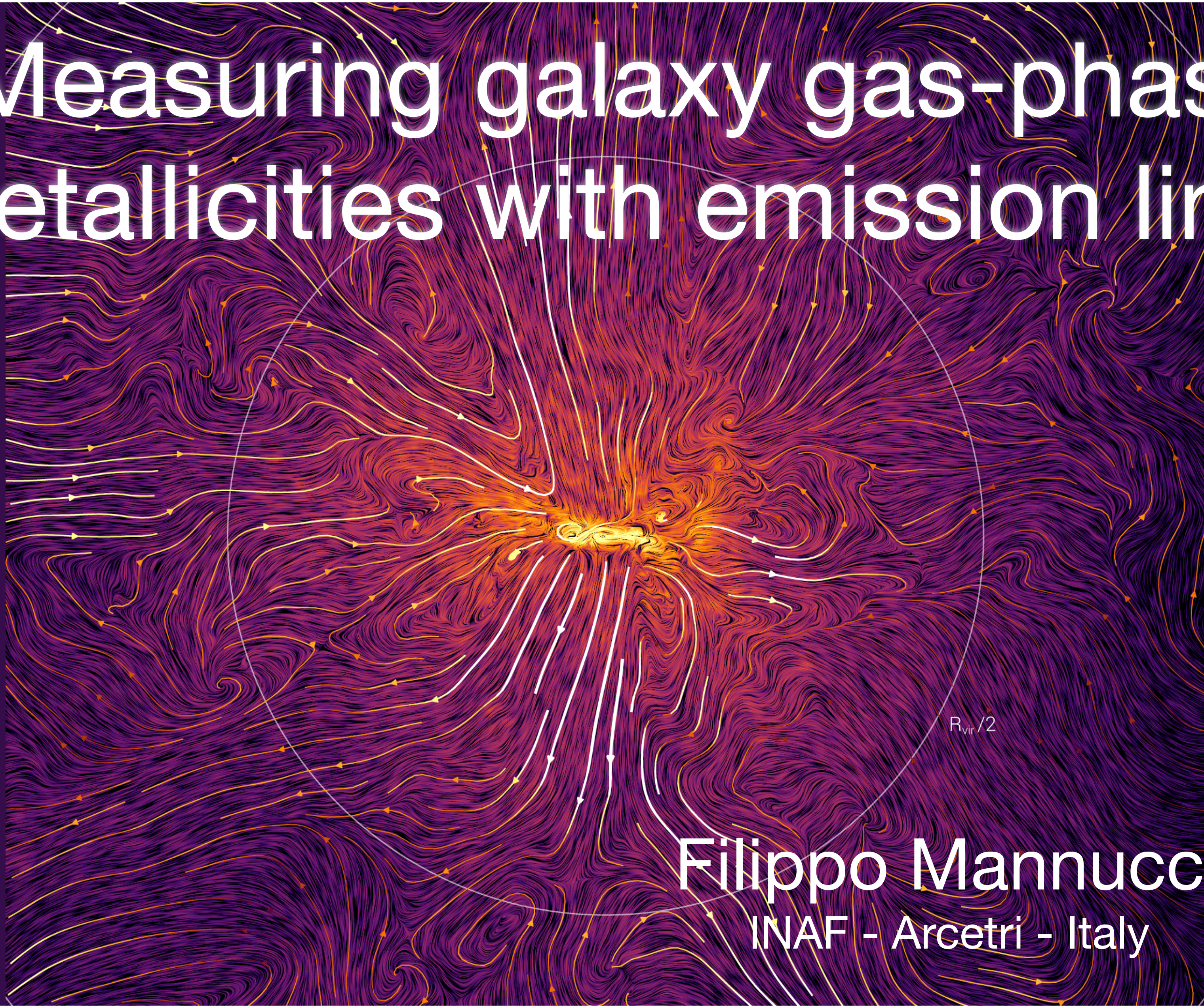
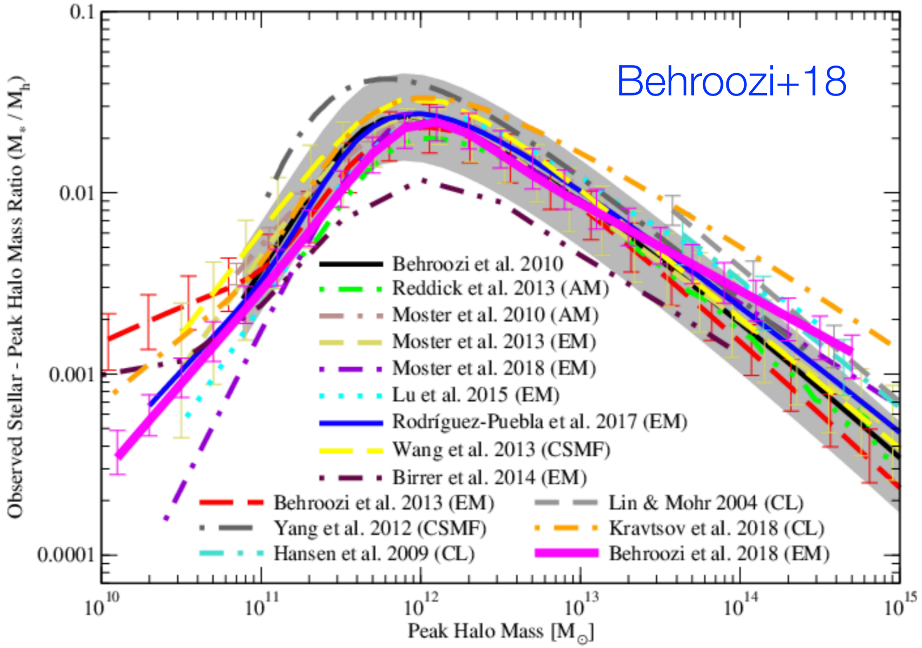
# Measuring galaxy gas-phase metallicities with emission lines

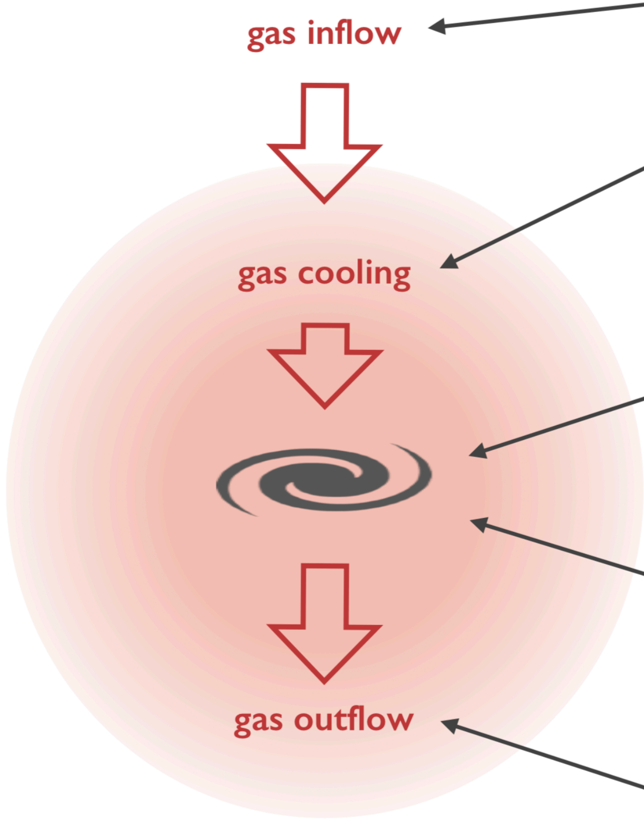



Filippo Mannucci
INAF - Arcetri - Italy

INAF - Arcetri

# The need for feedback




Man & Belli 18

**(i) Gas does not accrete**
- Cosmological starvation

**(ii) Gas does not cool**
- Virial shock heating
- AGN feedback
- Gravitational heating
- Stellar feedback

**(iii) Cold gas does not form stars**
- Morphological quenching
- Bar quenching
- AGN feedback
- Magnetic fields

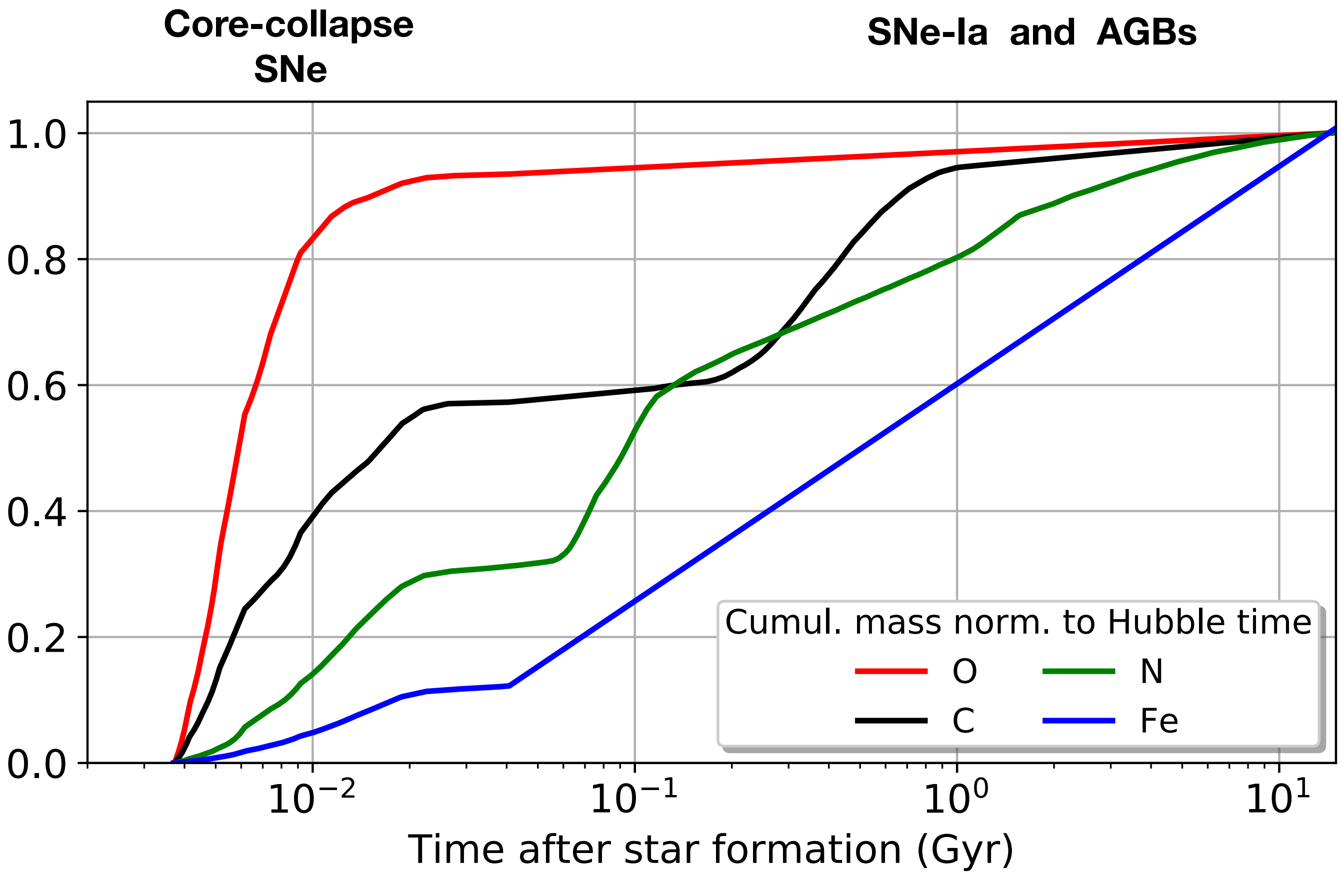
**(iv) Cold gas is rapidly consumed**
- Mergers
- Disk instabilities
- Positive AGN feedback

**(v) Gas is removed**
- AGN feedback
- stellar feedback
- ram-pressure stripping

Croton+06, Dekel+06, Martig+09, Fabian+12, Schawinski+14, Hopkins+14, Jaffe+15, Peng+15, Stark+16, Hirschmann+16, Harrison+17

# Time scales

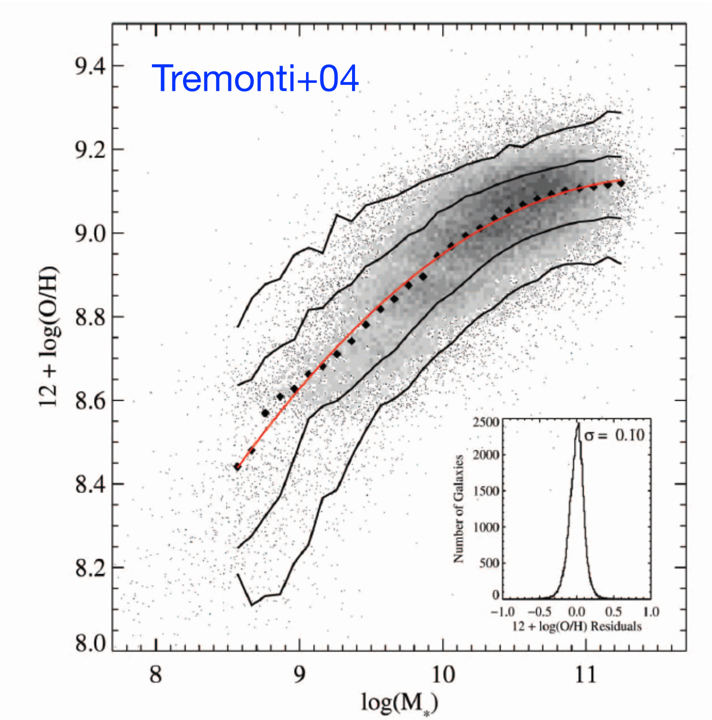
Amount of metals produced by an SSP normalized to a Hubble time



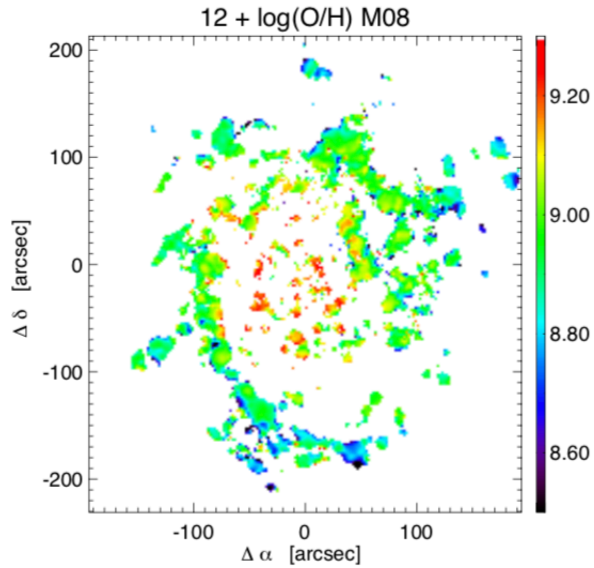

Maiolino & Mannucci+19

# Integrated and resolved

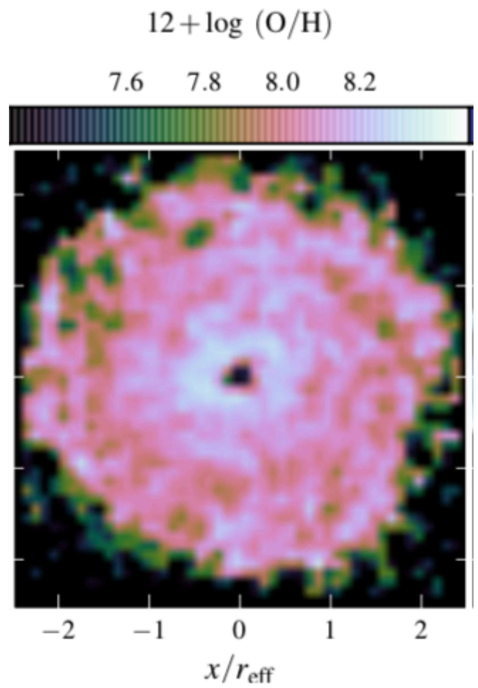
Integrated values for each galaxy




Resolved/gradients



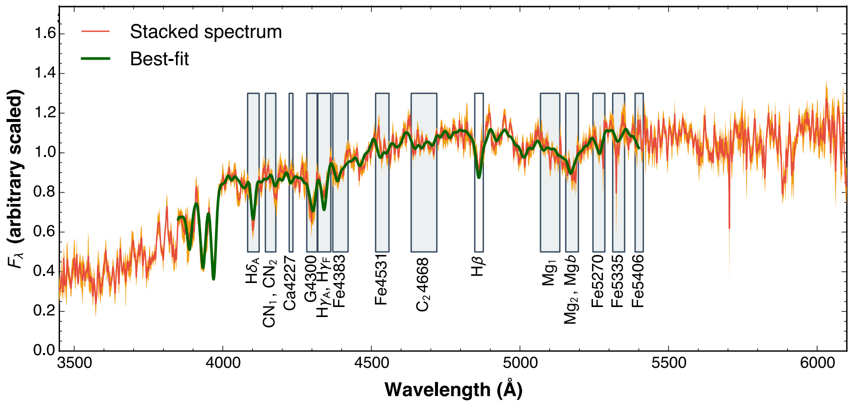

Belfiore+15



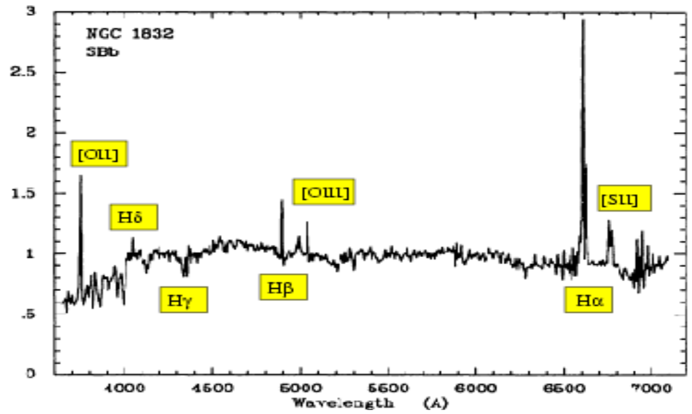

Tissera+16

# Metallicities

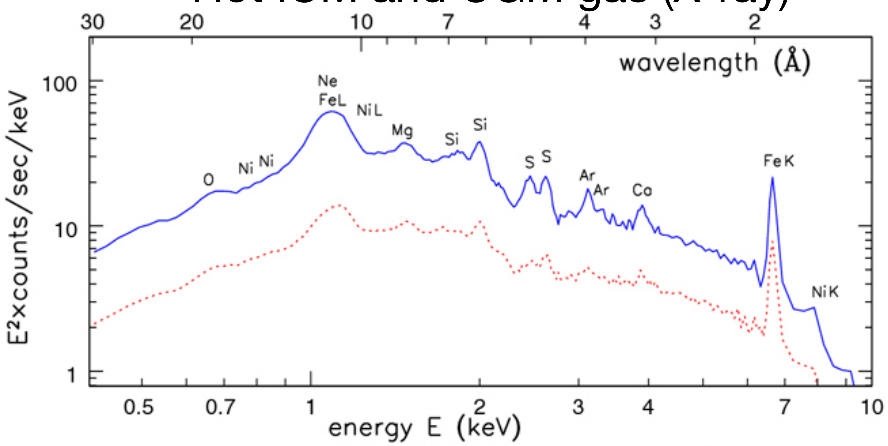
## Stellar metallicity (UV+opt+nearIR)



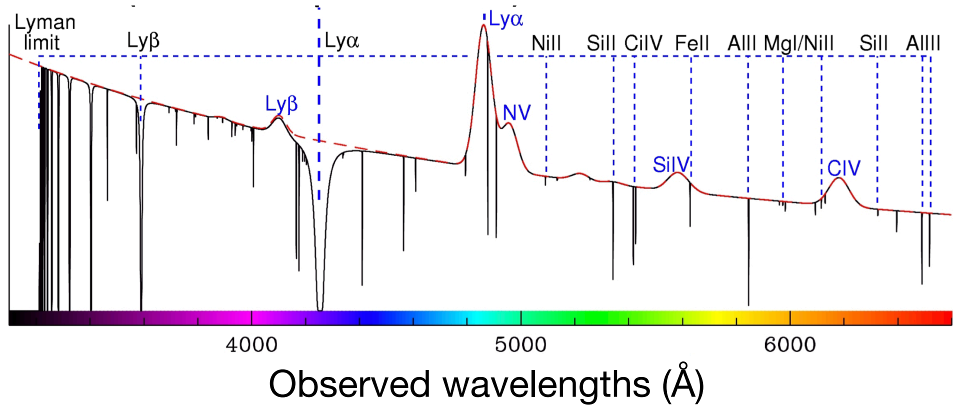

## warm ISM (UV+opt+nearIR)




## Hot ICM and CGM gas (X-ray)




## ICM/CGM (UV absorptions)

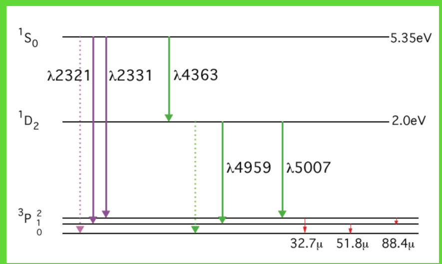


# Measuring Gas-phase metallicity

## 1. CEL → Te

[OIII] 4363/5007
[NII] 5755/6548
[SII] 6312/9532

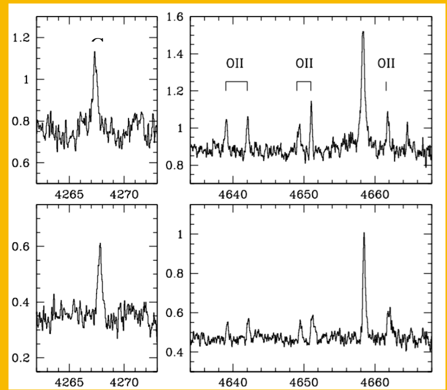
- homogeneous regions (Te, ne, X)
- *Hβ* and *CEL* from the same region
- LTE
- simple geometry




## 2. RL

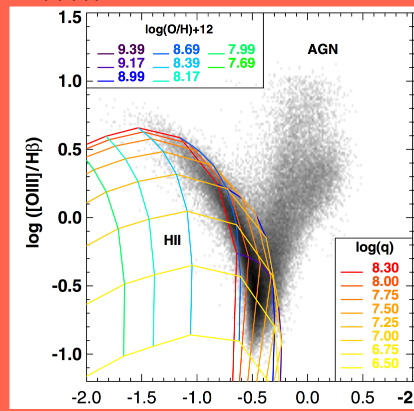
OII4650
CII4267

- most reliable?
- very faint lines
- different abundances from different lines
- inconsistencies




## 3. photo-models

- ionising continuum
- ionisation parameter
- gas density
- geometry
- abundance ratios
- dust distribution
- …..




**strong line method**

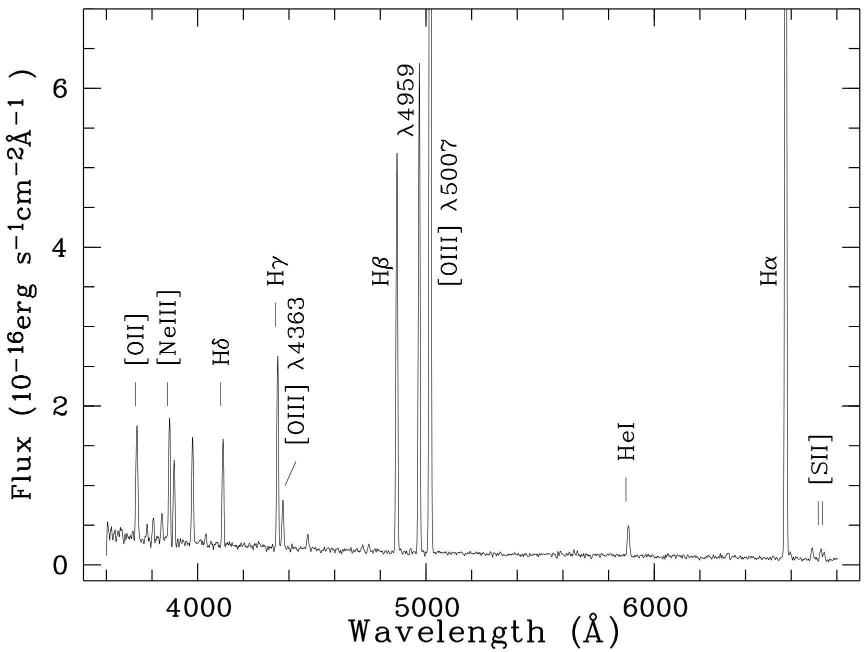
# Three methods

## 1. “direct” methods based on Collisionally-Excited lines (CEL)

$$\frac{N(X^{+i})}{N(H^{+})} = \frac{I(\lambda)}{I(H\beta)} \frac{\epsilon(H\beta)}{\epsilon(\lambda)}$$

$$\epsilon(\lambda) = \frac{hc}{\lambda} 8.63 \times 10^{-6} (\Omega/\omega_1) T_e^{-0.5} \boxed{e^{-\chi/kT_e}}$$

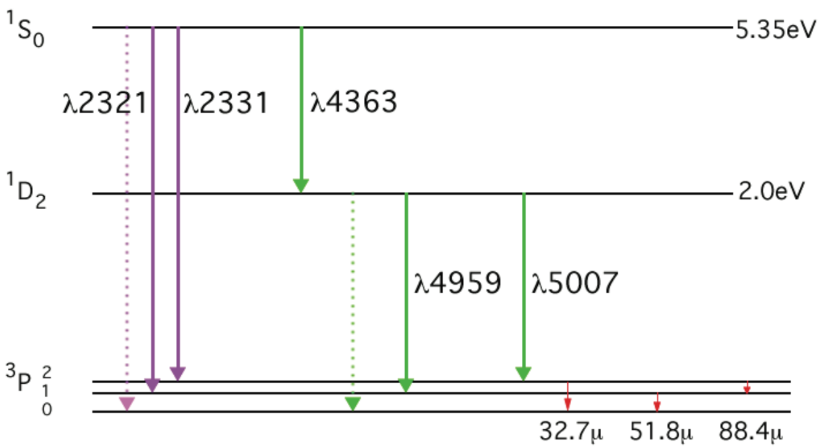
Measuring temperature: 'Te' Method




Kniazev+00

# Three methods

## 1. “direct” methods based on Collisionally-Excited lines (CEL)




Te from flux ratios of CEL lines with different excitation potential:

- [OIII]1661/5007
- [OIII] 4363/5007
- [OII]7320/3727
- [NII] 5755/6548
- [SII] 6312/9532

Trace different parts of the HII regions

Oxygen = main coolants → Te is anticorrelated with abundance
→ auroral line flux anticorrelate with abundance (very faint at Z>Z⊙)

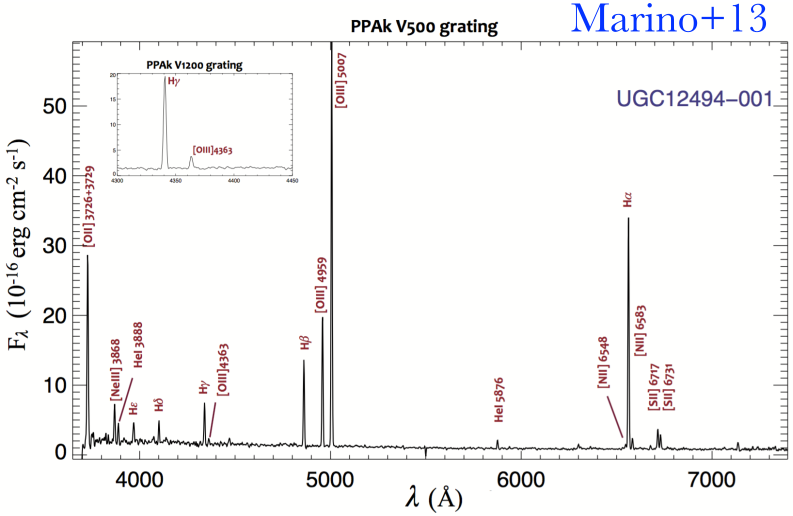
Auroral/Balmer ~ $10^{-2}$

# Three methods

## 1. "direct" methods based on Collisionally-Excited lines (CEL)

Hypotheses:
- isothermal regions
- *Hβ* and *CEL* from the same region
- LTE
- all relevant ionisation states observed

Marino+13




$$\text{[OIII]:} \quad \frac{j_{\lambda 4959} + j_{\lambda 5007}}{j_{\lambda 4363}} = \frac{7.90 \exp(3.29 \cdot 10^4/T)}{1 + 4.5 \cdot 10^{-4} n_e/T^{1/2}}$$

$$\text{[NII]:} \quad \frac{j_{\lambda 6548} + j_{\lambda 6583}}{j_{\lambda 5755}} = \frac{8.23 \exp(2.50 \cdot 10^4/T)}{1 + 4.4 \cdot 10^{-3} n_e/T^{1/2}}$$

Problem: I([OIII]4363)/(Hβ) ~ $10^{-2}$
- detected in low-Z local galaxies
- detected in stacks

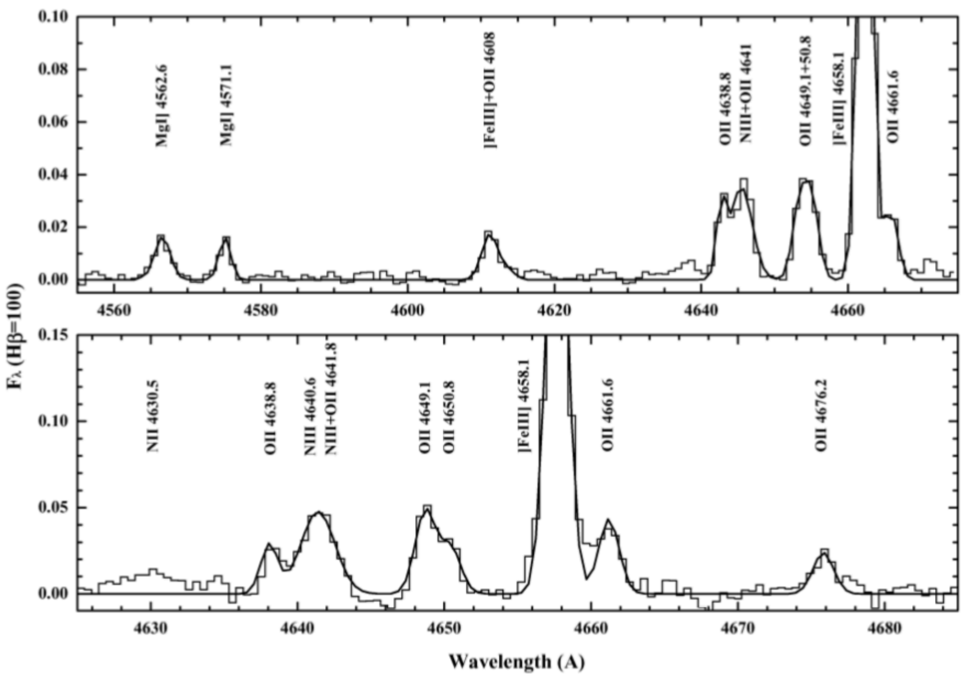
Dinerstein 90; Skillman 98; Garnett 02; Stasinska 07, Jones+15

# Three methods

## 2. “direct” methods based on recombination lines (RL)

$$\epsilon(\lambda) = h\nu q_{rec}(\lambda) = \frac{hc}{\lambda}\,\alpha_{eff}(\lambda),$$

$$\frac{N(\mathrm{X}^{i+1})}{N(\mathrm{H}^{+})} = \frac{\lambda(\text{Å})}{4861}\,\frac{\alpha_{\mathrm{eff}}(\mathrm{H}\beta)}{\alpha_{\mathrm{eff}}(\lambda)}\,\frac{I(\lambda)}{I(\mathrm{H}\beta)},$$




OI 8446,8447
OII 4639, 4642,4649
OIII 3265
OIV 4631,
NII 4237,4242,
NIII 4379
CII 4267
CIII 4647
CIV4657.

$$\frac{I(CII\lambda4267)}{I(H\beta)} \qquad \frac{I(OII\lambda4650)}{I(H\beta)} \sim 10^{-3}$$

Only a few regions

Peimbert+03,04, 07,14, Tsamis+03, Esteban+04,14; García-Rojas and Esteban 07, López-Sánchez+07, Toribio San Cipriano+17

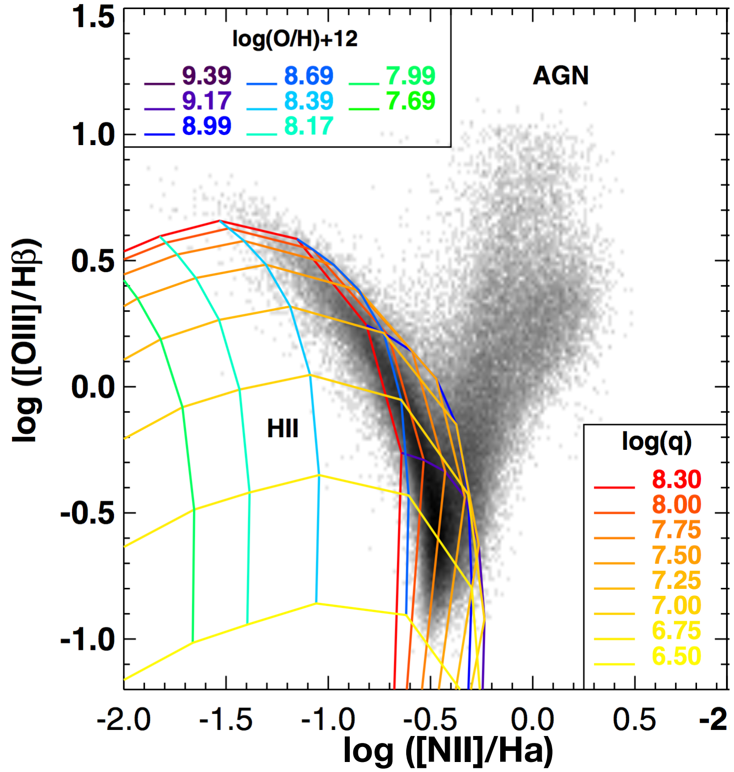
# Three methods

## 3. Photoinization models ("theoretical" method)

Kewley+14

Assumptions:

- shape of the ionizing continuum
- ionisation parameter
- gas density
- geometry
- chemical abundances
- dust distribution
- dust depletion
- clouds ionization bound
- constant density/pressure
- …..




Single regions rather than a statistical distribution

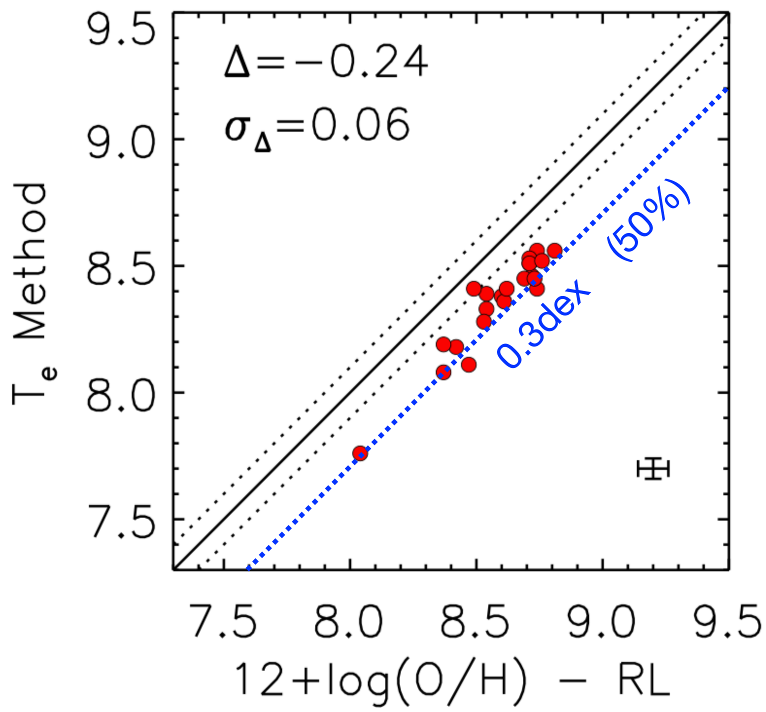
$U = q/c = Q_{ion}/(4\pi r^2 n_e c)$

CLOUDY (Ferland+13), Mappings (Binette+85; Sutherland and Dopita 93; Dopita +13)

# Large differences: RL vs. Te

- Te and RL only on a few HII regions
- Te only in low-Z galaxies, RL only at high-Z
- Z(RL) - Z(Te) ~ 0.2-0.3
- Constant, does not depend on HII properties

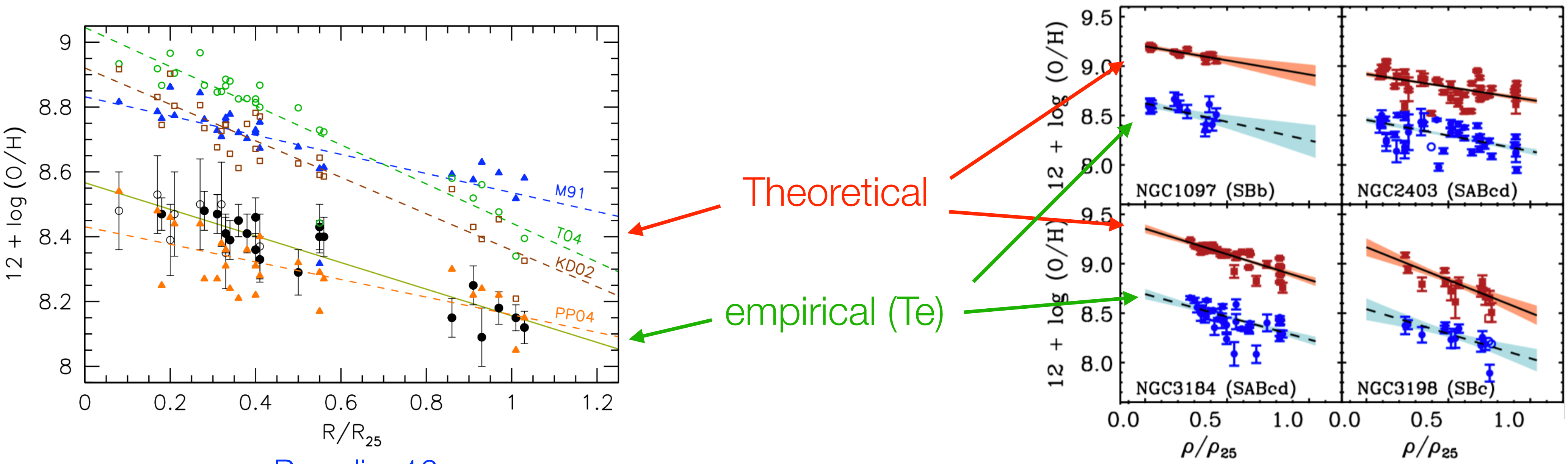
Lopez-Sanchez+12, Blanc+15




| Effect | Best value | |
|---|---|---|
| | Te | RL |
| Temperature fluctuations | | RL |
| High density clumps ($N_e$>$10^5$ $cm^{-3}$) | | RL |
| Chemical inhomogeneities | Te | |
| Flourescence | Te | |
| NLTE effects | | |
| Diffused Ionized gas (DIG) | | |

# Large differences: Te vs theoretical

Theoretical values usually higher (0.2-0.6) than Te ones



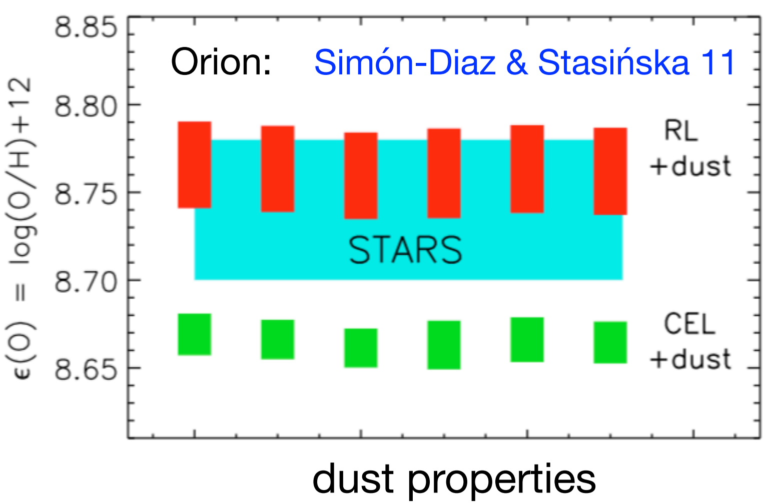

Bresolin+16 Moustakas+15

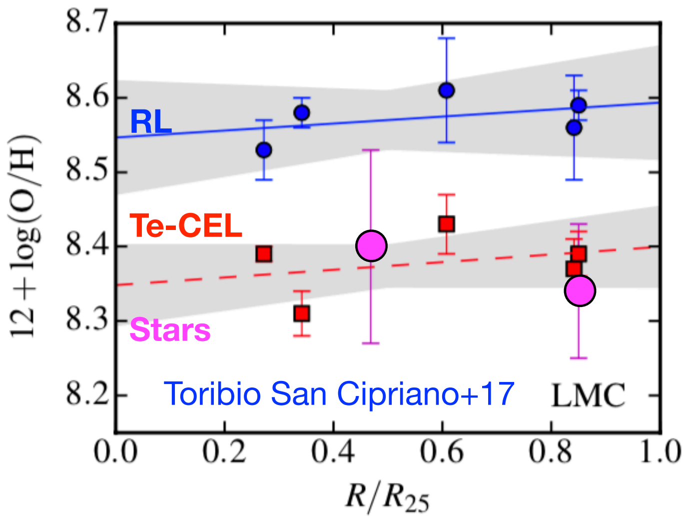
Bresolin+09, Simon-Diaz+10,11, Gazak+15, Davies+16

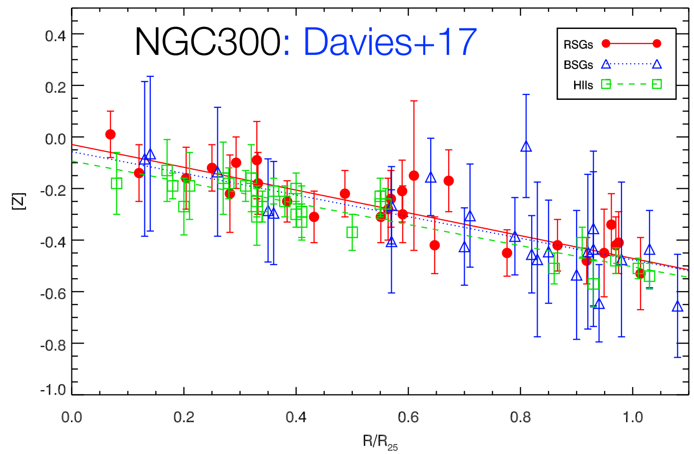
# Which (if any) is right?

Comparison with young stars, RSG and BSG

Reliable abundances based on high-res spectroscopy and stellar models



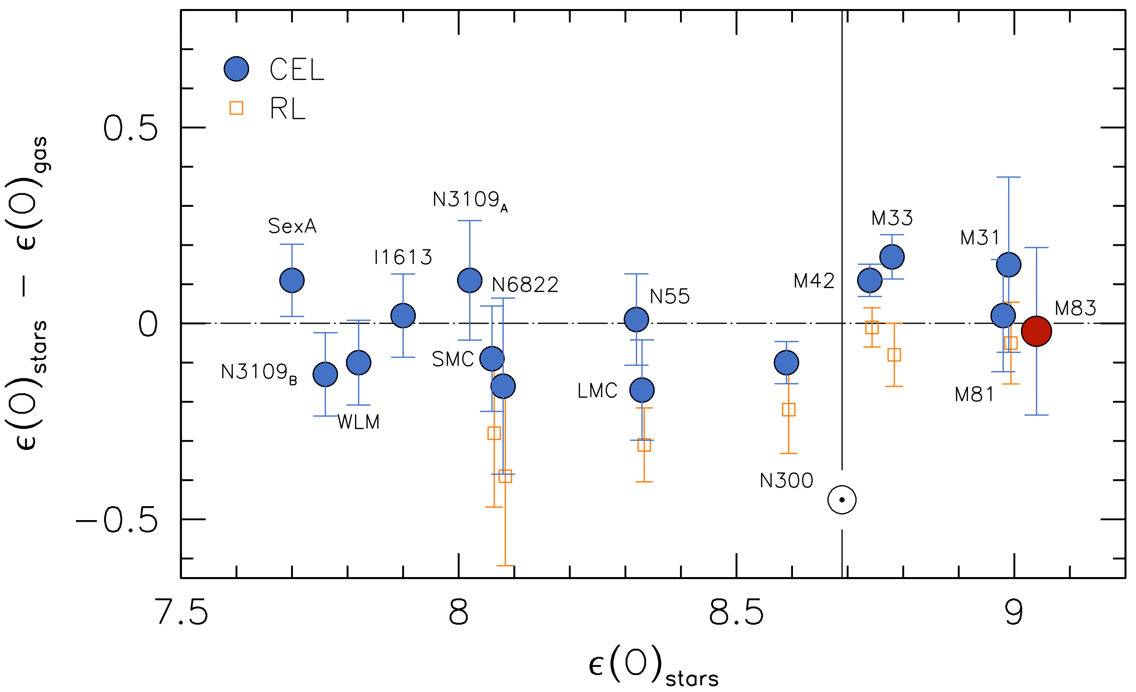




Conflicting results, depend on:

- How stellar metallicities are computed
- Abundance ratios assumed
- How RL and Te metallicities are computed
- Radial gradients inside galaxies
- Corrections for dust depletion

Bresolin+07, Simón-Diaz+10, Simón-Diaz & Stasińska 11, Kudritzki+12, Hosek+14, Lardo+15, Gazak+15, Bresolin+16; Davies+17, Toribio San Cipriano+17

# Measuring Gas-phase metallicity




Results:

- Agreement between empircal gas-phase and stellar metallicities
- Te-CEL works better over a large range of (sub-solar) metallicities
- RL better at high (super-solar) metallicities?

**Te-CEL**

# Strong line calibrations

Based on Te (emprical) or models (theoretical)

- measure metallicity with one of the previous methods
- compare metallicity with line flux ratios
- calibrate the relations
- HII and galaxies

1. Empirical

   Pilyugin 00,01, 03, Denicolò+02, Pilyugin & Thuan 05, Pérez-Montero & Díaz 2005, Stasińska 06; Yin+07; Peimbert+07, Pilyugin+10, 12; Marino+13;, Bianco+15, Brown+16, Pilyugin and Grebel 16, Curti+17,19

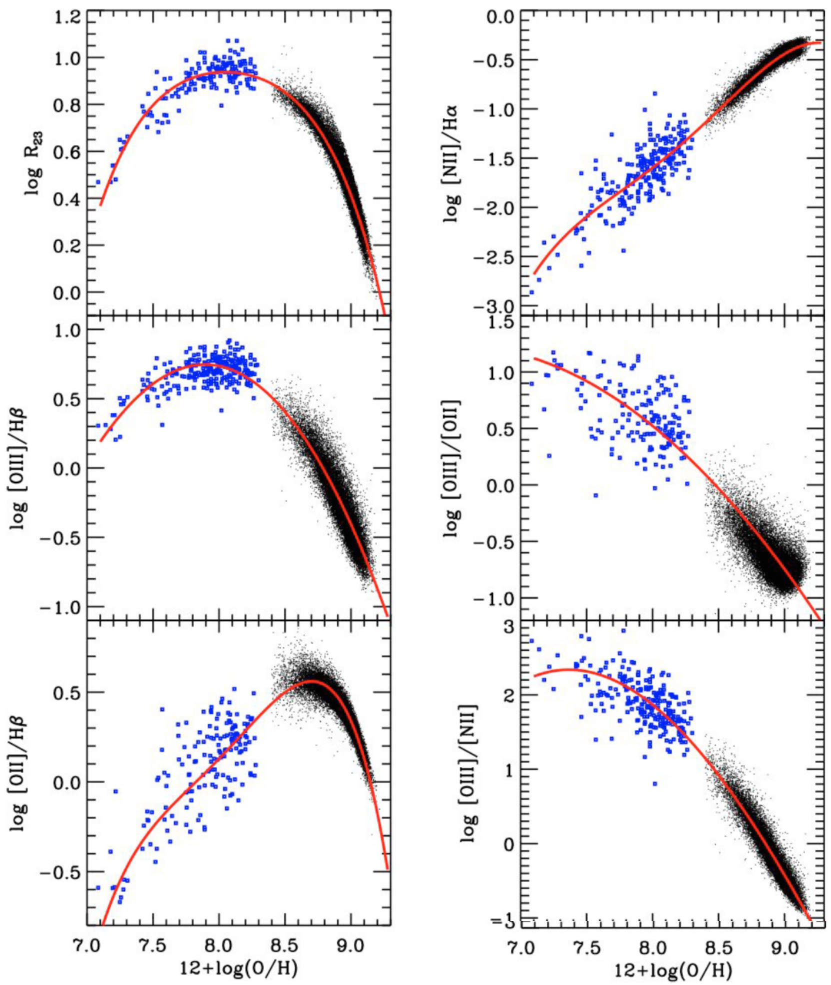
2. Theoretical

   McGaugh 91; Zaritsky+94; Dopita+00; Charlot & Longhetti 01; Kewley & Dopita 02, Kobulnicky & Kweley 04, Levesque+10, Tremonti+04, Dopita+13,16, Perez-Montero+14

3. Semi-empirical

   Alloin+79; Pagel +79; Edmunds & Pagel 84; McCall+85; Dopita & Evans 86; Skillman 89, Pettini & Pagel 04, Nagao+06, Maiolino+08,

Maiolino+08



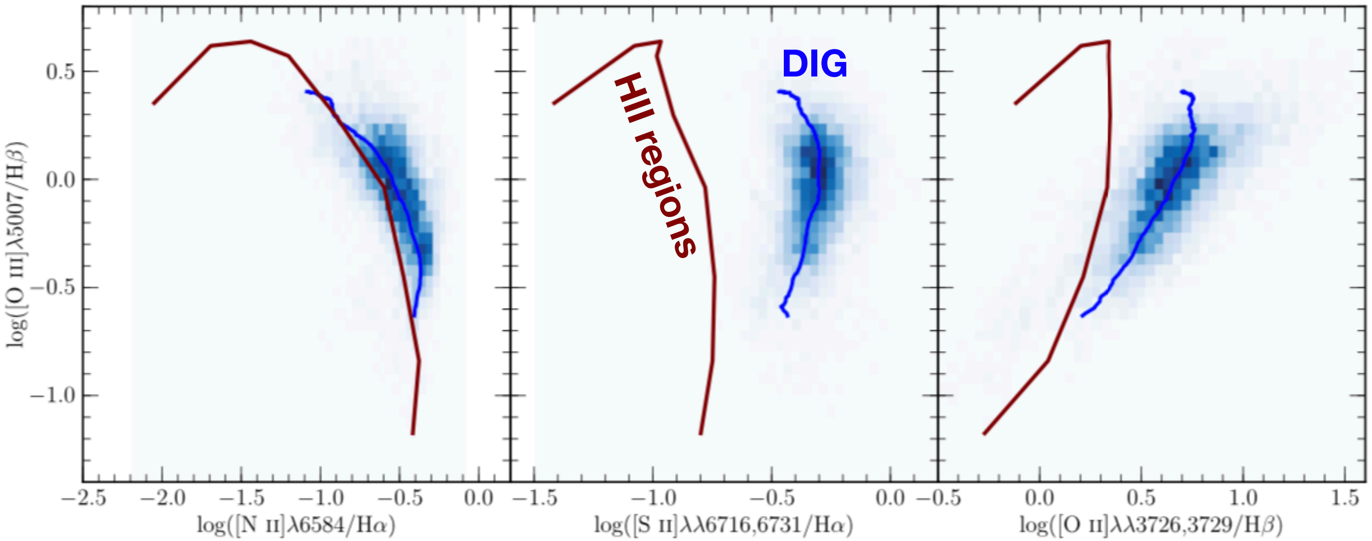
# Galaxies are not HII regions

Emission-line in galaxies from:

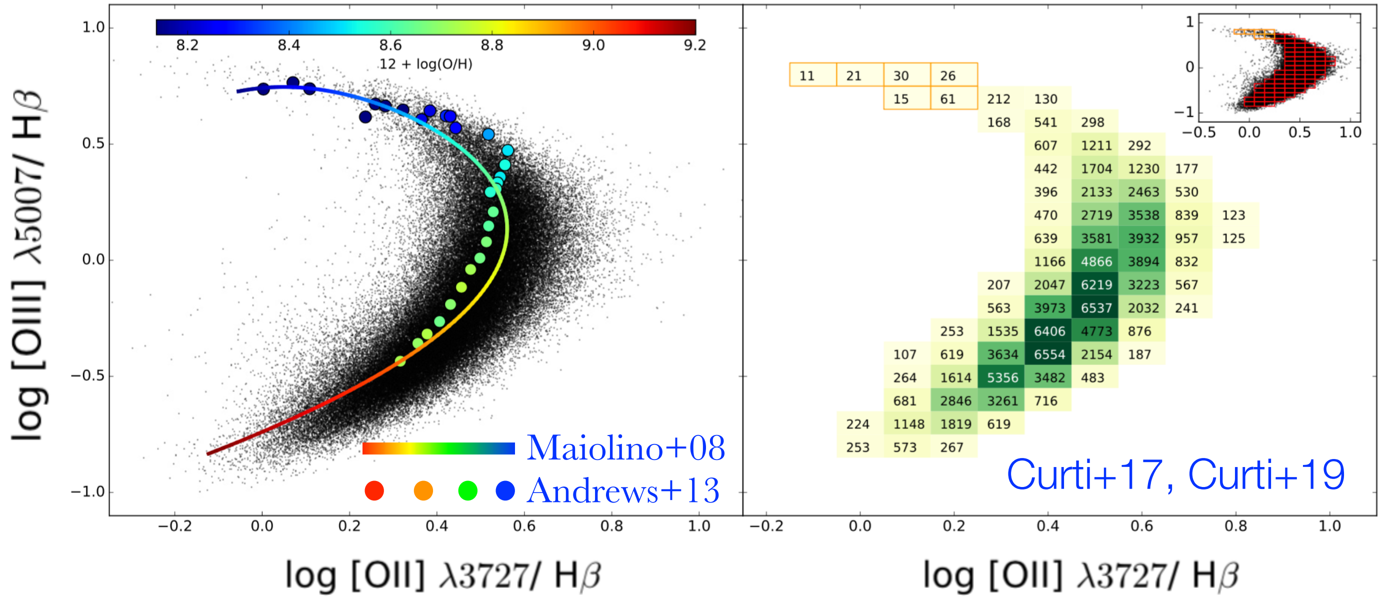
1. Many HII regions with different ages, metallicites, U, dust, luminosity, geometry, ...
2. Diffused ionized gas (DIG)

Galaxies to calibrate galaxies

Sanders+18



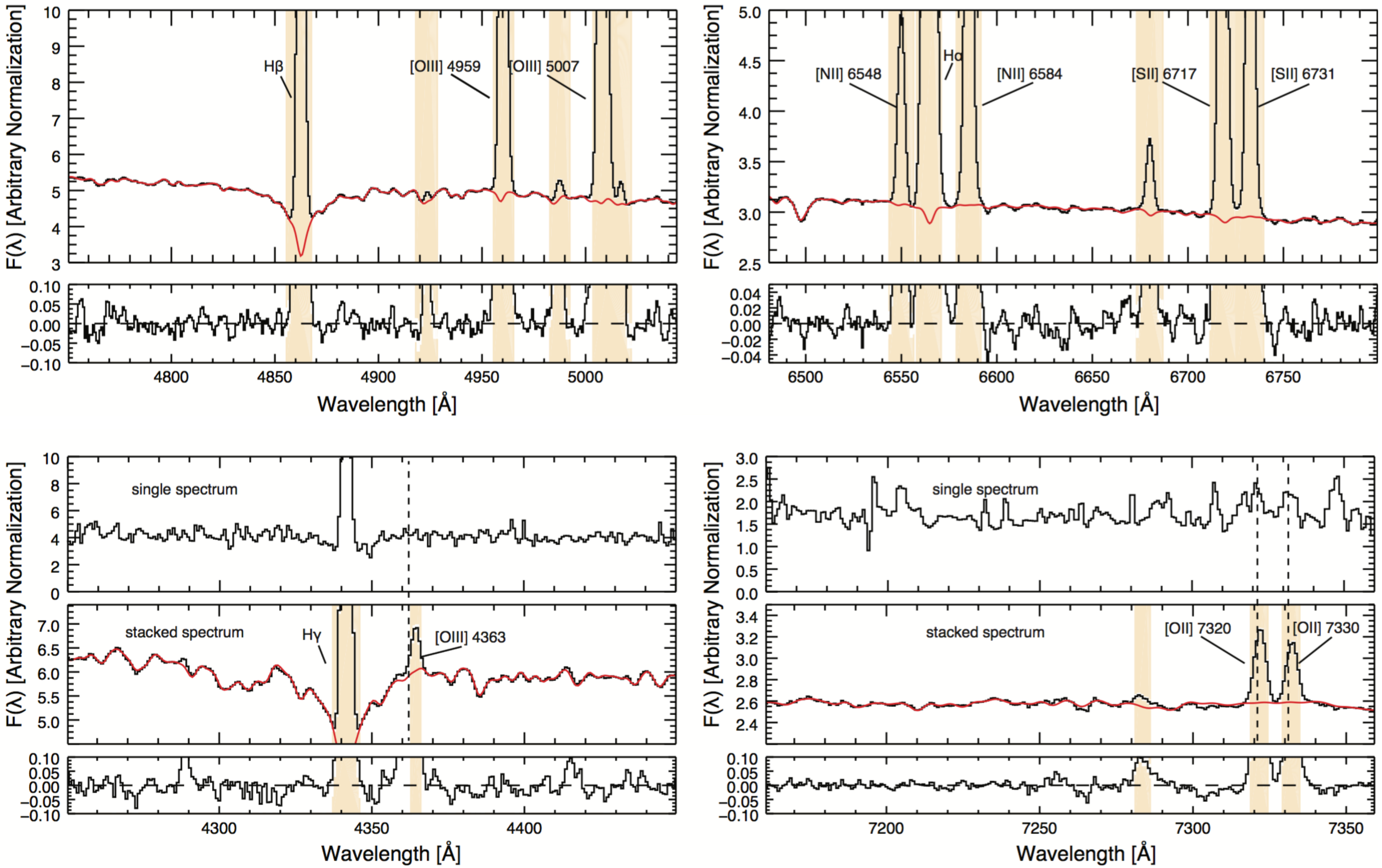
# Te-based empirical calibration for galaxies




- Detect Te auroral lines by stacking SDSS spectra
- same [OII]/Hβ and [OIII]/Hβ line ratios
    - strong-line method can be used
    - [OII]/Hβ and [OIII]/Hβ ∝ main ionization states of O
    - [OIII]/[OII] sensitive to ionization parameter
    - not assuming any particular combination (e.g. R23)
    - no assumptions on [N/O]

Liang+07, Brown+16

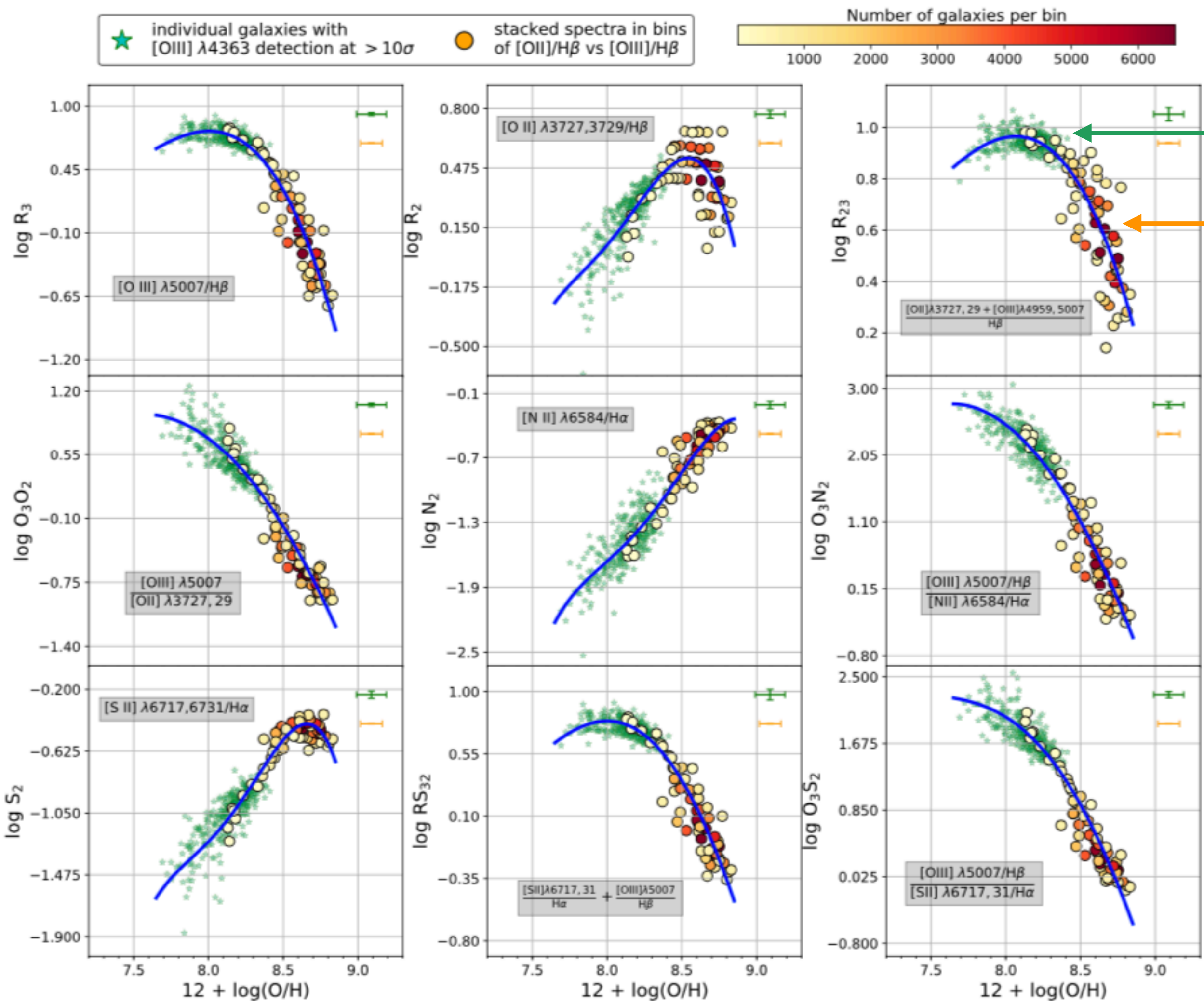
# Resulting spectra




| Line |
|---|
| (1) |
| [OII] λ3727 |
| [NeIII]λ3870 |
| [SII]λ4069 |
| Hδ λ4102 |
| Hγ λ4340 |
| [OIII] λ4363 |
| Hβ λ4861 |
| [OIII] λ4960 |
| [OIII] λ5007 |
| [NII] λ5756 |
| [NII] λ6549 |
| Hα λ6563 |
| [NII] λ6584 |
| [SII] λ6717 |
| [SII] λ6731 |
| [OII] λ7320 |
| [OII] λ7330 |

Curti+17

# Metallicity calibration




Single galaxies

Stacks

| Diagnostic | RMS | $\sigma$ |
|---|---|---|
| $R_2$ | 0.11 | 0.10 |
| $R_3$ | 0.09 | 0.07 |
| $O_3O_2$ | 0.15 | 0.14 |
| $R_{23}$ | 0.06 | 0.12 |
| $N_2$ | 0.16 | 0.10 |
| $O_3N_2$ | 0.21 | 0.09 |
| $S_2$ | 0.11 | 0.06 |
| $RS_{32}$ | 0.07 | 0.08 |
| $O_3S_2$ | 0.17 | 0.11 |

Curti+19 (subm.)

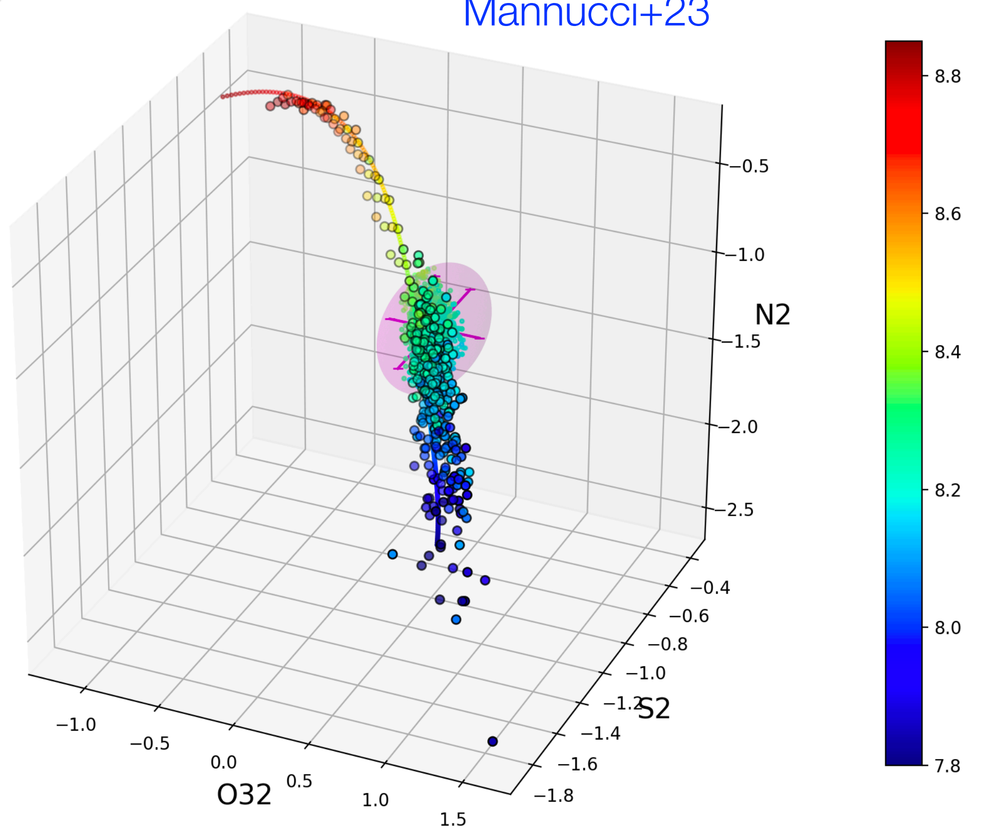
# Applying strong-line calibrations

1. Classic: all single line ratios $$\chi^2 = \sum_i \frac{(R_i^{obs} - R_i^{exp})^2}{\sigma_{obs}^2 + \sigma_R^2}$$

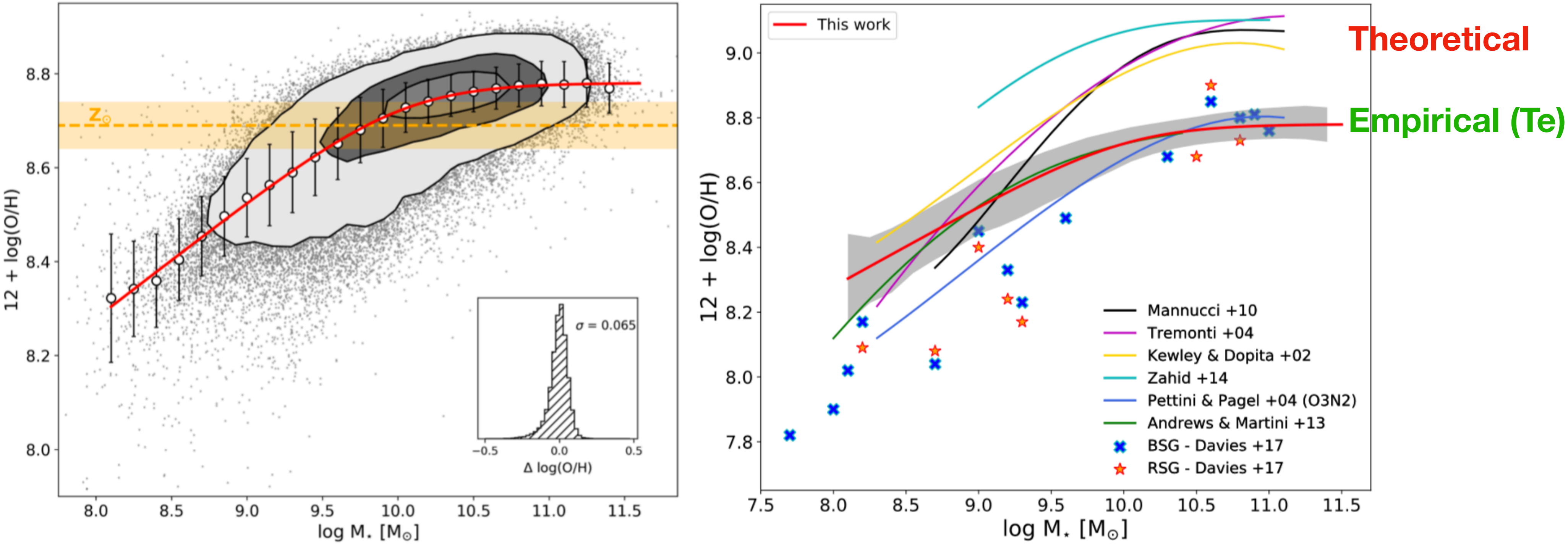
2. Multiple line fit (theoretical):
   - pyqz (Dopita+13)
   - HII-CHI-MISTRY (Pérez-Montero 14)
   - IZI (Blanc+15)
   - BEAGLE (Chavalier & Charlot 16)

3. Closest match (empirical)

Mannucci+23



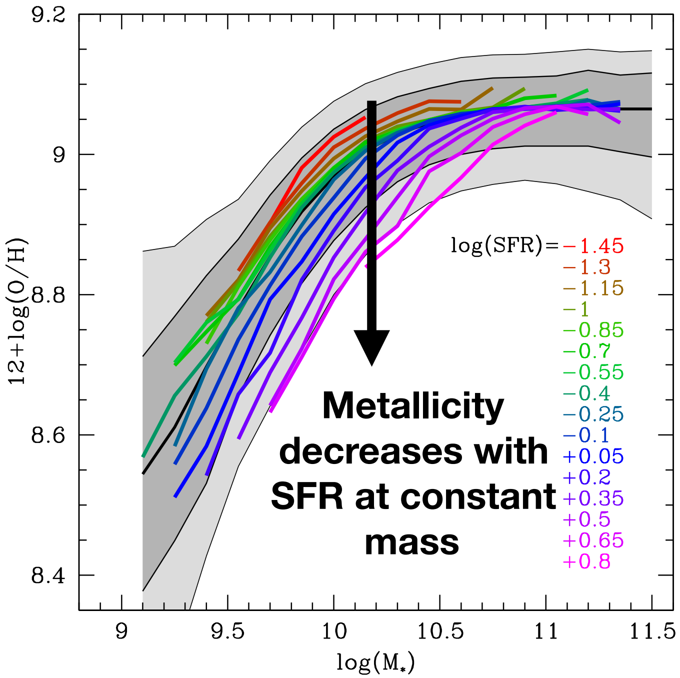
# Mass-metallicity relation




Curti+19

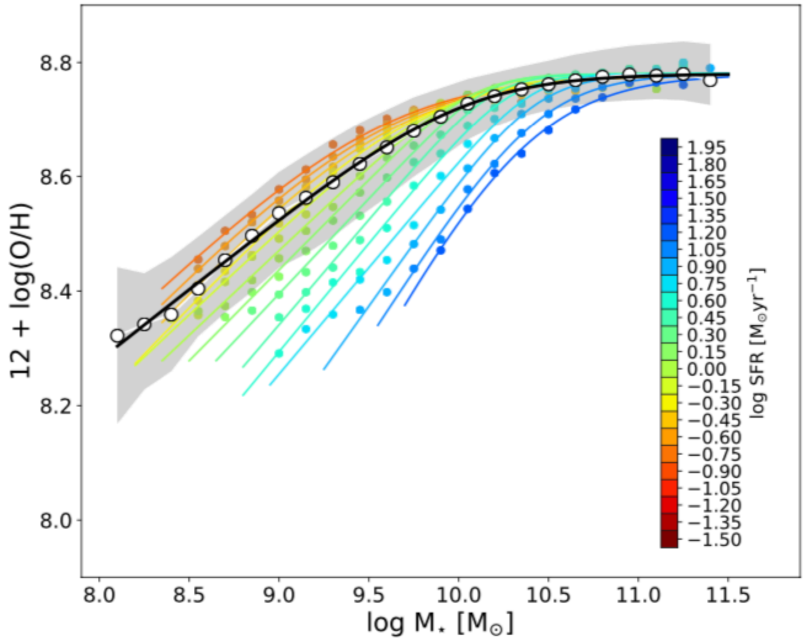
# Fundamental Metallicity relation (FMR)

Mannucci+10




(Semi)theoretical calibration

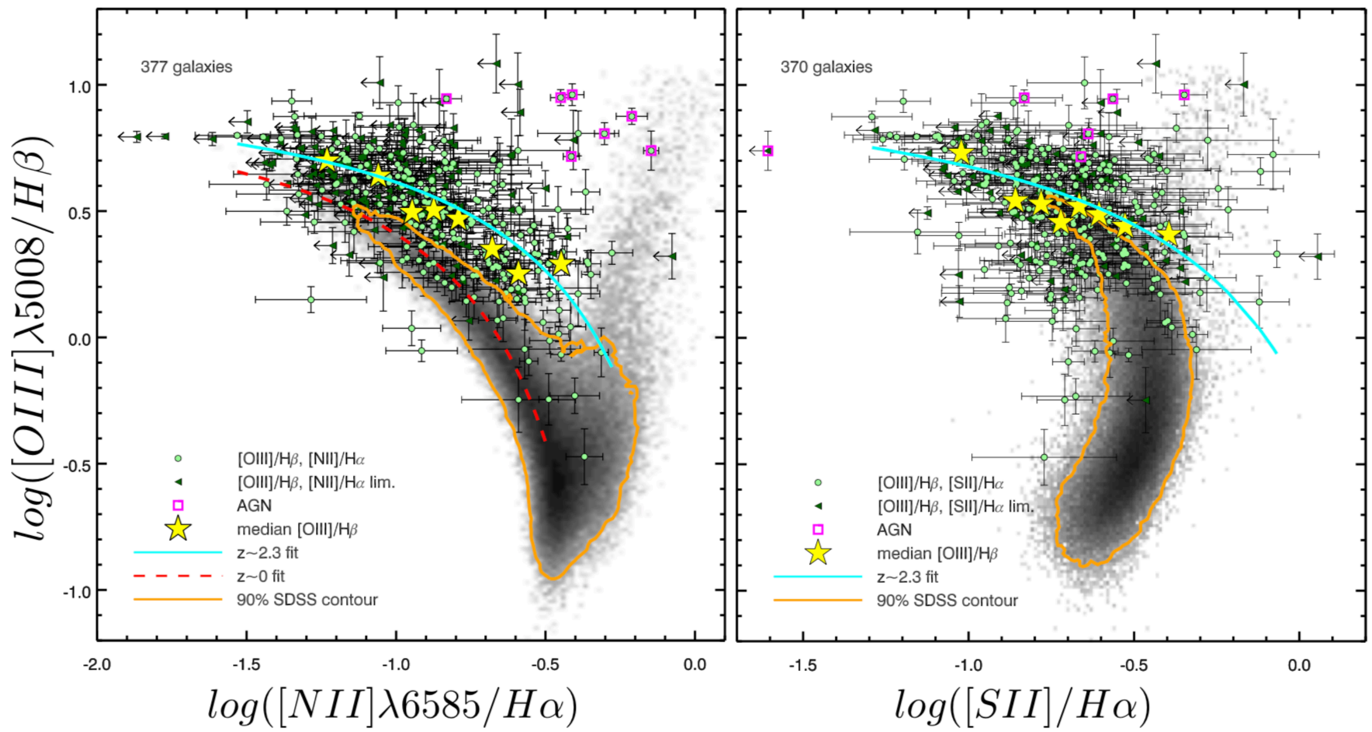
Curti+19




emprical (Te-CEL) calibration

# Evolution of ionization properties

Strom+17



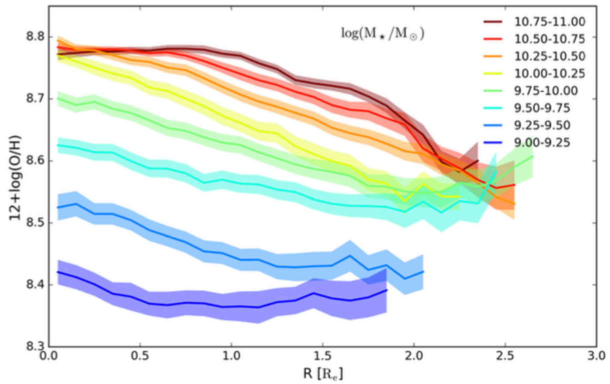

- Higher densities?
- Harder ionizing continuum?
- Higher ionization parameter?
- Different IMF?
- Higher sSFR?
- Higher N/O?
- Matter-bounded HII regions?
- Low luminosity AGN?
- Shocks?

Limited effect on metallicity?
(Jones+15, Patricio+18)

Shapley+05,15; Erb+06,10; Kriek+07; Liu+08; Hainline+09; Finkelstein+10; Yabe+12,14,15; Cullen+14; Newman+14; Masters+14; Hayashi+15; Salim+15; Sanders+16; Steidel+16; Trainor +16; Strom+17a,b; Kashino+17

# Metallicity maps at high redshifts: KMOS

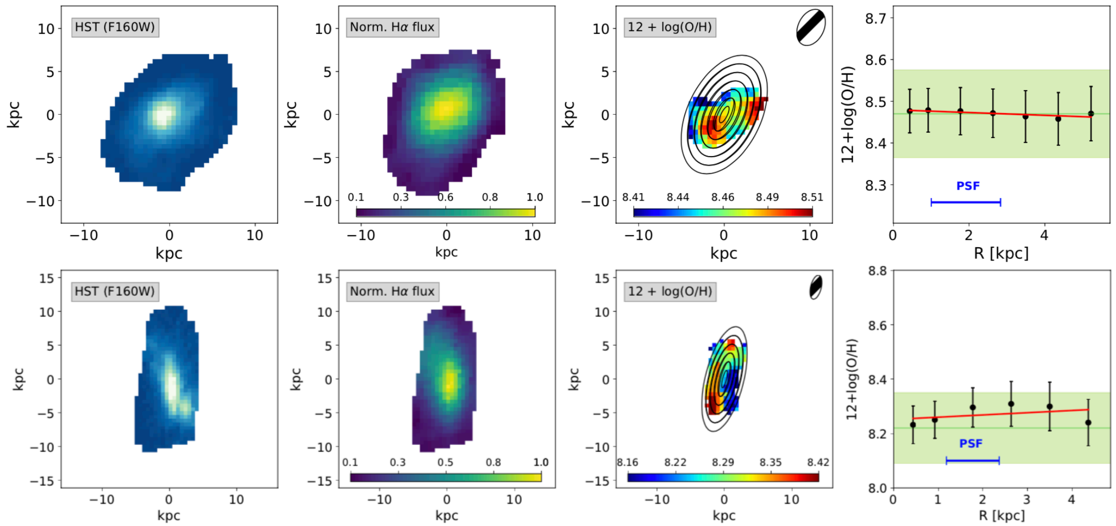
Belfiore+17




Local universe:

- HII, PN, young and old stars .....
- well-defined radial gradients

Curti+19




High redshift (z>1):

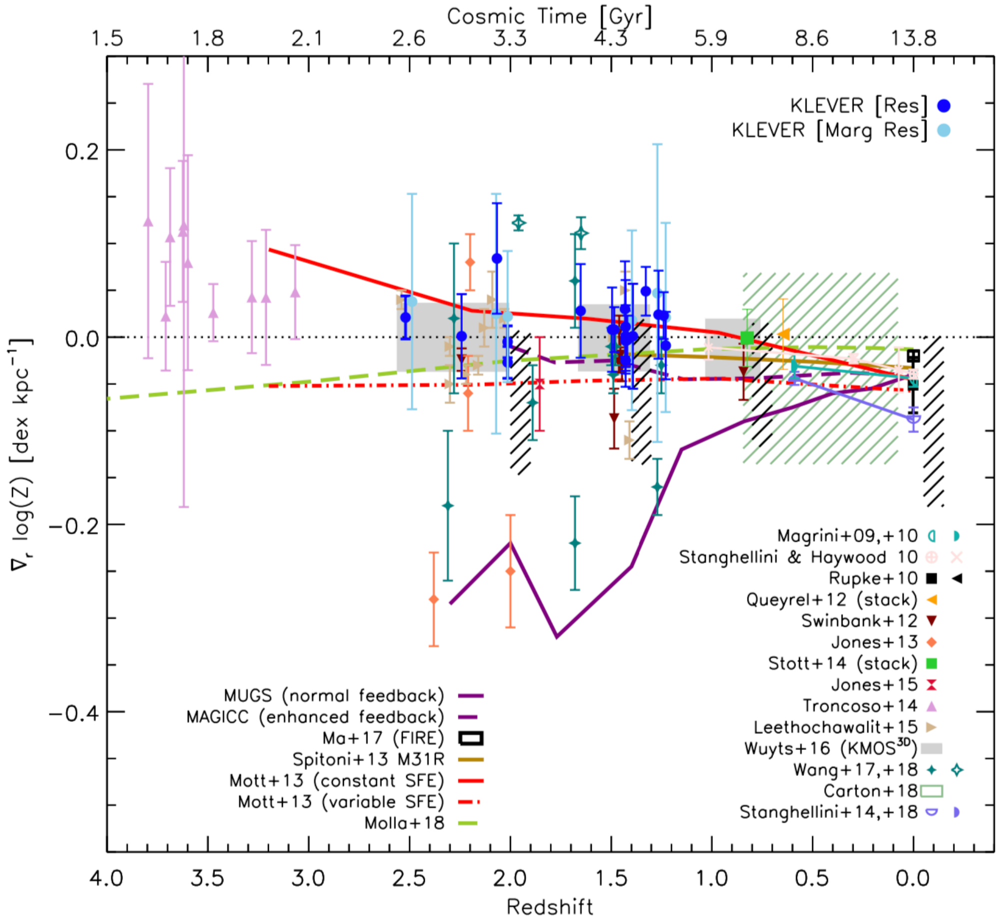
limitations due to spatial resolution and SNR

- Patchy distribution of metallicity
- Flat radial gradients due to azimuthal averaging
- A few have positive "gradients"

Cresci+10, Yuan+11, Queyrel+12, Swinbank+12; Jones+13, 15, Stott+14, Troncoso+14, Wuyts+16, Leethochawalit+16; Wang+17, Perna+18; Förster Schreiber+18

# Metallicity maps at high redshifts

Curti+19



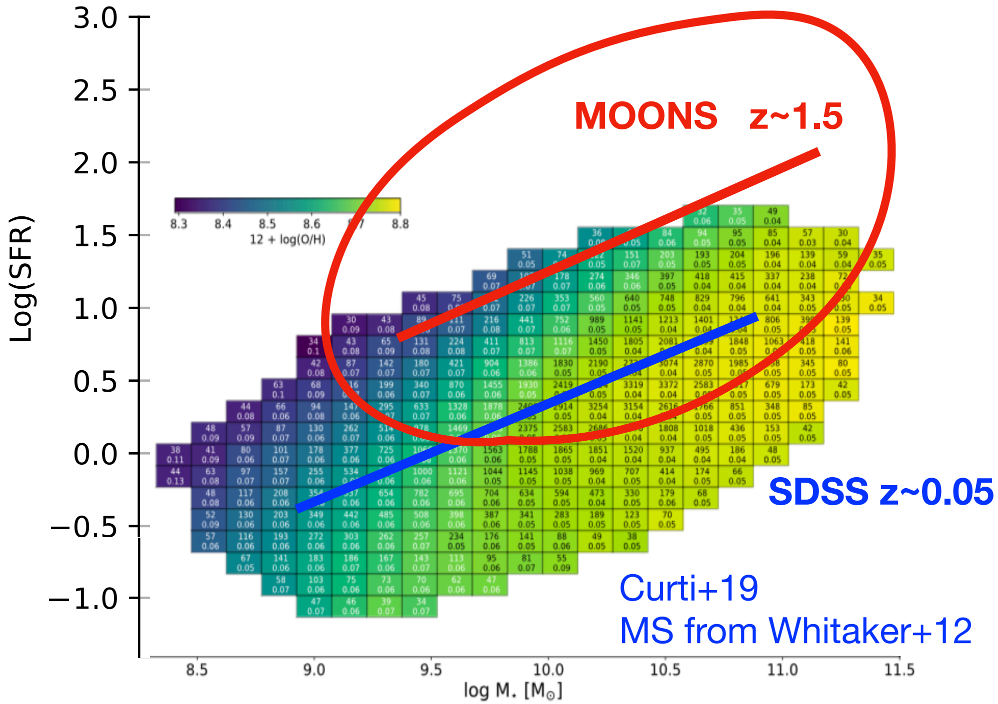

Flat radial gradients
due to azimuthal averaging

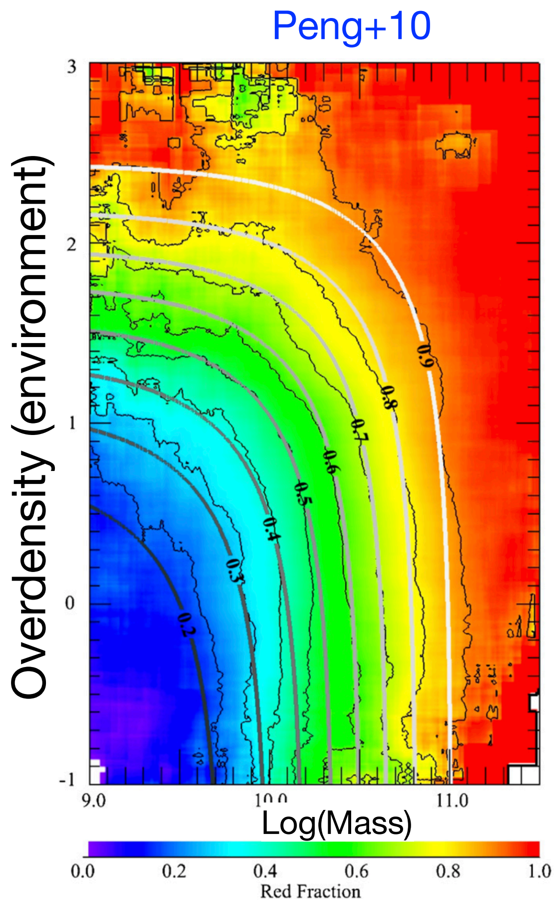
New statistics needed

# Spectroscopic requirements

Target galaxies:

- wide variety of input quantities (Mass, SFR, Environment, size, ...... )
- well known properties
- well defined selection function



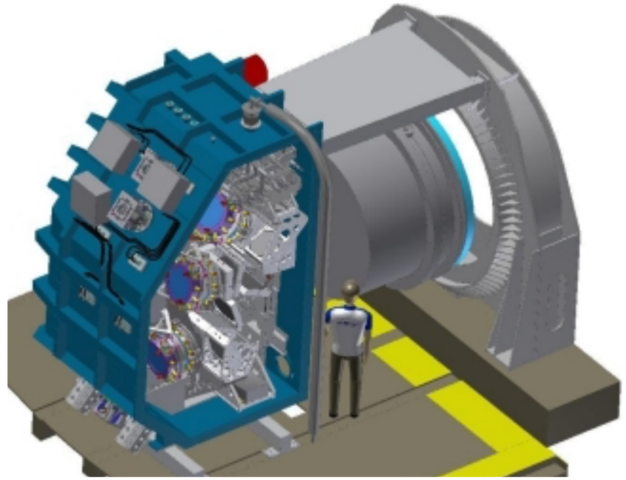



# Spectroscopic requirements

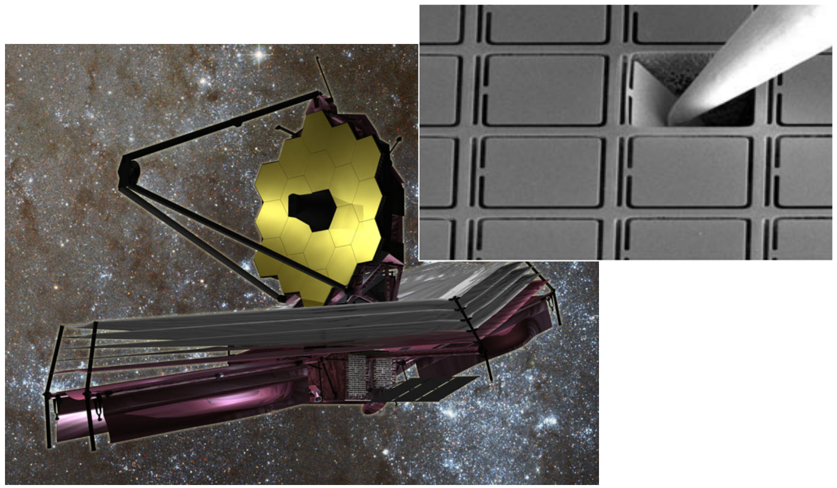
Observations:

- large wavelength range (many lines)
- high SNR on fainter strong lines (Te and RL out of reach for single objects, Te possible for stacks)
- integral-field spectroscopy
- large numbers of targets

**ESO/VLT**
**MOONS**



**NASA/ESA/CSA**
**JWST**



# Conclusions

- Two basic methods (Te-CEL and RL) differ by 0.2-0.3dex (~ a factor 2)
- Stellar metallicities show a better agreement with Te (at sub-solar metallicities)
- Empirical (Te-CEL) calibrations based on galaxies are available
- Strong-line methods have uncertainties but have no alternatives
- Incoming large spectroscopic surveys will be game-changing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REVIEW ARTICLE

Check for updates

**De re metallica: the cosmic chemical evolution of galaxies**

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