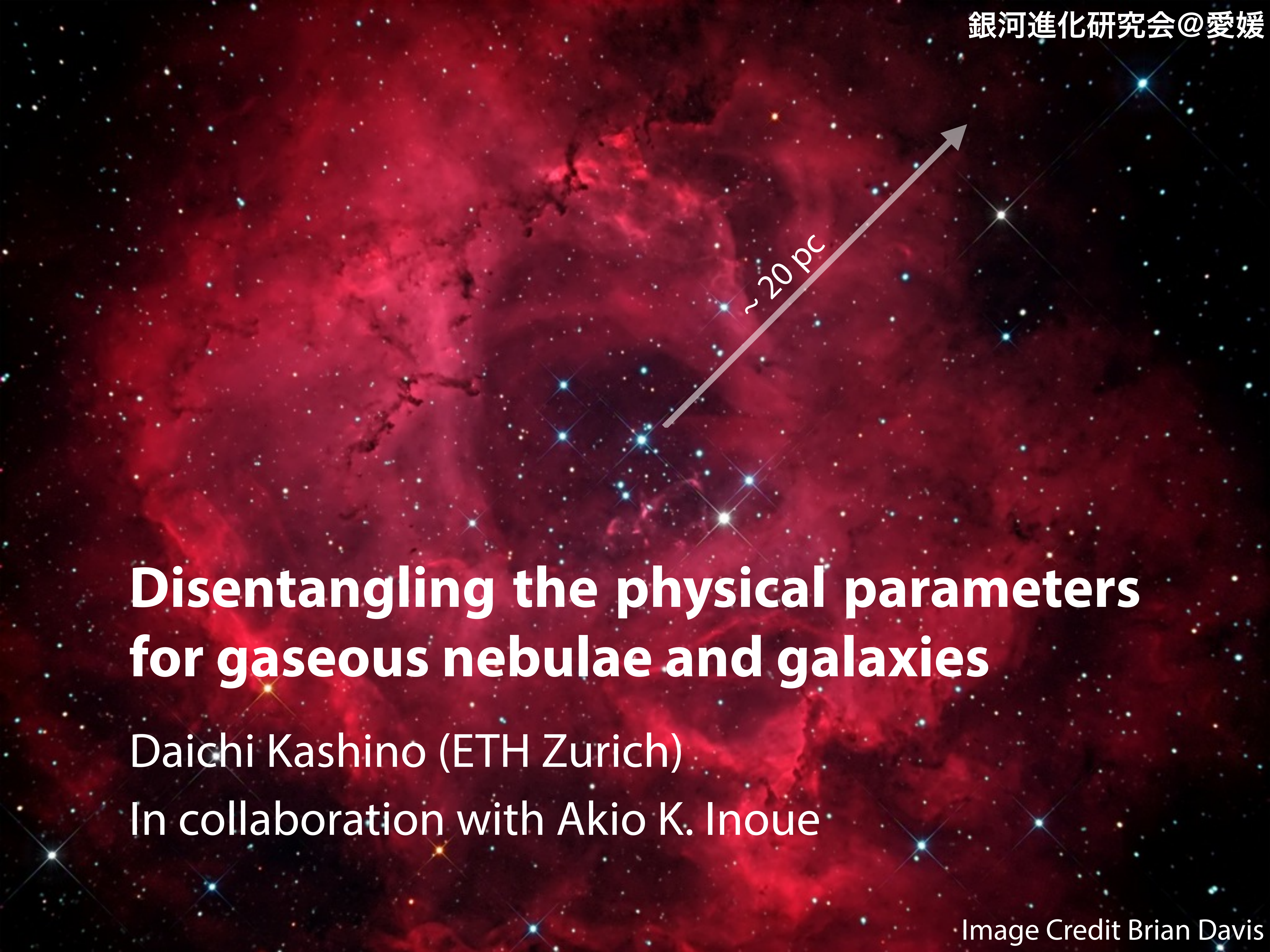
銀河進化研究会@愛媛



Disentangling the physical parameters for gaseous nebulae and galaxies

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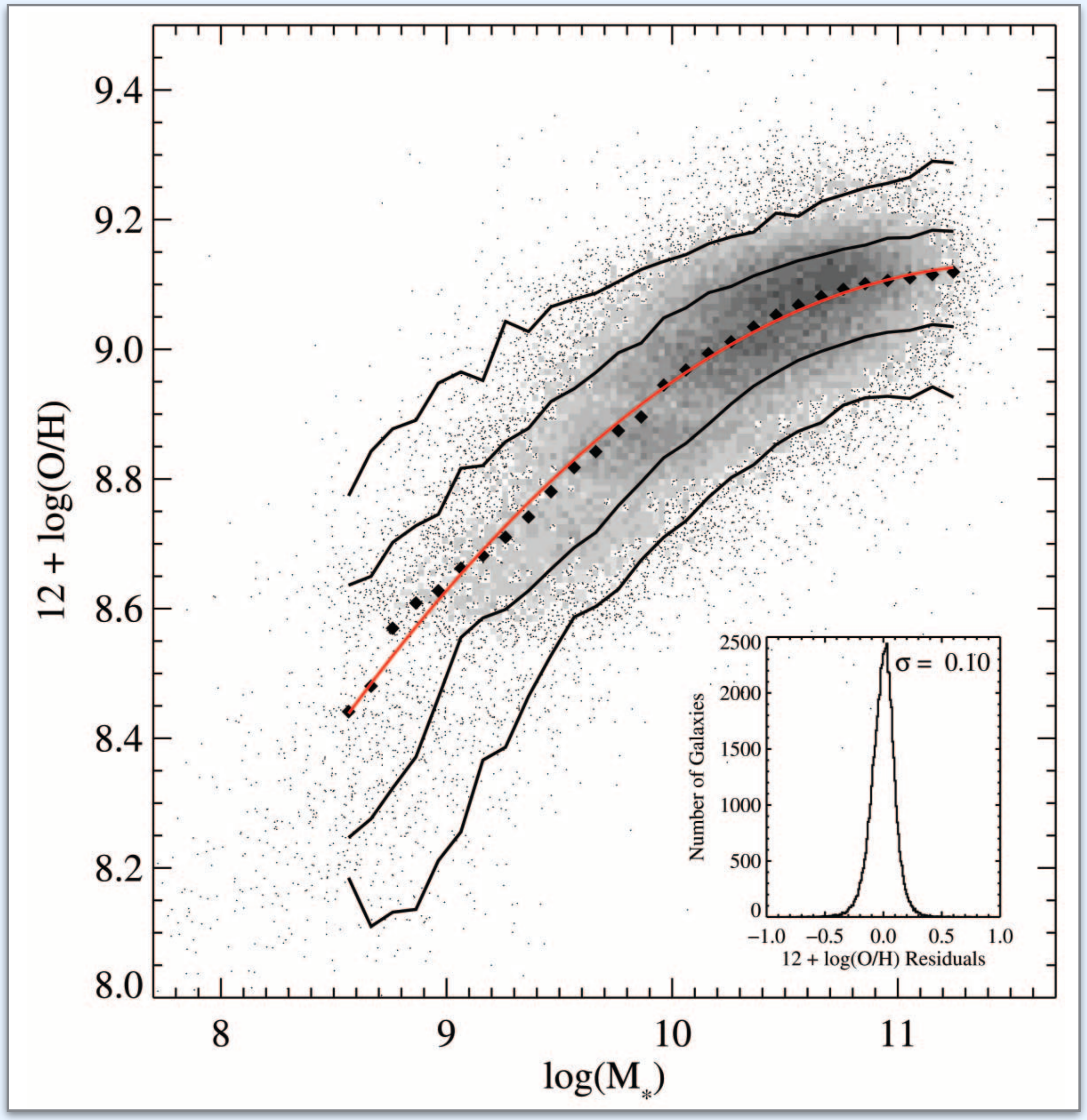
In collaboration with Akio K. Inoue

Image Credit Brian Davis

How do the gas properties connect with the galaxy's mass and SF activity?

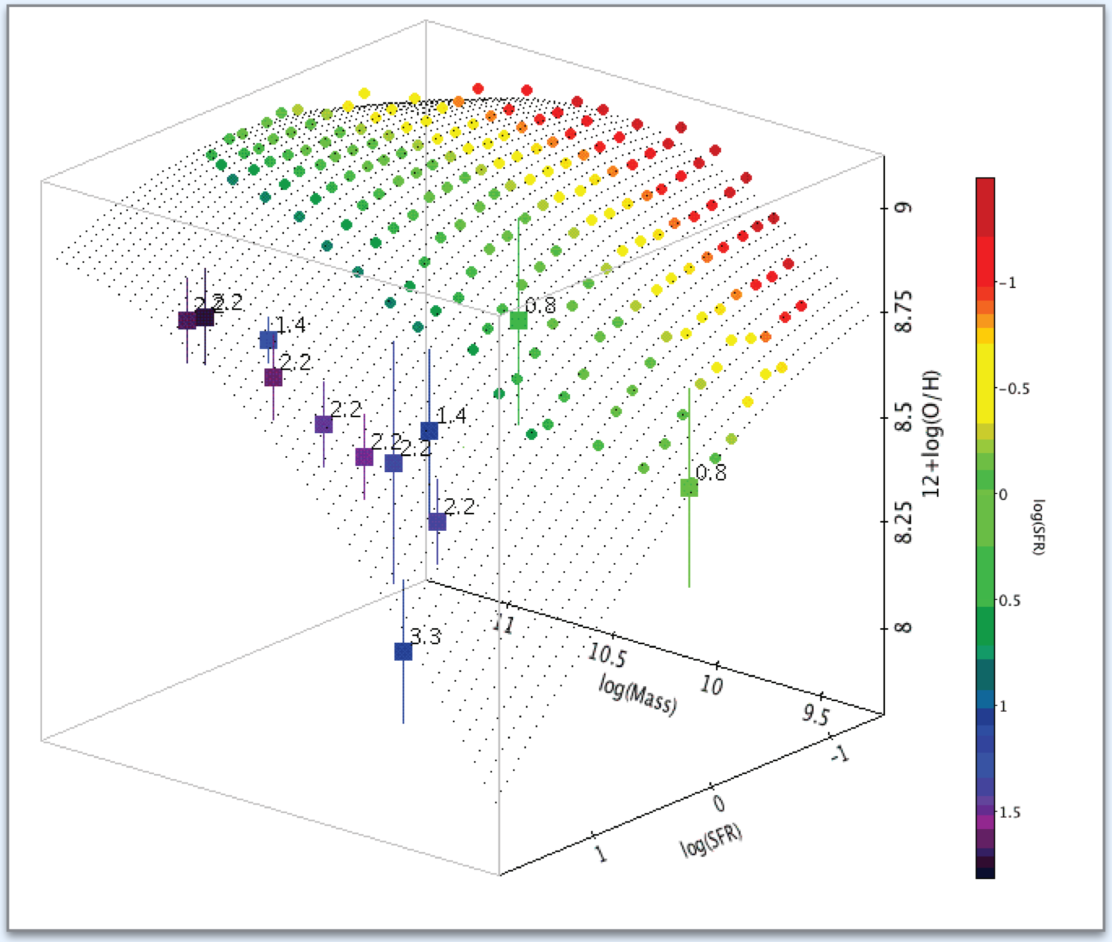
Mass—metallicity relation (MZR)

- Metallicity reflects the history of star formation, inflow and outflow of gas content.
- Established in the local Universe (z~0.07) using 53,000 galaxies from SDSS
- A tight correlation ~0.1 dex in Z at fixed M_*
- MZR evolves with redshift: now studied up to z~5

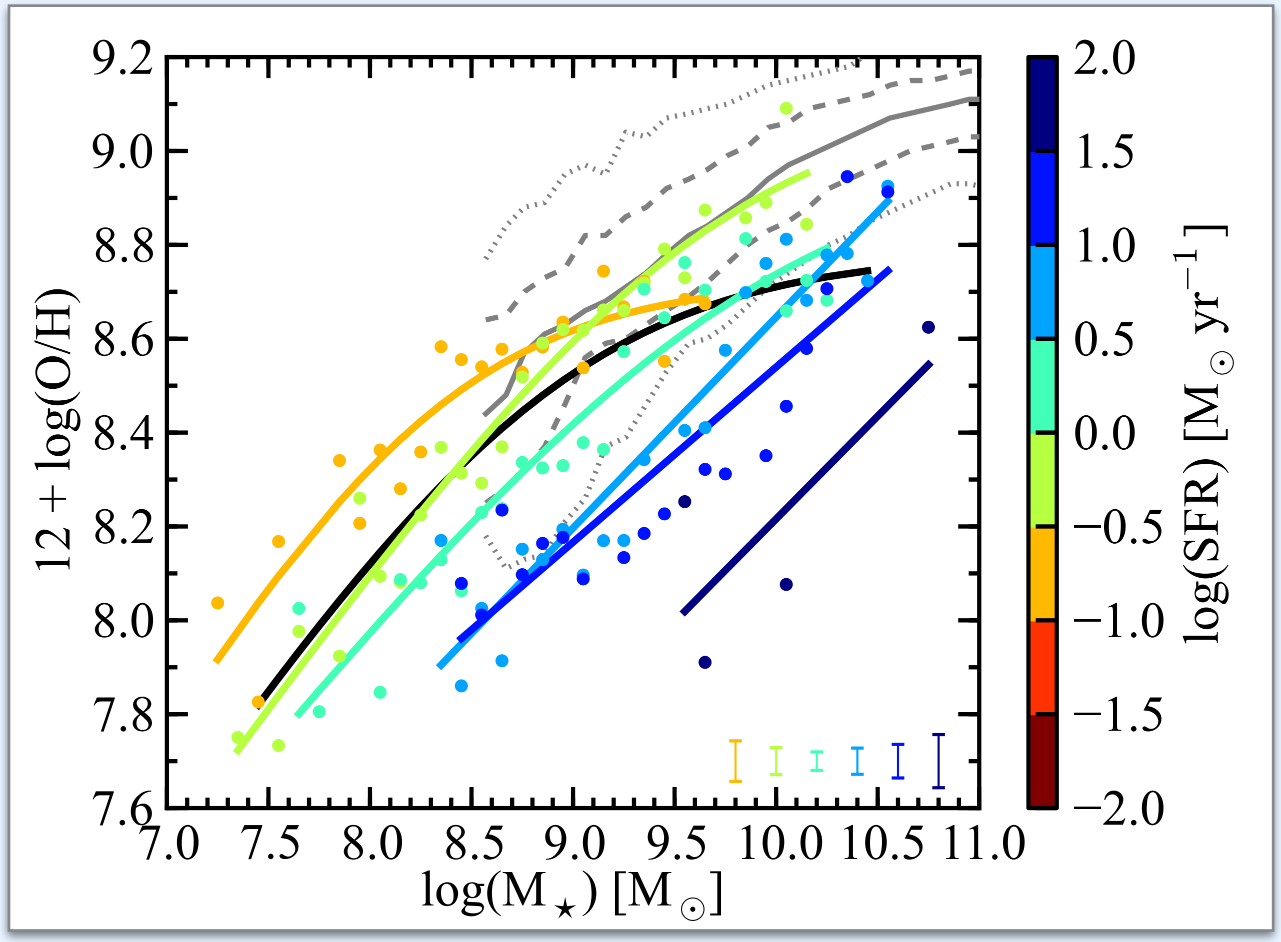


Tremonti+04

Mass—metallicity—SFR relation:



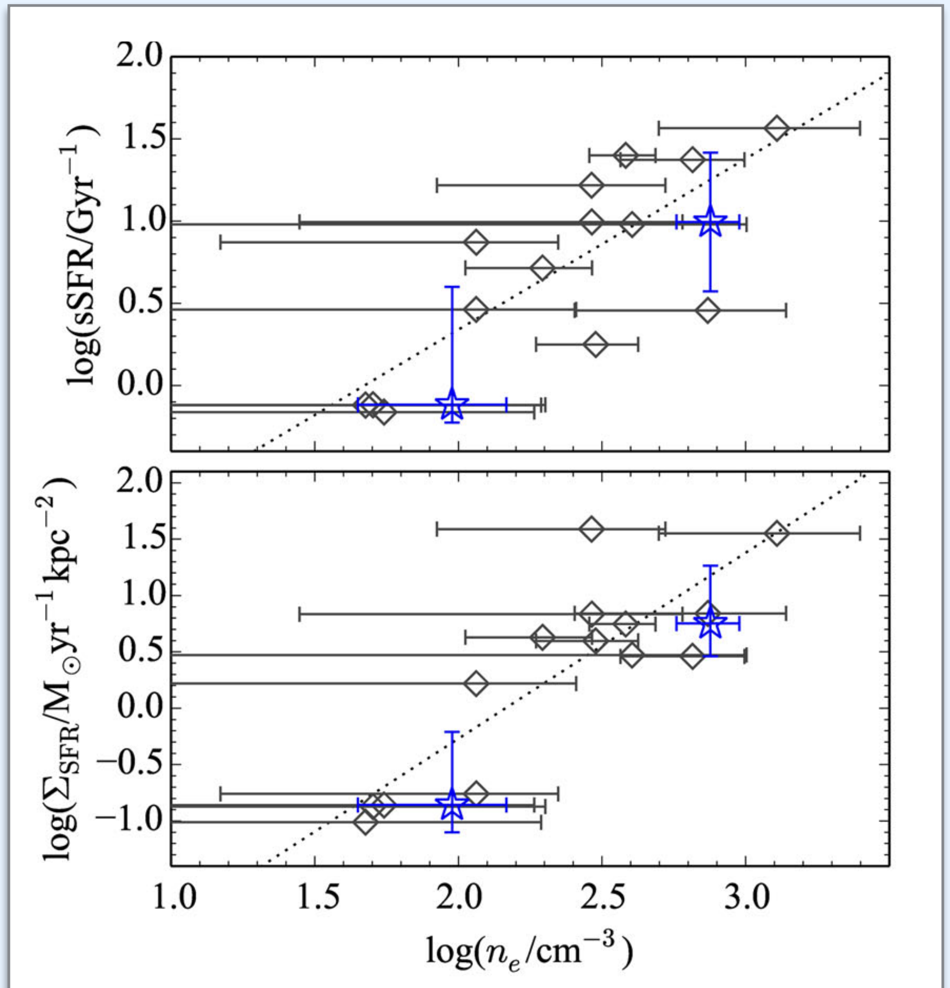
Mannucci+10



Andrews&Martini 13

- Metallicity is inversely correlated with SFR at fixed M_* at z~0.1.
- $Z(M_*$, SFR) has been proposed to be redshift-independent up to z~2 (Fundamental Metallicity Relation: FMR), while it remains under debate.
- Gas mass may play a central role: elevated inflow rate could enhance SFR while diluting metallicity.

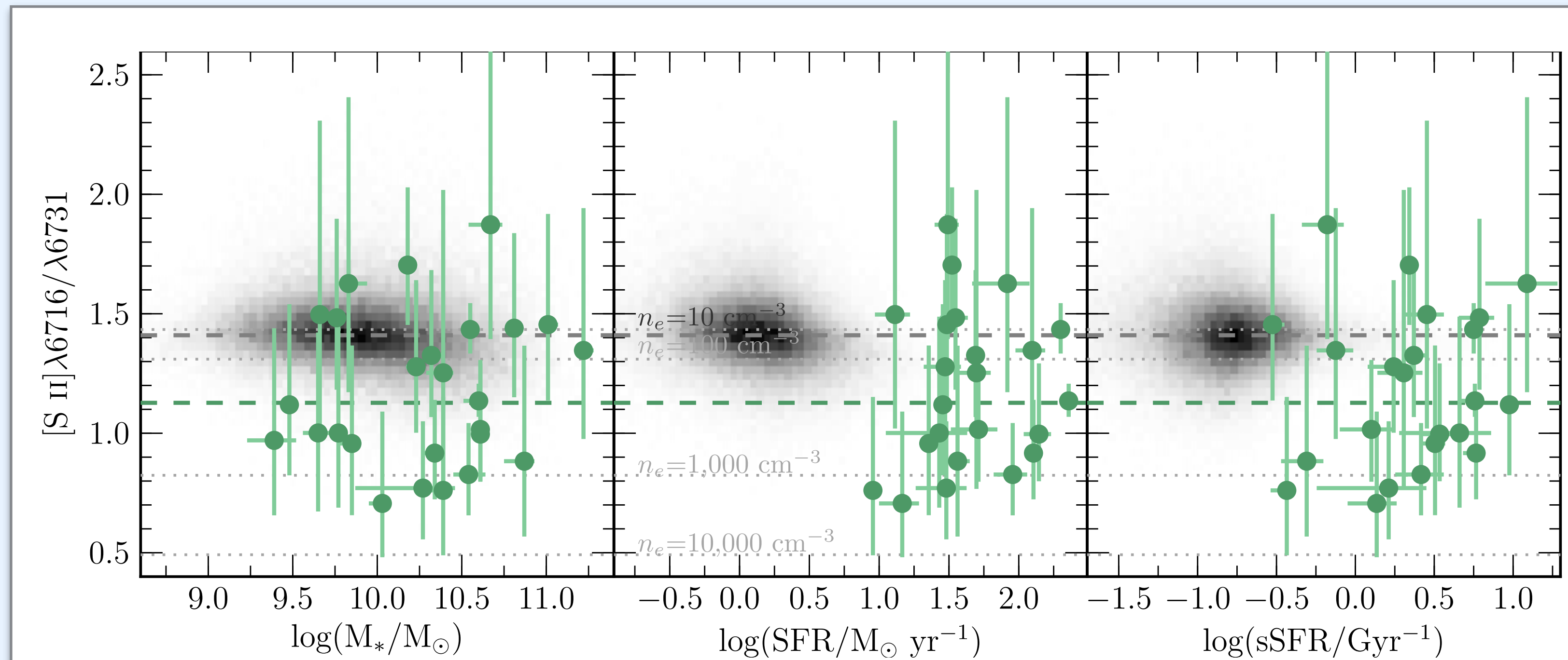
Electron density n_e of HII regions



◀Shimakawa+15

z~2.5

▼Sanders+15 z~2.3

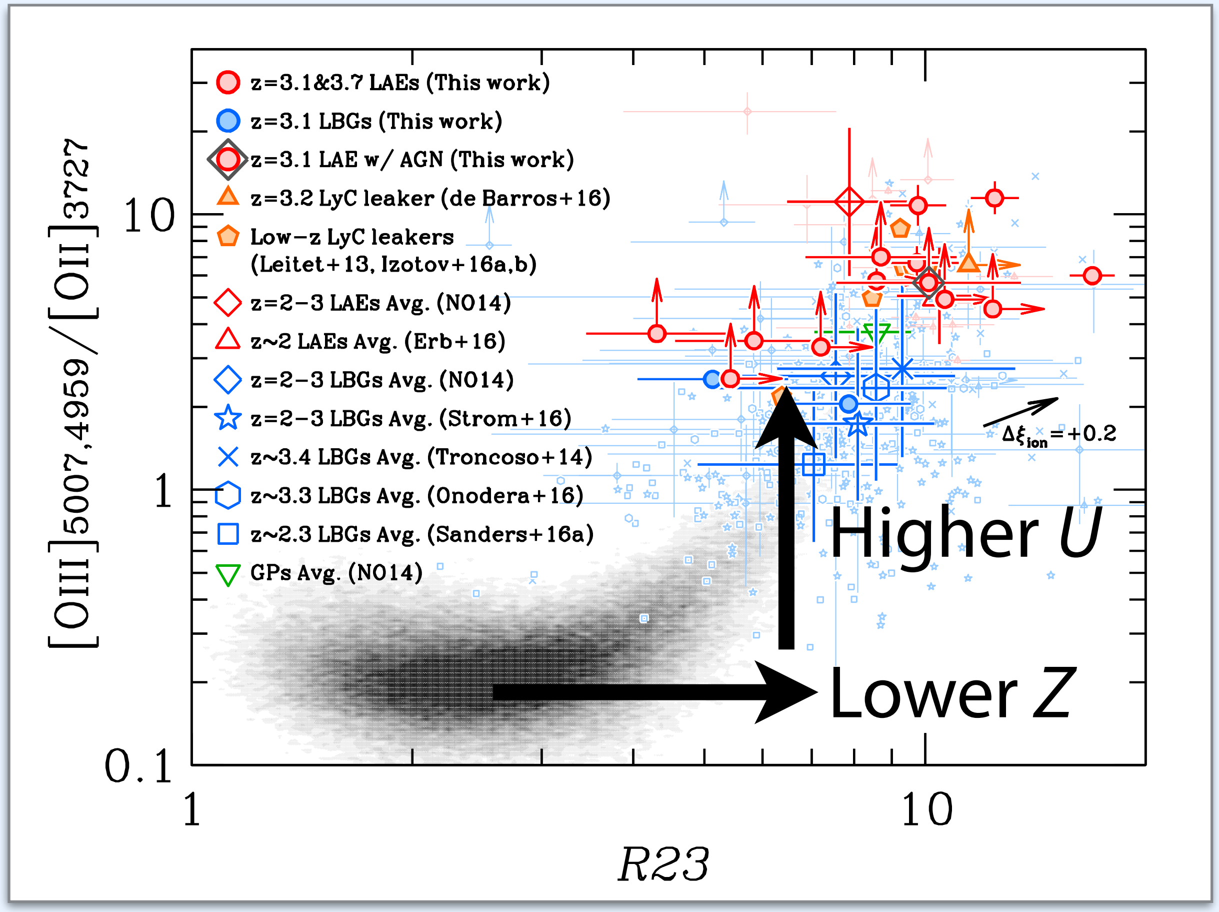


- Typical n_e ranges from a few to <100 cm^{-3} in the local SDSS galaxies
- At higher z (z≳1.5), n_e is often estimated to be >100–1000 cm^{-3}.
- may correlate with the global SF activity (sSFR and/or Σ_SFR).

Ionization parameter $U = S_{ion}/cn_H$ (c = speed of light)

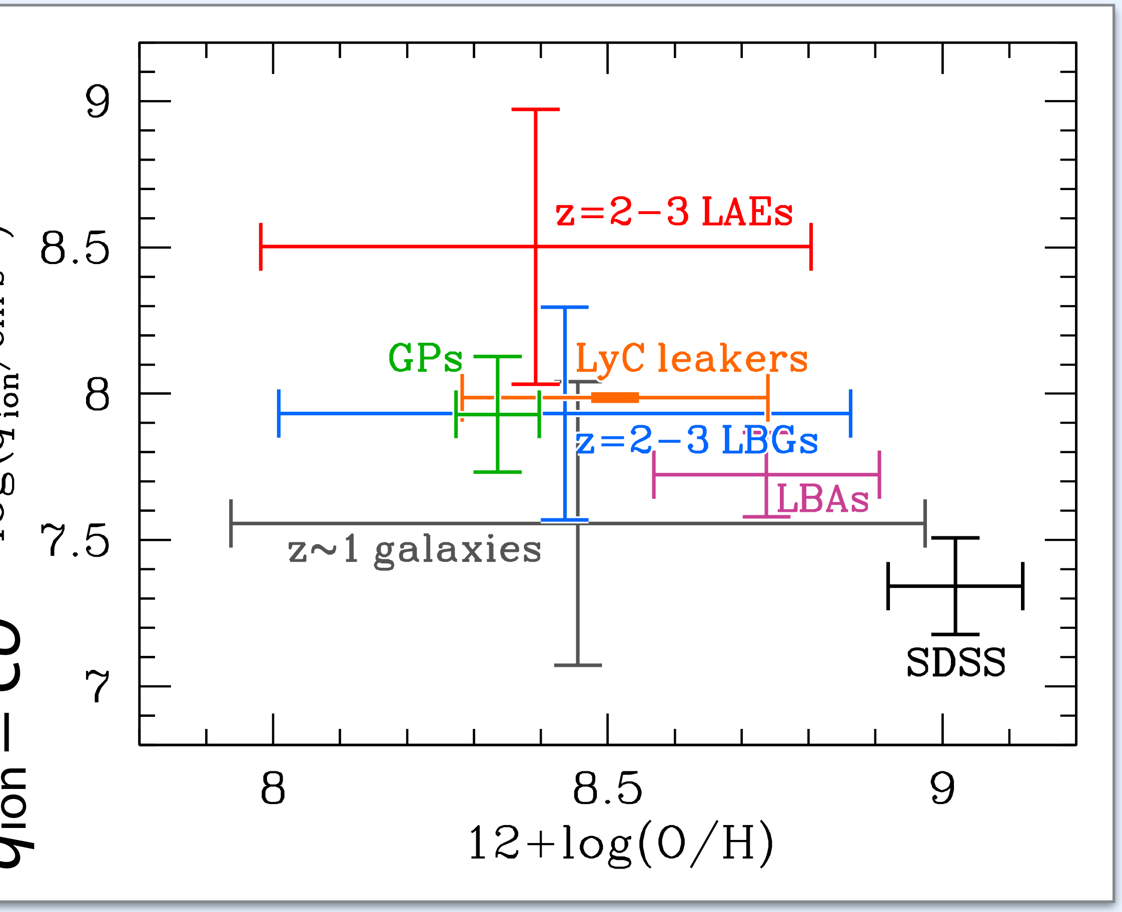
the ratio of ionizing photon flux to hydrogen density ($n_H \approx n_e$).

Nakajima+16



Nakajima+14

$q_{ion} = cU$



- Commonly estimated from [OIII]/[OII], but the Z-dependence has to be accounted for.
- Higher [OIII]/[OII] ratios are often measured for high-z LBGs and LAEs — possible strong correlation between U and sSFR
- Anticorrelation appears to exist between U and Z

Origins of the inverse *U*–*Z* correlations

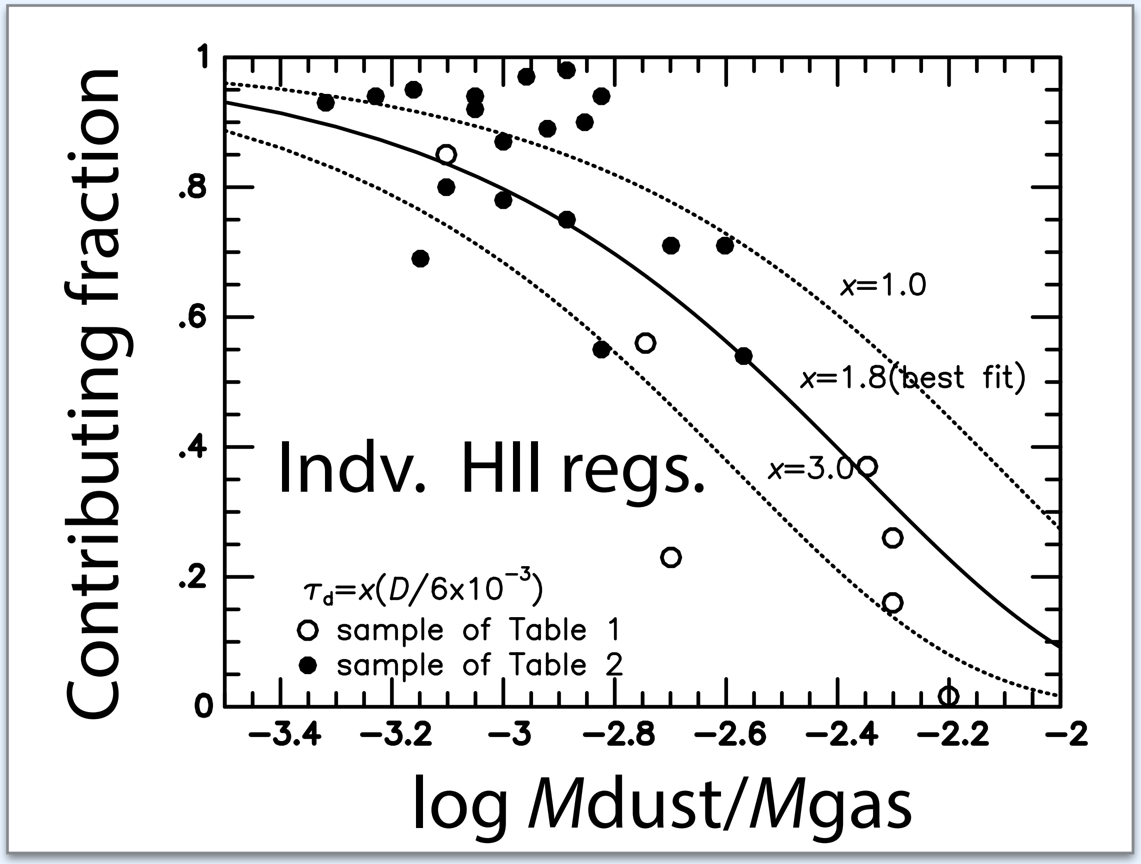
Theoretically, some explanations have been proposed.
(e.g., Dopita et al. 2006)

At higher *Z*, ionizing photons that contribute to ionization of the gas reduces because

- higher opacity of stellar winds absorb more ionizing photons.
- radiation energy is more efficiently converted into kinetic energy of the winds.
- higher dust content in the HII region absorb more ionizing photons.

▶ **Fraction of the "contributing" photons vs. dust-to-gas mass ratio**

Inoue+01, Inoue01



Origins of the inverse *U*–*Z* correlations

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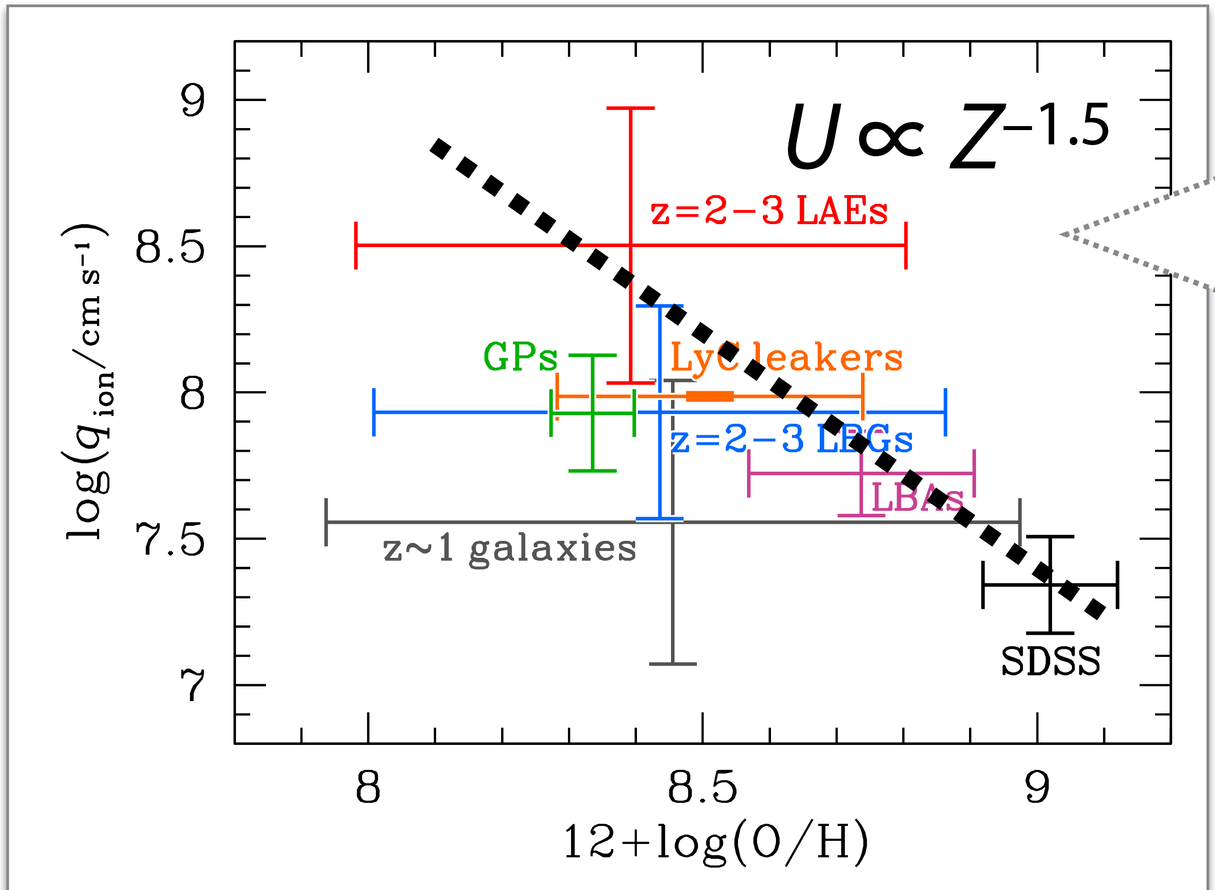
No observational confirmation of the “partial” anti-correlation

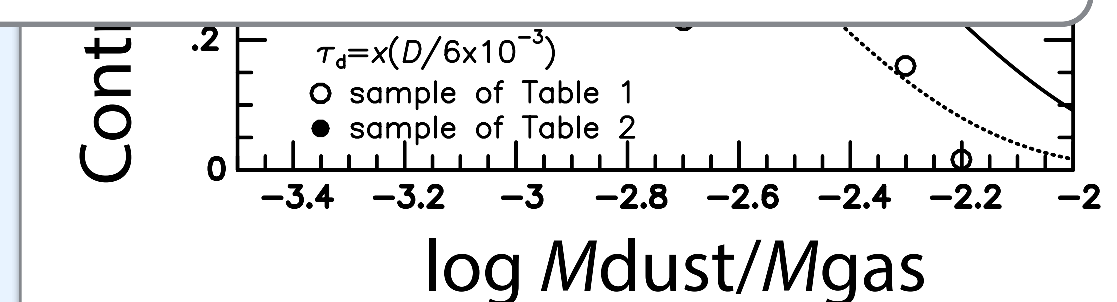


This “apparent” anticorrelation includes effects of changes in other parameters.

How strong is the “partial” (=“intrinsic”) dependence?

▶ **Fraction of the “contributing” photons vs. dust-to-gas mass ratio**

Inoue+01, Inoue01



The conditions of the gas and the global properties of host galaxies are connected through various physical processes.

Our goal:

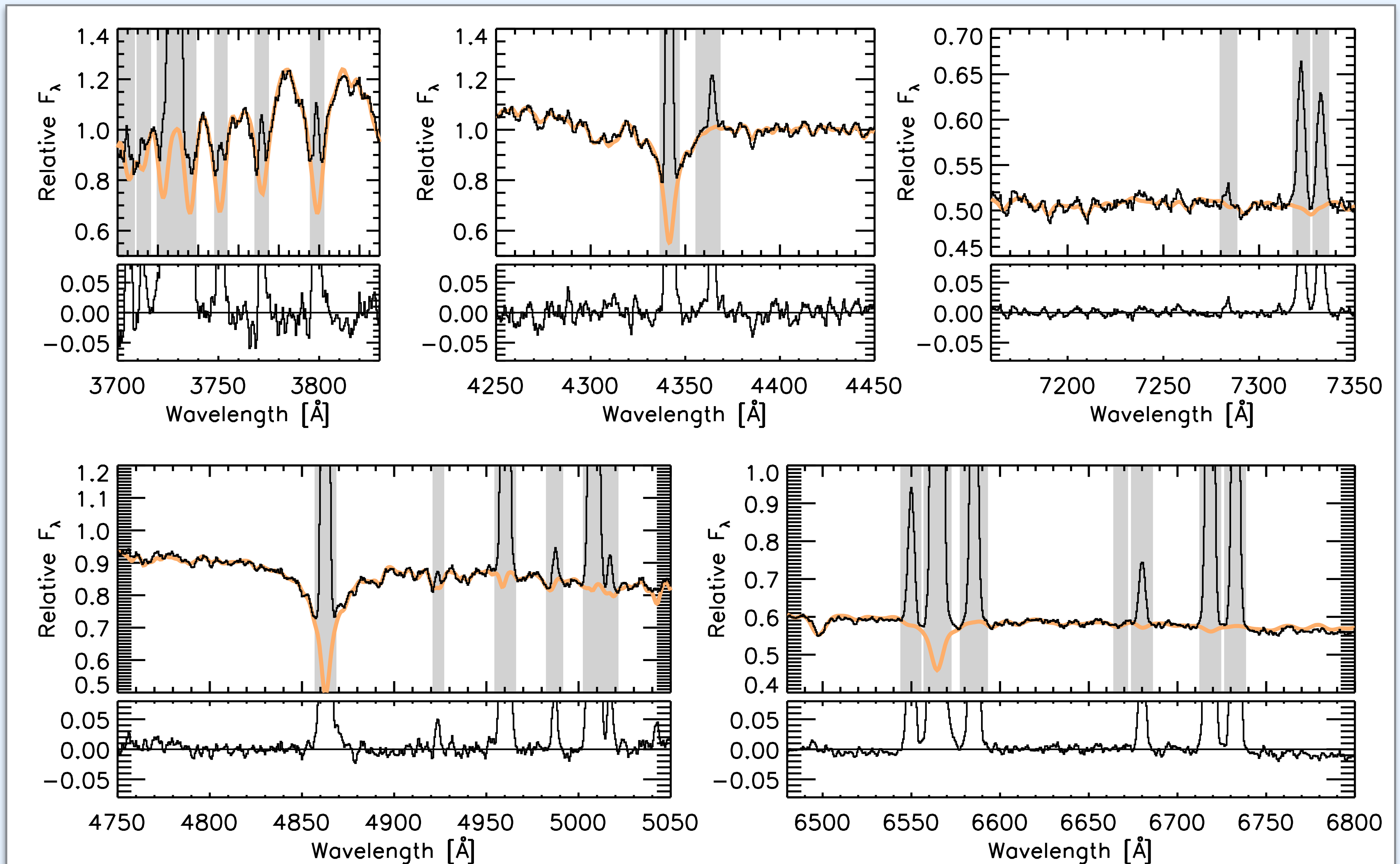
Quantifying the scaling relationships between them:
here M_*, sSFR, Z, n_e, and U
Especially, we aim to reveal their "partial" correlations.

It requires **"direct" metallicity estimates** to avoid systematic dependencies on other parameters inherent in the commonly-used strong-line indicators.

Data

2×10^5 galaxy spectra from SDSS DR7 (0.027≤z≤0.25)
Stellar mass and SFR from the MPA-JHU catalog

Composite spectra in M_*-sSFR bins
The direct method requires [OIII]4364 and/or [OII]7320,7330



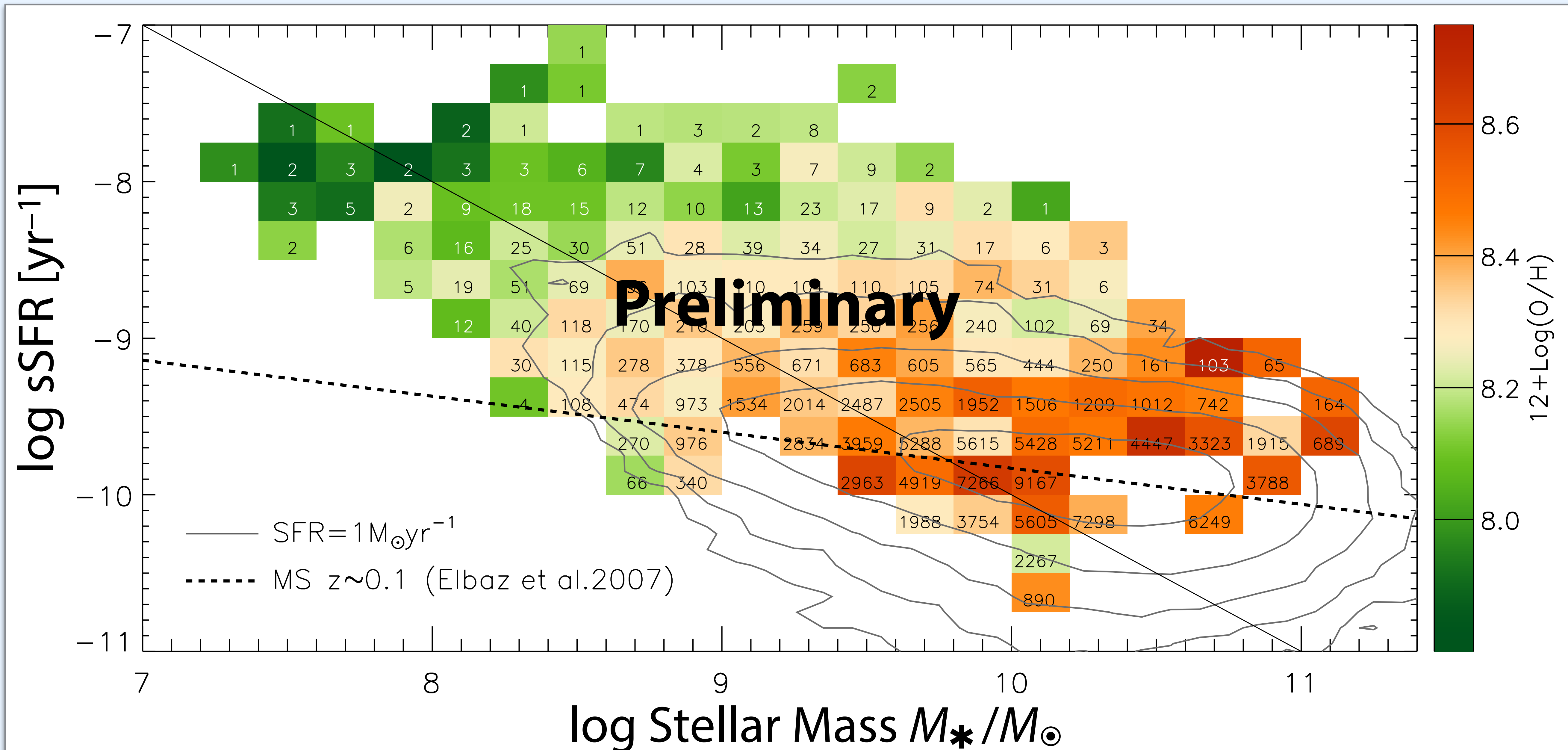
Example of stellar template subtraction

Gas-phase metallicity

via direct T_e method using [OIII]4363 and/or [OII]7320,30

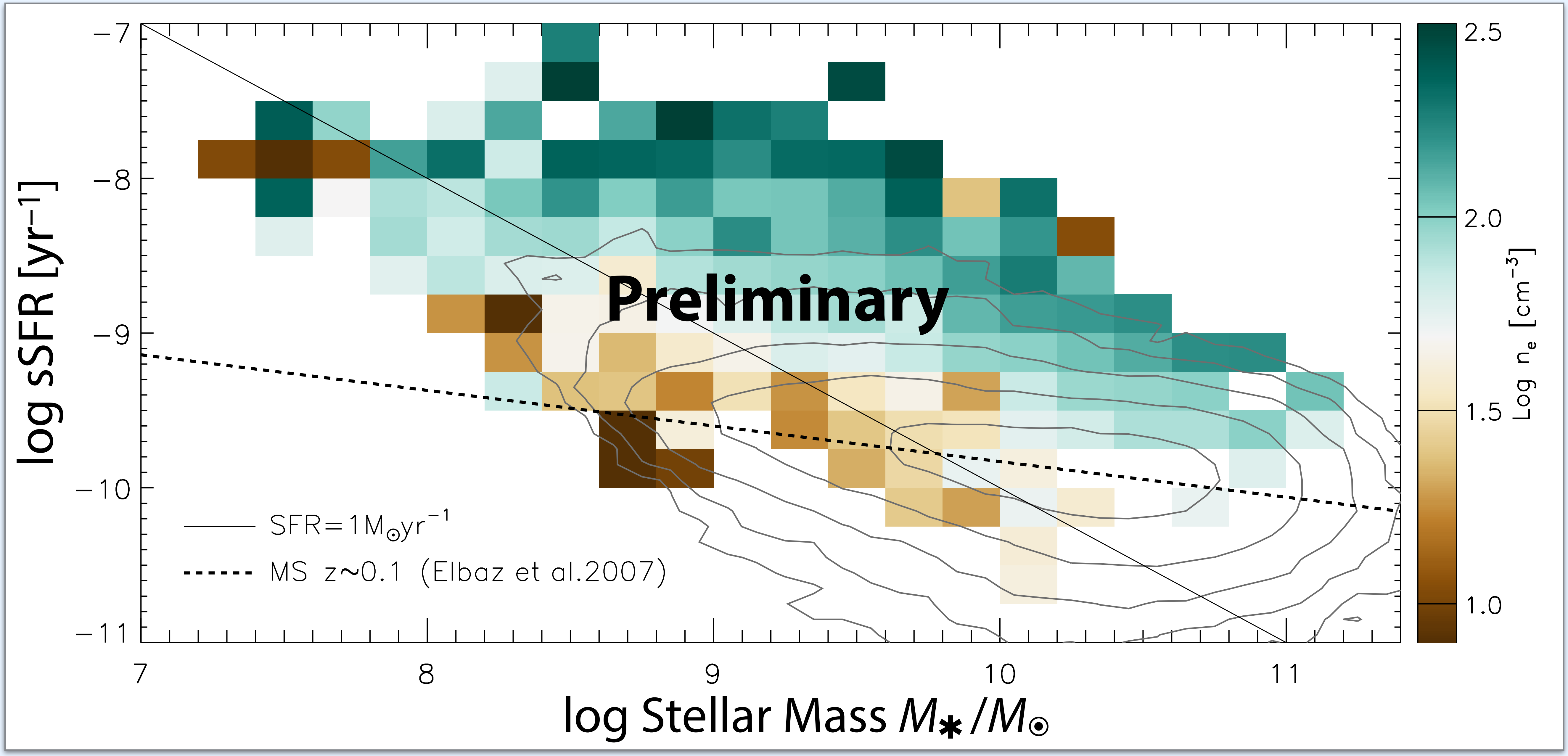
succeeded for N=133 stacks with $\Delta\log M_*$=0.2, Δlog sSFR=0.25

N_{gal}~1–10^4 per bin



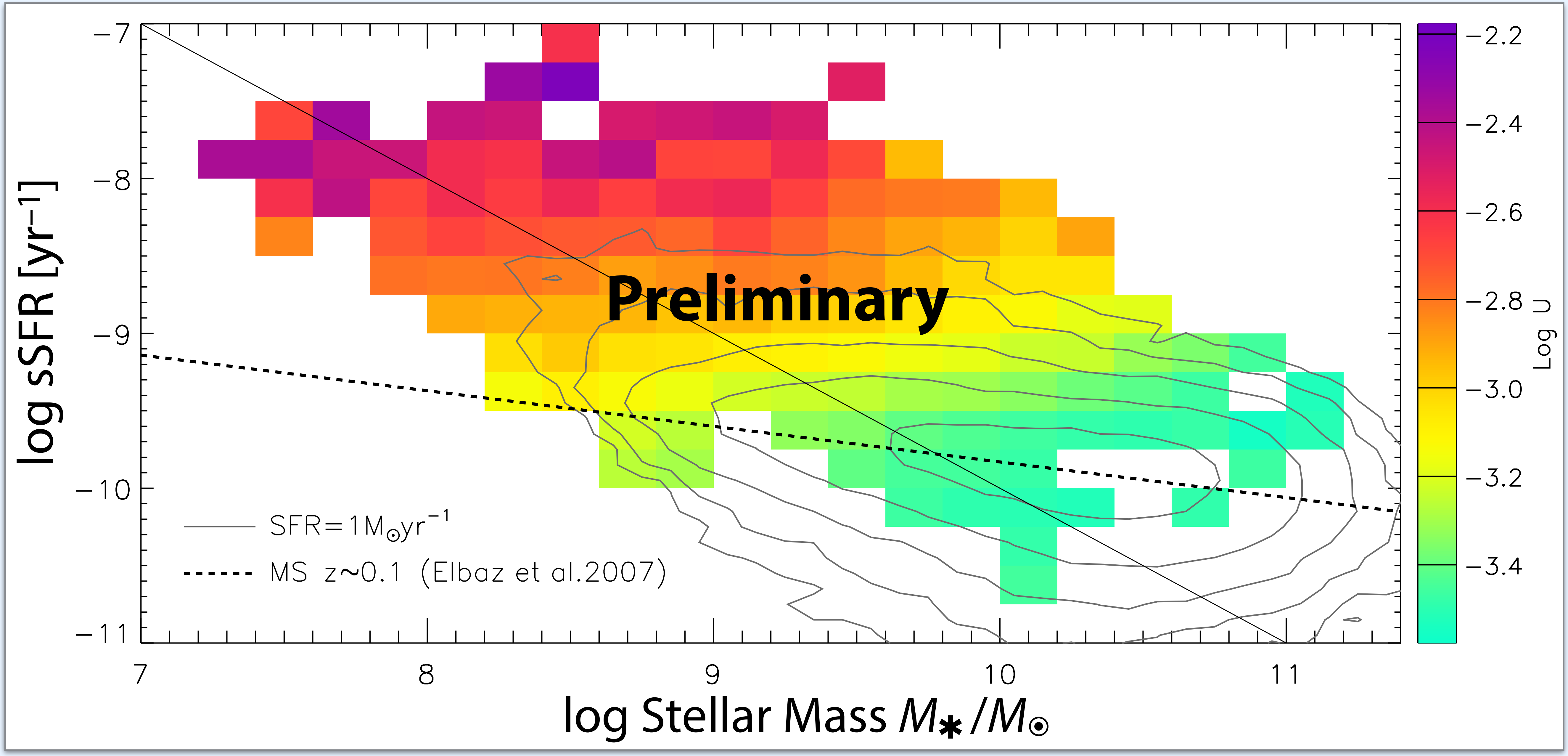
Electron density

via [SII] 6716,6731 doublet ratio, incl. the T_e dependence.

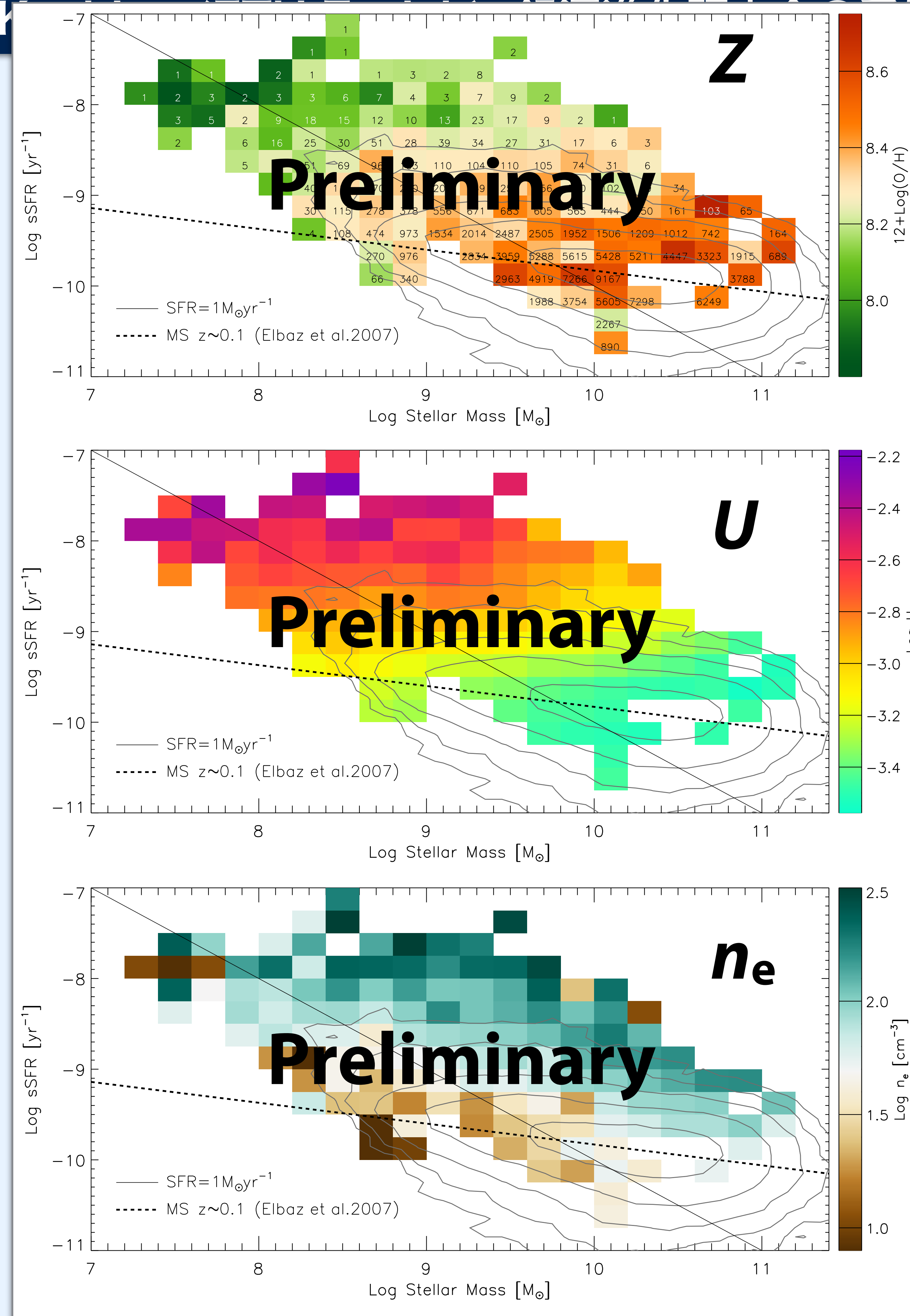


Ionization parameter

from [OIII]5007/[OII]3727, incl. the Z and n_e dependences.



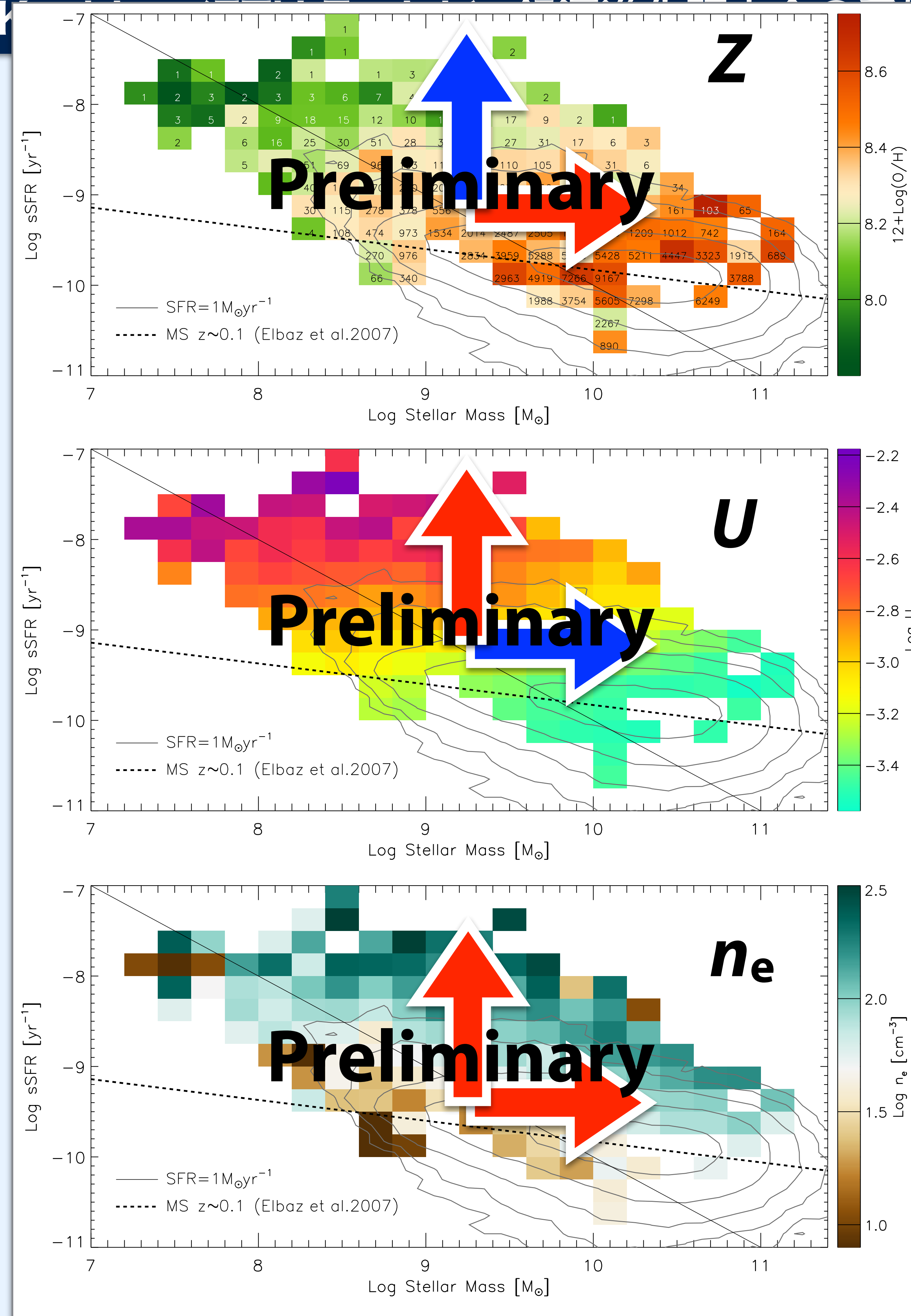
These key ISM parameters are all strong functions of M_* and sSFR.

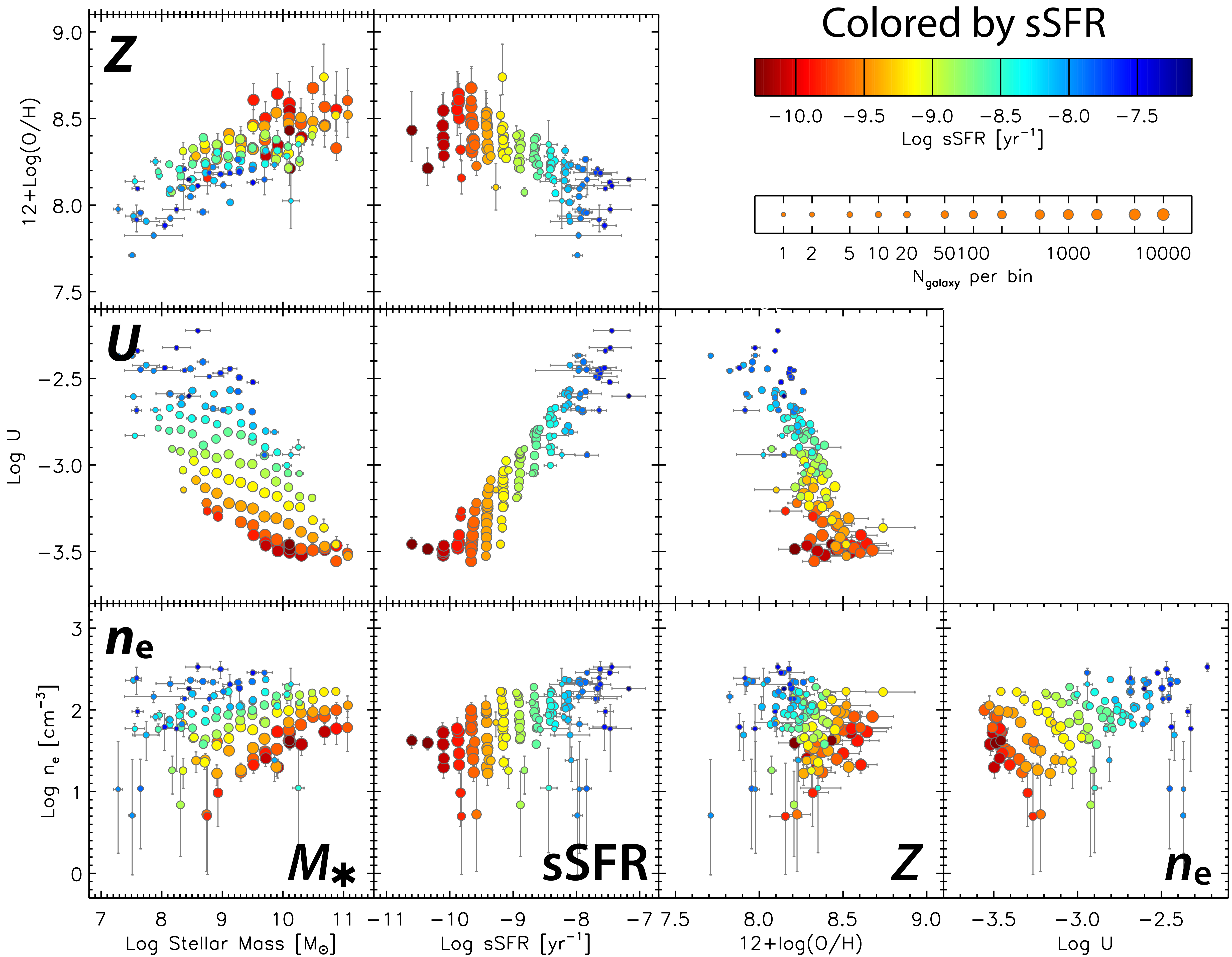


These key ISM parameters are all strong functions of M_* and sSFR.

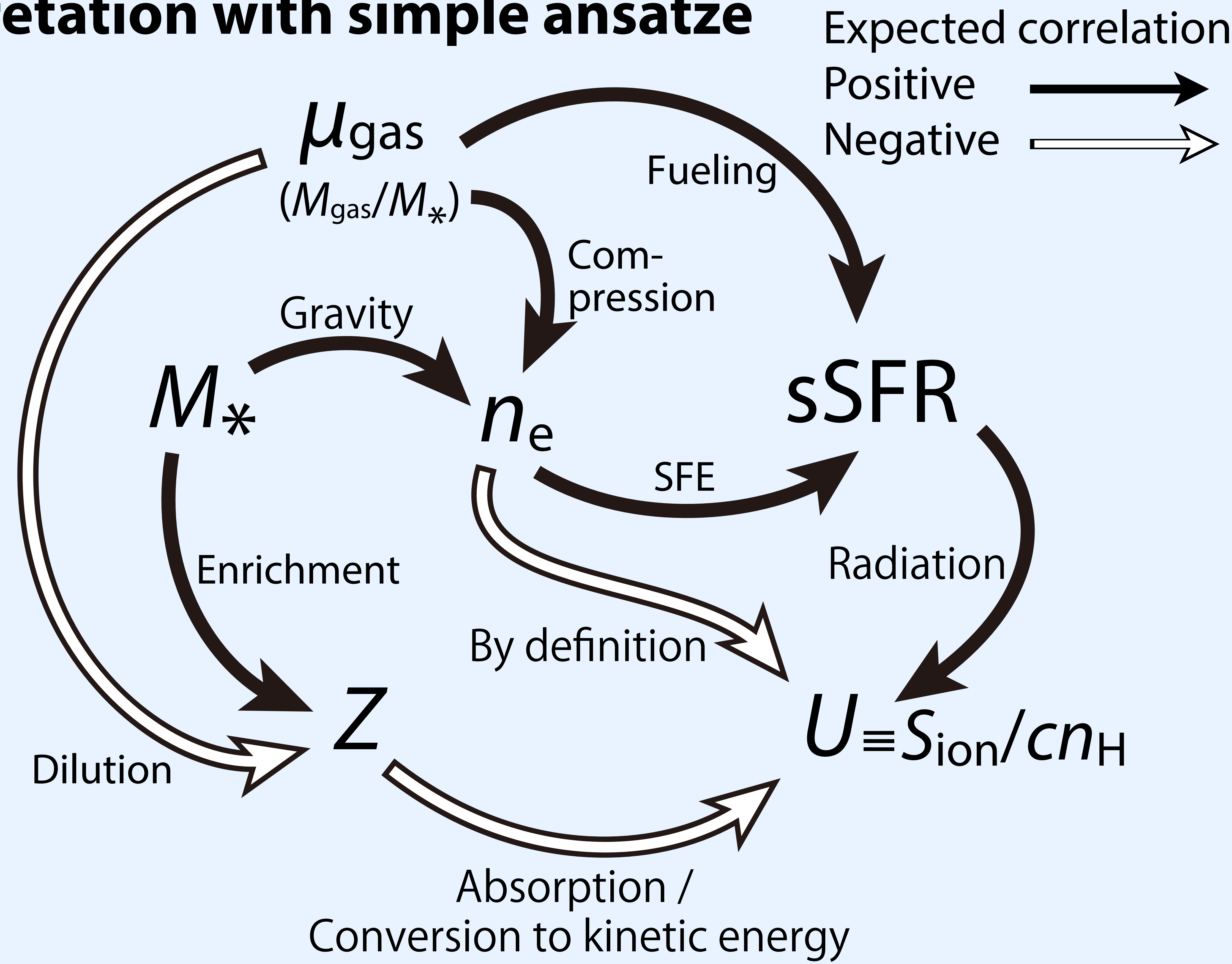
Increase

Decrease

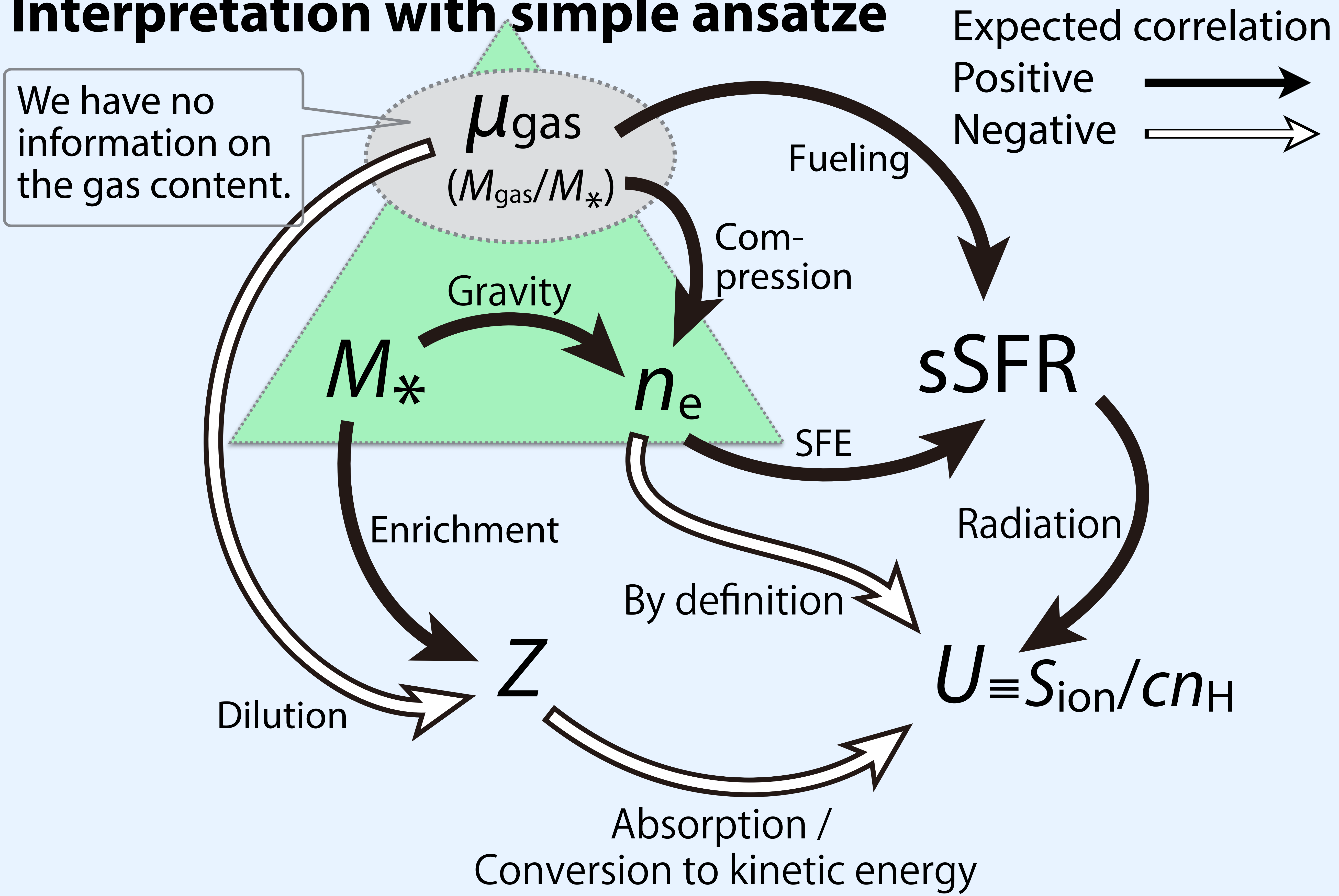



Colored by sSFR
−10.0 −9.5 −9.0 −8.5 −8.0 −7.5
Log sSFR [yr^{-1}]
1 2 5 10 20 50100 1000 10000
N_{galaxy} per bin
Z
U
n_e
M_*
sSFR
Z
n_e
12+Log(O/H)
Log U
Log n_e [cm^{-3}]
Log Stellar Mass [$M_\odot$]
Log sSFR [yr^{-1}]
12+log(O/H)
Log U

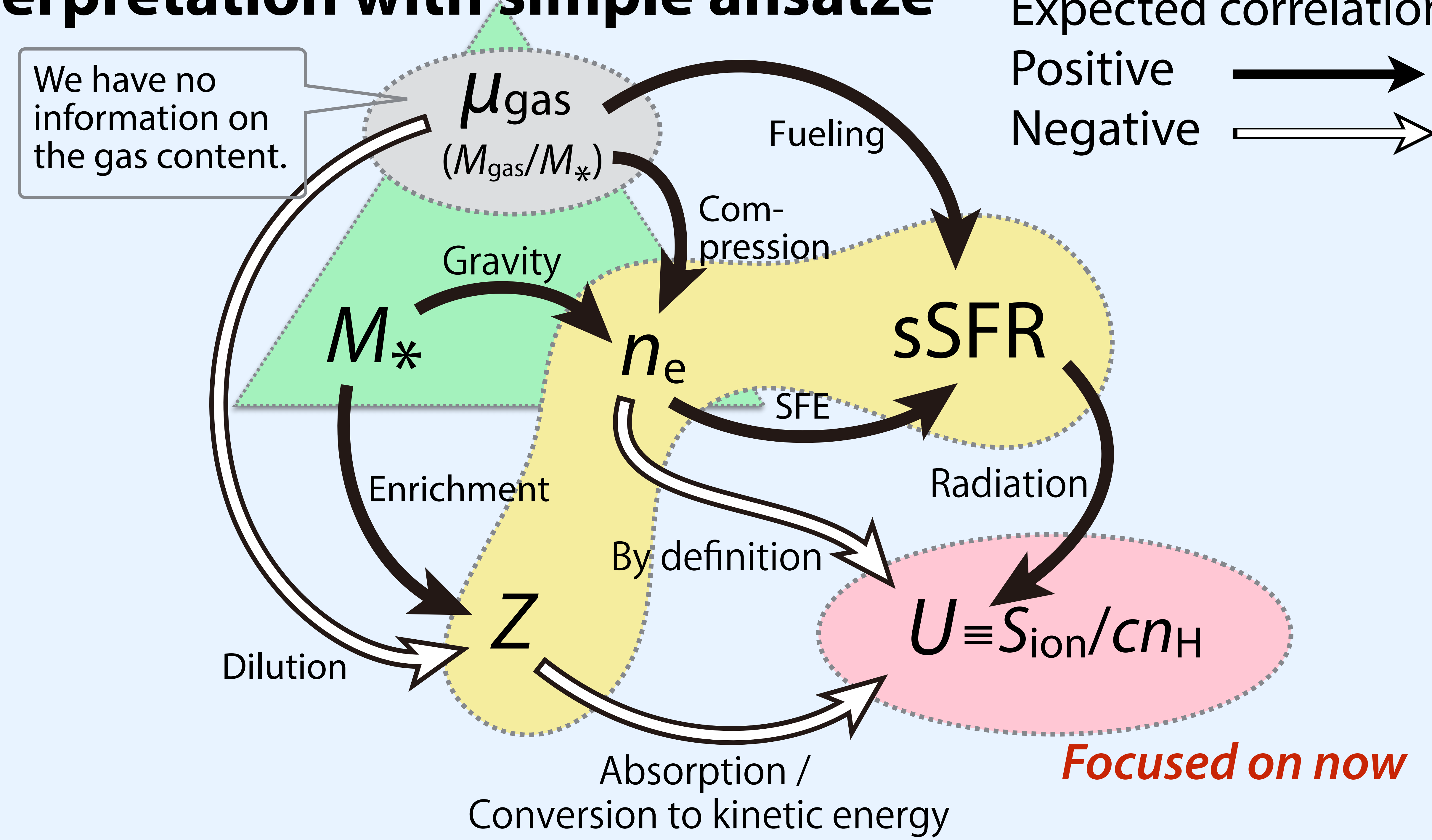
Interpretation with simple ansatze



Interpretation with simple ansatze



Interpretation with simple ansatze



Assuming a power law (linear in log):

$$\log \boldsymbol{U} = \boldsymbol{\alpha} \log \mathbf{sSFR} + \boldsymbol{\beta} \log (\mathbf{O/H}) + \boldsymbol{\gamma} \log \boldsymbol{n_e} + \text{Const.}$$

Results: dependencies of Ionization parameter $U \propto \mathrm{sSFR}^{\alpha} Z^{\beta} n_e^{\gamma}$

$\alpha = 0.55 \pm 0.01$
$\beta = -0.45 \pm 0.02$
$\gamma = -0.46 \pm 0.04$

Primarily controlled by sSFR, but also significantly "negatively" dependent on Z and n_e

Residual dependence after regressing onto sSFR:
y-axis = $\mathrm{Log}\, U - \alpha\, (\log \mathrm{sSFR/Gyr^{-1}})$

Color: Z

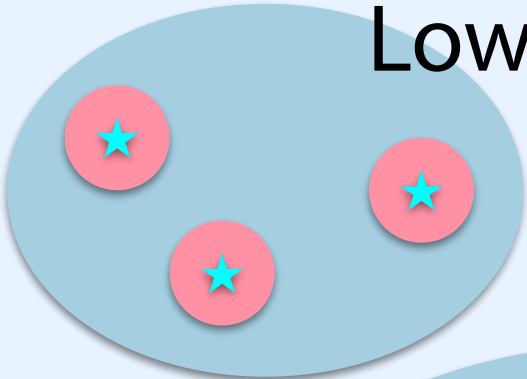
Color: n_e

Log n_e

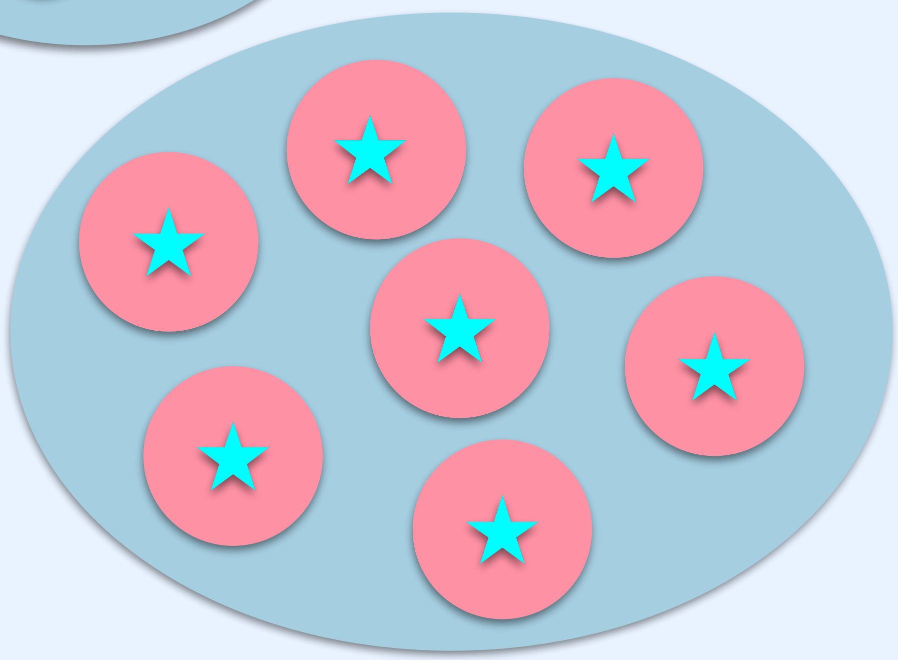
12+LogO/H

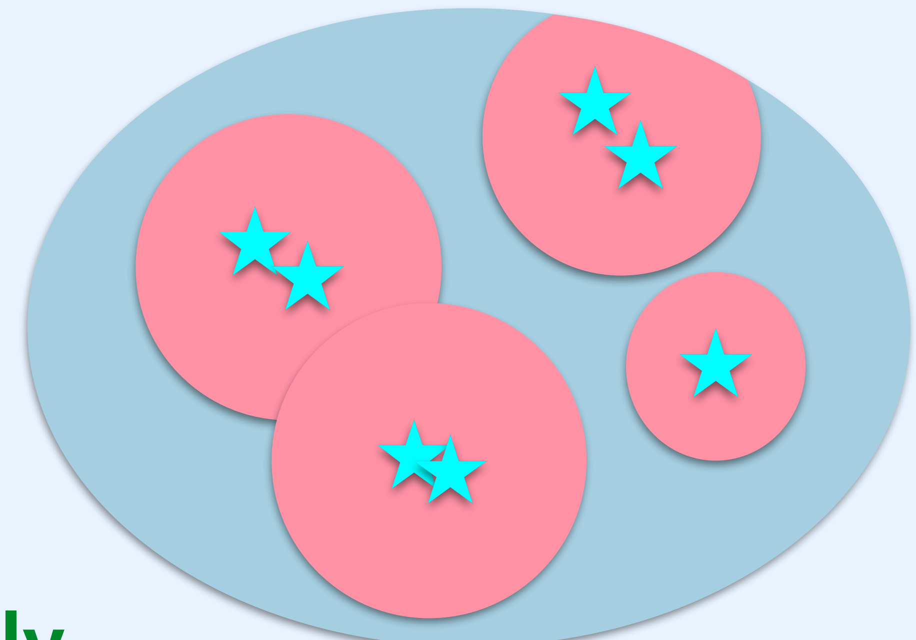
How does sSFR govern *U* ?

Lower-sSFR galaxy



Possible pictures of higher-sSFR galaxy (fixed M_*)





Increase in *N* of HII regions, but each of them is similar to those in lower-sSFR objects

➡ **No increase in the "local" ionization parameter**

Probably,…

- Enhanced SF in a single HII region

➡ increase in ionizing radiation

- Overlap of HII regions
- Escape of ionizing photons — "density-bounded" case

➡ effectively increase [OIII]/[OII] ratios

Summary and Caveats

Goal of this work was:
Quantifying the relationships between the key ISM and global parameters.

Observationally, we demonstrate that *U* is primarily controlled by sSFR, as well as that "partial" anti-correlations to *Z* and n_e exist.

Functional forms are obviously over-simplified.

Still, our results provide us with useful bench marks to be reproduced (on average) in galaxy models.

Many parameters are not considered:
Gas content, galaxy size (Σ_M and Σ_{SFR}), morphology, clumpiness, dust, escape fraction, diffuse HII gas, etc… may also affect the ISM conditions.

Beyond the local Universe with e.g., PFS and MOONS