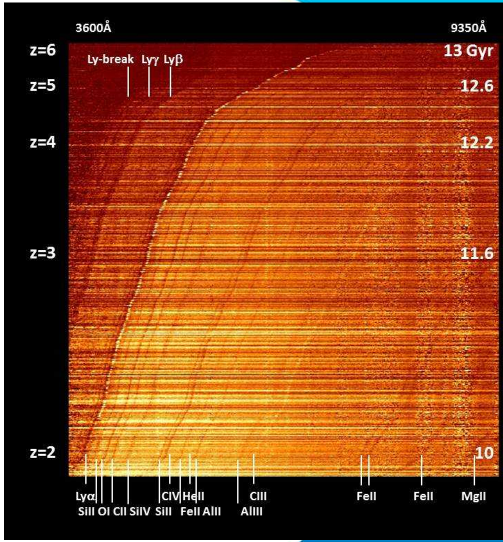
Diagnostic emission lines in the Early Universe



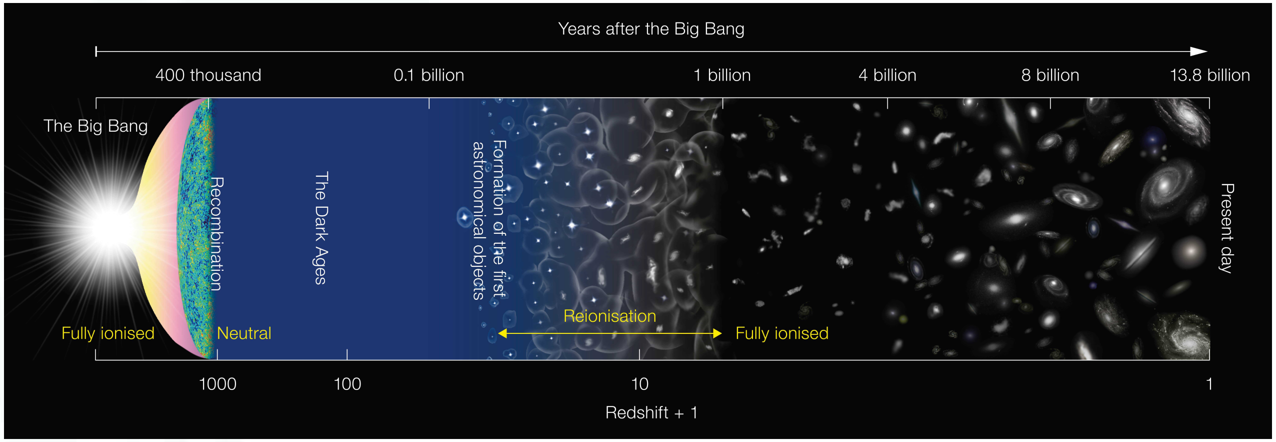
P. Theulé, J. Villa-Vélez, V. Buat, D. Burgarella, M. Boquien
L.M. Seillé, E. Pons, L. Trabelsi, O. Kalpogiannis

Laboratoire d'Astrophysique de Marseille, Aix-Marseille Université

"14th Serbian Conference on Spectral Line Shapes in Astrophysics"
June 19-23, 2023, Bajina Basta, Serbia

Scientific goals

→ to derive galaxy evolution relevant parameters (star formation history, initial mass function, density, metallicity, cosmic ray, photoradiation field, …) from the epoch of re-ionization (6<z<25) to now (z=0) from galaxies spectral energy distribution



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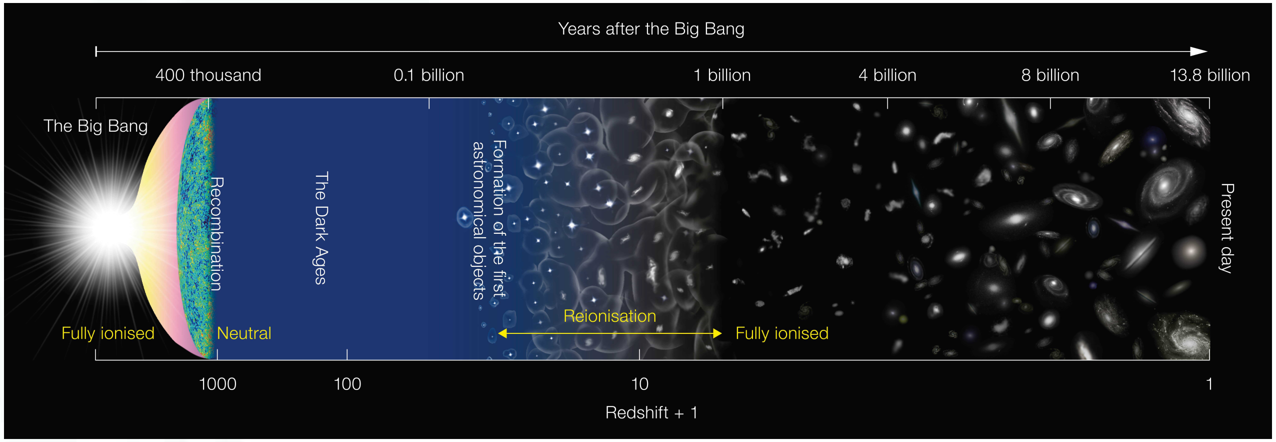

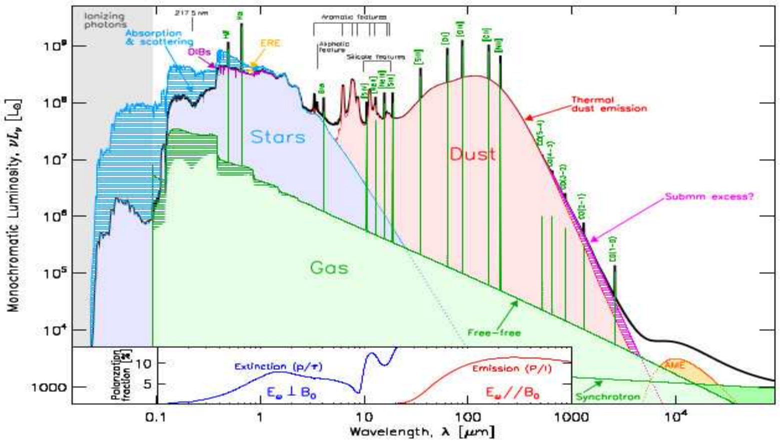

credit : F. Galliano et al. ARAA 2018

Scientific goals

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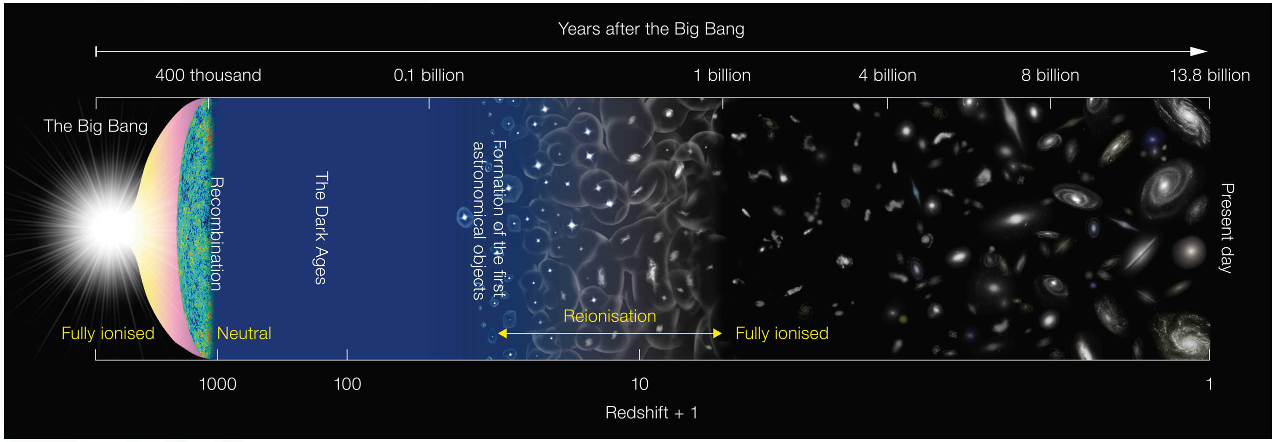
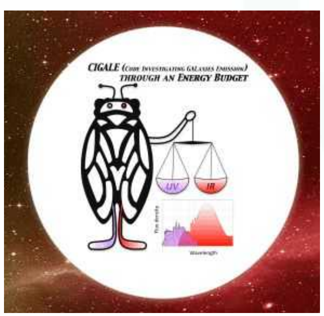


→ to combine spectro- and photometric analysis of galaxies around Cosmic Noon

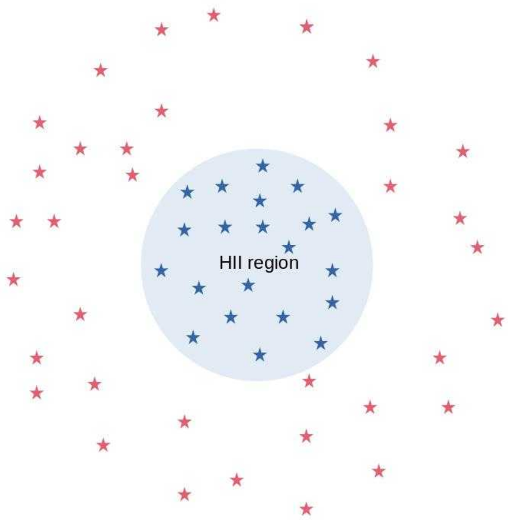


PhD Jorge Villa-Vélez :
Spectro-photometric Analysis Around Cosmic Noon:
Emission-Lines, Dust Attenuation, and Star Formation

Fitting spectral energy distributions of FMOS-COSMOS emission-line galaxies at $z \sim 1.6$:
Star formation rates, dust attenuation, and [OIII]λ5007 emission-line luminosities
Villa-Vélez J. A. , Buat V., Theulé P. , Boquien M., Burgarella D.,
Astronomy & Astrophysics, 2021

→ to generate mock spectra for next-coming instruments VLT/MOONS, Subaru/PFS, ELT/Mosaic

I. Starburst regions



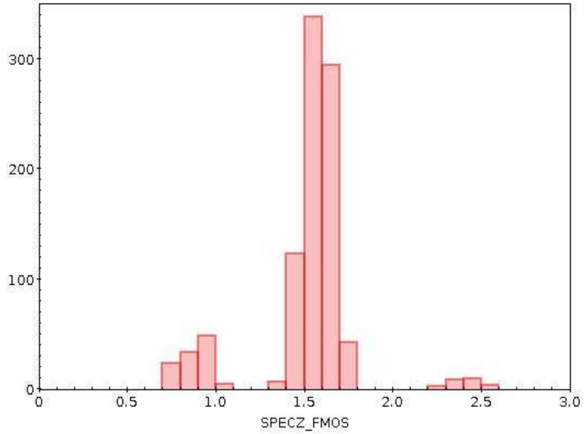
1. Technique validation on a reduced sample with spectroscopic data

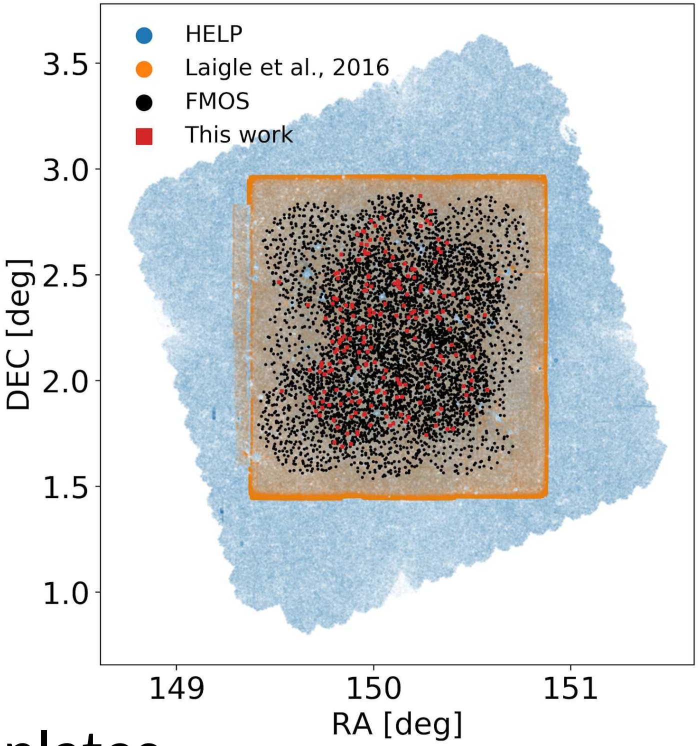
2. Extension to a larger sample

3. Updates on CIGALE line fitting capacities improvements

Selection of our COSMOS field sub-sample

- cross-matched of COSMOS2015 (Laigle et al. 2016) with the Subaru/FMOS-COSMOS catalog (Kashino et al., 2013 and Silverman et al. 2015) to get a 2508 galaxies sample
- 0.6 < z < 1.6 Hα and [OIII]5007 in MOONS spectral range
- UV-to-MIR SED fit
- 853 detected in Hα

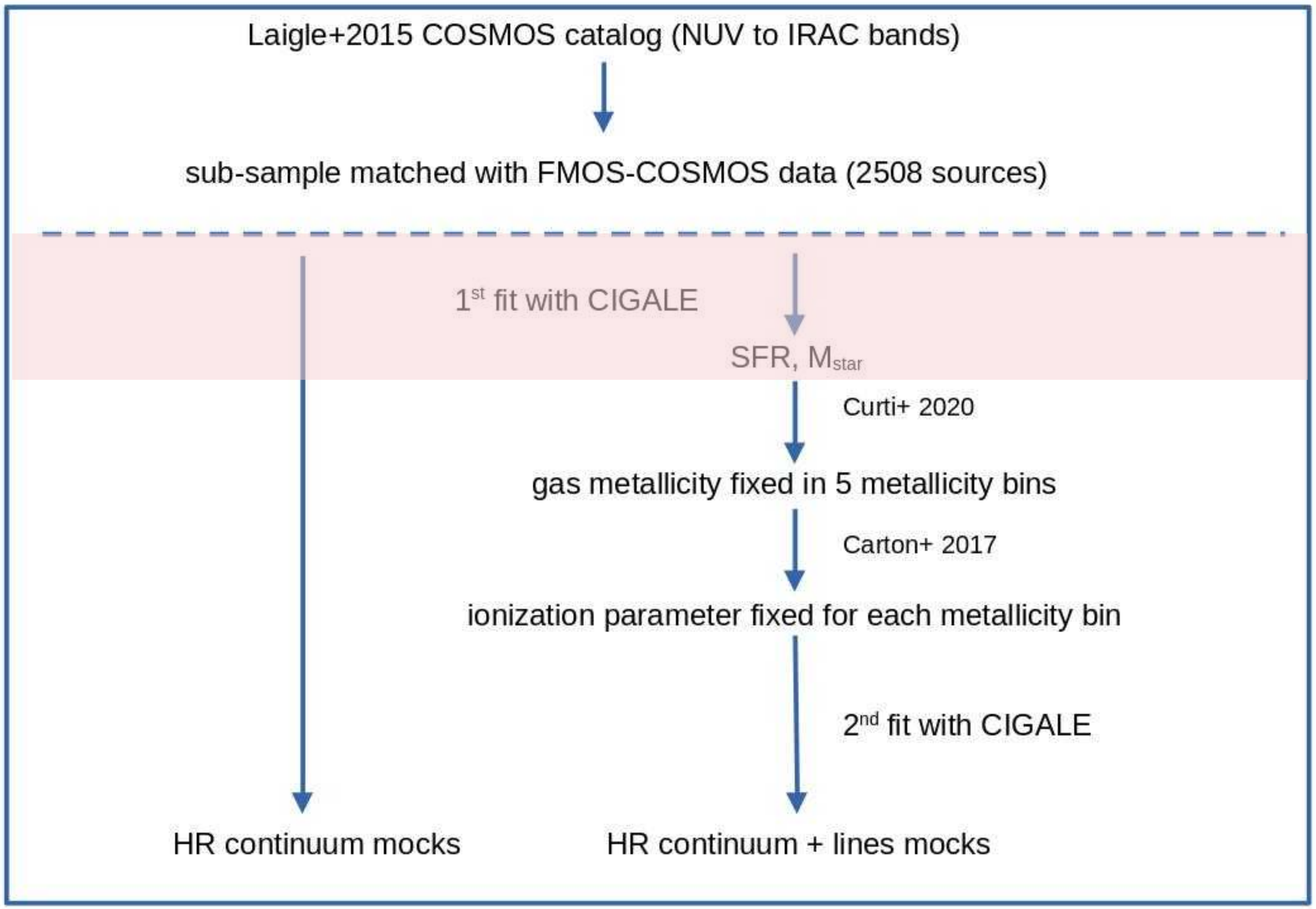


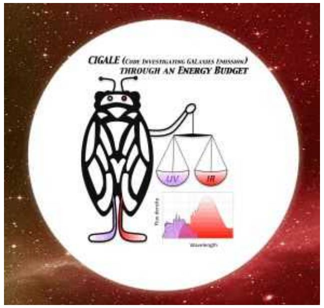


→ generate spectral templates

Mock spectra generation procedure

step 1

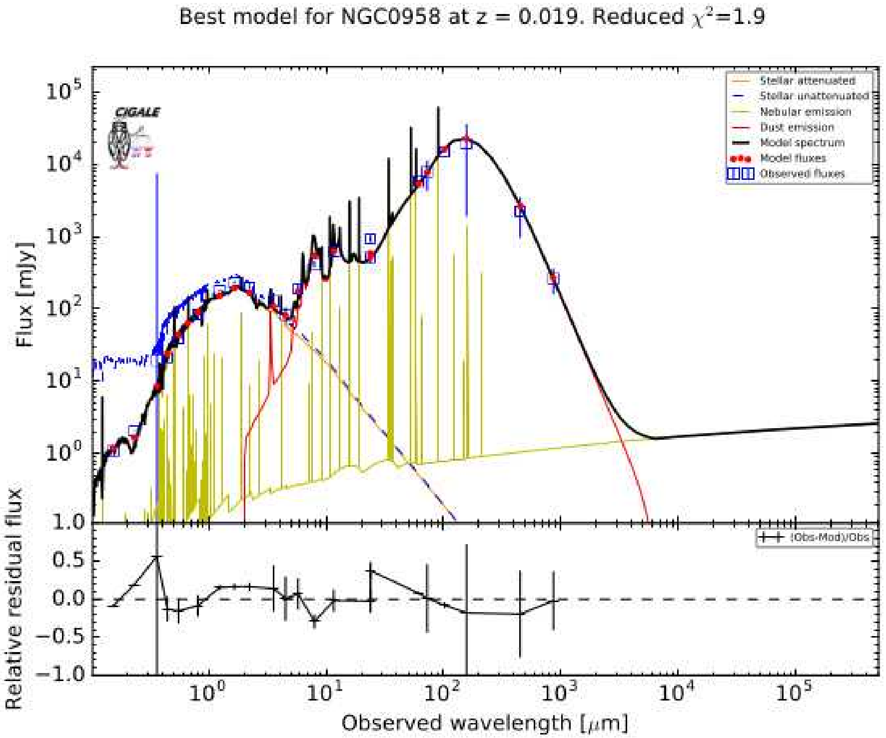




Step 1 : Fit of the UV-to-MIR photometric data

CIGALE = Code Investigating GALaxy Emission

- energy balance principle
- a SED fitting code (Bayesian analysis)
- produces mock spectra to compare with observations



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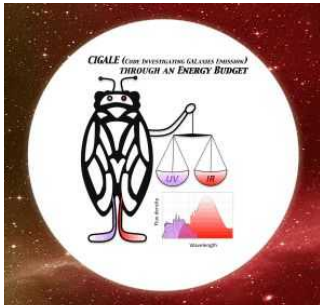

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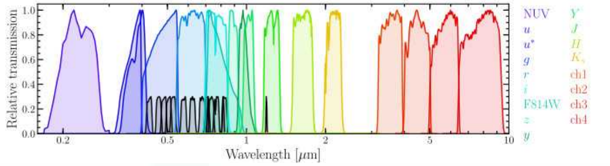
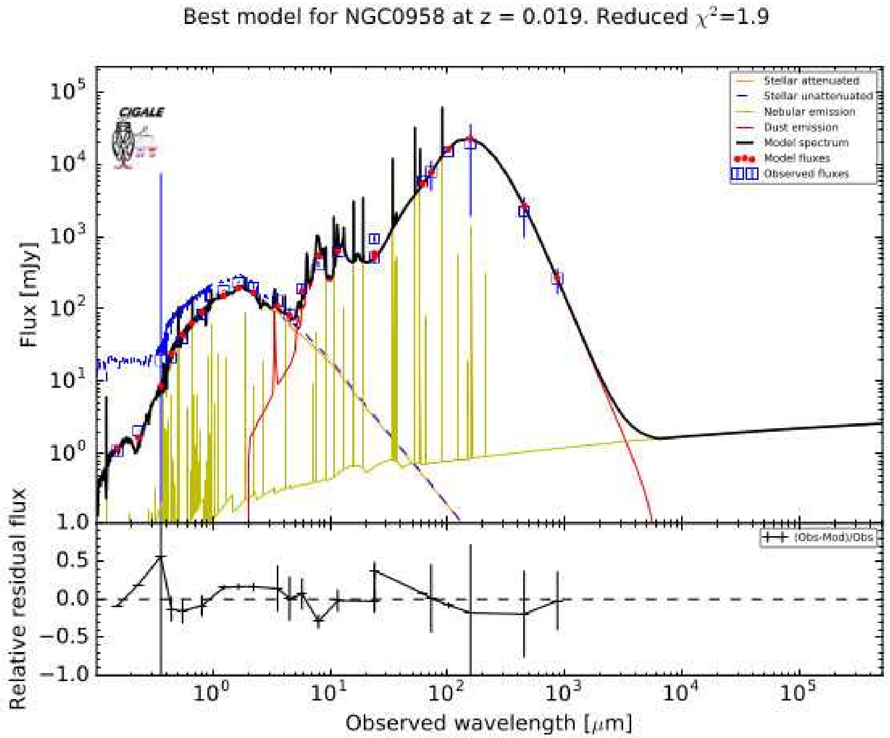


fit of the UV-to-MIR photometric data

→ SFH (star formation rates, stellar mass)

SFH = delayed + burst

Calzetti attenuation curves for the lines and for the continuum



Nebular emission lines modeling

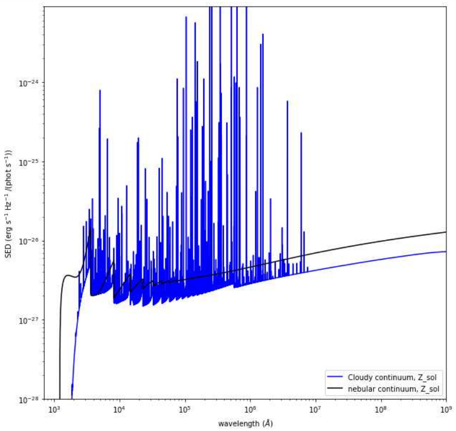
density n_H
metallicity ζ_O
elementary atomic abundances

the CIGALE nebular emission module

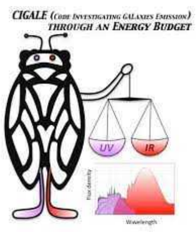
ionizing radiation field :
shape + intensity

BC03 SSP
U ionization parameter

H
He
C
N
O
Mg
Fe
...



nebular continuum + emission lines



(U, n_H, ζ_O)

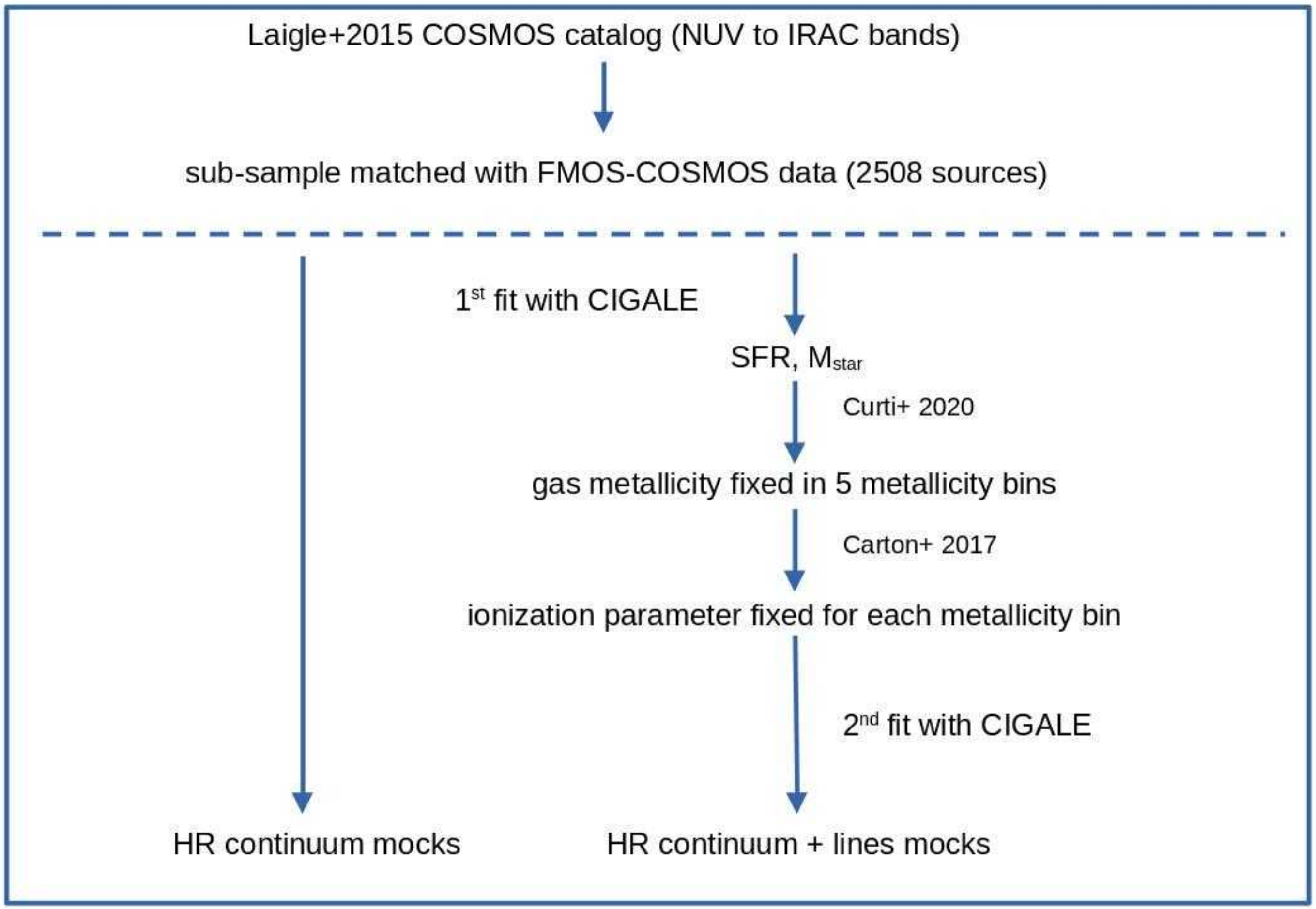
Cloudy & Associates

Photoionization simulations for the discriminating astrophysicist since 1978

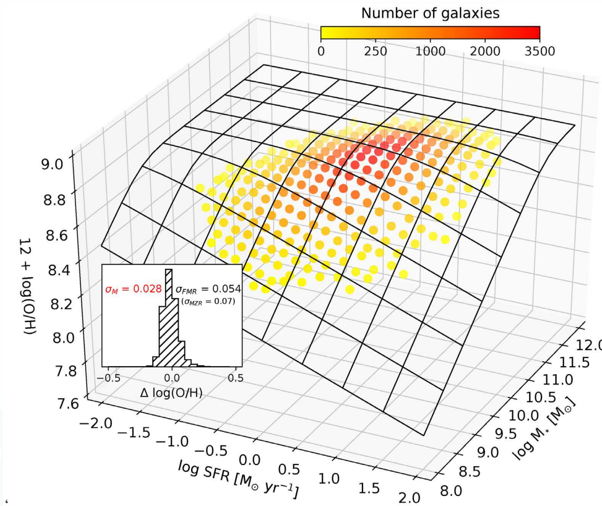
fixed extinction MW + Calzetti E_{B-V}= 0.44
variable extinction on line flux fitting

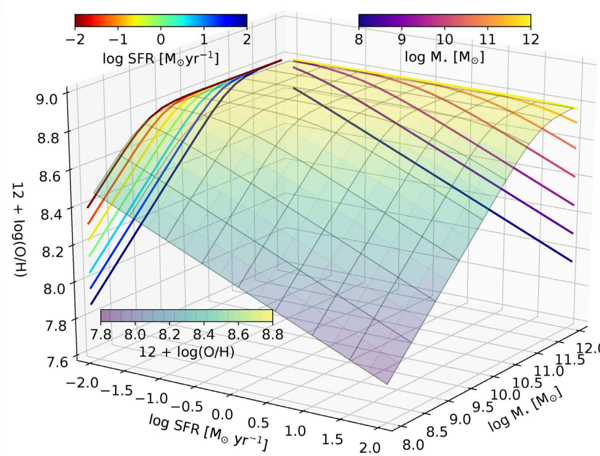
1. calculate the abundances of each species (chemical reaction networks)
2. calculate the populations for each level for each species (collisional/radiative level excitation)
3. compute radiative transfer for each emission line
4. generate a library of emission lines templates as a function of a set of parameters (U, n_H, ζ_O)

Mock spectra generation procedure



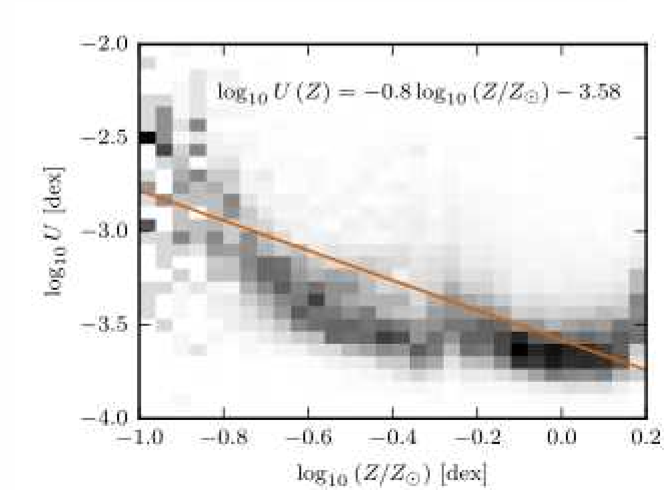
Nebular emission lines modeling





mass-metallicity -SFR relation

Curti et al. 2020



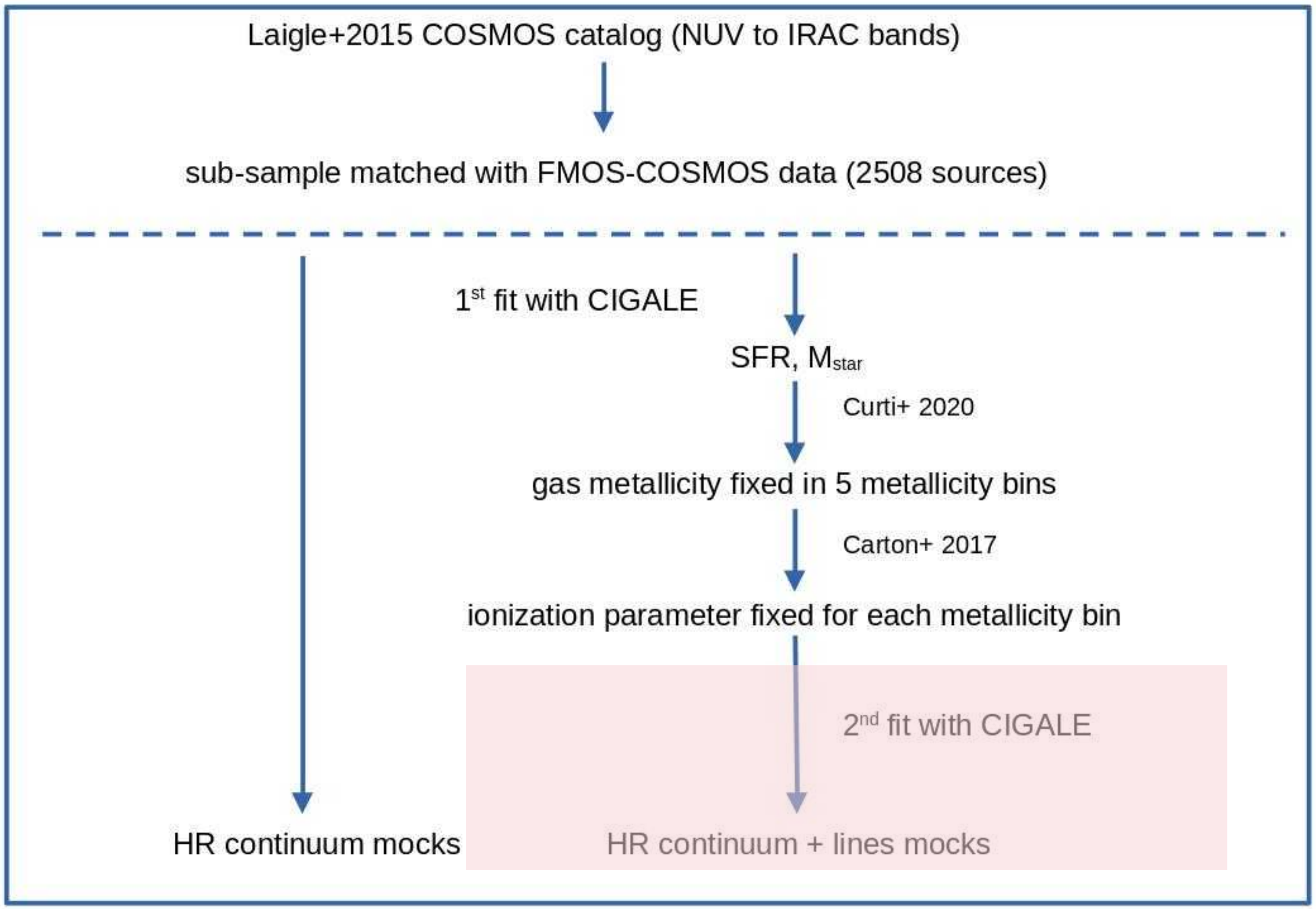
metallicity – ionization parameter relation

$\log_{10} U(Z) = -0.8 \log_{10} Z/Z_{\odot} - 3.58$

Carton et al. MNRAS 2017

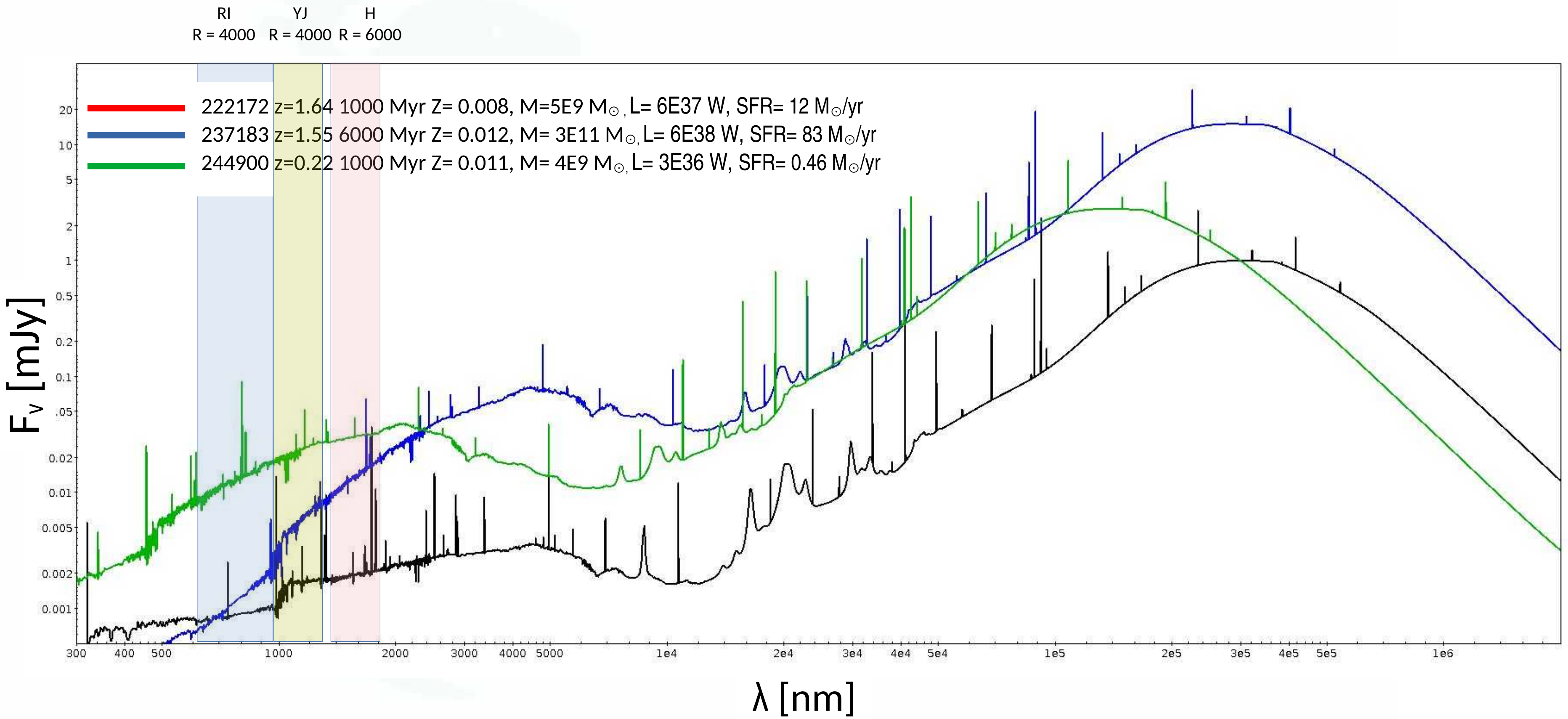
gas metallicity → star metallicity

Mock spectra generation procedure



step 2

Step 2 : mock catalog on the COSMOS field

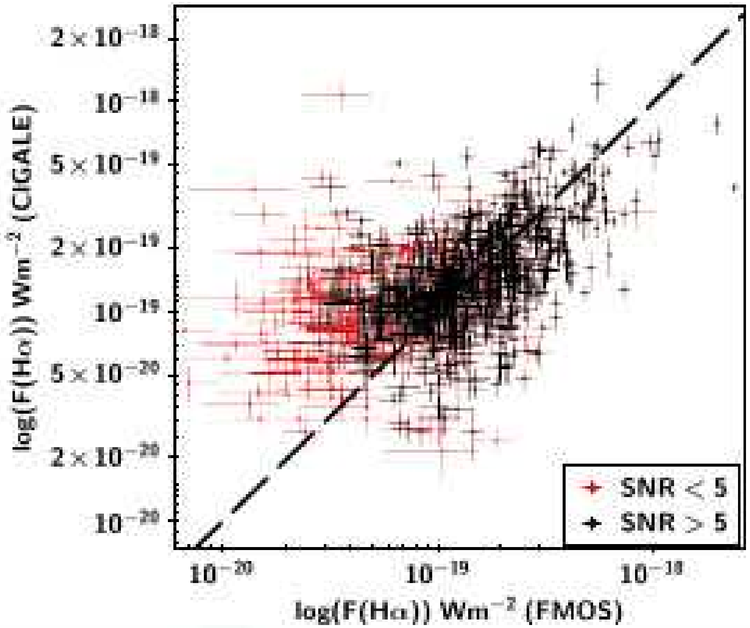


mock spectra for 2508 galaxies

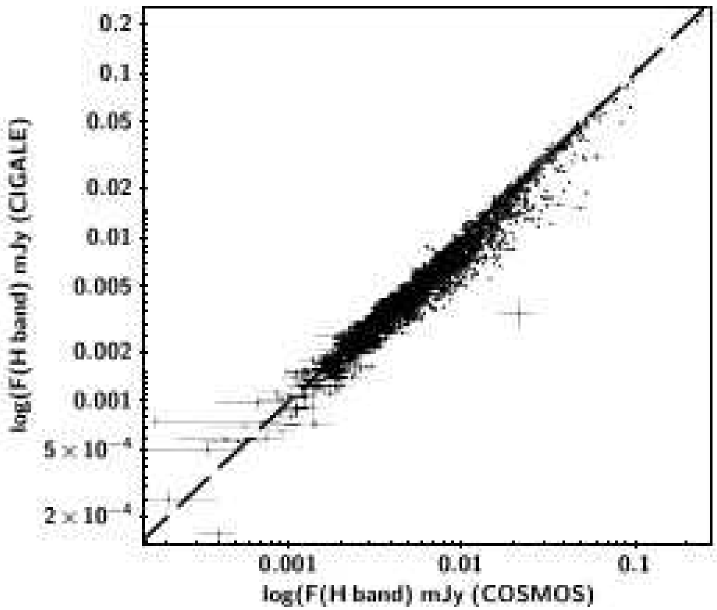
- continuum only
- continuum + lines (U fixed)

Results: comparison of observed and modelled flux

self-consistency checks

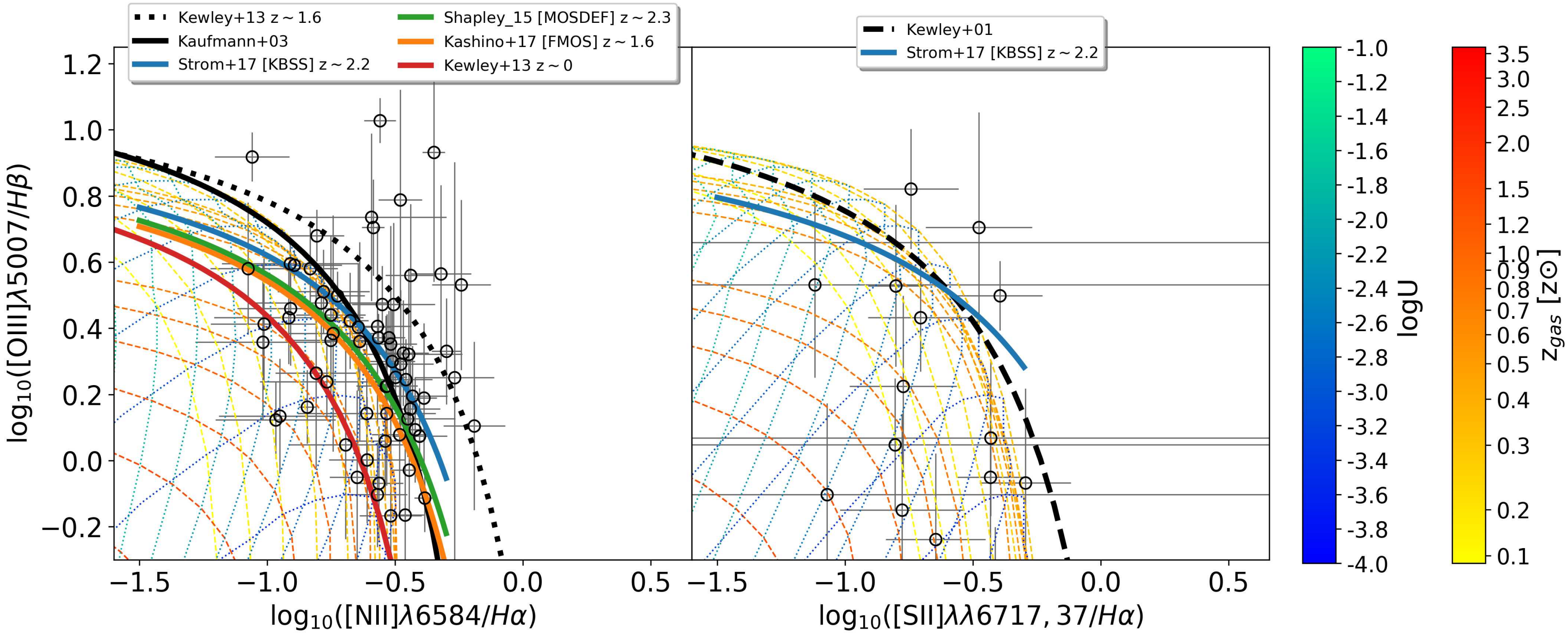


Hα fluxes. The agreement is quite good except for 6% of the sample plotted in red, correspond to measured fluxes with an SNR lower than 5



H-band fluxes: the agreement is excellent for the whole sample

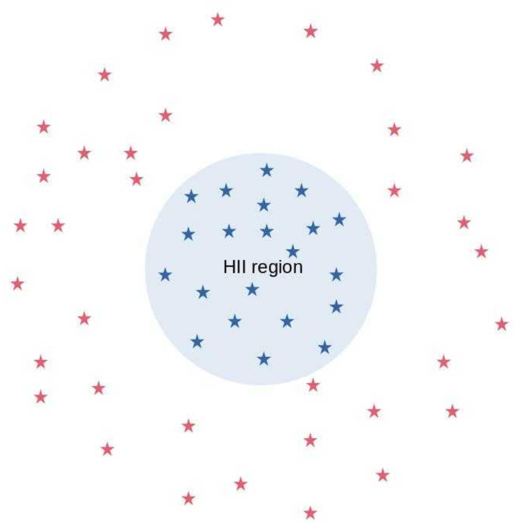
Results: excitation diagnostic diagrams



Baldwin-Phillips-Terlevich (BPT) diagrams

from Villa-Vélez et al. A&A 2021

I. Starburst regions



1. Technique validation on a reduced sample with spectroscopic data

2. Extension to a larger sample

3. Updates on CIGALE line fitting capacities improvements

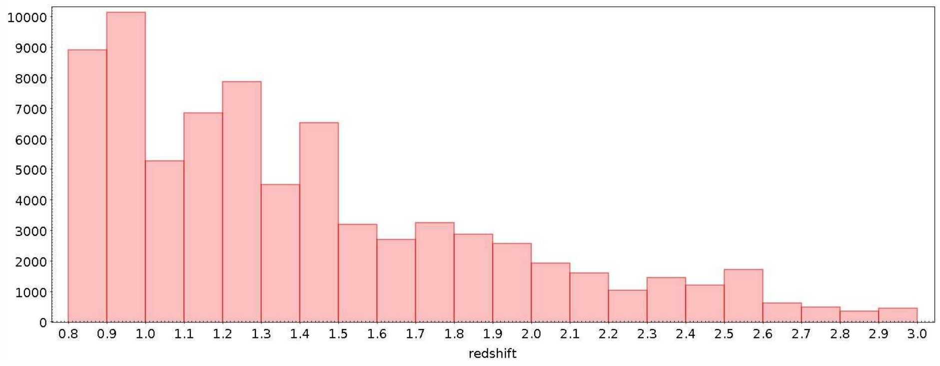
Mock spectra on a 61872 galaxy sample from COSMOS

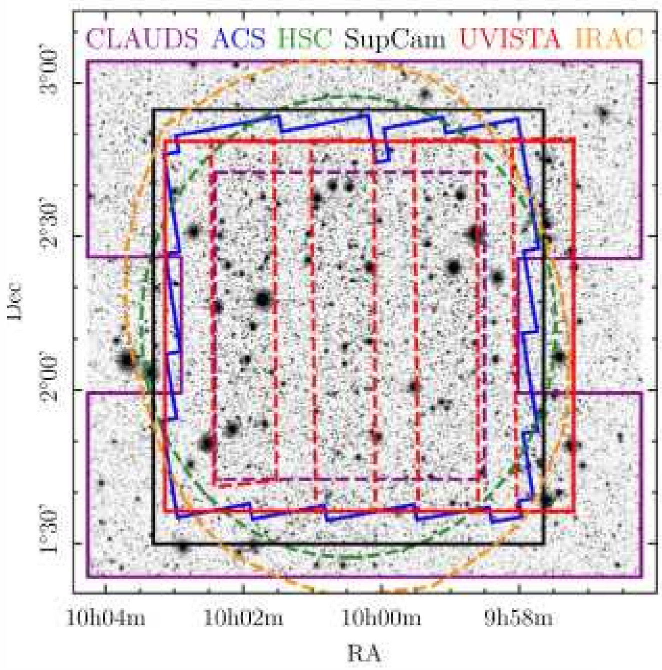
Weaver et al. ApJS 2022

sample selection :

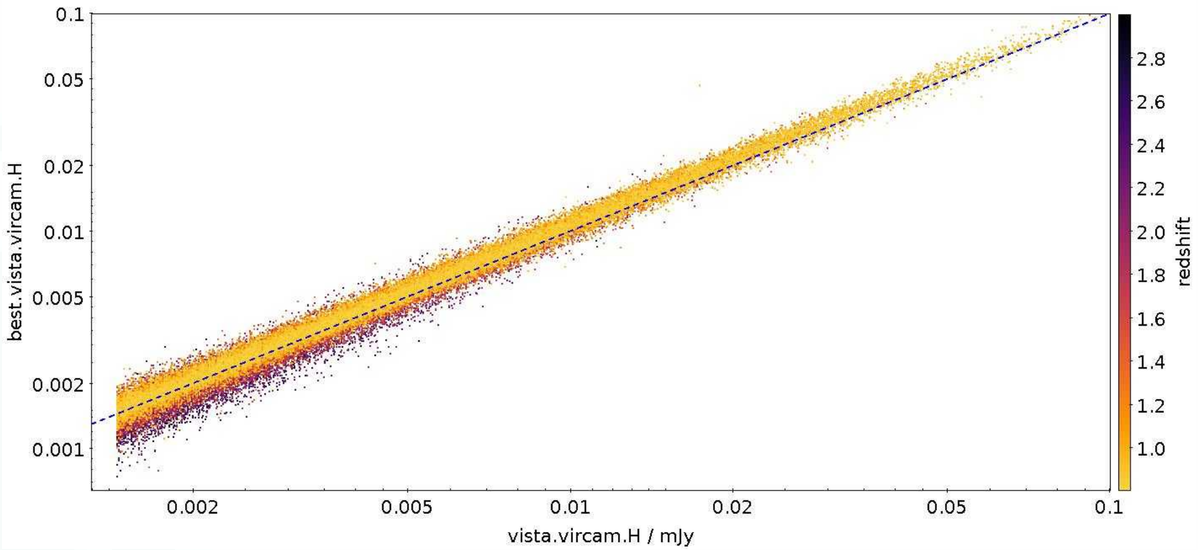
- the flux on the H band : mag(H) < 23.5 or flux > 1.4454 µJy
- the redshift : 0.8< z < 3
- object inside the UltraVista stripes deep region (1.792 deg^2 , Moneti et al. 2019)
- good HSC imaging quality (2.75 deg^2)
- good Subprime-Cam imaging quality (1.918 deg^2)
- reduced χ^2 <5 criterion

→ 1.792 deg^2 area, 61872 galaxies



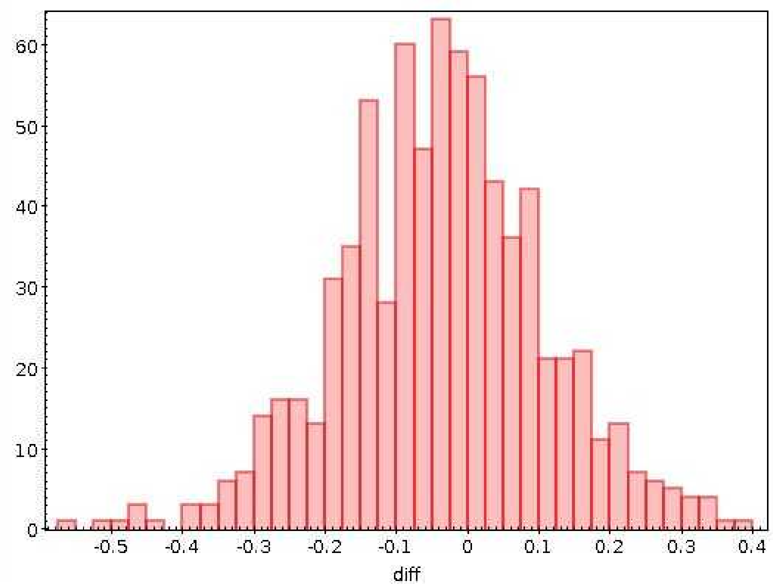


Consistency checks

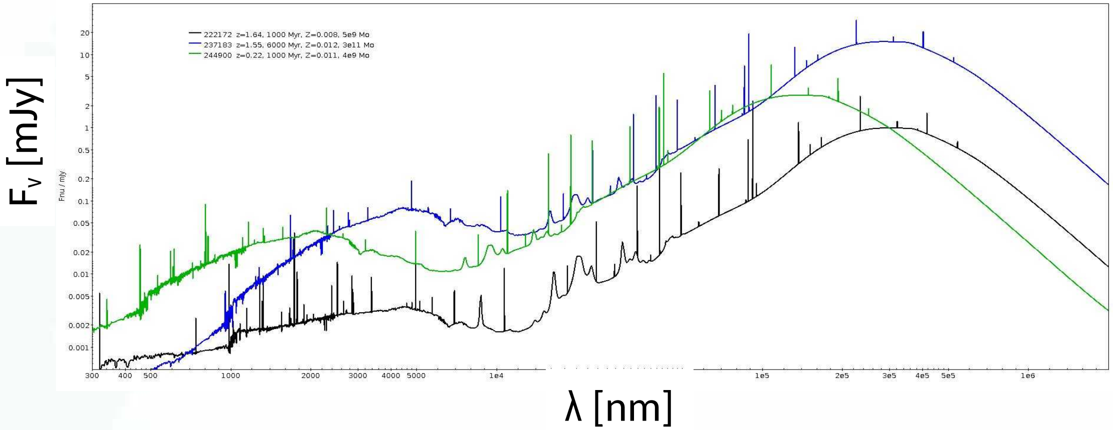


difference in M_{star}
CIGALE vs Le Phare

Weaver et al. ApJS 2022



Results: a library of spectral templates from COSMOS



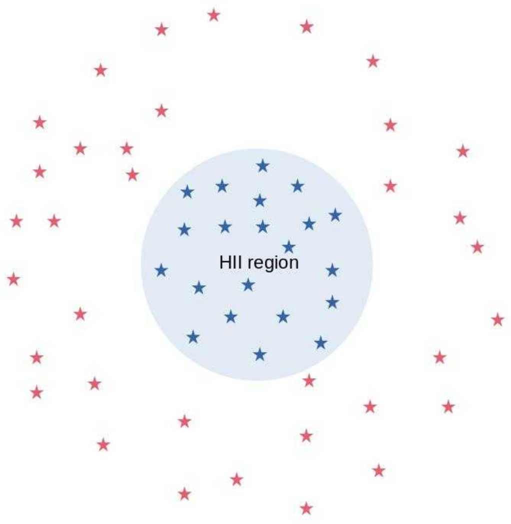
- freely available on the GASPAR/ASPIX LAM database

Archive of Spectrophotometry Publicly available In Cesam

Galaxy redshifts and physical parameters

- processed through the VLT/MOONS ETC

I. Starburst regions



1.1. Technique validation on a reduced sample with spectroscopic data

1.2. Extension to a larger sample

1.3. Updates on CIGALE line fitting capacities improvements

Updates on CIGALE line fitting capacities improvements

on HII regions

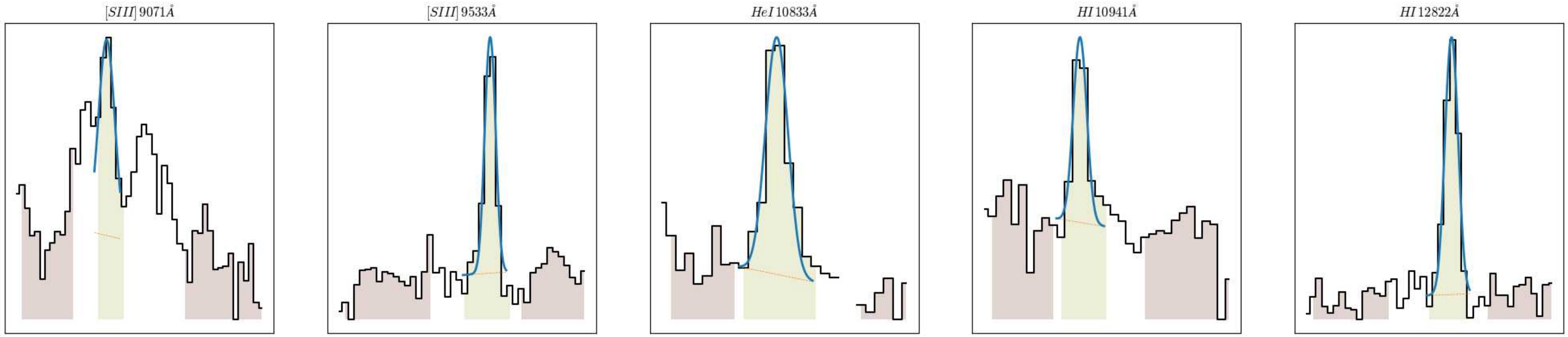
Use of the BPASS SSP library

SED fitting with equivalent width modeling in CIGALE

CIGALE computes the EWs from the modeled SED :

→ linear fit of the continuum taken on each side of the line (orange)
→ emission line with disentangled EWs for blended lines (green)

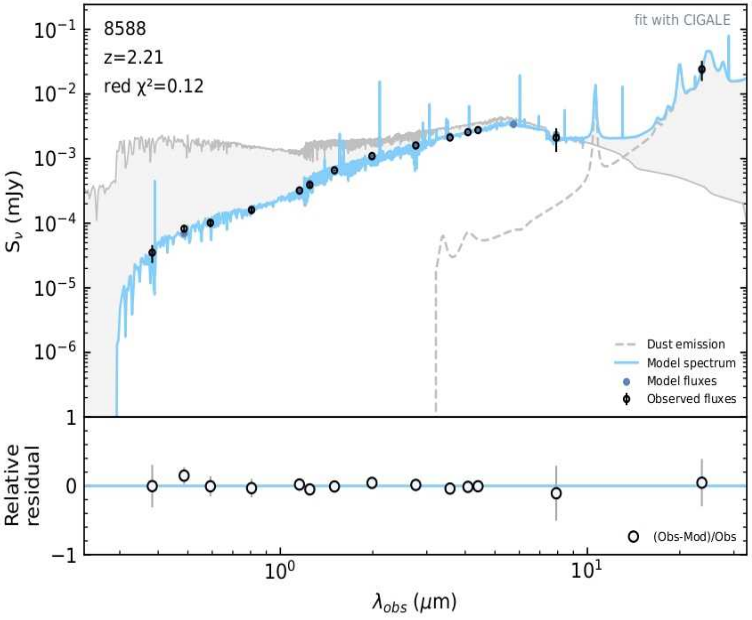
JWST observations with NIRCam and NIRSpec gratings, CEERS survey

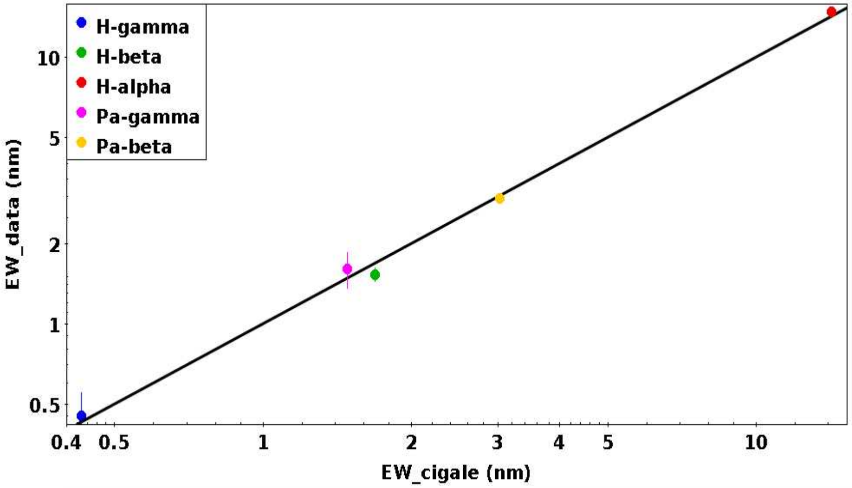


Credit : V. Fernandez

Updates on CIGALE line fitting capacities improvements

on HII regions



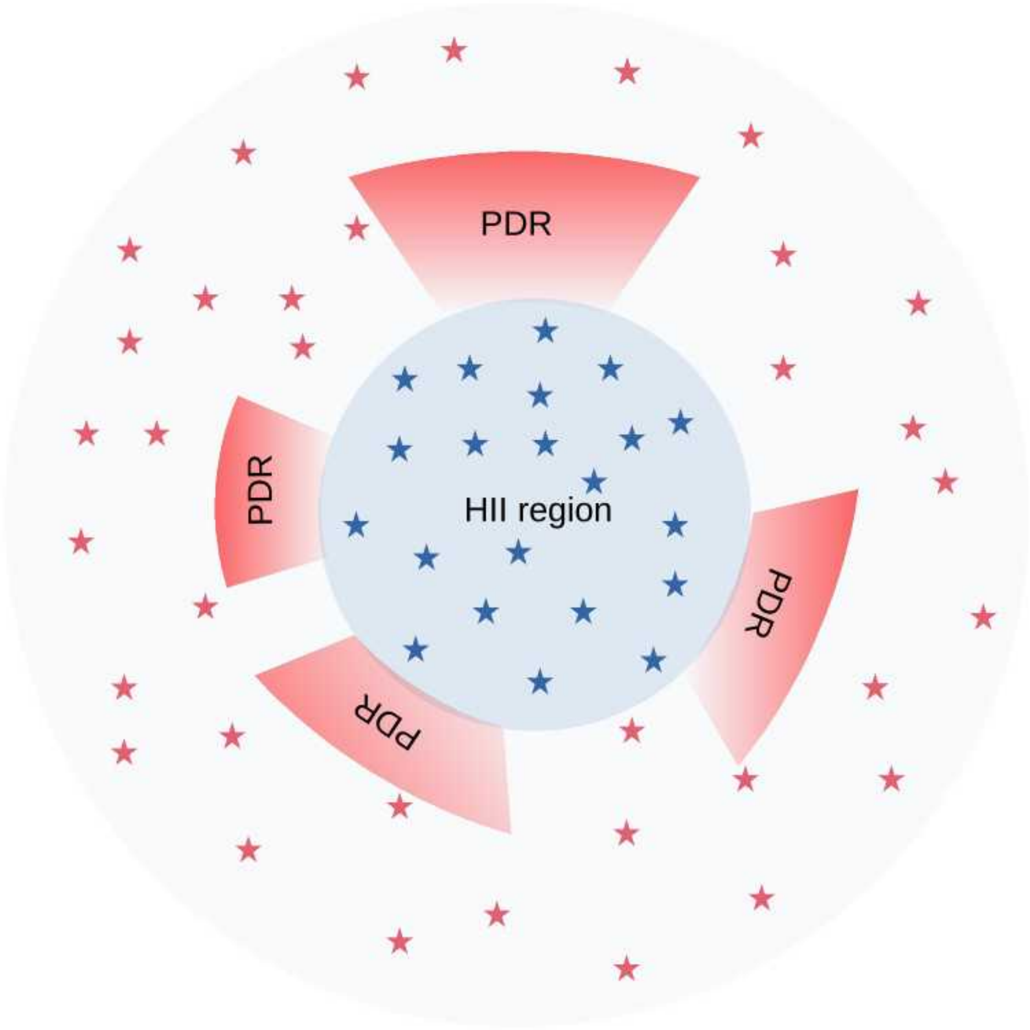


good agreement between the fit and the data

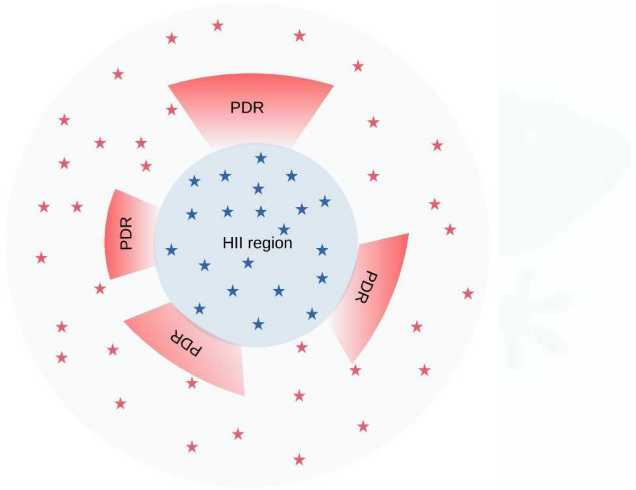
Fit combining CFHT, HST, NIRCam, IRAC and Spitzer photometry with 5 emission lines EWs from NIRSpec

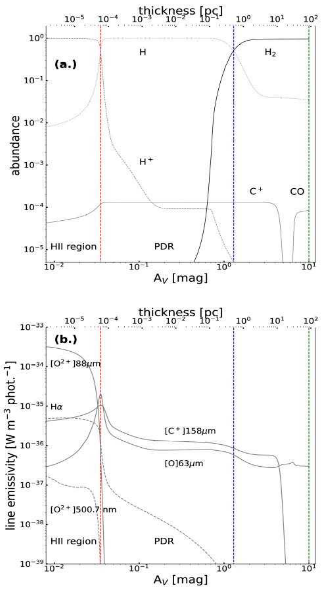
→ new EW CIGALE module adapted for MOONS

II. Starburst regions and photon dominated regions



Structure of a Photon Dominated Region (PDR)





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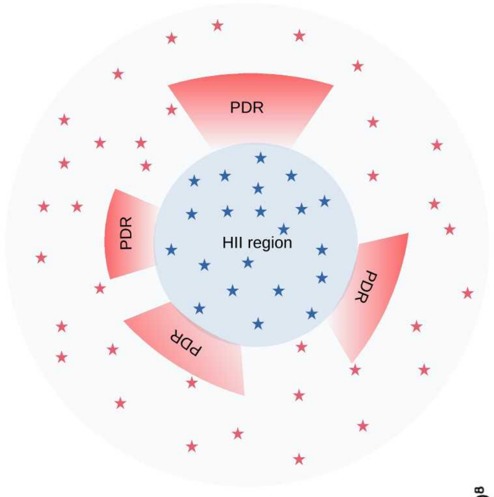

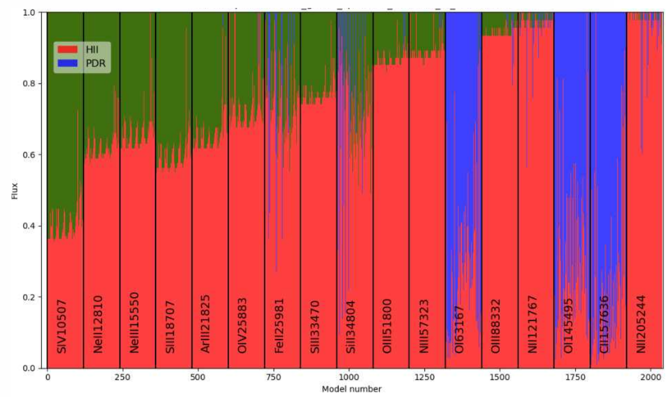

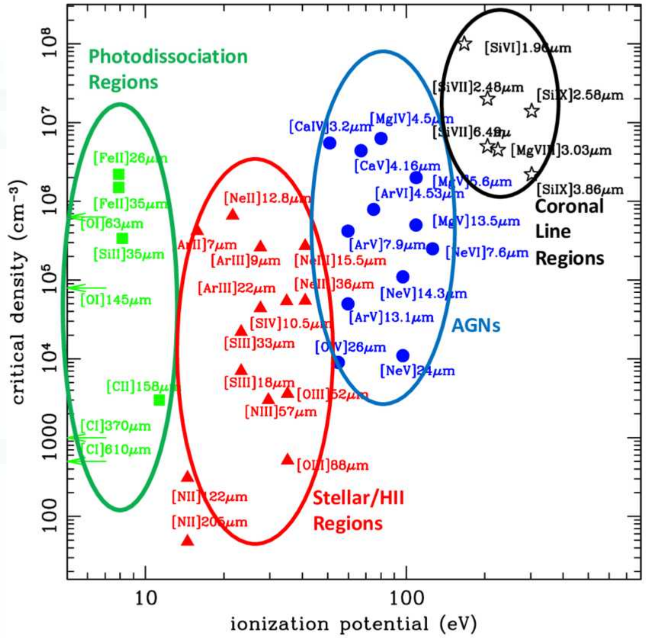

Spinoglio et al. PASA 2017

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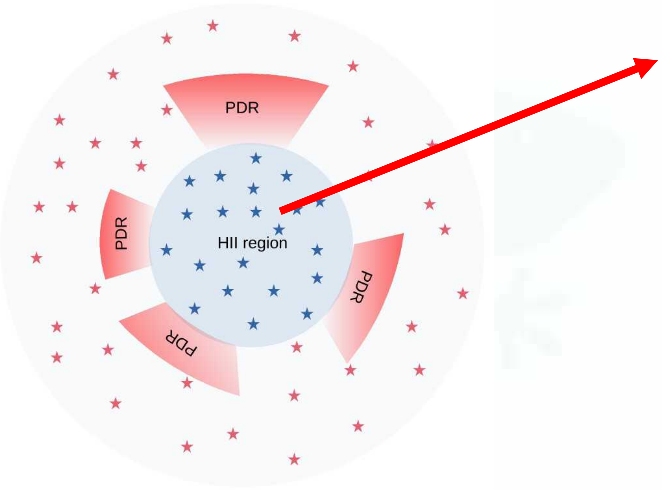

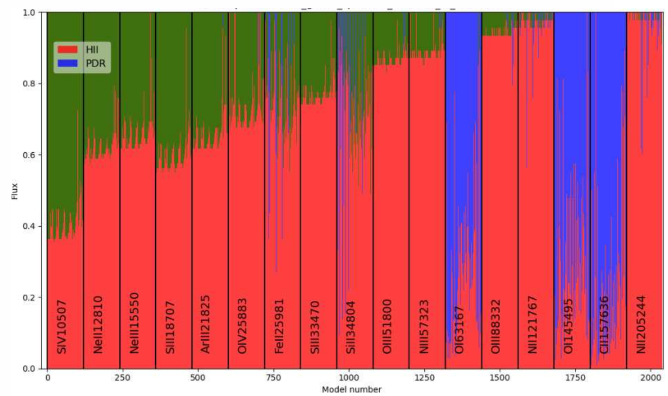

$$I = (1 - f_{cov}) \times I_{HII} \times g_{att}(\lambda)$$

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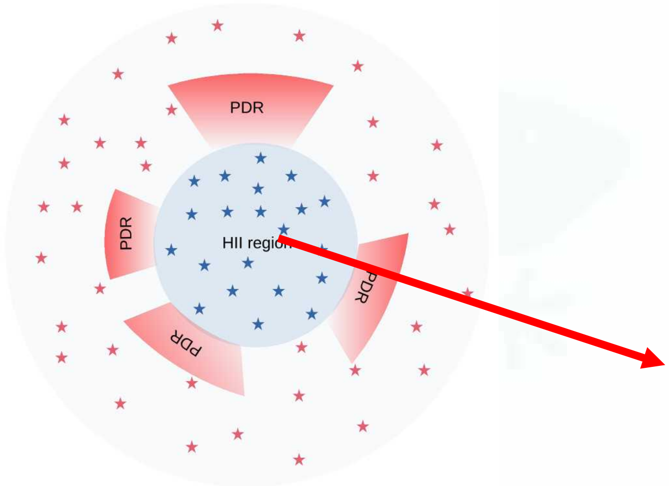

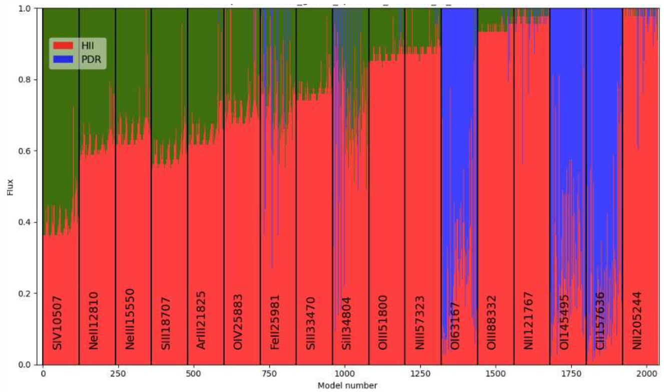

$$I = f_{cov} \times (I_{HII} * 10^{-A(\lambda)} + I_{PDR})$$

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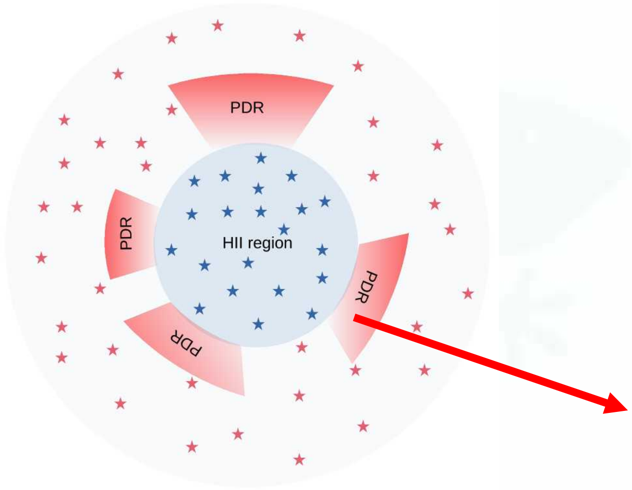

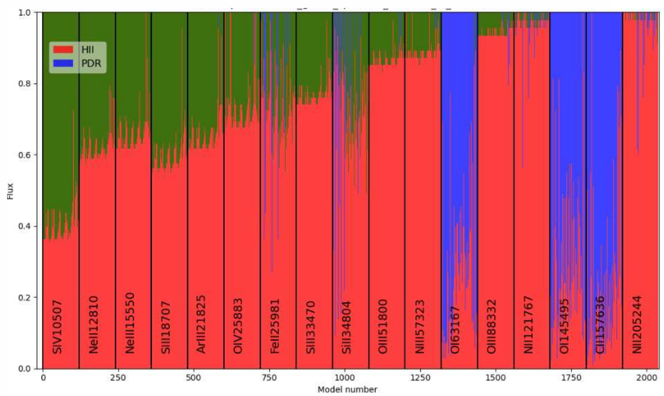

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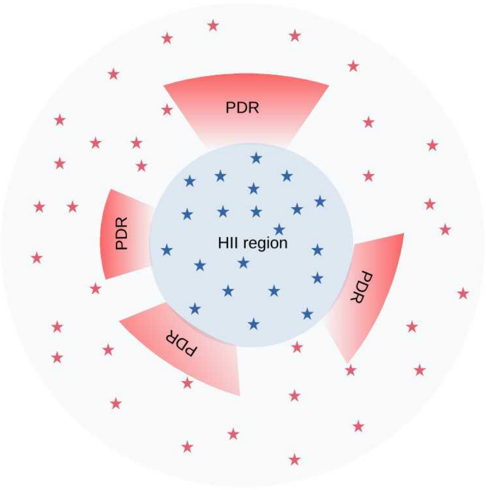

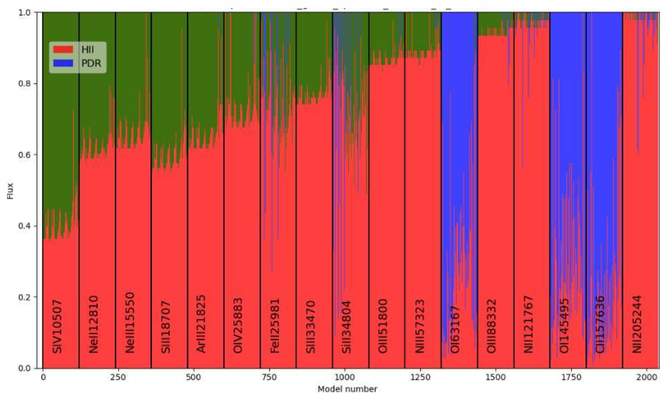

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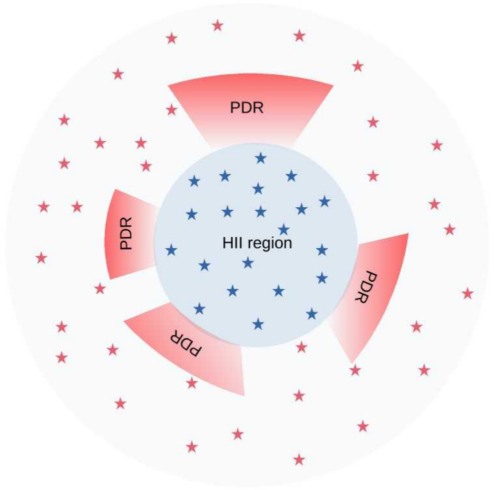

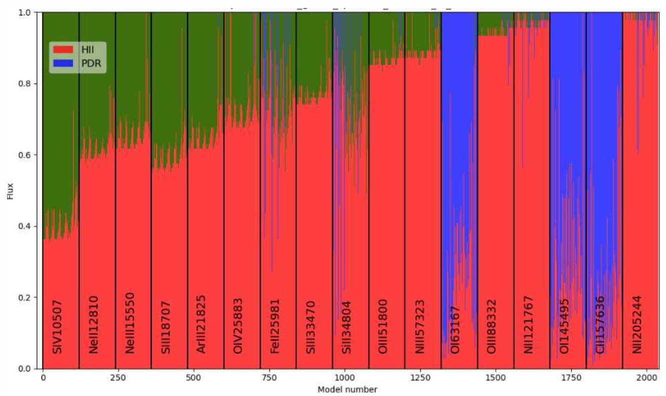

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no dust

no dust

dust

Nebular emission lines modeling

density $\mathbf{n_H}$
metallicity $\boldsymbol{\zeta_O}$
elementary atomic abundances

the CIGALE nebular emission module

ionizing radiation field :
shape + intensity

BC03 SSP
U ionization parameter

H
He
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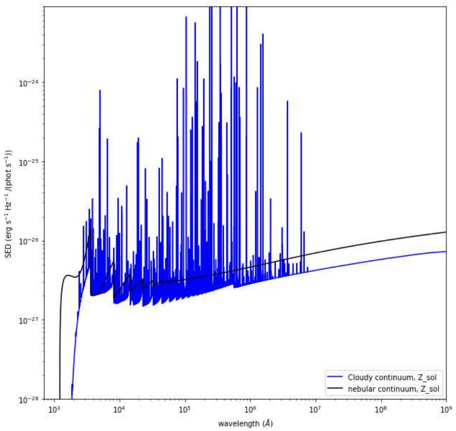
...



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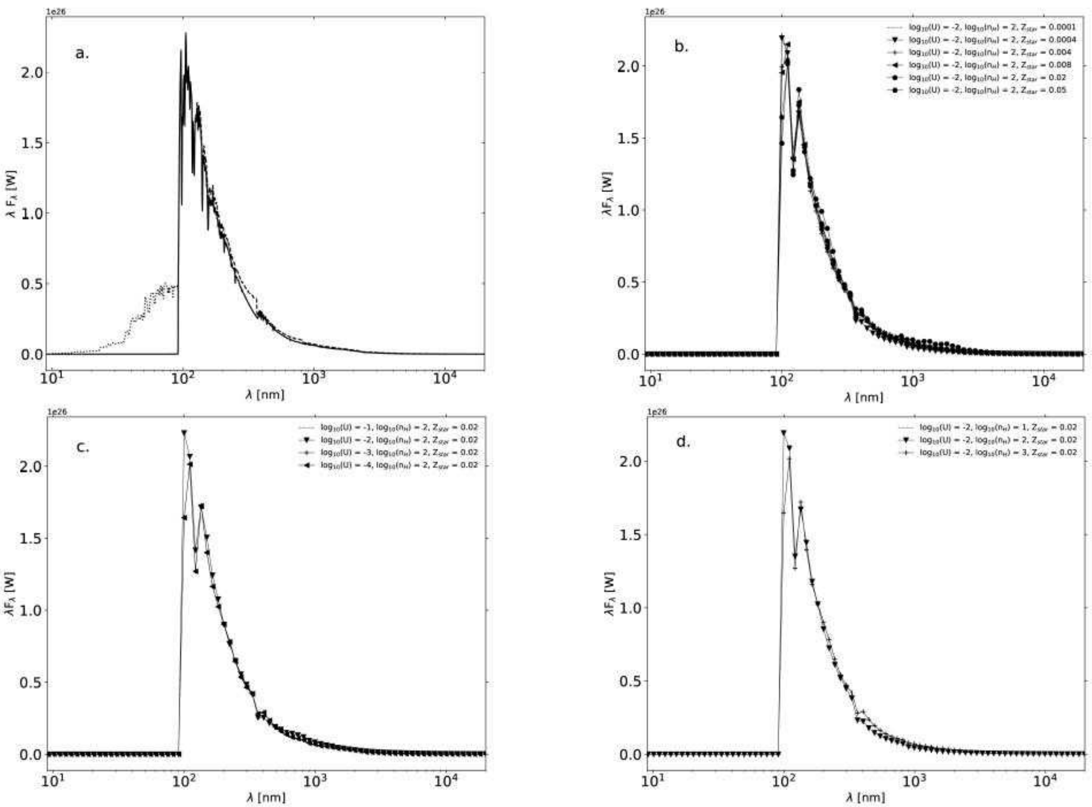
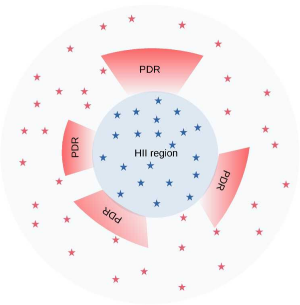
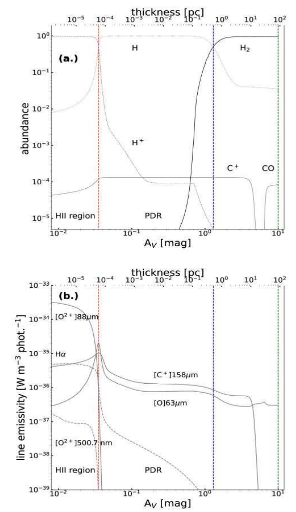
The photoionizing radiation field

BC03 single stellar population (age, stellar metallicity Z_{star})
+ Chabrier (100 M⊙) initial mass function







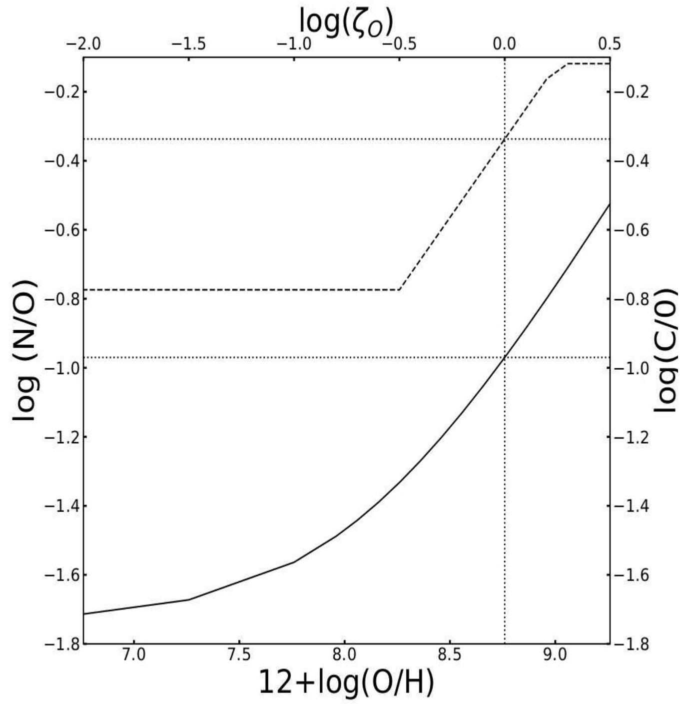
$$U \equiv \frac{Q(H)}{4\pi r_0^2 n(H) c} = \frac{N_{LyC}}{n(H)}$$

Elemental abundances and metallicity

local galactic concordance model (≠ solar abundances)

element	abundance	D
H	1	1.00
He	9.77×10^{-2}	1.00
C	2.65×10^{-4}	0.50
N	6.17×10^{-5}	0.89
O	5.75×10^{-4}	0.85
Ne	1.23×10^{-4}	1.00
Mg	3.63×10^{-5}	0.08
Al	2.69×10^{-6}	0.04
Si	3.16×10^{-5}	0.15
S	1.32×10^{-5}	1.00
Ar	2.51×10^{-6}	1.00
Fe	3.31×10^{-5}	0.05

$$\zeta_O = \frac{(O/H)}{(O/H)_{GC}}$$



$$(He/H) = 0.0835 * (1 + 0.17031 * \varsigma_O)$$

$$(C/O) = 10^{-0.8} + 10^{\log(2.272 + \log(O/H))}$$

$$(N/O) = 10^{-1.732} + 10^{\log(2.19 + \log(O/H))}$$

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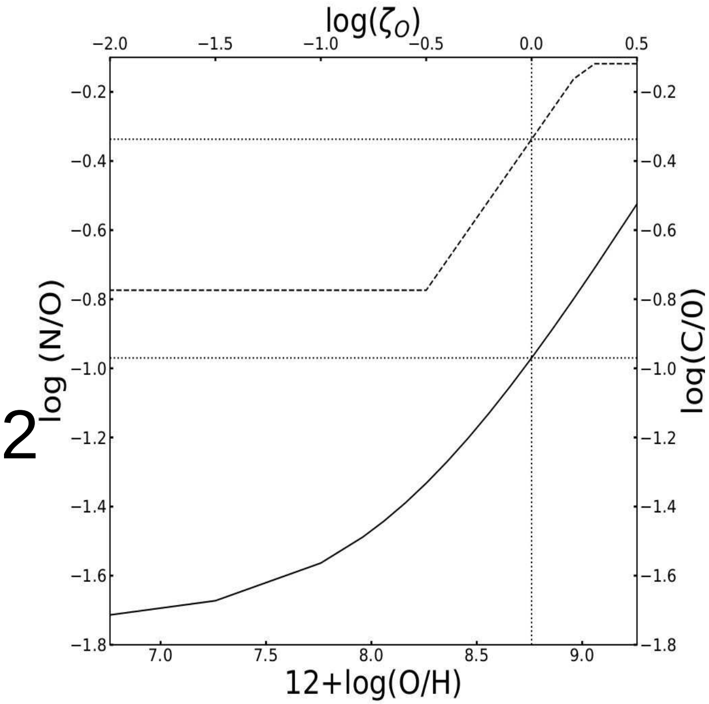
$\zeta_O = 1$

$\log \zeta_O = 0$

$Z_\Theta = 0.0142$



$$\zeta_O = \frac{(O/H)}{(O/H)_{GC}}$$

$$(He/H) = 0.0835 * (1 + 0.17031 * \zeta_O)$$

log $\zeta_O < 0$: submetallic galaxies

$$(C/O) = 10^{-0.8} + 10^{\log(2.272 + \log(O/H))}$$

log $\zeta_O > 0$: over-metallic galaxies

$$(N/O) = 10^{-1.732} + 10^{\log(2.19 + \log(O/H))}$$

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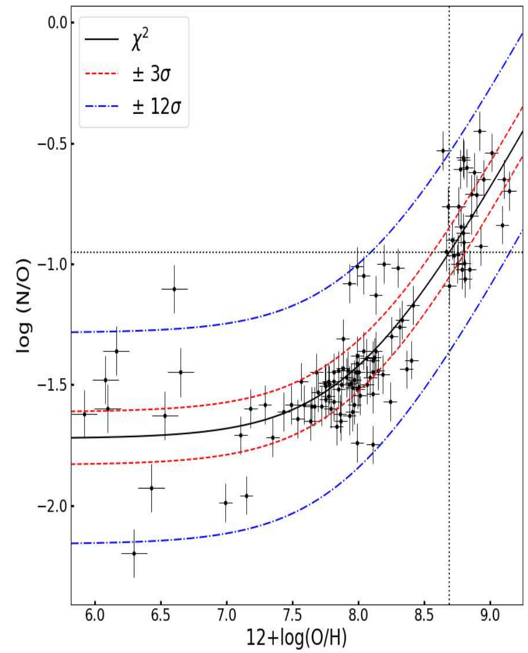

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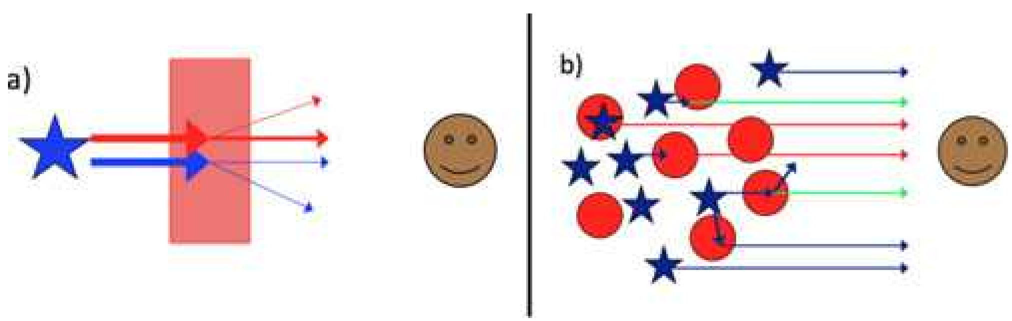
Dust attenuation $g_{att}(\lambda)$

$$I = (1 - f_{cov}) \times I_{HII} \text{ x } g_{att}(\lambda) + f_{cov} \times (I_{HII} \ast 10^{-A(\lambda)} + I_{PDR})$$

The lines are screened with the Milky Way extinction law of Cardelli et al. 1989 with R_V =3.1, which is typical of diffuse media, and Av = 1, which is typical of a galaxy

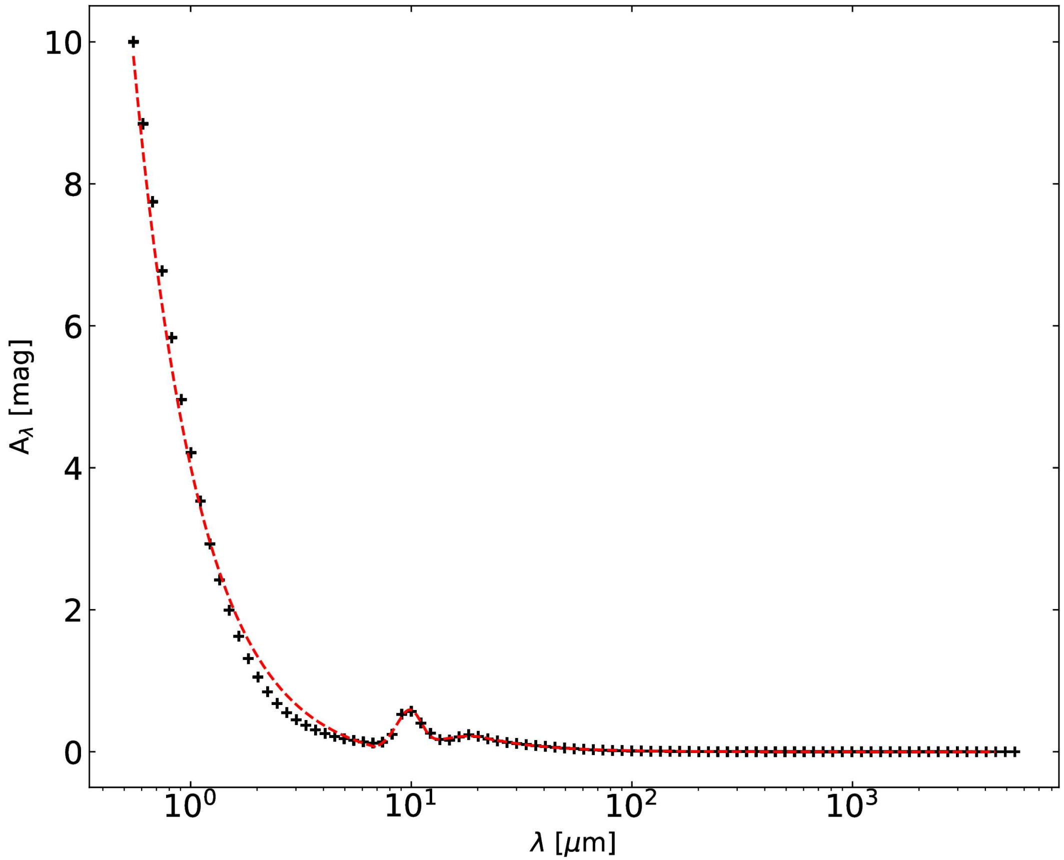
exctinction ≠ attenuation



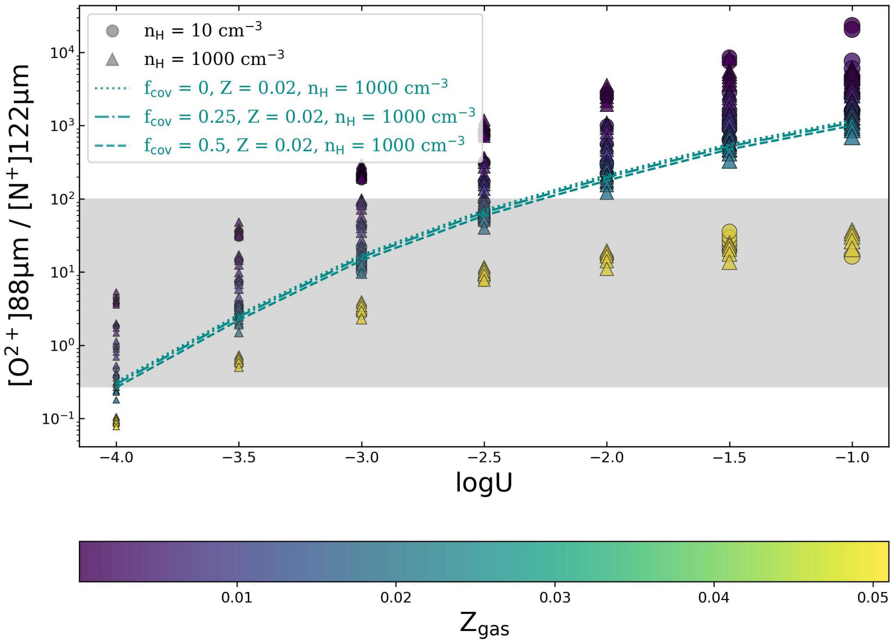
credit : D. Calzetti

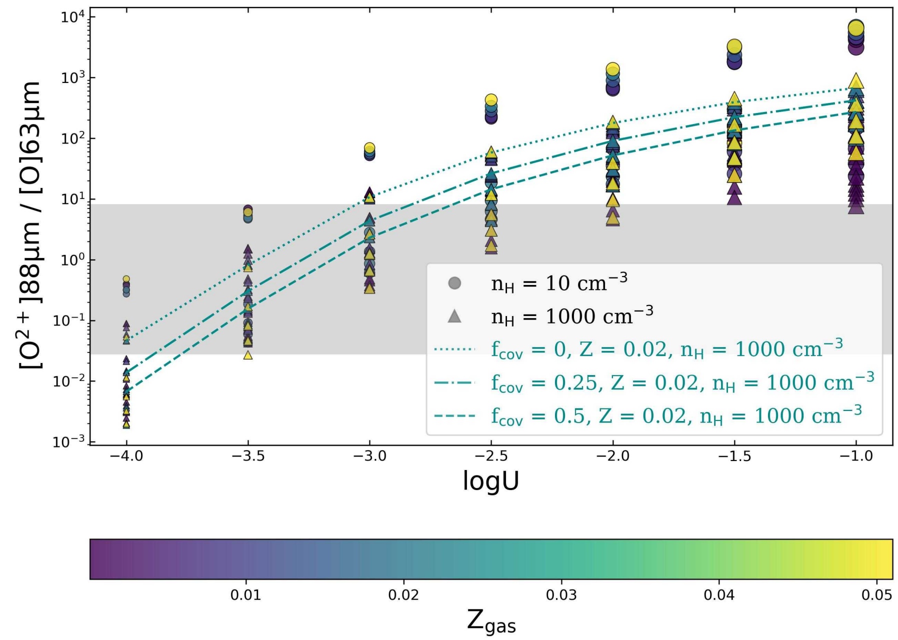
Dust extinction A(λ)

$$I = (1 - f_{cov}) \times I_{HII} \times g_{att}(\lambda) + f_{cov} \times (I_{HII} * 10^{-A(\lambda)} + I_{PDR})$$

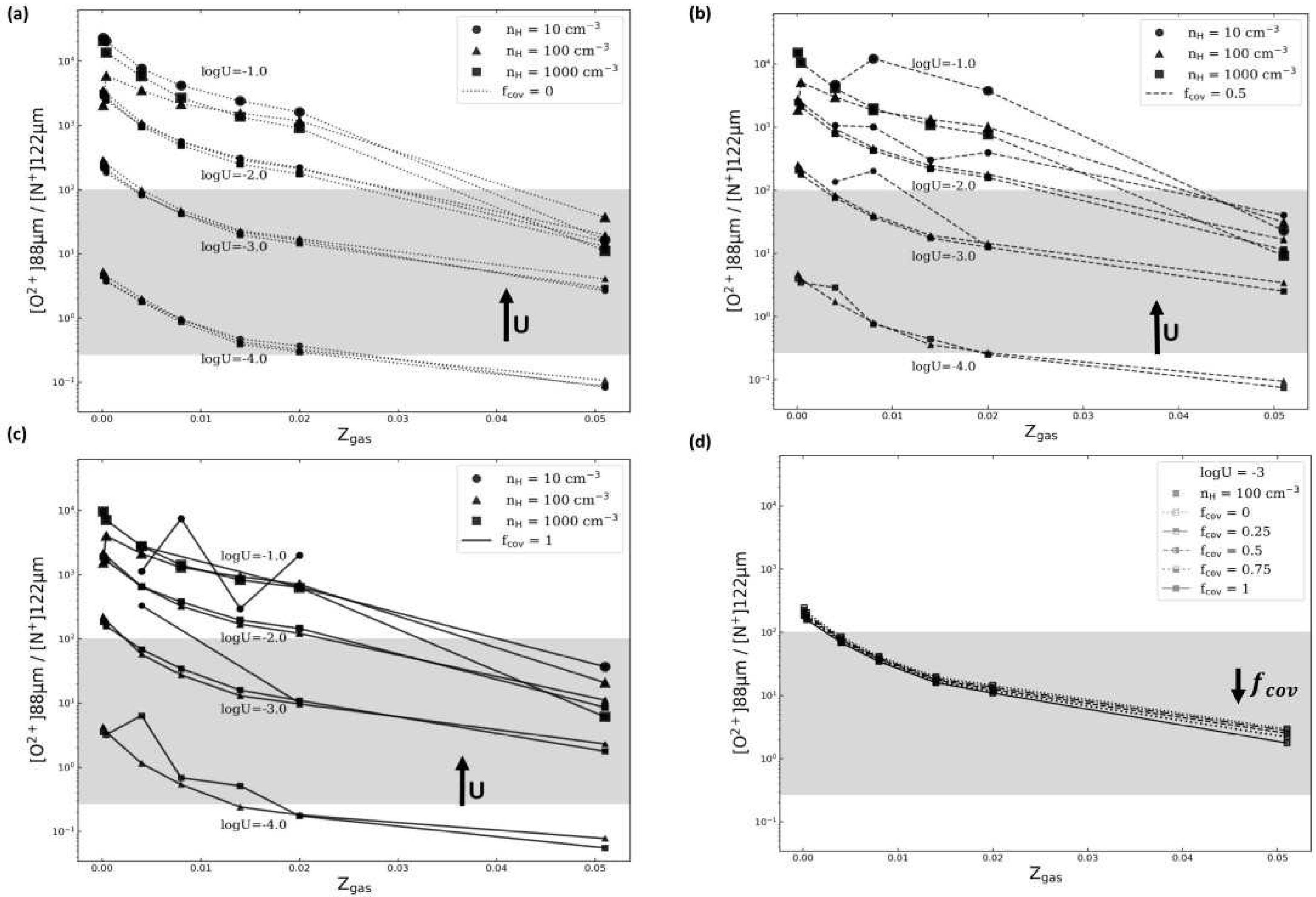


Tracers of the ionization parameters U

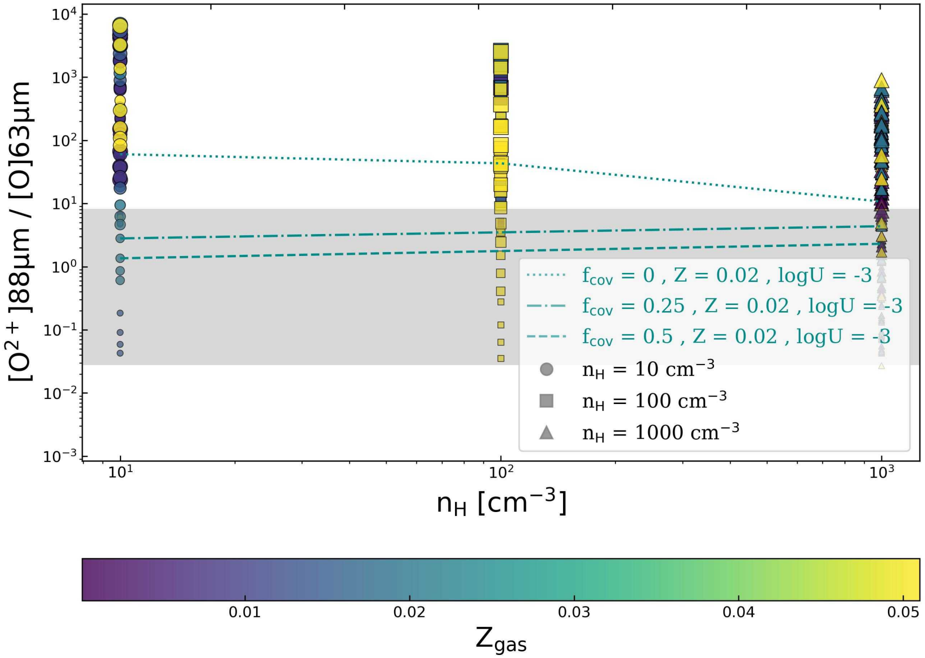


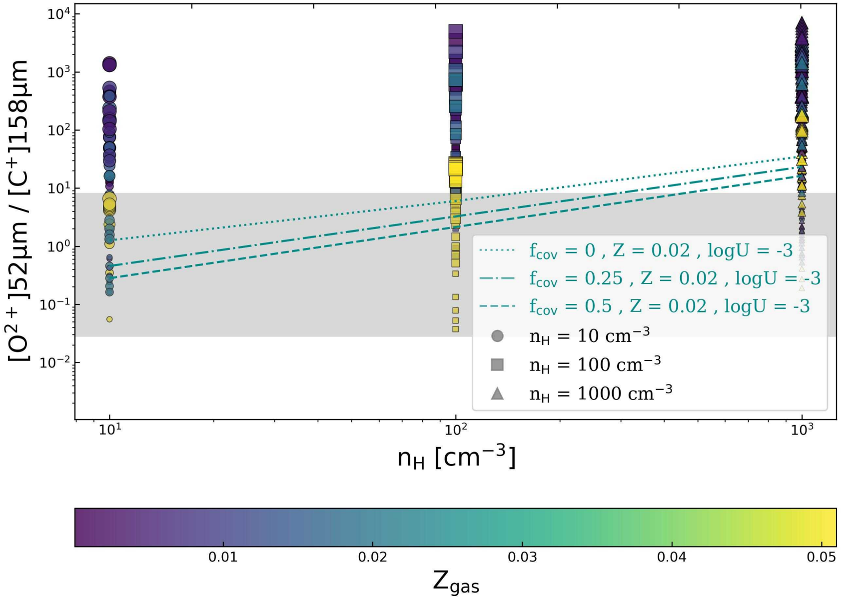


Tracers of the gas metallicity Z_{gas}

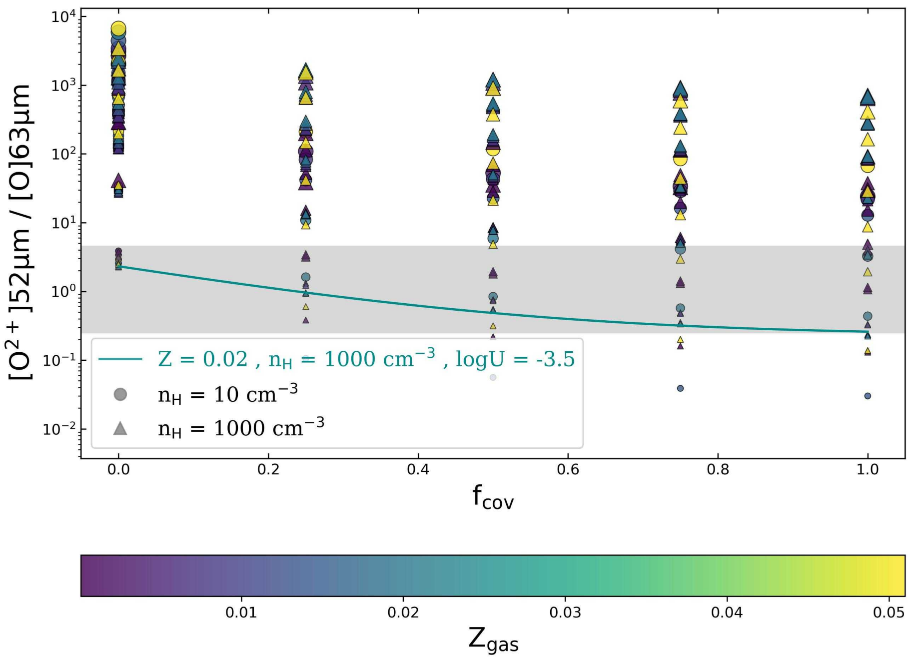


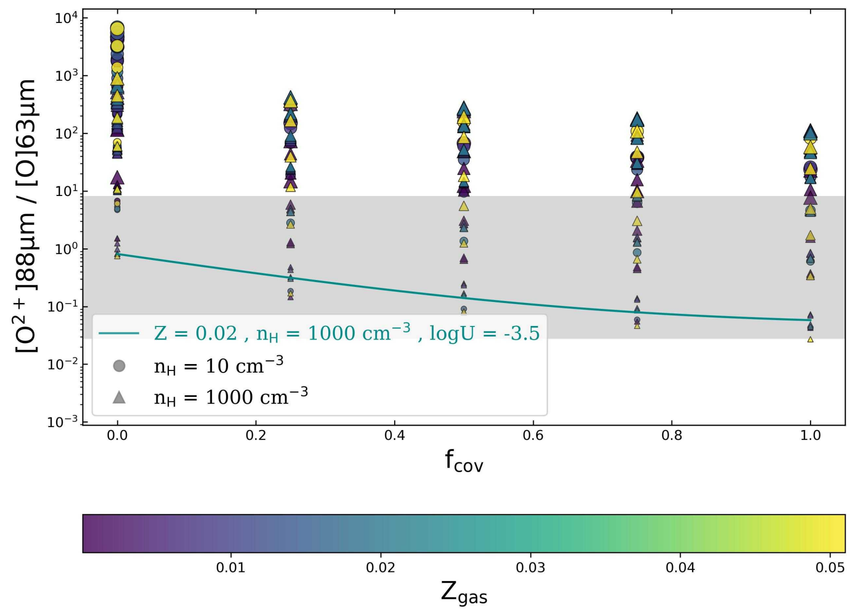
Tracers of the density n_H

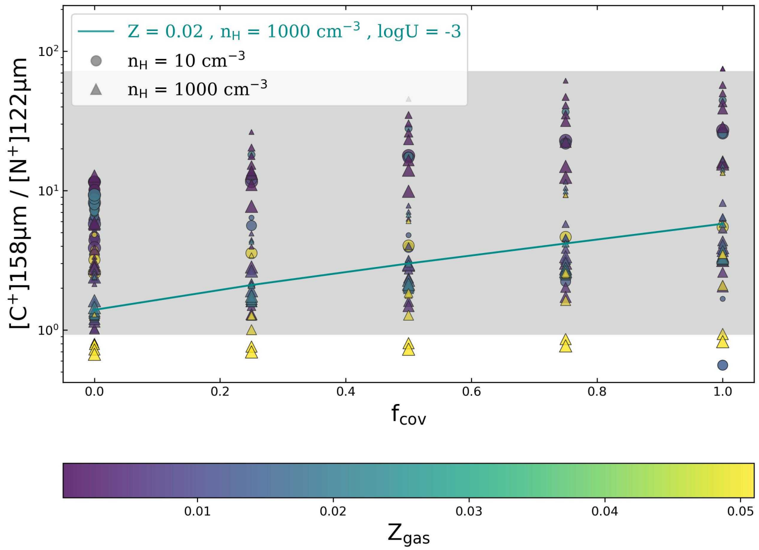




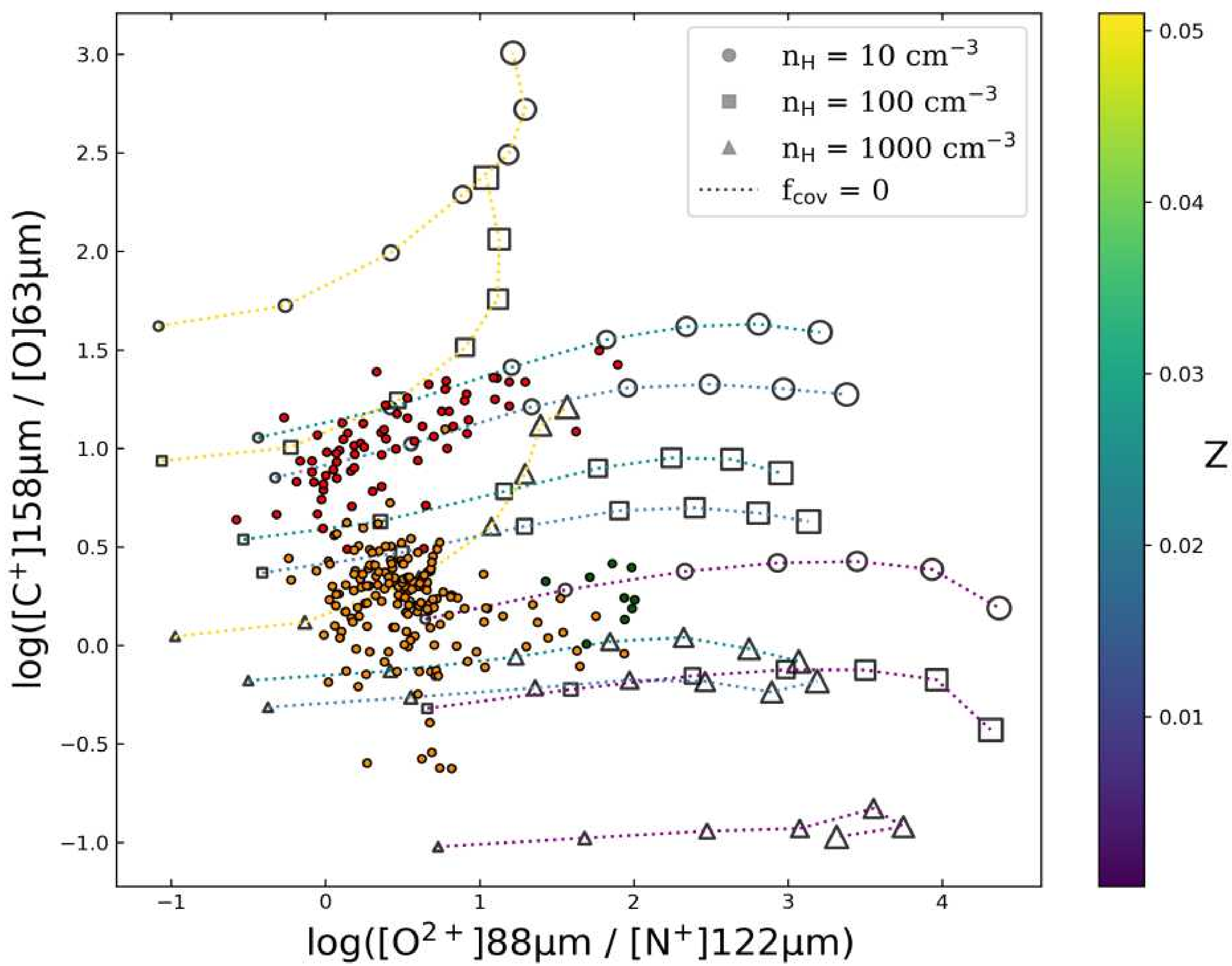
Tracers of the covering factor f_{cov}



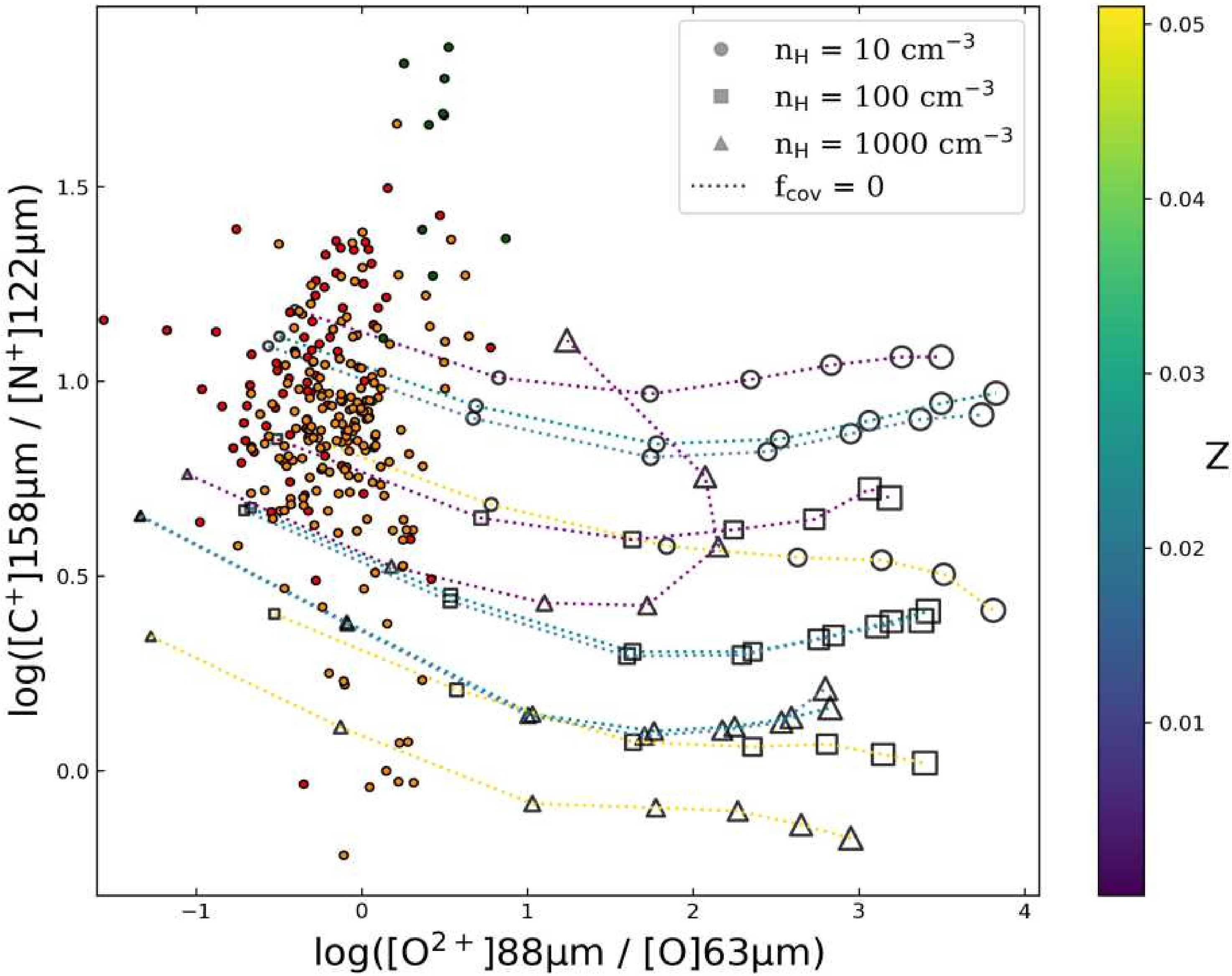




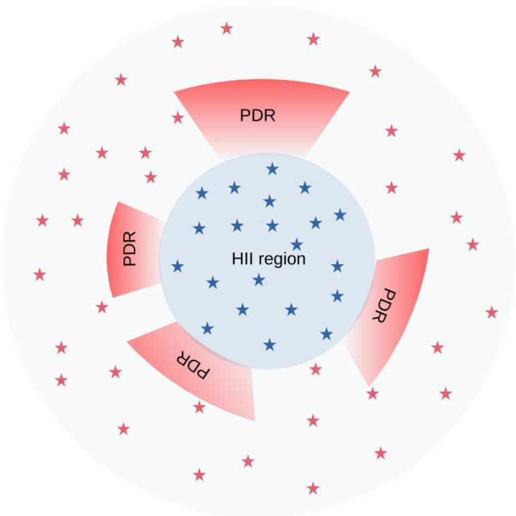
Infrared optical diagrams : the COON diagram



Infrared optical diagrams : the CNOO diagram



Starburst regions and photon dominated regions



Astronomy & Astrophysics manuscript no. IR_colors_lines_arXiv ©ESO 2022
November 11, 2022

Identification of Large Equivalent Width Dusty Galaxies at $4 < z < 6$ from Sub-mm Colours

D. Burgarella[1], P. Theulé[1], V. Buat[1], L. Gouiran[1] L. Turco[1] M. Boquien[2], T. J. L. C. Bakx[3,4], A. K. Inoue[5,6], Y. Fudamoto[4], Y. Sugahara[4,6], and J. Zavala[4]

Astronomy & Astrophysics manuscript no. article_HIIPDR ©ESO 2023
June 12, 2023

Modeling the spectral energy distribution of starburst galaxies : the role of photodissociation regions

P. Theulé[1], D. Burgarella[1], V. Buat[1], M. Boquien[2], L. Trabelsi[1], and O. Kalpogiannis[1]

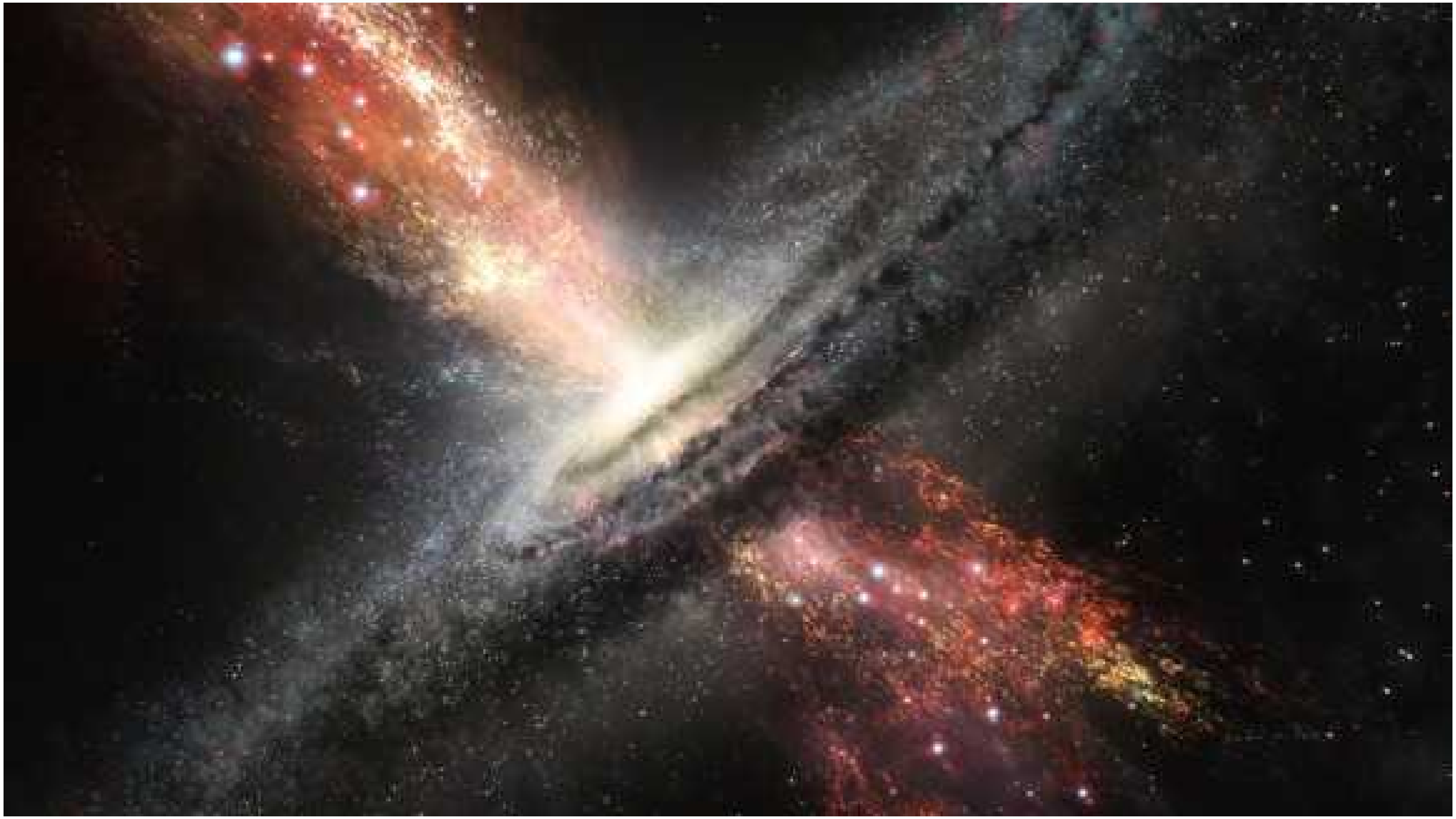
[1] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
e-mail: `patrice.theule@lam.fr`
[2] Centro de Astronomía (CITEVA), Universidad de Antofagasta, Avenida Angamos 601, Antofagasta, Chile

Received May 8, 2022; accepted March 16, 1997

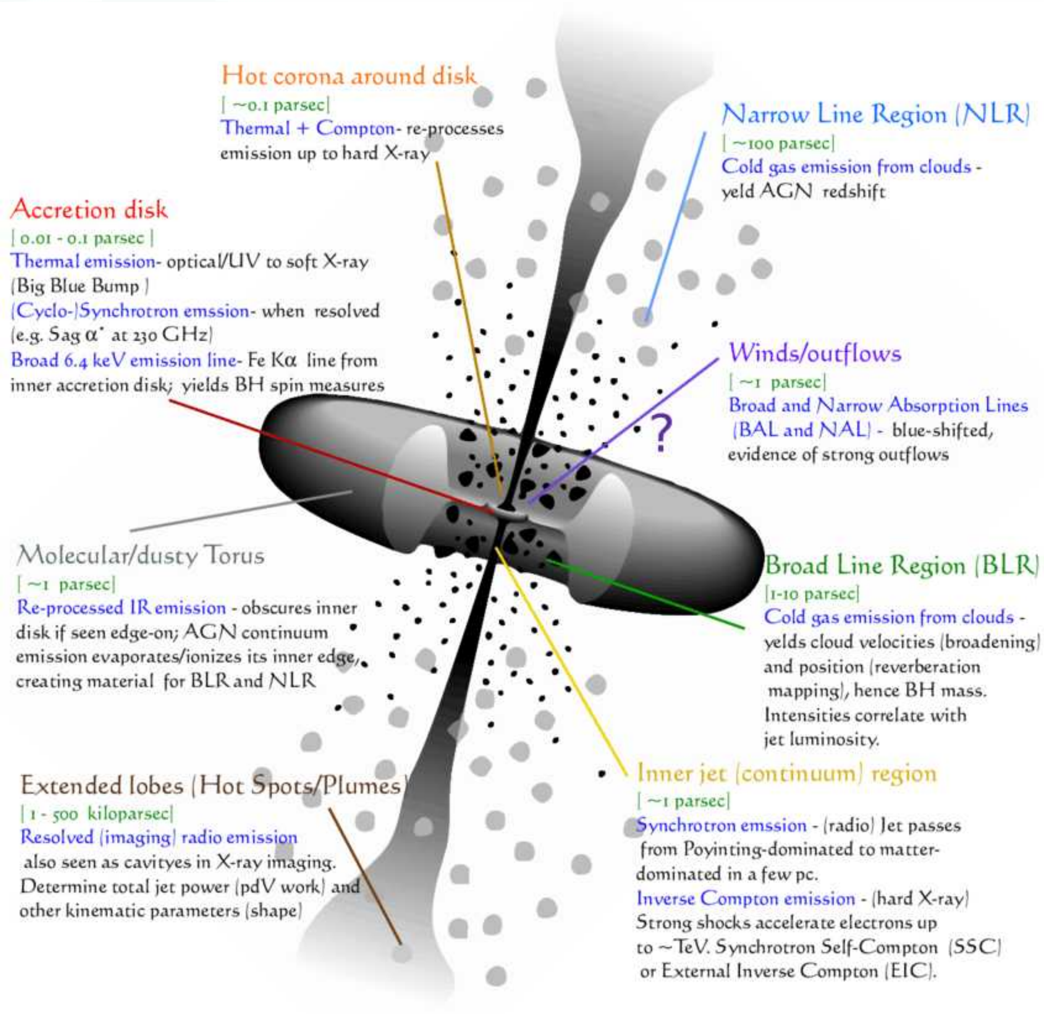
- useful diagnostic tracers
- strong correlation

→ new CIGALE module nebular_PDR

III. Active Galactic Nuclei hosting galaxies

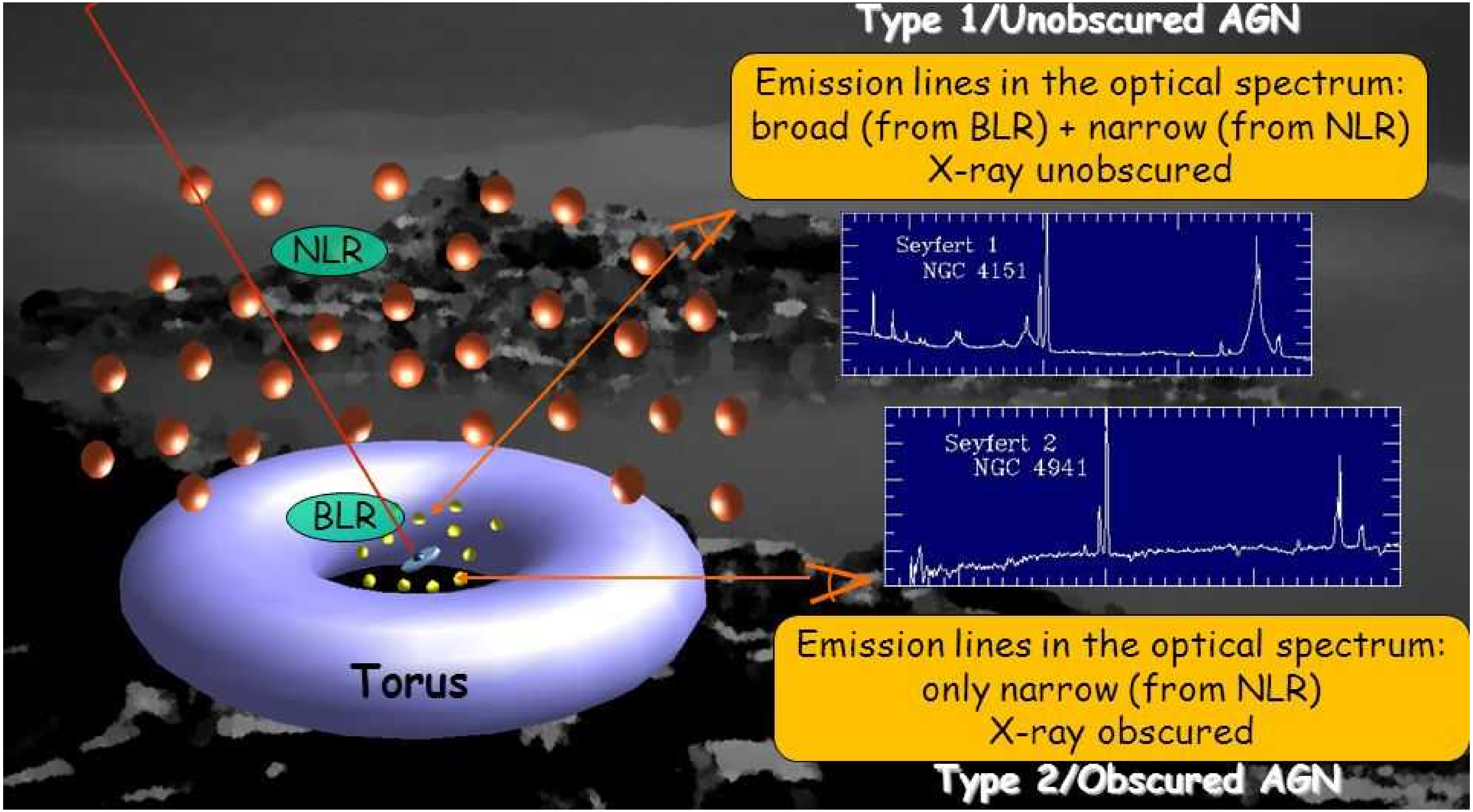


Anatomy of an Active Nuclei Galaxy

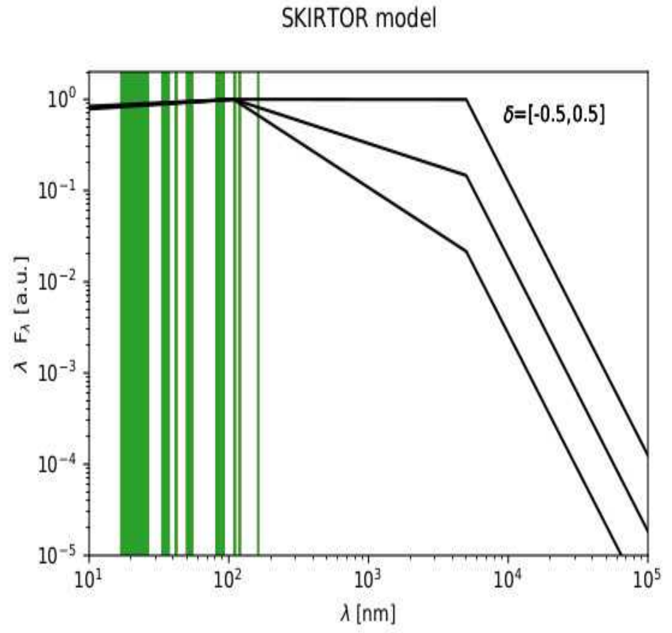


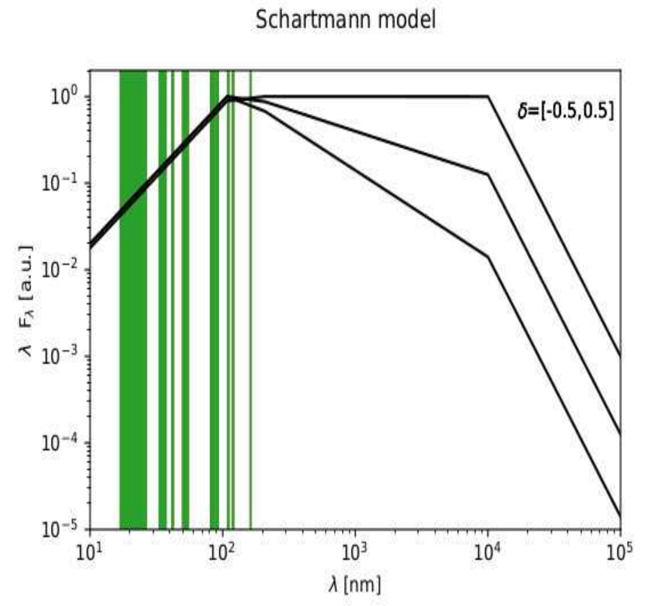
AGN spectra :

Narrow Line Regions (NLR) and Broad Line Regions (BLR)



The accretion disk radiation field





champ
ionisant :
forme +
intensité

δ, log U

$$U \equiv \frac{Q(H)}{4\pi r_0^2 n(H) c} = \frac{N_{LyC}}{n(H)}$$

Dust and dust attenuation

dust has a role both on the chemistry (depletion, surface chemistry) and on the radiative transfer (diffusion / absorption)

NLR : standard depletion

BLR : no depletion (all the grains are sublimated)

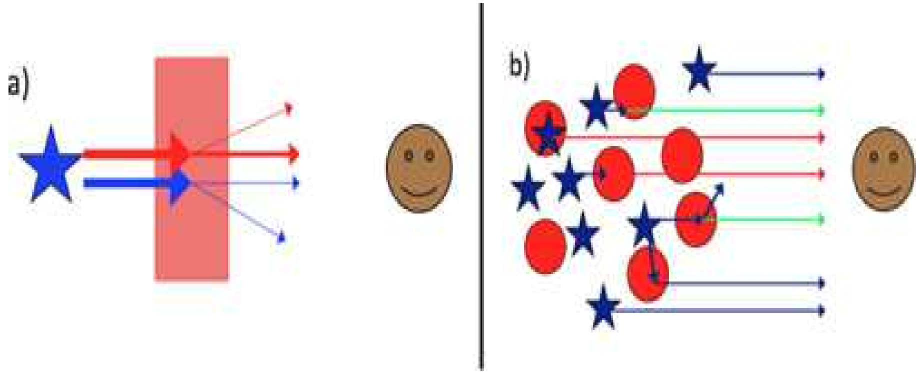
NLR et BLR : SMC attenuation law (polar dust)

$$I = I_0 * 10^{\frac{-A_\lambda}{2.5}}$$

$$A_\lambda = E(B-V) * 1.39\,\lambda_{\mu m}^{-1.2}$$ with E(B-V) =0.15

$\frac{H\alpha}{H\beta}$ 656 nm 486 nm

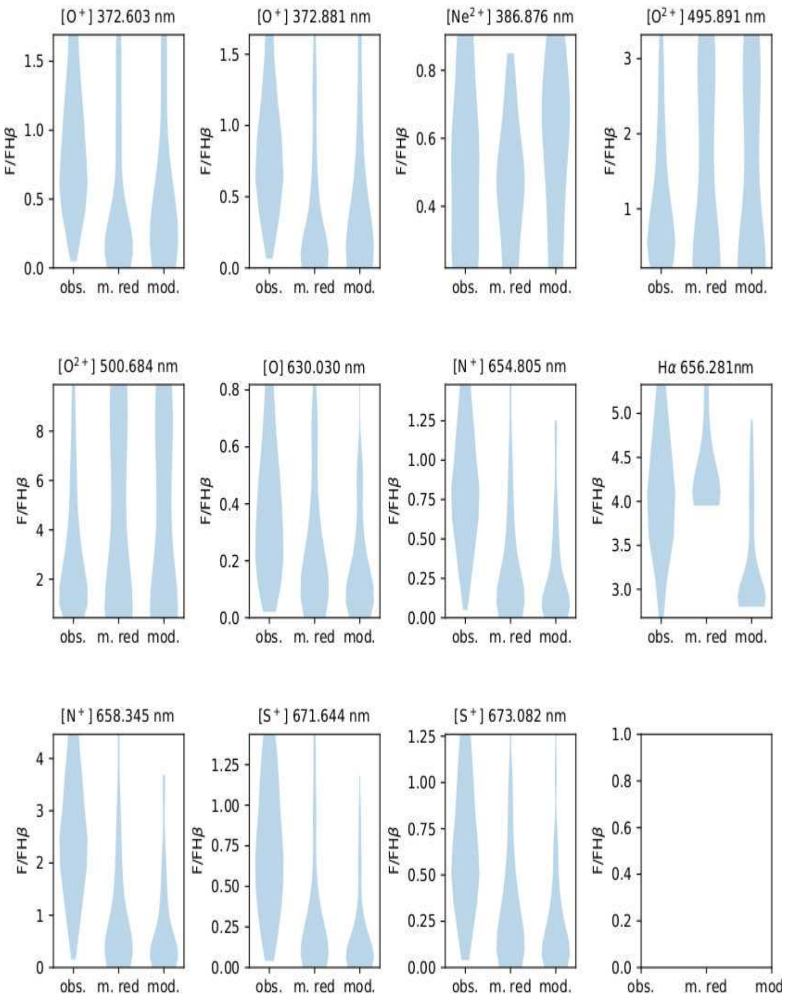
exinction ≠ attenuation



credit : D. Calzetti

Comparison models / observations

sample : 4XMM-DR9 x SDSS-DR12 catalogues (X source selection , 5σ)
17 emission lines for NLRs , 3 lines for BLRs



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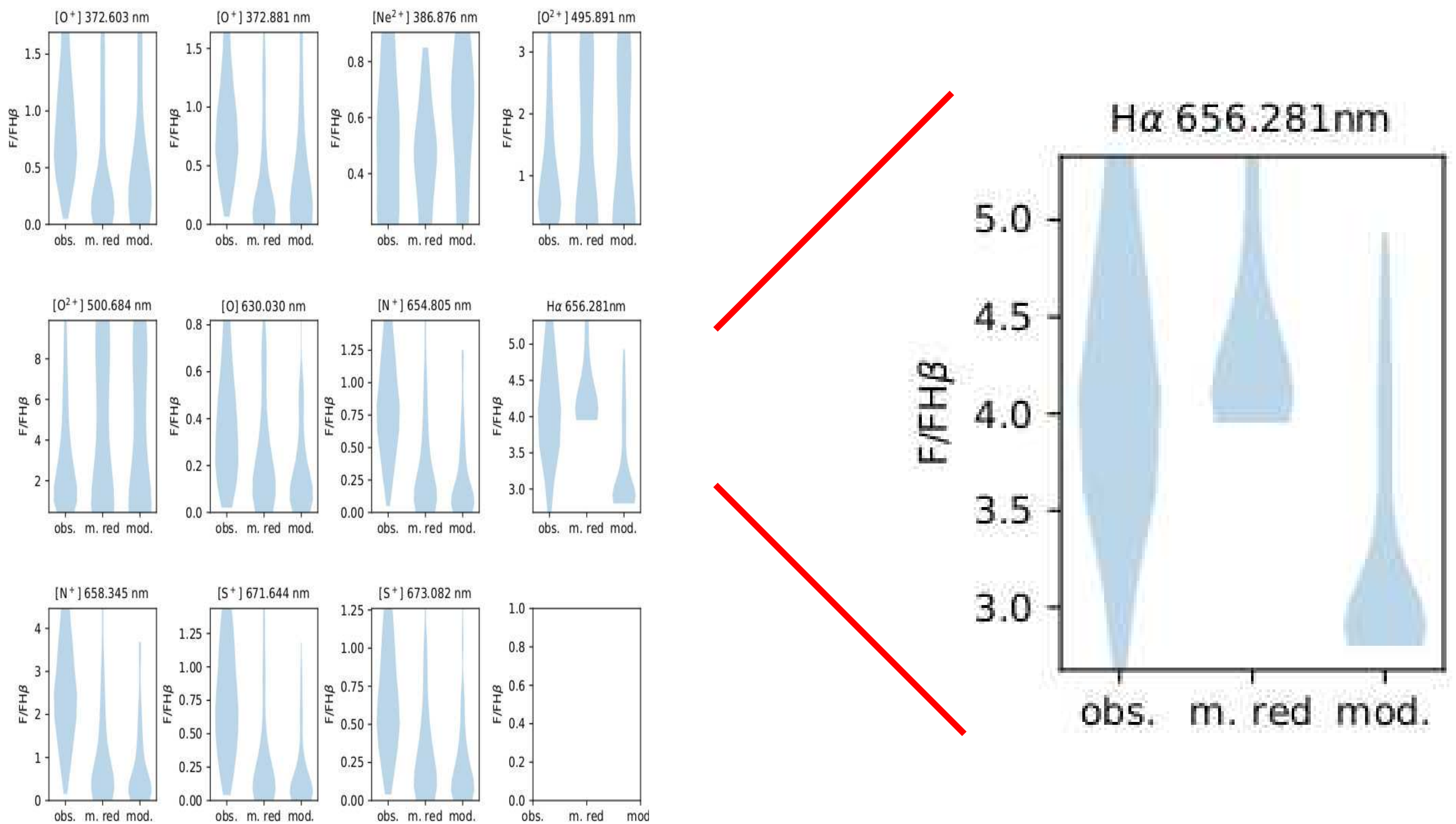

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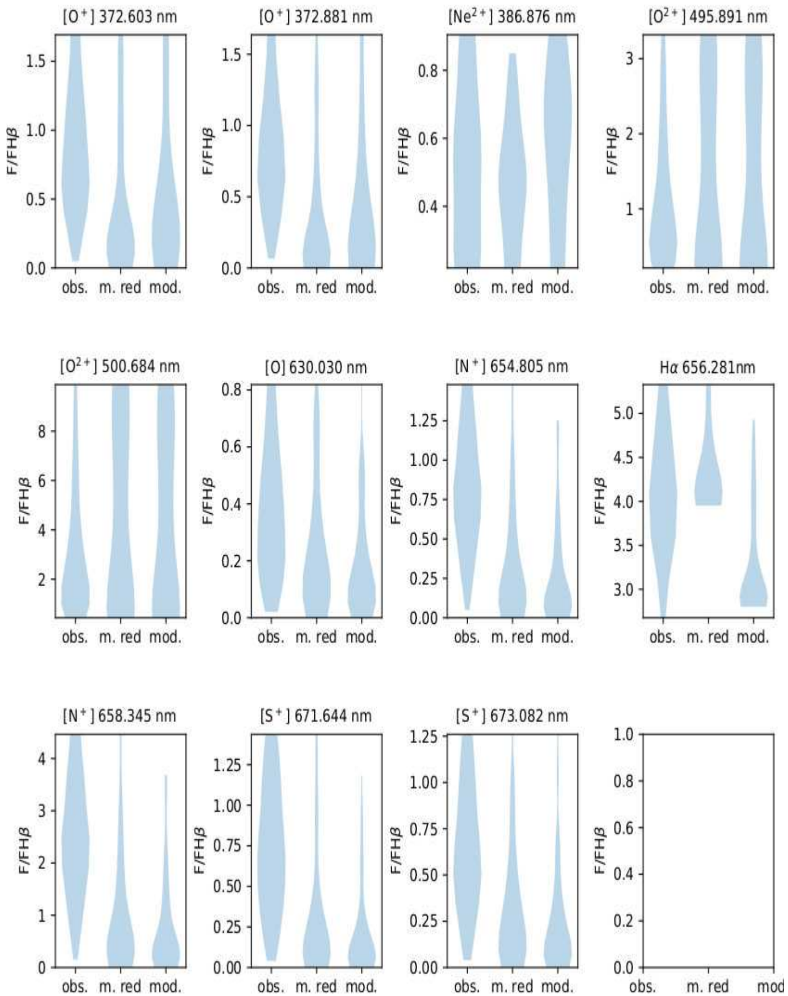
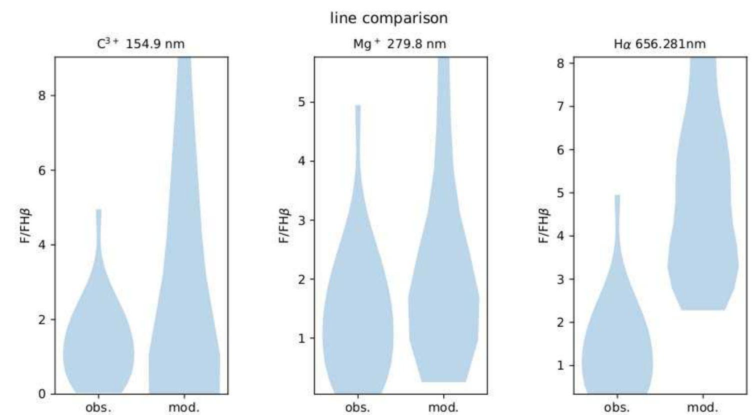
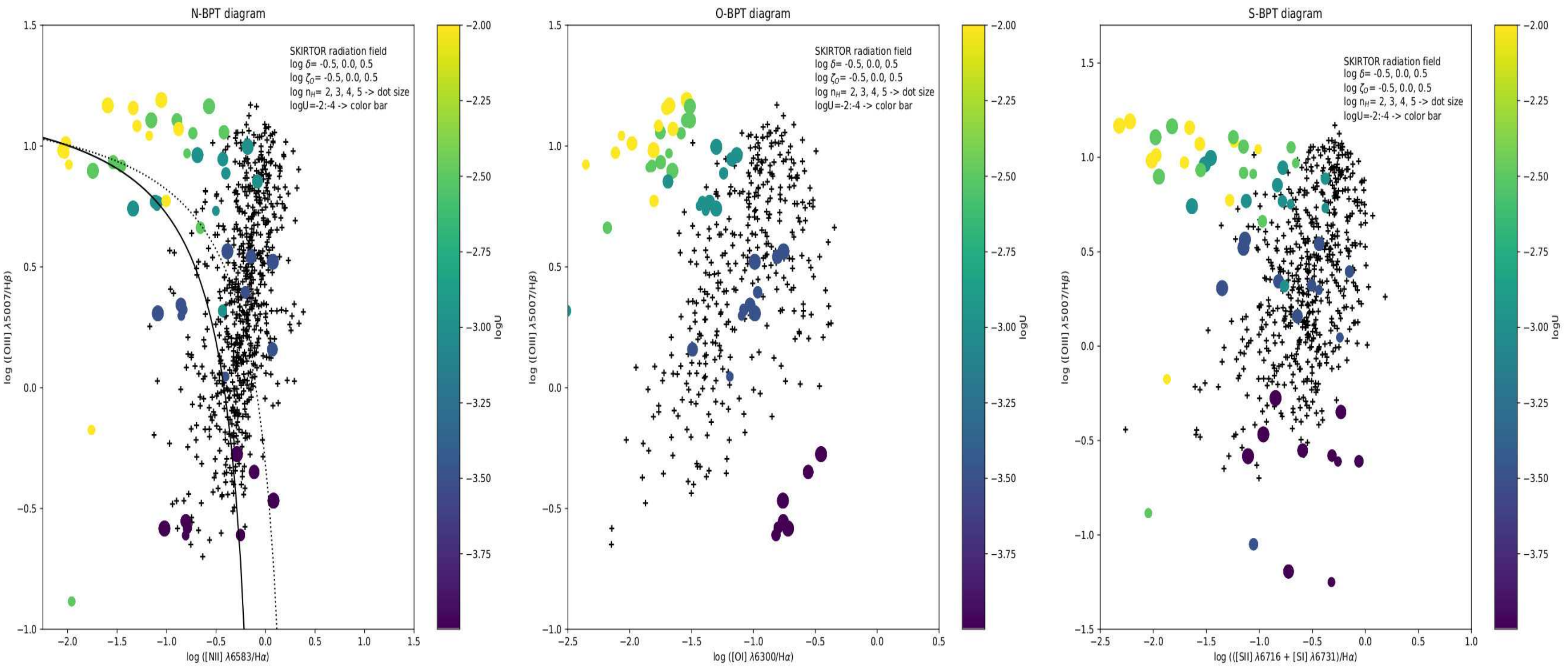




Optical diagnostic diagrams



most of the observations are covered

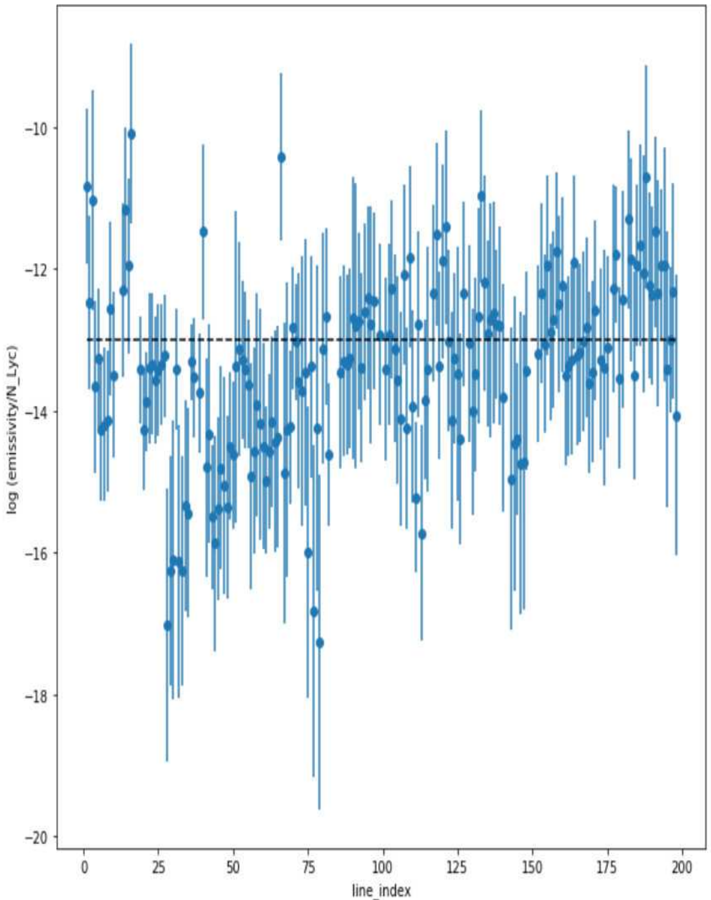
uncertainty on the elemental abundances

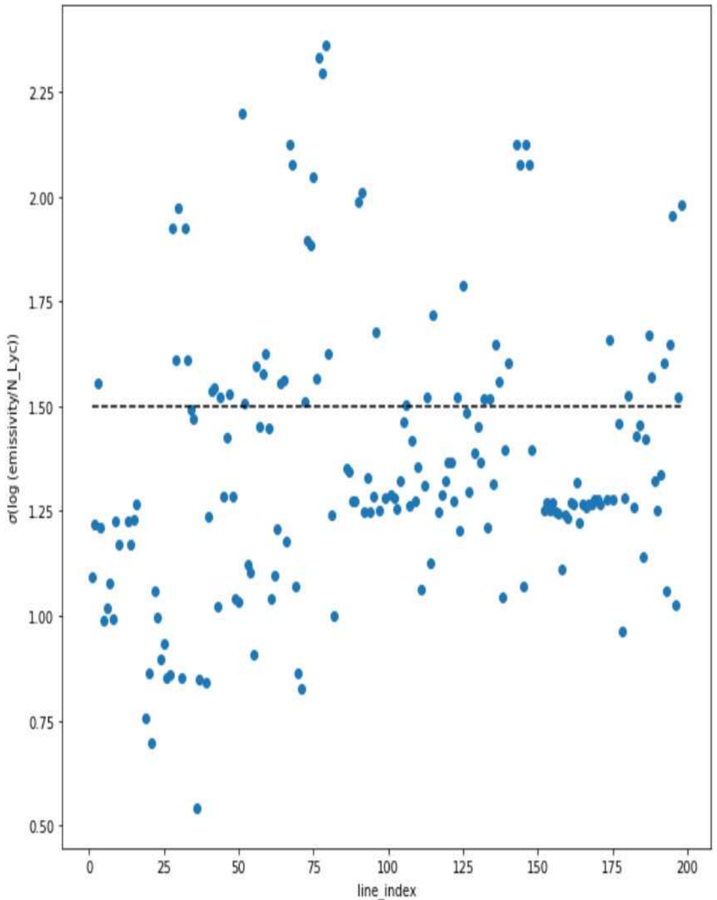
resulting degeneracy

Good spectroscopic diagnostics ?

good spectral diagnostic :

- strong intensity (observed)
- large variaton as a function of one parameter





Good spectroscopic diagnostics ?

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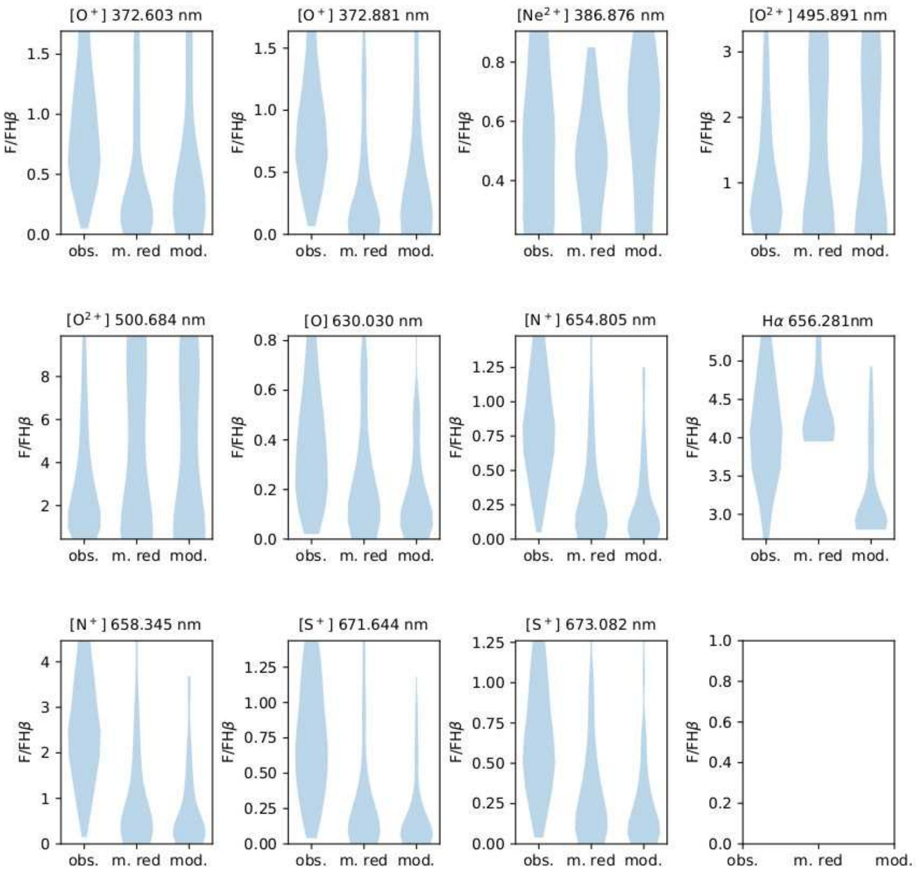
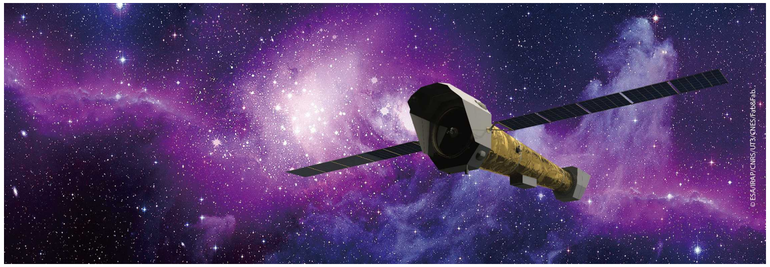
line	δ	ζ_O	n_H	U
VUV-UV				
He 2 30.3784 nm			m	
He 1 62.5563 nm			m	s
H 1 121.567 nm			s	s
Si 4 139.375 / 140.277 nm		w		
C 4 154.819 nm (blend 154.9)		w		
He 2 164.043 nm			m	
O 3 166.615nm (blend 166.6 nm)		w		
Si 3 188.271 / 189.203 nm		w		
C 3 190.668 /.873 nm (blend 190.8)		w		
Ne 4 242.166 nm		w		
Ne 4 242.428 nm		w		
Ne 5 342.603 nm		w		
O 2 372.603/372.881 nm				m
visible				
O 3 436.321 nm		w		
H 1 486.133 nm				m
O 3 495.891 nm			m	
O 3 500.684 nm			s	
N 2 658.345 nm				m
S 3 953.062 nm				m
IR				
S 4 10.5076 μm			m	
N 3 15.5509 μm				m
S 2 18.7078 μm				m
O 4 25.8832 μm			m	
Fe 225.9811 μm				m
Si 2 34.8046 μm			m	s
O 3 51.8004 μm			m	

Active Galactic Nuclei hosting galaxies



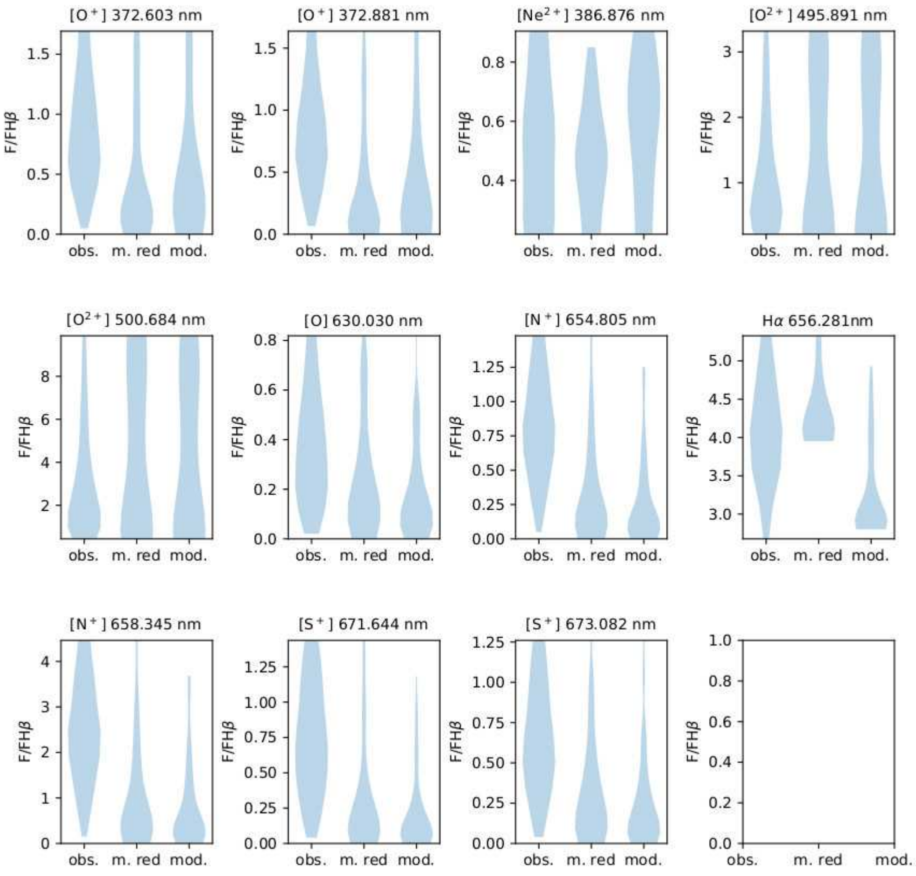
Theule et al. , 2024 in preparation

the ATHENA mission



new module nebular_AGN

Active Galactic Nuclei hosting galaxies

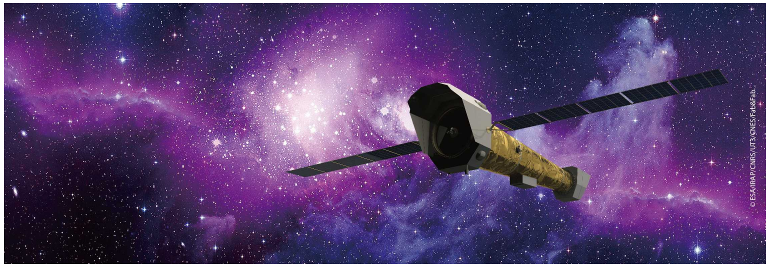


new module nebular_AGN

Theule et al. , 2024 in preparation

open post-doc position
starting January 2024

the ATHENA mission



Thank you for your attention