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e ciências do espaço

FADO

FITTING
ANALYSIS USING
DIFFERENTIAL EVOLUTION
OPTIMIZATION

A novel spectral population synthesis tool for the exploration of galaxy evolution

Jean Michel Gomes@Cambridge, 21 September 2017

Centro de Astrofísica
da Universidade do Porto

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

FADO
FITTING ANALYSIS USING DIFFERENTIAL EVOLUTION OPTIMIZATION

Gomes & Papaderos

www.spectralsynthesis.org
www.iastro.pt/research/tools.html

in collaboration with our PhD students Leandro Cardoso and Iris Breda and several IA researchers who have tested an earlier internal release of FADO

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

CALIFA Survey

ia
instituto de astrofísica
e ciências do espaço

SEL
GIFS

POPH
QUALIFICAR É CRESCER.

QREN
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
PORTUGAL 2007.2013

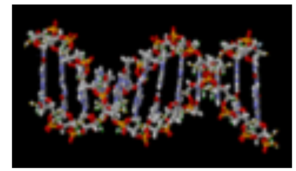
GOVERNO DA REPÚBLICA PORTUGUESA

UNIÃO EUROPEIA
Fundo Social Europeu

HEADLINES

1. Overview — **Population Synthesis**

2. FADO

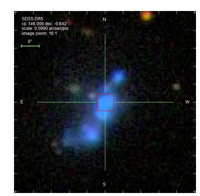


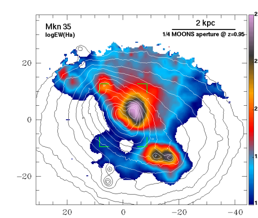
   2.1. FADO in a nutshell

   2.2. FADO pipeline

   2.3. FADO comparison

3. FADO Applications





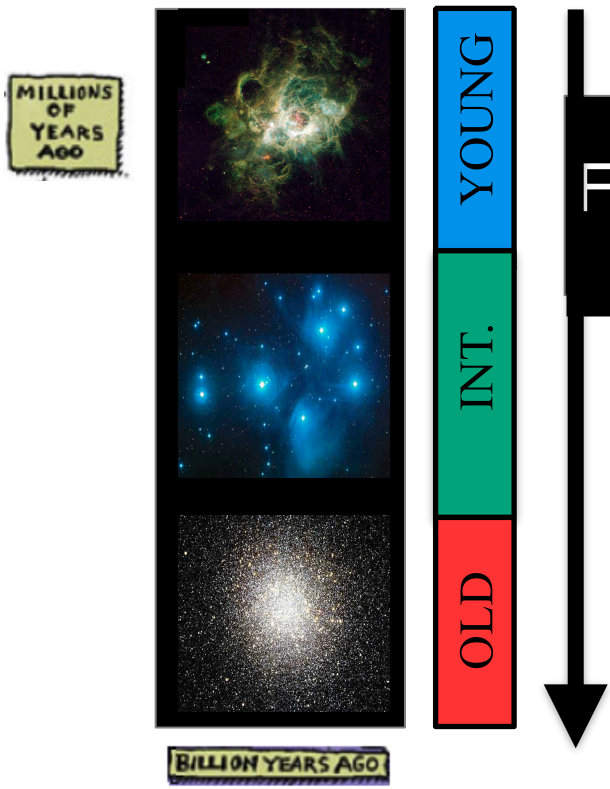
   3.1. SDSS: BCD & GP

   3.2. CALIFA IFU MRK 35

4. Final remarks

1. What is population synthesis?

- **Equation is expressed in terms of light fractions**



Light fractions of stellar populations
POPULATION VECTOR

$$F(\lambda)/F(\lambda_0) = \Sigma_j\, x_j\, B_j(\lambda)\, 10^{-0.4A_\lambda} \otimes G(v_\star, \sigma_\star)$$

2. FADO

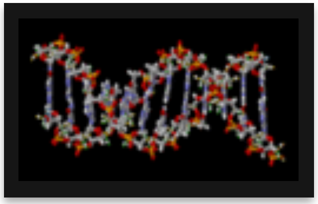
Fitting Analysis using Differential evolution Optimization

Gomes & Papaderos 2017 (A&A 603, 63)

- Next generation of population synthesis codes: motivated by Porto3D IFU post-processing pipeline & RemoveYoung

- Multi-objective mathematical programming: several conflicting objectives might be introduced in the formulation of an optimization problem (e.g., photometric bands, emission-lines, among others)

- Pareto optimal solutions



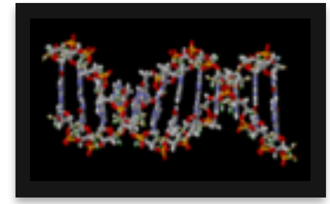
2. FADO

- Genetic optimization + Artificial Intelligence schemes

- Based on 3 main features:
  Breeding, Mutation and Selection Represented by Chromosomes, Biological inspiration. Ideal for multi-objective programming

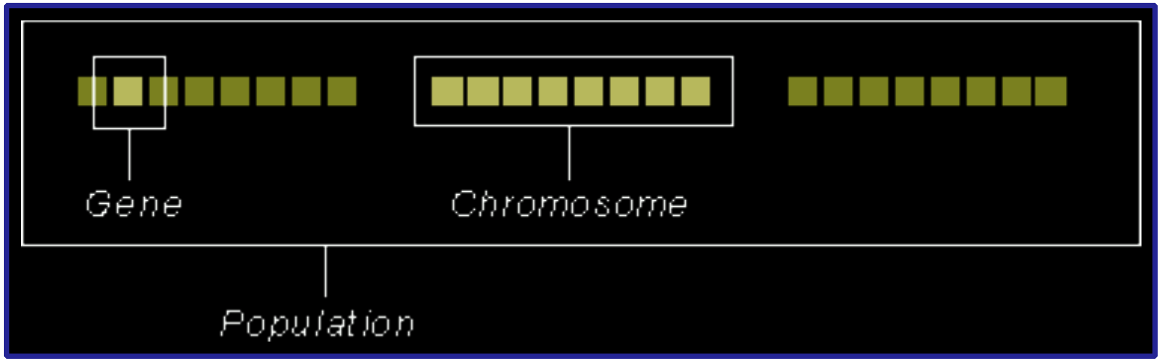
- Differential evolution is a method that optimizes a problem by iteratively trying to improve a candidate solution

- Chromosome convergence test for Pareto optimal solutions



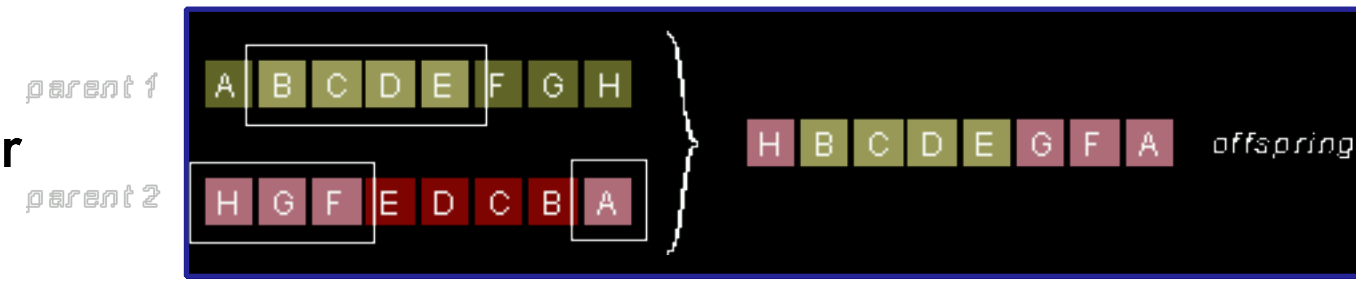
2. FADO

Fitting Analysis using Differential evolution Optimization

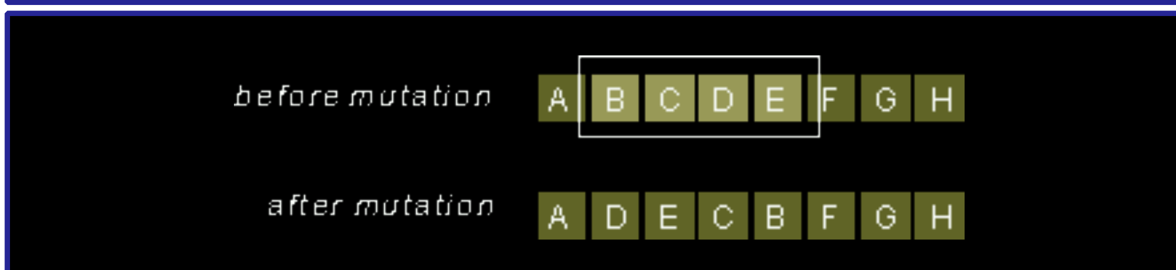


Genes: Parameters
Chromosome: Solution/Fit
Population: Ensemble of Fits

Crossover



Mutation



In a…

2.1. FADO in a nutshell

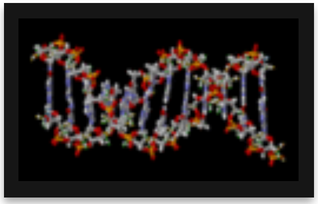
1- Computation and inclusion of the nebular continuum to the best-fitting SED;

2- PV that self-consistently accounts for the observed line luminosities and EWs (v.1 Balmer-line luminosities);

3- On-the-fly determination of the physical conditions in the ionized gas and determination/storage of emission-line fluxes, and their uncertainties;

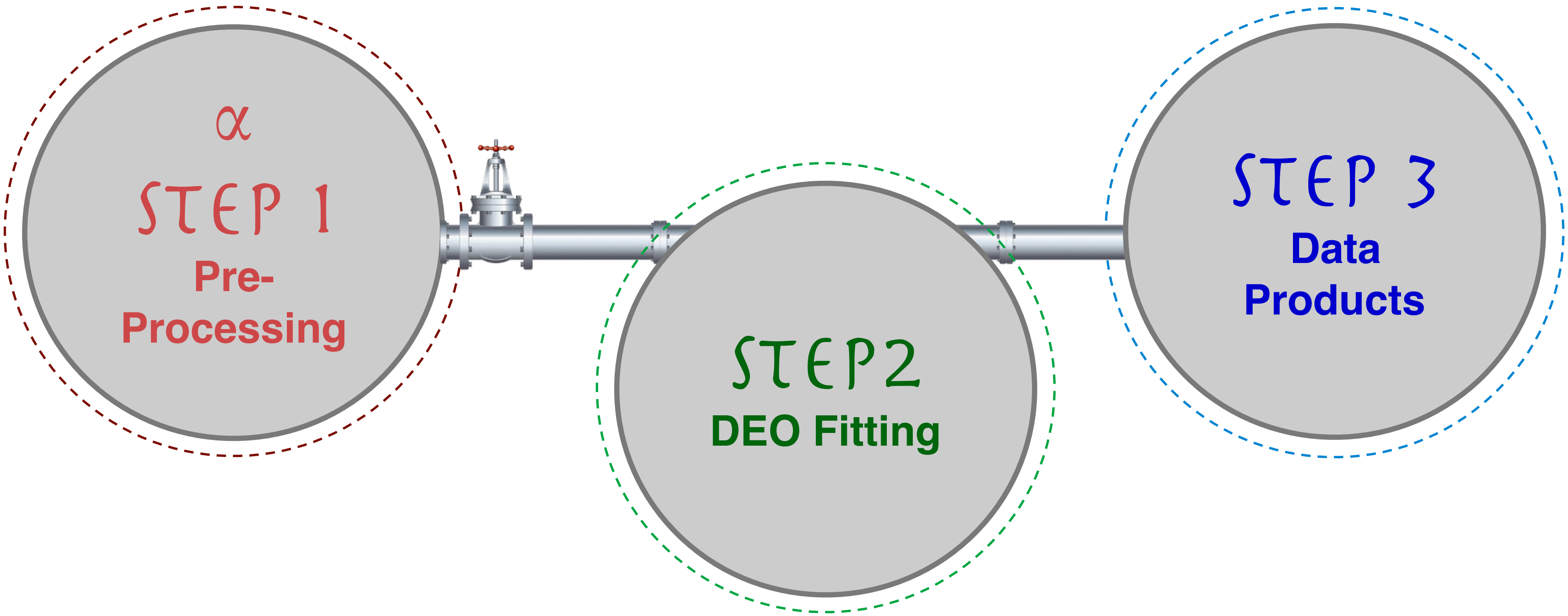
4- Automatically pre-classification of the input spectrum and on-the-fly optimization of the spectral fitting strategy using Artificial Intelligence (AI) techniques;

5- Computation and storage of uncertainties for all primary (e.g., PV, extinction, kinematics) and secondary products (e.g., mean stellar age and metallicity) from the spectral fit.

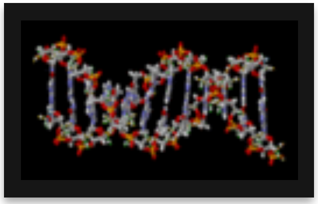


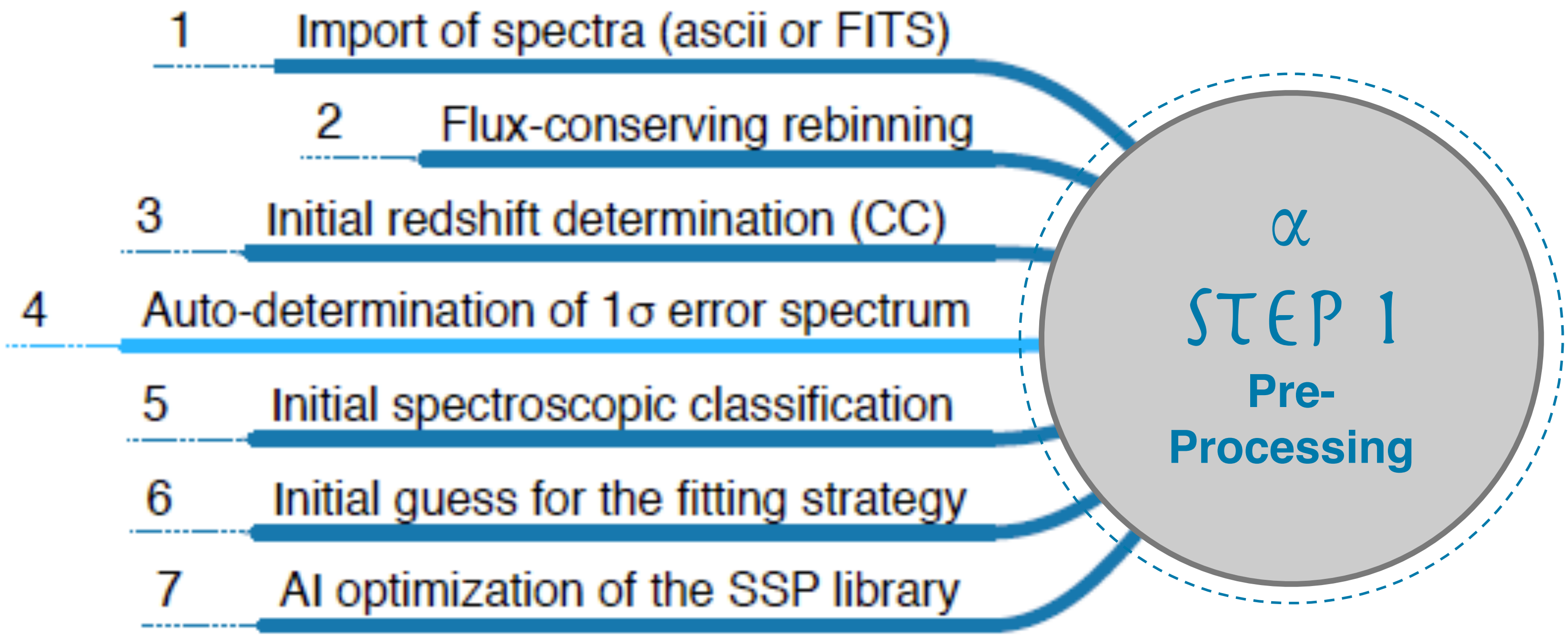
2.2. FADO pipeline

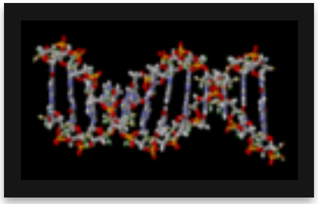
Single pipeline for analysis and having the data products

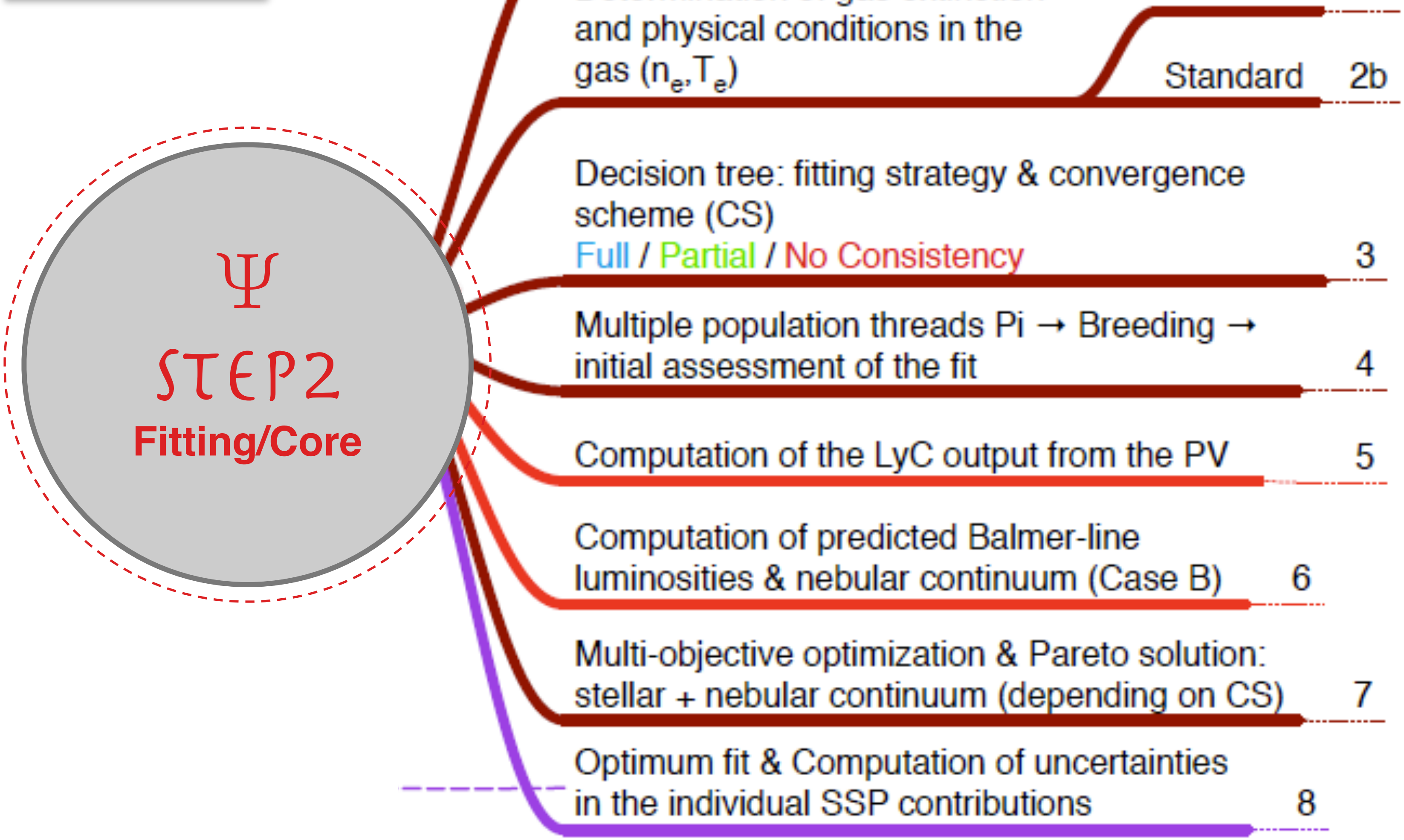


CORE routines of FADO

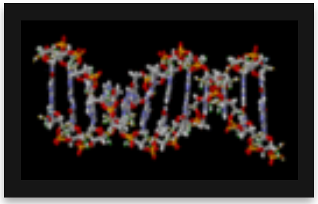


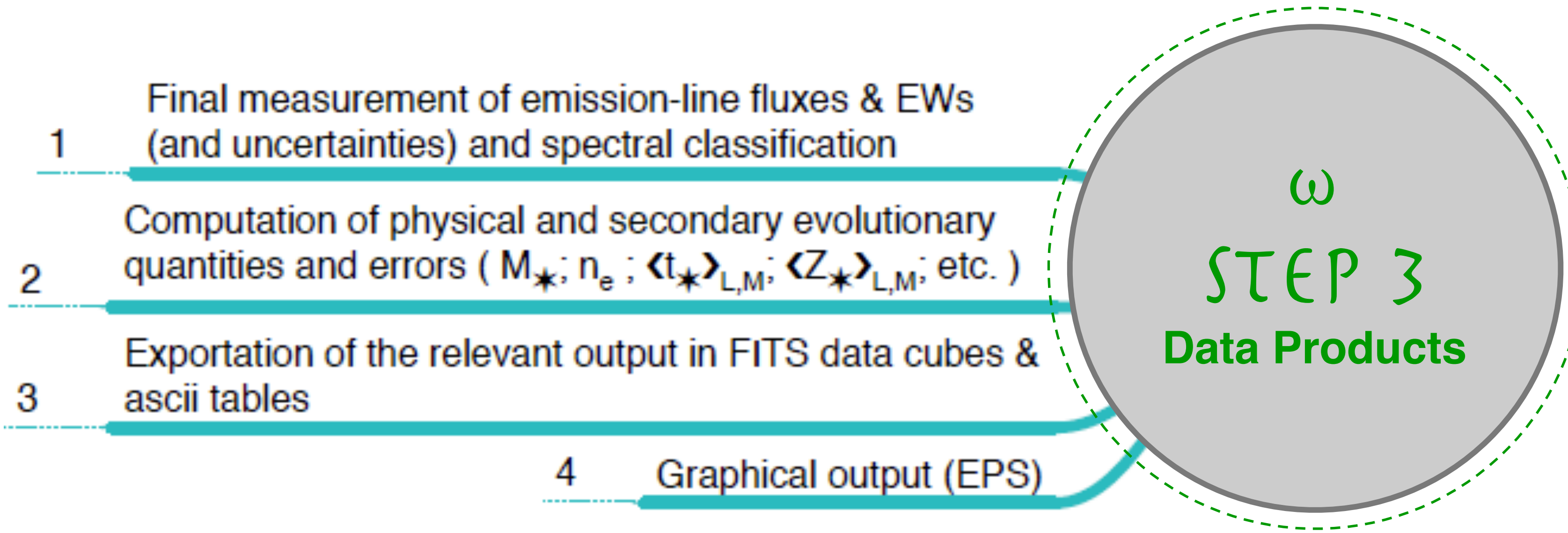

1 Import of spectra (ascii or FITS)
2 Flux-conserving rebinning
3 Initial redshift determination (CC)
4 Auto-determination of 1σ error spectrum
5 Initial spectroscopic classification
6 Initial guess for the fitting strategy
7 AI optimization of the SSP library
α
STEP 1
Pre-
Processing



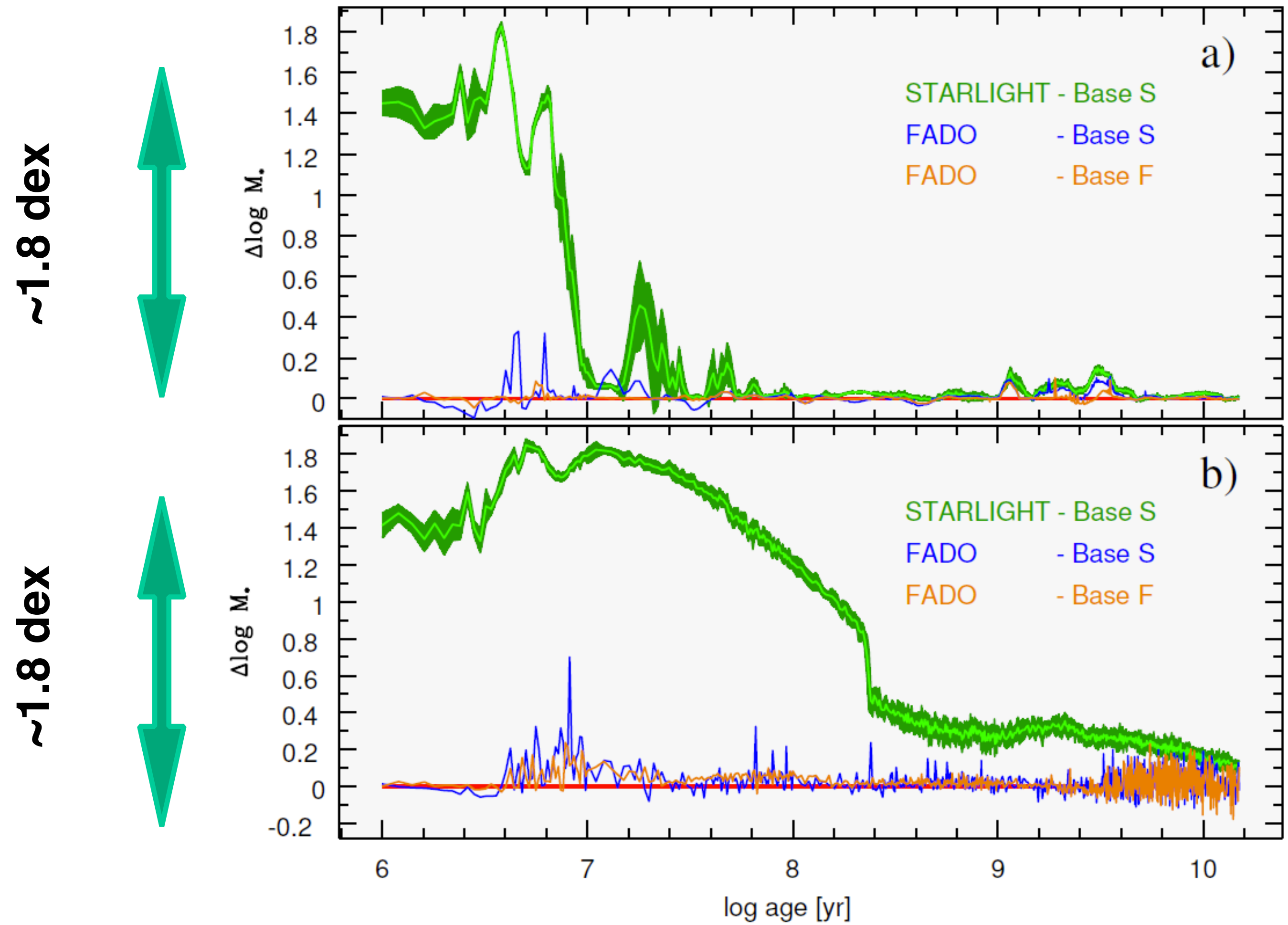


Ψ
STEP2
Fitting/Core
On-the-fly measurement of emission-line fluxes and EWs → quality check & BPT diagnostics
1
Determination of gas extinction and physical conditions in the gas (n_e,T_e)
FIVEL
2a
Standard
2b
Decision tree: fitting strategy & convergence scheme (CS)
Full / Partial / No Consistency
3
Multiple population threads Pi → Breeding → initial assessment of the fit
4
Computation of the LyC output from the PV
5
Computation of predicted Balmer-line luminosities & nebular continuum (Case B)
6
Multi-objective optimization & Pareto solution: stellar + nebular continuum (depending on CS)
7
Optimum fit & Computation of uncertainties in the individual SSP contributions
8




1 Final measurement of emission-line fluxes & EWs (and uncertainties) and spectral classification
2 Computation of physical and secondary evolutionary quantities and errors ($M_\star$; n_e ; $\langle t_\star \rangle_{L,M}$; $\langle Z_\star \rangle_{L,M}$; etc.)
3 Exportation of the relevant output in FITS data cubes & ascii tables
4 Graphical output (EPS)
ω
STEP 3
Data Products

2.3. FADO comparison with purely stellar models



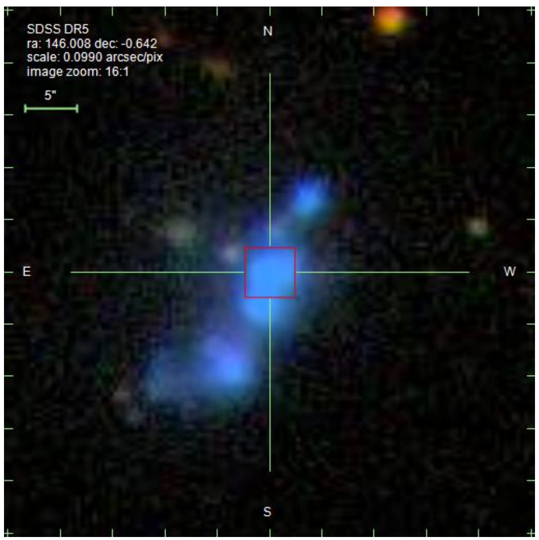
Instantaneous burst

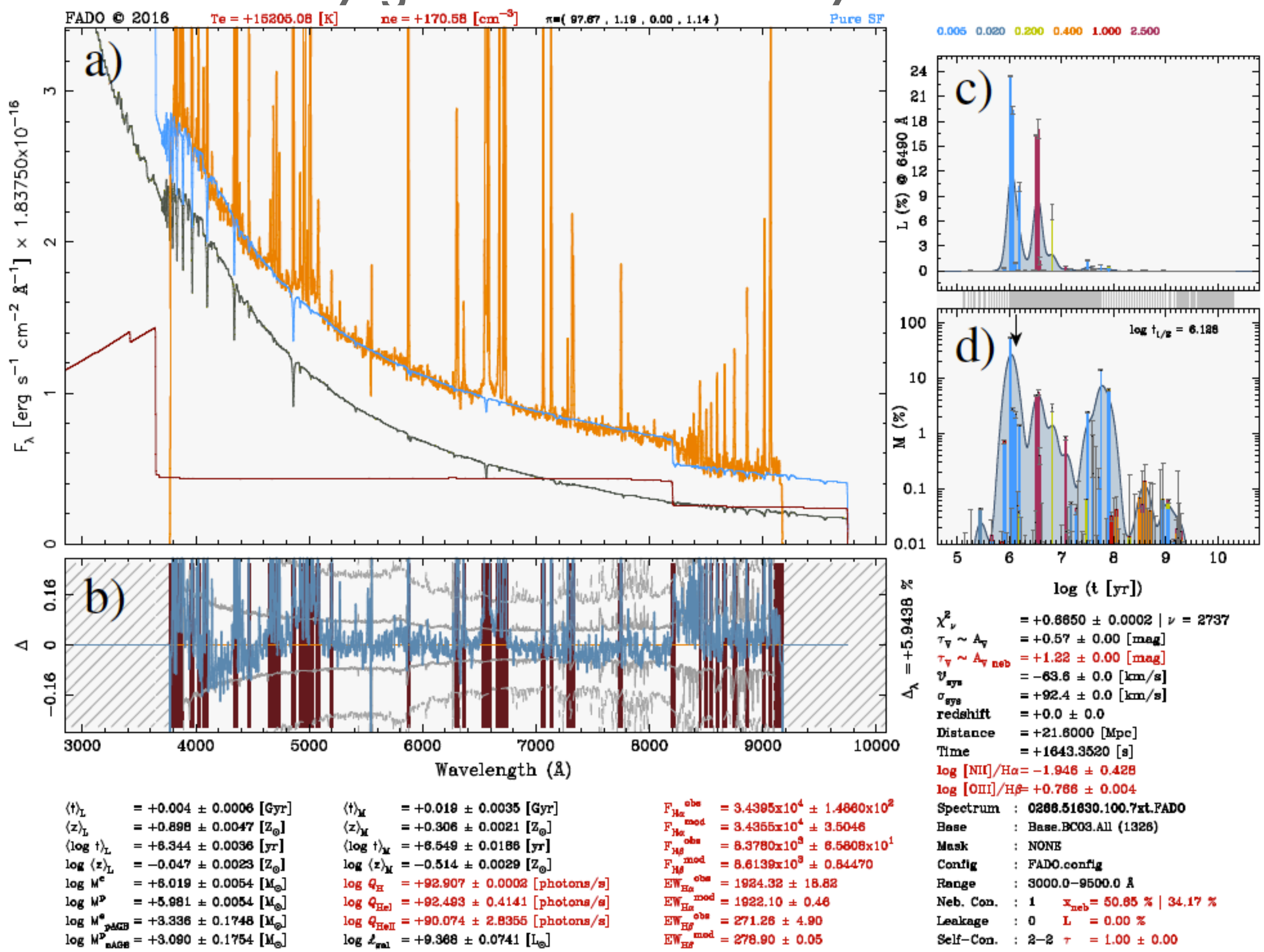
Continuous SF

3. FADO applications

3.1. CGCG 007-025a

Example from SDSS: Extremely gas contaminated system - BCD

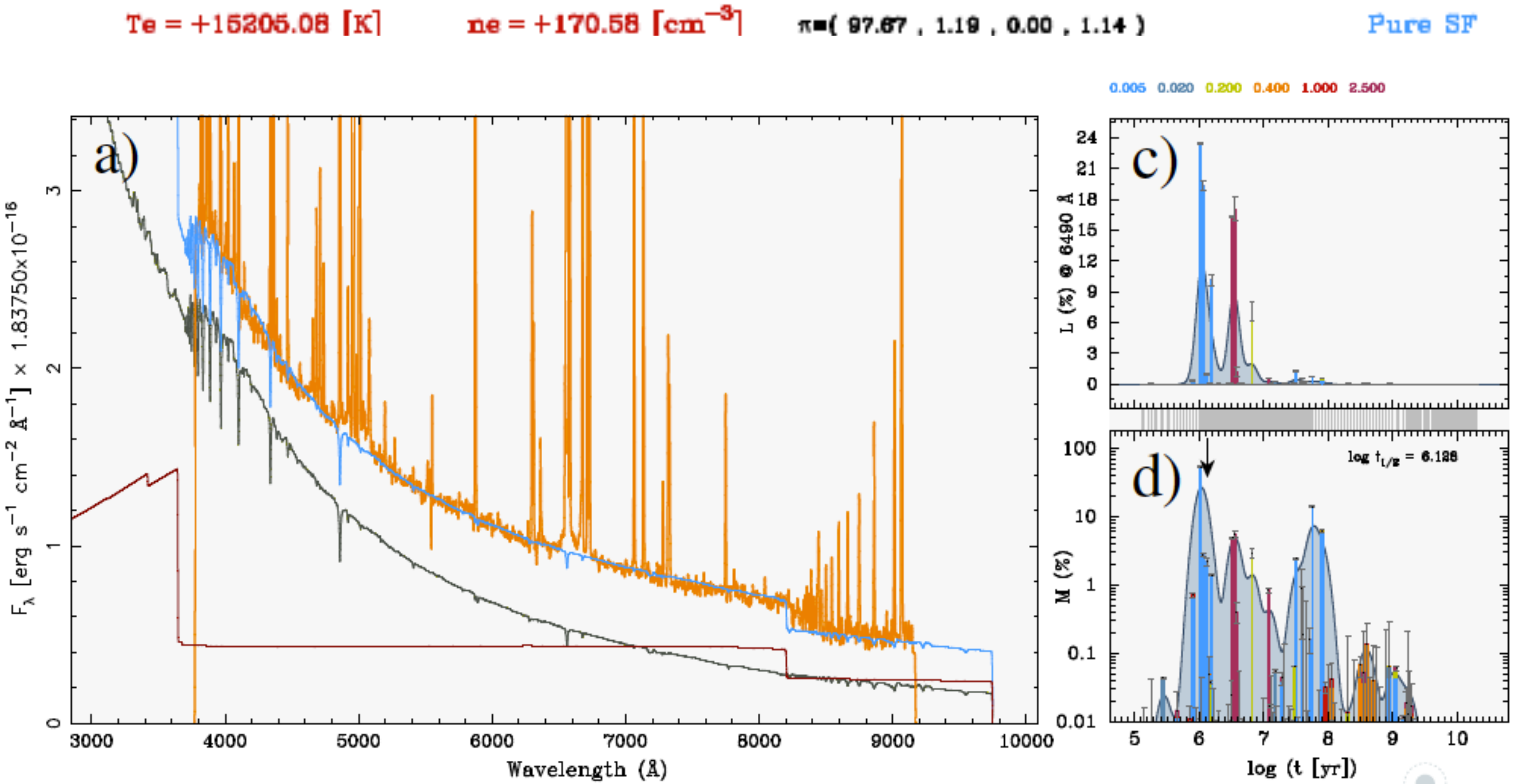




Gomes & Papaderos 2017

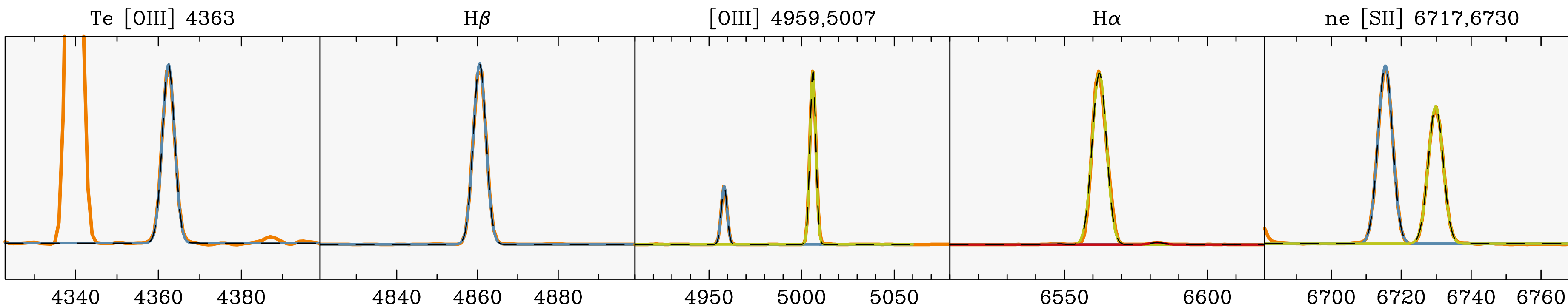
3.1. CGCG 007-025a

Example from SDSS: Extremely gas contaminated system - BCD



3.1. CGCG 007-025a

Output example from SDSS: Gas contaminated system - BCD

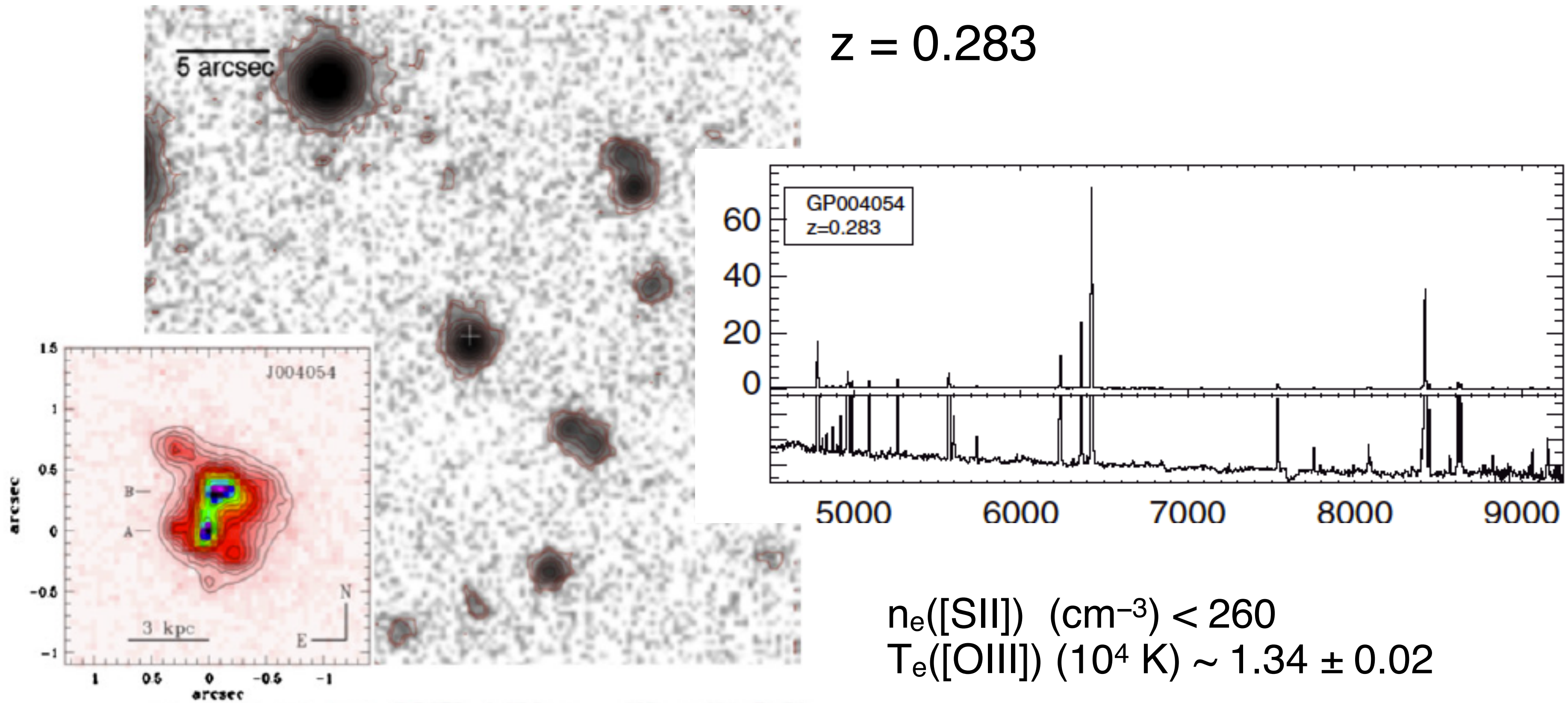


$\langle t \rangle_L$	$= +0.004 \pm 0.0006$ [Gyr]	$\langle t \rangle_M$	$= +0.019 \pm 0.0035$ [Gyr]	$F_{H\alpha}^{obs}$	$= 3.4395 \mathrm{x} 10^4 \pm 1.4860 \mathrm{x} 10^2$
$\langle z \rangle_L$	$= +0.898 \pm 0.0047$ [$Z_\odot$]	$\langle z \rangle_M$	$= +0.306 \pm 0.0021$ [$Z_\odot$]	$F_{H\alpha}^{mod}$	$= 3.4355 \mathrm{x} 10^4 \pm 3.5046$
$\langle \log t \rangle_L$	$= +6.344 \pm 0.0036$ [yr]	$\langle \log t \rangle_M$	$= +6.549 \pm 0.0186$ [yr]	$F_{H\beta}^{obs}$	$= 8.3780 \mathrm{x} 10^3 \pm 6.5808 \mathrm{x} 10^1$
$\log \langle z \rangle_L$	$= -0.047 \pm 0.0023$ [$Z_\odot$]	$\log \langle z \rangle_M$	$= -0.514 \pm 0.0029$ [$Z_\odot$]	$F_{H\beta}^{mod}$	$= 8.6139 \mathrm{x} 10^3 \pm 0.84470$
$\log M^e$	$= +6.019 \pm 0.0054$ [$M_\odot$]	$\log Q_H$	$= +92.907 \pm 0.0002$ [photons/s]	$EW_{H\alpha}^{obs}$	$= 1924.32 \pm 16.82$
$\log M^P$	$= +5.981 \pm 0.0054$ [$M_\odot$]	$\log Q_{HeI}$	$= +92.493 \pm 0.4141$ [photons/s]	$EW_{H\alpha}^{mod}$	$= 1922.10 \pm 0.46$
$\log M^e_{pAGB}$	$= +3.336 \pm 0.1748$ [$M_\odot$]	$\log Q_{HeII}$	$= +90.074 \pm 2.8355$ [photons/s]	$EW_{H\beta}^{obs}$	$= 271.26 \pm 4.90$
$\log M^P_{nAGB}$	$= +3.090 \pm 0.1754$ [$M_\odot$]	$\log \mathcal{L}_{gal}$	$= +9.368 \pm 0.0741$ [$L_\odot$]	$EW_{H\beta}^{mod}$	$= 278.90 \pm 0.05$

3.2. GP 004054

Green Pea example from Amorín et al. 2012

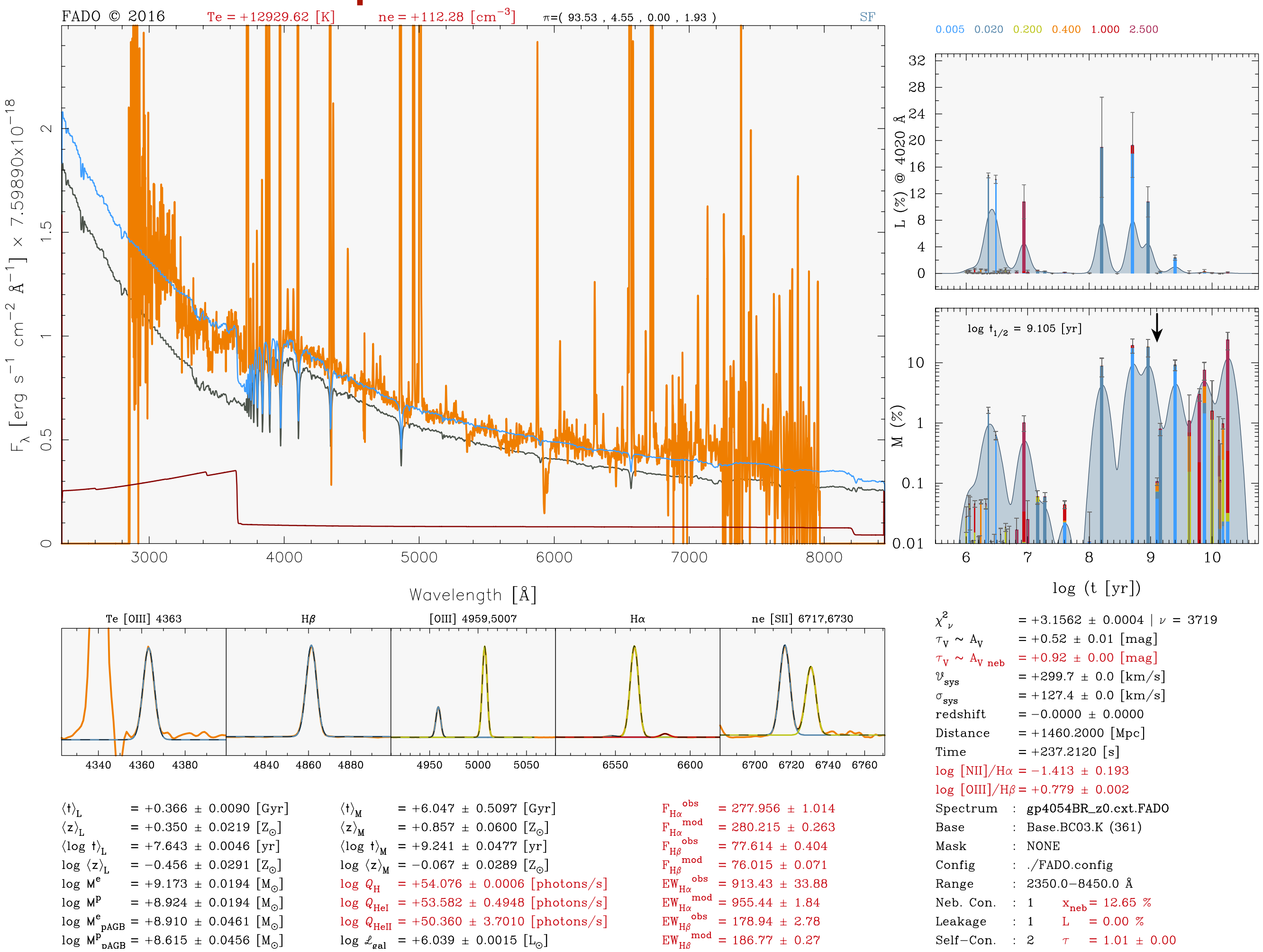
z = 0.283



n_e([SII]) (cm^{-3}) < 260
T_e([OIII]) (10^4 K) ~ 1.34 ± 0.02

3.2. GP 004054

Green Pea example from Amorín et al. 2012



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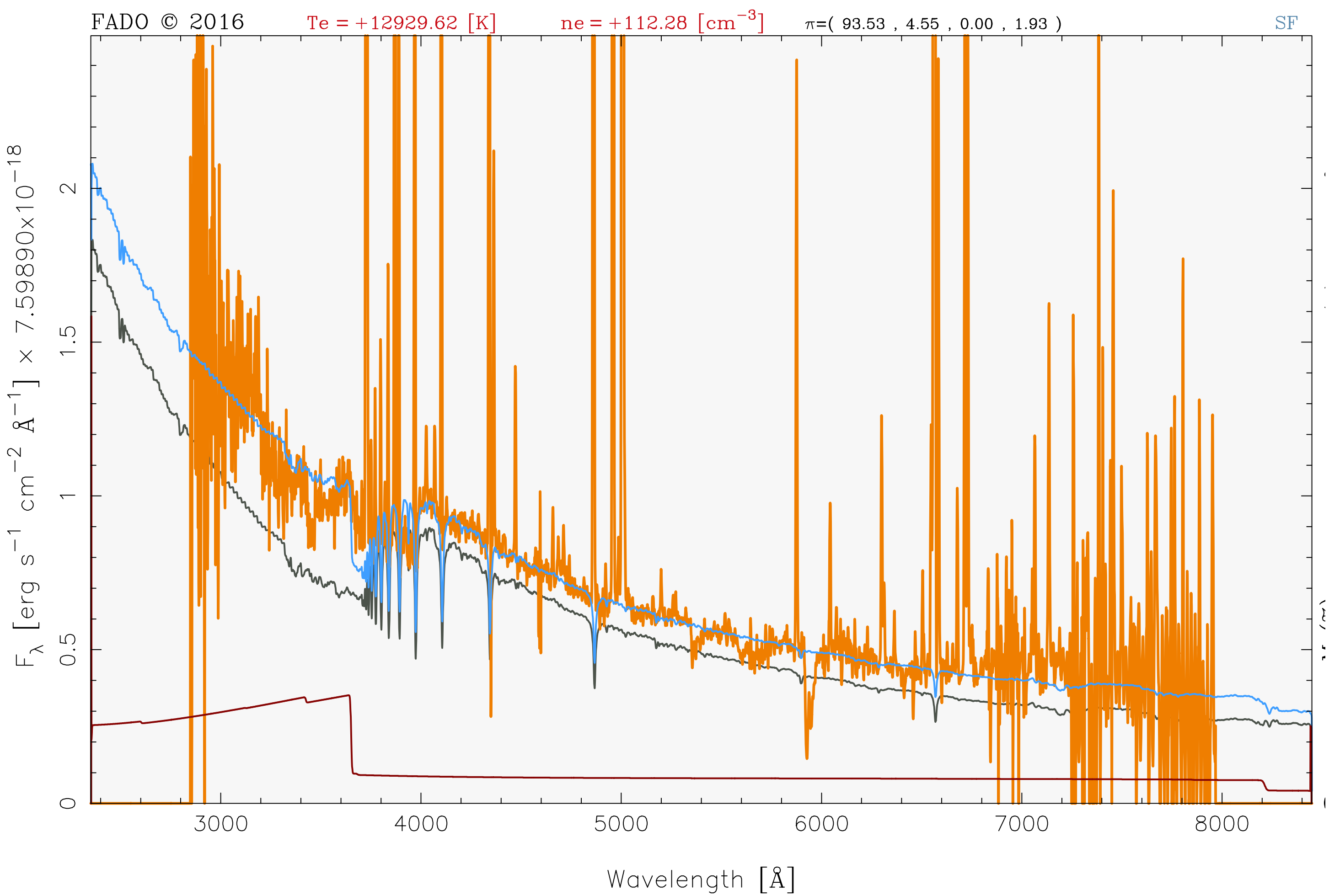
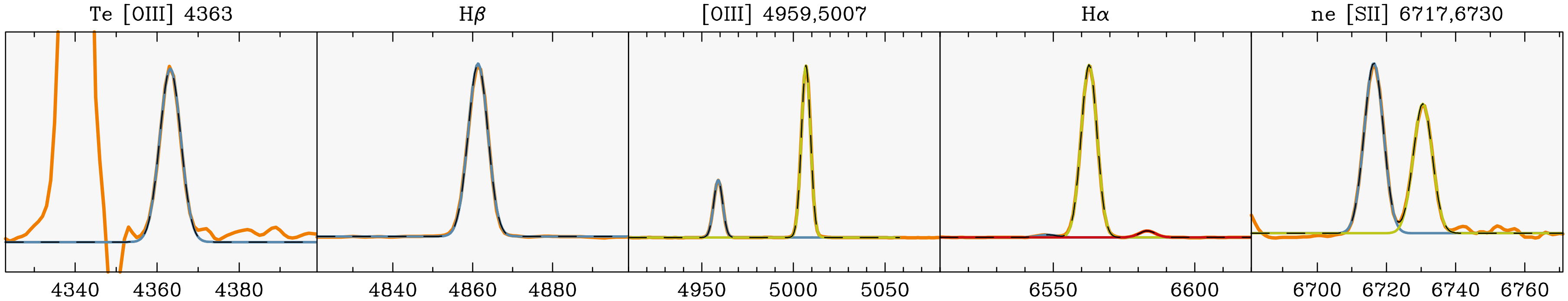
3.2. GP 004054

Green Pea example from Amorín et al. 2012



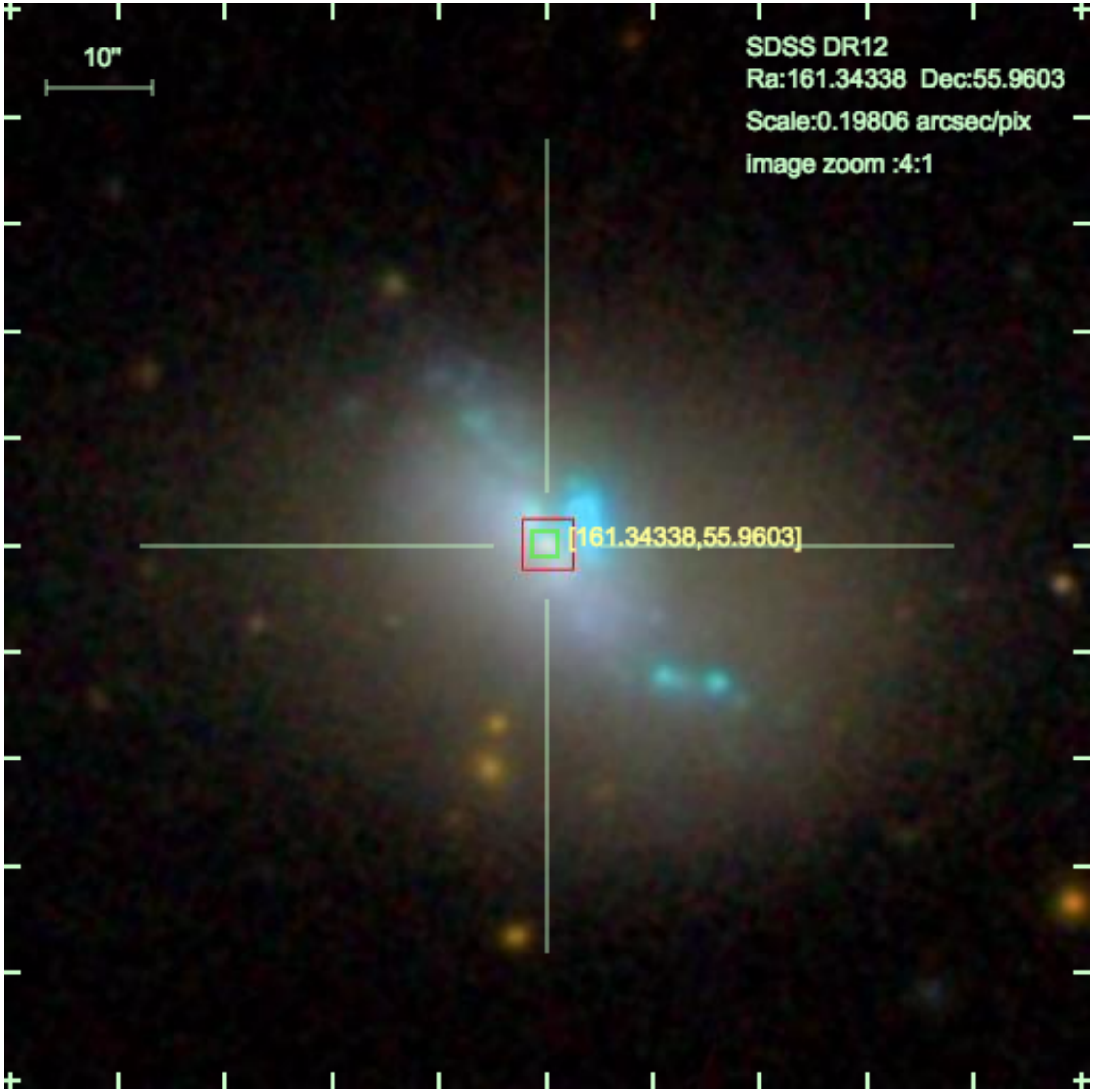
3.2. GP 004054

Green Pea example from Amorín et al. 2012



$\langle t \rangle_L = +0.366 \pm 0.0090$ [Gyr]	$\langle t \rangle_M = +6.047 \pm 0.5097$ [Gyr]	$F_{H\alpha}^{obs} = 277.956 \pm 1.014$
$\langle z \rangle_L = +0.350 \pm 0.0219$ [$Z_\odot$]	$\langle z \rangle_M = +0.857 \pm 0.0600$ [$Z_\odot$]	$F_{H\alpha}^{mod} = 280.215 \pm 0.263$
$\langle \log t \rangle_L = +7.643 \pm 0.0046$ [yr]	$\langle \log t \rangle_M = +9.241 \pm 0.0477$ [yr]	$F_{H\beta}^{obs} = 77.614 \pm 0.404$
$\log \langle z \rangle_L = -0.456 \pm 0.0291$ [$Z_\odot$]	$\log \langle z \rangle_M = -0.067 \pm 0.0289$ [$Z_\odot$]	$F_{H\beta}^{mod} = 76.015 \pm 0.071$
$\log M^e = +9.173 \pm 0.0194$ [$M_\odot$]	$\log Q_H = +54.076 \pm 0.0006$ [photons/s]	$EW_{H\alpha}^{obs} = 913.43 \pm 33.88$
$\log M^p = +8.924 \pm 0.0194$ [$M_\odot$]	$\log Q_{HeI} = +53.582 \pm 0.4948$ [photons/s]	$EW_{H\alpha}^{mod} = 955.44 \pm 1.84$
$\log M^e_{pAGB} = +8.910 \pm 0.0461$ [$M_\odot$]	$\log Q_{HeII} = +50.360 \pm 3.7010$ [photons/s]	$EW_{H\beta}^{obs} = 178.94 \pm 2.78$
$\log M^p_{pAGB} = +8.615 \pm 0.0456$ [$M_\odot$]	$\log \mathcal{L}_{gal} = +6.039 \pm 0.0015$ [$L_\odot$]	$EW_{H\beta}^{mod} = 186.77 \pm 0.27$

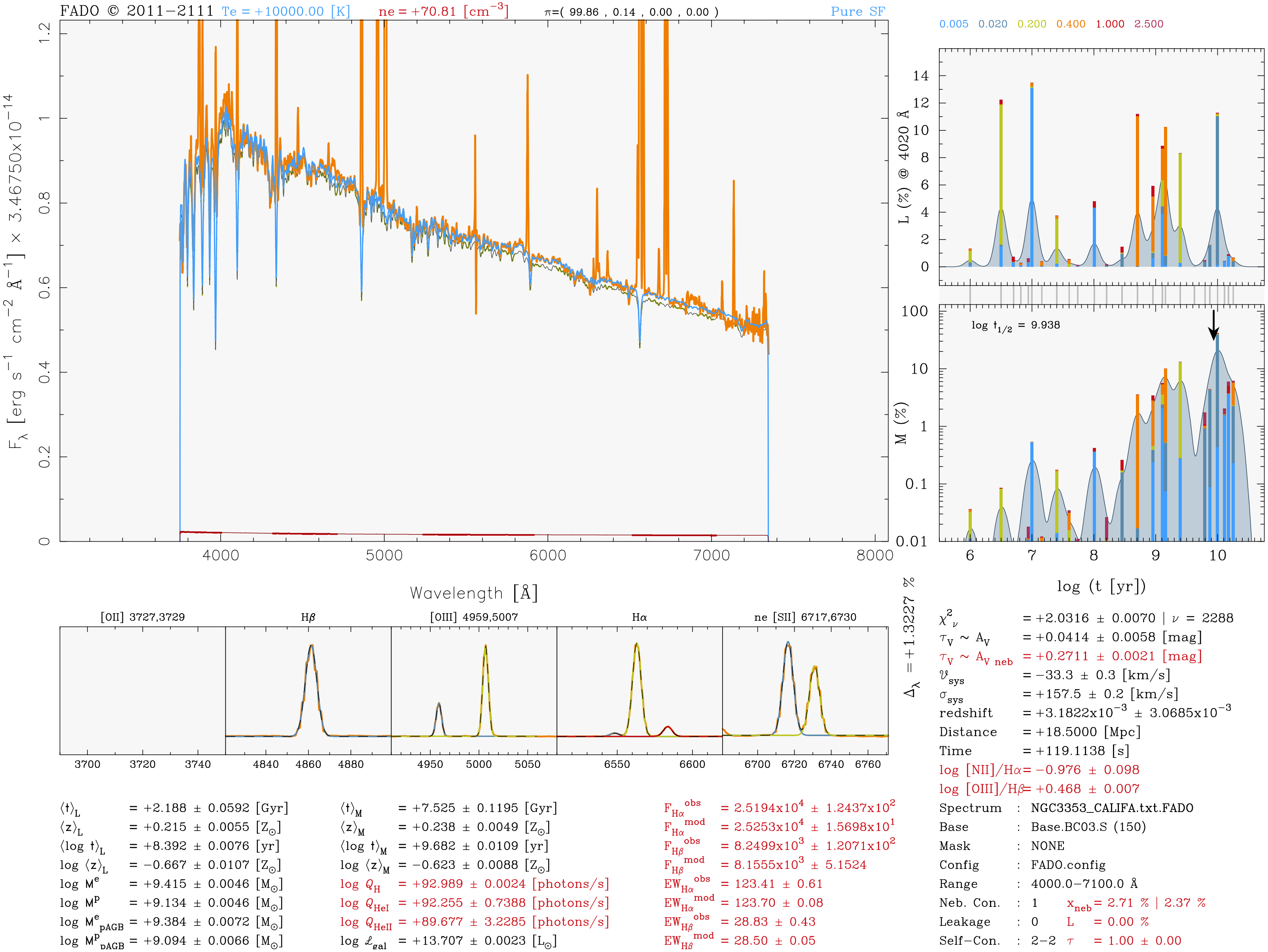
3.2 CALIFA MRK 35 / HARO 3

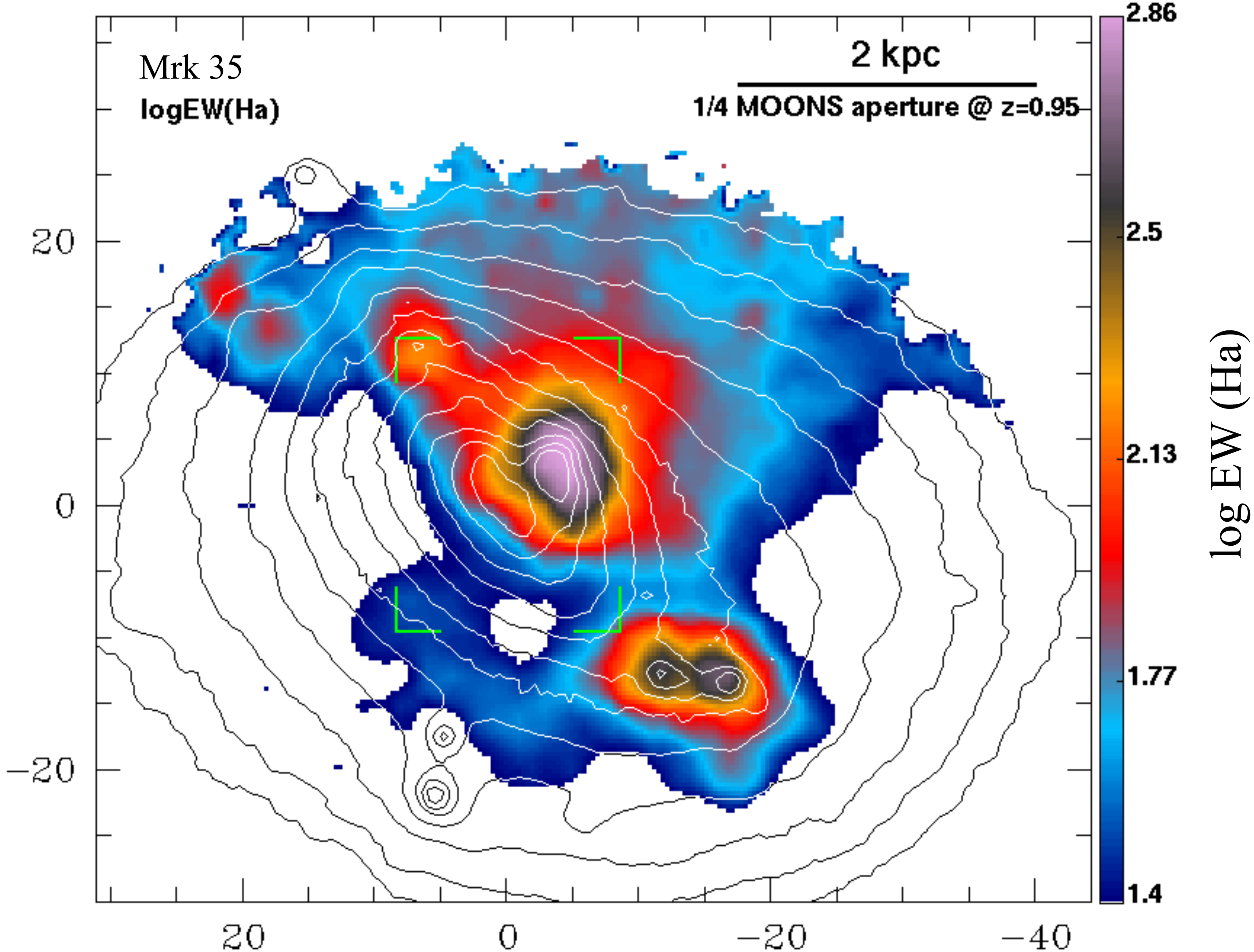


Preliminary results

An article to be presented in Gomes & Papaderos in prep.

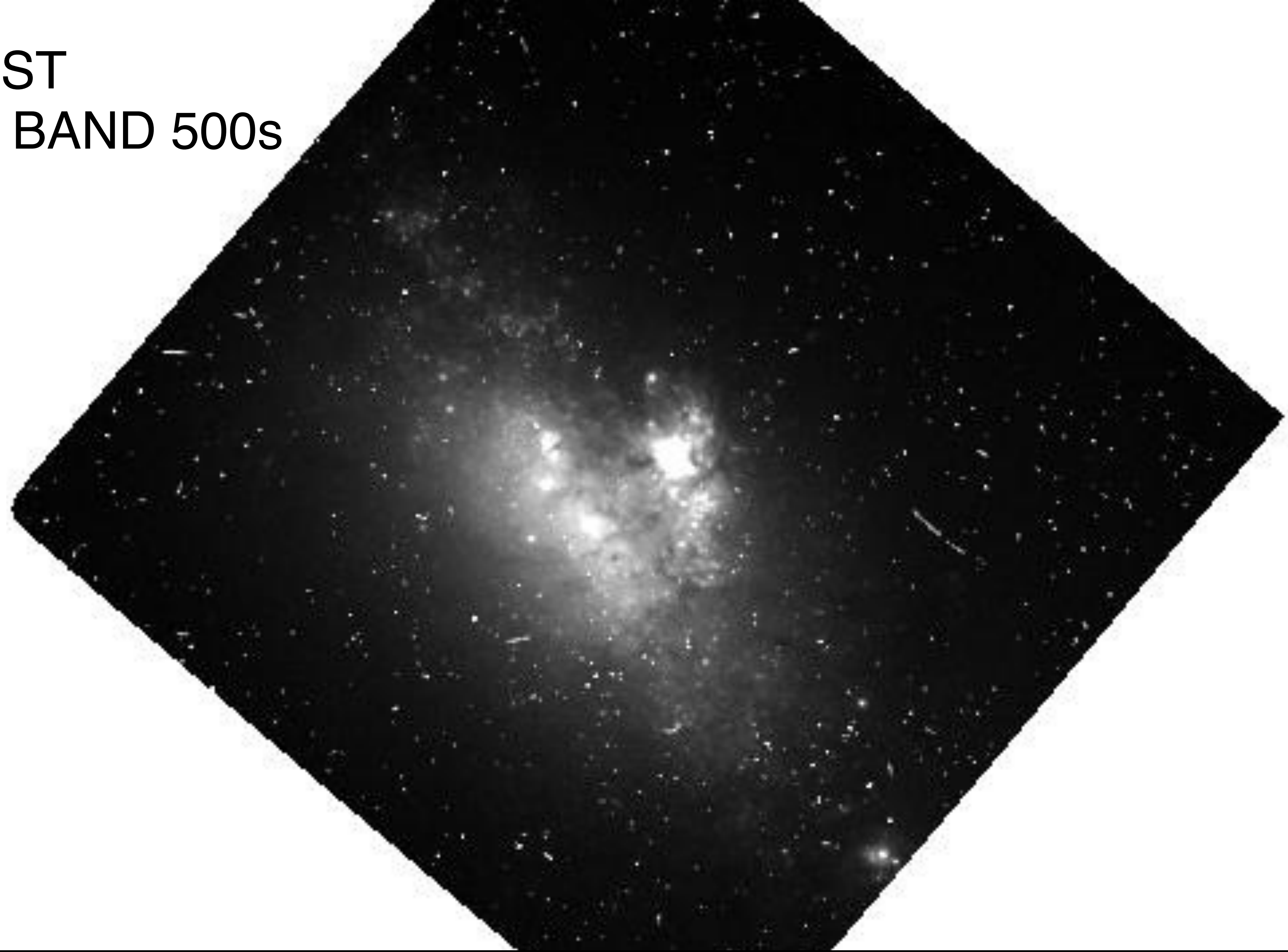
INTEGRATED spectrum from CALIFA



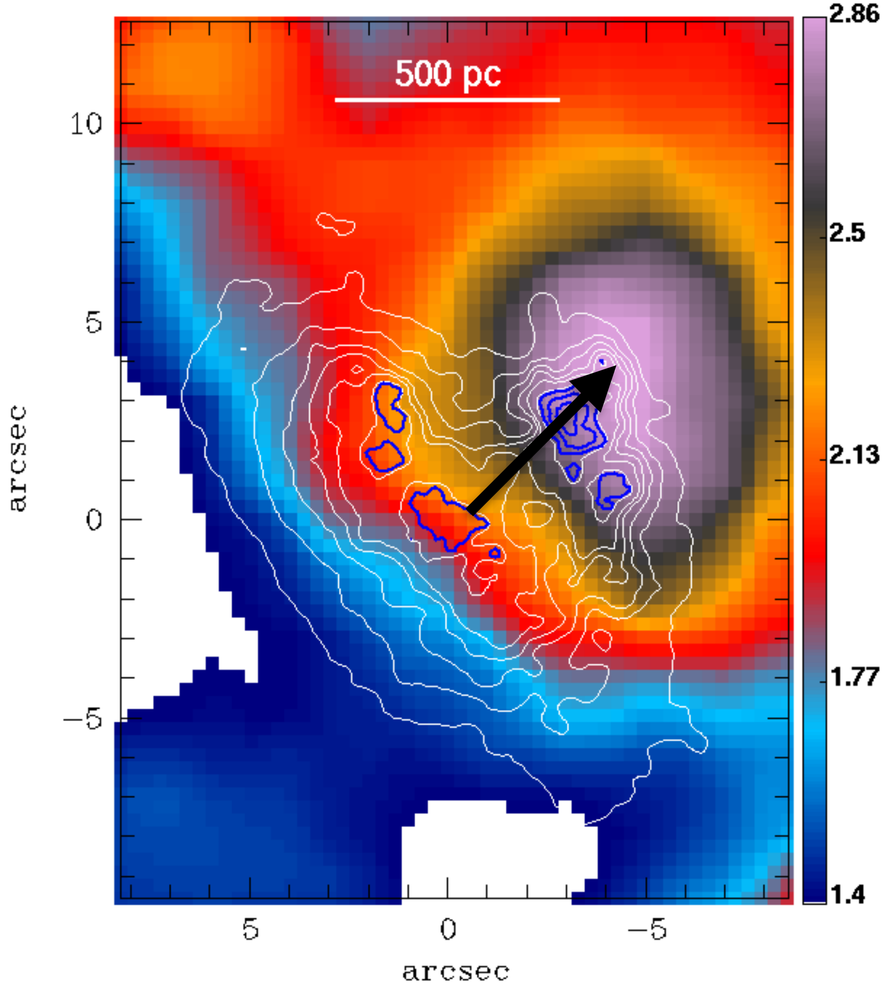


Gomes & Papaderos in prep.

HST
V BAND 500s



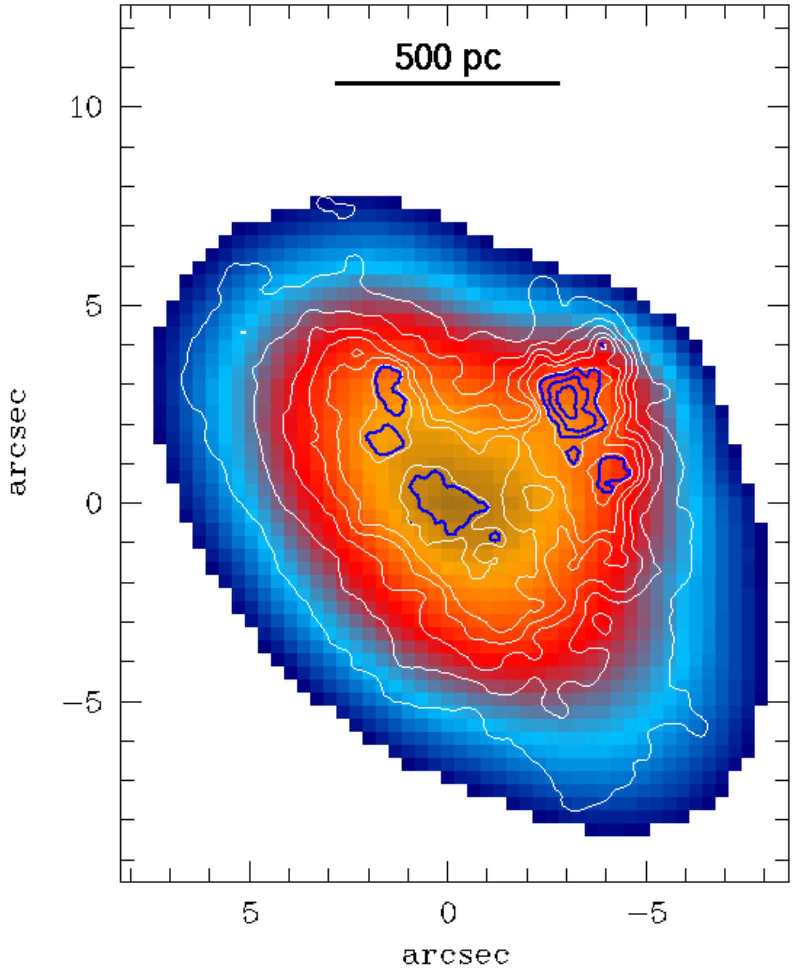
HST
V BAND 500s



Non-cospatiality
between
stars and gas

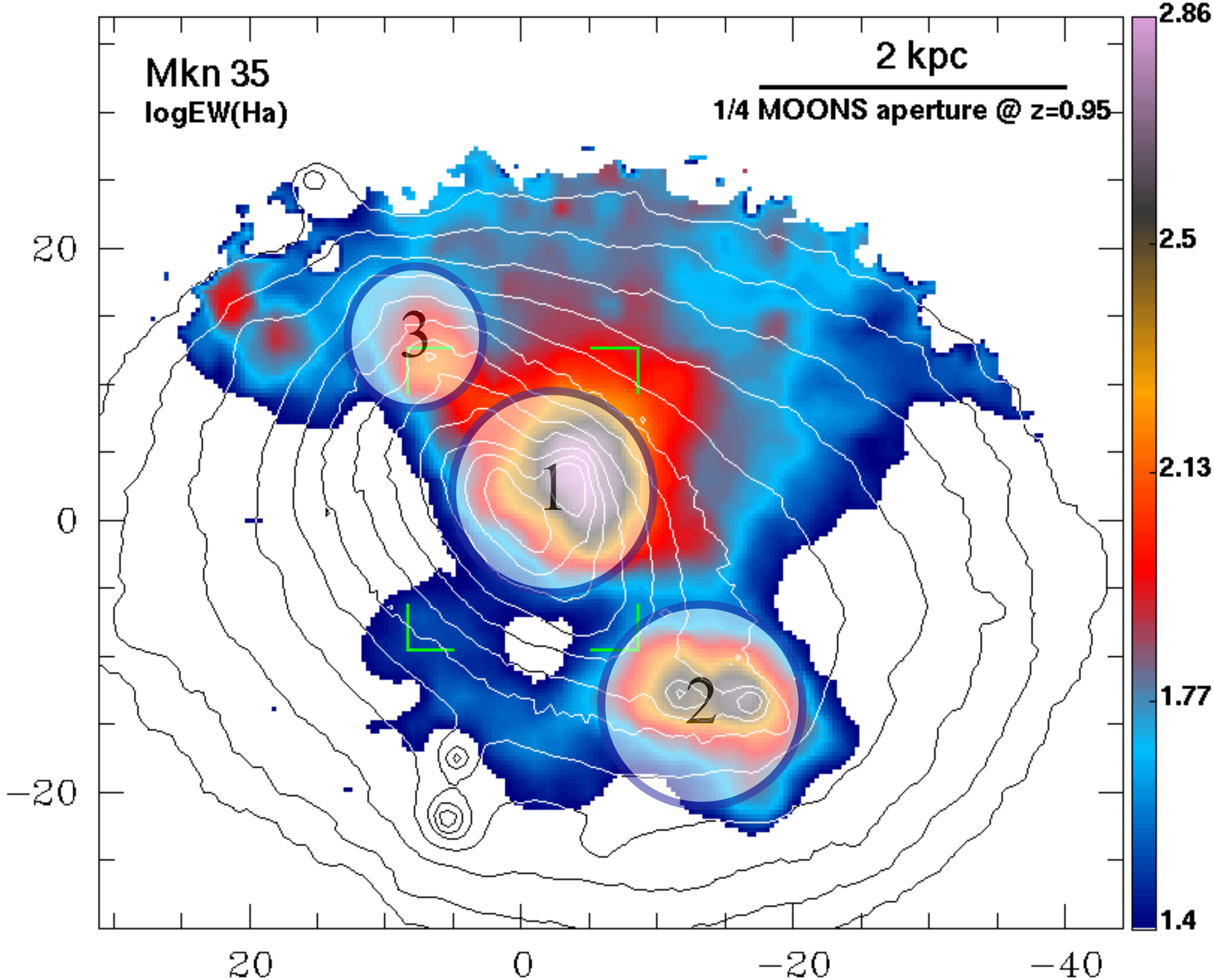
Simple Test

0.1" per pixel crossmatched astrometrically precision 0.1-0.15”

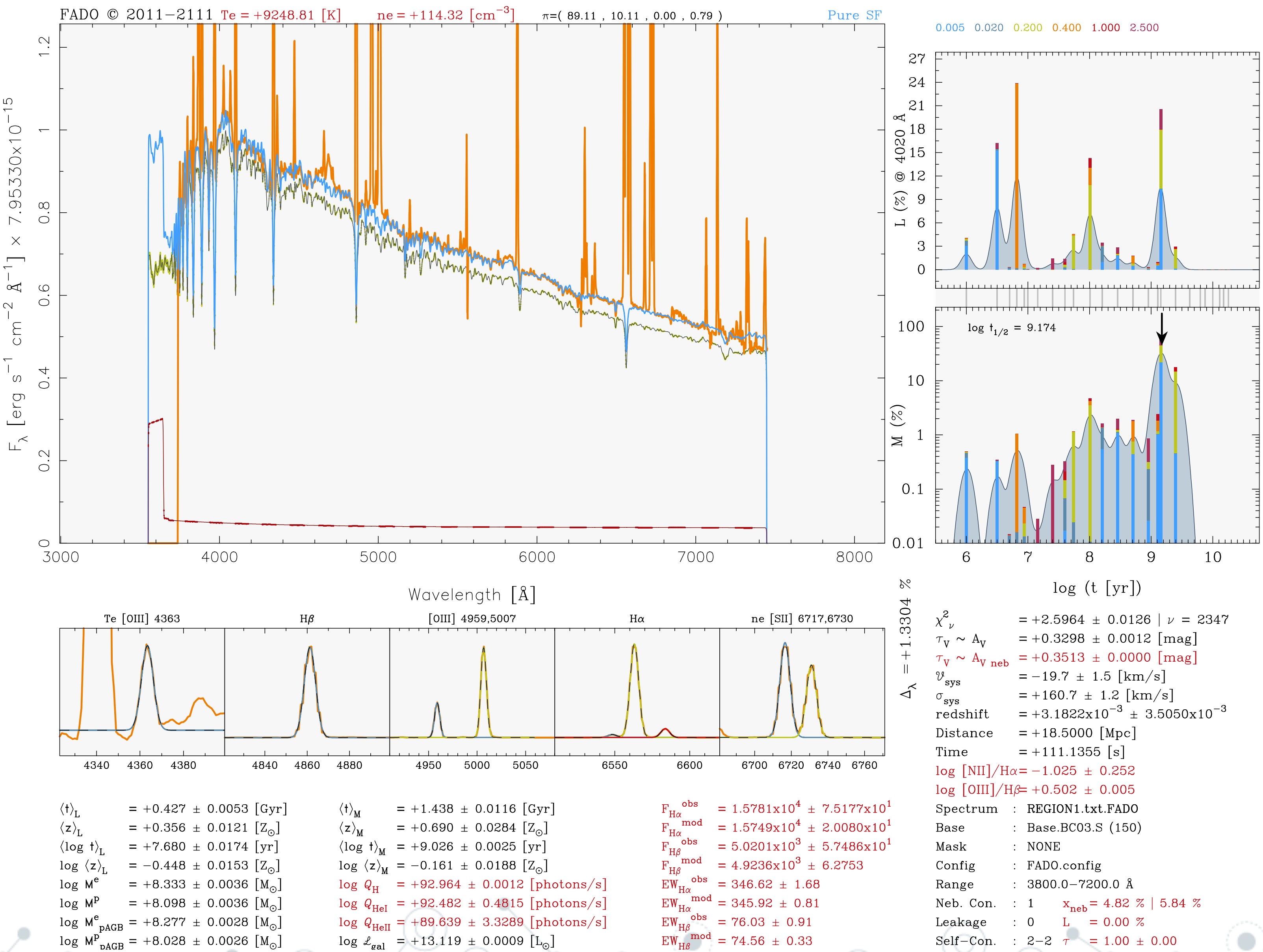


~6490-6590 Å
Cont. CALIFA

Gomes & Papaderos in prep.

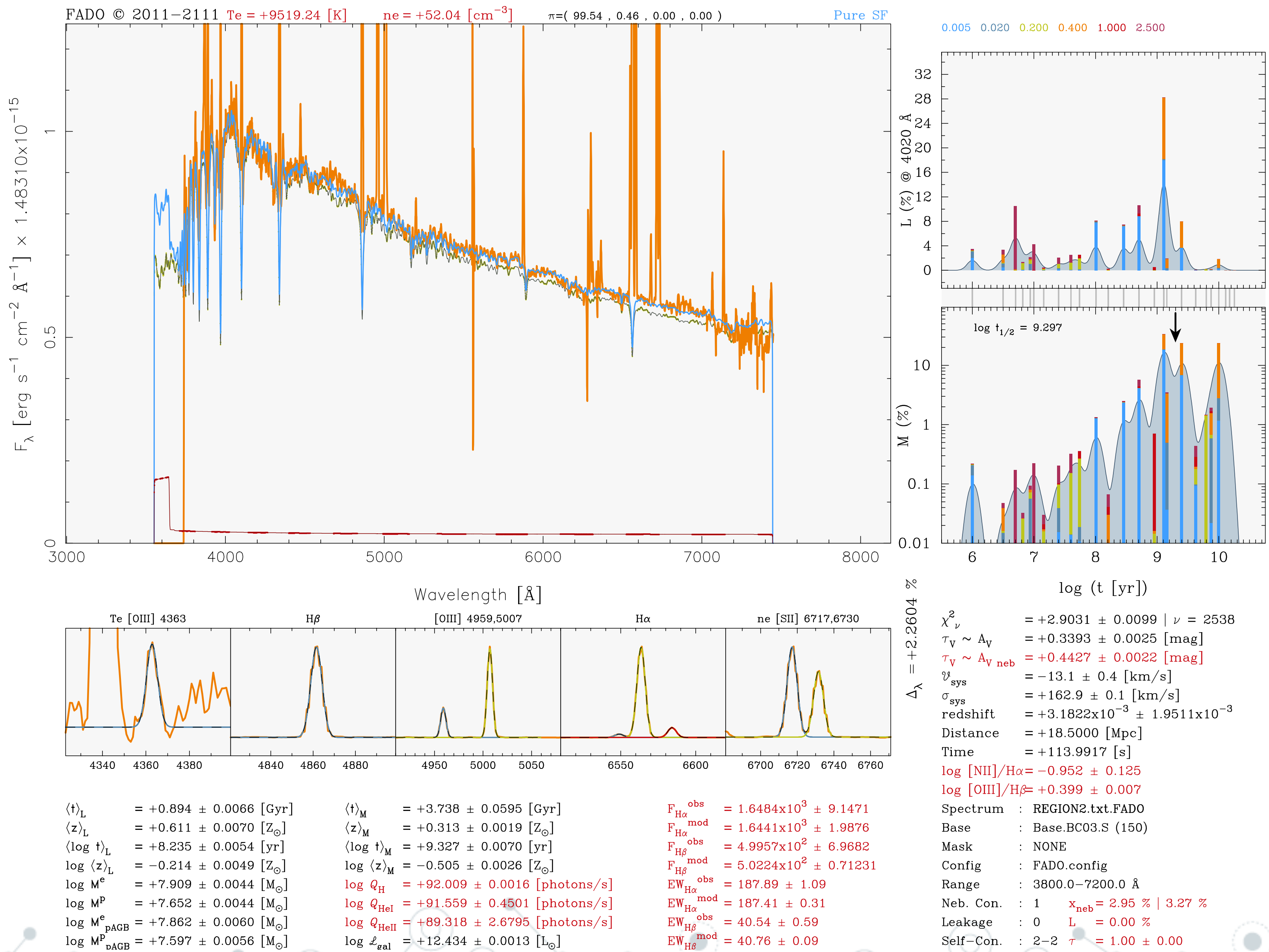


REGION 1



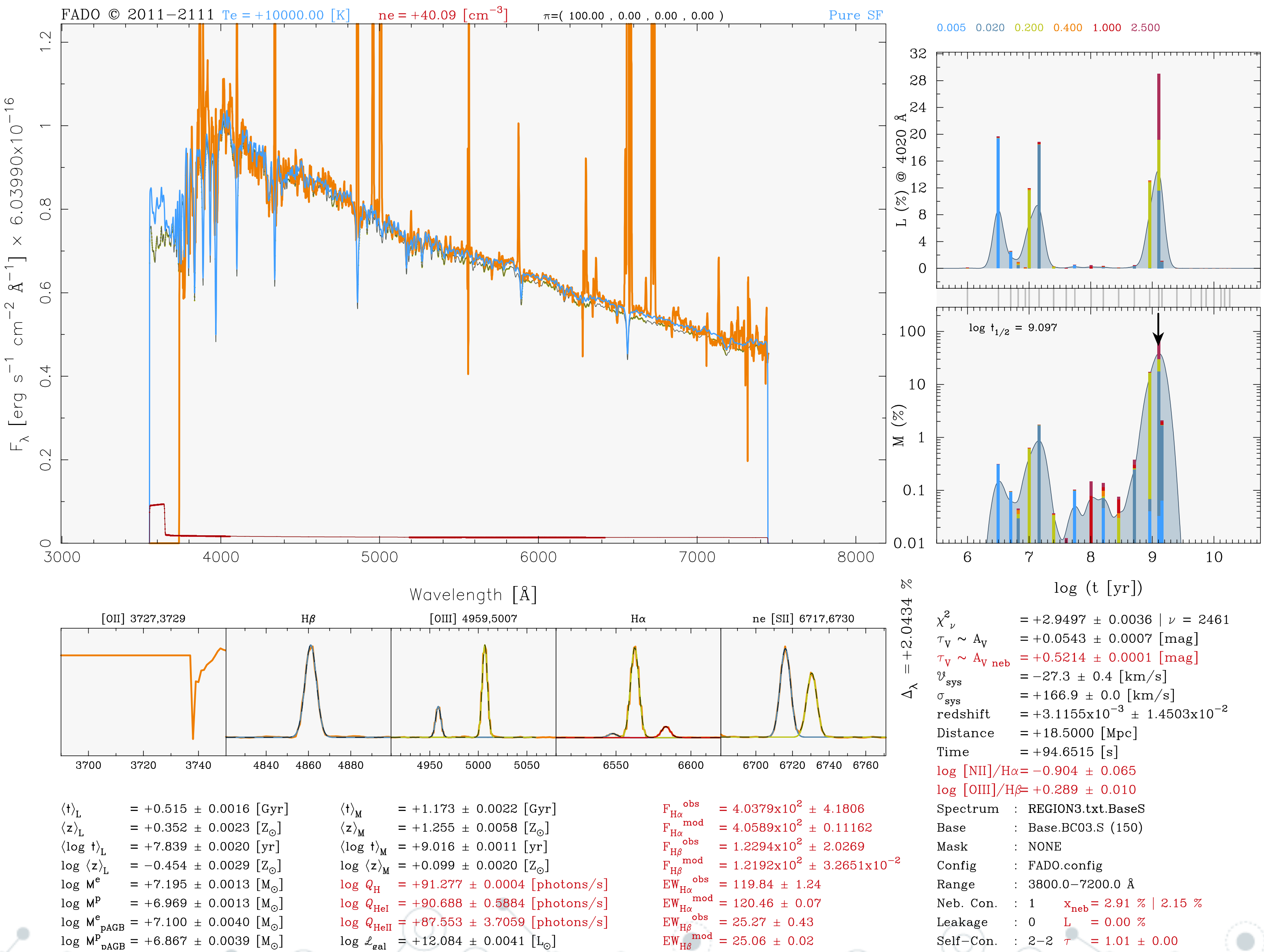
FADO © 2011–2111 Te = +9248.81 [K] ne = +114.32 [cm^{-3}] π=(89.11 , 10.11 , 0.00 , 0.79)
Pure SF
F_λ [erg s^{-1} cm^{-2} Å^{-1}] × 7.95330x10^{-15}
Wavelength [Å]
0.005 0.020 0.200 0.400 1.000 2.500
L (%) @ 4020 Å
M (%)
log $t_{1/2}$ = 9.174
log (t [yr])
Δ_λ = +1.3304 %
Te [OIII] 4363
Hβ
[OIII] 4959,5007
Hα
ne [SII] 6717,6730
χ^2_ν = +2.5964 ± 0.0126 | ν = 2347
$\tau_V \sim A_V$ = +0.3298 ± 0.0012 [mag]
$\tau_V \sim A_{V\ neb}$ = +0.3513 ± 0.0000 [mag]
v_{sys} = −19.7 ± 1.5 [km/s]
σ_{sys} = +160.7 ± 1.2 [km/s]
redshift = +3.1822x10^{-3} ± 3.5050x10^{-3}
Distance = +18.5000 [Mpc]
Time = +111.1355 [s]
log [NII]/Hα = −1.025 ± 0.252
log [OIII]/Hβ = +0.502 ± 0.005
Spectrum : REGION1.txt.FADO
Base : Base.BC03.S (150)
Mask : NONE
Config : FADO.config
Range : 3800.0–7200.0 Å
Neb. Con. : 1 x_{neb} = 4.82 % | 5.84 %
Leakage : 0 L = 0.00 %
Self–Con. : 2–2 τ = 1.00 ± 0.00
$\langle t \rangle_L$ = +0.427 ± 0.0053 [Gyr]
$\langle z \rangle_L$ = +0.356 ± 0.0121 [$Z_\odot$]
$\langle \log t \rangle_L$ = +7.680 ± 0.0174 [yr]
$\log \langle z \rangle_L$ = −0.448 ± 0.0153 [$Z_\odot$]
$\log M^e$ = +8.333 ± 0.0036 [$M_\odot$]
$\log M^P$ = +8.098 ± 0.0036 [$M_\odot$]
$\log M^e_{pAGB}$ = +8.277 ± 0.0028 [$M_\odot$]
$\log M^P_{pAGB}$ = +8.028 ± 0.0026 [$M_\odot$]
$\langle t \rangle_M$ = +1.438 ± 0.0116 [Gyr]
$\langle z \rangle_M$ = +0.690 ± 0.0284 [$Z_\odot$]
$\langle \log t \rangle_M$ = +9.026 ± 0.0025 [yr]
$\log \langle z \rangle_M$ = −0.161 ± 0.0188 [$Z_\odot$]
$\log Q_H$ = +92.964 ± 0.0012 [photons/s]
$\log Q_{HeI}$ = +92.482 ± 0.4815 [photons/s]
$\log Q_{HeII}$ = +89.639 ± 3.3289 [photons/s]
$\log \mathcal{L}_{gal}$ = +13.119 ± 0.0009 [$L_\odot$]
$F_{H\alpha}^{obs}$ = 1.5781x10^4 ± 7.5177x10^1
$F_{H\alpha}^{mod}$ = 1.5749x10^4 ± 2.0080x10^1
$F_{H\beta}^{obs}$ = 5.0201x10^3 ± 5.7486x10^1
$F_{H\beta}^{mod}$ = 4.9236x10^3 ± 6.2753
$EW_{H\alpha}^{obs}$ = 346.62 ± 1.68
$EW_{H\alpha}^{mod}$ = 345.92 ± 0.81
$EW_{H\beta}^{obs}$ = 76.03 ± 0.91
$EW_{H\beta}^{mod}$ = 74.56 ± 0.33

REGION 2



FADO © 2011−2111 Te = +9519.24 [K] ne = +52.04 [cm−3] π=(99.54 , 0.46 , 0.00 , 0.00) Pure SF
Fλ [erg s−1 cm−2 Å−1] × 1.48310x10−15
Wavelength [Å]
0.005 0.020 0.200 0.400 1.000 2.500
L (%) @ 4020 Å
log t1/2 = 9.297
M (%)
log (t [yr])
Δλ = +2.2604 %
Te [OIII] 4363
Hβ
[OIII] 4959,5007
Hα
ne [SII] 6717,6730
⟨t⟩L = +0.894 ± 0.0066 [Gyr]
⟨z⟩L = +0.611 ± 0.0070 [Z⊙]
⟨log t⟩L = +8.235 ± 0.0054 [yr]
log ⟨z⟩L = −0.214 ± 0.0049 [Z⊙]
log Me = +7.909 ± 0.0044 [M⊙]
log Mp = +7.652 ± 0.0044 [M⊙]
log Me pAGB = +7.862 ± 0.0060 [M⊙]
log Mp pAGB = +7.597 ± 0.0056 [M⊙]
⟨t⟩M = +3.738 ± 0.0595 [Gyr]
⟨z⟩M = +0.313 ± 0.0019 [Z⊙]
⟨log t⟩M = +9.327 ± 0.0070 [yr]
log ⟨z⟩M = −0.505 ± 0.0026 [Z⊙]
log QH = +92.009 ± 0.0016 [photons/s]
log QHeI = +91.559 ± 0.4501 [photons/s]
log QHeII = +89.318 ± 2.6795 [photons/s]
log ℒgal = +12.434 ± 0.0013 [L⊙]
FHα obs = 1.6484x10^3 ± 9.1471
FHα mod = 1.6441x10^3 ± 1.9876
FHβ obs = 4.9957x10^2 ± 6.9682
FHβ mod = 5.0224x10^2 ± 0.71231
EWHα obs = 187.89 ± 1.09
EWHα mod = 187.41 ± 0.31
EWHβ obs = 40.54 ± 0.59
EWHβ mod = 40.76 ± 0.09
χ2ν = +2.9031 ± 0.0099 | ν = 2538
τV ~ AV = +0.3393 ± 0.0025 [mag]
τV ~ AV neb = +0.4427 ± 0.0022 [mag]
vsys = −13.1 ± 0.4 [km/s]
σsys = +162.9 ± 0.1 [km/s]
redshift = +3.1822x10−3 ± 1.9511x10−3
Distance = +18.5000 [Mpc]
Time = +113.9917 [s]
log [NII]/Hα = −0.952 ± 0.125
log [OIII]/Hβ = +0.399 ± 0.007
Spectrum : REGION2.txt.FADO
Base : Base.BC03.S (150)
Mask : NONE
Config : FADO.config
Range : 3800.0−7200.0 Å
Neb. Con. : 1 xneb = 2.95 % | 3.27 %
Leakage : 0 L = 0.00 %
Self−Con. : 2−2 τ = 1.00 ± 0.00

REGION 3


FADO © 2011–2111 Te = +10000.00 [K] ne = +40.09 [cm^{-3}] π=(100.00 , 0.00 , 0.00 , 0.00) Pure SF
F_λ [erg s^{-1} cm^{-2} Å^{-1}] × 6.03990x10^{-16}
Wavelength [Å]
0.005 0.020 0.200 0.400 1.000 2.500
L (%) @ 4020 Å
M (%)
log $t_{1/2}$ = 9.097
log (t [yr])
Δ_λ = +2.0434 %
[OII] 3727,3729
Hβ
[OIII] 4959,5007
Hα
ne [SII] 6717,6730
χ^2_ν = +2.9497 ± 0.0036 | ν = 2461
$\tau_V \sim A_V$ = +0.0543 ± 0.0007 [mag]
$\tau_V \sim A_{V\,neb}$ = +0.5214 ± 0.0001 [mag]
v_{sys} = −27.3 ± 0.4 [km/s]
σ_{sys} = +166.9 ± 0.0 [km/s]
redshift = +3.1155x10^{-3} ± 1.4503x10^{-2}
Distance = +18.5000 [Mpc]
Time = +94.6515 [s]
log [NII]/Hα = −0.904 ± 0.065
log [OIII]/Hβ = +0.289 ± 0.010
Spectrum : REGION3.txt.BaseS
Base : Base.BC03.S (150)
Mask : NONE
Config : FADO.config
Range : 3800.0−7200.0 Å
Neb. Con. : 1 x_{neb} = 2.91 % | 2.15 %
Leakage : 0 L = 0.00 %
Self−Con. : 2−2 τ = 1.01 ± 0.00
$\langle t \rangle_L$ = +0.515 ± 0.0016 [Gyr]
$\langle z \rangle_L$ = +0.352 ± 0.0023 [$Z_\odot$]
$\langle \log t \rangle_L$ = +7.839 ± 0.0020 [yr]
$\log \langle z \rangle_L$ = −0.454 ± 0.0029 [$Z_\odot$]
$\log M^e$ = +7.195 ± 0.0013 [$M_\odot$]
$\log M^p$ = +6.969 ± 0.0013 [$M_\odot$]
$\log M^e_{pAGB}$ = +7.100 ± 0.0040 [$M_\odot$]
$\log M^p_{pAGB}$ = +6.867 ± 0.0039 [$M_\odot$]
$\langle t \rangle_M$ = +1.173 ± 0.0022 [Gyr]
$\langle z \rangle_M$ = +1.255 ± 0.0058 [$Z_\odot$]
$\langle \log t \rangle_M$ = +9.016 ± 0.0011 [yr]
$\log \langle z \rangle_M$ = +0.099 ± 0.0020 [$Z_\odot$]
$\log Q_H$ = +91.277 ± 0.0004 [photons/s]
$\log Q_{HeI}$ = +90.688 ± 0.5884 [photons/s]
$\log Q_{HeII}$ = +87.553 ± 3.7059 [photons/s]
$\log \mathcal{L}_{gal}$ = +12.084 ± 0.0041 [$L_\odot$]
$F_{H\alpha}^{obs}$ = 4.0379x10^2 ± 4.1806
$F_{H\alpha}^{mod}$ = 4.0589x10^2 ± 0.11162
$F_{H\beta}^{obs}$ = 1.2294x10^2 ± 2.0269
$F_{H\beta}^{mod}$ = 1.2192x10^2 ± 3.2651x10^{-2}
$EW_{H\alpha}^{obs}$ = 119.84 ± 1.24
$EW_{H\alpha}^{mod}$ = 120.46 ± 0.07
$EW_{H\beta}^{obs}$ = 25.27 ± 0.43
$EW_{H\beta}^{mod}$ = 25.06 ± 0.02

Summarizing - Comparison

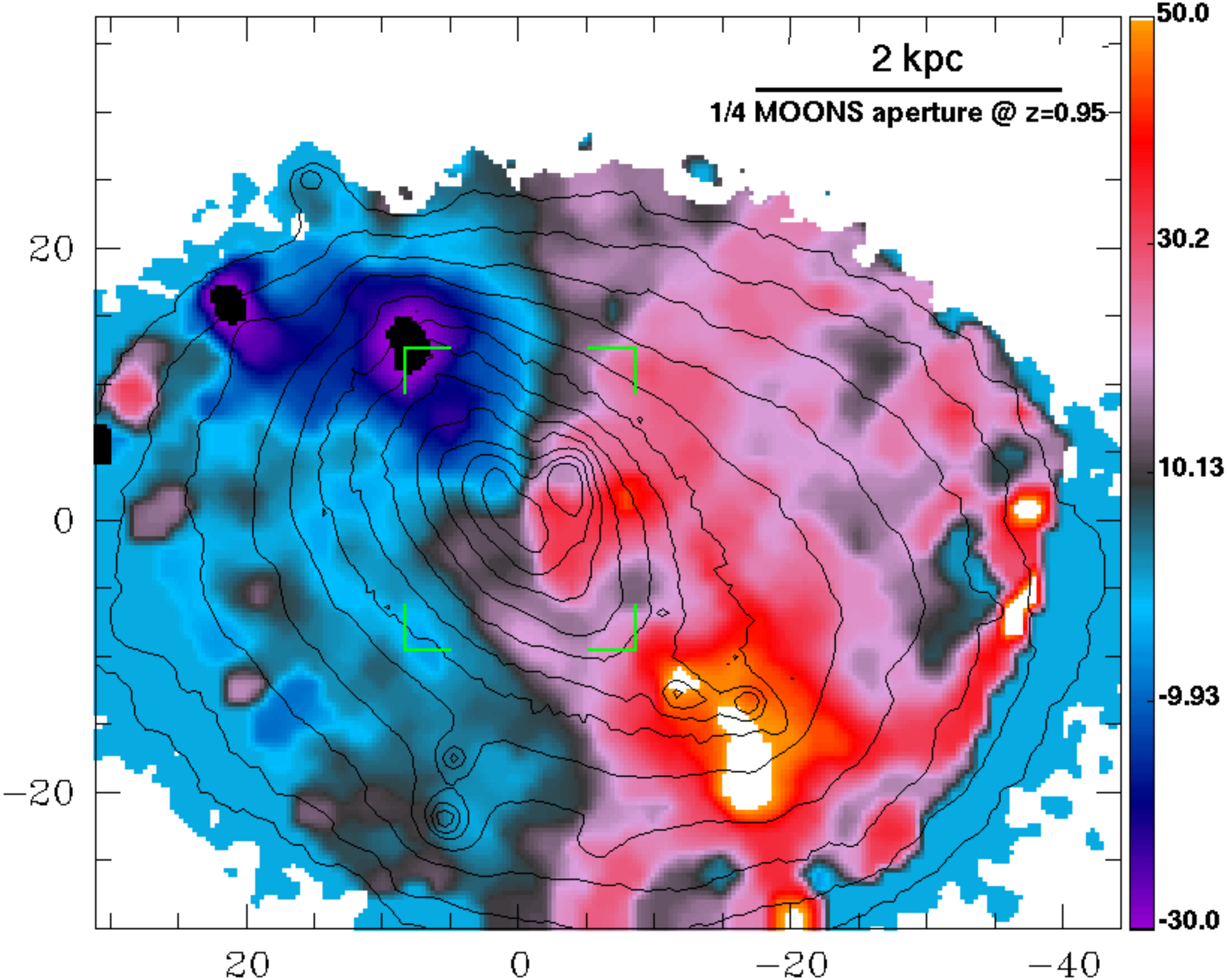
REGION 1	REGION 2	REGION 3	Integrated
EW~345 Å	EW~188Å	EW~120Å	EW~120Å
T_e = 9248K	T_e = 9519K	T_e = 10000K	T_e = 10000K
n_e = 114 cm^{-3}	n_e = 52 cm^{-3}	n_e = 40 cm^{-3}	n_e = 70 cm^{-3}
$\log M_{\star}$ = 8.741	$\log M_{\star}$ = 8.048	$\log M_{\star}$ = 7.558	$\log M_{\star}$ = 9.968
$\log M_{\star}$ = 8.098	$\log M_{\star}$ = 7.652	$\log M_{\star}$ = 6.969	$\log M_{\star}$ = 9.679
$\langle t_{\star}\rangle_L$ = 3.27	$\langle t_{\star}\rangle_L$ = 4.28	$\langle t_{\star}\rangle_L$ = 3.41	$\langle t_{\star}\rangle_L$ = 4.19
$\langle t_{\star}\rangle_L$ = 0.43	$\langle t_{\star}\rangle_L$ = 0.89	$\langle t_{\star}\rangle_L$ = 0.52	$\langle t_{\star}\rangle_L$ = 2.18
$\langle t_{\star}\rangle_M$ = 11.43	$\langle t_{\star}\rangle_M$ = 11.35	$\langle t_{\star}\rangle_M$ = 13.66	$\langle t_{\star}\rangle_M$ = 10.49
$\langle t_{\star}\rangle_M$ = 1.438	$\langle t_{\star}\rangle_M$ = 3.738	$\langle t_{\star}\rangle_M$ = 1.173	$\langle t_{\star}\rangle_M$ = 7.525

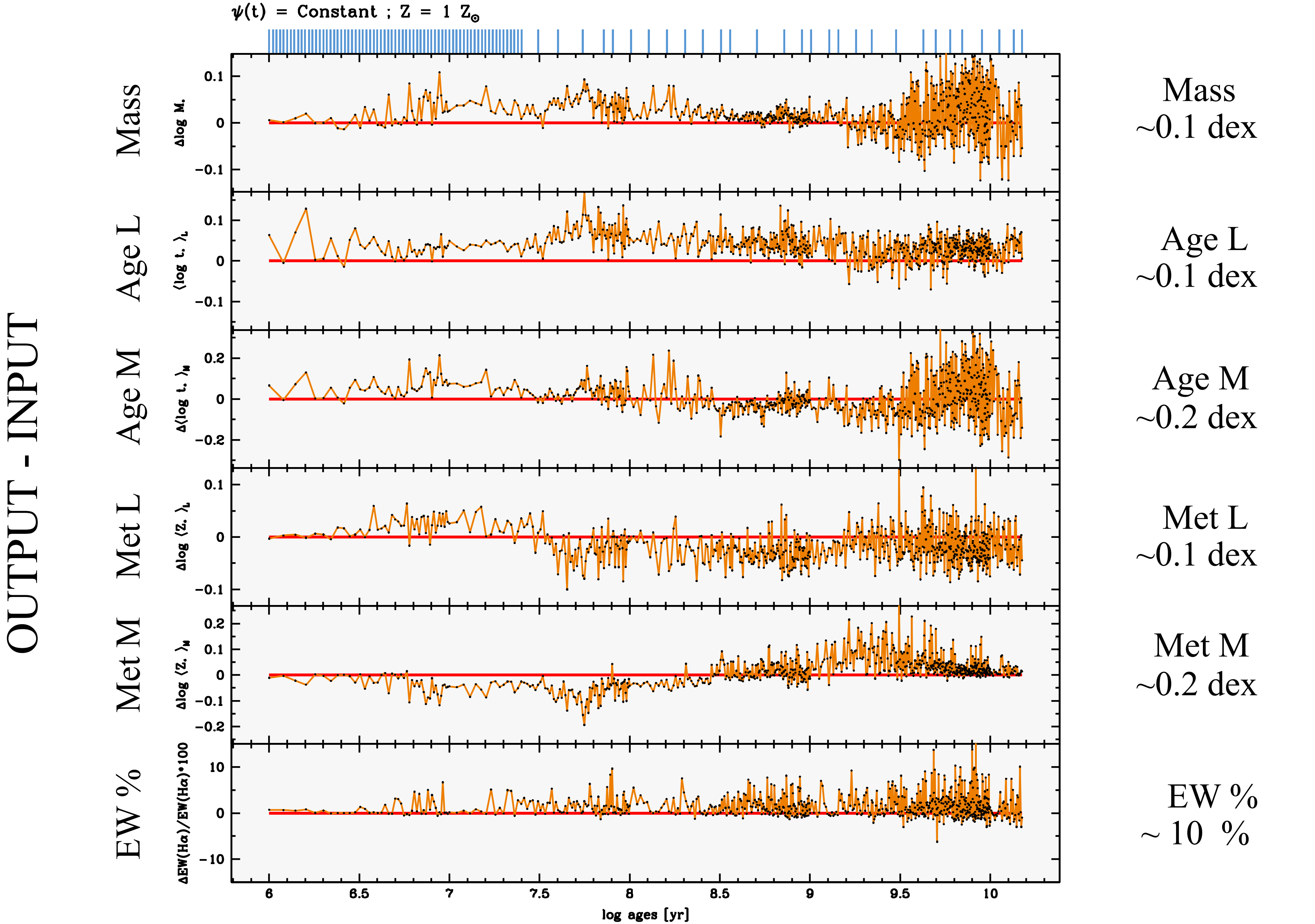
Purely stellar fitting biases

4. Final Remarks

Fitting Analysis using Differential evolution Optimization

- Examples representative of the peak of the cosmic SFR;
- Non-cospatiallity shown in IFU data for MRK 35, care with self-consistent modeling;
- Predicted overestimation of the stellar masses confirmed on real data when using purely stellar models (MRK 35);
- Overestimation of the mean stellar ages when using purely stellar models;


2 kpc
1/4 MOONS aperture @ z=0.95
50.0
30.2
10.13
-9.93
-30.0
20
0
−20
20
0
−20
−40


ψ(t) = Constant ; Z = 1 Z⊙
OUTPUT - INPUT
Mass
Age L
Age M
Met L
Met M
EW %
Δlog M*
⟨log t*⟩L
Δ⟨log t*⟩M
Δlog ⟨Z*⟩L
Δlog ⟨Z*⟩M
ΔEW(Hα)/EW(Hα)*100
log ages [yr]
Mass
~0.1 dex
Age L
~0.1 dex
Age M
~0.2 dex
Met L
~0.1 dex
Met M
~0.2 dex
EW %
~ 10 %