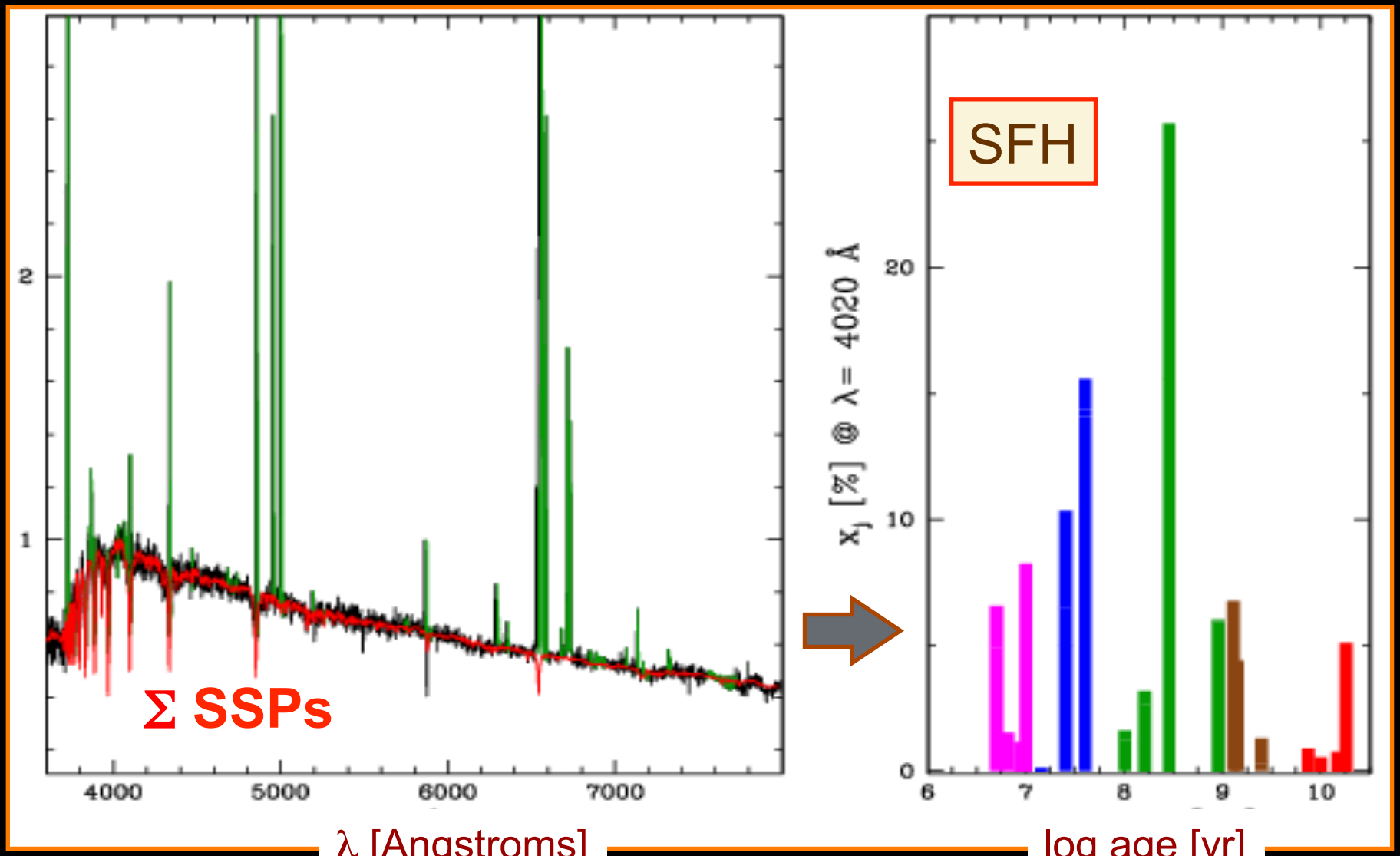
20 years of spectral synthesis (w/STARLIGHT) from 2004 to ~ 2024

Roberto Cid Fernandes – UFSC



OUTLINE

Old stuff / Review:

+ Spectral synthesis & STARLIGHT in ~ 10 slides
+ Things we've done with it: SDSS, CALIFA, ...

New stuff: More constraints

- ☑ Fit photometry: GALEX, 2MASS, …
- ☑ Fit Hα, Hβ, Hα/Hβ, … ➔ Differential extinction
- ☑ ~~Fit dust-reprocessed (FIR) luminosity~~

Why? More realistic / interesting modelling of galaxies ☺

Spectral Synthesis: Basic Recipe

- Computing a galaxy spectrum

IMF & SFH

$$L_{gal}(\lambda) = \sum_{*} L_{*}(\lambda) = \sum_{m,t,Z} N_{*}(m,t,Z)\ L_{*}(\lambda\ ;\ m,t,Z)$$

Galaxy spectrum

Sum over each star

Sum over m, t & Z's

Stellar spectrum as a function of m, t & Z

Spectral Synthesis: Basic Recipe

• Computing a galaxy spectrum

IMF & SFH

$$L_{gal}(\lambda) = \sum_{*} L_{*}(\lambda) = \sum_{m,t,Z} N_{*}(m,t,Z)\ L_{*}(\lambda\ ;\ m,t,Z)$$

Galaxy spectrum

Sum over each star

Sum over m, t & Z's

Stellar spectrum as a function of m, t & Z

• Simple Stellar Population: integrate over mass function

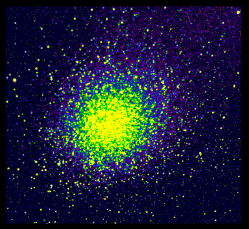
$$\sum_{m} N_{*}(m,t,Z)\ L_{*}(\lambda\ ;\ m,t,Z) = M_{SSP}(t,Z)\ \Lambda_{SSP}(\lambda\ ;\ t,Z)$$

Spectrum of an SSP(t,Z)

Spectral Synthesis: Basic Recipe


= M_1

+ M_2

+ M_3

+ ⋯

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \; \Lambda_{SSP}(\lambda ; t,Z)$$

Mass in populations of age t and metallicity Z
[M_o]

Spectrum of a SSP(t,Z) per unit stellar mass
[L_o / Å / M_o]

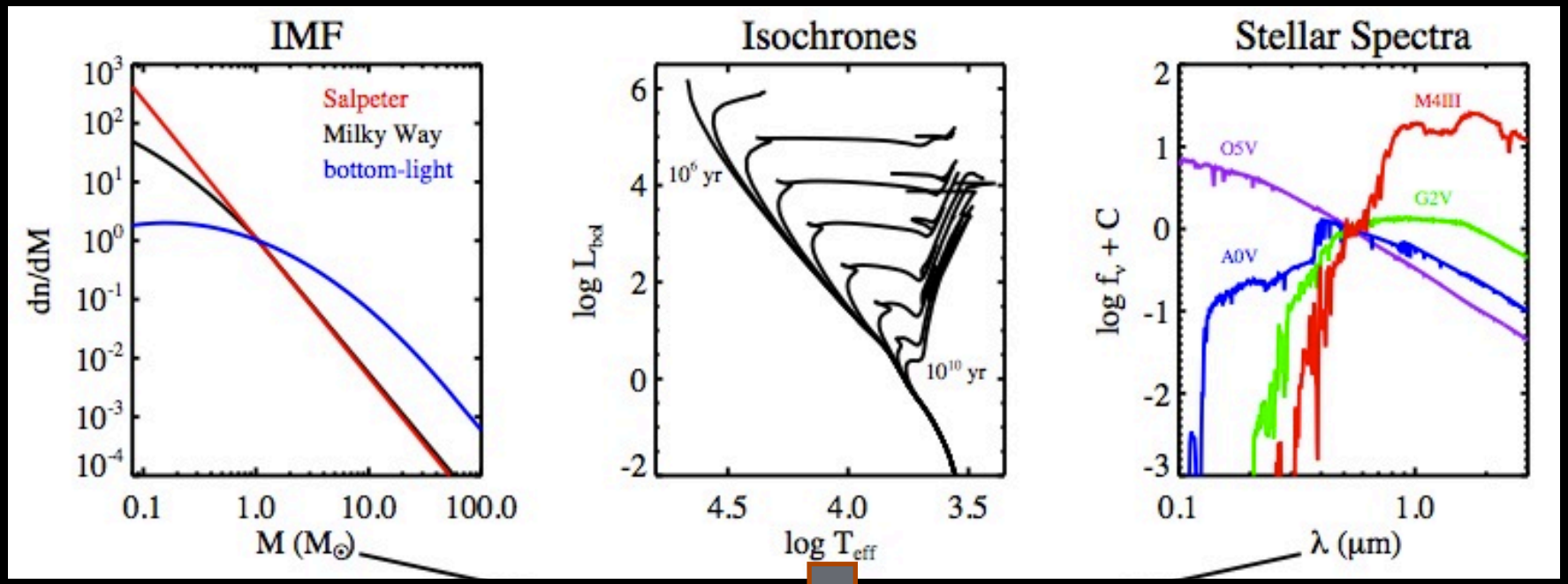
Star Formation History

= What we want to find!
(obs: non-parametric)

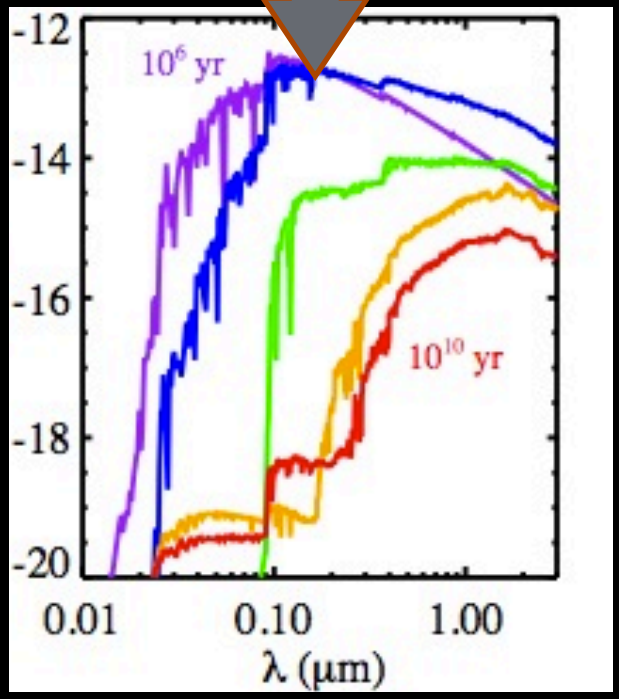
Spectral Base

Known from SSP-models
☺

SSP spectra: HOWTO



$\Lambda_{SSP}(\lambda ; t,Z)$



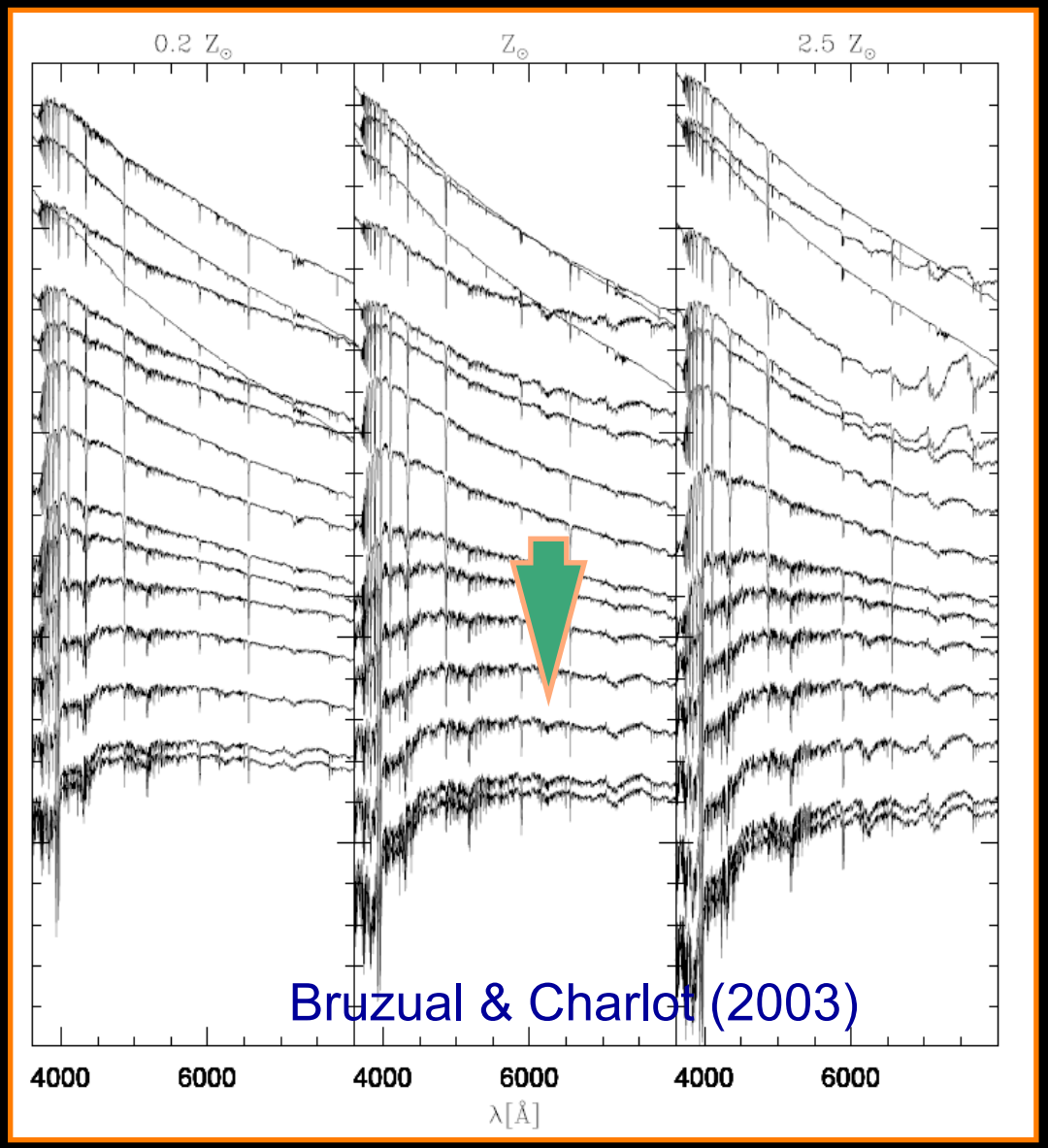
Critical ingredient!

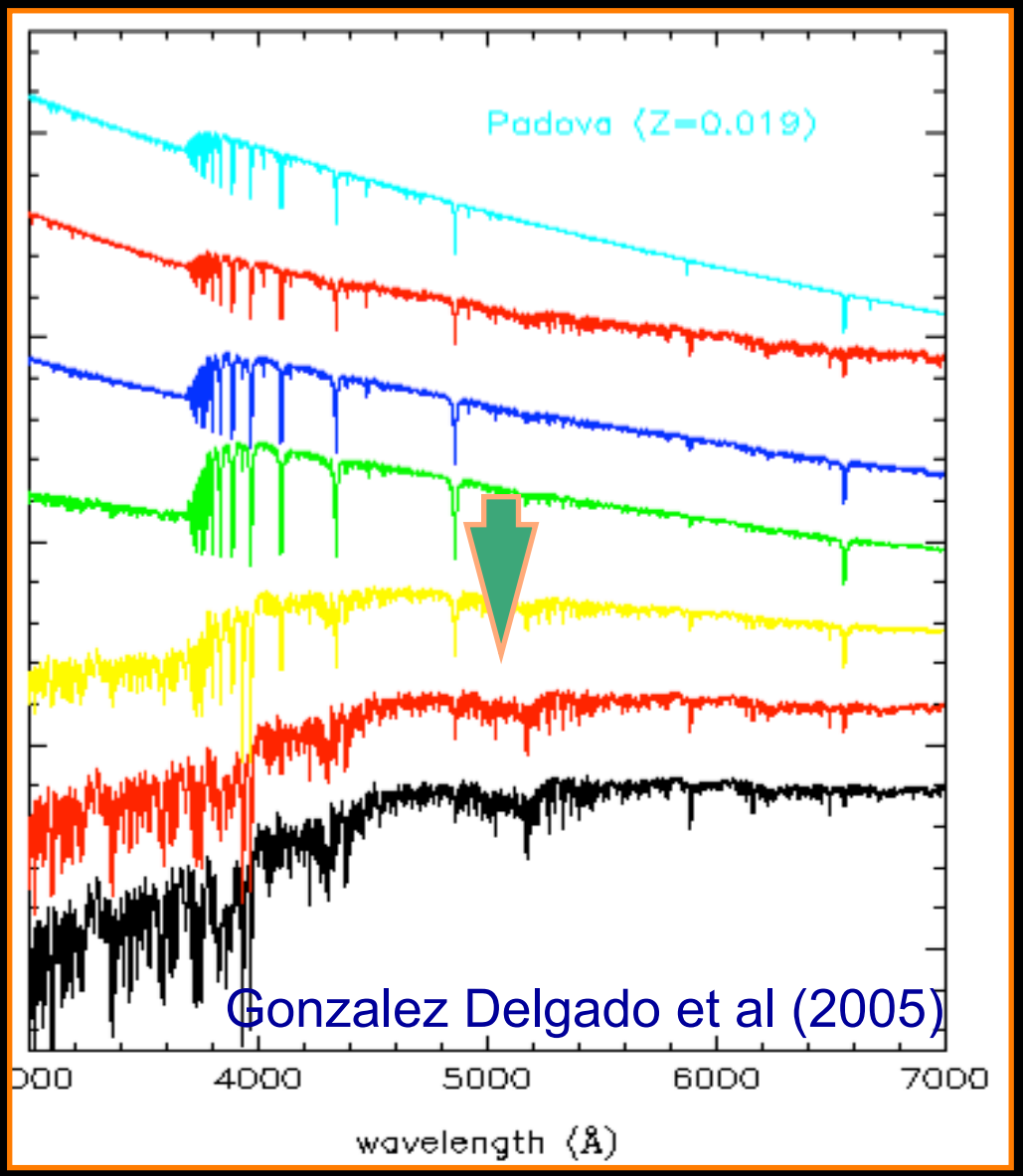
The dictionary which translates light to mass, age & Z

Conroy 2013

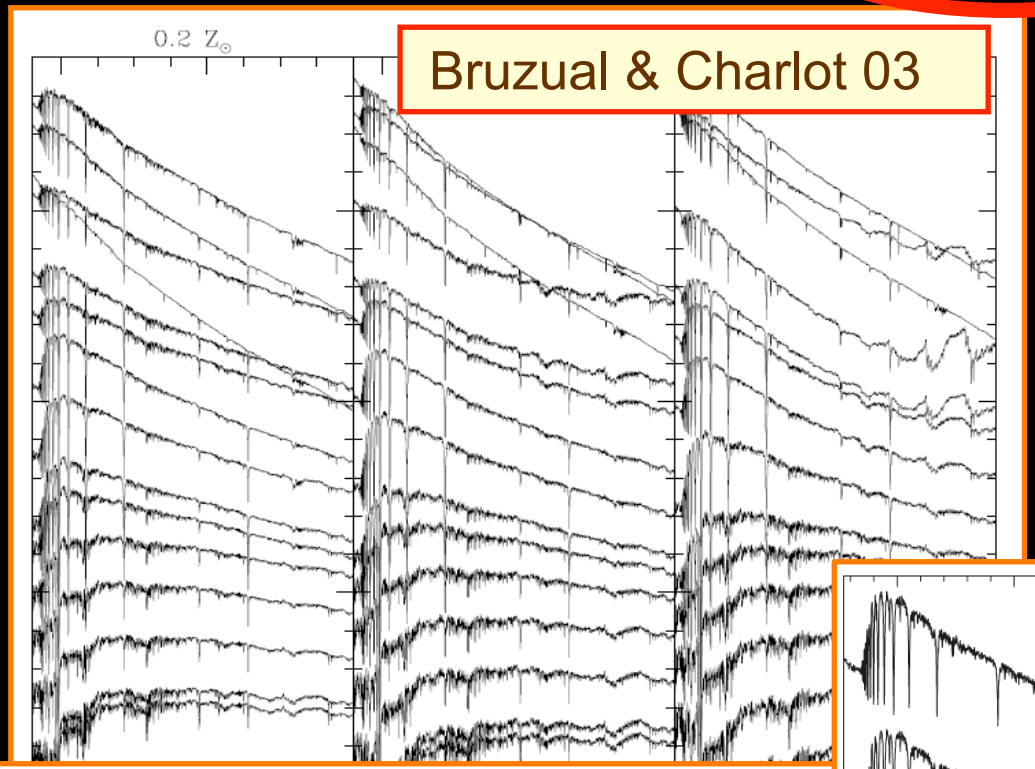
SSP spectra

Stellar Evolution + IMF + Libraries (+ tricks) = $\Lambda_{SSP}(\lambda ; t,Z)$ $[L_o/Å/M_o]$

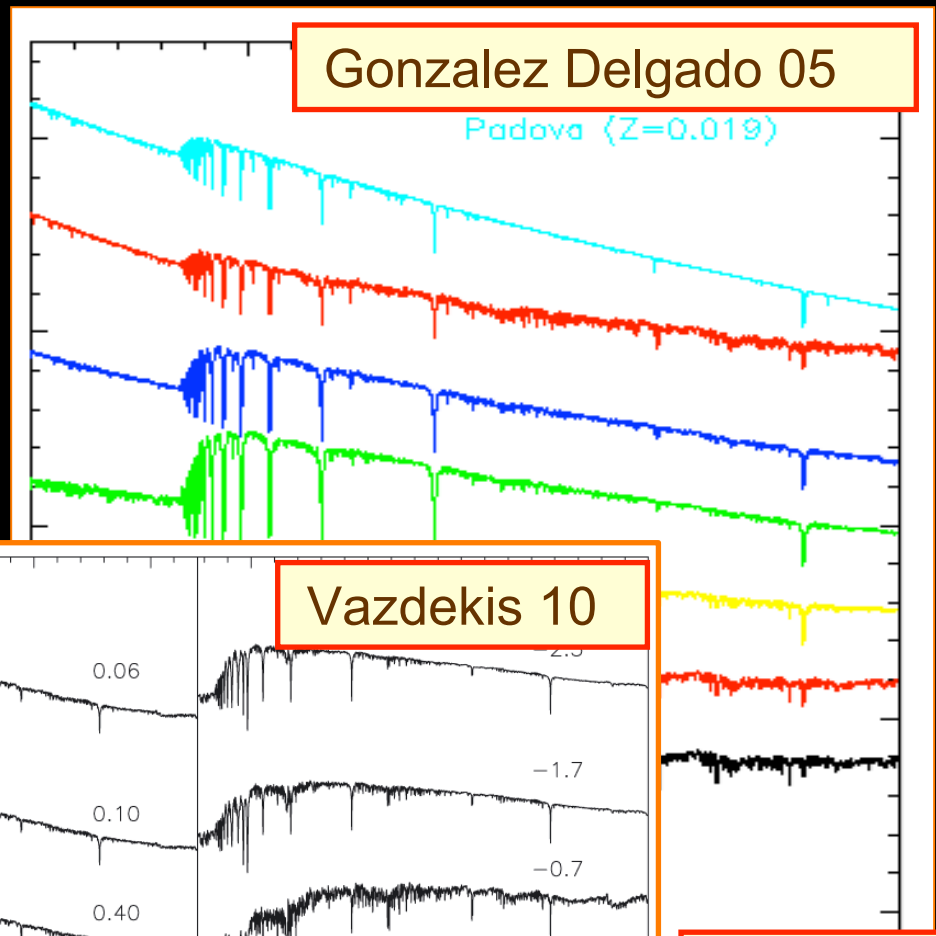




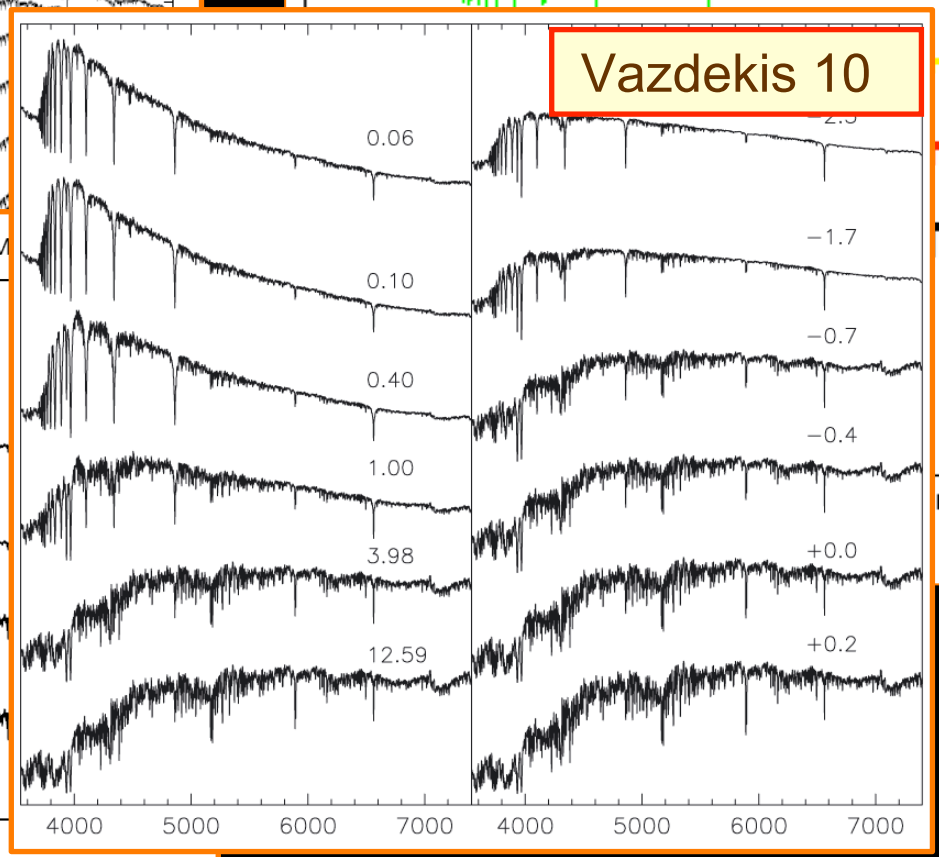
The main ingredient: SSP(λ;t,Z) ← evolutionary synthesis



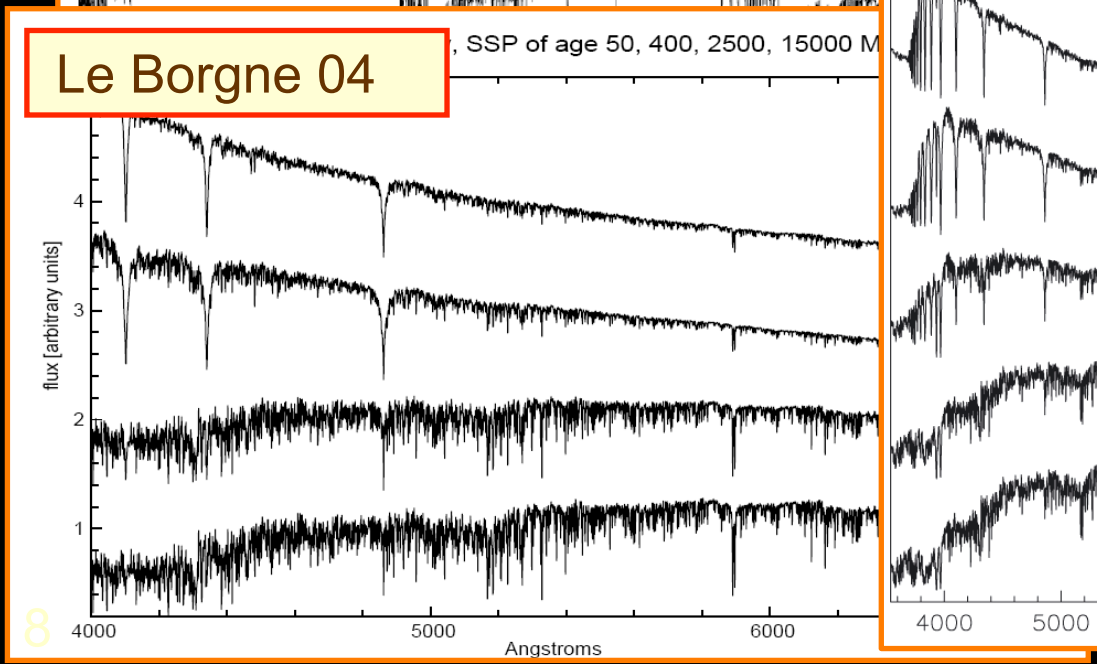
Bruzual & Charlot 03



Gonzalez Delgado 05



Vazdekis 10



Le Borgne 04

¿CB07?
¿CB08?
¿CB09?
…
¿CB16?
…

→ SFH(t,Z): 2 approaches

SFH → $L_{gal}(\lambda)$

Given a SFH, what is the resulting galaxy spectrum?

Evolutionary Population Synthesis

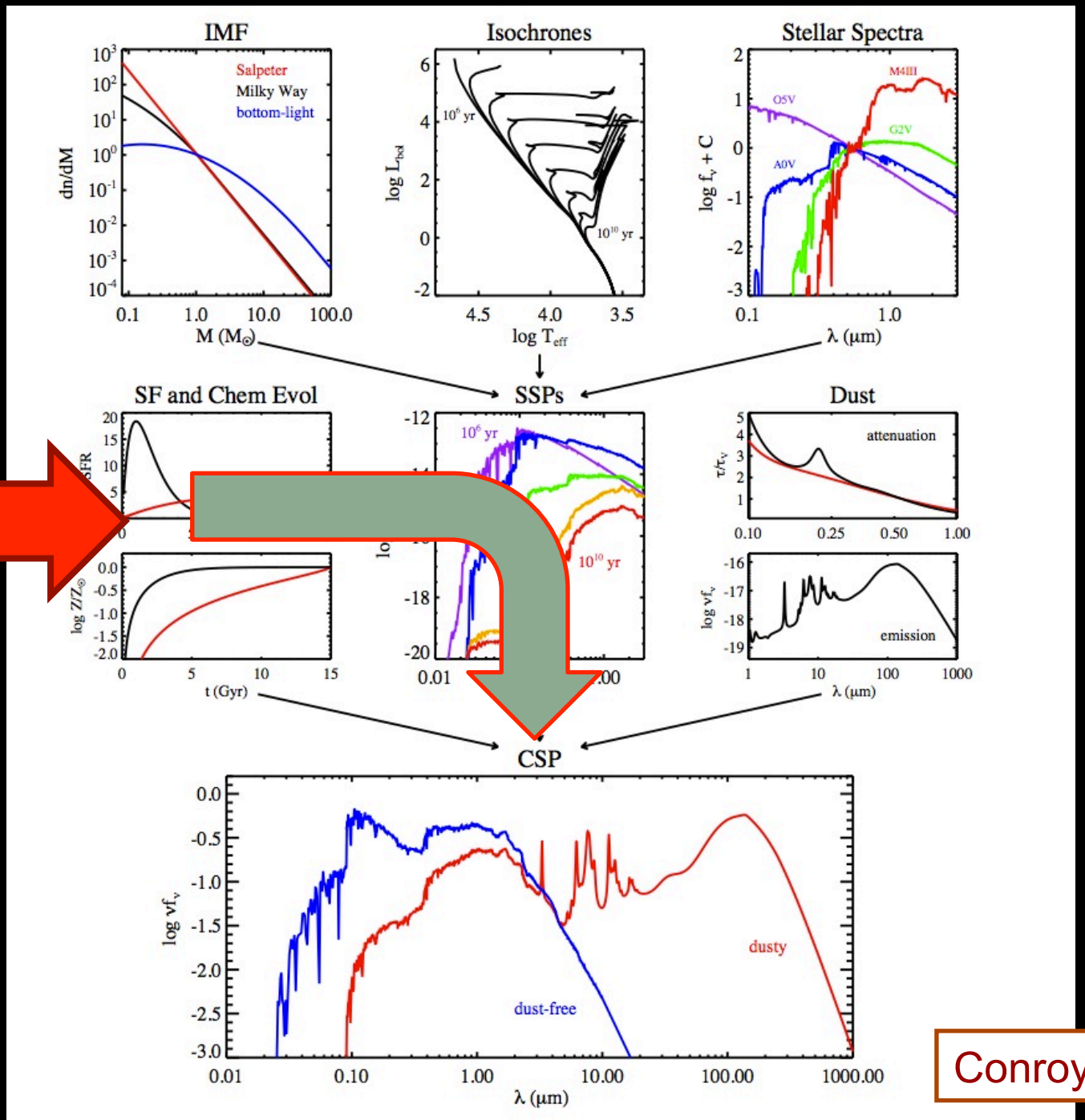
$L_{gal}(\lambda)$ → SFH

Given a galaxy spectrum, what is the SFH?

Inverse Population Synthesis

Forward spectral synthesis

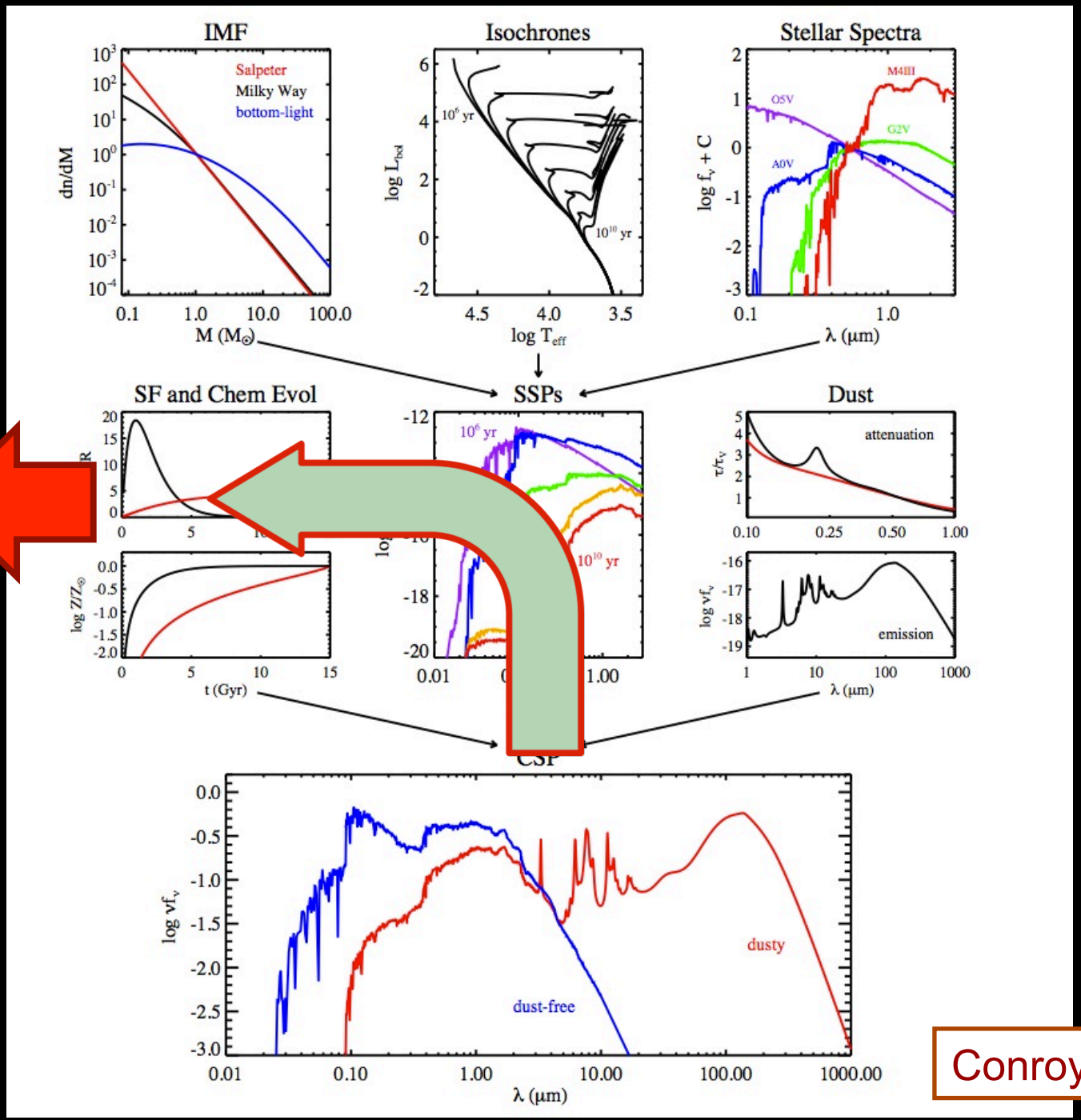
ASSUME
Star Formation History



Conroy 2013

Inverse spectral synthesis

DERIVE
Star
Formation
History



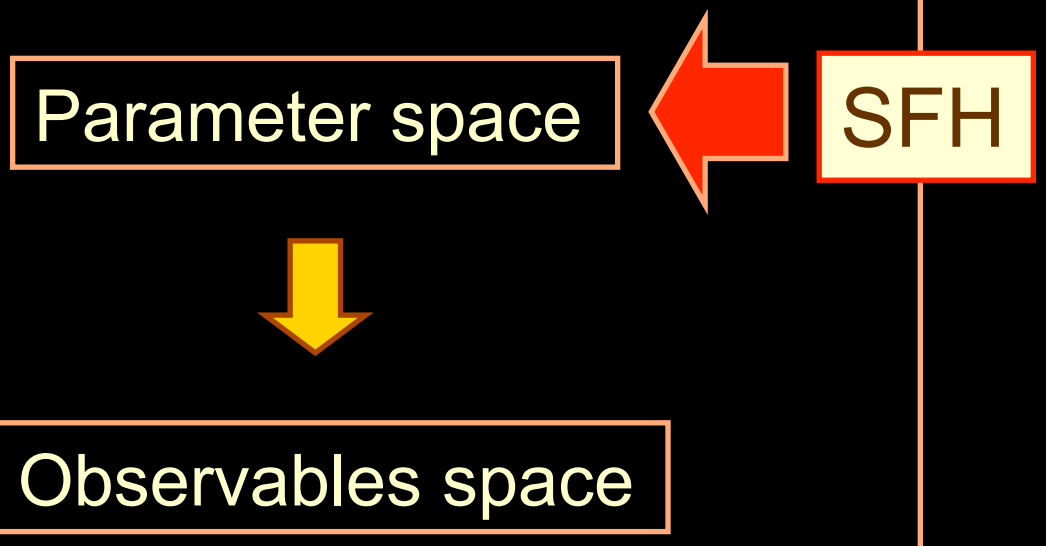
Conroy 2013

→ SFH(t,Z): 2 approaches

Evolutionary Pop Synthesis

= Forward Modeling
Predict spectra(t,Z,...)
Ab initio calculation of

$L_{gal}(\lambda \mid \text{SFH parameters})$



→ SFH(t,Z): 2 approaches

Evolutionary Pop Synthesis

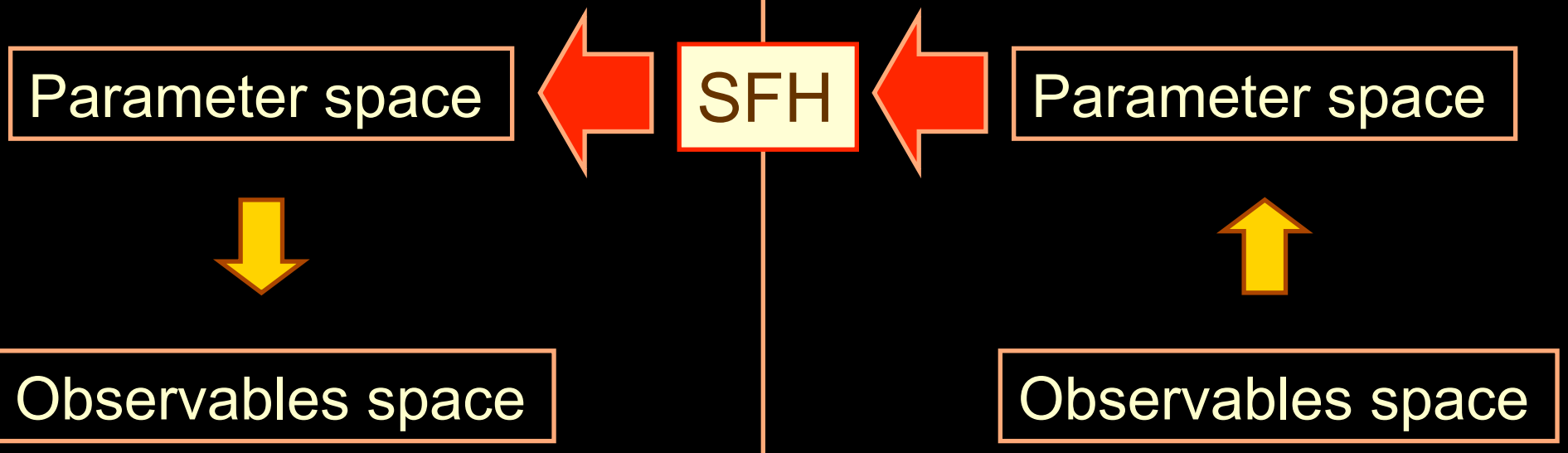
= Forward Modeling
Predict spectra(t,Z,...)
Ab initio calculation of

$L_{gal}(\lambda \mid \text{SFH parameters})$

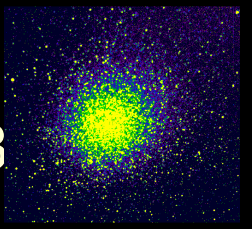
Inverse Pop Synthesis

= "Paleontology"
"Reverse engineering"
"Fossil Method"

Infer population parameters from an observed $L_{gal}(\lambda)$

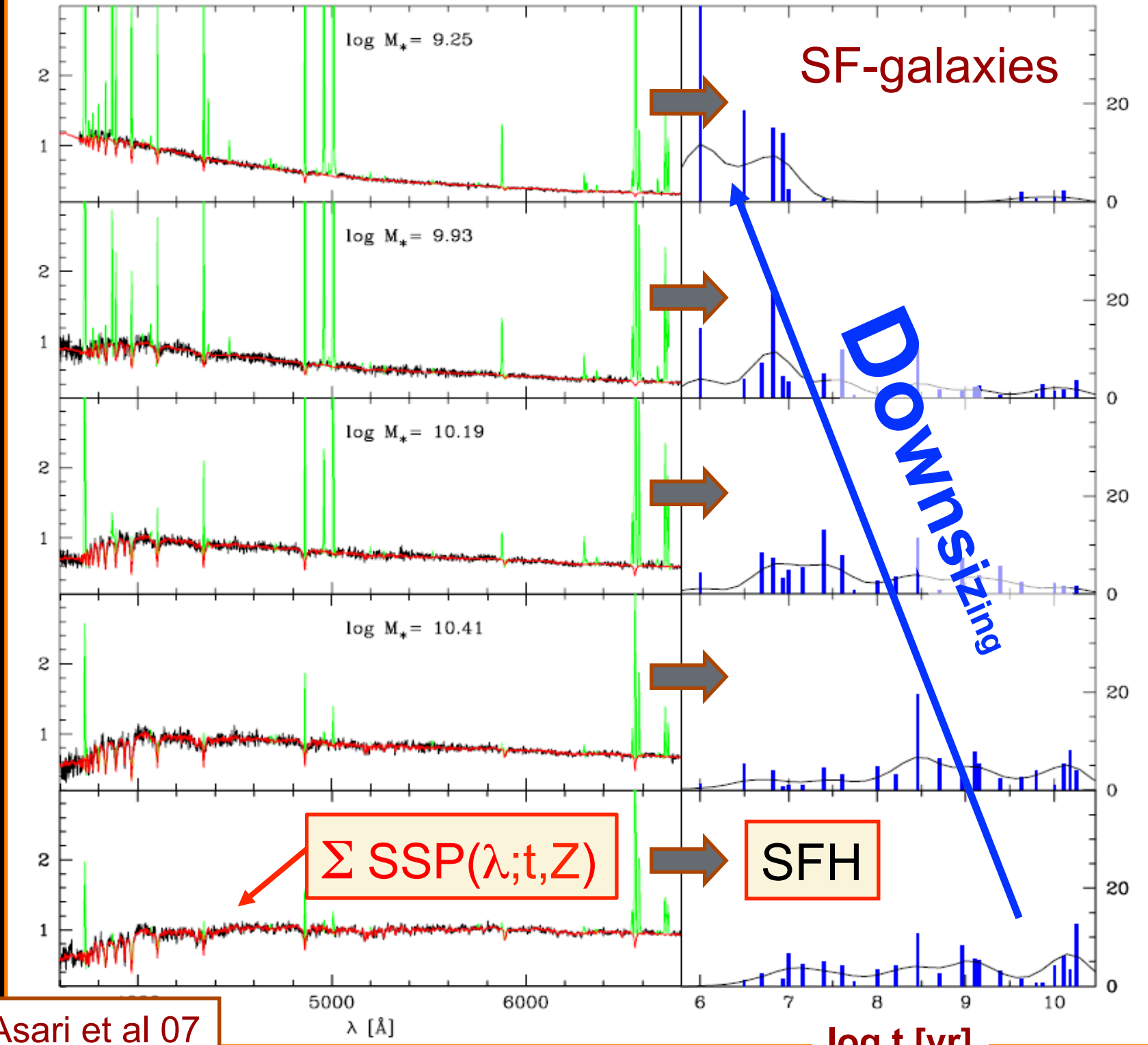


STARLIGHT: non-parametric spectral decomposition

$= M_1$  $+ M_2$  $+ M_3$  $+ \ldots$

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times \Lambda(\lambda;t,Z) \times e^{-\tau(\lambda)}$$

Observables Full spectrum	***SFH: mass or light fractions*** ➔ ***Pop Vector***	***Spectral Base*** SSPs from BC03, Granada, "CB07", Vazdekis, ...	***Dust*** ...



Asari et al 07

STARLIGHT: non-parametric spectral decomposition

Mon. Not. R. Astron. Soc. **355,** 273–296 (2004) doi:10.1111/j.1365-2966.2004.08321.x

The star formation history of Seyfert 2 nuclei

R. Cid Fernandes,[1⋆] Q. Gu,[2⋆] J. Melnick,[3⋆] E. Terlevich,[4⋆†] R. Terlevich,[4⋆†] D. Kunth,[5⋆] R. Rodrigues Lacerda[1⋆] and B. Joguet[5]

[1] *Departamento de Física, CFM, Universidade Federal de Santa Catarina, PO Box 476, Florianópolis 88040-900, SC, Brazil*
[2] *Department of Astronomy, Nanjing University, Nanjing 210093, China*
[3] *European Southern Observatory, Alonso de Cordova 3107, Santiago, Chile*
[4] *Instituto Nacional de Astrofisica, Optica y Electrònica, Tonantzintla, Puebla, México*
[5] *Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France*

Mon. Not. R. Astron. Soc. **358,** 363–378 (2005) doi:10.1111/j.1365-2966.2005.08752.x

Semi-empirical analysis of Sloan Digital Sky Survey galaxies – I. Spectral synthesis method

Roberto Cid Fernandes,[1⋆] Abílio Mateus,[2⋆] Laerte Sodré, Jr,[2⋆] Grażyna Stasińska[3⋆] and Jean M. Gomes[1⋆]

[1] *Departamento de Física, CFM, Universidade Federal de Santa Catarina, PO Box 476, 88040-900 Florianópolis, SC, Brazil*
[2] *Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, SP, Brazil*
[3] *LUTH, Observatoire de Meudon, 92195 Meudon Cedex, France*

- MOPED

The Complete Star Formation History of the Universe

Alan Heavens, Benjamin Panter, Raul Jimenez, James Dunlop

- VESPA

Recovering galaxy star formation and metallicity histories from spectra using VESPA

Rita Tojeiro (IfA, Edinburgh), Alan F. Heavens (IfA, Edinburgh), Raul Jimenez (UPenn), Ben Panter (IfA, Edinburgh)

- STECKMAP

STEllar Content and Kinematics from high resolution galactic spectra via Maximum A Posteriori

P. Ocvirk (1), C. Pichon (2), A. Lancon (1), E. Thiebaut (3) ((1) Observatoire Astronomique de Strasbourg, (2) Institut d'Astrophysique de Paris, (3) Observatoire de Lyon)

- ULySS

Spectroscopic ages and metallicities of stellar populations: validation of full spectrum fitting

M. Koleva, Ph. Prugniel, P. Ocvirk, D. Le Borgne, C. Soubiran

- STARLIGHT

Semi-empirical analysis of SDSS galaxies: I. Spectral synthesis method

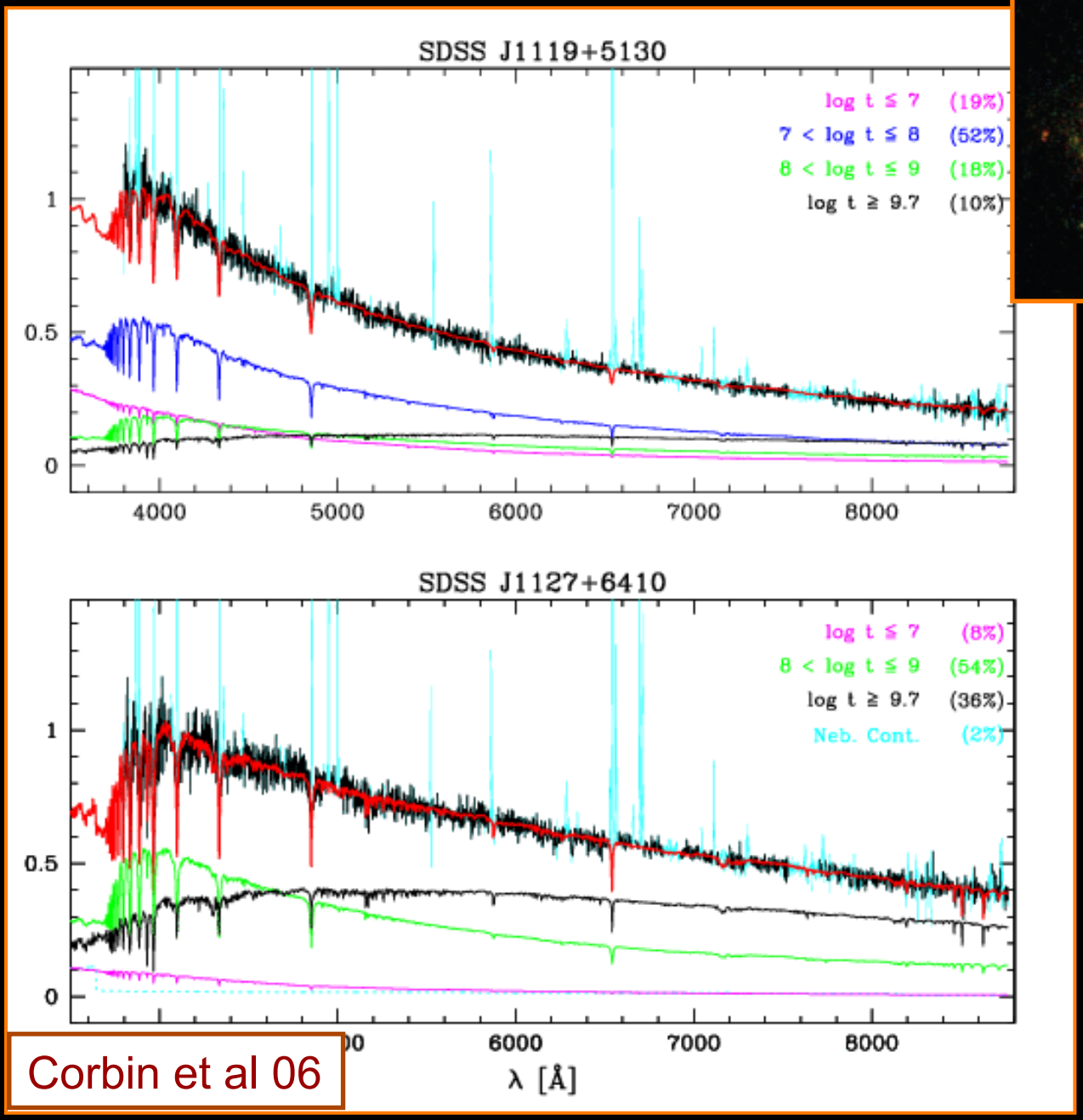
R. Cid Fernandes (1), A. Mateus (2), L. Sodre (2), G. Stasinska (3), J. M. Gomes (1) ((1) Universidade Federal de Santa Catarina, Brazil; (2) IAG/USP, Brazil; (3) LUTH, Observatoire de Meudon, France)

- pPXF

The Atlas3D Project – XXX. Star formation histories and stellar population scaling relations of early-type galaxies

Richard M. McDermid, Katherine Alatalo, Leo Blitz, Frederic Bournaud, Martin Bureau, Michele Cappellari, Alison F. Crocker, Roger L. Davies, Timothy A. Davis, P. T. de Zeeuw, Pierre-Alain Duc, Eric Emsellem, Sadegh Khochfar, Davor Krajnovic, Harald Kuntschner, Raffaella Morganti, Thorsten Naab, Tom Oosterloo, Marc Sarzi, Nicholas Scott, Paolo Serra, Anne-Marie Weijmans, Lisa M. Young

Ultra Compact Blue Dwarf Galaxies



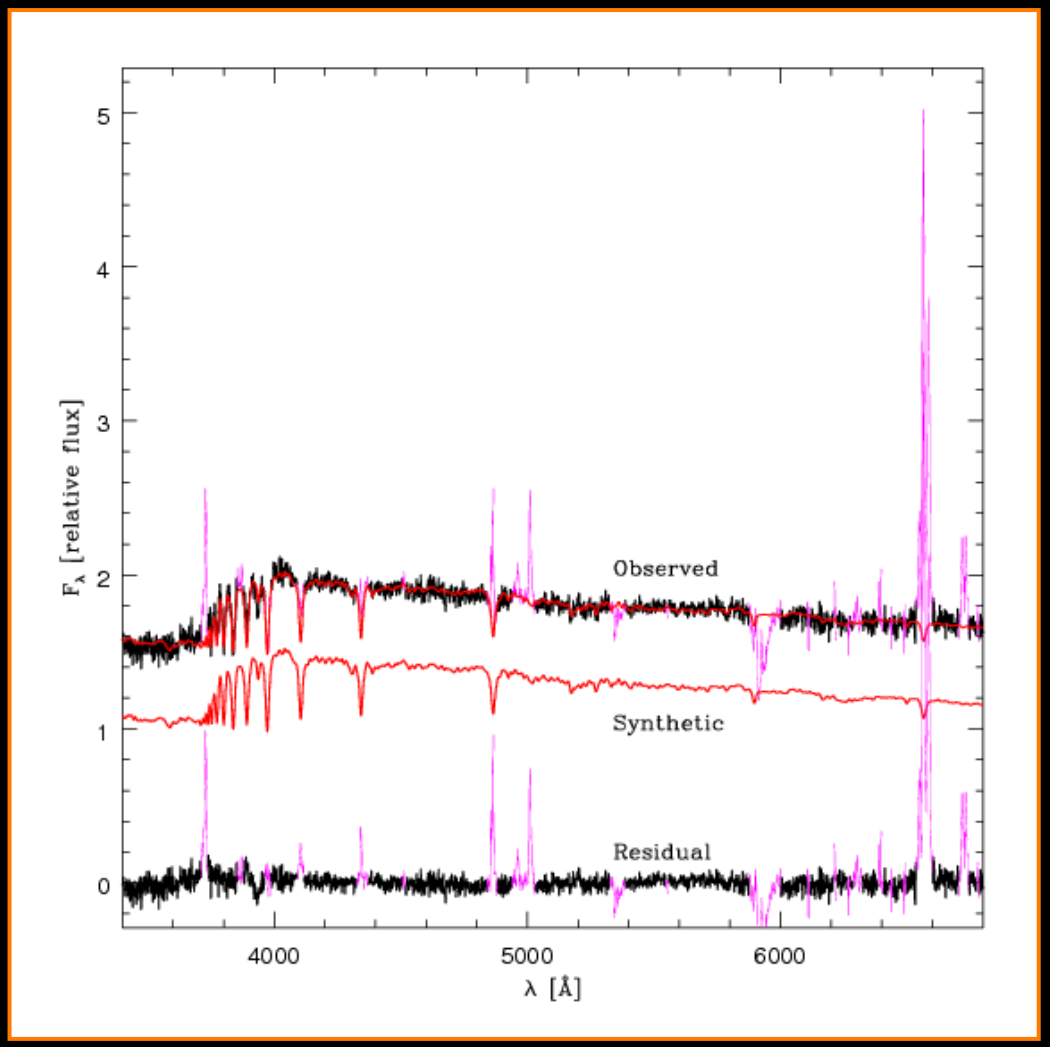
Corbin et al 06

Spectral Base:

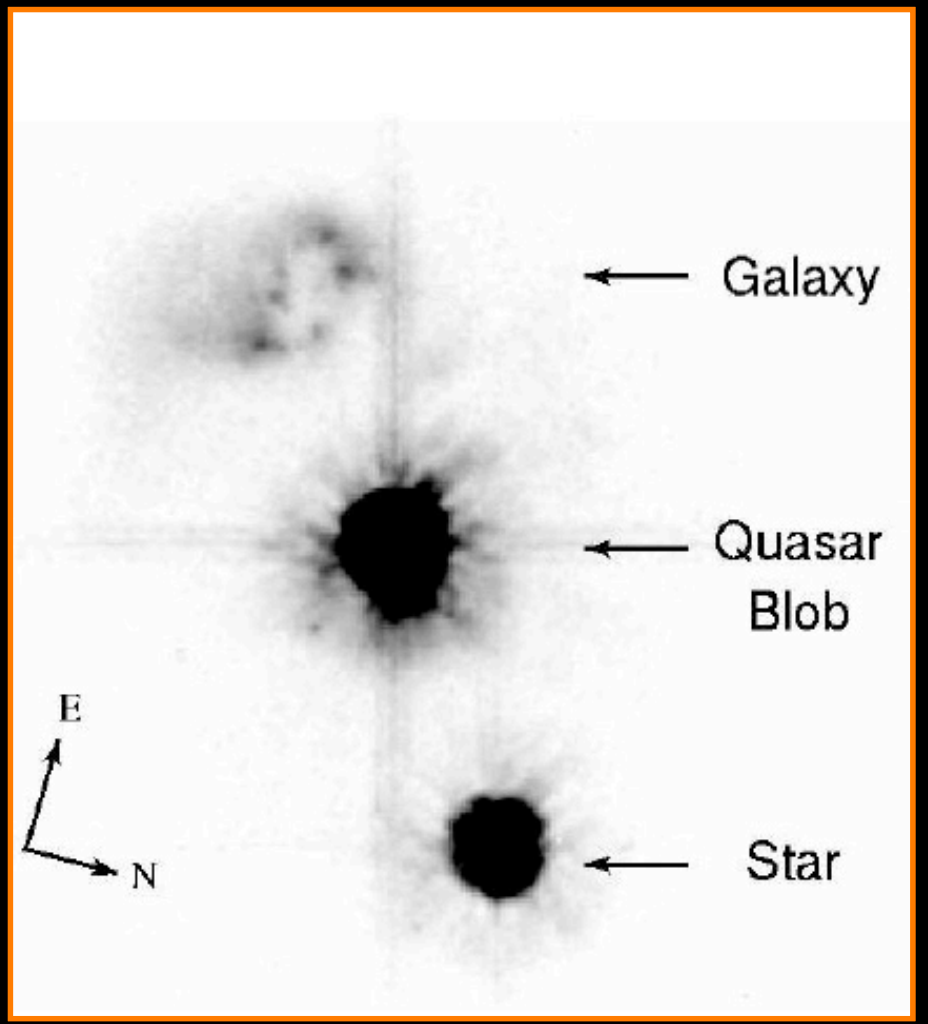
- 25 ages
- Z_0 / 50 SSPs !!
- Nebular Continuum
- SMC extinction curve

A weird galaxy next to the “naked” quasar

HE0450-2958: The (in)famous “homeless” quasar

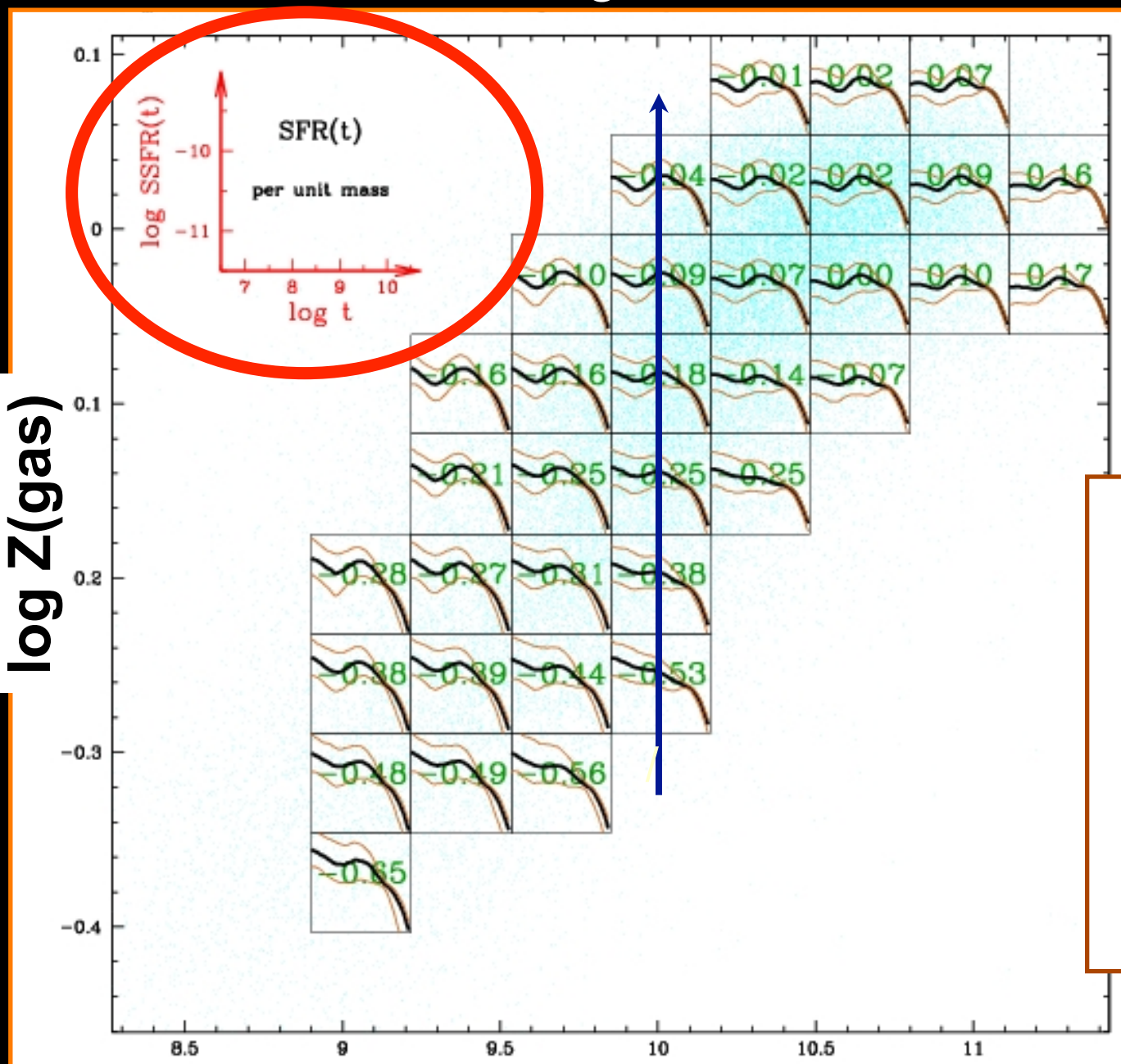


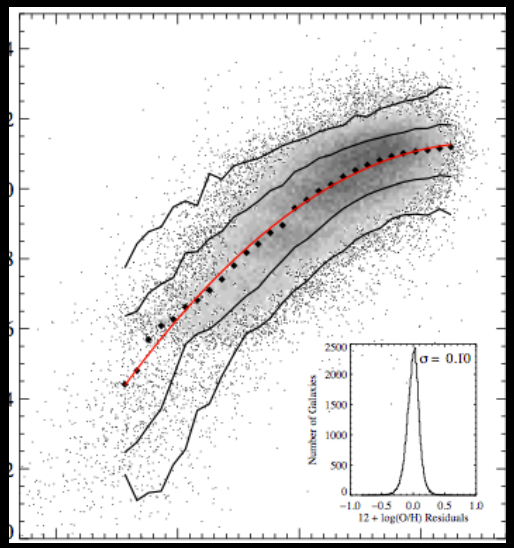
Merrit et al 06



Magain et al 06

The M_*–Z_{gas}–SFH relation





the currently fashionable "Fundamental" M-Z-SFR relation…

Mannucci 10
Lara López 10
Yates 12
…

Never Published et al 07

NaD "excess" ➔ cold ISM ➔ dust

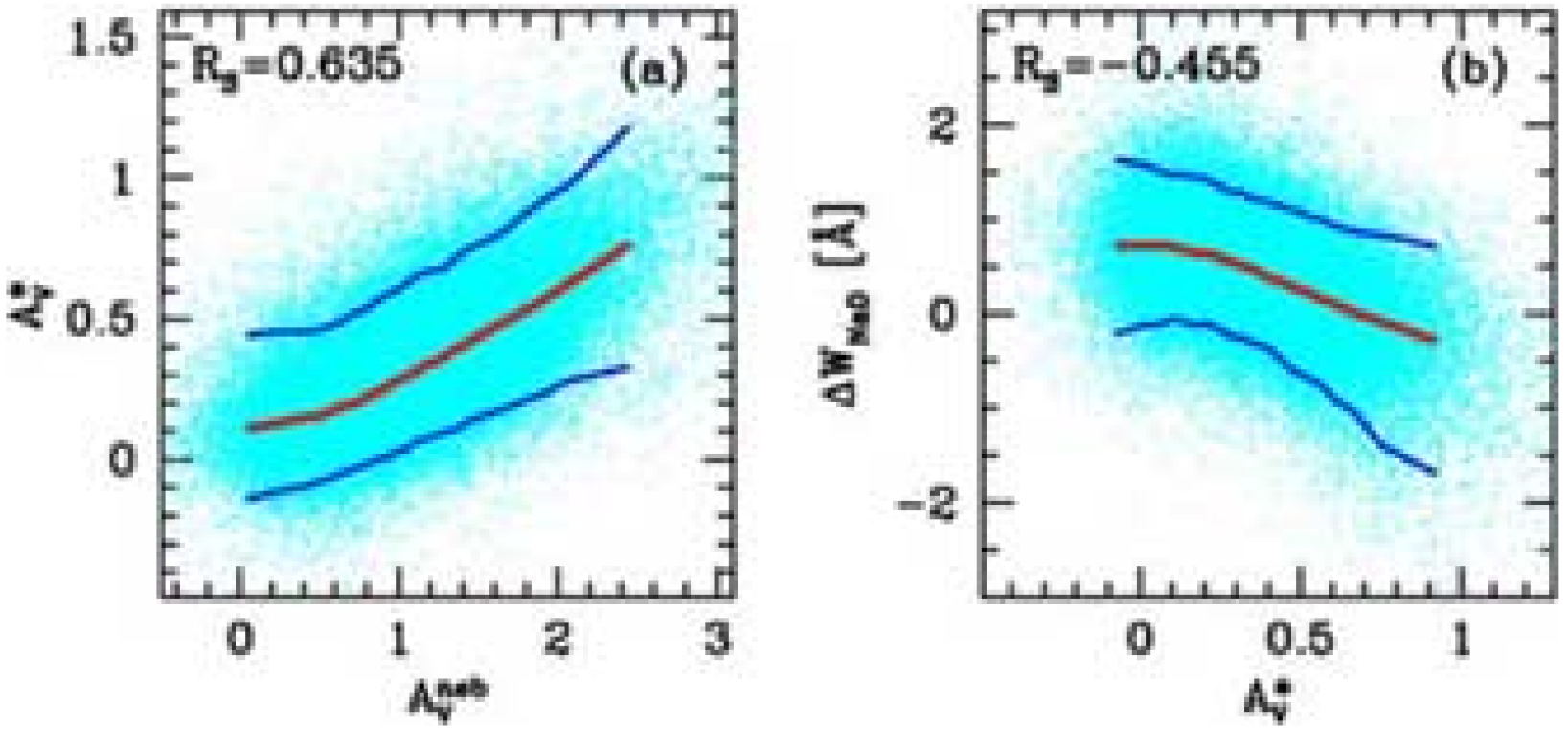


Figure 4. (a) Relation between stellar and nebular extinctions for the SF sample. Lines indicate the 5, 50 and 95 percentiles. (b) Equivalent width of the ISM component of the Na D doublet (as measured from residual spectra) against the stellar extinction.

Asari et al 07

CasJobs

http://casjobs.starlight.ufsc.br/casjobs/submitjob.aspx?resubmit=true&taskname=My+Query&targest=starlight_

Apple (128) Amazon eBay Yahoo! News (1224)

Starlight Spectral Synthesis Code SEAGal CASJOBS

Schema Query History MyDB Import Output Profile Queues Logout

Context: starlight_DR7 | Table (optional): MyTable_9 | Task Name: My Query

Samples Recent Clear Line 1, Col 1

```
select (log(F_5007)/log(F_4861)) as O3Hb, (log(F_6584)/log(F_6563)) as N2Ha into mydb.MyTable_5 from (select t5
                    t4861.flux as F_4861, t4861.sn as SN_4861,
                    t6563.flux as F_6563, t6563.sn as SN_6563,
                    t6584.flux as F_6584, t6584.sn as SN_6584
   from el_fit as t5007, el_fit as t4861, el_fit as t6563, el_fit as t6584
  where t5007.id_line = 5007 and t4861.id_line = 4861 and t6563.id_line = 6563 and t6584.id_line = 6584 and
        t5007.synID = t4861.synID and t5007.synID = t6563.synID and t5007.synID = t6584.synID) as e
 where SN_5007 > 3 and SN_4861 > 3 and SN_6563 > 3 and SN_6584 > 3 and
       F_5007 > 0 and F_4861 > 0 and F_6584 > 0 and F_6563 > 0
```

Contact

$Name: v3_5_16 $,$Revision: 1.70 $, Last modified: Tuesday, January 19, 2010 at 9

A&A 473, 411–421 (2007)
DOI: 10.1051/0004-6361:20077436

Astronomy & Astrophysics

The direct oxygen abundances of metal-rich galaxies derived from electron temperature⋆

Y. C. Liang[1,2], F. Hammer[2], S. Y. Yin[1,3,4], H. Flores[2], M. Rodrigues[2], and Y. B. Yang[2,1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, PR China
e-mail: ycliang@bao.ac.cn
[2] GEPI, Observatoire de Paris-Meudon, 92195 Meudon, France
[3] Department of Physics, Hebei Normal University, Shijiazhuang 050016, PR China
[4] Department of Physics, Harbin University, Haerbin 150086, PR China

---

THE ASTROPHYSICAL JOURNAL, 695:259–267, 2009 April 10 doi:10.1088/0004-637X/695/1/259

OUTLIERS FROM THE MASS–METALLICITY RELATION. II. A SAMPLE OF MASSIVE METAL-POOR GALAXIES FROM SDSS

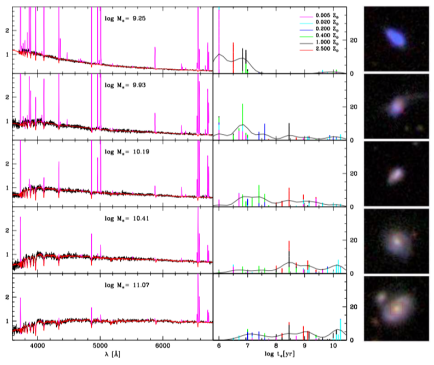
MOLLY S. PEEPLES, RICHARD W. POGGE, AND K. Z. STANEK
Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA; molly@astronomy.ohio-state.edu, pogge@astronomy.ohio-state.edu, kstanek@astronomy.ohio-state.edu
Received 2008 September 4; accepted 2009 January 13; published 2009 March 30

Spectral fitting with STARLIGHT

Roberto Cid Fernandes
Universidade Federal de Santa Catarina, Florianópolis, Brazil
April 11, 2007

Abstract

This document describes the public distribution of the STARLIGHT spectral synthesis code, version 04, available from www.starlight.ufsc.br.

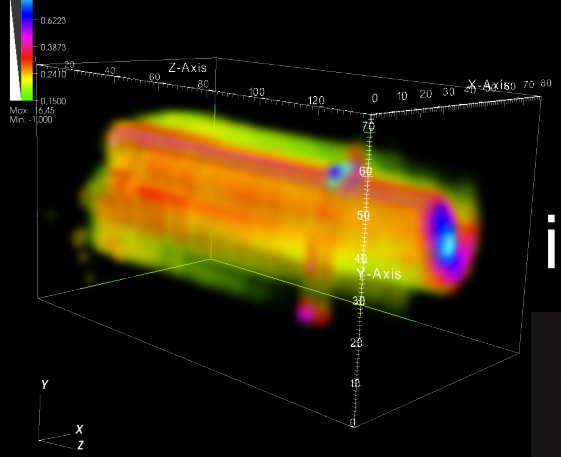


Serendipitous discovery of a strong-lensed galaxy in integral field spectroscopy from MUSE

Lluís Galbany[1⋆], Thomas E. Collett[2], Jairo Méndez-Abreu[3,4], Sebastián F. Sánchez[5], Joseph P. Anderson[6], Hanindyo Kuncarayakti[7,8].

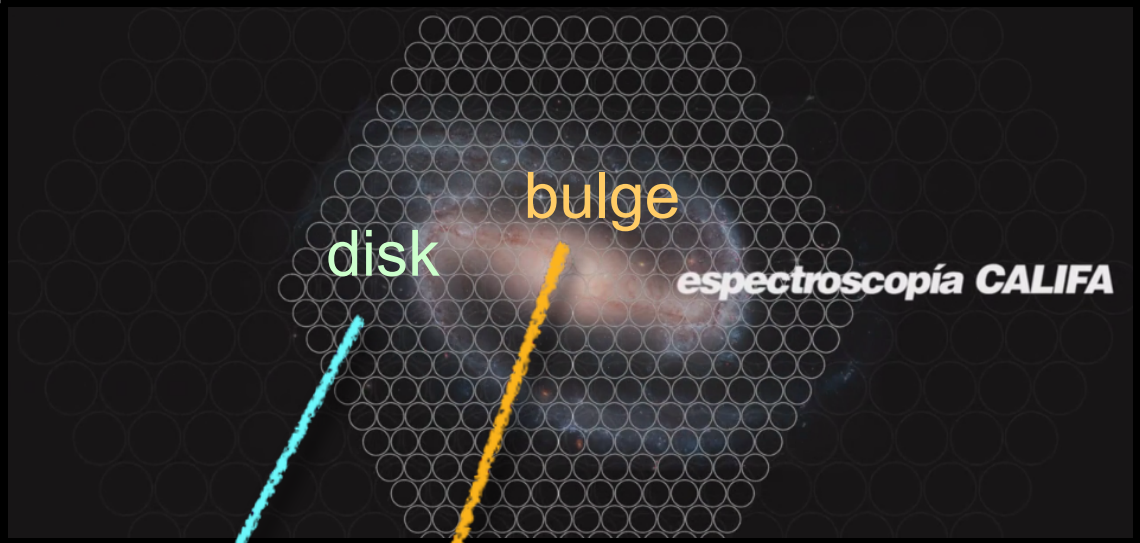
A direct test of density wave theory in a grand design spiral galaxy

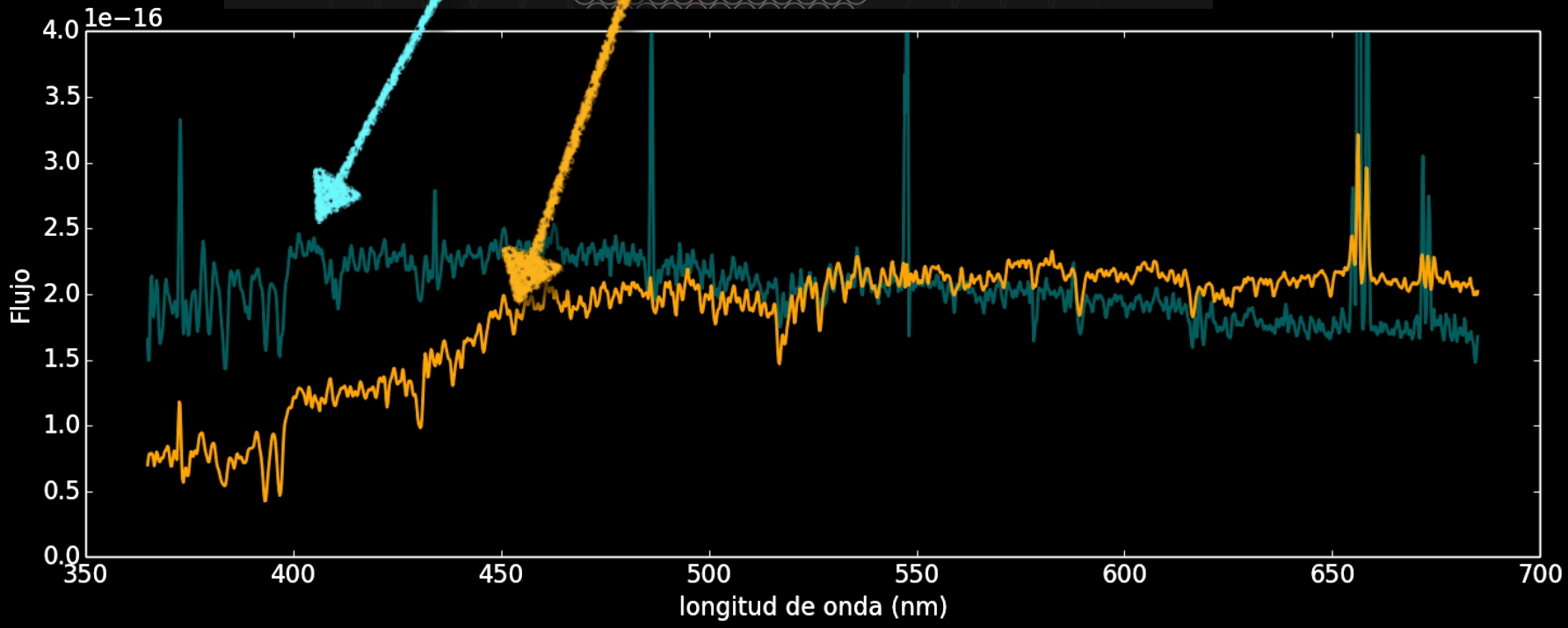
Thomas G. Peterken[1], Michael R. Merrifield[1], Alfonso Aragón-Salamanca[1], Niv Drory[2], Coleman M. Krawczyk[3], Karen L. Masters[4,3], Anne-Marie Weijmans[5], and Kyle B. Westfall[6]



Also in 3D: CALIFA

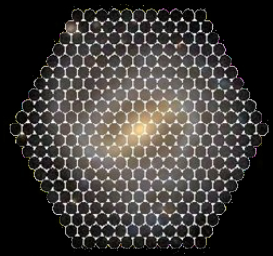
info on disk, bulge, nucleus, bar, ...

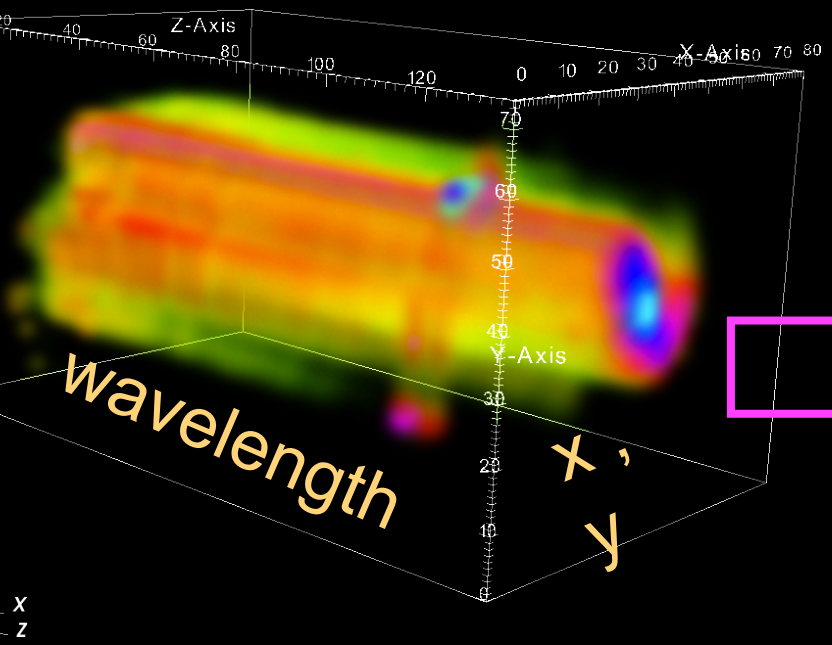




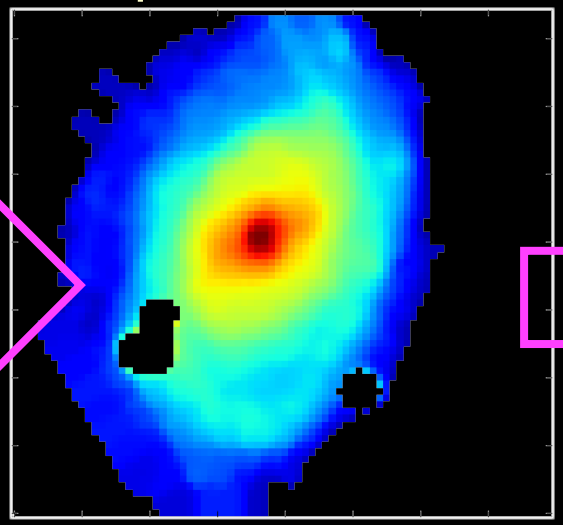
The **PyCASSO** pipeline

Python **CA**lifa **S**tarlight **S**ynthesis **O**rganizer

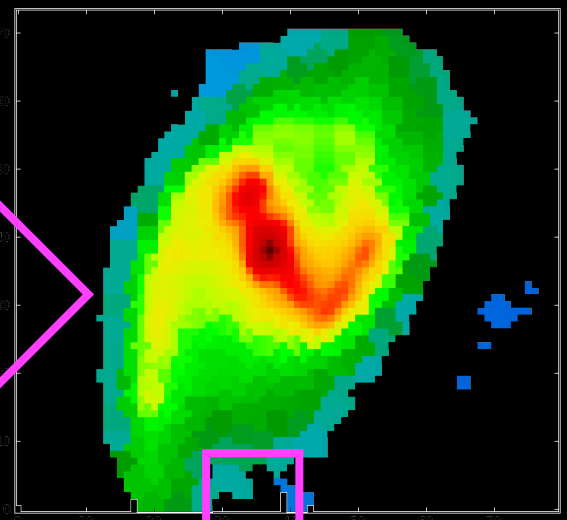




Cleaning: spatial & spectral masks



Voronoi binning: S/N > 20



N ~ 1000 individual spectra:

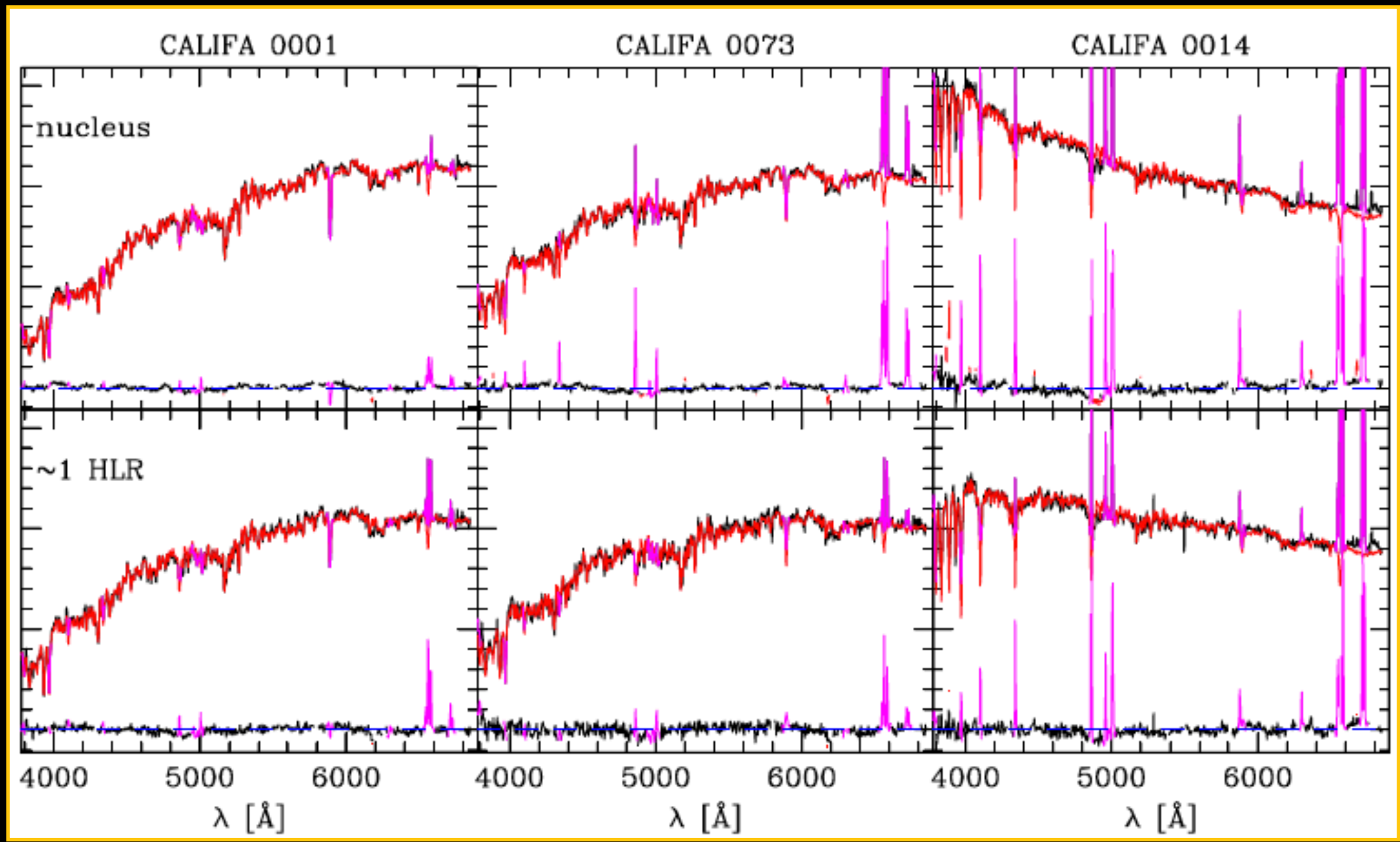
- $F_z(\lambda)$ and its error
- Spectral masks - $m_z(\lambda)$
- Bad pixel flags - $b_z(\lambda)$
- Correlated errors
- Galactic extinction
- Rest-framing & resampling

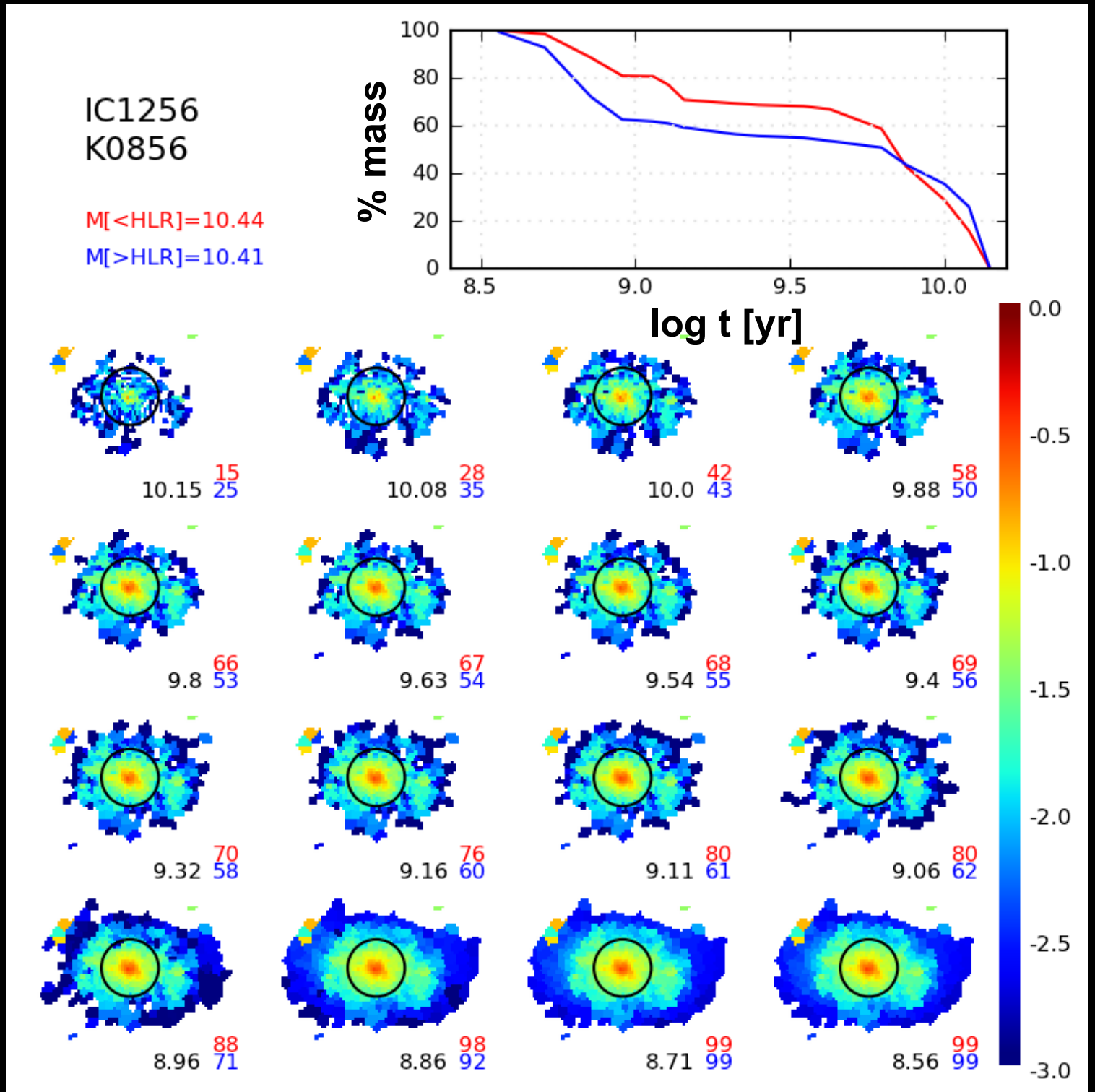
STARLIGHT

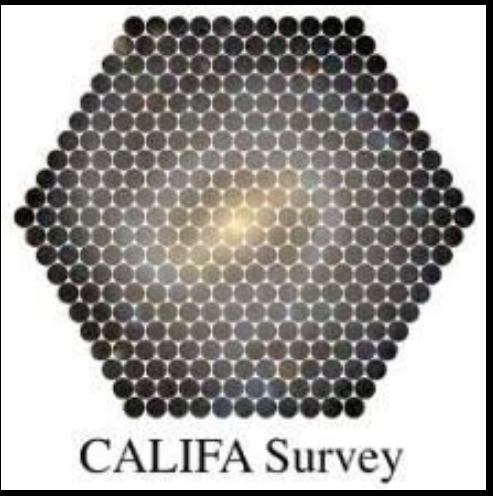
M_* , v_* ,σ_*, A_V, <age$_*$>, <Z_*>, SFH, ...

as a function of (x,y) !!

Example spectral fits: Nucleus and @ R = 1 HLR



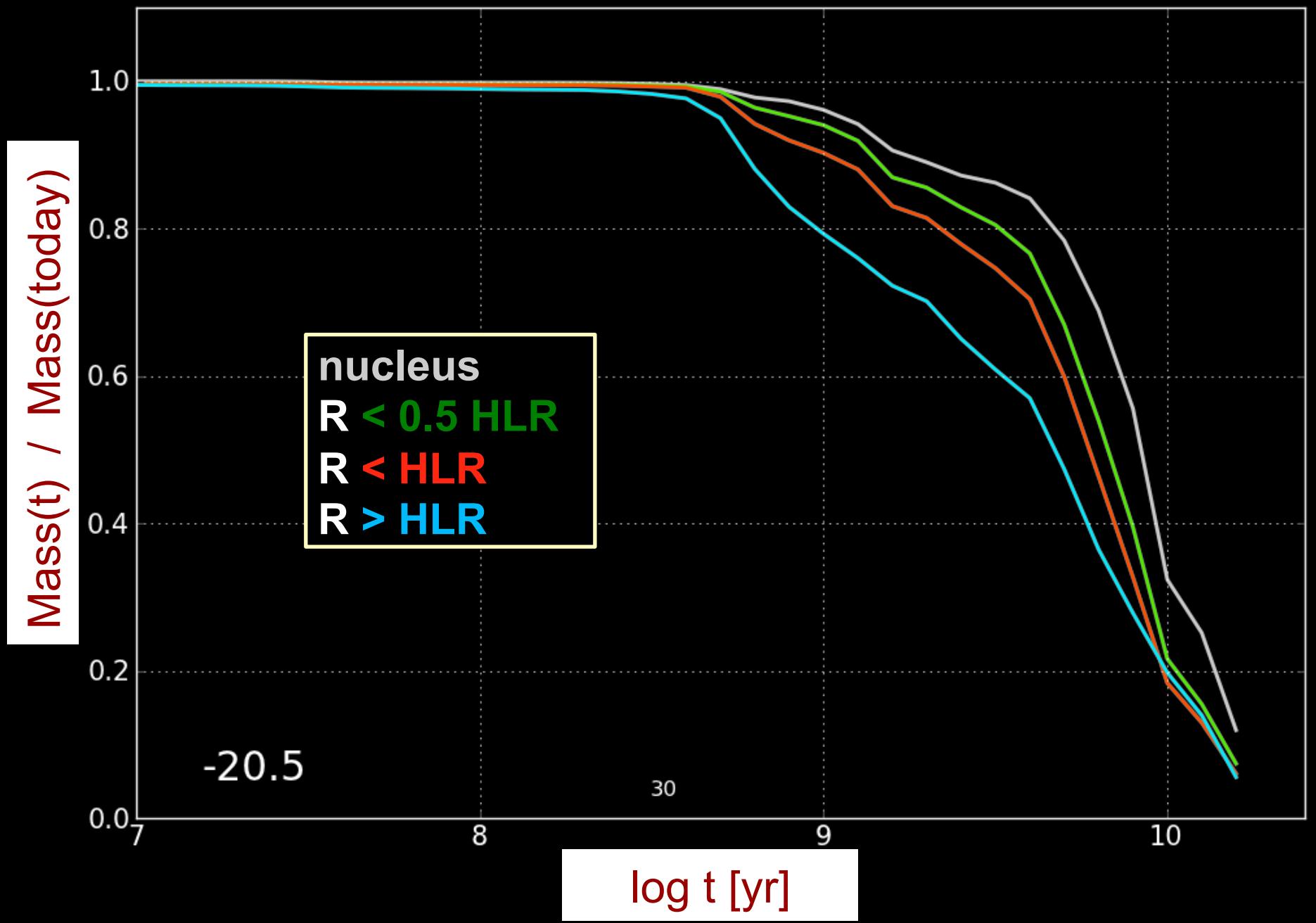




Spatially resolved mass assembly history

...

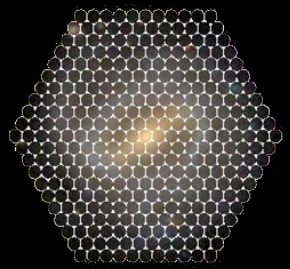
Spatially resolved mass assembly history



Enrique Pérez

Roberto Cid Fernandes

Rosa González Delgado



Ruben García-Benito

➔ *Galaxies grow inside out*

- *Mass builds up faster for more massive galaxies*
- *Downsizing = Downsizing(R)*
- *Etc = Etc(x,y,t) ...*

André Amorim

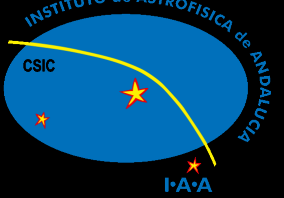
Clara Cortijo

Rafael López

Bernd Husemann

Sebastián F. Sánchez

Damián Mast



Caveats / weaknesses

☹ Limited λ-range (optical spectra)
☹ Fits only star's light (no gas / dust emission)
☺ SFH very flexible (non-parametric)
☹ … but single τ attenuation model too simplistic!

New stuff: More constraints

☺ Fit photometry: GALEX, ~~2MASS, …~~
☺ Fit (recombination) emission lines: Hα, Hβ, Hα/Hβ
~~☺ Fit dust-reprocessed (FIR) luminosity~~

$$\chi^2 = \chi^2_{\rm OPT} + \chi^2_{\rm PHO} + \chi^2_{\rm REL} + \chi^2_{\rm FIR}$$

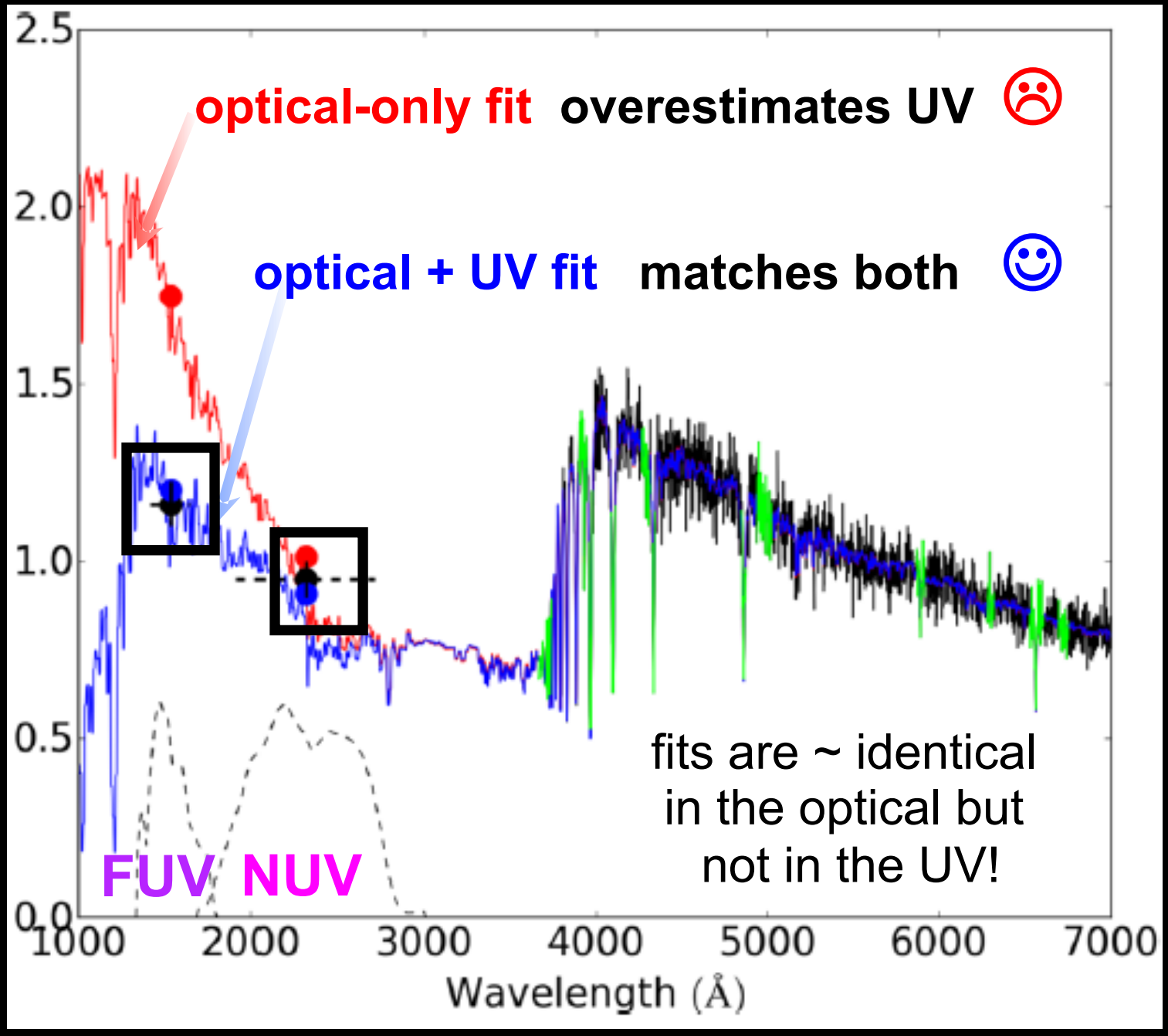
☺ New constraints allow more complex/realistic 2 τ's model

Part I

- Adding photometry to STARLIGHT

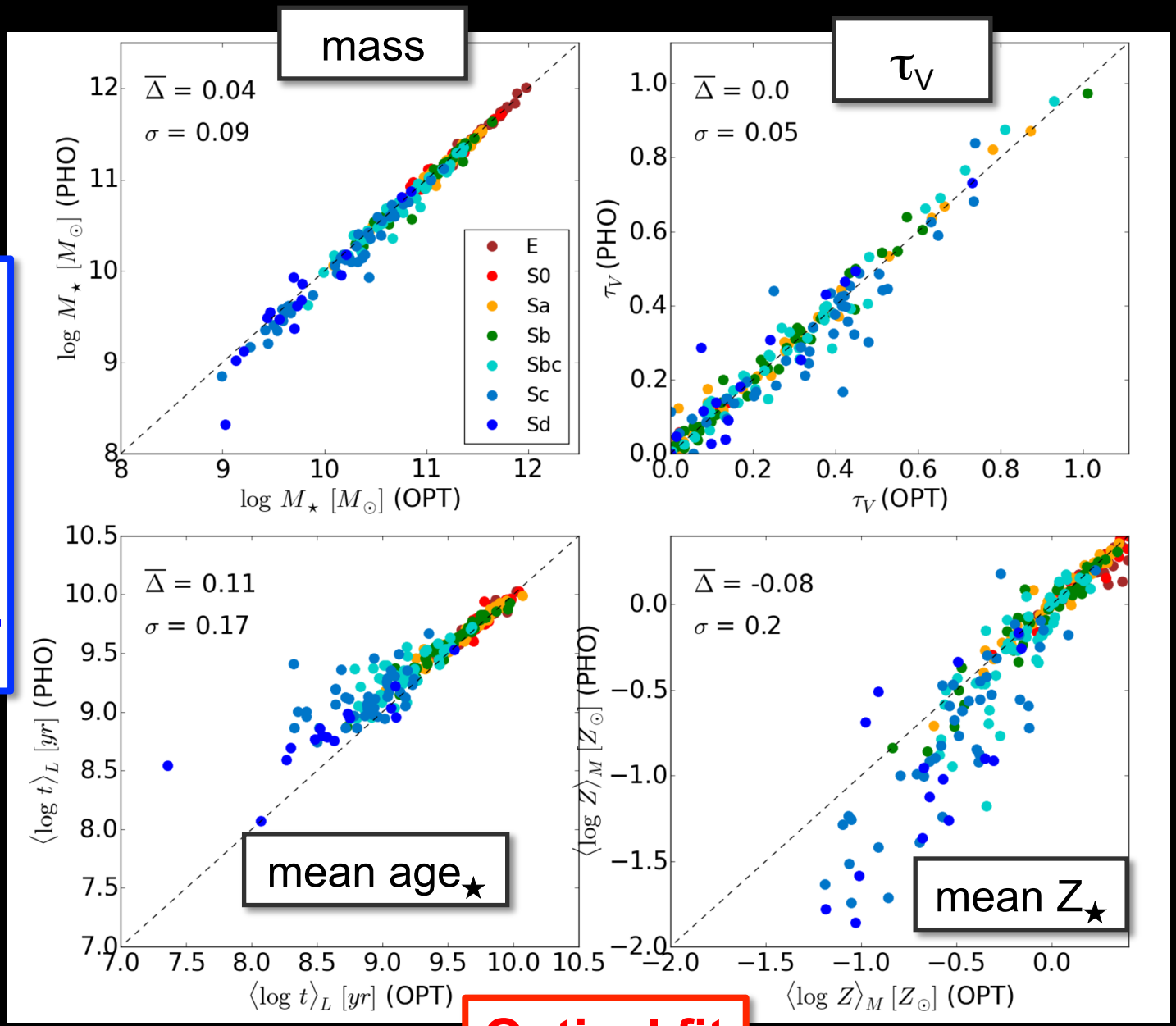
Simultaneous spectroscopic and photometric analysis of galaxies with STARLIGHT: CALIFA+*GALEX*

López Fernández et al 16



Simultaneous spectroscopic and photometric analysis of galaxies with STARLIGHT: CALIFA+*GALEX*

López Fernández et al 16

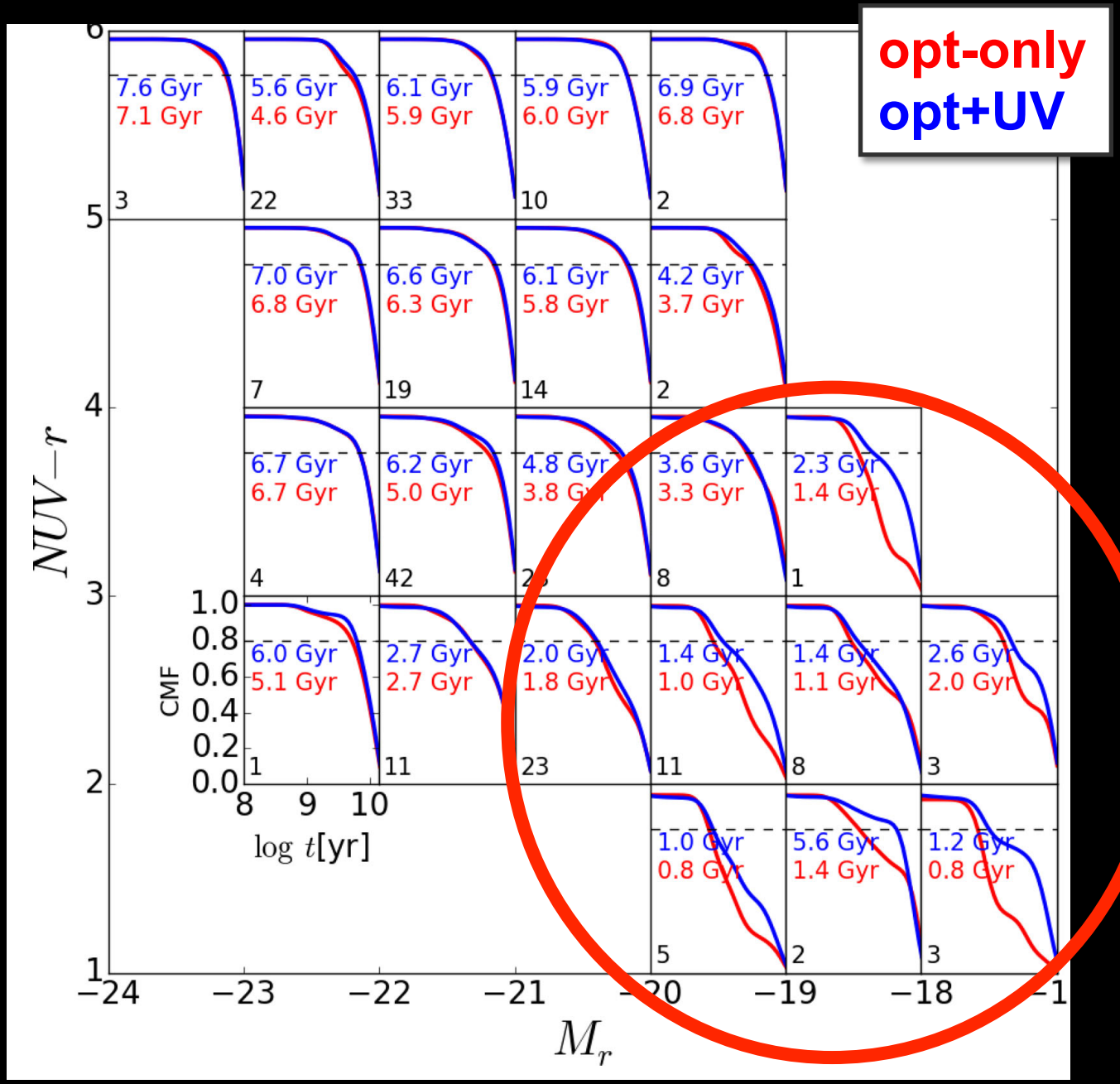


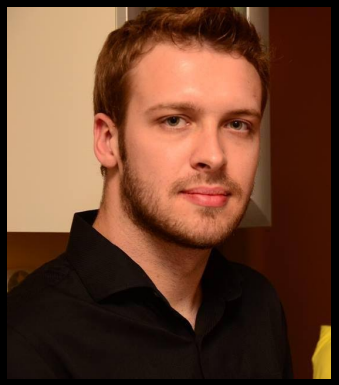
Simultaneous spectroscopic and photometric analysis of galaxies with STARLIGHT: CALIFA+*GALEX*

López Fernández et al 16

Rafael
López Fernández

- SFH changes are only significant for low mass, late type galaxies, which become a bit older with UV-data.

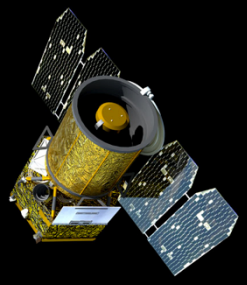




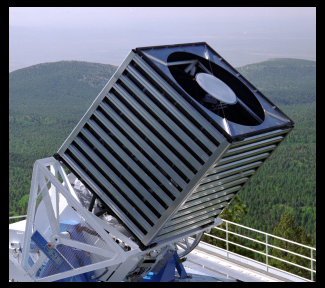
Simultaneous analysis of SDSS spectra and GALEX photometry with STARLIGHT: Method and early results

A. Werle,[1]★ R. Cid Fernandes,[1] N. Vale Asari,[1,2,3] G. Bruzual,[4] S. Charlot[5], R. Gonzalez Delgado[6] and F. R. Herpich[1,7]

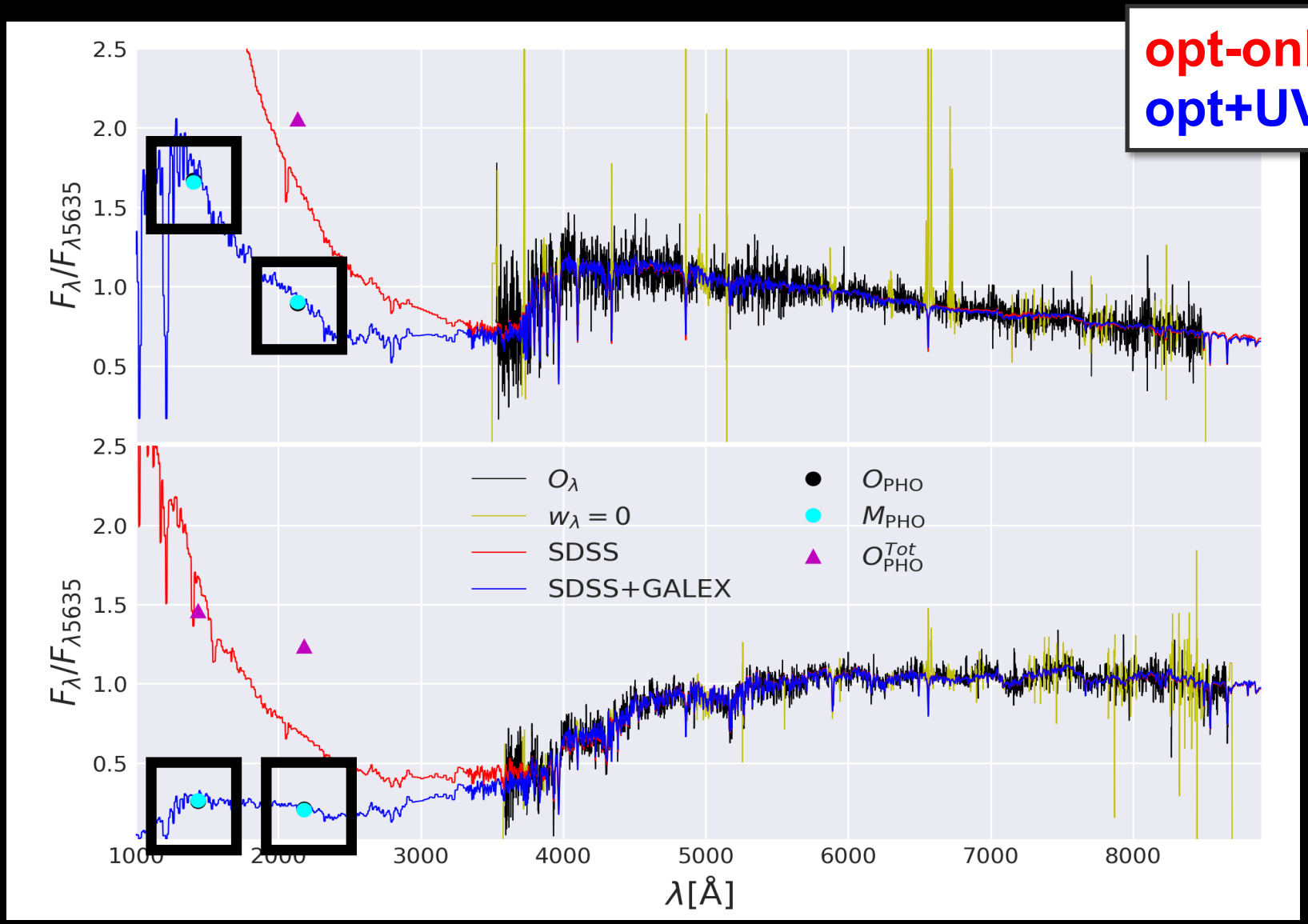
Ariel Werle

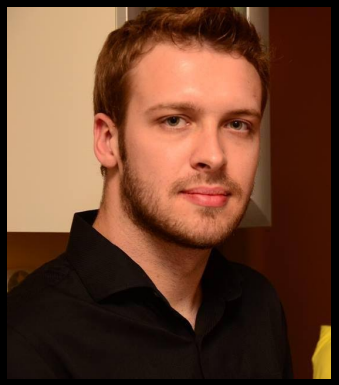


GALEX



SDSS

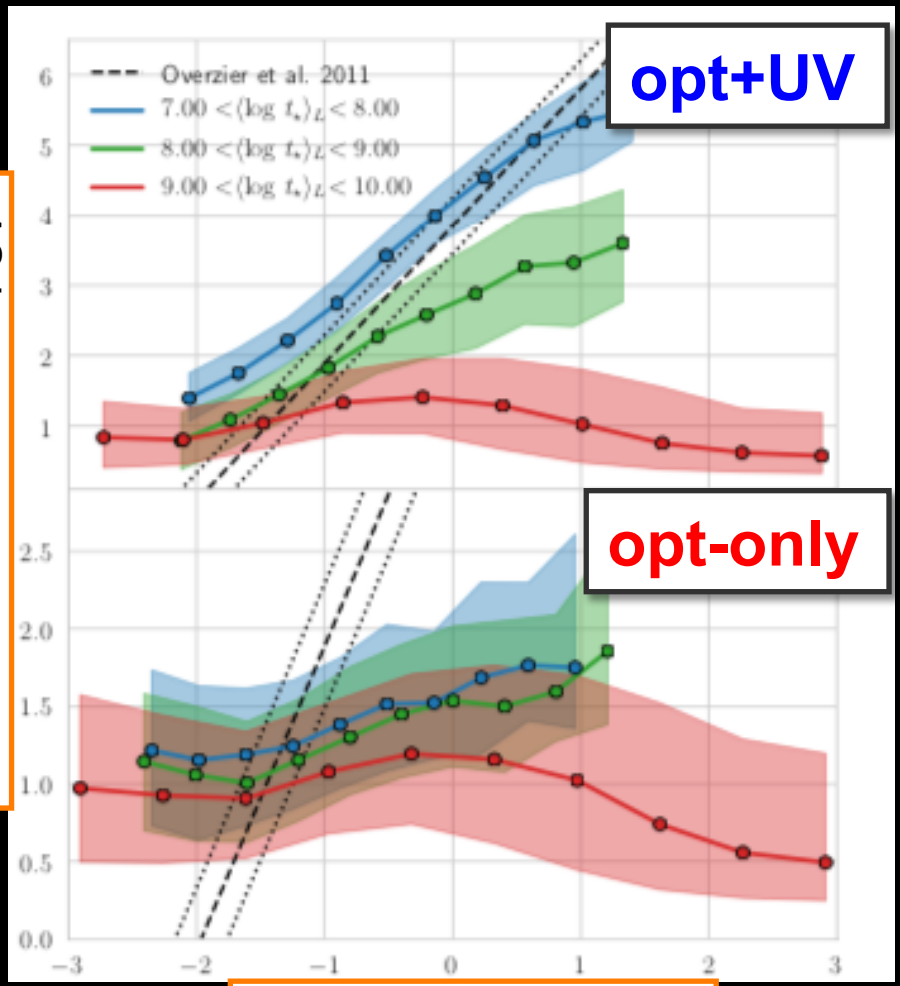


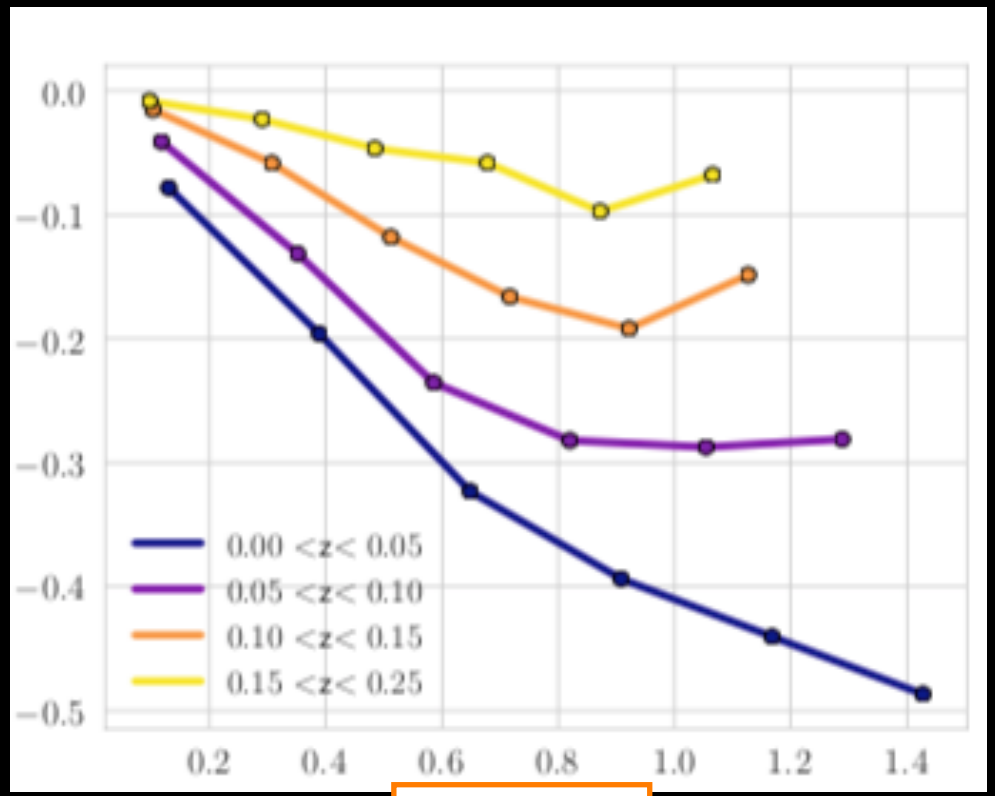


Simultaneous analysis of SDSS spectra and GALEX photometry with STARLIGHT: Method and early results

A. Werle,[1]★ R. Cid Fernandes,[1] N. Vale Asari,[1,2,3] G. Bruzual,[4] S. Charlot[5], R. Gonzalez Delgado[6] and F. R. Herpich[1,7]

+ Hints on nature of the extintion law





Part II

- Adding (recombination) emission lines to STARLIGHT fits
- A more realistic / less ridiculous treatment of dust: fits with 2 τ's

Fitting Hα & Hβ w/STARLIGHT

- $L(H\alpha) \sim k_{H\alpha} \times Q_H \times e^{-q(H\alpha) \times \tau}$
- $L(H\beta) \sim k_{H\beta} \times Q_H \times e^{-q(H\beta) \times \tau}$

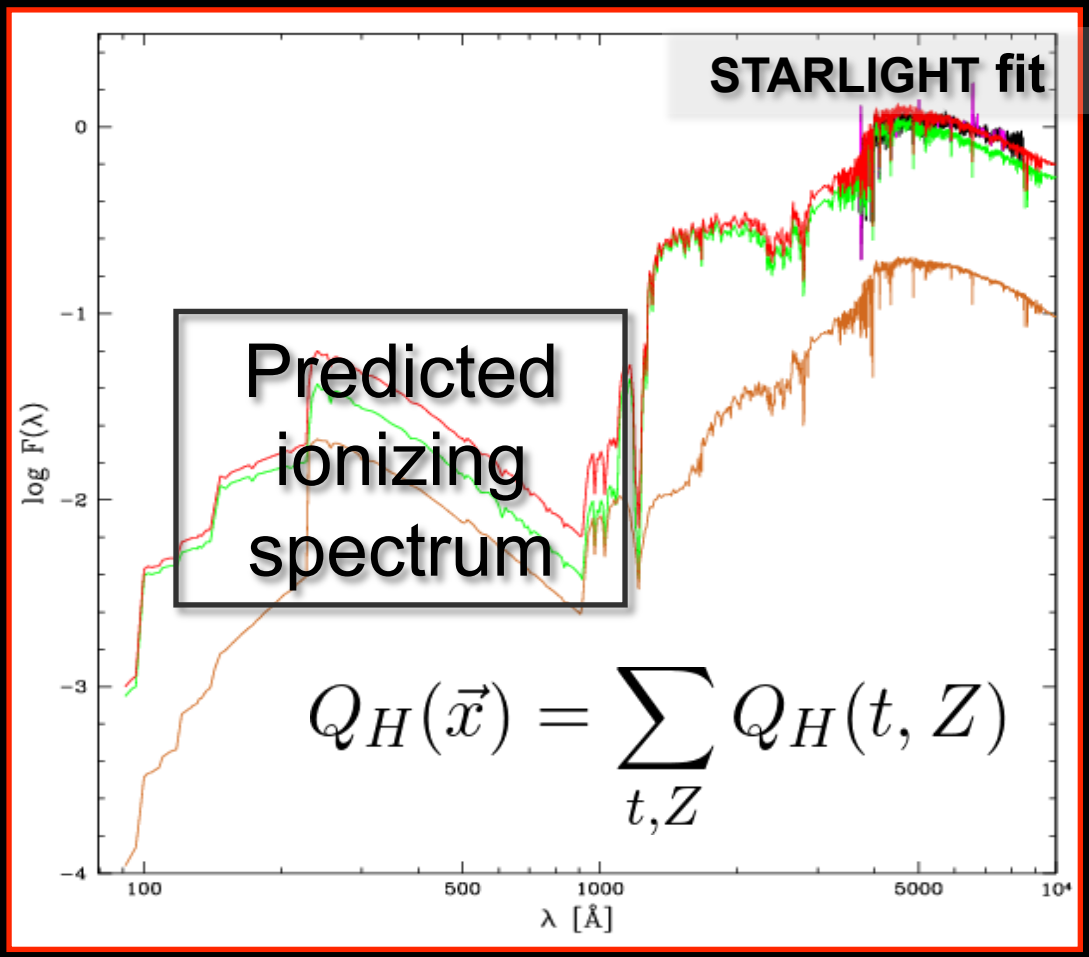
☺ Fitting line luminosities constrains ionizing stellar populations and τ, …

😐 … but relies on SSP models @ λ < 912 Å

☺ Fitting line ratios is more sensible / robust.

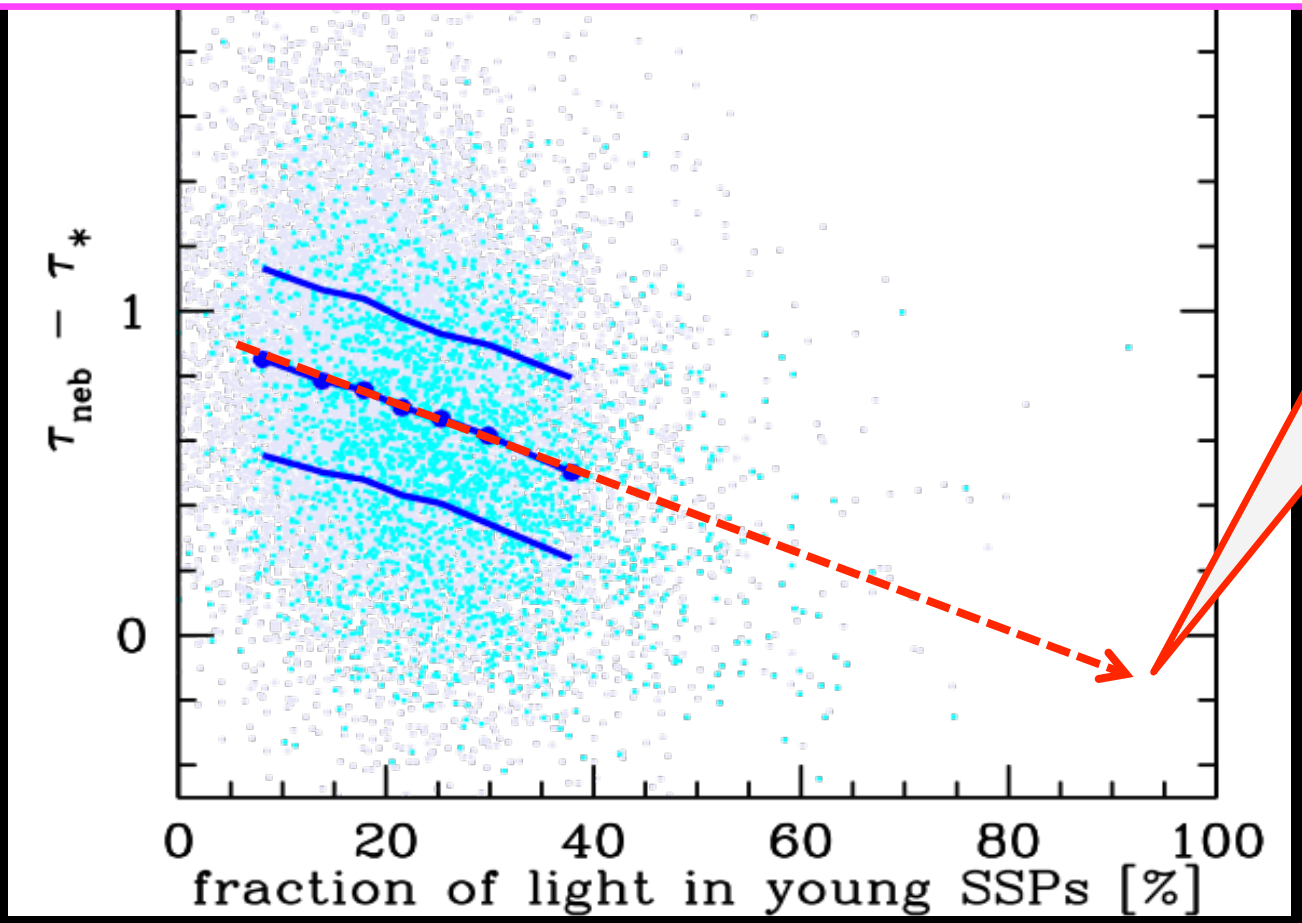
$$H\alpha/H\beta = k_{H\alpha}/k_{H\beta}\ e^{-[q(H\alpha) - q(H\beta)] \times \tau}$$

$$\chi^2 = \chi^2_{\rm OPT} + \chi^2_{\rm REL}$$

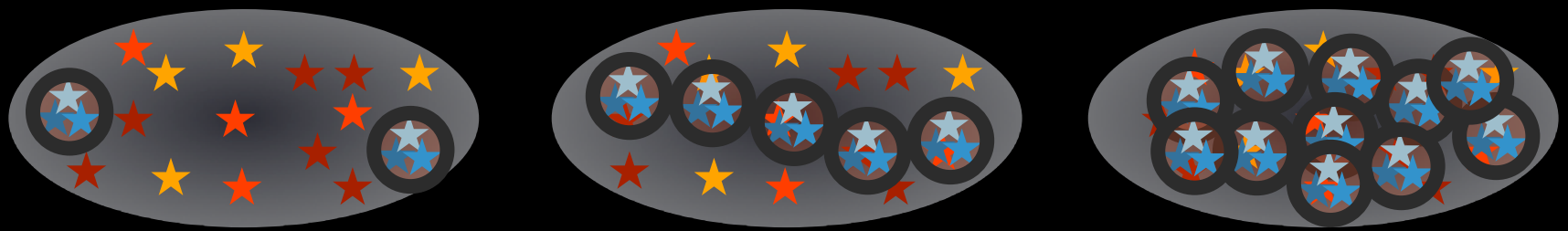


Dust x stellar populations in single τ fits

$$\tau_\star \approx \tilde{\tau} \equiv x_Y \tau_Y + (1 - x_Y)\tau_O$$

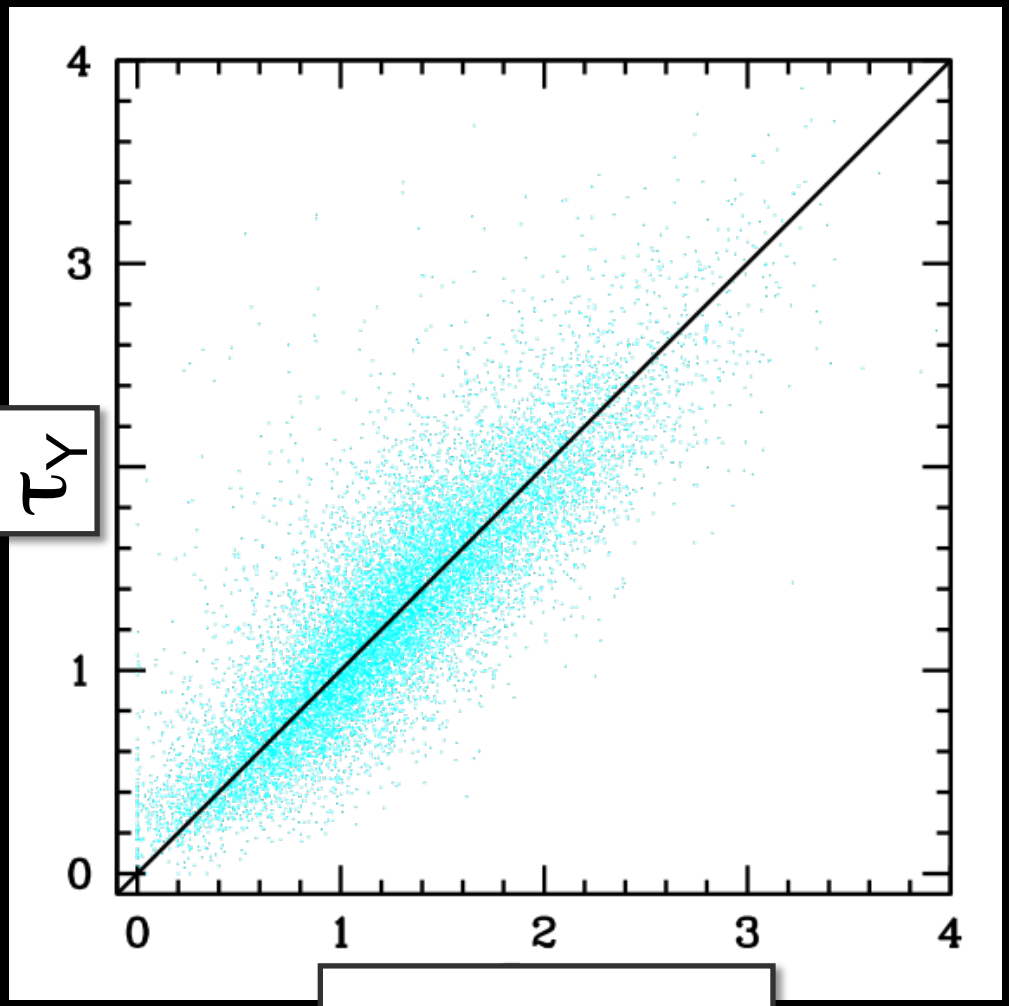


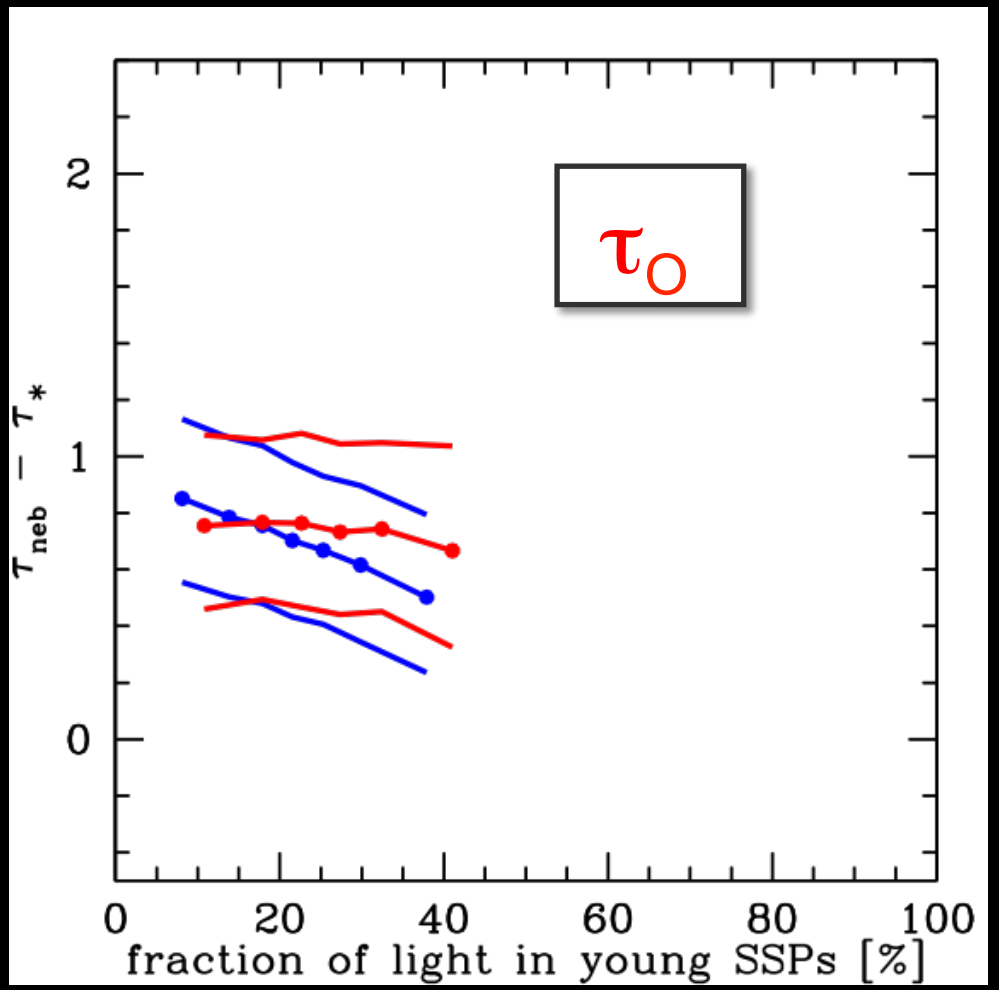
No differential extinction when looking at SF regions

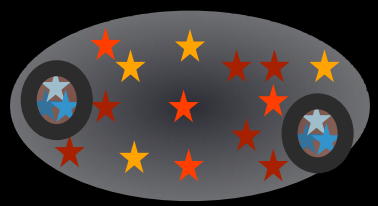


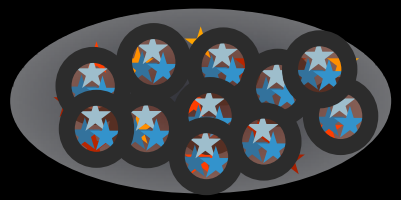
Tests w/14000 SF galaxies

- STARLIGHT fits to optical spectra AND Hα/Hβ

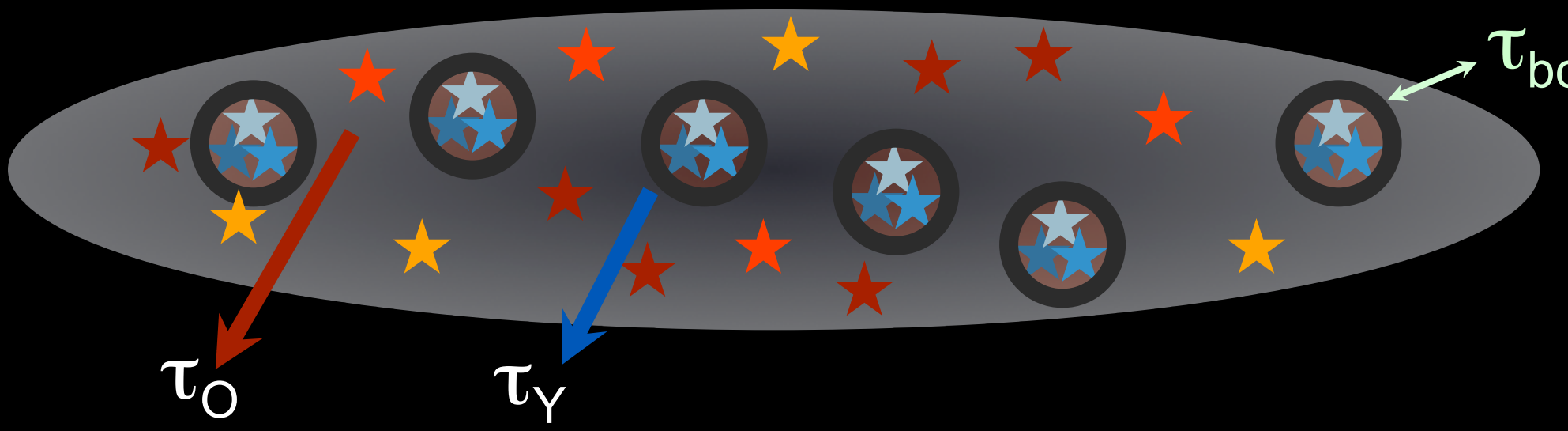








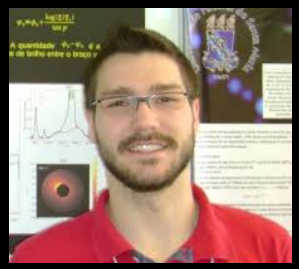
Towards a more realistic model: 2 τ's



$$\tau(t,Z) \sim \tau(t) = \begin{cases} \tau_Y = \tau_o + \tau_{bc} & t \lesssim 10^7 \text{ yr} \\ \tau_O & t \gtrsim 10^7 \text{ yr} \end{cases}$$

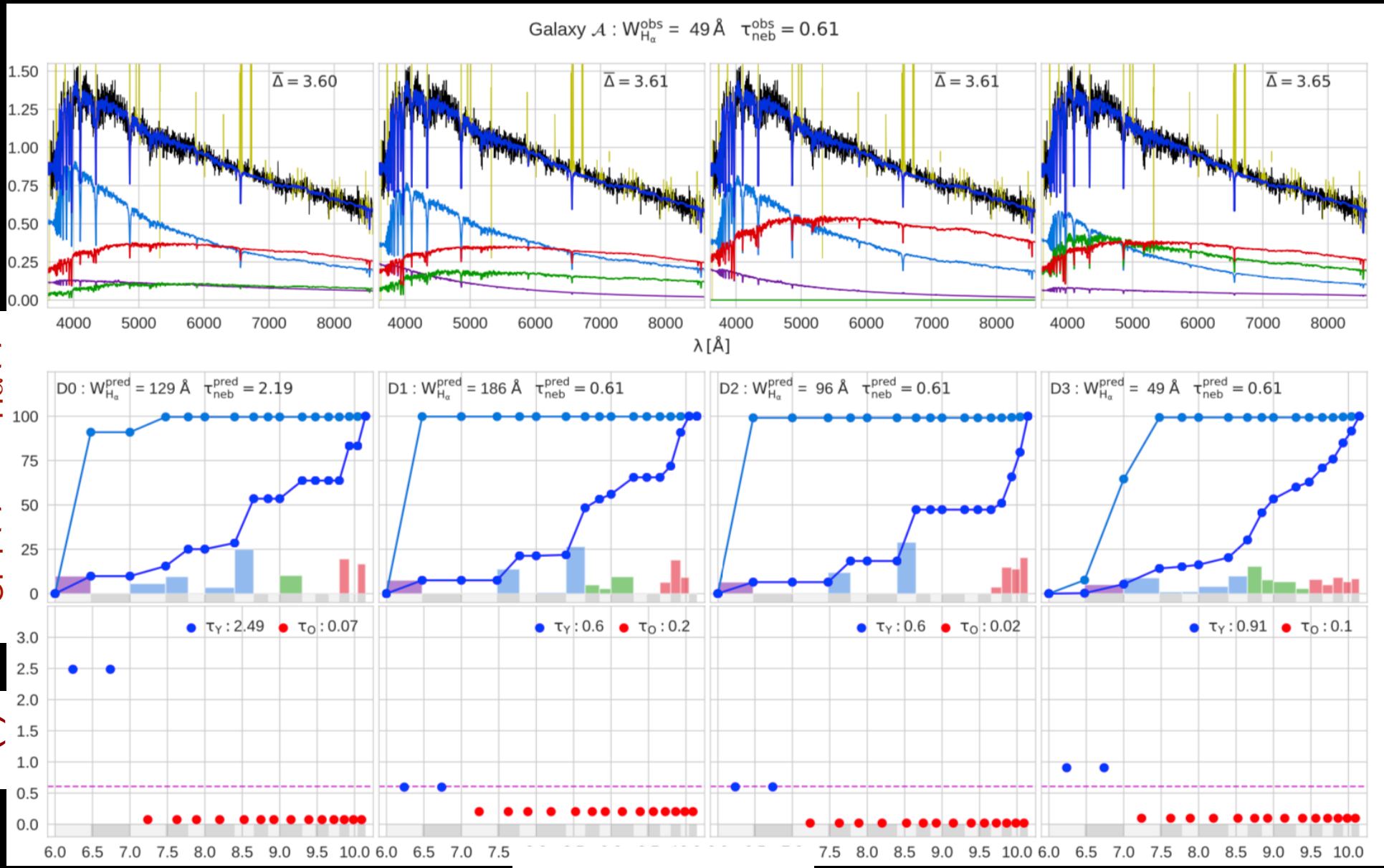
$$\tau_Y \approx \tau_{neb} = \tau(H\alpha/H\beta)$$

- Observed Hα/Hβ constrains τ_Y
- Continuum constrains τ_O & τ_Y



Experiments in full spectral fitting with differential dust attenuation

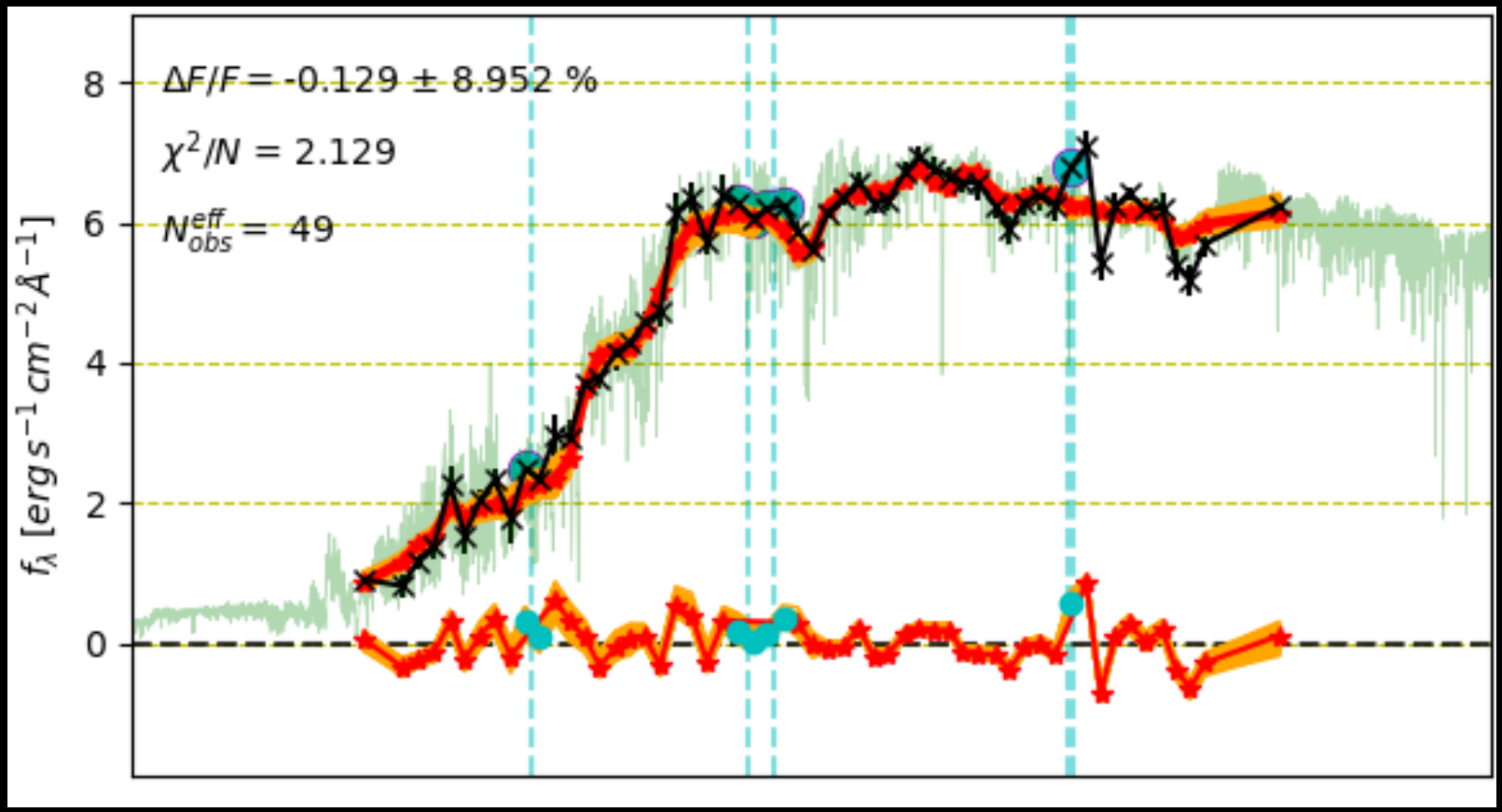
J. Schimoia[1]★, R. Cid Fernandes[1], F. R. Herpich[2,1], N. Vale Asari[1], A. Werle[2,1]



Part III

- AlStar = an algebraic starlight
- Fits spec + phot + em lines

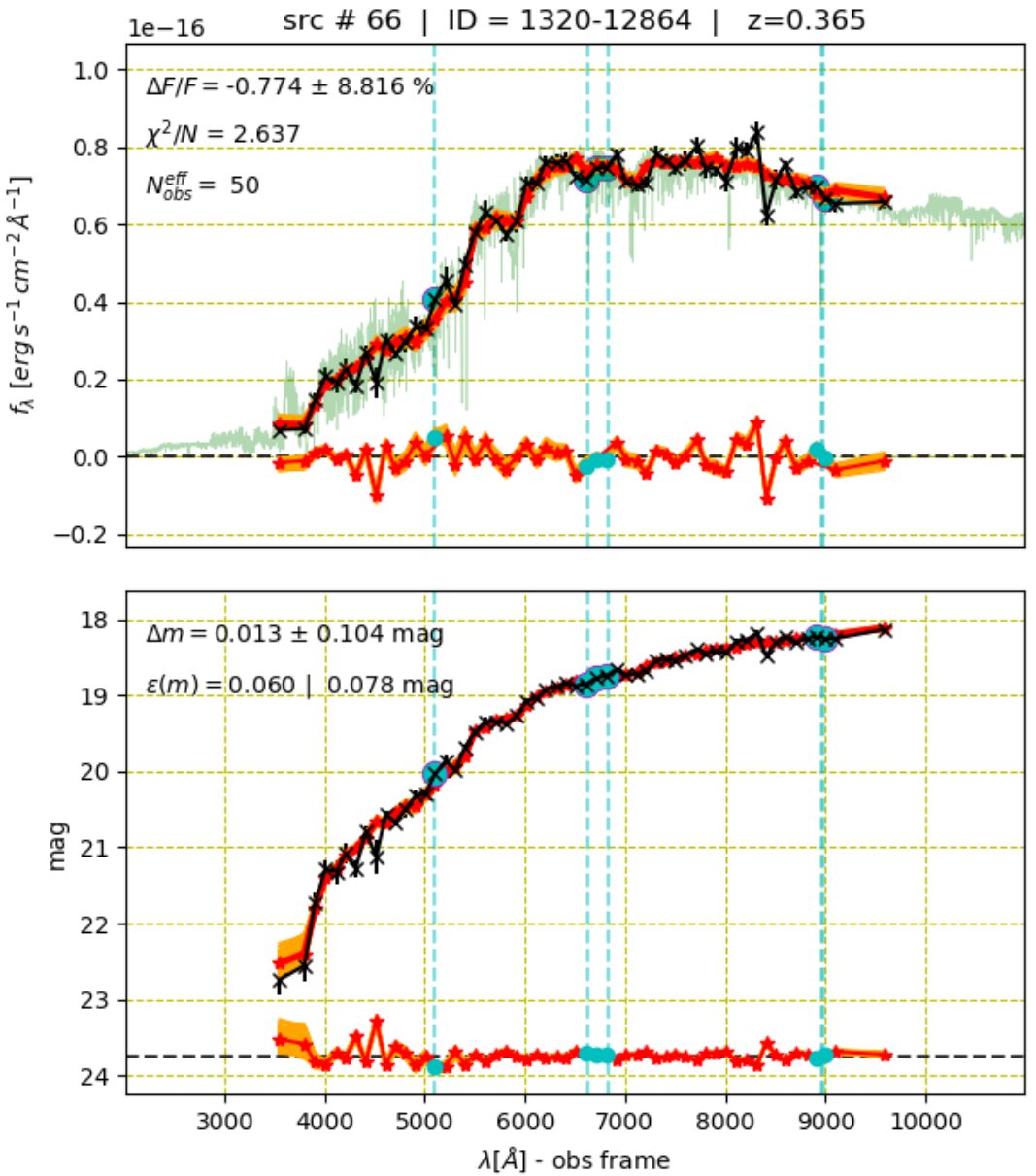
Non-parametric star-formation histories for JPAS galaxies: 1st results

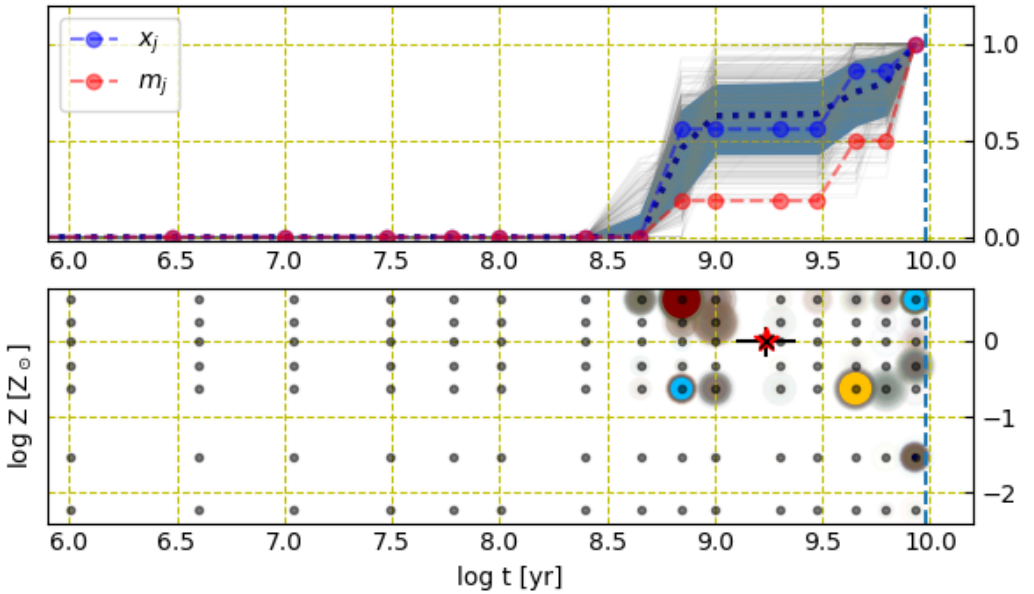


- ✧ Roberto Cid Fernandes
- ✧ André de Amorim
- ✧ Ariel Werle
- ✧ Rosa González Delgado
- ○ Daniel Ruschel Dutra
- ○ Natalia Vale Asari
- ○ William Schoennel

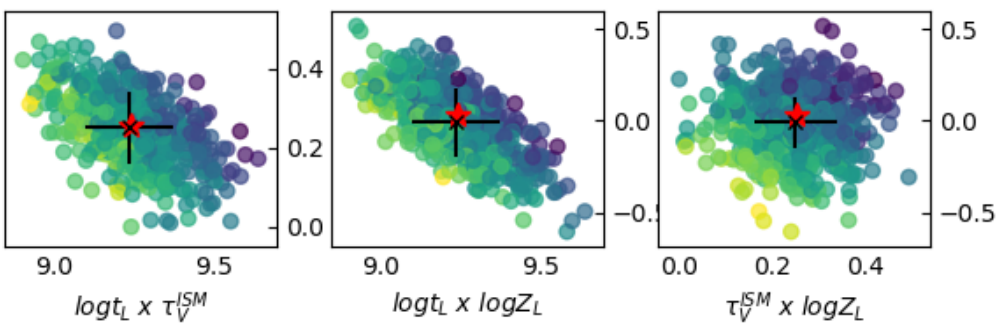
GRUPO DE ASTROFÍSICA
GAS - UFSC
BRASIL

AIStar for J-data: 1st tests 7/10 (z = 0.36)

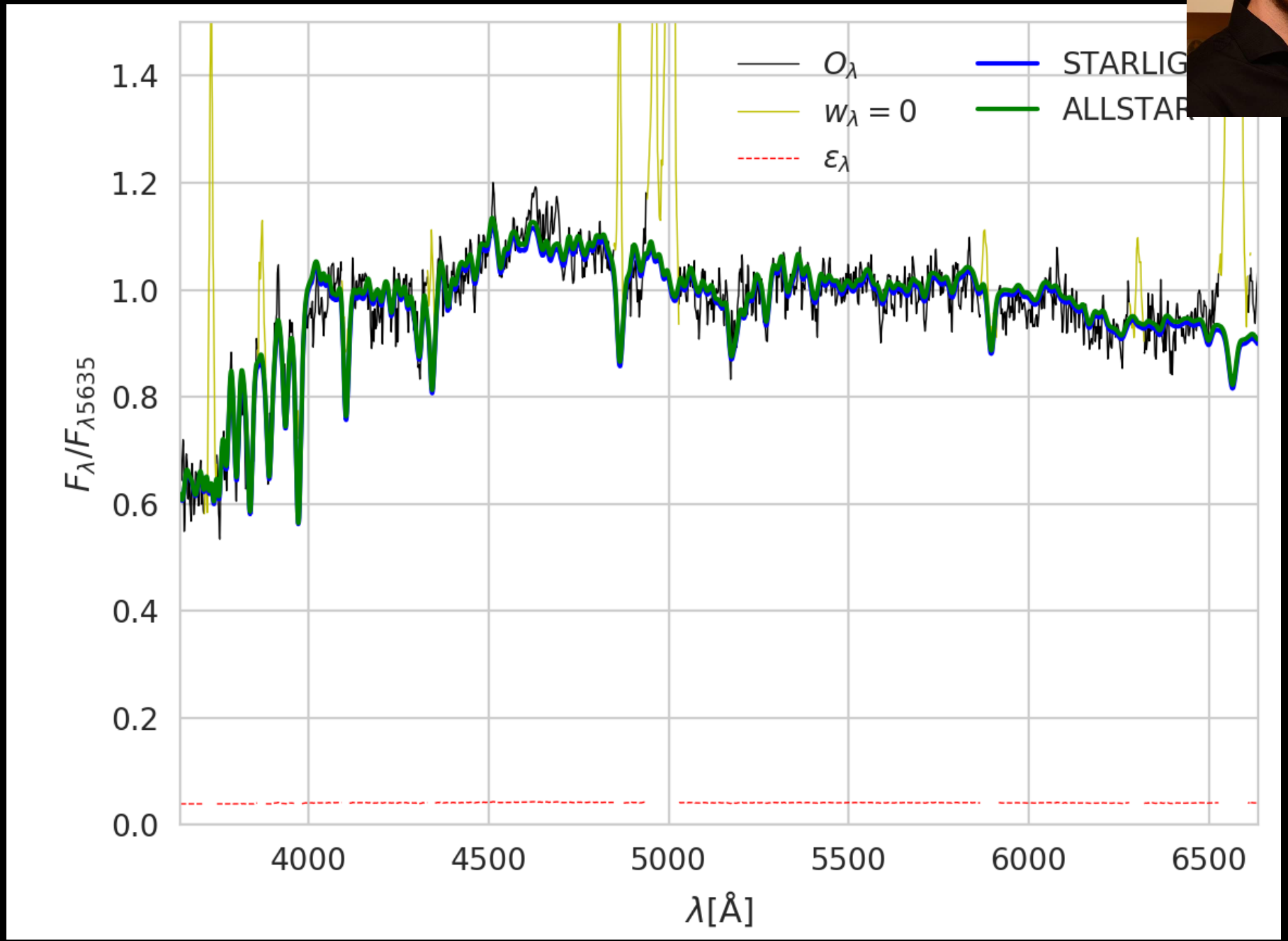




$logM$ = 11.30	11.26 ± 0.11
$logt_L$ = 9.24	9.24 ± 0.14
$logZ_L$ = 0.03	-0.01 ± 0.19
τ_V^{ISM} = 0.25	0.25 ± 0.09
τ_V^{BC} = 0.00	-0.00 ± 0.09



AlStar x STARLIGHT … same results ☺



AlStar x STARLIGHT … same results ☺