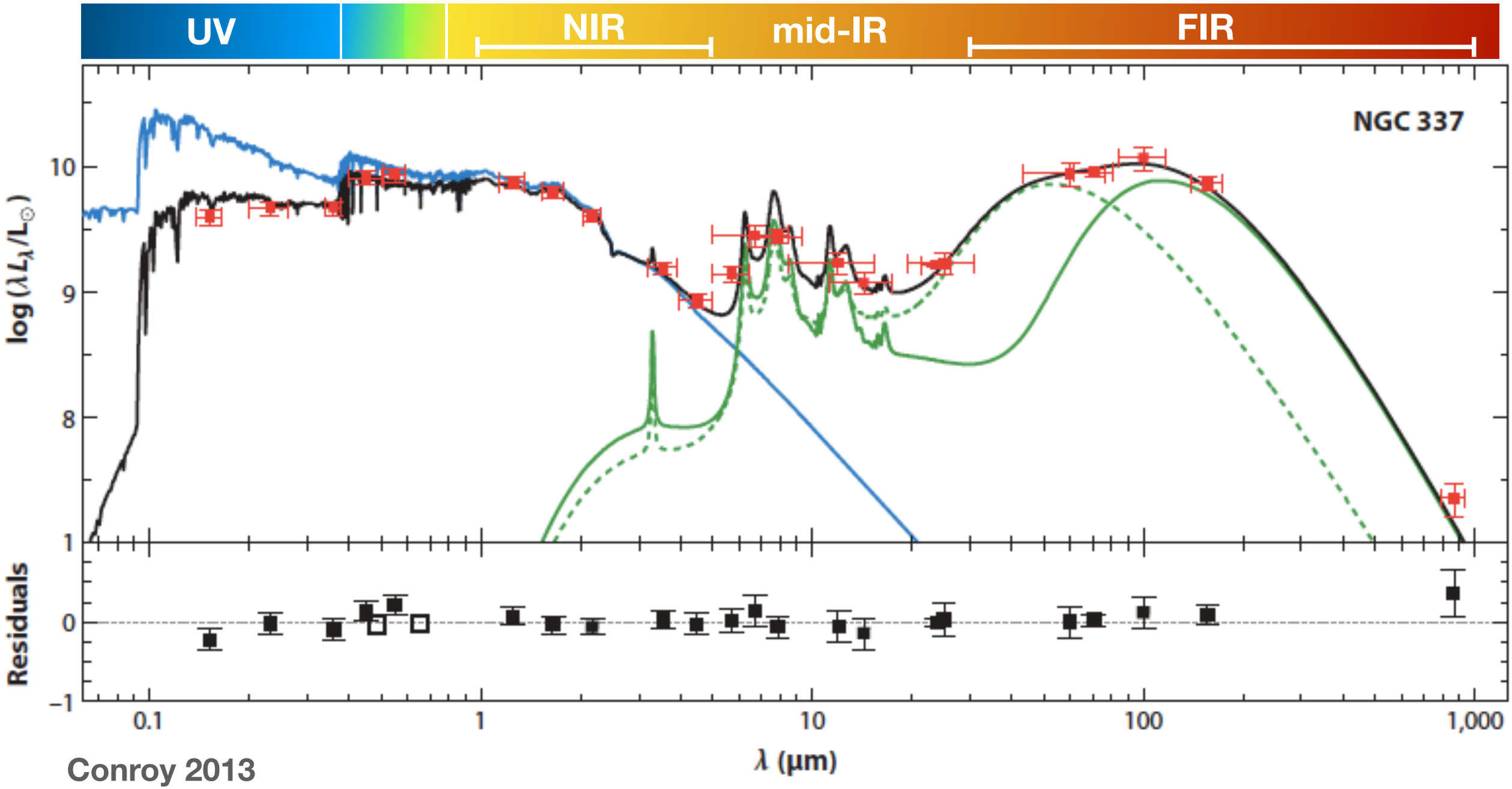
Turning it the other way around: estimate galaxy properties from observed SEDs



Conroy 2013

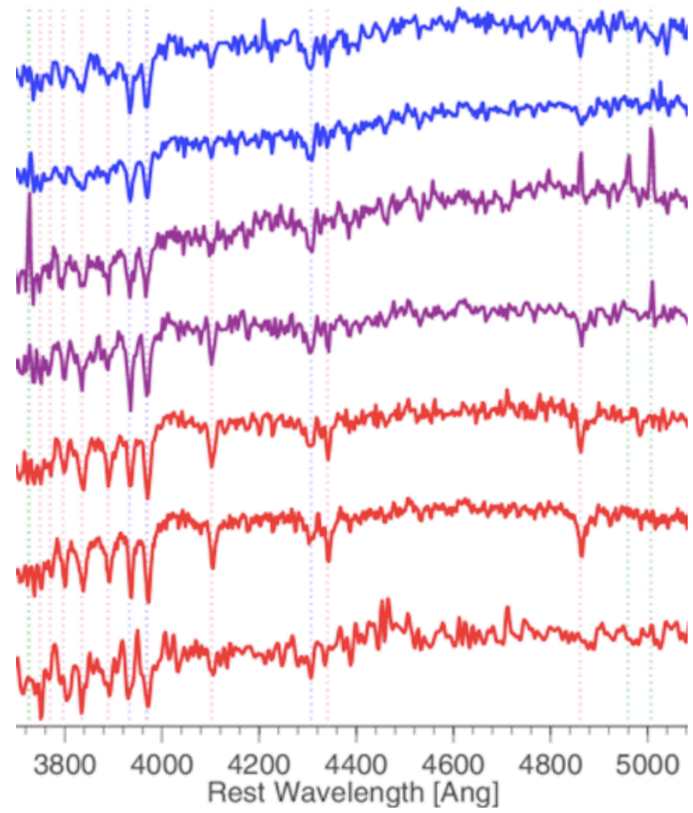
Turning it the other way around: estimate galaxy properties from observed SEDs

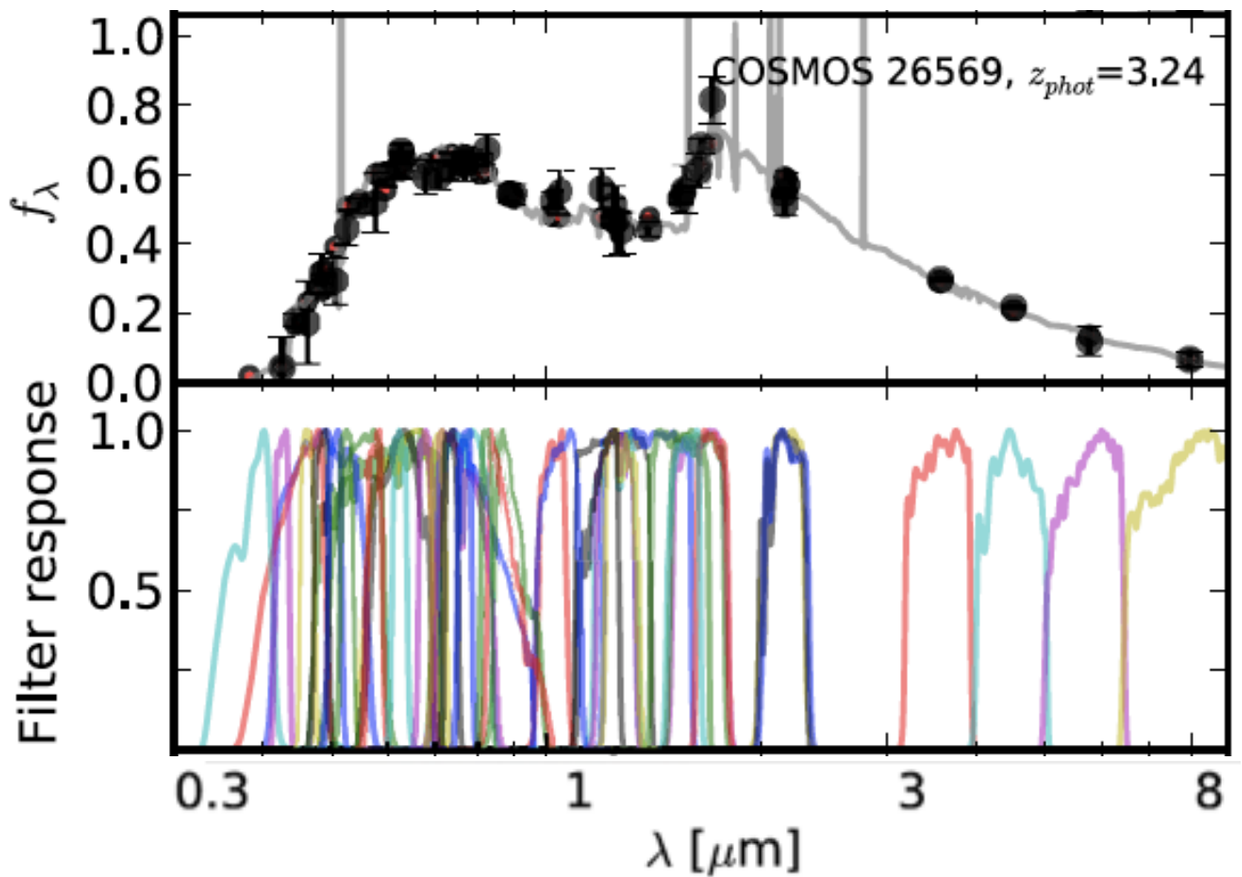
What do we have:

- ☐ spectra
  (or spectral features / indices)

- ☐ color (broad/medium/
  narrow-band SEDs)

(resolved / unresolved ?)





Turning it the other way around: estimate galaxy properties from observed SEDs

What do we have:

- ☐ spectra
  (or spectral features / indices)
- ☐ color (broad/medium/
  narrow-band SEDs)

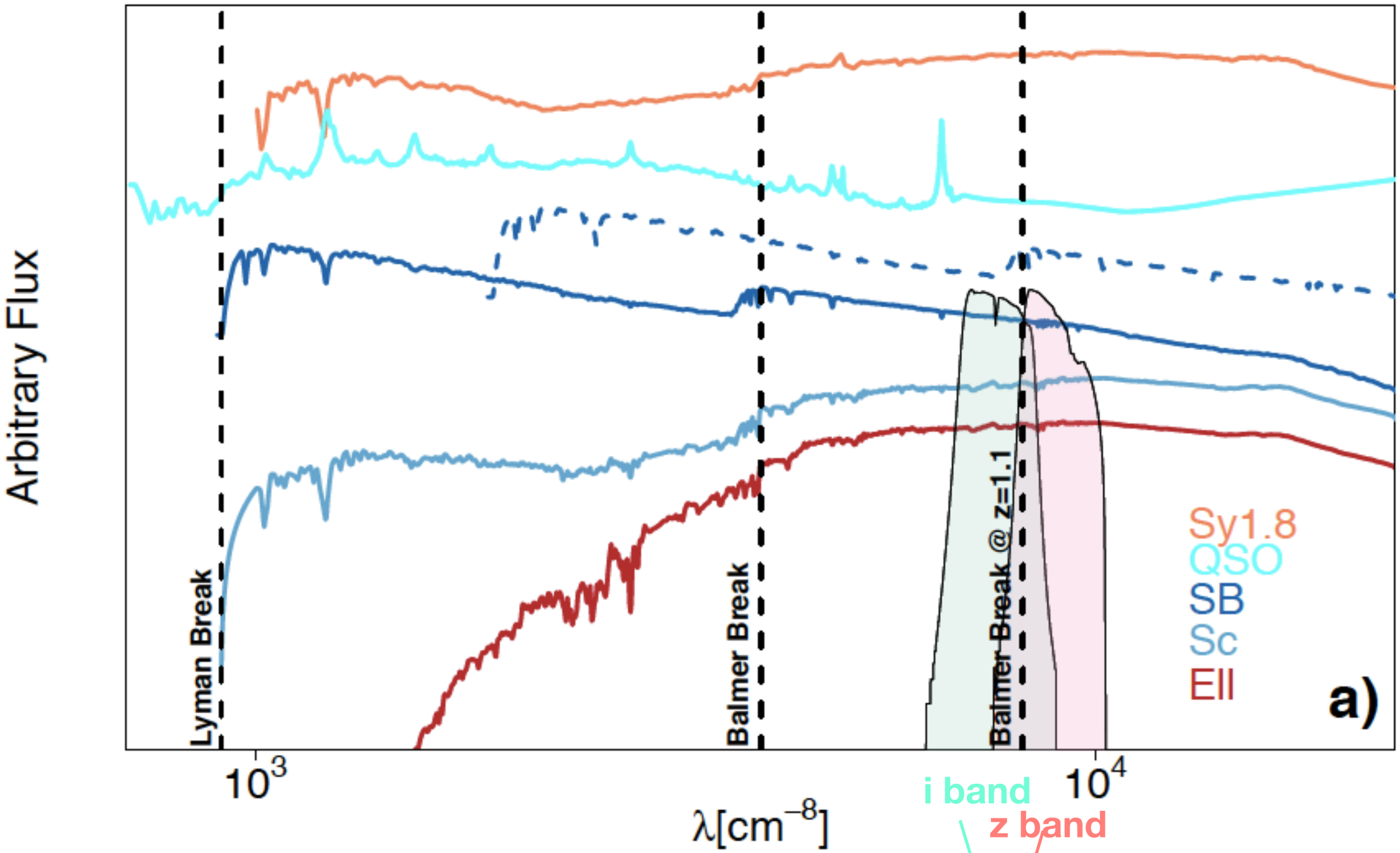
(resolved / unresolved ?)

What do we want:

- ☐ stellar mass
- ☐ stellar age / SFH / SFR
- ☐ metallicity (stellar / gas)
- ☐ dust mass / temperature
- ☐ AGN ?
- ☐ galaxy redshift
- ☐ ...

Photometric redshift

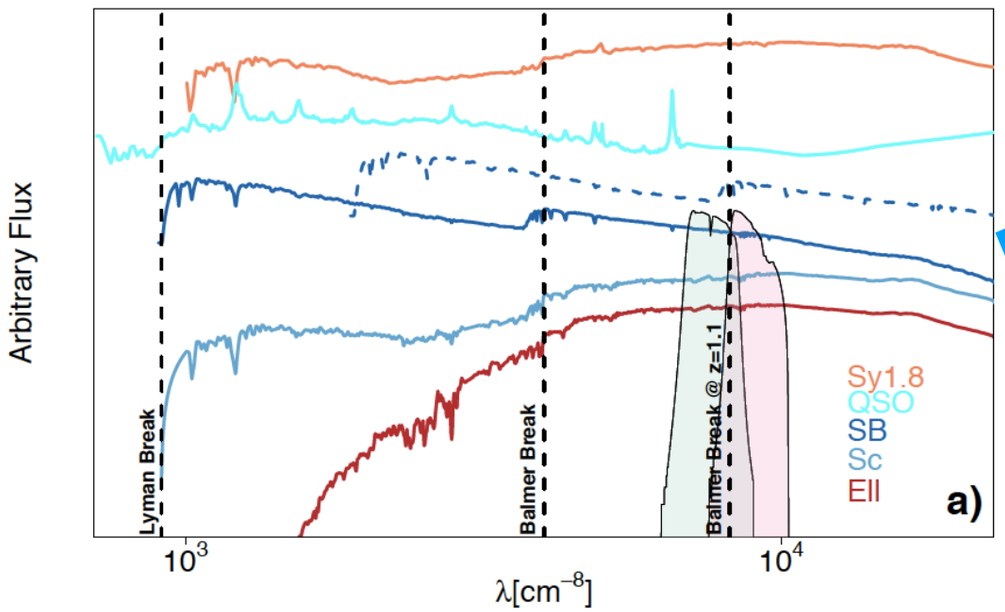
many approaches, but main principle is:

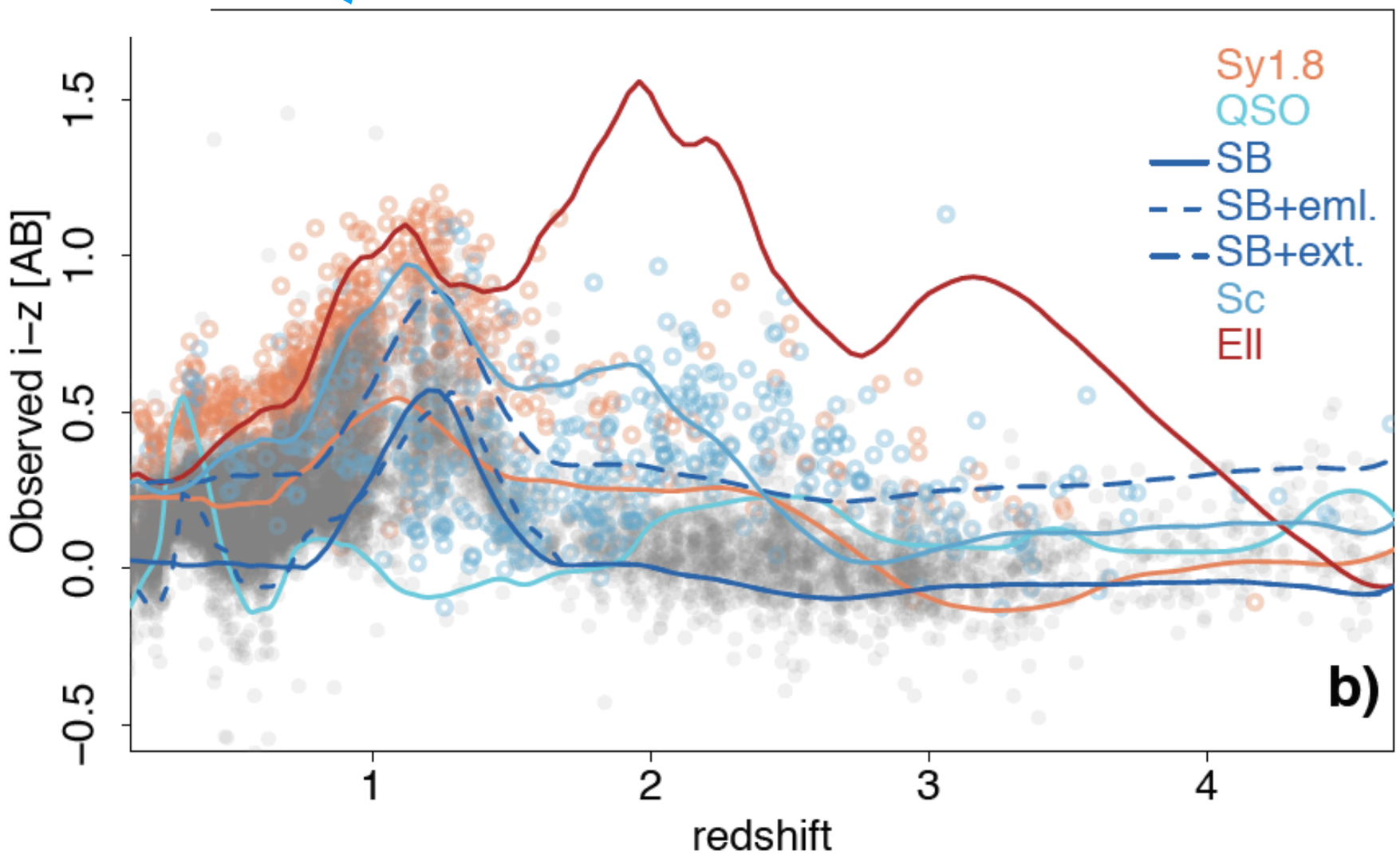


Salvato et al. 2018

one color: i - z (observed)

Photometric redshift

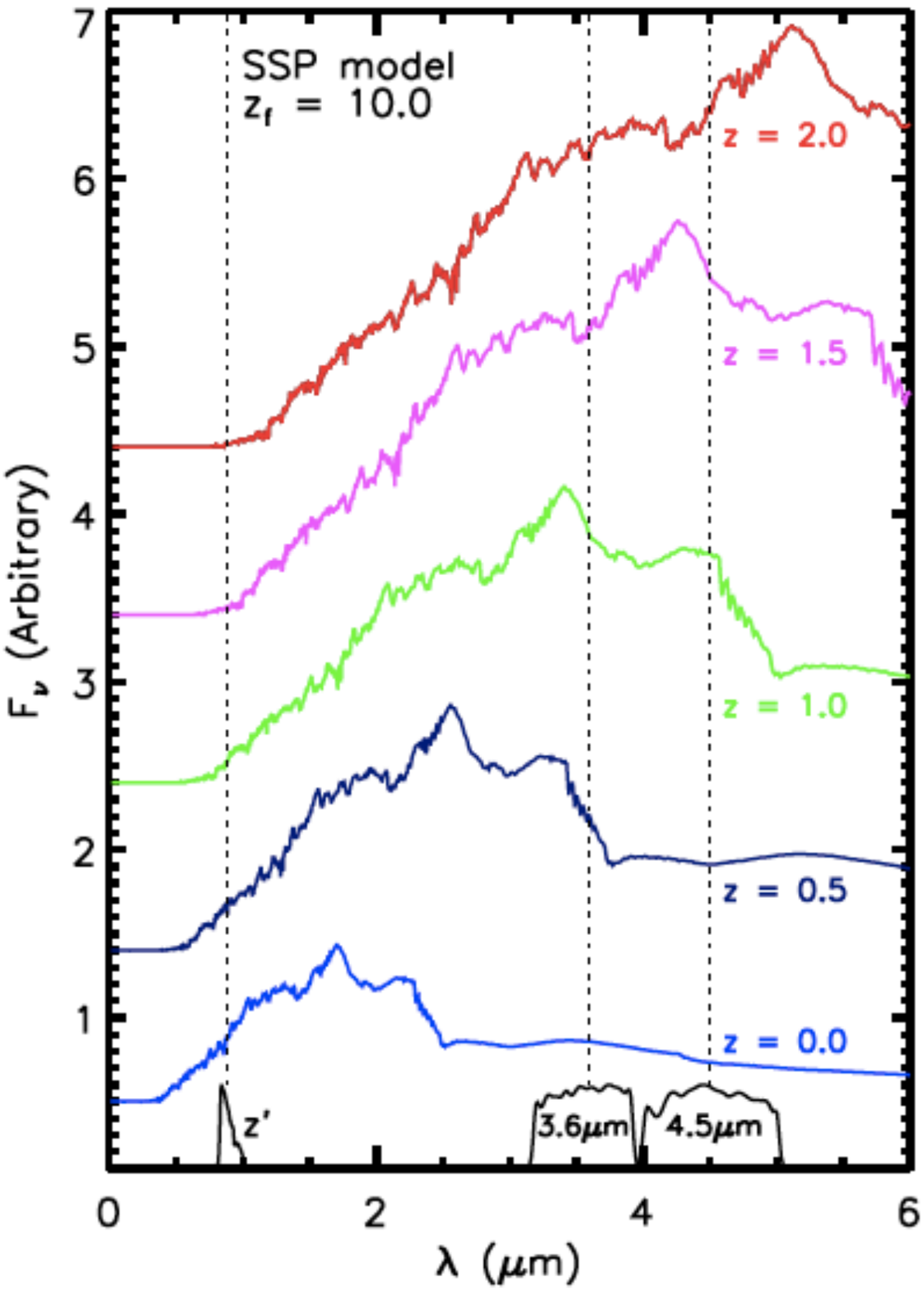


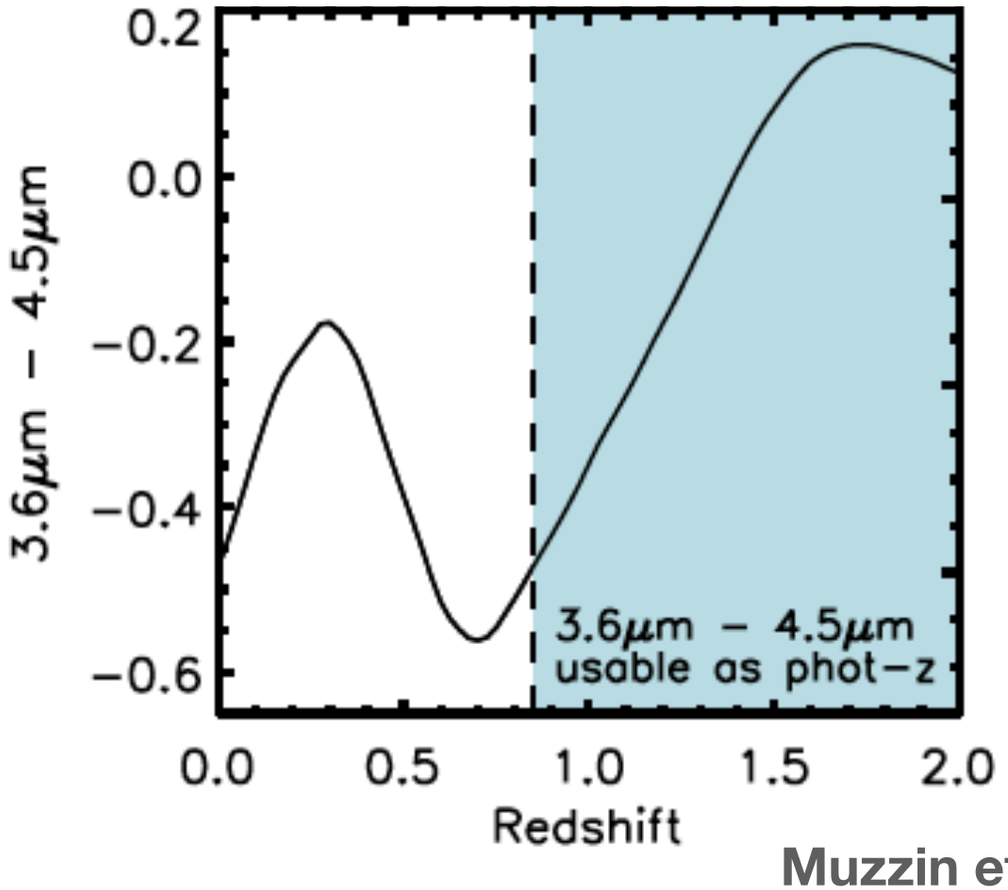


Salvato et al. 2018

Photometric redshift

with one color…

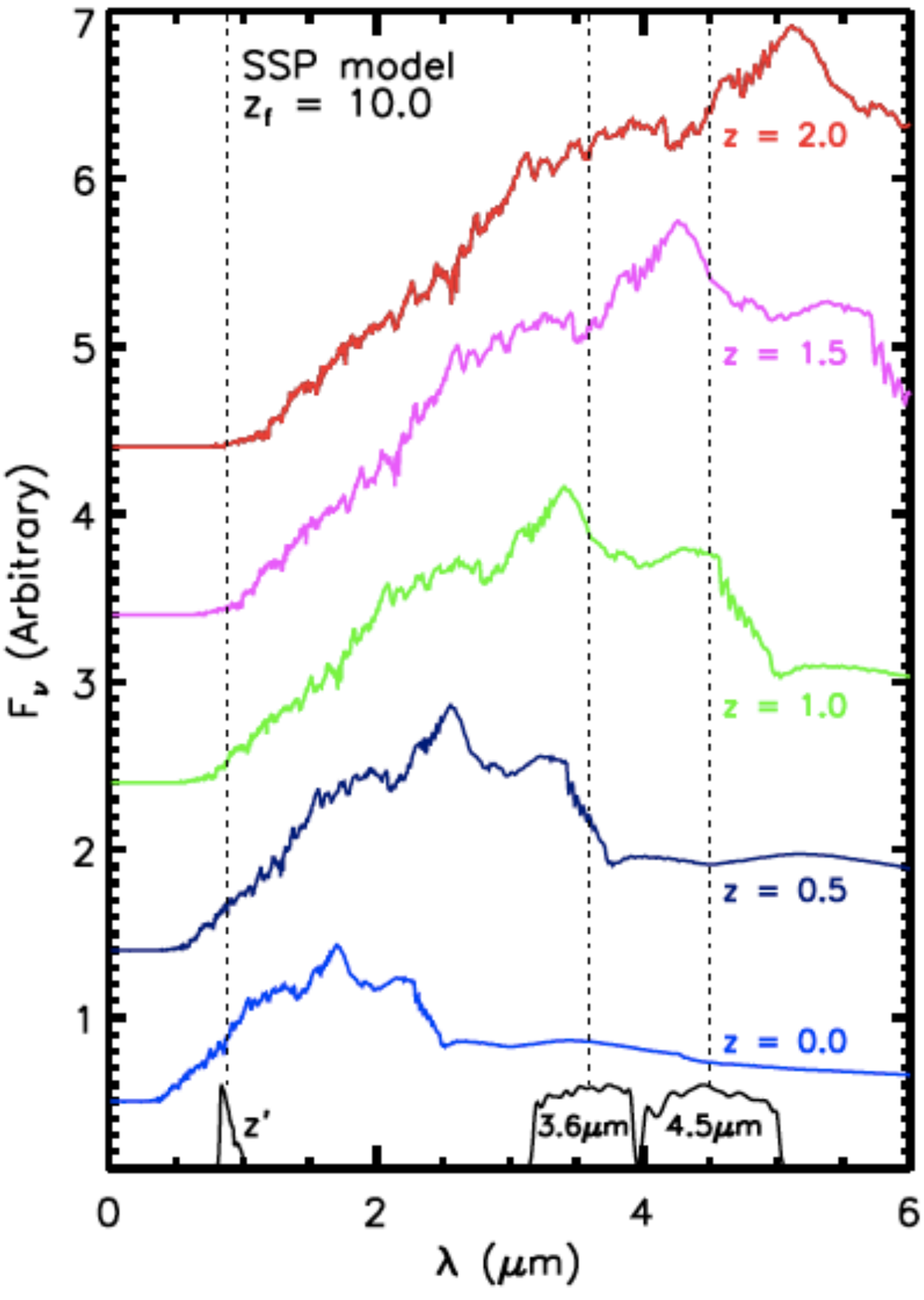




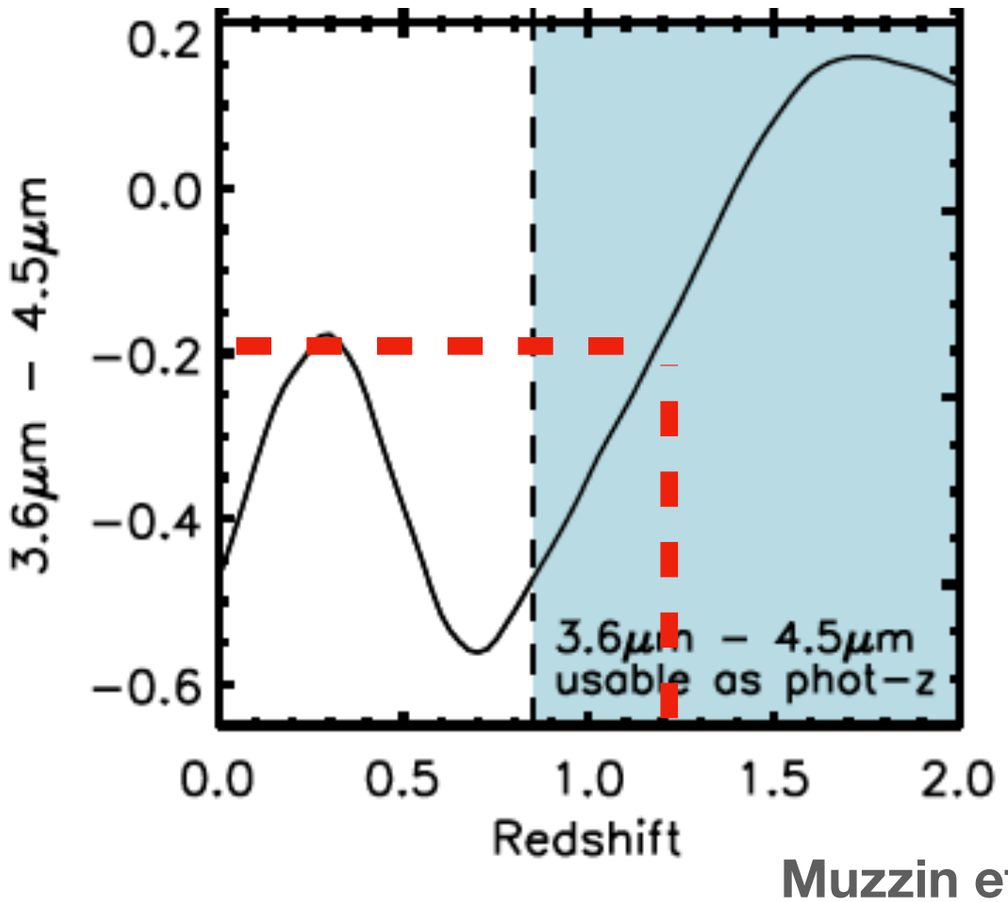
Muzzin et al. 2013

Photometric redshift

with one color…



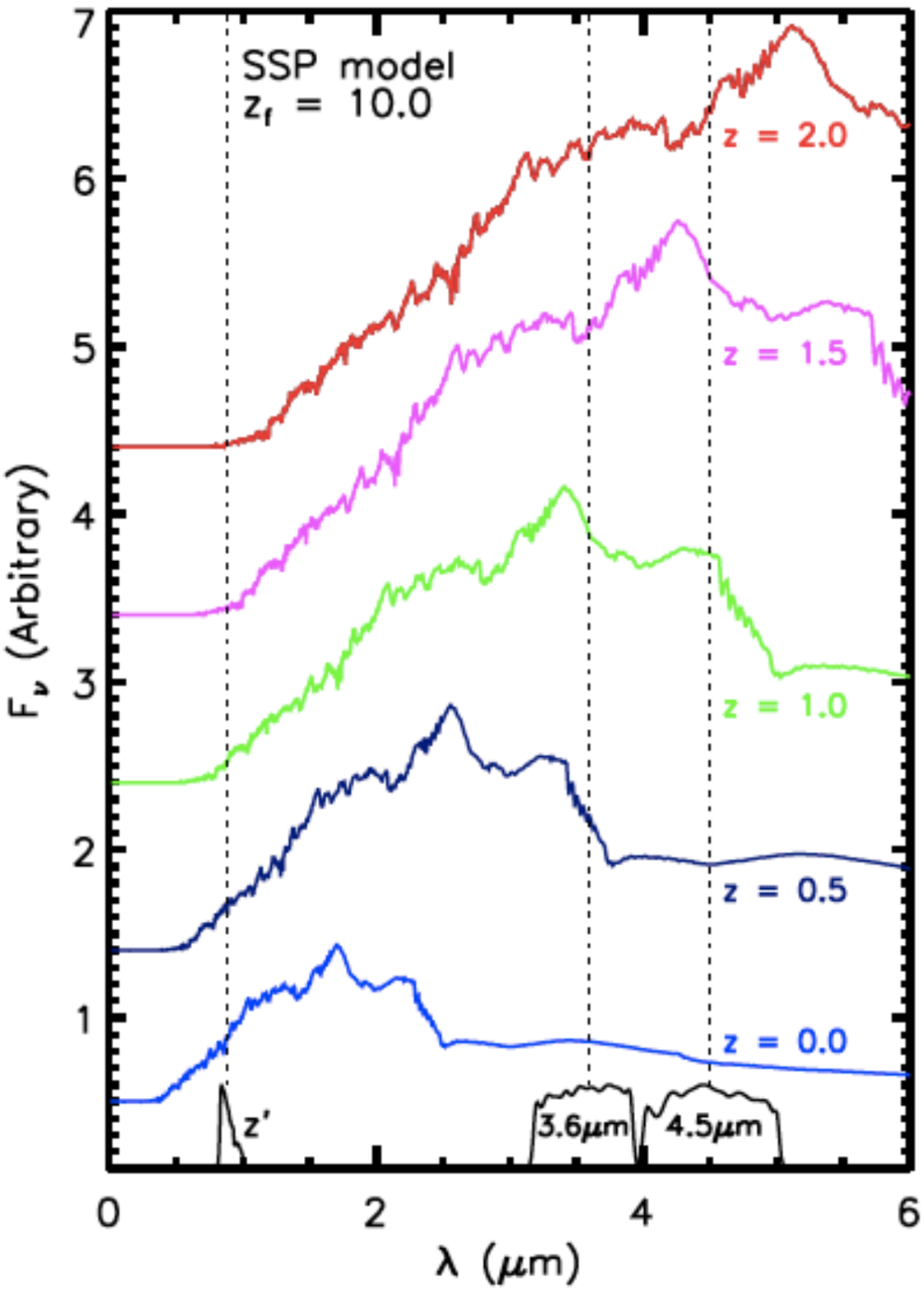
z>1.2

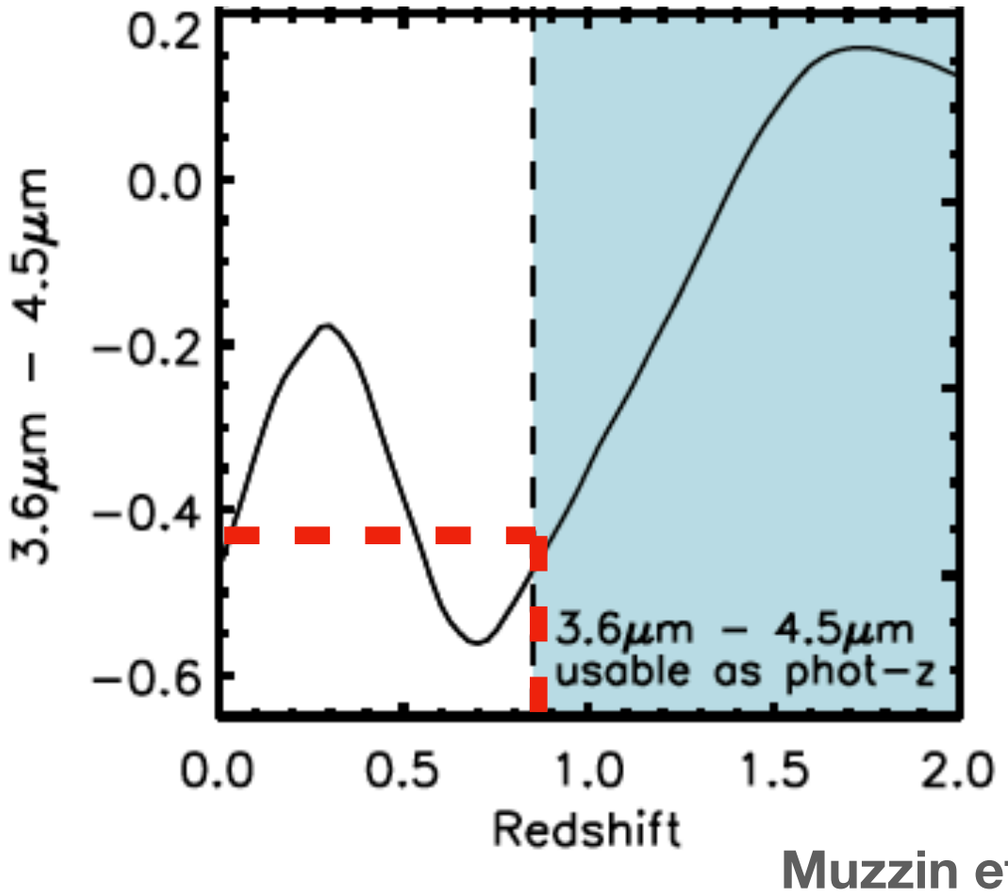


Muzzin et al. 2013

Photometric redshift

with one color…

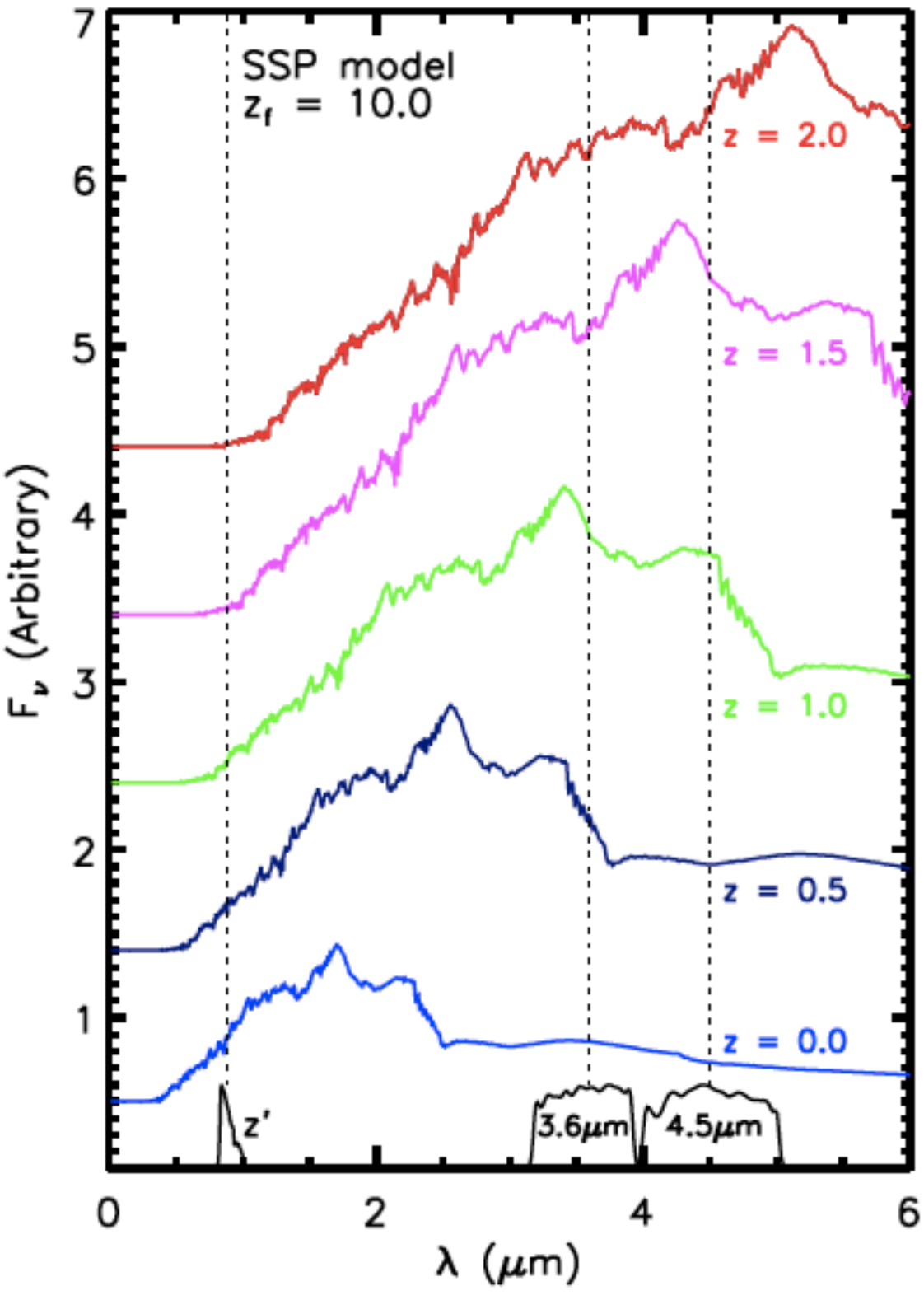


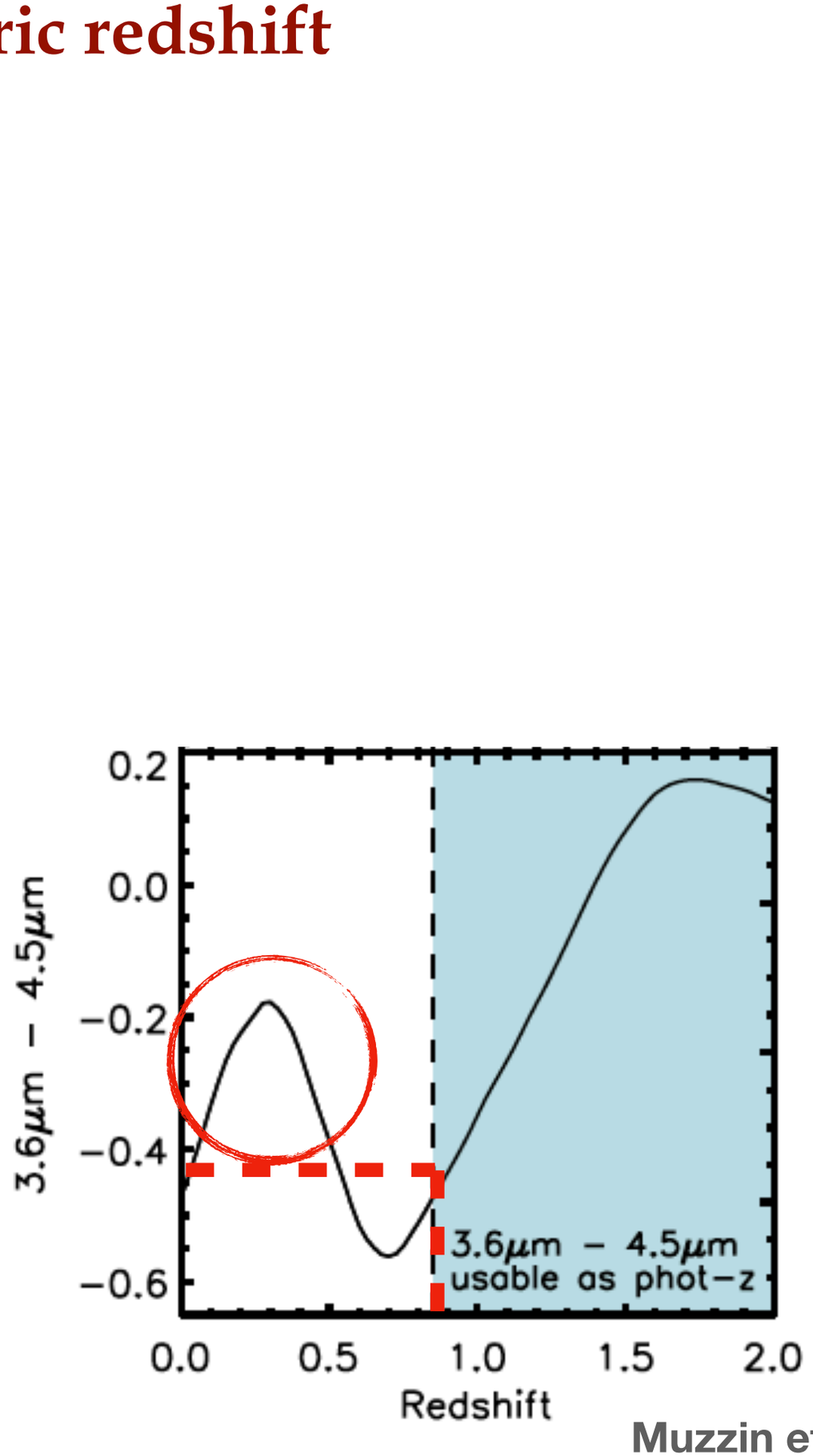


Muzzin et al. 2013

Photometric redshift

with one color…

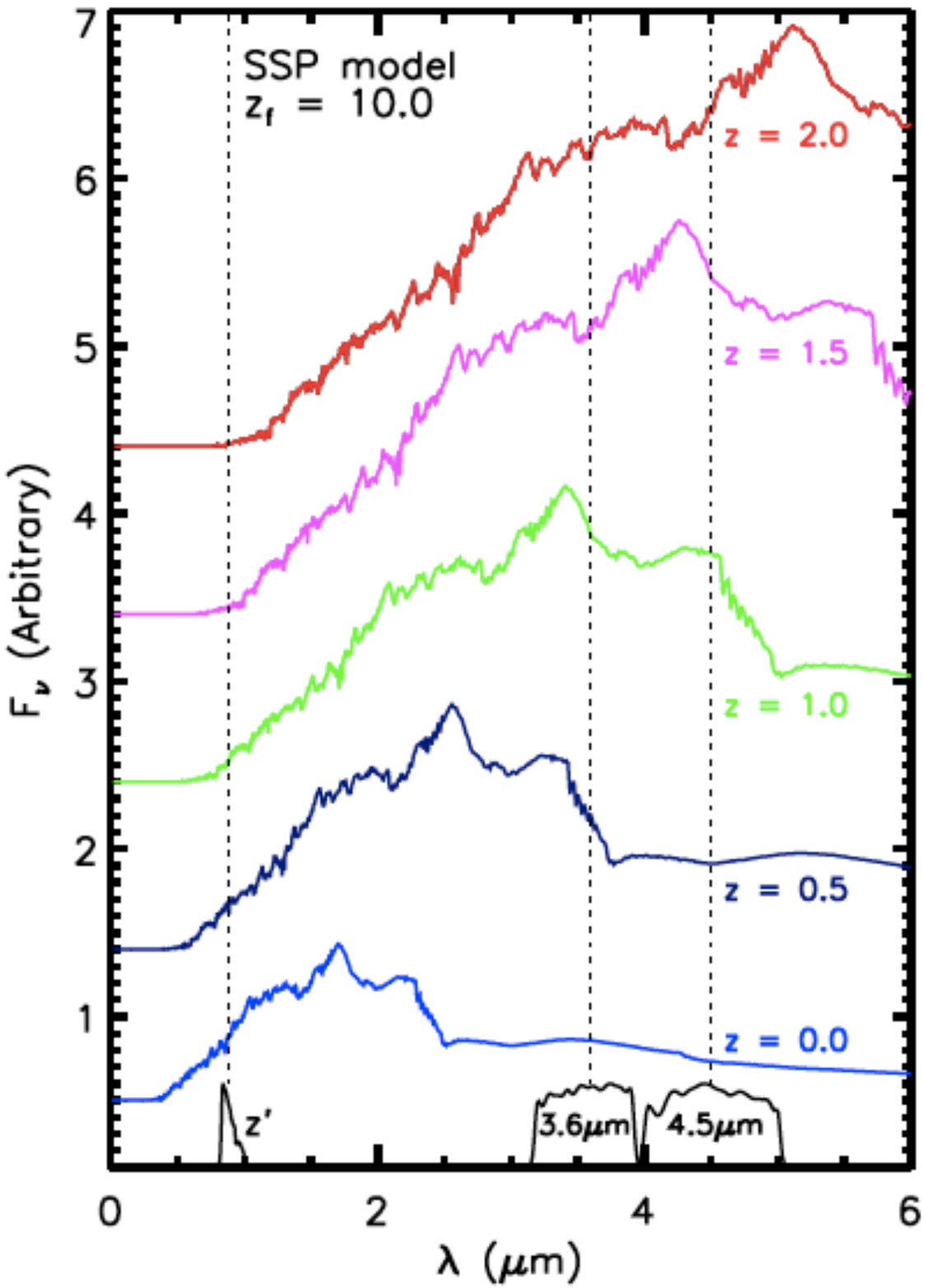




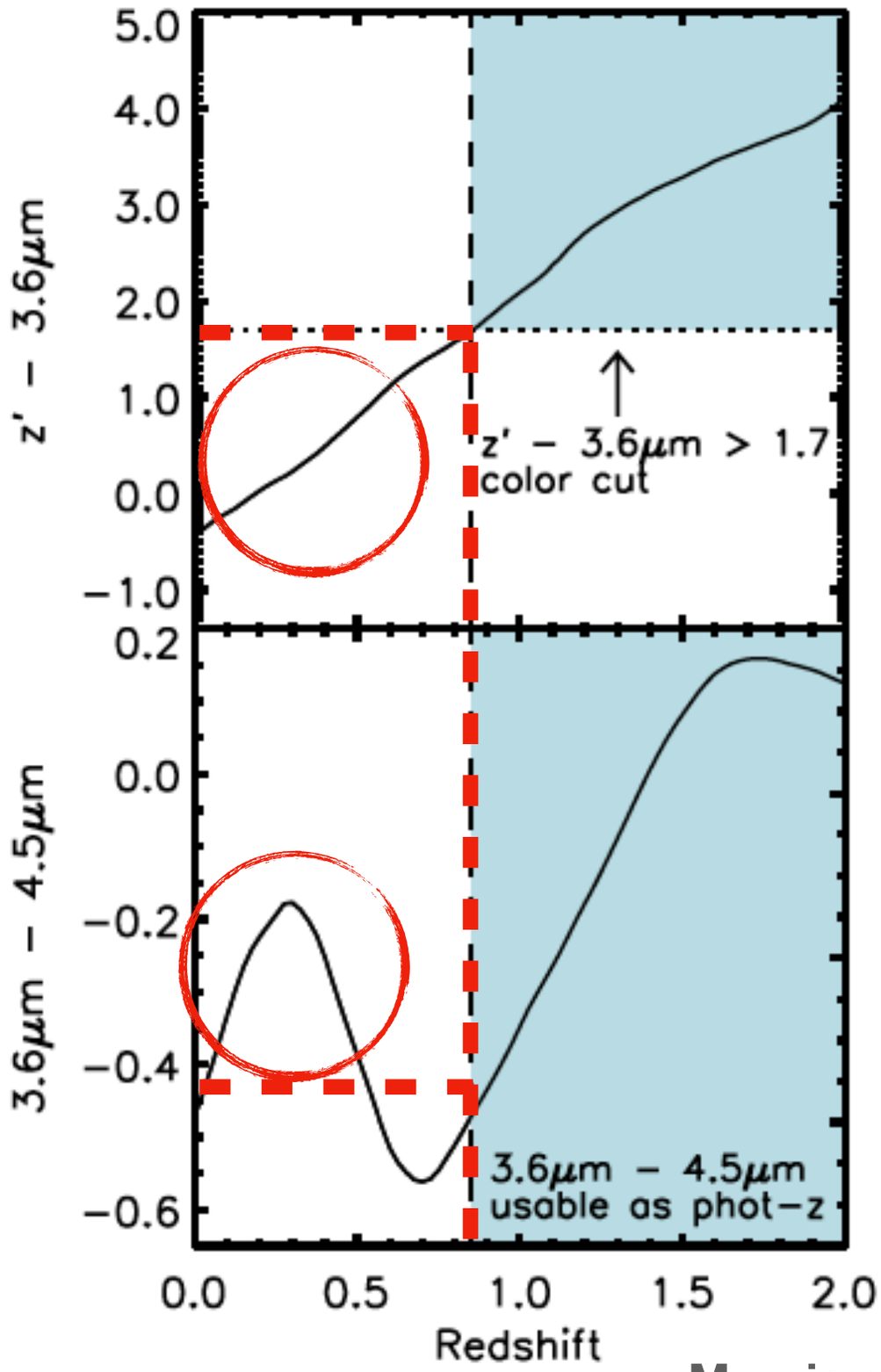
Muzzin et al. 2013

Photometric redshift

… or maybe two



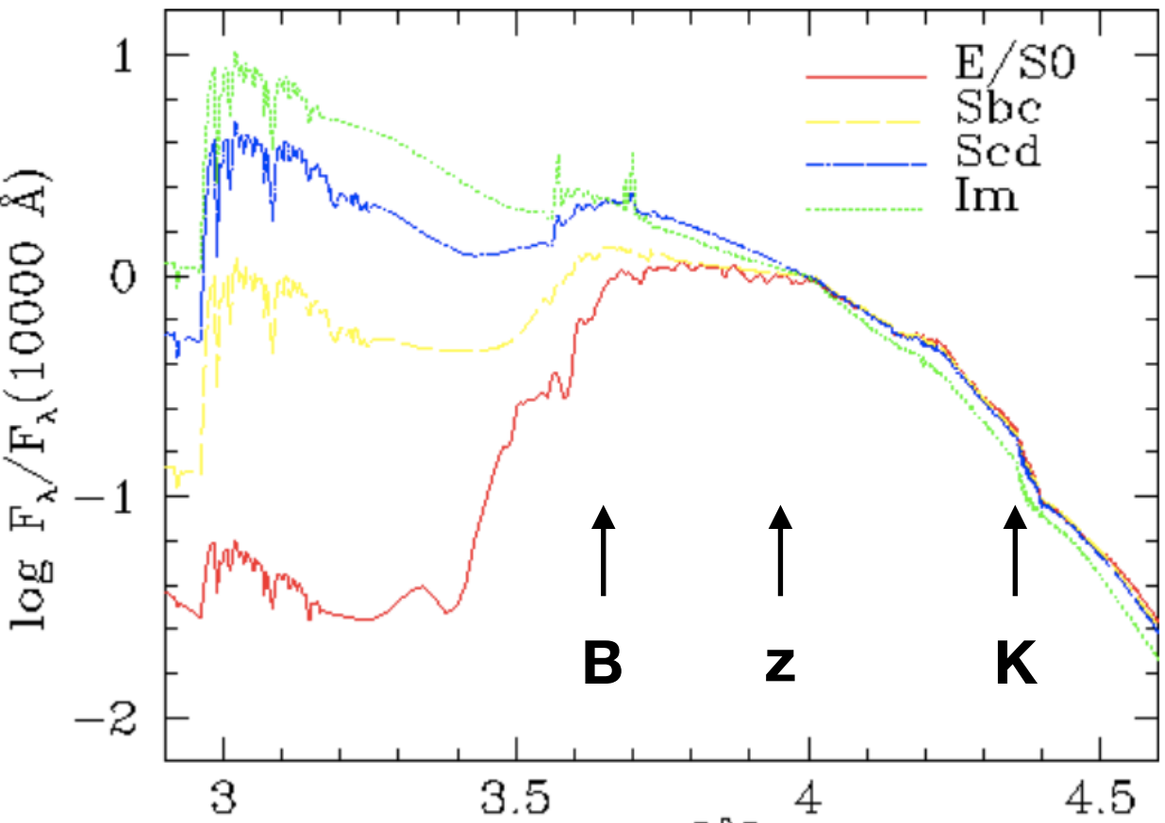
z>0.9



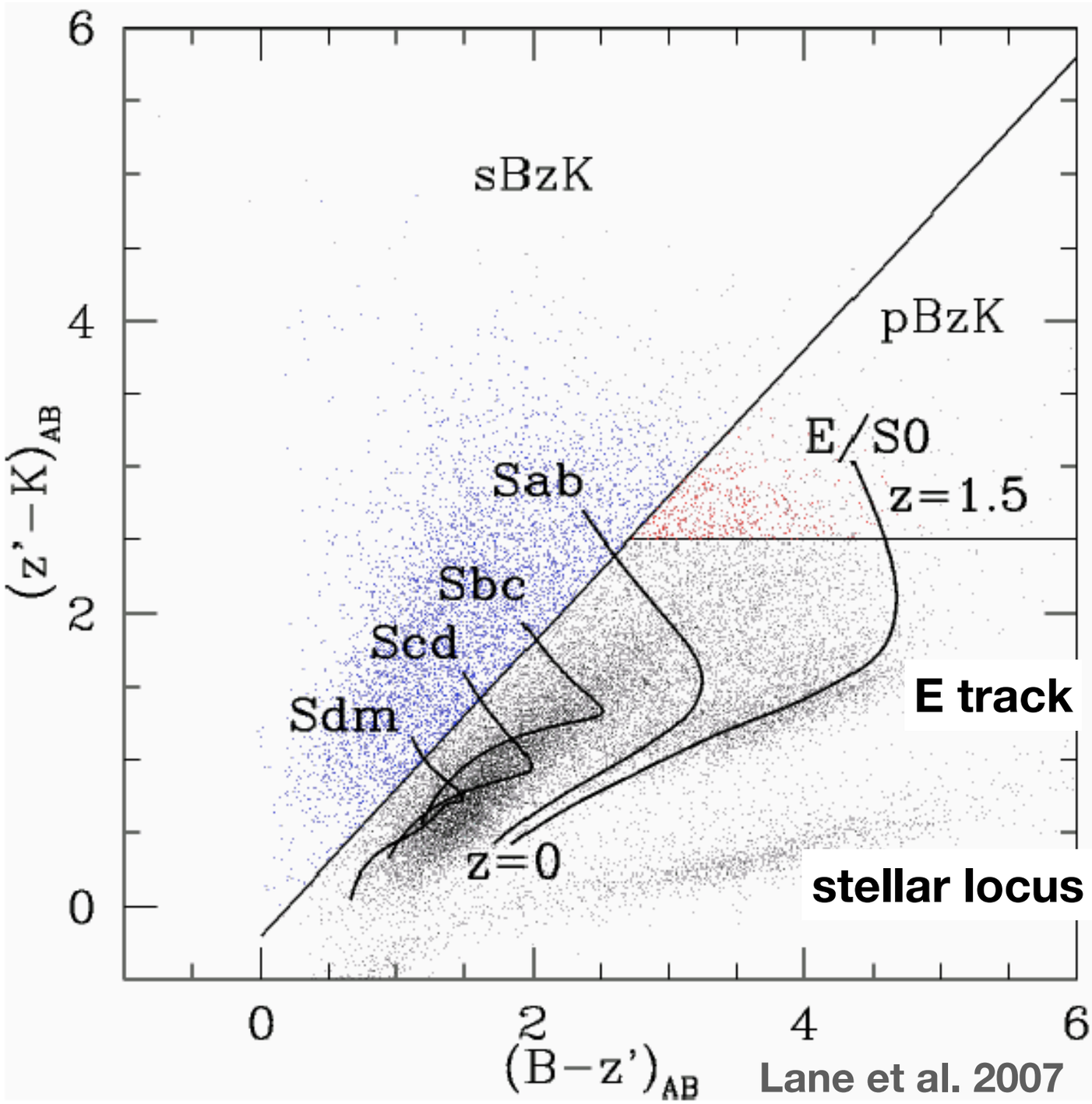
Muzzin et al. 2013

Photometric redshift

… or maybe two



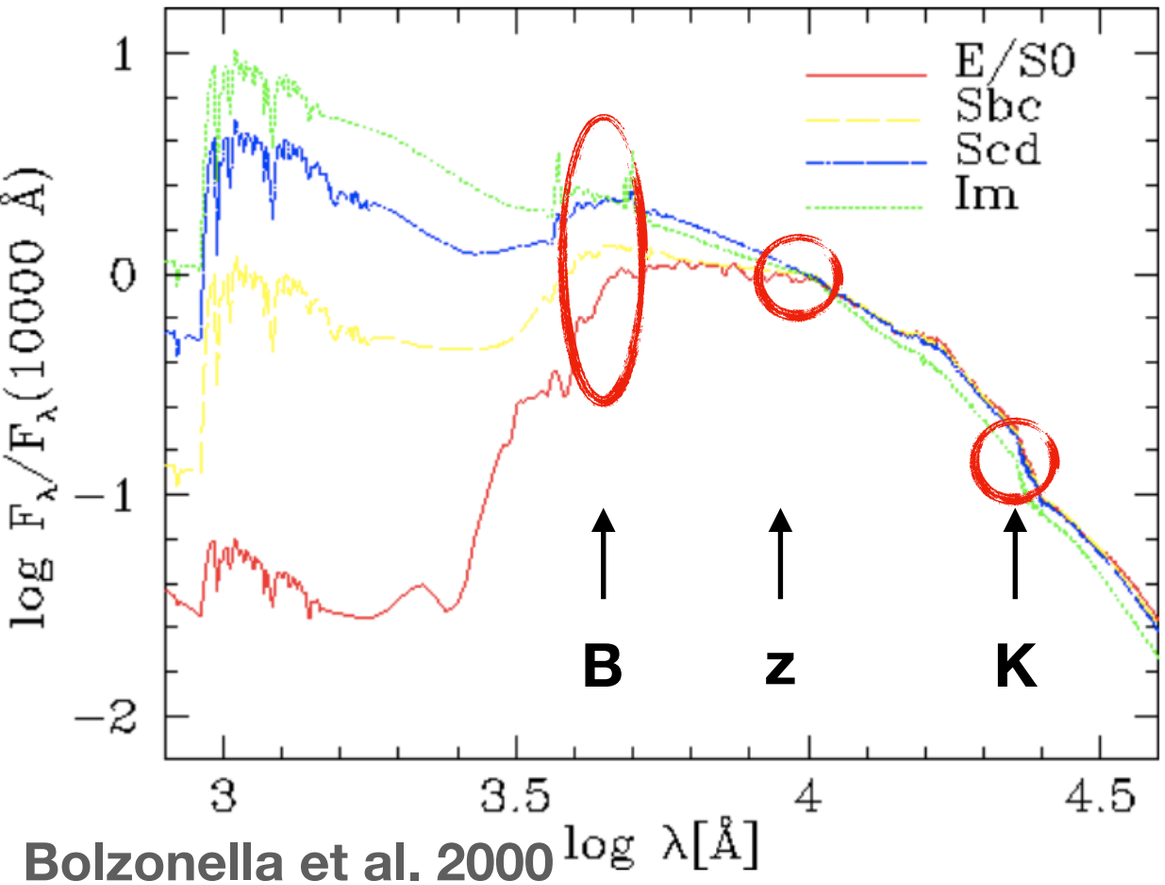
Bolzonella et al. 2000



Lane et al. 2007

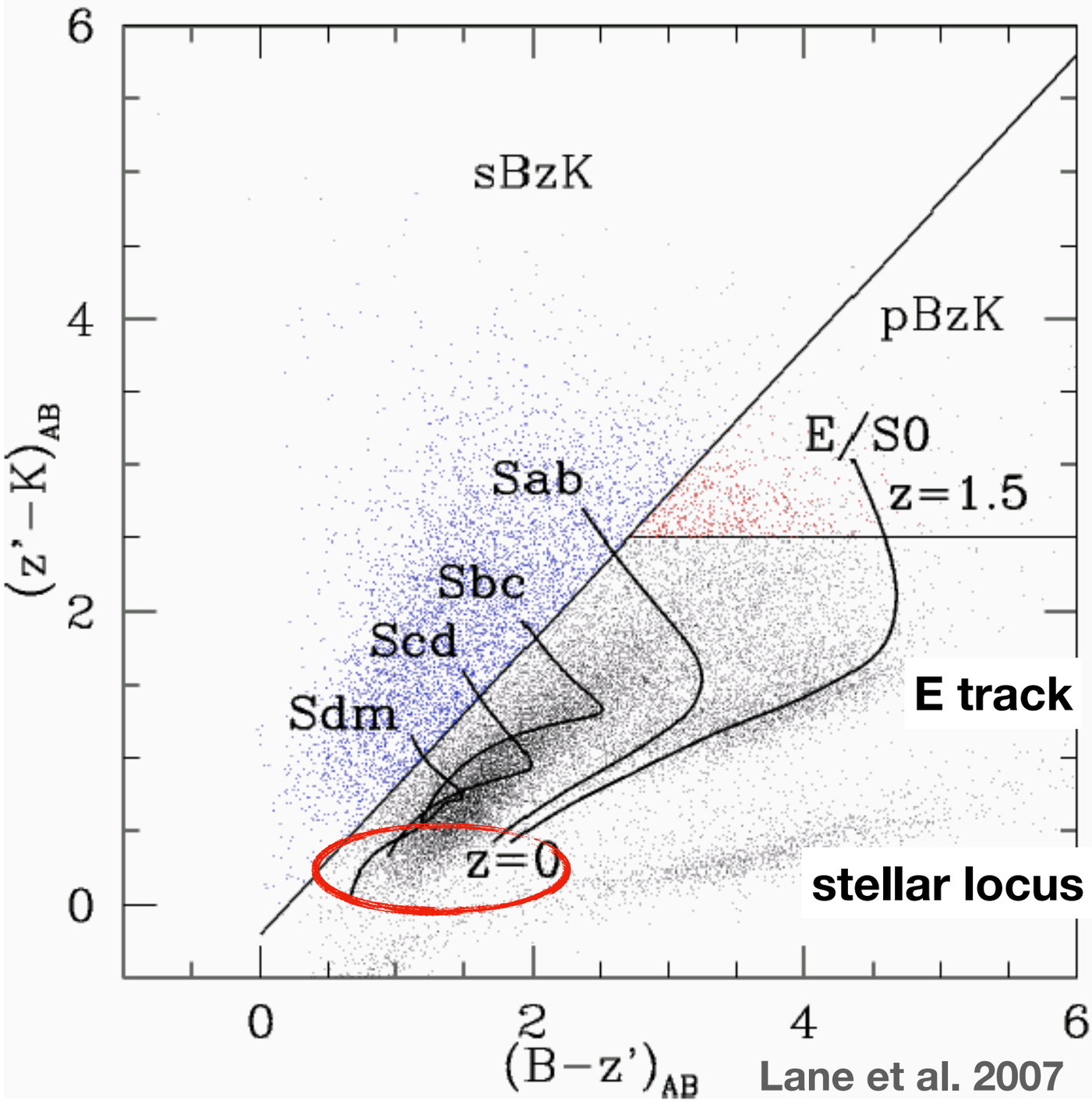
Photometric redshift

… or maybe two



Bolzonella et al. 2000

z>1.5

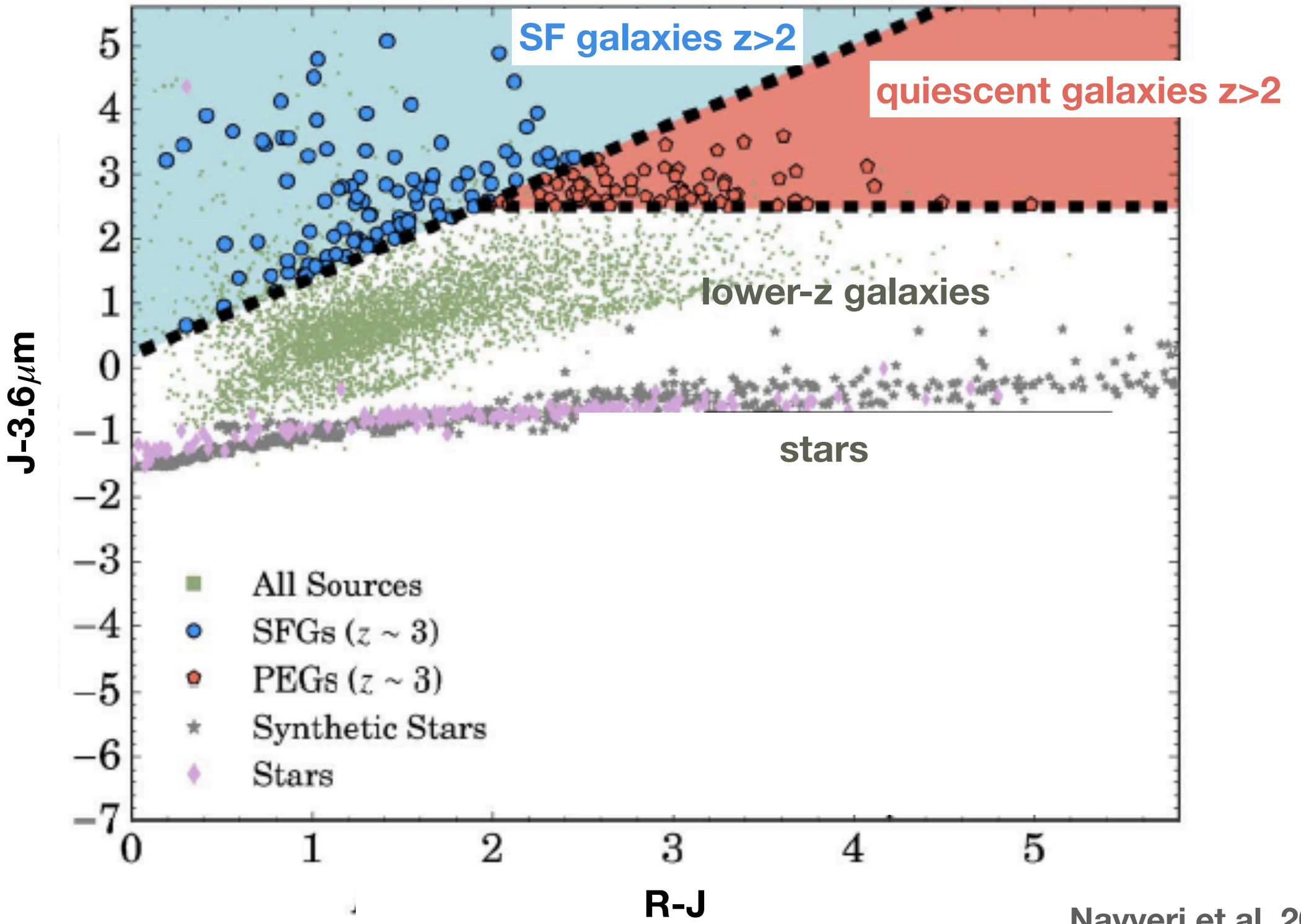


Lane et al. 2007

Photometric redshift

… or maybe two

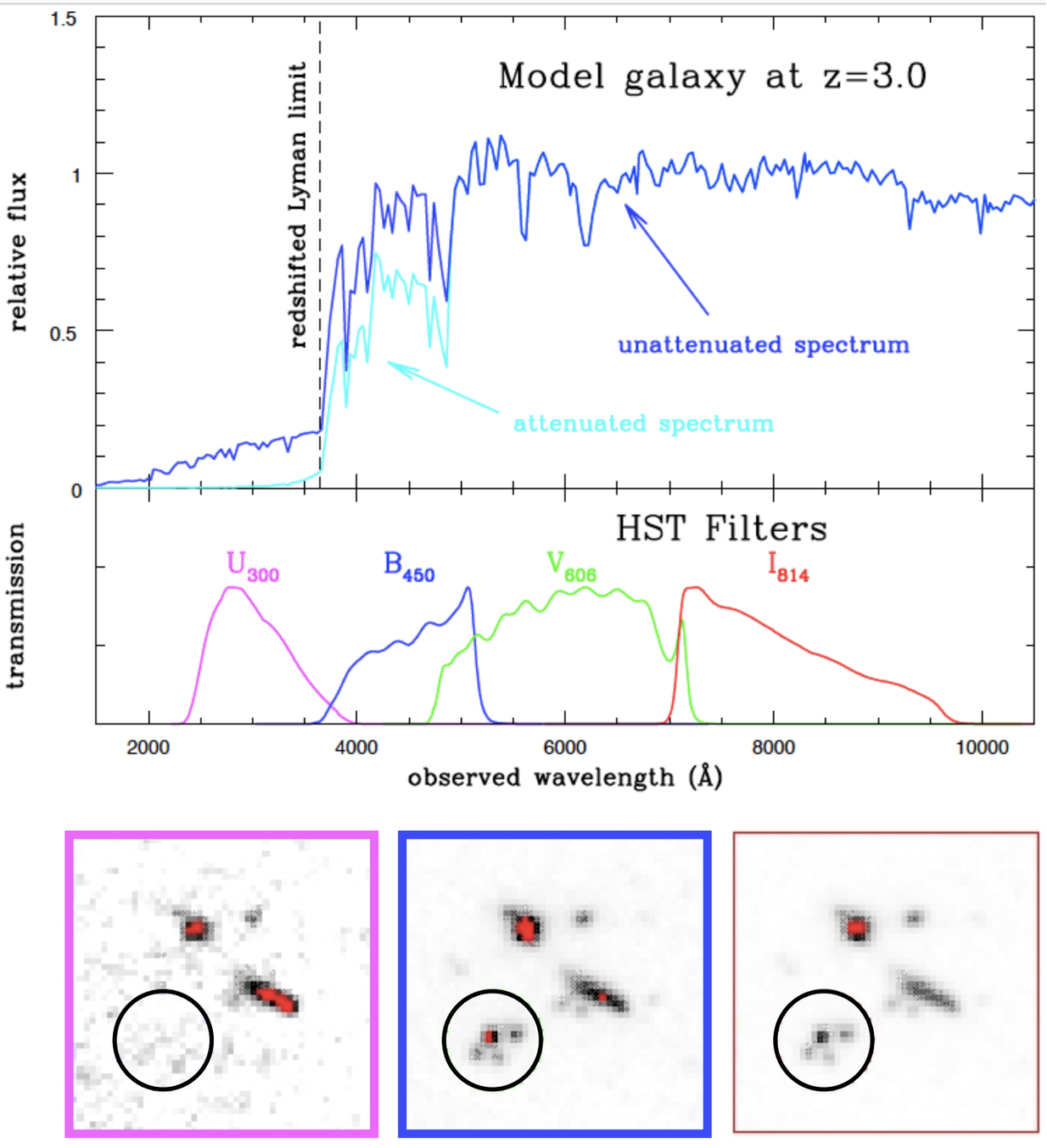
z>2



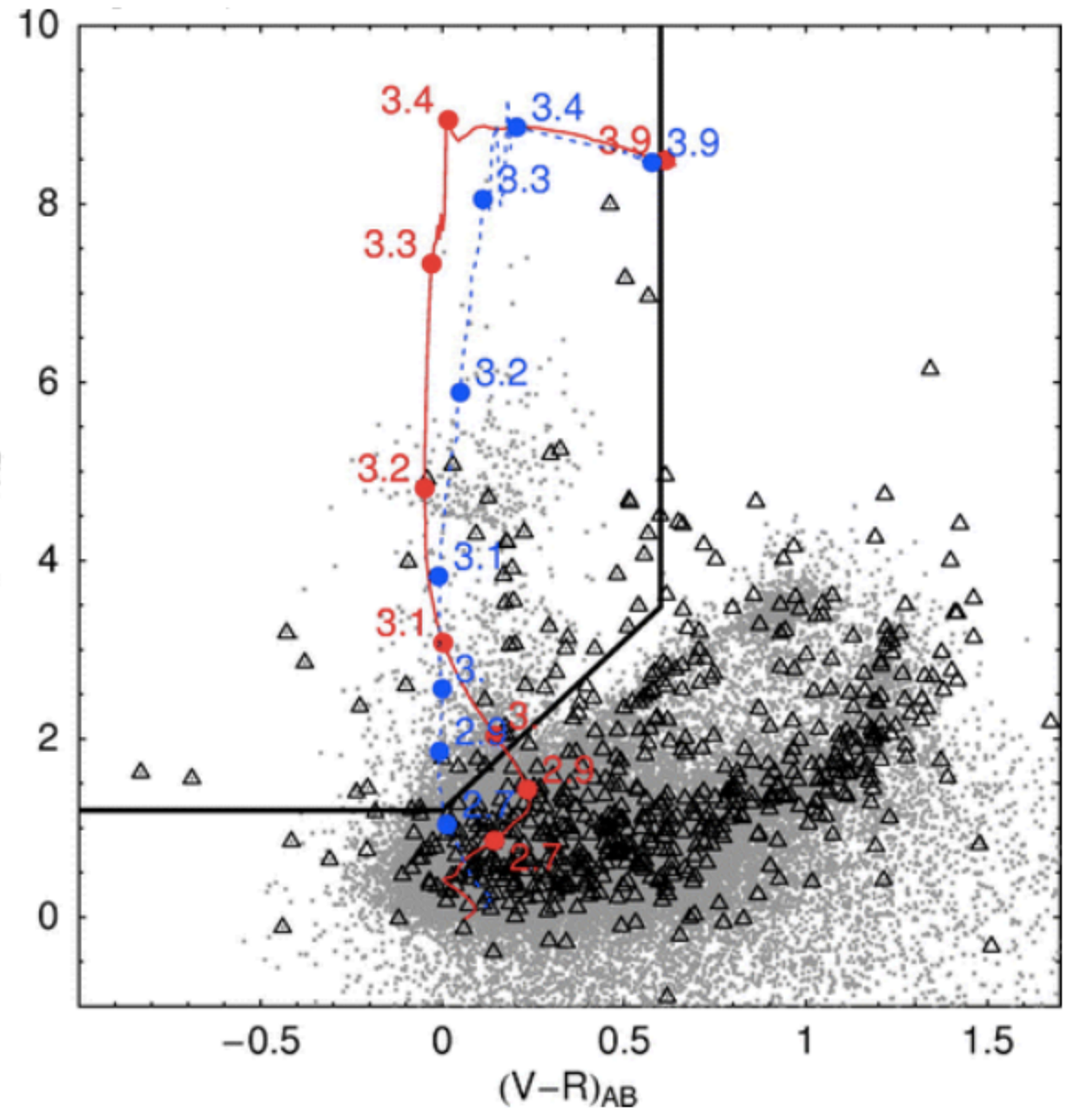
Nayyeri et al. 2017

Photometric redshift

… or maybe two



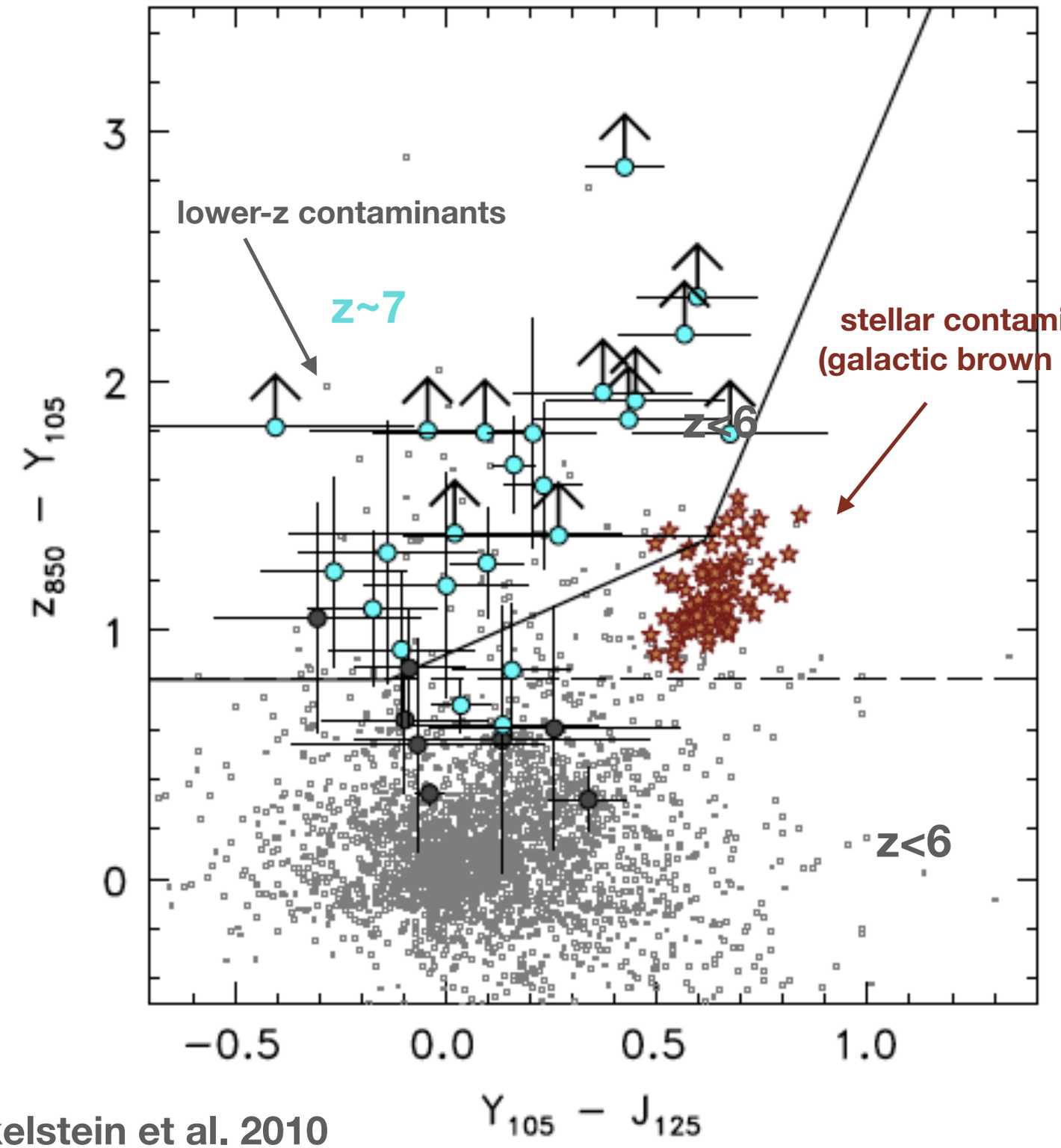
z>3



Steidel et al. 1996, Dickinson 1998

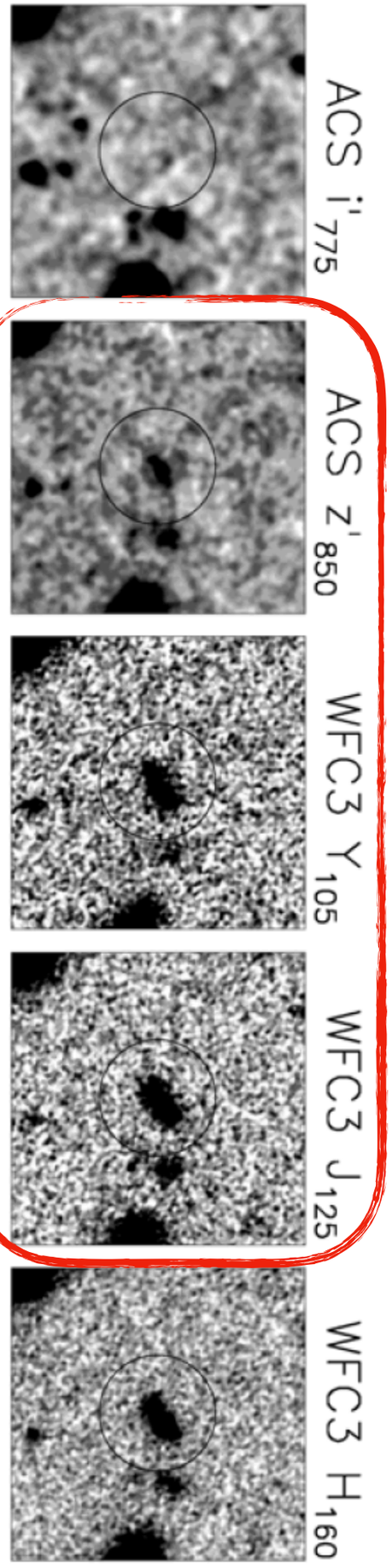
Photometric redshift

… or maybe two



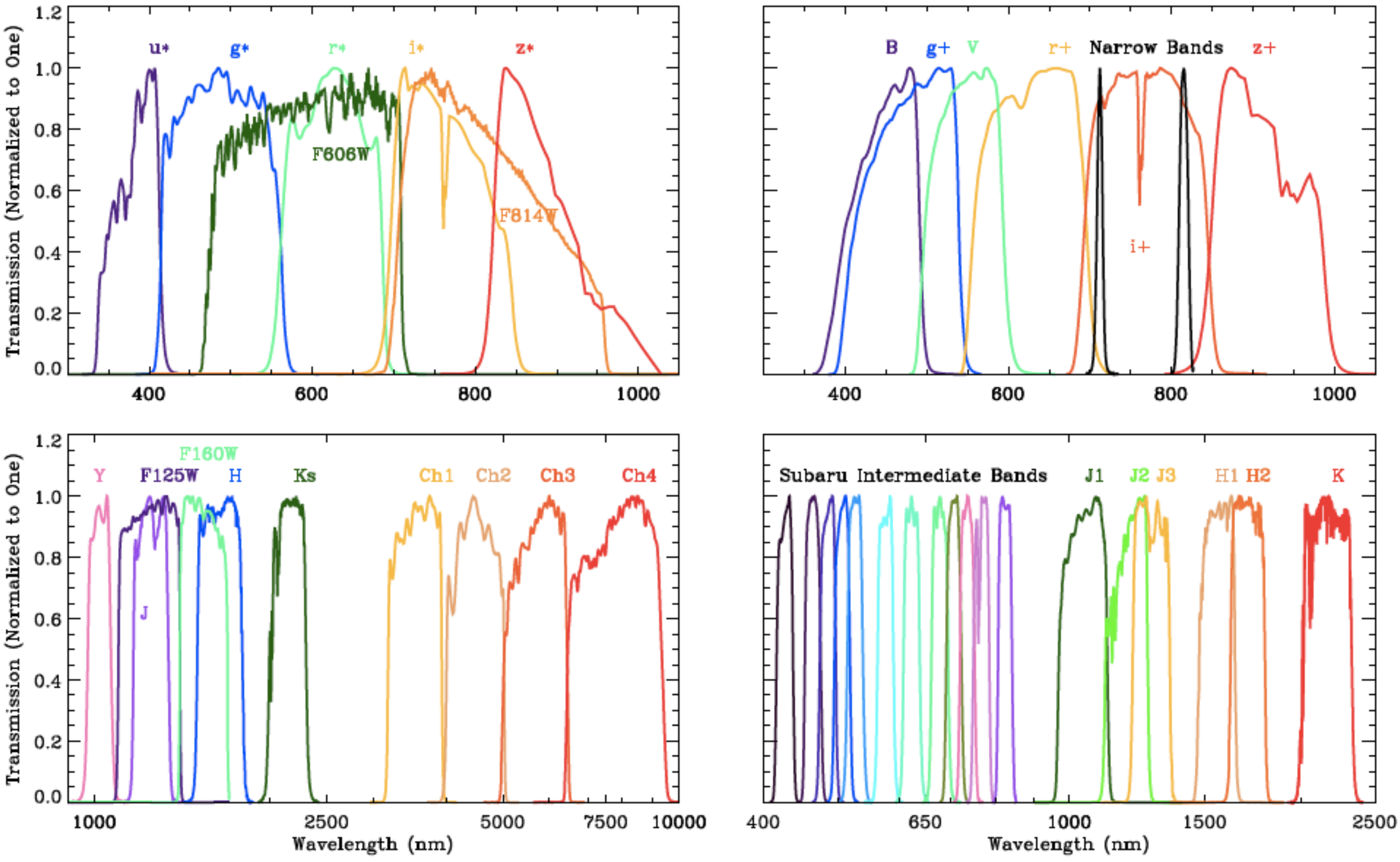
Finkelstein et al. 2010

z>6



Photometric redshift

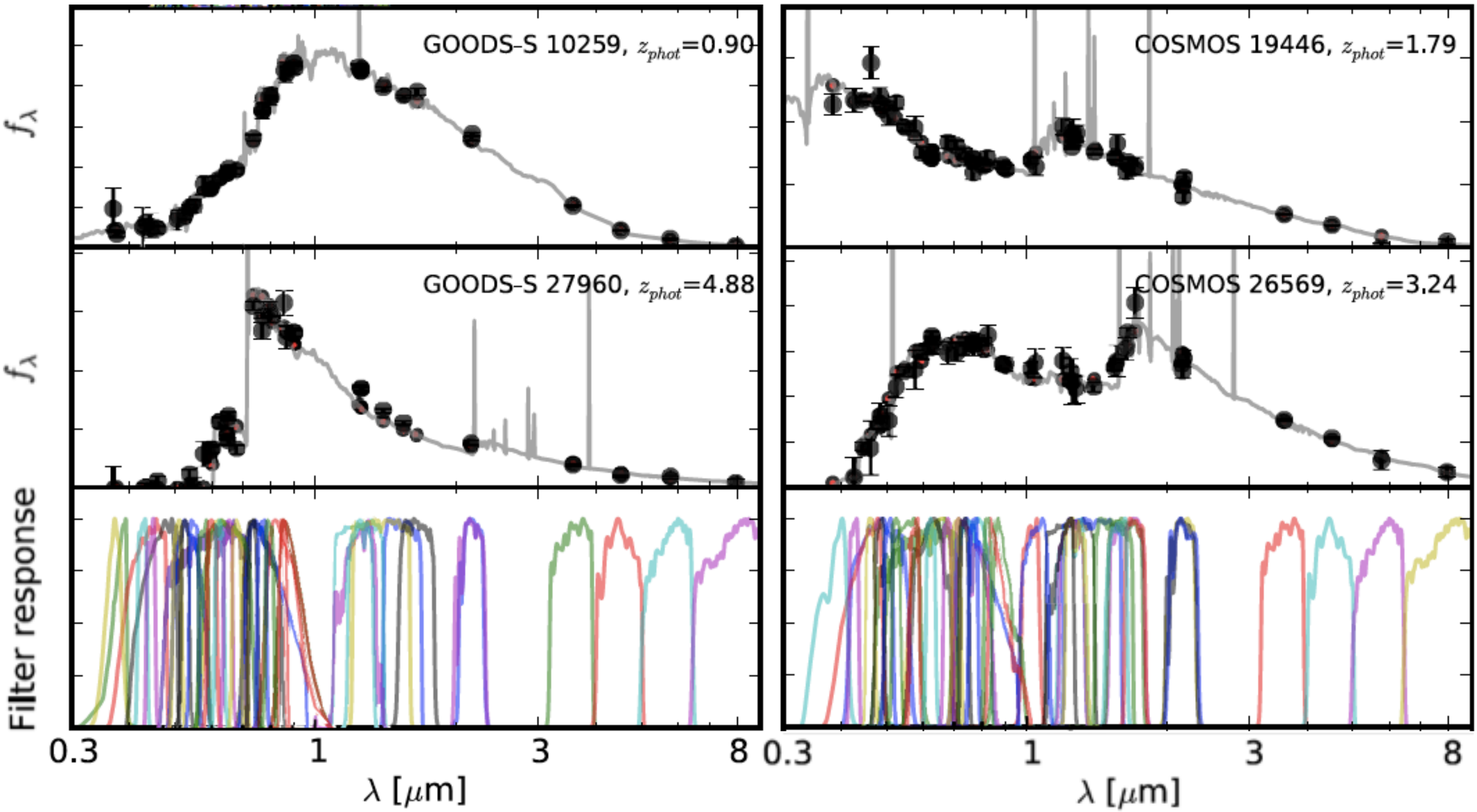
but in the best studied extragalactic deep fields, much more than two colors…



Nayyeri et al. 2017

Photometric redshift

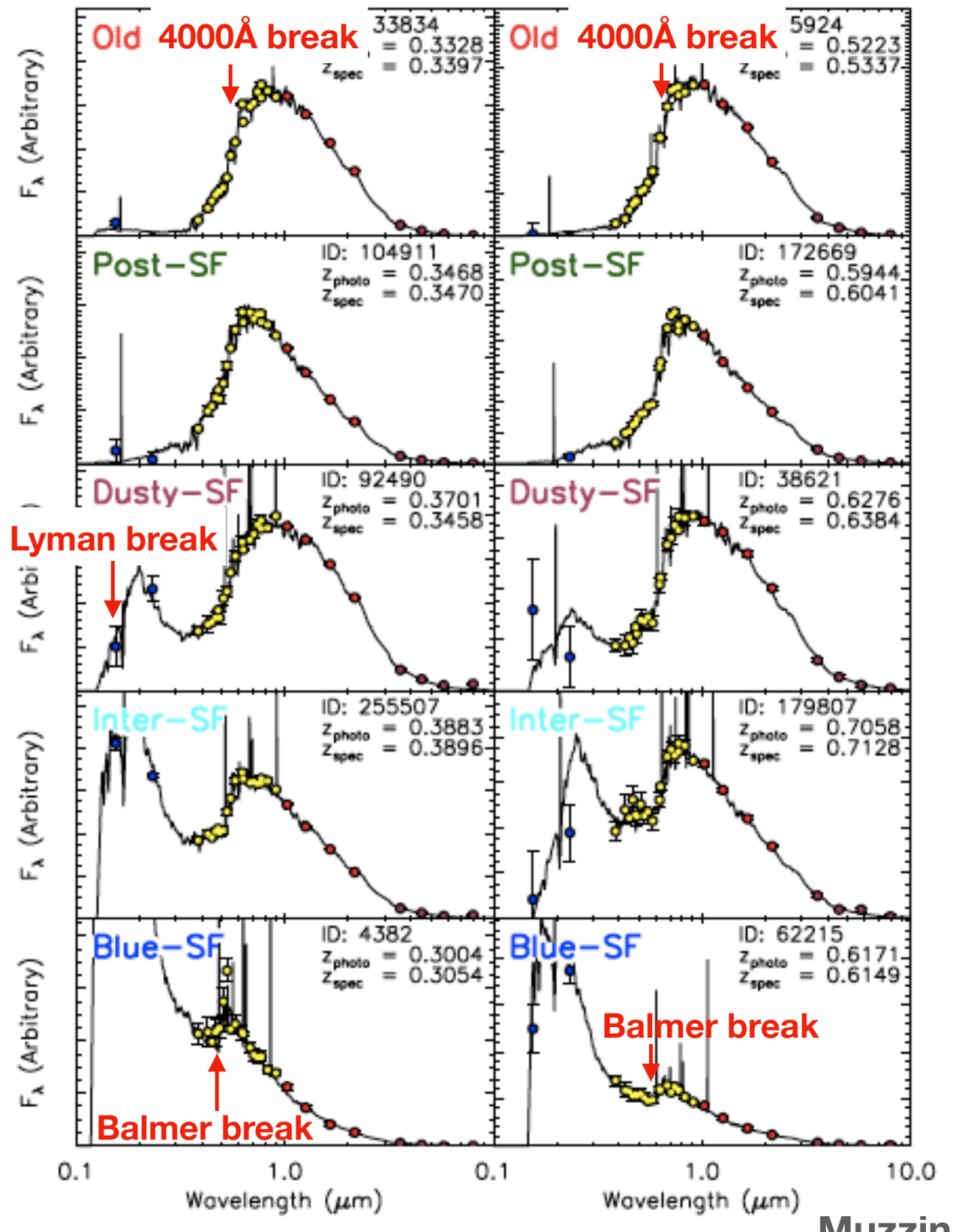
going full spectral coverage



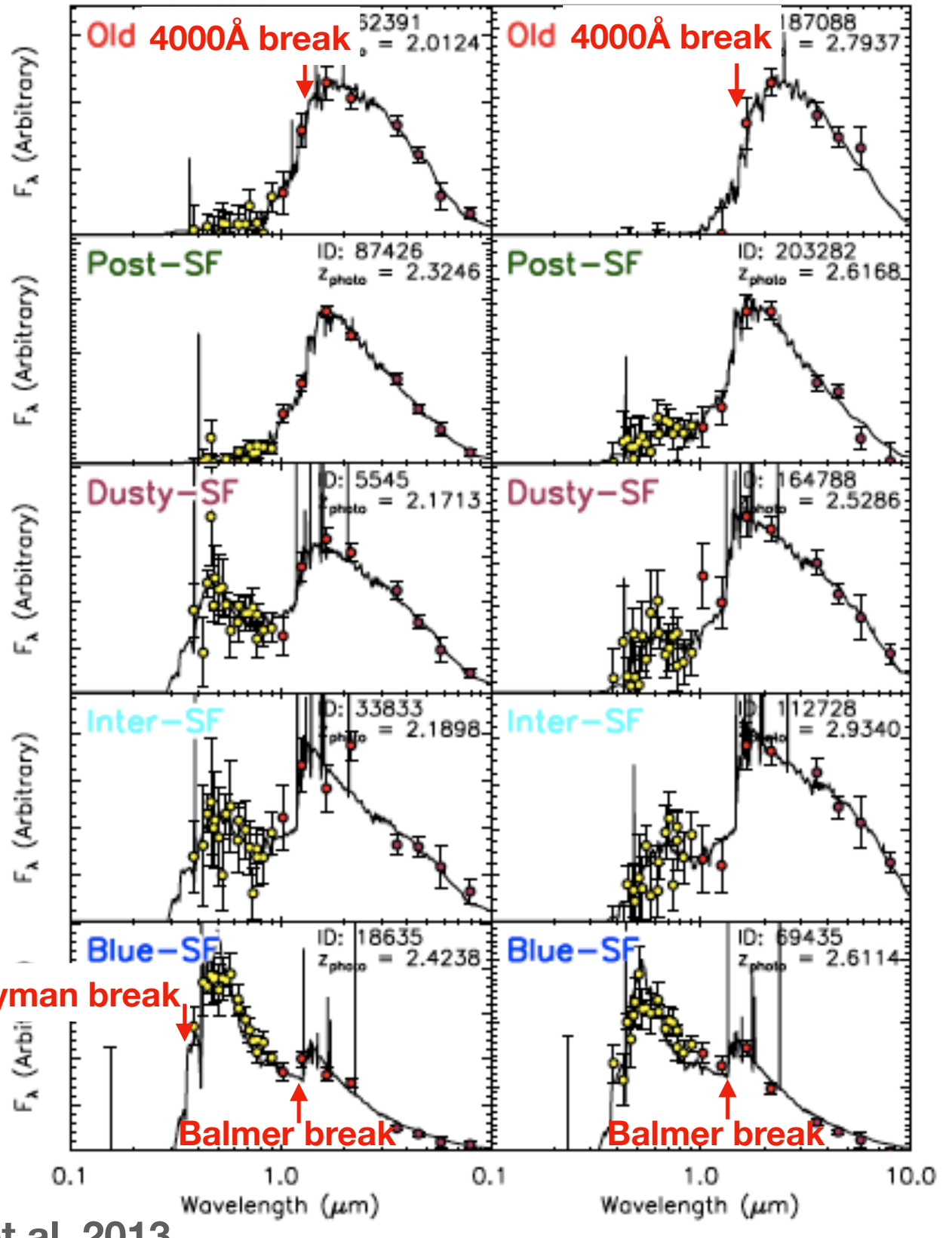
Skelton et al. 201

Photometric redshift

low redshift (z~0.3-0.7)



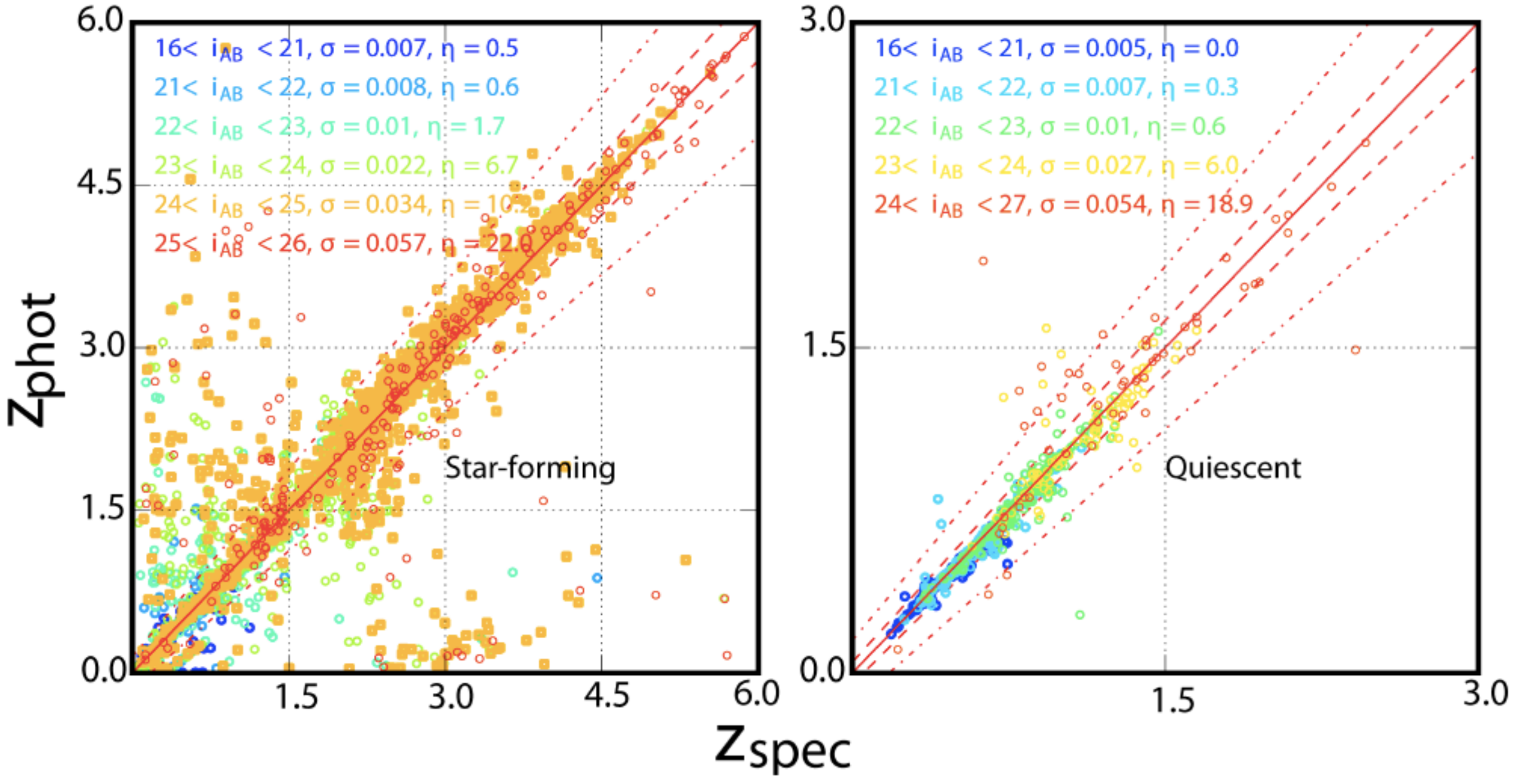
high redshift (z~2-3)



Muzzin et al. 2013

Photometric redshift

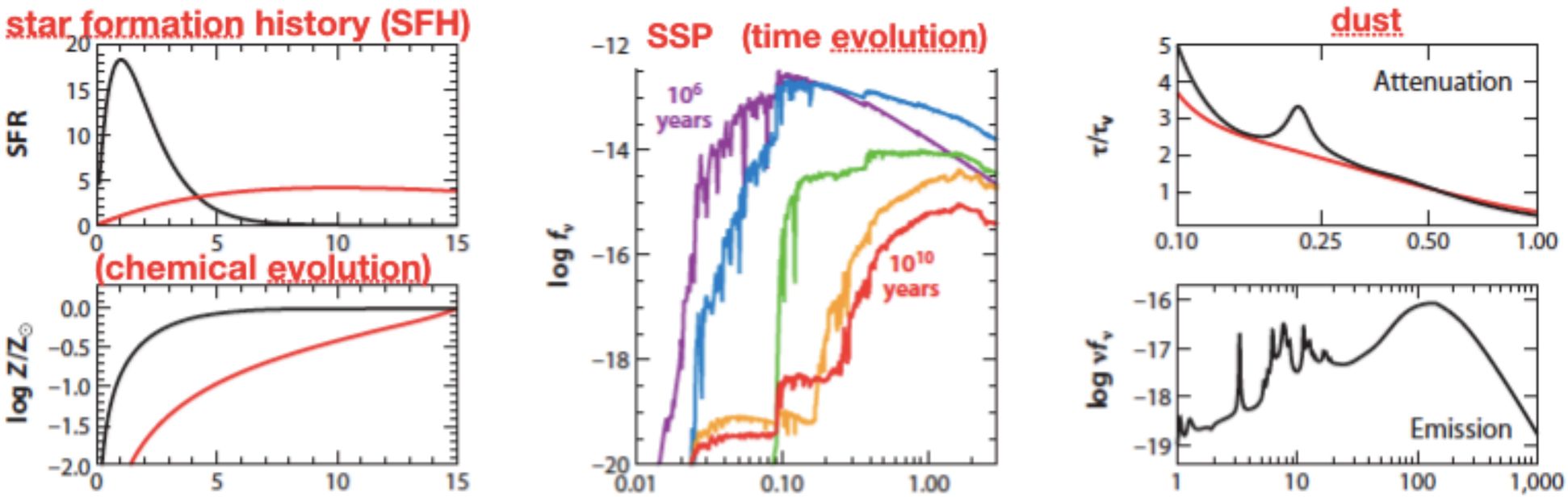
going full spectral coverage



Laigle et al. 2016

Stellar population properties

a couple things to keep in mind…

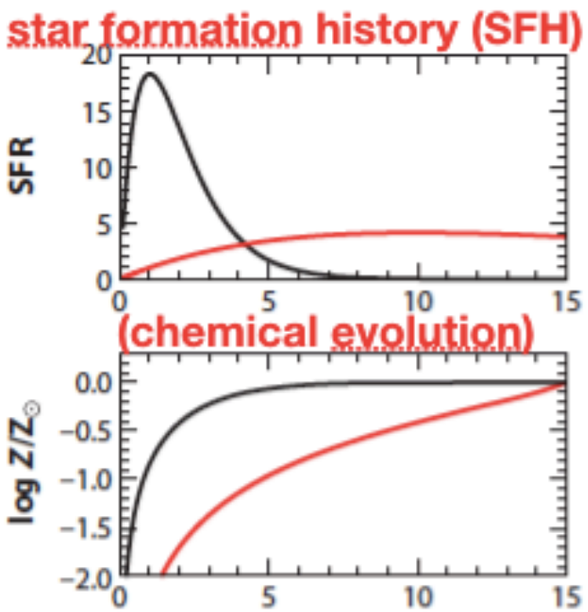


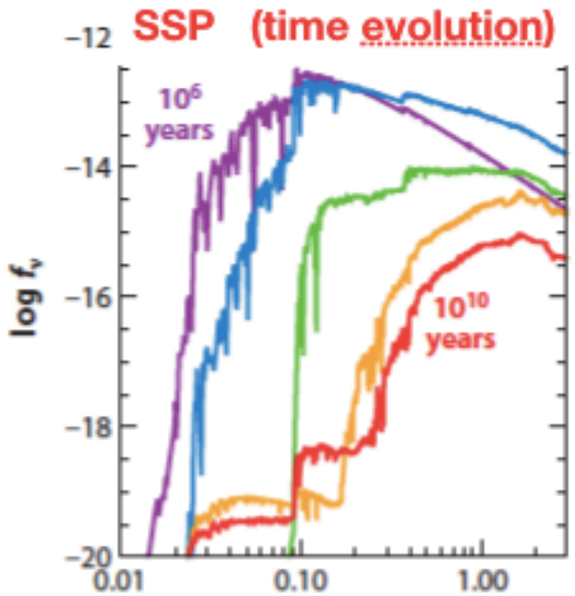
Conroy 2013

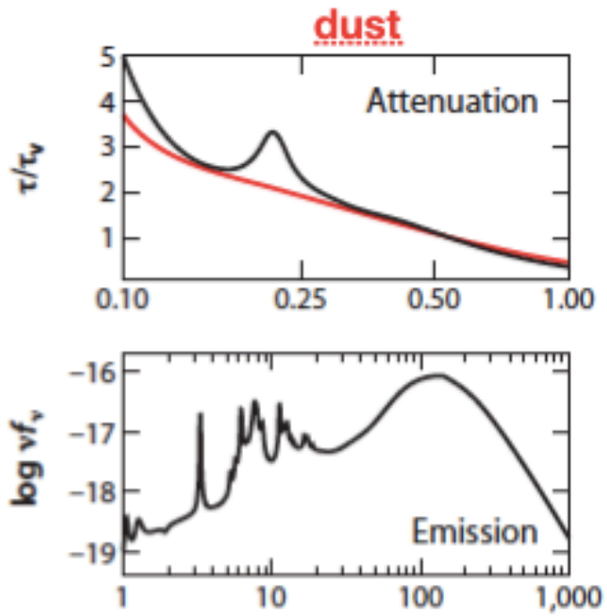
$$f_{\rm CSP}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\rm max}} \left({\rm SFR}(t-t') P(Z, t-t') f_{\rm SSP}(t', Z) e^{-\tau_d(t')} + A\, f_{\rm dust}(t', Z) \right) {\rm d}t'\, {\rm d}Z$$

Stellar population properties

a couple things to keep in mind…







Conroy 2013

degeneracies between age/SFH, metallicity, dust

energy balance

dust attenuation

dust emission

$$f_{\rm SSP}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\rm max}} \left({\rm SFR}(t-t') P(Z, t-t') f_{\rm SSP}(t', Z) e^{-\tau_d(t')} + A\, f_{\rm dust}(t', Z) \right) {\rm d}t'\, {\rm d}Z$$

SFH

chemical evolution

SSP spectra

SSP age

SSP metallicity

Mass- and light-weighted ages

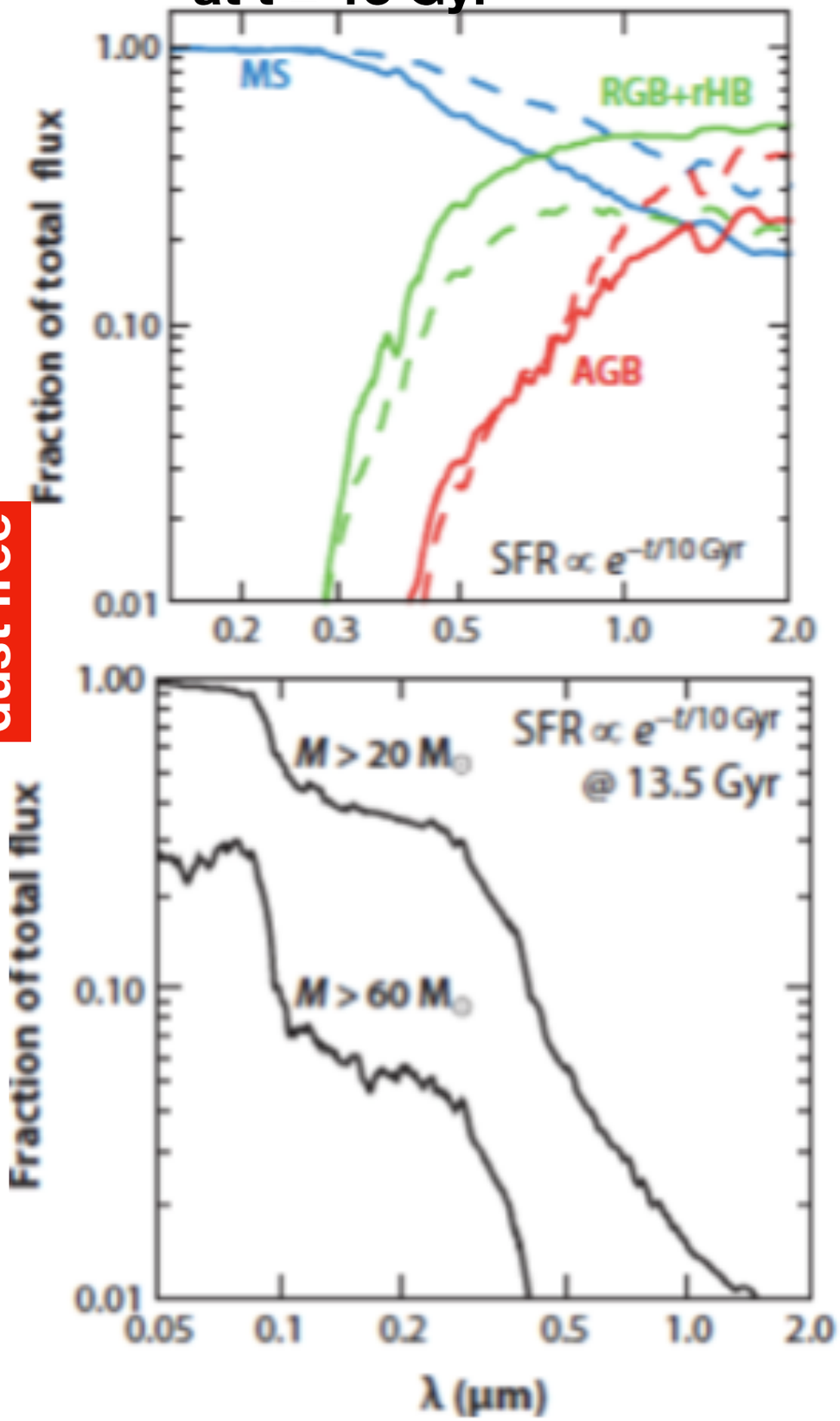
Furthermore …

——— at t = 1 Gyr

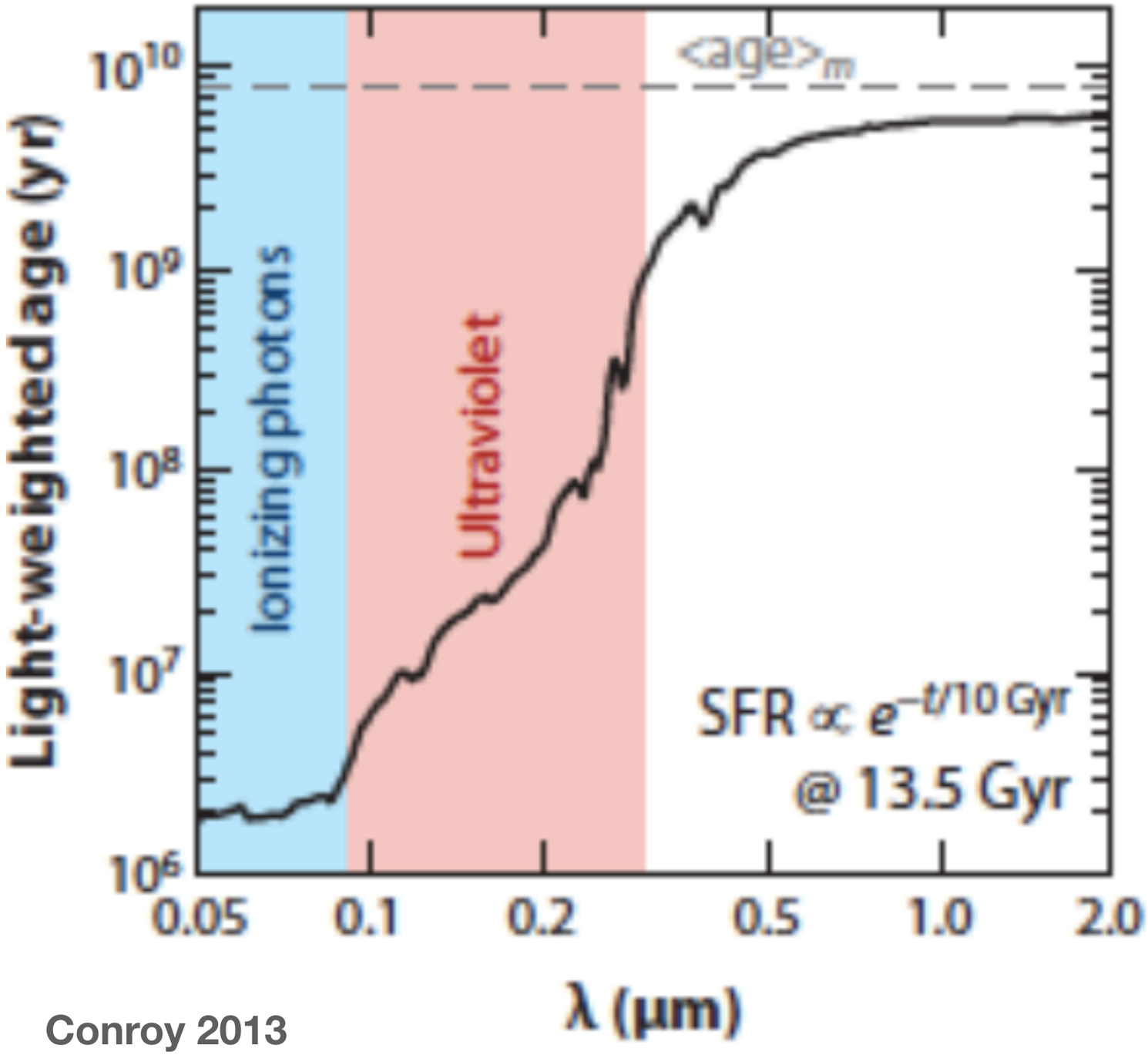
- - - - - at t = 13 Gyr

SFR(t) ∝ $e^{-t/10\ Gyr}$

dust free



light- vs. mass-weighted age as a function of wavelength at 13.5 Gyr

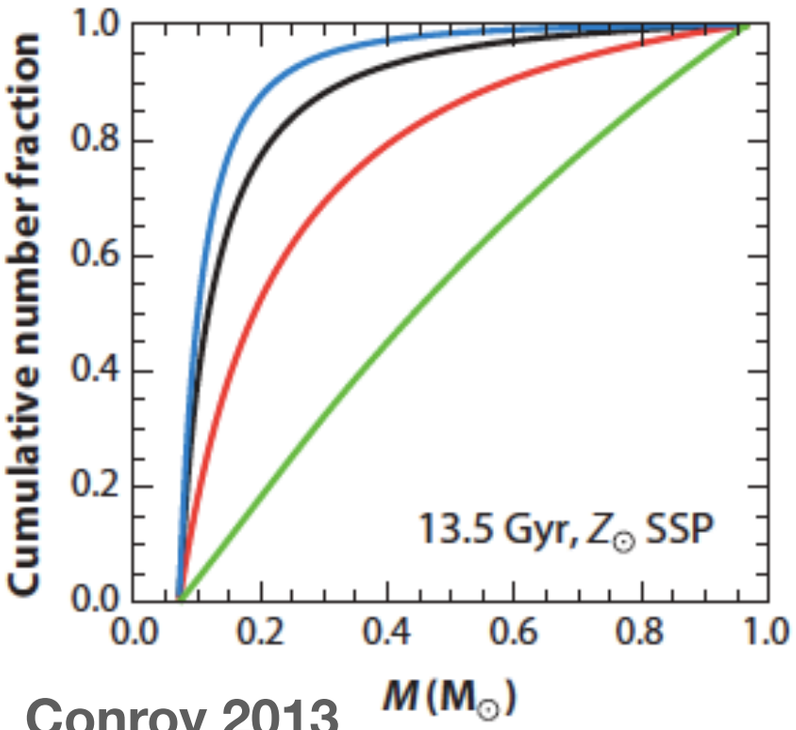


Conroy 2013

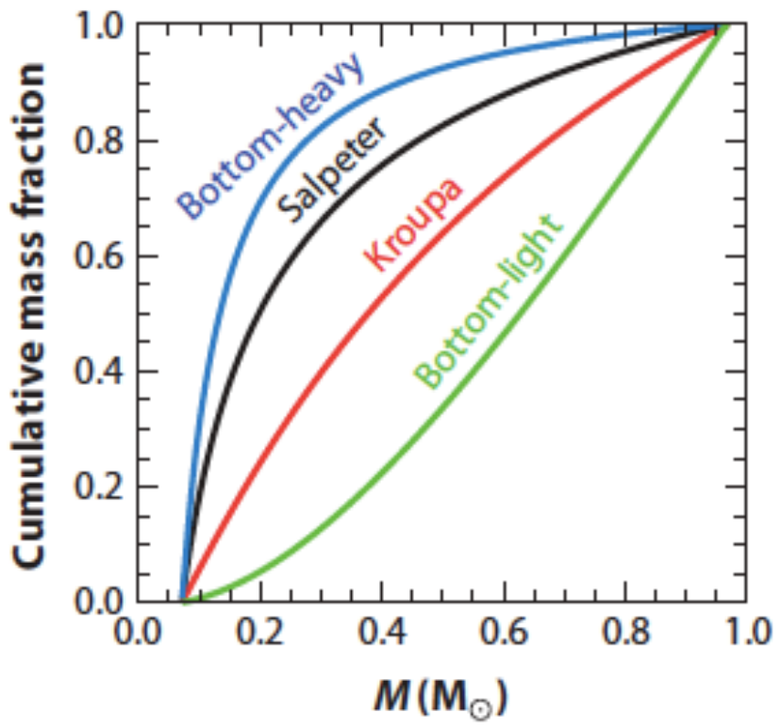
Contribution of stars of different mass to total stellar mass and flux

SSP at t = 13.5 Gyr

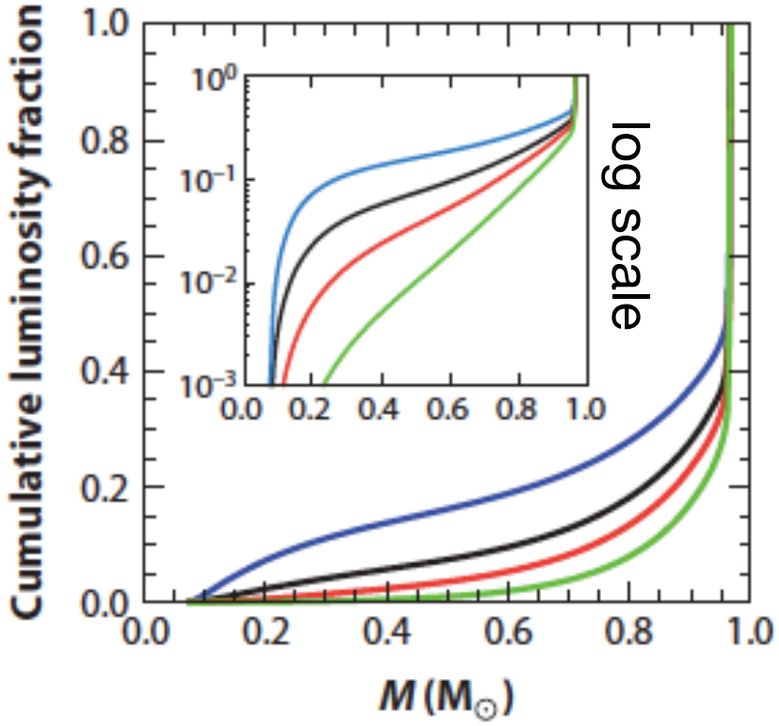
contribution to number of stars



total stellar mass

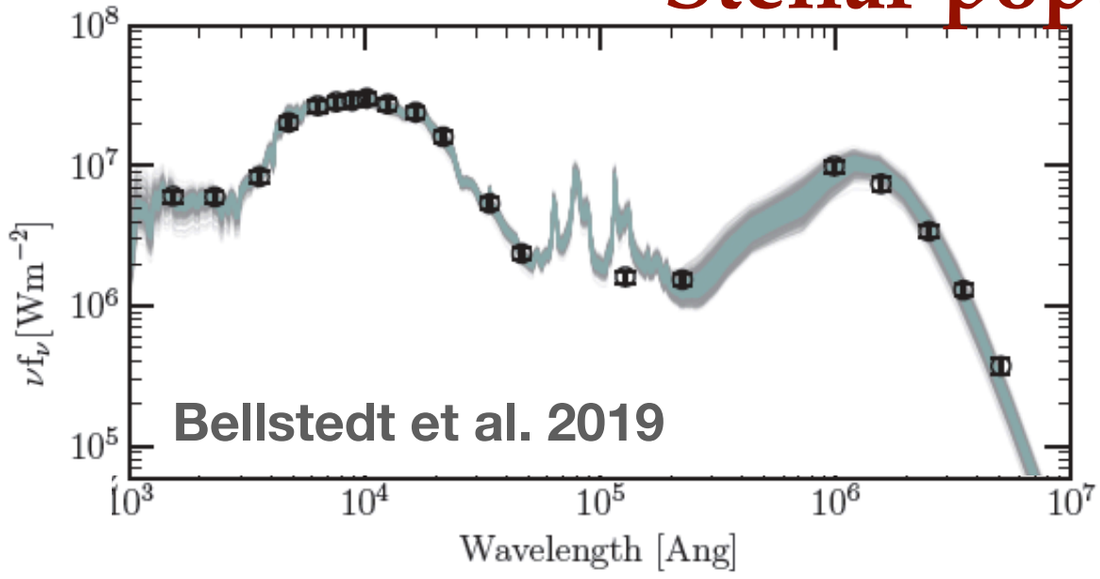


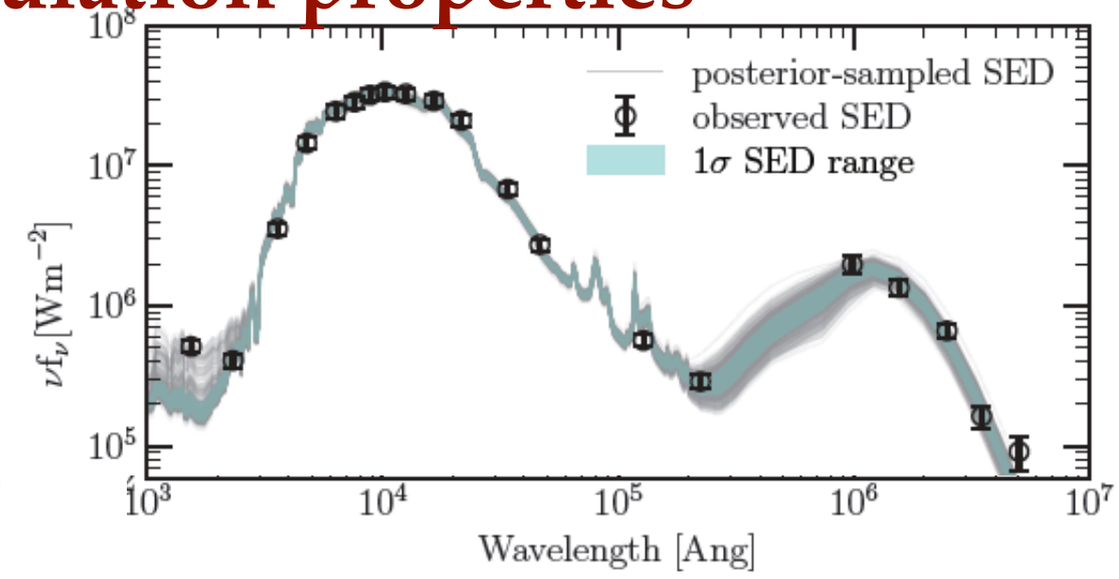
total luminosity



Conroy 2013

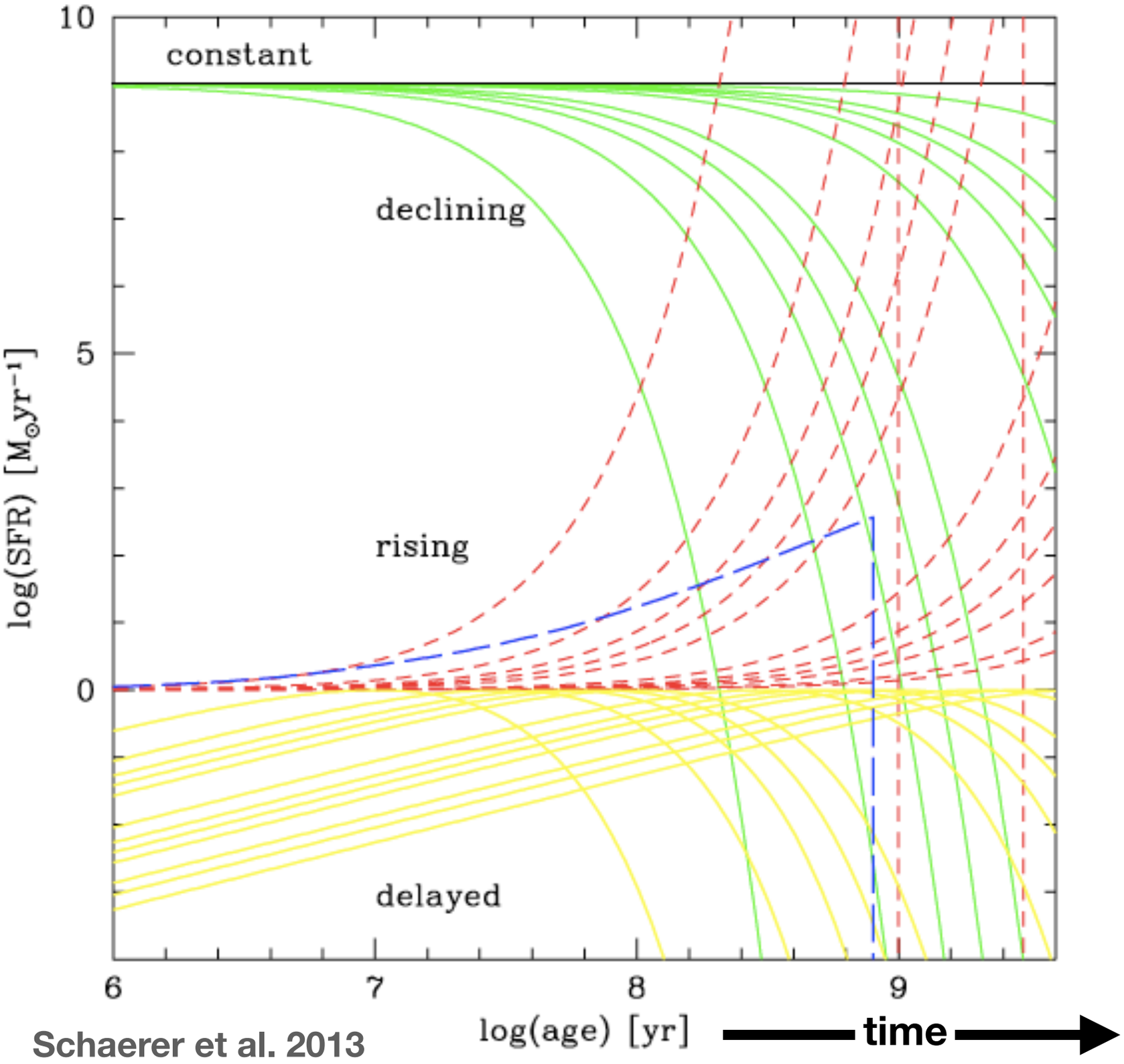
Stellar population properties





Stellar population properties

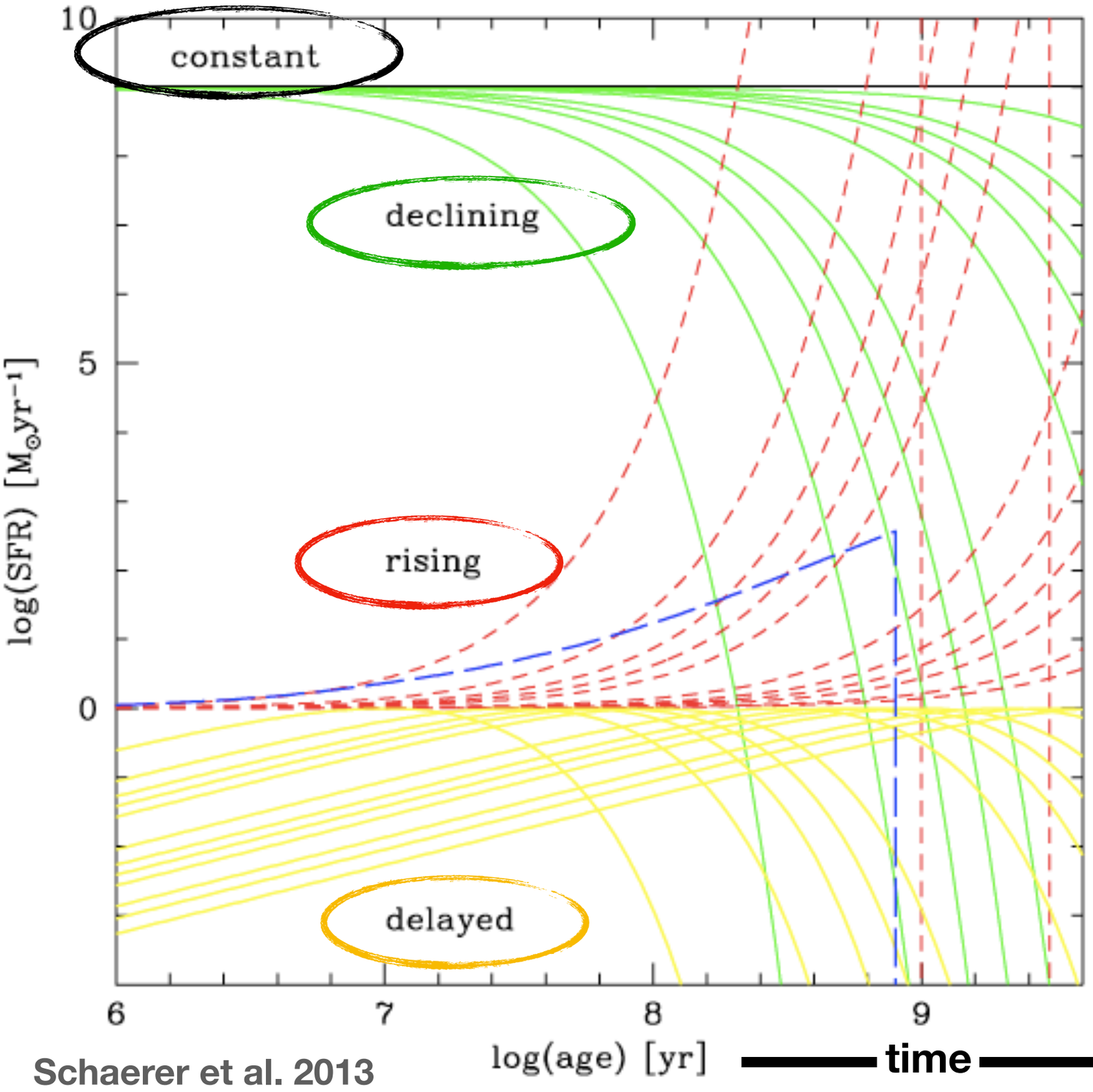
parametric star formation histories



Schaerer et al. 2013

Stellar population properties

parametric star formation histories



Schaerer et al. 2013

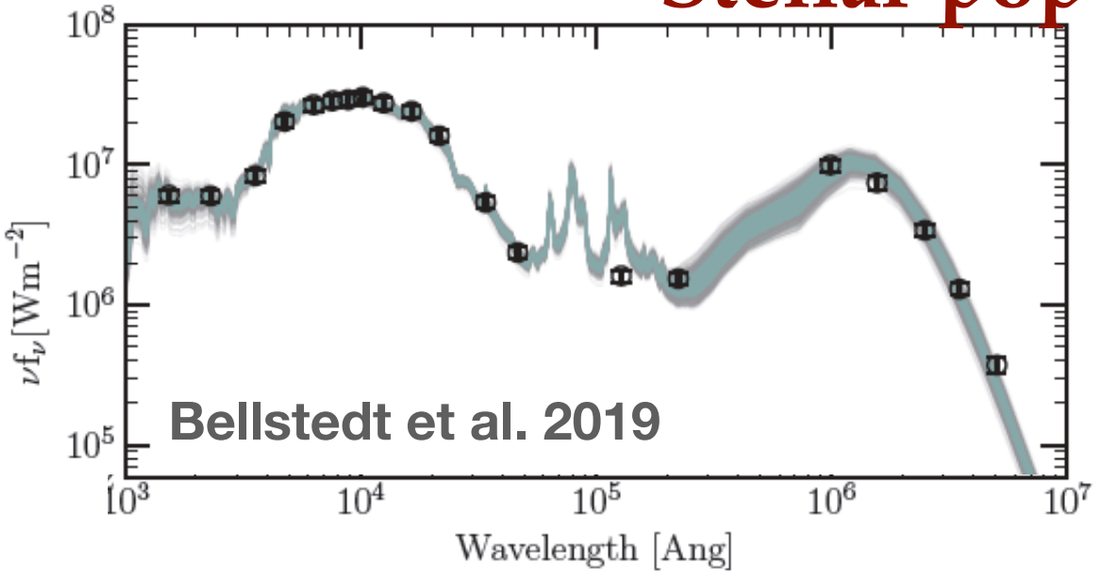
SFR(t) = constant

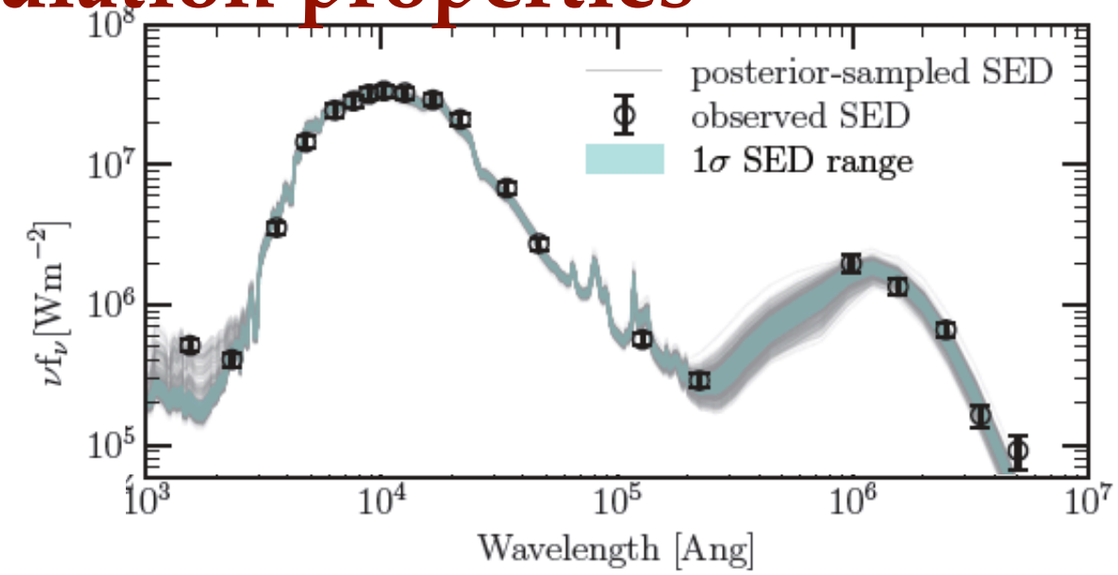
SFR(t) ∝ $e^{-t/\tau}$

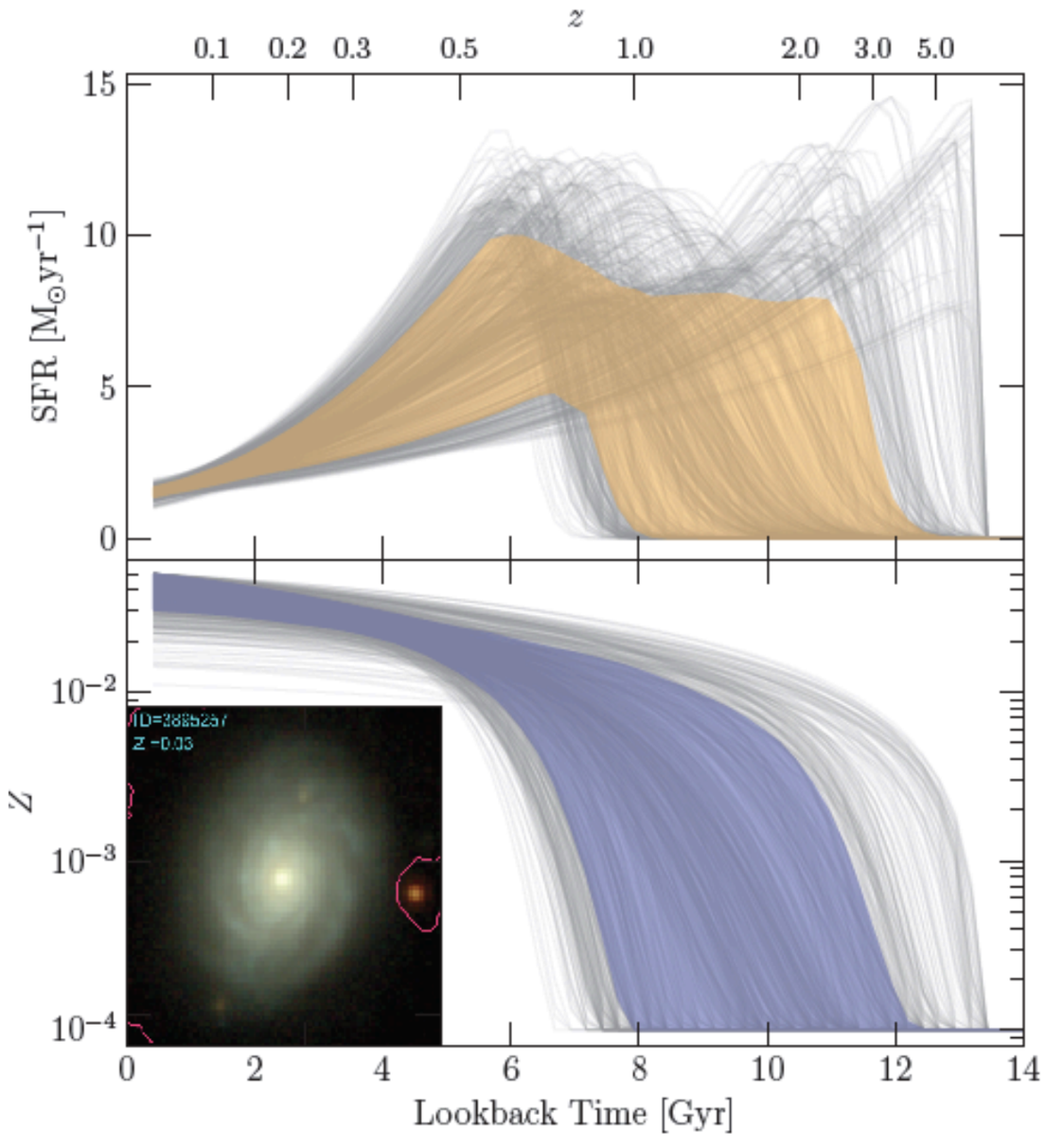
SFR(t) ∝ $e^{t/\tau}$

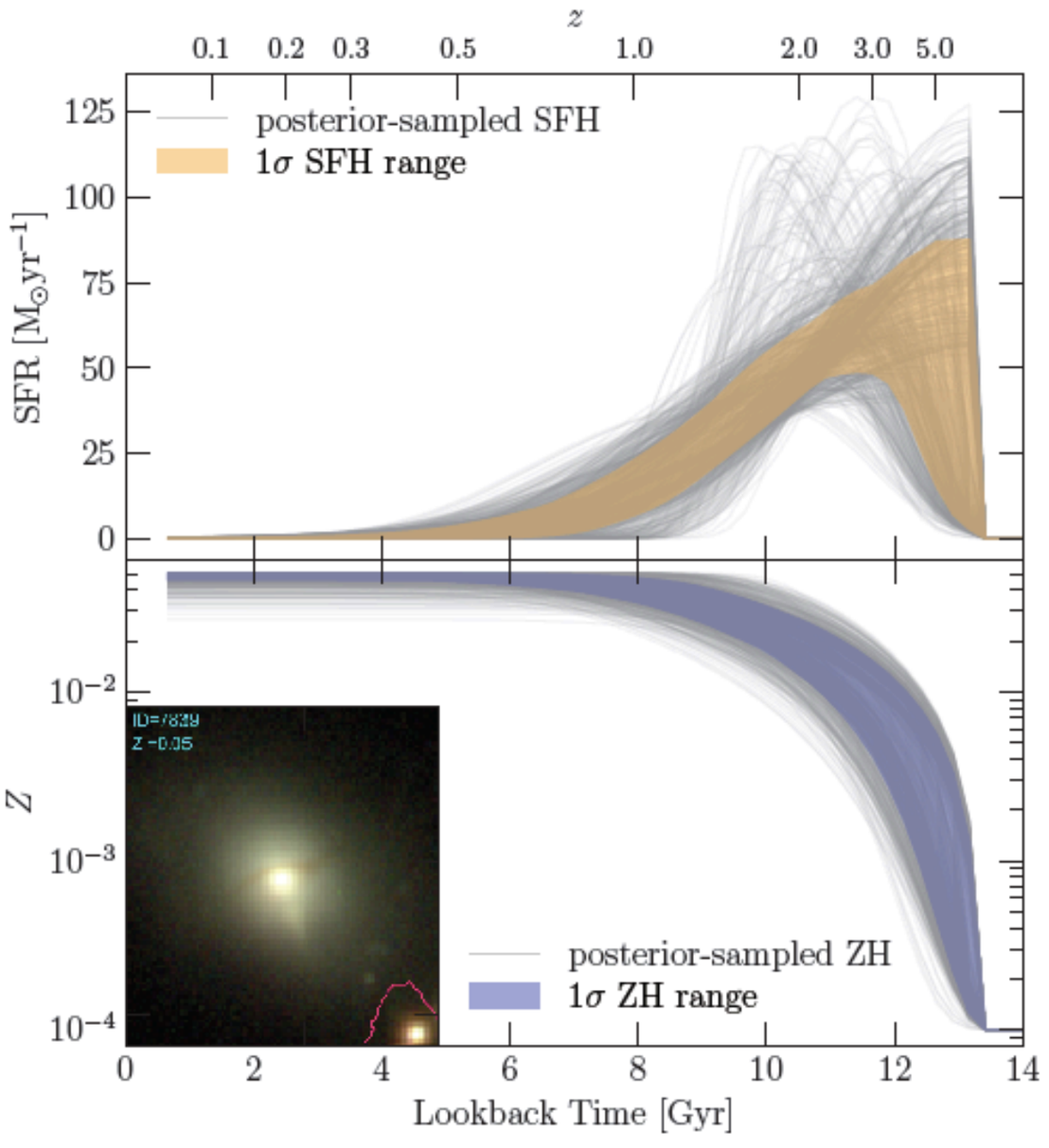
SFR(t) ∝ t $e^{t/\tau}$

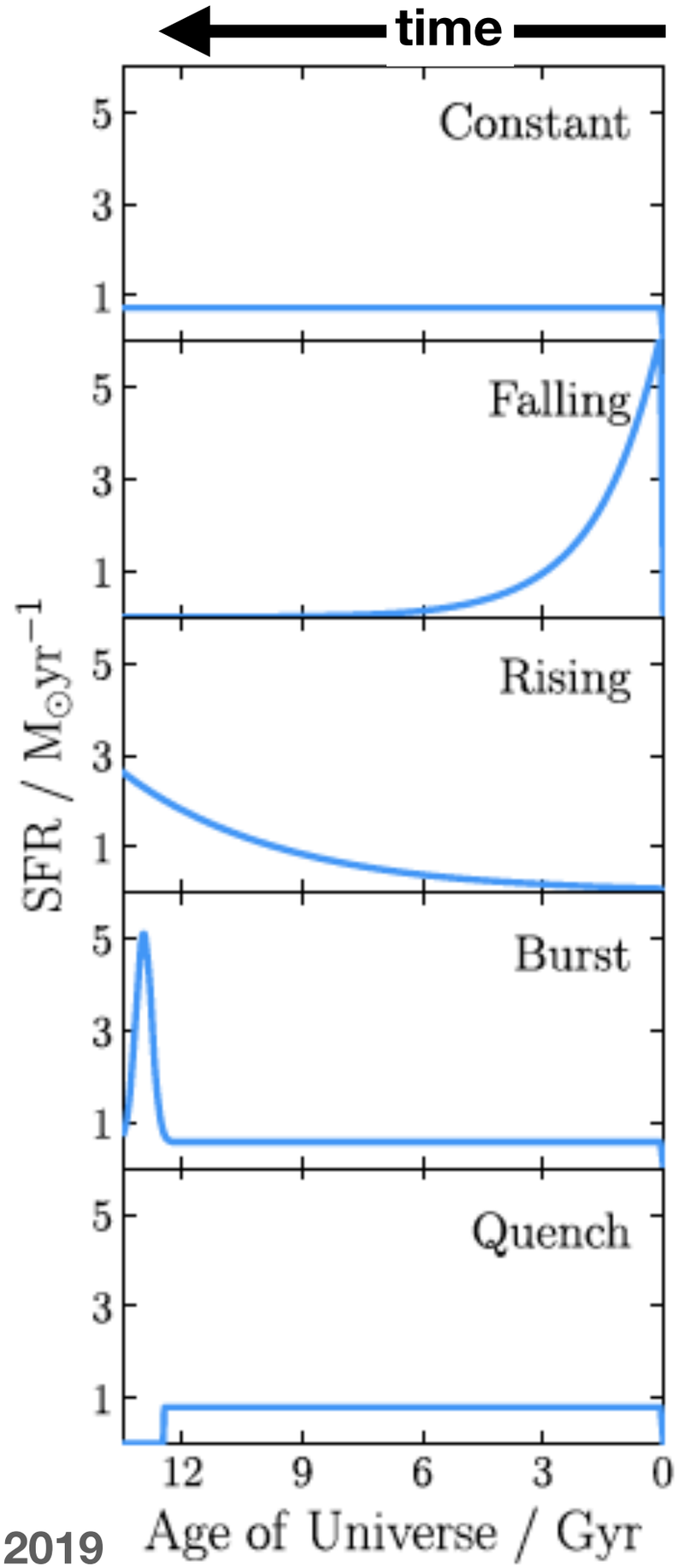
Stellar population properties











Carnall et al. 2019

SFR(t) ∝ $e^{-t/\tau}$ **SFR(t) ∝ t $e^{-t/\tau}$** **SFR(t) ∝ $[(t/\tau)^{\alpha} + (t/\tau)^{-\beta}]^{-1}$**

Tau Delayed DPL

time

Constant

Falling

Rising

Burst

Quench

SFR / $M_{\odot} yr^{-1}$

Age of Universe / Gyr

Age of Universe / Gyr

Carnall et al. 2019

$SFR(t) \propto e^{-t/\tau}$ | $SFR(t) \propto t\, e^{-t/\tau}$ | $SFR(t) \propto [(t/\tau)^{\alpha} + (t/\tau)^{-\beta}]^{-1}$

Tau | Delayed | DPL

time

Constant

Falling

Rising

Burst

Quench

(a)

one example galaxy from SAM
on cosmological simulation

SFR ($M_\odot$/yr)

(b)

Z ($Z_\odot$)

look−back time (Gyr)

Pacifici et al. 2012

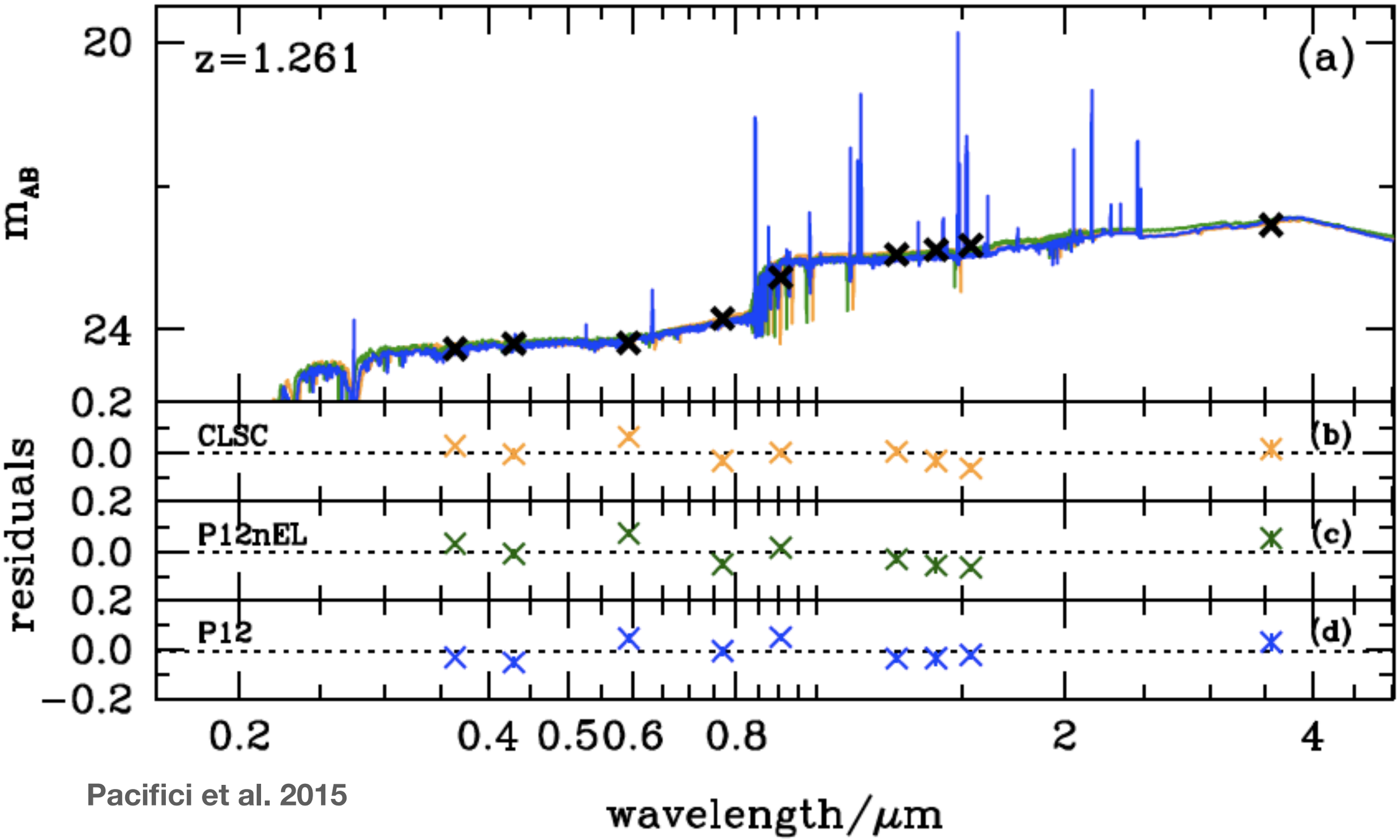
time

Age of Universe / Gyr

Carnall et al. 2019

Age of Universe / Gyr

Broad-band SED fitting for stellar population properties



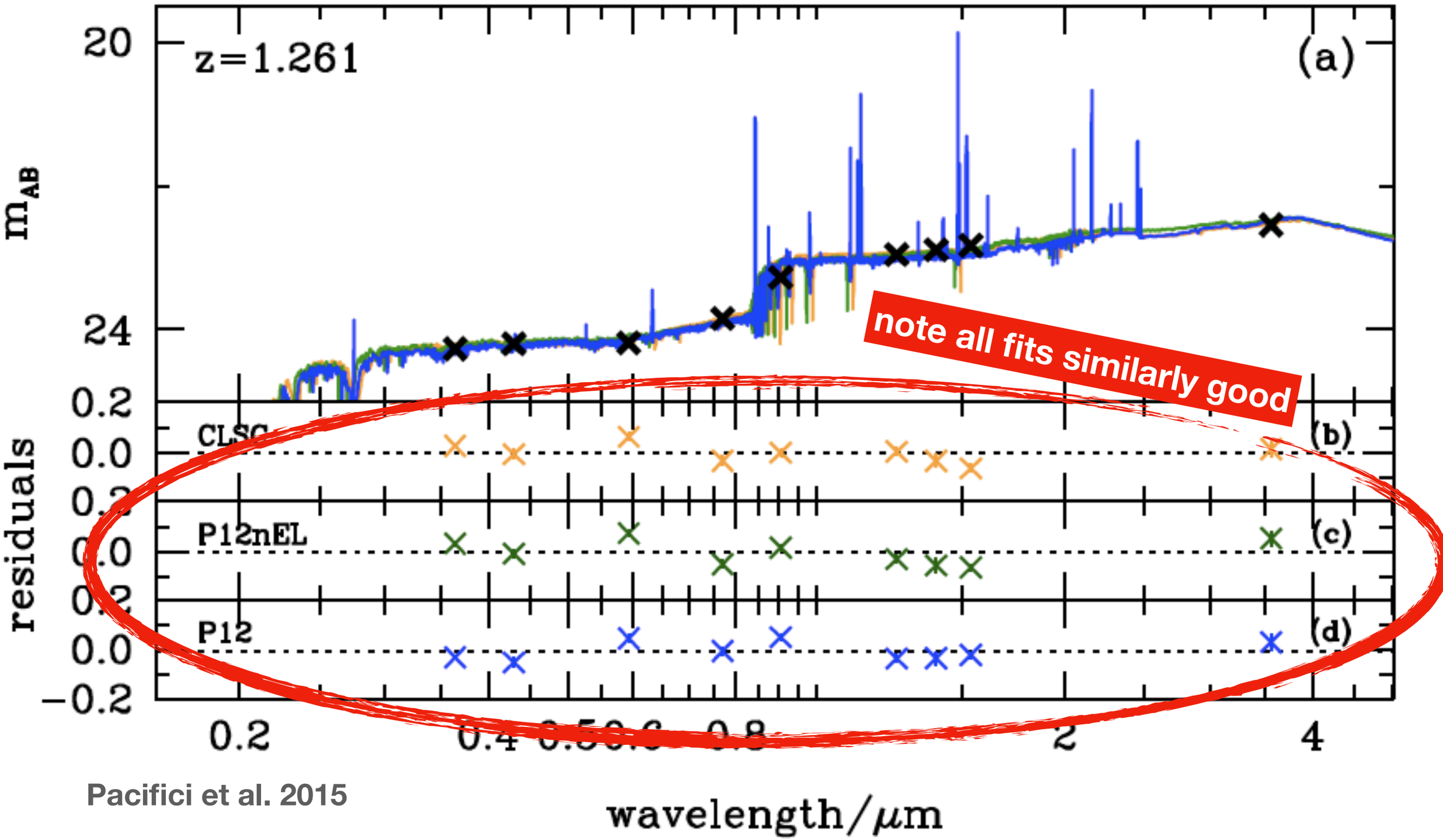
Pacifici et al. 2015

standard modeling with parametric SFHs, single metallicity, no emission lines

more realistic SFH, chemical evolution, dust attenuation modeling

more realistic SFH, chemical evolution, dust attenuation modeling , plus emission lines

Broad-band SED fitting for stellar population properties



Pacifici et al. 2015

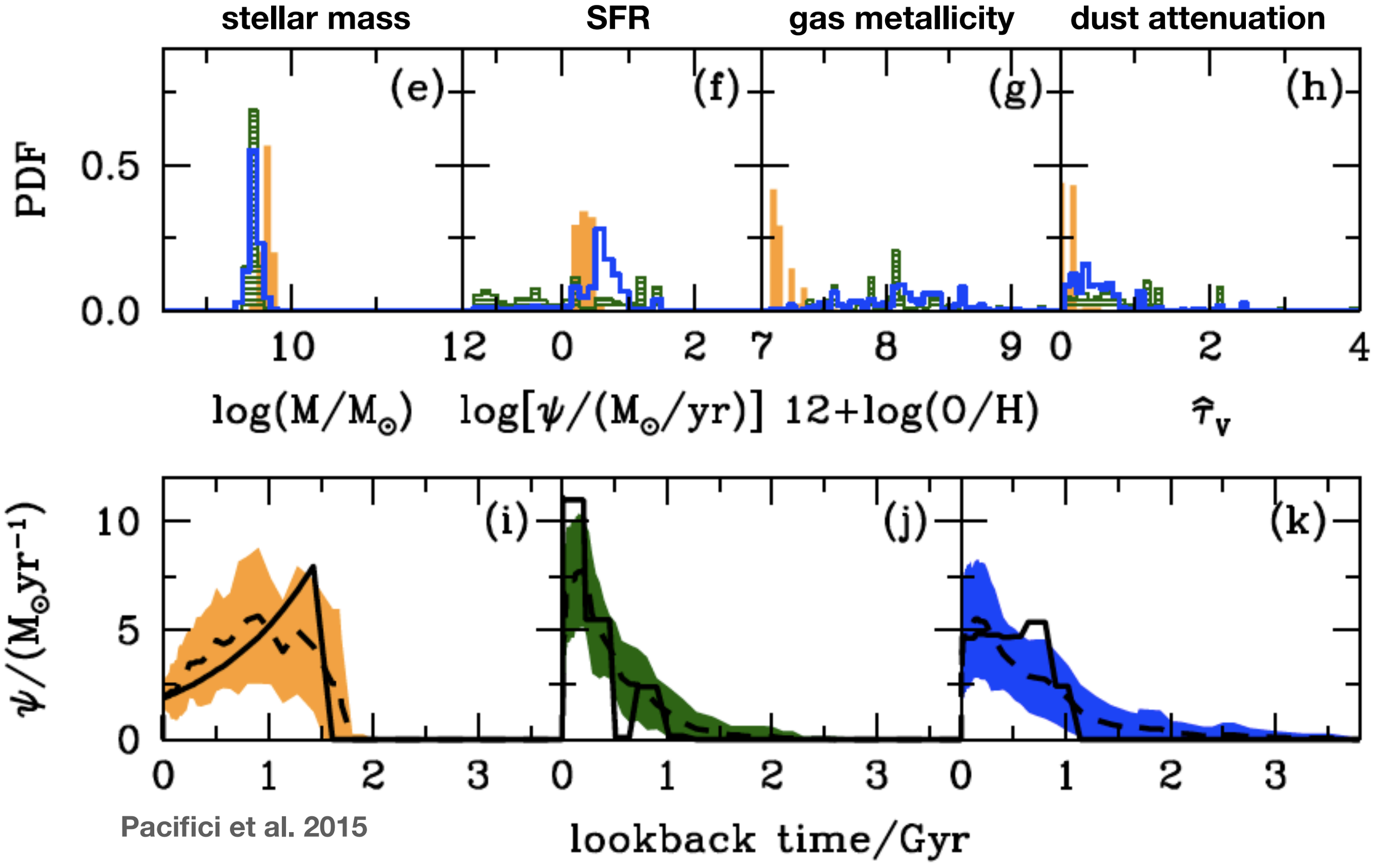
standard modeling with parametric SFHs, single metallicity, no emission lines

more realistic SFH, chemical evolution, dust attenuation modeling

more realistic SFH, chemical evolution, dust attenuation modeling , plus emission lines

Broad-band SED fitting for stellar population properties

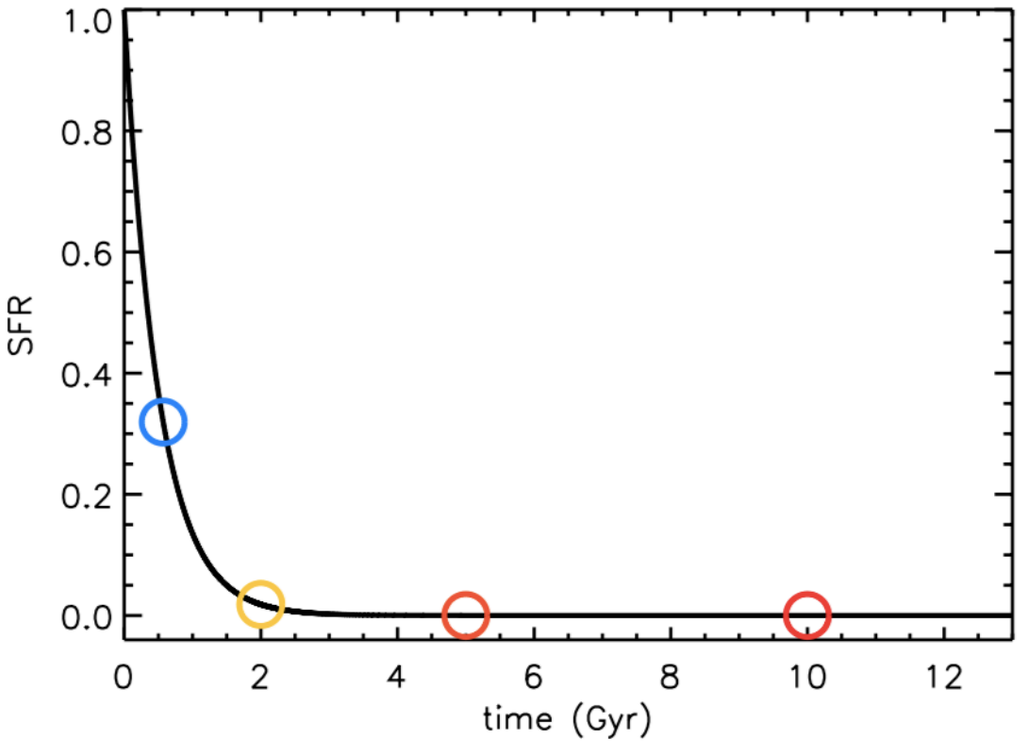
... but quite different retrived parameters

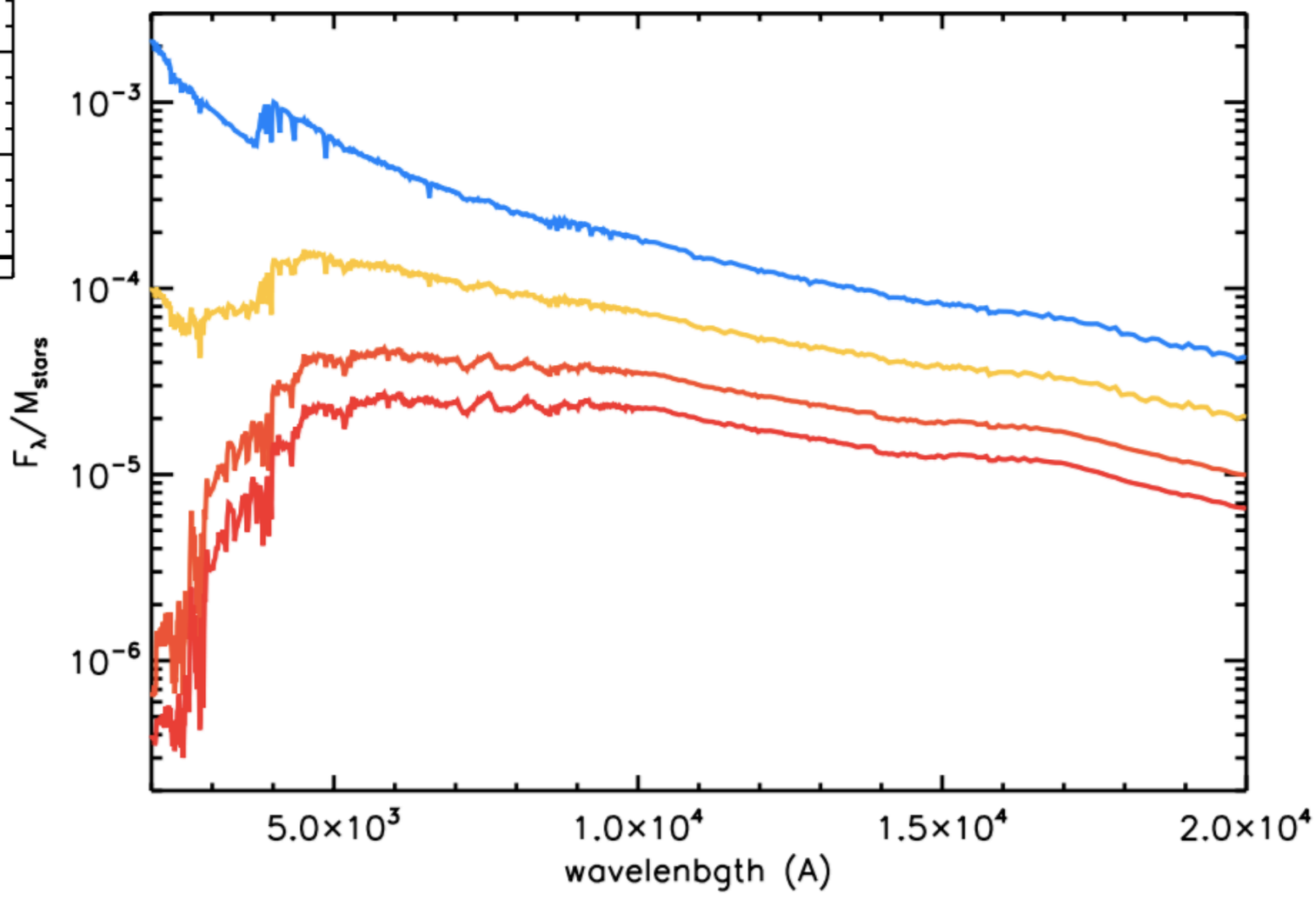


Pacifici et al. 2015

Stellar mass

Mass to light ratio (M/L) correlates with galaxy color → can get a stellar mass estimate even from one (well chosen) color (and one magnitude) only





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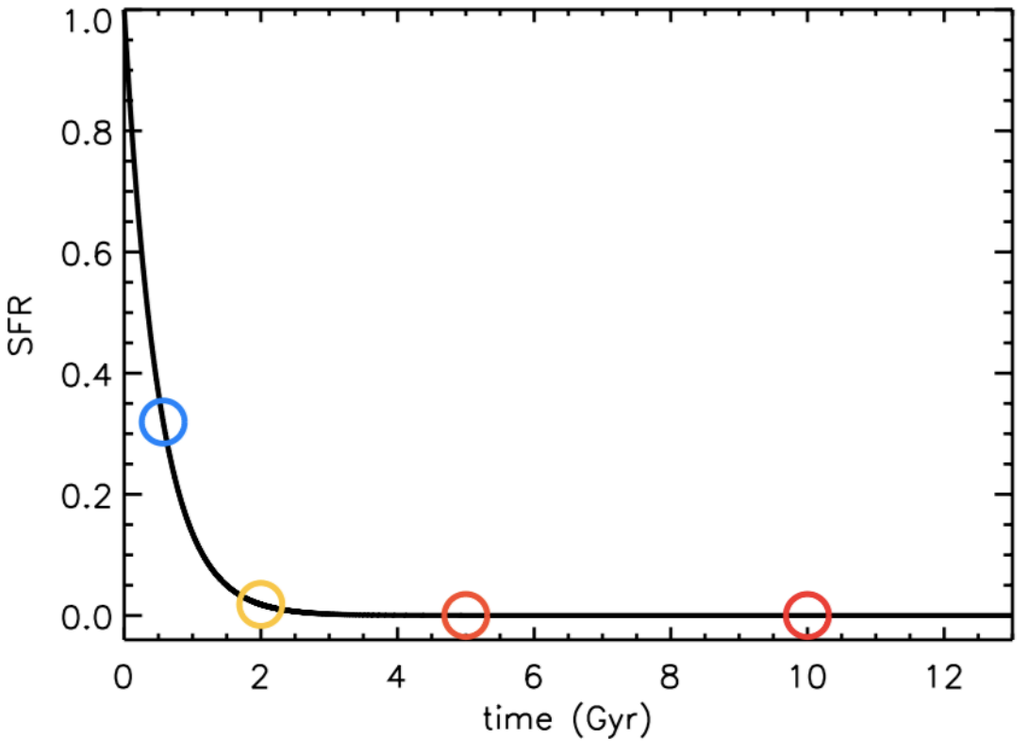

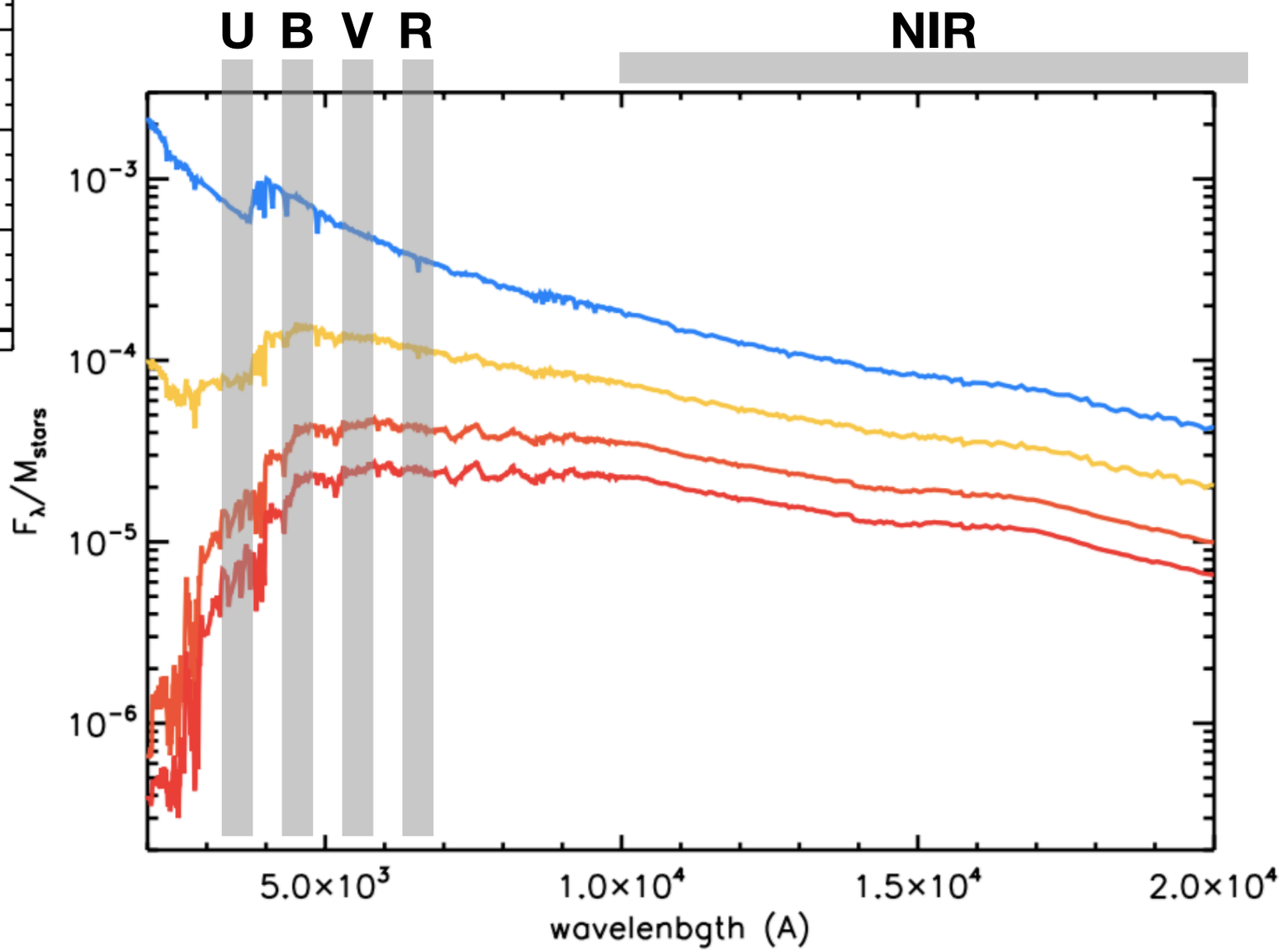

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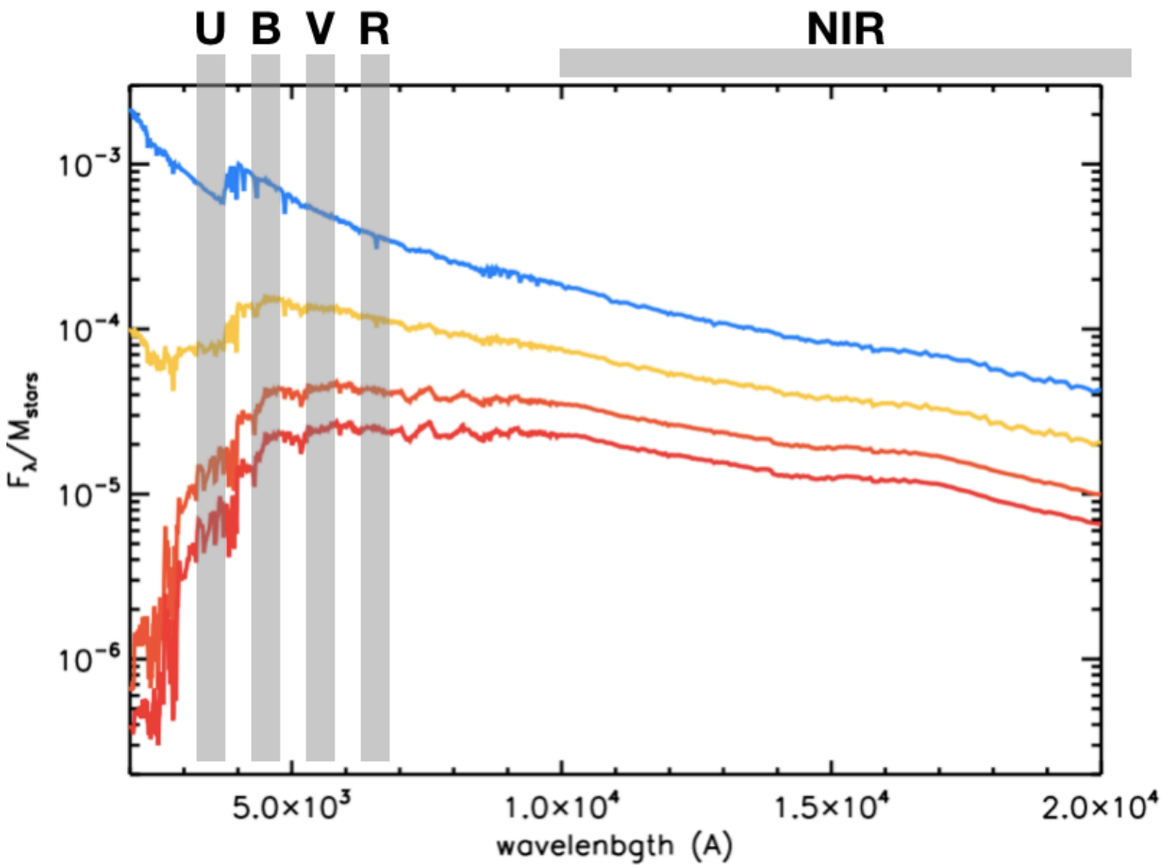
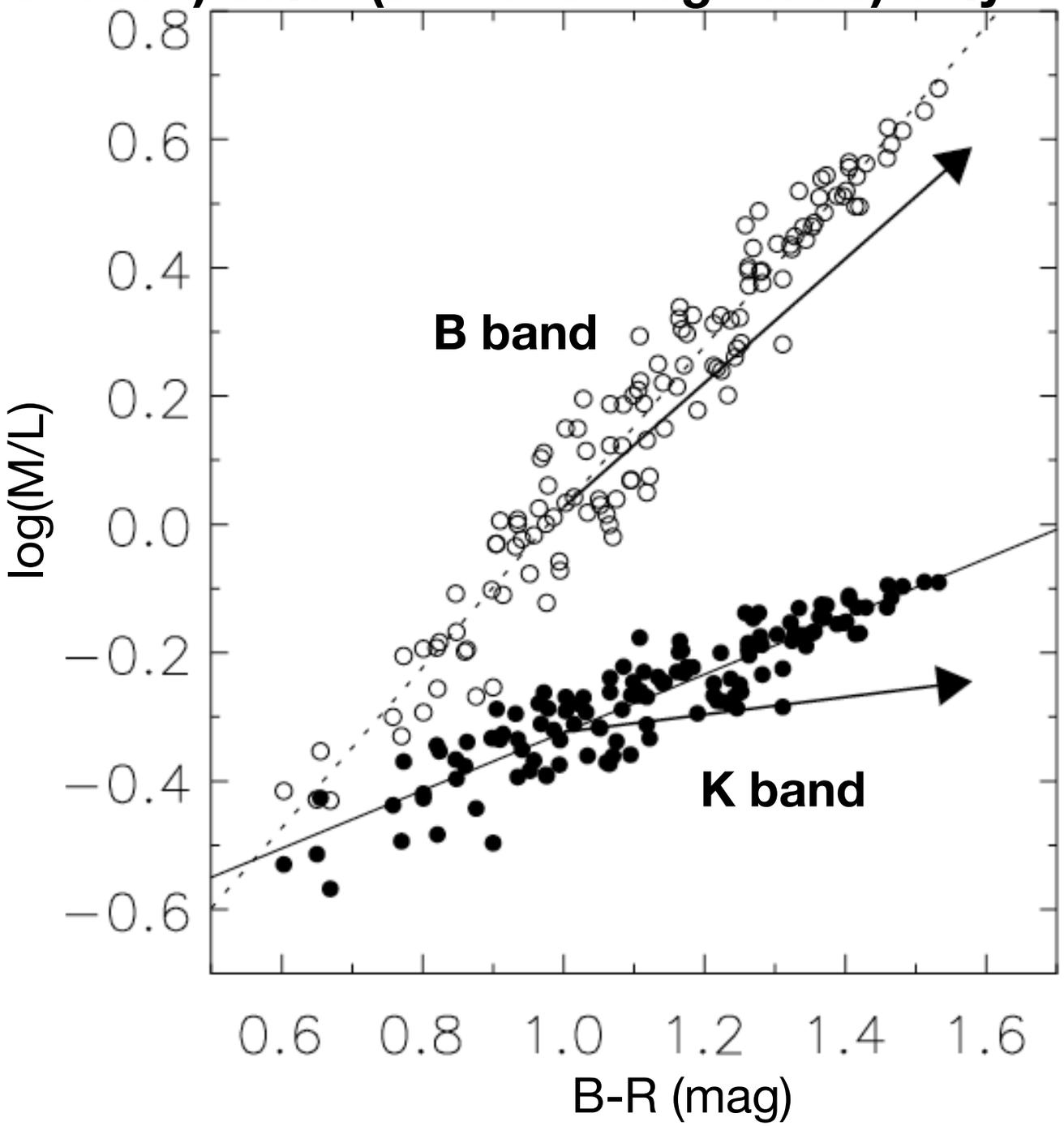
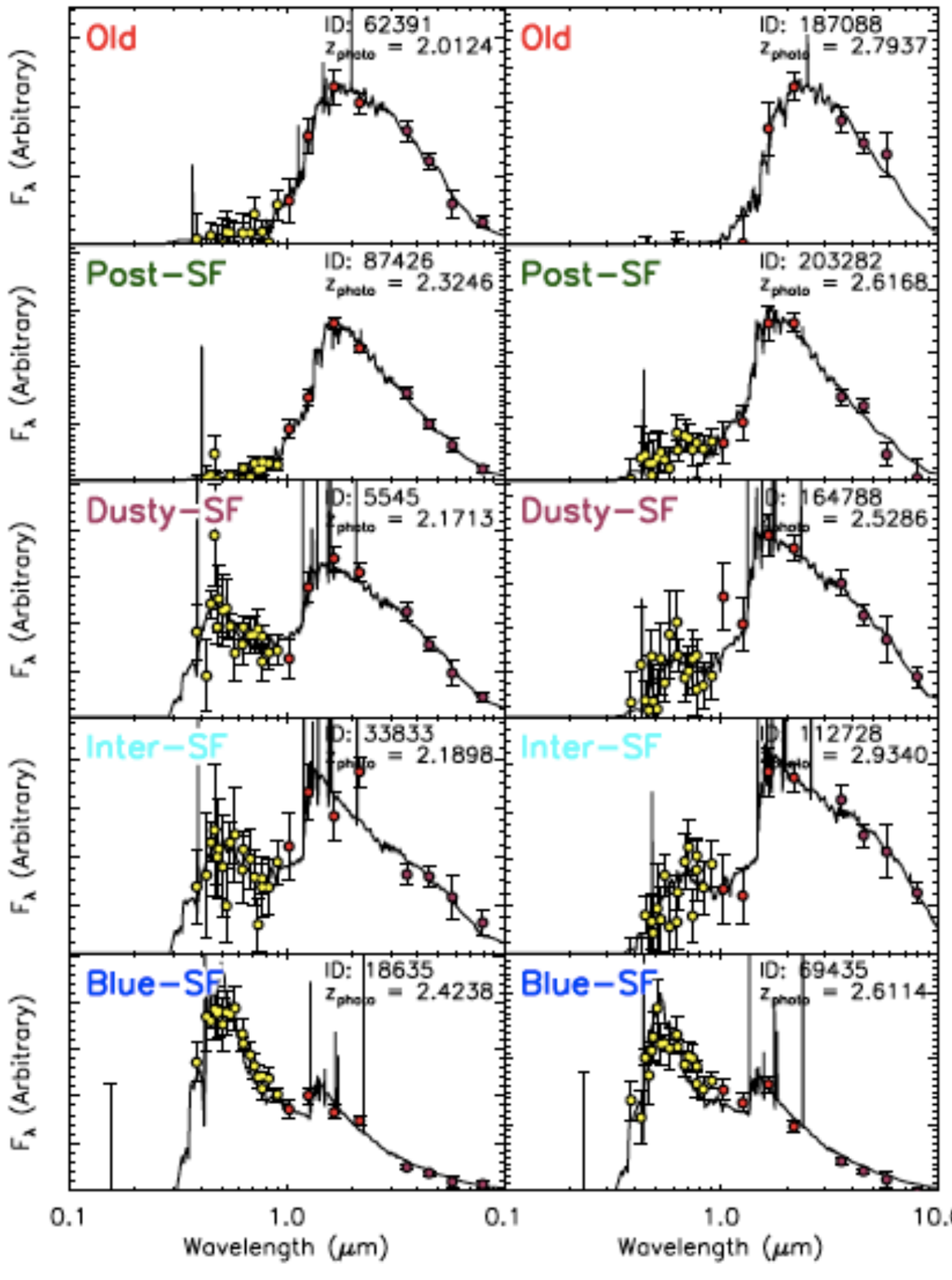




Bell & de Jong 2001

Stellar mass

going full spectral coverage

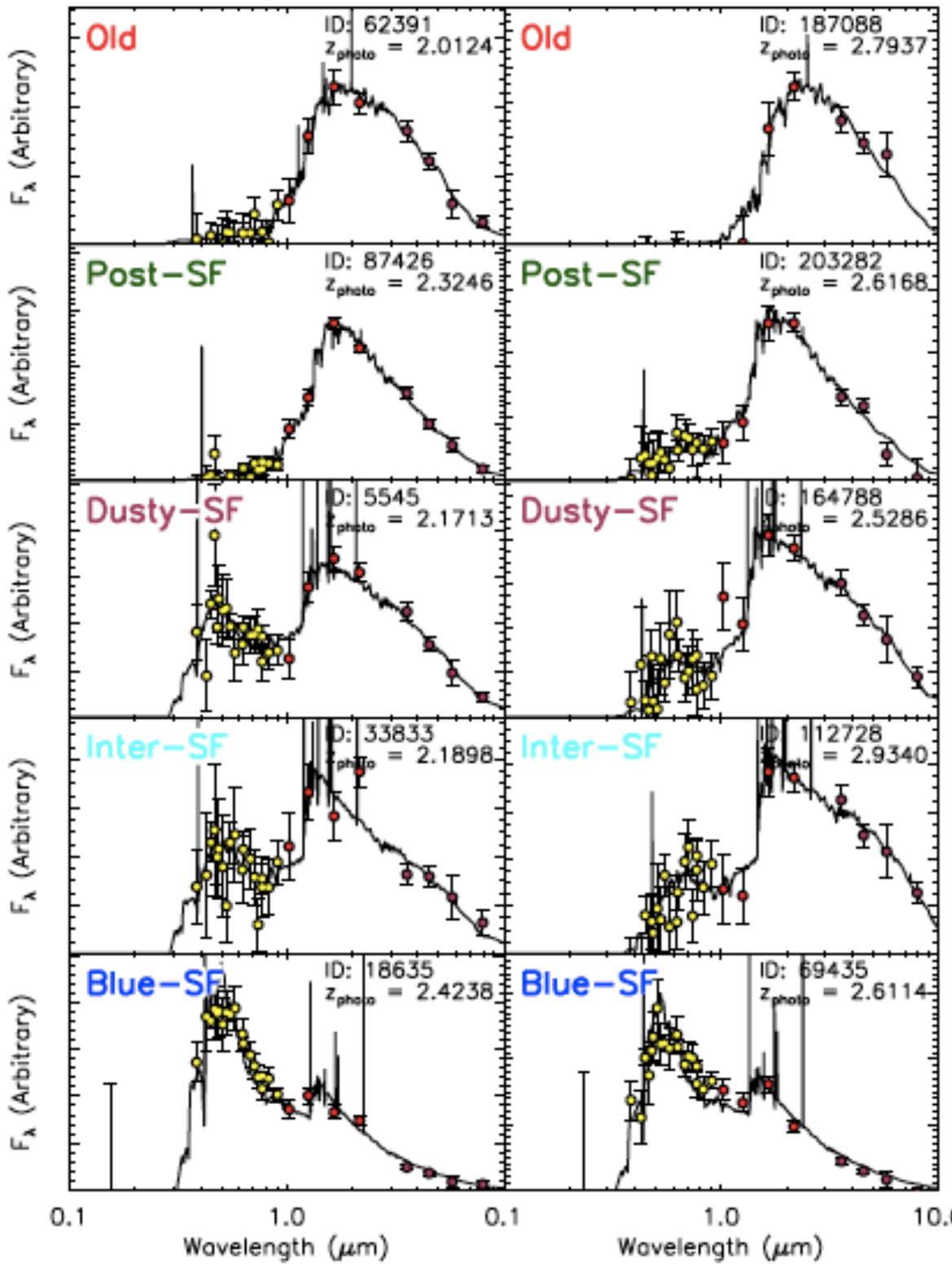


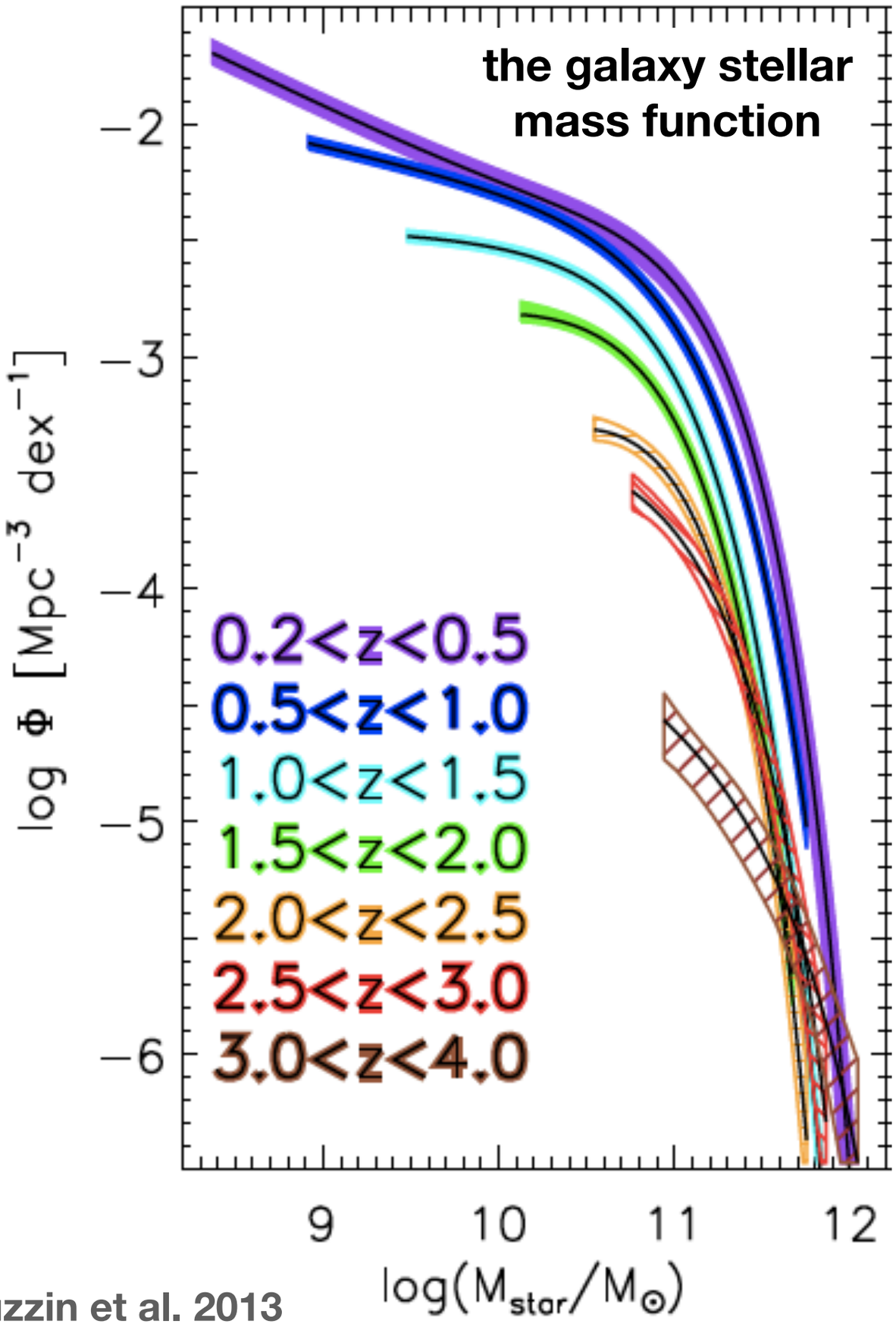
mass estimates are determined essentially from flux scaling of the best-fitting template

Muzzin et al. 2013

Stellar mass

going full spectral coverage

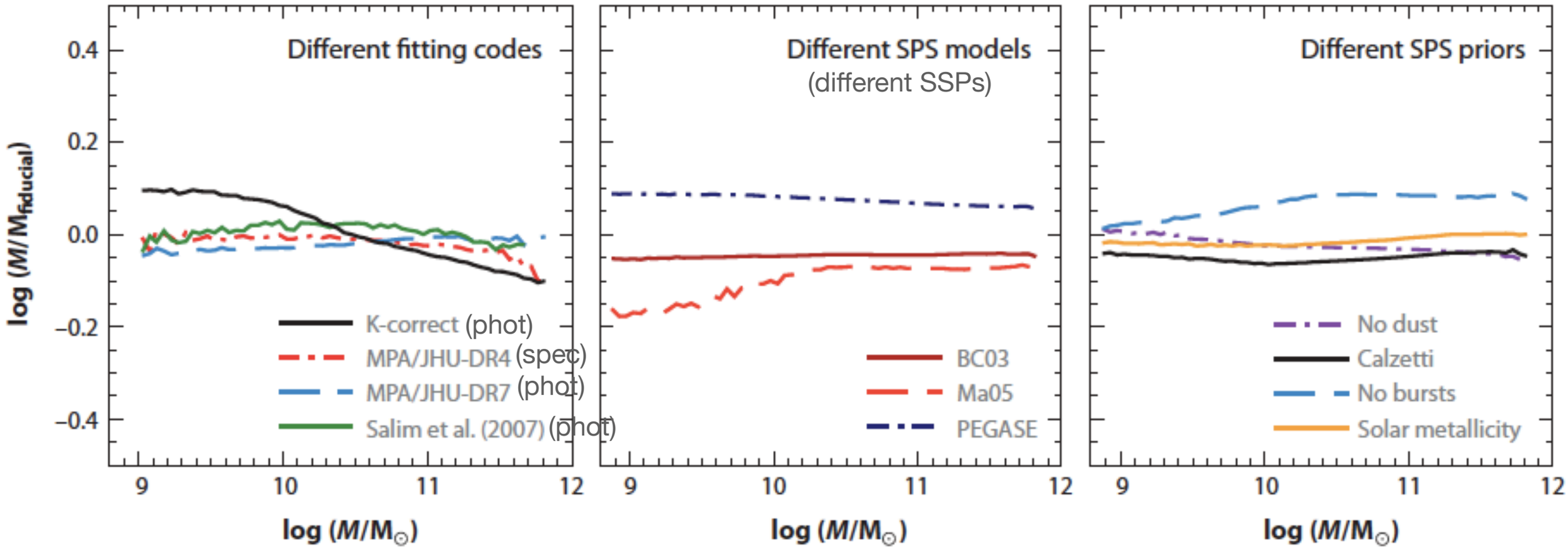




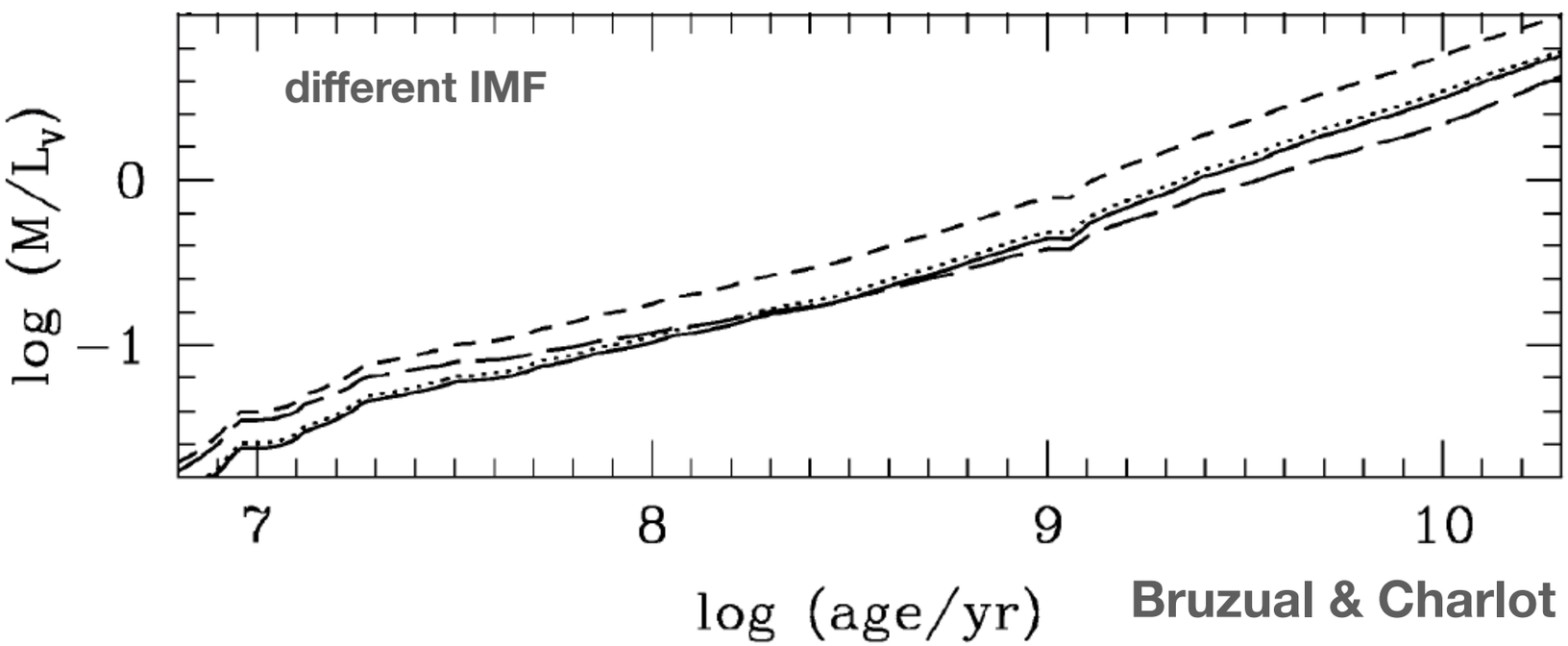
Muzzin et al. 2013

Stellar mass

BUT…



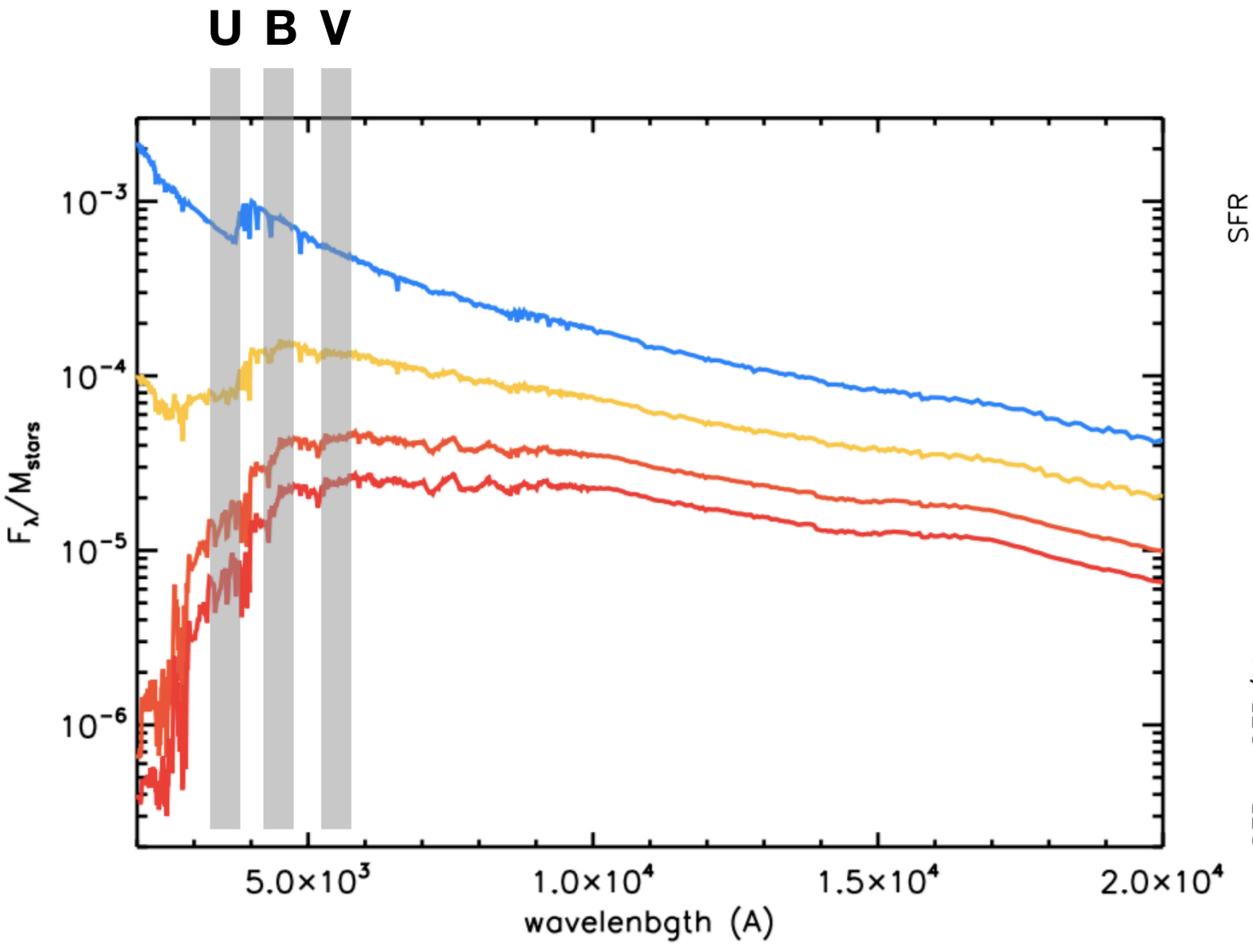
Conroy 2013

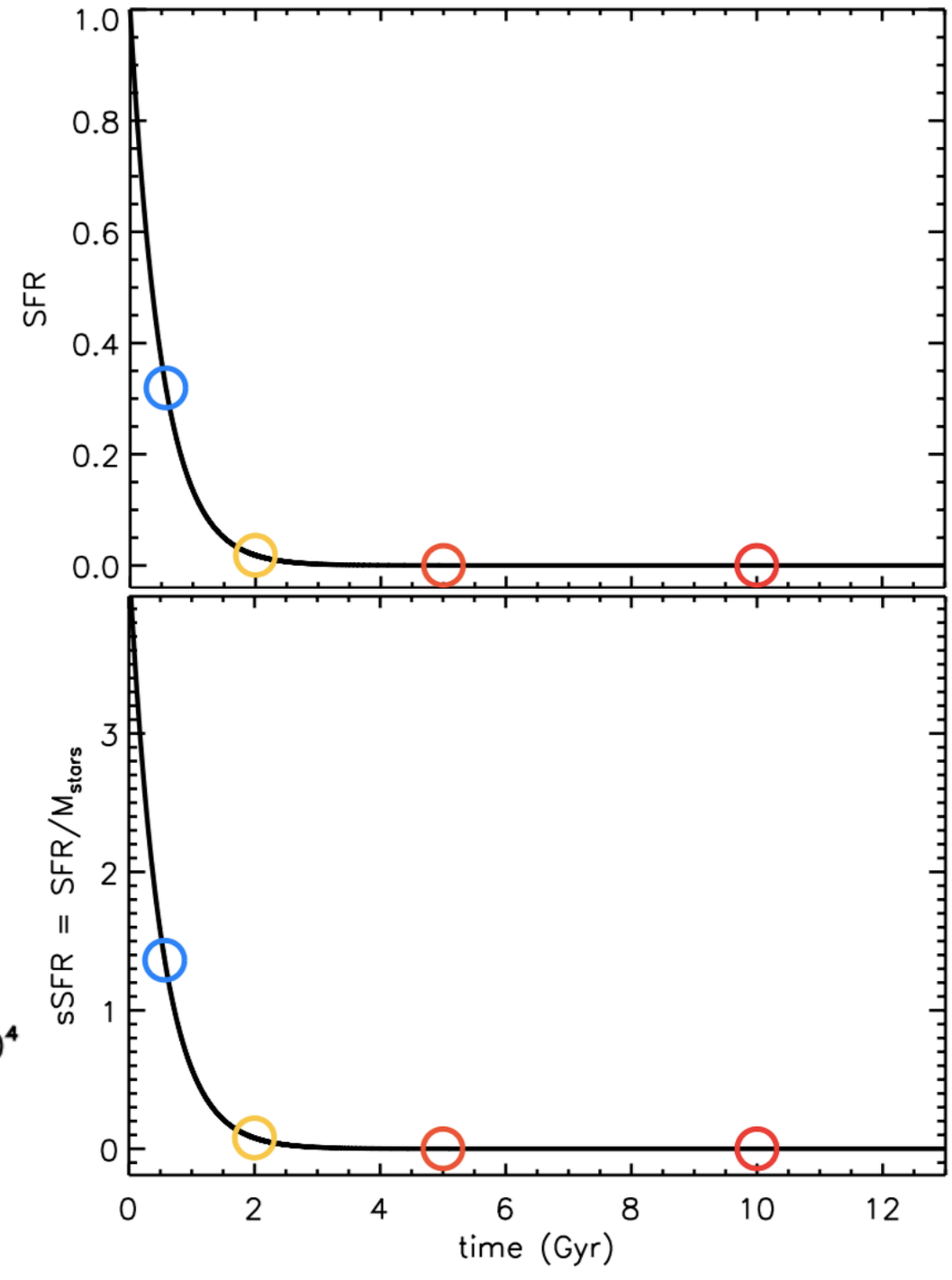


Bruzual & Charlot 2003

Broad stellar population age / specific star formation rate

intrinsic colors of a stellar population correlate with age / sSFR
→ constrain stellar population properties with one color… ?





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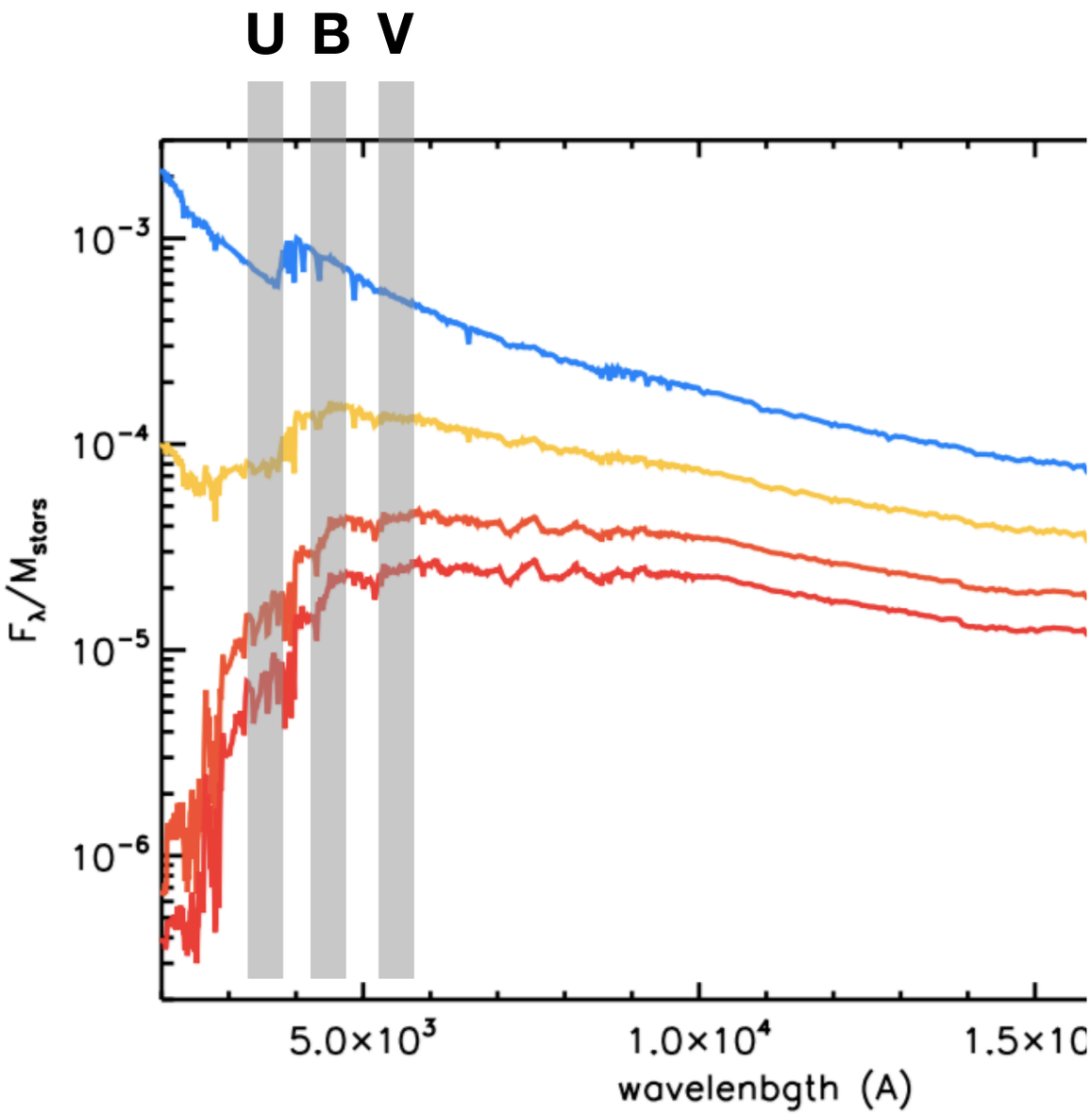

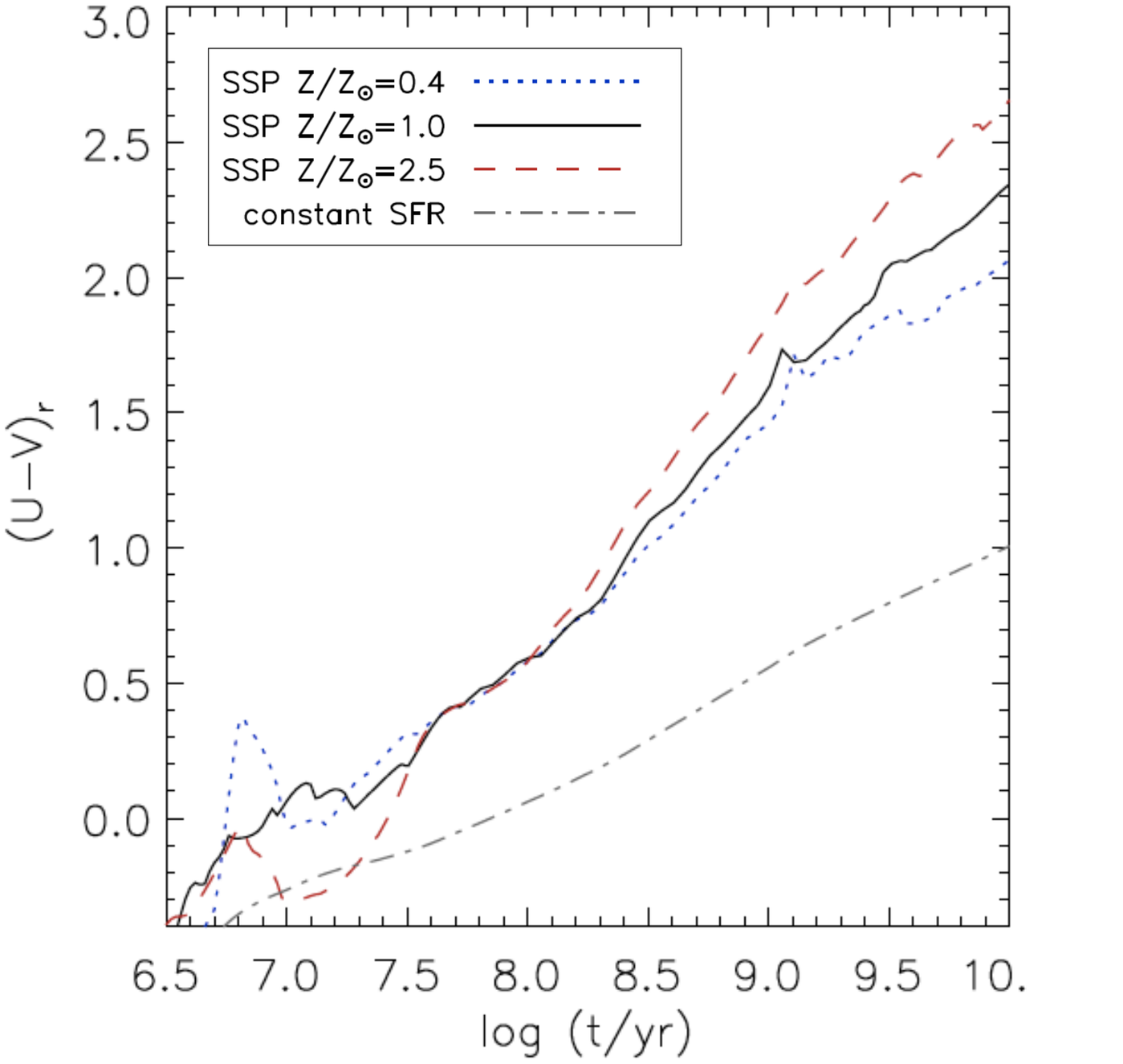

Hernán-Caballero et al. 2013

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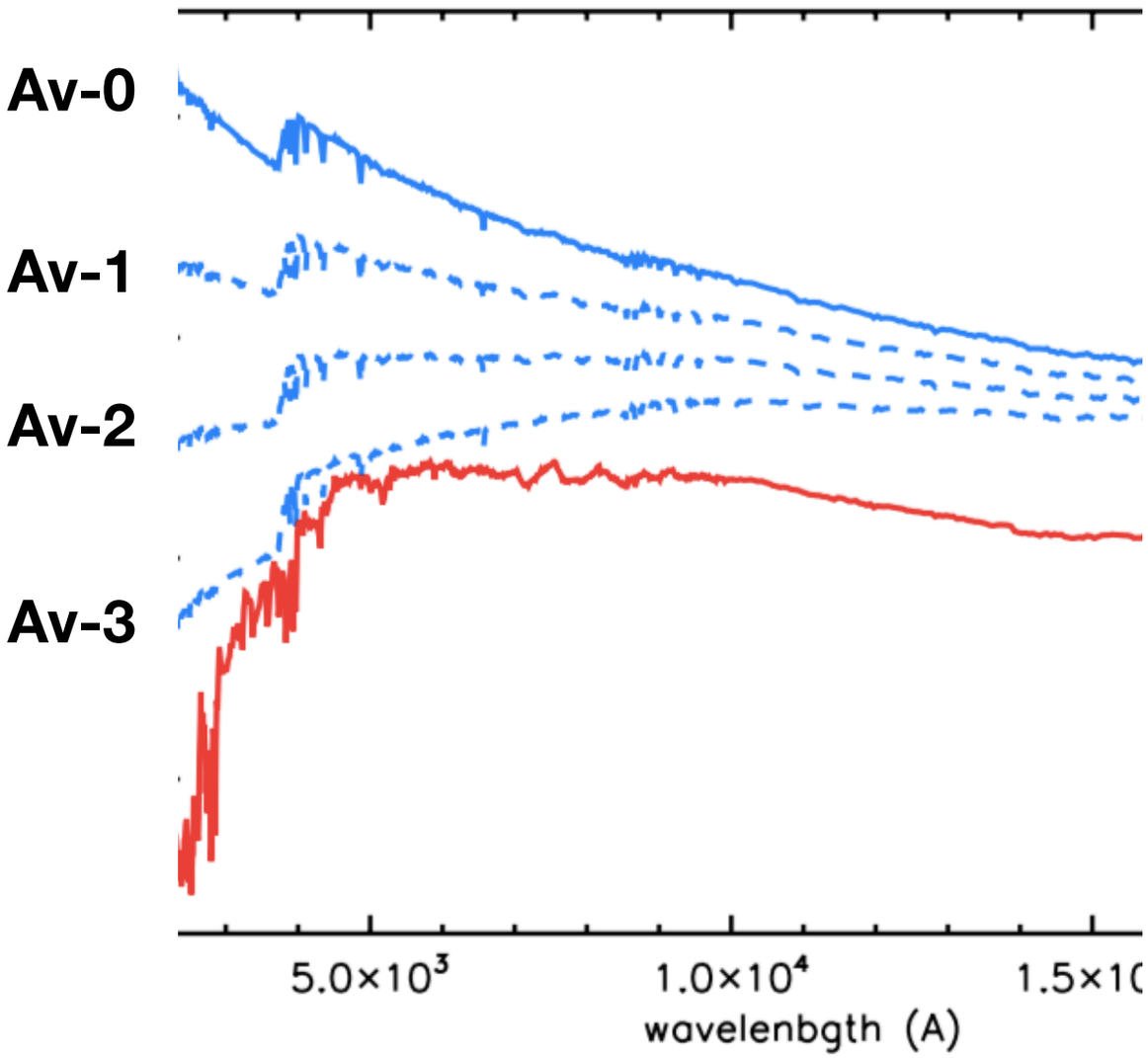
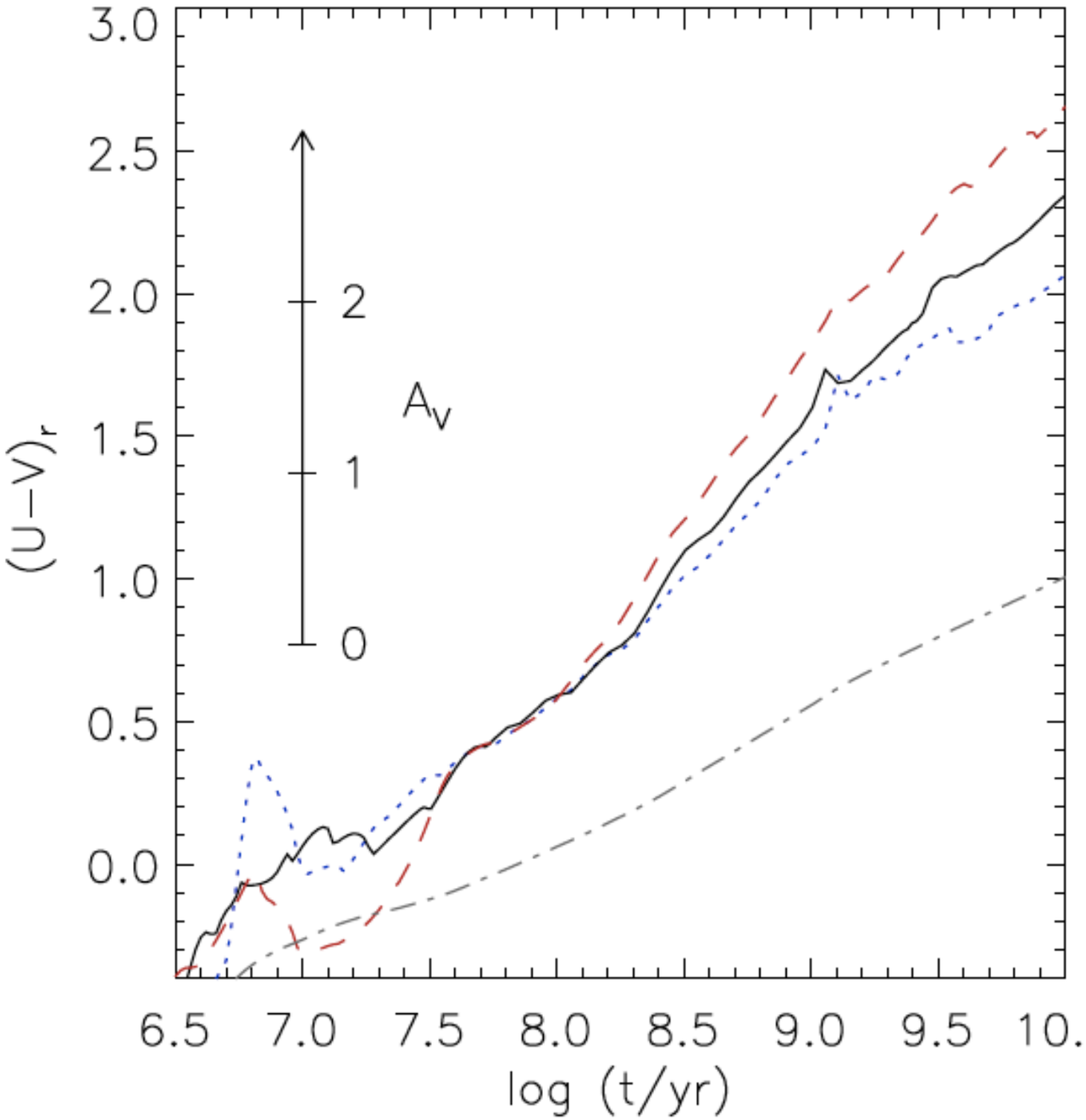
BUT beware of dust !





Hernán-Caballero et al. 2013

Broad stellar population age / specific star formation rate

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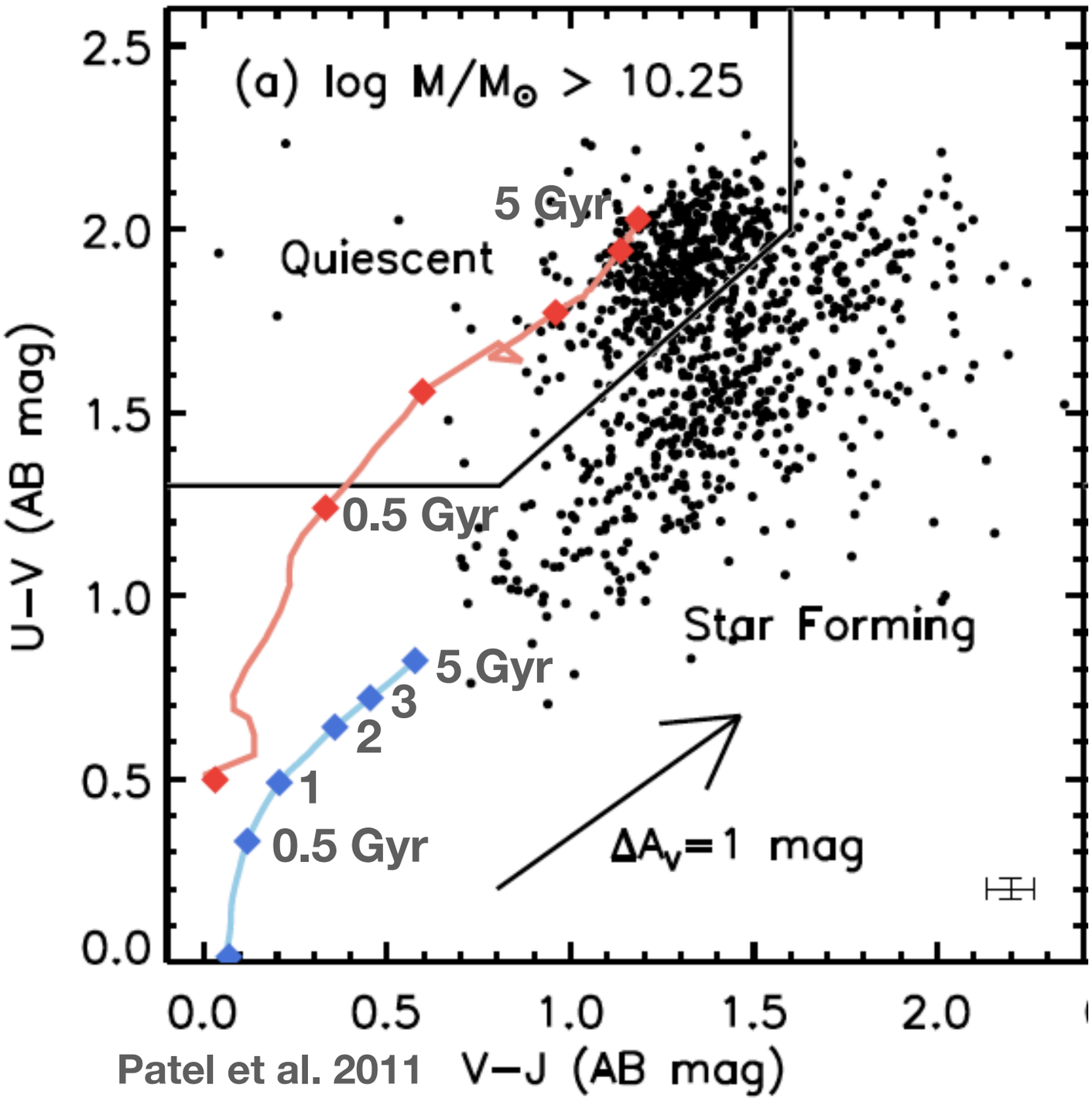
→ constrain stellar population properties with one color… ?

BUT beware of dust !

The combination of UV/optical and NIR (restframe!) colors may do the trick



Patel et al. 2011

Broad stellar population age / specific star formation rate

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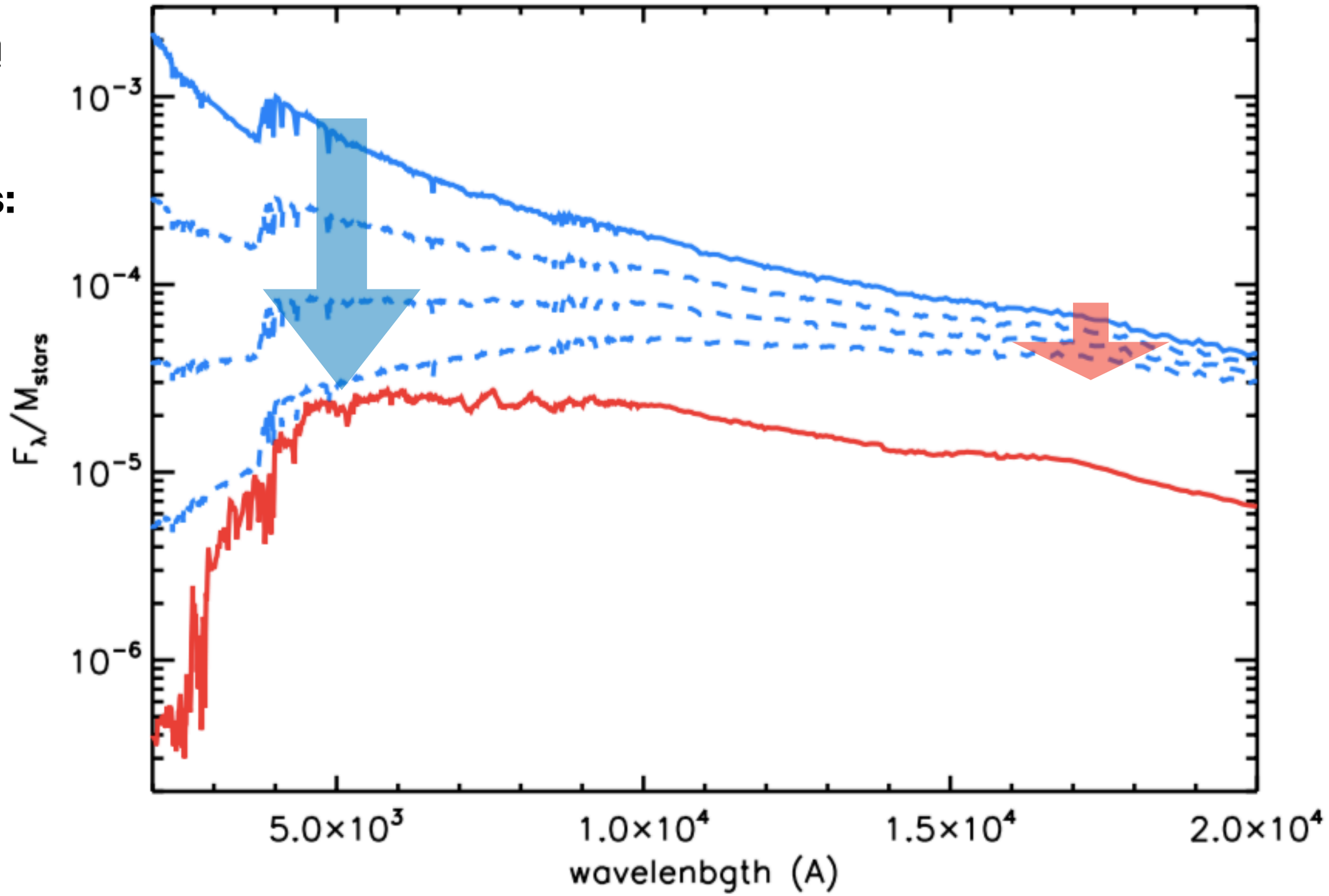
BUT bey

How it works:



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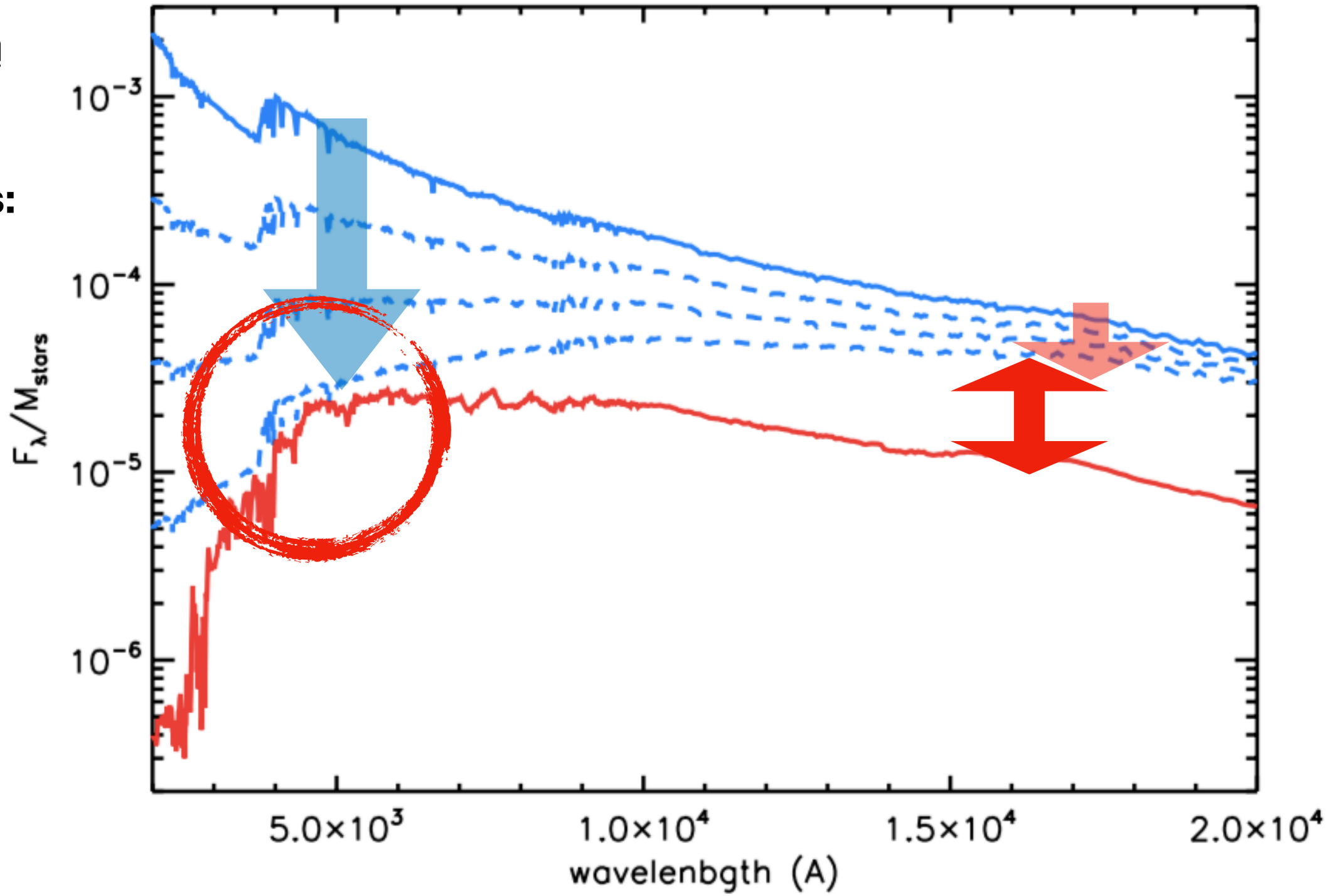

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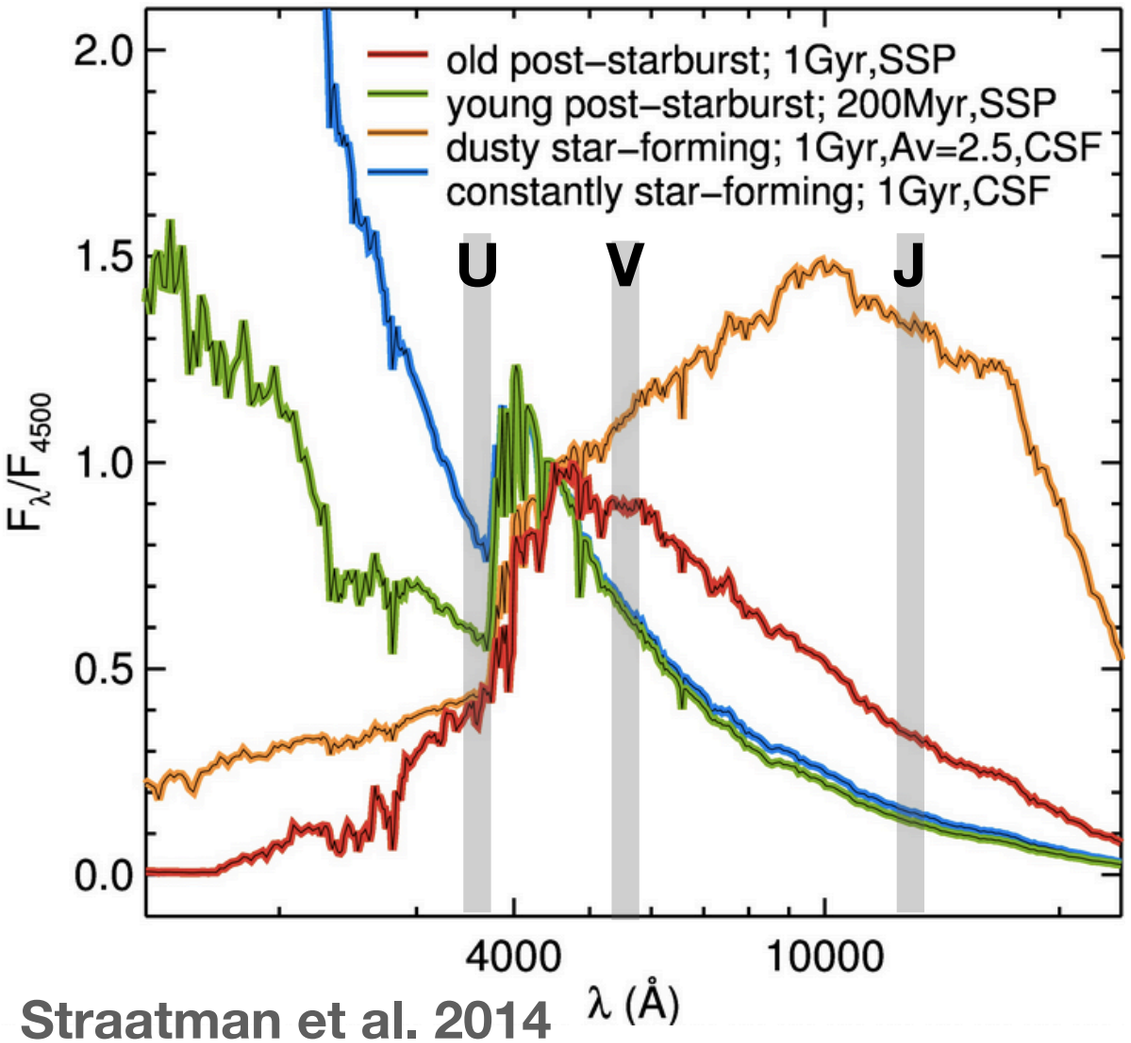
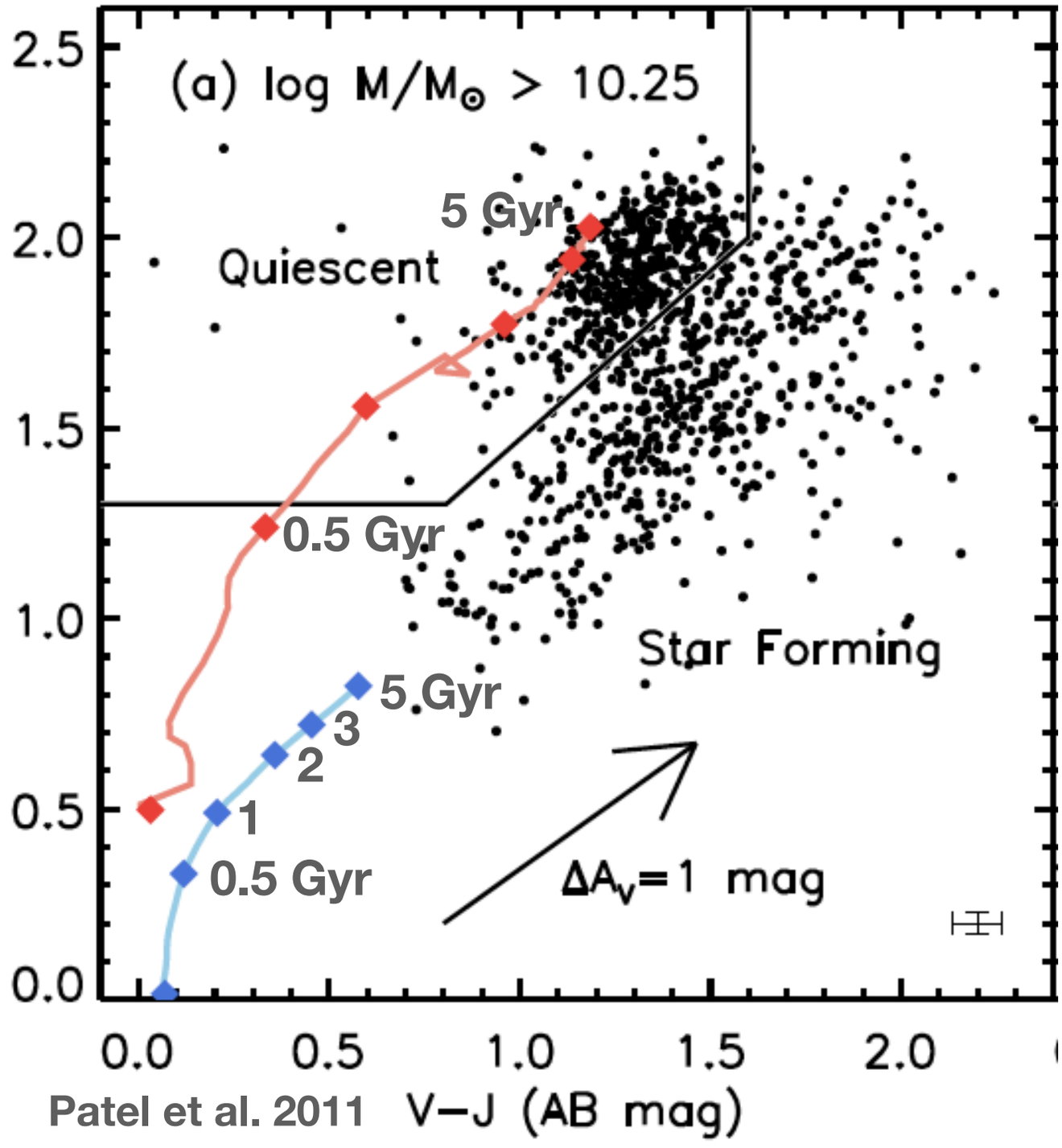


Straatman et al. 2014

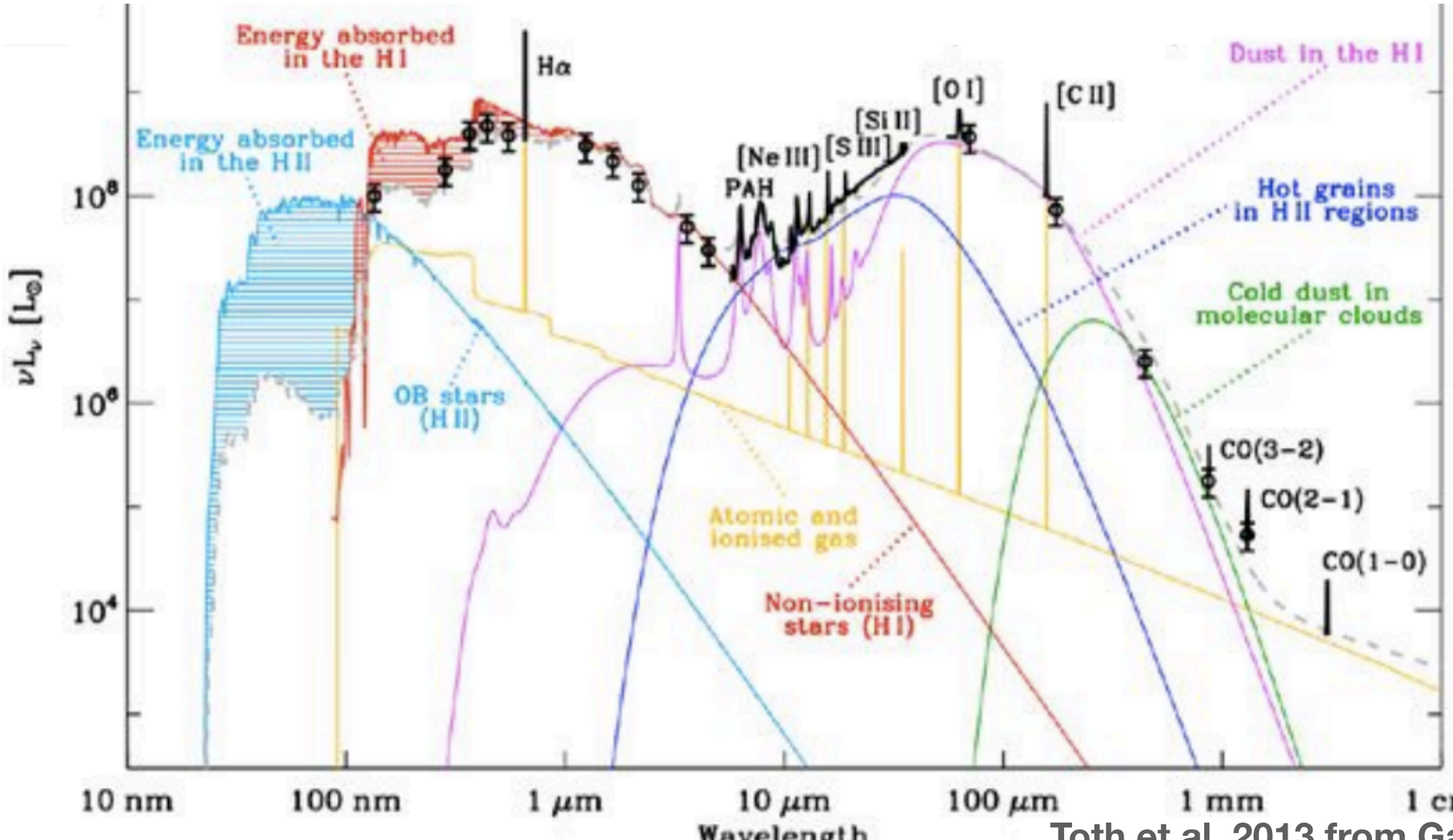


Patel et al. 2011

Star formation rates

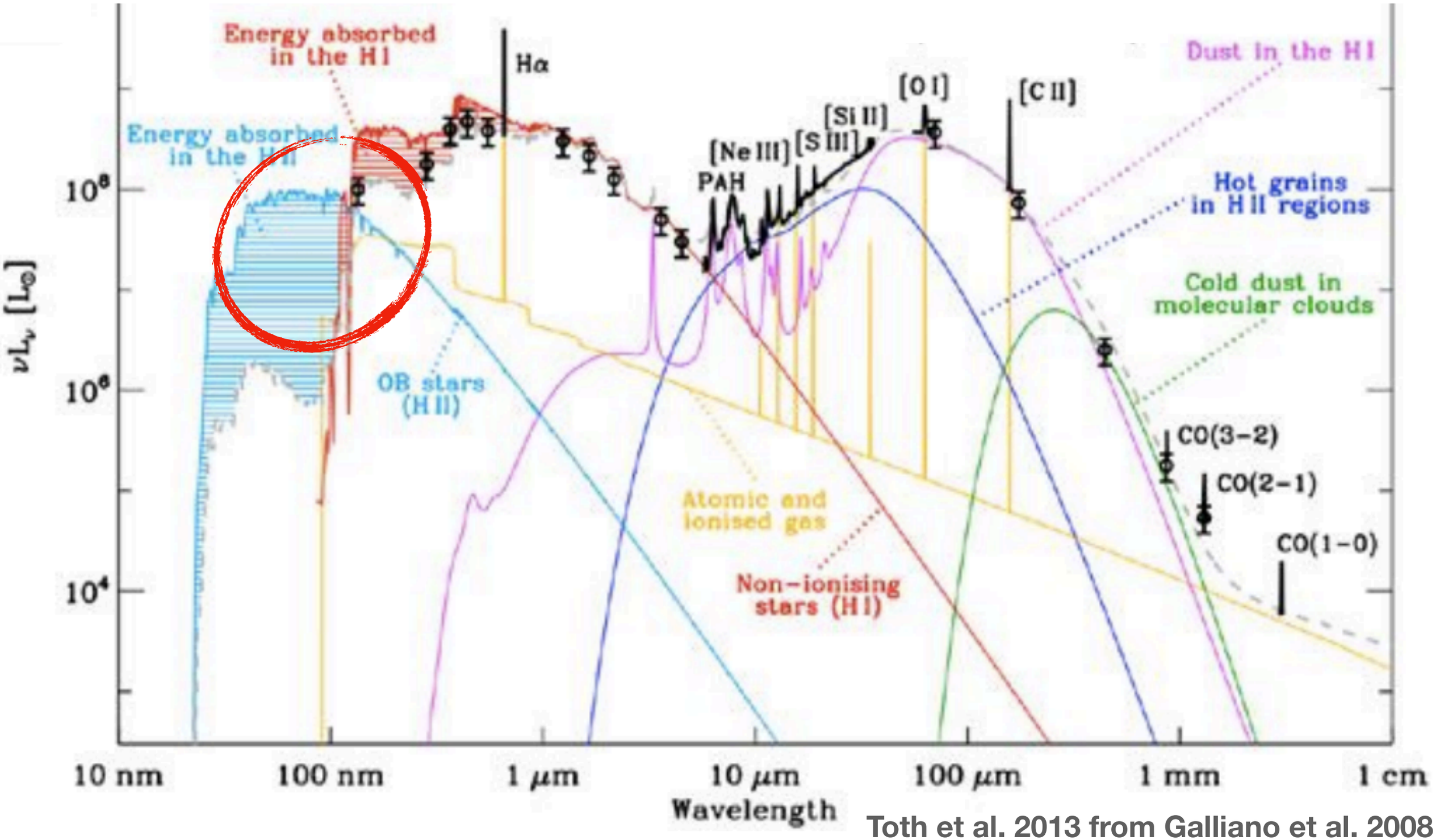
The estimate of the rate at which stars are being formed (on timescales of order 10-100x Myr) in a (unresolved) galaxy relies on measurements of luminosities (continuum or emission line) sensitive to the emission of short-lived (massive) stars.

One then converts the luminosity of massive stars to “the galaxy SFR” with some assumptions (e.g. that SFR has been constant over the timescale of the SFR estimator, that the IMF is “known” (and sampled at all masses) so that the number of massive stars probed can be extrapolated to the total number of stars being formed).



Toth et al. 2013 from Galliano et al. 2008

Star formation rates



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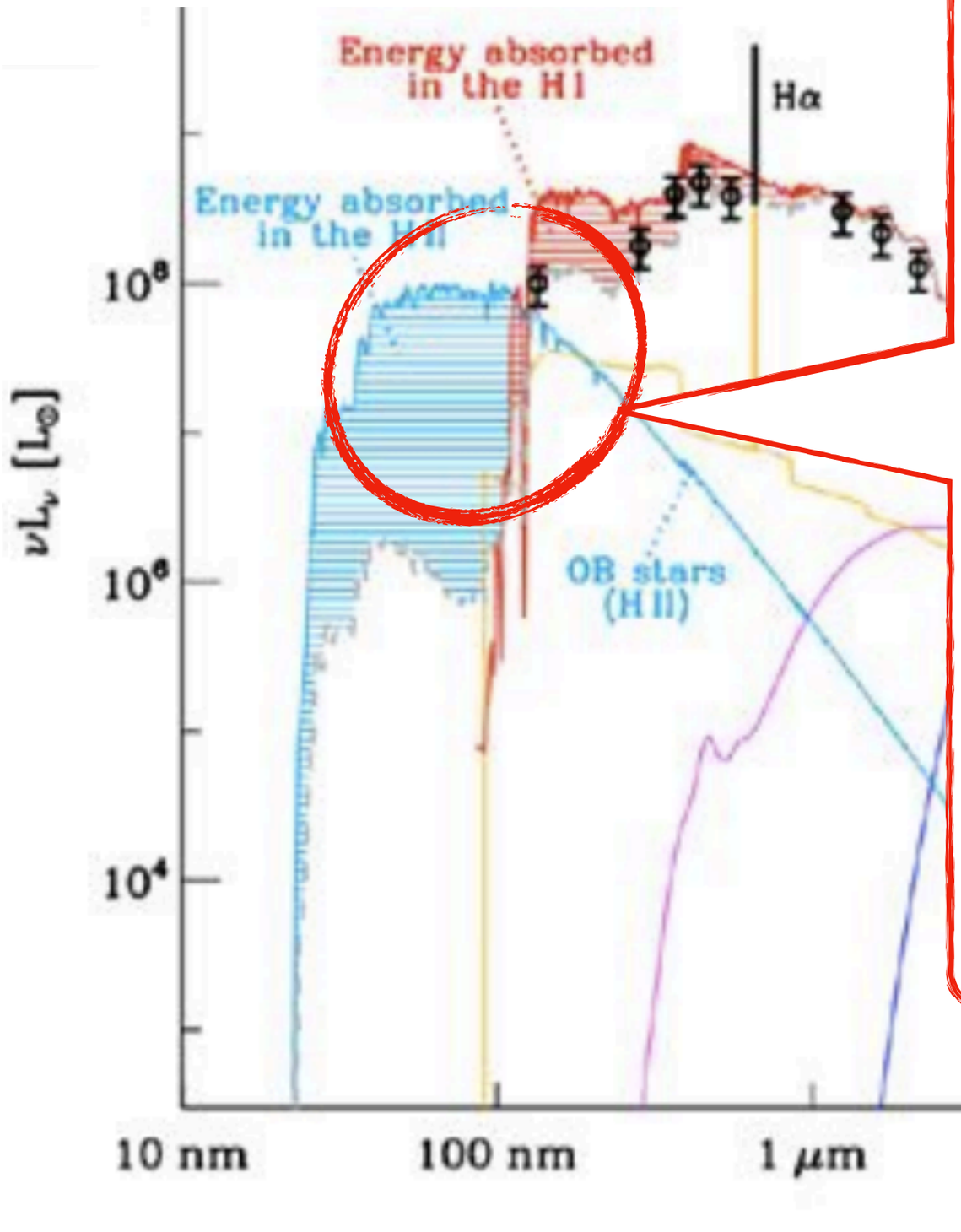
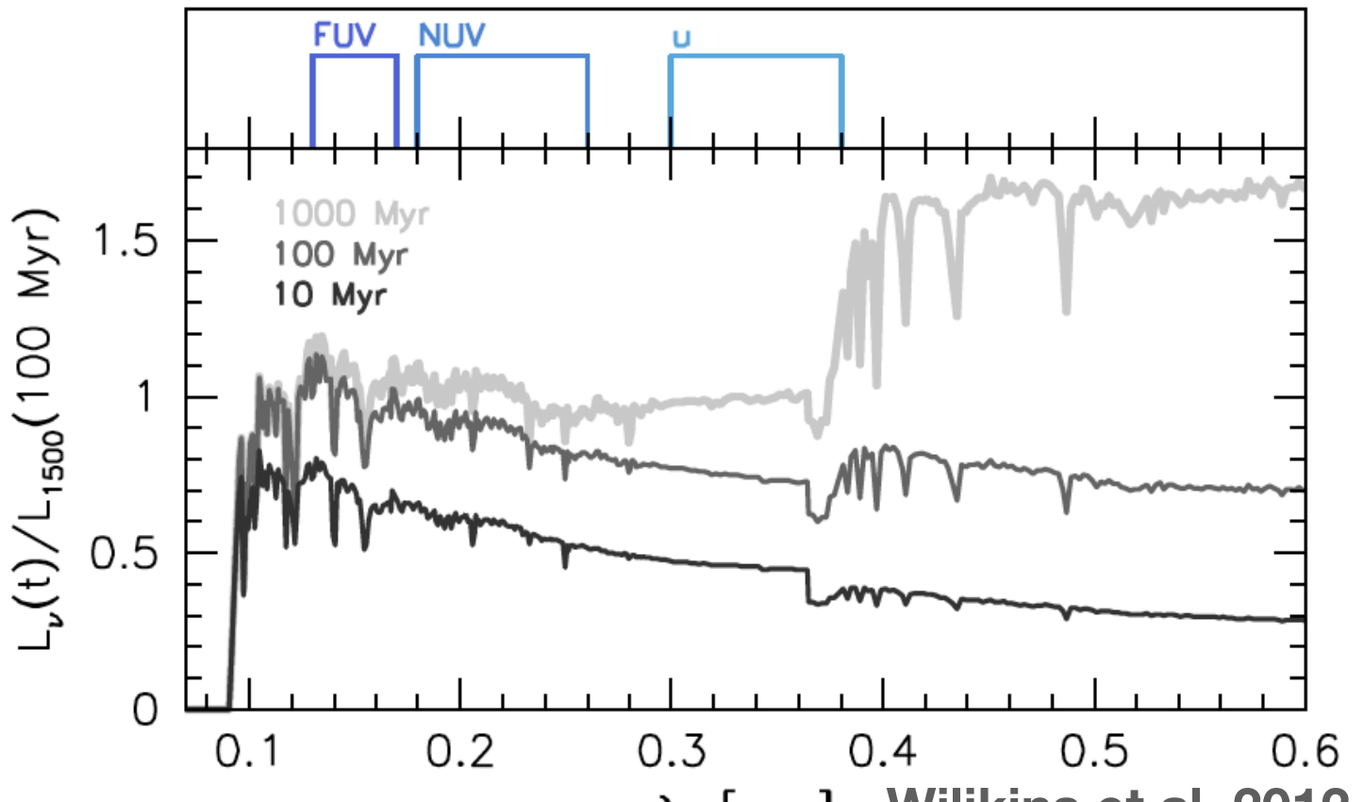


Toth et al. 2013 from Galliano et al. 2008



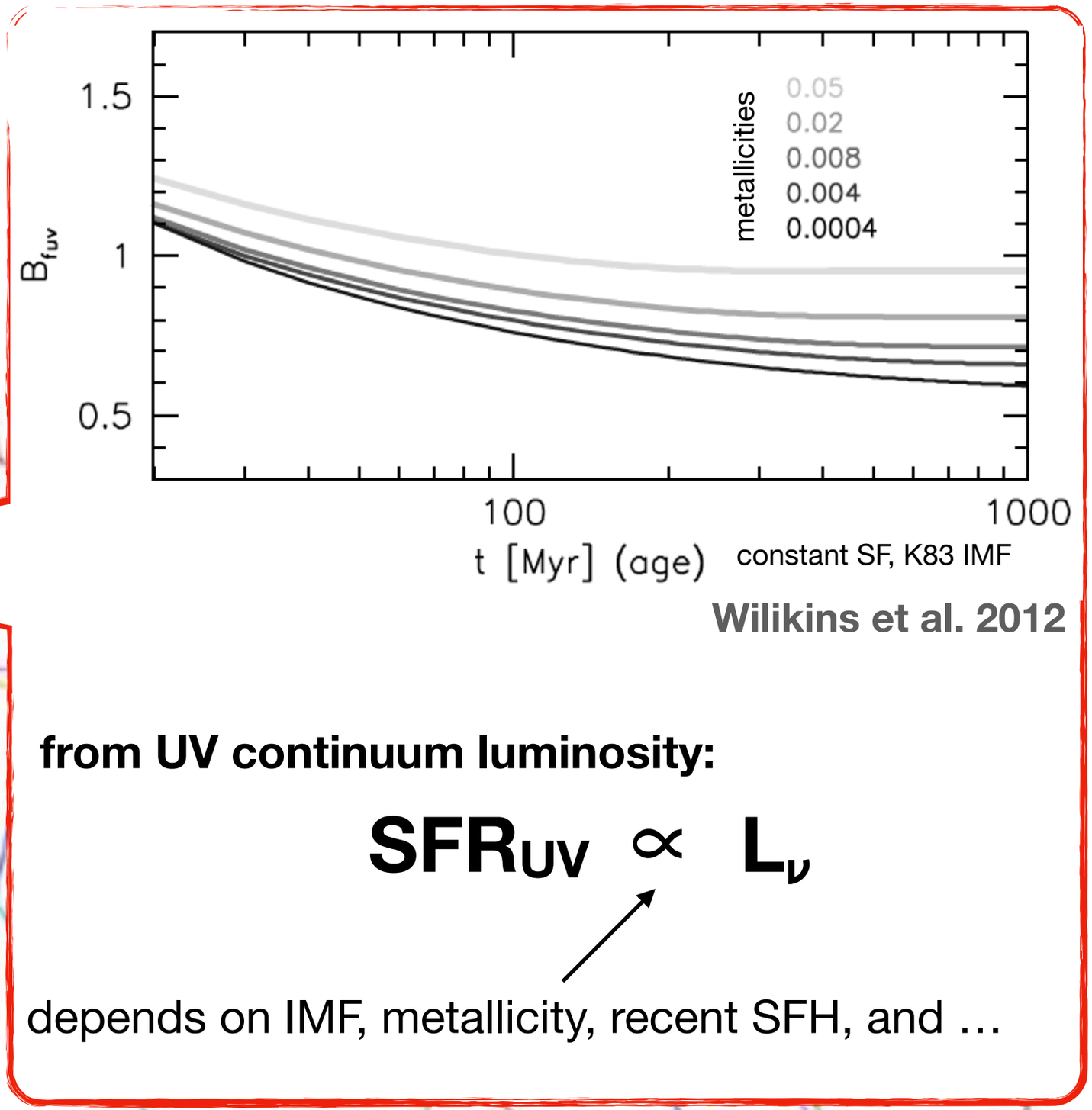
Wilikins et al. 2012

from UV continuum luminosity:

$$\mathbf{SFR_{UV} \propto L_\nu}$$

ν in **1500-2500 Å range**, F**ν** relatively flat, contribution from older populations is small

Star formation rates

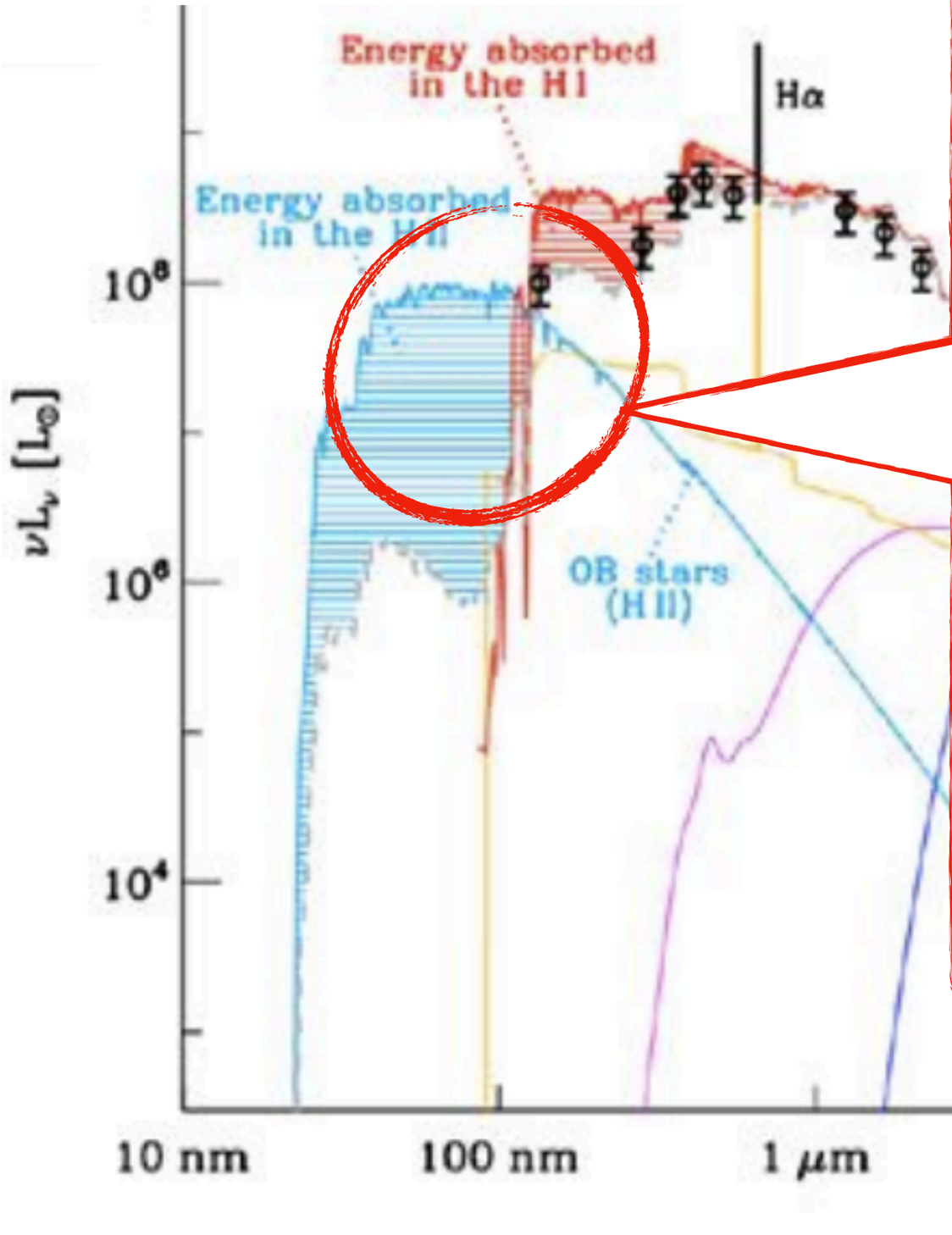


Wilikins et al. 2012

from UV continuum luminosity:

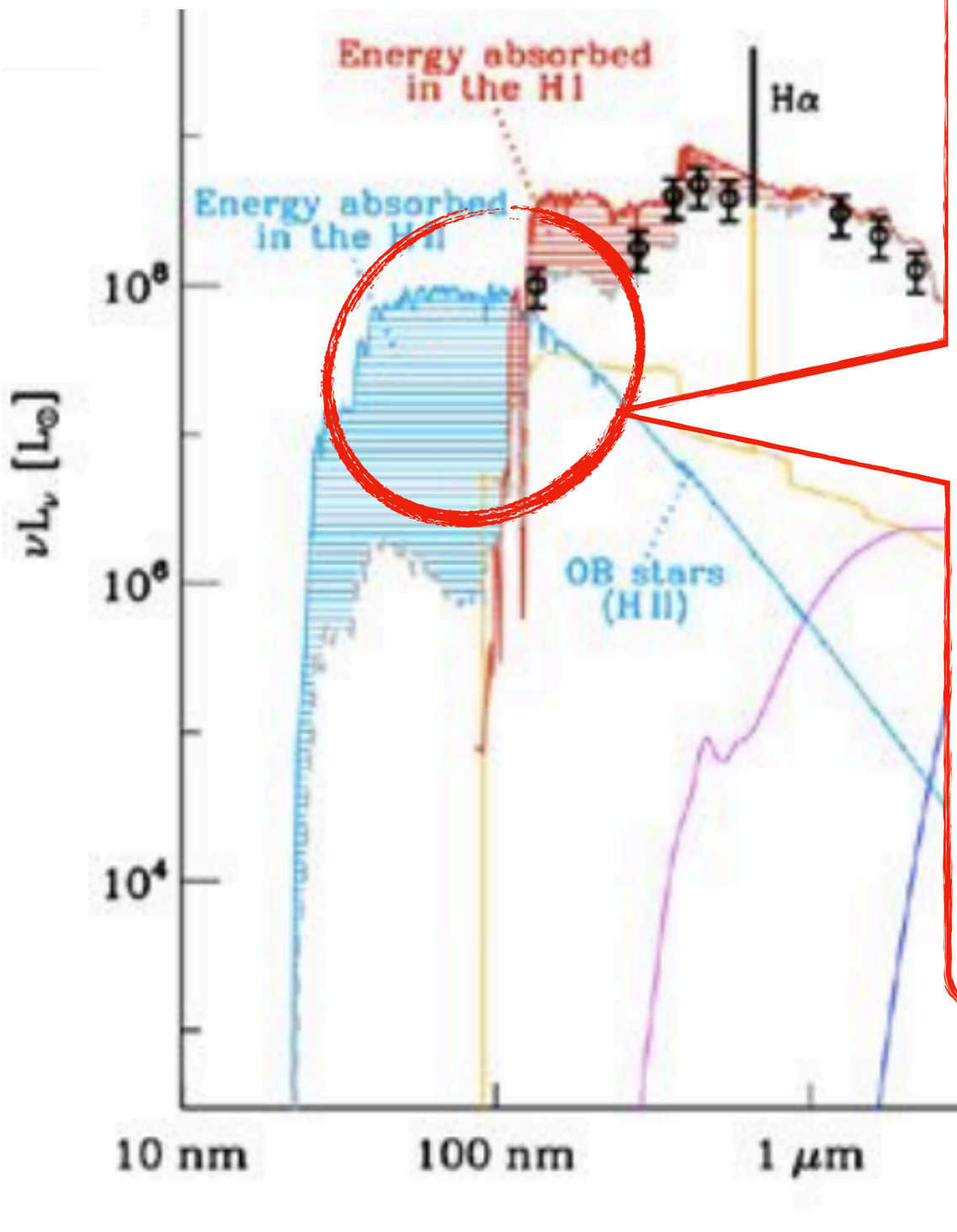
$$SFR_{UV} \propto L_\nu$$

depends on IMF, metallicity, recent SFH, and …

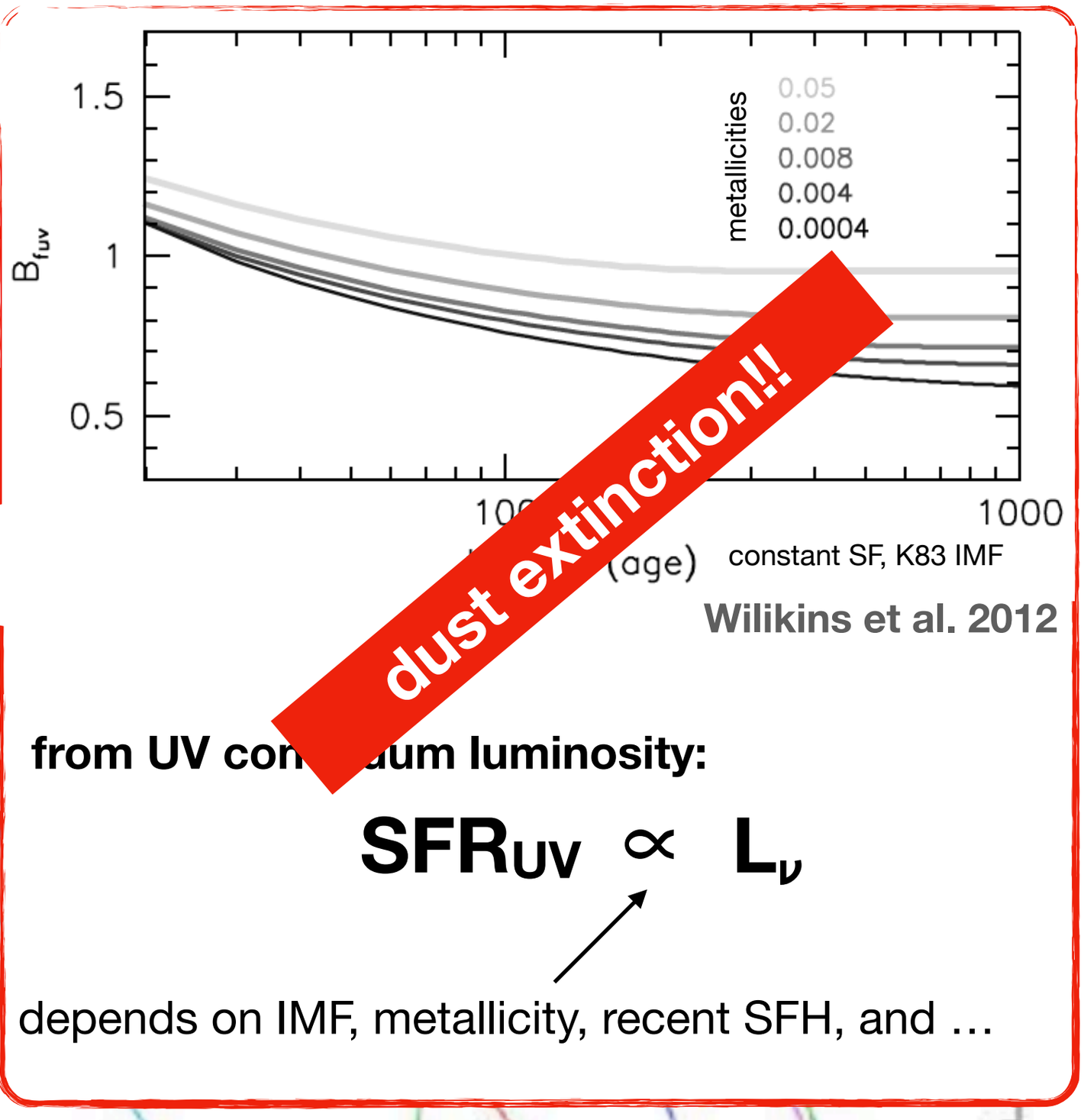


Toth et al. 2013 from Galliano et al. 2008

Star formation rates



Toth et al. 2013 from Galliano et al. 2008



Wilikins et al. 2012

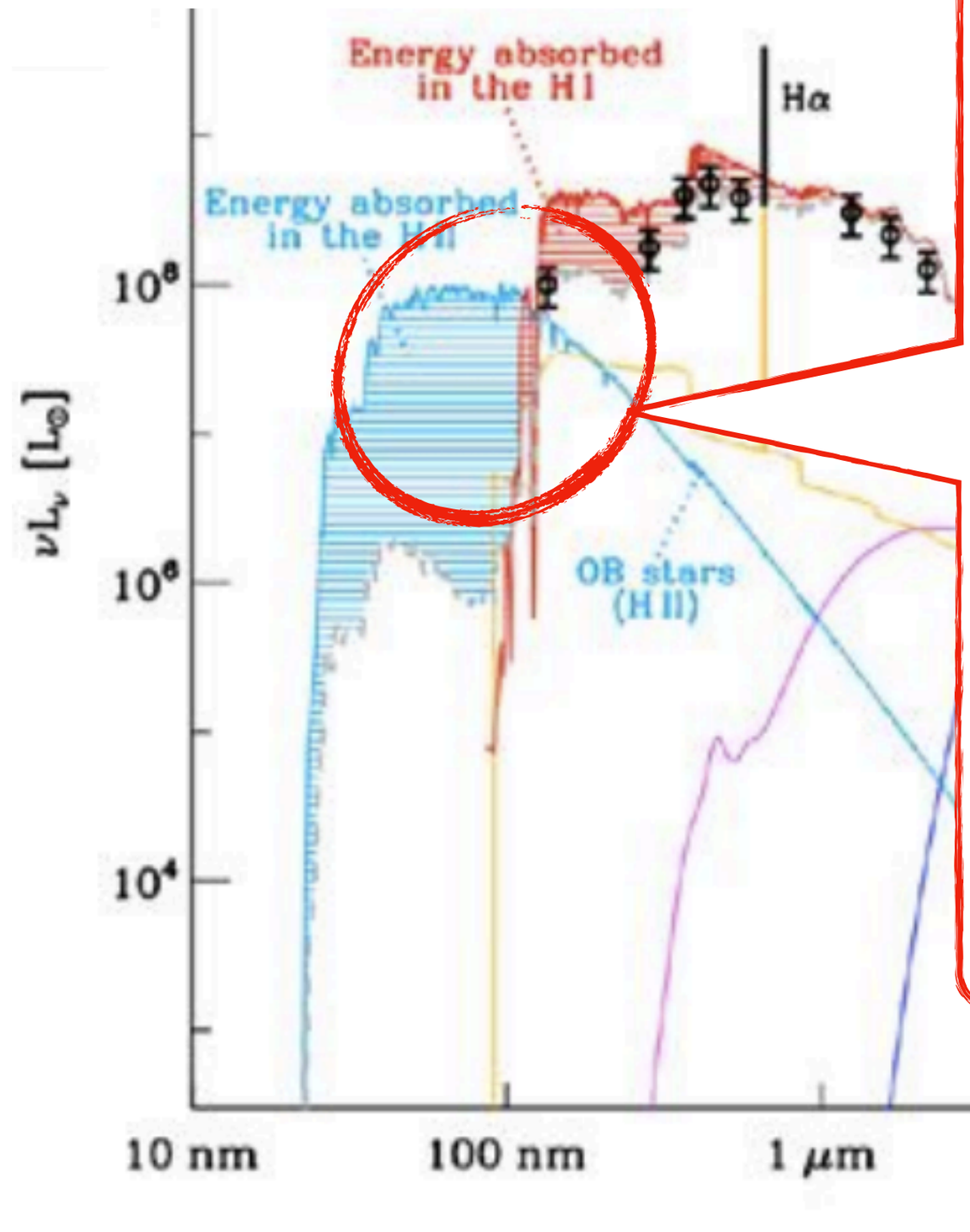
dust extinction!!

from UV continuum luminosity:

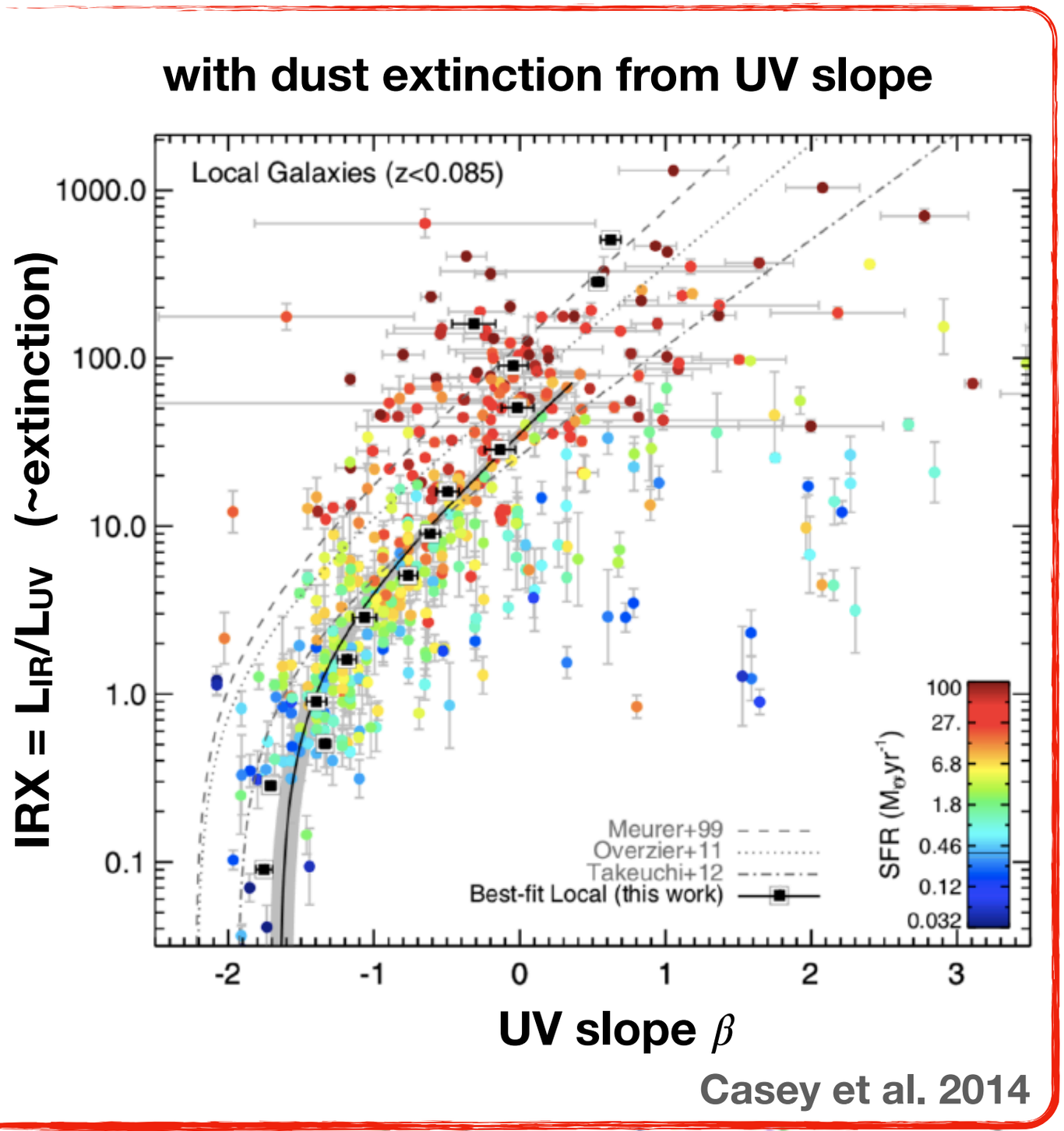
$$SFR_{UV} \propto L_\nu$$

depends on IMF, metallicity, recent SFH, and …

Star formation rates

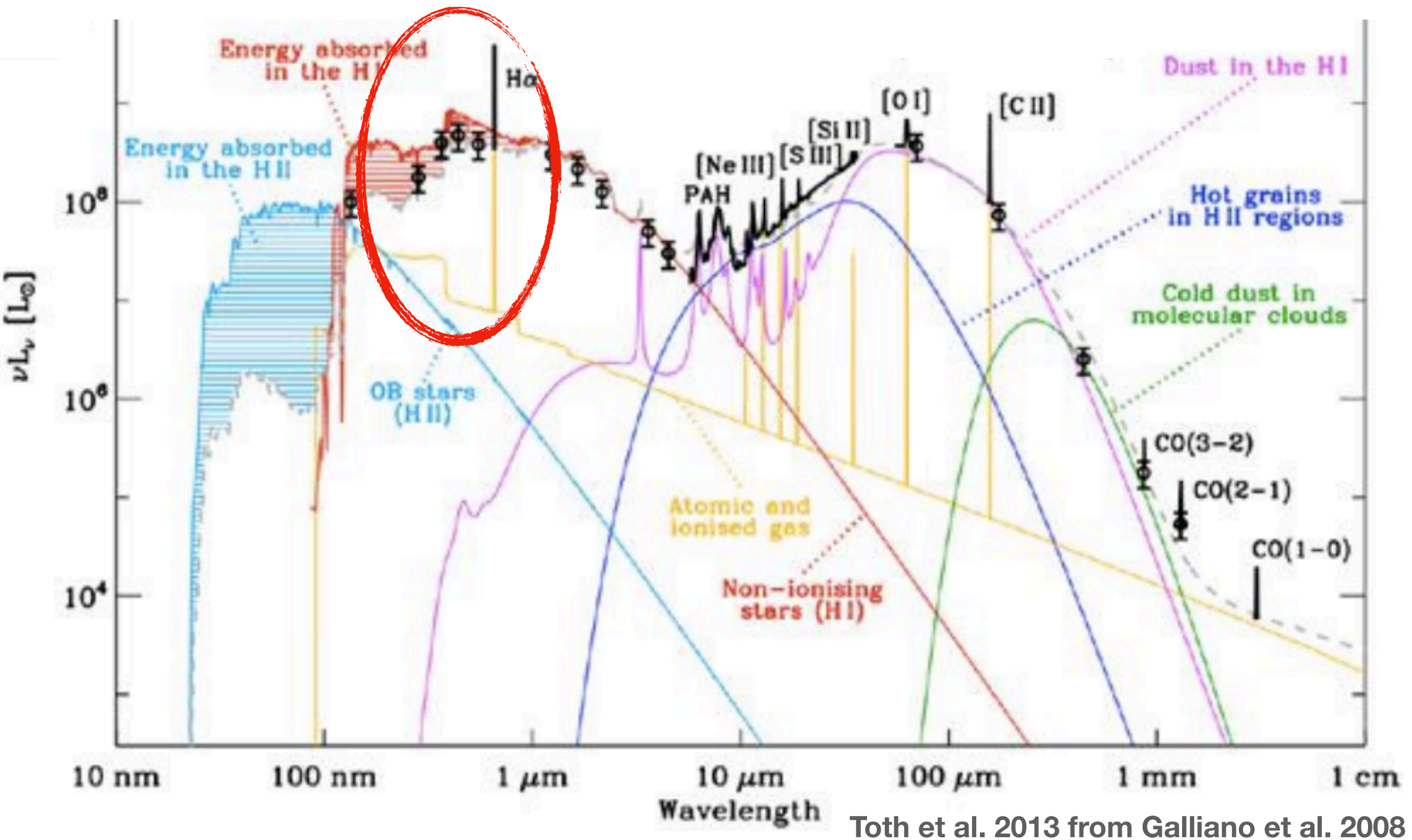


Toth et al. 2013 from Galliano et al. 2008



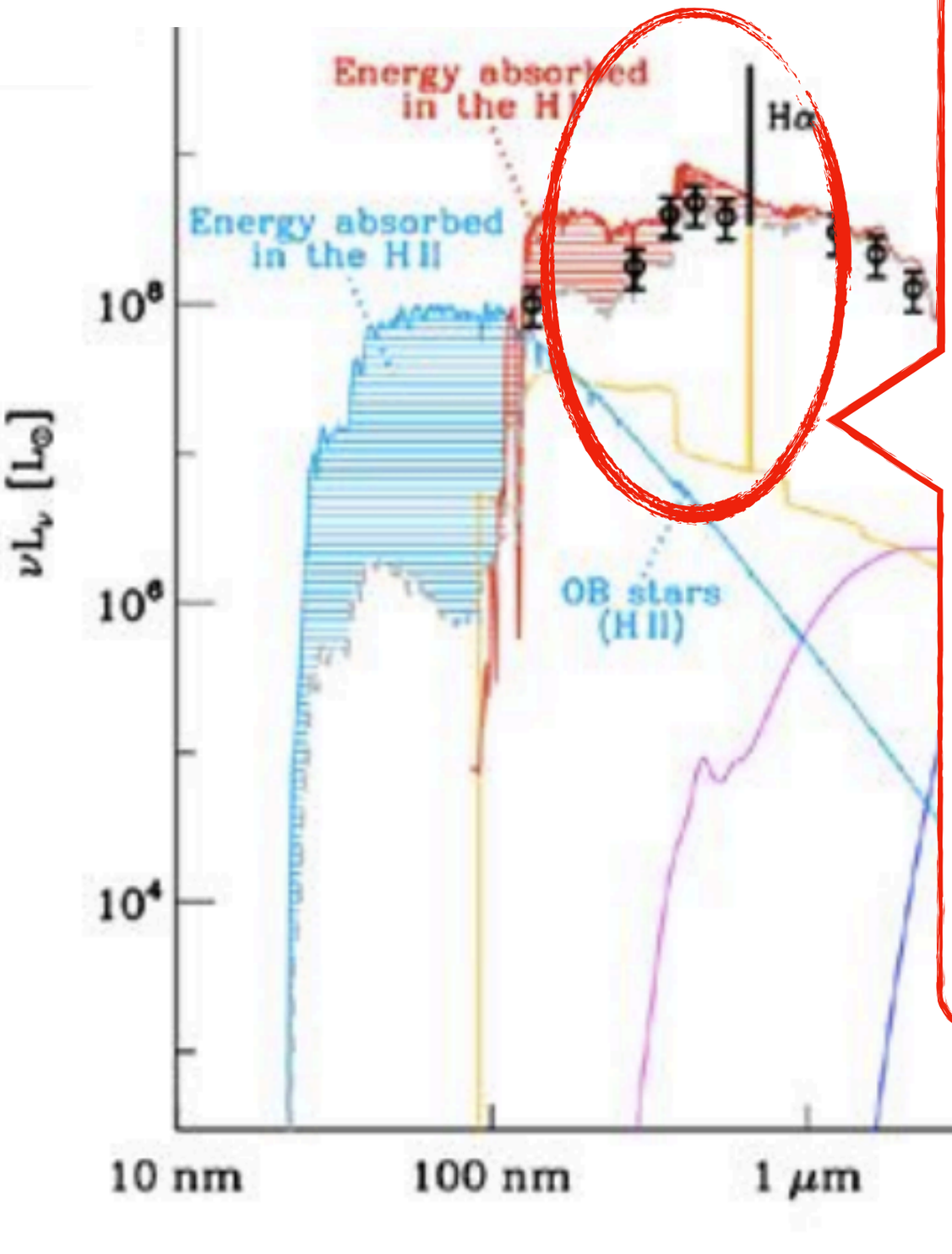
Casey et al. 2014

Star formation rates



Toth et al. 2013 from Galliano et al. 2008

Star formation rates



from UV /optical emission lines tracing ionised gas

Only stars more massive than ~20 $M_\odot$ produce a significant ionising photon flux (the flux is reduced by 100x between 5 and 10 Myr from the star formation burst). Lines more commonly used:

hydrogen recombination lines, most often H_α

$$\mathbf{SFR_{H\alpha} \propto L_{H\alpha}}$$

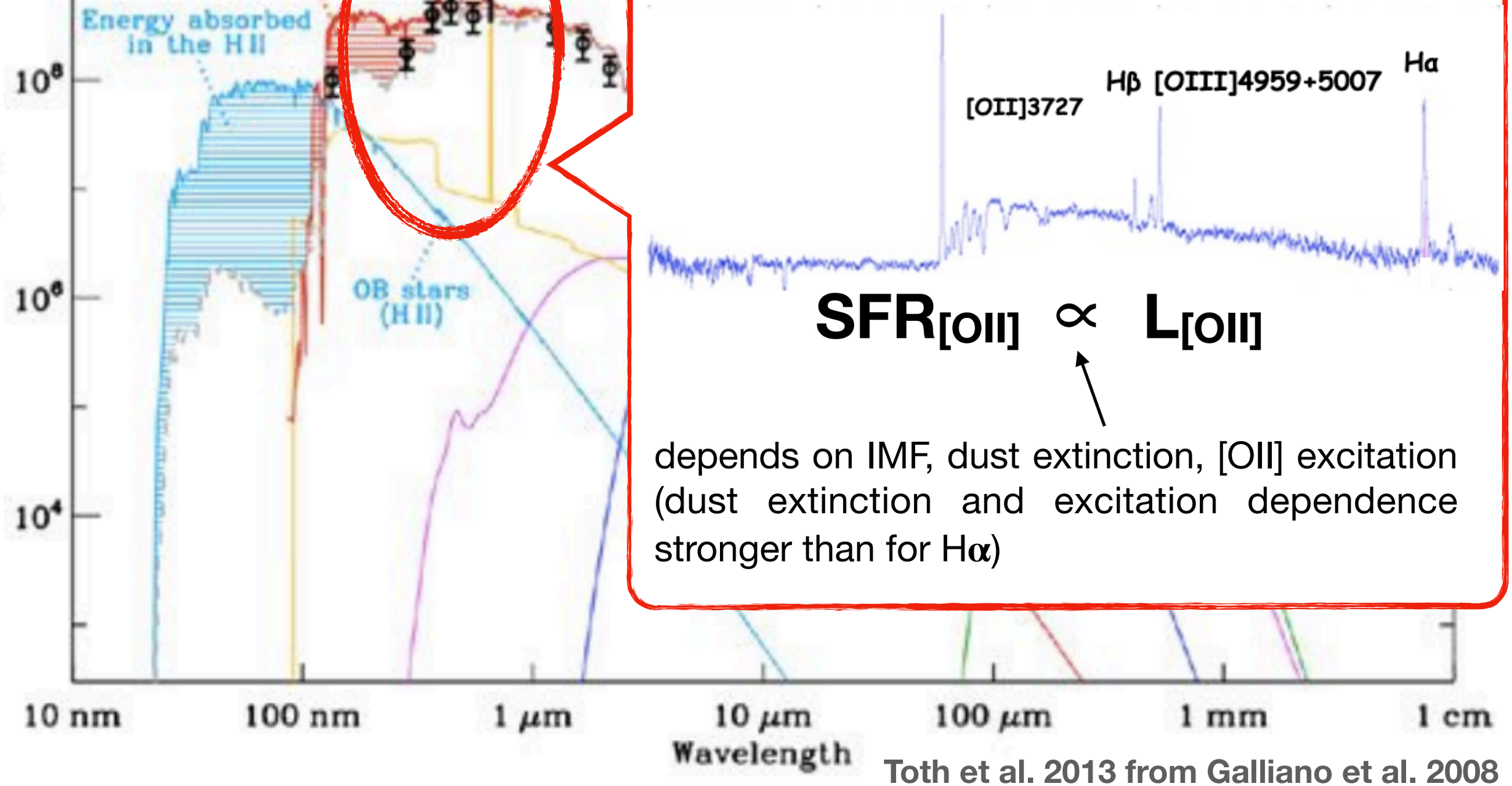
depends on IMF, dust extinction, …

Toth et al. 2013 from Galliano et al. 2008

Star formation rates

from UV /optical emission lines tracing ionised gas

At z>0.5 the Hα line is shifted out of the visible range. The strongest suitable line is then the [OII] doublet at 3727Å.

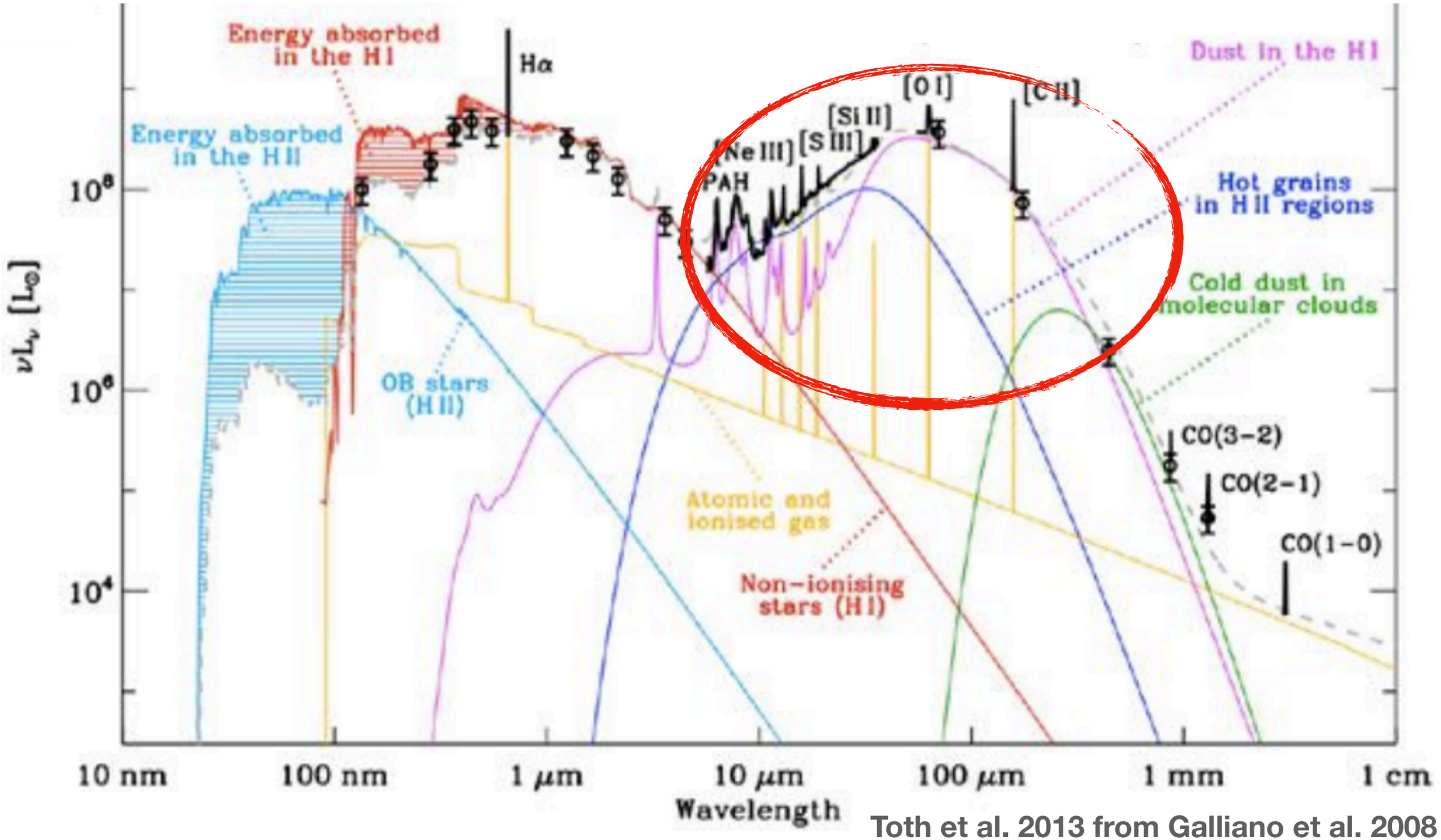


$$SFR_{[OII]} \propto L_{[OII]}$$

depends on IMF, dust extinction, [OII] excitation (dust extinction and excitation dependence stronger than for Hα)

Toth et al. 2013 from Galliano et al. 2008

Star formation rates

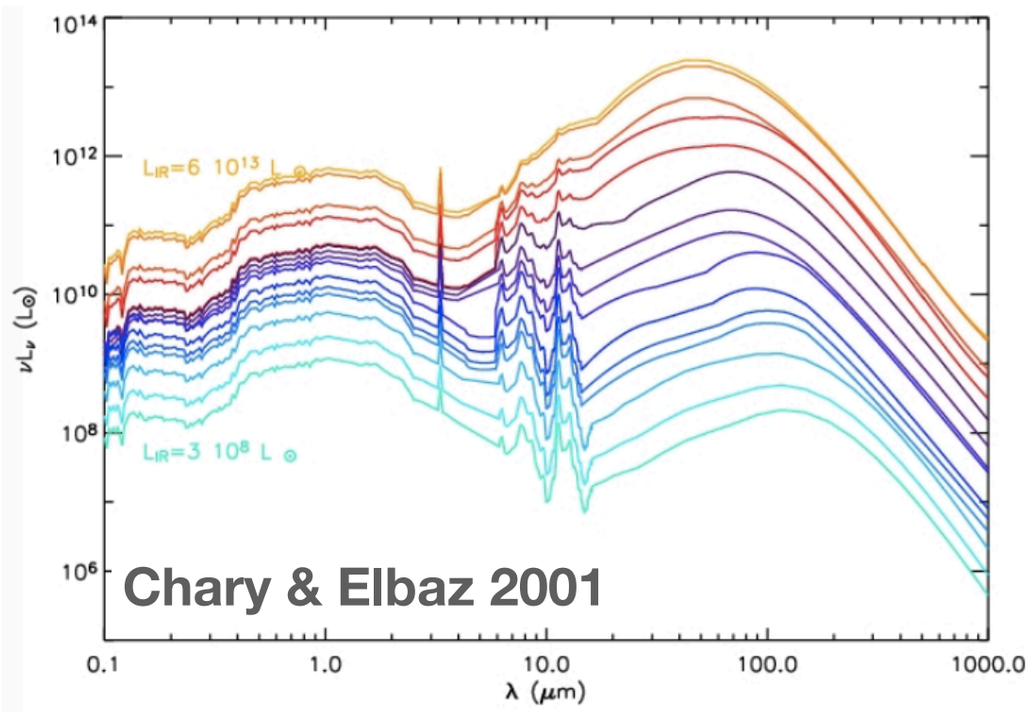


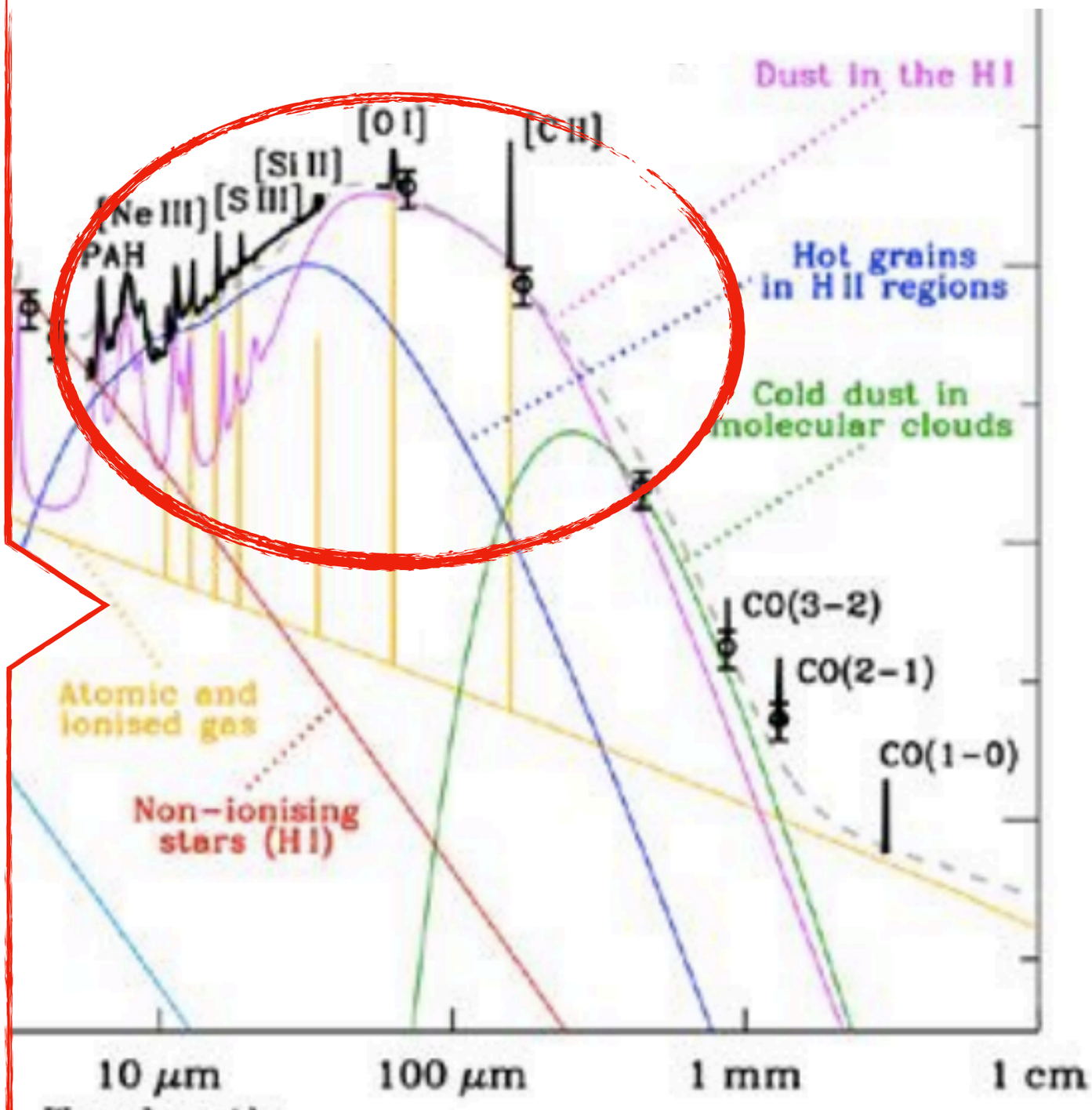
Toth et al. 2013 from Galliano et al. 2008

Star formation rates

from IR emission:

from IR luminosity



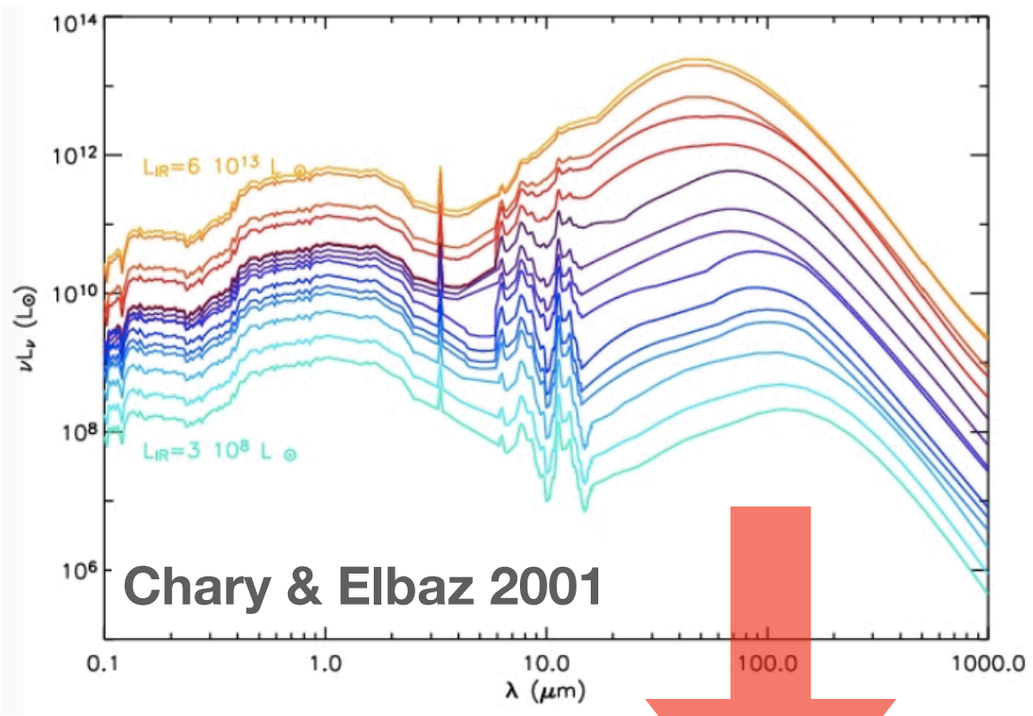


Toth et al. 2013 from Galliano et al. 2008

Star formation rates

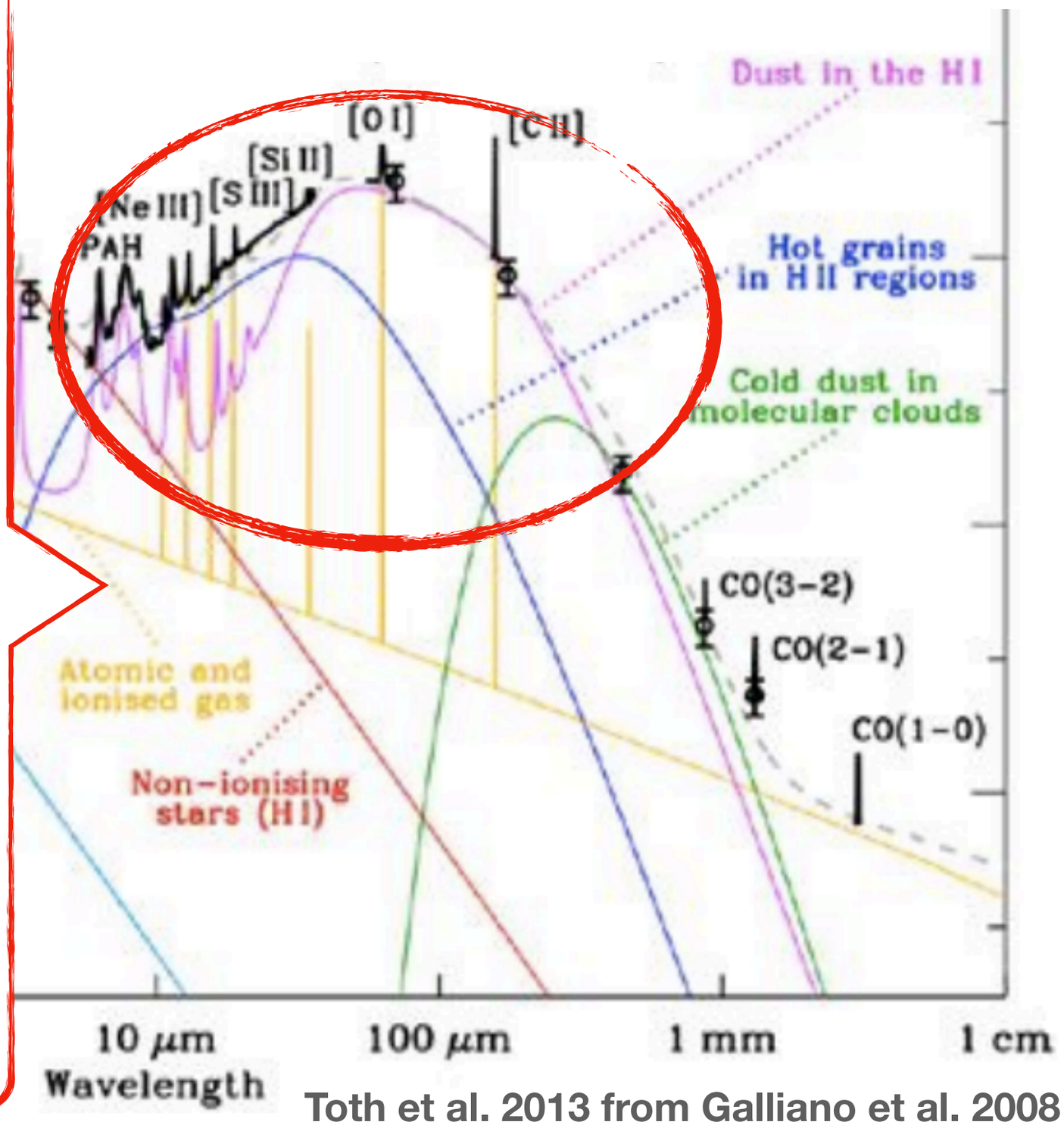
from IR emission:

from IR luminosity



estimate (or extrapolate to) total IR luminosity

$SFR_{IR} \propto L_{IR}$

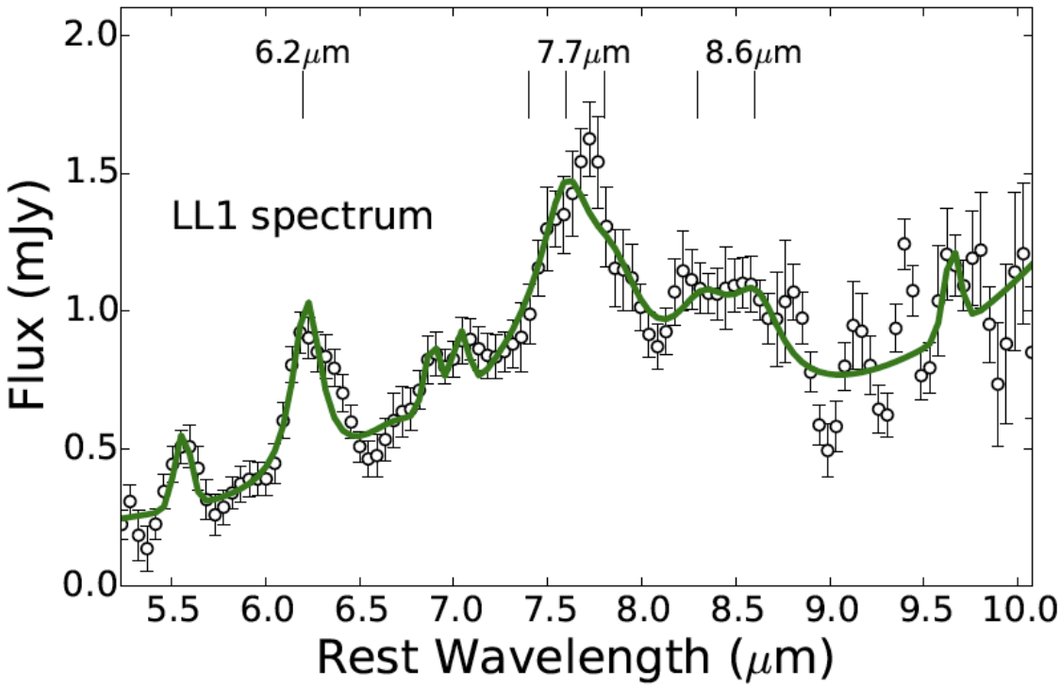


Toth et al. 2013 from Galliano et al. 2008

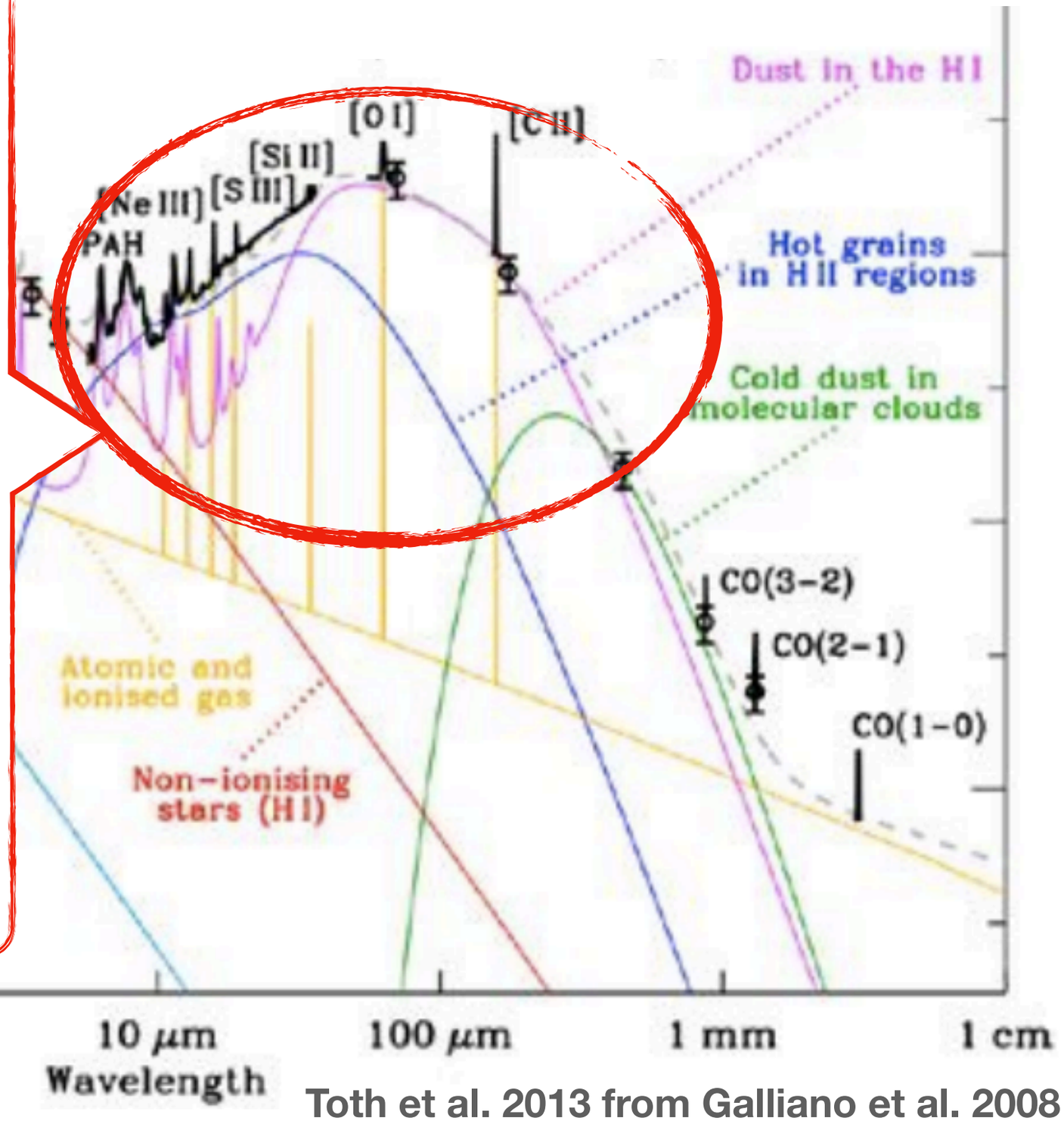
Star formation rates

from IR emission:

from PAH features

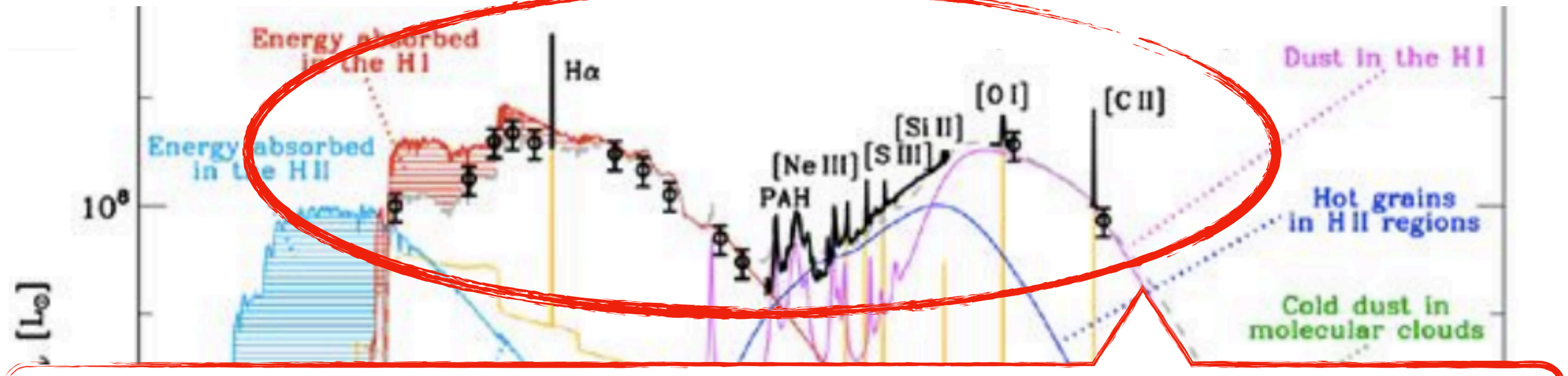


Shipley et al. 2016

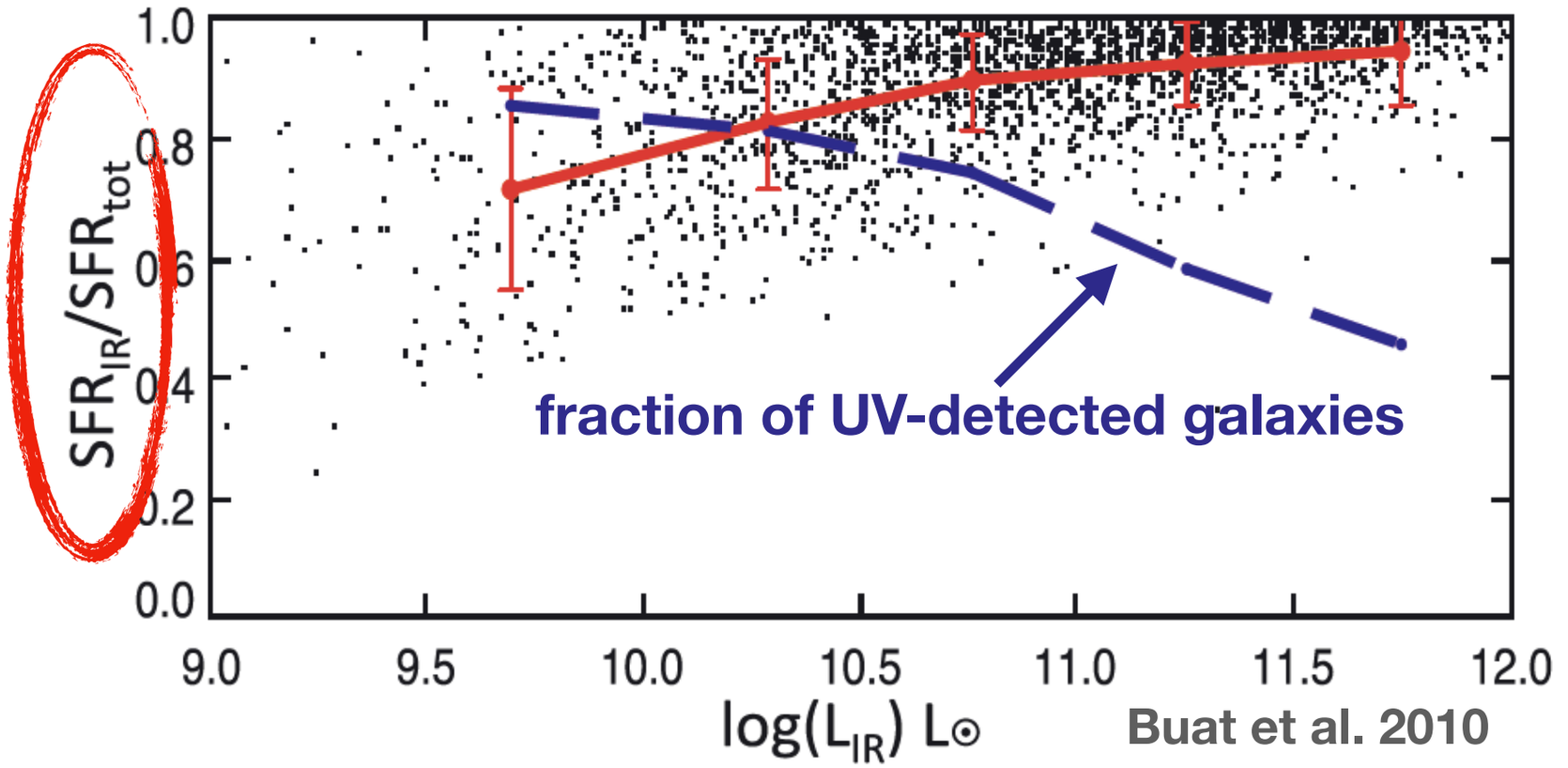


Toth et al. 2013 from Galliano et al. 2008

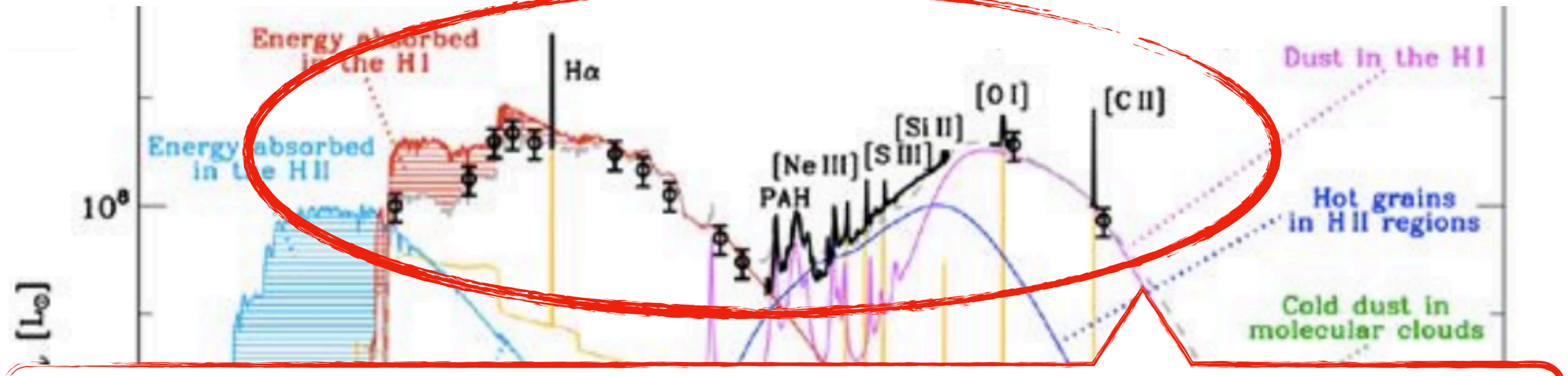
Star formation rates

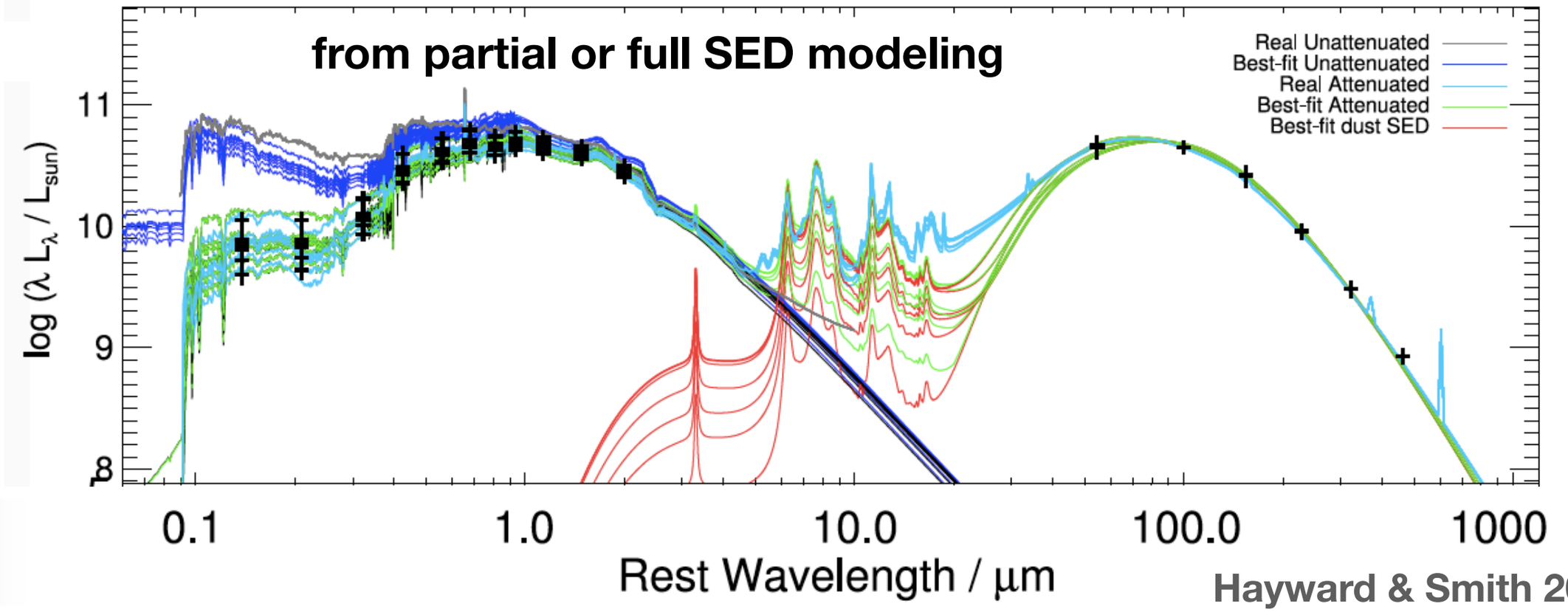


combining UV and IR SFR estimates



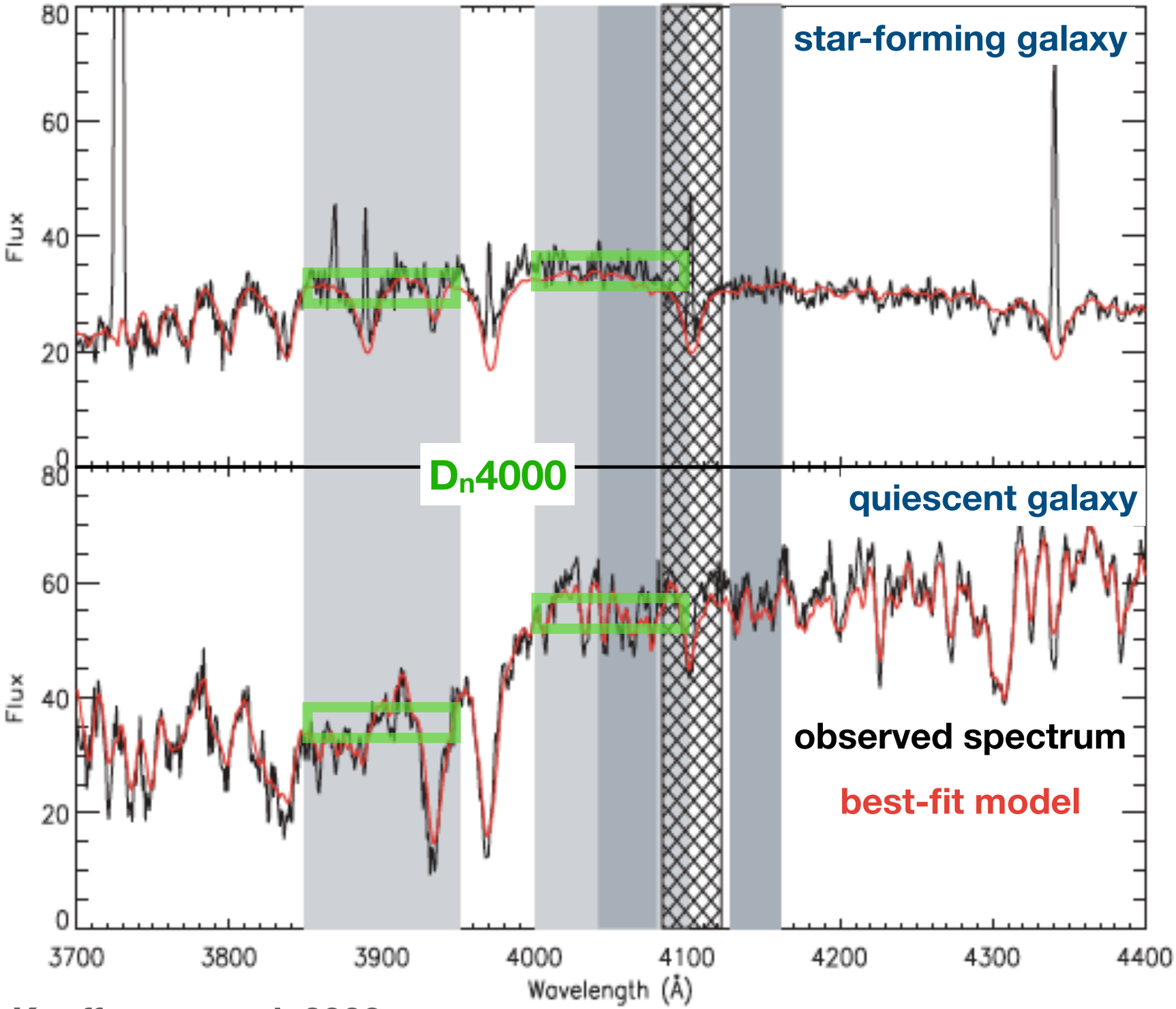
Star formation rates





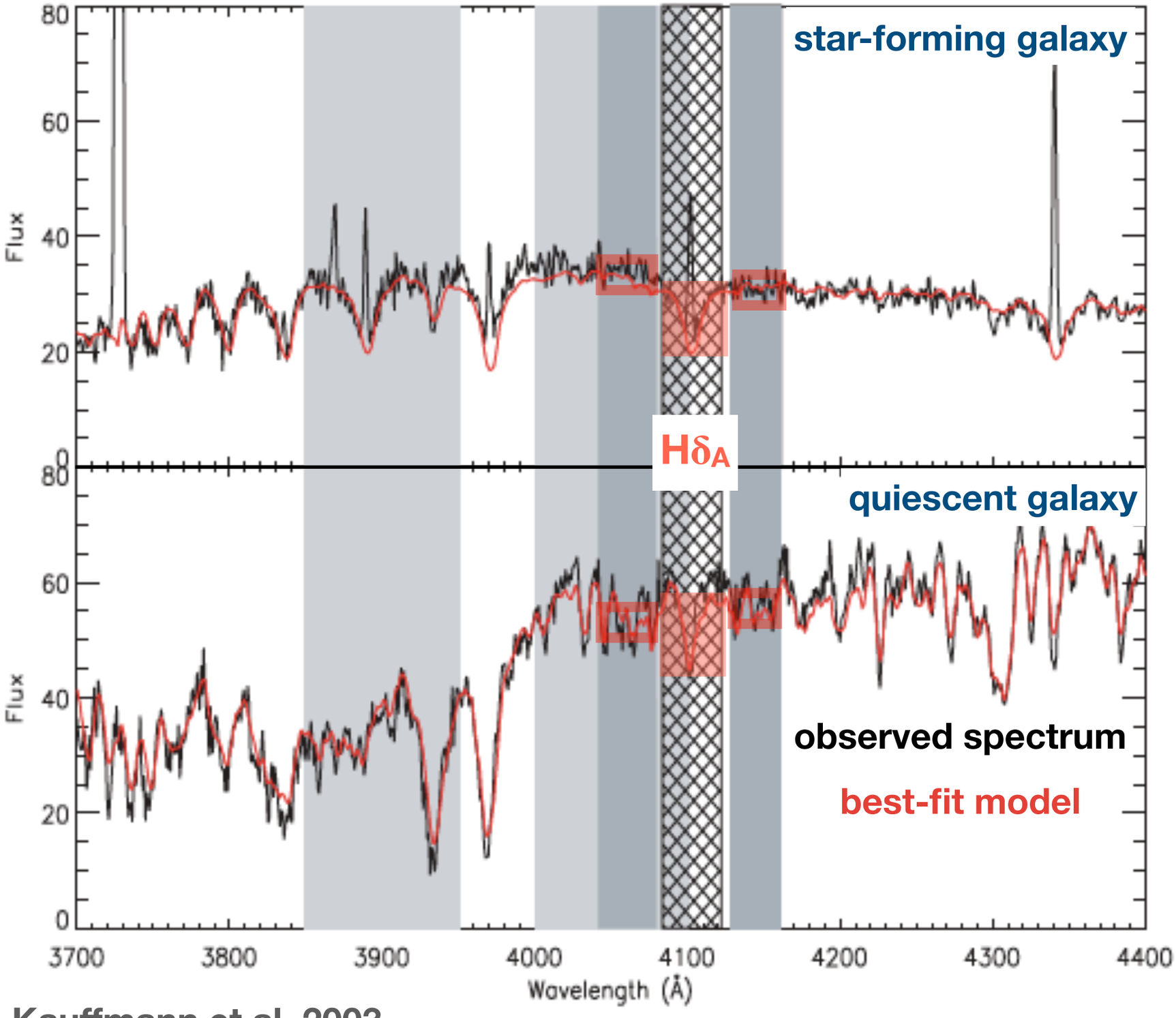
Hayward & Smith 2014

Stellar ages, star formation histories and metallicities



Kauffmann et al. 2003

Stellar ages, star formation histories and metallicities



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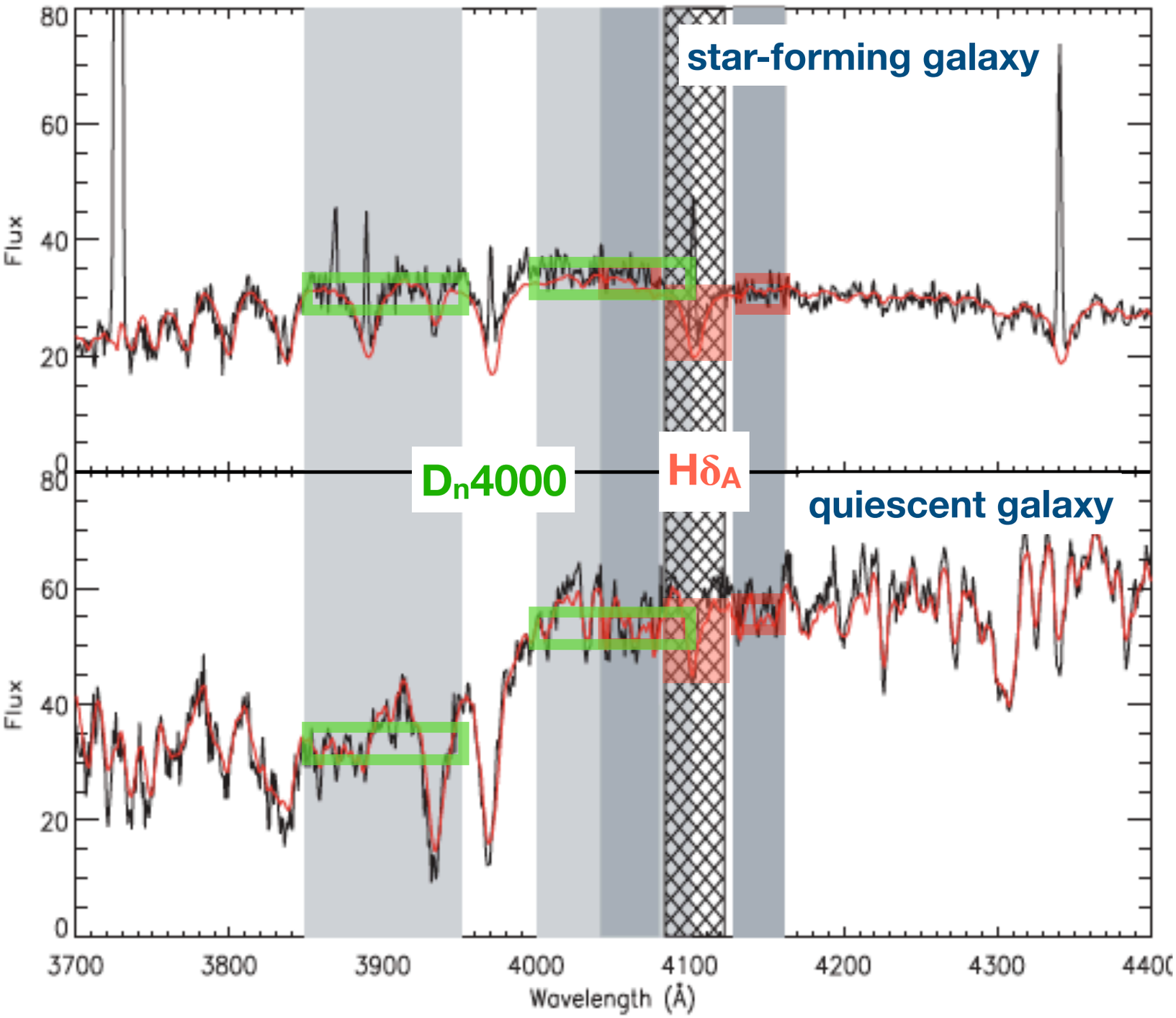
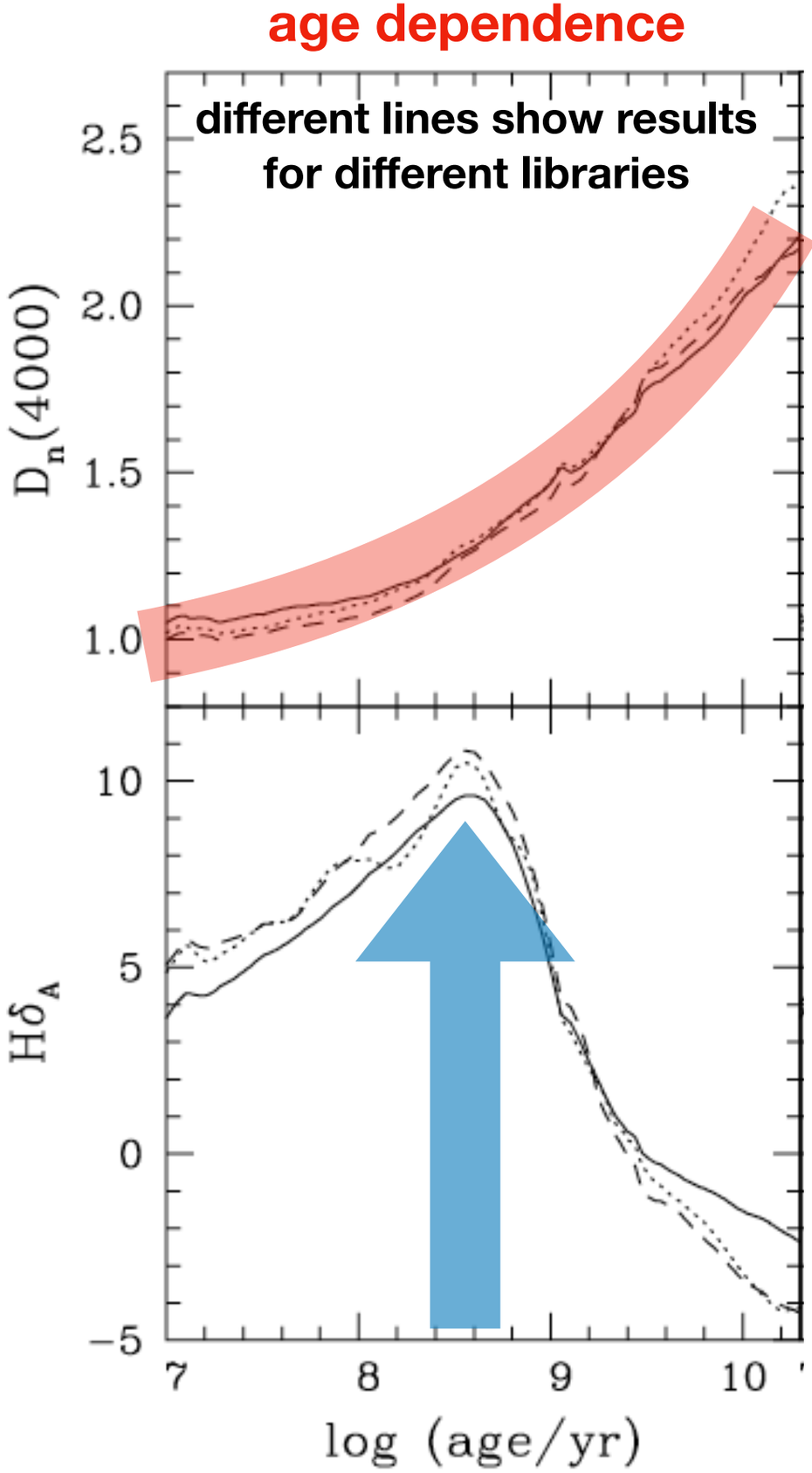
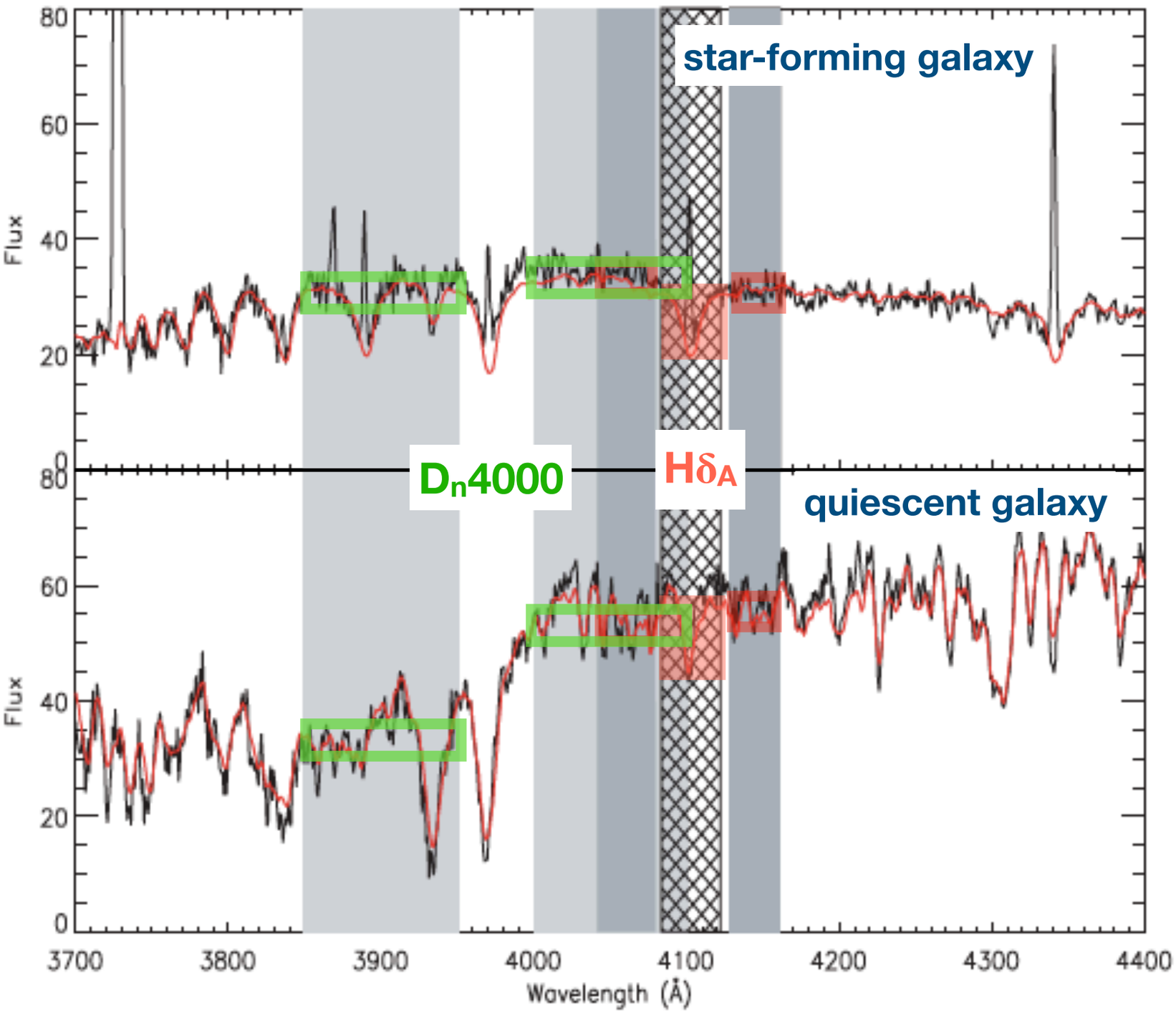


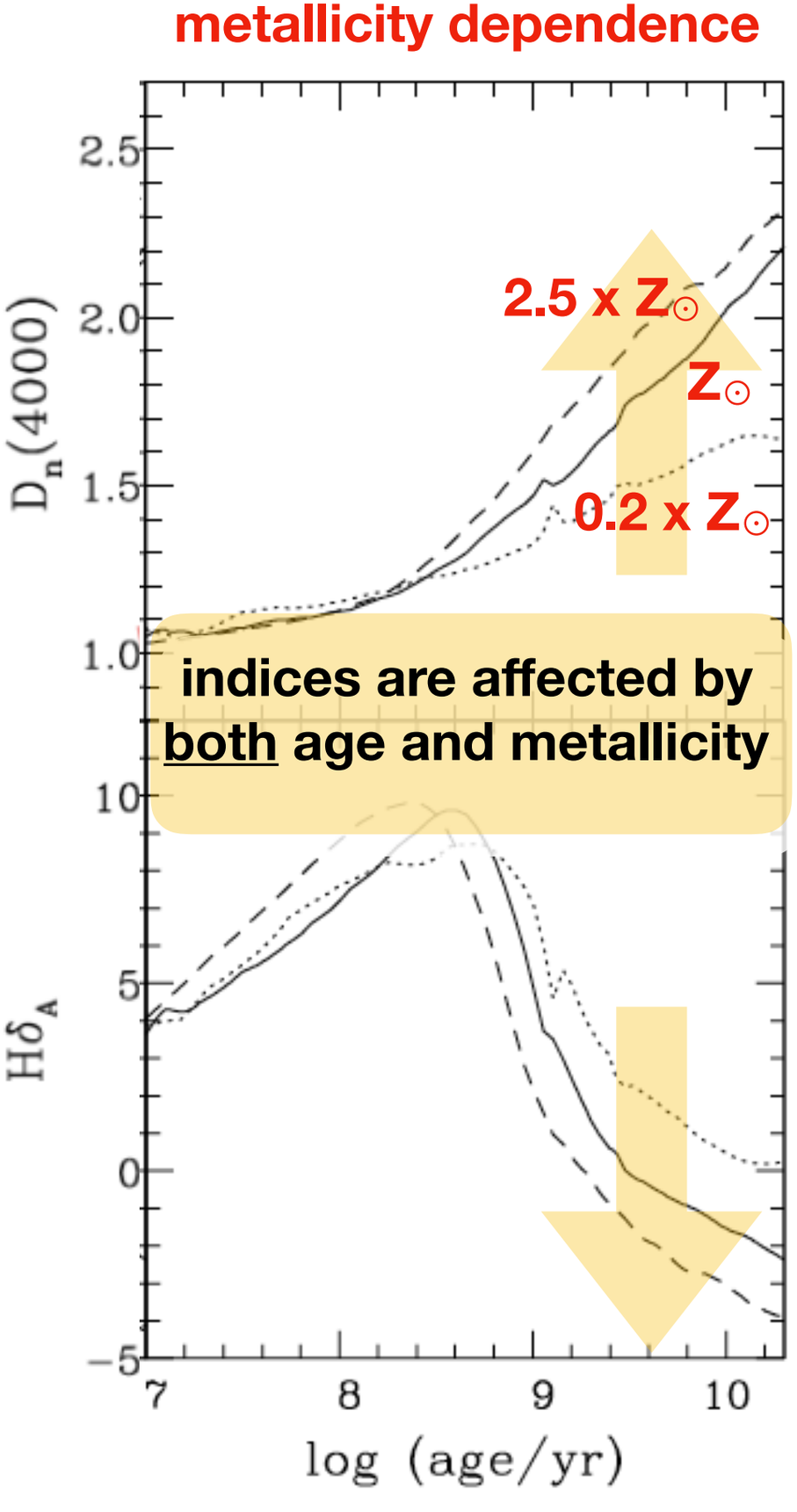
Kauffmann et al. 2003



Stellar ages, star formation histories and metallicities

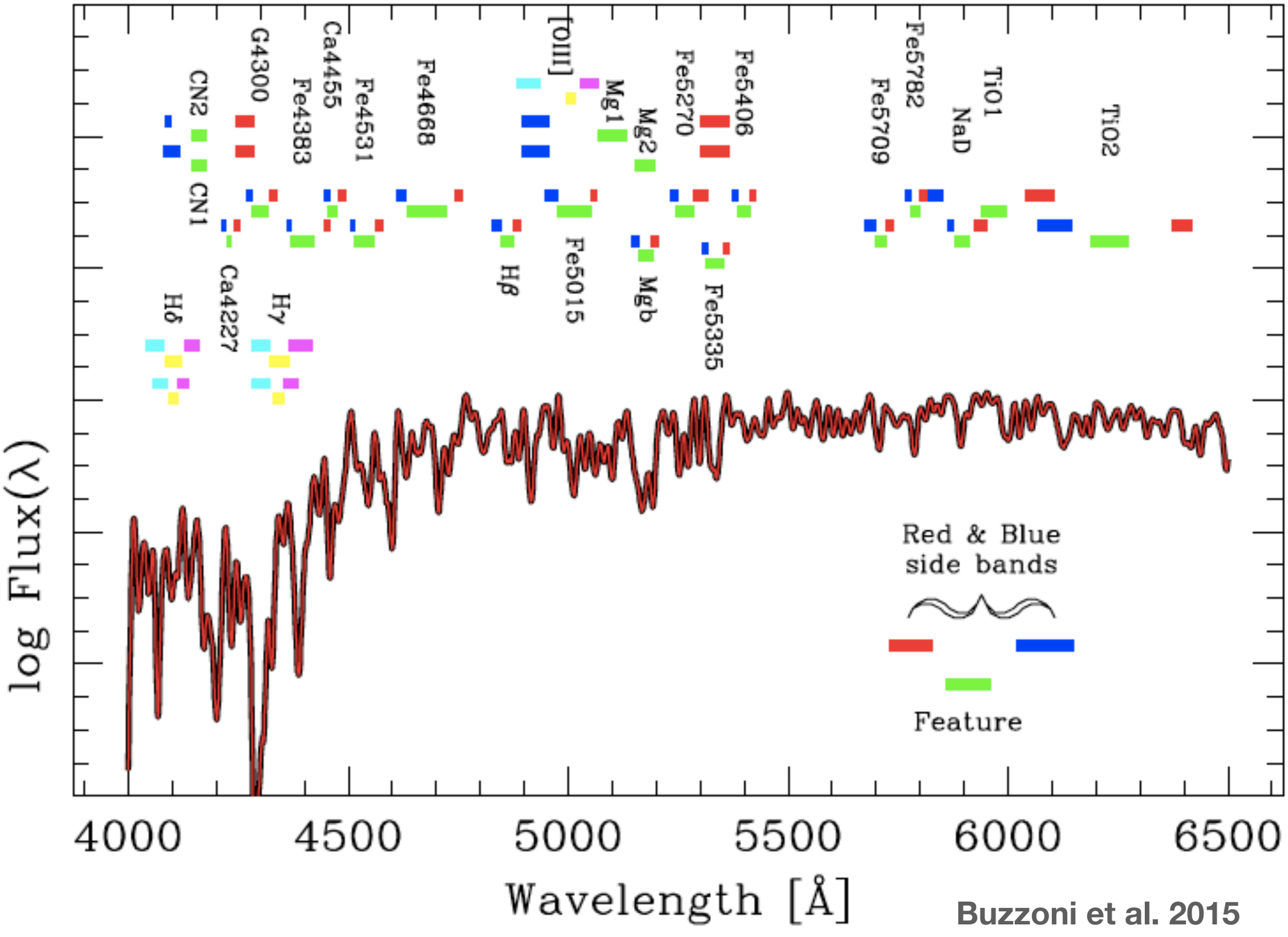


Kauffmann et al. 2003



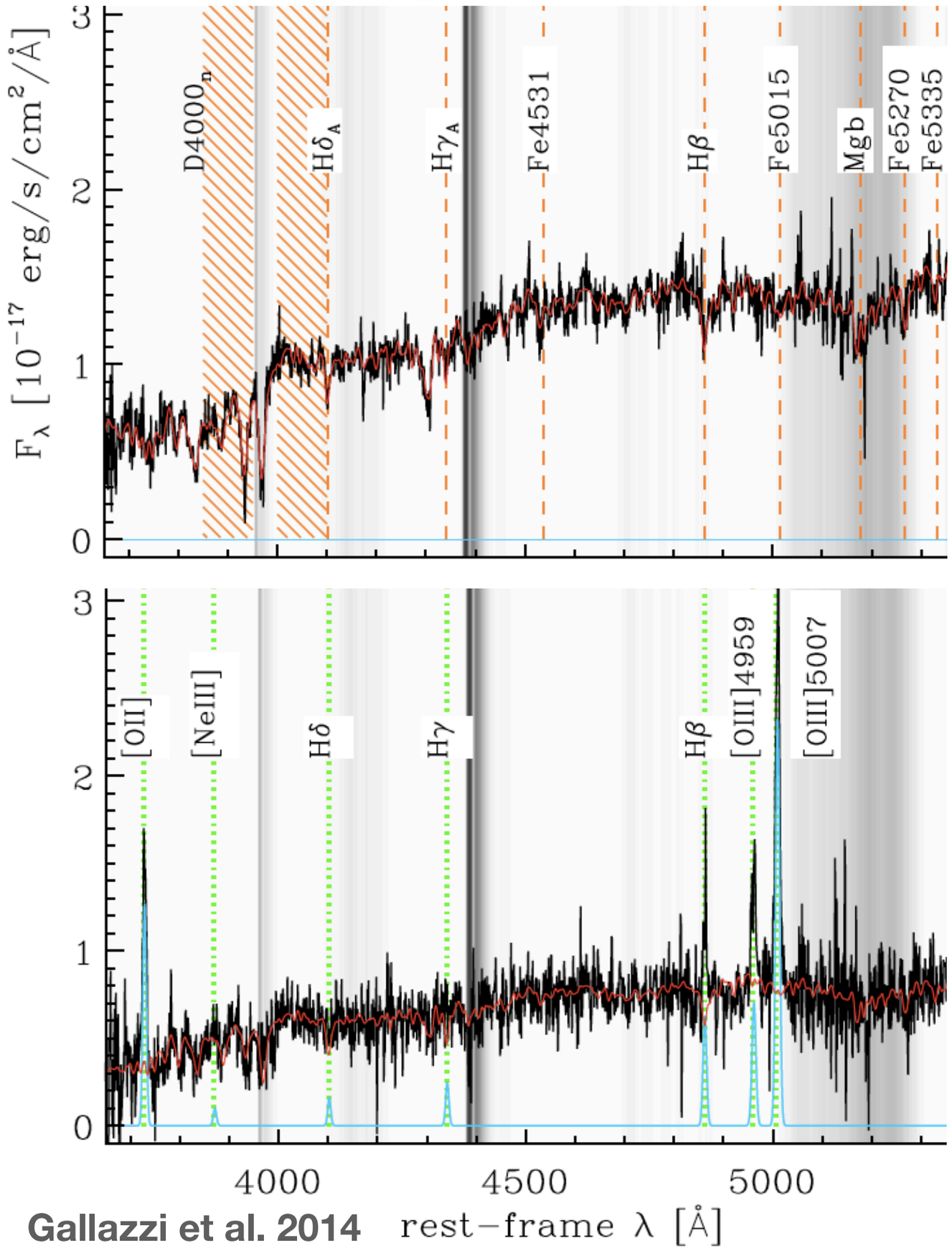
Stellar ages, star formation histories and metallicities

… no spectral index is a pure age or metallicity indicator

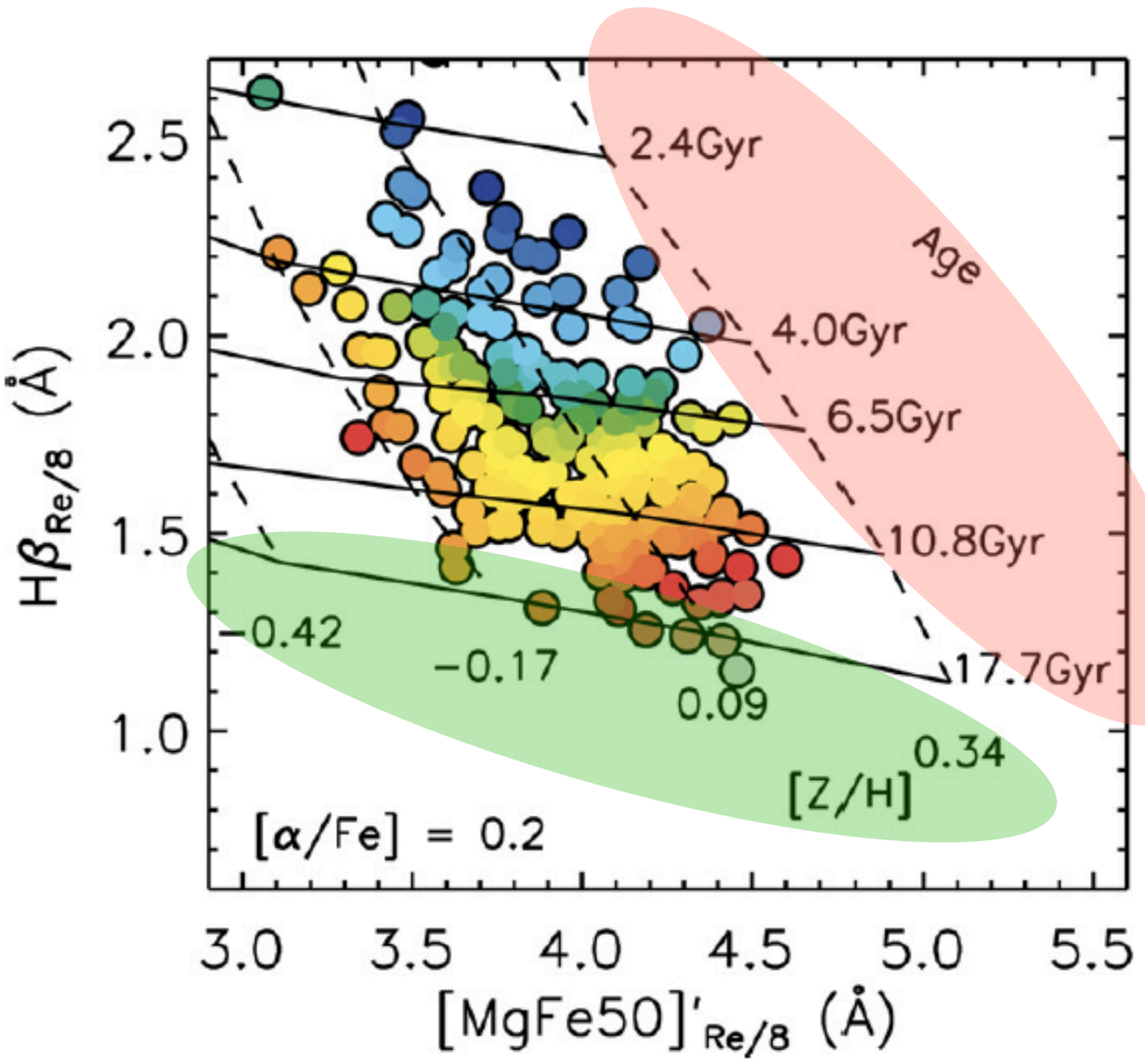


Buzzoni et al. 2015

Stellar ages, star formation histories and metallicities



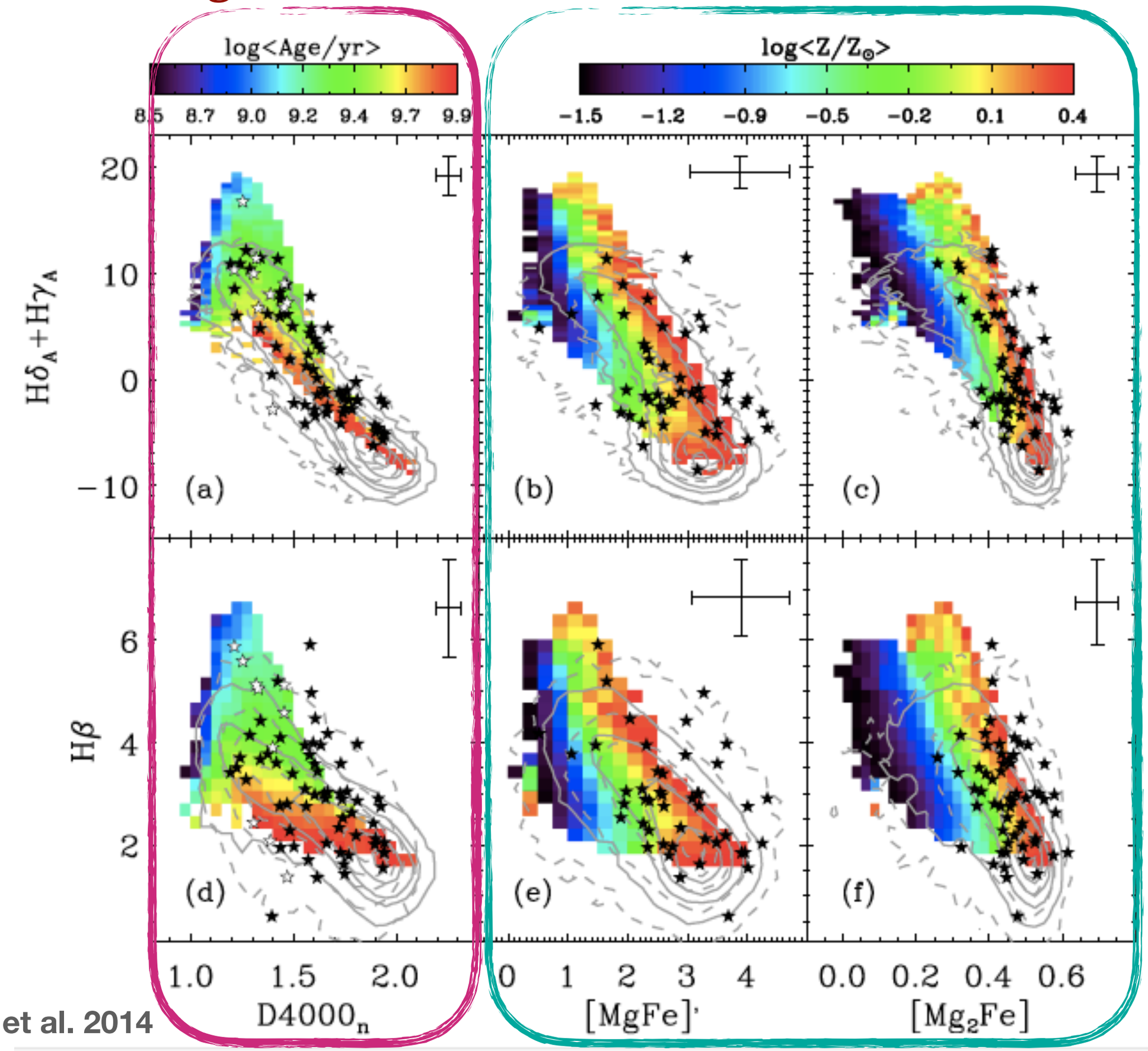
Gallazzi et al. 2014



McDermid et al. 2014

… but combinations of indices (grids) can estimate age and metallicity

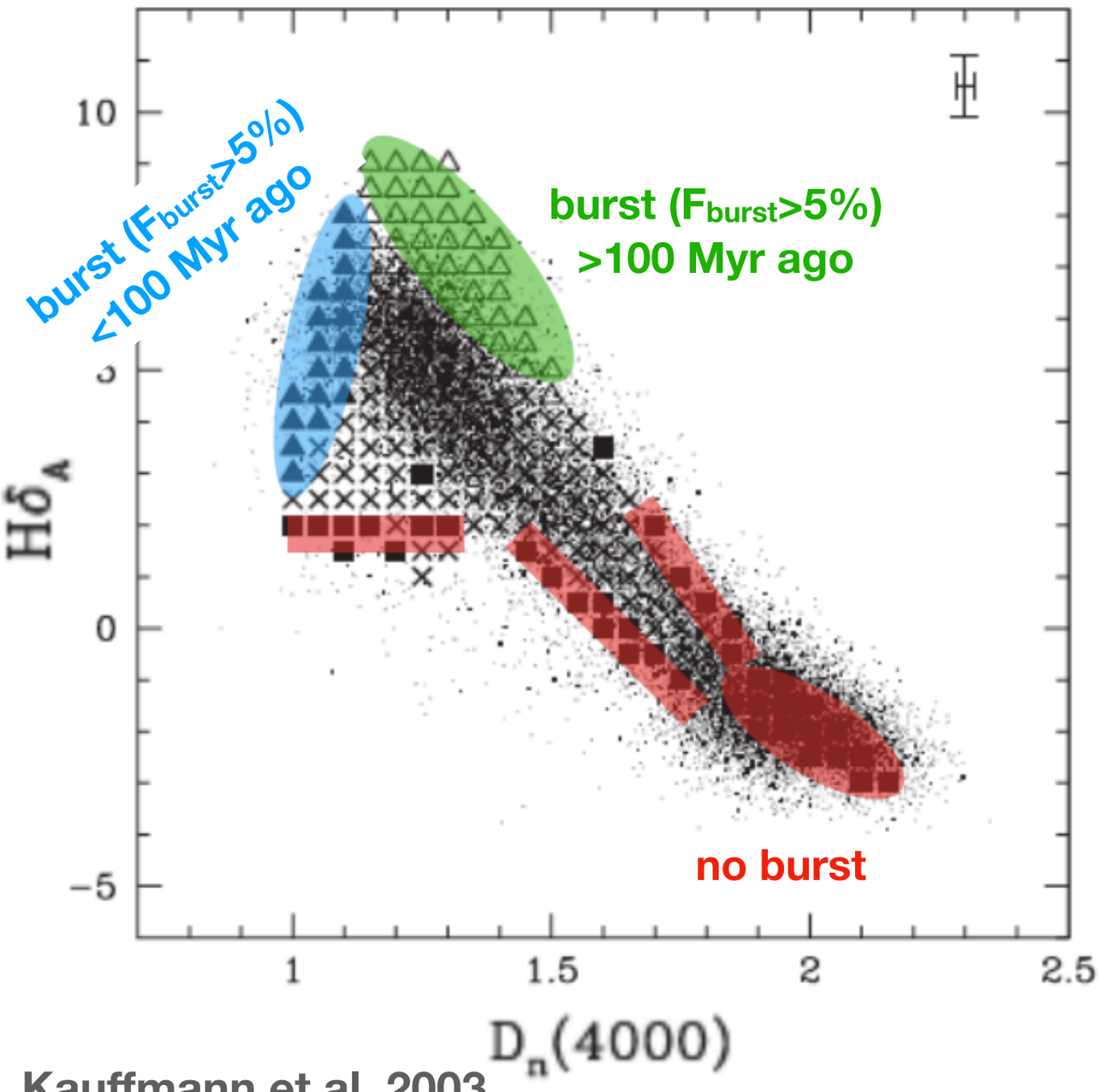
Stellar ages, star formation histories and metallicities



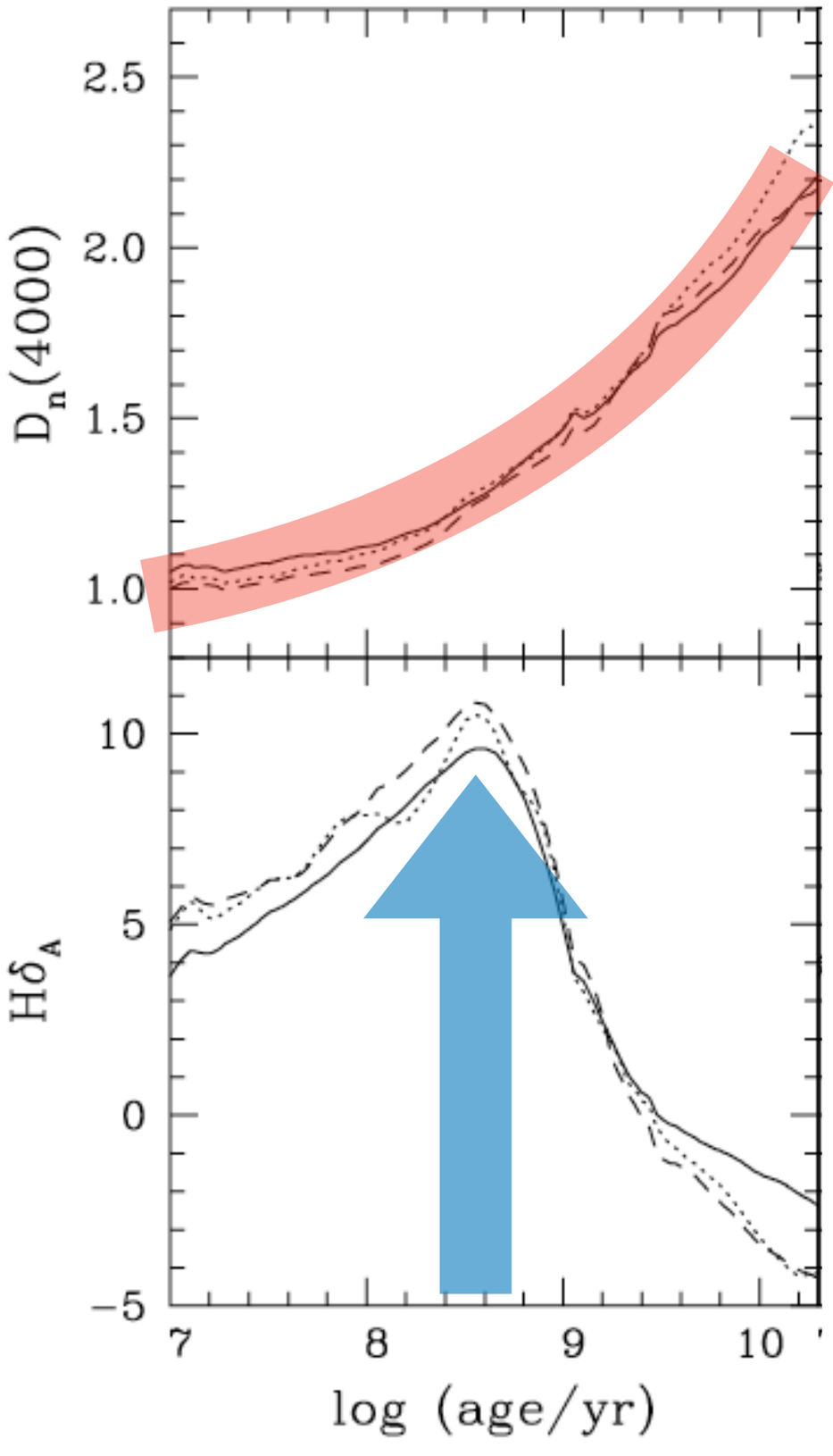
Gallazzi et al. 2014

Stellar ages, star formation histories and metallicities

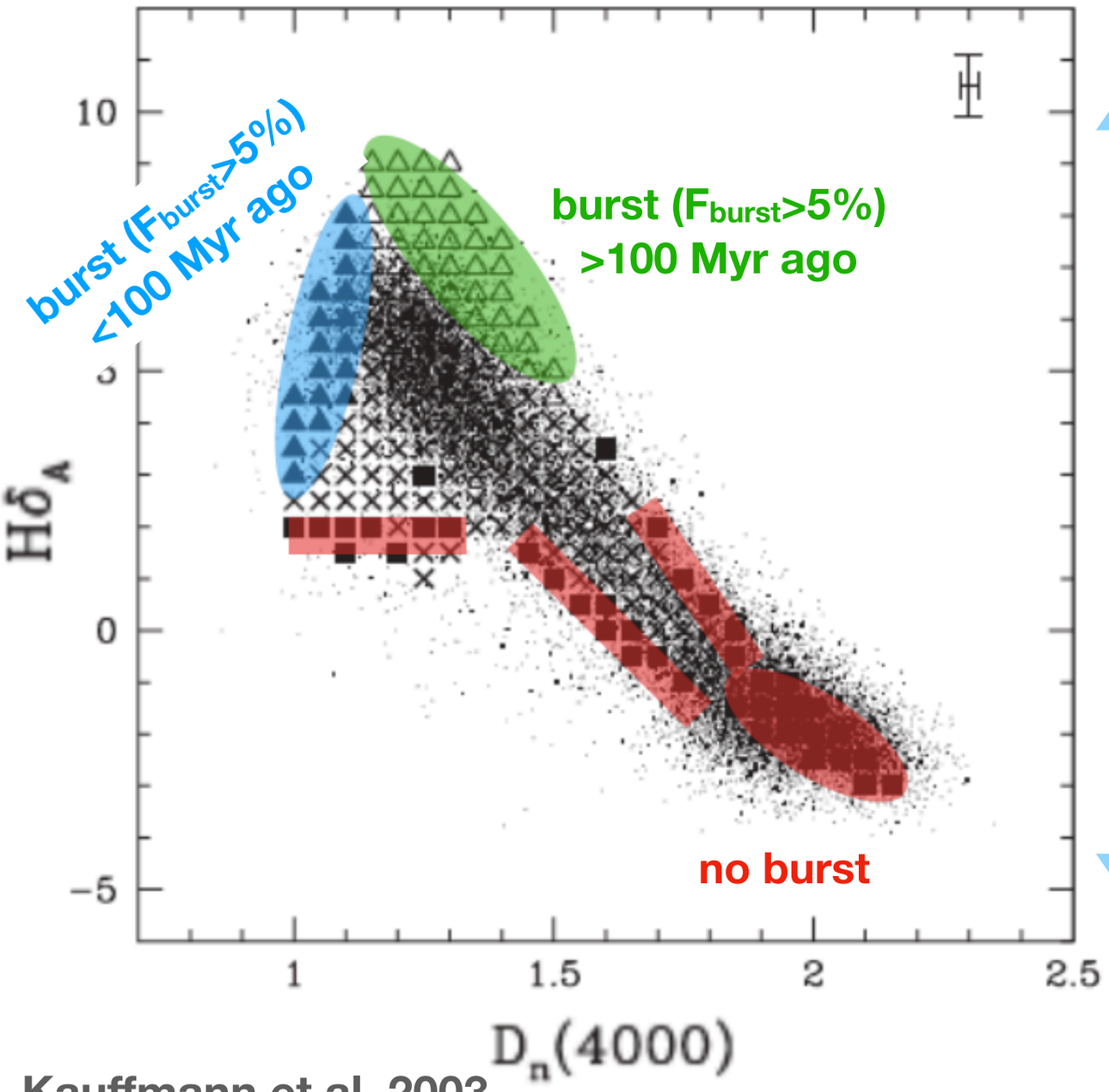
rough constraints on (recent) SFH



Kauffmann et al. 2003

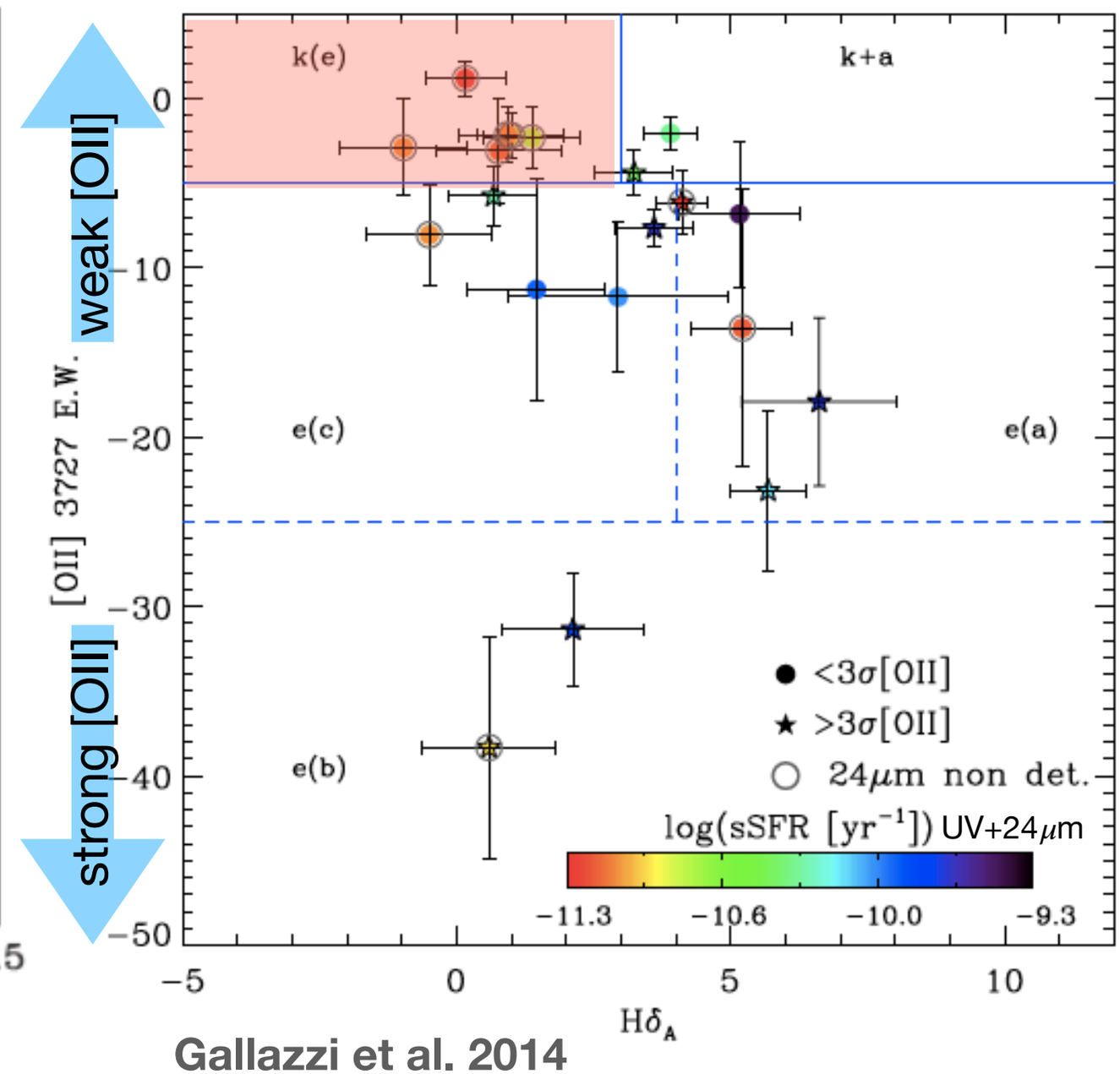


Stellar ages, star formation histories and metallicities



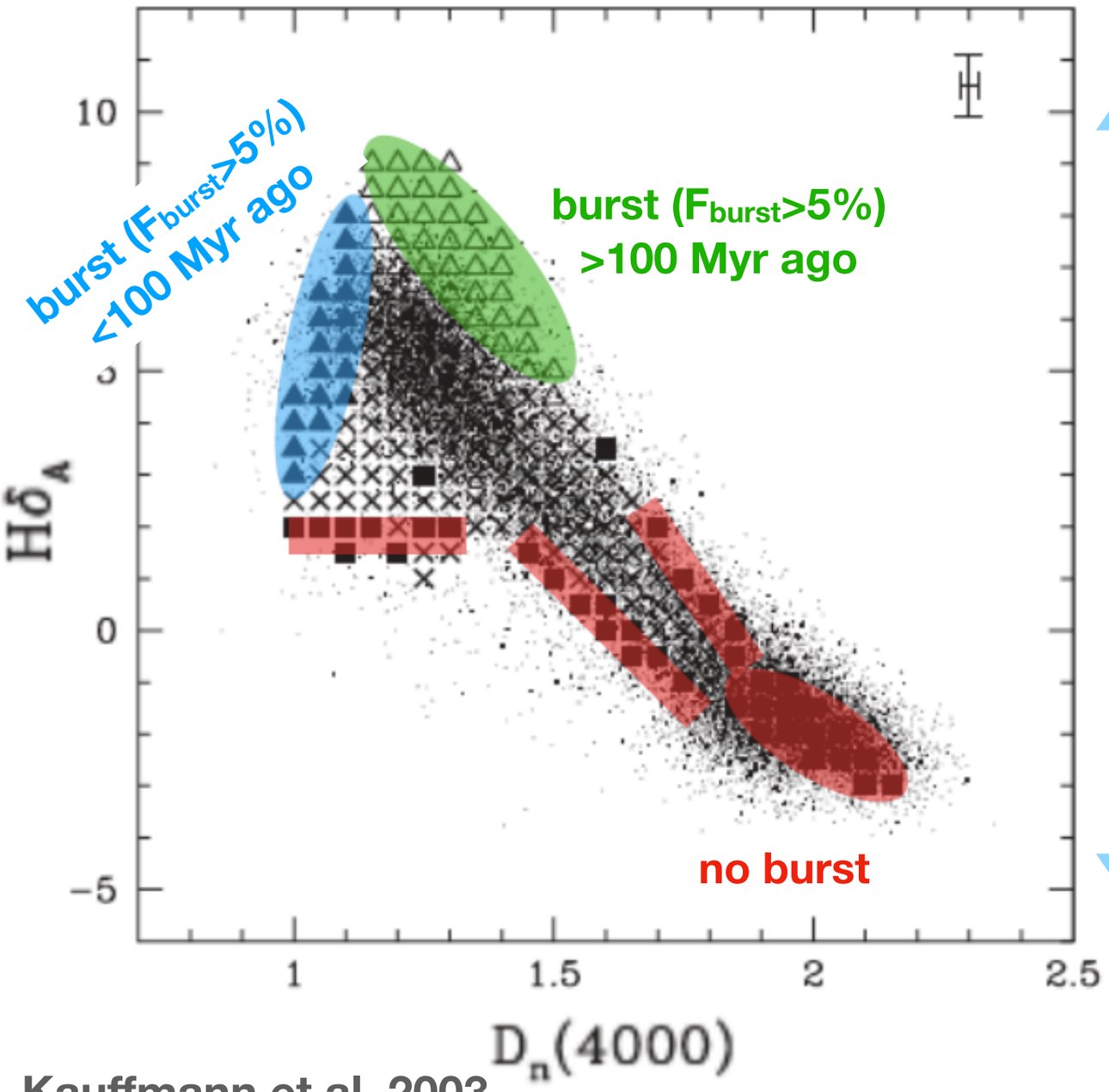
Kauffmann et al. 2003

no star formation
in past 1-1.5 Gyr



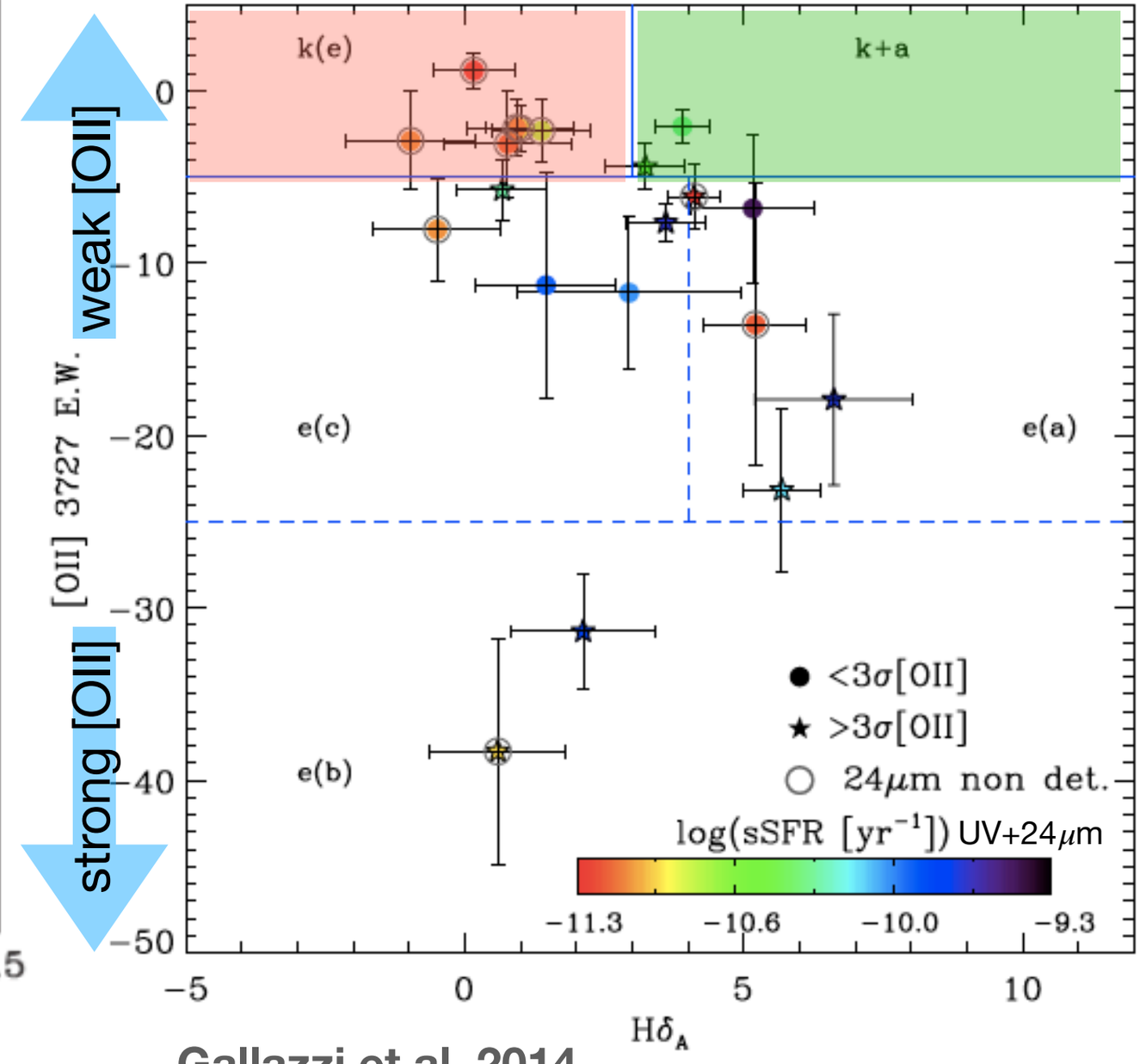
Gallazzi et al. 2014
(Poggianti et al. 2009)

Stellar ages, star formation histories and metallicities



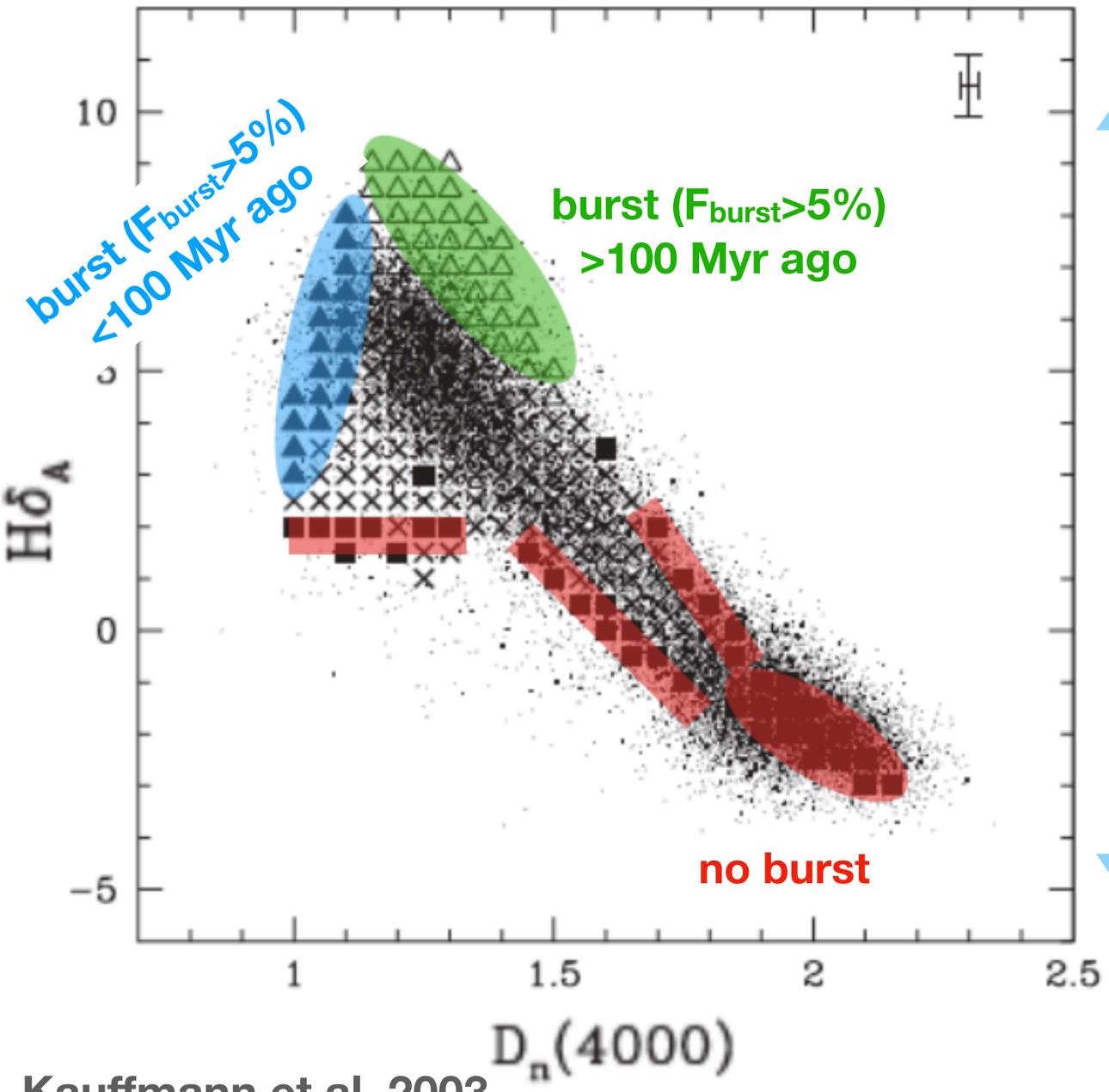
Kauffmann et al. 2003

no [OII], strong Hδ: SF terminated between 50 Myr and 1.5 Gyr



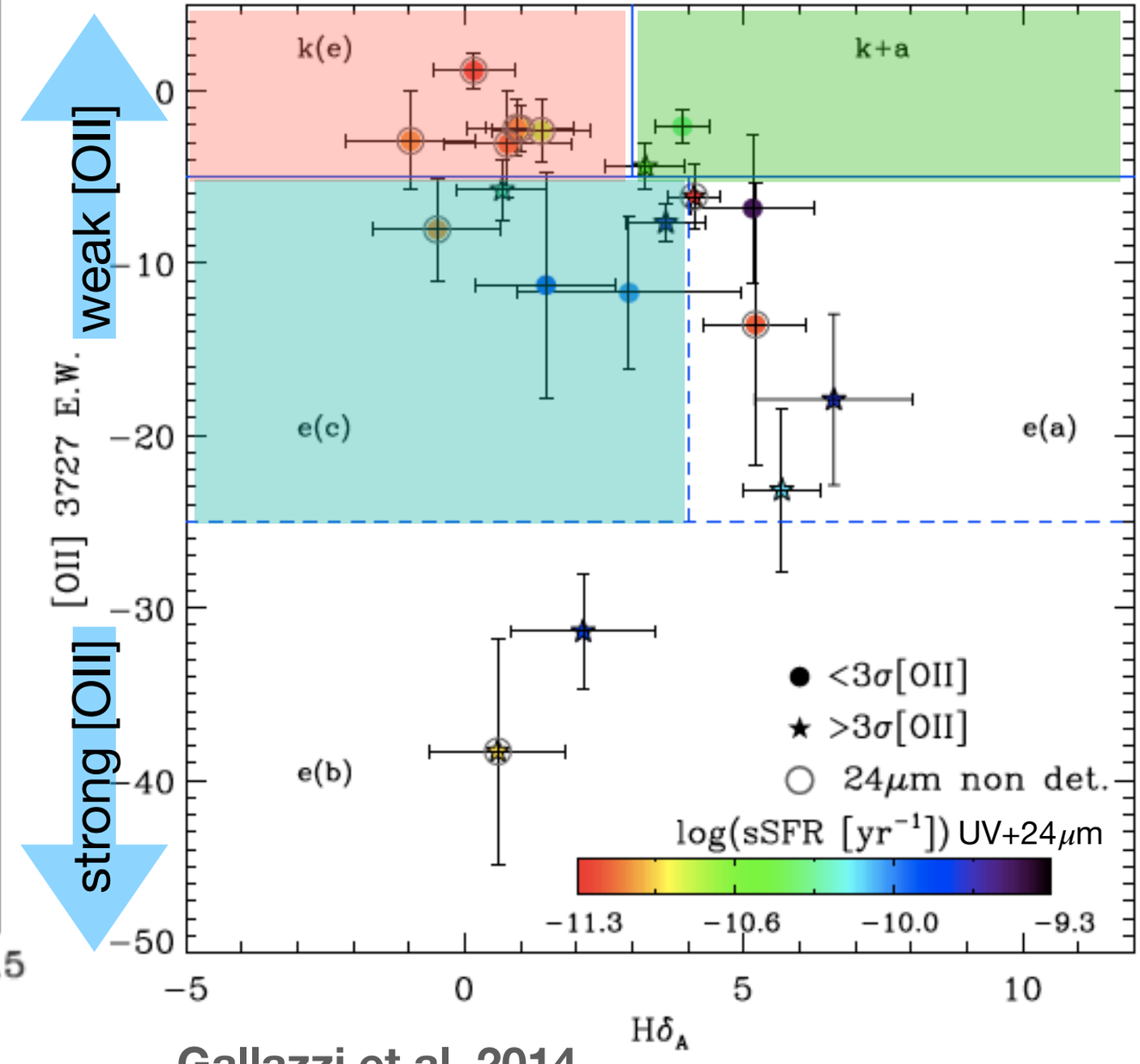
Gallazzi et al. 2014
(Poggianti et al. 2009)

Stellar ages, star formation histories and metallicities



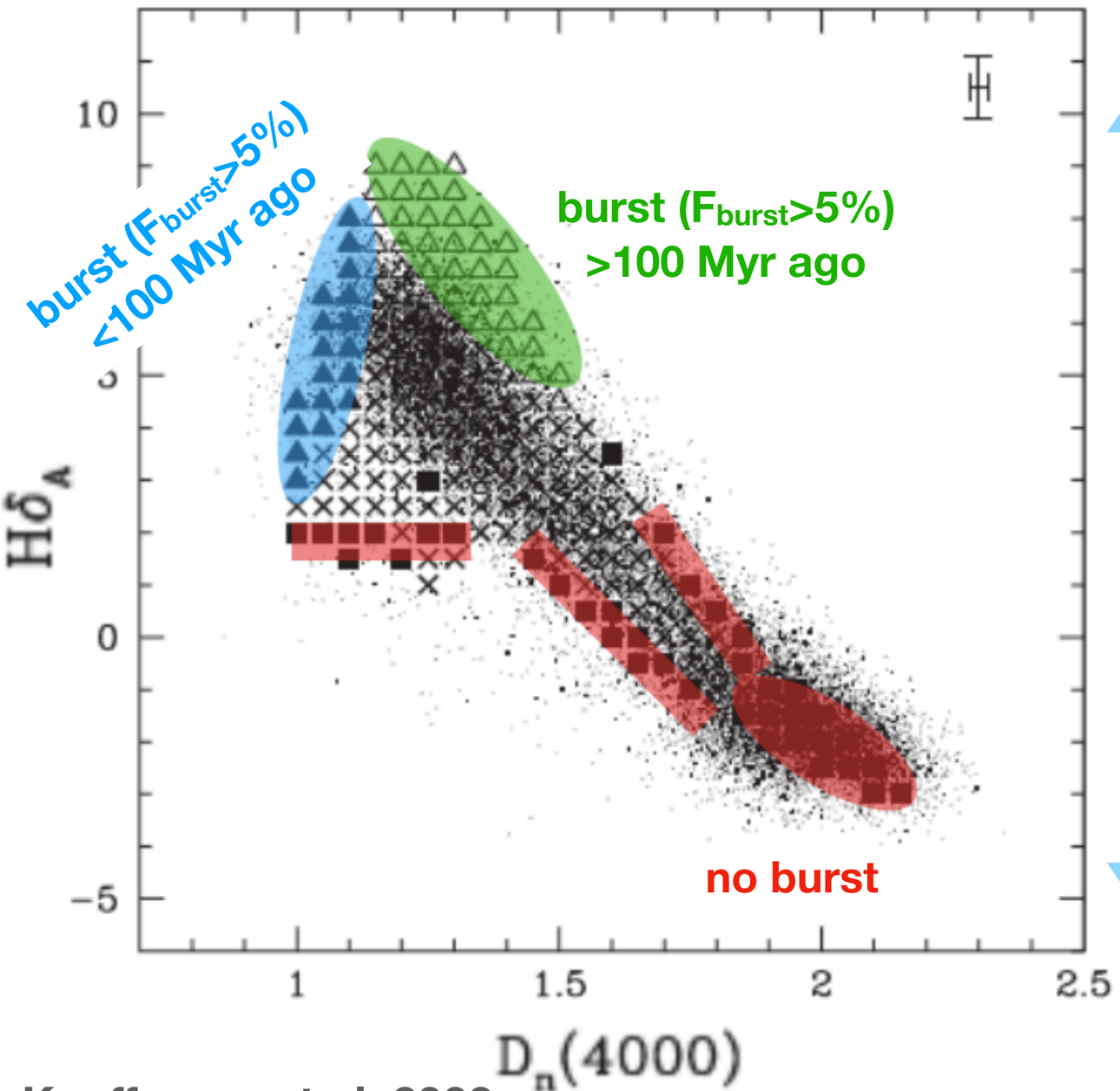
Kauffmann et al. 2003

moderate [OII], weak Hδ: continuous SF with no sudden variation



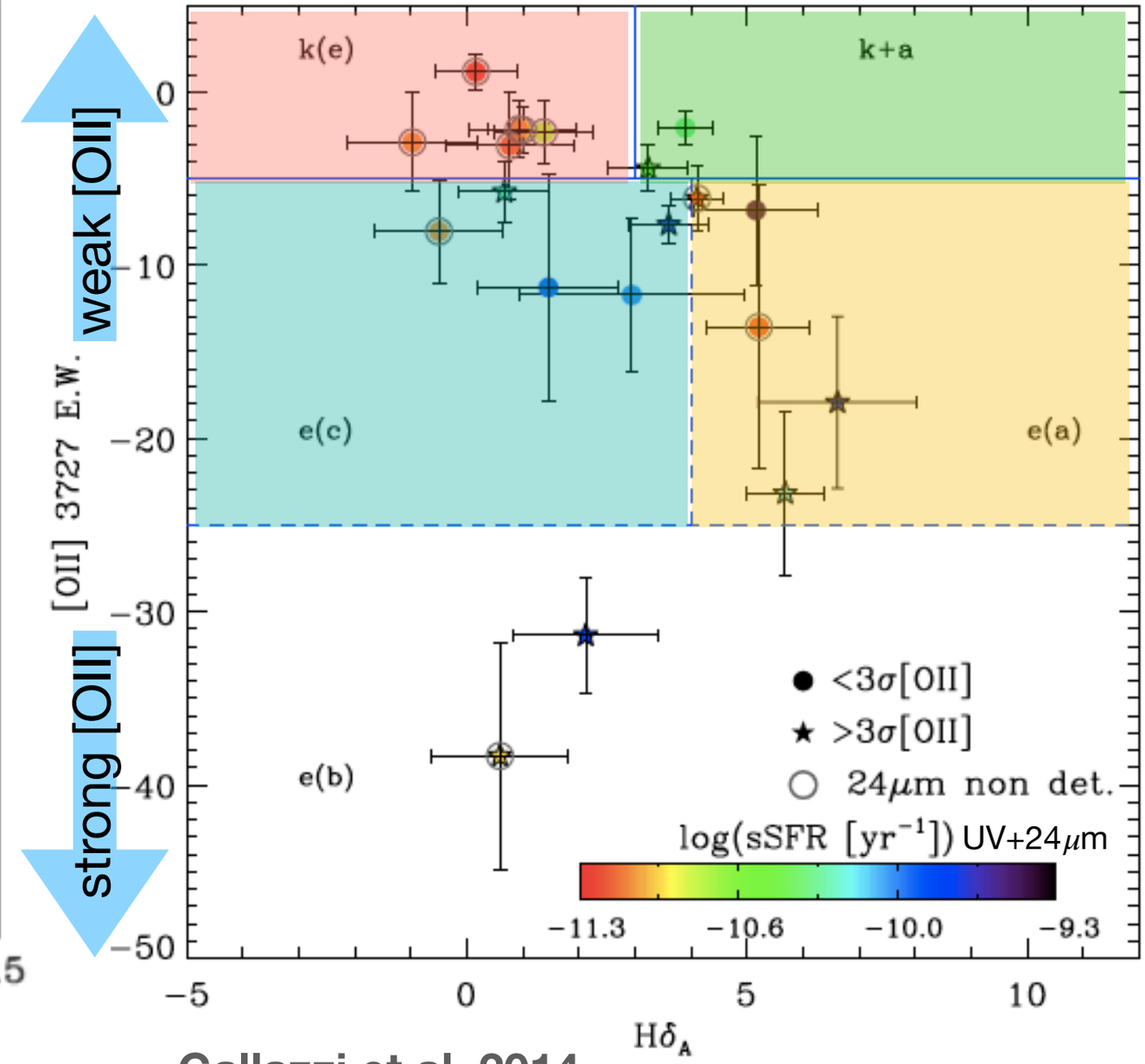
Gallazzi et al. 2014
(Poggianti et al. 2009)

Stellar ages, star formation histories and metallicities



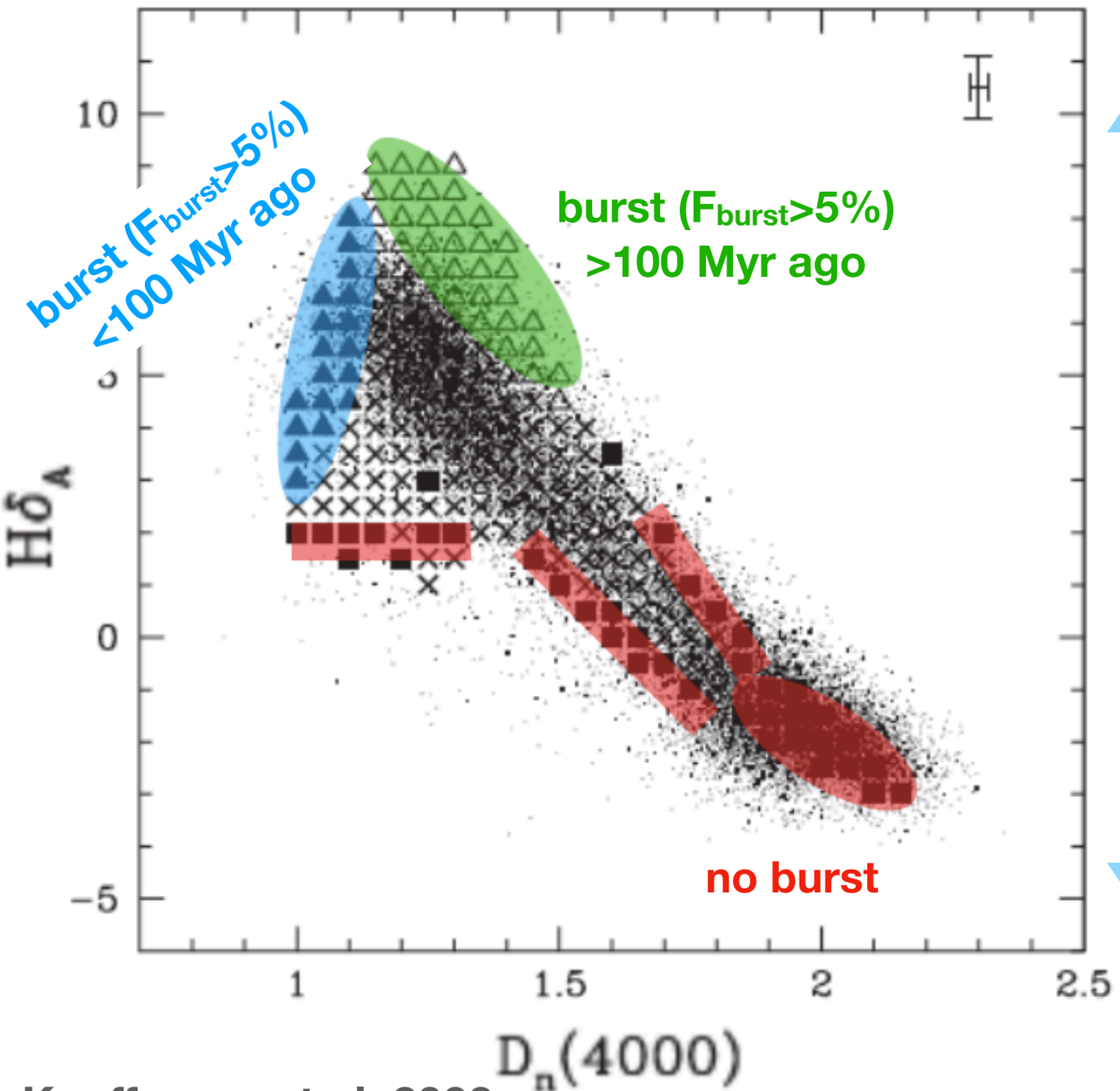
Kauffmann et al. 2003

(at low z) dusty ongoing starbursts?
(or post-starbursts with residual SF)



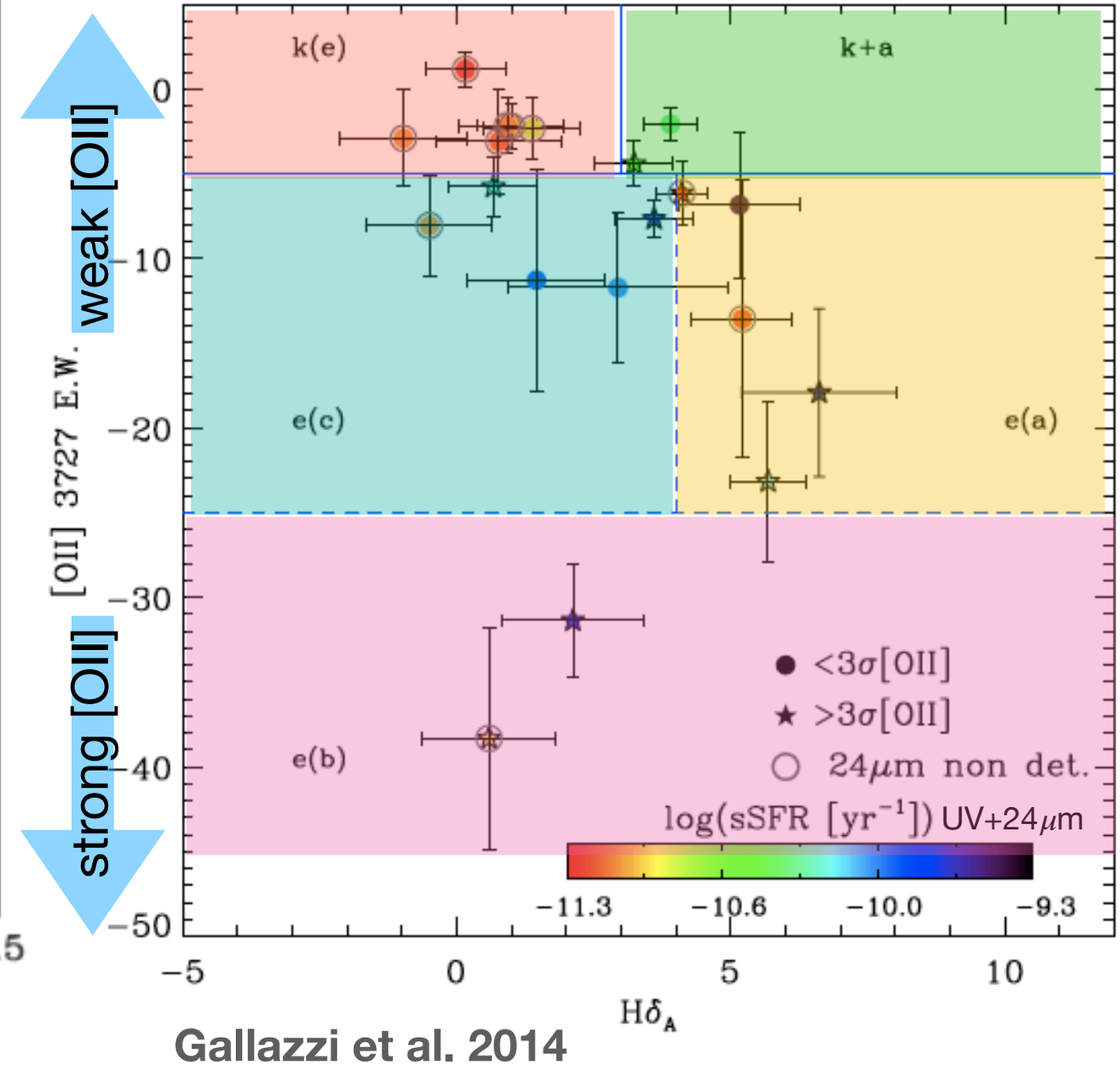
Gallazzi et al. 2014
(Poggianti et al. 2009)

Stellar ages, star formation histories and metallicities



Kauffmann et al. 2003

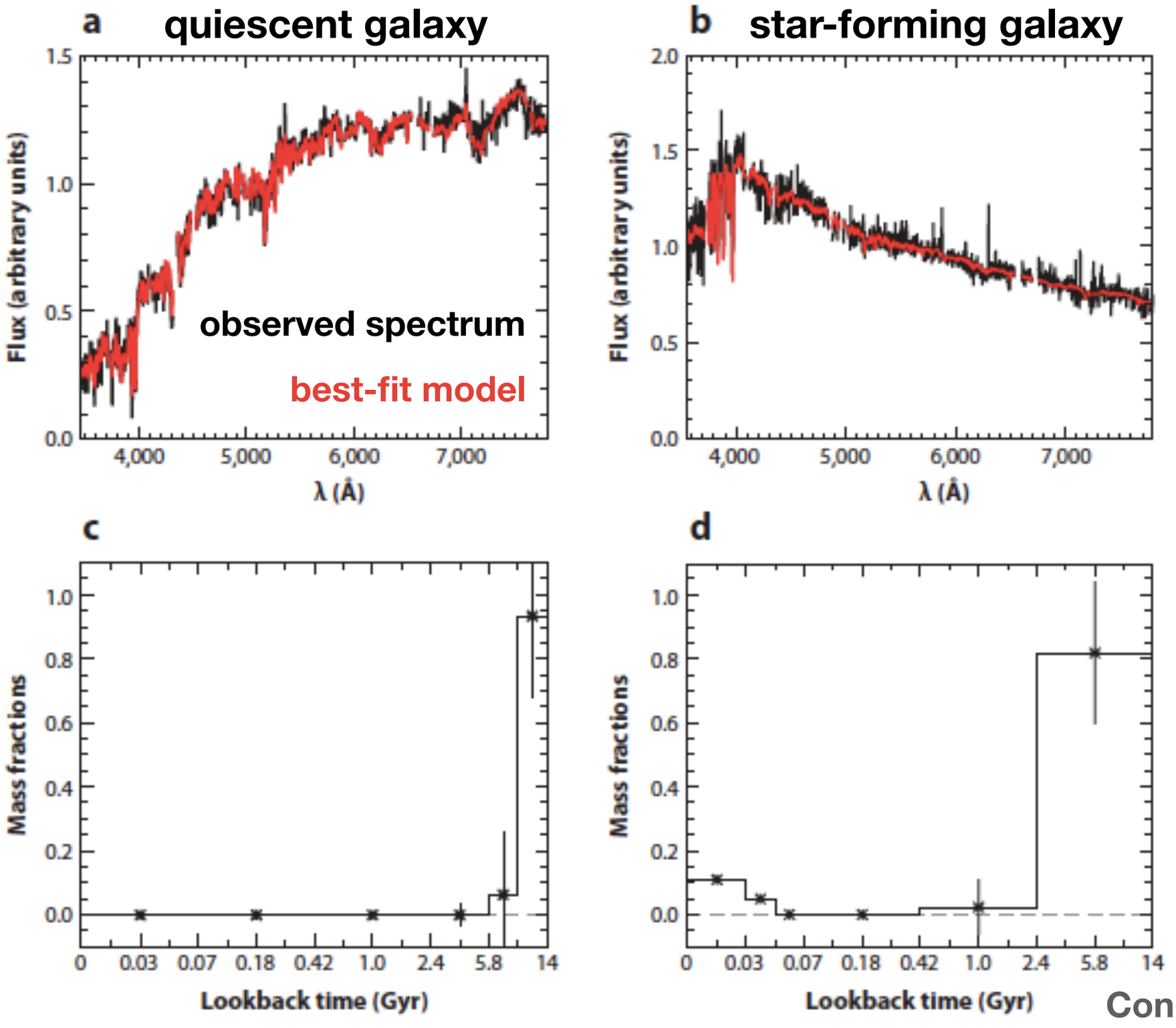
strong emission-line starbursts (current SF > past average) **and/or low extinction**



Gallazzi et al. 2014
(Poggianti et al. 2009)

Stellar ages, star formation histories and metallicities

with sufficient spectral coverage and spectral resolution
can attempt reconstruction of the SFH

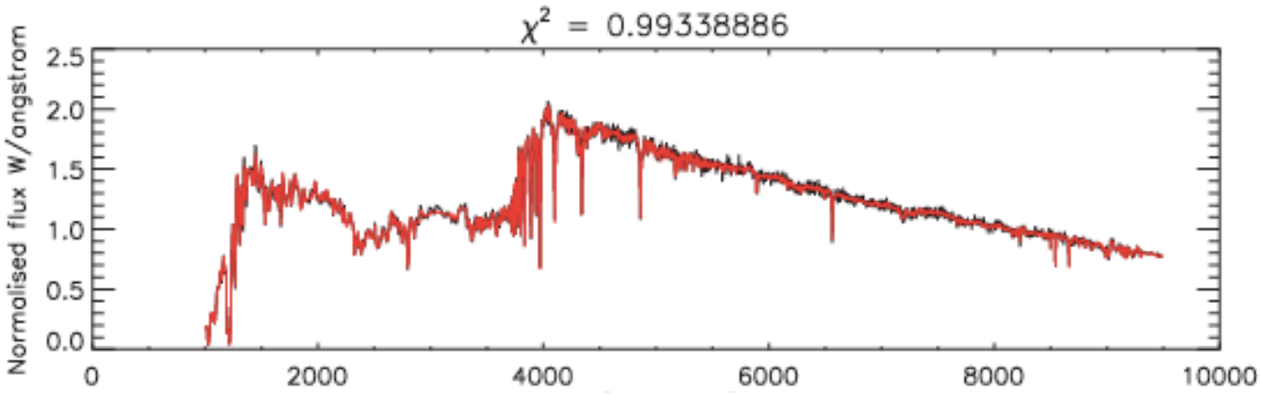


Conroy 2013

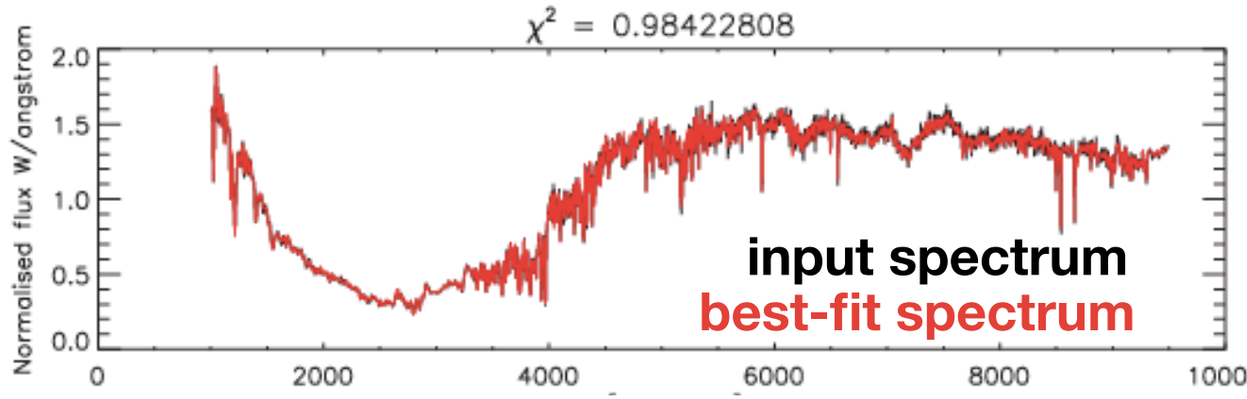
Stellar ages, star formation histories and metallicities

with sufficient spectral coverage and spectral resolution
can attempt reconstruction of the SFH

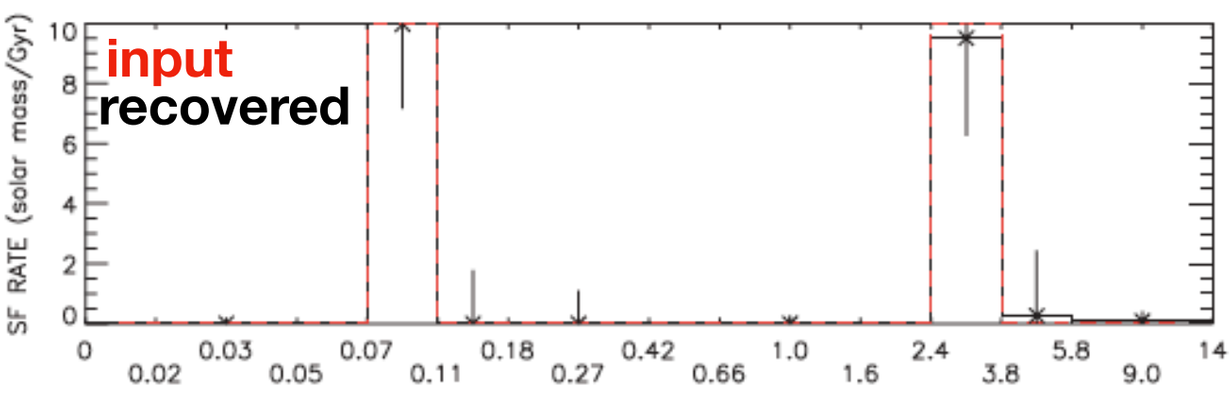
performance on synthetic galaxies



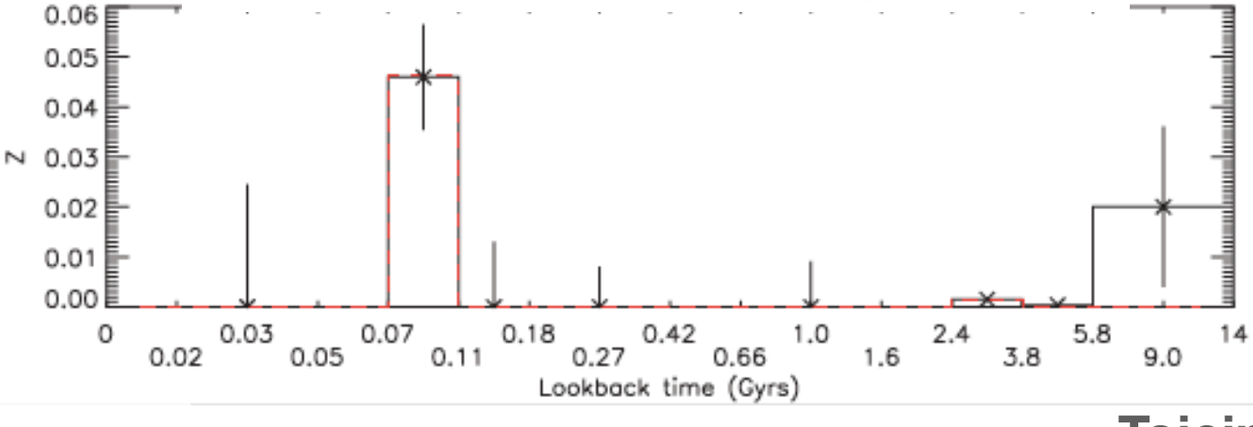
recovered vs. true SFH

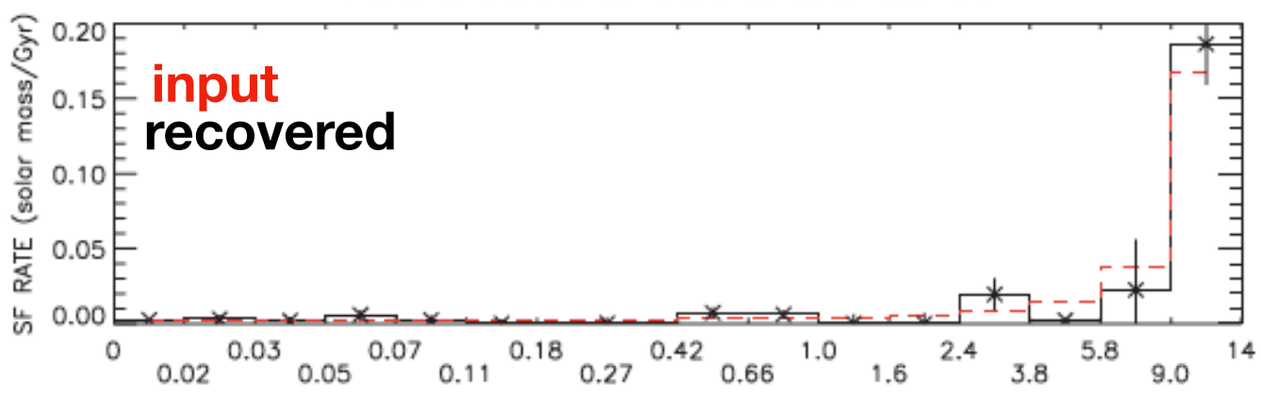


recovered vs. true SFH

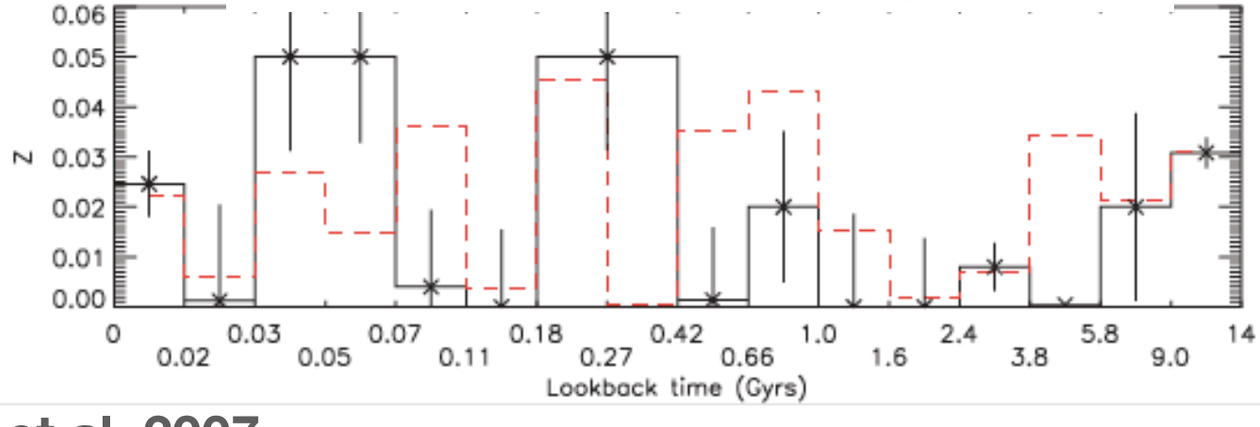


recovered vs. true metallicity evolution





recovered vs. true metallicity evolution

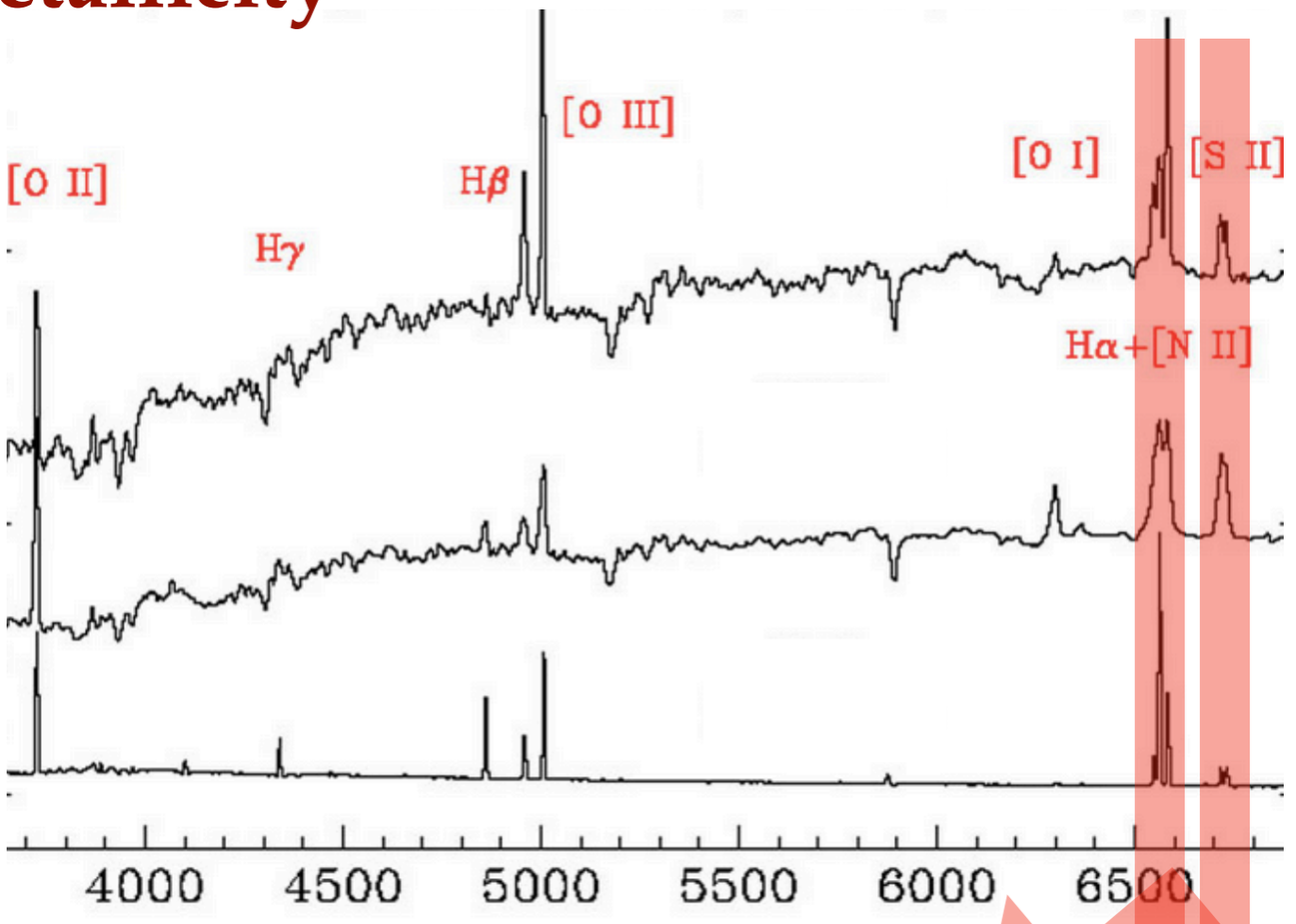


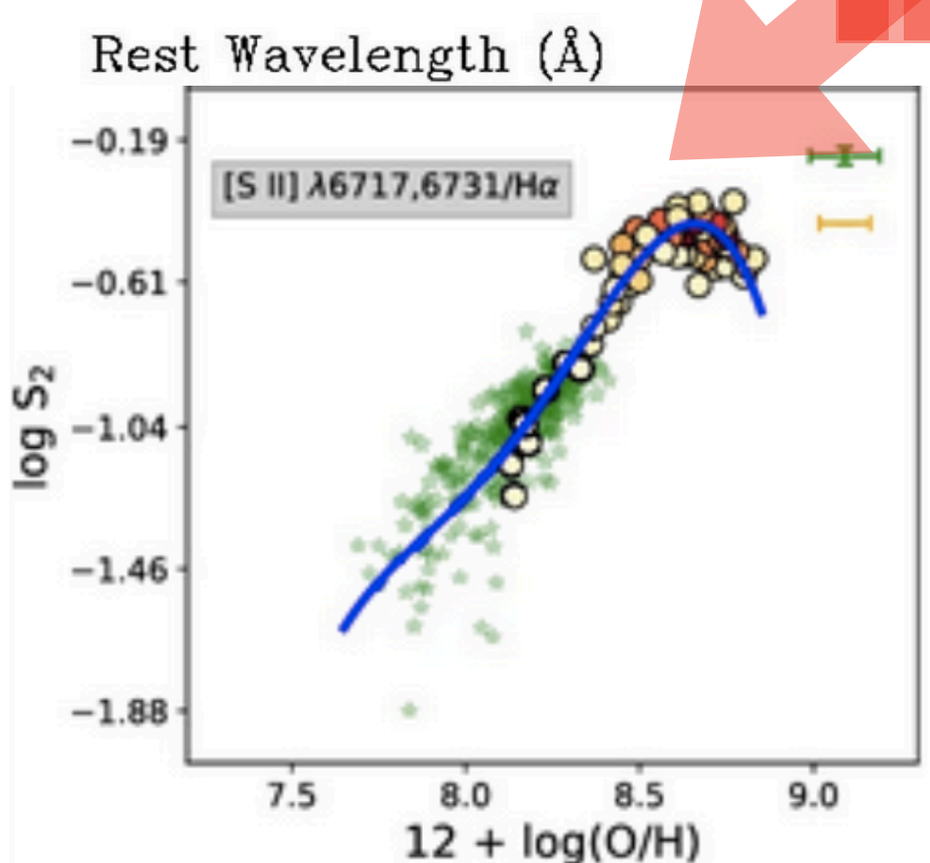
Tojeiro et al. 2007

Gas metallicity

via strong emission line flux ratios

Different calibrations involving different lines





Gas metallicity

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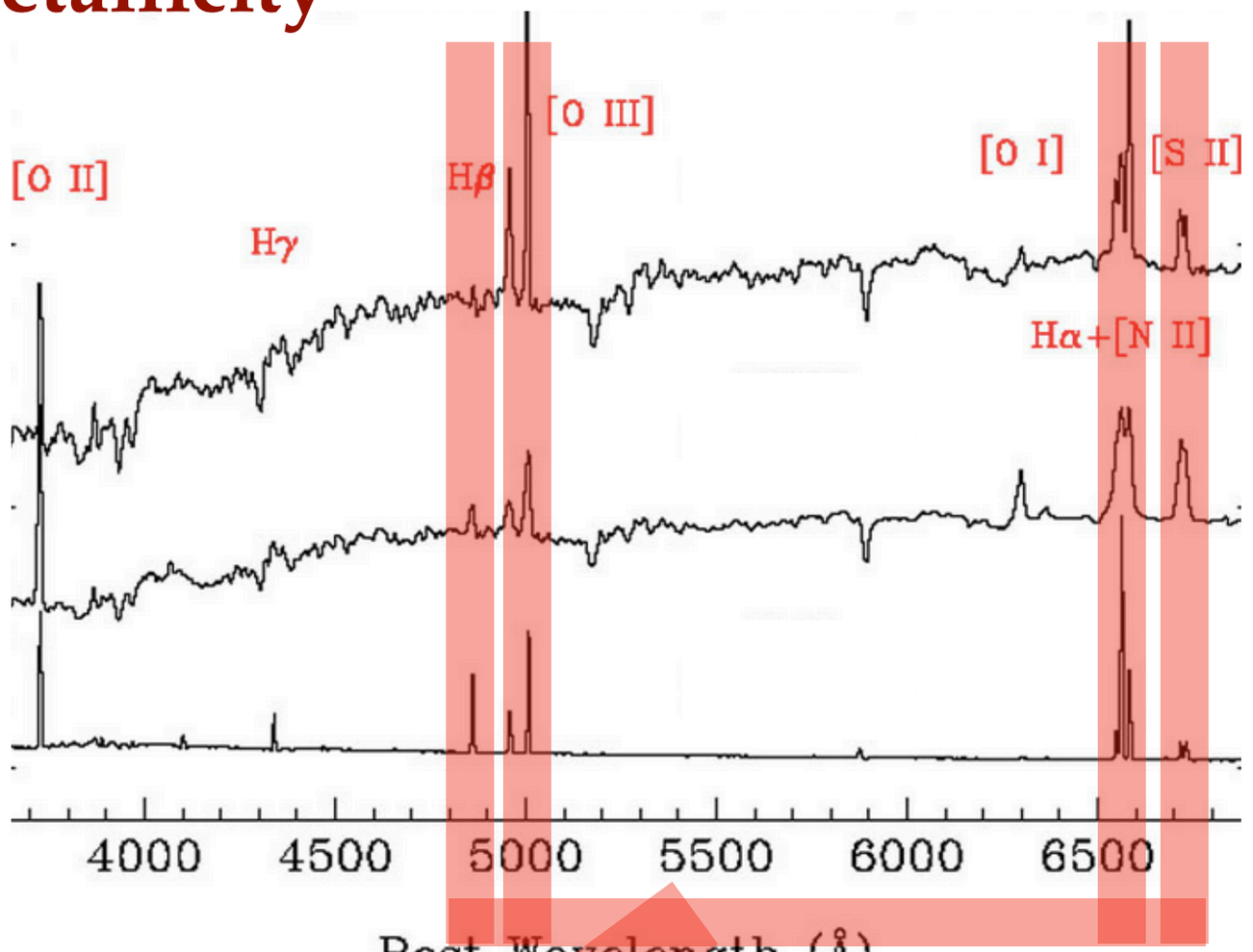
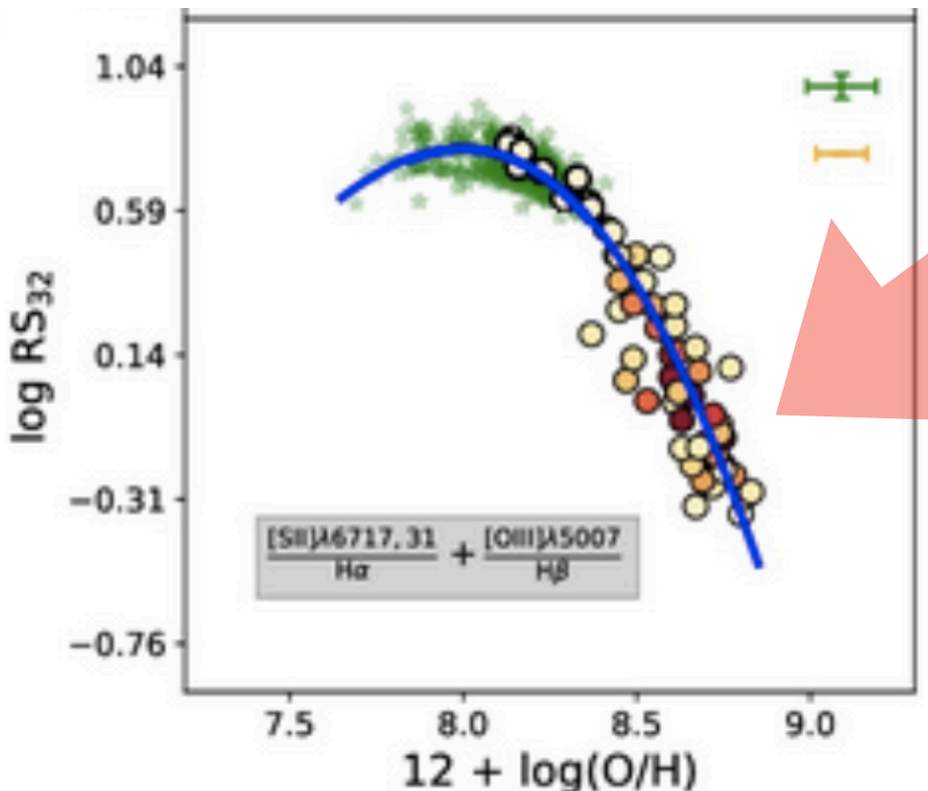
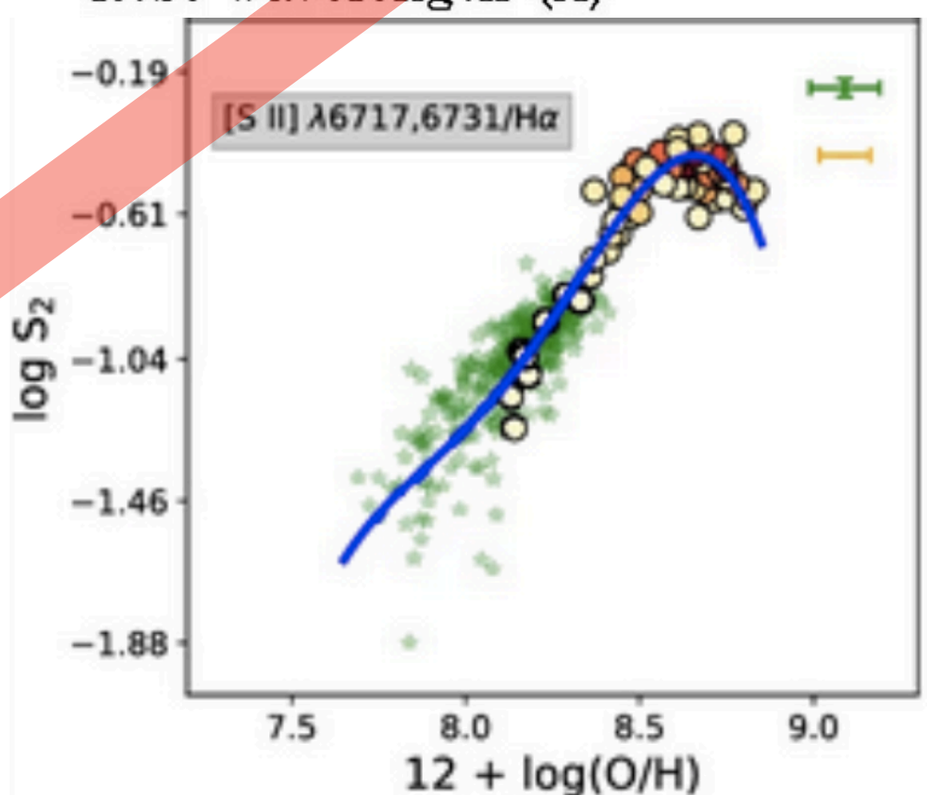
Different calibrations involving different lines

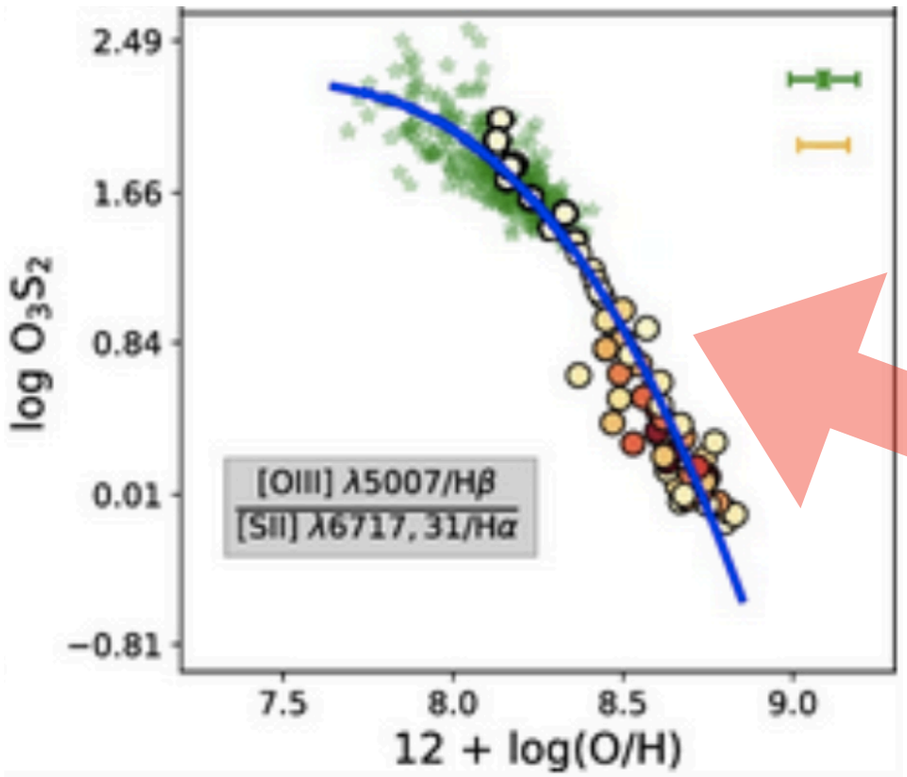


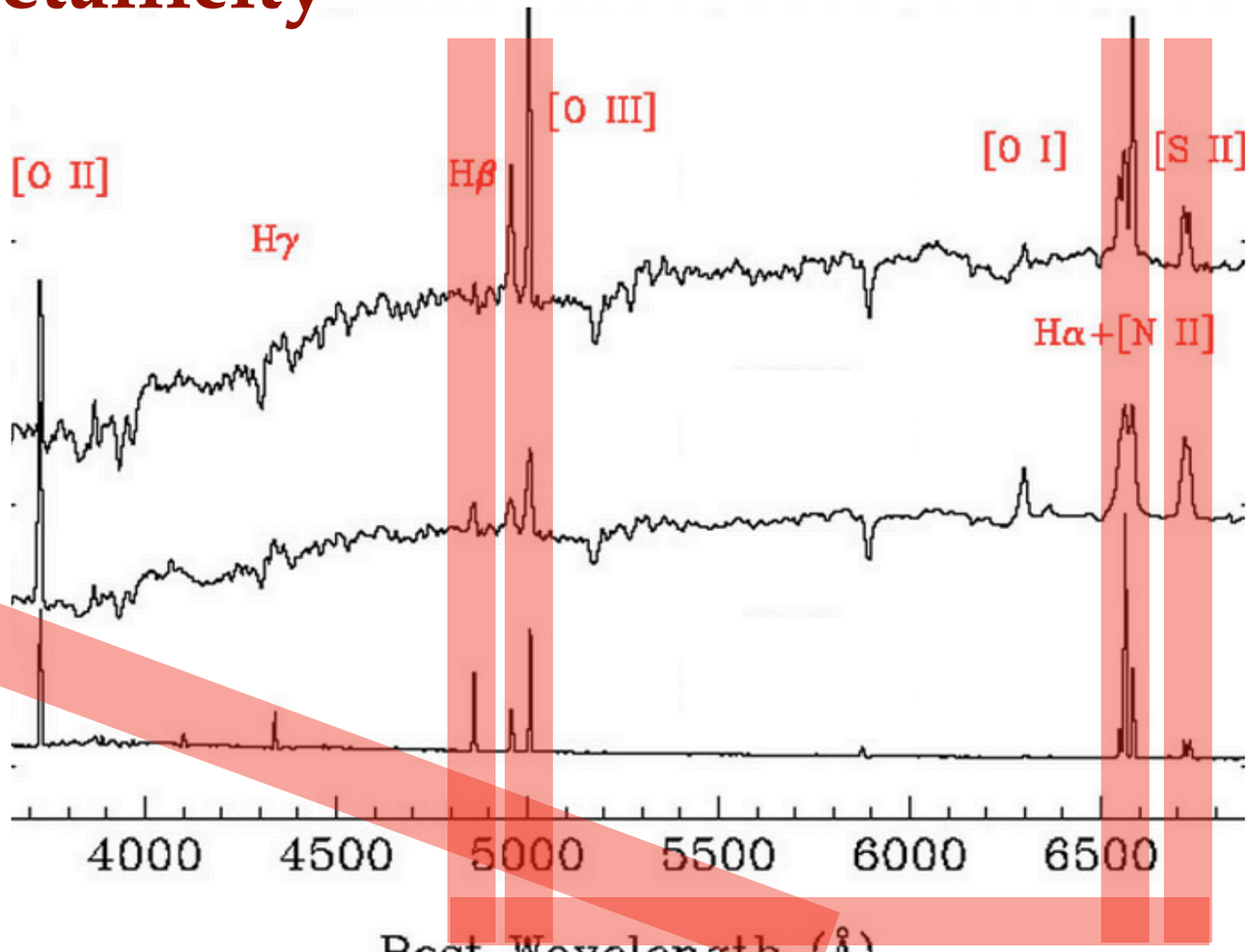


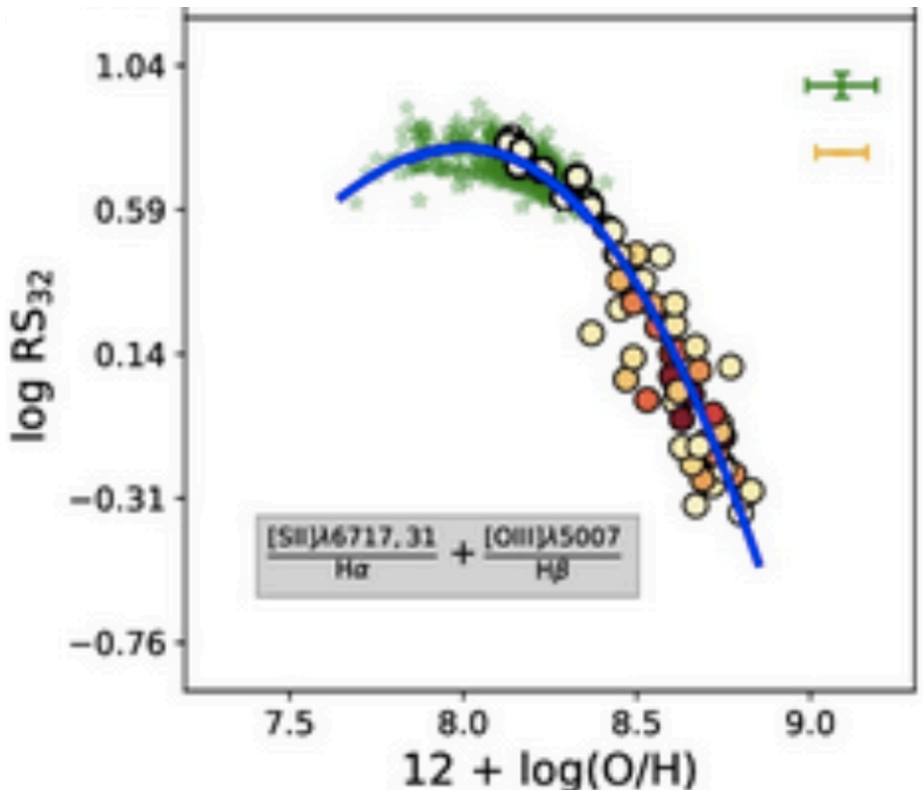


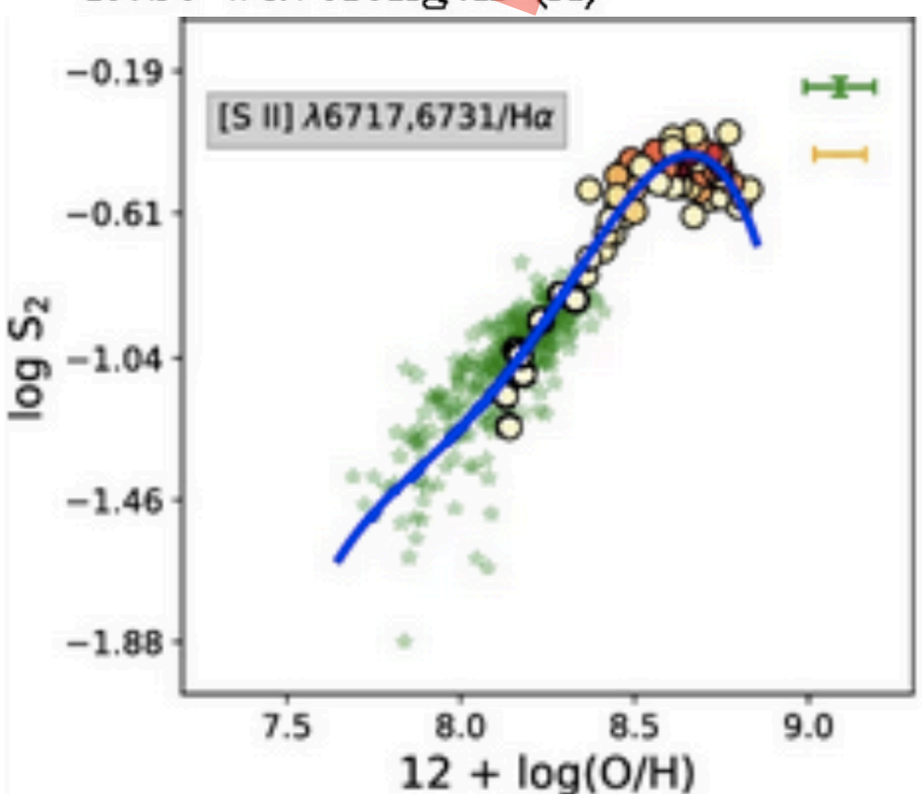
Gas metallicity

via strong emission line flux ratios



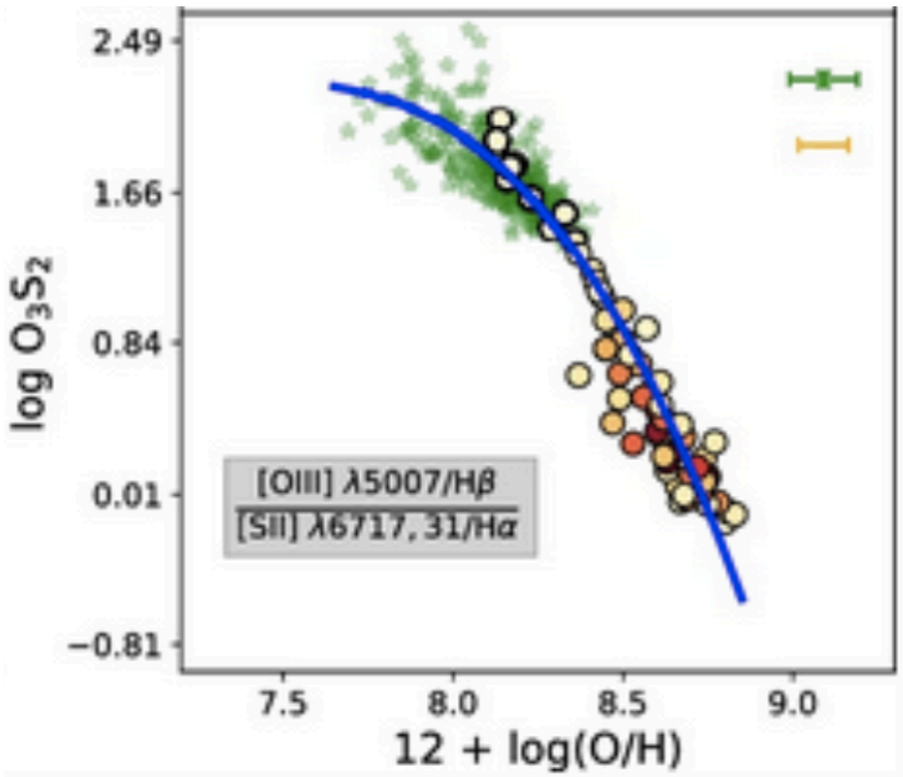


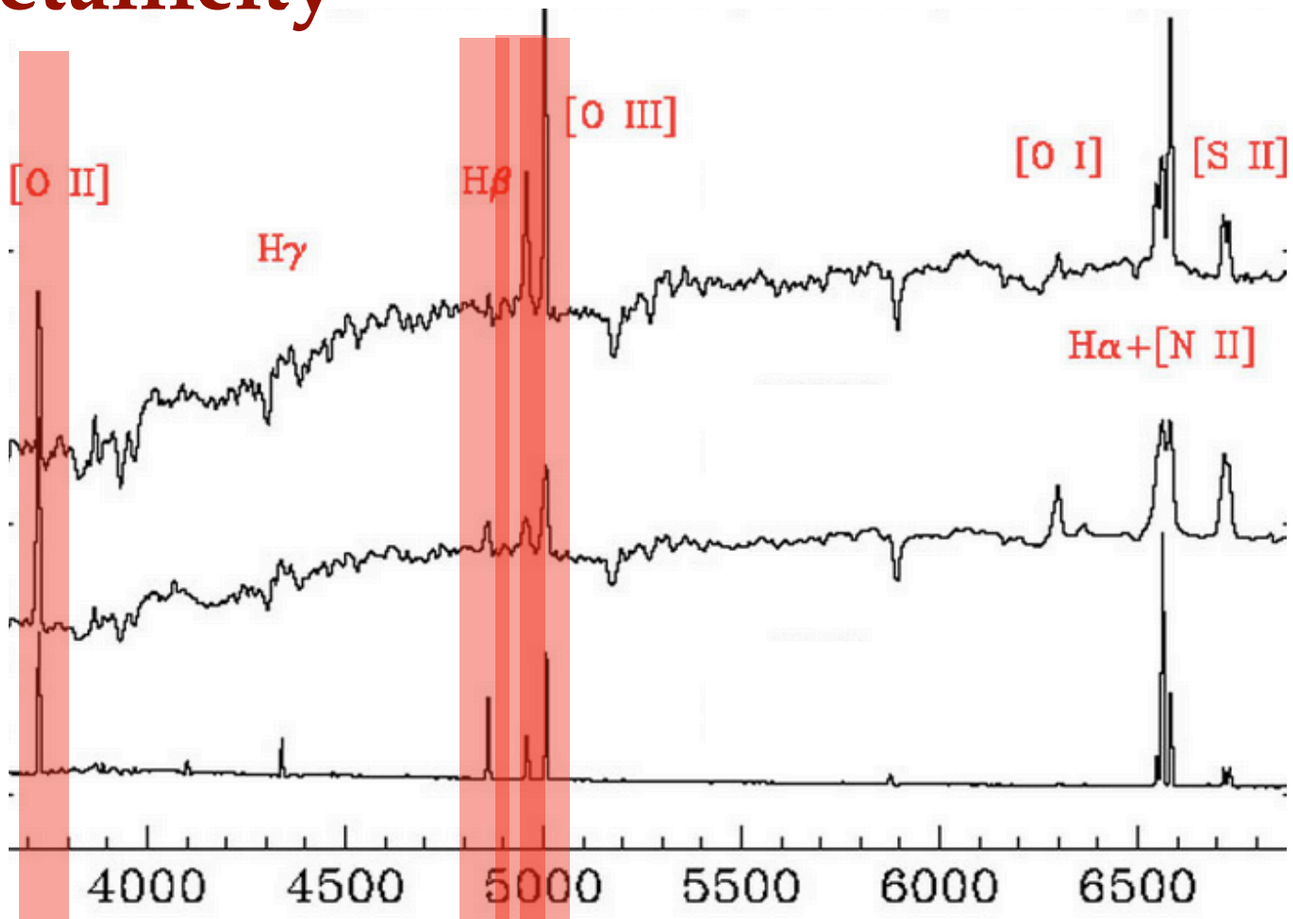


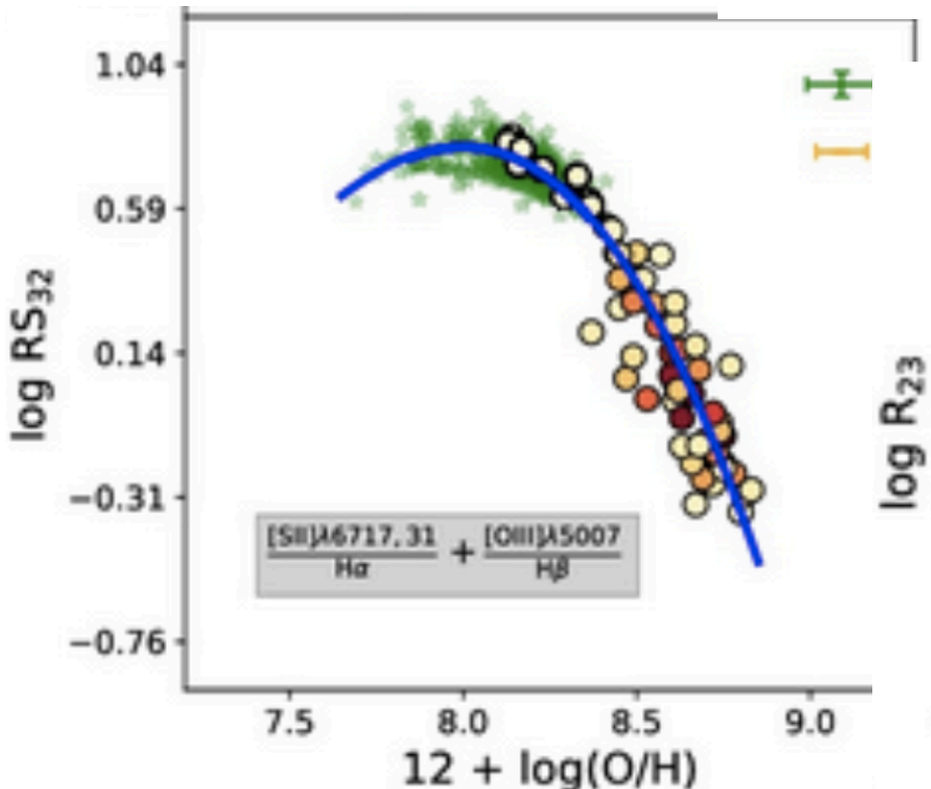


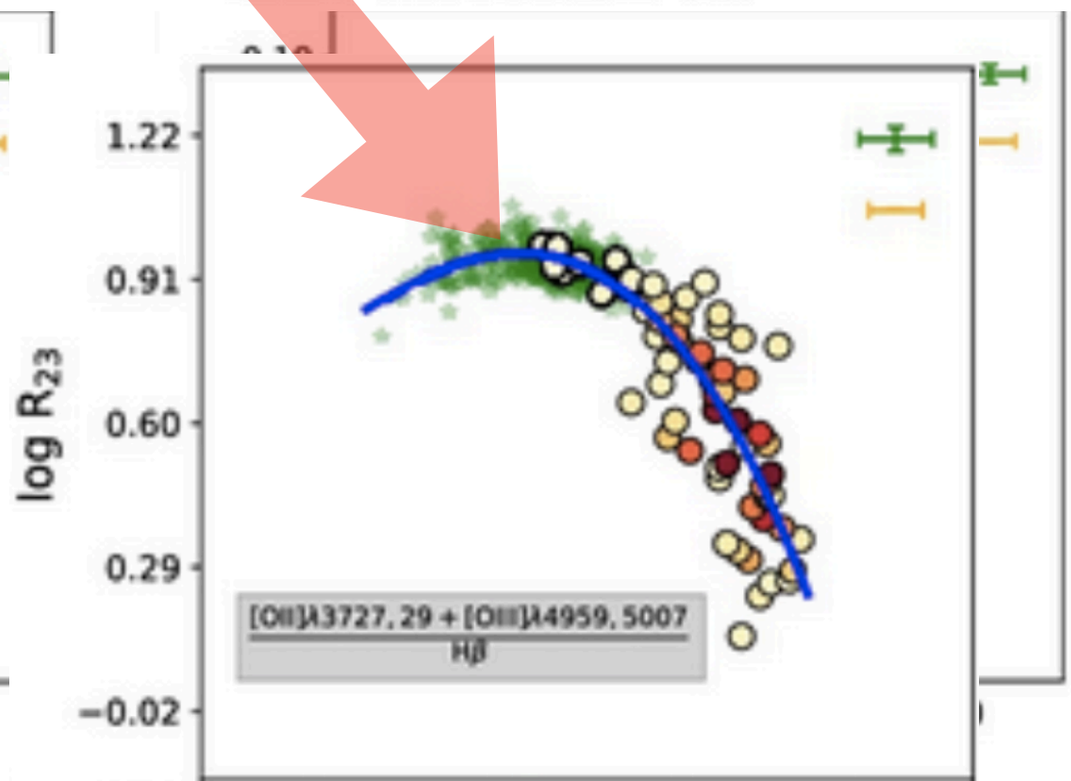
Gas metallicity

via strong emission line flux ratios



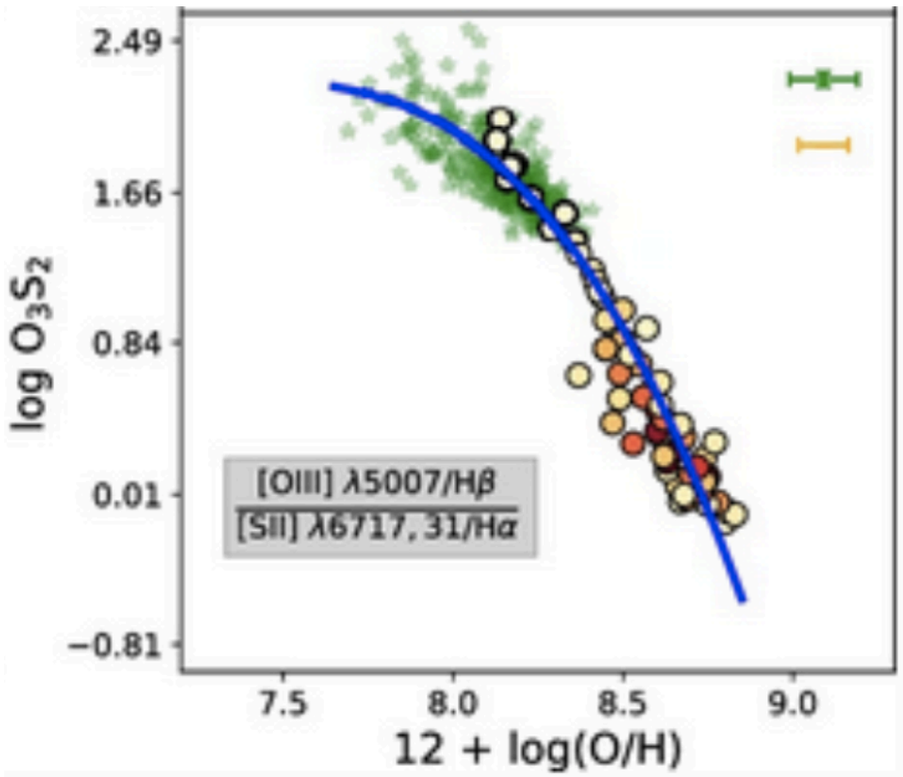


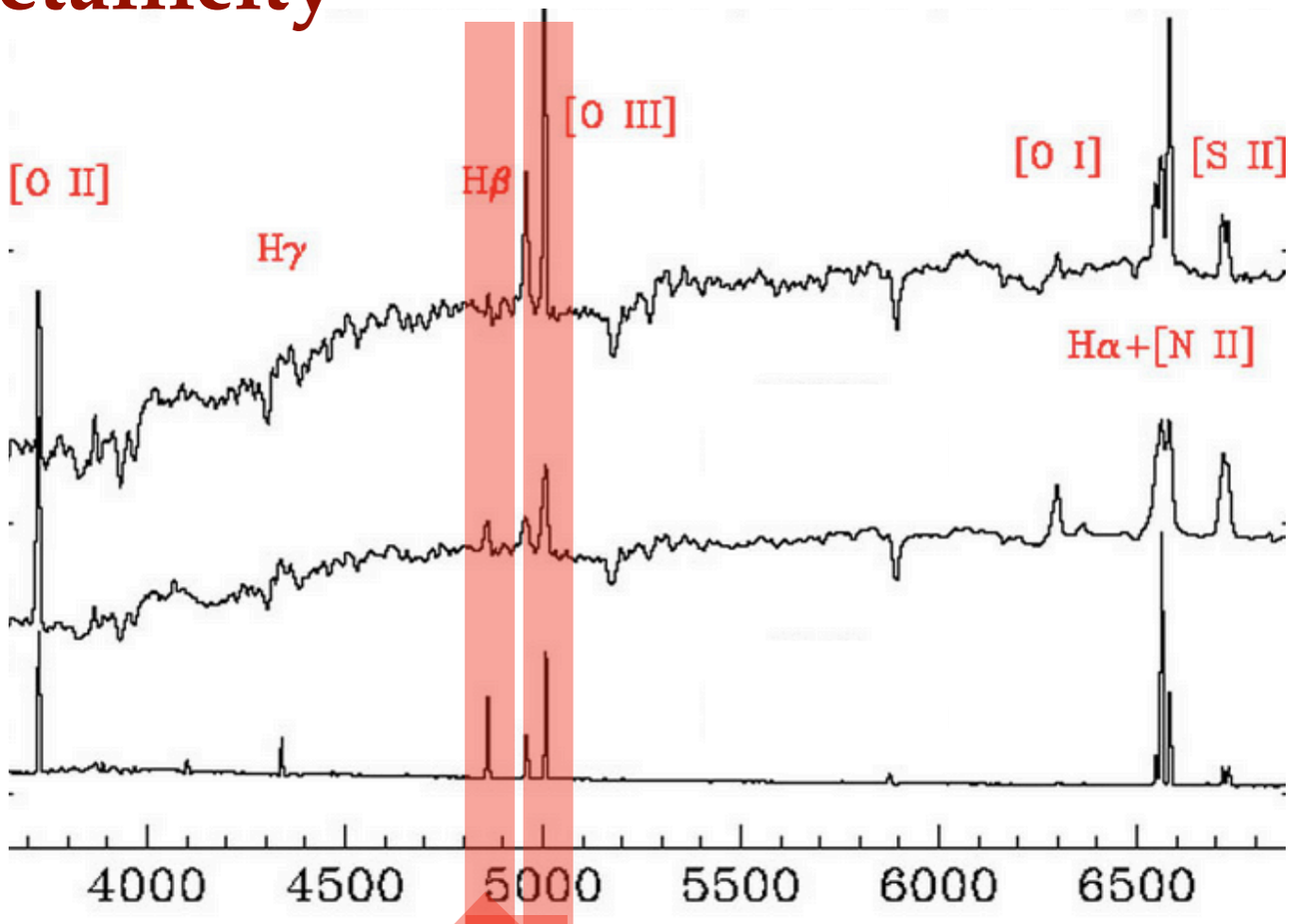


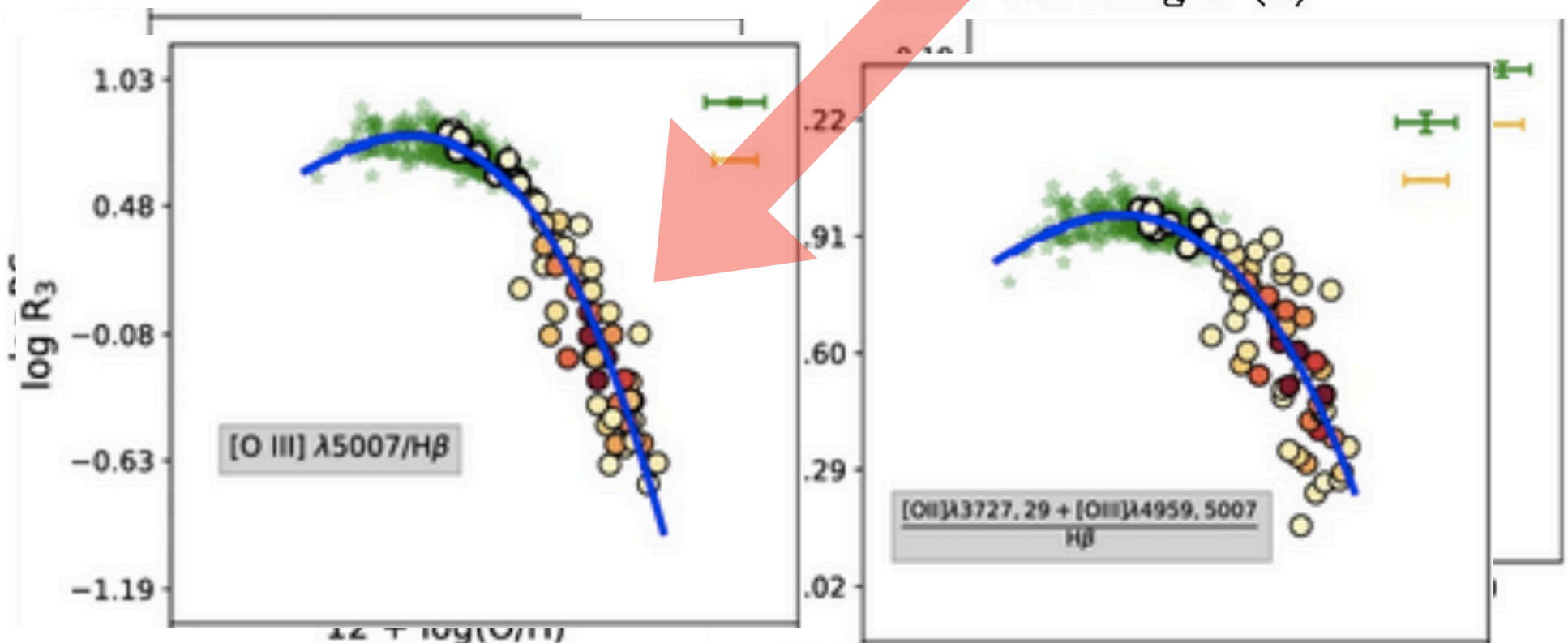


Gas metallicity

via strong emission line flux ratios

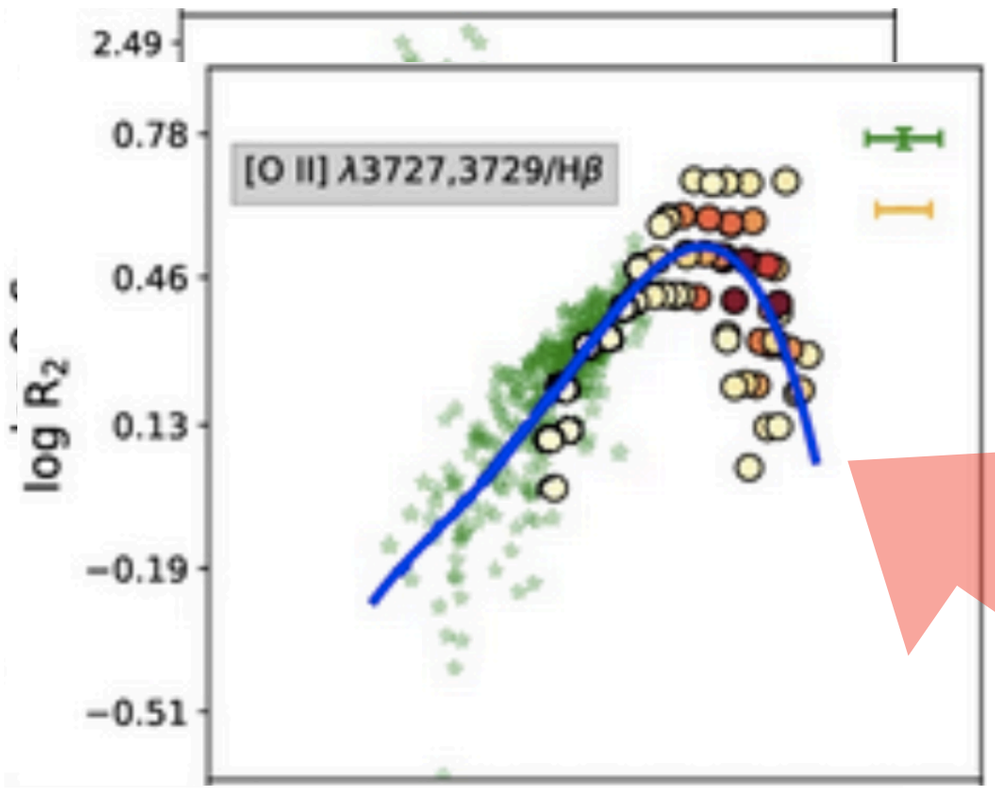


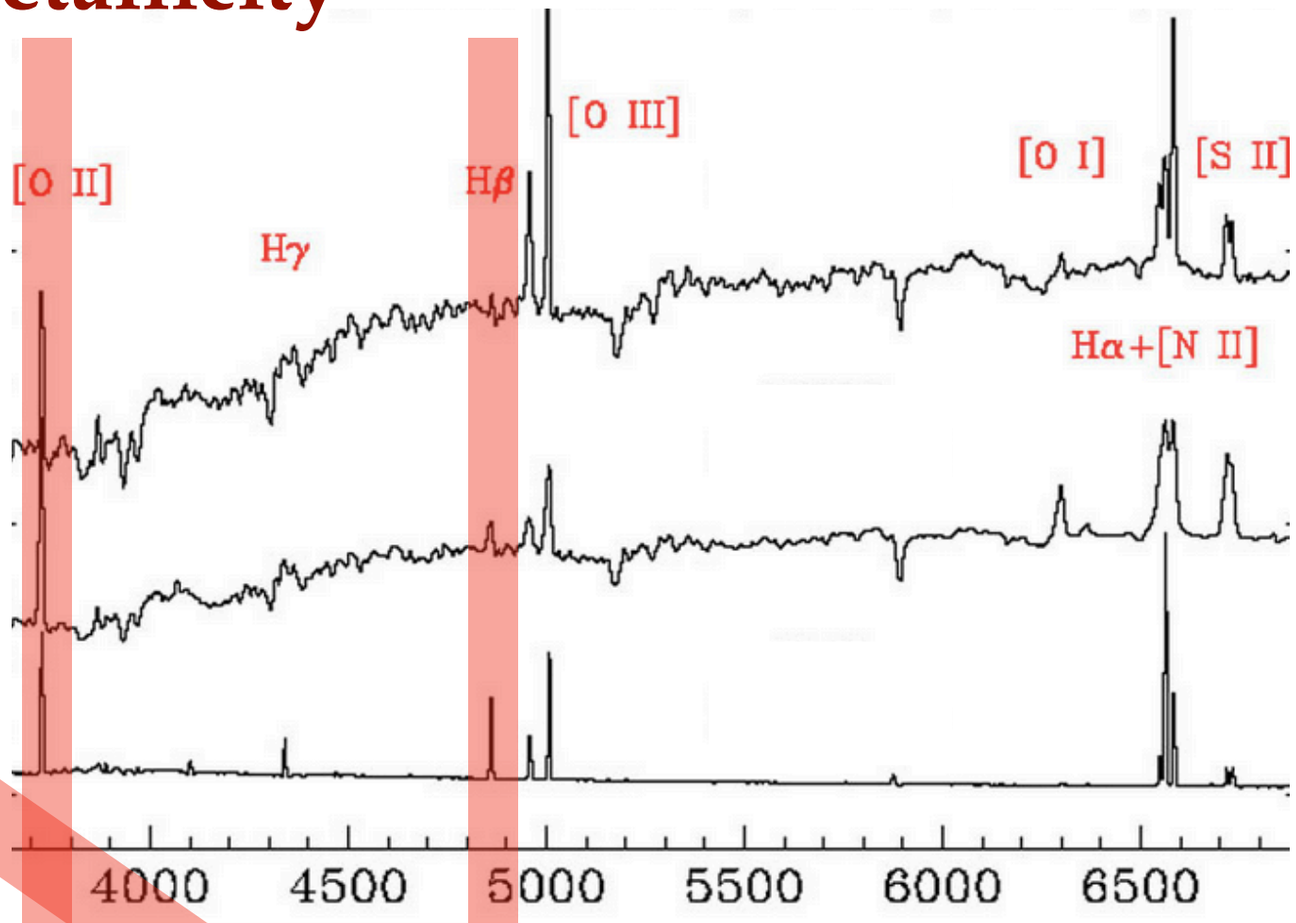


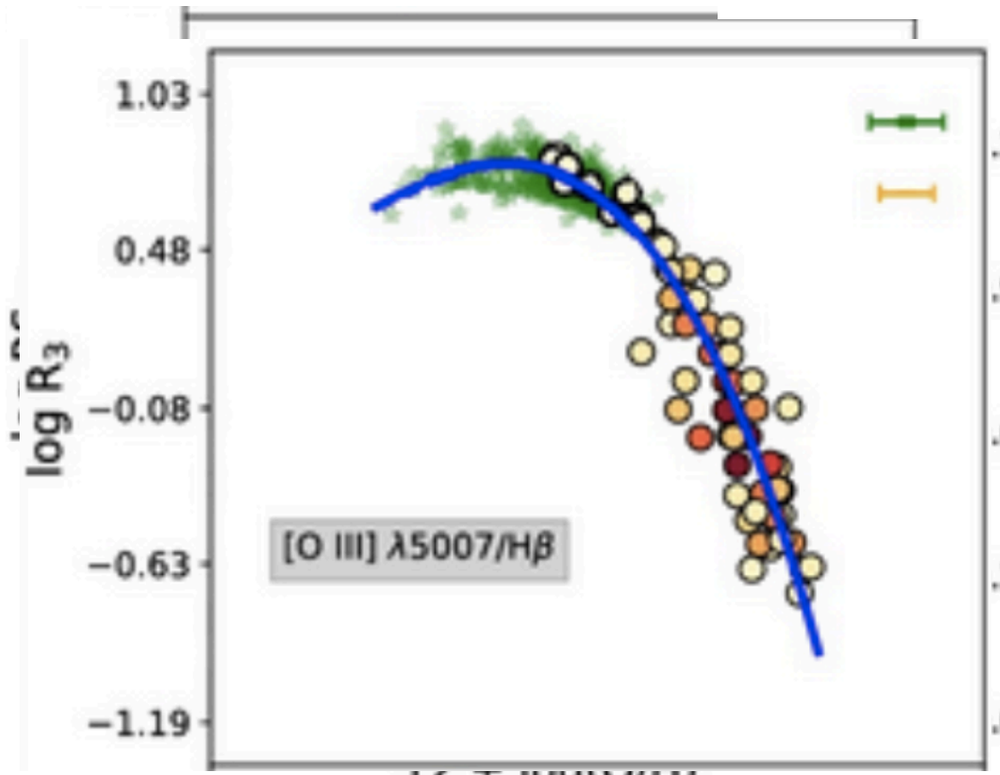


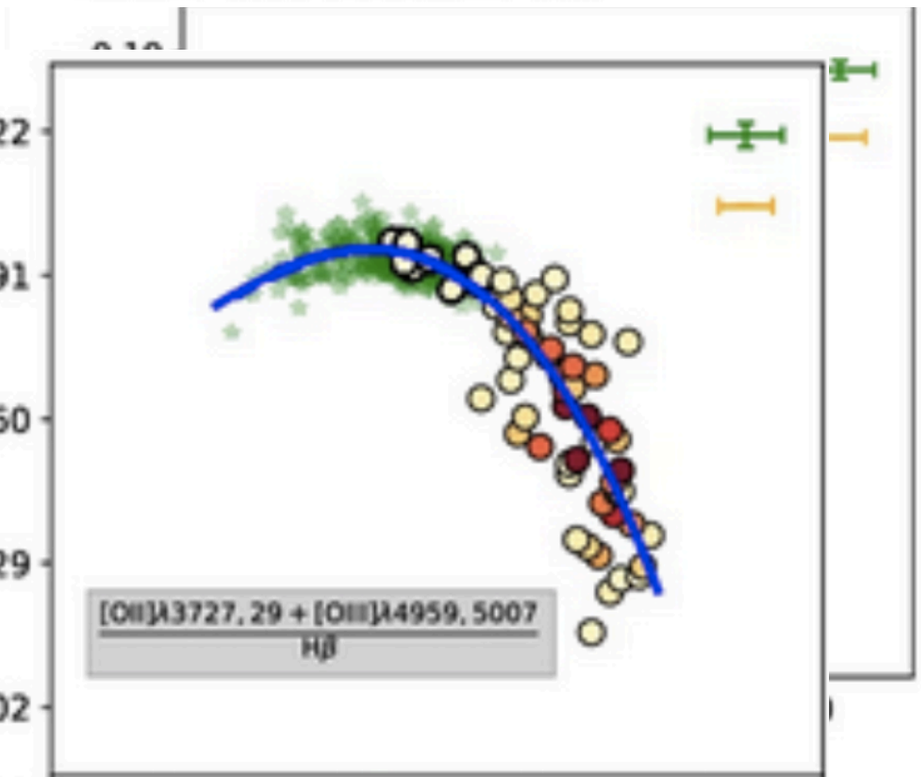
Gas metallicity

via strong emission line flux ratios



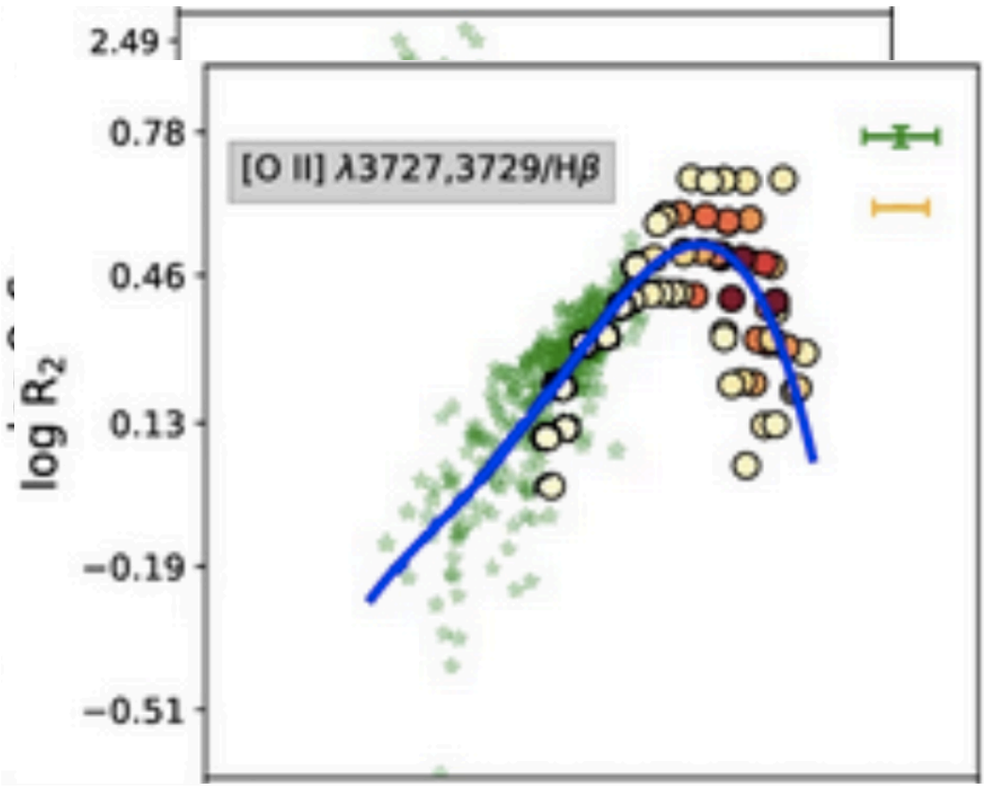


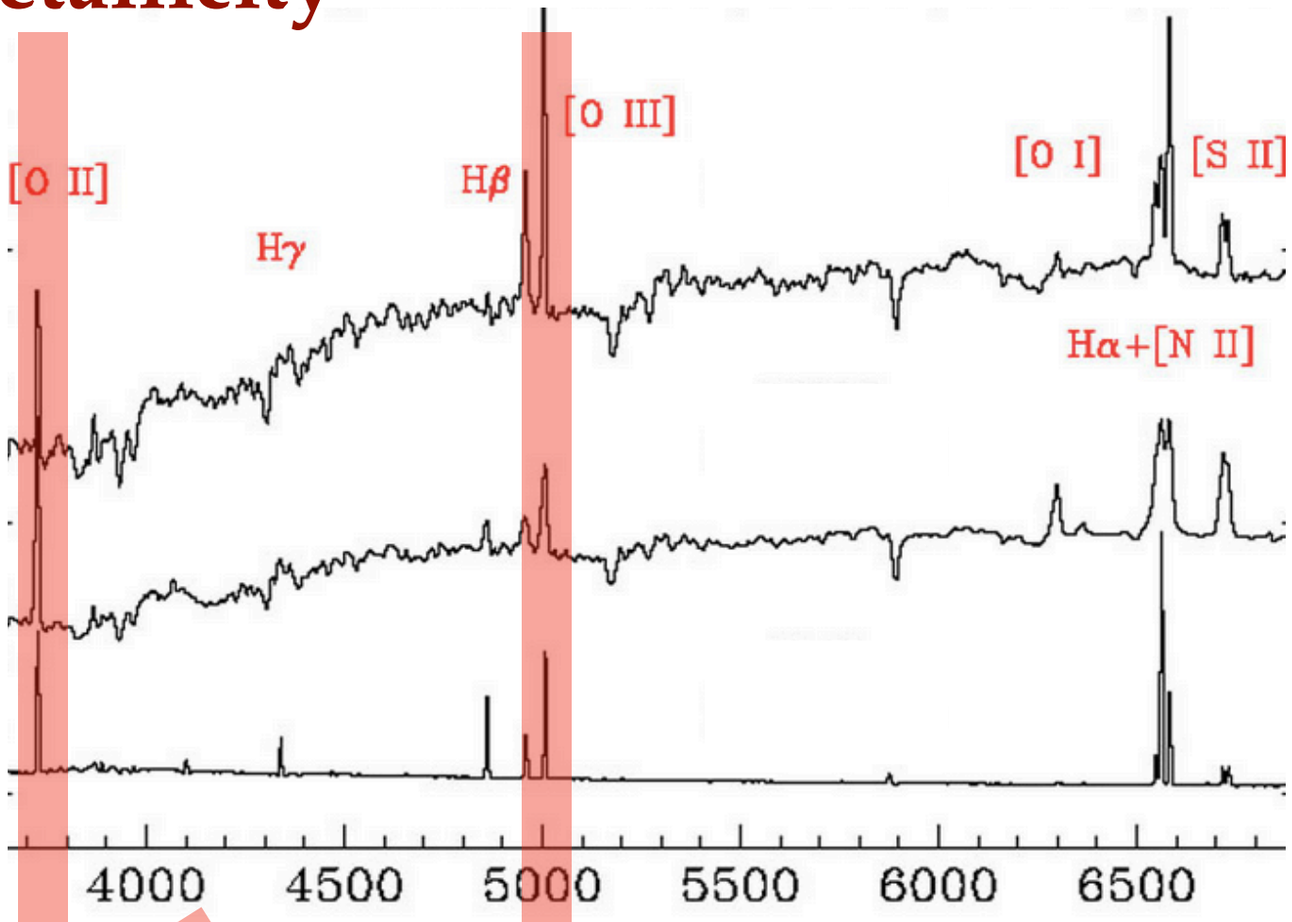




Gas metallicity

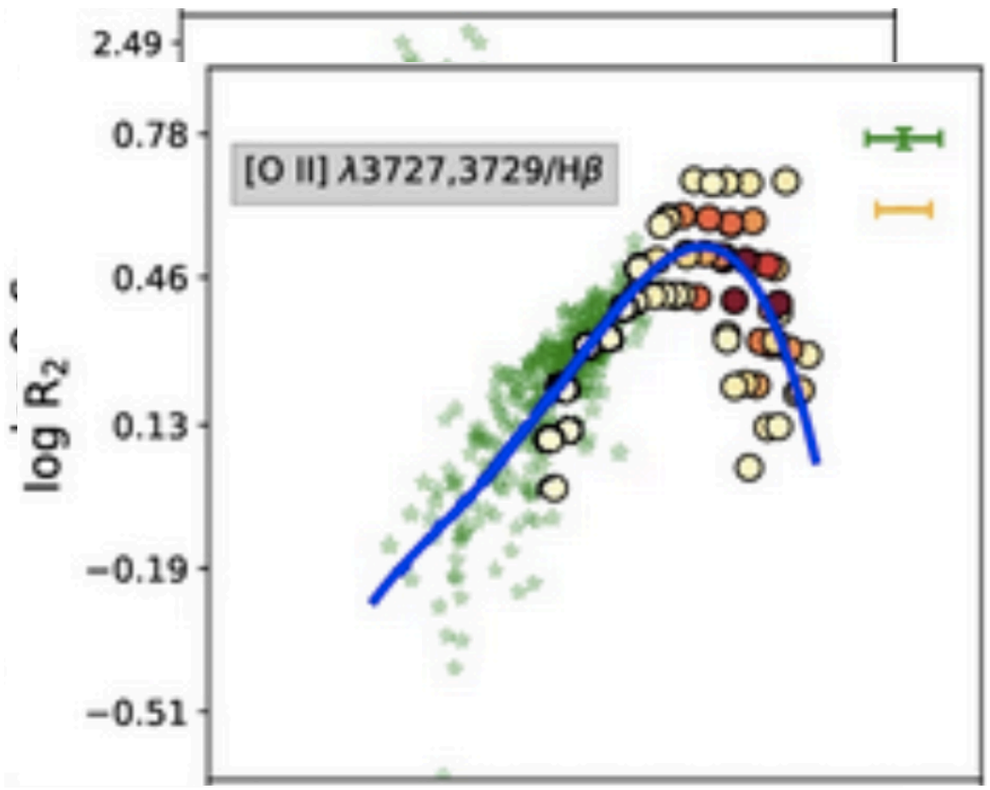
via strong emission line flux ratios

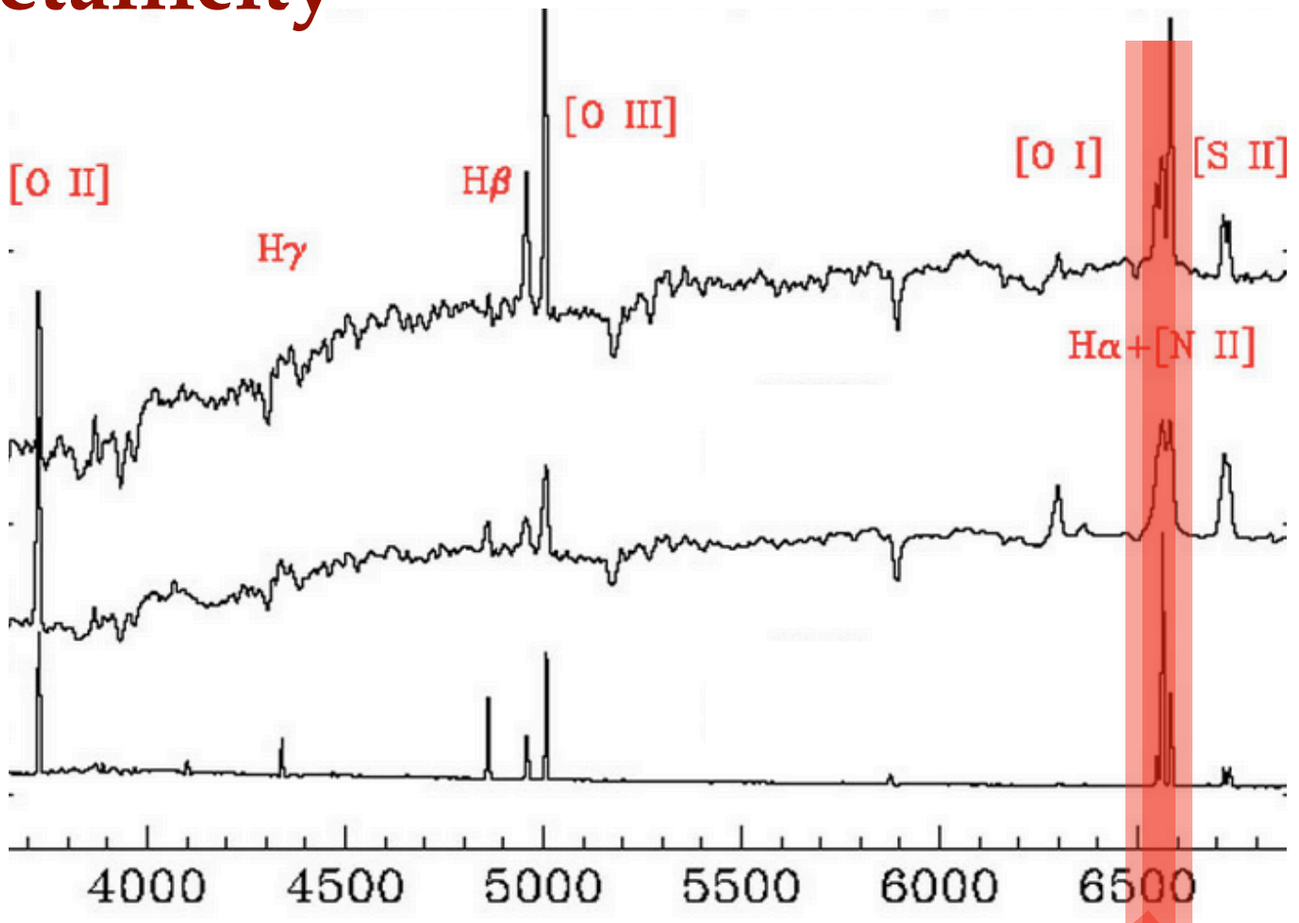


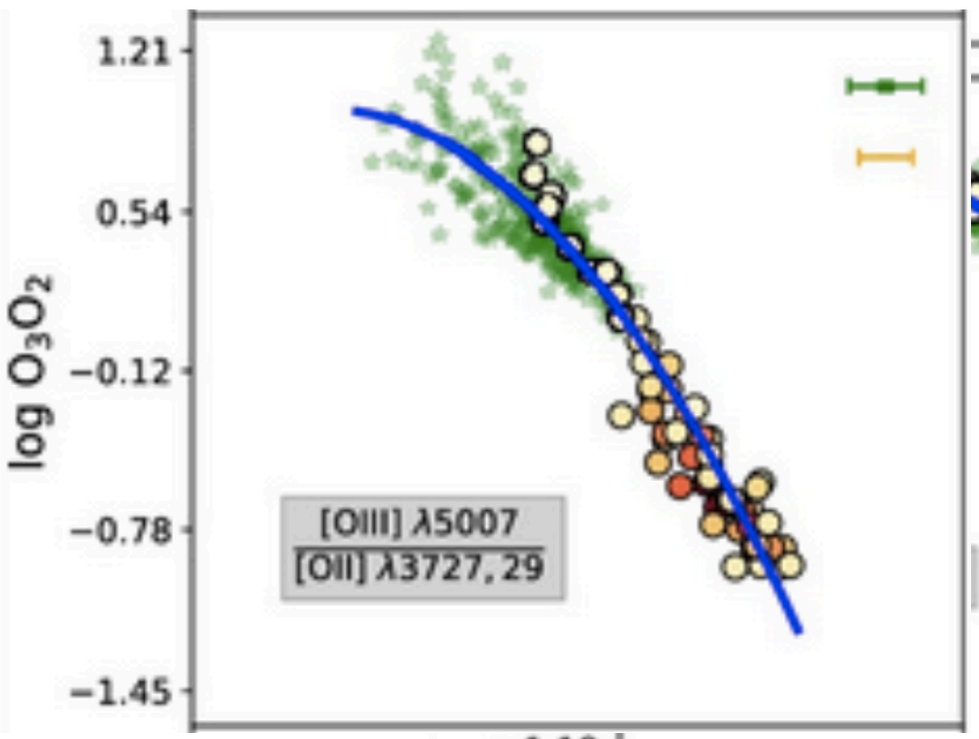


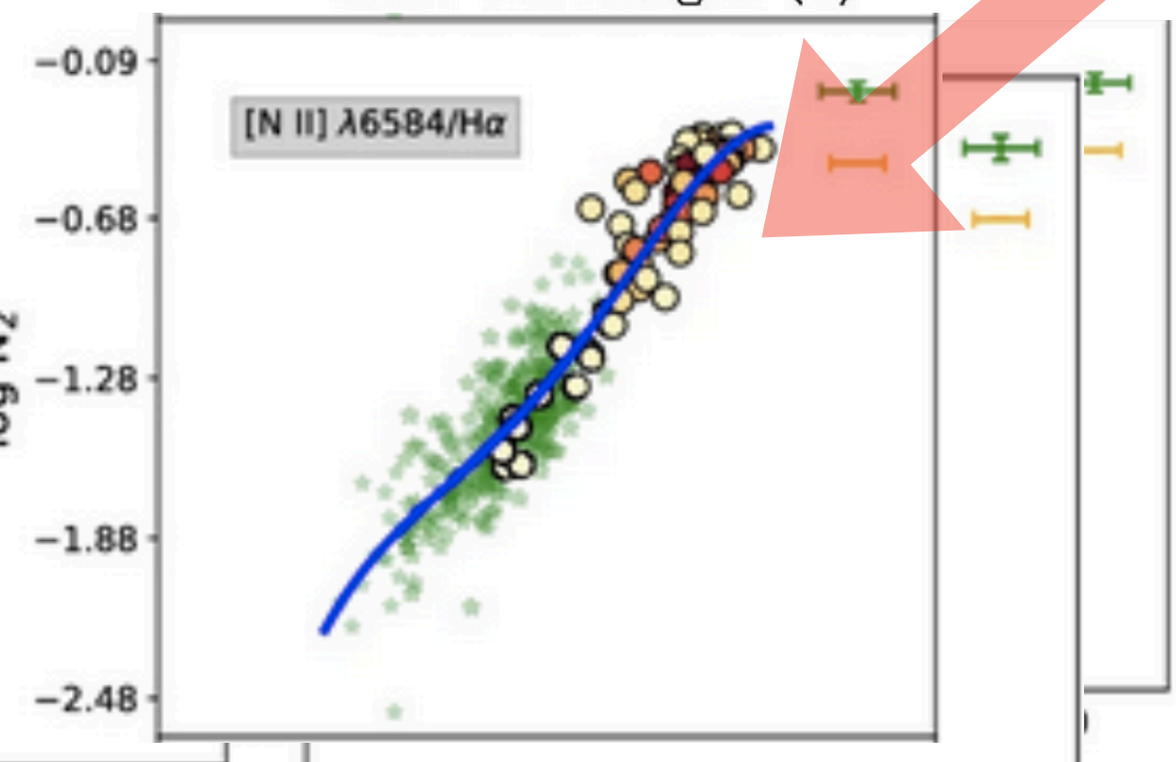
Gas metallicity

via strong emission line flux ratios



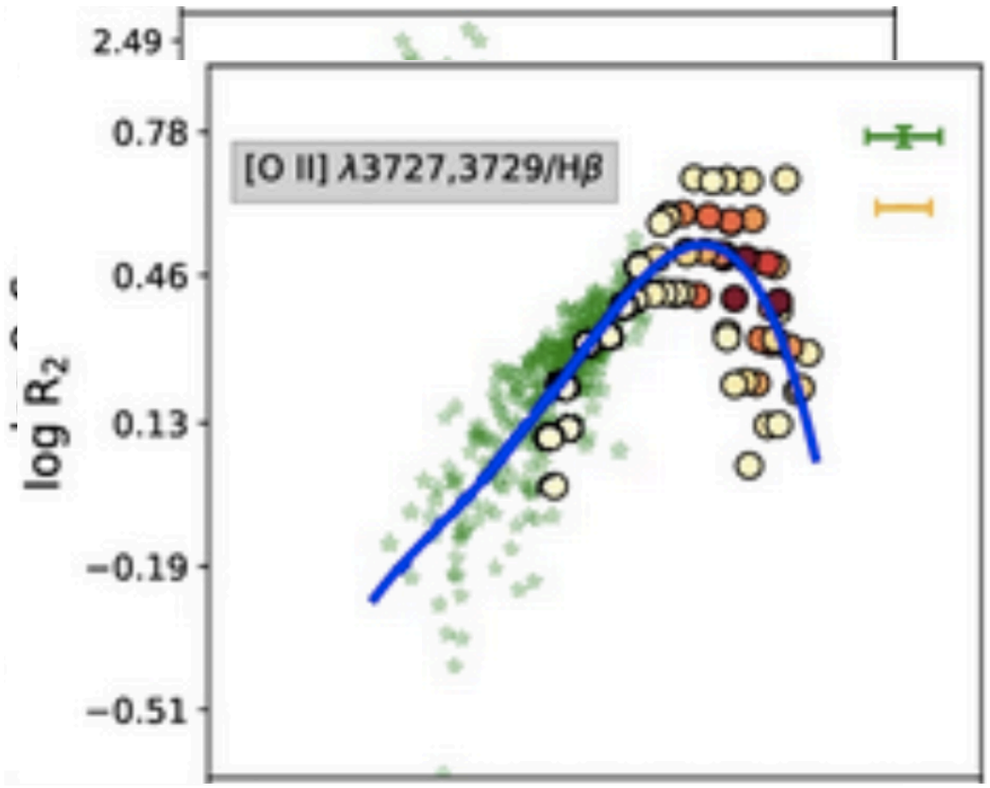


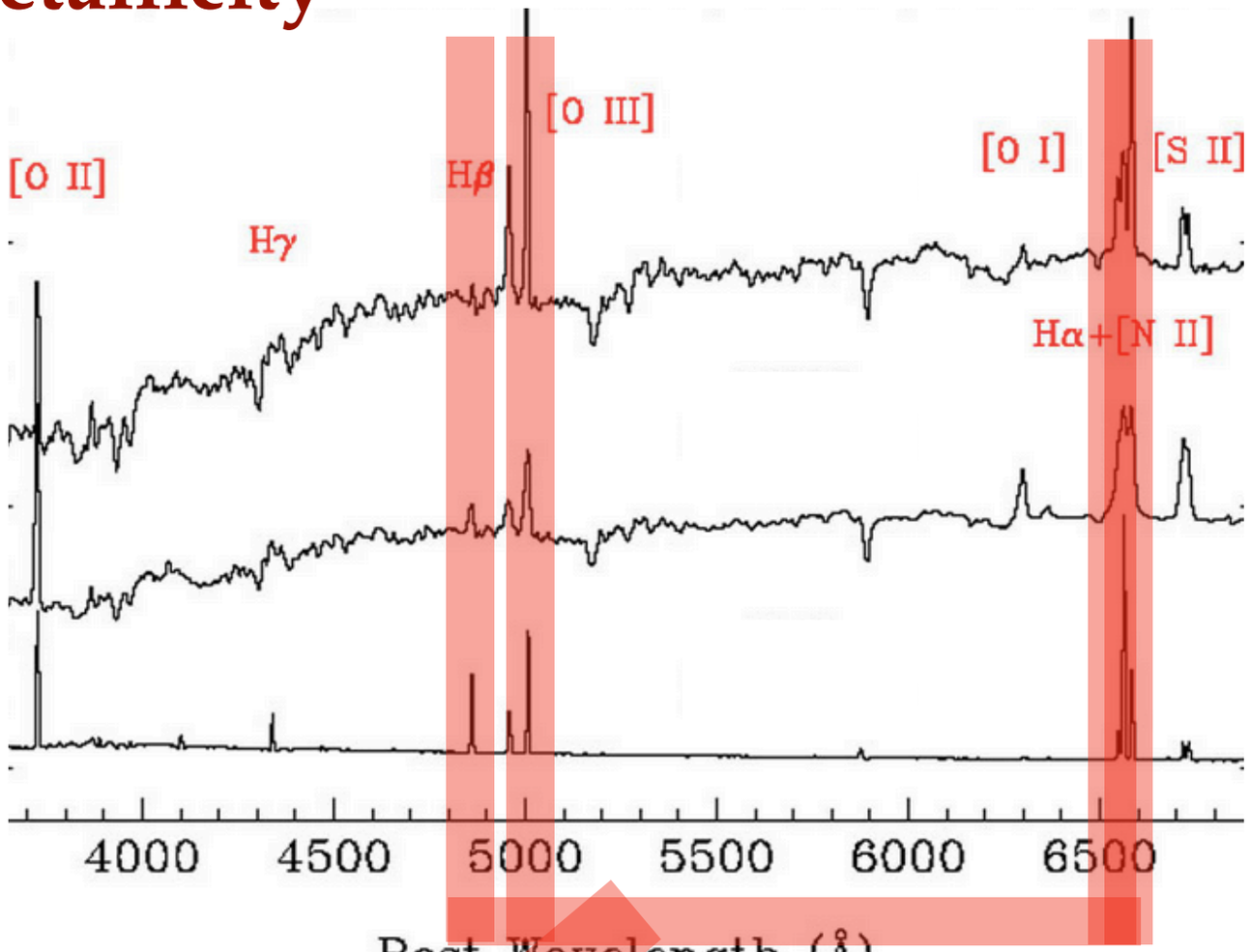


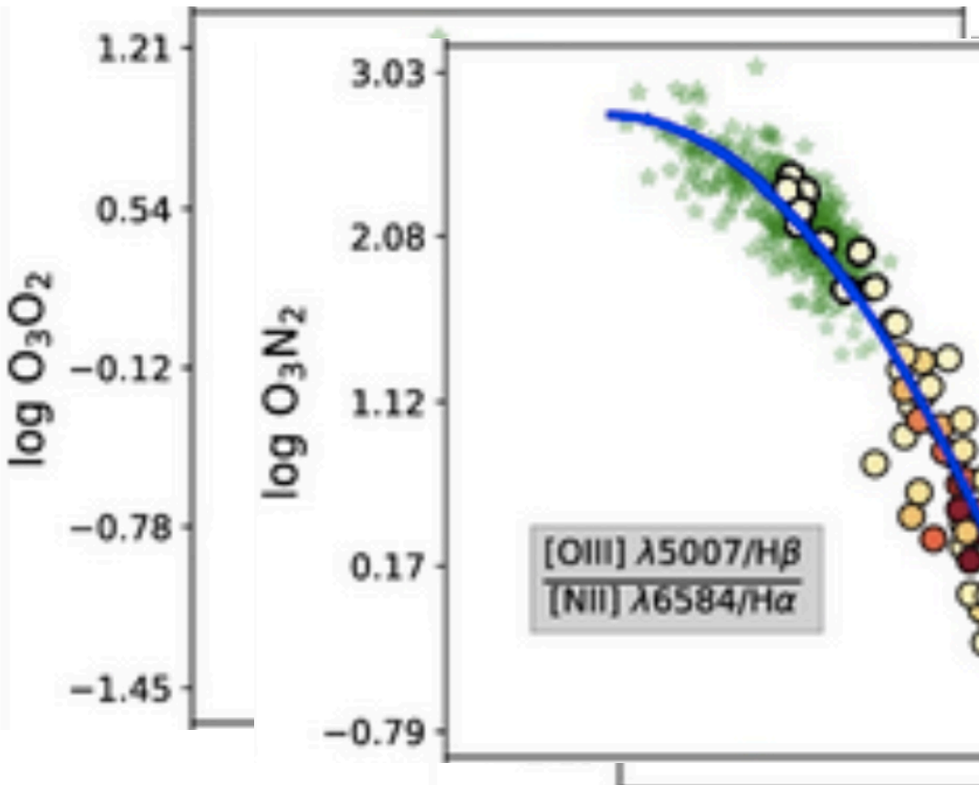


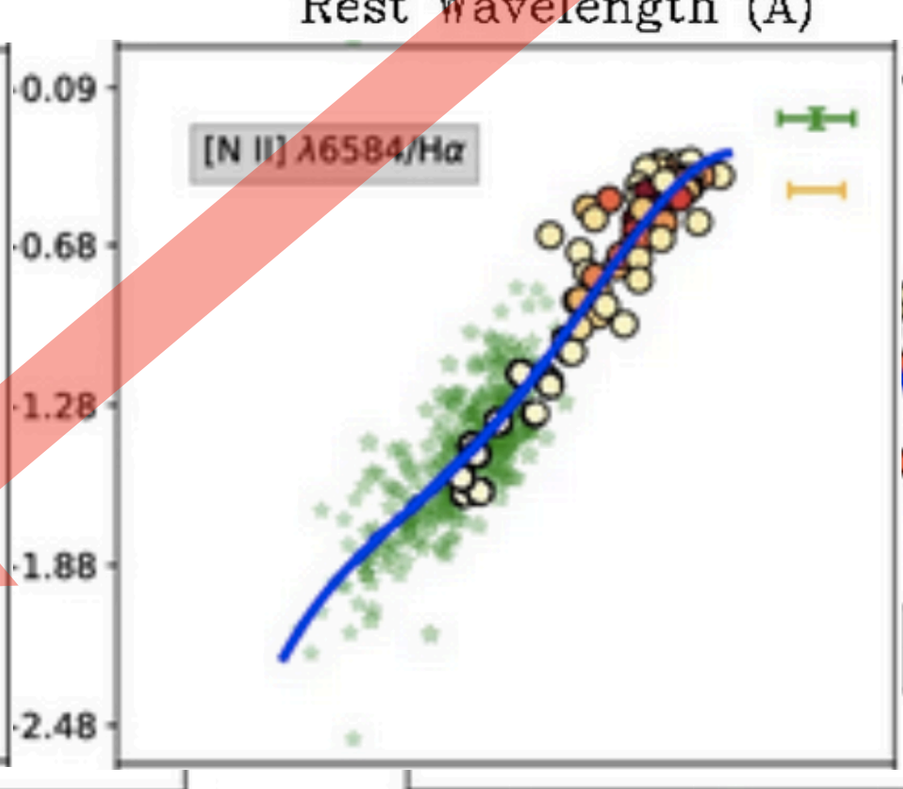
Gas metallicity

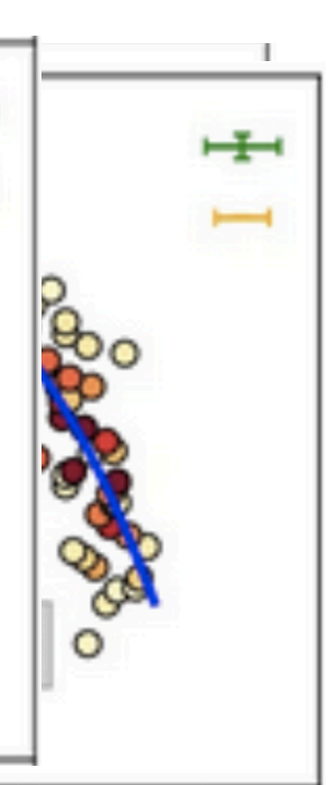
via strong emission line flux ratios



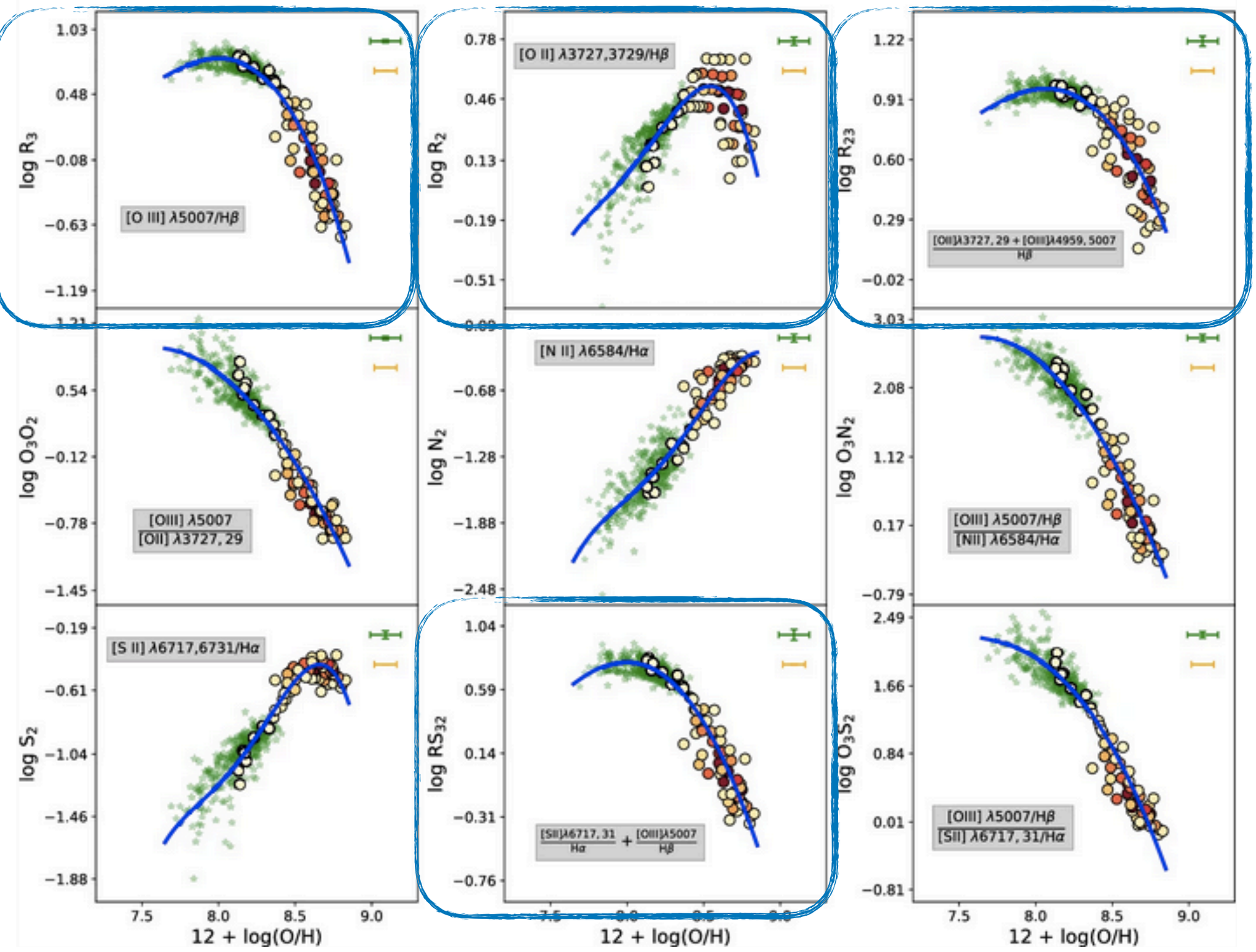








Gas metallicity

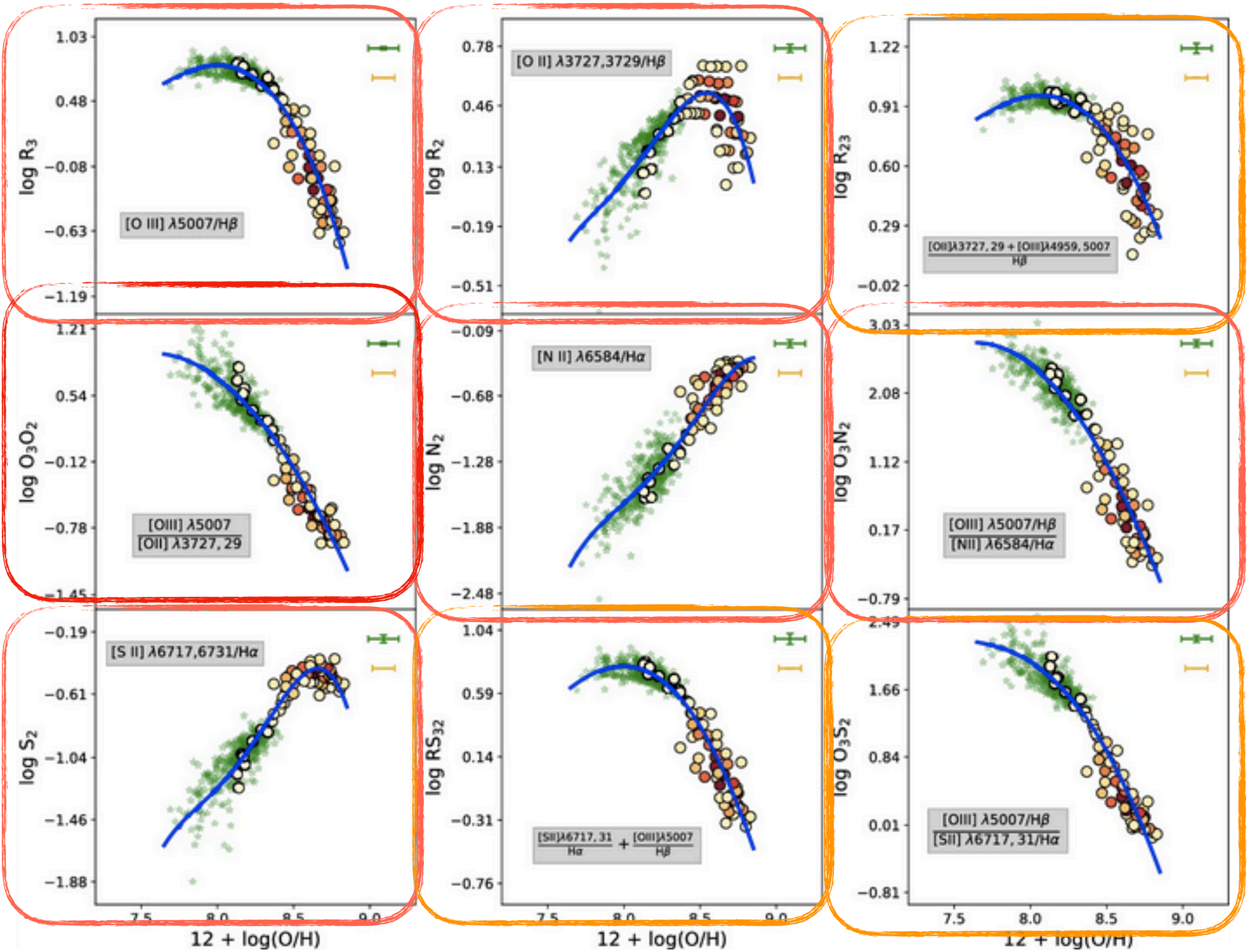


BUT…

- double valued

Maiolino & Mannucci 2019

Gas metallicity



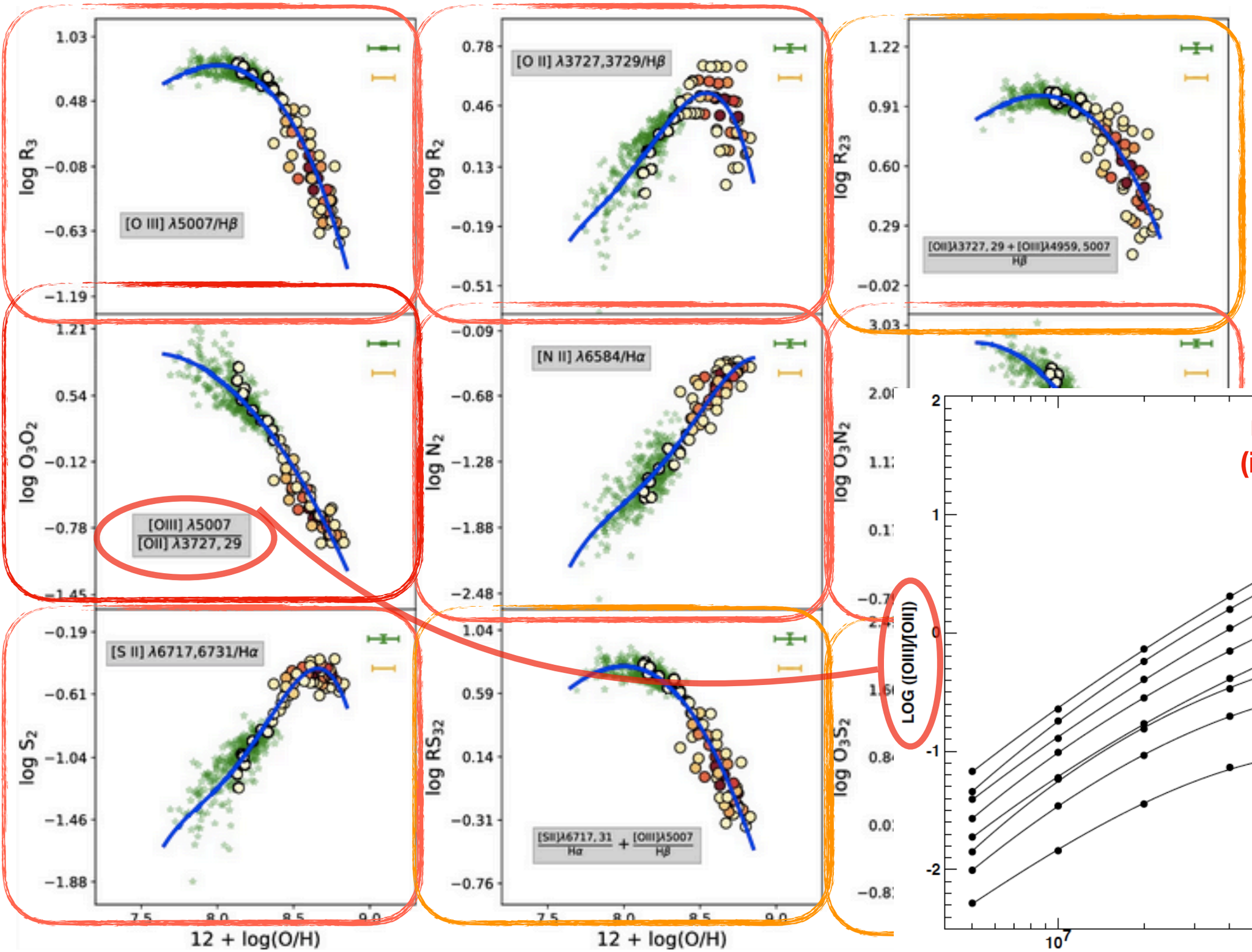
BUT…

- double valued

- secondary/strong dependence on ionization parameter

Maiolino & Mannucci 2019

Gas metallicity



BUT…

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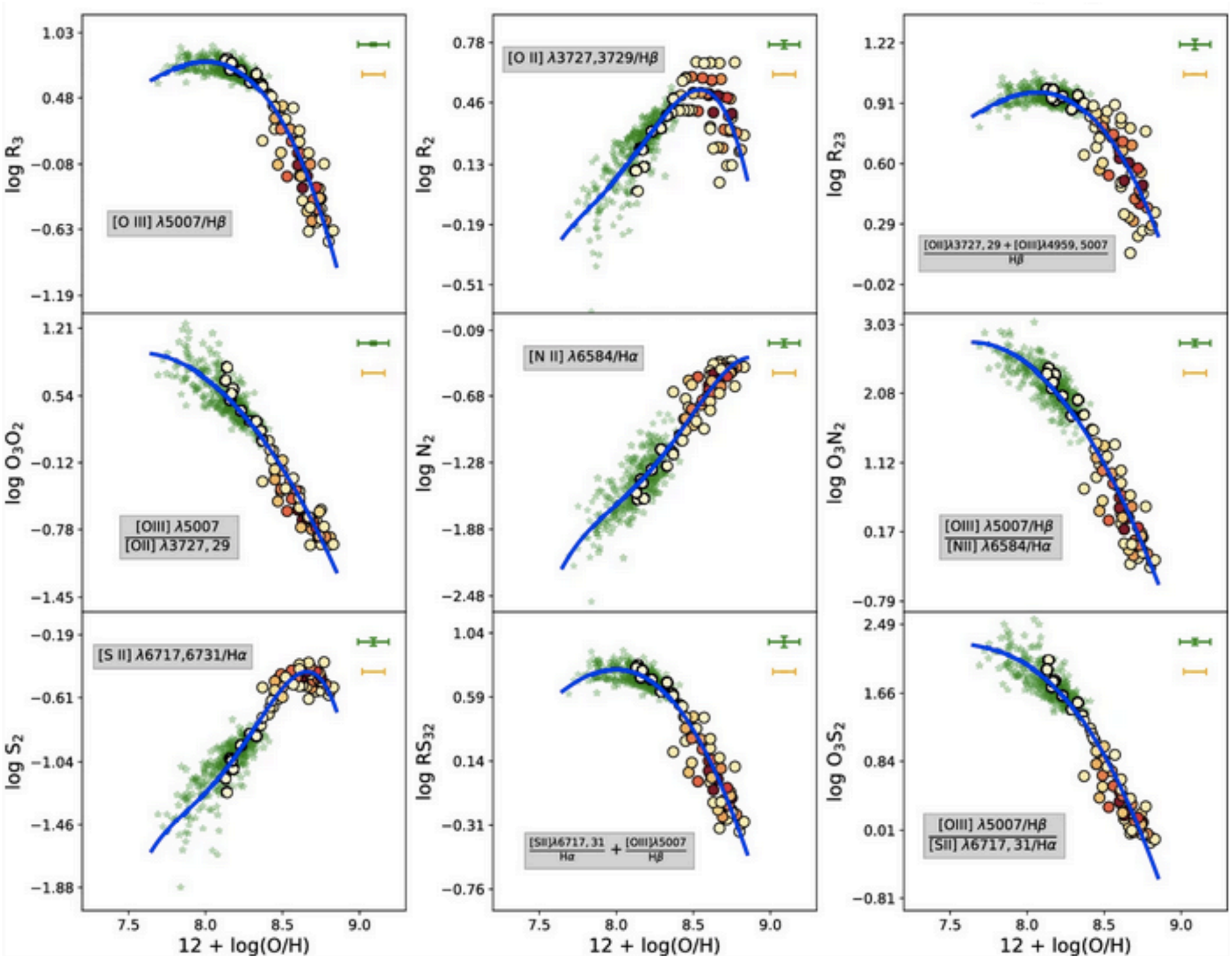
Maiolino & Mannucci 2019

Gas metallicity



BUT…

- double valued

- secondary/strong dependence on ionization parameter

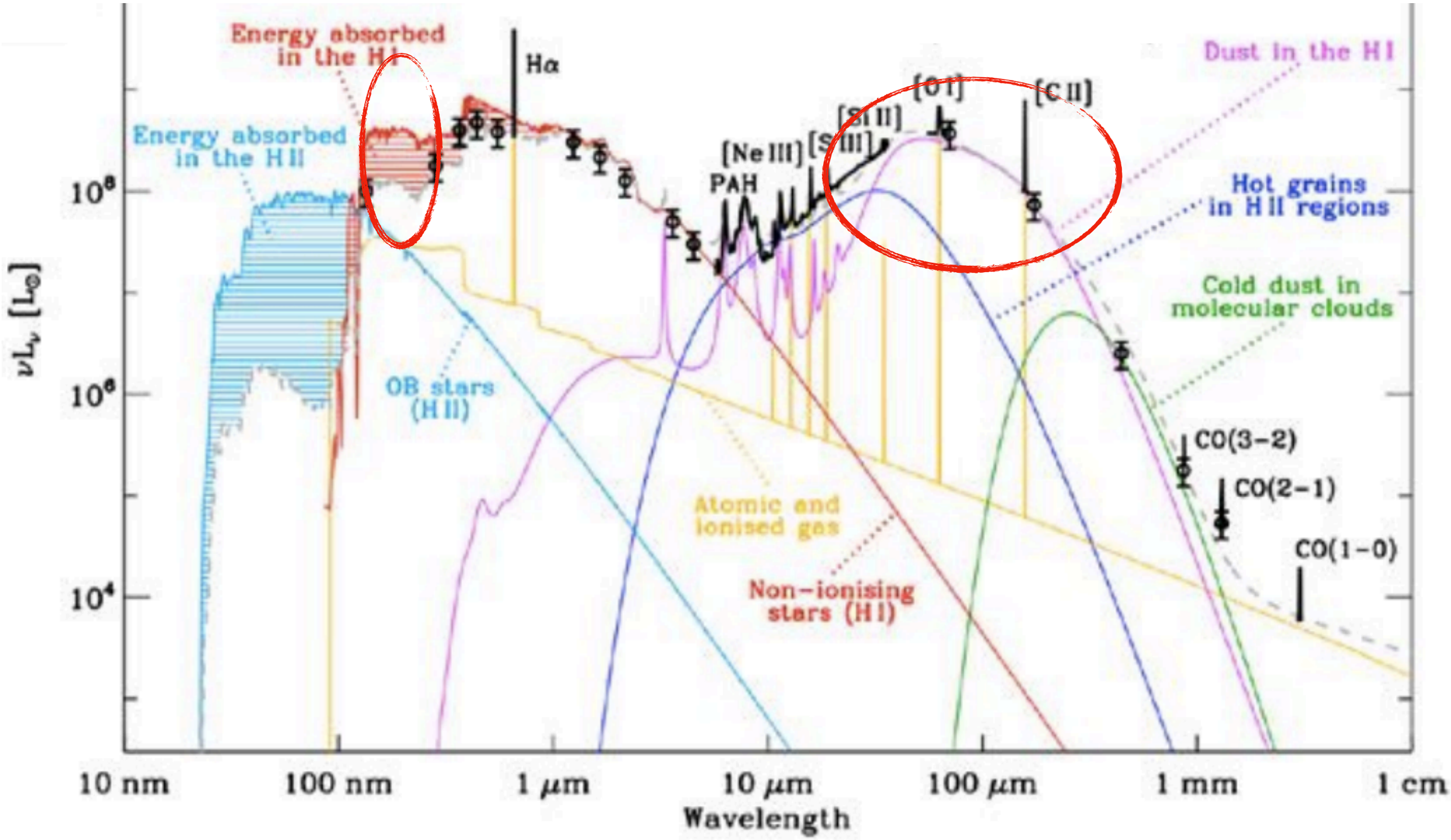
- … …

The combination of multiple line diagnostics can help…

Maiolino & Mannucci 2019

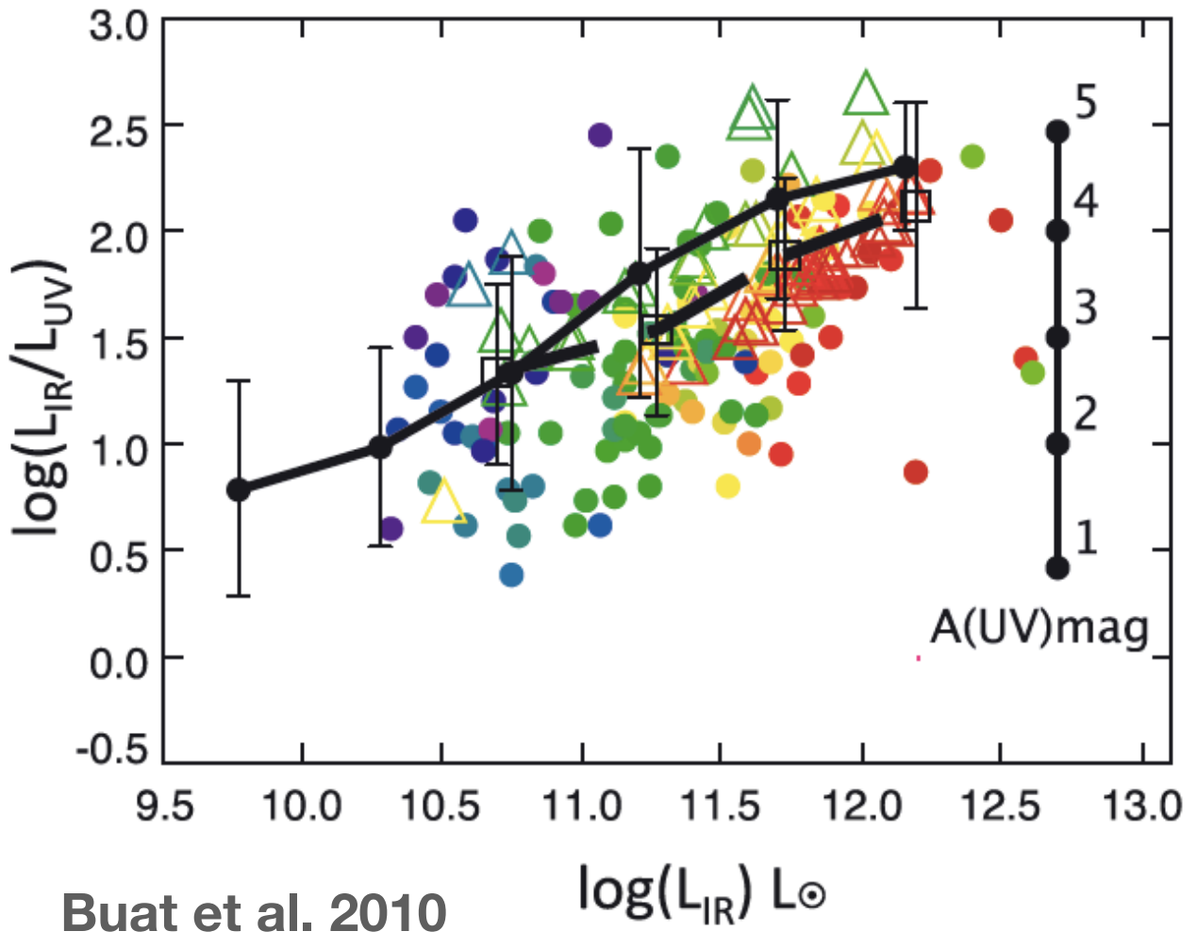
dust extinction

Dust



Dust

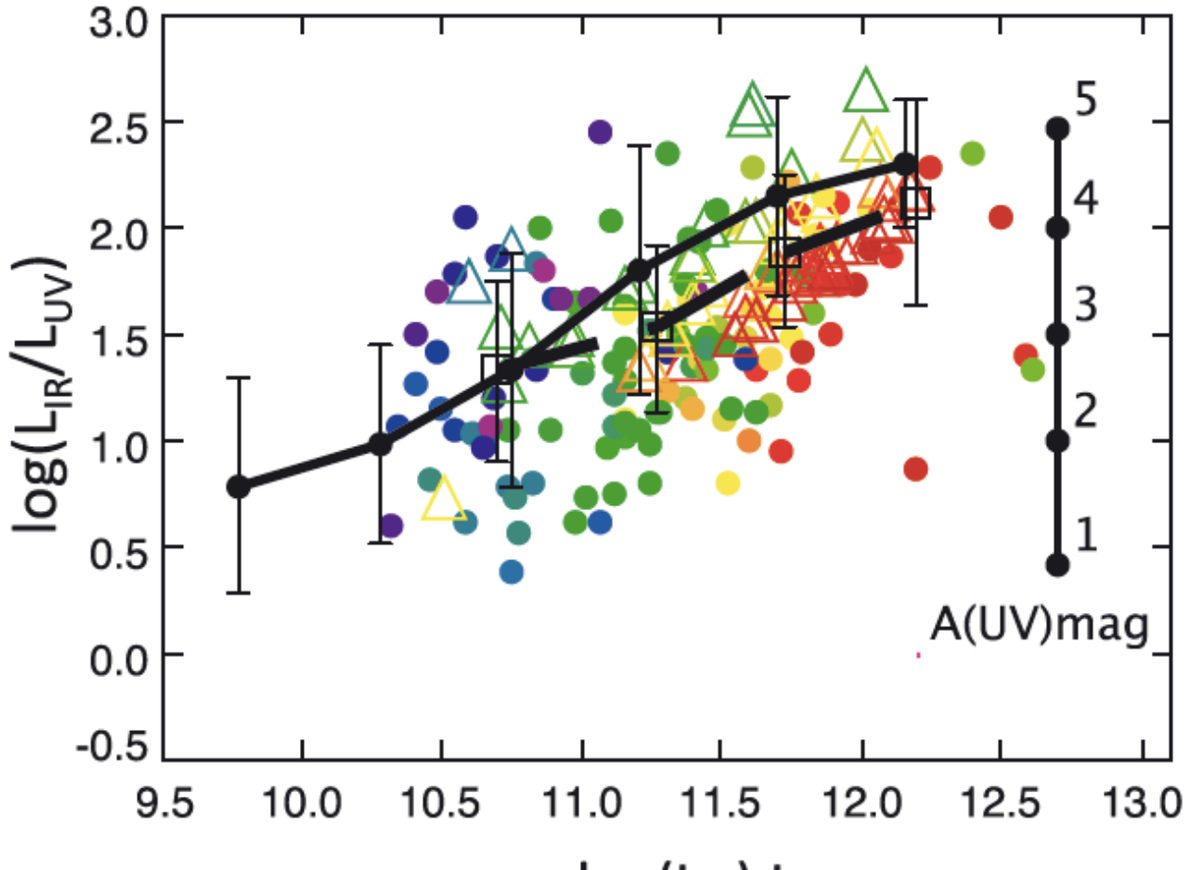
dust extinction from L_{IR}/L_{UV}



Buat et al. 2010

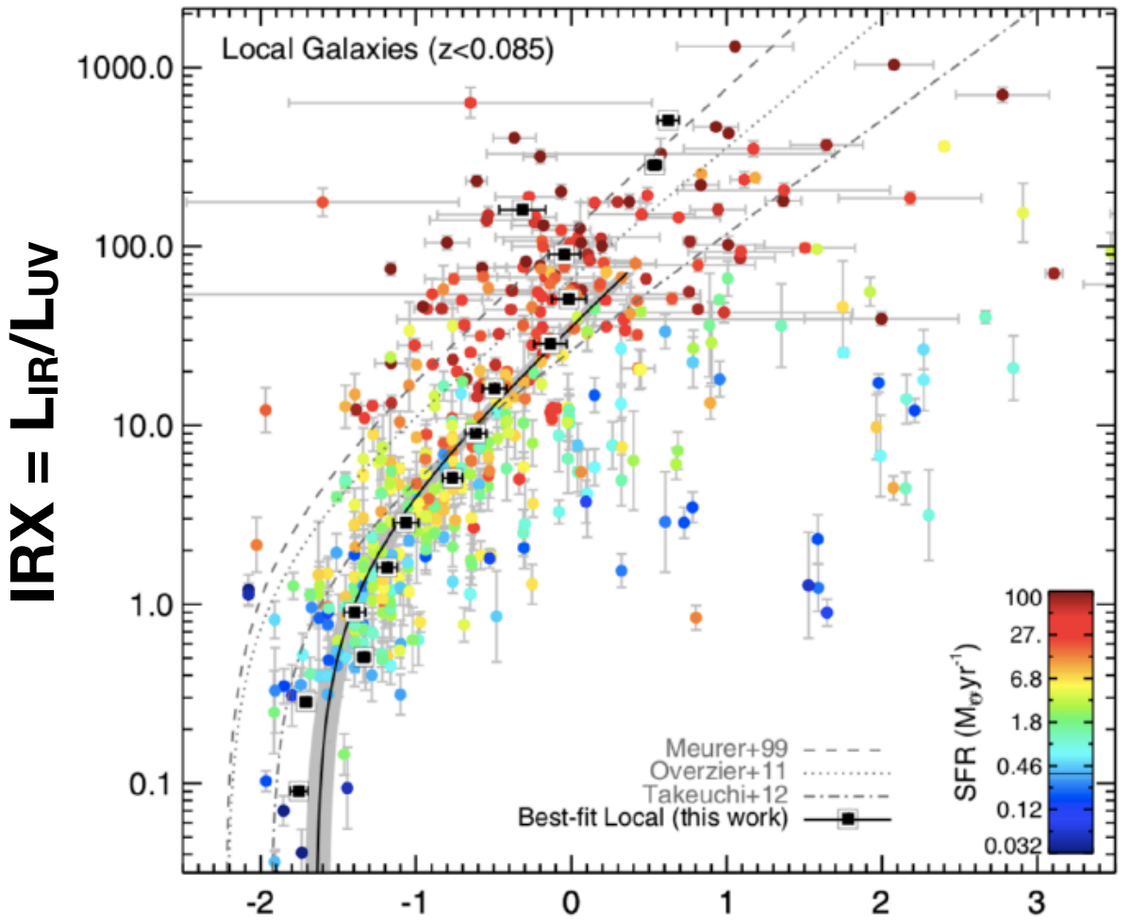
Dust

dust extinction from L_{IR}/L_{UV}



Buat et al. 2010

dust extinction from UV slope

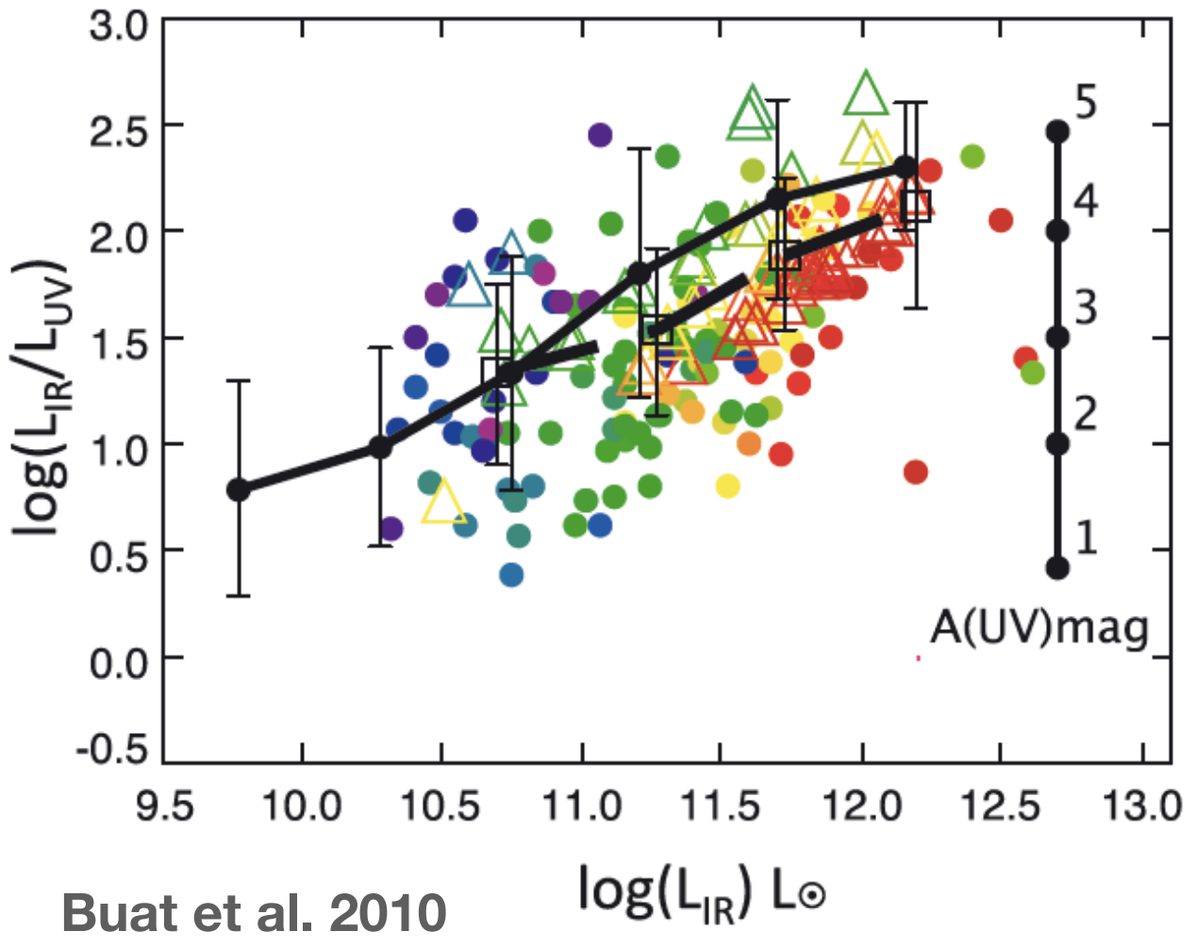


Casey et al. 2014

UV slope β

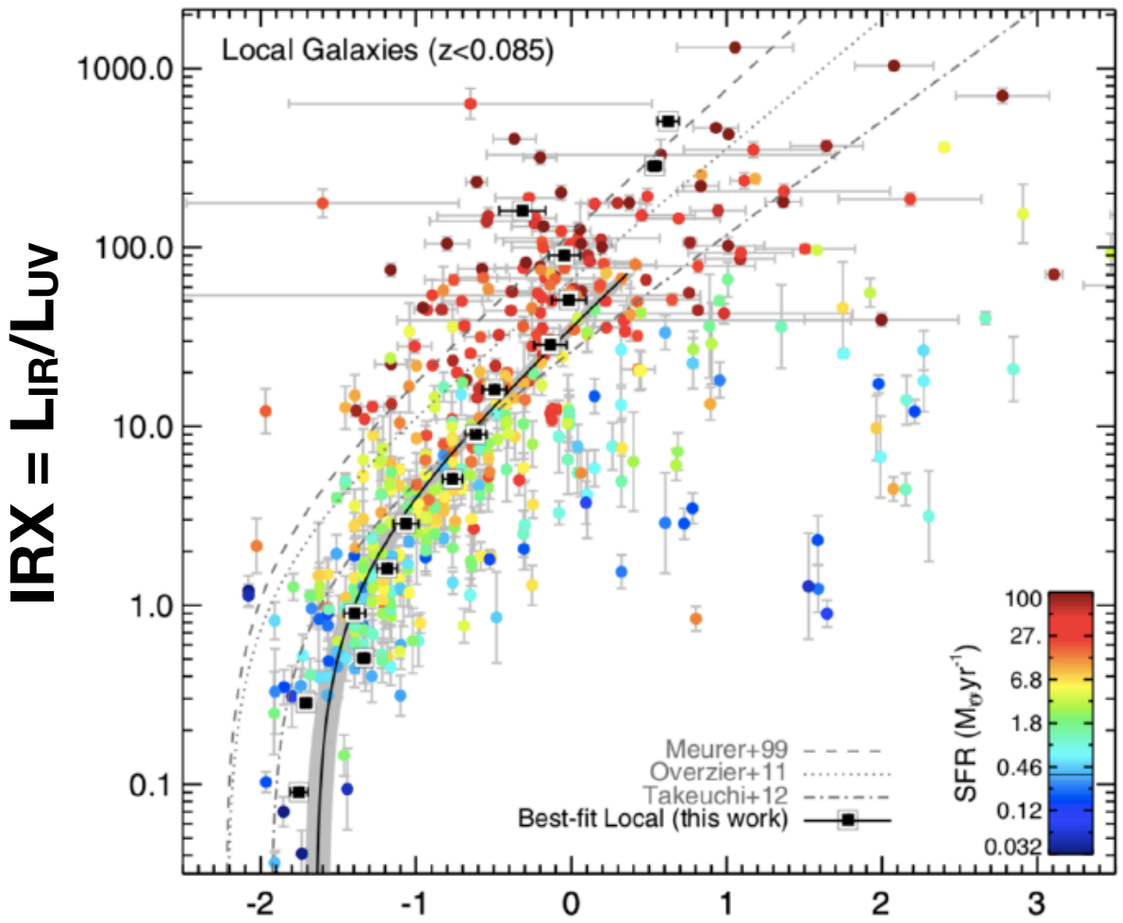
Dust

dust extinction from L_{IR}/L_{UV}



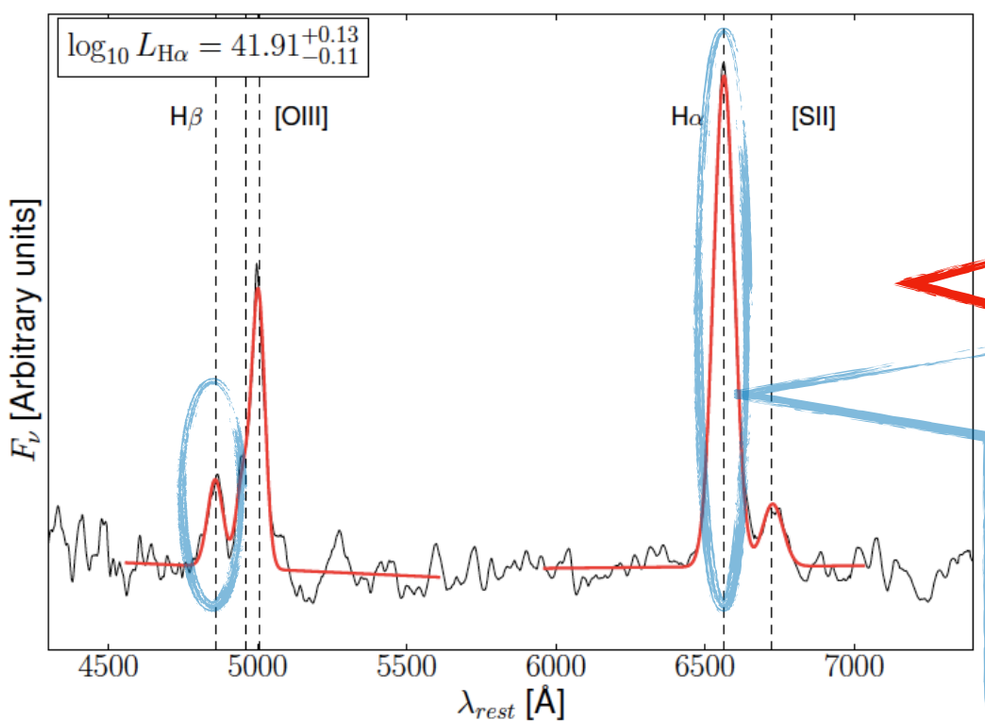
Buat et al. 2010

dust extinction from UV slope



Casey et al. 2014 **UV slope β**

dust extinction from Balmer decrement

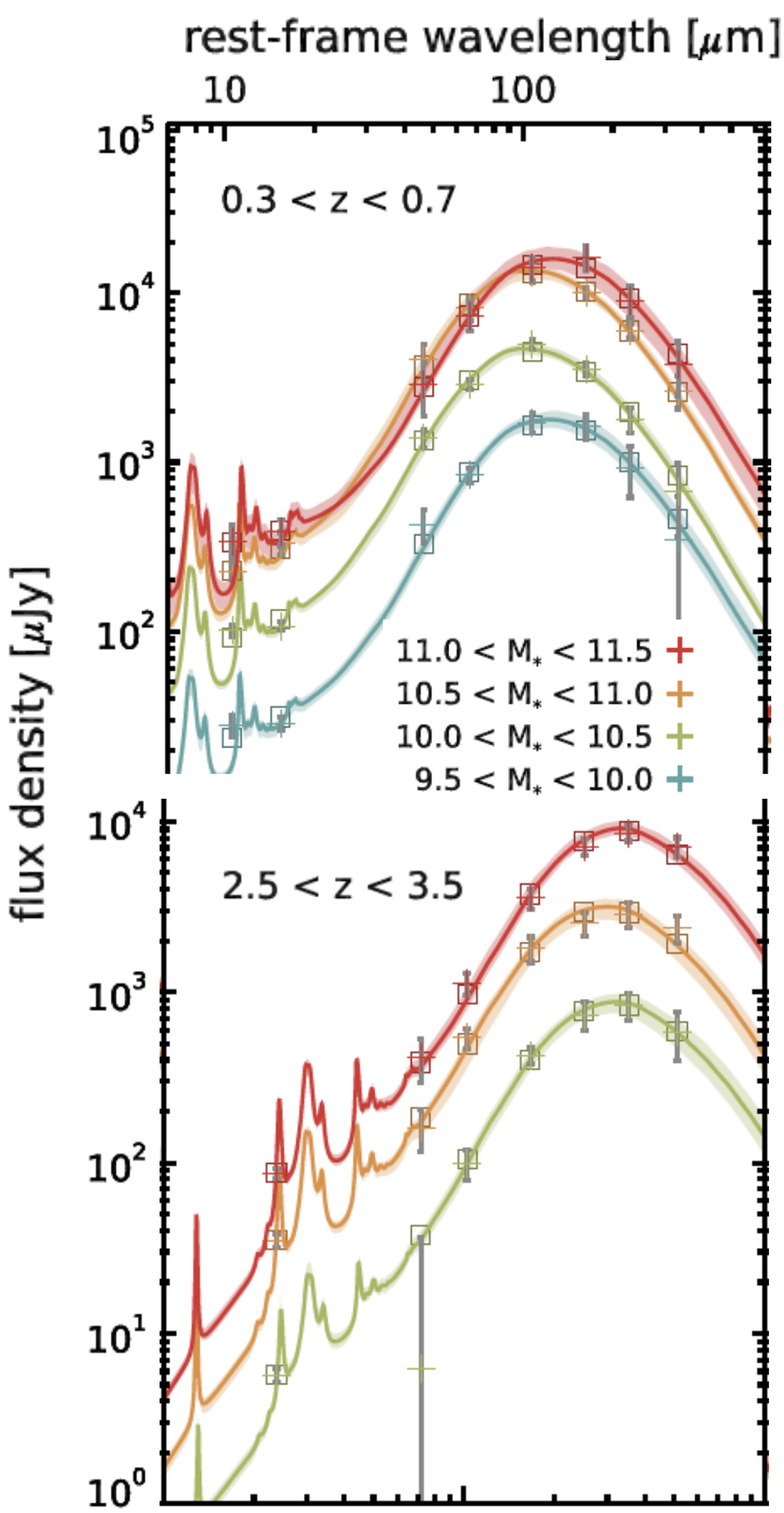


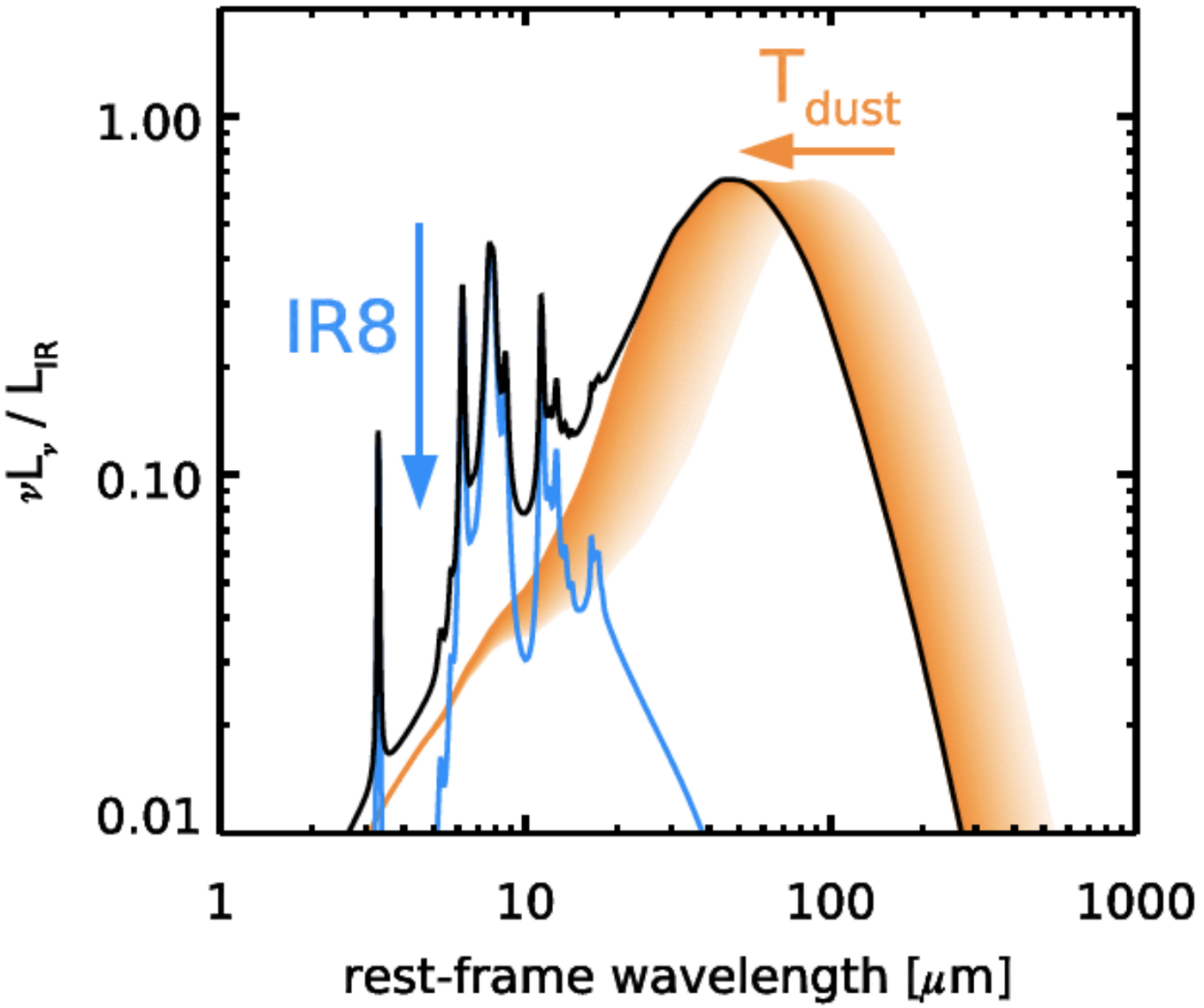
Balmer decrements are the flux ratios of the emission components of Balmer lines relative to Hβ: $D_{34}=F(H_\alpha)/F(H_\beta)$, $D_{54}=F(H_\gamma)/F(H_\beta)$, …

$F(H_\alpha)/F(H_\beta)$ is known theoretically (with some assumptions). Dust extinction affects the two lines differently (different wavelengths) ⇒ comparison of observed vs. theoretical value constrains dust extinction

Dust

modeling of the IR SED also constraints dust content and properties (mass, temperature)

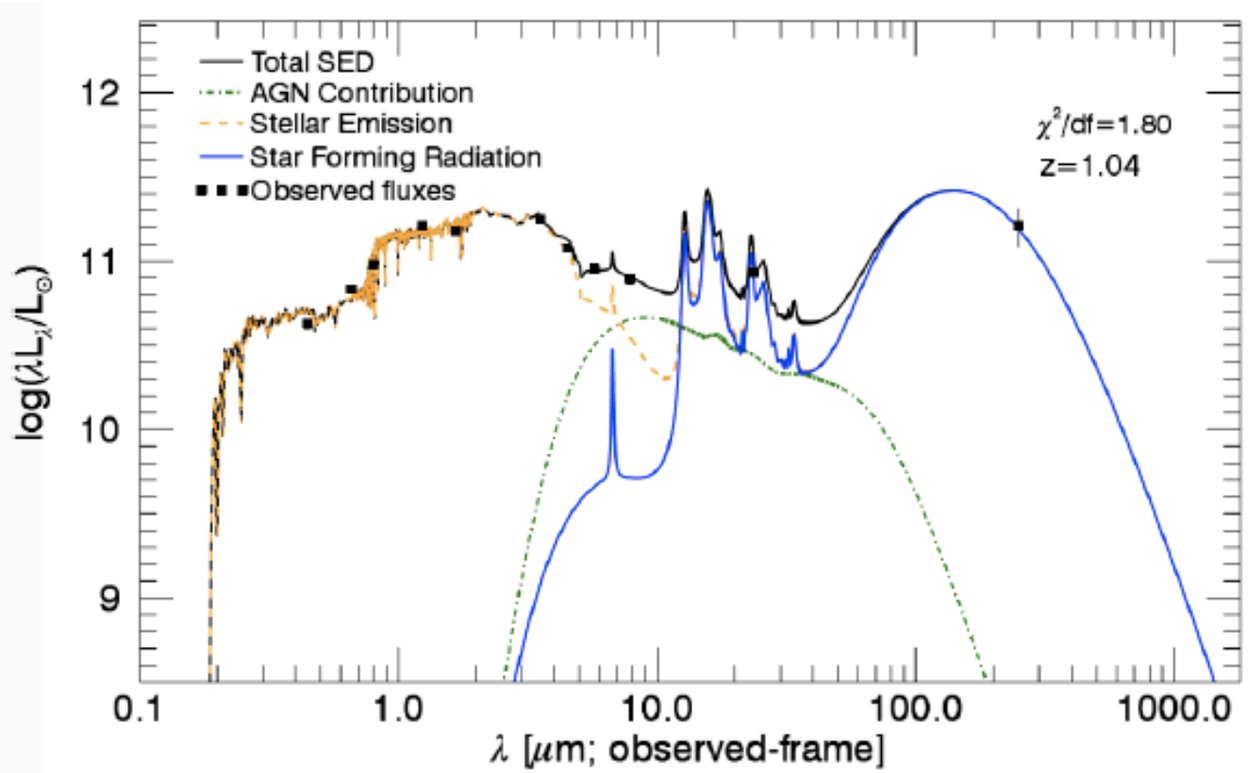


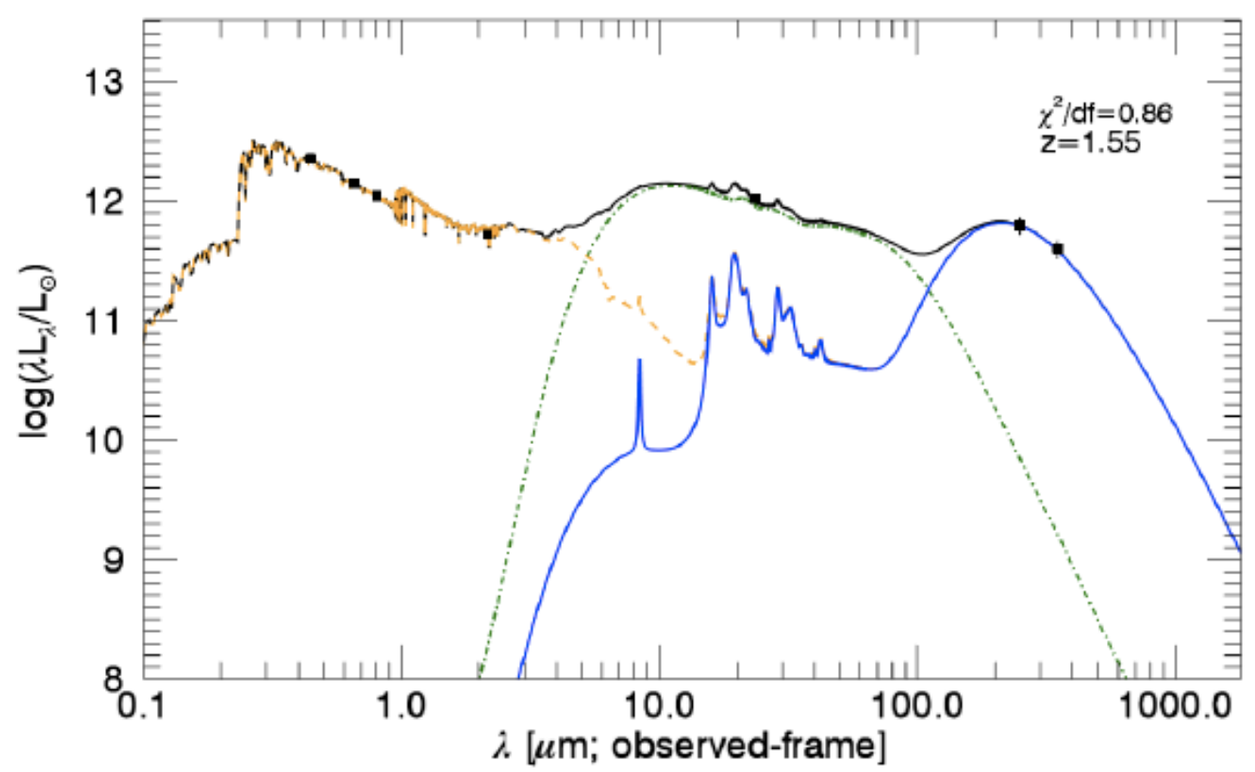


Schreiber et al. 2018

AGN

SED modeling can be used to estimate AGN flux contribution
(at the same time constraining the AGN contamination to the SFR estimate)

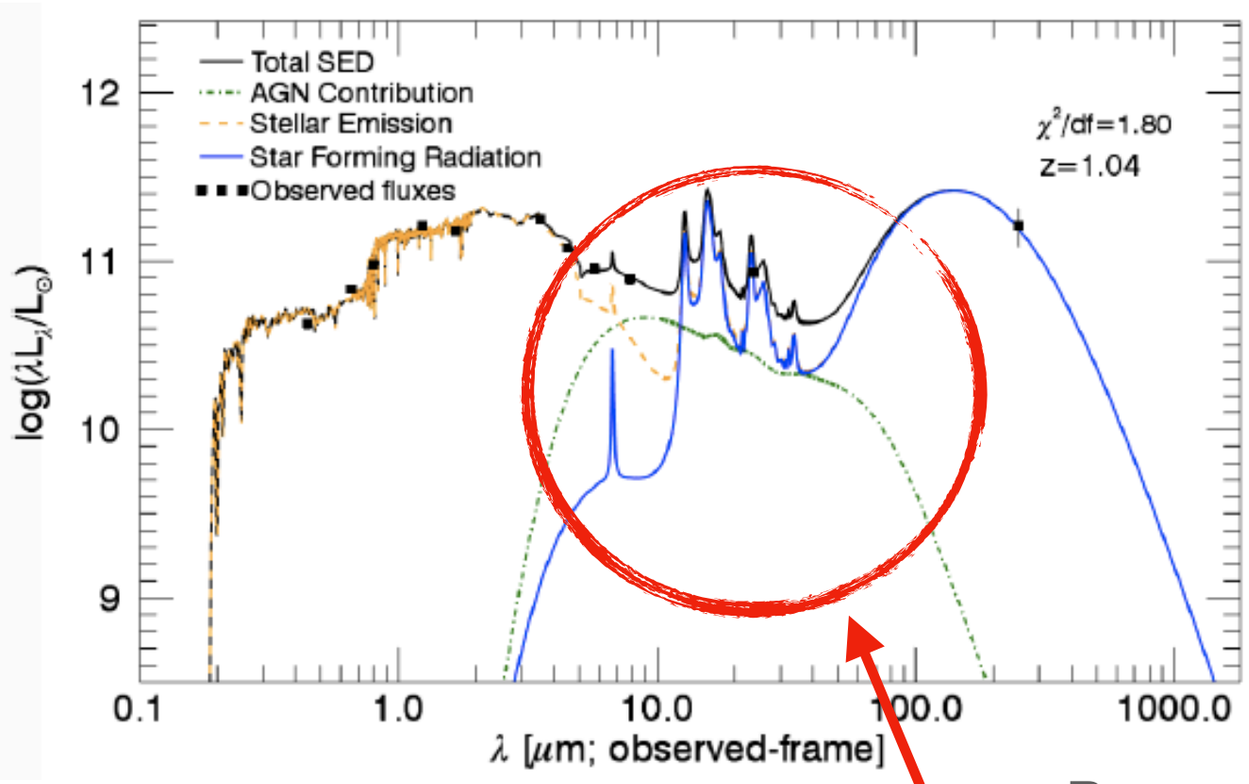


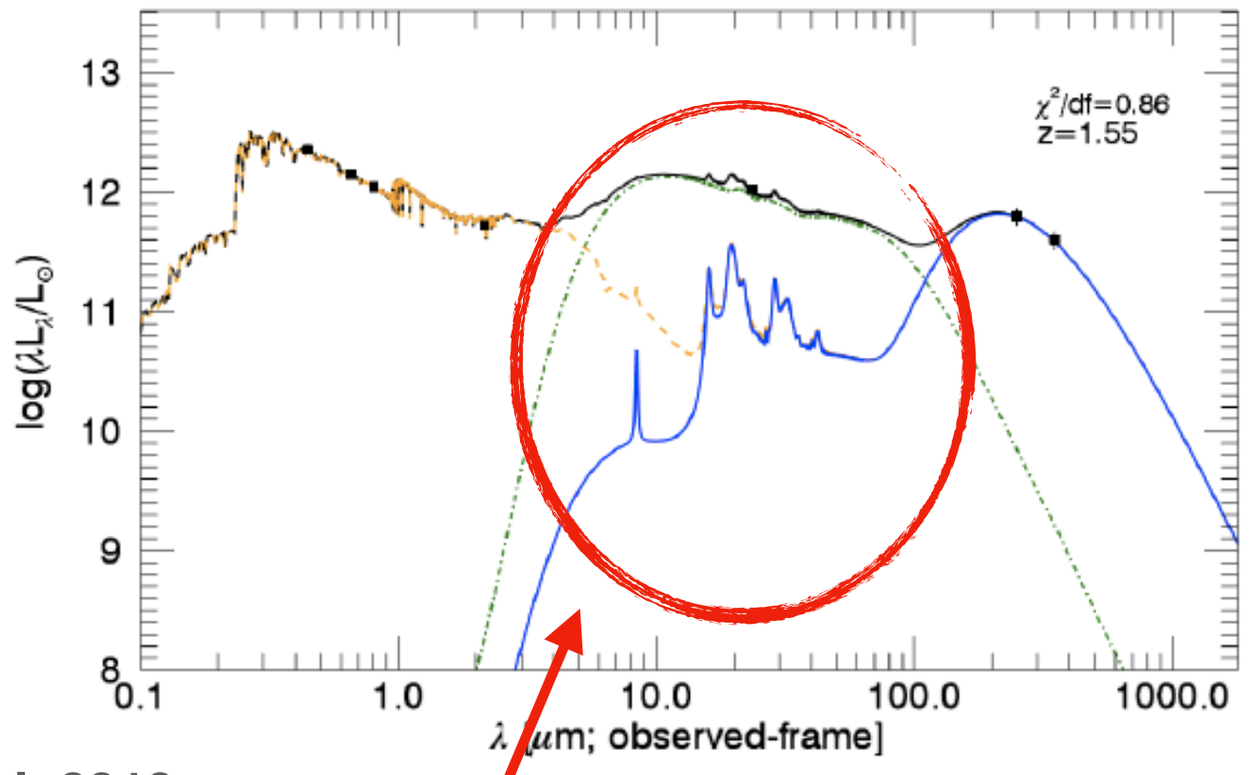


Brown et al. 2019

AGN

2-color selection at NIR/mid-IR wavelengths has also been used for AGN selection





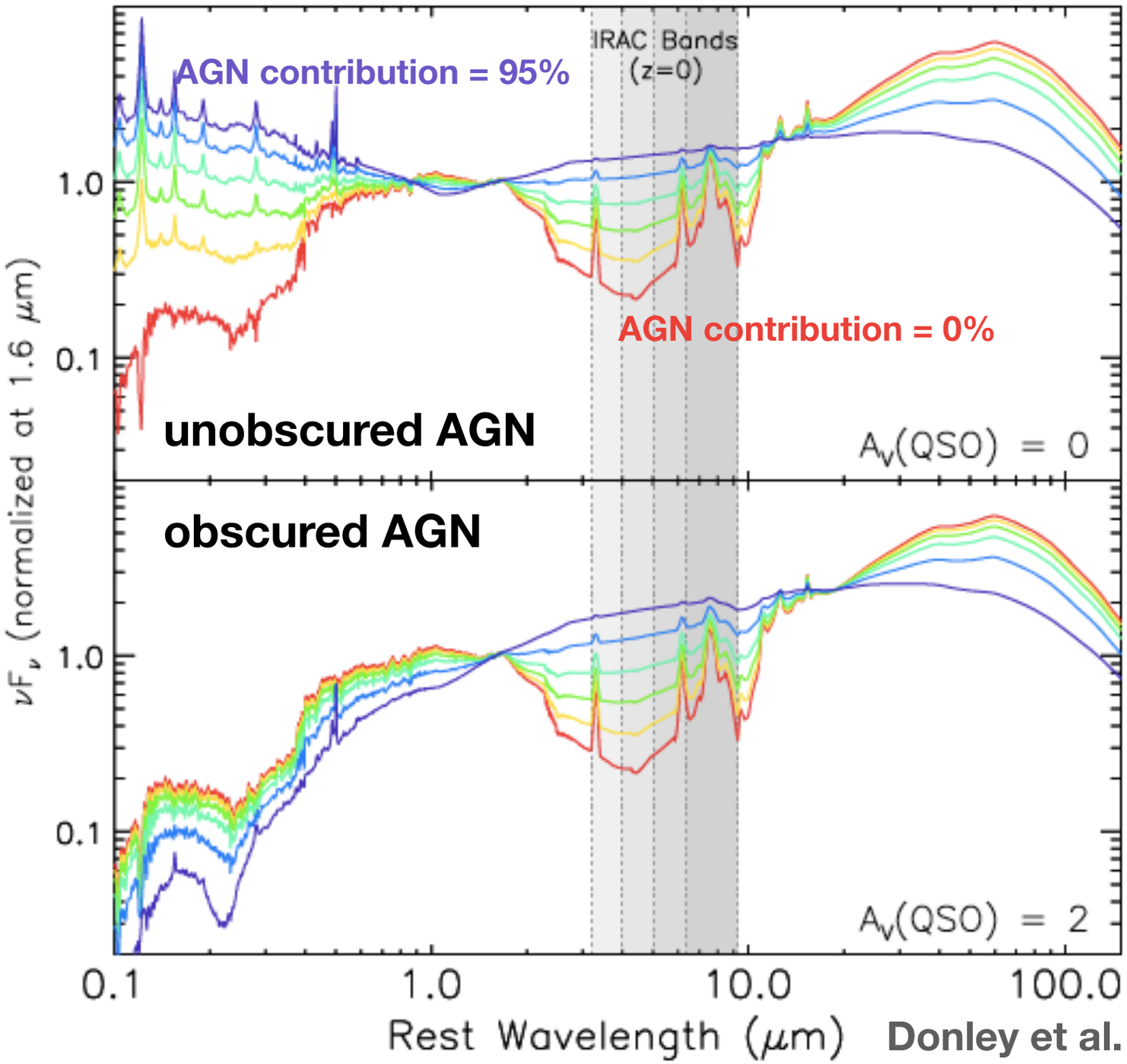
Brown et al. 2019

AGN fills in the dip between stellar emission and dust emission

AGN

2-color selection at NIR/mid-IR wavelengths has also been used for AGN selection

combination of SF + AGN SED with variable AGN contribution (from 0% to 95%) at 1-10 μm



Donley et al. 2012

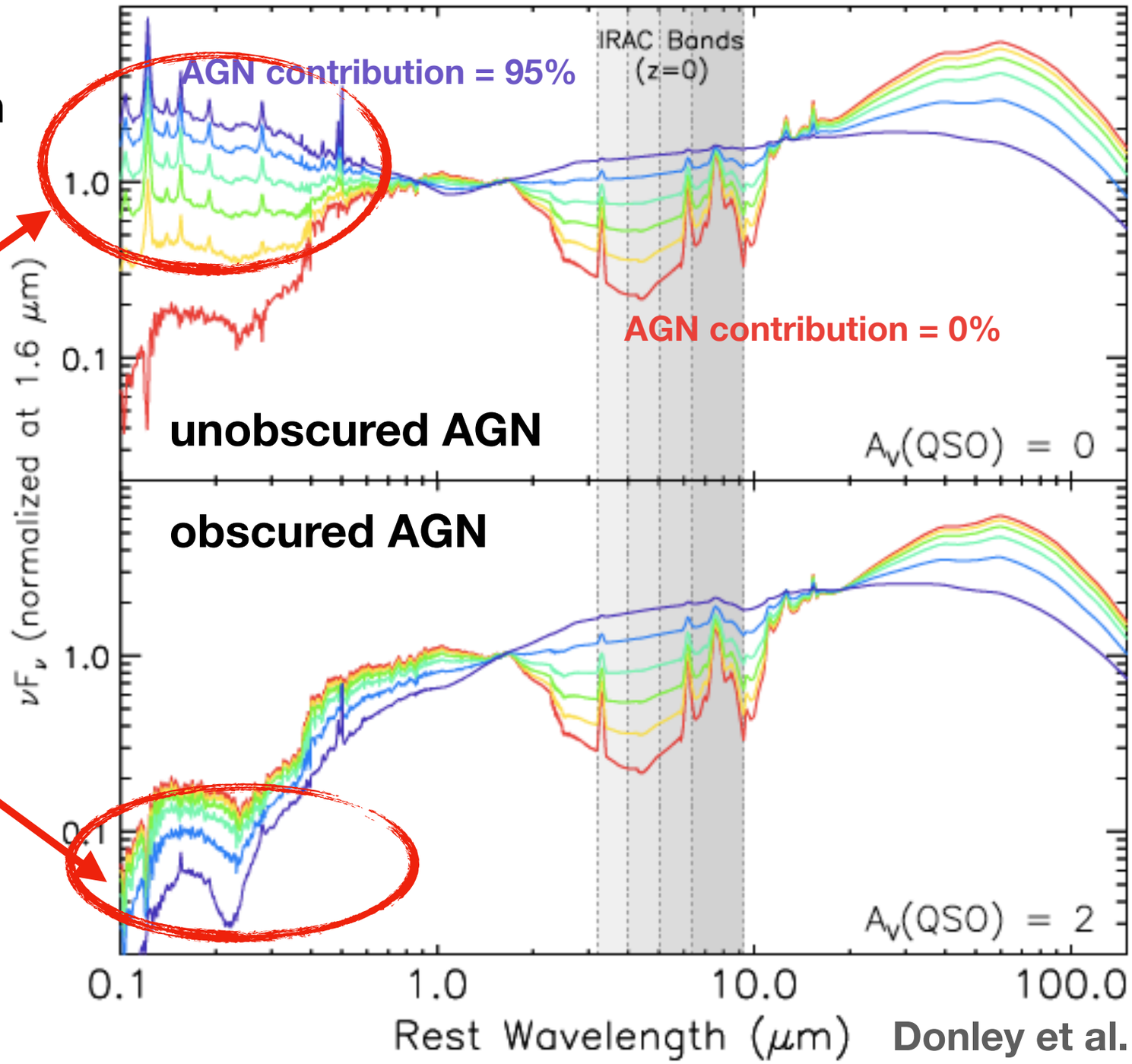
AGN fills in the dip between stellar emission and dust emission

AGN

2-color selection at NIR/mid-IR wavelengths has also been used for AGN selection

combination of SF + AGN SED with variable AGN contribution (from 0% to 95%) at 1-10 μm

luminous obscured and unobscured AGNs have very different SEDs here



Donley et al. 2012

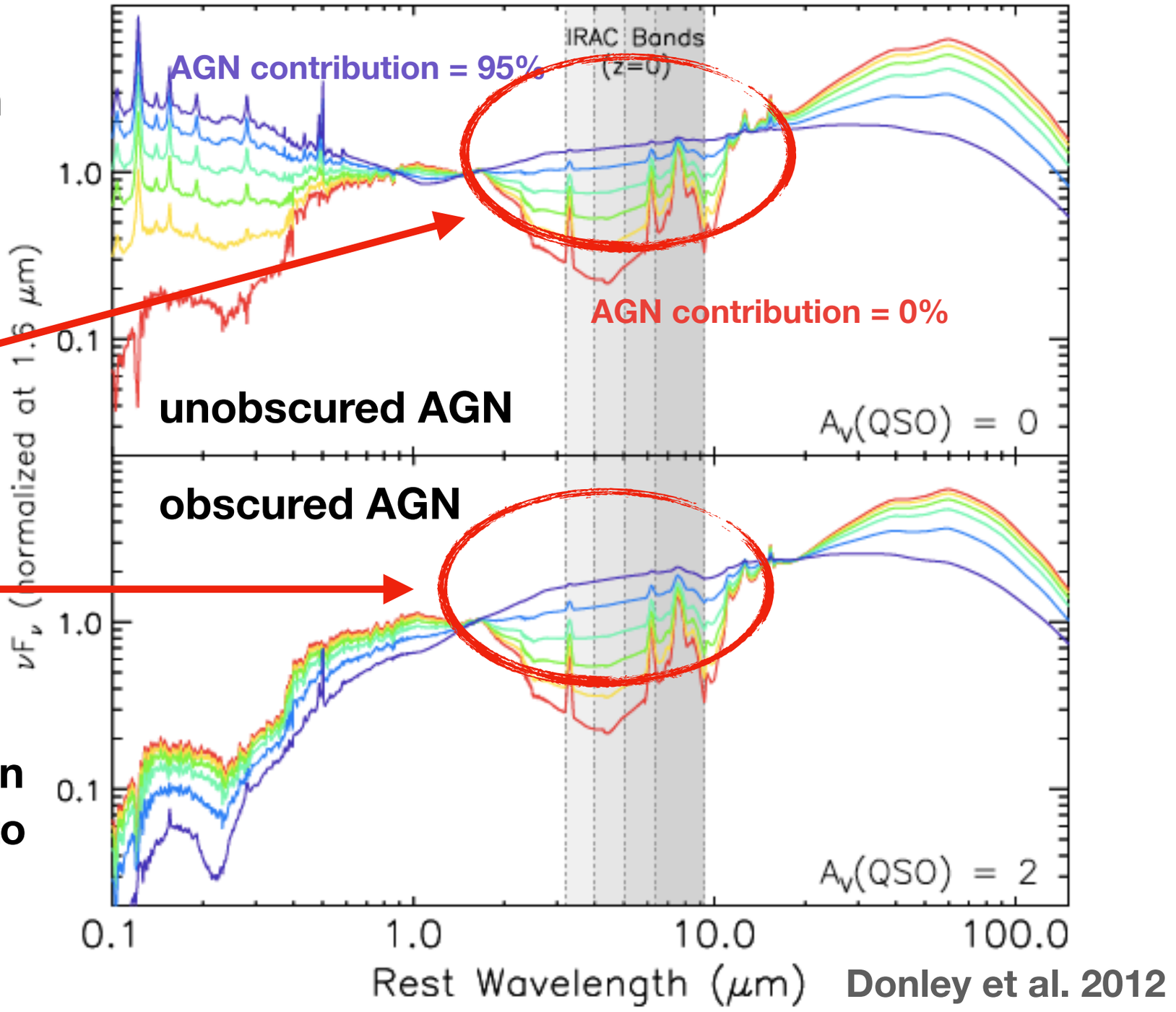
AGN

2-color selection at NIR/mid-IR wavelengths has also been used for AGN selection

combination of SF + AGN SED with variable AGN contribution (from 0% to 95%) at 1-10 μm

but similar power-law behaviour here

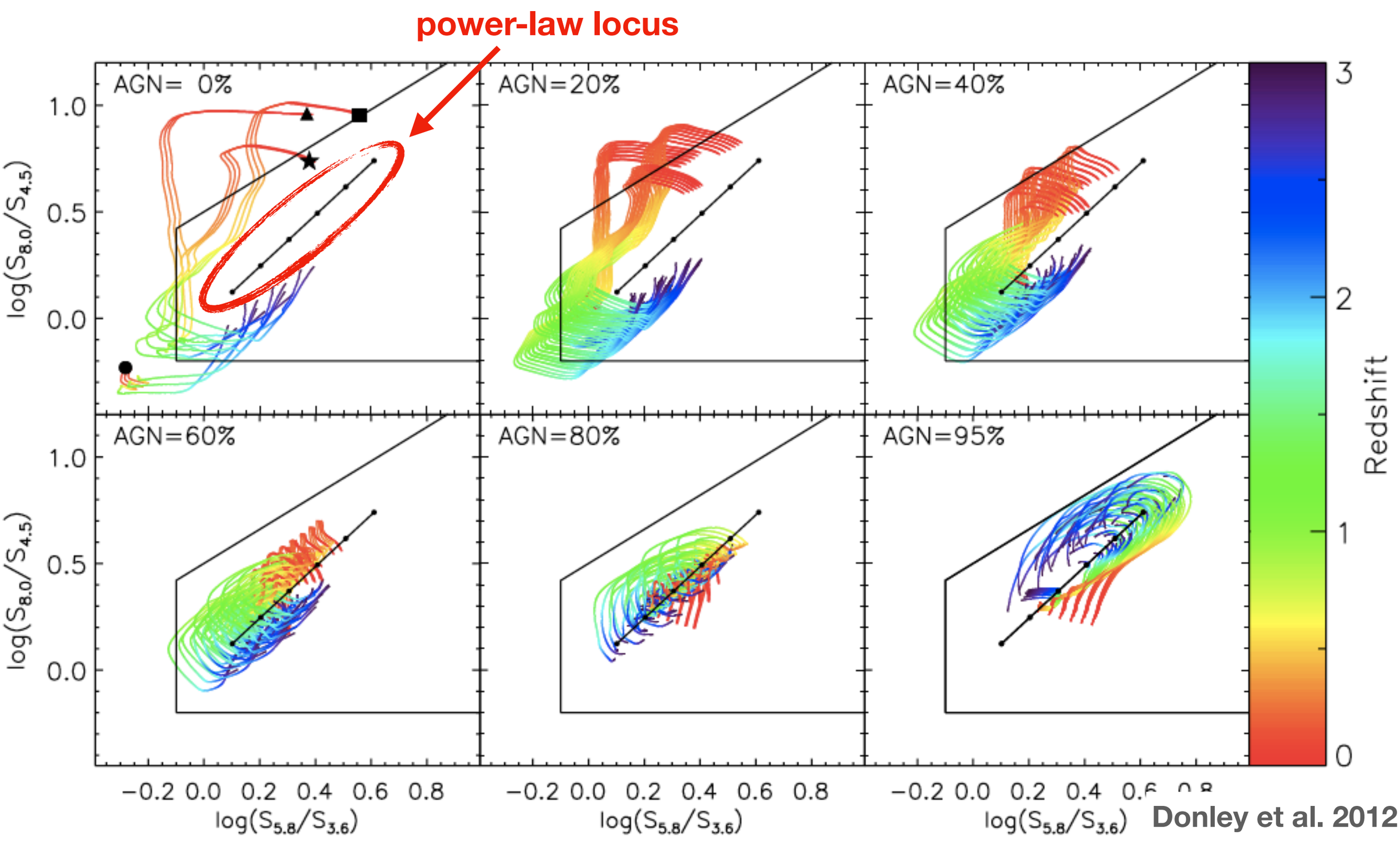
various color selection criteria in the 3-10 μm range exploit this to select mid-IR luminous AGNs



Donley et al. 2012

AGN

2-color selection at NIR/mid-IR wavelengths has also been used for AGN selection



Donley et al. 2012

AGN

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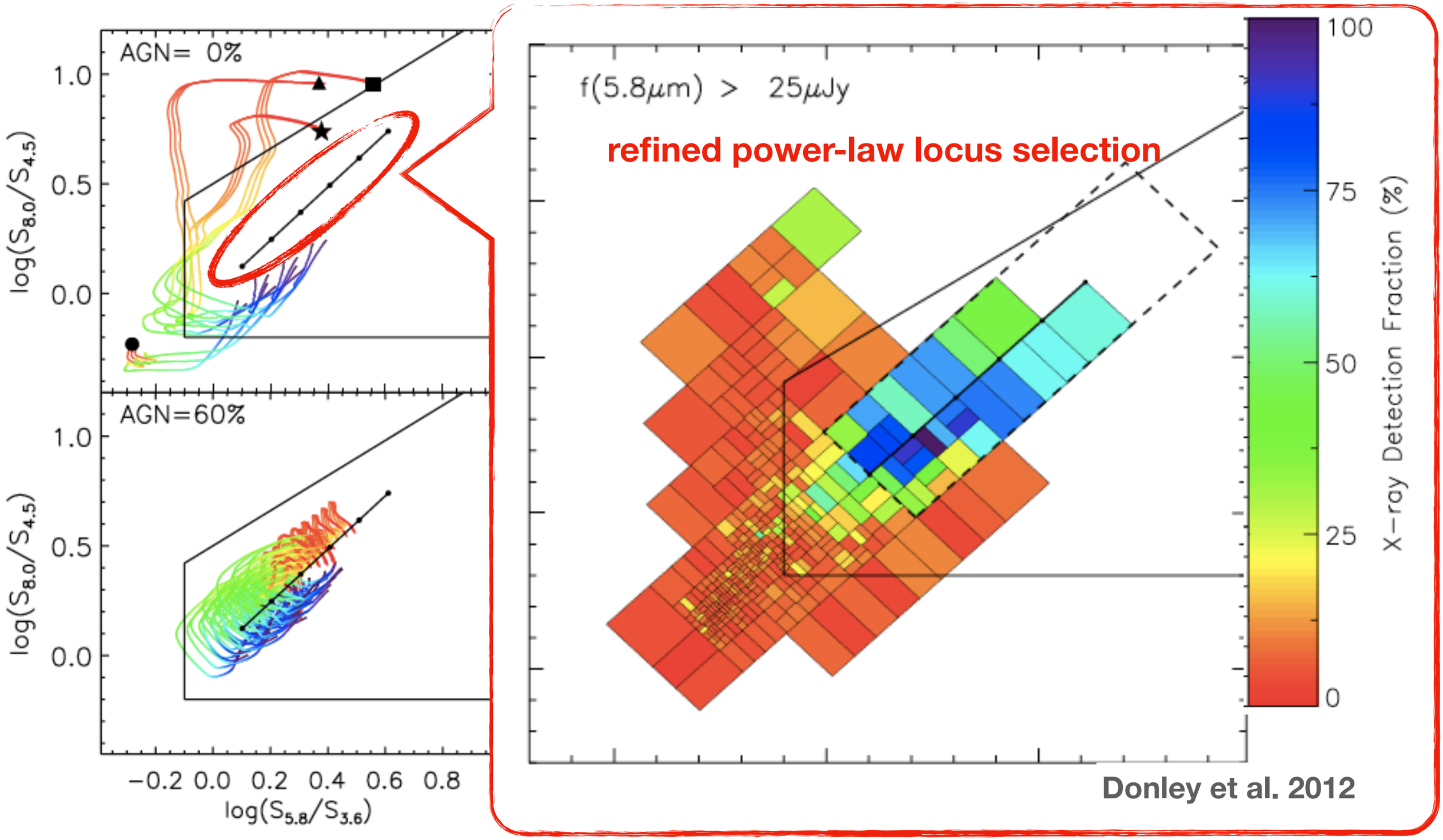
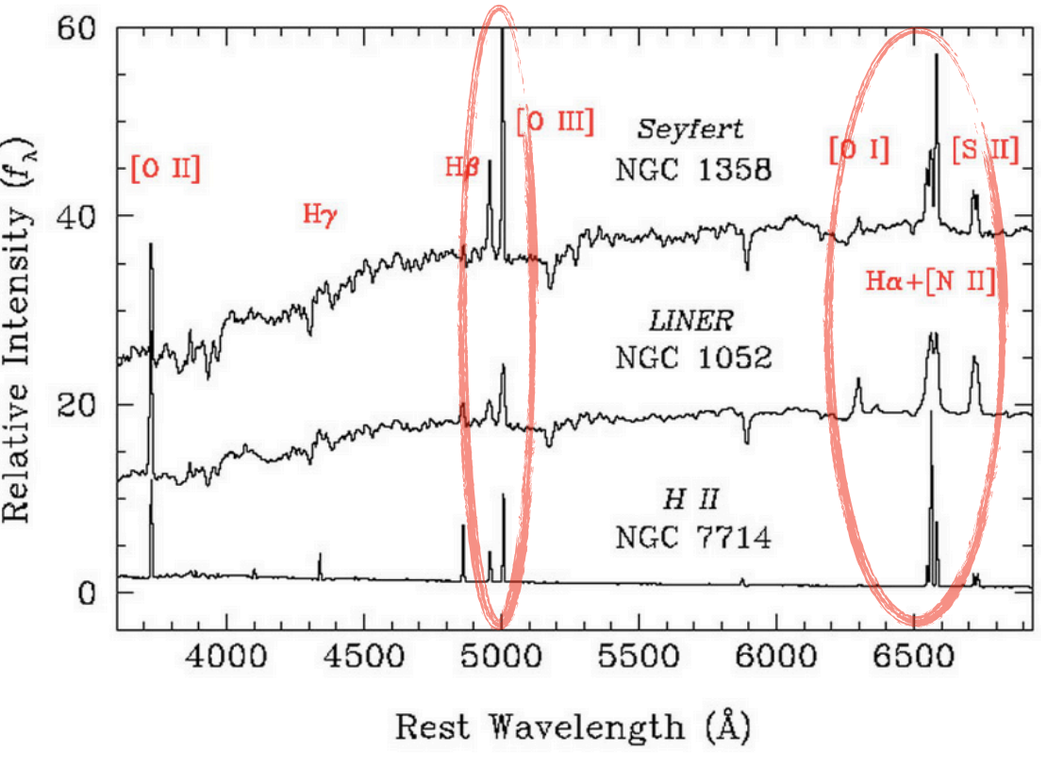


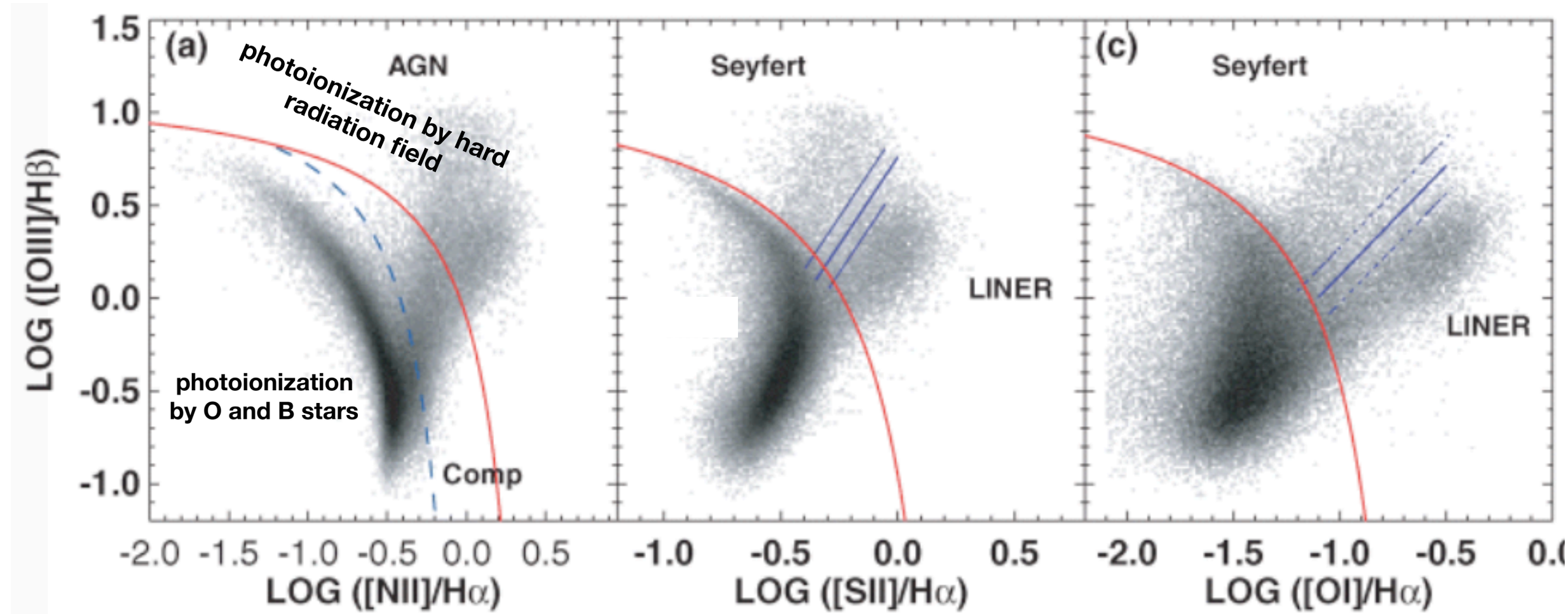
Donley et al. 2012

AGN



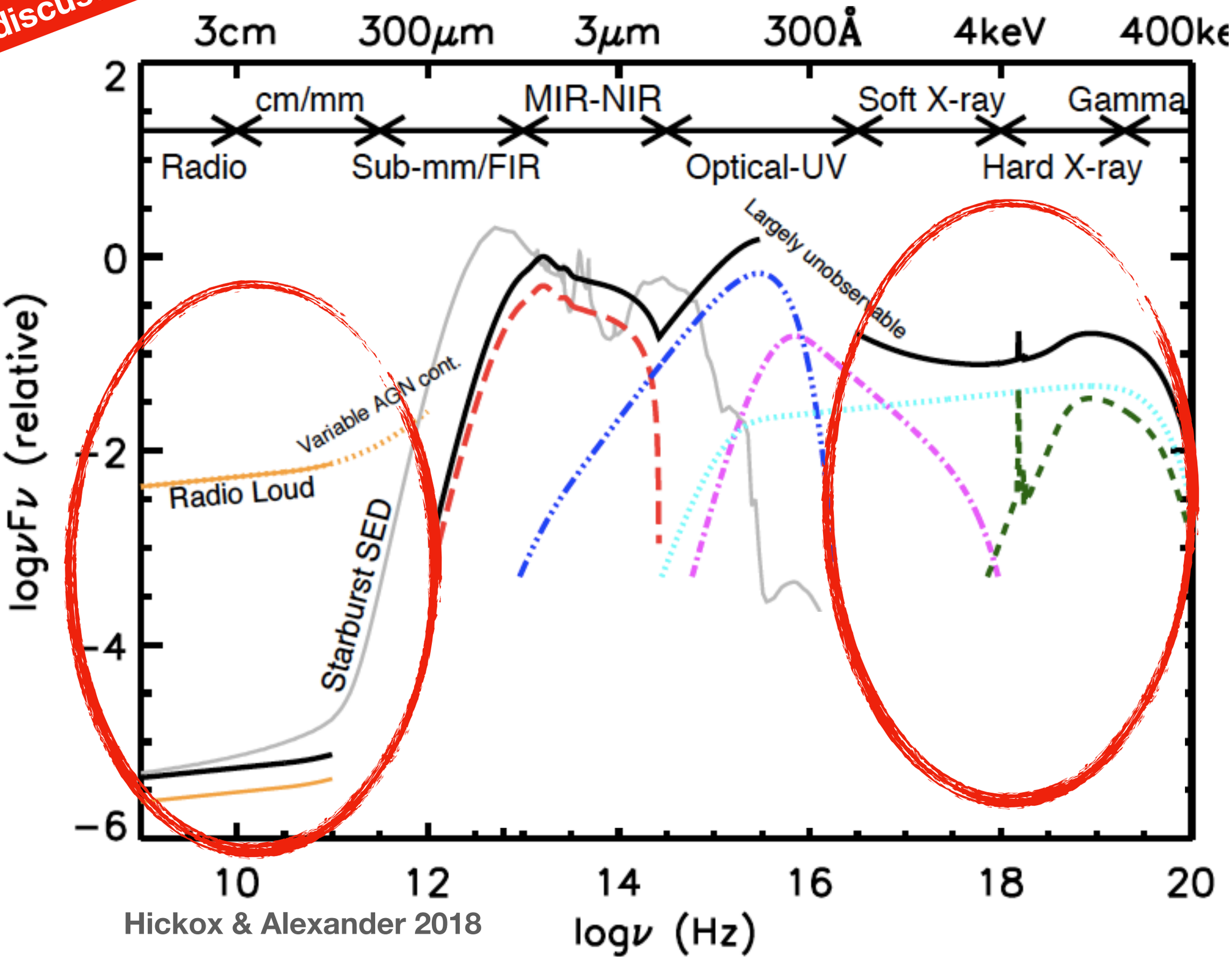
AGN identification by line intensity ratios:
BPT (Baldwin, Philips & Terlevich, 1981) diagram(s)

specific line combinations sensitive to ionization level of the gas, hardness (~mean photon energy) of radiation field, …



X-ray and mm-radio wavelengths critical for probing SF, AGN and gas!

not discussed here BUT



Hickox & Alexander 2018