Dust attenuation toward HII regions in distant star-forming galaxies

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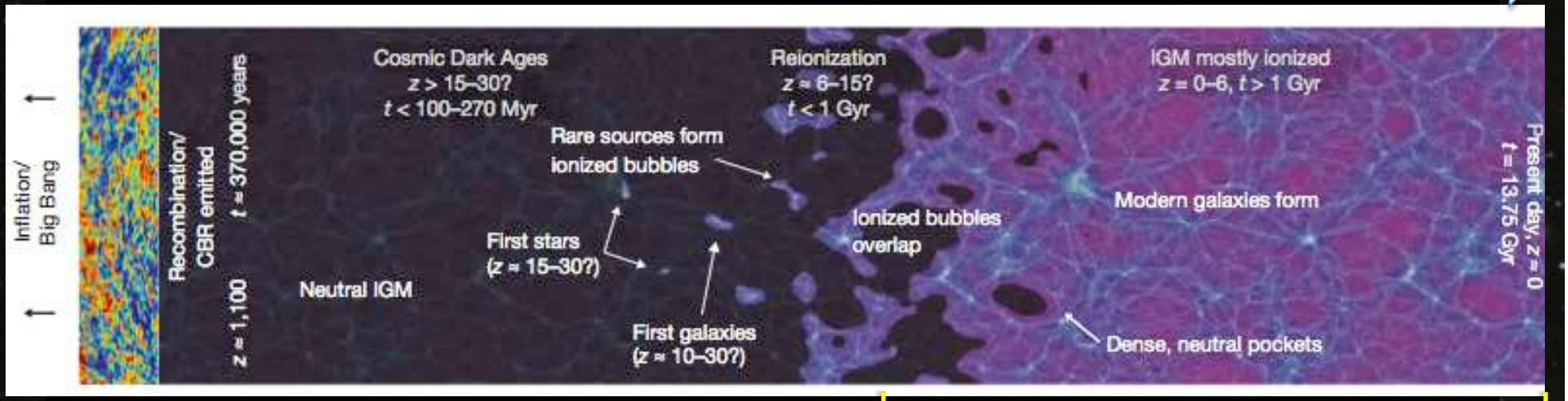
1. General context
2. Method and data
3. Results
4. Conclusions

General context

Galaxy formation and cosmic reionization



Robertson et al. 2010

Galaxy evolution and mass assembly

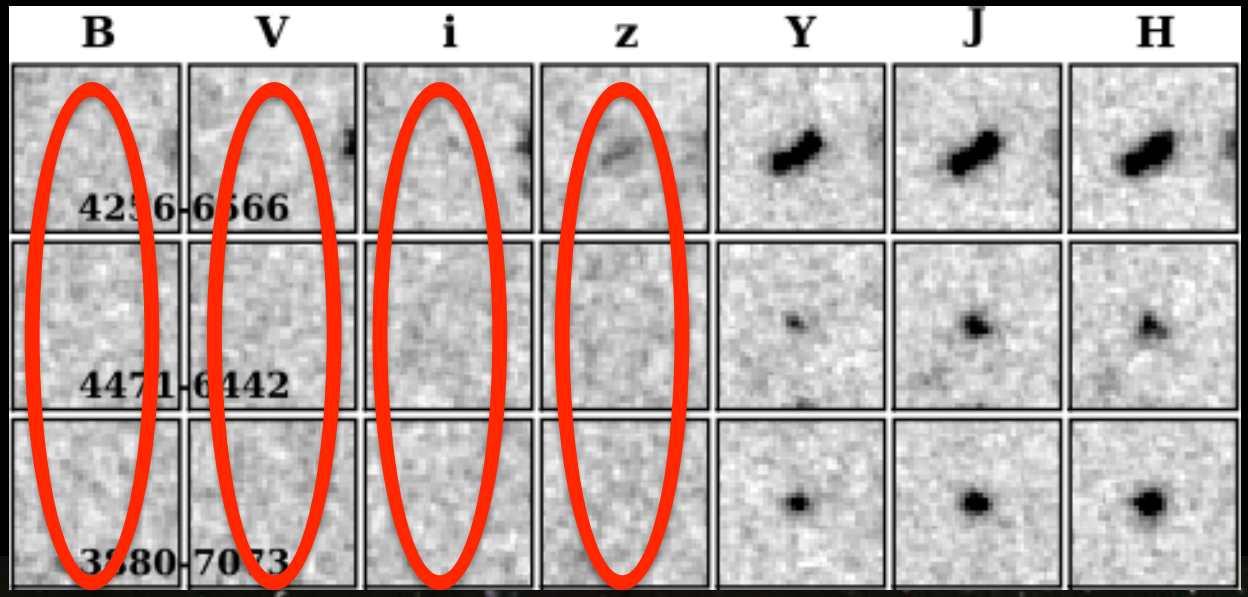
- Need accurate parameter estimation

General context

Λ-CDM model: z~2 = Universe ~3.2 Gyr

In theory, we could reconstruct a « movie » of the galaxy evolution...

Easier to detect star-forming galaxies ➔ Brighter!
How to detect them? The Lyman Break technique.



Oesch et al. 2010

General context

Once detected, we have to derive their physical properties:

Stellar mass, Star Formation Rate (SFR), age, dust extinction, metallicity, etc…

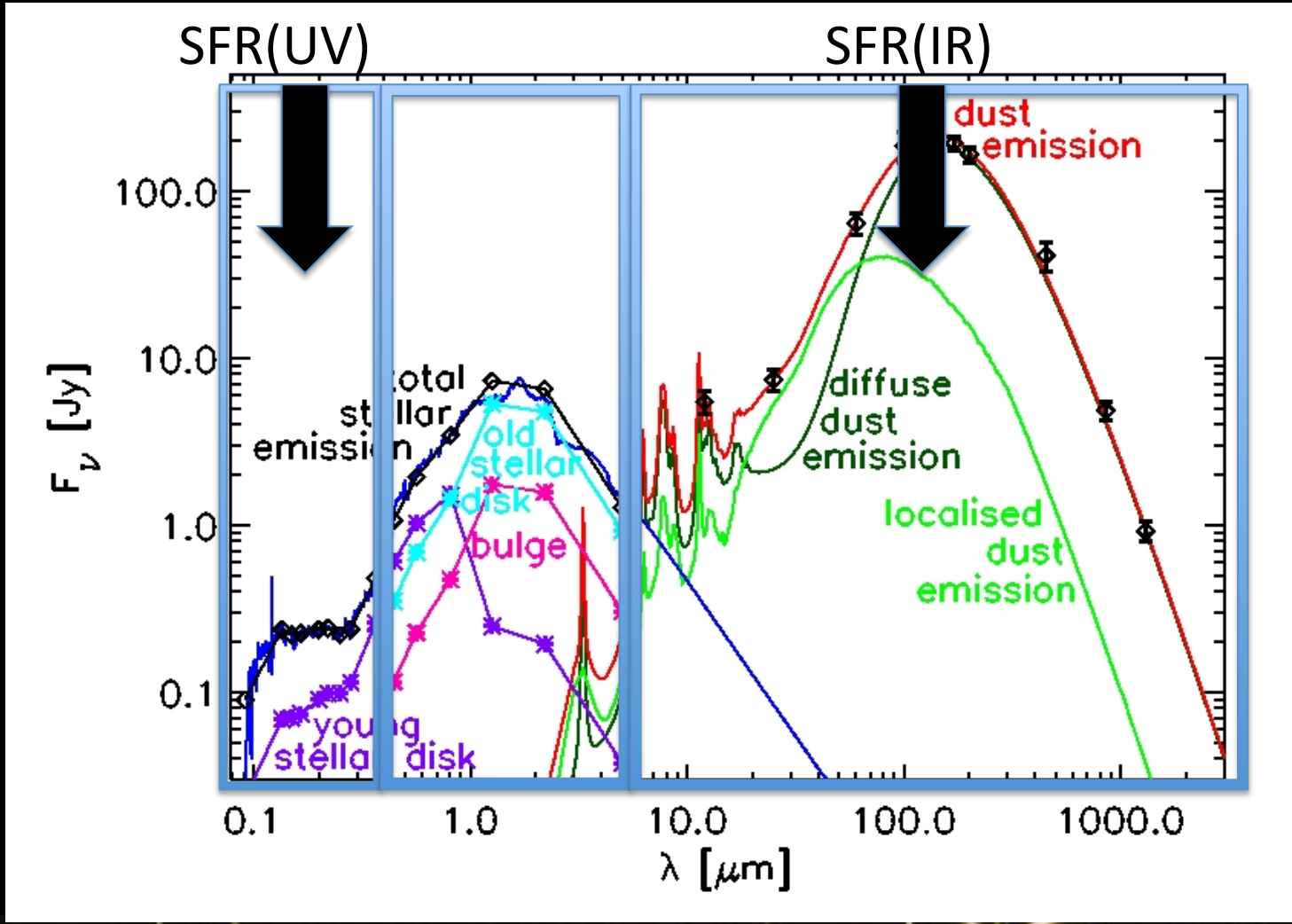
- Emission line diagnostic: Hα/Hβ (dust extinction), corrected Hα flux (SFR), ([OIII]λ5007+[OII]λ3727)/Hβ (metallicity)

Unfortunately, main optical emission lines redshifted in the near-infrared: only recently possible to measure up to z~3.8 with new instruments (MOSFIRE, KMOS)

- At high-z: Spectral Energy Distribution (SED) fitting

General context

Principle: compare multiwavelength data with theoretical or empirical templates



Popescu et al. 2011

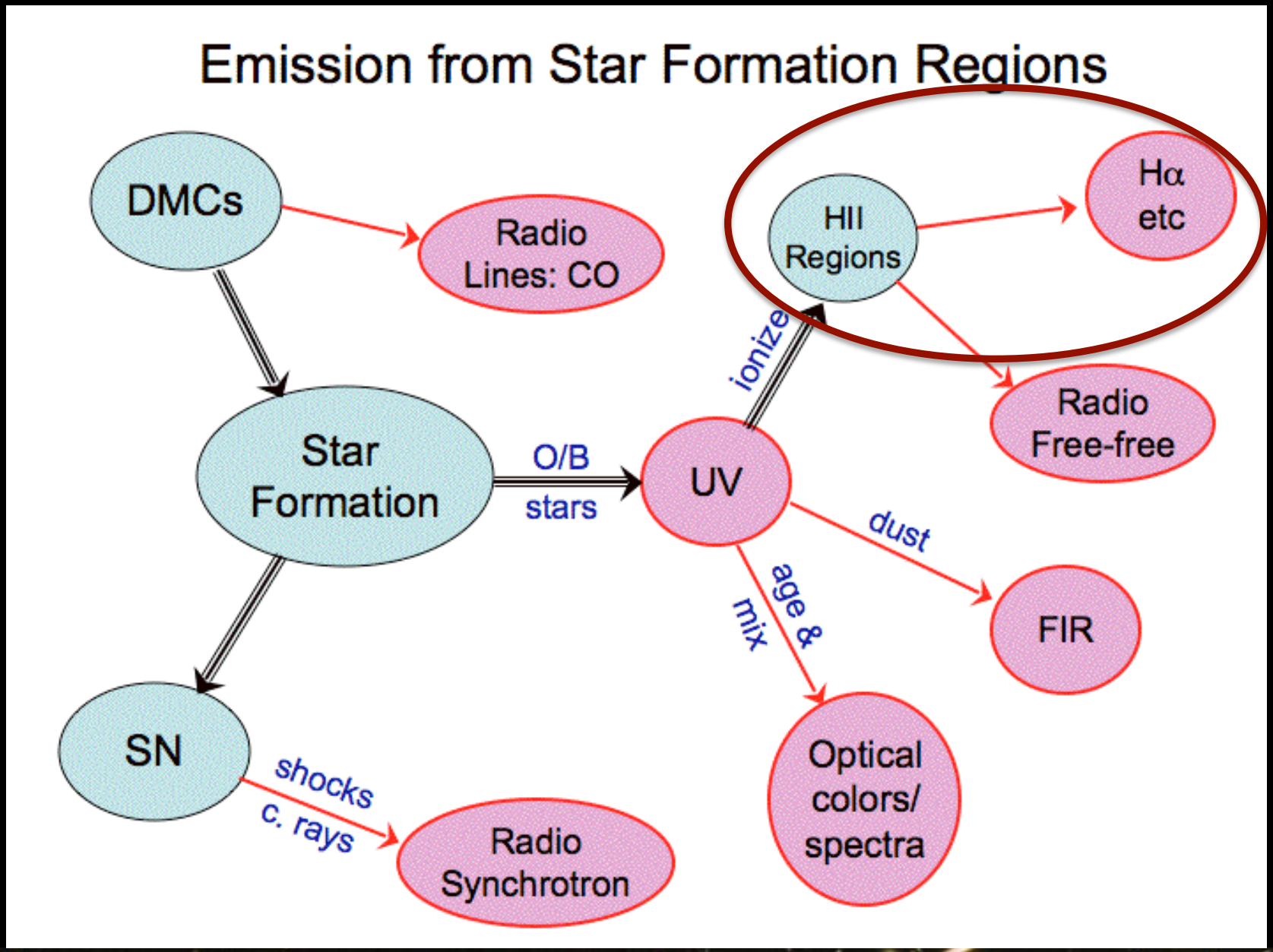
General context

In theory, we can recover most of the physical properties of distant galaxies, BUT we need to assume:

- Population synthesis and spectral evolution models
- Initial Mass Function (IMF)
- Star Formation History (SFH)
- Extinction curve
- Lyman forest

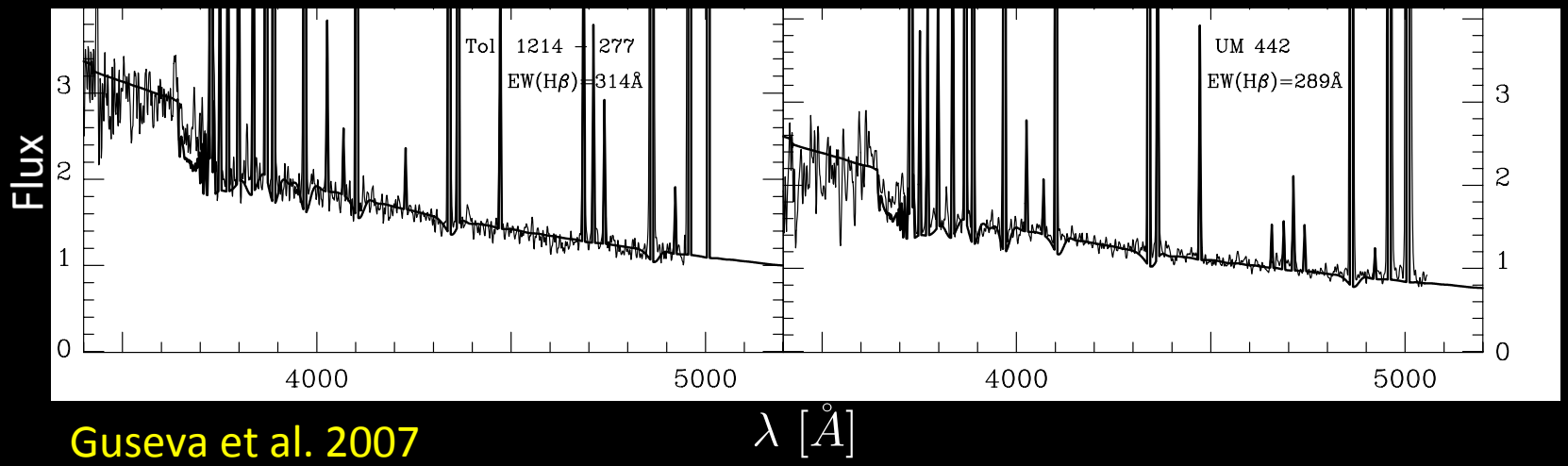
We try to recover the SFH, but we need to assume one to perform SED fitting.
Does IMF evolve with redshift (or stellar mass)?
No empirical evidence about the extinction curve at high-z (yet…)

General context

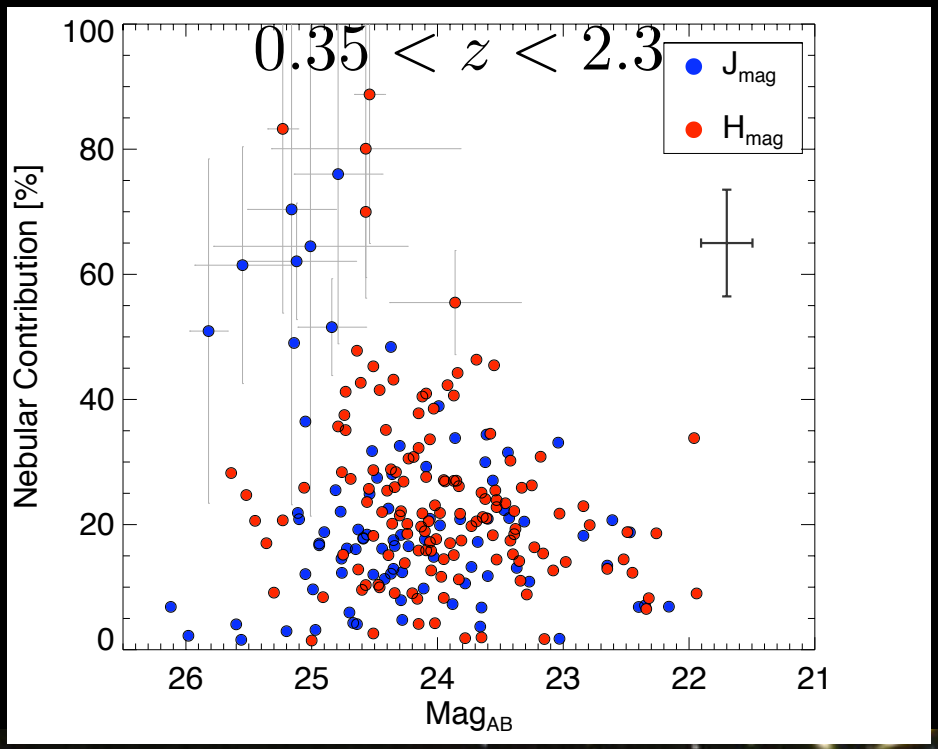


https://www.astro.virginia.edu/class/whittle/astr553/Topic11/Lecture_11.html

General context



Guseva et al. 2007

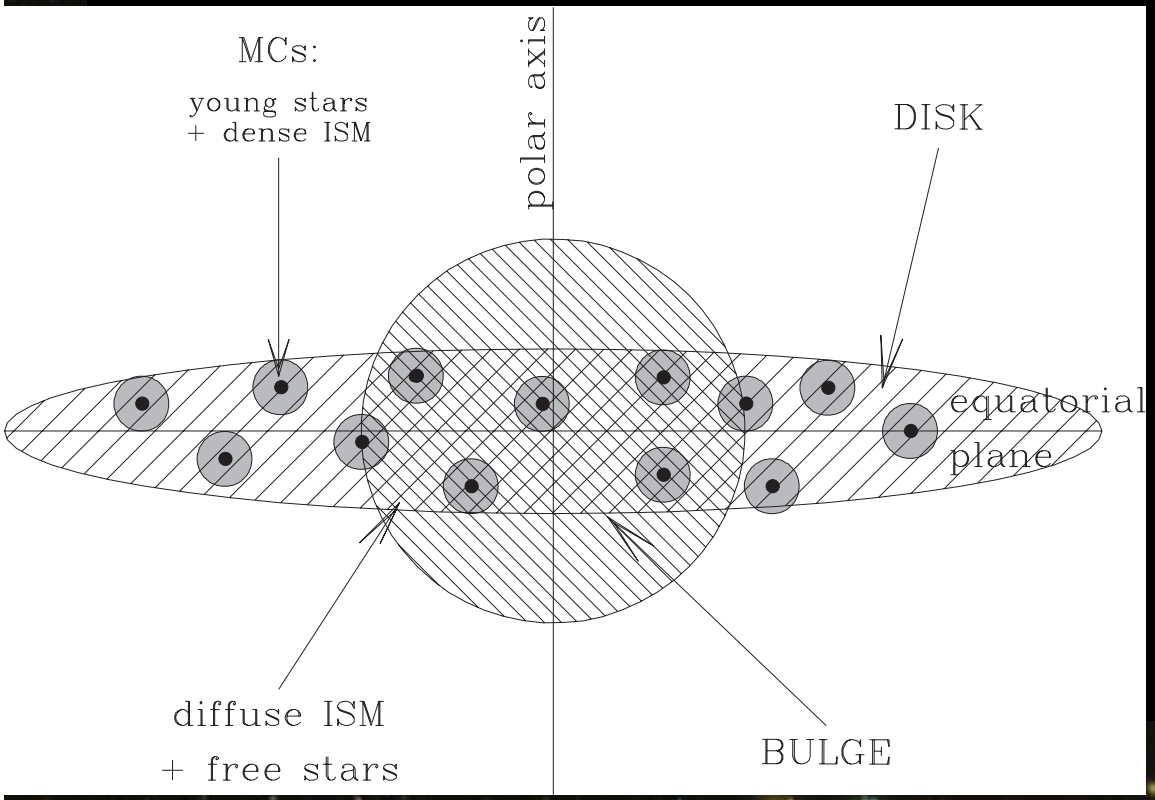


Atek et al. 2011

General context

Differential attenuation: Calzetti et al. 1994

➔Local star-forming galaxies: difference in optical depth between the Balmer emission Hα and Hβ is about a factor 2 larger than the difference in the optical depth between the continuum underlying the two Balmer lines.



$E(B-V)_{stel} = 0.44 \times E(B-V)_{neb}$

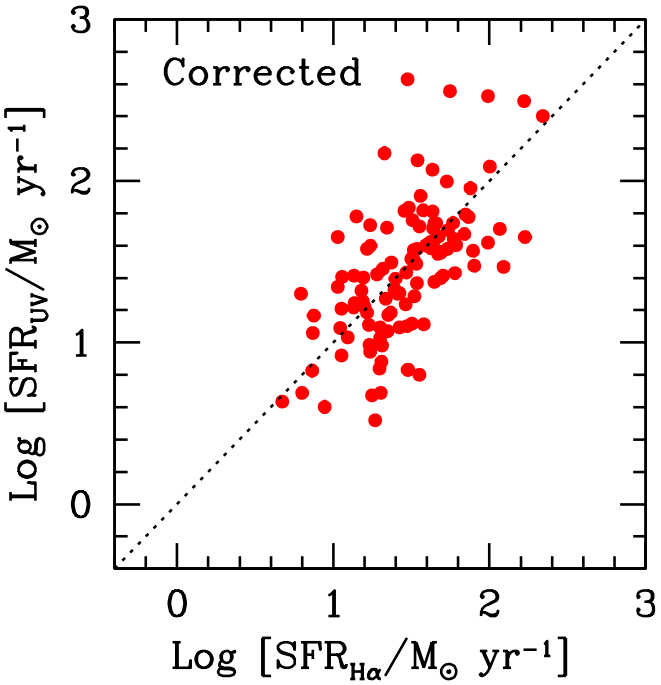
Calzetti et al. 2000

Walcher et al. 2010

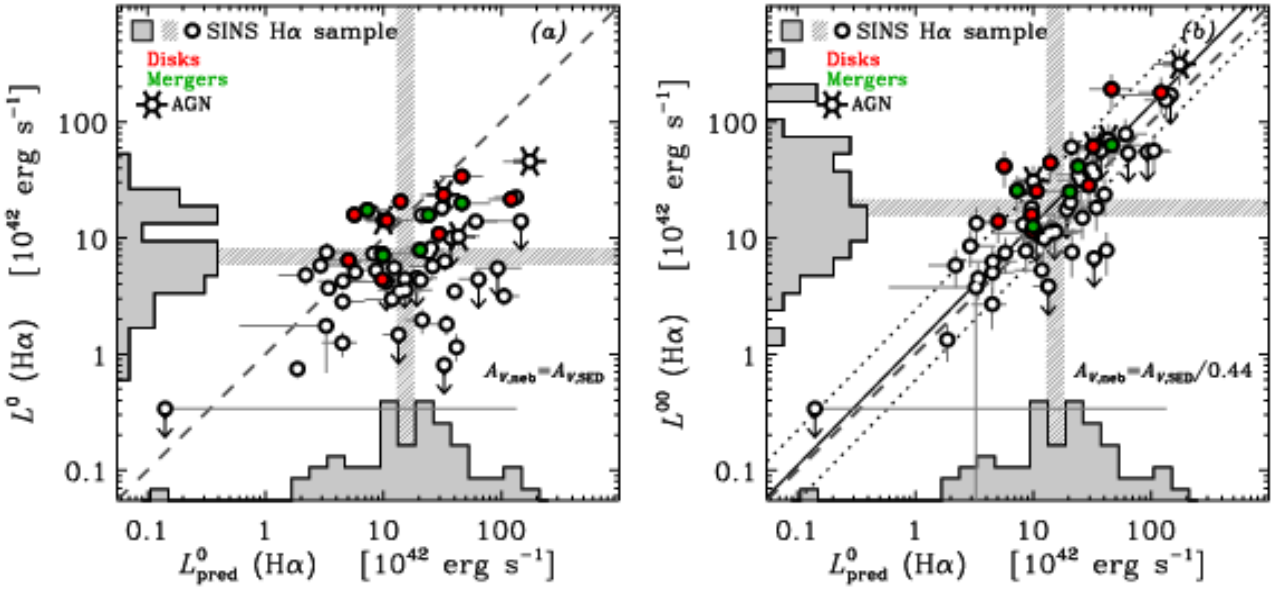
General context

Differential attenuation: what's happening at high-redshift?

Balmer lines redshifted in the near-infrared at z~2: no direct measurement (until recenty: MOSFIRE, KMOS)



Erb et al. 2006

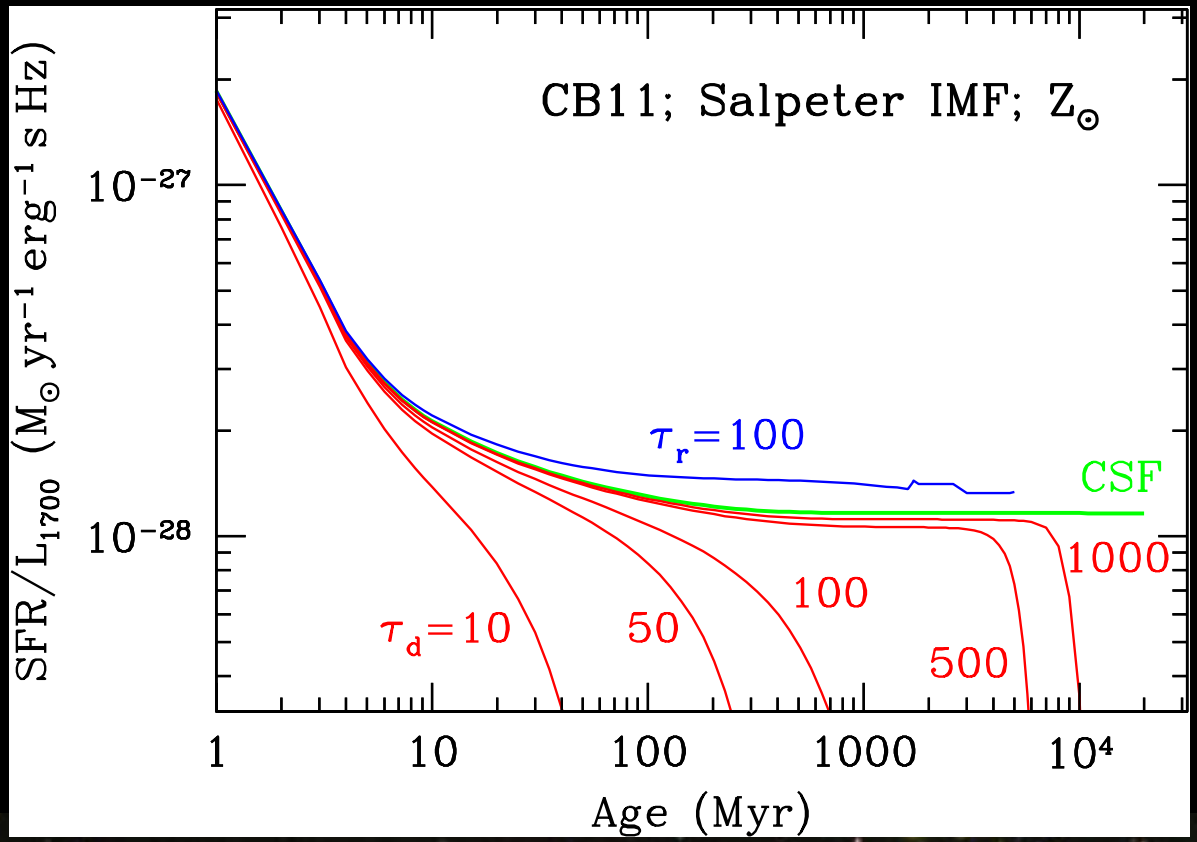


Förster Schreiber et al. 2009

General context

Differential attenuation: what's happening at high-redshift?

Inconsistency between SFR(UV) and SFR(Hα) possible with episodic star formation episode: no need for extra attenua-tion

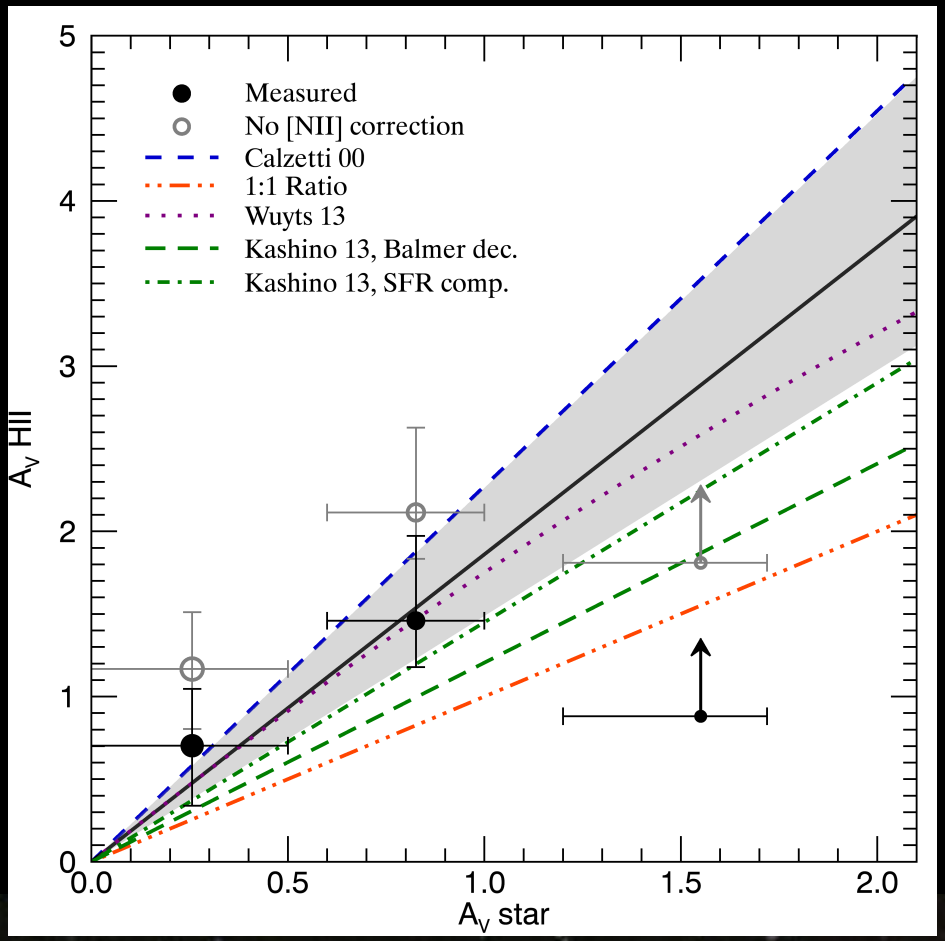


Reddy et al. 2012

General context

Differential attenuation: what's happening at high-redshift?

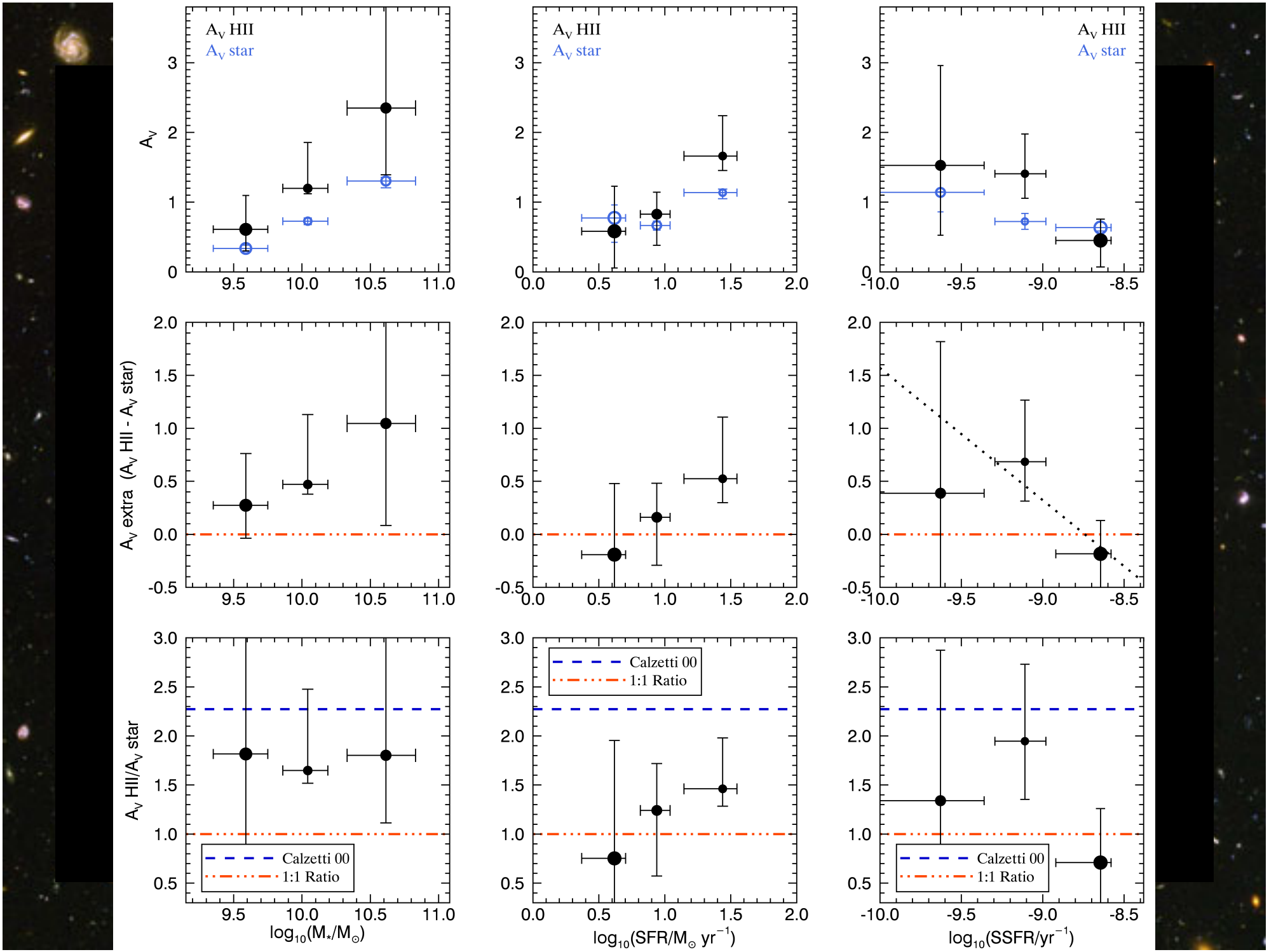
Recent results from HST/WFC3 grism survey at z~1.5: Price et al. 2014



Stacking in different bins:

A_V
Stellar mass
Star formation rate
Specific SFR (SFR/stellar mass)

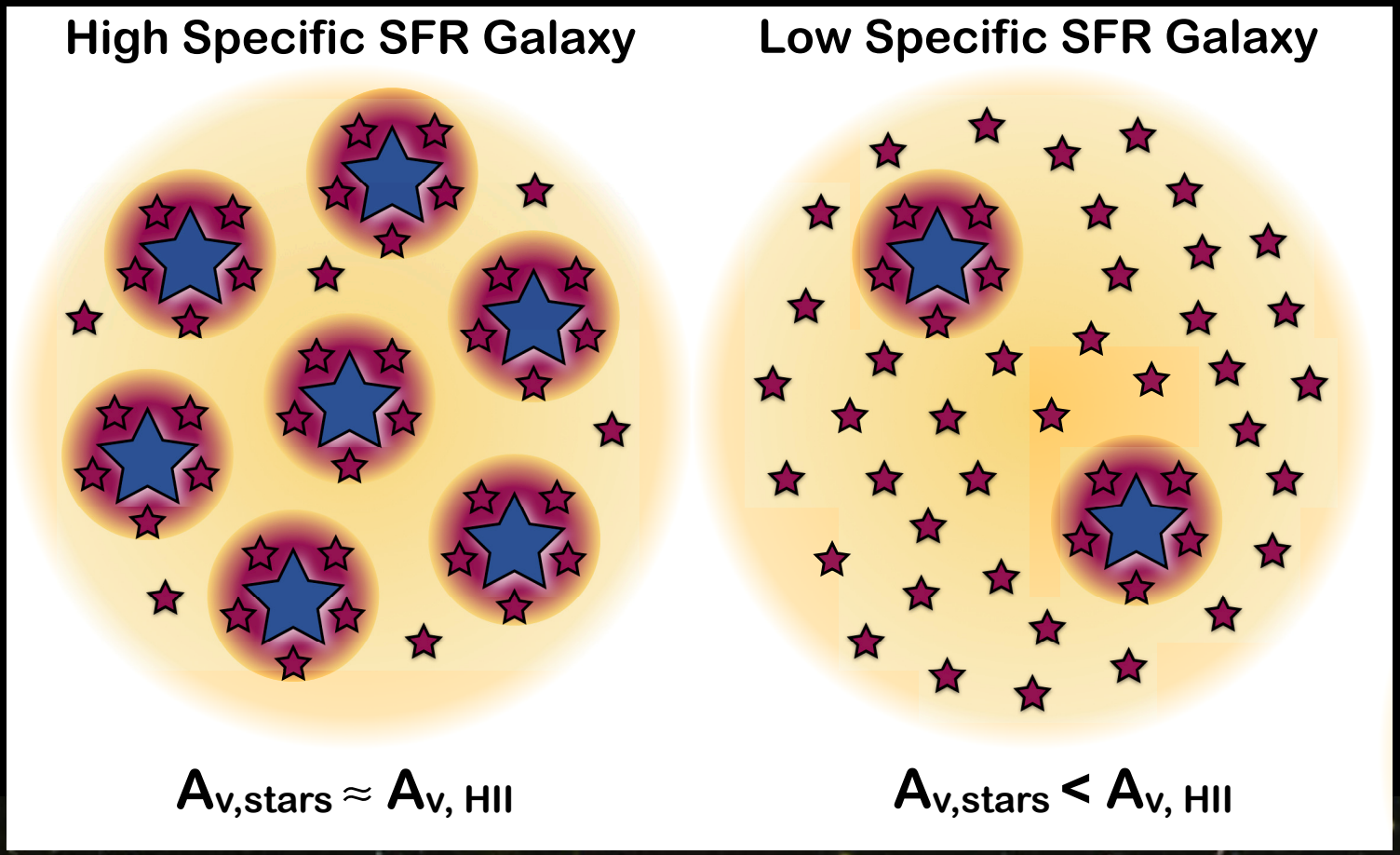
$E(B\text{-}V)_{stel} = 0.54 \times E(B\text{-}V)_{neb}$


A_V HII
A_V star
A_V
A_V extra (A_V HII - A_V star)
A_V HII/A_V star
Calzetti 00
1:1 Ratio
log10(M*/M⊙)
log10(SFR/M⊙ yr^-1)
log10(SSFR/yr^-1)

General context

Differential attenuation: what's happening at high-redshift?

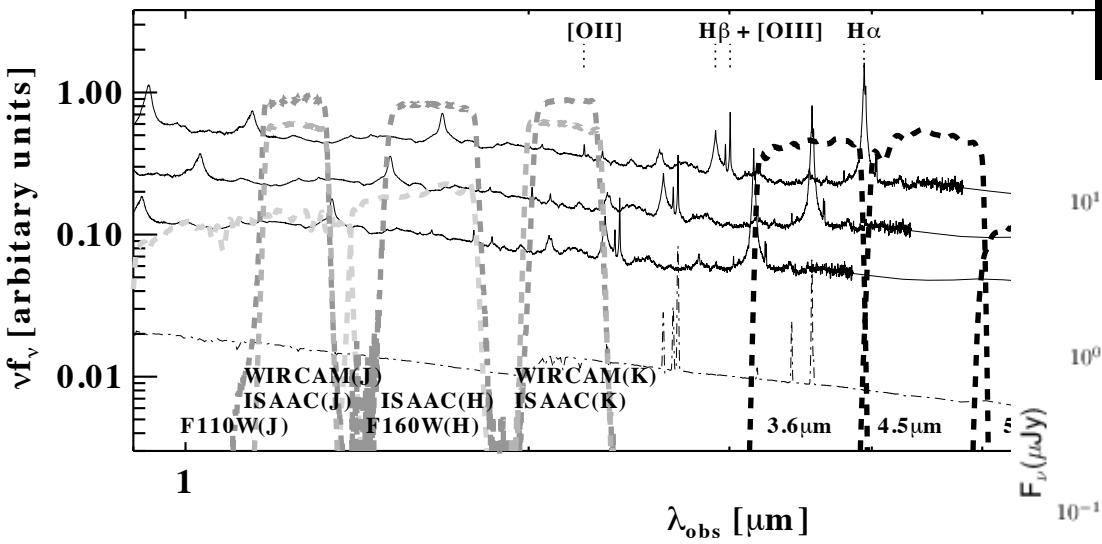
Recent results from HST/WFC3 grism survey at z~1.5: Price et al. 2014



General context

Differential attenuation: what's happening at high-redshift?

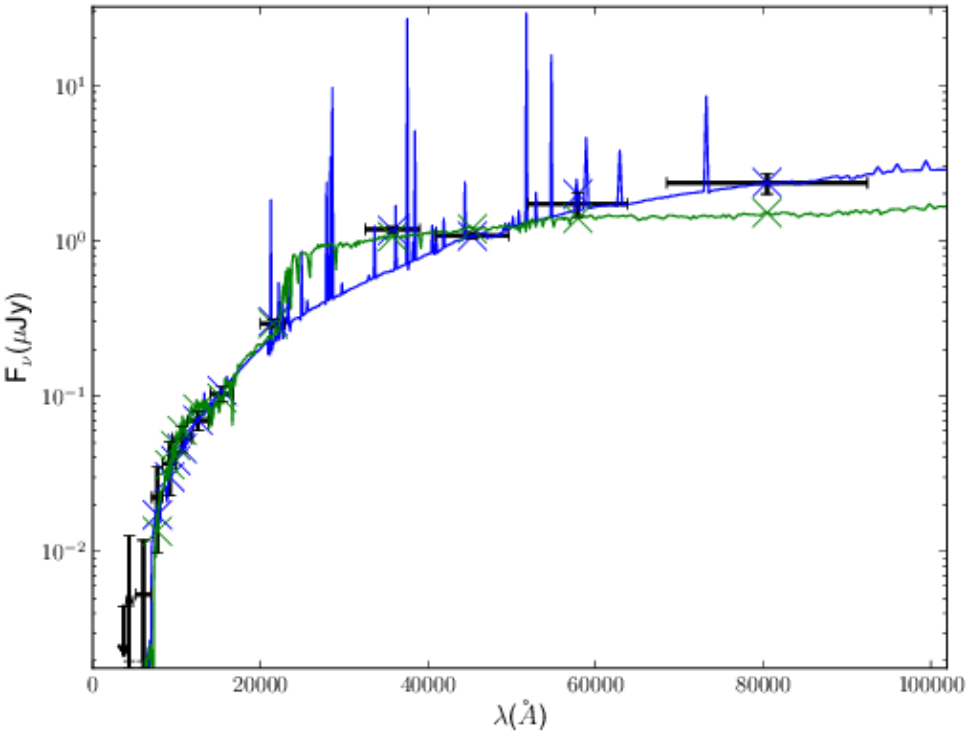
Implication at high-z: strong emission lines affect Spitzer/IRAC band at z>3.7



Shim et al. 2011

Generally, studies at z>3.7 assume:

$E(B\text{-}V)_{stel} = E(B\text{-}V)_{neb}$



Nayyeri et al. 2014

Method and data

Fit Spectral Energy Distributions accordingly with all available observables:

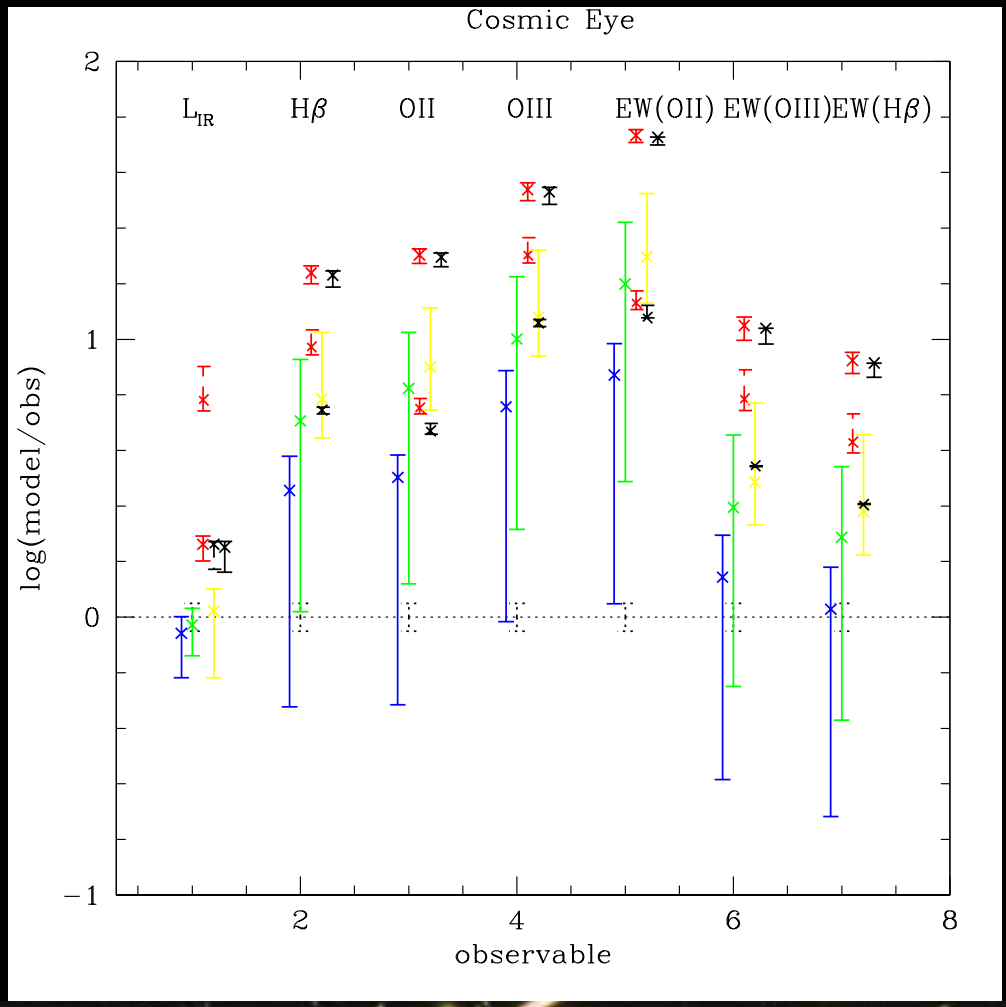
➔Broad band photometry

➔Infrared luminosity

➔Emission line fluxes

Can break degeneracies and provide constrains on SFH, attenuation law, etc…

E.g. Cosmic Eye



Sklias et al. 2014

Method and data

Inclusion of nebular emission in synthesis models and SED fits (*HyperZ*), Bolzonella et al. 2000:

- Compute Lyman continuum photon number
- Assume $f_{esc}(LyC)=0$
- Compute and add nebular continuum proportional to this number
- Compute and add Hβ flux for typical ISM (Krueger et al. 1995) + add other lines according to empirical ratios (Anders & Fritze-v. Alvensleben 2003, Osterbrock & Ferland 1996)

See Schaerer & de Barros 2009, 2010

- ***Apply same attenuation to both stellar and nebular emission***

Other synthesis models: Le Phare, CIGALE, PEGASE, ZEBRA, …

Method and data

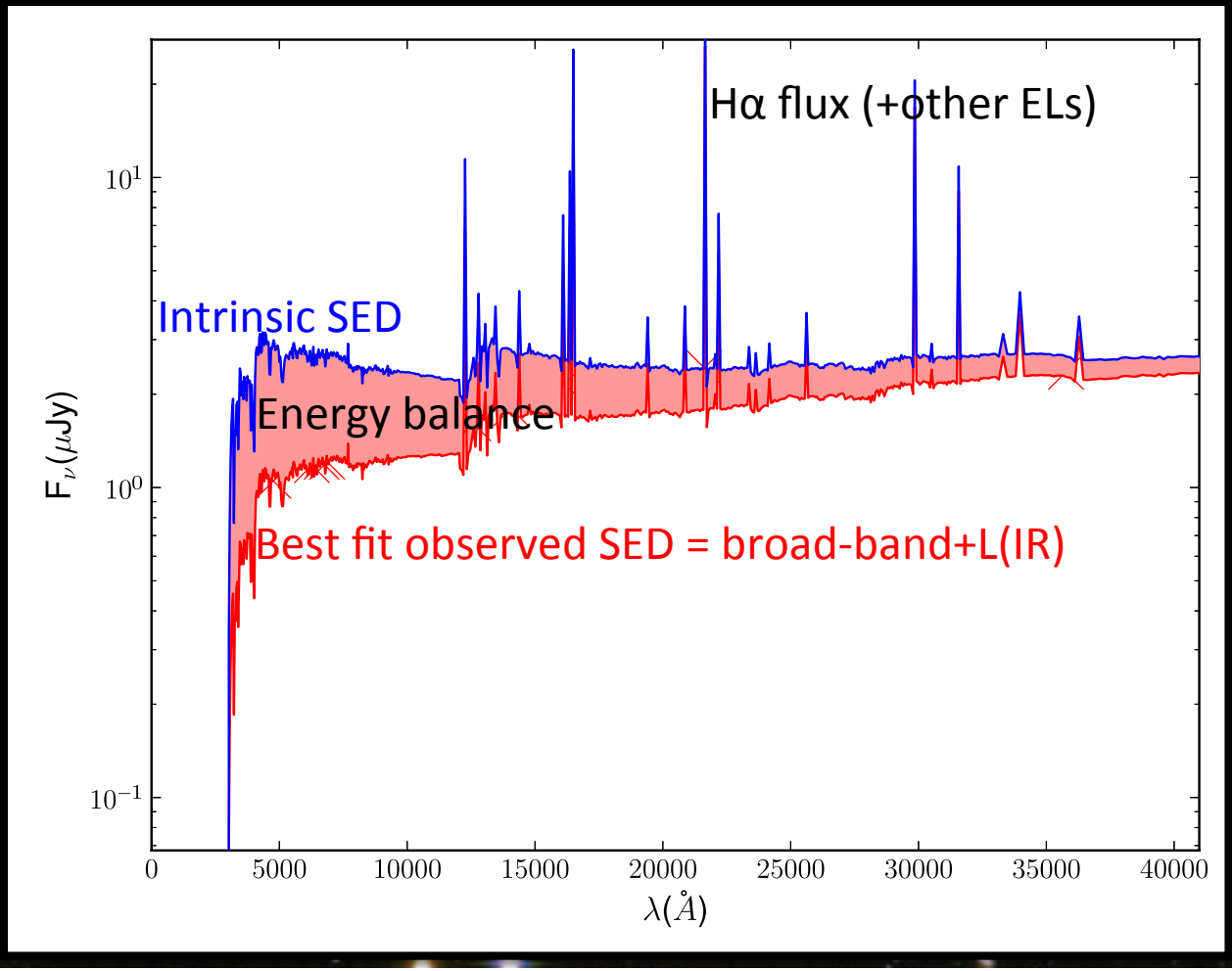
Sample: 2389 star-forming galaxies (BM, BX, LBG criteria: Steidel et al. 2003; Adelberger et al. 2004; Steidel et al. 2004) spectroscopically confirmed (Lyα or ISM).
Photometry from U to 8.0μm band.

Emission line sample: 149 galaxies with Hα (and/or [NII]λ 6583, [OIII]λ5007, Erb et al. 2006, Kulas et al. 2012, Kulas et al. 2013)
EL+MIPS 24μm sample: 41 galaxies (21 individual detections and 20 non-detections, Shivaei et al. 2014)

Defining three samples: MIPS sample, MIPS detected sample, entire sample

Method and data

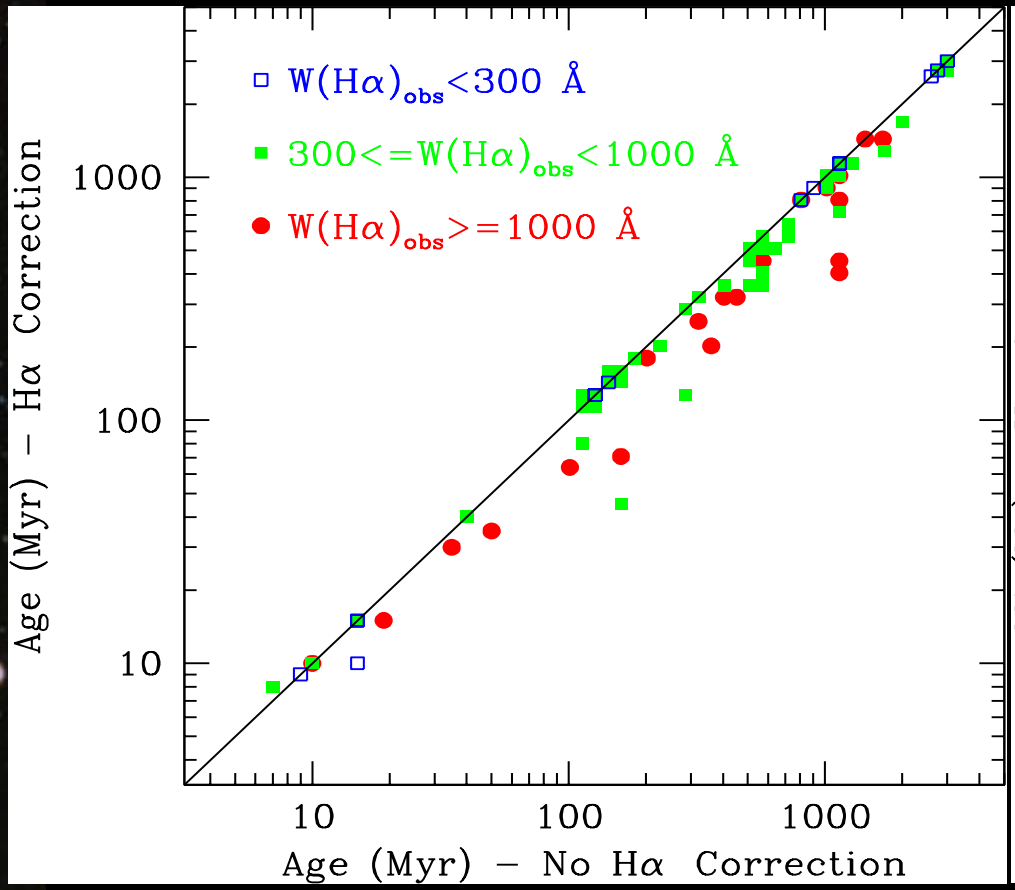
Reproducing EL fluxes for the EL+MIPS sample
From MIPS 24m fluxes➔L(IR)
Chary & Elbaz 2001 calibration

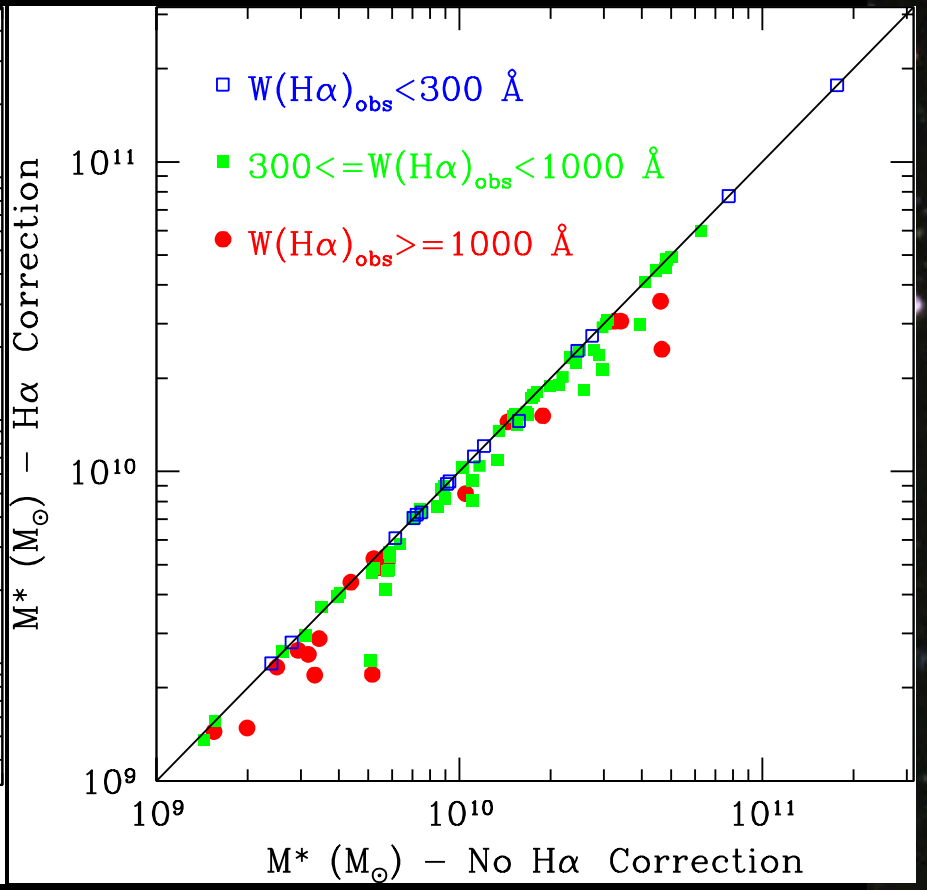


Method and data

➢Apply same attenuation to both stellar and nebular emission

Why? Small EL impact on physical parameter estimation @z~2





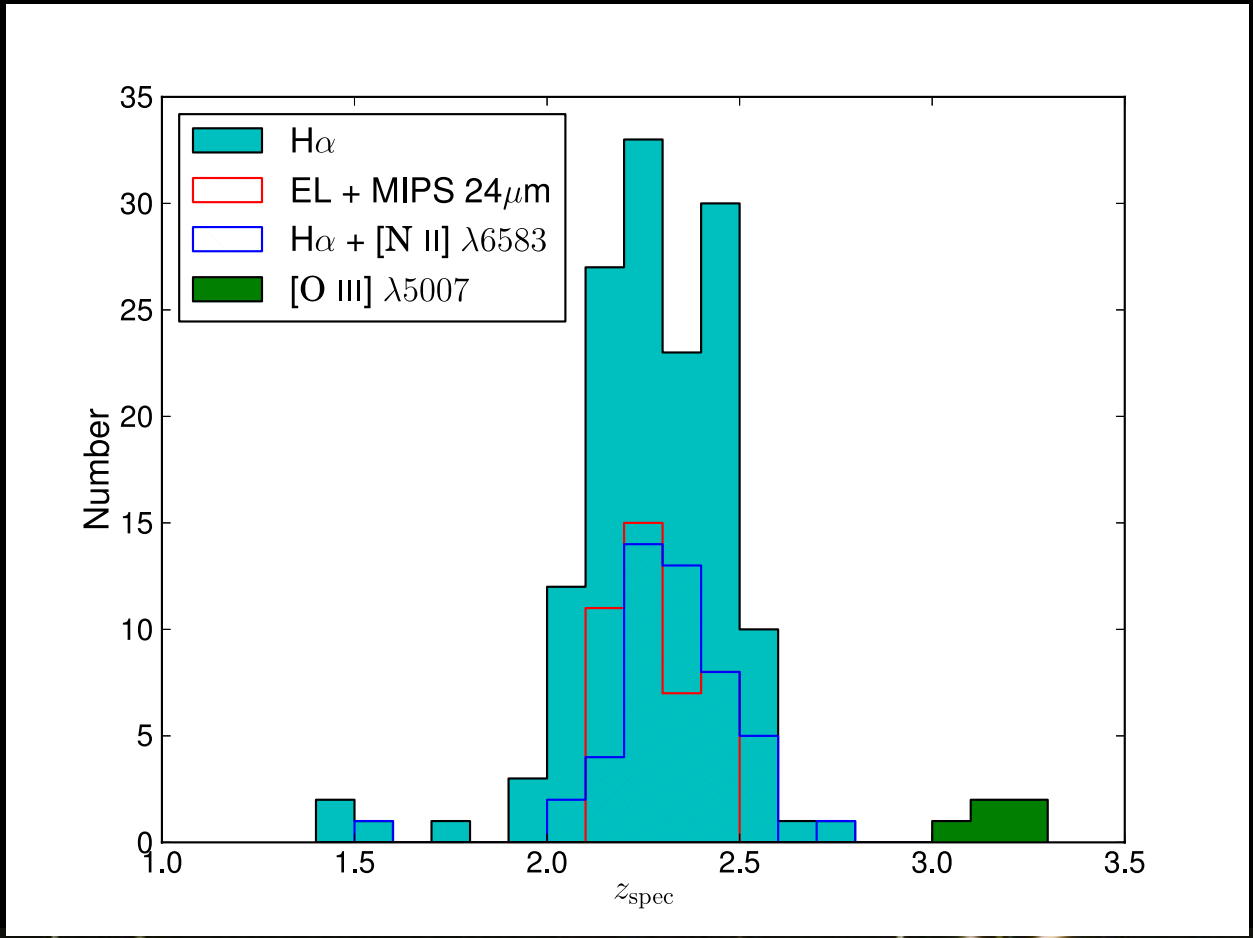
Reddy et al. 2010

Method and data

Lyα measurements: 122/149 galaxies

44/122: Lyα emitters

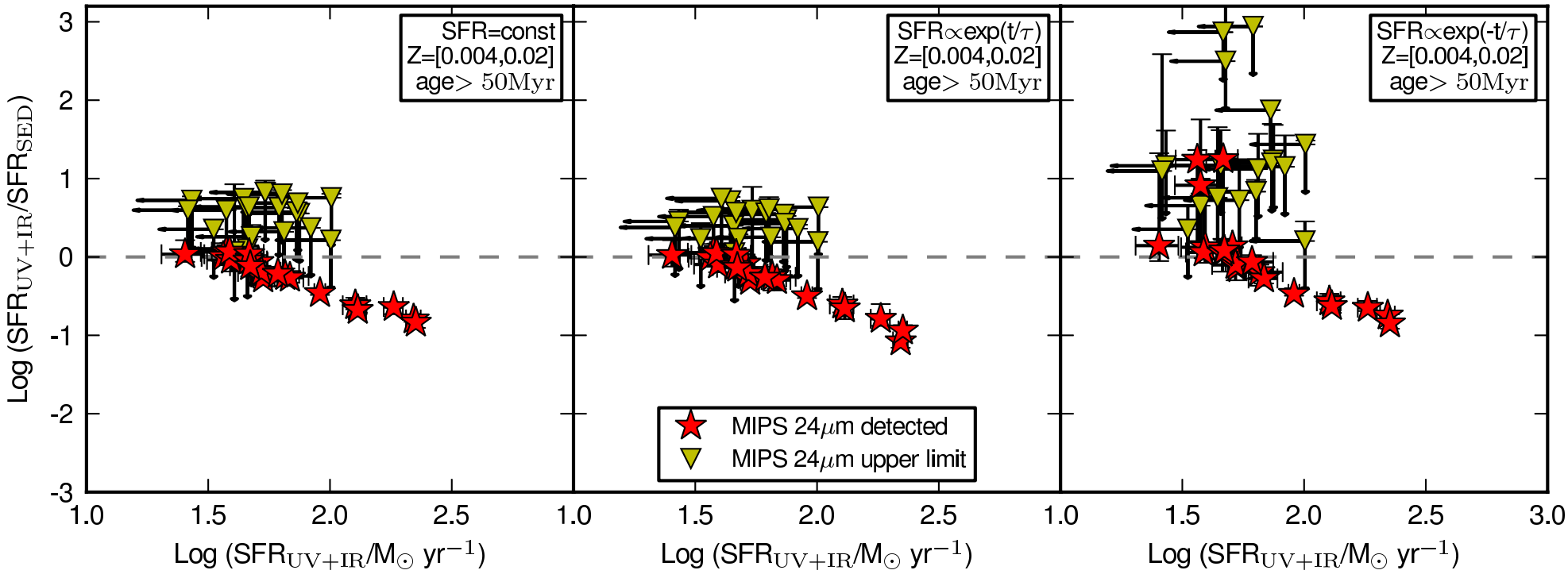
EW(Lyα)<10A for more than 22 galaxies: f(Lyα) set to zero



de Barros, Reddy & Shivaei 2014, in prep

Results

SFR(SED) vs SFR(UV+IR) Kennicutt 1998



6 ULIRGs (L(IR)>$10^{12}L_{sun}$) in our sample

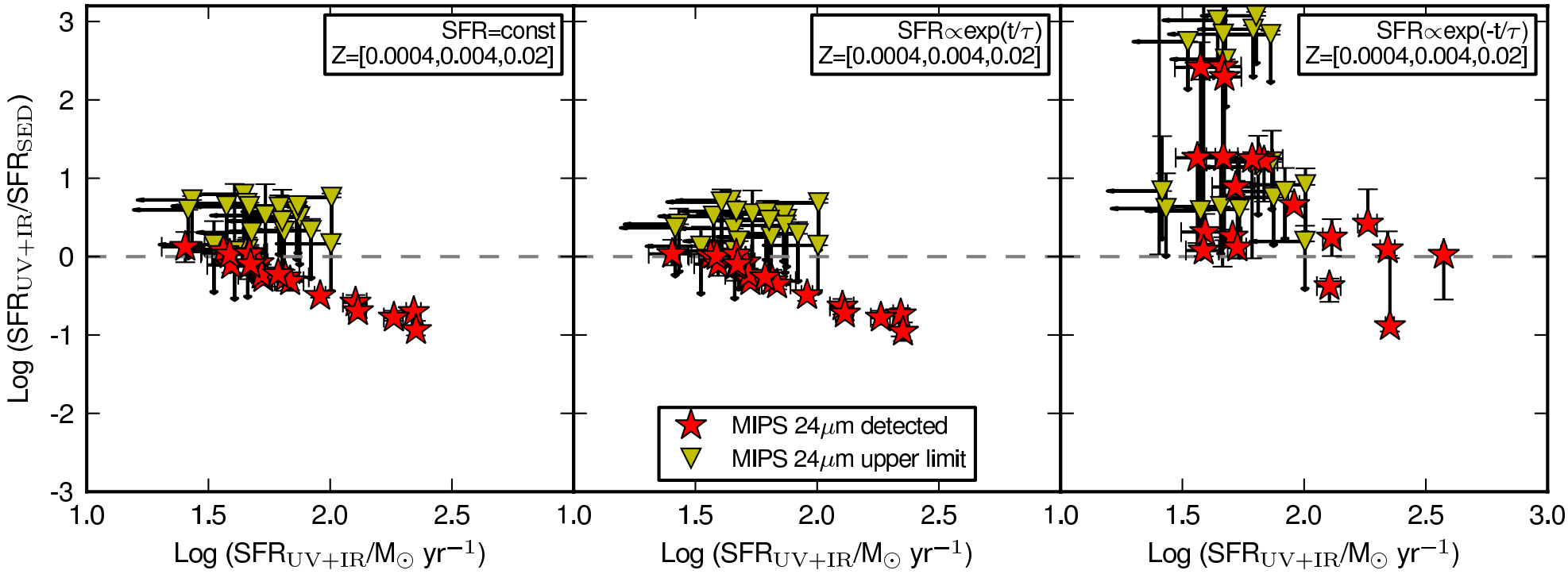
$2.25 < A_V < 5.8$

$X_r^2 > 70$

Rest of the sample: consistent

Results

SFR(SED) vs SFR(UV+IR) Kennicutt 1998

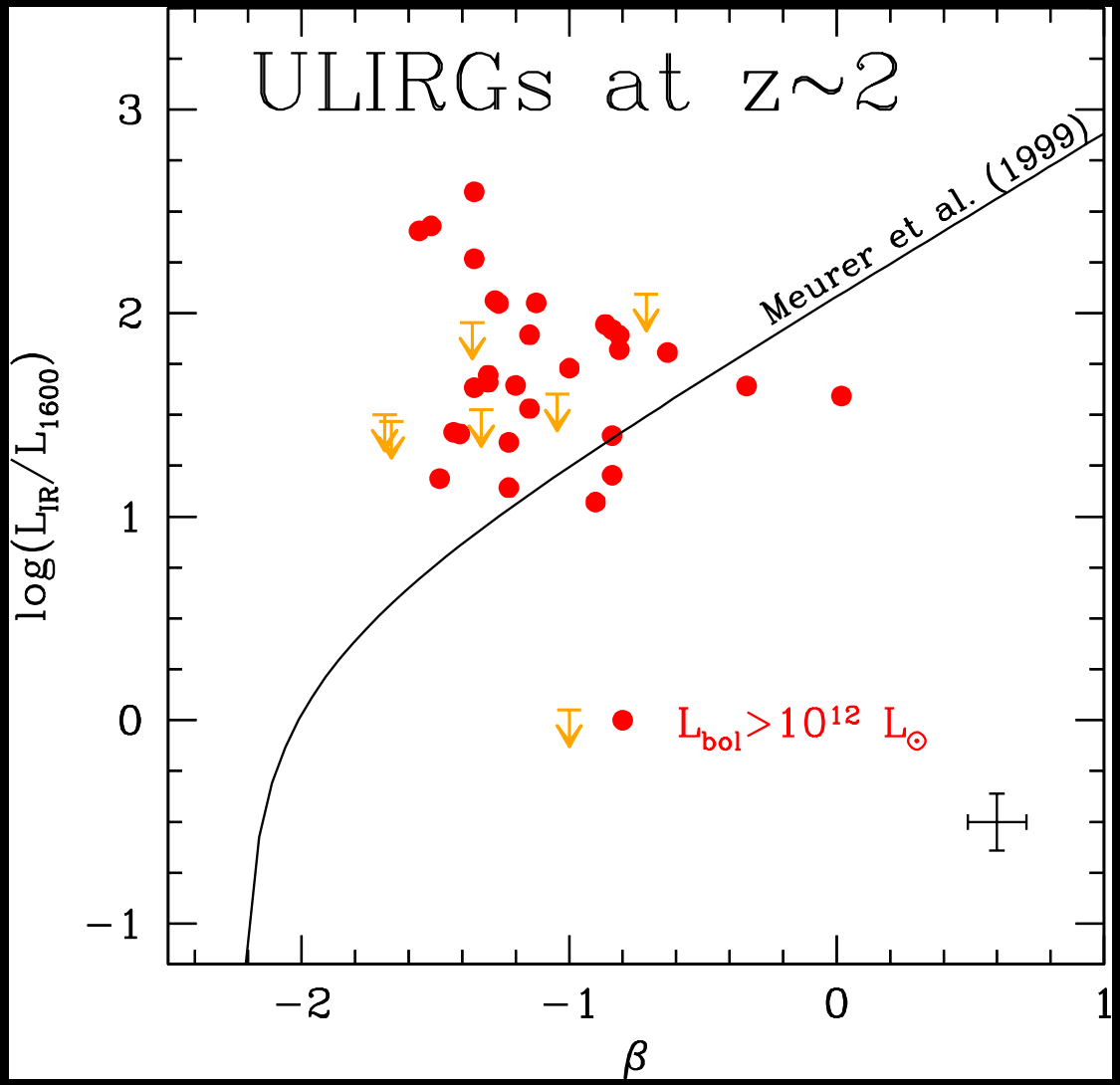


Relaxing assumptions

Not really a better fit: $X_r^2 > 50$

Results

SFR(SED) vs SFR(UV+IR) Kennicutt 1998



Reddy et al. 2010

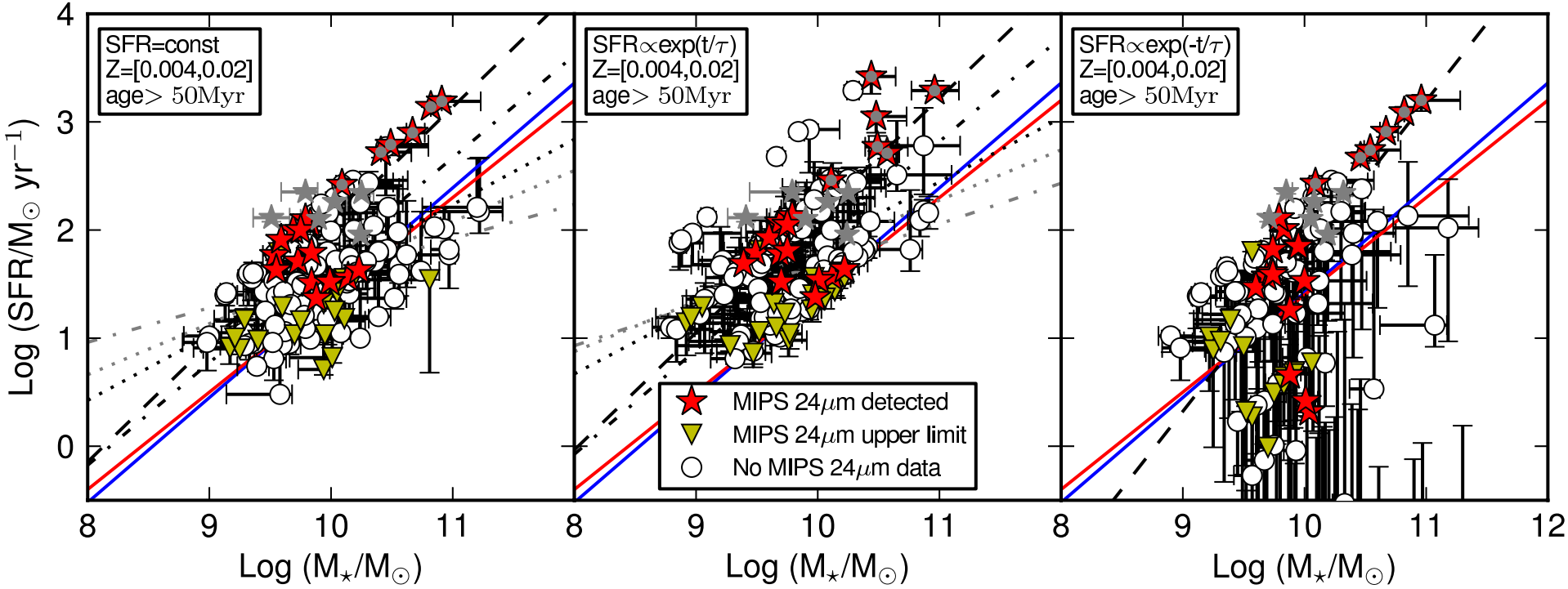
Other attenuation law?

ULIRGs: two methods to derive physical parameters

1) « Pure » SED fitting
2) SFR(UV+IR) + SED fitting without assuming energy conservation

Results

Physical properties of the sample: star formation main sequence



Red and blue lines: Daddy et al. 2007 and Reddy et al. 2012

MIPS detected: dashed lines

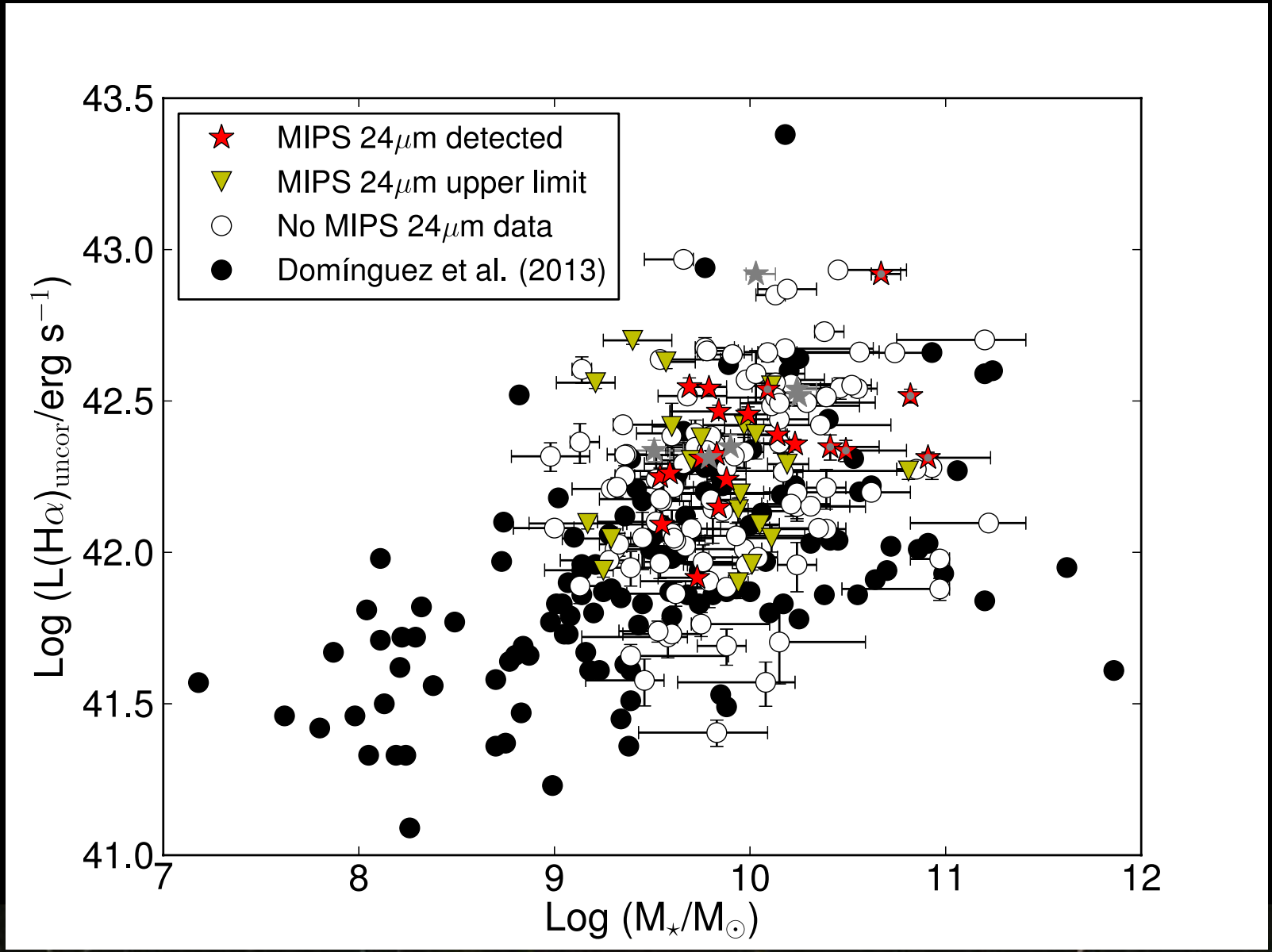
MIPS data: dash-dot lines

Entire sample: dotted lines

Grey lines and symbols: ULIRGs = SFR(UV+IR) and SED fitting

Results

Physical properties of the sample: Hα luminosity



Results

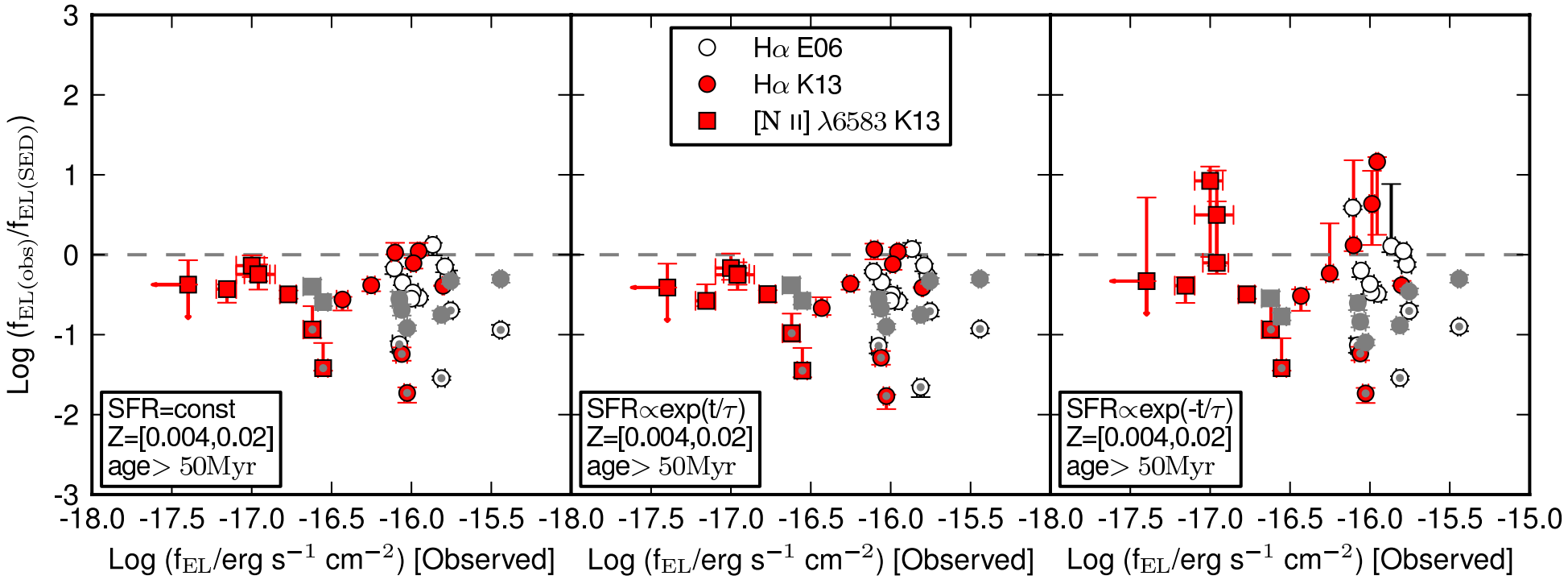
Physical properties of the sample:

- ❑Consistent with z~2 star-forming galaxies in terms of stellar mass and star formation rate
- ❑Consistent with z~1.5 star-forming galaxies in terms of Hα fluxes

➢Our sample (and subsamples: MIPS observed sample) is representative of typical z~2 star-forming galaxies, while affected by several biases (UV selection, MIPS detection, …)

Results

Reproducing emission line fluxes for the MIPS detected sample

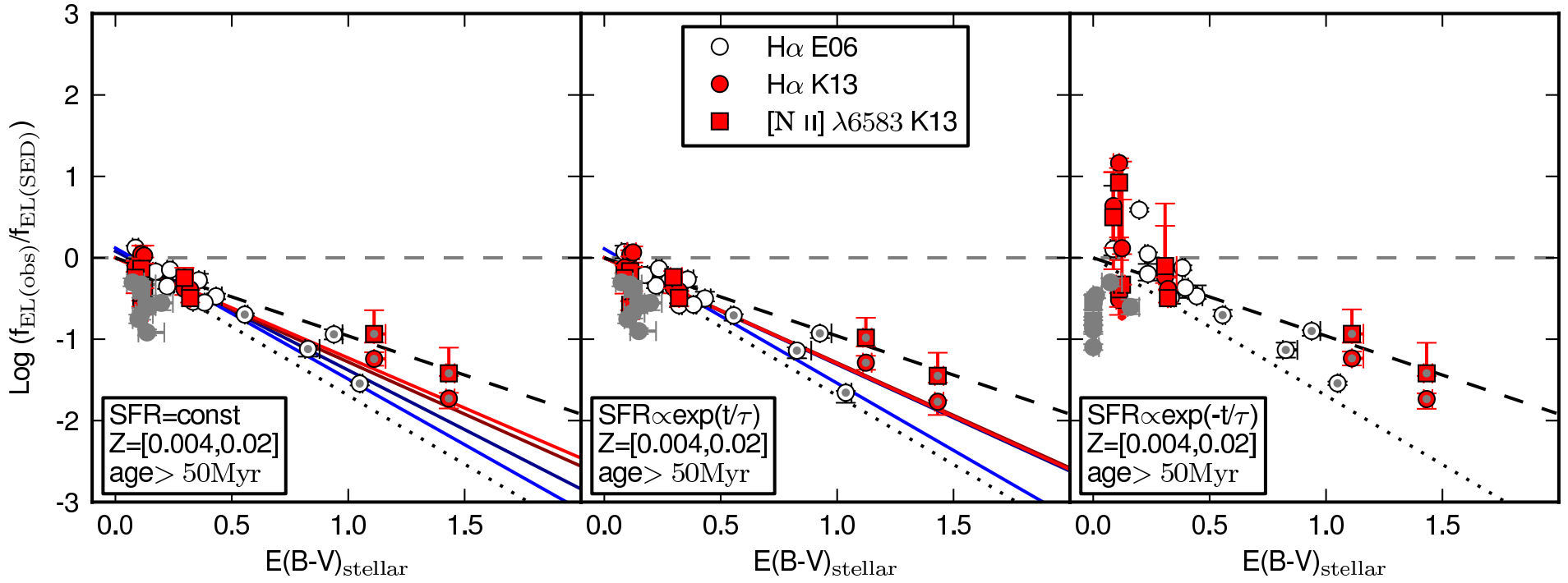


Emission line fluxes overpredicted

To understand why: correlation between log Δf_{EL} and physical properties (Price et al. 2014)

Results

Reproducing emission line fluxes for the MIPS detected sample



Usual interpretation of Calzetti et al. 2000:

$A_{H\alpha} = 7.55 \times E(B-V)_{stellar}$ (dotted line)

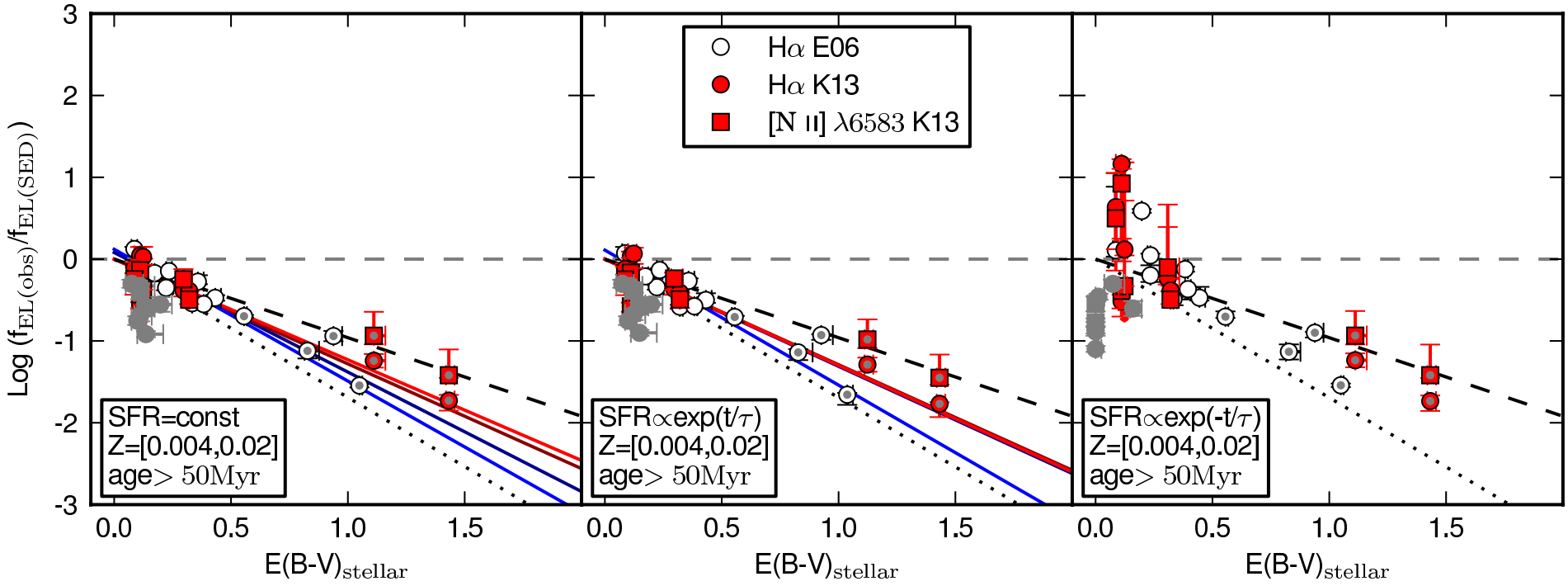
Steidel et al. 2014: usual interpretation = misunterpretation

$E(B-V)_{nebular}$ derived with line-of-sight law (e.g. Cardelli et al.1989):

$A_{H\alpha} = 5.72 \times E(B-V)_{stellar}$ (dashed line)

Results

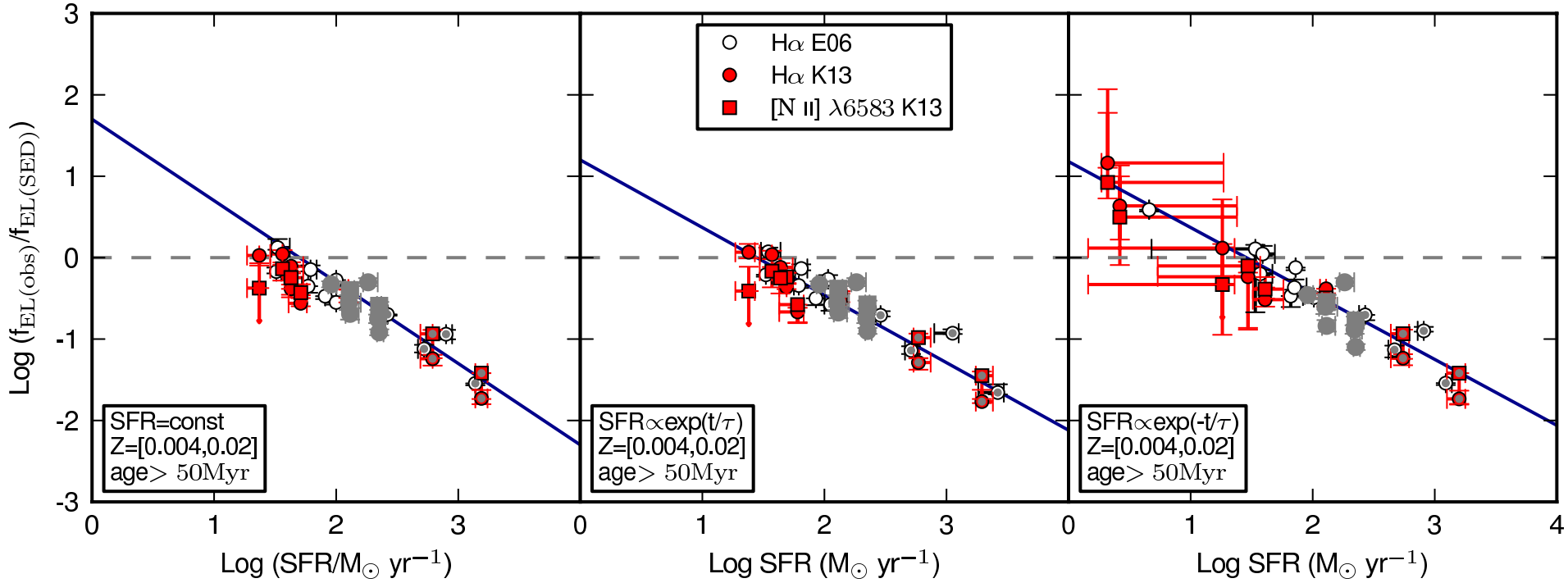
Reproducing emission line fluxes for the MIPS detected sample



$$E(B\text{-}V)_{nebular} = (1.98 \pm 0.05) \times E(B\text{-}V)_{stellar}$$

Results

Correlation between extra attenuation and other properties



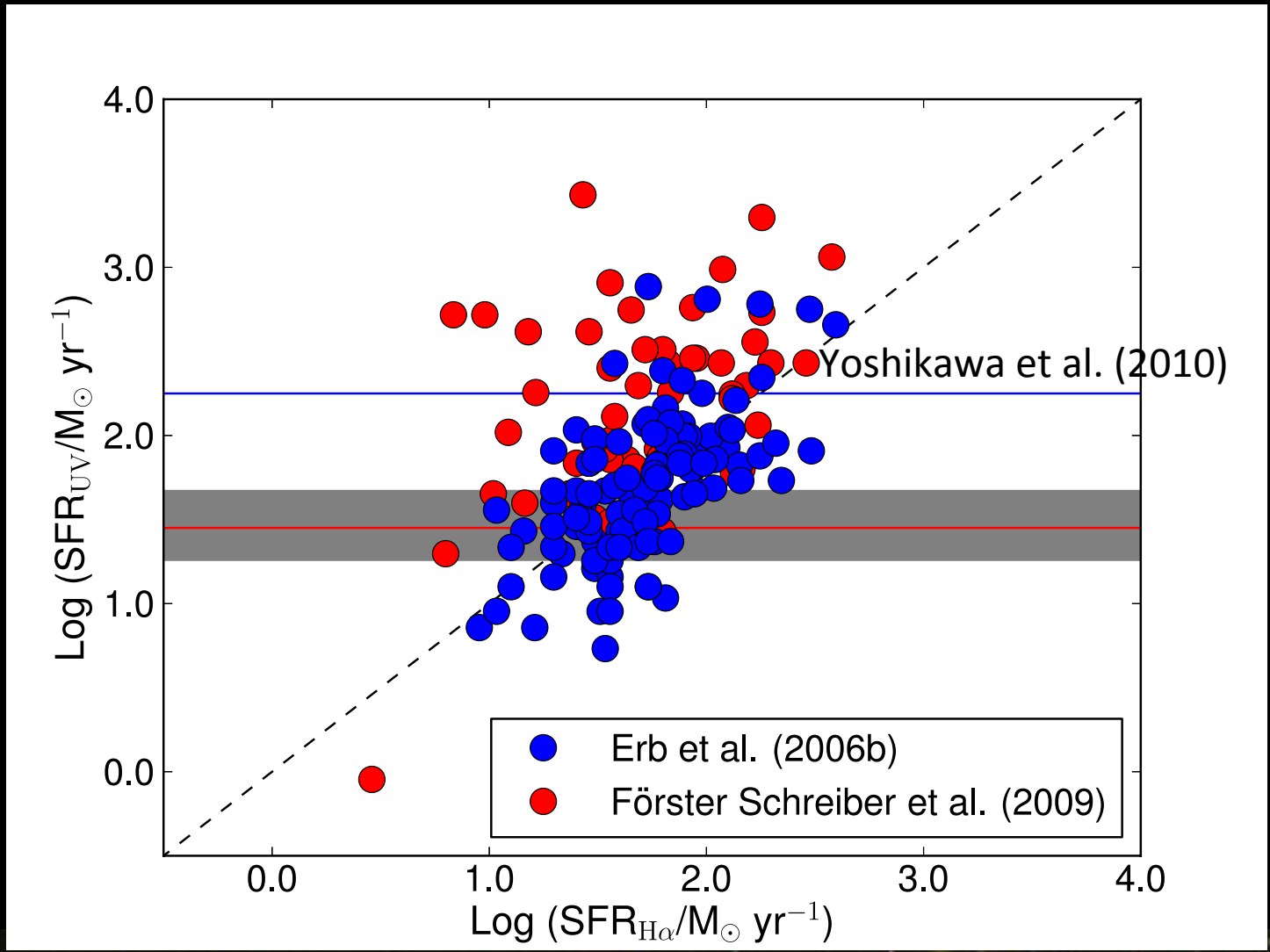
High anti-correlation with log SFR ($r < -0.8$), but SFR_{SED} and $f_{EL(SED)}$ are not independent

$\log \Delta f_{EL} = 0$ for log SFR = 1.45+/-0.20

Results

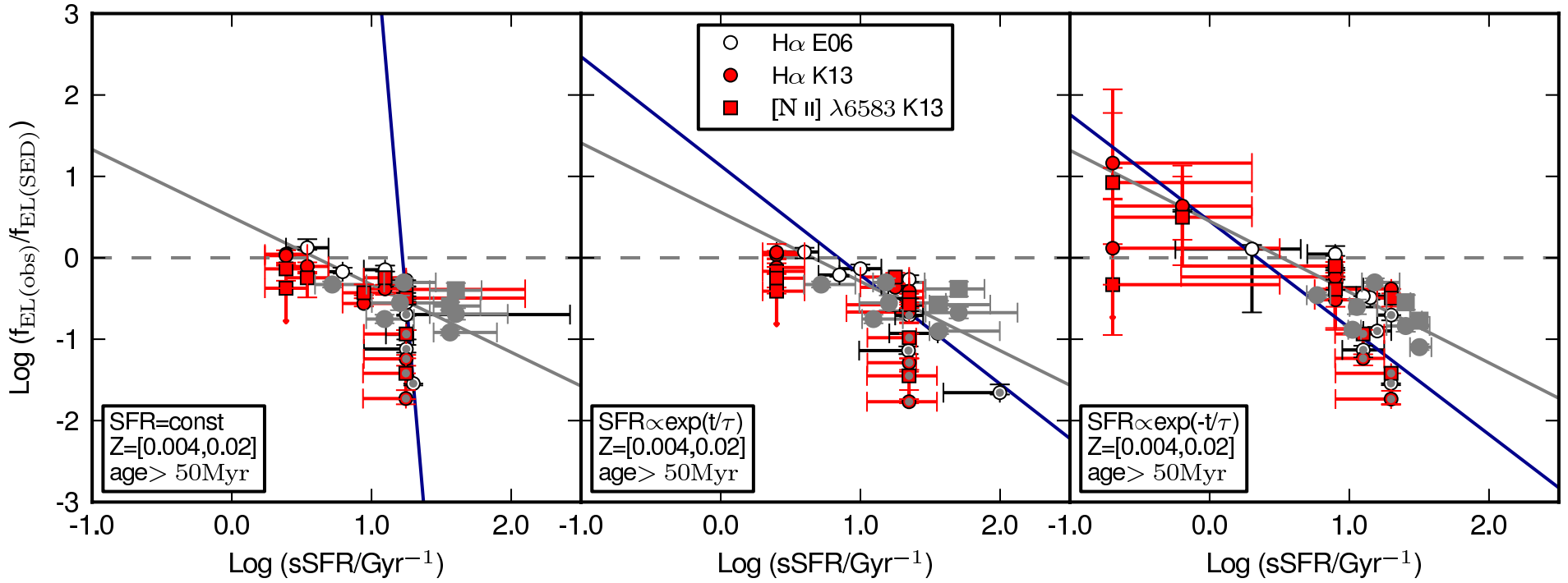
Correlation between extra attenuation and SFR

Can we explain discrepancies at z~2?



Results

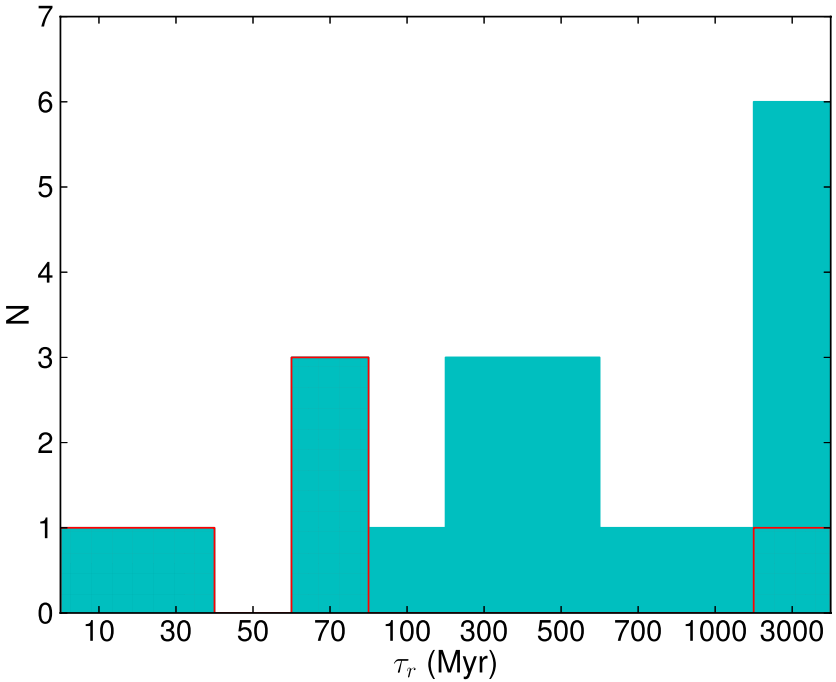
Correlation between extra attenuation and other properties

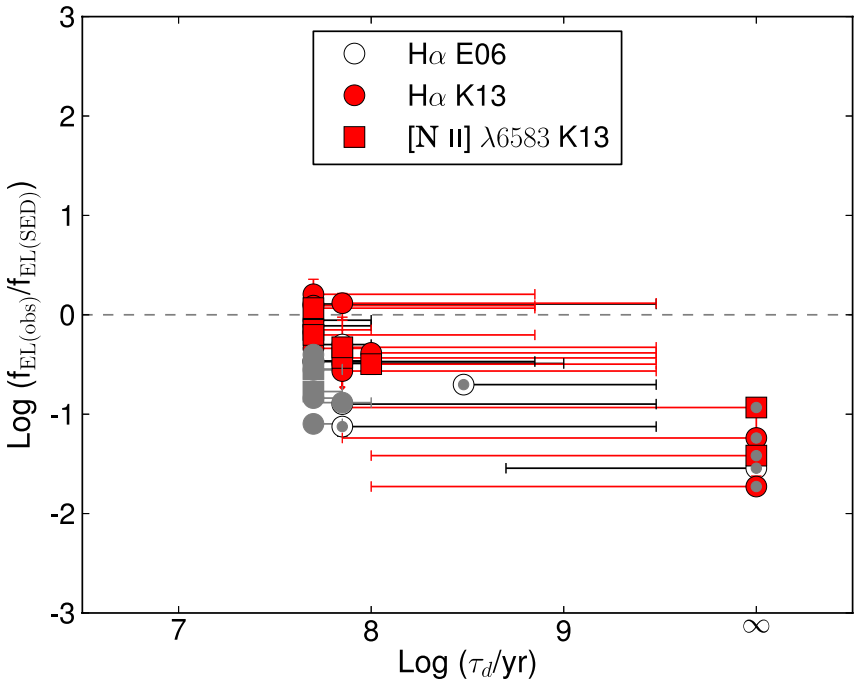


No correlation between sSFR and Δf_{EL}: tension with Price et al. 2014

Results

Other results:



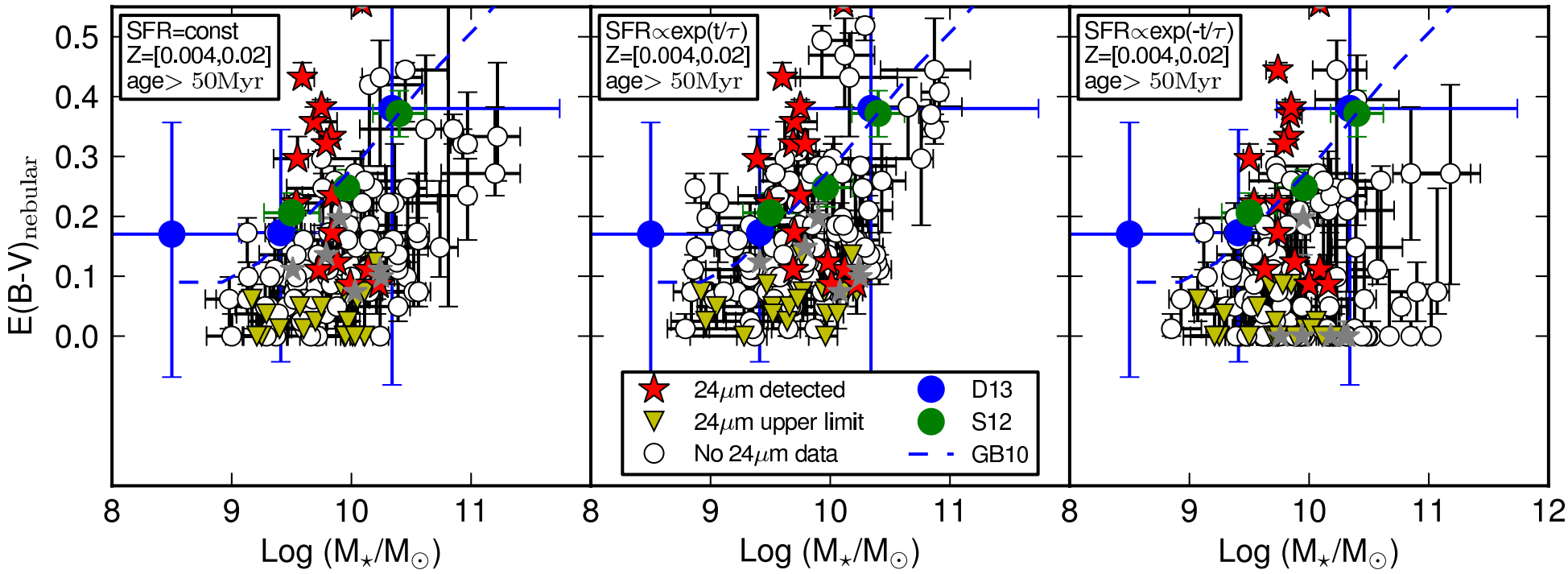


Implication for the SFH:

τ_d>70 Myr and τ_r>~500 Myr

Results

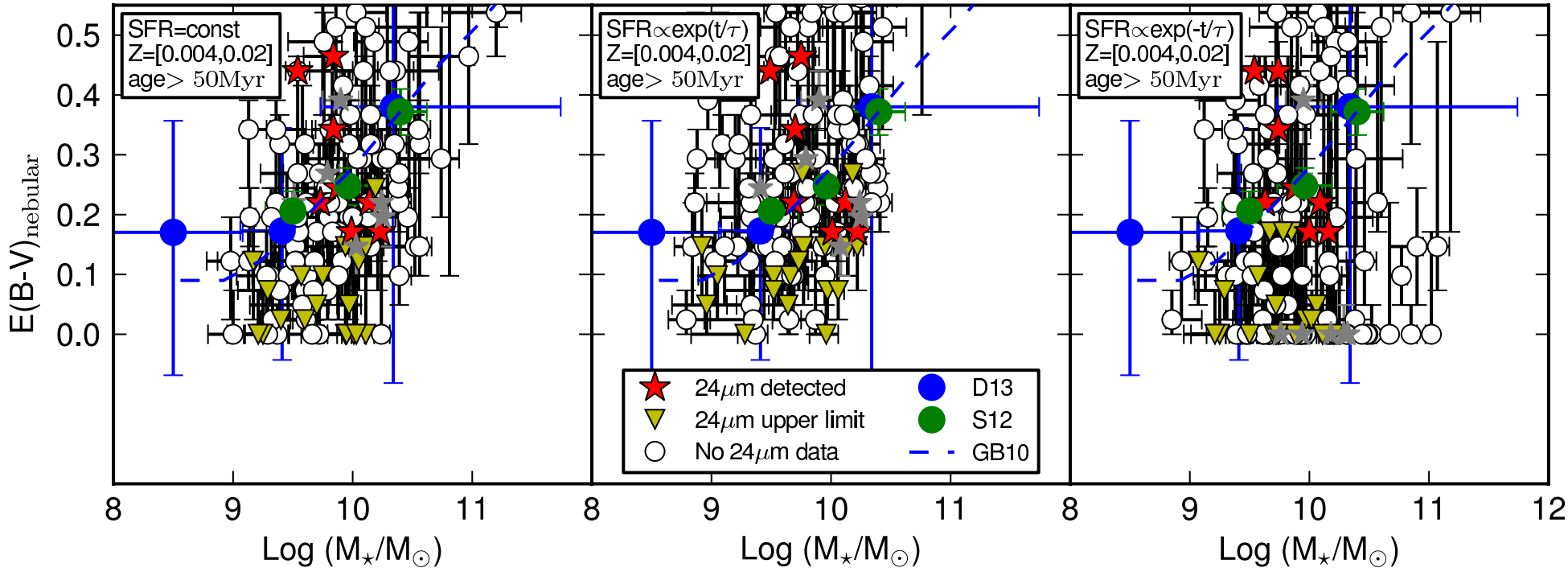
Other results:



Stellar mass vs dust extinction relation: seems to hold from z~0 to z~2

Results

Other results:



Stellar mass vs dust extinction relation: seems to hold from z~0 to z~2

Conclusions

Sample as large as possible with broad-band photometry, IR, and emission line measurements:

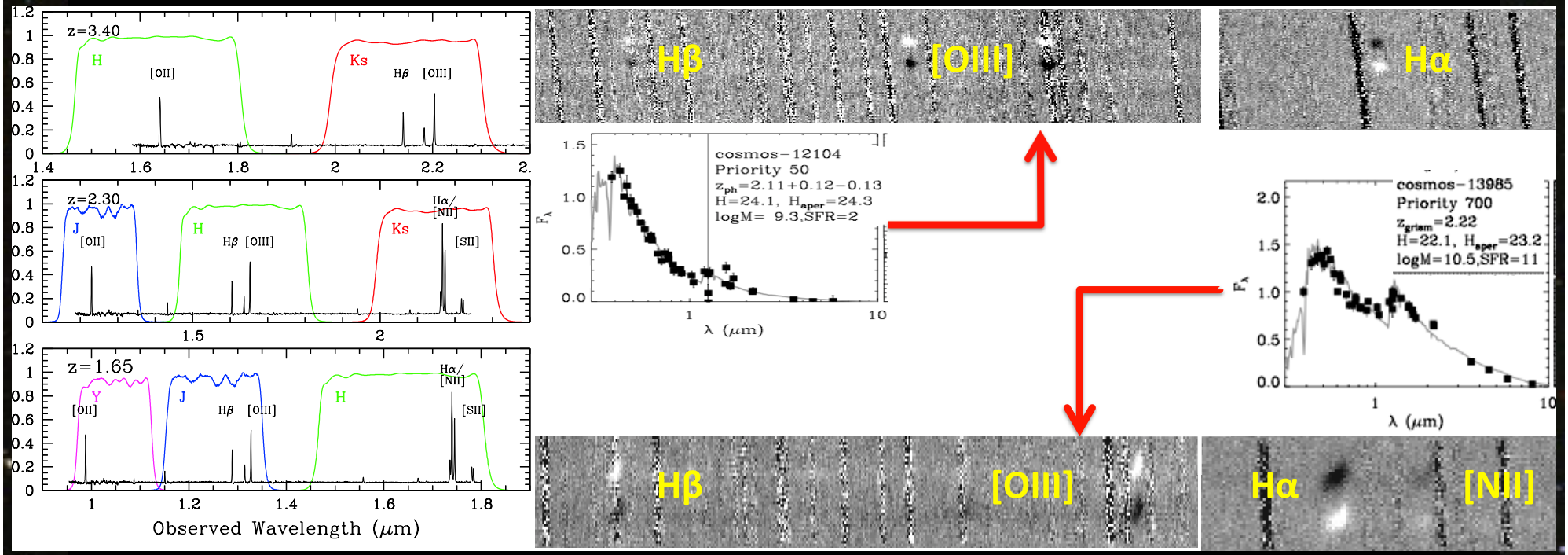
- Physical properties of the ULIRGs: seem more consistent to assume energy conservation to derive all the properties (stellar mass, dust attenuation)
- Extra attenuation toward nebular emission:

$$E(B\text{-}V)_{nebular} = (1.98+/-0.05) \times E(B\text{-}V)_{stellar}$$

- Tight correlation with log SFR: could explain difference among previous studies (Erb et al. 2006, Förster Schreiber et al. 2009)
- Unified picture for extra attenuation
- Our code is able to reproduce observed emission line fluxes
- Tension with some Price et al. 2014 results: sSFR vs. $\Delta E(B\text{-}V)$

- Implications at higher-z on SFR, sSFR, stellar mass, …?

Coming next



MOSFIRE Deep Evolution Field - MOSDEF survey

PIs: Shapley, Coil, Kriek, Mobasher, Reddy, Siana

z~1.5 to z~2.5, ~2000 galaxies

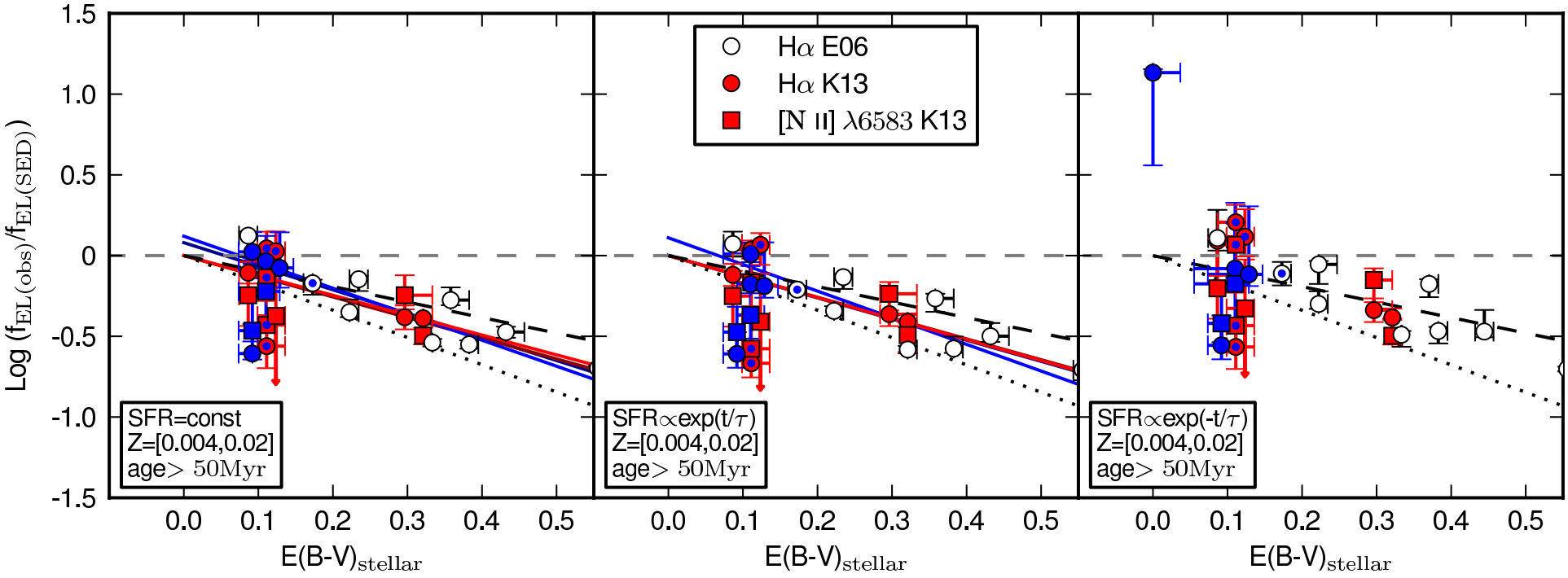
Should provide a « final » answer about the extra-attenuation toward nebular emission (also KMOS-3D survey)

➔**explain physical reasons for the correlations!**

➔**evolution with redshift?**

Thanks!

Keck & Subaru

Results

SMC attenuation law impact