Star Formation Rate Estimations at $0.5 \leq z \leq 0.9$ with the VIMOS Public Extragalactic Redshift Survey

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From galaxies to cosmology with deep spectroscopic surveys
A tribute to Olivier Le Fèvre

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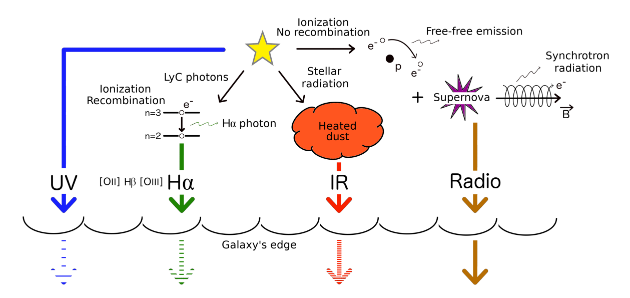
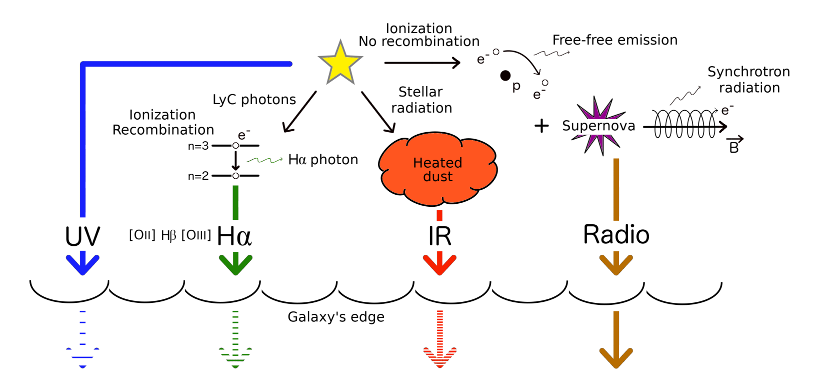
Star Formation Rate & Calibrators

- Formation and evolution of galaxies depend on the build-up of stellar mass throughout time (SFR)
- More and more global surveys at higher redshift allow the study of SFR at different times
- SFR measurements over cosmic time gives us information about the galaxies at different epochs of the Universe



Toolbox with several SFR indicators needed

SFR tracers



Skąd wiadomo, ile gwiazd rodzi się w galaktyce?

(Miguel Figueira, Delta, 01/11/21)

Motivations

Which continuum bands and lines trace consistently the SFR up to $z \sim 0.9$

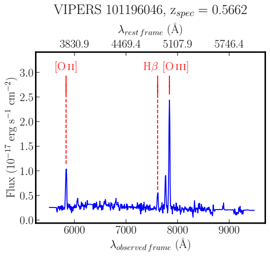
Similar bands and calibrations at low-redshift ? ($z \leq 0.3$)

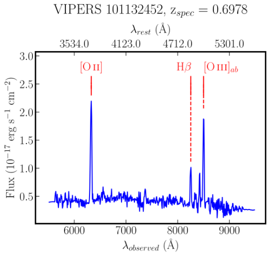
The VIMOS Public Extragalactic Redshift Survey

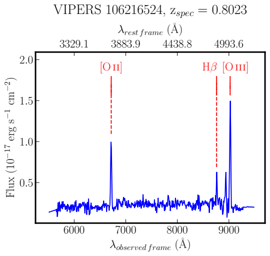
Guzzo and VIPERS Team [2013], Garilli et al. [2014], Scodeggio et al. [2018]

Spectroscopic survey of ~80 000 galaxies with $0.4 \leq z \leq 1.2$

- CFHTLS ugriz K_s bands (optical/NIR part of the spectrum)
- Cross-correlation with GALEX (UV part of the spectrum)
- Cross-correlation with WISE, *Spitzer*, *Herschel* (IR part of the spectrum)
- Detection of spectral lines: Hβ, [O II]λ3727, [O III]$\lambda\lambda$4959,5007







VIPERS star-forming galaxies ($0.5 \leq z \leq 0.9$)

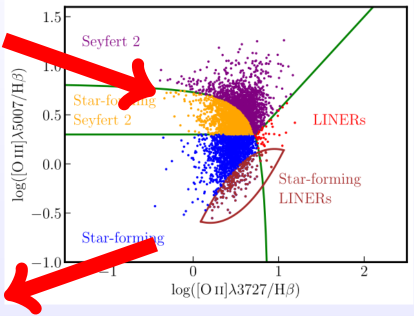
Reliable galaxies

1) 99% confidence on z_{spec}
   - $3 \leq z_{flag} \leq 4.5$
2) Lines measurements
   - $EW \geq 3\sigma$
   - $S/N \geq 7$

Sample selected

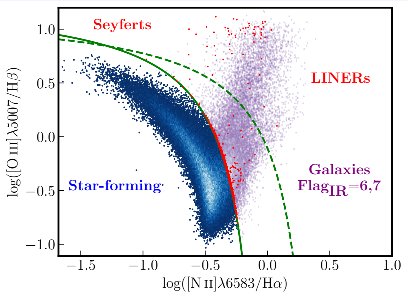
SF + SF/Seyfert2
3457 galaxies at $0.5 \leq z \leq 0.9$

Blue BPT diagram
Lamareille [2010]



GSWLC star-forming galaxies ($0 \leq z \leq 0.3$)

Catalog flags	Initial catalog	Good SED ($\chi_r^2 < 5$)	*GALEX* data	L_{IR}–WISE	MGS
	640 659	595 586	209 628	154 623	149 712
Lines S/N	Cross-correlation MPA-JHU			S/N selection	
	149 374			93 605	



Galex-SDSS-Wise Legacy Catalog ($z \leq 0.3$)

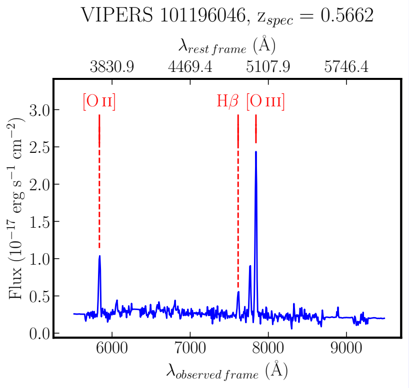
- 12/22µm→ L_{TIR} →Additional constraint (SED+L_{TIR} fitting)
- BPT diagram [Baldwin et al., 1981] SF/Seyfert limit [Kauffmann et al., 2003]

Sample selected

91 533 SF galaxies at $z \leq 0.3$

Above $z \sim 0.5$...

SFR from Hα commonly used to calibrate other bands.
At $0.5 \leq z \leq 0.9$, Hα shifted out of the optical window



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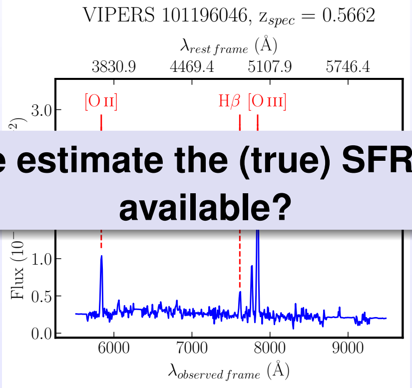


How can we estimate the (true) SFR if Hα is not available?

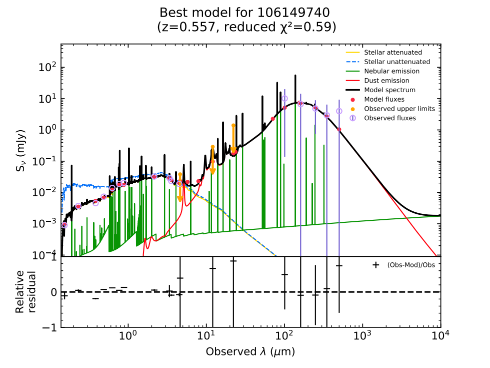
With CIGALE!

Burgarella et al. [2005], Noll et al. [2009], Boquien et al. [2019]

- Code Investigating GALaxy Emission (CIGALE) reconstructs the SED using the principle of energy-balance

Stellar radiation absorbed
=
Emission in IR

- Multiwavelength data available (UV to IR)
- **Reconstruction of the galaxies' SED**
  1) VIPERS (this work)
  2) GSWLC [Salim et al., 2016, 2018]
- Estimation of SFR but also rest-frame luminosities, attenuation for each band, etc...



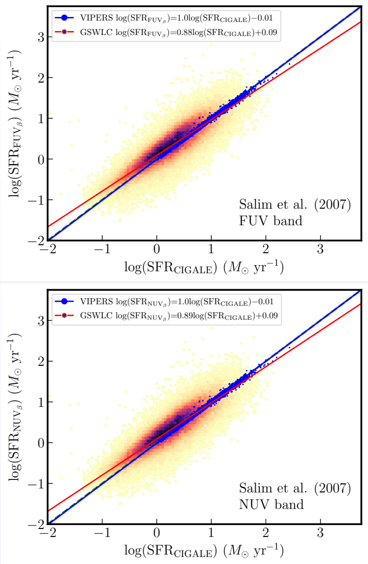
SFR from FUV & NUV bands

Emission in the FUV/NUV bands (massive stars)

- Dust attenuation is significant at these wavelengths (1500 and 2300 Å)

  CIGALE value (CF00):
  A(FUV) = 2 mag
  A(NUV) = 1.6 mag

- Correction based on FUV and NUV magnitudes, based on β_{UV}, based on a general value
- $A_{FUV} = 3.71 + 1.78\beta_{UV}$
- $A_{NUV} = 2.80 + 1.35\beta_{UV}$



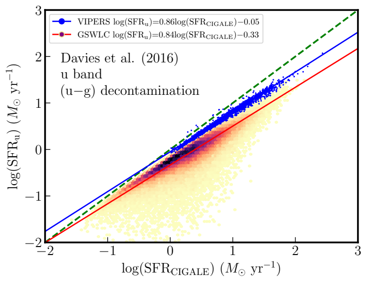
SFR from u-band

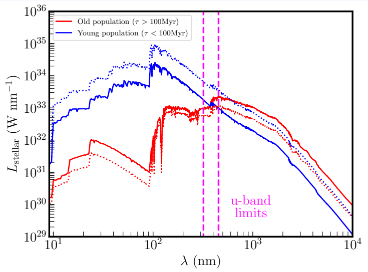
Emission in the u-band (young and old stars)

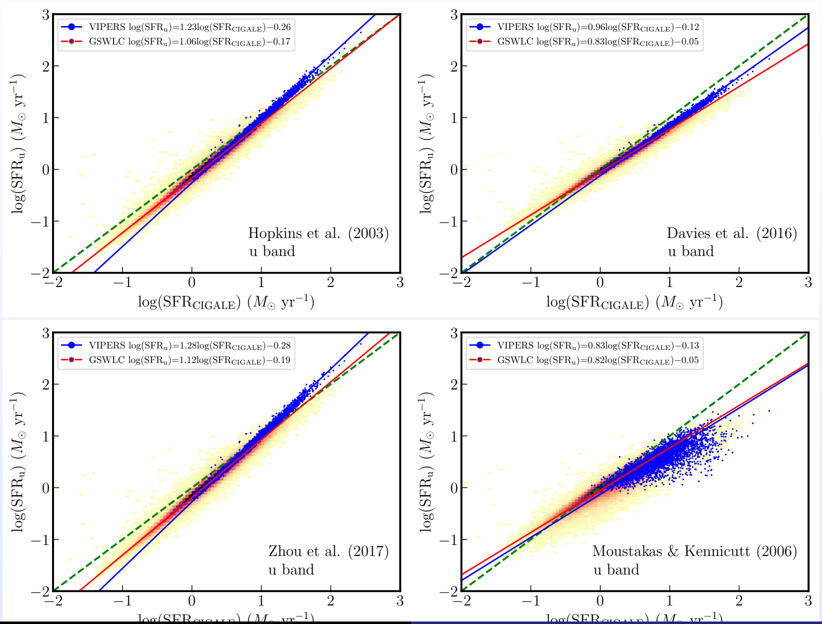
- u-band is contaminated by the old stellar population.

Prescott et al. [2009]: 11% at $z = 1$
Boquien et al. [2014]: 39% at $1 \leq z \leq 2$
Moustakas and Kennicutt [2006]: Scatter due to attenuation at low D4000

- Davies et al. (2016): Correction based on $u - g$
- Contamination from CIGALE old/young stars in the u-band
- Estimated contamination for VIPERS: 36%
- No relation with $u - g$ color



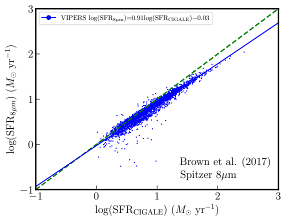


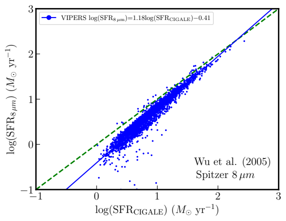

VIPERS log(SFRu)=1.23log(SFRCIGALE)−0.26
GSWLC log(SFRu)=1.06log(SFRCIGALE)−0.17
Hopkins et al. (2003)
u band
VIPERS log(SFRu)=0.96log(SFRCIGALE)−0.12
GSWLC log(SFRu)=0.83log(SFRCIGALE)−0.05
Davies et al. (2016)
u band
VIPERS log(SFRu)=1.28log(SFRCIGALE)−0.28
GSWLC log(SFRu)=1.12log(SFRCIGALE)−0.19
Zhou et al. (2017)
u band
VIPERS log(SFRu)=0.83log(SFRCIGALE)−0.13
GSWLC log(SFRu)=0.82log(SFRCIGALE)−0.05
Moustakas & Kennicutt (2006)
u band
log(SFRu) (M⊙ yr−1)
log(SFRCIGALE) (M⊙ yr−1)

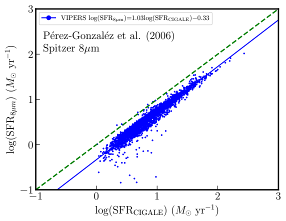
SFR from 8 μm emission

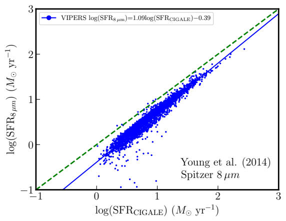
Emission at 8µm originates (PAHs, stars and dust)

- Contamination at 8µm:
  10% [Wu et al., 2005, Engelbracht et al., 2005]
  33% [Pérez-González et al., 2006]
- Contamination estimated from CIGALE $\rightarrow$ 5%
- Difficult to estimate the SFR with 8 μm emission









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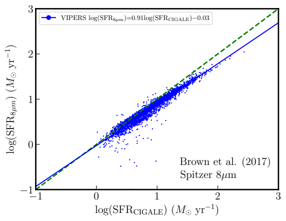
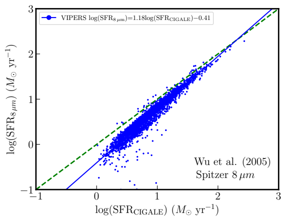
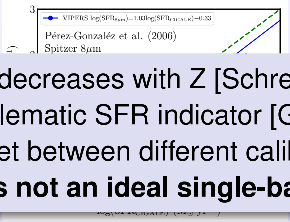
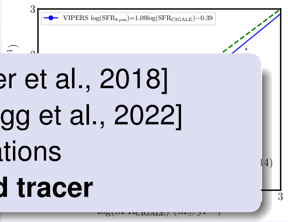






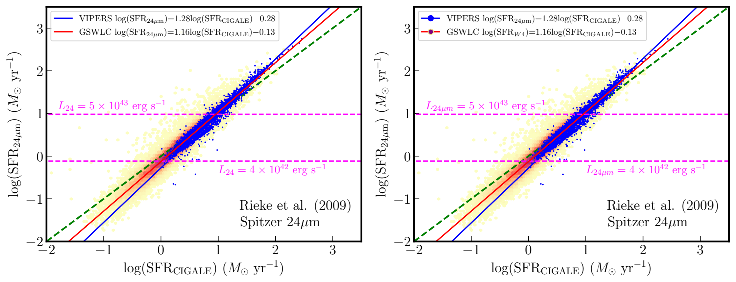


IR8=L_{TIR}/L_8 decreases with Z [Schreiber et al., 2018]
8 μm is a problematic SFR indicator [Gregg et al., 2022]
Offset between different calibrations
8 μm is not an ideal single-band tracer

SFR from 24 μm emission

Emission at 24 μm originates from dust reprocession

- Good SFR tracer [Chary and Elbaz, 2001, Wuyts et al., 2008, Magdis et al., 2012, Dale et al., 2014]



- **Non-linear behaviour should be included**
  $L_{24\mu m}$ does not increase proportionally with L_{TIR}, [Calzetti et al., 2010]
- **Preferably calibrated on whole galaxies**
  Difference of $T_{\rm dust}$ from whole galaxies and H II regions

SFR calibrations with spectral lines

Rest-frame luminosities for photometric bands

→ k-correction needed

Dependent on templates

Line measurements are **independent** of CIGALE

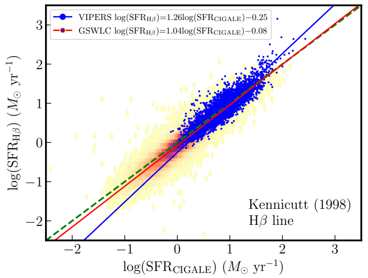
SFR from Hβ and [O II] spectral lines

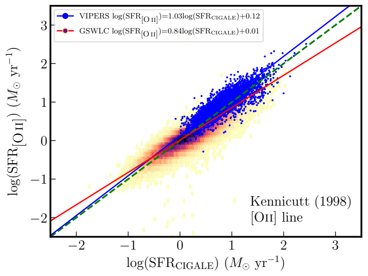
Hβ line

- Hα not available in VIPERS for the redshift range studied ($0.5 \leq z \leq 0.9$)
- Assuming the usual Balmer decrement: H$\alpha = 2.86$Hβ
- Corrected from stellar absorption = 2 Å (In agreement with CIGALE)

[O II] line

- $SFR = 1.41 \times 10^{-41}\ L$[O II]
  1) [N II]/Hα = 0.5
  2) [O II]/Hα from specific sample
- Good estimation of the SFR without metallicity dependence and [O II]/Ha





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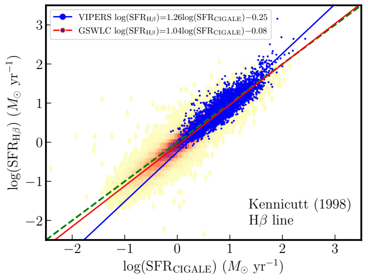
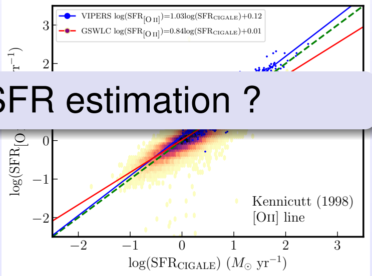


[O II] line

- $SFR = 1.41 \times 10^{-41}\ L$[O II]

Can we improve the SFR estimation ?

- Good estimation of the SFR without metallicity dependence and [O II]/Ha



Estimation of the metallicity

R_{23} parameter [Pagel et al., 1979]

$$R_{23} = \frac{[\mathrm{OII}]\lambda3727 + [\mathrm{OIII}]\lambda\lambda4959,5007}{H\beta}$$

- R_{23} is double-valued
- Ratio [O III]/[O II] used to distinguish the lower and higher branch [Nagao et al., 2006]

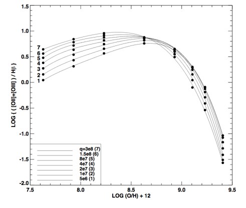


Figure: R_{23} for different ionization parameters [Kewley and Dopita, 2002]

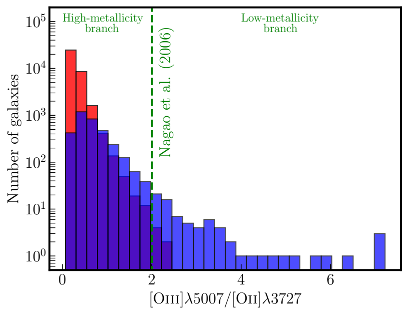


Figure: [O III]/[O II] for GSWLC (red) and VIPERS (blue)

High-metallicity galaxies only

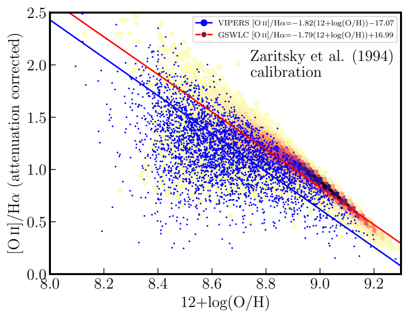
Estimation of the metallicity

Metallicity [Zaritsky et al., 1994]

$$log(O/H) + 12 = \begin{cases} 9.265 - 0.33x - 0.202x^2 \\ \qquad - 0.207x^3 - 0.333x^4, \\ x = log(R_{23}), \\ \\ \text{Valid for } log(O/H) + 12 > 8.4. \end{cases} \quad (1)$$

$$[\text{O II}]/\text{H}\alpha = \begin{cases} (-1.82 \pm 0.08)x + (17.07 \pm 0.70) \text{ (VIPERS)}, \\ (-1.79 \pm 0.07)x + (16.99 \pm 0.65) \text{ (GSWLC)}, \\ (-1.75 \pm 0.25)x + (16.73 \pm 2.23), \\ \text{[Kewley et al., 2004].} \\ \\ x = 12 + log(O/H) \end{cases} \quad (2)$$

Good agreement with Kewley and Dopita [2002]



Correction reddening and metallicity

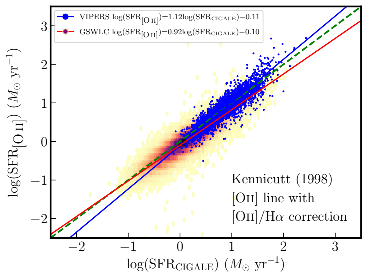
O II - reddening

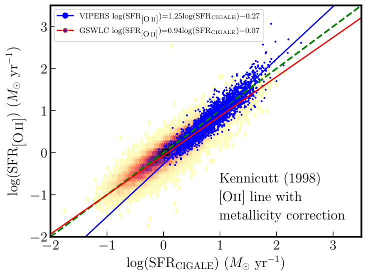
- $SFR = 6.8 \times 10^{-42} L_{[O\ II]}$
- $SFR = 7.6 \times 10^{-42} L_{[O\ II]}$
- Reddening correction decreases the scatter

O II - metallicity

$[O\ II]/H\alpha = -1.82 \times (12 + log(O/H)) - 17.07$ (VIPERS)
$[O\ II]/H\alpha = -1.79 \times (12 + log(O/H)) + 16.99$ (GSWLC)

- Correcting for metallicity decreases the scatter.
- Pilyugin [2001], Tremonti et al. [2004], Kobulnicky et al. [1999] calibrations give a similar scatter





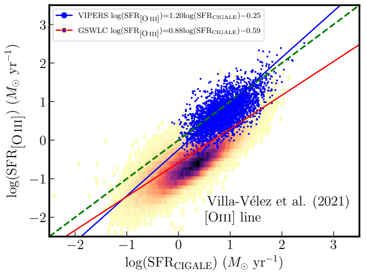
SFR from [O III] line

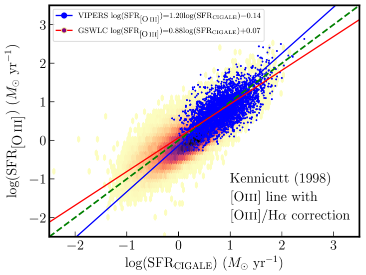
O III - direct calibration

- Calibration from Villa-Vélez et al. [2021] ($1.40 \leq z \leq 1.68$)
- Good agreement for VIPERS only

O III - reddening

- SFR=$5.6 \times 10^{-42} L_{[\mathrm{O\ III}]}$ (VIPERS)
- SFR=$1.6 \times 10^{-42} L_{[\mathrm{O\ III}]}$ (GSWLC)
- Calibrations change for different samples
- Highest scatter between all the spectral lines

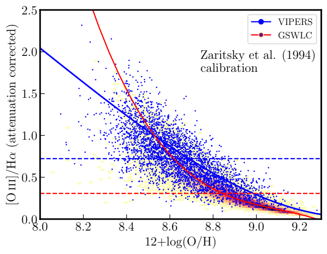




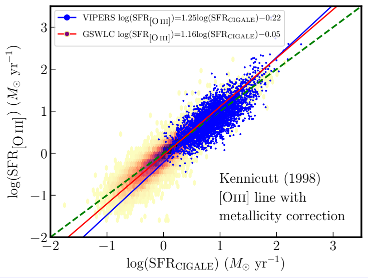
Correction for metallicity

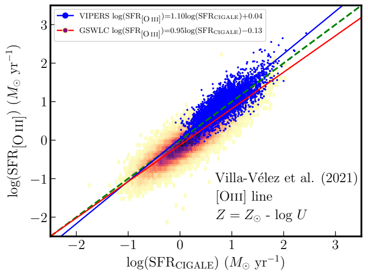
Metallicity from GSWLC/VIPERS

- Inclusion of metallicity decreases the scatter



- Metallicity from Villa-Vélez et al. [2021]
  1) Grid depends on log(U) - Z
  2) q from Kewley and Dopita [2002] through [O III]/[O II]





SFR calibrations at $0 \leq z \leq 0.9$

- GSWLC and VIPERS are processed through CIGALE $\Longrightarrow$ SFR, L_{FUV}, L_{NUV}, etc...
- Relation between SFR and rest-frame luminosity for each band (attenuation corrected)

$$\log[\mathrm{SFR}_{\mathrm{band}}\ (M_\odot\ \mathrm{yr}^{-1})] = A \times \log[L_{\mathrm{band}}(\mathrm{units})] + B$$

Rest-frame band	A	B	Luminosity range	Unit
FUV	1.04±0.01	−21.99±0.02	$2.1 \times 10^{19} < L < 4.7 \times 10^{23}$	$\mathrm{W\ Hz^{-1}}$
NUV	1.03±0.01	−21.81±0.01	$3.9 \times 10^{19} < L < 4.3 \times 10^{23}$	$\mathrm{W\ Hz^{-1}}$
u-band	1.11±0.0	−23.62±0.01	$8.3 \times 10^{19} < L < 4.5 \times 10^{23}$	$\mathrm{W\ Hz^{-1}}$
8 μm	0.85±0.01	−18.53±0.14	$3.9 \times 10^{21} < L < 4.4 \times 10^{24}$	$\mathrm{W\ Hz^{-1}}$
24 μm	0.81±0.0	−18.22±0.01	$7.3 \times 10^{20} < L < 2.6 \times 10^{25}$	$\mathrm{W\ Hz^{-1}}$
L_{TIR}	0.99±0.01	−9.97±0.03	$3.7 \times 10^{8} < L < 4.8 \times 10^{12}$	$L_\odot$
Hβ	0.94±0.01	−38.34±0.04	$9.3 \times 10^{38} < L < 1.0 \times 10^{44}$	$\mathrm{erg\ s^{-1}}$
[O II]λ3727	0.96±0.01	−39.69±0.07	$6.4 \times 10^{39} < L < 1.1 \times 10^{44}$	$\mathrm{erg\ s^{-1}}$
[O III]λ5007	0.89±0.01	−35.94±0.35	$4.4 \times 10^{38} < L < 6.1 \times 10^{43}$	$\mathrm{erg\ s^{-1}}$

Comparisons of SFR calibrations

Comparison done with the Concordance Correlation Coefficient.

CCC = Pearson coefficient + Deviation from $y = x$

Reference (1)	Catalog – Band (2)	N (3)	m (4)	b (5)	Pearson (6)	Mean (7)	Scatter (8)	CCC (9)	CCC_{GV} (10)
FUV									
Brown et al. [2017]	V – (Calzetti)	3 457	1.21	−0.28	0.99	0.09	0.10	0.94	0.91
	G – (Calzetti)	91 533	0.95	−0.06	0.83	0.02	0.30	0.83	
	V – (Hao)	3 457	1.05	−0.04	0.99	0.01	0.05	0.99	0.94
	G – (Hao)	91 533	0.95	0.02	0.88	−0.02	0.25	0.88	
Davies et al. [2016]	V	3 457	0.82	0.0	0.99	0.16	0.07	0.87	0.88
	G	91 533	0.67	0.12	0.85	−0.07	0.25	0.82	
Salim et al. [2007]	V	3 457	1.0	−0.01	1.00	0.02	0.03	0.99	0.94
	G	91 533	0.88	0.09	0.87	−0.08	0.24	0.86	
NUV									
Davies et al. [2016]	V	3 457	0.80	−0.13	0.97	0.29	0.10	0.67	0.79
	G	91 533	0.59	0.07	0.80	−0.01	0.29	0.76	
Salim et al. [2007]	V	3 457	1.0	−0.01	1.00	0.02	0.03	0.99	0.93
	G	91 533	0.89	0.09	0.87	−0.08	0.24	0.86	
Rosa-González et al. [2002]	V	3 457	1.09	0.08	0.47	−0.11	0.32	0.43	0.78
	G	91 533	0.83	0.33	0.86	−0.20	0.25	0.77	

Summary

Comparison of SFR (continuum and lines) of star-forming galaxies at $0 \leq z \leq 0.9$ (GSWLC-VIPERS) *(Figueira et al. under review)*

- Reconstruction of galaxies' SED $\longrightarrow$ catalog of properties
- Tight correlation between the UV/u band/24 μm/L_{TIR} (rest-frame) with SFR
  $\rightarrow$ Low-z calibrations give good estimations of SFR up to $z \sim 0.9$
- Hβ and [O II] perform reliably at $0 \leq z \leq 0.9$
- Correction of metallicity decreases the scatter for [O II] and [O III]
- Set of calibrations from FUV to L_{TIR} and spectral lines at $0 \leq z \leq 0.9$ (GSWLC + VIPERS)

Thank you for your attention!