Extent of the last star formation episode of Red Sequence galaxies up to z=2.5

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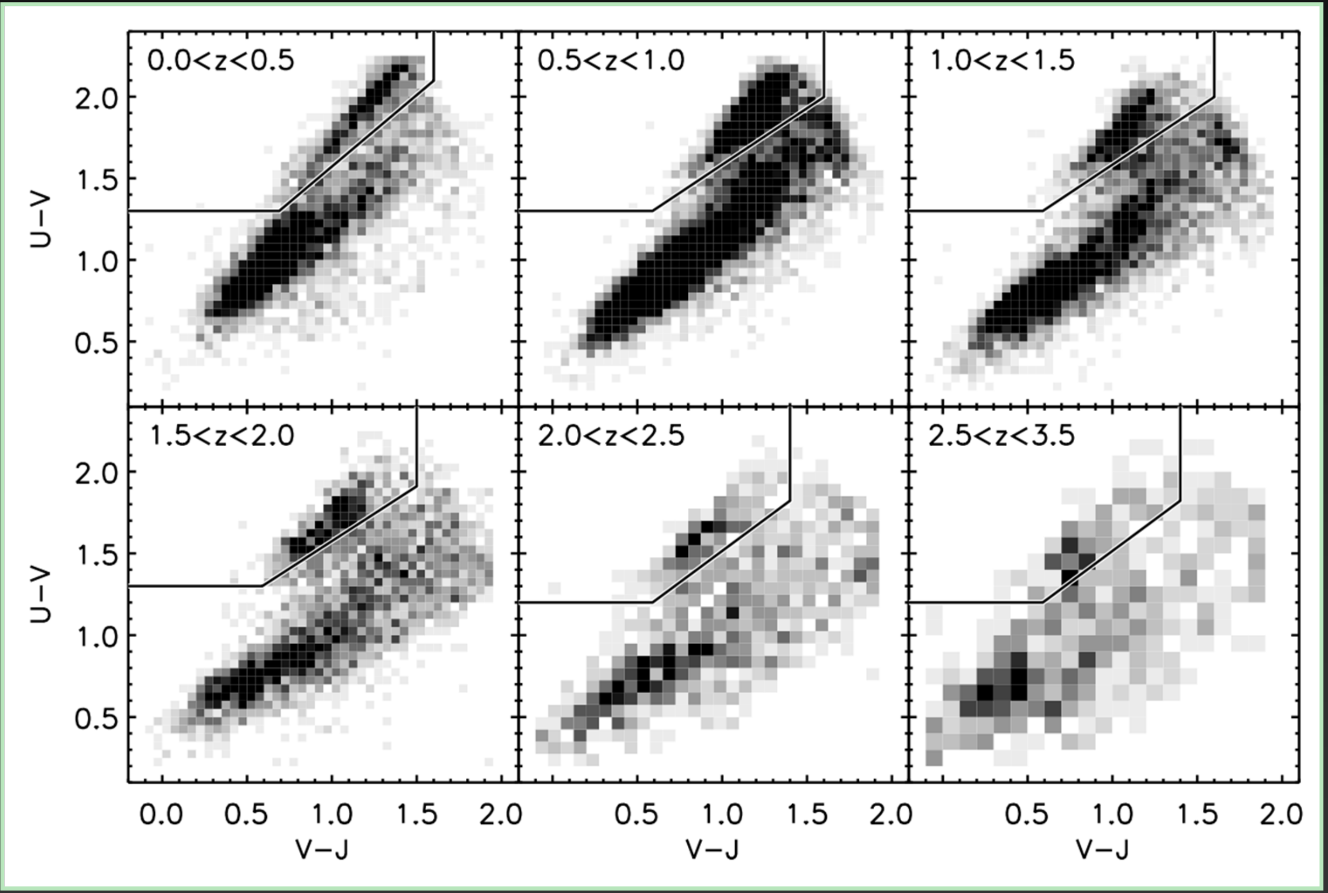
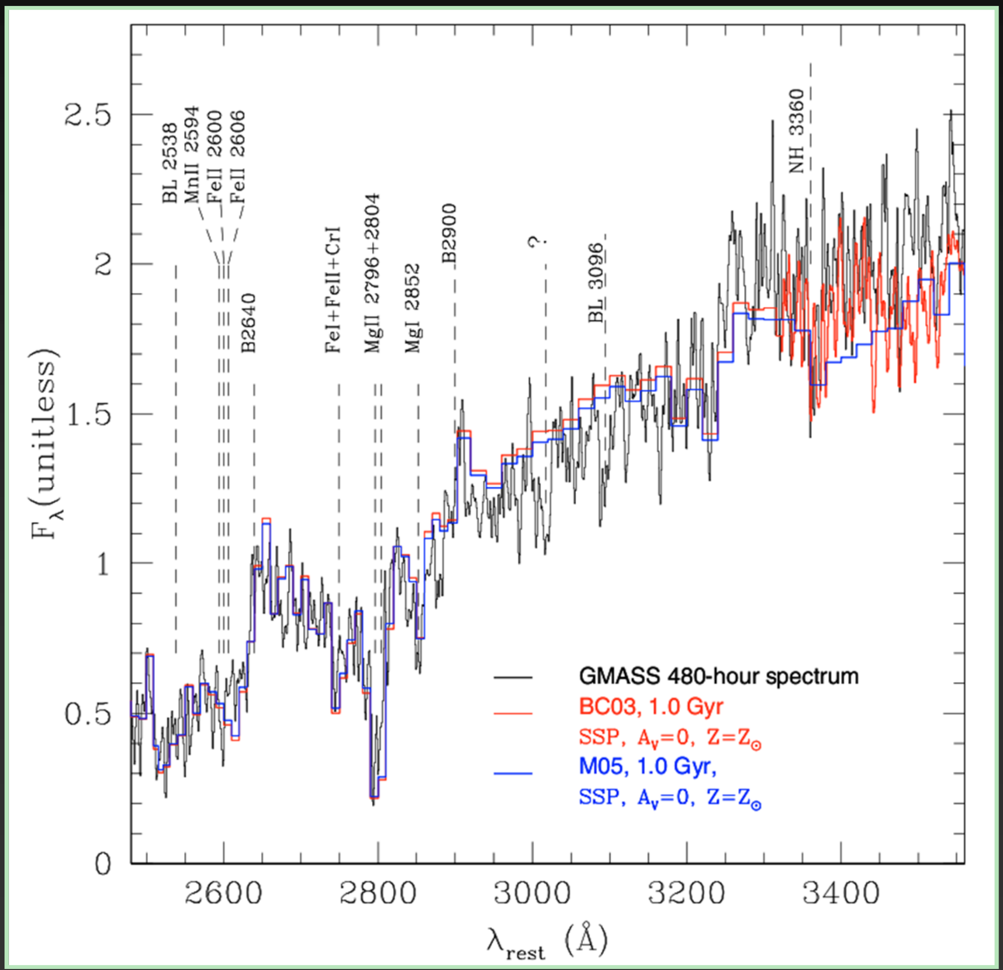
Red Sequence observed since z~2

- Galaxies bimodality in CM diagrams exists up to z~2 (Williams+09, Brammer +11, Whitaker+11)
- In agreement with mass downsizing in mass (Kodama+07, Pérez-González+08) and against traditional hierarchical scenarios (De Lucia+06)



Whitaker et al. (2011)

Massive quiescent galaxies at z~2



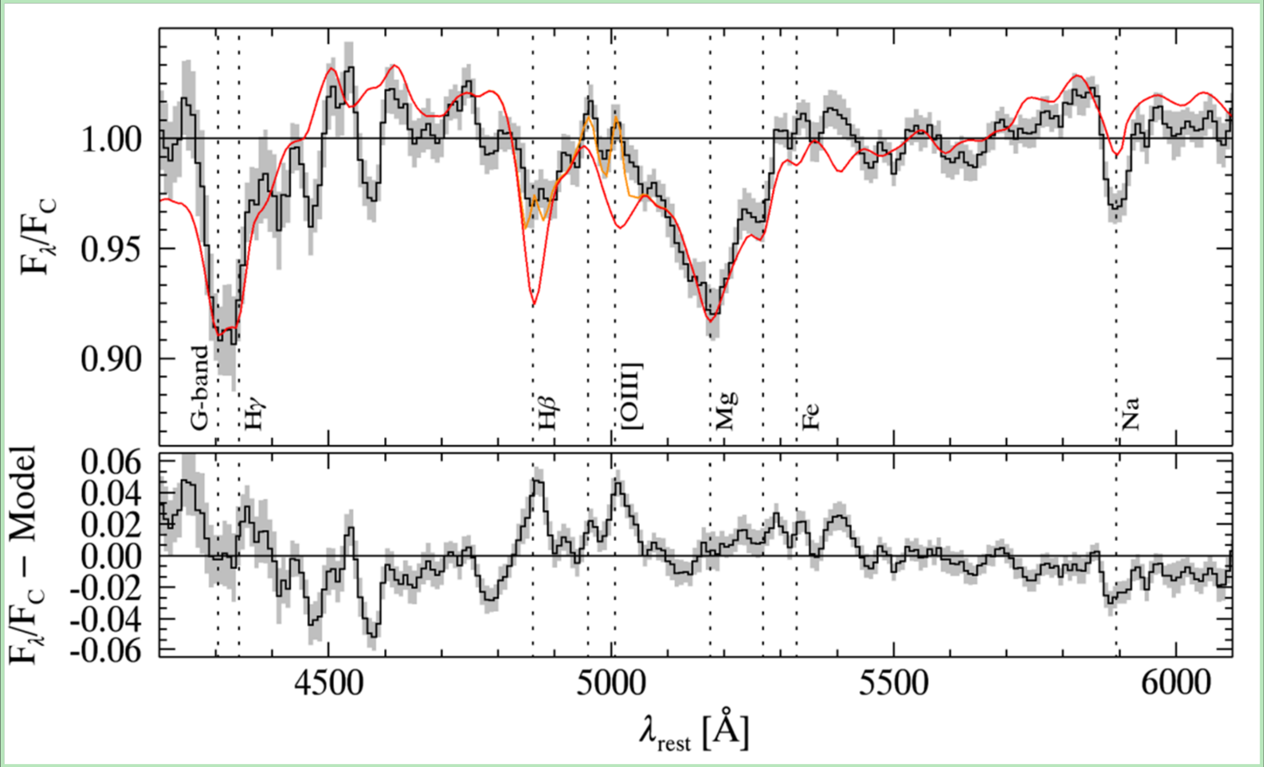
Cimatti et al. (2008)

- **Some spectroscopically confirmed, basically through stacks (Cimatti+08, Whitaker+13, Nastasi+14)**
- **Concentrated morphology (Cimatti+08, Peth+15)**
- **Thought to be assembled at z> 2 and evolve nearly passively since then (+some minor role of gas infall and minor merging, Cimatti+08)**

The evolutionary scenario seems to be more complex…

1. Continuous arrival to RS even at higher masses (van de Sande+12, Belli+15, Hahn+15)
2. Suppression of SF at $z<2$ not abrupt (Kriek+11)
3. Size evolution by x2-3 from $z\sim2$ to $z=0$ require additional mechanisms (Cimatti+08, Whitaker+12)
4. Significant morphology evolution among massive galaxies down to $z\sim1$ (Buitrago+13, Talia+14)
5. Number density of quiescent massive rises by x2 since $z\sim1.5 \rightarrow z\sim0.7$ (Daddi+05, EM+10, Prieto+13, Choi+14, Prieto & EM15)
6. Properties of blue E/S0's with mass and z (Huertas-Company+11, Sil'chenko+12)
7. AGN cannot be the key quenching mechanism (Yesuf+15)

How quiescent and old are these galaxies?



Whitaker et al. (2013)

- Stack of 171 red (UVJ) galaxies of HST/WFC3 G141 data
- log M/Msun > 10.5
- 1.4<z<2.2

⇓

- SSP-ages ~1.6 Gyr
- [OIII] and Hβ residual emission

- Are massive RS galaxies at z~2 really so "quiescent" and "old"?

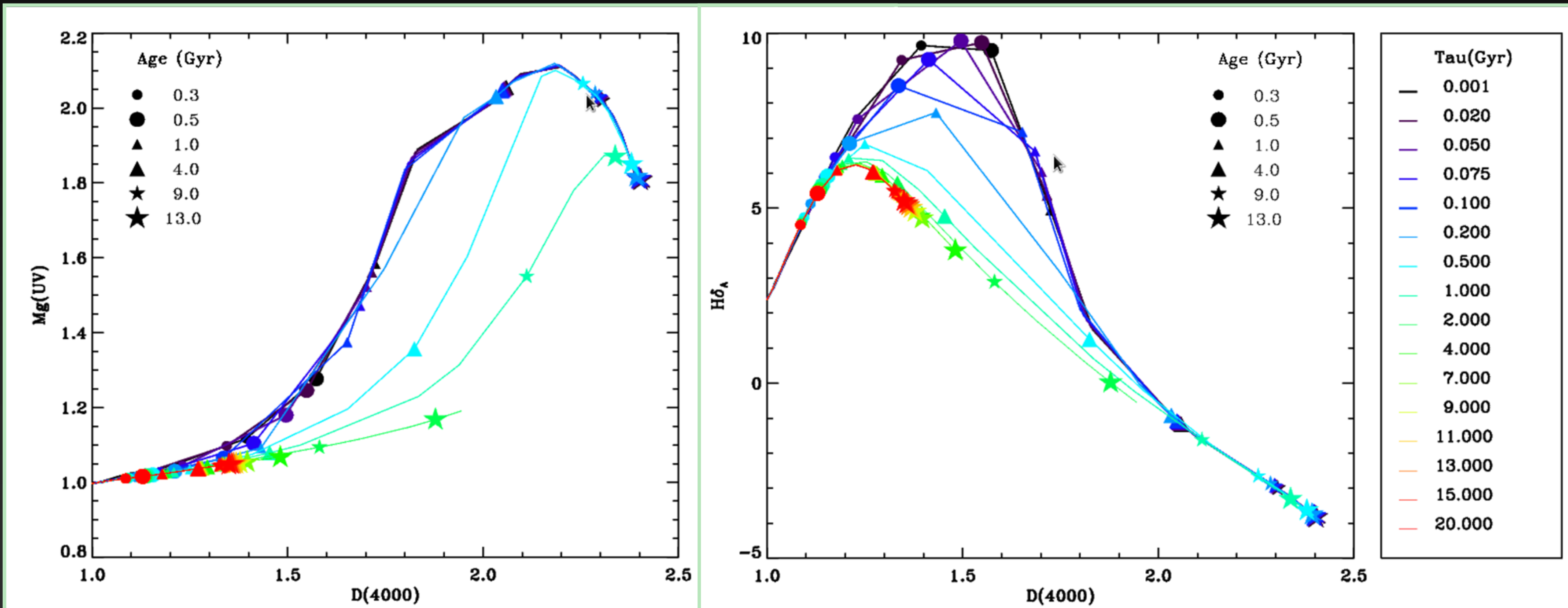
Goal

- **Investigate level of quiescence of RS massive galaxies at $1.4<z<2.2$**

- **<u>How</u>: estimate ages and SF timescales using τ models and indices to break degeneracies**
- **<u>Why</u>: photometry-spectroscopy combination provides complementary diagnostics from NUV to NIR (old populations from SHARDS, recent SF from grism)**

<u>Whitaker+13</u>	<u>Present study</u>
- G141	- SHARDS +G102 + G141 + broad-band (Barro+11a,b,13, Pérez-González+13)
- H (F140W) < 22.8	- H (F140W) < 25.5, Y(F105W) < 24
- $\Delta z / z \sim 0.0035$	- $\Delta z/z \sim 0.03$ (Barro+11)
- CANDELS (171 UVJ-selected)	- GOODS-N (23 if SHARDS+grism)
- SSP models	- τ models

Spectral indices traced by SHARDS



- Mesh of τ models (B&C03) : ≠ ages, τ, A(V), Z
- Libraries of indices at different resolutions
- Diagrams that distinguish ages > 0.3 Gyr and τ > 0.5Gyr:

Mg(UV)–D4000   β2640–Mg(UV)   TiO2–D4000   CaT–D4000   HδA –D4000

Data selection

General:
- UVJ (Whitaker+11, +13)
- log M/Msun > 8

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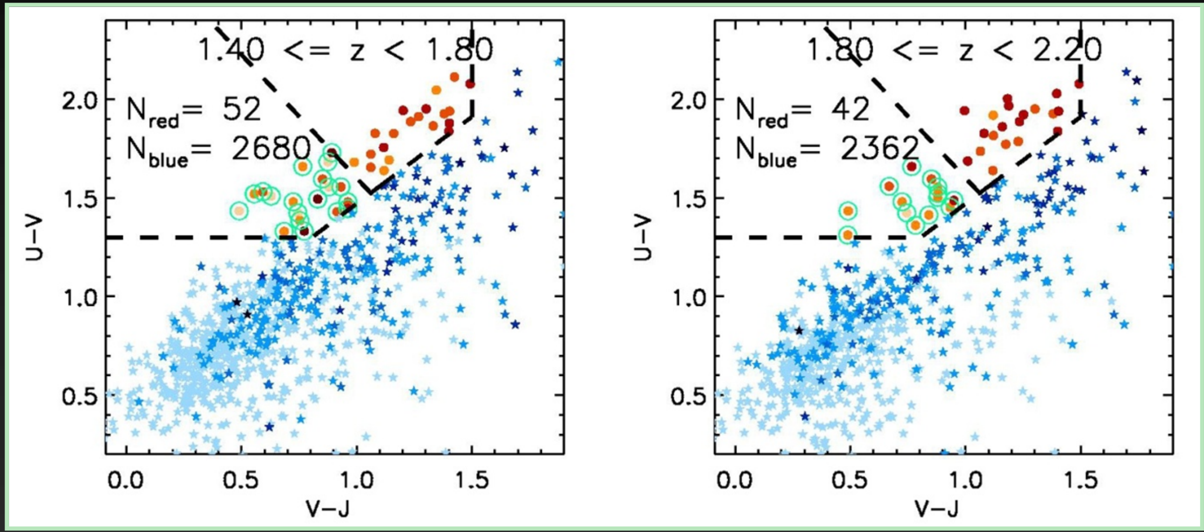
N total = 703
N G141 = 409
N G102 = 253



For this study:
- log M/Msun > 10.5
- 1.4<z<2.2

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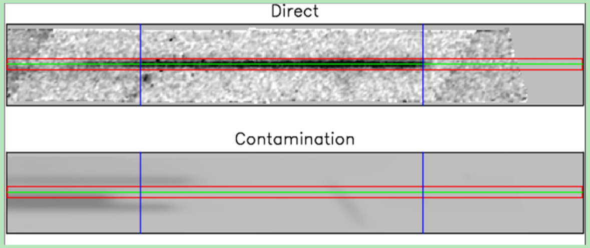
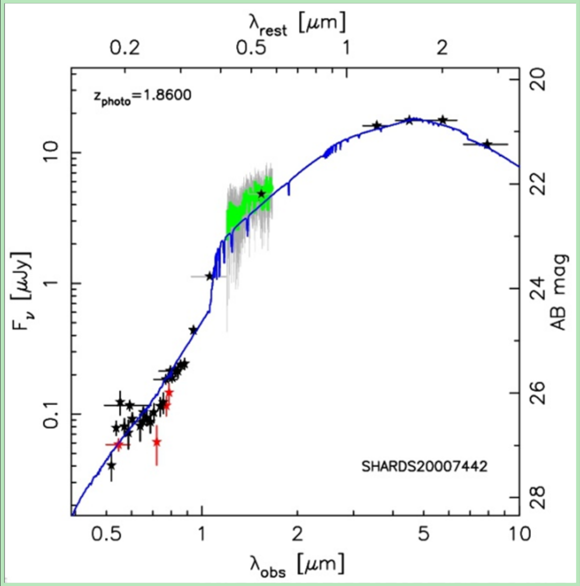
N total = 63
N G141 = 21
N G102 = 6

N SHARDS+grism = 23





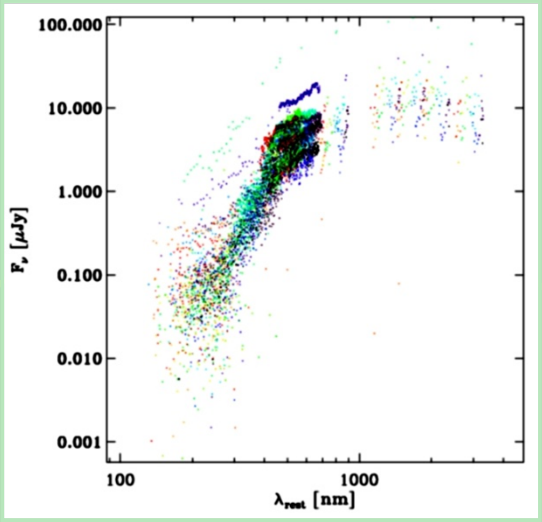
Two stacking approaches

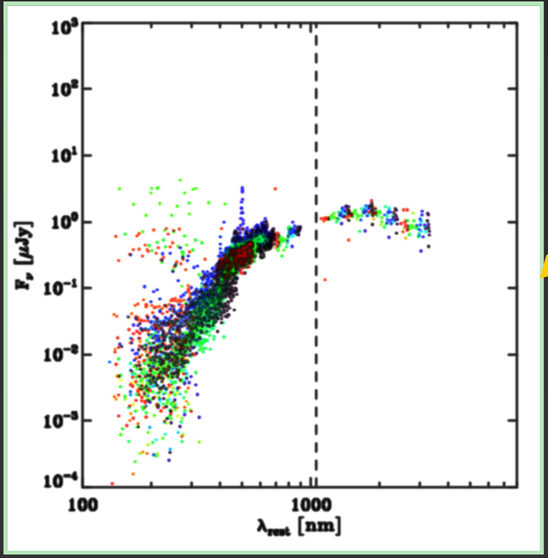
1) Cimatti+08 way: all data

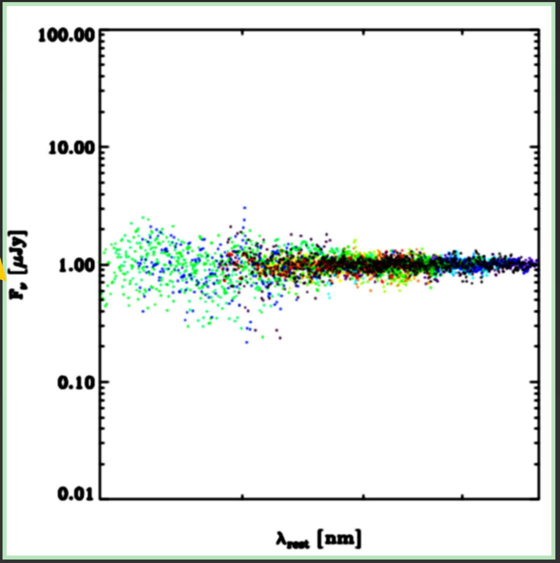
- Normalizing to Y-band
- Continuum constrains extinction (all data)
- Indices of absorptions/breaks in UV to constrain solutions of age (SHARDS, grism)

2) Whitaker+13 way: grism

- Normalizing to continuum
- Emission and absorption lines in grism and (some) in SHARDS constrain better age and τ



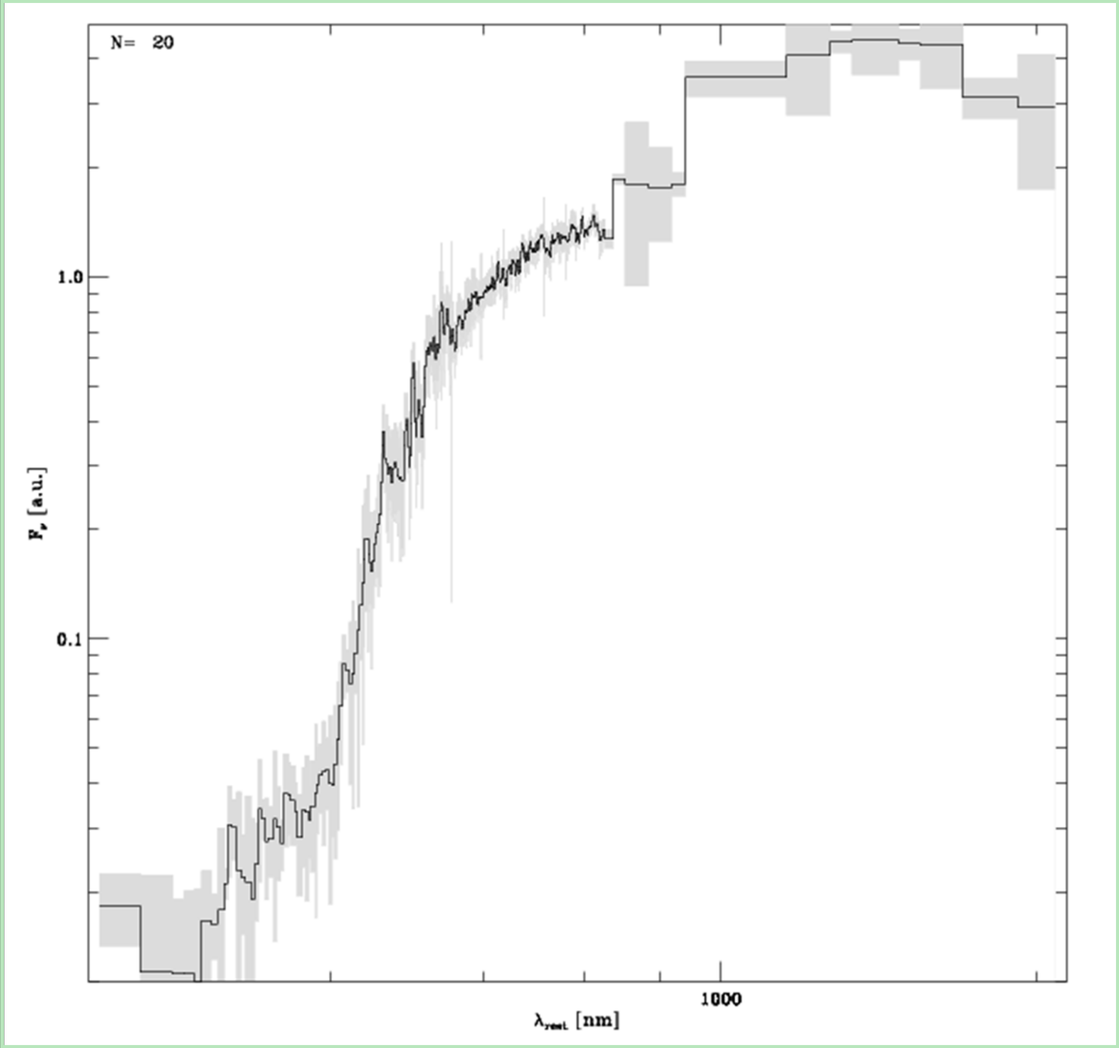




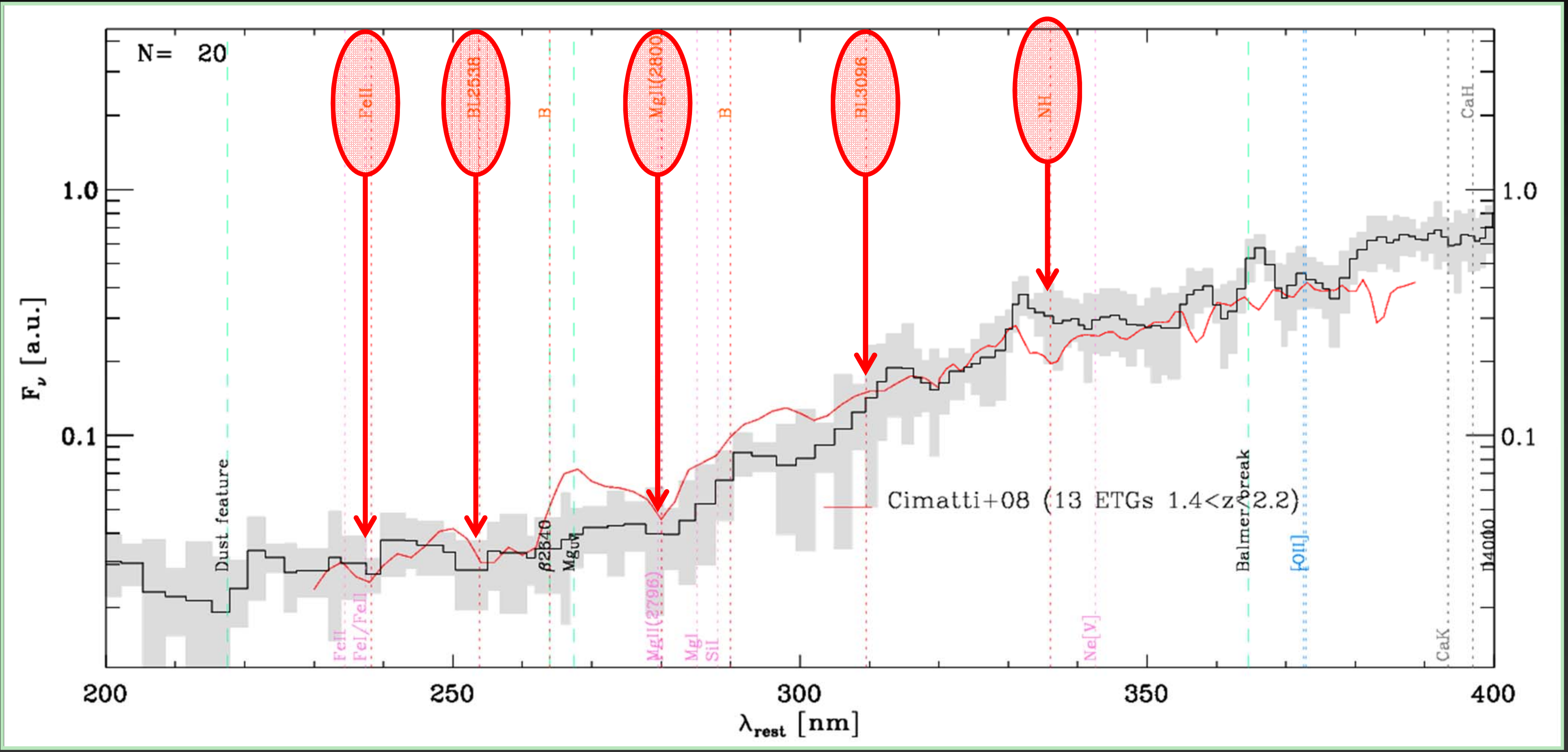
1) Results:
Y-norm stack UVJ massive @1.4<z<2.2 (total)

- Removed 3 ELGs in the sample

⇒ Stack of 20 objects

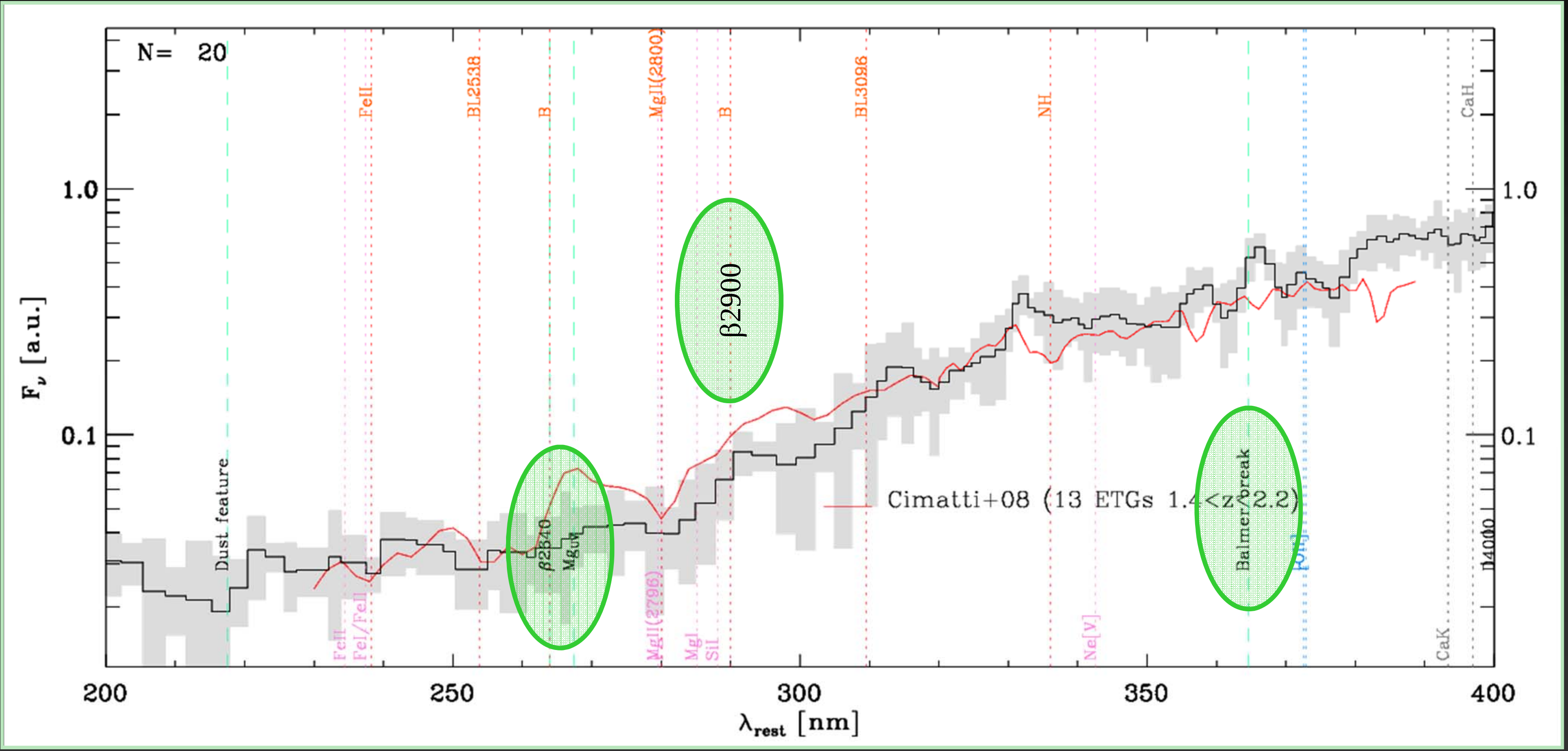


1) Results:
Y-norm stack UVJ massive @1.4<z<2.2 (NUV)



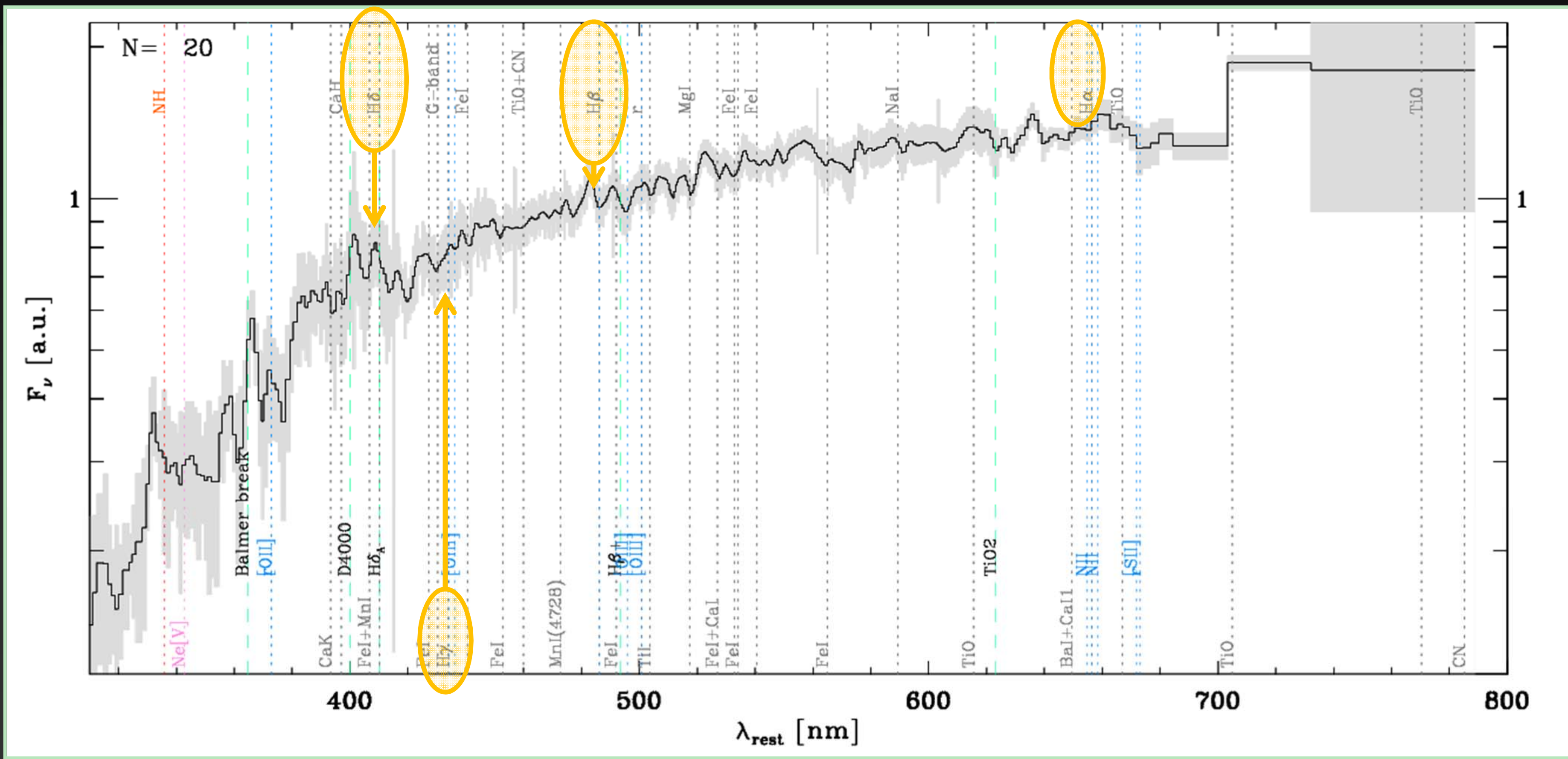
- **Similar absorption features as stack of 13 passive galaxies 1.4<z<2 in NUV (Cimatti+08)**

1) Results:
Y-norm stack UVJ massive @1.4<z<2.2 (NUV)



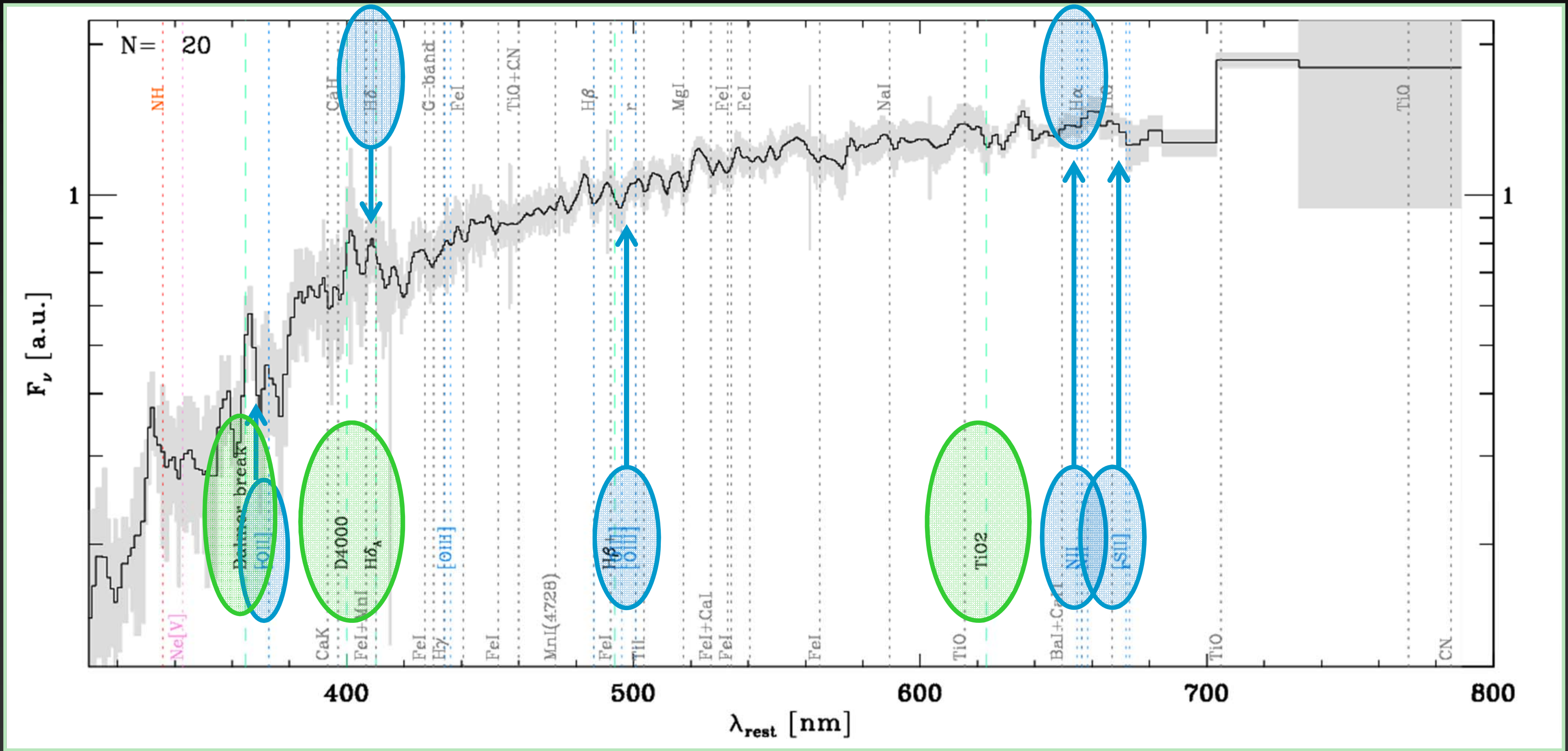
- **Stack of SHARDS data samples λ2640, λ2900 breaks, and Mg(UV) feature**

1) Results: Y-norm stack UVJ massive @1.4<z<2.2 (optical)



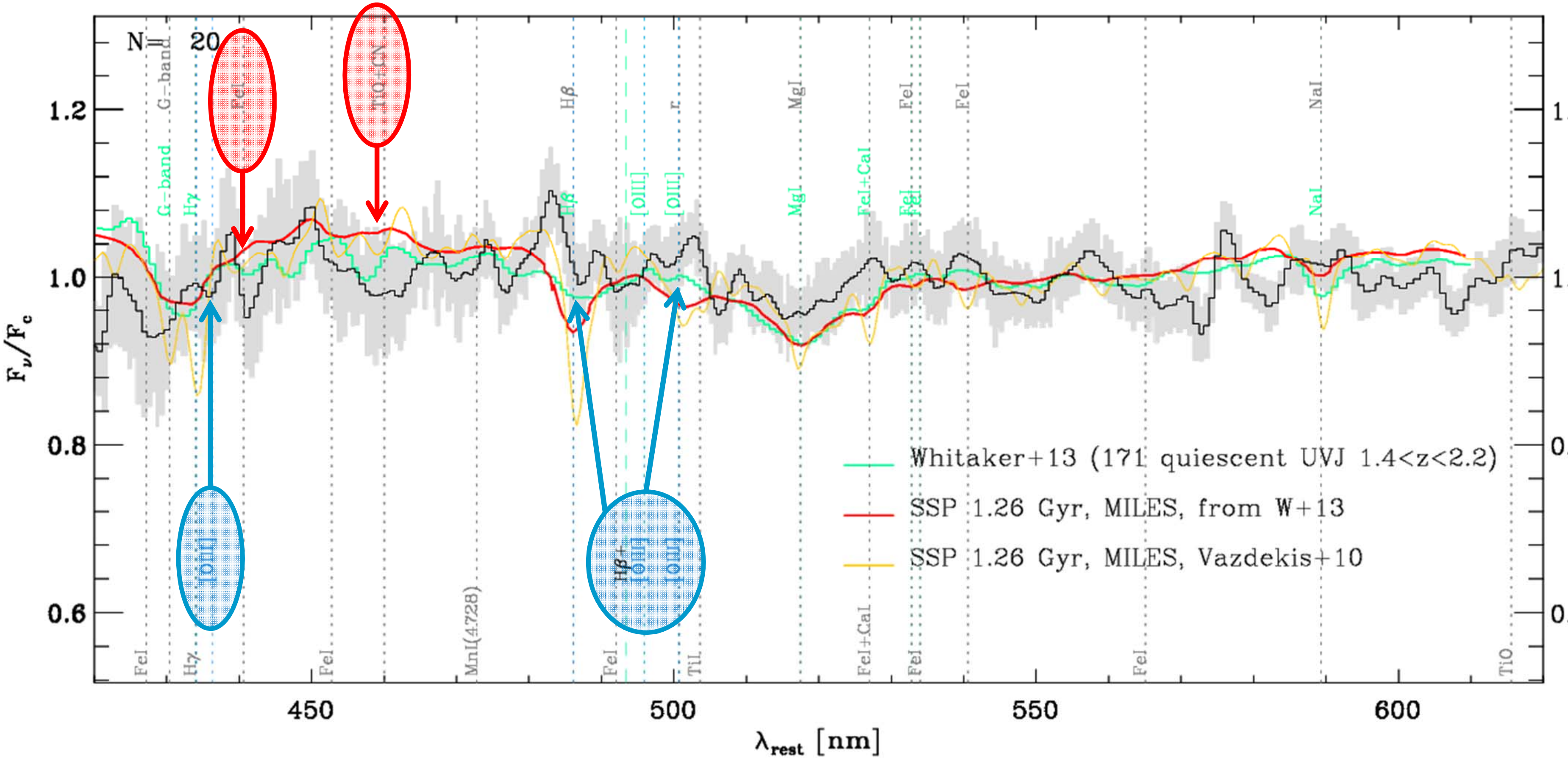
- Several absorption features, e.g., CaK and H, G-band, FeI, Mg, NaI, (TiO?)
- Not prominent Balmer absorption lines

1) Results:
Y-norm stack UVJ massive @1.4<z<2.2 (optical)



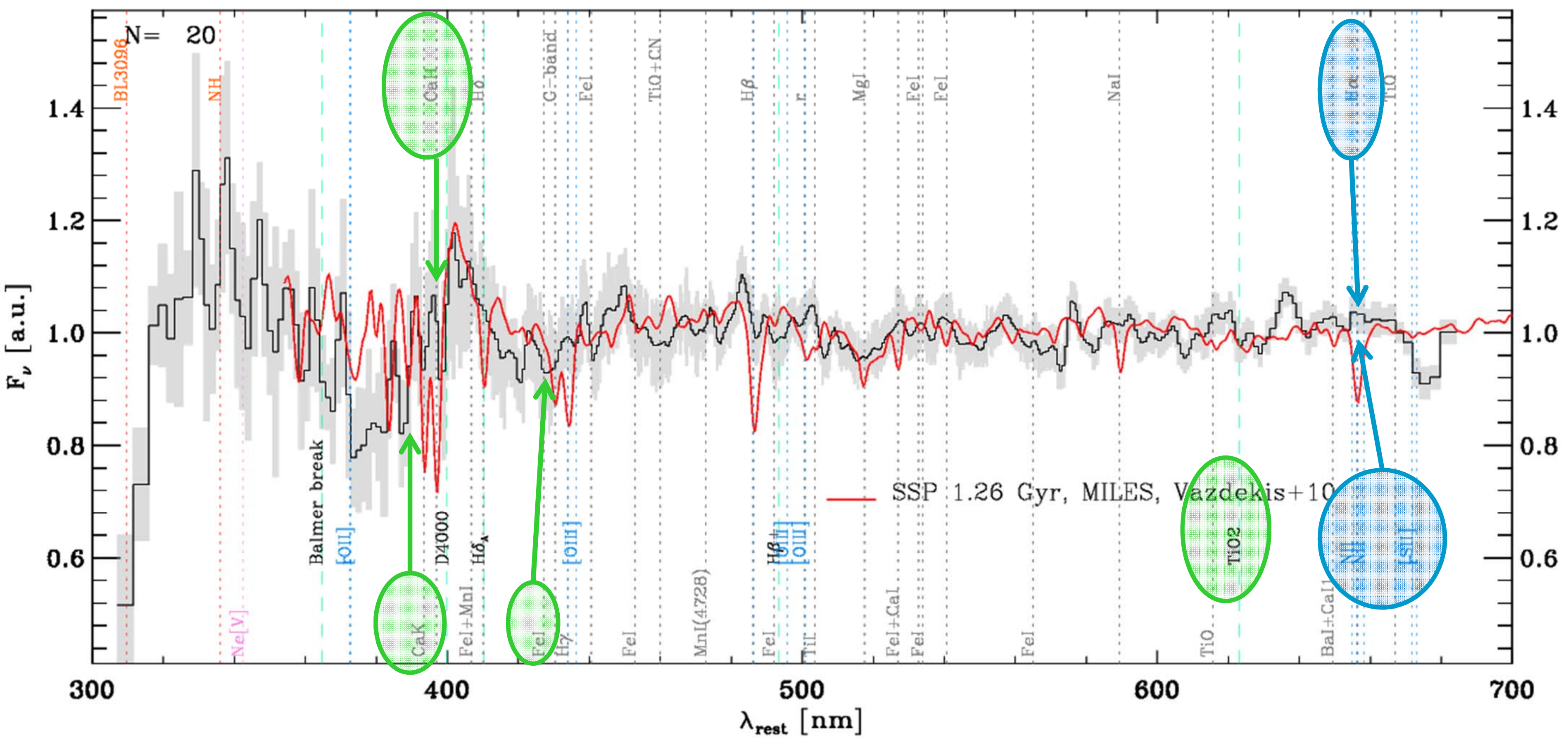
- Clear emission features, even in Balmer lines
- Stack of grism data samples breaks Balmer and λ4000 breaks, and HδA and TiO2 indices

2) Results:
Cont.-norm stack UVJ massive @1.4<z<2.2



- We detect the same absorption features as Whitaker+13 (lower)
- But more emission in [OIII], Hβ, and higher absorption in some lines

2) Results:
Cont.-norm stack UVJ massive @1.4<z<2.2



- Slightly wider λ coverage than Whitaker+13 (lower)
- We can trace some additional features

What's next?

1. Additional tests to reliability of stacks (young/old)

2. Fit τ models to Y-band normalized stack → constrain age, τ, A(V)

3. Measure indices to check consistency of solutions in index-index diagrams → reduce degeneracy of solutions

4. Adapt models to run synthesizer in continuum-normalized mode

5. Fit cont.-normalized stack to these models using previous constraints → final robust age, τ estimates for these galaxies

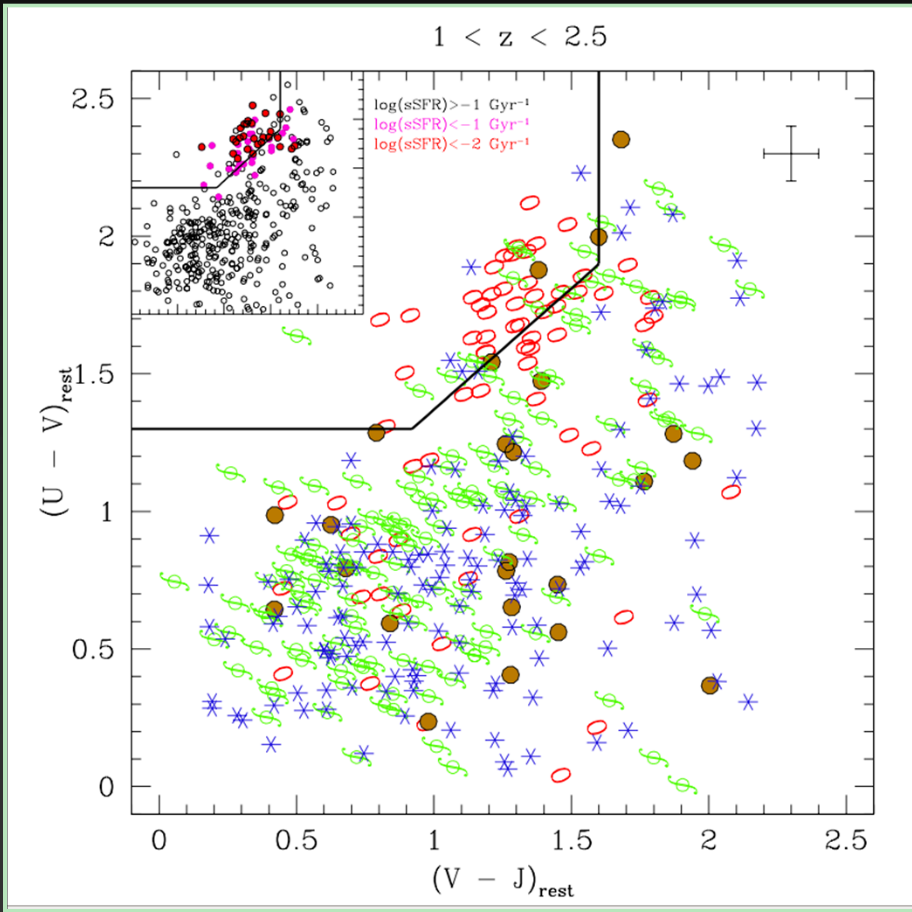
Summary

1. Analysis of a sample of 62 massive red (UVJ) galaxies at 1.4<z<2.2 in GOODS-N to characterize their level of quiescence and ages
2. SEDs from rest-frame NUV to NIR combining GTC/OSIRIS SHARDS data, HST/WFC3 in G102 and G141, and ancillary broad-band data from Rainbow database (23 objects if SHARDS+grism data)
3. Selection of most appropriate index-index diagrams to break age - τ degeneracy in τ models

4. Y-band normalized stack: absorption features characteristic of evolved populations in NUV (as Cimatti+08), but low Balmer absorption lines and relevant [OIII], [NII] emission in optical
5. Continuum-normalized stack: stronger residual SF than Whitaker+13 stack, weaker absorption features

6. Working on combination of results from best-fit models to both stacked spectra and index-index diagrams to constrain age and SF decaying timescale

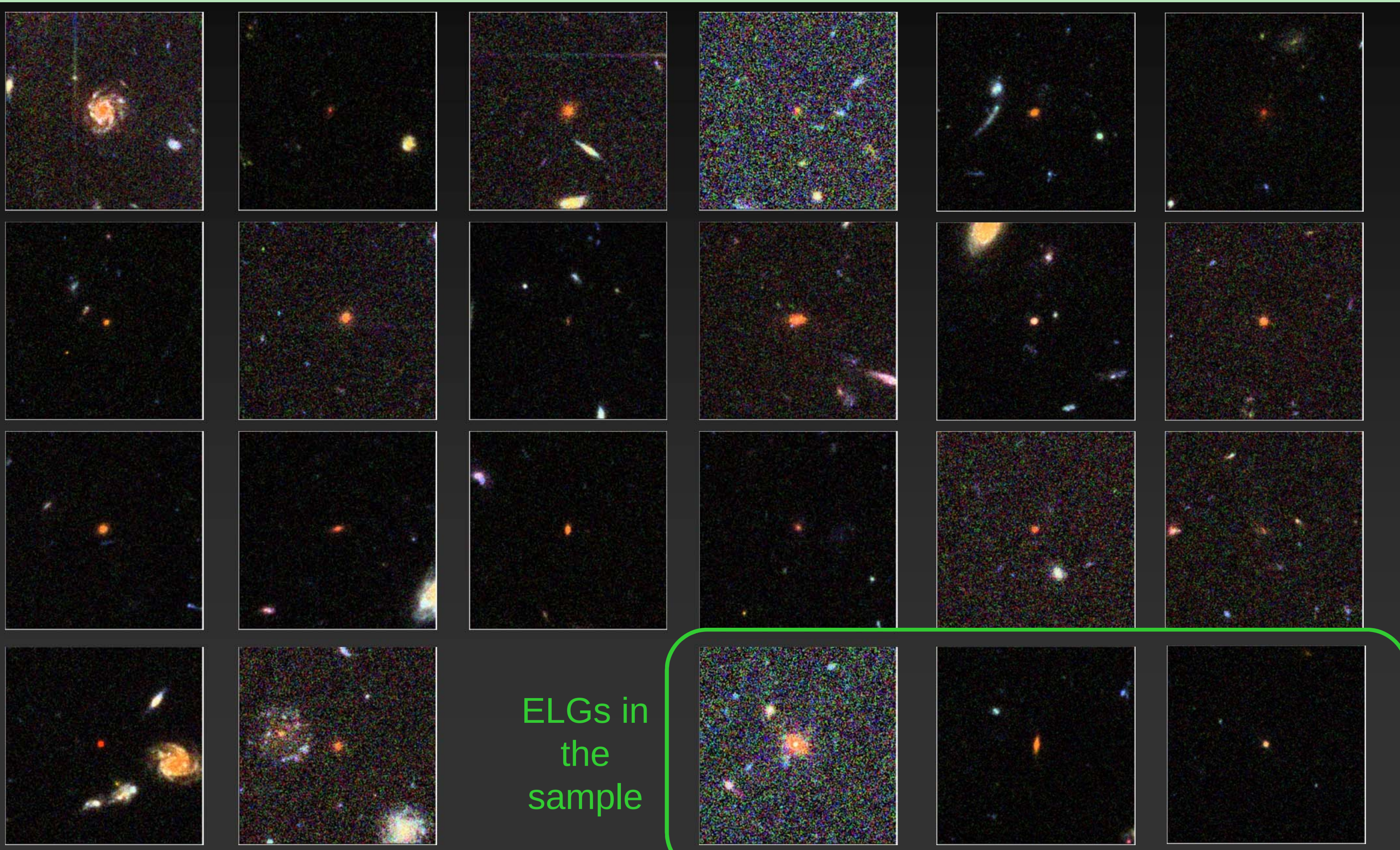
The evolutionary scenario seems to be more complex…



Talia et al. (2014)

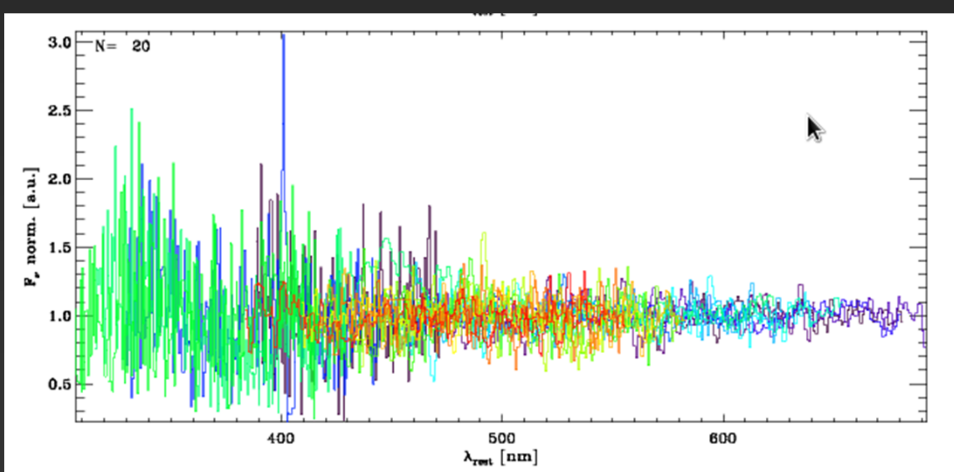
1. Continuous arrival to RS even at higher masses (van de Sande+12, Belli+15, Hahn+15)
2. Suppression of SF at z<2 not abrupt (Kriek+11)
3. Size evolution by x2-3 from z~2 to z=0 require additional mechanisms (Cimatti+08, Whitaker+12)
4. Significant morphology evolution among massive galaxies down to z~1 (Buitrago+13, Talia+14)

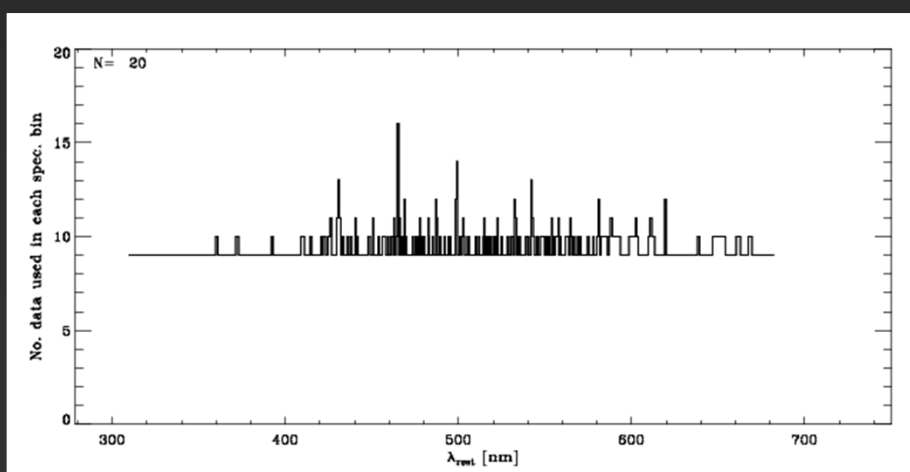
Morphologies



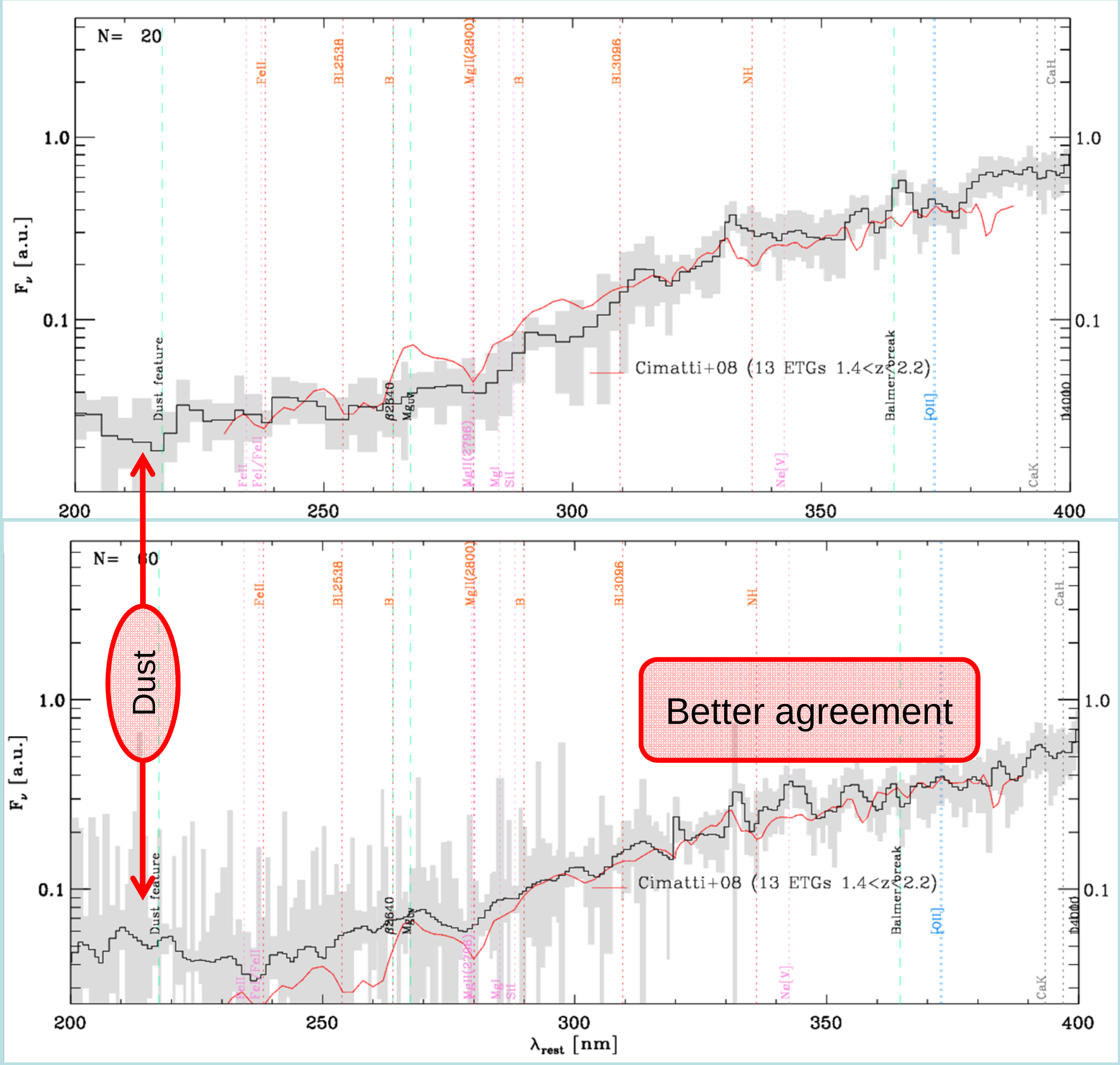
Stacking methods

- Normalization to continuum vs. Normalization to flux in λ range
- Median vs. Mean
- STD errors vs. Bootstrap errors
- Fixed resolution in λ ranges vs. Adaptive spectral resolution
- Smoothing vs. No smoothing
- Rebinning prior stacking vs. No rebinning prior stacking
- Weighting by S/N vs. No weighting





Comparison of stacks with different selections



Results:
1) Y-norm stack of massive galaxies at 1.4<z<2.2