STELLAR POPULATION SYNTHESIS TO IMPROVE TEMPLATES FOR PHOTOMETRIC REDSHIFTS ESTIMATION

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PHENIICS FEST, IJCLAB

MAY 16, 2024

OUTLINE

1. A few words on redshift
2. Estimation from photometry : how can we do?
3. Template fitting for photometric redshift
    1. How does it work?
    2. What to improve?
    3. Photo-z, Dust and SPS
4. Conclusion

A FEW WORDS ON REDSHIFT

- Einstein's field equations of General Relativity :

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Friedmann-Lemaître-Robertson-Walker solution for a homogeneous and isotropic Universe :

$$ds^2 = c^2 dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2) \right)$$

- "Redshift" : analogous to Doppler shift in wavelengths of emitted photons, equivalently defined with the scale factor

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} \iff \lambda_{obs} = (1+z)\lambda_{em}$$

$$z = \frac{a_0 - a(t)}{a(t)} \iff a_0 = (1+z)a(t)$$

Redshift : essentially a measure of time

- Expansion rate ("Hubble constant" H_0 for t = today) :

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

$$H(z)^2 = H_0^2 \left(\Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + \Omega_\Lambda + \Omega_{k,0}(1+z)^2 \right)$$

Expansion of the universe : related to its contents and the redshift.
Dark Energy ↔ Acceleration of the expansion : probe contents at various redshifts

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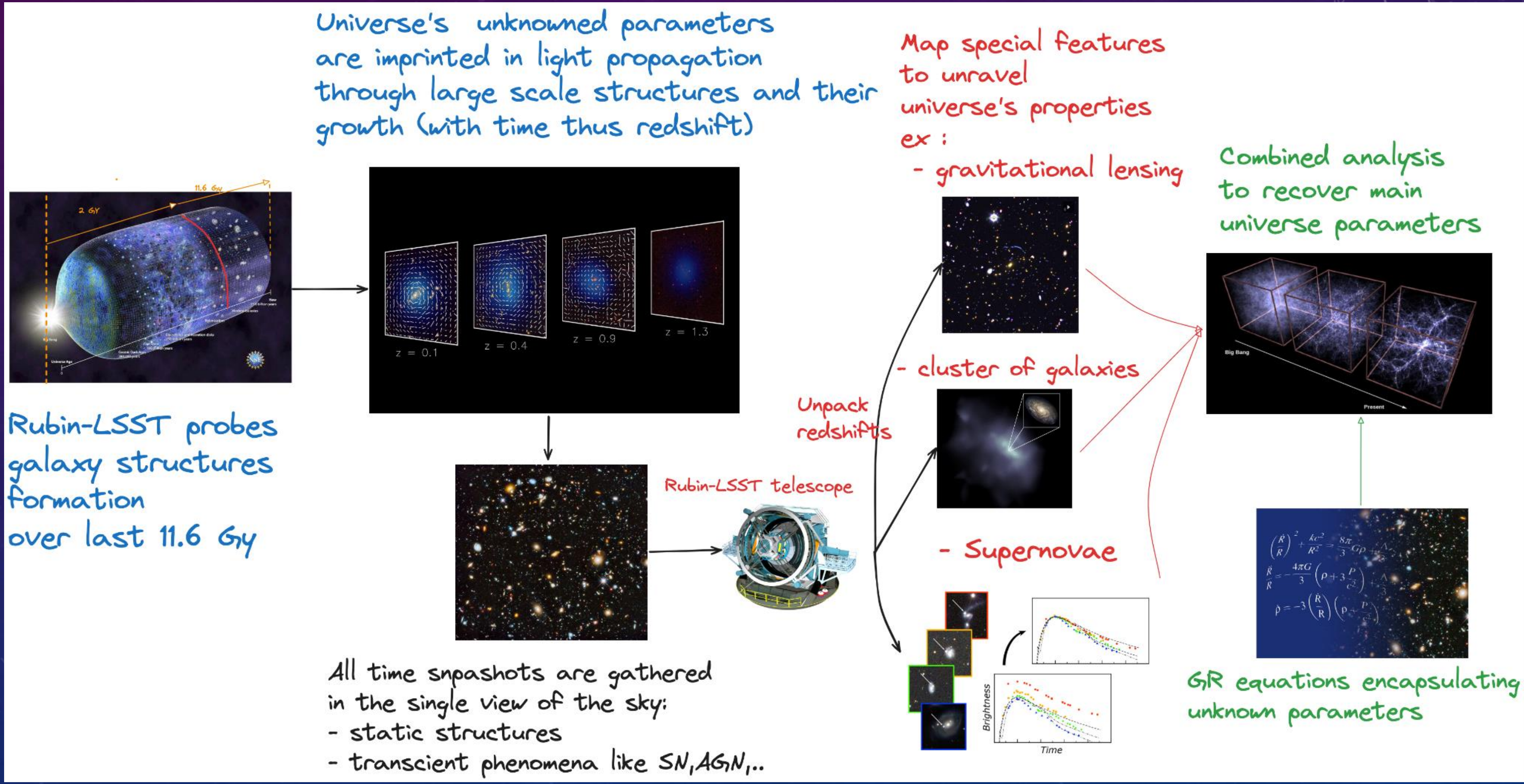

A FEW WORDS ON REDSHIFT

Redshift : analogous to Doppler shift in wavelengths of emitted photons.

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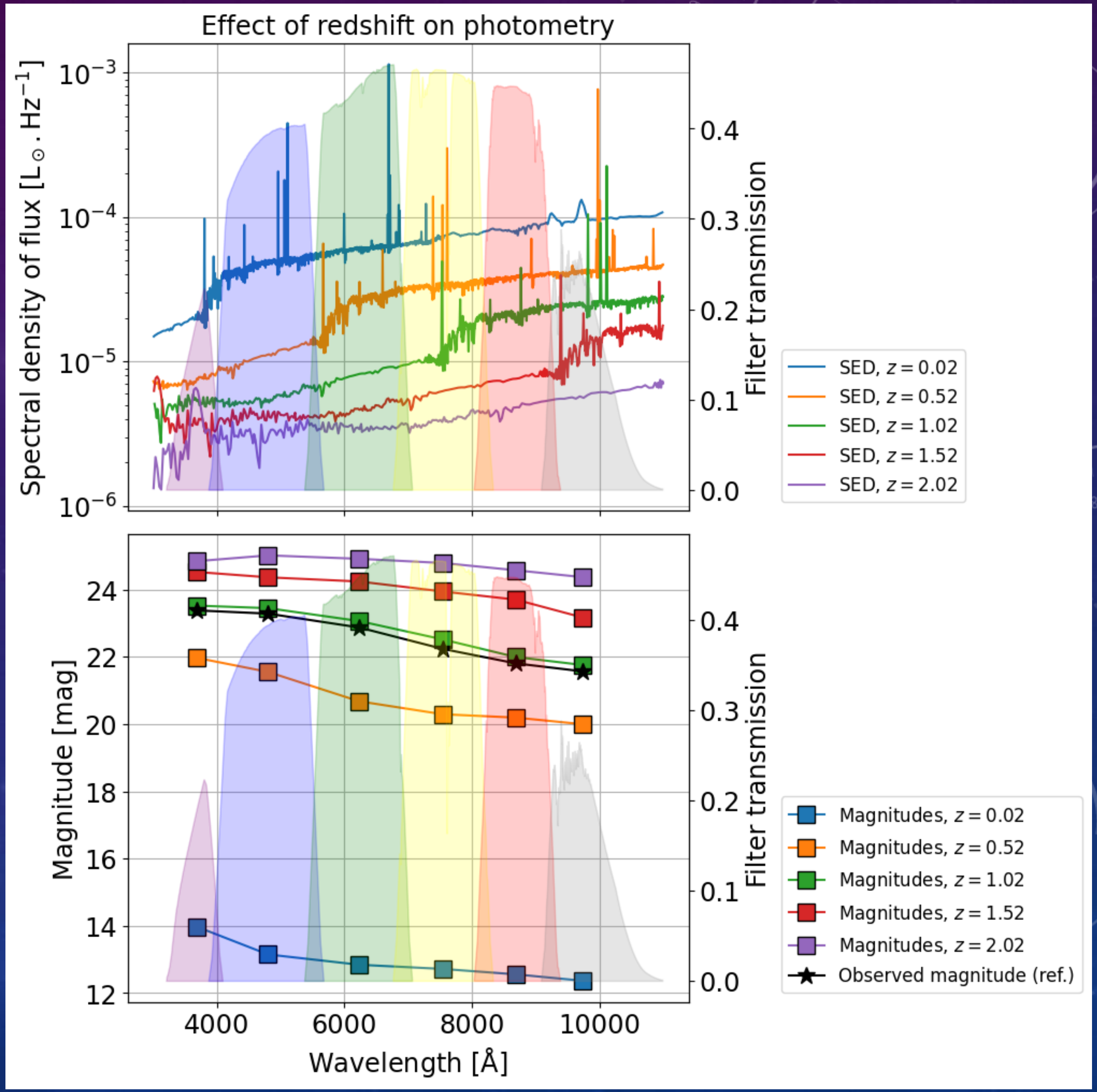
Usually computed via **spectrometry**.

Cosmological surveys (like LSST) : too many galaxies

- Spectroscopy excluded
- Redshift must be estimated from photometry, *i.e.* measuring light through wide-band filters.
- Only 6 filters in visible range for LSST. Other surveys (*e.g.* Euclid) use other passbands (infrared).

σ **Photometric redshift among the most significant sources of errors in cosmological parameters estimation**



ESTIMATION FROM PHOTOMETRY : HOW CAN WE DO?

- Historical method : template fitting
  (BPZ : Benítez, 2000 ; LEPHARE : Arnouts *et al.*, 1999 & Ilbert *et al.*, 2006)
  = compare observations to theoretical photometry from a set of well-known templates (SED)
  - Pros : easy (in theory) ; representative of established physics ; can include the effects of many physical phenomena
  - Cons : SED templates from local Universe may not match actual galaxies in distant Universe ; degeneracies
- Trending : neural networks *et al.*
  (FlexZBoost : Izbicki & Lee, 2017)
  = train the code on a dataset {photometry + redshift} then estimate the redshift of observed {photometry}
  - Pros : fast once trained ; very accurate ; suited to statistics on large datasets (cosmological surveys)
  - Cons : training sets not representative of all study cases (too shallow, simulated, different photometry bands, *etc.*)

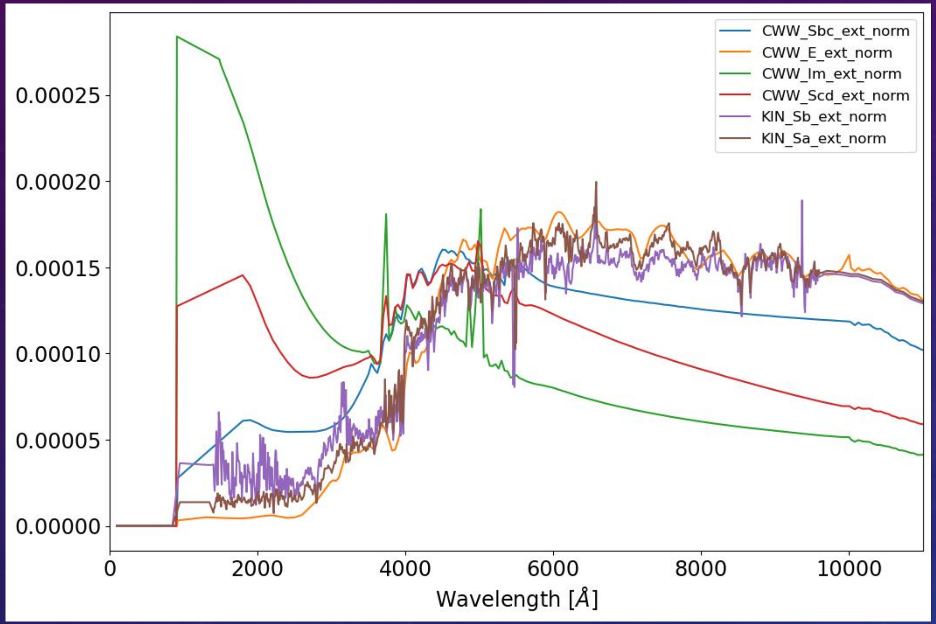
Both techniques suffer from representativeness issues, *i.e.* the availability of template SEDs and training data respectively

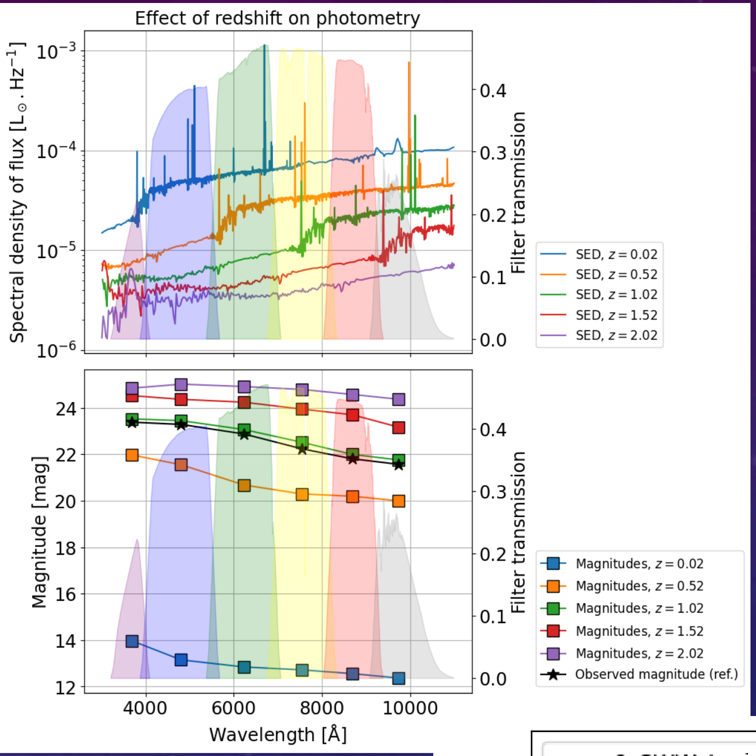
My PhD somehow

Future surveys + improved simulations

TEMPLATE FITTING : HOW DOES IT WORK?

Spectral Energy Distribution (SED) of various galaxy morphologies serve as *templates* :





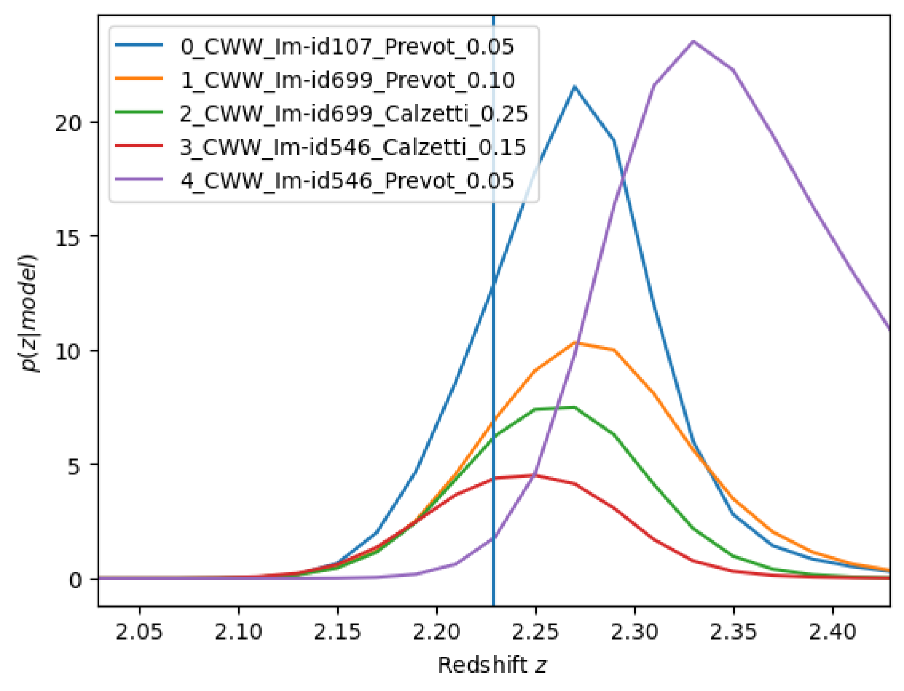
i. Recomputed for many redshift values

ii. Their photometry (fluxes in passbands) is computed

iii. Observations are compared to these references to build probability distributions of redshift values.

$$P(z) = \sum_{\text{models}} P(z \cap \text{model})$$

iv. The most likely redshift is selected : the "**photometric redshift**"



TEMPLATE FITTING : WHAT TO IMPROVE?

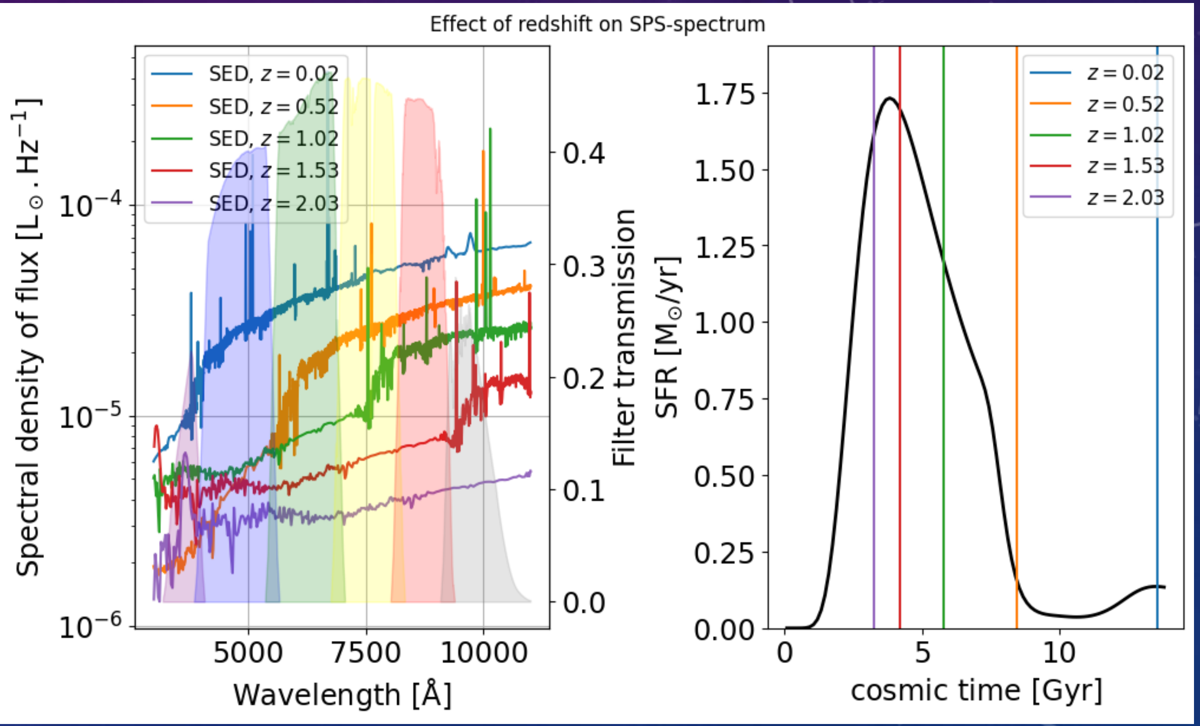
Template spectrum shifted
+ its stellar content adjusted to the epoch of emission.
Aim : better representativeness of templates at higher z

The key : representativeness.

The issue : well-calibrated templates are mostly local, observations will be distant.

The fix : use Stellar Population Synthesis (SPS) and Star Formation History (SFH) to improve SED templates.

The idea : compare the radiation emitted by "young" galaxies to "younger" versions of the templates, as the stellar content evolves with time.



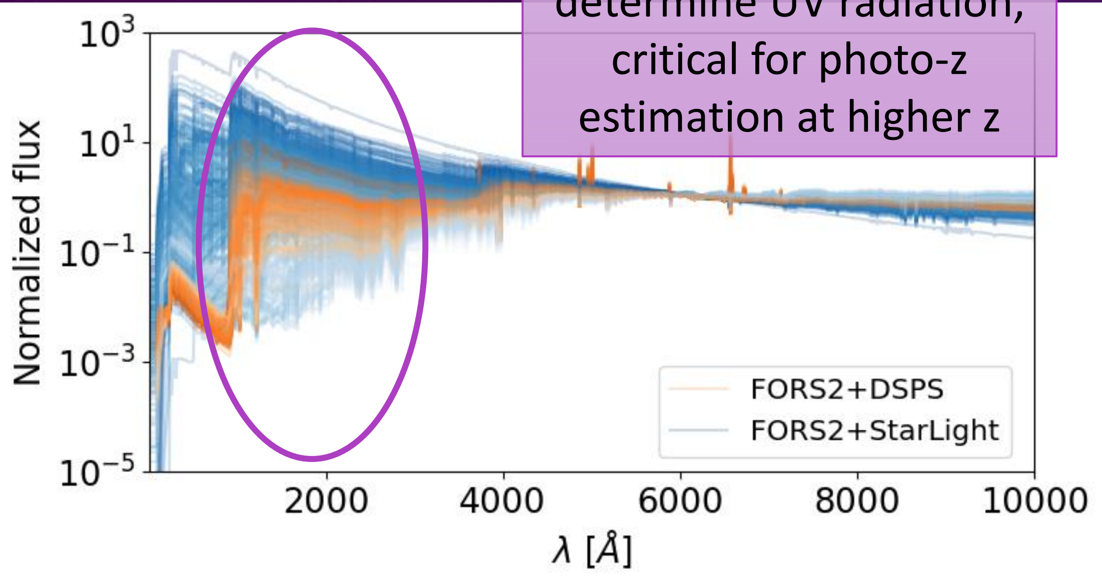
Galaxies = stars + dark matter + other (dust, gas…)

Emit the light we observe (~ black body)

Alter the signal

→ **SPS = fit models of galaxy contents to observations** → **Use the results as (or instead of) SED templates**

PHOTO-Z, DUST AND SPS

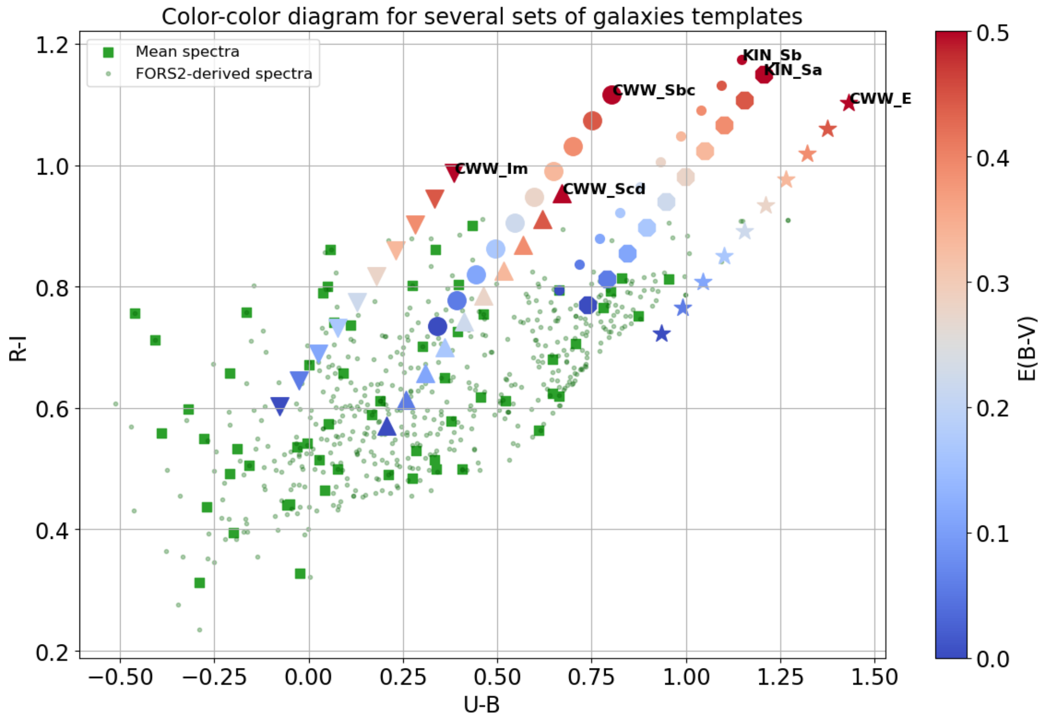


Dust extinction and SFR determine UV radiation, critical for photo-z estimation at higher z

Dust :

- ✓ necessary for good representativeness
- × Yields degeneracies with photo-z

→Requires careful treatment



UV-light :

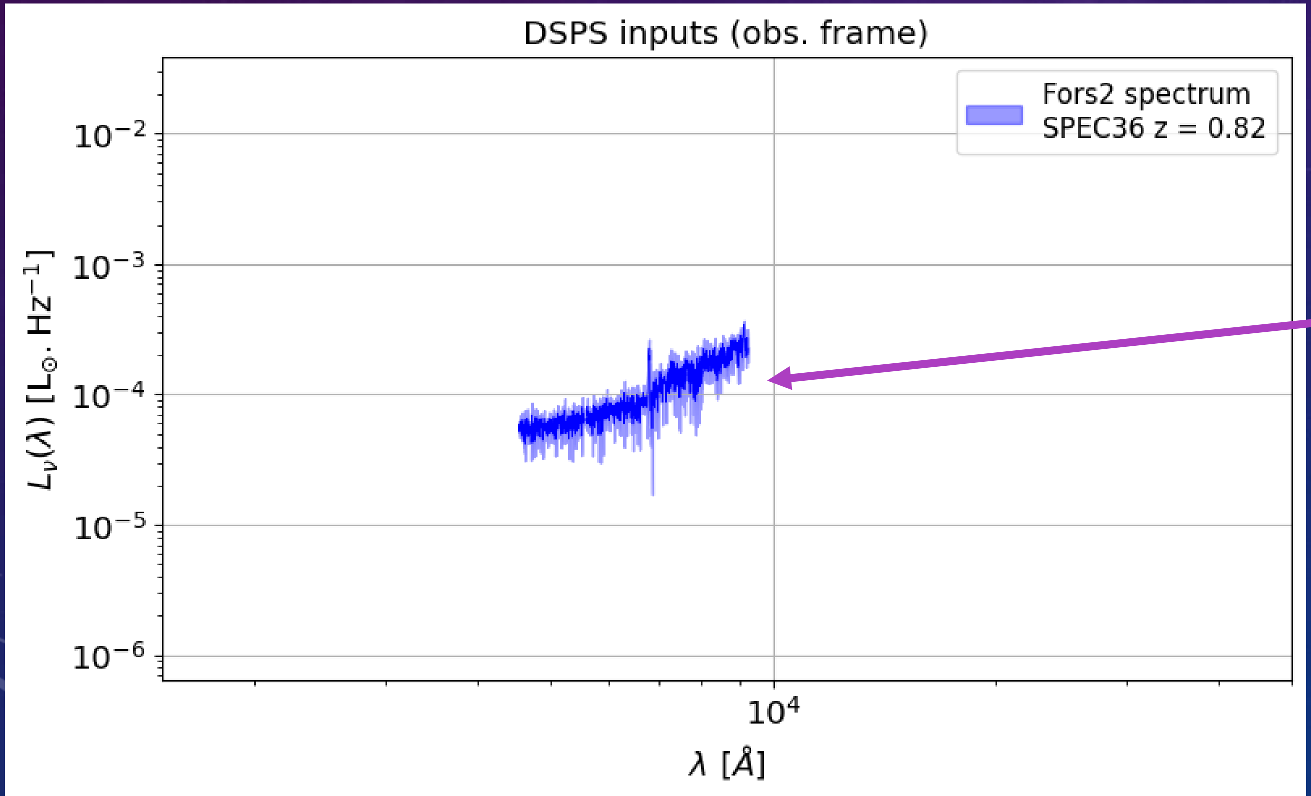
- Shifted into visible : key to high z
- Related to Star-formation
- Absorbed by dust

Good photo-z = Star-formation + dust

PHOTO-Z, DUST AND SPS

Guideline :

- UV in templates is key to good photo-z
- Observations in UV can yield SFR and hints to dust,
- Observations in infrared can constrain dust (via re-emission),
- Spectroscopy (emission lines) can constrain SFR.



Observed spectra from FORS2 at VLT (Giraud *et al.*, 2011)

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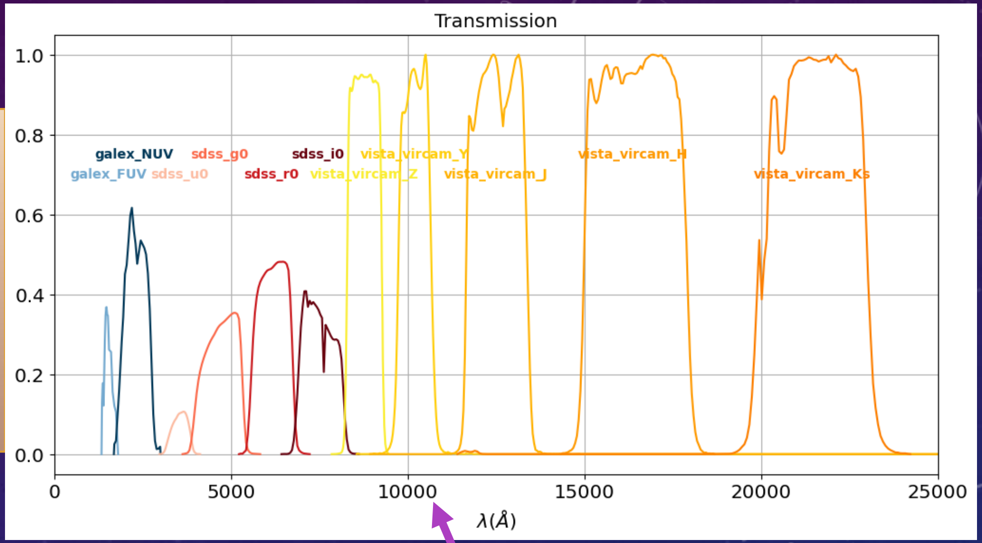

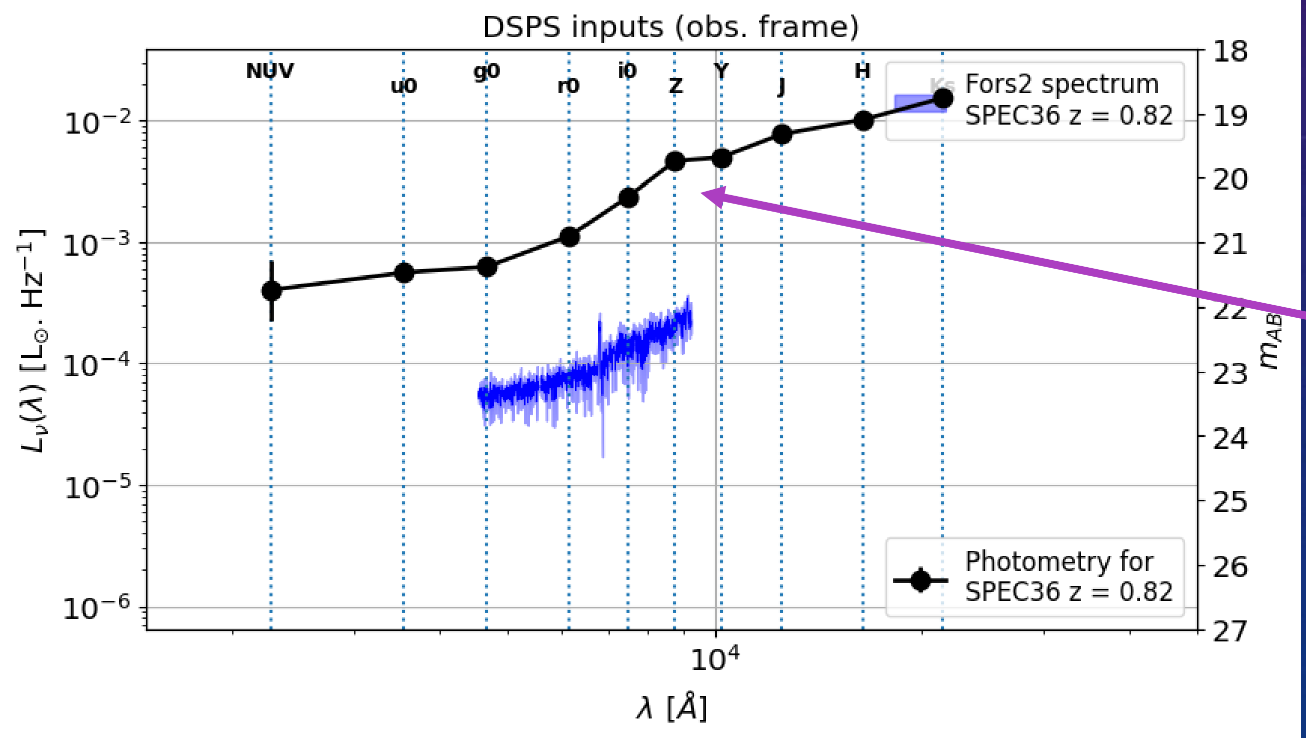

Cross-matched with photometry from UV to IR
(Kuijken *et al.*, 2019 ; Morrissey *et al.*, 2007)

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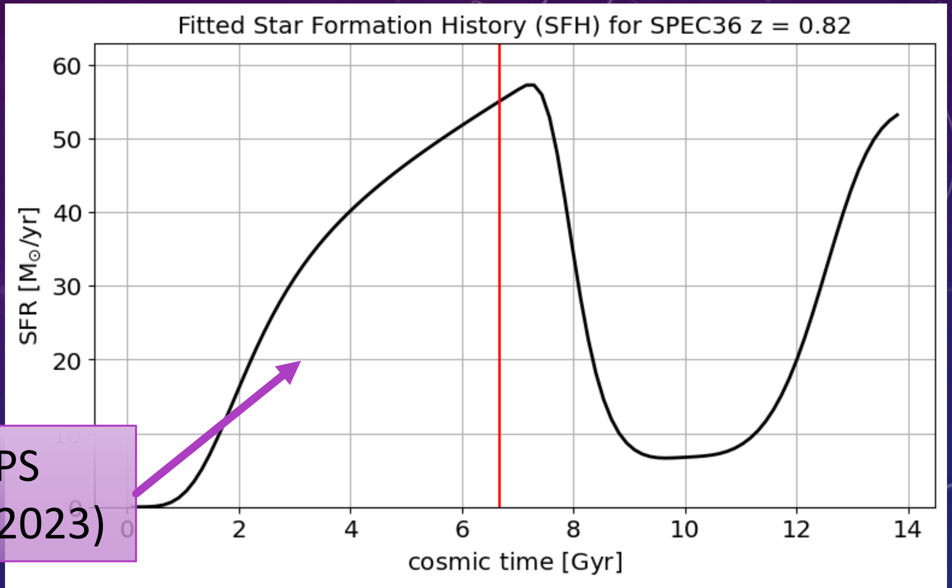
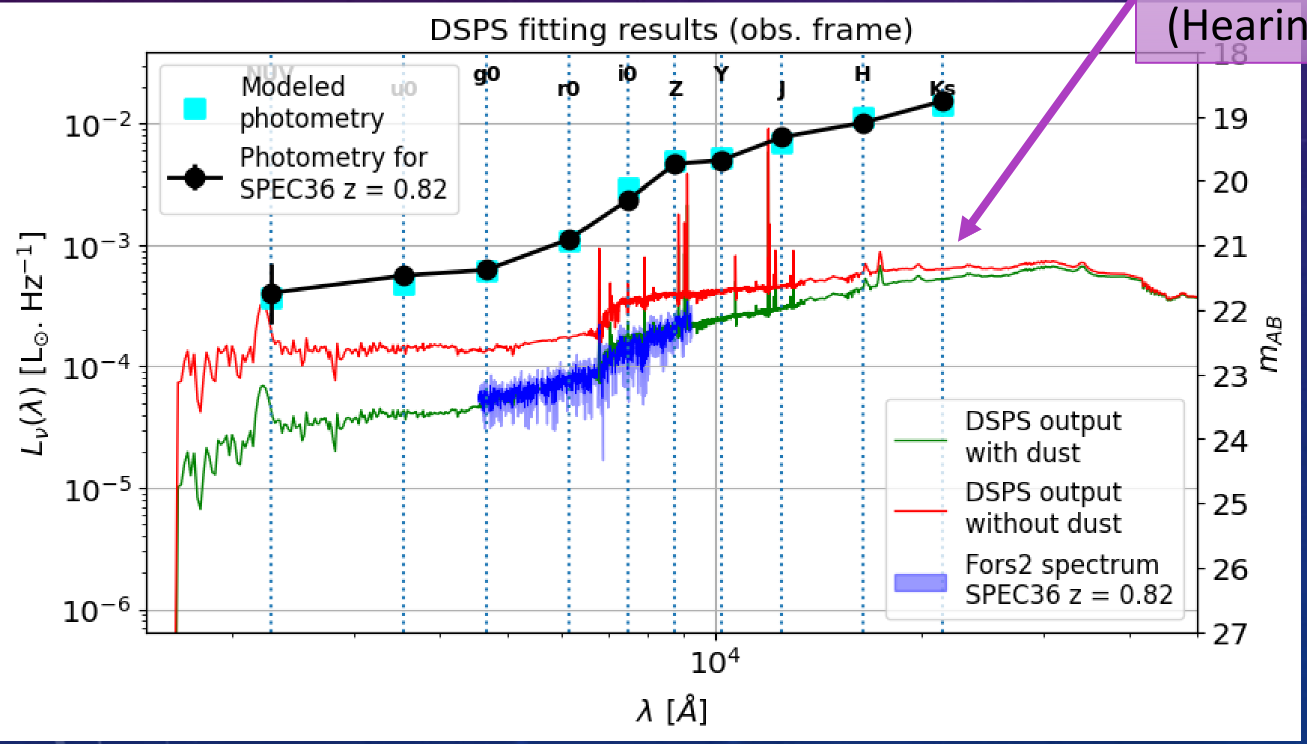
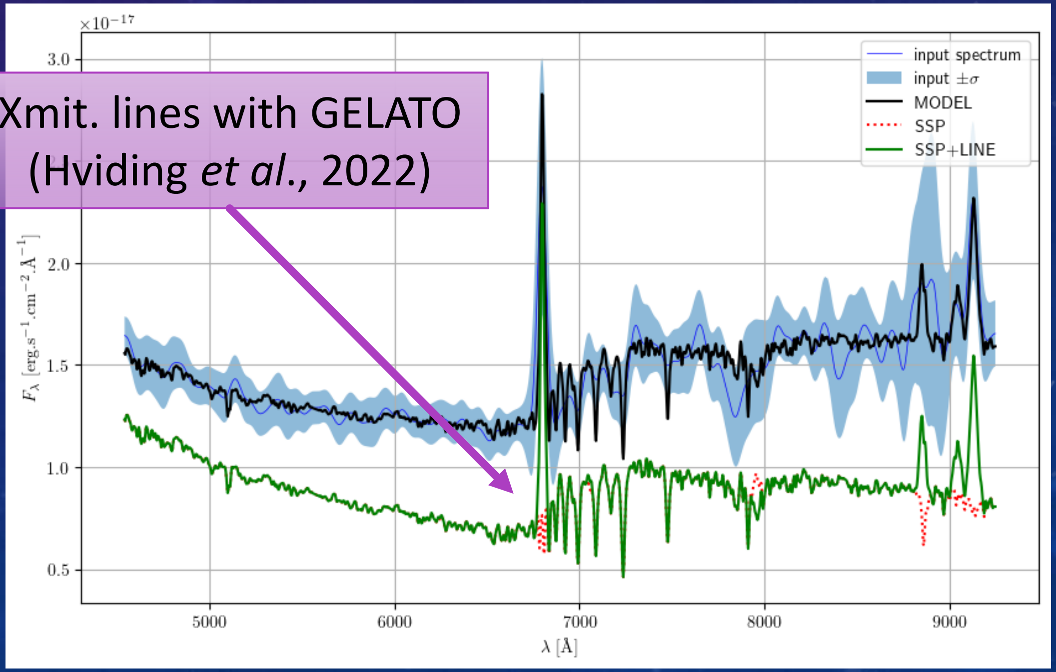


Fit with DSPS
(Hearin *et al.*, 2023)



Xmit. lines with GELATO
(Hviding *et al.*, 2022)



CONCLUSION AND TAKEAWAYS

- Aim : improve existing and/or generate new sets of templates for photo-z
- Data : FORS2, COSMOS2020, LSST+Euclid? etc.
- Tools : LEPHARE++ or other photo-z, DSPS and CIGALE for stellar population, GELATO for lines detections
- Ideas and prospects :
  - identify spectral / stellar properties of good templates (emphasis on UV)
  - explore hybrid methods (TF+ML) thanks to numerous spectra + SPS
  - improve model selection within photo-z codes

Thank you for your attention

What we're trying to avoid :