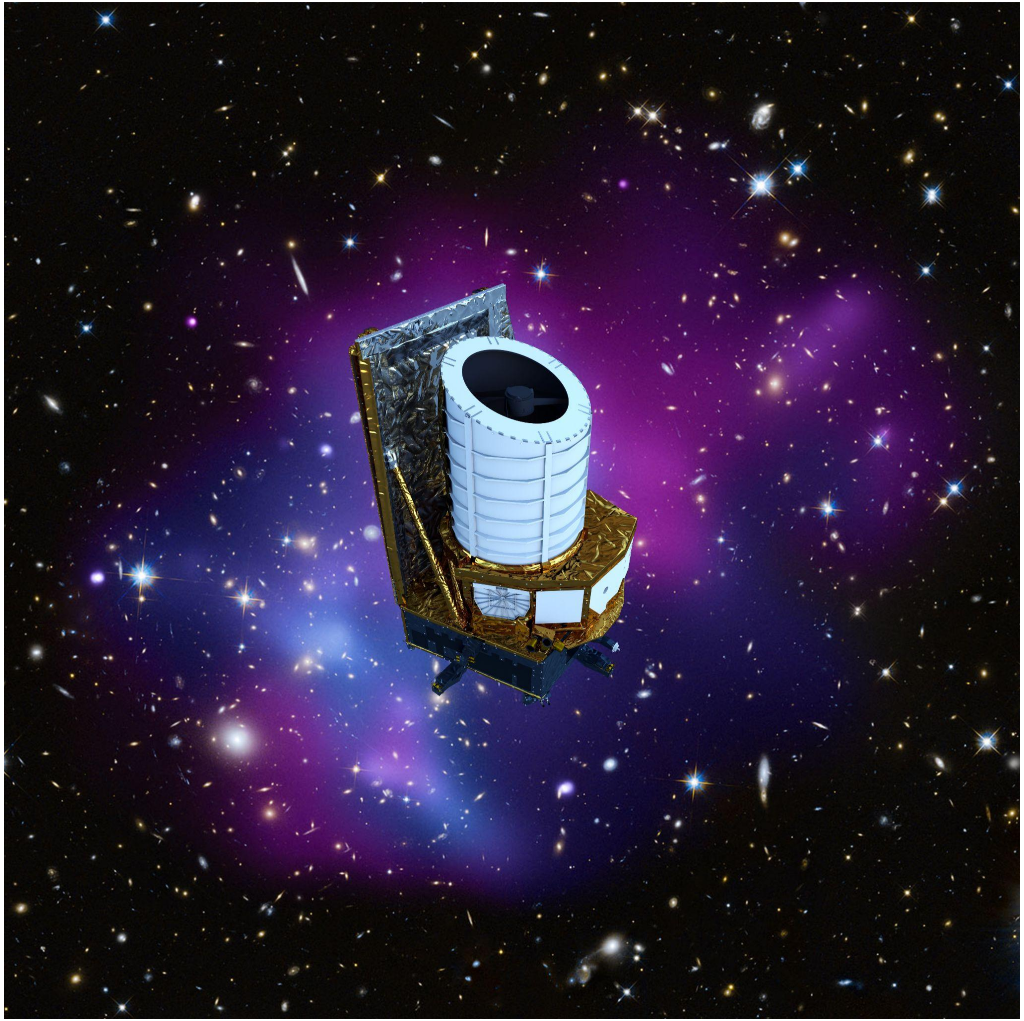
The Spectral Energy Distributions (SEDs) of Faint Galaxies

Why is this so hard?

Will Hartley, Ecogia science talk
01 November 2021

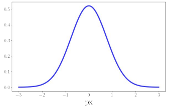
The *Euclid* mission

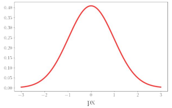
- ★ M-class mission; launch ~winter 2022/23
- ★ 1.2m primary mirror
- ★ 15,000 deg.^{2} survey (VIS~25, 10σ) + ~40 deg.^{2} of deep, reference fields
- ★ Primary science: characterising expansion history of the Universe, using weak gravitational lensing.
- ★ Two main instruments:
  - ○ VIS: broad filter imaging for measuring galaxy shapes. Critical sampling of PSF.
  - ○ NISP: imaging and slitless spectroscopy in the near-infrared.
- ★ To be combined w ground-based imaging for photometric redshifts etc..
- ★ OU-PHZ (lead @ Geneva): photo-z, object classification, **SED measurement**.

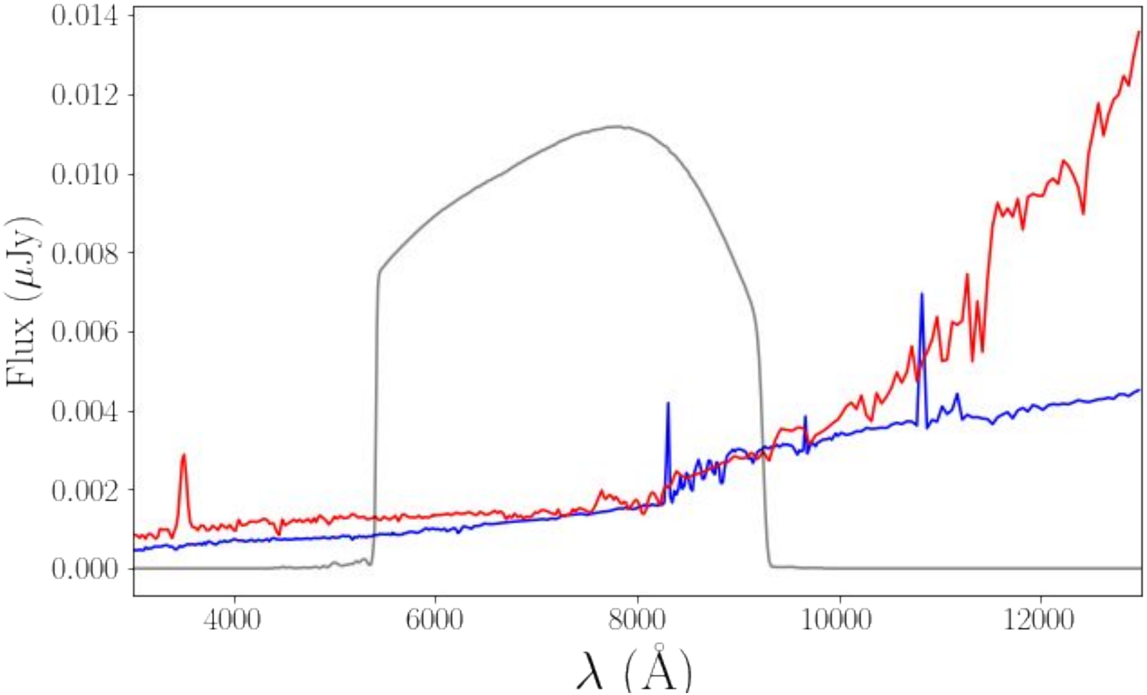


The VIS PSF is *chromatic*

PSF size (and ellipticity) changes with wavelength



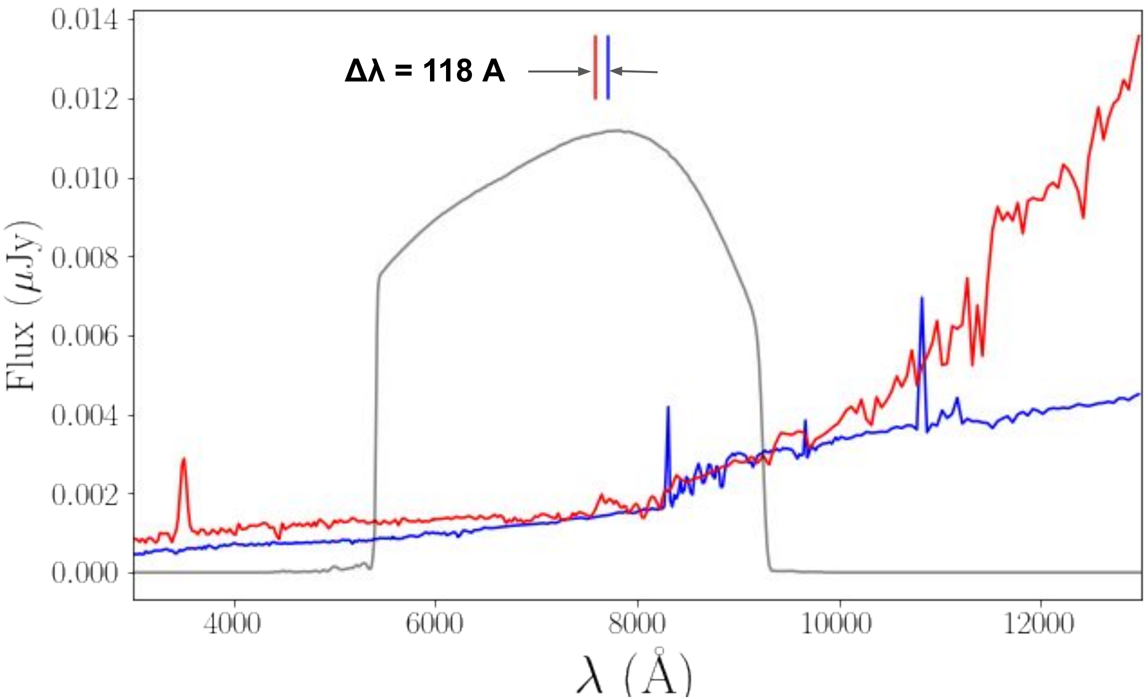




-> Need to know the SED of every galaxy in order to construct its unique and correct PSF!

The VIS PSF is *chromatic*

- The average SED-weighted mean wavelength of VIS must be known to better than **~3 A** (across each set of galaxies used).



-> This could turn out to be more difficult than our requirement on mean redshift.

Galaxy SED estimation

- Fundamental aspect of a great range of extra-galactic science.
- Also required for photo-z estimation via model fitting.

- ~quarter to half-century-old fields -> So surely this should be a solved problem by now?

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Method 1) Average empirical SEDs via spectrophotometry (e.g. narrow / medium bands) per galaxy "type" -> fit to target photometry.

- CWW template SEDs set the standard.

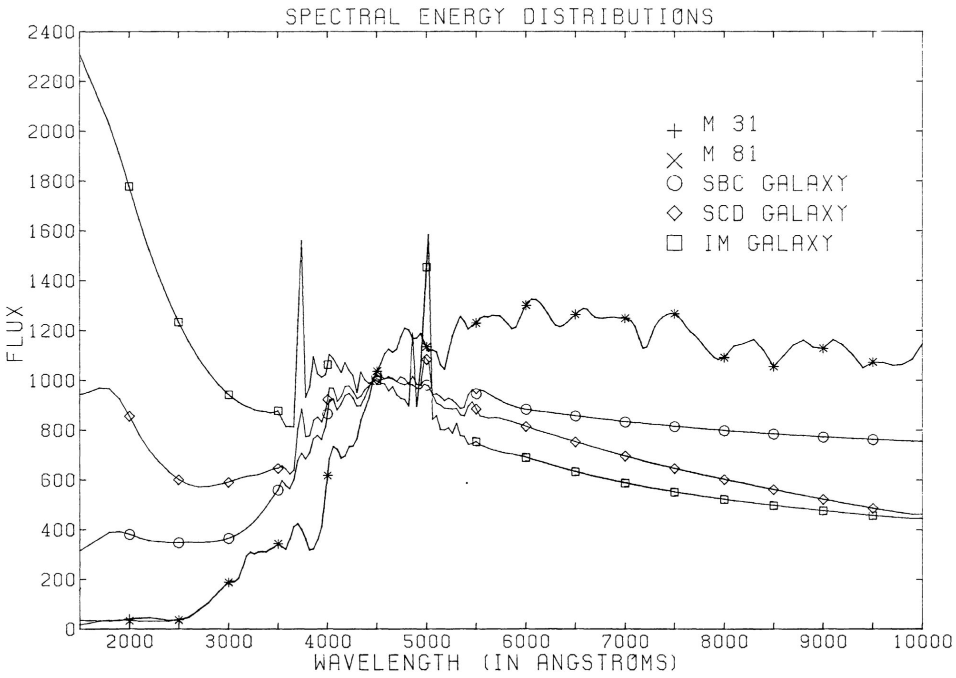
- Added to by Kinney et al. (1993) to include starbursts.

- Still used as generic test set for code development, tests and demonstrations today - sometimes even for science analyses.

- More recent sets combine empirical SEDs with theoretical model templates.

- Similar but more sophisticated: PCA / NMF decomposition.

Coleman, Wu & Weedman (1980)



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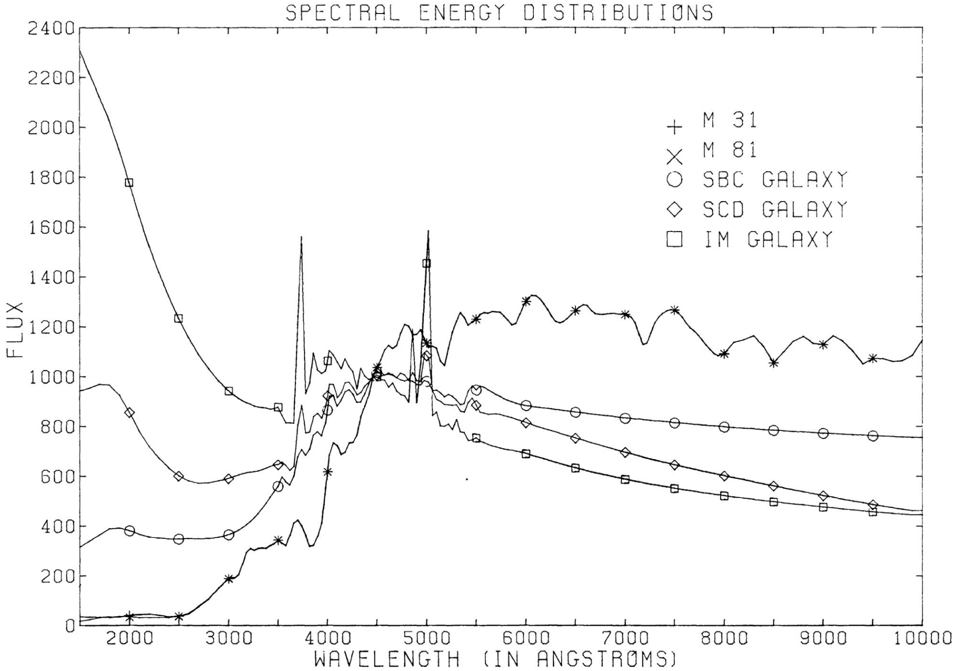

Method 1) Average empirical SEDs via spectrophotometry (e.g. narrow / medium bands) per galaxy "type" -> fit to target photometry.

Problem I:

> "It is our feeling that ultraviolet continuous spectra can be deduced for the galaxies observed with uncertainties of order ±0.1 mag.....
>
> ...We feel that far more significant sources of uncertainty are the intrinsic differences among the ultraviolet spectra for galaxies of the same type. These substantially exceed a few tenths of a magnitude and are emphasized in the conclusion of § IV. It is these intrinsic differences that make impossible accurate descriptions of generalized ultraviolet spectra for galaxies."

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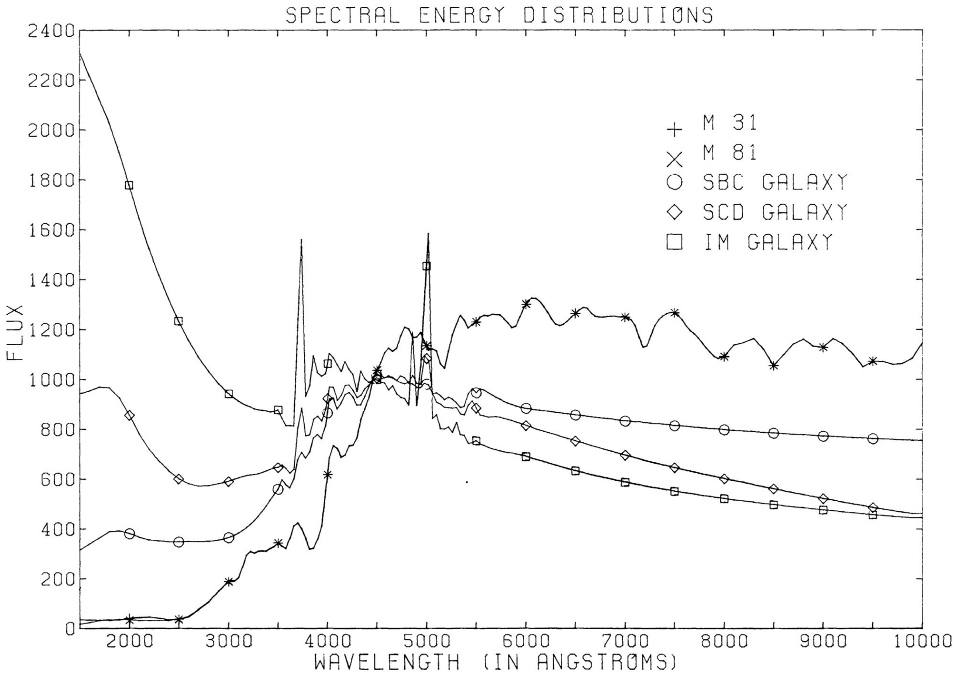

Method 1) Average empirical SEDs via spectrophotometry (e.g. narrow / medium bands) per galaxy "type" -> fit to target photometry.

Problem II:

> ".... Such calculations may be irrelevant to nature, of course, because they do not include galaxy evolution."

i.e. the SEDs represent z=0 galaxies, and are not appropriate to higher-z galaxies.

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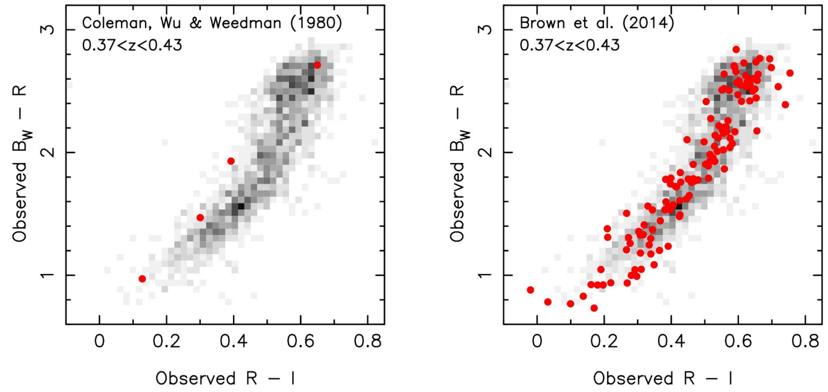
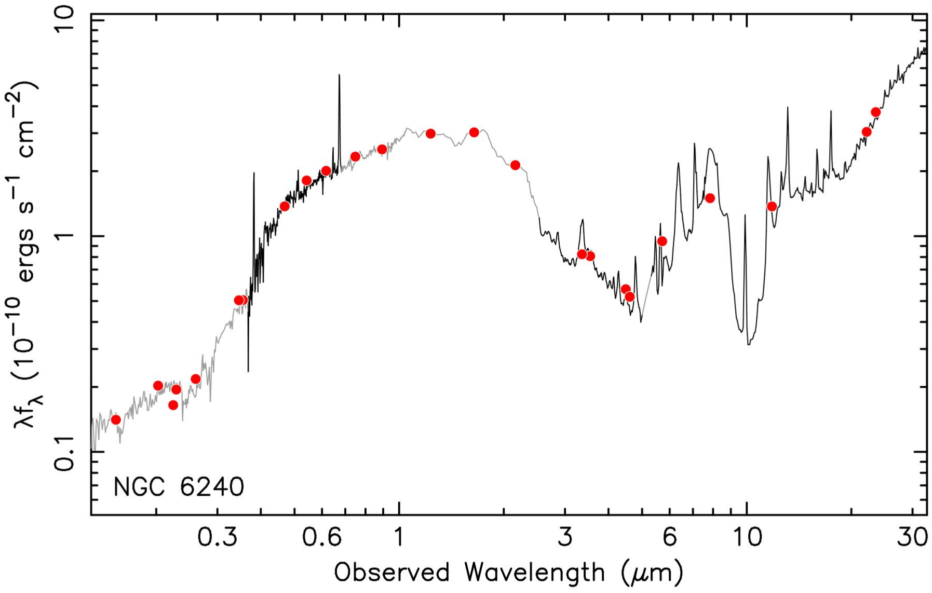
Method 2) Representative set of example galaxies with well-calibrated spectra.

- In principle solve problem I of the average SED method. But...
- Strong bias towards bright objects - can we truly obtain a representative sample?
- Spectra are limited in wavelength range, so typically extended with models
- Is the flux calibration good enough?
- Can't really solve problem II, at least not at Euclid depths.





Brown et al. (2014)

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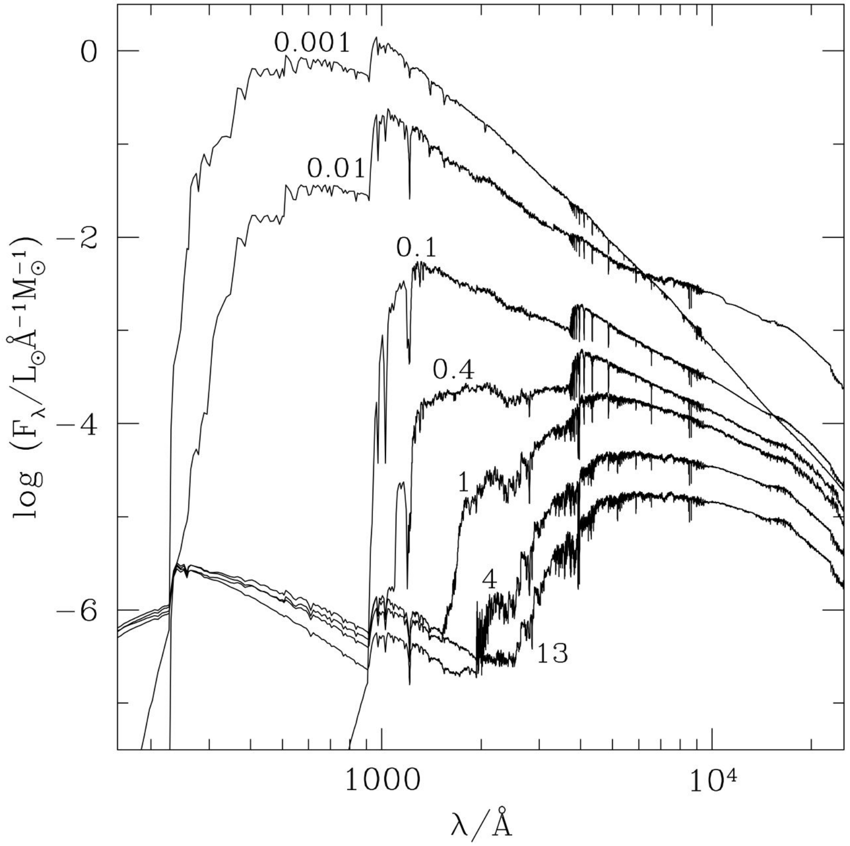
Method 3) Model theoretical spectra (e.g. SSP)

- Model space is complex and restricted at the same time (star-formation histories, metallicity).
- Some combinations of stellar age and metallicity poorly calibrated.
- Models including binary evolution are still a somewhat young field.
- Biases with redshift when using standard SSP libraries are known -> biases in SED.
- Perhaps most useful in combination with other methods.



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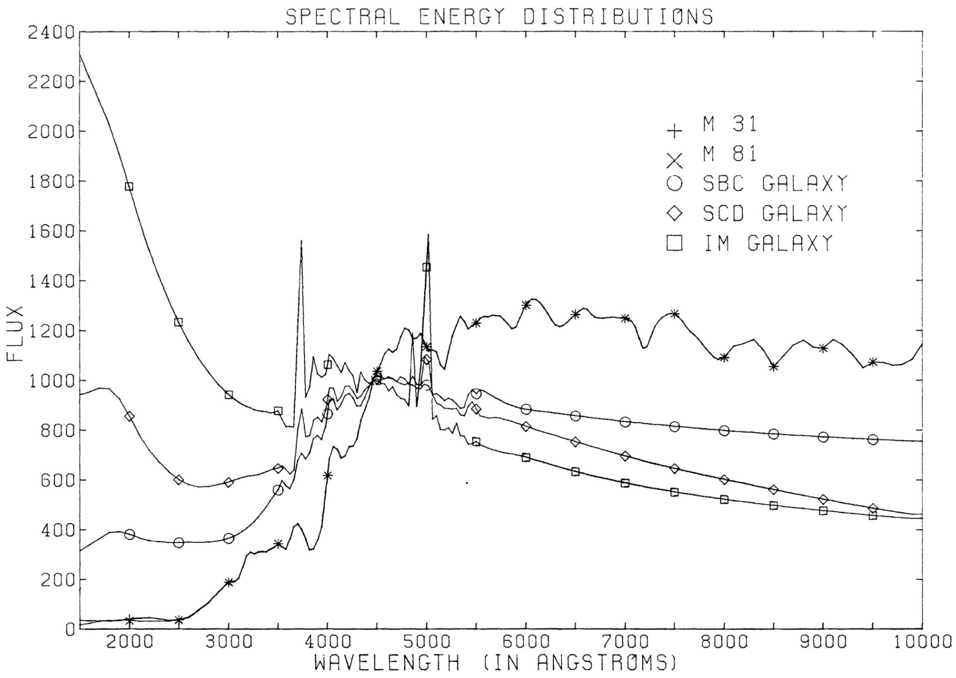
Method 4) Sample directly via medium / narrow-band data

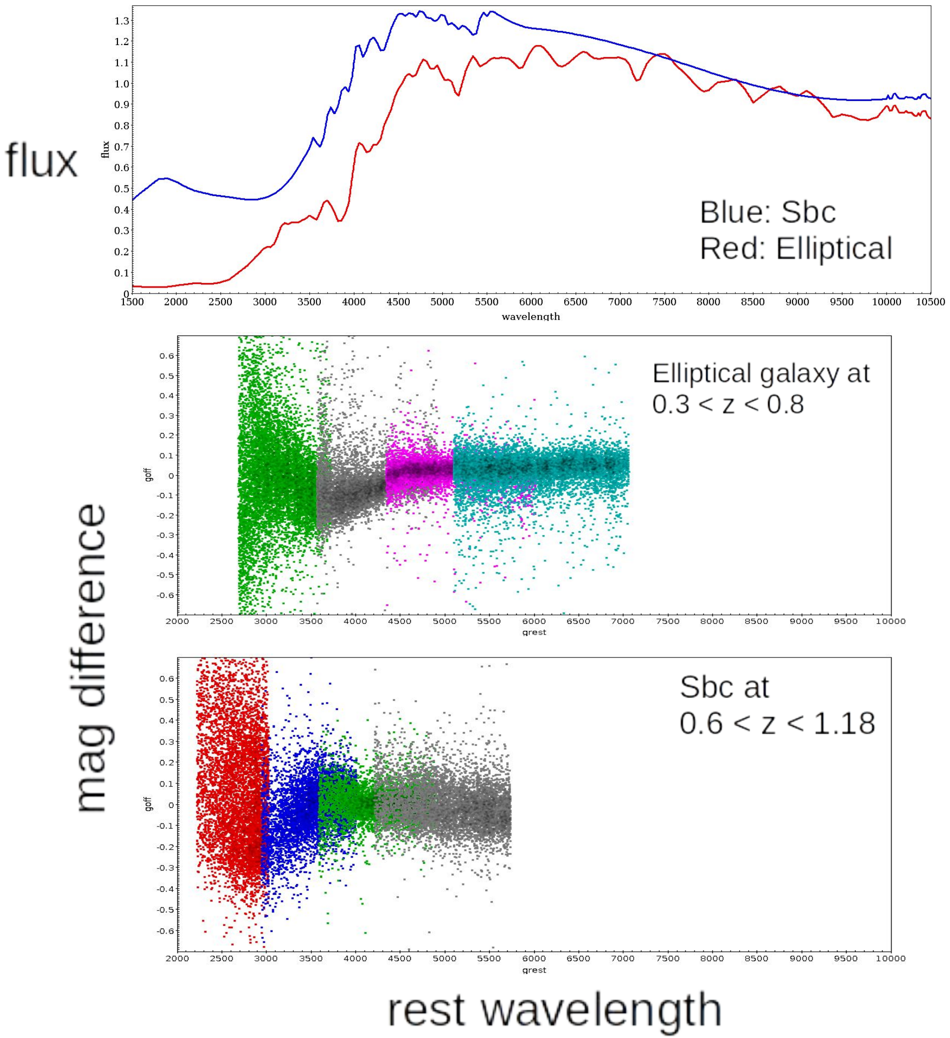
- Imagine we could get spectro-photometry for each target galaxy, rather than just a handful. Would that be good enough?
- Too expensive to observe every Euclid galaxy, but maybe a representative sample could be observed.
- Large-scale data sets exist or coming (PAUS, COSMOS, SHARDS, SphereX).
- Some are deep enough for Euclid (many are not).

Coleman, Wu & Weedman (1980)



Evolving Galaxy SEDs

- Work from 2016, for DES Y1.
- Use the fact that the mean wavelength of a filter probes different rest wavelengths at different redshifts.
- With a large well-sampled redshift data set we can find the best-fit template at the spectroscopic redshift, and compute differences between the expected and measured fluxes.
- Different coloured points in the plots correspond to different photometric passbands (*griz*).



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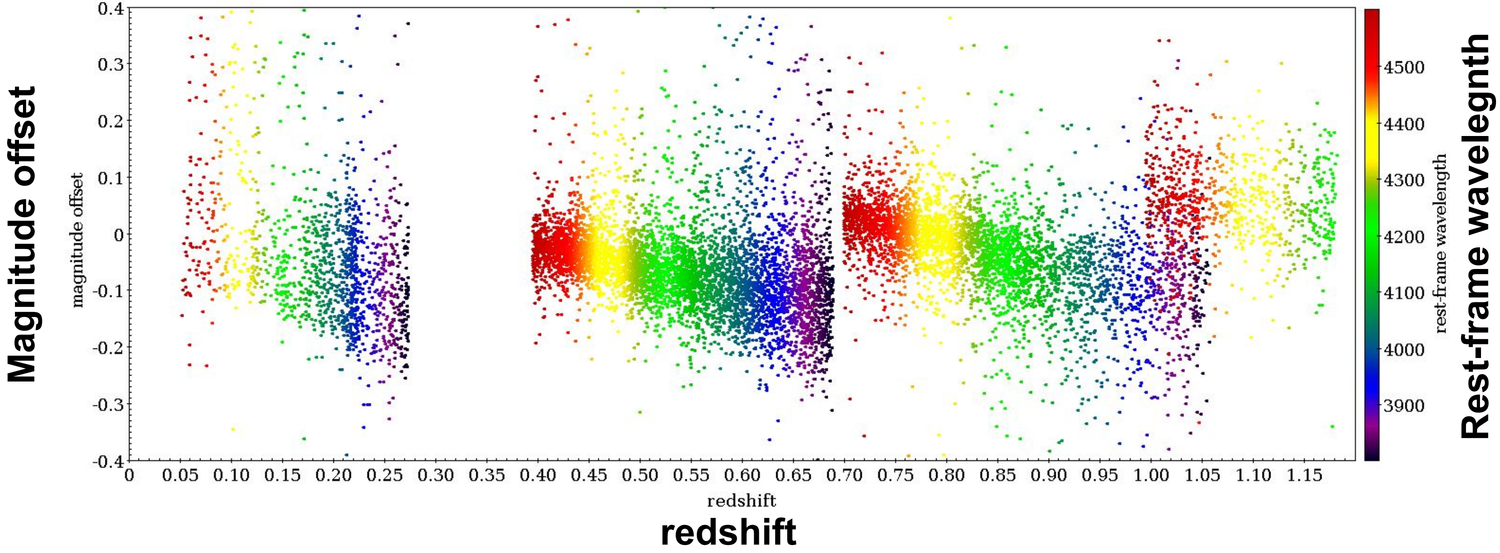
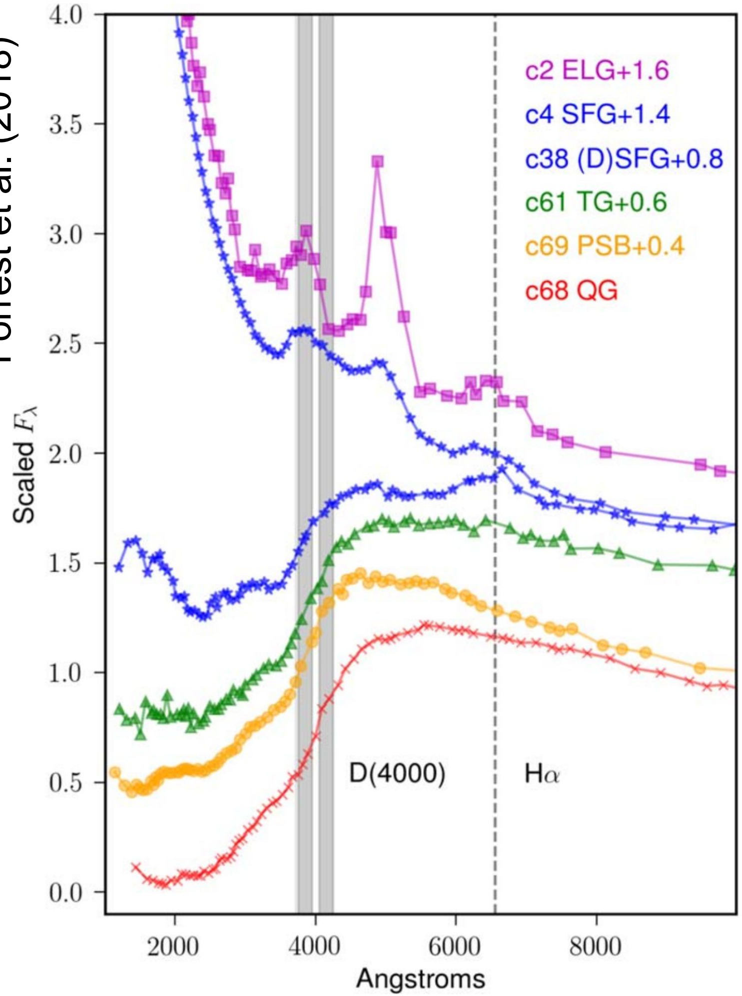


- In practice, need a greater number of narrower bands for this to work.
- Better data for this exist, e.g. COSMOS, but perhaps more fruitful to define new SEDs at high-z.

Evolving Galaxy SEDs

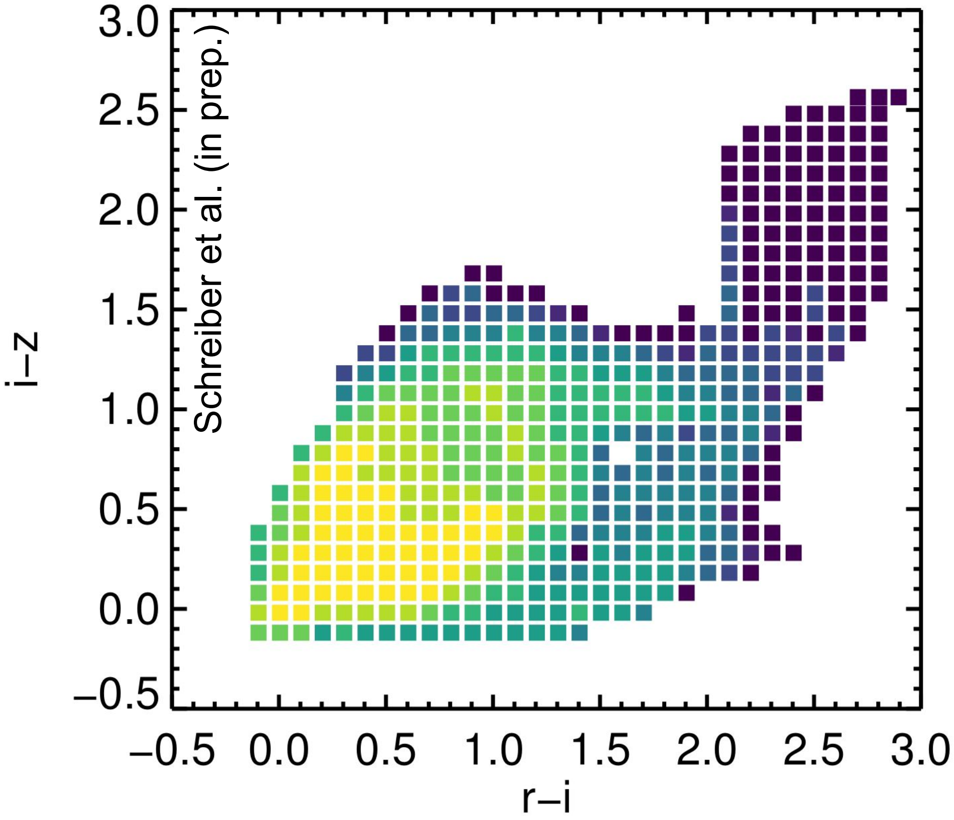
- Forrest et al. (2018), compute photo-z for COSMOS+zFOURGE data.
- Construct synthetic narrow-band photometry from their best fit templates.
- Group objects by SED similarity.
- For groups of >18, used observed photometry to form new templates (71 SEDs in total).
- Span a wide range in redshift (v. few at low-z).
- How do we link from one redshift to another?
- Doesn't fully solve our initial problem I.

Forrest et al. (2018)

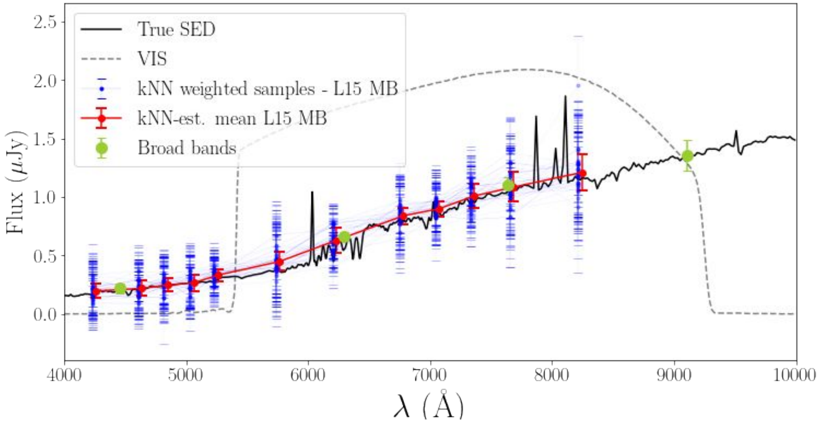


ColourGrid - idealised, simulated set-up

- Simulated galaxy sample rendered into a set of 6D hyper cubes.
- In each cube, true SEDs are averaged to form an SED for that cube.
- These SEDs used directly as obs frame SEDs in simple TF.
- -> This is essentially machine learning.
- Side length of the cubes adjusted to meet Euclid requirements.
- i.e. perfect set-up -> not possible in reality, because we don't have true, noiseless SEDs for all objects.
- But it's the only thing that has been shown to work so far.
- **Closest we can get is sampled SEDs via narrow / medium-bands.**



What we have right now



- Example simulated SED
- Nearest-neighbour match to COSMOS (L15).
- BB: uBRizYJH
- Red line: trapz interpolation

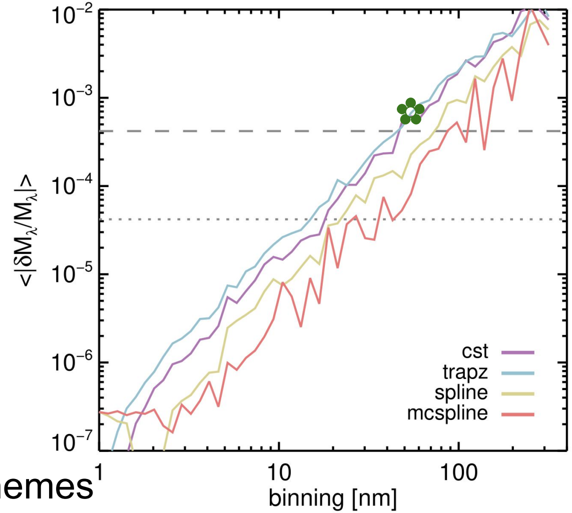
Issues:

- Not yet clear how better interp. schemes respond to noise in sampled SED.
- MB wavelength sampling ~50 nm.
  - -> Calibration req., < 1%
- Unlikely SuprimeCam will be available to fill in the λ > 830 nm hole, as assumed by CS+.
- Sample variance from COSMOS field size will probably matter, because req. are so tight. Needs quantifying.
  - -> Possibly need SXDS, VVDS-2hr too.

Dash: Total error budget

Dotted: Sampling budget

Coloured lines: Interp. schemes



Schreiber et al. (in prep.)

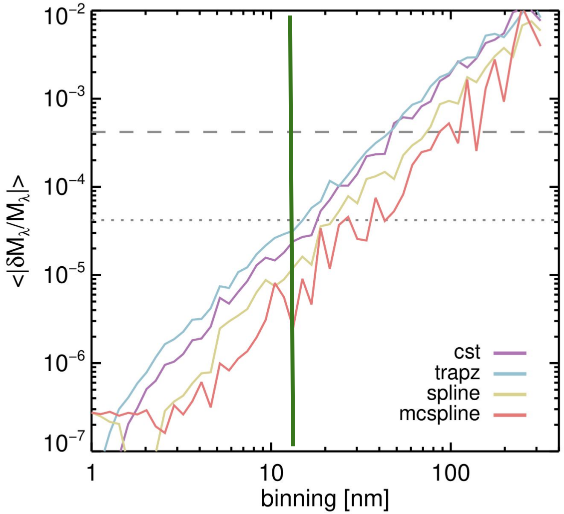
A possible better option: SHARDS-like data

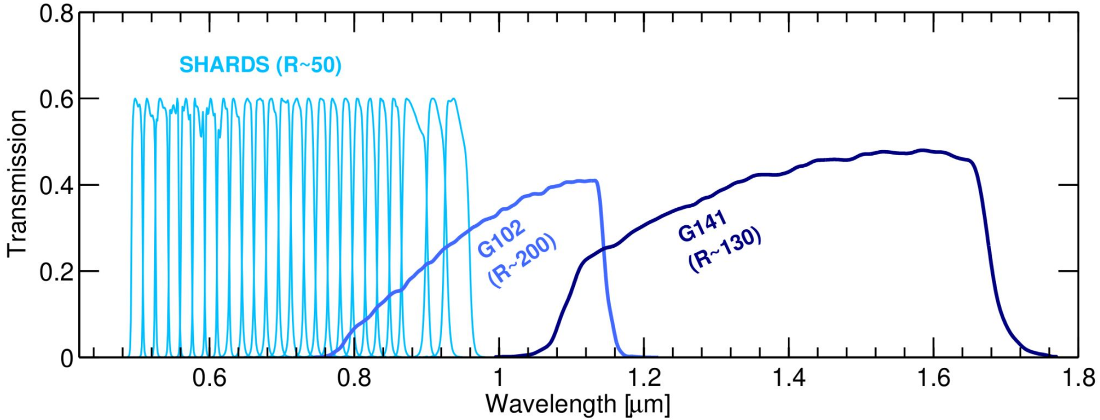
SHARDS is a multi-medium-band survey of GOODS-N.

- 220hrs OSIRIS on the GTC (10.4m).
- Contiguous sampling in wavelength, R~50 (Δλ ~ 15 nm)
- Even simple interpolation scheme meets req.

Problem I: it's in the wrong part of the sky (GOODS-N, we need equatorial fields)

Problem II: it's a very small field -> sample variance.





Barro et al. (2019)

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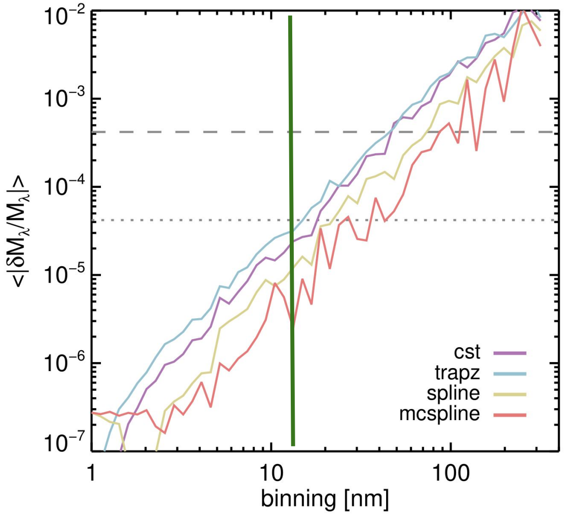
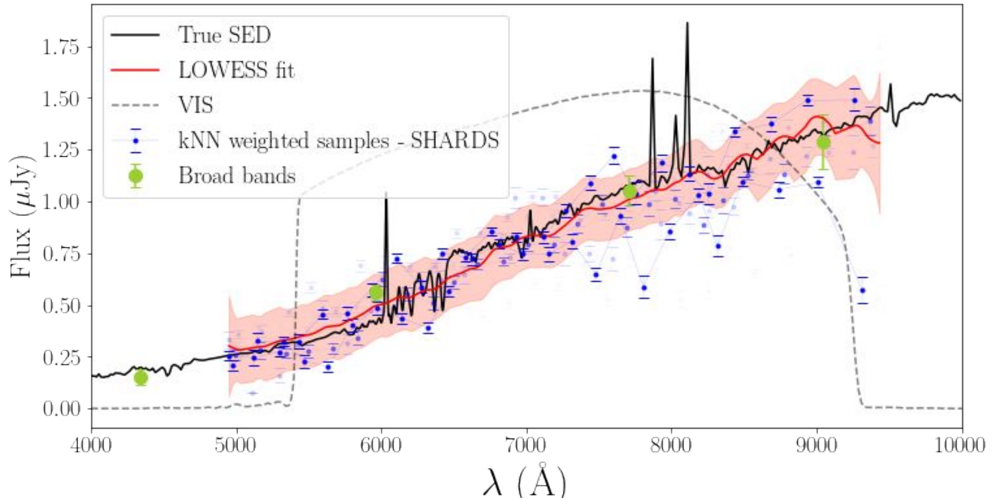
- Strong filter variation -> sampling effectively continuous.
- Small f.o.v. (7.8 x 7.8 arcmin unvignetted)
- x25 filters -> a lot of observing time for even modest sized fields!
- **Is SHARDS-like data over some fraction of SXDS a feasible idea?**



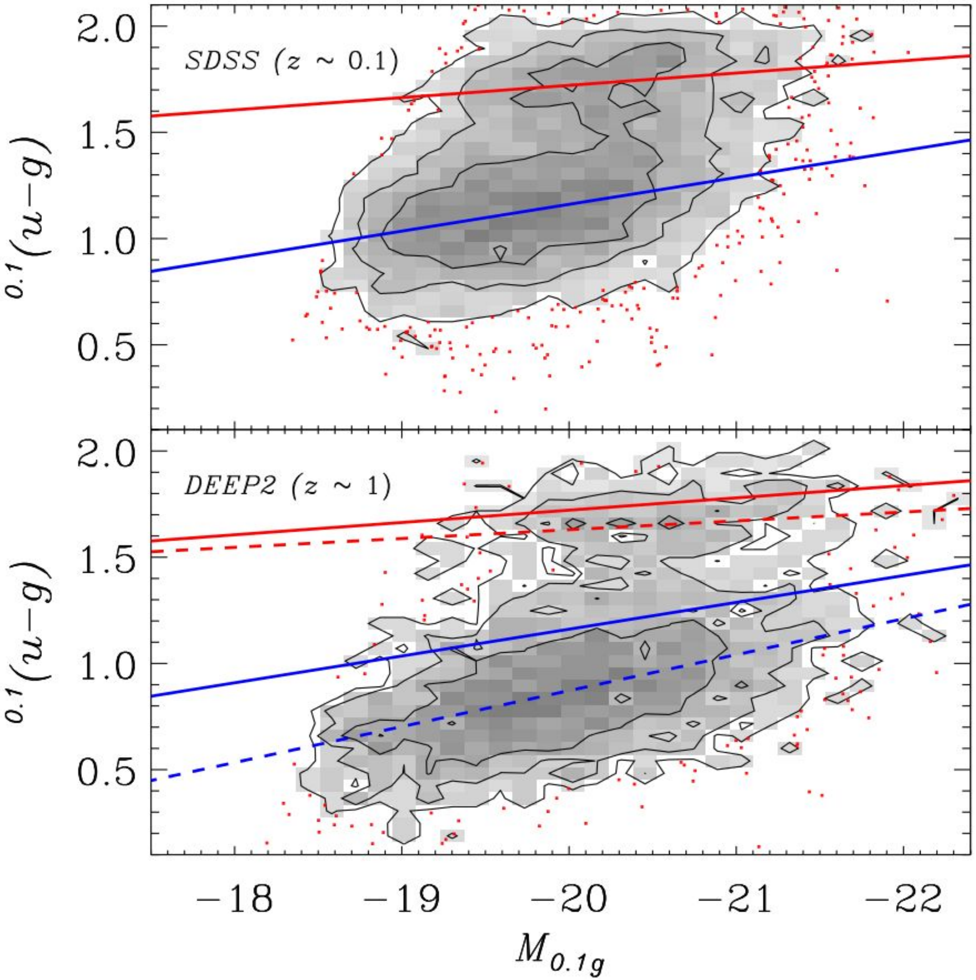


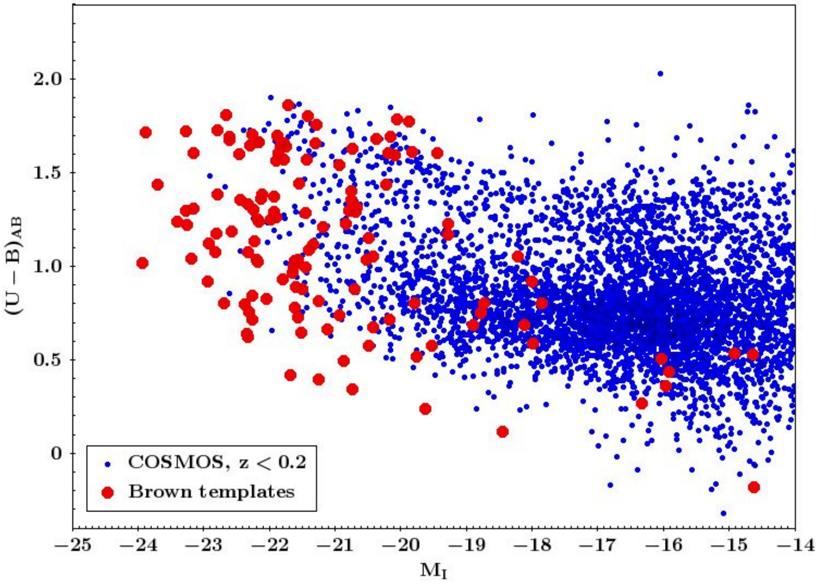
Plot shows a good example, VIS = 24 (AB)

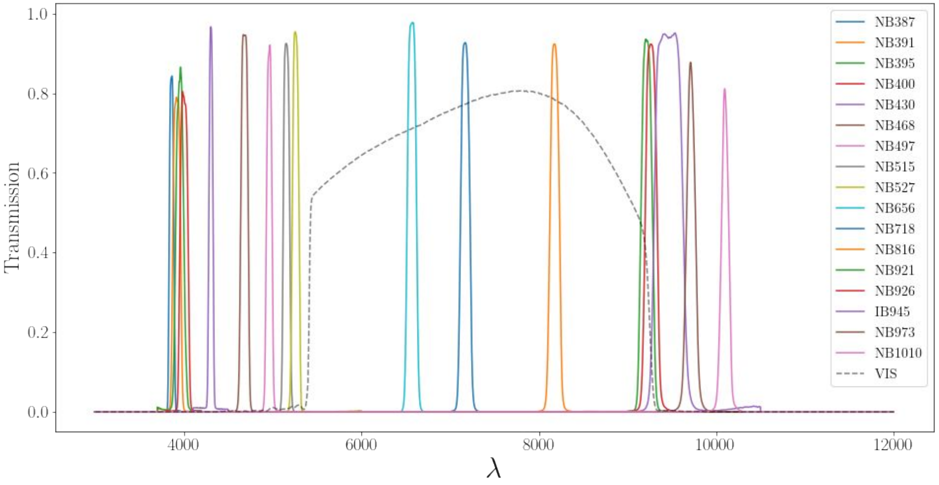
Ref sample size: 5320 galaxies
C.f. COSMOS: > 200,000

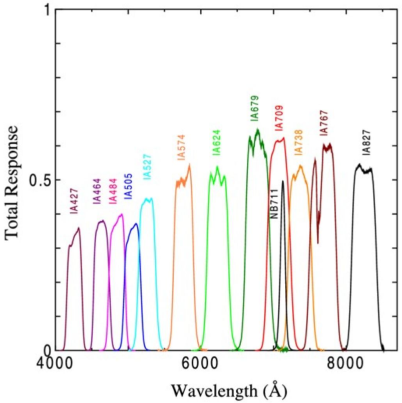
Summary

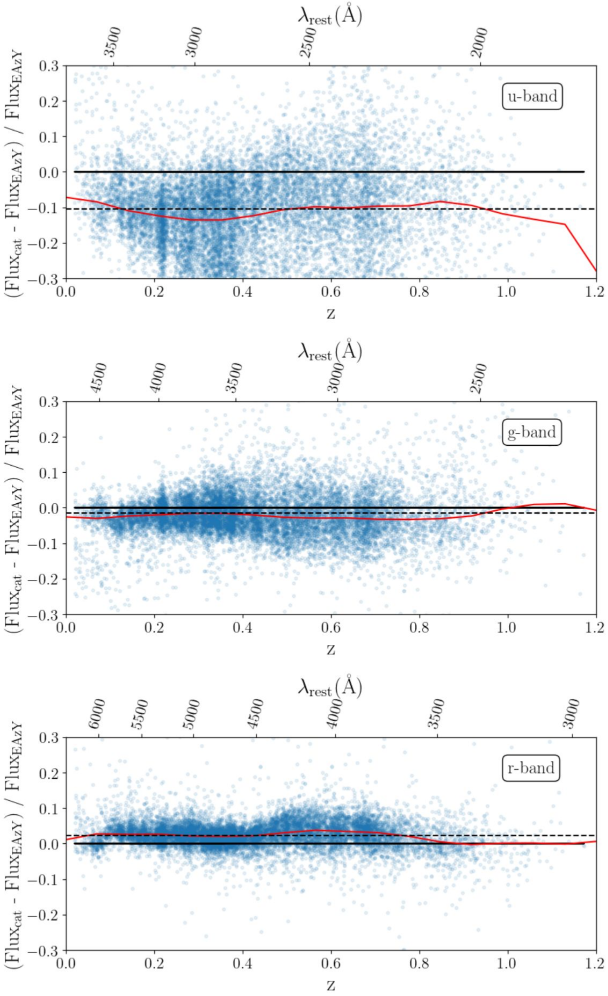
- Accurately estimating the SEDs of Euclid galaxies may prove to be our most difficult task in OU-PHZ.
- Traditional methods to do this have long-standing limitations and problems that we are yet to solve.
- The method that we are confident will work, and is ready to go, is hampered by a lack of data.
- That necessary data is extremely expensive, and unlikely to be collected.
- We’ll have to gather together many strands of research to solve this problem.


SDSS (z ~ 0.1)
DEEP2 (z ~ 1)
$^{0.1}(u-g)$
$M_{0.1g}$
2.0
1.5
1.0
0.5
−18
−19
−20
−21
−22


COSMOS, z < 0.2
Brown templates
$(U-B)_{AB}$
M_I
2.0
1.5
1.0
0.5
0
−25
−24
−23
−22
−21
−20
−19
−18
−17
−16
−15
−14

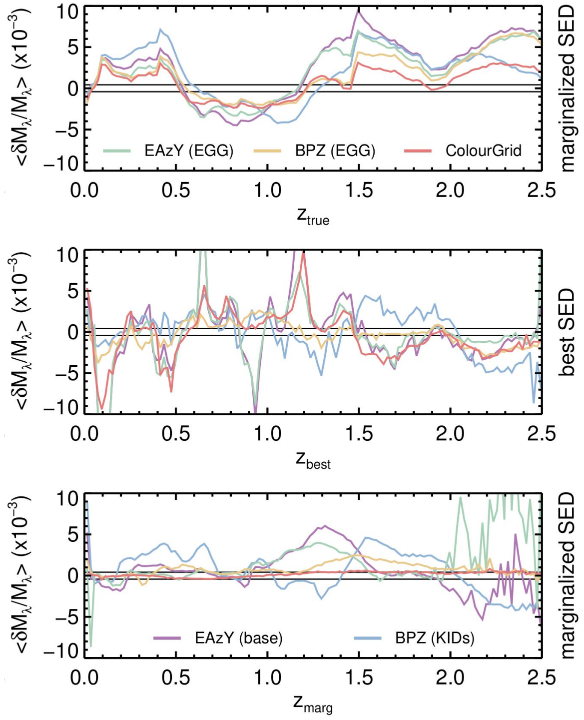

Transmission
λ
NB387
NB391
NB395
NB400
NB430
NB468
NB497
NB515
NB527
NB656
NB718
NB816
NB921
NB926
IB945
NB973
NB1010
VIS


Total Response
Wavelength (Å)
IA427
IA464
IA484
IA505
IA527
IA574
IA624
IA679
IA709
NB711
IA738
IA767
IA827


λrest (Å)
(Fluxcat - FluxEAzY) / FluxEAzY
z
u-band
g-band
r-band

Recap: Schreiber et al. (in prep.)

- Building on Eriksen & Hoekstra (2018), with more realistic sims, Euclid-like set-up.
- Natural assumption would be to use template fitting, but present implementations fall short.
- Only ColourGrid meets requirements, by design.
- Even then, only via marginalising over SED.



- ❑ Black lines: requirement
- ❑ Blue: BPZ, simple templates (+ interp)
- ❑ Yellow: BPZ, matched templates (sub-set)
- ❑ Purple: EAzY, old linear comb.
- ❑ Green: EAzY, matched template pairs (sub-set)
- ❑ Red: Optimised solution (~SOM-like)

M_λ - SED metric (~mean SED-weighted VIS wavelength)