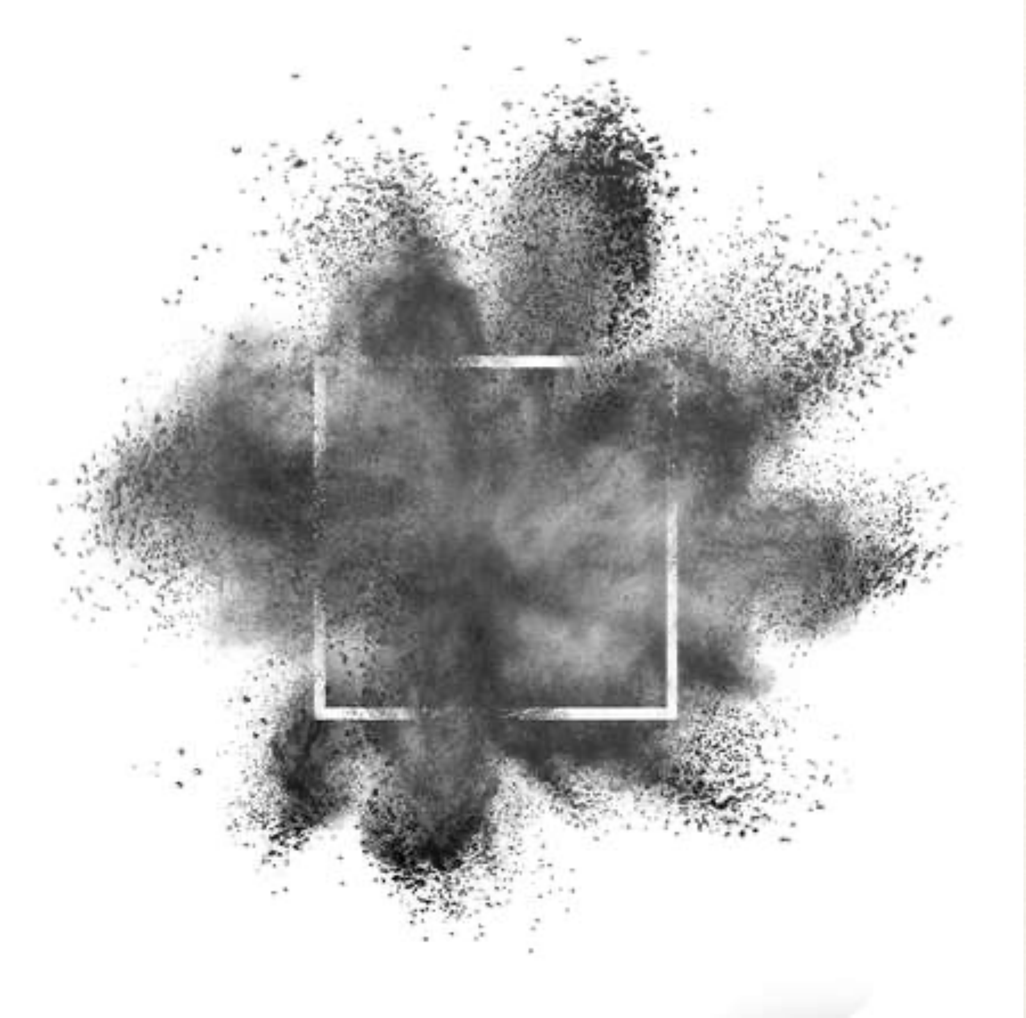


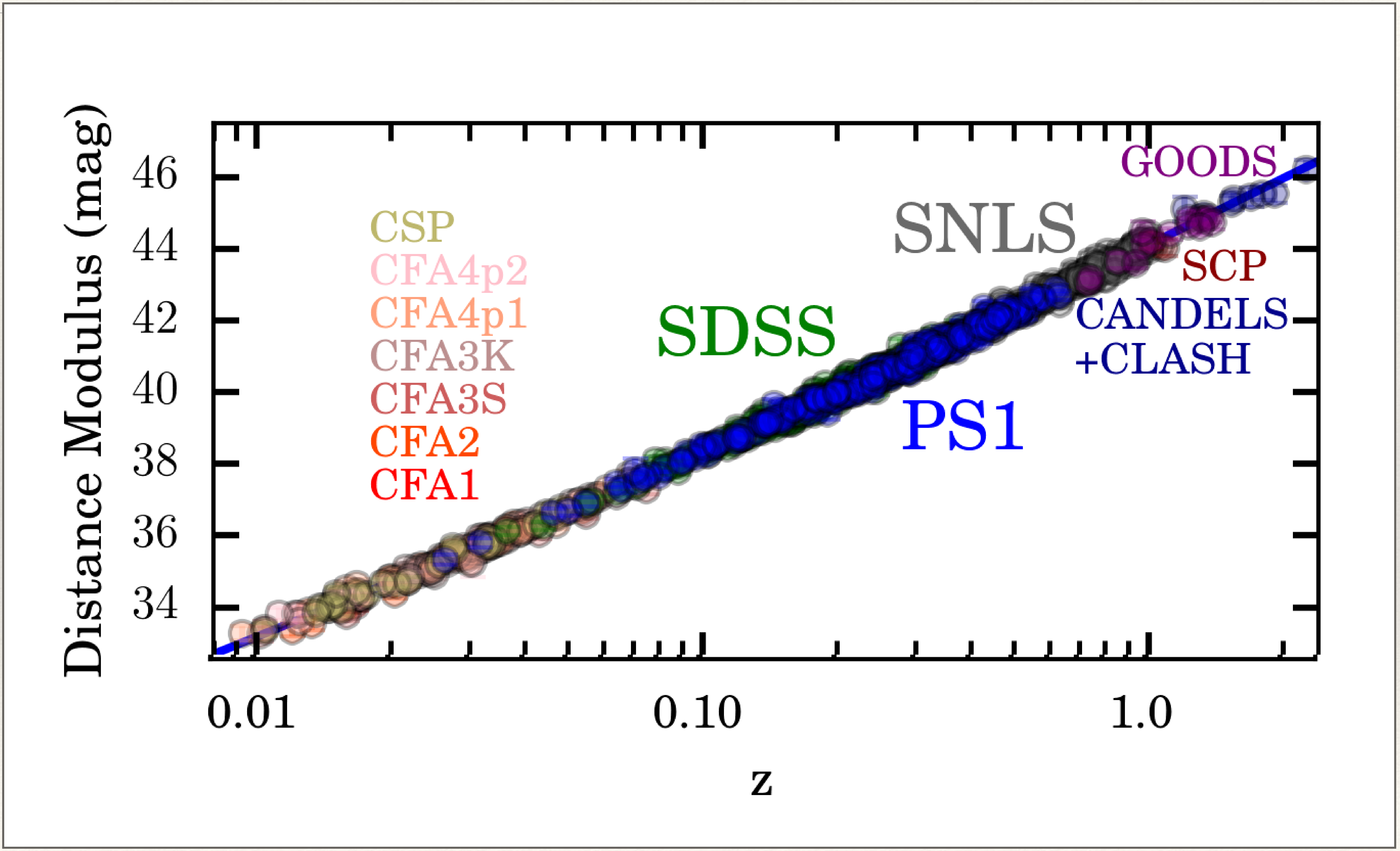
Supernova Cosmology

Part 2

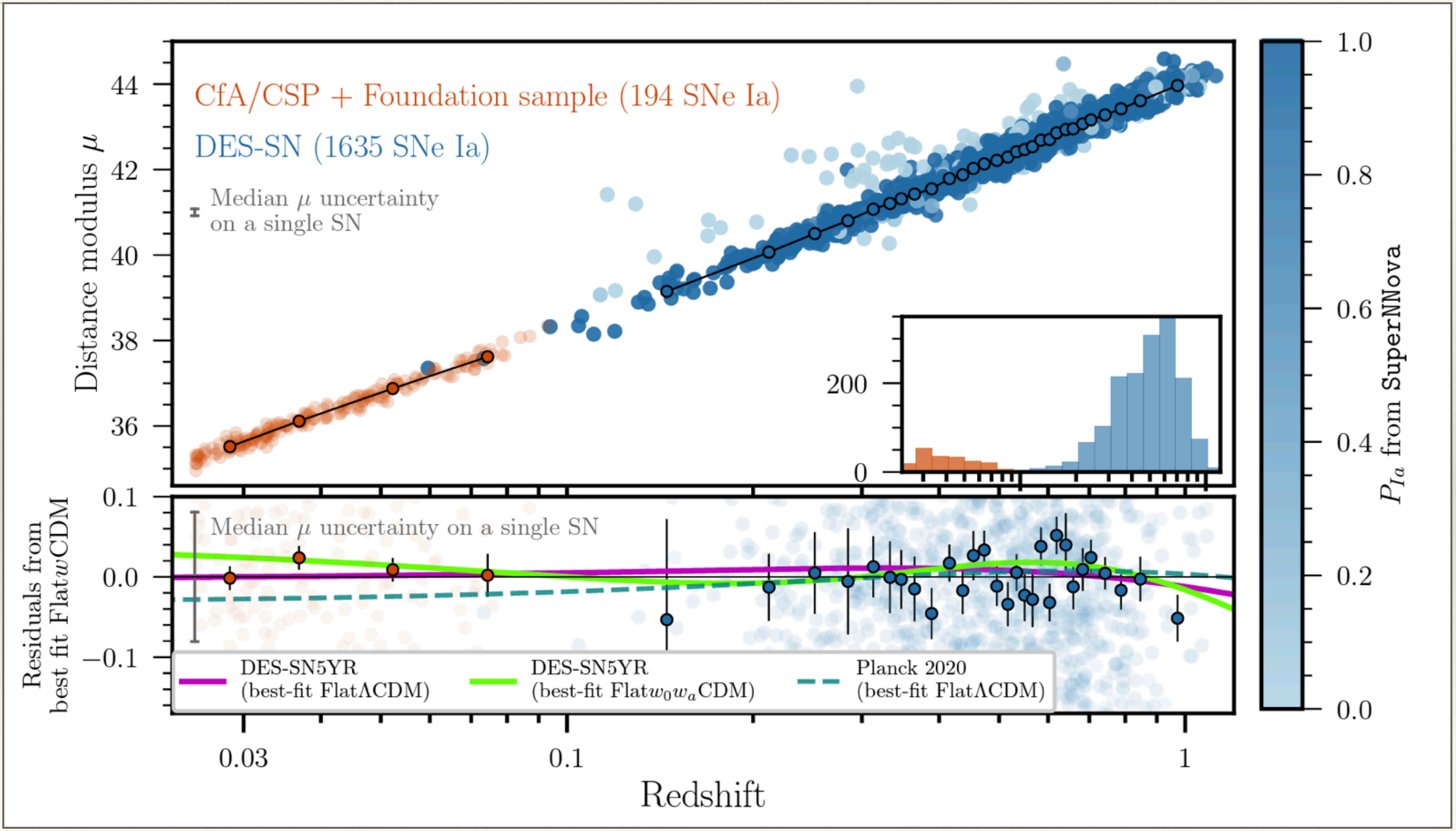
Mathew Smith | Lancaster University, UK

mat.smith@lancaster.ac.uk

Combining samples



Combining samples



Depth

Large aperture : high redshift

Area/Volume

Number/type of expected transients

Cadence

Quickly evolving transients, well sampled light curves

Wavelength coverage

Changes discovery space, provides physical information

Finding faint transients

To detect faint objects, need a sensitive imaging system

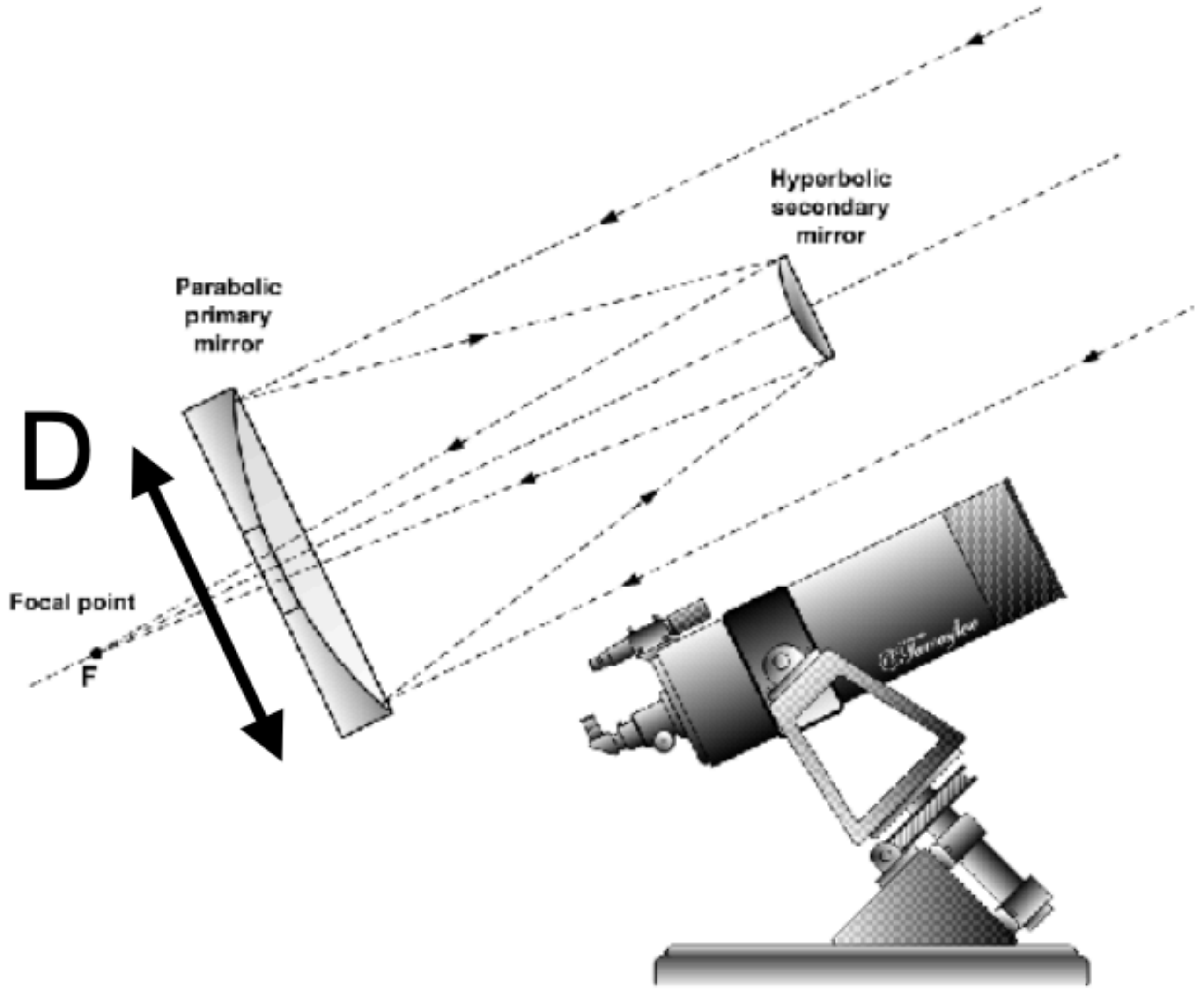
Primarily determined by *aperture* — how big is your telescope

Assuming source is brighter than sky background, the magnitude of the faintest object you can see increases roughly with the primary mirror as

$m_1 - m_0 = 5 \times \log(D_1/D_0)$

where D is the diameter of your telescope

i.e. you can see 5 mags fainter for each decade of aperture size



Finding faint transients

ASAS-SN: D = 0.14m, limit ~ 17 mag

GOTO: D = 0.4m, limit ~ 19 mag

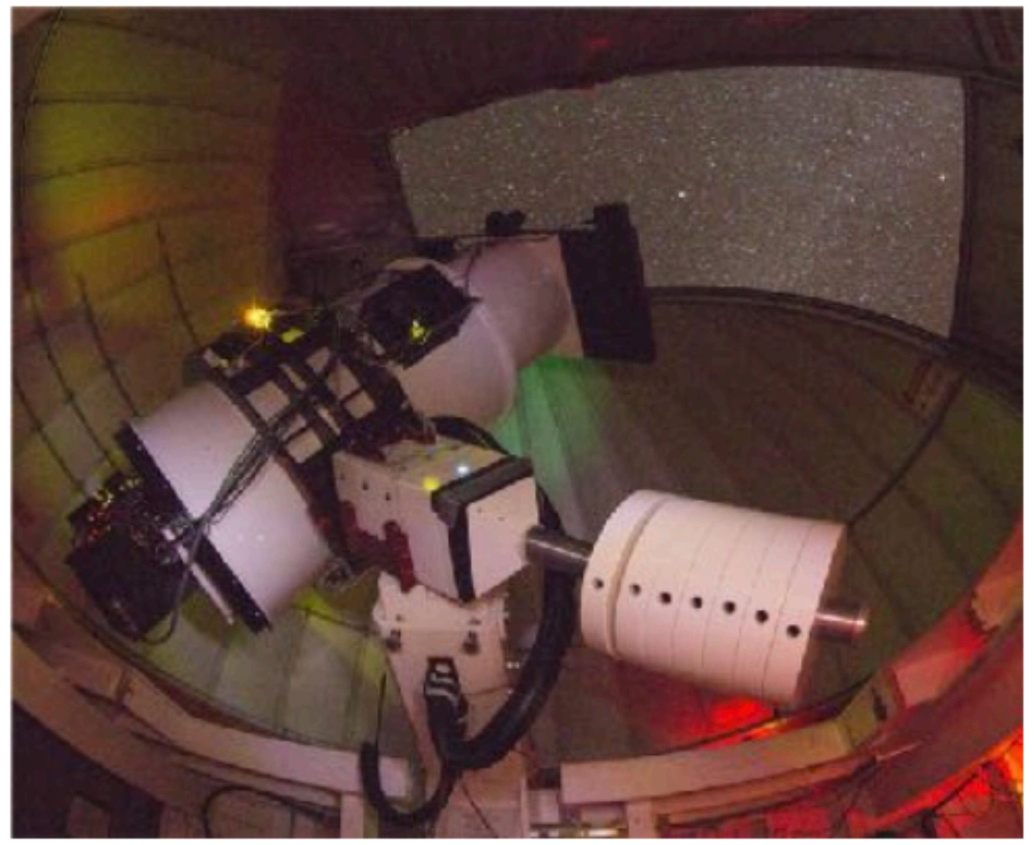
ATLAS: D = 0.5m, limit ~ 19.5 mag

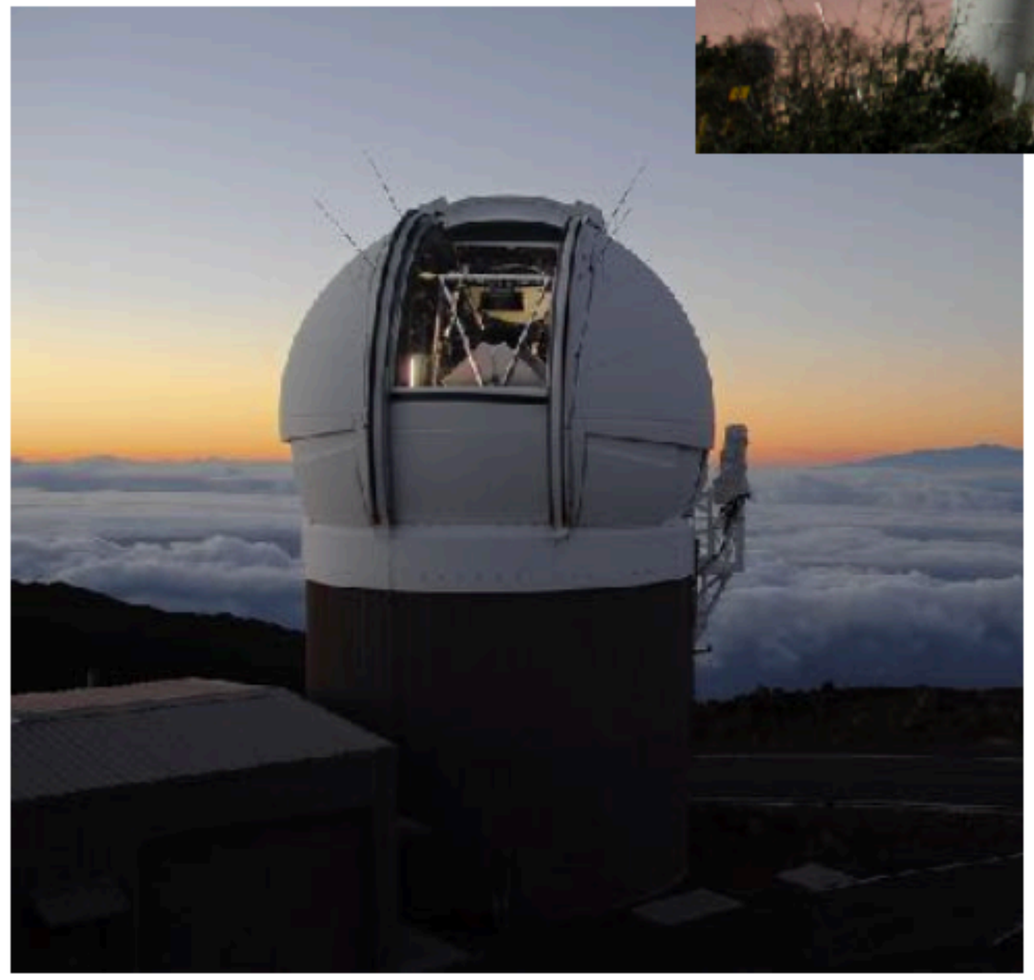
ZTF: D = 1.2m, limit ~ 20.5 mag

Pan-STARRS: D = 1.8m, limit ~22.5 mag

Rubin: D = 8.4m, limit ~25 mag!

N.B. Not quite 5 log(D), as also different exposure times!






HSC,
1.7 deg²
MegaCam,
1.0 deg²
DES,
2.5 deg²
PTF/iPTF, 7.3 deg²
ZTF, 47 deg²
PS1, 7 deg²
LSST, 9.6 deg²
1 deg

Zwicky Transient Facility | *Since 2018*

3 filters (g, r, i)

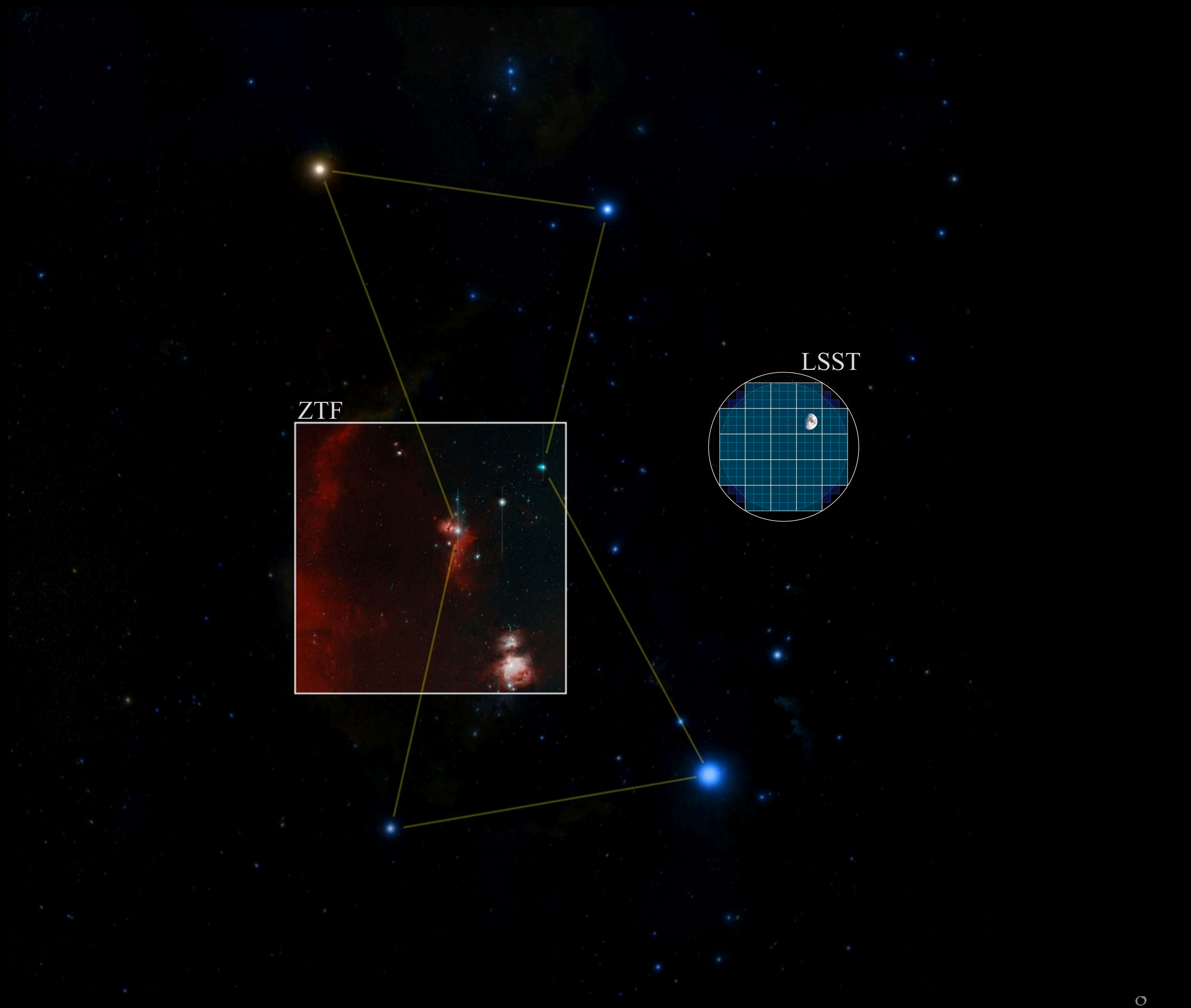
FoV **47** deg²

surveys **3750** deg²/h

20.5 mag 5 σ depth

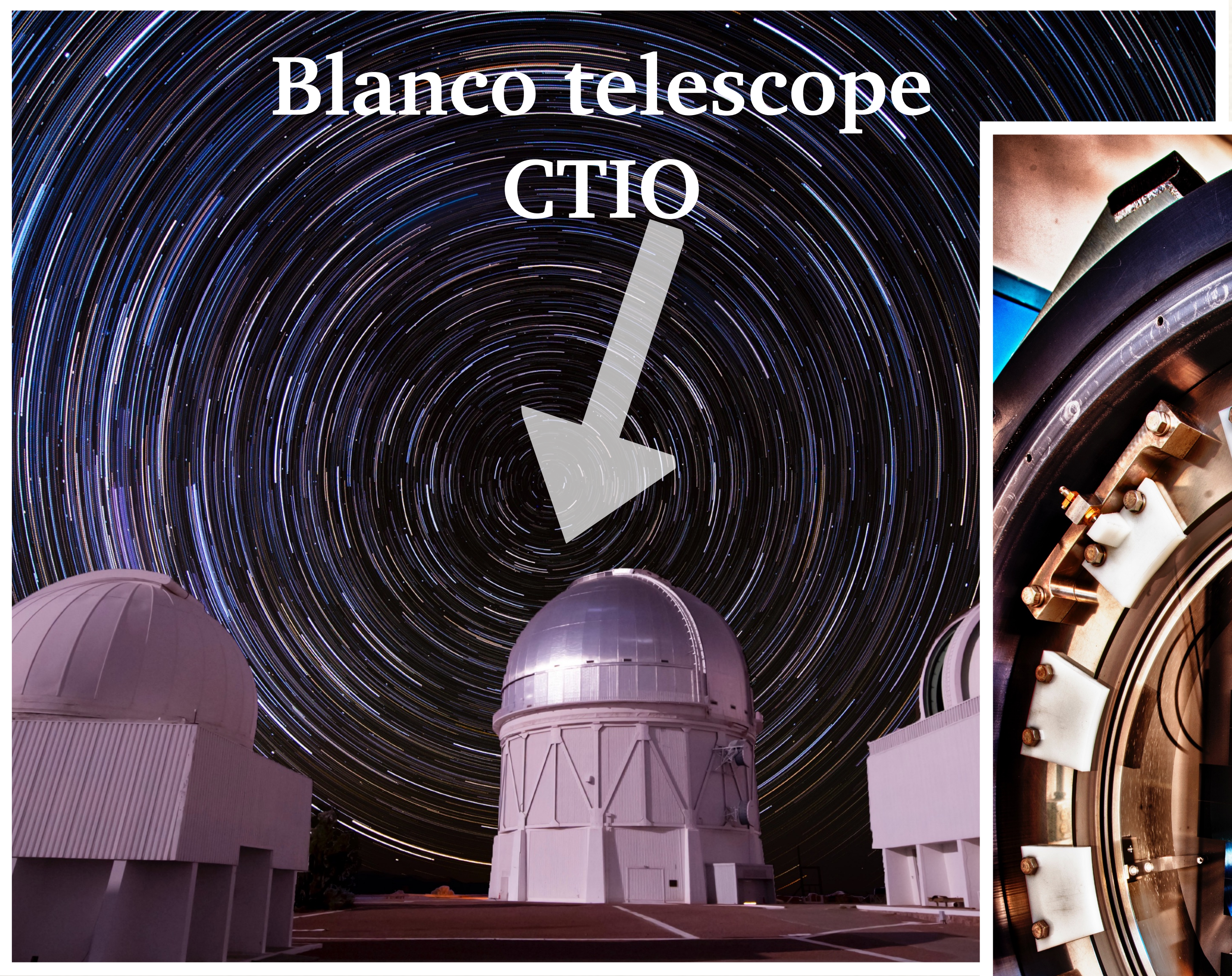
1 arcsec/pixel

dedicated spectroscopy

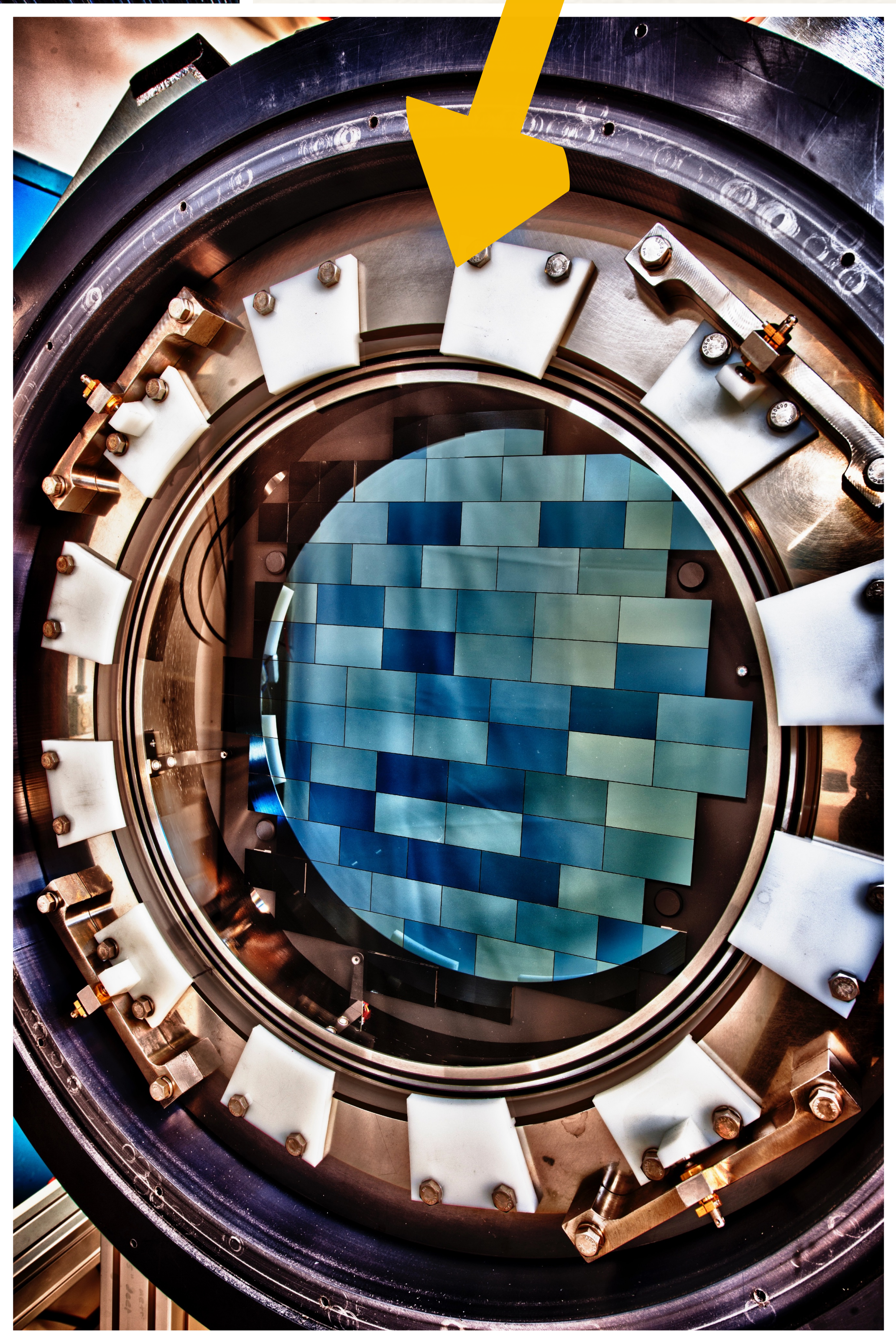


THE DARK ENERGY SURVEY

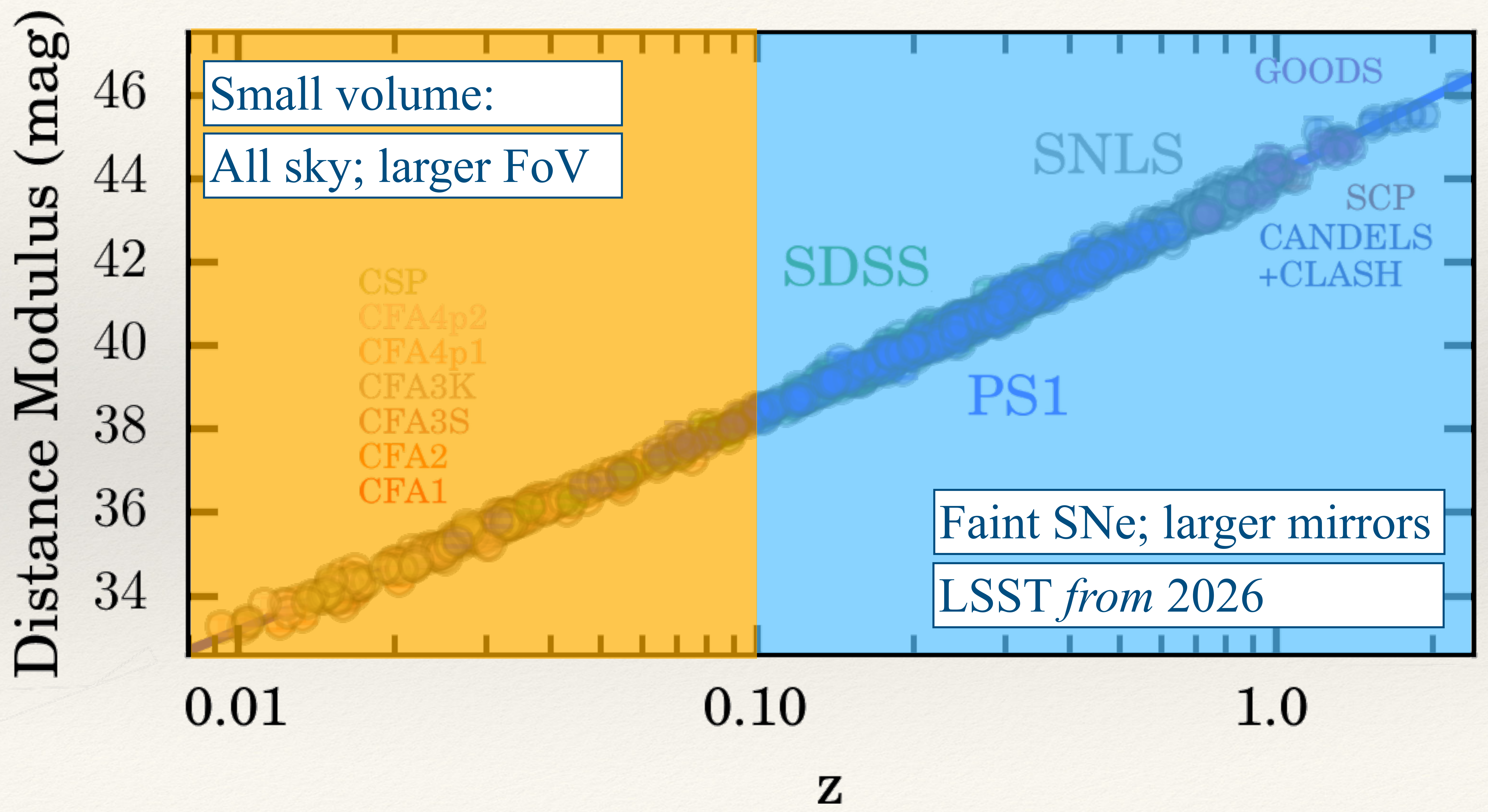
- 5 year supernova program (2013-2018)
- 10 x 2.7 deg^2 DECam fields
- DECam has <u>red sensitive</u> CCDs
- 4 filters in griz
- 8 shallow, 2 deep with~ 7 day cadence
- Depth ~23.5 mag in shallow fields, ~24.5 mag in deep fields



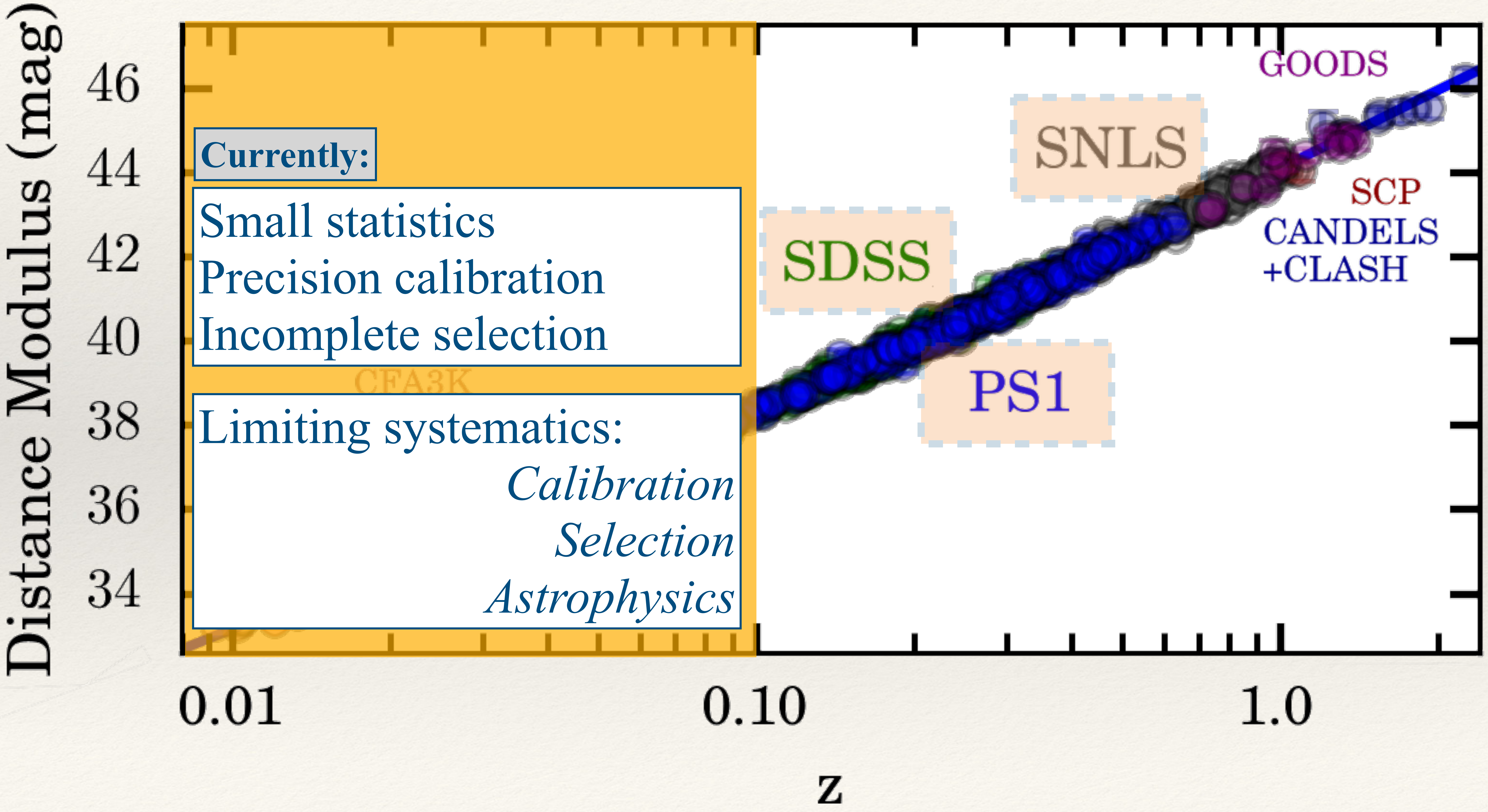
The Dark Energy Camera (DECam)



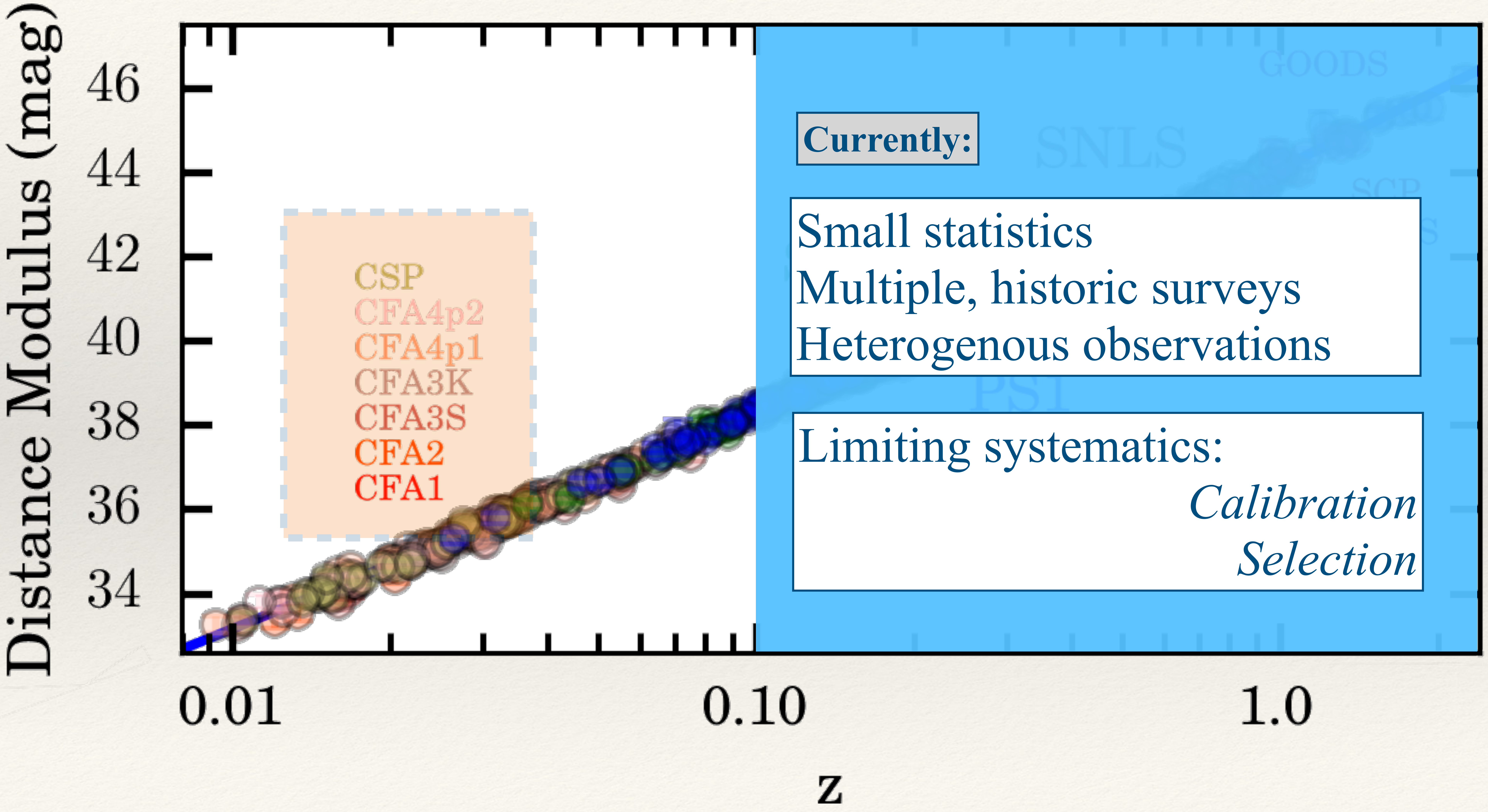
SNIa Cosmology: Simplified



high-z cosmology: STATE-OF-THE-ART



SNIa Cosmology: Today



Currently:

Small statistics
Multiple, historic surveys
Heterogenous observations

Limiting systematics:
Calibration
Selection

Calibration

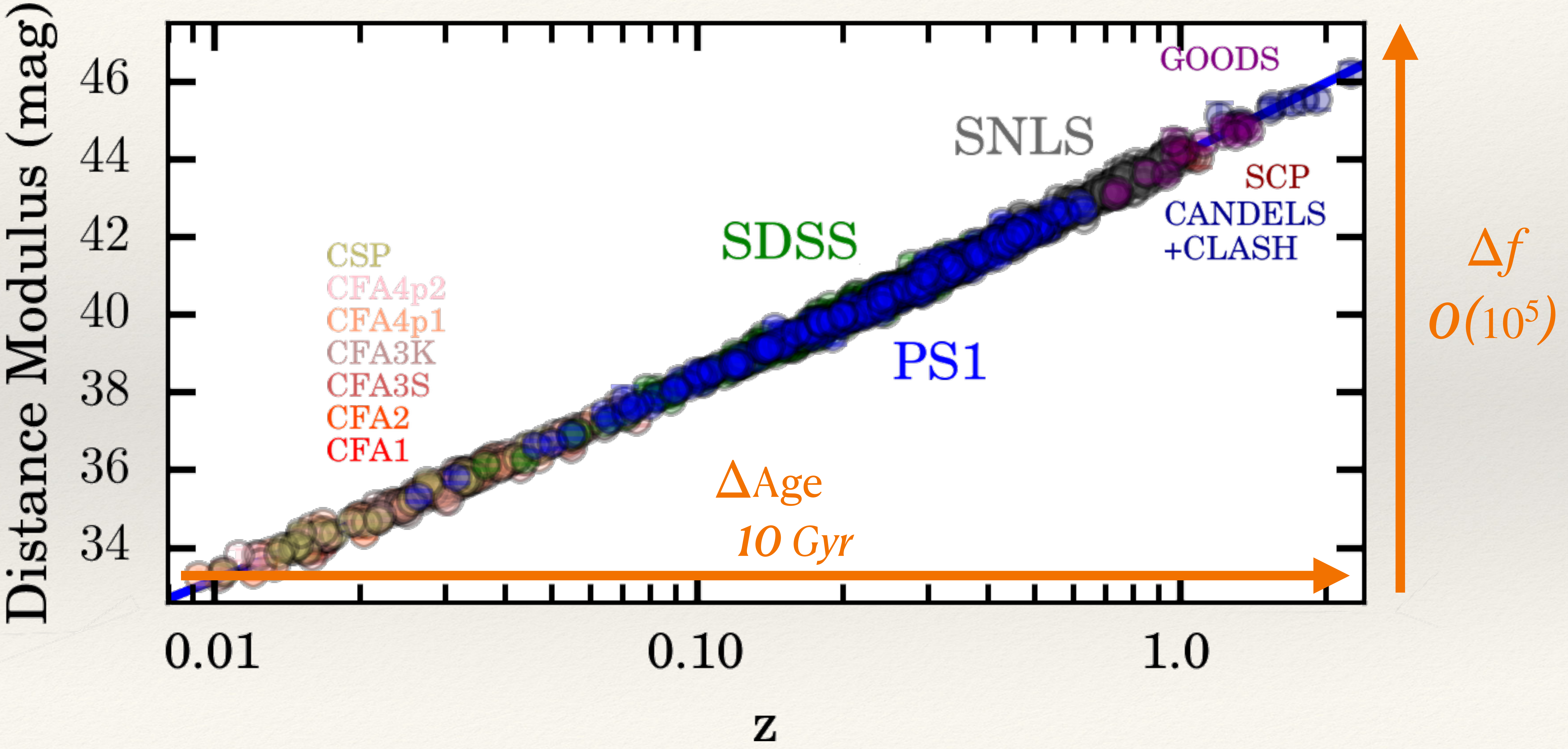
Will we get the same measurement if we observe a SN Ia under different conditions ?

1. Photometric surveys

2. Filters

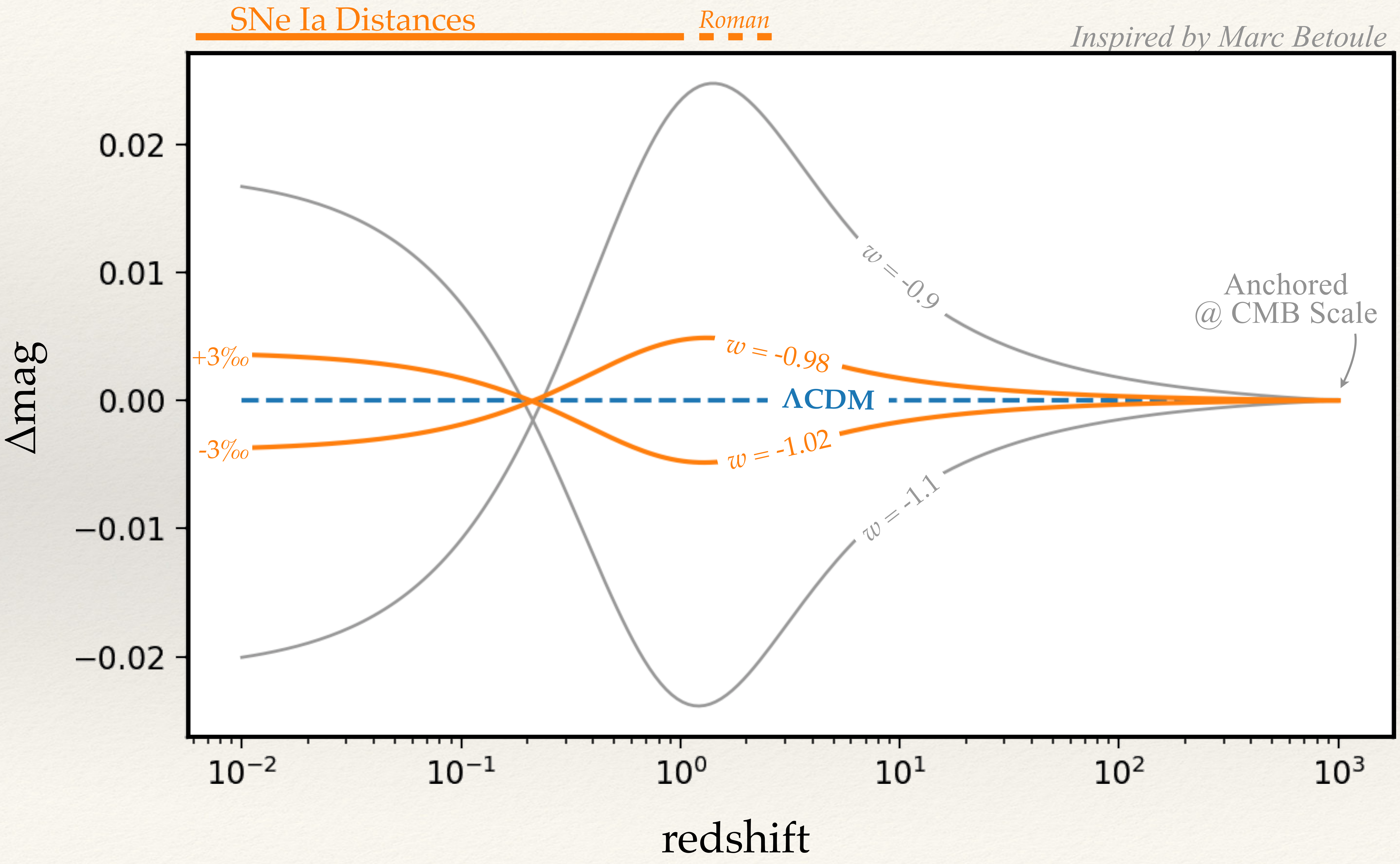
3. Spectroscopic surveys

SNIa Cosmology: In Context



Type Ia Supernova Cosmology | *w*

Stats & Precision

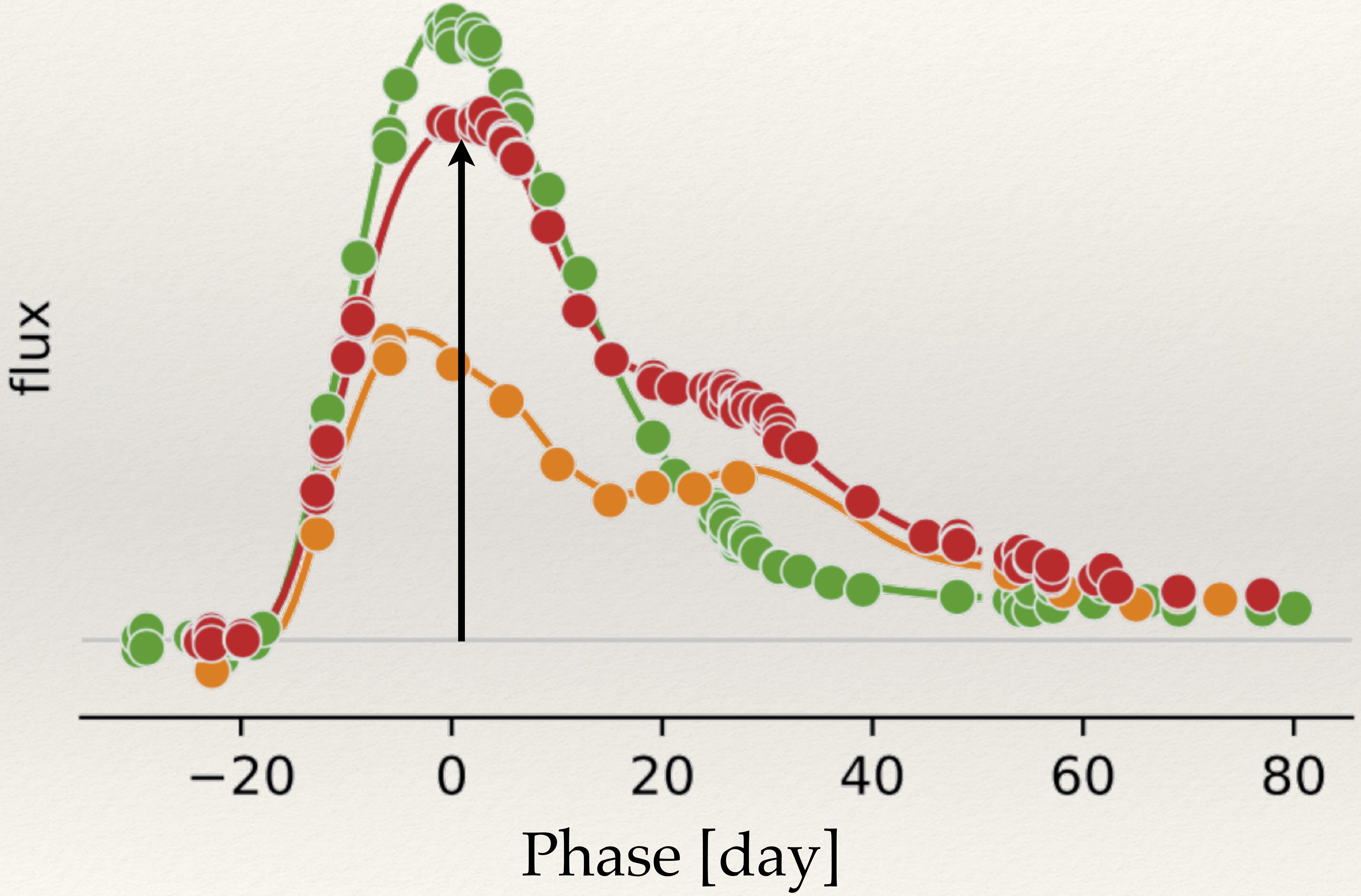


SNe Ia
→ Δmag=15%

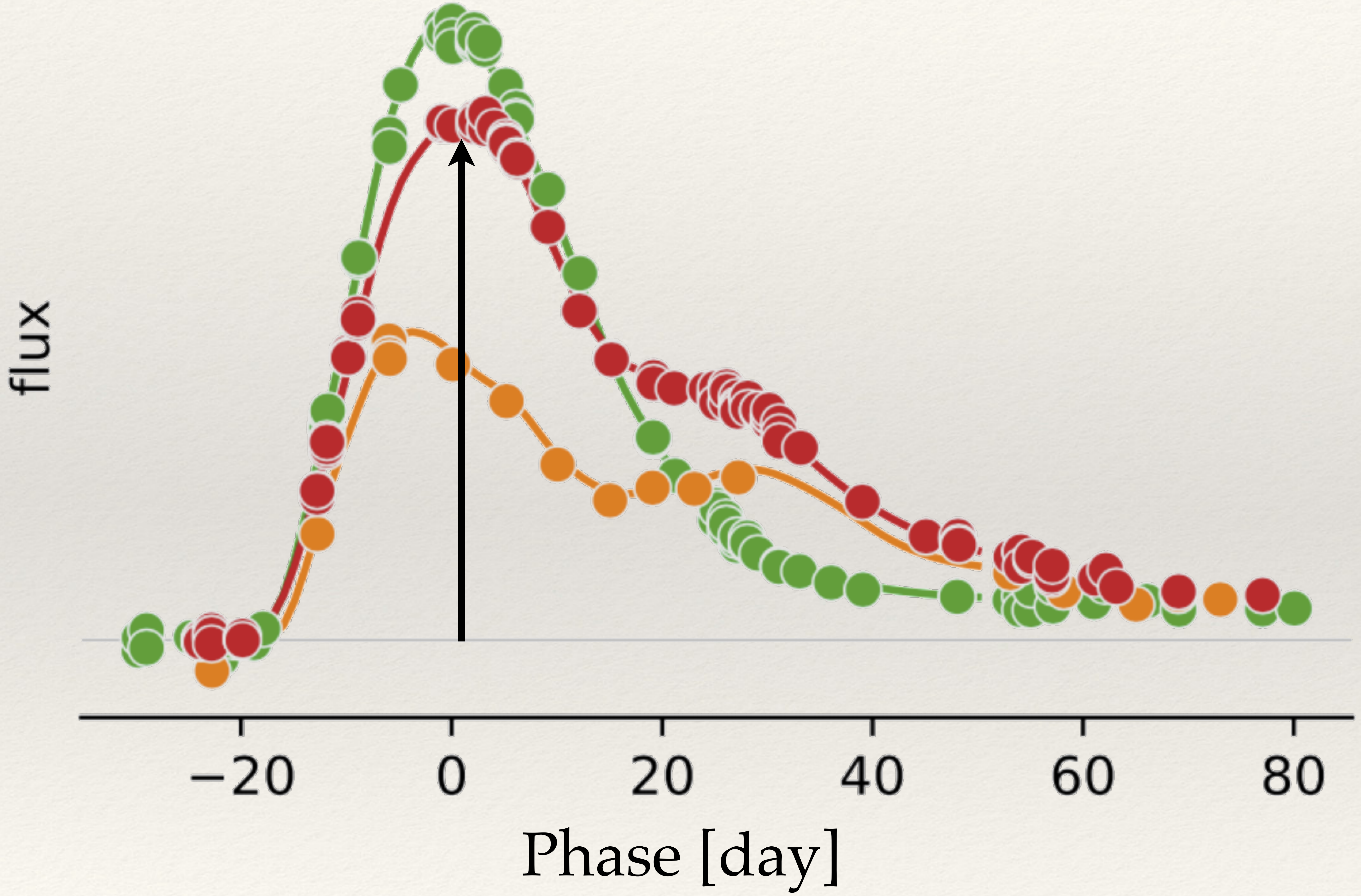
O(5000) SNe Ia
→ Δmag=0.2%

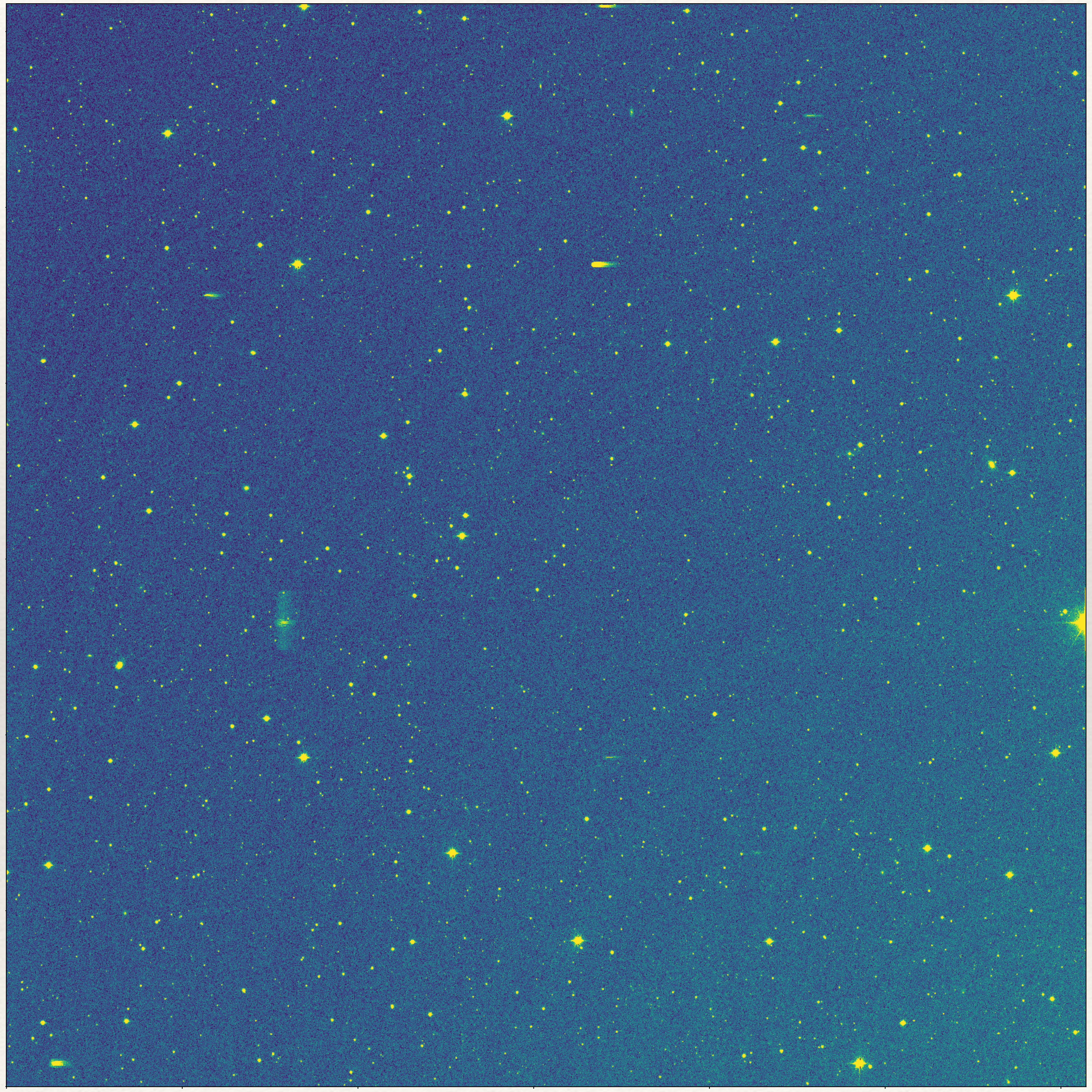
Photometric Accuracy
→ Δmag=0.1%

What are we measuring

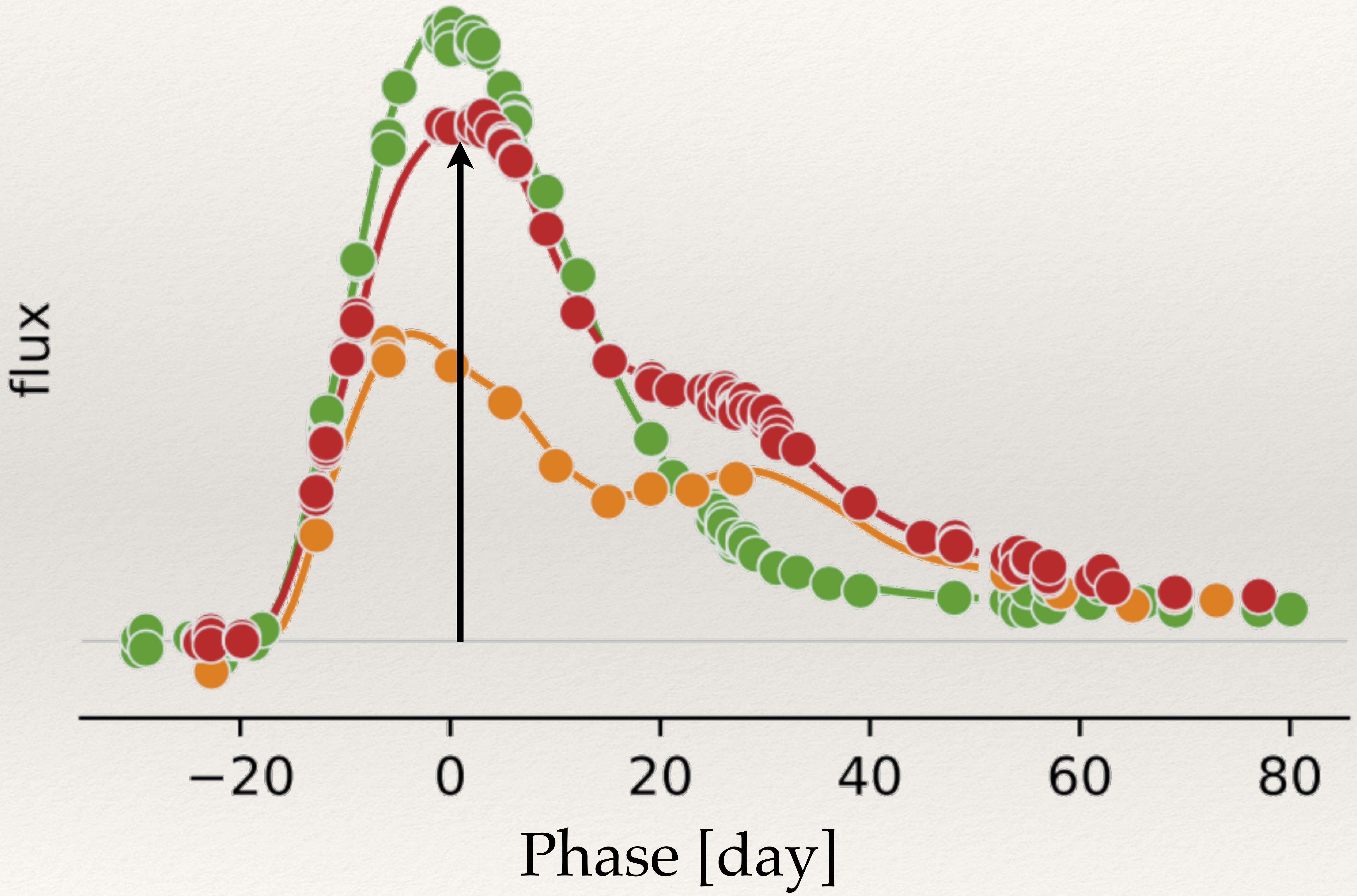


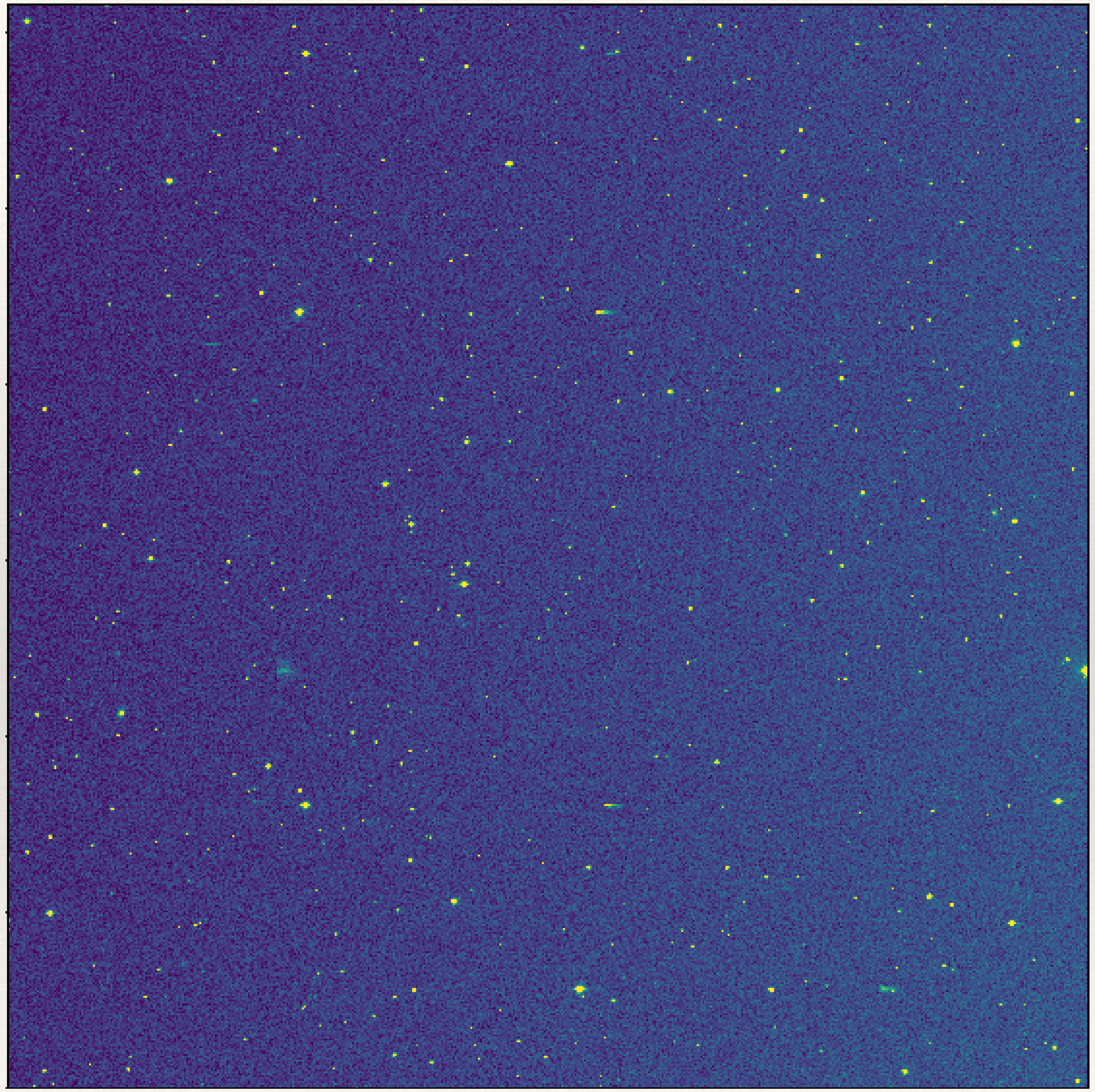
What are we measuring



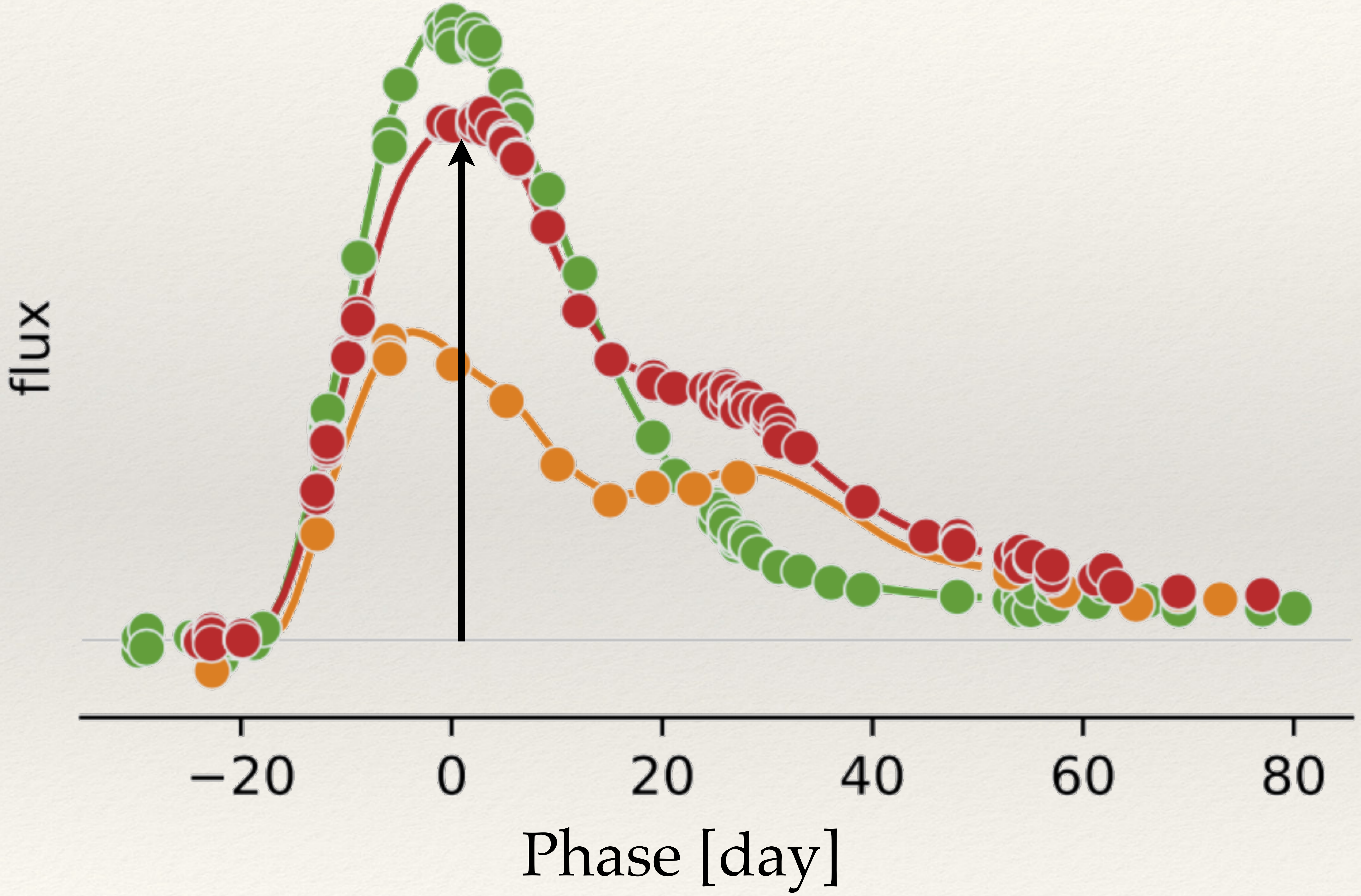


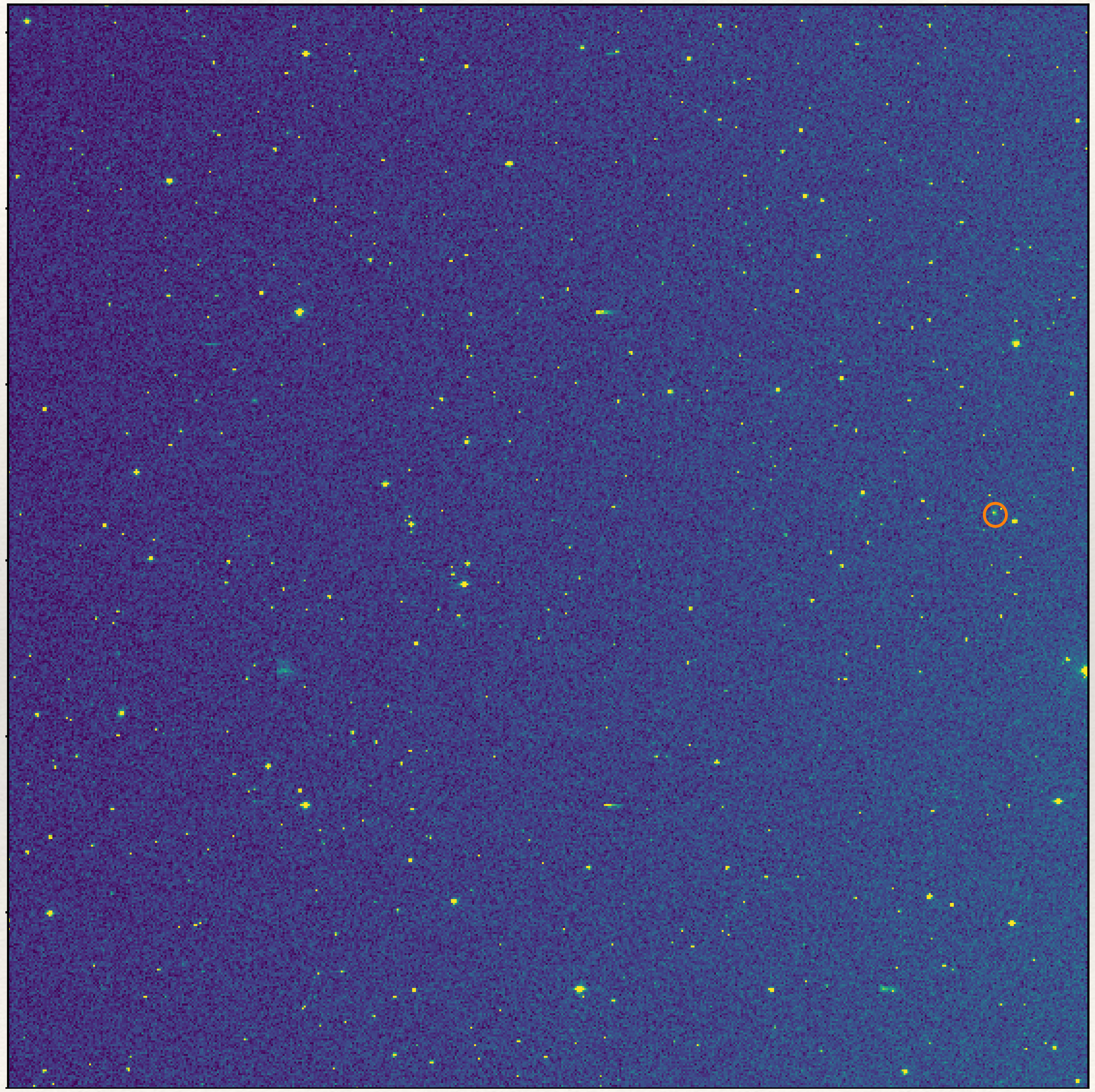
What are we measuring



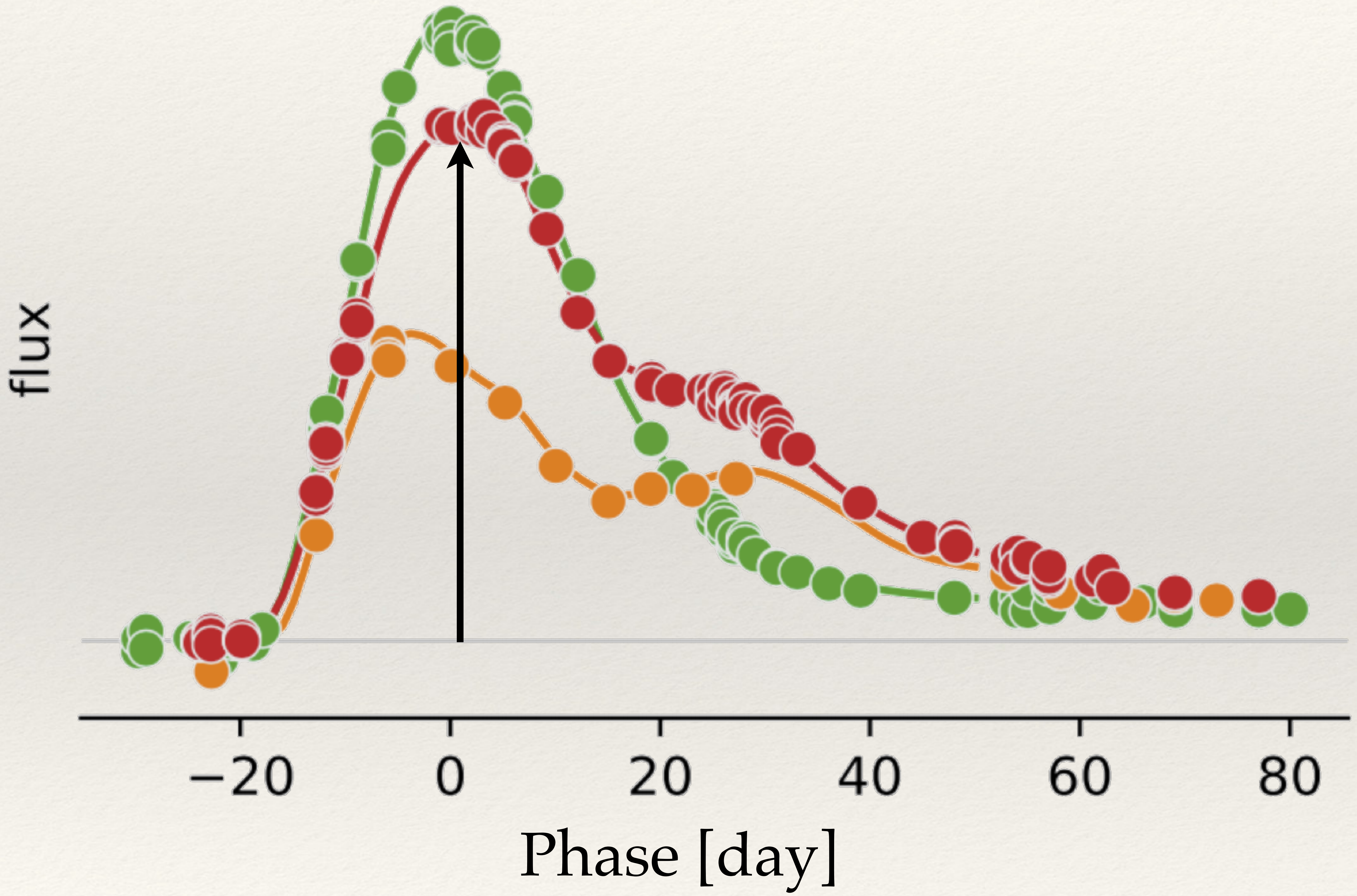


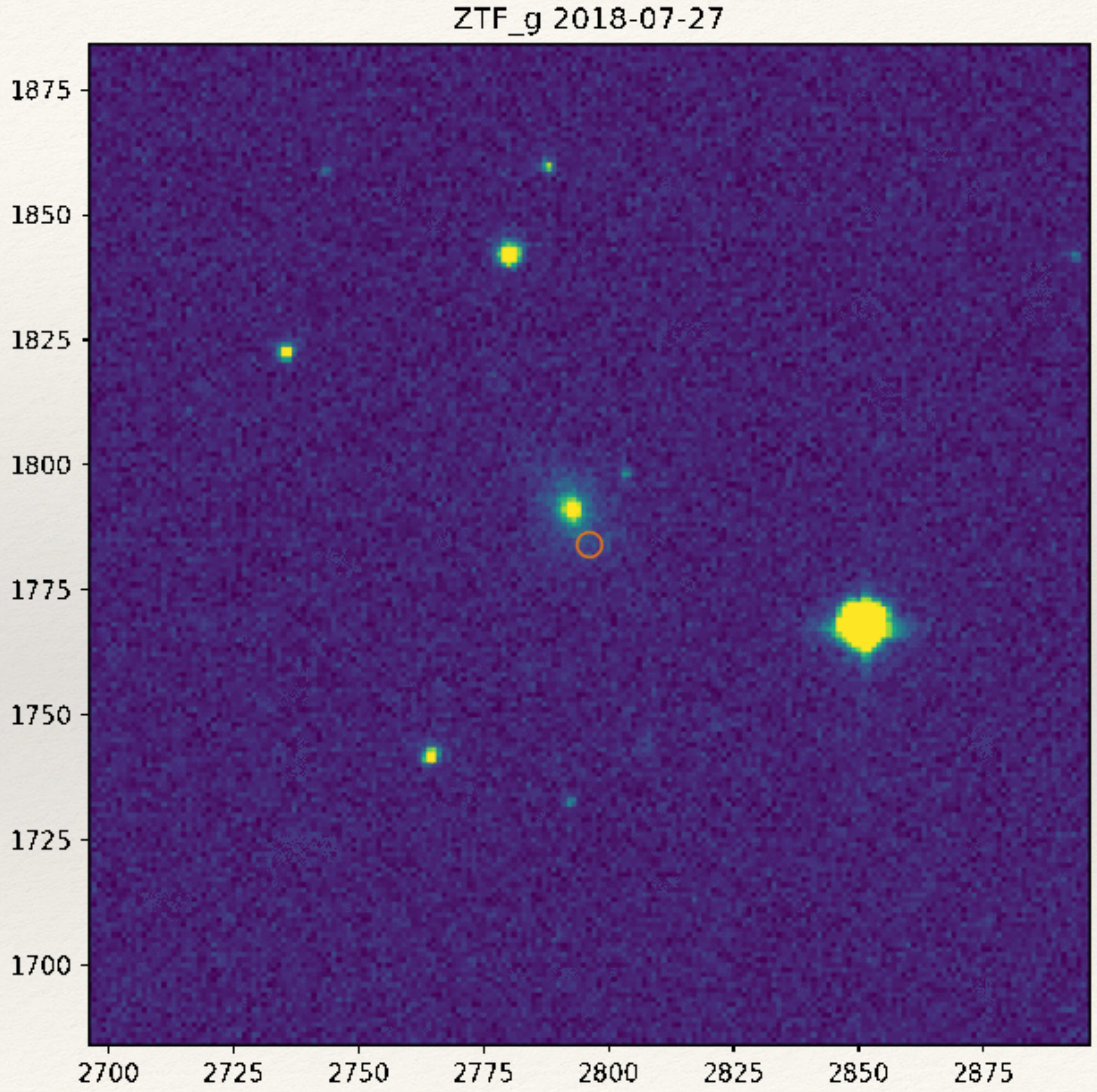
What are we measuring



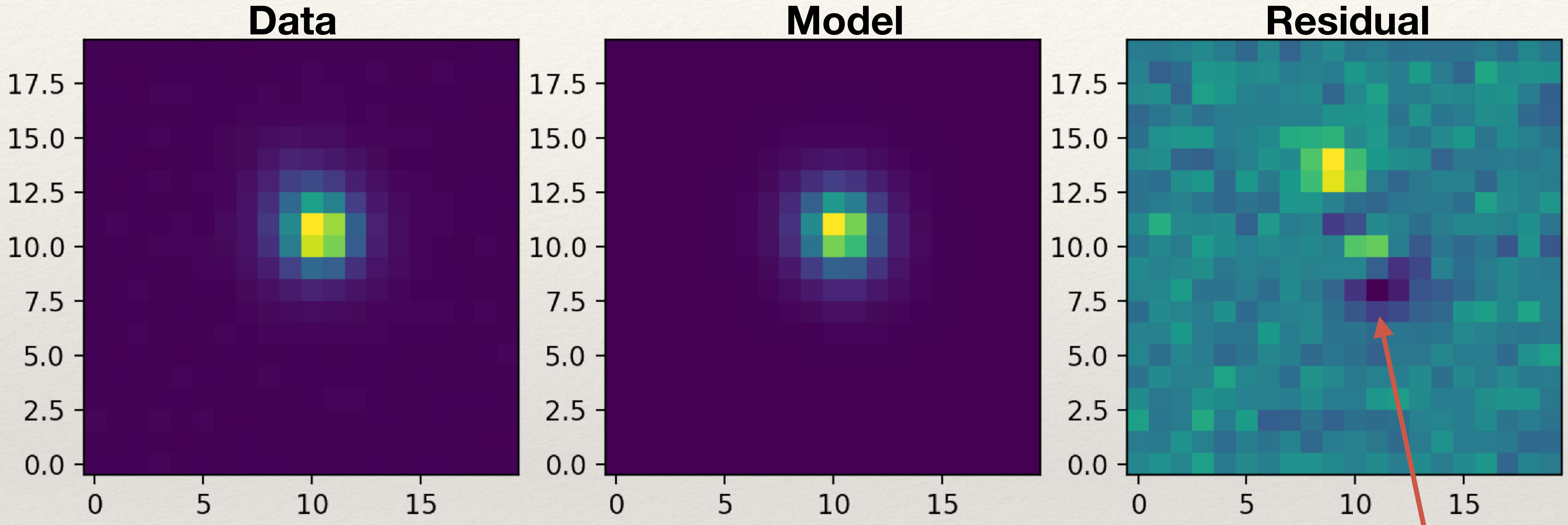


What are we measuring



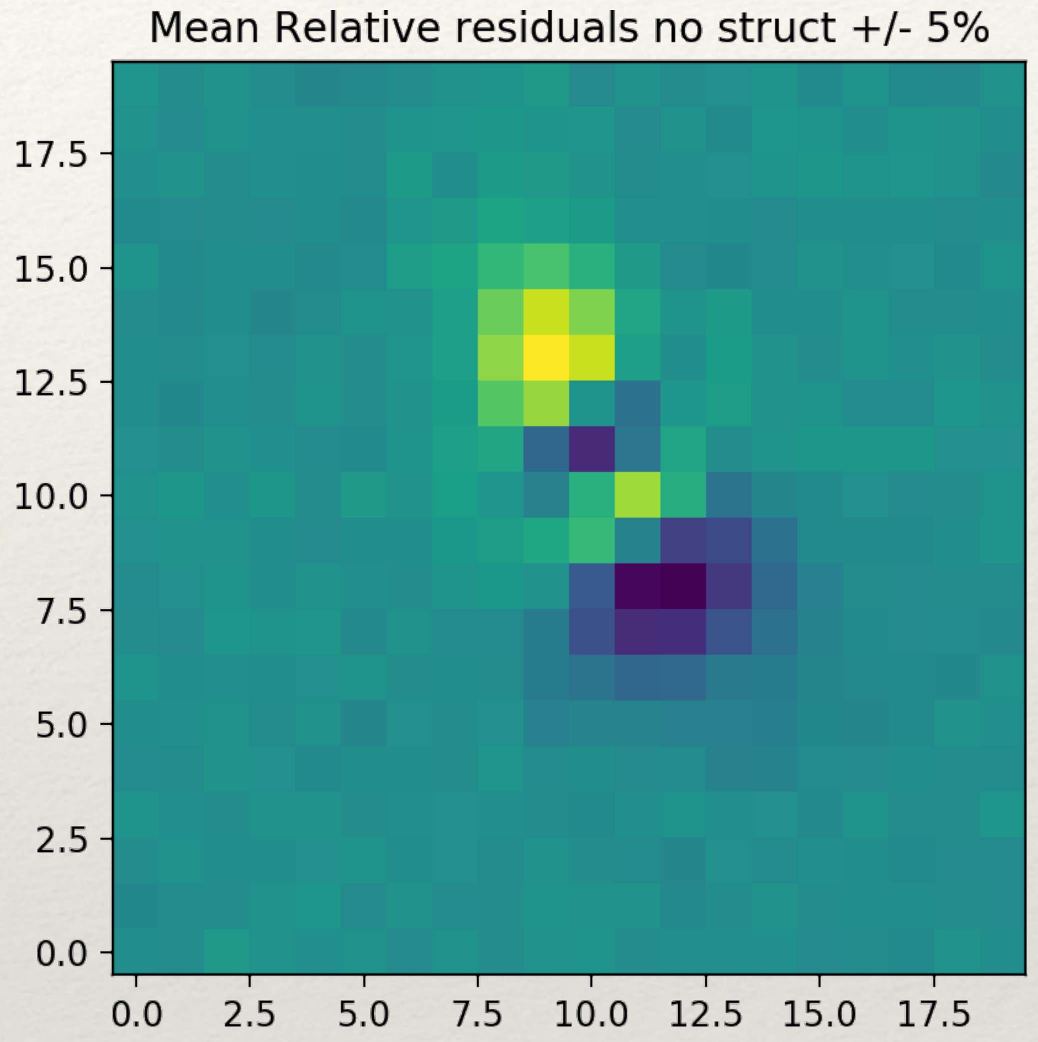


PSF Modeling



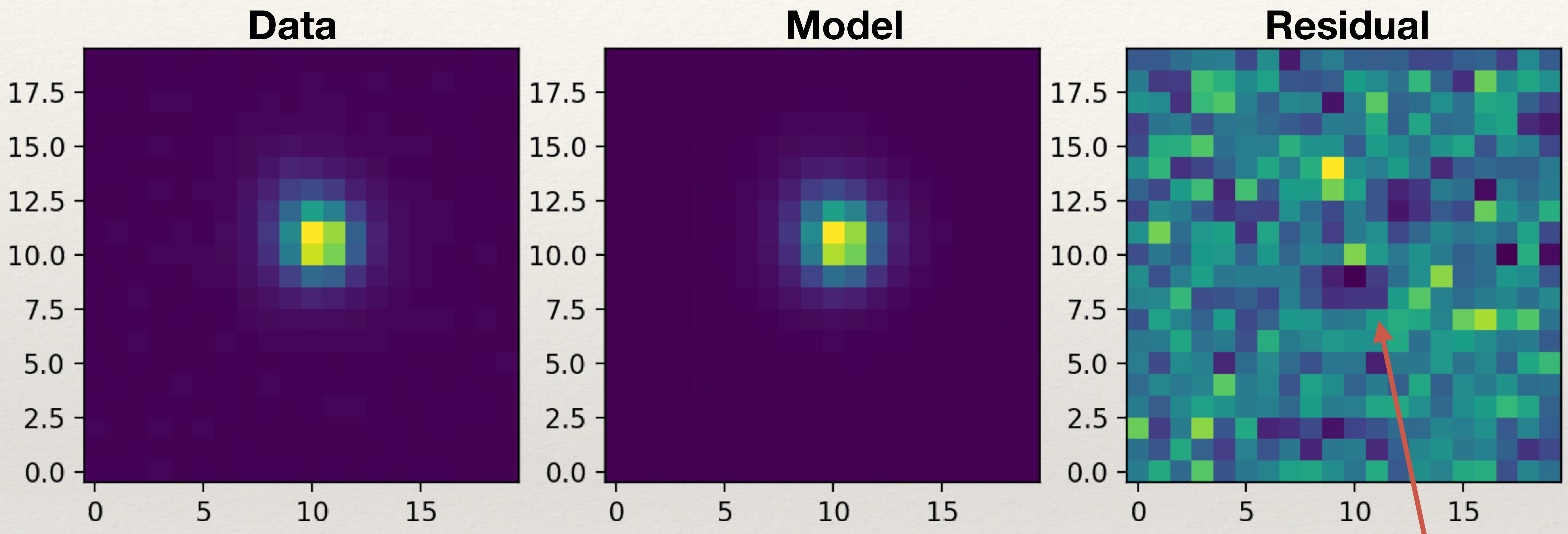
$\phi =$ **Moffat**

15% in flux



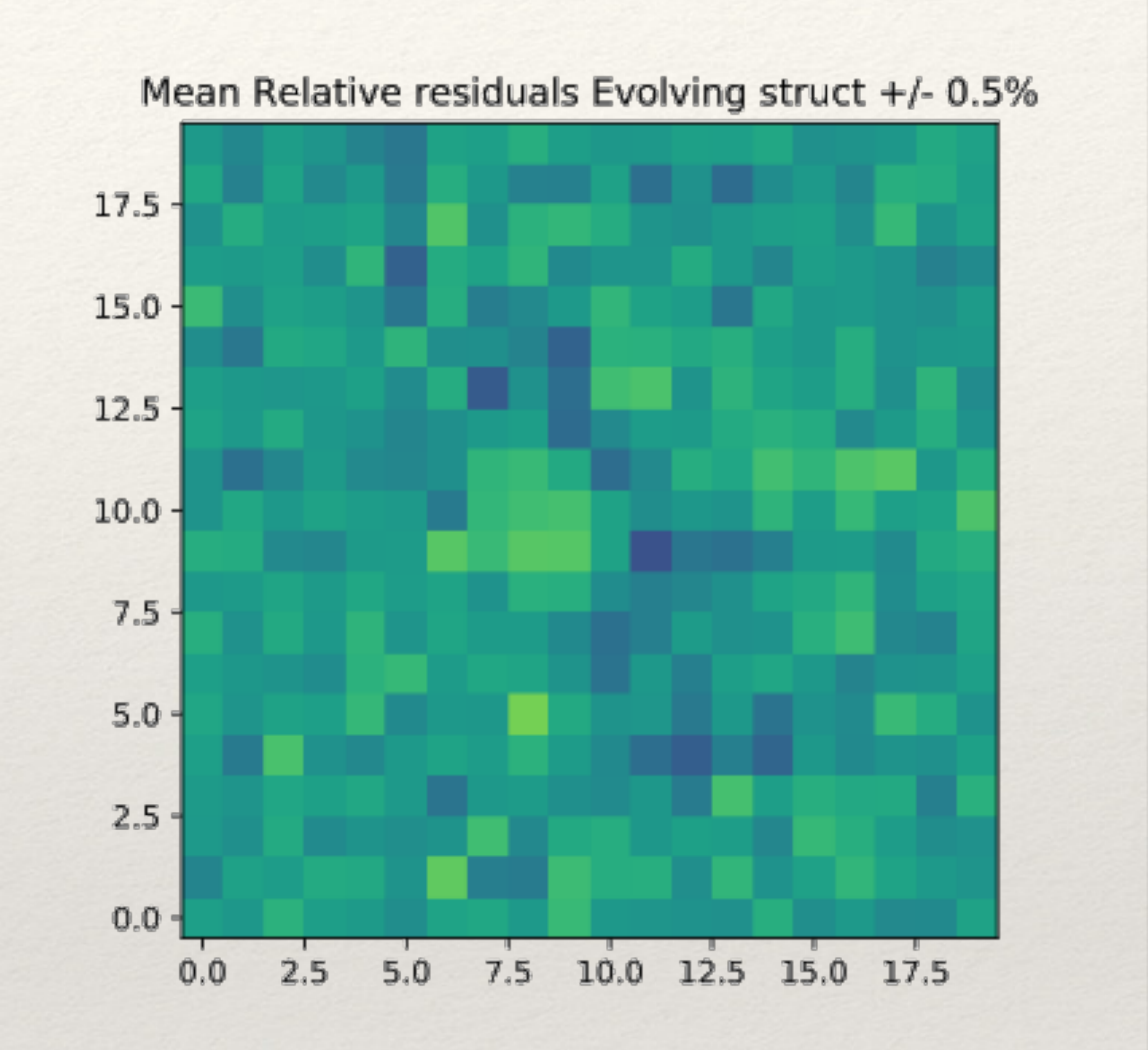
Mean over the 100 stars

PSF Modeling



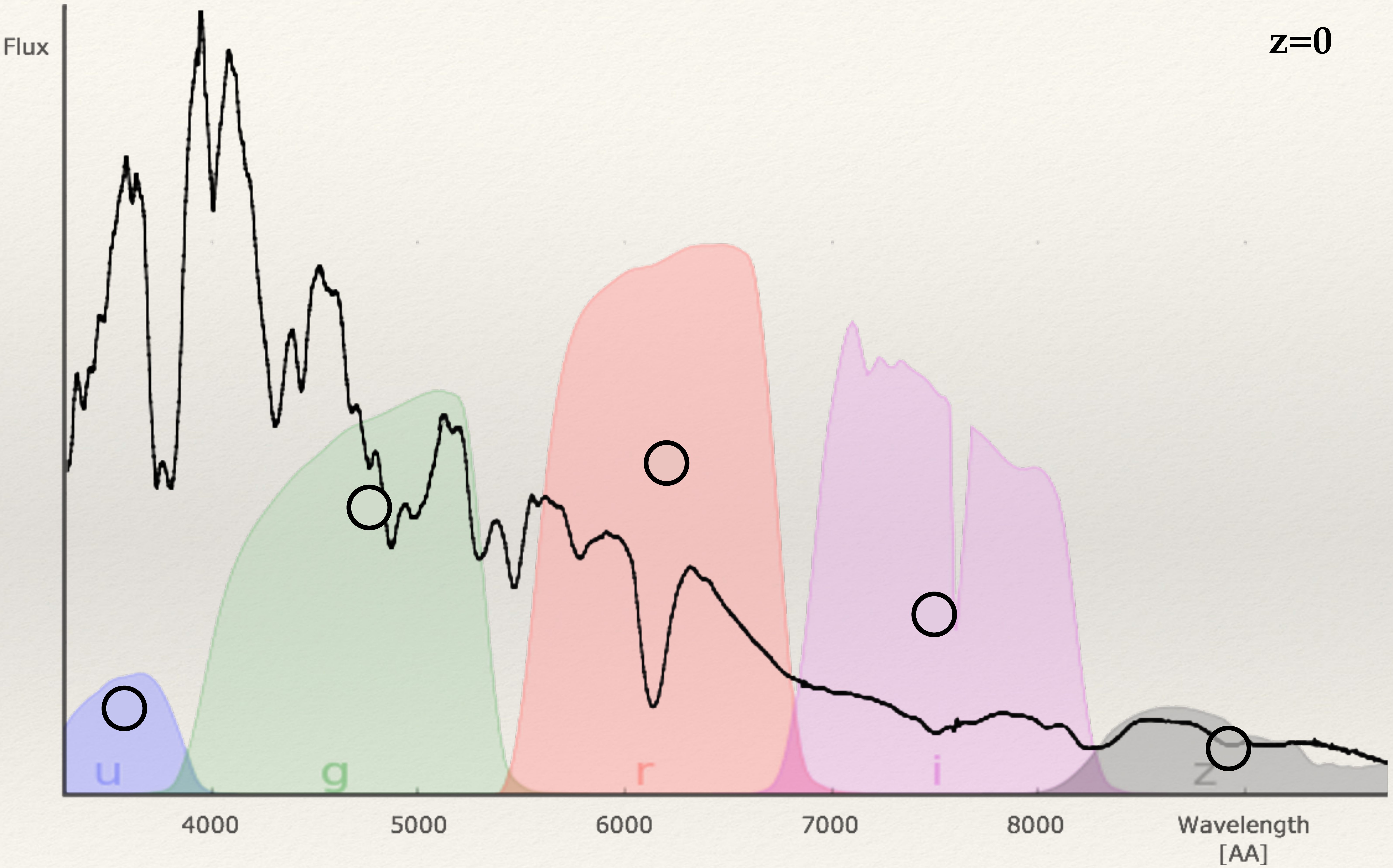
$$\phi = \textbf{Moffat} + c_0 R_0 + c_x R_x x + c_y R_y y$$

5% in flux

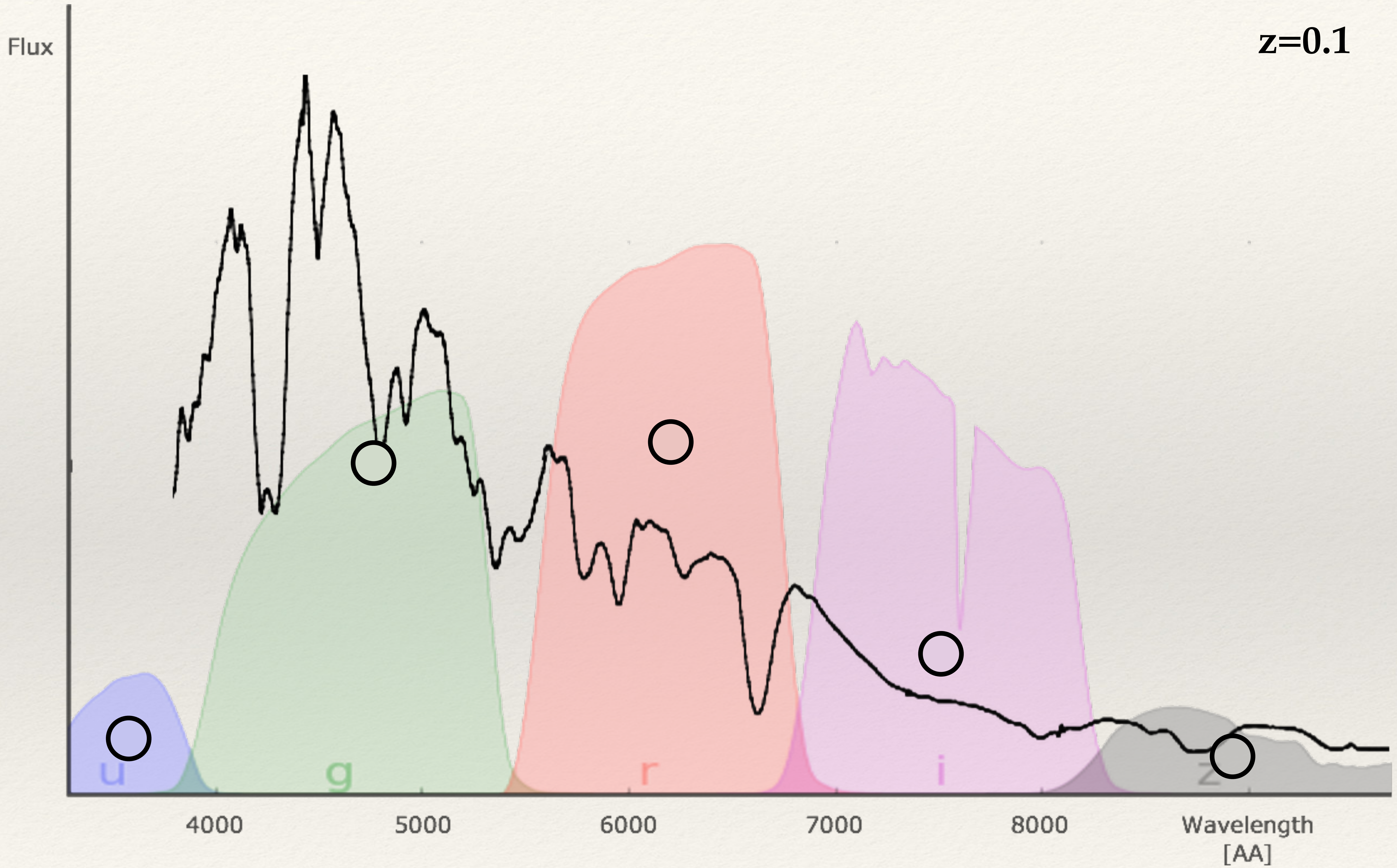


Mean over the 100 stars

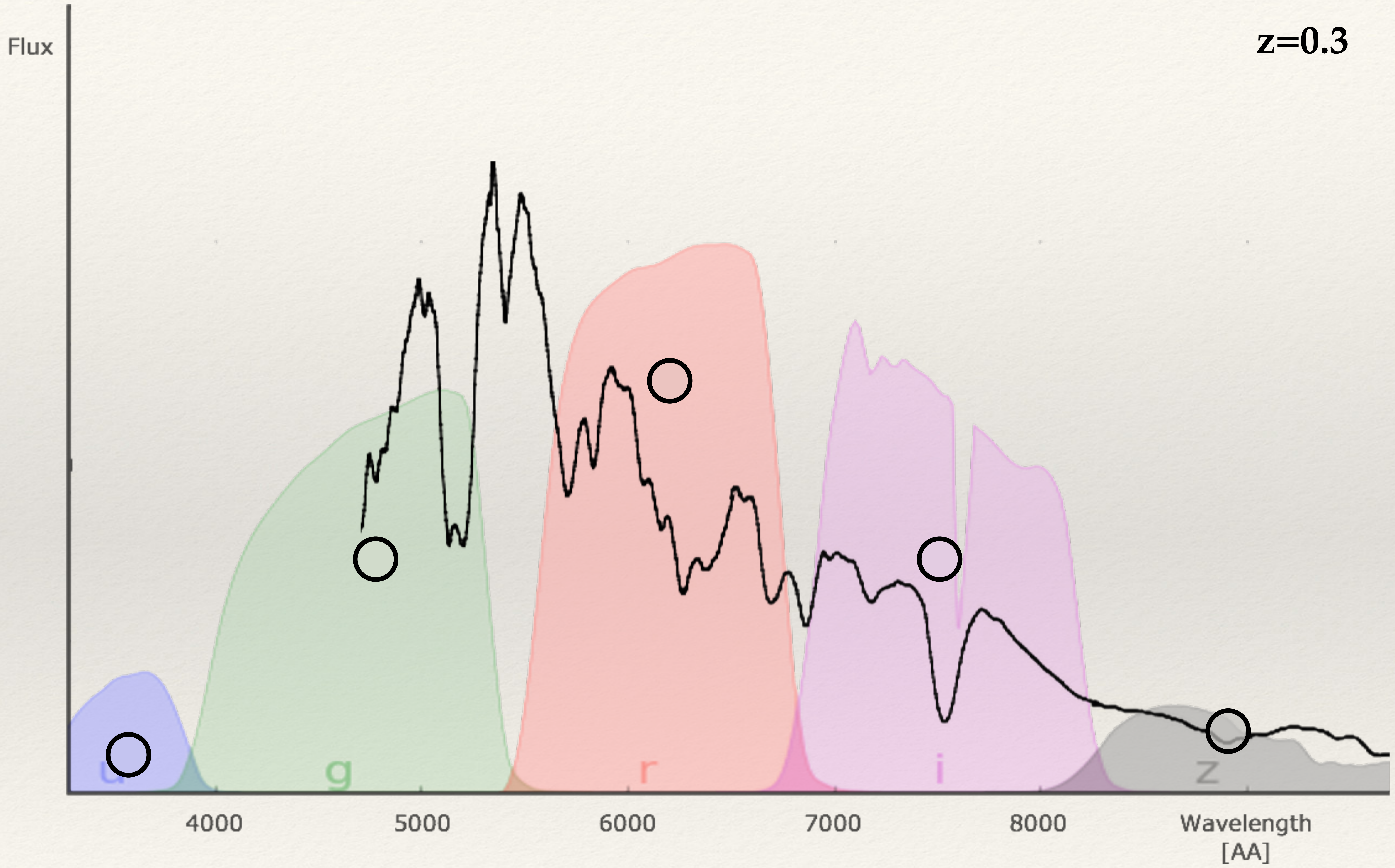
What are we measuring | *Integrated fluxes*



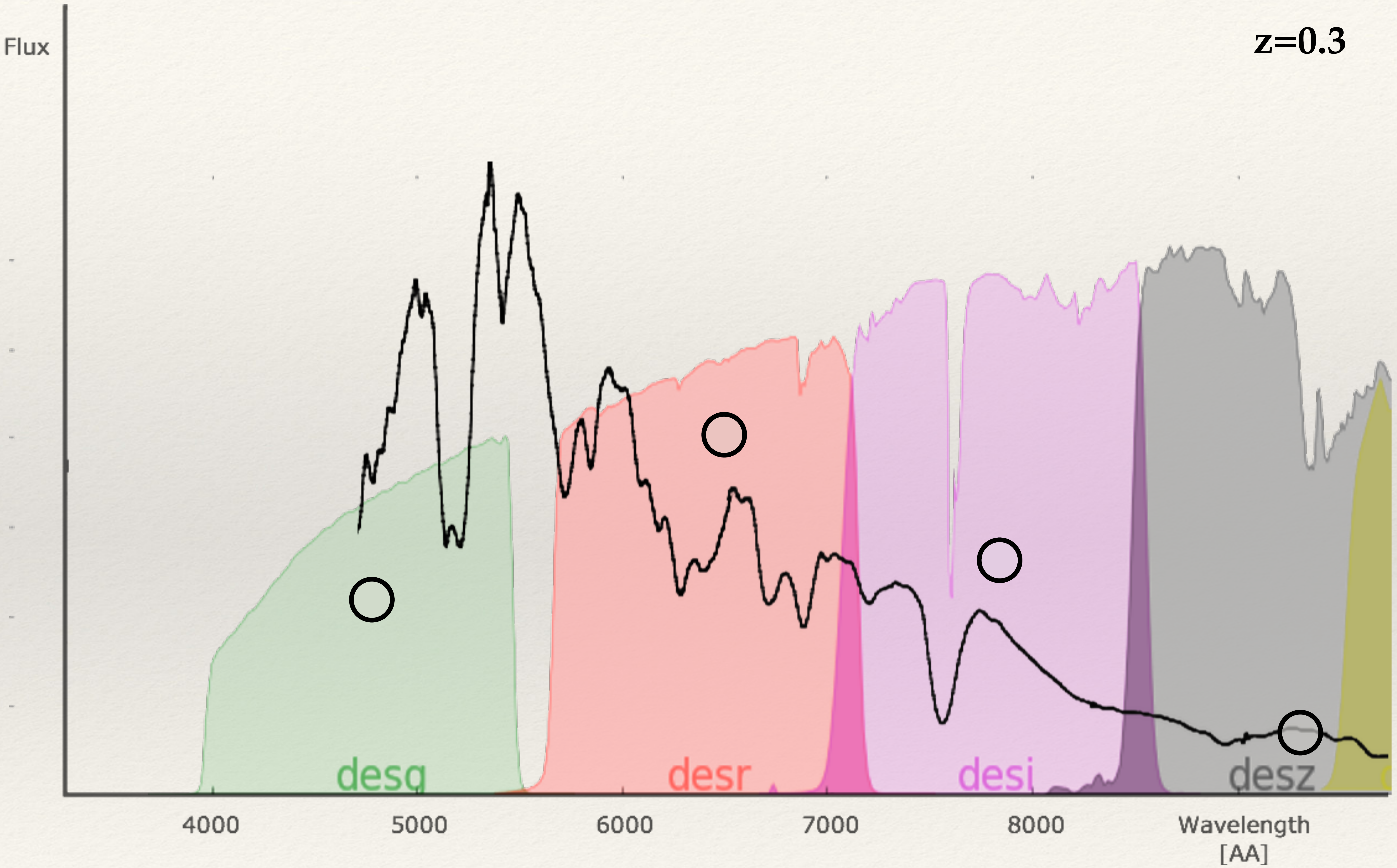
What are we measuring | *Integrated fluxes*



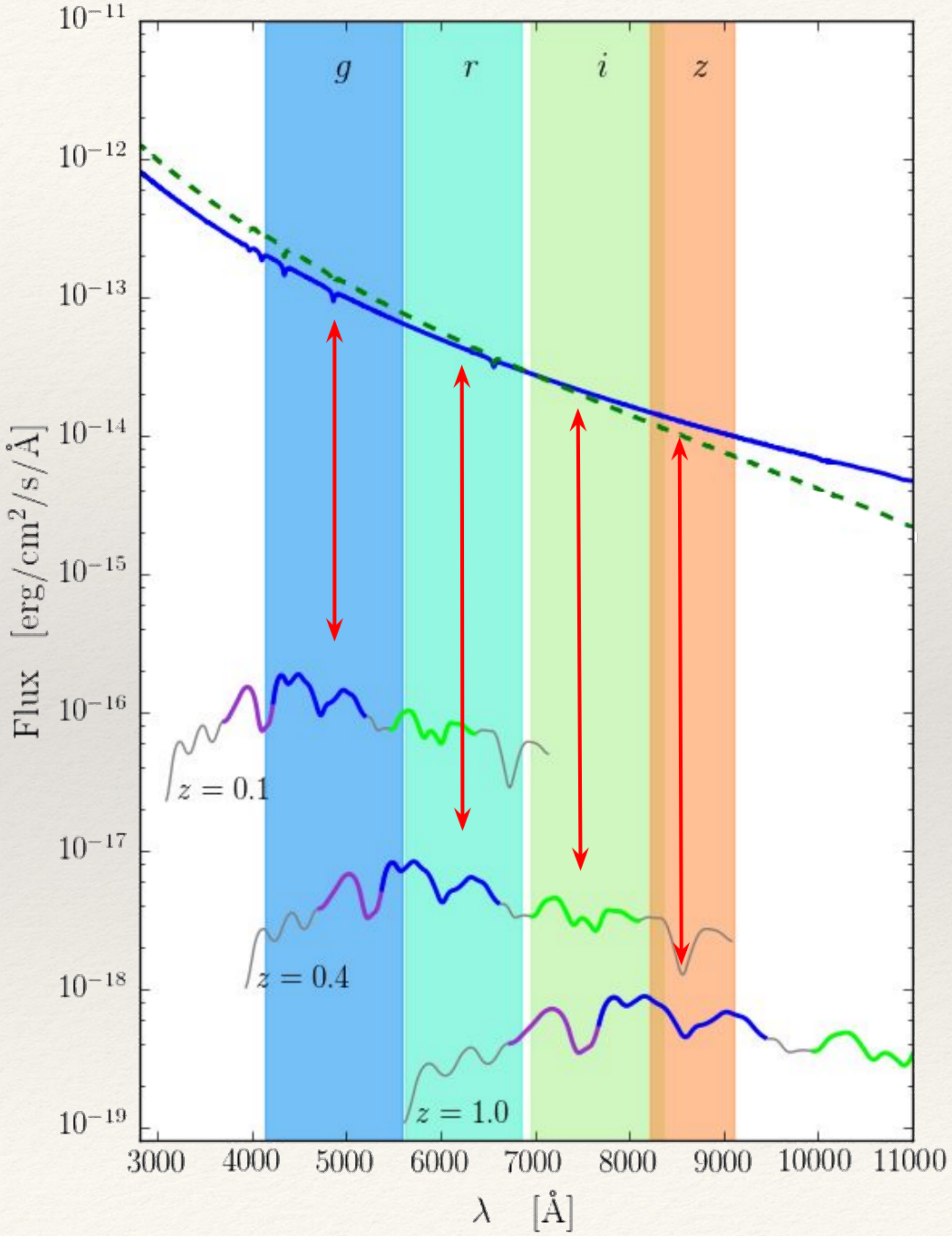
What are we measuring | *Integrated fluxes*



What are we measuring | *Integrated fluxes*

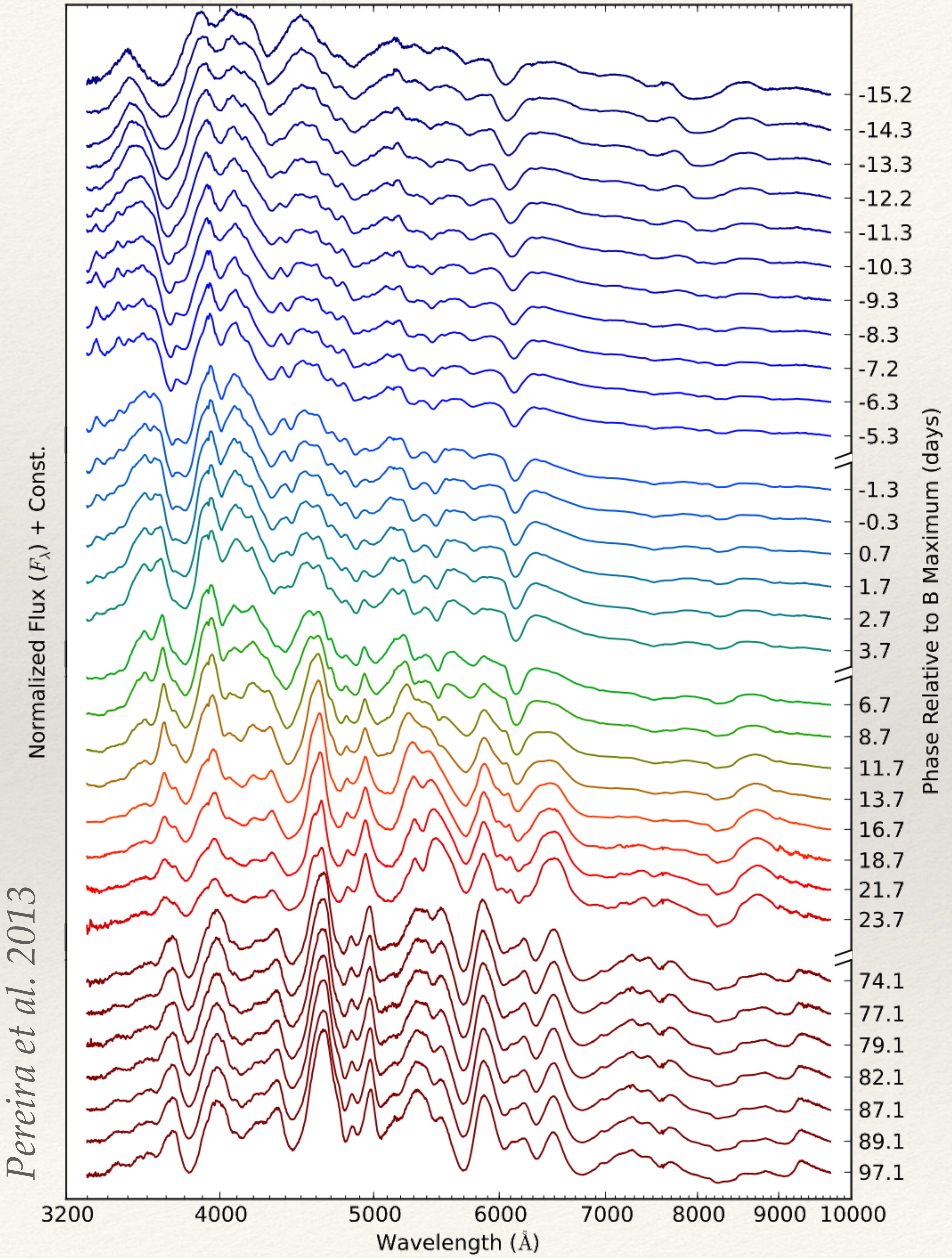


Flux Calibration



Spectro-photometric Survey | *SNfactory*

Pereira et al. 2013



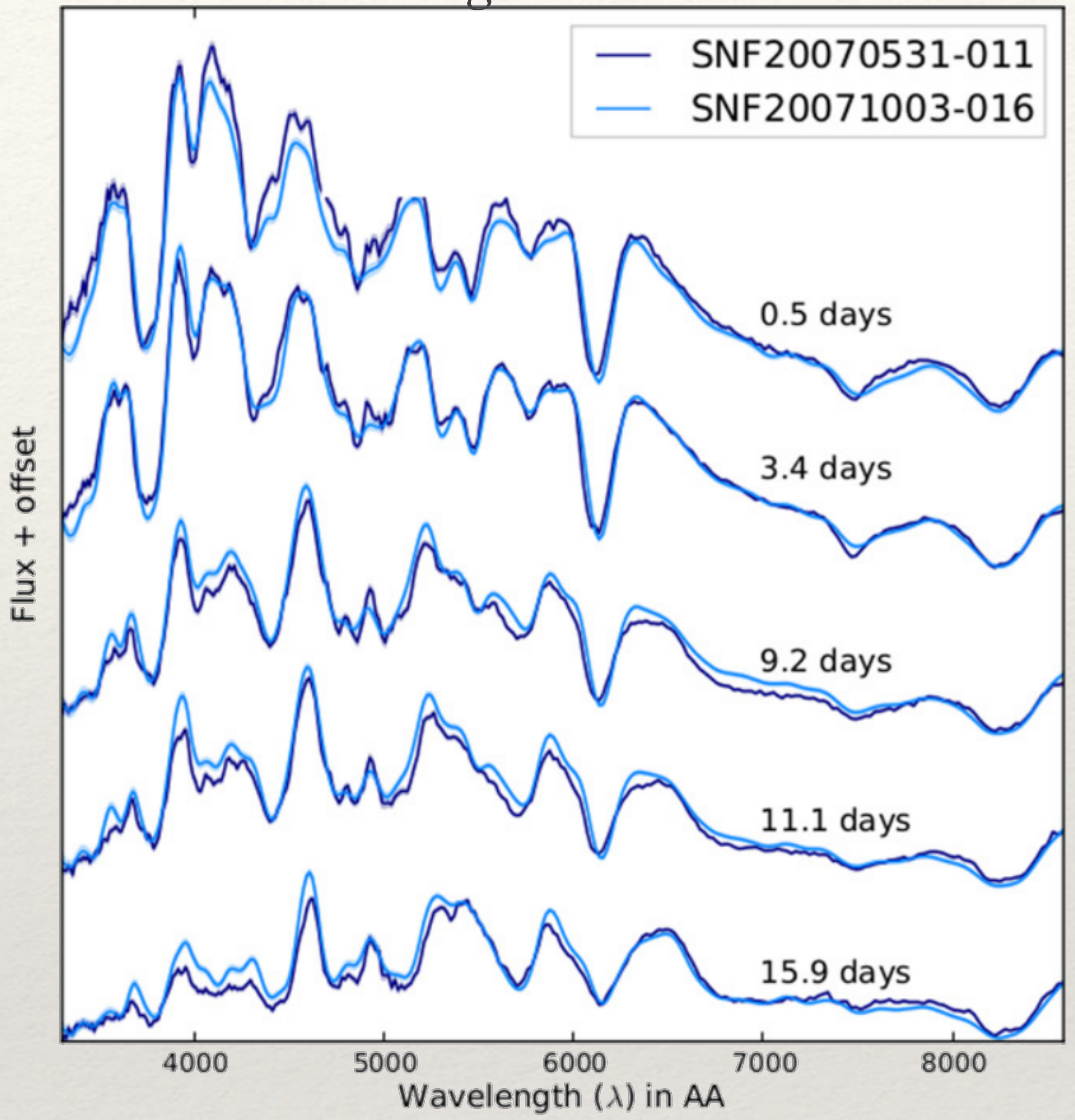
Pro

- Could use any filter to generate light-curves
- Sees detailed spectro-features
- Opens new standardization techniques

Cons

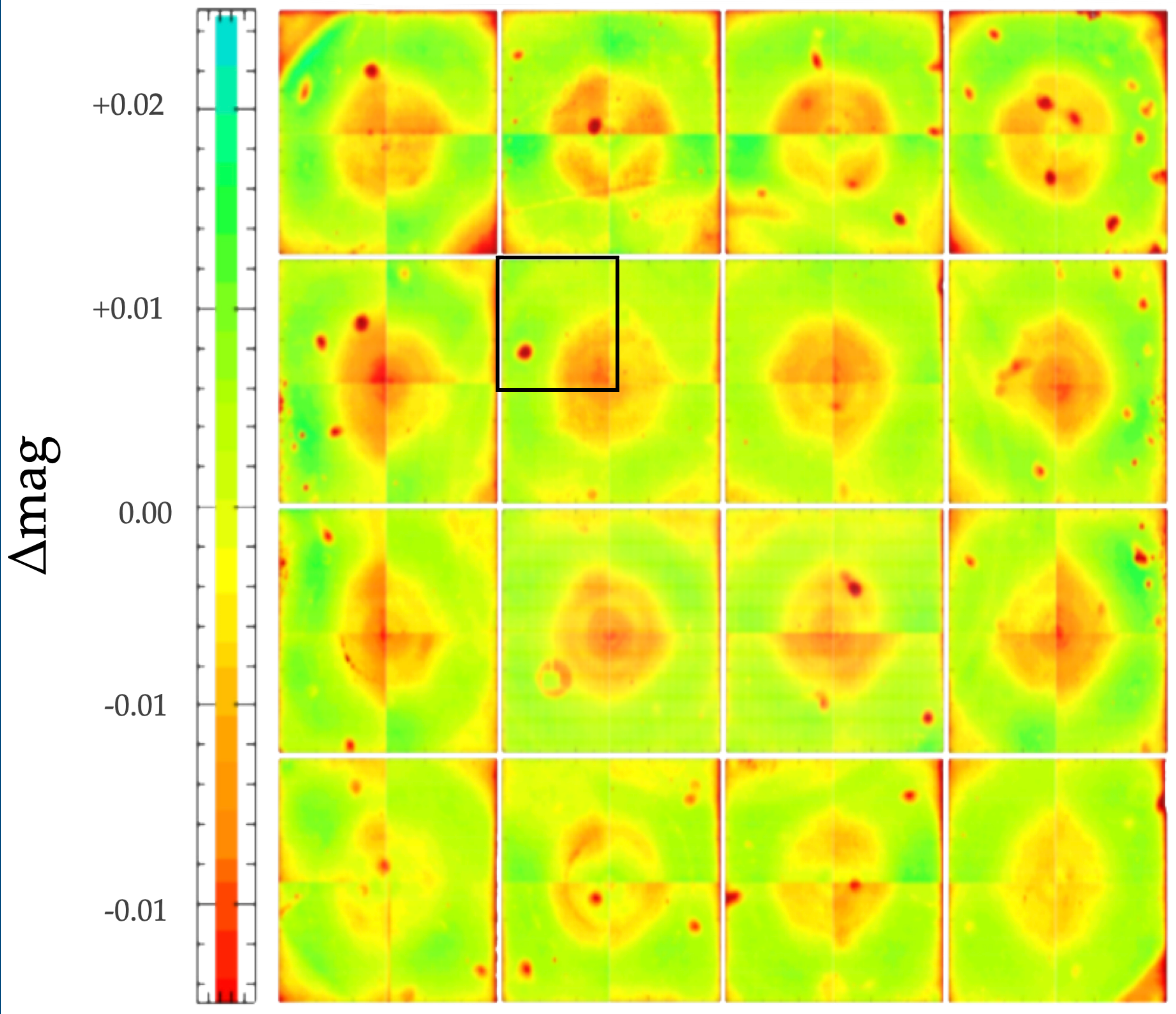
- Very expansive (like +++)
- Very hard to calibrated (like ++)
- Not proven *that* necessary (so far)

"twining" | Fakhouri et al. 2015



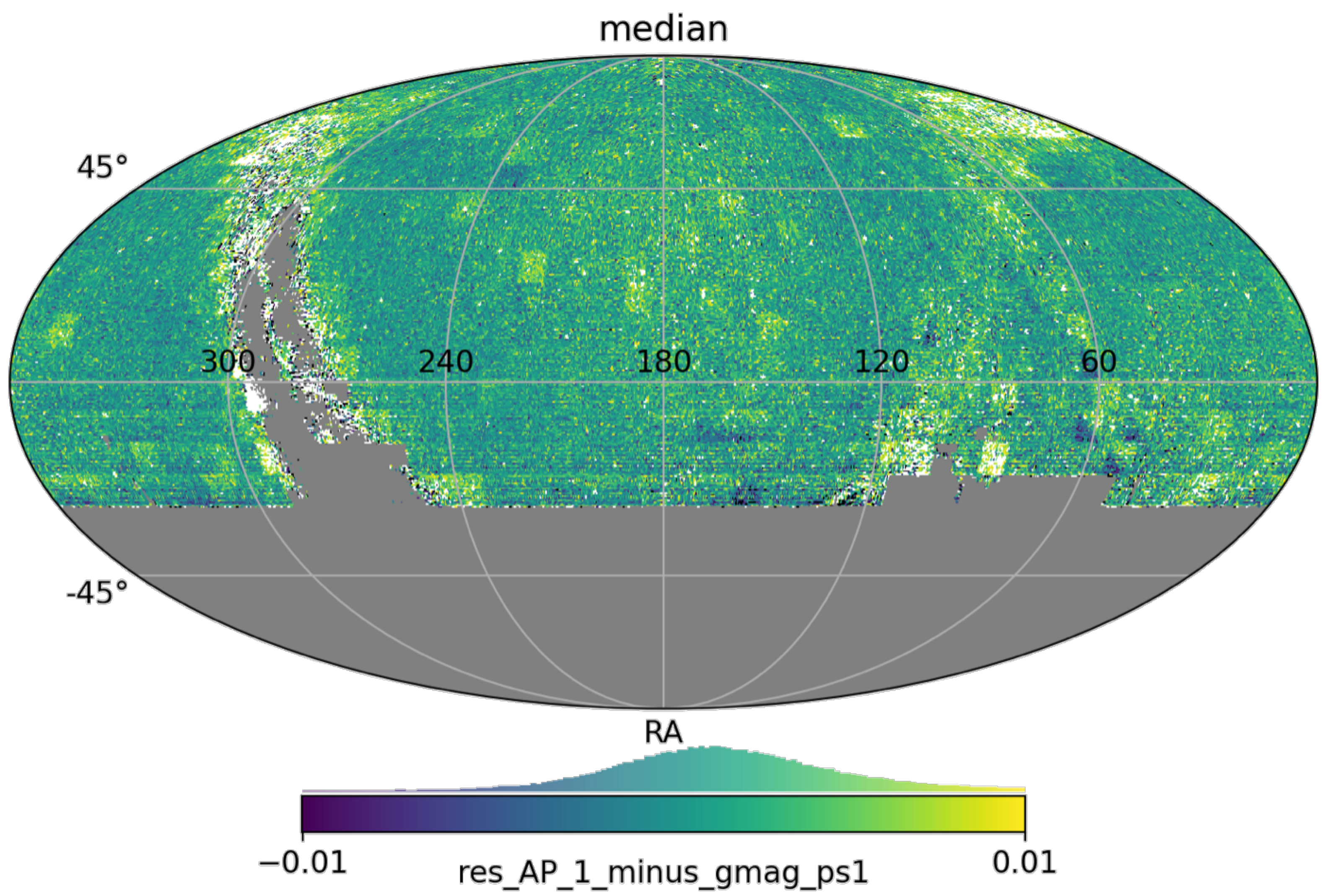
Flux Calibration

Sensor issues



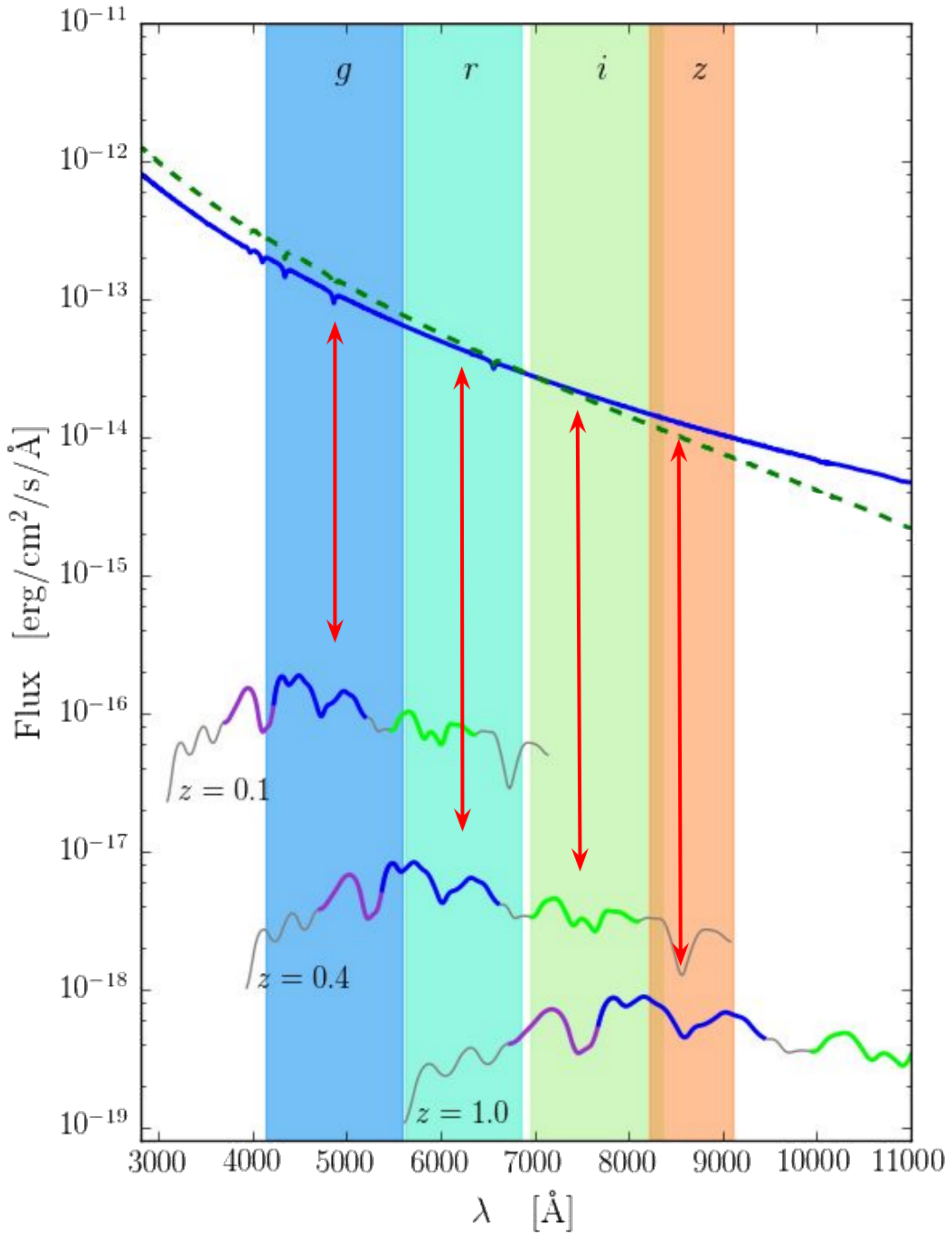
Credit: Andrew Drake

Survey issues



Credit: Benjamin Racine

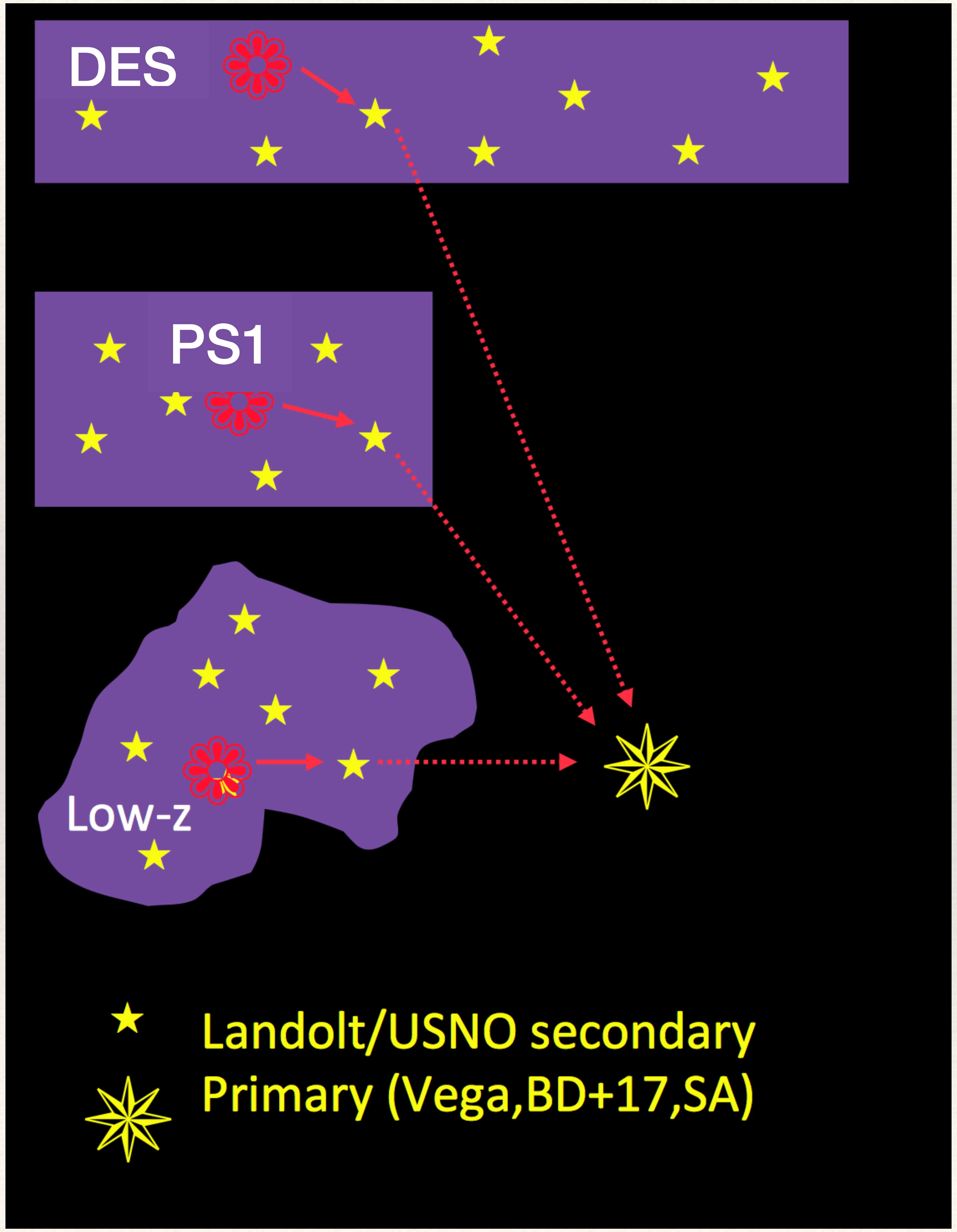
Cross-survey / redshift issues



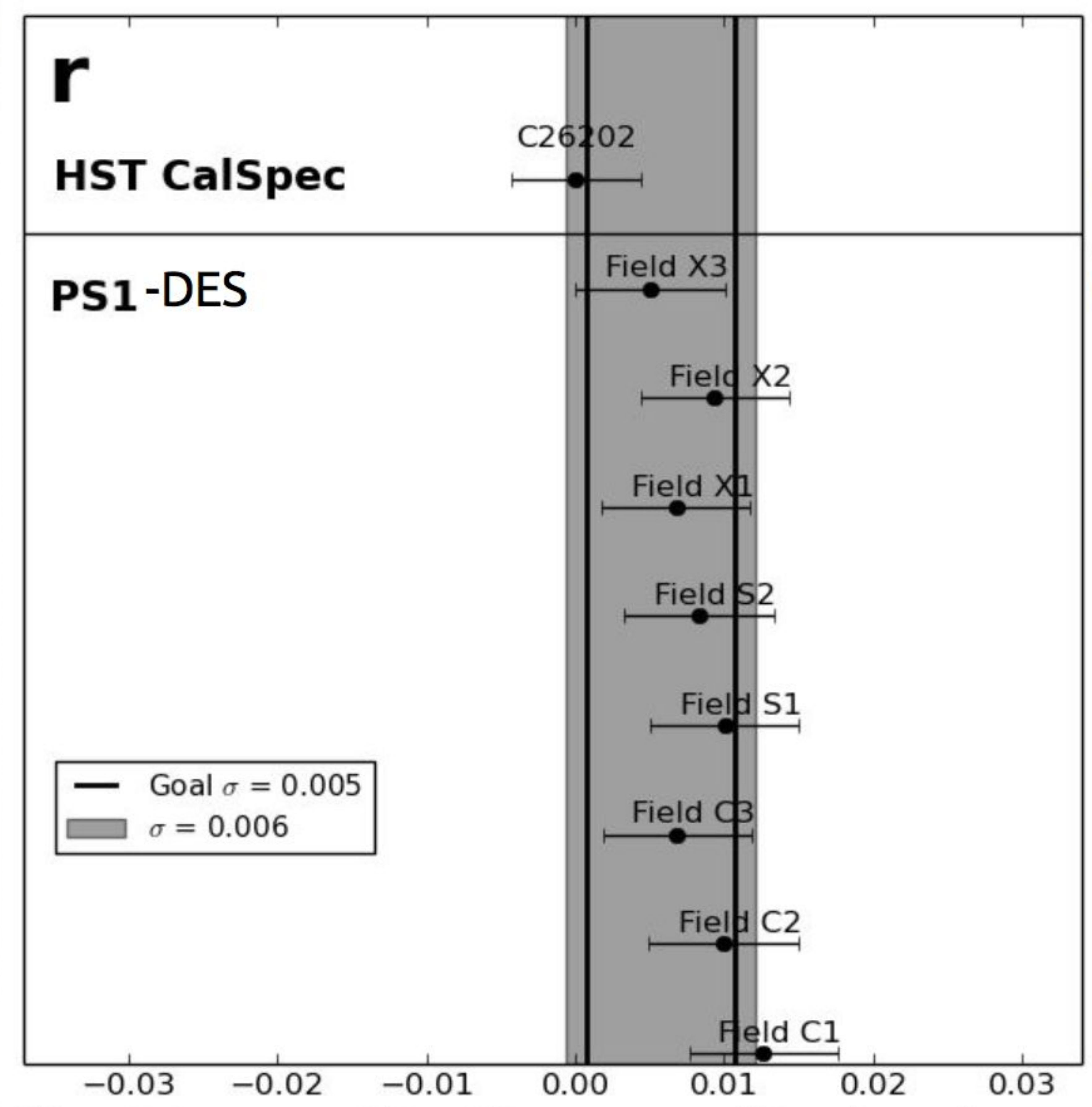
Credit: Nicolas Regnault

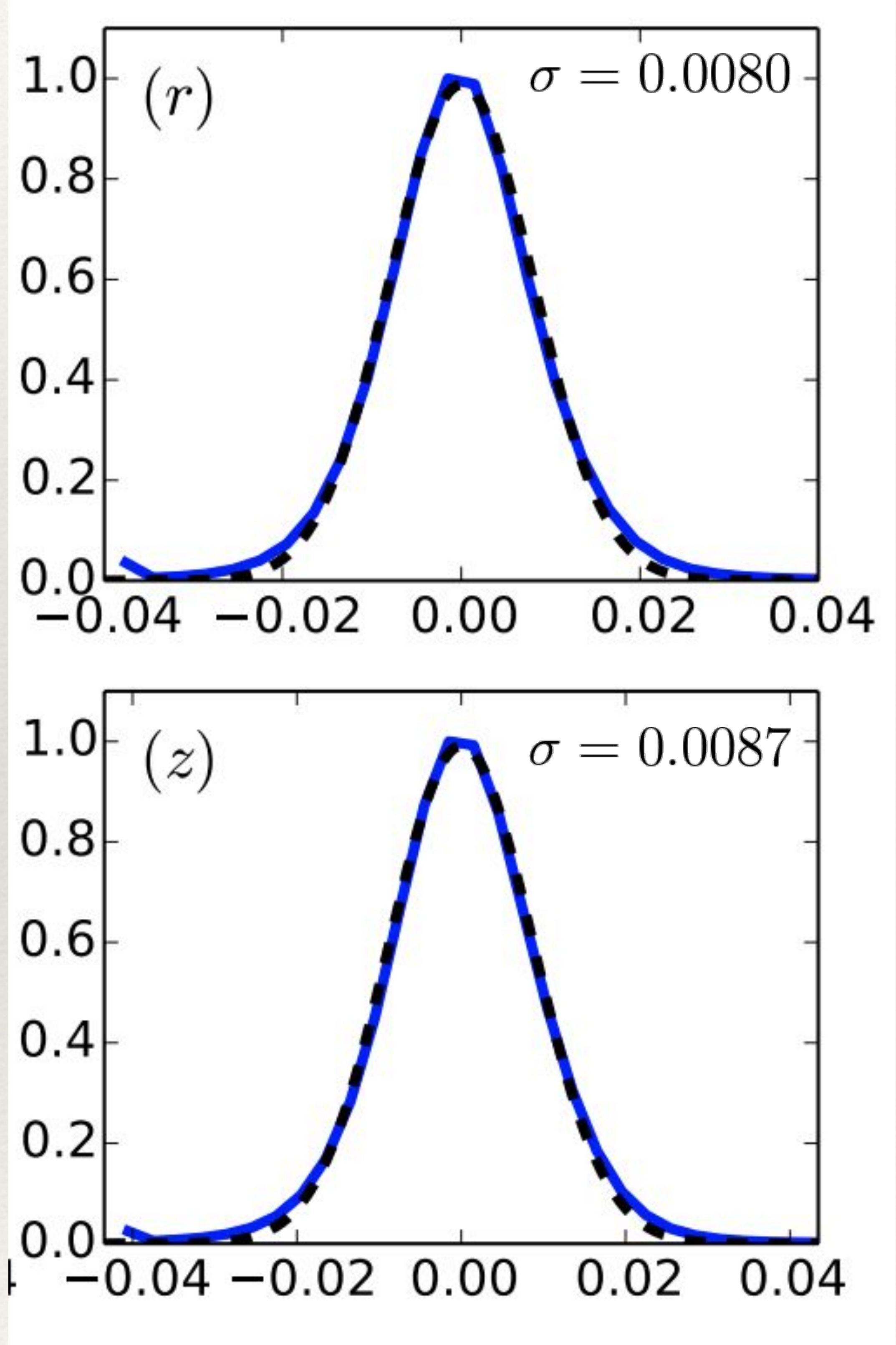
The Hubble diagram today: 36 different filter-sets, many obsolete:
required *relative* accuracy : 0.01mag

Flux Calibration

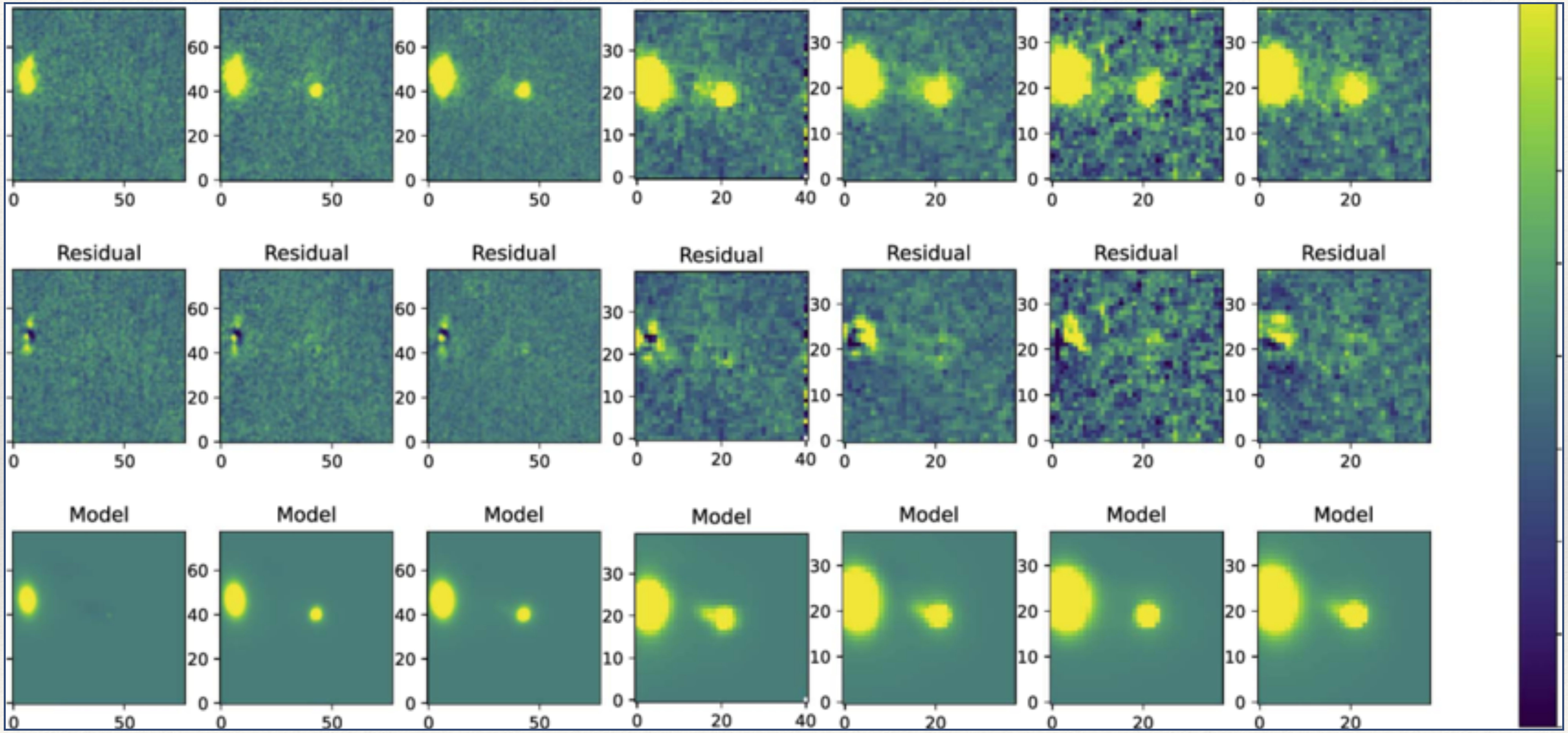


Repeated measurements of thousands of Tertiary Standard Stars



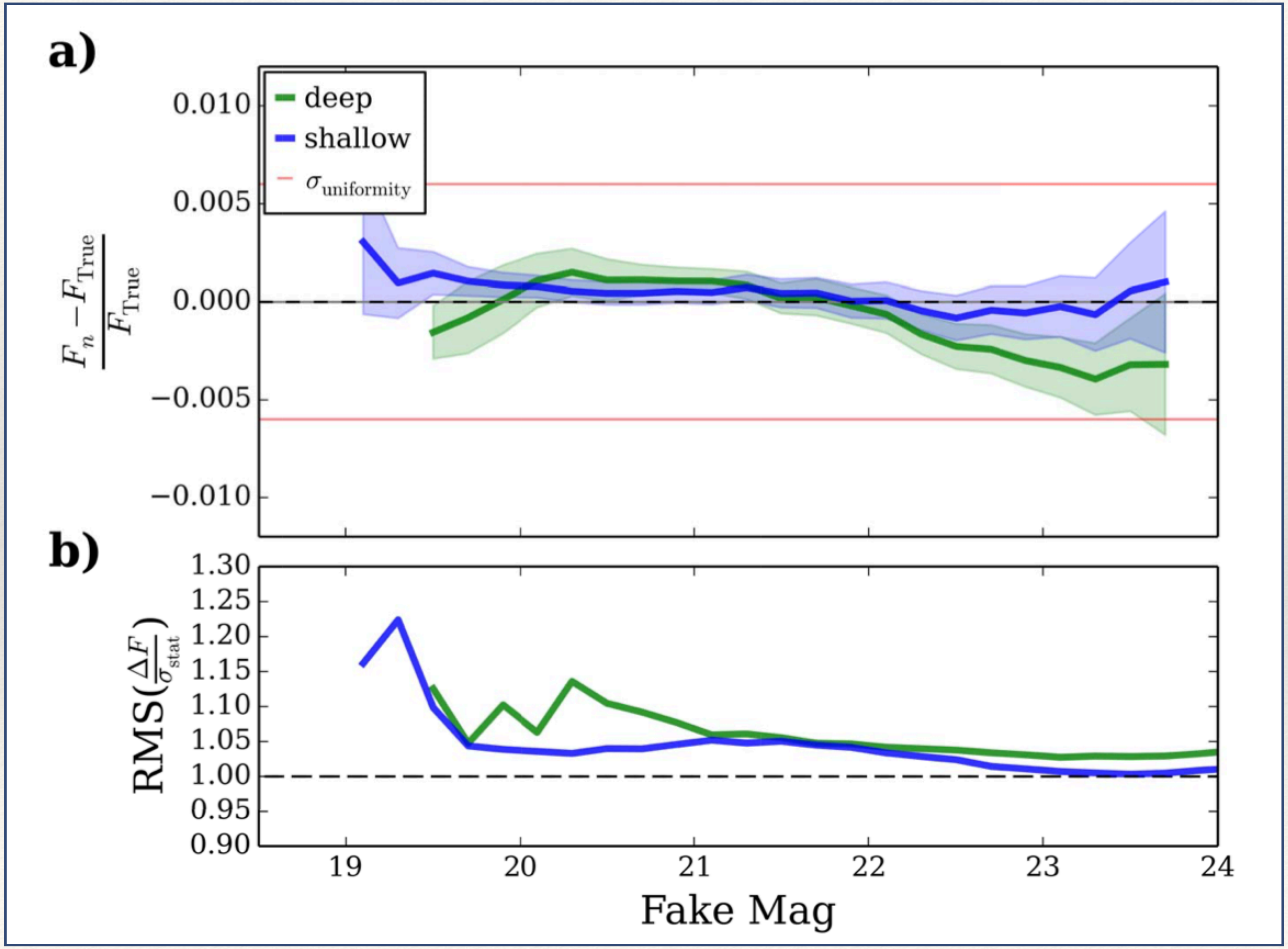


Scene model photometry (SMP)



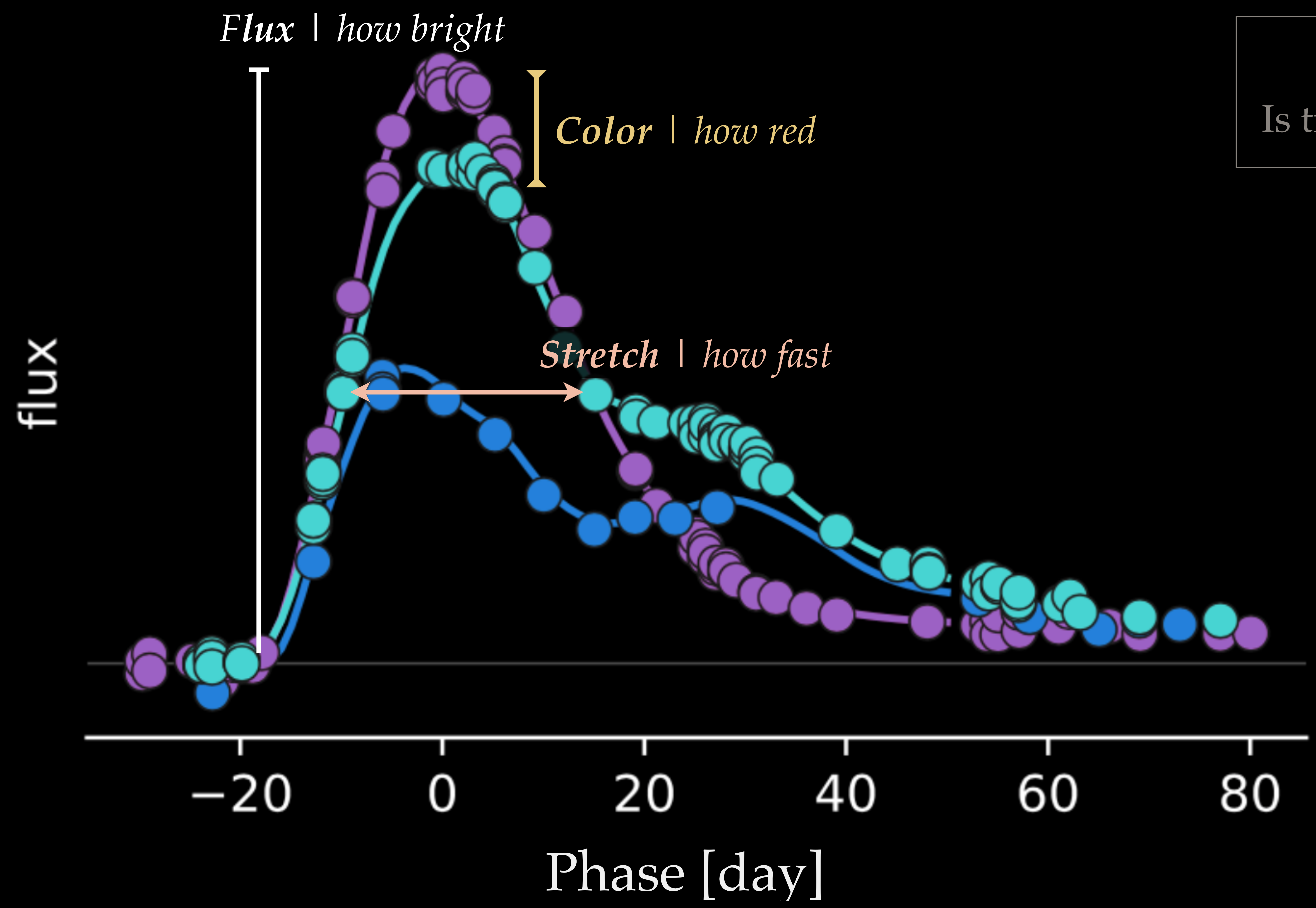
Simultaneous fit of both the object and environment: no need for templates

Fake injections



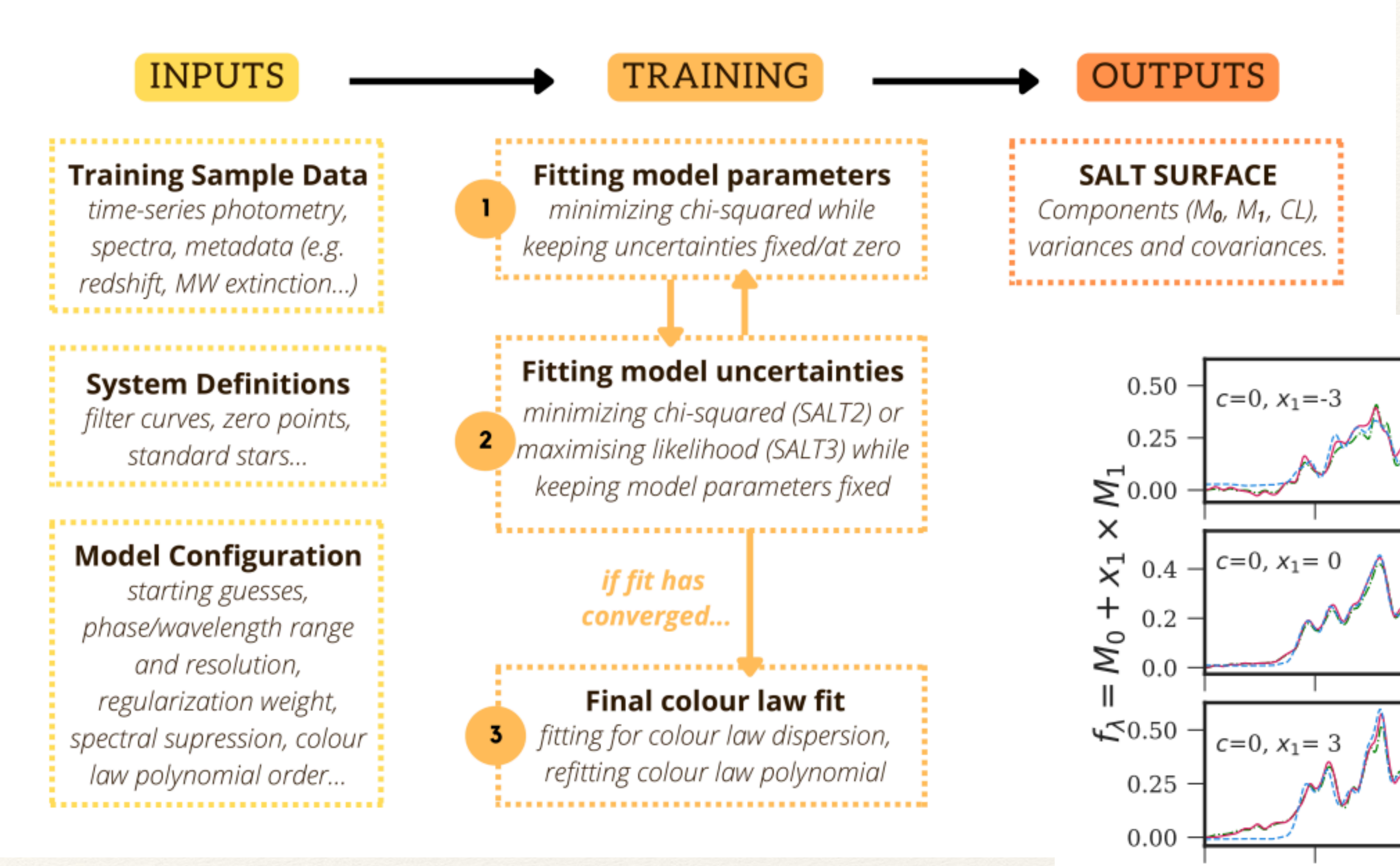
Ensures reproducibility

Obtaining flux, stretch & color

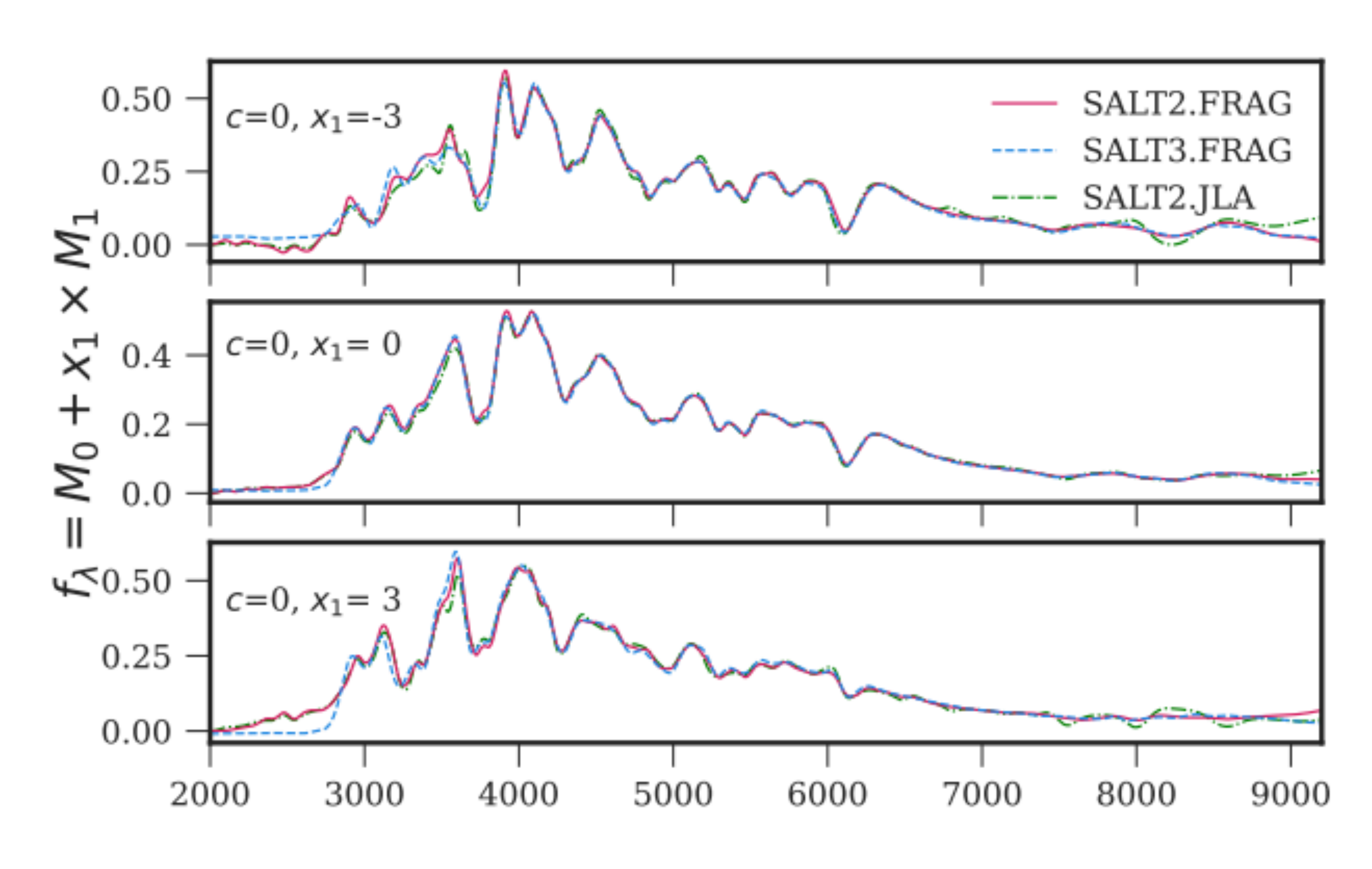


The SALT algorithm
Is trained on literature data

SALT parameterisation

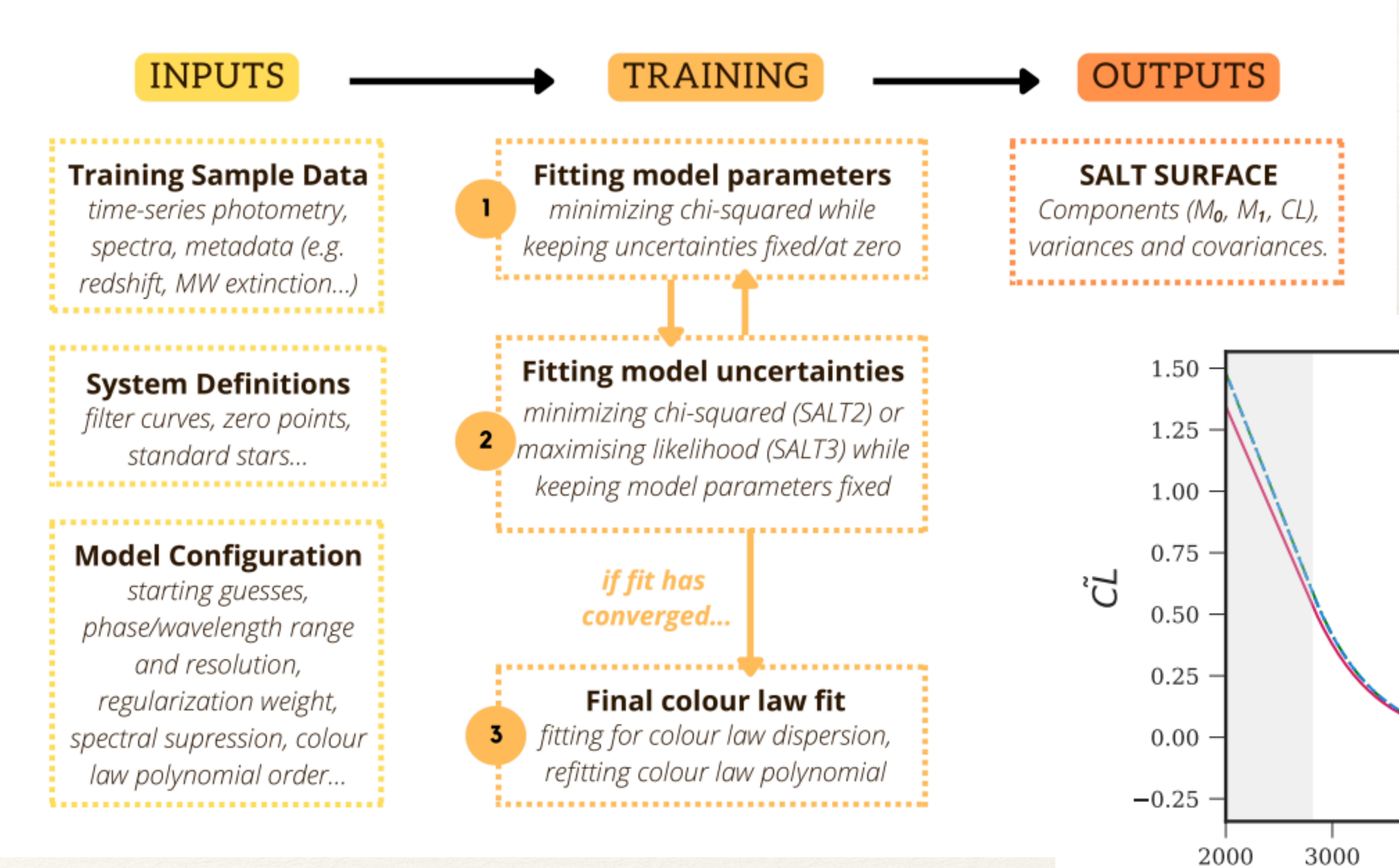


2 parameters + CL

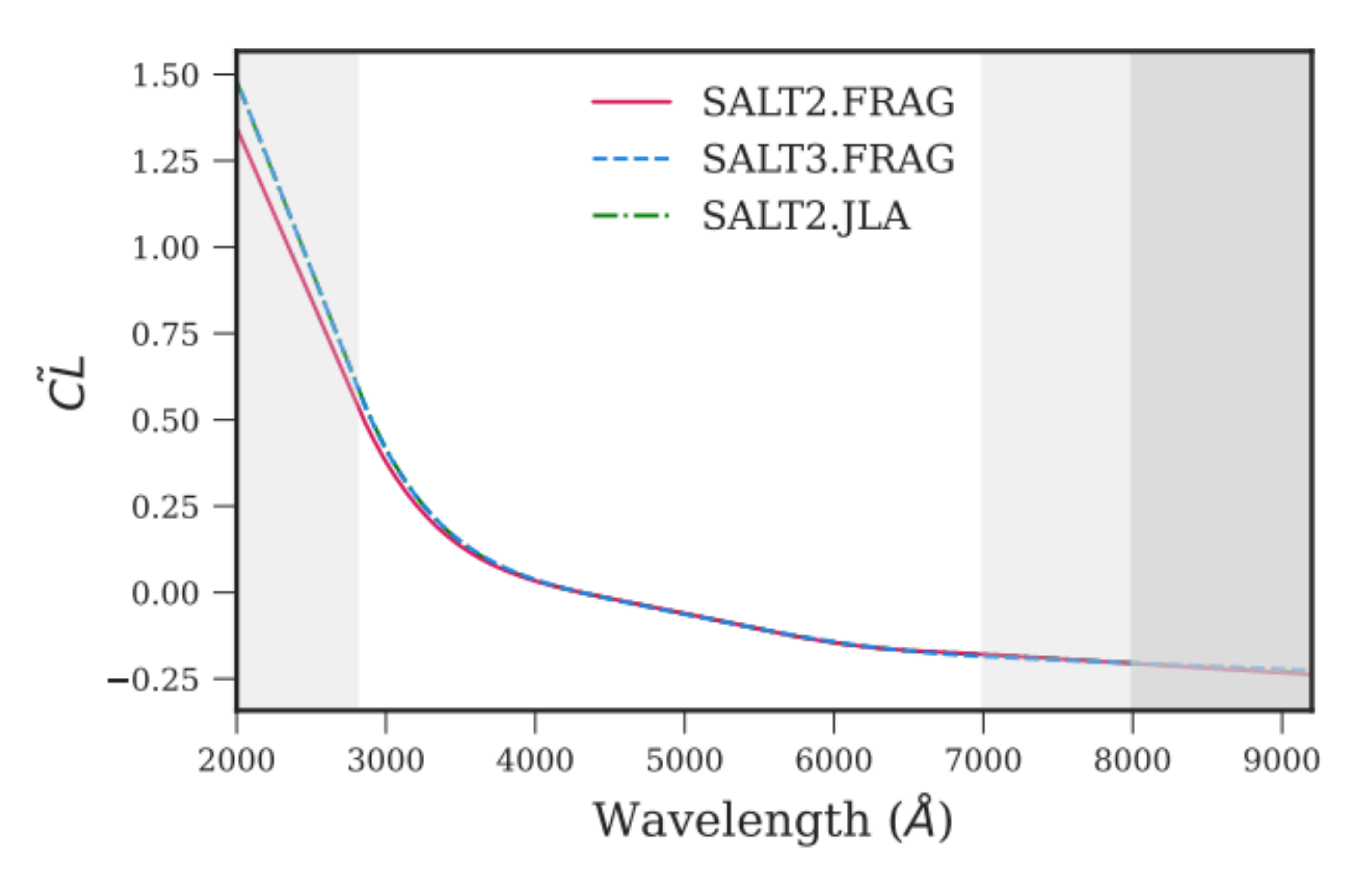


An SED model of how SNeIa evolve

SALT parameterisation

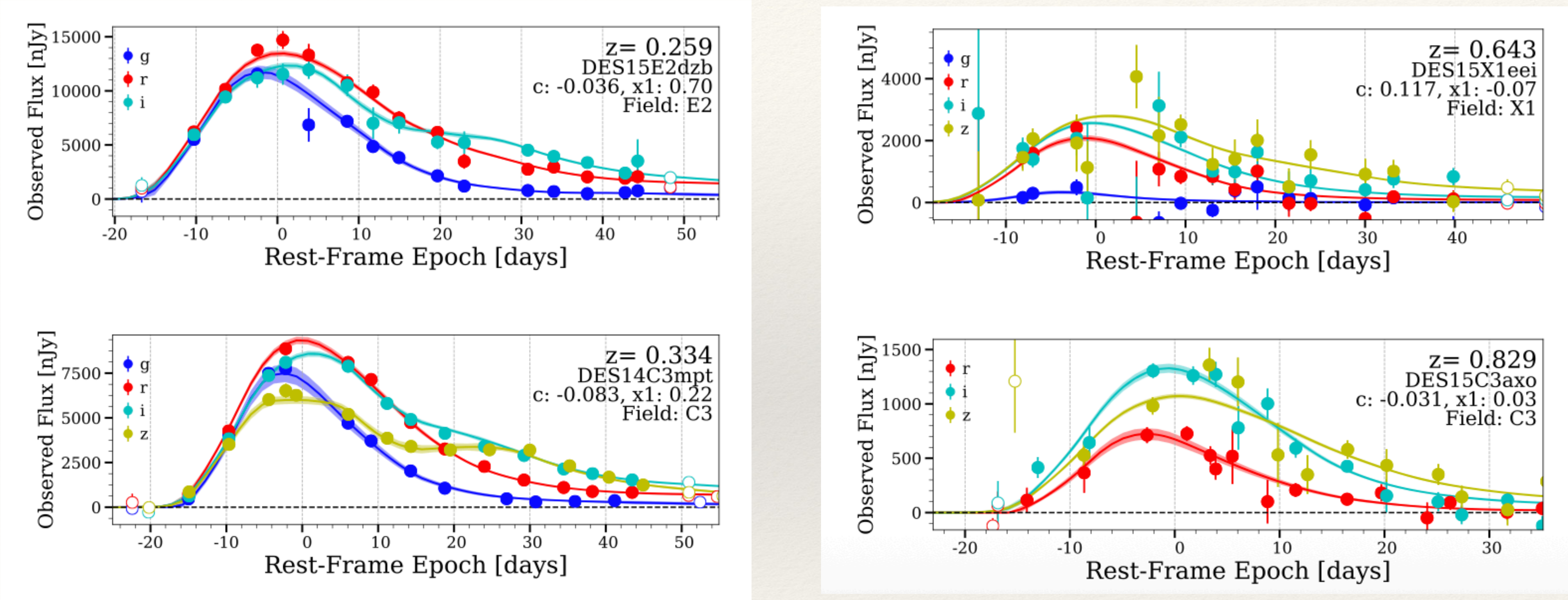


2 parameters + CL

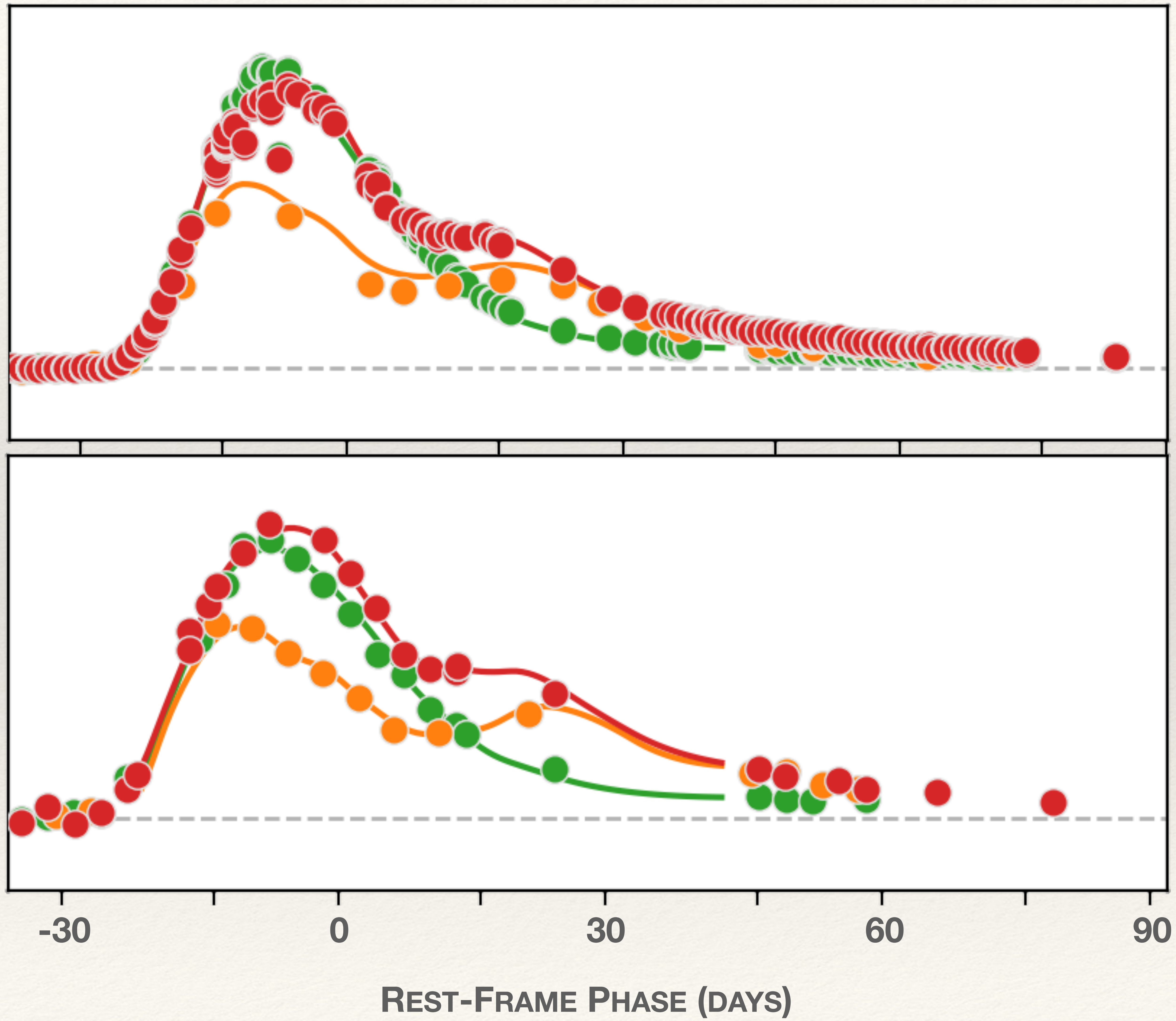


An SED model of how SNeIa evolve

Results @ high-z



Results @ low-z



Summary

SN Cosmology requires uniform photometry for SNe across the sky, orders of magnitude different in flux

All analysed on the same absolute system

Light-curves are parameterised into 3 components (brightness, stretch, colour)

Follow up

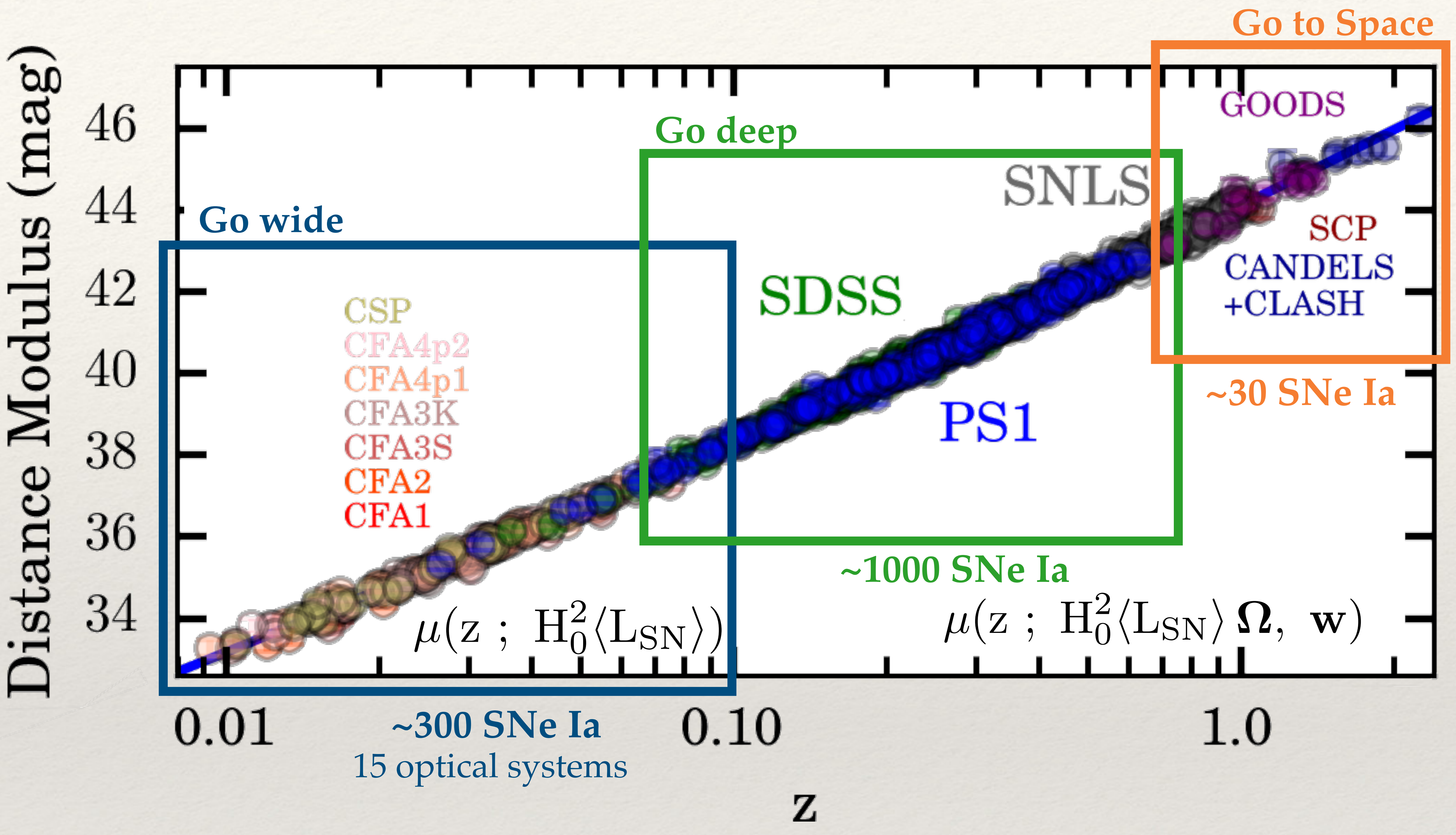
What could be the issue with selection effects ?

1. Selection effects

2. Photometric classifications

3. Simulations

Follow Ups | *Typing and Selection effect*



1. Find SNeIa
Rare | 1/galaxy/1000yr
Transient | 2 weeks rising

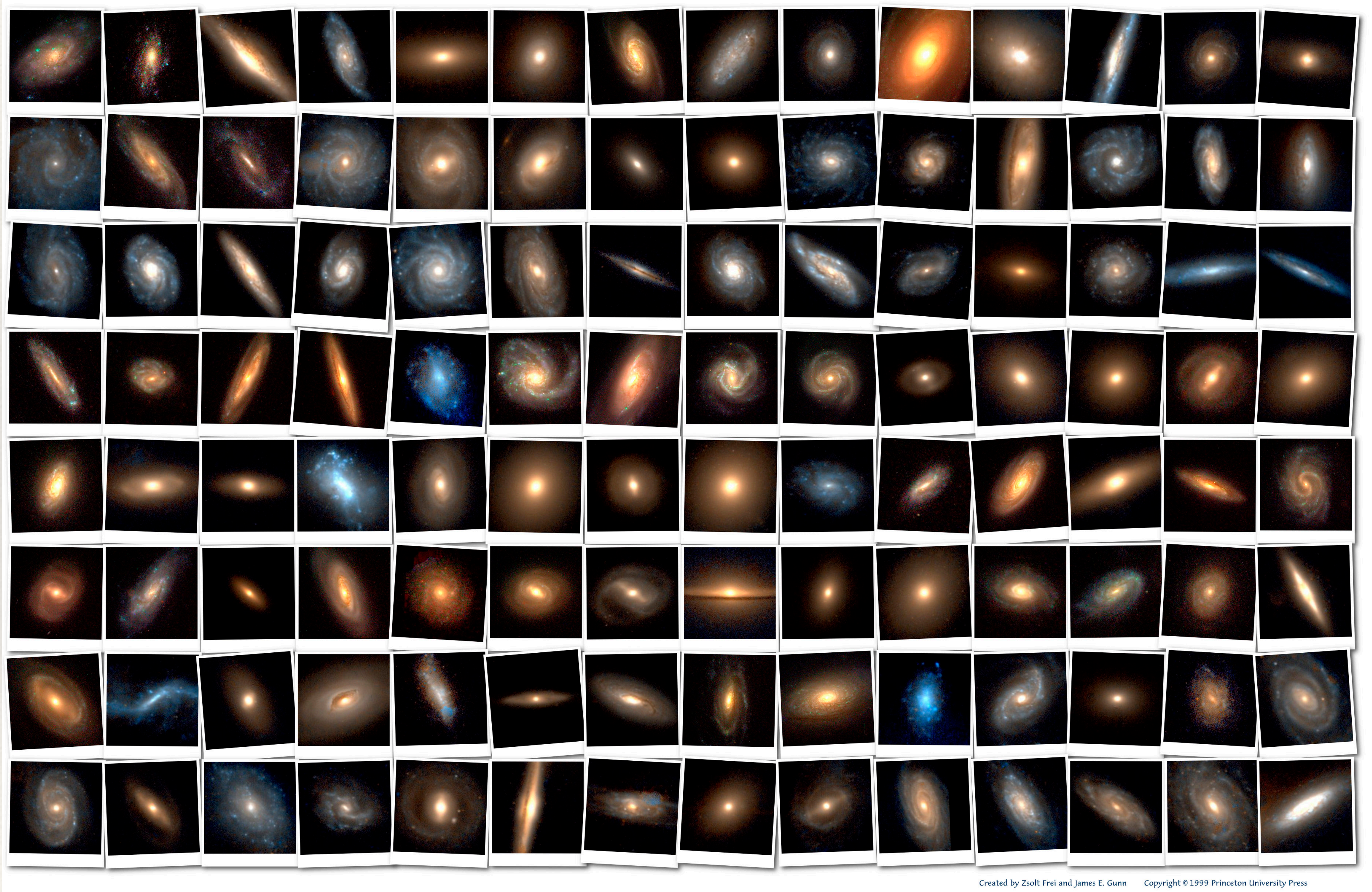
2. Build a Lightcurve
Same instrument or not?
(usually not at low-z)

3. Type
Get a Spectrum to make sure it actually is a "Ia"

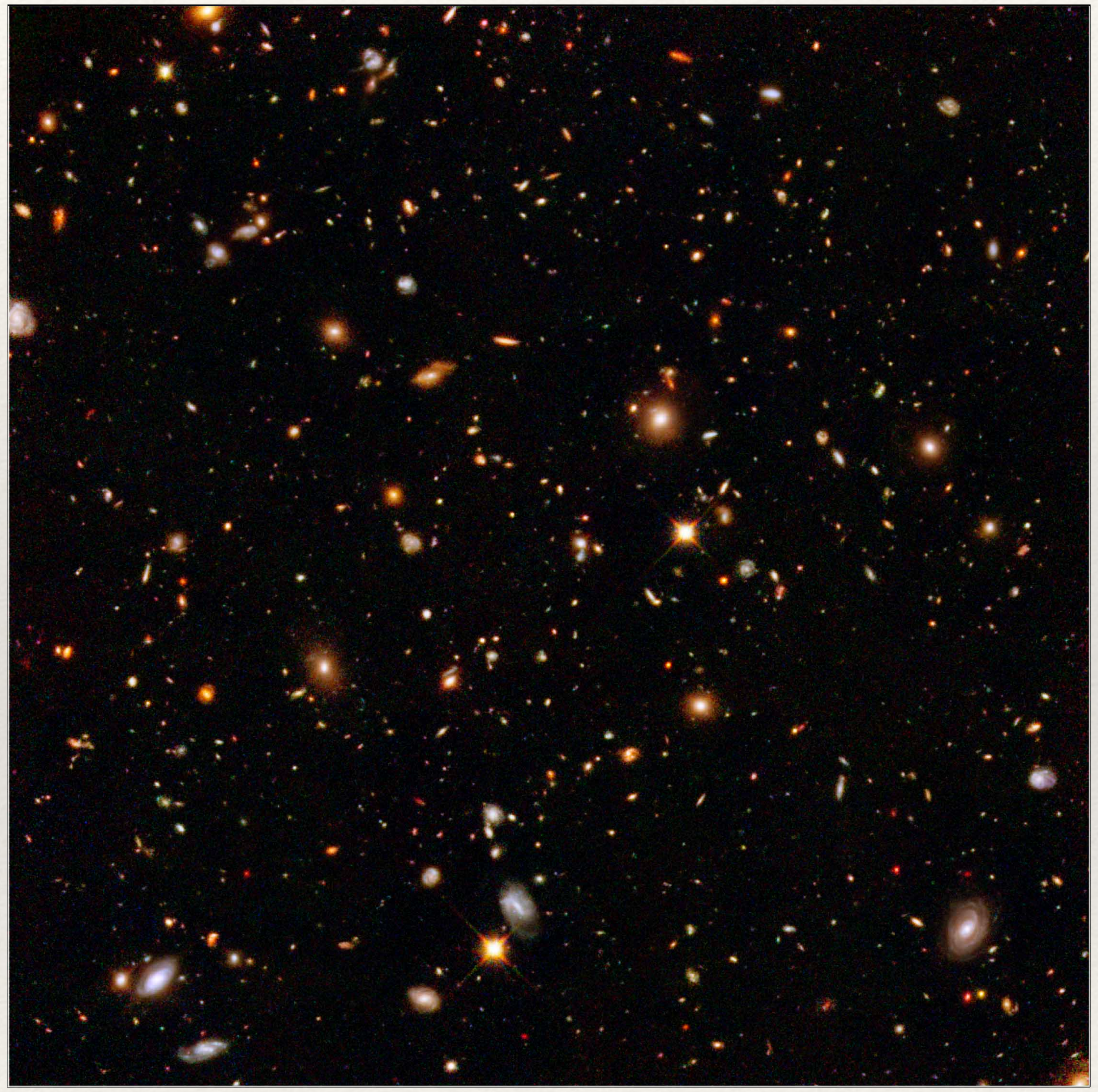
Difficulty : Sample selection ***(targeted survey and Malmquist bias)***

Question of Search

Targeted Surveys



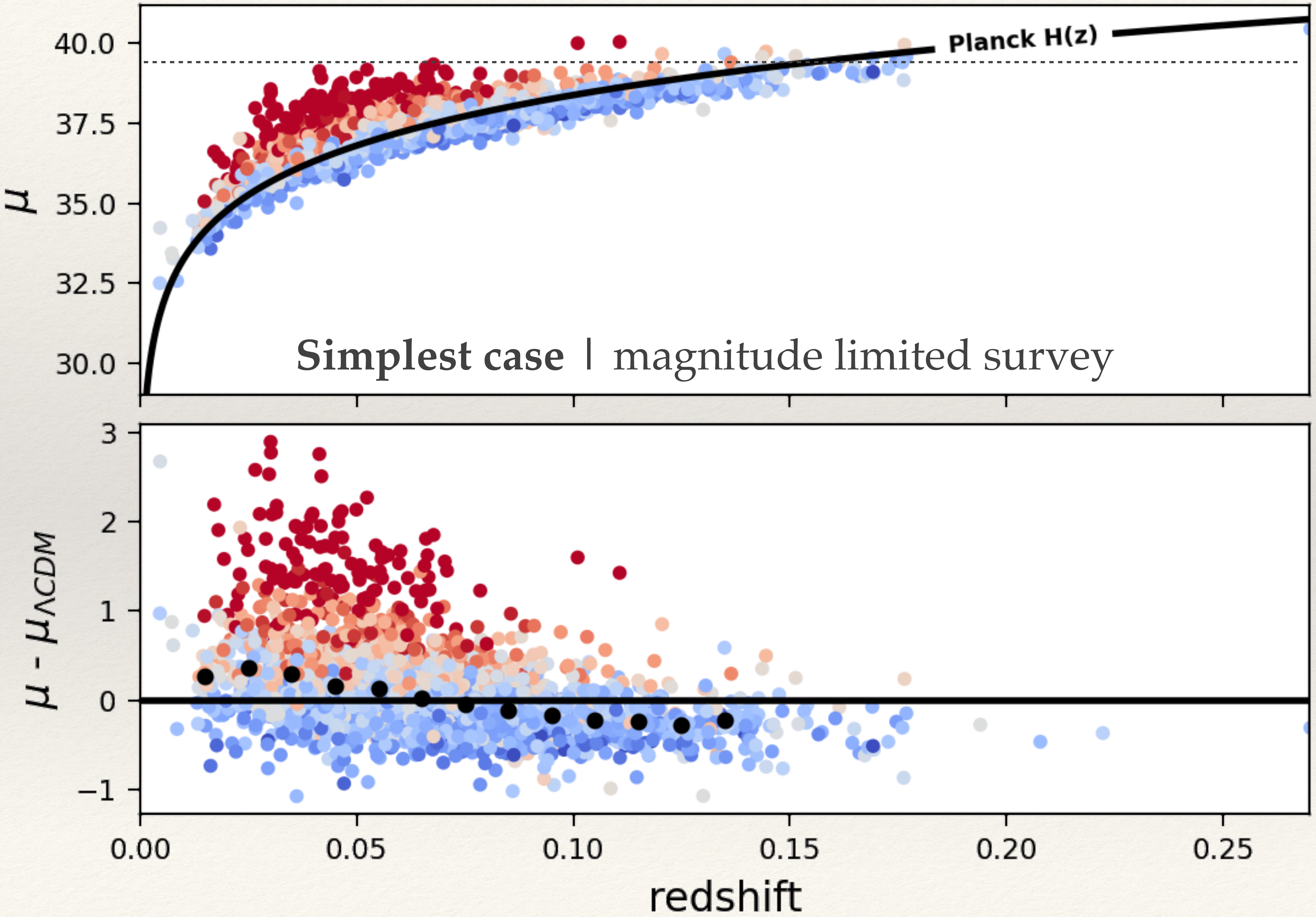
Un-targeted Surveys



Hubble Ultra Deep Field • Infrared
Hubble Space Telescope • NICMOS

NASA, ESA and R. Thompson (University of Arizona) STScI-PRC04-07b

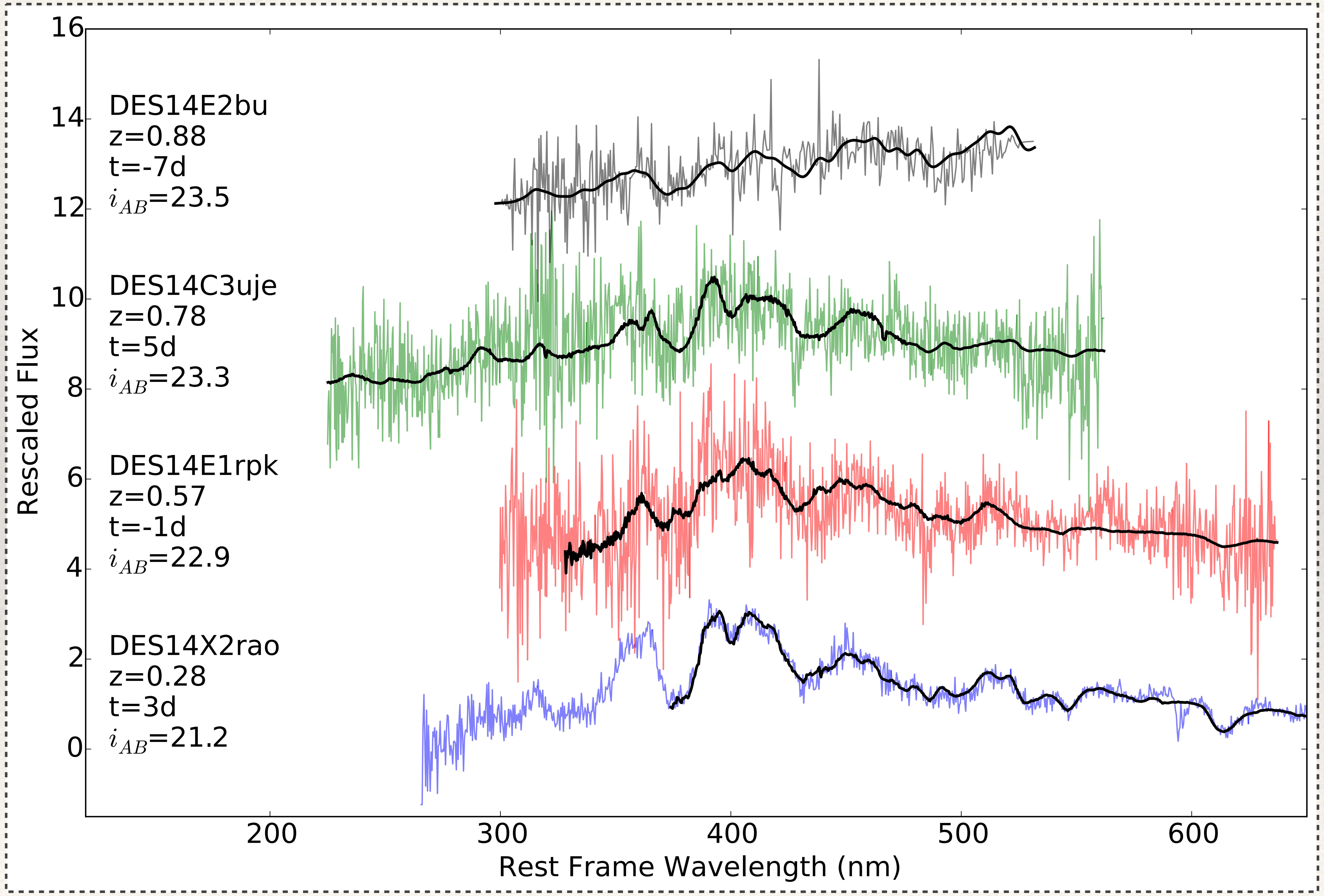
Selection effect | *bias cosmology*



$$\mu = m - M$$

Selection effect | *spectroscopy*

High redshift | Large volume | lots of *faint* SNe

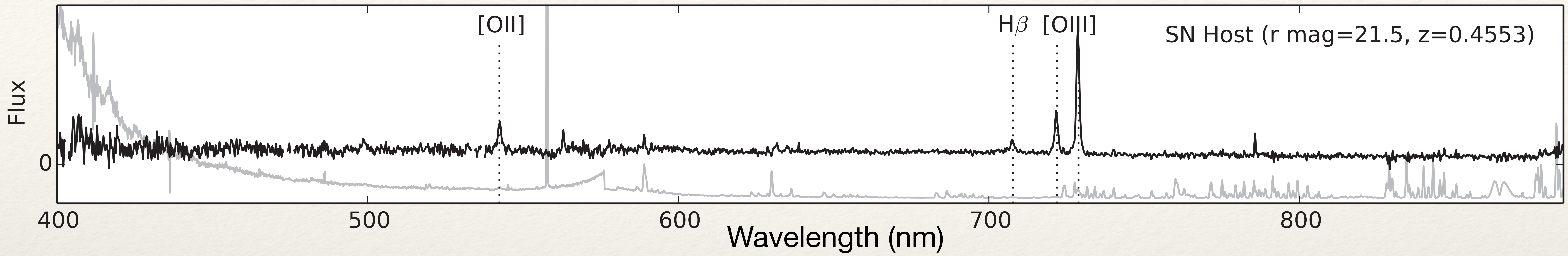


SNe Ia are *defined* by their spectral features
Redshifts are essential

Requires 4m-class:
Limited facilities & resources

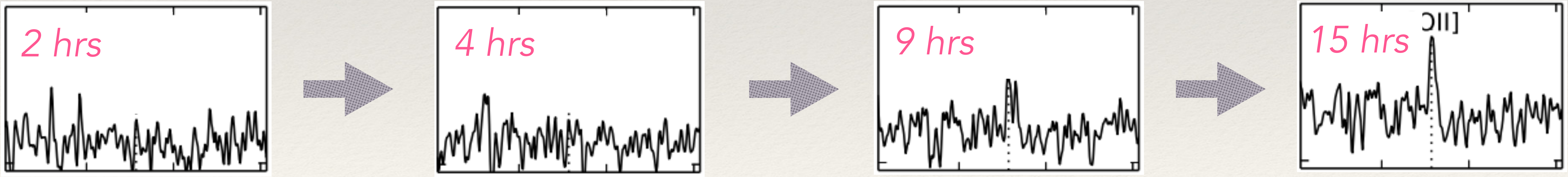
Biases towards blue, remote events

Selection effect | *spectroscopy*



High redshift | Large volume | lots of *galaxies* hosting *faint* SNe

Forego spectroscopic confirmation; integrated observations of galaxies to obtain redshifts
Requires 4m-class IFU & time



Biases due to mis-classification / mis-association

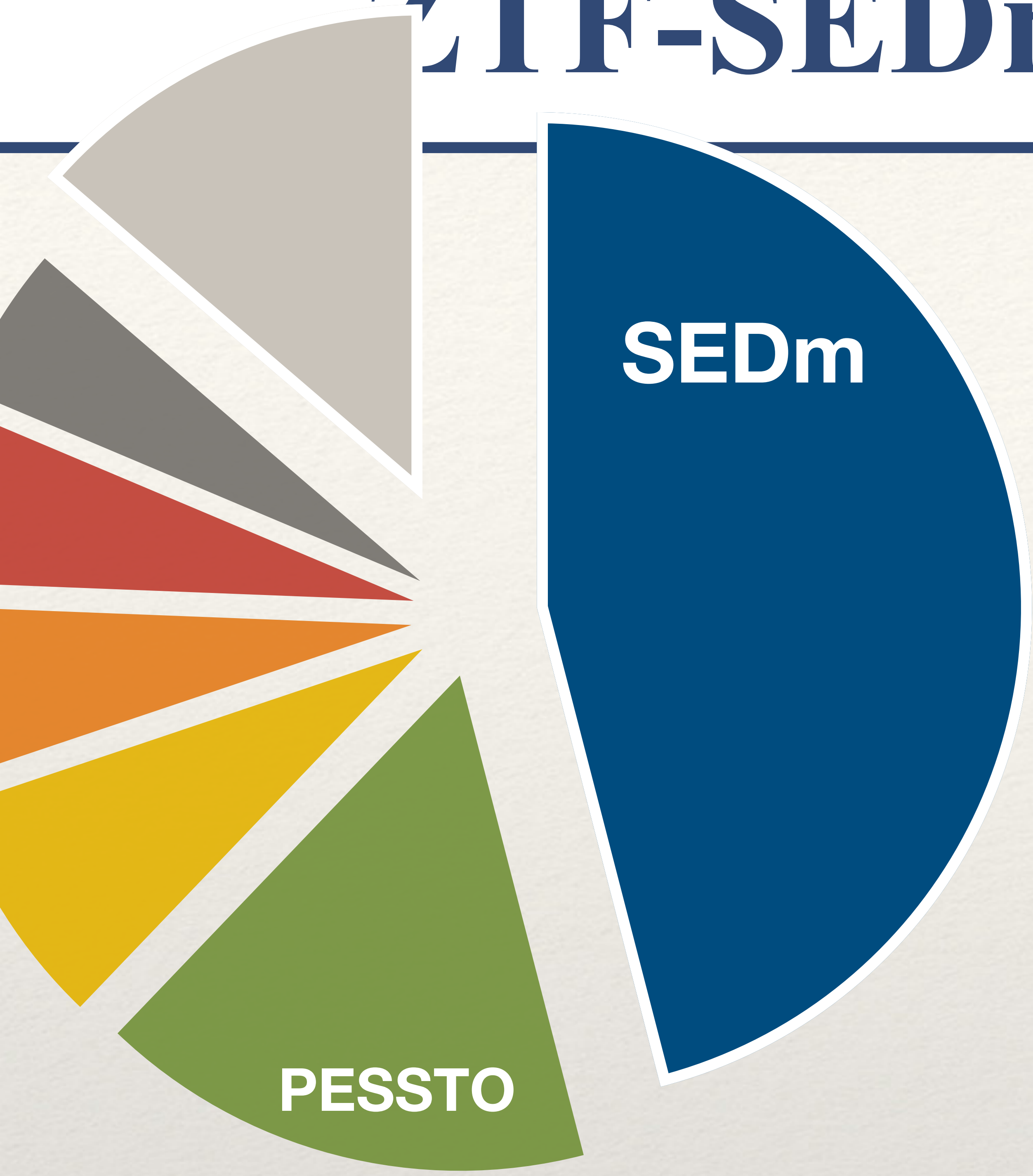
Low Redshift Today: automated spectroscopy

Previously: heterogeneous due to targeted photometry

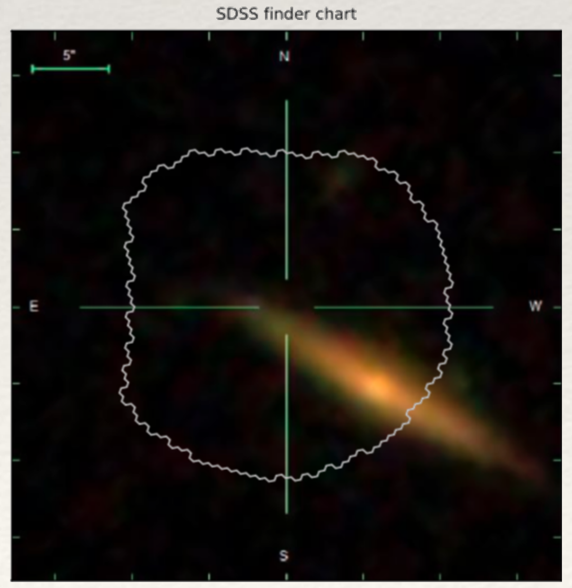
ZTF-SEDm | *Very Low resolution Spectrograph*

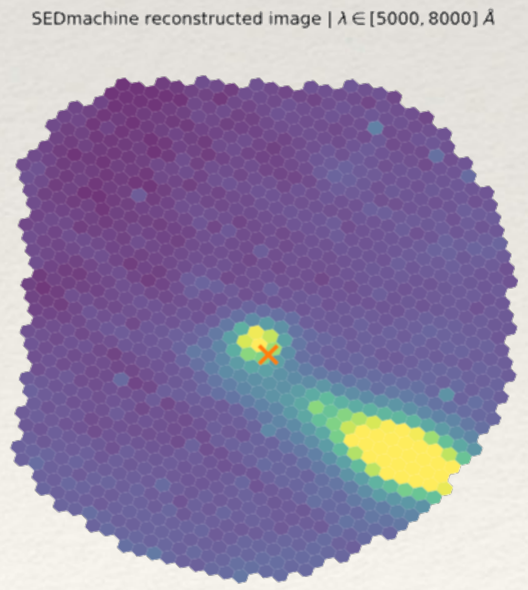
Rigault et al. 2019

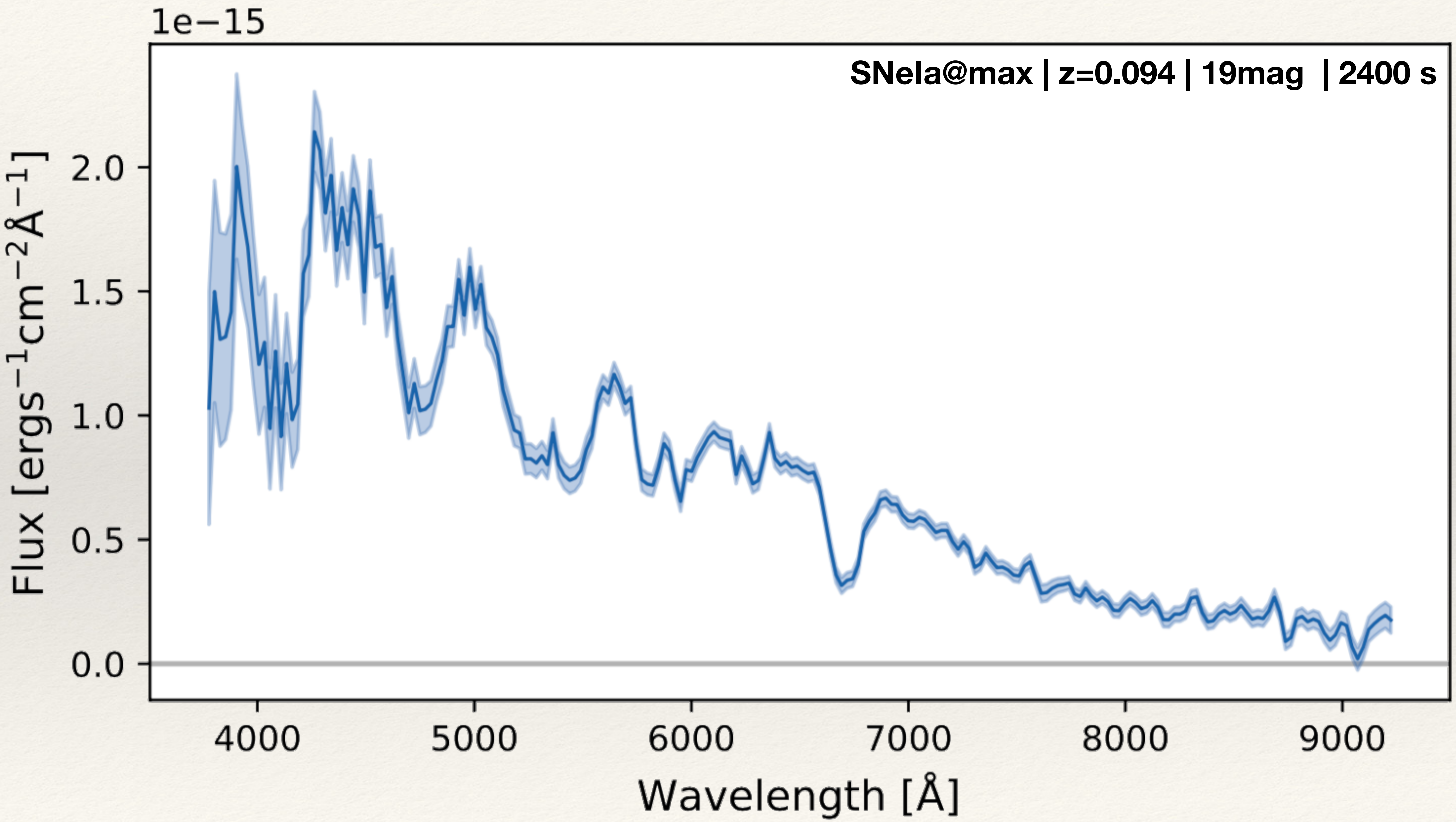
Flux calibrated spectrum & typing available ~5min after end of exposure

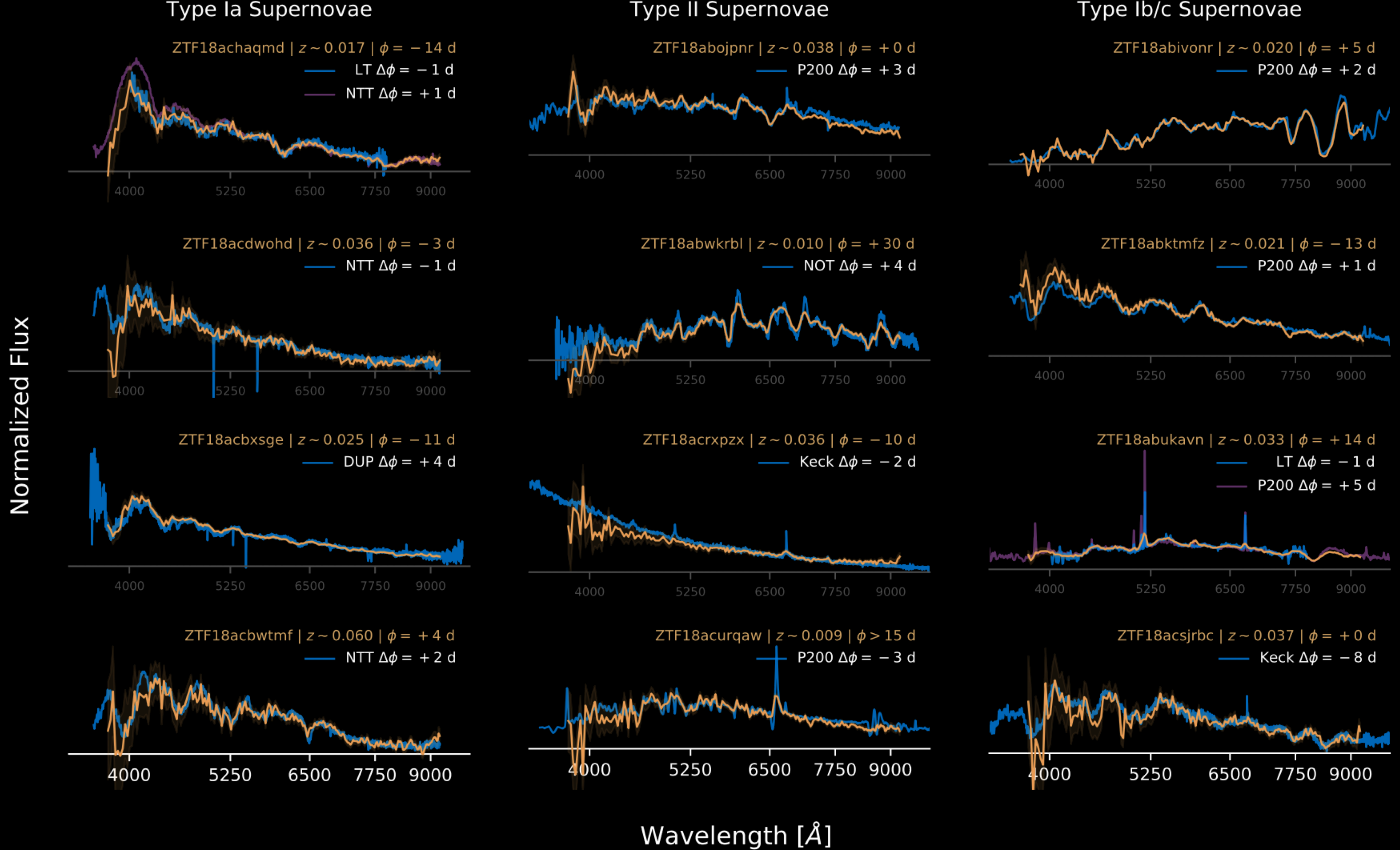


Source: Transient Name Server





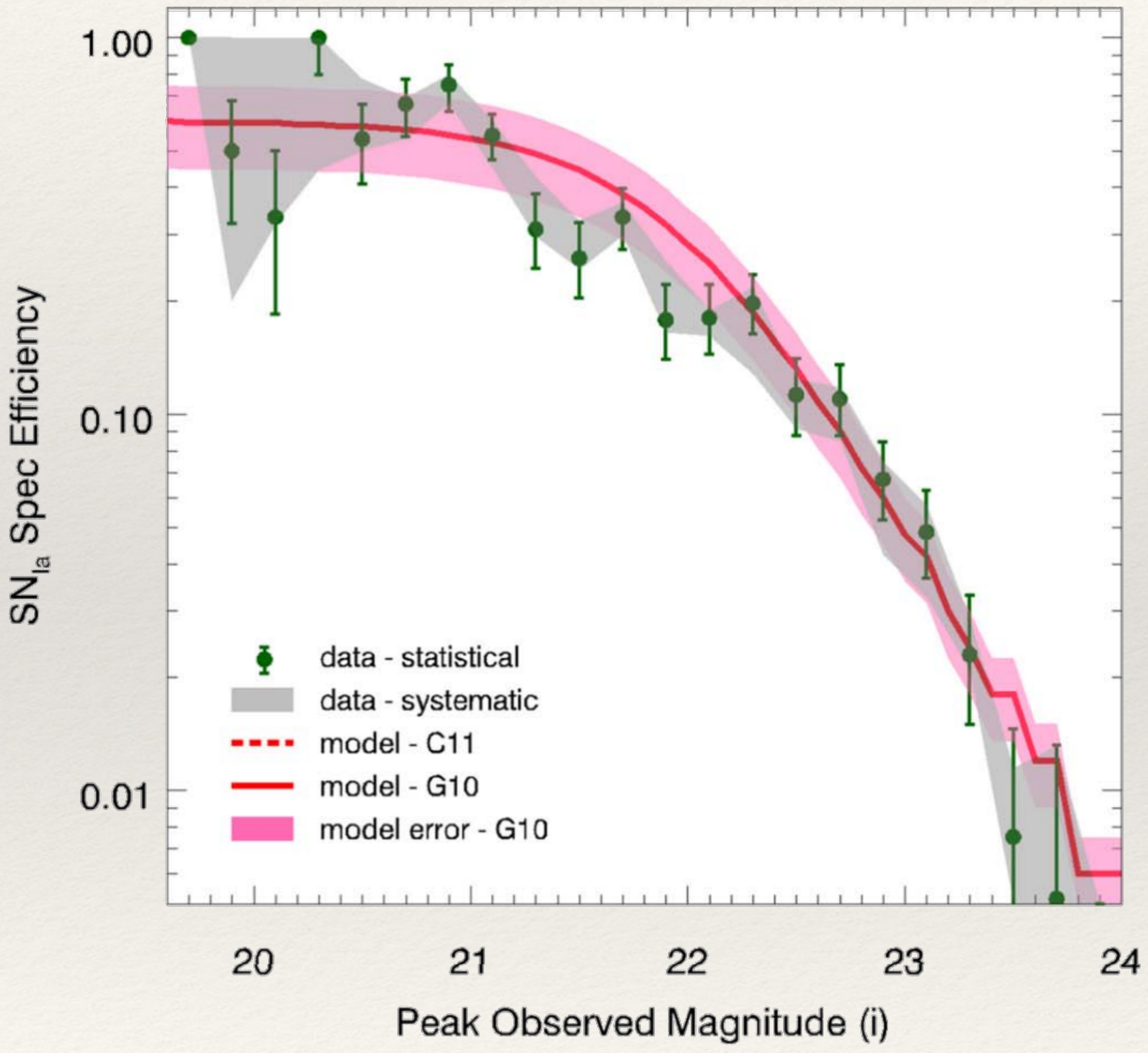




Rigault et al. 2019

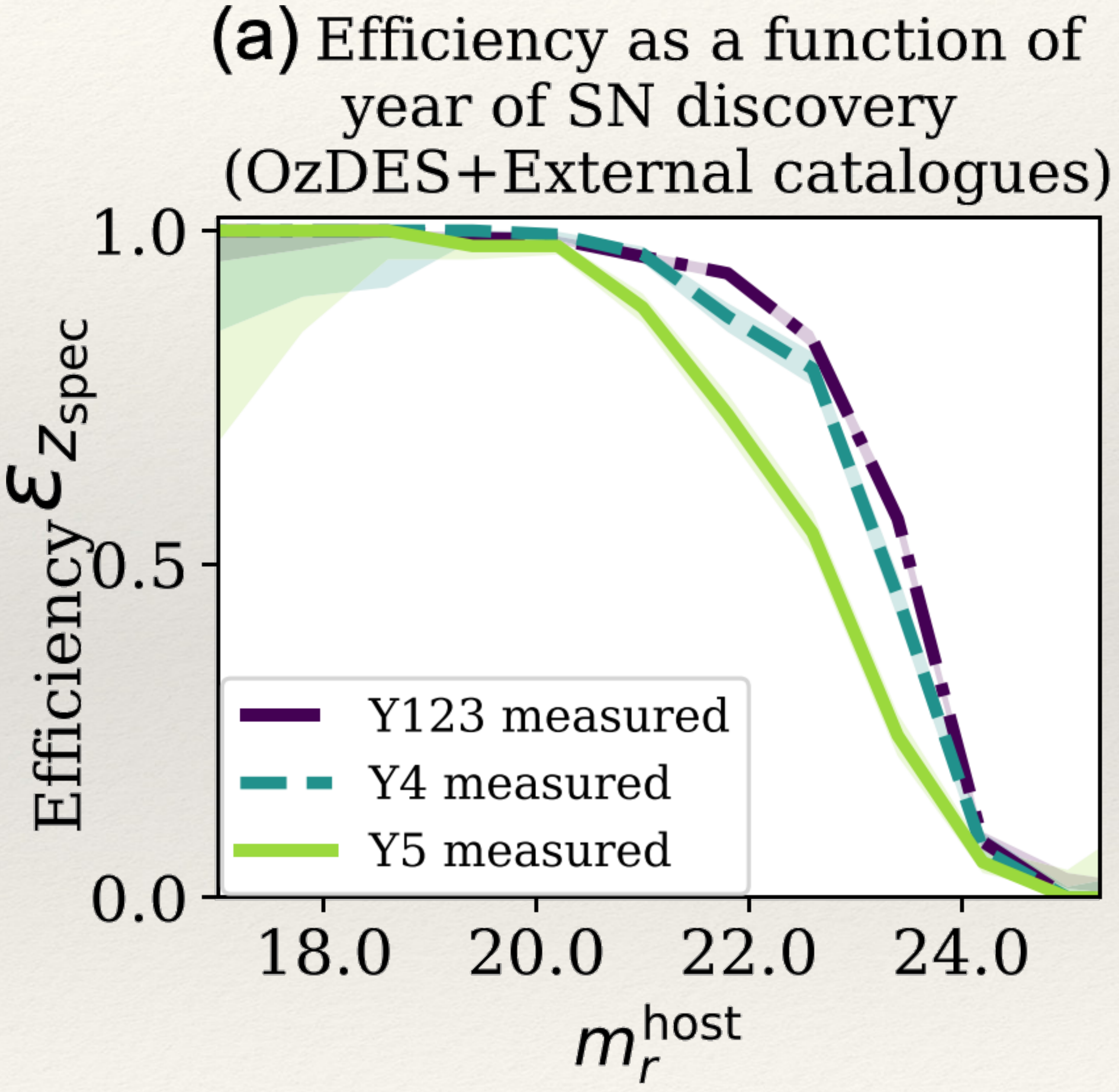
Spectroscopic selection function

SN spectrum



Smith et al. 2020

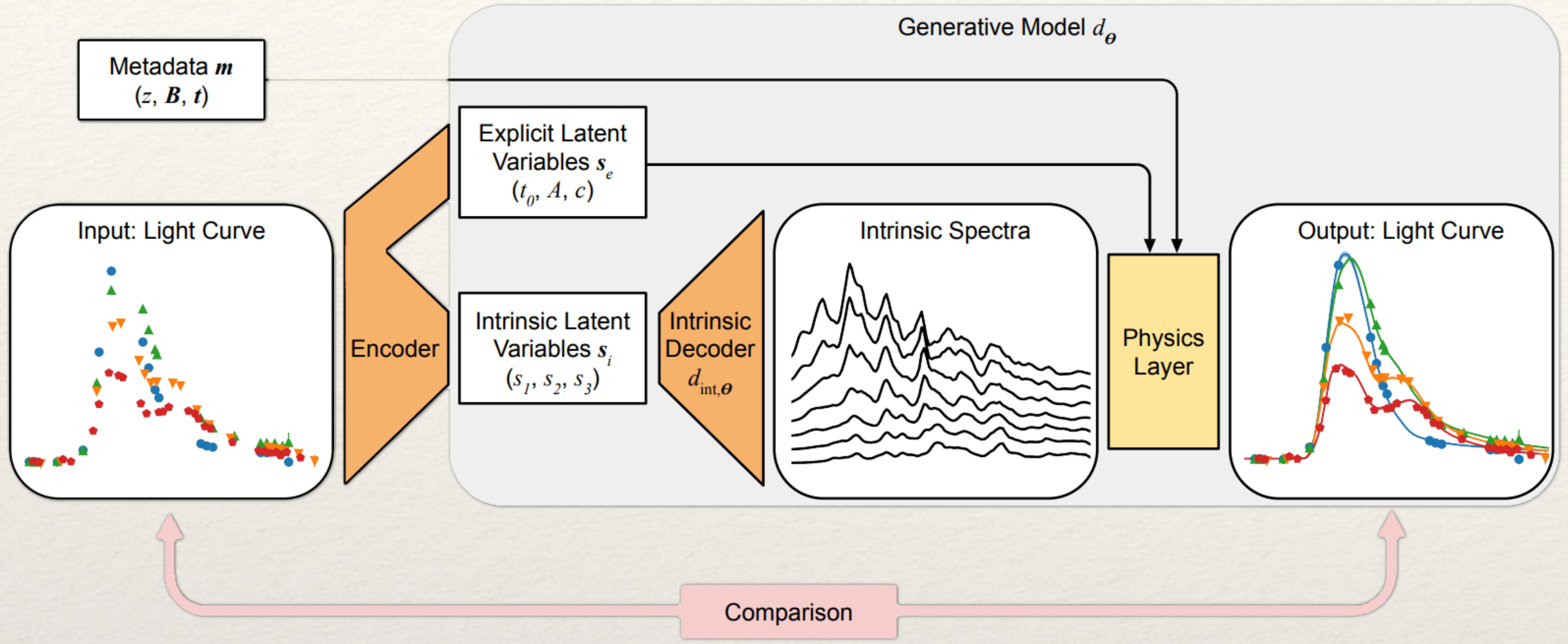
Host redshift



Vincenzi et al. 2021

Photometric typing | *parsnip*

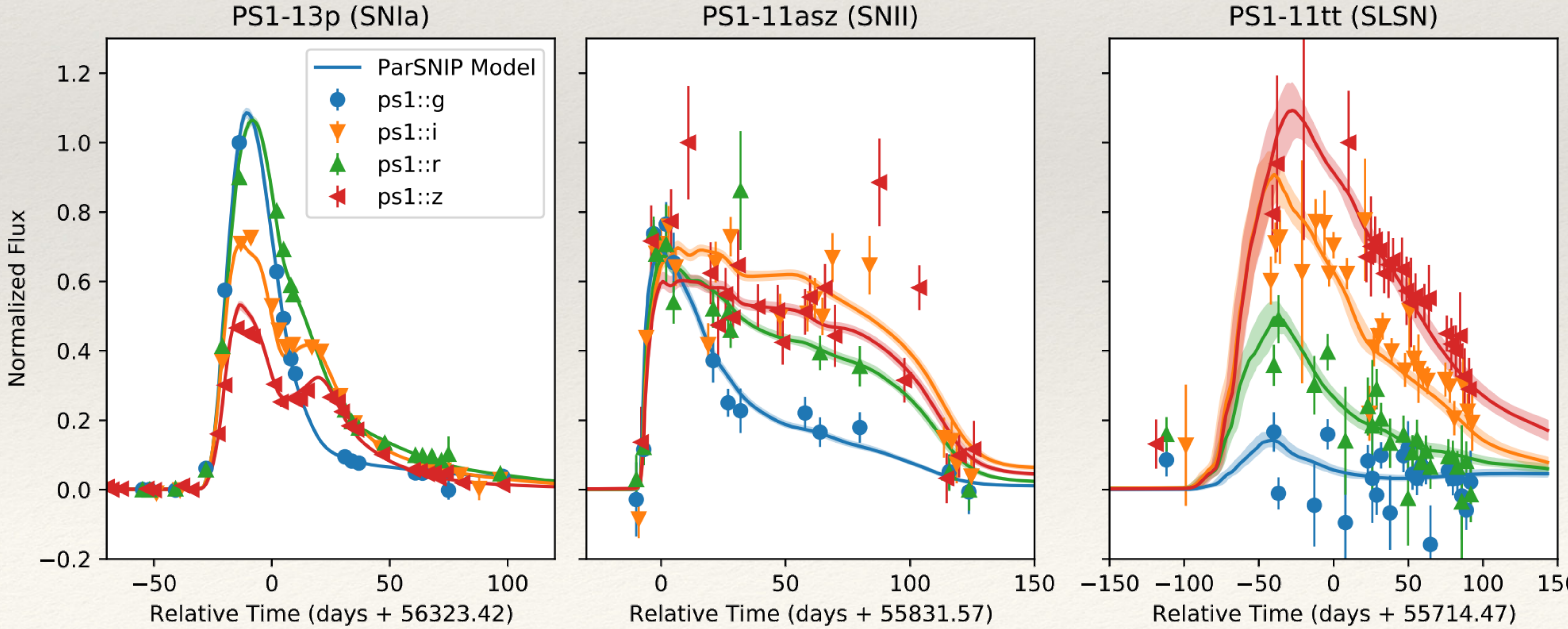
Boone et al. 2021 | *see also e.g. SuperNNova (Moller et al. 2018), Scone (Qu et al. 2021)*

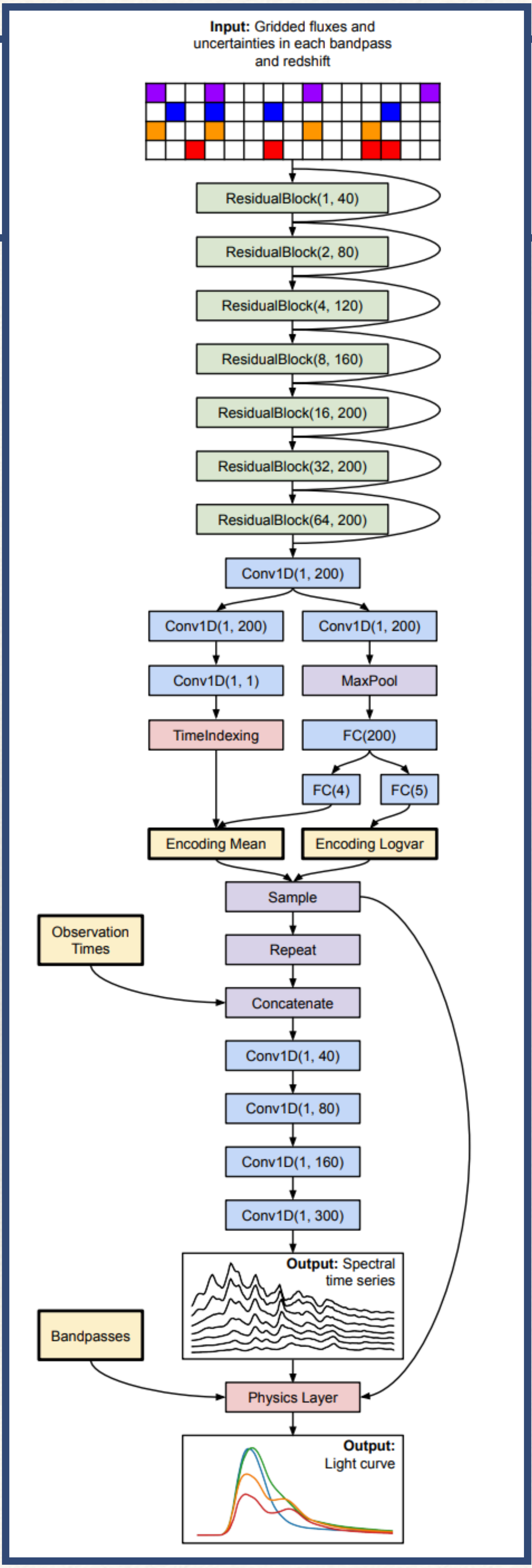


Requires understanding of all SNe types

95+% accuracy for SNeIa

Probabilistic implementation

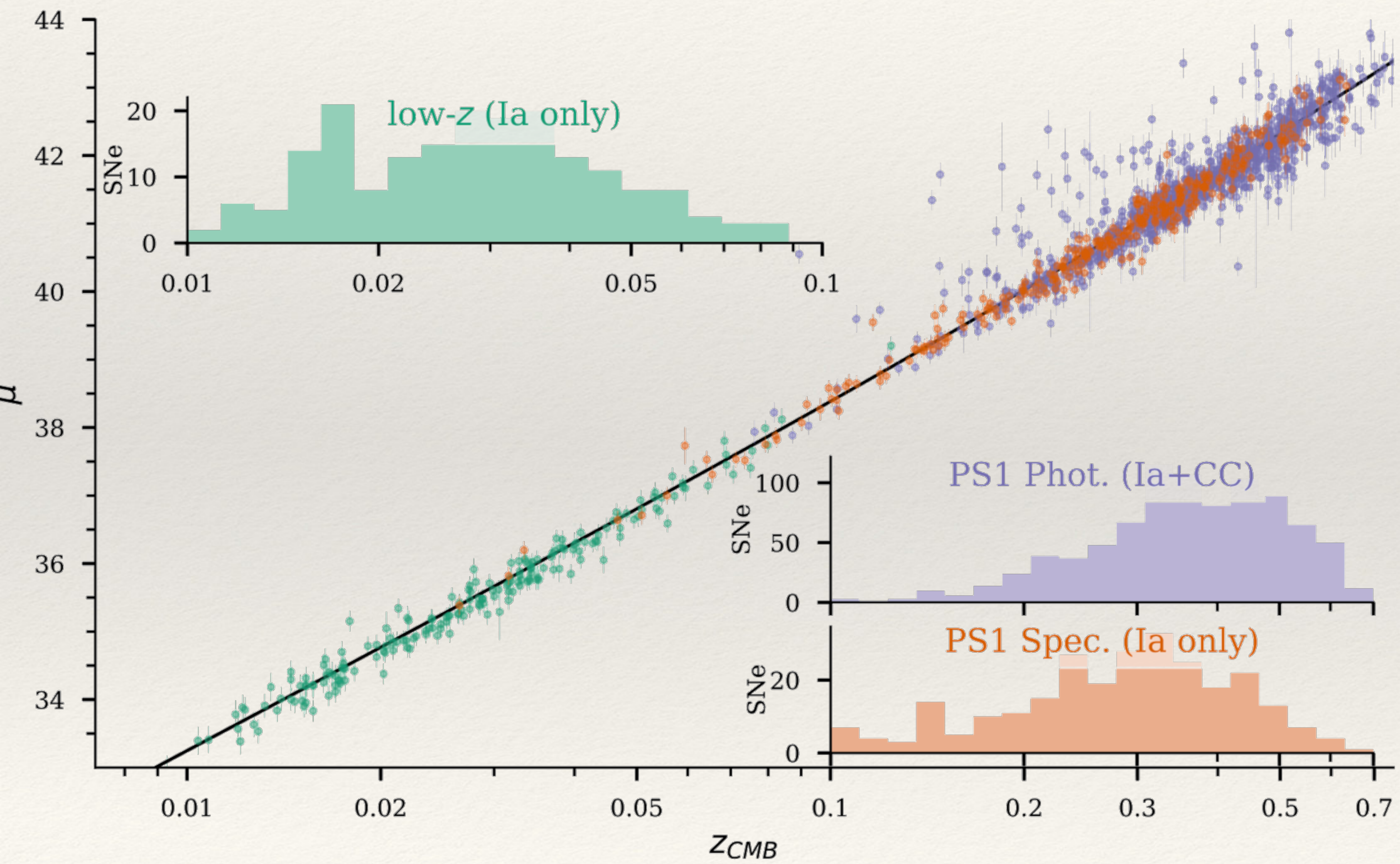




Follow Ups | *New Challenge Photo-typing*

Can we do accurate cosmology with photo-typing ?
(Fit for SNIa cosmology & non Ia redshift evolutions)

Jones et al. 2018



Vincenzi et al. 2021

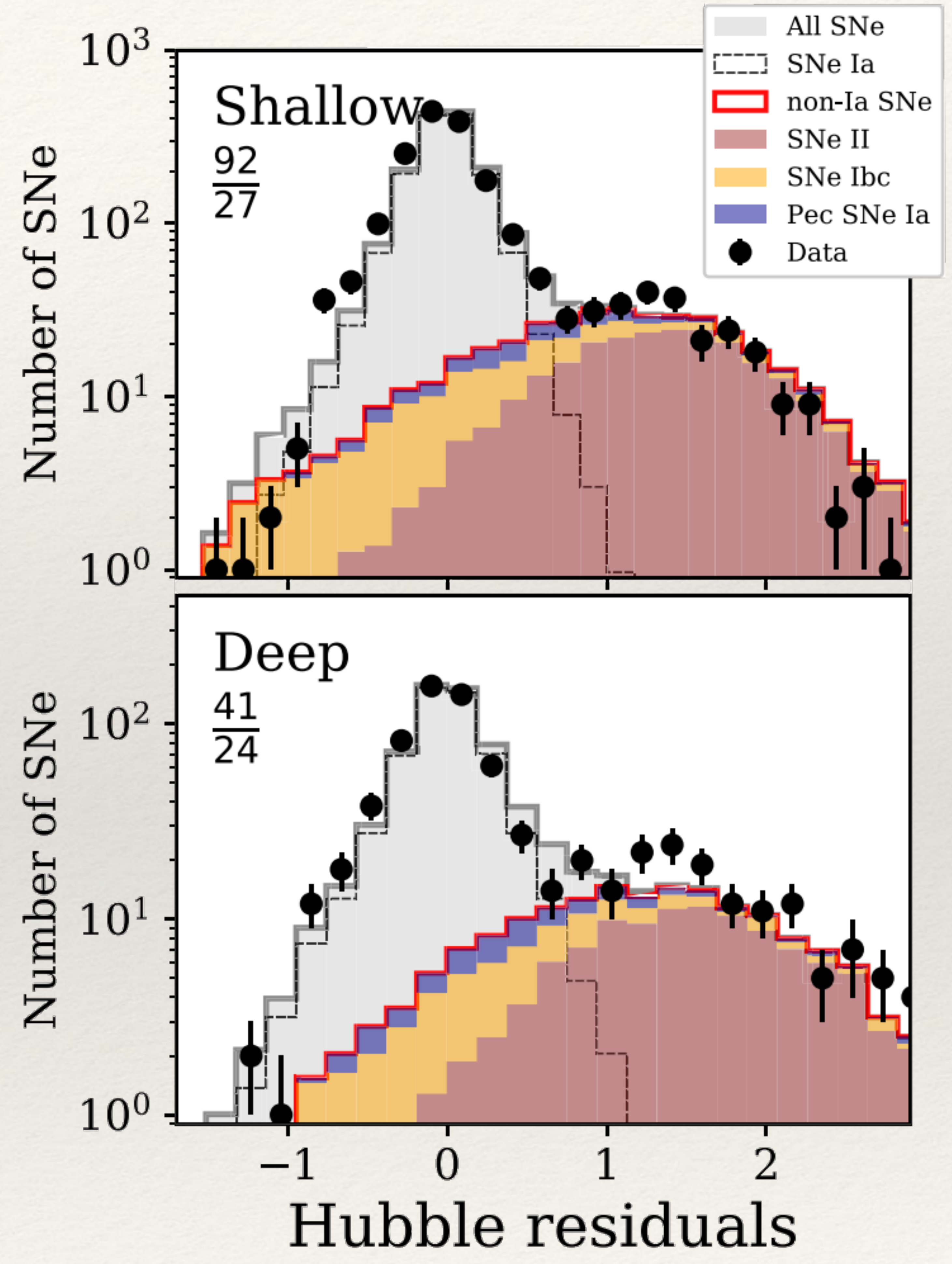
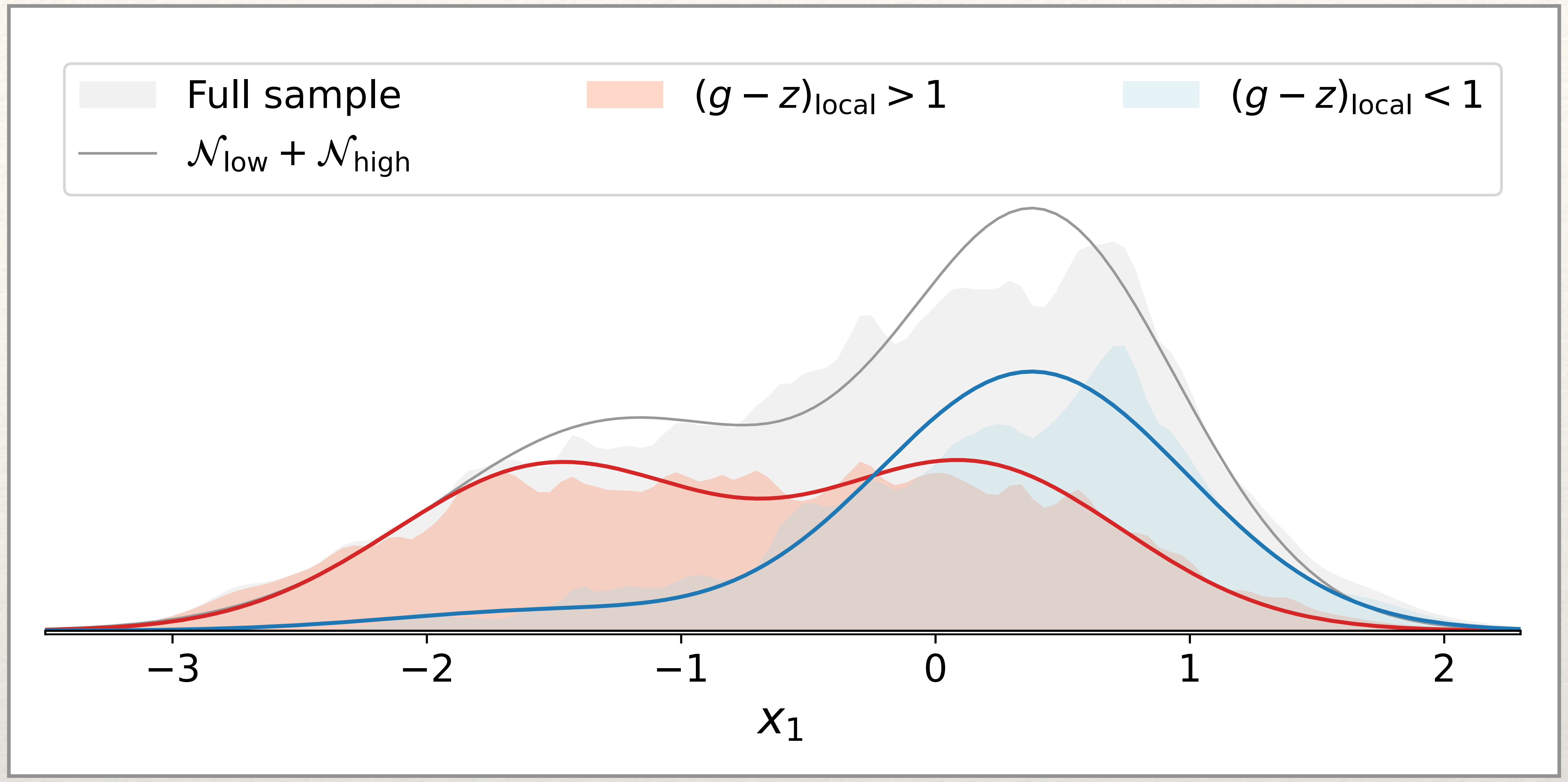


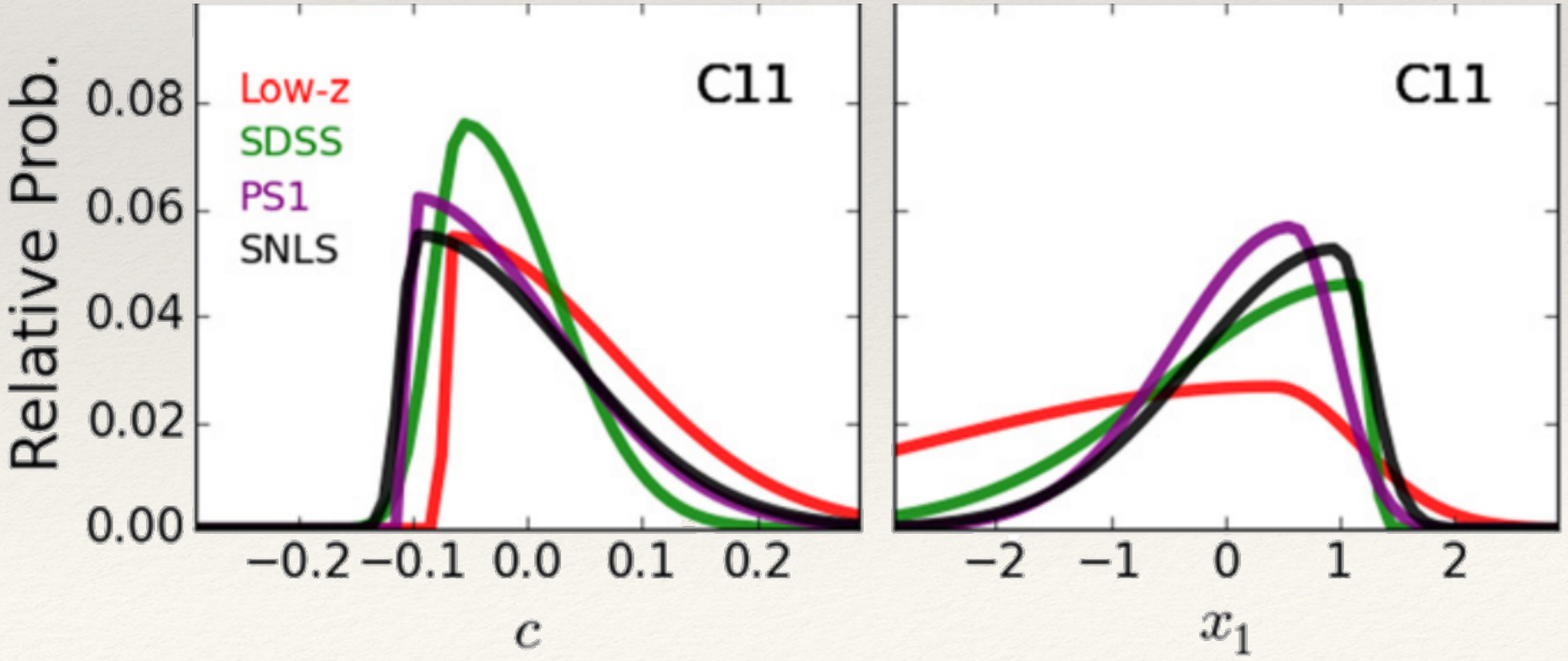
Figure 9. As Fig. 8 but for Hubble residuals.

Implications for cosmology

Very different measurements of the same quantity for different surveys at different redshifts

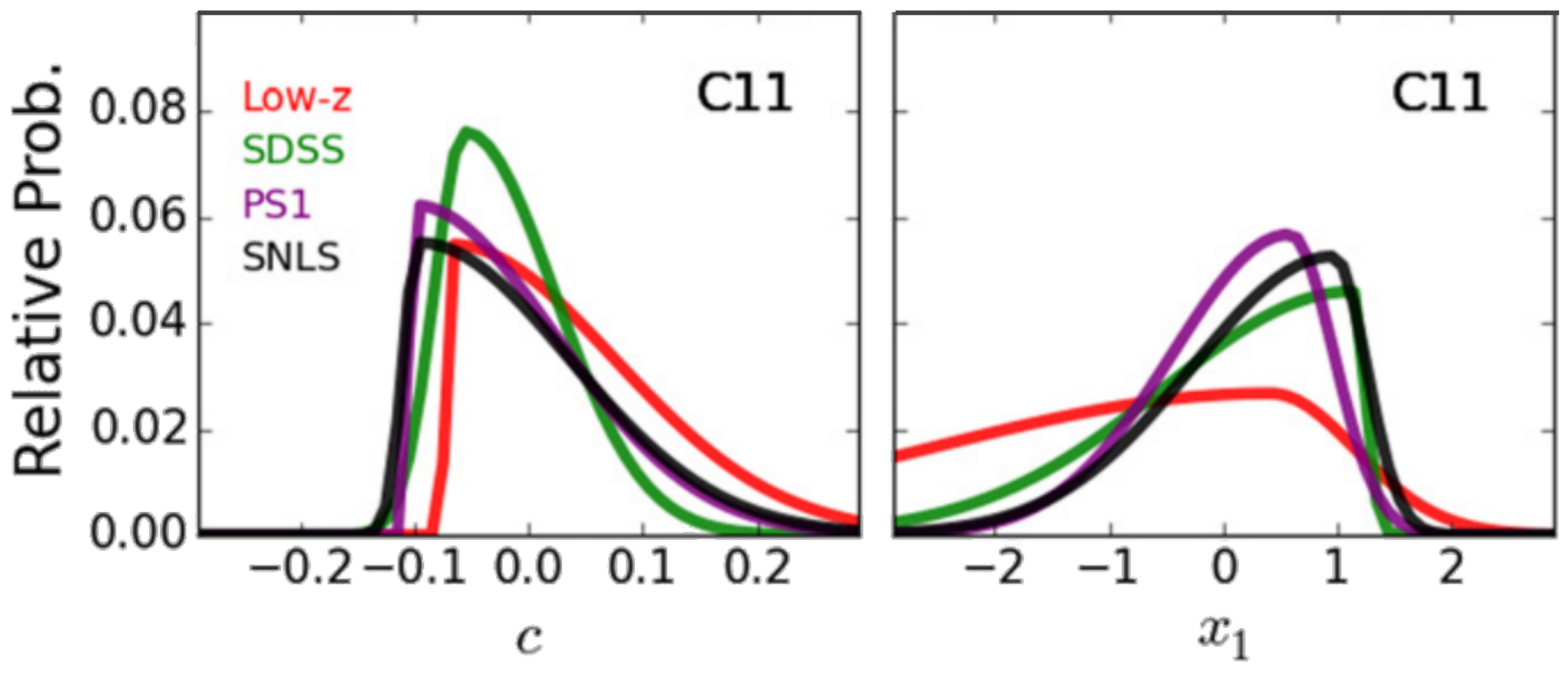
How can we correct for this bias?





Simulating your survey to see what you missed

Assume underlying population



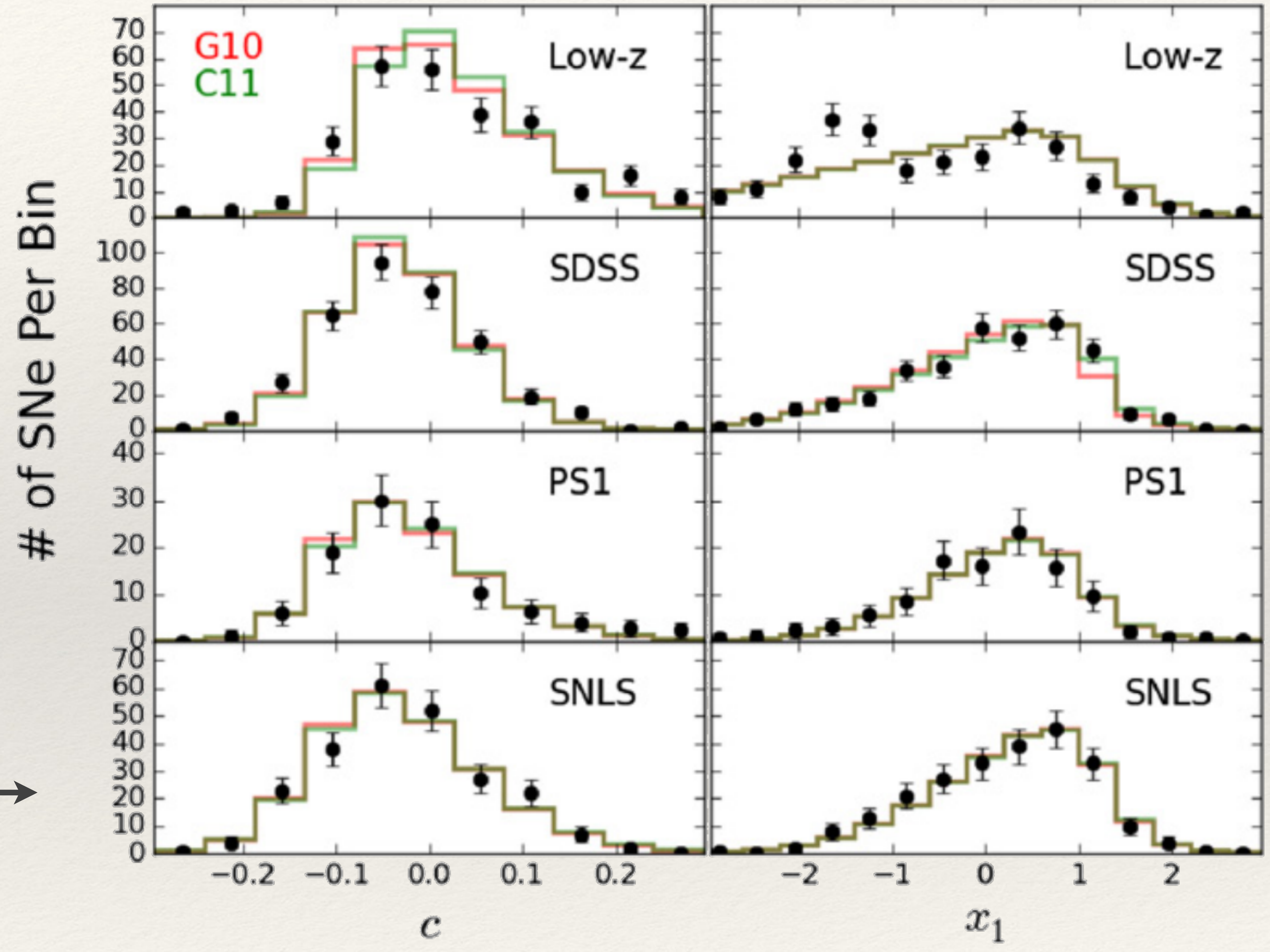
Apply what you know about your survey

Survey

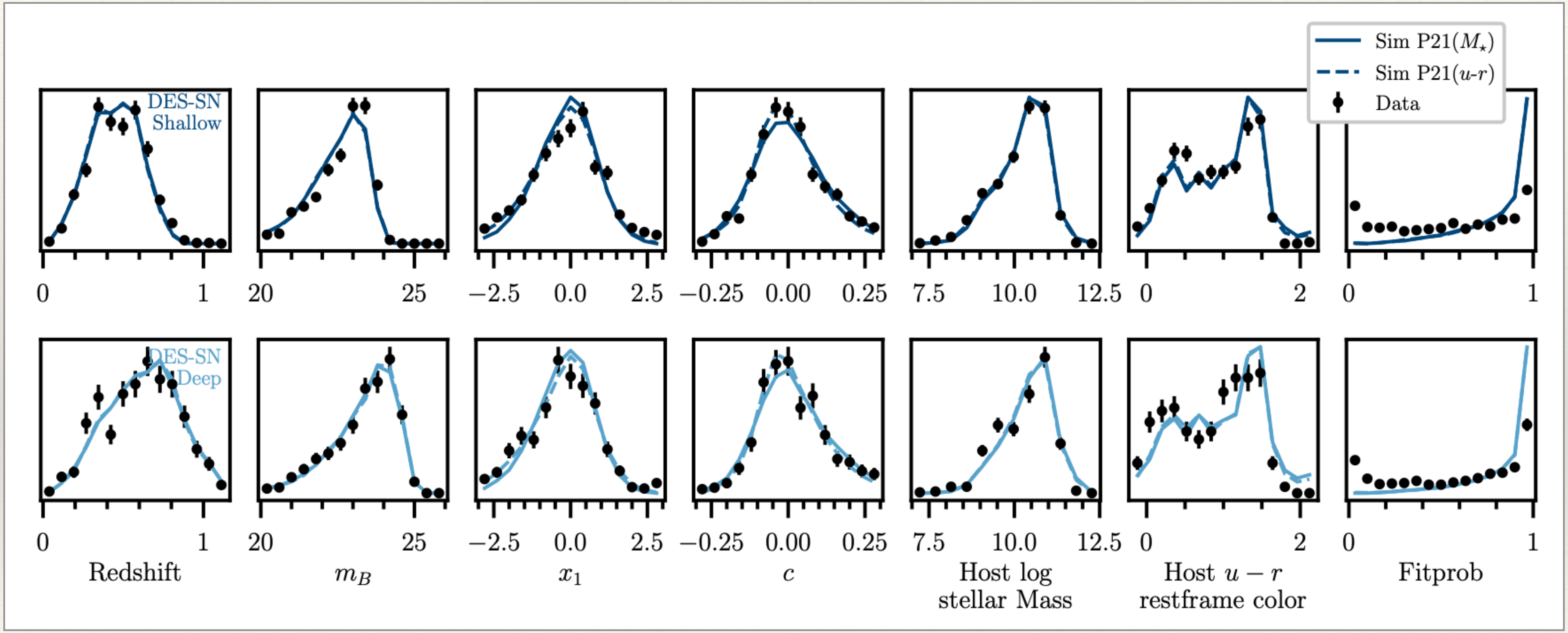
Create fake lightcurves etc.

Fit mock data

compare to data

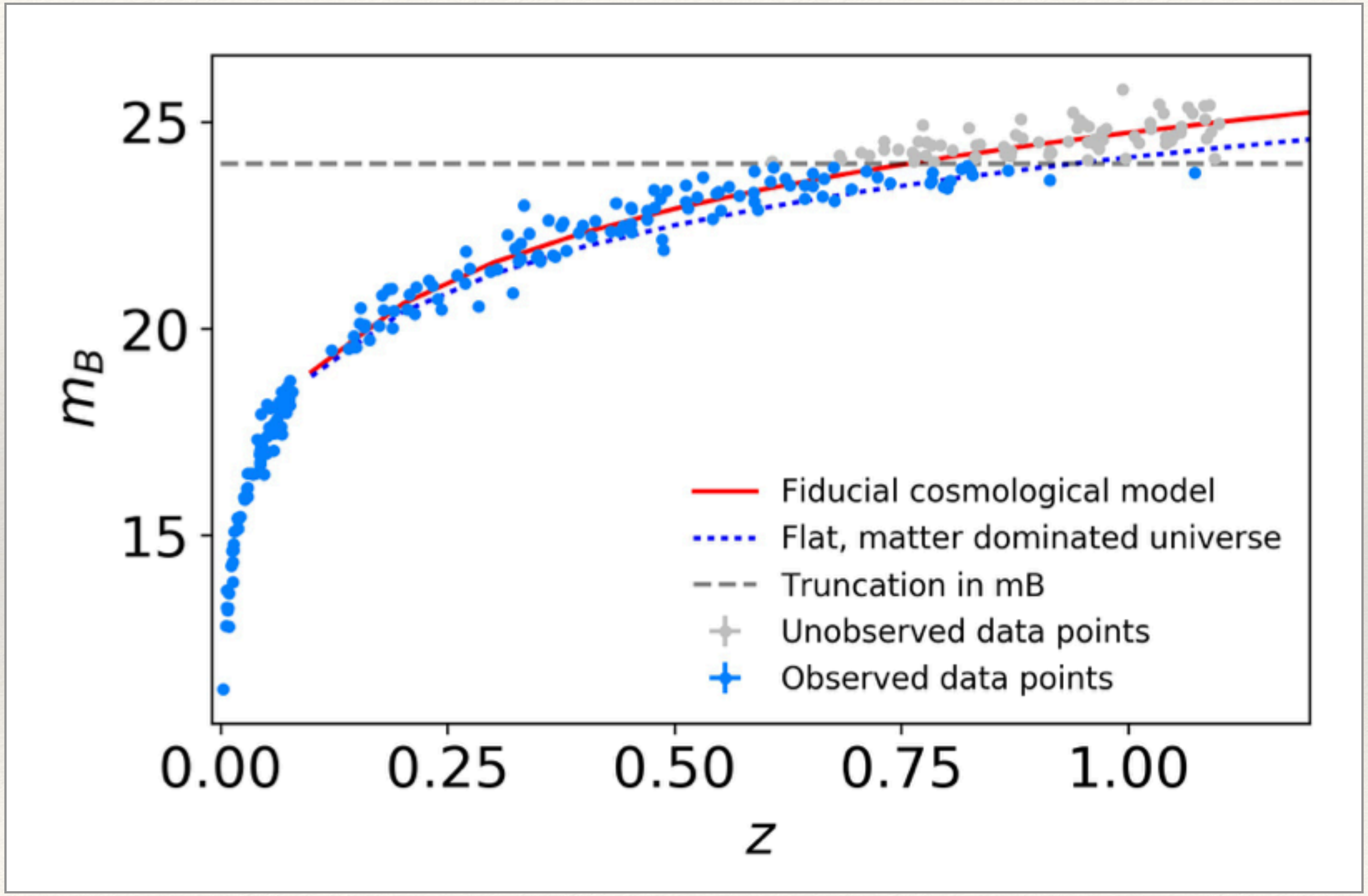


Simulating your survey to see what you missed



Validation by varying all known sources of uncertainty (e.g. filter transmission; spec-eff)

Correcting for biases



For any population with scatter:

Malmquist bias

(fainter events are lost)

Selection effects

(e.g. spectroscopic selection)

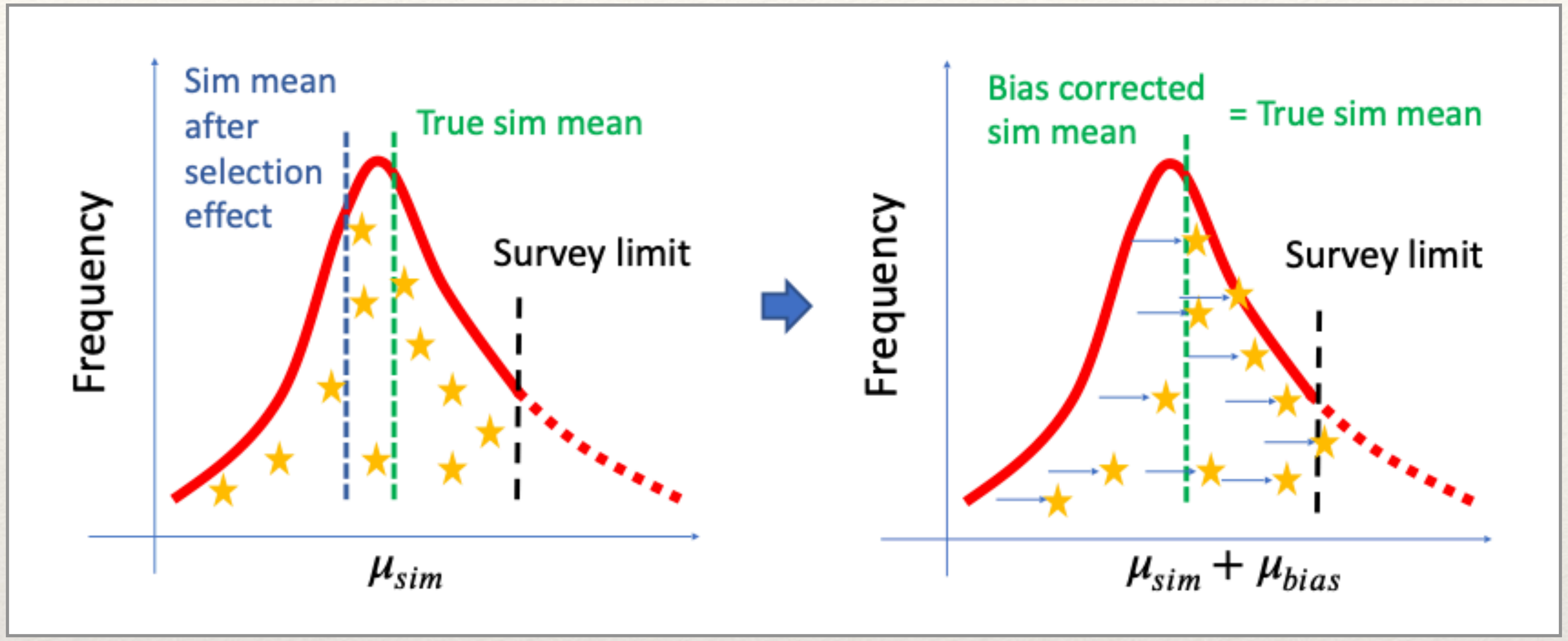
S/N

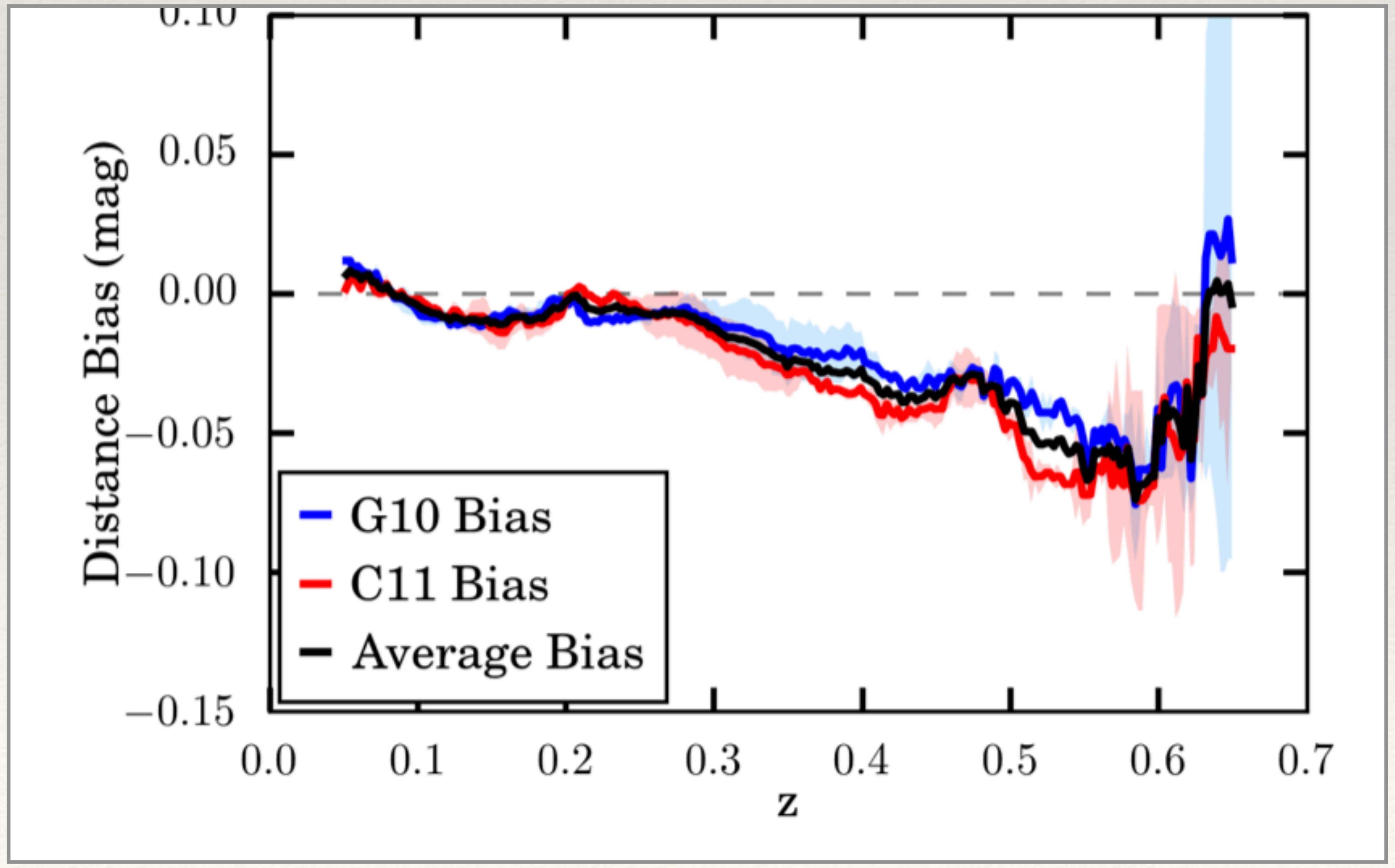
(intrinsic/measured parameter differences)

will lead to biases in distance

Correcting for biases

BBC





For simulations we know the truth

Determine the correction to distance required

Loop over all parameters

$\mu_{\rm bias} = f(z, x_1, c, \text{environment})$

Small dependence on assumed cosmology

Computationally expensive : statistical methods (Unity; EDRIS) forthcoming

Summary

SN Cosmology requires that we compare the same supernova at high and low redshift

Differences in selection (spectroscopic and photometric) can cause biases

Biases are corrected using simulations