Photometric Redshift Primer:
Template-based Photo-z's

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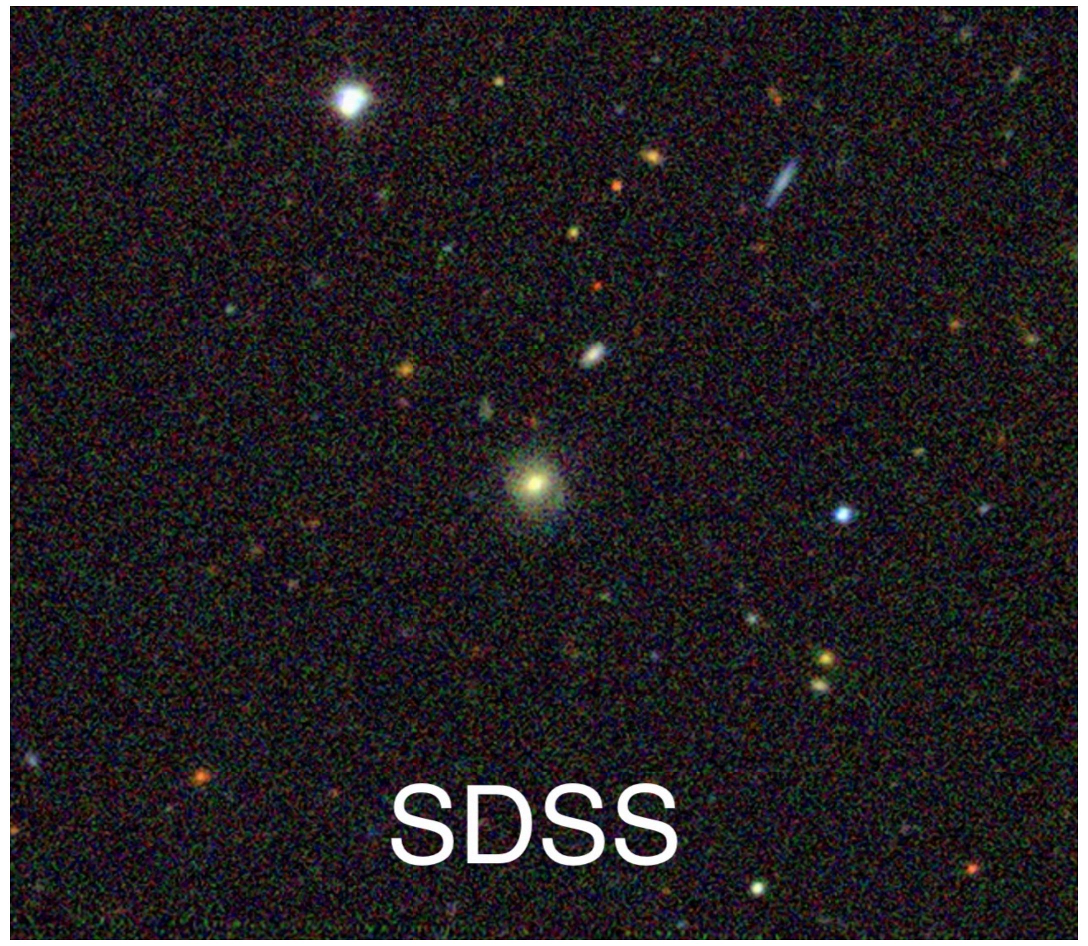
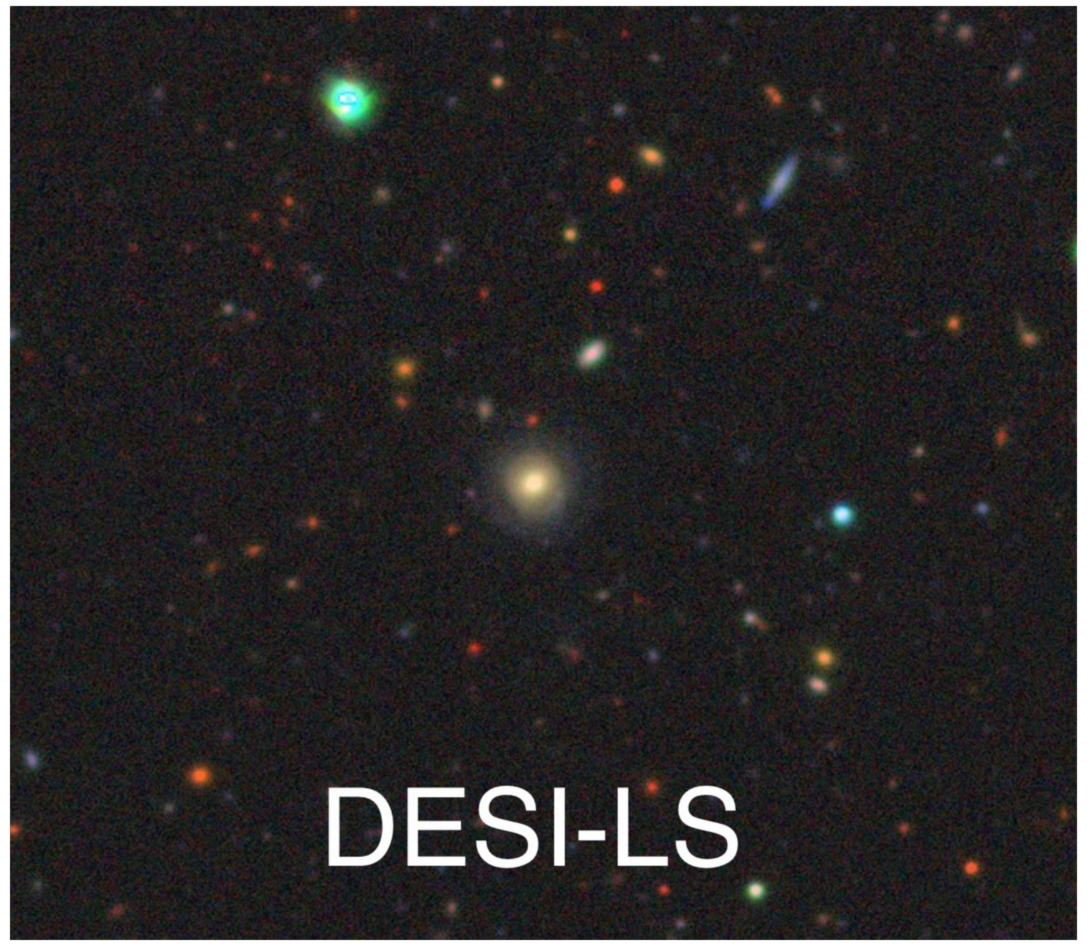
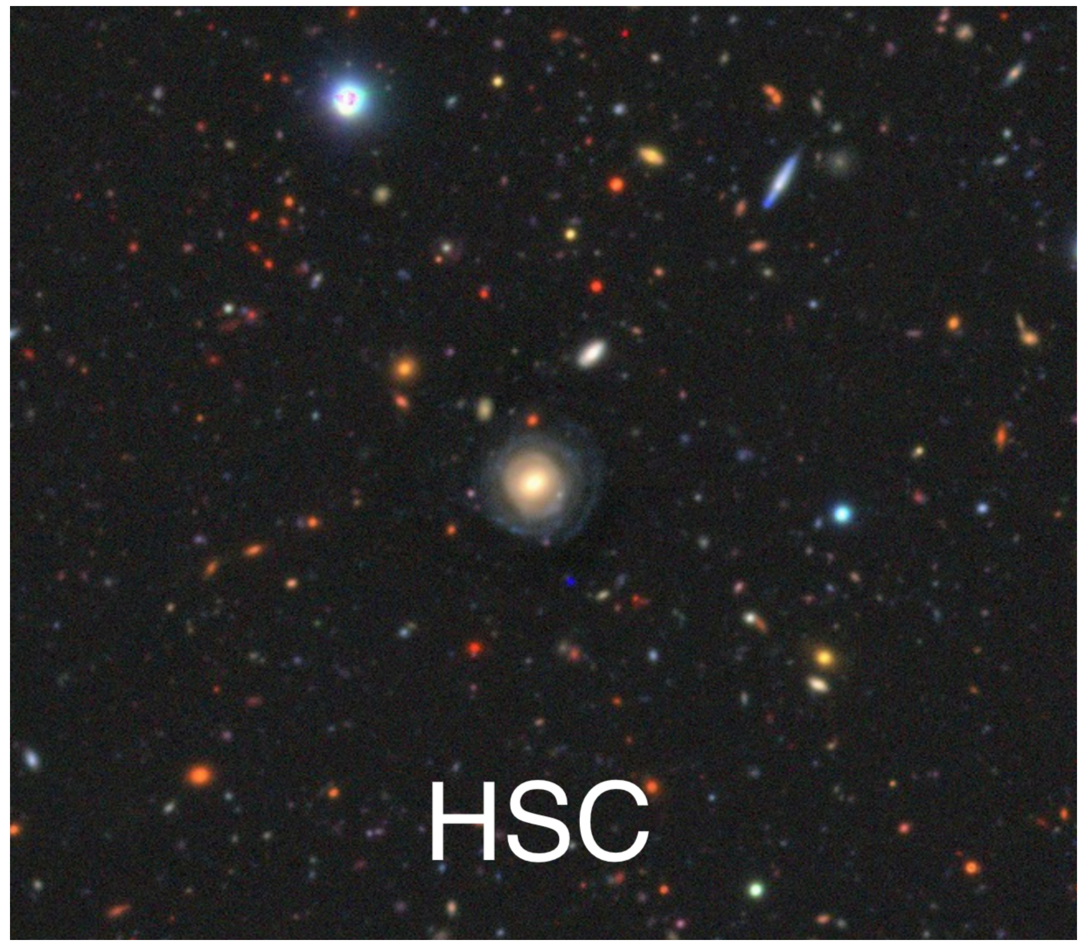
9.11.2024

Next Generation Wide-Field Imaging Surveys: LSST + Roman

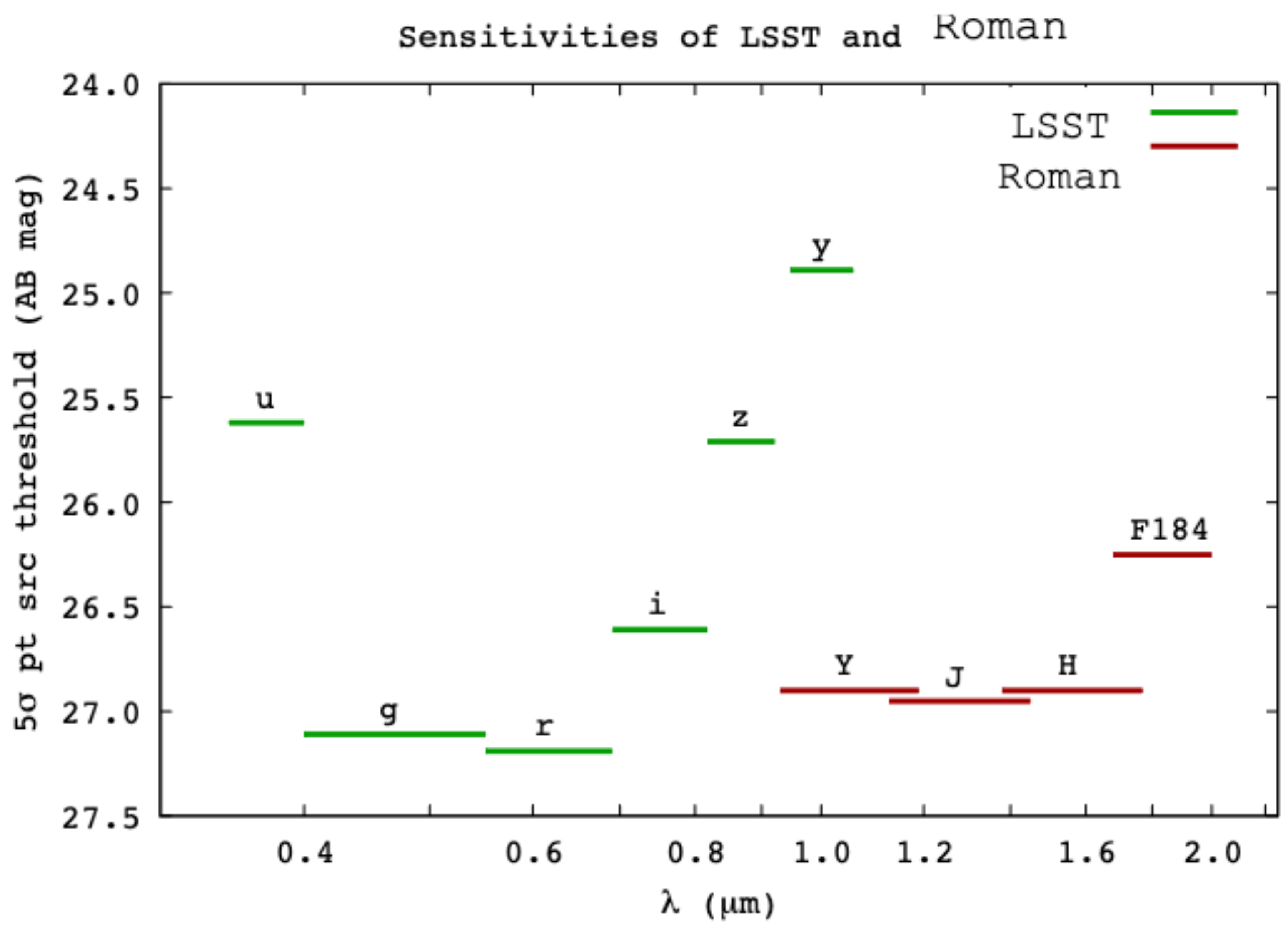






Roman-like

LSST-like

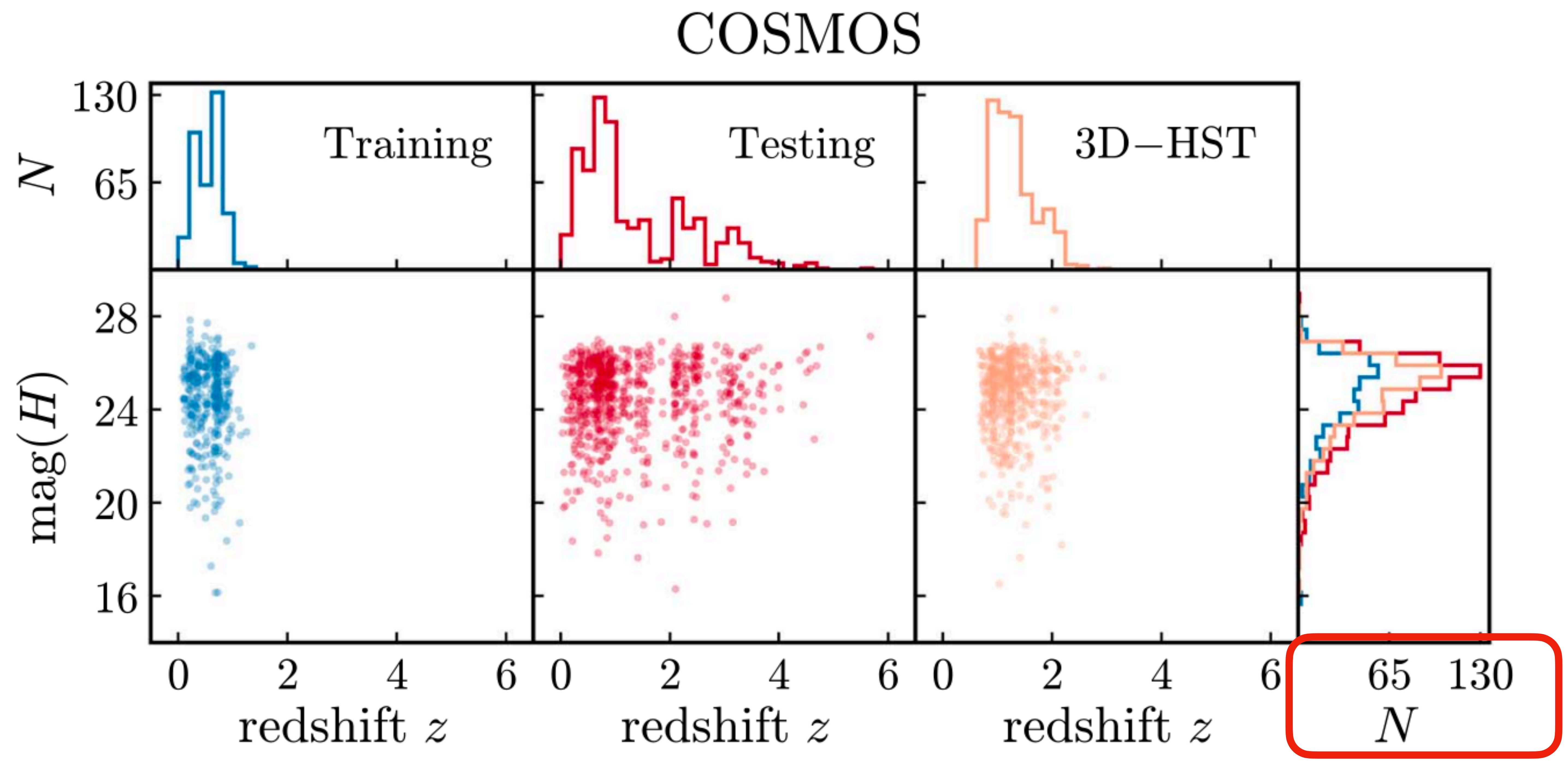


Eifler et al. (2023)

Deep optical-NIR coverage of **10^9 (LSST)** and **10^8 (Roman)** galaxies over **1000's sq deg.**

Need redshifts for key LSST/Roman science drivers: cosmology, galaxy evolution, transients.

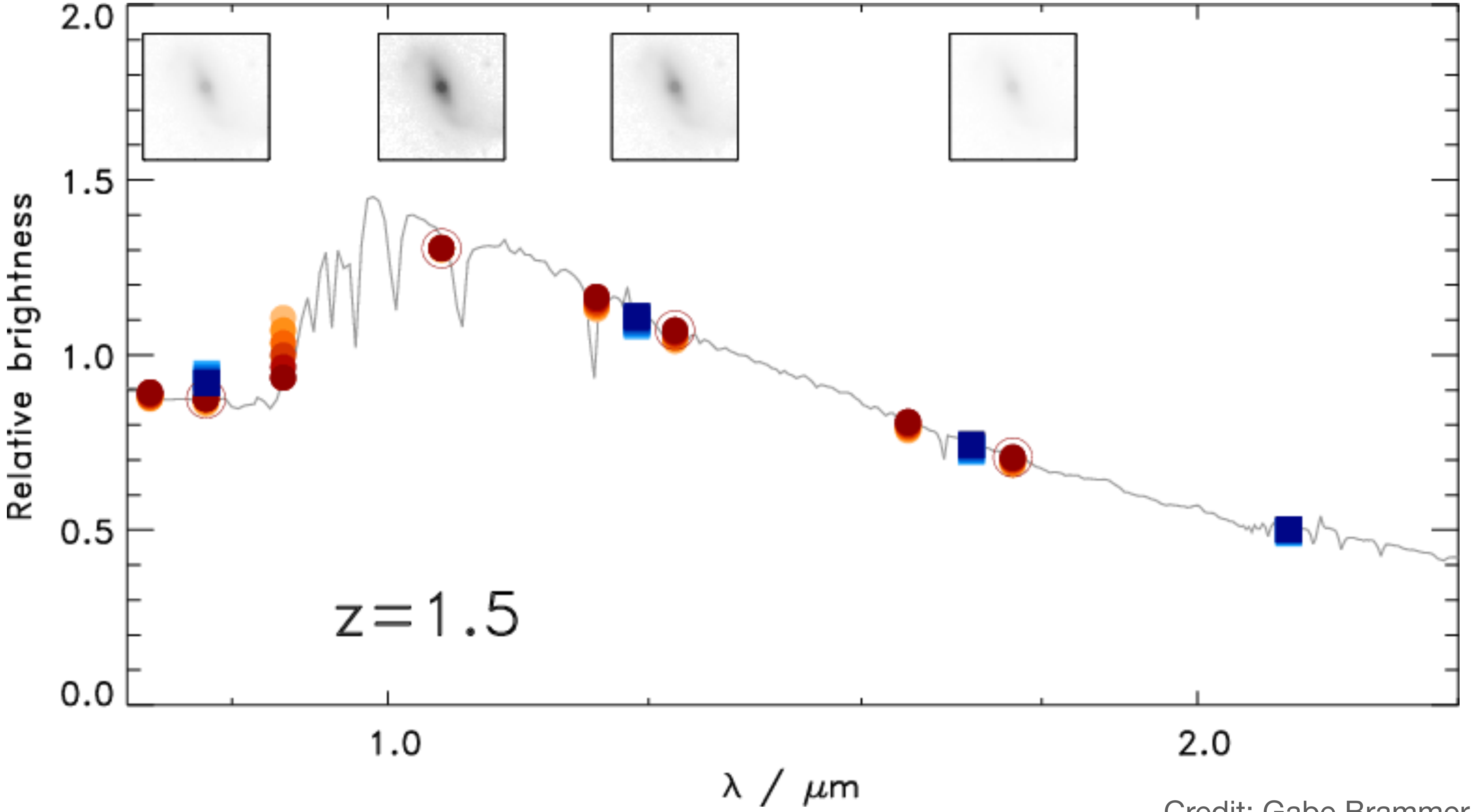
Spectroscopic Redshifts for LSST/Roman Prohibitively Costly



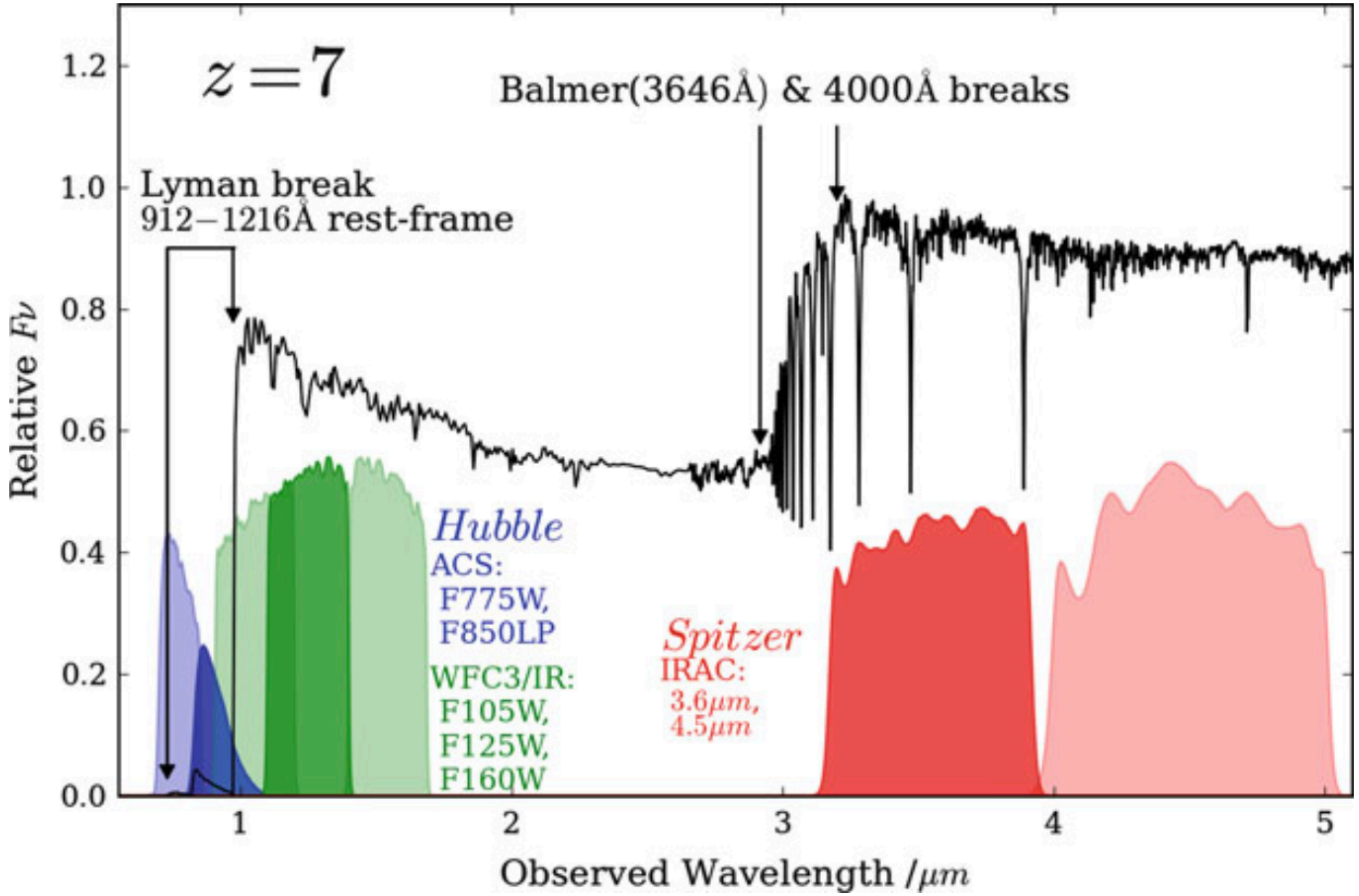
Spec-z's down to LSST/Roman depths for 30,000 galaxies will require ***years*** of dark time on a 10-m class telescope (Newman et al. 2015).

Must Rely on Photometric Redshifts

Kodra et al. (2023)



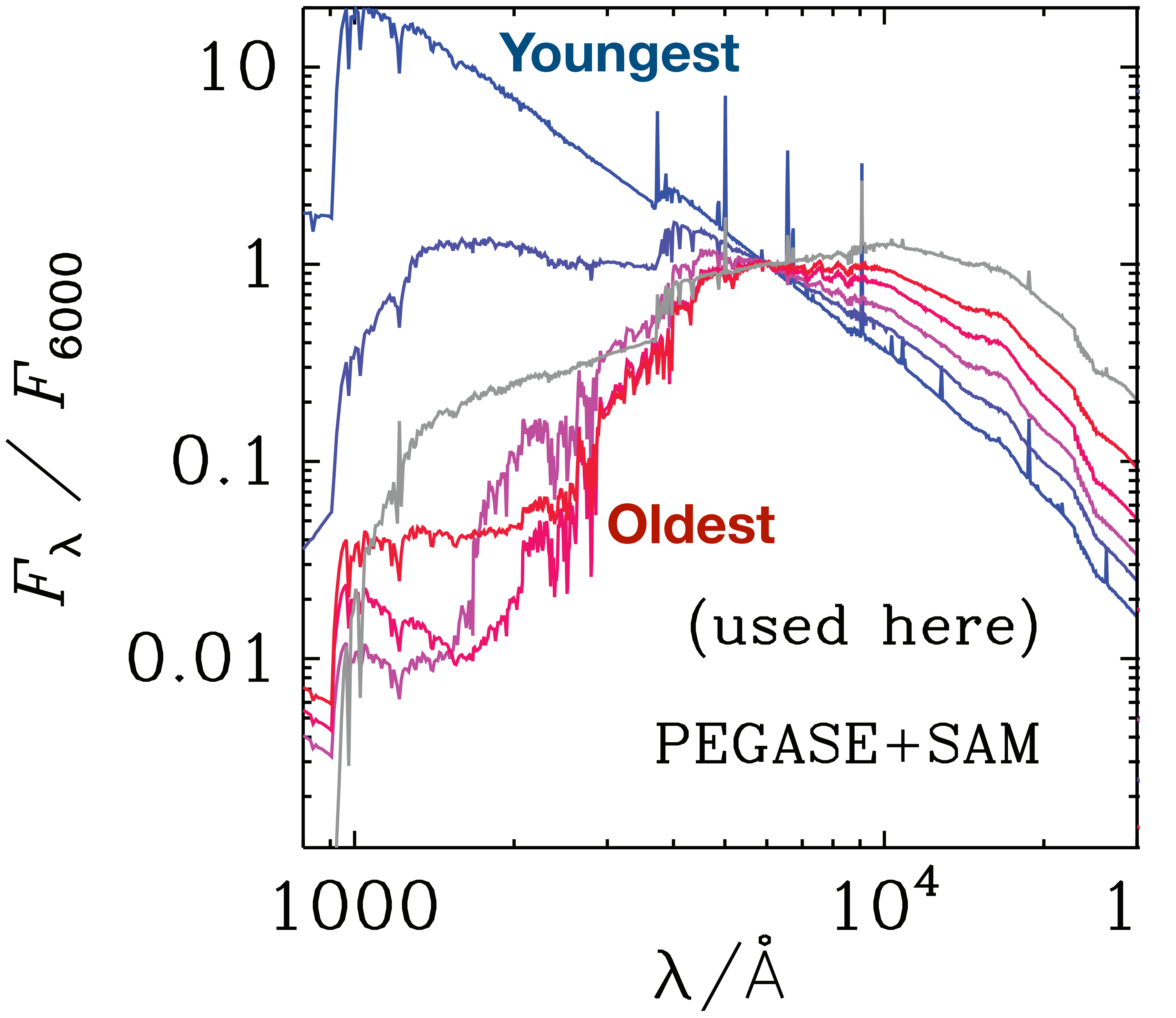
Credit: Gabe Brammer



Estimate Photo-z's from Broad Spectral Features

esp. Lyman and Balmer/4000A breaks

Dunlop (2012)



Older Stellar Populations Have Stronger Breaks

- Photo-z's are more precise for redder galaxies.
- At higher-z, blue galaxies with younger stellar populations dominate, so determining photo-z's is more difficult.

Brammer et al. (2008)

Photo-z Methods

Data-Driven

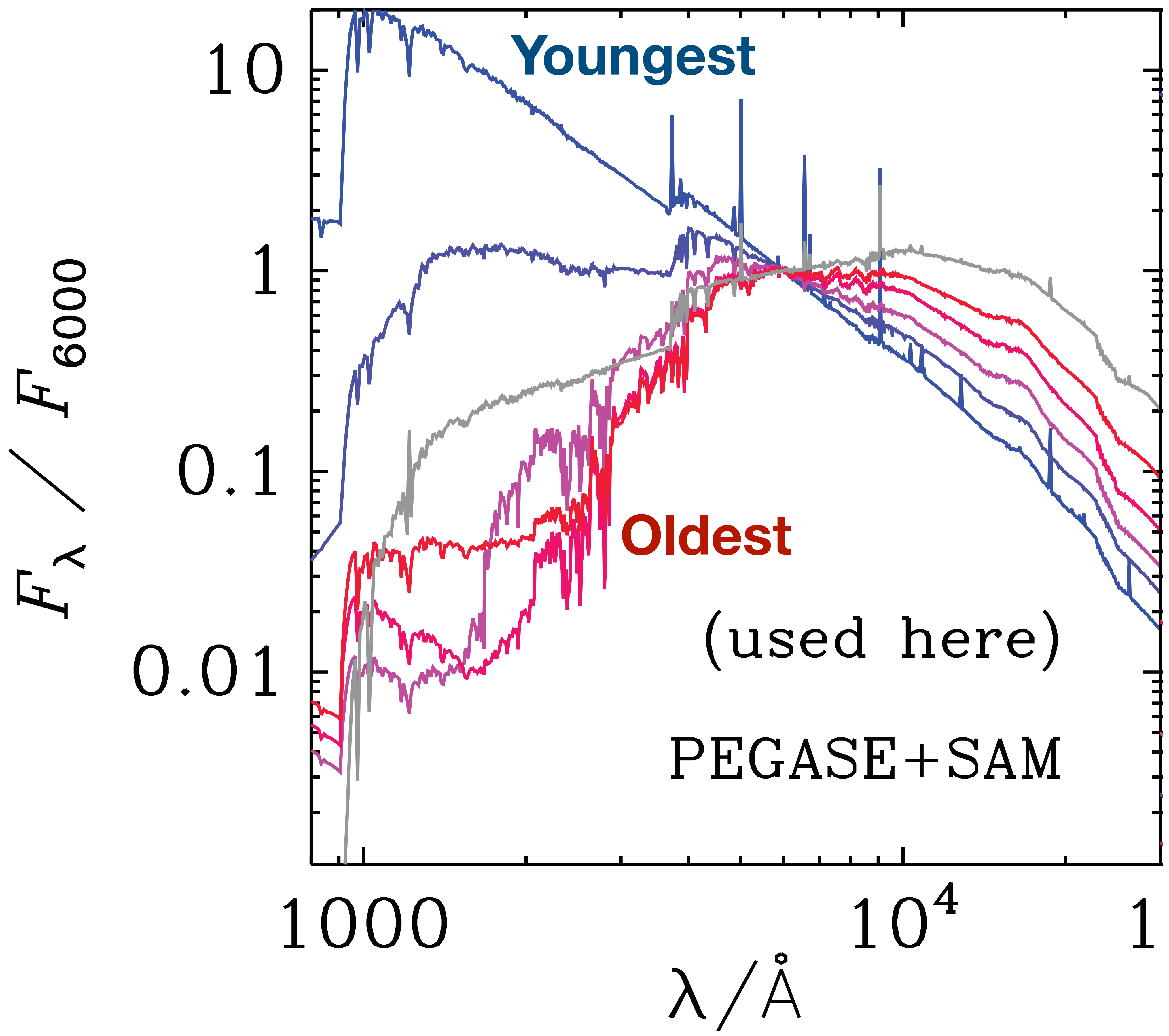
- Train machine learning model on galaxies with photometry and spec-z's.
- If training data is representative, then ***can be very accurate***.
- However, ***extrapolate poorly*** outside of training data (and spec-z's for faint galaxies are incredibly resource-intensive).

Template-based

- ***Leverage knowledge of galaxy physics*** by finding best match of galaxy spectral template and redshift to the observed photometry.
- Much more reliable for regimes of color-redshift space sparsely covered by spec-z's.
- But, ***spec-z's are still needed to calibrate*** photometric and model uncertainties (e.g., template mismatch).

Encoding Galaxy Physics: Spectral Templates

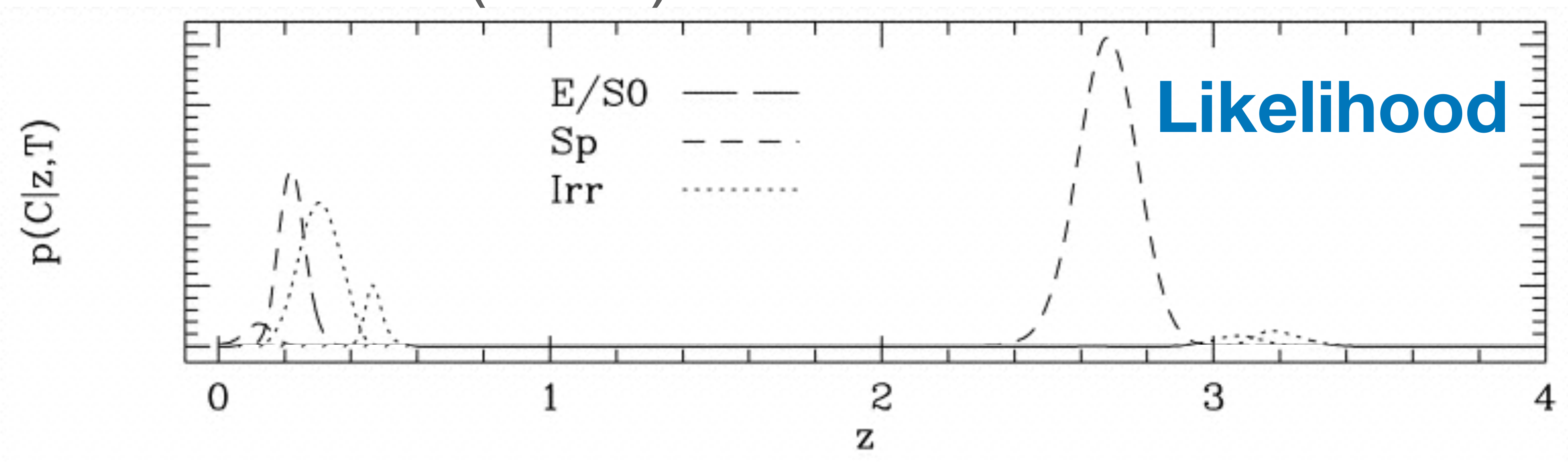
- **Stellar Populations**
  - Empirical vs. theoretical templates
  - Combine templates?
- **Gas/dust processing**
  - Dust
  - Emission lines
  - IGM opacity
- **Ideally, templates span the range of galaxy colors.**



Brammer et al. (2008)

Bayesian Framework: Photo-z Probability Distribution Functions (PDFs)

Benitez (2000)



p(colors | z, templates) = exp(-χ^2(z) / 2)

χ^2-minimization: finding the best fit template and redshift

Template Flux (at redshift z for template i in filter j)

$$\chi^2_{z,i} = \sum_{j=1}^{N_{\text{filt}}} \frac{\left(T_{z,i,j} - F_j\right)^2}{\left(\delta F_j\right)^2},$$

Observed Flux (in filter j)

Observed Flux Error (in filter j)

Sum over filters

Brammer et al. (2008)

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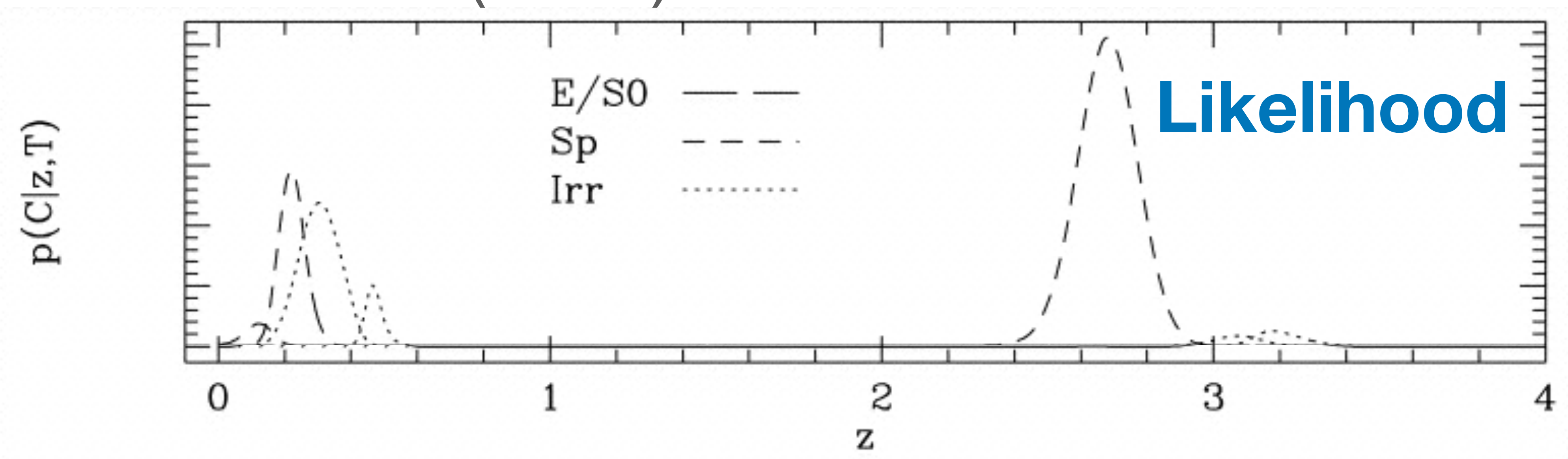
Benitez (2000)



p(colors | z, templates) = exp(-$\chi^2(z)$ / 2)

Templates and/or photometric errors are often tweaked to account for:

- **observational uncertainties** in
  - filter transmission curves
  - photometric zero points

- **theoretical uncertainties** in
  - mismatch between spectral templates and real galaxy spectra.

Requires spec-z data sets!

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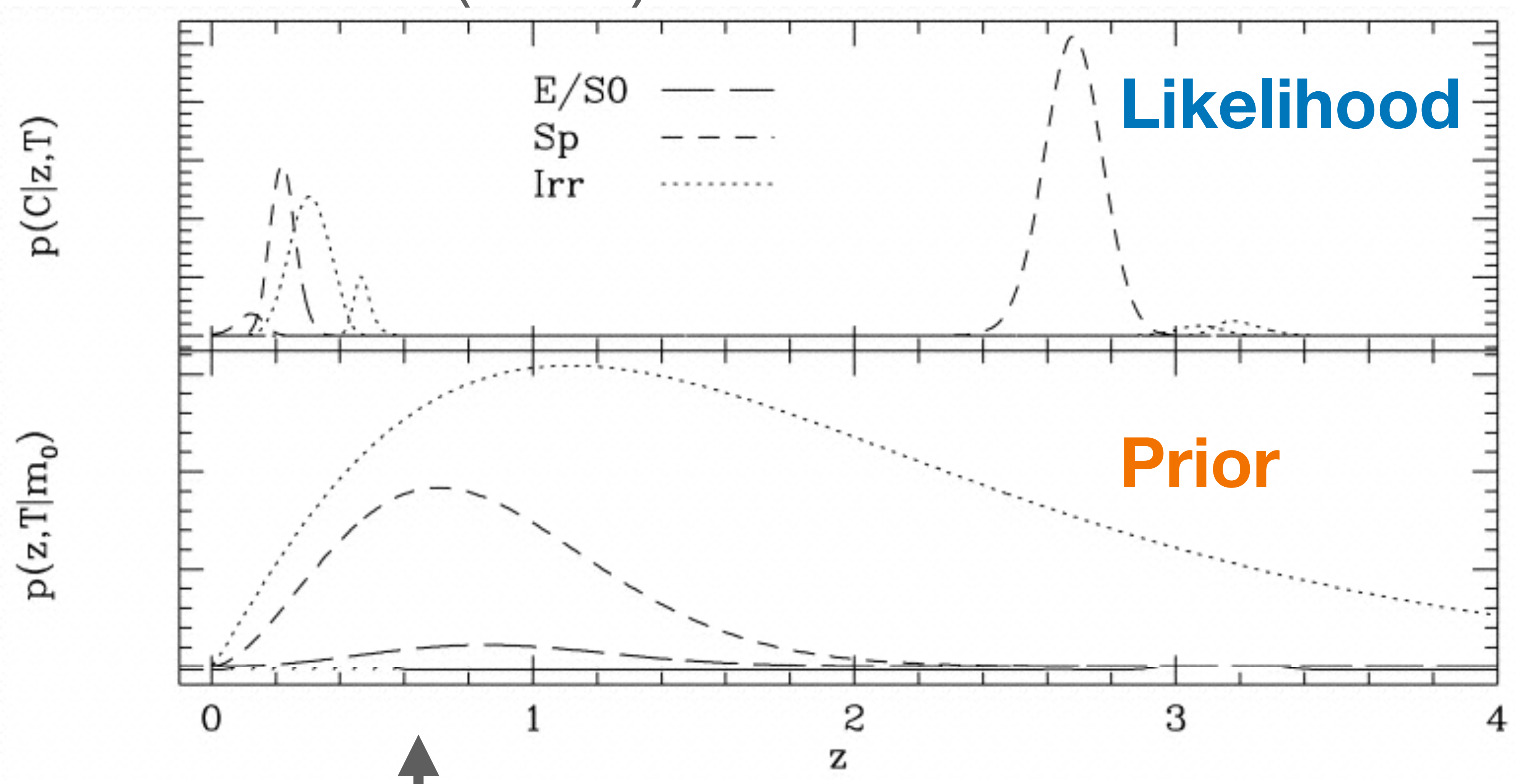
Benitez (2000)



p(colors | z, templates) = exp(-χ^2(z) / 2)

p(z, templates | m_0)

apparent magnitude

Brighter galaxies are more likely to live at low-z.

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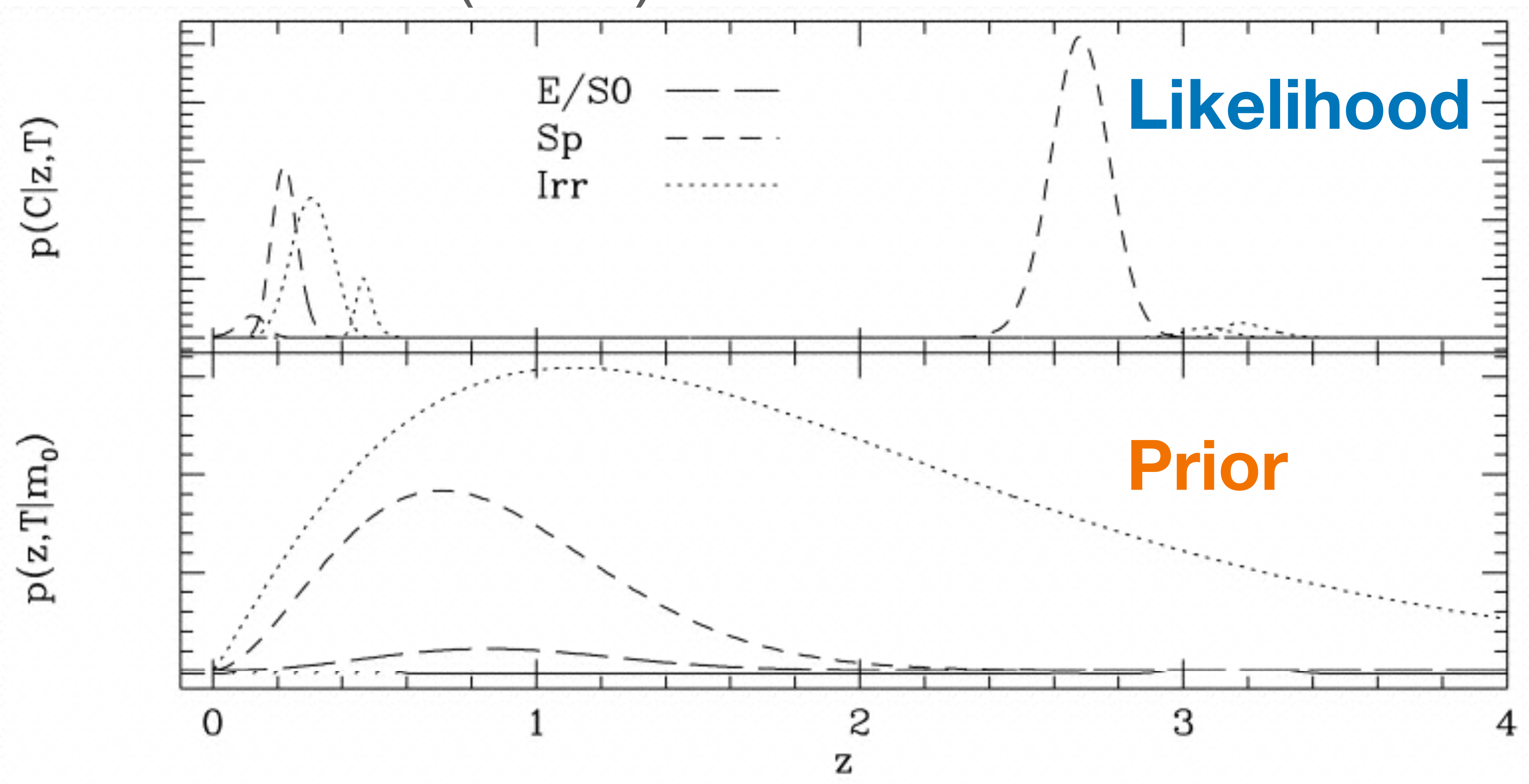
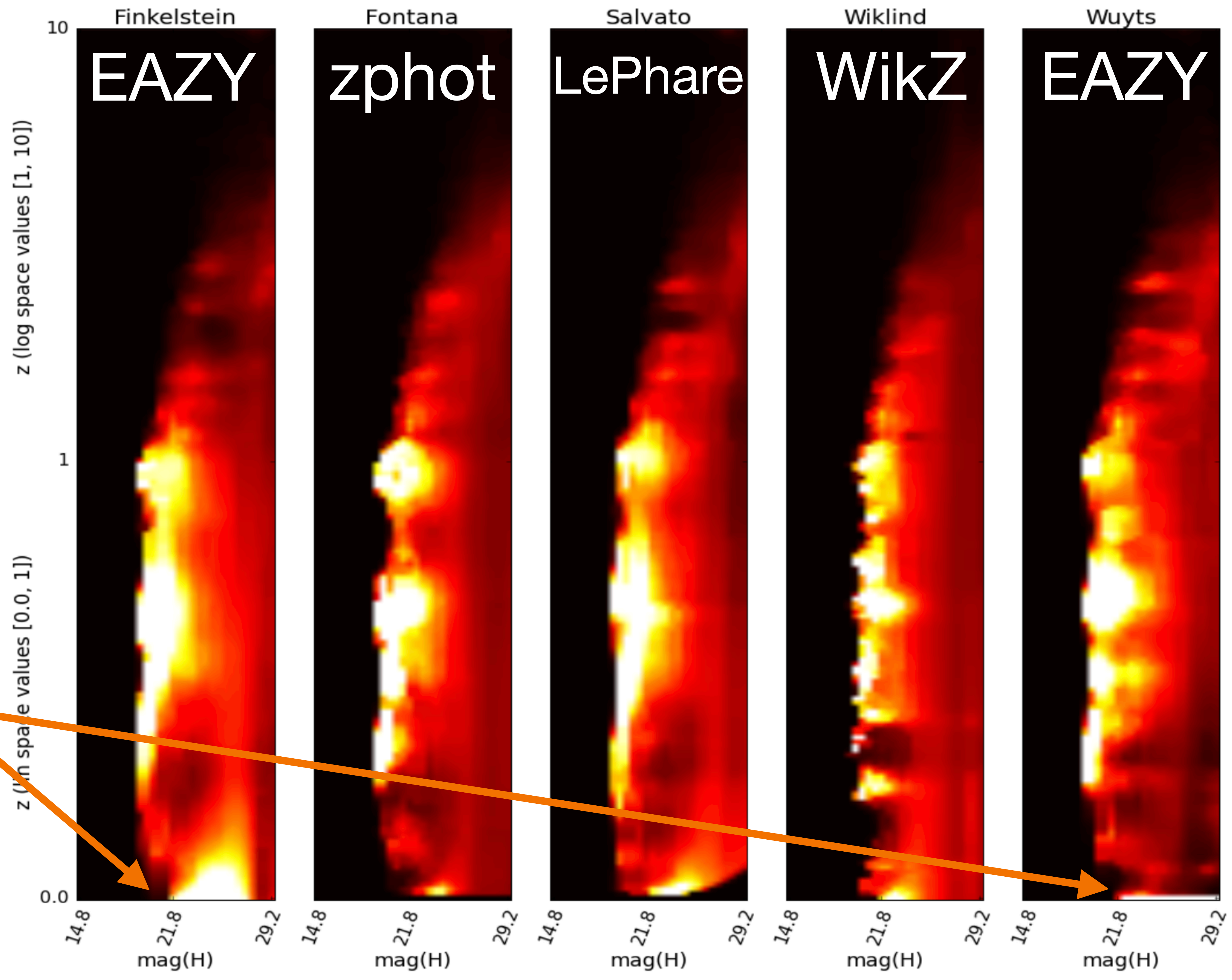


Even with the same photo-z code running on the same input photometry for bright galaxies, different priors can produce different photo-z posterior PDFs.

Stacked Photo-z Posterior PDFs in CANDELS EGS

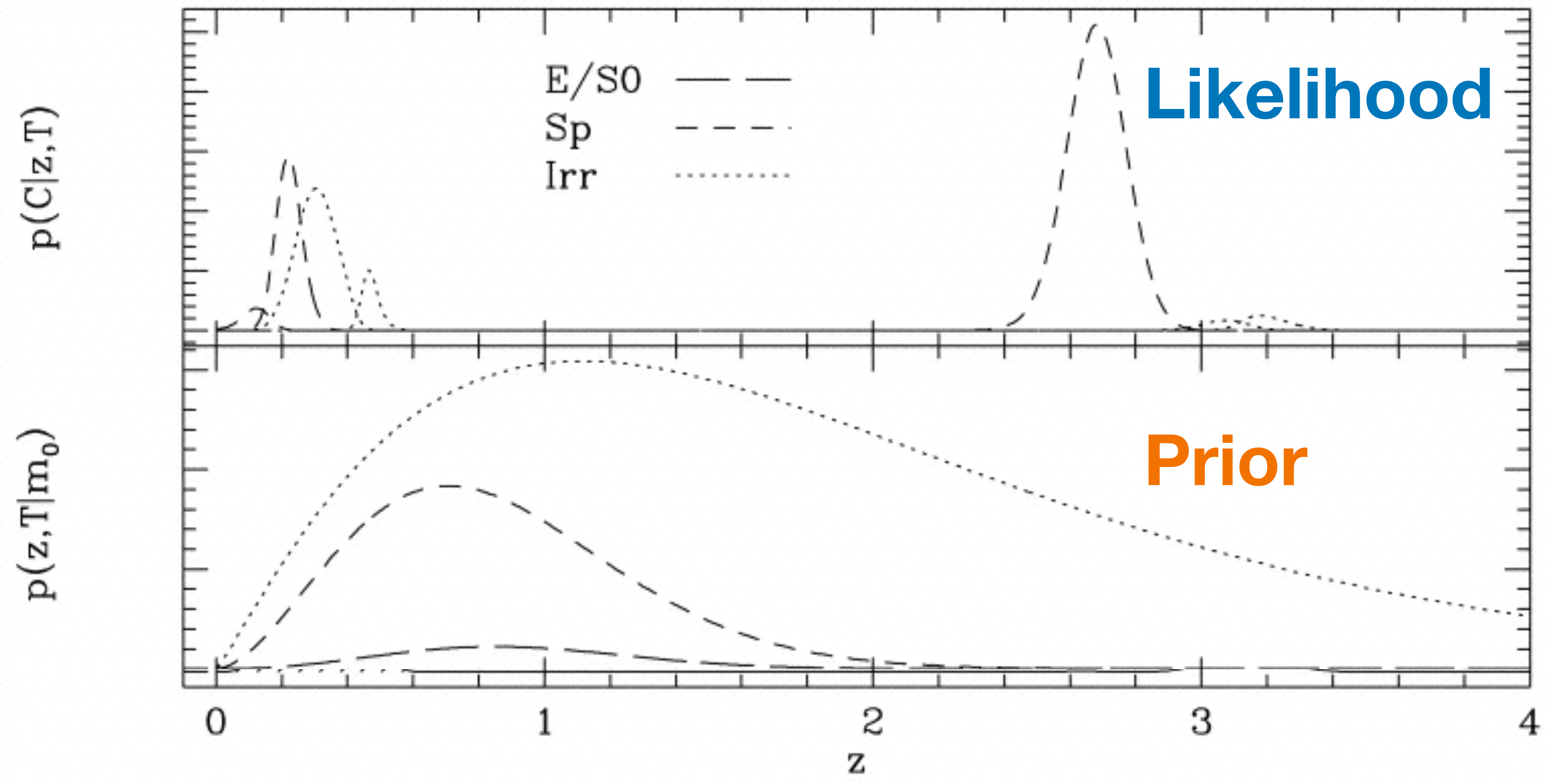


H-band magnitude

Credit: Dritan Kodra

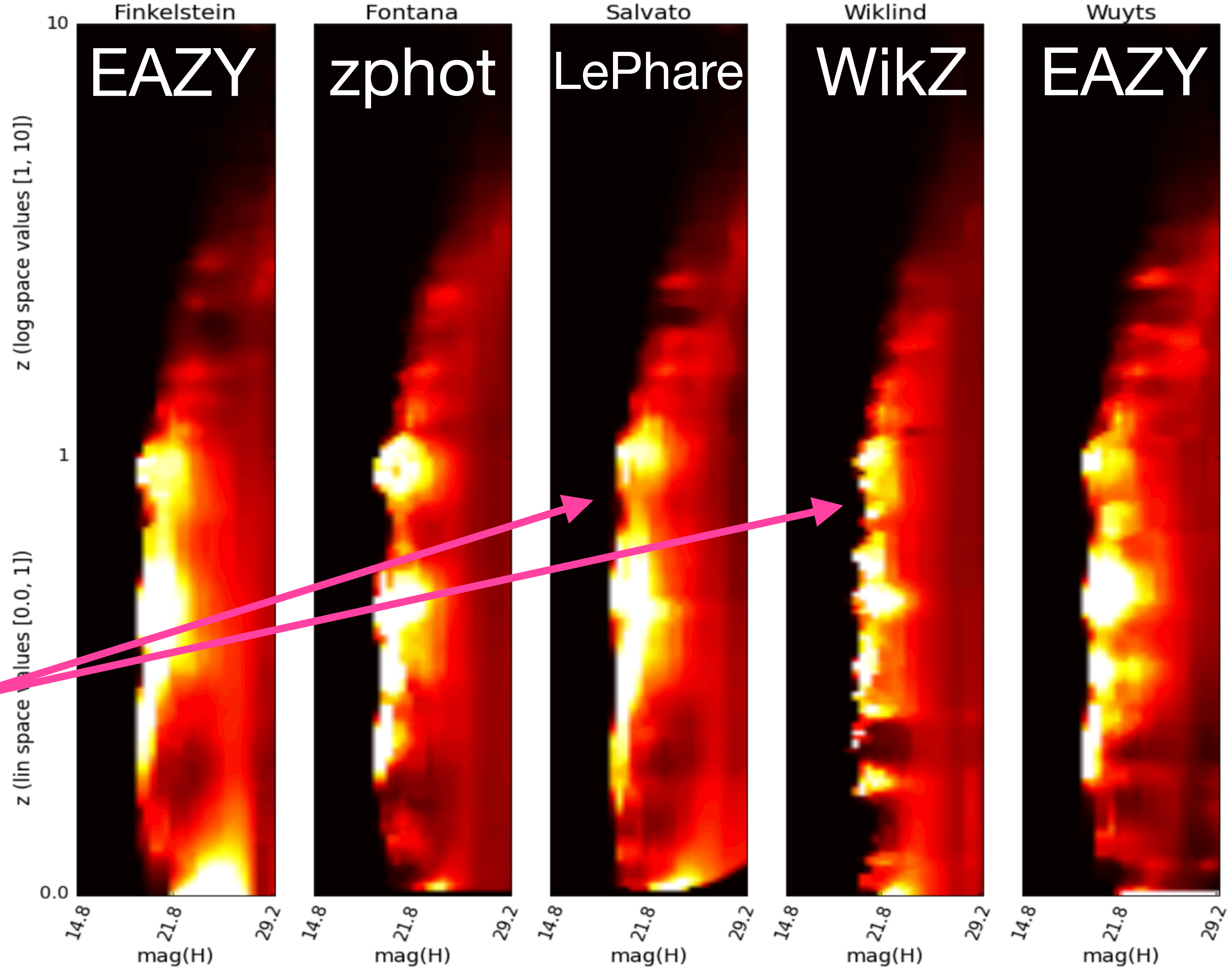
Bayesian Framework: Photo-z Probability Distribution Functions (PDFs)

Benitez (2000)



Different codes disagree on the redshift of large scale structure due to implicit priors baked into the codes/template sets.

Stacked Photo-z Posterior PDFs in CANDELS EGS



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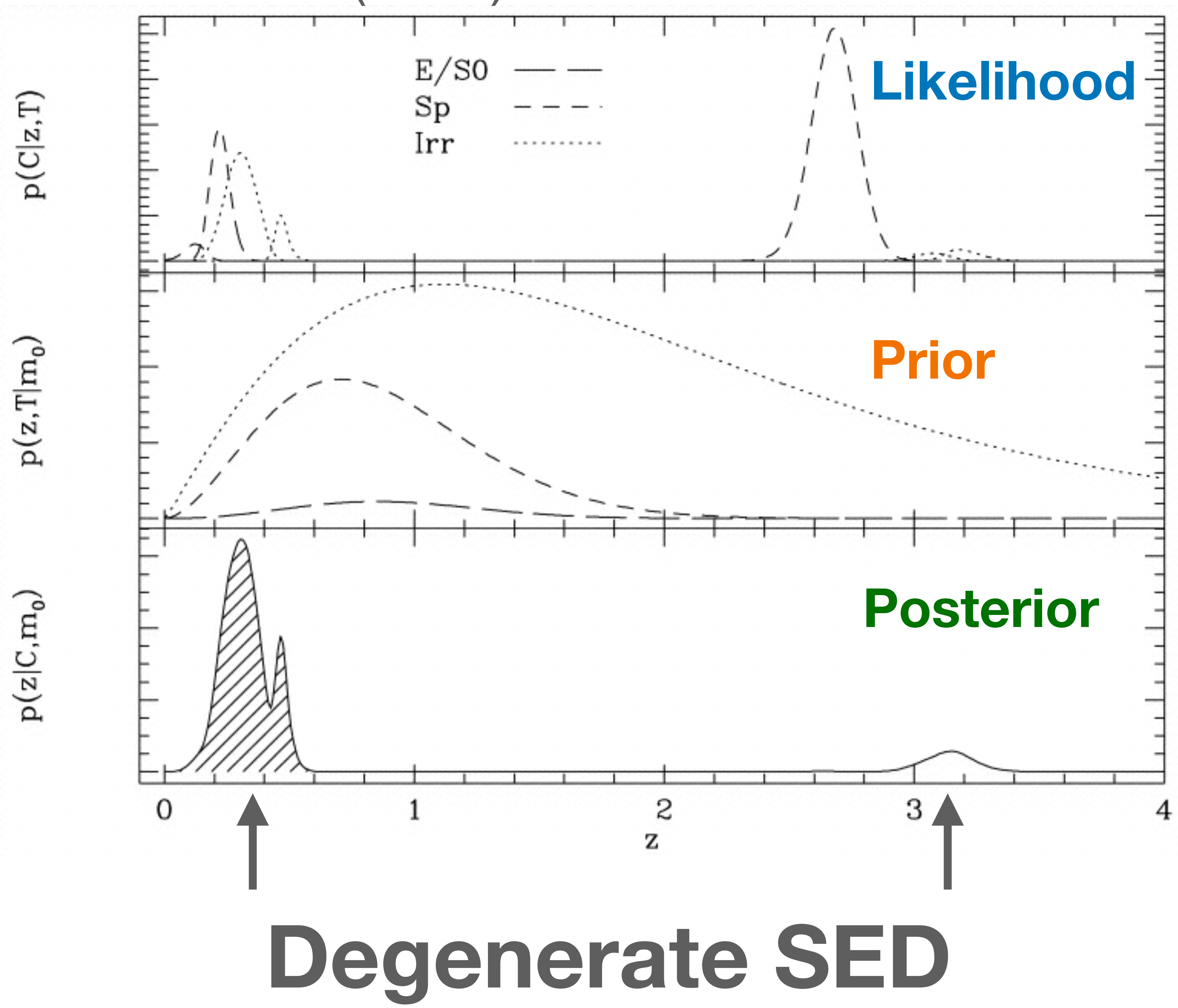


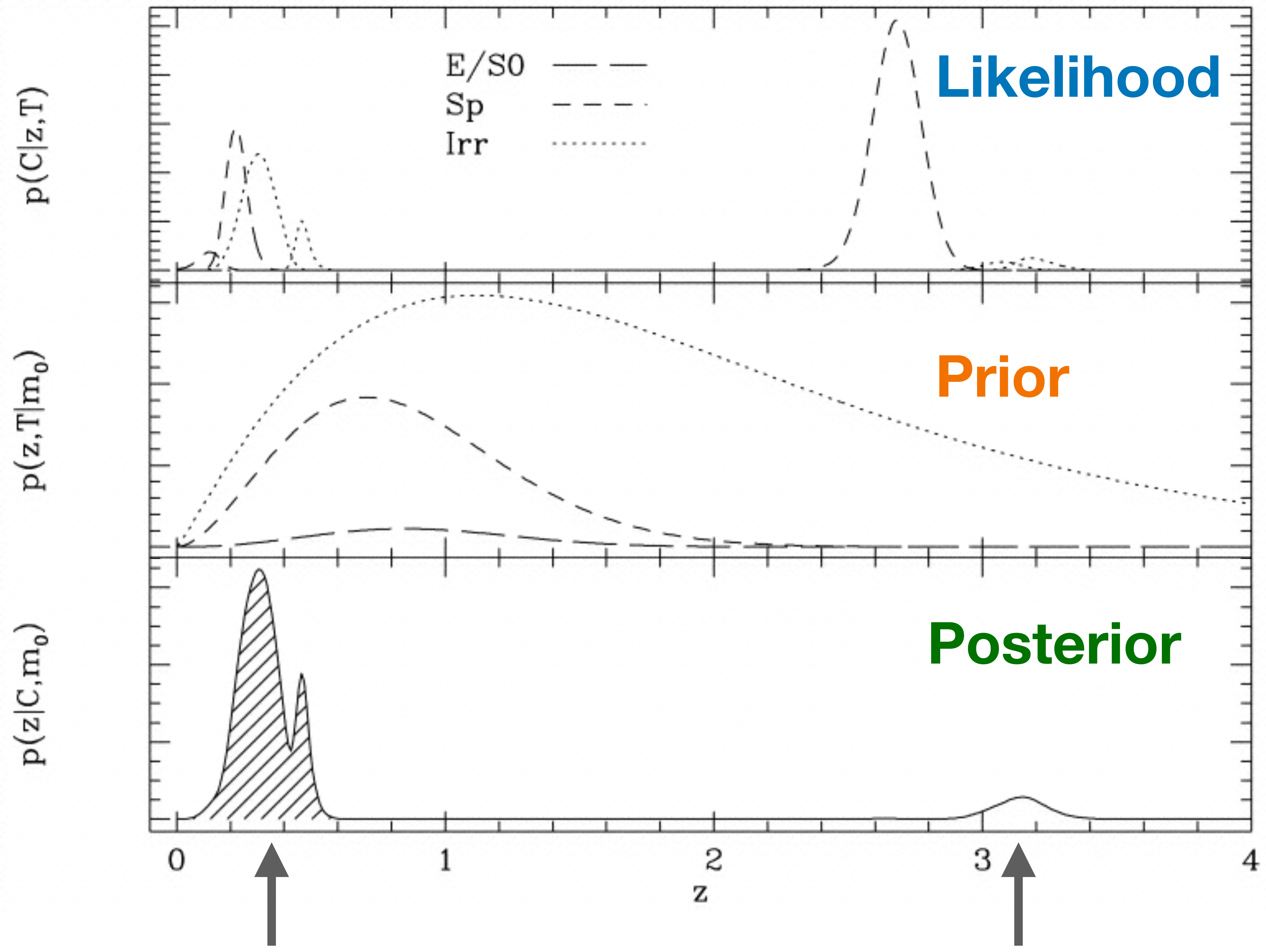
$p(\text{colors} \mid z, \text{templates}) = \exp(-\chi^2(z) / 2)$

$p(z, \text{templates} \mid m_0)$

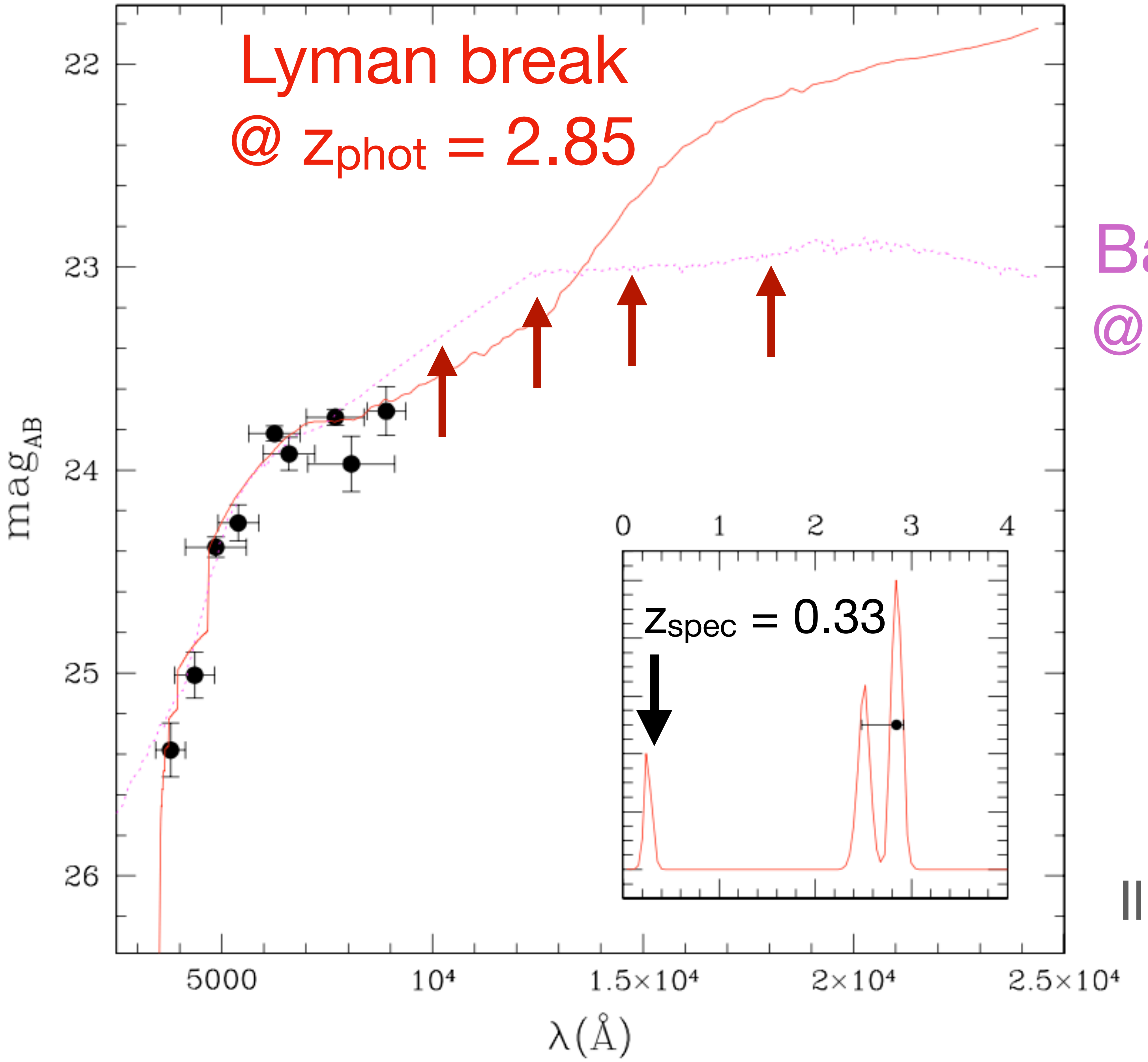
$p(z \mid \text{colors}, m_0) \propto p(\text{colors} \mid z) * p(z \mid m_0)$

Bayesian Framework: Photo-z Probability Distribution Functions (PDFs)

Benitez (2000)



Degenerate SED



Balmer break
@ z_{phot} = 0.24

Ilbert et al. (2006)

Roman NIR bands will be key for breaking degeneracies in optical SEDs

Bayesian Framework: Photo-z Probability Distribution Functions (PDFs)

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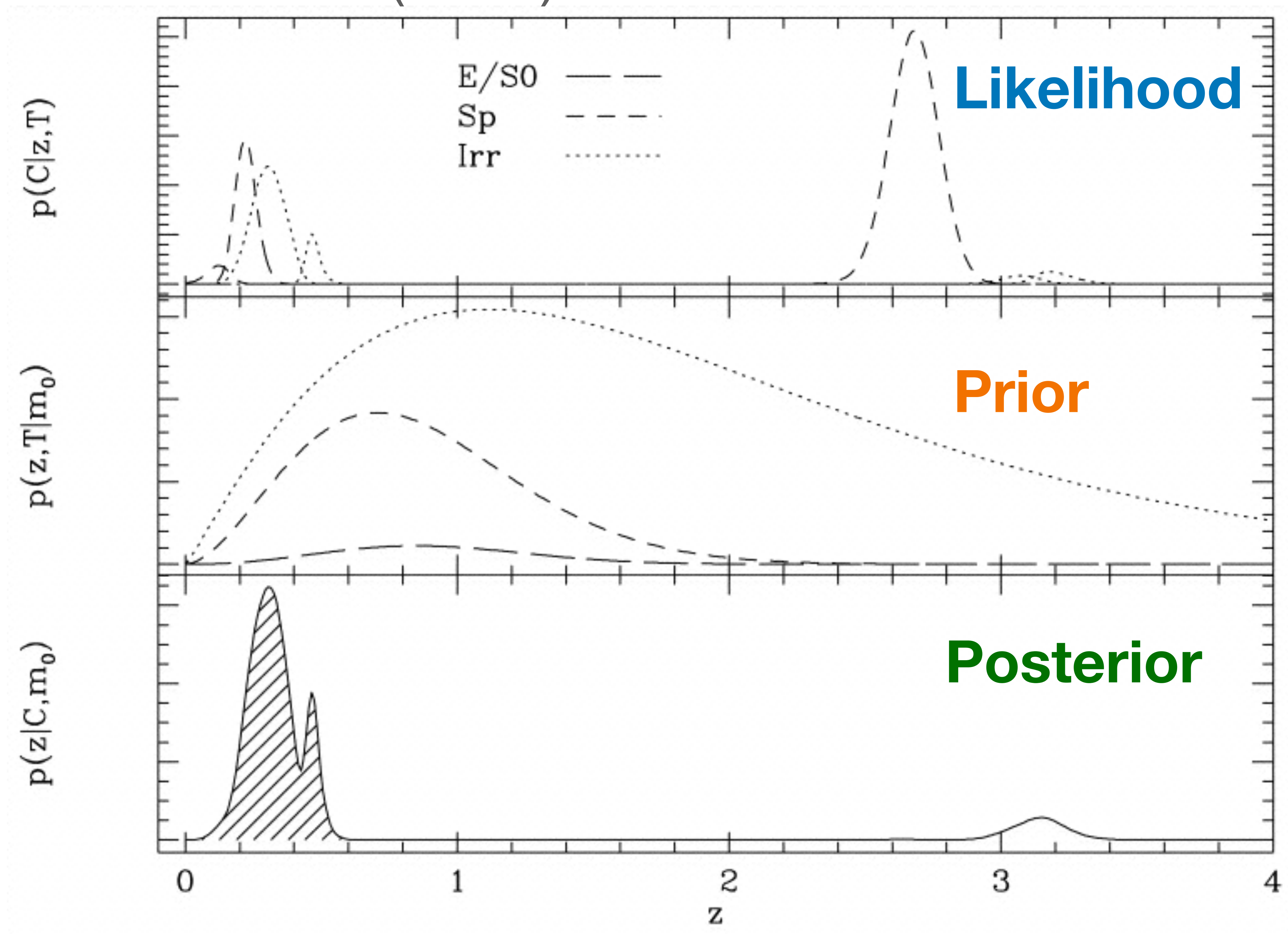

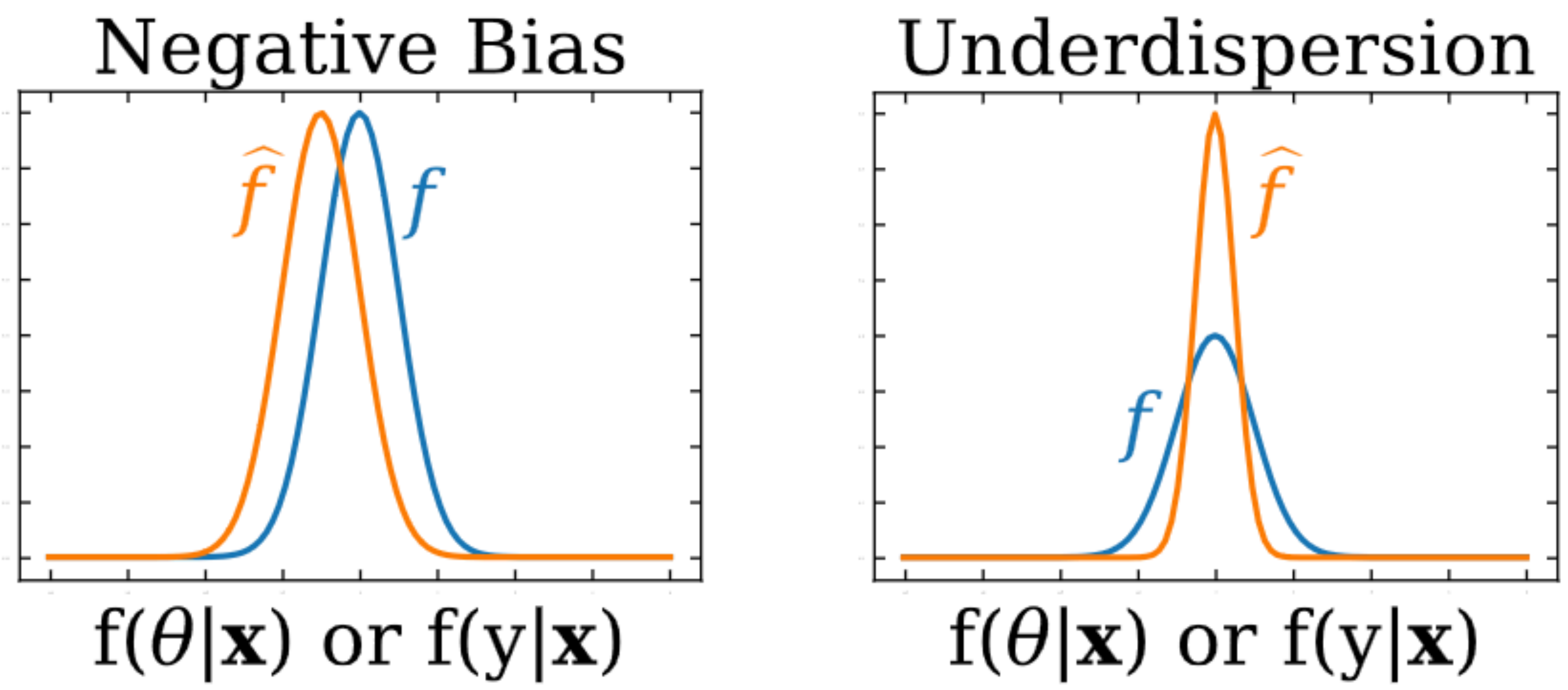

Dey et al. (2022)

Posterior PDFs are often biased or underdispersed

⇩

Need spectroscopic data for calibration!

Takeaways

- Need photo-z's for LSST/Roman science.
- Template-based photo-z methods are especially useful for regimes of color-redshift space with sparse spectroscopic coverage.
- Use χ^2**-minimization** to find best match of redshift+template to observed photometry.
- But many choices (template sets, dust, emission lines), so **need spectroscopic data for calibration**!