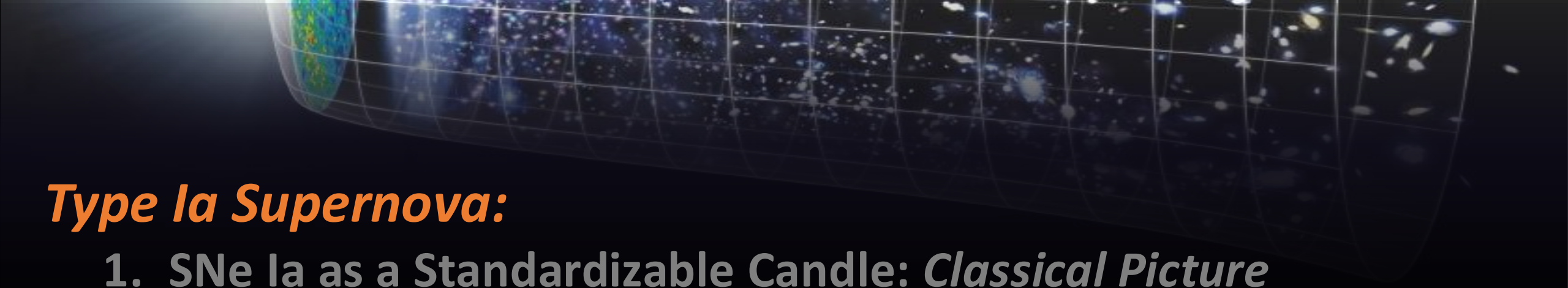
Type Ia Supernova: A Standardizable Candle

CosmoVerseSchool @ Sofia May 25-29

Y. S. Murakami | Johns Hopkins University



Type Ia Supernova:

1. SNe Ia as a Standardizable Candle: *Classical Picture*
2. SNe Ia in Distance Ladder: *Coding Demo*
3. **Assessing Sysetematics & New Surveys: *Modern Picture***

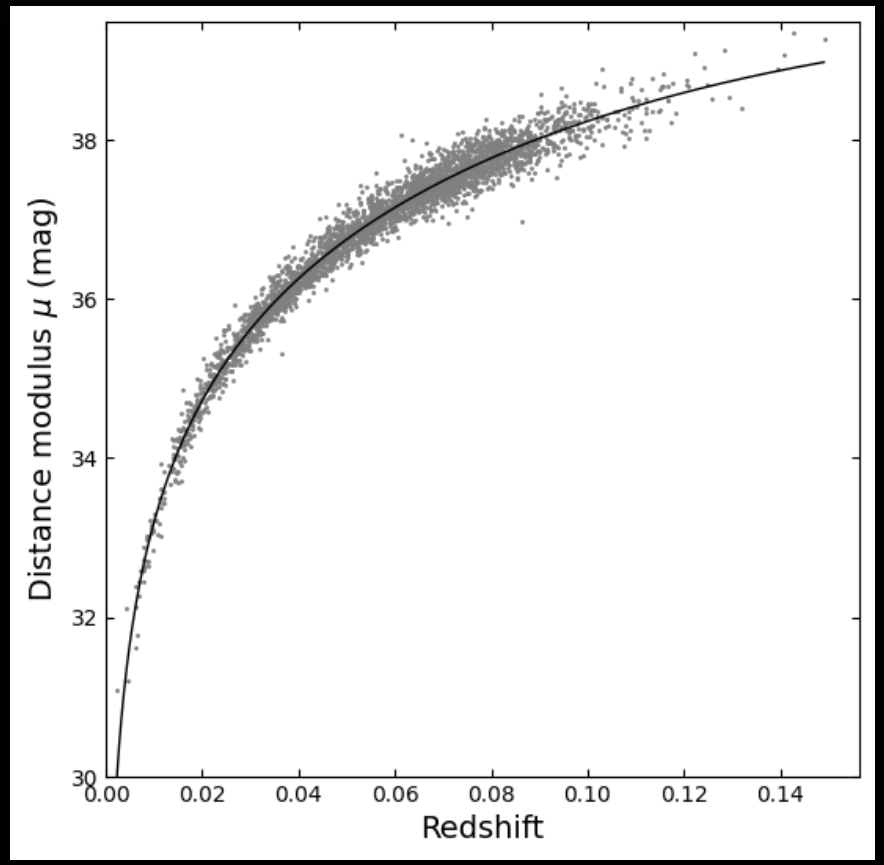
- What is a Type Ia supernova?
- How does it help cosmology?
- Where does the data come from?
- How can I use data for my own analysis?
- Outlook – a new generation of supernova cosmology

Type Ia Supernova in Modern Cosmology

Part I: The Primary Challenge
Part II: Further Standardization
Part III: Supernova Cosmology in 2030s

Type Ia Supernova in Modern Cosmology

Part I: The Primary Challenge

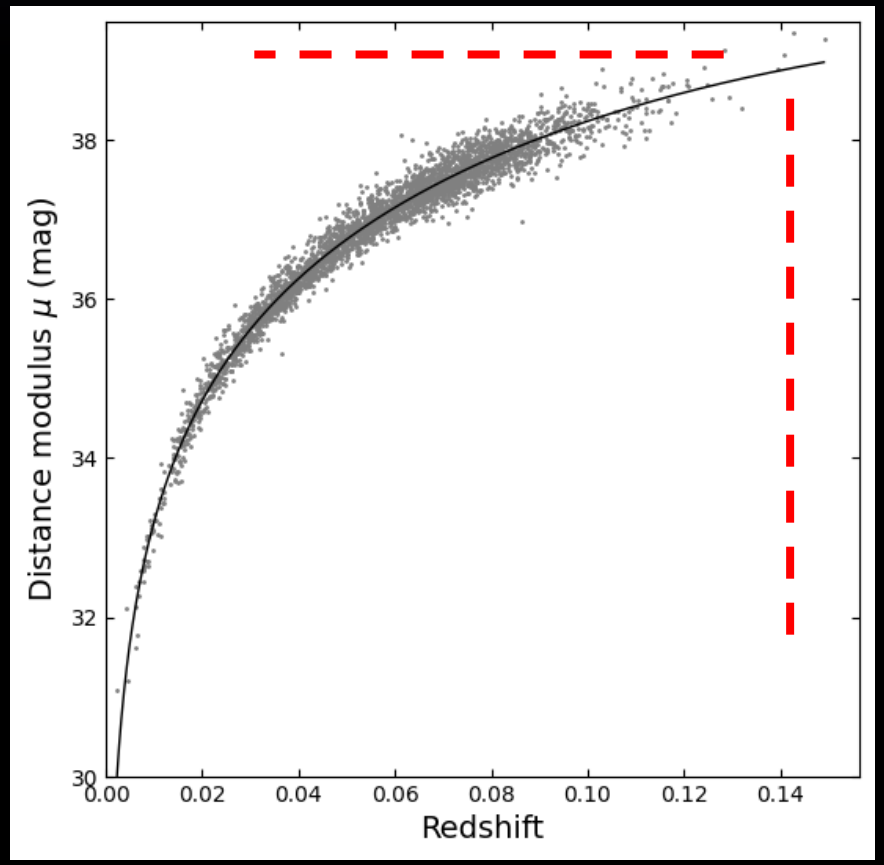


- ✅ Tripp Standardization: applied
- ✅ Spectroscopically confirmed ”normal” SNe Ia
- ✅ Host galaxy spectroscopic redshifts

Can we fit ΛCDM to this data? – No, Not yet

Type Ia Supernova in Modern Cosmology

Part I: The Primary Challenge

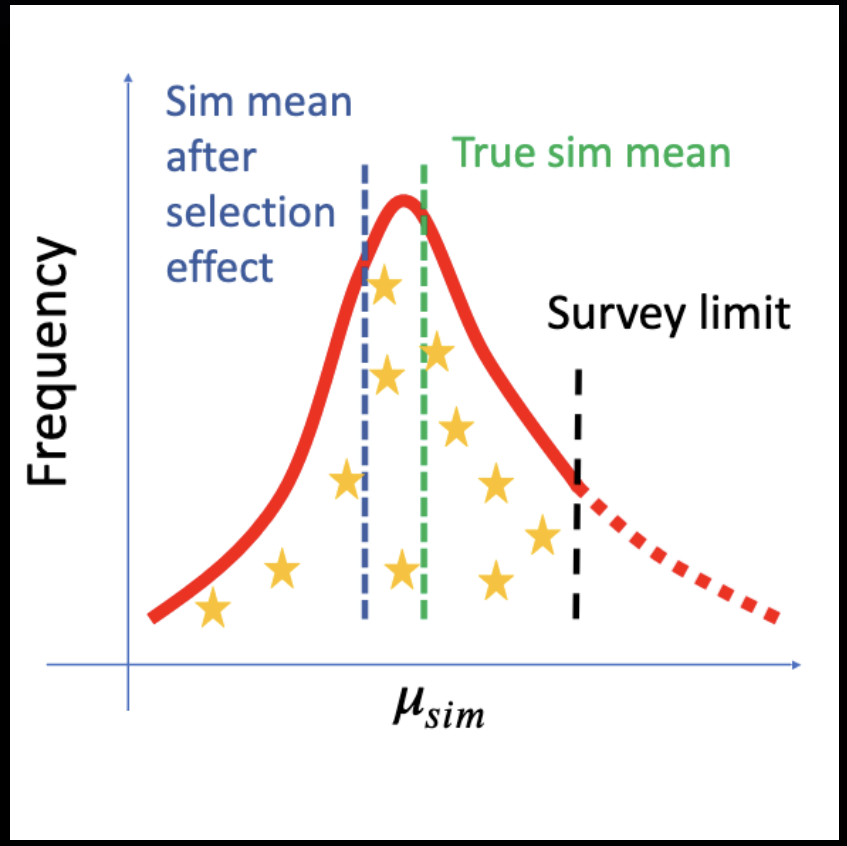


Telescopes/Surveys do not have “redshift range”

They are limited by magnitudes
(but the exact threshold varies every day)

Type Ia Supernova in Modern Cosmology

Part I: The Primary Challenge



Vincenzi+25

Telescopes/Surveys do not have “redshift range”

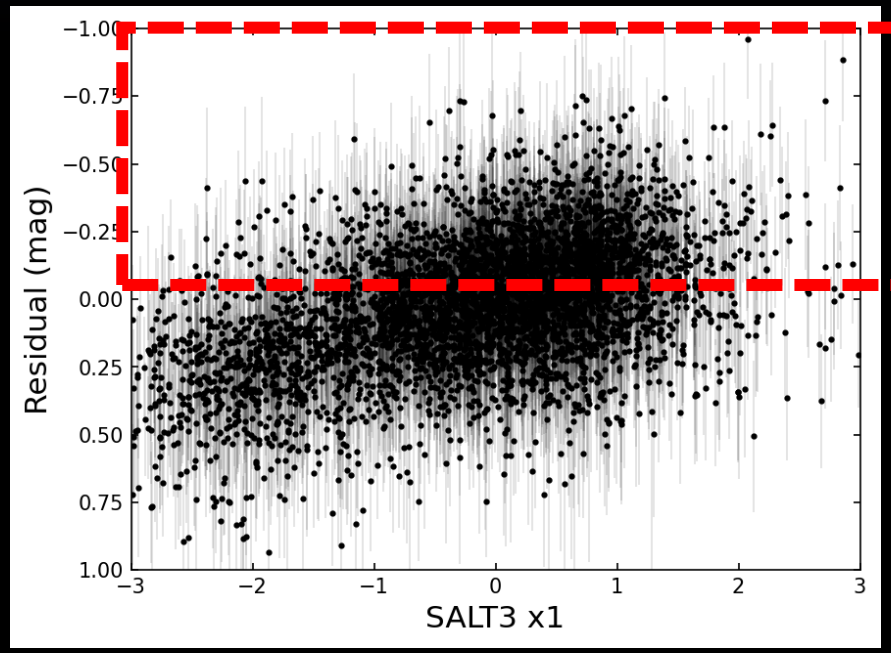
They are limited by magnitudes
(but the exact threshold varies every day)

How can we correct this?

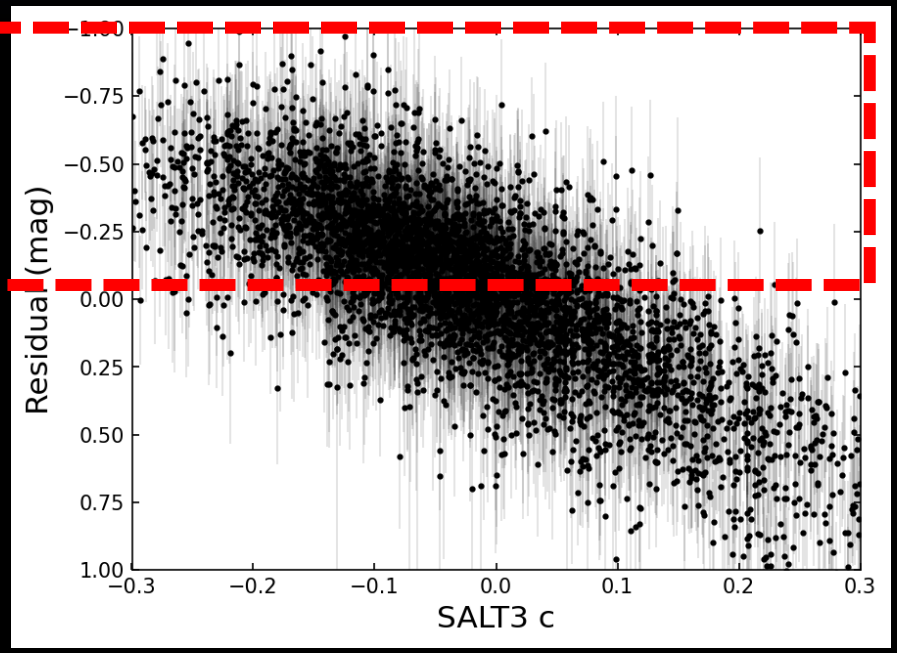
Bias Correction

We selectively observe bluer SNe & slow-declining SNe near magnitude limit

Brightness



Fast ← decline → slow



Blue ← color → Red

Bias Correction

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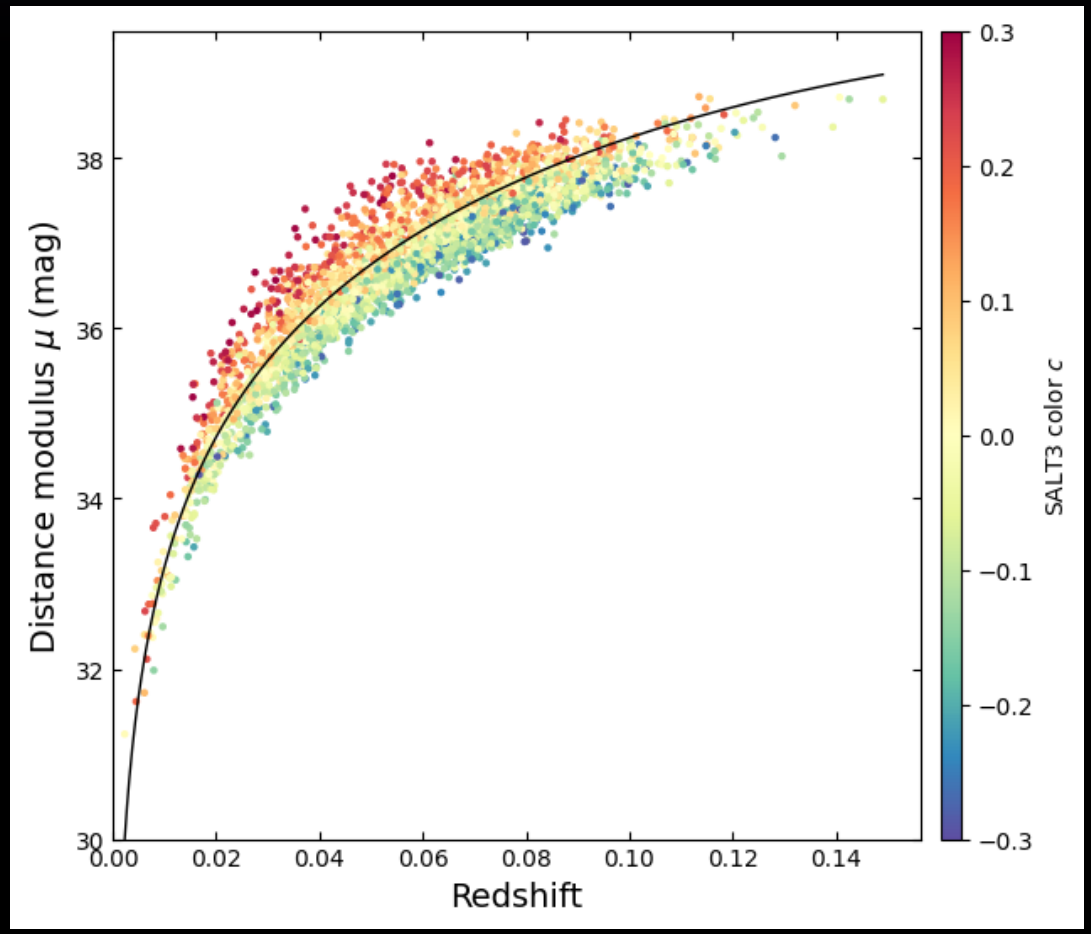

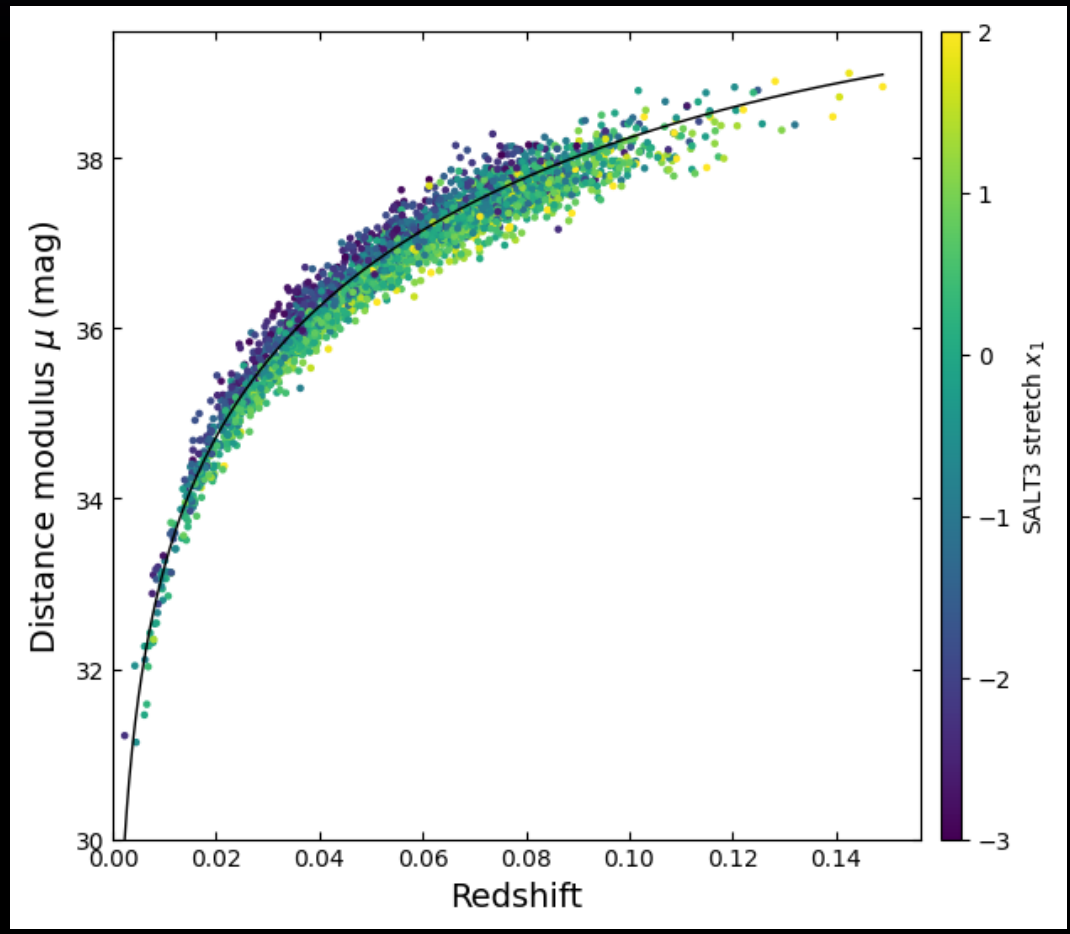

Bias Correction

- If observing condition limits the completeness of samples, the cosmology is biased
- Well-known, well-established effect: Malmquist bias (we only observe the brighter ones)

Two ways to account for this:

1. Apply a correction so that
   mean of corrected data = mean of true, underlying population

2. Quantify prior and fit a hierarchical Bayesian model

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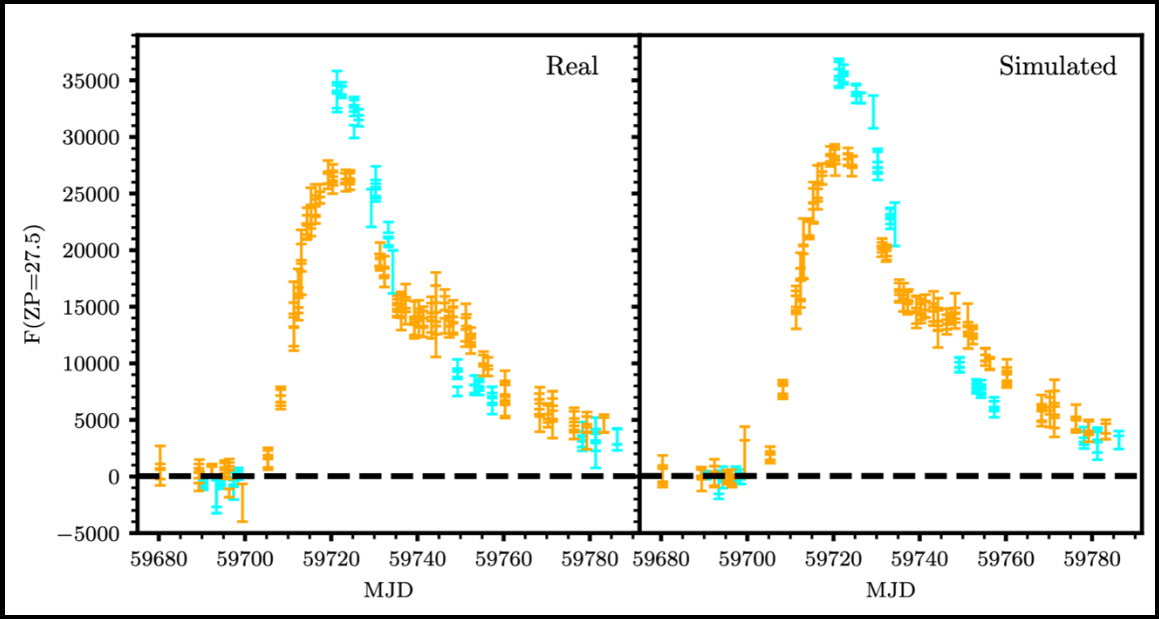
Run a full-scale forward model simulation

Bias Correction

Simulation = carbon copy of survey strategy

- Survey Strategy (rolling or follow-up? Cadence? Exposure time?)
- Observing conditions (limiting magnitude, dome closure, cloud coverage, etc.)
- Photometry noise
- Light-curve fitting – extract key parameters

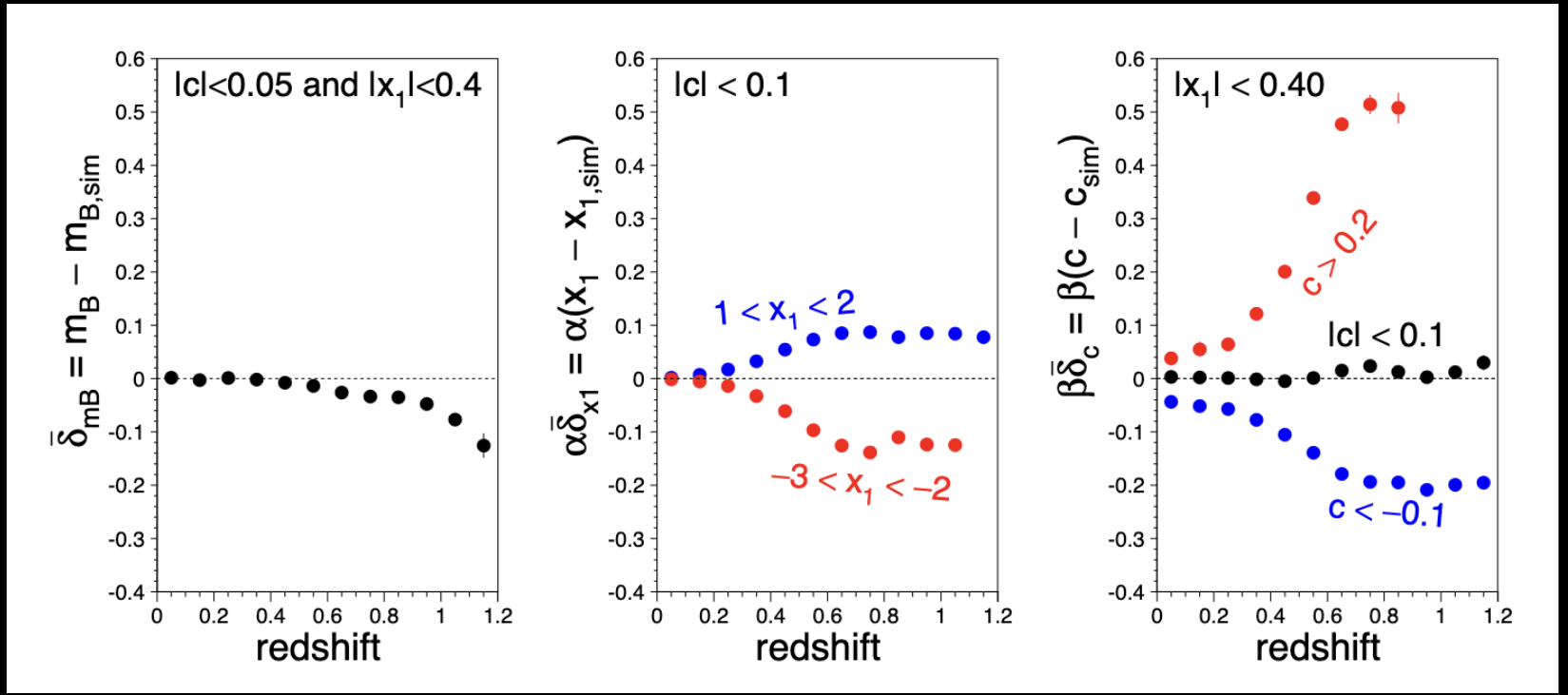


Inject realistic SNe Ia data in simulation and ask:
How often can we recover it?
How accurate is that recovery?

TITAN sim: Tweddle+ in prep.

Bias Correction

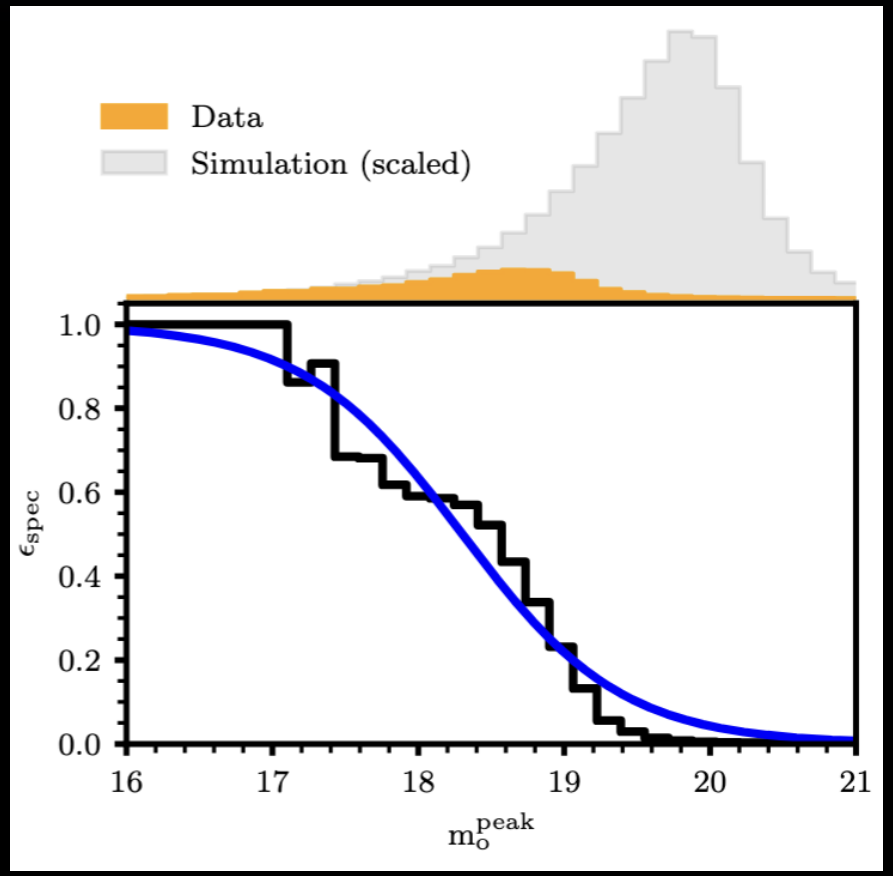
We selectively observe bluer SNe & slow-declining SNe near magnitude limit



BBC: Kessler & Scolnic 2016

Bias Correction

Malmquist bias is not the only selection bias



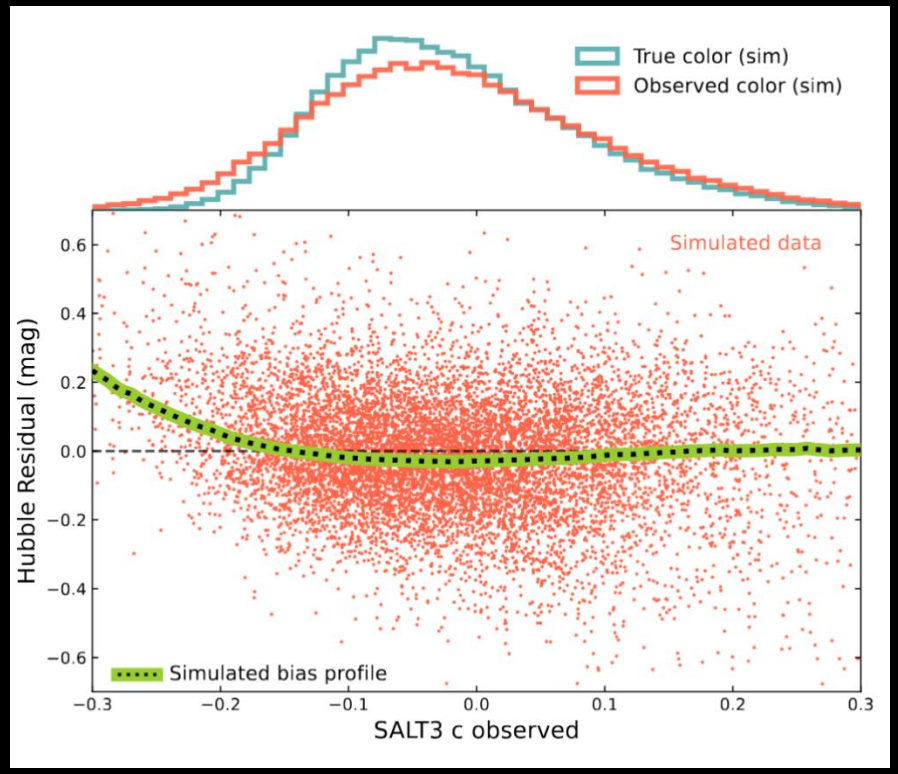
Tweddle+ in prep.

Detection/follow-up efficiency:

- Goes down with redshift
- Depends on detection/follow-up strategy
- Lower efficiency = more possible bias

Bias Correction

Malmquist bias is not the only selection bias



Murakami+ in prep.

Detection/follow-up efficiency:

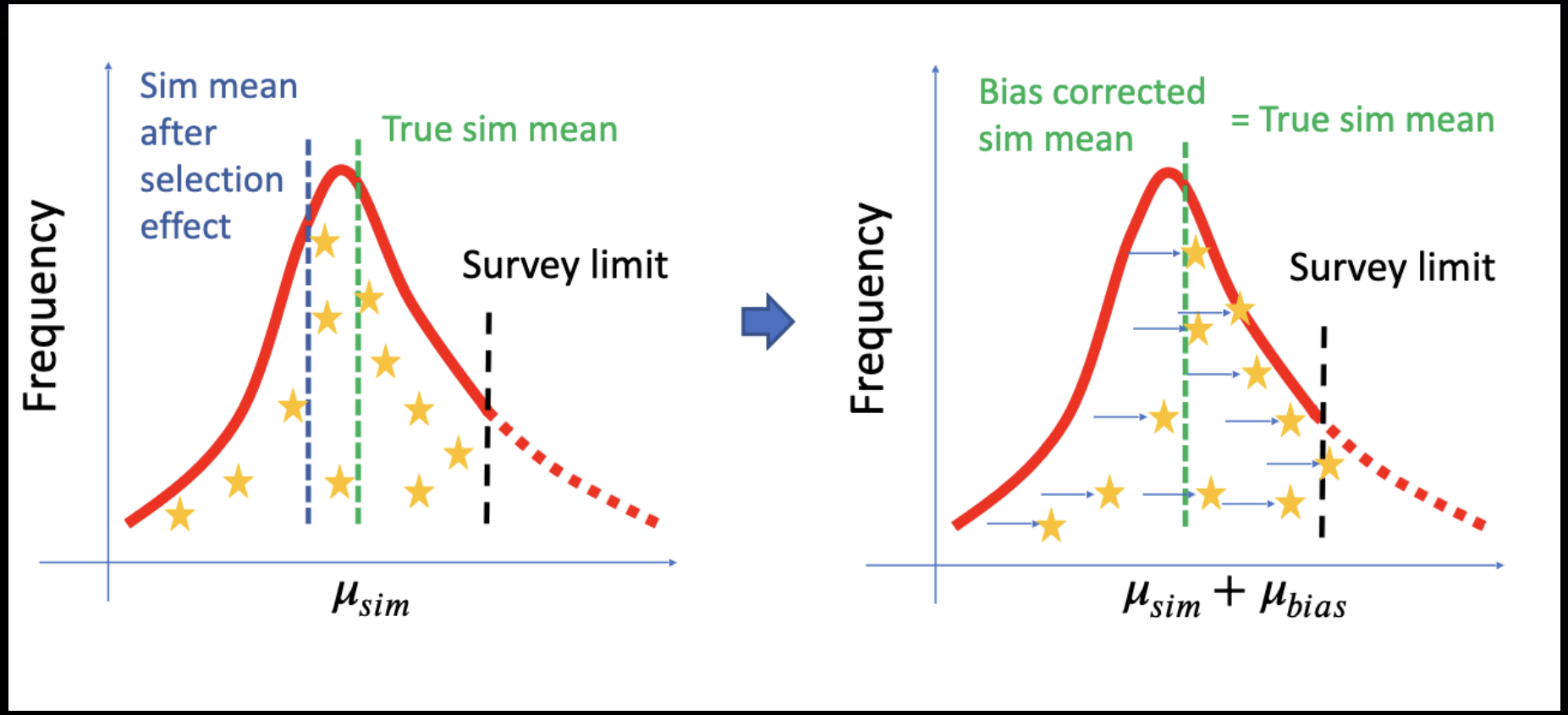
- Goes down with redshift
- Depends on detection/follow-up strategy
- Lower efficiency = more possible bias

Parameter noise:

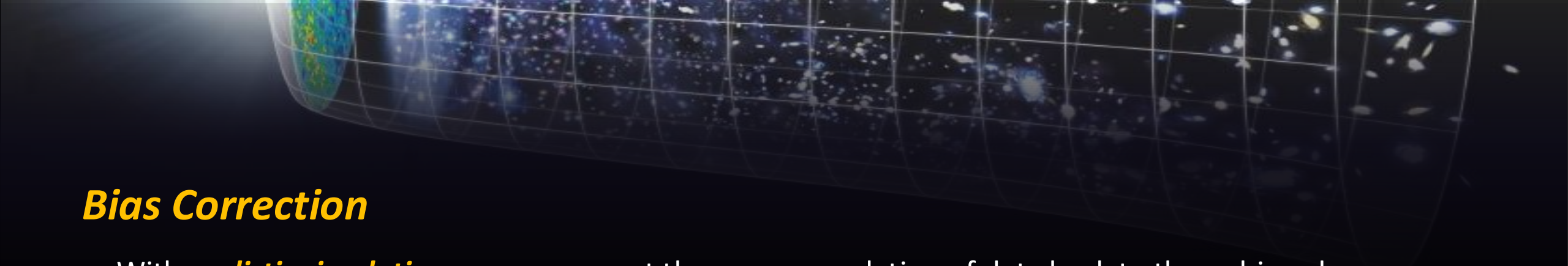
- SNe get over- or under-corrected when noise makes the observed color or stretch deviate from true values

Bias Correction

With realistic simulation, we can correct the mean population of data back to the unbiased mean



Vincenzi+25



Bias Correction

With ***realistic simulation***, we can correct the mean population of data back to the unbiased mean

… what is a "realistic" simulation?
How do we determine the SNe Ia population to inject?

Bias Correction

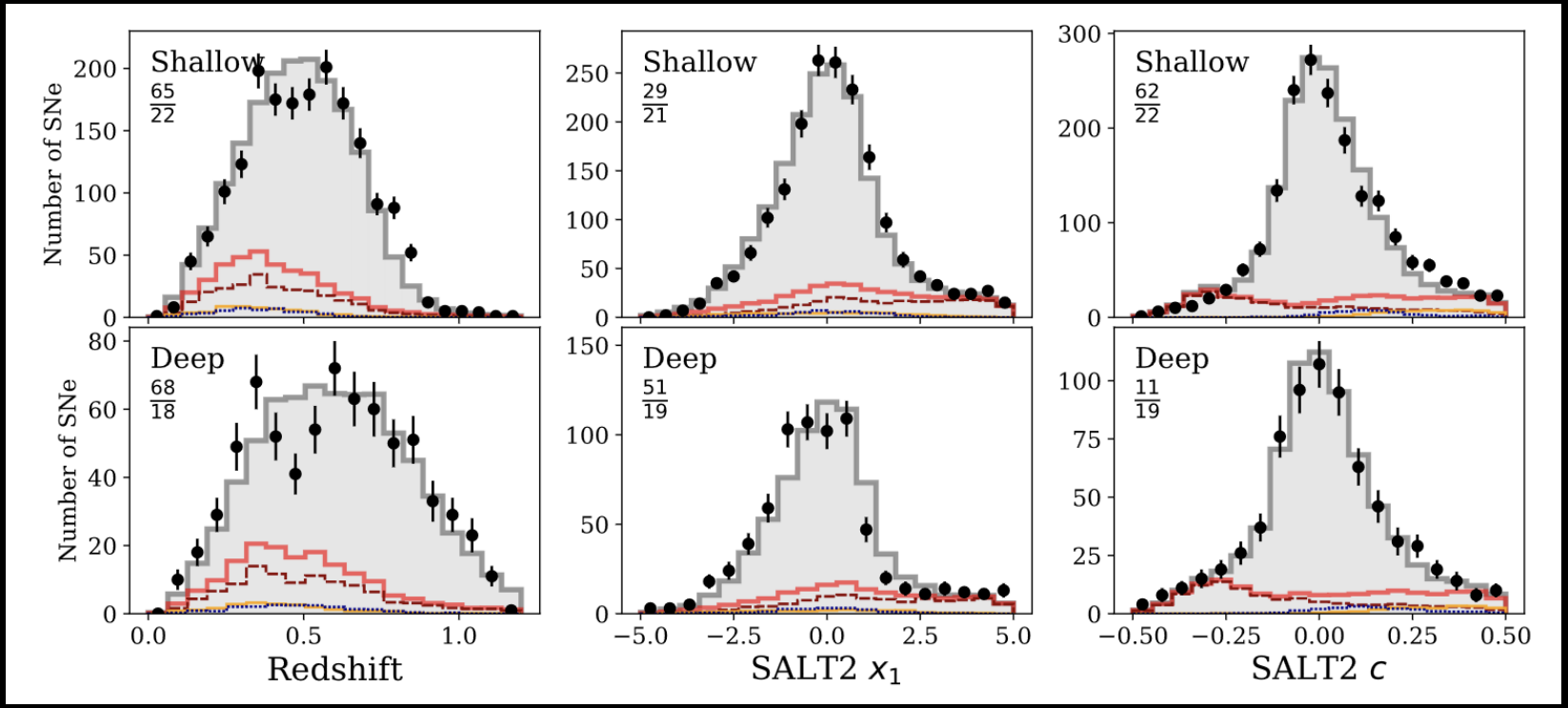
Selecting parameters for simulated SNe Ia

What we can change:

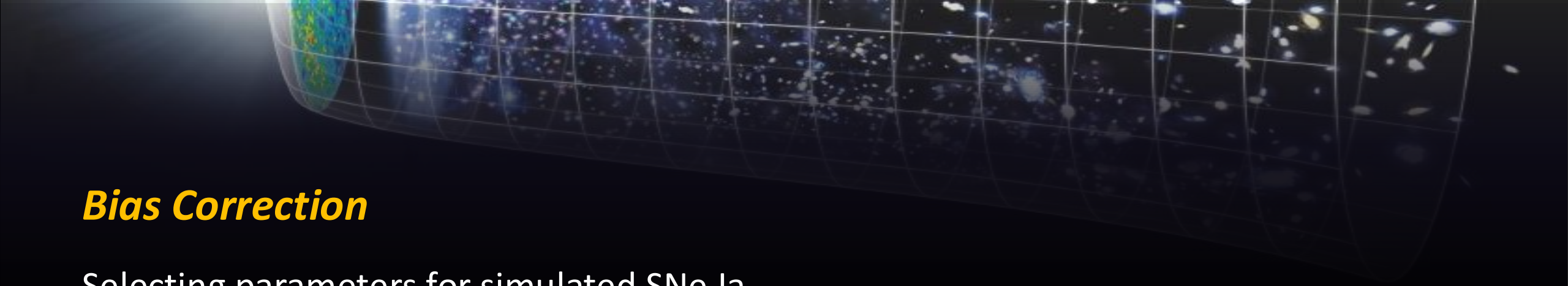
- Input population (distribution of SNe Ia properties over redshift)

What we cannot change:

- Survey information
- Physics of SNe Ia



DES simulation: Vincenzi+2020



Bias Correction

Selecting parameters for simulated SNe Ia

What we can change:

- Input population (distribution of SNe Ia properties over redshift)

Choice of input population introduces systematic uncertainty!

What we cannot change:

- Survey information
- Physics of SNe Ia

Bias Correction

Selecting parameters for simulated SNe Ia

What we can change:

- Input population (distribution of SNe Ia properties over redshift)

What we cannot change:

- Survey information
- Physics of SNe Ia

Effect on bias-corrected mag, per systematic, per SN

$$C_{z_{ii} z_{ij},\mathrm{syst}} = \sum_{k=1}^{K=87} \frac{\partial \Delta \langle \mu_{\mathrm{SYS}} \rangle_{z_{ii}}}{\partial \mathrm{SYS}_k} \frac{\partial \Delta \langle \mu_{\mathrm{SYS}} \rangle_{z_{ij}}}{\partial \mathrm{SYS}_k} \sigma_k^2,$$

Dhawan+2020

Uncertainty of the parameter in question

Re-run full simulation, apply biascor, assess its effect numerically, and repeat!

Bias Correction

Selecting parameters for simulated SNe Ia

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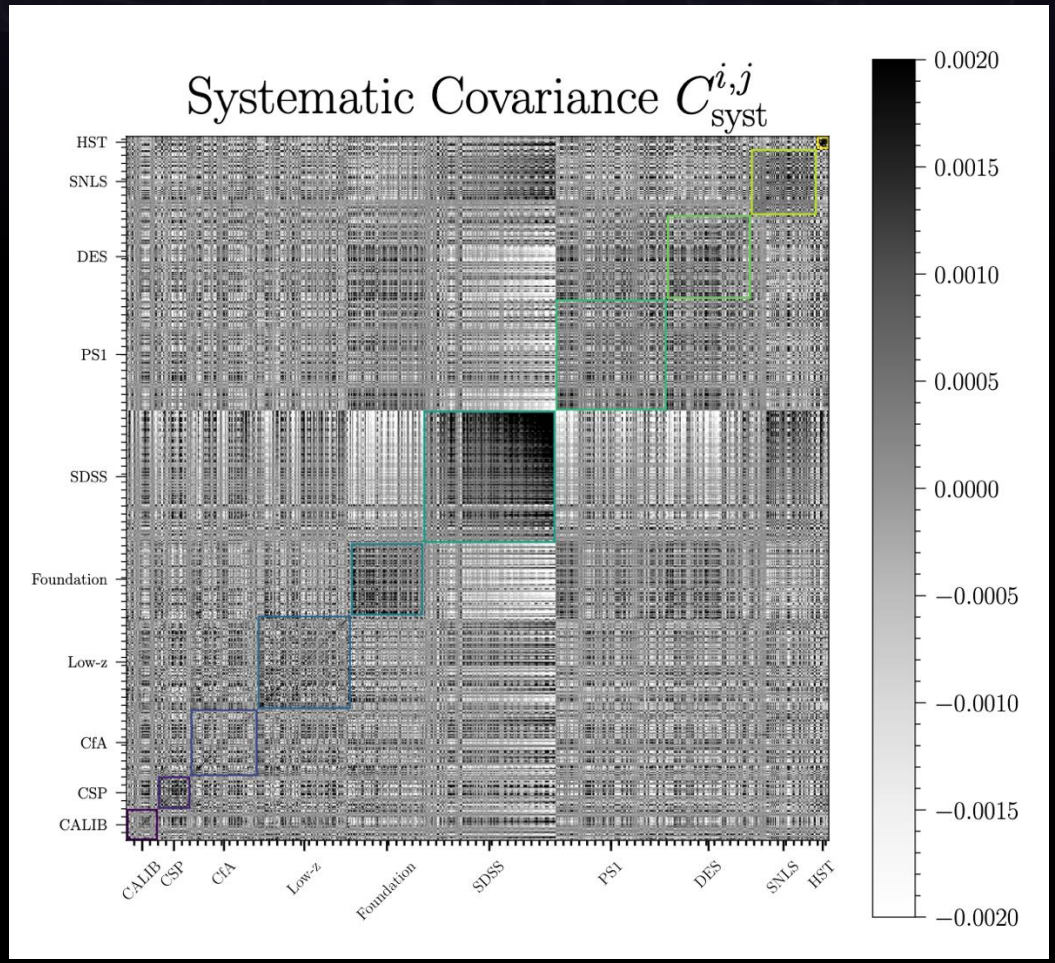


Pantheon+ systematic covariance matrix: Brout+2022

Bias Correction

Selecting parameters for simulated SNe Ia

What we can change:

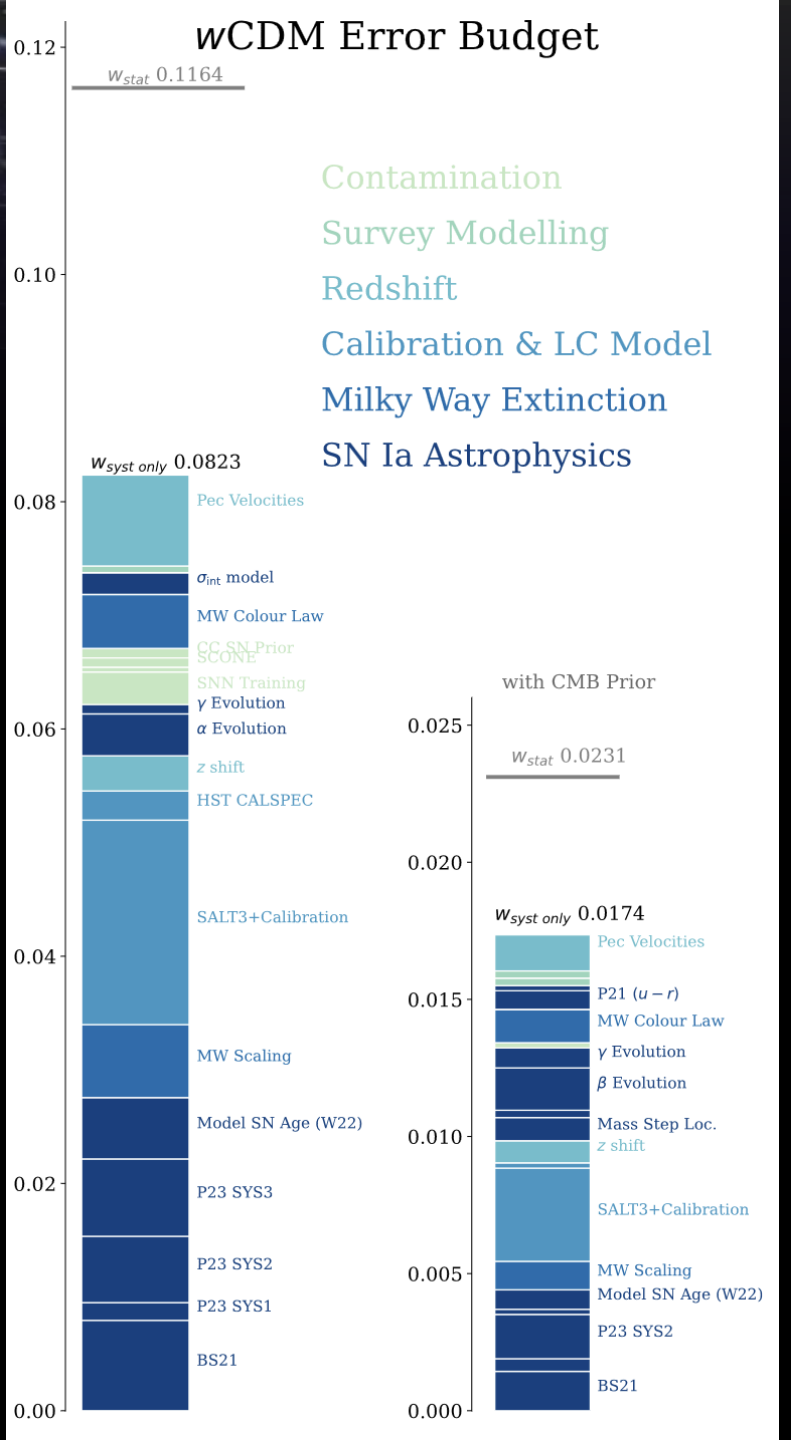
- Input population (distribution of SNe Ia properties over redshift)

This dominates the systematic uncertainty as of 2026

What we cannot change:

- Survey information
- Physics of SNe Ia

DES5YR reanalysis
Popovic+25



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Bias Correction

Selecting parameters for simulated SNe Ia

What we can change:

- Input population (distribution of SNe Ia properties over redshift)

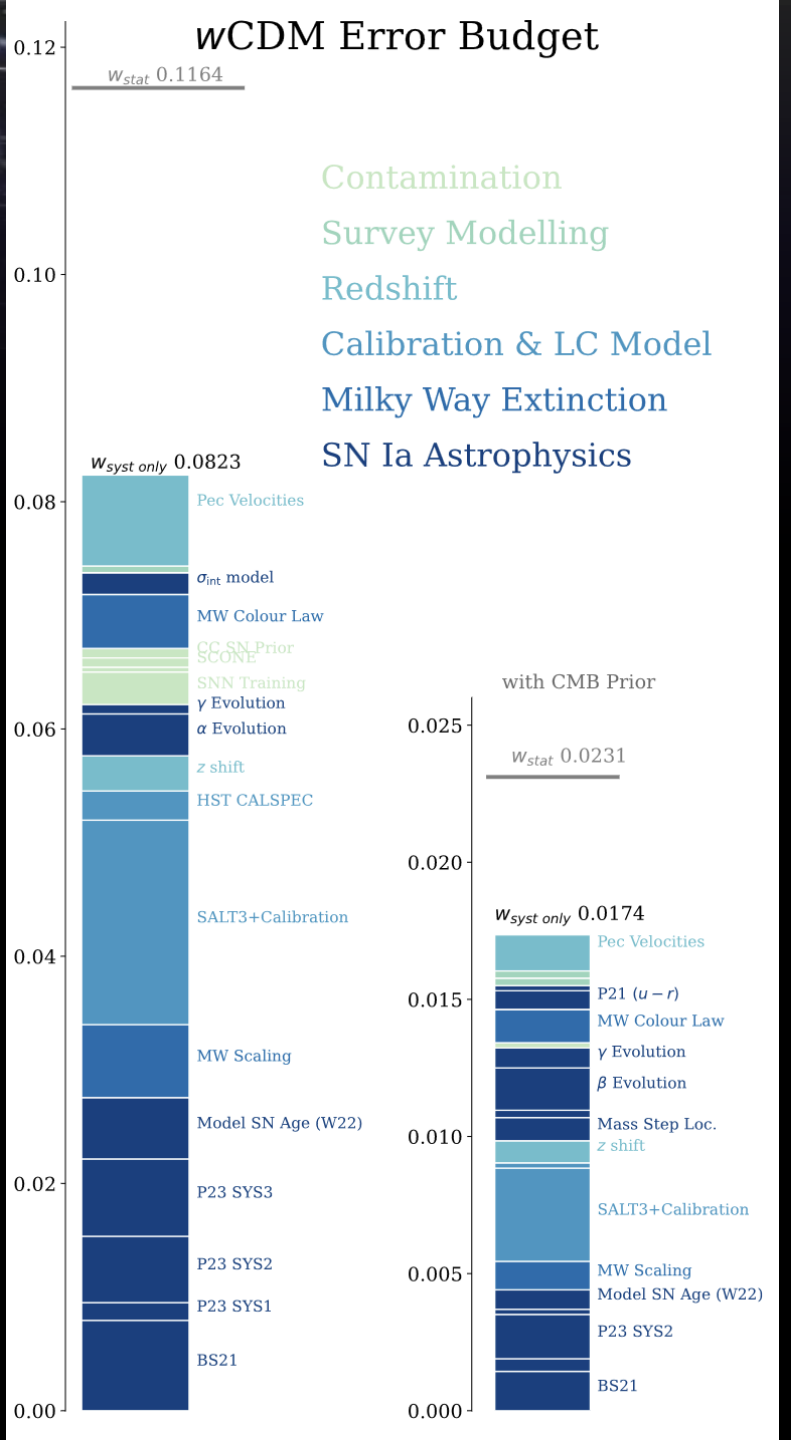
This dominates the systematic uncertainty as of 2026

→ *How can we reduce this?*

What we cannot change:

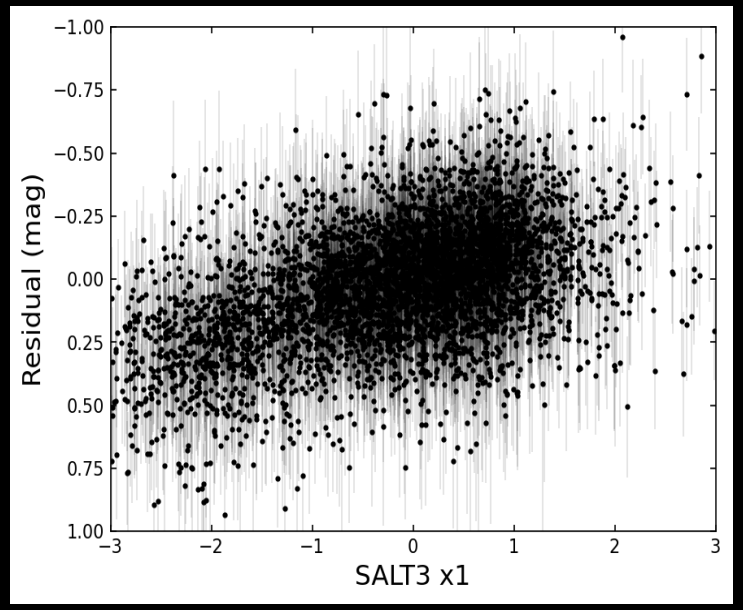
- Survey information
- Physics of SNe Ia

DES5YR reanalysis
Popovic+25

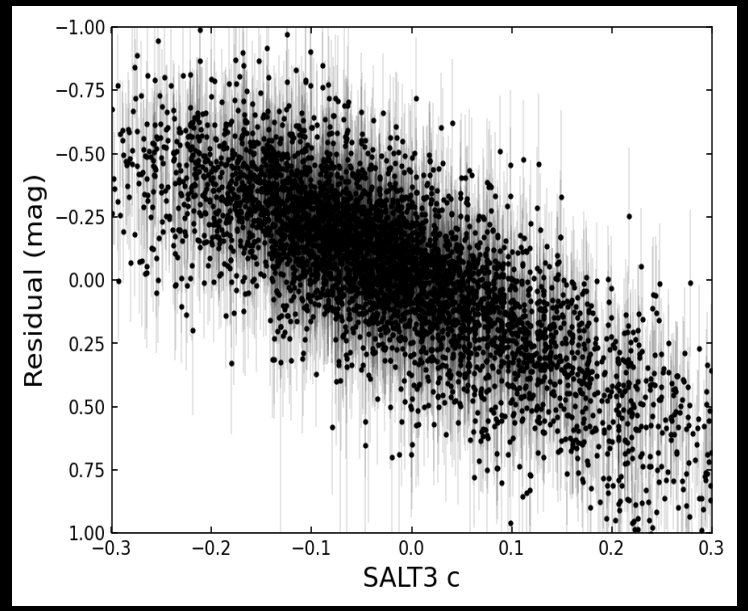


Pushing the empirical correction to the limit: host galaxy mass-dependency

Brightness



Fast ← decline → slow



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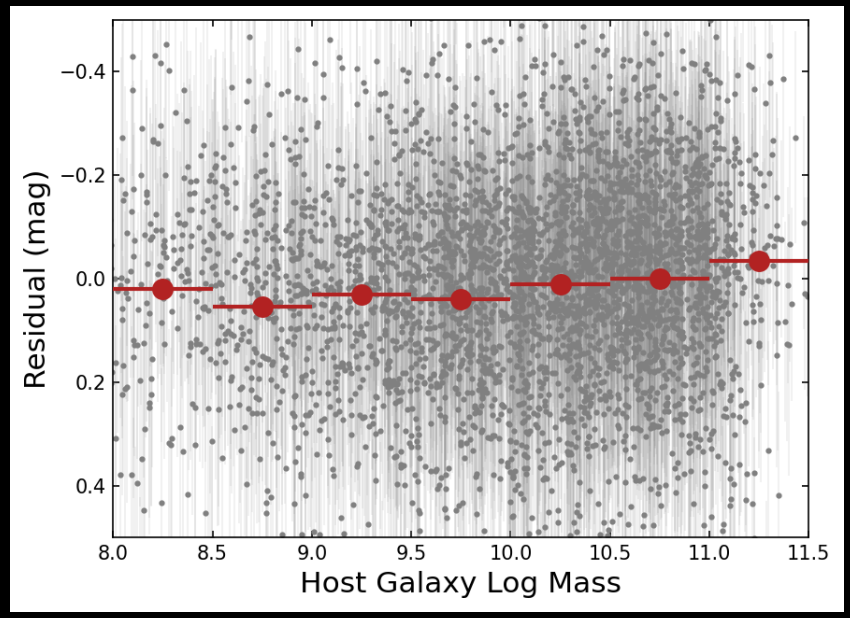
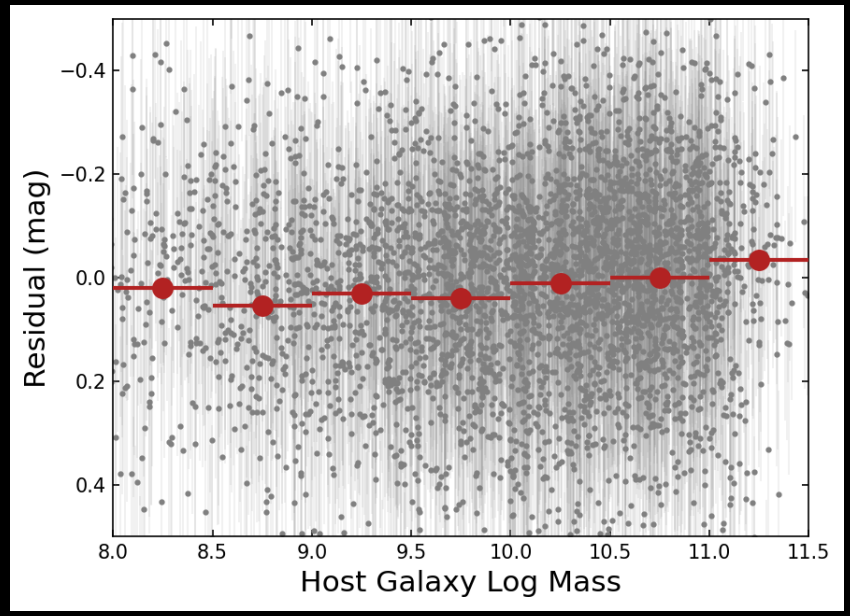


Blue ← host galaxy → Heavy

Pushing the empirical correction to the limit: host galaxy mass-dependency

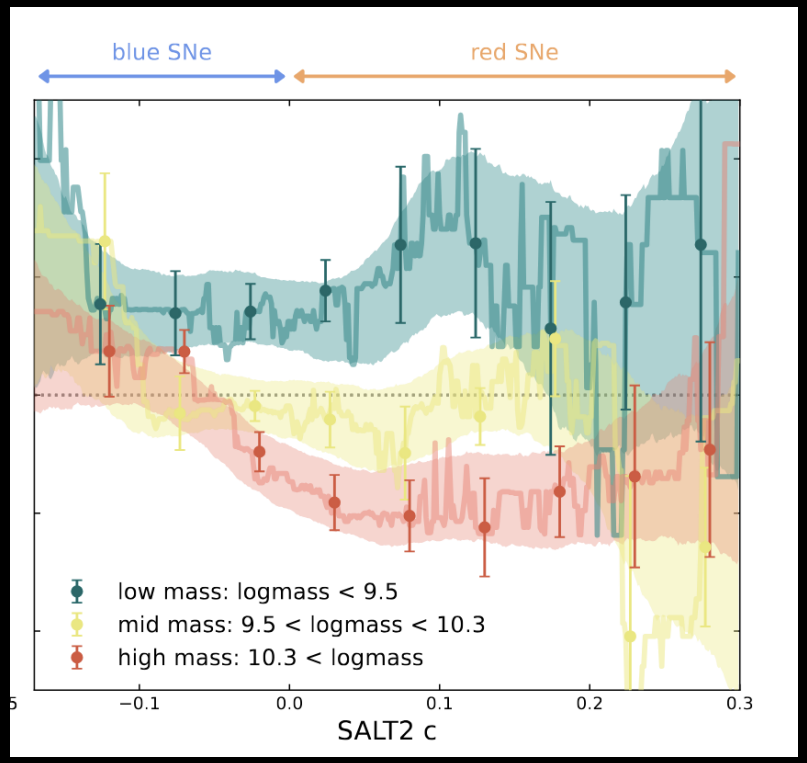
A simple ”mass-step” correction has been used

- Easy to implement (completely empirical)
- Removes most of the host dependency (~0.05 mag level)
- Problem: Not physics-driven



Blue ← host galaxy → Heavy

Recent efforts to tie empirical host-dependency to astrophysics: Brout & Scolnic (BS21) model



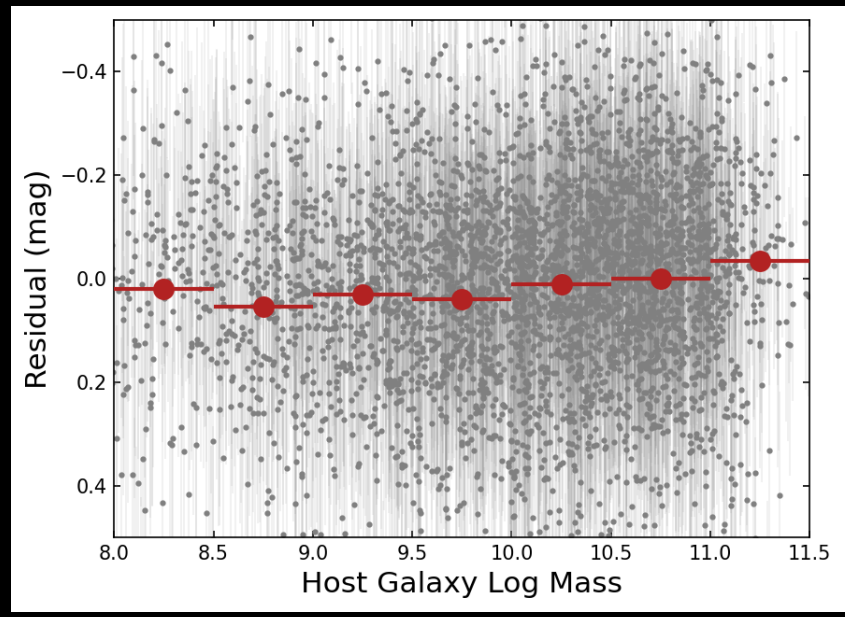
Murakami & Scolnic 2025

Host mass-dependency is SN color-dependent:

→ Attribute it to Dust (BS21)

→ Efficiently reduces scatter

→ Success in Pantheon+, DES



Blue ← host galaxy → Heavy

Bias Correction

Selecting parameters for simulated SNe Ia

What we can change:

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Now includes BS21 model Uncertainty!

What we cannot change:

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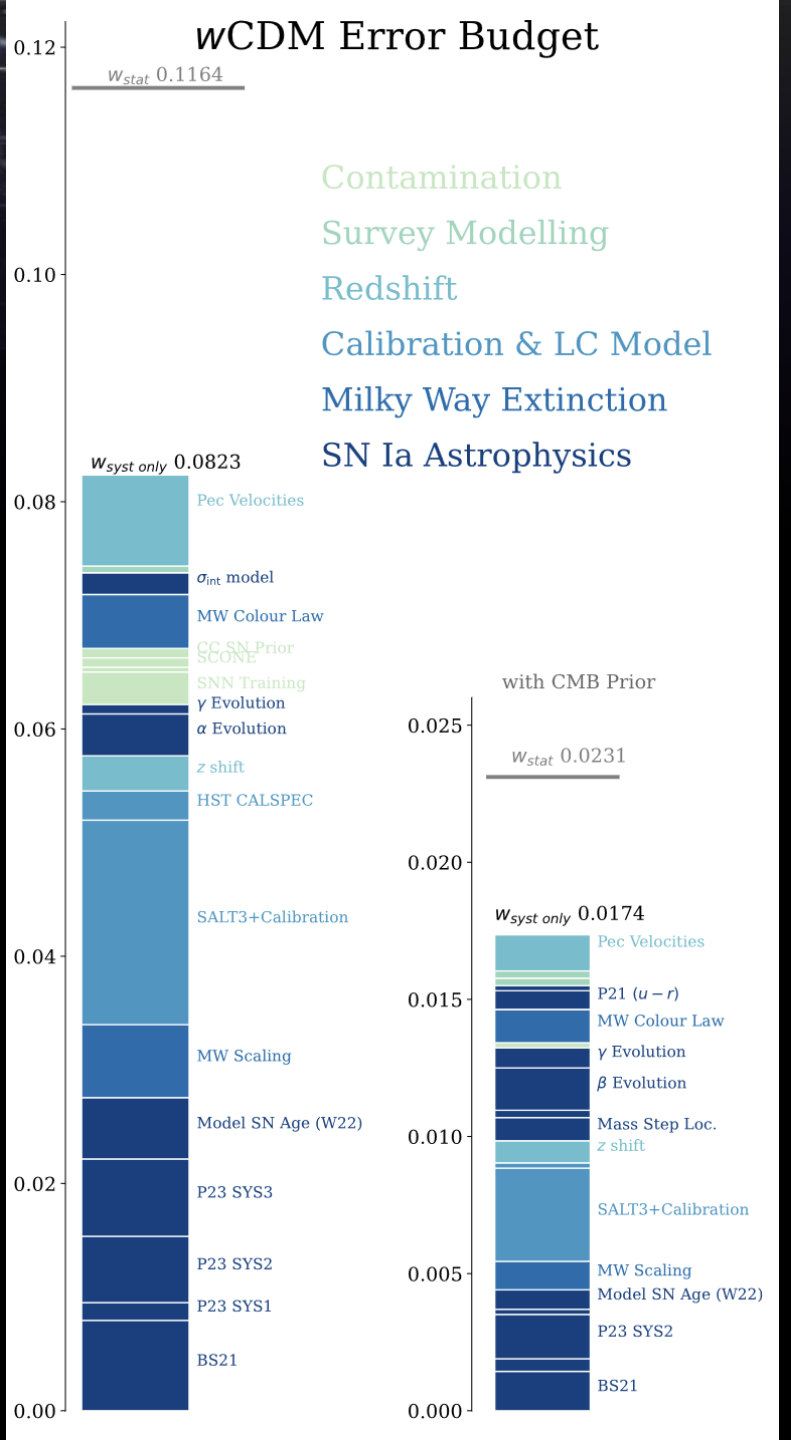
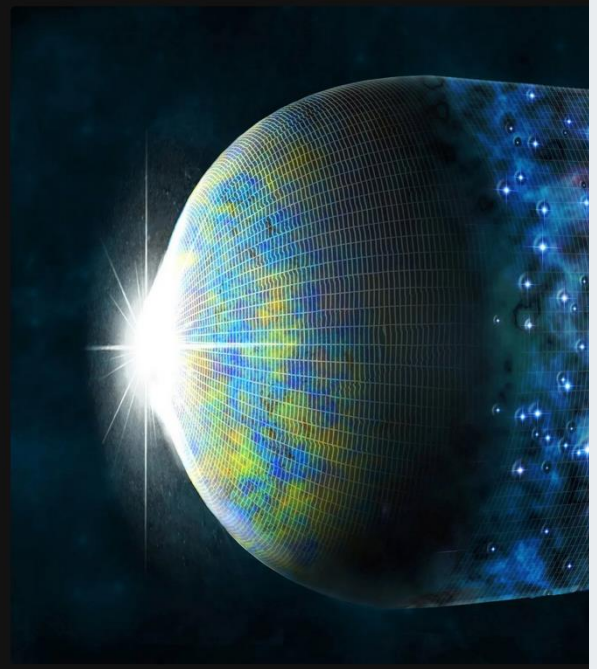
DES5YR reanalysis
Popovic+25



The Universe is Decelerating and Standard Candles Aren't So Standard According to a New Stu

By Brian Koberlein - November 13, 2025 01:47 PM UTC | Cosmolo



Our Universe Has Already Entered Decelerating Phase, Study Sugg

Nov 6, 2025 by News Staff

Published in
Astronomy
Featured
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Dark energy
Expanding Universe
Galaxy
Hubble Tension
Standard candle
Standard Model
Type Ia supernova
Universe

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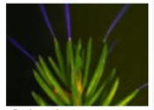
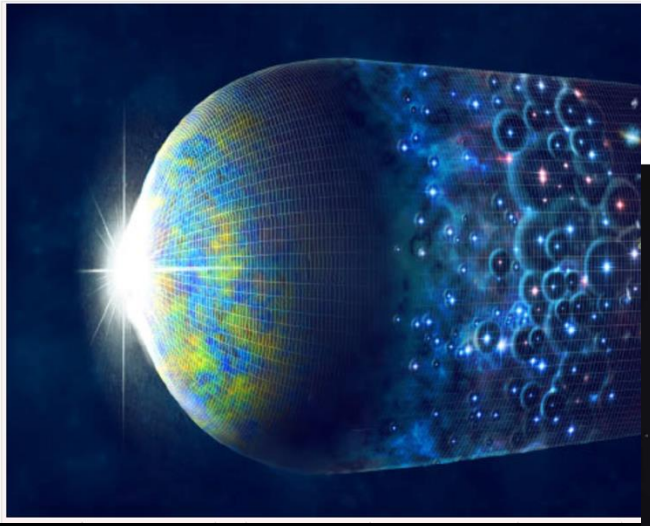


Scientists Observe Electrical Discharges on Trees under

New research from Yonsei University in Seoul, Korea, casts d
long-standing theory that dark energy is driving distant gala
increasingly faster; instead, it shows no evidence of an accele
Universe. If the results are confirmed it could open an entirel
in scientists' quest to uncover the true nature of dark energy,
'Hubble tension,' and understand the past and future of the U



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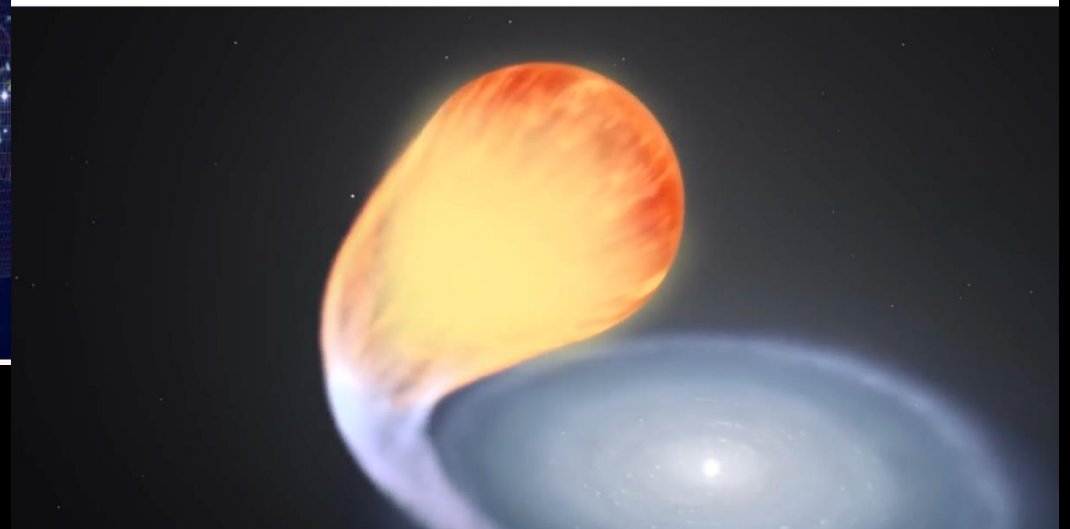
Are astronomers wrong about dark energy? New study casts doubt on universe's accelerating expansion

UPDATED NOV 20, 2025

By Jacopo Prisco



A debate on Age-Luminosity effect: Do SNe Ia age with the universe (and get brighter)?

Episode IX

AGE-LUMINOSITY EFFECT

Numbers of papers have debated over the exact extent and the correct interpretation of Age-Luminosity effect for SNe Ia, including...

Rose+2019; Kang+2020; Rose+2020; Lee+2020; Zhang,YM+2021; YM+ 2021; Chung+2023; Ching+2025; Son+2025

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **538,** 3340–3350 (2025) https://doi.org/10.1093/mnras/staf497
Advance Access publication 2025 March 27

Strong progenitor age bias in supernova cosmology – I. Robust and ubiquitous evidence from a larger sample of host galaxies in a broader redshift

Chul Chung
Department of A

Accepted 2025 M

ABSTRACT

Type Ia super
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In this study,
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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **544,** 975–987 (2025) https://doi.org/10.1093/mnras/staf1685
Advance Access publication 2025 November 6

Strong progenitor age bias in supernova cosmology – II. Alignment with DESI BAO and signs of a non-accelerating universe

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Department of Astronomy & Center for Galaxy Evolution Research, Yonsei University, Seoul 03722, Korea

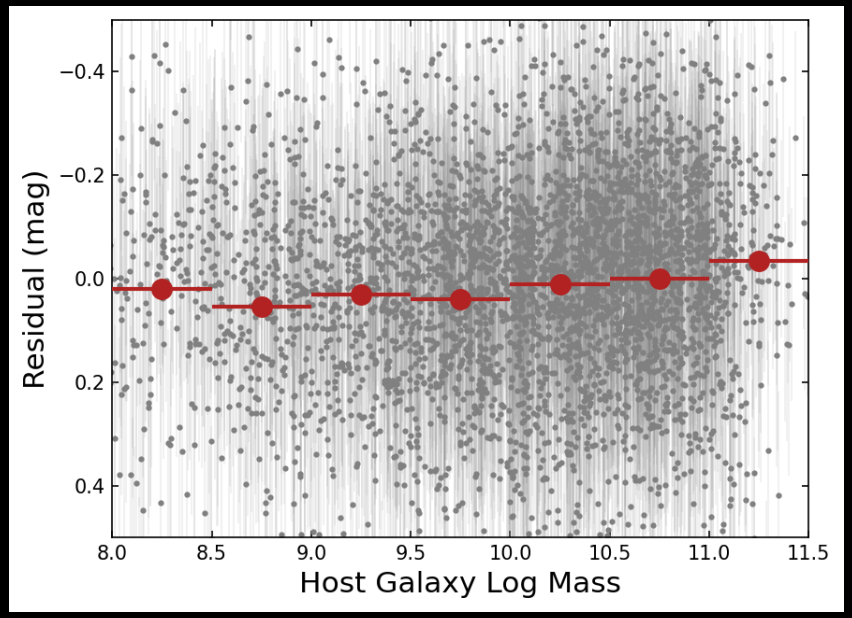
Accepted 2025 September 29. Received 2025 September 28; in original form 2025 August 28

ABSTRACT

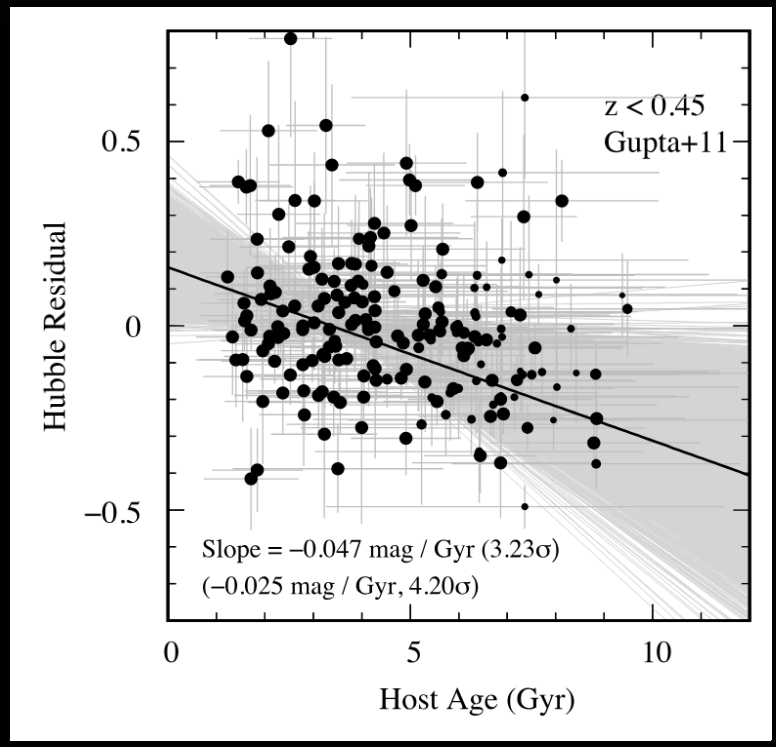
Supernova (SN) cosmology is based on the key assumption that the luminosity standardization process of Type Ia SNe remains invariant with progenitor age. However, direct and extensive age measurements of SN host galaxies reveal a significant (5.5σ) correlation between standardized SN magnitude and progenitor age, which is expected to introduce a serious systematic bias with redshift in SN cosmology. This systematic bias is largely uncorrected by the commonly used mass-step correction, as progenitor

S25:

1. Host galaxy age correlates with HR
2. This correlation is applicable to progenitor age



Blue ← host galaxy → Heavy

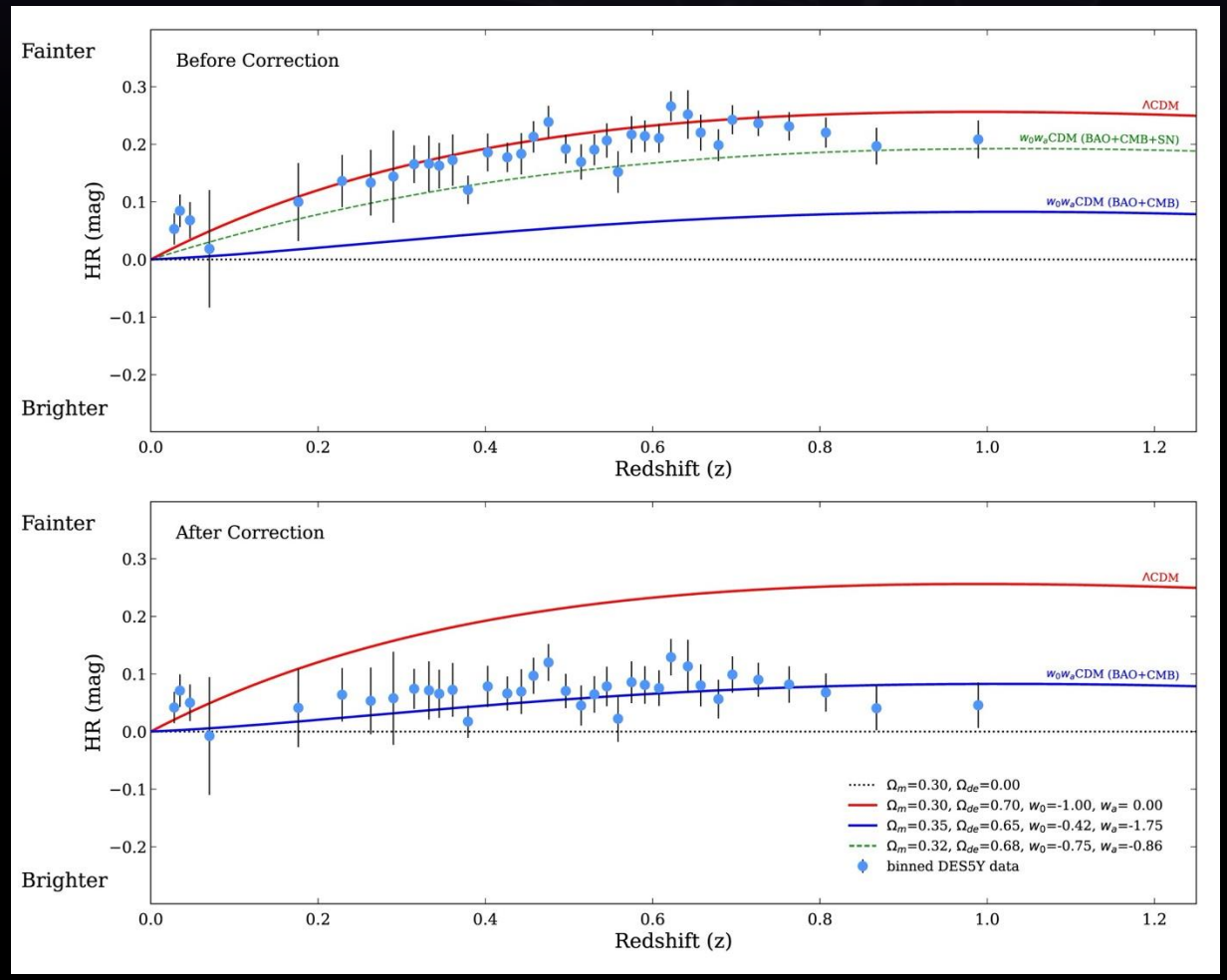


Chung+2025

Young ← host age → Old

S25: Applies “age shift prediction” to cosmology

Q: why is this fundamentally different from how SNe Ia cosmology is done?



S25: Applies “age shift prediction” to cosmology

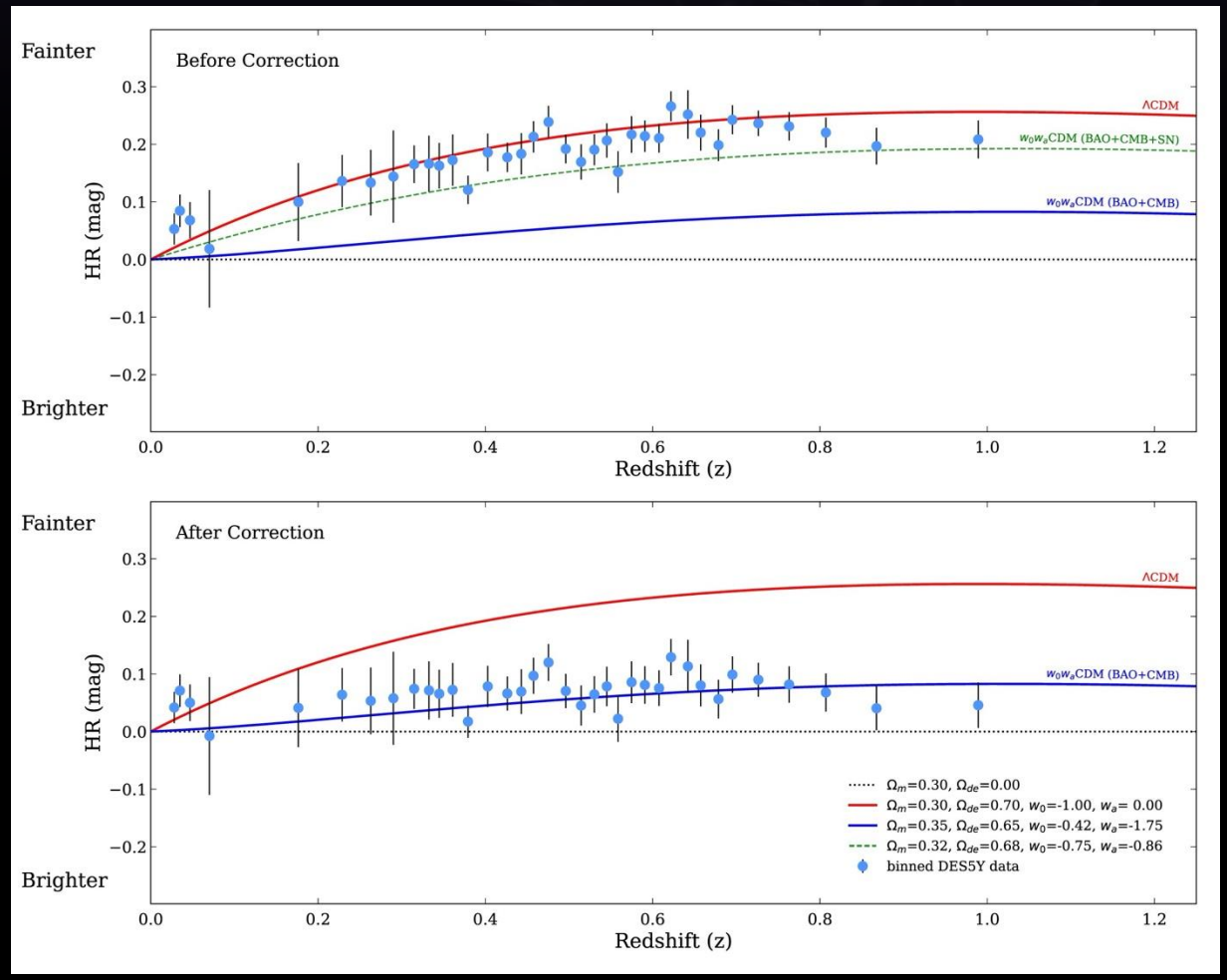
Q: why is this fundamentally different from how SNe Ia cosmology is done?

A:
Bias correction is based on observables

- We don’t just apply f(z)
- Need simulations to obtain f(z,c,x_1,…)

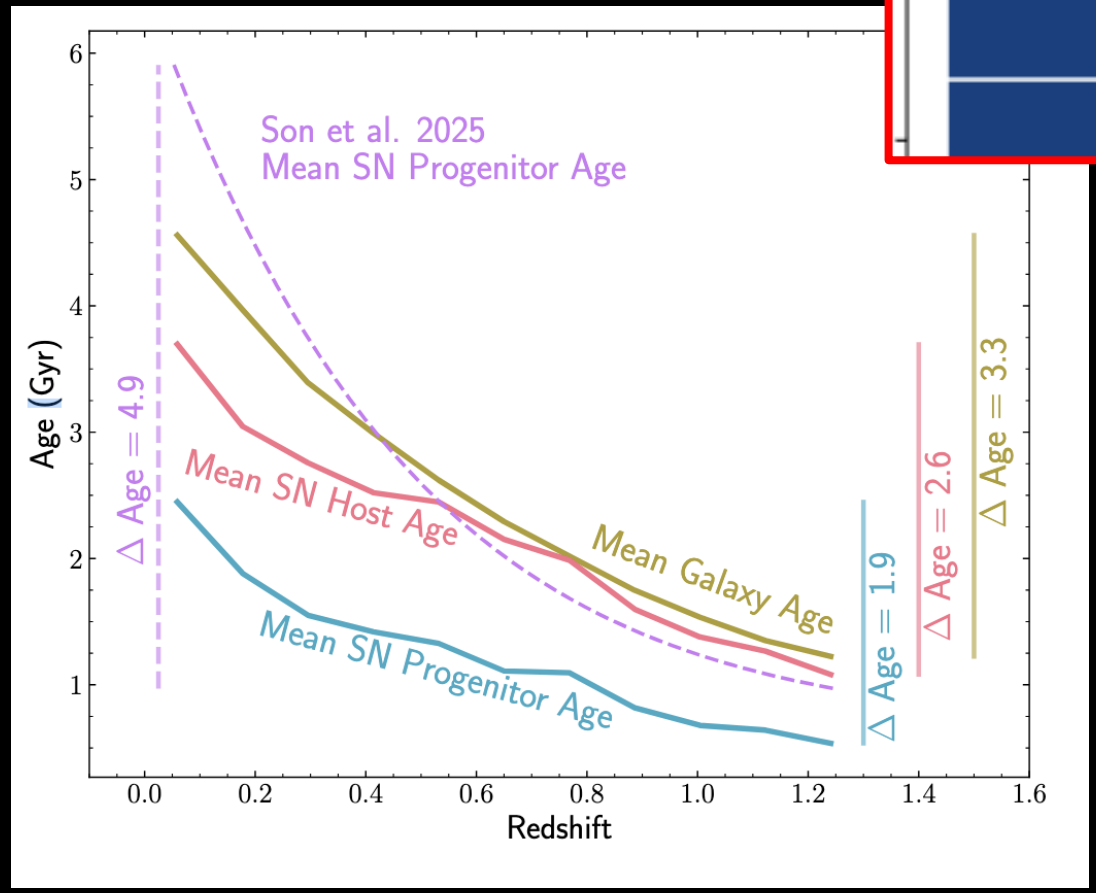
Selection effect:

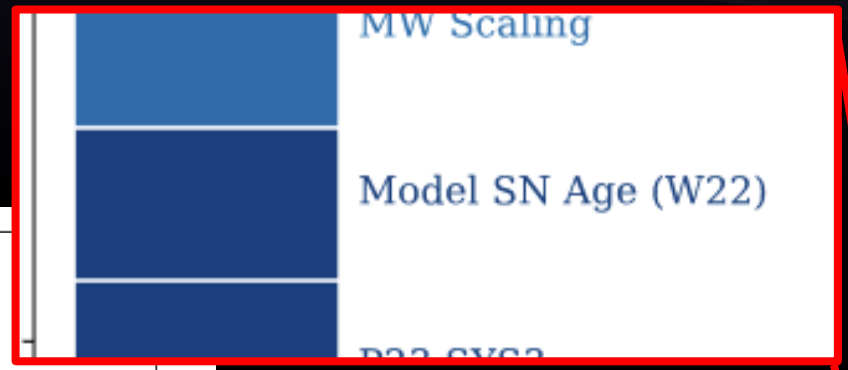
- At higher-z, we only observe brighter (“older”) population
- This reduces the average age shift



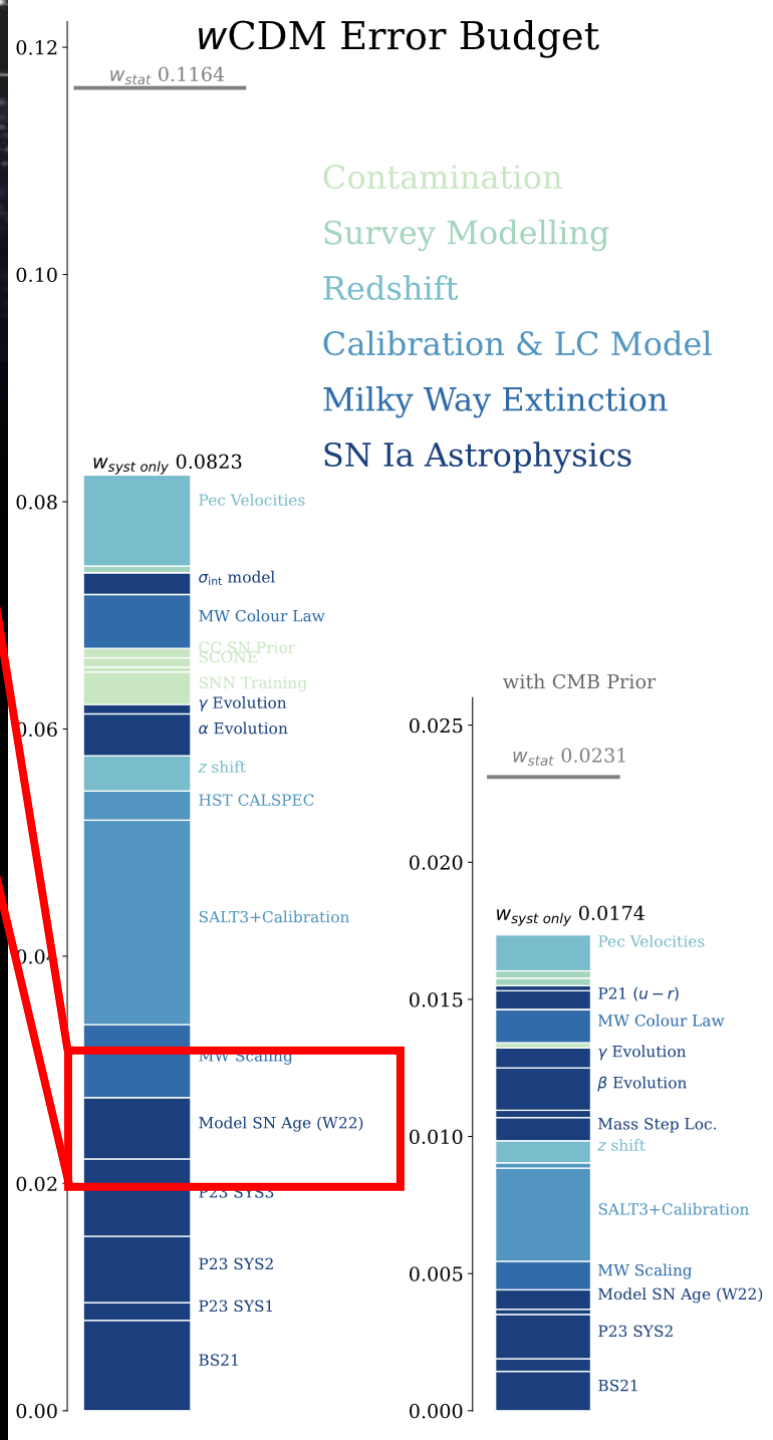
S25: Applies “age shift prediction” to cosmology

DES covariance matrix
already includes this effect!





Wiseman+26



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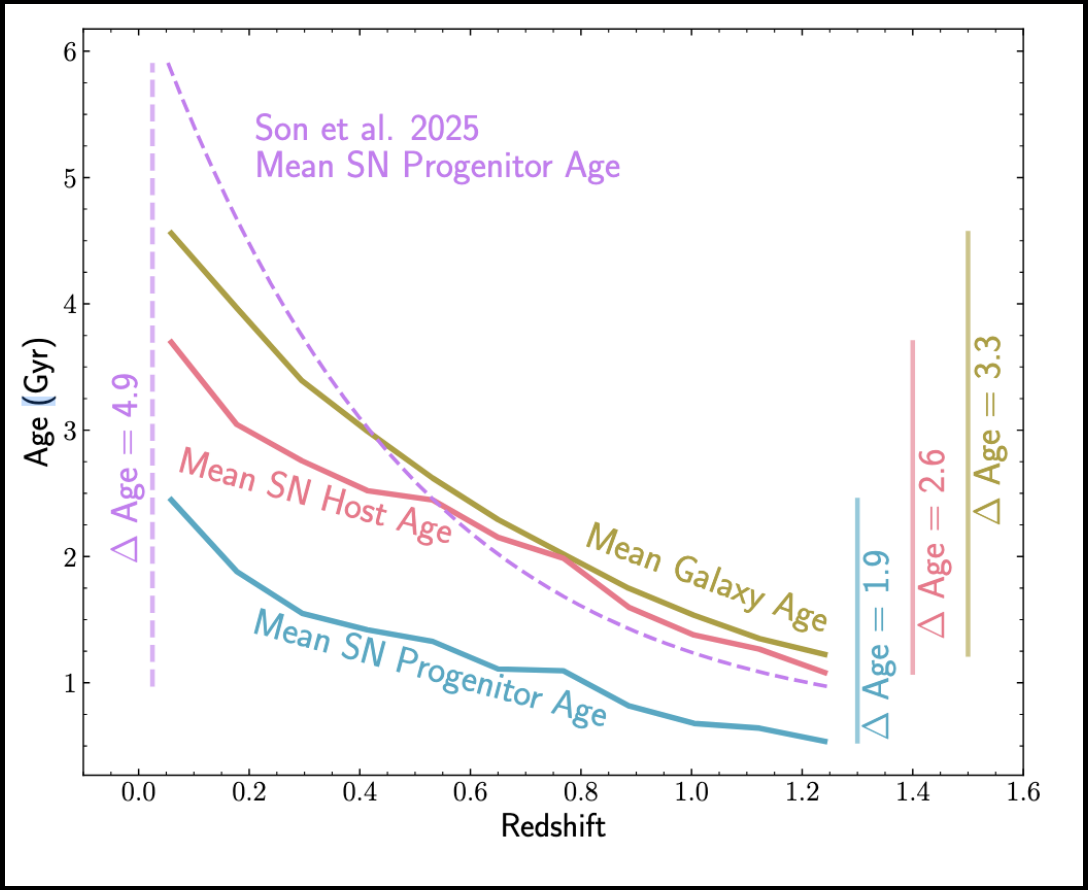
already includes this effect!



Wiseman+26

DES5YR host spec-z requirement makes strong sampling preference toward high-mass hosts

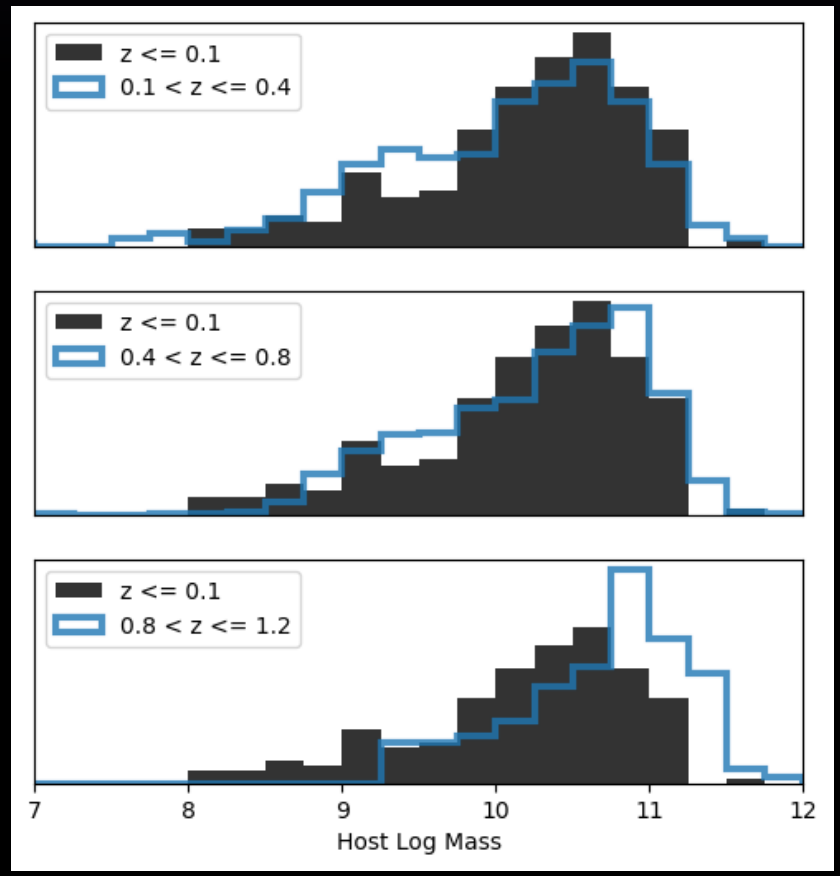


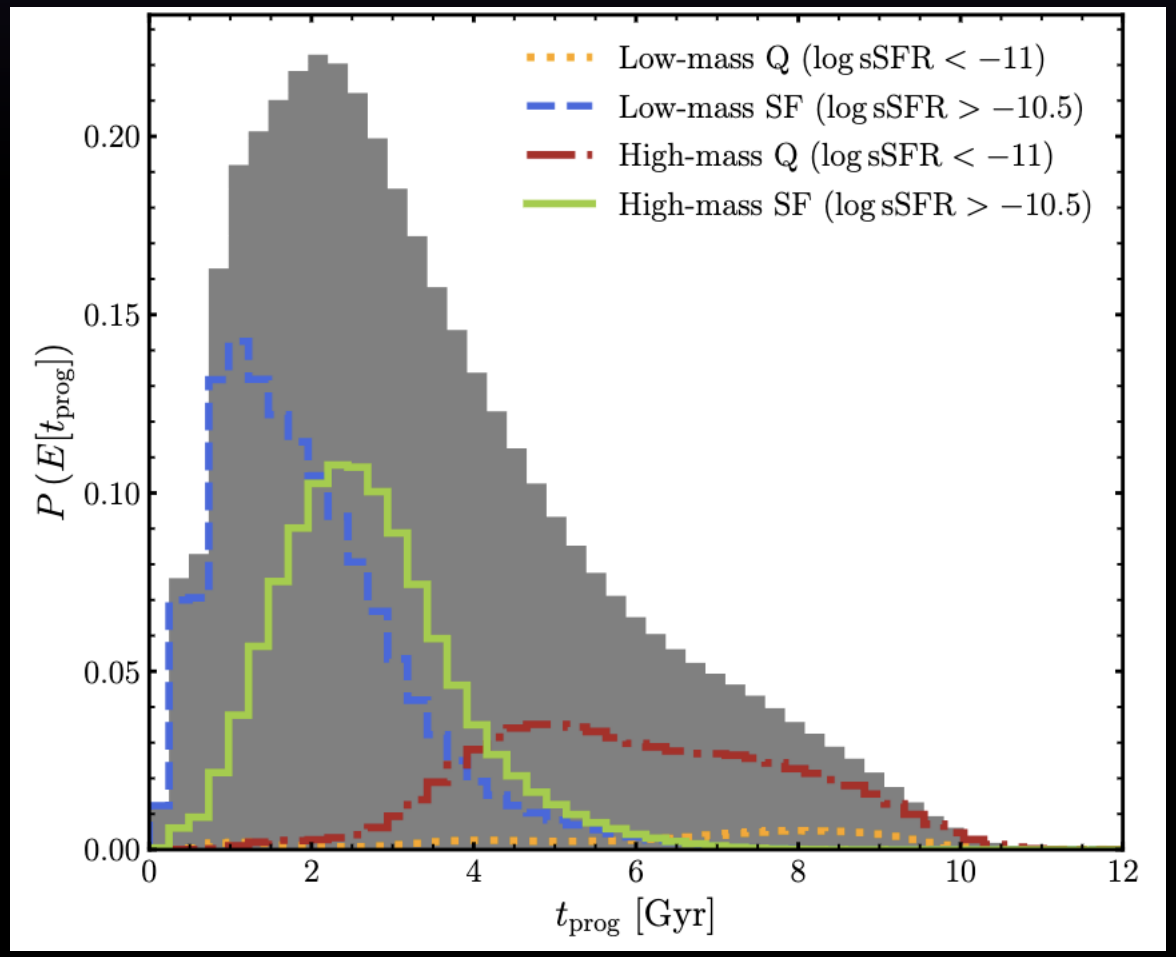
Image: YM

S25: says Hubble Tension can be solved with age

Indeed, a recent study by D. Scolnic et al. (2025) indicates that the Hubble tension is becoming even more severe in this case. If this possibility is confirmed by direct age measurements of stellar populations in host galaxies, even a 2–3 Gyr difference in the average age between the second and third rungs could significantly reduce (by 3–4.5 per cent, $\Delta H_0 = 2.2$–3.3 km s^{-1} Mpc^{-1}) the value of the Hubble constant while increasing its systematic error. This, in turn, could substantially alleviate the Hubble tension.

Problem solved!
Maybe we should go home…?

S25: says Hubble Tension can be solved with age



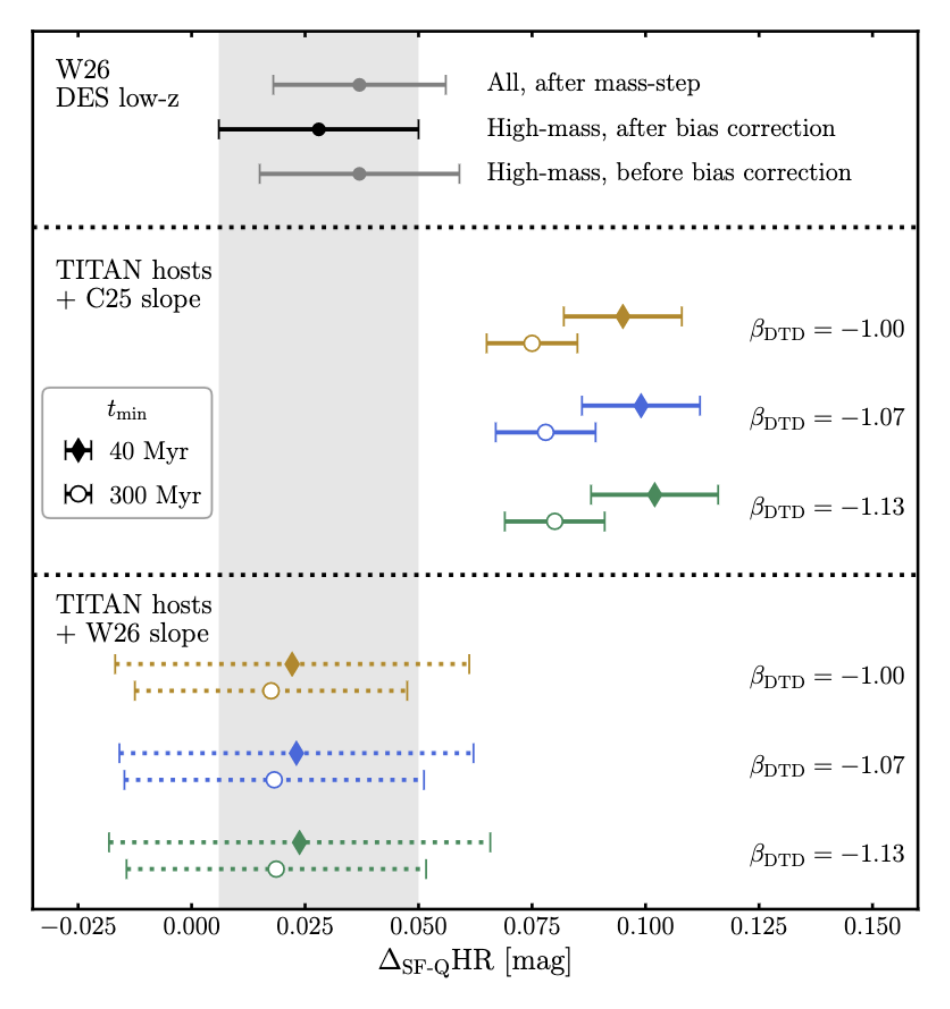
Murakami+26

Cepheid hosts = Star-Forming = produces young SNe

→ Hubble-flow SNe are limited to those from star-forming galaxies (Riess+22)

→ Age effect is nonexistent even if S25 model is correct

S25: says Hubble Tension can be solved with age

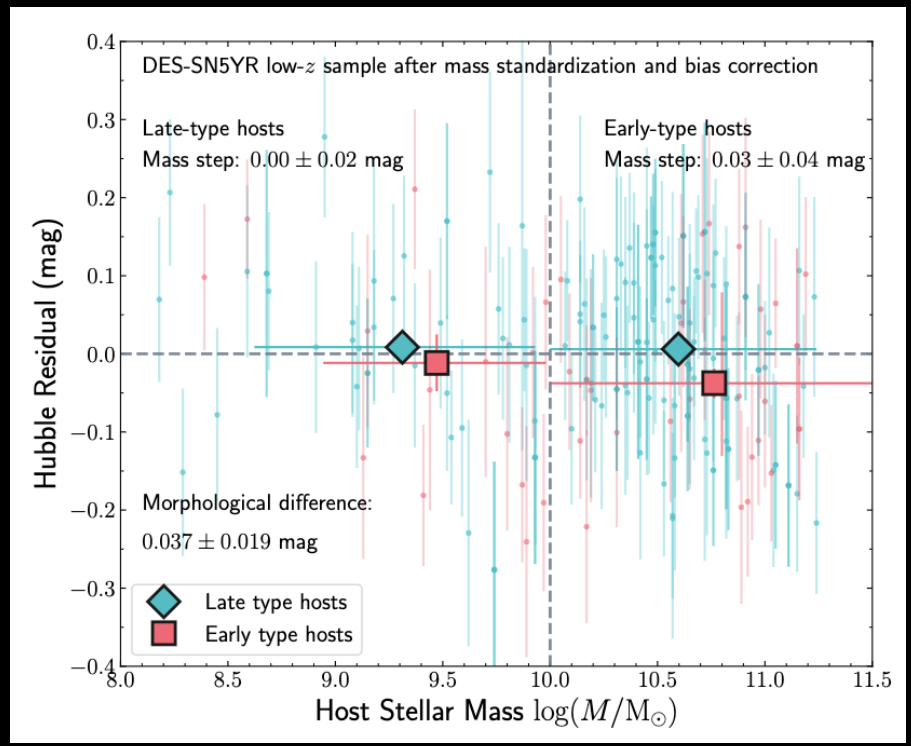


Murakami+26

Further analysis with DES data:

→ S25 model is inconsistent with data

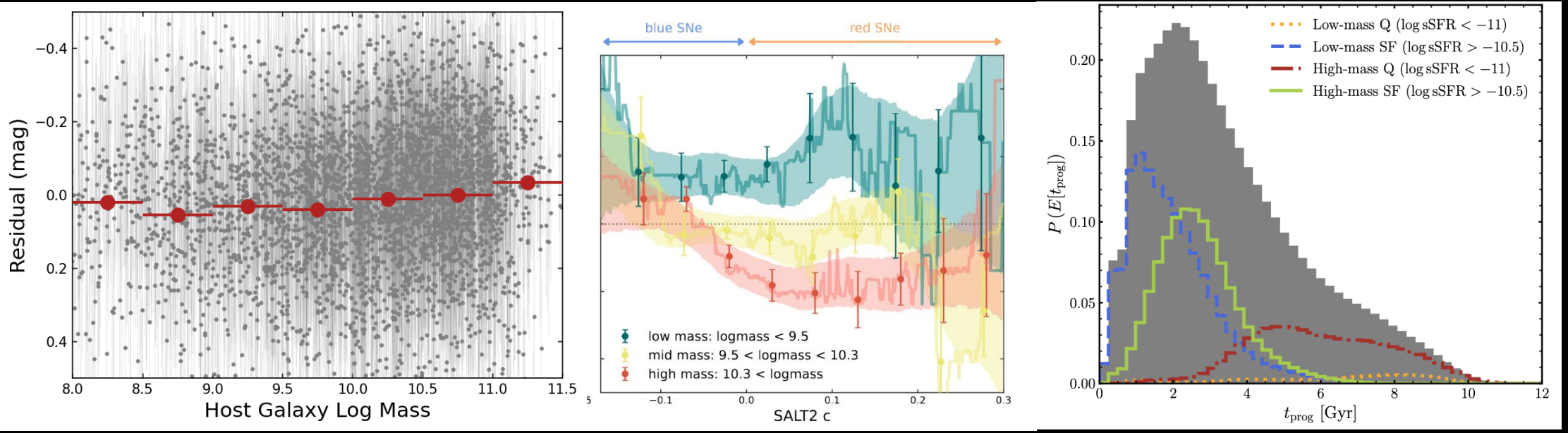
→ Even less likely that this affects H_0



Wiseman+26

Part II: Further Standardization / host-dependent bias corrections

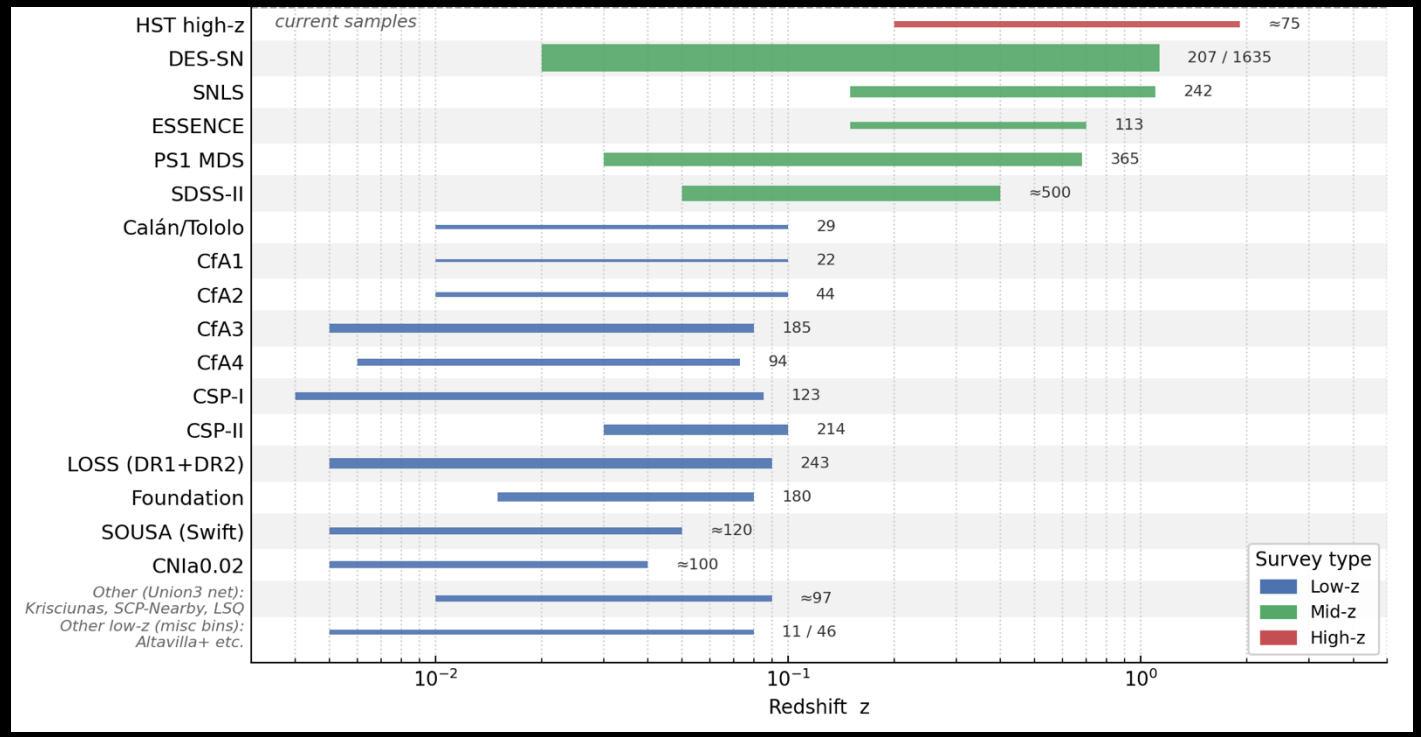
- Known host-dependency is already taken care of (mostly) w/ empirical methods
- The above limits uncertainty at the level relevant with next-gen surveys
- Ongoing efforts: build even more realistic, physically driven simulation

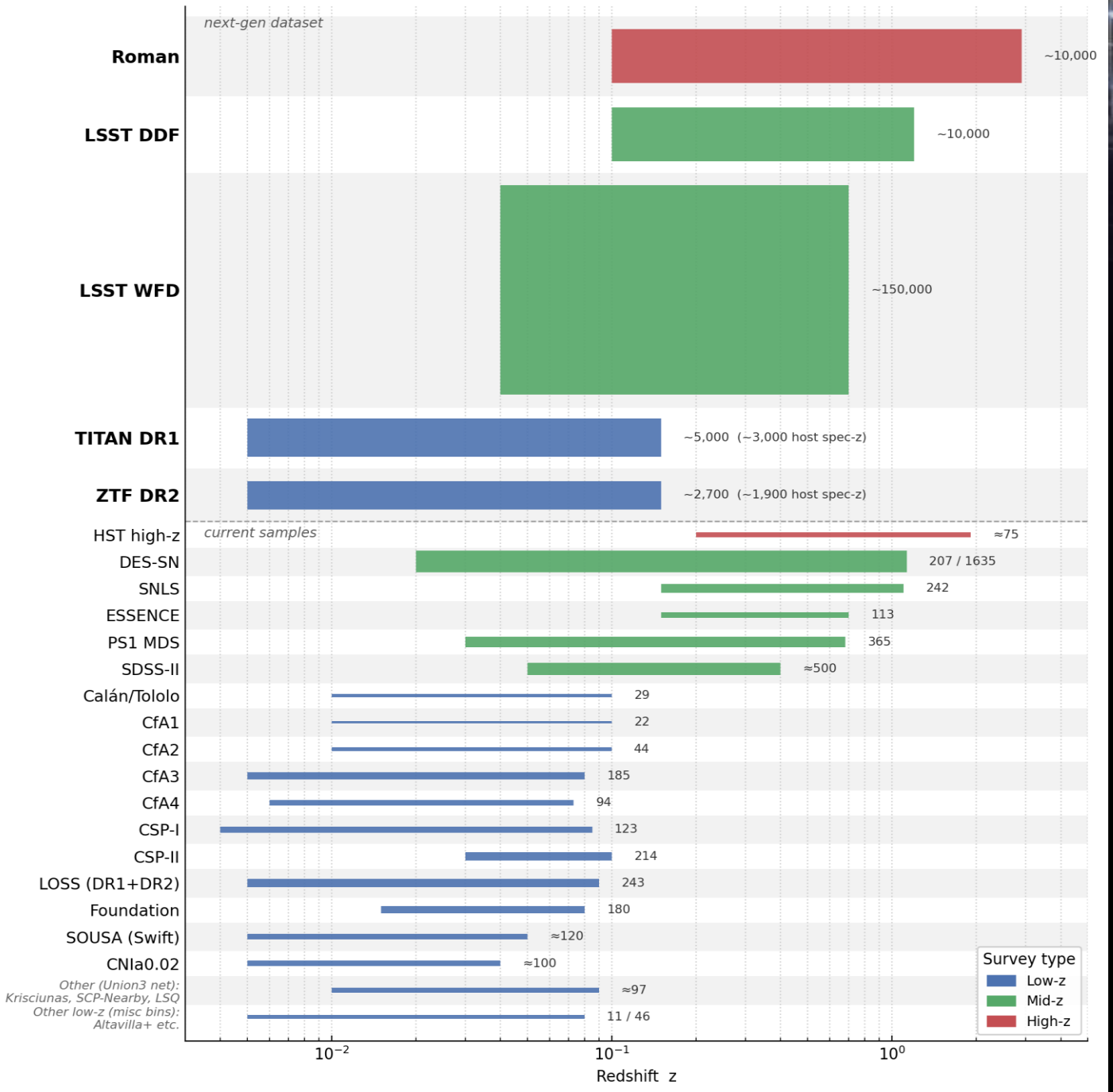


Type Ia Supernova in Modern Cosmology

Part I: The Primary Challenge
Part II: Further Standardization
Part III: Supernova Cosmology in 2030s

Something is about to happen…





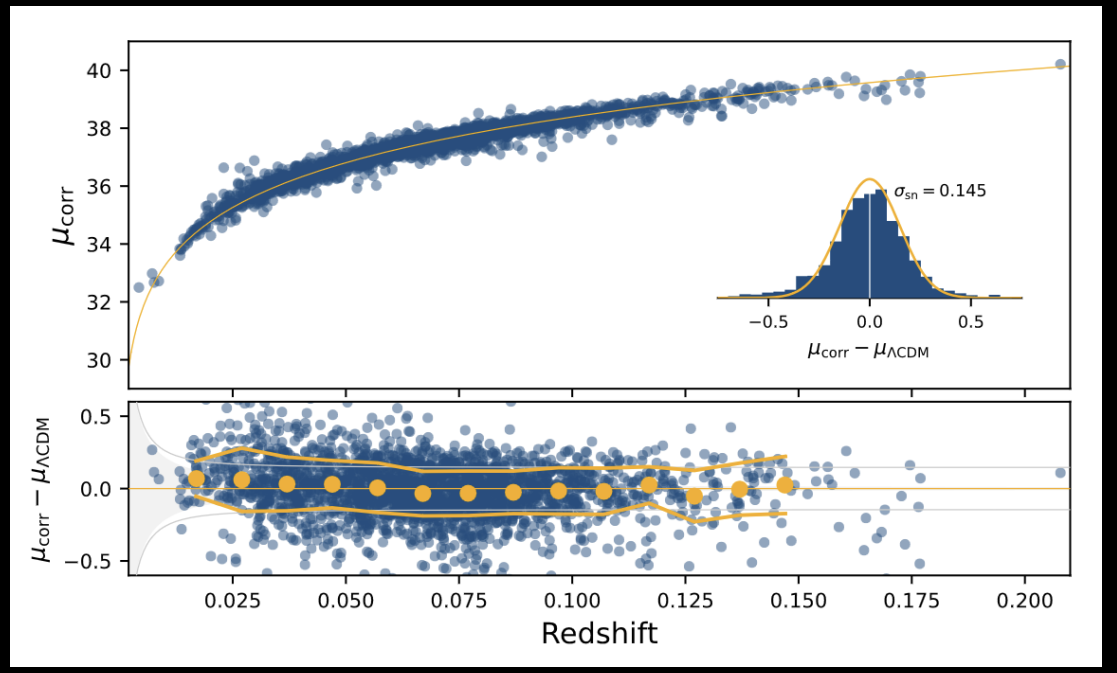
Bar thickness ∝ √N on the same absolute scale as the compilation figure, so next-gen bars show projected impact relative to current samples.
Next-gen (bold): LSST WFD ~150,000 + DDF ~10,000, Roman ~10,000 (z to ~2.9), ZTF DR2 ~2,700, TITAN DR1 ~5,000. Projected cosmology-grade counts; z-ranges approximate.

Next-gen datasets completely changes the picture!

Low-z: 15x increase
Mid-z: 10x increase
High-z: 100x increase

ZTF: Zwicky Transient Facility

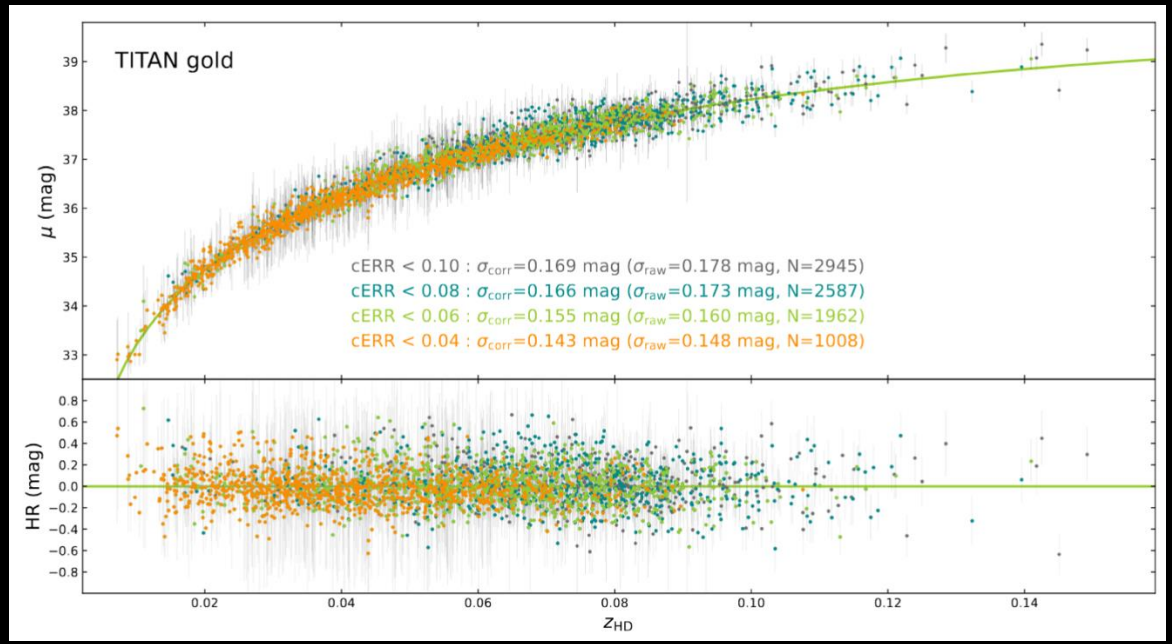
- Low-z survey
- Spectroscopic classification
- Spec-z for host galaxies when available



Rigault+24

TITAN: Type Ia Supernova Trove from ATLAS in the Nearby universe

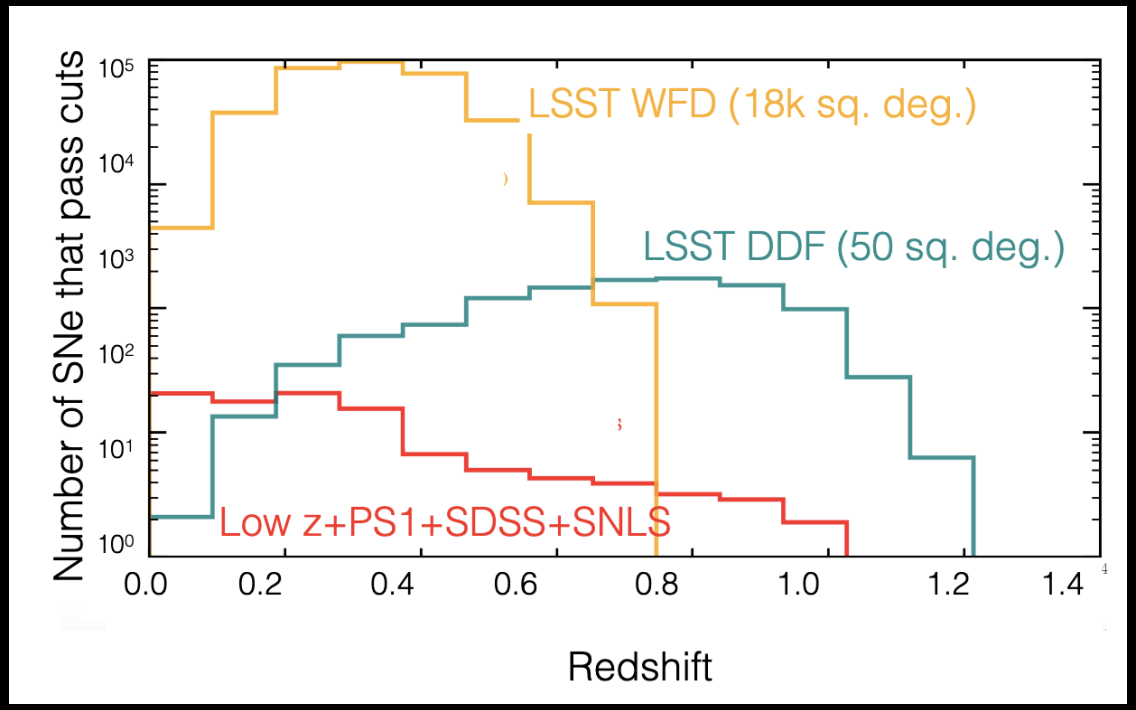
- Low-z, all-sky survey
- Spectroscopic classification
- Spec-z for host galaxies
- Extensive host galaxy catalog and physical properties



Murakami+ in prep.

LSST: Legacy Survey of Space and Time

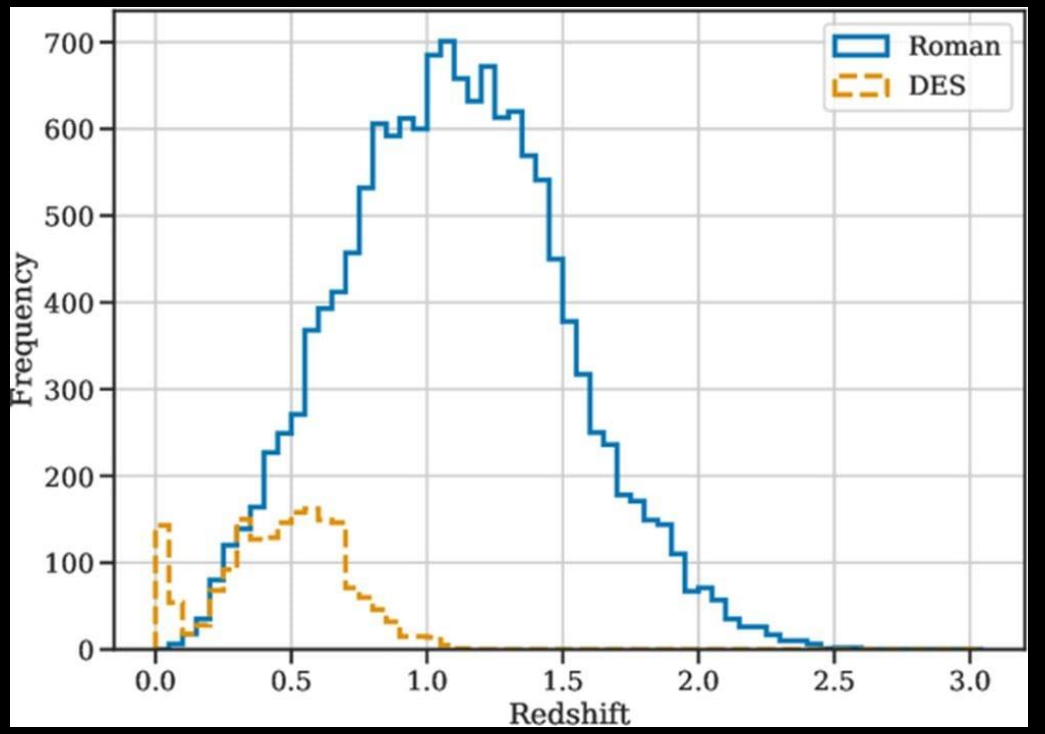
- Mid-z, wide-field survey
- Relies on other telescopes for follow-up
- Well-calibrated photometric system



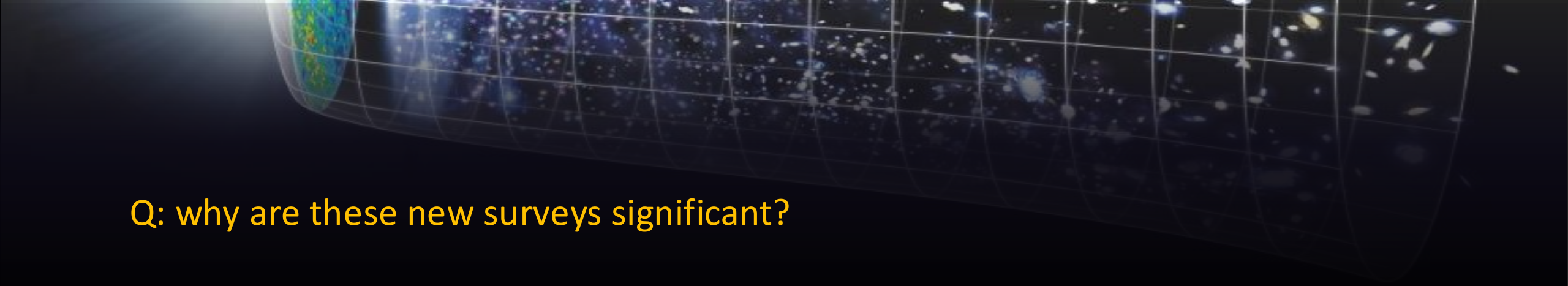
Snowmass2021

Roman Space Telescope

- High-z space telescope
- Pushes the redshift range up to z~3
- HST-level photometry but ~18x wider



Rose+2025



Q: why are these new surveys significant?

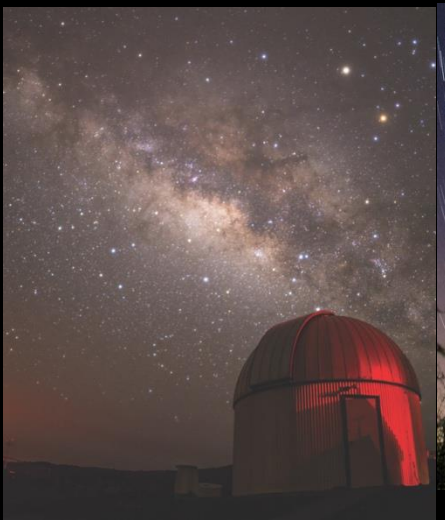
Q: why are these new surveys significant?

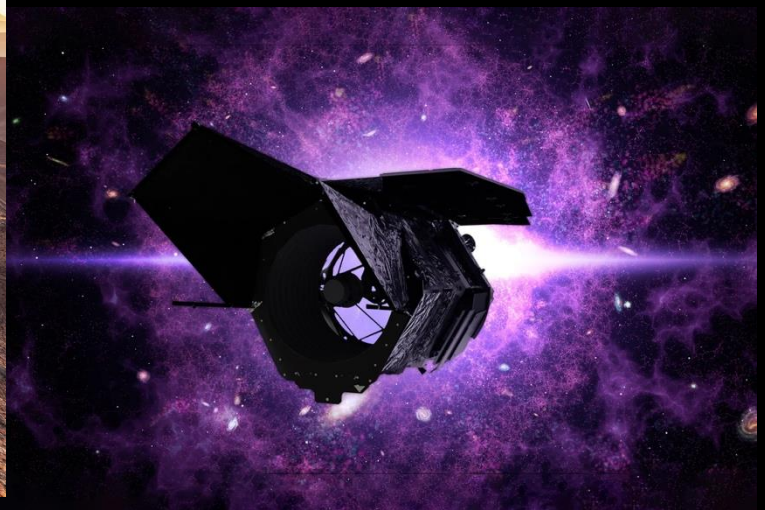
A: they all reduce systematic uncertainties in different ways.

Low-z:
Volume-limited dataset for studies of intrinsic population
Probes late-time dark energy

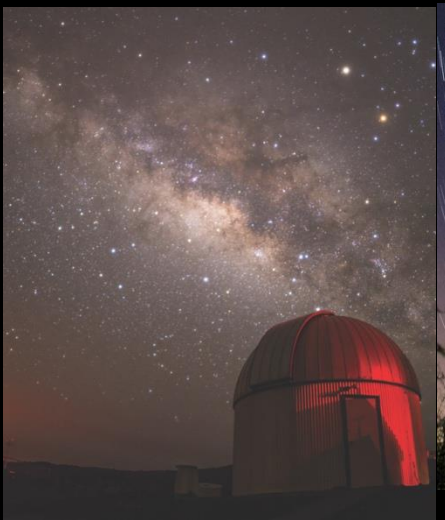
Mid-z:
Single photometric system across Λ- and matter-dominated era

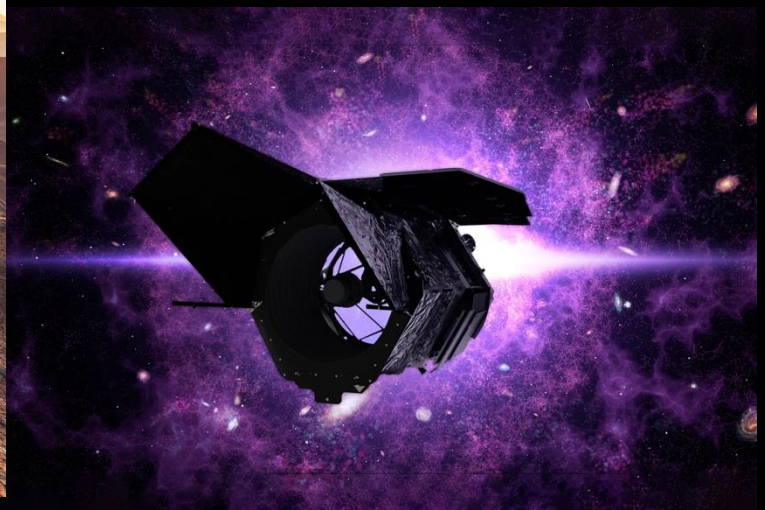
High-z:
Anchors cosmology in matter-dominated era (more leverage on w)





Q: Are they going to solve the Hubble tension?





Q: Are they going to solve the Hubble tension?

A: Not directly. Systematics in SNe Ia is not the leading source of H_0 tension.
But through constraints of expansion history,
they will indirectly point us to the right direction!




Fig. 1: Nova the cat

Type Ia Supernova:

1. **SNe Ia as a Standardizable Candle: *Classical Picture***
2. **SNe Ia in Distance Ladder: *Coding Demo***
3. **Assessing Sysetematics & New Surveys: *Modern Picture***

- What is a Type Ia supernova?
- How does it help cosmology?
- Where does the data come from?
- How can I use data for my own analysis?
- Outlook – a new generation of supernova cosmology