Astrophysical transients as cosmological probes

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Astroparticle Physics, XXXIII cycle

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GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Outline

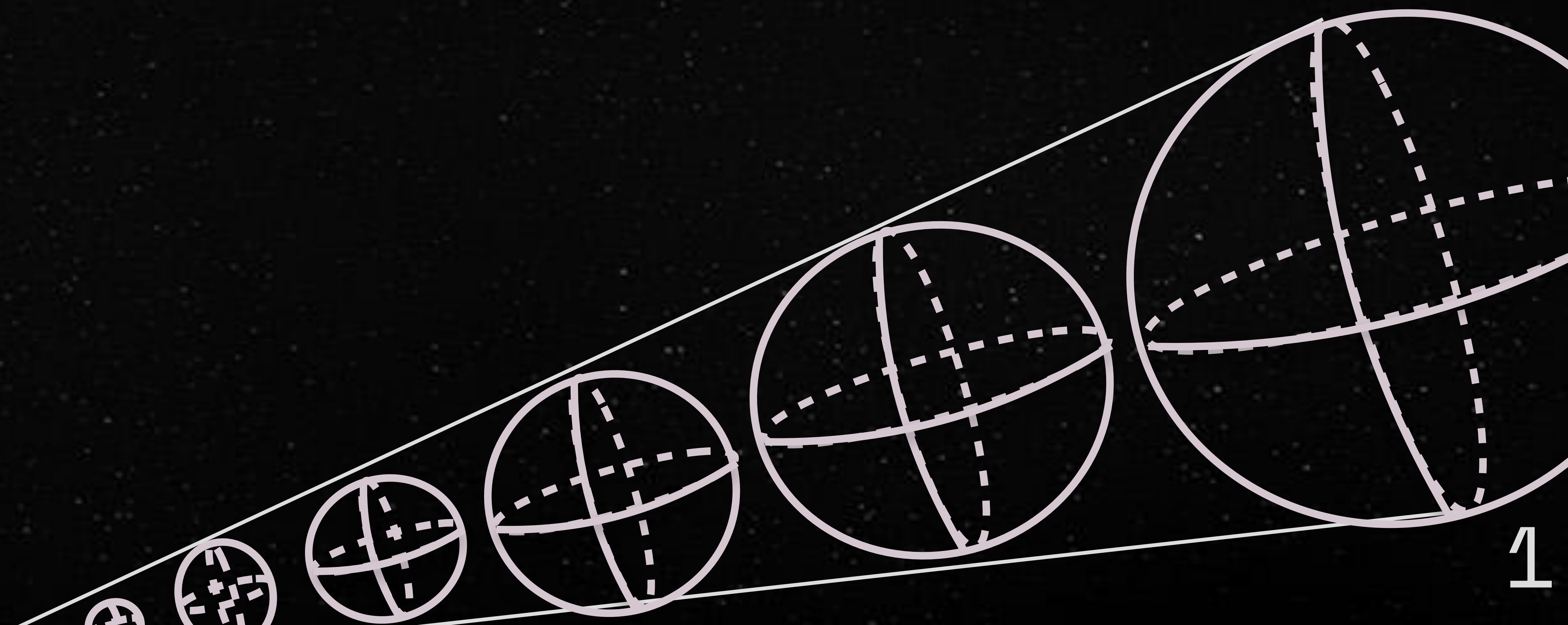
01 Introduction
History, Motivation

02 SNe Ia + SBF
Calibration of SNe Ia luminosity using SBF distances

03 SLSNe as cosmo. probes
Standardisation of SLSNe-I in UV

04 KNe standardisation
Standardisation of KNe

05 Summary



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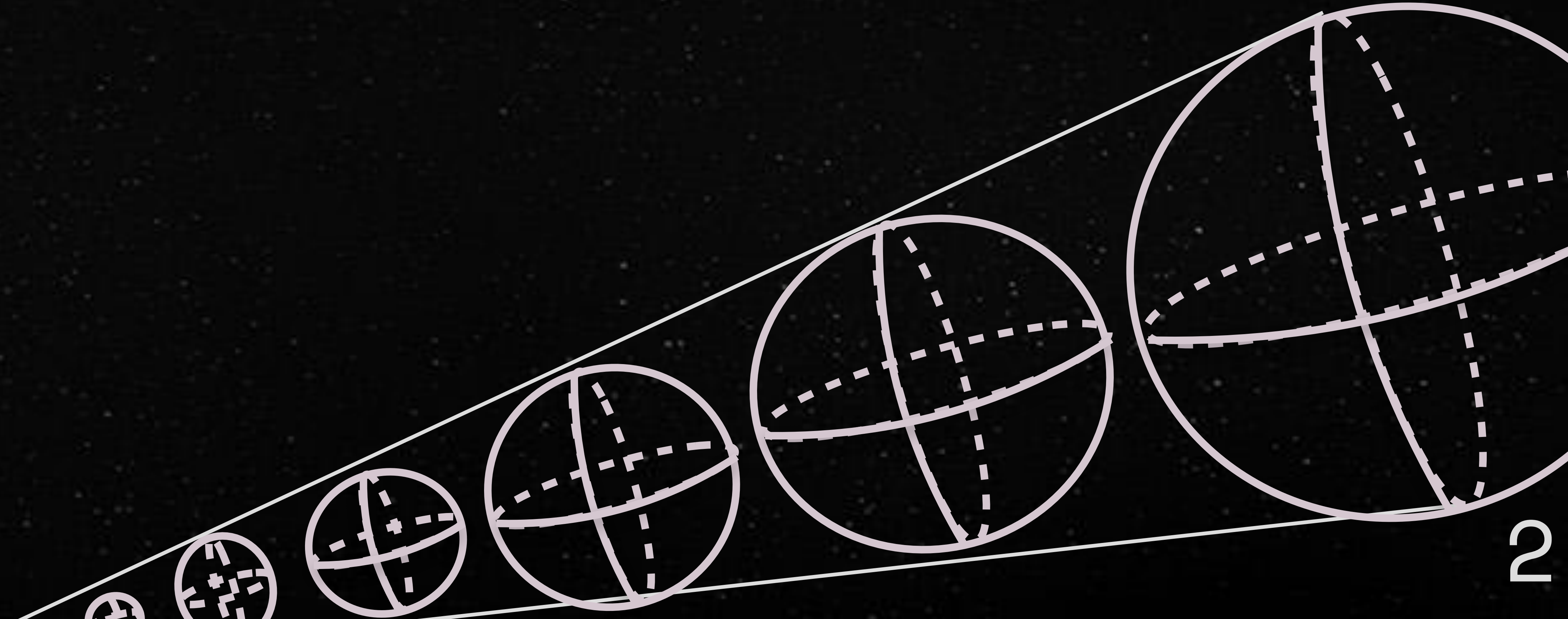
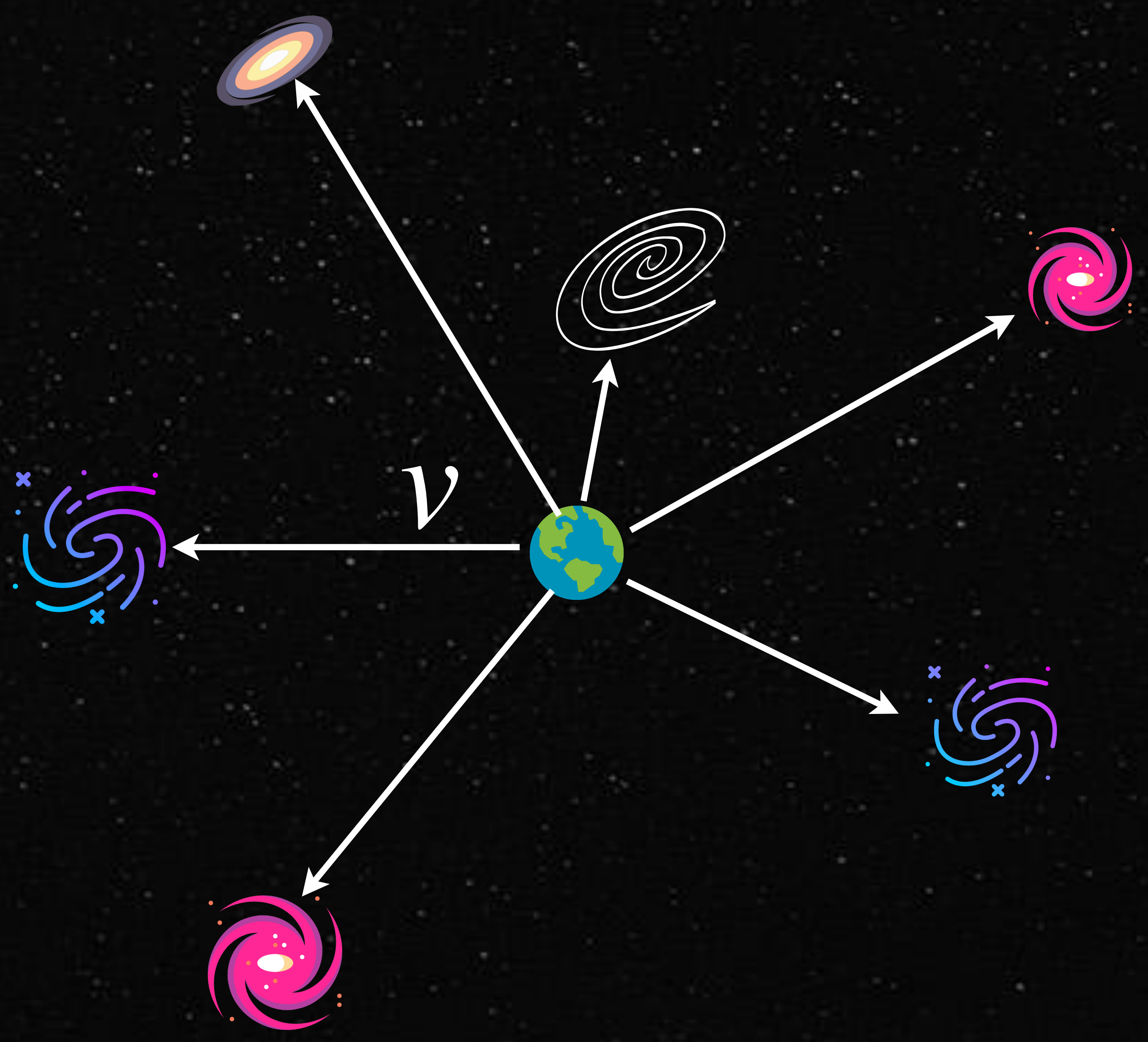


Introduction

Year : 1929

Edwin Hubble



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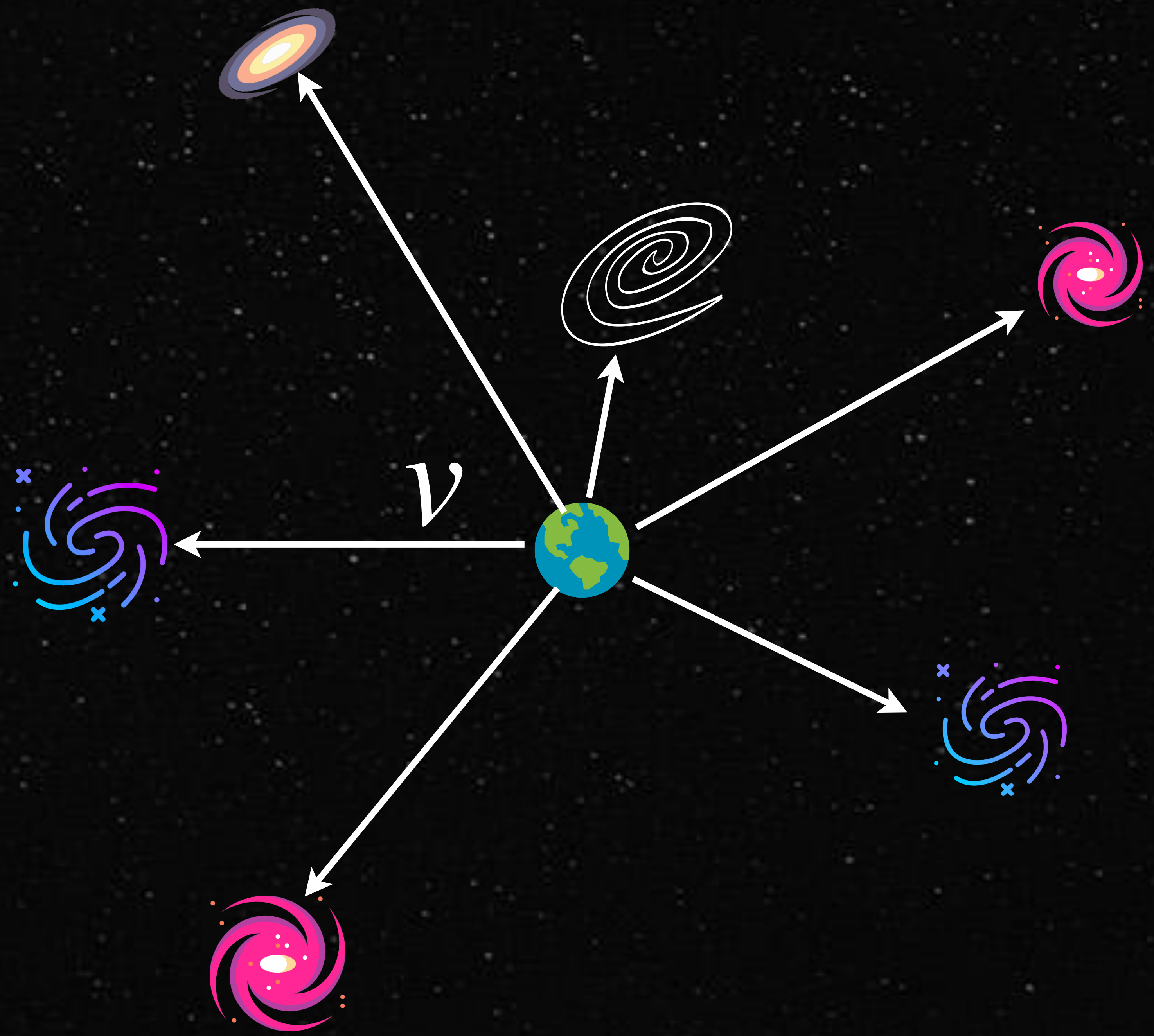

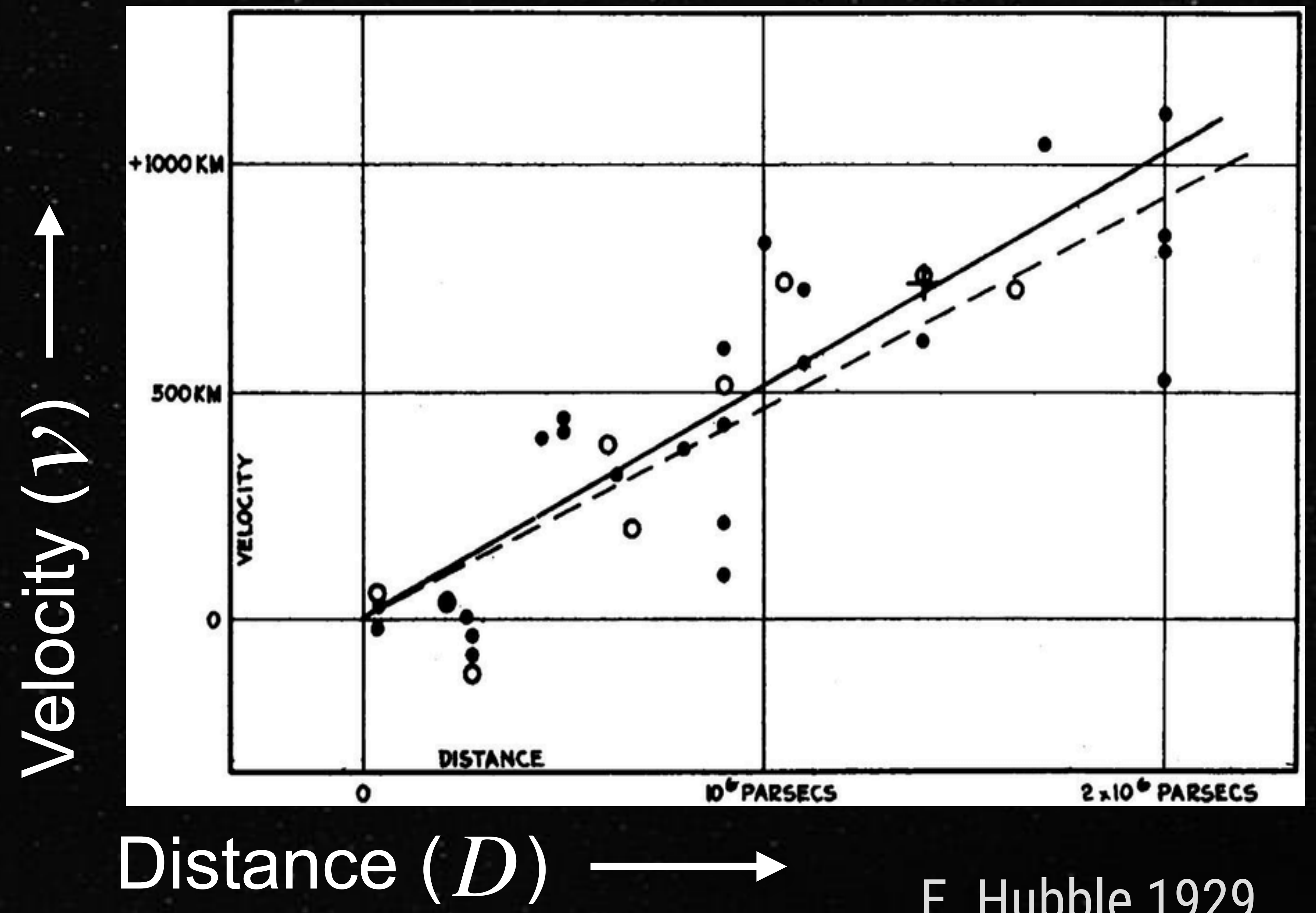

E. Hubble 1929

Hubble-Lemaître Law : $v = H_0 D$

Hubble Constant

Introduction

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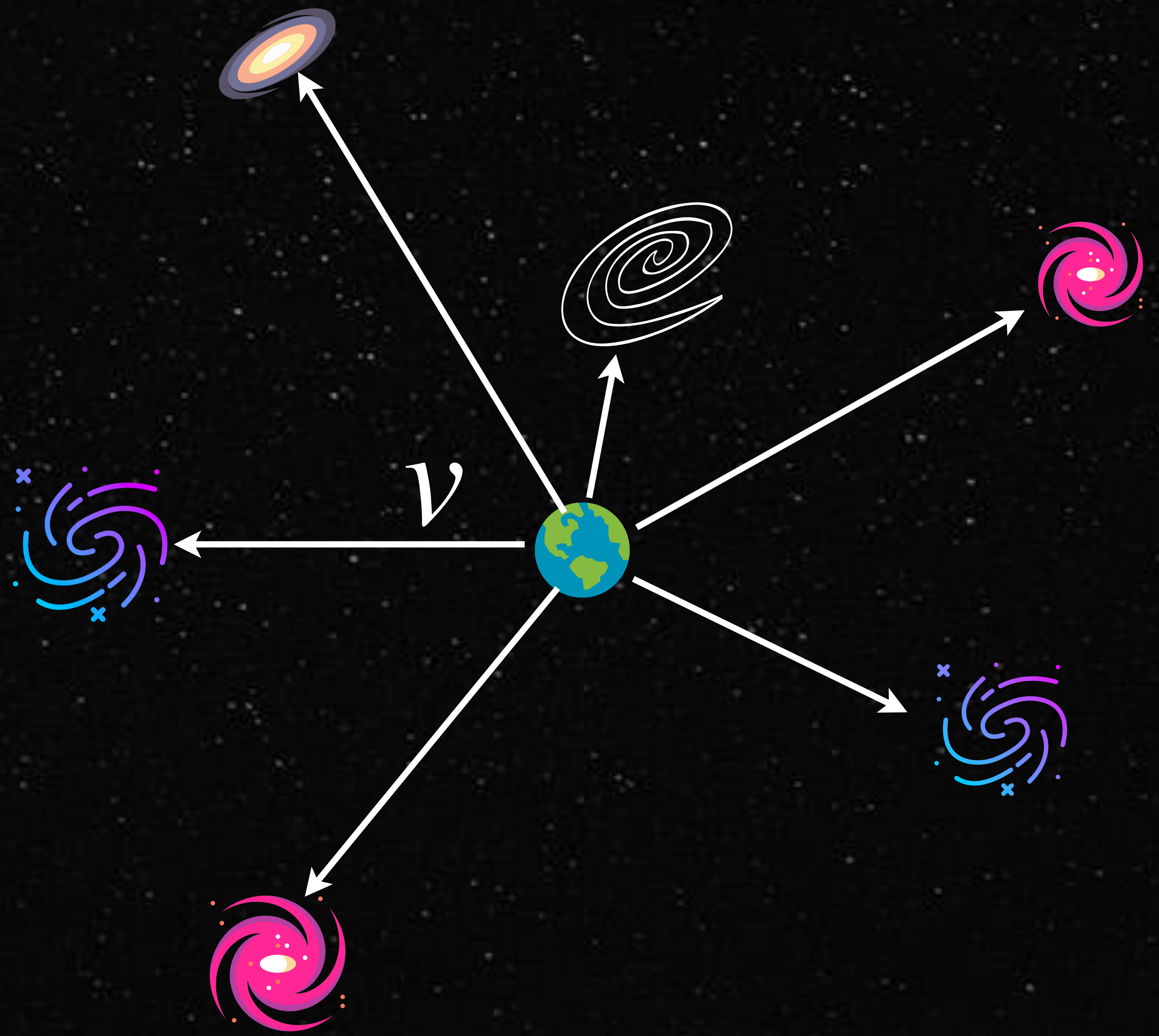

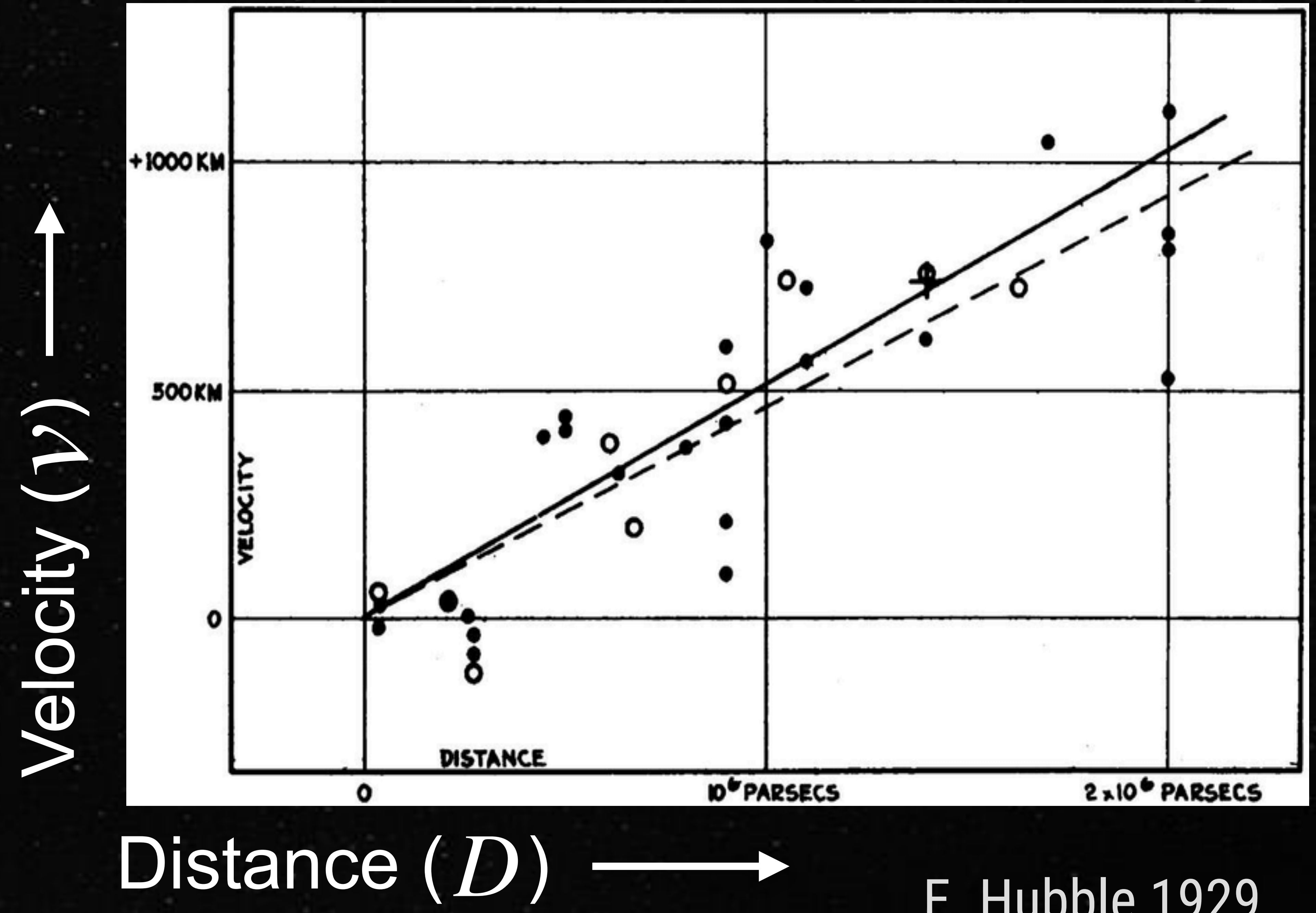

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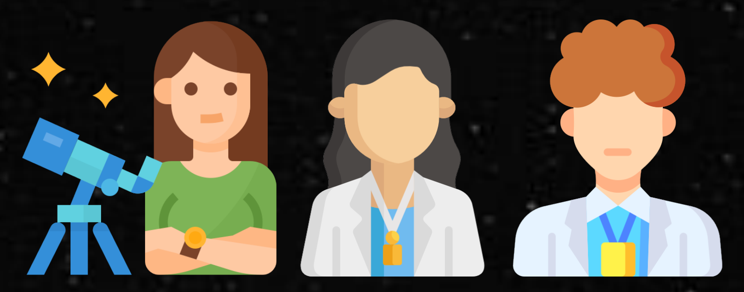
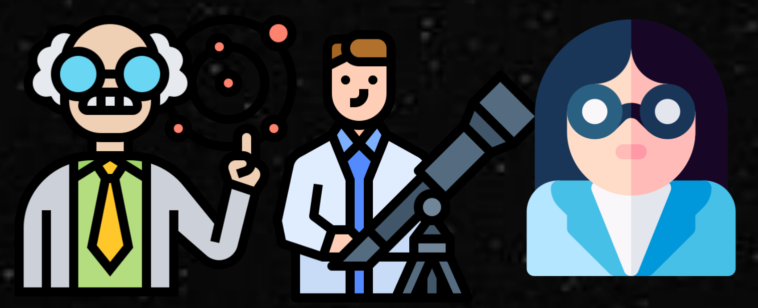
The Universe is expanding!

Year : 1998

The supernova
Cosmolgy Project



High-z supernova
Project



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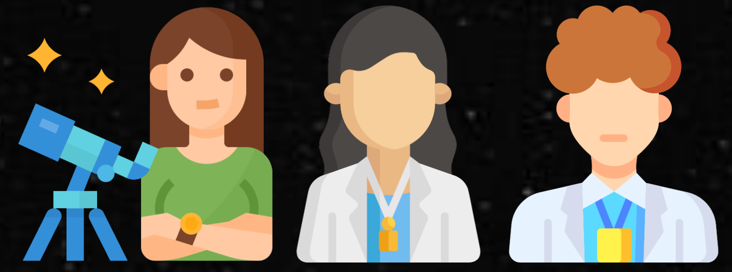

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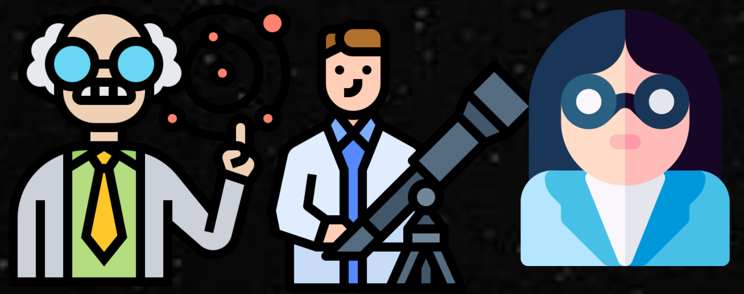

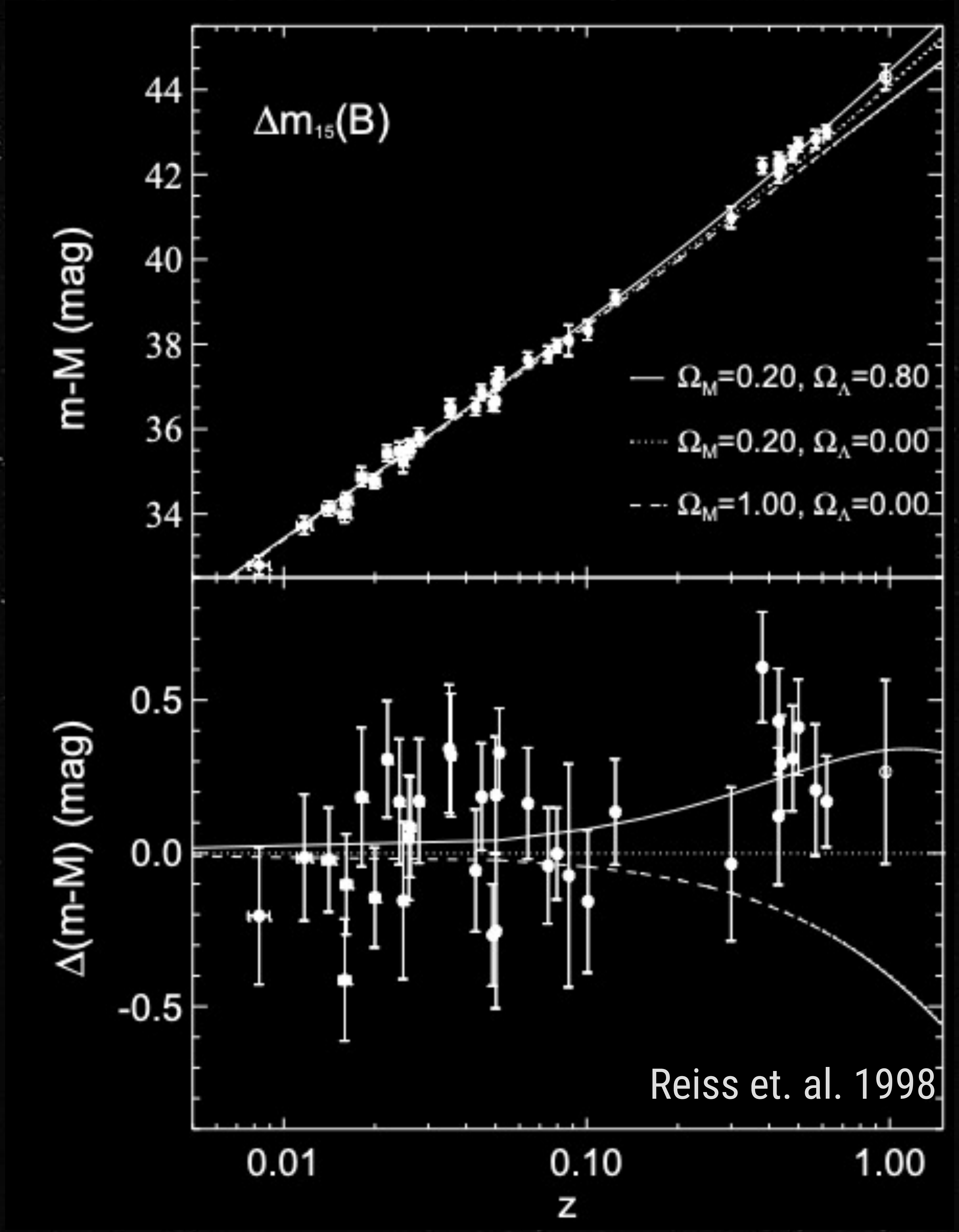

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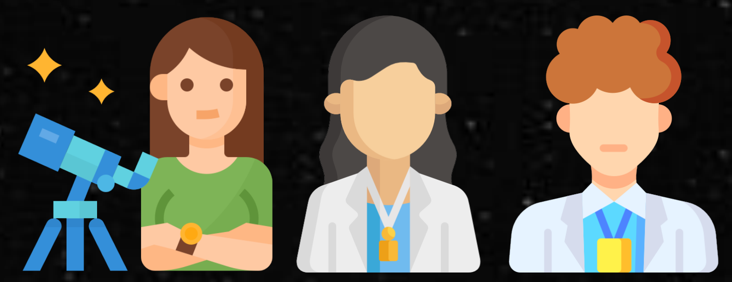

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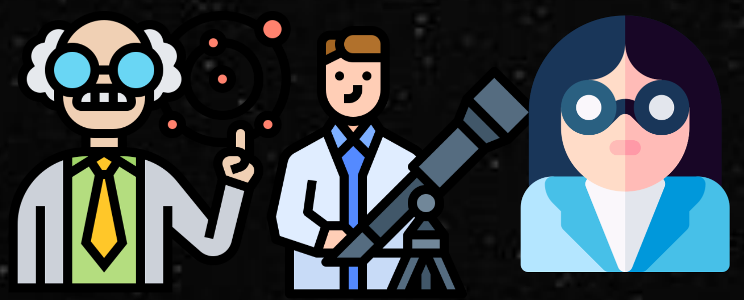

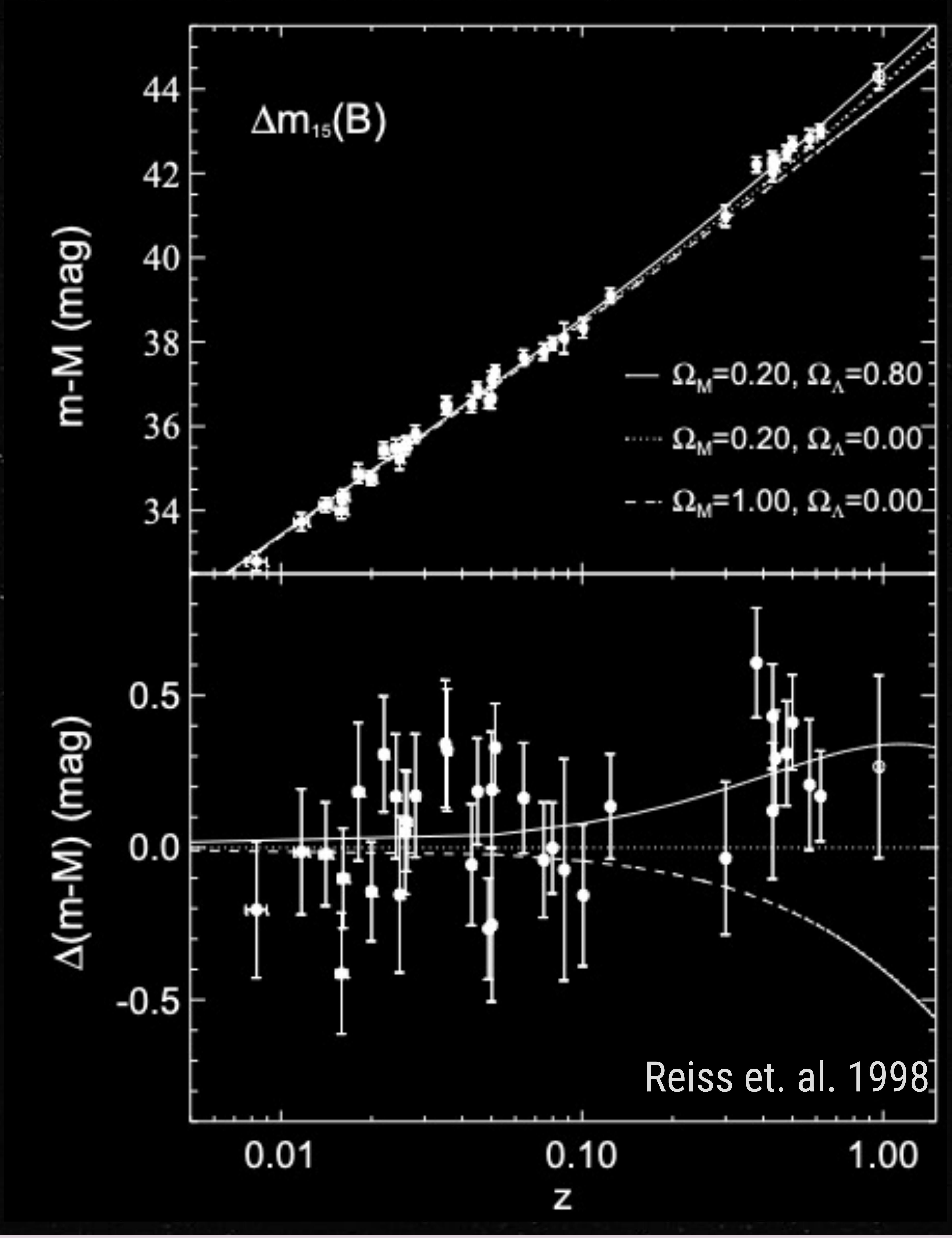

The expansion of the Universe is accelerating!!

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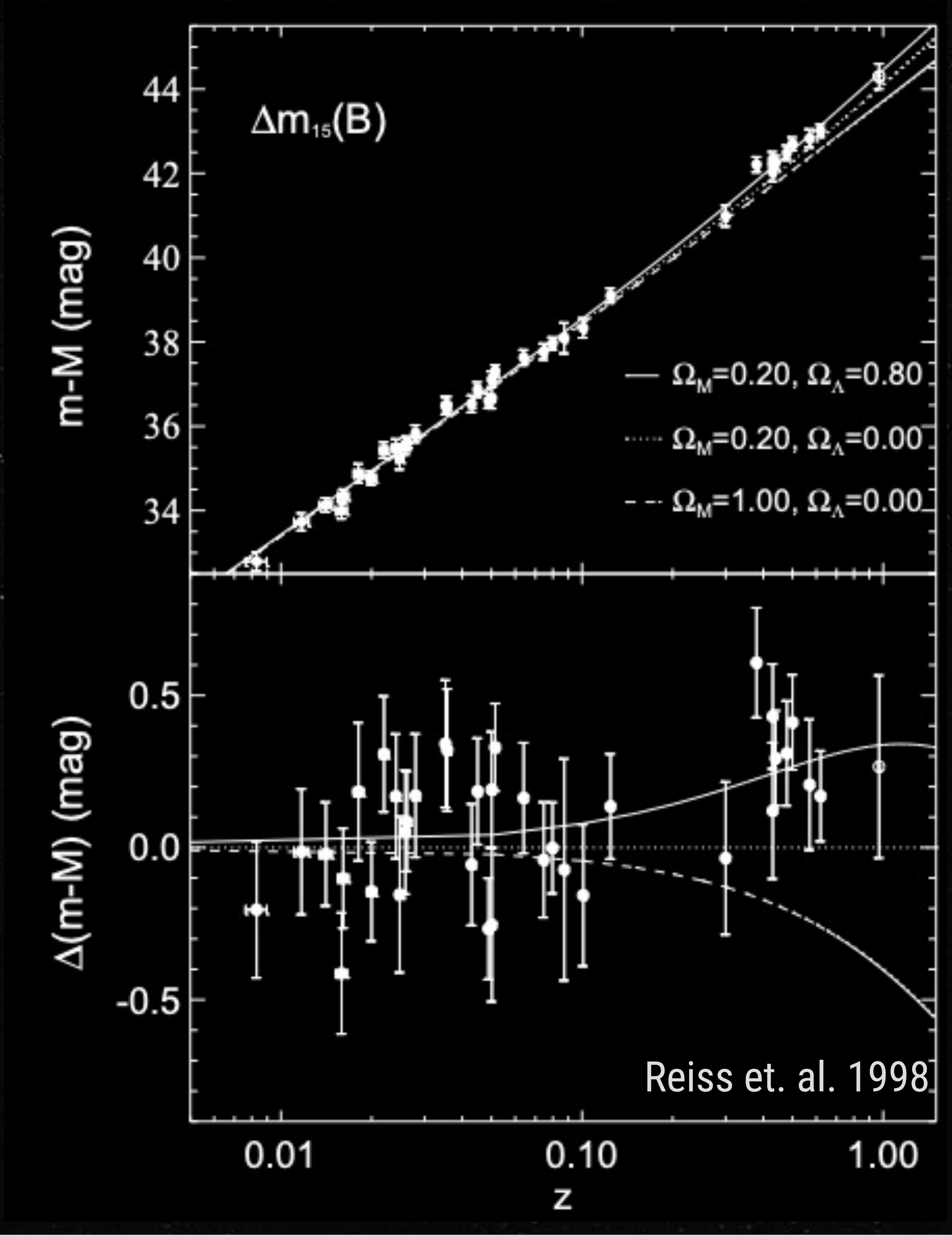

Dark Energy ??

Energy of empty space

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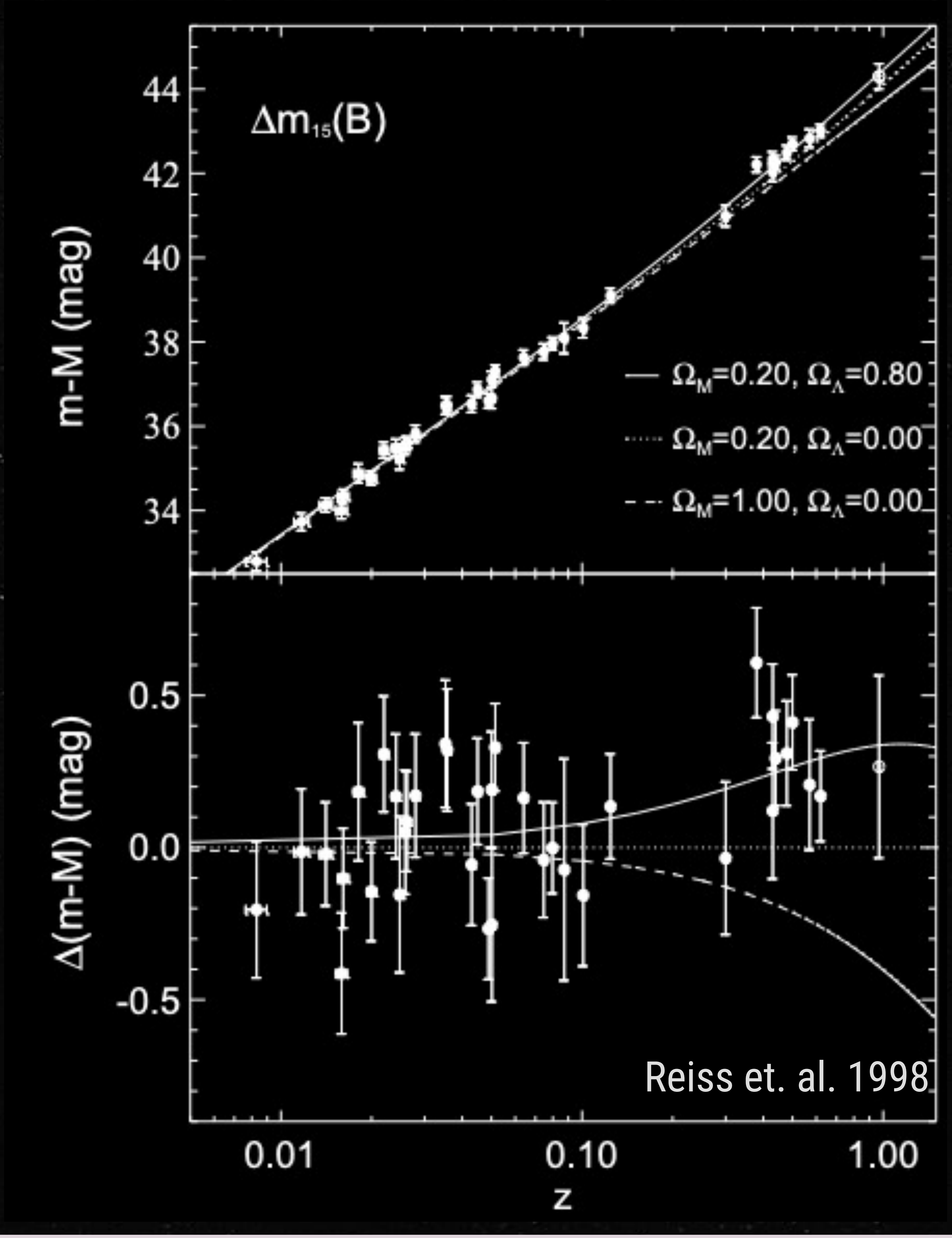


Dark Energy ??

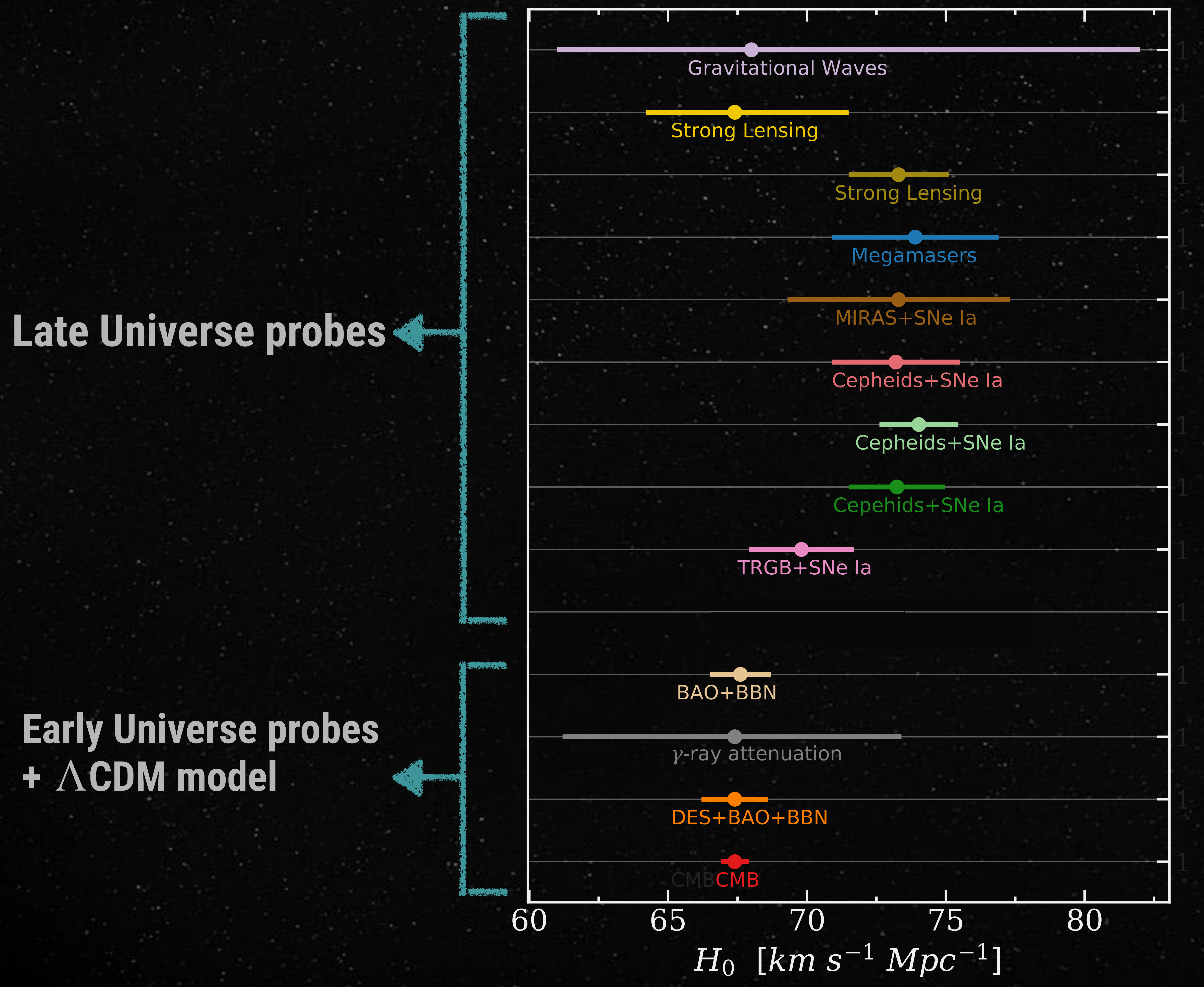
Energy of empty space

Λ CDM model

Cosmological constant with Non-zero value

The expansion of the Universe is accelerating!!

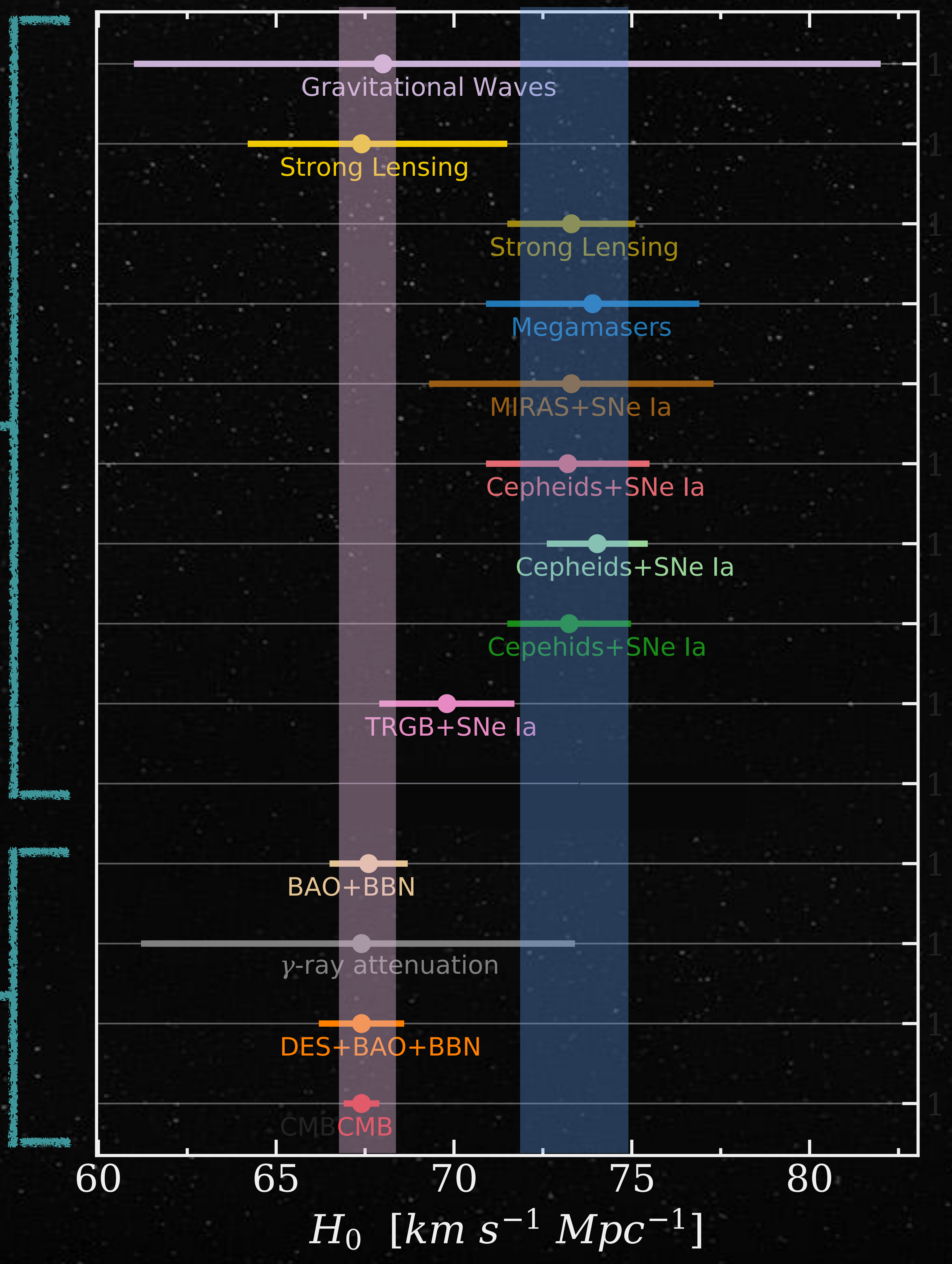
Hubble Tension



Hubble Tension

Late Universe probes

Early Universe probes
+ ΛCDM model



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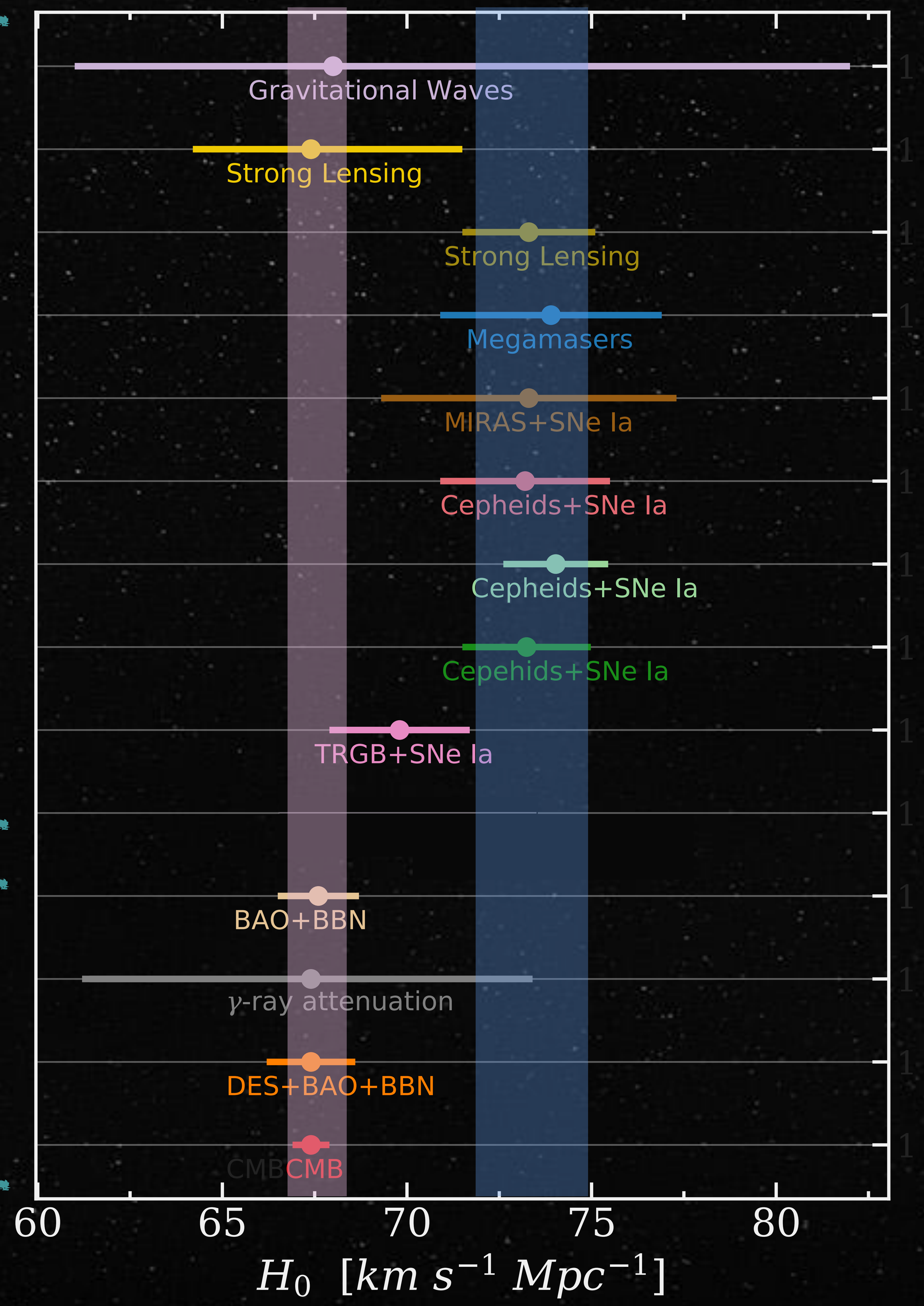

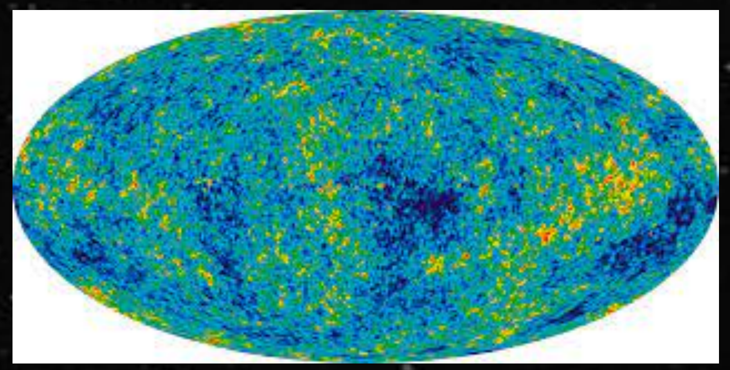

$H_0 = 67.4 \pm 0.5$

$H_0 = 73.5 \pm 1.4$

Hubble Tension

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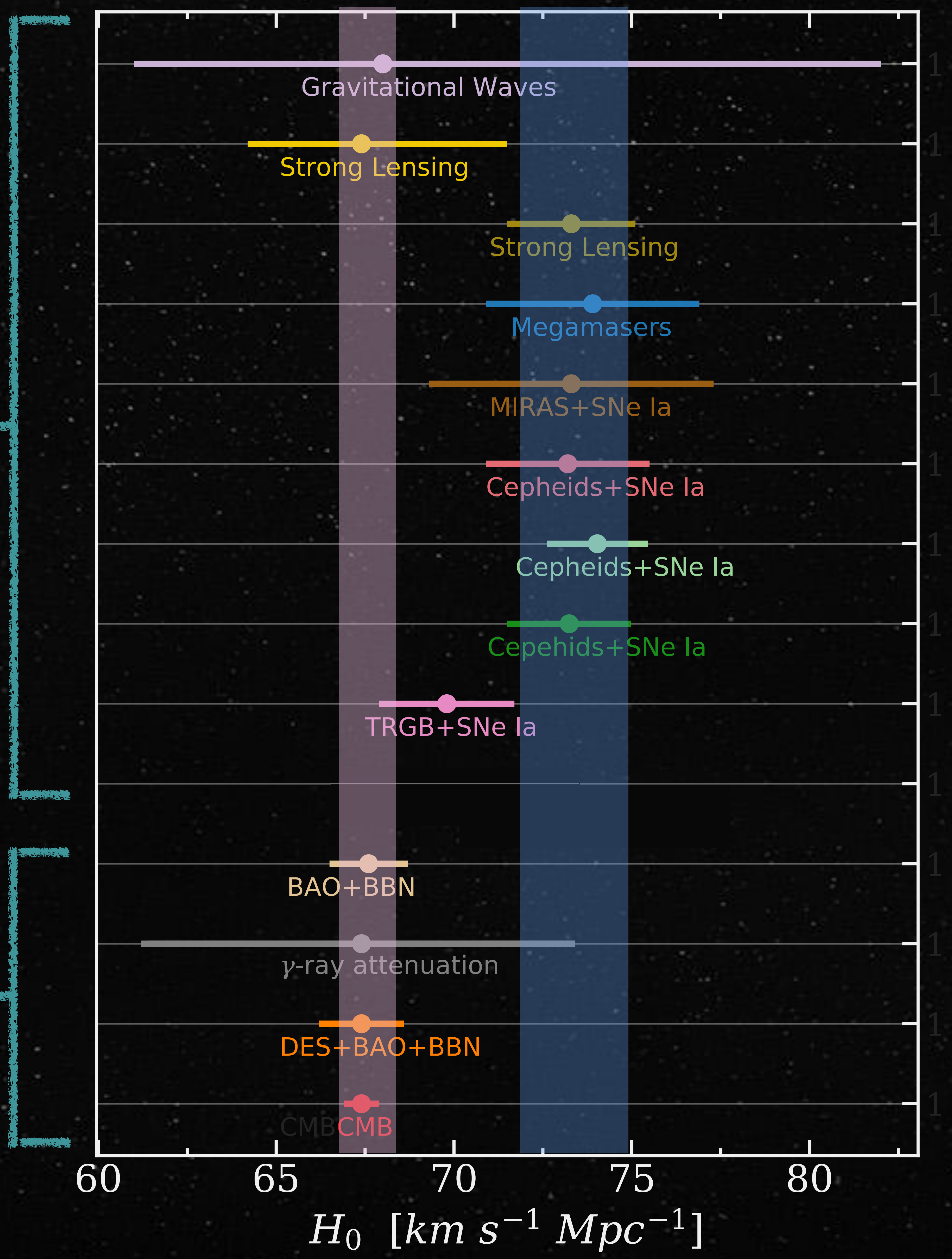

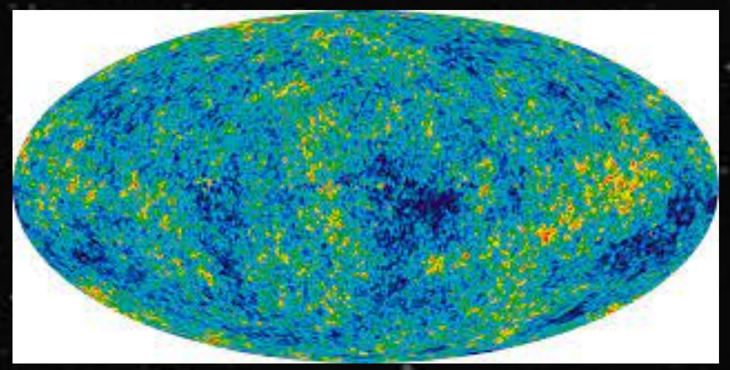

$H_0 = 67.4 \pm 0.5$

$H_0 = 73.5 \pm 1.4$

Systematics
OR
New Physics??

Alternative measurements!!

My work

My work

SNe Ia + SBF

A new measurement of the Hubble constant (H_0) using SNe Ia calibrated with surface brightness fluctuation distances (SBF)

My work

SNe Ia + SBF

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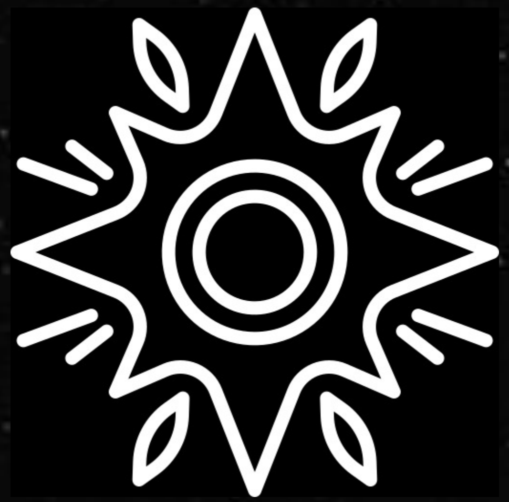
SLSNe in UV

Study of high redshift superluminous supernovae and their use as cosmological probes

My work



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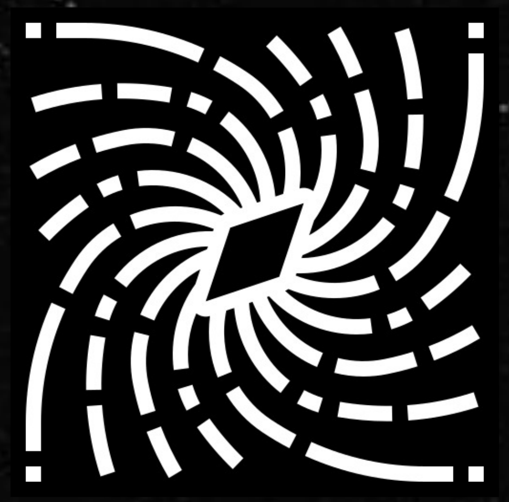

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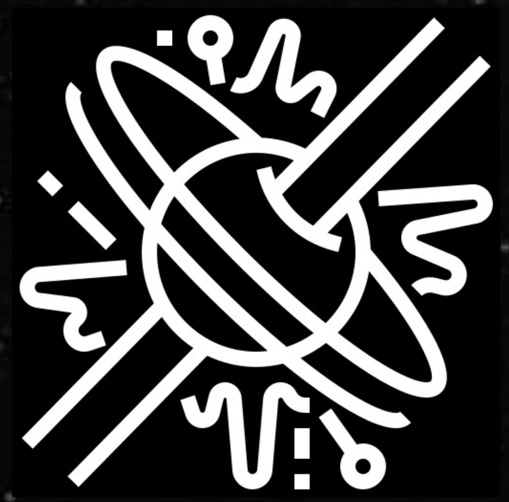
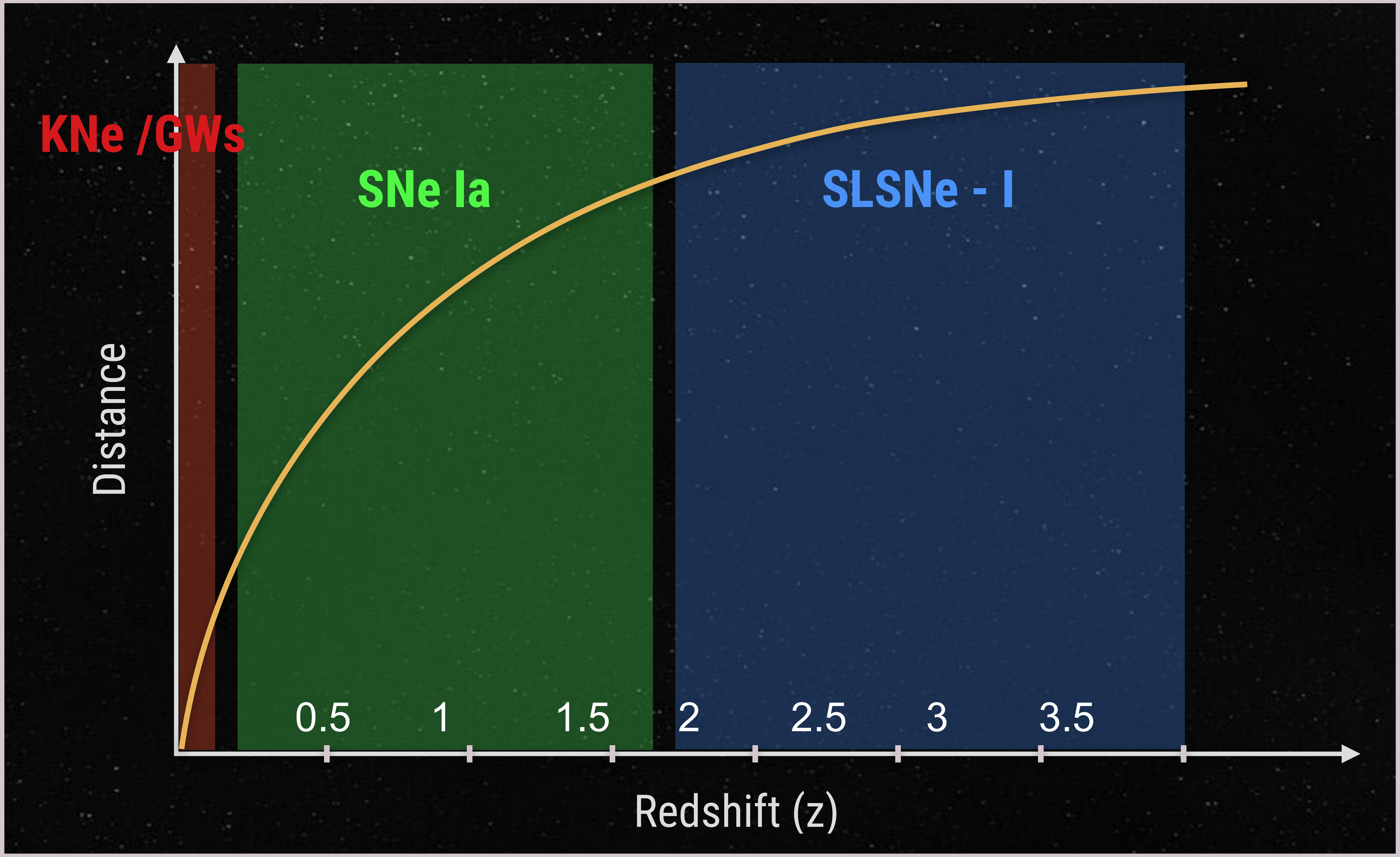


Kilonovae

Standardising Kilonovae and their use as distance indicators to measure the H_0

My work

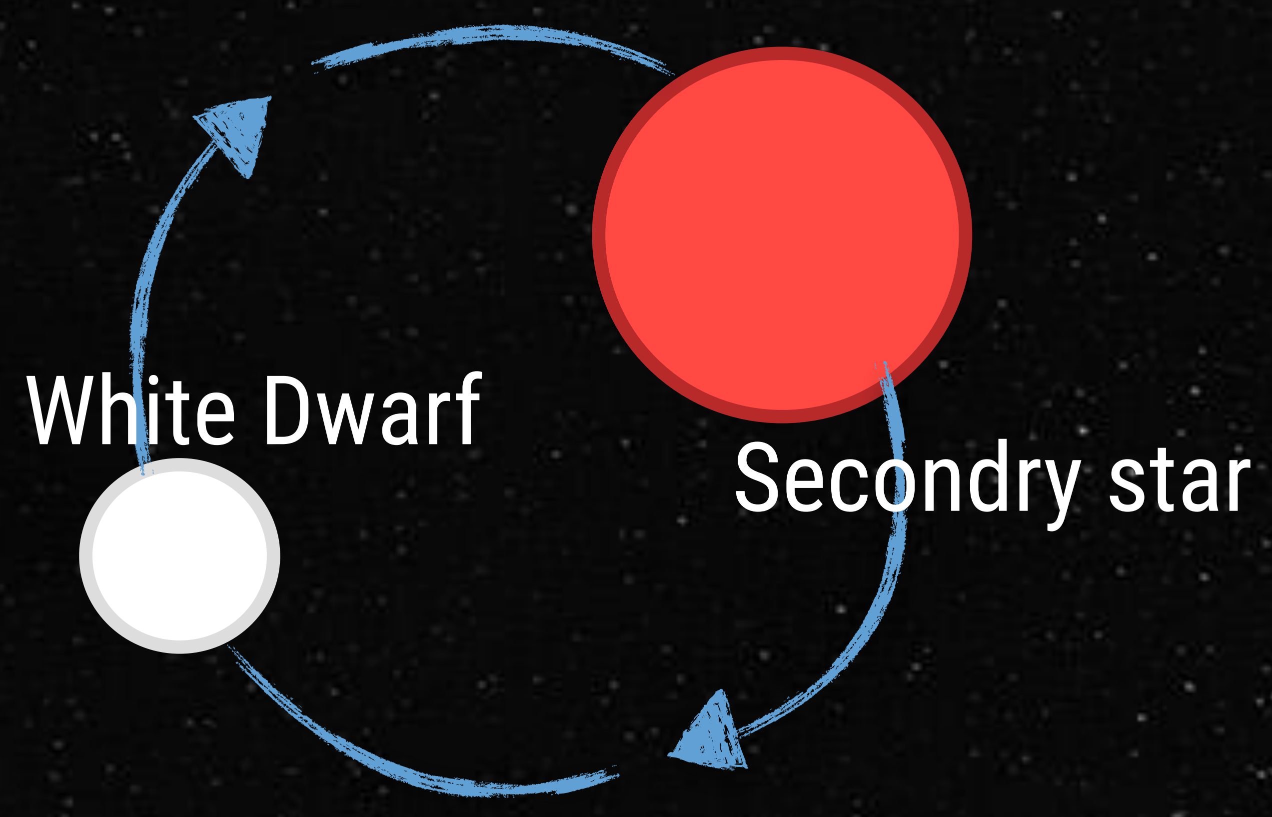


01

Supernova Type Ia calibrated with SBF

A new measurement of H_0 using SNe Ia calibrated with SBF

SNe Ia as standard Candles



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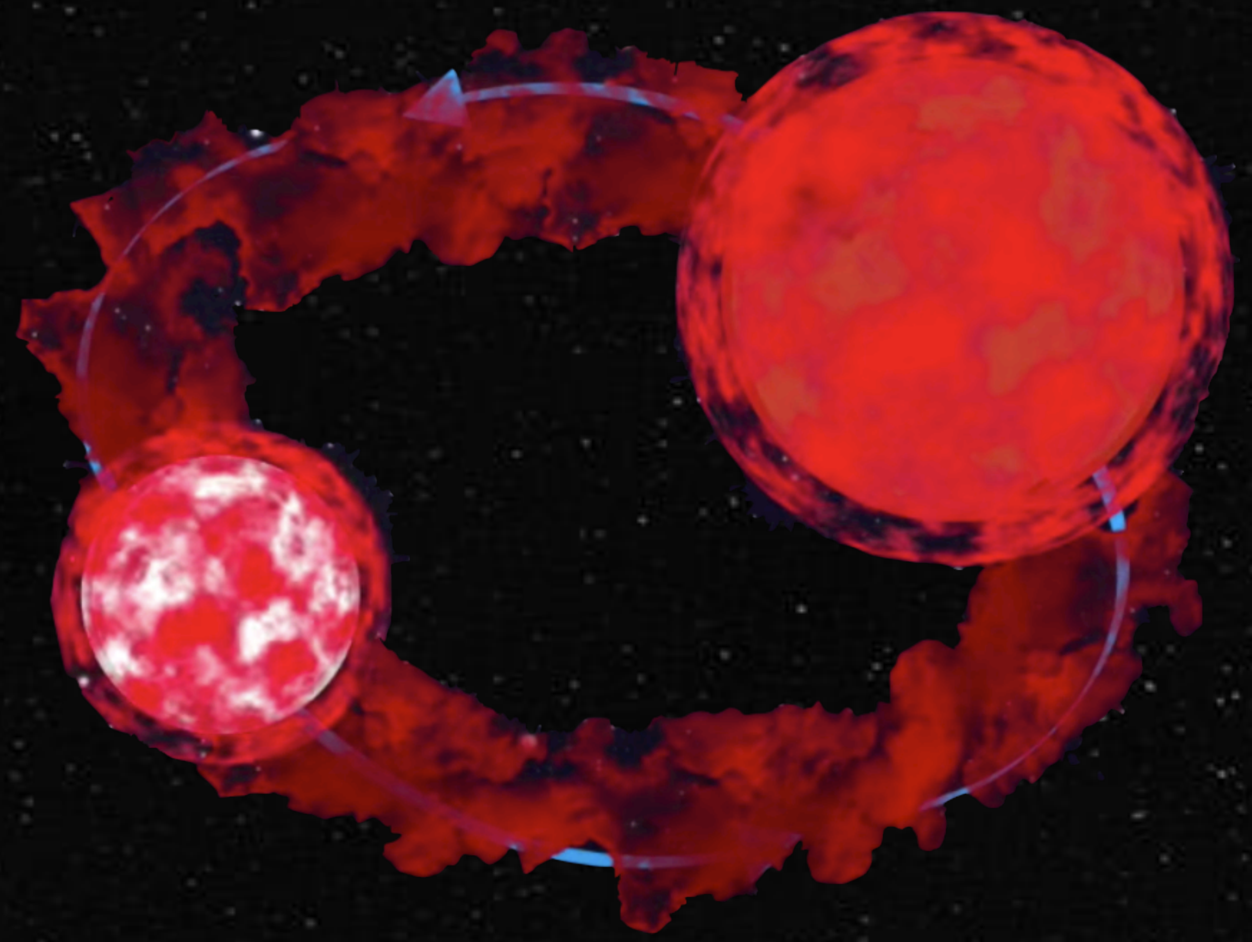

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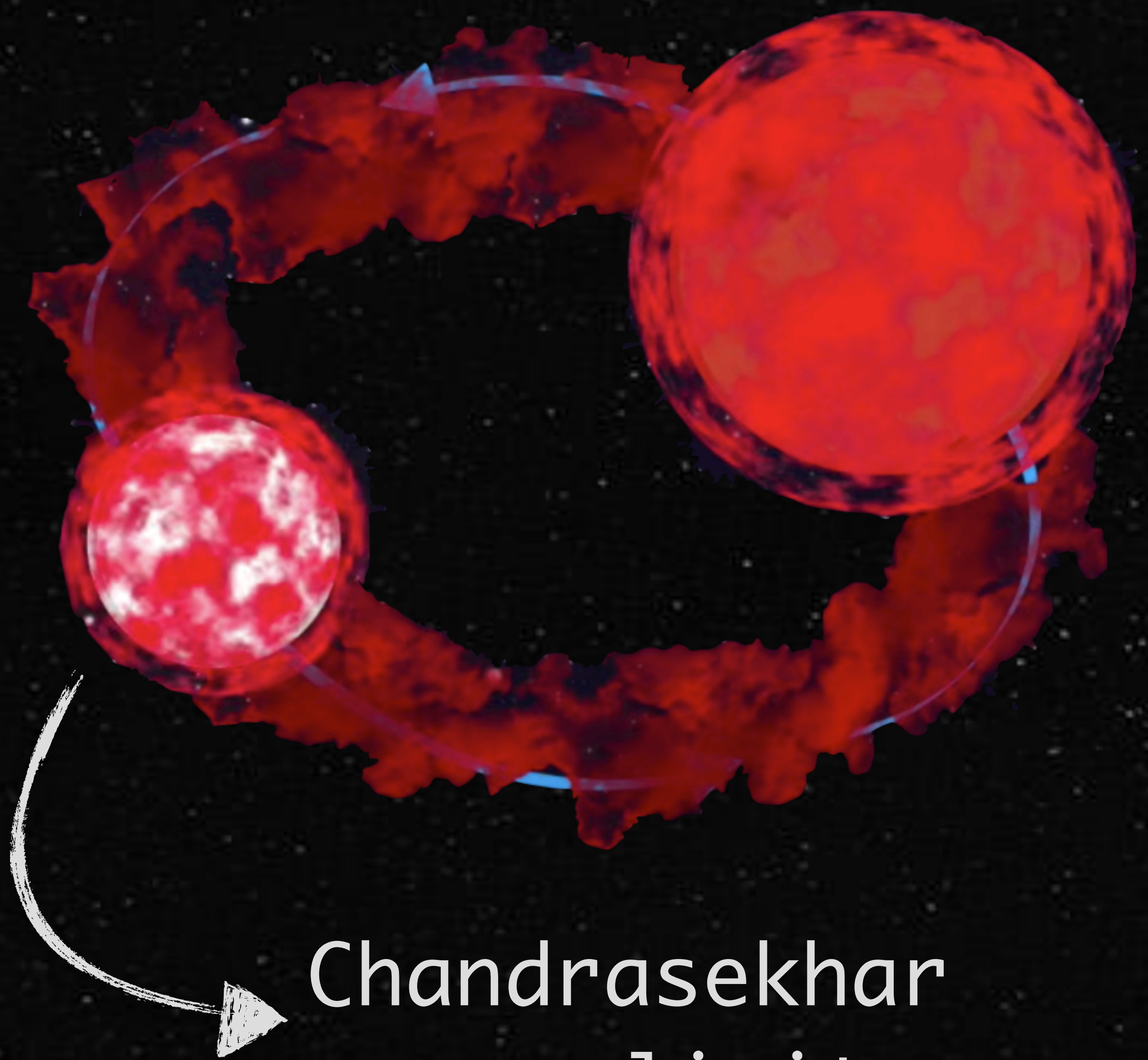
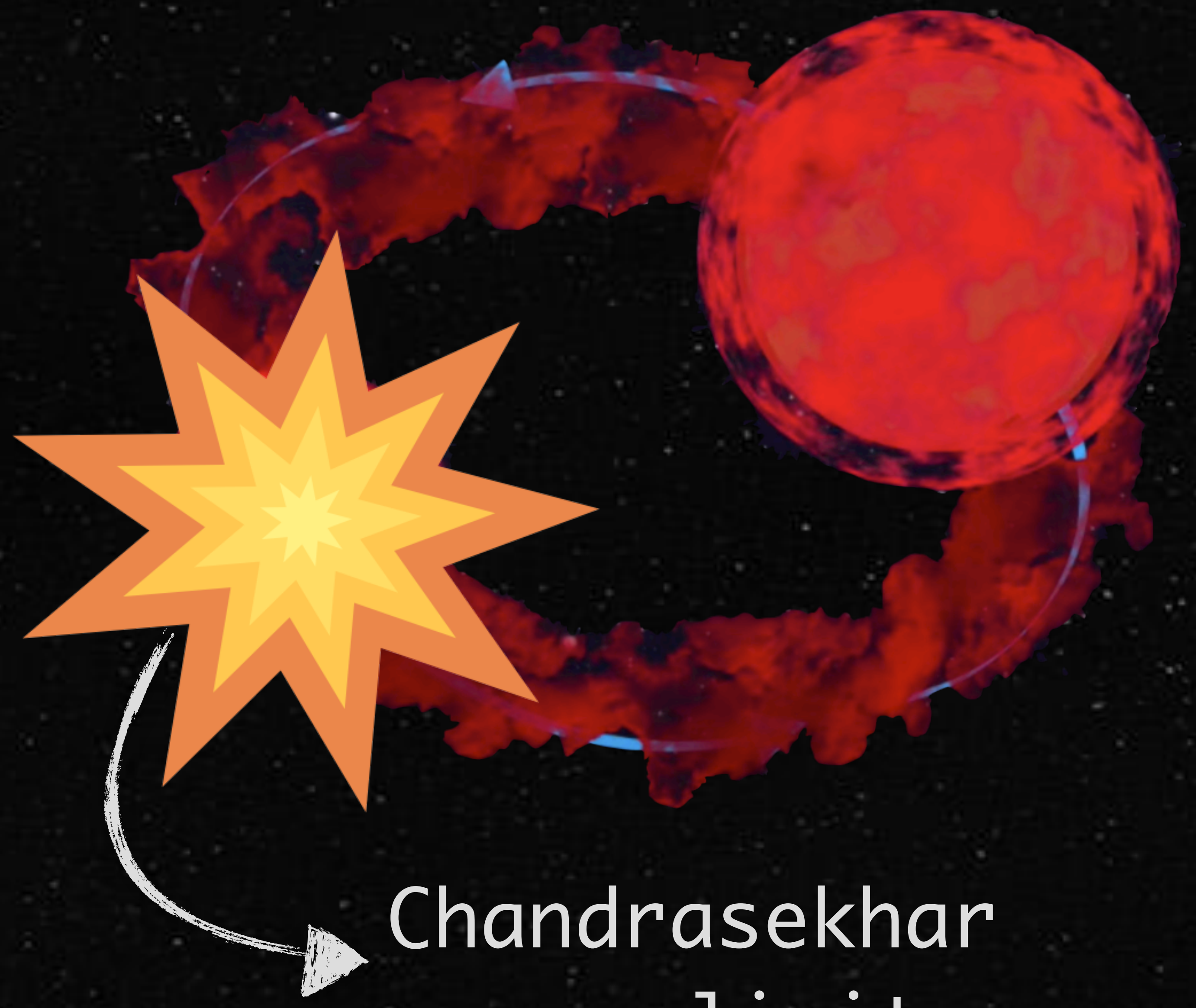


Chandrasekhar
mass limit
$1.38\ M_{\odot}$

SNe Ia as standard Candles



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Total energy ~ 10^{49} erg

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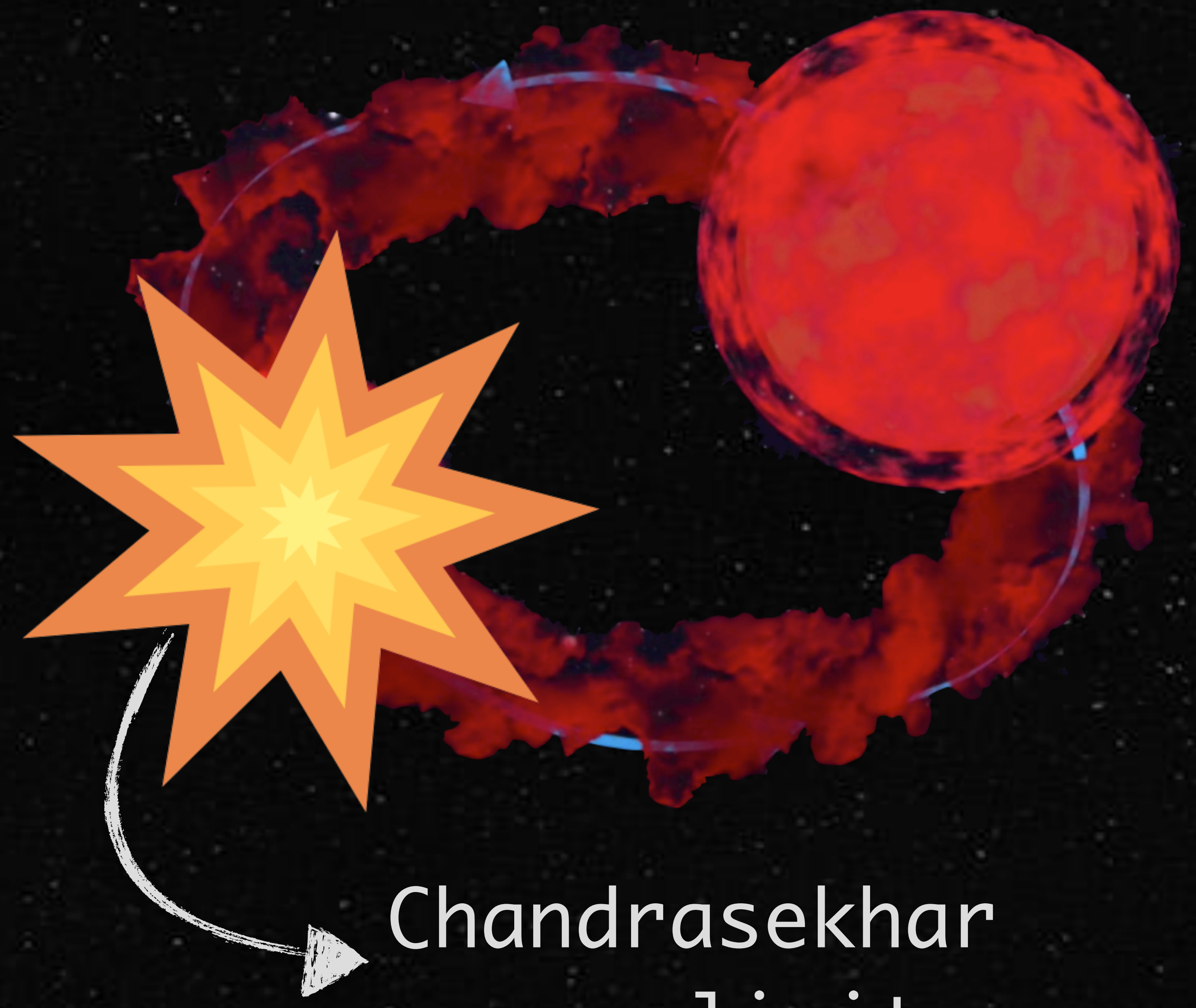

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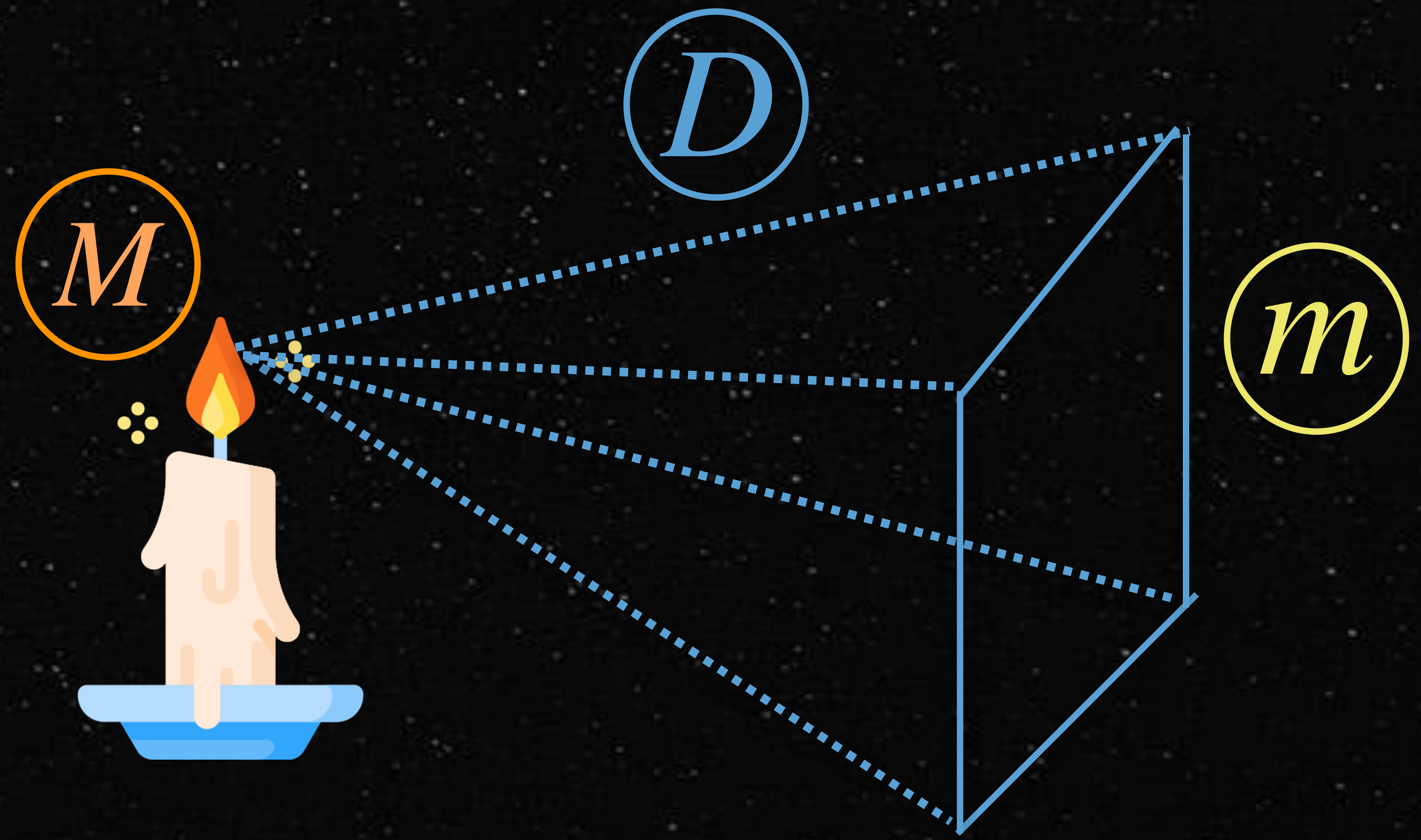
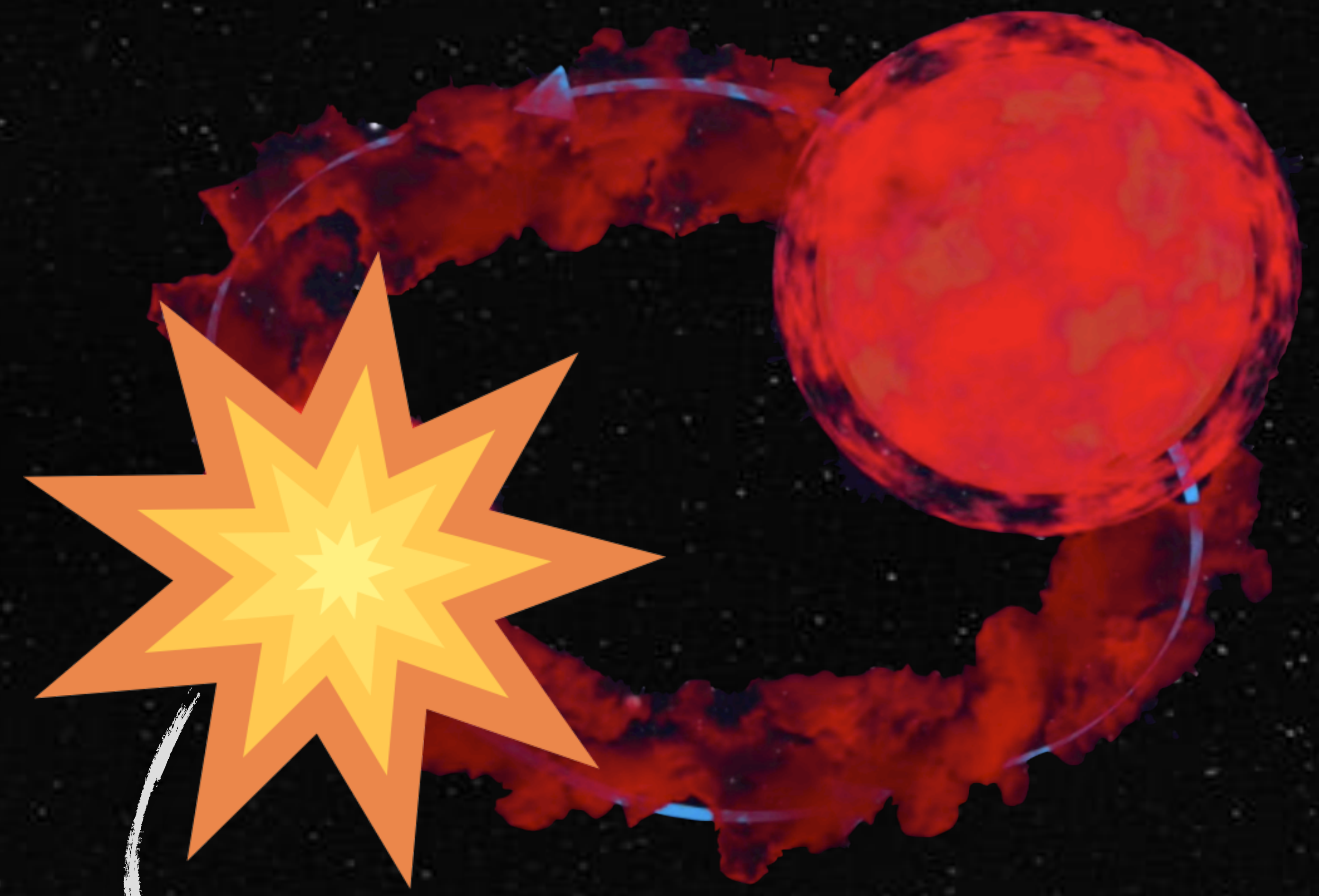


Standard Candle

$$m - M \sim \log D = \mu$$

SNe Ia as standard Candles



Chandrasekhar mass limit $1.38\ M_\odot$

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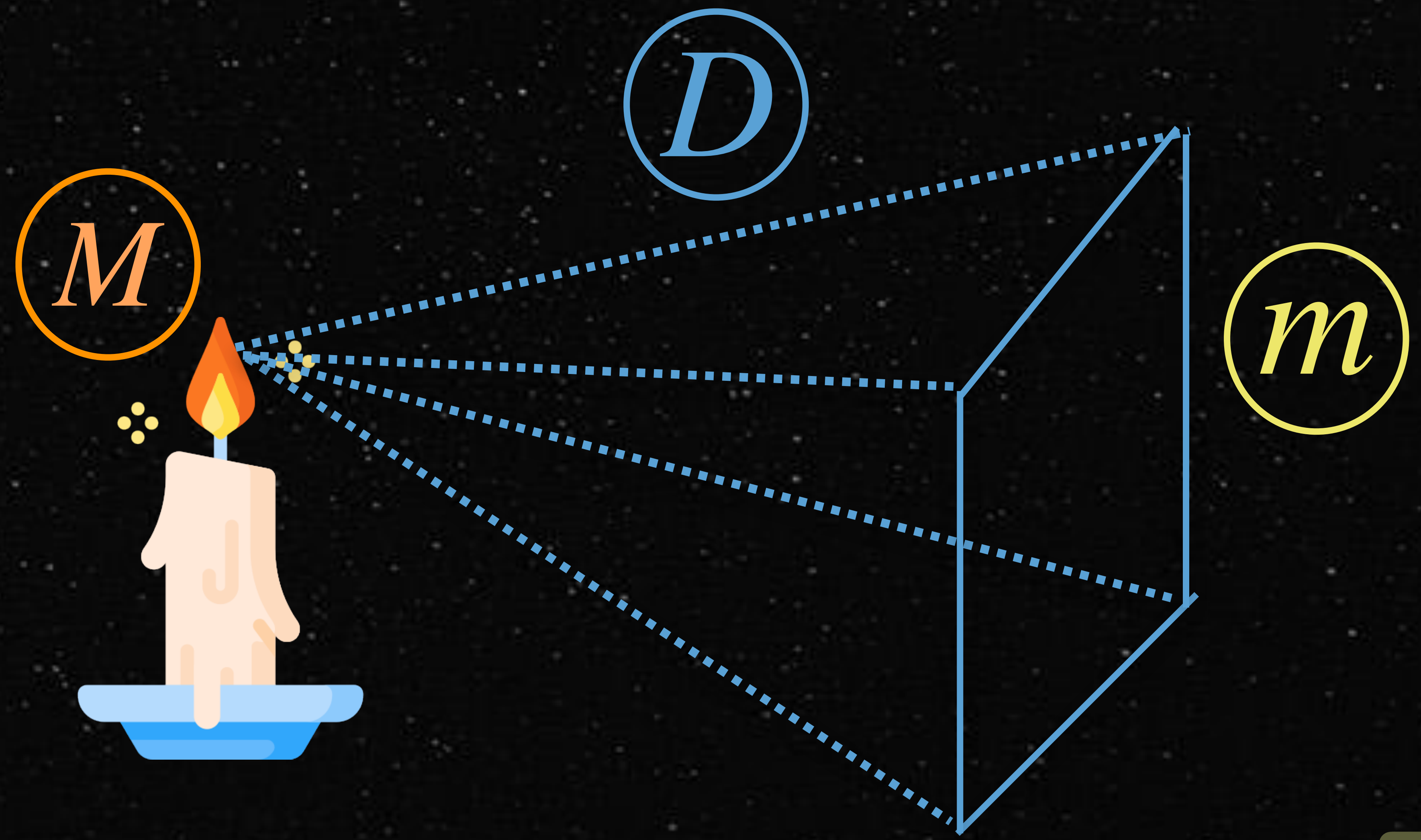

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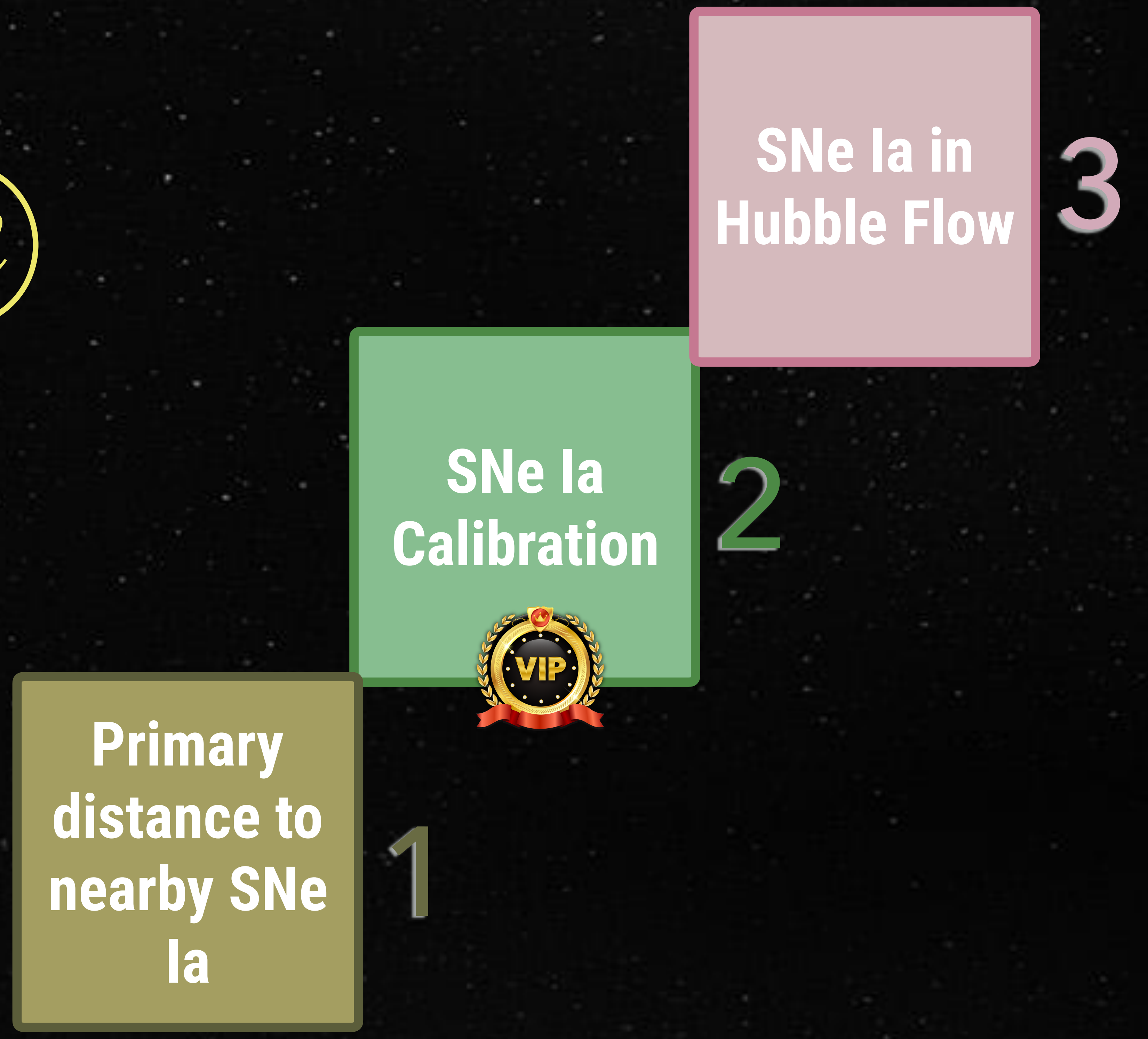

Cosmic Distance ladder

Motivation

SNe Ia Calibration

We have: Cepheid Variable Stars – SHOES [Riess et. al. 2016, 2019, 2021]

We need

ALTERNATIVE

What about other nearby indicators?
(e.g. TRGB [Freedman et.al. 2019])

COMPLEMENTARY

What about SNe Ia in Early type galaxies?

Motivation

SNe Ia Calibration

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What about other nearby indicators?
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COMPLEMENTARY

What about SNe Ia in Early type galaxies?

Use Surface Brightness Fluctuations (SBF) as SNe Ia Calibrator

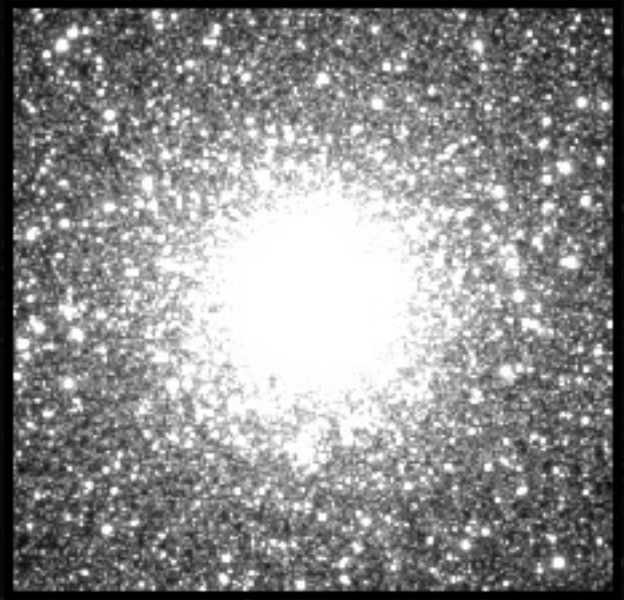
Goals

01 Measure H_0 using SBF calibrated SNe Ia distances

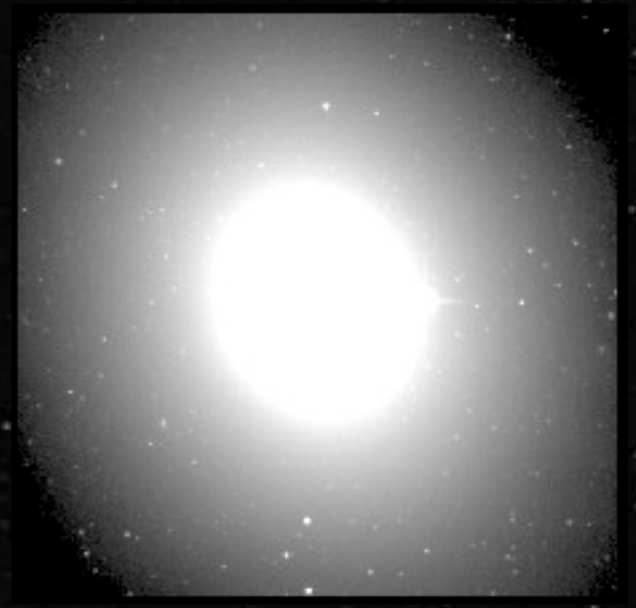
02 Compare SBF and Cepheids as SNe Ia calibrators

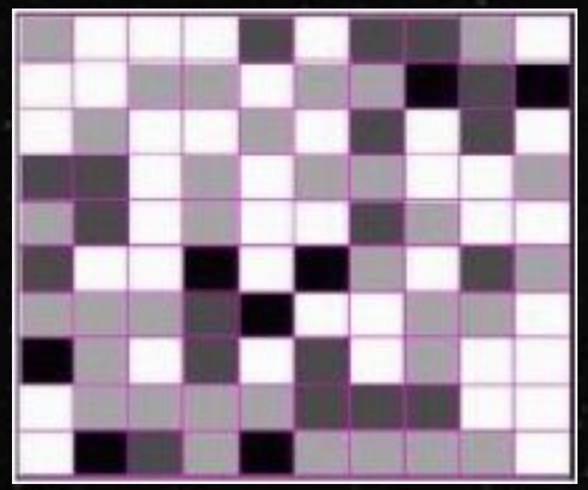
How does SBF work?

Nearby Galaxy

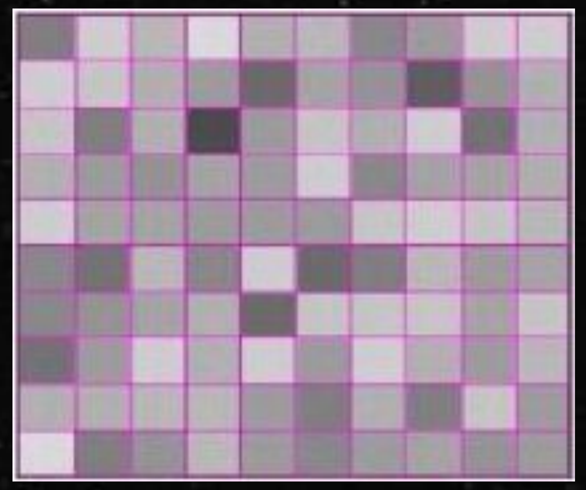


Distant Galaxy





More Fluctuations

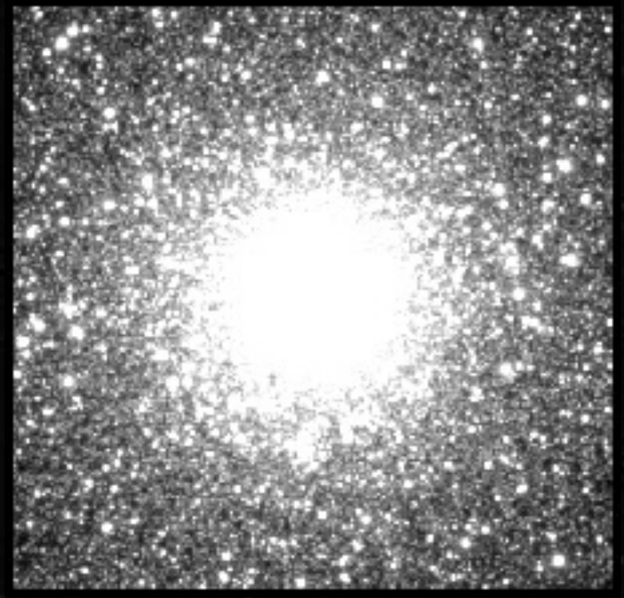


Less Fluctuations

Surface Brightness is independent of distance but variance goes inversely with distance.

How does SBF work?

Nearby Galaxy



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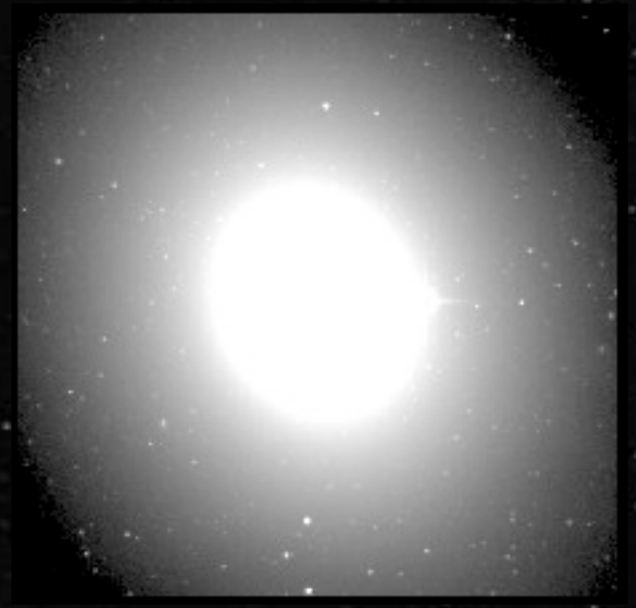

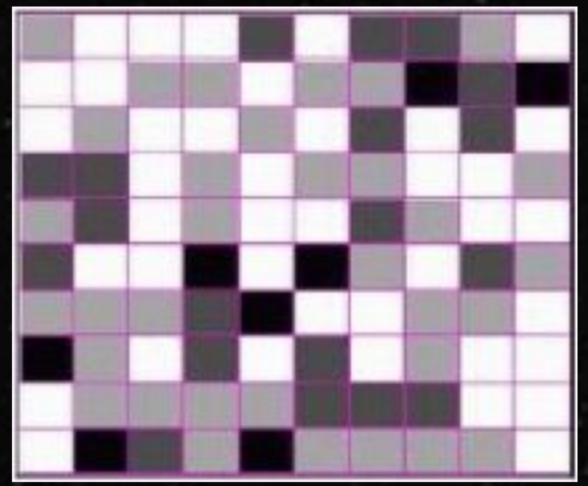

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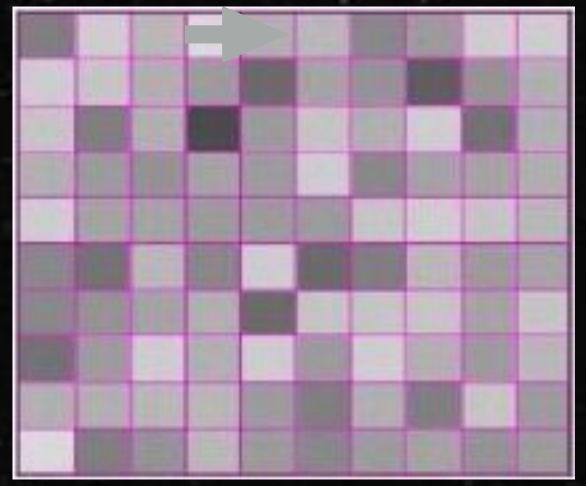

Less Fluctuations

Surface Brightness is independent of distance but variance goes inversely with distance.

Some Important points:

- ✦Needs a knowledge of Galactic modelling and stellar population, works well on E/S0 types - galaxies with homogeneous stellar populations.
- ✦less reddening in older populations
- ✦Does not need resolved stellar photometry and periodic observations
- ✦Reaches larger distances → larger samples
- ✦Future : JWST and Vera C. Rubin obs. will augment the sample in terms of number and distance

Calibrator Sample

- ✦A sample of SNe whose host galaxies have SBF distance estimates
- ✦Removing outliers: Fast decliners (s_BV > 0.5), highly red (color < 0.3), data quality and cadence, optical light curves (B and V band)

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24 SNe Ia

SBF Calibrator Sample

From existing SBF catalogs in literature

Calibrator Sample

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24 SNe Ia

SBF Calibrator Sample

From existing SBF catalogs in literature

19 SNe Ia

SHOES Calibrator Sample

From Riess et. al. 2016

Calibrator Sample

✦A sample of SNe whose host galaxies have SBF distance estimates

✦Removing outliers: Fast decliners (s_BV > 0.5), highly red (color < 0.3), data quality and cadence, optical light curves (B and V band)

24 SNe Ia

SBF Calibrator Sample

From existing SBF catalogs in literature

19 SNe Ia

SHOES Calibrator Sample

From Riess et. al. 2016

96 SNe Ia

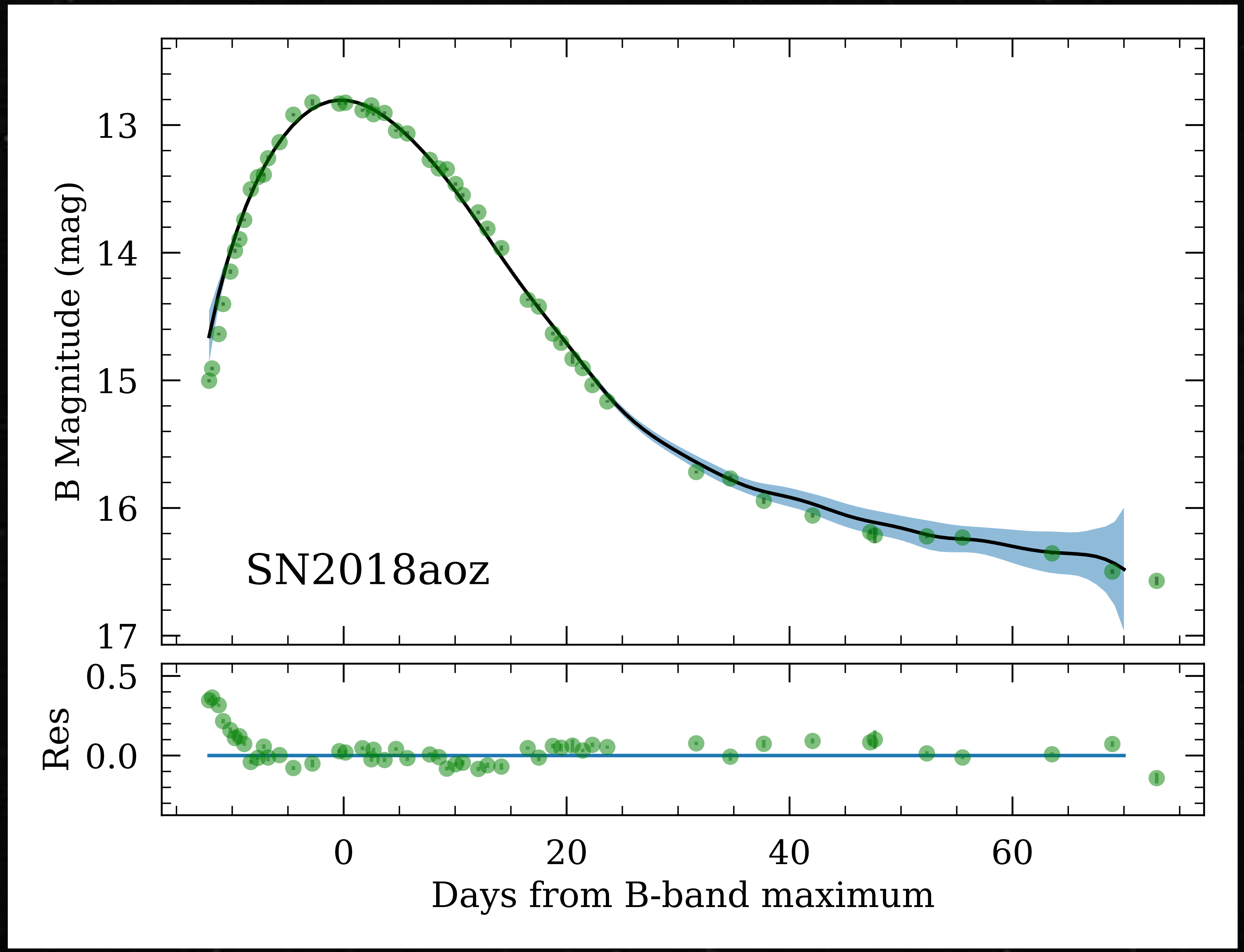
Hubble Flow sample

From the PANTHEON sample [Scolnic et al. 2018]

$0.02 < z < 0.08$

Light Curve Fitting

- Light Curve (LC) fitting with SNooPy [C. Burns et al. 2011] - Facilitates a python environment for fitting SNe Ia light curves
- Performs K-corrections and galactic extinction correction
- Get LC shape (s_{BV}), B-band maximum (m_B) and color $(m_B - m_V)$



Fit each light curve in the three samples

SNe Ia luminosity calibration

In 1993, M.Phillips

How fast a SNe Ia fades is correlated to its Intrinsic brightness!

SNe Ia luminosity calibration

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$$M = P^0 + P^1(s_{BV} - 1)$$

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$$M = P^0 + P^1(s_{BV} - 1) + R(m_B - m_V)$$

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since $$m = M + \mu$$

SNe Ia luminosity calibration

$$m_B = P^0 + P^1(s_{BV} - 1) + R(m_B - m_V) + \mu_{calib}$$ → **Calibrator sample**

$$\mu_{cosmo} = f(z, H_0)$$ → **Hubble flow sample**

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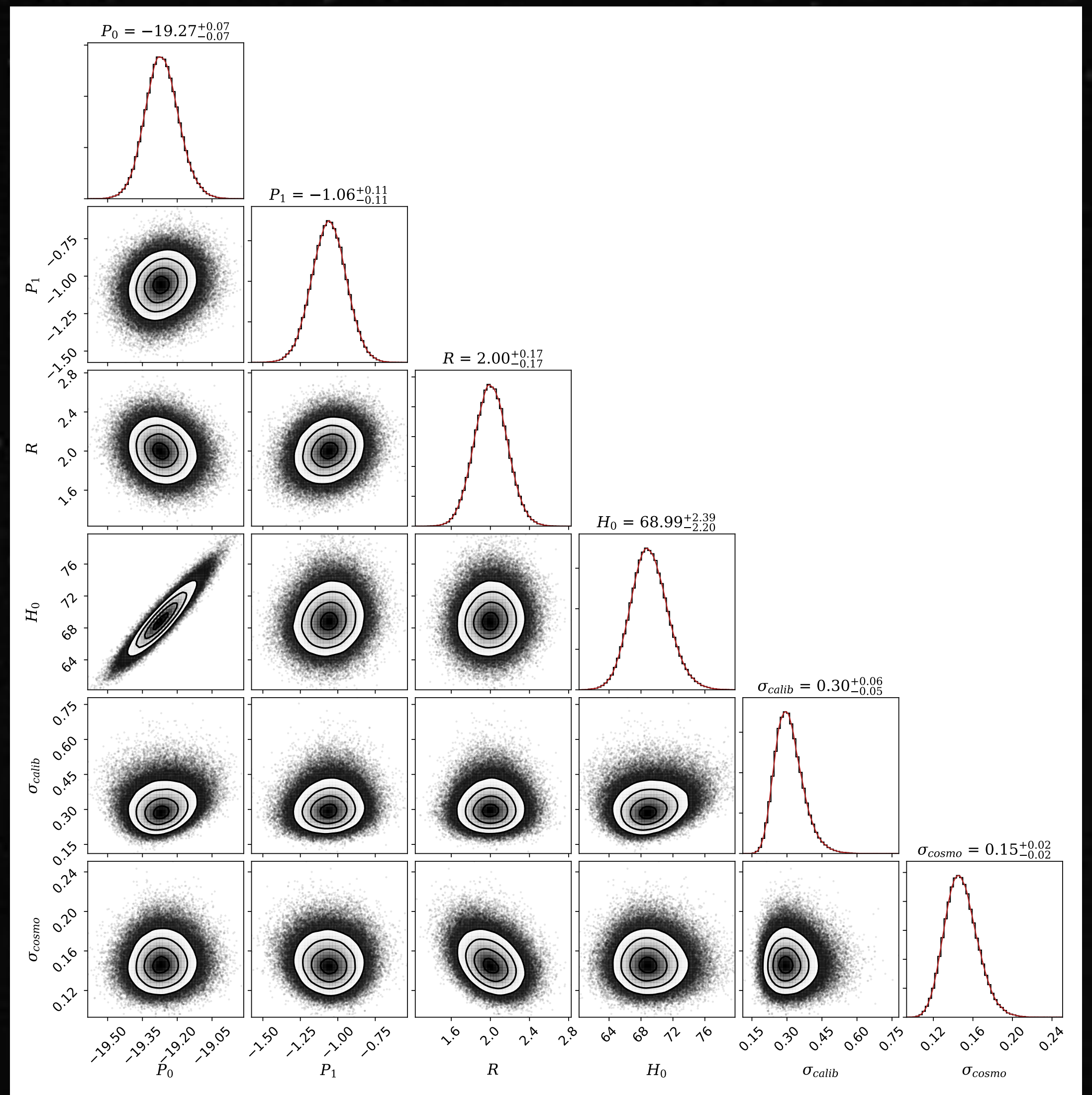
LC data

Models

→ **Bayesian Framework** →



Rigorous error estimation

SNe Ia luminosity calibration

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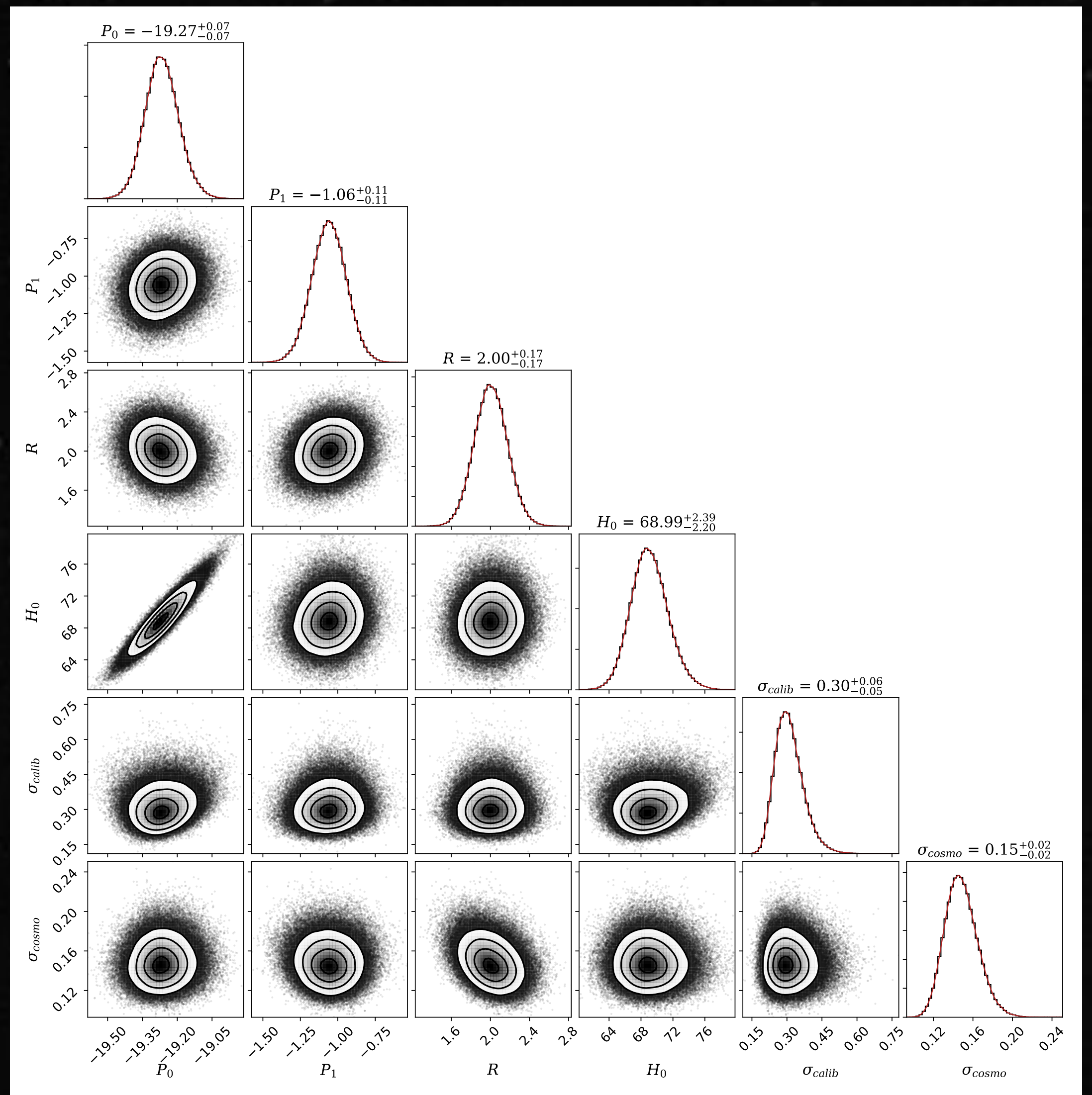
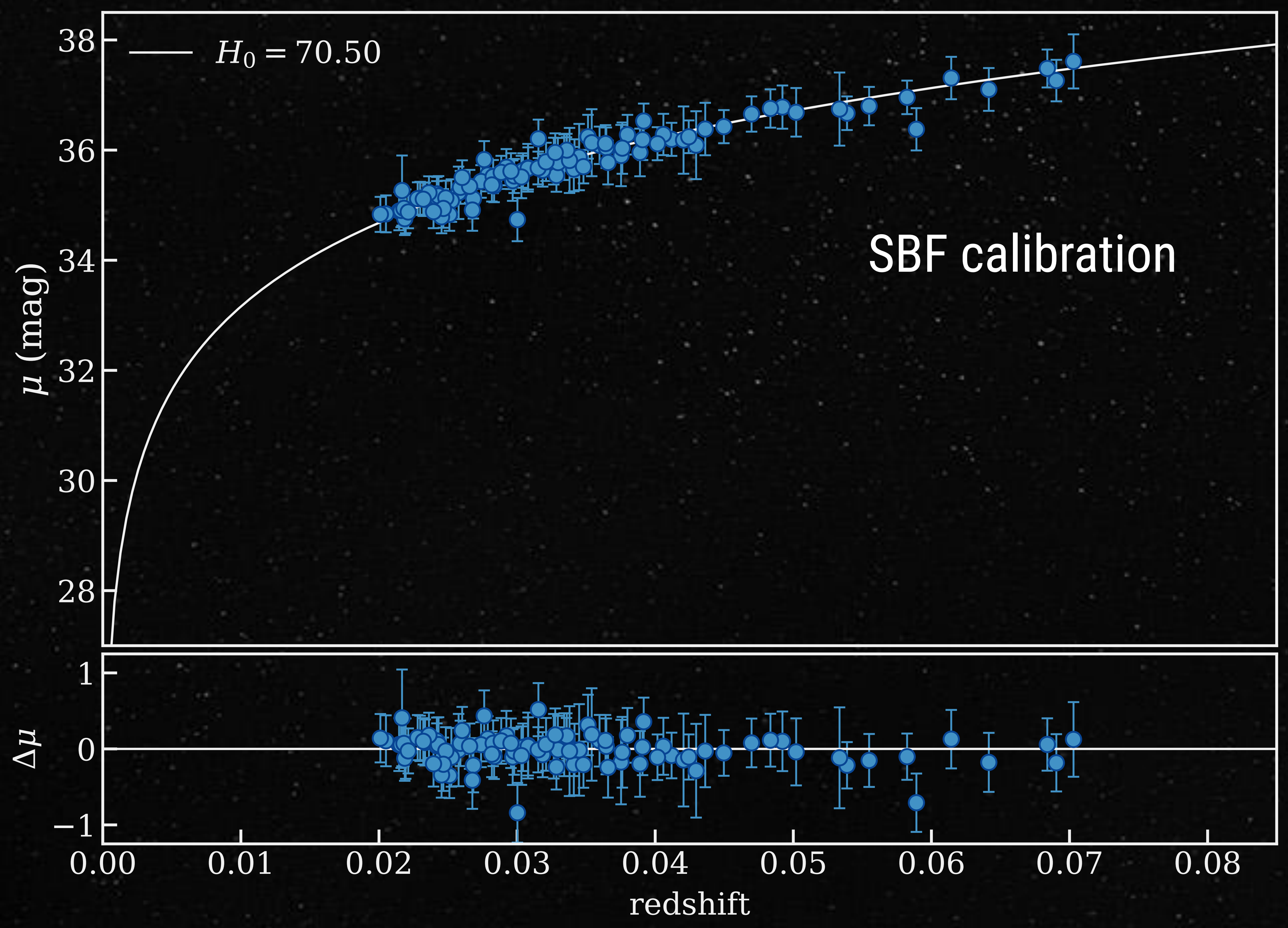
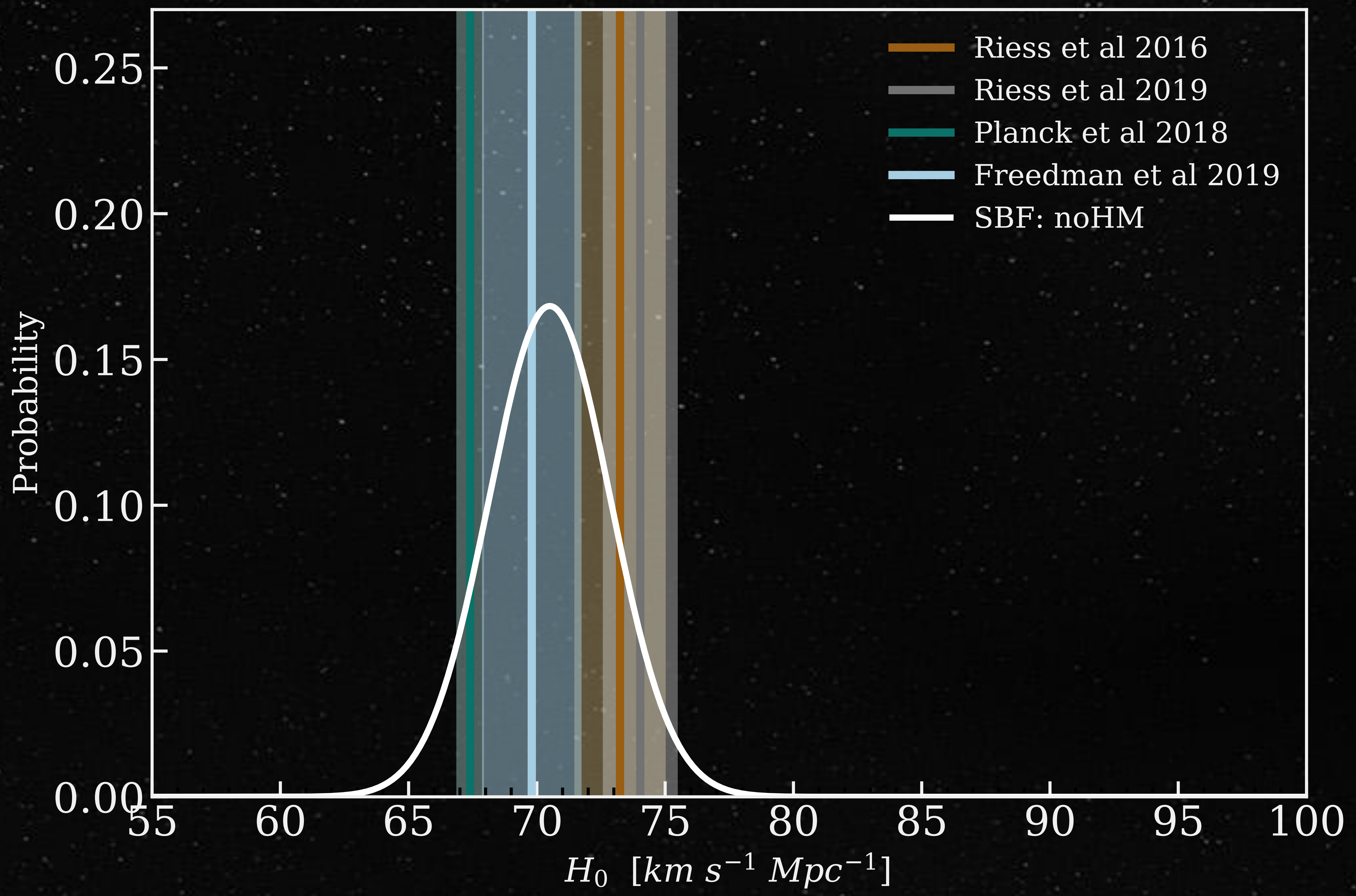


Rigorous error estimation

We simultaneously fit for the hyperparameters (P_0, P_1, R) and H_0

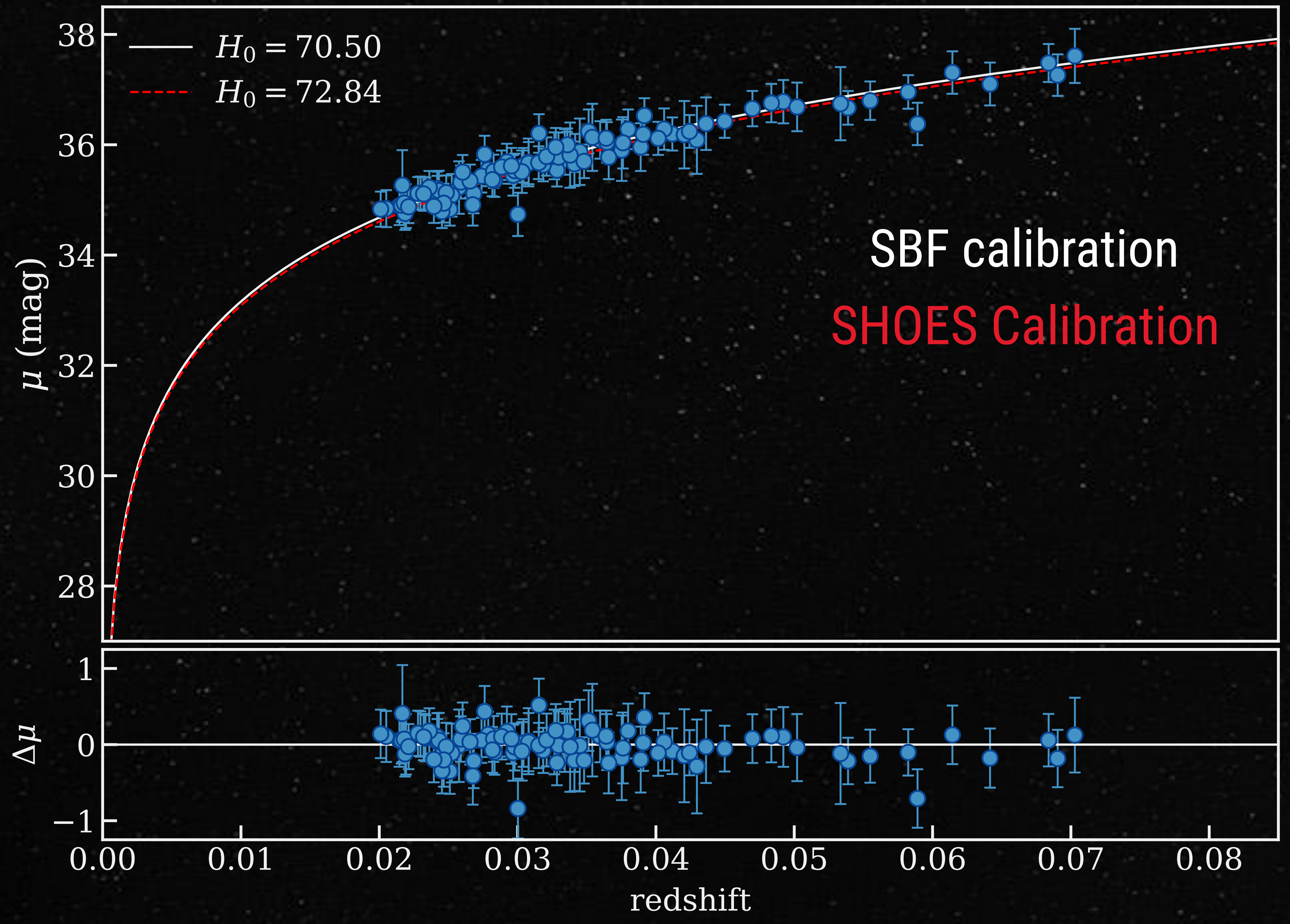
Hubble Constant

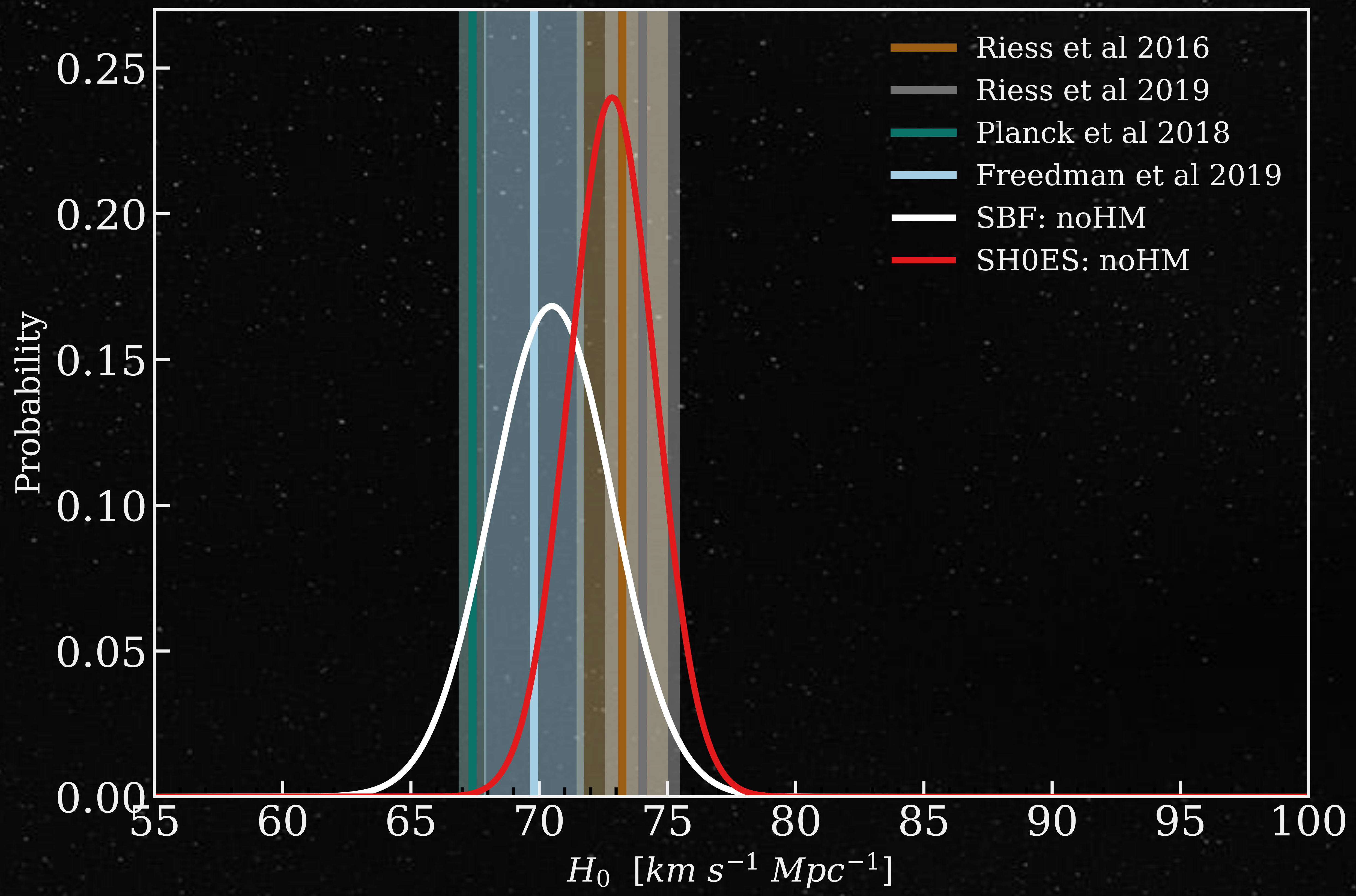




$$H_0 = 70.50 \pm 2.37$$
Km s^{-1} Mpc^{-1}

Hubble Constant



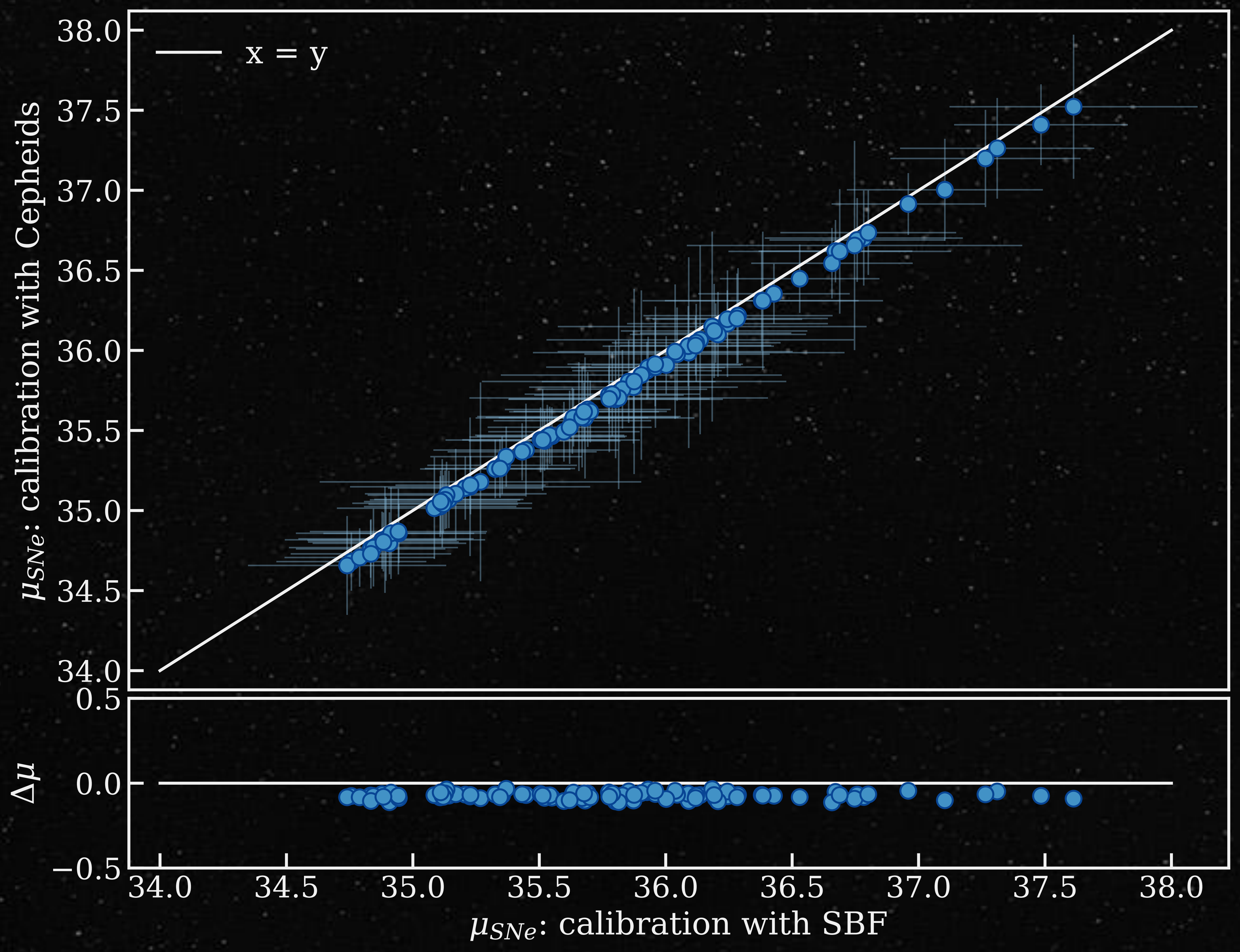


$$H_0 = 70.50 \pm 2.37$$ Km s^{-1} Mpc^{-1}

$$H_0 = 72.84 \pm 1.66$$ Km s^{-1} Mpc^{-1}

→ Consistent with Riess et al 2016 $(H_0 = 73.24 \pm 1.74)$

Distance Moduli comparison



$$\overline{\Delta\mu} = 0.07 \pm 0.02 \text{ mag}$$

$$\sim 3.3\,\% \text{ in } H_0$$

SBF calibration provides a longer distance scale as compared to Cepheids by ~3.3% !

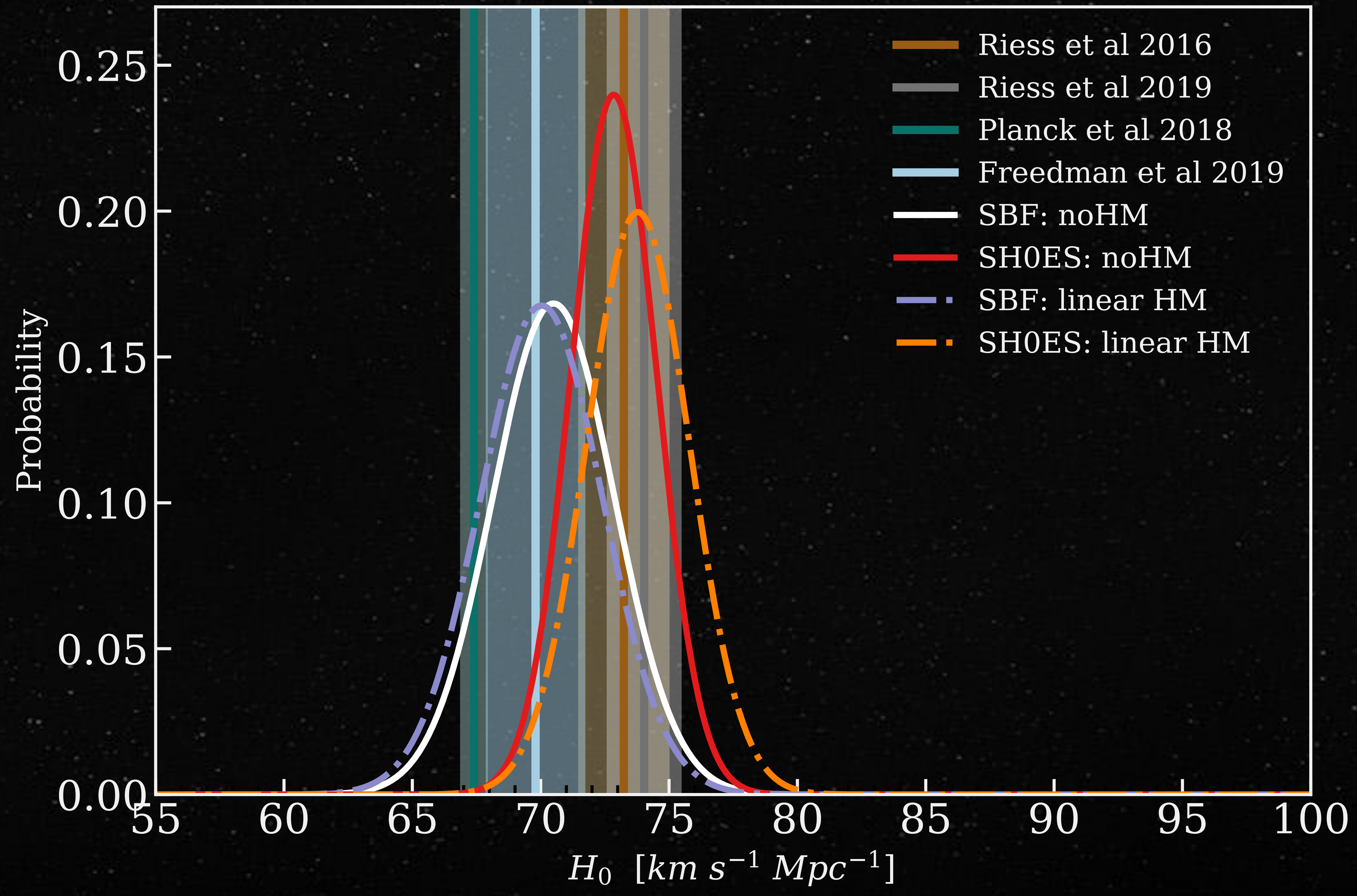
?? SNe Ia in early types are brighter ??

[M.V. Pruzhinskaya et al. 2020], [SyedA. Uddin et al.2020]

Difference may be attributed to different environments and/or progenitor properties of the two calibration samples.

Host Mass dependnece (linear)

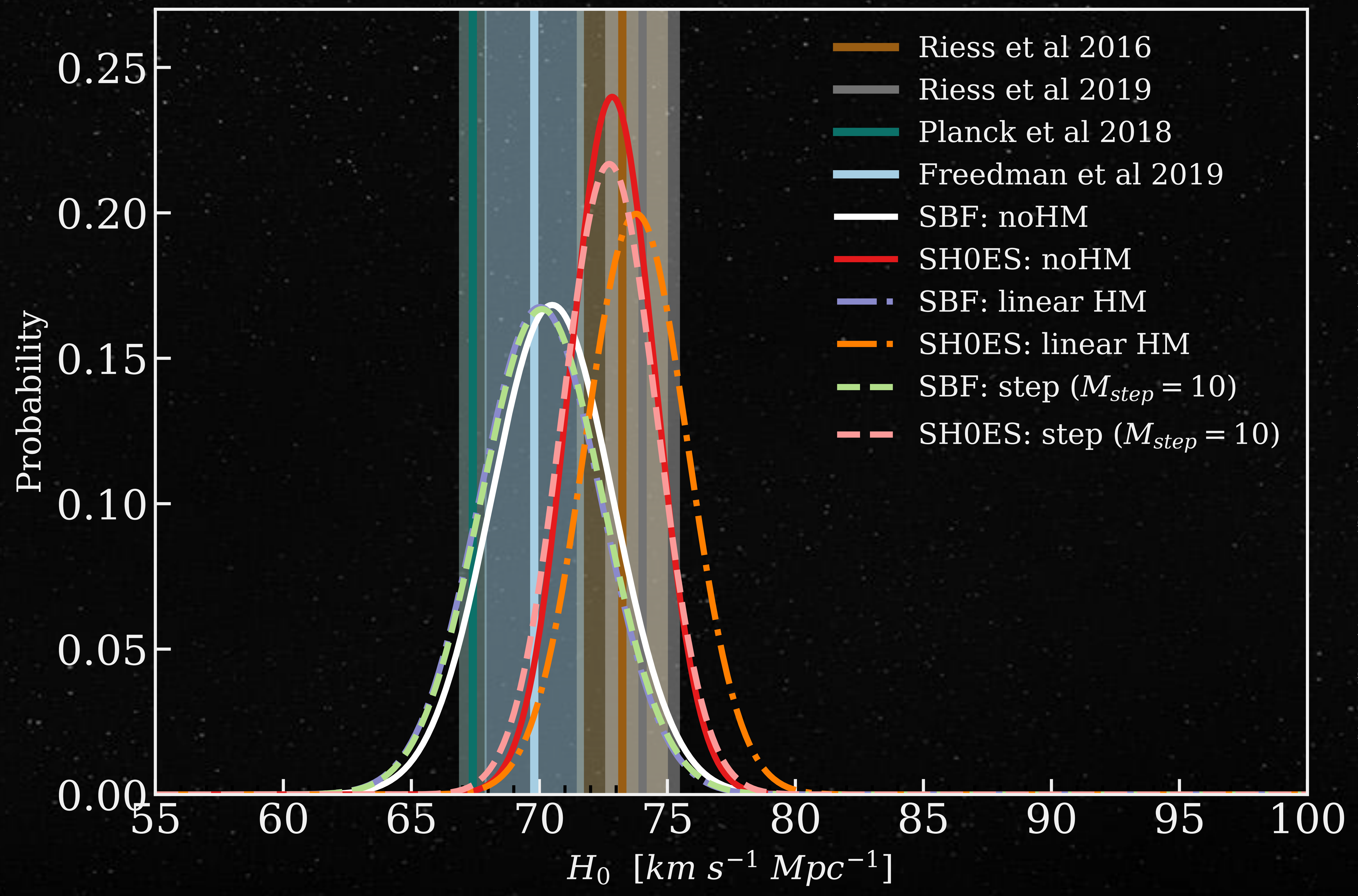
$$m_B = P^0 + P^1(s_{BV} - 1) + R(m_B - m_V) + \boxed{\alpha(log\frac{M_*}{M_\odot} - M_0)} + \mu_{calib}$$



Host Mass dependnece (Step)

$$m_B = P^0 + P^1(s_{BV} - 1) + R(m_B - m_V) + \boxed{\alpha_{step}} + \mu_{calib}$$

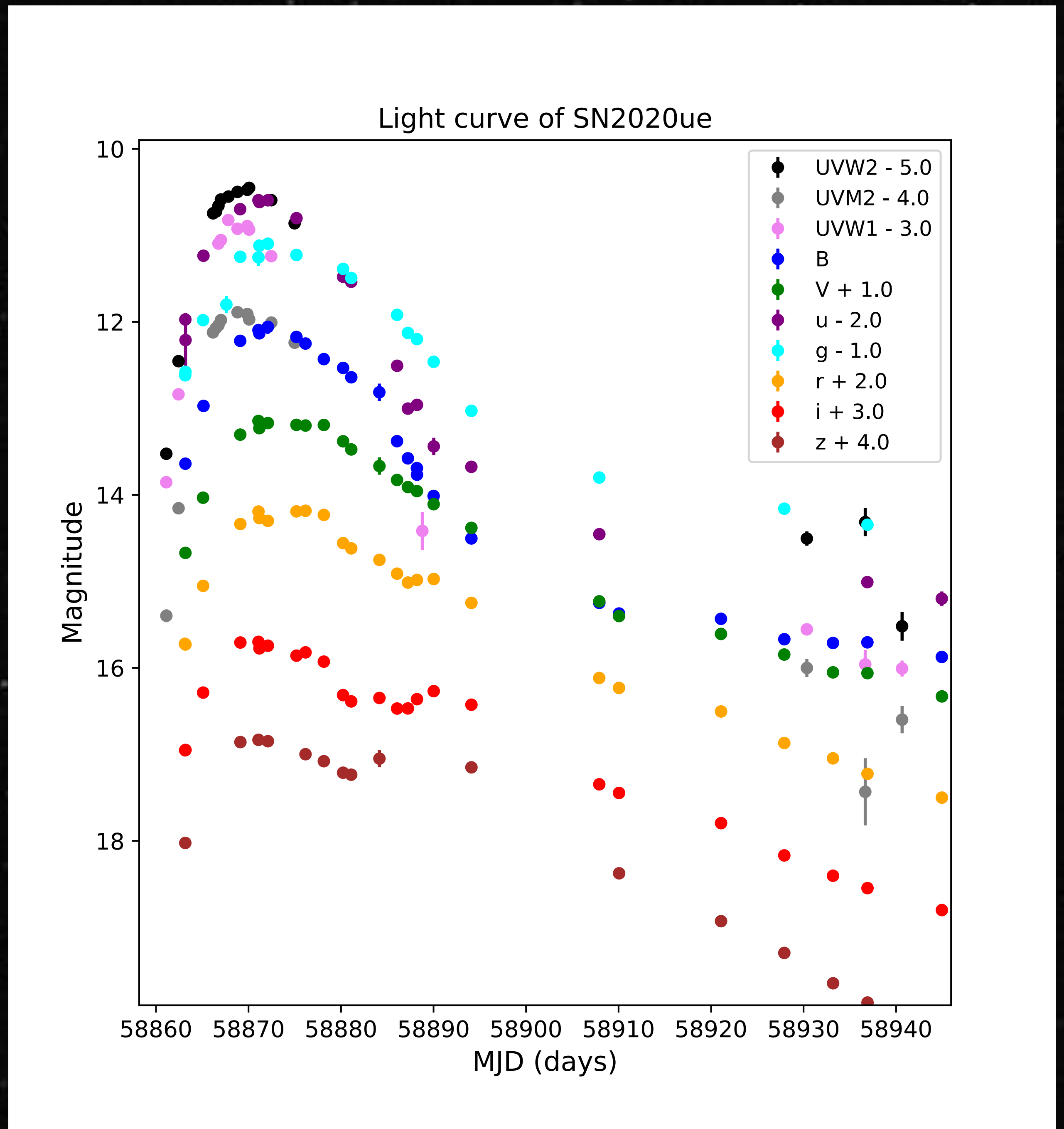
where $\alpha_{step} \neq 0$ for $logM_* < 10$, else it is zero



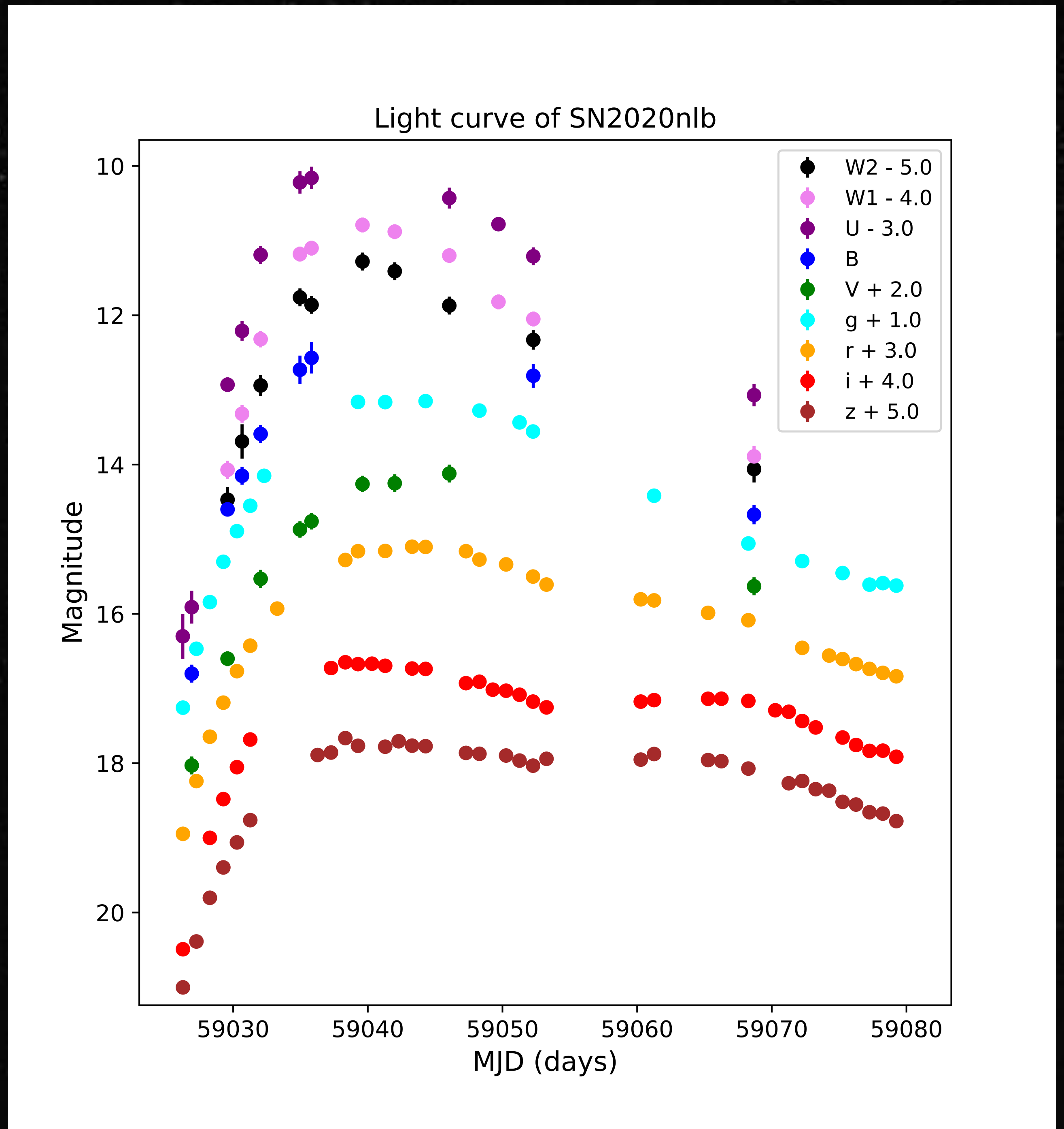
Mass correction does not account for the difference. The dependence on progenitor scenarios remains a possible astrophysical intepretation for the observed differences.

New data

SN2020ue
in NGC4636



SN2020nlb
in M85



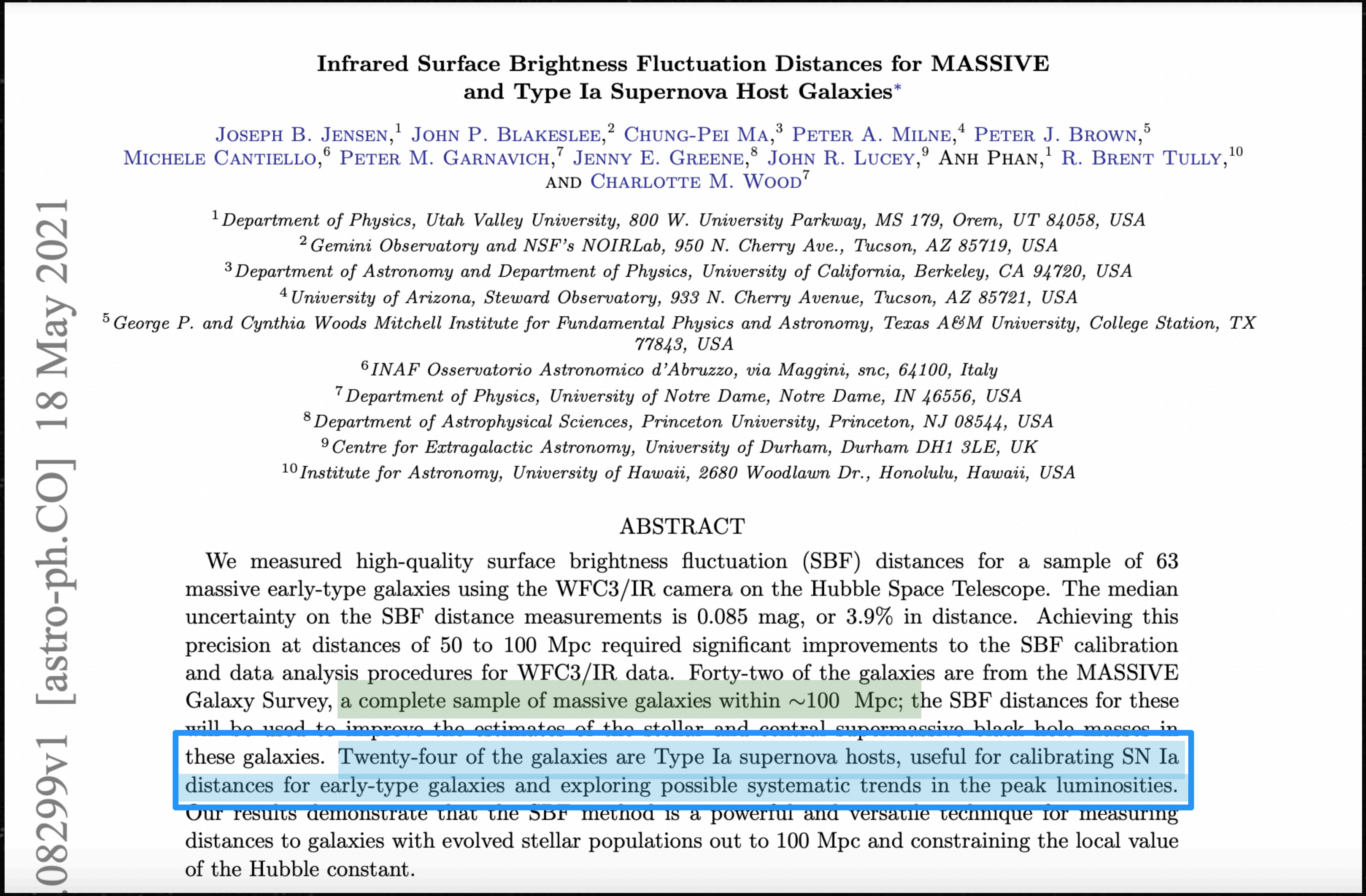
SN2021qvv
in NGC4442

Coming soon…

Data in optical and UV bands from UVOT and Young Supernova Survey (YSE) [Jones et. al. 2021]

N Khetan, L Izzo, et. al. 2021 *(In prep)*

New data



.08299v1 [astro-ph.CO] 18 May 2021

Infrared Surface Brightness Fluctuation Distances for MASSIVE and Type Ia Supernova Host Galaxies*

Joseph B. Jensen,[1] John P. Blakeslee,[2] Chung-Pei Ma,[3] Peter A. Milne,[4] Peter J. Brown,[5] Michele Cantiello,[6] Peter M. Garnavich,[7] Jenny E. Greene,[8] John R. Lucey,[9] Anh Phan,[1] R. Brent Tully,[10] and Charlotte M. Wood[7]

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[2] *Gemini Observatory and NSF's NOIRLab, 950 N. Cherry Ave., Tucson, AZ 85719, USA*
[3] *Department of Astronomy and Department of Physics, University of California, Berkeley, CA 94720, USA*
[4] *University of Arizona, Steward Observatory, 933 N. Cherry Avenue, Tucson, AZ 85721, USA*
[5] *George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA*
[6] *INAF Osservatorio Astronomico d'Abruzzo, via Maggini, snc, 64100, Italy*
[7] *Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA*
[8] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[9] *Centre for Extragalactic Astronomy, University of Durham, Durham DH1 3LE, UK*
[10] *Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, Hawaii, USA*

ABSTRACT

We measured high-quality surface brightness fluctuation (SBF) distances for a sample of 63 massive early-type galaxies using the WFC3/IR camera on the Hubble Space Telescope. The median uncertainty on the SBF distance measurements is 0.085 mag, or 3.9% in distance. Achieving this precision at distances of 50 to 100 Mpc required significant improvements to the SBF calibration and data analysis procedures for WFC3/IR data. Forty-two of the galaxies are from the MASSIVE Galaxy Survey, a complete sample of massive galaxies within ~100 Mpc; the SBF distances for these will be used to improve the estimates of the stellar and central supermassive black hole masses in these galaxies. Twenty-four of the galaxies are Type Ia supernova hosts, useful for calibrating SN Ia distances for early-type galaxies and exploring possible systematic trends in the peak luminosities. Our results demonstrate that the SBF method is a powerful and versatile technique for measuring distances to galaxies with evolved stellar populations out to 100 Mpc and constraining the local value of the Hubble constant.

24 SNe Ia hosts with latest SBF distance estimates!

Conclusions

1. **SBF can be used as SNe Ia calibrators!**
2. H_0 value sits midway between the tension range
3. SNe Ia luminosity correlates with the host type, the ones hosted in early types seem to be brighter compared to the ones in late types
4. Unifrom SBF distances with updated zero-point
5. Explore more properties of host galaxies with future surveys

Khetan et al. 2021

02

Superluminous supernovae as cosmological probes

The restframe Ultraviolet of superluminous supernova: Potential as cosmological probes

Superluminous Supernovae (SLSNe)

radiated energy
~10^{51} erg

High peak luminosity
~ 2 mags brighter than SNe Ia

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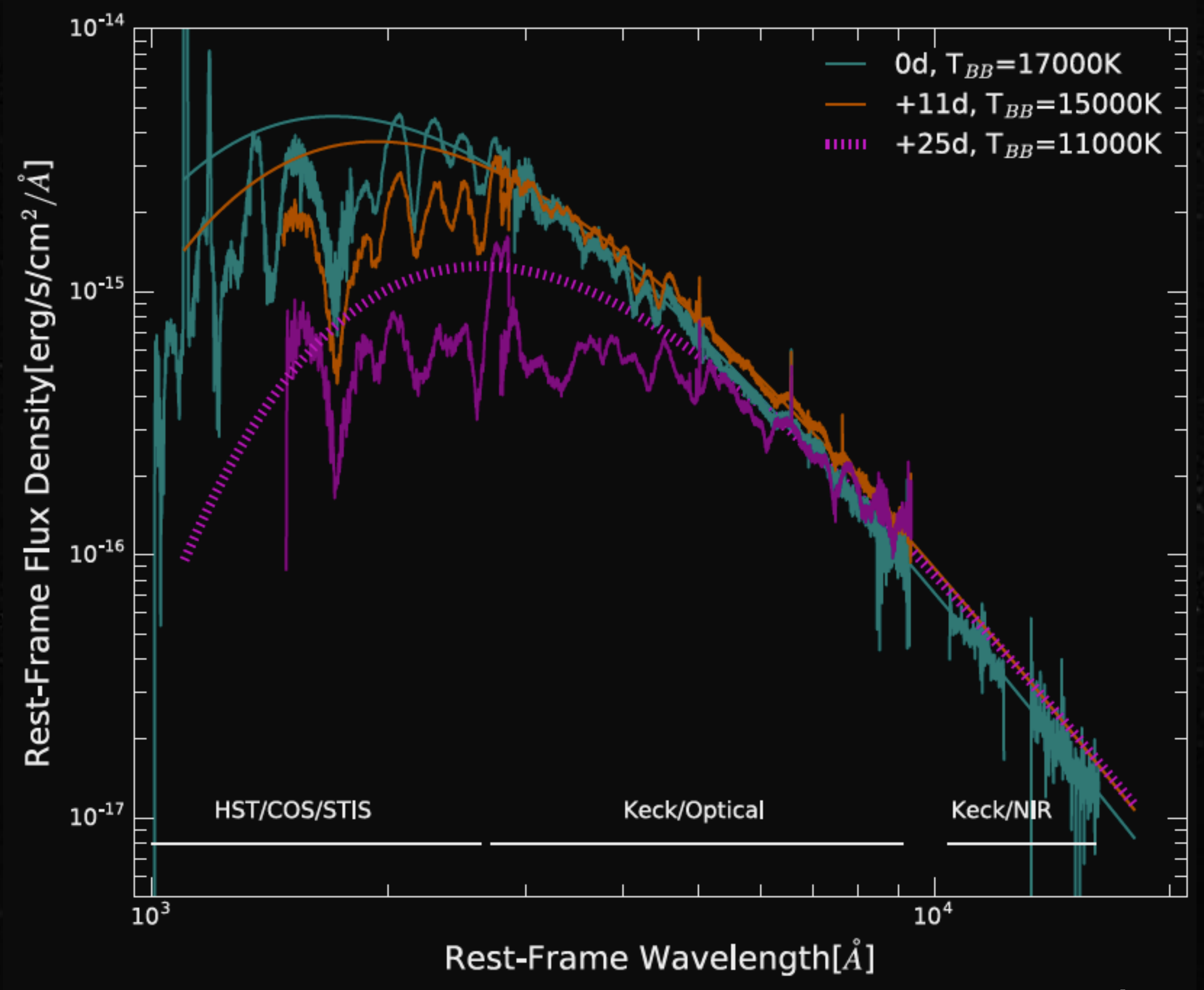
very blue events
UV-luminous



Yan et. al. 2016

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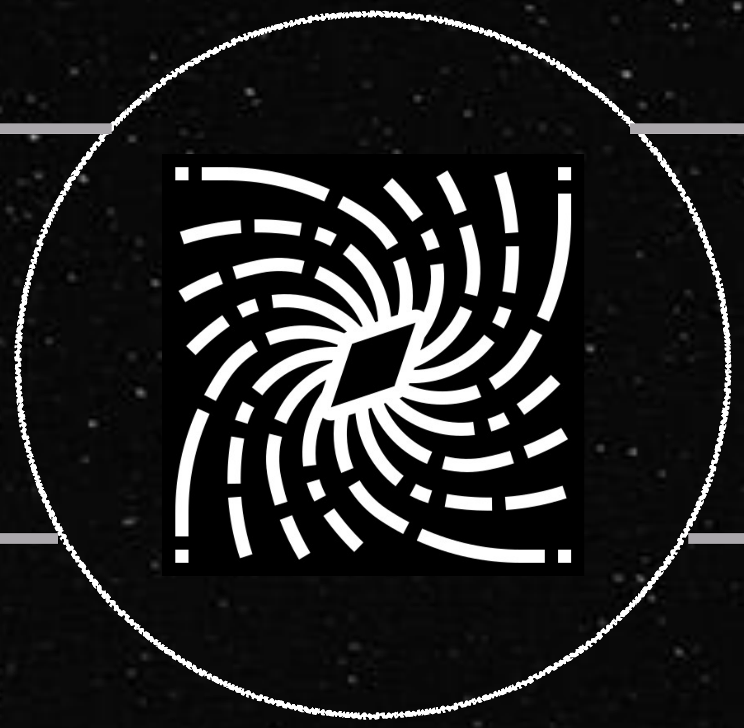
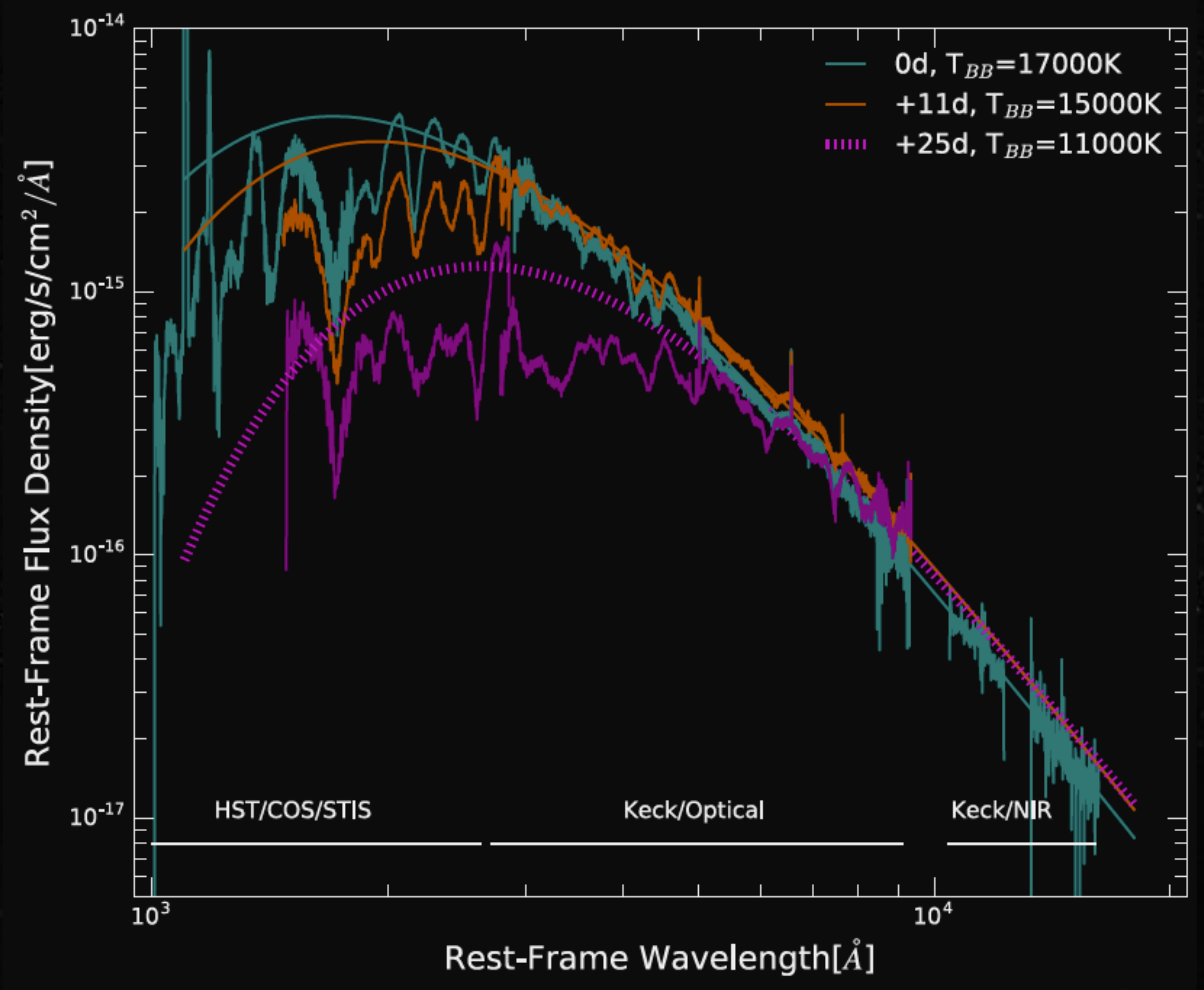


Slowly evolving
light curves

very blue events
UV-luminous



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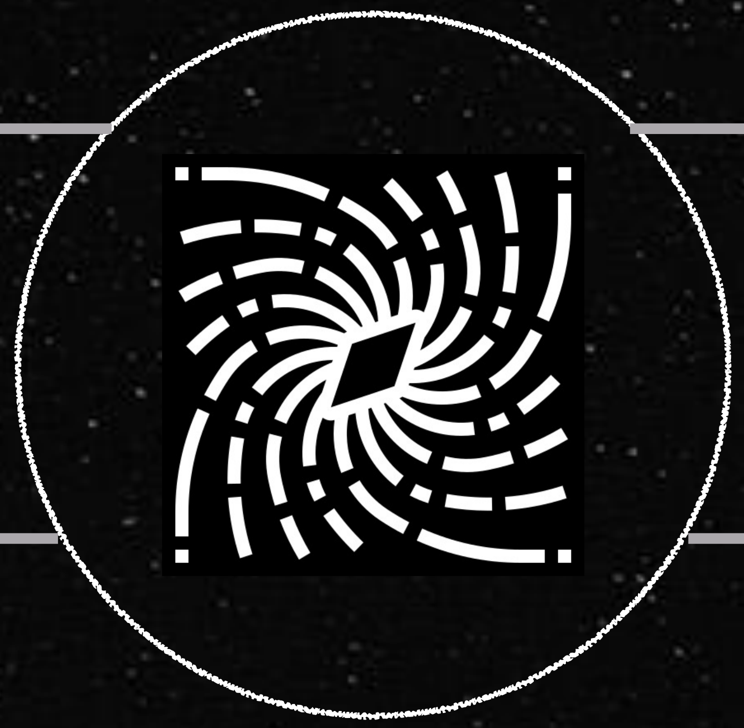

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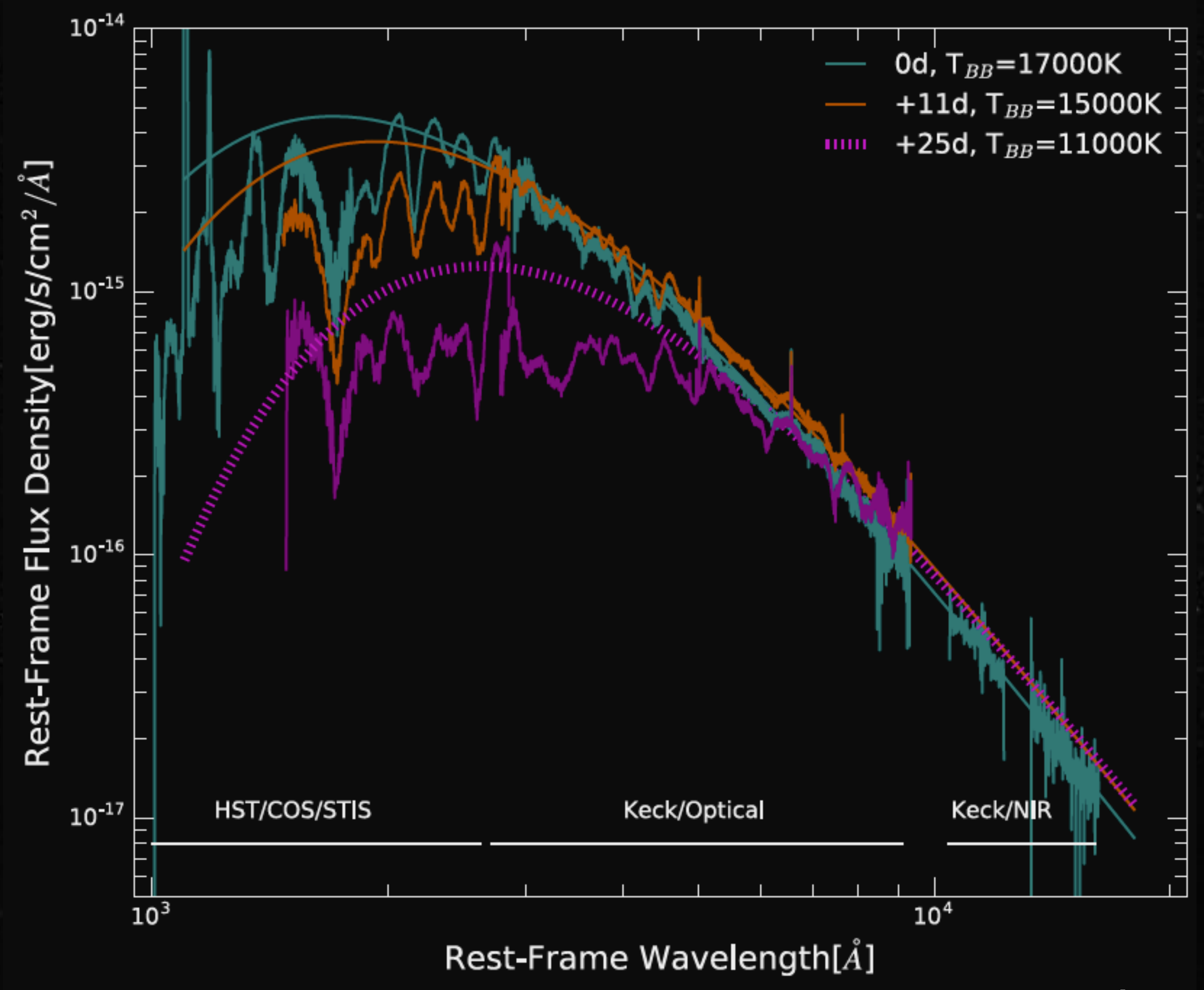
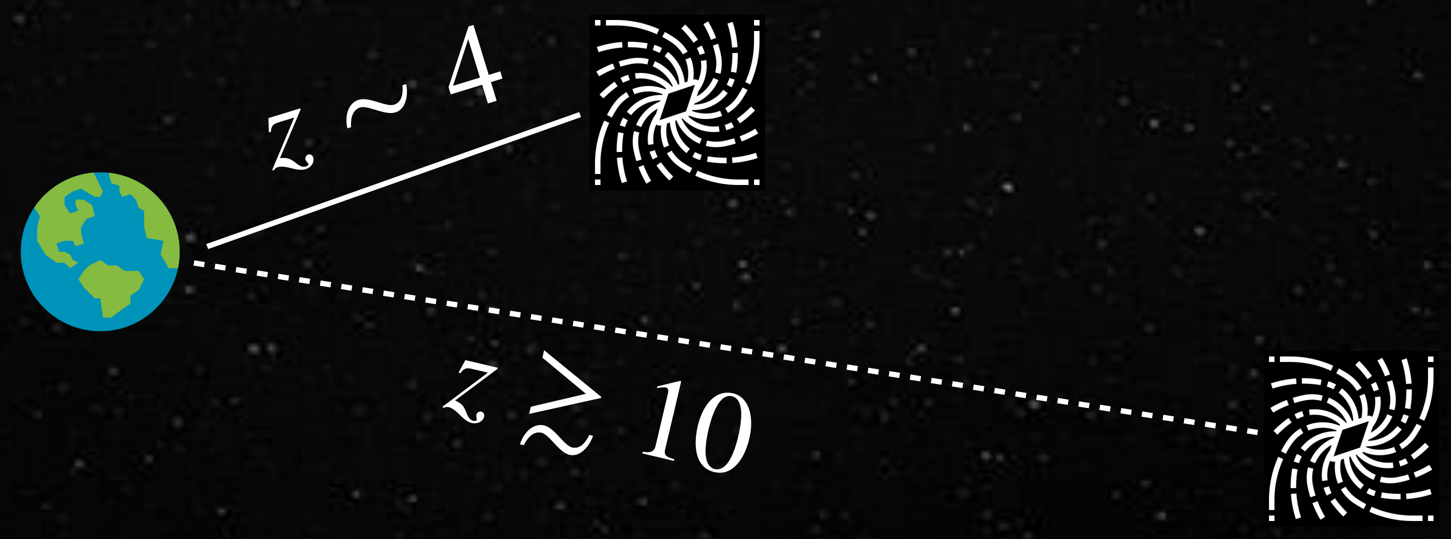


Yan et. al. 2016

Detectable at high redshifts

UV continuum at high redshifts is observed in optical and NIR bands on earth



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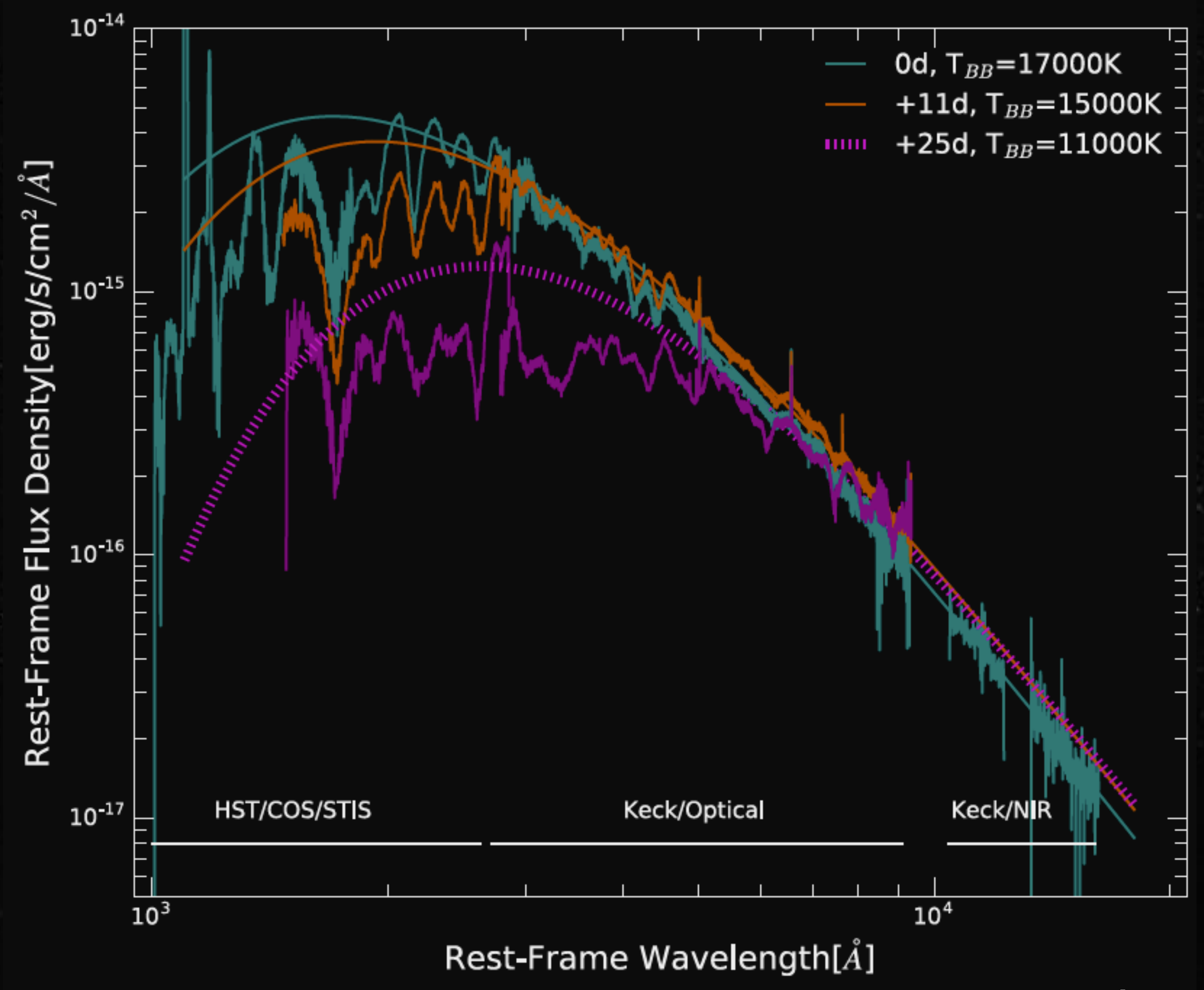

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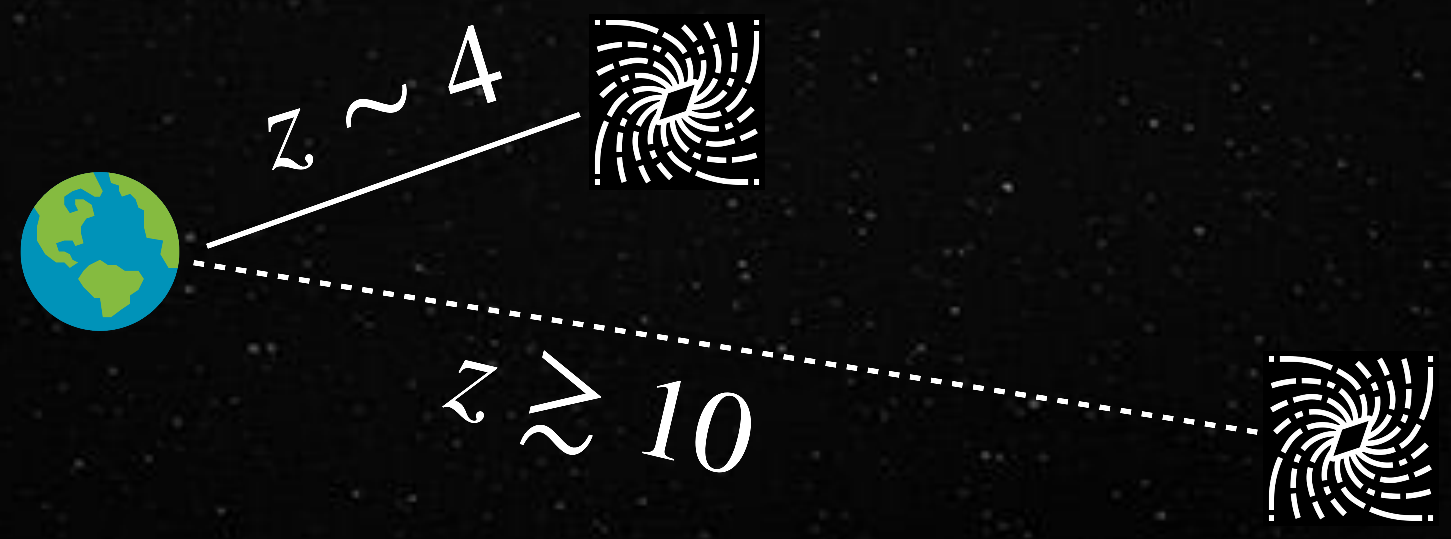

Tool to probe the high redshift Universe

Appealing tools to probe the high redshift Universe – Future Transient surveys

SLSNe-I for Cosmology

Progenitor Scenario
Explosion Mechanism

Homogenous behaviour of SLSNe-I

Proposed as Cosmological probes
beyond the redshifts possible for SNe Ia

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Inserra et. al. 2014, 2020 determined correlation
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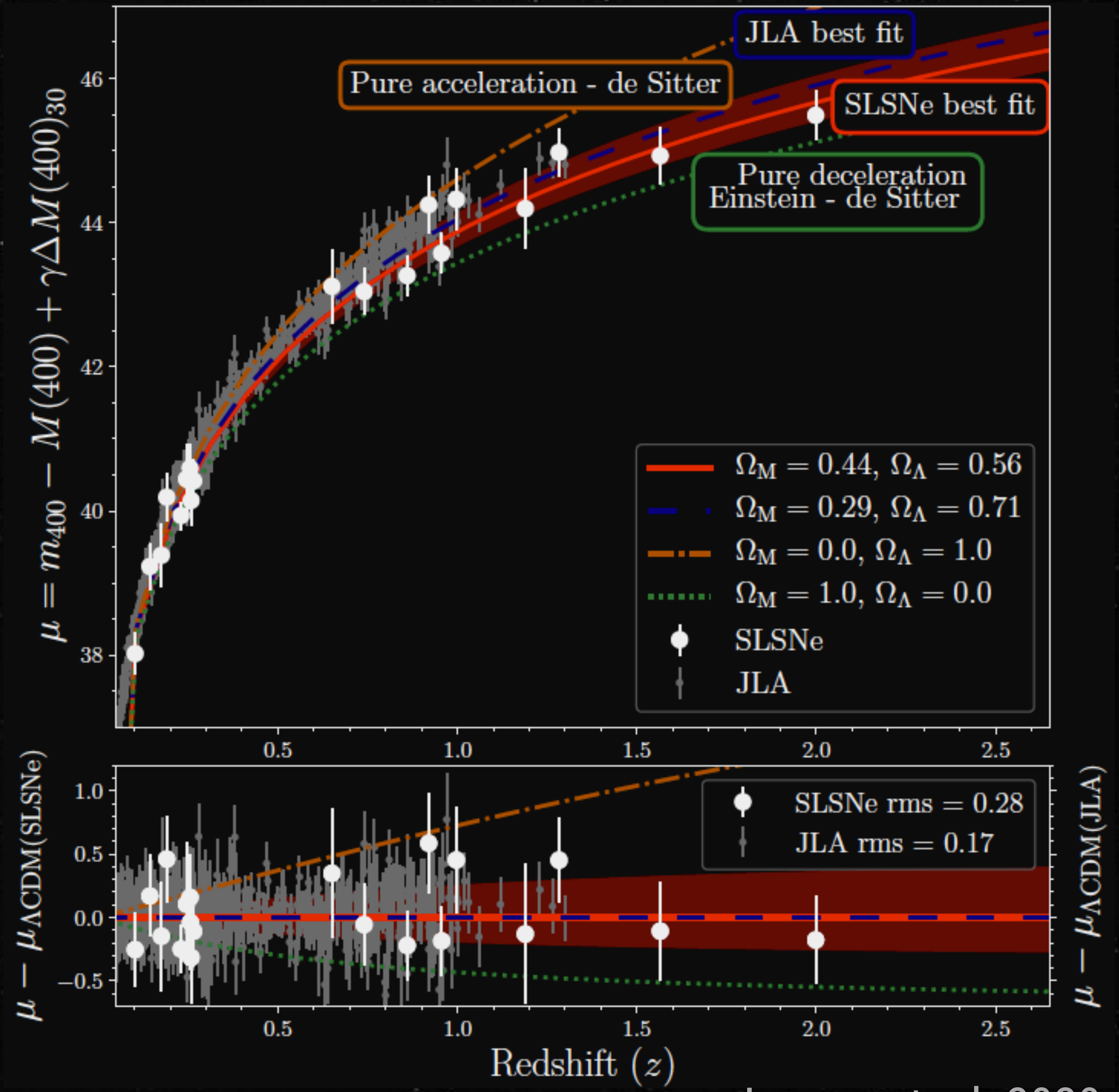

Inserra et. al. 2020

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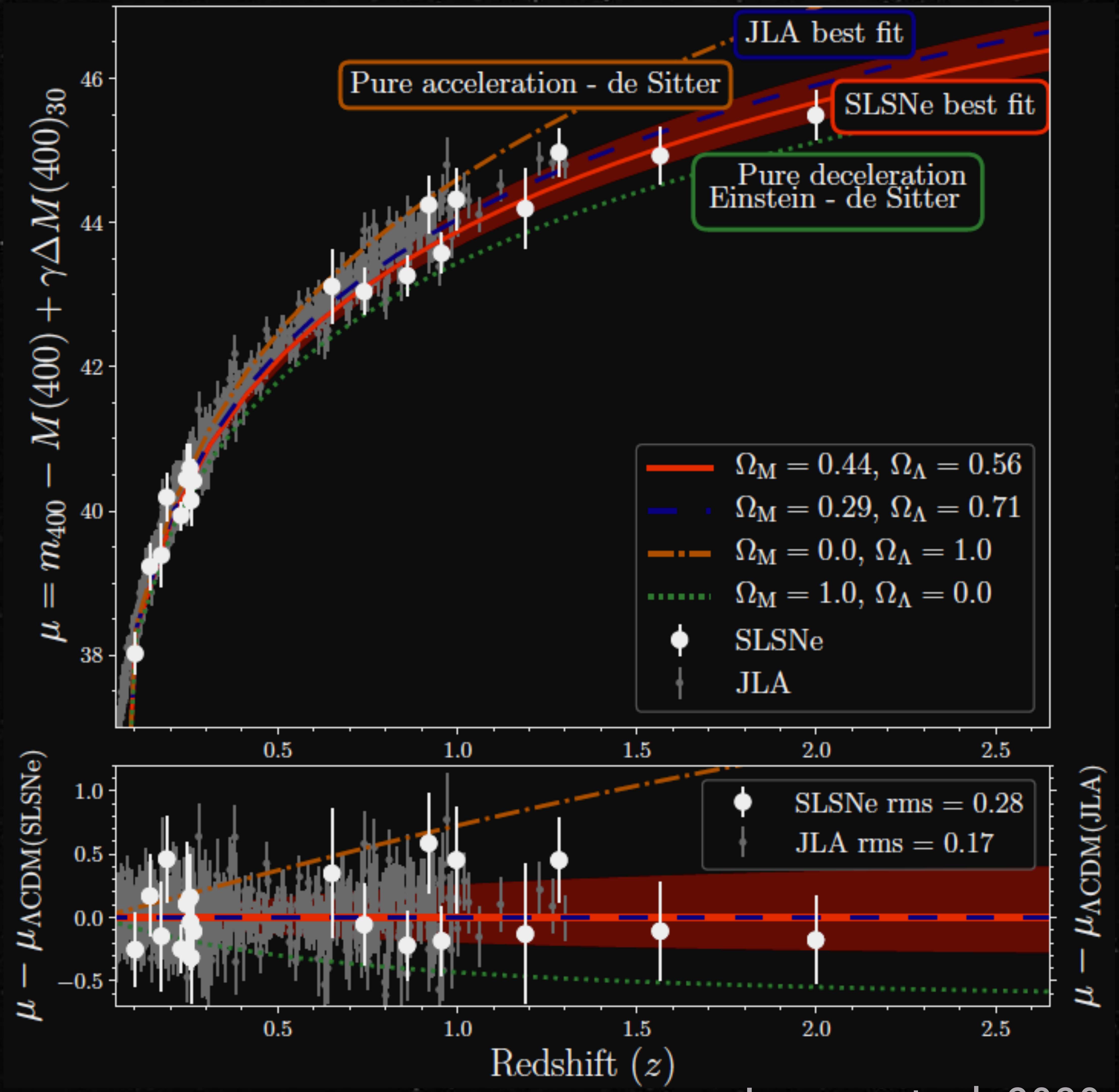
High redshift probes are especially important to distinguish between various DE models



Inserra et. al. 2020

Goal and Motivation

01 Probe the rest frame UV of SLSNe-I and investigate their standardisation at UV wavelengths

02 Find correlation between peak mag and rise phase properties

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Standardisation at UV

To use SLSNe as a complementary tool to SNe Ia at high redshifts,
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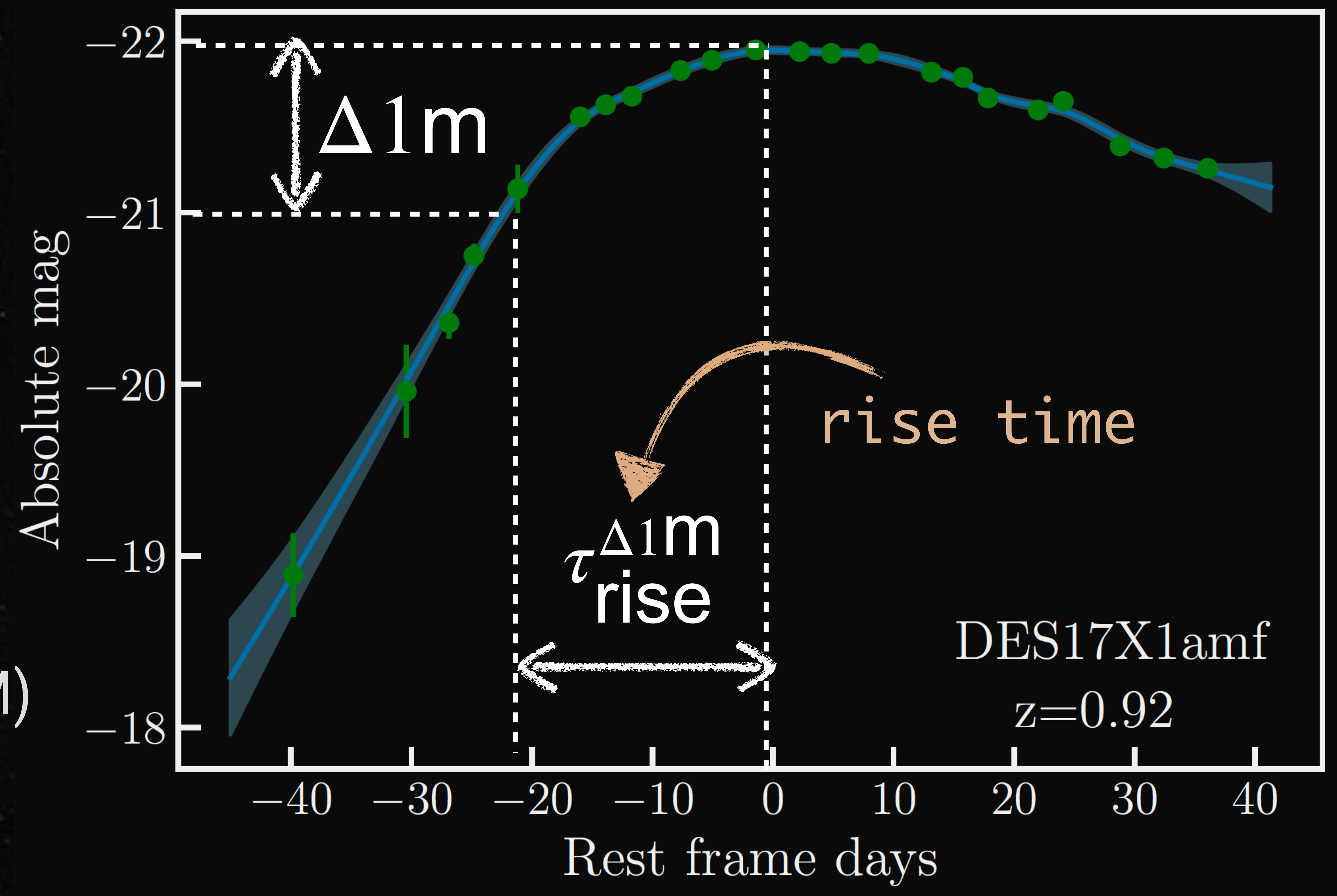
Peak mag and Rise phase

1. More consistent behavior at early epoch (later interaction with CSM)
2. Effects from dust creation
3. Analogy with SNe Ia



SLSNe-I samples

1. Redshift of SLSN $z \geq 1$
2. Data coverage in the rising phase of the light curve
3. Photometry in the rest-frame UV/NUV filters

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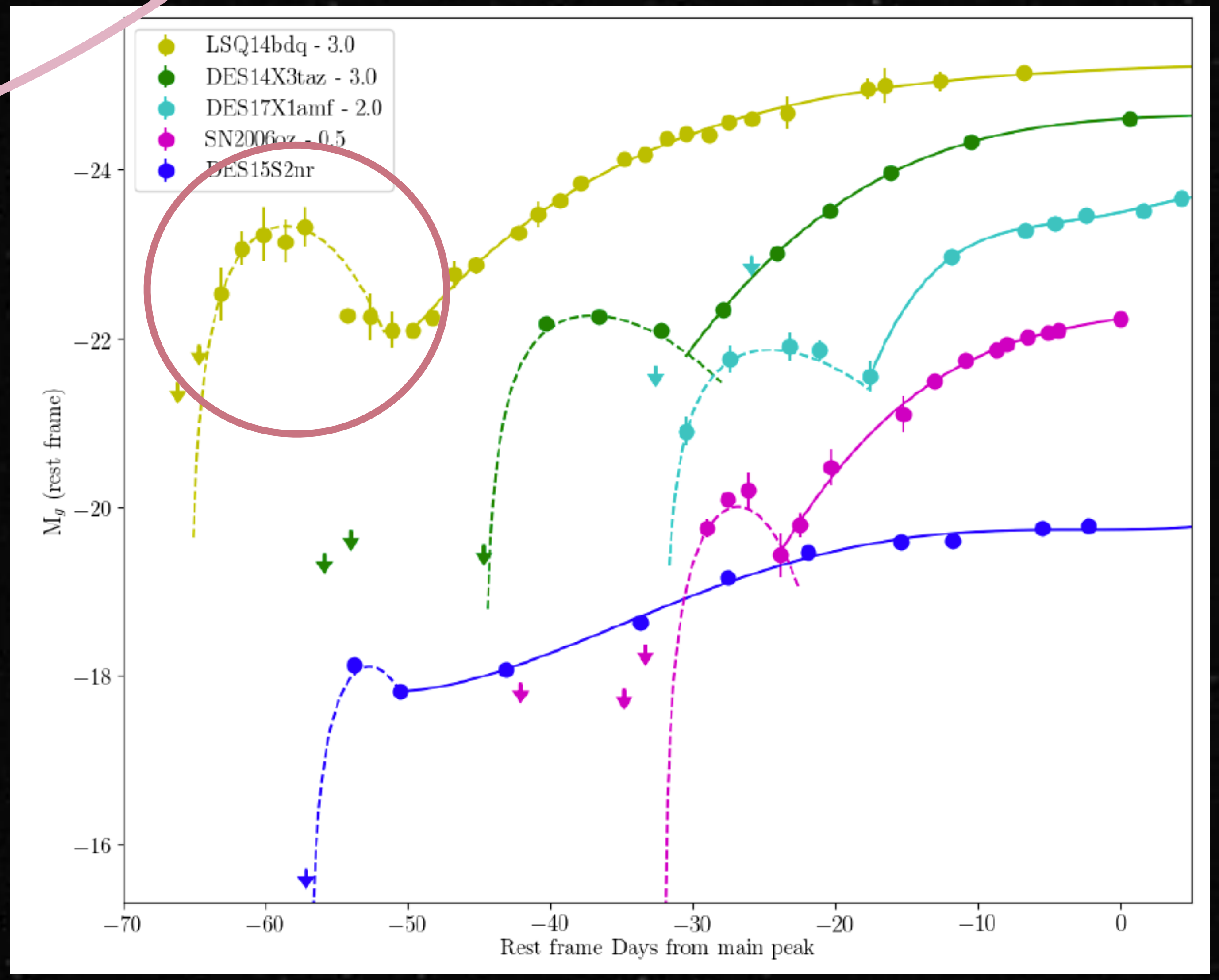

Angus et al. 2019

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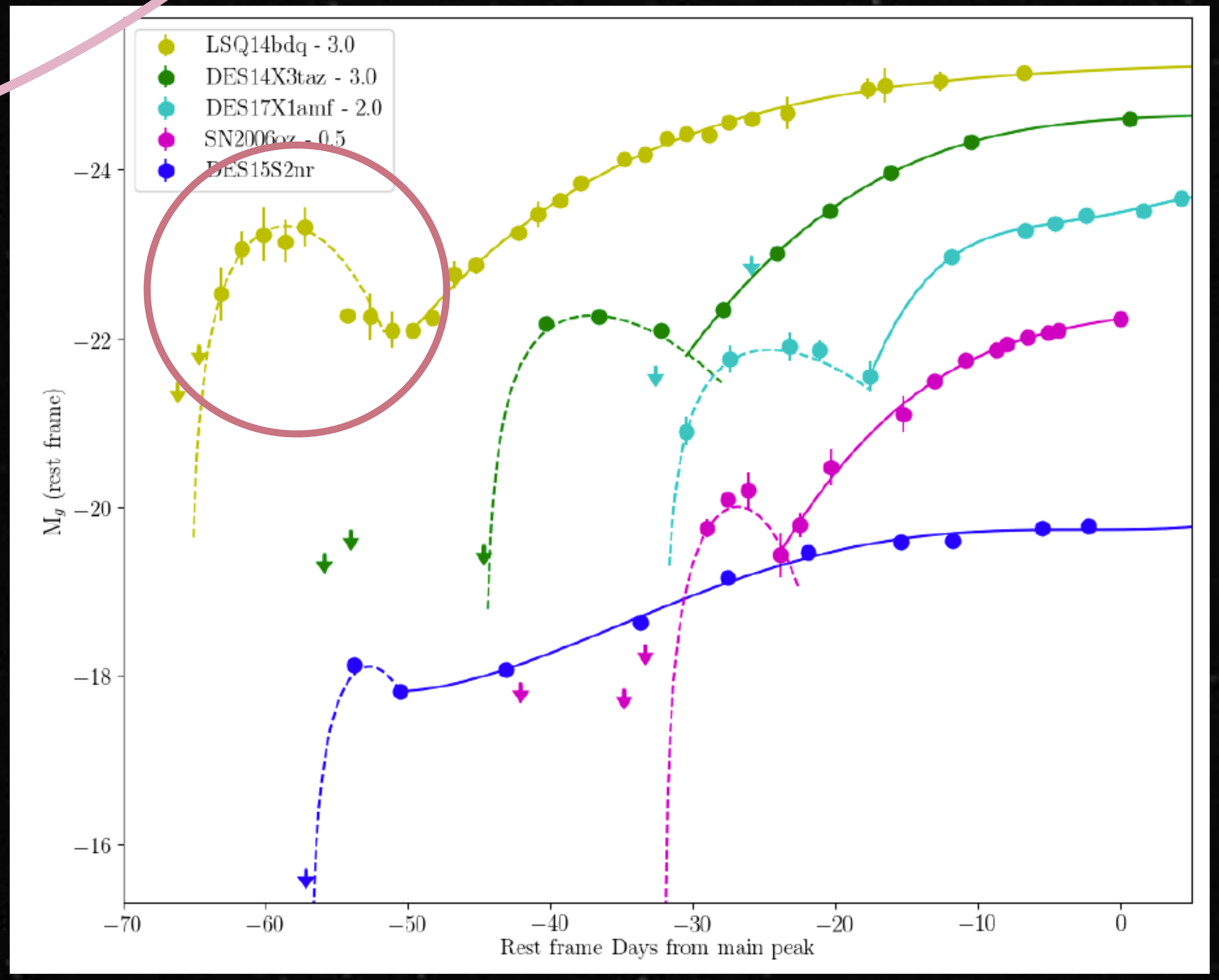

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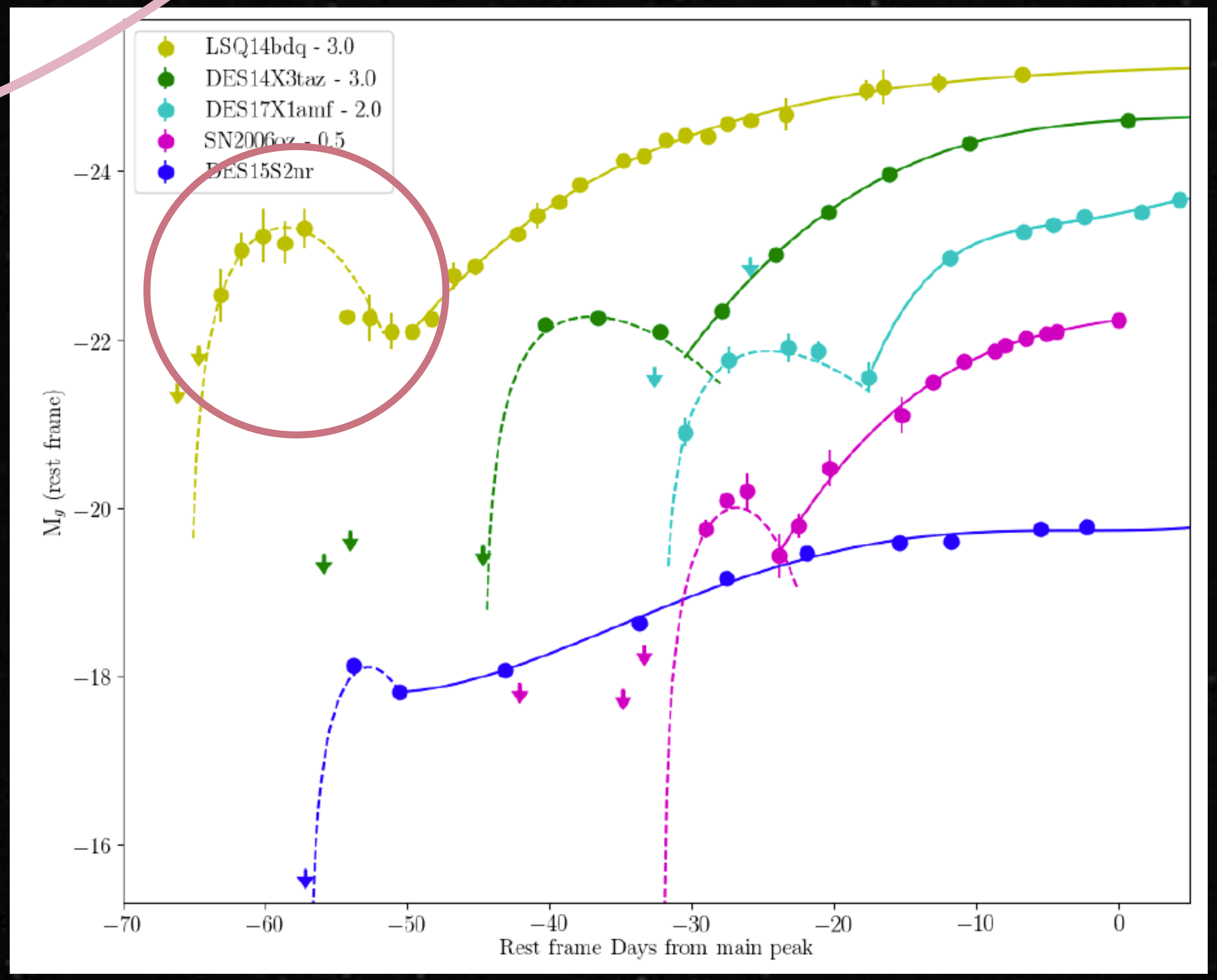

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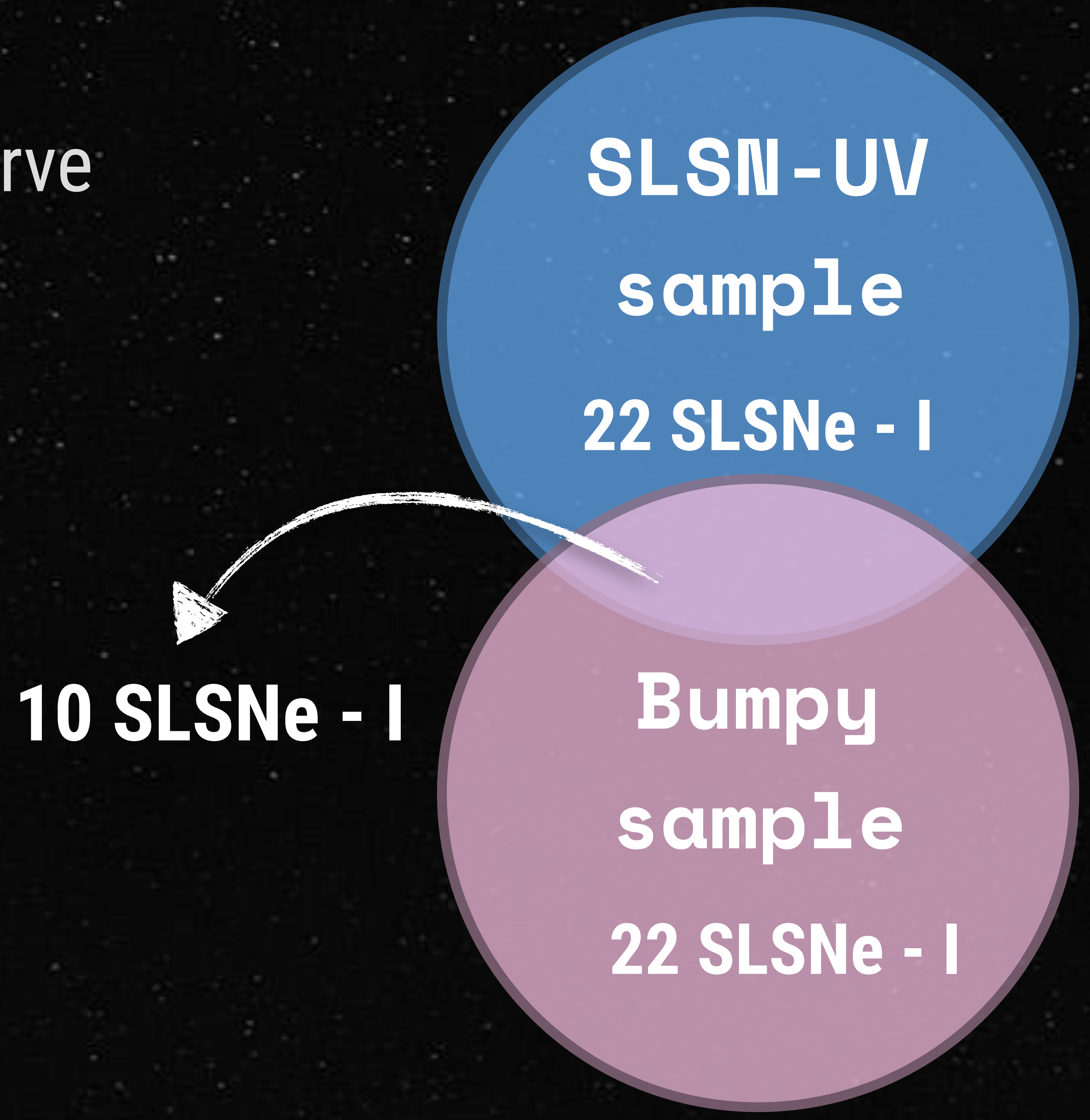

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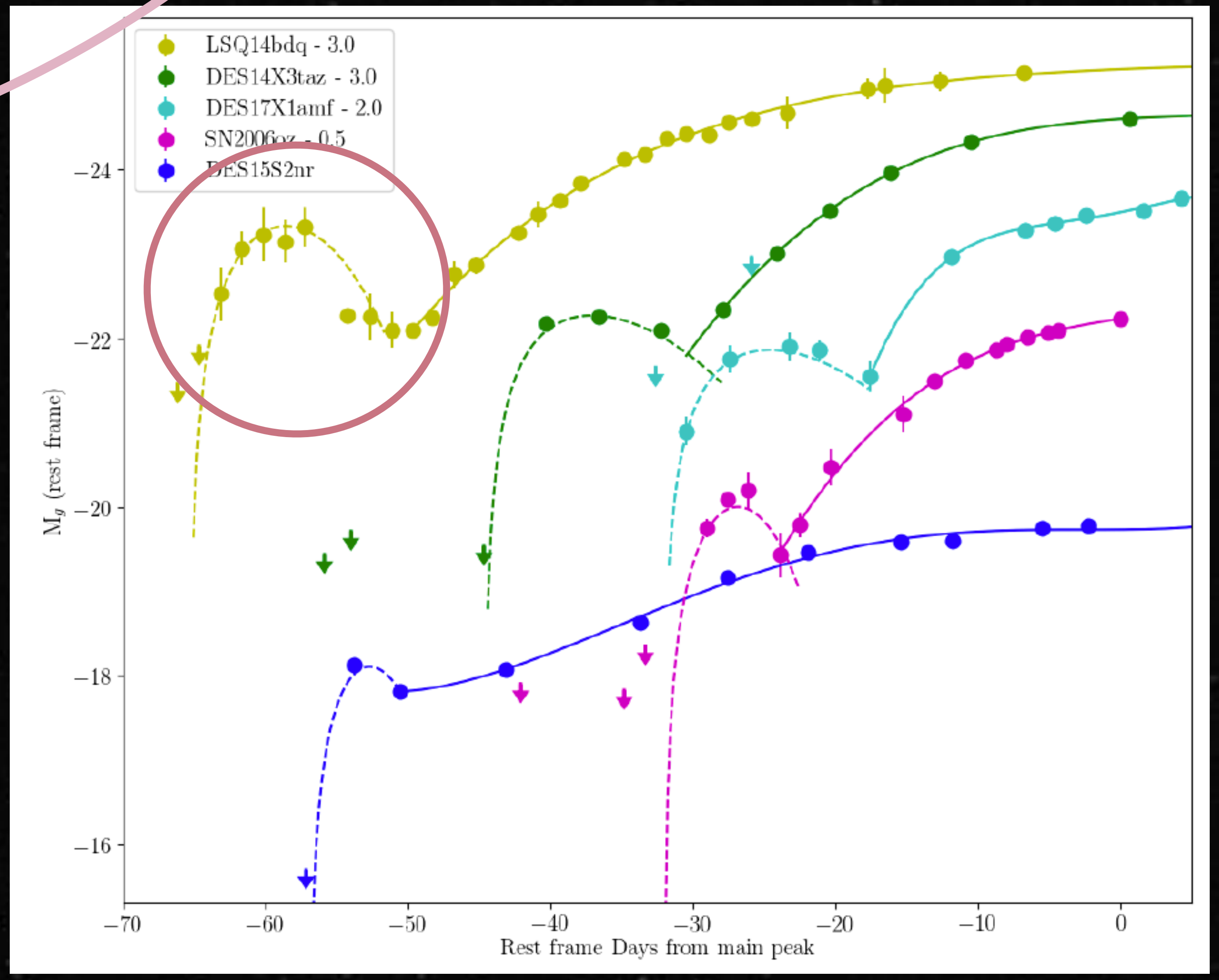


Angus et al. 2019

SLSN-UV sample

22 SLSNe - I

13 Gold

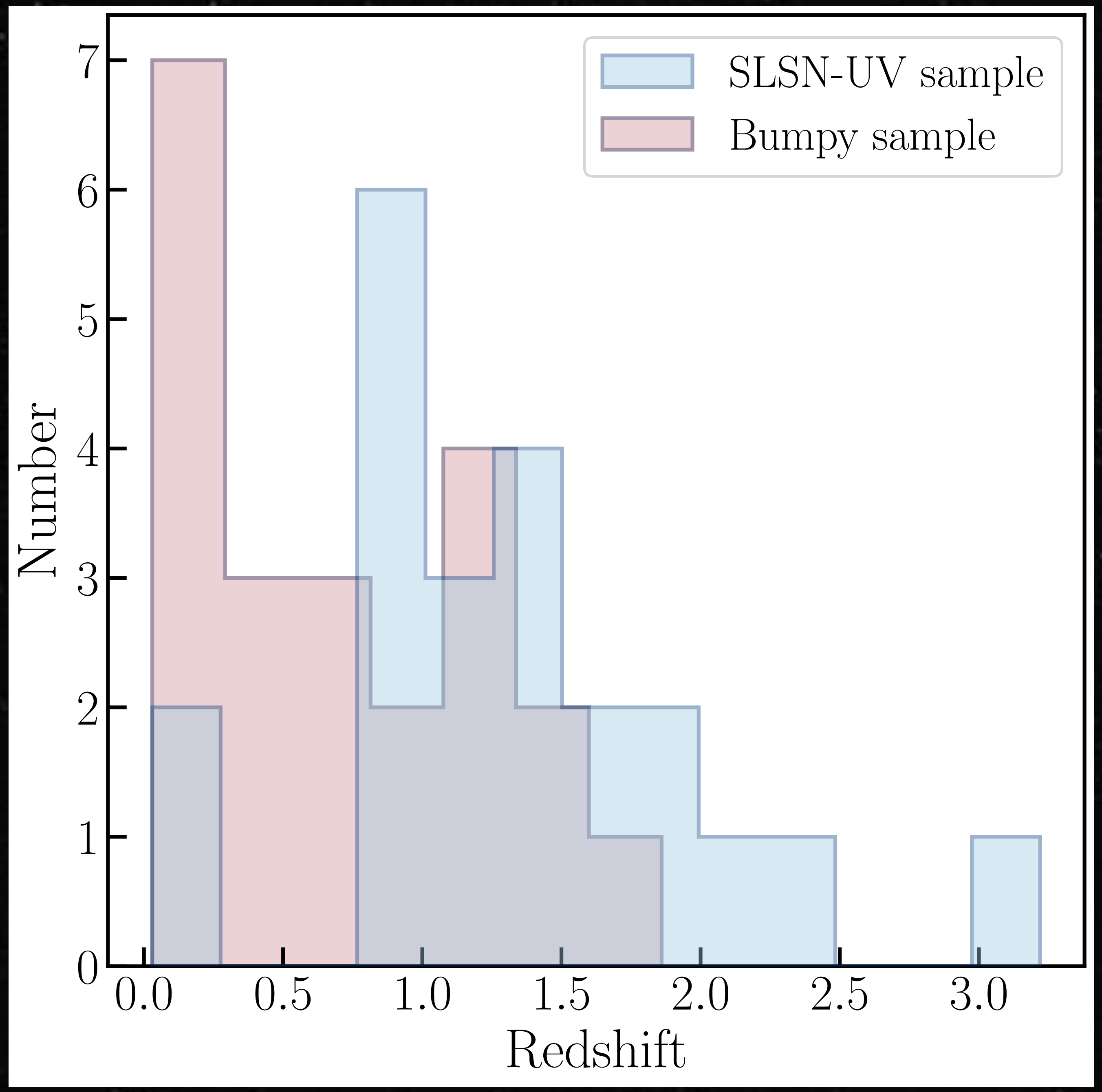
10 SLSNe - I

Bumpy sample

22 SLSNe - I

15 Gold

UV Synthetic filters



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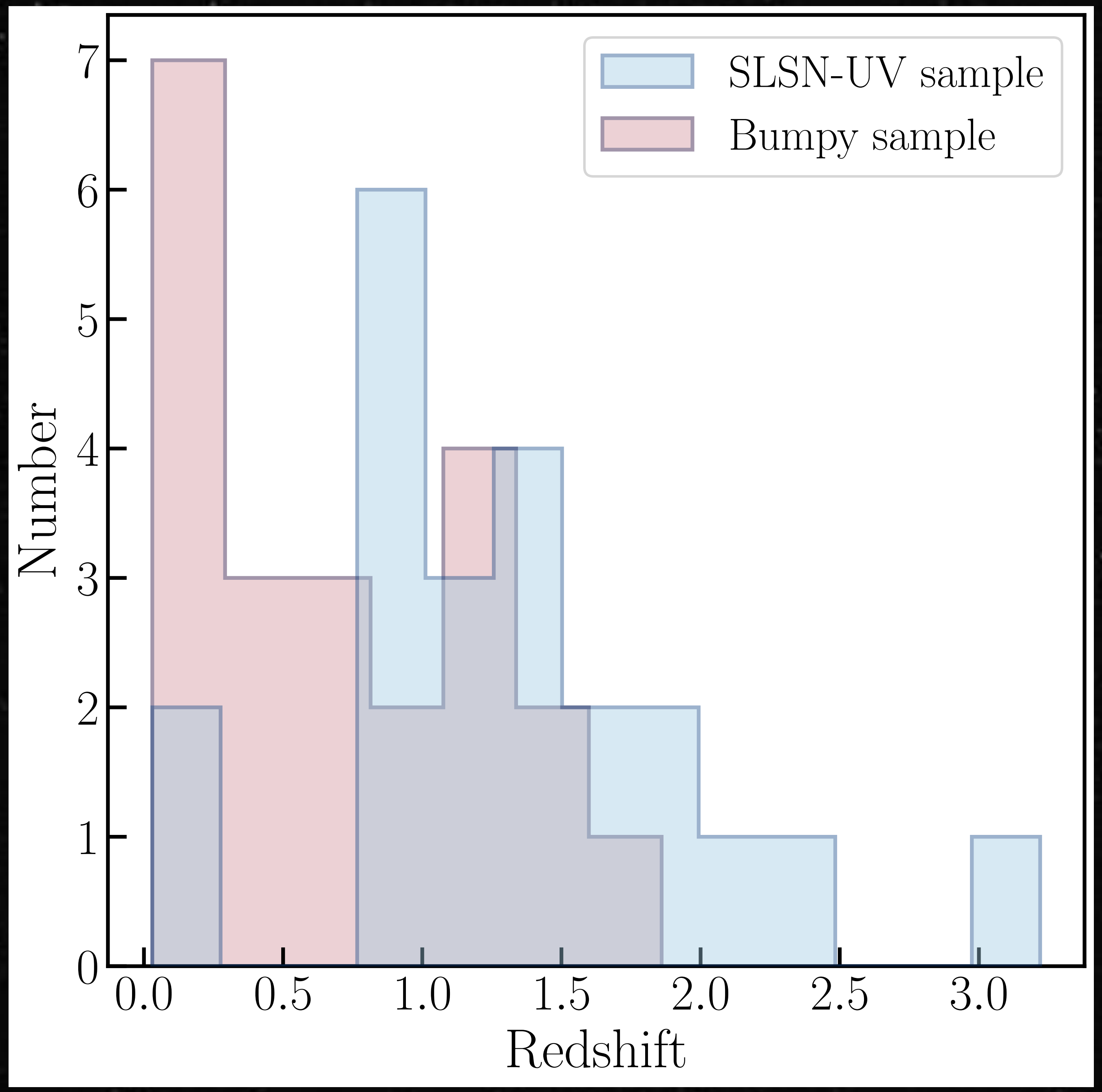
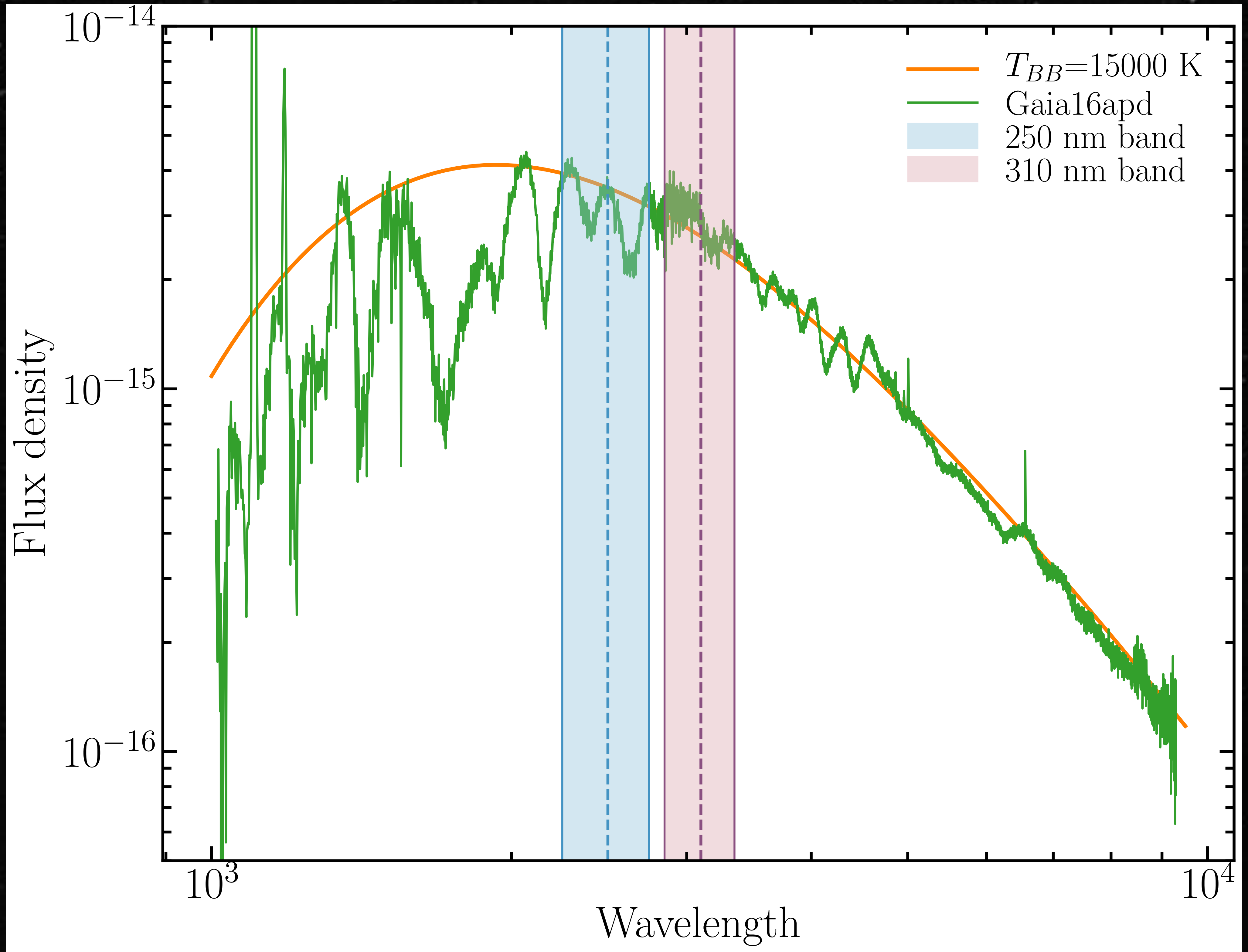


2500Å band

3100Å band



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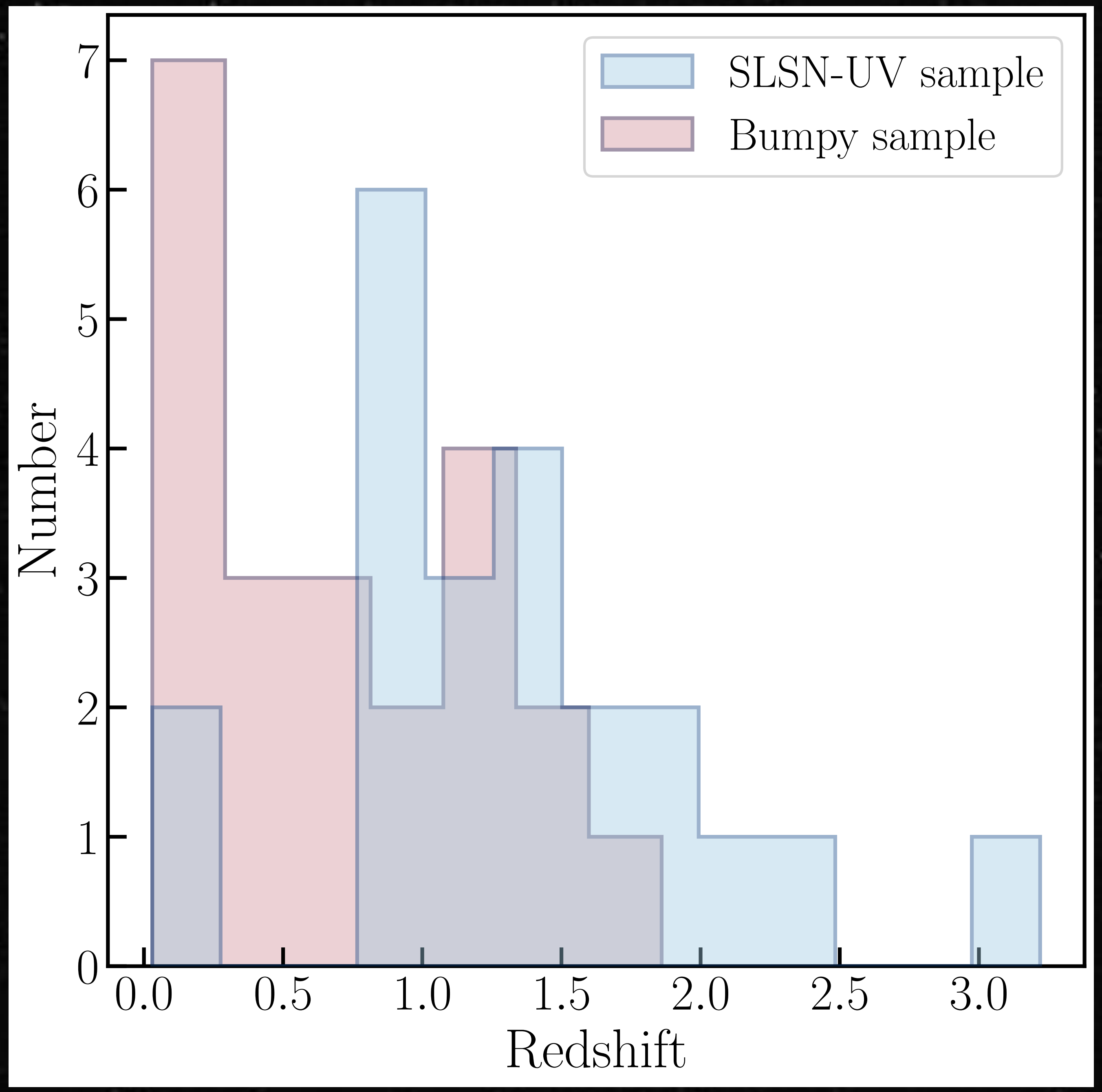

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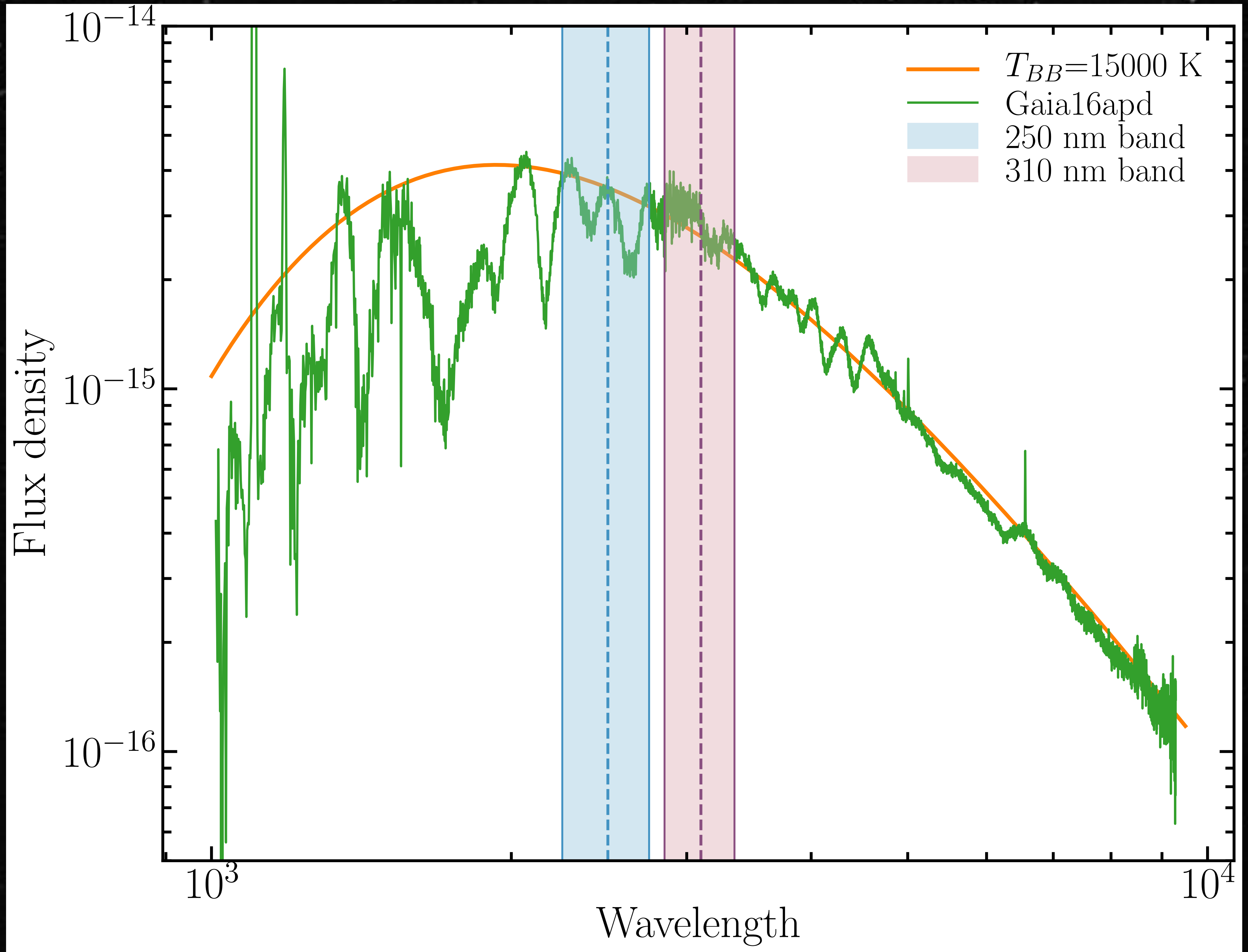
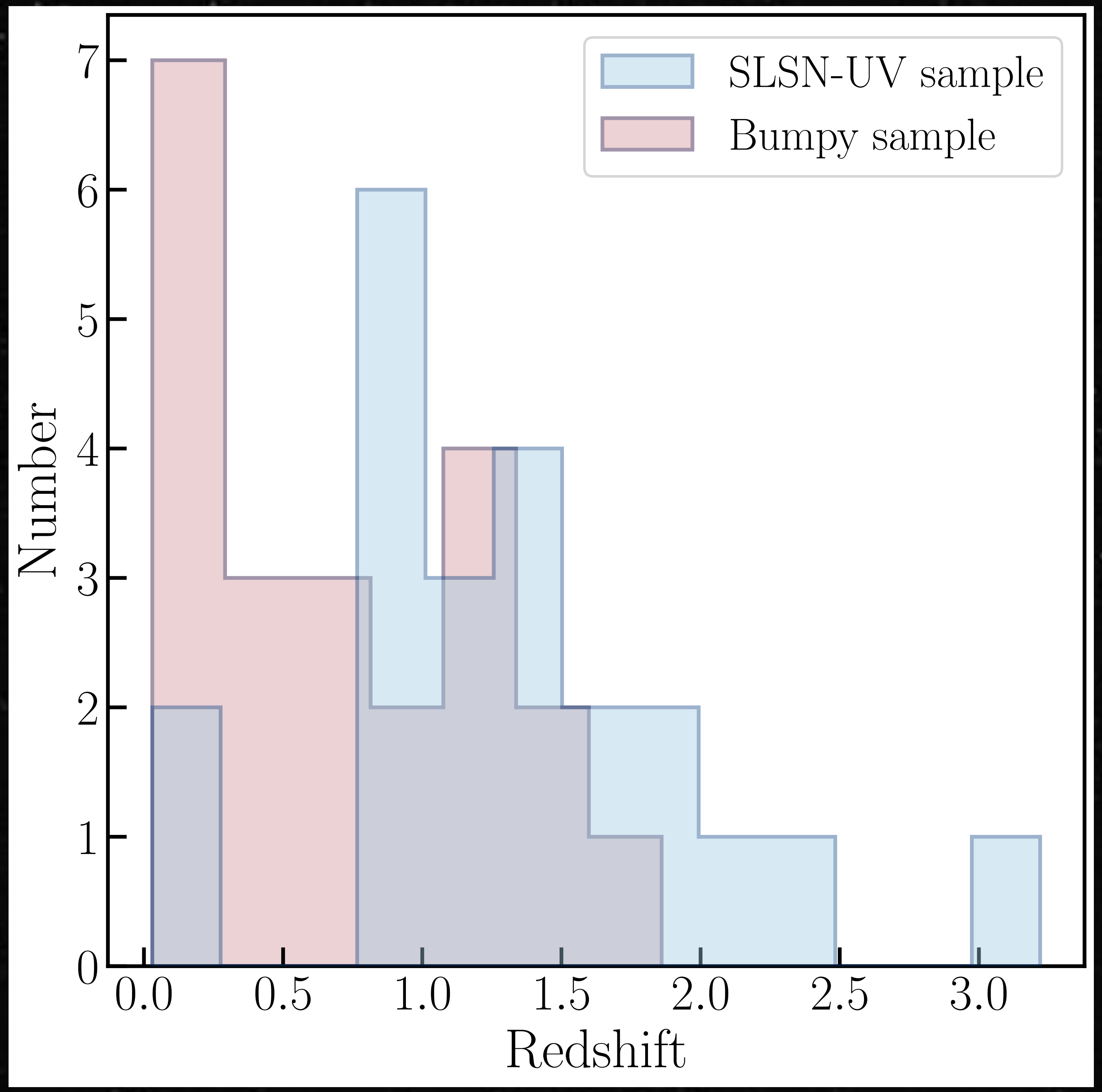
3100Å band

Choose the observer frame filter closest to respective synthetic bands in their rest frame



Synthetic filters



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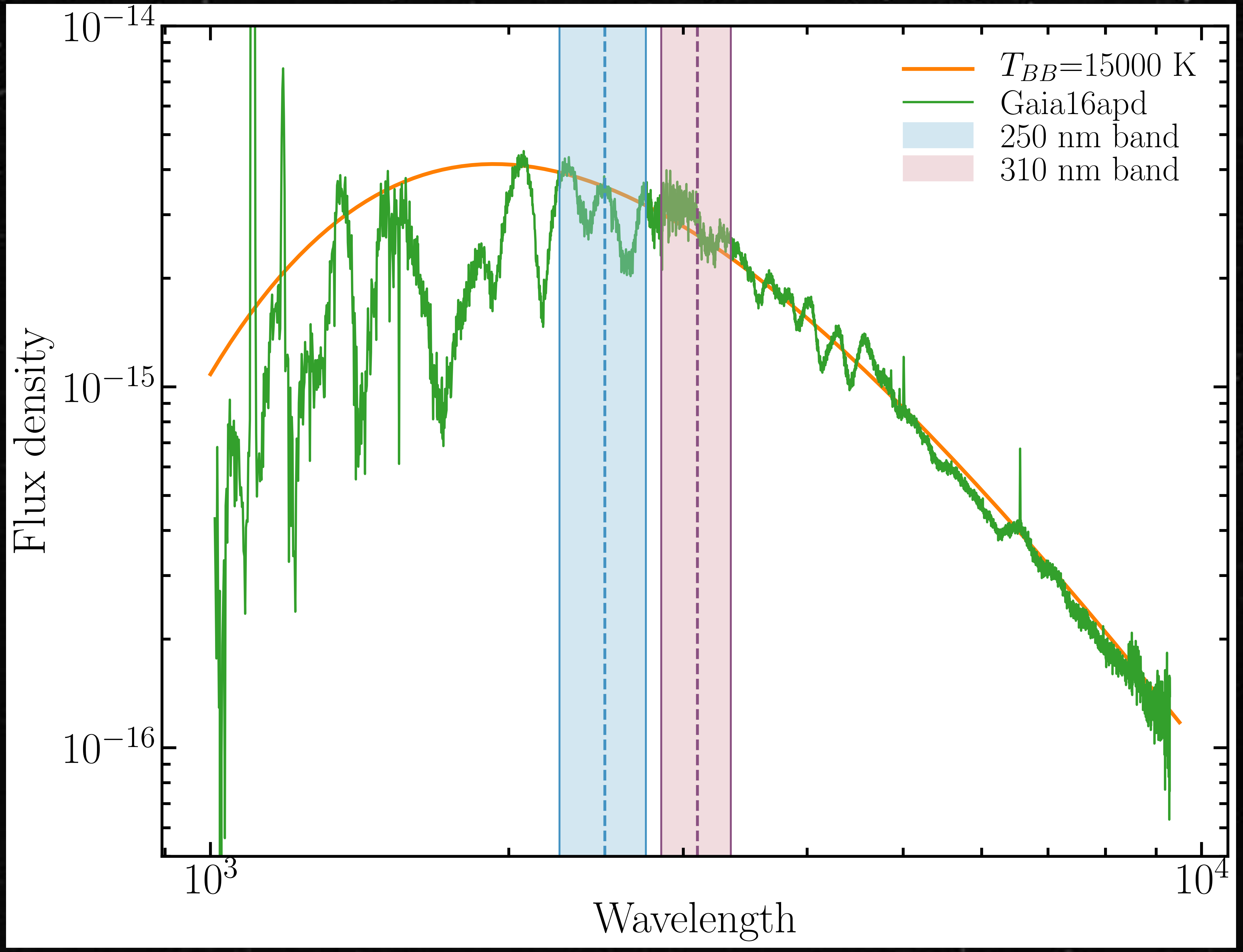

Cross filter *K*-corrections

- 2500 Å band — **Absorption lines** - Calculated using spectrum of Gaia16apd - considered as standard
- 3100 Å band — **Continuum dominated** - Calculated using normalised Blackbody function at 15000K

Light Curve Fitting

Gaussian Process Regression (GPR) for fitting the light curves

Non-parametric - GPR removes any assumption on the light curve shape

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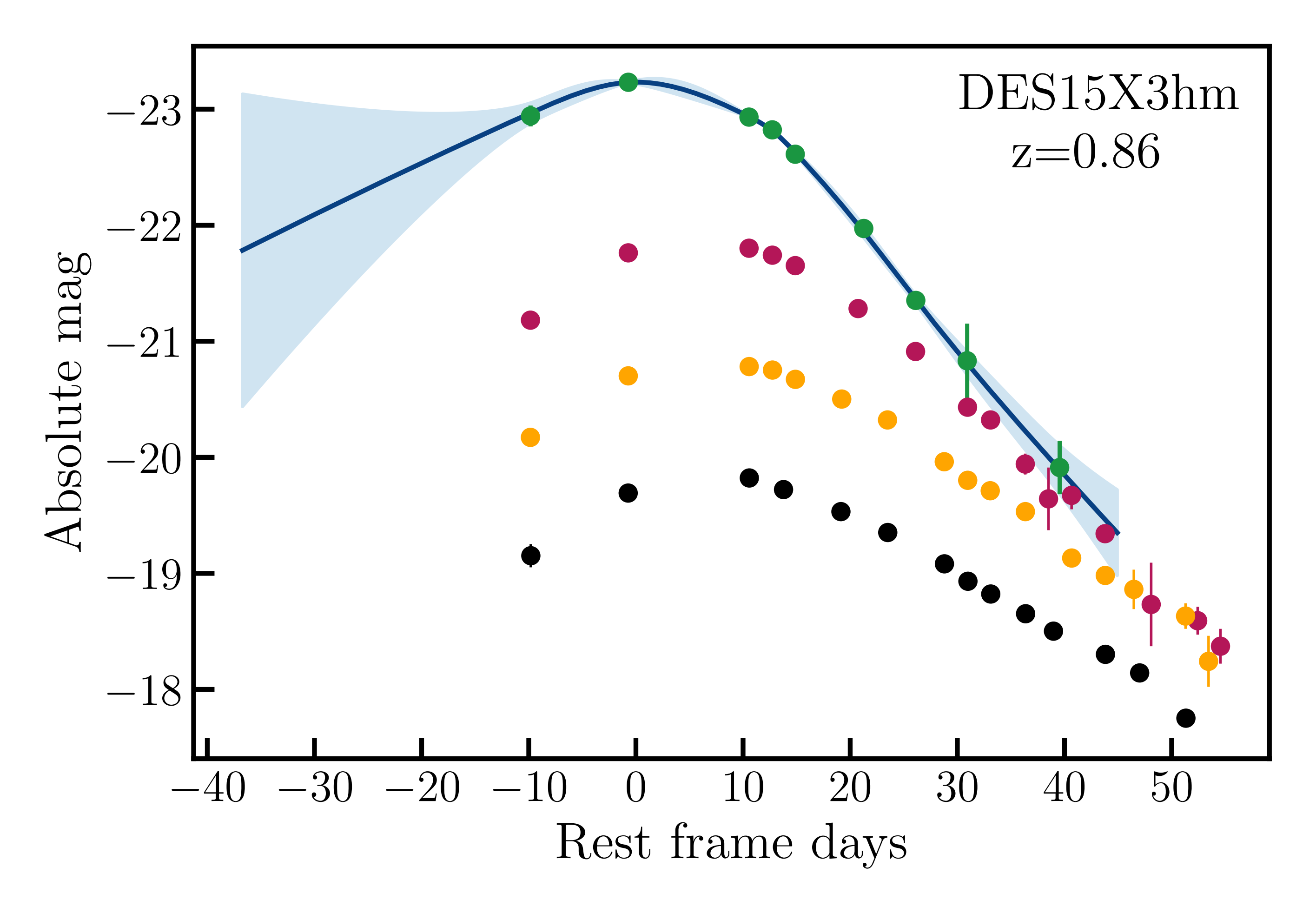
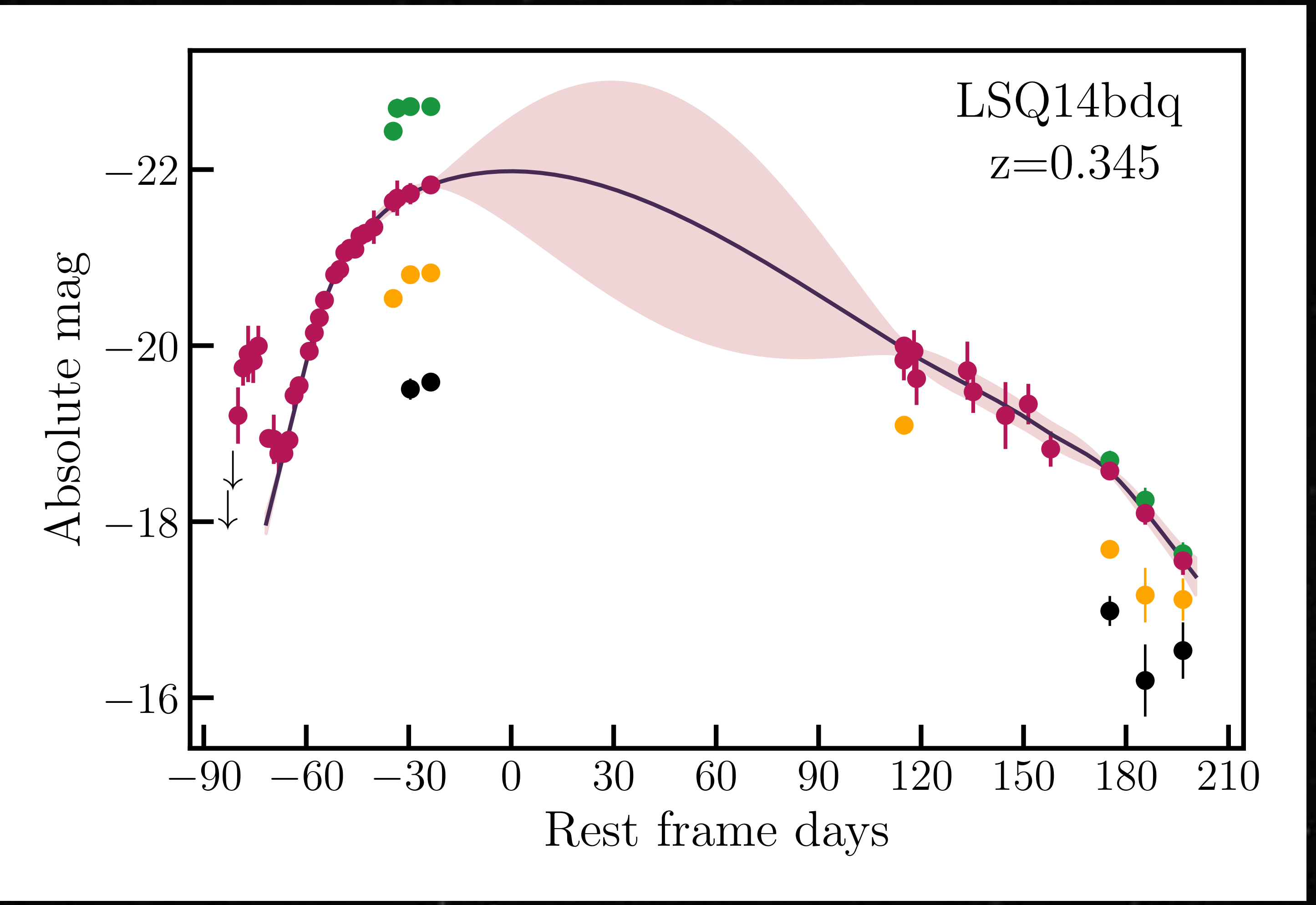
Determine the peak absolute magnitude $M_0(X)$ and rise time $\tau_{\text{rise}}^{\Delta 1\text{m}}$

Errors on peak magnitude are estimated intrinsically





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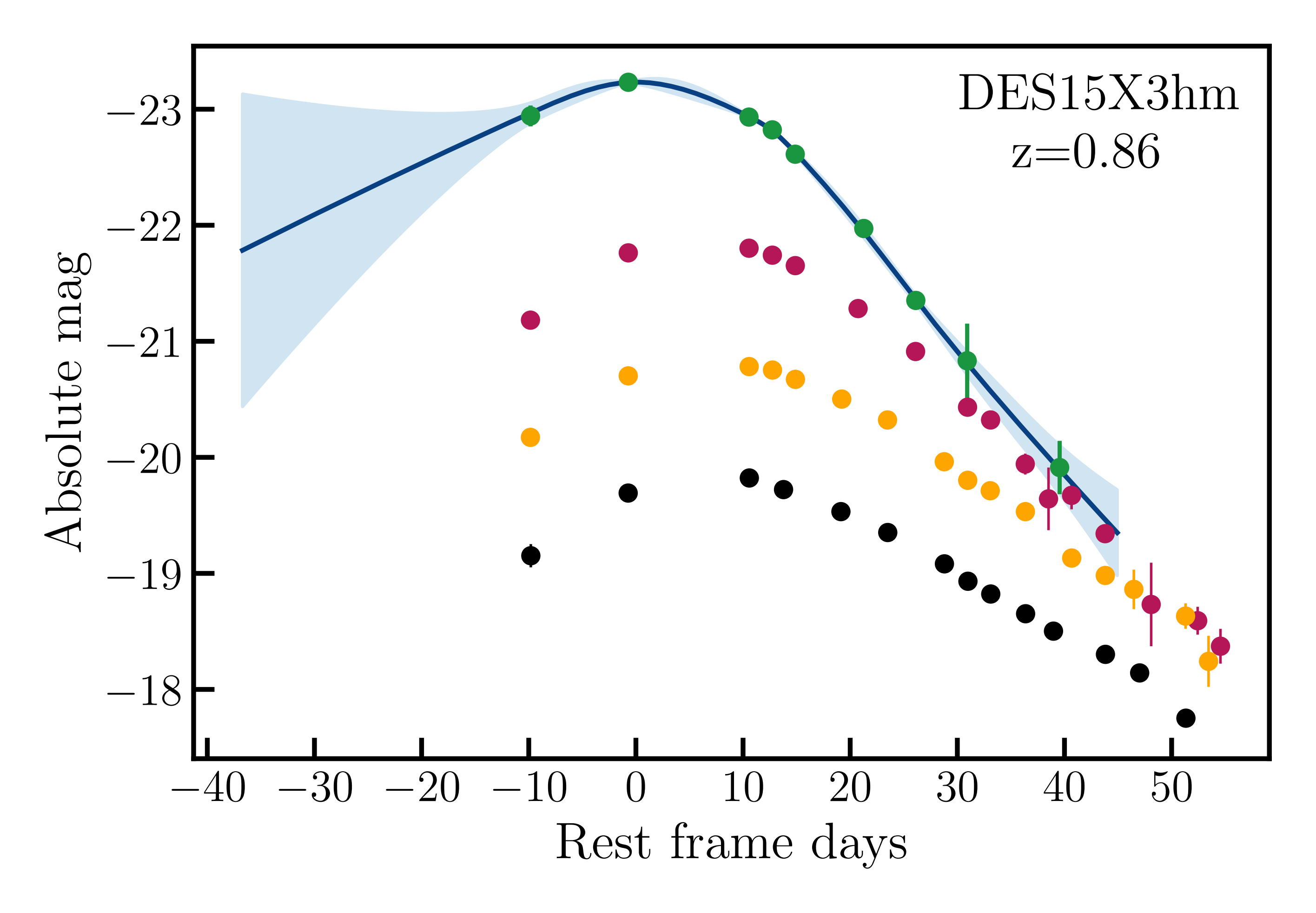

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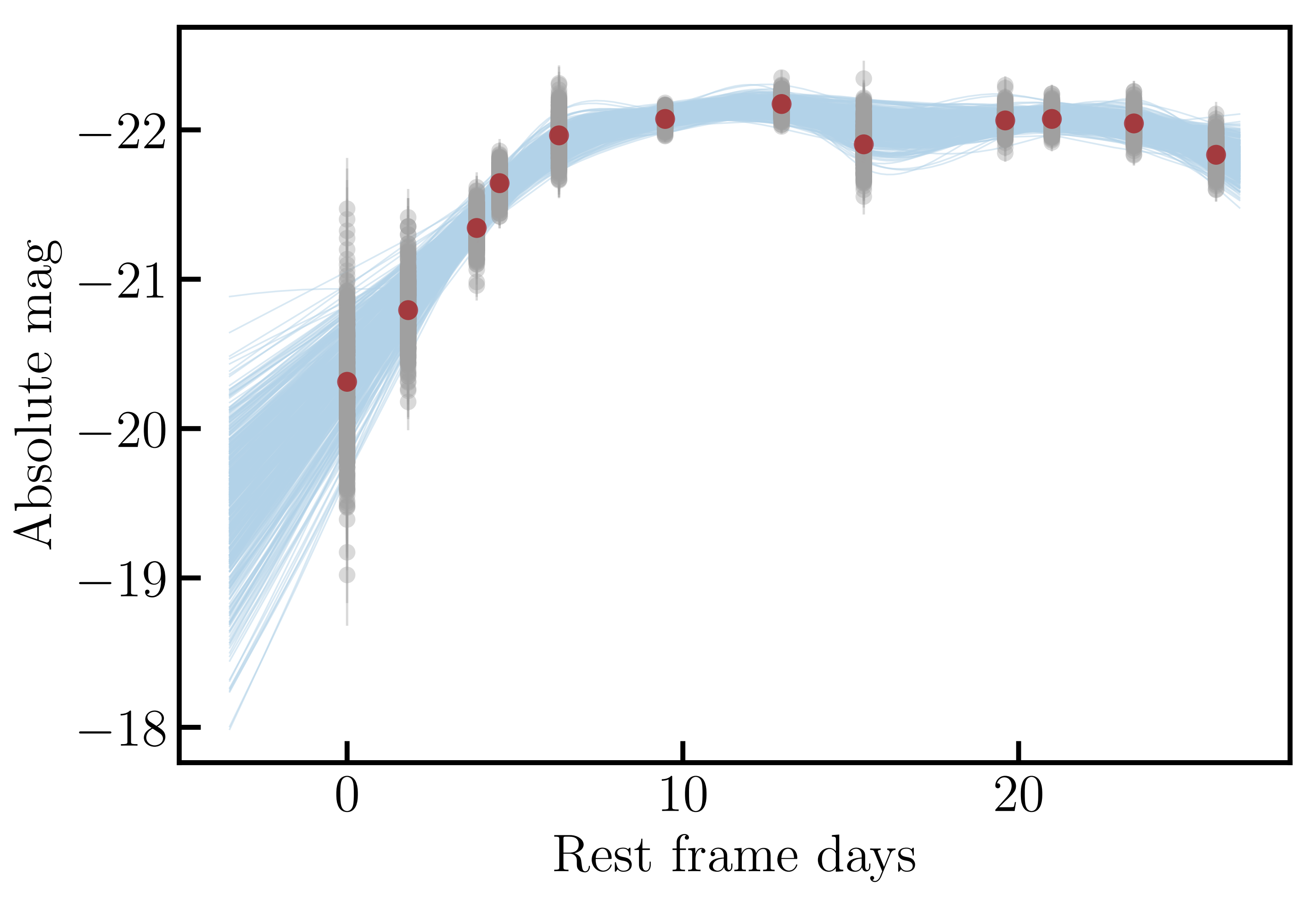
Error on Rise time

Data resampling technique with Monte Carlo

Evaluate peak epoch and epoch for 1 mag below peak for each realisation

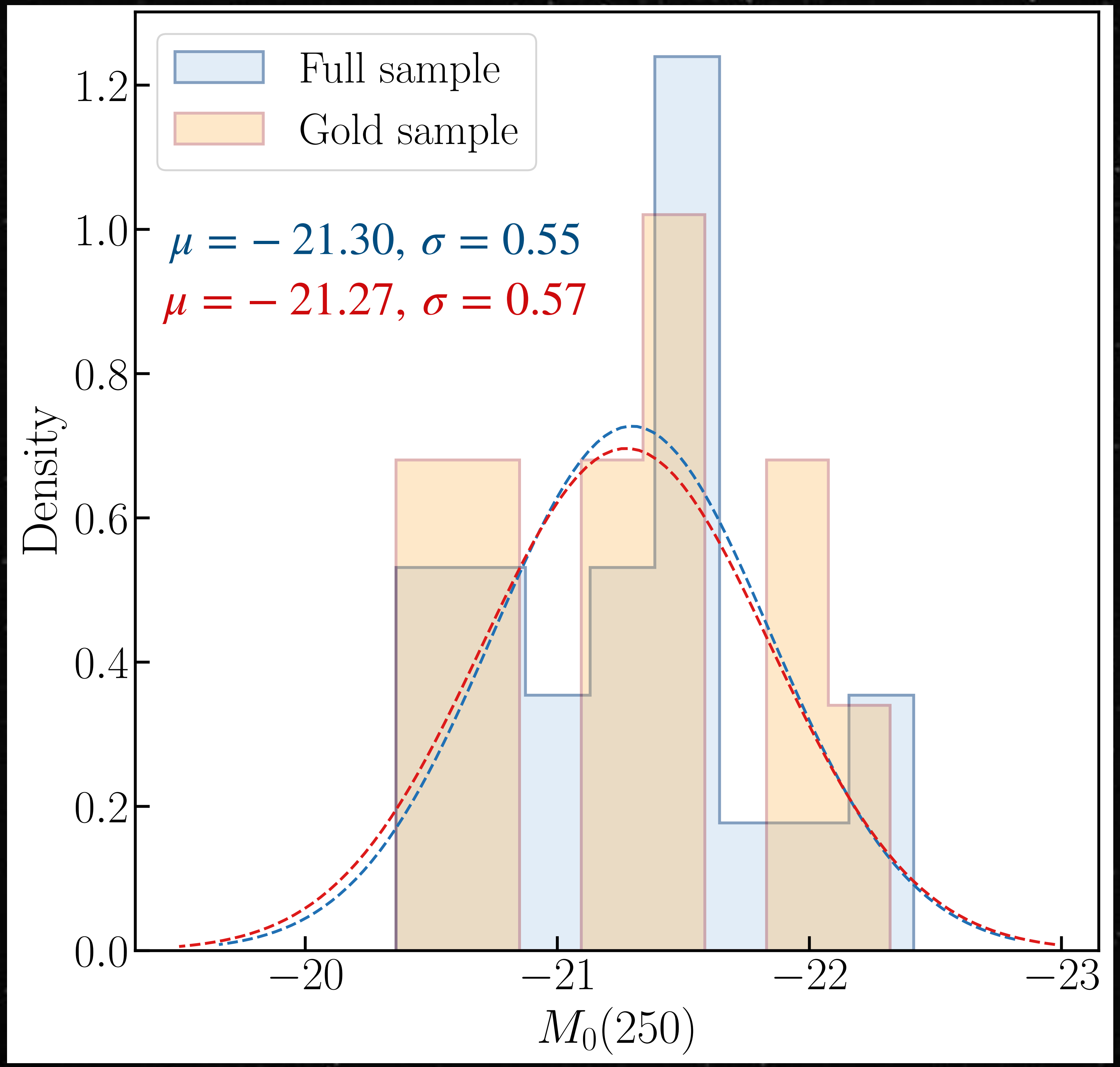
Estimate the variance in the distribution of measured parameters



Peak Magnitudes

Frequency distribution of uncorrected (*raw*) Peak magnitudes

SLSN-UV sample 250nm



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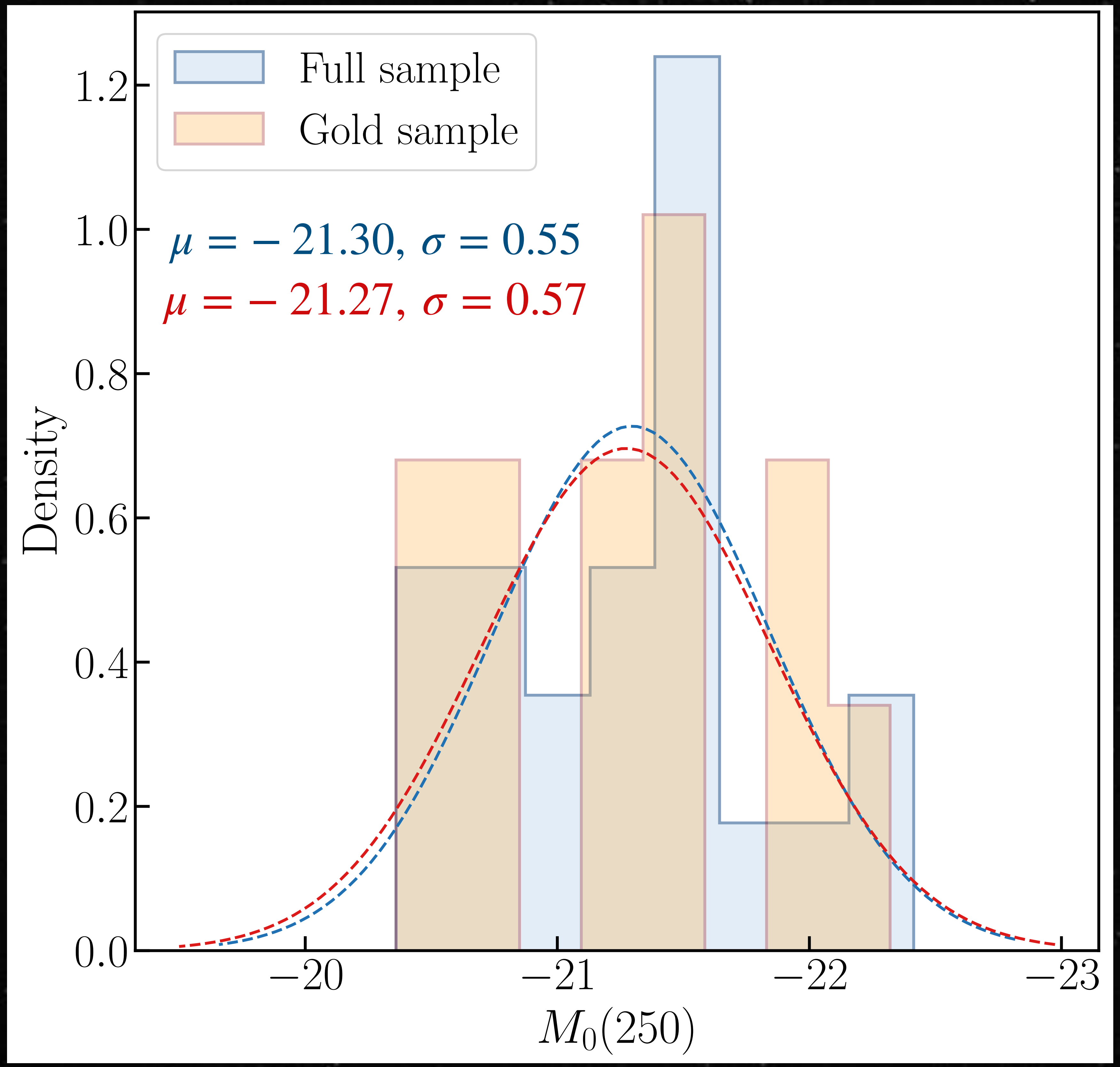
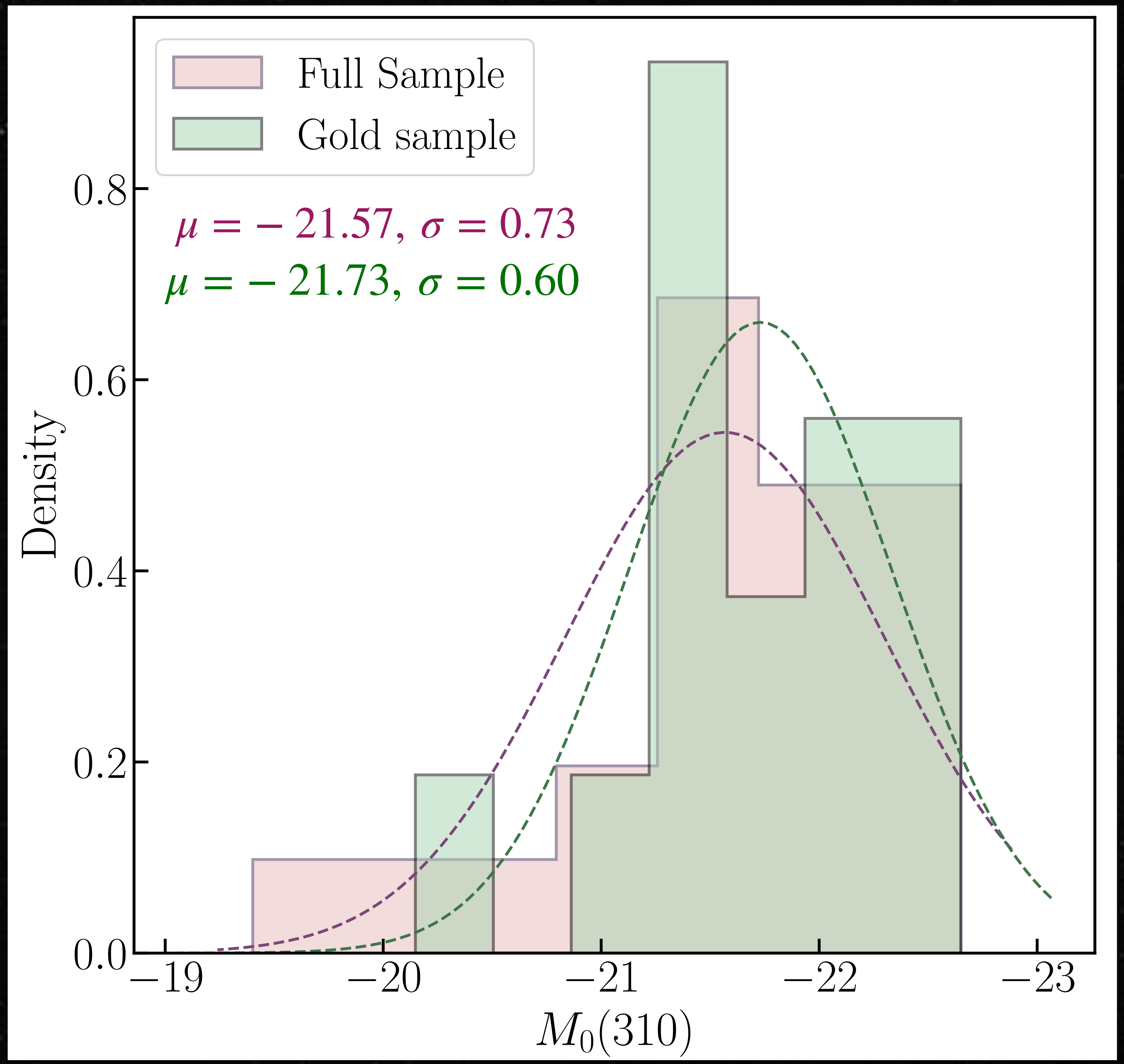


Bumpy sample 310nm

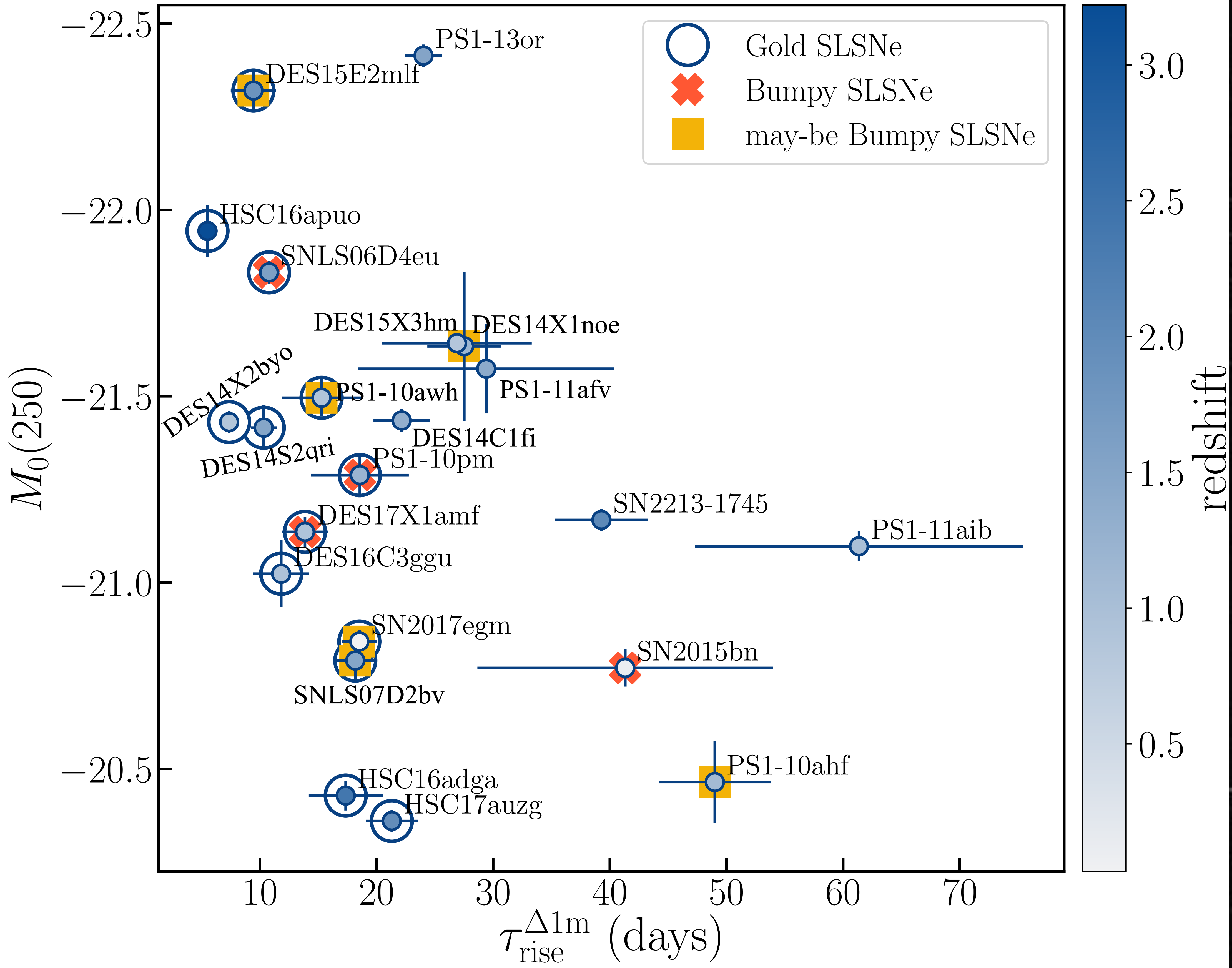


$\sigma \sim 0.6$

Peak magnitude - Rise time relation

Bayesian regression for determining the correlations - Variance of the likelihood is weighted

SLSN-UV sample at 250 nm



Brighter SLSNe rise faster

Peak magnitude - Rise time relation

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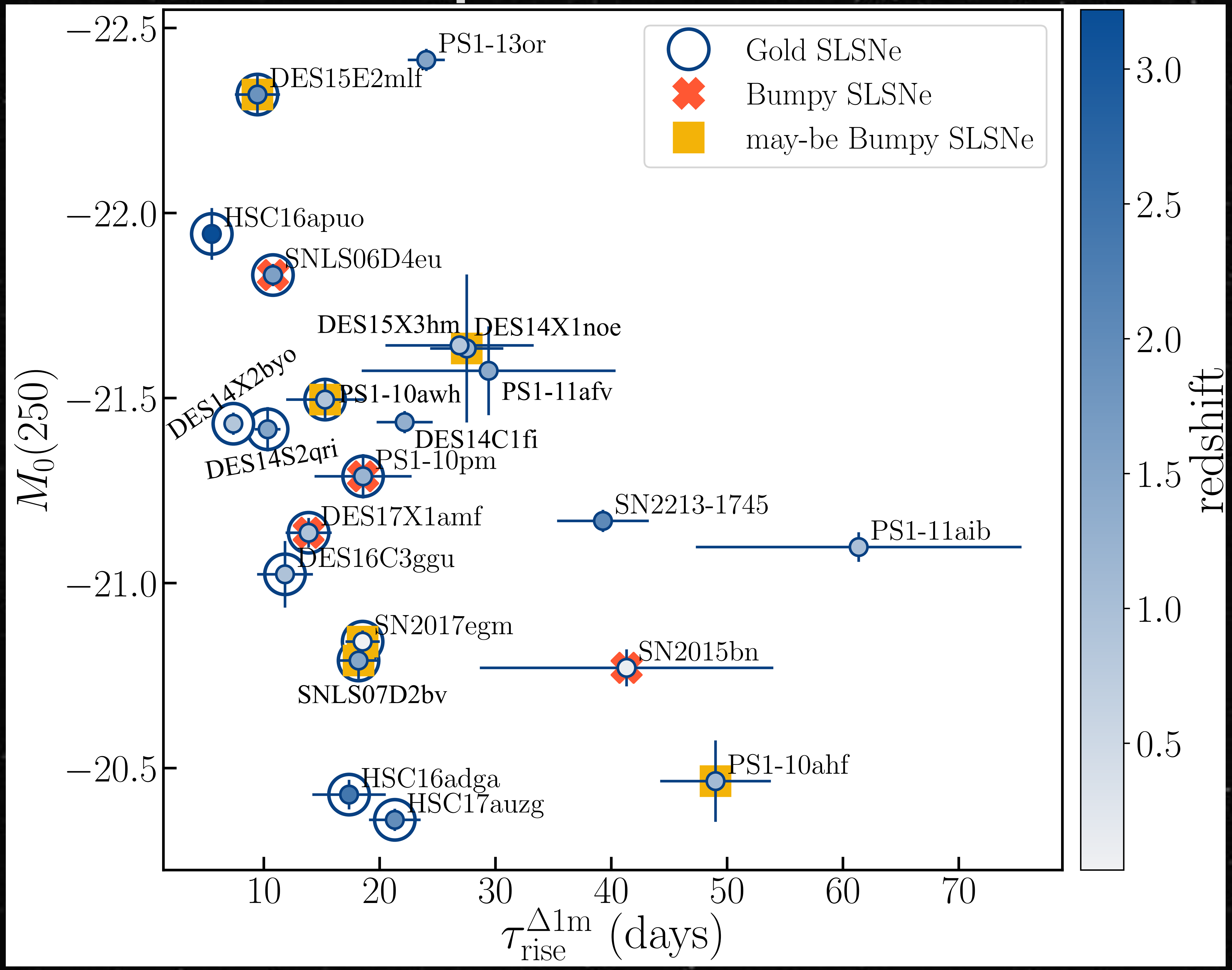
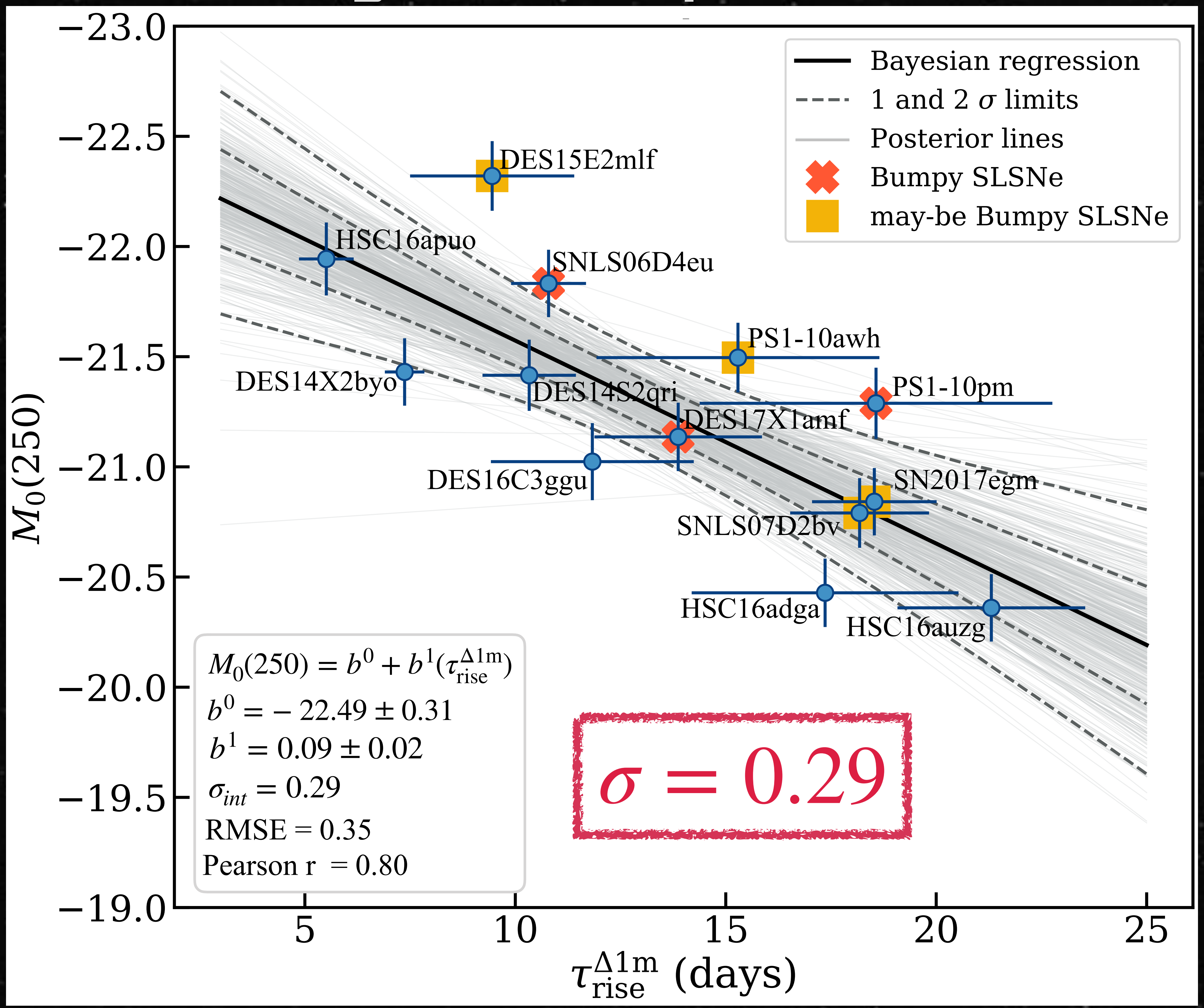


SLSN-UV gold sample



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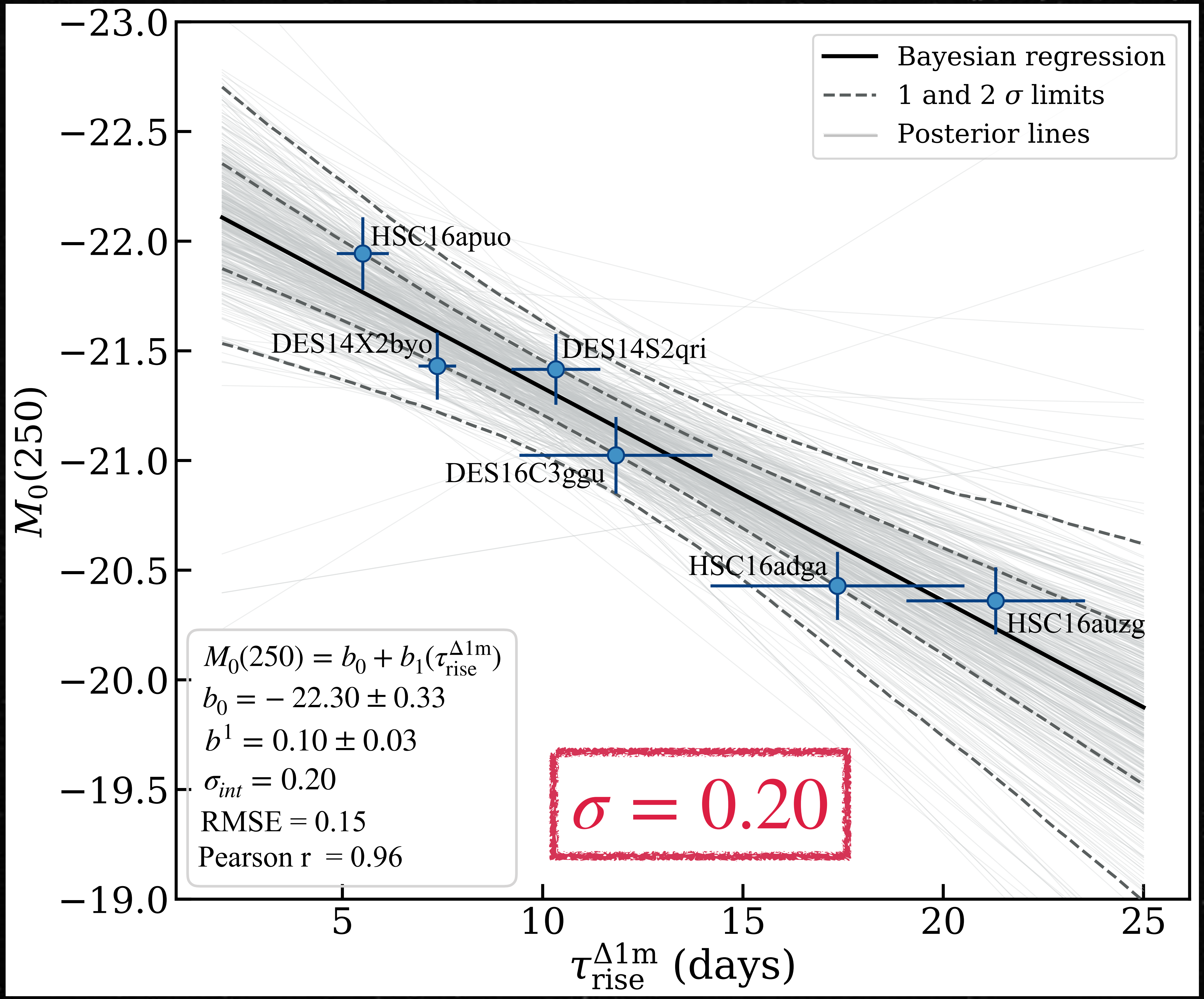

Suggests Bumpies could be different population

Peak magnitude - Rise time relation

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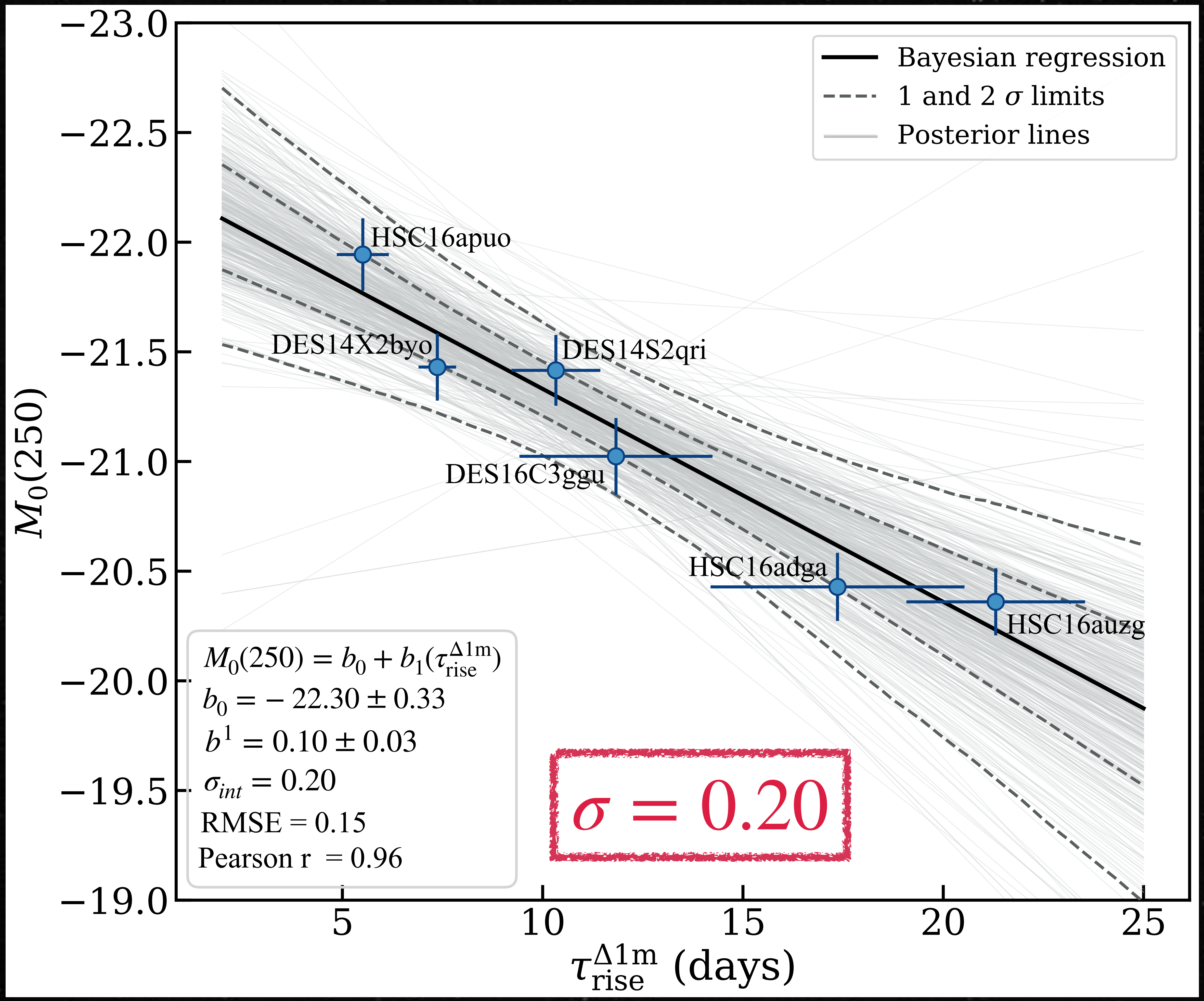
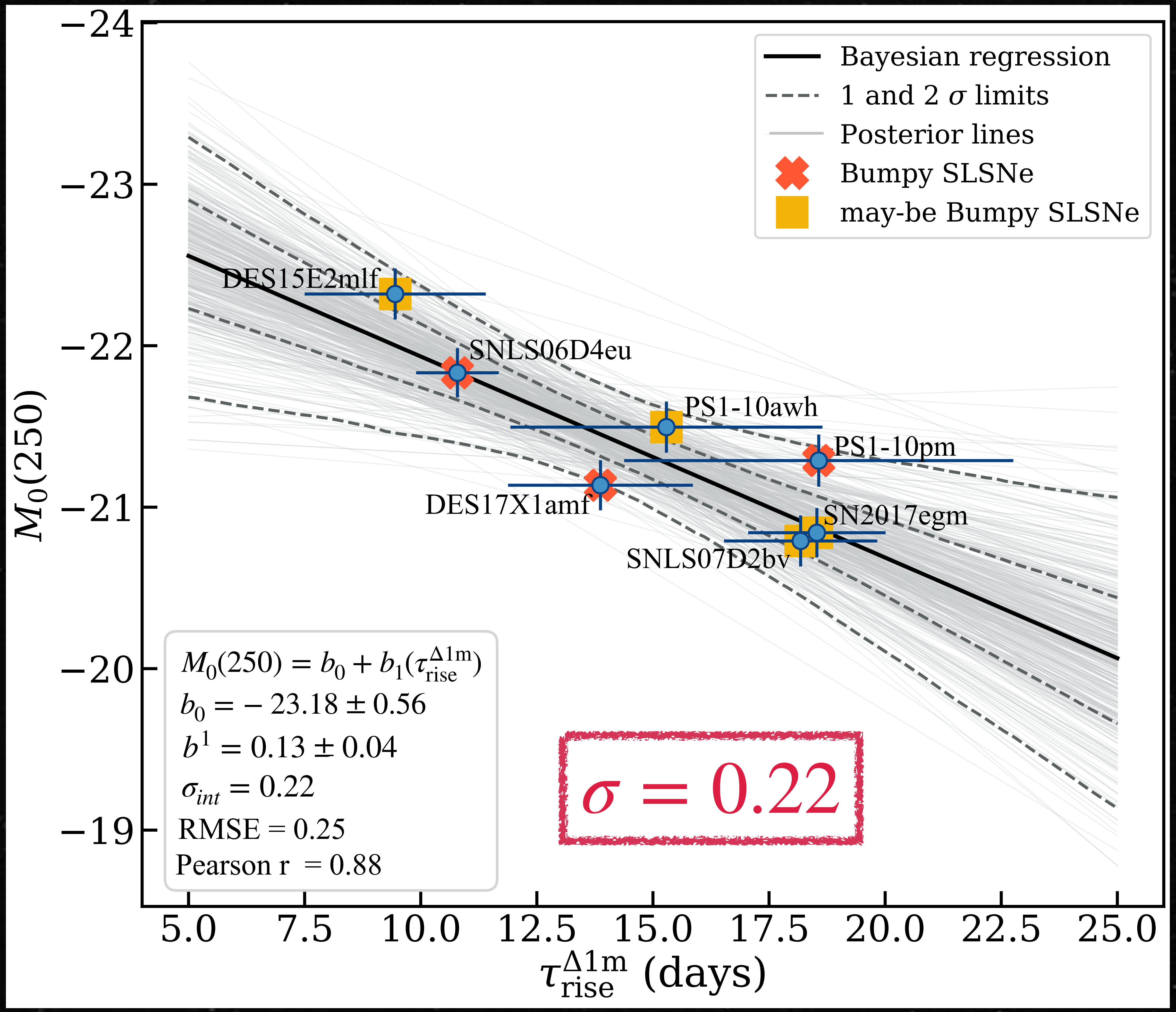
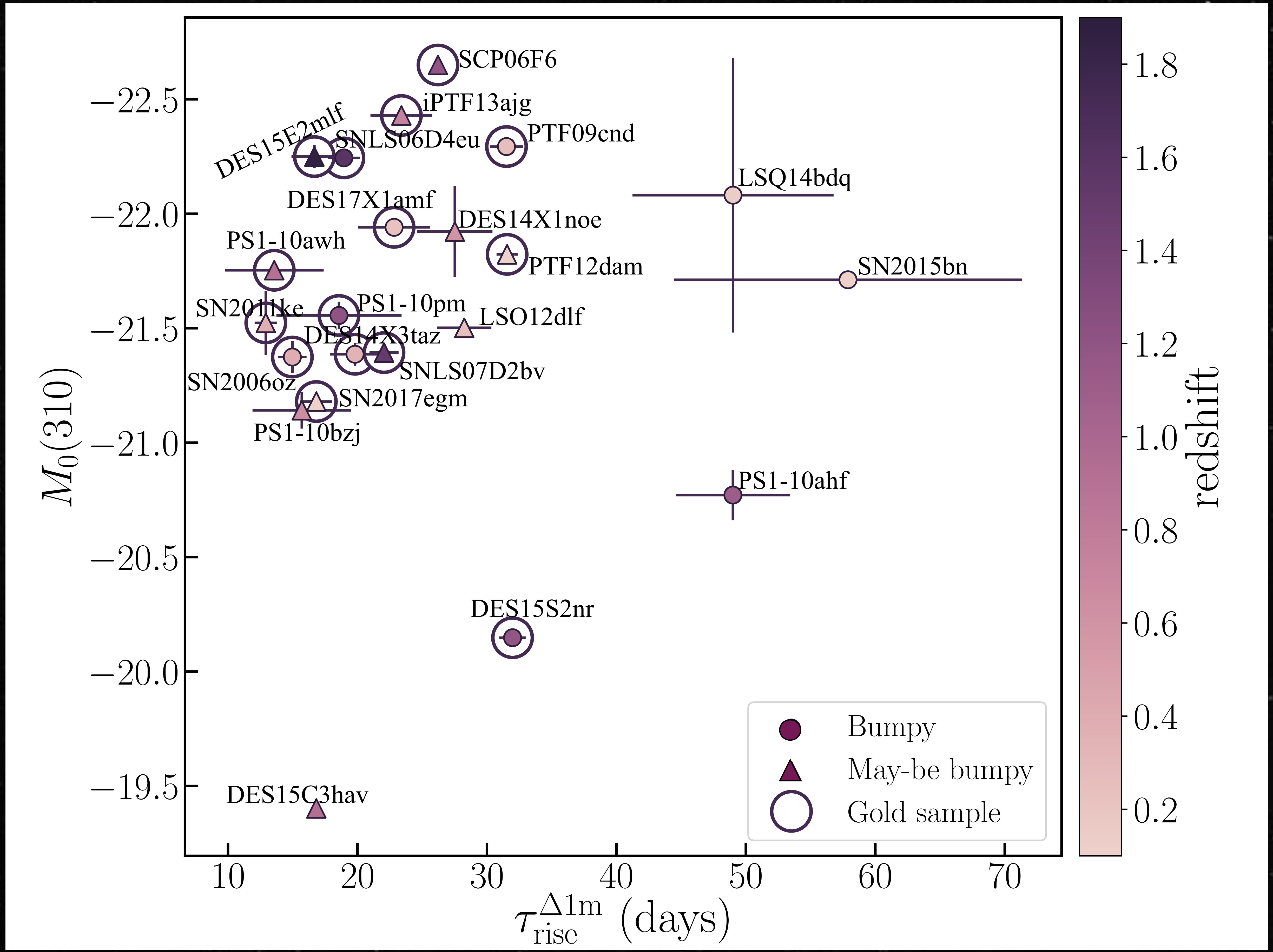




Suggests Bumpies could be different population

Peak magnitude - Rise time relation

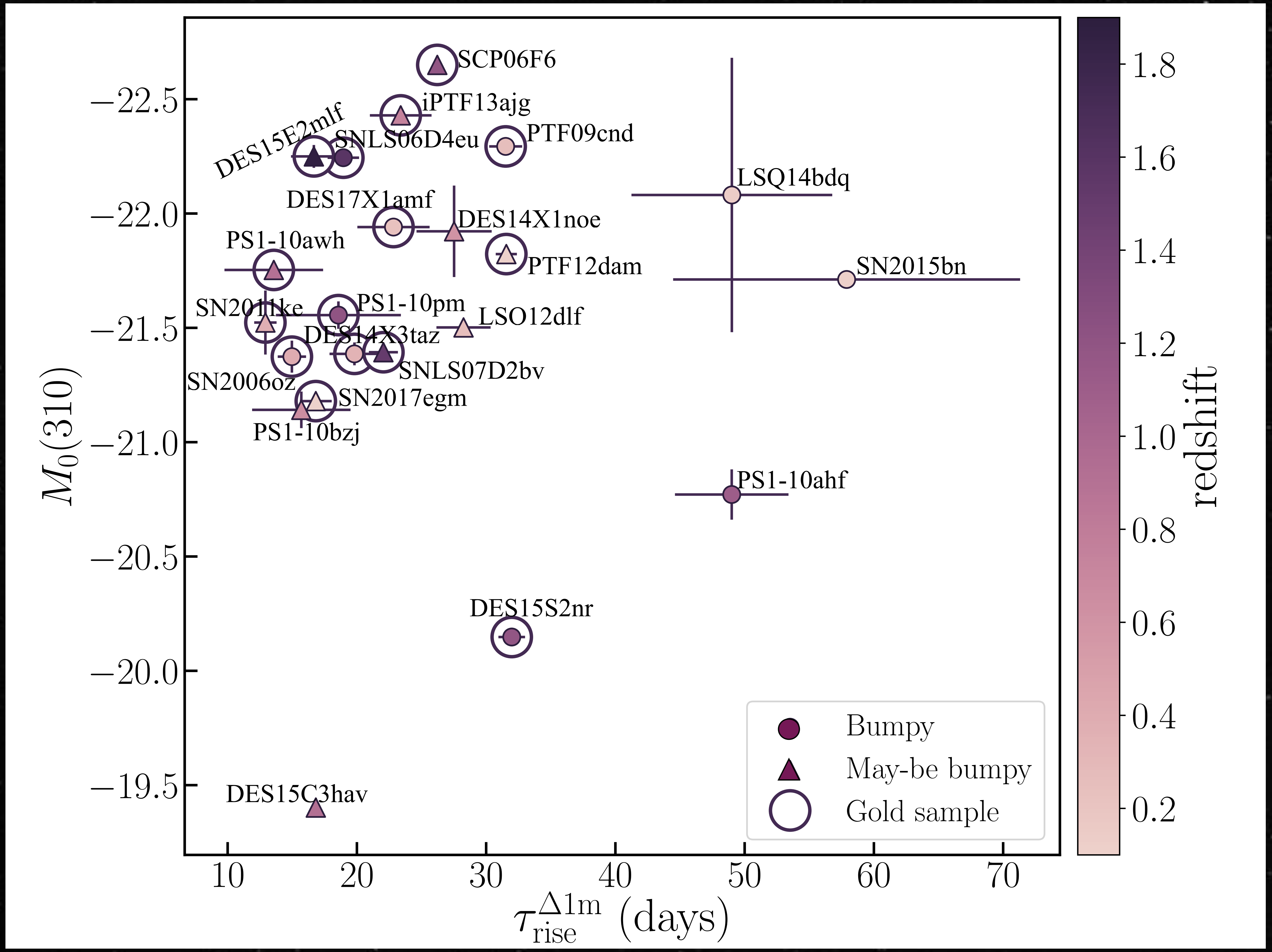
Bumpy sample at 310 nm



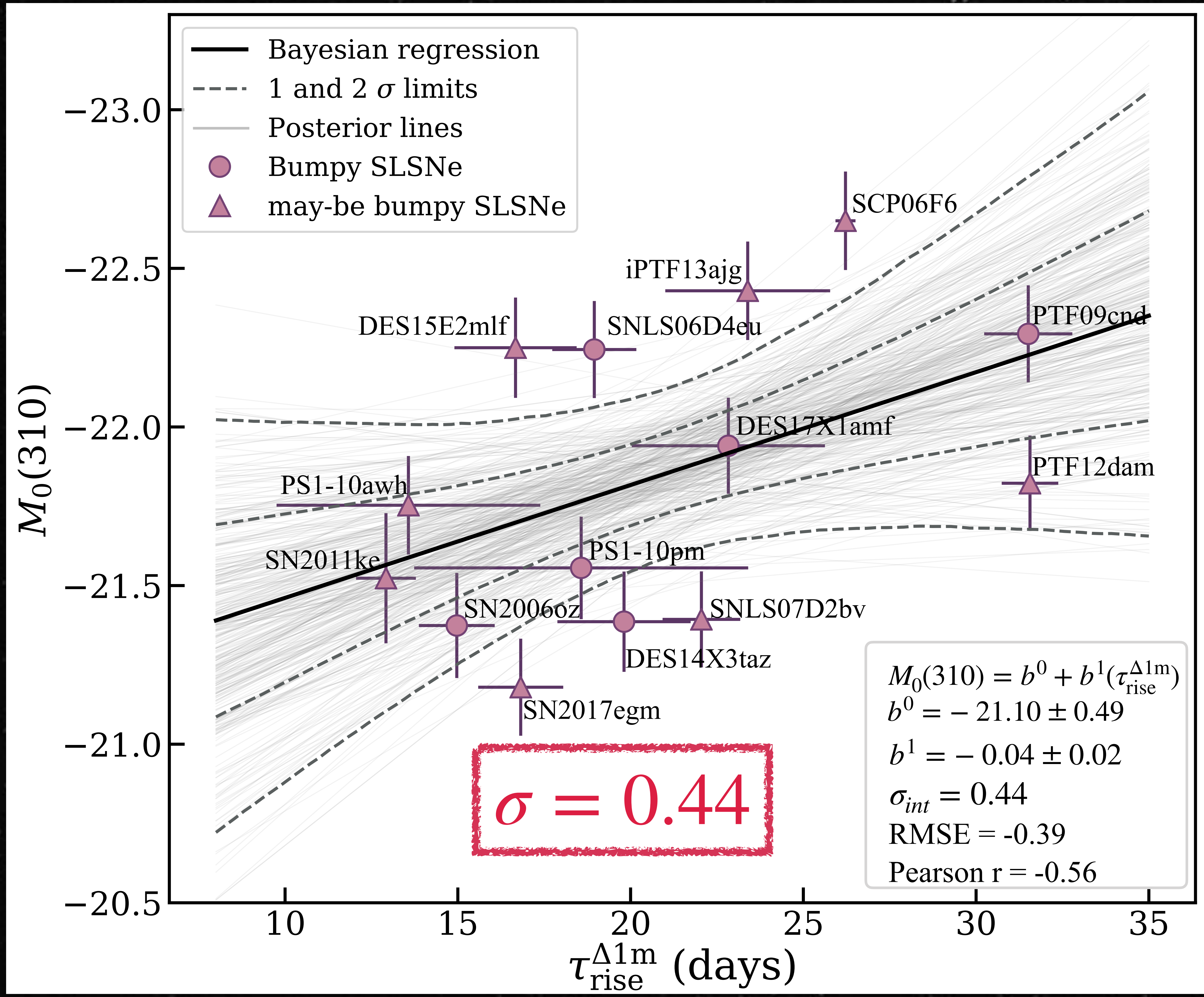
Brighter SLSNe rise slower for the Bumpy sample at 310nm

Peak magnitude - Rise time relation

Bumpy sample at 310 nm



Gold Bumpy sample at 310 nm



Brighter SLSNe rise slower for the Bumpy sample at 310nm

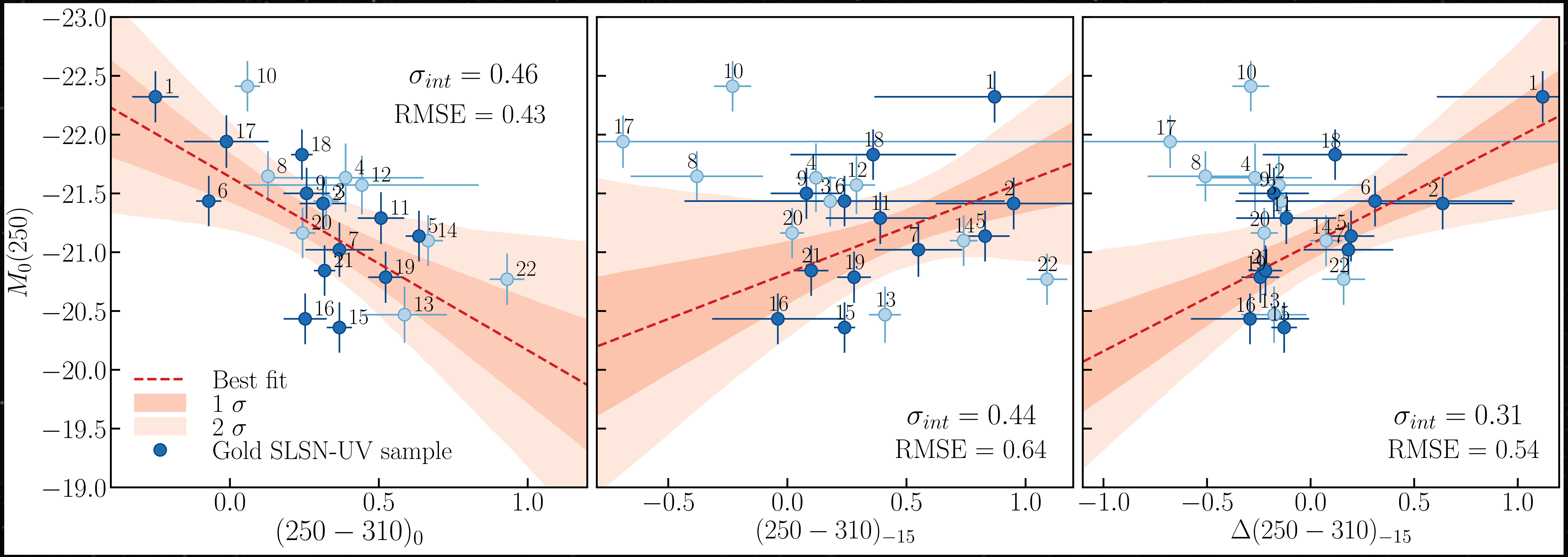
Peak magnitude - Color relation

SLSN-UV sample 250nm	Color at peak	Color at 15 days before peak	Change in color from 15 days before peak to peak
	$(250-310)_0$	$(250-310)_{-15}$	$\Delta(250-310)_{-15}$

Peak magnitude - Color relation

SLSN-UV sample 250nm

Color at peak	Color at 15 days before peak	Change in color from 15 days before peak to peak
$(250-310)_0$	$(250-310)_{-15}$	$\Delta(250-310)_{-15}$



Peak magnitude - Color relation

Bumpy sample 310nm

Color at peak	Color at 15 days before peak	Change in color from 15 days before peak to peak
$(310-400)_0$	$(310-400)_{-15}$	$\Delta(310-400)_{-15}$

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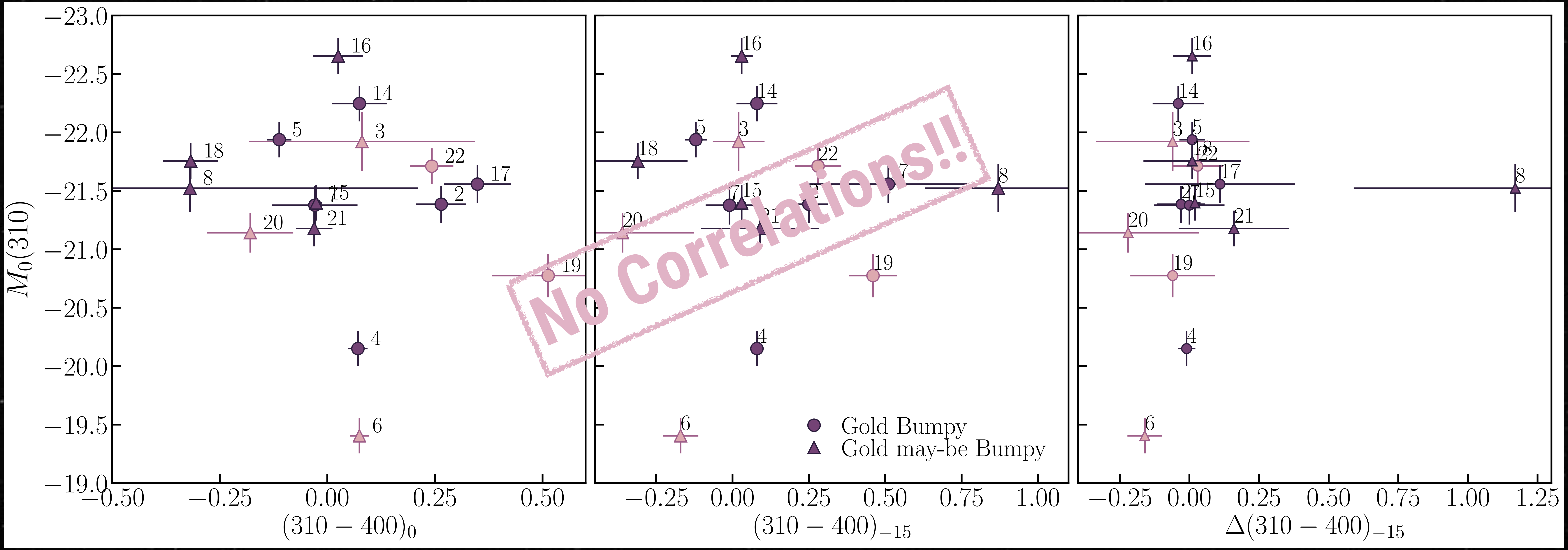
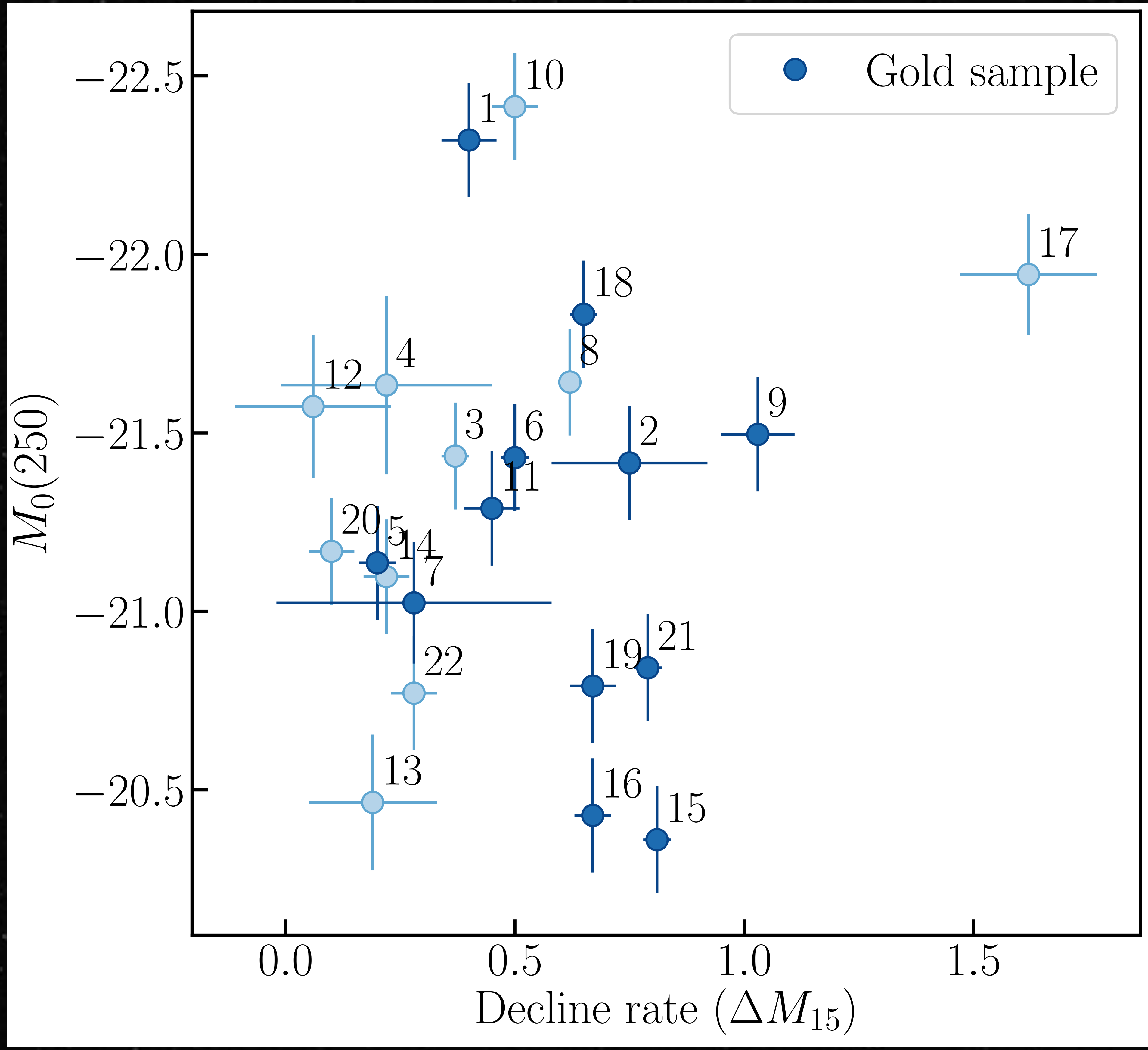


Peak magnitude - Decline rate

SLSN-UV sample
250nm



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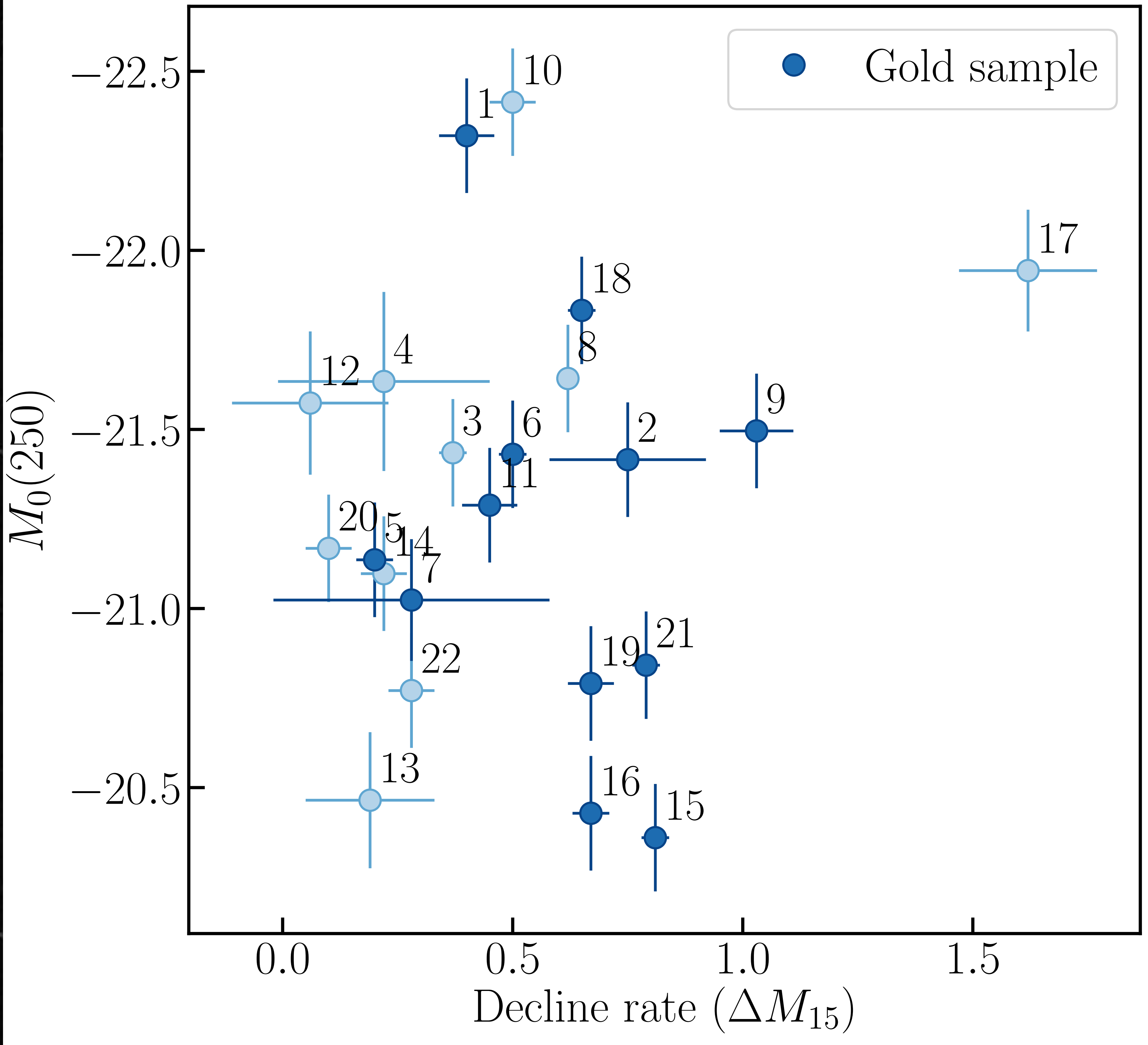
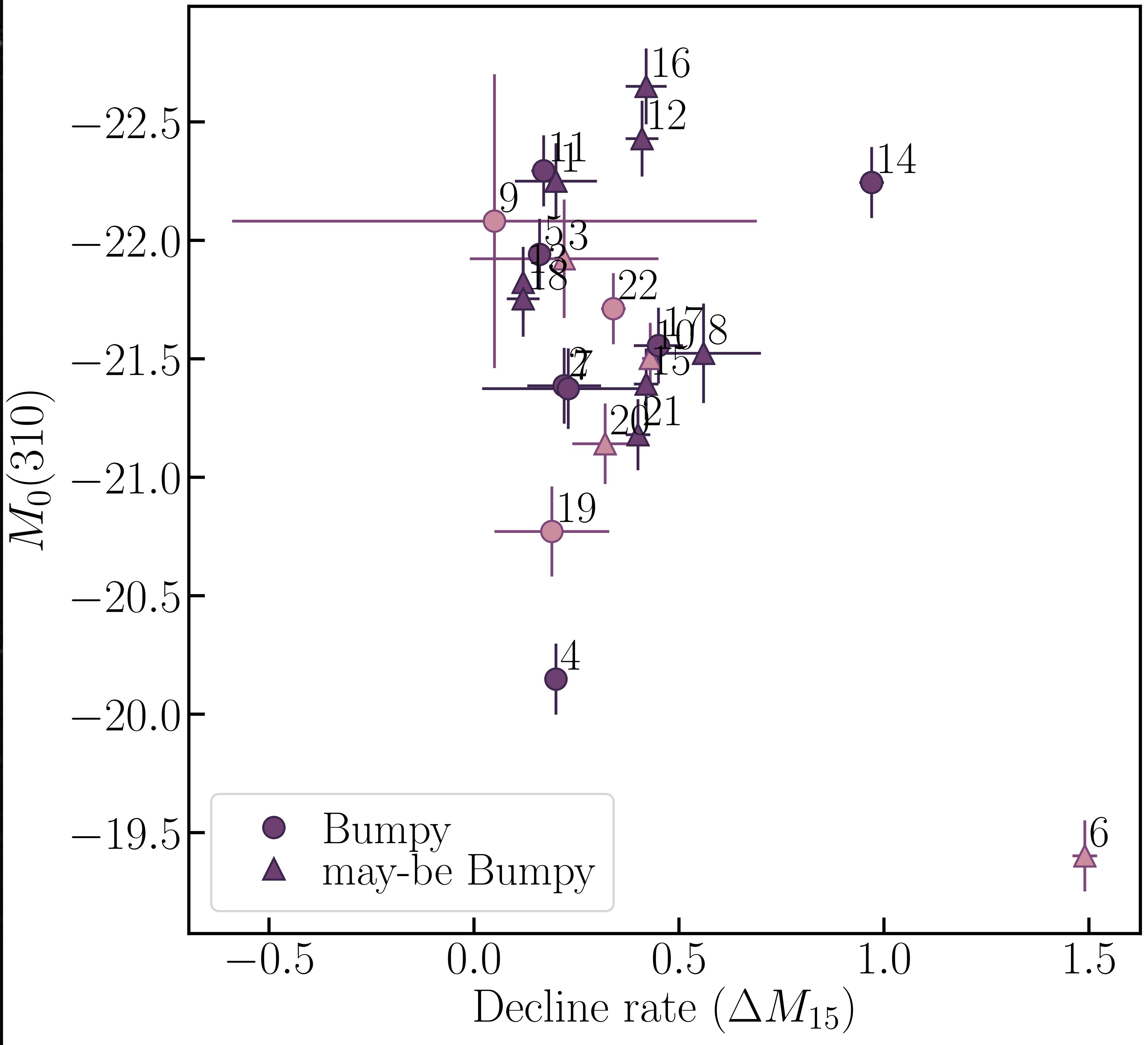


Bumpy sample
310nm



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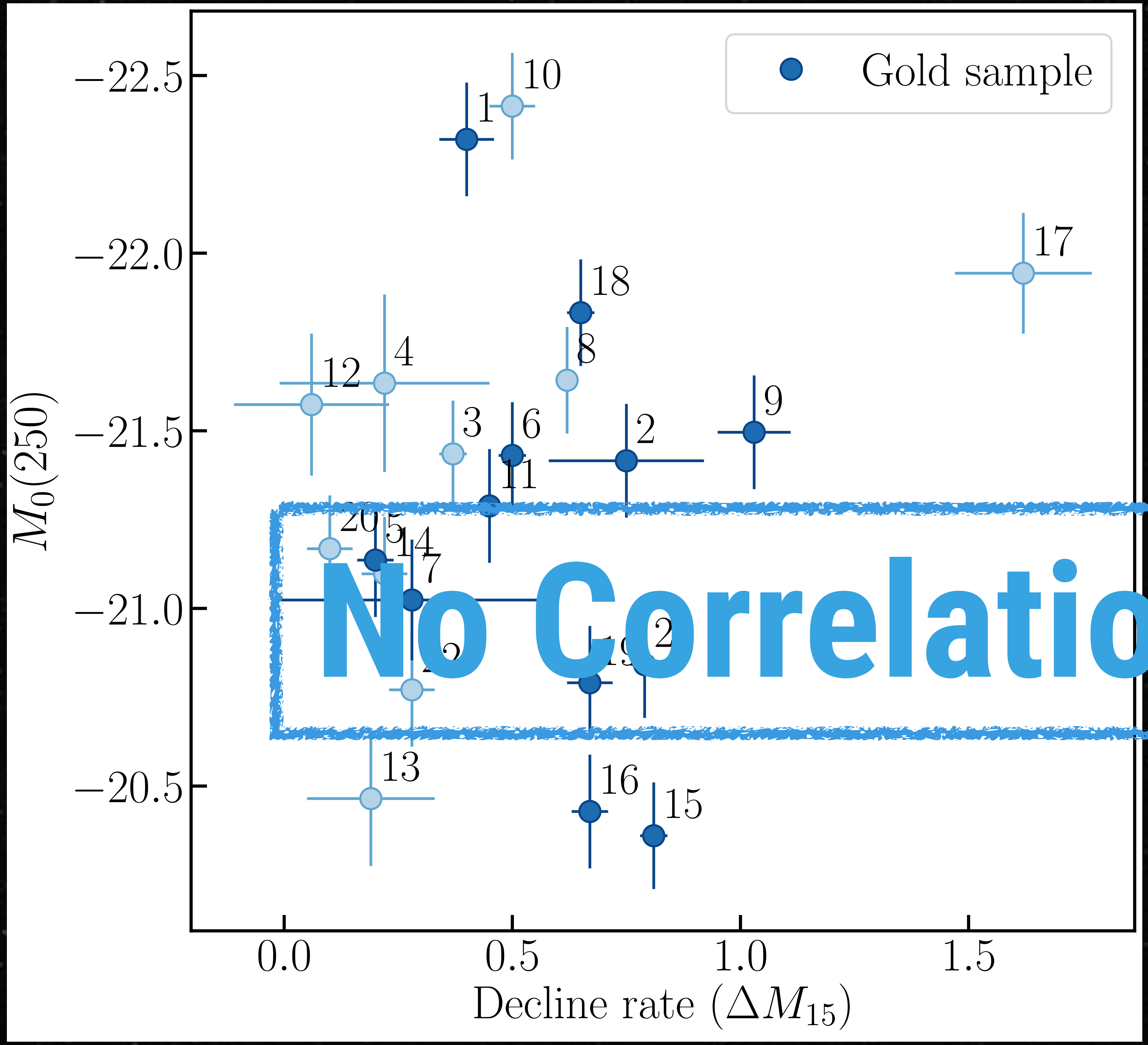
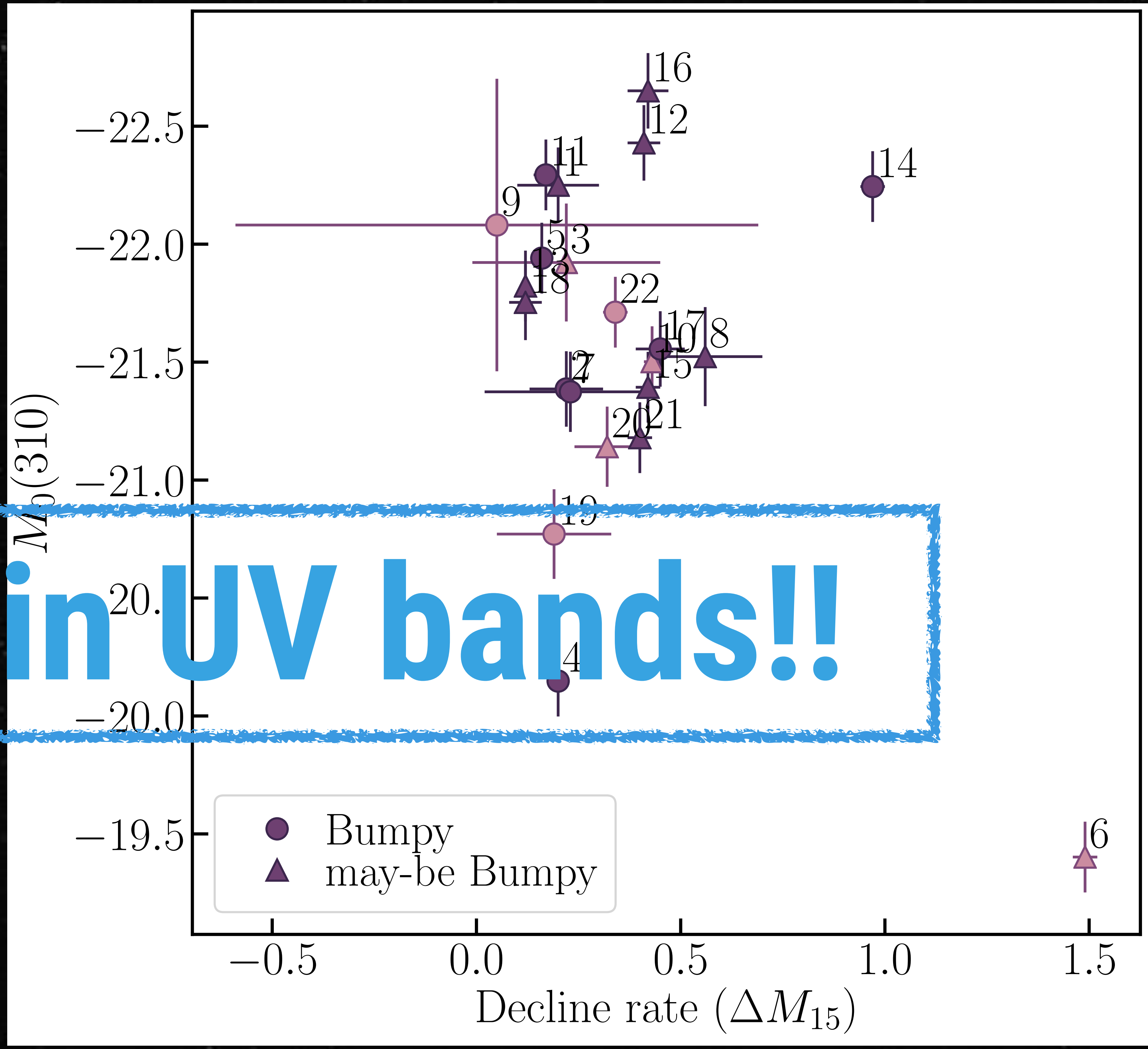


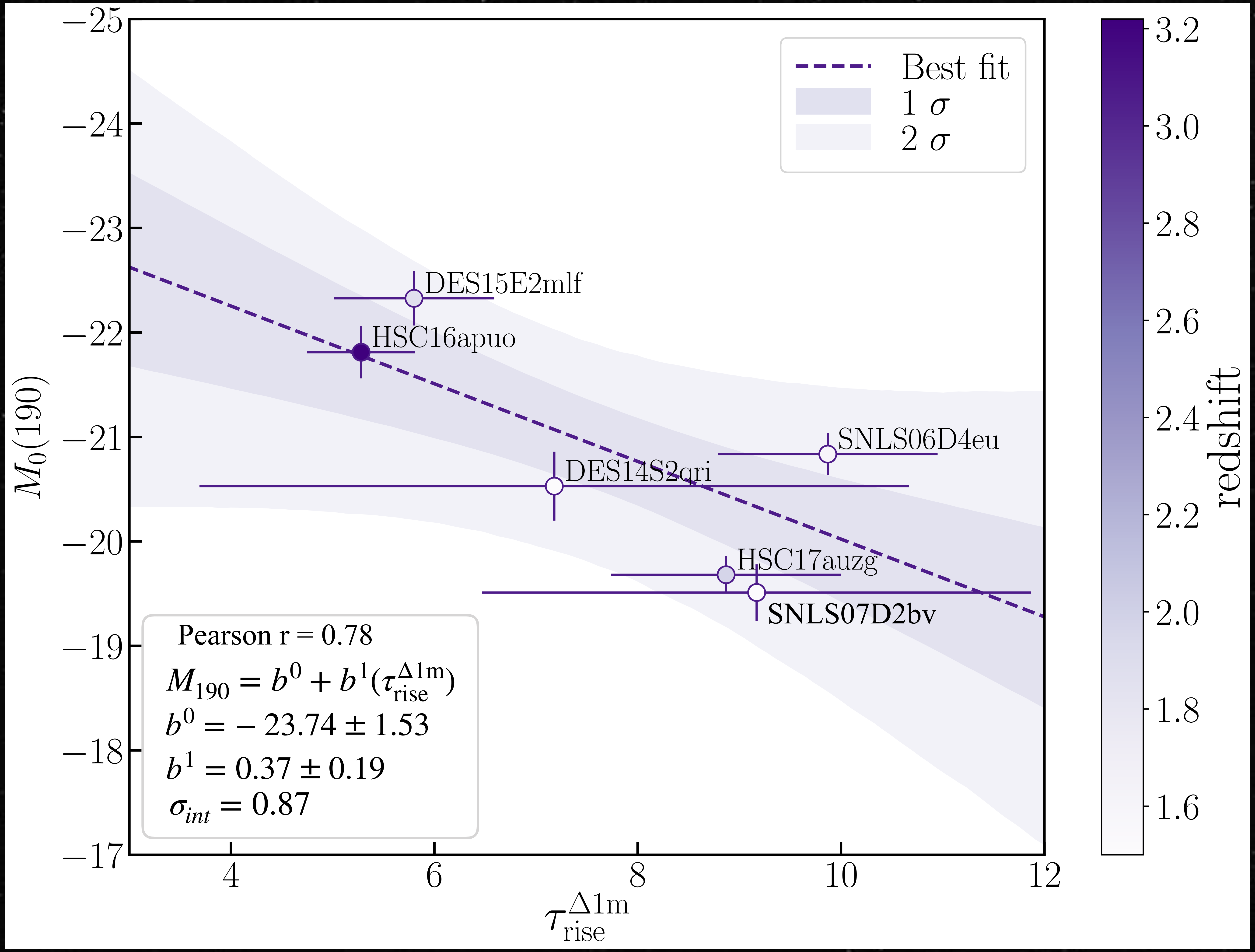


No Correlation in UV bands!!

Highest redshift

SLSN-UV sample
190nm

6 SLSNe which probe this range



Conclusions

SLSNe can be detected in their rest frame UV up to z ~ 7

1. SLSNe-I show promise as standardisable distance indicators in UV/NUV bands

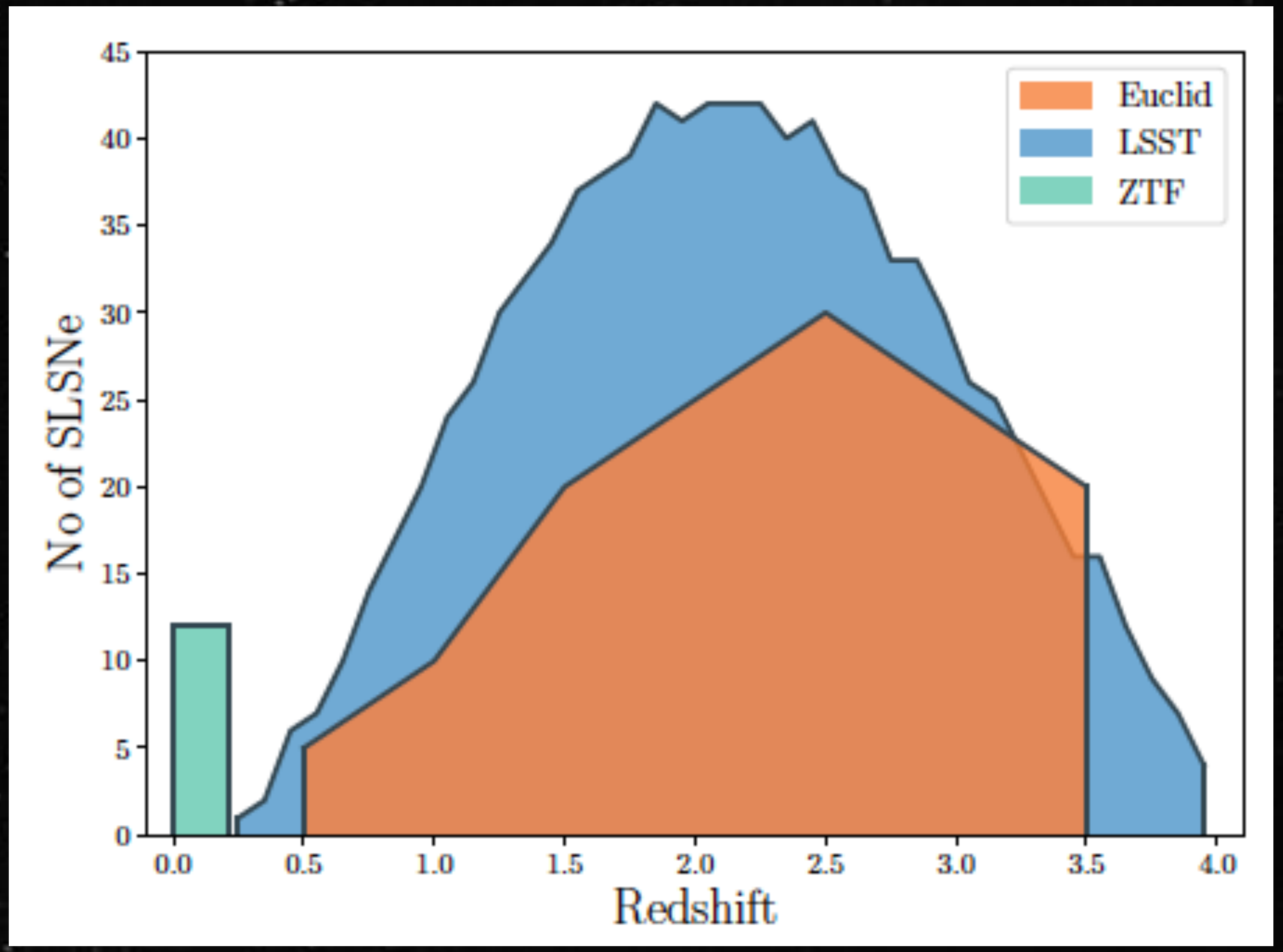
2. Peak magnitude - rise time correlations show $\sigma \sim 0.29$ mag

3. Rise time correlations is improved $(\sigma \sim 0.2)$ eliminating bumpy SLSNe - Suggestion of different population

4. Weak correlation with colors indices at 250 nm band

5. NO correlation between peak mag and decline at UV bands

6. Larger data samples needed to further test the observed results.



Inserra et al. 2020

Khetan et al. (to be submitted)

03

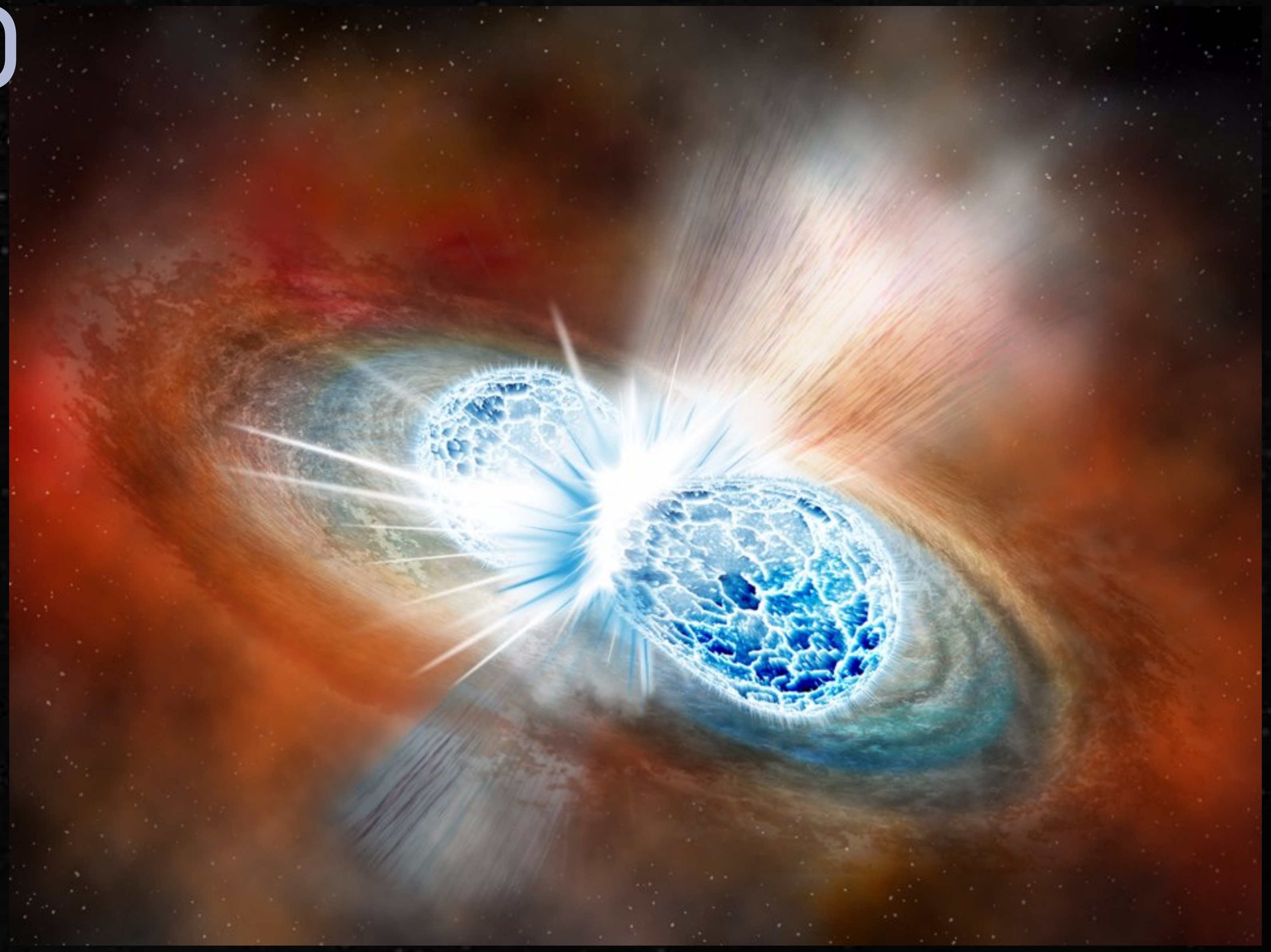
KNe as distance Indicators

Standardizing KNe and their use as standard candles to measure H_0

Kilonova

Coalescence of Compact Binary Objects (NS, BH)

Produce gravitational waves as well as EM emissions



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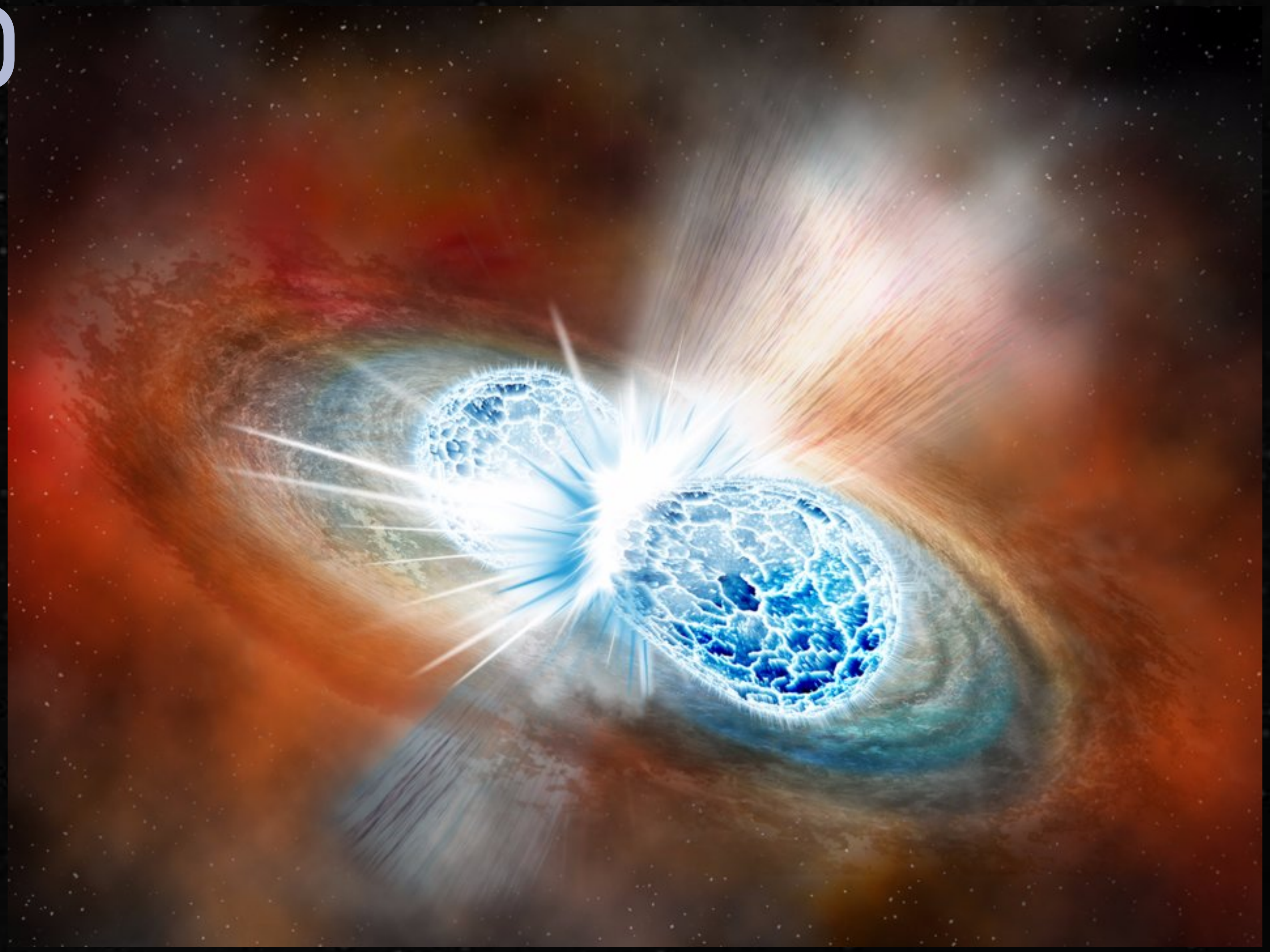
Sub-relativistic ejecta undergoes r-process

Enriches our Universe with Heavy elements (lanthanides and Actinides)



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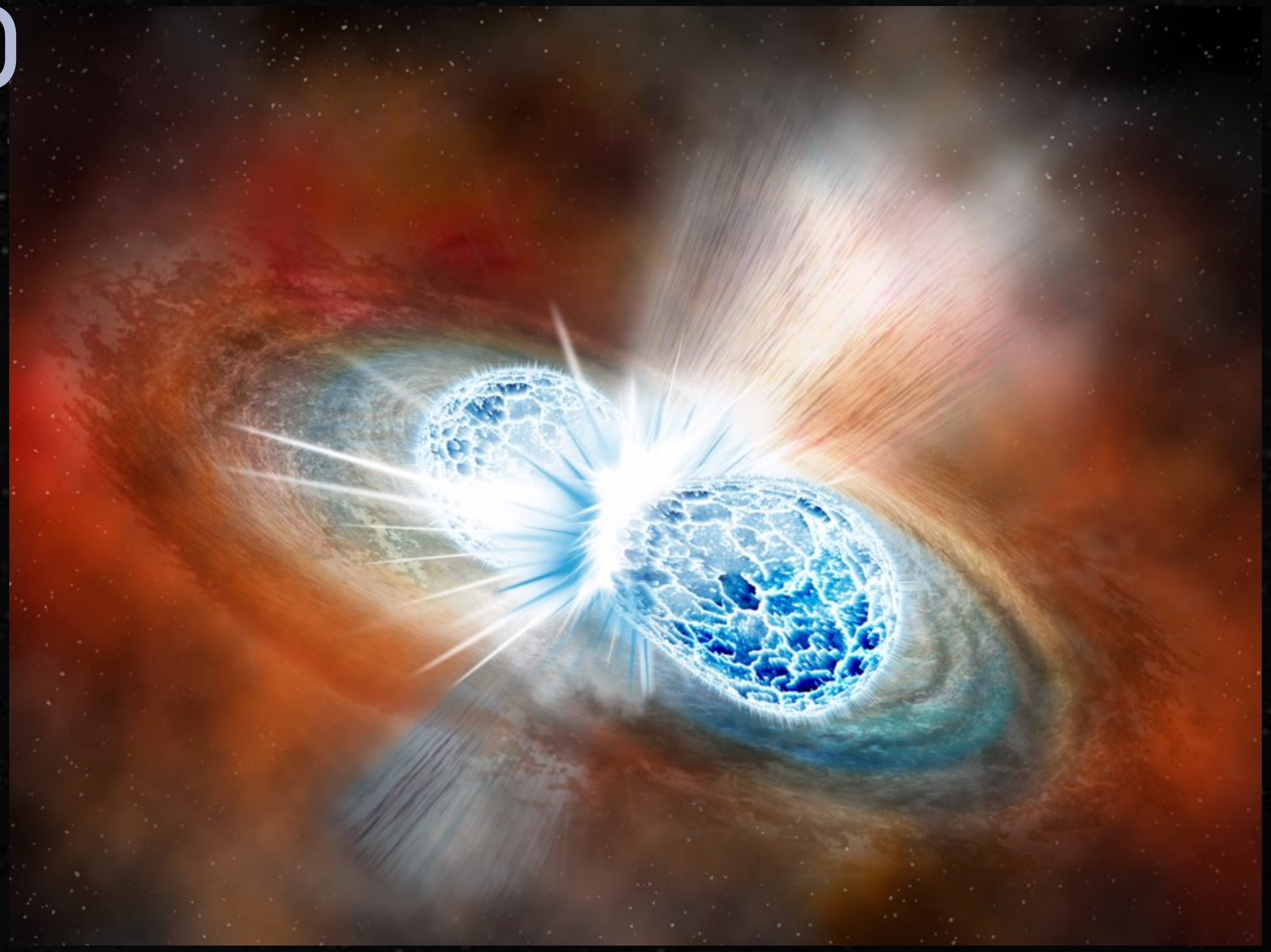

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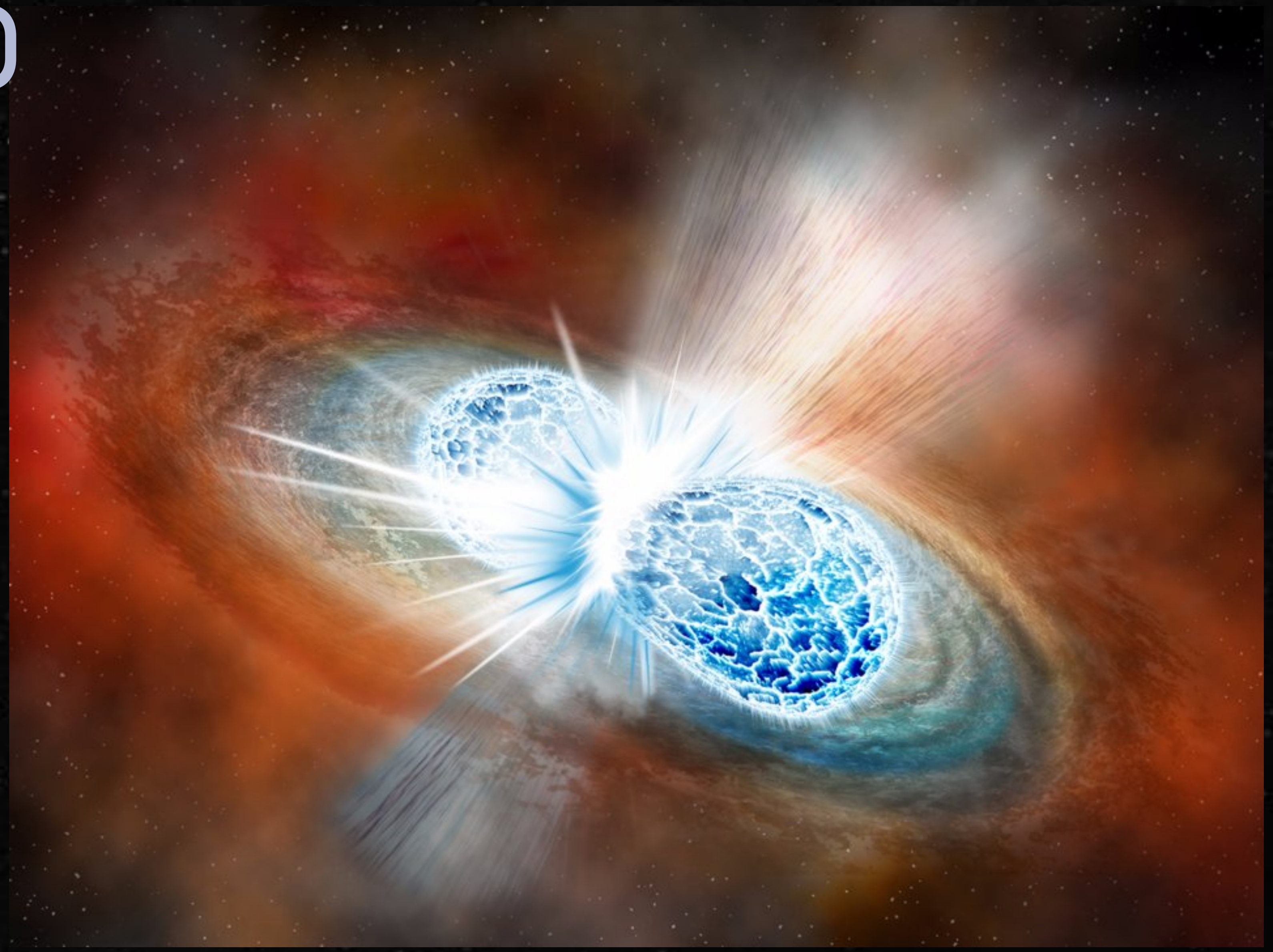

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GW170817
Merger of two neutron stars accompanied with detection of a Kilonova

Kilonova as distance indicators

GW170817 provided constrain on H_0

Independent of cosmic ladder

→ GWs provide the Luminosity distance

→ EM counterpart provide the redshift

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Parallels between SNe Ia and KNe

1. Both transients (believed to be) triggered by merger of compact objects under a narrow mass range
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Could KNe be standardised to be used as distance indicators like SNe Ia ?

- Using techniques similar to SNe Ia standardisation to measure distances based on KN light curve

Kilonova standardisation

Based on Semi-analytic models of Arnett and Chatzopoulos, observed light curve properties depend on

01 Ejecta Mass M_{ej}

02 Ejecta Velocity v_{ej}

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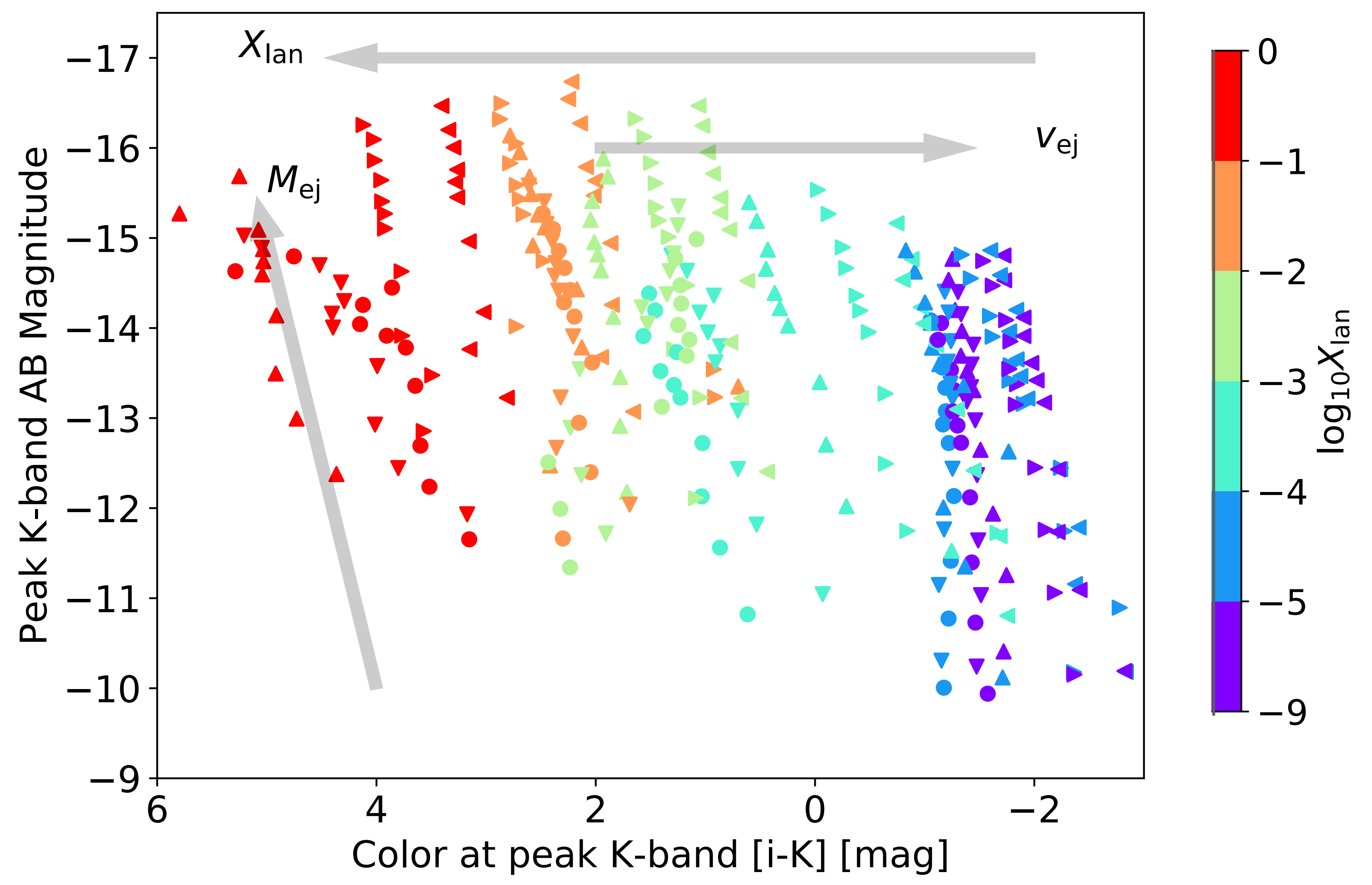
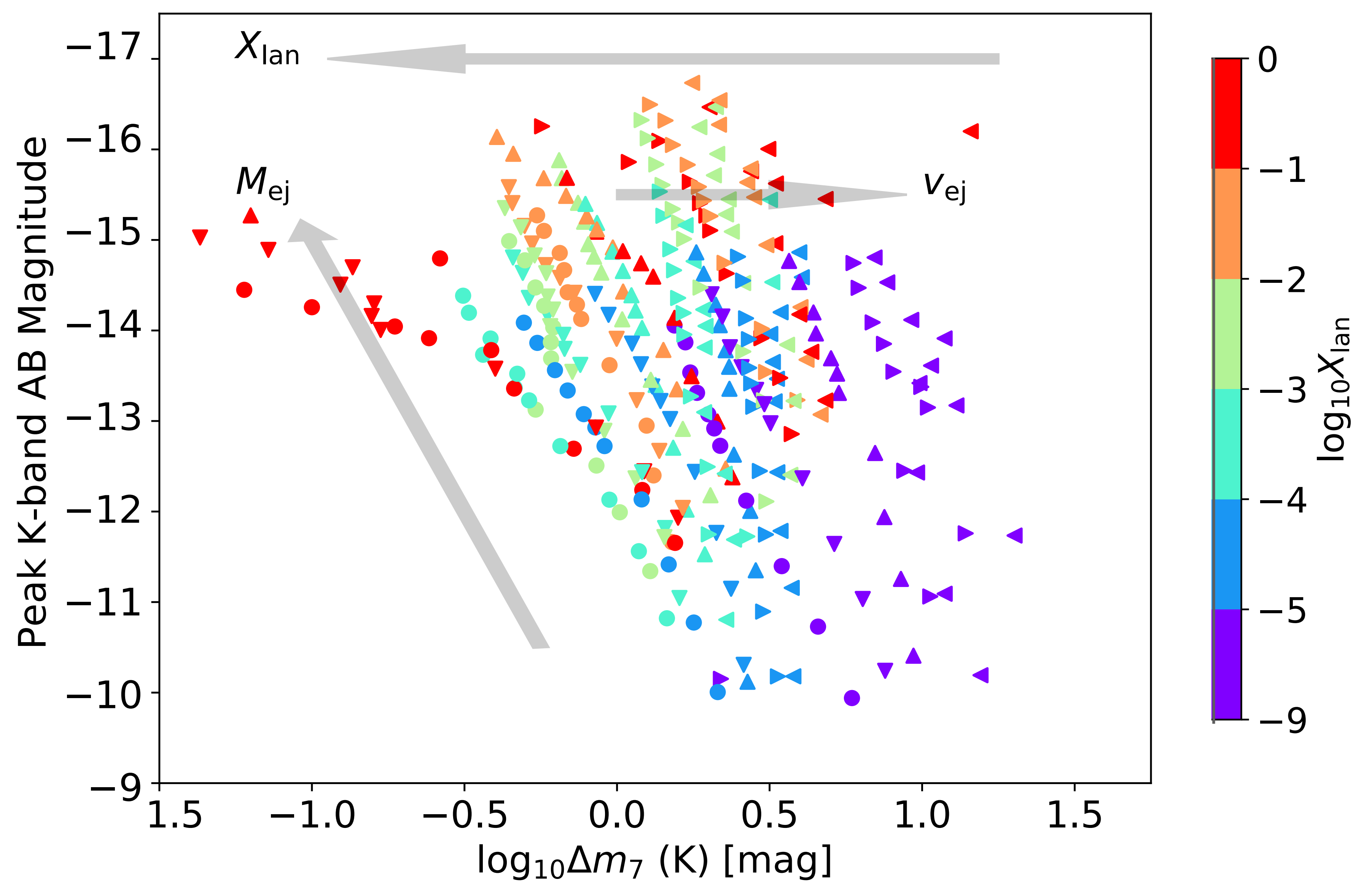
↓

Explore the color-mag and decay rate - mag diagrams





Kilonova standardisation

Two types of peak luminosity correlations:

Kilonova standardisation

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01 Observable quantities; decline rate and color
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$$M_0 = f(\Delta m_7,\ m_i - m_K)$$

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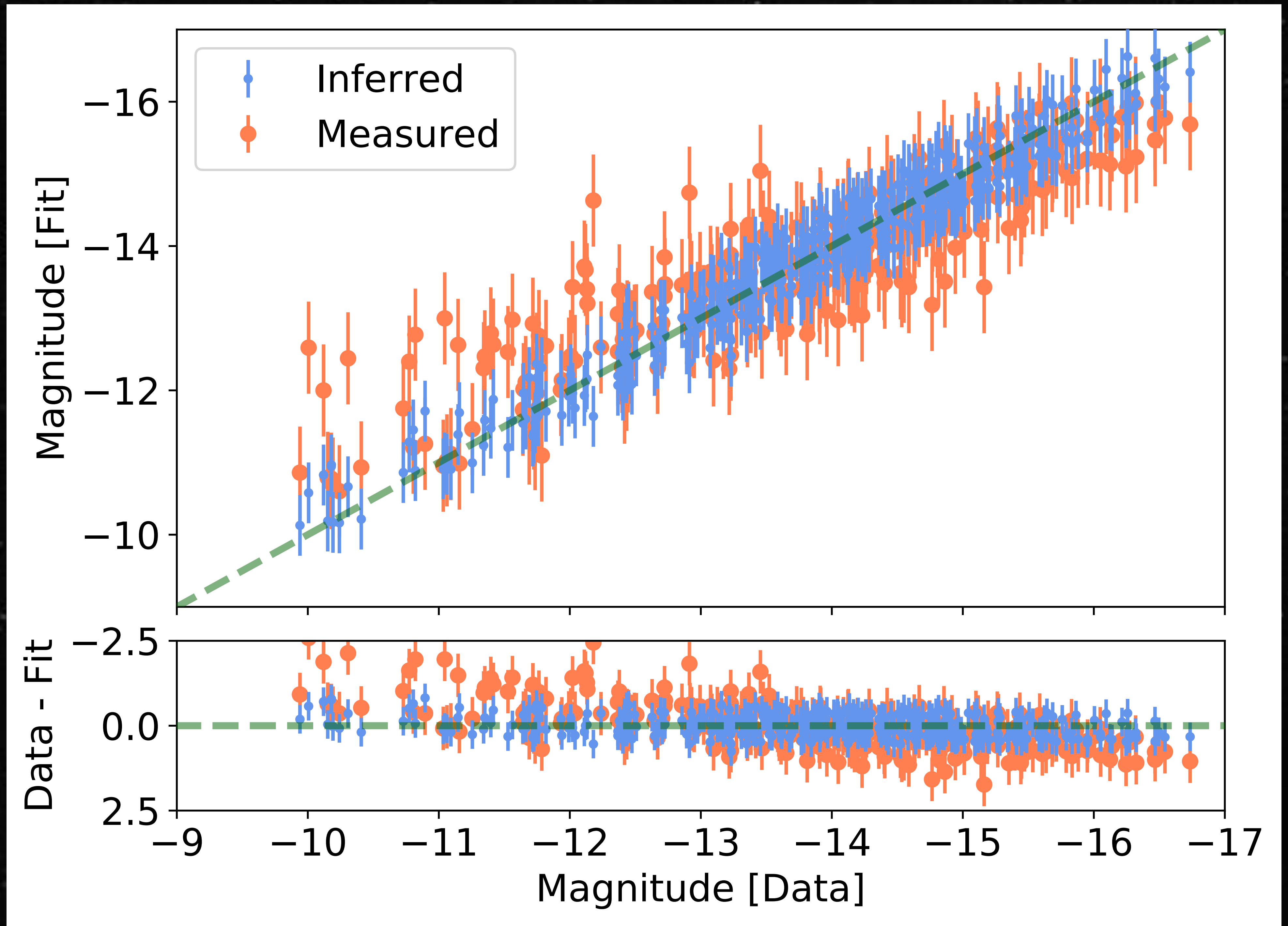

Performance of the fits compared to the models of Kasen et. al. 2017

Results

Fit results are applied on the measured posteriors of M_{ej}, v_{ej} and X_{lan} for **GW170817**

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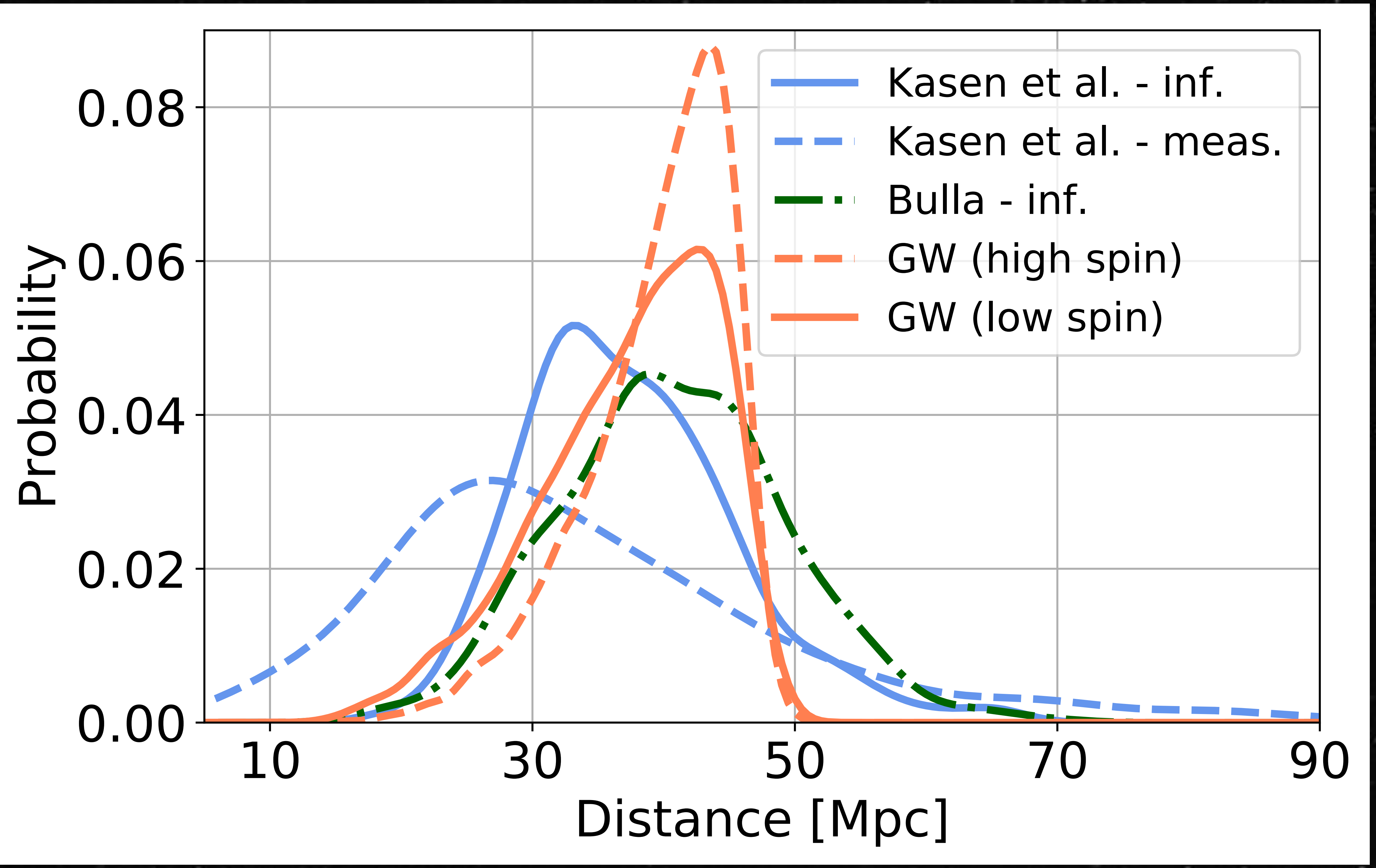

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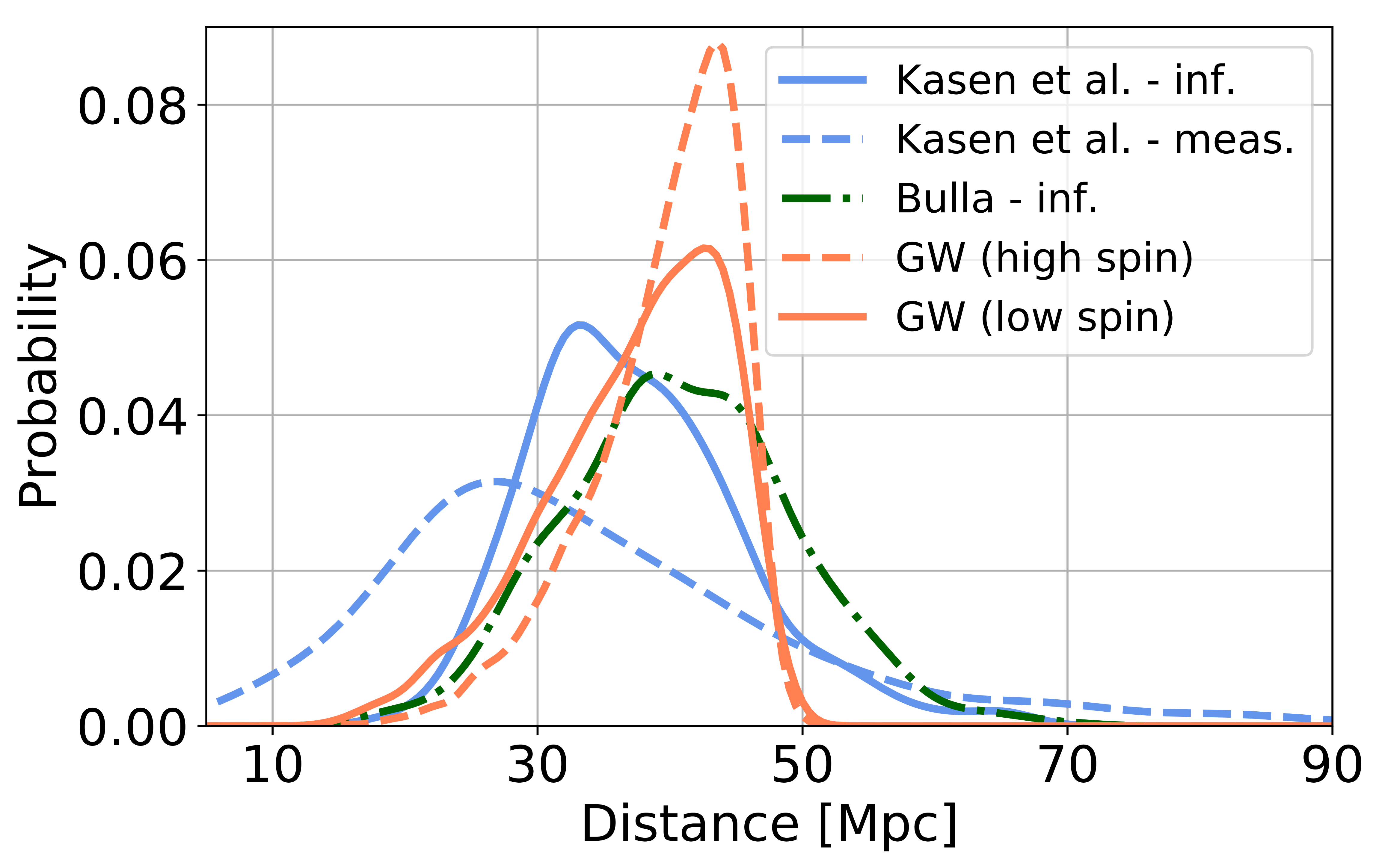

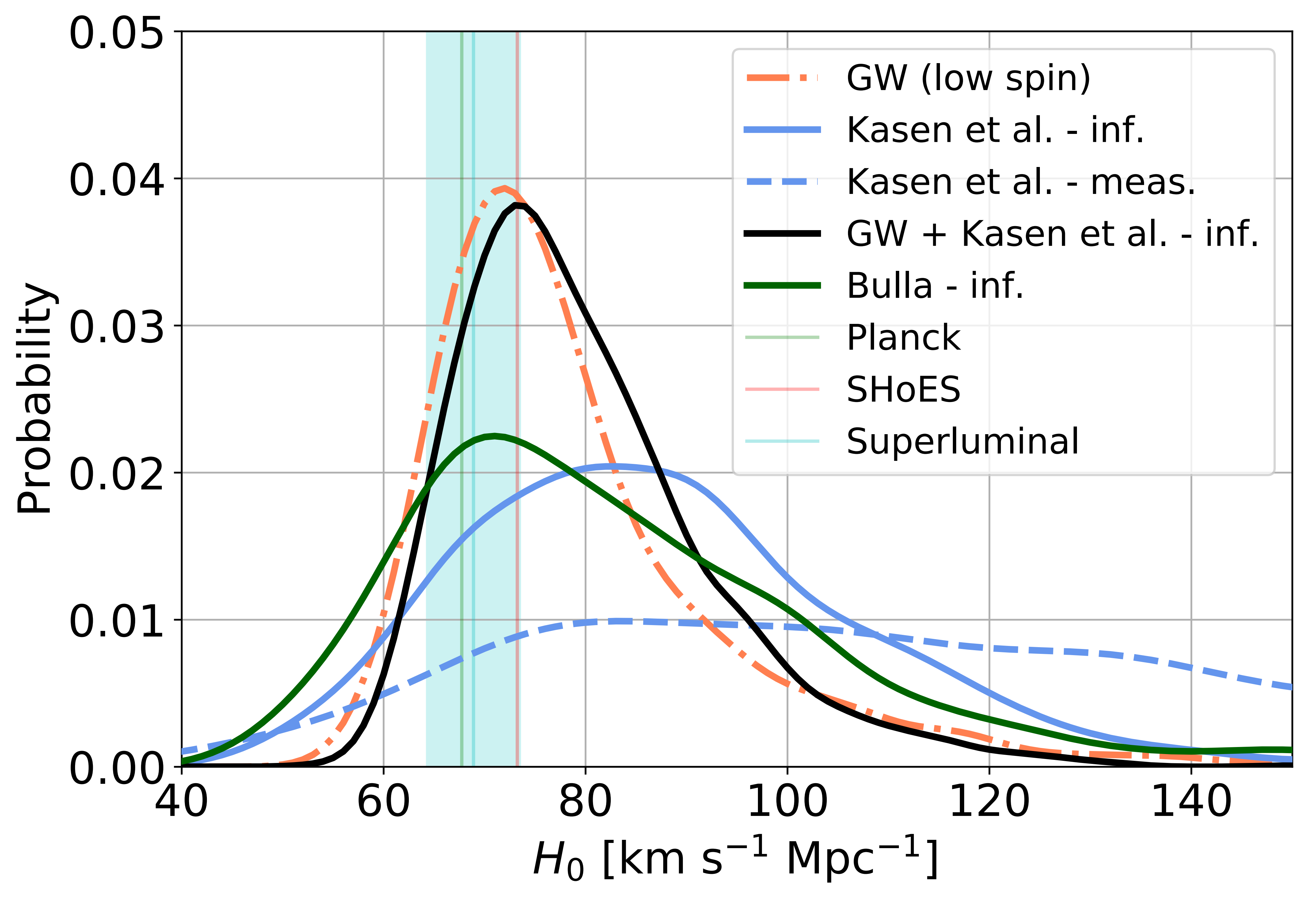

$D = 31^{+17}_{-11}$ Mpc $\quad$ $D = 37^{+8}_{-7}$ Mpc

$H_0 = 109^{+49}_{-35}$ Km s^{-1} Mpc^{-1} $\quad$ $H_0 = 85^{+22}_{-17}$ Km s^{-1} Mpc^{-1}

Conclusions

1. New technique to use KNe as distance Indicators
2. My contribution : Modelling the peak luminosities with observed and inferred quantities
3. Error bars are large — Only 1 data point
4. ~20 and 170 events are required for 6% and 2% measurement respectively
5. Important prospects for Future multi-messenger surveys

Coughlin et. al. 2020a, 2020b; including N. Khetan

Summary

Advancing the standardisation techniques for 3 different transients for their use as cosmological probes.

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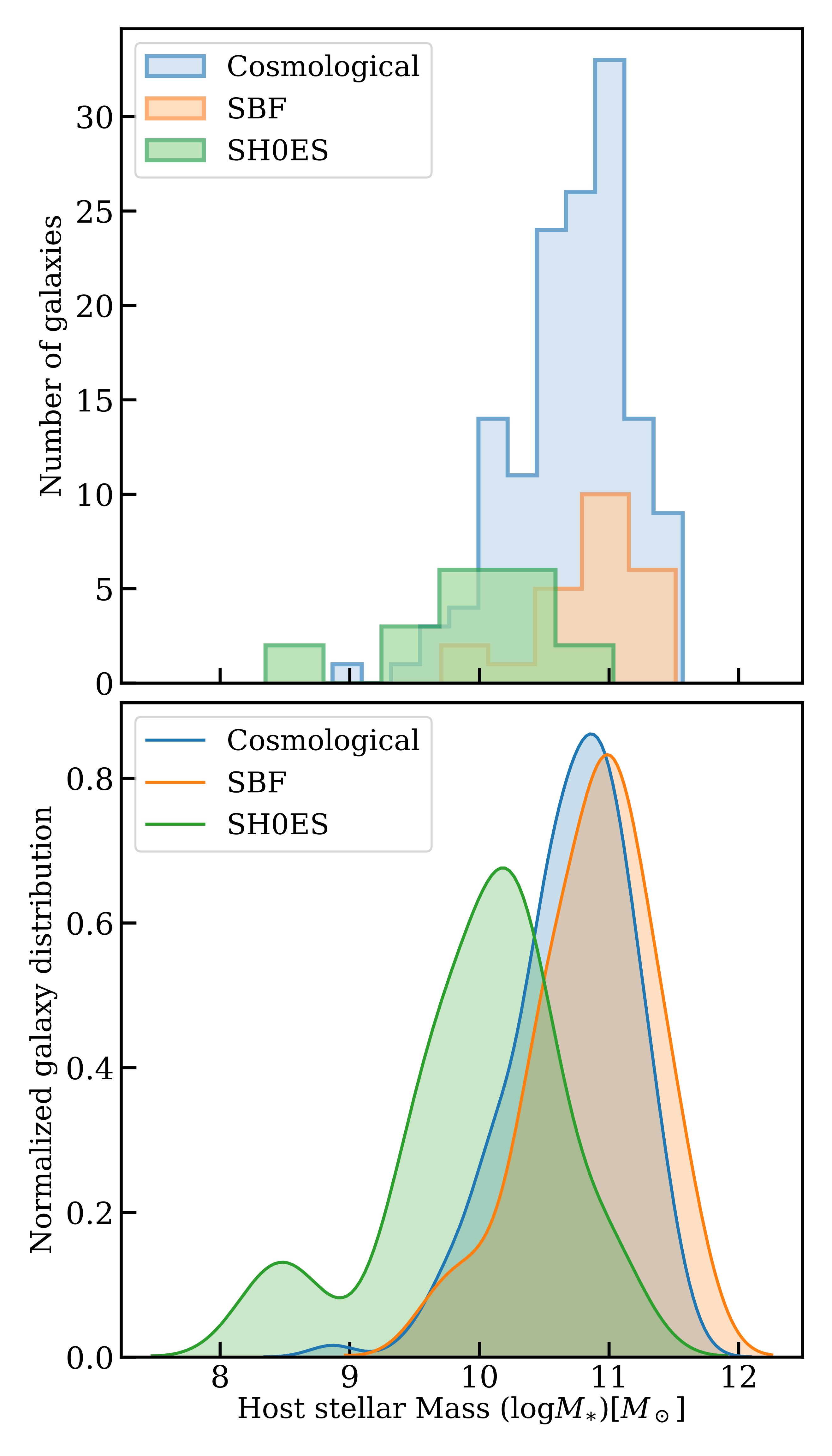
Kilonovae

- Technique to standardise KNe based on light curve properties
- Independent of information from GW - Can be used on KNe samples
- Model dependent, More data needed.

Back-up

Mass dist.



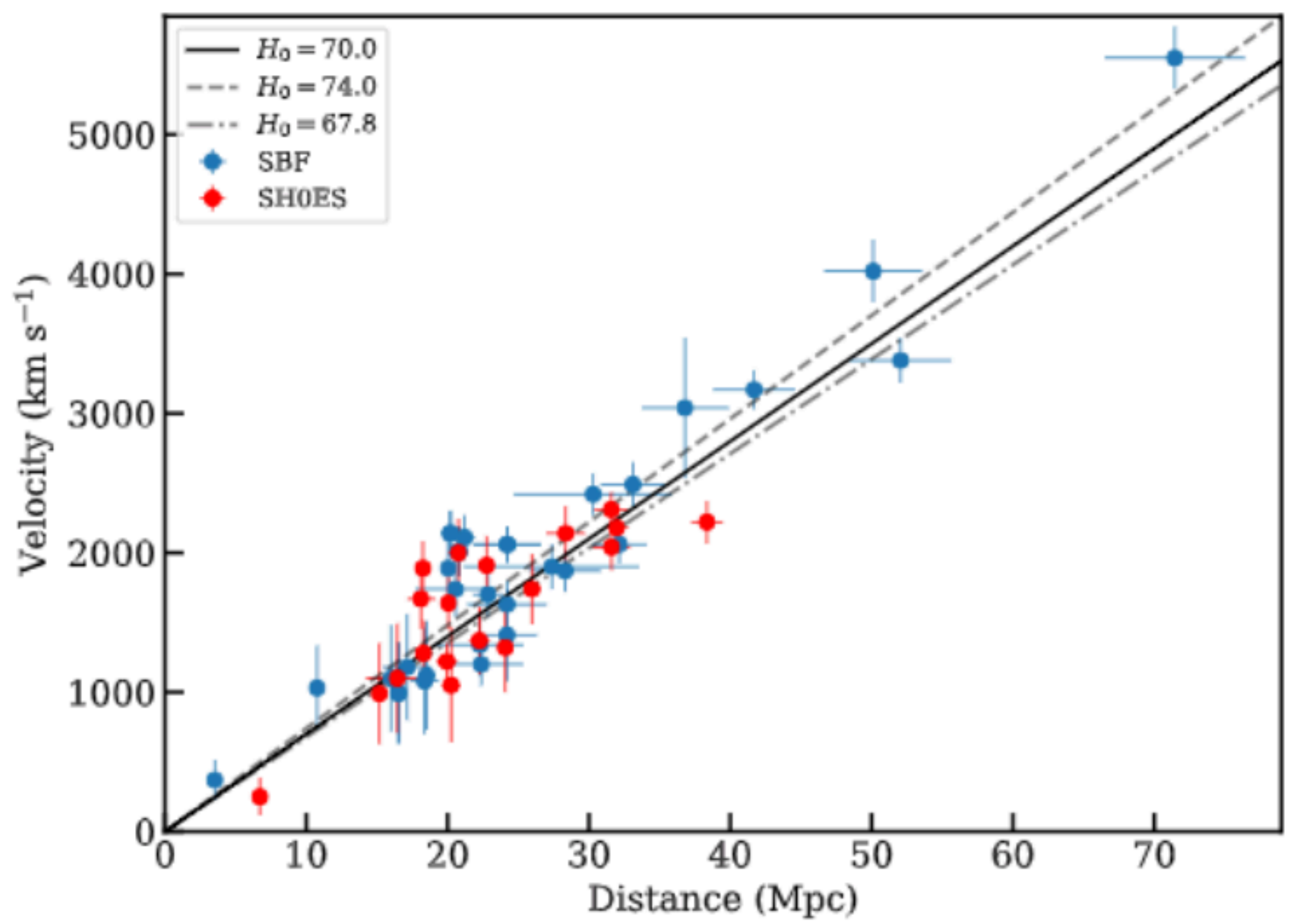
Cosmological
SBF
SH0ES
Number of galaxies
30
25
20
15
10
5
0
Cosmological
SBF
SH0ES
Normalized galaxy distribution
0.8
0.6
0.4
0.2
0.0
8
9
10
11
12
Host stellar Mass (logM_*)[$M_\odot$]

LMC distance

Old Value = 18.50 +- 0.10
With latest Value of LMC = 18.477 +- 0.004

H0 value with SBF calibration increases by 1%
71.16 +- 2.38

H0 value with SHOES calibration increases by 0.8%
73.38 +- 1.66



$H_0 = 70.0$
$H_0 = 74.0$
$H_0 = 67.8$
SBF
SH0ES
Velocity (km s^{-1})
0
1000
2000
3000
4000
5000
0
10
20
30
40
50
60
70
Distance (Mpc)

z	N_{sample} (mag)	P_0 (mag)	P_1	R (mag)	$\sigma_{int,calib}$ (mag)	$\sigma_{int,cosmo}$
SBF Calibration						
$0.009 < z < 0.075$	140	-19.271 ± 0.073	-1.08 ± 0.111	2.026 ± 0.163	0.310	0.177
$0.02 < z < 0.075$	96	-19.266 ± 0.073	-1.059 ± 0.116	2.005 ± 0.168	0.310	0.148
Cepheid Calibration						
$0.009 < z < 0.075$	140	-19.160 ± 0.048	-0.995 ± 0.112	2.148 ± 0.162	0.174	0.176
$0.02 < z < 0.075$	96	-19.159 ± 0.046	-0.992 ± 0.116	2.158 ± 0.166	0.171	0.145

$$\ln \mathcal{L}_{calib} = -\frac{1}{2}\sum_{i=1}^{N_{calib}} \frac{(m_B^i - m_B^T)^2}{\sigma^2_{calib,i}} - \frac{1}{2}\sum_{i=1}^{N_{calib}} \ln 2\pi\sigma^2_{calib,i}$$

and

$$\ln \mathcal{L}_{cosmo} = -\frac{1}{2}\sum_{j=1}^{N_{cosmo}} \frac{(m_B^j - m_B^T)^2}{\sigma^2_{cosmo,j}} - \frac{1}{2}\sum_{i=j}^{N_{cosmo}} \ln 2\pi\sigma^2_{cosmo,j}\,,$$

while the combined log likelihood is

$$\ln \mathcal{L} = \ln \mathcal{L}_{calib} + \ln \mathcal{L}_{cosmo}.$$

$$\sigma^2_{calib,i} = \sigma^2_{m_B,i} + \sigma^2_{\mu_{SBF},i} + (P^1\sigma_{s_{BV},i})^2 + (R\sigma_{m_B-m_V,i})^2 - 2R\sigma^2_{m_B,i} + \sigma^2_{int,calib}\ , \quad (10)$$

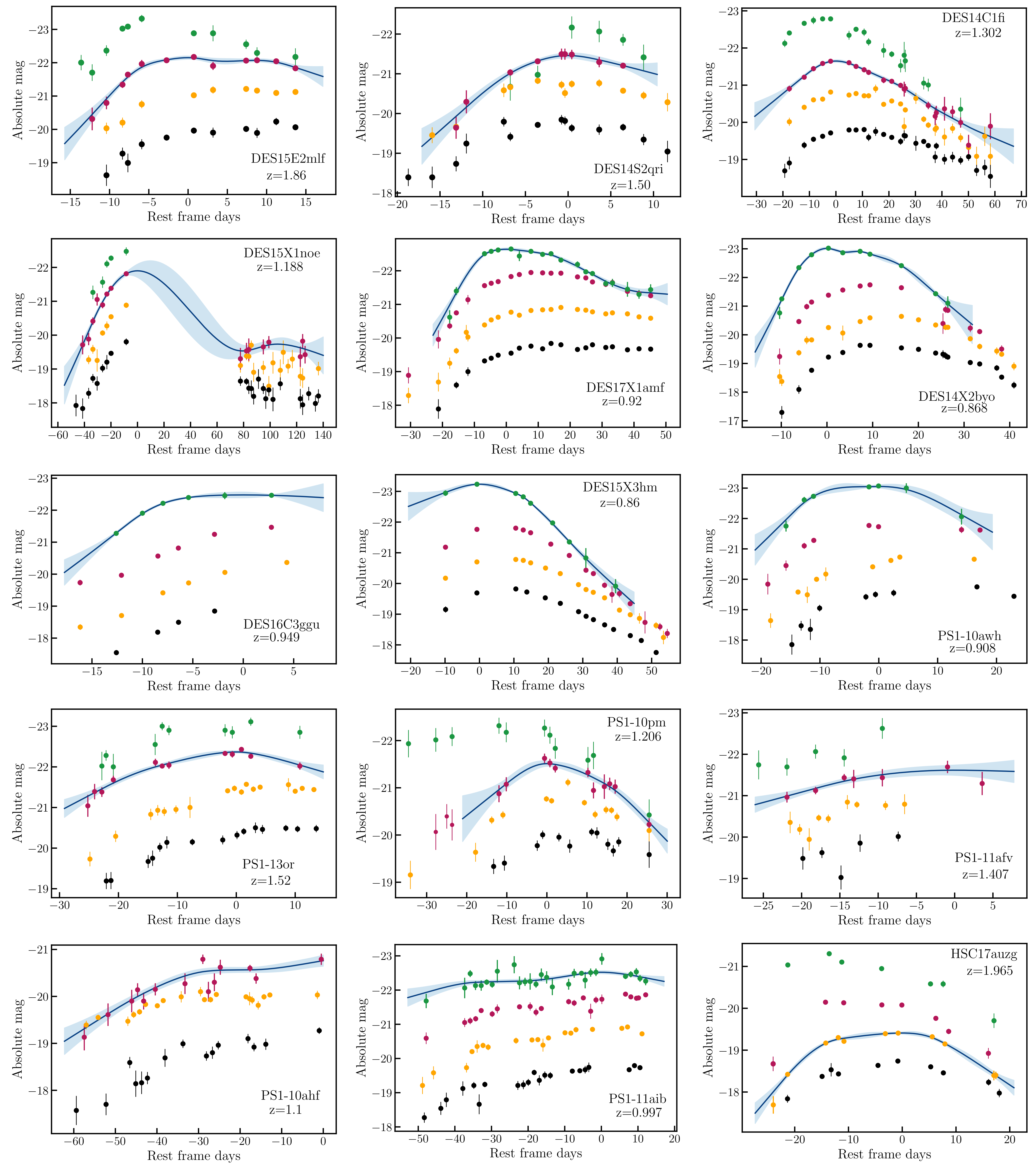
and the total variance for an object j in cosmological sample is

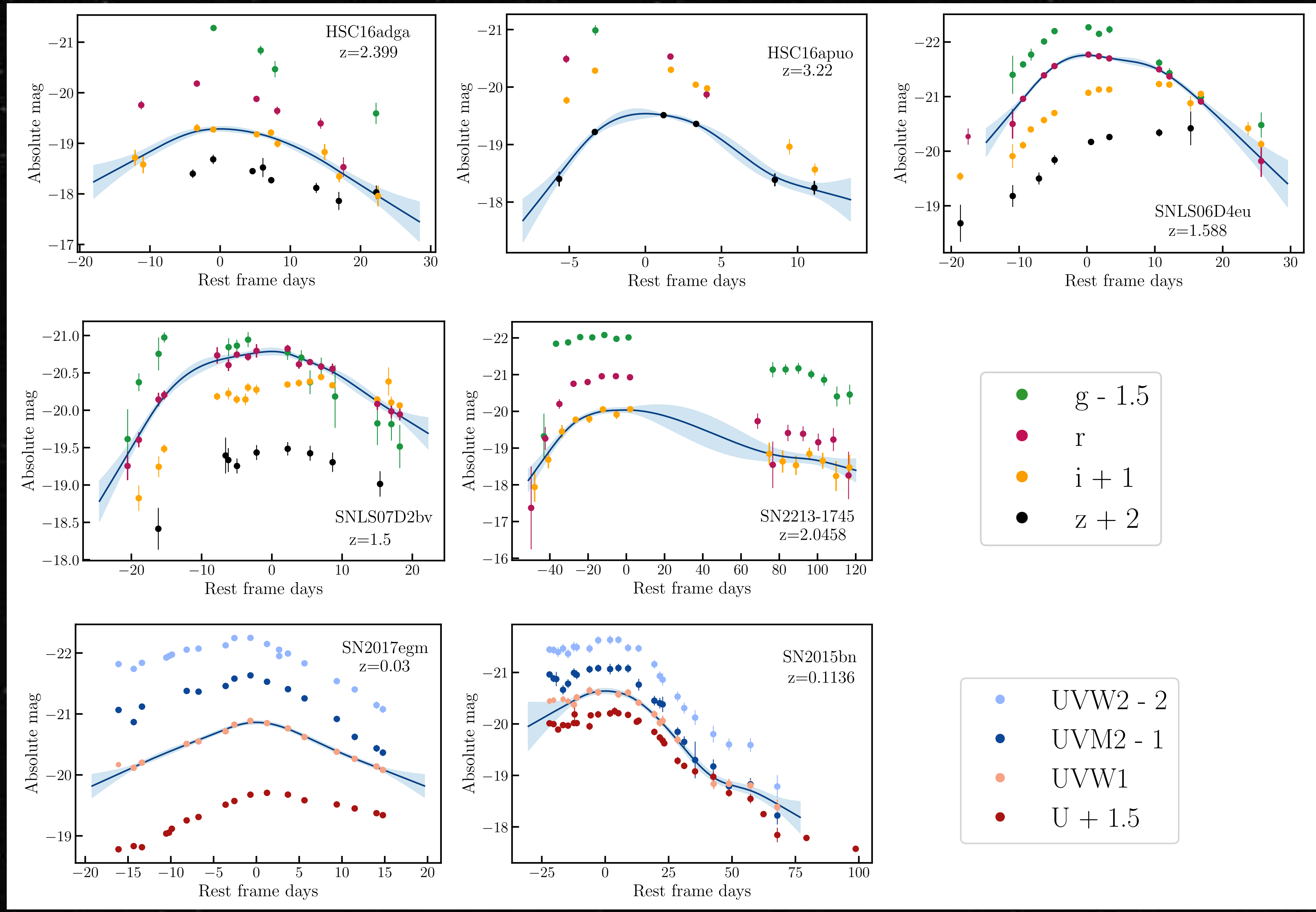
$$\sigma^2_{cosmo,j} = \sigma^2_{m_B,j} + (P^1\sigma_{s_{BV},j})^2 + (R\sigma_{m_B-m_V,j})^2 - 2R\sigma^2_{m_B,j} + \sigma^2_{int,cosmo}. \quad (11)$$

Table 6. Adopted Systematic uncertainties on H_0

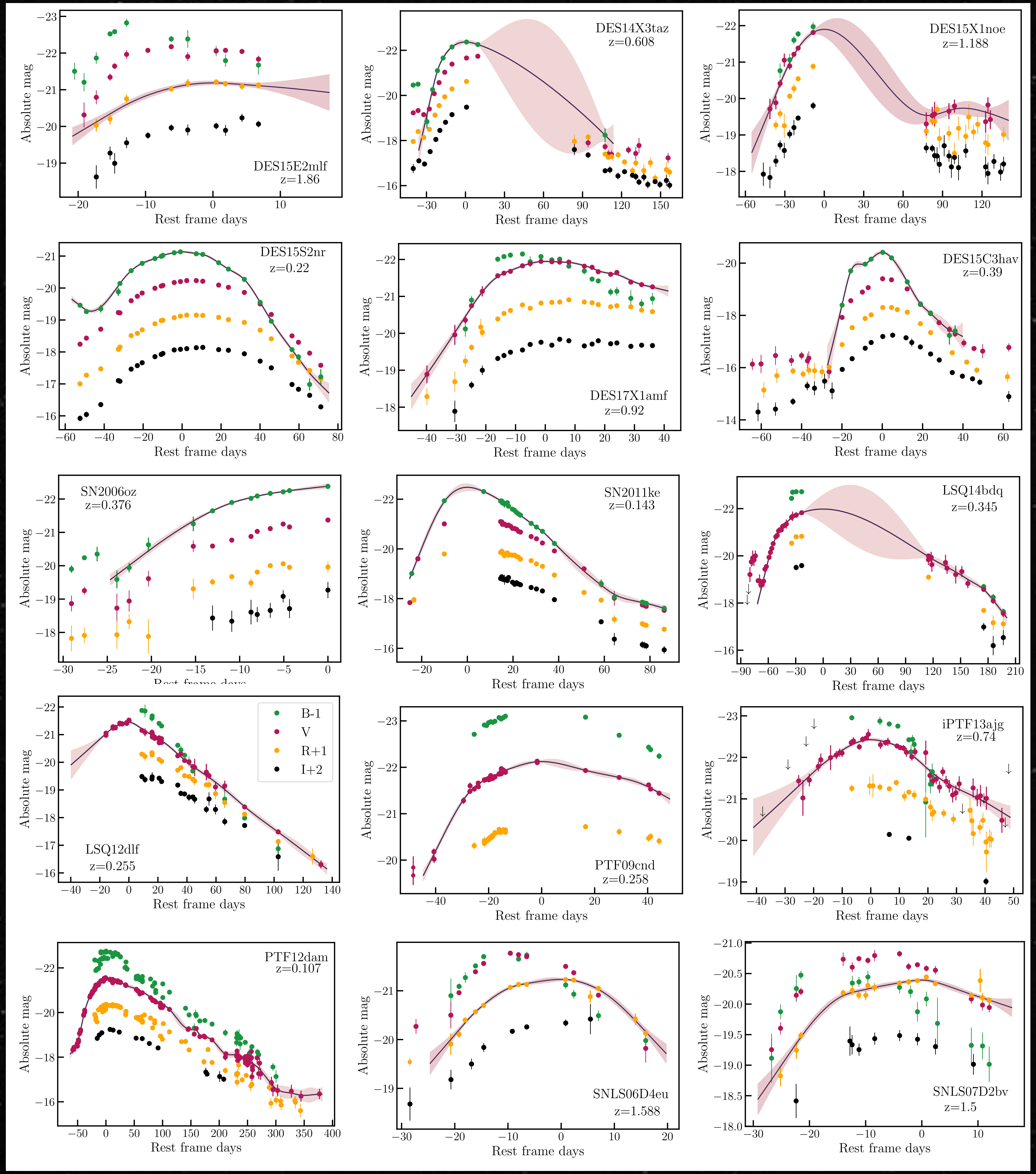
Uncertainty	magnitude	% error
SBF tie to Cepheid ZP	0.1 mag	4.6%
B-band fit	0.012 mag	0.55 %
V-band fit	0.019 mag	0.87 %
s_{BV} estimate	0.03 mag	1.4 %
Total	0.106 mag	4.8 %

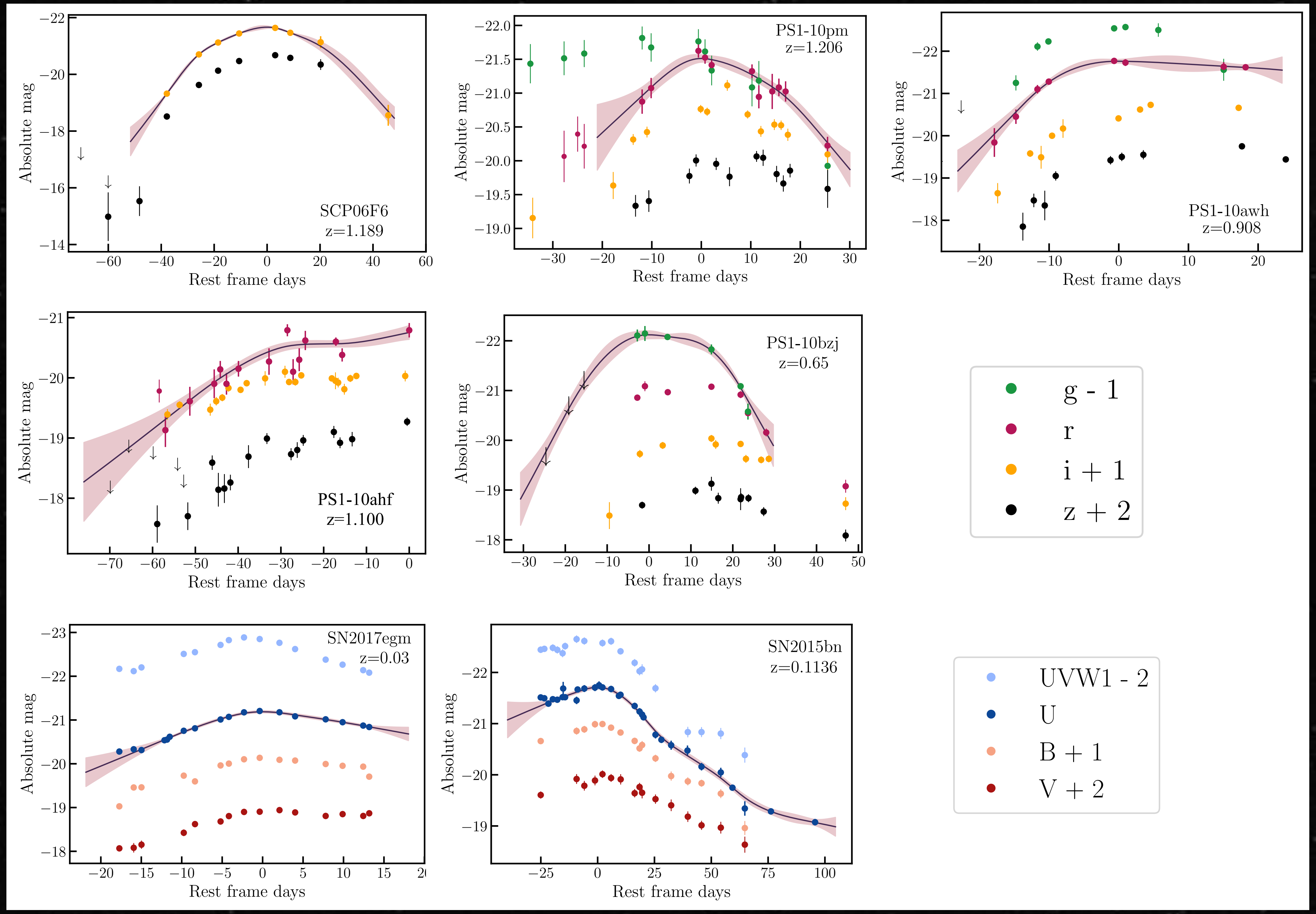
SLSN-UV sample



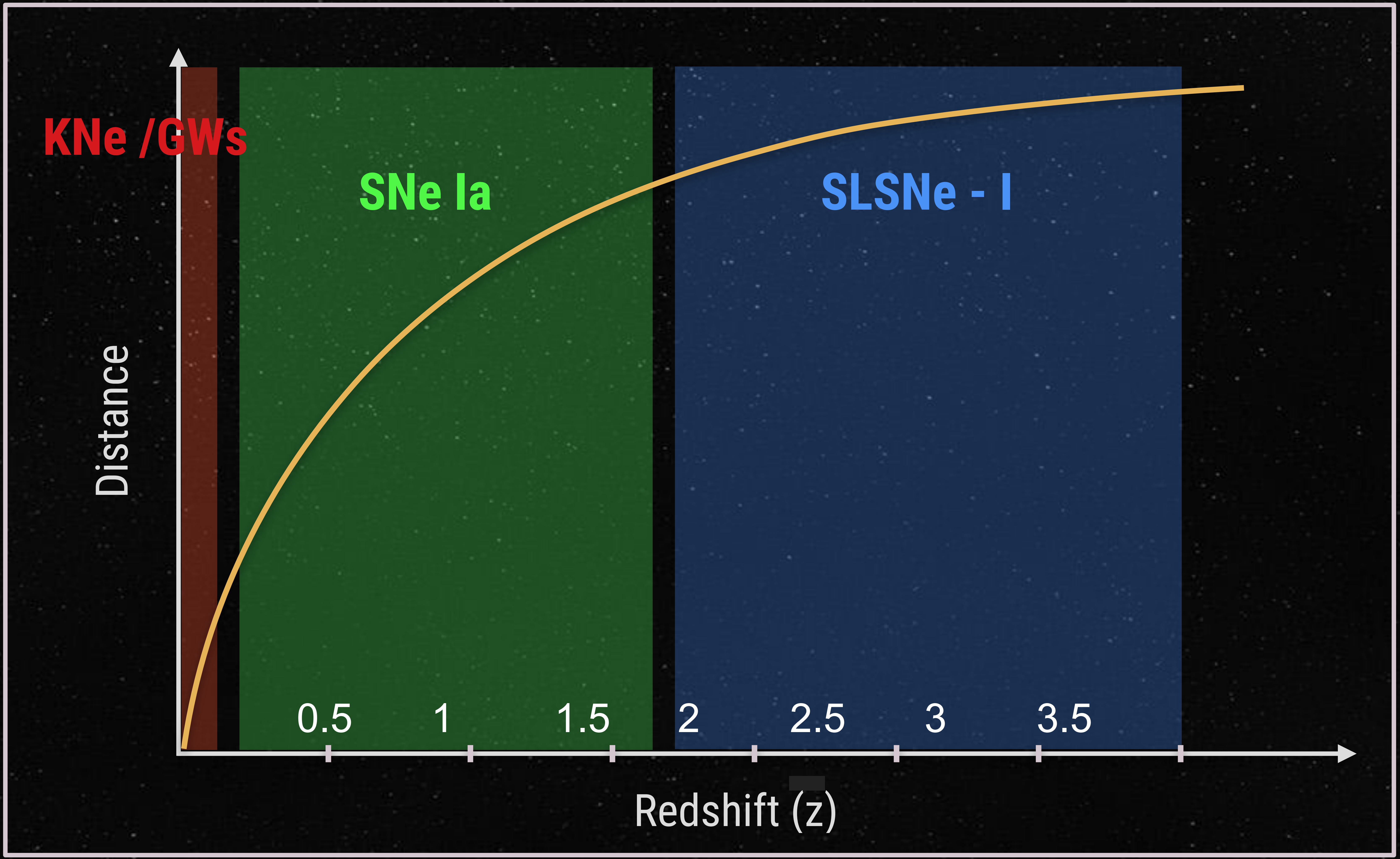


Bumpy SLSNe


DES15E2mlf
z=1.86
DES14X3taz
z=0.608
DES15X1noe
z=1.188
DES15S2nr
z=0.22
DES17X1amf
z=0.92
DES15C3hav
z=0.39
SN2006oz
z=0.376
SN2011ke
z=0.143
LSQ14bdq
z=0.345
LSQ12dlf
z=0.255
B-1
V
R+1
I+2
PTF09cnd
z=0.258
iPTF13ajg
z=0.74
PTF12dam
z=0.107
SNLS06D4eu
z=1.588
SNLS07D2bv
z=1.5
Absolute mag
Rest frame days


SCP06F6
z=1.189
PS1-10pm
z=1.206
PS1-10awh
z=0.908
PS1-10ahf
z=1.100
PS1-10bzj
z=0.65
g - 1
r
i + 1
z + 2
SN2017egm
z=0.03
SN2015bn
z=0.1136
UVW1 - 2
U
B + 1
V + 2
Absolute mag
Rest frame days

Summary



"Remember to look up at the stars, and not down at your feet"

-Stephen Hawking