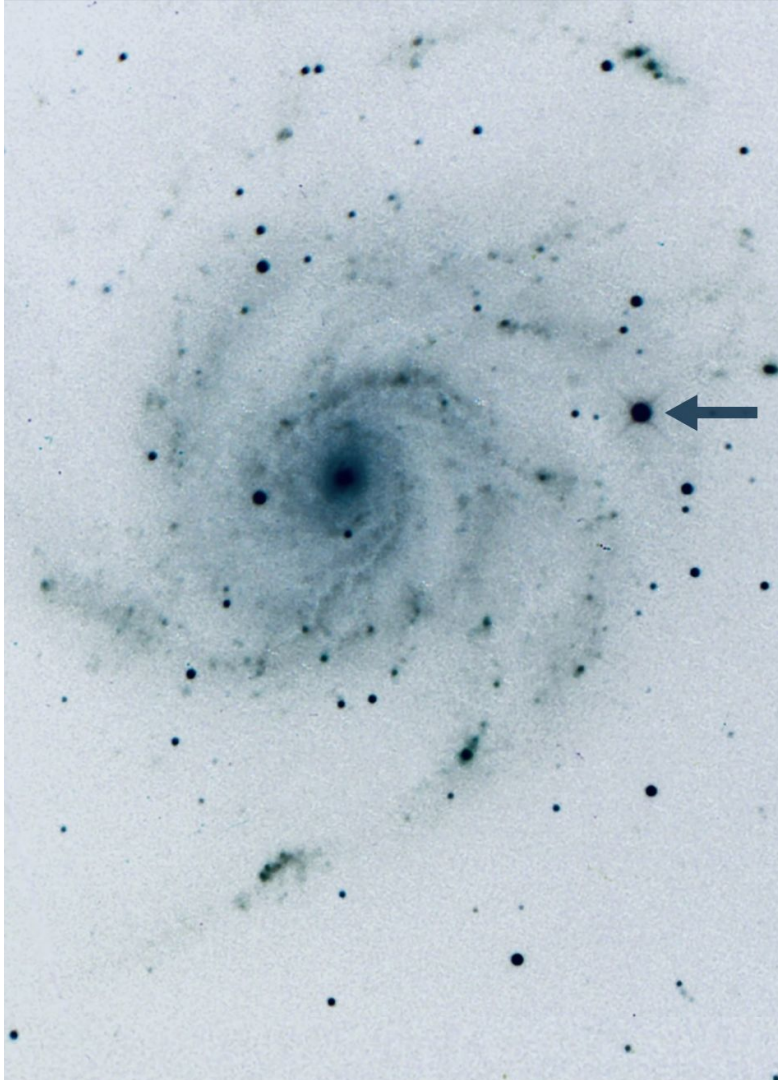
# Tracing the cosmic expansion using Type Ia Supernovae

Maria Vincenzi, Dillon Brout,
Dan Scolnic, the *Pantheon+ team*
and many others

LNF - Sept 13th, 2023

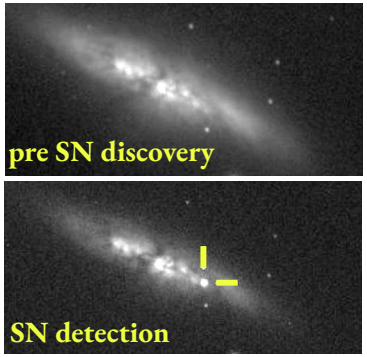


Duke Cosmology

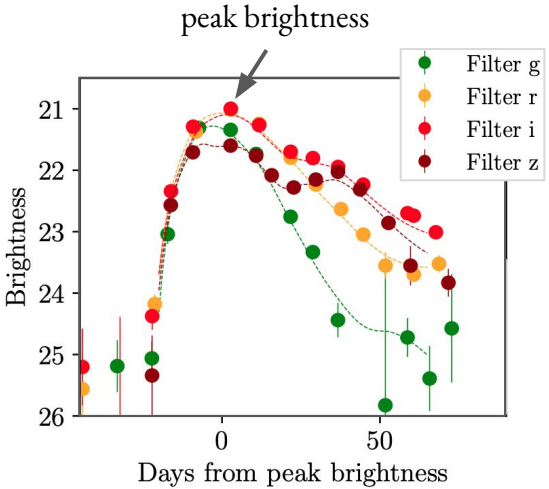
VERA C. RUBIN OBSERVATORY

NANCY GRACE ROMAN SPACE TELESCOPE

# Type Ia Supernovae: the ideal tool to measure cosmic distances




**Very homogeneous <u>intrinsic brightness at peak</u>**
(<10% scatter) after **several empirical** corrections.



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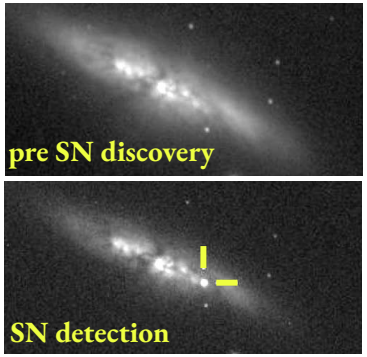


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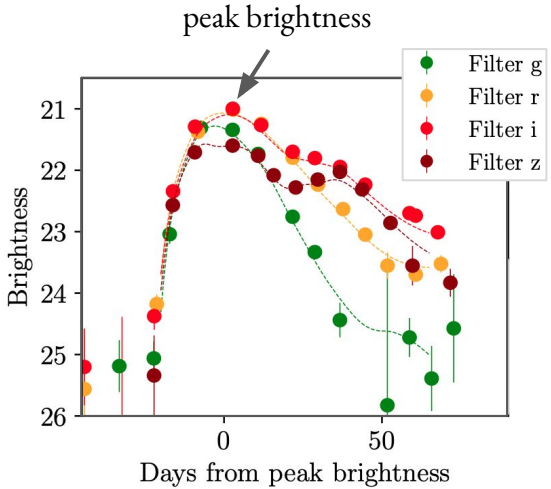


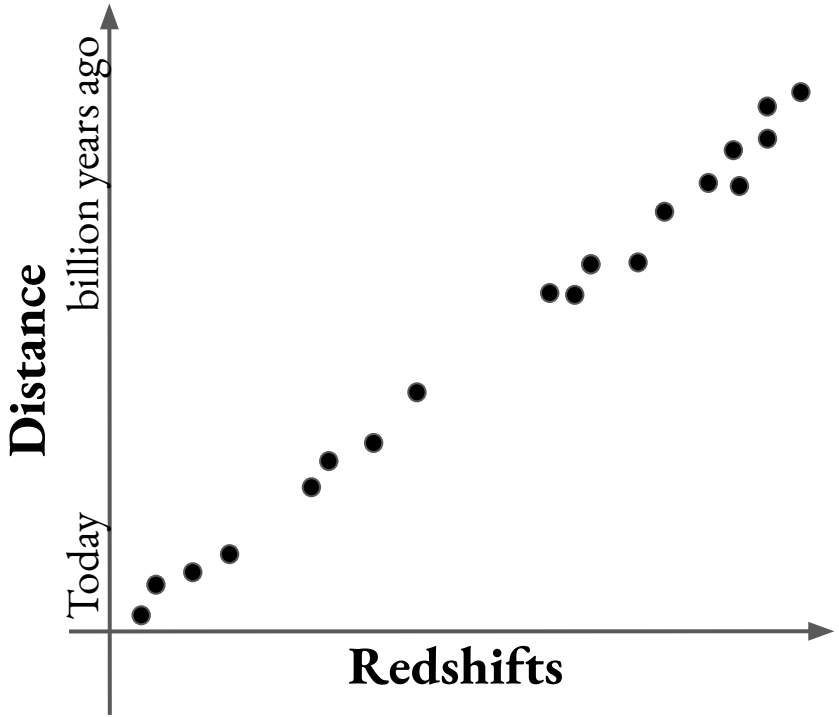

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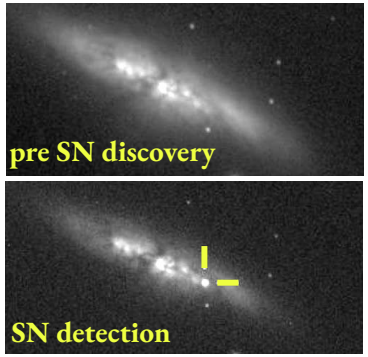


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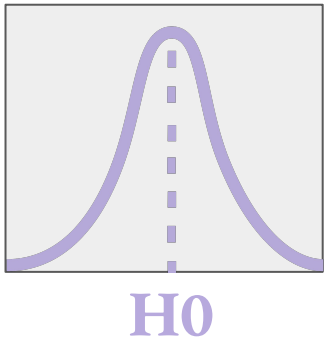


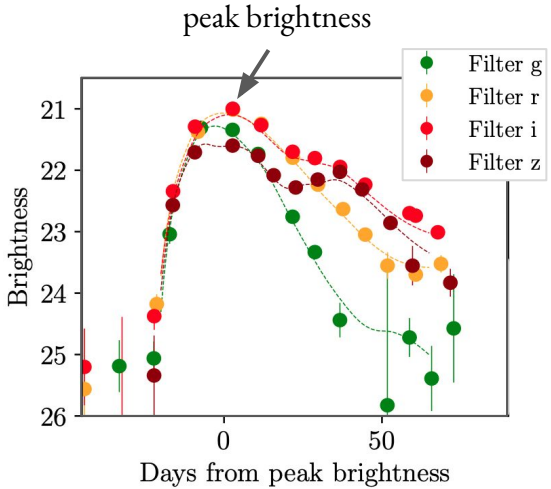


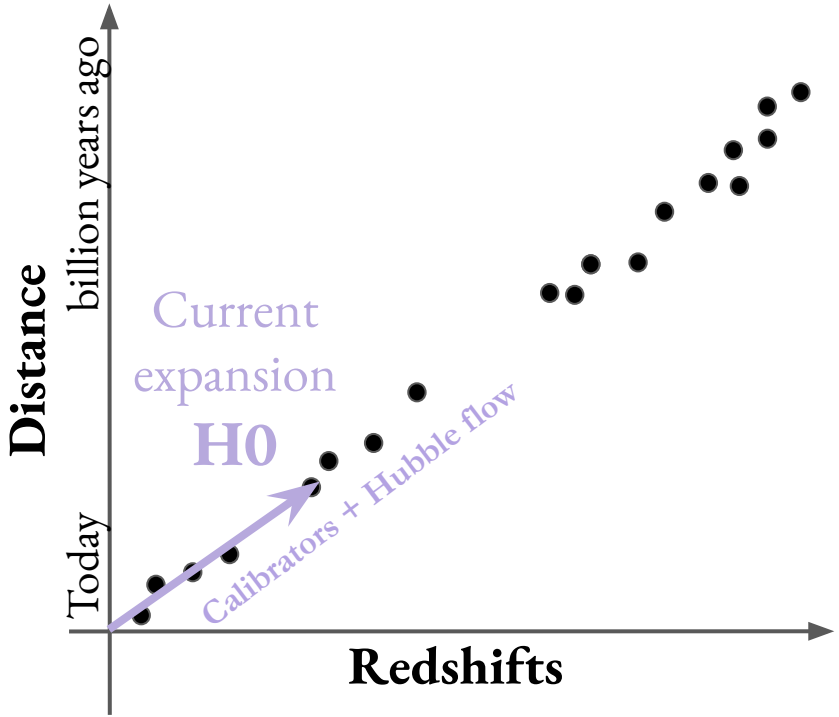

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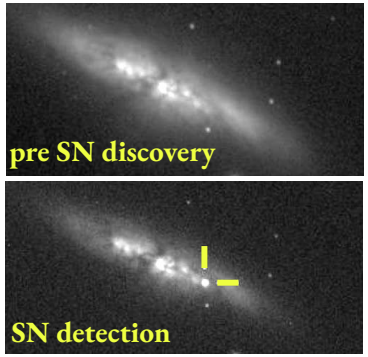


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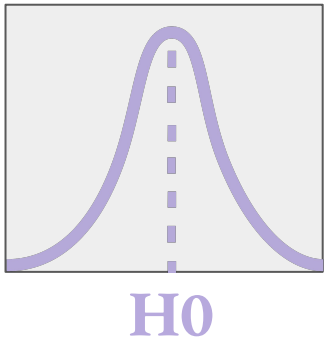
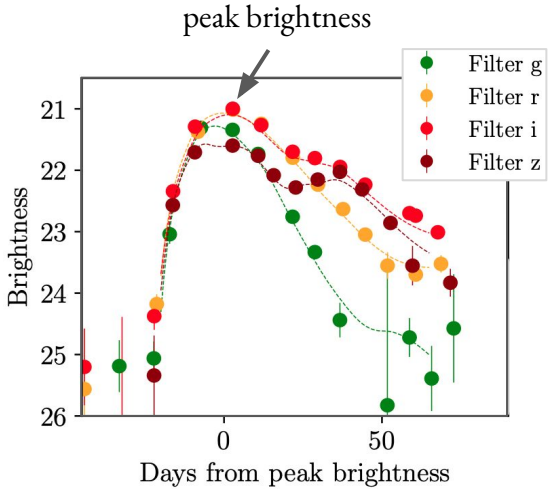
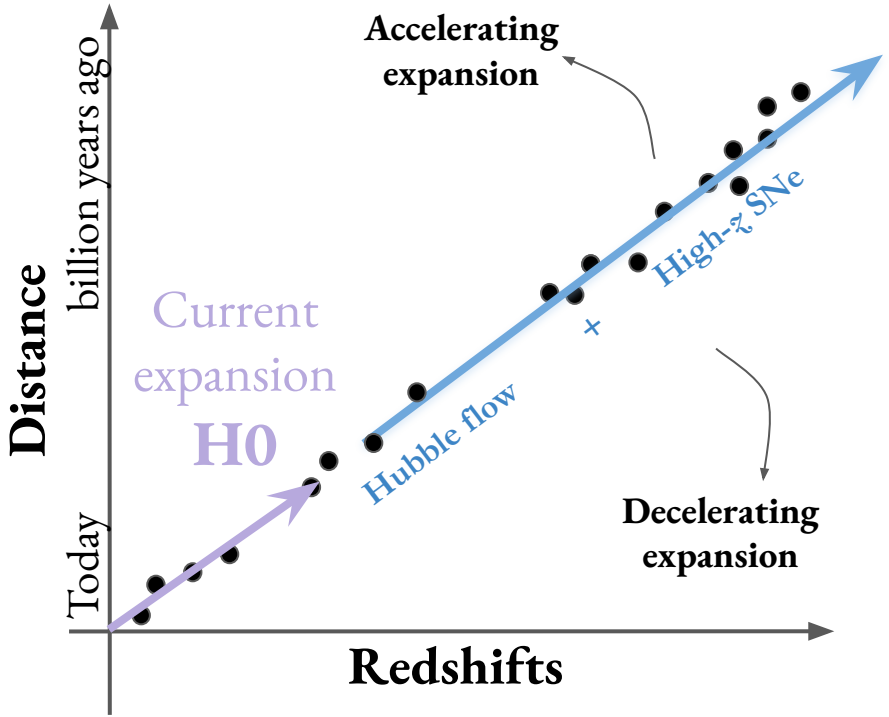
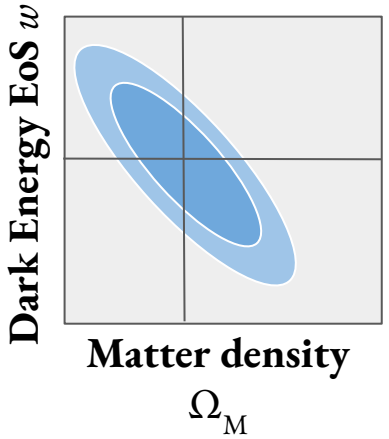


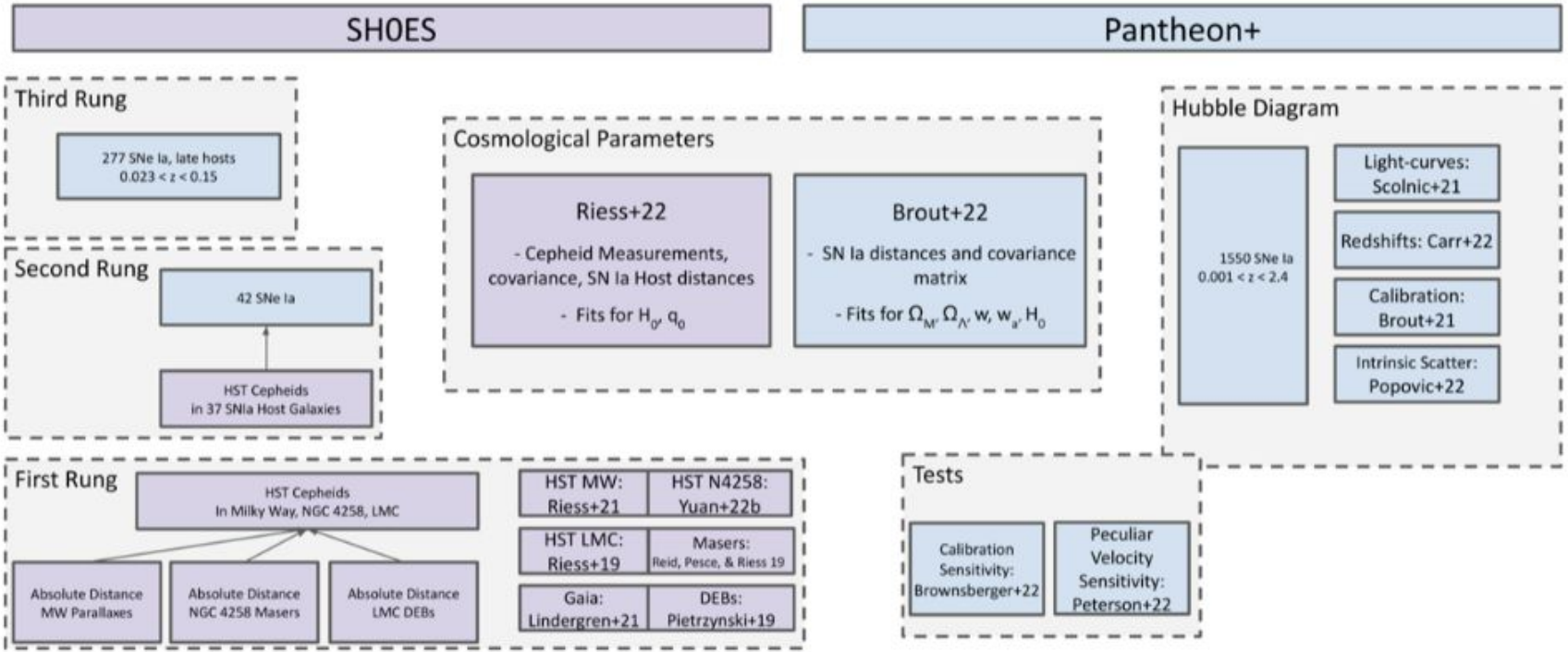



# Recent Results from SH0ES and Pantheon+

## To address the community and achieve 1km/s/Mpc uncertainty



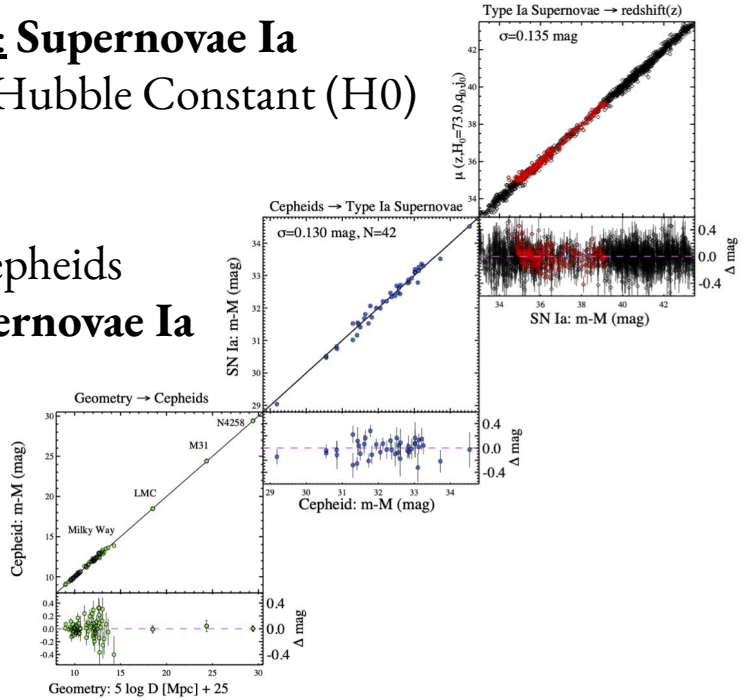
# $H_0$ : The Cosmic Distance Ladder Method Tells us the Current Expansion Rate

SH0ES

3rd: **Supernovae Ia**
→ Hubble Constant (H0)

2nd: Cepheids
→ **Supernovae Ia**

1st: Geometry
→ Cepheids




Riess,+21

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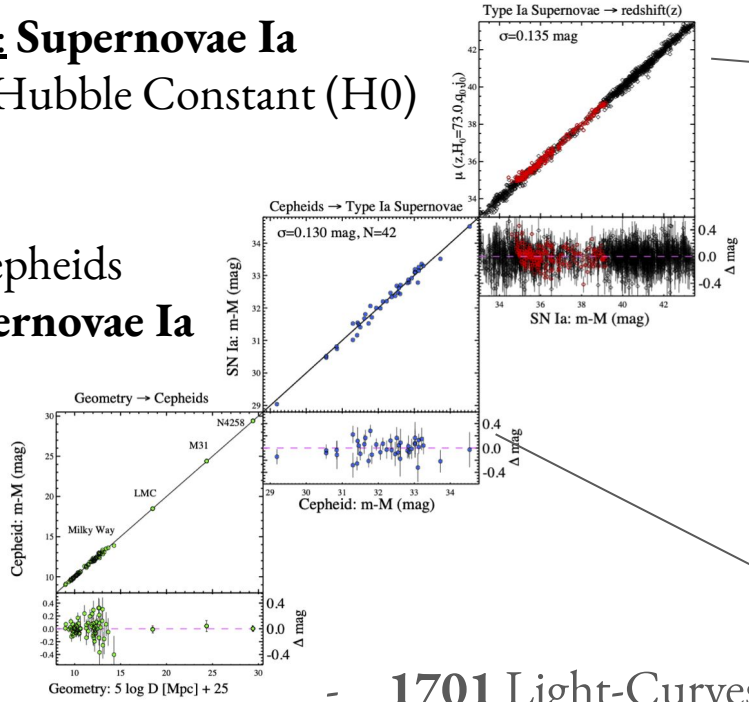
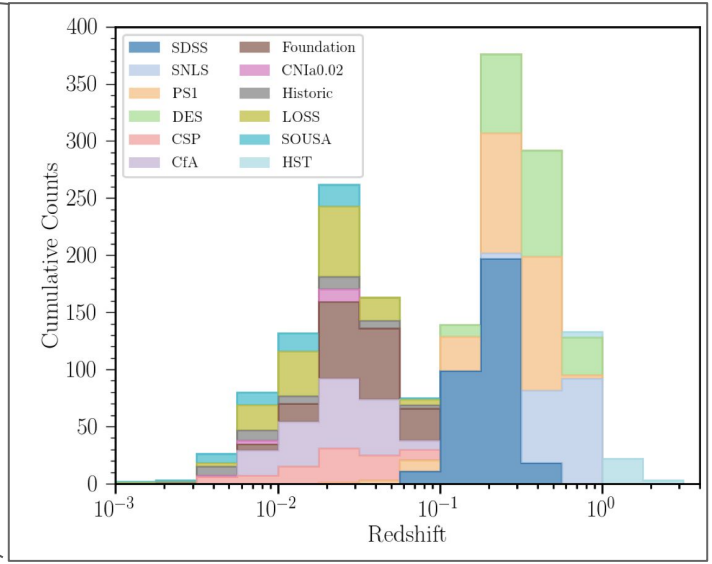


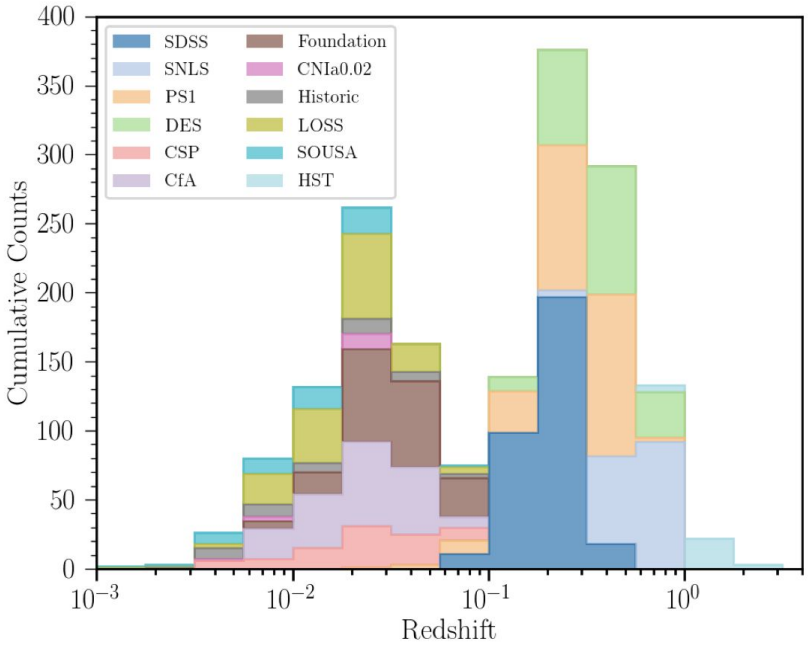

## Pantheon+ compilation




- **1701** Light-Curves between 0.001<z<2.3, **300** in Hubble flow
- **Recalibrated** 18 surveys, 25 systems, 105 filters
- SN calibrators from **19→42** and complete at z<0.01

Riess,+21

# The Pantheon+ Compilation of SNe



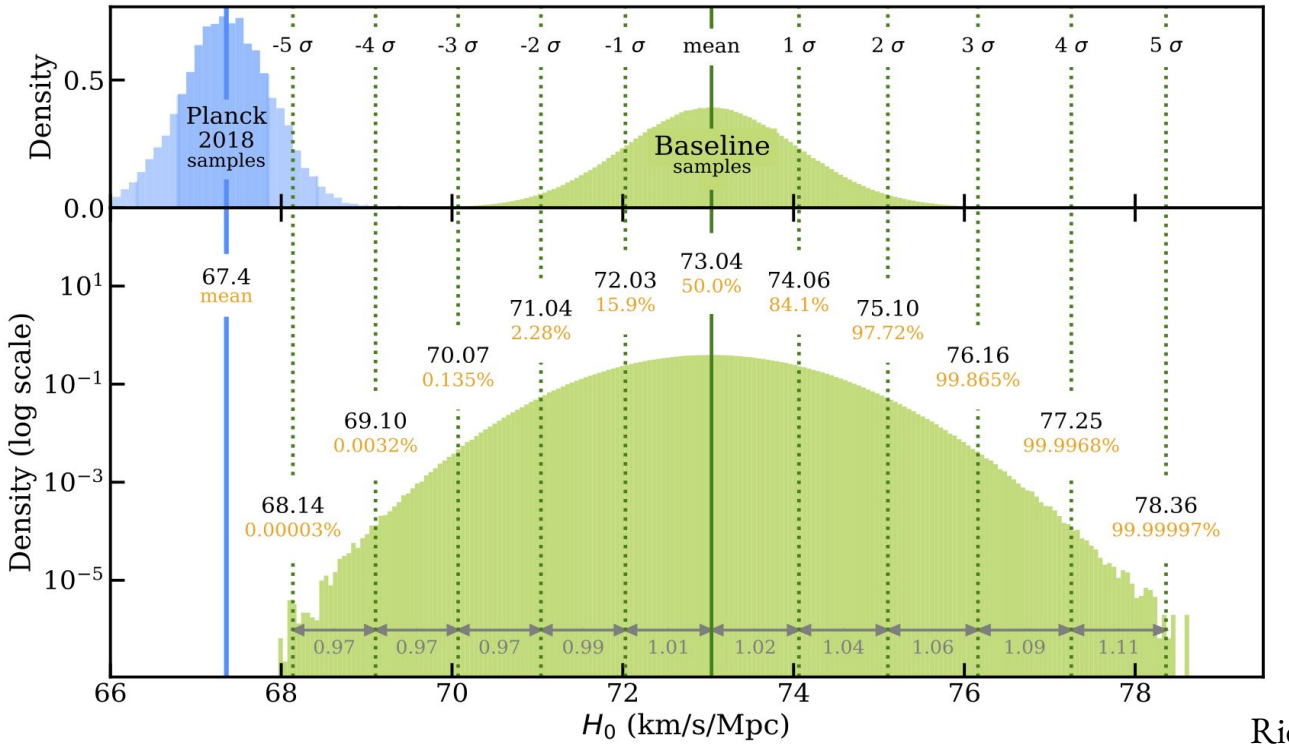

- **1701** Light-Curves of 1550 unique SNe from 0.001<z<2.3
- **Recalibrated** 18 surveys, 25 systems, 105 filters
- More than doubles SN calibrators from **19→42** and complete at z<0.01
- Now have an average of 2 photometric systems for each SN that is in a cepheid host (78 light curves in 42 hosts)

Scolnic et al 2022

# $H_0$: SH0ES reaches >5σ

+ΛCDM

Planck 67+-0.5 SH0ES 73+-1




Riess et al. 21

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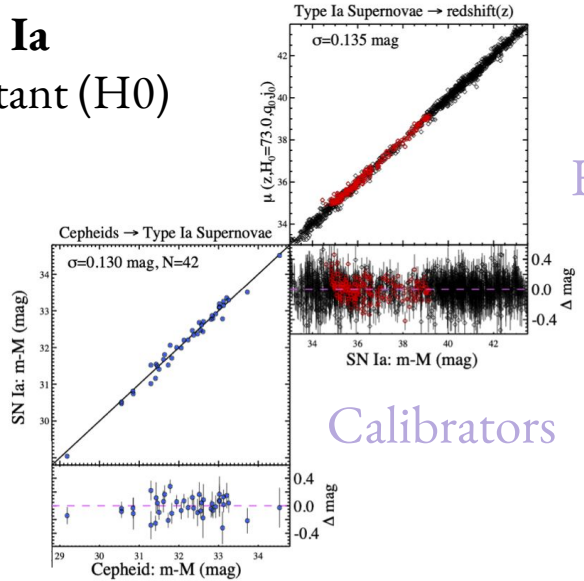
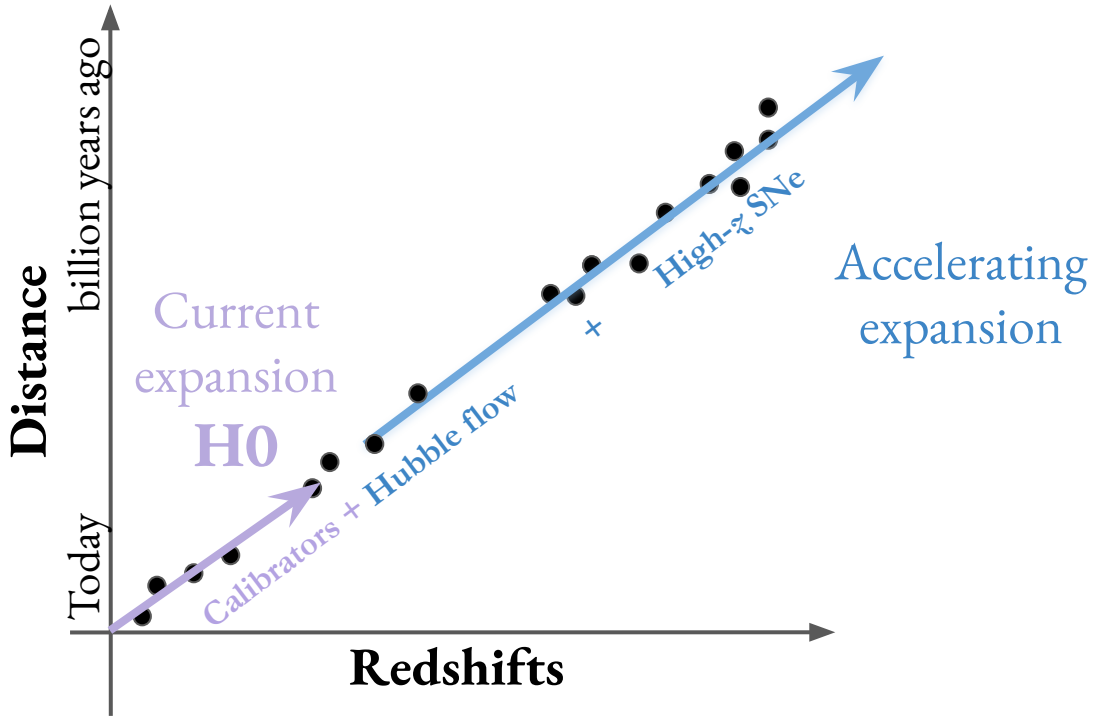



Hubble flow

Calibrators

# The Robustness of SNe in the Distance ladder:



# The Robustness of SNe in the Distance ladder: Is it calibration?

If all SN surveys can have a *residual* calibration error (beyond nominal expectation)...
How could these impact H0, w?

Miscalibrated inter-survey systematics → **H0 uncertainty no larger than 0.2 km/s/Mpc**."

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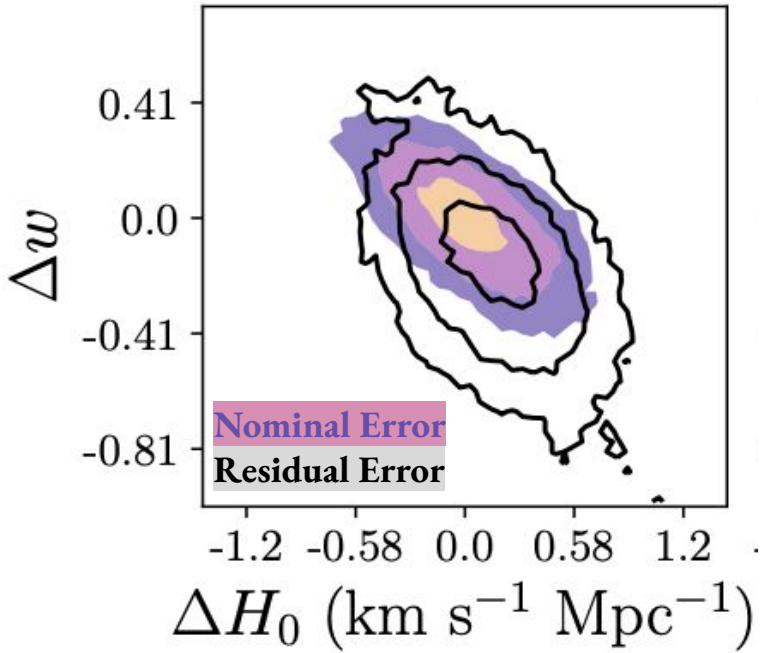
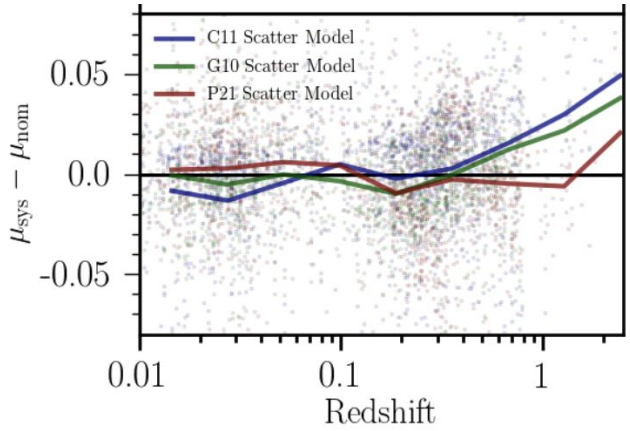



Note that using only CSP in Hubble flow can cause a -1.1km/s/Mpc bias in H0.

Brownsberger et al. 2023

# The Robustness of SNe in the Distance ladder: Is it dust?

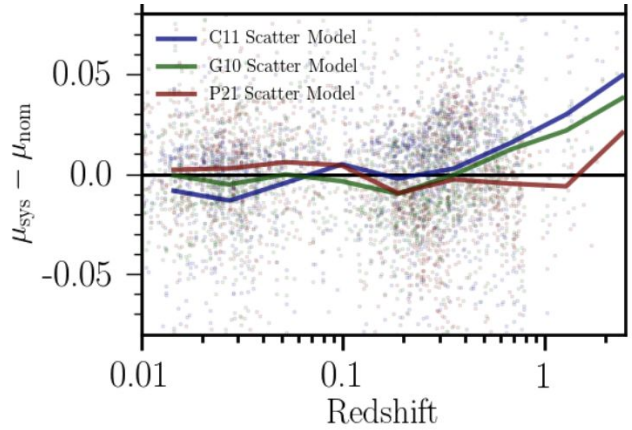
Pantheon+ marginalizes over **dust variation** at a population level. → **H0 uncertainty** related to SN Ia dust modelling **no larger than 0.4 km/s/Mpc**.

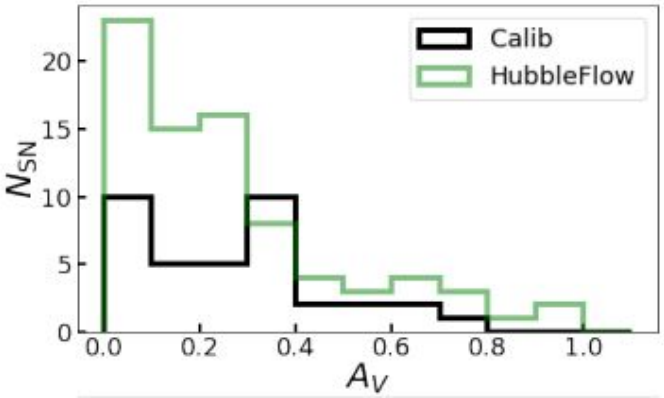



Popovic et al 2021,
Meldorf et al 2022/2023

# The Robustness of SNe in the Distance ladder: Is it dust?

Pantheon+ marginalizes over **dust variation** at a population level. → **H0 uncertainty** related to SN Ia dust modelling **no larger than 0.25 km/s/Mpc**.



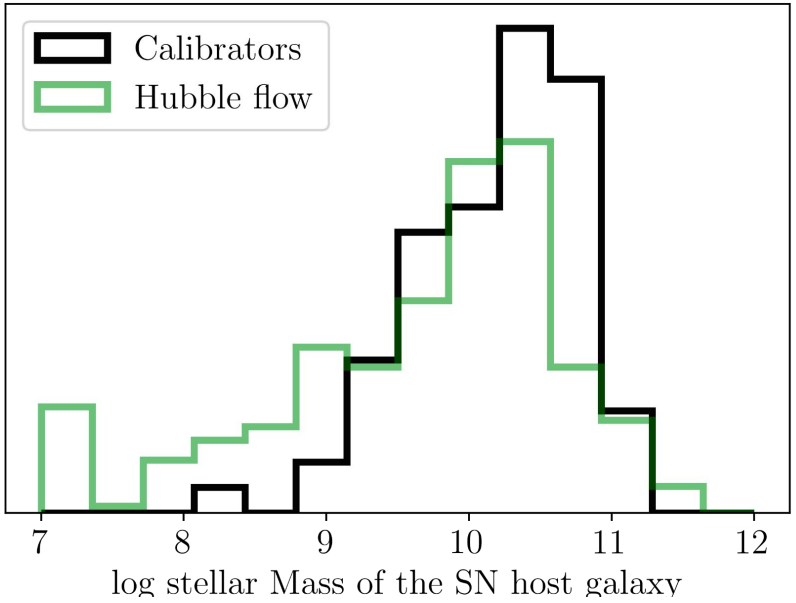

Independent work by the BayeSN team (*Mandel*+). Near-Infrared+Optical SNIa can get dust fits for each SN/Host individually → H0=75!

Popovic et al 2021,
Meldorf et al 2022/2023

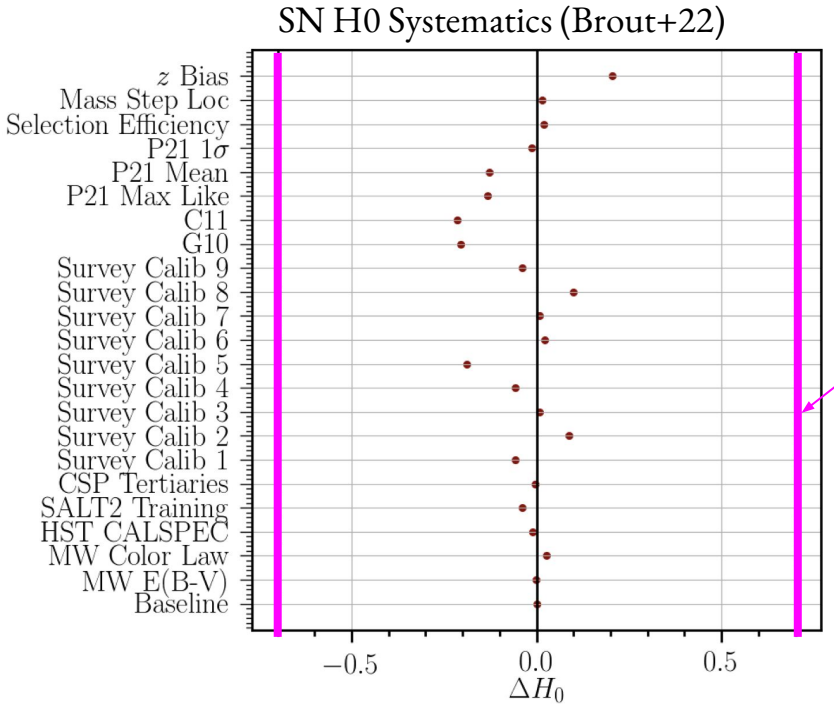
# The Robustness of SNe in the Distance ladder: Is it age?

In Pantheon+ (and Riess et al 2016), we select **only Hubble flow SNe found in star forming environments** → consistent with calibrators.

Pantheon+ find no evidence for any residual brightness step related to SN environment/age.



# In the end, the SNe comprise less than ⅓ of the H0 error budget.

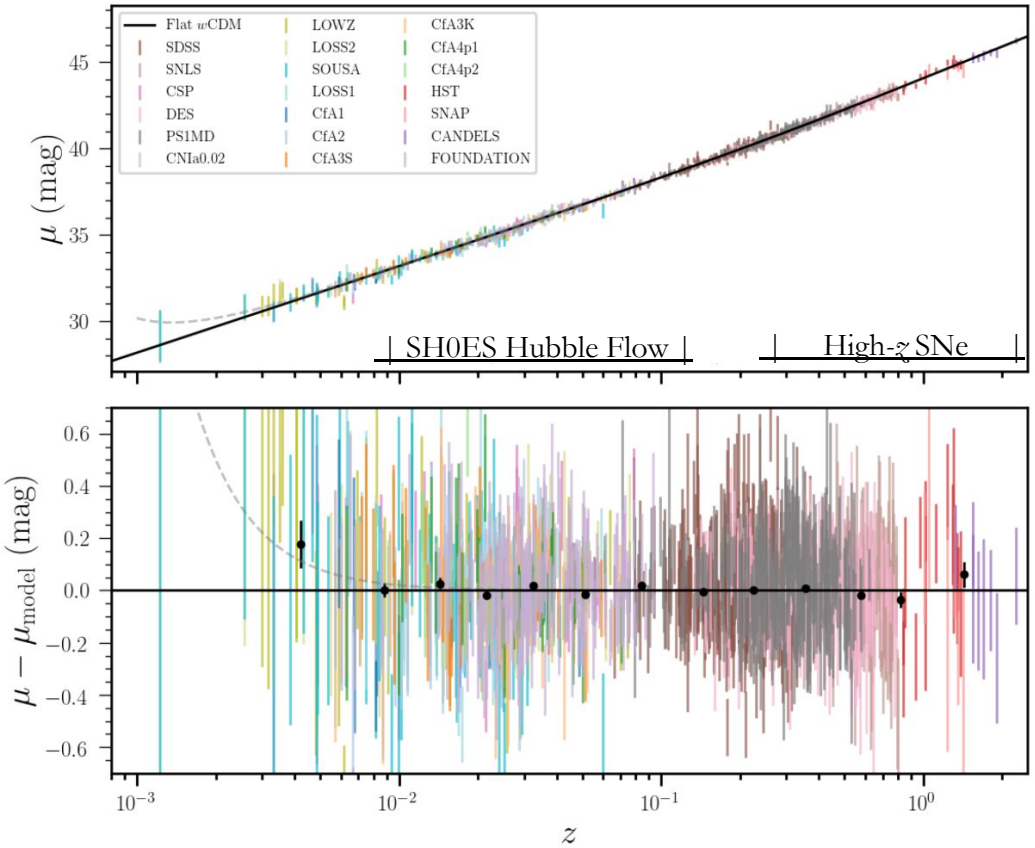



Brout+22

Reported SN uncertainty on H0

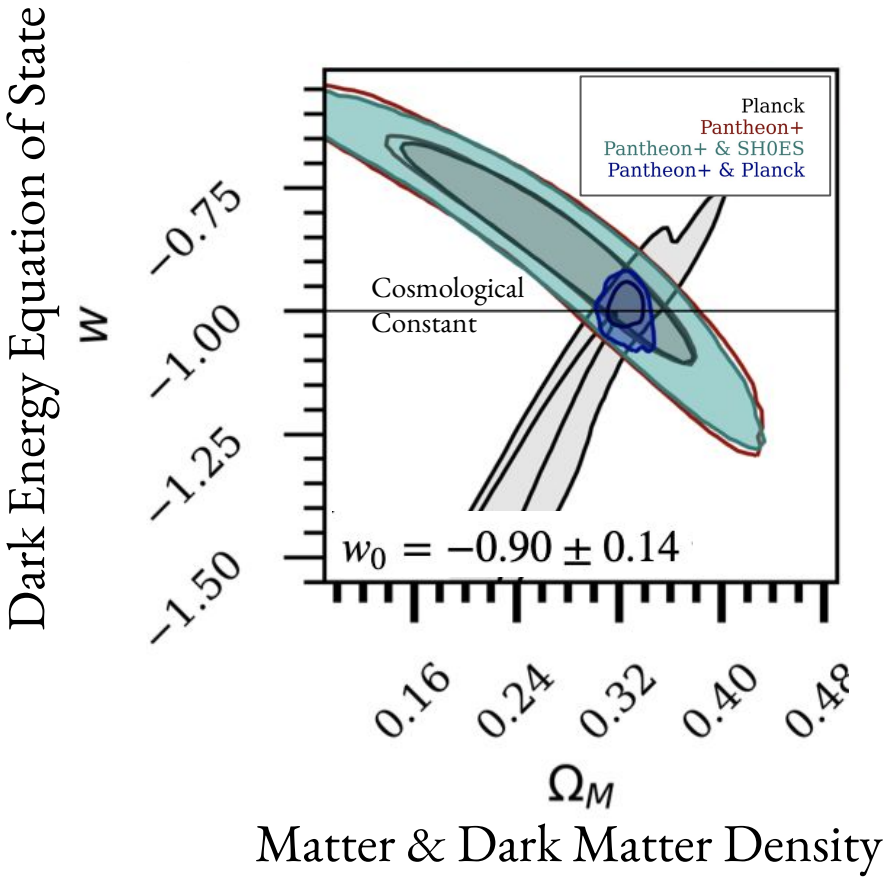
<u>Bottom line: It's hard to get below 72.5 without throwing out data…</u>

# Pantheon+ Hubble diagram for **Dark Energy *w*** measurements




Brout et al 2022

# Pantheon+ beyond ΛCDM: constraining the DE EoS

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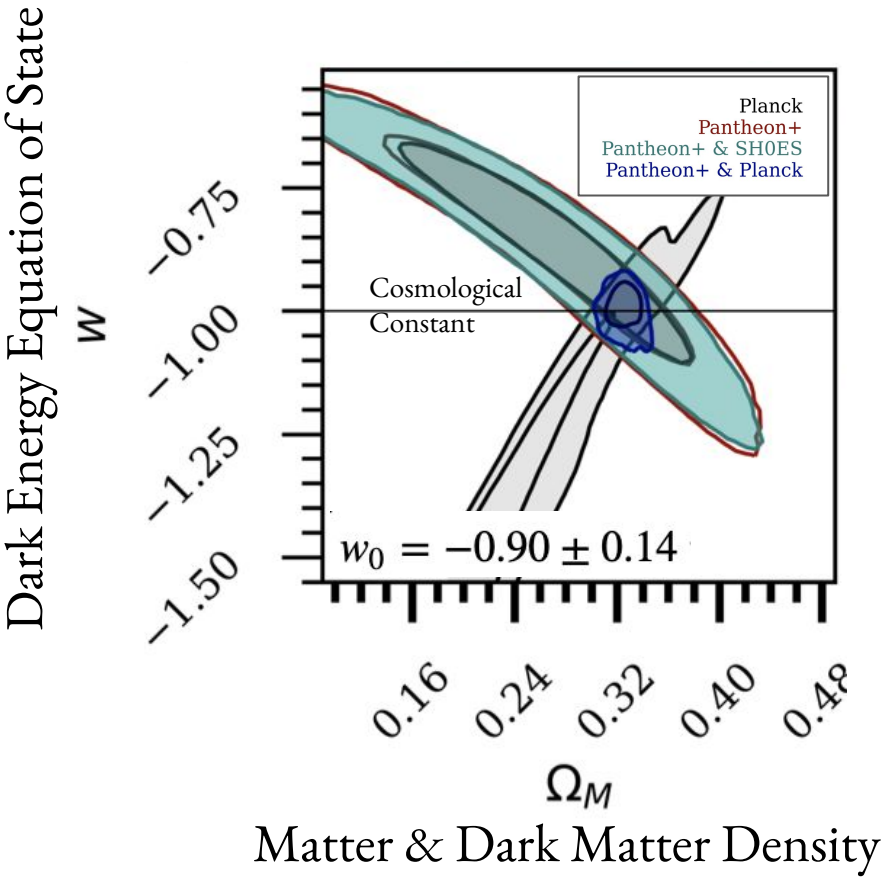


- Incorporates over 115 sources of systematic uncertainty *and not dominated by systematics!*

Brout et al 2022

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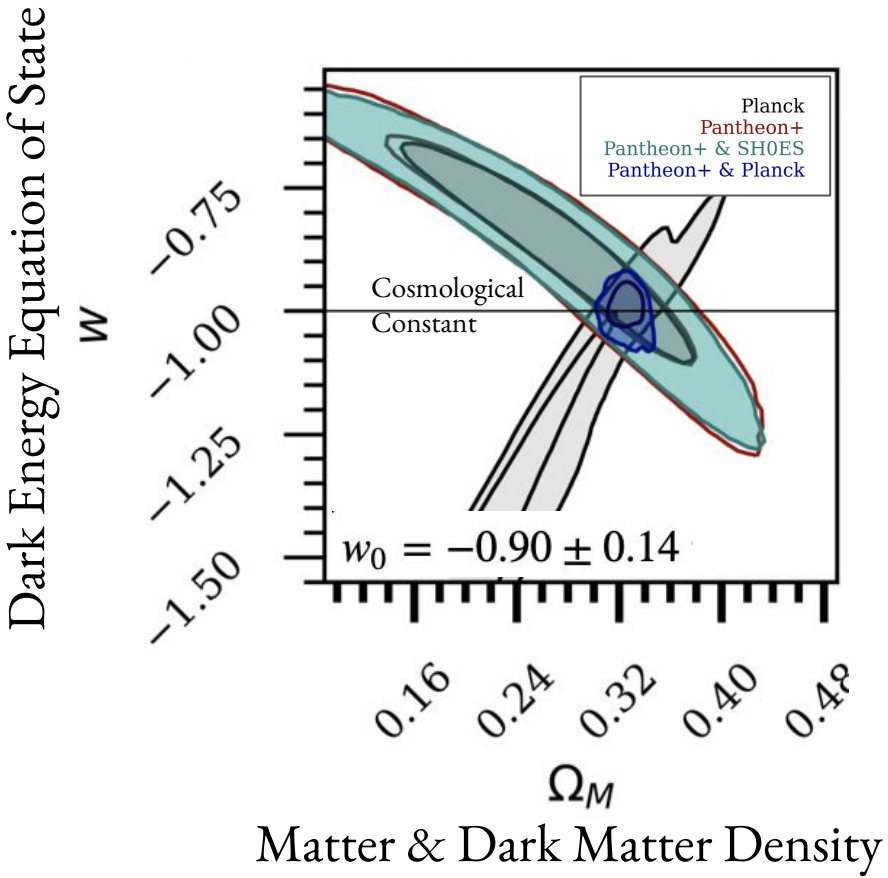


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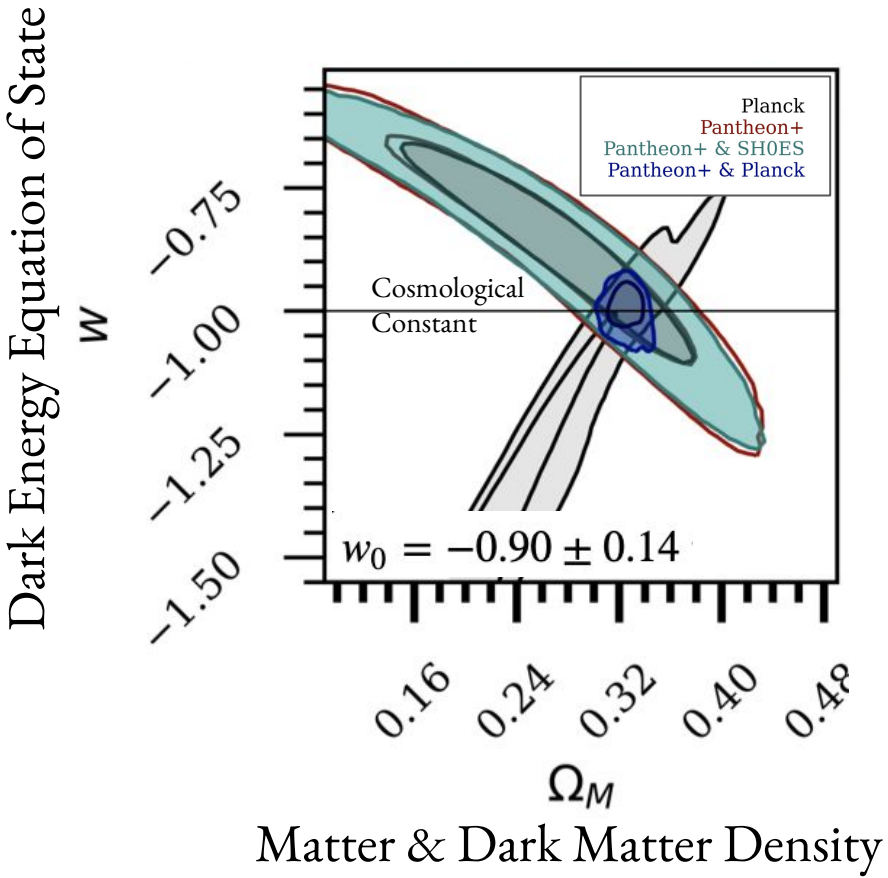


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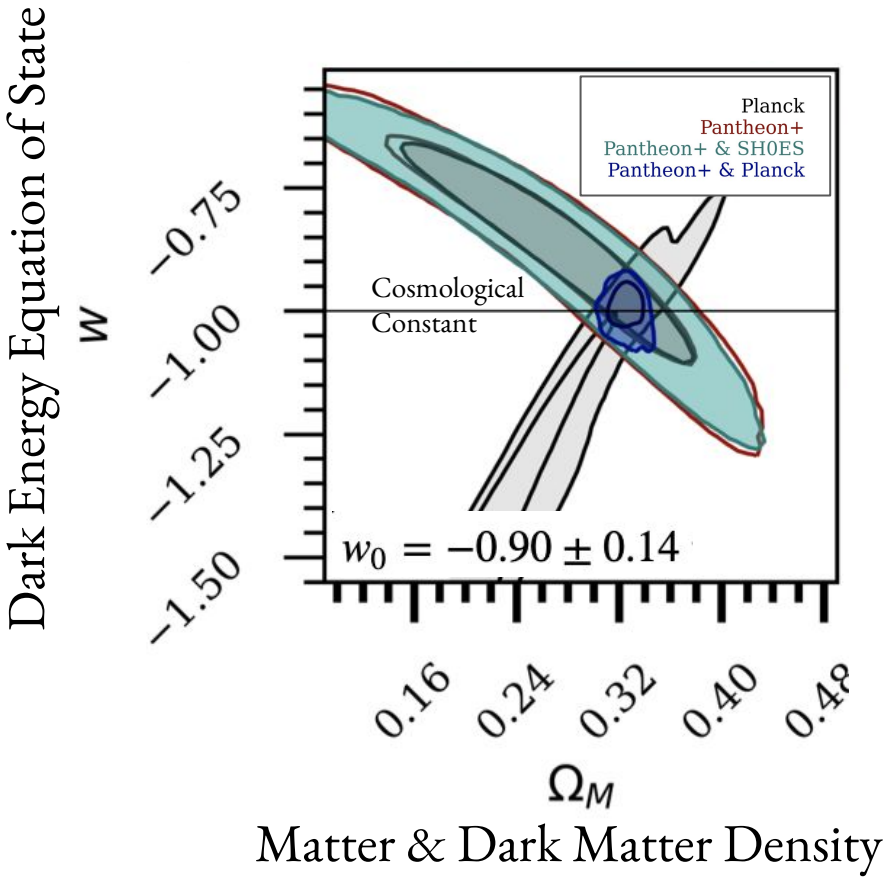


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- Data and likelihoods available publicly and now widely used.

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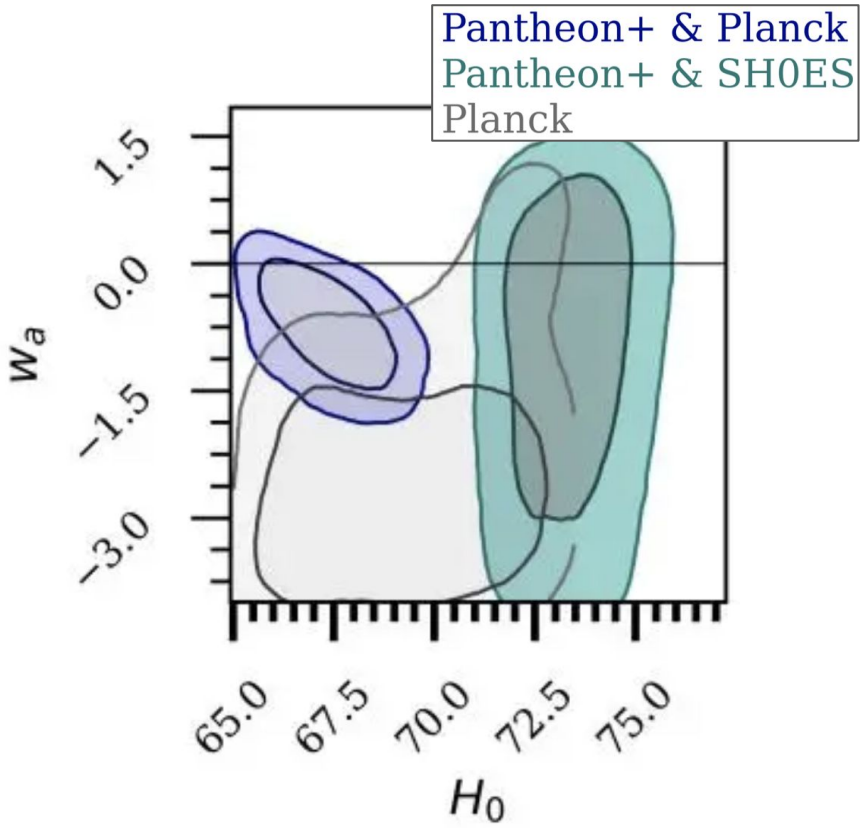


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- Figure of merit 2x better than Pantheon (2018)

- **Consistent with $w$=-1 (ΛCDM)**

- Data and likelihoods available publicly and now widely used.

- Pantheon+ SNe provide one of the best constraint on evolving dark energy models (consistent with zero).

SN Only

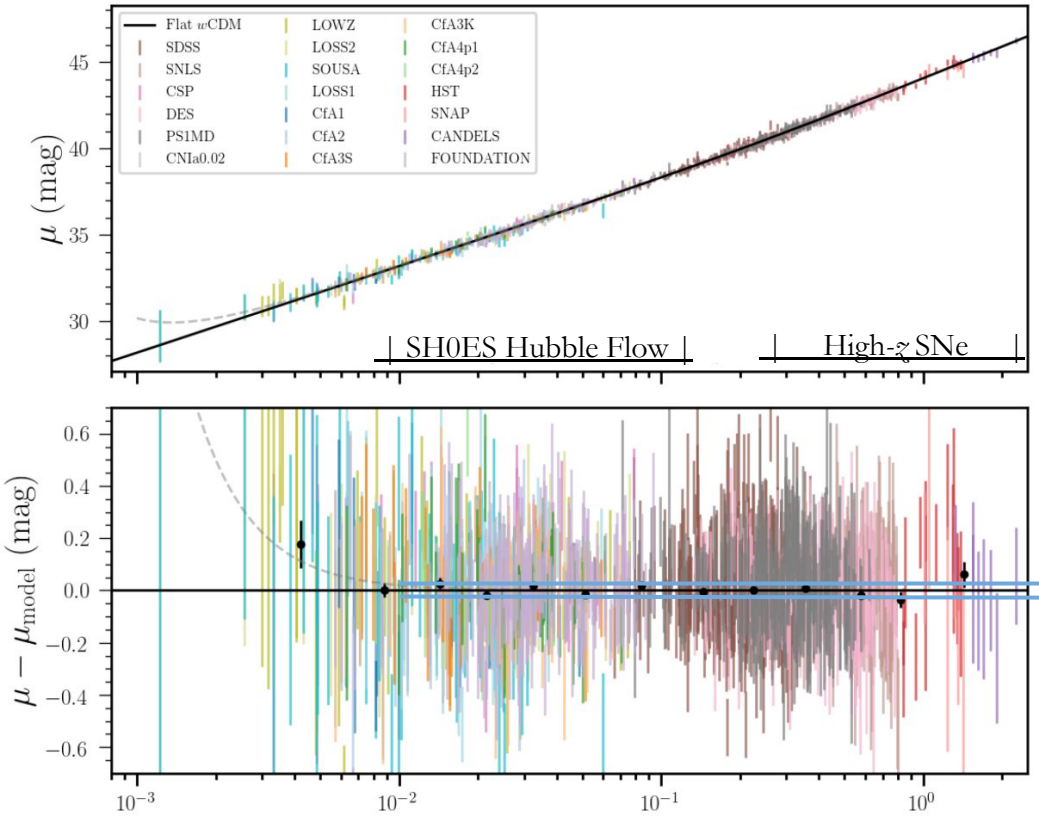
$$w_a = -0.1^{+0.9}_{-2.0}$$

SN+Planck+BAO

$$w_a = -0.65^{+0.28}_{-0.32}$$

Brout et al 2022

# SNe Ia are used for Hubble Constant $H_0$ and Dark Energy $w$




Brout et al 2022

For $w$, measuring changes of **0.02** mag over $\Delta z$ of **1.0**

Dark Energy and Dark Matter

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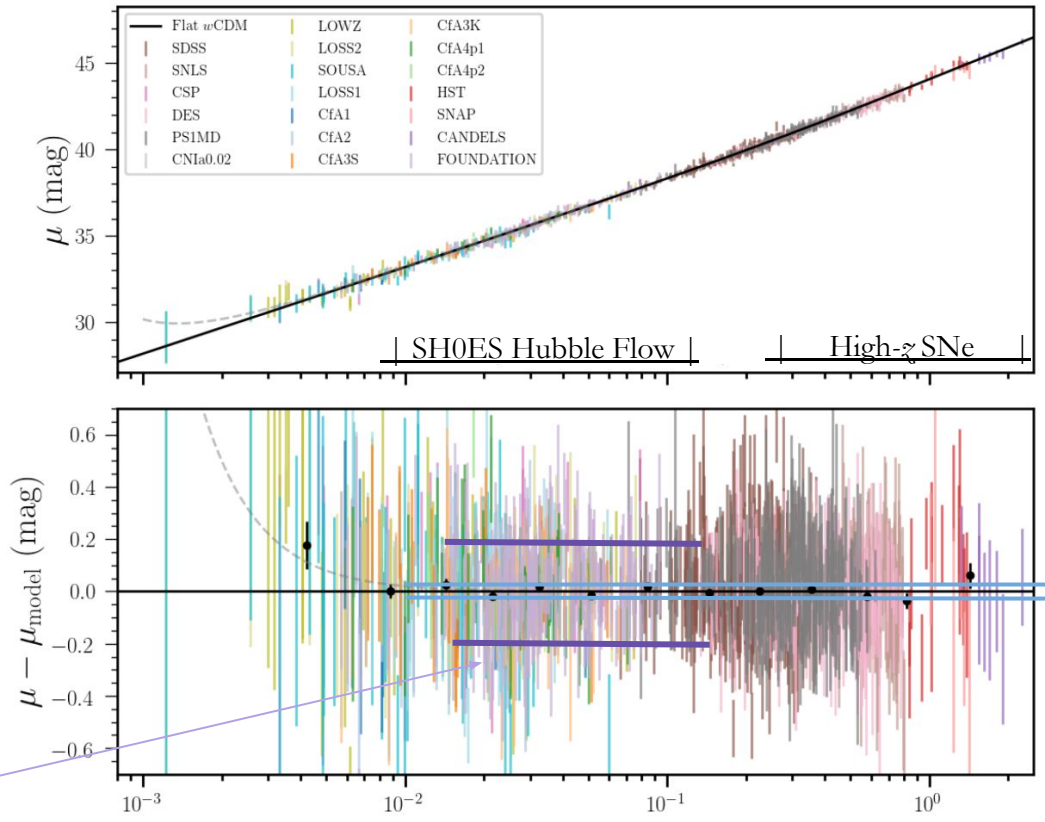


Brout et al 2022

H0

For $H_0$, the 'Hubble tension' is **0.20** mag over Δz of **0.1**

For *w*, measuring changes of **0.02** mag over Δz of **1.0**

Dark Energy and Dark Matter

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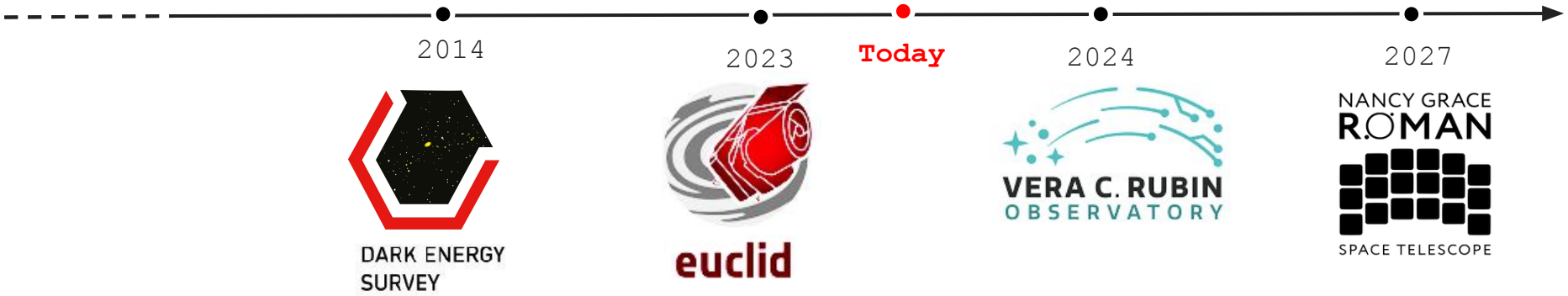

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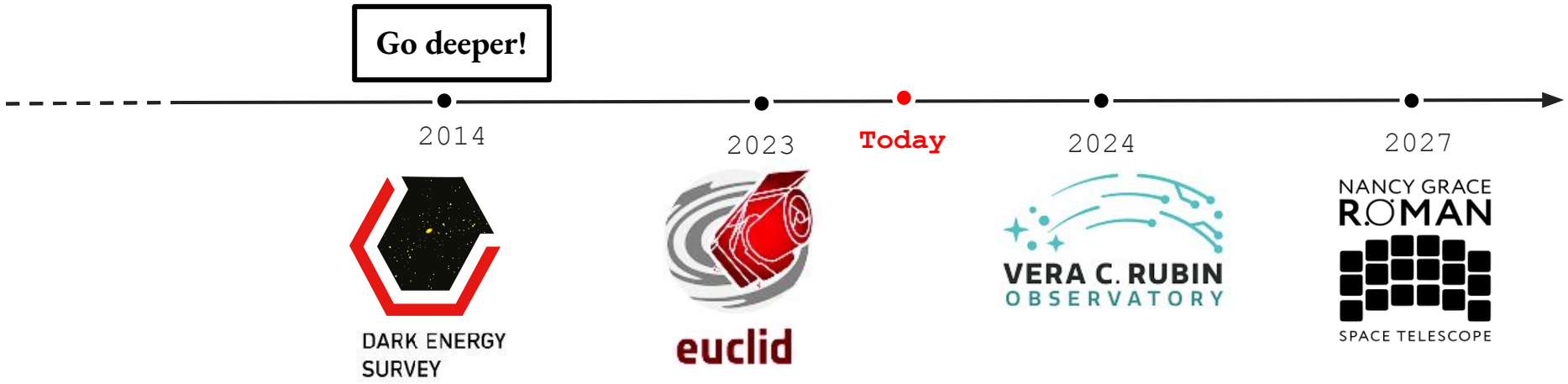
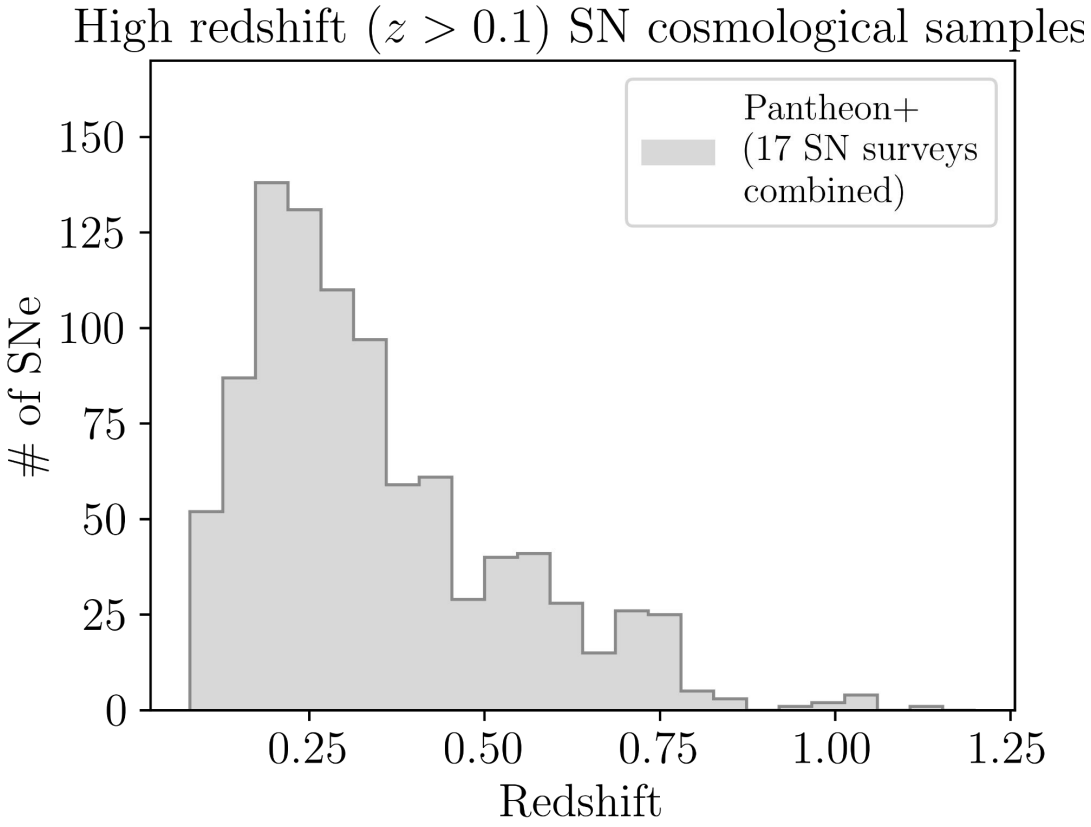


# The Dark Energy Survey: new Dark Energy constraints




Vincenzi et al in prep.

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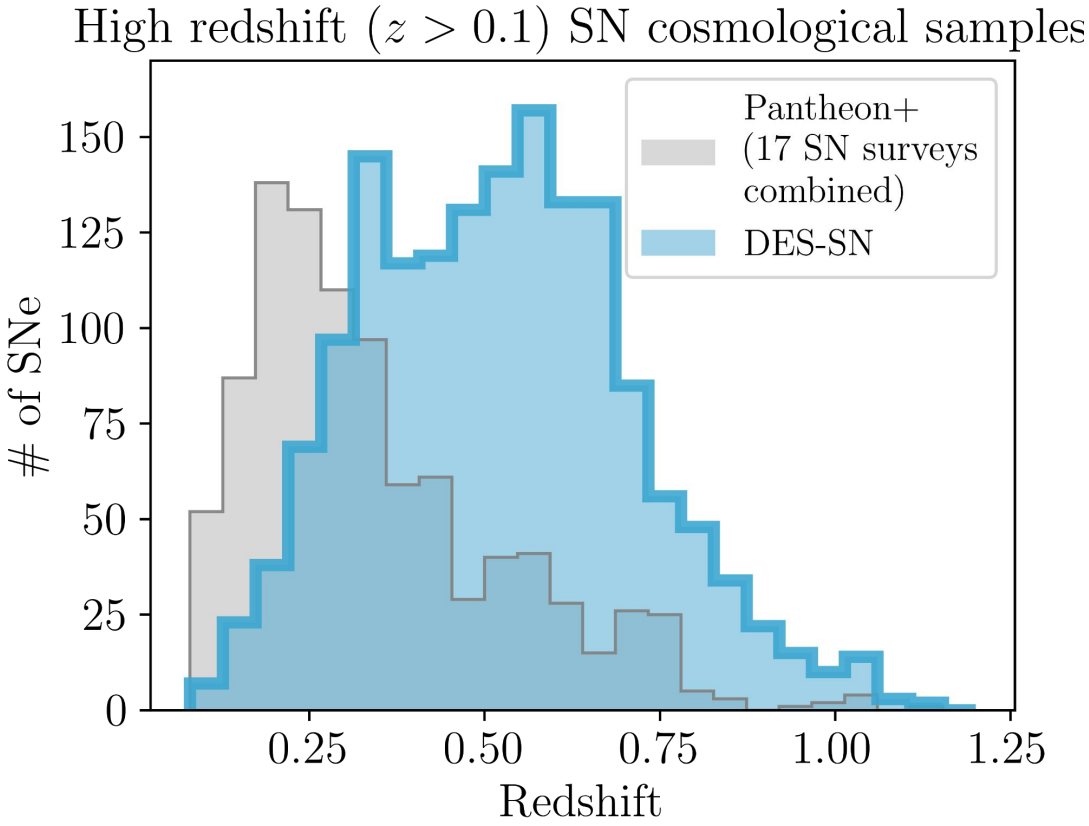


- **1600** new high-z SNe
- x4 SNe at redshifts $z$>**0.4**
- new way of collecting SN Ia cosmological samples → no spectroscopic follow-up but machine learning

Vincenzi et al in prep.

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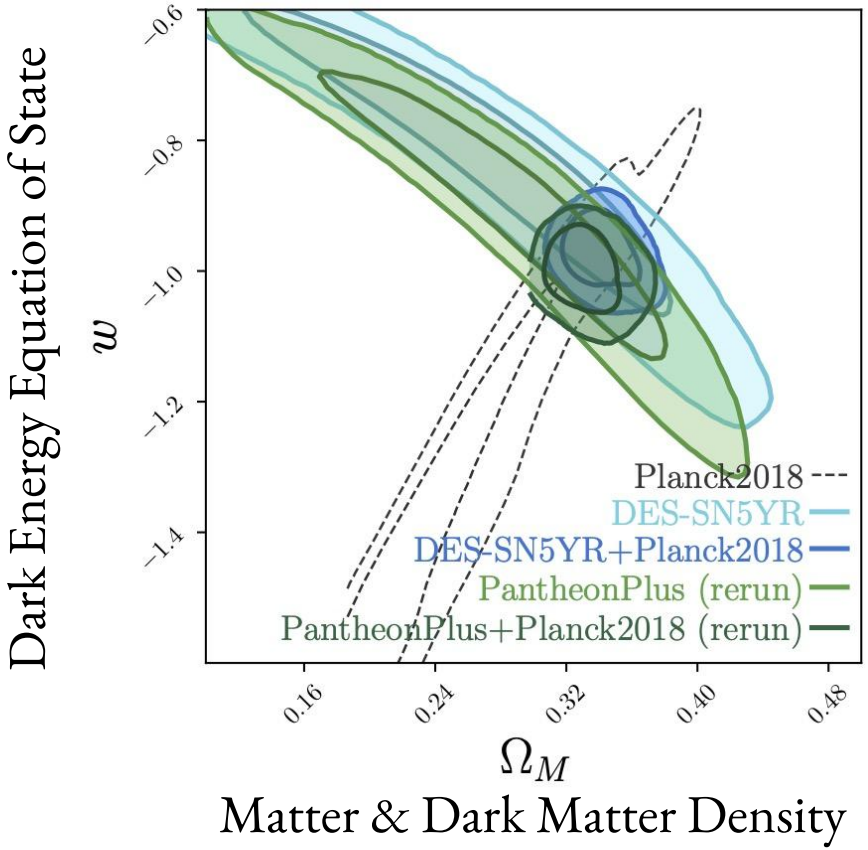


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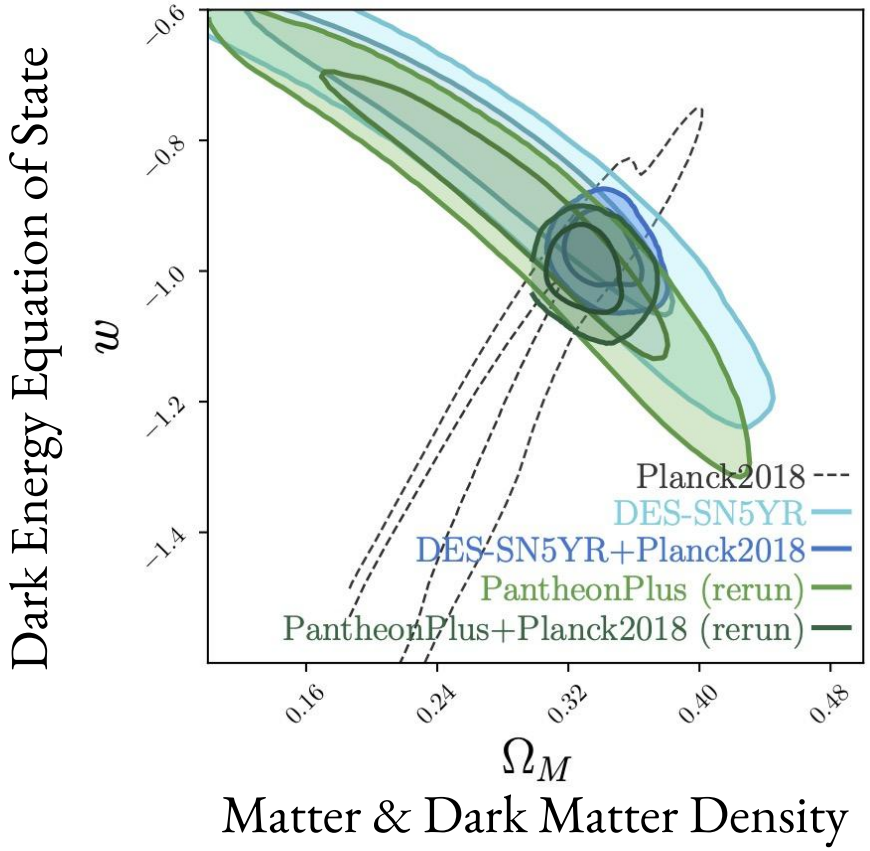



- **1600** new high-z SNe
- x4 SNe at redshifts $z$>**0.4**
- new way of collecting SN Ia cosmological samples → no spectroscopic follow-up but machine learning
- **Top systematics:** photometric calibration and dust/SN astrophys.
- **Consistent with $w$=-1(ΛCDM)**

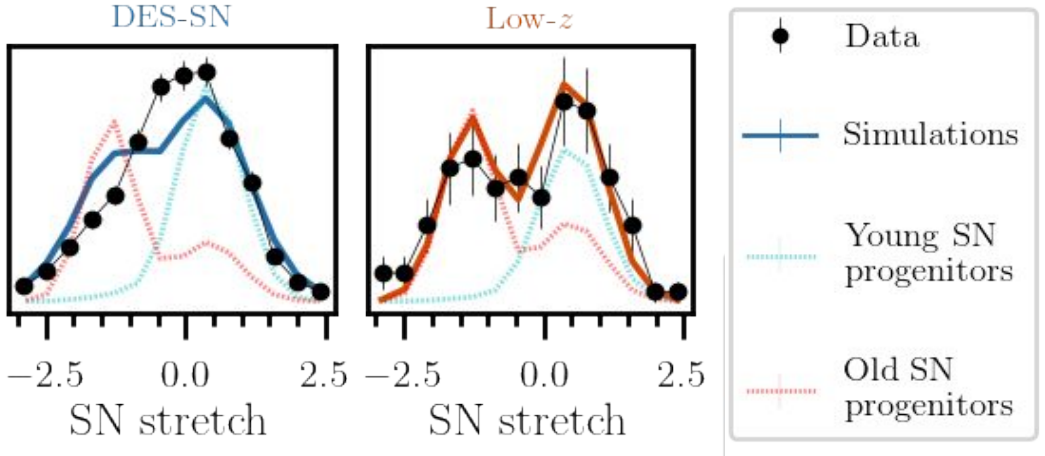
SN data suggests ΛCDM is working pretty well across 11 billion years of cosmic history!

The DES Collaboration, in prep.

# SKIP: The Dark Energy Survey: new Dark Energy constrain

**Dust models:** further testing of implemented in Pantheon+ (everything works fairly well!)

For the first time, we implemented a model of **SN age.** If there's a "age" step, it's <0.04 mag (i.e. it doesn't explain the tension, and in P+ we are only considering star-forming hosts anyway)



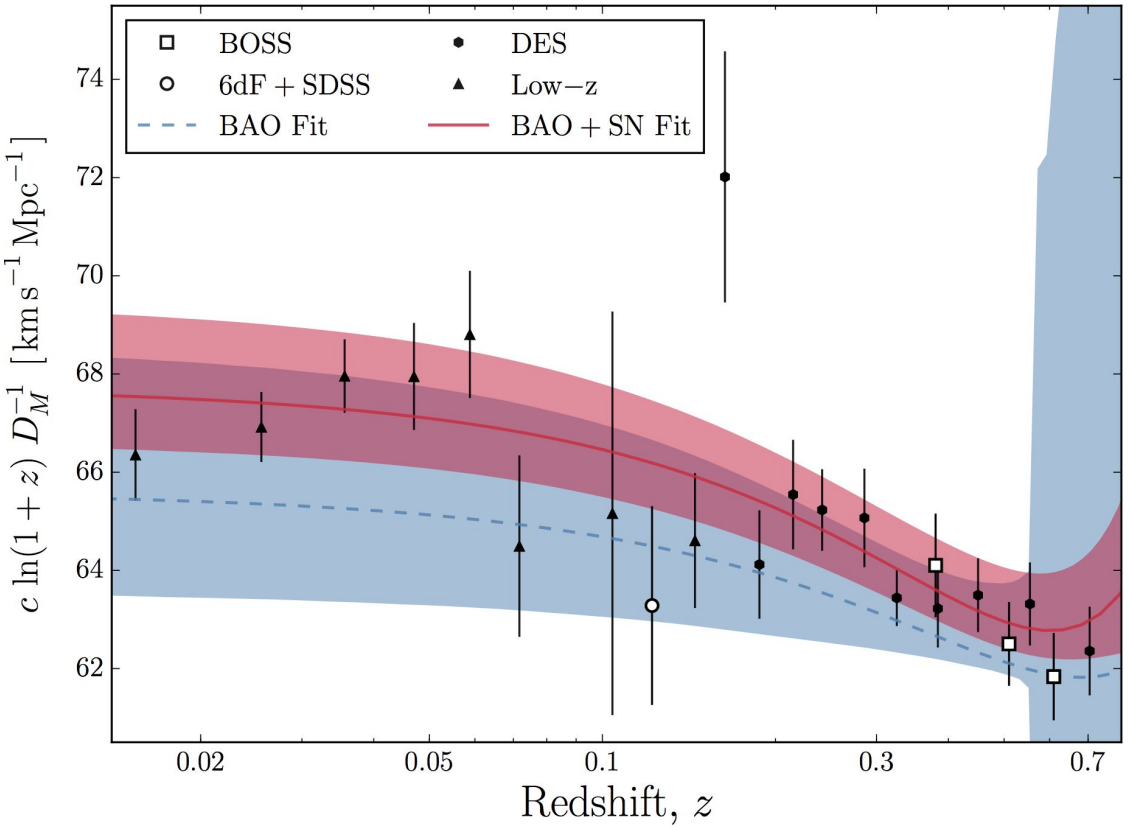

Wiseman et al 2022, Vincenzi et al in prep.

# SKIP: DES has also been used to measure H0

Combining SNe with BAO and the early universe constraint on sound horizon r_s

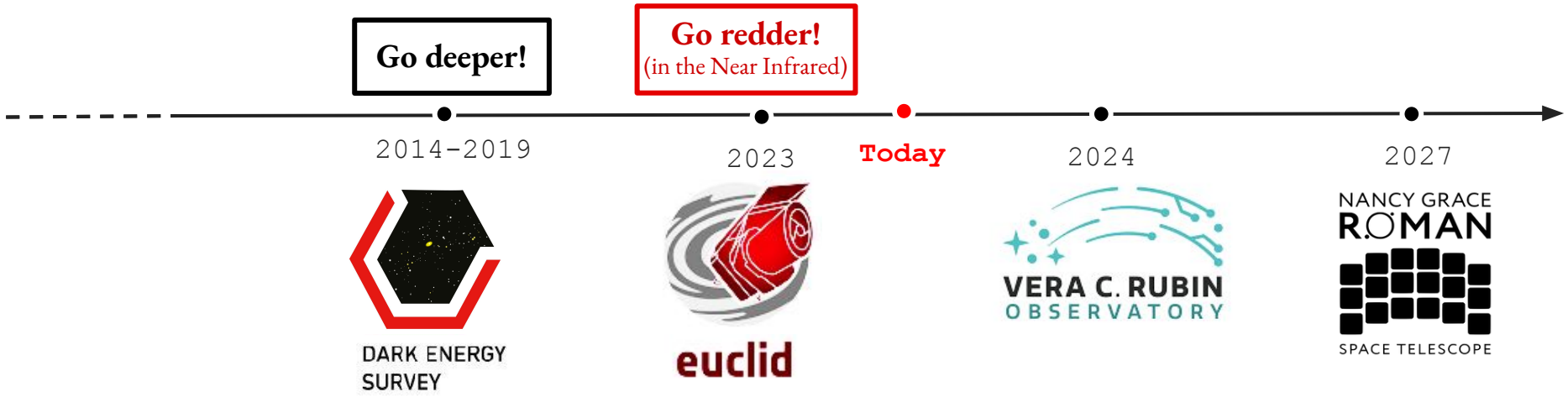
$H_0$ = 67.77+- 1.30 km/s/Mpc

(First H0 inverse distance ladder systematic error budget.)

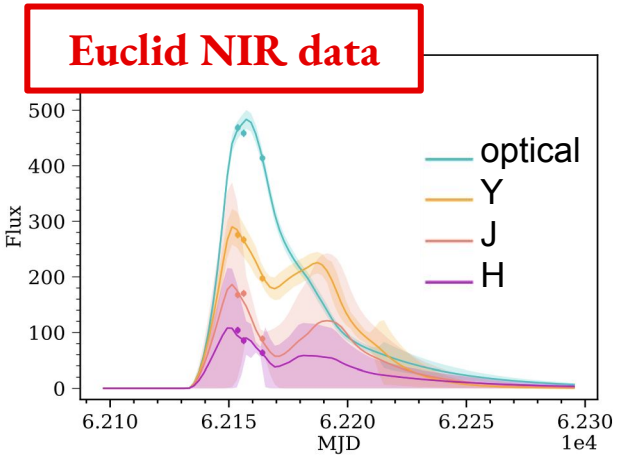



Macaulay et al 2018

# Where is SN Ia cosmology heading to?



# Euclid: solving the dust mystery after 20 years?




Bailey, Vincenzi et al 2022

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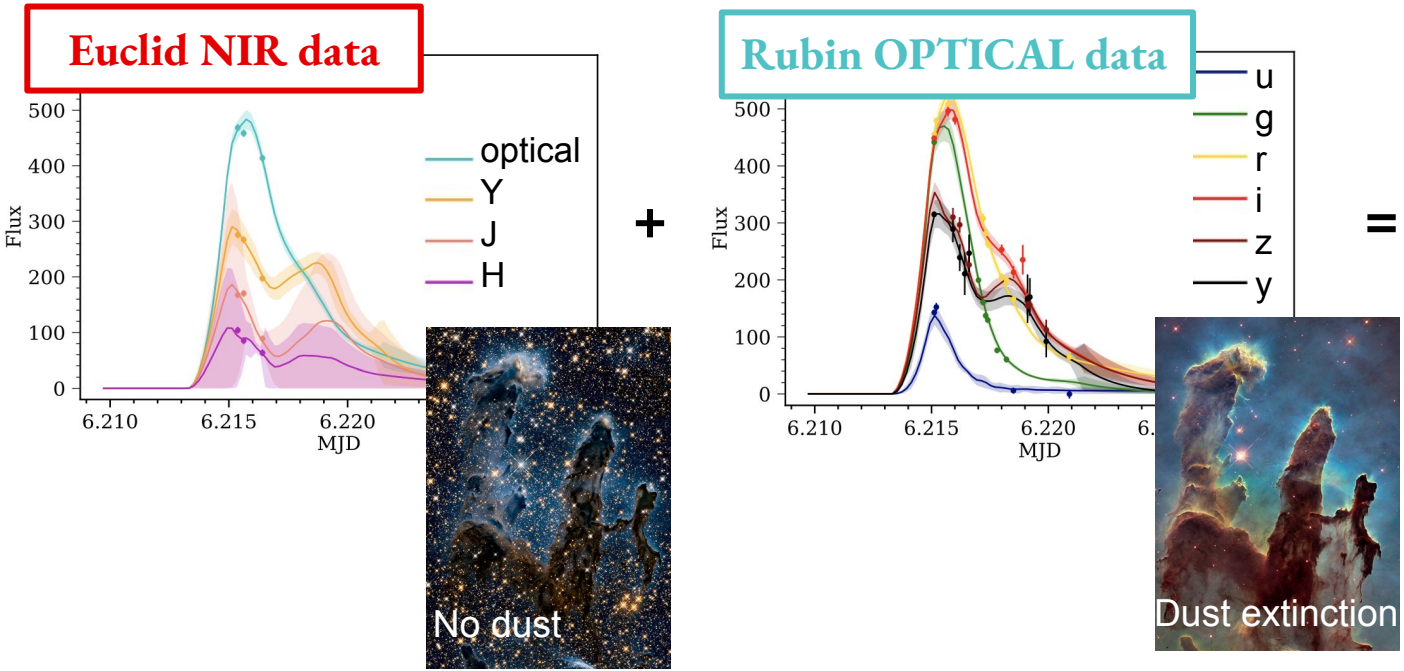


Disentangle ***extrinsic dust*** and ***intrinsic properties***

Bailey, Vincenzi et al 2022

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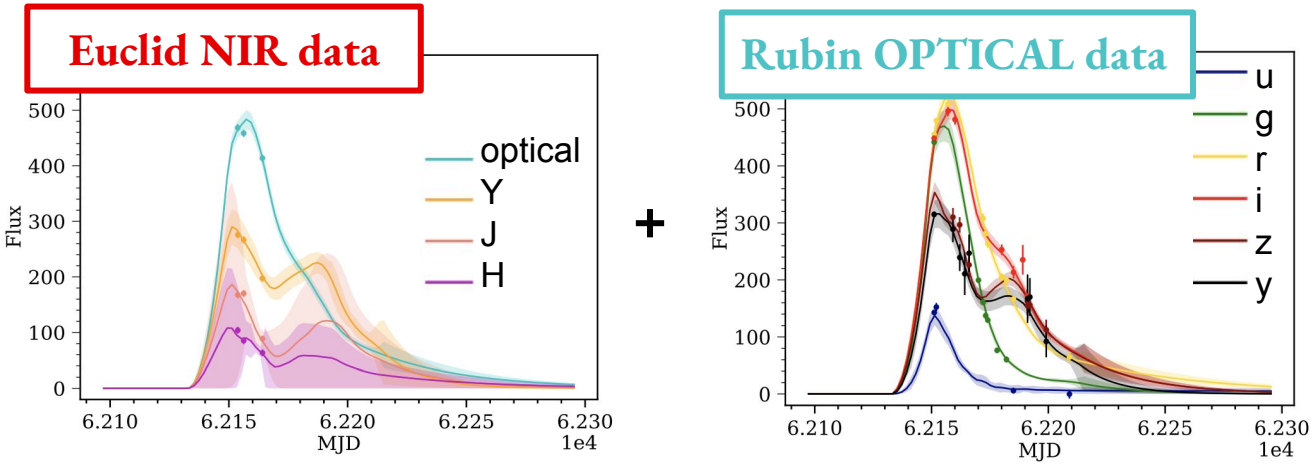


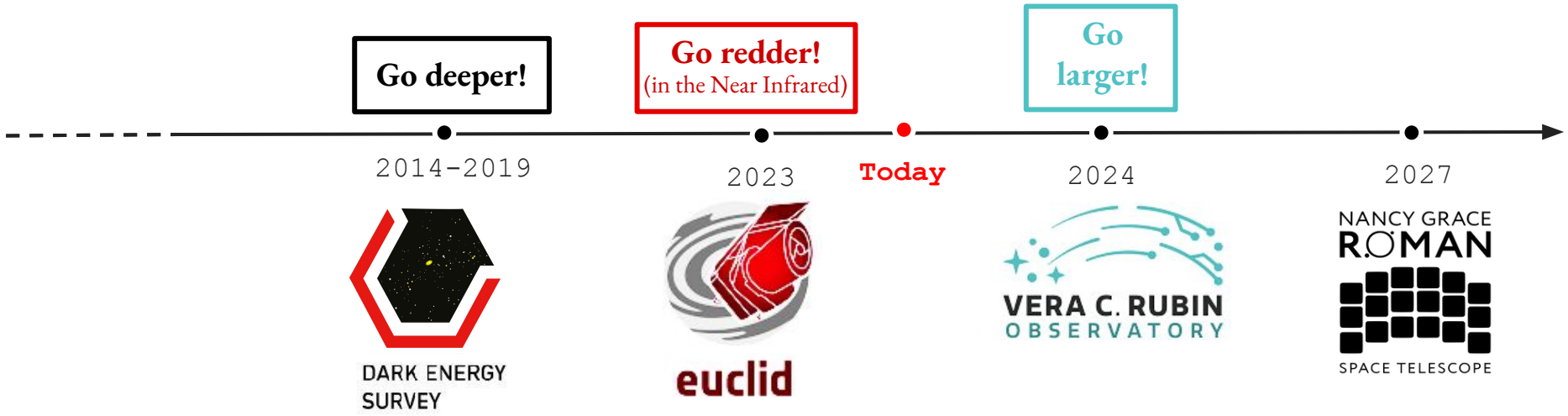

Disentangle ***extrinsic dust*** and ***intrinsic properties***

**~3700 SN Ia lightcurves** with good optical and NIR data from Rubin and Euclid.

We will be able to determine with **4σ** confidence whether ***extrinsic dust extinction*** is largely the cause of SN Ia intrinsic scatter.

Bailey, Vincenzi et al 2022

# Where are SN Ia cosmological experiments going next?

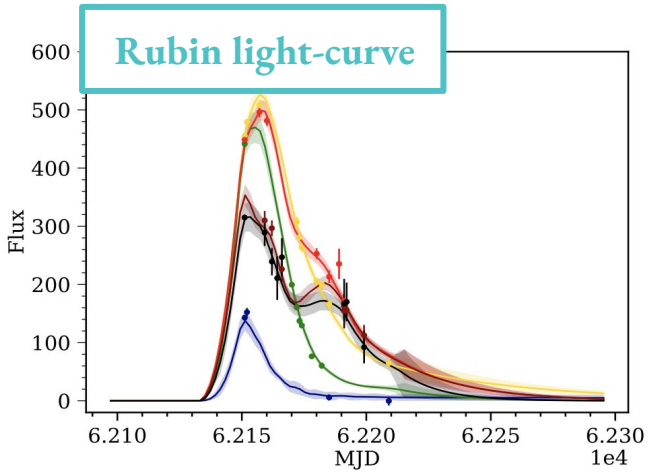


# Rubin+TiDES: a new era for SN Ia and transient science

**Key Info on Rubin:**

- 18,000 sq. deg. (DESx600)
- 10 years survey

**1.2 million** SNe Ia lightcurves
for cosmology**...but we need redshifts!**



# Rubin+TiDES: a new era for SN Ia and transient science

**Key Info on Rubin:**

- 18,000 sq. deg. (DESx600)
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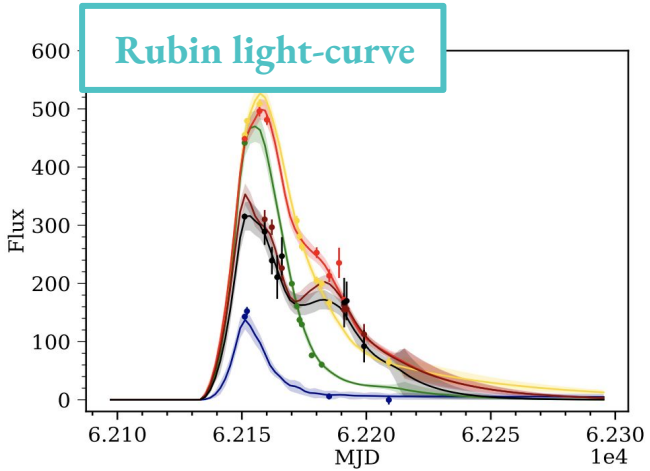
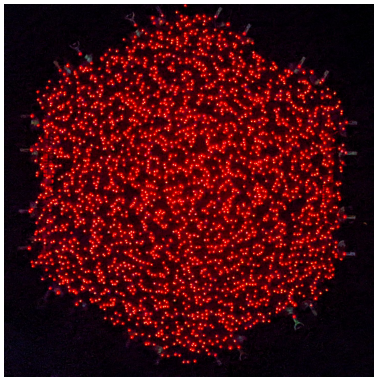
**Key Info on 4MOST/TiDES:**

- On 4MOST, 2400-fibre spectrograph
- South Hemisphere, like Rubin!

**1.2 million** SNe Ia lightcurves for cosmology**...but we need redshifts!**

The *only* spectroscopic follow-up program currently planned for Rubin!

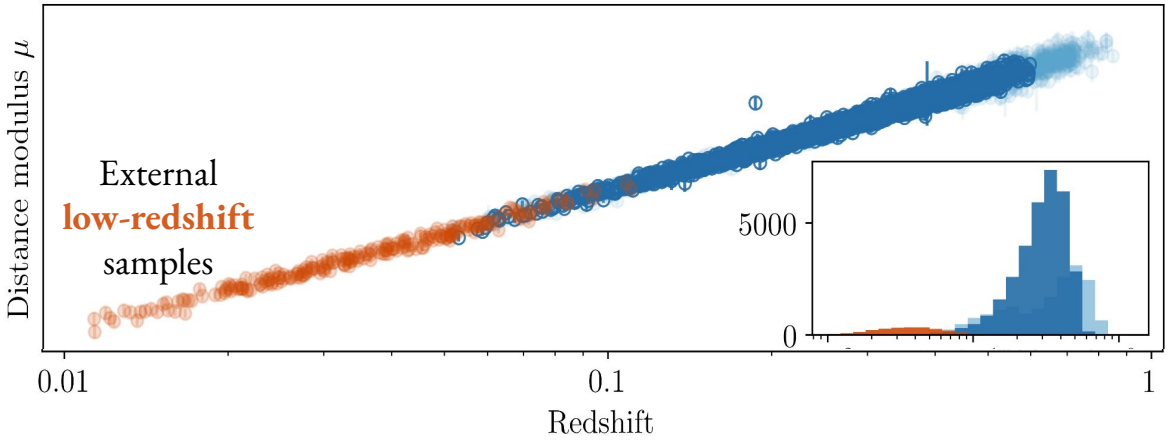


**Spectroscopy is needed for:**

- Redshifts
- Live transient spectroscopy

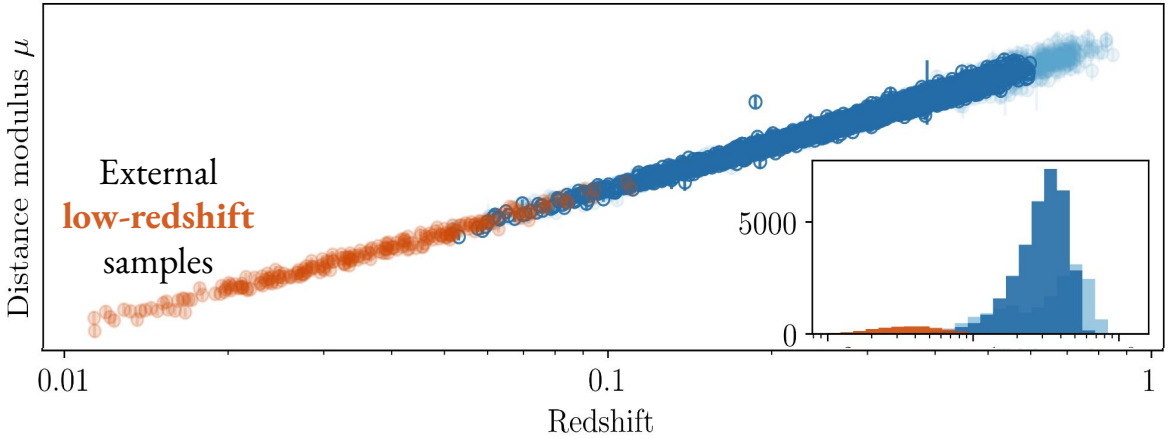
# Rubin+TiDES: a new era for SN Ia and transient science




**25k SN Ia spectra +**
**30k SN host redshifts**

Frohmaier, Vincenzi in prep.

# Rubin+TiDES: a new era for SN Ia and transient science

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**Improve understanding of SN systematics...**

- Select only sub-samples of SN hosts/environment and test different progenitor scenarios
- **Use spectroscopy to constrain improve standardization**

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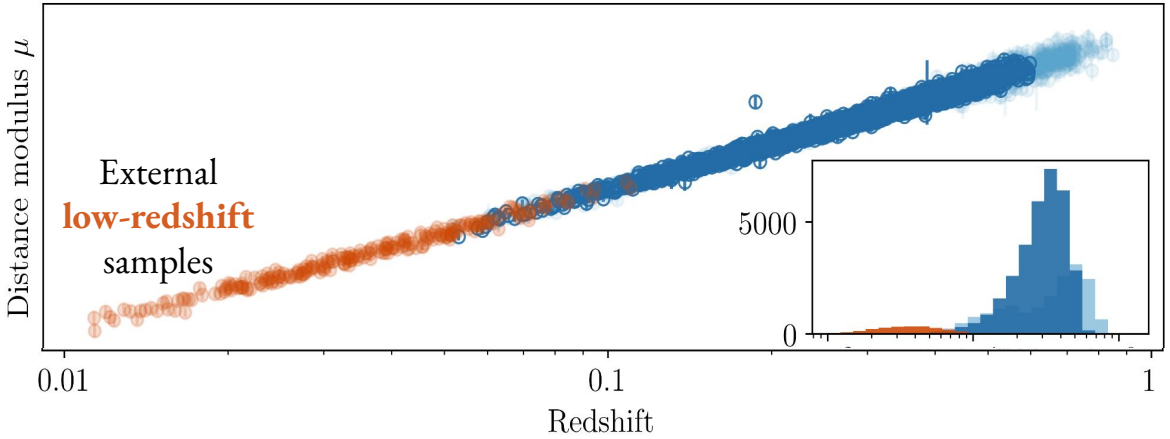


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**Improve understanding of SN systematics...**

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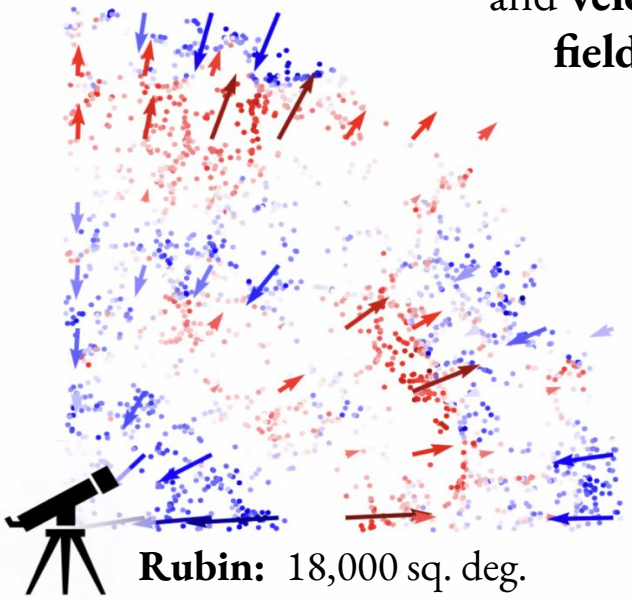
- **Use spectroscopy to constrain improve standardization**

**Push cosmological measurements...**

- Test a wide range of **Dark Energy** Equation of State models across 11 Gyr
- **A new way of testing GR** and **ΛCDM** using SN Ia pec. velocities

# **Testing GR and ΛCDM with SN Ia test it:** Constraining the growth rate of structure using SNe Ia peculiar velocities

**GR + ΛCDM** → **galaxy density** and **velocity fields**



**Rubin:** 18,000 sq. deg.

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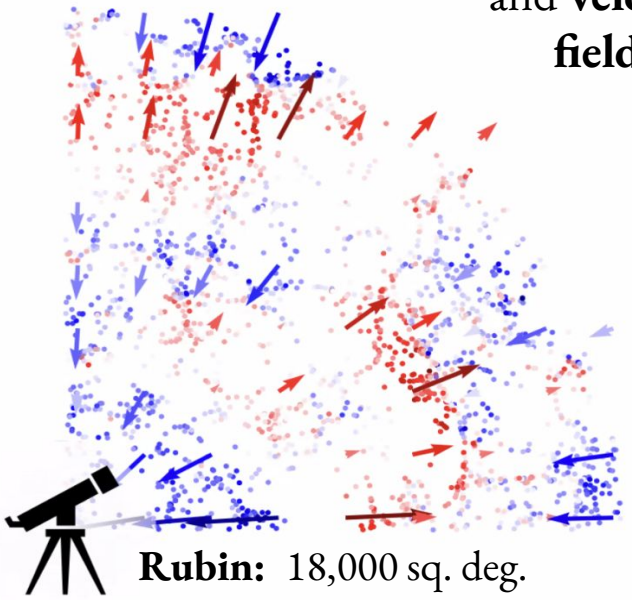

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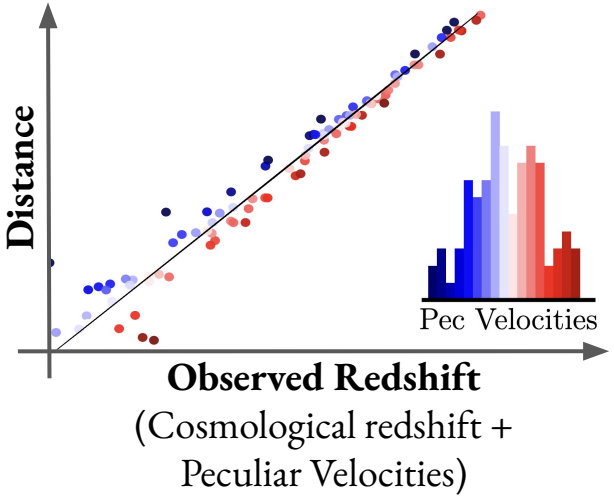


(Cosmological redshift + Peculiar Velocities)

- SNe Ia are a very powerful tool to measure galaxies' **peculiar velocities.**
- SNe Ia allows to reconstruct the **galaxy velocity fields** and constrain the growth rate of structures

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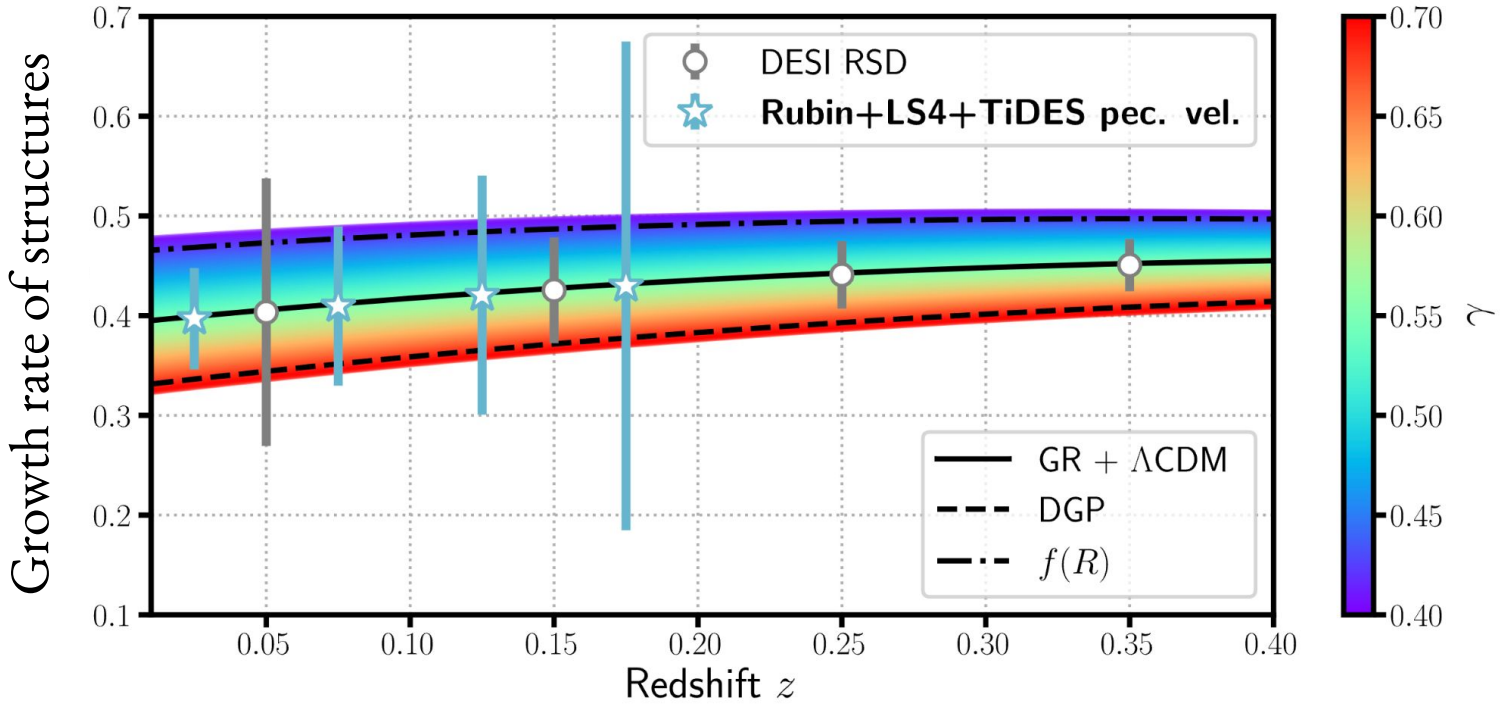
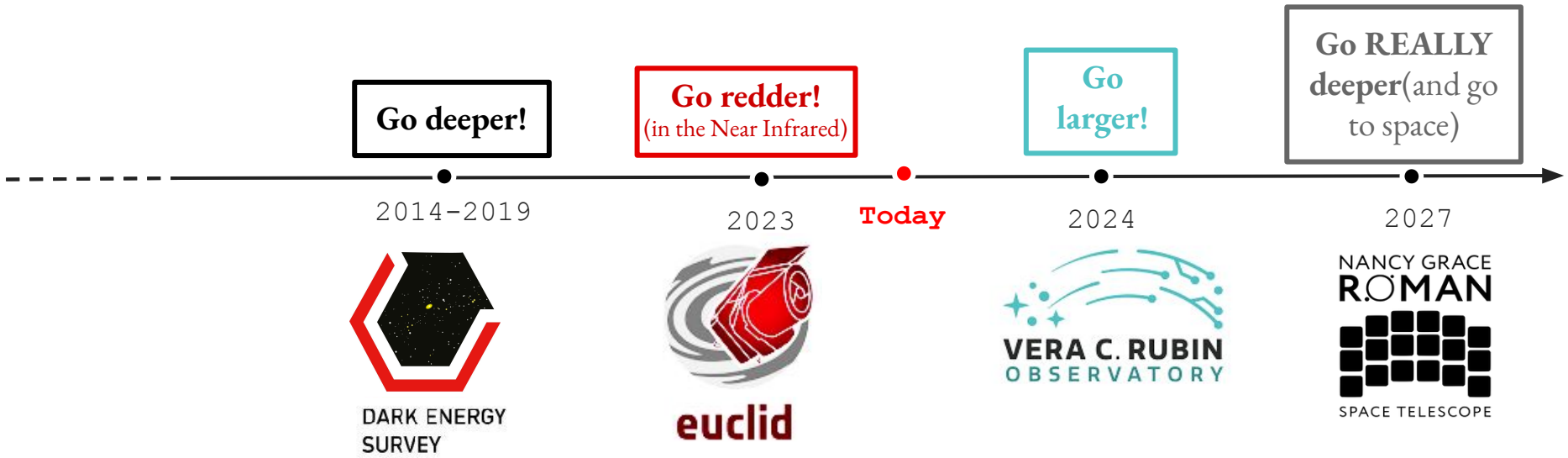



**Adapted from Carreres et al 2023**

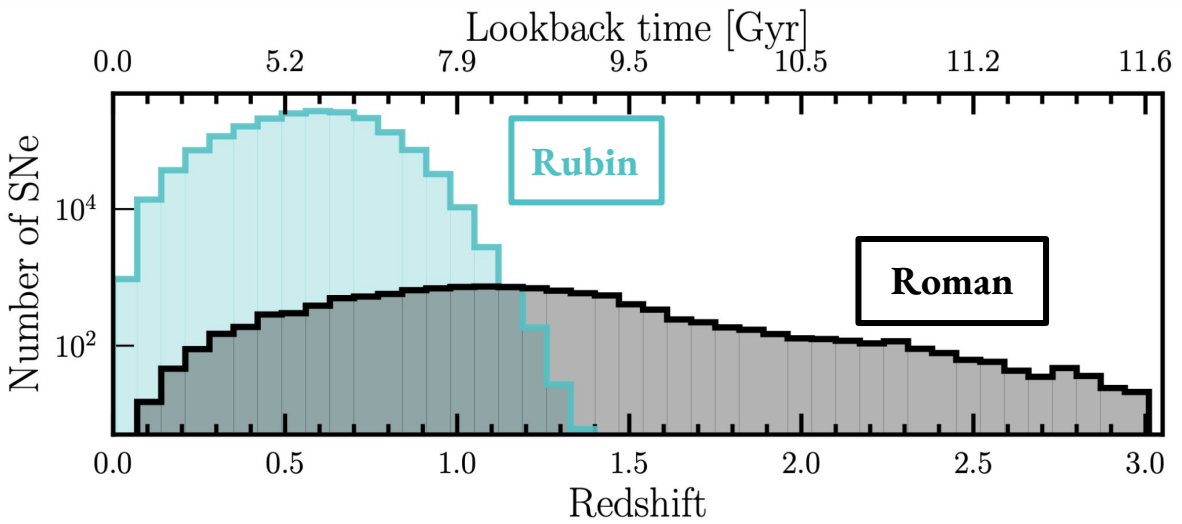
**MV**, Howlett, Frohmaier et al. (in prep.)

# Where are SN Ia cosmological experiments going next?

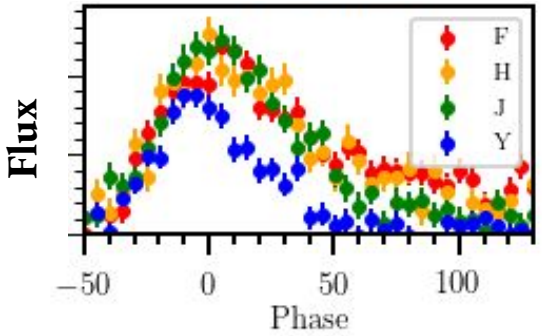


# Roman: pushing SN Ia cosmology to redshift z~3

As Euclid, Roman is also a NIR space-telescope, with focus on transient science.




**Typical SN Ia light-curve from Roman at z~2**




Rose, **MV et al. in prep.**

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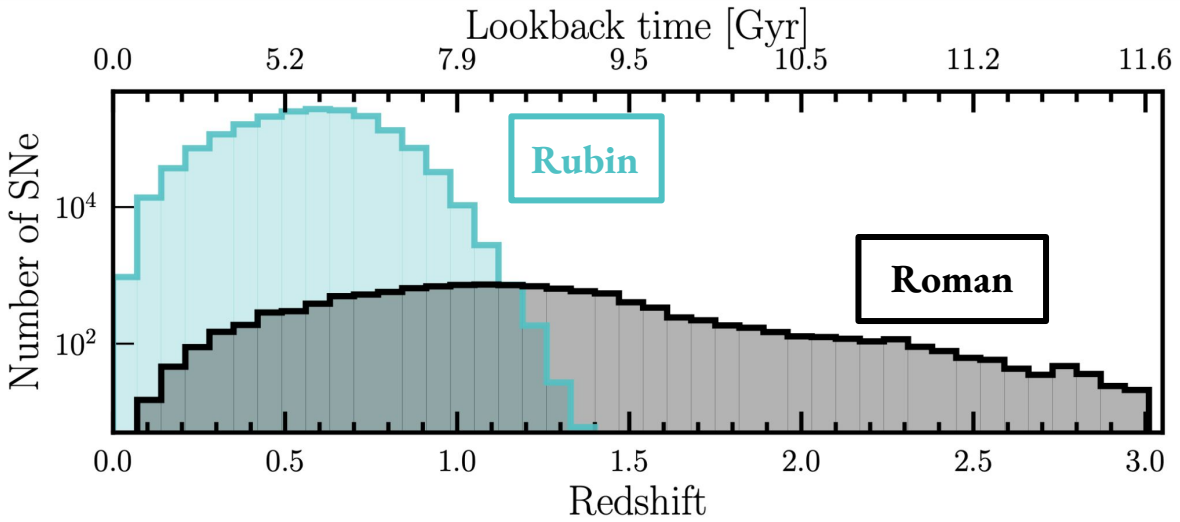


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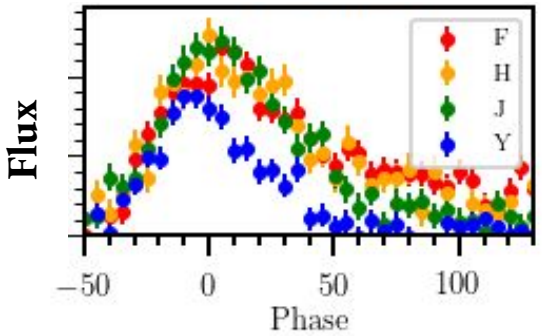


Constraining **expansion** above **z~3**

**Weak lensing on SNe Ia** to constrain $\sigma_8$

Rose, **MV et al. in prep.**