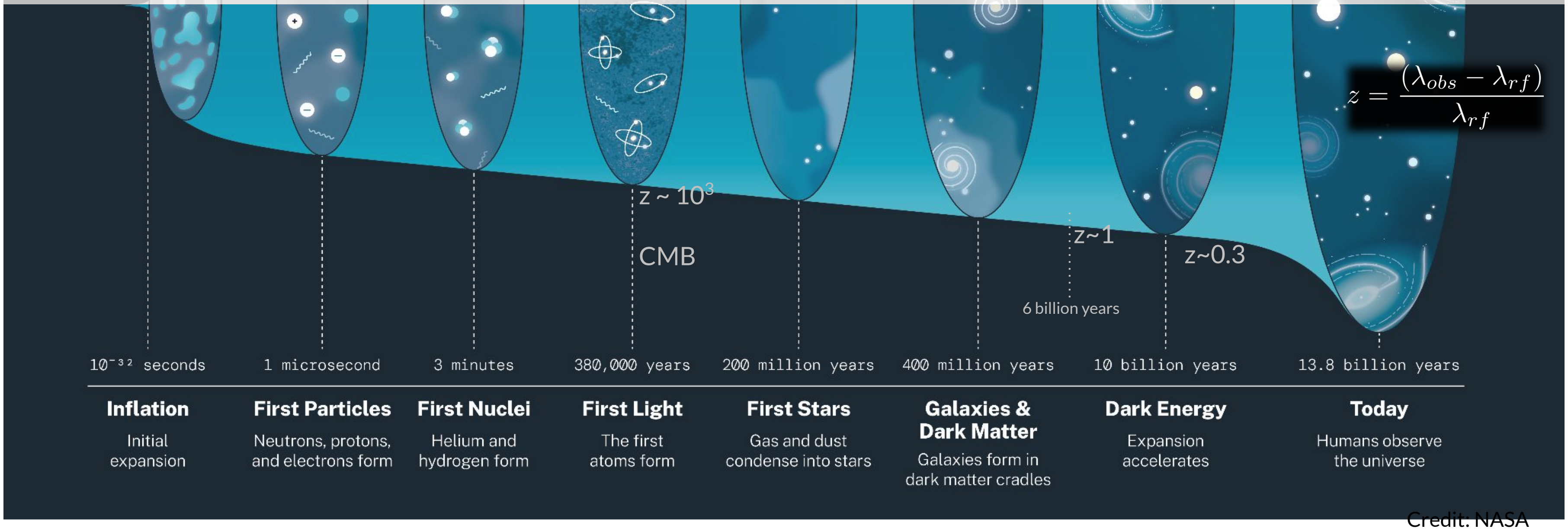
The Dark Energy Supernova Program 5YR: Cosmological constraints with the DES Hubble Diagram of ~1500 new Type Ia Supernovae

Bruno Sánchez on behalf of the Dark Energy Survey collaboration

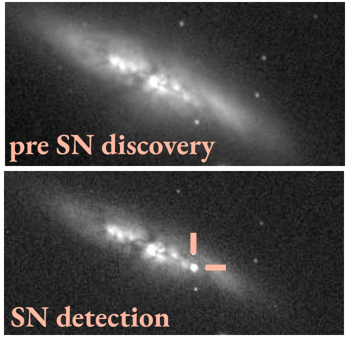
THE DARK ENERGY SURVEY

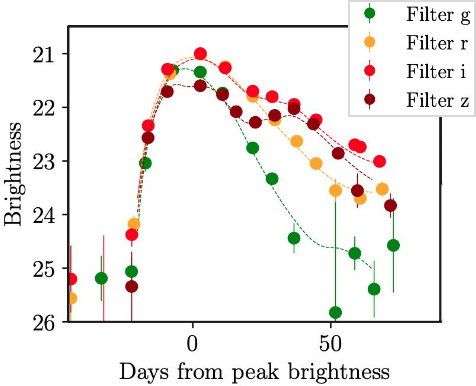
A *history* of our universe: The Cosmological Standard model



Credit: NASA

Type Ia Supernovae as standard candle





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

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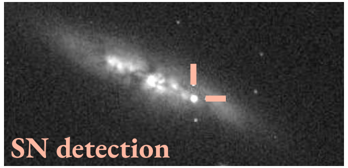

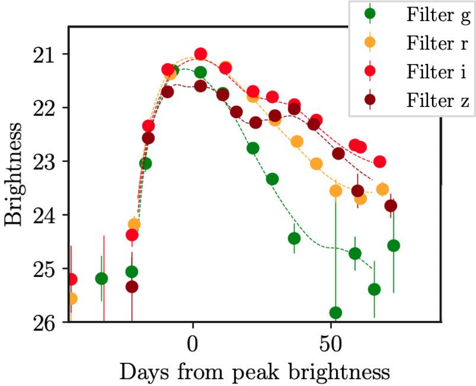

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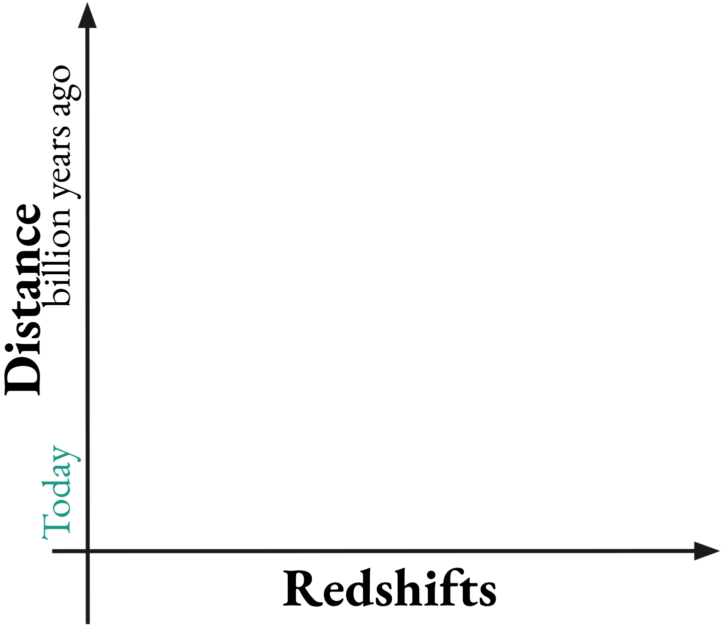

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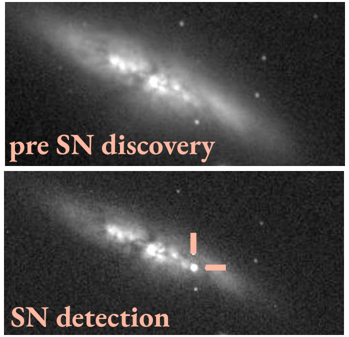

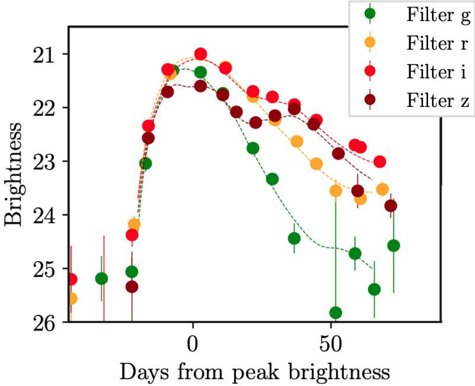

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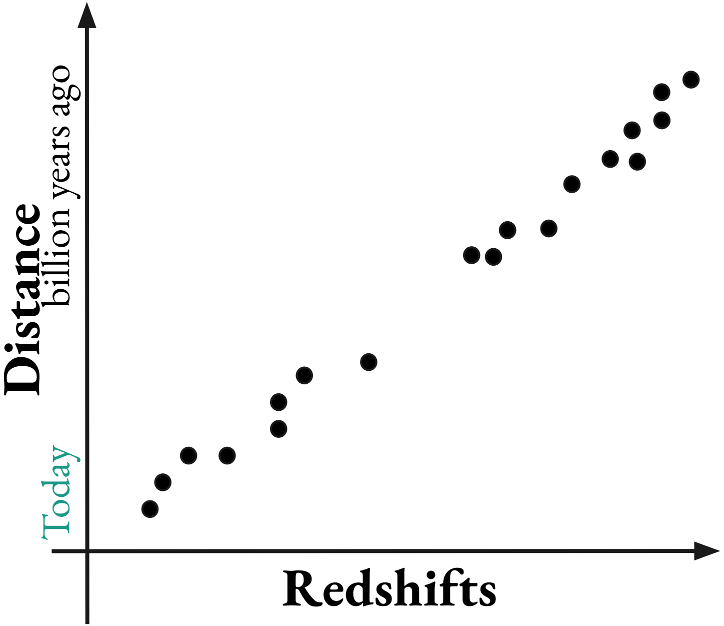

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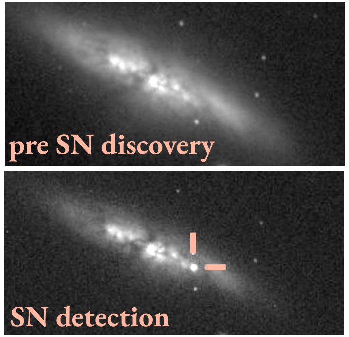

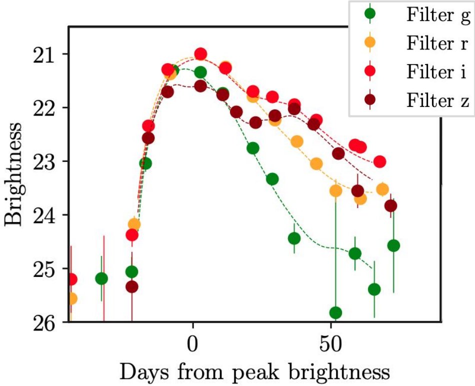

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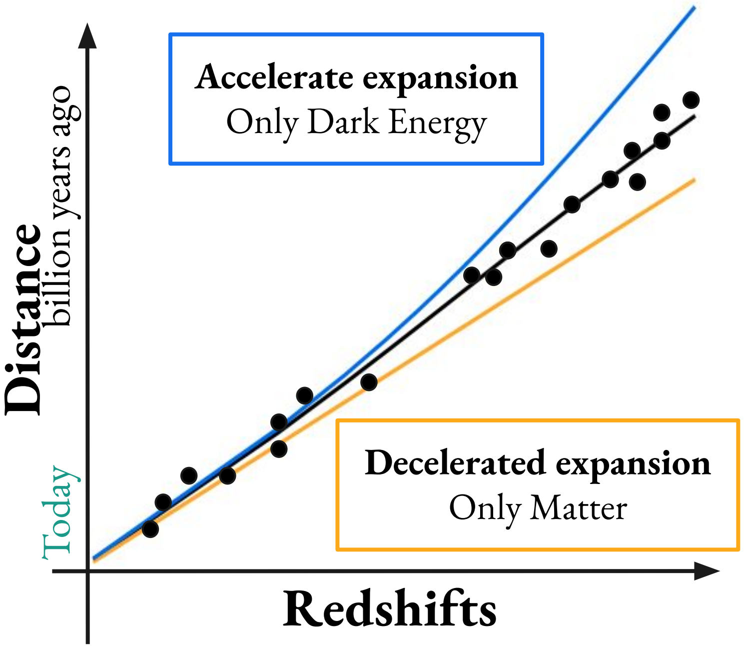

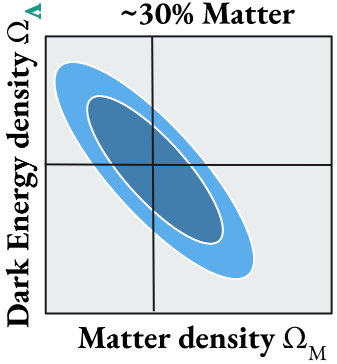

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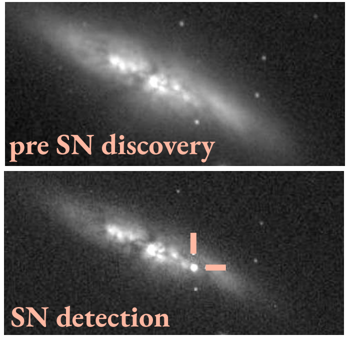

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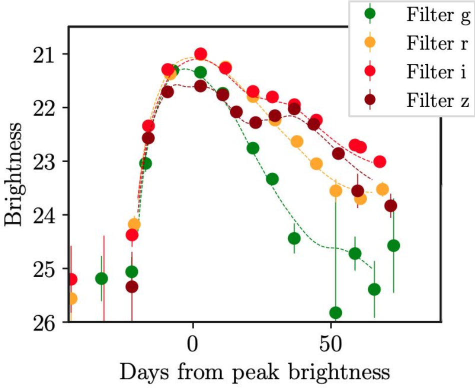
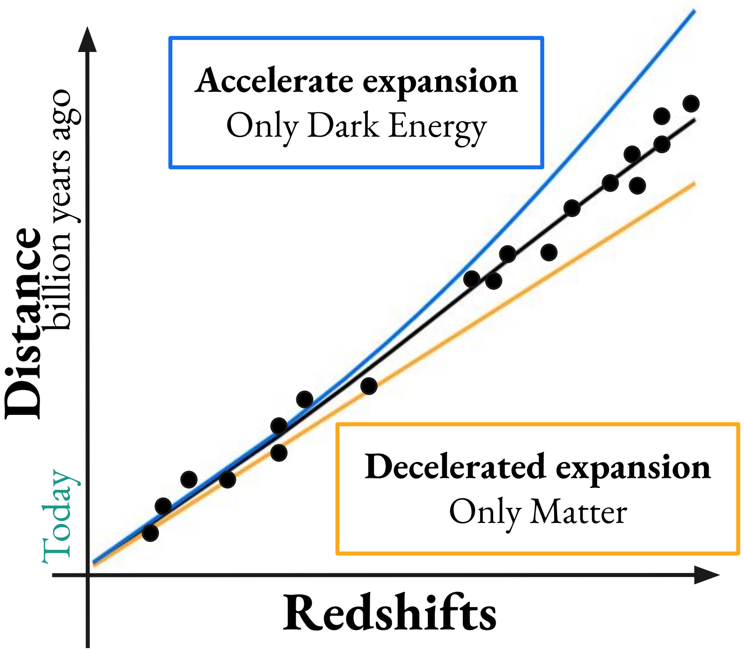
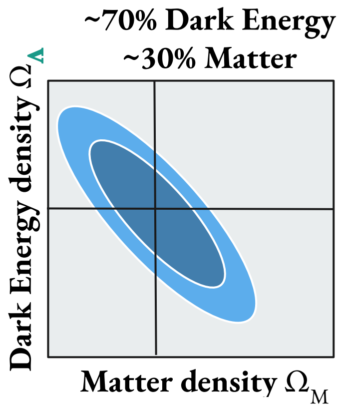
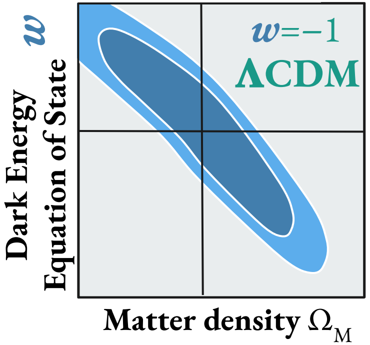


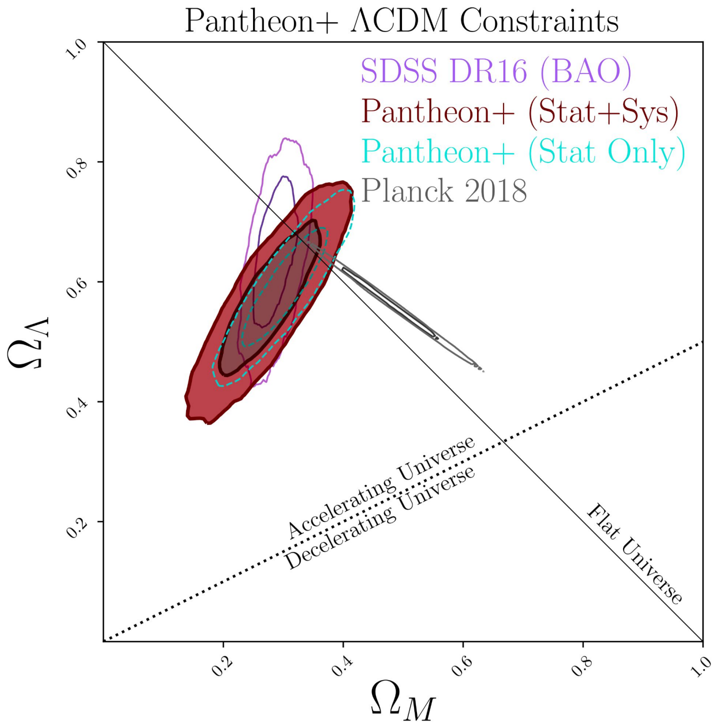


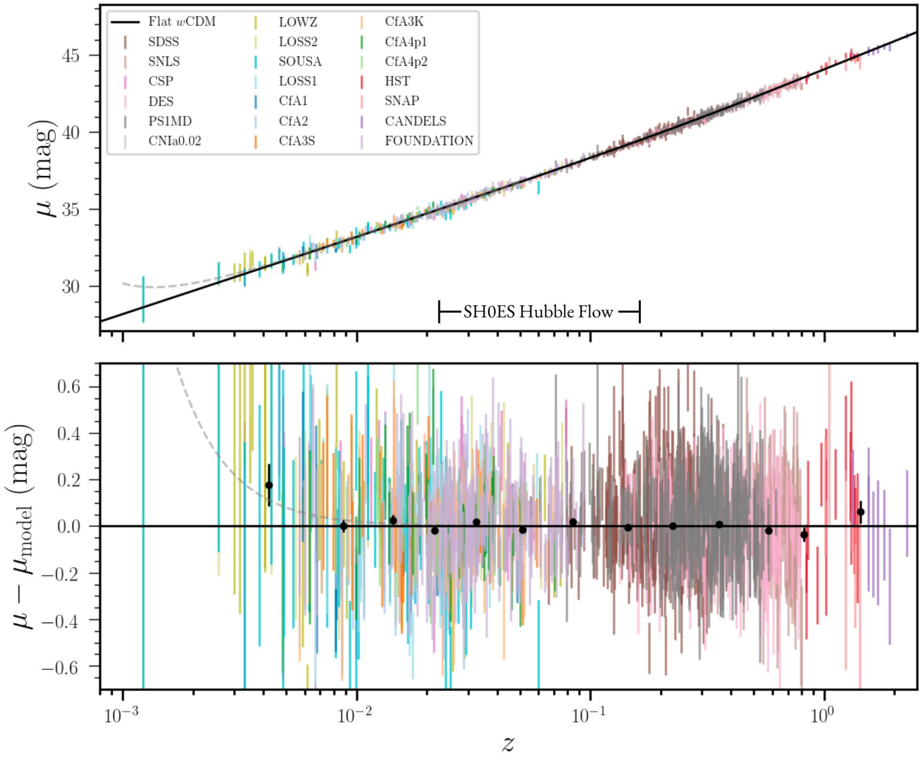




$$\Omega_\Lambda(z) \sim \Omega_\Lambda (1+z)^{3(1+w)}$$

Cosmology with Type Ia Supernovae: state of the art





Pantheon+ (Brout et al. 2022)

A single survey for SNIa Cosmology:

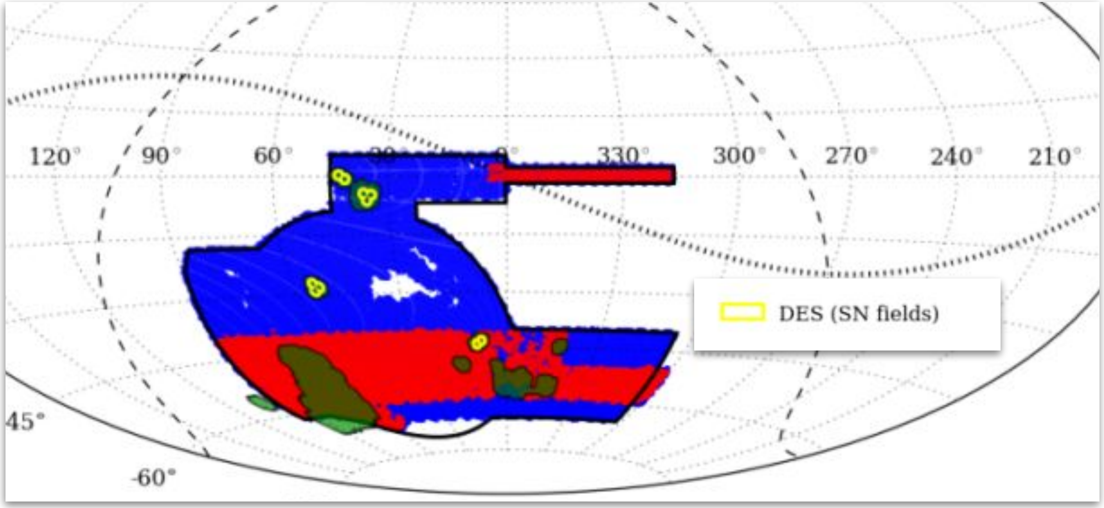
Dark Energy Survey Y5 SNIa analysis

THE DARK ENERGY SURVEY

The DES Supernova Working Group

The Dark Energy Survey (DES)

- Started observing in 2013
- DECam on the Victor M. Blanco Telescope
  - ugrizY filters
- Six years (758 nights)
  - 3 year preliminary SN results
  - 5 year final SN results
- Multi-probe survey
  - Supernovae
  - Gravitational Lensing
  - Galaxy Clusters
  - Baryon Acoustic Oscillations



THE DARK ENERGY SURVEY

The Dark Energy Survey (DES)

THE DARK ENERGY SURVEY + OzDES

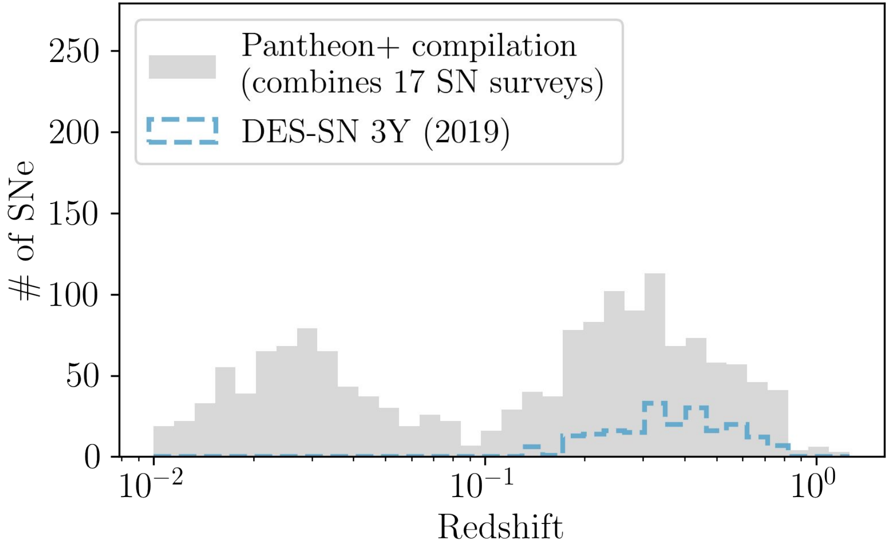
- DES-SN observations in **10 fields**
  - **8 shallow** fields
  - **2 deep** fields
- **5 years** of **~27 sq. deg**
- Detection of transients using Difference Image Analysis (Kessler et al 2015)
- Candidate veto using machine learning (Goldstein et al. 2015)
- Parallel spectroscopic follow-up with **AAT** in the OzDES survey

Survey run between
2014-2019

Publication of the first ~200
DES SN 3YR
2019

Publication of the results
from the DES SN 5YR
2023-2024

The Dark Energy Survey (DES) SN Y5



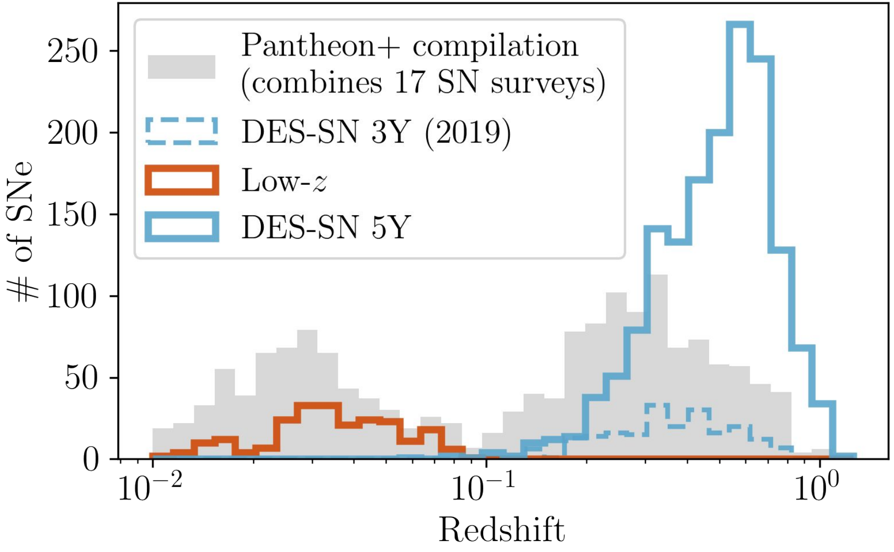
Brout et al. (2021)

State-of-the-art, before the **DES SN-Y5: Pantheon+**

Compilation of spec confirmed SN Ia (including ~200 DES SN Ia)

Vincenzi et al. (in Internal Review), DES Collaboration, in prep.

The Dark Energy Survey (DES) SN Y5



With the **DES Supernova program…**

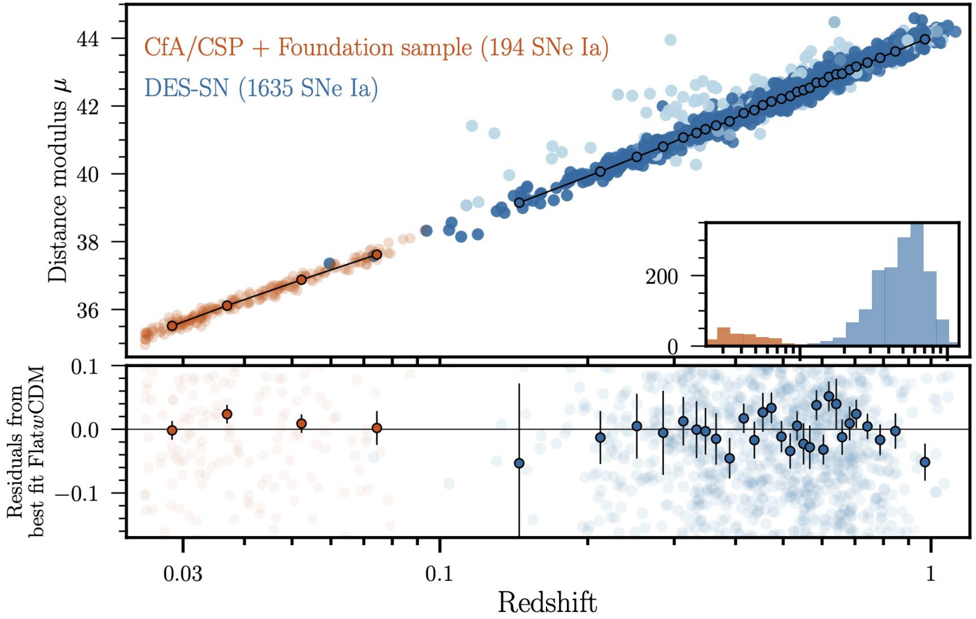
~1600 SNe Ia

This is the **largest** and **deepest high-z** SN sample from a **single telescope ever compiled**

- Well defined sample selection
- Spectroscopic redshifts from OzDES

Vincenzi et al. (2024), DES Collaboration et al. 2024

The Dark Energy Survey (DES) SN Y5



Vincenzi et al. (2024), DES Collaboration et al. 2024

This is the **largest** and **deepest high-z** SN sample from a **single telescope ever compiled (0.10 < z < 1.13)**

We show additional SNIa from low-z sample

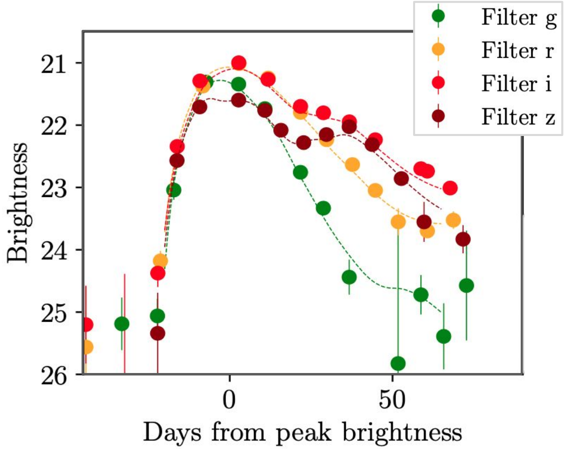
The DES-5YR analysis keys:

1. **Building the Data Set**: find SNe, **measure** and **calibrate** their **photometry**, find the SN **host galaxy**;
2. **Simulating** DES-SN samples that look like the *observed* sample;
3. Classification to get a **pure** sample of SNe Ia
4. Modelling SN **dust extinction**, **SN progenitor physics**
5. **Error budget: Systematic uncertainties > Statistical uncertainties**

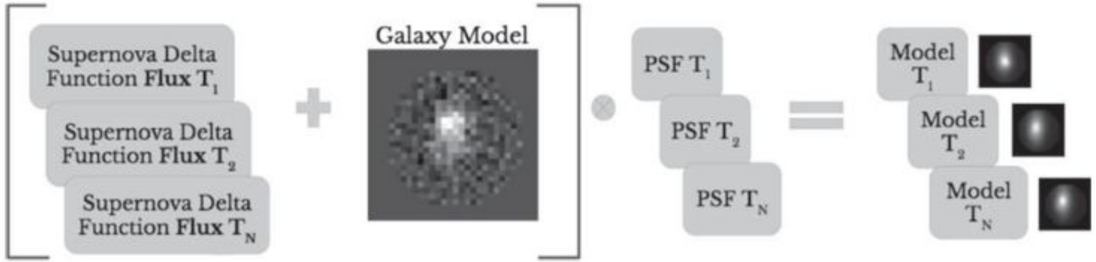
Building the dataset: Scene Modelling Photometry

It's an ***image forward modelling*** technique to obtain accurate fluxes and errors of transients on galaxy hosts.


Dillon Brout,
Bruno Sanchez, et al.

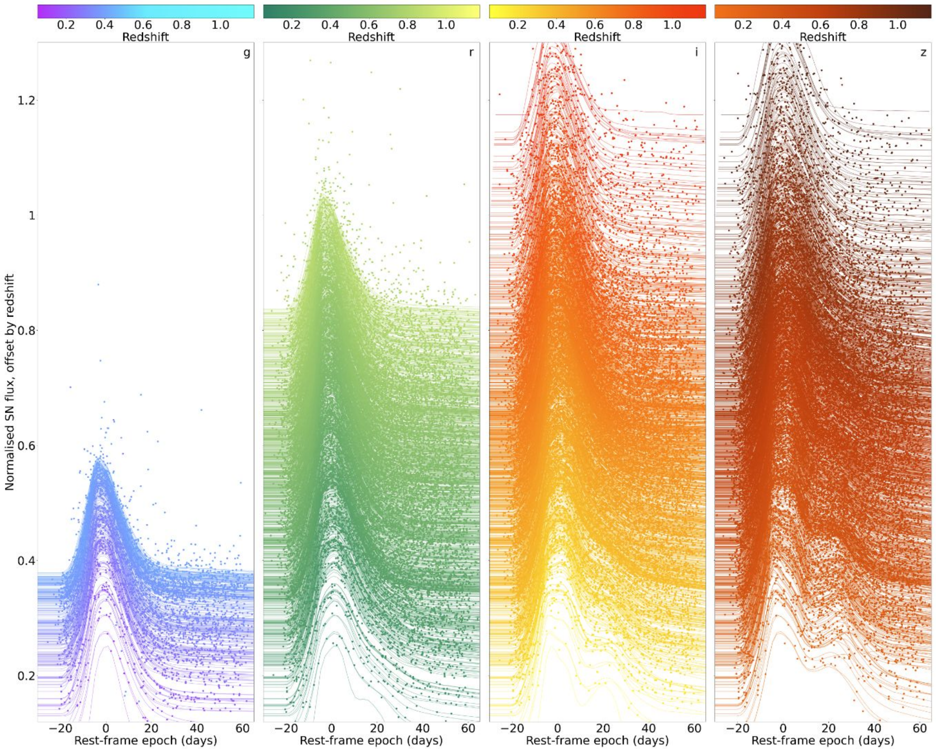


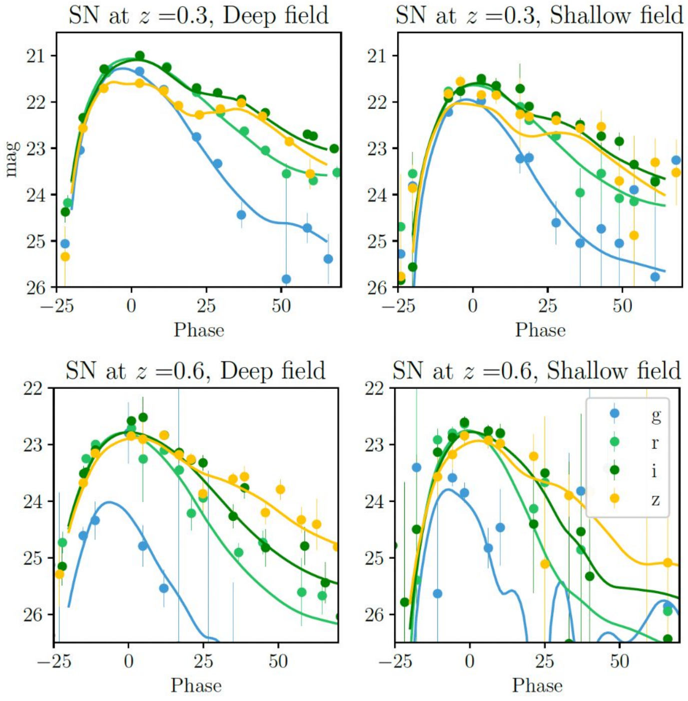
$$M = (G + f_t \delta_{x,y}) \otimes P_t$$



Brout et al. 2019; Sanchez et al. (in Internal Review), DES Collaboration, in prep.

Building the dataset: Final Lightcurves



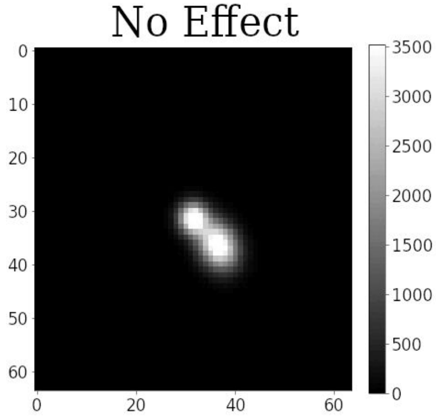


Building the dataset: Photometry corrections

Differential Chromatic Refraction
Correction for λ-dependent atmospheric effects on SN PSF.
New DCR calibration.

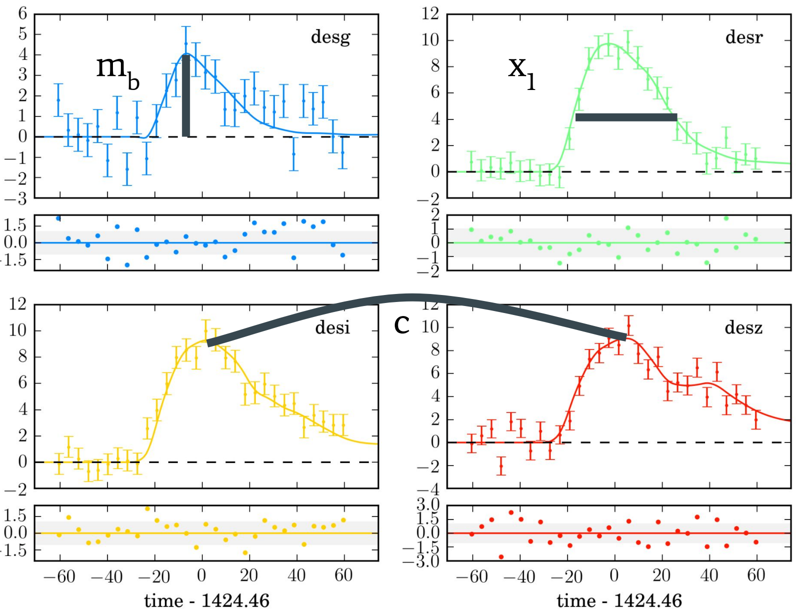
SNIa final accuracy < 5mmag

Jason Lee
Maria Acevedo
Masao Sako



Lee, Acevedo, Sako et al. 2022

SALT Modeling of SNIa light curves



Spectral Energy Distribution vs time template surfaces

SALT Light curve Fit

$$\mu_{SN} = m_B + \alpha x_1 - \beta c - M + \Delta\mu_{bias}$$

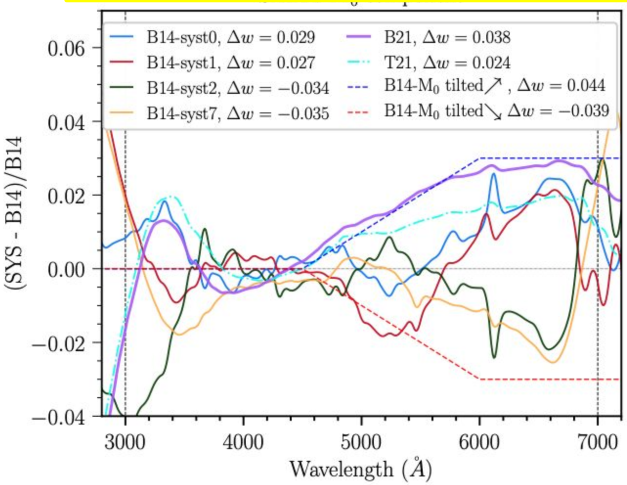
Tripp (1998)

Nuisance Parameter

Calculated | Observable | Unknown

Building the dataset: Survey and SNIa Model Calibration

Light-curve modelling using new **SALT3** model (Kenworthy et al 2021)



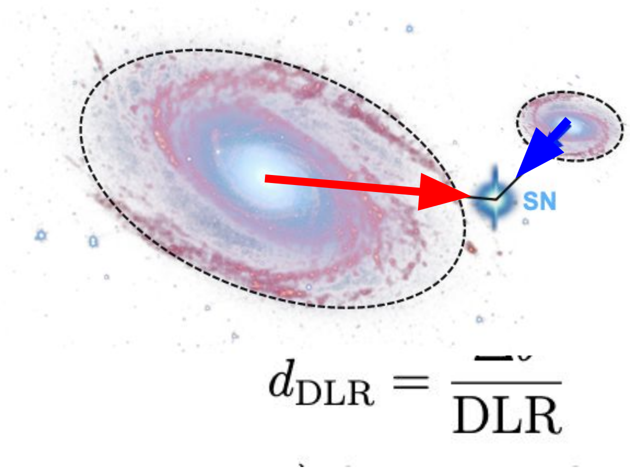
Georgie Taylor

- **SALT3** trained on x1.5 larger data
- **SALT3** goes **redder**, where DES has lots of high-quality data
- Calibration uncertainties incorporated in the light-curve model training process as well as the fitting process.
- Validation against previous models

Brout et al. 2022, Taylor et al 2023

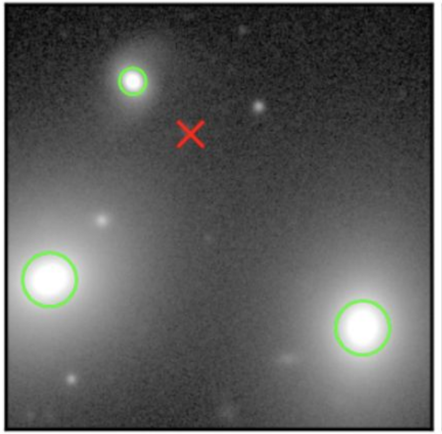
Building the dataset: Finding the SNIa hosts

We associate using DLR method using deep DES coadd images of hosts, and validate with detailed simulations for mismatches



Sullivan+2006, Wiseman+2020, Qu+2023

2008bf

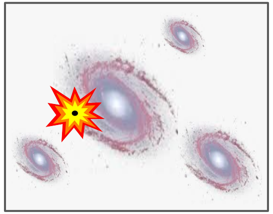


Host Mismatch systematics are less than 10% of total error budget.

Helen Qu

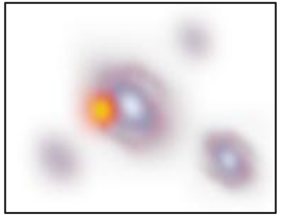
"Simulations that match a number of the host galaxy properties of DES predict a 1.4% missassociation rate."

Modelling the sample and the survey: Characterizing selection functions



Model the astrophysical components:
- Supernovae (Ia & "contaminants")
- Galaxies (star-forming, passive)
- Dust

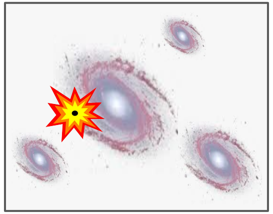
+



Model the survey
- observational noise,
- selection effects,
- cadence...


Kessler et al 2019, Vincenzi et al. (2021, 2023)

Modelling the sample and the survey: Characterizing selection functions



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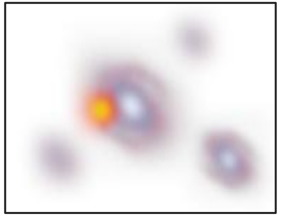

Model the survey

- observational noise,
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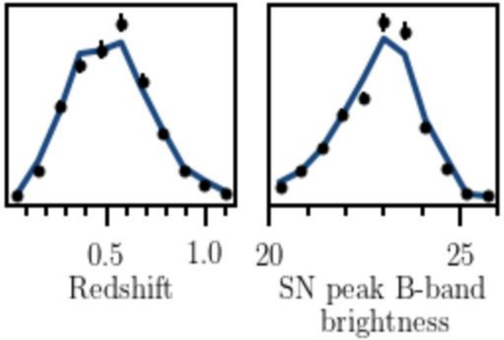
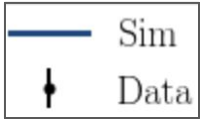
Modelling SN properties...





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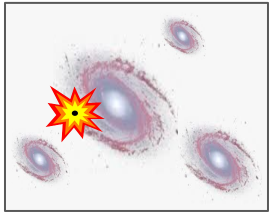

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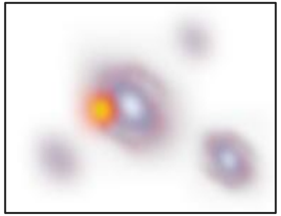

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- observational noise,
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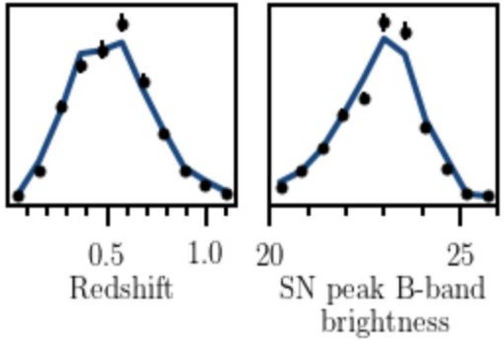
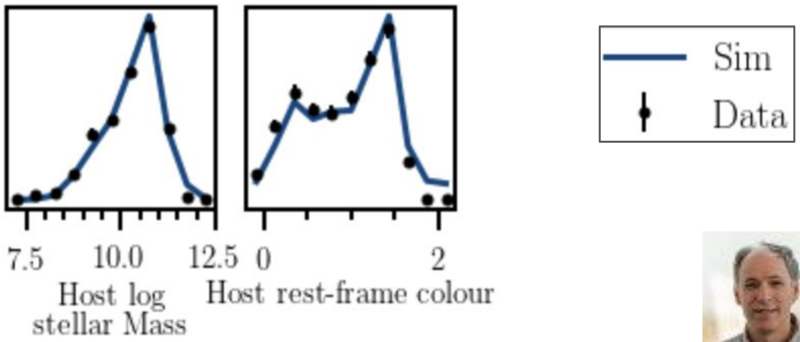
Modelling SN properties...

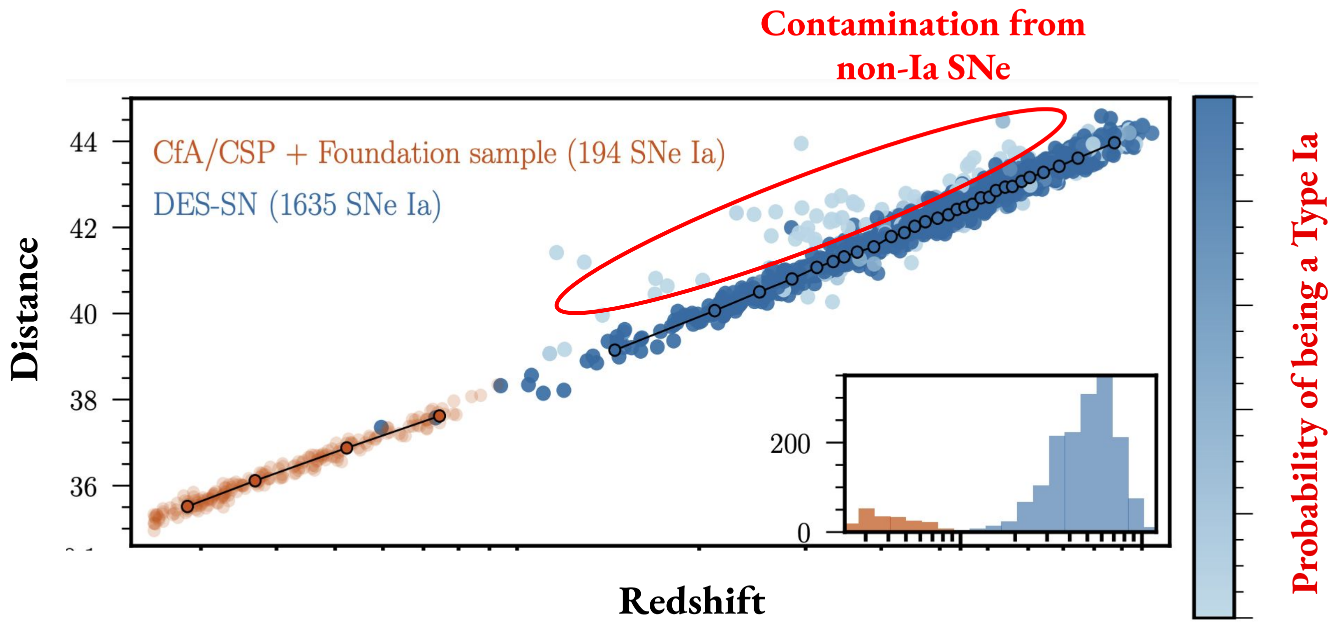


...and their host galaxies.



Kessler et al 2019, Vincenzi et al. (2021, 2023)

Classification of SNIa: Machine Learning for light-curve photometric classification

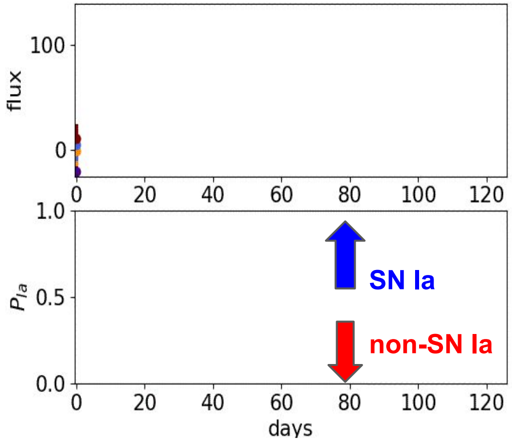


Training and testing classifiers in order to asses cosmological biases is a major task

We used 3 classifiers developed independently, and trained with mixes of data and simulations

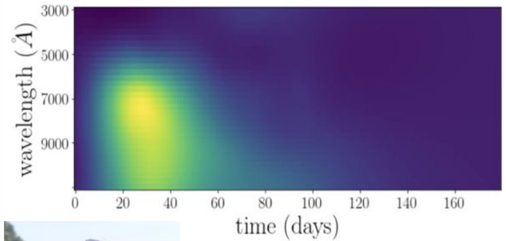
Moller et al 2019,2023
Qu et al. 2021
Vincenzi et al. (2021, 2023)

Classification of SNIa: Machine Learning for light-curve photometric classification



Recurrent Neural Network
Moller et al 2019, 2021

SCONE



Convolutional Neural Networks,
Qu et al 2019

SNIRF

SN Identification Random Forest

Kovacs&Kuhlmann

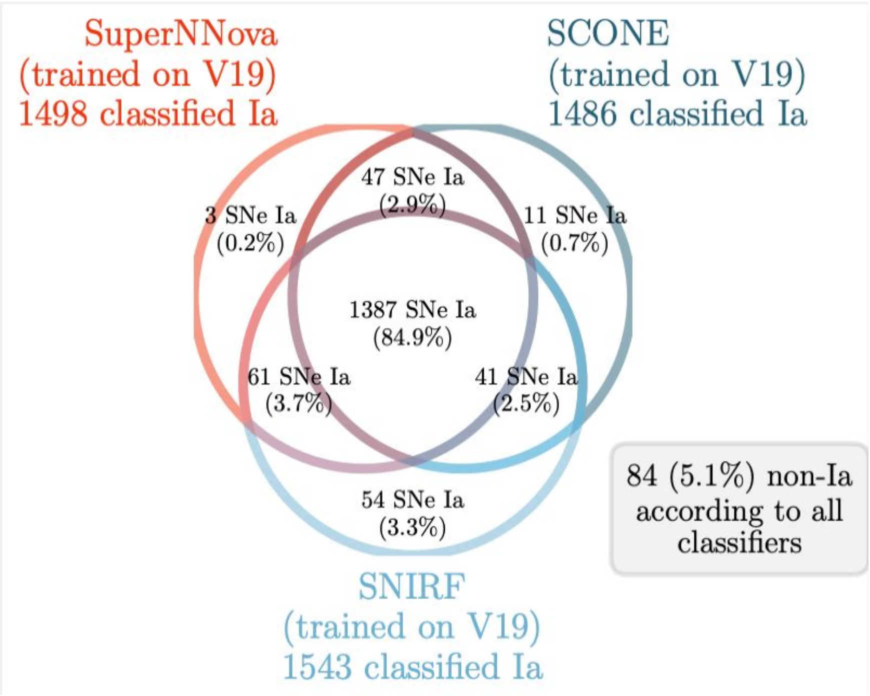
Key results:

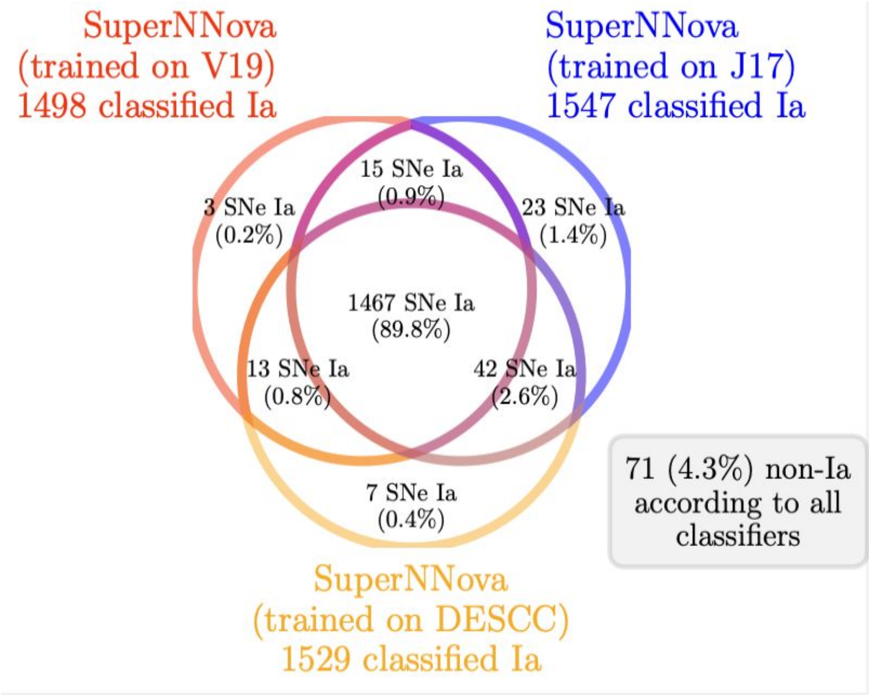
1) ML classifiers **perform remarkably well**
   - >98.5% purity
   - >99.0% efficiency

(tested on *independent* training/testing simulations)

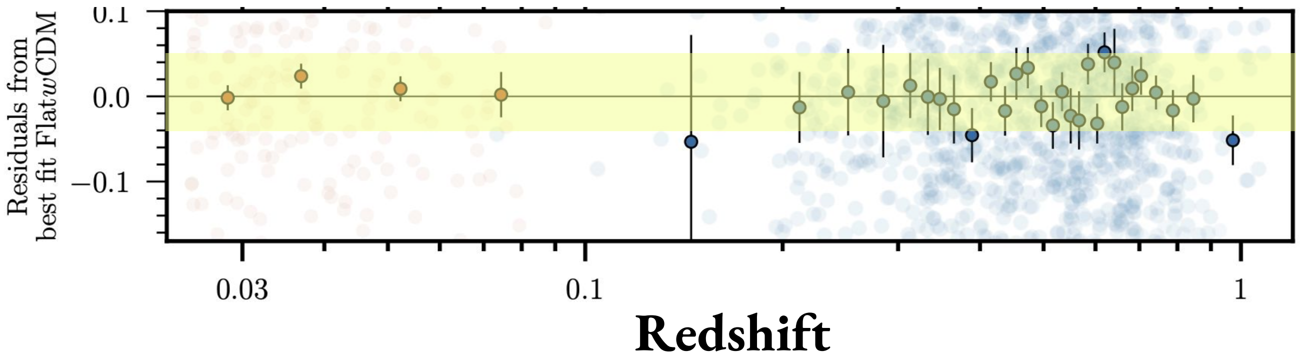
2) **Cosmological biases are negligible!** (<< statistical uncertainties across all our tests)

Classification of SNIa: Machine Learning for light-curve photometric classification





Modelling dust extinction and SN progenitors



10% unexplained scatter

Extrinsic origin:
dust extinction corrections?

Intrinsic origin:
Different SN Ia progenitors with different intrinsic brightnesses?

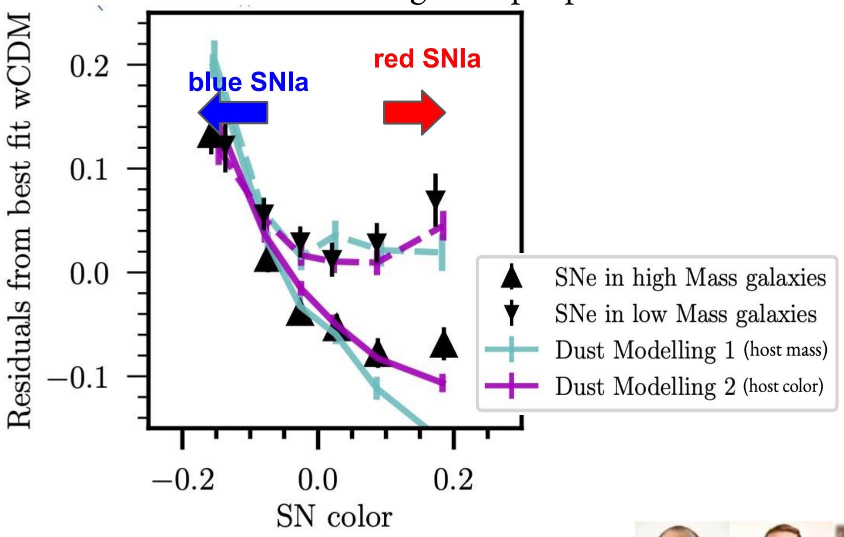
Brout and Scolnic 2021,
Popovic et al. 2021,
Vincenzi et al. 2024

Rigault et al. 2019,
Nicholas et al. 2021,
Wiseman, et al. 2021

Modelling dust extinction and SN progenitors

***Extrinsic origin*: Dust**

Forward modelling dust properties



Brout and Scolnic 2021, Popovic+2021,2023, Kelsey+2023,Vincenzi+2024

Rigault et al. 2019, Nicholas et al. 2021, Wiseman, et al. 2021

Modelling dust extinction and SN progenitors

***Extrinsic origin:* Dust**

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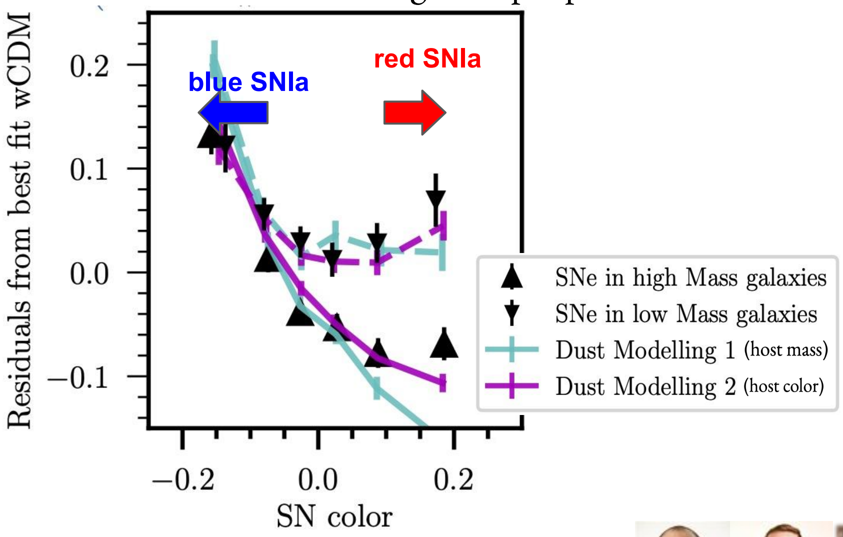
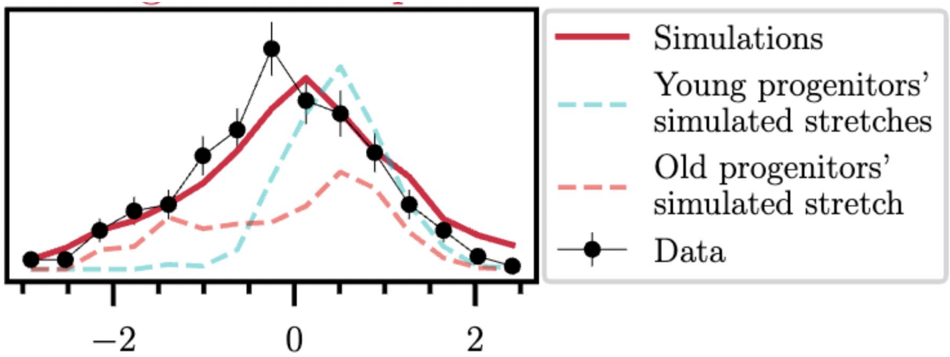


Brout and Scolnic 2021, Popovic+2021,2023, Kelsey+2023,Vincenzi+2024

Intrinsic origin: SN Ia progenitors

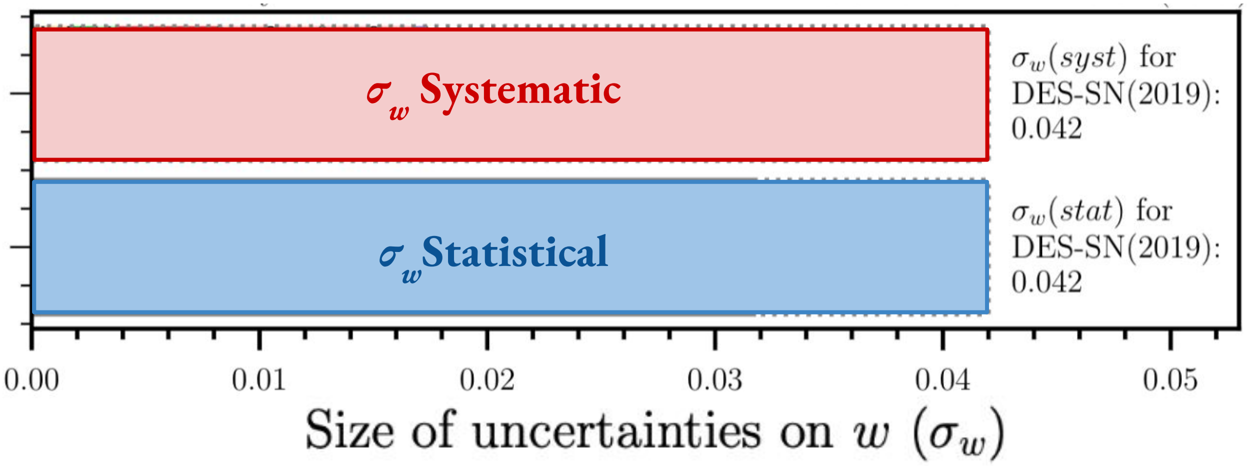
Forward modelling correlations between SN age / SN host / SN stretch



Rigault et al. 2019, Nicholas et al. 2021, Wiseman, et al. 2022

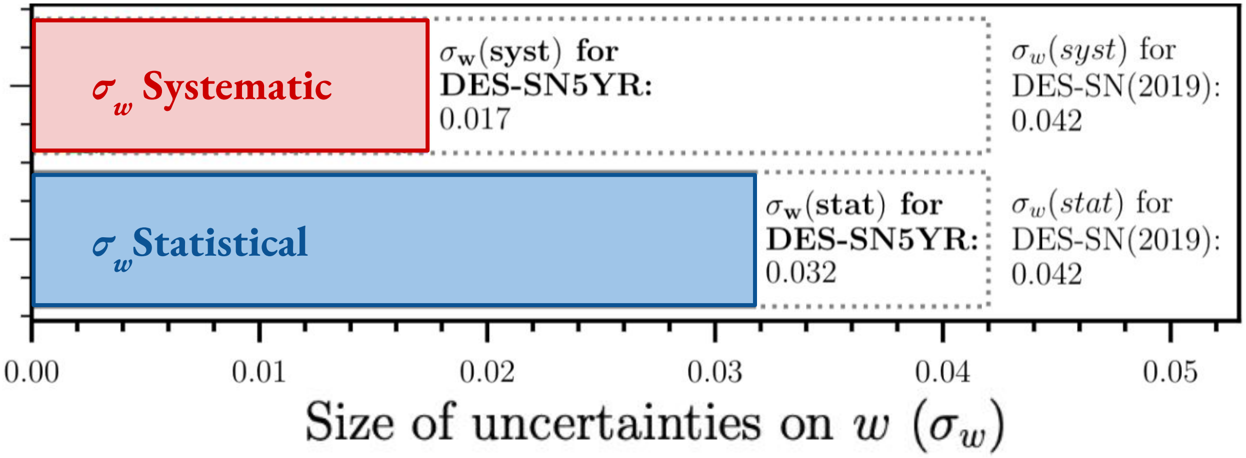
Cosmological constraint uncertainties
Statistical or Systematic dominated?

First DES-SN analysis in 2019, using **~200 DES SNe Ia**, we were already hitting systematic floor



Cosmological constraint uncertainties
Statistical or Systematic dominated?

With the DES-SN5Y sample using the ~1500 SNIa we find that
Systematics error contribution << **Statistical errors** !

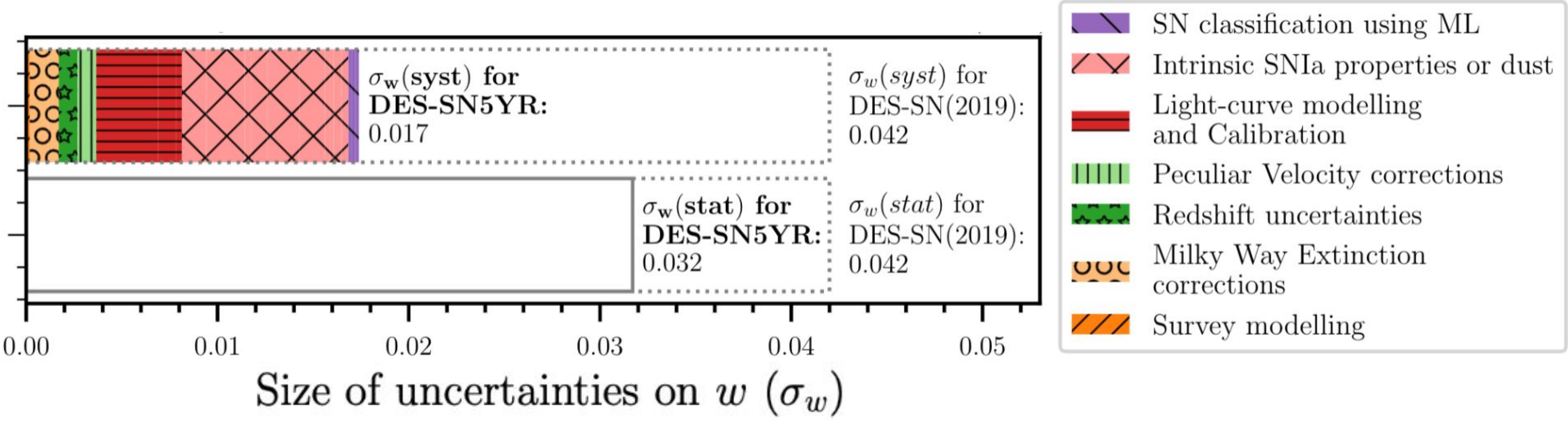


Vincenzi et al. 2024, The DES Collaboration, 2024

Cosmological constraint uncertainties

Statistical or Systematic dominated?

With the DES-SN5Y sample using the ~1500 SNIa we find that
Systematics error contribution << **Statistical errors** !



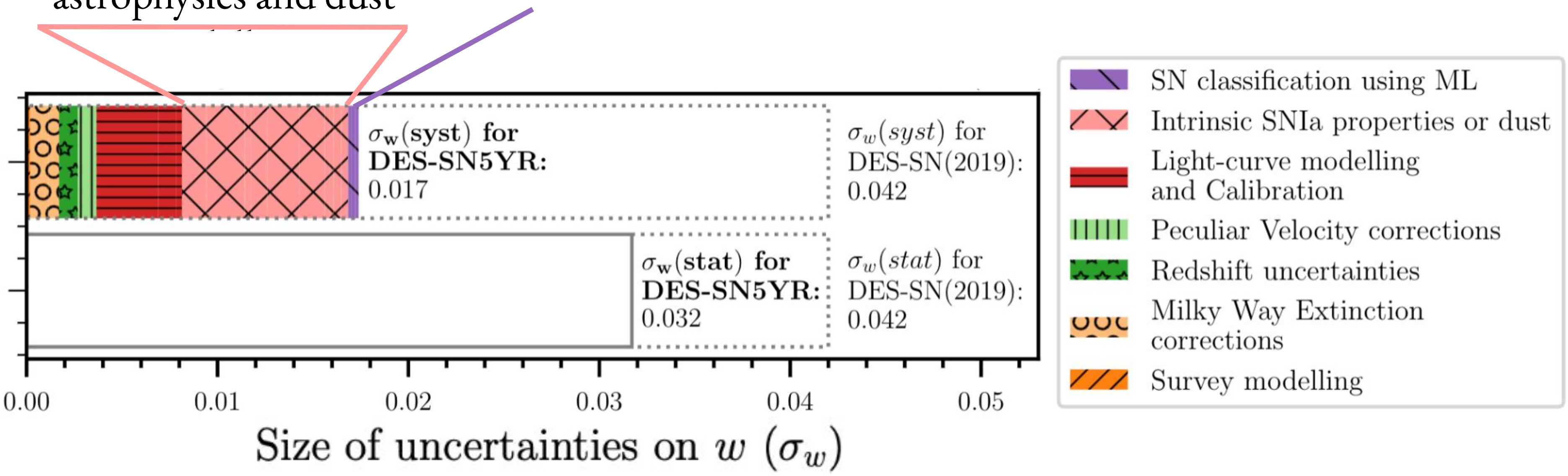
Vincenzi et al. 2024, The DES Collaboration, 2024

Cosmological constraint uncertainties

Statistical or Systematic dominated?

Top Systematics: SN Ia astrophysics and dust

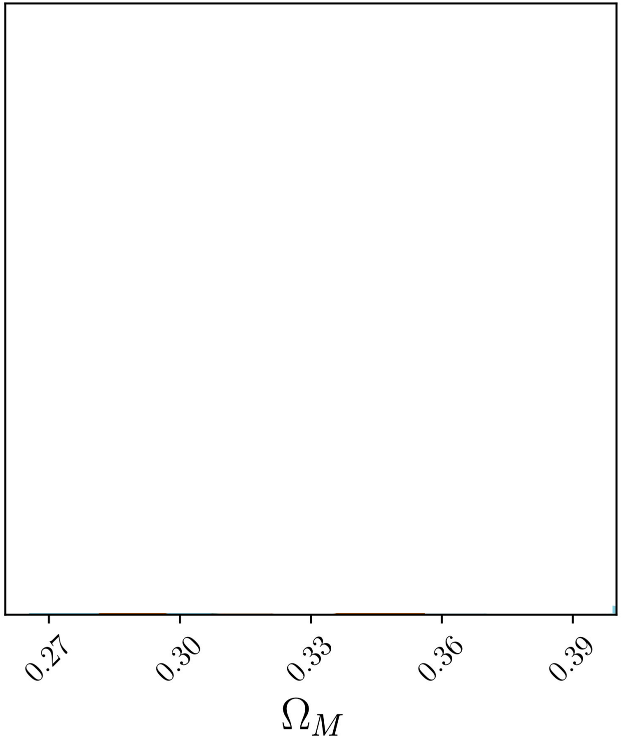
Smaller Systematics: SN Classification



Vincenzi et al. 2024, The DES Collaboration, 2024

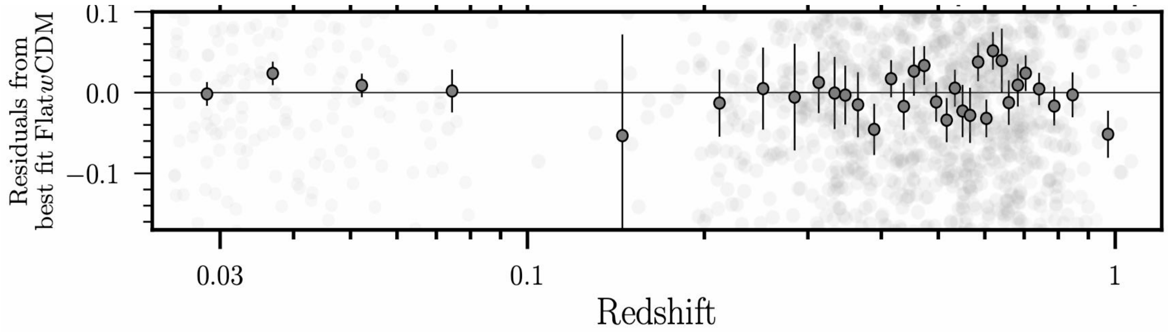
Cosmological Constraints from DES-SN5Y

Constraints on **Flat ΛCDM** Universe - Ω_M Matter Density



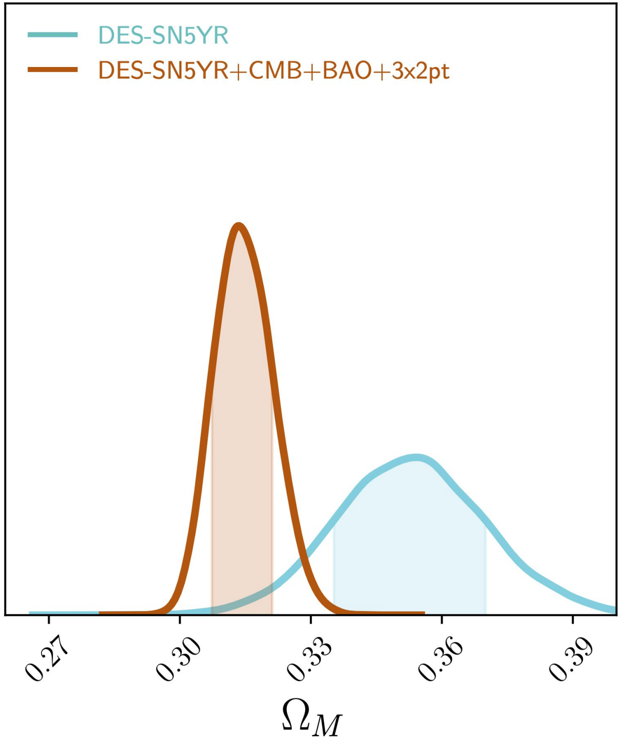
The DES Collaboration, 2024

Residuals from best fit Flat*w*CDM



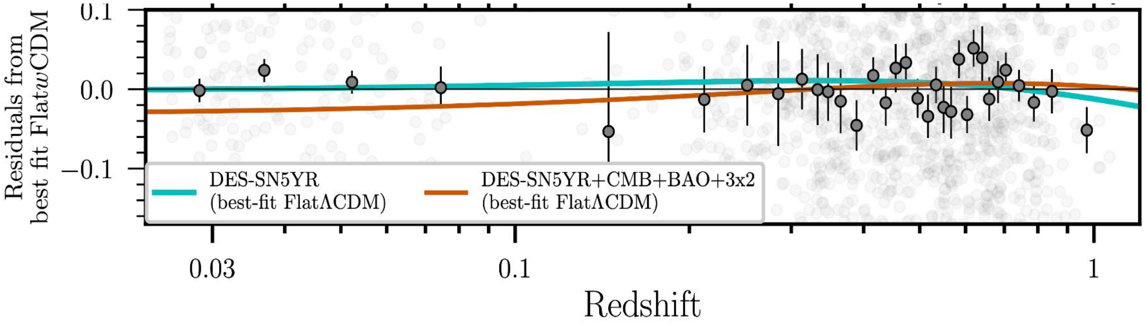
Cosmological Constraints from DES-SN5Y

Constraints on **Flat ΛCDM** Universe - Ω_M Matter Density



DES-SN alone $\Omega_M = 0.352 \pm 0.017$

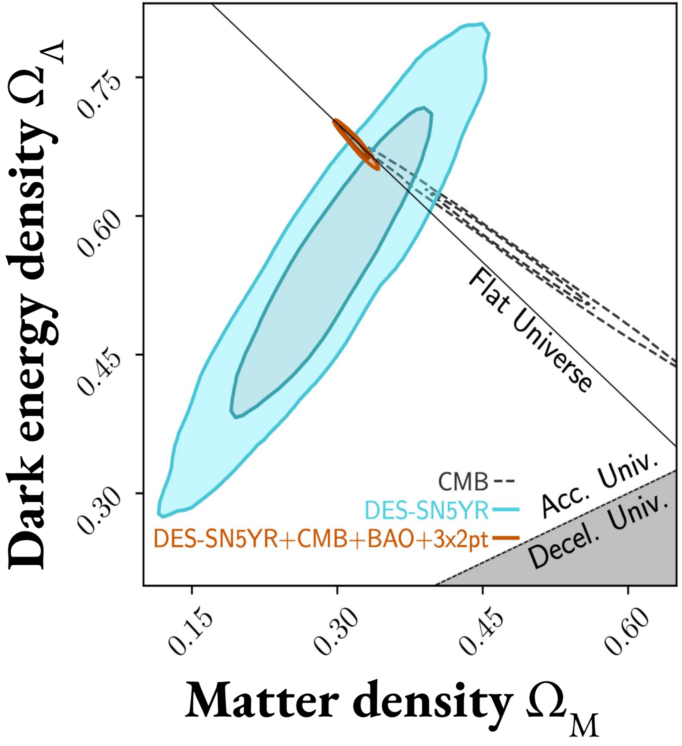
DES5YR + CMB + BAO + 3x2pt $\Omega_M = 0.315 \pm 0.007$



The DES Collaboration, 2024

Cosmological Constraints from DES-SN5Y

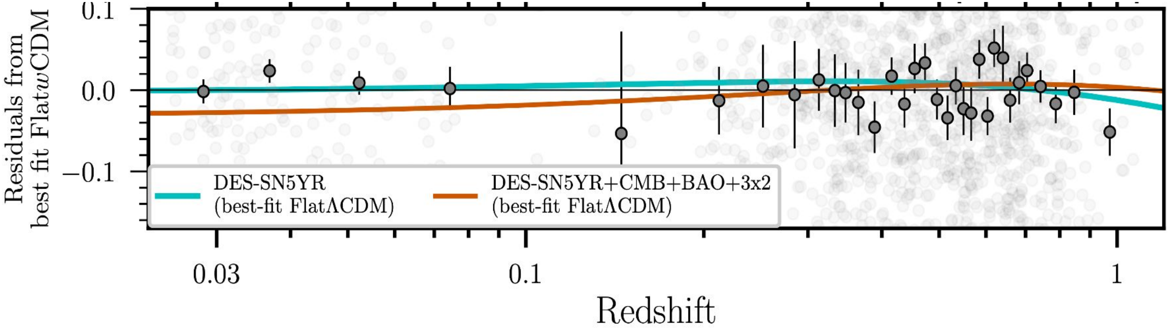
Constraints on ΛCDM | Ω_M Matter Density & Ω_Λ Dark Energy Density



DES-SN alone

$$\Omega_M = 0.291^{+0.063}_{-0.065}$$
$$\Omega_k = 0.16 \pm 0.16$$

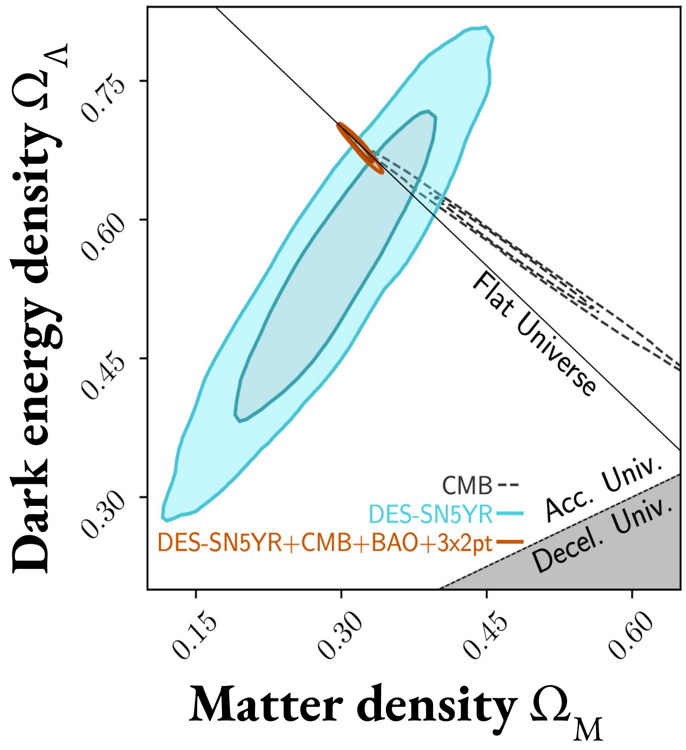
Expansion is accelerating at 99.99998% confidence



The DES Collaboration, 2024

Cosmological Constraints from DES-SN5Y

Constraints on ΛCDM | Ω_M Matter Density & Ω_Λ Dark Energy Density



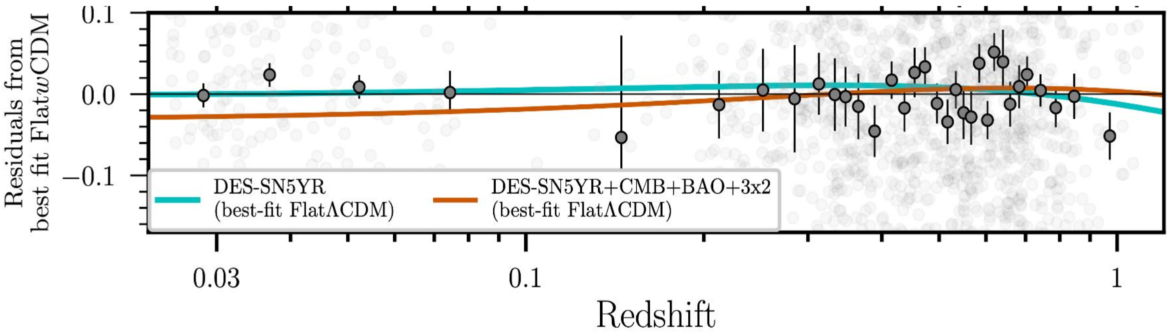
DES-SN alone

$$\Omega_M = 0.291^{+0.063}_{-0.065}$$
$$\Omega_k = 0.16 \pm 0.16$$

Expansion is accelerating at 99.99998% confidence

DES5YR + CMB + BAO + 3x2pt

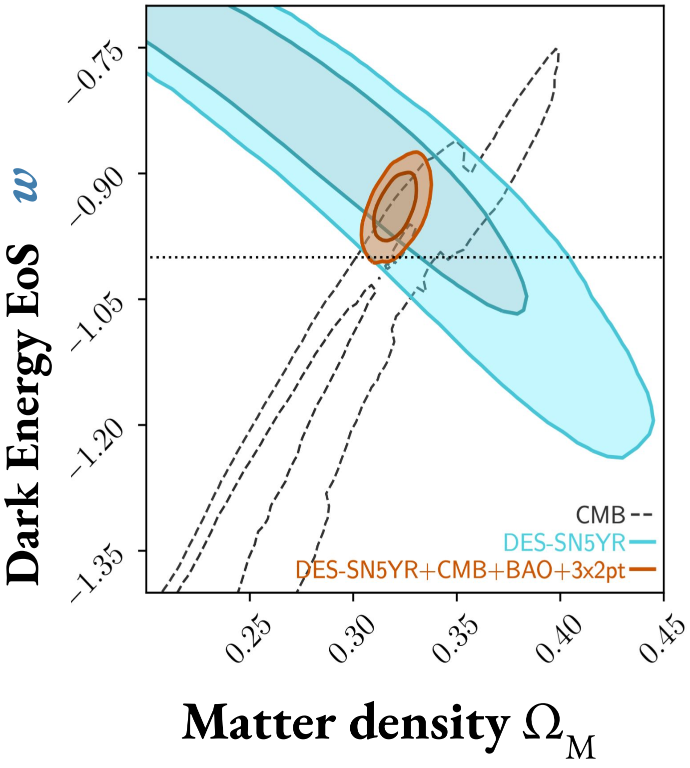
$$\Omega_M = 0.318^{+0.011}_{-0.010}$$
$$\Omega_k = 0.002 \pm 0.003$$



The DES Collaboration, 2024

Cosmological Constraints from DES-SN5Y

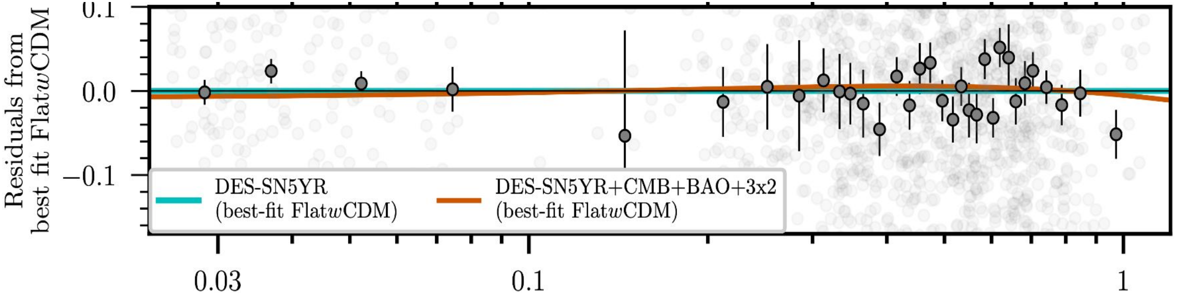
Constraints **Flat *w*CDM** | Ω_M Matter Density & *w* Dark Energy Equation of State



Dark Energy Equation of State (EoS):
$w = -1 \rightarrow$ cosmological constant

DES-SN alone $w = -0.80^{+0.14}_{-0.16}$

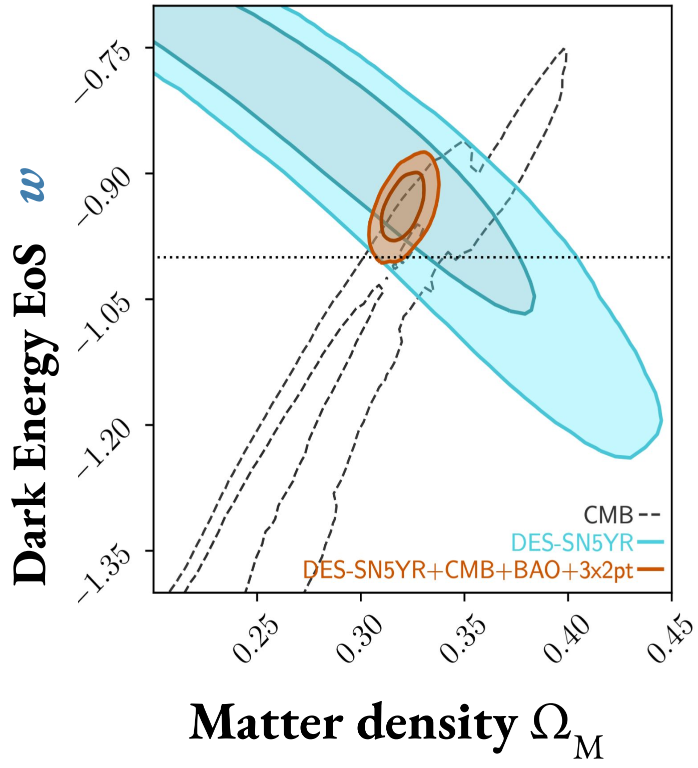
DES5YR + CMB + BAO + 3x2pt
$w = -0.941 \pm 0.026$



The DES Collaboration, 2024

Cosmological Constraints from DES-SN5Y

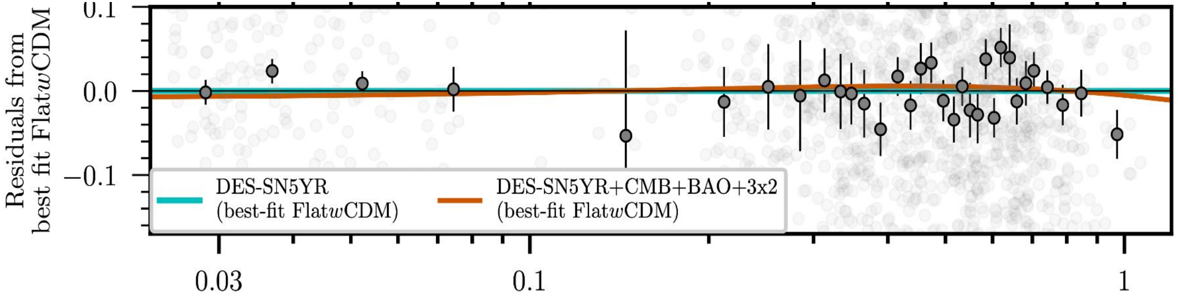
Constraints **Flat *w*CDM** | Ω_M Matter Density & ***w*** Dark Energy Equation of State



Dark Energy Equation of State (EoS):
$w = -1 \rightarrow$ cosmological constant

DES-SN alone $w = -0.80^{+0.14}_{-0.16}$ (~1.25σ to -1)

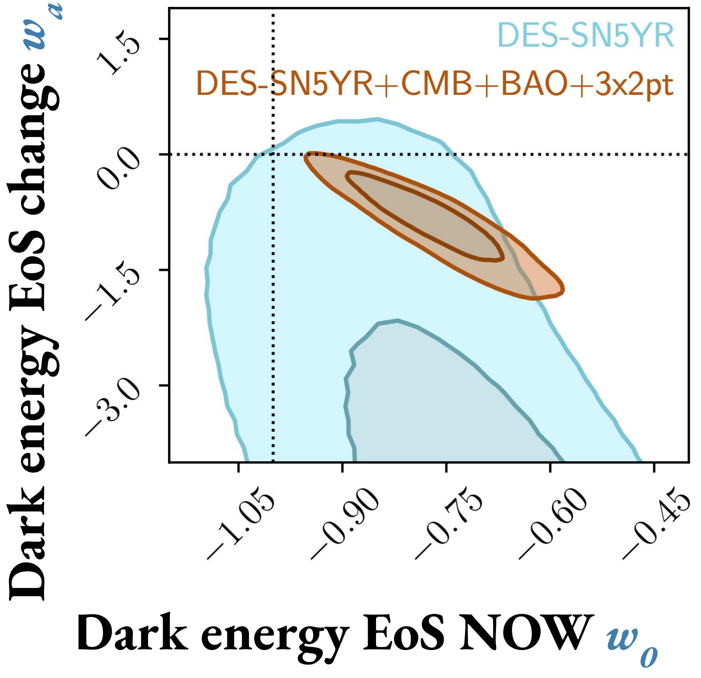
DES5YR + CMB + BAO + 3x2pt
$w = -0.941 \pm 0.026$ (~2.25σ to -1)



The DES Collaboration, 2024

Cosmological Constraints from DES-SN5Y

Constraints **Flat w_0w_aCDM** | w Dark Energy Equation of State Now and Evolution



$$w(a) = w_0 + (1-a)w_a$$

DES-SN alone

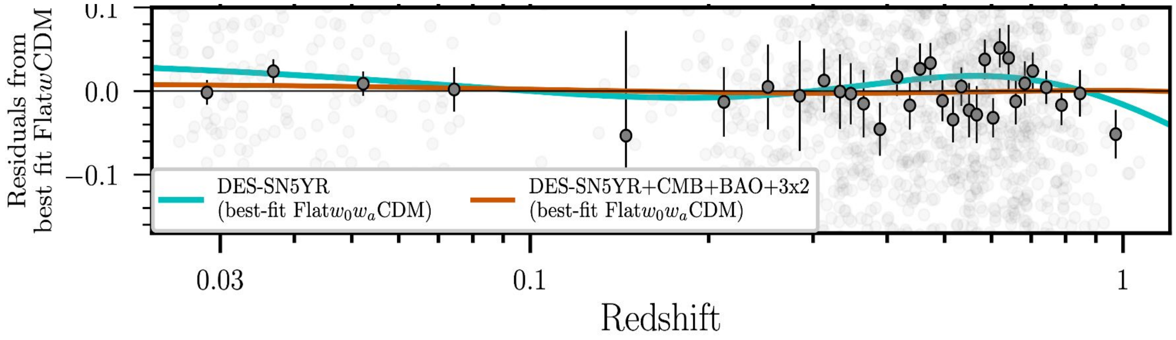
$w_0 = -0.36^{+0.36}_{-0.30}$

$w_a = -8.8^{+3.7}_{-4.5}$

DES5YR + CMB + BAO + 3x2pt

$w_0 = -0.773^{+0.075}_{-0.067}$

$w_a = -0.83^{+0.33}_{-0.42}$

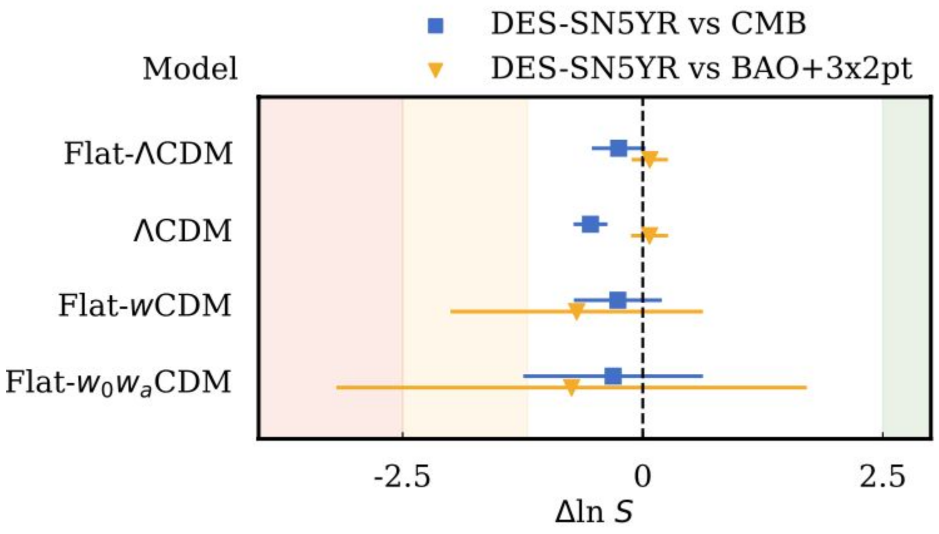


The DES Collaboration, 2024

Are these results consistent?

Suspiciousness measurement between datasets (prior independent, similar to Bayes ratio)

We find no significant tensions in the used datasets

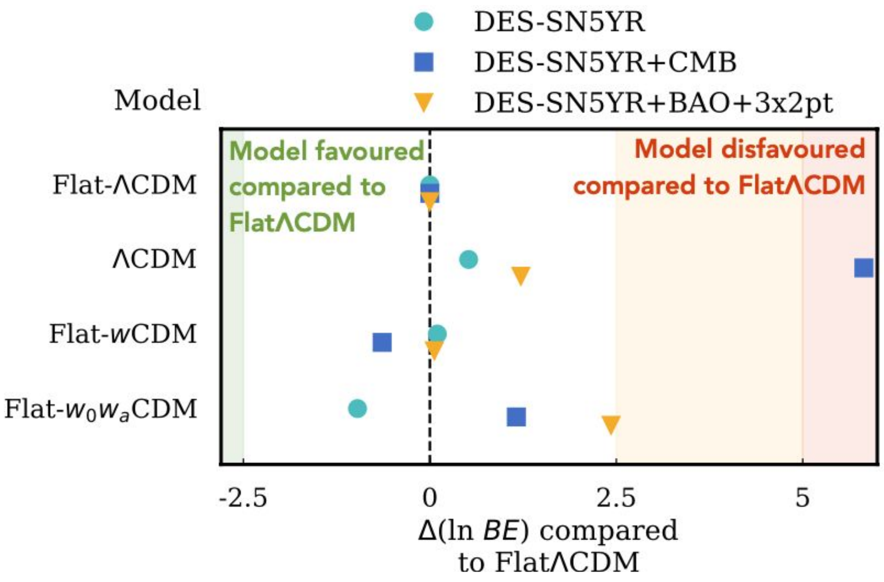


Is there a preferred model?

Relative Bayesian Evidence

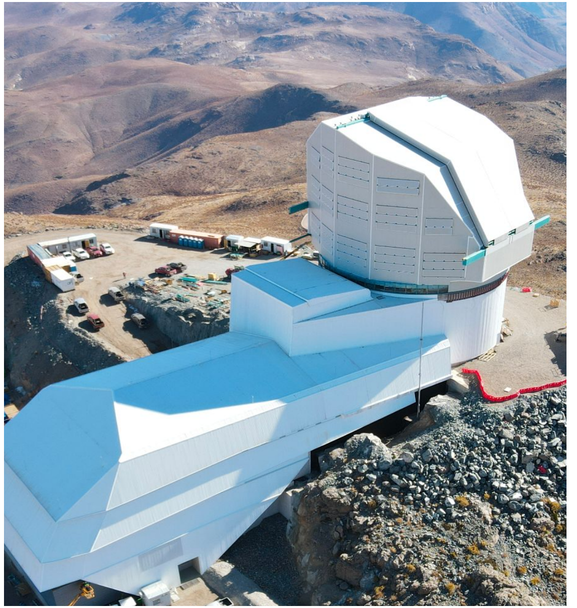
We use this to understand how to interpret the parameter values we obtain

Most favoured model using all the data is the standard Flat-ΛCDM



The future of SNIa Cosmology: Vera Rubin LSST Survey

	THE DARK ENERGY SURVEY	VERA C. RUBIN OBSERVATORY
Footprint	30 sq deg	18,000 sq deg
Timing	Finished in 2019	Starting 2025!
Light-curve sampling	5–6 days cadence	3–9 days cadence
Duration of the survey	5 years	10 years
High-quality SN Ia light-curves (after cuts)	~2500	~ **1 million**



Conclusions

- DES has surveyed the sky and obtained the **largest single instrument High-redshift SNIa sample** ever collected with 1635 (#$PIa_{>0.5}$ = 1499)
- DES -5YR is the resulting sample with ~1500 new SNIa, using photometric Machine Learning classification
- The photometric pipeline achieved ~5mmag accuracy, including several new corrections
- Using several new models to understand systematics, and large data-like simulations to assess their impact on Cosmology

Conclusions

- We find staggering evidence that the universe expansion is indeed accelerating
- The best fit to our data is the standard Flat-ΛCDM
- We find that deviations from $\boldsymbol{w = -1}$ are at most ~1.25σ and ~2.25σ
- We can see that varying $\boldsymbol{w}$ is preferred when allowing for it, but this model is not strongly favored, making this inconclusive
- We can safely say that the data favours in any case $\boldsymbol{w}$≥-1 ruling out models with lower EoS.

Conclusions

- DES Paves the way for Photometric Classified SNIa samples
- The future SNIa Cosmological probe will be the Vera Rubin LSST Survey
  - Starting commissioning this 2024
  - Will yield 2 orders of magnitude increase in statistical sample
- Combinations with new low-z samples like ZTF could strongly improve our constraints and provide state of the art results until LSST first DR
- New astrophysical modeling of SNIa and its environment can also push further our systematics control, preparing for LSST sample size

Extra slides

Full cosmological parameter table

	Ω_M	Ω_K	w_0	w_a	χ^2/dof
DES-SN5YR (no external priors)					
Flat-ΛCDM	0.352 ± 0.017	-	-	-	1649/1734=0.951
ΛCDM	$0.291^{+0.063}_{-0.065}$	0.16 ± 0.16	-	-	1648/1733=0.951
Flat-wCDM	$0.264^{+0.074}_{-0.096}$	-	$-0.80^{+0.14}_{-0.16}$	-	1648/1733=0.951
Flat-w_0w_aCDM	$0.495^{+0.033}_{-0.043}$	-	$-0.36^{+0.36}_{-0.30}$	$-8.8^{+3.7}_{-4.5}$	1641/1732=0.948
DES-SN5YR + Planck 2020					
Flat-ΛCDM	$0.338^{+0.016}_{-0.014}$	-	-	-	2237/2349=0.952
ΛCDM	$0.359^{+0.014}_{-0.016}$	0.010 ± 0.005	-	-	2231/2348=0.950
Flat-wCDM	$0.337^{+0.013}_{-0.011}$	-	$-0.955^{+0.032}_{-0.037}$	-	2234/2348=0.951
Flat-w_0w_aCDM	$0.325^{+0.016}_{-0.012}$	-	-0.73 ± 0.11	$-1.17^{+0.55}_{-0.62}$	2231/2347=0.951
DES-SN5YR + SDSS BAO and DES Y3 3×2pt					
Flat-ΛCDM	$0.330^{+0.011}_{-0.010}$	-	-	-	2194/2212=0.992
ΛCDM	$0.327^{+0.012}_{-0.011}$	0.030 ± 0.034	-	-	2194/2211=0.992
Flat-wCDM	$0.323^{+0.011}_{-0.010}$	-	$-0.922^{+0.035}_{-0.037}$	-	2188/2211=0.989
Flat-w_0w_aCDM	0.334 ± 0.012	-	$-0.778^{+0.088}_{-0.080}$	$-0.93^{+0.46}_{-0.53}$	2191/2210=0.992
DES-SN5YR + Planck 2020 + SDSS BAO and DES Y3 3×2pt					
Flat-ΛCDM	0.315 ± 0.007	-	-	-	2791/2828=0.987
ΛCDM	$0.318^{+0.011}_{-0.010}$	$0.002^{+0.004}_{-0.003}$	-	-	2825/2827=0.999
Flat-wCDM	0.321 ± 0.007	-	-0.941 ± 0.026	-	2785/2827=0.985
Flat-w_0w_aCDM	0.325 ± 0.008	-	$-0.773^{+0.075}_{-0.067}$	$-0.83^{+0.33}_{-0.42}$	2782/2826=0.984

Systematics

Table 6. Sources of Uncertainty

Baseline	Size[a]	Systematic	Label
Calibration and Light-curve Modeling (Section 6.1)			
SALT3 surfaces & ZP	1/10	10 covariance realizations	'SALT3+Calibration'
HST Calspec 2020 Update	1	5 mmag/7000Å	'HST Calspec'
SN Ia properties and astrophysics (Section 6.2)			
Dust-based model Popovic et al. (2021a) ('P21($M_\star$)')	1/3	3 realizations from MCMC dust model fitting code	'P21 dust pop 1/2/3'
	1	Original BS21 dust parameters	'BS21'
	1	Splitting on $u - r$	'P21($u - r$)'
Empirical modeling of x_1-$M_\star$ correlations	1	Modeling SN age following Wiseman et al. (2022)	'Model SN age'
No α evolution	1	$\alpha(z) = \alpha_0 + \alpha_1 \times z$	'α Evolution'
No β evolution	1	$\beta(z) = \beta_0 + \beta_1 \times z$	'β Evolution'
No γ evolution	1	$\gamma(z) = \gamma_0 + \gamma_1 \times z$	'γ Evolution'
Mass step location at $10^{10} M_\odot$	1	$10^{10.3} M_\odot$	'Mass Location'
$\sigma_{\rm int}$ modeling with scaling+additive scatter terms (eq. 9)	1	Scaling term only	'$\sigma_{\rm int}$ modeling'
Milky Way extinction (Section 6.3)			
MW scaling Schlafly & Finkbeiner (2011)	1	5% scaling	'MW scaling'
MW color law R_V=3.1 and F99	1/3	R_V=3.0 and CCM	'MW color law'
Host and survey modeling (Section 6.4)			
SN host catalog by Qu et al. (2023)	1	SN host catalog using DES-SVA galaxy catalog	'DES SV catalog'
Efficiency $\epsilon_z^{\rm spec}$ presented by V21	1	Shift of ±0.2 mag in the efficiency curves	'Shift in host spec eff'
Contamination and photometric classifiers (Section 6.5)			
Classification using SuperNNova	1	SCONE, SNIRF	
Classifier training sample simulated using V19 templates	1	J17 templates, DES CC templates ('`SuperNNova` training')	
Core-collapse SN prior using V19 simulation	1	Polynomial fit as in Hlozek et al. (2012)	'CC SN prior'
Redshift (Section 6.6)			
Peculiar velocities using 2M++	1	2M++(Line-of-sight integration) or 2MRS	'Pec Velocities'
No redshift shift	1/6	$\Delta z = 4 \times 10^{-5}$	'Redshift shift'

[a]Weighting adopted for each source of systematic uncertainty when building the systematic covariance matrix (see also Eq. 11). In Sec. 6, we provide an explanation for the weights that are different from 1.

Systematics

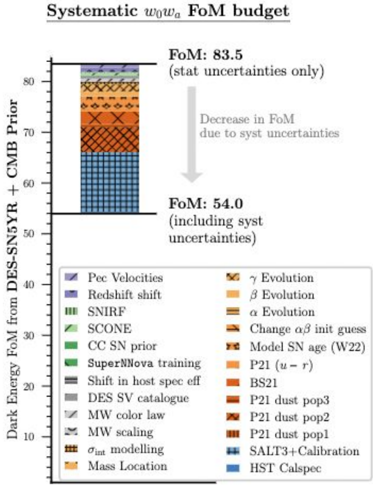


Figure 16. Decrease in the DES-SN5YR Figure of Merit (FoM) when including systematic uncertainties. Similarly to the systematic error budget presented in Fig. 12, we highlight the sources of systematic uncertainties that degrade the FoM the most.

Table 7. Size of Systematic uncertainty (SN-only, no CMB prior). A detailed description of the different sources of systematics and the labelling conventions are presented in Sec. 6 and Table 6.

Systematic	$\sigma_{w,\rm syst}$ *	$\%\sigma_{\rm tot}$	$\delta w^{\dagger}_{\rm syst}$
Total Stat+Syst	0.152	100	−0.032
Total Statistical	0.132	87	0.000
Total Systematic ($\mathcal{C}_{\rm unbin}$)	0.076	50	−0.032
Calibration & LC model	0.057	15	
SALT3+Calibration	0.052	34	−0.036
HST Calspec	0.006	4	0.002
SN Ia astrophysics	0.133	35	
P21 dust pop 1	0.019	12	−0.010
P21 dust pop 2	0.024	16	0.003
P21 dust pop 3	0.020	13	−0.004
P21$(u-r)$	0.000	0	0.048
Dust model as in BS21	0.027	18	−0.006
Model SN age (Sec. 6.2.3)	0.000	0	0.048
Change $\alpha\beta$ initial estimate	0.002	1	0.000
α Evolution	0.020	13	−0.008
β Evolution	0.000	0	−0.007
γ Evolution	0.011	7	−0.001
Mass step location	0.000	0	−0.002
$\sigma_{\rm int}$ modeling	0.013	8	−0.002
Milky Way extinction	0.034	9	
MW 5% scaling	0.020	13	−0.011
MW colour law CCM	0.014	9	−0.003
Survey modeling	0.015	4	
DES SV catalog	0.009	6	0.002
Shift $\epsilon_z^{\rm spec}$	0.005	4	0.002
Contamination	0.028	7	
Classifier SCONE	0.006	4	−0.000
Classifier SNIRF	0.013	9	−0.003
SuperNNova different training	0.006	4	−0.000
Core-collapse SN prior	0.003	2	−0.000
Redshift	0.037	10	
Redshift shift	0.012	8	0.002
Peculiar velocities	0.025	16	−0.012

† Shift in w when including ONLY this systematic;

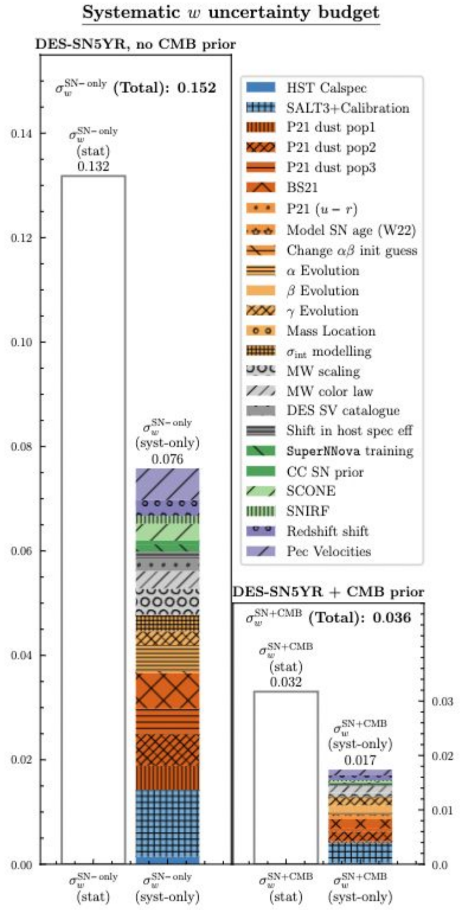
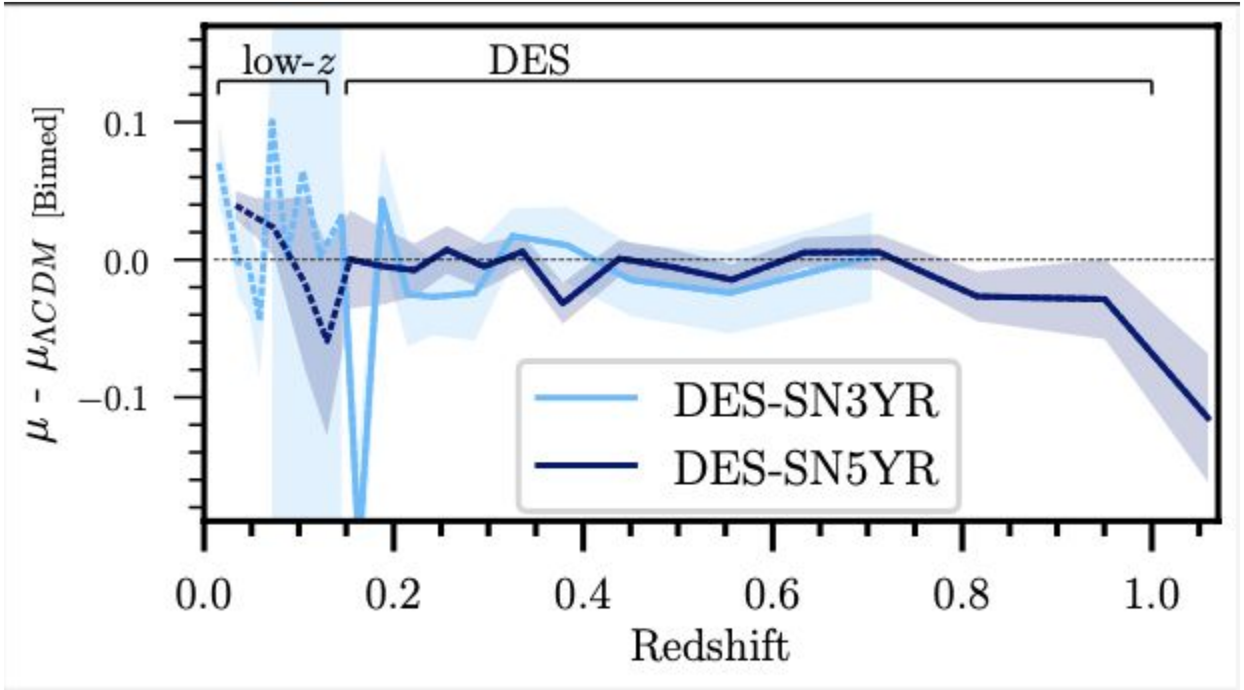


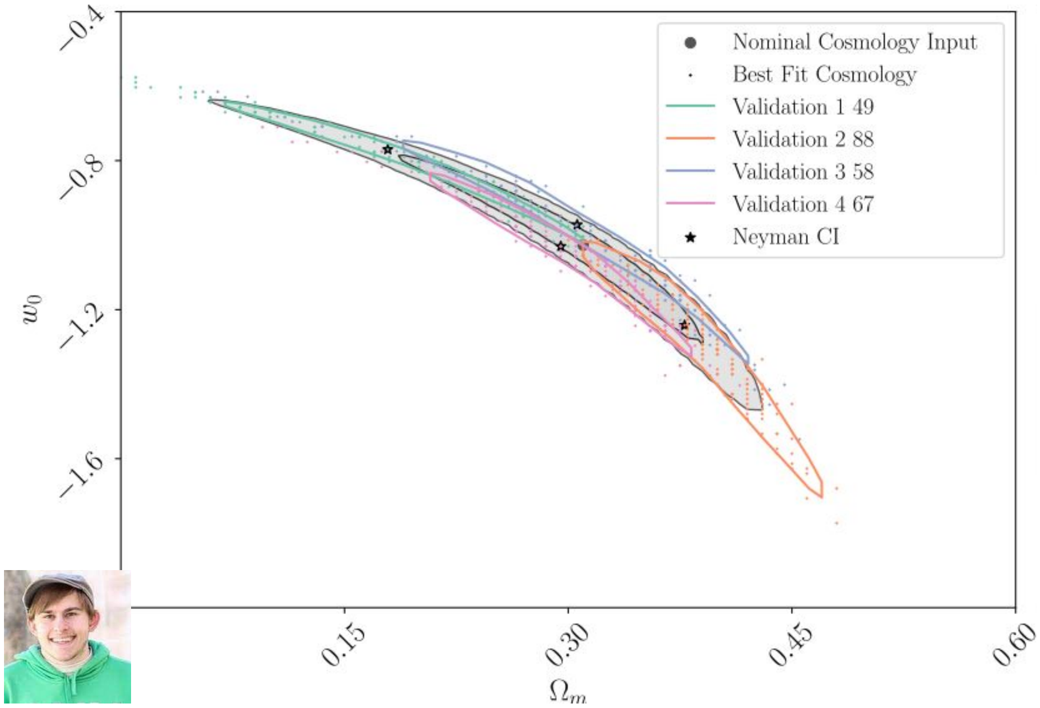
Figure 12. Systematic error budget on w and comparison with statistical uncertainty on w. We present results both with and without including a CMB prior (left and right plots respectively, note the different y-axis scale in the two plots). The different sources of systematic uncertainty considered in this analysis are presented in Table 6 and 7 and described in detail in Section 6.

Residuals DES 5YR and 3YR



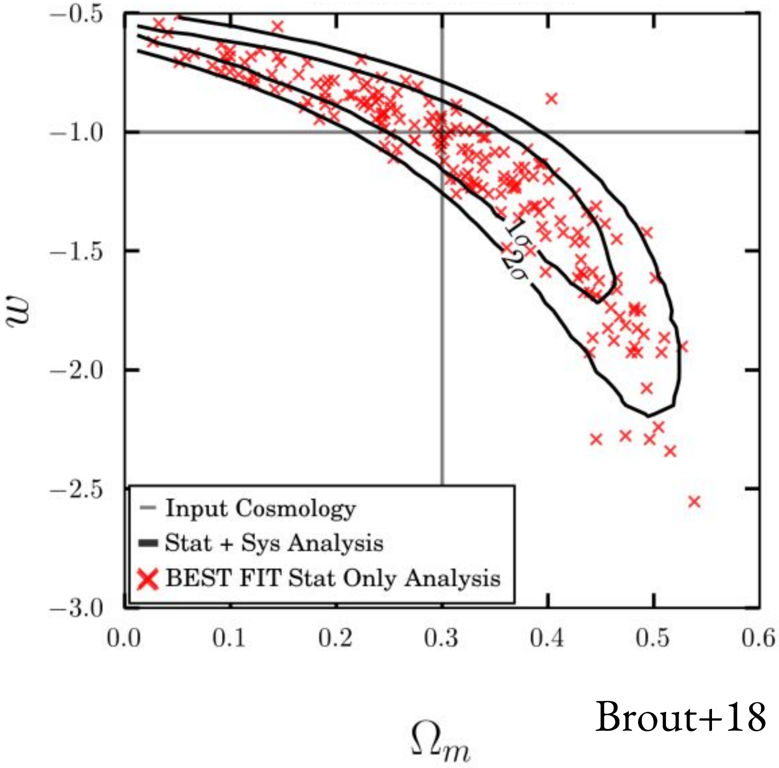
DES Analysis Methodology validation

Statistical



Armstrong et al 2023

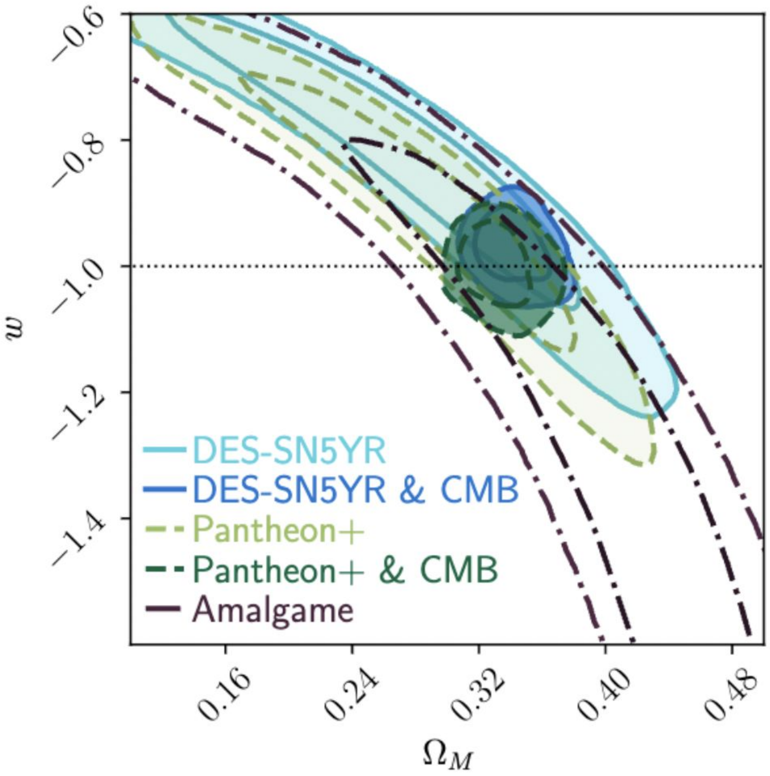
Systematic



Brout+18

Combination with other photometric samples

- Using Pantheon+ spectroscopically classified sample
- Amalgame: SDSS and PS1 photometric classified samples
- DES Also using photometric classification
- SNIa are disjoint samples, except for spec-SNIa from DES (included in Pantheon+)
- CMB priors not used in Amalgame



Full contours for Flat $w_0 w_a$CDM

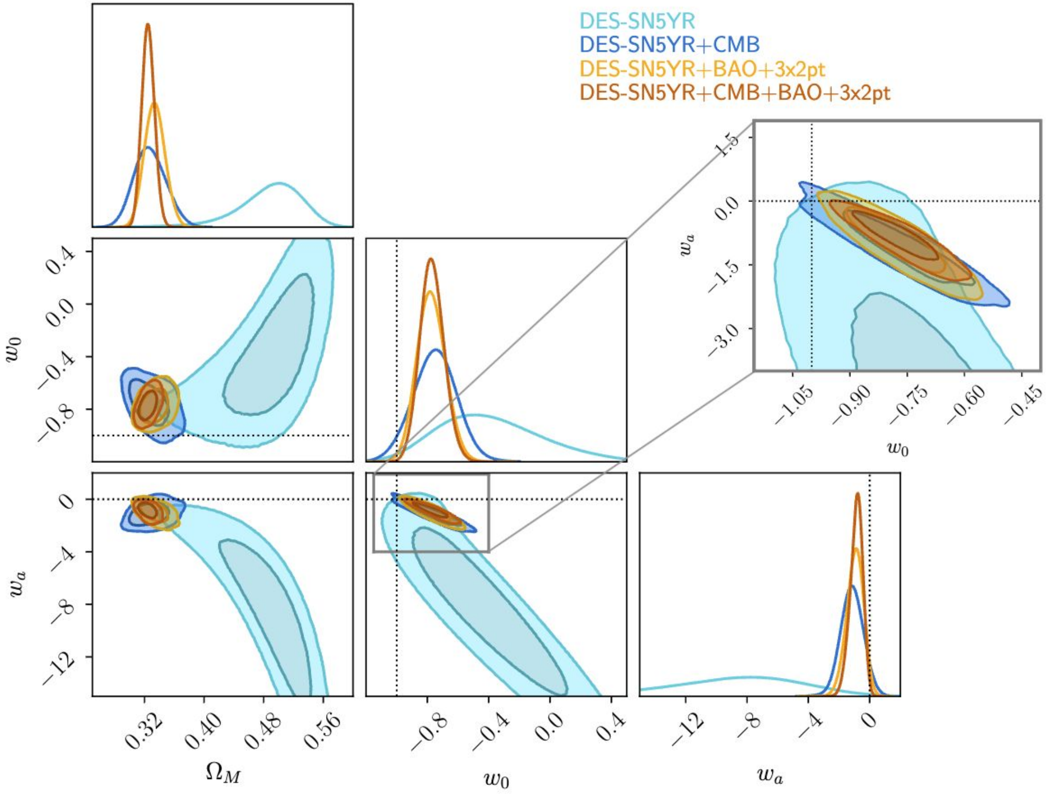


Figure 8. Same as Fig. 6 but for $w_0 w_a$CDM model. The dashed crosshairs mark the equation of state values for a cosmological constant, i.e. $(w_0, w_a) = (-1, 0)$. The residuals between the DES-SN5YR best fit Flat-$w_0 w_a$CDM w.r.t. Flat-wCDM model are presented in Fig. 4.

Residuals of DES Hubble Diagram