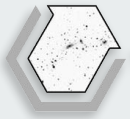
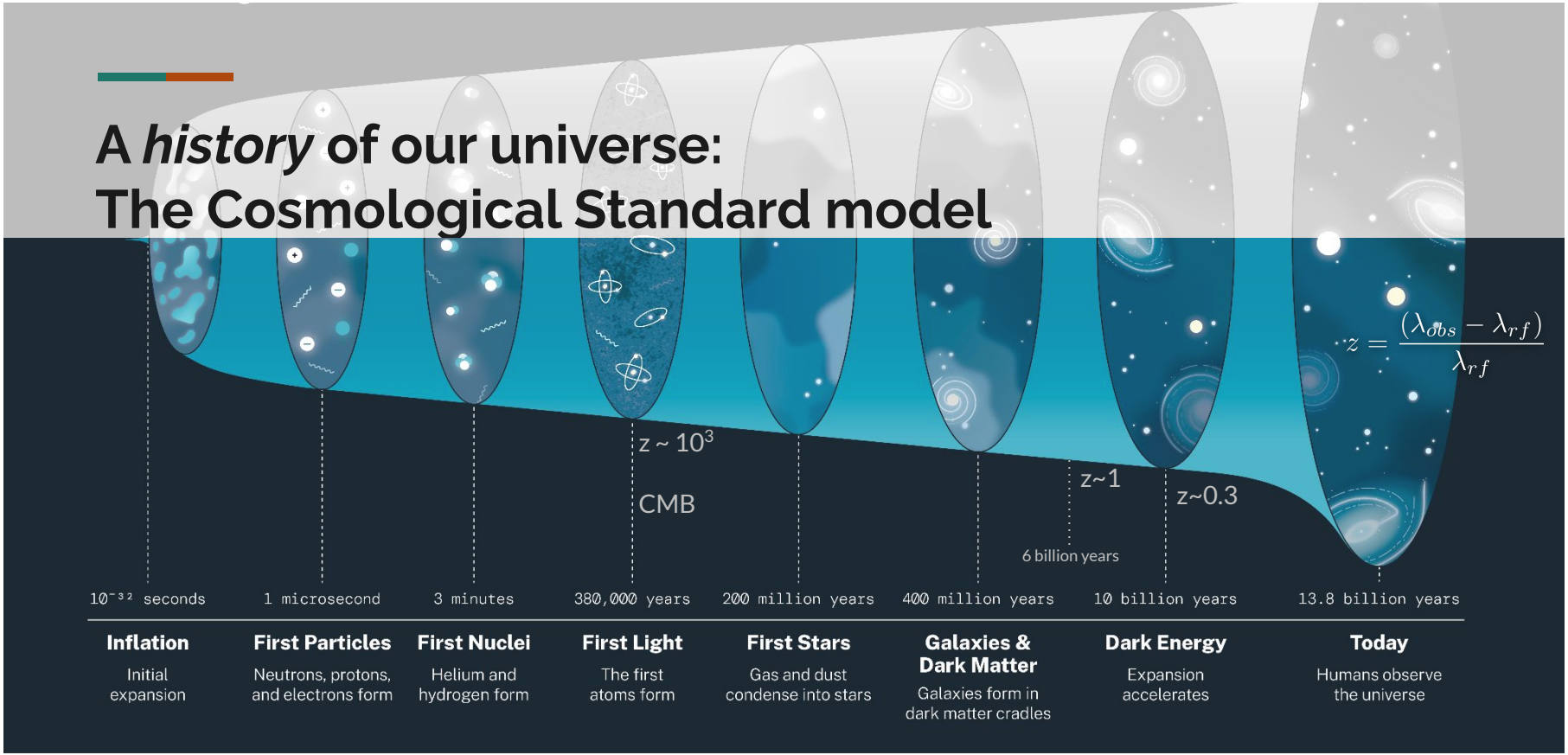
Transient SNIa Photometry on Synoptic Surveys: From DES SN 5YR to early LSST data

Bruno Sánchez (& of course many many others :D)



THE DARK ENERGY SURVEY

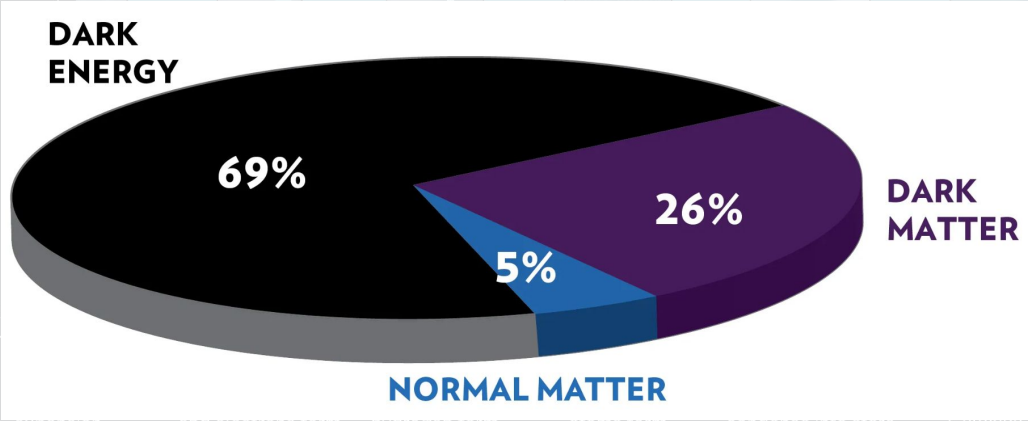
A *history* of our universe: The Cosmological Standard model

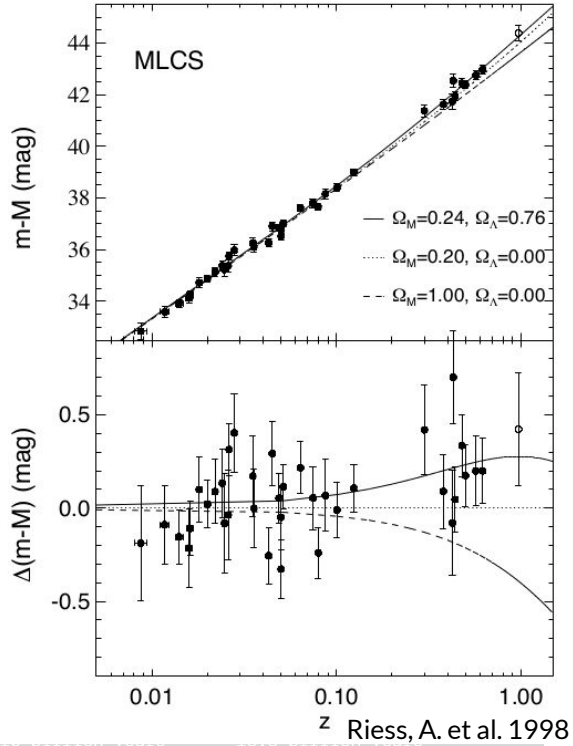


Credit: NASA

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

What is the ΛCold-Dark-Matter in two slides?



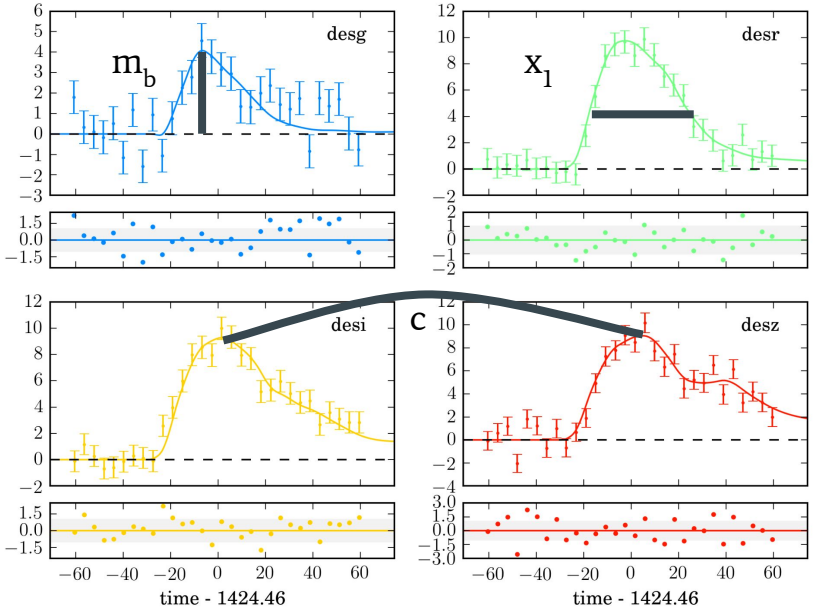


Riess, A. et al. 1998

$q_0 < 0$ *if* $w = -1$

Credit: NASA

Type Ia Supernovae as standard candle



Contamination and Bias correction

SALT Light curve Fit

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

Tripp (1998)

Nuisance Parameter

Calculated | Observable | Unknown

Type Ia Supernovae as standard candle

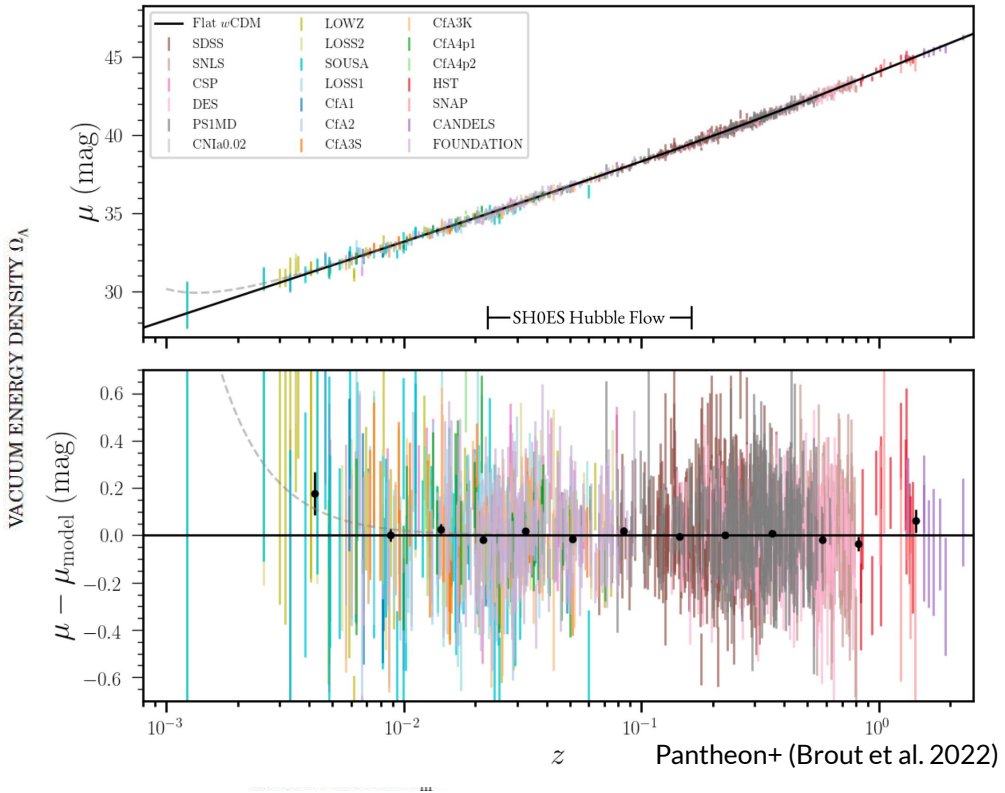
Current precision cosmology uses ensembles of SNIa samples at different redshift ranges

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

These probes constraint a flat universe model with cosmological constant (concordance model)

Best samples to do this are the ones that are internally self consistent in calibration.

Cross-calibration is possible, such as in Pantheon+. Their biggest systematic is inter-survey calibration



Pantheon+ (Brout et al. 2022)

Type Ia Supernovae as standard candle

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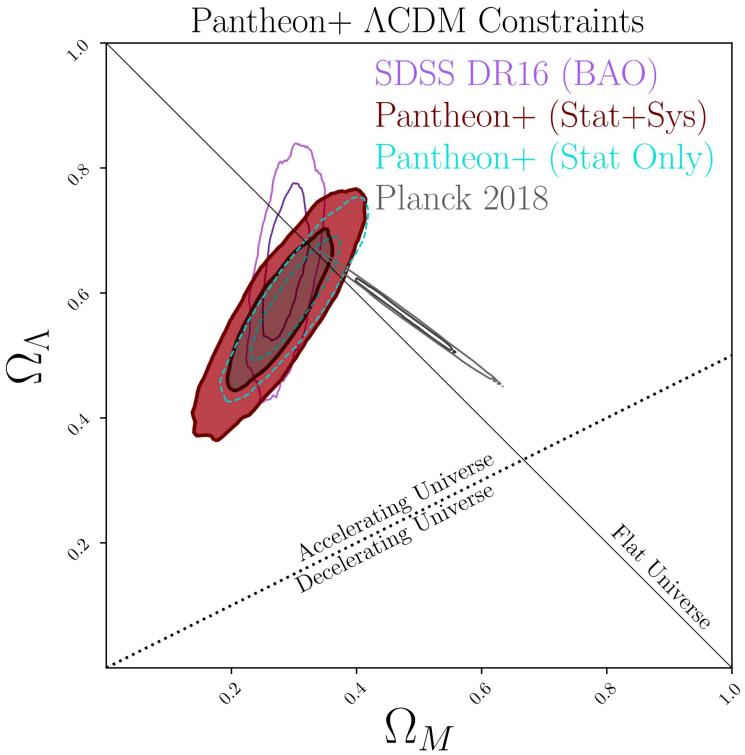
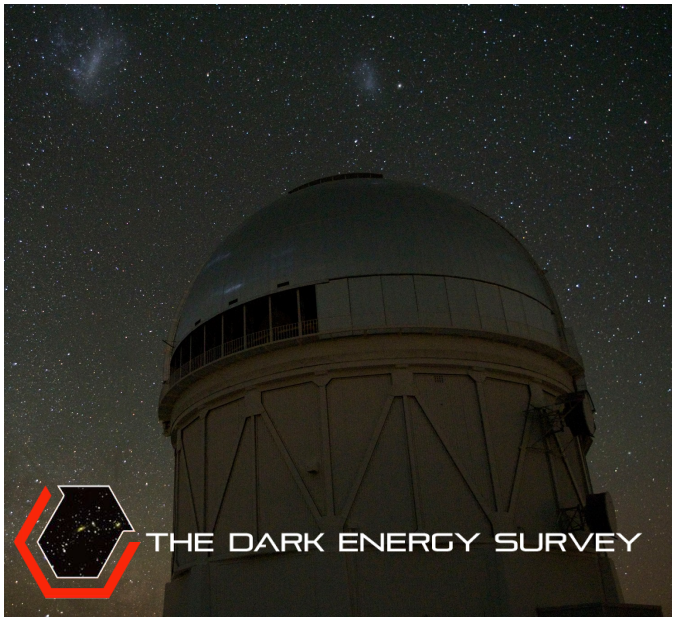


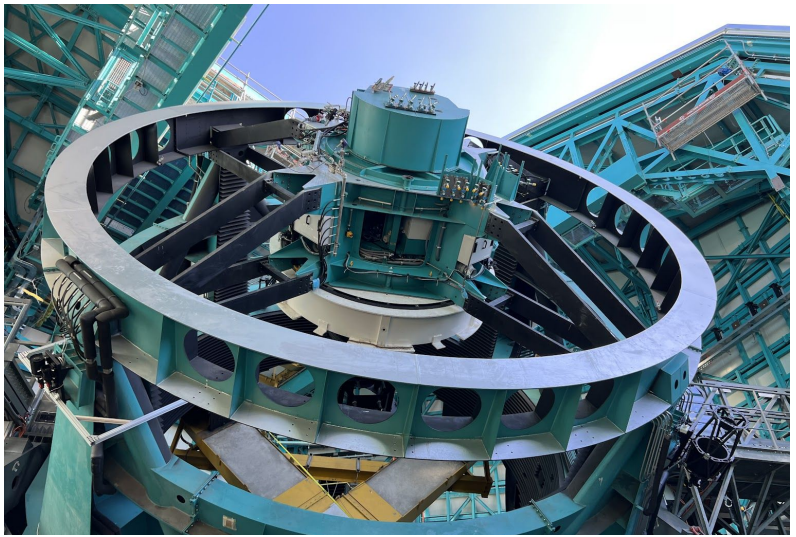
Pantheon+ (Brout et al. 2022)

Type Ia Supernovae as a Survey Cosmological Probe

In this talk I am going to introduce two Sky Surveys that represent the **Present** of Type Ia Supernova Cosmology



And the **Future** of Type Ia Supernova Cosmology



LSST Legacy Survey of Space and Time

VERA C. RUBIN OBSERVATORY

The present survey for SNIa Cosmology:

Dark Energy Survey Y5 SNIa analysis

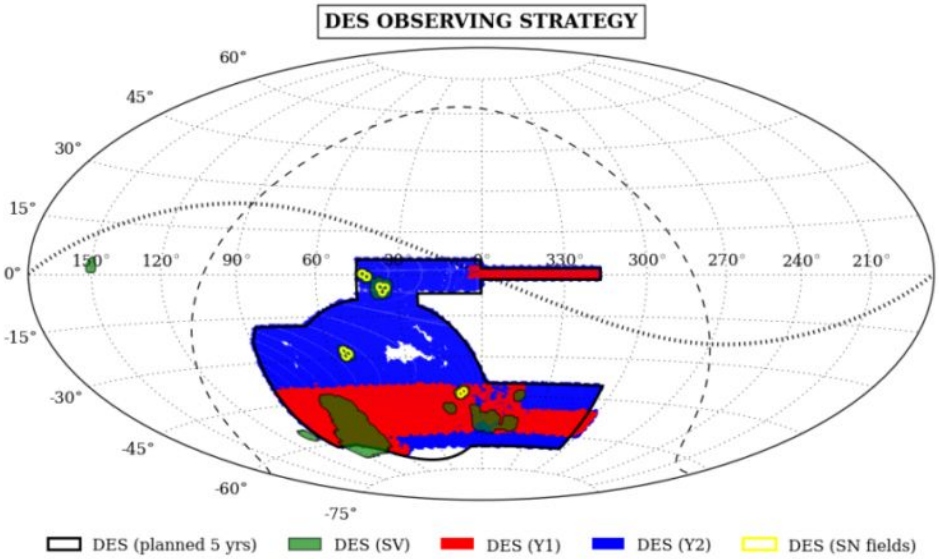
The DES Supernova Working Group

THE DARK ENERGY SURVEY

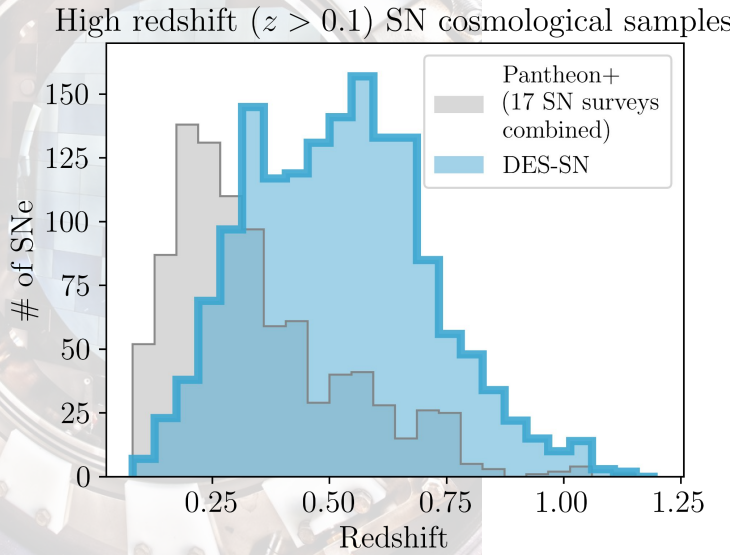
Work done with D. Brout, K. Herner, M. Sako, M. Vincenzi, D. Scolnic, R. Kessler, M. Acevedo, J. Lee, B. Popovic, B. Rose, R. Chen, G. Taylor, T. Davis, M. Sullivan, & many others @ DES

The Dark Energy Survey (DES)

- DES-SN observations in 10 fields
  - 8 shallow fields
  - 2 deep fields
- Detection of transients using Difference Image Analysis (Kessler et al 2015)
- Candidate veto using machine learning (Goldstein et al. 2015)
- Photometry of candidates using forced Point Spread Function fitting



The Dark Energy Survey (DES) SN Y5



With the **DES Supernova program…**

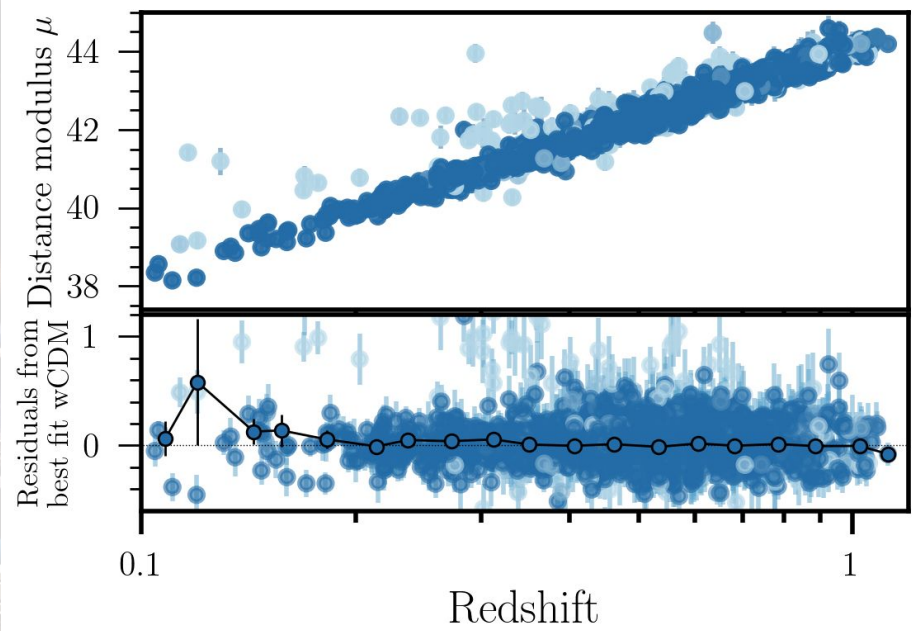
~1600 SNe Ia

This is the current **largest deep** SN sample from a **single telescope ever compiled**

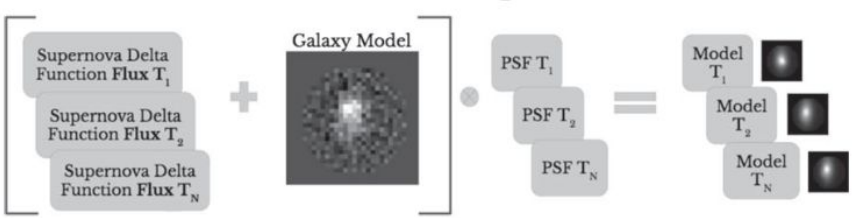
- Well defined sample selection
- Spectroscopic redshifts from OzDES

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

The Dark Energy Survey (DES) SN Y5



1) Accurate photometry SMP



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

Scene Modelling Photometry method for DES Y5

Technique developed in Brout et al. 2019; and used in the analysis of *DES Y3* (B19)

Table 1: Technique Comparison and Pipeline Improvements From `DiffImg` to SMP in DES-SN5YR

Stages	DIFFIM	SMP Y5
Template	Science Verification Images	Any high quality images taken before or after transient
Catalog for Zeropoint	Science Verification Catalog	Y6 Forward Model Global Calibration
Photometry for Zeropoint	Source Extractor `MAG_AUTO`	PSF Photometry
Tertiary Star Proper motion	Not Consistent	Linear fit over 5 Years
Astrometry	Science Verification	Updated in Bernstein et al. (2017)
SN Position	Forced at average`DiffImg`position across filters	Varied position per filter (common across all epochs)
Host Galaxy Profile	From `DiffImg` template	Forward model fitted per filter
Flux Measurement	DIA + Forced PSF Photometry	Forward model Scene + Forced PSF Photometry but with varied position across all images

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

Scene Modelling Photometry method for DES Y5

We fit the model with MCMC sampling after data preparation:

- For each image we obtain:
  - PSF spatially variant in the image field
  - Stars proper motions
  - Zeropoint using latest FGCM catalog (Sevilla & Noarbe et al. 2021)
  - Cutouts on the SNe prior centroid of 30x30 px
- Each image is scaled to fixed ZP
- SNe centroid is floated w/prior 2" on DIA centroid
- The χ2 is calculated inside a 13 px radius
- Only sky variance in the χ2: variance results preserve optimal statistical estimations for faint sources
- We ensure convergence only in the central region of the galaxy model

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

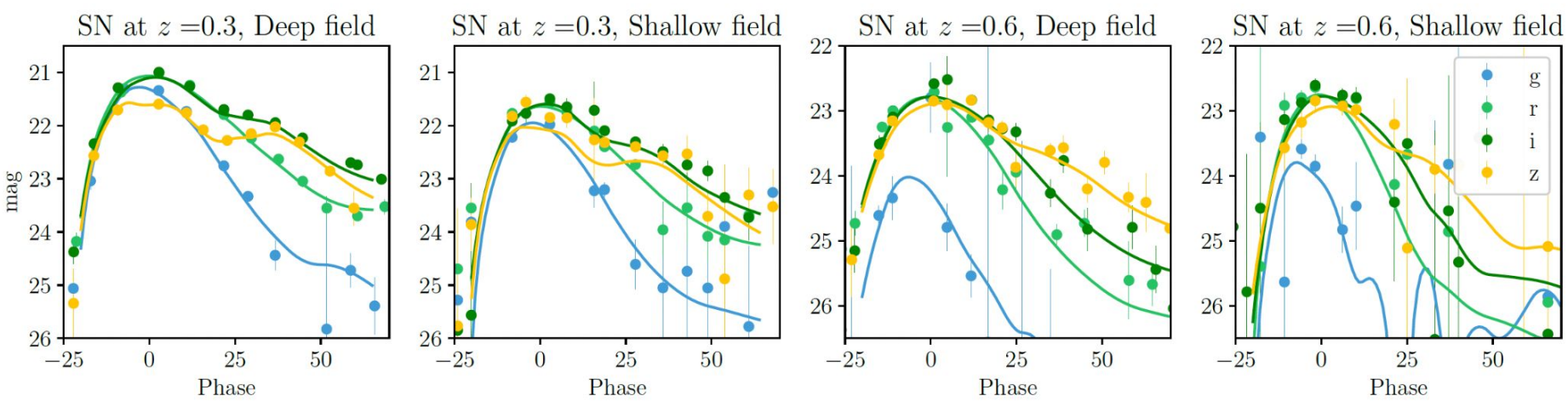
$$\chi^2 = \sum_{ij,t} \frac{(M_{ij,t} - D_{ij,t})^2}{\sigma^2_{sky_t}}$$

$$\sigma_{t_i} = \sigma^2_{\rm SMP} + \sigma^2_{\rm source} + \sigma^2_{\rm hostgal}$$

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

Scene Modelling Photometry method for DES Y5

Some example Light-curves from DES Y5 with SMP



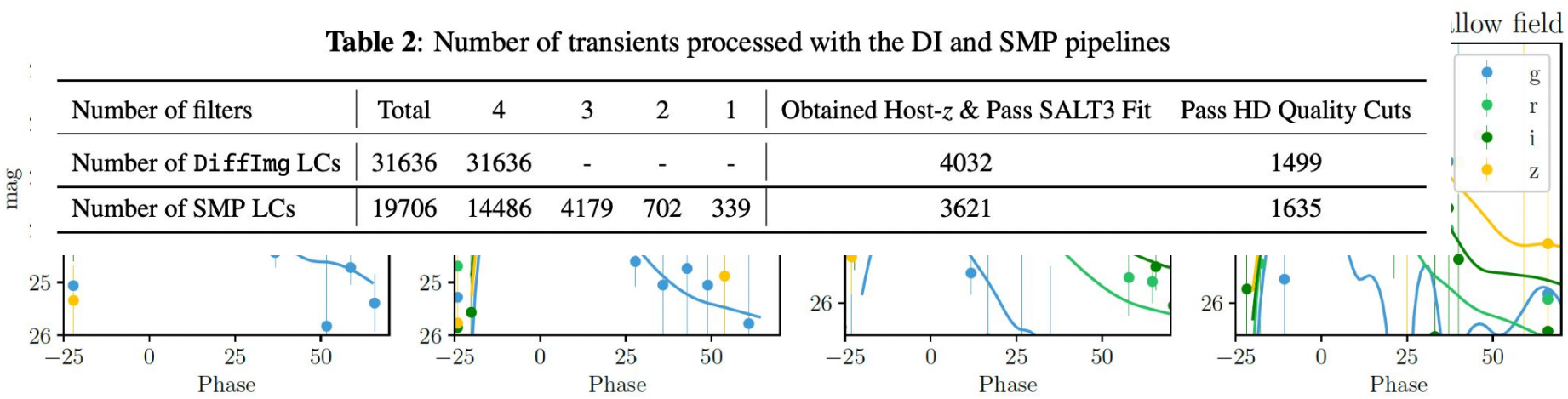
Sanchez et al. (in Internal Review), DES Collaboration, in prep.

Scene Modelling Photometry method for DES Y5

Some example Light-curves from DES Y5 with SMP

Table 2: Number of transients processed with the DI and SMP pipelines

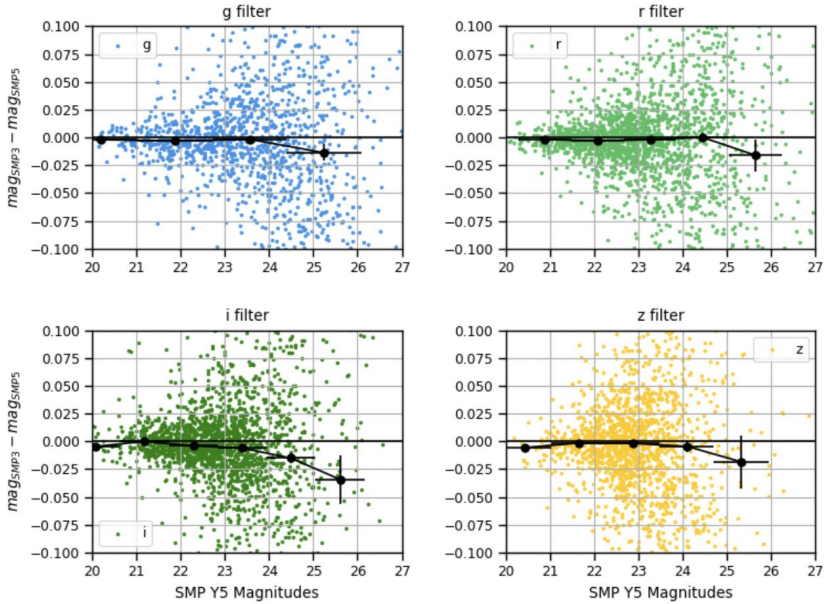
Number of filters	Total	4	3	2	1	Obtained Host-z & Pass SALT3 Fit	Pass HD Quality Cuts
Number of `DiffImg` LCs	31636	31636	-	-	-	4032	1499
Number of SMP LCs	19706	14486	4179	702	339	3621	1635



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

Scene Modelling Photometry method for DES Y5

Comparison with DES Y3 analysis (first implementation of SMP) shows great agreement



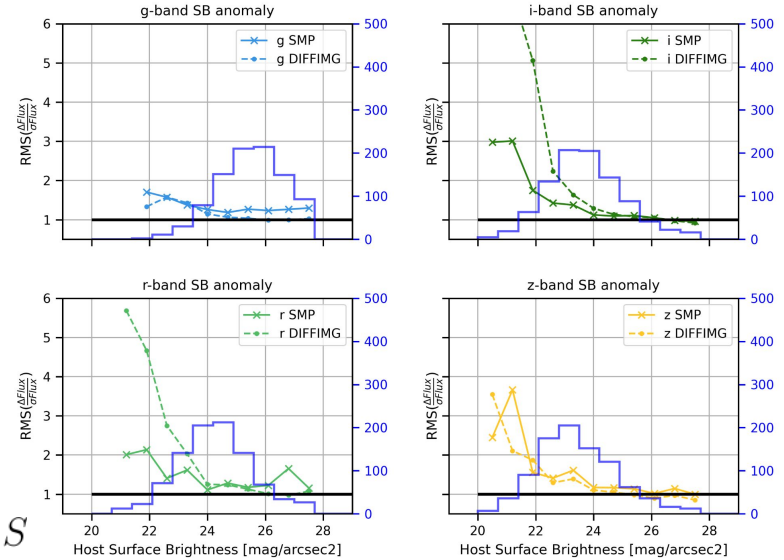
Sanchez et al. (in Internal Review), DES Collaboration, in prep.

Scene Modelling Photometry method for DES Y5

Comparison with DES Y3 analysis (first implementation of SMP) shows great agreement
Less bias than the ~5 mmag uncertainty in calibration

SNIa photometry is greatly improved and we see that in many effects, from simple scatter values to some cosmology parameter shifts

SMP: Zero flux regime (z > 0.25)



$$\sigma_f = \sigma_{\rm stat} \times S$$

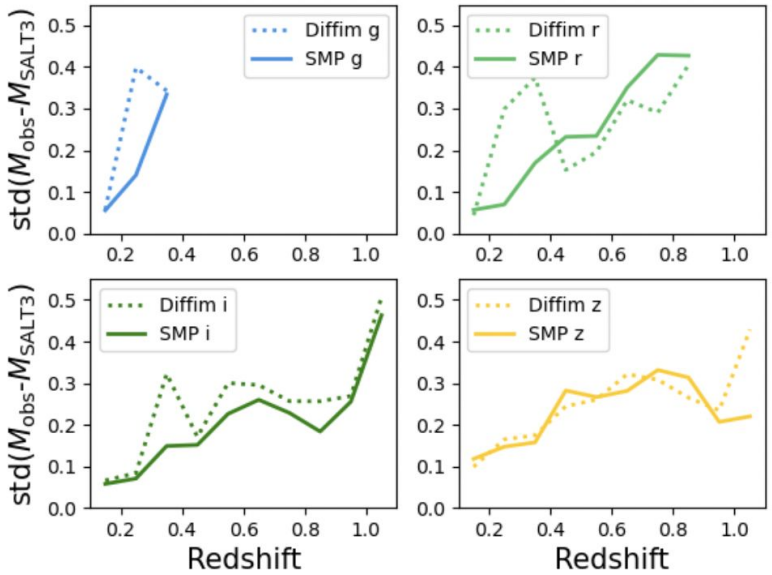
Sanchez et al. (in Internal Review), DES Collaboration, in prep.

Scene Modelling Photometry method for DES Y5

Comparison with DES Y3 analysis (first implementation of SMP) shows great agreement
Less bias than the ~5 mmag uncertainty in calibration

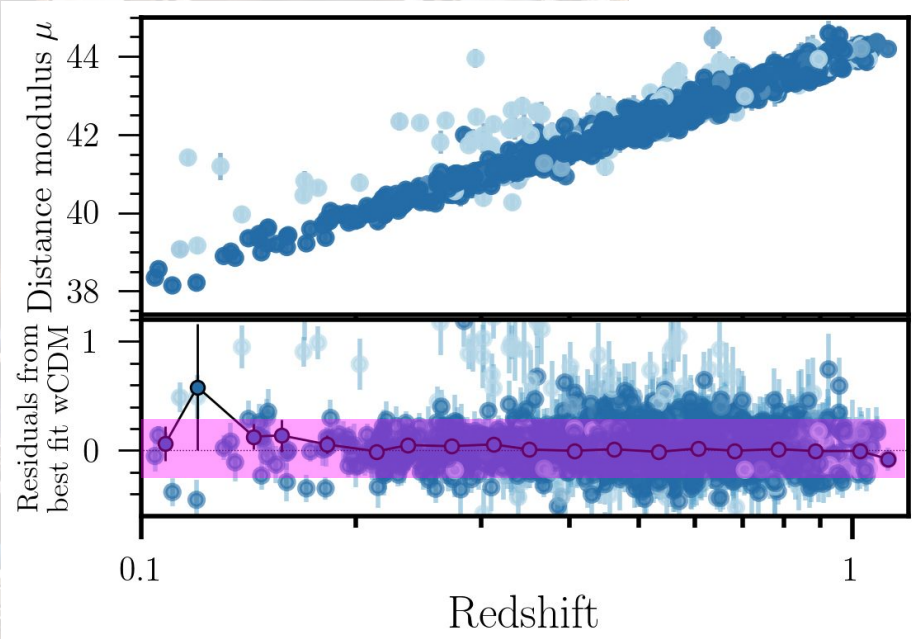
SNIa photometry is greatly improved and we see that in many effects, from simple scatter values to some cosmology parameter shifts

Also the residuals when using SALT model fitting show a reduction in scatter



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

The Dark Energy Survey (DES)



1) Exquisite photometry SMP

2) **Machine learning** to identify likely SN Ia

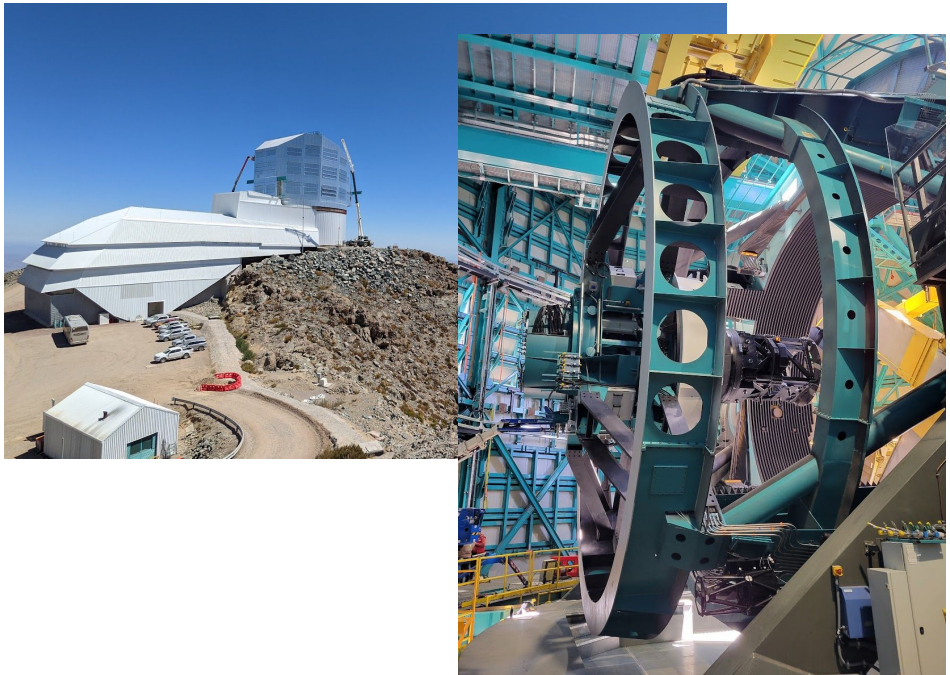
3) Modelling SN Ia **intrinsic scatter** and systematics

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

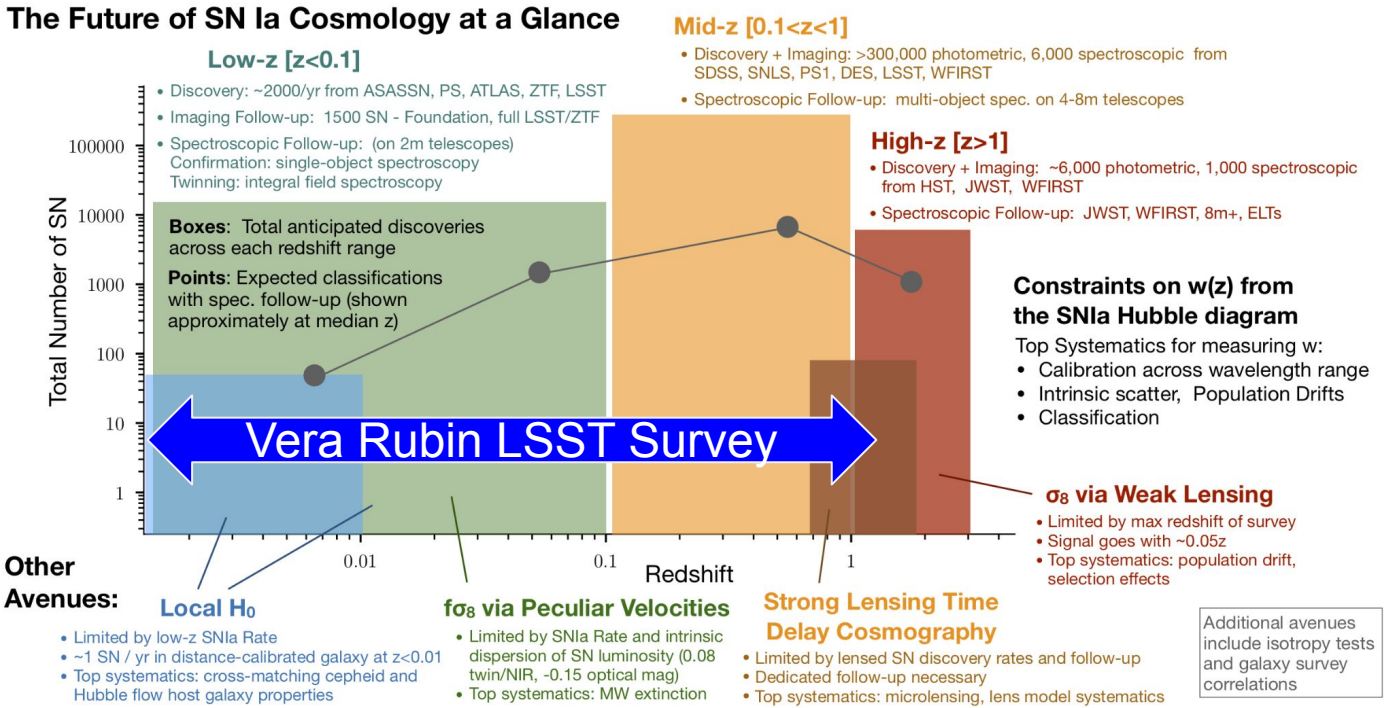
The Vera Rubin Legacy Survey of Space and Time

A revolutionary instrument that will yield an unprecedented data set for all kinds of science:

- Cosmology
- Exploration of the time domain
- Cataloguing the Solar system
- The structure and formation of our galaxy



Surveys for Type Ia Supernova Cosmology



Scolnic et al. 2019 (1903.05128)

What is DIA and why is it relevant for LSST or SNIa?

- LSST will observe ~20,000 deg^2 cadence ~3 nights.
- LSST will detect ~10^6 transient sources per night

- SNIa are one of the key Dark Energy probes for DESC
- LSST will increase SNIa sample size 100-fold w.r.t. precursor surveys (up to z ~1.2)
- Cosmology inference:
  - Expect significant reduction in statistical error
  - Requirements for SNIa cosmology in LSST includes minimizing systematic errors
    - Photometric biases
    - Selection biases

Difference Image Analysis (DIA) is the cornerstone of the transient detection pipelines: critical for Cosmology with SNIa

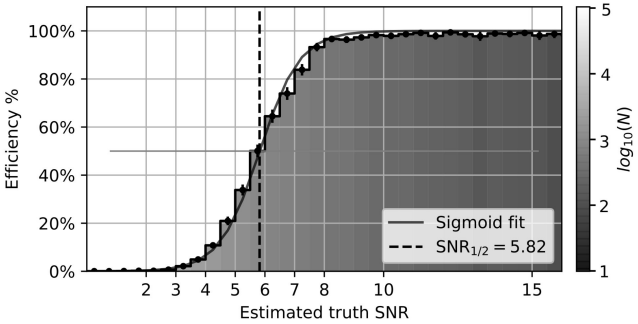
Assessment of DIA

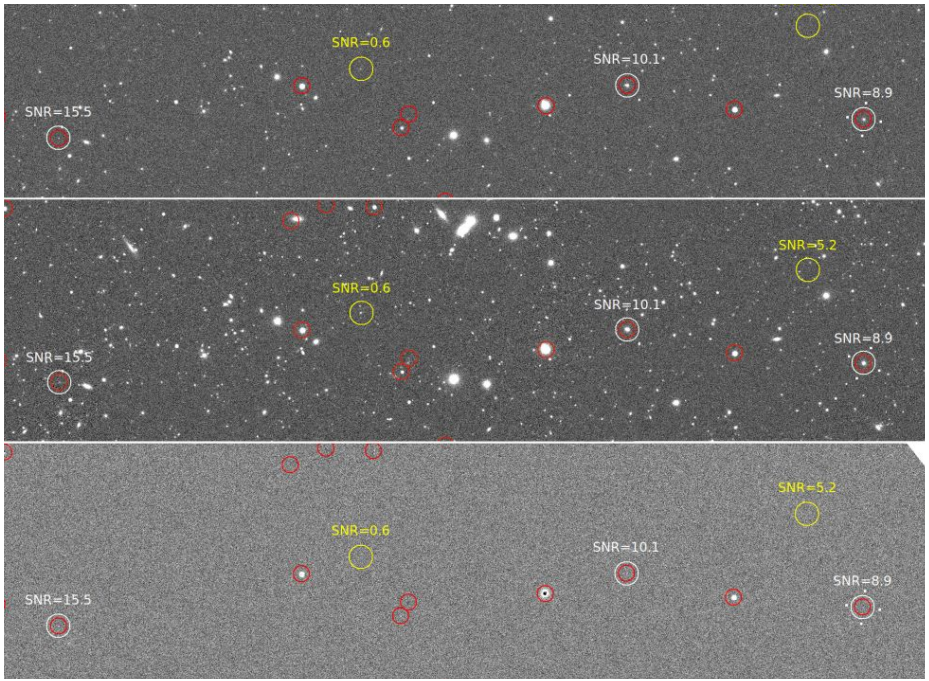
DIA Processing of DC2 images

DC2: precise simulation of LSST data
5 years of 300 sq. deg.

We processed 15 sq. deg and obtained SNIa

- Template creation (Image Co-addition)
- Image subtraction
- False Candidate pruning
- Use of LSST pipelines for image processing





DC2 Analysis with LSST DIA pipelines

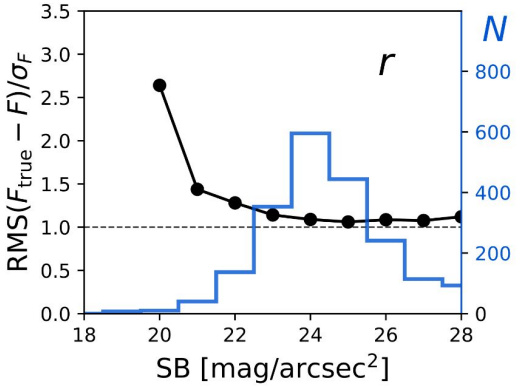
We run aperture photometry on templates (0.”9 radius), at SNIa locations to obtain the local Surface Brightness

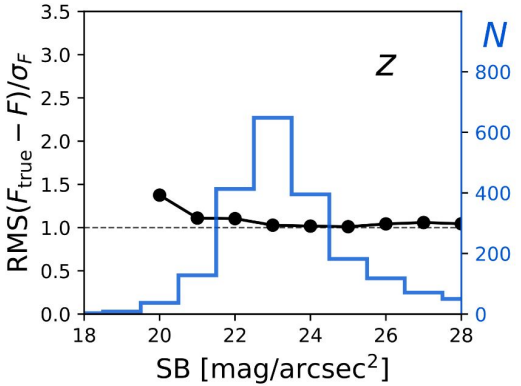
Similar behavior as observed by Kessler 2015 for DES “SB anomaly”

Table 8: $m_{SB}(RMS_{pull}=2)$[a] for each DC2 band.

u_{SB}	g_{SB}	r_{SB}	i_{SB}	z_{SB}	y_{SB}
–[b]	22.1	20.5	19.8	19[c]	–[b]

[a] Surface brightness [mag/arcsec^2] where flux-uncertainty scale is ~ 2
[b] Scale is always < 2
[c] Estimated from extrapolation





DC2 Analysis with LSST DIA pipelines

Results show that DC2 WFD can be compared to DES SN results.

This summary would be great to track commissioning results and data release results during operations.

Table 7: Difference image properties for DC2 and DES.

	DC2-g	DES-g^*	DC2-i	DES-i^{**}
$m_{1/2}$	24.7	24.5	23.5	23.5
$\mathrm{SNR}_{1/2}$	5.57	5.61	5.84	5.36
$m_{\mathrm{SB}}(\mathrm{RMS}_{\mathrm{pull}}=2)$	22.1	22.0	19.8	21.5
$\overline{D_{\mathrm{art}}}$	1080	520	680	730
$f_{5\sigma}(\%)$	0.24	0.49	0.16	0.25
$f_{10\sigma}(\%)$	0.09	0.09	0.04	0.06

* From DES SN Deep fields, to match DC2-g depth.
** From DES SN Shallow fields, to match DC2-i depth.

Recovery of Cosmological parameters

Processed light curves from SNIa in DC2, worked on photometric analysis, error correction, etc.
Light curve standardization, sample simulation for bias corrections and application of cuts for cosmology analysis.

Finally, performed bias corrections and cosmological parameter fit

		From Cosmology Fit			From BBC Fit		
Data Set	N_{Events}	$\Delta w = w - w_{\text{true}}$	$\Delta\Omega_M = \Omega_M - \Omega_M^{\text{true}}$	χ^2/ν	$\Delta\alpha = \alpha - \alpha_{\text{true}}$	$\Delta\beta = \beta - \beta_{\text{true}}$	$\sigma_{\text{int}}/\sigma_{\text{int}}^{\text{true}}$
DC2+SimLow-z	655	-0.032 ± 0.046	-0.007 ± 0.013	11/8	-0.004 ± 0.010	-0.15 ± 0.14	1.02
DATA-like Sim	2061	-0.002 ± 0.026	0.001 ± 0.009	12/8	0.004 ± 0.005	-0.12 ± 0.06	0.94

Feasibility of SMP on LSST WFD?

Processed light curves from SNIa in DC2 WFD yielded $\sim 10\ \mathrm{deg}^{-2}\mathrm{yr}^{-1}$ Hubble Diagram SNIa

Linearly extrapolating up to the full ~20k sq. deg over 10 years: #SNIa in HD ~2M (modulo cadence, which for DC2 is outdated)

This means that DES-SMP is not deployable as is in the future WFD sample

Developing a faster Scene Modelling Photometry (SMP) is also on the critic path for Cosmology with SNIa

Existing efforts known to me:

- Of course ZTF SMP pipeline
- Light curve extraction with STARRED (Martin Millon et al.)
- Michael Wood-Vasey & Connor Stone AstroPhot package
- DES SN team porting to DC2 (early phase)
- ?

Conclusions

- SNIa Cosmology probe is an essential tool to constraint our current cosmology model parameters
- Scene Modelling Photometry gives us the most accurate transient flux measurements for final analysis of SNIa standard candles in DES probe
- Largest SNIa sample with single instrument so far
- Look out for the new DES SN cosmology papers!

- New surveys like the Vera Rubin Observatory LSST will build up on the great work done by DES and many others to carry the most precise measurement of ***w*** with a single instrument
- Difference Image Analysis is at the heart of everything time-domain related in Vera Rubin Observatory LSST
- Current efforts will improve on an already very good pipeline!