Unblinded SN Cosmology from the full 5 Years of the Dark Energy Survey

Fermilab "Wine and Cheese" – Aug 18th, 2023

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DARK ENERGY SURVEY

BOSTON UNIVERSITY

U.S. DEPARTMENT OF ENERGY

The DES-SN Working Group!

Early career scientist driven!

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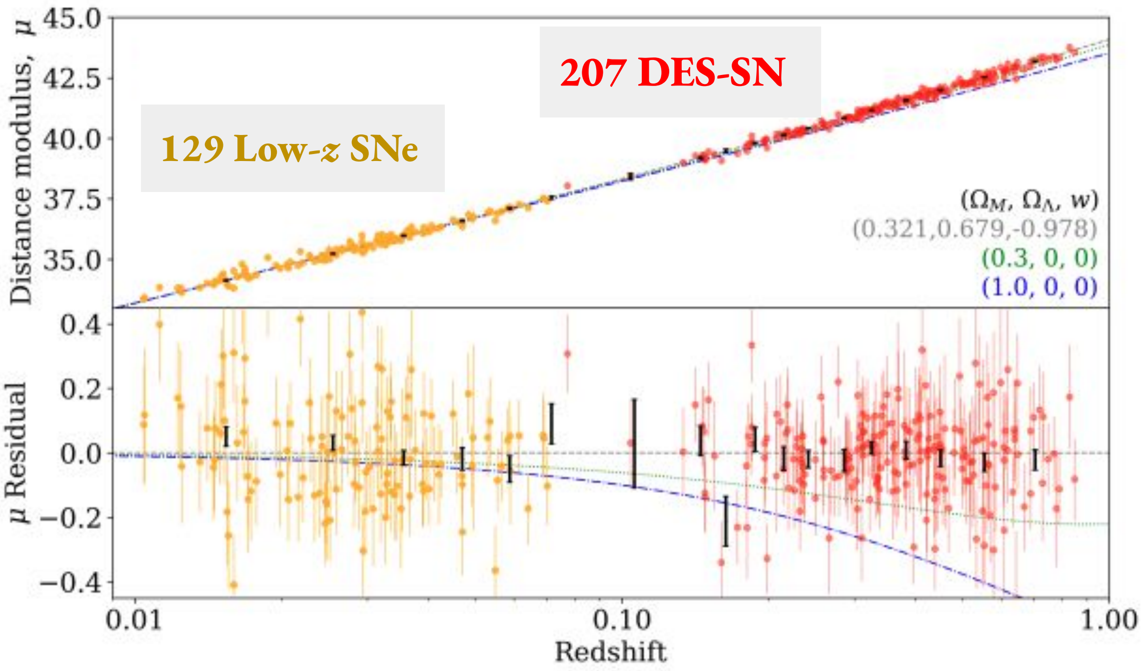
5YR Analysis Co-Lead Maria Vincenzi

Early career scientist driven!

Hubble Diagram in DES-SN Year 3

(our preliminary analysis of 1/10th of our dataset)



Abbott et al. 2018

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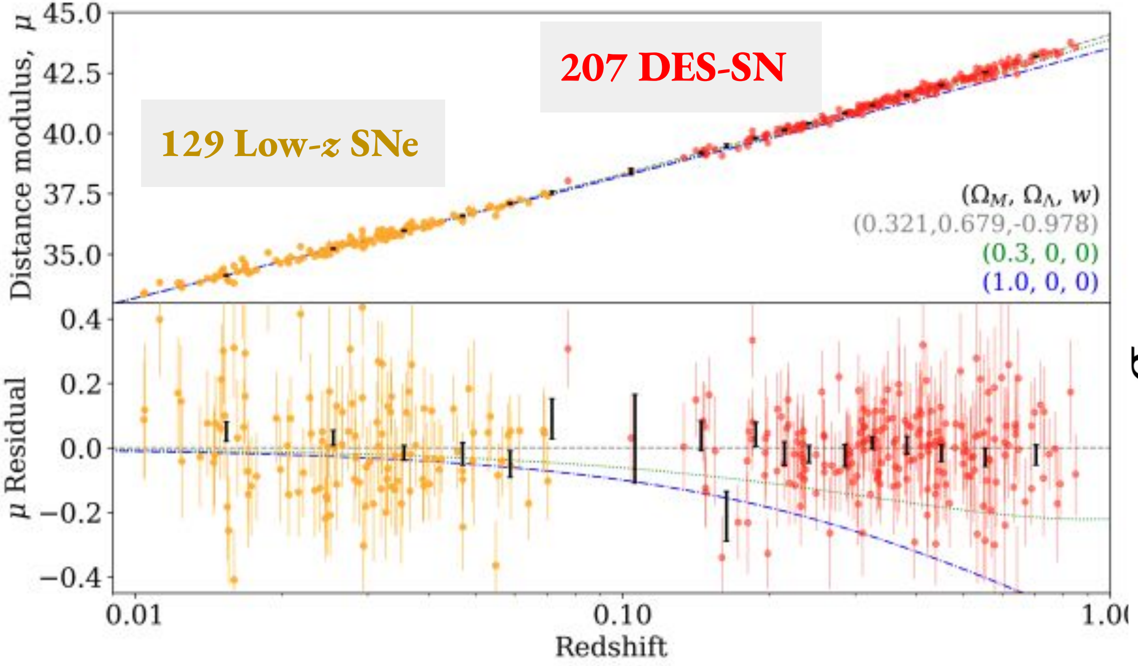
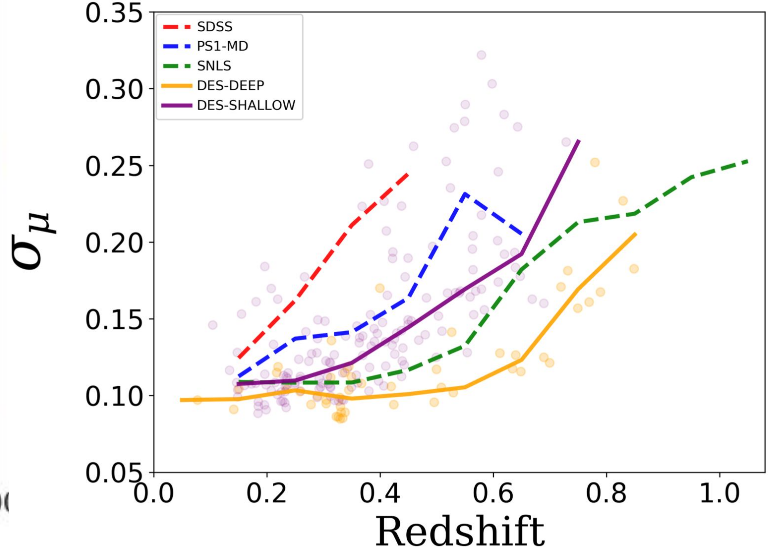


Abbott et al. 2018

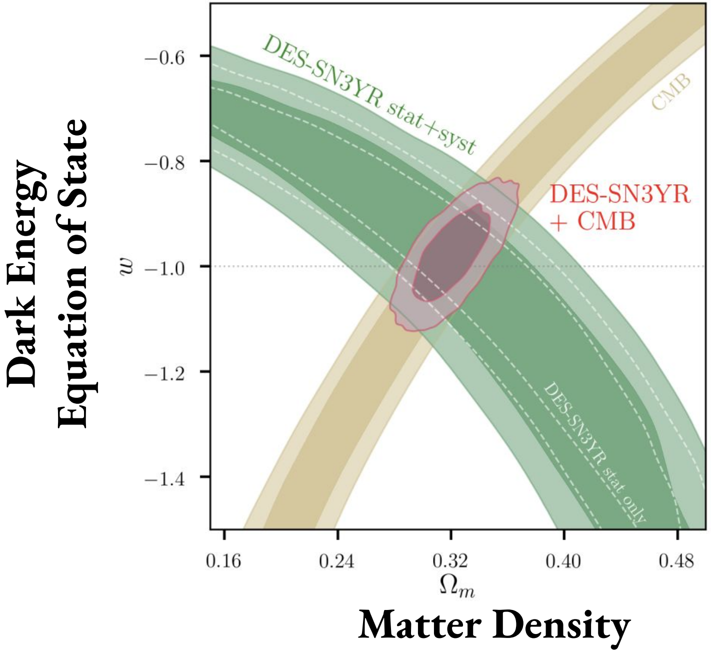
The best constraints on distance of any high redshift SN survey to date!



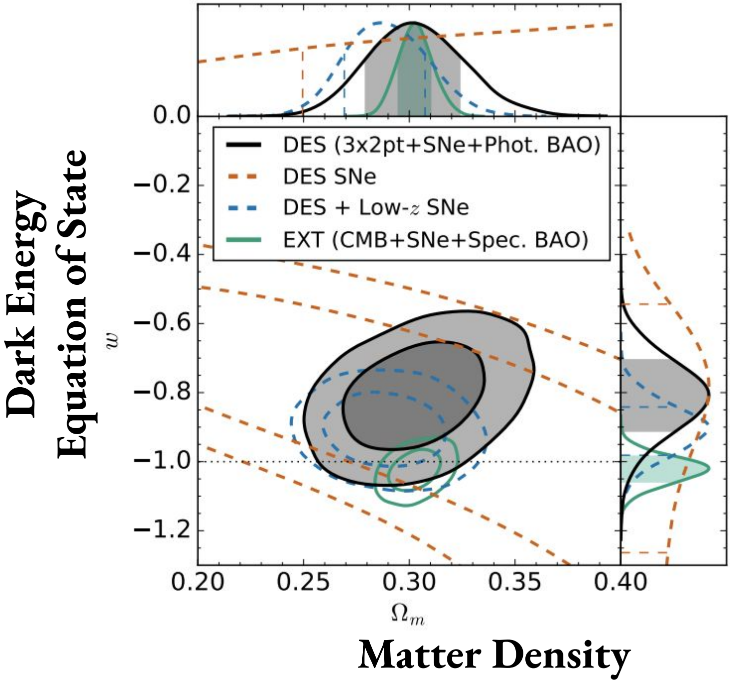
Brout et al. 2018b

DES-SN Year 3 Cosmology Constraints

Equation of state of dark energy consistent with a cosmological constant



First single photometric probe to independently rule out a no dark energy universe.



Let’s take a step back.

DES is really two separate multi-band imaging surveys.

i) **Wide Field** (yellow →)

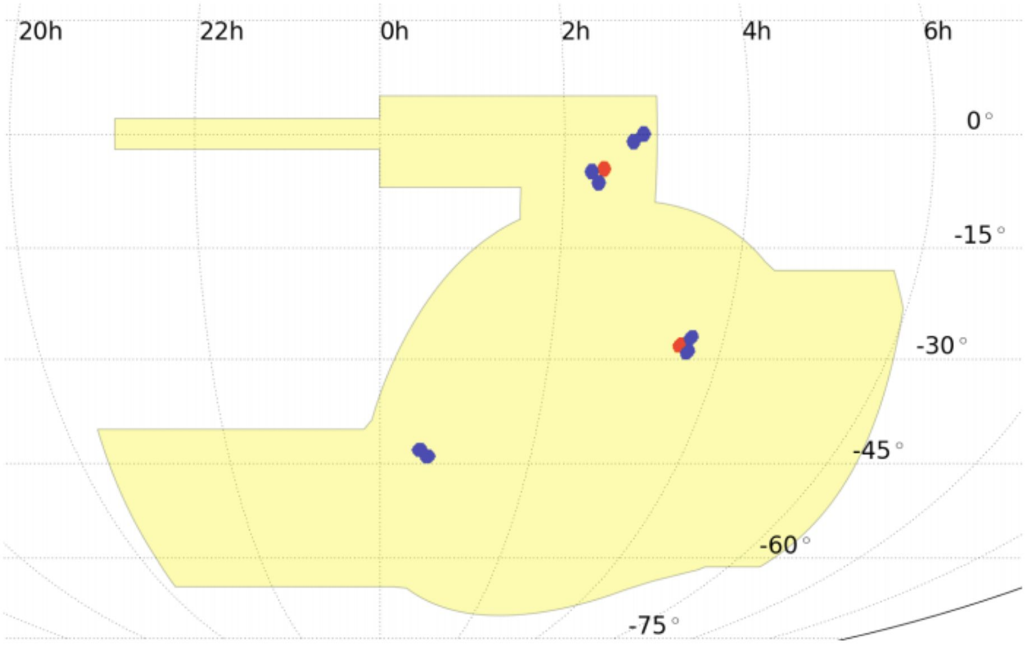
5000sqdeg

10 Obs/5 years

ii) **Transient Fields** (blue/red →)

30sqdeg / 10 pointings

5-7day cadence



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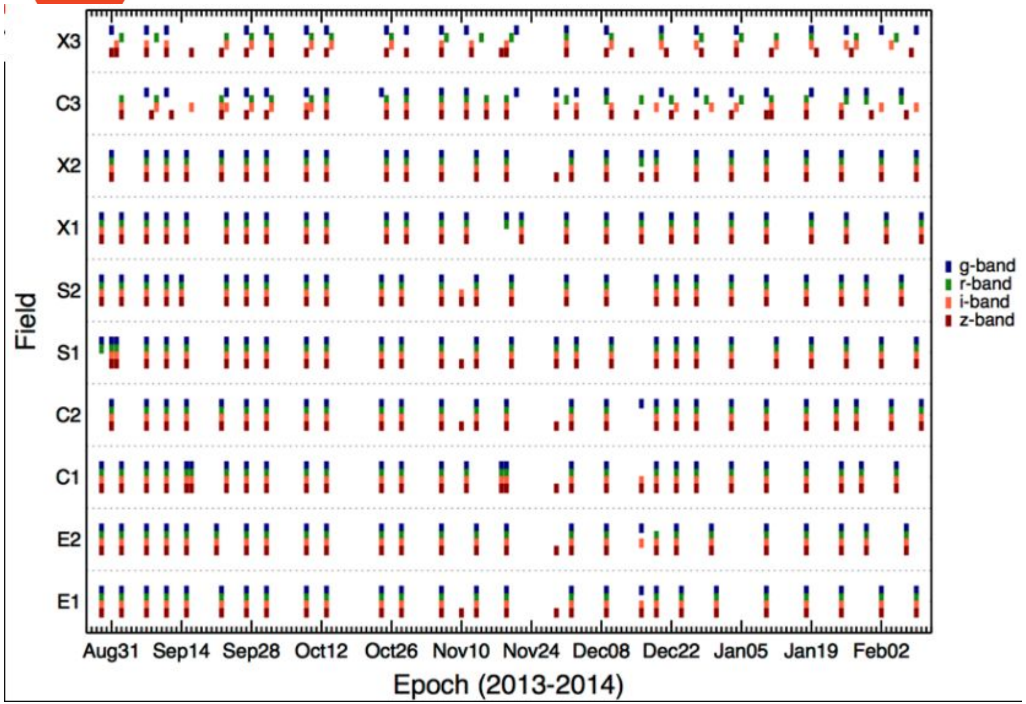

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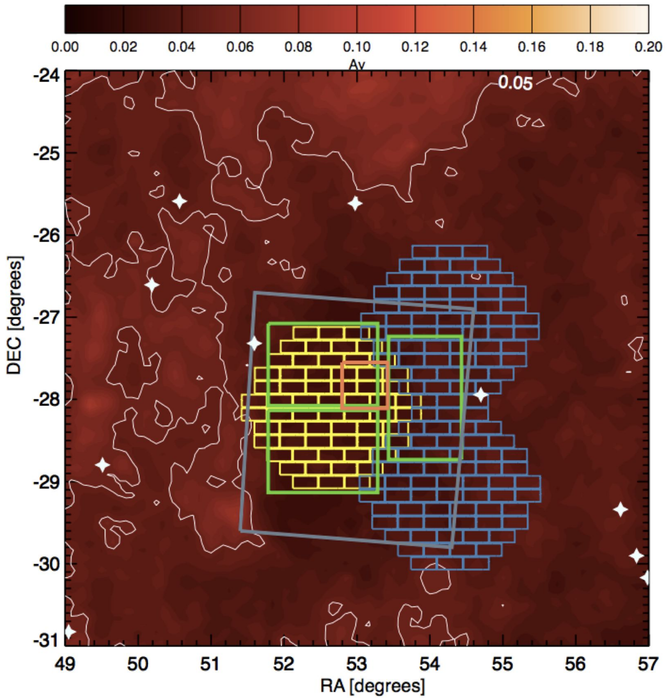

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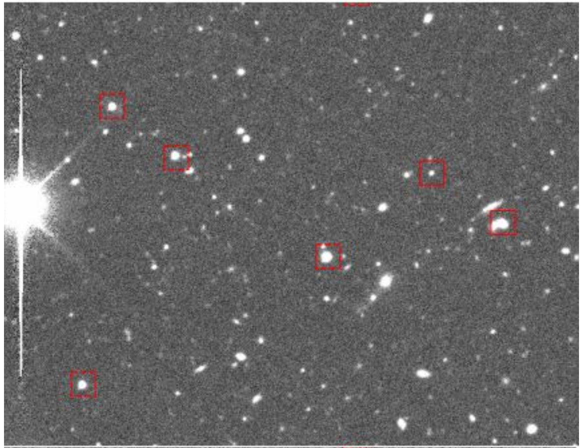
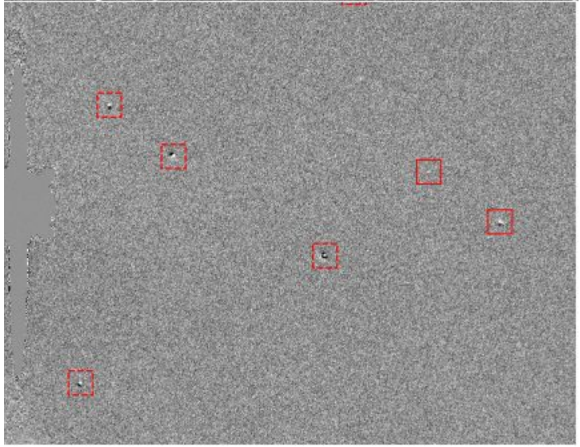
Search Image



Difference Image



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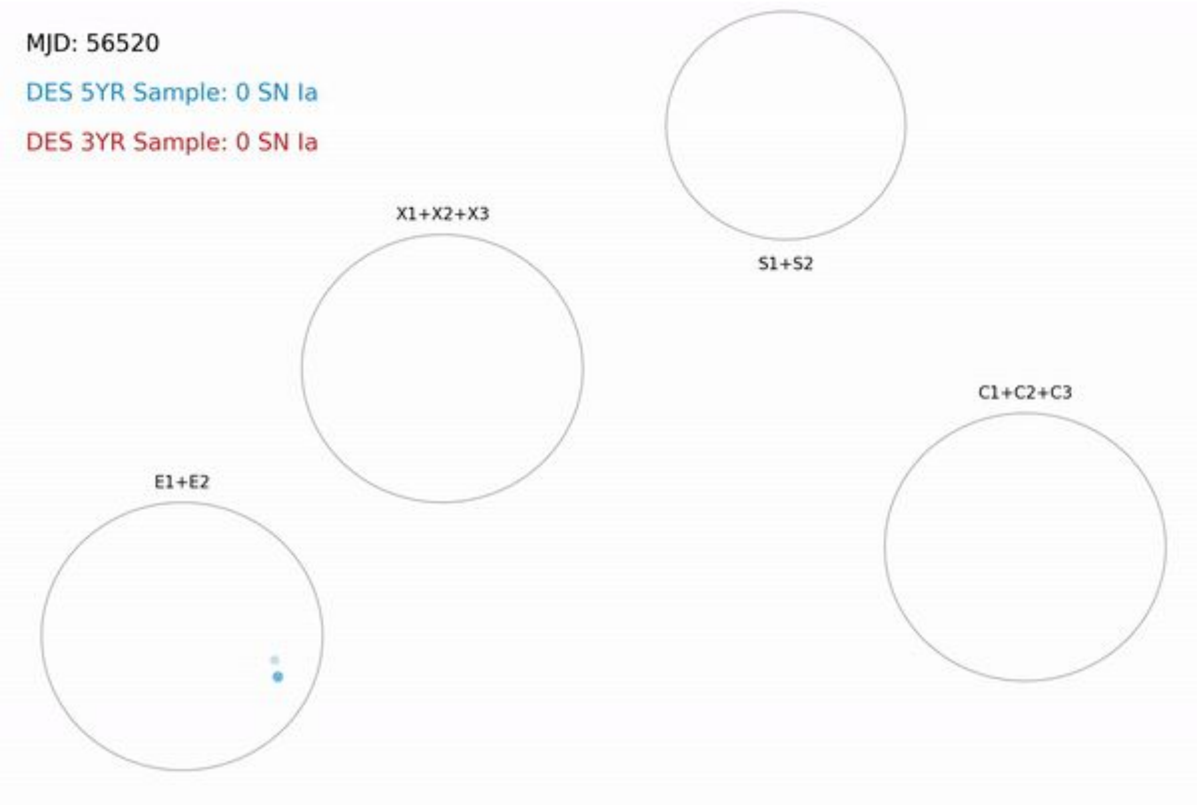
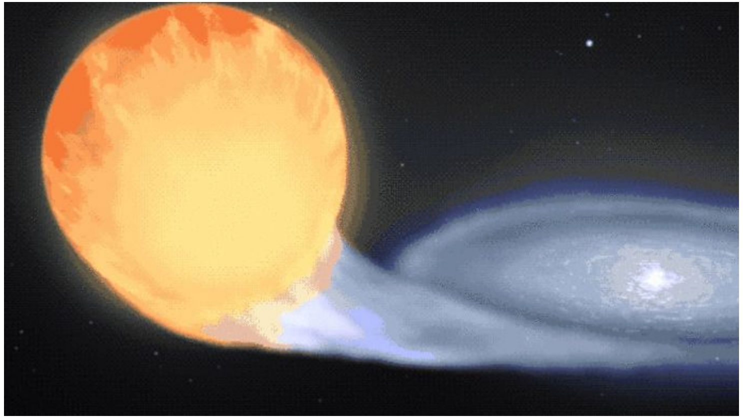
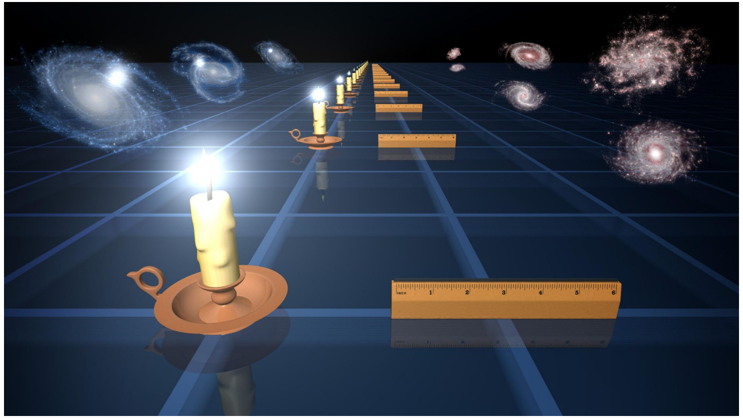
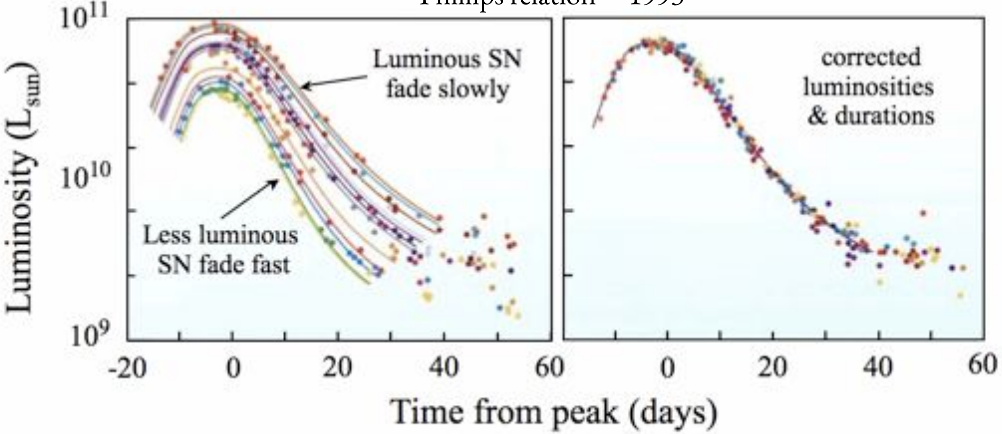


Supernovae Ia (SNe Ia) can be seen across the universe and are standard*izable* candles.





"Phillips relation" - 1993



- Correct (10%) for a stretch-luminosity relation (Ni56) and <u>a color-luminosity relation (i.e. dust)</u>.

- The ratio of the *intrinsic* to *apparent* luminosity provides the luminosity-distance (d_L) of the supernova.

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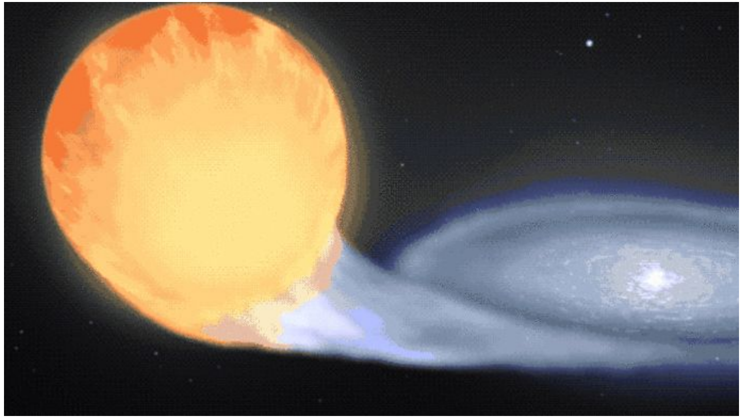

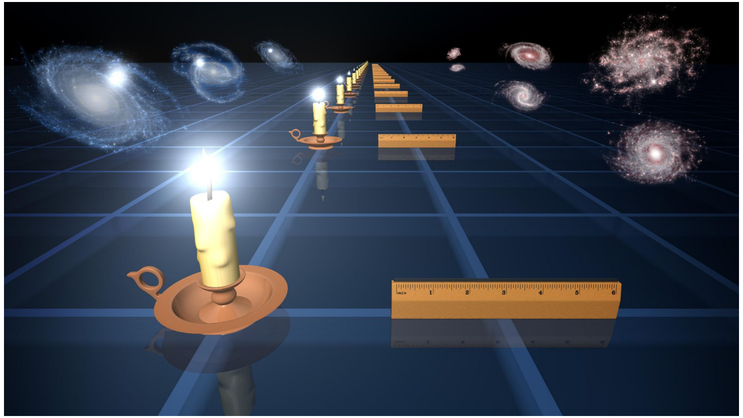

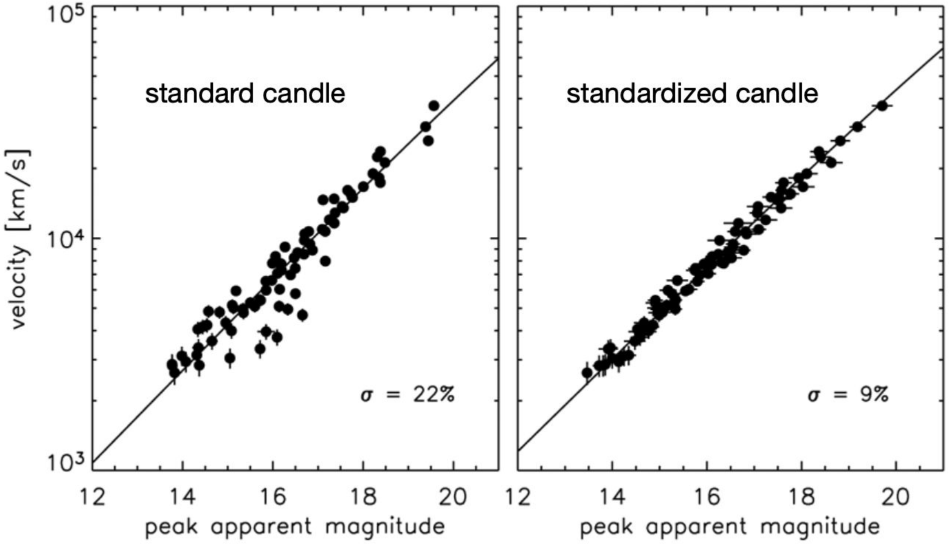

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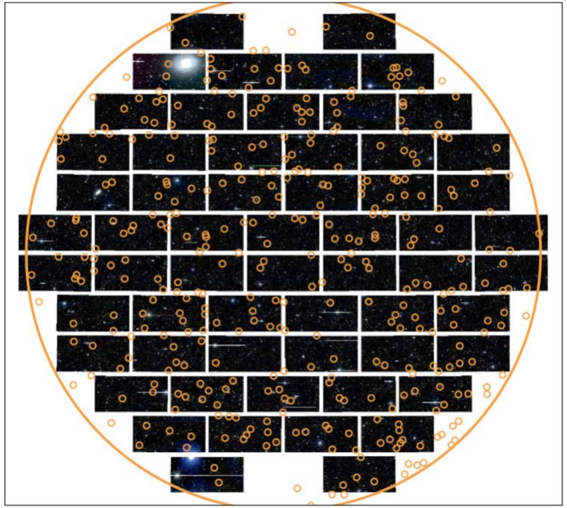
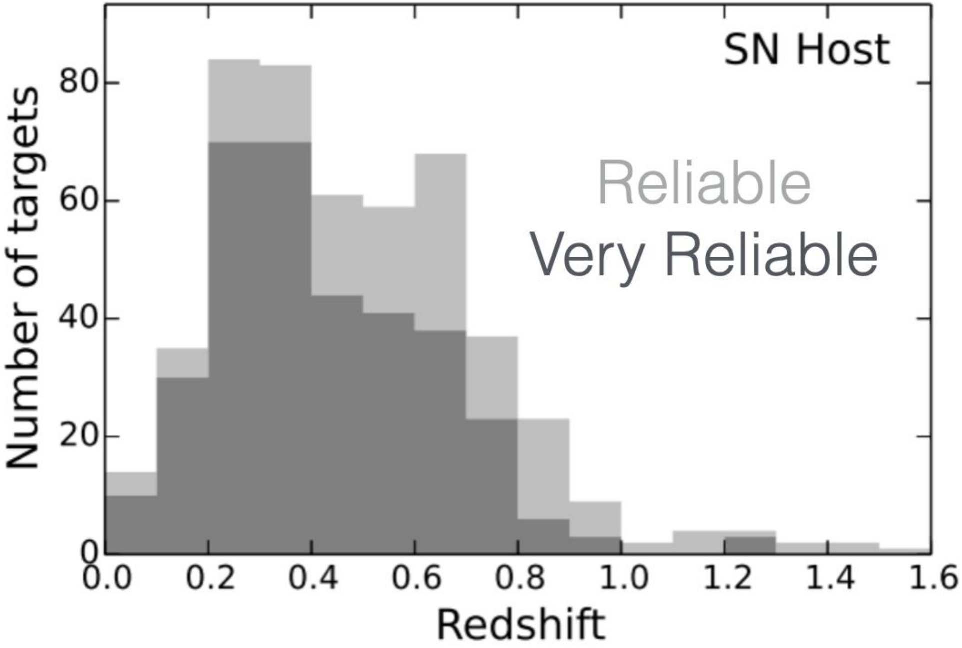
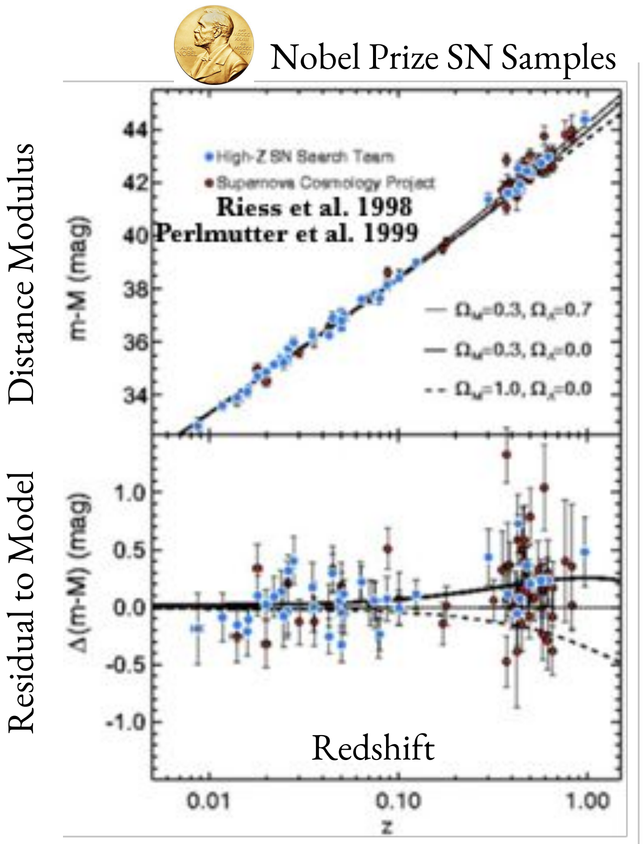
Photometry from DECam, Spectroscopic redshifts from OzDES





SNe Ia as a Probe of the Standard Model of Cosmology (ΛCDM)



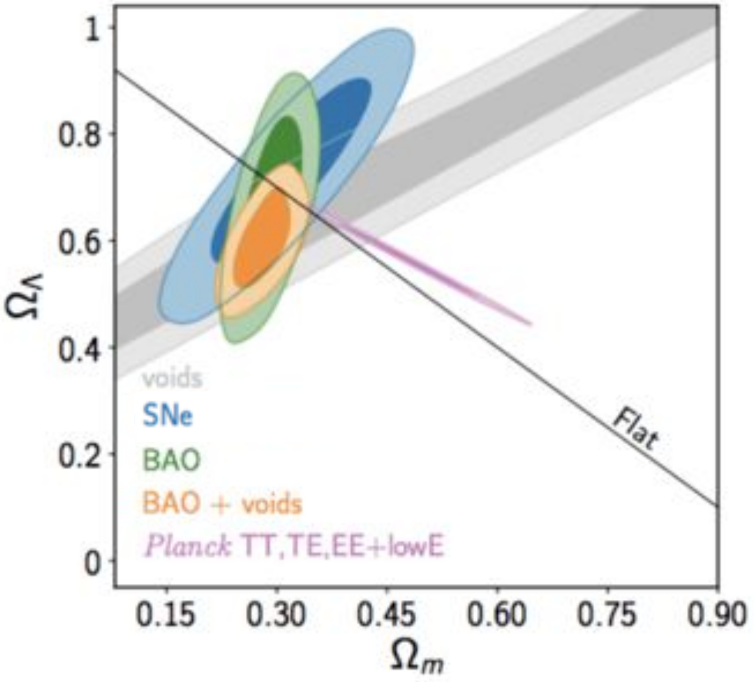
- SNIa as *relative* distance indicators (standard*izable* candles) revealed that the universe is accelerating (due to so-called dark energy).

- To constrain cosmological parameters we compare observed luminosity distances to model based distances:

$$d_L(z) = (1+z)\, c \int_0^z \frac{dz'}{H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}}$$

SNe Ia are a unique and precise probe that remain a key pillar of cosmology

They probe a massive span of the history of the univer (>10 billion years): from dark energy domination in th present universe to (dark)matter domination.



Dark Energy Density

Matter Density

But we still have many unanswered questions that SNe will help address

What is the cause of cosmic acceleration/dark energy?

- Is it the vacuum energy/cosmological constant or something else?
- Is dark energy evolving?
- Is it in fact isotropic and homogeneous?

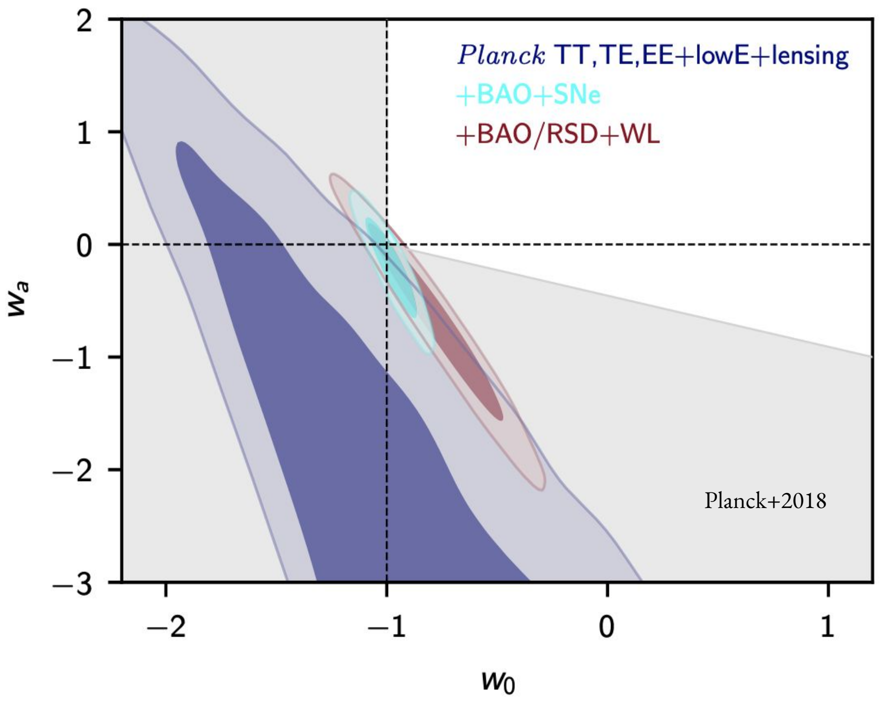
The Cosmological Constant problem

- Why is the observed cosmological constant 120 orders of magnitude smaller than theoretical expectation?

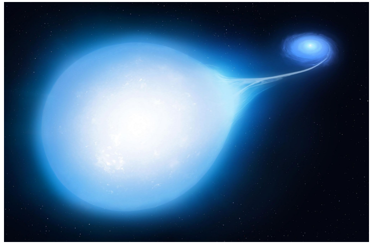
Does ΛCDM stand up to the test?

- Hubble Constant *Crisis* - The 'end-to-end' test doesn't pass.
- S8 *Tension?* Is it related to H0 tension?

Evolving Dark Energy



Route to the SNIa Hubble Diagram



Model SN & host demographics and potential mismatch

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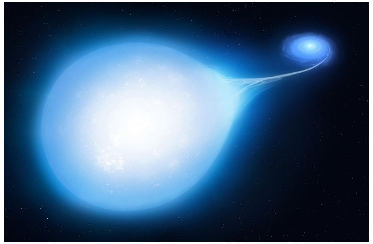

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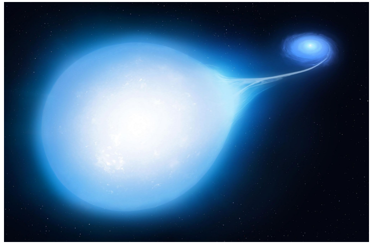

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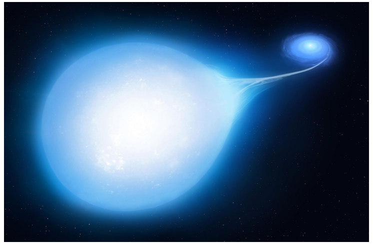

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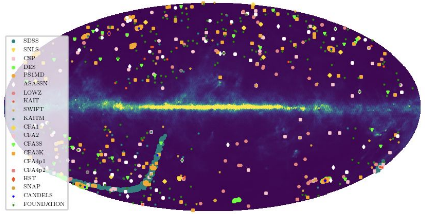

Cross-Calibrate telescopes/instruments/filters

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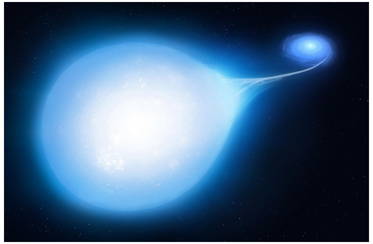

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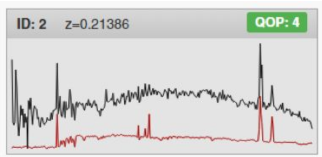

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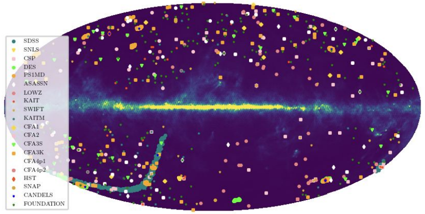

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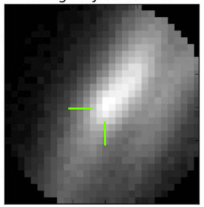
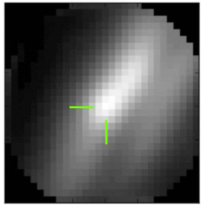
DECam

image MJD 56536.0



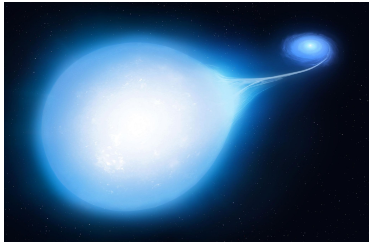
Model

model



Forward modeling of SN flux and galaxy model

Route to the SNIa Hubble Diagram



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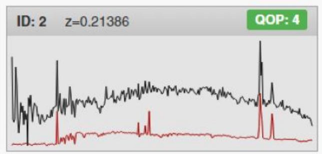

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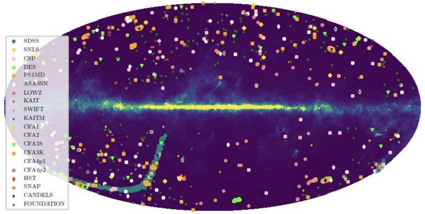

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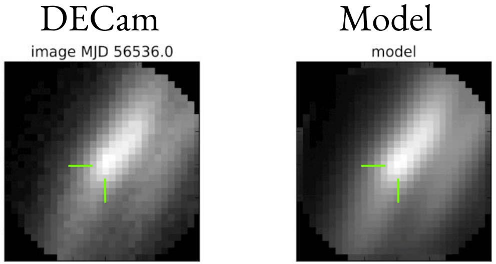

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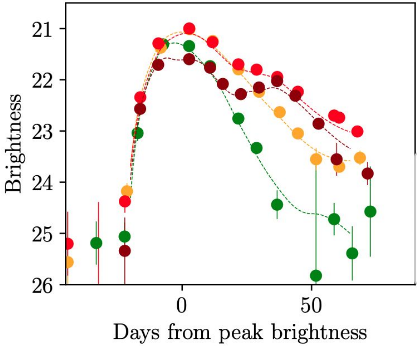
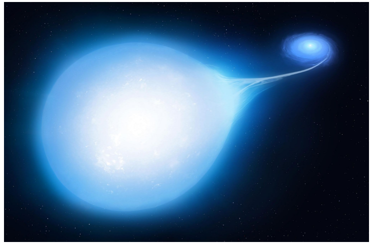


Standardize light curves

Route to the SNIa Hubble Diagram



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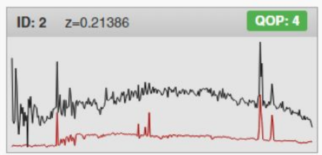

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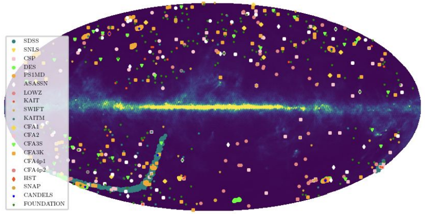

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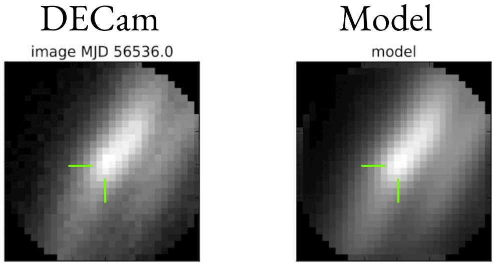

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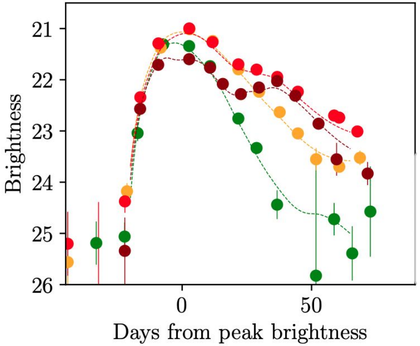

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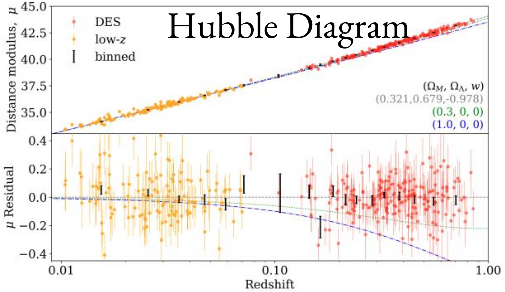
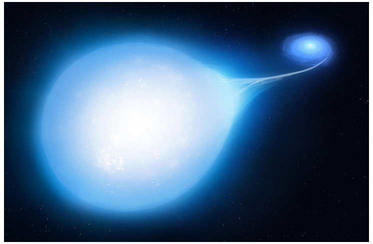


Determine distances and systematic covariance

Route to the SNIa Hubble Diagram



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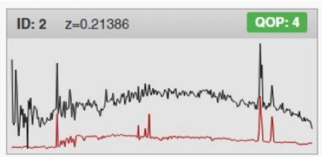

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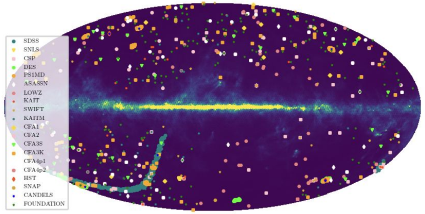

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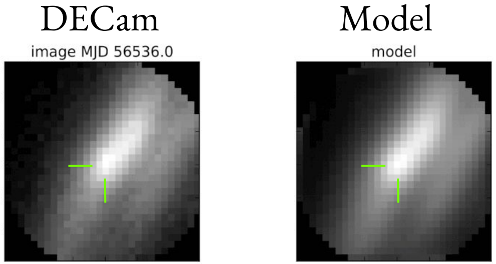

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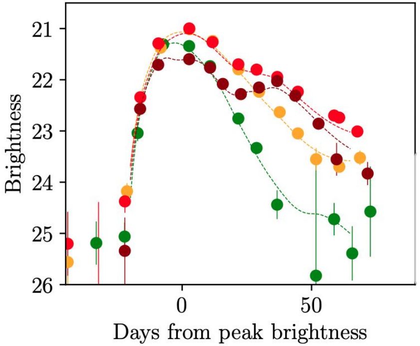

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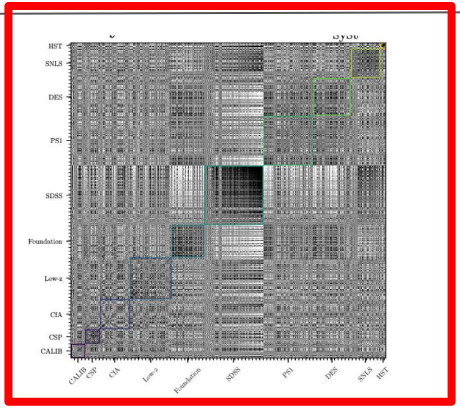


Determine distances and systematic covariance

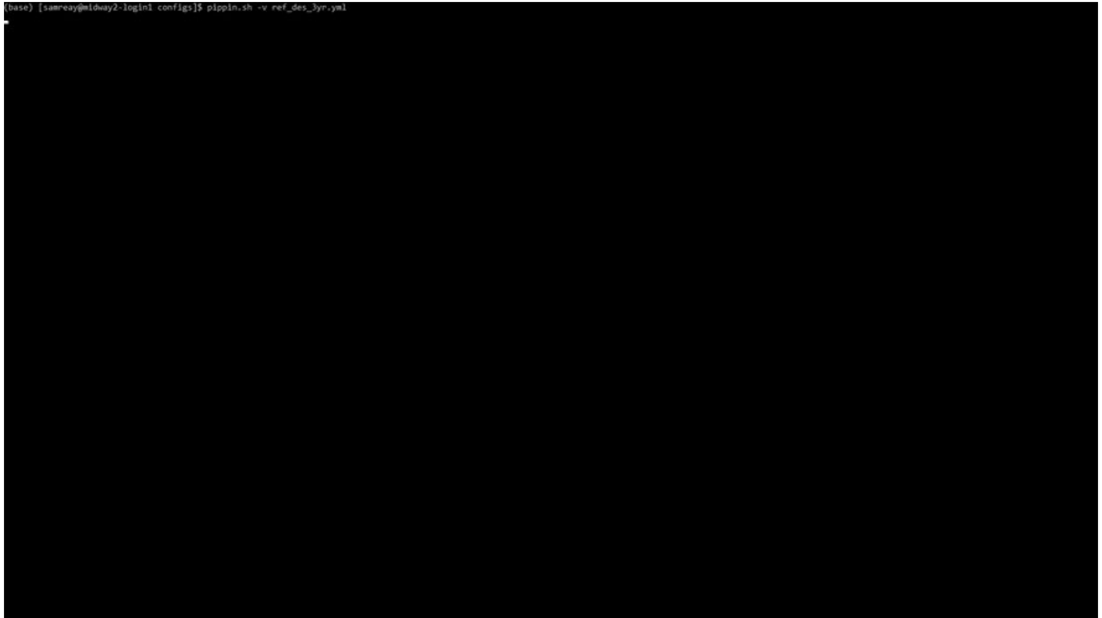
PIPPIN: A pipeline for SN cosmology

Patrick Armstrong

Evolved out of the needs of the DES3YR analysis

Facilitates easy analysis variants and parallelization

Now being used heavily in LSST DESC



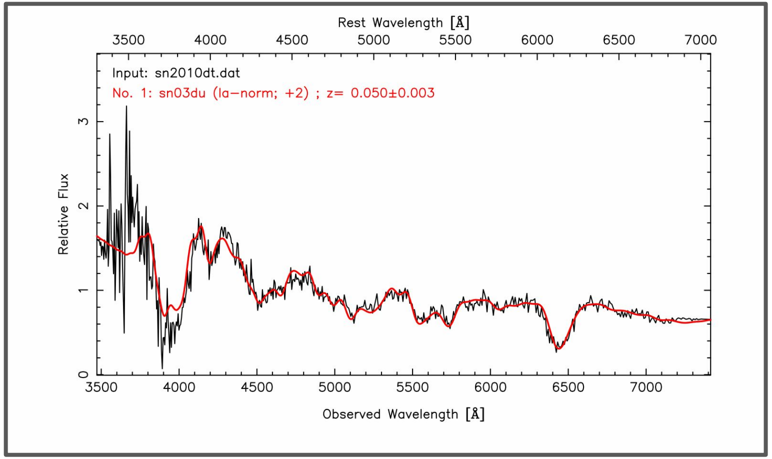
github.com/dessn/Pippin

Hinton & Brout 2020

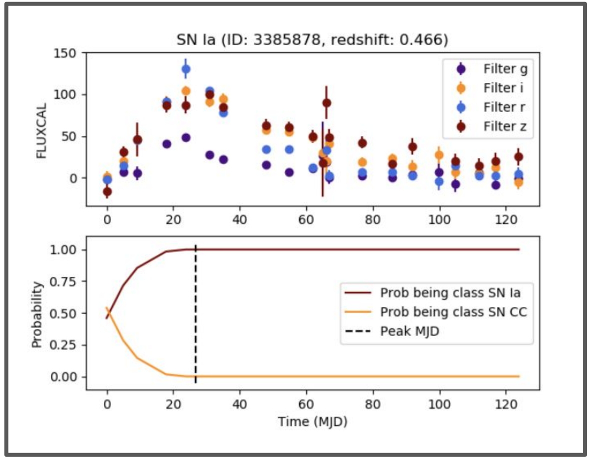
DES-SN Full 5 Year Analysis

We had ~30,000 transient candidates in DES-SN.

Classification of Type Ia SNe with



Or



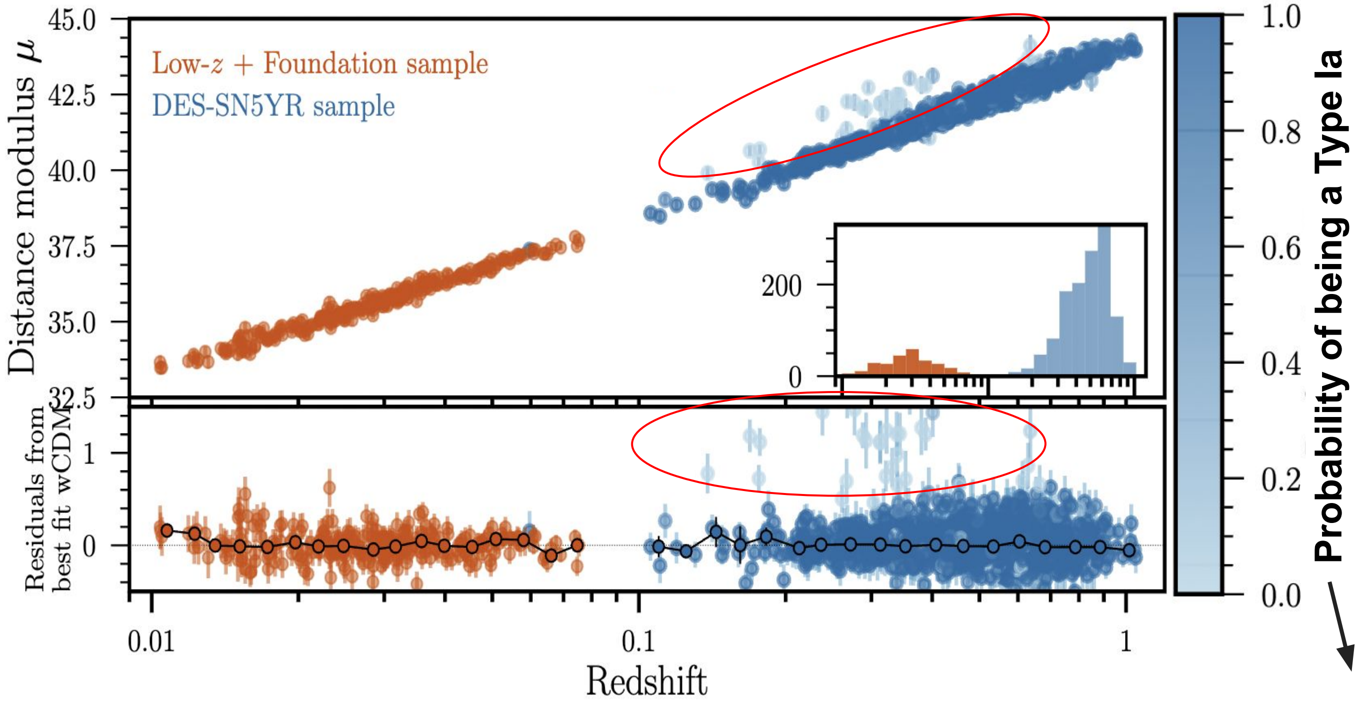
Spectrum of SN

With 4 filters

207 Type Ia in first 3 years
DES3YR

Order of Magnitude more "likely" Type Ia
DES5YR (and how LSST will do it)

The Dark Energy Survey SN sample



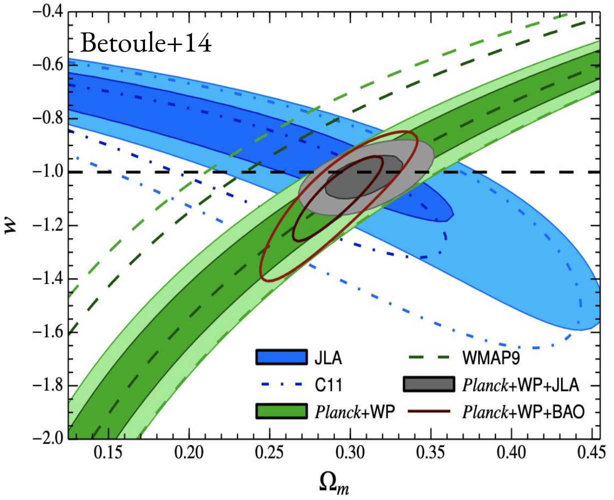
The DES SN sample is the **largest** and **deepest** SN sample from a **single telescope ever compiled**

~1700 SNe Ia

- SN classification using the most advanced machine learning techniques

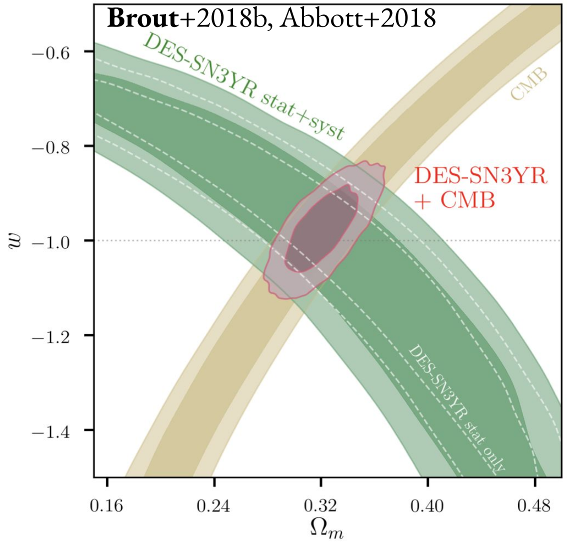
Past analyses have already been pushing on the systematic error floor.

Joint Light Curve Analysis 2014



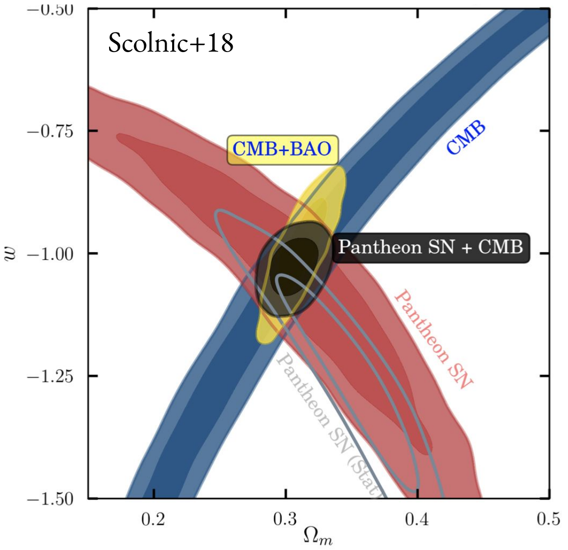
Sys Errors 60% larger than Stat

Dark Energy Survey 3YR 2018



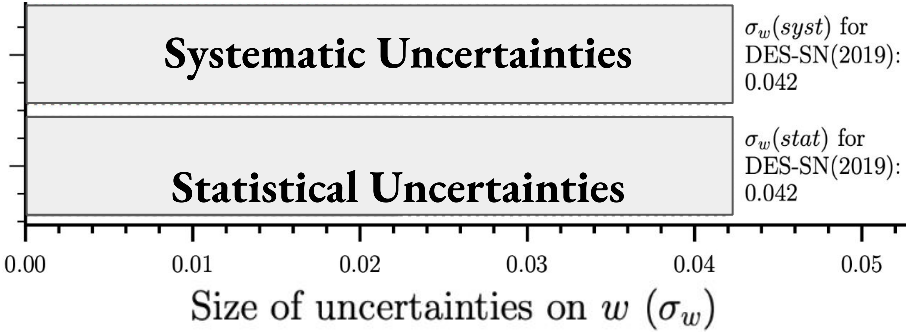
Sys Errors Equal to Stat

Original Pantheon 2018



Sys Errors 20% larger than Stat

The path forward to push down on uncertainties as identified from DESSN- 3YR was:



1. Simulating DES-SN samples that looks like the observed sample from first principles.
2. Modelling the astrophysics of Milky Way, Host Galaxy, and SN Dust as well as SN progenitor physics
3. Calibration of DECAM and External Surveys that are used in the SNIa model training.

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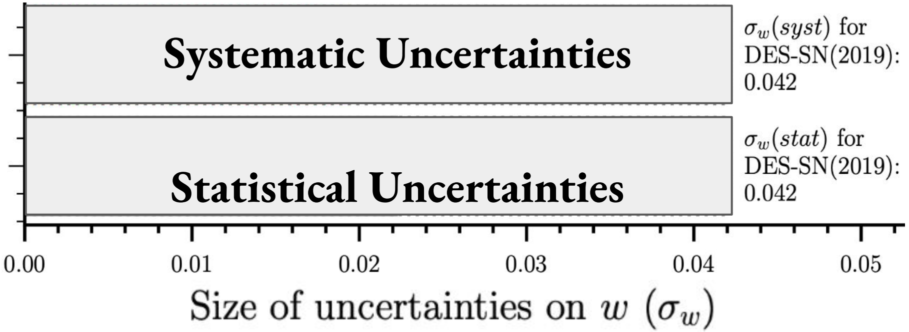


1. Simulating DES-SN samples that looks like the observed sample from first principles.
2. Modelling the astrophysics of Milky Way, Host Galaxy, and SN Dust as well as SN progenitor physics
3. Calibration of DECAM and External Surveys that are used in the SNIa model training.

+ Two added challenges:

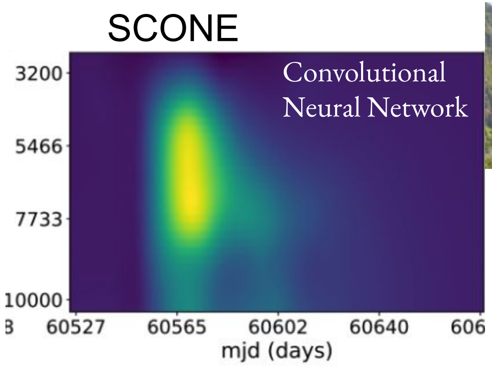
  1) selecting a **pure** sample of SNe Ia with ML

  2) without a spectrum of SN & Host, there can be **host mis-association**

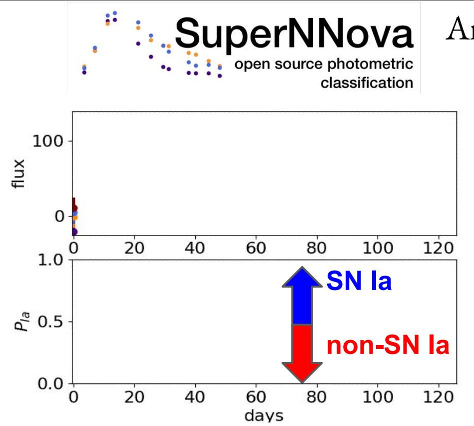
Photometric SN Type Classification

Real-time spectra of SNe was not feasible in DES.

Helen Qu



Anais Moller



Supernova Identification with Random Forest (SNIRF)

Eve Kovacs

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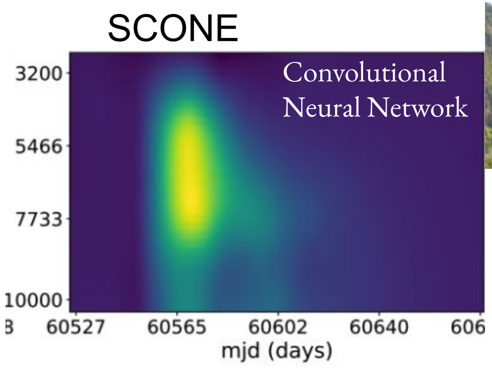
We have developed the infrastructure to employ 3 new classification algorithms for DES SN Cosmology.

Helen Qu



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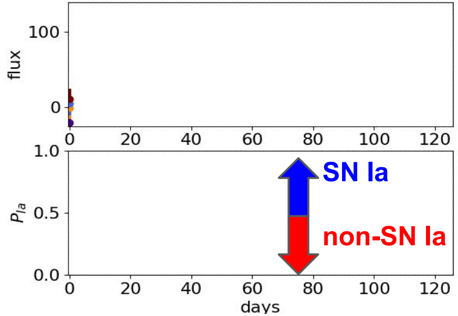

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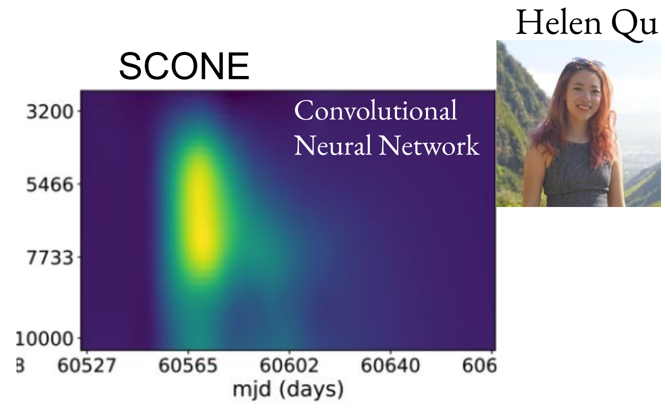

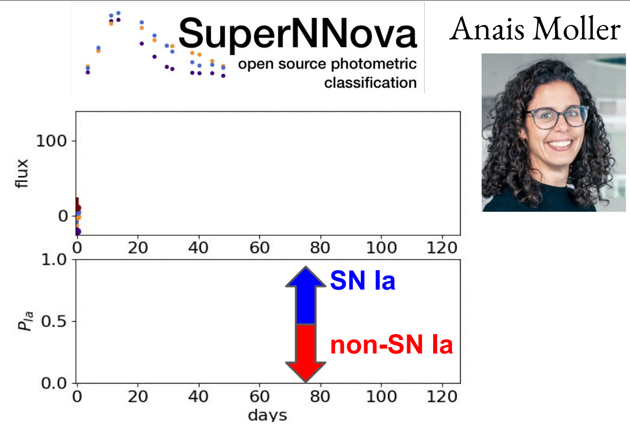

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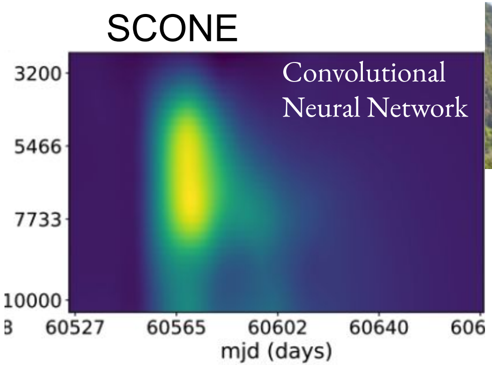
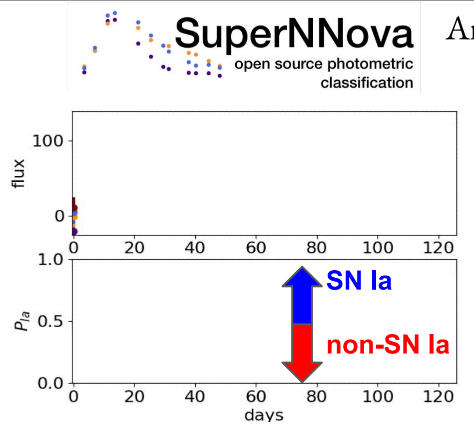
- The classifiers do really well on DES griz (98/97 purity/efficiency) high-redshift sample.
- As long as your classifier probabilities are well calibrated, the cosmology likelihood can handle misclassifications (Vincenzi+21)

Helen Qu



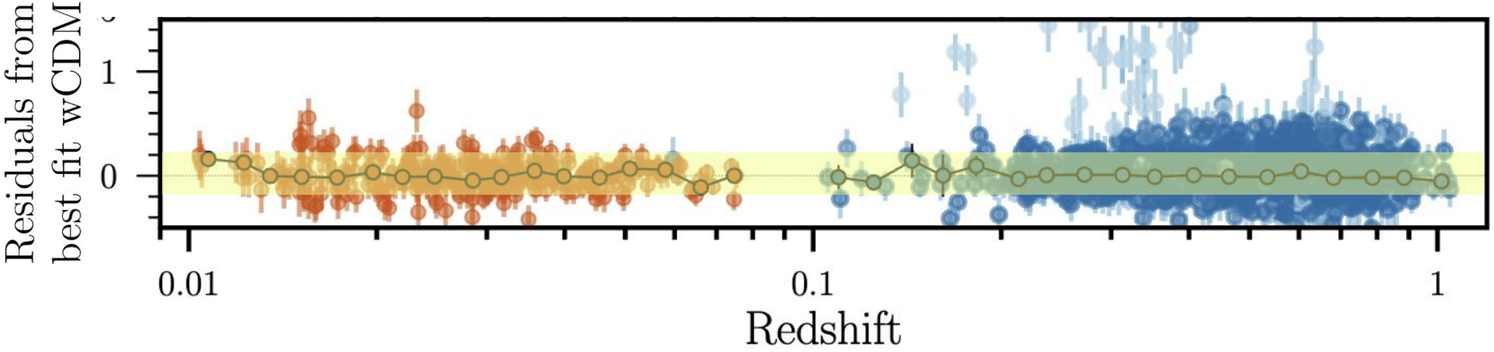
Anais Moller



Supernova Identification with Random Forest (SNIRF)

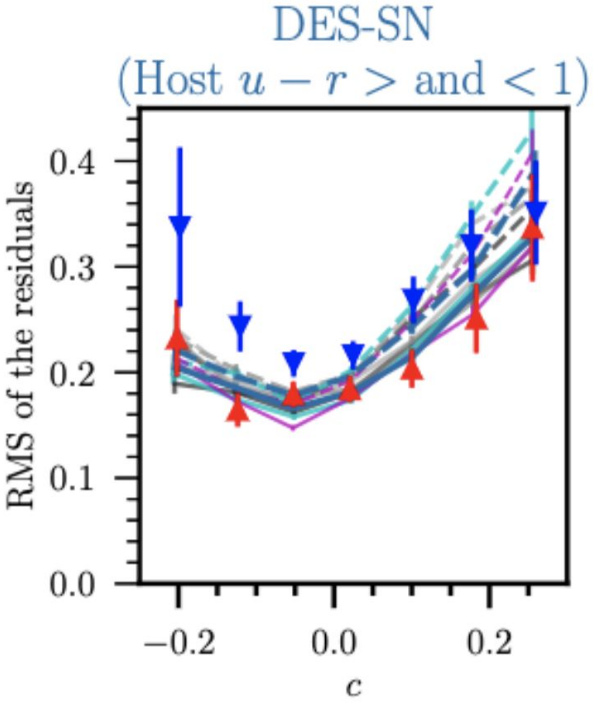
Eve Kovacs

Modelling SNe and their intrinsic/host properties



10% unexplained scatter

The intrinsic scatter of SNe Ia



Brodie Popovic

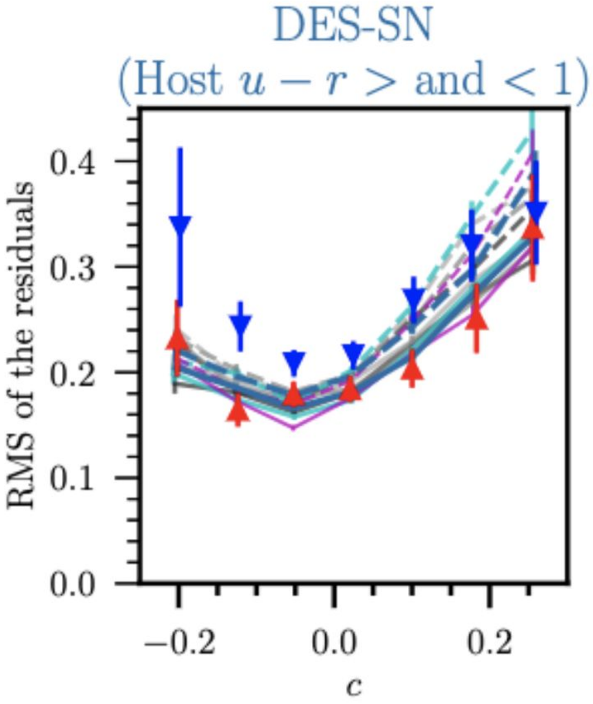
Phil Wiseman

Rebecca Chen

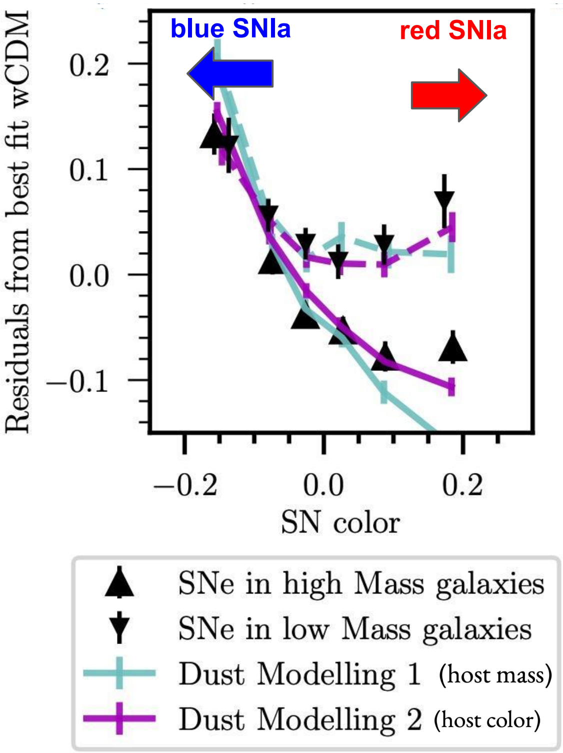
Lisa Kelsey

Popovic et al 2021, Kelsey et al 2022, Chen et al. 2022, Wiseman et al 2022

The intrinsic scatter of SNe Ia



Modelling extrinsic dust...



Brodie Popovic

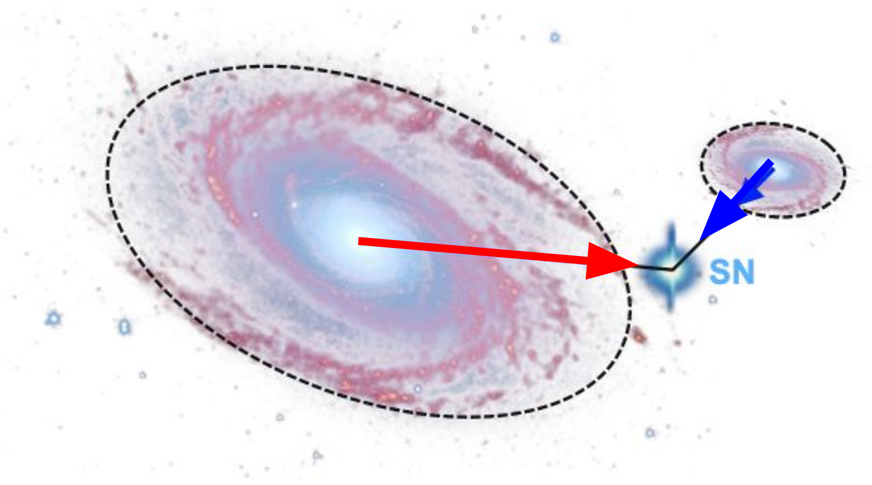
Phil Wiseman

Rebecca Chen

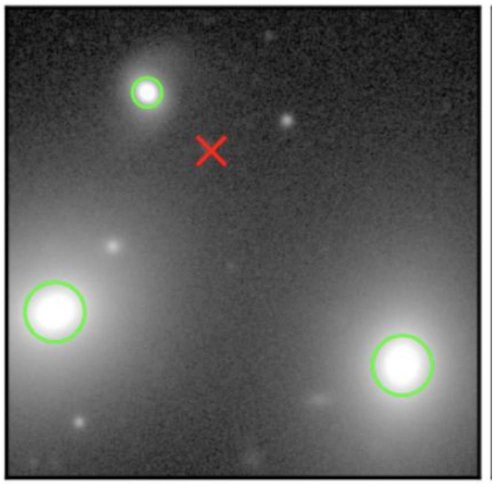
Lisa Kelsey

Popovic et al 2021, Kelsey et al 2022, Chen et al. 2022, Wiseman et al 2022

We've Done a Deep Dive on Host Galaxy Associations.



2008bf

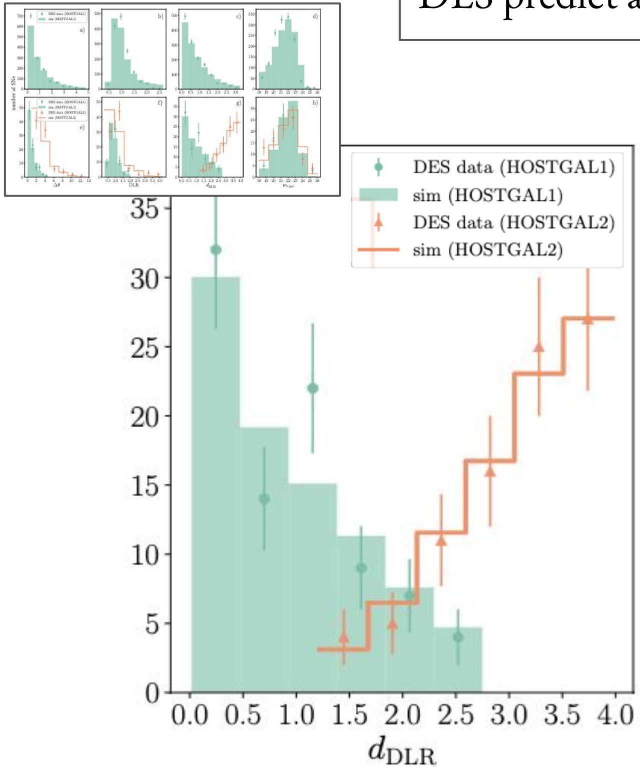


$$d_{\mathrm{DLR}} = \frac{\Delta\theta}{\mathrm{DLR}}$$

DES Deep Dive on Host Galaxy Associations.

Helen Qu

“Simulations that match a number of the host galaxy properties of DES predict a 1.4% missassociation rate.” - Qu et al. 2023



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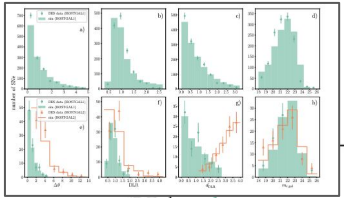
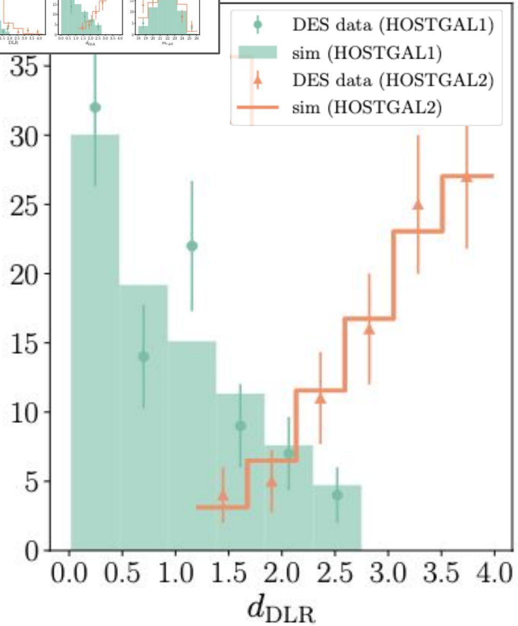
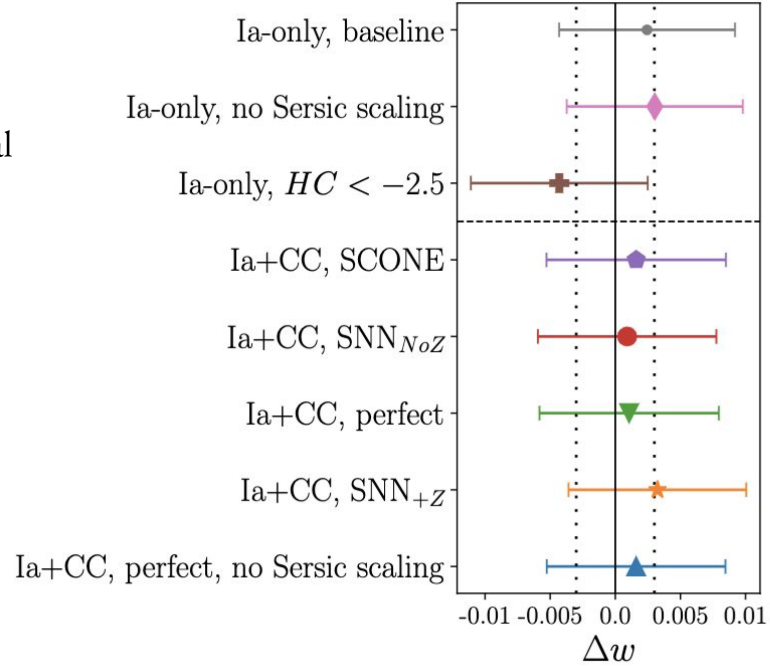




Also account for potential systematic variants in the methodology →



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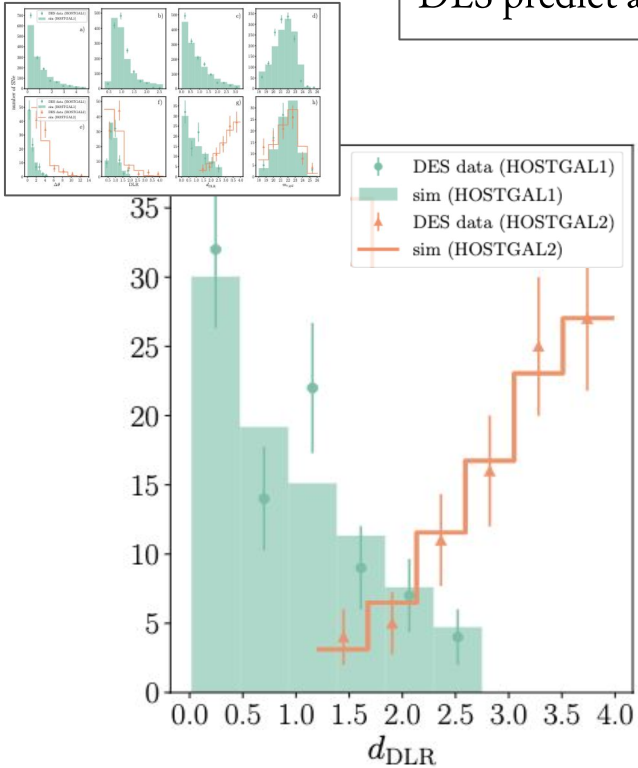
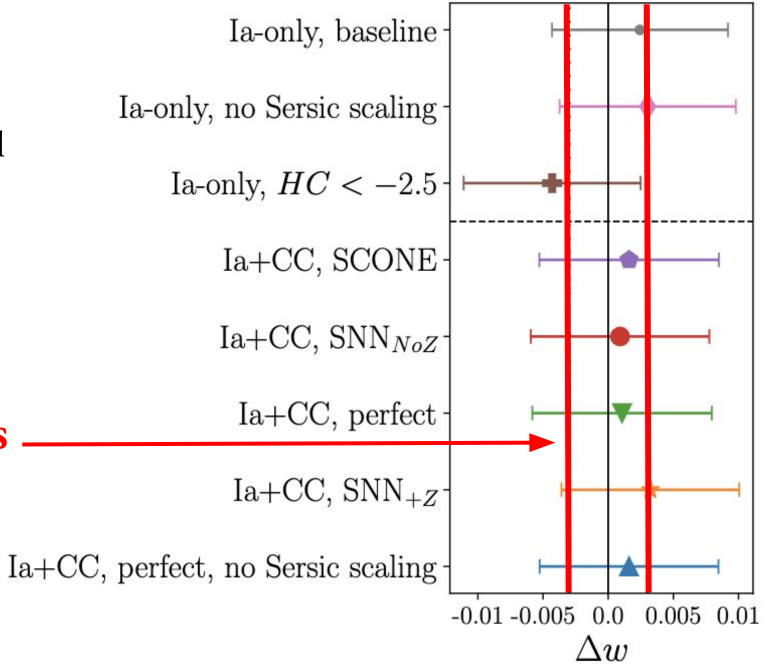
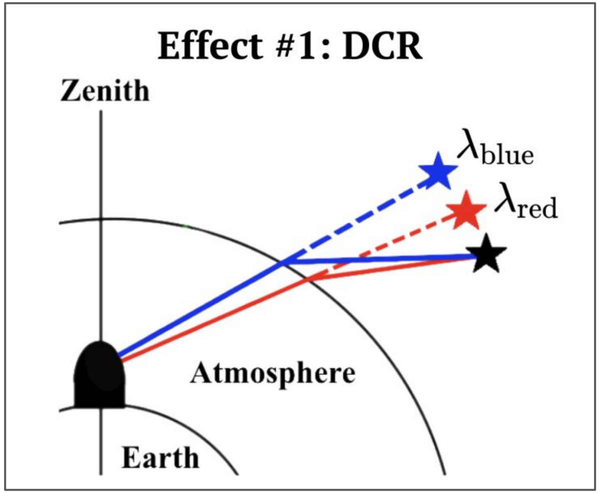


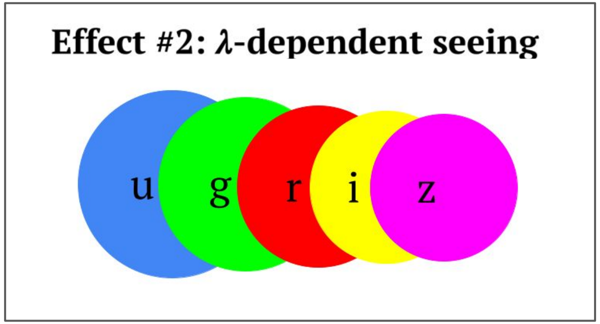
Also account for potential systematic variants in the methodology →

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

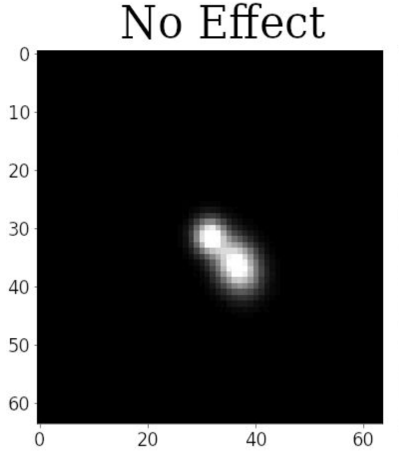


DES Now Accounting Atmospheric Effects





Exaggerated for visual impact



Lee,Acevedo et al. 2023

Jason Lee

Maria Acevedo

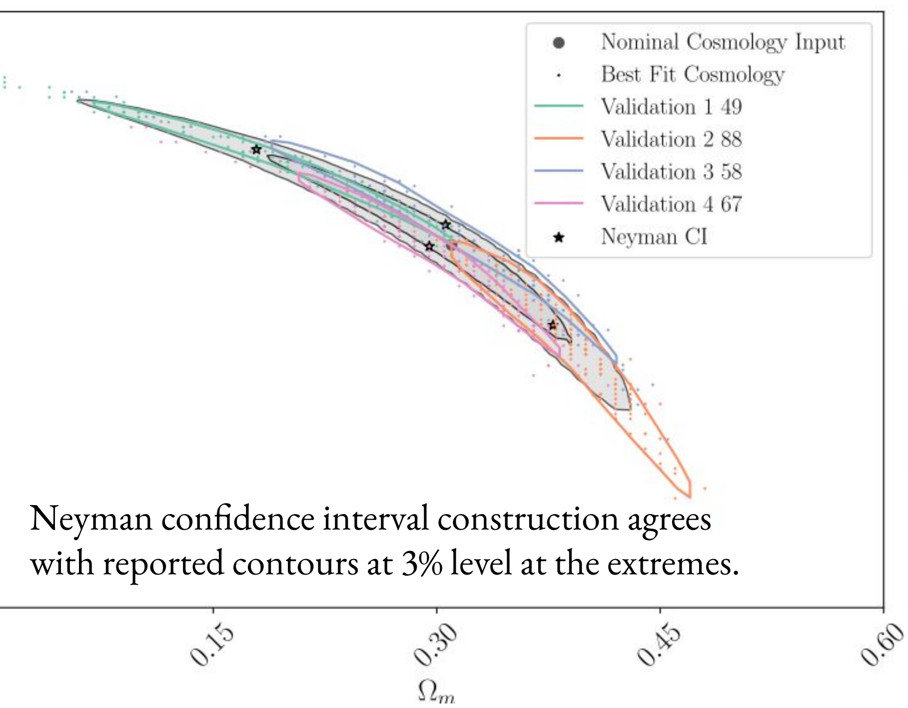
The typical SN Ia SED is very different (and evolves) compared to the typical stellar SED used for zeropointing.

Positional effects are subdominant to PSF shape and seeing effects for DES.

LSST will have better seeing, be observing in u band, and with wider range of airmass so this will be important to nail down (ongoing work w/ PIFF).

DES Analysis Methodology validation

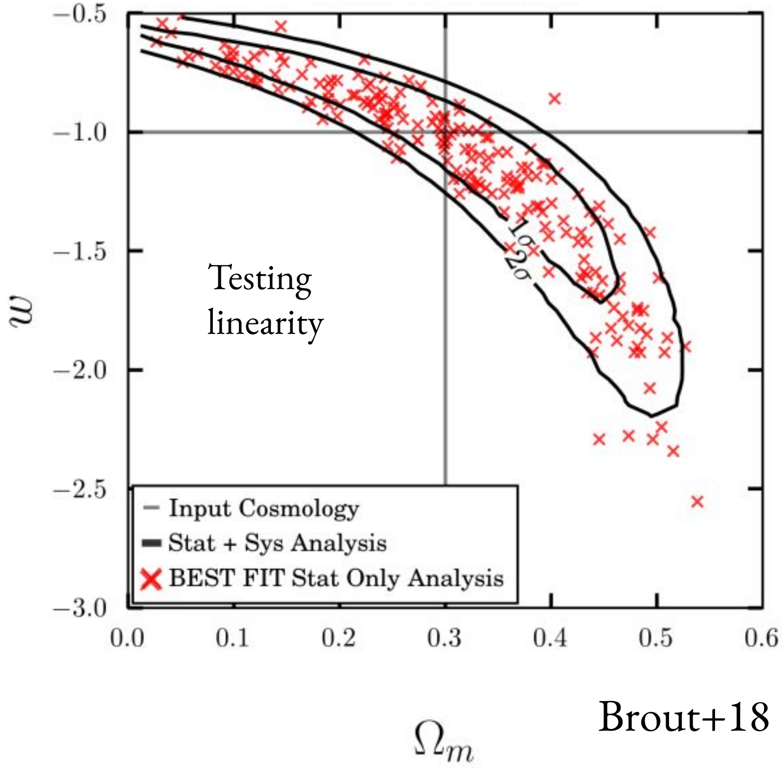
Statistical



Neyman confidence interval construction agrees with reported contours at 3% level at the extremes.

Armstrong et al 2023

Systematic



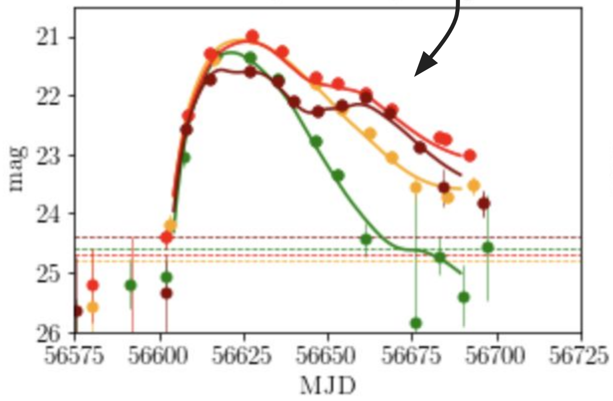
Testing linearity

Brout+18

We have pushed on the single largest systematic: SNIa Model Calibration

Georgie Taylor

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



Taylor et al, submitted

- **SALT3-GT** trained on x1.5 larger data
- **SALT3-GT** model rest frame wavelength range goes both **bluer** and **redder**, where DES has lots of high-quality data
  - **Blue** - because DES has lots of high redshift (z>0.9) data.
  - **Red** - Because of DECam's deep depleted CCDs at low/moderate redshift.
- Calibration systematic uncertainties incorporated in the light-curve model training process as well as the fitting process.
- Validation against previous models.

Binning is Sinning!

Binning is Sinning (Supernova Version): The Impact of Self-Calibration in Cosmological Analyses with Type Ia Supernovae

Brout, Hinton, and Scolnic et al 2020 - (applied to DES/LSST-like analysis in **Kessler, Vincenzi, and Acevedo in prep**)

Exoplanets

Binning is sinning: morphological light-curve distortions due to finite integration time

David M. Kipping[1,2]*

[1] *Harvard-Smithsonian Center for Astrophysics, 60, Garden Street, Cambridge, MA 02138, USA*

[2] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK*

David W Hogg
@davidwhogg

If "binning is sinning" then "stacking is hacking".

1:53 AM · Nov 20, 2018 · Twitter Web Client

Large Scale Structure

Two-point statistics without bins: A continuous-function generalization of the correlation function estimator for large-scale structure

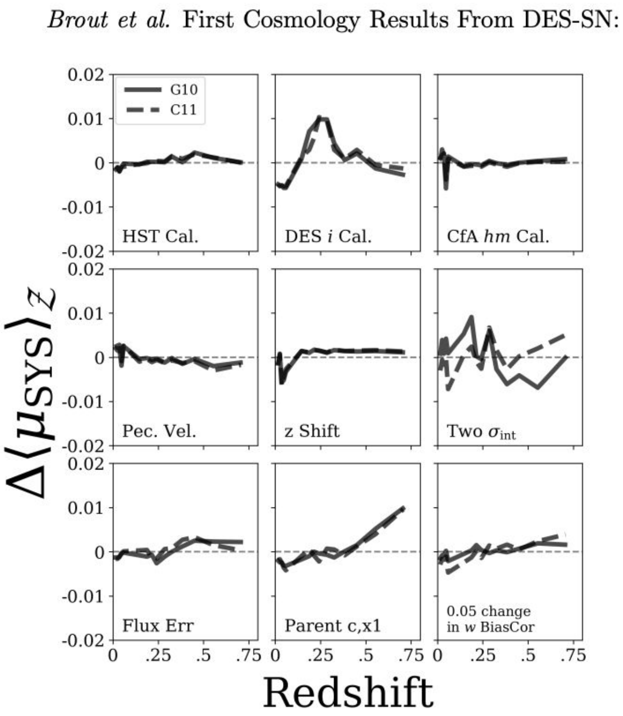
Kate Storey-Fisher[1] and David W. Hogg[1, 2, 3, 4]

Trash the bins! A new estimator for the 2-pt correlation function can provide a continuous estimation, no binning necessary - and it is more accurate with fewer components. This means fewer costly mocks, and even a direct measurement of the BAO scale! ✨ 🙌 ✨

@katestoreyfish

All recent SNIa cosmological analyses were "sinners".

DES3YR



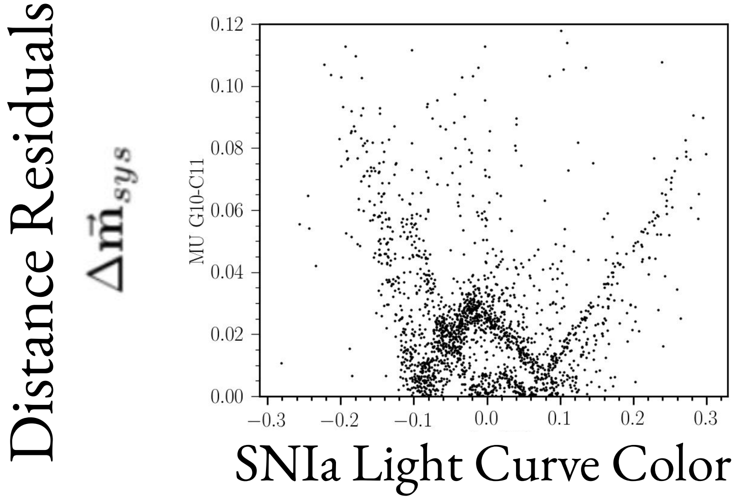
The Join Light Curve Analysis (2014)

and

Rubin LSST Science Requirements Doc (Mandelbaum+18)

Binning loses information

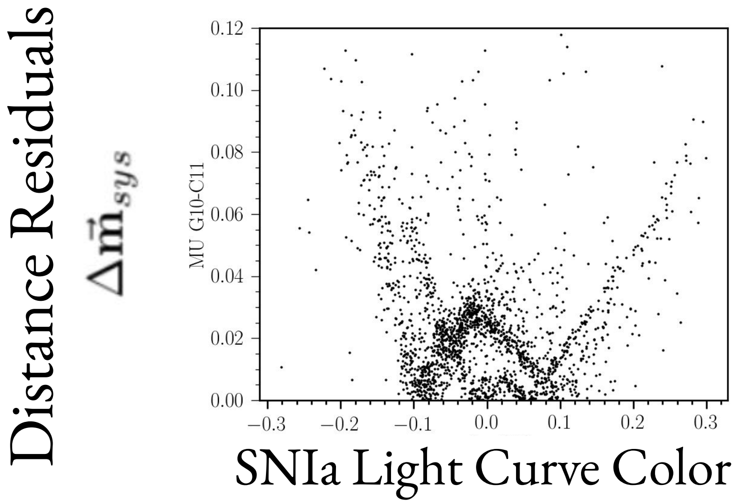
Collapsing all of this beautiful information about systematics into a single dimension - redshift

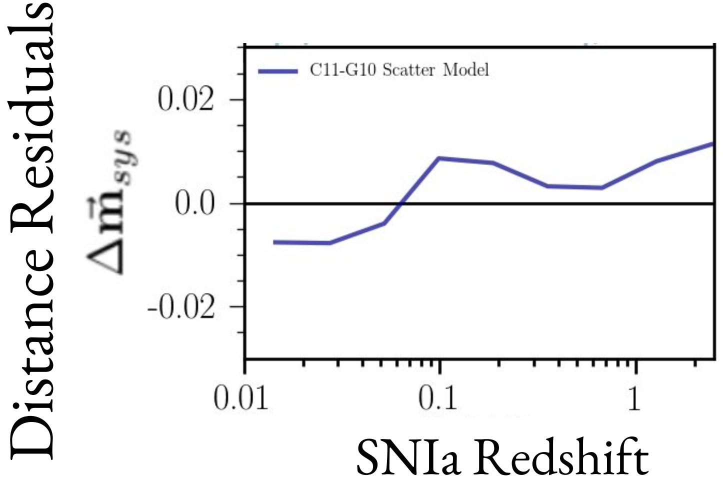


Binning loses information

Collapsing all of this beautiful information about systematics into a single dimension - redshift

And this dimension is degenerate with cosmology!





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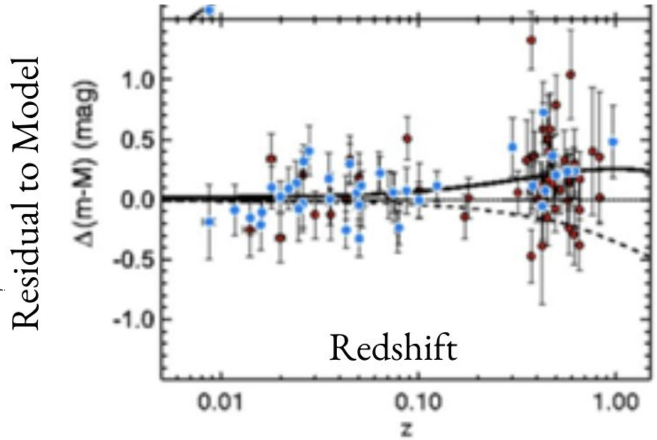
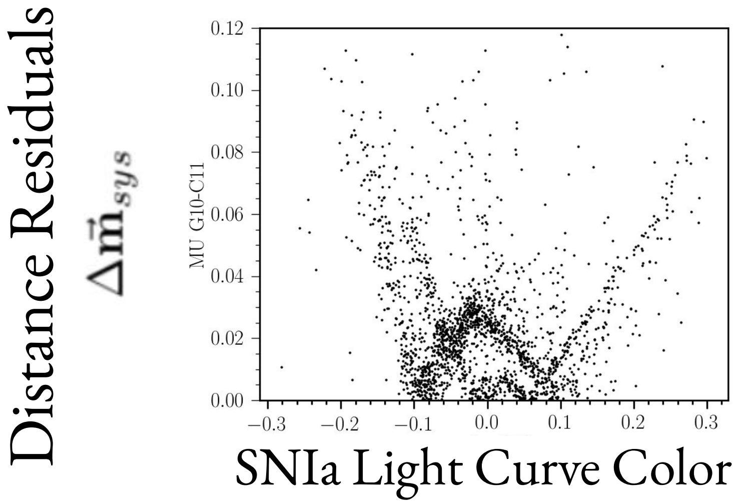
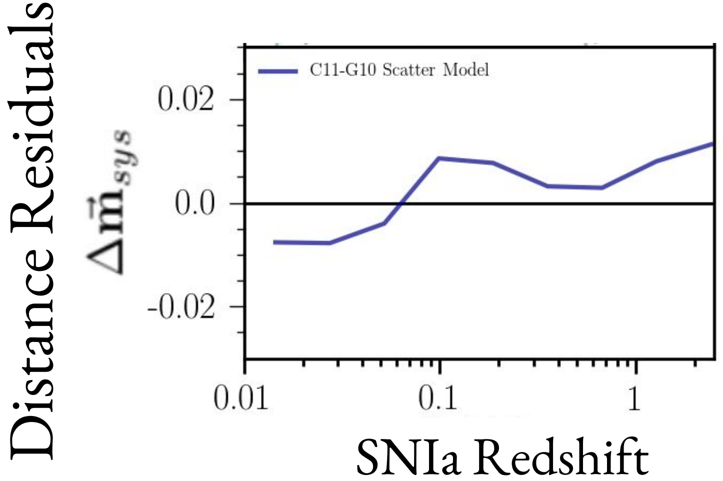
A



osmology!





Systematics can actually be 'self calibrated' down in size by the dataset itself.

Motivated by Faccioli+11

$$\Delta = \vec{\mathbf{m}}_{\rm nom} + S_{sys} \times \Delta\vec{\mathbf{m}}_{sys} - \vec{\mathbf{m}}_{\rm mod}(\Omega_M, w, \mathrm{H}_0)$$

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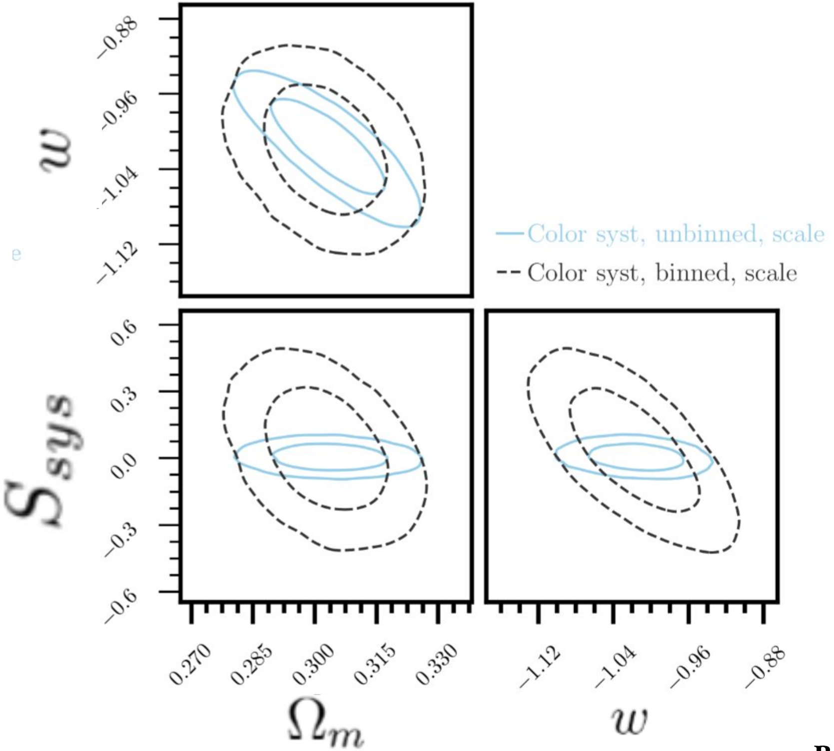
Color Dependent Systematic



Brout, Hinton, Scolnic 2020

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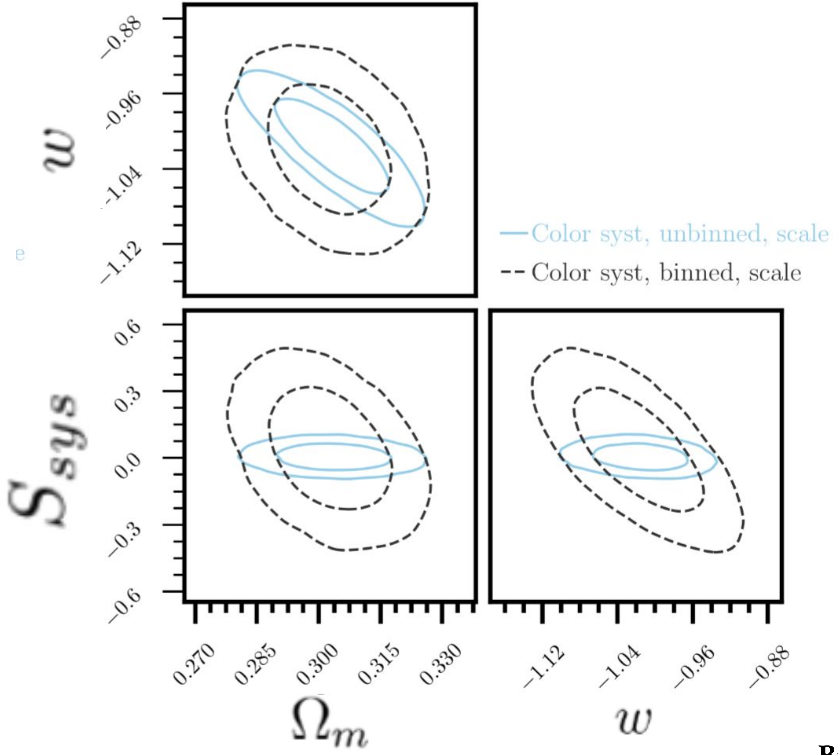
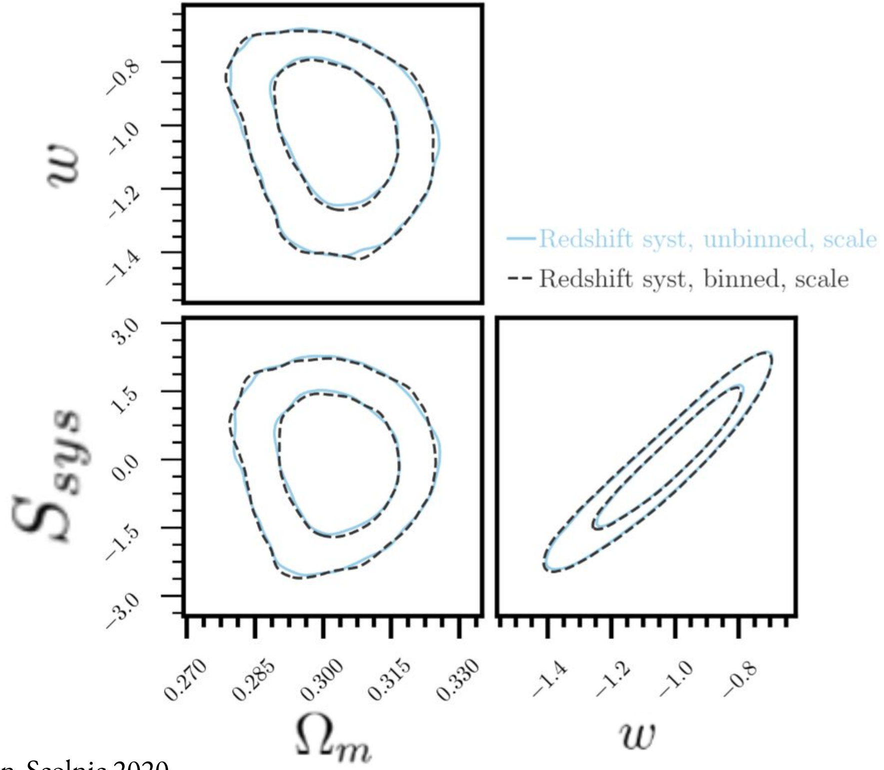


Redshift Dependent Systematic



Brout, Hinton, Scolnic 2020

Simply by not binning we get a factor of 1.5x reduction in systematics!

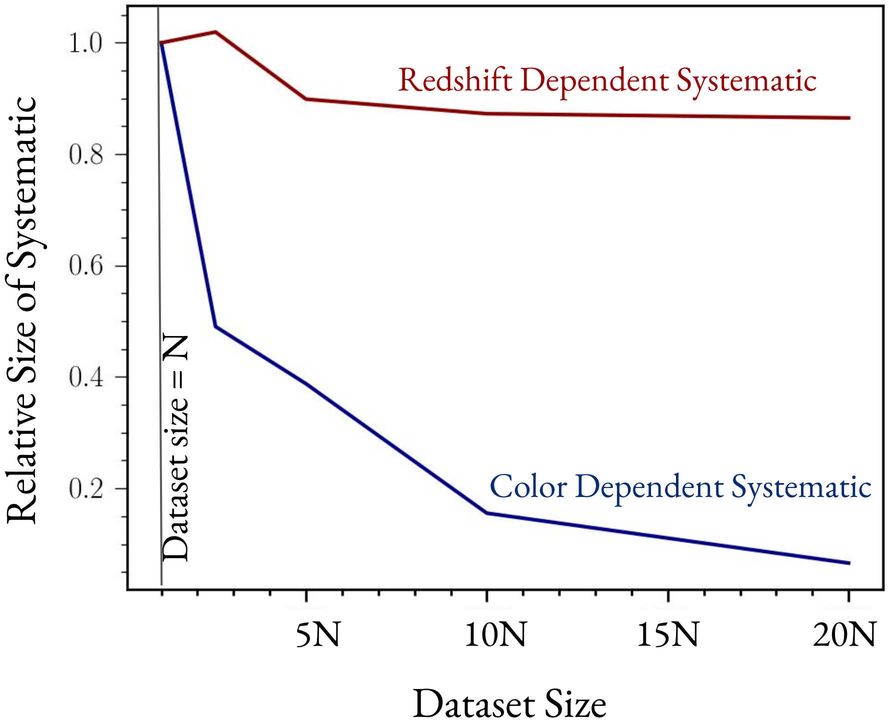
Table 6 of Brout+22

Description[b]	$\sigma w_{\mathrm{sys}}^{\mathrm{binned}}$	$\sigma w_{\mathrm{sys}}^{\mathrm{unbinned}}$
SN/Host Astrophysics	0.017	0.010
Calibration & Photometry	0.022	0.013
Survey Modeling	0.014	0.004
Redshifts	0.012	0.012
All Systematics	0.029	0.019

Factor of 1.5x

The kicker is that this systematic self-calibration ability grows with the size of your dataset!!!

Brout, Hinton, & Scolnic 2021



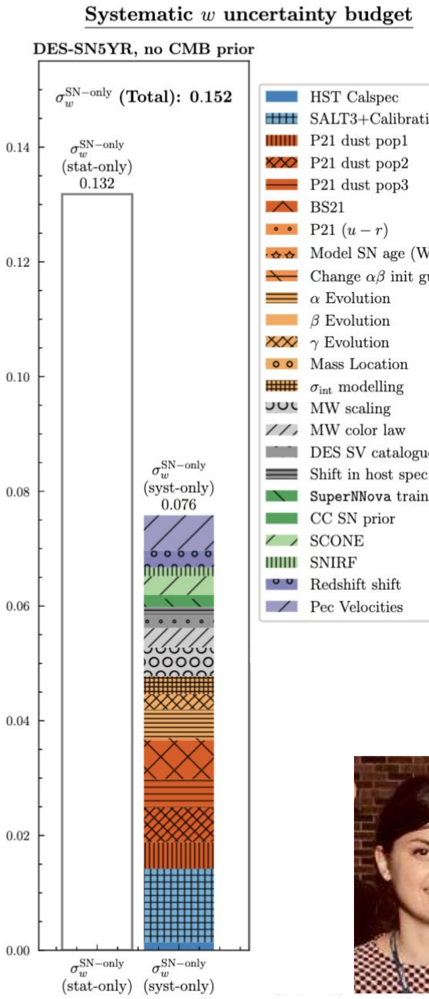
This is incredibly exciting for the next generation of experiments (e.g. LSST)

So what is driving our error budget?

Lessons learned from DES

30+ Systematic uncertainties but not dominated by systematics anymore!

Key takeaway is there aren't really any big killers that we don't foresee being able to push down the floor.



Vincenzi et al. in prep.

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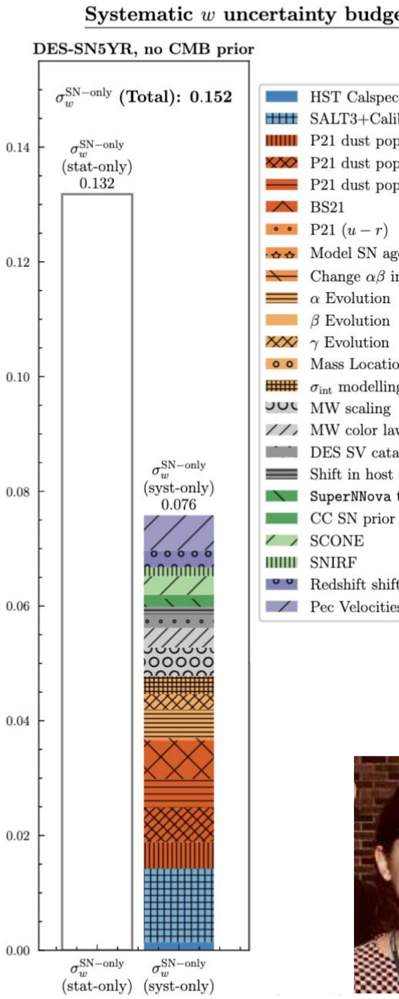
Smallest Systematic:

1. Classification! 🥳



Vincenzi et al. in prep.

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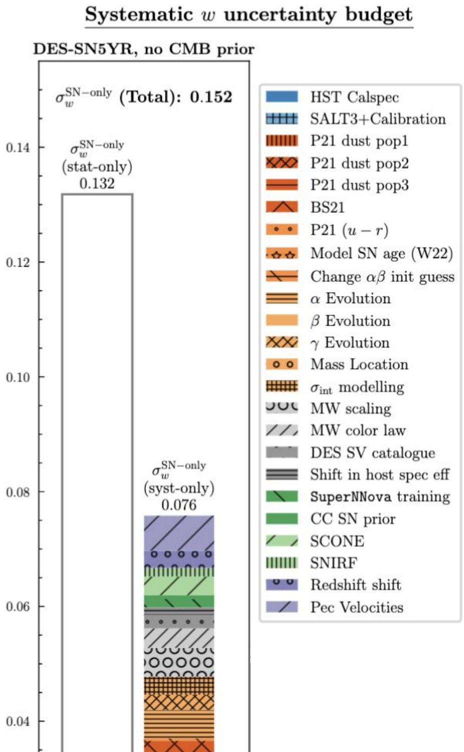
Smallest Systematic:

1. Classification! 🥳

Top Systematics (for traditional analyses):

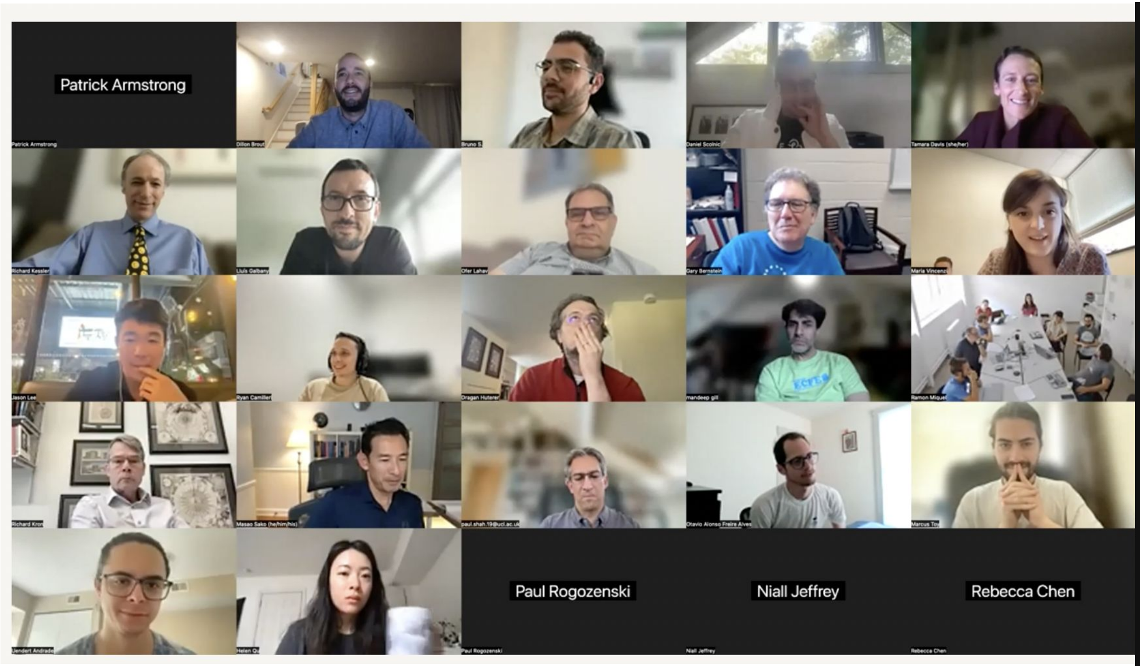
1. Calibration (training and fitting).
2. SN Host Dust Properties.

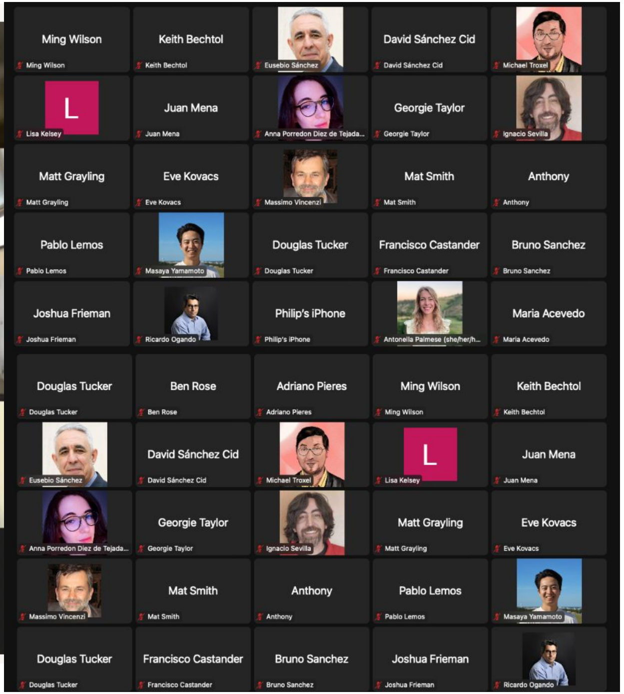
This is how we identify the critical path for LSST!



Vincenzi et al. in prep.

Unblinding Results





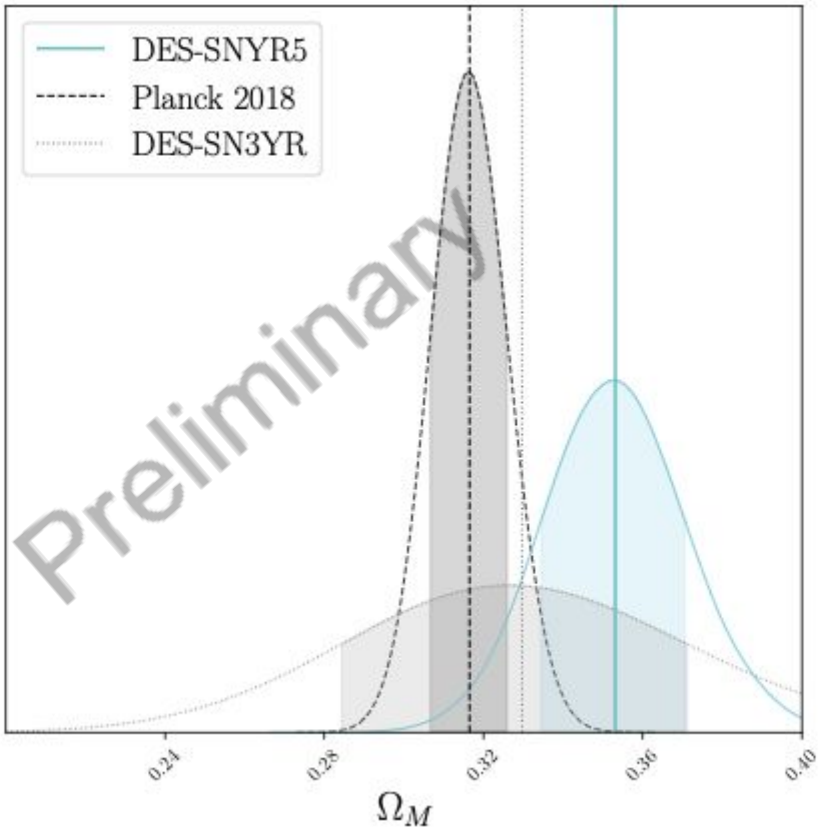
Flat-ΛCDM

Fitted parameters: $\{\Omega_M\}$

Alone and compared to DES3YR

Preliminary

Model	Ω_M
DES-SN3YR	0.331 ± 0.038
DES-SN5YR	0.353 ± 0.018



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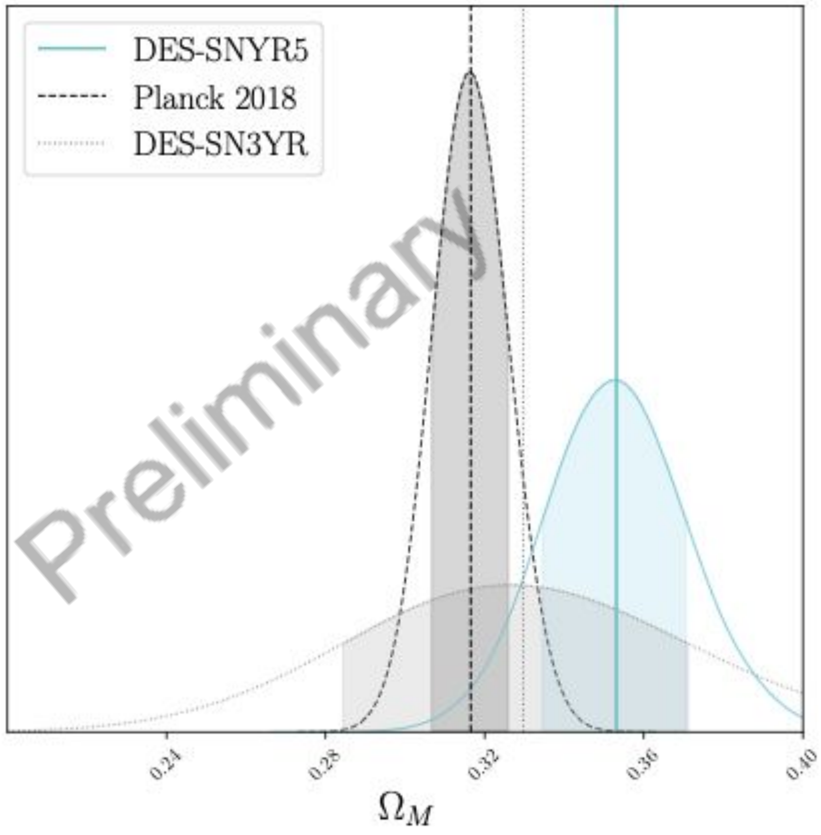


ΛCDM (curvature allowed)

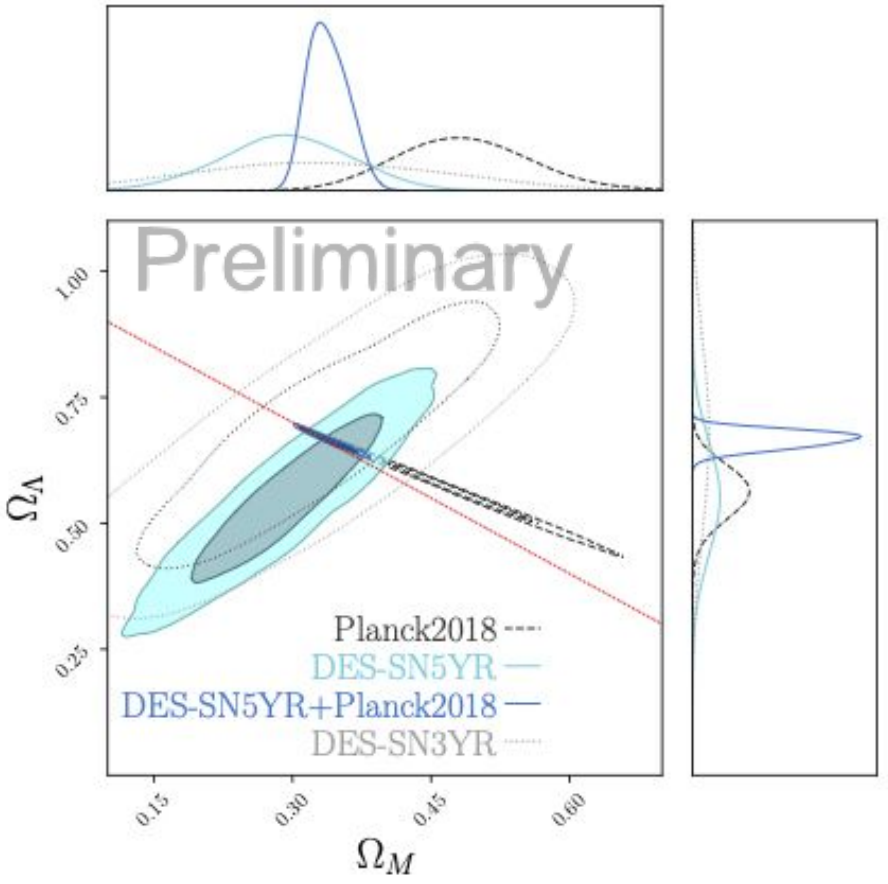
Fitted parameters: $\{\Omega_M, \Omega_\Lambda\}$

Preliminary

Model	Ω_m	Ω_Λ
DES-SN5YR	$0.290^{+0.075}_{-0.065}$	$0.55^{+0.11}_{-0.12}$
DES-SN5YR+Planck2018	$0.330^{+0.028}_{-0.017}$	$0.672^{+0.014}_{-0.022}$

Curvature Omega_k = 1.002 +/- 0.03

Need dark energy at >4.5sigma from DES5YR!



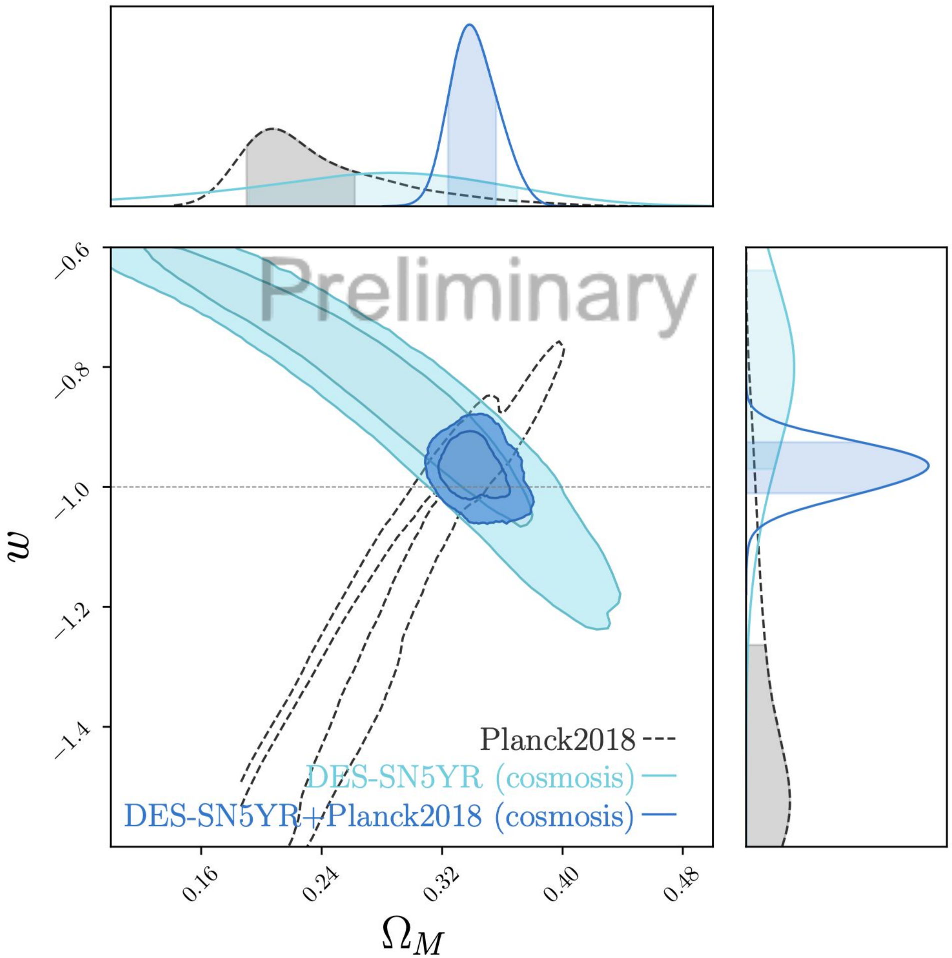
Flat-*w*CDM

Fitted parameters: $\{\Omega_M, w\}$

Alone and with a Planck prior

Preliminary

Model	Ω_m	w
DES-SN5YR	$0.284^{+0.092}_{-0.104}$	-0.80 ± 0.18
DES-SN5YR+Planck2018	$0.339^{+0.019}_{-0.017}$	$-0.967^{+0.047}_{-0.049}$

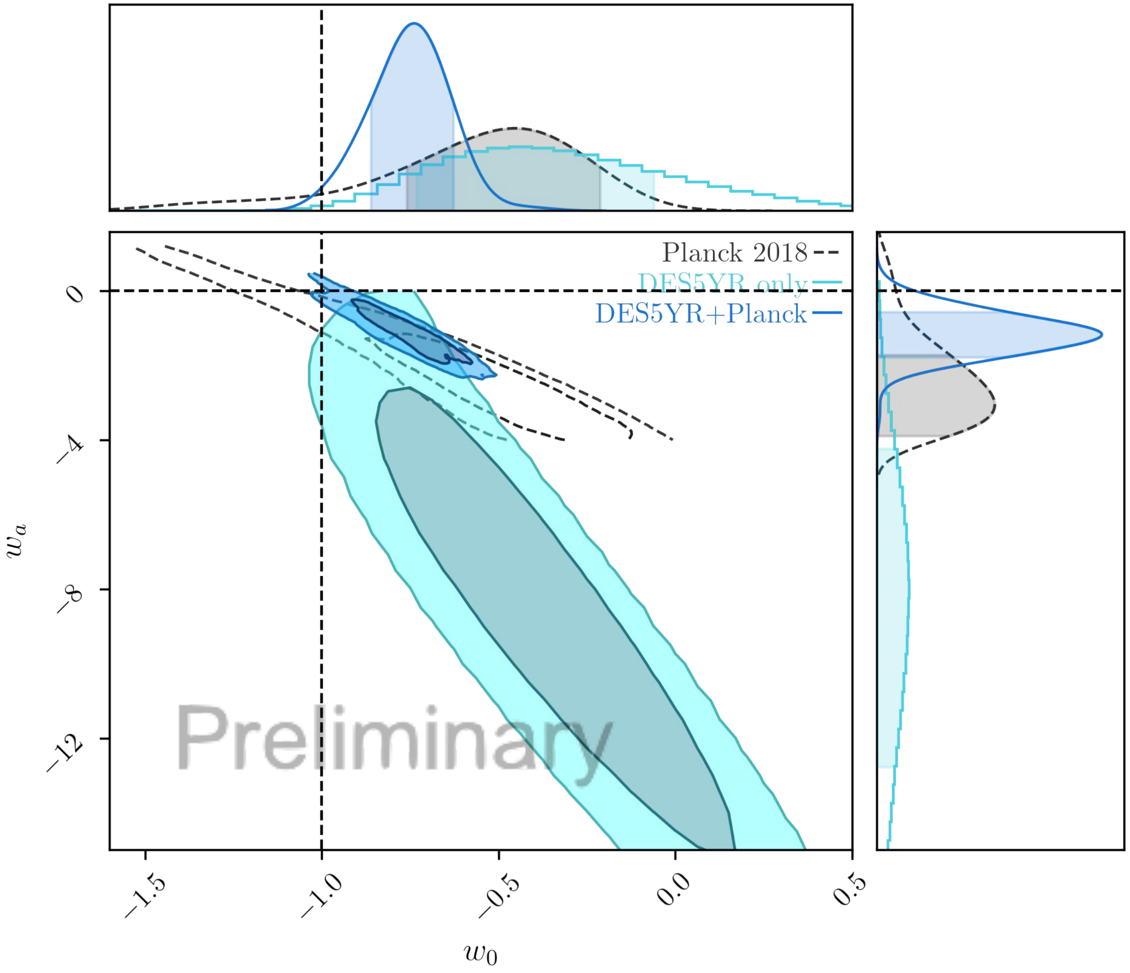


Flat-w_aCDM

Fitted parameters: {Ω_M,w0, wa}

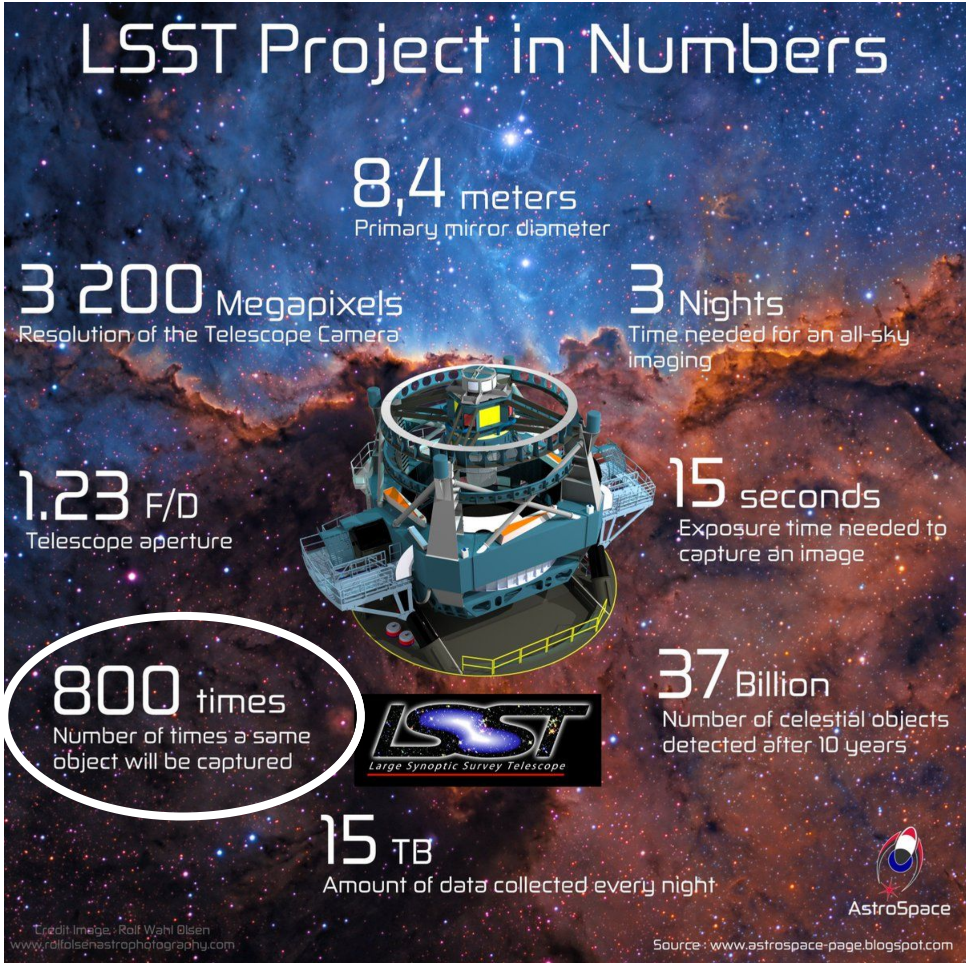
Alone and with a Planck prior

Model	w_0	w_a
DES5YR only	$-0.44^{+0.38}_{-0.29}$	$-8.0^{+3.8}_{-4.8}$
DES5YR+Planck	$-0.74^{+0.11}_{-0.12}$	$-1.17^{+0.62}_{-0.60}$



Coming soon! (~Summer 2025)

VERA C. RUBIN OBSERVATORY



Vera Rubin Observatory LSST SNe will be a revolution!

DES

Weak Lensing	5000 sqdeg

VERA C. RUBIN
OBSERVATORY

Vera Rubin Observatory LSST SNe will be a revolution!

	DES	LSST
Weak Lensing	5000 sqdeg	18,000 sqdeg

VERA C. RUBIN
OBSERVATORY

Vera Rubin Observatory LSST SNe will be a revolution!

	DES	LSST
Weak Lensing	5000 sqdeg	18,000 sqdeg
Supernova Ia	30 sqdeg	

VERA C. RUBIN
OBSERVATORY

Vera Rubin Observatory LSST SNe will be a revolution!

	DES	LSST
Weak Lensing	5000 sqdeg	18,000 sqdeg
Supernova Ia	30 sqdeg	18,000 sqdeg

VERA C. RUBIN
OBSERVATORY

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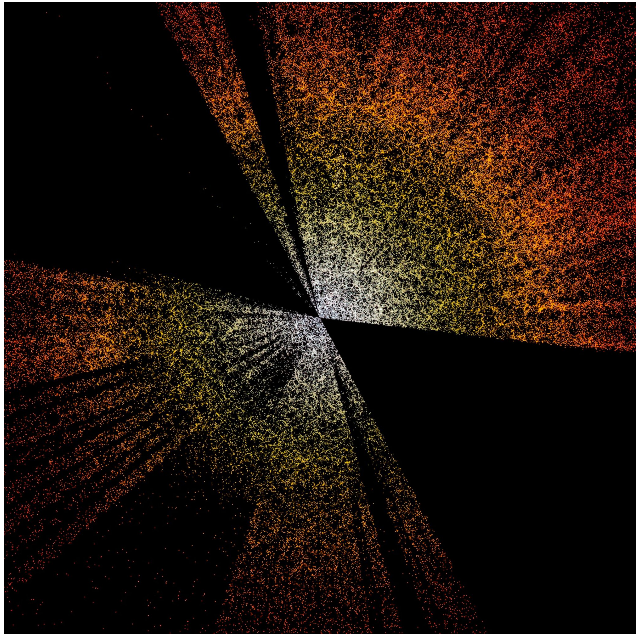
LSST is fundamentally a time domain survey of the ***entire*** night sky.



Summary and Conclusion

- DES photometric SN sample is the **largest** and **deepest** SN sample (0.1<z<1.2)

- **Improved modelling** of:
  - host galaxy and selection effects;
  - contamination from non-Ia
  - dust and intrinsic SN properties

- A leap in understanding and treatment of systematics!

- Hints at interesting physics on the horizon when comparing with Planck/CMB.

- DES has significantly shaped the priorities of future surveys like that of Rubin LSST to make them a success.

THE DARK ENERGY SURVEY

Thank you to:

DECam builders

DES shift-takers

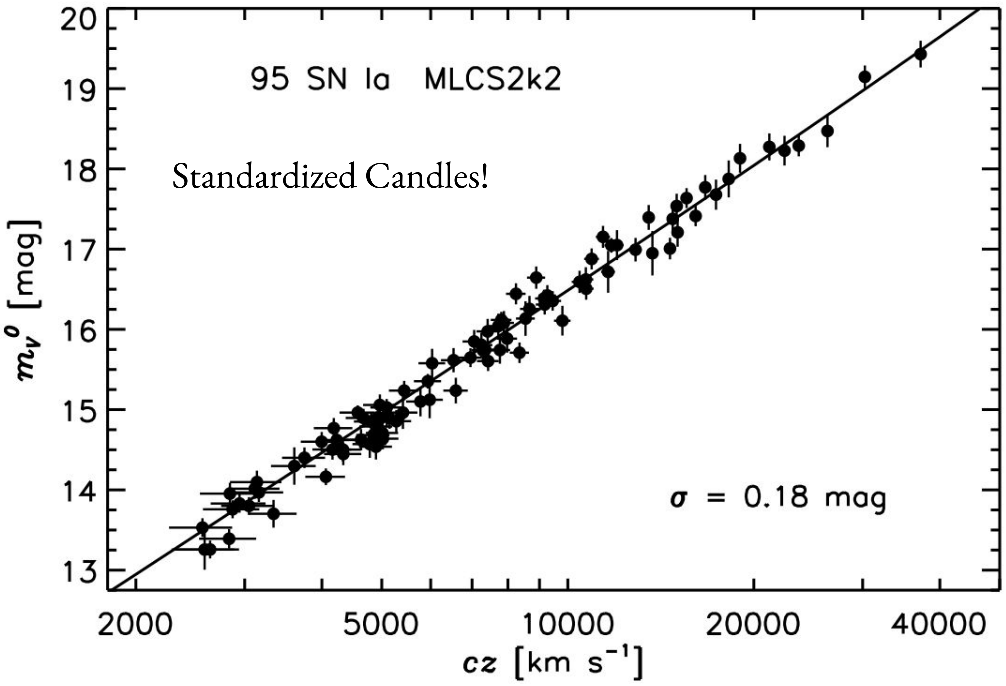
Data Processing

OzDES

Calibration

The straightforward answer to SNIa Evolution

Jha, Riess, Kirshner 2007



How do we know?

SNIa in the smooth `Hubble Flow' are the key.

e.g. for 0.02<z<0.1, z_obs ~ z_cosmological

We can compute relative distances with negligible dependence on cosmological parameters… (there is no H0 in this plot)

This Hubble Flow sample spans the full range of SNIa light curve parameters, host types (ages, masses etc).

Conclusions and Future

THE DARK ENERGY SURVEY

DES Photometric sample is the largest and deepest SN sample ($0.1<z<1.2$)

Excellent modeling of survey and non-Ia contamination in the Hubble Diagram suggests that biases are $<1\%$ when using deep learning photometric classifiers.

This dataset is an important testing ground for Vera Rubin so I encourage you to get your hands dirty with real SN data!

Beyond Standard Ia Cosmology

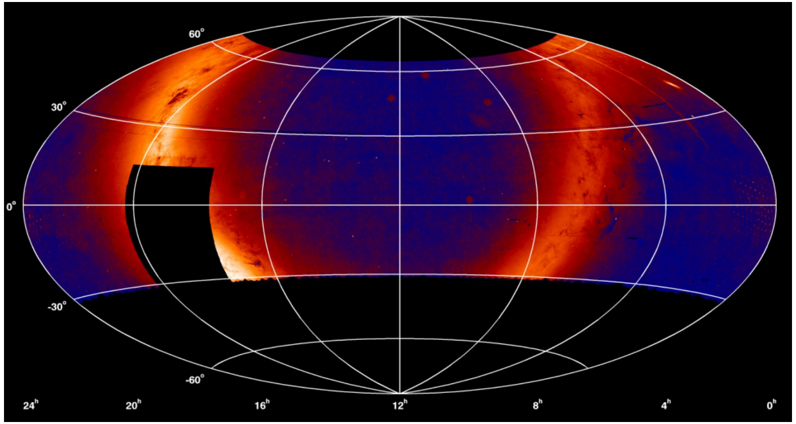
- **Cosmology with SNe Ia in LRGs** (Chen et al. 2022)
- **SLSN Cosmology** (Inserra et al. 2020)
- **SN II Cosmology** (De Jaeger et al 2020)
- **Weak Lensing of SNe Ia** (Macaulay et al 2020)
- **SN Ia rates** (Wiseman et al 2020)
- **Core collapse templates and luminosity functions** (Hounsell et al in prep)
- **Exotic Transients** (Pursiainen et al 2020, Gutierrez et al 2020, Wiseman et al 2020b, Grayling et al 2020, Angus et al 2019)
- and more!

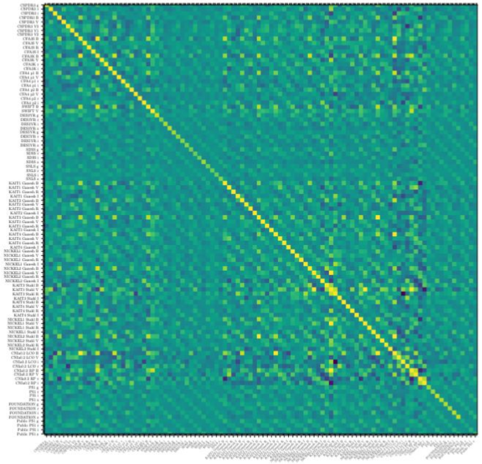
The Cross Calibration of SN Surveys (Brout et al. 2023b)

-Retrains SN Ia model on newest calibration

-Calibrated Filter Covariance

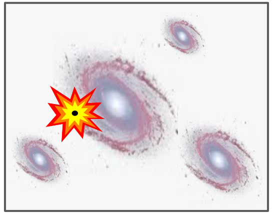
Utilizes PS1 all sky catalog to tie all 18 surveys together.





2. Modelling the sample and the survey

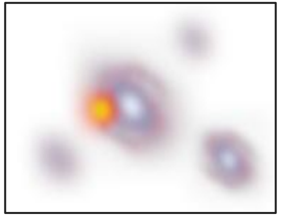
i.e. simulating a DES sample that looks like the “true” sample



Model the astrophysical components:

- Supernovae (Ia & “contaminants”)
- Galaxies (star-forming, passive)
- Dust

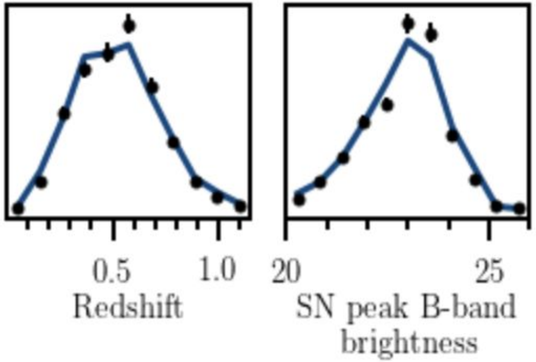
+



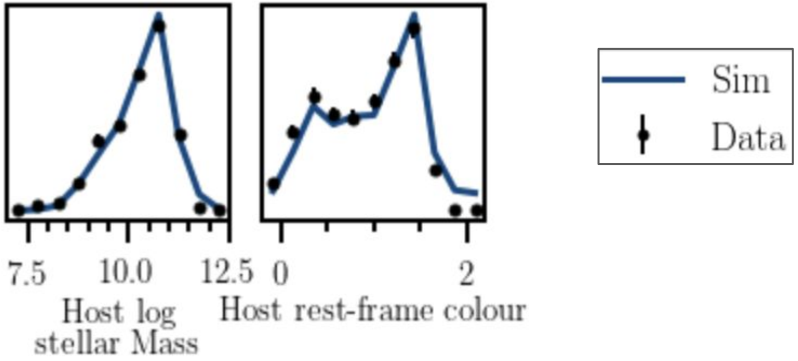
Model the survey

- observational noise,
- selection effects,
- cadence...

Modelling SN properties...



...and their host galaxies.



MV et al. 2019, **MV** et al. 2020