The Hubble Constant with Type Ia supernovae

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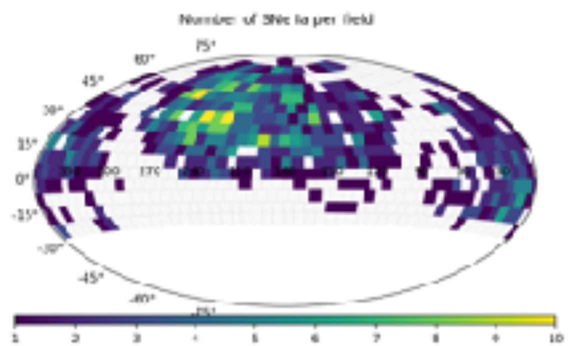
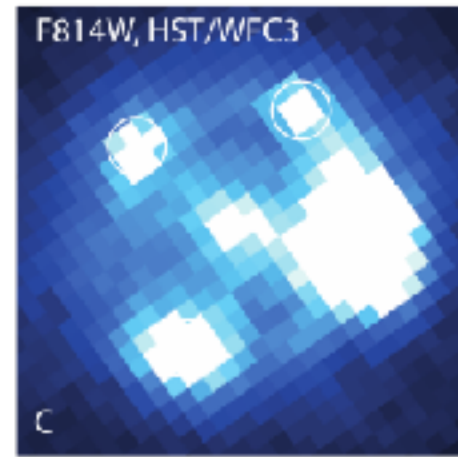
& iPTF /ZTF Cosmology Groups**

IIT-H Seminar, July 19 2021

Outline

Motivation: Why Type Ia supernovae





Dust + systematics

Mortsell, .., **S.D.** 2021a
Mortsell, .., **S.D.** 2021b

Distance ladder with ZTF

Dhawan et al. 2020c
Dhawan, Jha, Leibundgut 2018
Dhawan et al. to be submitted

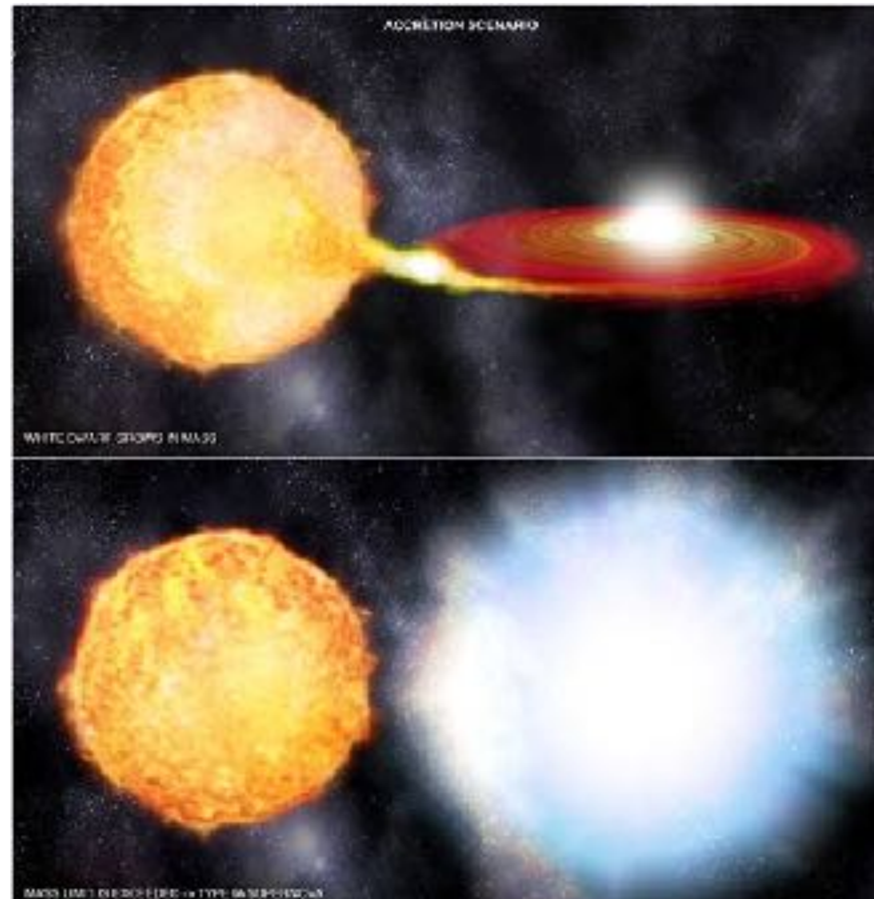
Strongly lensed Supernovae

Dhawan et al. 2020b
Mortsell et al. 2020
Johansson et al. 2020

What are Type Ia supernovae?

Bright, stellar candles

NOT standard; calibratable



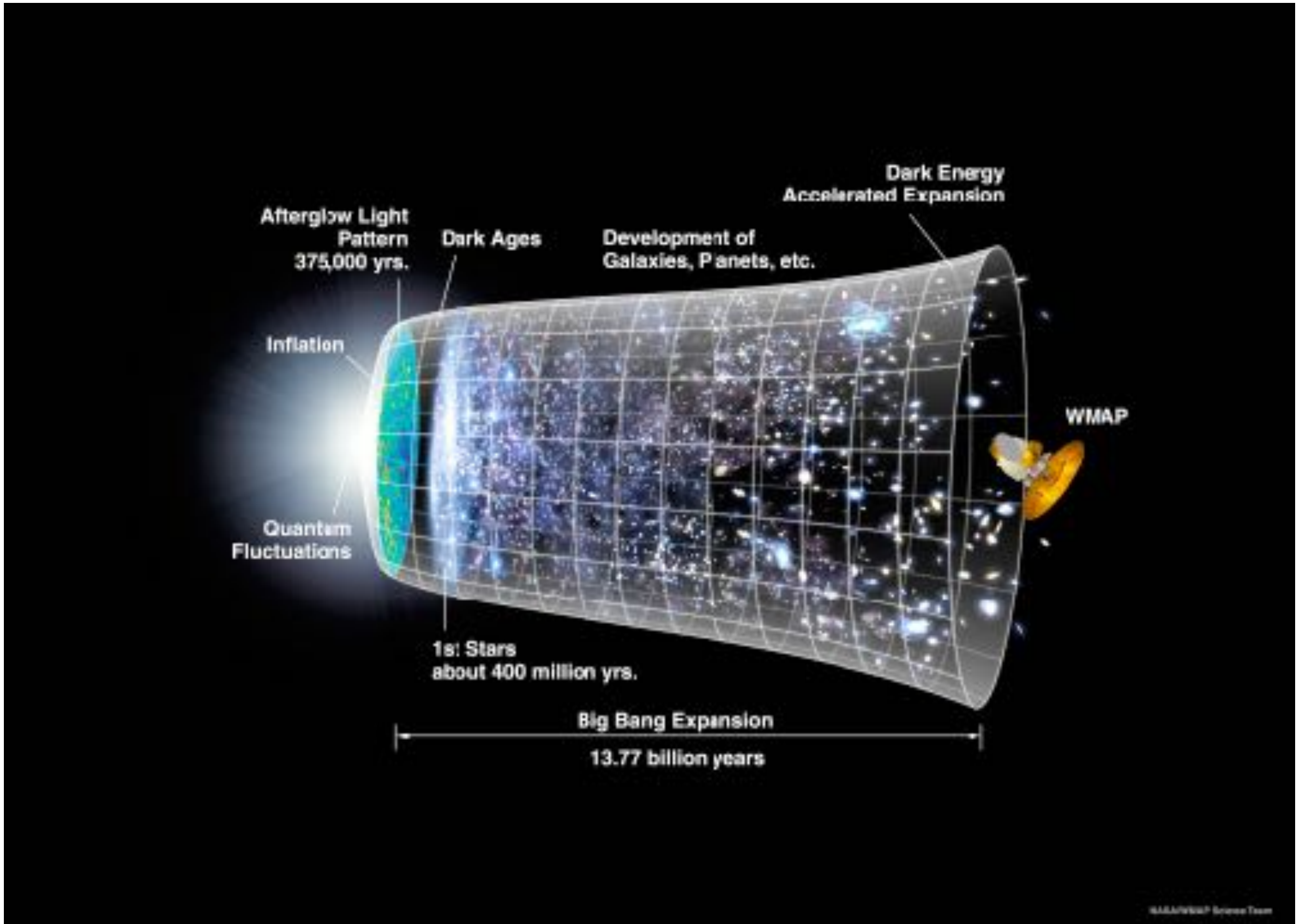
Used in discovery of dark energy

In all types of galaxies

Expansion history

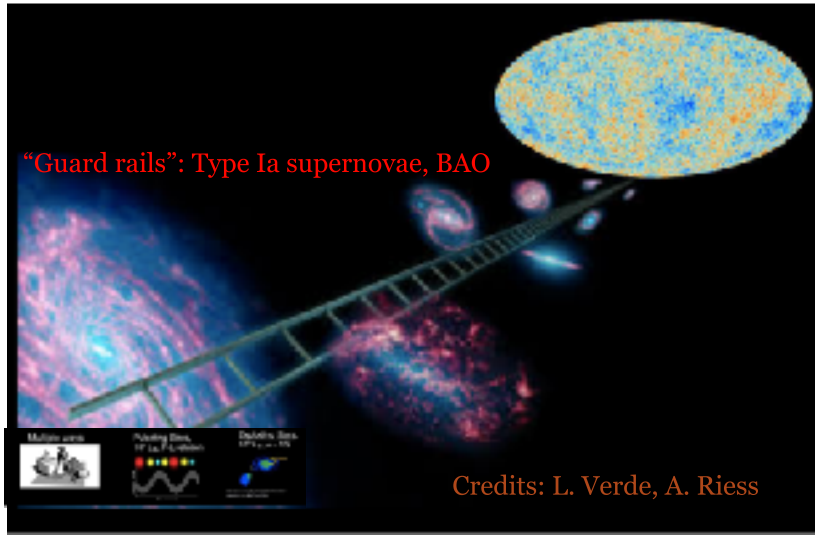
- What causes accelerated expansion?
- What is the rate of current expansion?

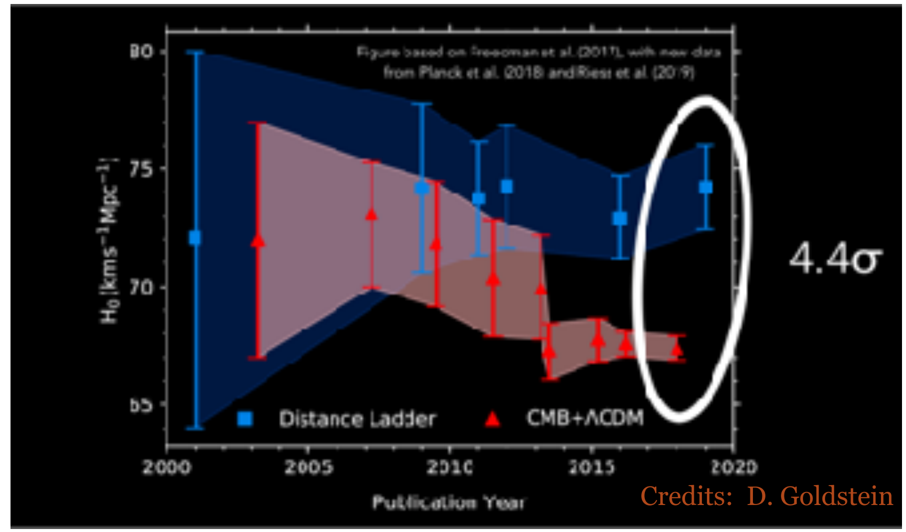
- Constrain growth of structure



Measuring H_0

- H_0: Absolute scale of the universe
- End-to-end test of background expansion



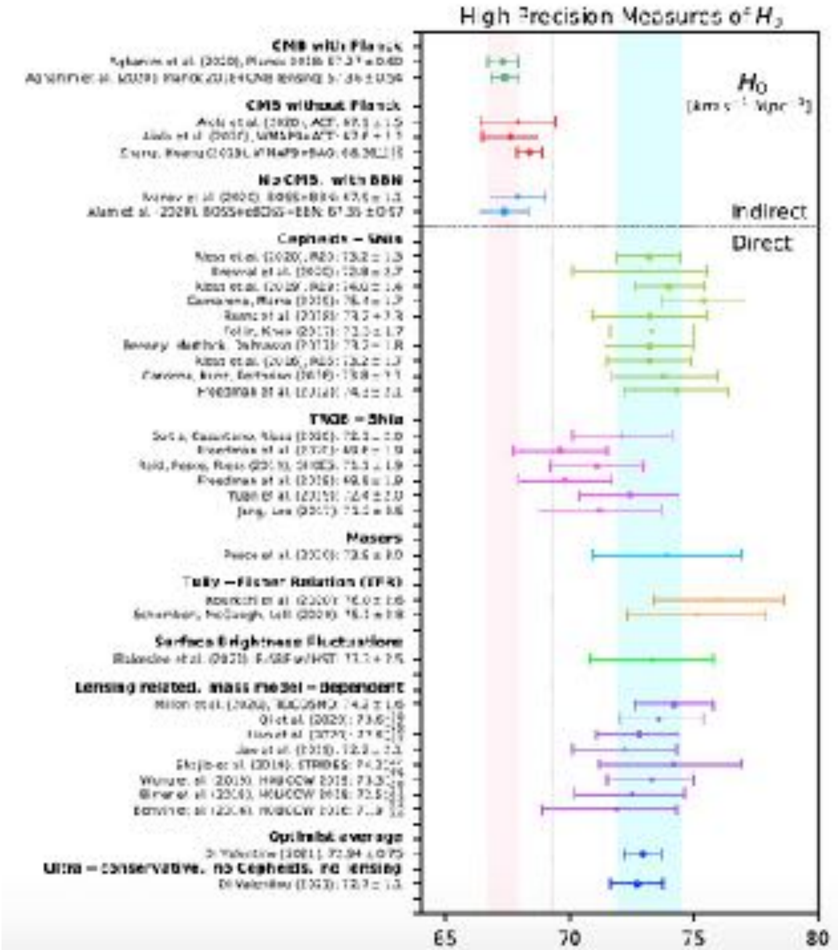


- New physics? (No clear solution, currently, e.g. Knox + Millea 2018)
- Unknown Systematics?

Need independent checks

- Unaccounted for systematics
- Independent distance ladder
- Novel absolute distance measurement (e.g. lensed transients, standard sirens)

Current Status



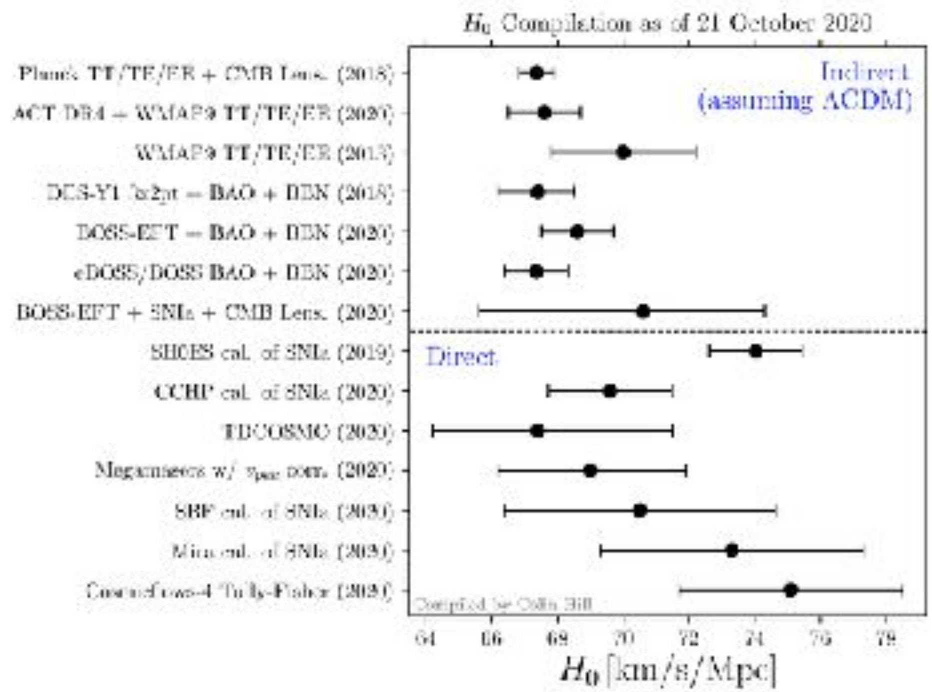


Figure from review by Di Valentino et al. (left) see also Hill et al. (right)

Local distance ladder H_0

Second rung: peculiar velocity noise
Third rung: Absolute luminosity calibration

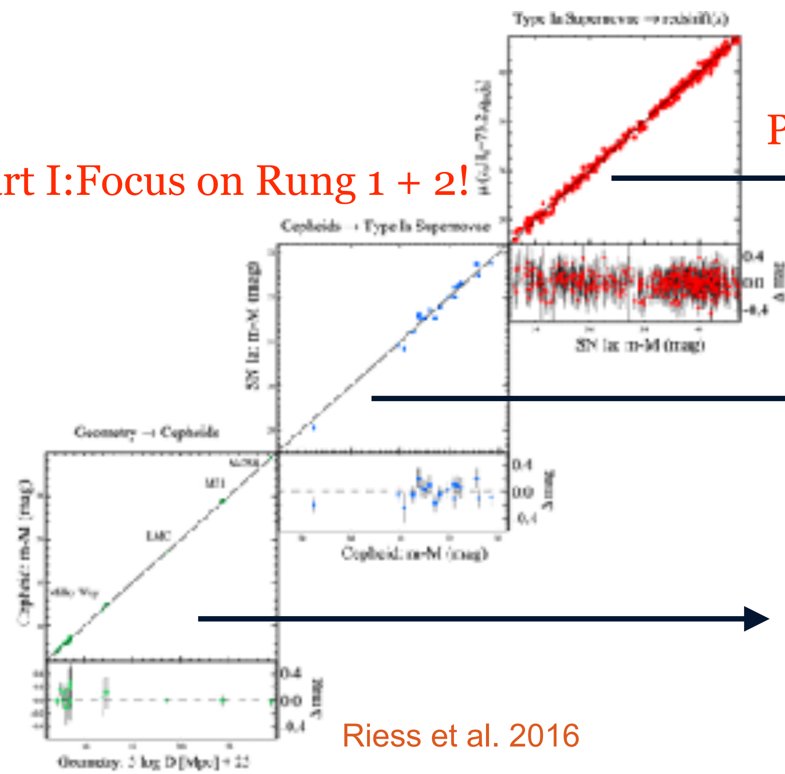
- Type Ia supernovae: Hubble flow (0.03 < z < 0.15)
    - Calibrated with Cepheid or TRGB distances
    - Second rung calibrated with independent, primary anchors

SNe Ia need to be standardised in the **OPTICAL**

Robustness tests
- primary rung (e.g. Breuval+ 2020)
- secondary rung (e.g. Follin + Knox 2018)
- Bayesian Hierarchical Model (Cardona+2017, Feeney+2018)
- tertiary rung: presented here

Part II:Focus on Rung 2 + 3!

Part I:Focus on Rung 1 + 2!



~ 200 Type Ia supernovae; Multiple surveys

19 distances to SN hosts: Multiple systems/surveys

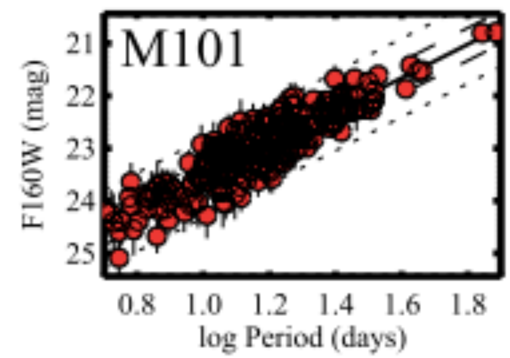
Several primary calibrators: Independent cross-checks

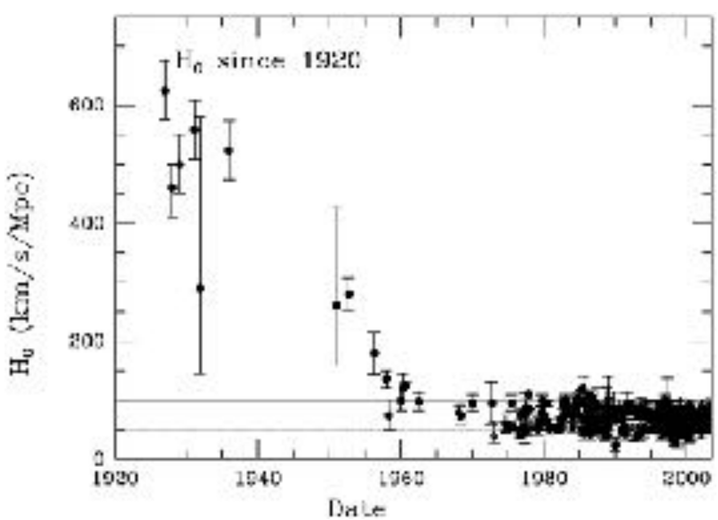
Riess et al. 2016

Cepheids as distance indicators

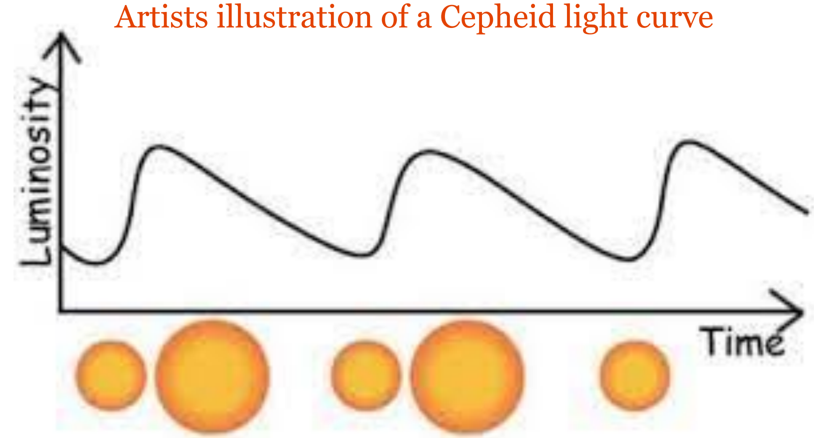
- Pulsating variable stars
- Developed as precise distance indicators
- Correcting for Period - Luminosity (P-L) relation (Leavitt + Pickering 1912)
  - Correct for colour: the "Wesenheit" relation
  - Metallicity - luminosity relation

Minimise corrections by observing in the NIR





Artists illustration of a Cepheid light curve



Dust as a systematic

- Parametrised by total to selective absorption R_V
- Milky Way dust properties vary
    - Ensemble average is ~ 3.1; sightlines vary from 1 -> 6
- Shifts luminosity in one direction => i.e. dimming
    - Reddens the source SED

Small, non-negligible differences in the NIR

The Astrophysical Journal, 886:108 (24pp), 2019 December 1 Fitzpatrick et al.

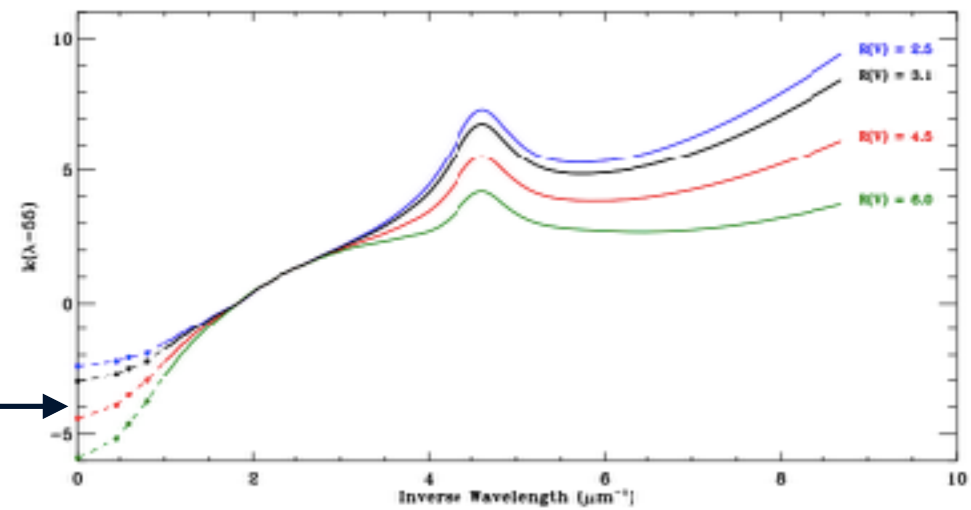


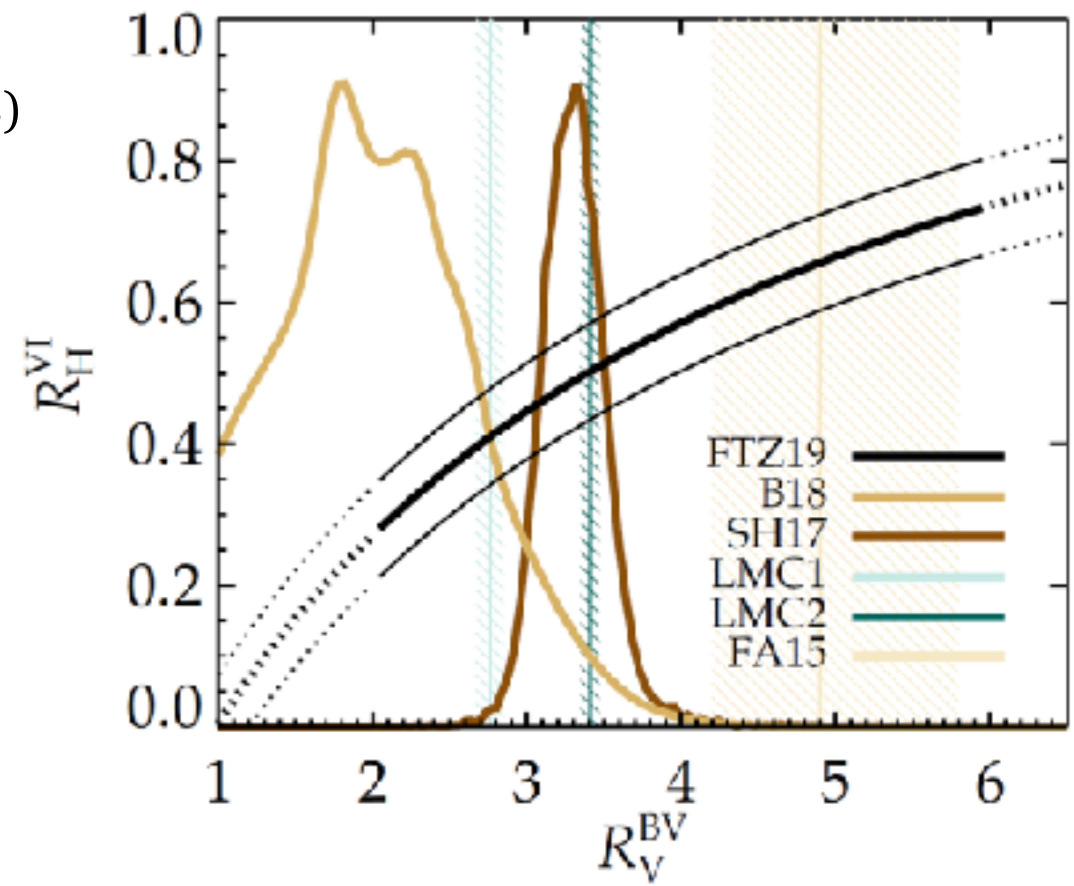
Figure 8. $R(V)$-dependent NIR-through-UV extinction curves from this study, shown for several values of $R(V)$. The curves were produced from the data in Table 3 using Equation (9).

Motivation to explore

Dust properties vary a lot!

Varying sightline seen in MW, LMC
High R_v in N4258

Non-MW R_v: in SN hosts (B18)



$$R_H^{VI} \sim R_W \sim R_E$$

Oskar Klein centre

Cepheid colour calibration

- 1) Wesenheit magnitudes

Madore 1982

$$m_H^W = m_H - R_W(V-I)$$

2) Colour excess calibration

$$m_H^W = m_H - R_E\,\hat{E}(V-I)$$

$$\hat{E}(V-I) = (V-I) - \langle V-I\rangle_0$$

Case 1) in fiducial SHOES analyses; $R_E = R_W = 0.386$, motivated by Fitzpatrick dust law $R_V = 3.1$ for all galaxies

How a differential R_E impacts H_0

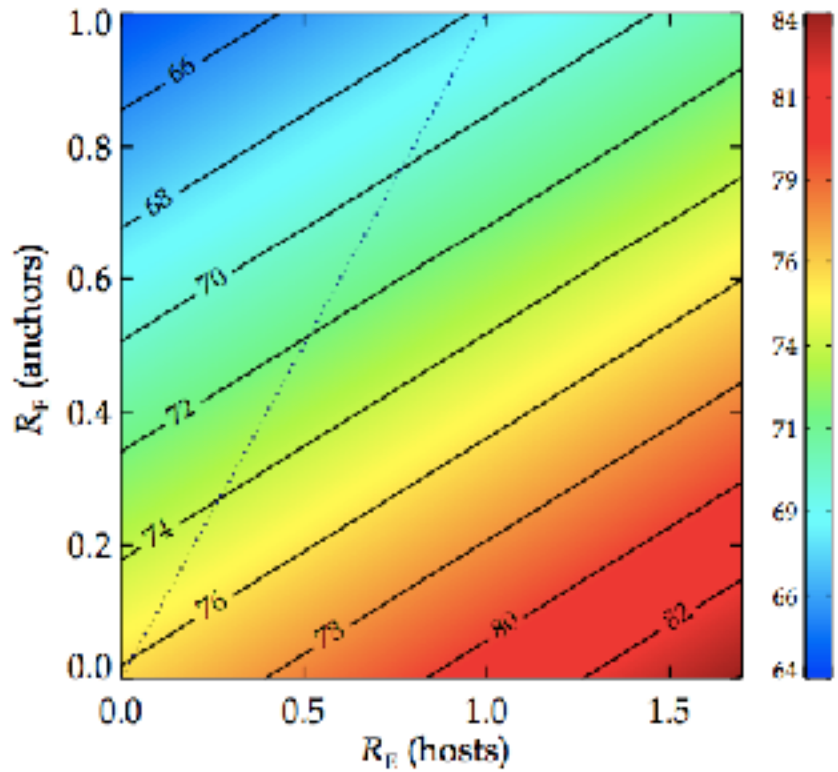
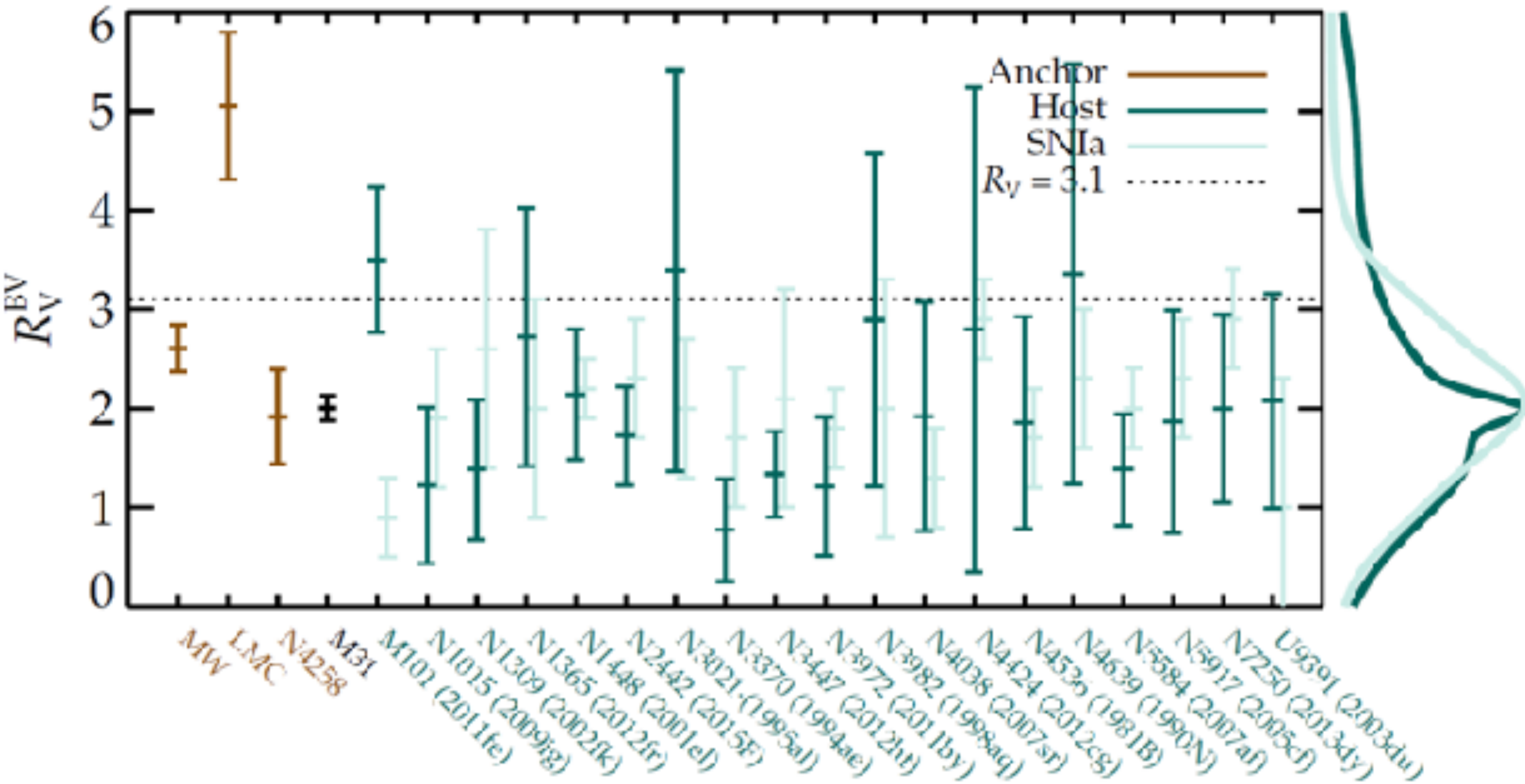


Figure 6. H_0 as a function of R_E in the SNIa hosts and the anchor galaxies when color calibrating Cepheids with respect to the estimated color excess $R_E\,\bar{E}(V-I)$.

No reason for int + dust together -> look at "excess"

Colour excess calibration



$$H_0 = 71.8 \pm 1.6 \;\; (70.9 \pm 1.7)$$

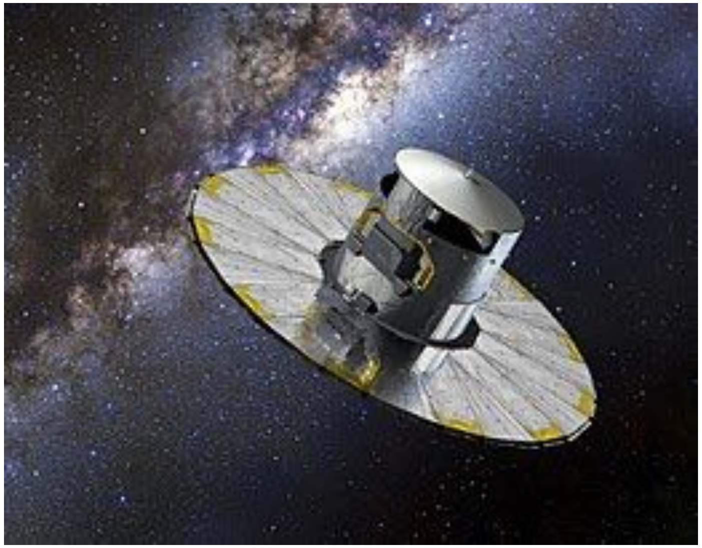
Tension from 4.1 -> 2.7σ

Gaia parallaxes

- Gaia parallaxes have a sys. zp offset
  - Due to varying angle b/w telescopes

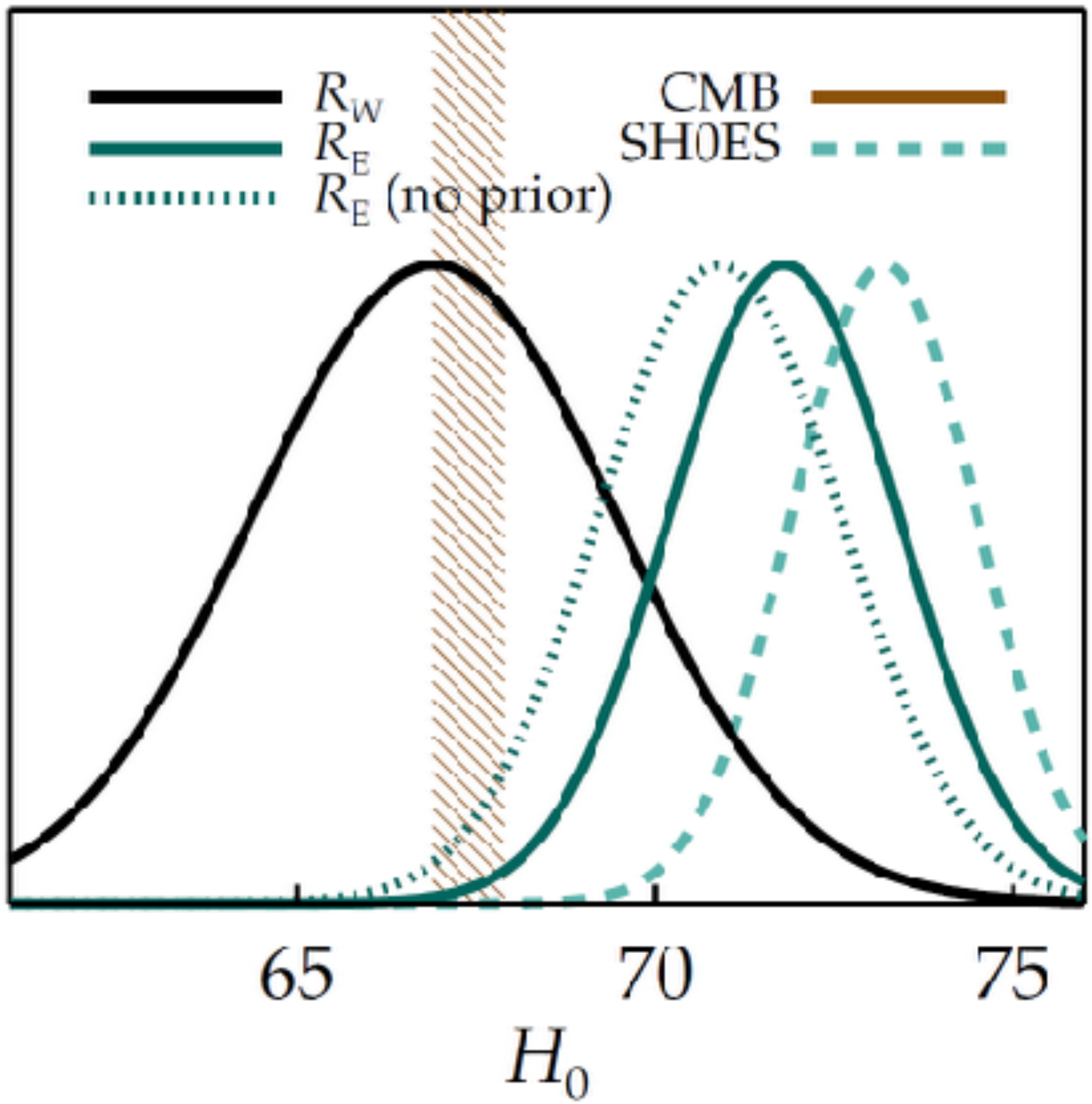
  - zp depends on colour, mag, ecl. latitude (Lindegren+ 20)

    see also Main Appelaniz +21, Vasiliev & Baumgardt+21
  - H_0 changes by ~ 5.7 km/s/Mpc
- Using companion parallax (Breuval+20) ΔH_0 is ~ 1 km/s/Mpc



Riess parallax -> 2.3 - 2.5 σ tension
Breuval parallax -> 1.6 σ tension
No gaia -> 1.6 σ tension

Updated "tension"



Type Ia supernovae from ZTF

The Zwicky Transient Facility

P48: 1.2m discovery Schmidt telescope

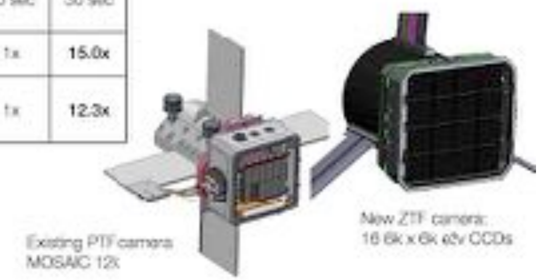
Dedicated classification with P60: SEDm

ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg²	47 deg²
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**15.0x**
Relative Volumetric Survey Rate	1x	**12.3x**

3750 deg²/hour
⇒ 3π survey in 8 hours

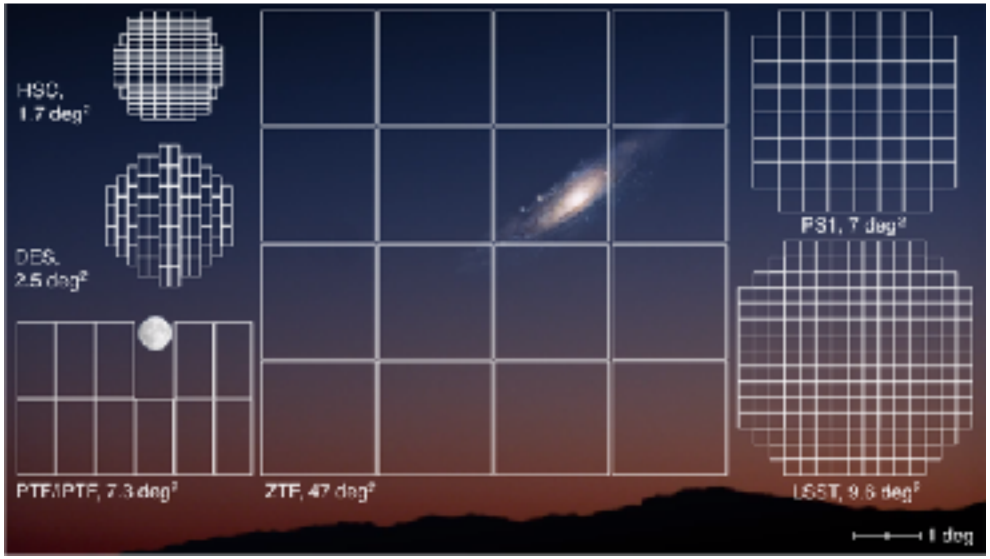
>250 observations/field/year
for uniform survey

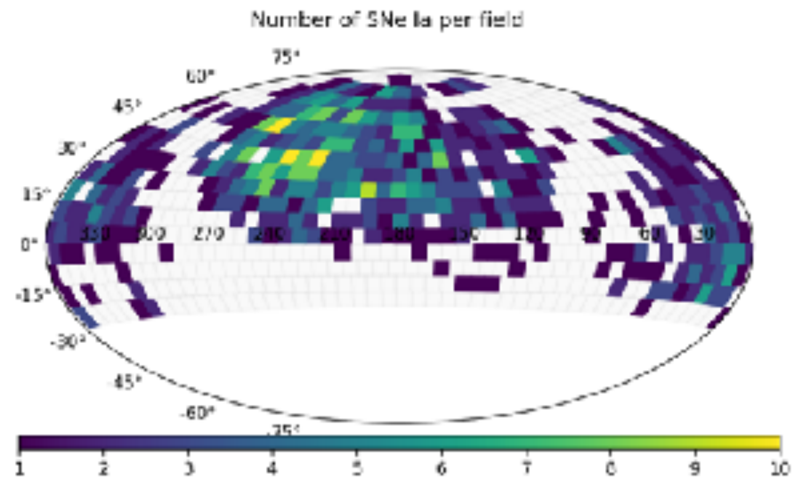


> 5500 SN discoveries
~ 5000 in ZTF Phase I
Phase II began ~ Nov. 2020

ZTF Year 1 sample

Dhawan+'21, MNRAS, submitted





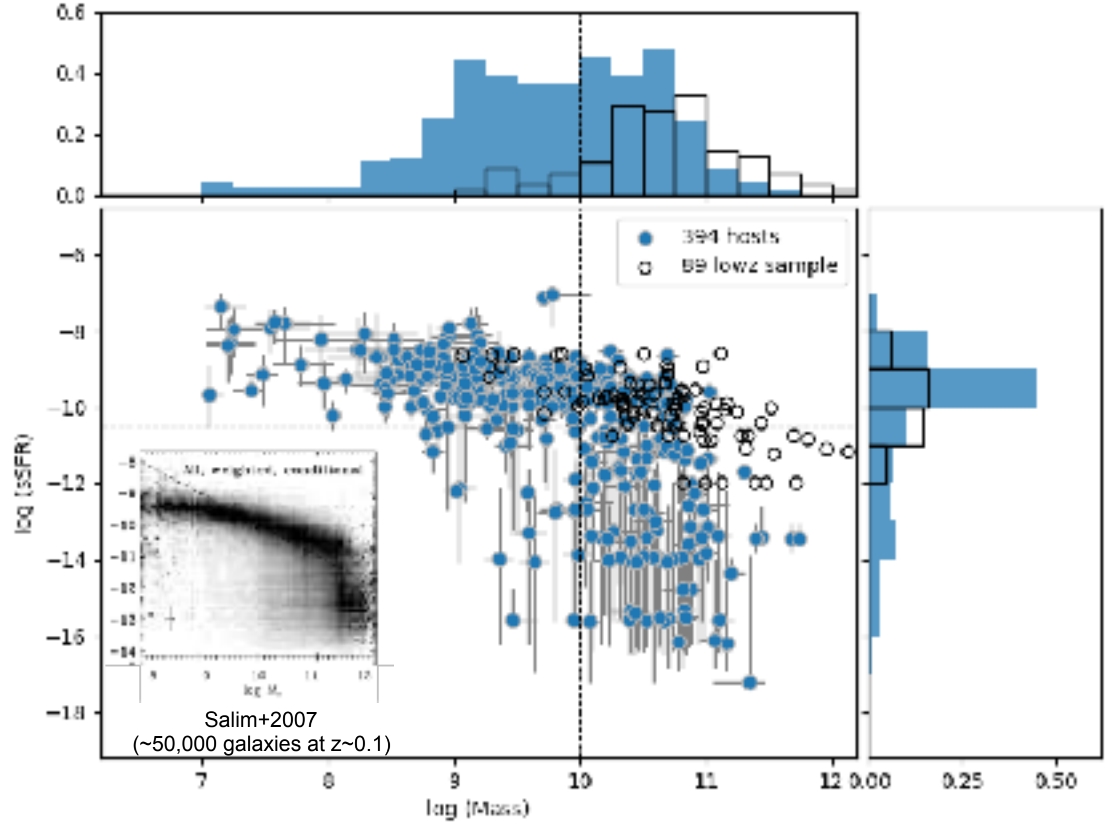
Legacy for Rubin; Roman in future

- ZTF -> successor of iPTF at Palomar
  - 47 sq. degree field of view
- ~800 SNe Ia (Y1) in the Hubble flow; total ~ 3000
- All sky: needed for LSS studies
- Untargeted survey

- New probe of growth of structure
- (TO DO:) Bulk flow + anisotropy studies
- Test directional dependence of H_0
  - low-z for dark energy with Rubin

Testing environmental dependence

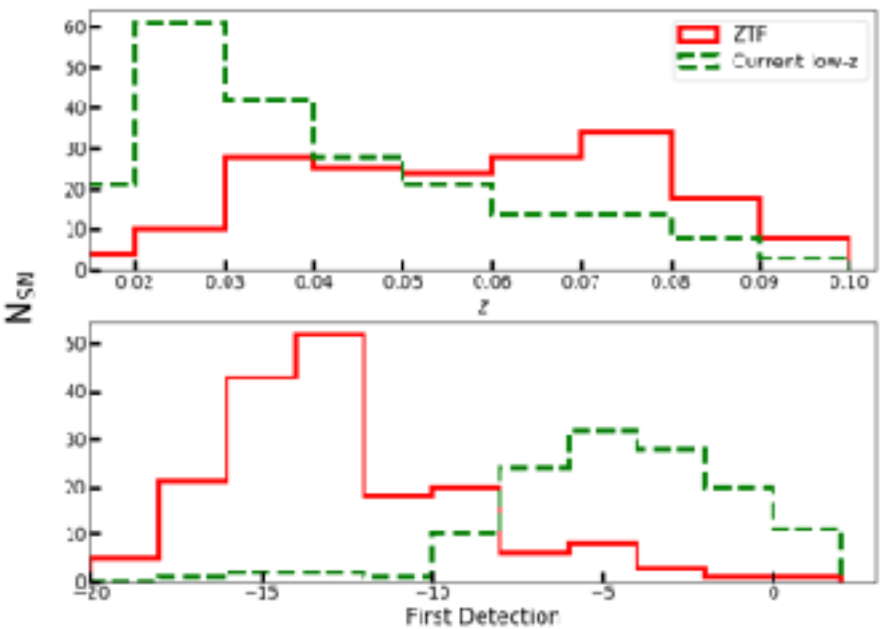
Kim et al. in prep



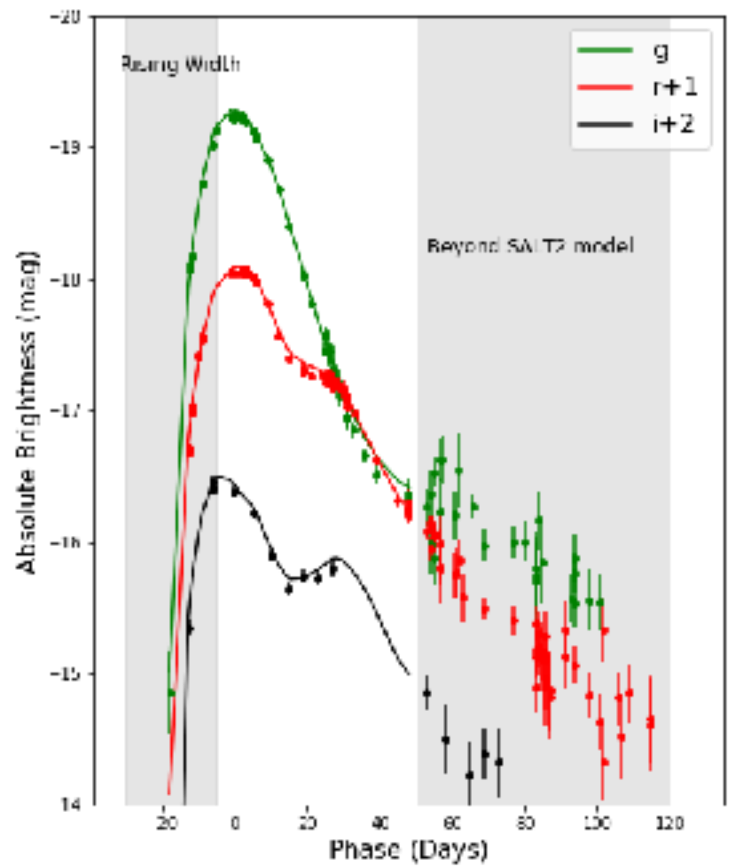
Is SN luminosity dependent on host galaxy local properties?
- Potential claims of bias upto 5%
- Untargeted survey to sample underlying host distribution

Improved Distances

Dhawan+'21, MNRAS, submitted



- for z <= 0.05, lc beyond +100 days
- Improve existing SN distance model



Early light curve for improving distances

-Improving distances with early lightcurves
  - Novel early width standardisation
- Higher median redshift => lower peculiar velocity error

Preparing for Cosmology

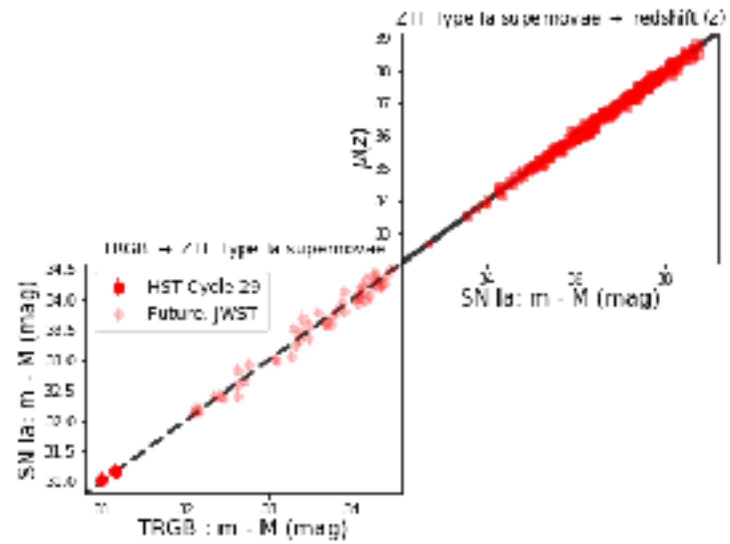
Dhawan+'21, MNRAS, submitted

310 SNe with host galaxy redshift
Greater than all lowZ combined (~150 SNe)

~ 500 SNe w/o host-z: get spec post survey

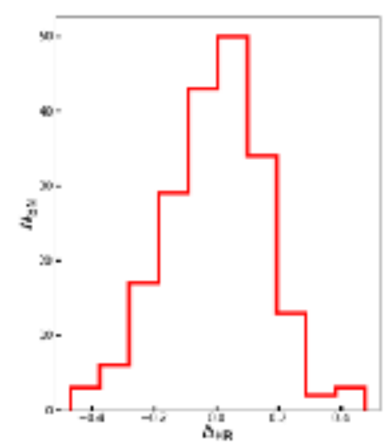
Total gold sample (all-z; Y1) ~ 450 SNe

Single system calibrator + Hubble Flow?



ZTF σ_{rms} = 0.16 mag
LowZ σ_{rms} = 0.20 mag

ZTF <z> = 0.062
LowZ <z> = 0.031



Expected improvements to pipeline => reduced rms

Strongly lensed Type Ia supernovae: H_0 and beyond

Time-delay cosmography

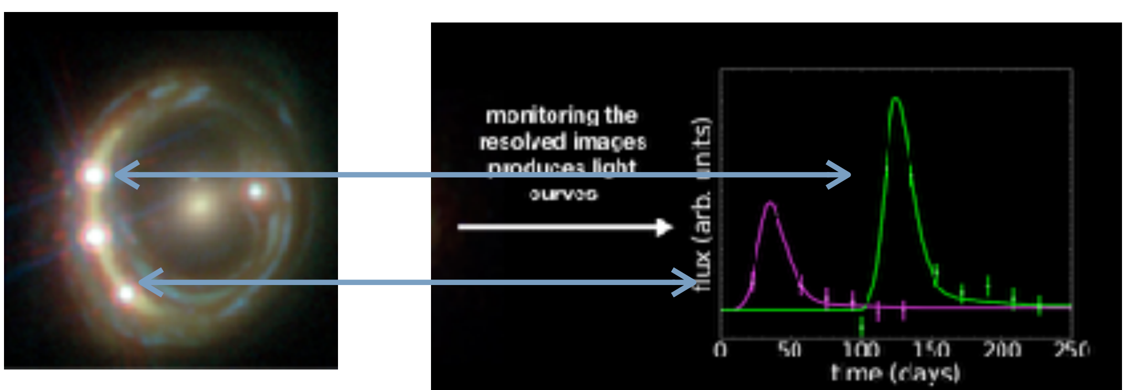
- < 3% measurement of H_0 with lensed quasars
- Independent discovery method to glSNe
  - glSNe => “standardisable candle”
- First proposed for SNe in Refsdal 1964

Time delay, Time-delay distance, Lens potential (from mass model)

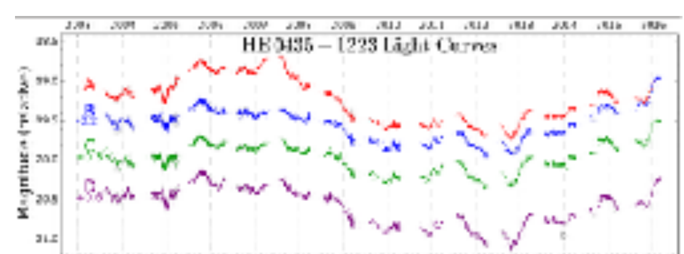
$$\Delta t \propto D_{\Delta t} \times \phi_{\mathrm{lens}} \Rightarrow D_{\Delta t} \propto \frac{1}{H_0}$$

Benefits of glSNe Ia

- Well-understood light curves + SEDs
- Much less monitoring required (few weeks compared to years for QSOs)
- “Standardisable” luminosity => break modelling degeneracies (e.g. mass-sheet transform Birrer+20)
- Lower impact of microlensing systematics
- Discovered using magnification ==> less bias from high separation events



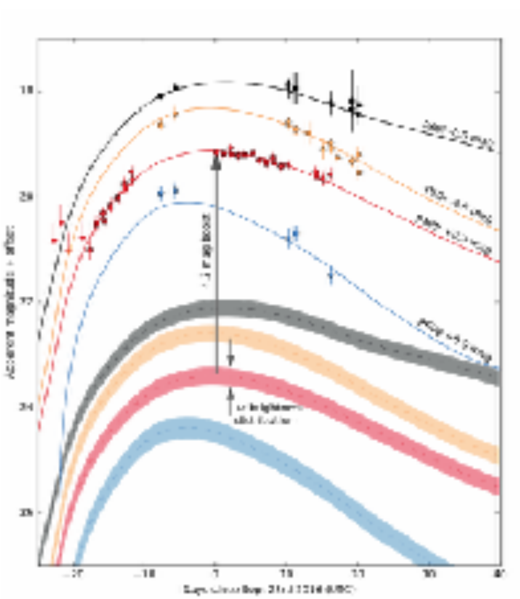
Typical lensed SN and QSO light curves



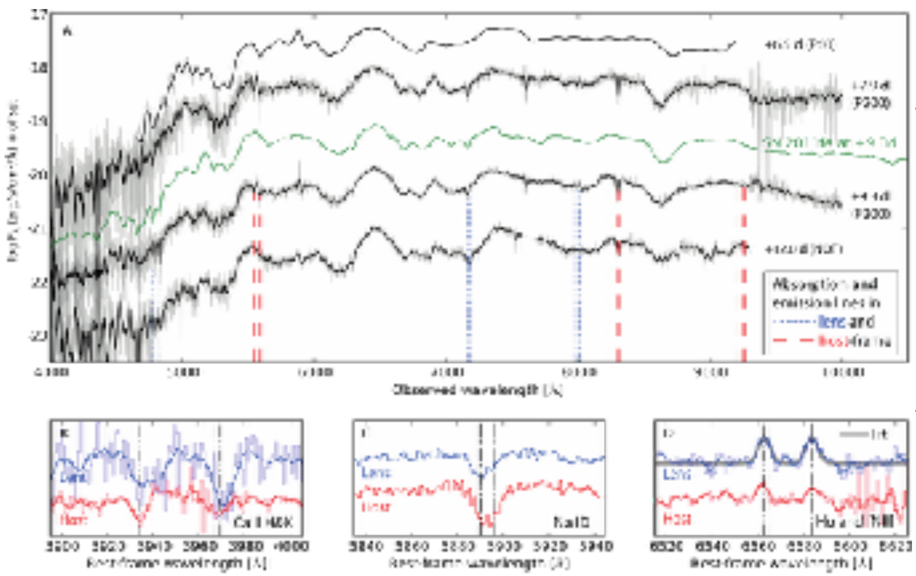
iPTF16geu: Discovery

>50 times brighter than normal SNIa at z~0.4: a 30σ outlier!

Goobar+ 2017



Perfect spectral match to z=0.409 SN Ia
+ intervening galaxy at z=0.216



"Typical" SNIa redshifted to z=0.409

Absorption lines from host galaxy and another galaxy in the line of sight

Perfect match to z=0.409 SN Ia + intervening galaxy at z=0.216

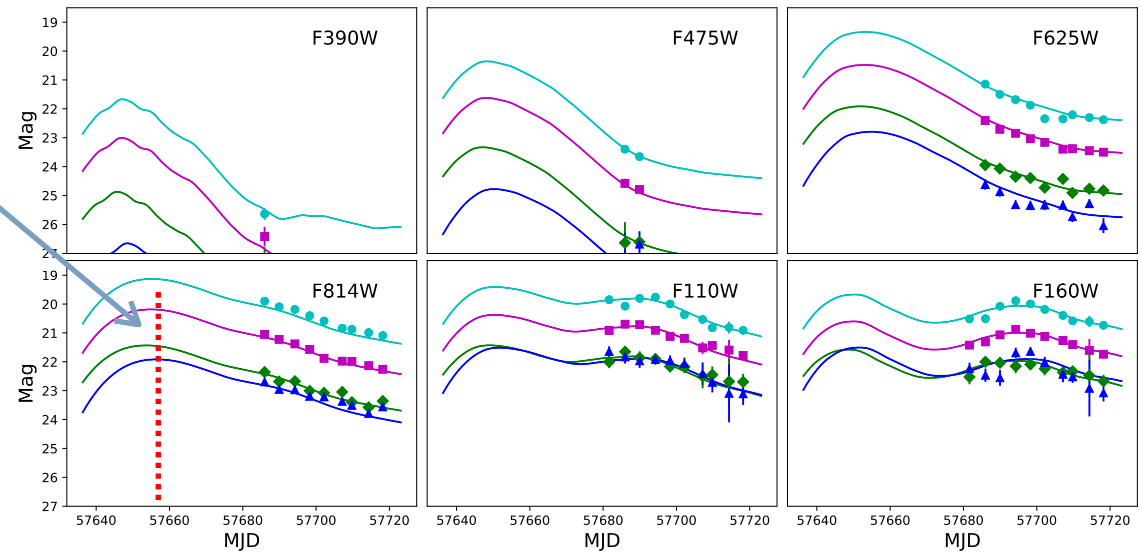
iPTF16geu: Resolved lightcurves

Very small time-delays (~ 1 day):
Not ideal for measuring H_0

Coverage began post-maximum
=> large errors (~ 0.7 - 1 day)

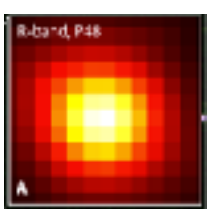
Max. light simulations
=> five times smaller error

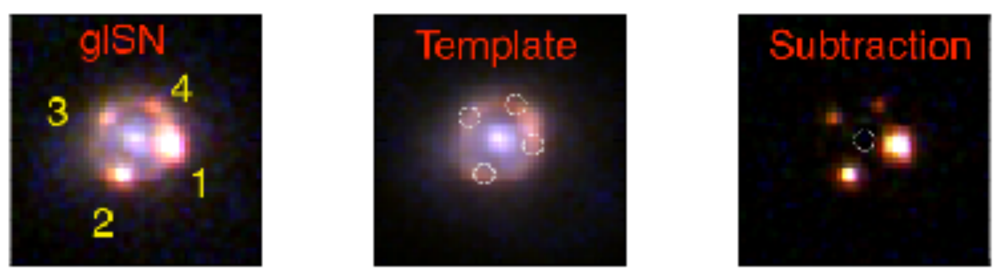
Model independent approach with
NIR second max => consistent Δt



HST/WFC resolved image, template and subtraction => not possible for QSOs!!

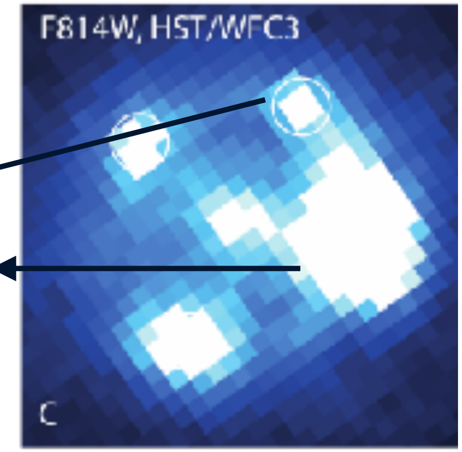
Ongoing + future surveys => longer time-delay systems
10 day delay measurable at ~ 2%





iPTF16geu: Magnification + extinction

Preliminary magnification (μ) ~ 52
With extinction correction 67+/-3



Probing the inner kpc of the lens => galaxy DM profiles

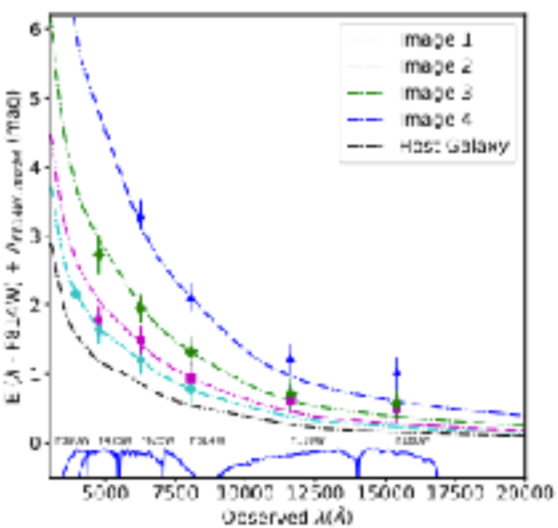
Surprisingly high magnification (μ)
In general relativity, $P(\mu) \propto \mu^{-3}$ +selection effects.
(E.g., μ=5 happens 1000 more often, yet not seen)

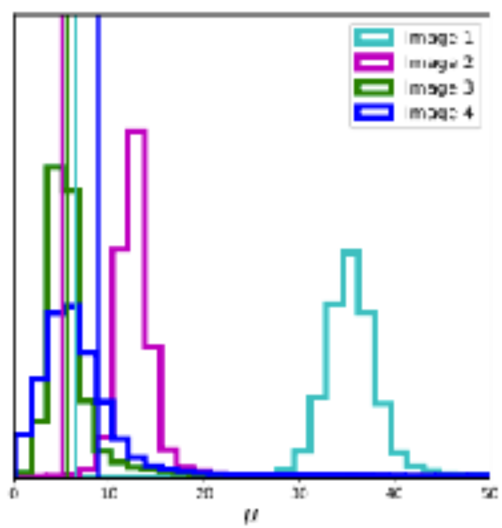
Surprisingly different brightness?

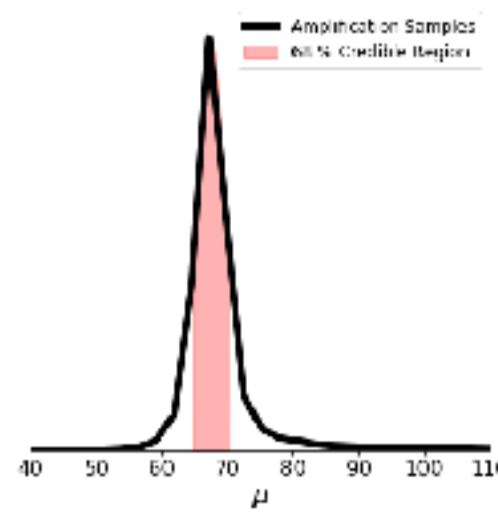
Is this a selection effect or something fundamental? ==> need more objects

Important to get multi-band, resolved photometry -> extinction estimates
Flux ratios differ from model prediction -> combination of microlensing + extinction

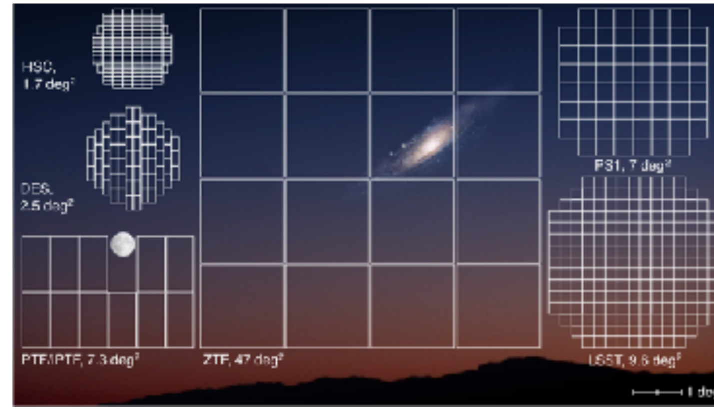
Details of modelling in Mortsell+20







ZTF1+2: Search for glSNe



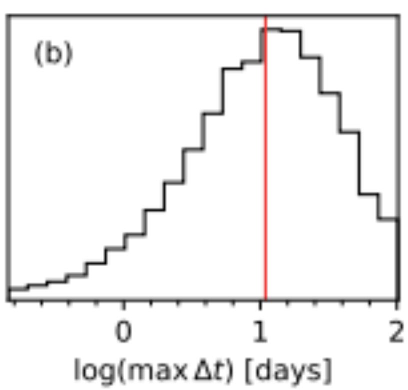
- Ongoing search in partnership (+public) data
    - High-cadence partnership survey
        + i-band survey

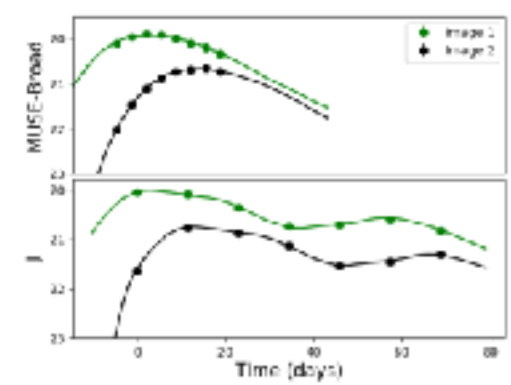
- Archival search for lensed SN candidates
    - Classification with P60, P200, Keck (were heavily COVID-hit)
    - High resolution follow-up with Keck, VLT

- Expected number ~ 1 - 3 per year

Deeper spectroscopy needed for vetting

Expected distribution of time delays + resolved light curve expected for ZTF glSN





Conclusions + Outlook

- Tested potential systematics in local distance ladder
  - Cepheid colour calibration reduces H_0 tension
  - Gaia parallaxes not currently @ required precision

- ZTF Year 1 sample
  - Largest compilation of low-z SNe Ia
  - All sky: tests of anisotropy, large scale structure
  - “First go” analysis => small luminosity scatter

- Strongly lensed SNe Ia
  - iPTF16geu: exceptionally magnified
  - Small time-delay: not ideal for H_0
  - Extinction constraints in each LoS
  - Ongoing work with ZTF to discover more glSNe