A uniform ZTF-TRGB distance ladder

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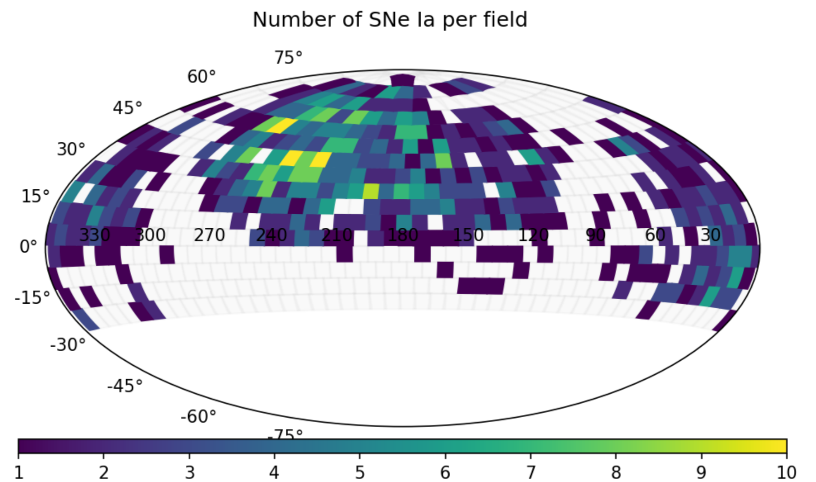
with: ZTF Cosmo WG + Carnegie-Chicago Hubble Program
Dhawan et al. 2022, MNRAS, 510, 2
Dhawan et al. 2022, ApJ submitted; arxiv: 2203.04241

Cosmo From Home 2022, 07 July

Outline

ZTF DR1 sky distribution



Motivation

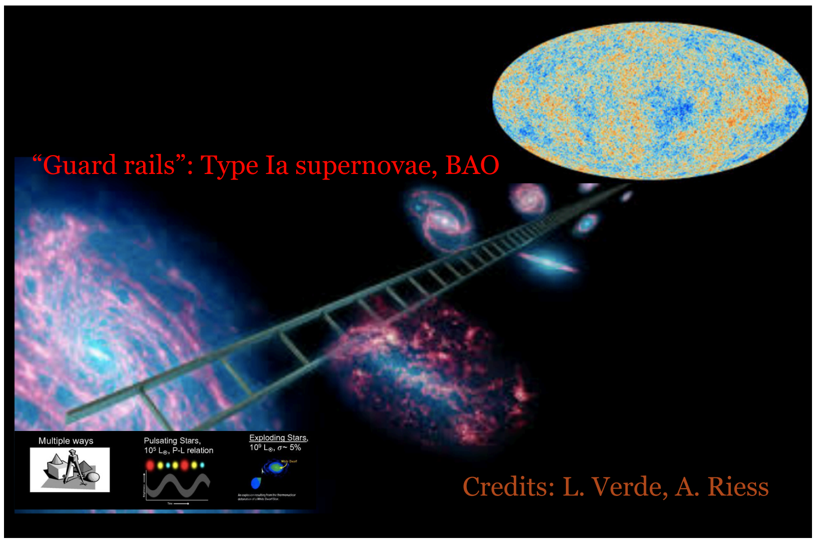
ZTF DR1 Type Ia supernova sample

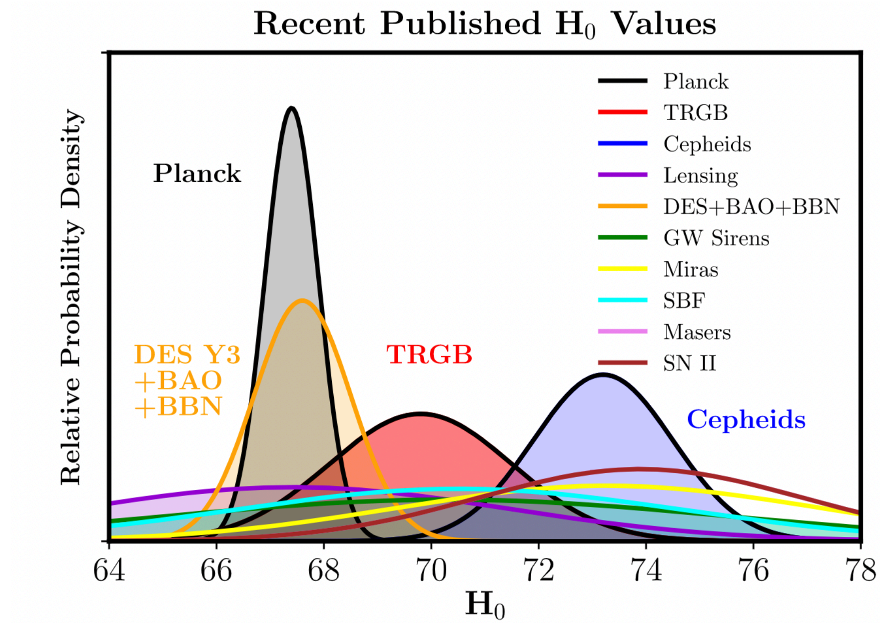
Uniform ZTF - TRGB distance ladder

Motivation

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

Credits: Freedman 2021





- New physics? (No clear solution, currently, e.g. Knox + Millea 2020)

- Unknown Systematics?

Need independent methods

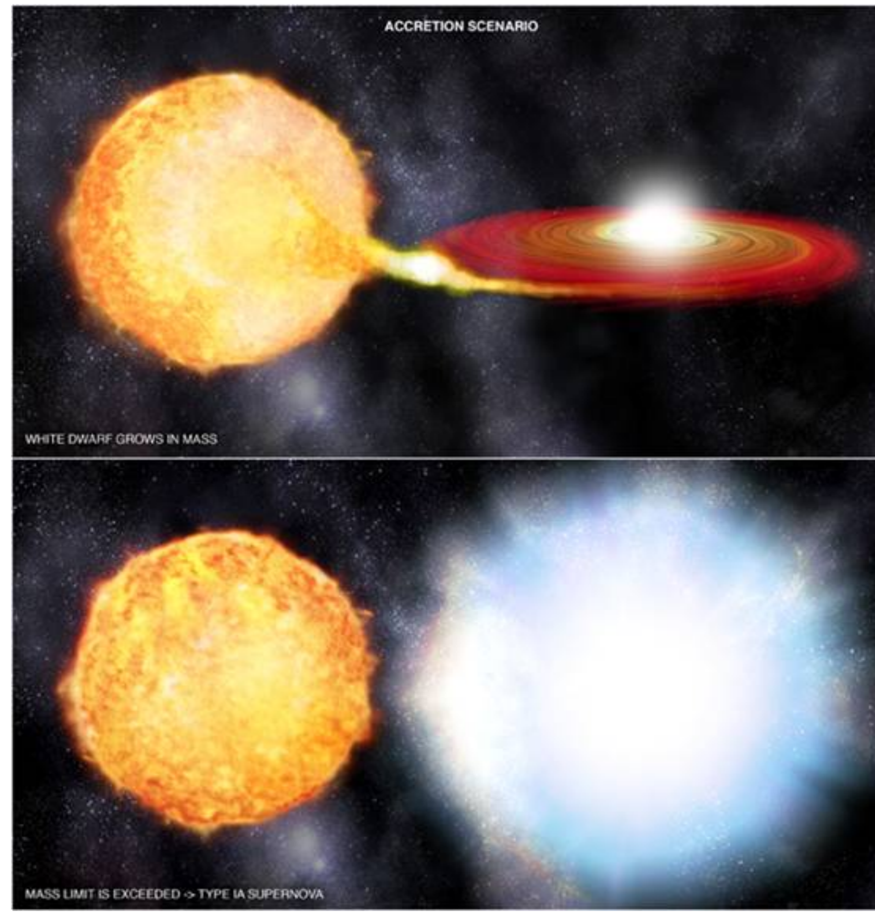
Focus of today's talk!

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

What are Type Ia supernovae?

Bright, stellar candles

NOT standard; calibratable



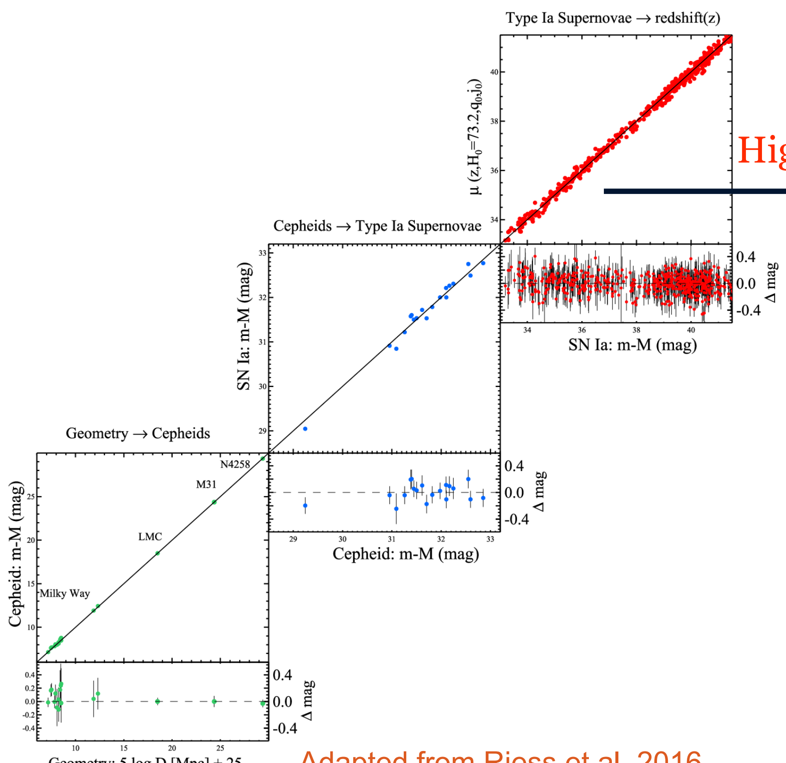
Discovery of dark energy

In all types of galaxies

Cosmic Distance Ladder

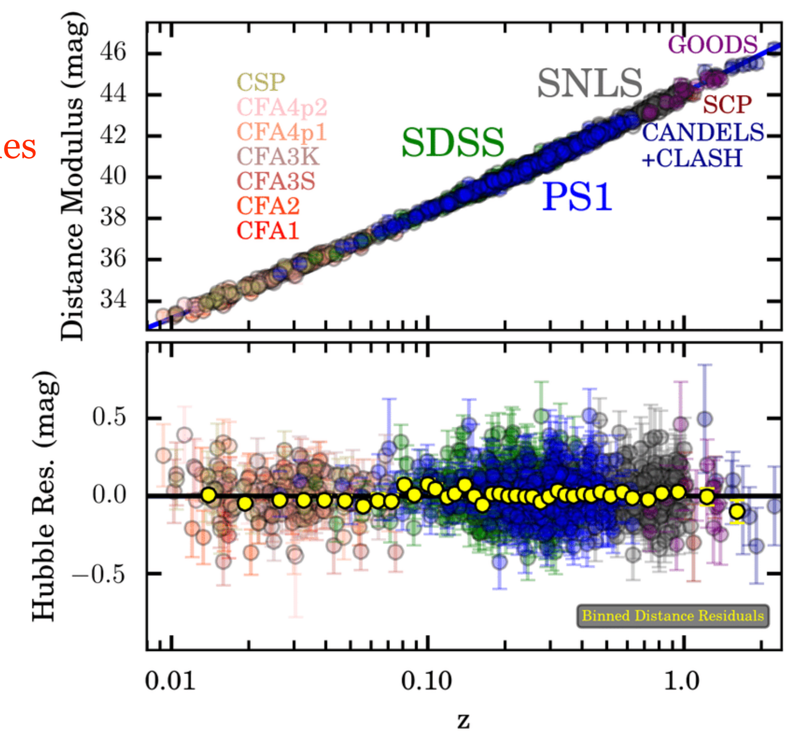
- Type Ia supernovae: Hubble flow (z ~ 0.1 and lower)
  - Calibrated with Cepheid or TRGB distances
  - Second rung calibrated with independent, primary anchors

SNe Ia from many different telescopes + targeted surveys



Adapted from Riess et al. 2016

High-z; DE studies

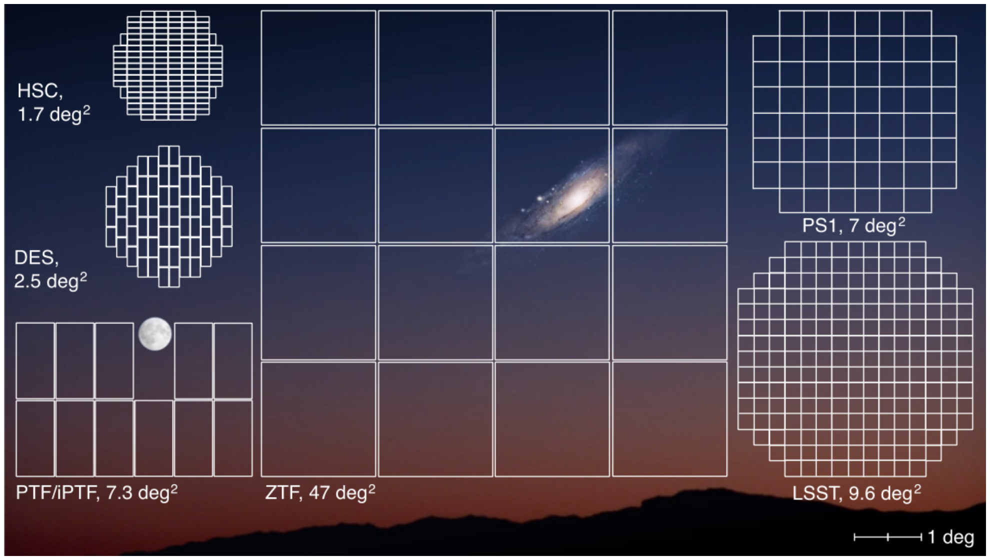


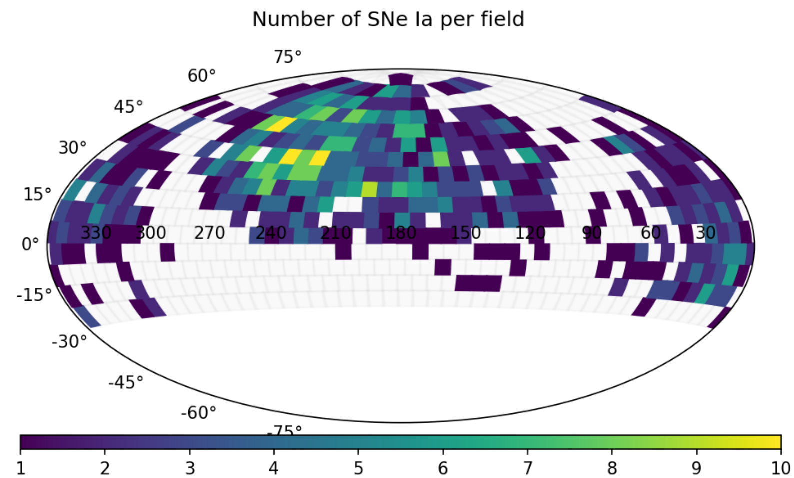
Scolnic et al. 2018

Type Ia supernovae from ZTF

ZTF Year 1 sample

SD+22a



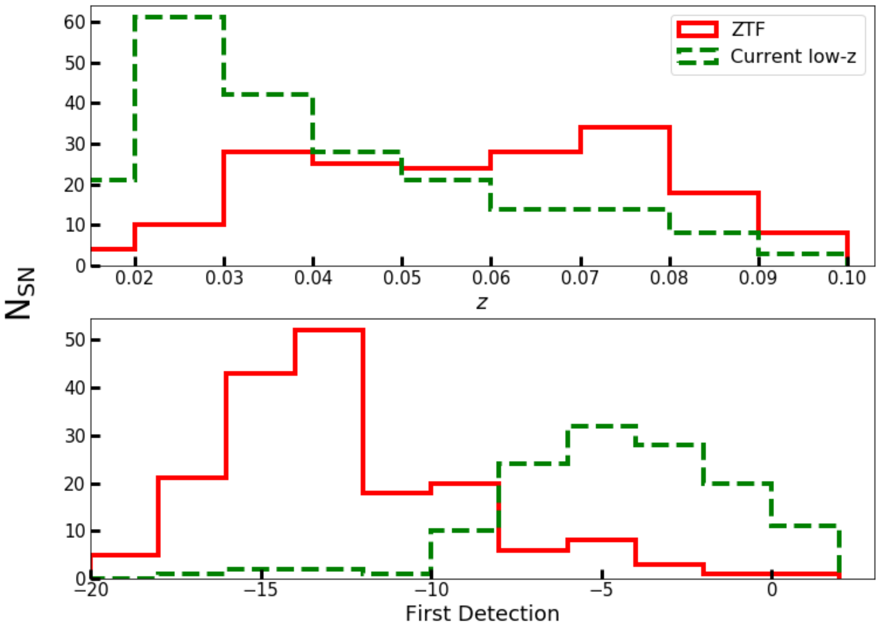


Legacy for Rubin; Roman in future

- 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

Improved Distances

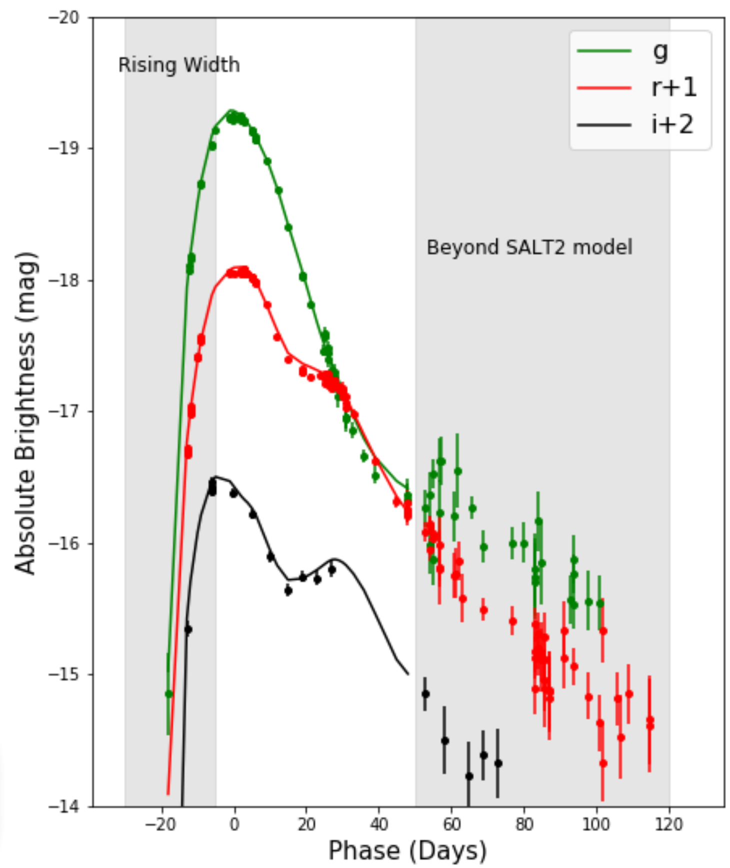


σ_{rms} (ZTF) = 0.17 mag
σ_{rms} (Current low-z) = 0.2 mag

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

Dhawan+'22

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



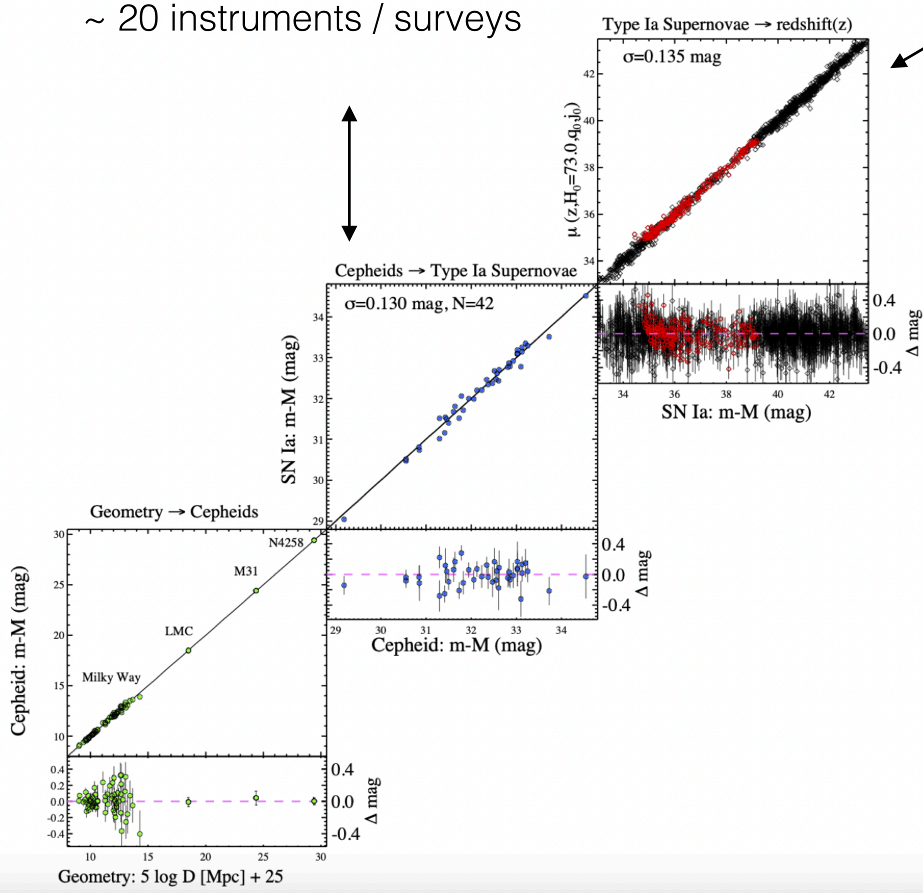
Early light curve for improving distances

A uniform ZTF-TRGB distance Ladder

Cepheid Distance Ladder

~ 20 instruments / surveys
ZTF already has ~ 750
Hubble flow SNe Ia in DR1
~ 3000 in Phase I

~ 20 instruments / surveys

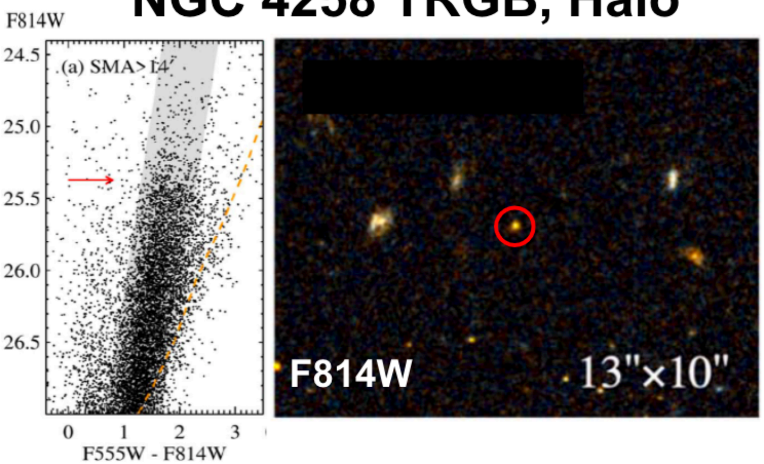


Riess et al. 2022

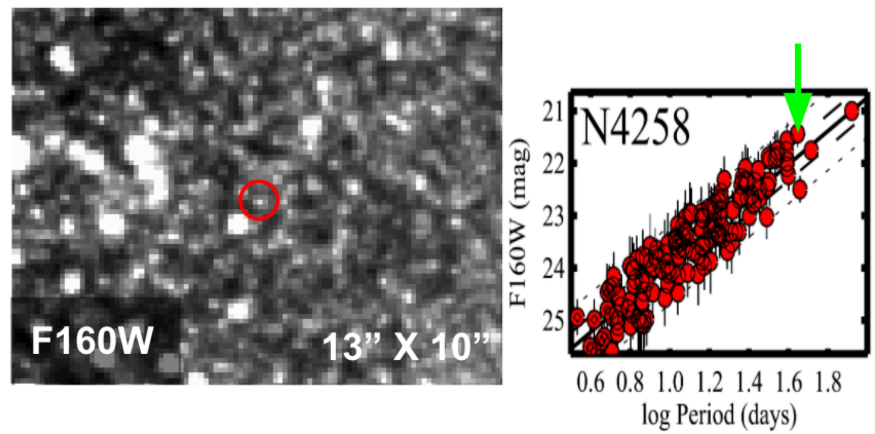
Why TRGBs?

Jang et al. 2021

NGC 4258 TRGB, Halo



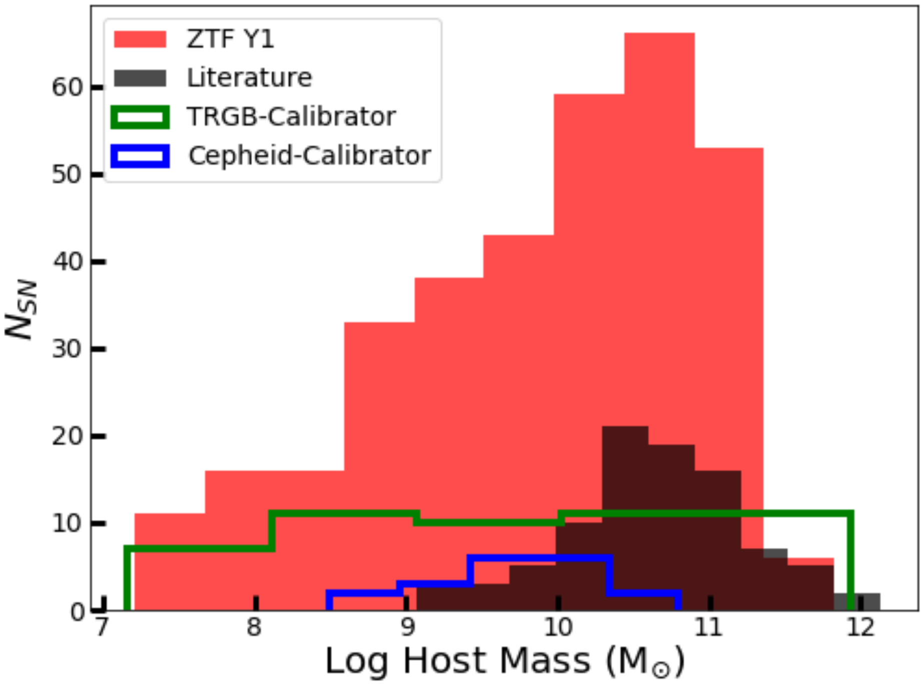
NGC 4258 Cepheids, Disk



- Found in SN Ia hosts of all ages
- Less crowded environments than Cepheids
- Less prone to reddening, metallicity systematics than Cepheids (Mortsell+2021a,b; Efstathiou 2020)
- Single observation is enough -> no period inference
- Potentially “easier” measurement in JWST era -> NIR bright

Why ZTF-TRGB?

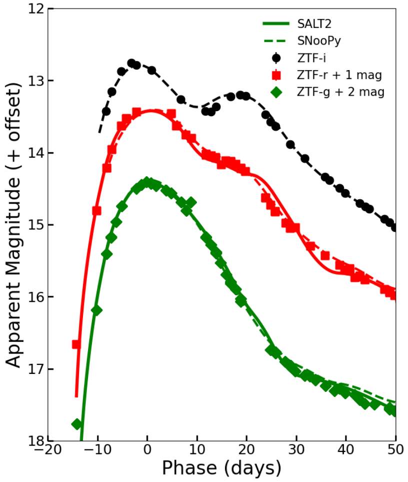
- ZTF is untargeted -> probing underlying environmental properties
- Cepheid calibrators -> strong preference for young hosts
- TRGBs in all hosts -> “matches” ZTF well.

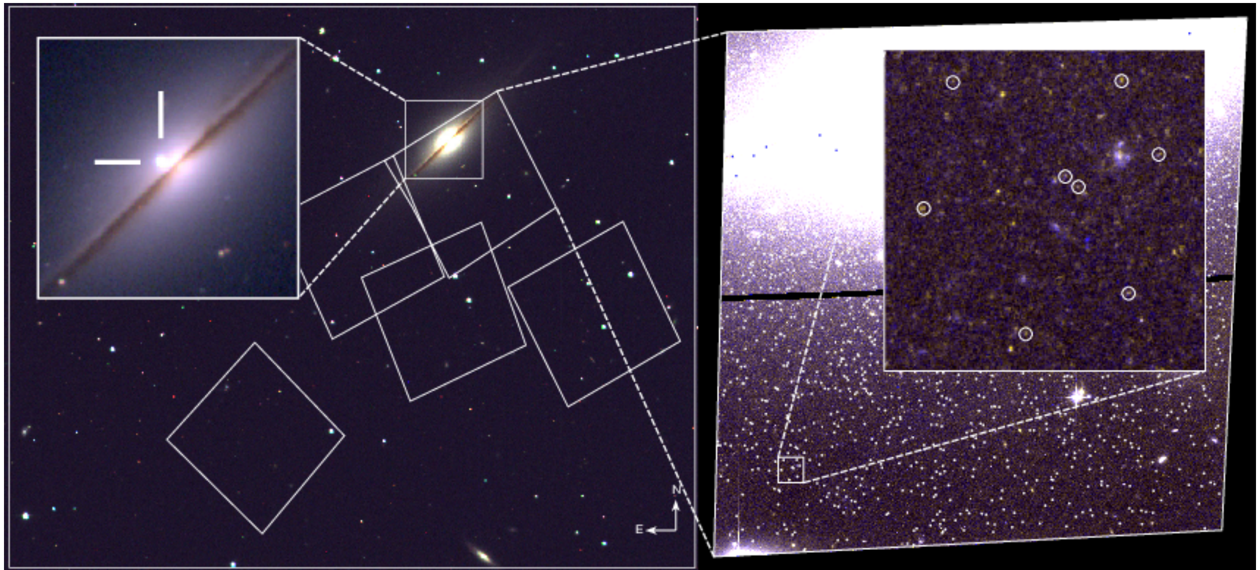


Host mass distribution of ZTF and TRGB calibrators compared to Cepheids (HST C29 proposal)

ZTF Calibrator Sample

- 6 objects within D_L < 20 Mpc (HST feasibility)
- One with good TRGB distance -> ZTF21abiuvdk (SN2021rhu)
- 7 fields from HST ACS/WFC



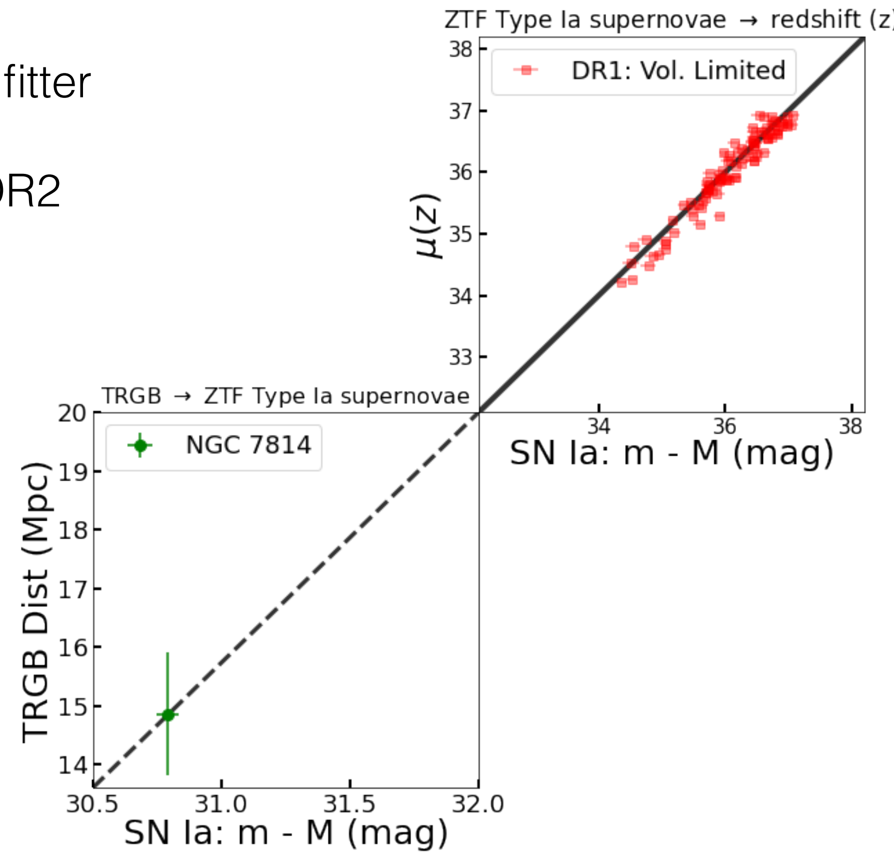


SD+22b, ApJ. Subm.

Current ZTF Distance Ladder

- Single calibrator -> increase to 6 with HST C30
- Small impact of sample selection, LC fitter
- Hubble flow of ~ 200 SNe Ia -> ZTF DR2 upcoming
- H_0 = 76.94 +/- 6.4 km/s/Mpc

SD+22b, ApJ. Subm.



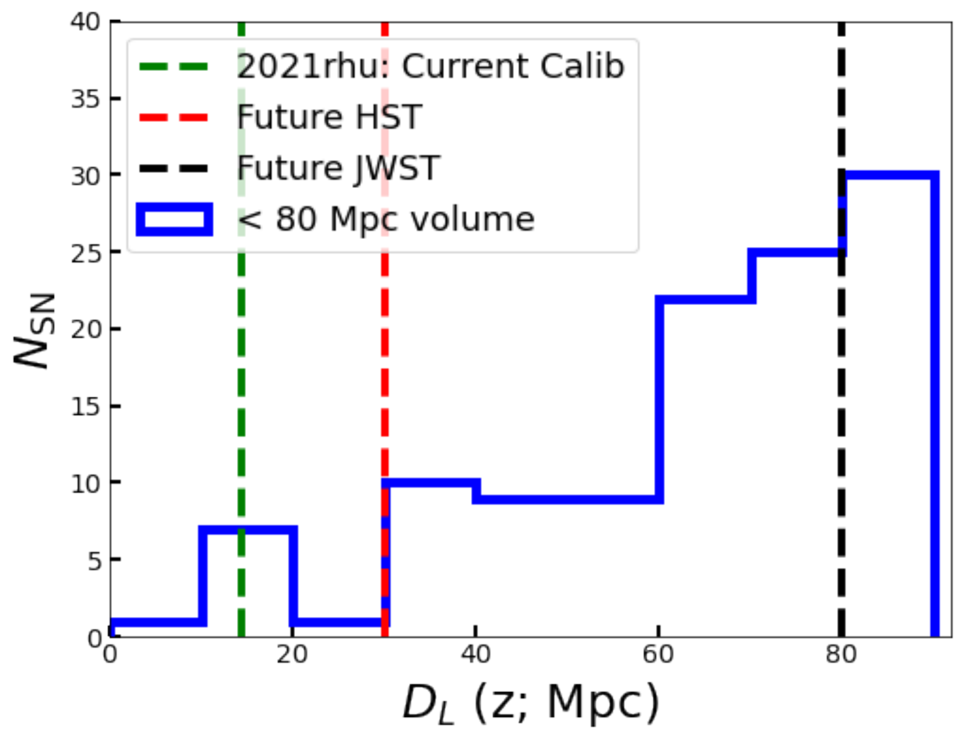
Outlook with JWST

- 106 SNe Ia with accurate distances at D_L < 80 Mpc

- Augmented Hubble Flow sample

- Vol. limited cal. sample

SD+22b, ApJ. Subm.



Conclusions

- Dark Energy model systematics subdominant
  - Important at 1% level

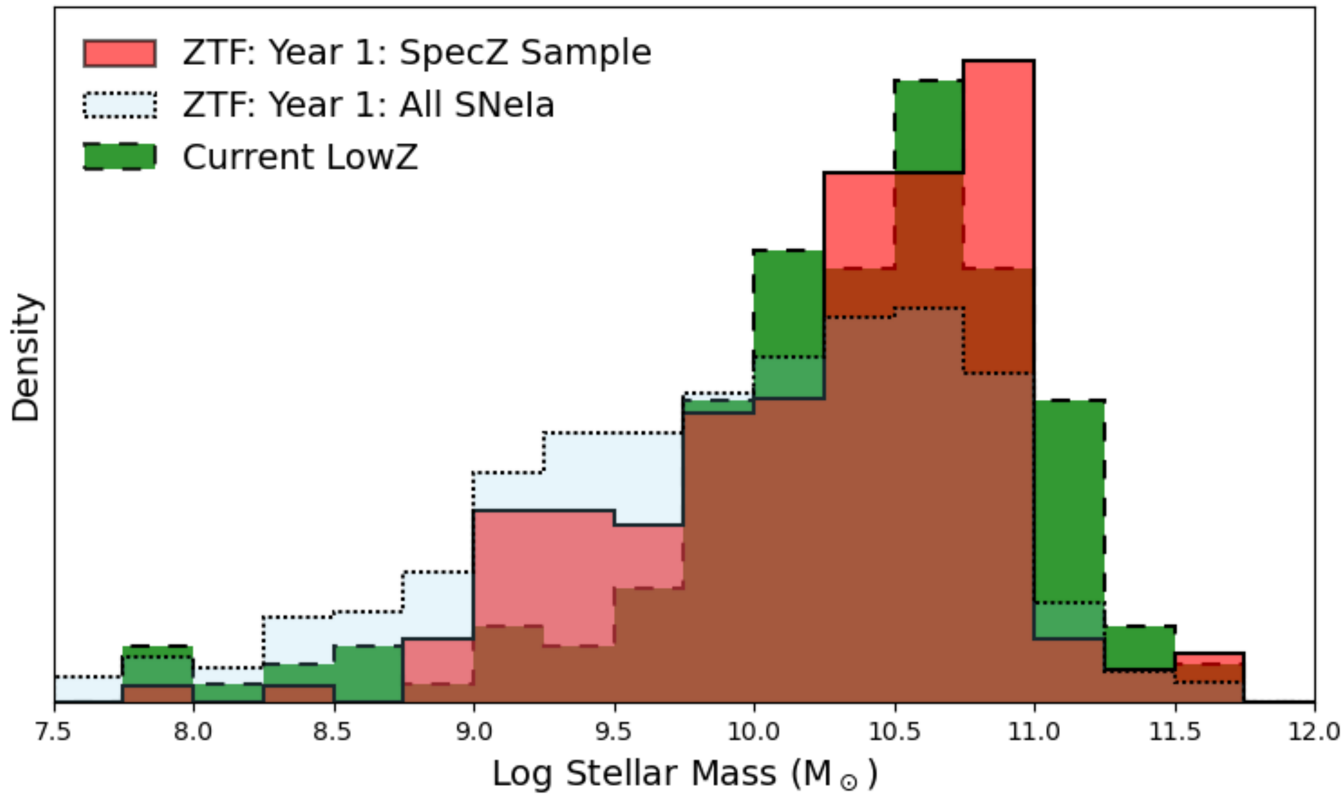
- ZTF DR1: homogeneous, untargeted sample of 750 SNe Ia
  - Improved distances with early light curves
  - Probing environmental biases

- Sizable calibrator sample on the same system
  - Distances from HST < 20 Mpc, NIRCam < 80 Mpc
  - First pilot study H_0 = 76.94 +/- 6.4 km/s/Mpc

- TRGB: excellent standard candles
  - > 100 host galaxies within JWST capabilities

ZTF Host Galaxies

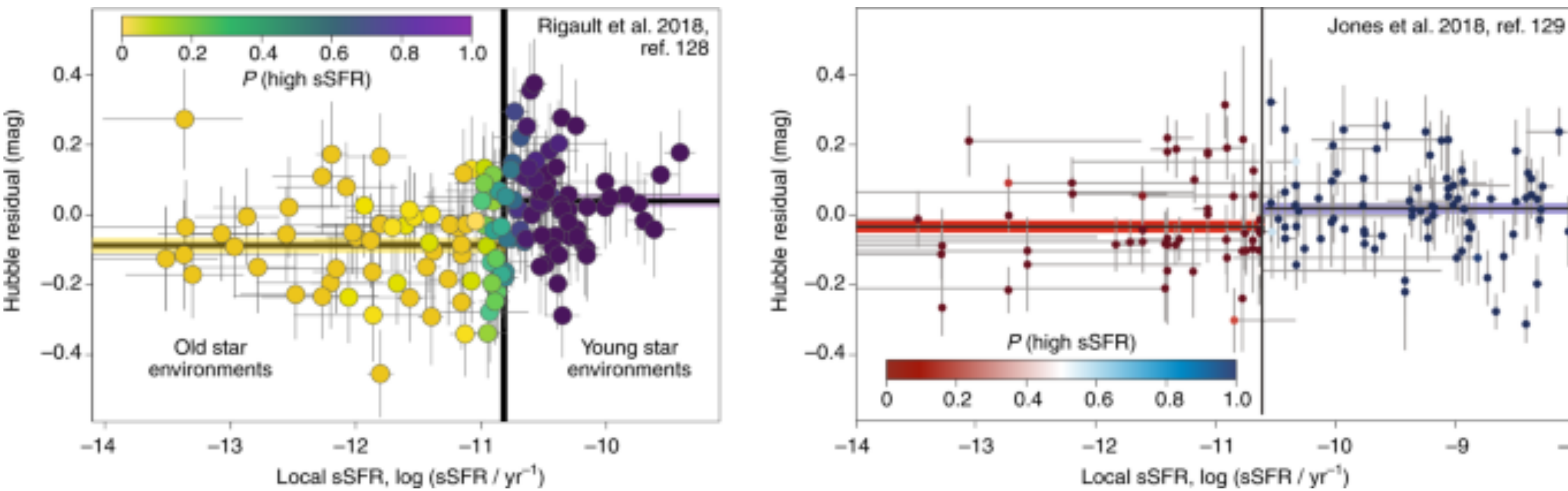
SD+22a



Higher ratio of low-mass to high-mass hosts

- Entire DR1 sample: 761 SNe Ia
- Spec-z: 305 SNe Ia -> post survey redshifts

Testing environmental dependence



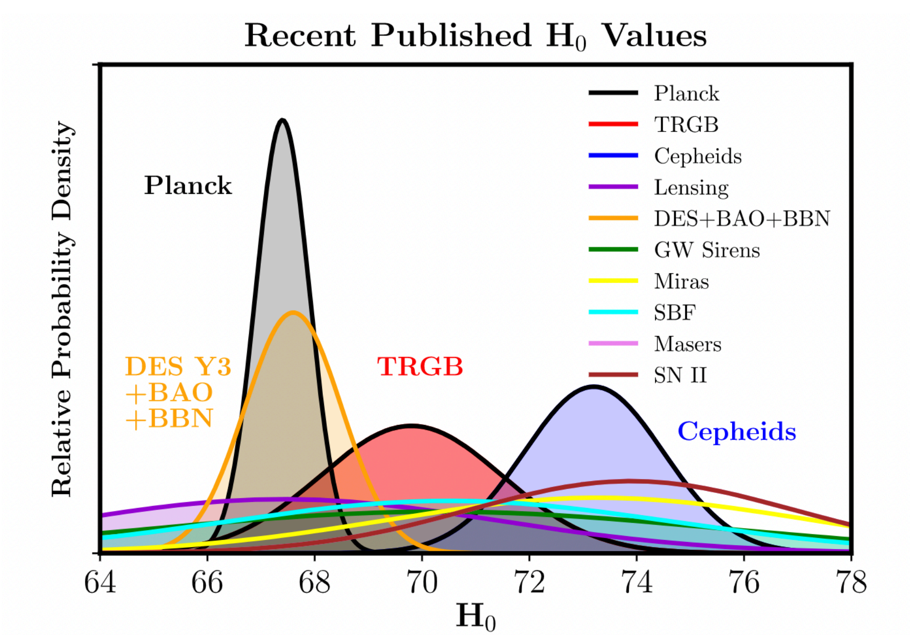
Is SN luminosity dependent on host galaxy local properties?
- Potential claims of bias upto 5% -> other claims < 1%
- Untargeted survey to sample underlying host distribution

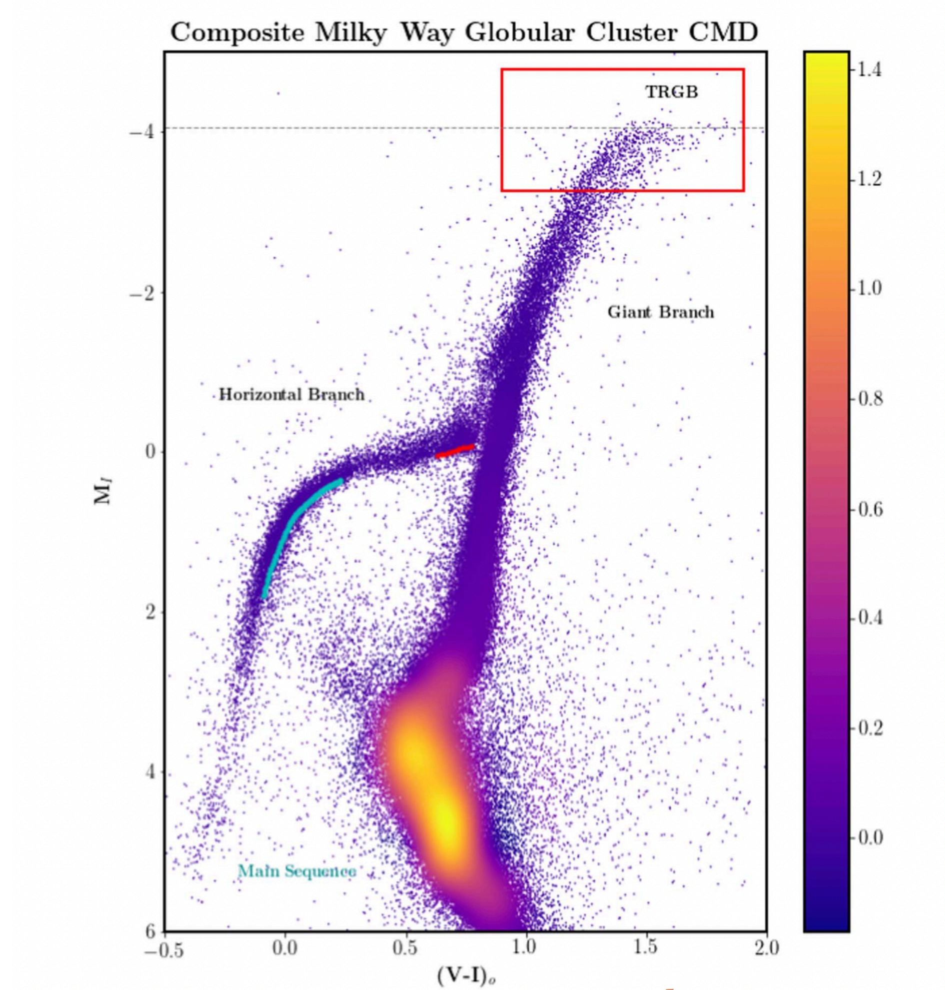
The Tip of the Red Giant Branch

Important **standard** candle

Well understood physics (He flash)

TRGB H0 not in tension





Freedman 2021

Dark Energy Model + SN systematics

Accounting for covariance between calibrators and **all** Hubble flow SNe
Combined likelihood => use for dark energy inference

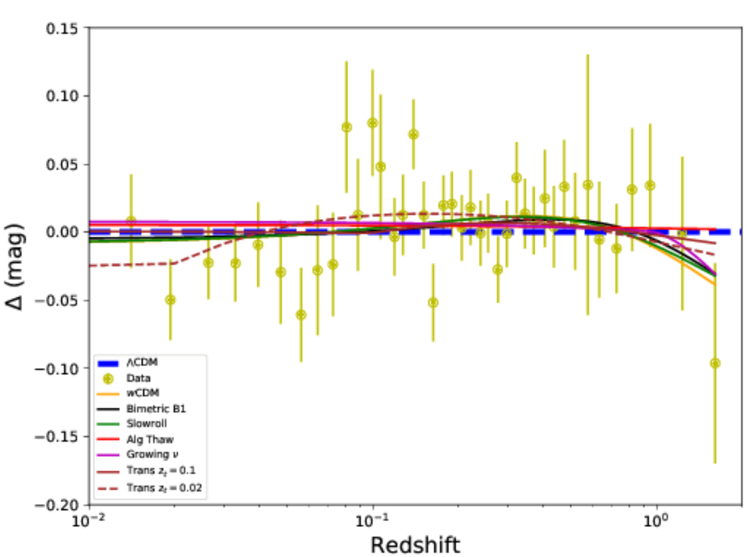
Modelling sources of systematics

Model assumption shift in H_0 ~ 0.7 %
SN Ia systematic error shift ~ 1%

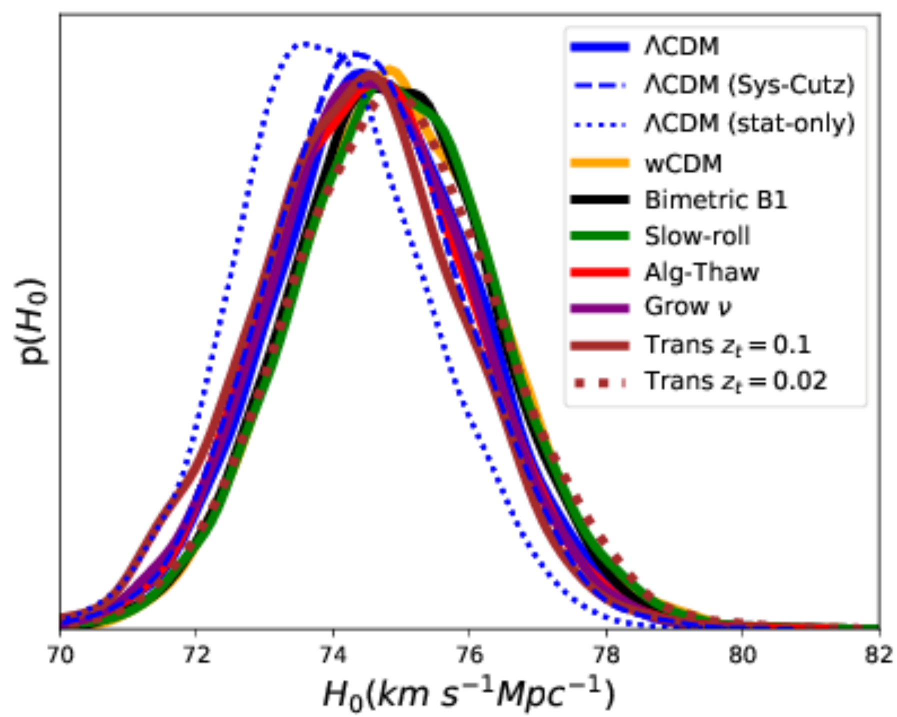
Low-z from > 10 systems

Some targeted programs

Now used for Pantheon+ & SH0ES '22



SD, Brout, Scolnic+ 2020c



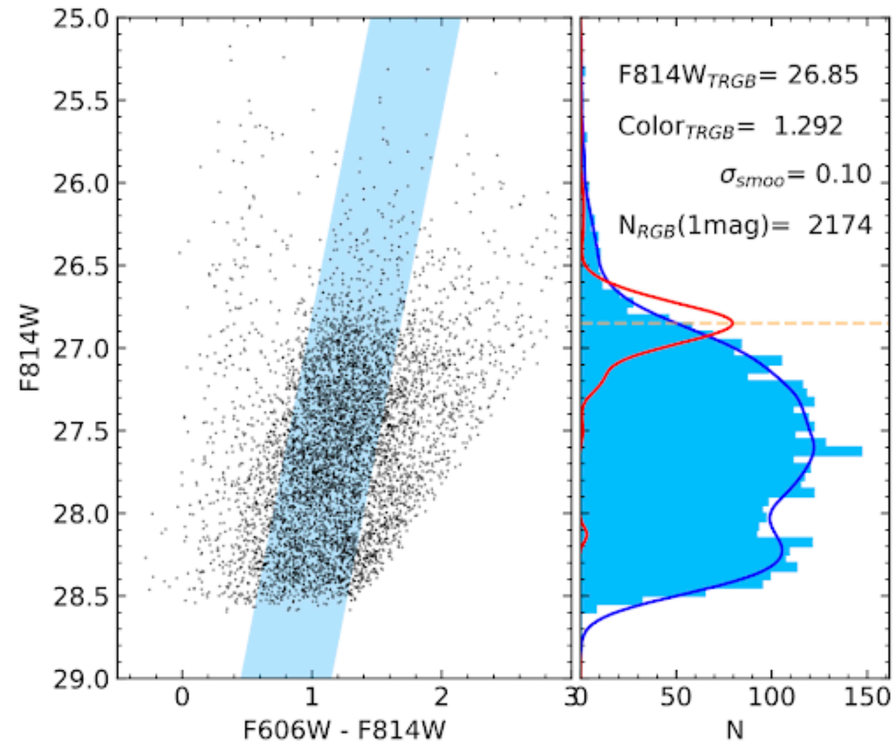
See also, transition models in Benevento, Hu, Raveri 2020

TRGB distance estimate

- CCHP pipeline for tip detection (Jang et al. 2021)
  - Absolute calibration to Freedman 2021

SD+22b, ApJ. Subm.

- 3 Fields far away from the disk
- Edge detection with Sobel Filter
  - Histogram binning with 0.01 mag
  - Gaussian smoothing with 0.1 mag



The Zwicky Transient Facility

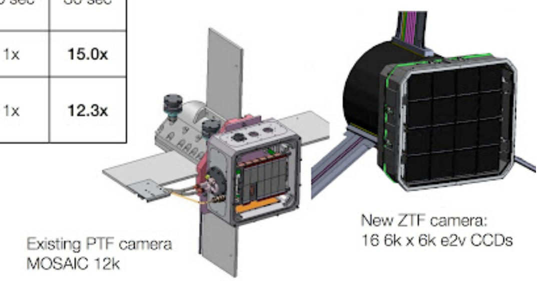
P48: 1.2m discovery Schmidt telescope

ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
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 deg^2/hour
⇒ 3π survey in 8 hours

>250 observations/field/year
for uniform survey



Dedicated classification with P60: SEDm

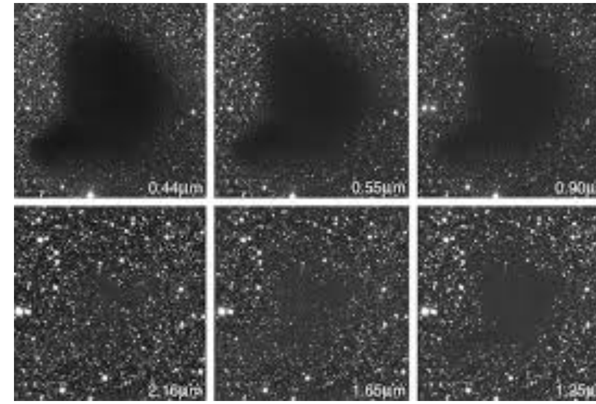
\> 5500 SN discoveries
~ 5000 in ZTF Phase I
Phase II began ~ Nov. 2020

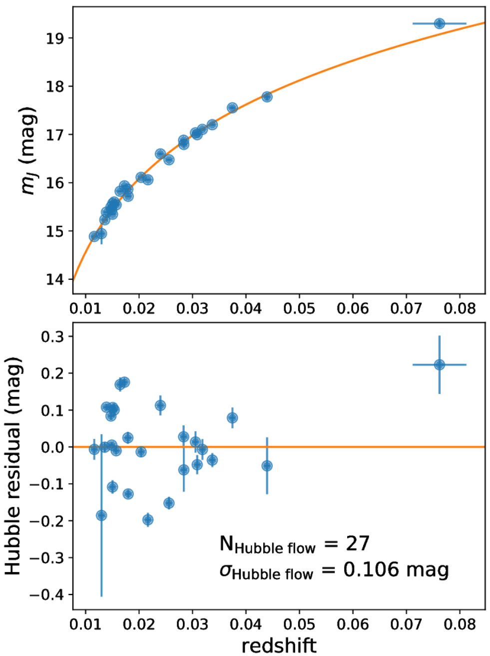
Total Number of SNe: 5581 I Ia: 3507 I II: 1280 I Ib: 121 I Ic: 132 I Ib/c: 21 I Ic-BL: 47 I SLSNe: 178

GROWTH Followup Marshal

Near Infrared Standard Candles

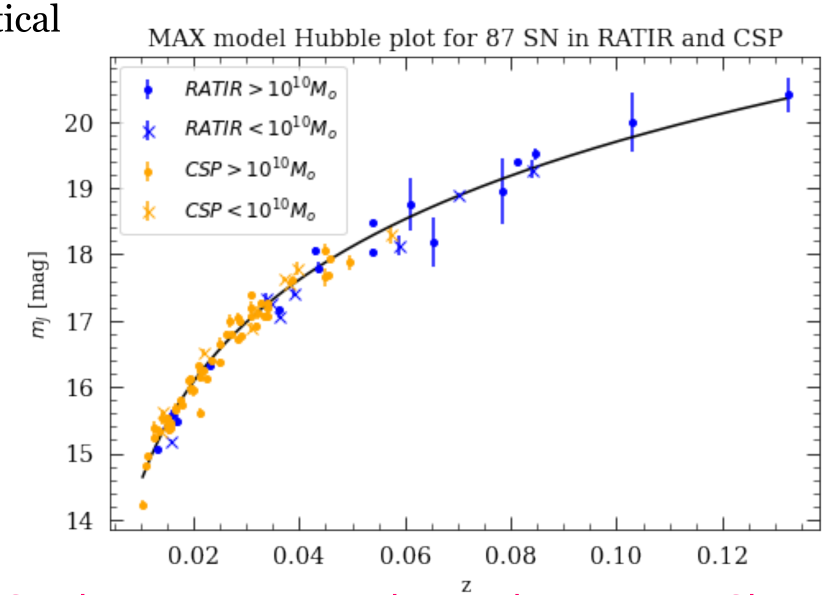
Does non-standard dust extinction cause high H_0?
Are SNe standard candles in the NIR? => future distance scale





SD+'18a

- NO stretch / colour corrections
- Model independent light curve fits
- σ_{int} ~ 0.1 mag
  - for comparison: optical ~ 0.5 mag
- Consistent value with the optical



"Mass step": important for cosmology
- Debate on significance in NIR
- No 'step' seen in new sample

Credits: summer undergrad at IoA, T. Chant
see also, Johansson,SD, et al. 2021

Time-delay cosmography

- Independent discovery method to lensed quasars
  - glSNe => “standardisable candle”

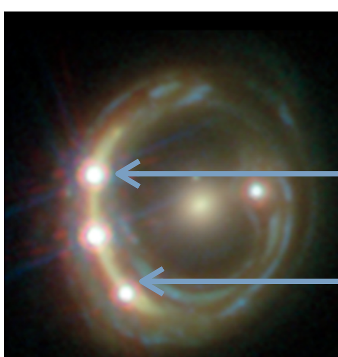
- First proposed in Refsdal 1964 (for SNe, used for QSOs)

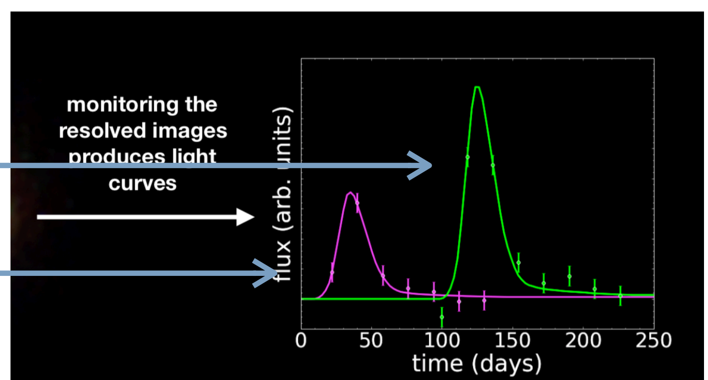
Time delay — Time-delay distance — Lens potential (from mass model)

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

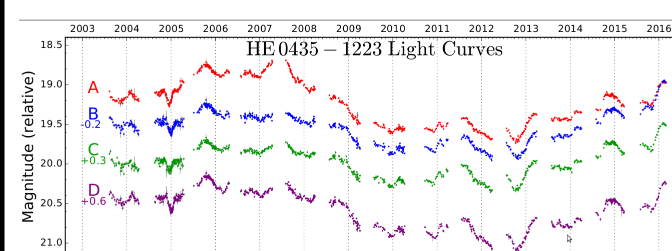
Advantages of glSNe Ia

- Well-understood light curves + SEDs
- Much less monitoring required (few weeks compared to years for QSOs)
- “Standardisable” luminosity => break modelling degeneracies (e.g. Birrer, SD, Shajib, 21)
- Lower impact of microlensing systematics
- Discovered using magnification ==> less bias from high separation events

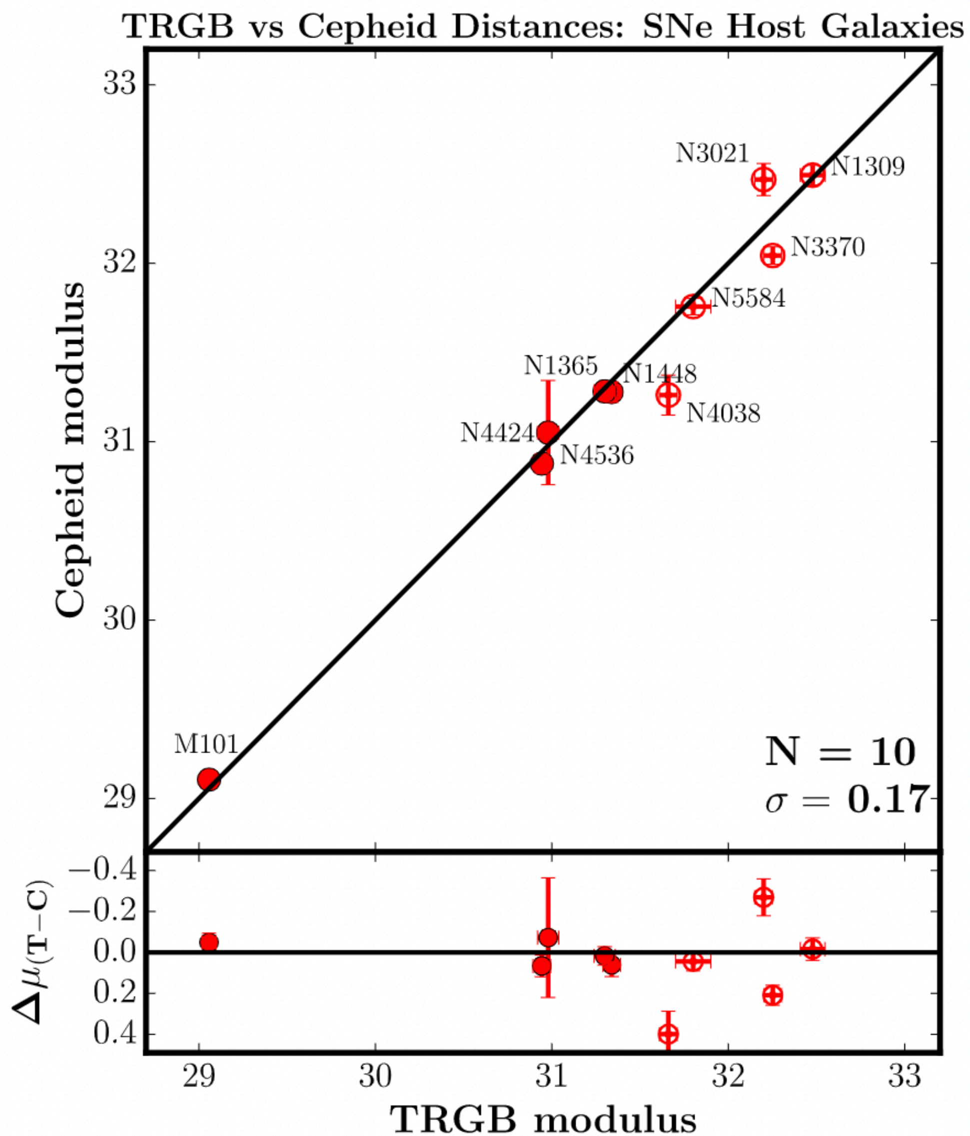




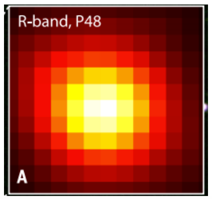
Typical lensed SN and QSO light curves



TRGB-Cepheid Consistency

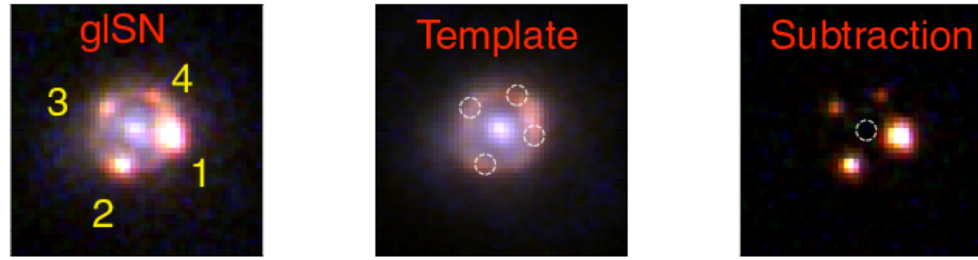


iPTF16geu: Resolved lightcurves

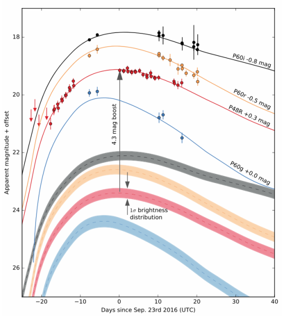


Discovery in unresolved data

Follow-up: HST / AO



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



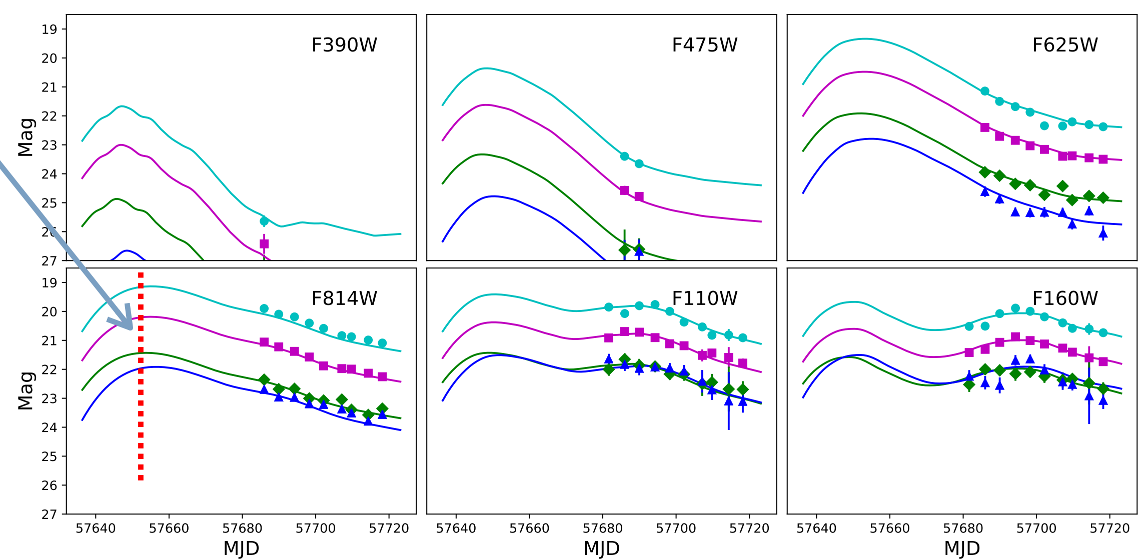
>50 times brighter than normal SNIa at z~0.4: a 30σ outlier!

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

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



iPTF16geu: Magnification + extinction

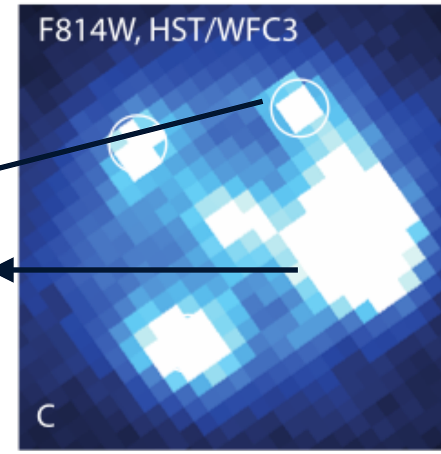
Preliminary magnification (μ) ~ 52
With extinction correction 67+/-3

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

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

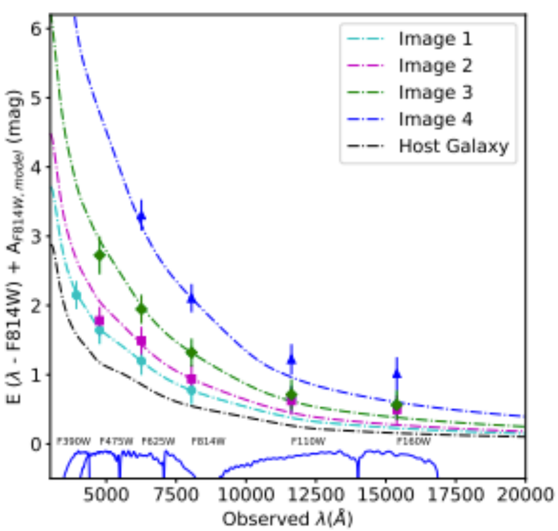
Surprisingly high magnification (μ)
In general relativity, $P(\mu) \propto \mu^{-3}$ +selection effects.

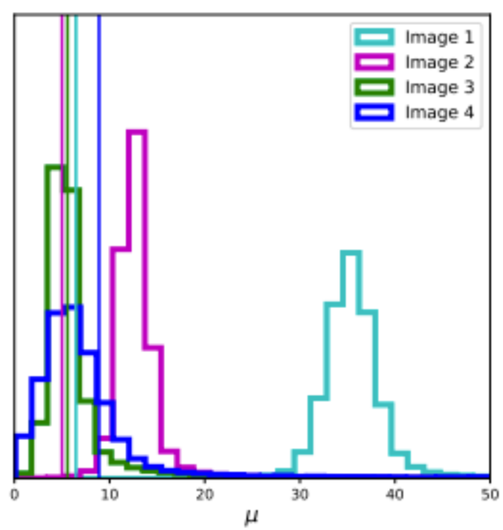
Surprisingly different brightness?

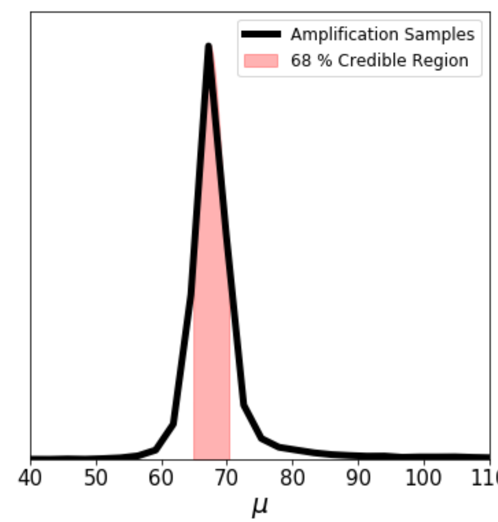


(E.g., μ=5 happens 1000 more often, yet not seen)
Is this a selection effect or something fundamental? ==> need more objects

Modelling details in Mortsell,.., SD, … +’21







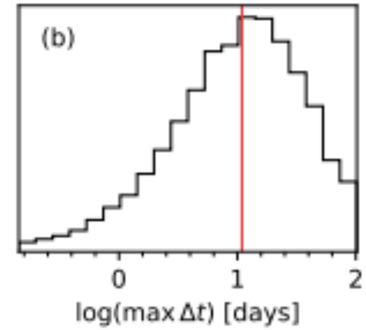
ZTF Search for glSNe

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

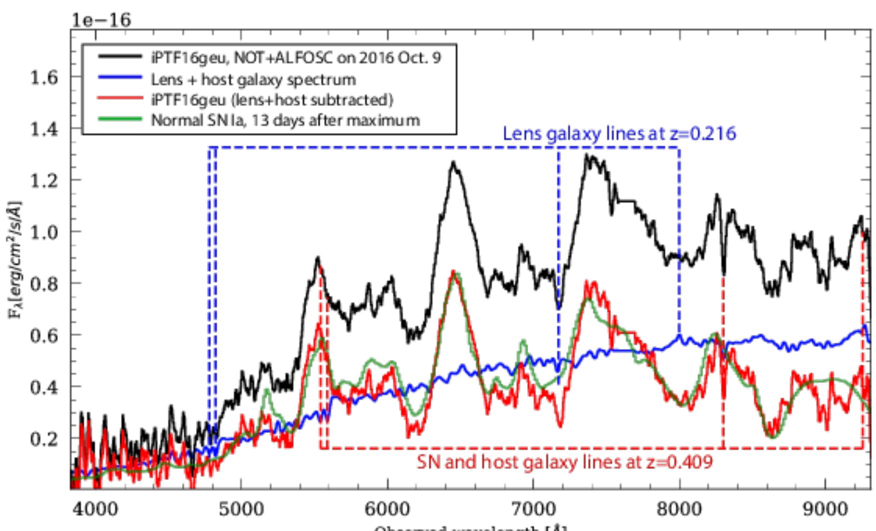
Spectroscopic classification necessary
  - Classification with P60,INT, P200 (were heavily COVID-hit)
  - High resolution follow-up with Keck, VLT

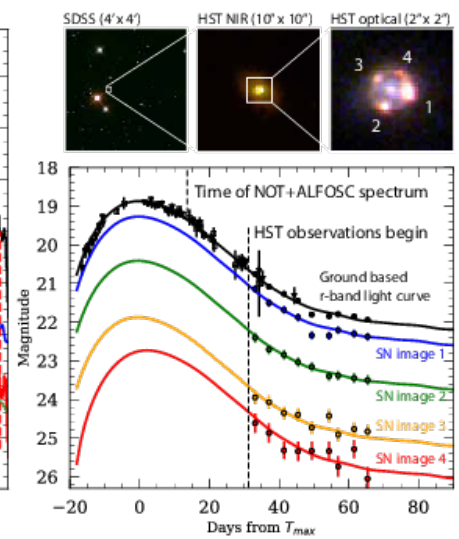
- Expected number ~ 1 - 3 per year: At magnitude limit ~ 20.5 mag
  - Current spectroscopic coverage ~ 18.5 mag

Deeper spectroscopy needed for vetting



Expected distribution of time delays



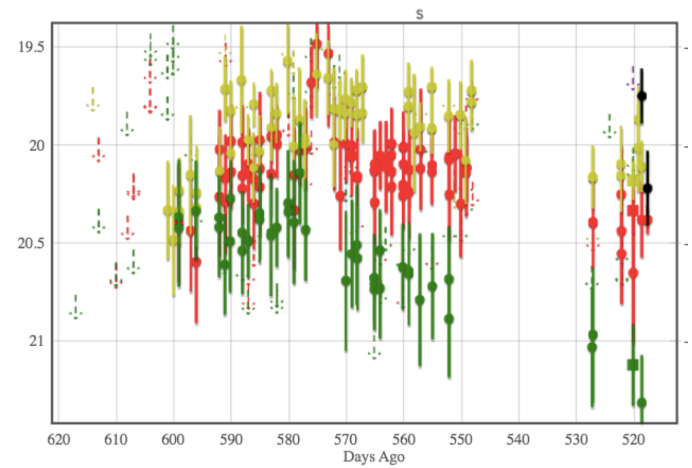


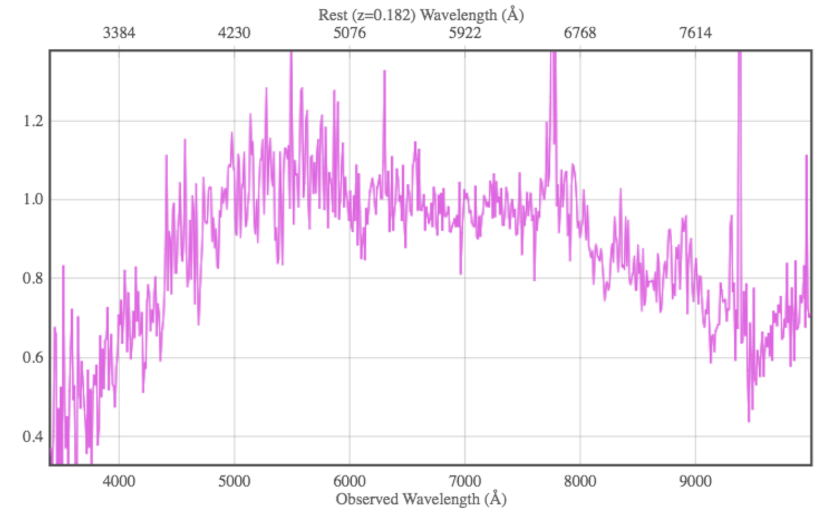
Spectra from Johansson, SD, … + '21

Interesting Candidates

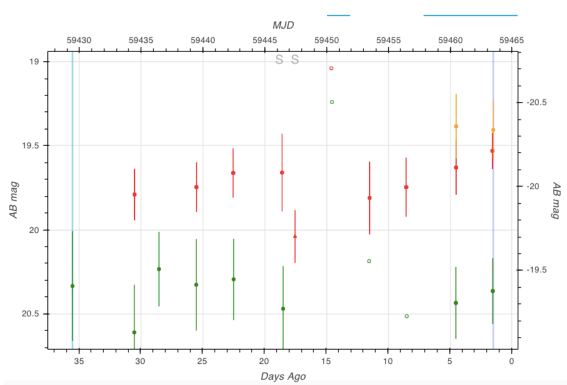
Contaminants are interesting themselves

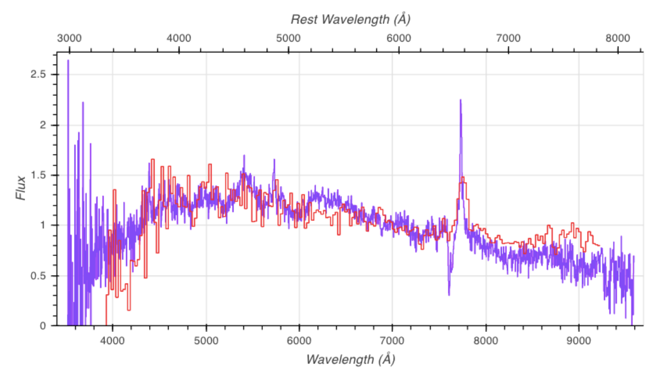
Contaminant false positives: SLSNe, blazars
With stacked images: higher-z SNe Ia





Bright (M > -20), red Type II-P, only 4 seen in a sample of few hundred SNe (Perley+'20)



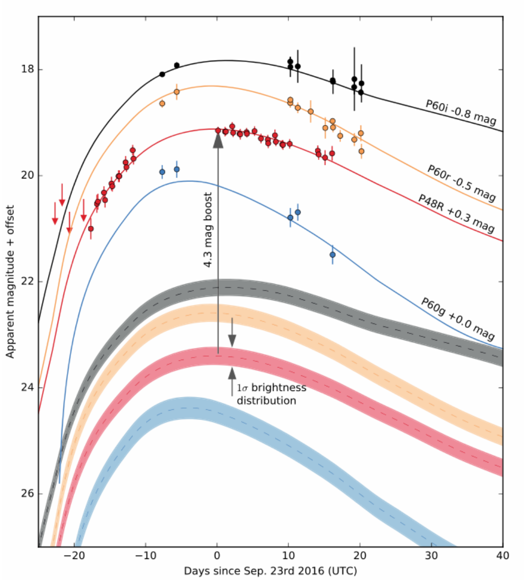


Bright (M > -20), red Ia-CSM; interacting SN

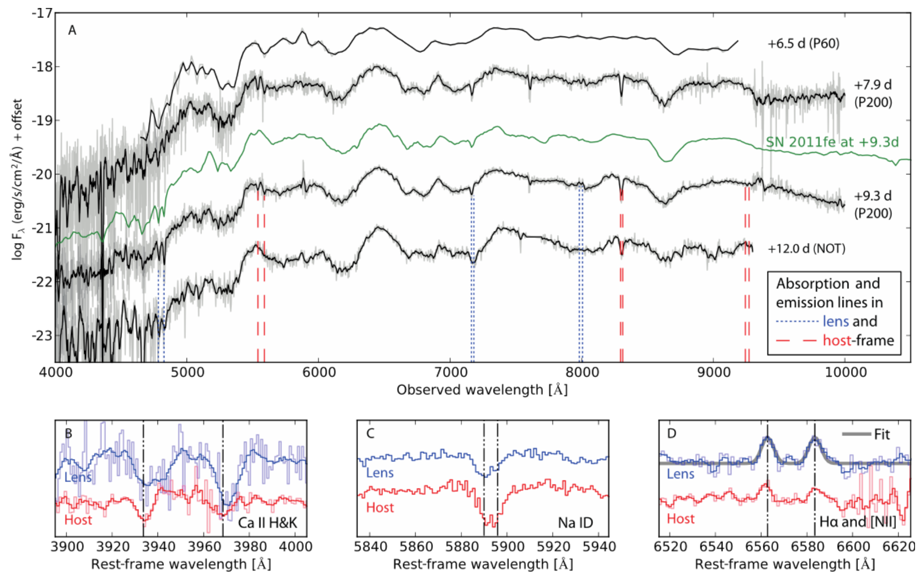
iPTF16geu: Discovery

>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

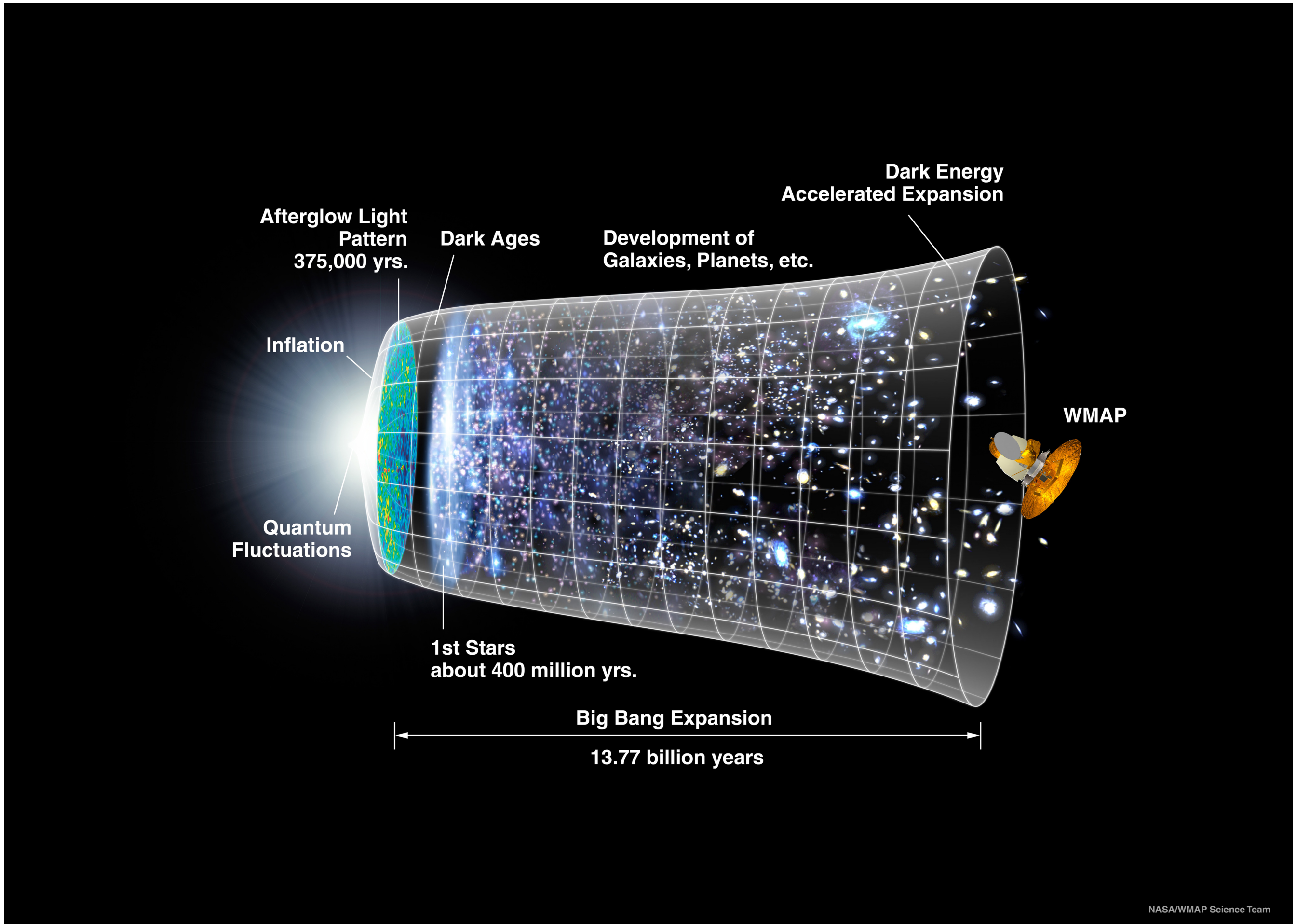
Absorption lines from host galaxy and another galaxy in the line of sight

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

Expansion history

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

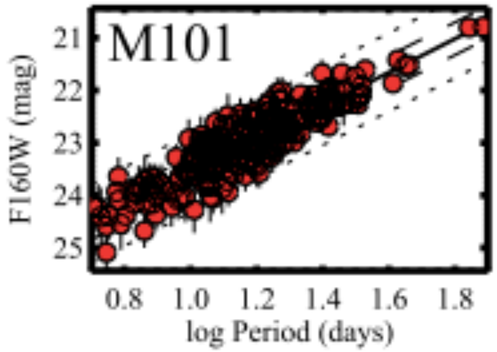
- Constrain growth of structure

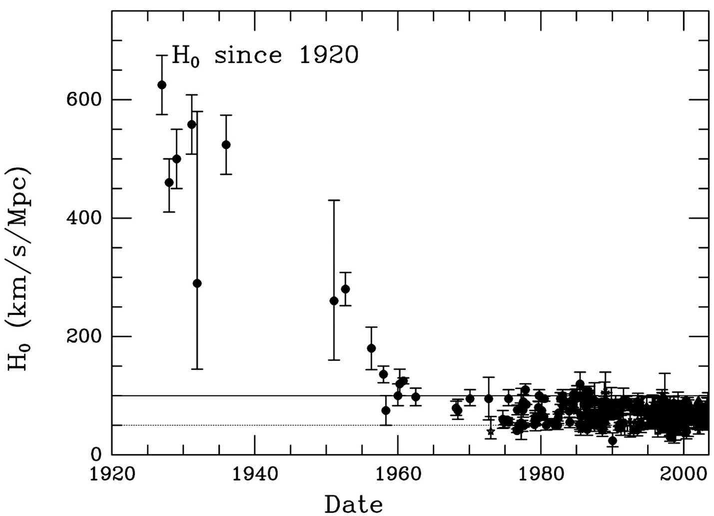


Cepheids as distance indicators

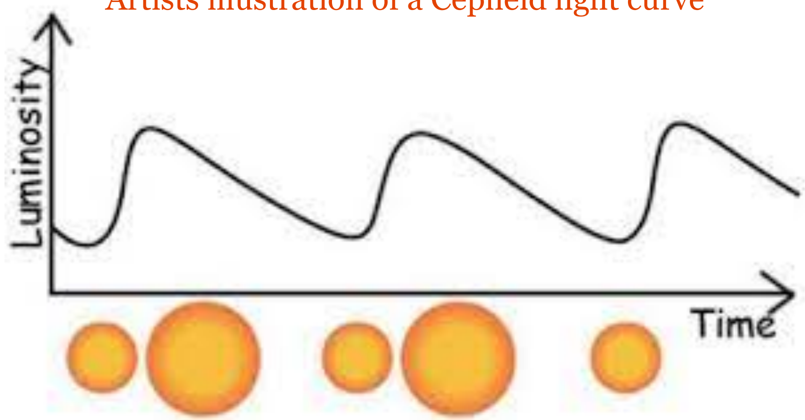
- Pulsating variable stars
- Developed as precise distance indicators
- Correcting for Period - Luminosity (P-L) relation (Leavitt + Pickering 1912)
  - Correct for colour: the “Wesenheit” relation
  - Metallicity - luminosity relation

Minimise corrections by observing in the NIR

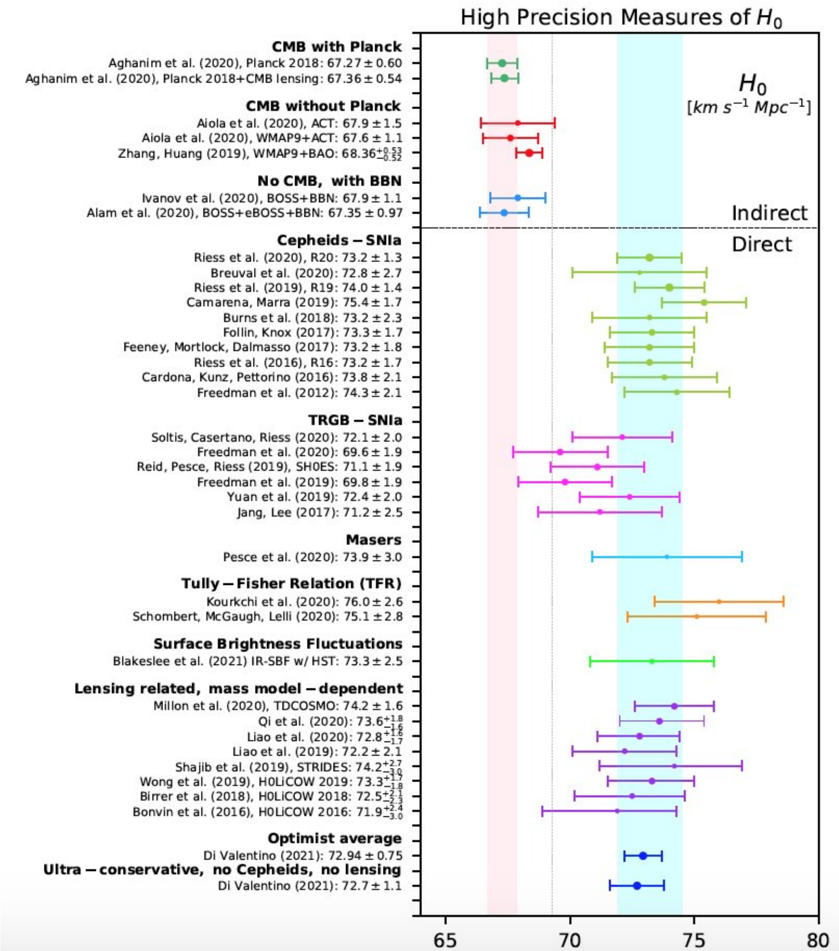




Artists illustration of a Cepheid light curve



Current Status



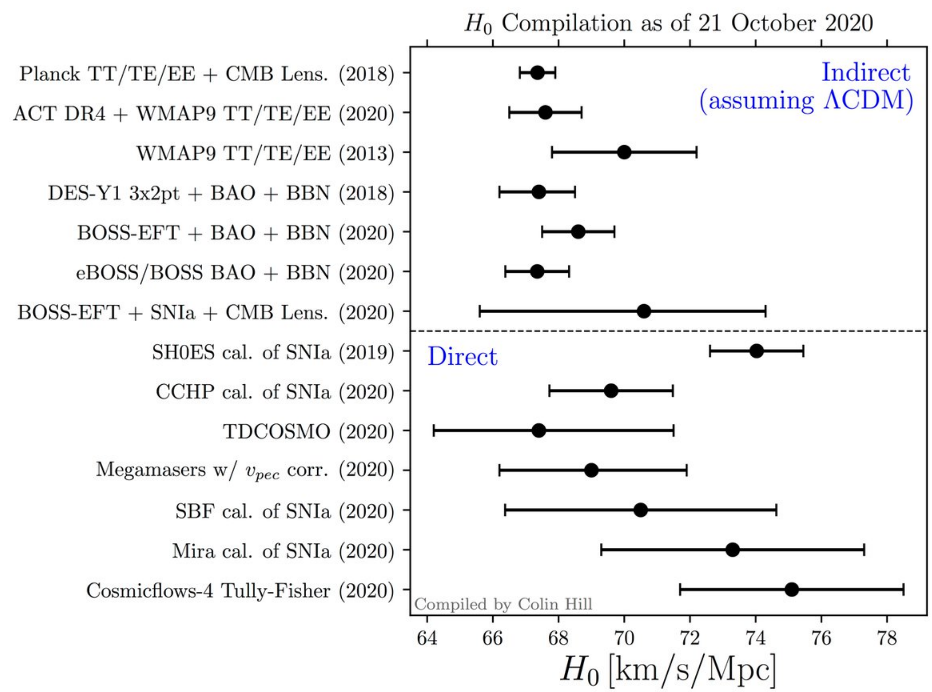


Figure from review by Di Valentino et al. (left) see also Hill et al. (right)

Updated "tension"