A Uniform ZTF-TRGB distance ladder

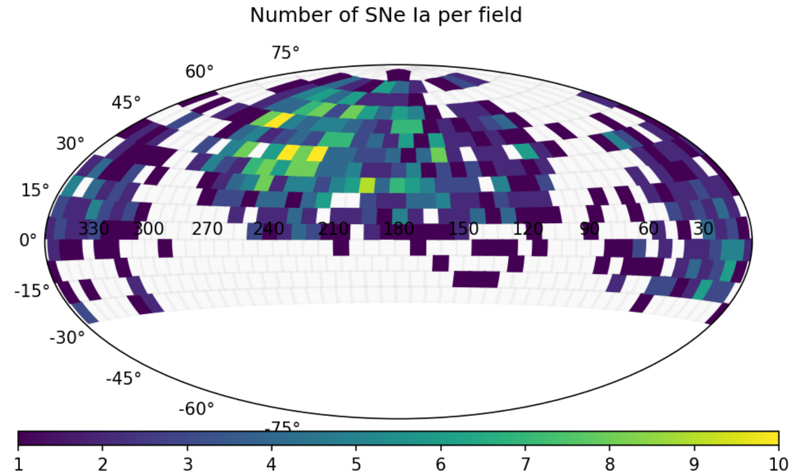
Suhail Dhawan

Marie Sklowdowska Curie Fellow
Institute of Astronomy & JRF, Lucy Cavendish College, Cambridge

with: ZTF Cosmo WG + Carnegie-Chicago Hubble Program

Tensions in Cosmology, Corfu, 08 September 2022

Outline



Motivation

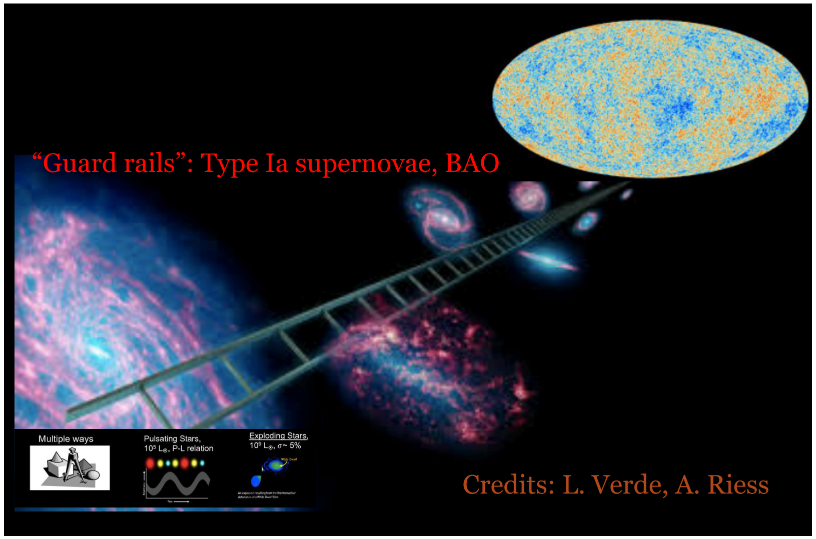
ZTF: DR1 sample (Dhawan+22, MNRAS,510,2)

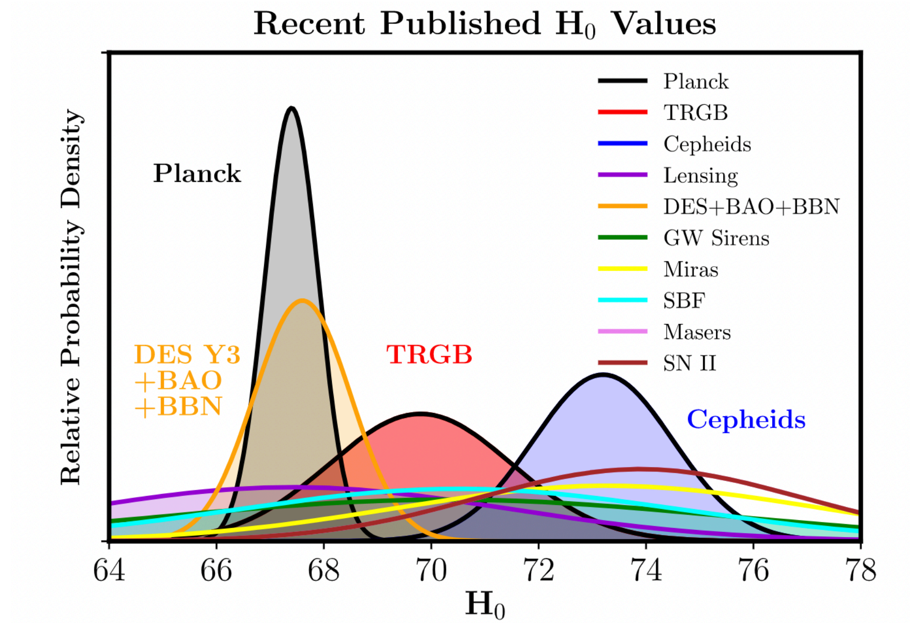
ZTF-TRGB distance ladder (Dhawan+22,ApJ, 9354, 185)

Motivation

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

Credits: Freedman 2021





- New physics? (e.g. Knox & Millea 2020, Schoenberg+, Shah+)

- Unknown Systematics?

Need independent methods

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

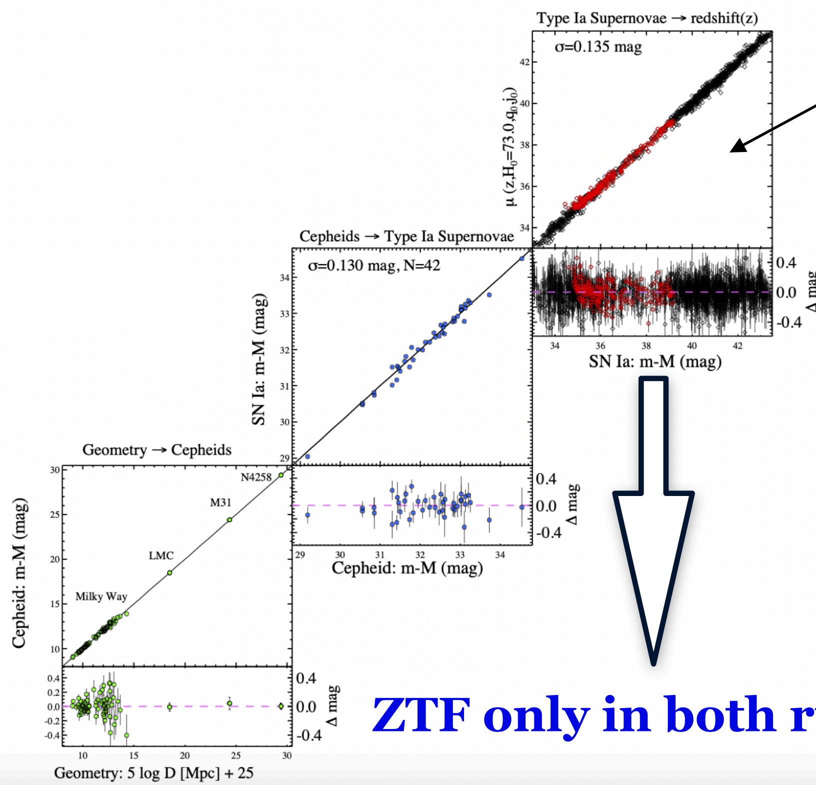
Focus of today's talk!

Cosmic Distance Ladder

- Type Ia supernovae: Hubble flow (z ~ 0.02 and higher)
  - Calibrated with Cepheid or TRGB distances
  - Second rung calibrated with independent, primary anchors

Heterogeneous systems at low-z!

Amazing work done to X-cal!



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

ZTF only in both rungs

Riess et al. 2022

Type Ia supernovae from the Zwicky Transient Facility

The Zwicky Transient Facility

P48: 1.2m discovery Schmidt telescope

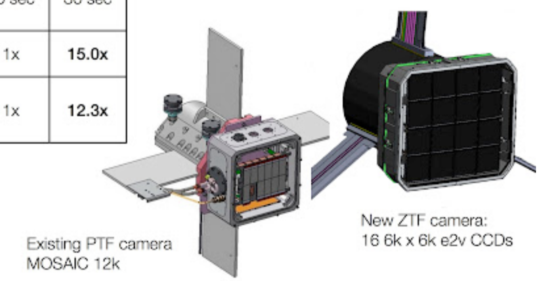
Dedicated classification with P60: SEDm

ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 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



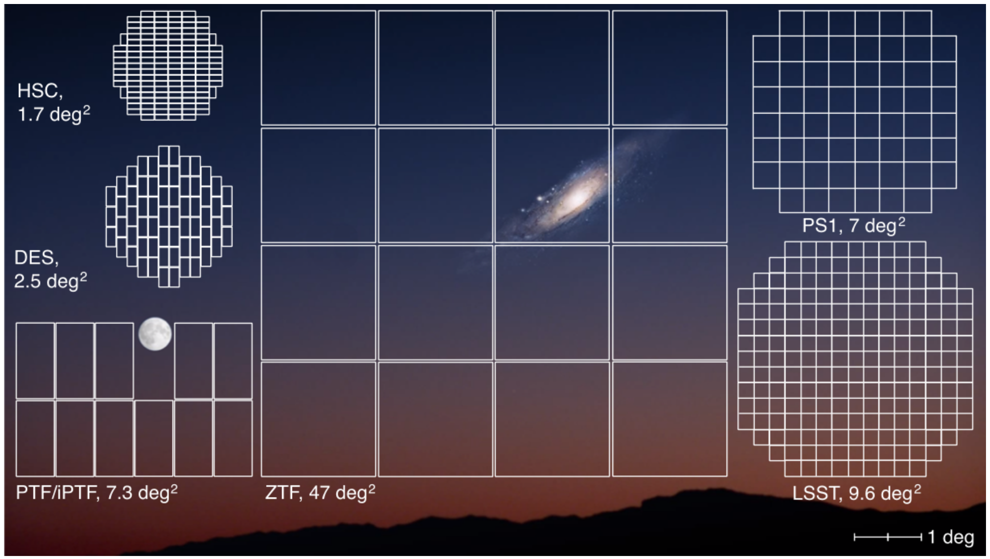
~ 5000 in ZTF Phase I
Phase II began ~ Nov. 2020

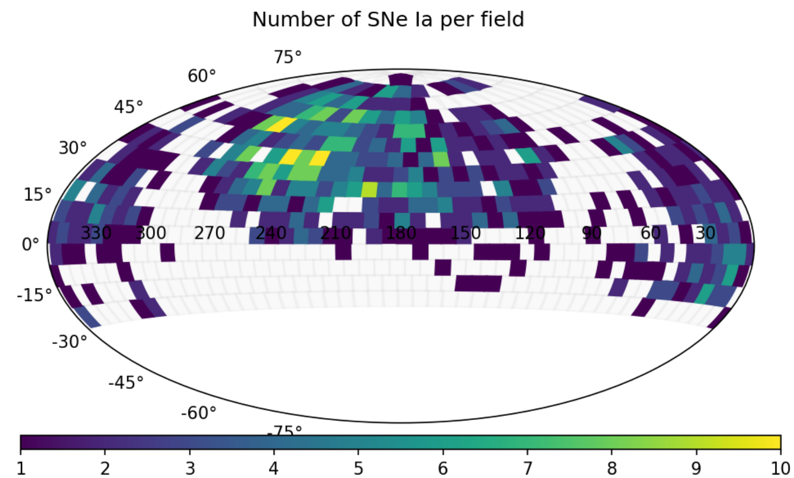
Total Number of SNe: 5581 I Ia: 3507 I II: 1280 I Ib: 121 I Ic: 132 I Ib/c: 21 I Ic-BL: 47 I SLSNe: 178

GROWTH Followup Marshal

ZTF Year 1 sample

SD+22a



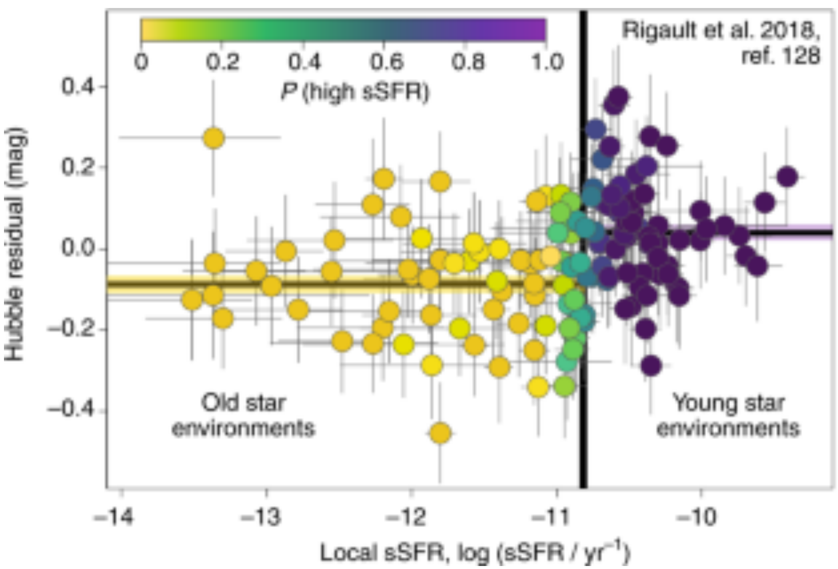


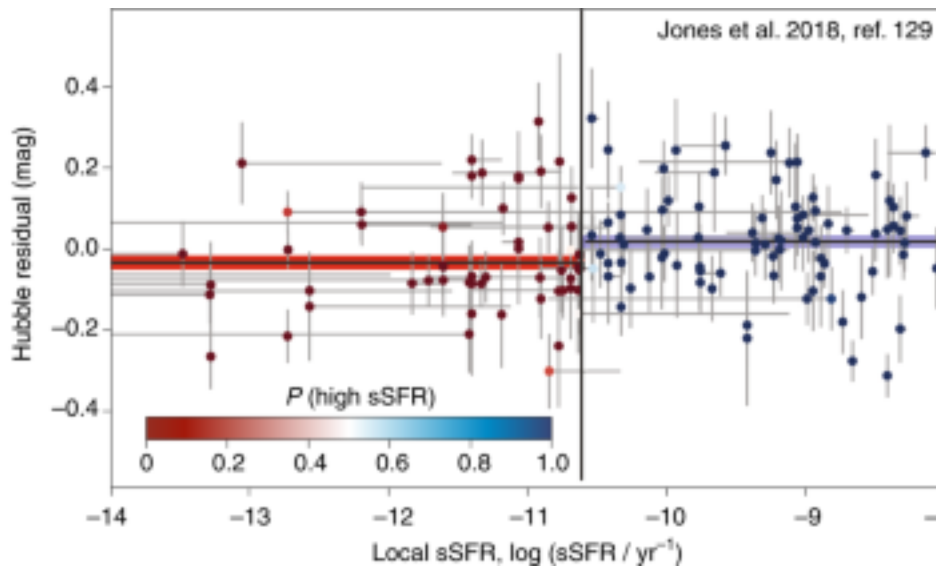
Legacy for Rubin; Roman in future

- 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

Testing environmental dependence



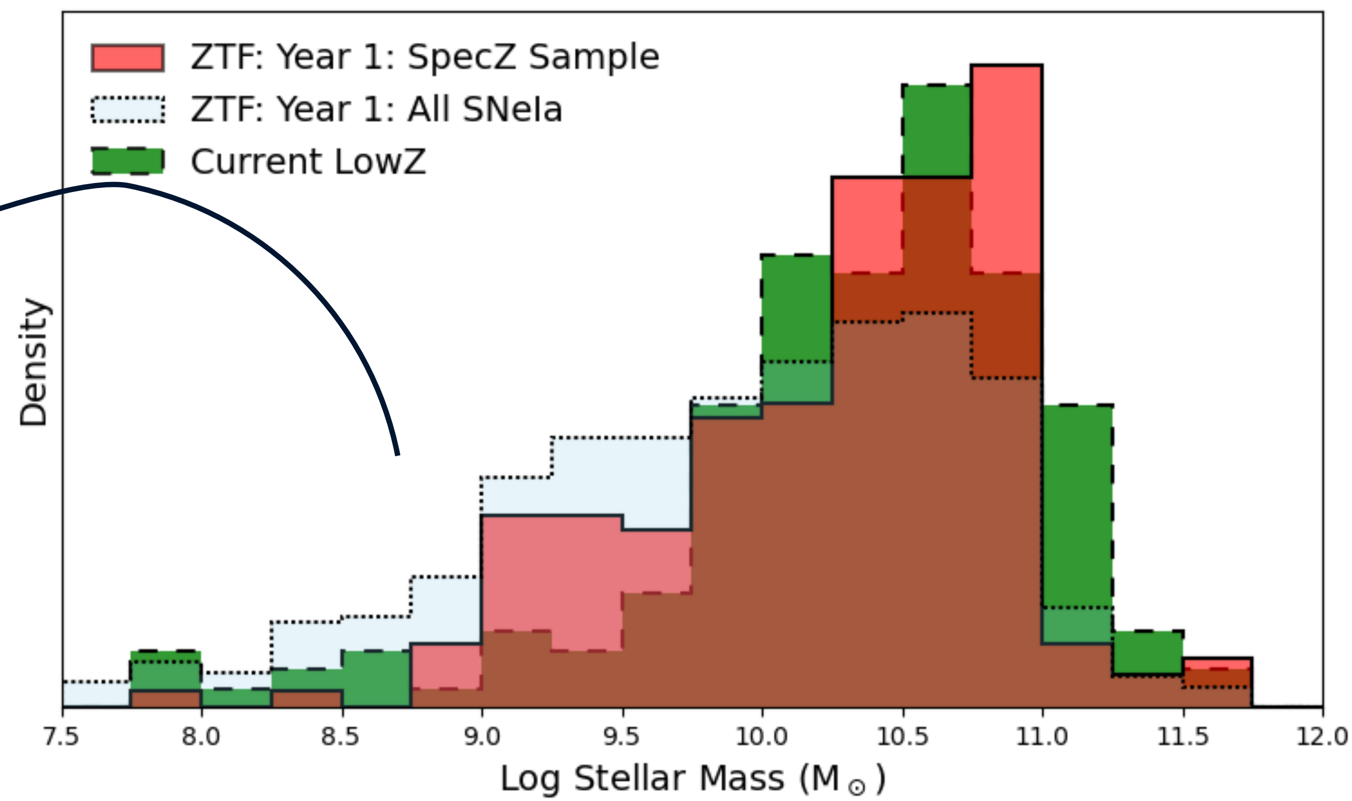


Is SN luminosity dependent on host galaxy local properties?
- Potential claims of bias upto 5% -> other claims < 1%
- Untargeted survey to sample underlying host distribution

ZTF Host Galaxies

SD+22a

Remaining redshifts from DESI

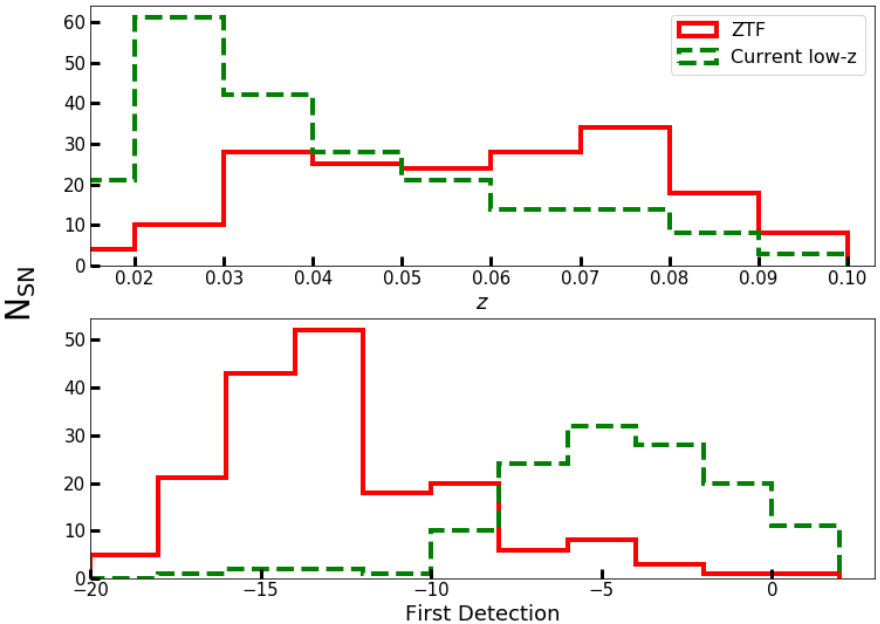


Higher ratio of low-mass to high-mass hosts

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

Improved Distances

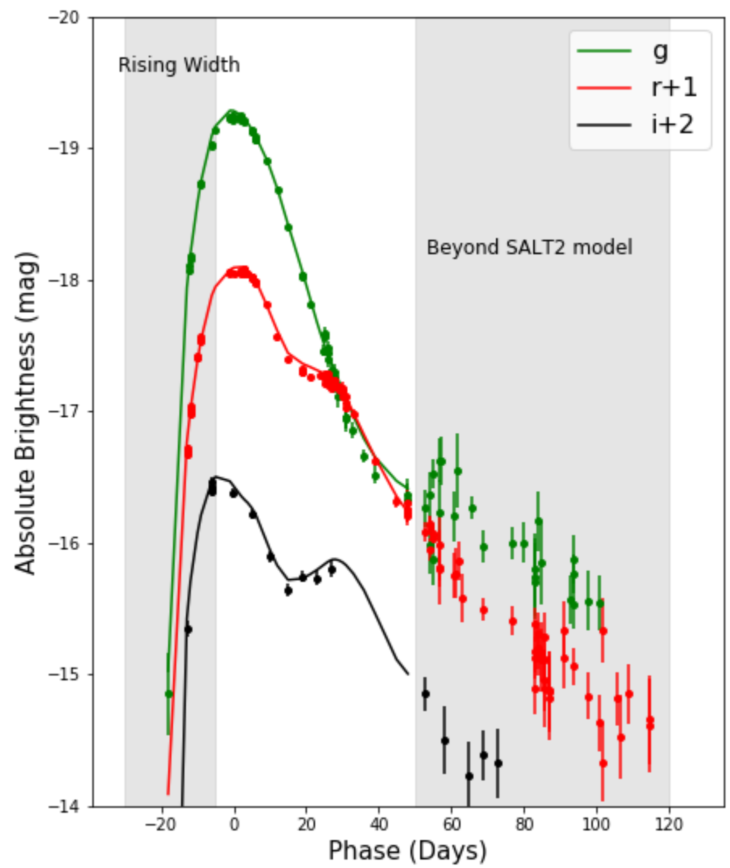
SD+22a



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

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

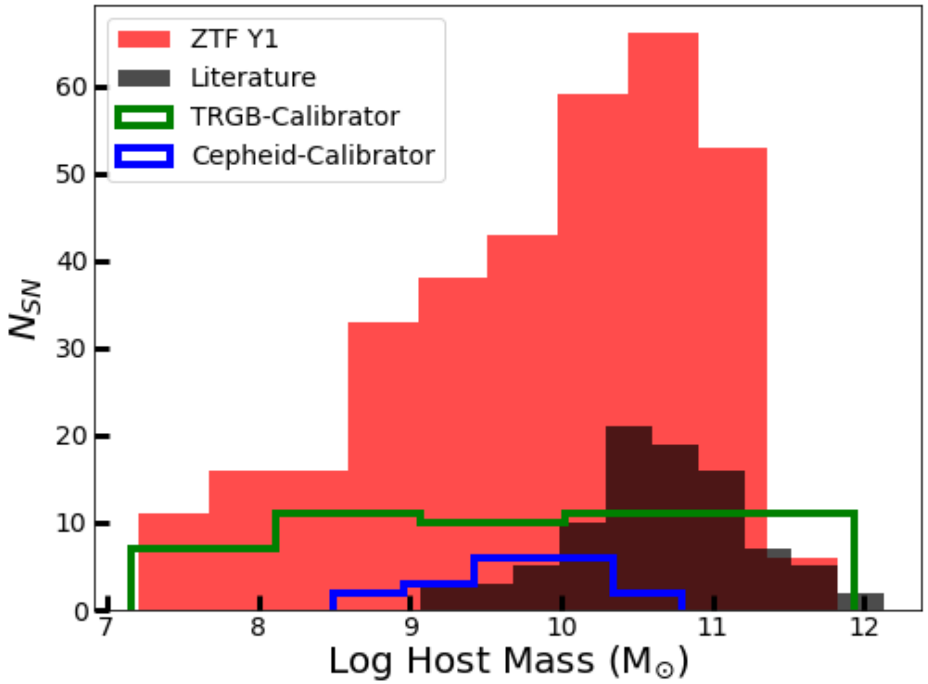


Early light curve for improving distances

A uniform ZTF-TRGB distance Ladder

Primary Distance Indicators

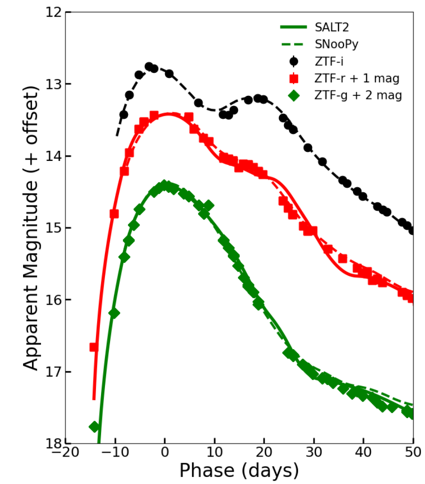
- TRGBs found in SN Ia hosts of all ages
- Less crowded environments than Cepheids
- Less prone to reddening, metallicity systematics than Cepheids (Mortsell+2021a,b; Efstathiou 202C`
- TRGBs fainter than Cepheids

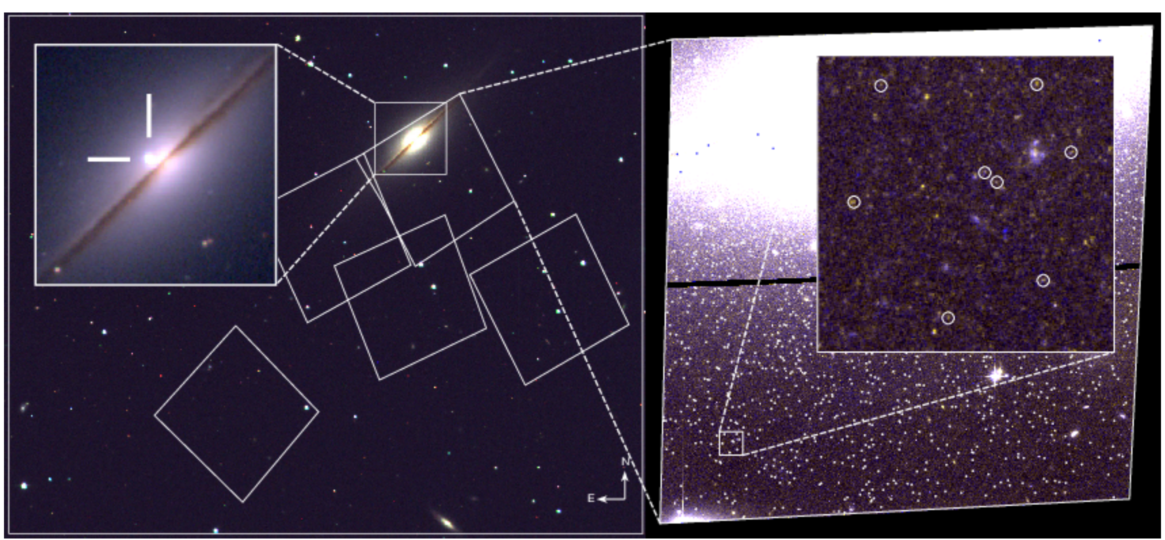


See also talks by T. Hoyt, W. Freedman

ZTF Calibrator Sample

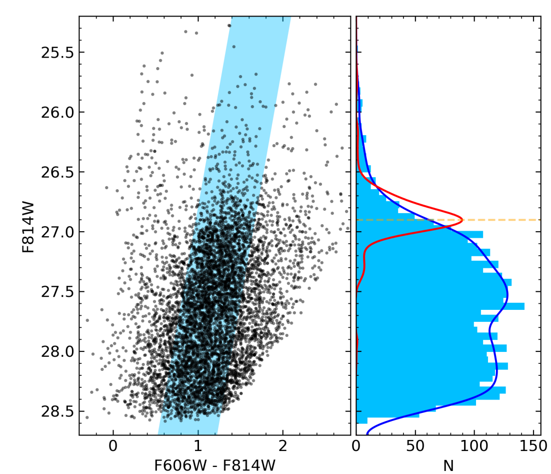
- 6 objects within D_L < 20 Mpc (HST feasibility)
- One with good TRGB distance -> ZTF21abiuvdk (SN2021rhu)
- 7 fields from HST ACS/WFC





SD+22b

Credit: IS Jang

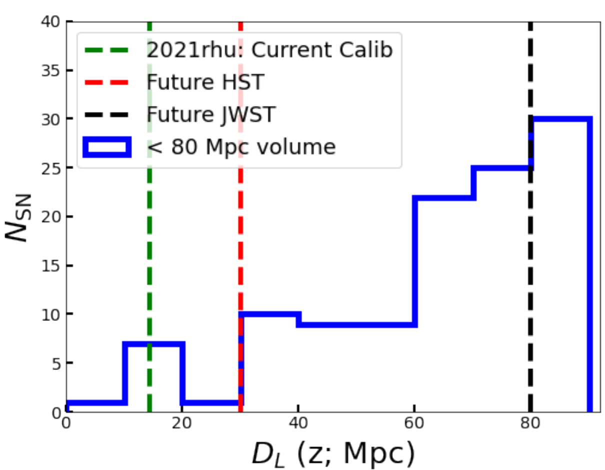


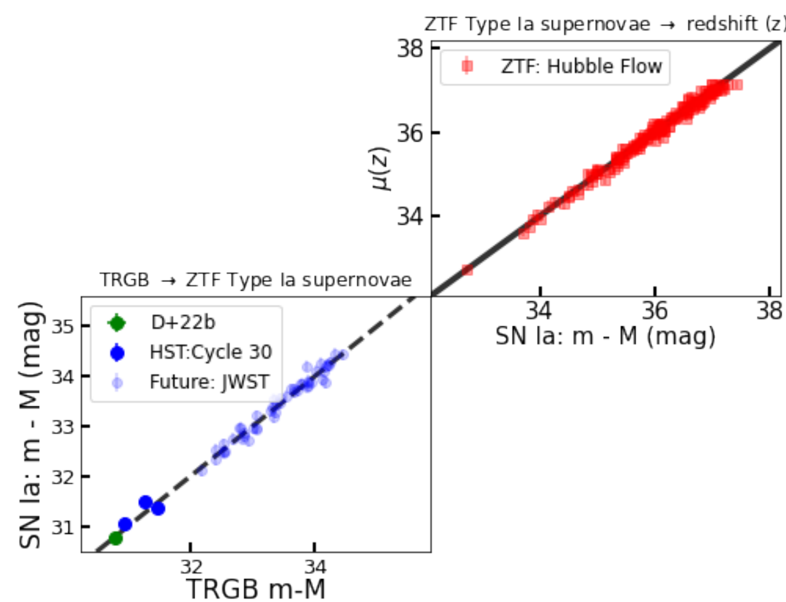
Current Distance Ladder +Outlook

- Single calibrator -> increase to 6 with HST C30
- Small impact of sample selection, LC fitter
- Hubble flow of ~ 200 SNe Ia -> ZTF DR2 upcoming
- 106 SNe Ia with accurate distances at D_L < 80 Mpc
- H_0 = 76.94 +/- 6.4 km/s/Mpc

+ ZTF DR2 this year! ~ 3000 SNe Ia

SD+22b





Conclusions

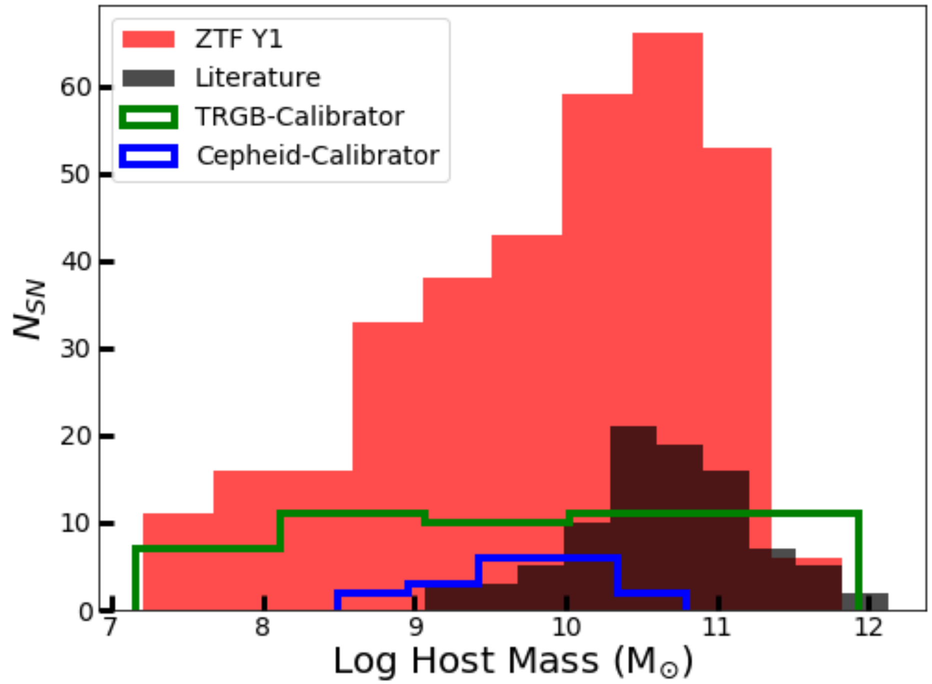
- ZTF DR1: homogeneous, untargeted sample of 750 SNe Ia
    - Improved distances with early light curves
    - Probing environmental biases

- TRGB: excellent standard candles
    - > 100 host galaxies within JWST capabilities
    - Distances from HST < 20 Mpc, NIRCam < 80 Mpc
    - First pilot study H0 = 76.94 +/- 6.4 km/s/Mpc

    + ZTF DR2 upcoming

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 C30 proposal)

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
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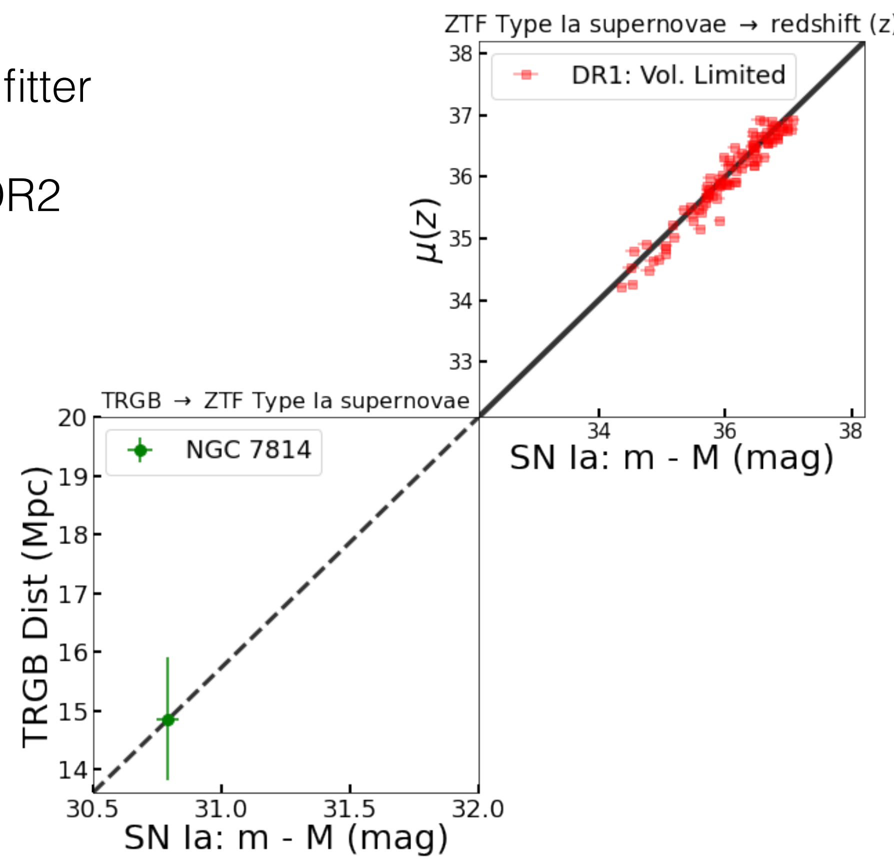
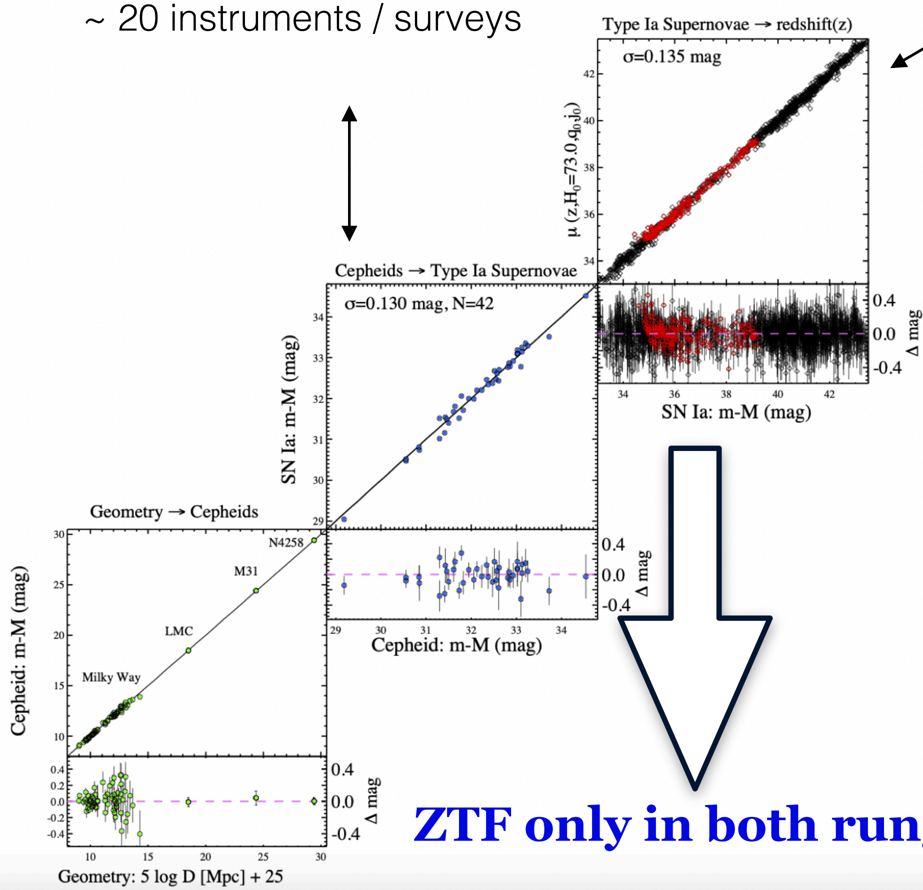
SD+22b



Cepheid Distance Ladder

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

~ 20 instruments / surveys



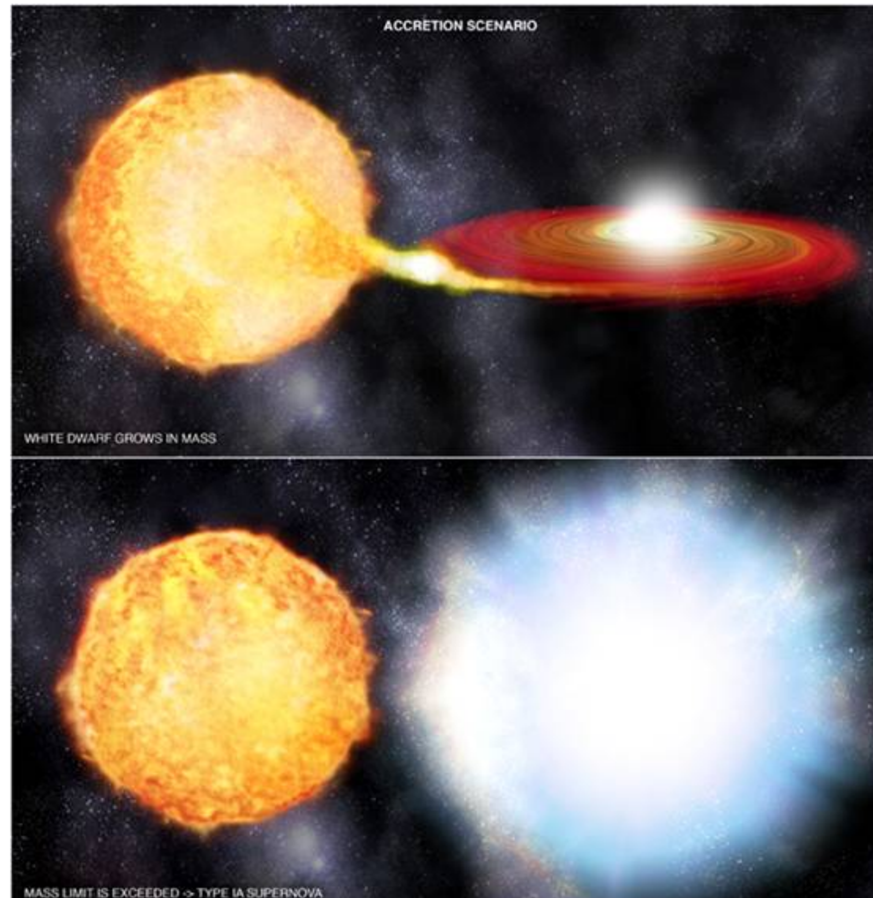
ZTF only in both rungs

Riess et al. 2022

What are Type Ia supernovae?

Bright, stellar candles

NOT standard; calibratable

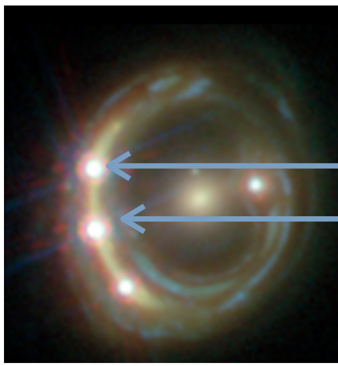


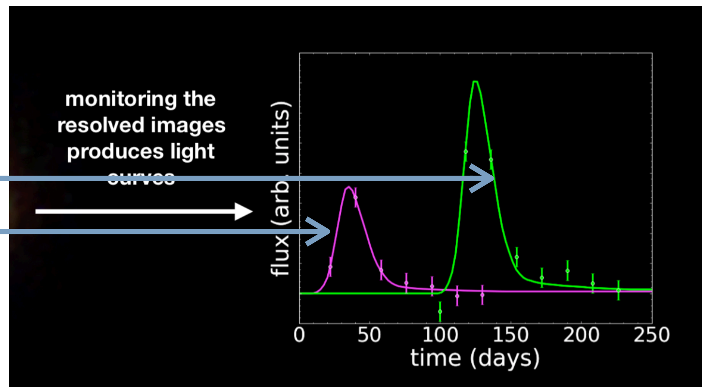
Discovery of dark energy

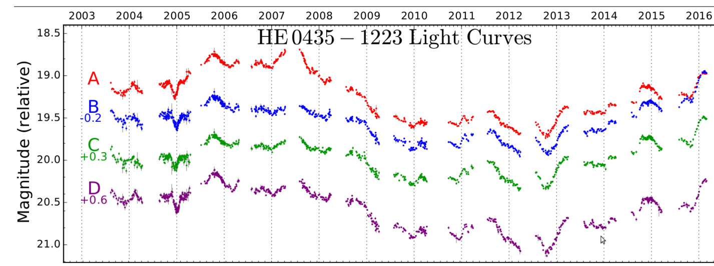
In all types of galaxies

Time-delay cosmography

Typical lensed SN and QSO light curves



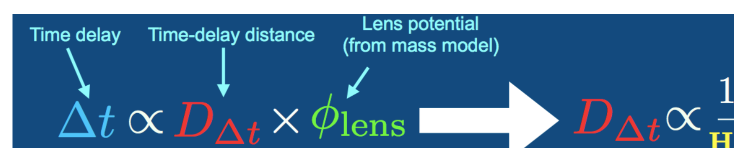




Advantages of glSNe Ia

- Much less monitoring required
- “Standardisable” luminosity => break modelling degeneracies (e.g. Birrer, SD, Shajib, 21)
- Lower impact of microlensing systematics

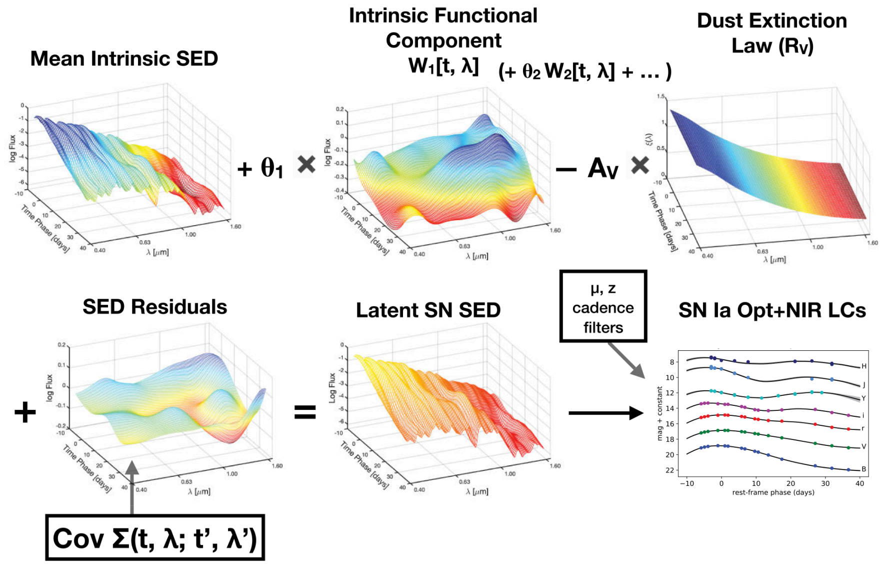
- Independent discovery method to lensed quasars
  - glSNe => “standardisable candle”



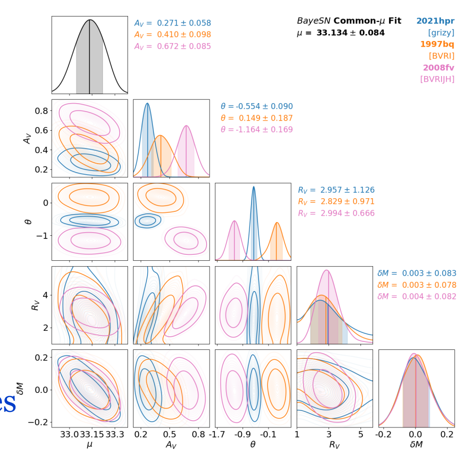
- First proposed in Refsdal 1964 (for SNe, used for QSOs)

Refining Supernova Distances

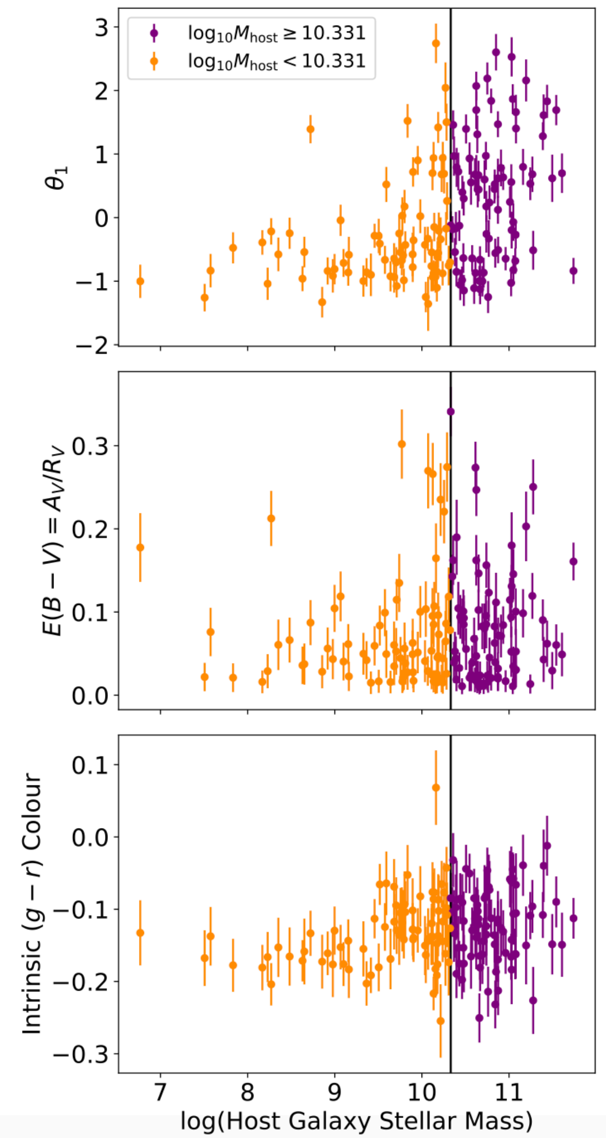
BayeSN model



SED model to infer LC shape, absorption and distance (Mandel+2020)



Joint fits to siblings!-> better distances
Ward,… SD, et al. in prep.



SN parameters as a function of host galaxy mass (**Thorp**+2021)

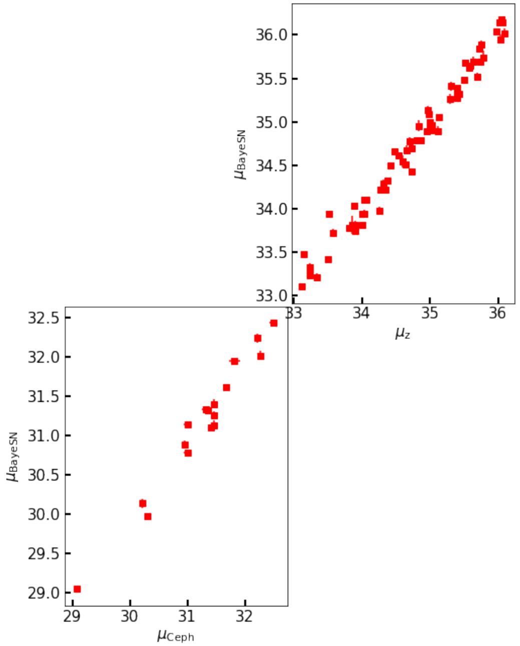
First H_0 constraints

- NIR is uniform with low scatter
- Optical through NIR modelling
  - Important to infer dust properties

- Uncertainties 15 - 20% better than optical only
  - Key step to reduce SNIa systematics

SD+22c in prep.

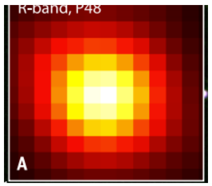
Training on ZTF DR2 ongoing
-> apply to uniform distance ladder



Still blinded to H_0

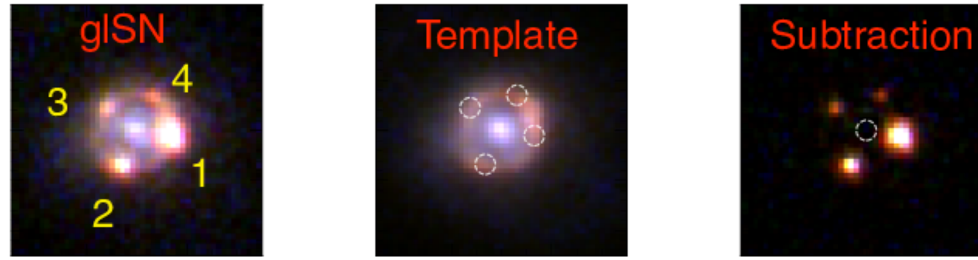
Strongly Lensed Supernovae

iPTF16geu: Resolved lightcurves

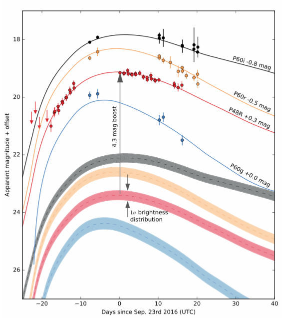


Discovery in unresolved data

Follow-up: HST / AO



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



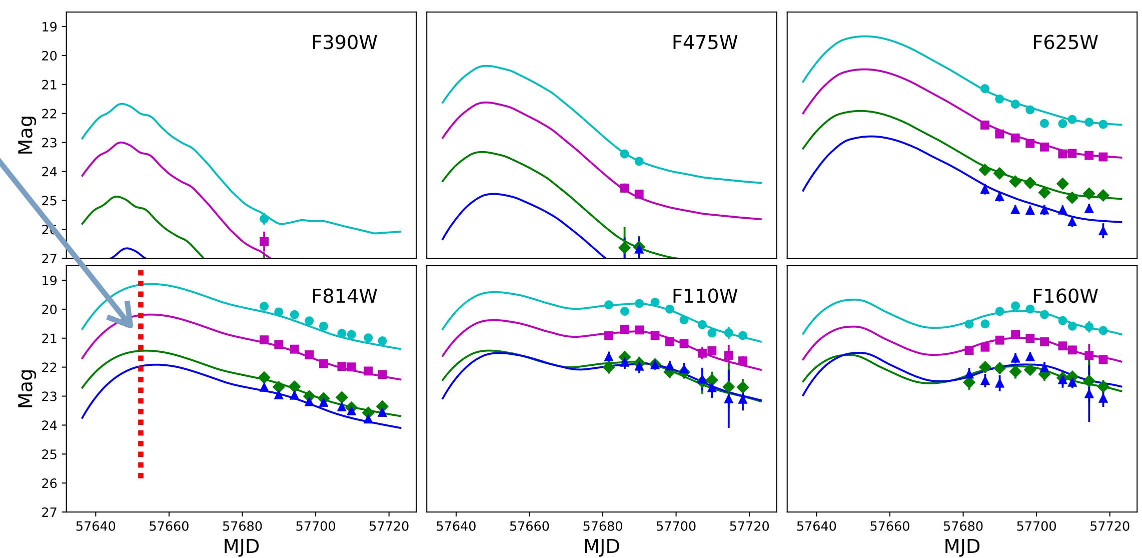
>50 times brighter than normal SNIa at z~0.4: a 30σ outlier!

SD+2020b

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



iPTF16geu: Magnification + extinction

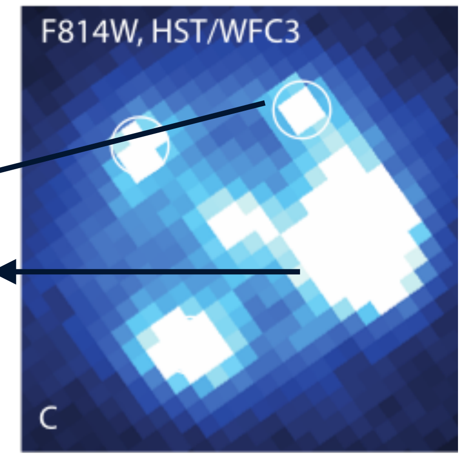
Preliminary magnification (μ) ~ 52
With extinction correction 67+/-3

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

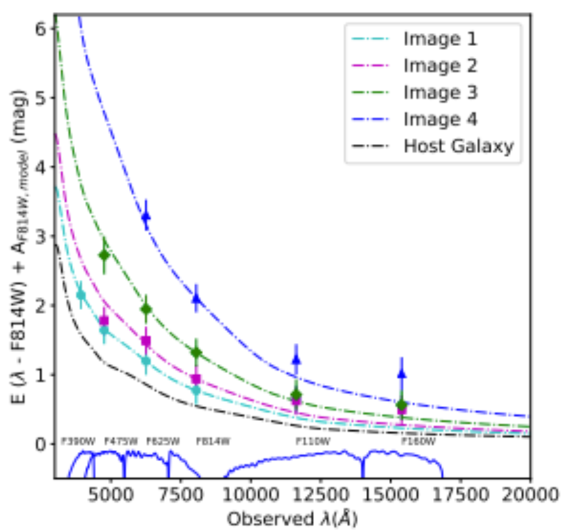
Probing the inner kpc of the lens => galaxy DM profiles

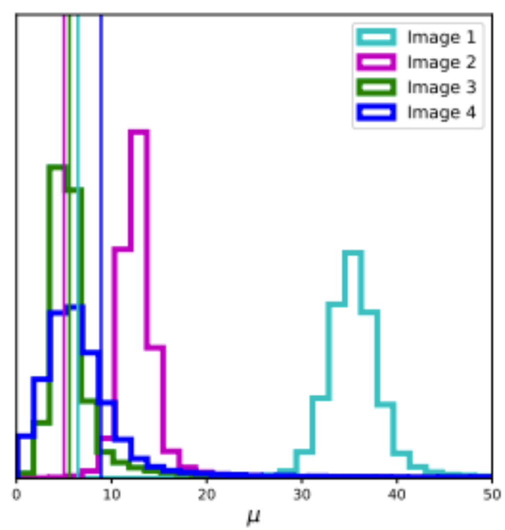
Surprisingly high magnification (μ)

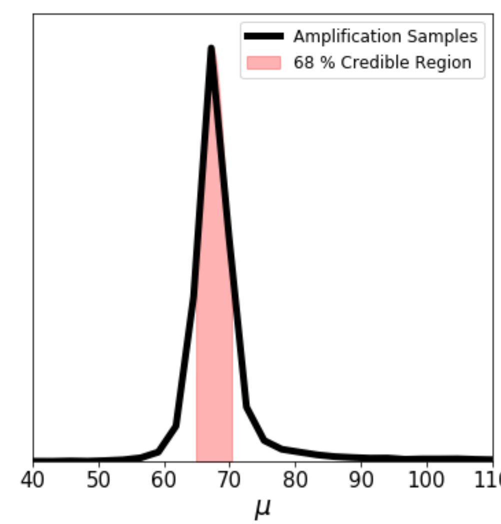
Surprisingly different brightness?



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







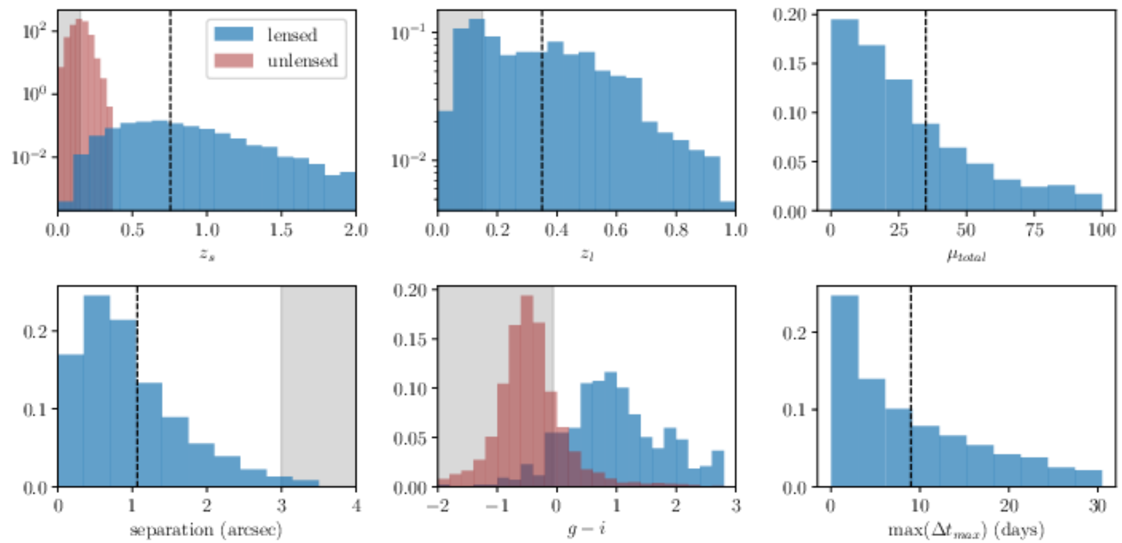
ZTF Search for glSNe

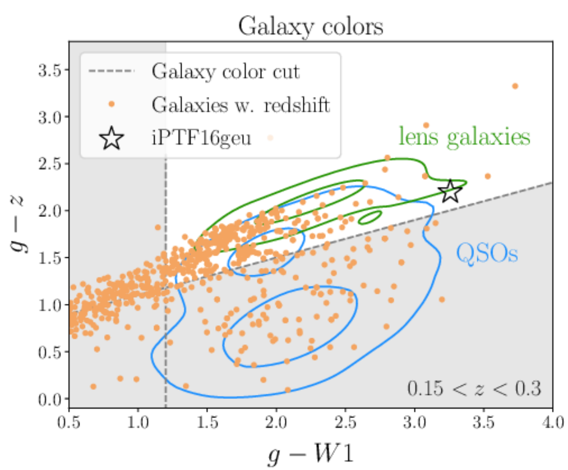
- Ongoing search in partnership (+public) data
  - High-cadence partnership survey
    - \+ i-band survey

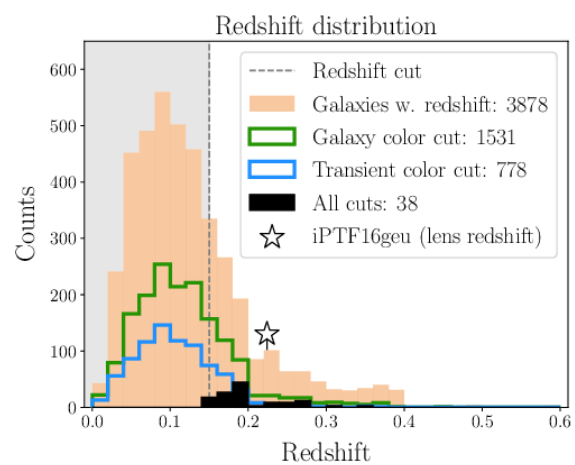
Spectroscopic classification necessary
  - Classification with P60,INT, P200 (were heavily COVID-hit)
  - High resolution follow-up with Keck, VLT

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

Deeper spectroscopy needed for vetting







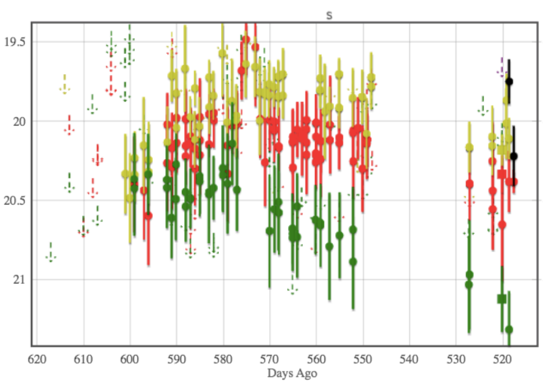
Candidate selection from ZTF archival data (Sagues-Carracedo,.., SD, et al. in prep)

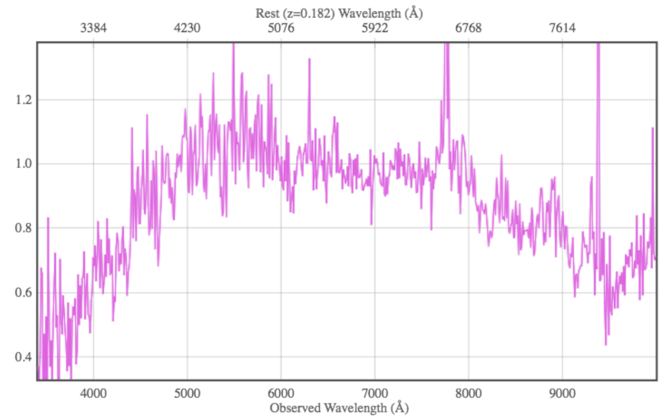
Interesting Candidates

Contaminant false positives: SLSNe, blazars

With stacked images: higher-z SNe Ia

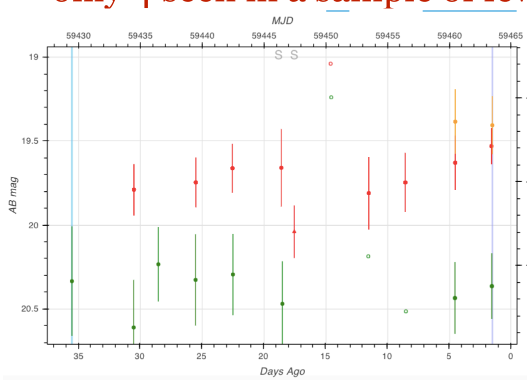
Contaminants are interesting themselves

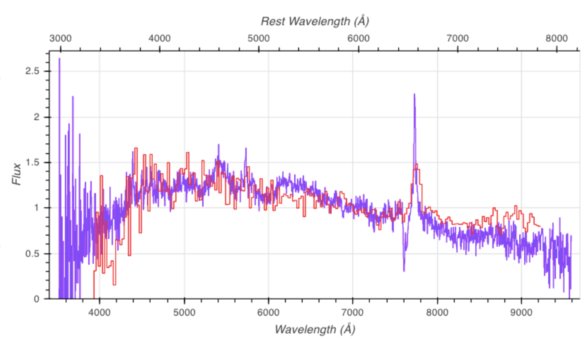


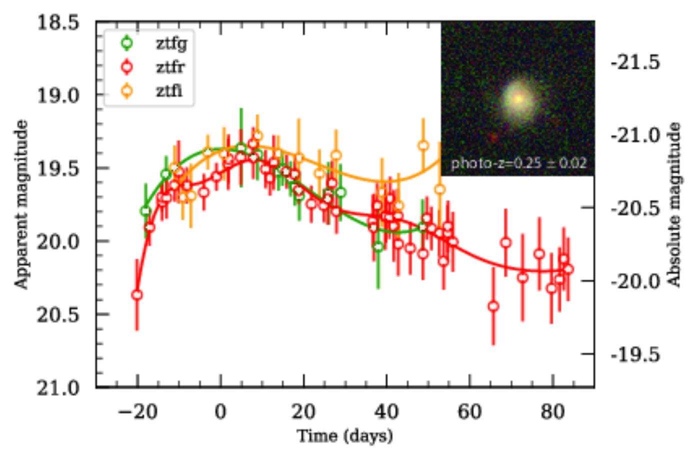


Bright (M > -20), red Type II-P,
only 4 seen in a sample of few hundred SNe (Perley+'20)

Archival search: need spectroscopy to vet





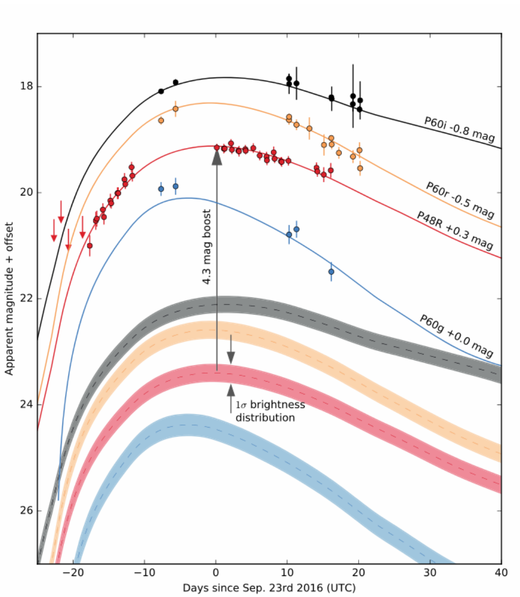


Bright (M > -20), red Ia-CSM; interacting SN

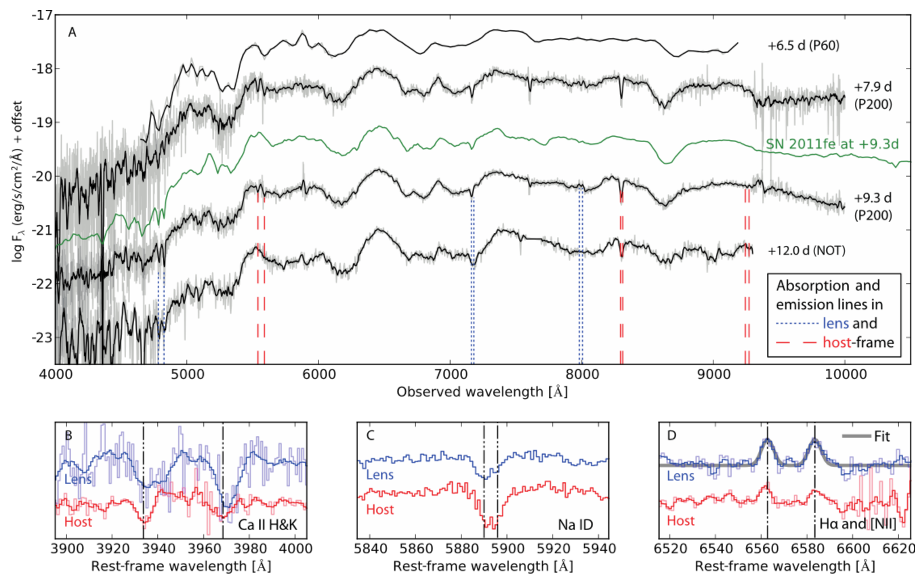
iPTF16geu: Discovery

>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

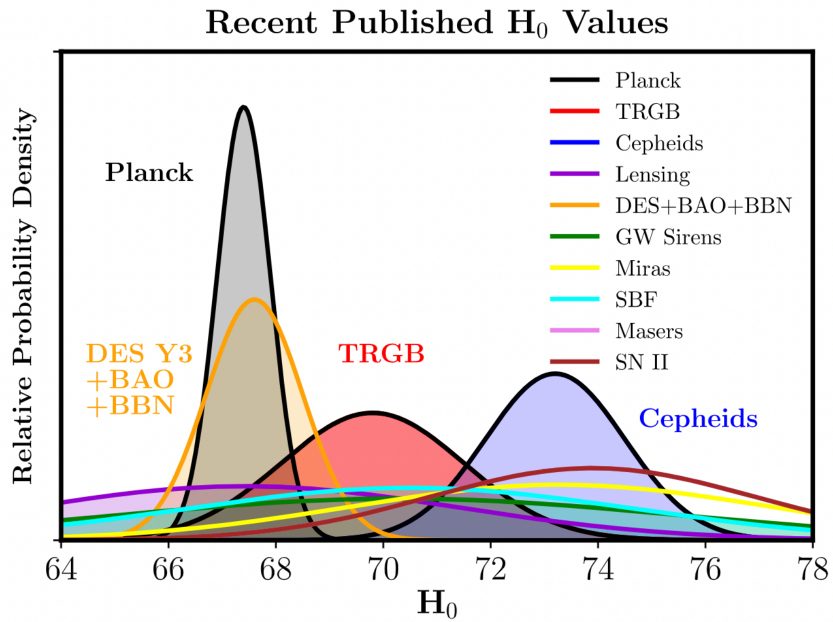
Perfect match to z=0.409 SN Ia + intervening galaxy at z=0.216

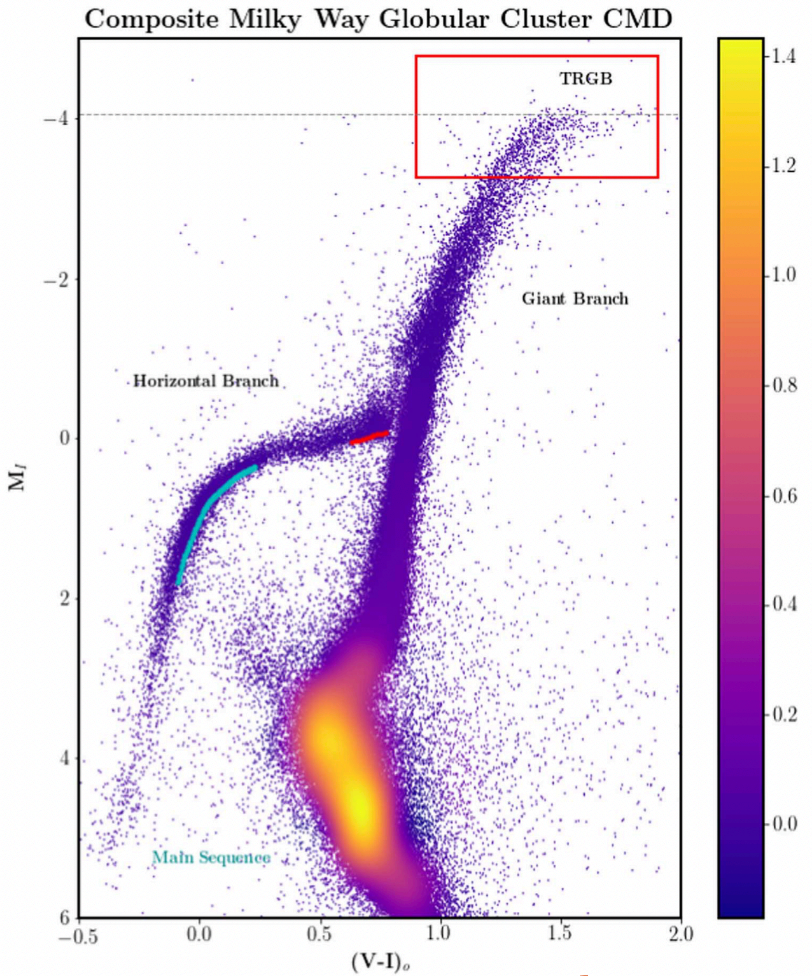
The Tip of the Red Giant Branch

Important **standard** candle

Well understood physics (He flash)

TRGB H0 not in tension





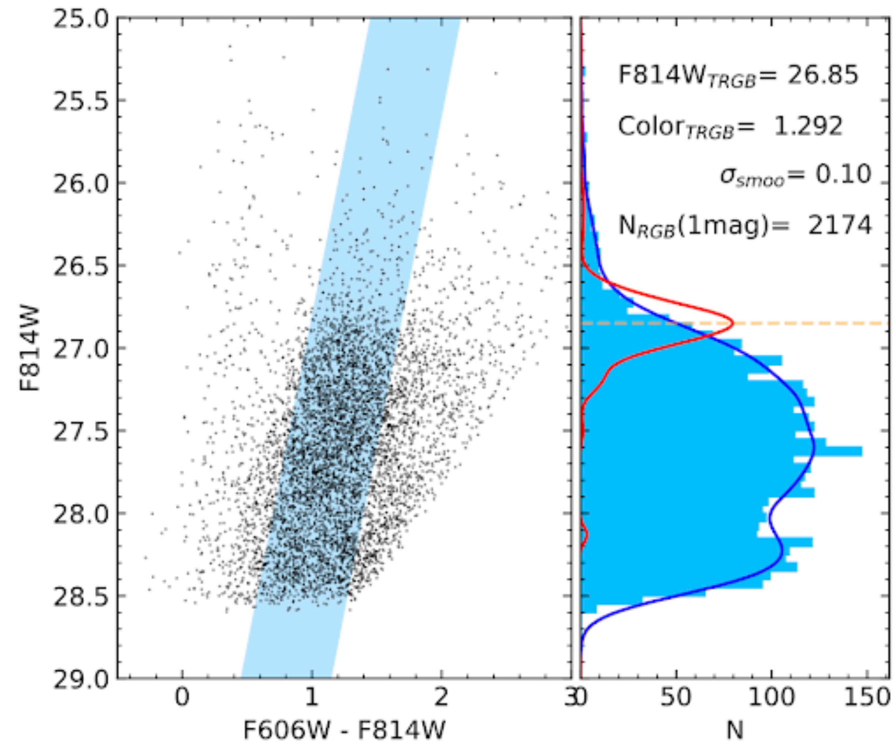
Freedman 2021

TRGB distance estimate

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

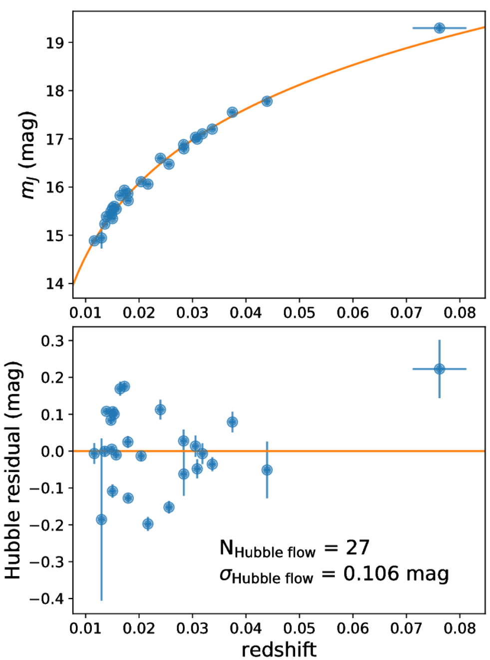
SD+22b, ApJ. Subm.

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



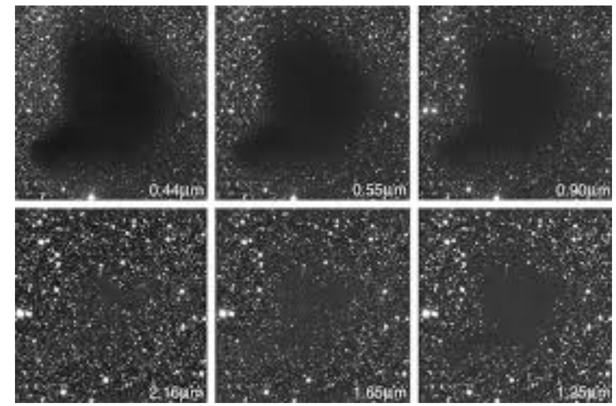
Near Infrared Standard Candles

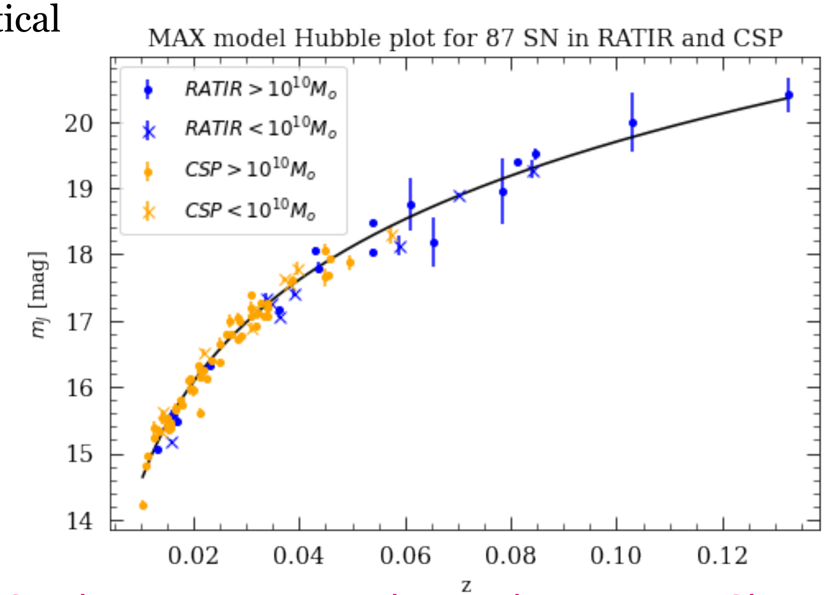
Does non-standard dust extinction cause high H_0?
Are SNe standard candles in the NIR? => future distance scale



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

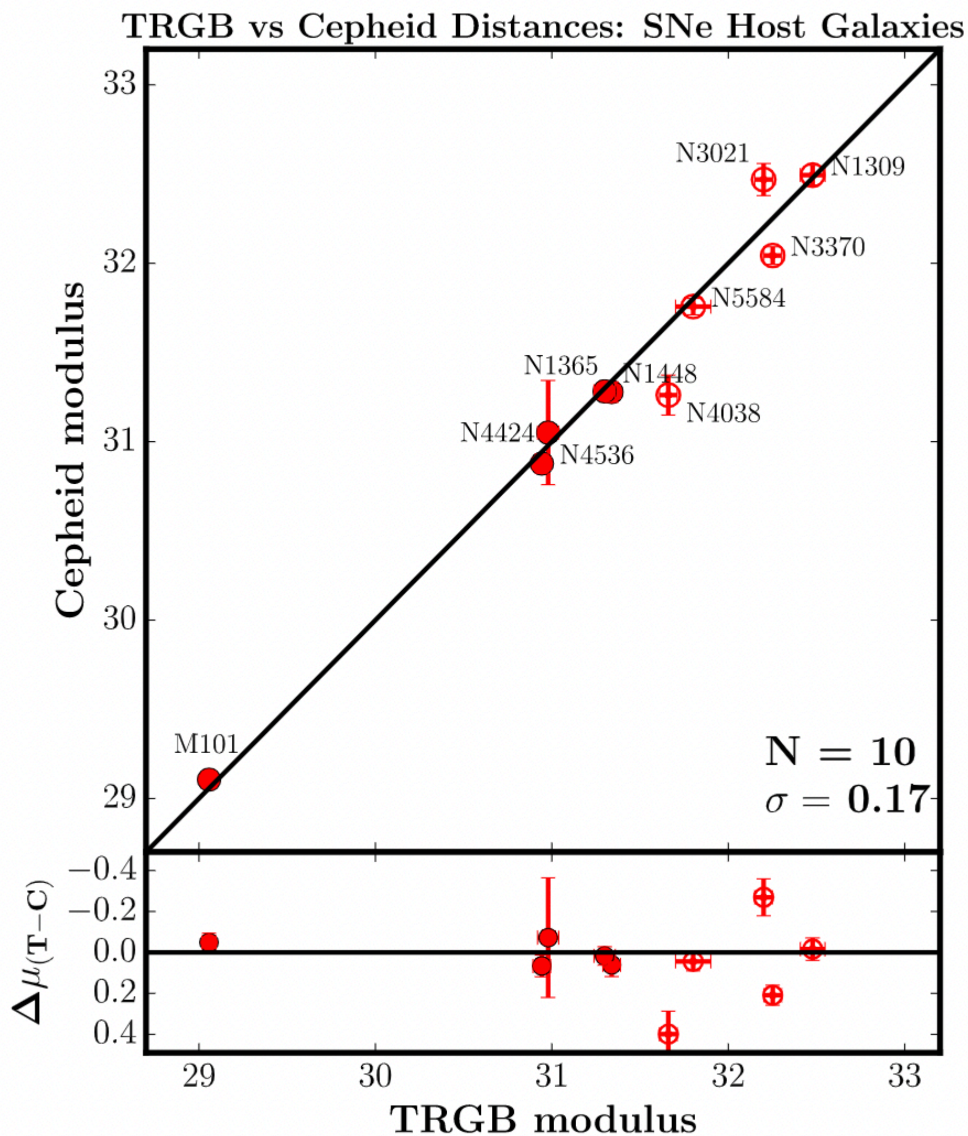




"Mass step": important for cosmology
- Debate on significance in NIR
- No 'step' seen in new sample

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

TRGB-Cepheid Consistency



Lensed SNe

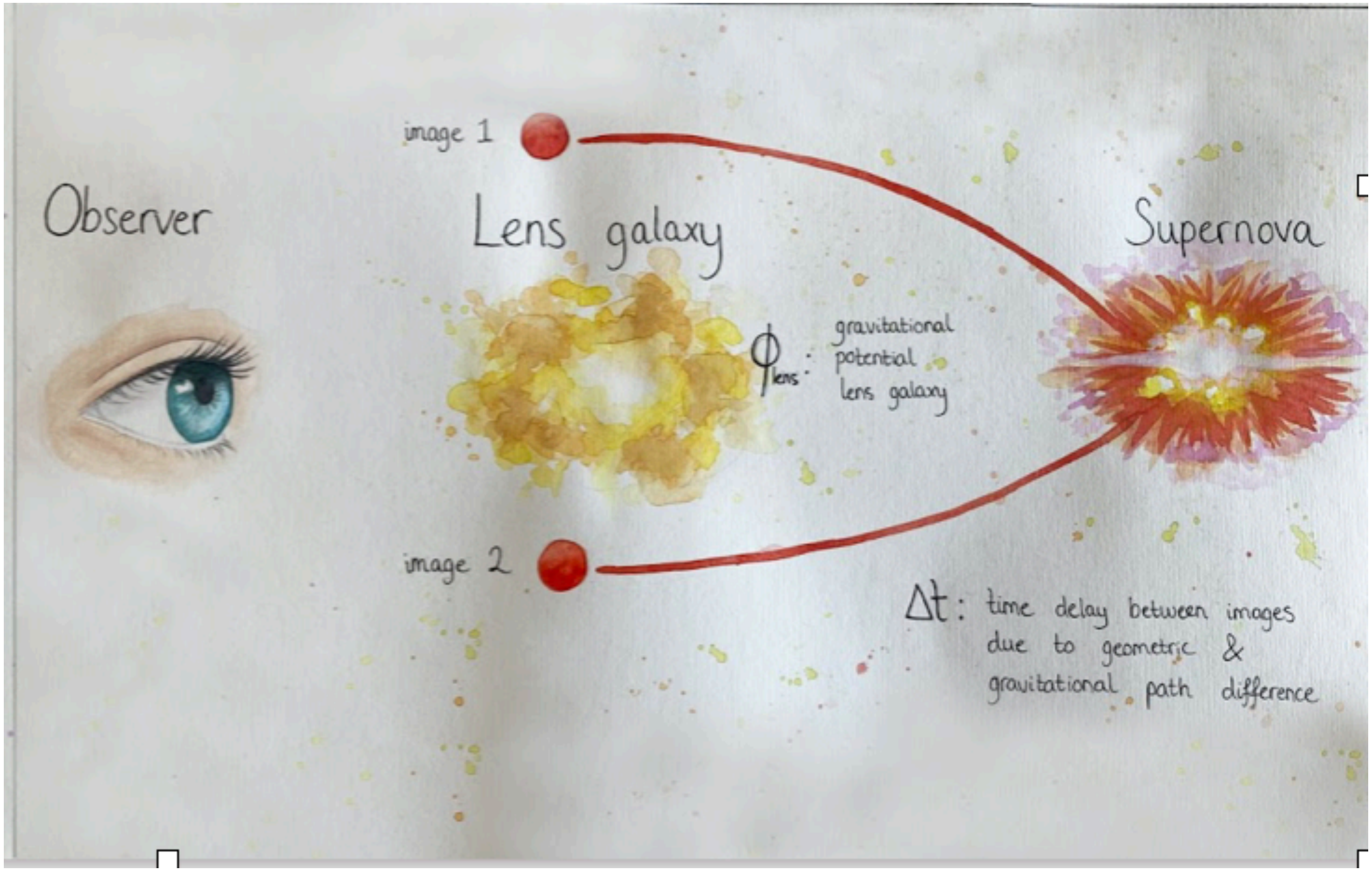


image 1
Observer
Lens galaxy
Supernova
ϕ_{lens} : gravitational potential lens galaxy
image 2
Δt : time delay between images due to geometric & gravitational path difference

Dark Energy Model + SN systematics

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

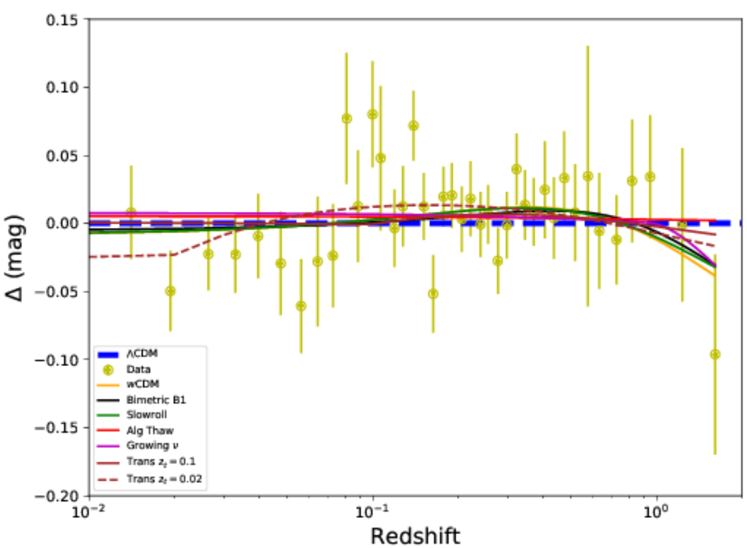
Modelling sources of systematics

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

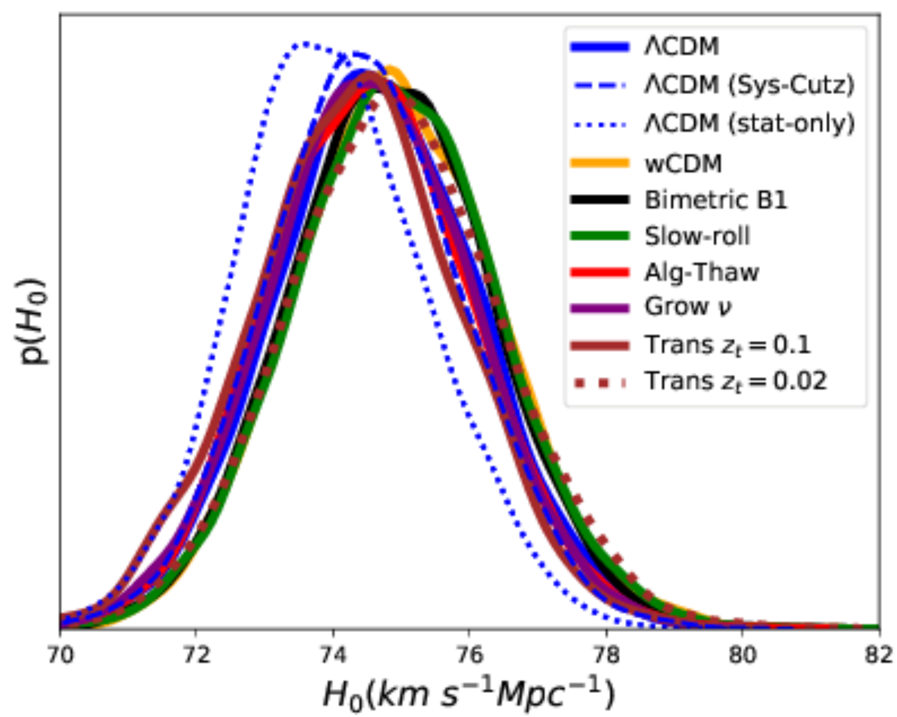
Low-z from > 10 systems

Some targeted programs

Now used for Pantheon+ & SH0ES '22



SD, Brout, Scolnic+ 2020c

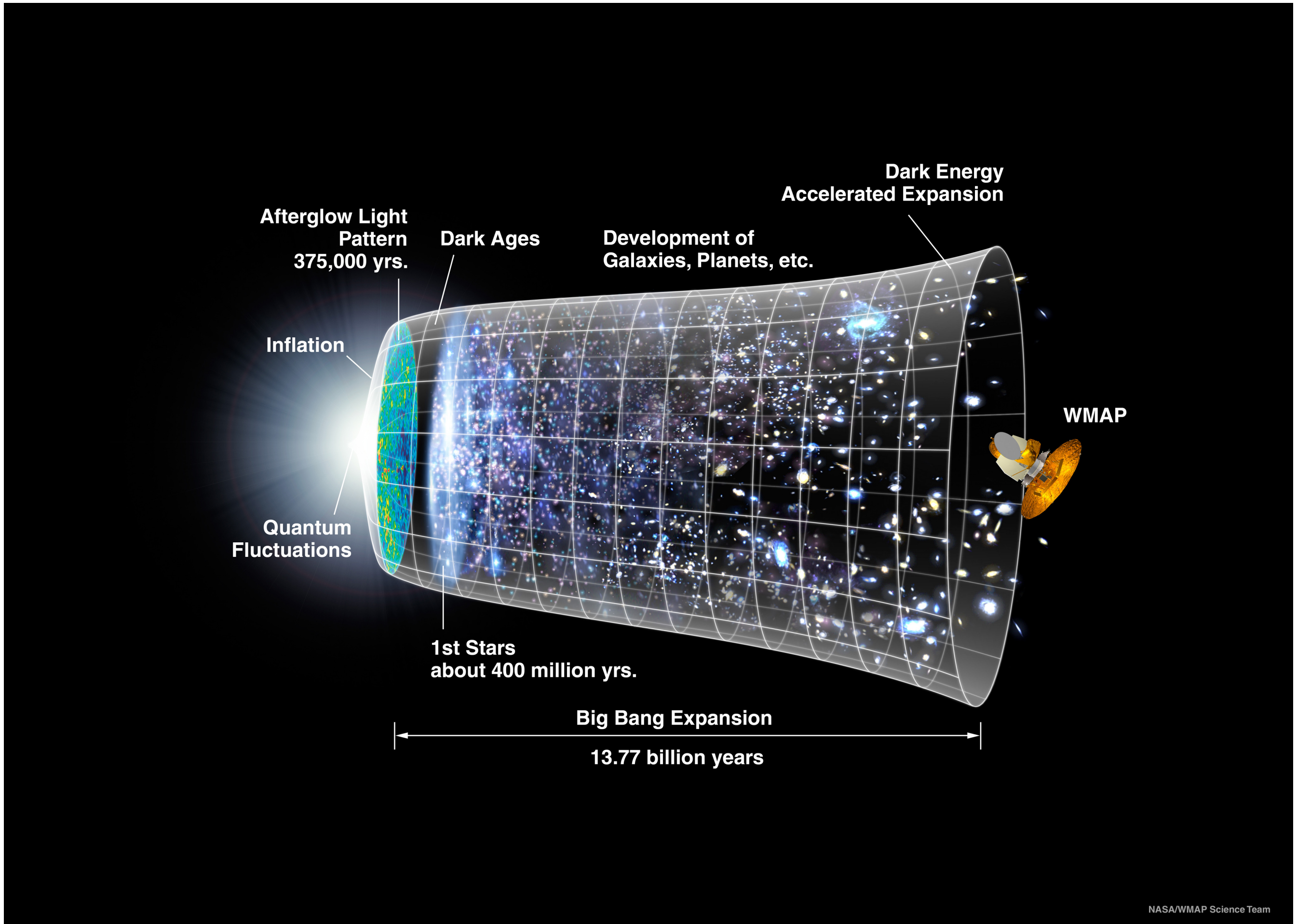


See also, transition models in Benevento, Hu, Raveri 2020

Expansion history

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

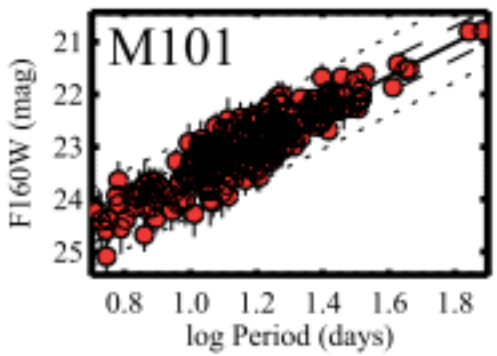
- Constrain growth of structure

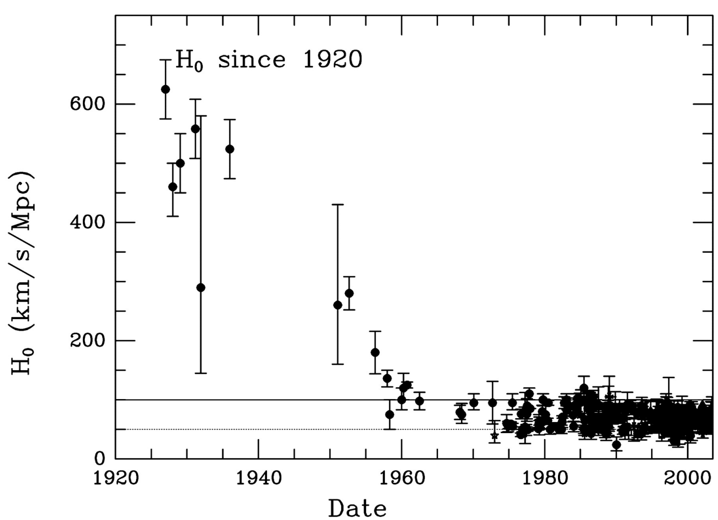


Cepheids as distance indicators

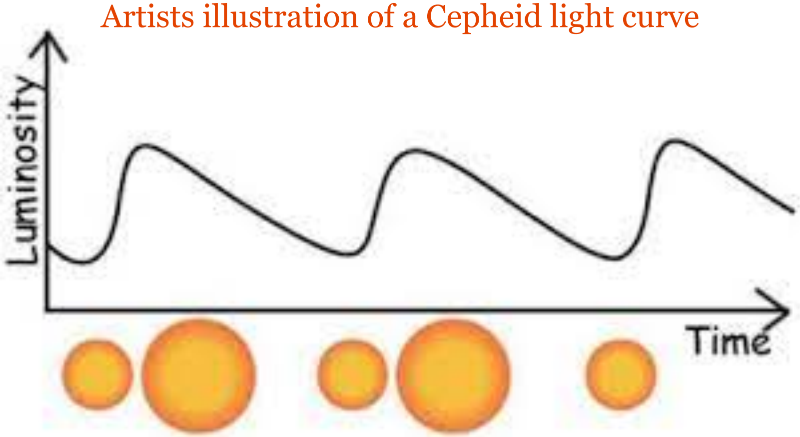
- Pulsating variable stars
- Developed as precise distance indicators
- Correcting for Period - Luminosity (P-L) relation (Leavitt + Pickering 1912)
  - Correct for colour: the "Wesenheit" relation
  - Metallicity - luminosity relation

Minimise corrections by observing in the NIR

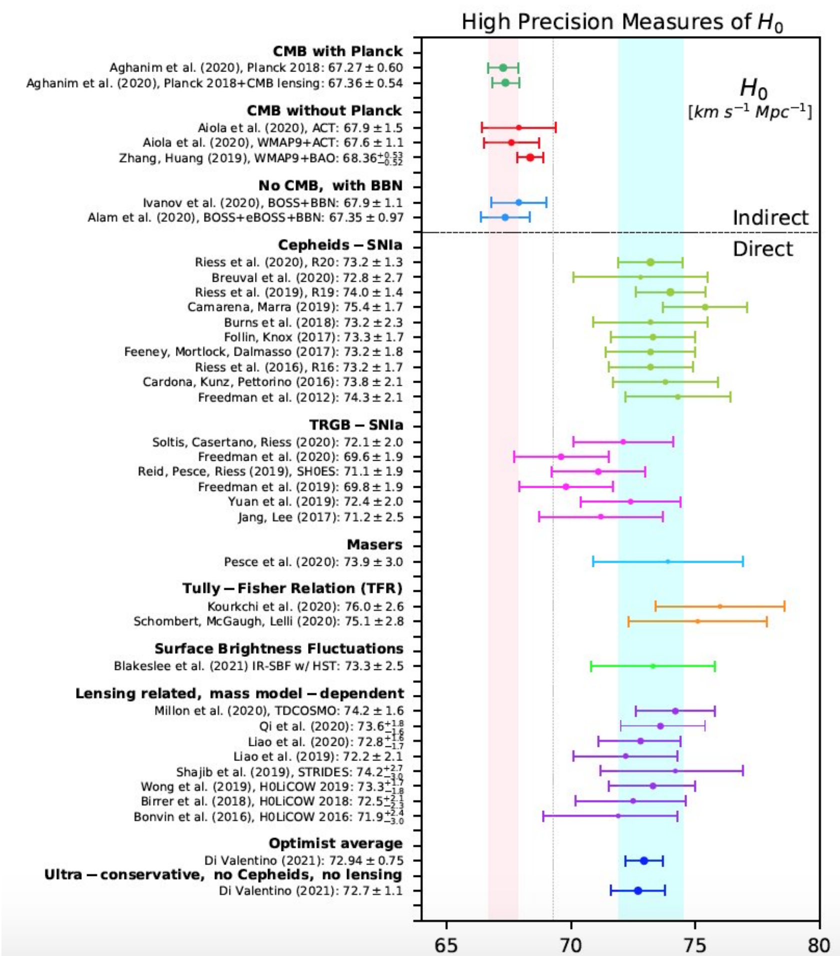




Artists illustration of a Cepheid light curve



Current Status



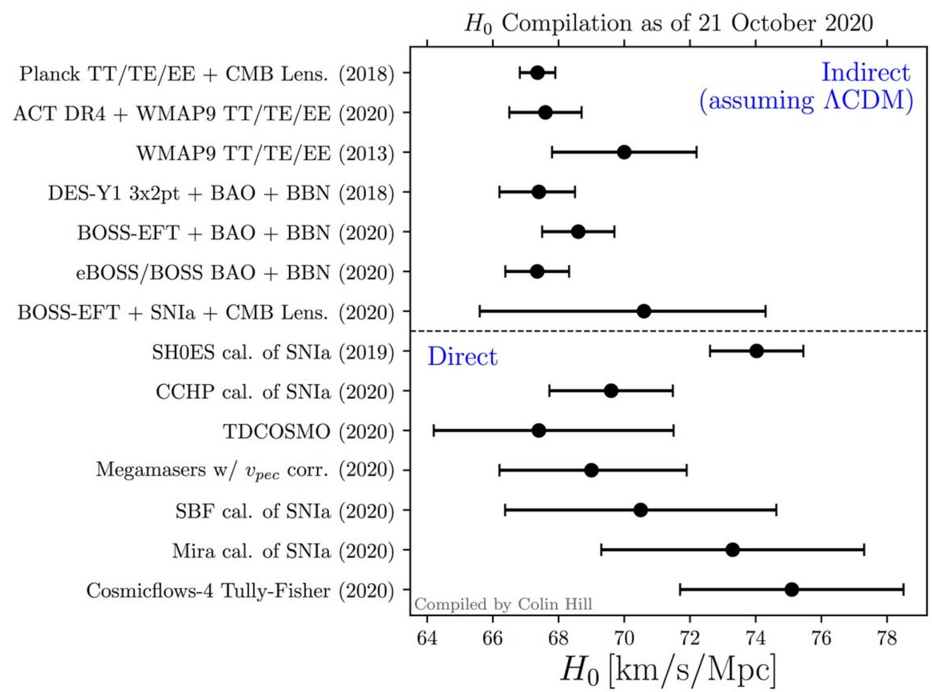
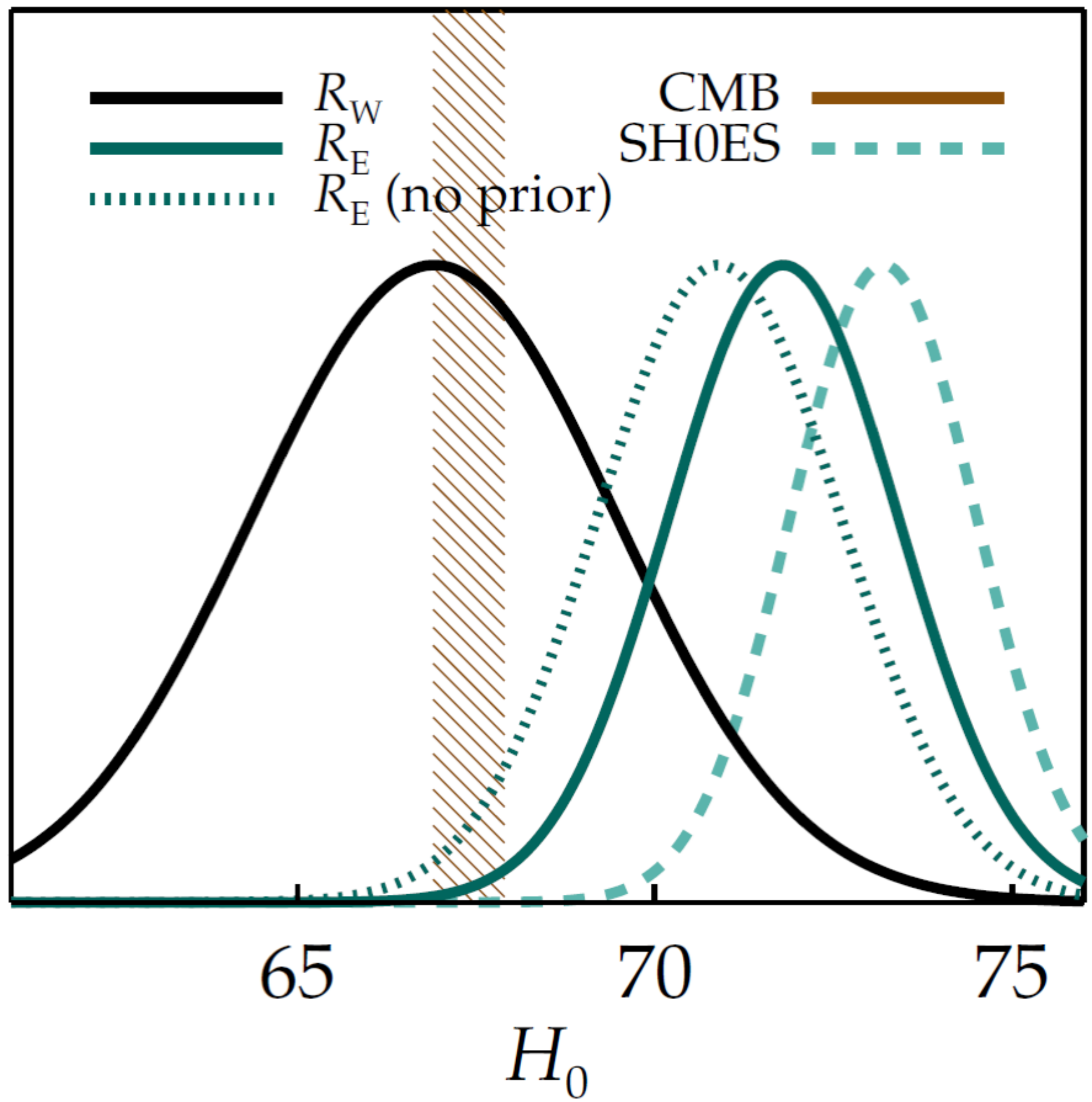
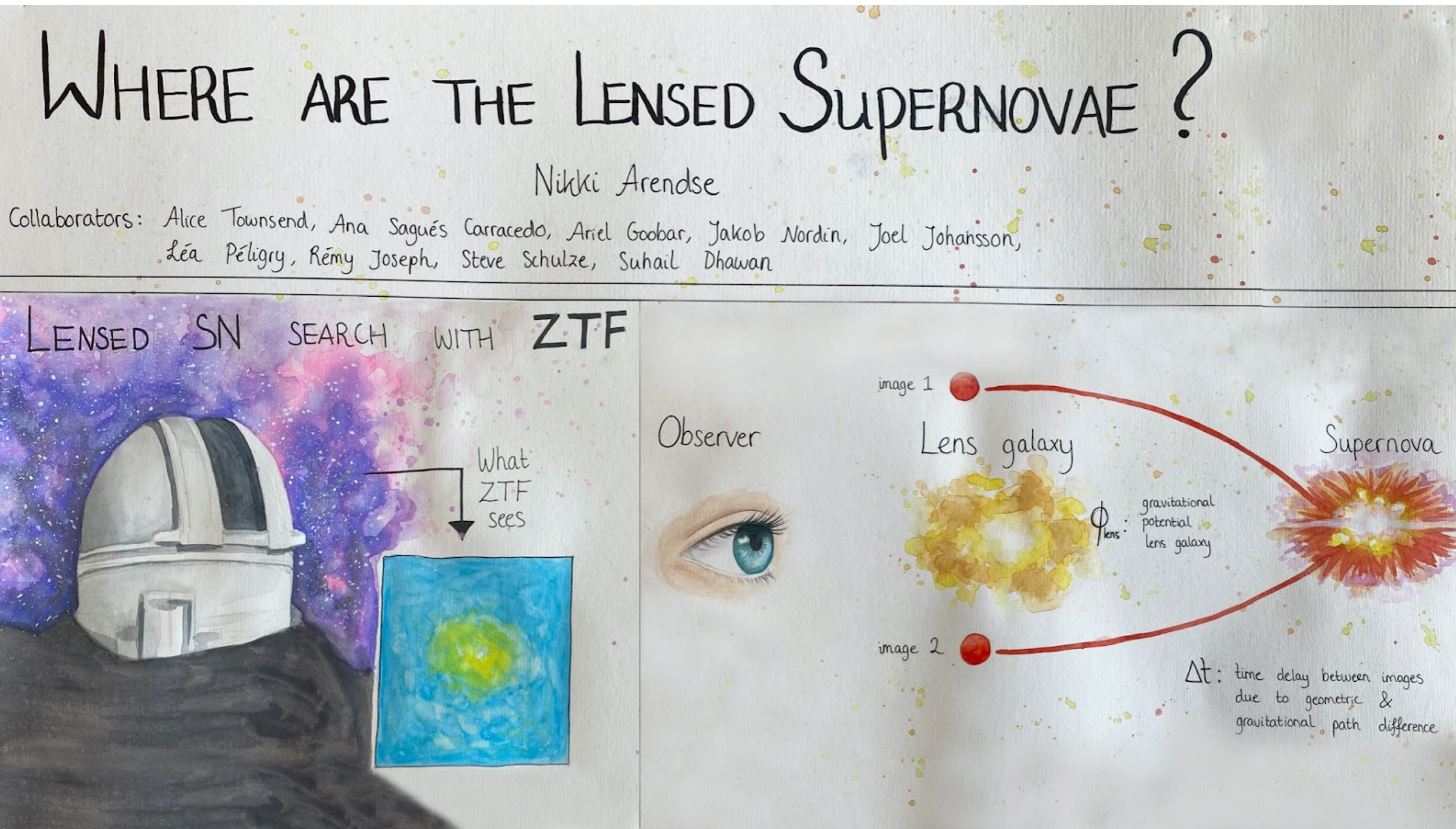


Figure from review by Di Valentino et al. (left) see also Hill et al. (right)

Updated "tension"




WHERE ARE THE LENSED SUPERNOVAE ?
Nikki Arendse
Collaborators: Alice Townsend, Ana Sagués Carracedo, Ariel Goobar, Jakob Nordin, Joel Johansson, Léa Péligry, Rémy Joseph, Steve Schulze, Suhail Dhawan
LENSED SN SEARCH WITH ZTF
What ZTF sees
Observer
image 1
Lens galaxy
Supernova
ϕ_{lens}: gravitational potential lens galaxy
image 2
Δt: time delay between images due to geometric & gravitational path difference