The Hubble Constant from Supernovae: Strong Lensing and the Distance Ladder

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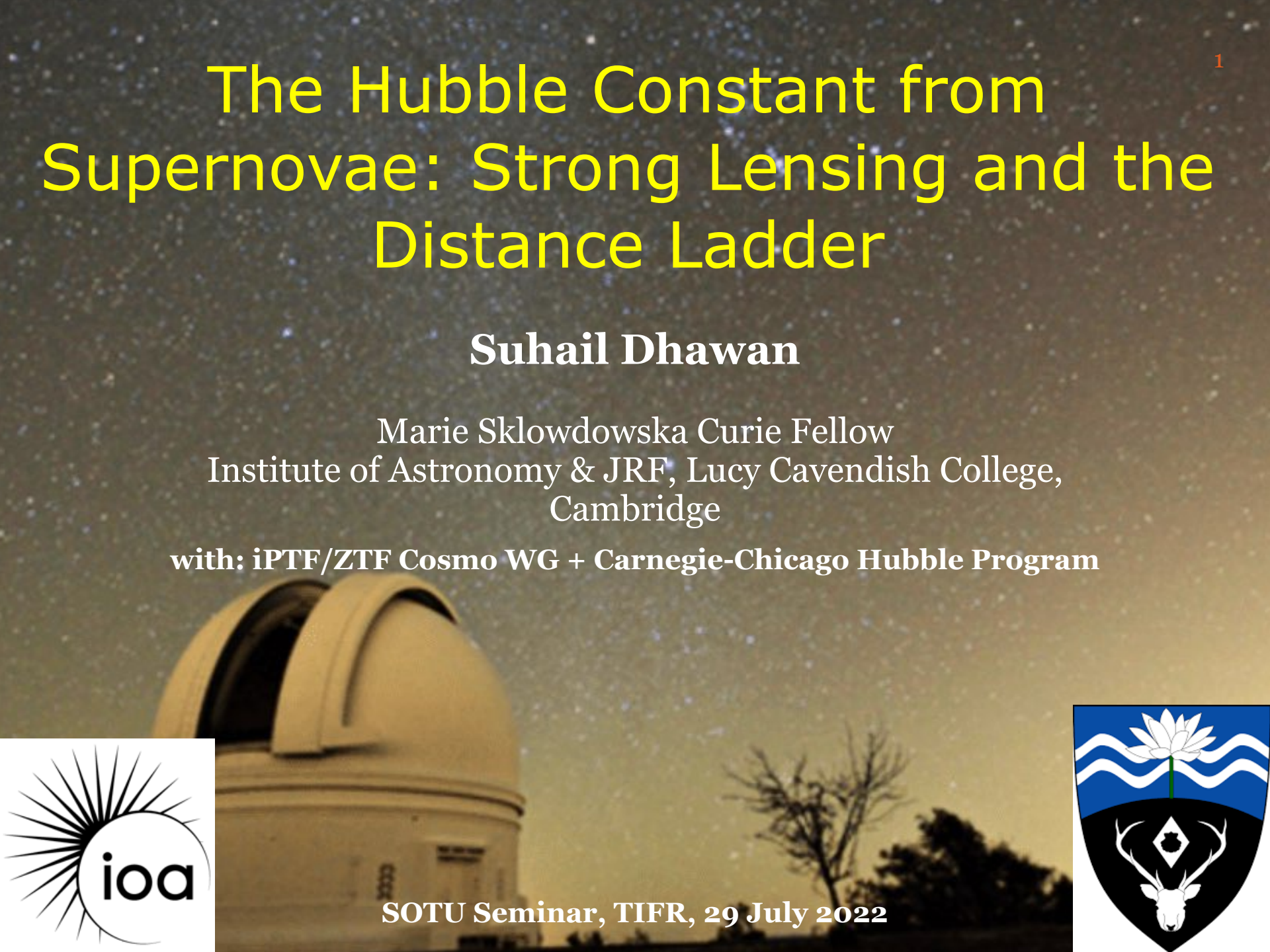
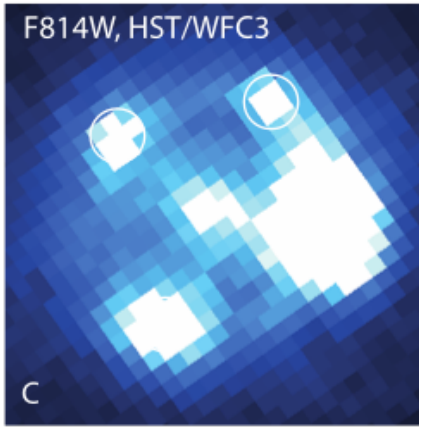
with: iPTF/ZTF Cosmo WG + Carnegie-Chicago Hubble Program



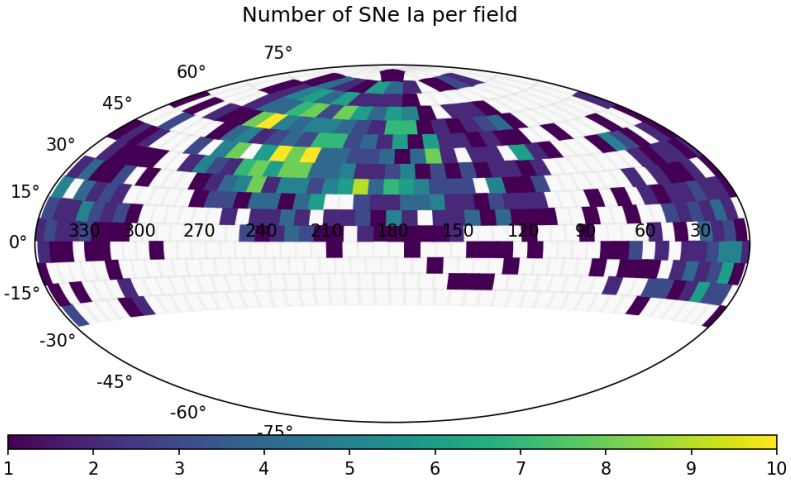
SOTU Seminar, TIFR, 29 July 2022

Outline

HST image of iPTF16geu



ZTF DR1 sky distribution



Motivation

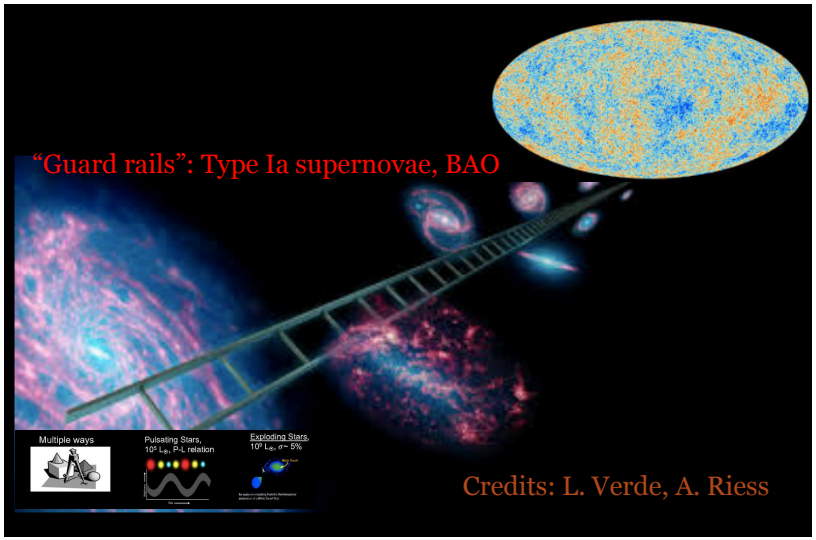
Local distance ladder: Single SN Survey estimate
Hierarchical BayeSN modelling of SN distances

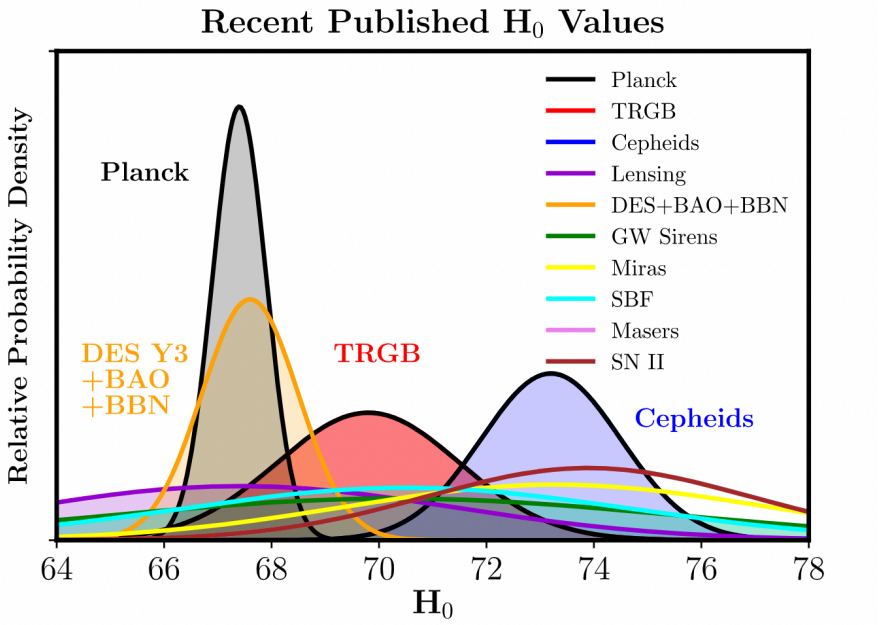
Strongly lensed supernovae: Independent probe of Ho

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

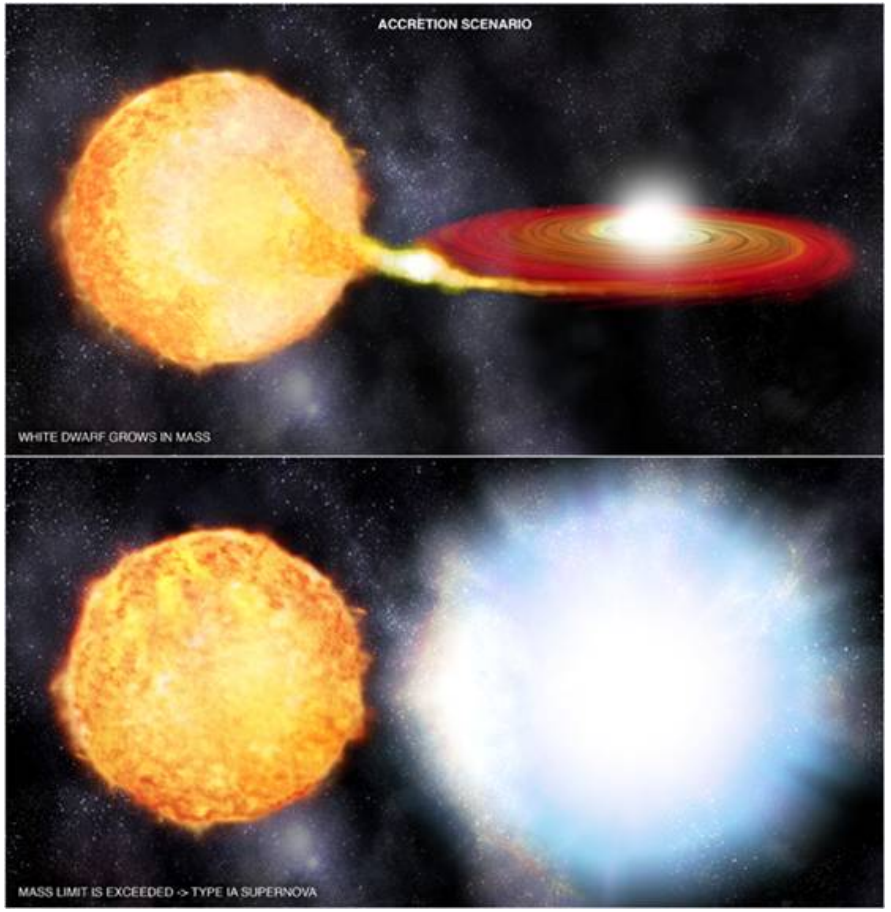
Focus of today's talk!

- 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



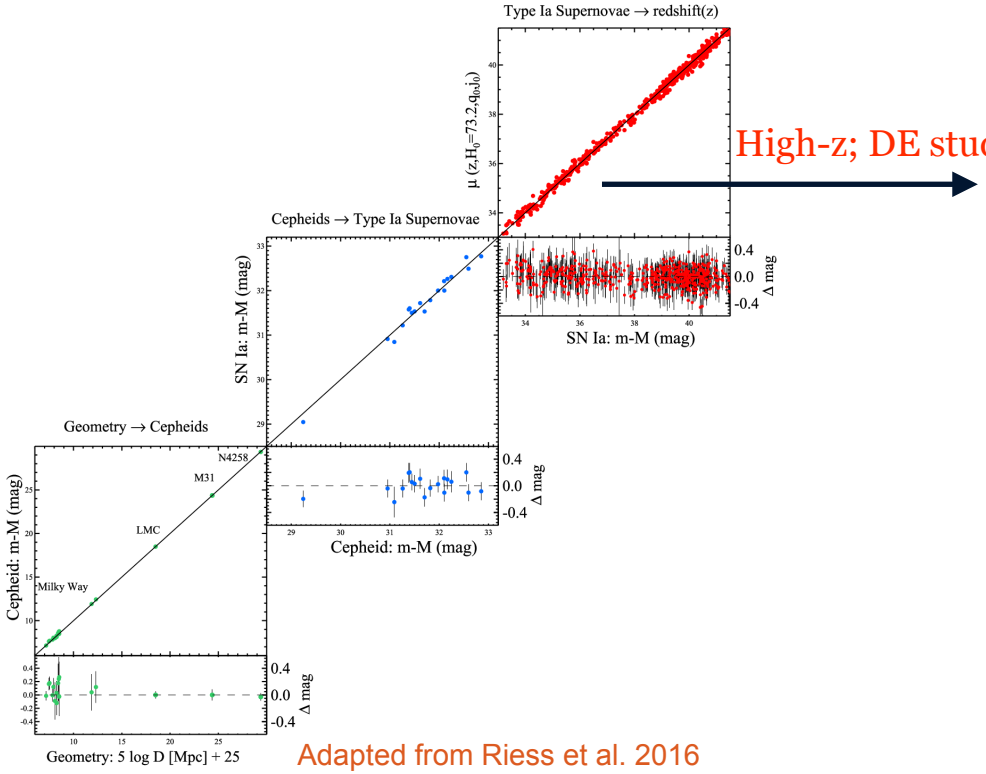
Discovery of dark energy

In all types of galaxies

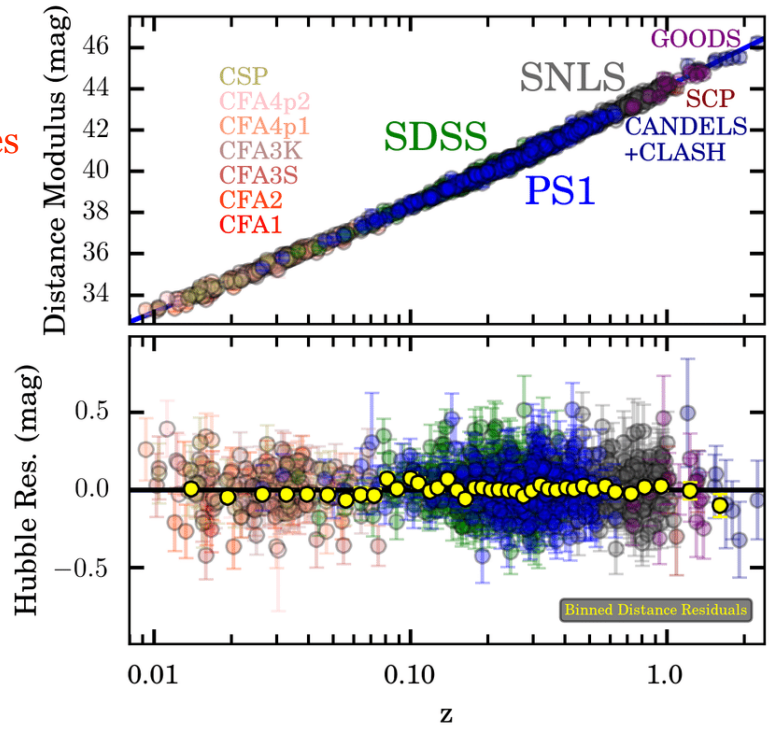
Cosmic Distance Ladder

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

Many, heterogeneous photometric systems at low-z!



High-z; DE studies

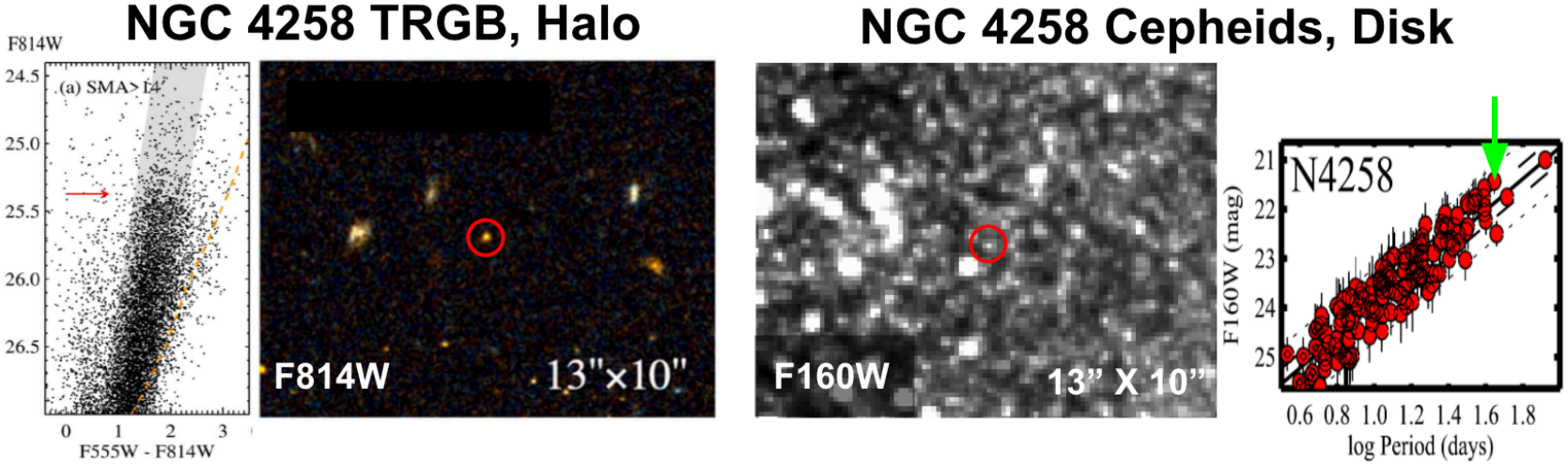


Adapted from Riess et al. 2016

Scolnic et al. 2018

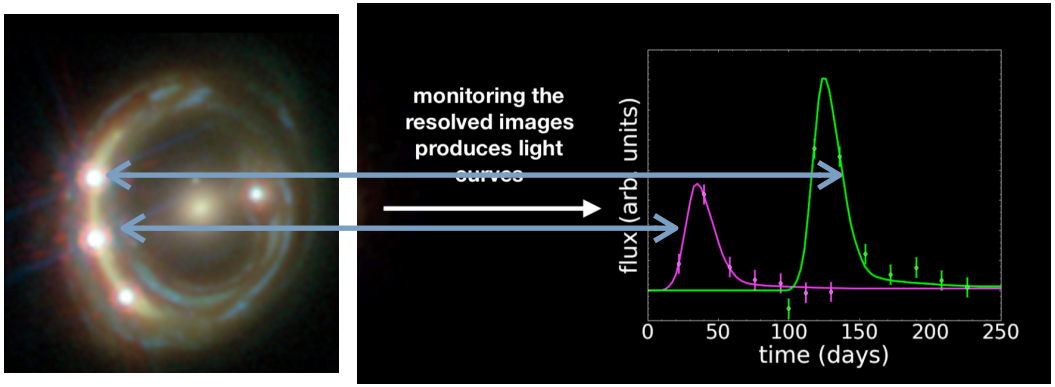
Primary Distance Indicators

Jang et al. 2021

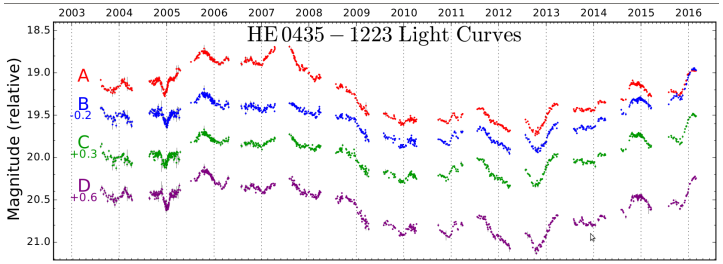


- Found in SN Ia hosts of all ages
- Less crowded environments than Cepheids
- Less prone to reddening, metallicity systematics than Cepheids (Mortsell+2021a,b; Efstathiou 2020)
- TRGBs fainter than Cepheids

Time-delay cosmography



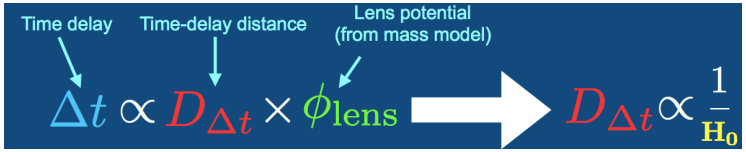
Typical lensed SN and QSO light curves



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)

Type Ia supernovae from the Zwicky Transient Facility

The Zwicky Transient Facility

P48: 1.2m discovery Schmidt telescope

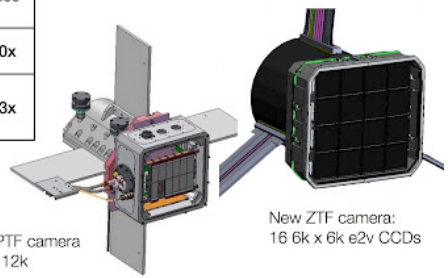
Dedicated classification with P60: SEDm

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



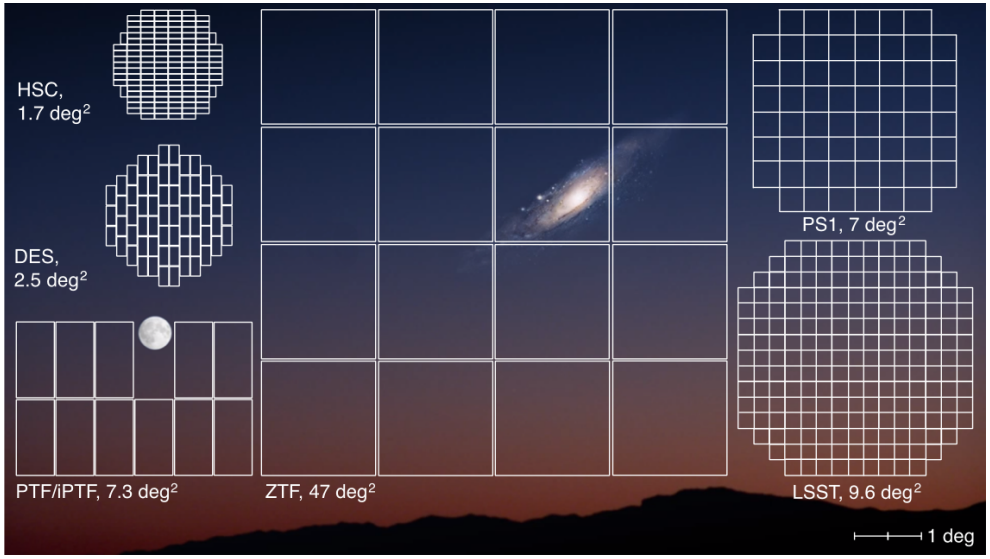
> 5500 SN discoveries
~ 5000 in ZTF Phase I
Phase II began ~ Nov. 2020

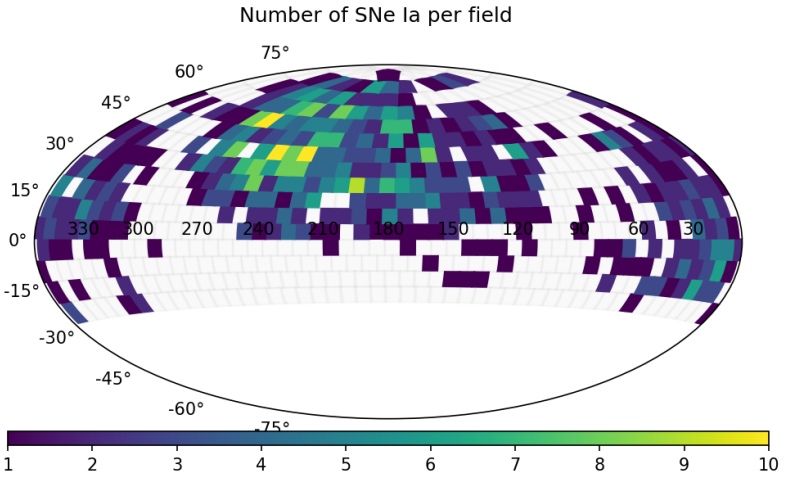
Total Number of SNe: 5581 | Ia: 3507 | II: 1280 | Ib: 121 | Ic: 132 | Ib/c: 21 | Ic-BL: 47 | SLSNe: 178

GROWTH Followup Marshal

ZTF Year 1 sample

SD+22a

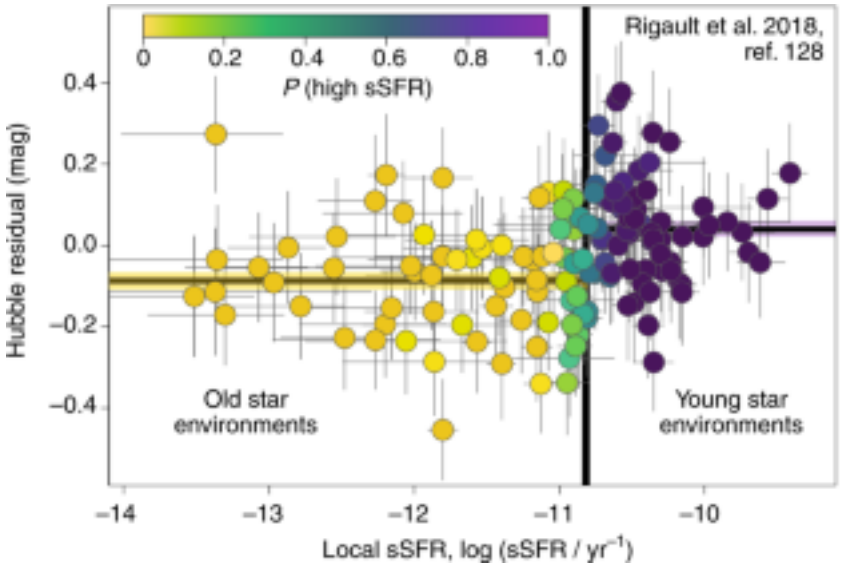


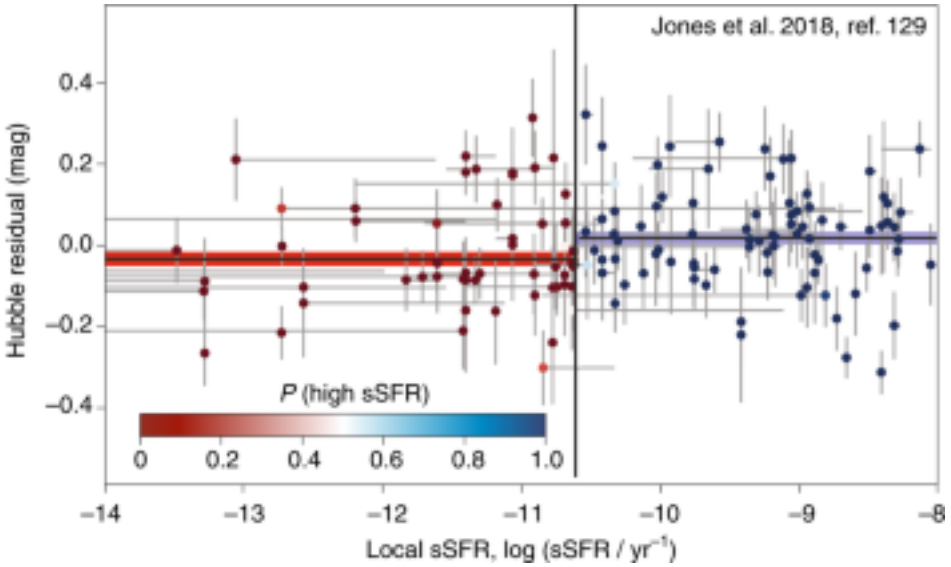


Legacy for Rubin; Roman in future

- 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



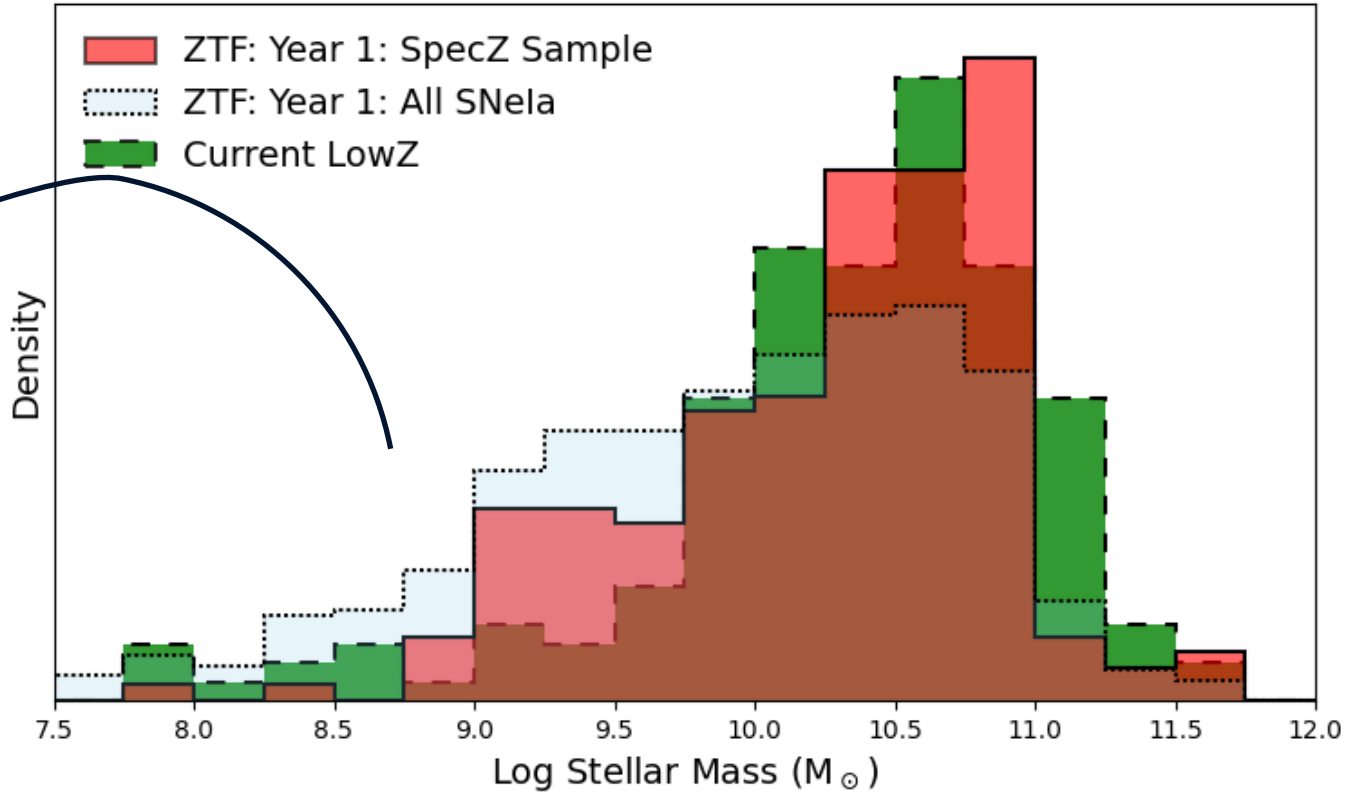


Is SN luminosity dependent on host galaxy local properties?
- Potential claims of bias upto 5% -> other claims < 1%
- Untargeted survey to sample underlying host distribution

ZTF Host Galaxies

SD+22a

Remaining redshifts from DESI

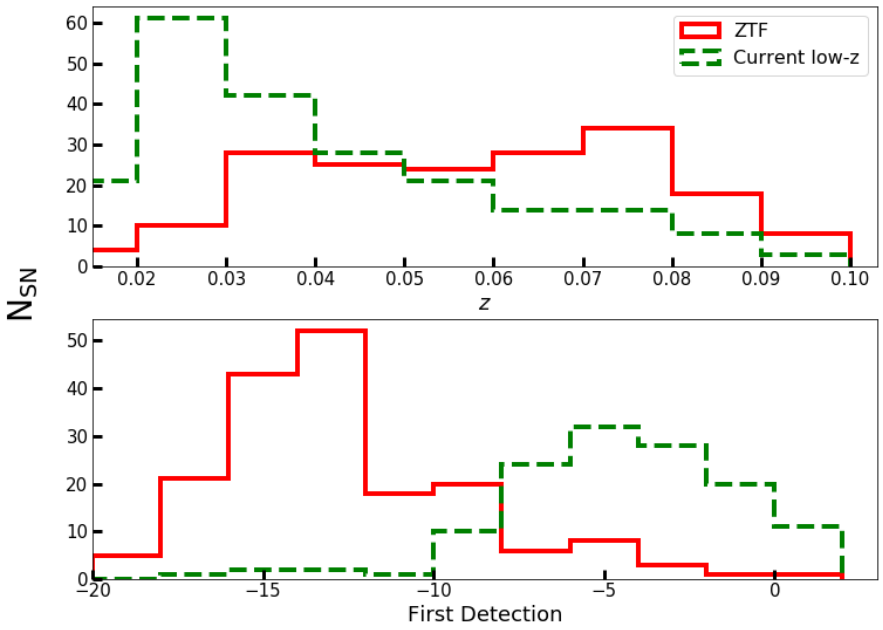


Higher ratio of low-mass to high-mass hosts

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

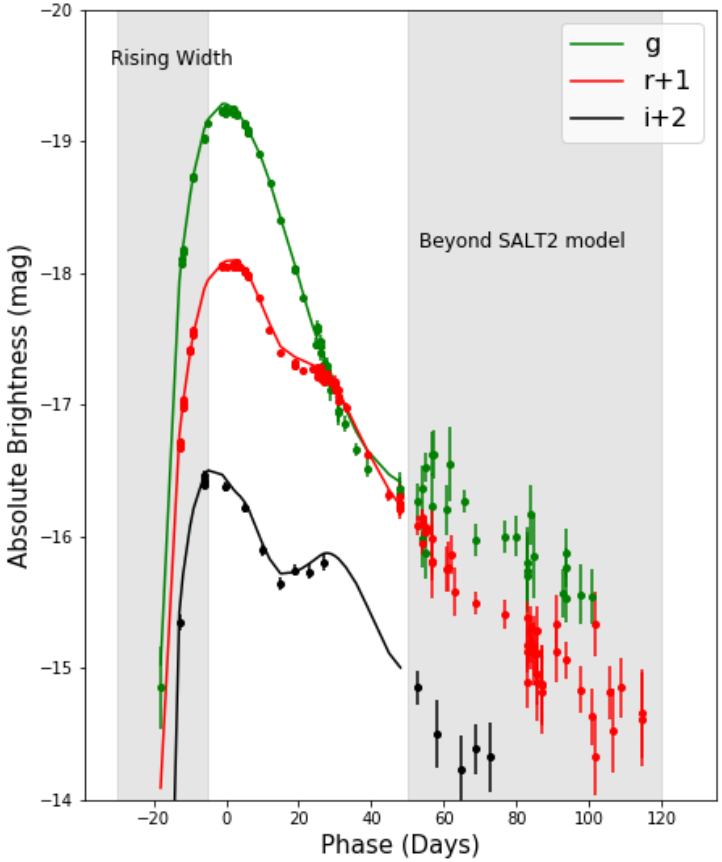
Improved Distances

SD+22a



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

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



Early light curve for improving distances

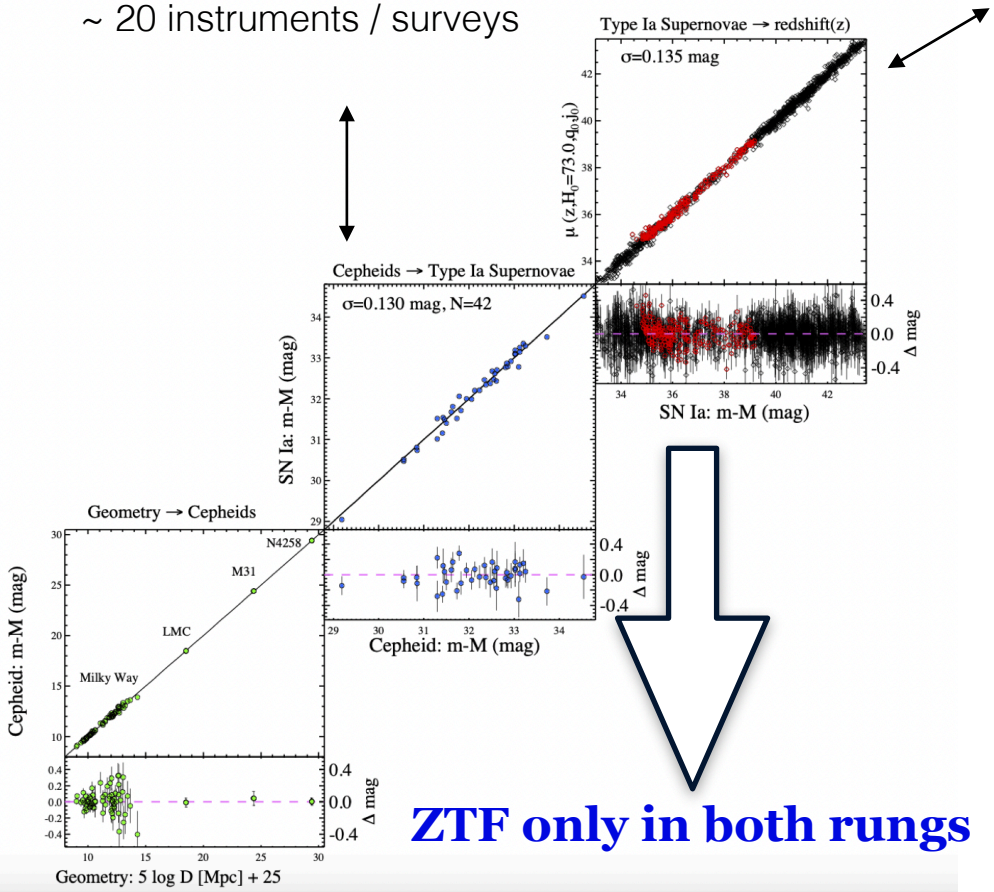
- Improving distances with early lightcurves
  - Novel early width standardisation
- Higher median redshift => lower peculiar velocity error

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

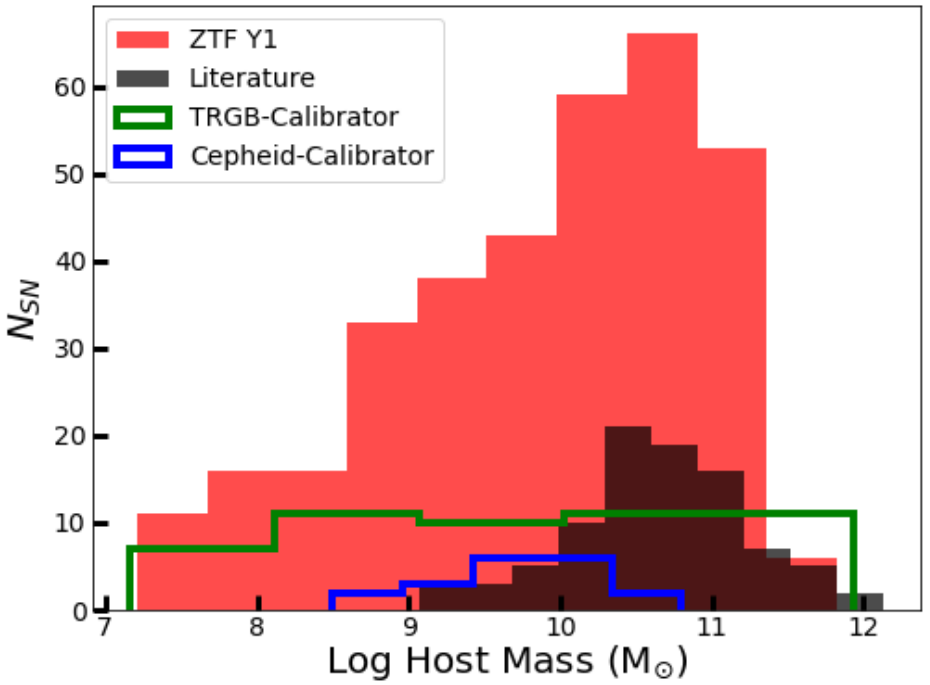


ZTF only in both rungs

Riess et al. 2022

Why ZTF-TRGB?

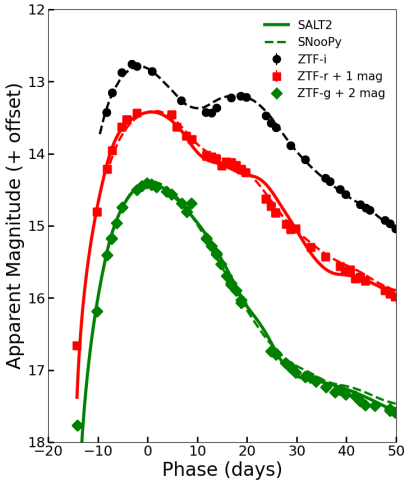
- ZTF is untargeted -> probing underlying environmental properties
- Cepheid calibrators -> strong preference for young hosts
- TRGBs in all hosts -> “matches” ZTF well.

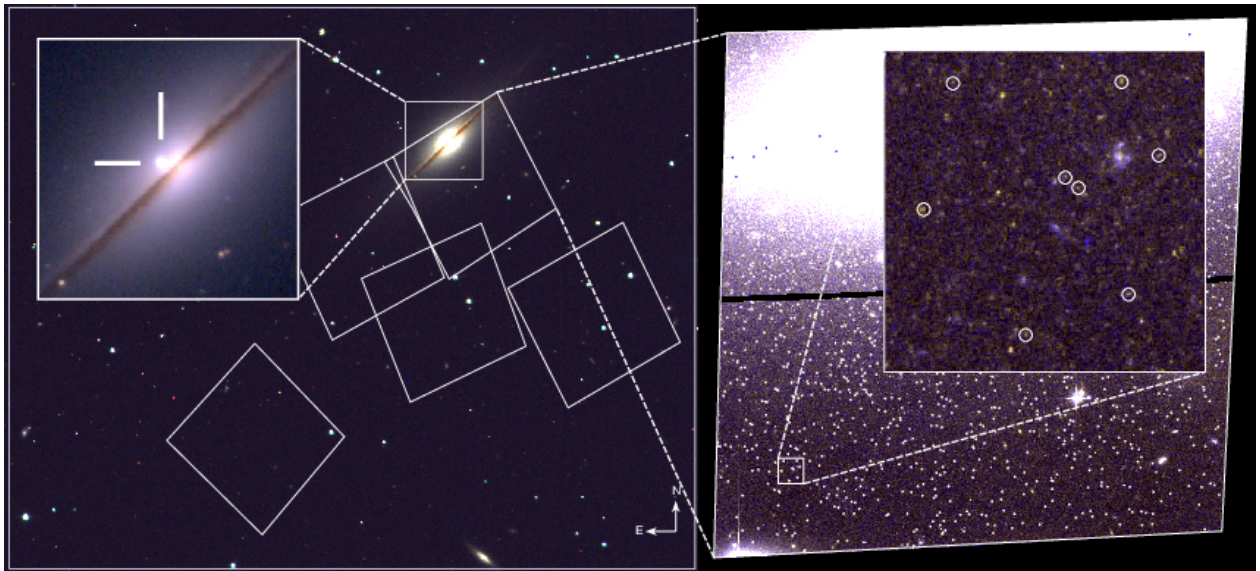


Host mass distribution of ZTF and TRGB calibrators compared to Cepheids (HST C30 proposal)

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

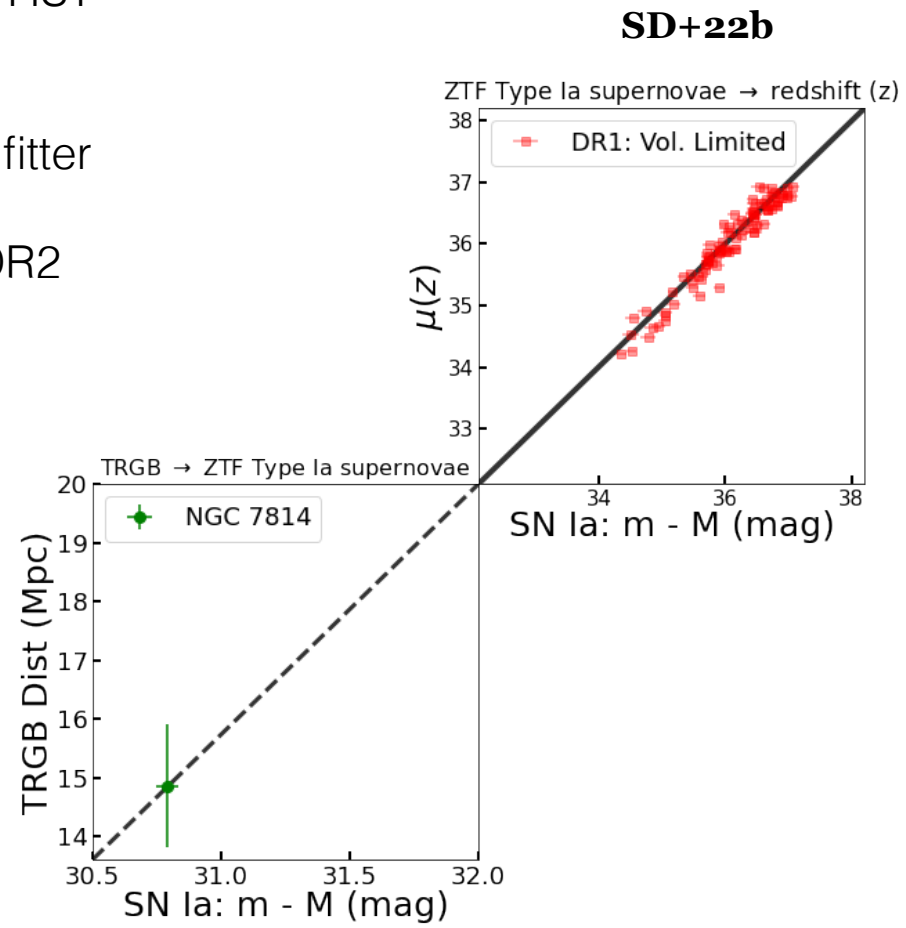




SD+22b

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

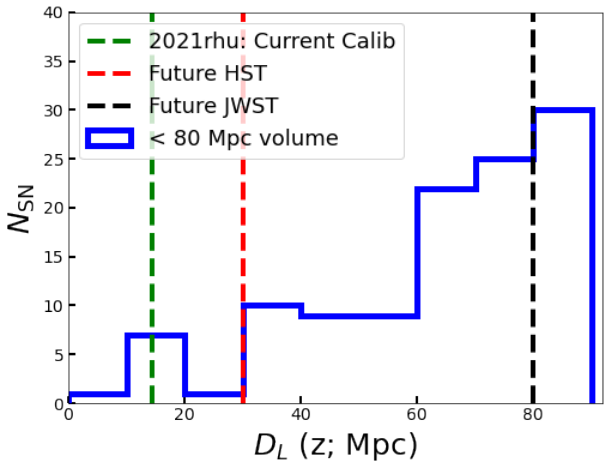


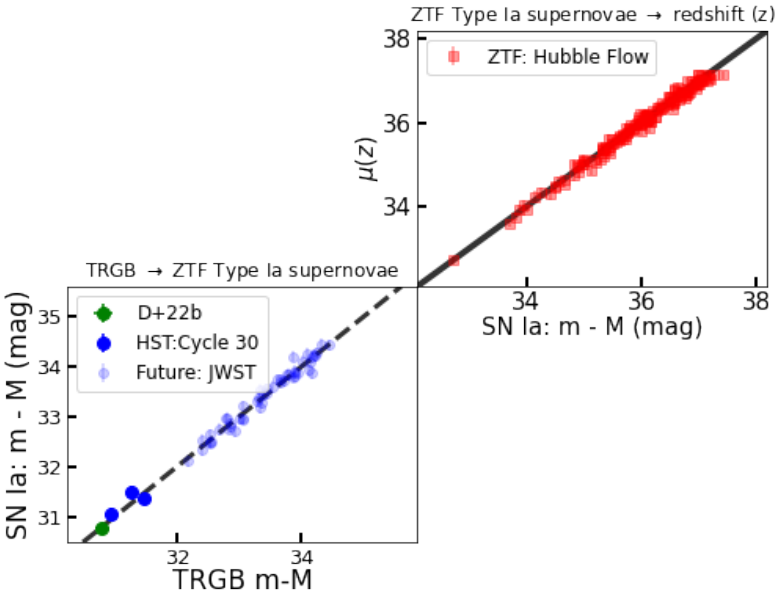
Outlook with JWST + DR2

- 106 SNe Ia with accurate distances at D_L < 80 Mpc
- Augmented Hubble Flow sample
- Vol. limited cal. sample

+ ZTF DR2 this year! ~ 3000 SNe Ia

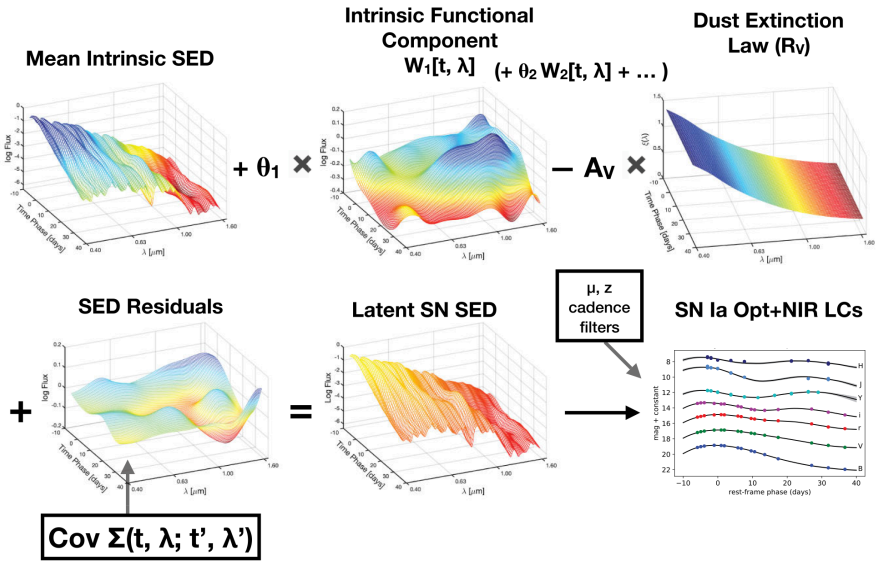
SD+22b



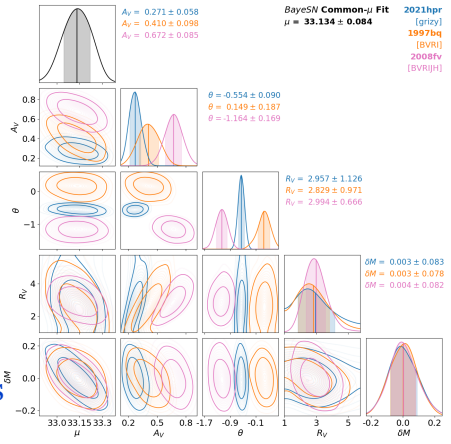


Refining Supernova Distances

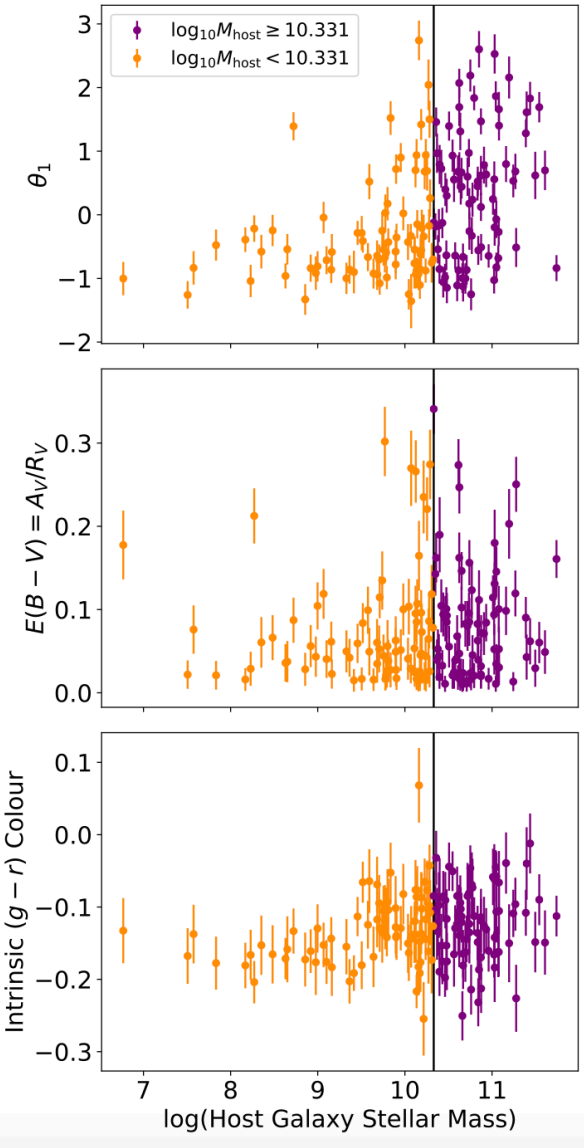
BayeSN model



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 H0 constraints

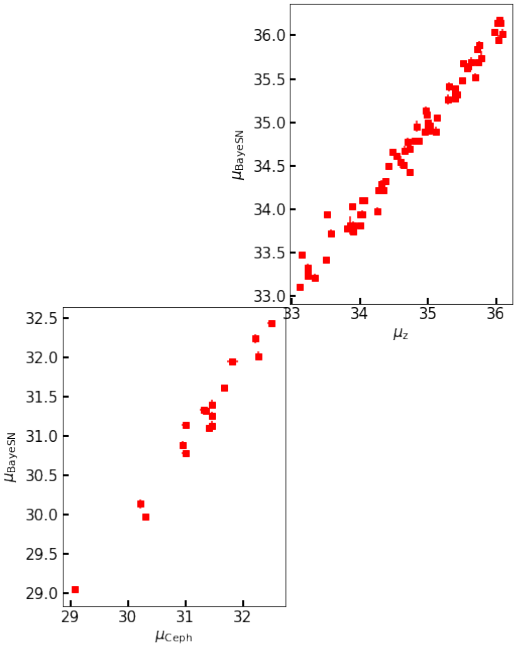
- NIR is uniform with low scatter
- Optical through NIR modelling
  - Important to infer dust properties

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

SD+22c in prep.

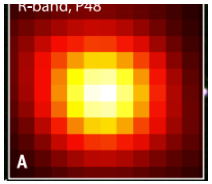
Training on ZTF DR2 ongoing
-> apply to uniform distance ladder

Still blinded to H0



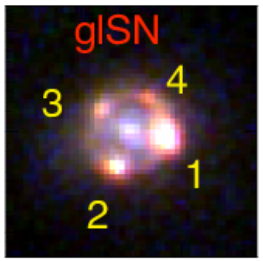
Strongly Lensed Supernovae

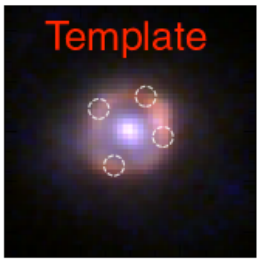
iPTF16geu: Resolved lightcurves

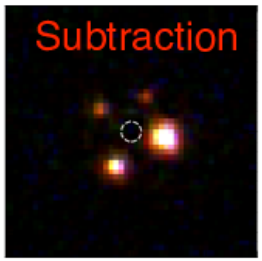


Discovery in unresolved data

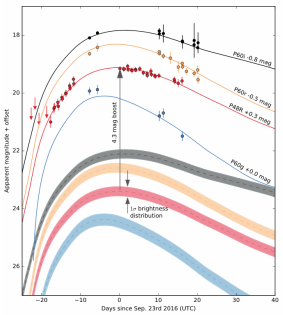
Follow-up: HST / AO







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



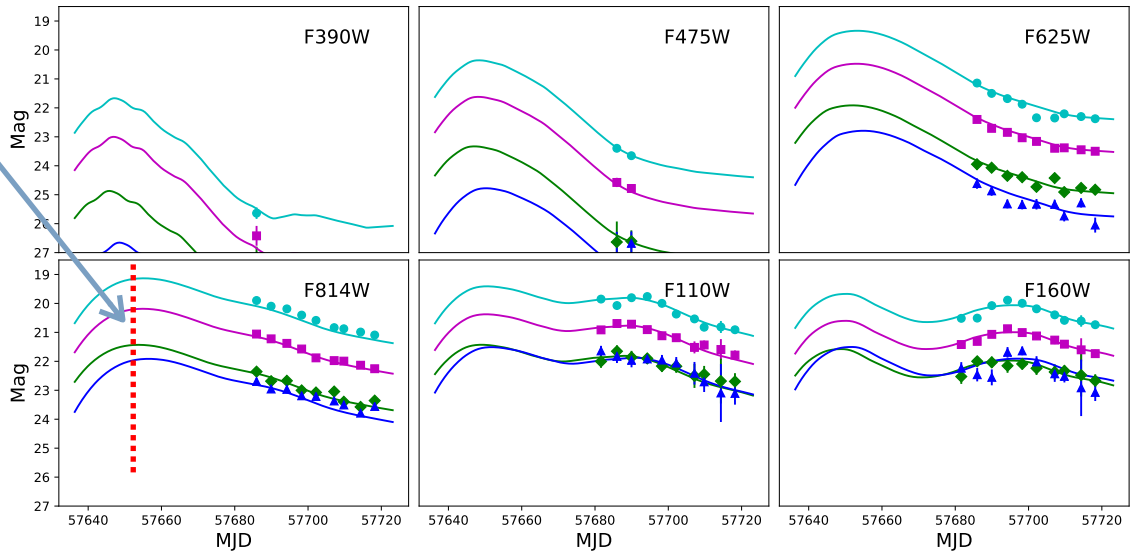
>50 times brighter than normal SNIa at z~0.4: a 30σ outlier!

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

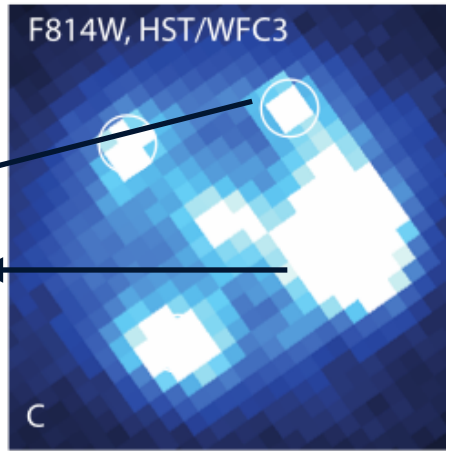
Preliminary magnification (μ) ~ 52
With extinction correction 67+/-3

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

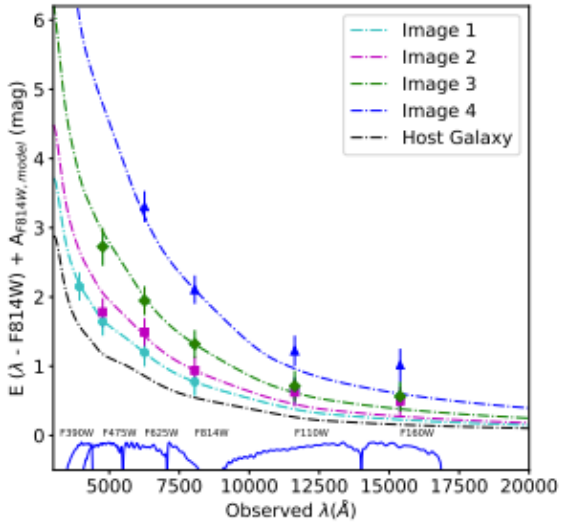
Probing the inner kpc of the lens => galaxy DM profiles

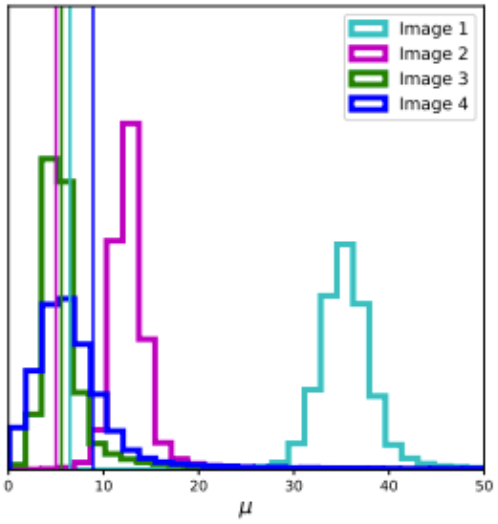
Surprisingly high magnification (μ)

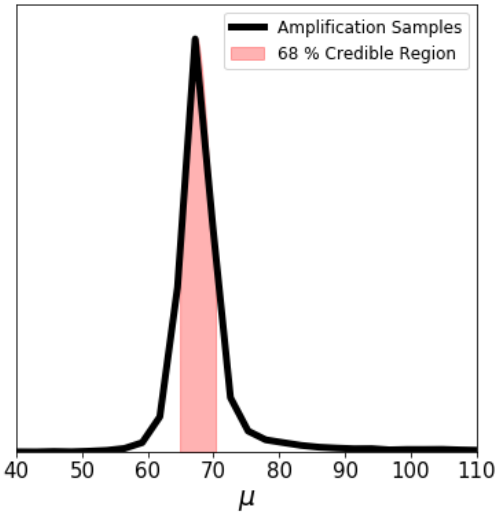
Surprisingly different brightness?



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







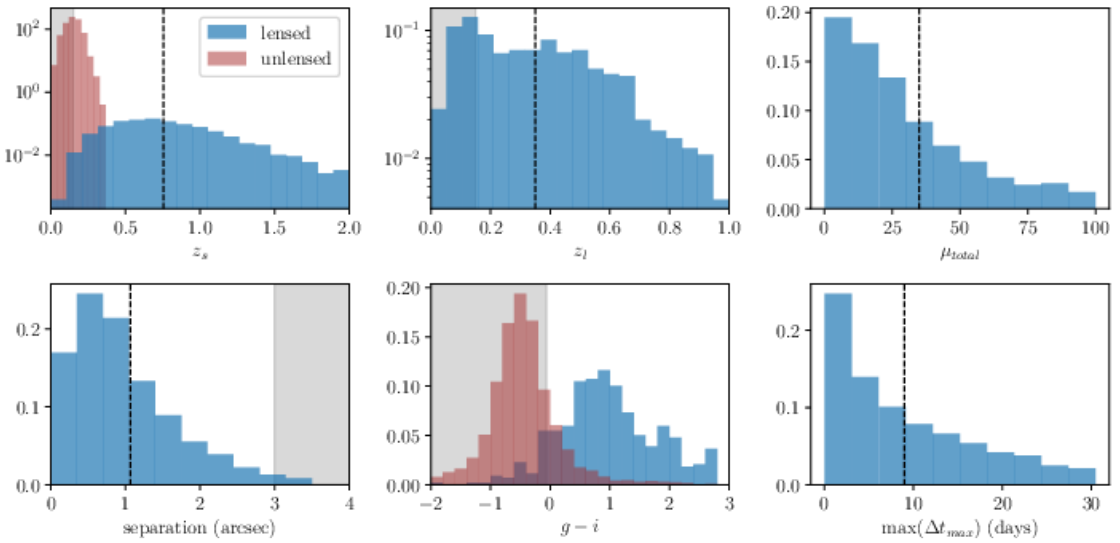
ZTF Search for glSNe

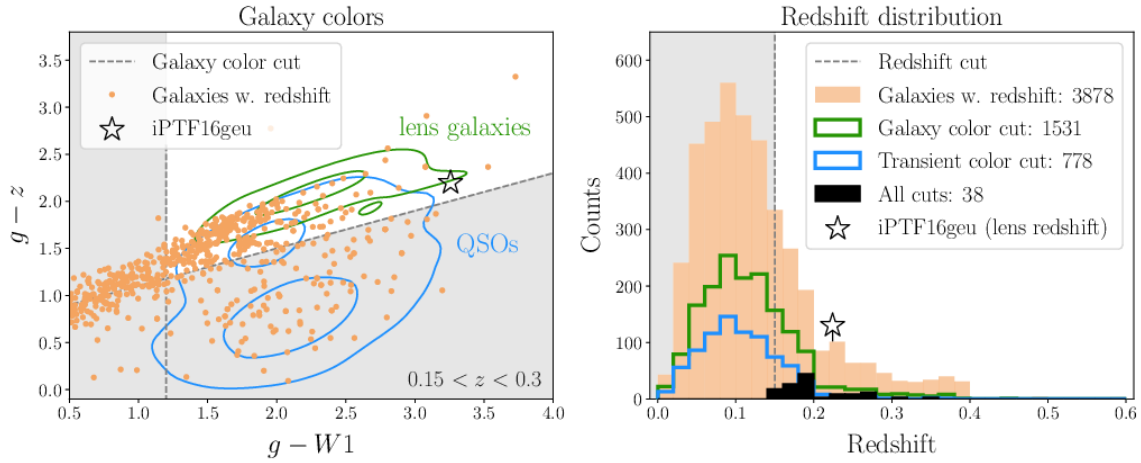
- Ongoing search in partnership (+public) data
  - High-cadence partnership survey
    - \+ i-band survey

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





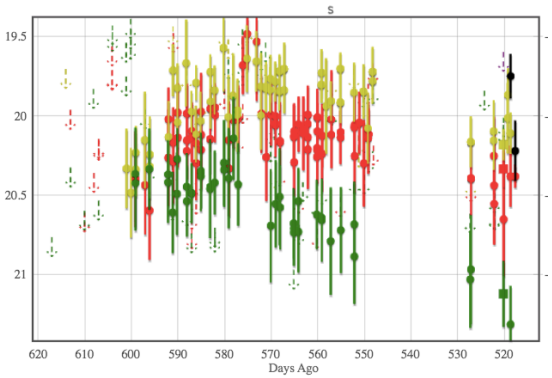
Candidate selection from ZTF archival data (Sagues-Carracedo,.., SD, et al. in prep)

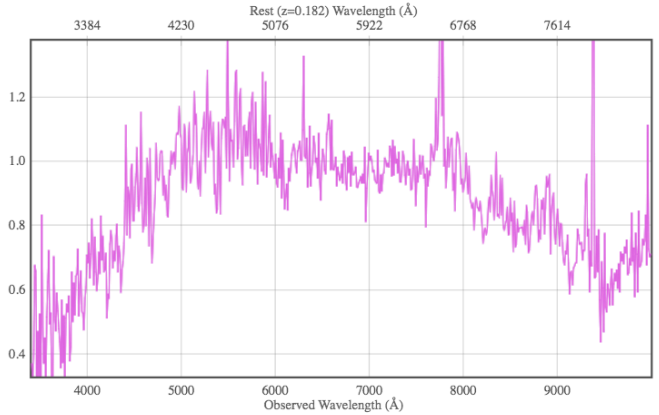
Interesting Candidates

Contaminant false positives: SLSNe, blazars

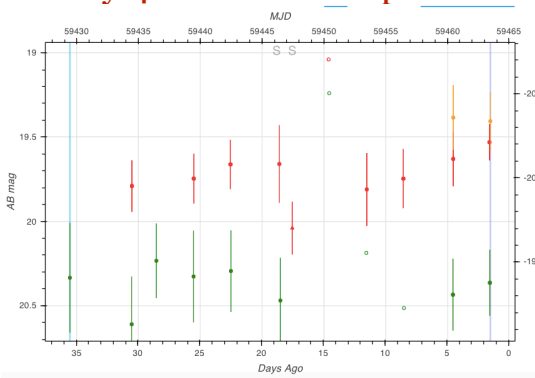
With stacked images: higher-z SNe Ia

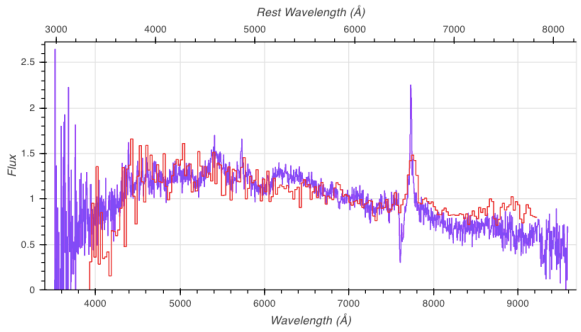
Contaminants are interesting themselves





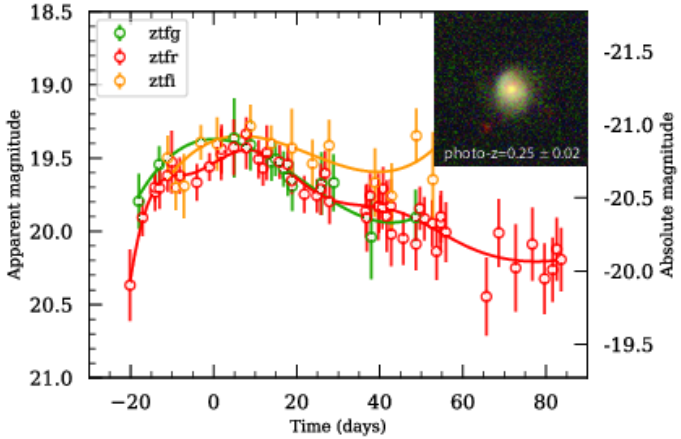
Bright (M > -20), red Type II-P,
only 4 seen in a sample of few hundred SNe (Perley+'20)





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

Archival search: need spectroscopy to vet



Conclusions

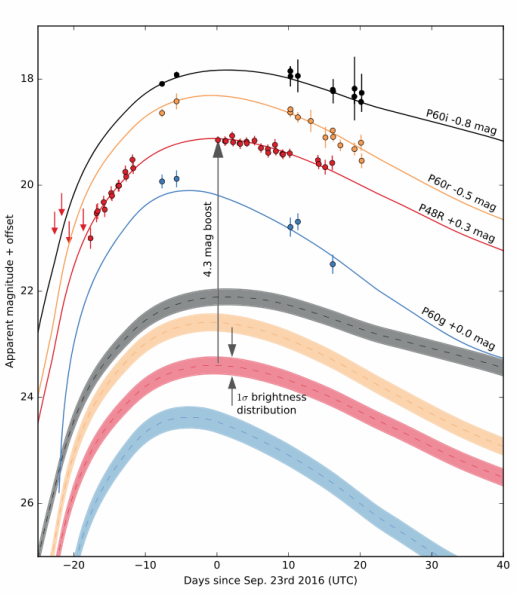
- ZTF DR1: homogeneous, untargeted sample of 750 SNe Ia
  - Improved distances with early light curves
  - Probing environmental biases

- TRGB: excellent standard candles
  - > 100 host galaxies within JWST capabilities
    - Distances from HST < 20 Mpc, NIRCam < 80 Mpc
    - First pilot study H_0 = 76.94 +/- 6.4 km/s/Mpc
    + ZTF DR2 upcoming

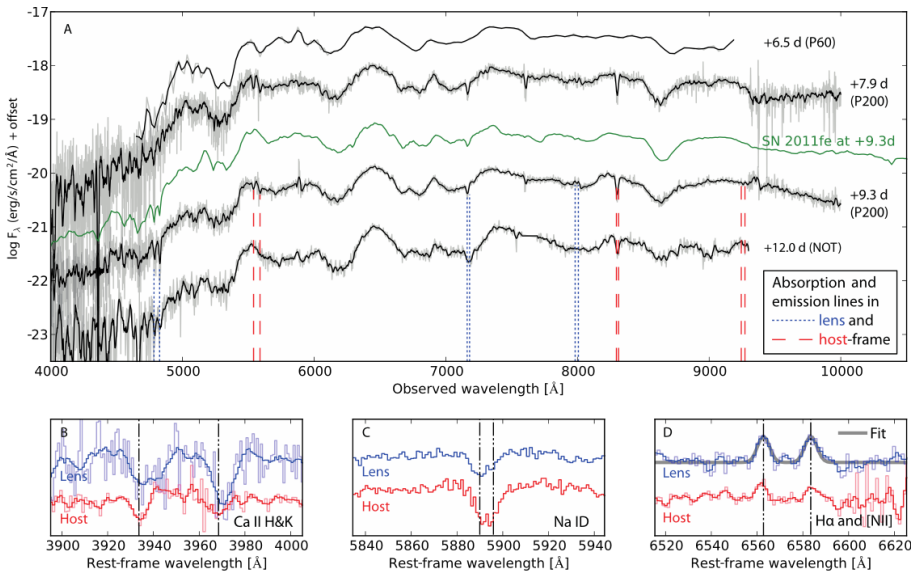
- Strongly lensed SNe Ia
  - iPTF16geu: exceptionally magnified
  - Extinction constraints in each LoS
  - ZTF search: spectroscopy limited
    - Interesting non-lensed SNe by-product

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

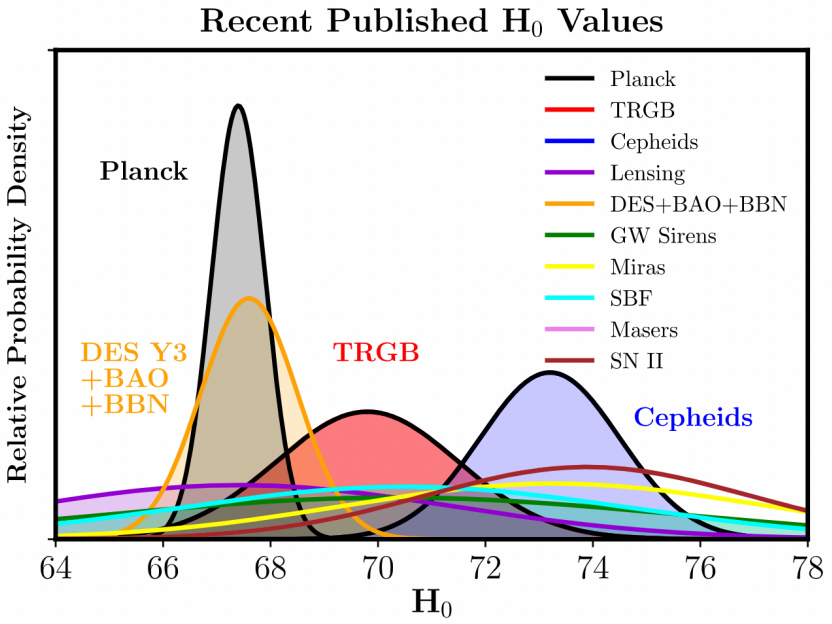
Perfect match to z=0.409 SN Ia + intervening galaxy at z=0.216

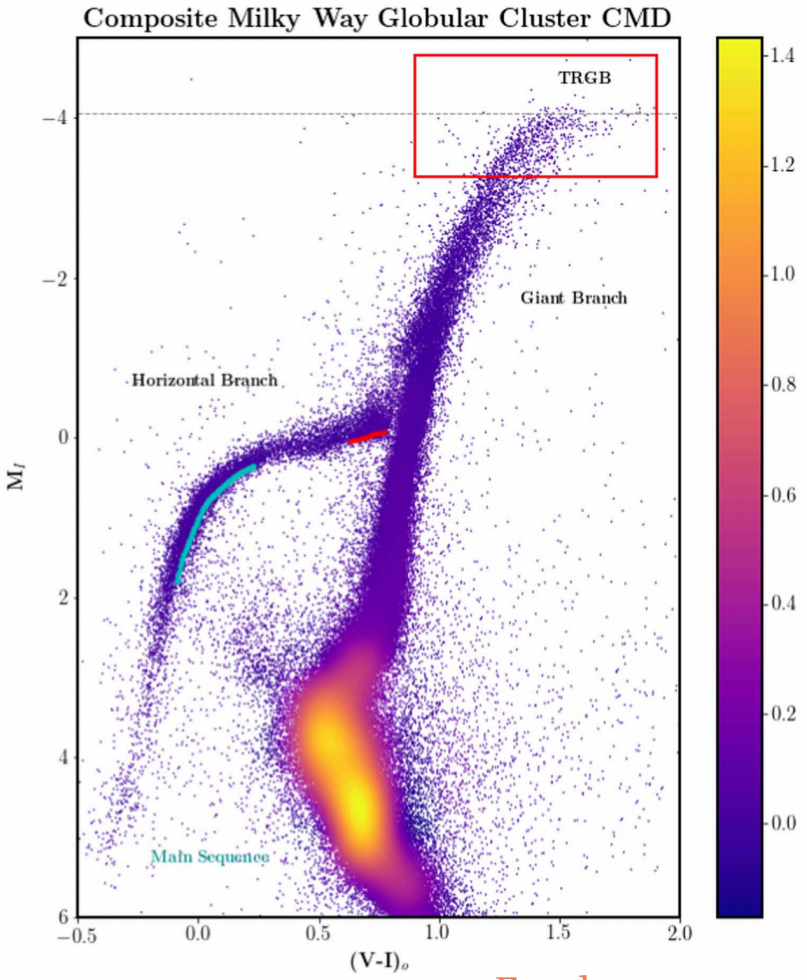
The Tip of the Red Giant Branch

Important **standard** candle

Well understood physics (He flash)

TRGB Ho not in tension





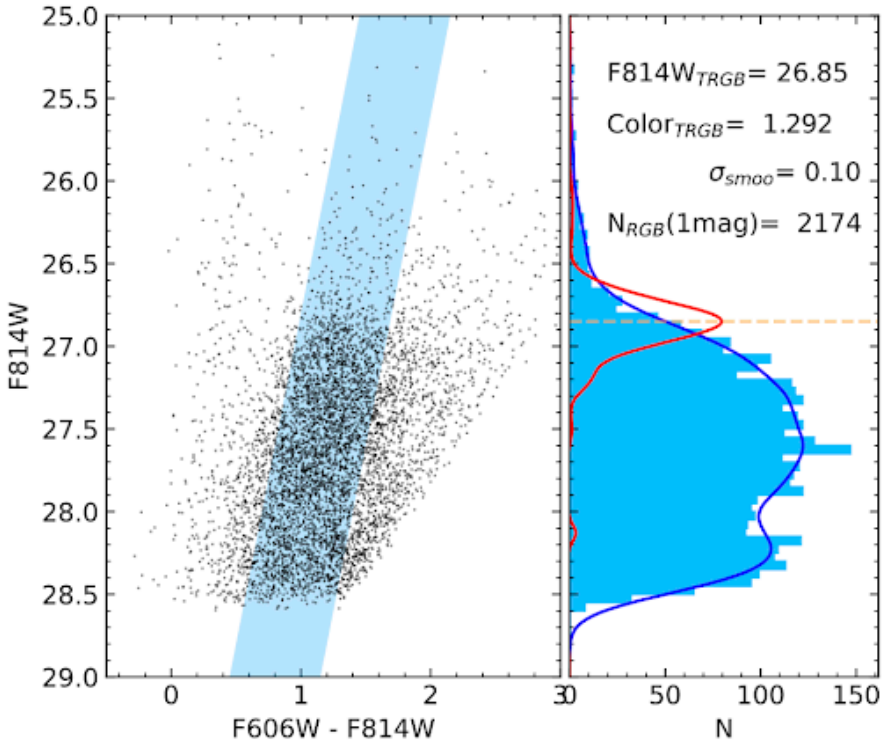
Freedman 2021

TRGB distance estimate

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

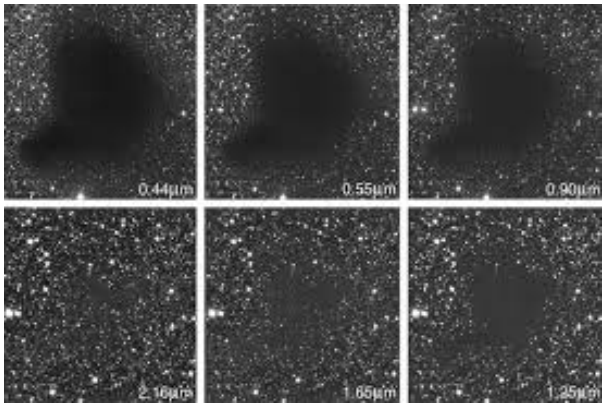
SD+22b, ApJ. Subm.

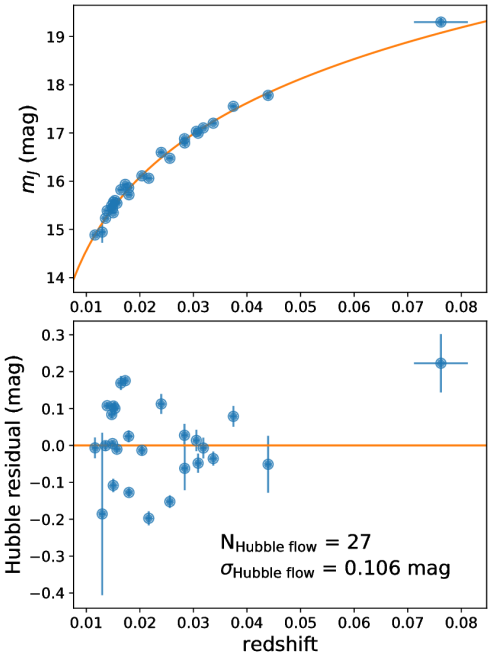
- 3 Fields far away from the disk
- Edge detection with Sobel Filter
  - Histogram binning with 0.01 mag
  - Gaussian smoothing with 0.1 mag



Near Infrared Standard Candles

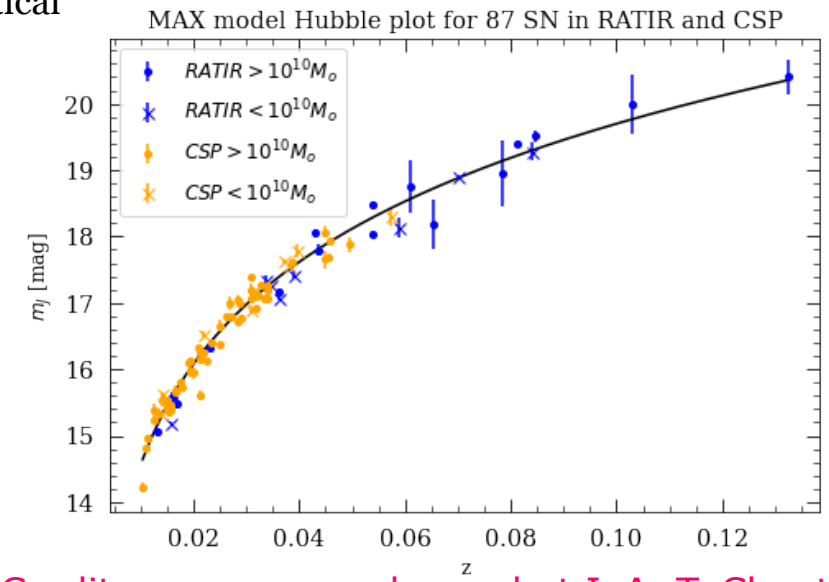
Does non-standard dust extinction cause high Ho?
Are SNe standard candles in the NIR? => future distance scale





SD+'18a

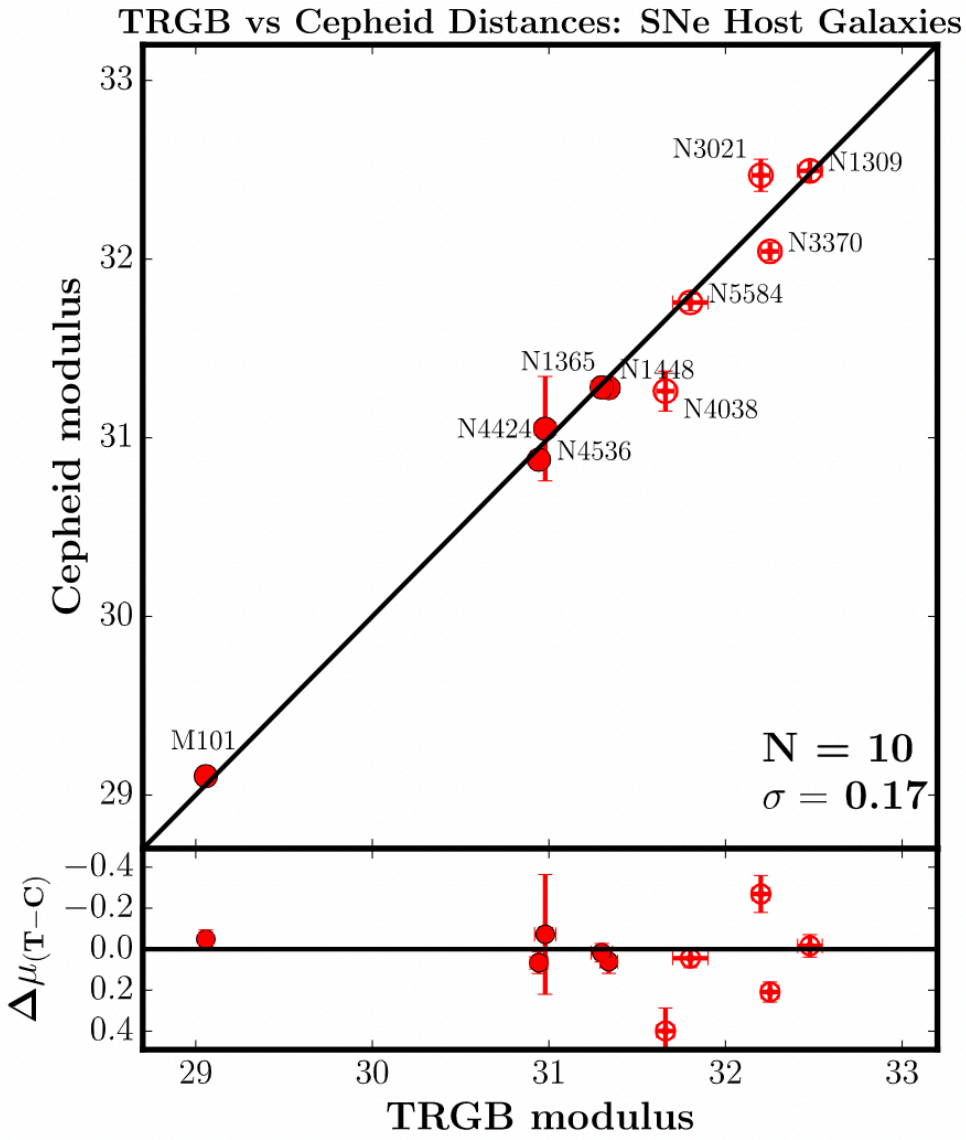
- NO stretch / colour corrections
- Model independent light curve fits
- σ_{int} ~ 0.1 mag
  - for comparison: optical ~ 0.5 mag
- Consistent value with the optical



"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

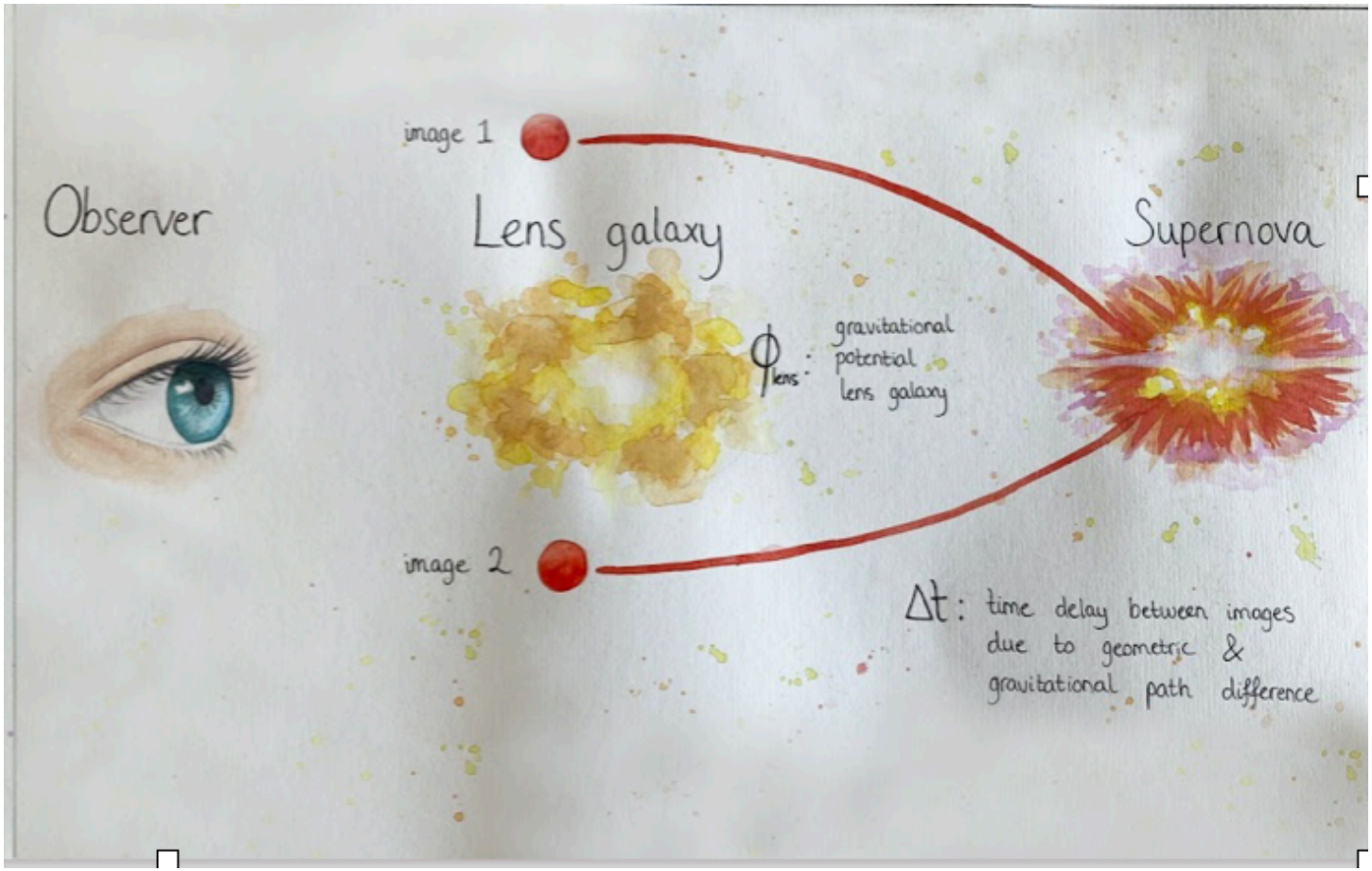


image 1
Observer
Lens galaxy
Supernova
ϕ_{lens}: gravitational potential lens galaxy
image 2
Δt: time delay between images due to geometric & gravitational path difference

Dark Energy Model + SN systematics

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

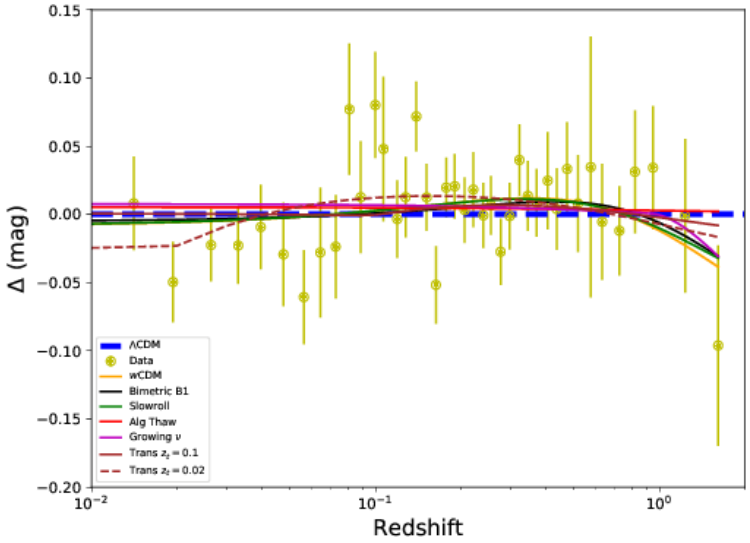
Modelling sources of systematics

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

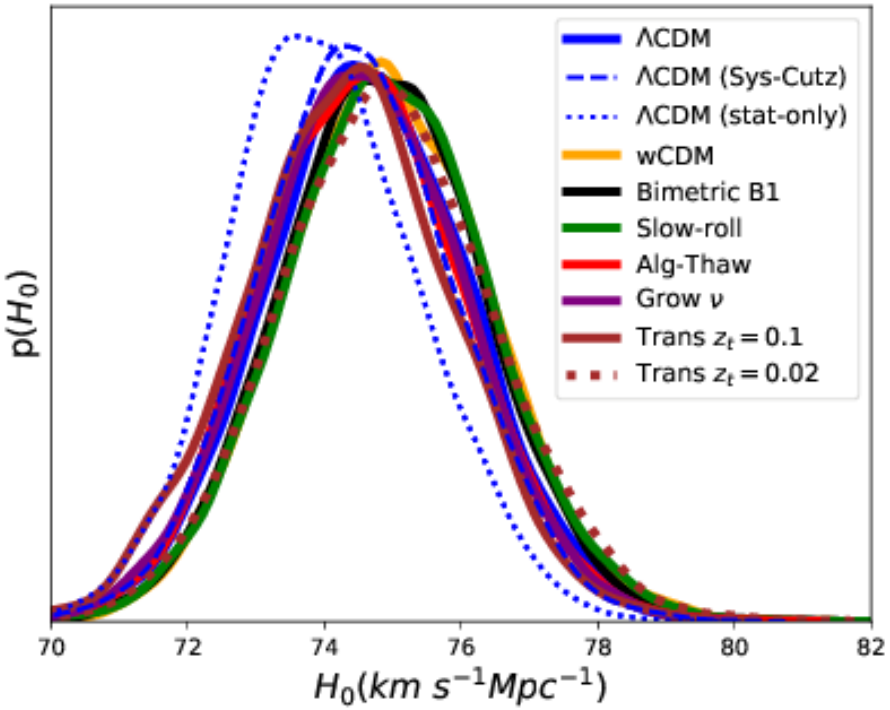
Low-z from > 10 systems

Some targeted programs

Now used for Pantheon+ & SH0ES '22



SD, Brout, Scolnic+ 2020c

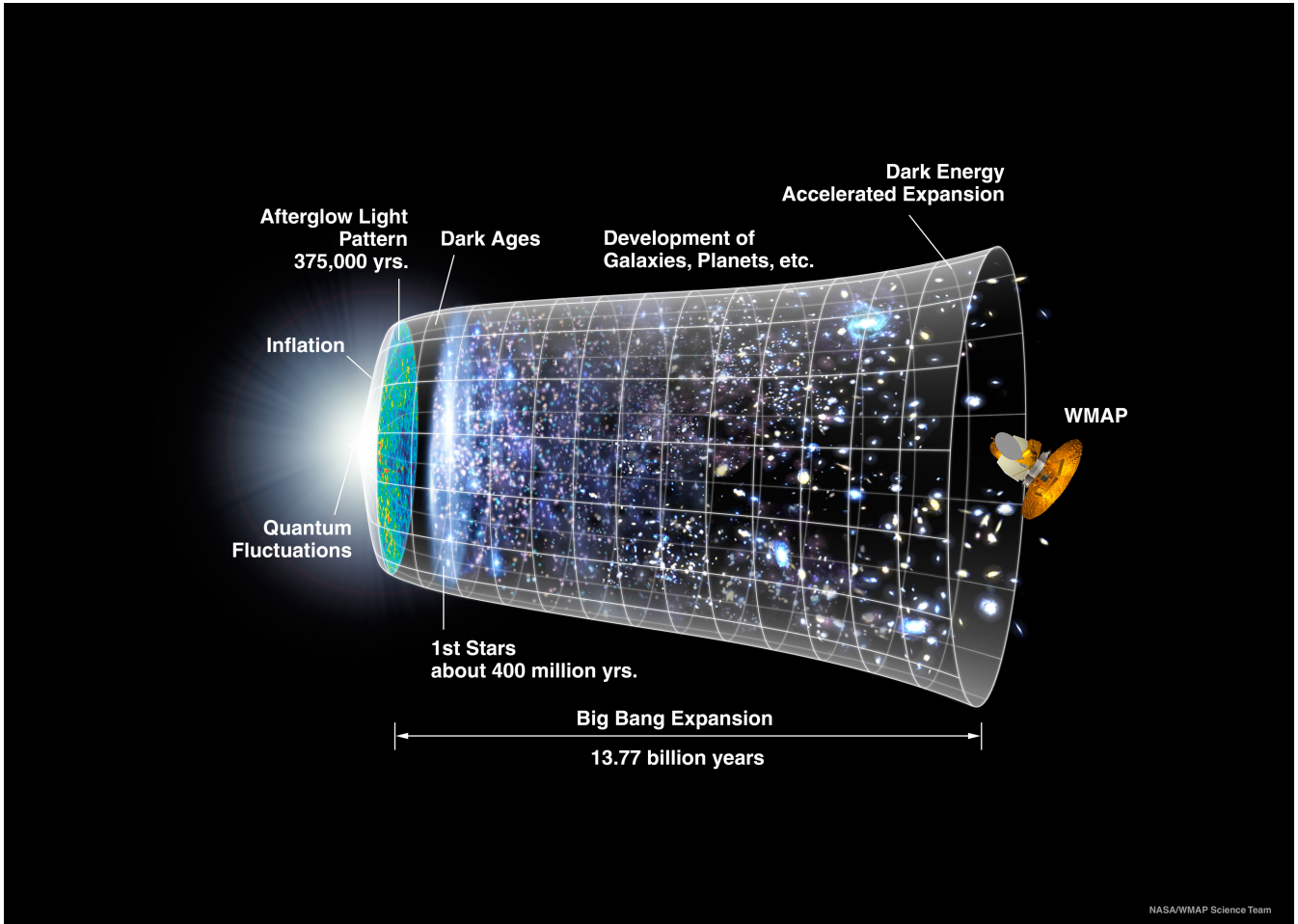


See also, transition models in Benevento, Hu, Raveri 2020

Expansion history

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

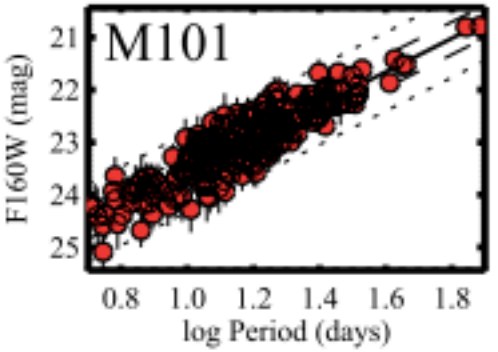
- Constrain growth of structure

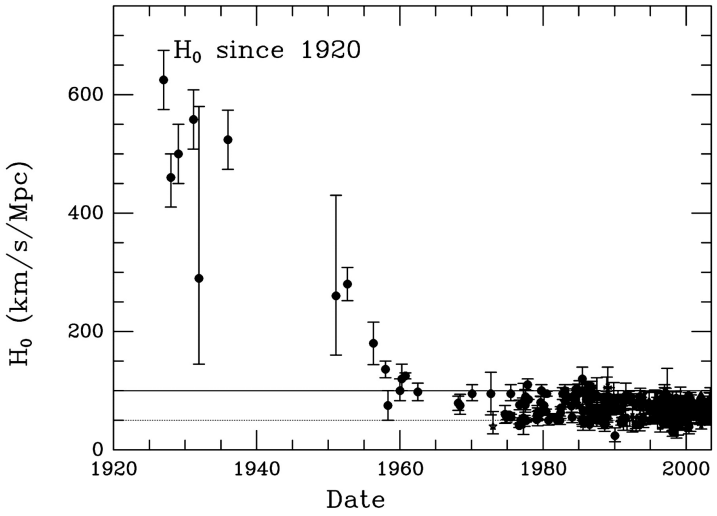


Cepheids as distance indicators

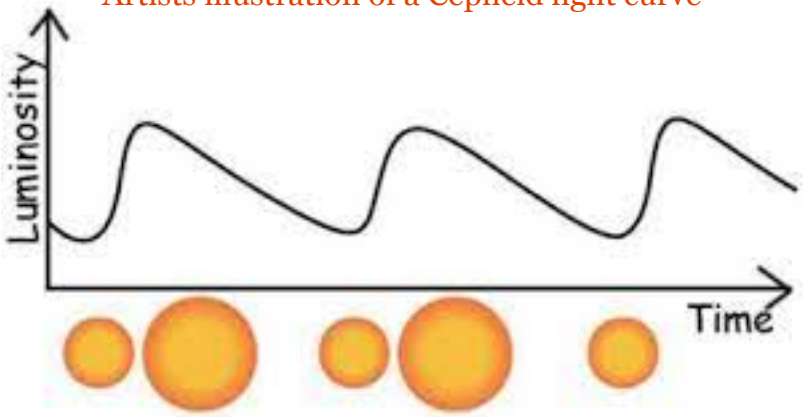
- Pulsating variable stars
- Developed as precise distance indicators
- Correcting for Period - Luminosity (P-L) relation (Leavitt + Pickering 1912)
  - Correct for colour: the "Wesenheit" relation
  - Metallicity - luminosity relation

Minimise corrections by observing in the NIR

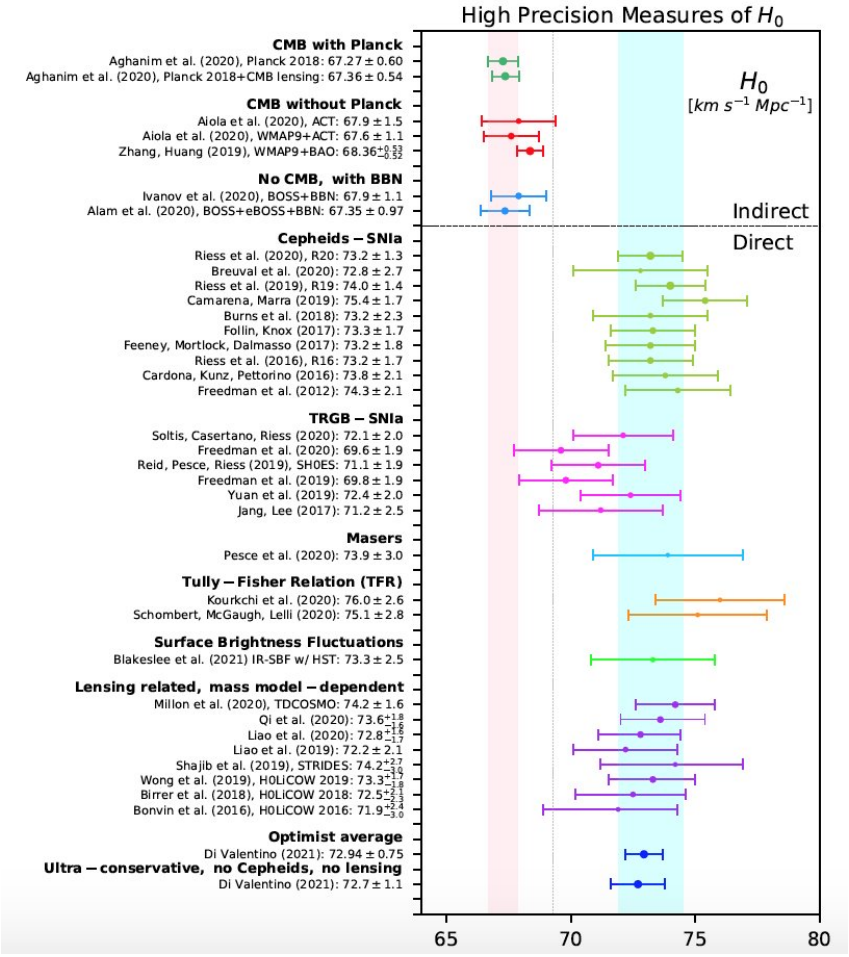




Artists illustration of a Cepheid light curve



Current Status



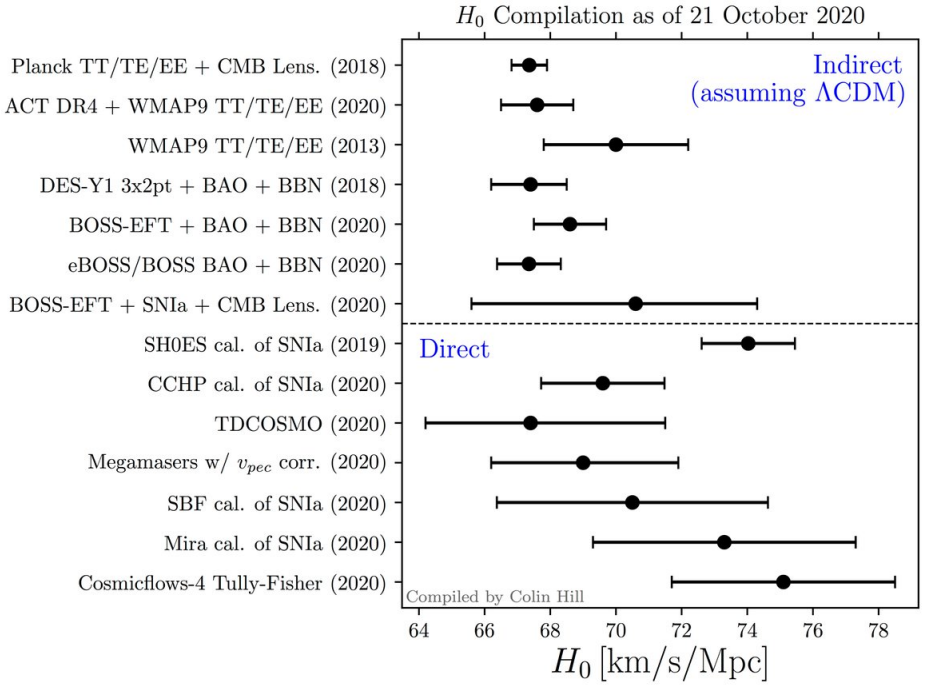
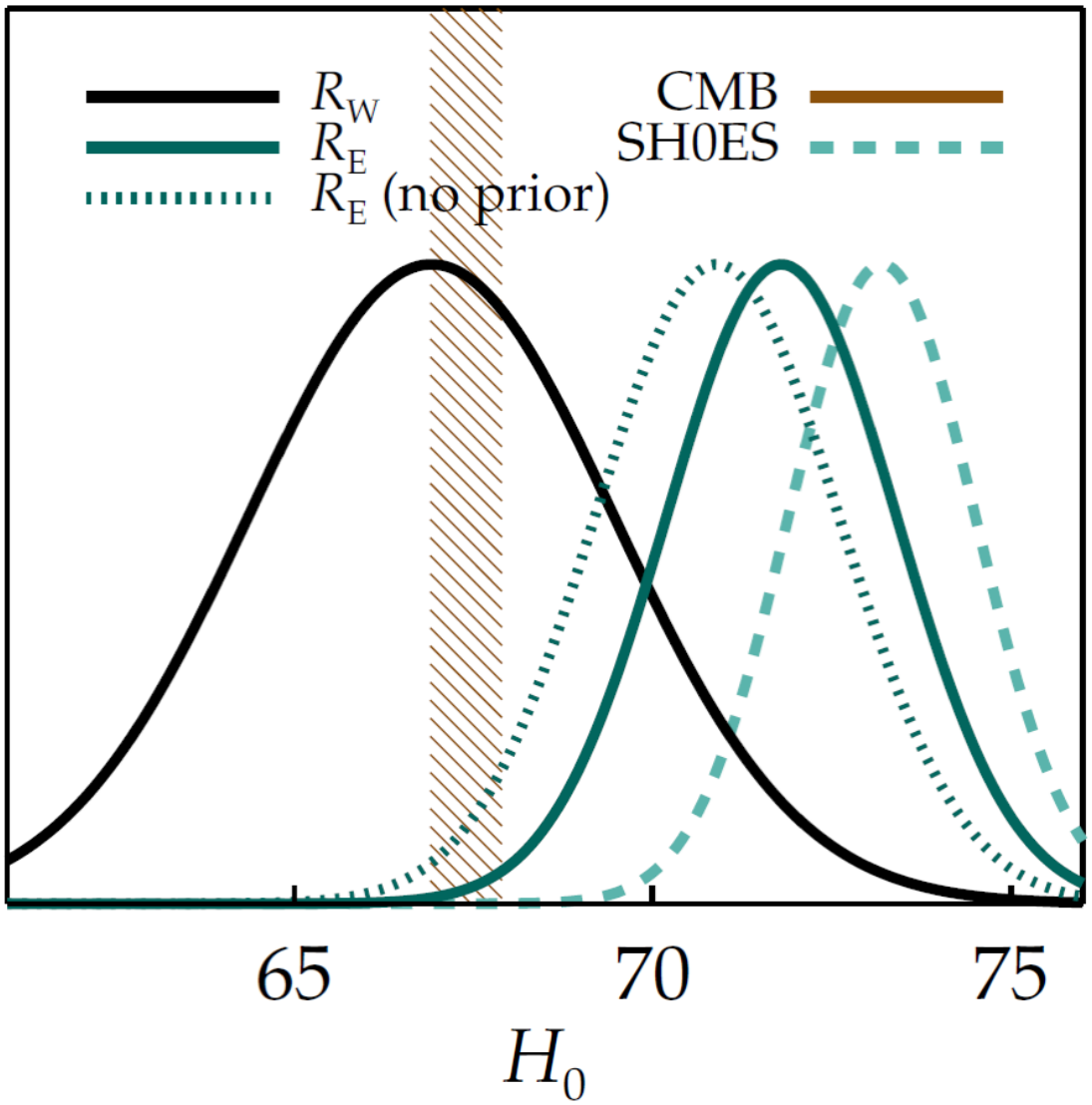


Figure from review by Di Valentino et al. (left) see also Hill et al. (right)

Updated "tension"



Oskar Klein centre

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