Strongly Lensed Supernovae: New cosmological and astrophysical probes in the time-domain era

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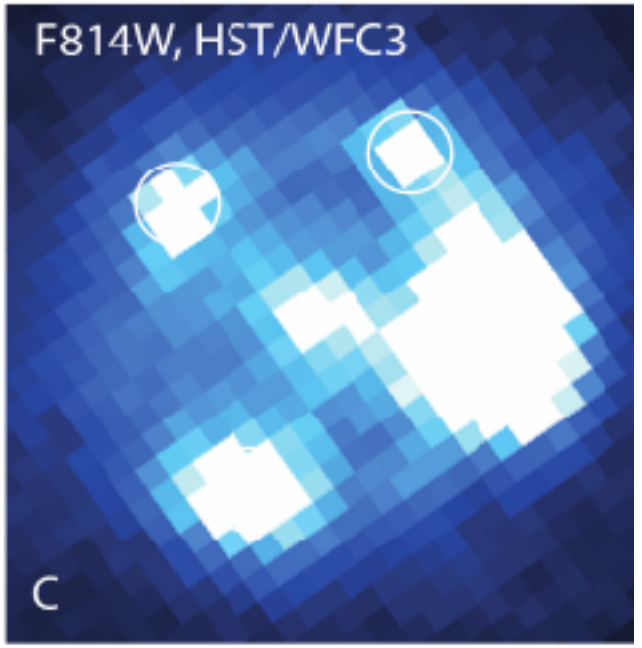
with: LSST DESC + iPTF/ZTF Cosmo WG

SOTU Seminar, TIFR, 19 December 2023

Outline



Motivation

Recent discoveries

SD+20b; Mortsell, **SD** et al., 2021; Johansson, .. **SD**, et al. 2021; Goobar et al., Nat. As, 2023

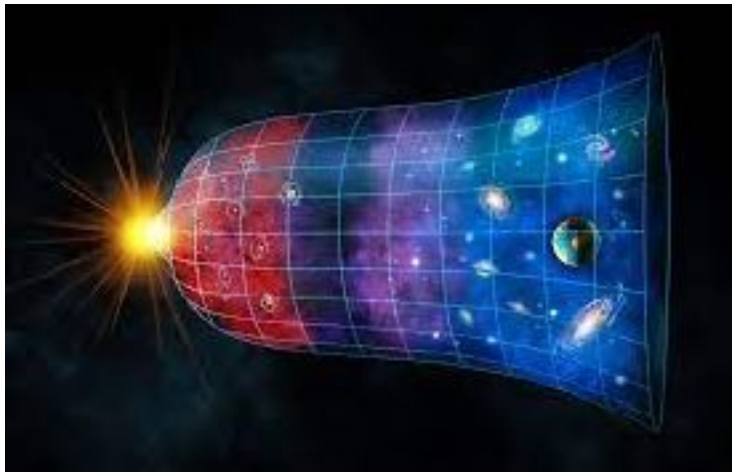
Towards precision cosmology with LSST

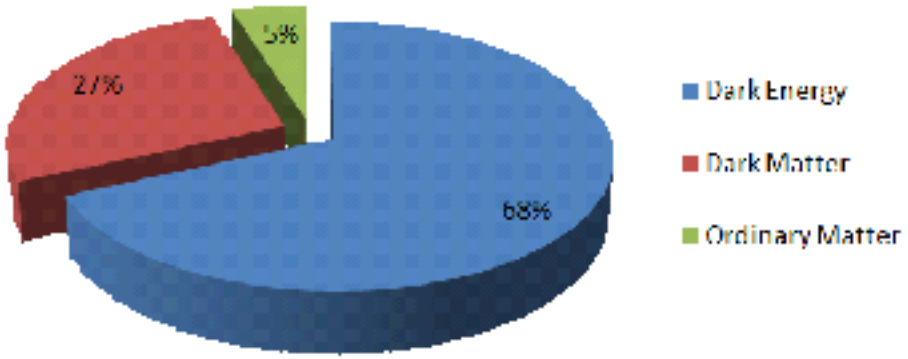
Arendse,**SD**, et al.; **SD**+Pierel in prep., Birrer, **SD**, Shajib, 2022

Ongoing work: time-delay inference, JWST, curvature

Crascall-Kennedy,**SD**, et al. in prep., Hu + **SD** to be submitted

Motivation





Well tested standard model: ΛCDM

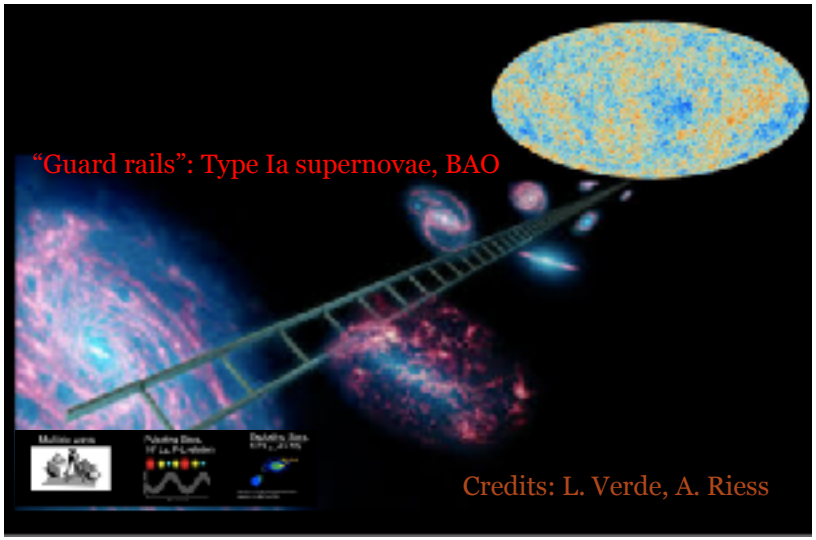
Theoretical problems: what is dark energy + dark matter?

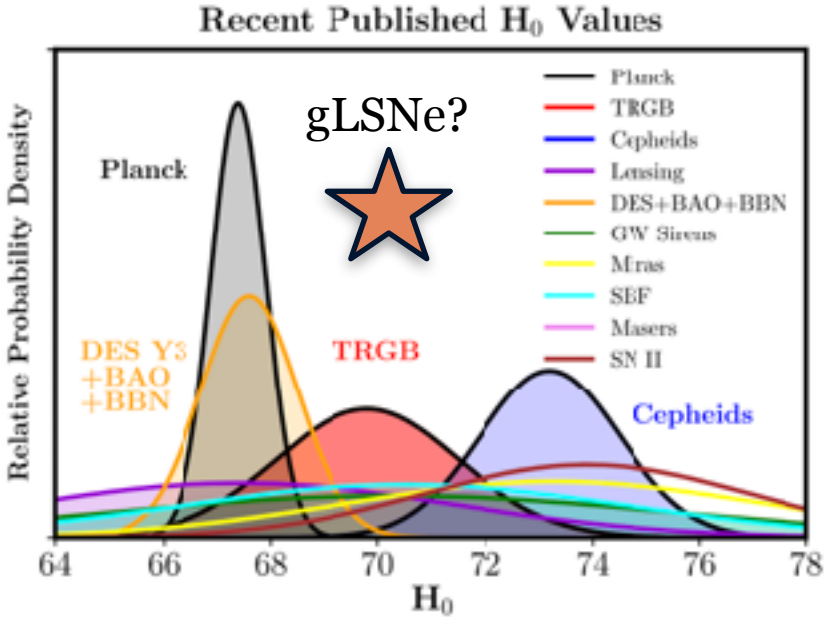
Observational problems appearing with increased precision

Motivation

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

See also Scolnic+2023





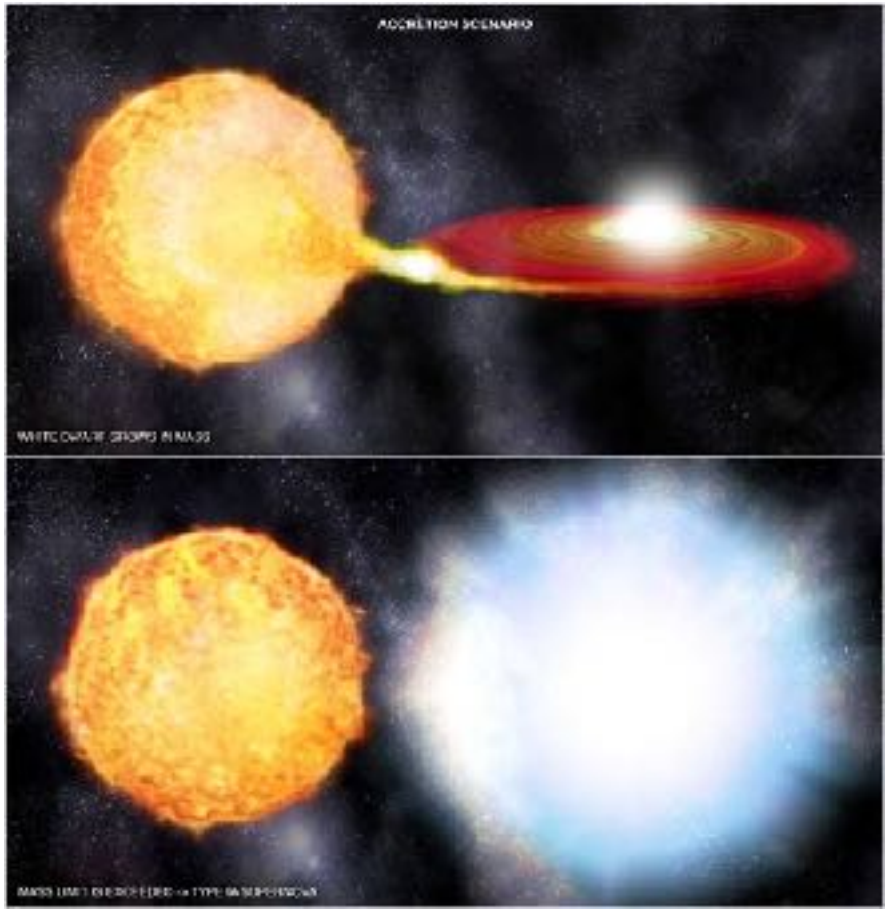
- New physics?
- Unknown Systematics?

Need independent methods

- **Novel absolute distance measurement (e.g. lensed transients)**

What are Type Ia supernovae?

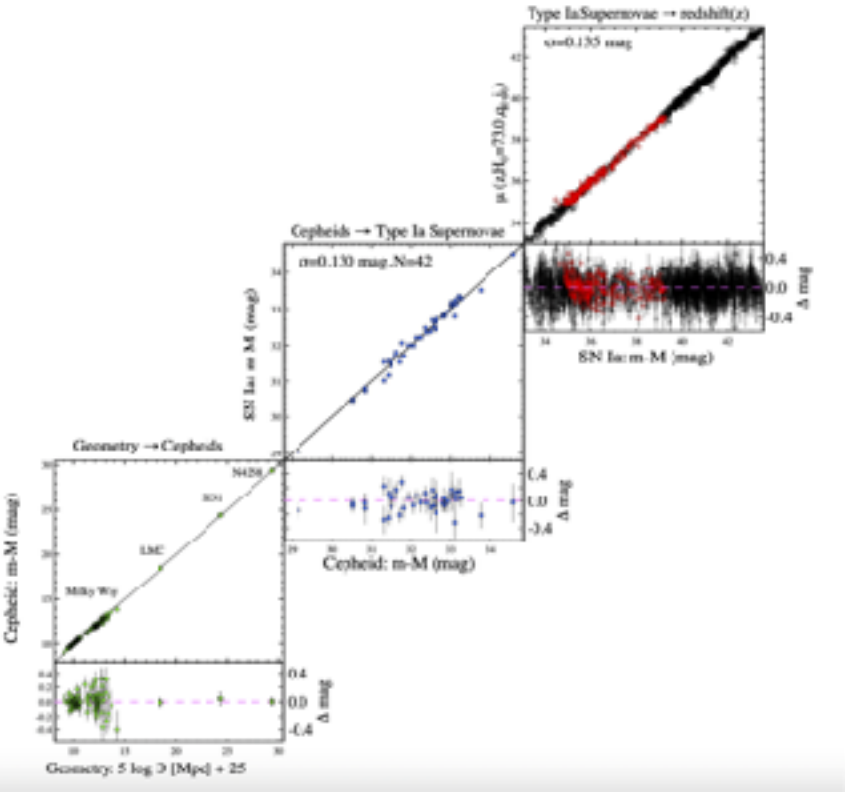
NOT standard but calibratable -> small scatter, reduce lensing uncertainties



dark energy systematics -> lensing helps study high-z SN physics

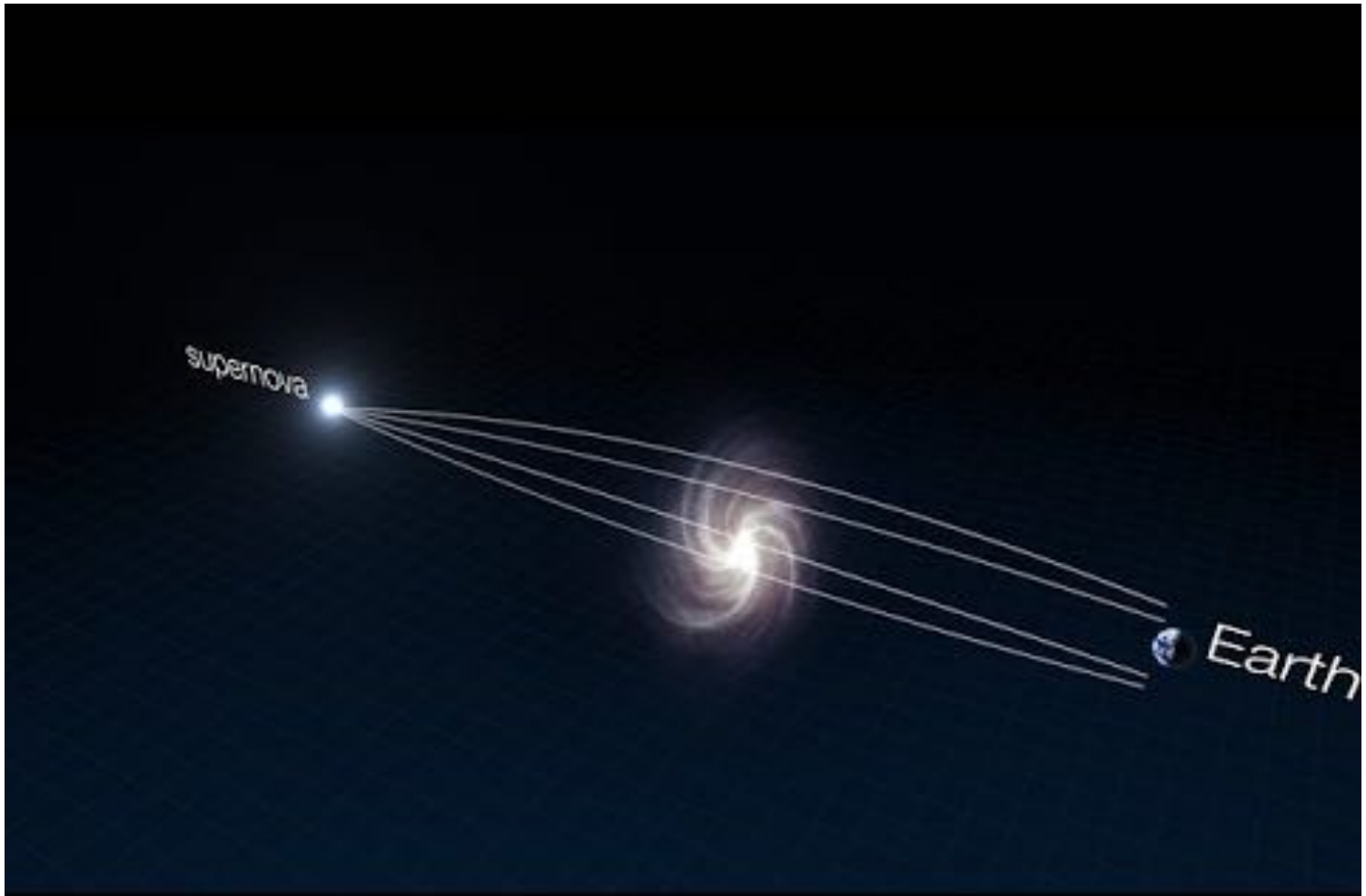
Cosmic Distance Ladder

- Current most accurate method for direct H_0 inference
- Type Ia supernova luminosity calibrated to Cepheids / TRGB
- Cepheids/TRGB calibrated to local distances, e.g. parallax, DEBs



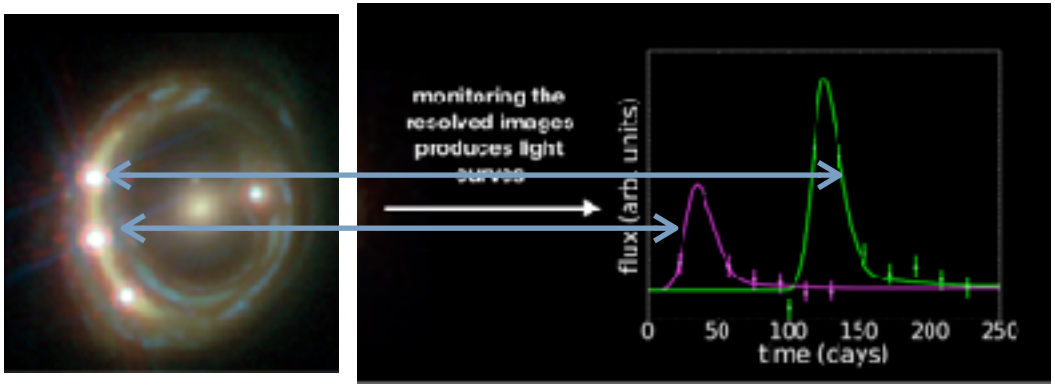
Riess et al. 2022

Strongly lensed transients

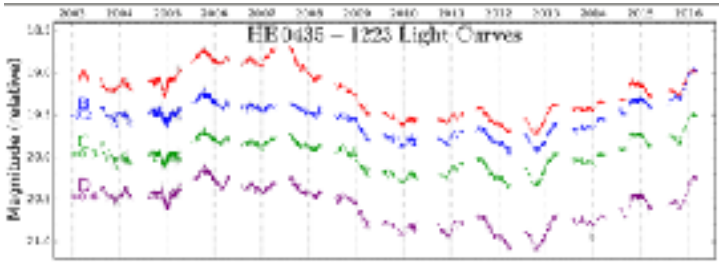


Credits: ESO, L. Calcada

Time-delay cosmography



Typical lensed SN and QSO light curves



Completely Independent of unlensed SNe

* NOT * luminosity distance

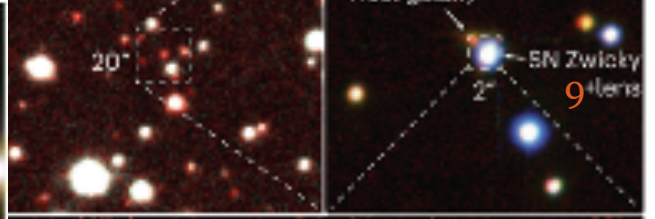
- Independent discovery method to lensed quasars
  - glSNe => “standardisable candle”
  - Lower impact of microlensing systematics

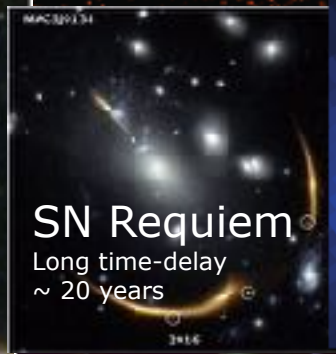
- First proposed in Refsdal 1964 (for SNe, used for QSOs)

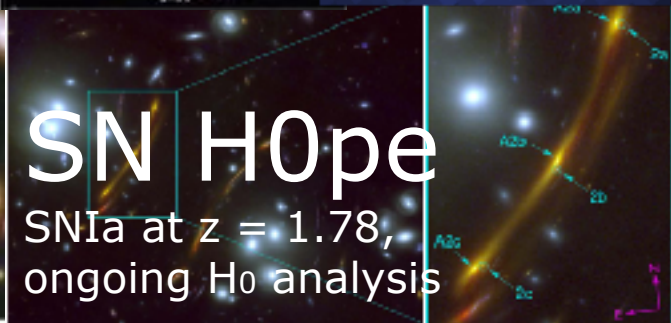
Recent Discoveries

SN Refsdal

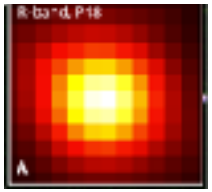
IIP-87A-like; H_0 to ~ 7%





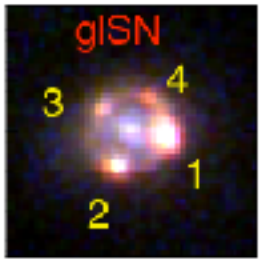


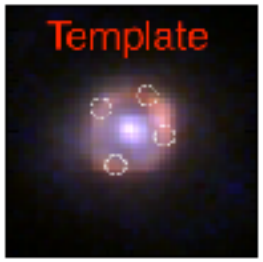
First Resolved lensed SN Ia

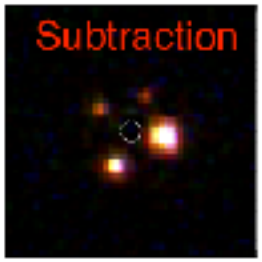


Discovery in unresolved data

Follow-up: HST / AO

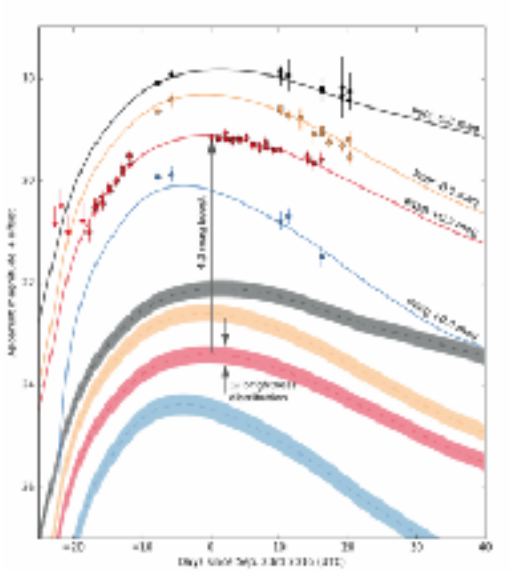


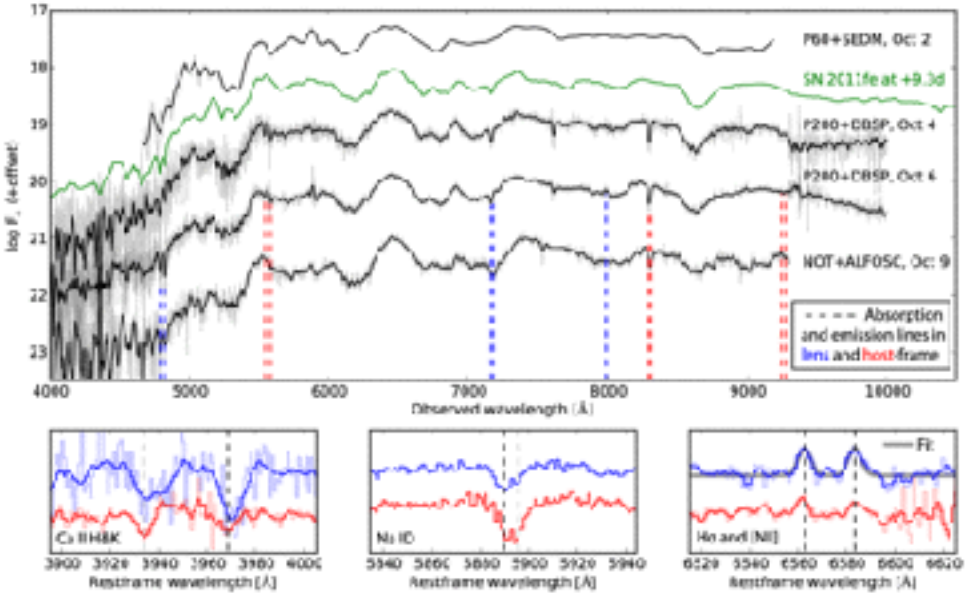




HST/WFC resolved image, template and subtraction => not possible for QSOs!

>50 times brighter than normal SNIa at z~0.4: a 30σ outlier! (Goobar+2017)





Higher resolution spectra -> second redshift from lens (Goobar+2017)

Time-Delay Estimation

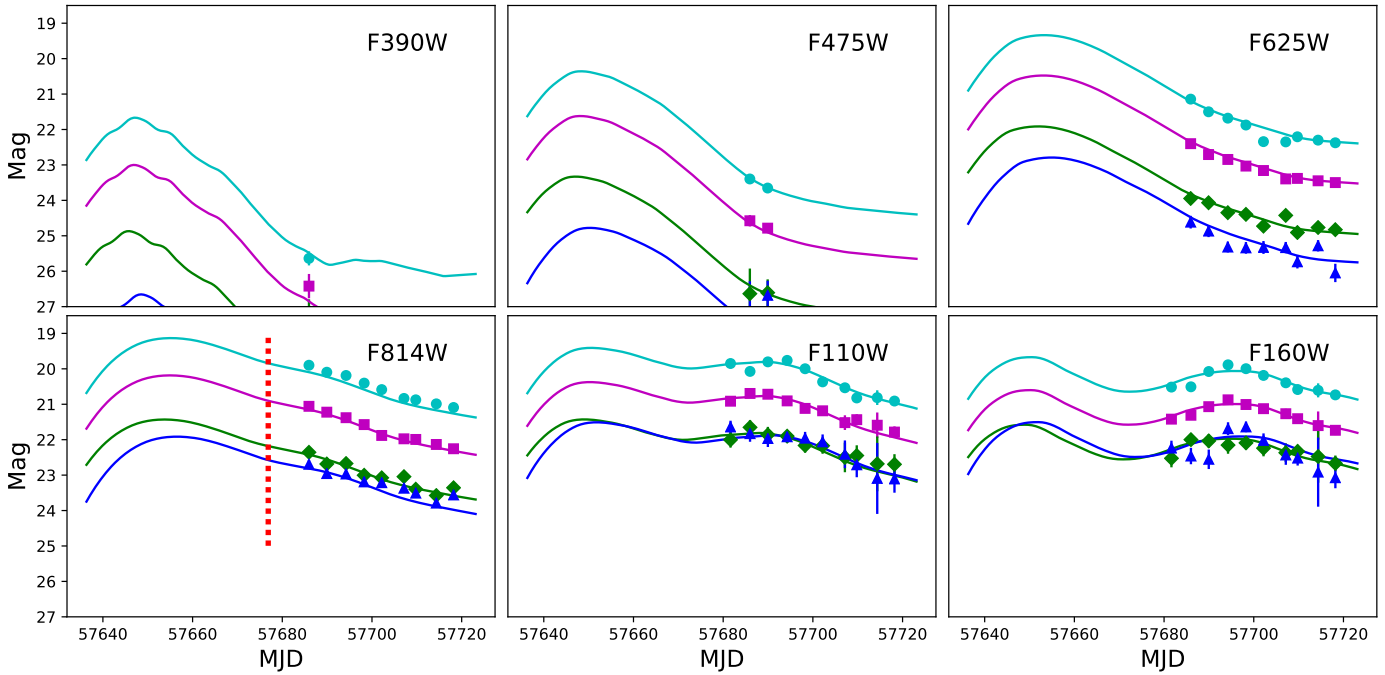
Very small time-delays (~ 1 day):
Not ideal for measuring H_0

Max. light simulations
=> five times smaller error

Long wavelength lever arm for extinction constraints

Just a few orbits: errors ~ 1d

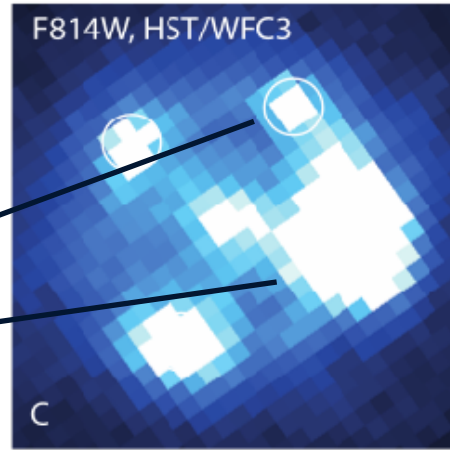
SD+20b



iPTF16geu: Magnification + extinction

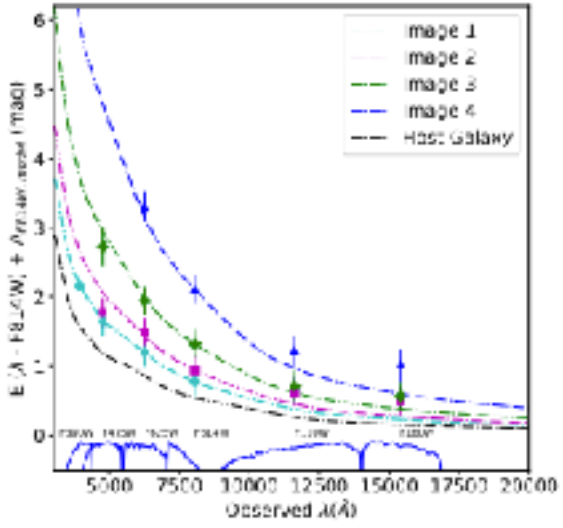
Important probe of dust in lens galaxy
LoS Rv < Milky Way values

Model independent lensing magnification

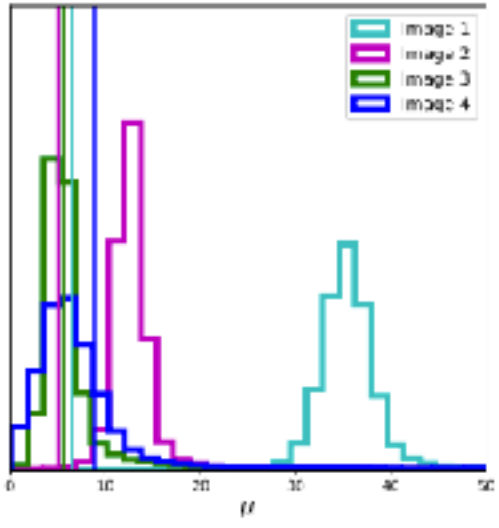


Surprisingly different brightness?

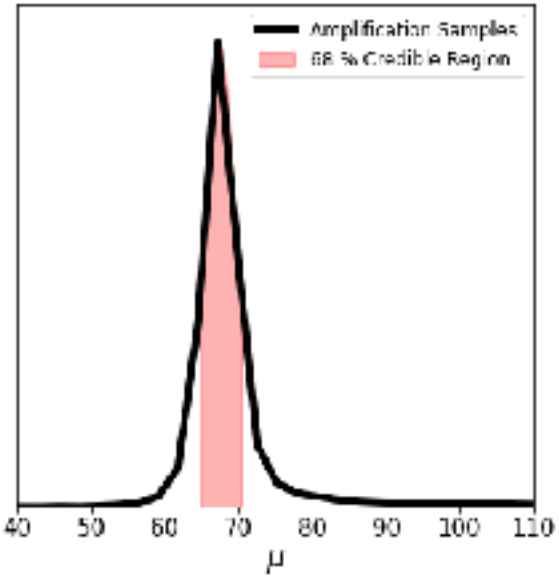
Preliminary magnification (μ) ~ 52
With extinction correction 67+/-3



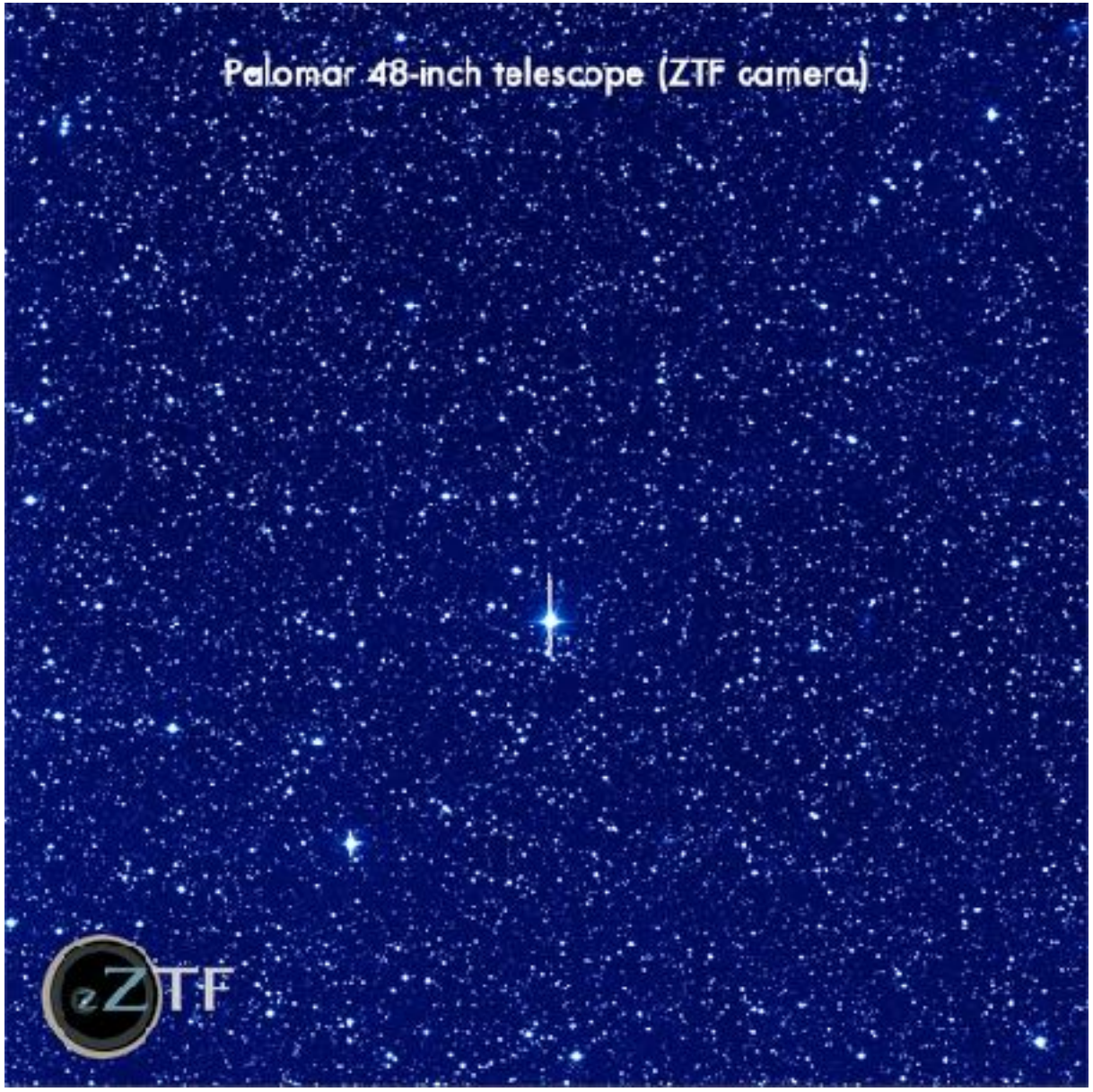
Spectroscopy in Johansson,.., SD, +'21



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



First lensed SN with ZTF

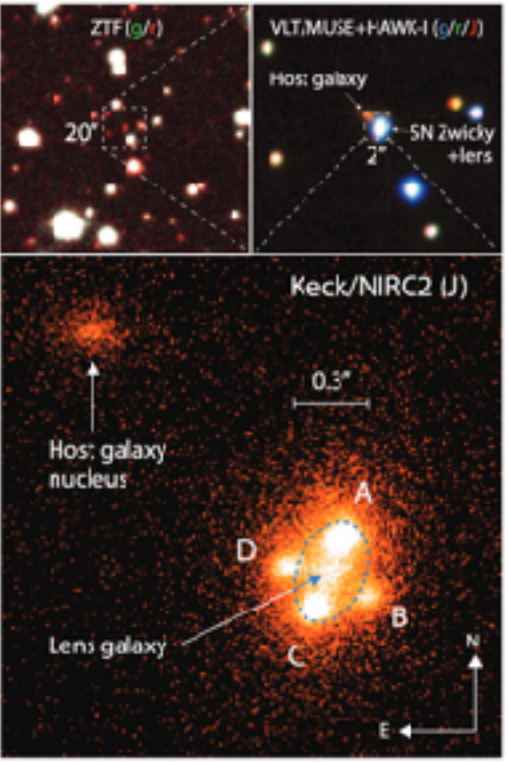


Credits: J. Johansson, N. Arendse

SN Zwicky!

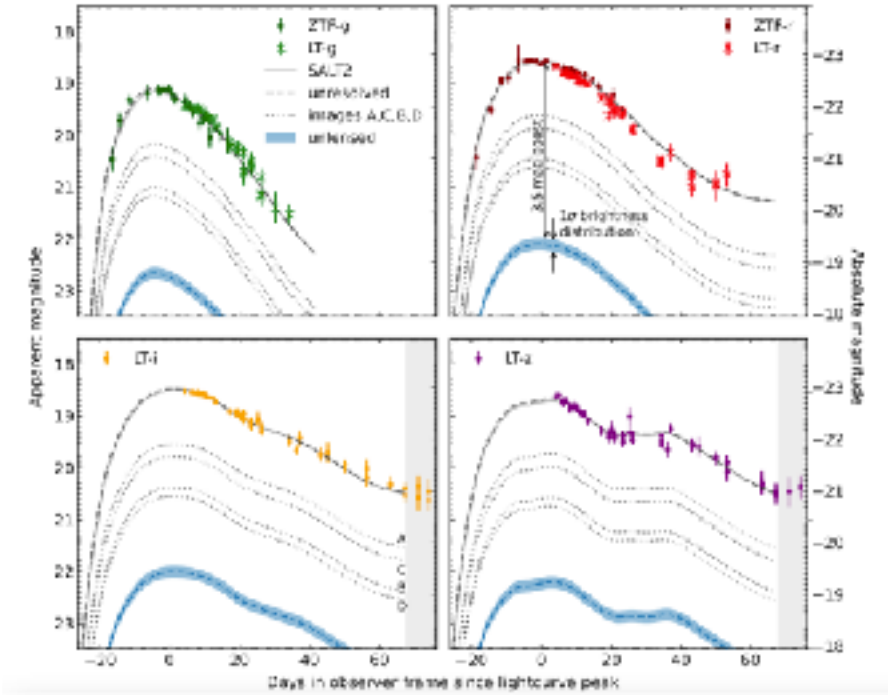
Multiband P48+ LT data
Accurate extinction constraints
PI: Dhawan, Perley

1”



~ 0.3”

0.01”

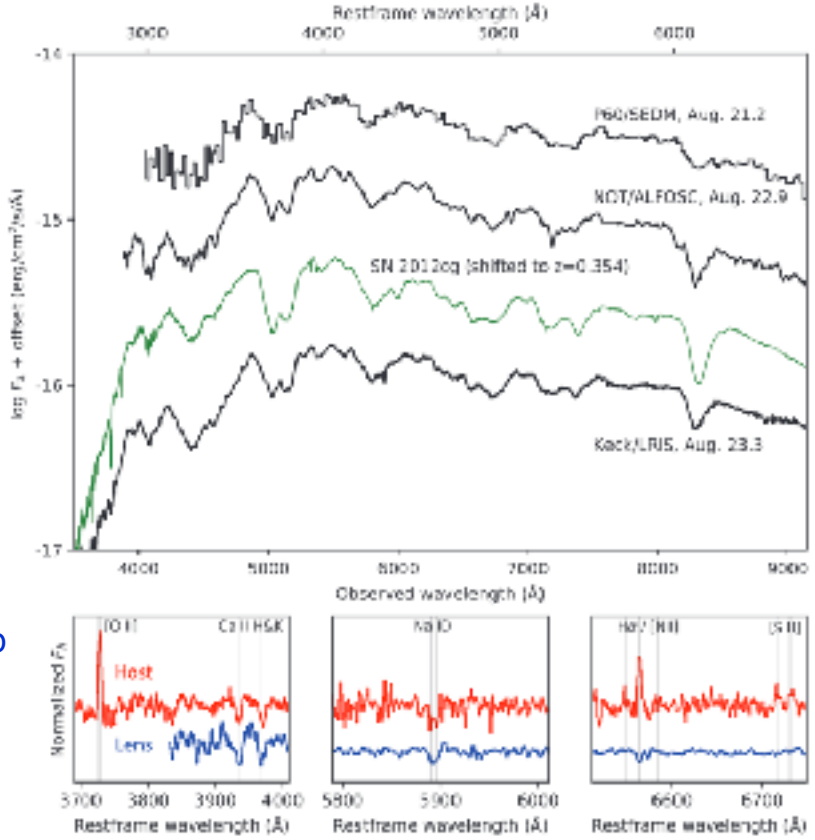


Small telescopes vital for bright lensed SNe

~ 3.5 mag > SN Ia at z_s =0.354
Low extinction in host + lens
Compact system θ_E < 0.2”: study central stellar IMF

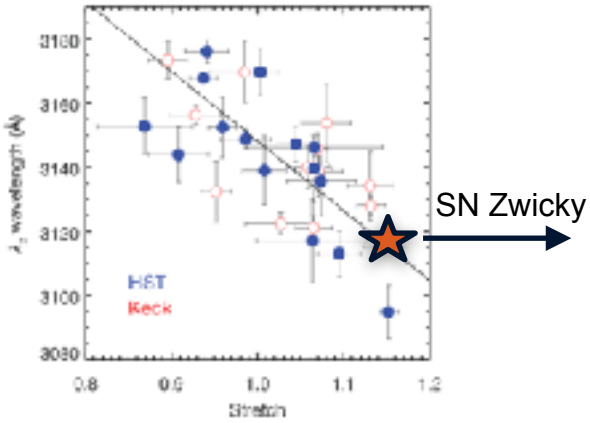
(Goobar,…, **SD** +, Nat. As., submitted)

Spectroscopy of lensed SNe



SN Zwicky spectra compared to local SN 2012cg

Johansson, **SD+**, in prep



Comparison to low-z SNe sample from Maguire +2012

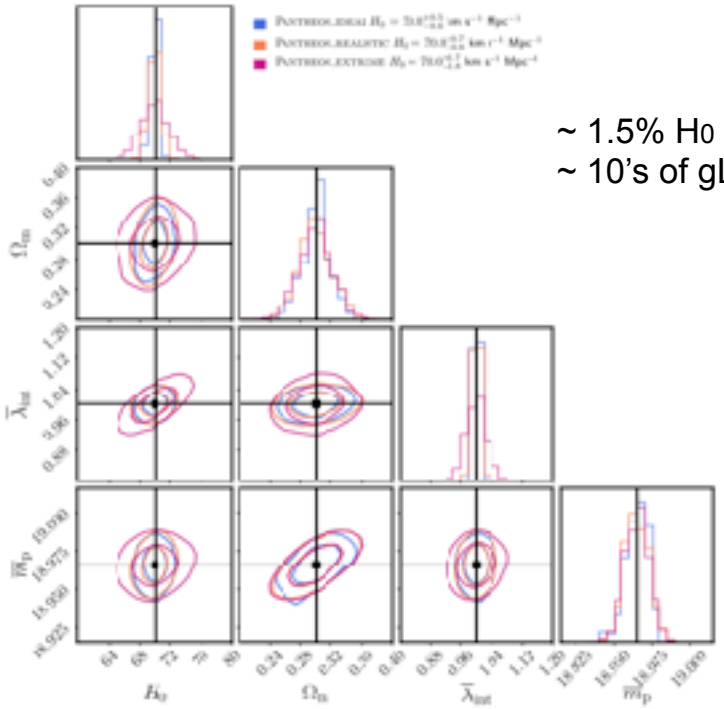
No signs of cosmic spectroscopic evolution!

JWST NIRCam + NIRSpec
Nebular observations of SN Zwicky

What's next!

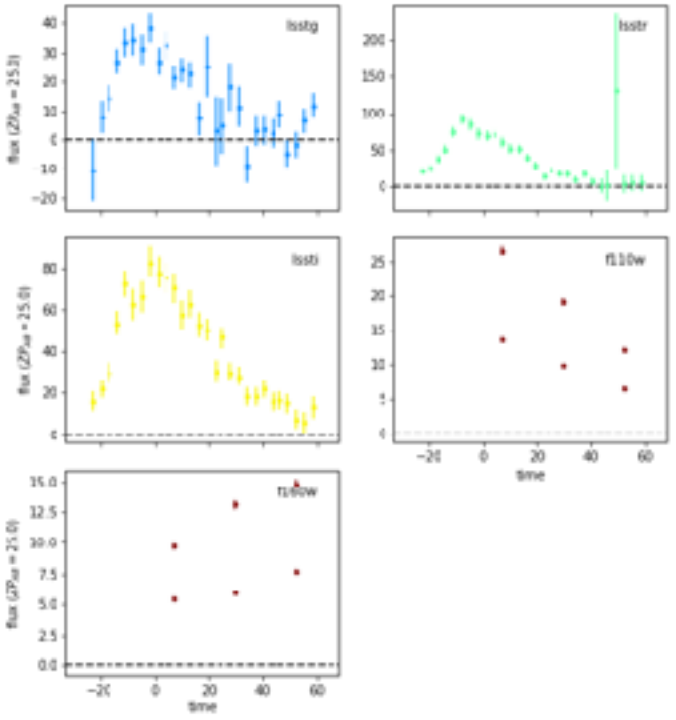
Vera C. Rubin Observatory

Gearing up for LSST



~ 1.5% H0 with LSST
~ 10's of gLSNe

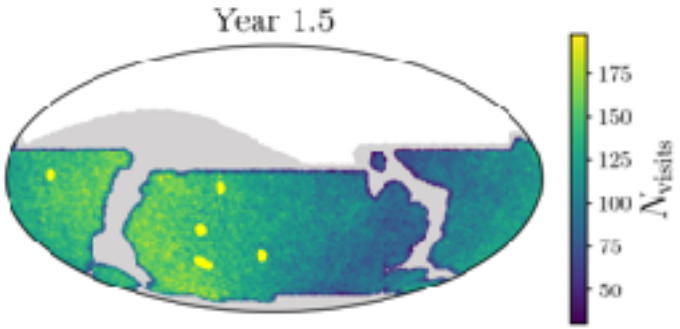
Birrer, SD, Shajib, 2022

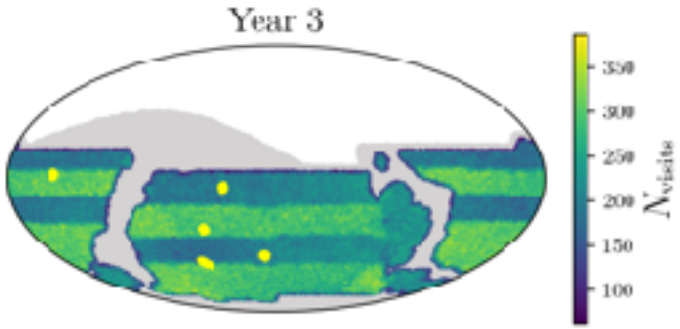


Resolved photometry breaks degeneracies
Three epochs sufficient to 5%,
> 3 filters needed for < 3% time-delays

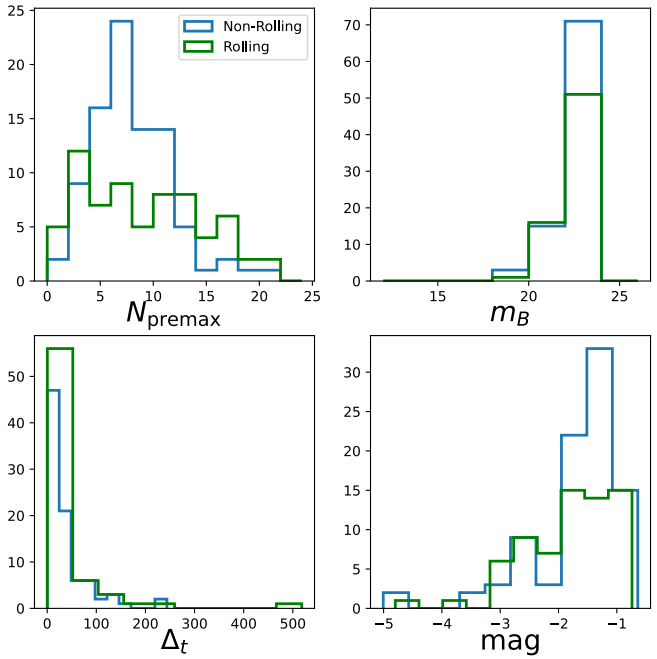
High-Cadence LSST + sparse space-based follow-up (SD + Pierel in prep.)

Detectability in LSST





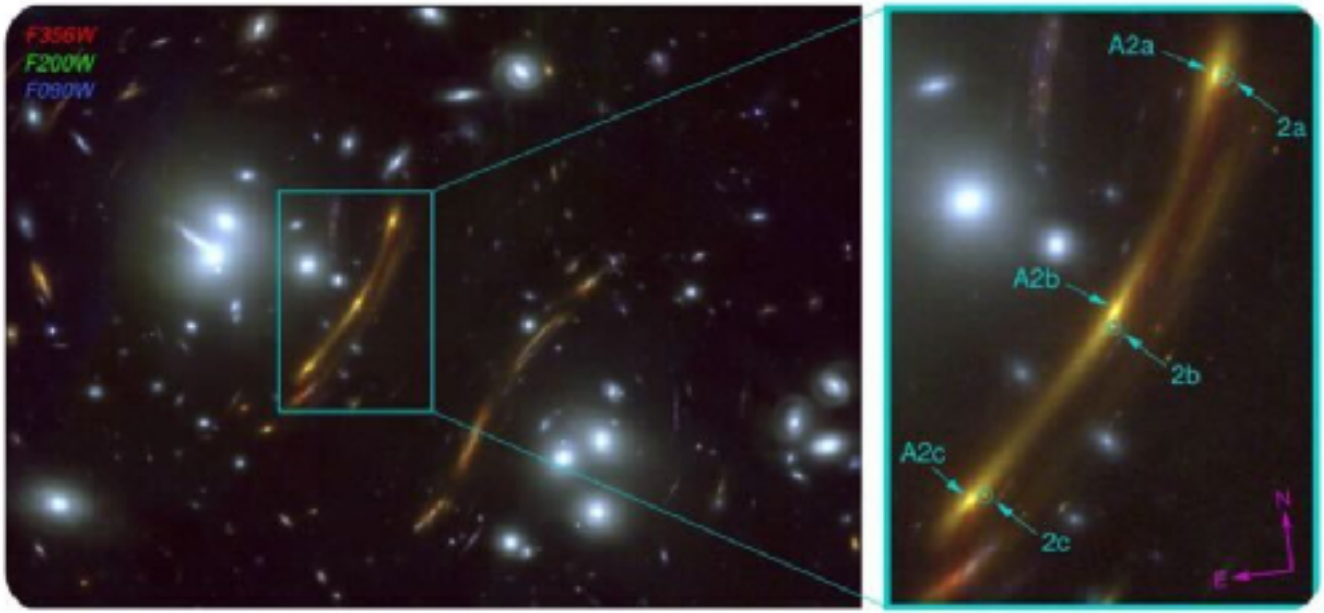
Baseline v3.0 cadence
Many 10's expected per year: ~ 20 with large Δt
Rolling has fewer -> denser sampling



Several with early sampling for discovery
Bright for 4m spec classification
Long time delays for cosmology

Arendse, **SD**,+, MNRAS, submitted

SN H0pe



Triply imaged SN Ia at z =1.78

Cluster lens, long expected time-delay

Multiband follow-up with NIRCam (F090W-> F444W)

Expected H_0 at 10% -> 7% with reference epochs

Important to test spectroscopic time-delays

Pierel,., SD, et al. in prep.

Spectroscopic Time-Delay

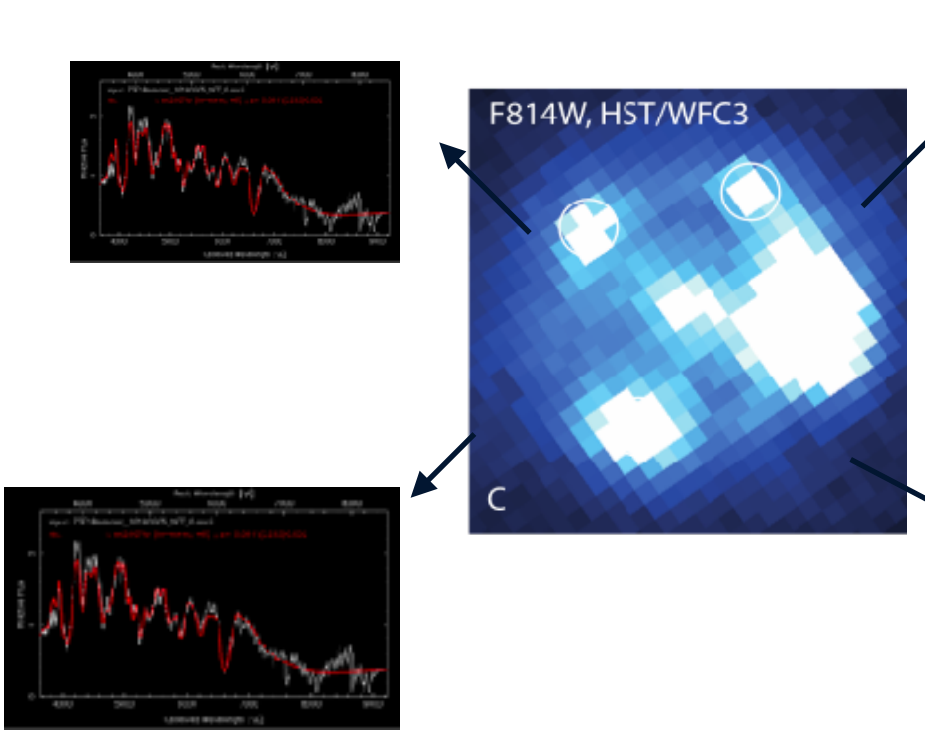
Spectroscopic time-delay: “one-shot” method (Johansson+2021 for 16geu)

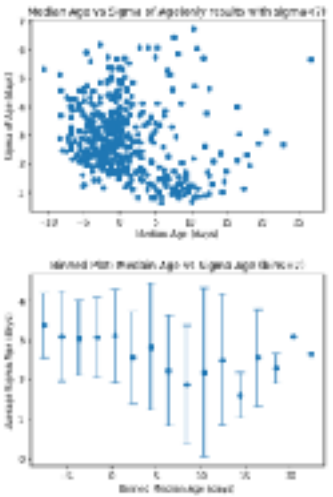
Cross-correlate against template spectra

Small errors (< 2d) near maximum light

Works similarly well for core-collapse SNe

Example SNID fit for a typical low-z SNIa spectrum





Crascall-Kennedy, SD+ in prep.

What's ongoing: JWST!

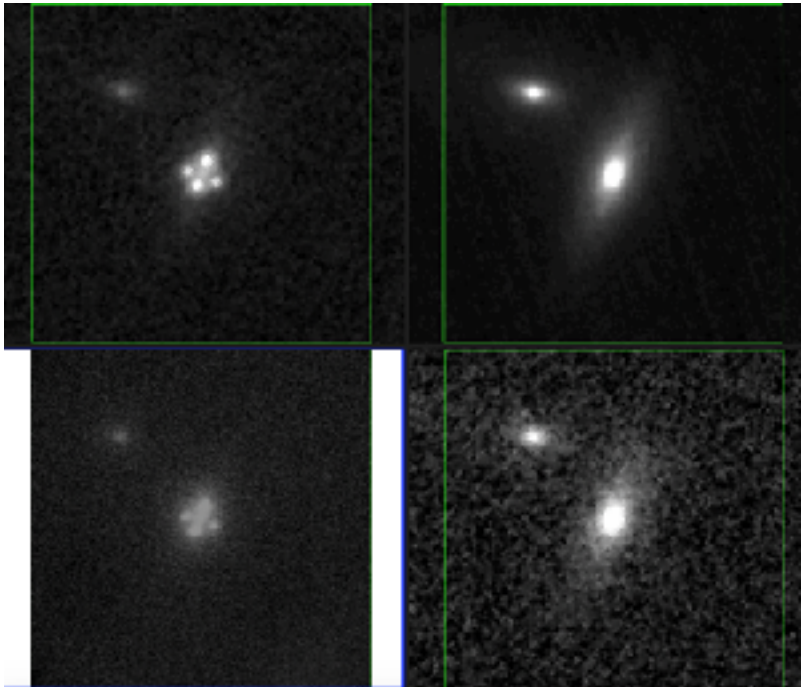
Nebular phase (~ 1 year post explosion) observations

Four filter photometry + spectra (NIRCam + NIRSpec IFU)

Important for post-explosion host + lens modelling

Nebular spectra -> shed light on progenitors

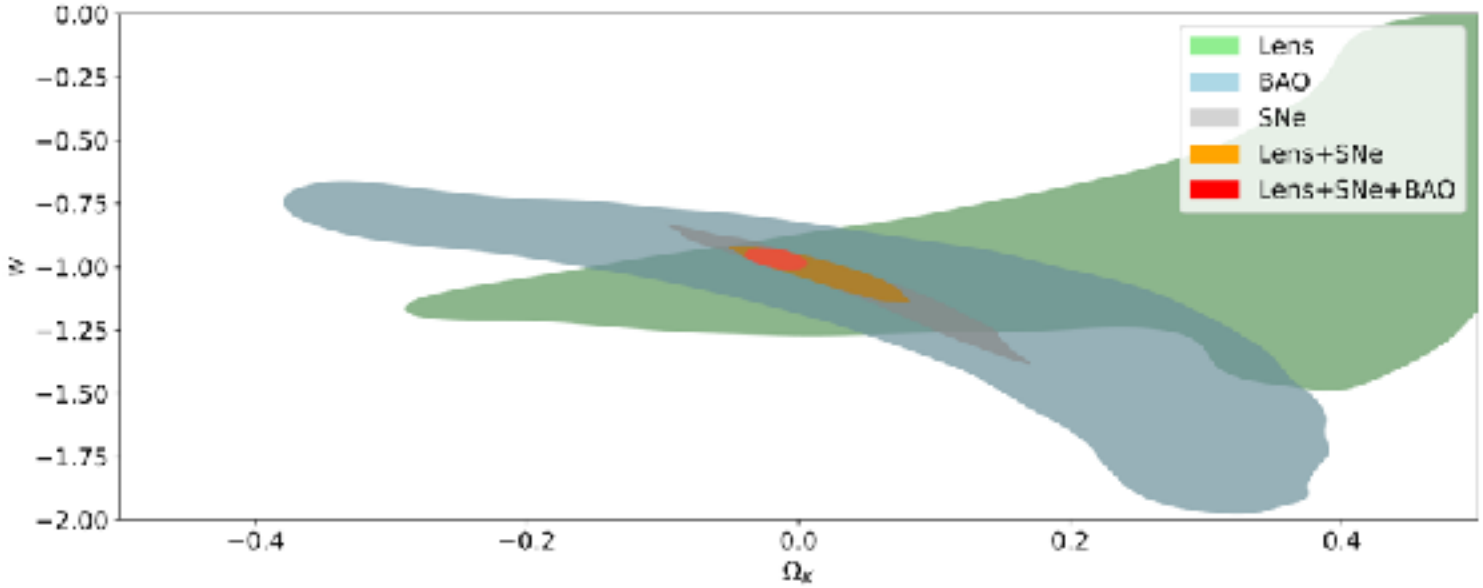
NIRCam image of host +lens



What's ongoing: Spatial Curvature Constraints

- Simultaneous dark energy and curvature constraints

- Weak constraints from lensing -> orthogonal to SNe+BAO
  - Breaks degeneracy : Improves Ω_K by factor 2



Hu & **SD**, MNRAS, to be submitted

Conclusions

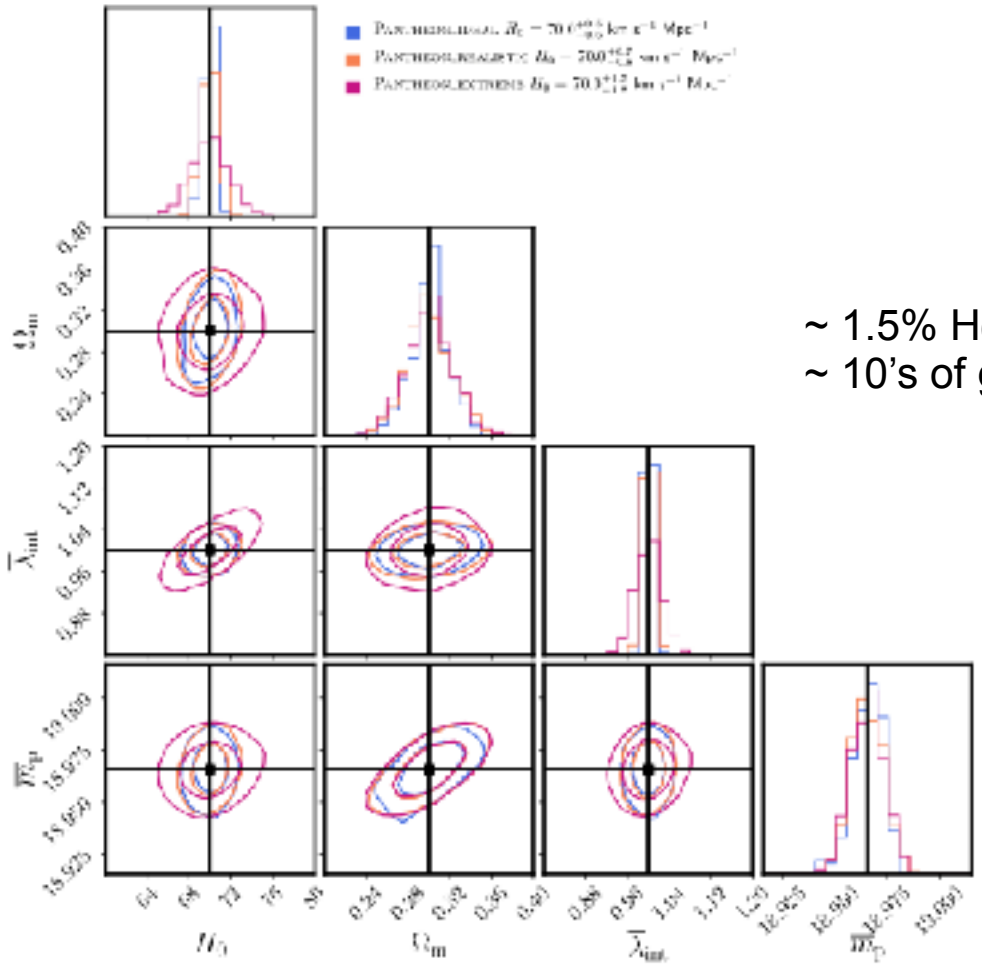
- Current survey discoveries
  - 16geu: Deviation of extinction from MW
  - No sign of cosmic spectroscopic evolution
  - Compact lens of SN Zwicky -> exotic DM?

- Forecasts for cosmology
  - Independent H_0 at 1.5% with LSST
  - Detect a large sample with feasible spectroscopy

- New inference methods
  - Spectroscopic time-delay at < 2d error

- Excellent complement to SNeIa for curvature

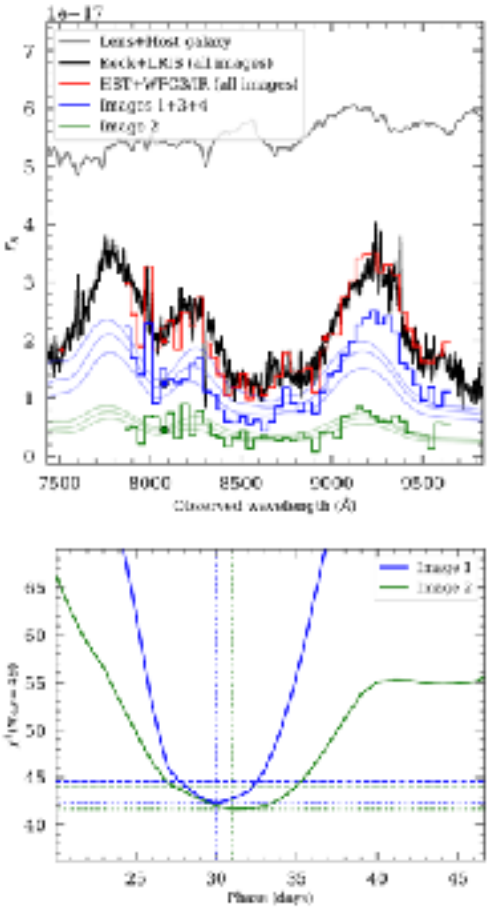
Gearing up for LSST



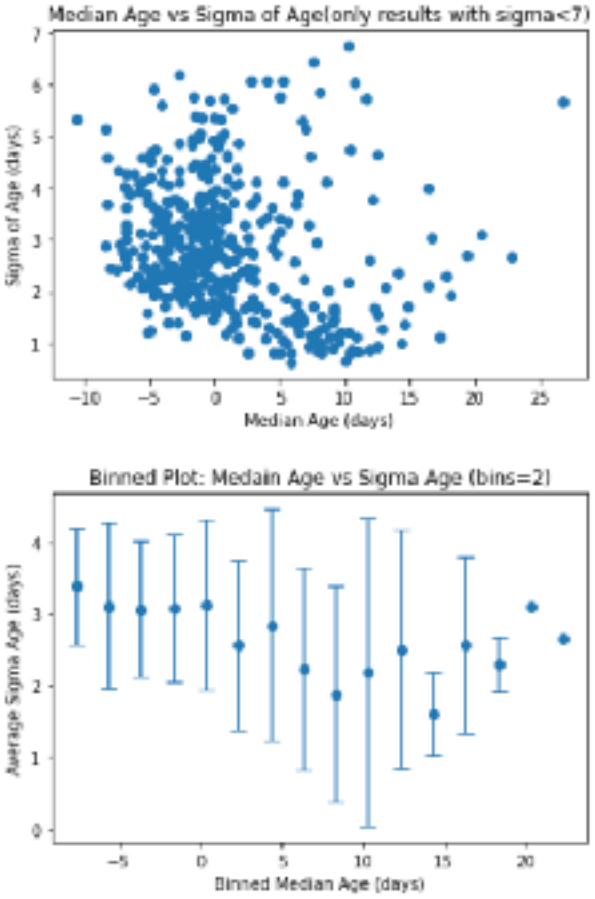
~ 1.5% H_0 with LSST
~ 10's of gLSNe

Birrer, **SD**, Shajib, 2022

Time-delay Inference



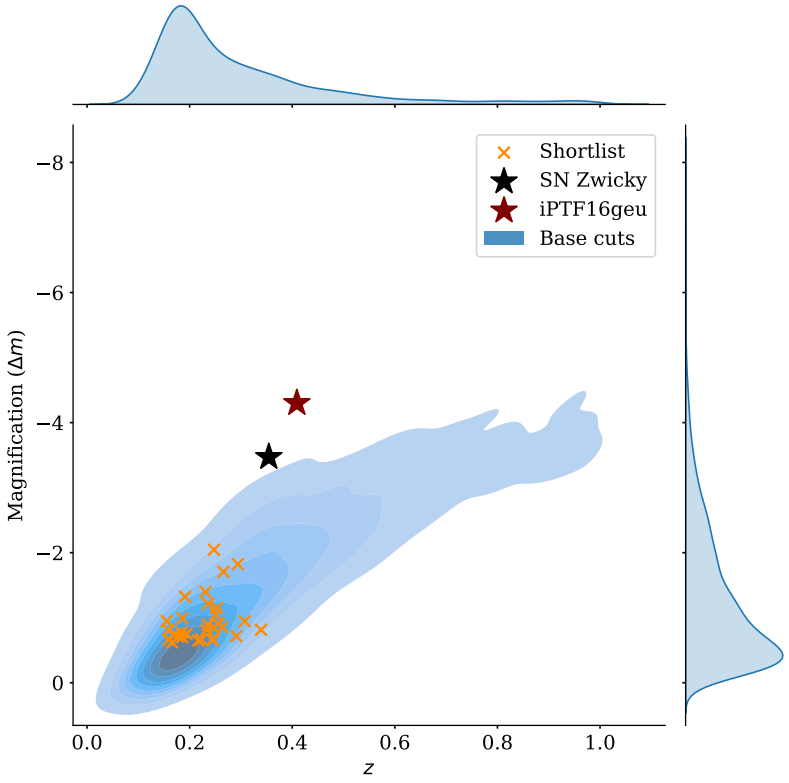
Spectroscopic time-delay: “one-shot” method
(Johansson+2021, JWST NIRSpec)



SNID: low errors (< 2d) with maximum light spectra
Similarly low for CCSNe
(L. Crascall-Kennedy, SD in prep.)

ZTF archive search for lensed SNe

- Systematic search for strongly lensed SNe Ia in the ZTF archive.
- Applying cuts based on simulations.
    - Cuts on photo-z, distance to host, peak absolute magnitude, SN and host colours.
- 31 930 alerts —> 30 candidates.
- Paper out this year!

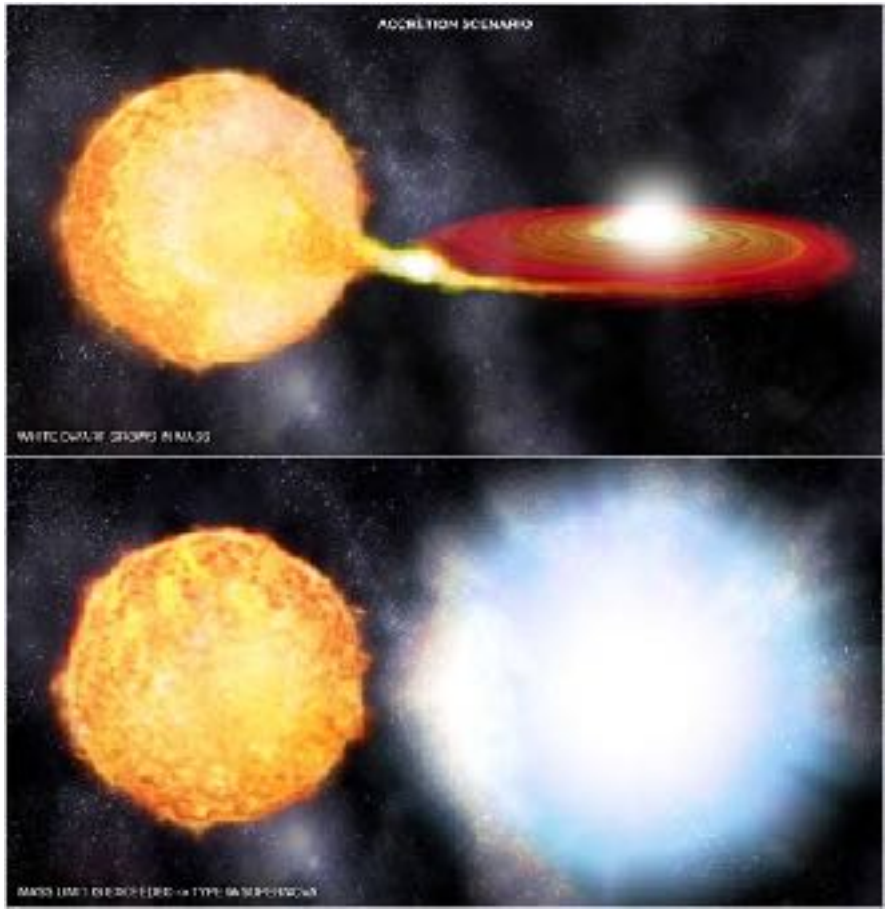


Magnification vs. z for the best 7000 candidates (base cuts), and the shortlist candidates.

A. Townsend, J. Nordin (HU Berlin), S. Dhawan (Cambridge) A. Goobar, A. Sagues Carracedo, B. J. Johansson, N. Arendse, S. Schulze, E. Mörtsell (OKC),

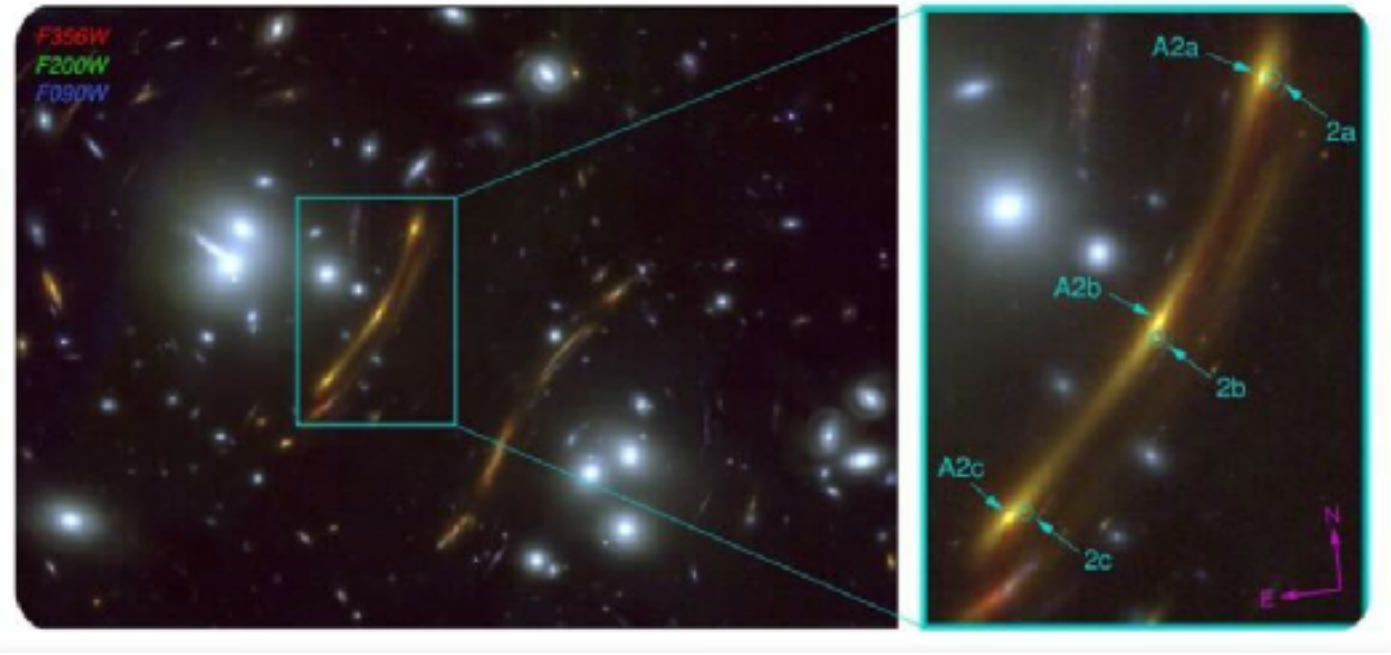
What are Type Ia supernovae?

NOT standard but calibratable -> small scatter, reduce lensing uncertainties



dark energy systematics -> lensing helps study high-z SN physics

SN Hope



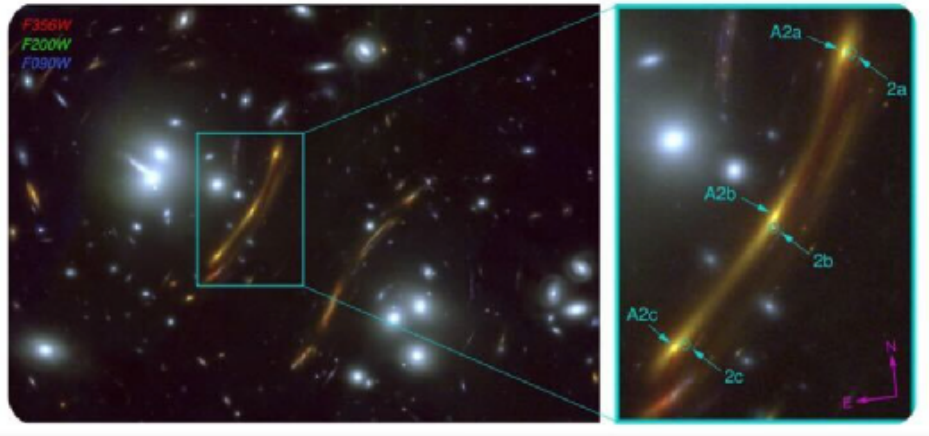
Discovery in NIRCAM obs of PLCK G165.7+67 ; PEARLS program

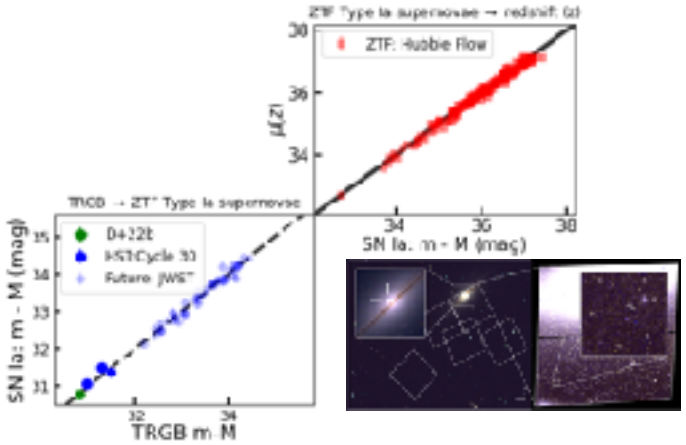
Cluster lens, long expected time-delay

Triply imaged SN Ia at z ~ 2; Follow-up with DDT ongoing

PhD in Time-Domain Cosmology

Suhail Dhawan (sd919; K01)



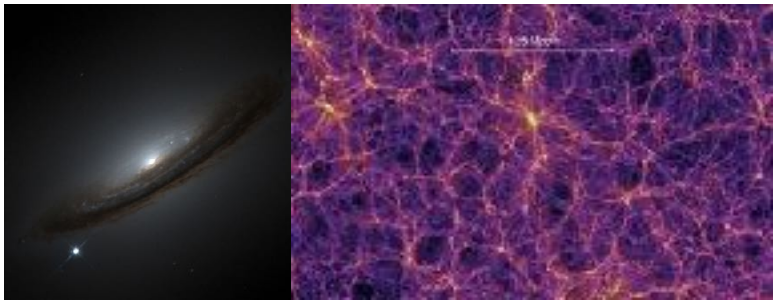


Strongly Lensed Supernovae

- Discovery with Vera C. Rubin Observatory
- Analyses with JWST IFU data
- Novel methods with current surveys

Local Hubble Constant

- Uniform, large Type Ia supernova datasets
- New distance indicators



Structure growth with SNe

- Bulk flows from local superstructures
- $f\sigma_8$ with Type Ia supernovae