The Hubble Constant with explosive transients: A View from the Zwicky Transient Facility

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Cosmology from Home, Parallel Talk August 25 2020

Outline

- Motivation
  - Why measure H_0?
  - Independent distance measures
- Recent papers: Systematics and novel probes
  - Local distance ladder: Impact of dark energy model
  - Strongly Lensed Type Ia supernovae
- Ongoing work: Zwicky Transient Facility
  - Cosmology status update: Year 1 sample
  - Preliminary results
  - Lensed SN search
- Summary and Outlook

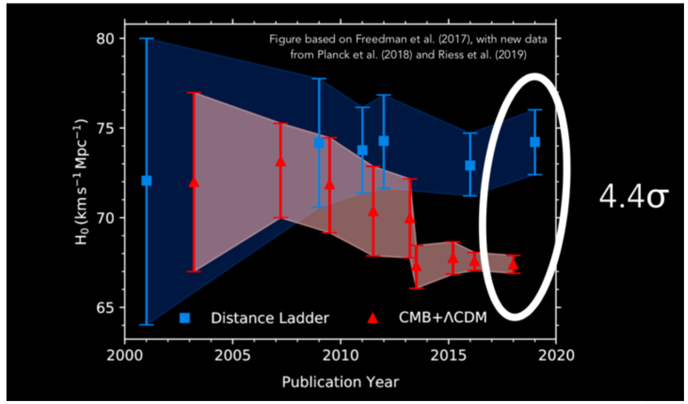
Why measure H0

- New physics? (No clear solution, currently)
- Unknown Systematics?

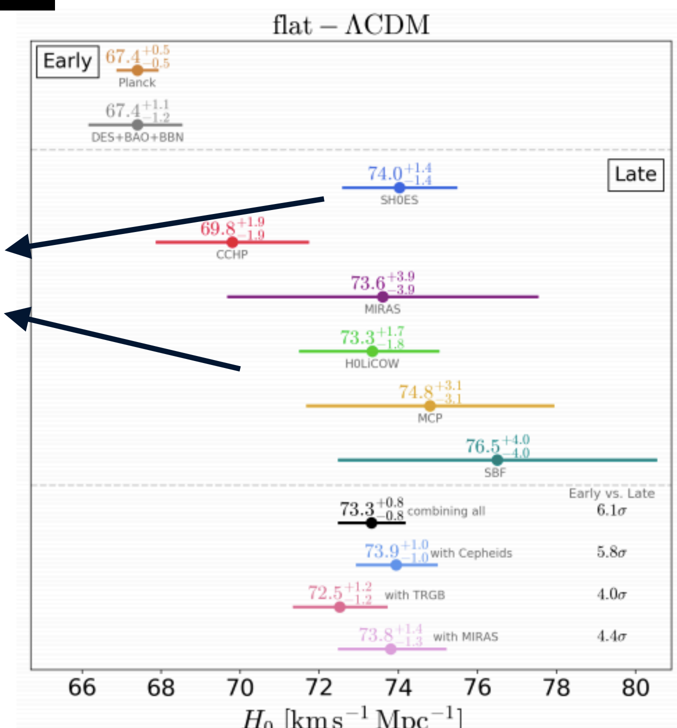
Need independent checks

Different calibration of distance ladder

Completely different absolute distance measurement (e.g. time-delay distances, standard sirens)



INDEPENDENT METHODS!



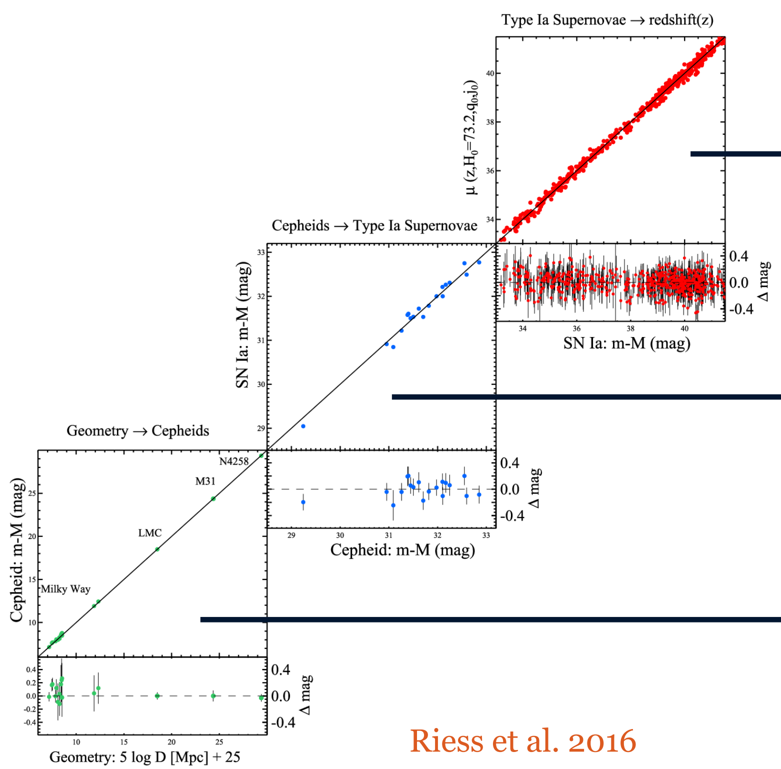
Verde et al. 2019

Plot courtesy: V Bonvin https://github.com/shsuyu/H0LiCOW-public/tree/master/H0_tension_plots centre

Local Distance Ladder

- Type Ia supernovae: Hubble flow (0.03 < z < 0.15)
  - Calibrated with Cepheid distances (19 galaxies -> 38! Next Year(?)
  - Cepheids calibrated with five independent anchors
    - LMC Detached Eclipsing binaries
    - Maser distance to NGC 4258
    - 3 independent methods for Milky Way Parallaxes

Method improved for decades.
Independent calibrators



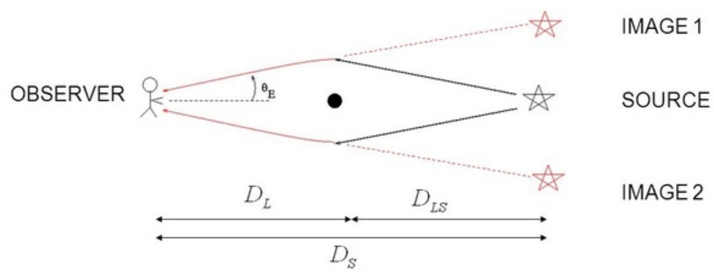
Riess et al. 2016

~ 200 Type Ia supernovae

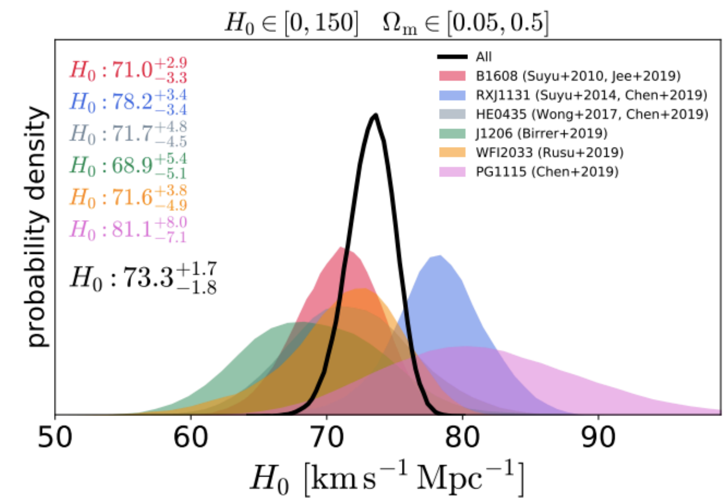
19 Cepheid distances to SN hosts

Calibrate Cepheids:
Gaia DR2, HST Spatial Scanning,
HST FGS, LMC DEB, Water Masers

Time-delay cosmography



Wong et al. 2019

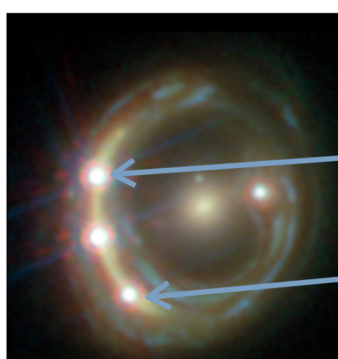


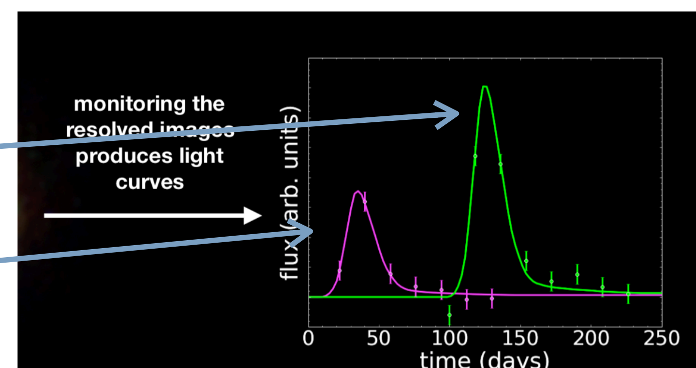
- 6 lensed quasars
  - Doubles and quads
  - 2.4% measurement of H_0

- High angular separation ==> possible bias to high H_0? (Collett & Cunnington 2016)

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

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





Local H_0: Role of dark energy

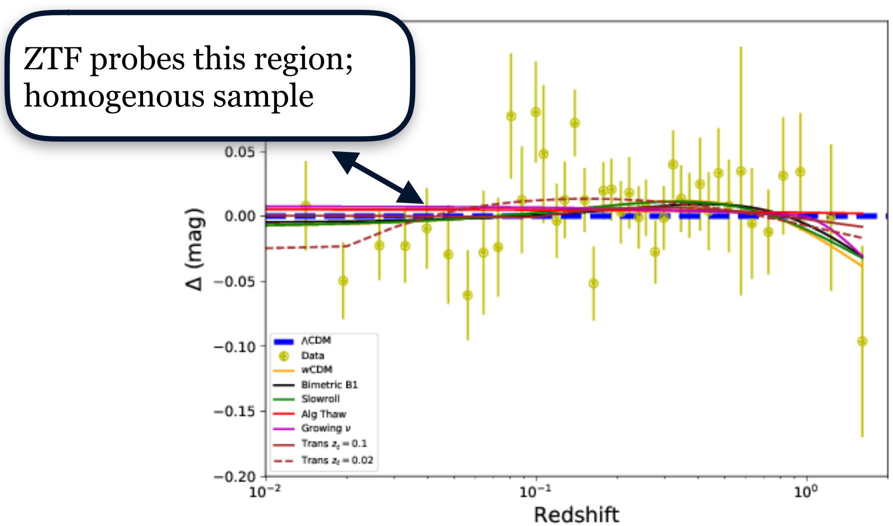
Impact of dark energy model

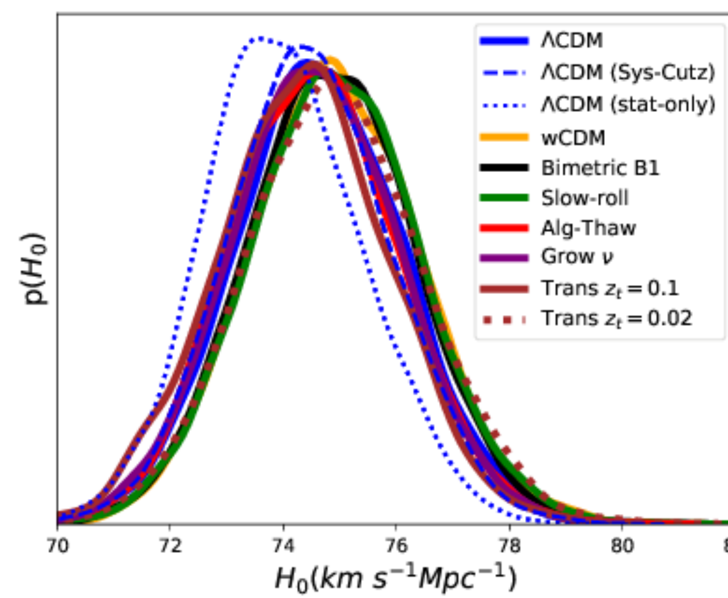
Accounting for covariance between calibrators and Hubble flow SNe

- Modelling different sources of systematics (Scolnic et al. 2018; Brout et al. 2019)
  - Host galaxy - luminosity correlation
  - Photometric calibration
  - Intrinsic scatter model

Shift in H_0 ~ 0.6 km^{-1} s^{-1} Mpc^{-1}
SN Ia systematic error ~ 0.8 km^{-1} s^{-1} Mpc^{-1}

Dhawan, Brout, Scolnic et al. 2020c





See also, complementary constraints in Benevento, Hu, Raveri 2020

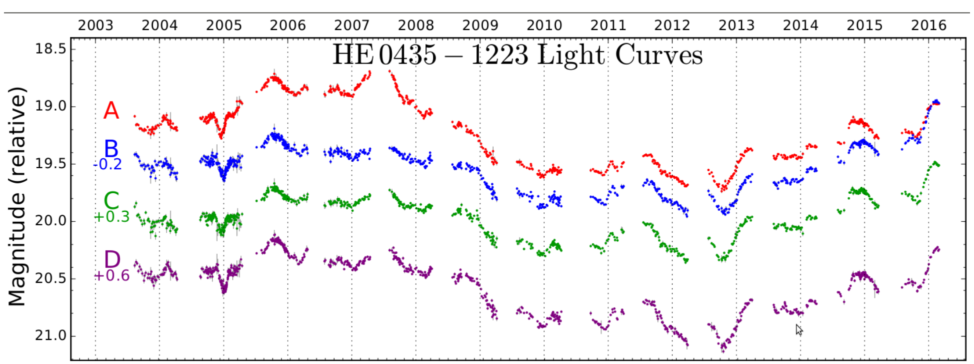
Strongly lensed Type Ia supernovae: Novel probe of H_0

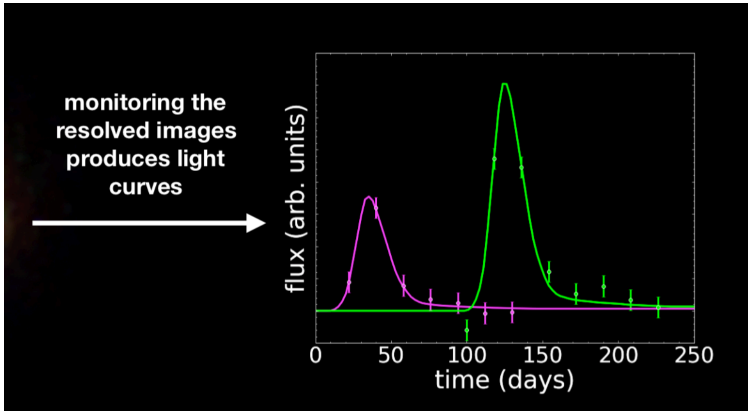
Why lensed SNe?

- Lensed SNe are rarer => proposed in 1964, first discovery in 2015!!
    - Many lensed quasars discovered, followed-up

Benefits of SNe Ia

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





Typical lensed QSO and SN light curves

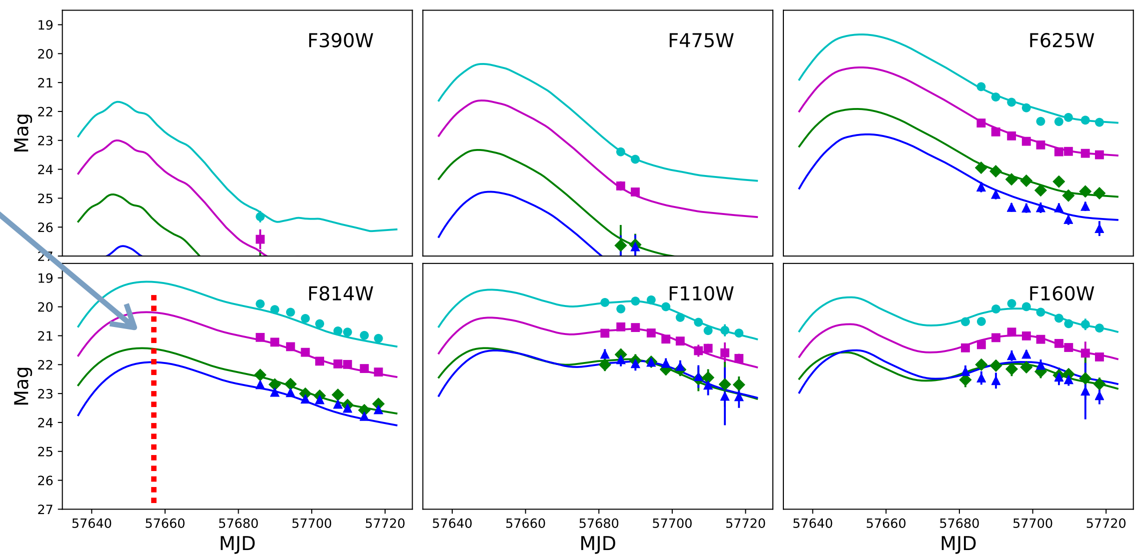
Time delay Estimation

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

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

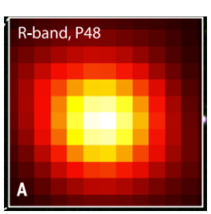
Max. light simulations
=> five times smaller error

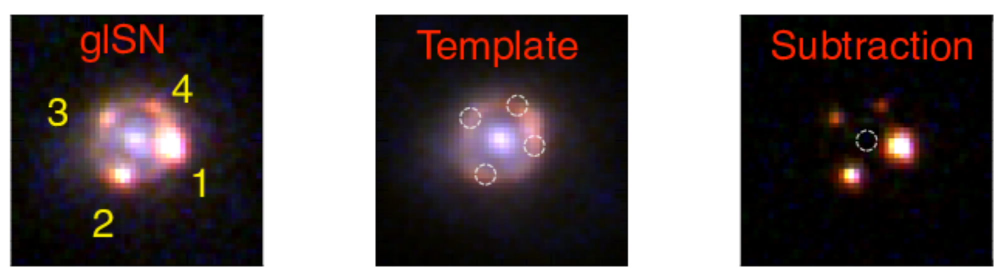
Model independent approach with
NIR second max => consistent Δt



Individual light curves for the resolved images of iPTF16geu (Dhawan et al.2020a)

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





Magnification + extinction

Surprisingly high magnification (μ), if coming from galaxy lens alone!

In general relativity, P(μ) ∝μ^{-3} +selection effects. (E.g., μ=5 happens 1000 more often, yet not seen)

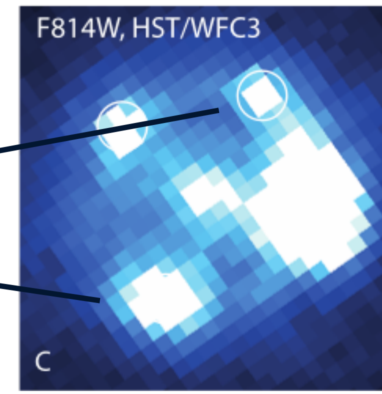
Is this a selection effect or something fundamental? ==> need more objects

Preliminary magnification (μ) ~ 52

With extinction correction 67+/-3

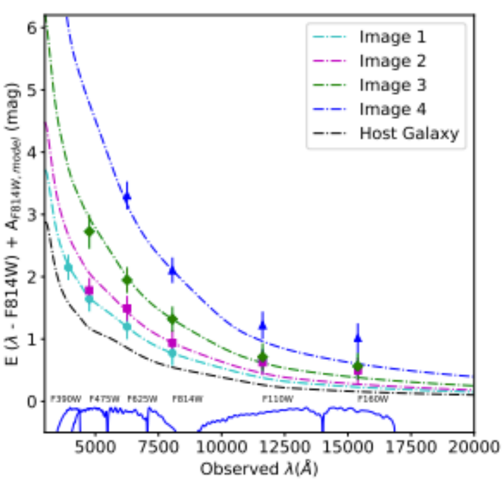
Hence, important to get multi-band, resolved photometry

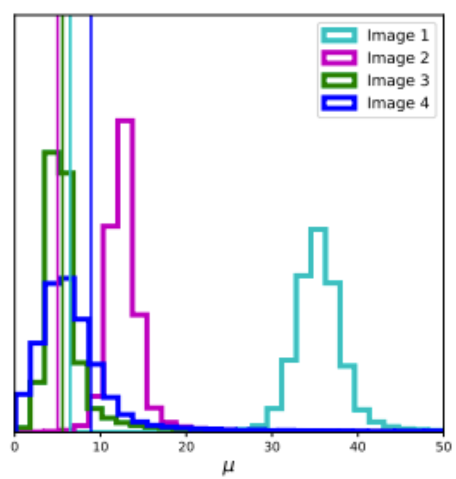
Surprisingly different brightness?

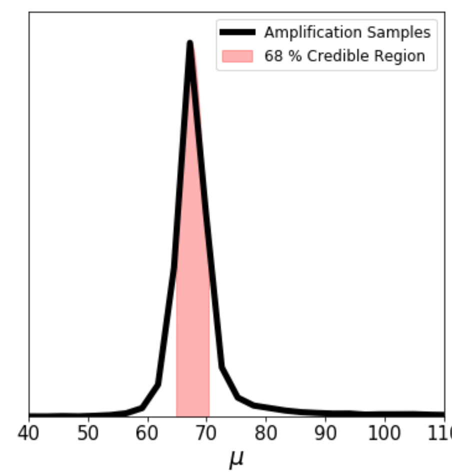


Extinction estimates for 4 LoS in z ~ 0.2 galaxy

Dhawan et al. 2020

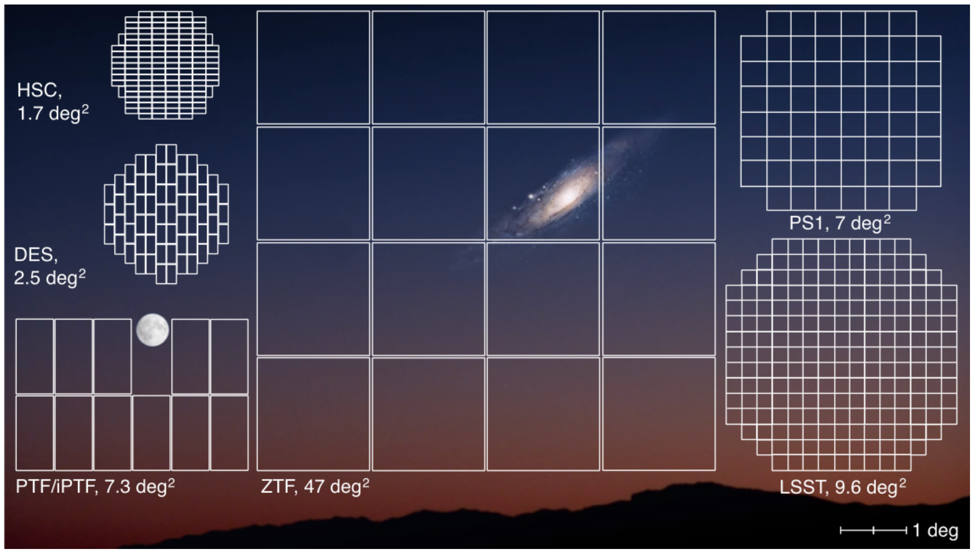






ZTF: Type Ia supernova Hubble diagram
+ Lensed SN search

ZTF: Status Update

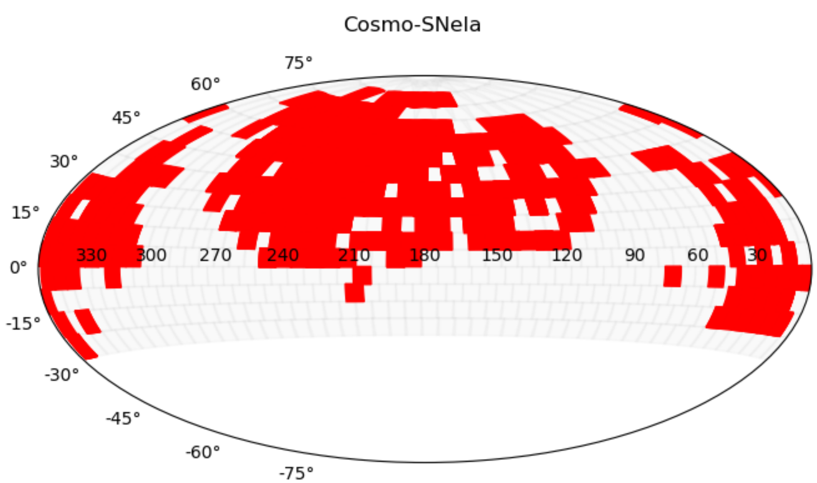


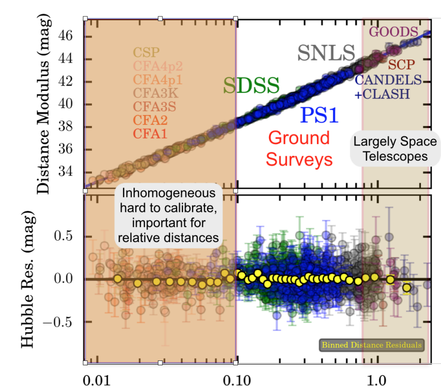
15 X scanning compared to iPTF
~ 1700 'normal' Type Ia supernovae
10 * current literature sample

Single system search + follow-up
- Minimise calibration systematics
- Untargeted; quantify selection bias

Data spans **even** beyond SN model
- Use to retrain model
- Well-sampled rise time

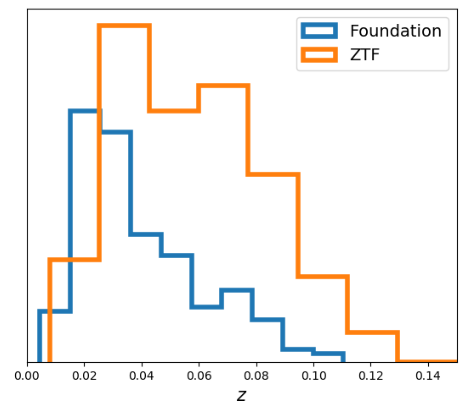
Probe large scale structure
Complete sample -> directional H_0



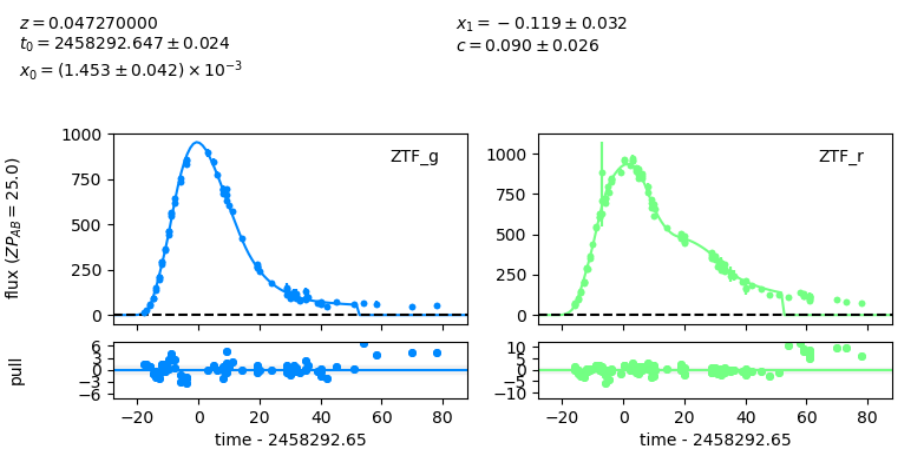


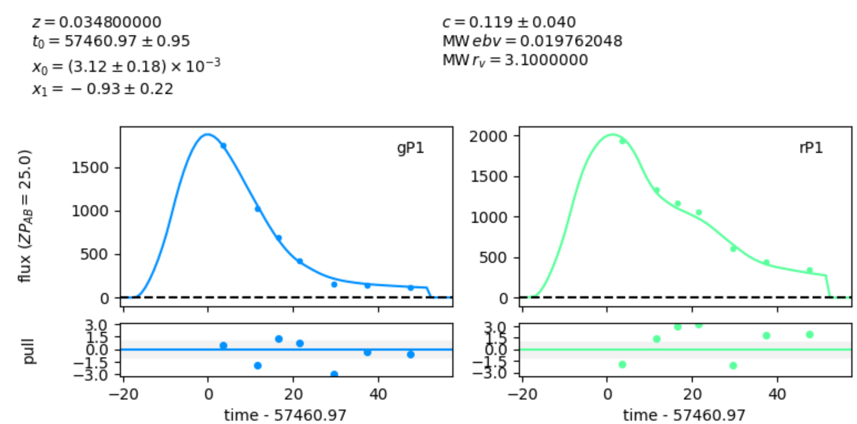
Year 1 sample

- 800 SNe Ia, 300 with host redshift "gold sample"
  - Already greater than all existing low-z anchor sample combined
  - Data extends beyond current SN Ia "SALT2" model (example: bottom left SN)
    - Critical to improve the model
    - Late time data can also constrain SN physics
  - Caught extremely early compared to literature sample
    - Uniquely test new standardisation techniques
- Median redshift is ~ 2 * literature sample
  - Lower impact of peculiar velocity errors



Example light curve from ZTF extending beyond the SALT2 model (left) and Foundation (right)

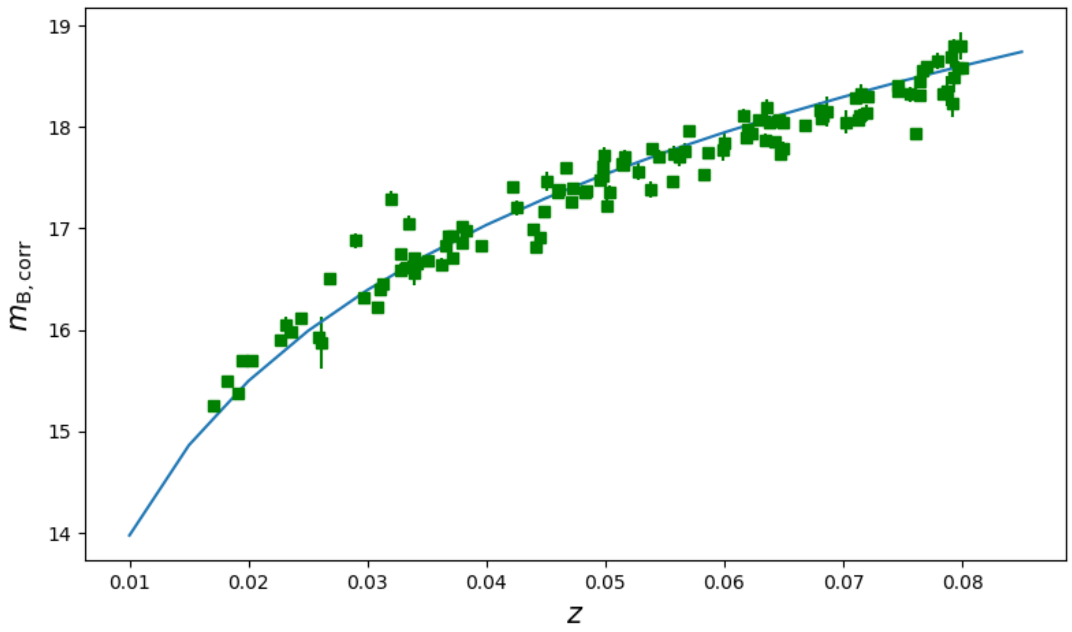




Preliminary Hubble Diagram

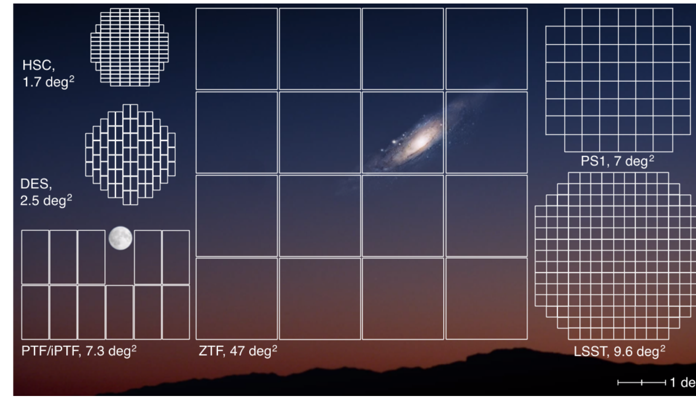
- fit the empirical SALT2 SNIa model
    - Error dominated by model covariance
- Standardise the peak luminosity
    - Fit for intrinsic scatter
    - Blind to other cosmological + SN parameters

- σ_{rms} < 0.15 mag, smaller than the literature sample



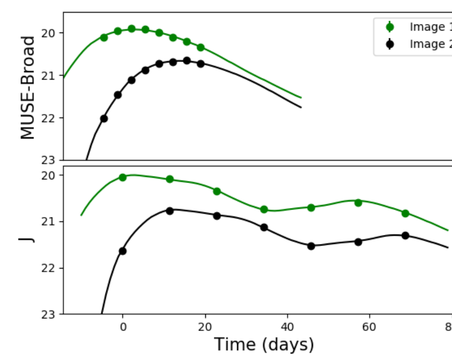
Dhawan et al. in prep

ZUDS: Searching for glSNe

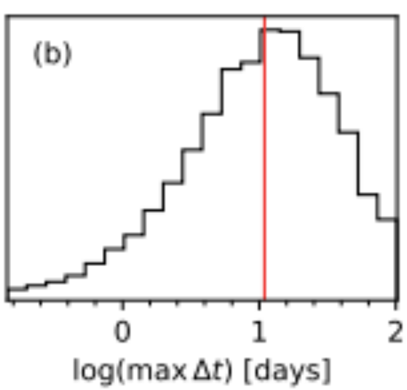


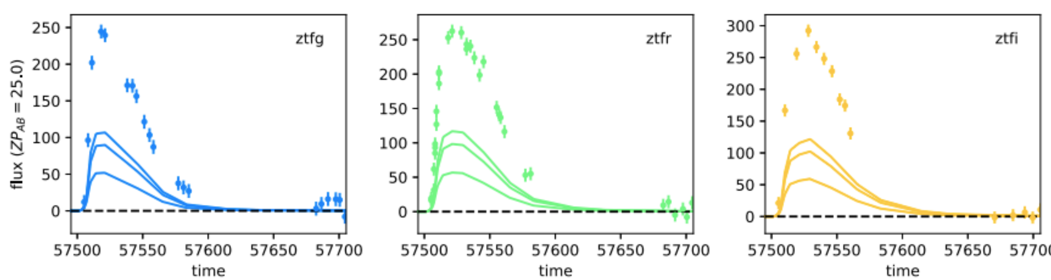
- 45 ZTF fields: ~ 2100 sq. degrees
  - g,r,i,i,g,r every clear night to 20.5 mag
  - Weekly stacks to ~ 21.5 mag; deeper for clearer weather
  - Novel image processing pipeline (D. Goldstein)

- Aim to find few glSNe
  - Classification with P60, P200, Keck
  - High resolution imaging /spectroscopy with Keck, VLT



Expected distribution of time delays + expected light curves for ZTF glSNe Ia





Summary + Outlook

- Local distance ladder H_0
  - Insensitive to assumed cosmological model
  - Testing host galaxy correlations with ZTF

- First multiply imaged, resolved lensed SN Ia
  - Magnification insensitive to assumptions on extinction
  - Can measure extinction in each line-of-sight
  - Time-delays too small for H_0 inference

- ZTF has observed ~ 1700 SNe Ia in 3 filters
  - Test the role of SN Ia environments
  - Year 1 sample studies ongoing

- Ongoing and future searches for glSNe
  - ZUDS preparation ongoing

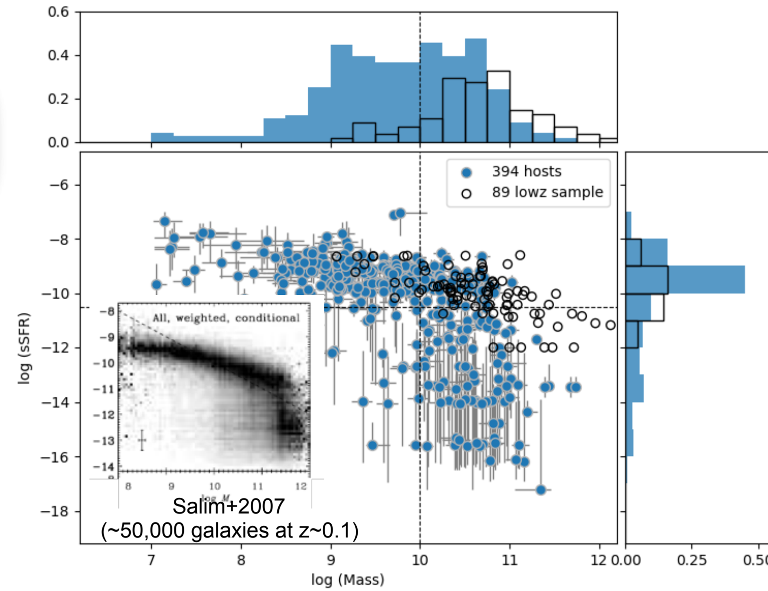
Outstanding SN Ia systematics

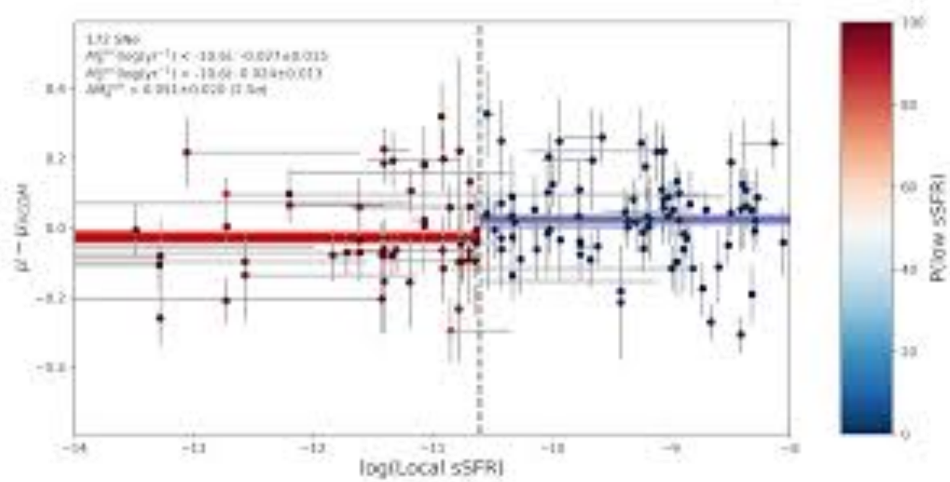
Oskar Klein centre

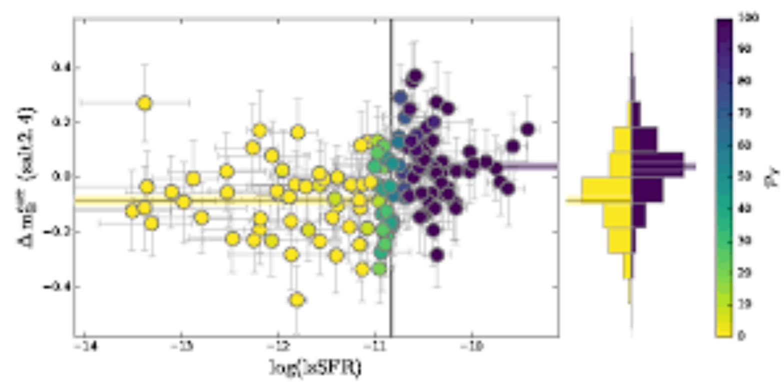
Is SN luminosity dependent on host galaxy properties?

Does the correlation bias H_0 and dark energy inference?

ZTF probes underlying distribution of host properties





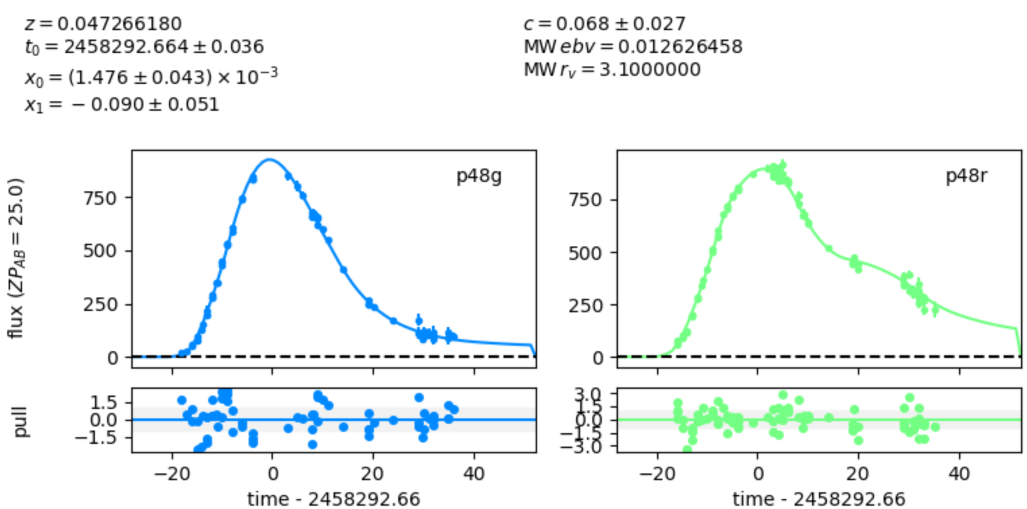


Jones et al. 2018; Rigault et al. 2019

Year 1 Cosmology sample

300 SNe with host-galaxy spectroscopic redshifts
3 day cadence g+r band observations; 4 day cadence i-band over 6700 deg2
Subsample have high-cadence g+r observations

- Custom made pipeline to reprocess photometry
  - Deeper reference image, higher quality subtractions, more

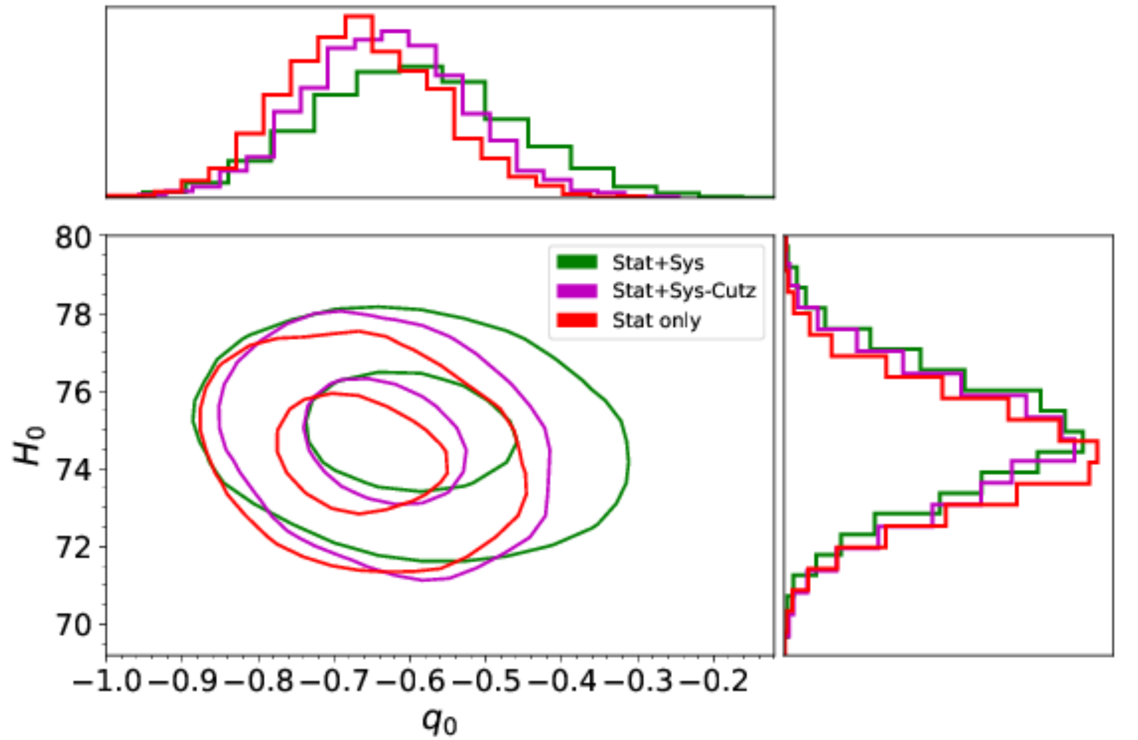


Cosmographic Expansion

- No assumption on energy densities
  - Expand H(z) in redshift
  - Simultaneous fit for q_0 and H_0

- $q_0 = -0.59 +/- 0.14$
  - Consistent with standard value of -0.55

Dhawan, Brout, Scolnic et al. 2020c



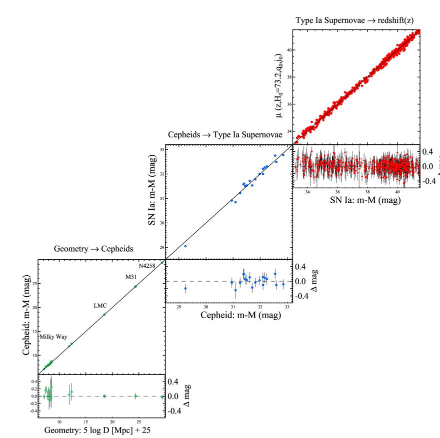
Impact of dark energy model

Fiducial Analysis (e.g. Riess et al. 2016, 2019; also holds for other secondary calibrators, e.g. TRGBs)

- $z < 0.15$ SNe Ia ==> ~ linear regime of Hubble diagram
- Assumed cosmology: $q_0 = -0.55$ (from high-z SNe, hence, not completely independent)
- No covariance accounted for between calibrator and Hubble flow SNe Ia

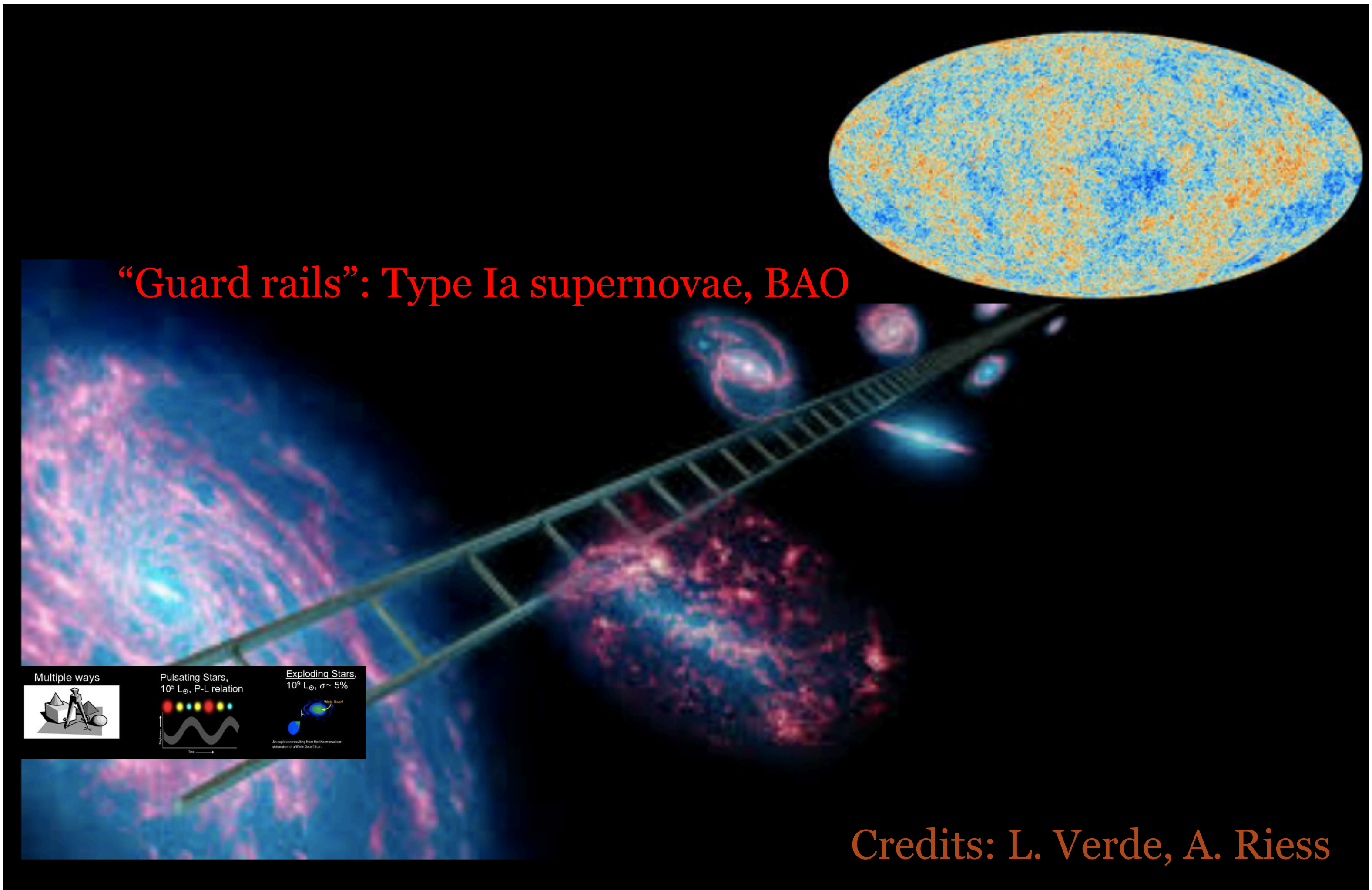
Q1: What is the impact of the cosmological model assumption?

Q2: What is the impact of covariant systematics between rungs?



Why measure H_0?

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



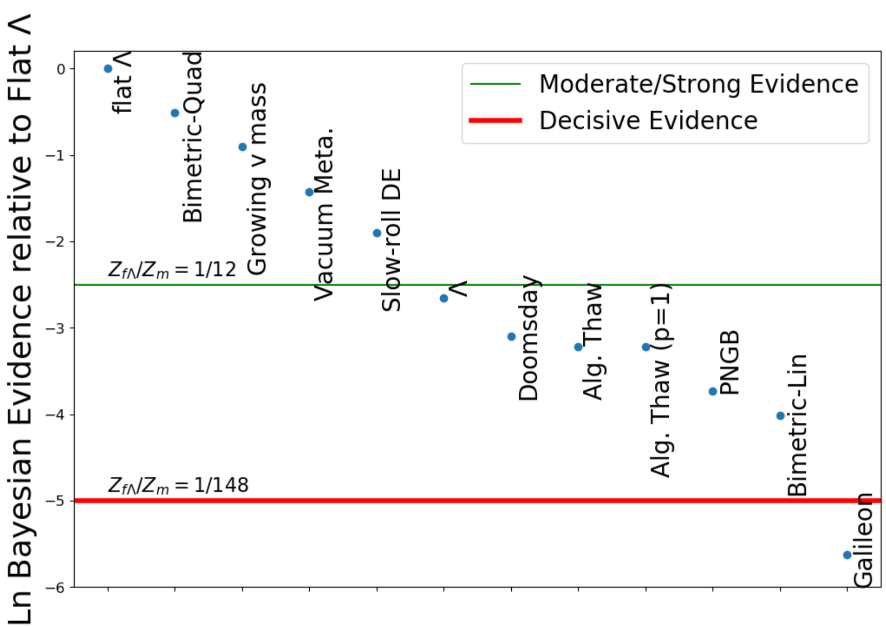
Standard Sirens: Breaking distance-inclination degeneracy

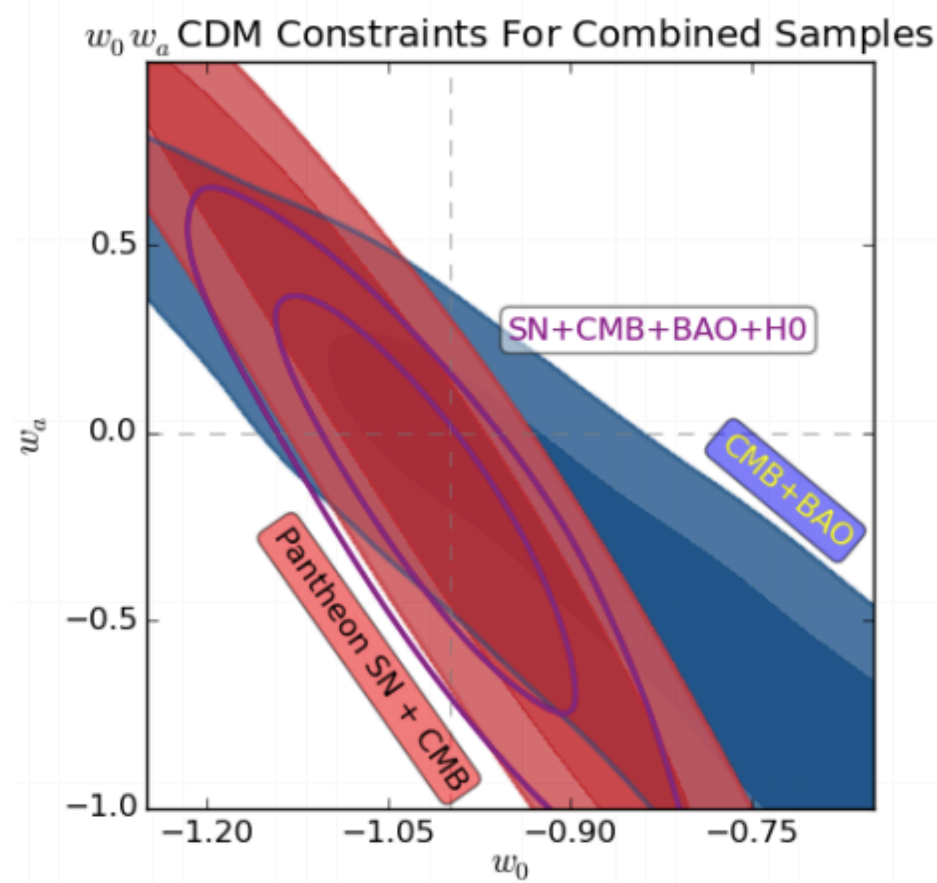
Why other dark energy models?

Exotic dark energy not excluded; many models predict observables well

Does non-standard model assumption affect H_0?

Dhawan et al. 2017b





H_0 from standard sirens

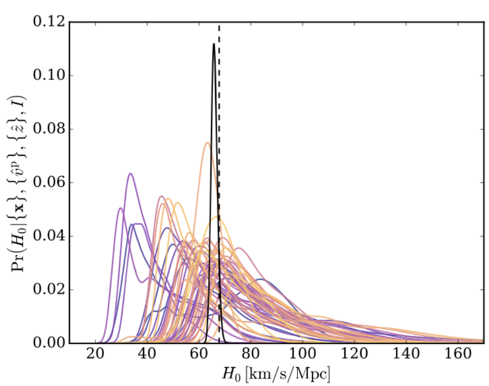
$$v_H = H_0 d$$

EM transient => Host galaxy redshift

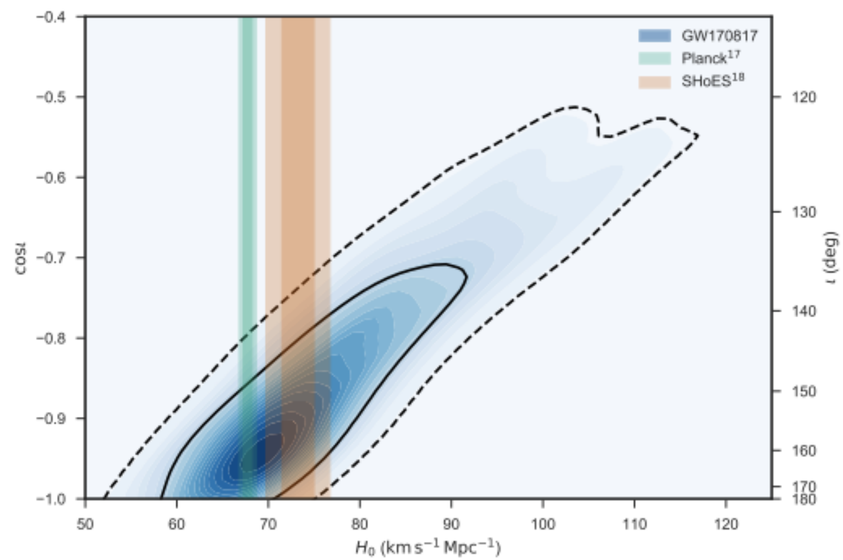
GW distance

Completely independent of calibration

- Forecast ~ 2% with ~ 50 events
  - Currently only 1 event
  - Luminosity distance degenerate with inclination
  - Rates are uncertain



Feeney et al. 2019

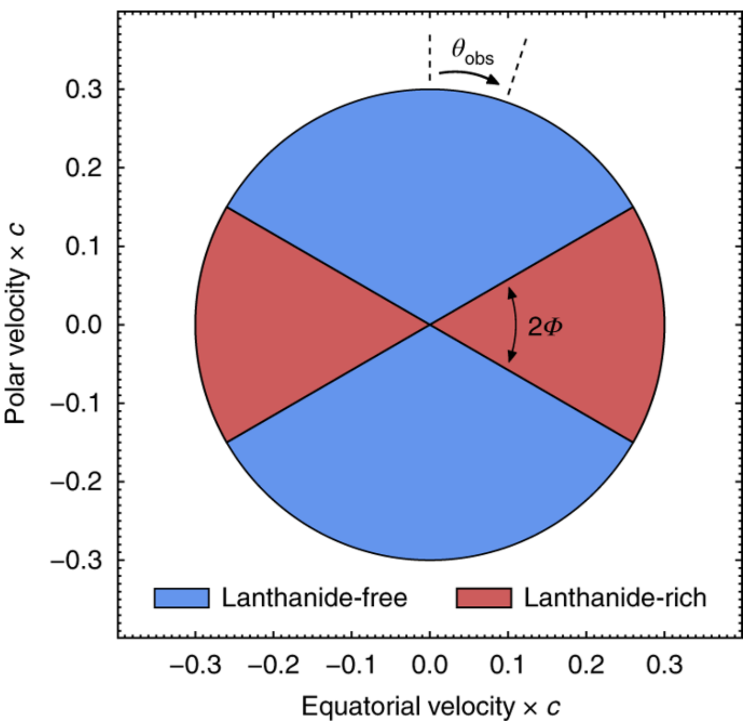


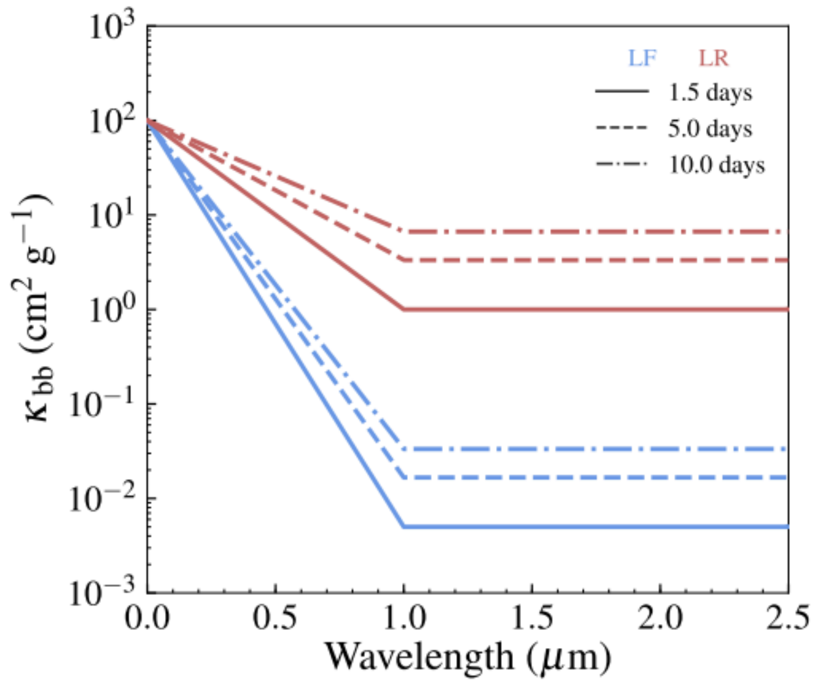
Abbott et al. 2017

Kilonova ejecta models

- Two component model describes GW170817
  - Explosion physics motivated
- Parametrized opacity from Tanaka et al. 2018
- Computed finer grid in ejecta parameters
  - Marginalised over ejecta mass, half-opening angle, temperature

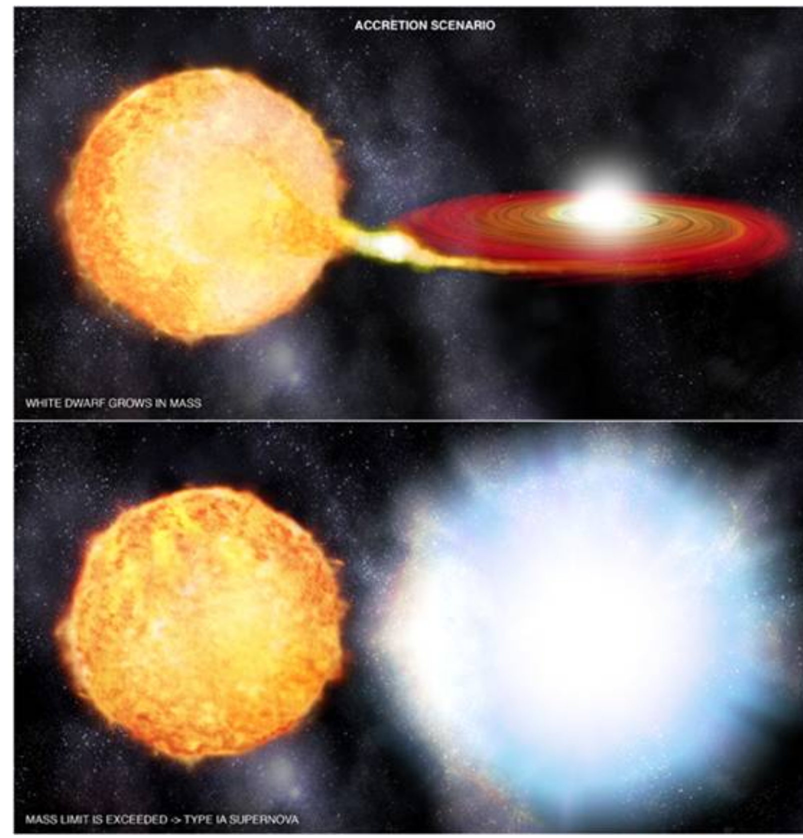
Bulla 2019





Why Type Ia supernovae?

- Bright explosions ==> Seen far away
- Can be standardised to low scatter
    - Heterogeneous optical display
    - Empirical relations to calibrate



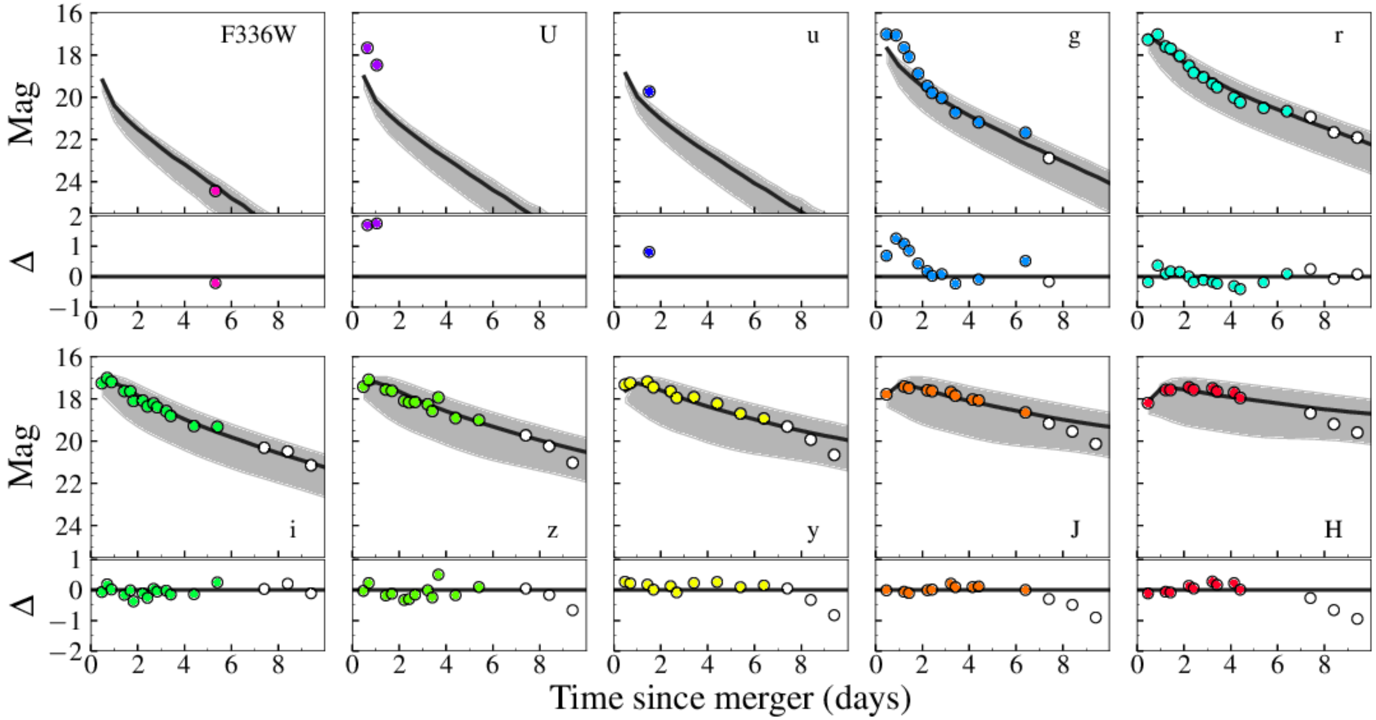
- NOT an absolute distance => needs calibration
- NOT a standard candle => needs correction

Coherent framework for dark energy + H_0; needs systematics quantified

Constraining the observer angle

- Total of 2200 models (adapted from Bulla 2019)
  - Fitted to AT2017gfo photometry: UV to NIR coverage
  - Most sensitive to NIR data

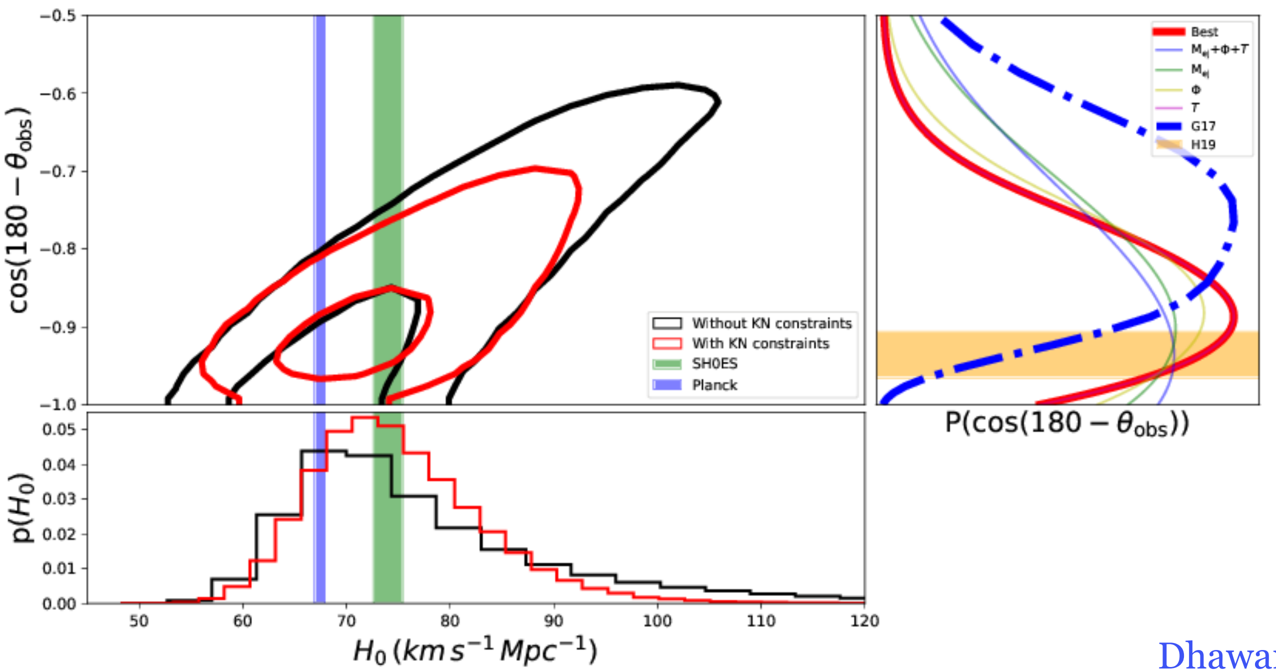
Parameter	Range	Step	Best fit
M_{ej} ($M_\odot$)	[0.01, 0.1]	0.01	0.05
T (K)	[3000, 9000]	2000	5000
Φ(°)	[15, 75]	15	30
$\cos(\theta_{obs})$	[0, 1]	0.1	0.9



Dhawan, et al. 2020b

Combined EMGW H_0

- EMGW sources: Distance ladder independent H_0
  - Degeneracy with inclination
  - Independent EM constraints
  - Improvement of 25%
- Consistent with VLBI constraints
  - Promising route for LIGO O3/O4 events



Dhawan et al. 2020b

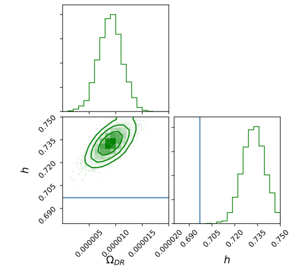
Novel Cosmology?

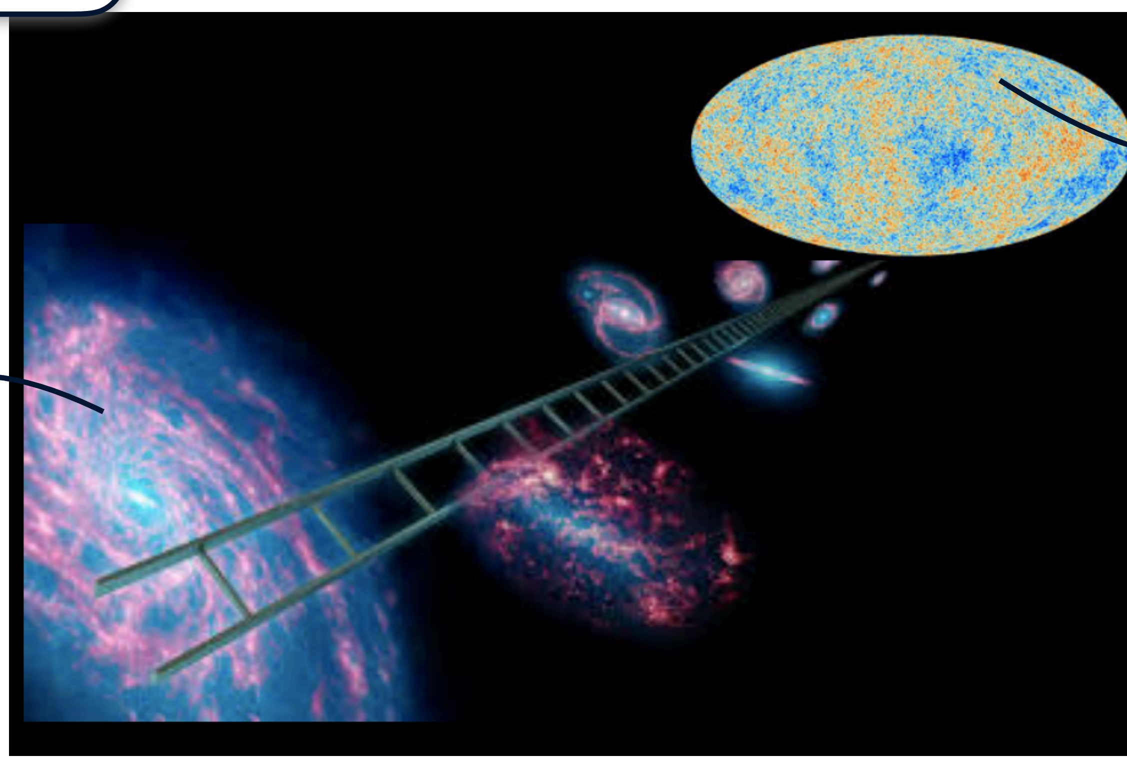
No clear theoretical model, yet

Could it be unknown systematics?

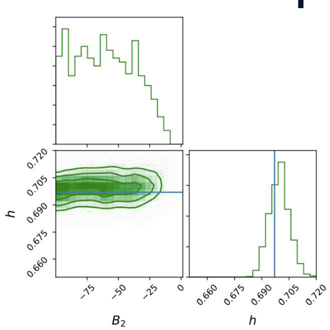
Independent methods needed

Early universe => Could be?
No physically consistent model works





Late universe ->> Λ

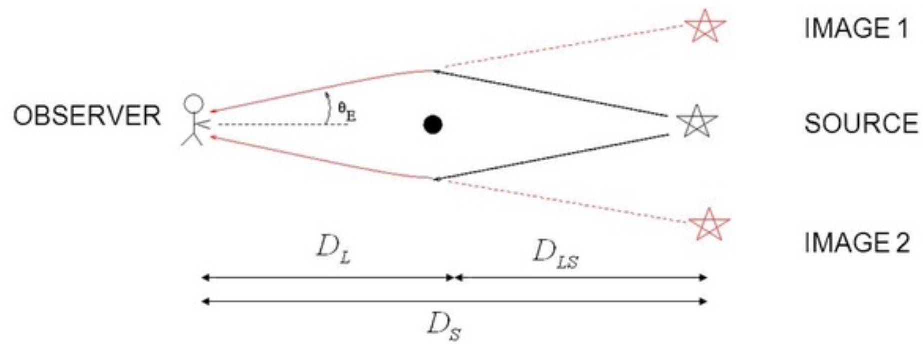


Mortsell & SD, 2018, JCAP
see also Bernal+2016, JCAP, Poulin+2019 PhRvL; Kreisch+2020, PhRvD

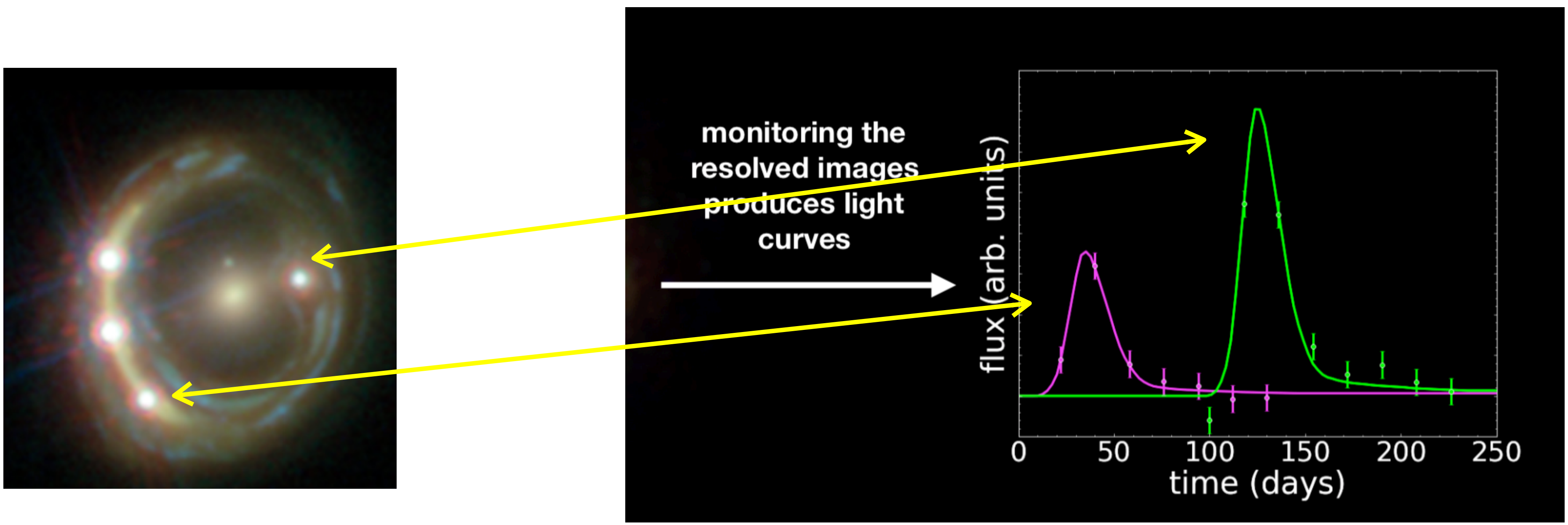
Standard Clocks: Strongly lensed Type Ia supernovae

H_0 from Time-delay distances

- Favourable alignment ==> multiple images
  - Time-delay + lens model => H_0
  - Independent of cosmic distance ladder
  - Lensed transient: Quasars are abundant



$$\triangle t \sim (\triangle\theta)^2 (H_0)^{-1}$$



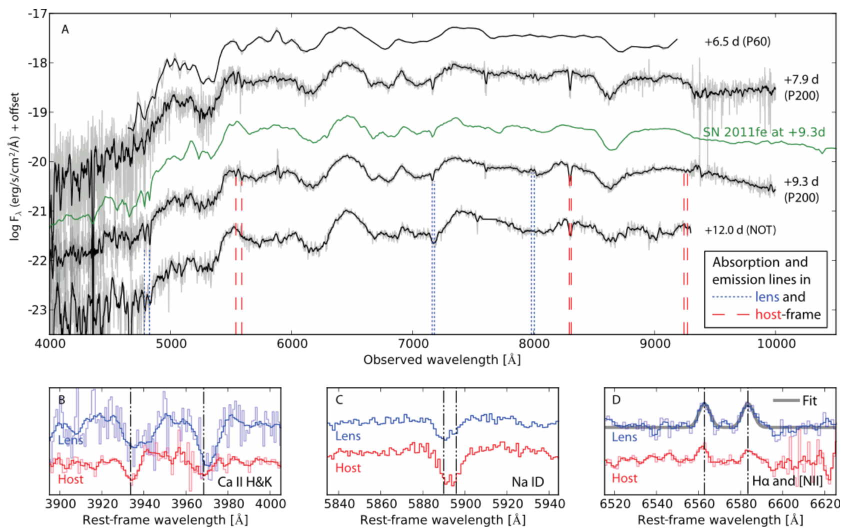
H_0 from time-delays, proposed by Refsdal 1964

Discovery of iPTF16geu

Oct 2

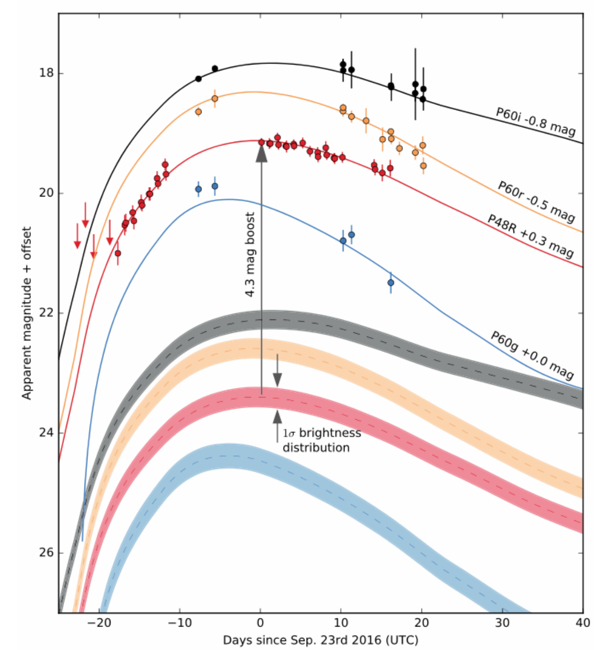
"Typical" SNIa redshifted to z=0.409

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

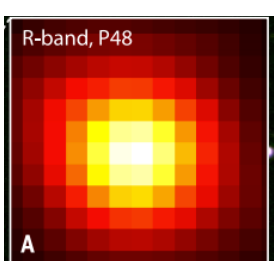


>50 times brighter than normal SNIa at z~0.4: a 30σ outlier!

Goobar+ 2017



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

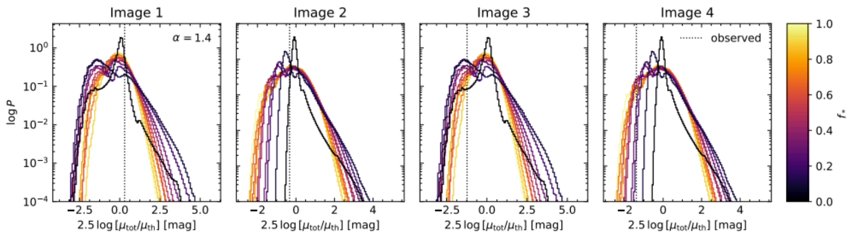


P48 image of 16geu; multiple images not resolved

Backup Slides

Discrepancy with models?

- Image brightnesses differ
  - Lens model predicts similar brightness
- Differential extinction
  - Image 4 heavily extinguished
  - 6 x fainter than Image 1 *after* correction
- Microlensing consistent with corrected luminosity



Mortsell et al. 2020 submitted

Updated microlensing probabilities in Mortsell et al. 2020
STAY TUNED!!

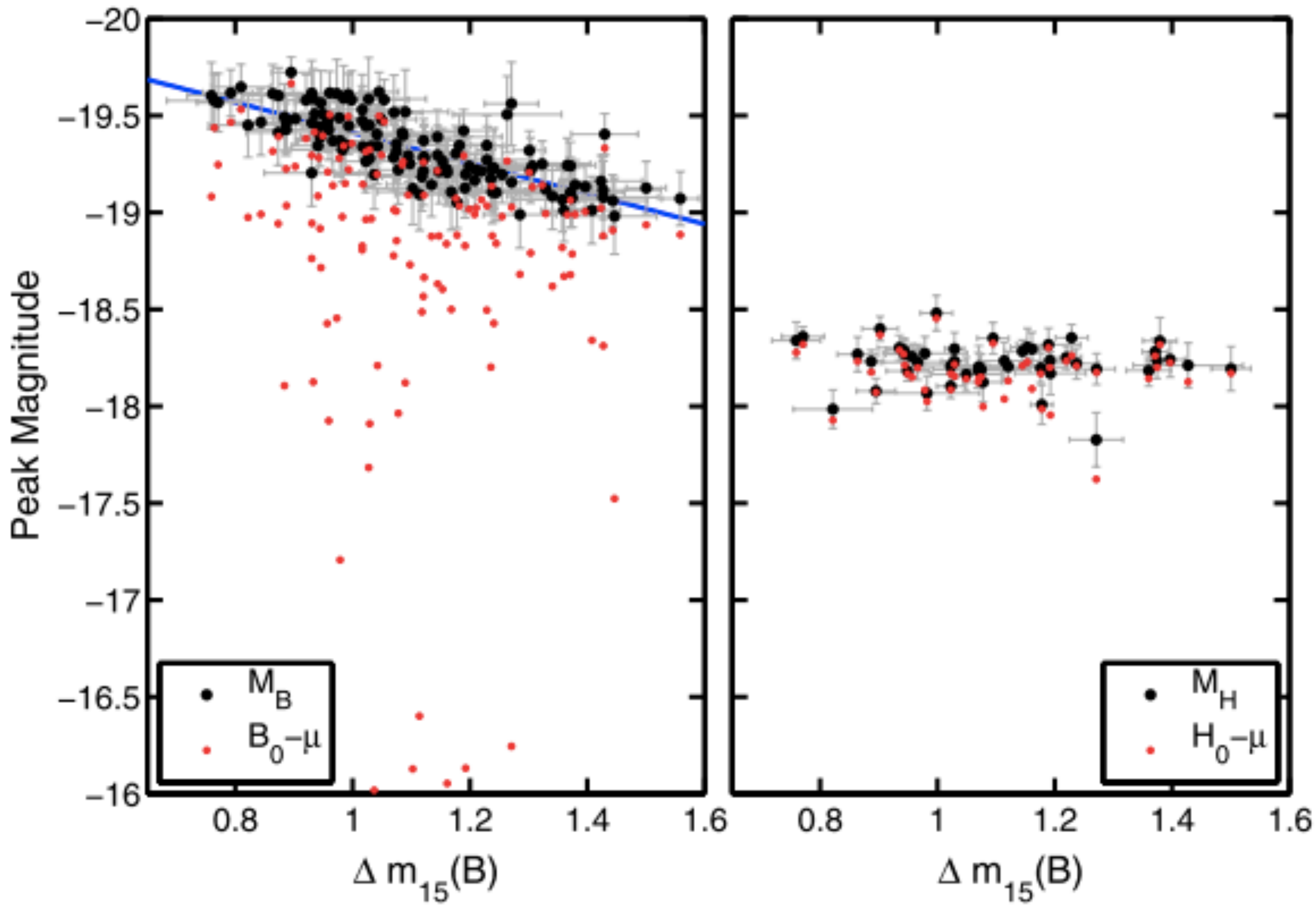
Part I: Summary

- Local distance ladder systematics
  - NIR H_0 agrees with optical: Dust, intrinsic scatter subdominant
  - NIR has small statistical errors ==> important complement for the future

- Covariance between calibrators and Hubble Flow SNe
  - Assumed dark energy model shifts $H_0 < 0.6\%$
  - SN systematics may cause small shifts ($< 0.8\%$)
  - Constraints on q_0 consistent with standard cosmology
  - No strong evidence for low-z transitions

Why the NIR?

- Reduced extinction from host galaxy dust
- Lower luminosity scatter

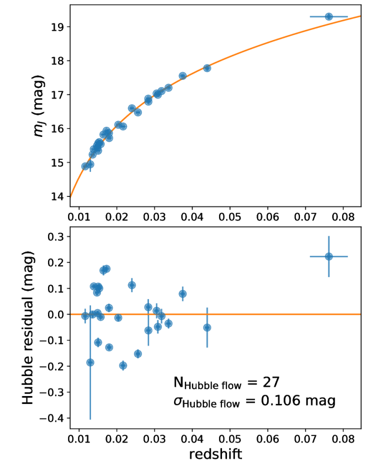


Mandel et al. 2011, CfA SN program

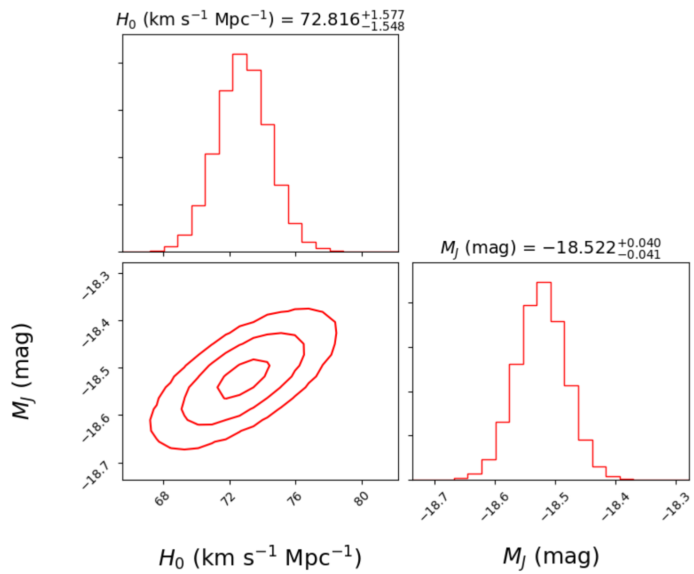
H_0 from the NIR

- Model independent light curve fits
- Combine the calibrators and Hubble flow
    - Calibrators: Absolute M_J
    - Hubble flow: M_J and H_0
    - Combination breaks degeneracy
- H_0 = 72.8 ± 1.6 (statistical) ± 2.7 (systematic) km/s/Mpc
- σ_{int} ~ 0.1 mag
- Consistent with optical H_0

(confirmed with larger sample, e.g. Burns et al. 201)



Dhawan et al. 2018a



Resulting posterior distribution of M_J and H_0 (Dhawan et al. 2018)

Systematics checks for H_0

Systematics checks: local H_0

- Cepheid systematics (Follin & Knox 2017)
- Bayesian hierarchical model (Feeney et al. 2017)
- Recomputed Cepheid distances (Cardona et al. 2017)
- Blind analysis (Zhang et al. 2017)

- SN Ia in the NIR (this talk; Dhawan et al. 2018a)
- Cosmological model in distance ladder (Dhawan et al. 2020, submitted)

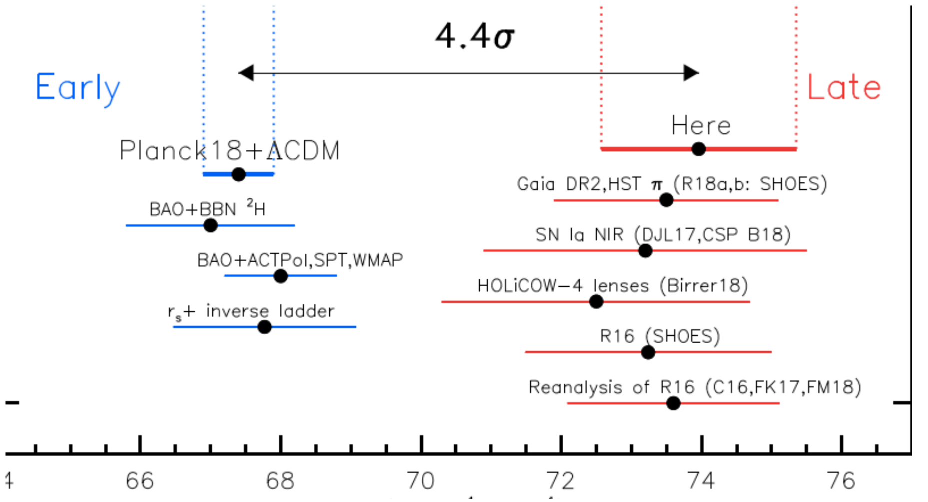
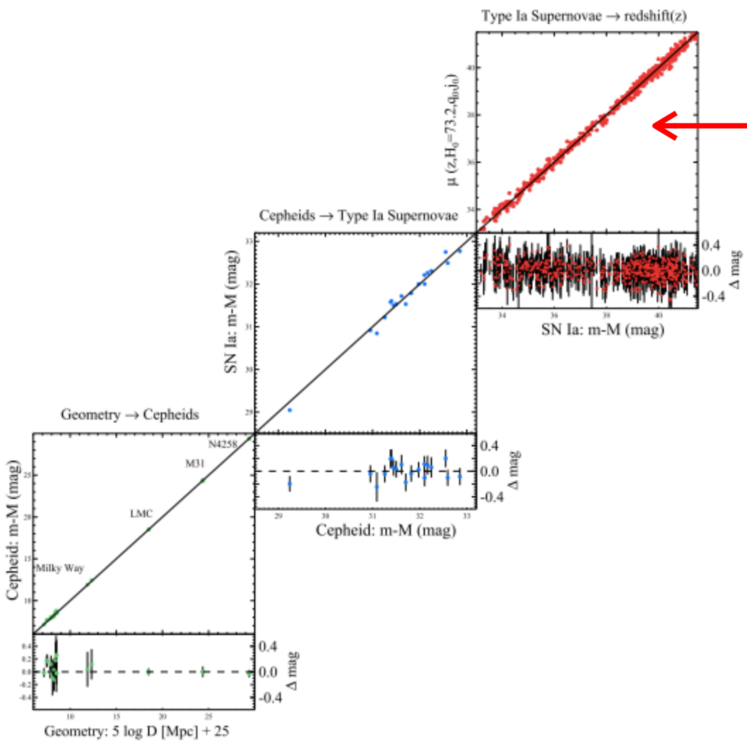
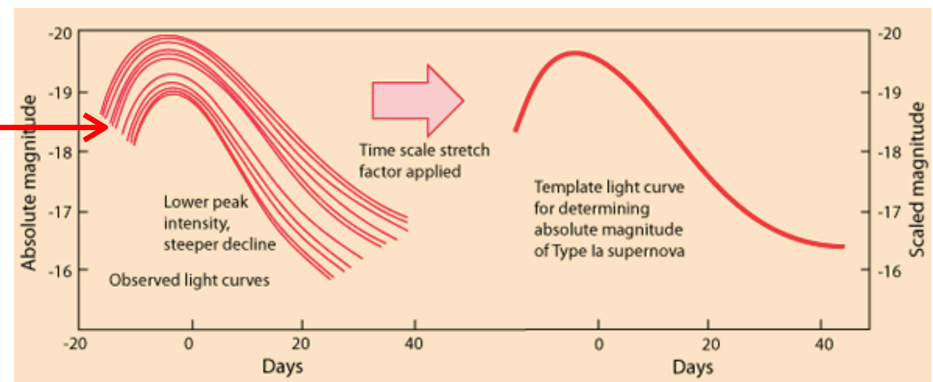


Figure:(Top) Systematics checks on H_0 inferred from the early universe and the local measurement (adapted from Riess et al. 2019).

Local distance ladder

- Optical peak luminosity needs to be corrected
    - Width-luminosity relation
    - Colour-luminosity relation
    - Correlate with properties of hosts





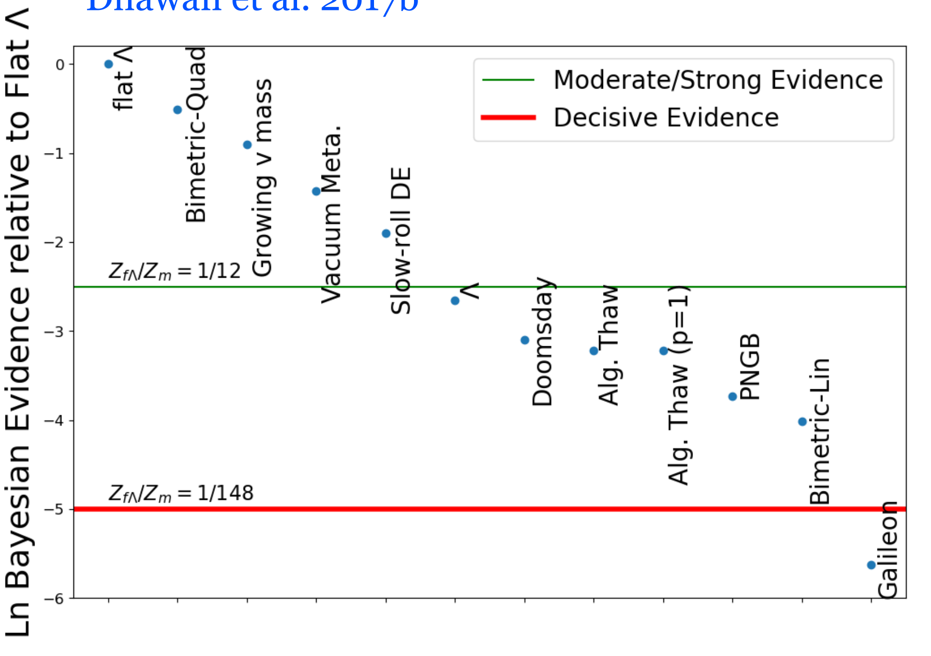
Exotic dark energy models

- Relax assumption on cosmology

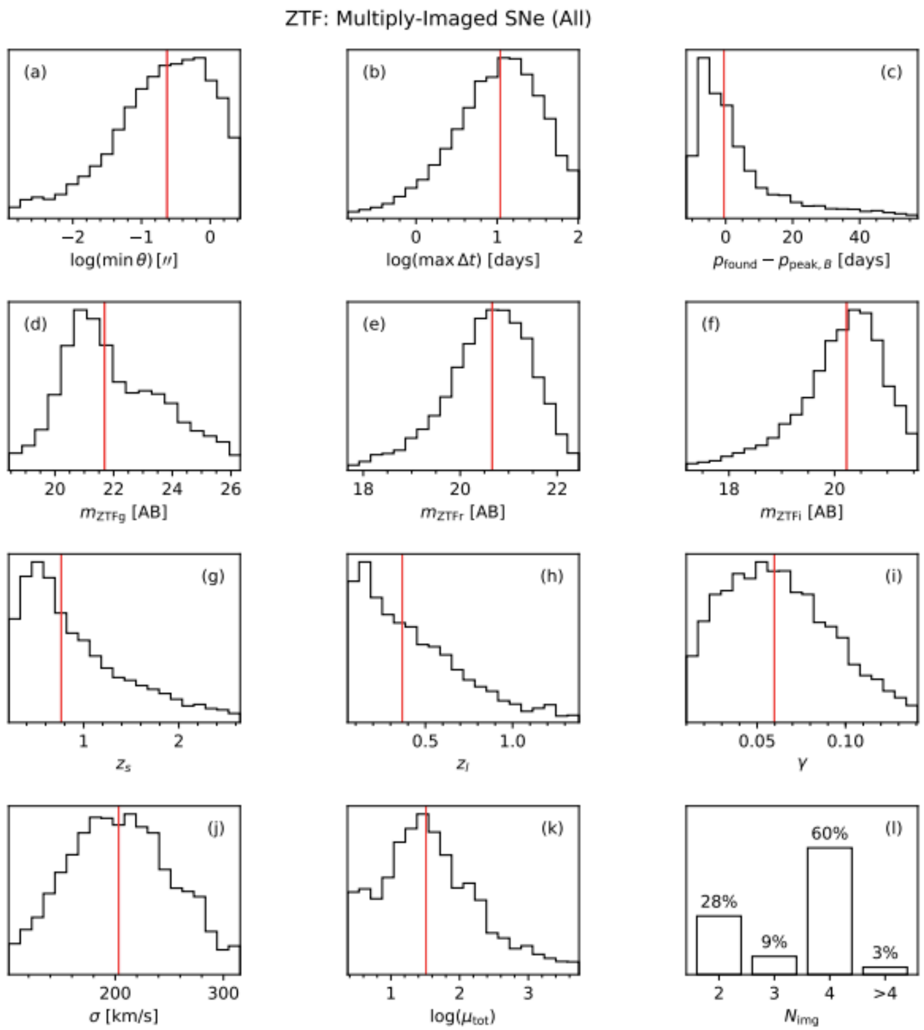
- Simultaneously fit for H_0 and dark energy
  - Use all **Pantheon** SNe Ia ($0.01 < z < 2.3$)
  - Calibrate to **SHOES** absolute magnitude

- Several different physical motivations (allowed by high-z data)
  - Modified gravity
  - Dynamical scalar fields
  - Low-z transitions

Dhawan et al. 2017b



Expected properties



Median ~ 10 day time-delay
~ 60% quads ~ 30 % doubles

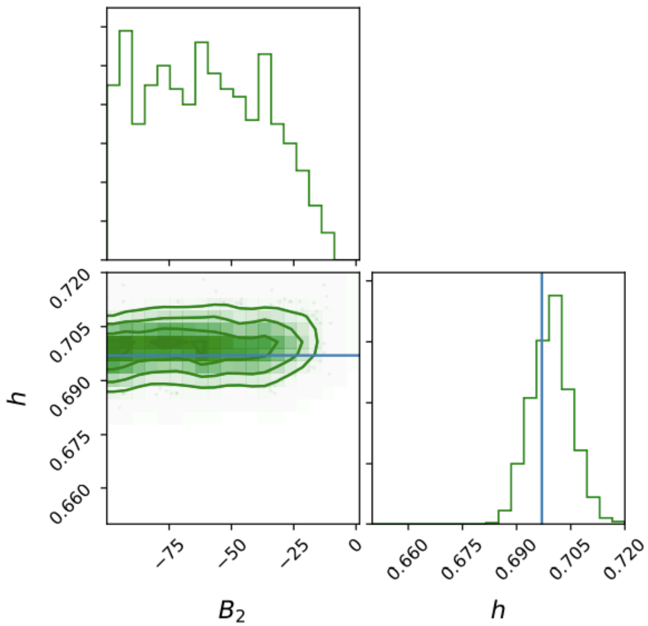
Goldstein et al. 2018

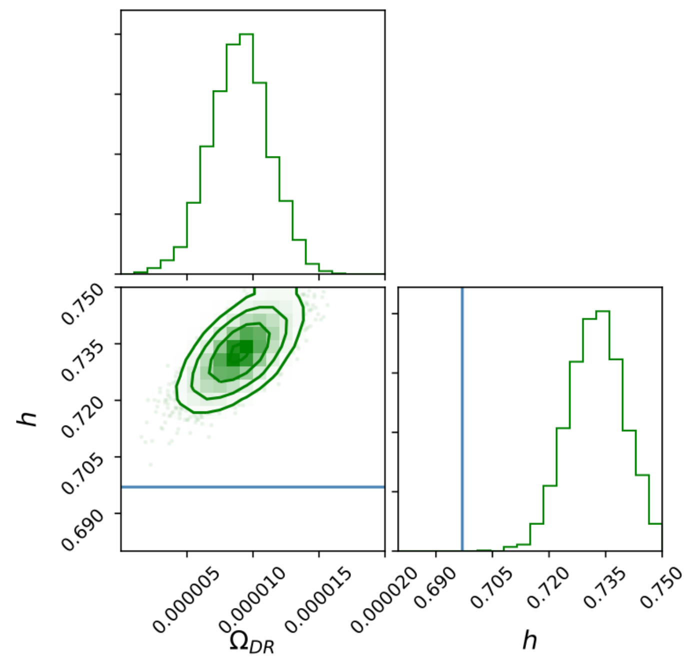
Finding glSNe with ZTF!

Fig Credit: J. Johansson

Is it an early universe solution?

- Late universe cosmologies converge to LCDM limit
- Early universe modification (see also Bernal et al. 2016, Lemos et al. 2018): e.g. radiation-like term
  - Alters sound horizon, gives larger inferred H_0





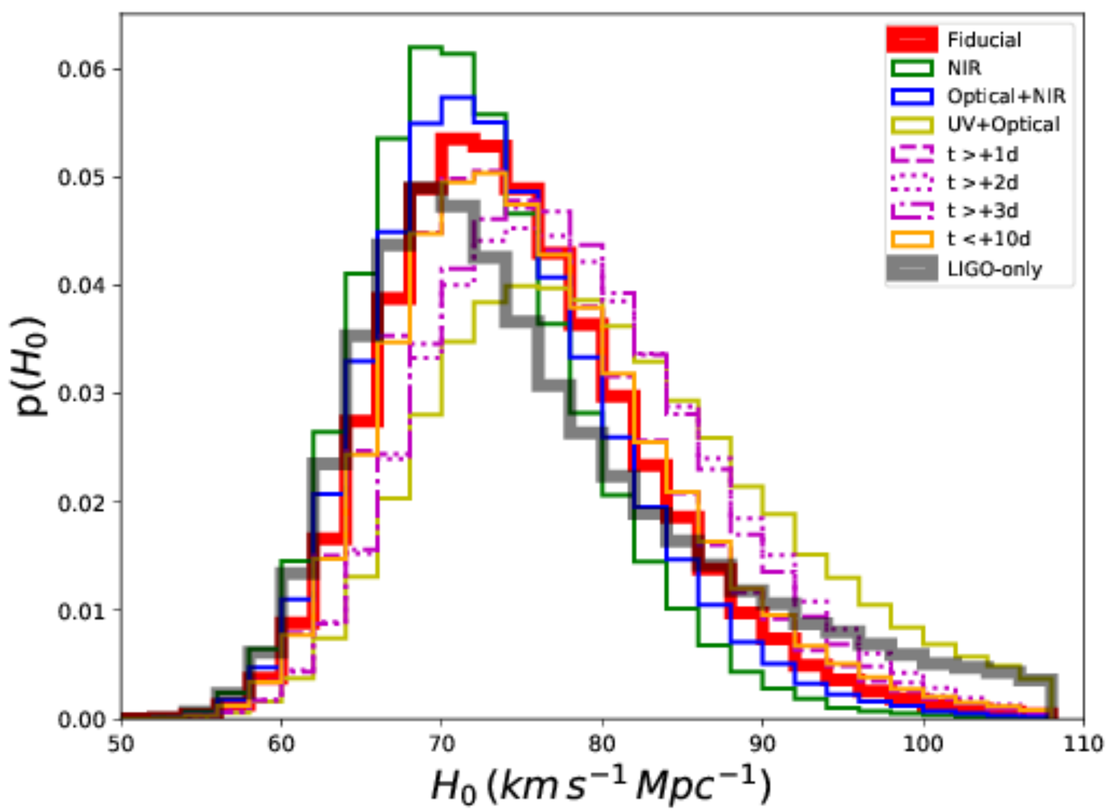
Mortsell & Dhawan, 2018

Testing the standard candle hypothesis

- Using Cepheid distances from R16
- J-band: single filter fits
- Direct fits to data: No templates
- Applying standard candle hypothesis (no corrections)

Figure: The calibrator and Hubble flow samples. The low intrinsic scatter validates the standard candle hypothesis (**Dhawan** et al 2018a)

Future kN observations

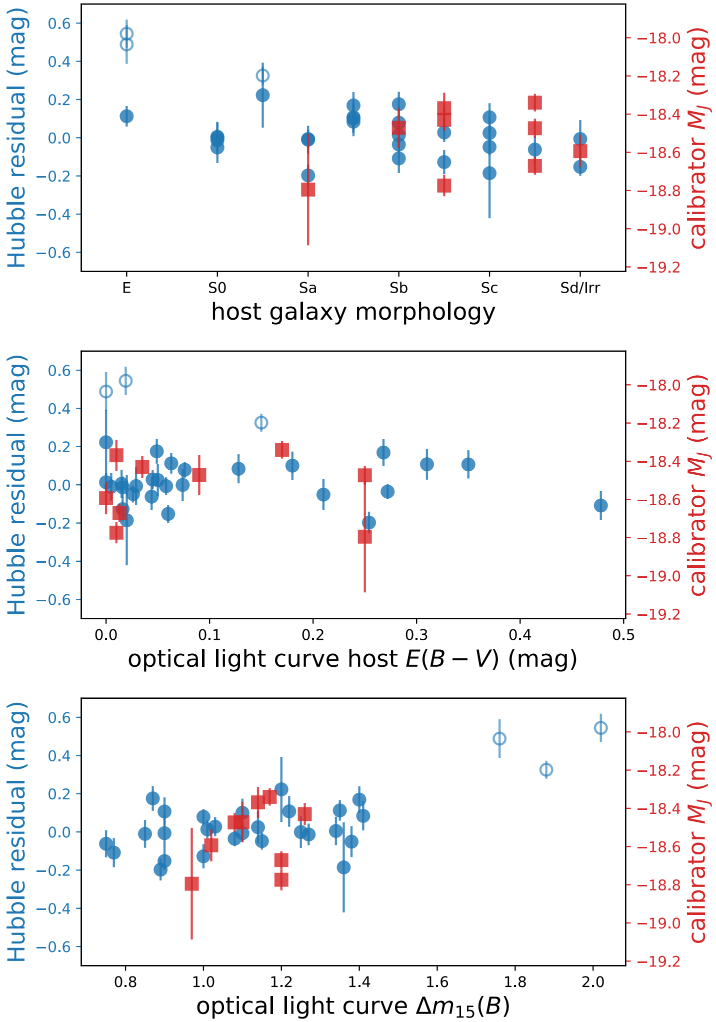


- Different wavelength ranges
  - NIR is most constraining
- Restricting phase ranges
  - t < +2 d crucial
    - Improvement drops by factor 2

Dhawan et al. 2019b, submitted

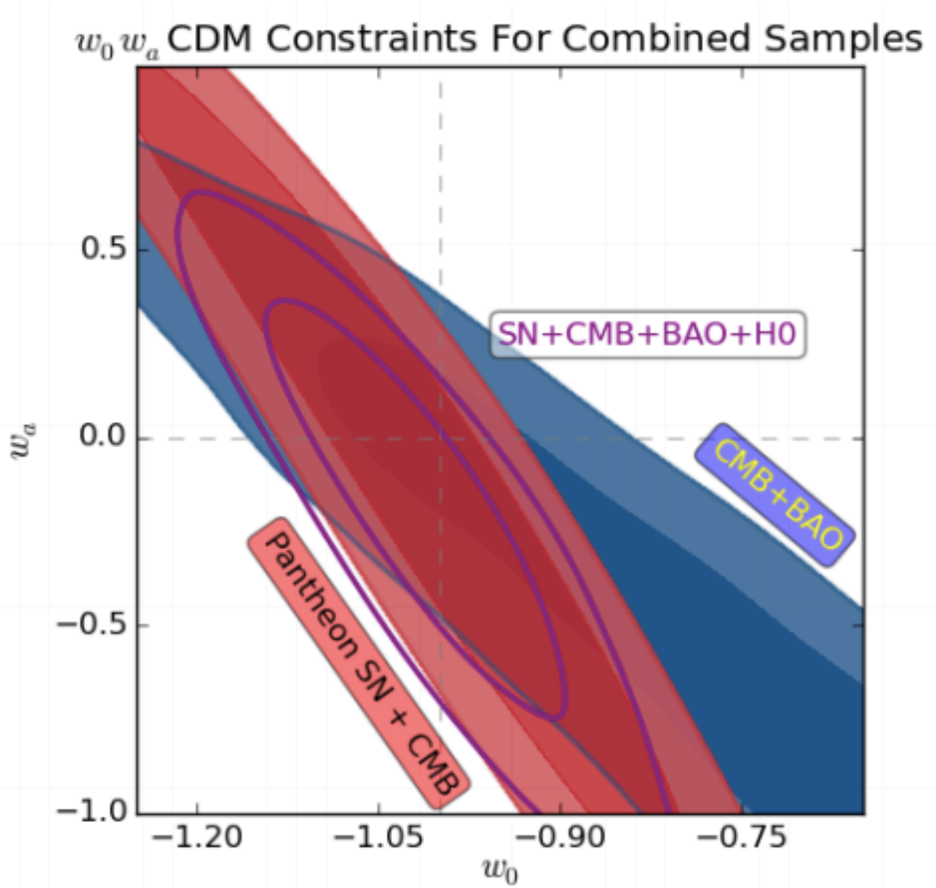
What could resolve the tension?

Diagnostics

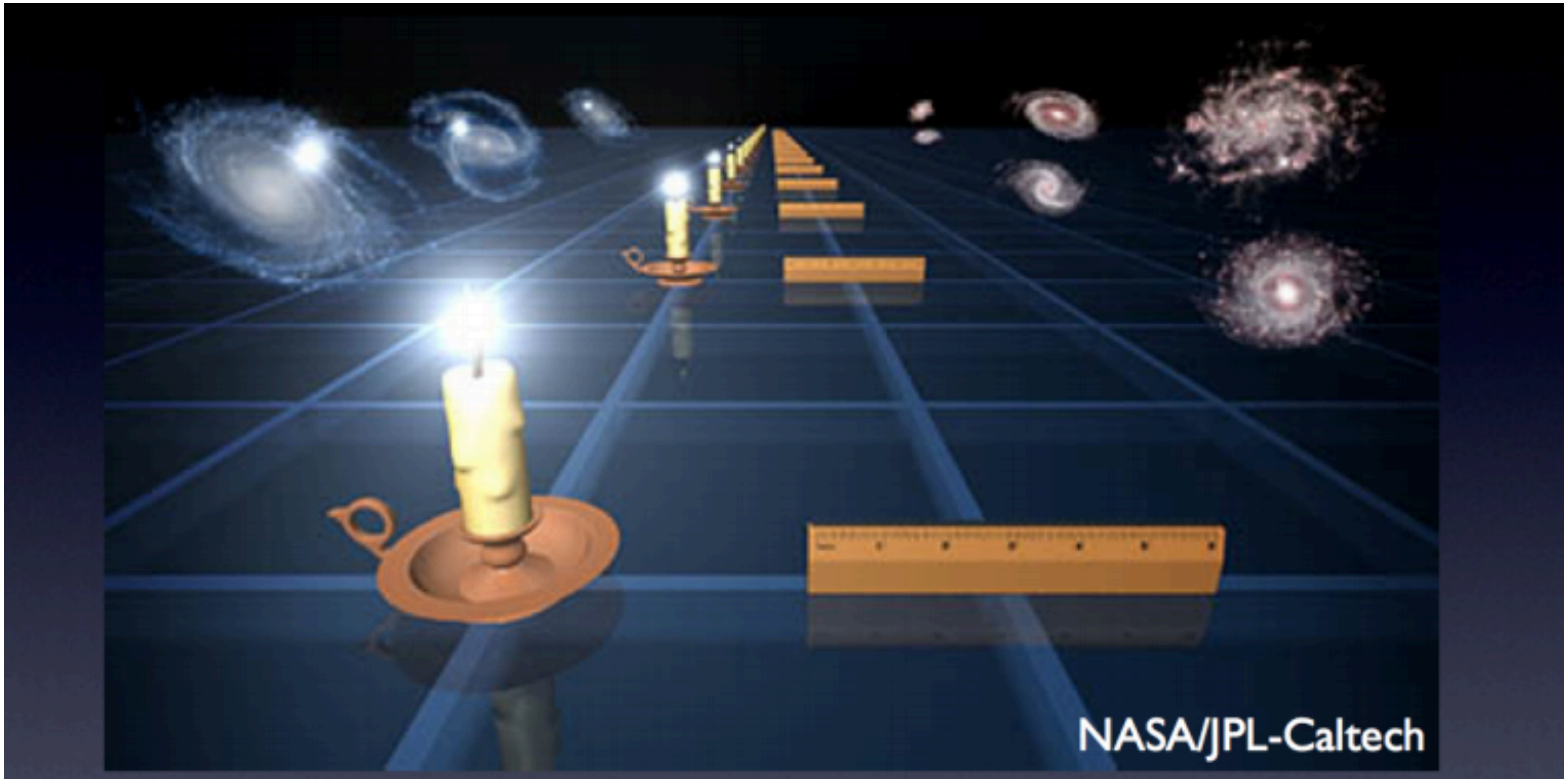


Motivation

While the standard model is established, do alternatives fare better?



Candles and rulers



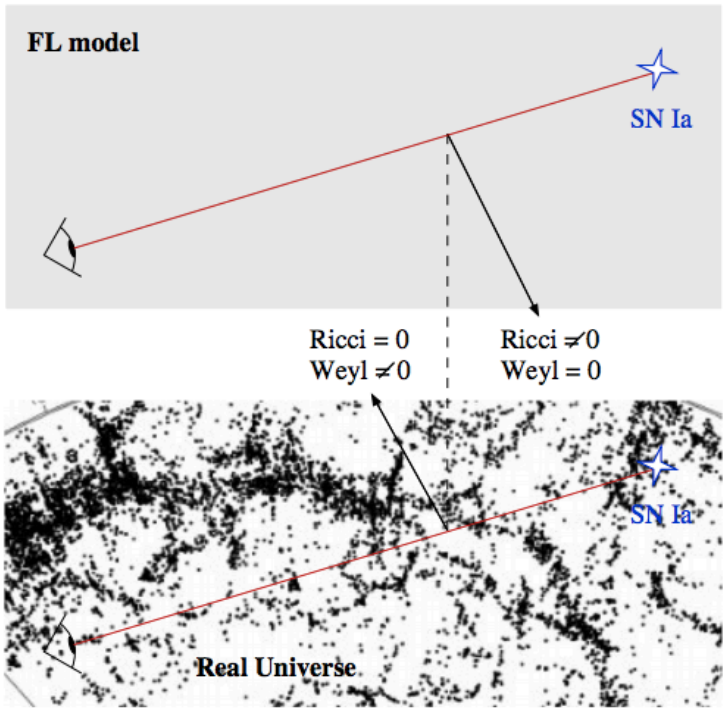
Type Ia supernovae

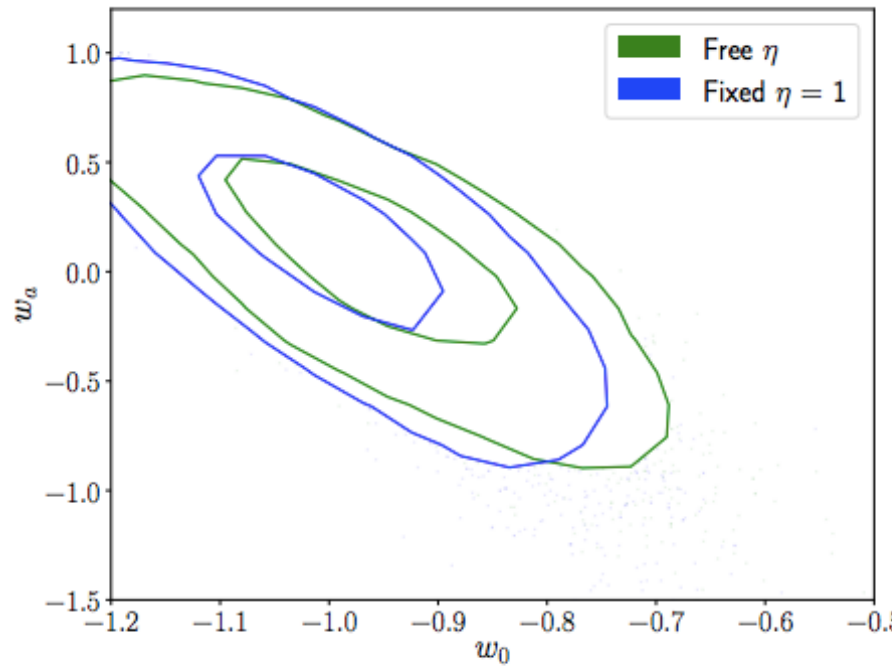
Excellent for relative distances
Absolute magnitude not known a priori

Baryon Acoustic Oscillation

Absolute calibration to r_s

Impact of inhomogeneities





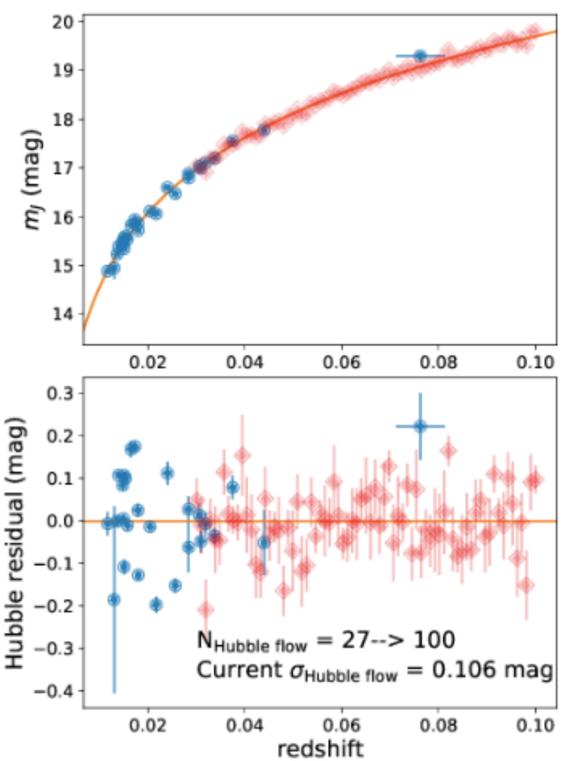
$$QD'' + \left(\frac{2Q}{1+z} + \frac{Q'}{2}\right)D' + \frac{3}{2}\eta\Omega_{\rm M}(1+z)D = 0,$$

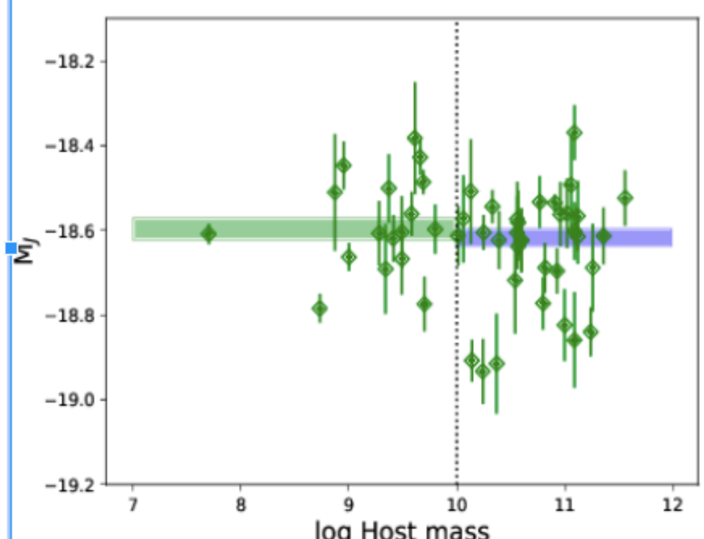
$$Q(z) = \Omega_{\rm M}(1+z)^3 + \Omega_{\rm K}(1+z)^2 + \Omega_{\rm DE}(z,w)$$

- FRW metric assumes homogeneity
  - Accounting for focussing from compact objects
  - No bias in DE inference
  - Future SNe can constrain f_p

What’s coming!

- VIRCAM follow-up: Single system in the Hubble flow
- Is there an NIR host mass step?





Impact of inhomogeneities

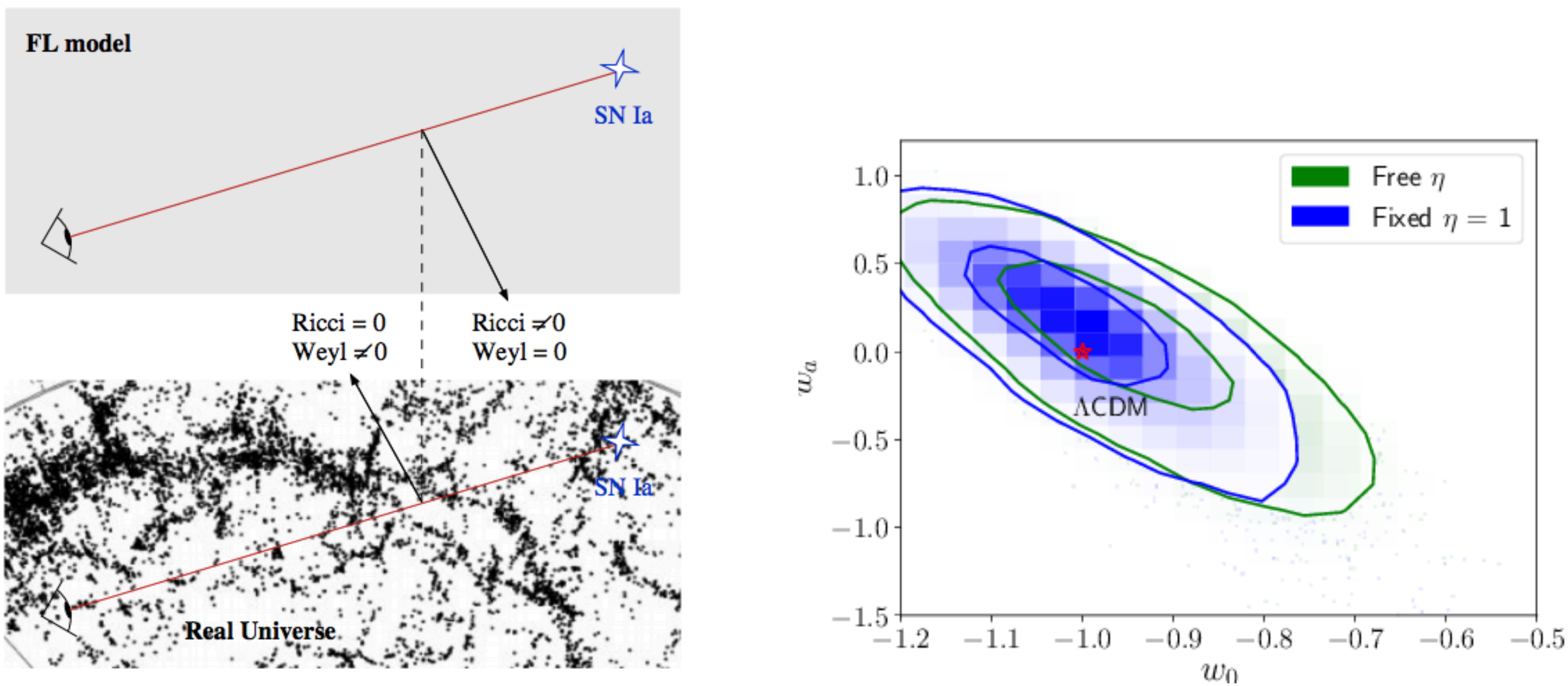
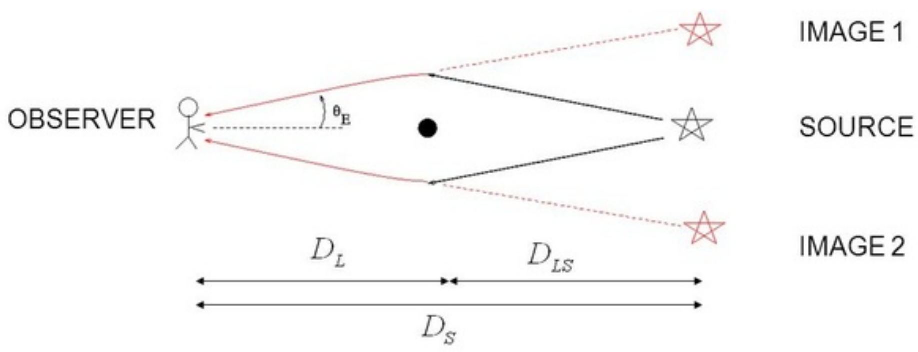


Figure: The impact of impact of departures from homogeneity on dark energy inference (**Dhawan** et al. 2018c)

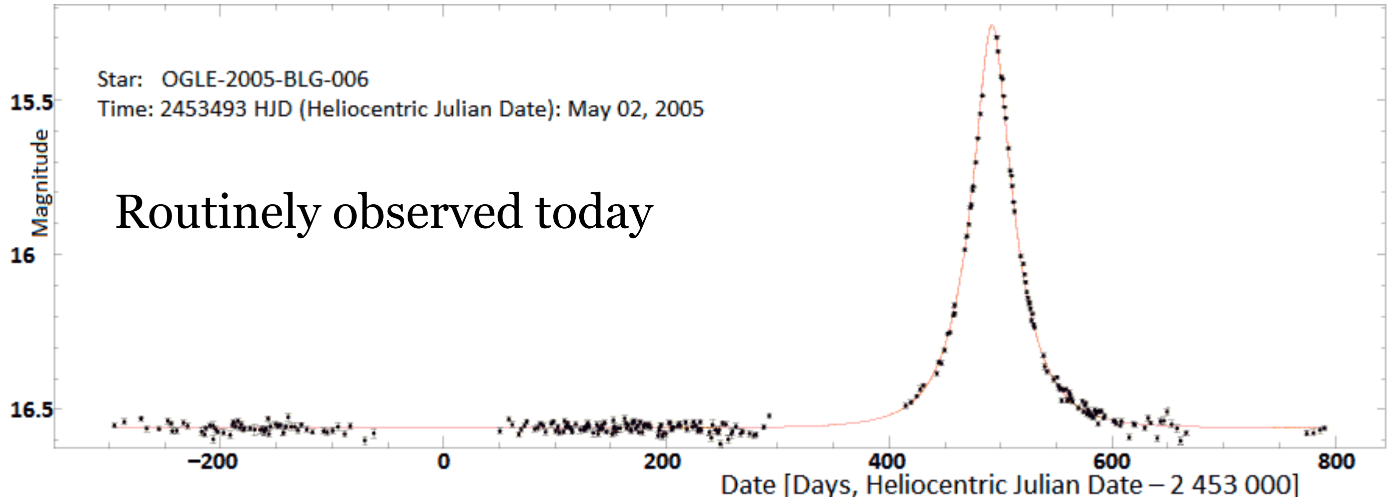
Gravity in action: *micro lensing*

Single Point Mass Lens

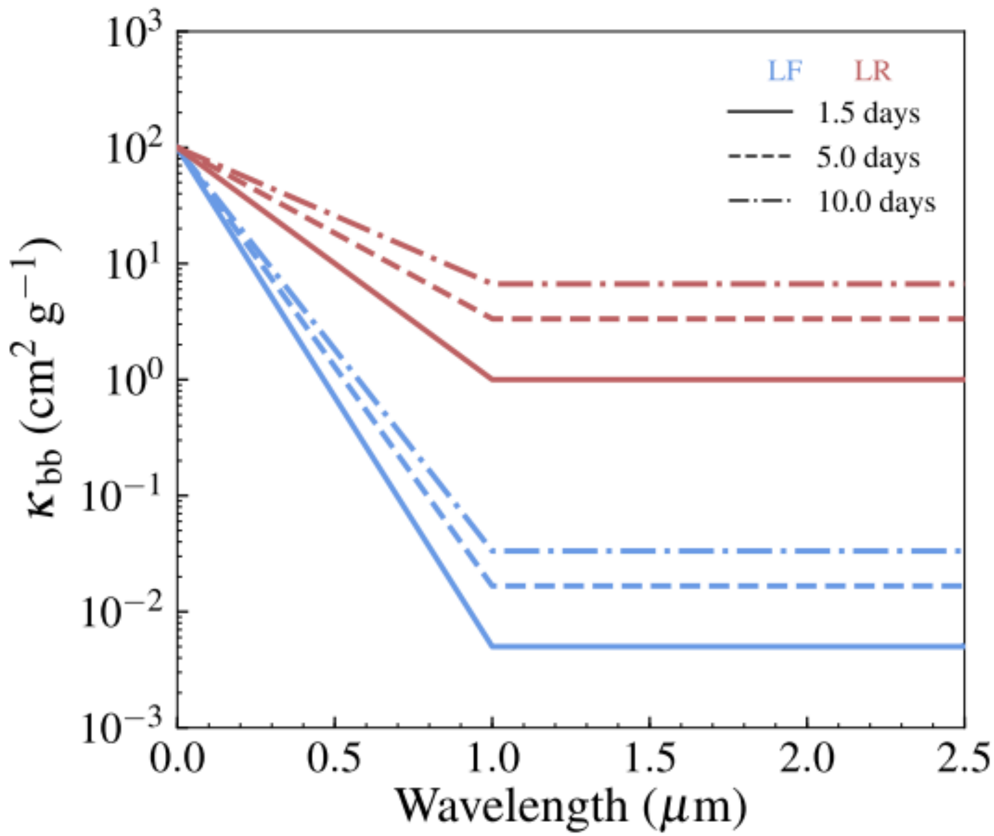


Einstein radius: $R_E = \sqrt{\dfrac{4GM_{tot}D_{LS}}{c^2 D_L D_S}}$

If lens mass is small, e.g., a stellar object, image separation is too small (micro arcseconds) to be spatially resolved by astronomical instruments. Looks like one object, just brighter as long as lens is in front!



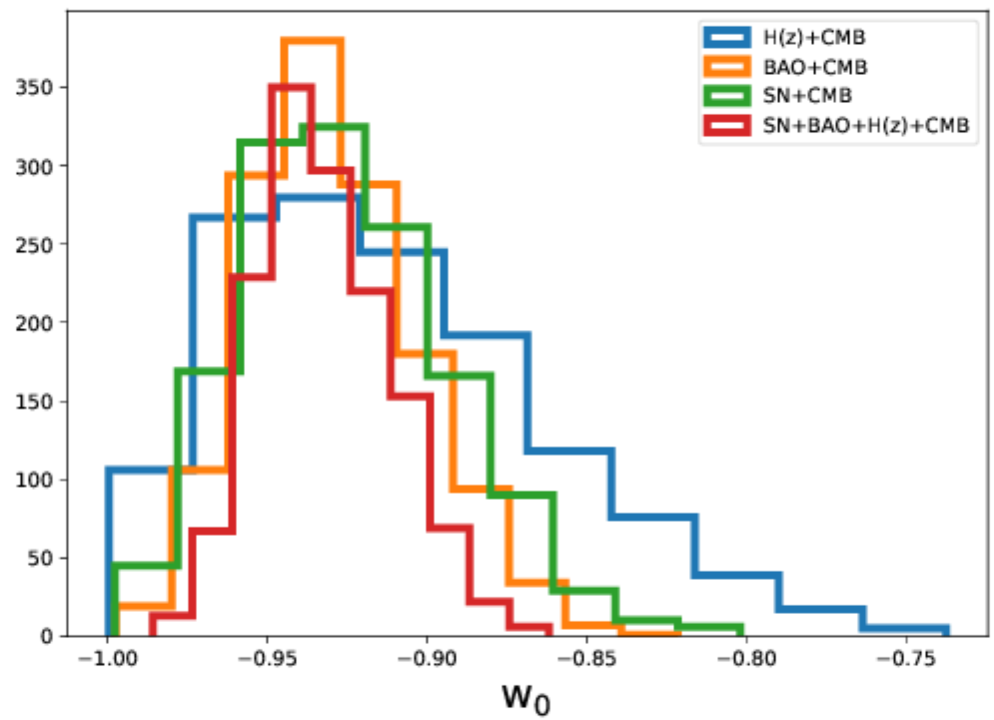
kN opacity assumption



Future missions

Algebraic thawing from flat Λ

- For w_0 = -0.92 and higher: decisively discriminate
- For w_0 = -0.94 and higher: moderately
- Current 95 % C.L. w_0 < -0.77



Dhawan et al. 2017b, JCAP