Dark Energy and H_0 with standard candles and clocks (+sirens)

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Outline

Candles:

Dark energy:

- Comparing models of acceleration

H_0:

- Near Infrared Hubble Diagram $\Rightarrow$ what is H_0?
- H_0 tension $\Rightarrow$ new physics??

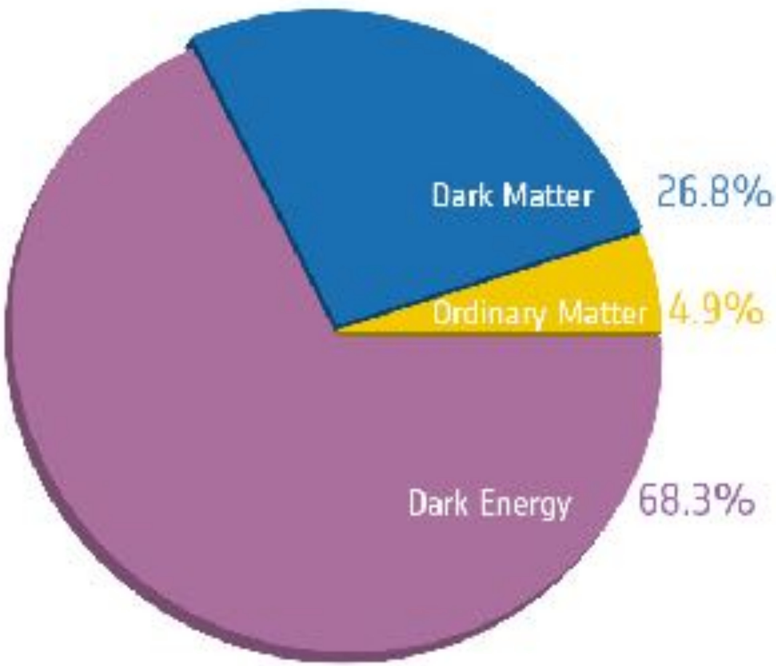
Clocks:

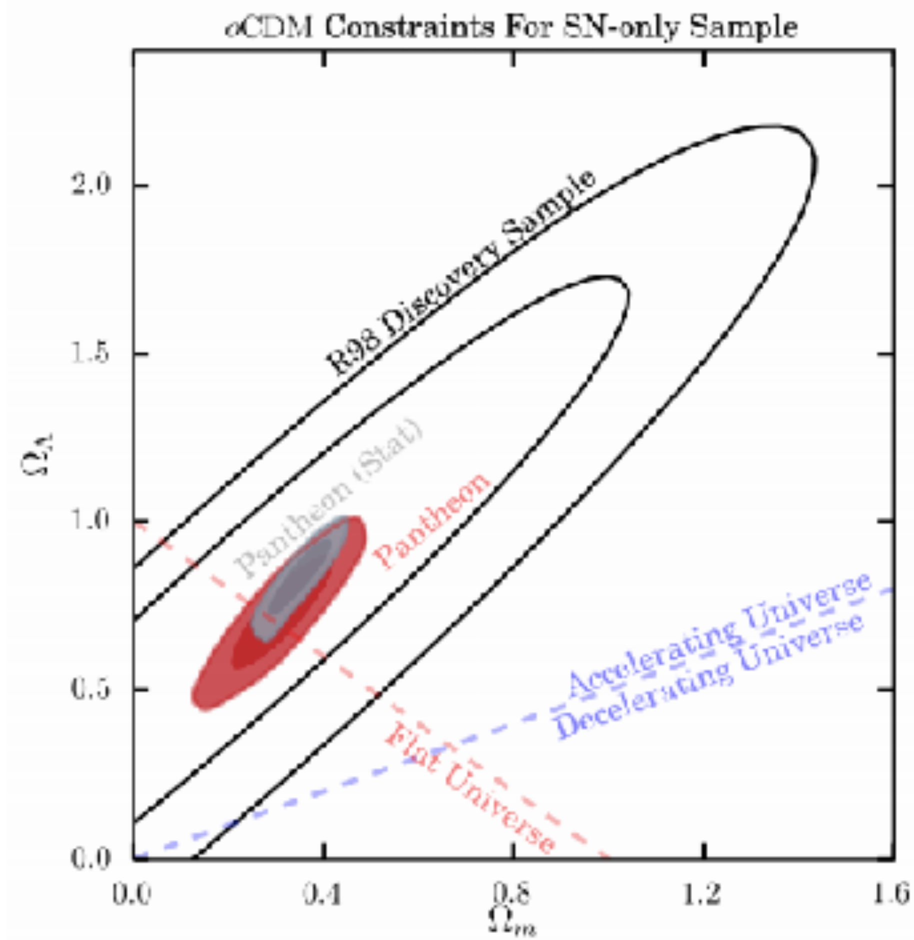
- Time-delay cosmography: lensed supernovae
  - First resolved strongly lensed SN Ia

Sirens:

- Kilonova constraints on inclination -> H_0?

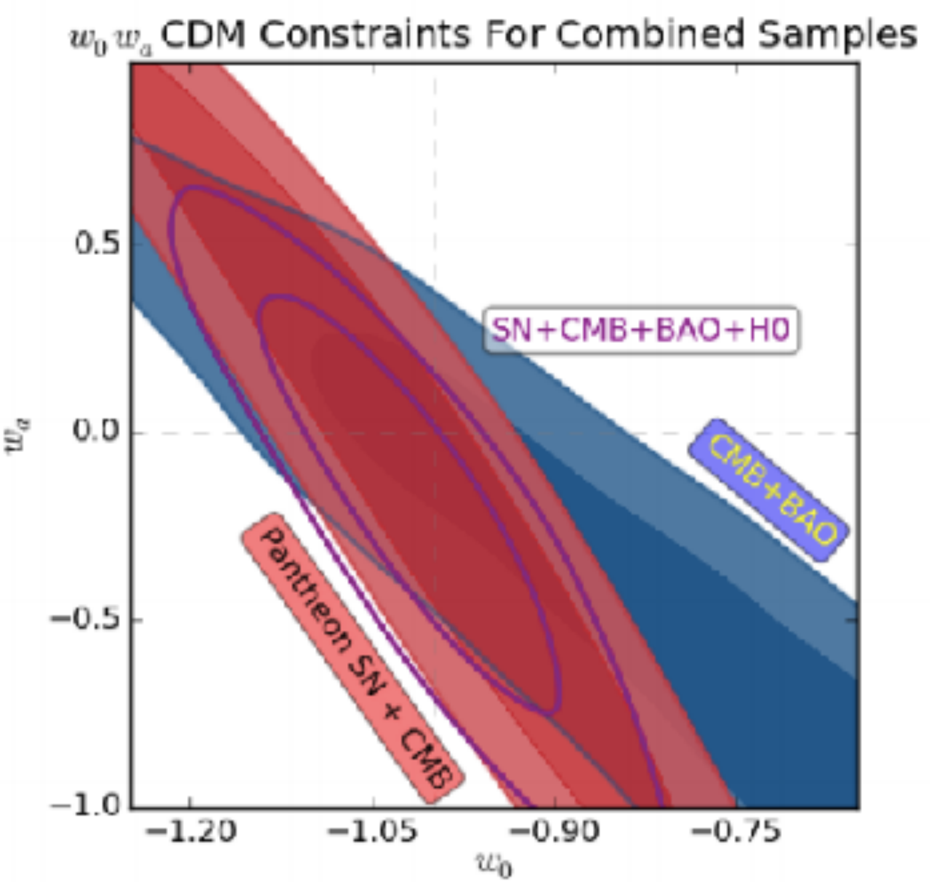
Standard Cosmological Model

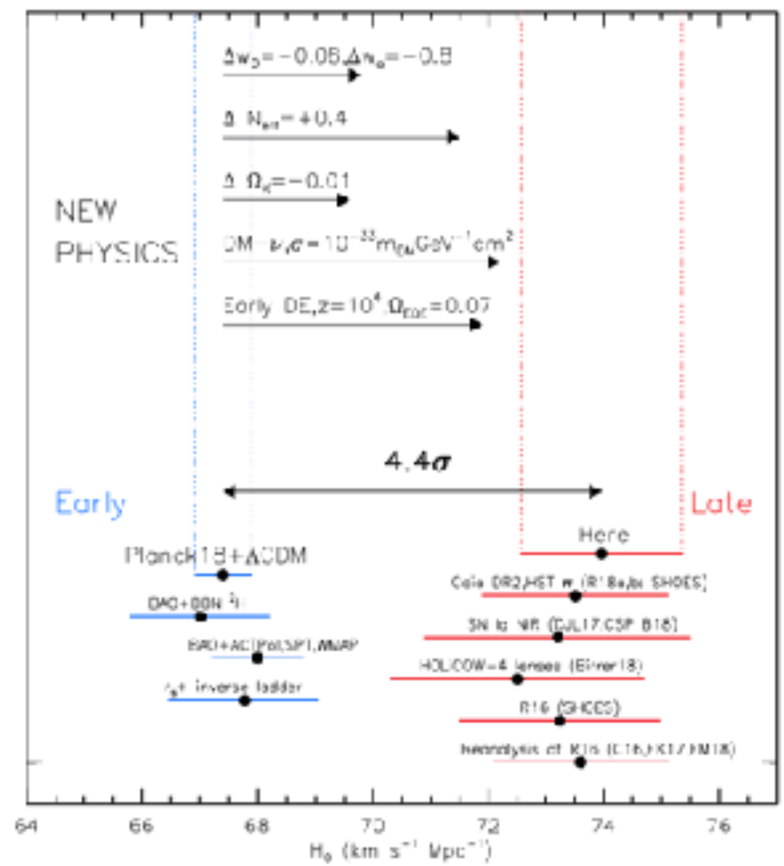




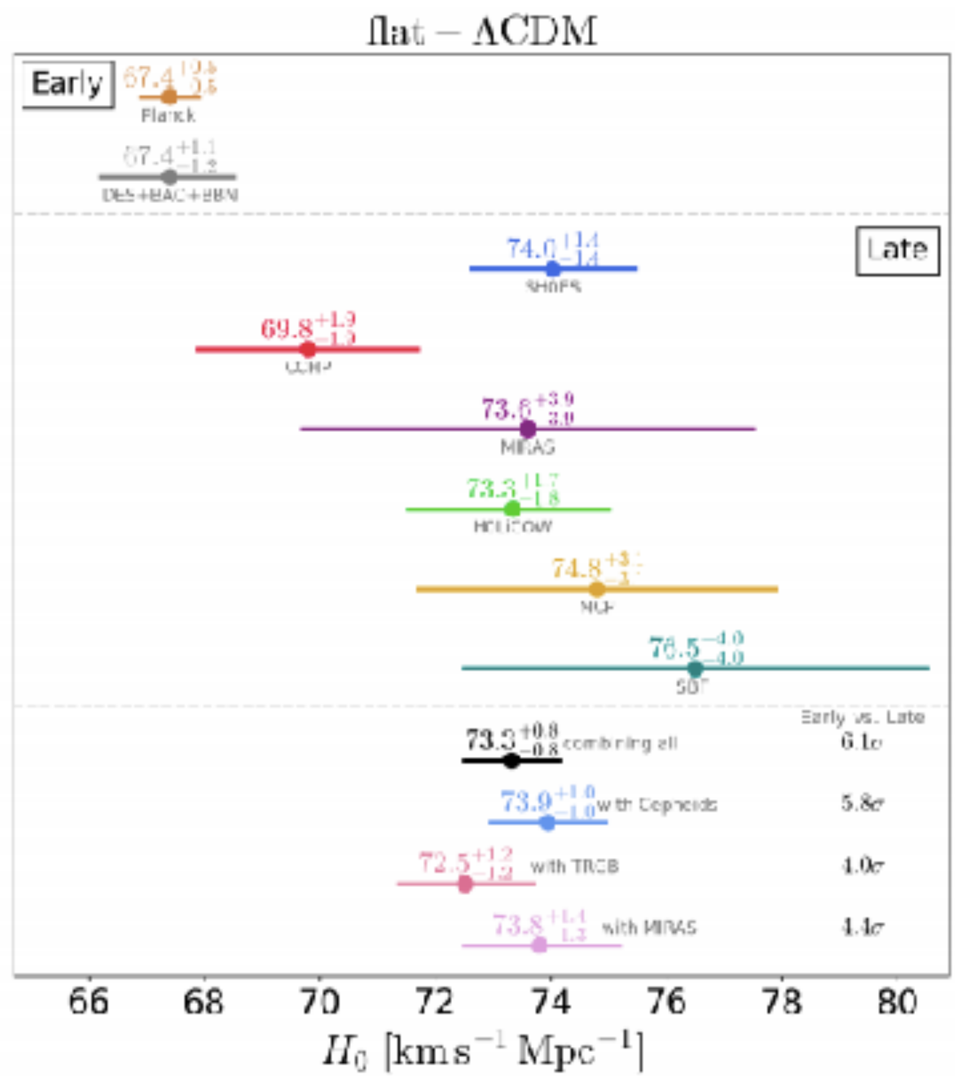
Motivation

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





Local H_0

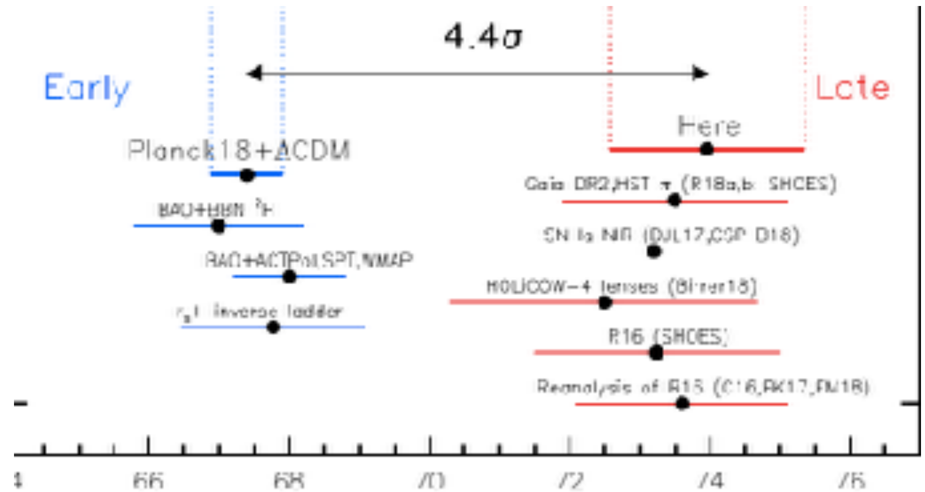


Verde et al. 2019

Independent estimates of H_0

Systematics checks: local H_0
- Cepheid systematics (Follin & Knox 2017)
- Bayesian hierarchical model (Feeney et al. 2017)
- Blind analysis (Zhang et al. 2017)
- SN Ia in the NIR (this talk; Dhawan et al. 2018a)

Systematics checks: Early Universe
- Primordial Deuterium + BAO (Addison et al. 2017)
- Primordial Deuterium + Clustering + BAO (DES Collaboration 2017)



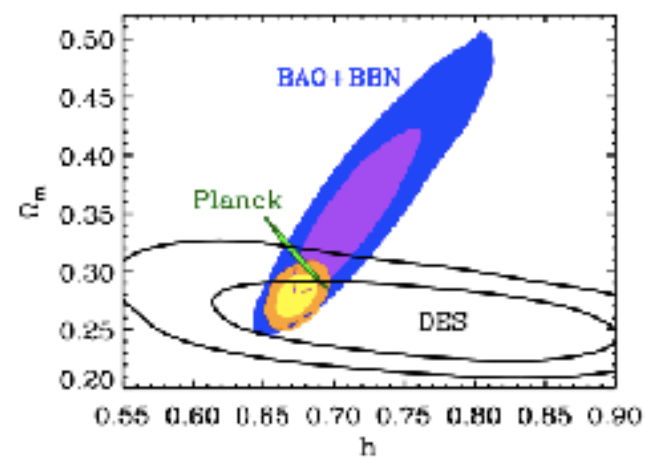
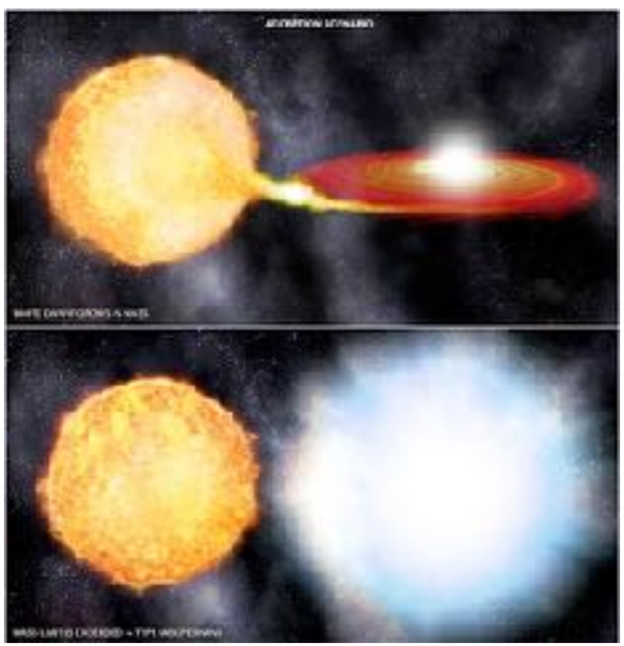
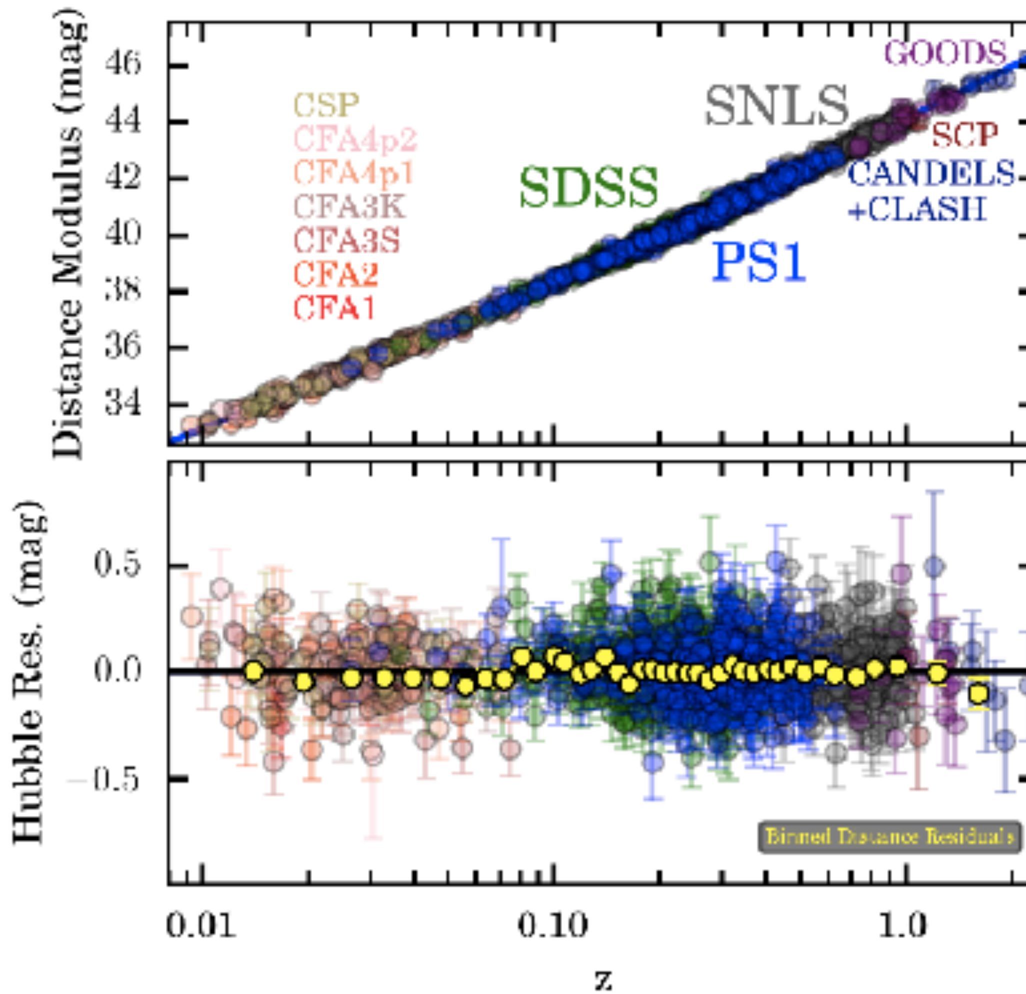


Figure:(Top) Systematics checks on H_0 inferred from the early universe and the local measurement (adapted from Riess et al. 2019). (Bottom) The constraints on matter density and h from DES without the CMB anchor in the early universe

Dark Energy with SNe

- NOT an absolute distance
- NOT a standard candle





Constraining dark energy: Model Comparison

Several explanations for accelerated expansion

- Motivated by Scalar Fields and Modified Gravity

- Following "Beyond Lambda": Rubin et al. 2009

- Thawing Quintessence (e.g. Linder 2015)
  - Algebraic
  - Linear Potential (Doomsday)
  - Pseudo-Nambu-Goldstone Boson (PNGB)

- Slow-roll dark energy (Slepian & Gott 2014)

- Growing Neutrino Mass (Wetterich 2007; Amendola et al. 2008)

- Vacuum Phase Transition (Caldwell et al. 2006)

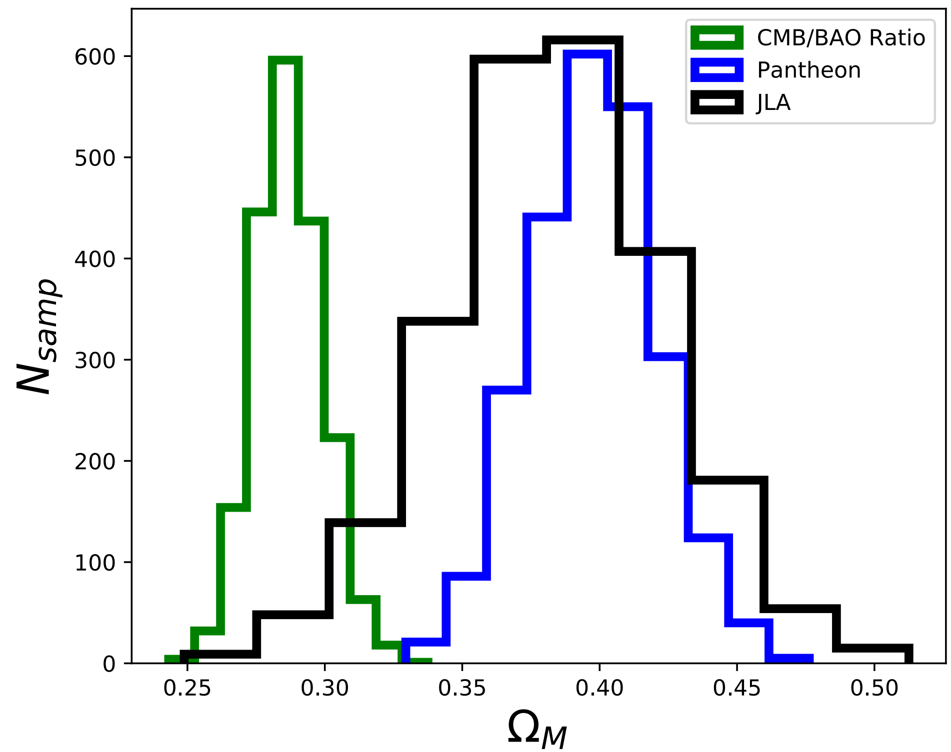
- Bimetric Gravity (von Strauss et al. 2012; Comelli et al. 2012)
  - Linear Interaction
  - Linear and Quadratic Interaction

Combining probes is key!

- Bimetric gravity: Linear interaction
- Same number of parameters as LCDM
- CMB/BAO and SNe fit data well
    - Resulting parameter values do not match
    - Start to exclude model at ~ 2-2.5

    - Improvements in SNe Ia increase tension to ~ 4.5

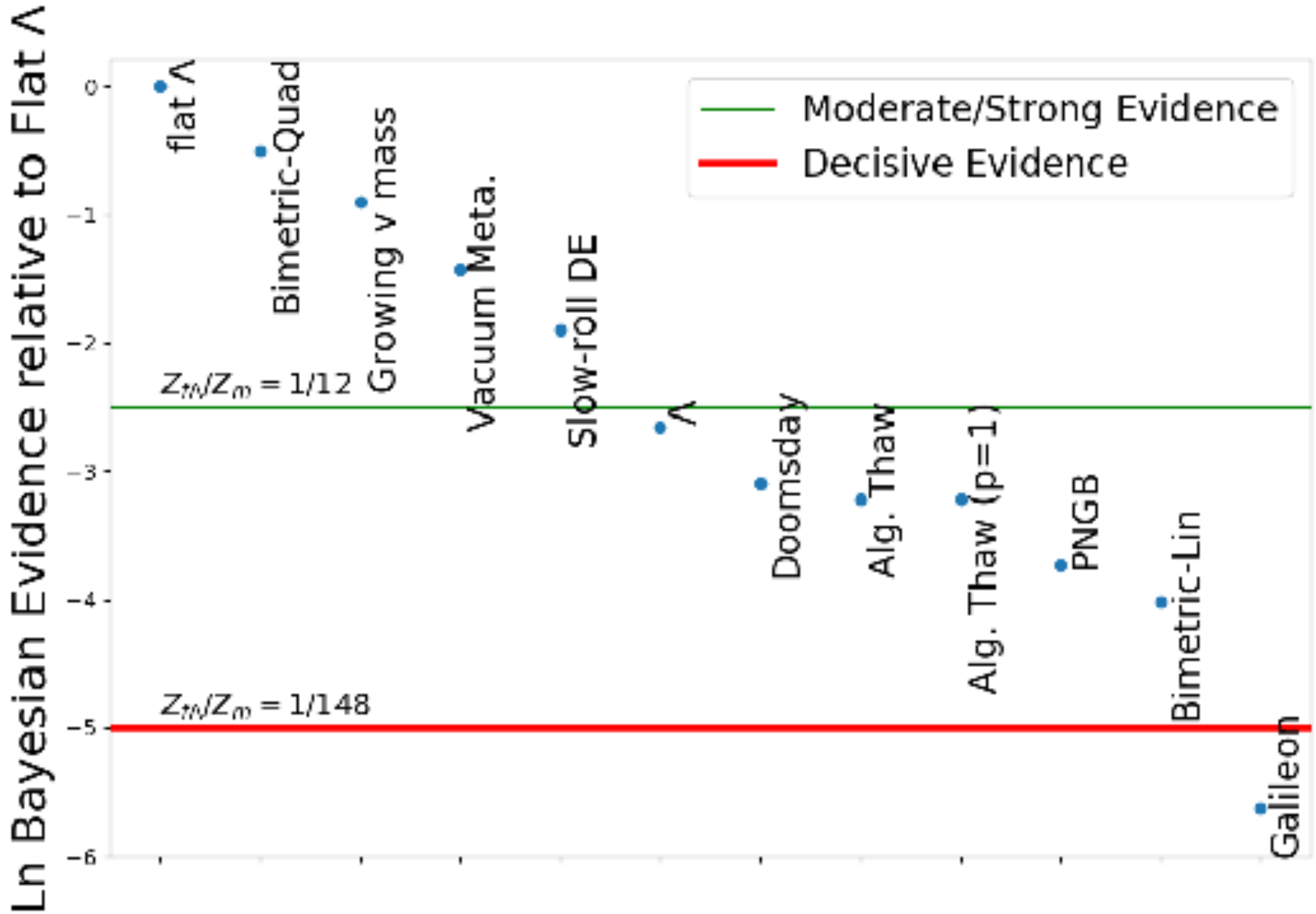
$$\frac{H^2}{H_0^2} = \frac{\Omega_M(1+z)^3}{2} + \sqrt{\left(\frac{(\Omega_M(1+z)^3)^2}{2}\right)^2 + 1 - \Omega_M}$$



Dhawan et al. 2017b, JCAP; 2019, JCAP, to be submitted

Bayesian Model Selection

- Some complicated models moderately excluded
- However, models like vacuum phase transition still viable
- Simple modified gravity models don't fit

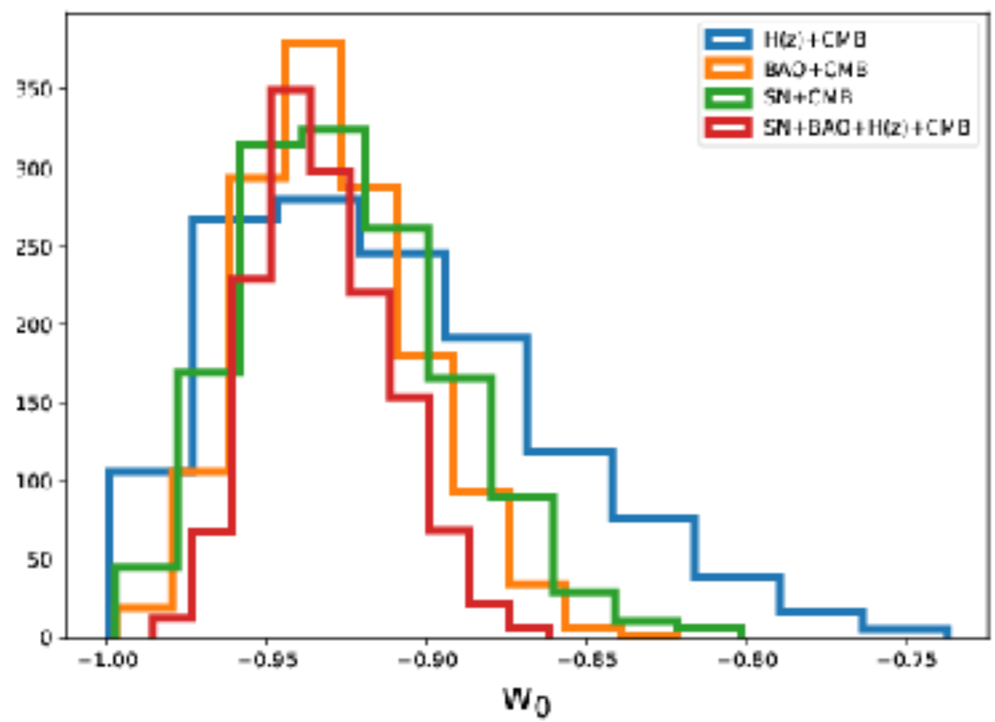


Dhawan et al. 2017b, JCAP

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

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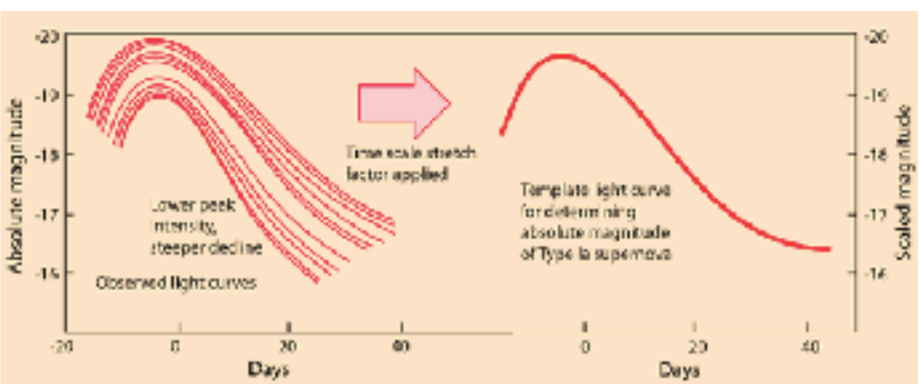
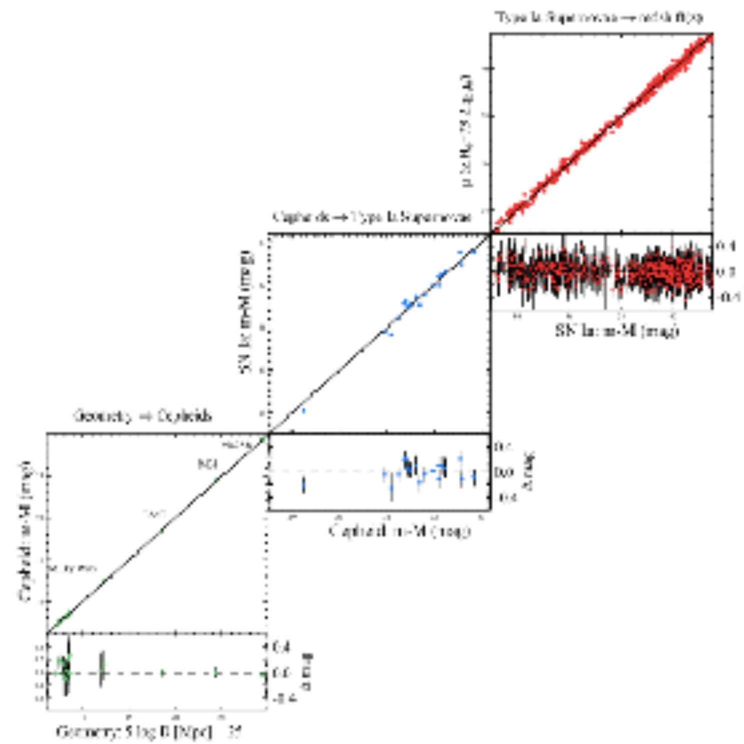
Investigations of H_0:
Testing Supernova systematics

Local distance ladder

- Calibrate SN luminosity
  - Cepheid distances to SN hosts
  - Cepheids calibrated with anchors

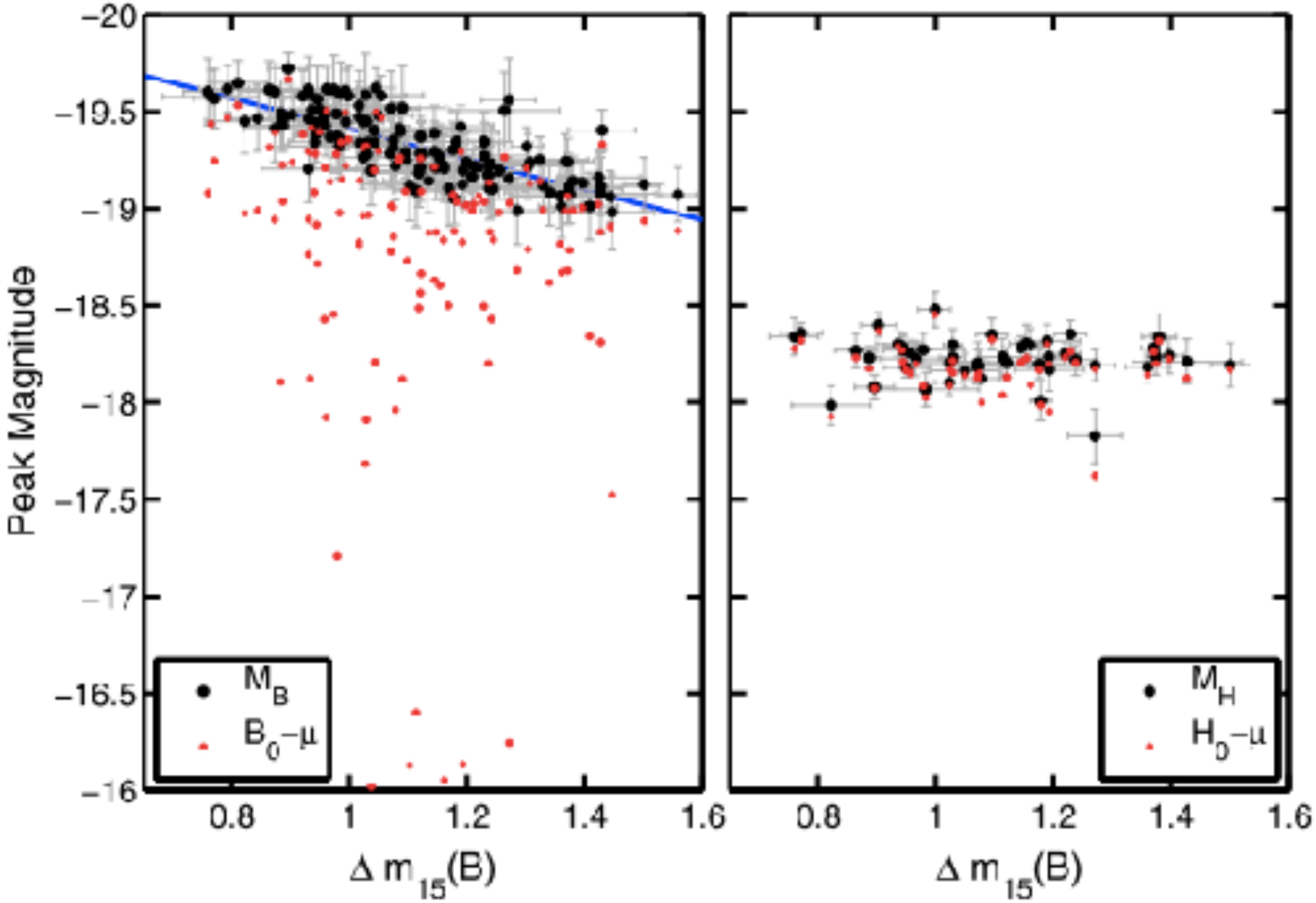
- Optical peak luminosity needs to be corrected
  - Width-luminosity relation
  - Colour-luminosity relation
  - Correlate with properties of hosts





Why the NIR?

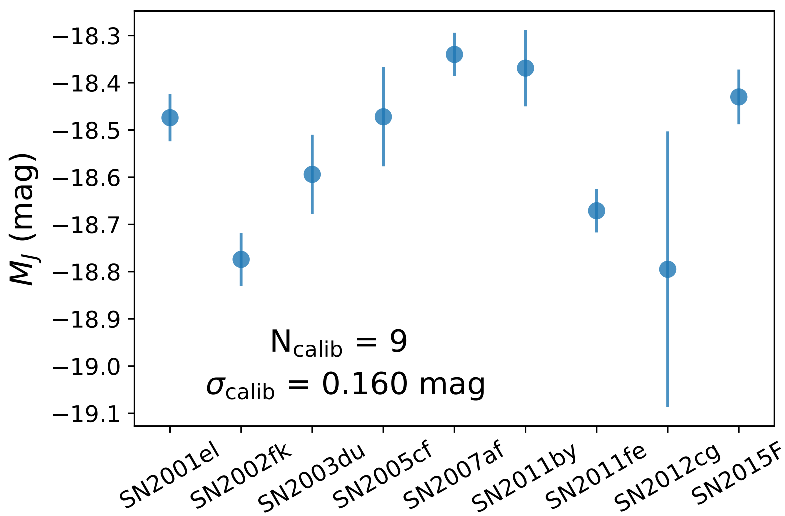
- Reduced extinction from host galaxy dust
- Lower luminosity scatter



Mandel et al. 2011, CfA SN program

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)



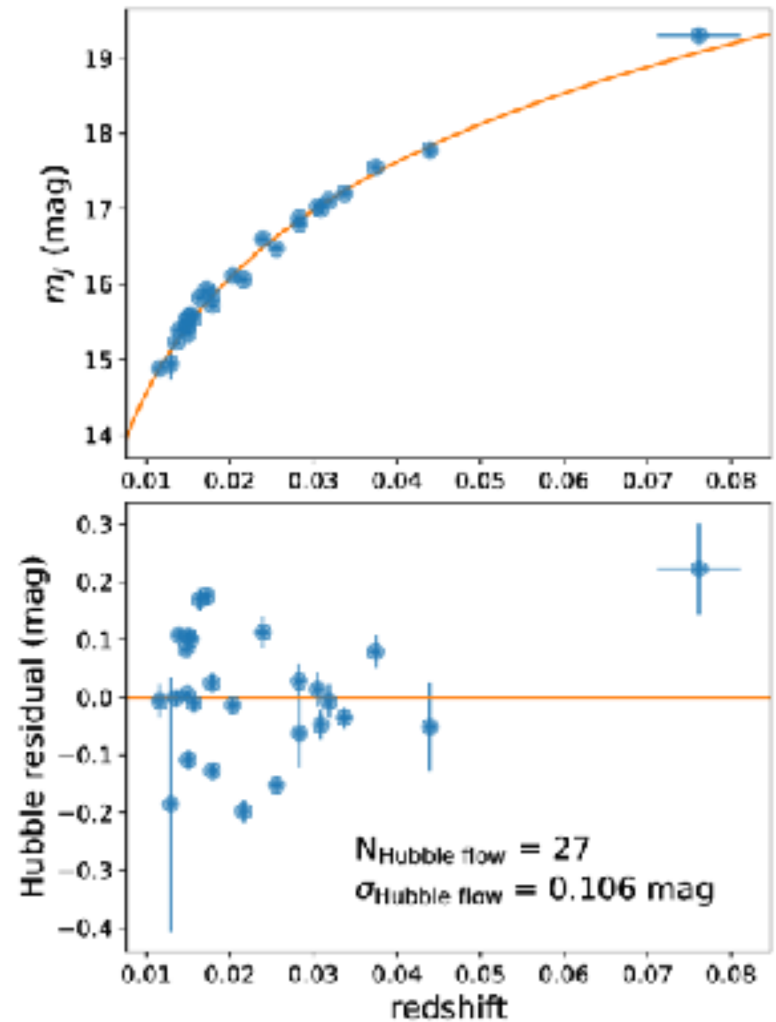
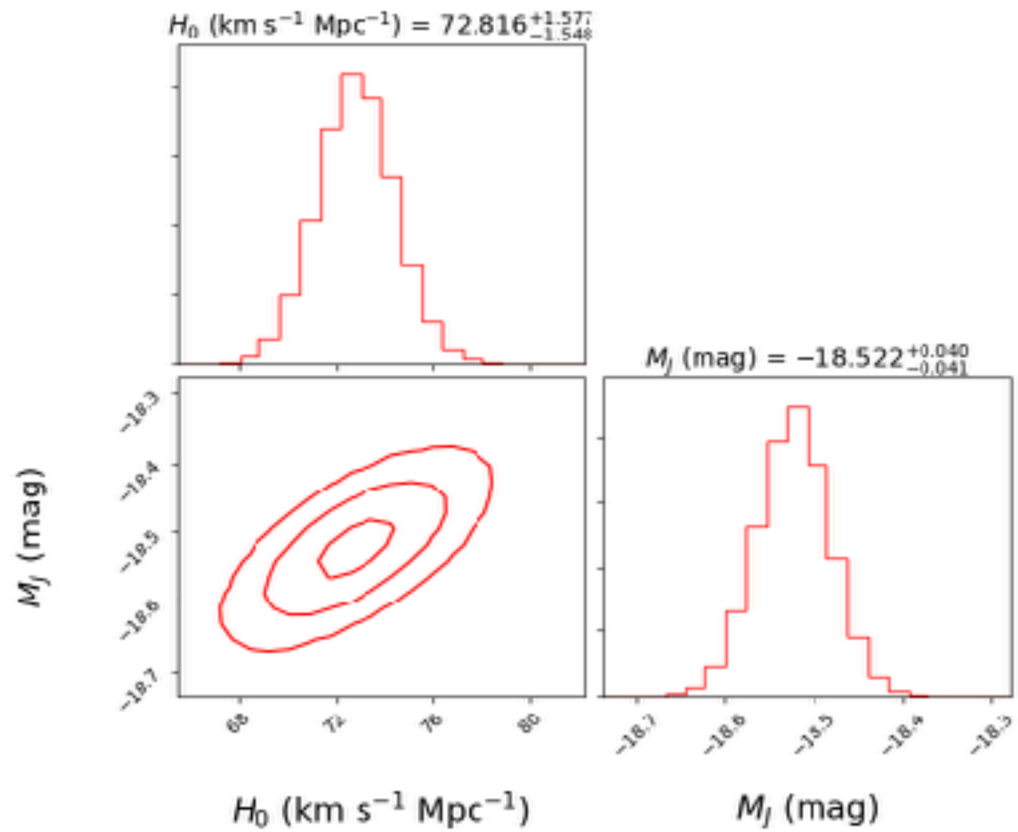


Figure: The calibrator and Hubble flow samples. The low intrinsic scatter validates the standard candle hypothesis (**Dhawan** et al 2018a)

H_0 from the NIR

- Combine the calibrators and Hubble flow
  - Calibrators: Absolute M_J
  - Hubble flow: M_J and H_0
  - Combination breaks degeneracy
- $H_0 = 72.8 \pm 1.6$ (statistical) $\pm$ 2.7 (systematic) km/s/Mpc
- $\sigma_{int} \sim 0.1$ mag
- Consistent with optical H_0

(see also Burns et al. 2018 with complete CSP sample)

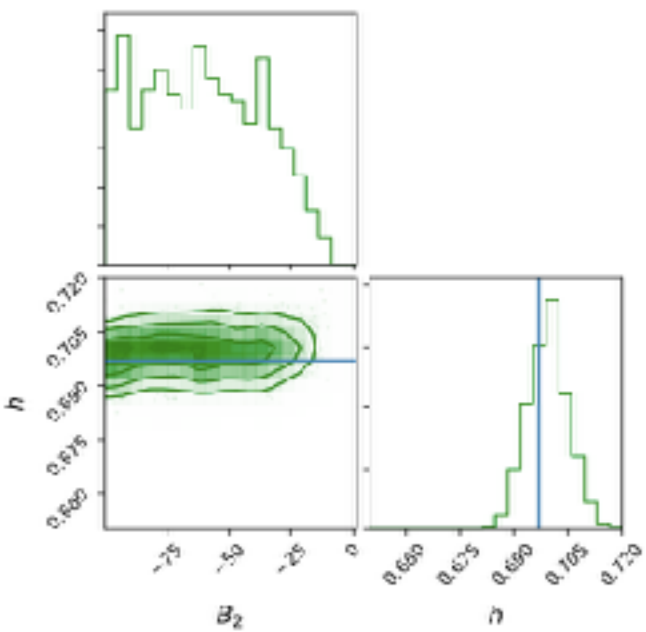


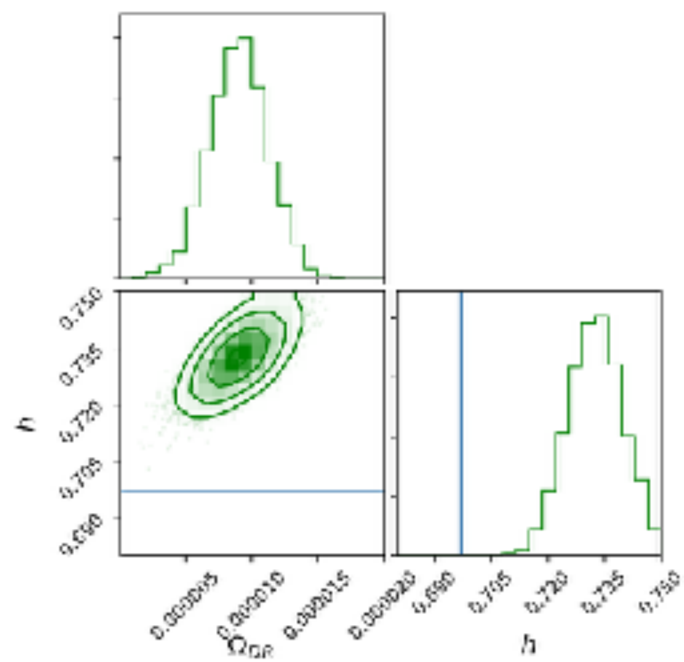
Dhawan et al. 2018a, A&A

Investigations of H_0: Cosmological resolutions of Hubble tension

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



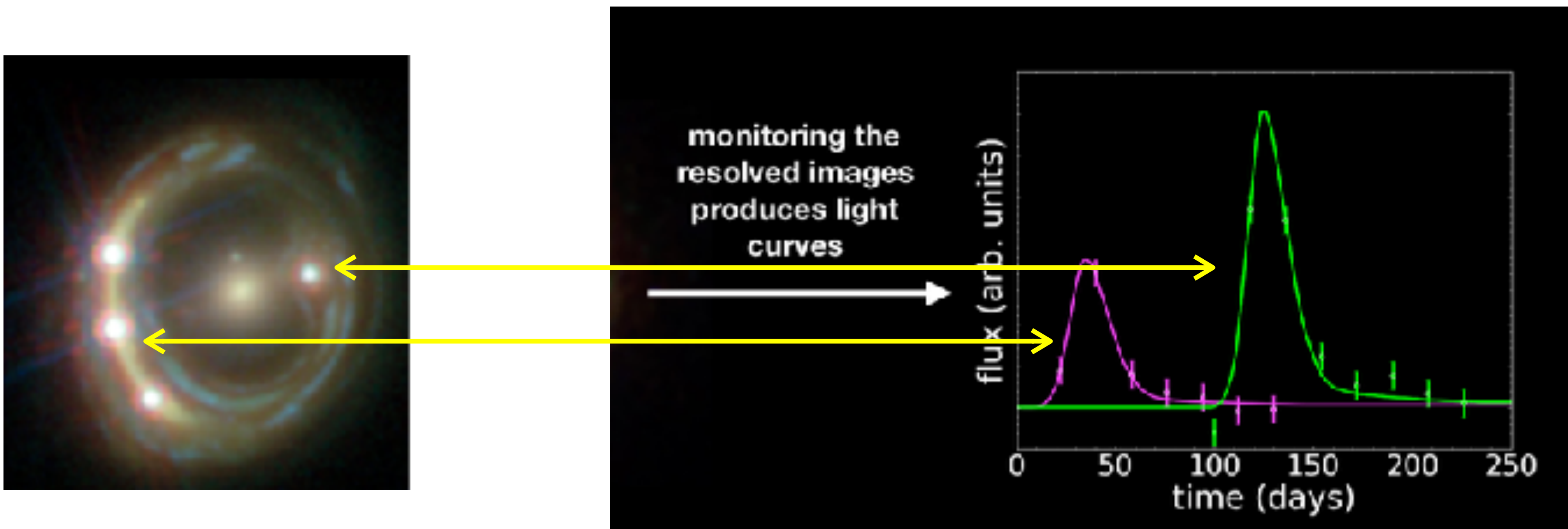


Mortsell & Dhawan, 2018, JCAP

Cosmography with time-delays: Strongly lensed supernovae

H_0 + q_0: Independent probes Time-delay distances

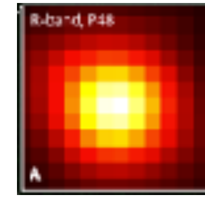
- Along with systematics checks, independent probes of H_0 and q_0
- Time-delays between multiple images of transients (Refsdal 1964)
    - Has been used with quasars; lensed SNe rarer, but now found!



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

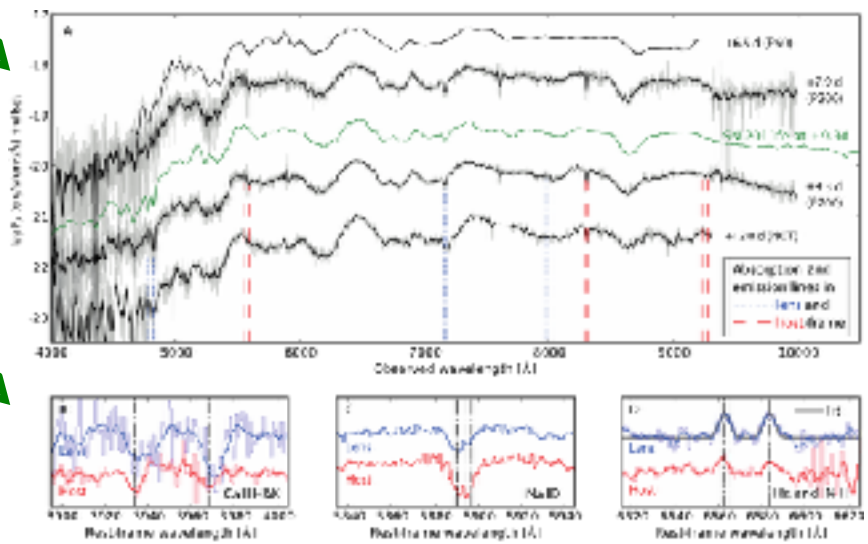
iPTF16geu: Discovery

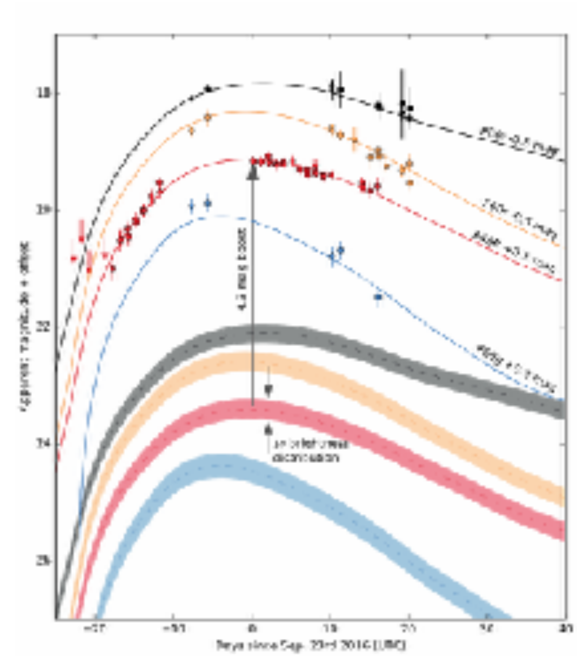
Oct 2



"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

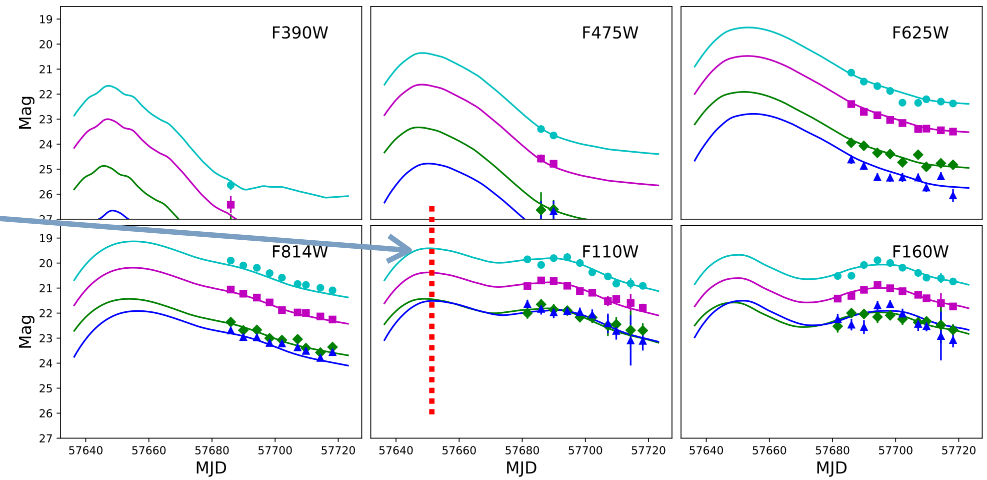
>50 times brighter than normal SNIa at z~0.4: a 30σ outlier!

Goobar+ 2017

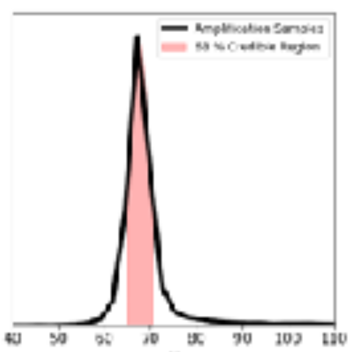
iPTF16geu: Follow-up and resolved photometry

Multi-band light curves fitted allowing for differential extinction in the lens and same extinction in the host

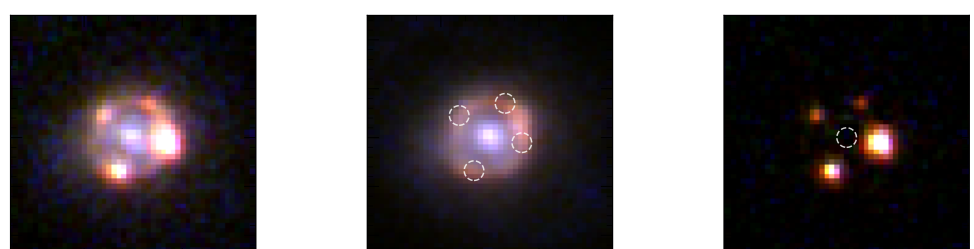
Very small time-delays: highly symmetric system (matches models; More et al. 2017, Mortsell et al. in prep)
Not ideal for H_0
Ongoing surveys will find larger time-delay systems



Also: surprisingly high magnification (μ), if coming from galaxy lens alone!
In general, $P(\mu) \propto \mu^{-3}$ +selection effects. (E.g., μ=5 happens 1000 more often, yet not seen)



RGB image of iPTF16geu from HST WFC3 (bottom) and individual light curves for the resolved images (top; **Dhawan** et al.2019, MNRAS, submitted)



Finding glSNe with ZTF: Year 1 end of operations

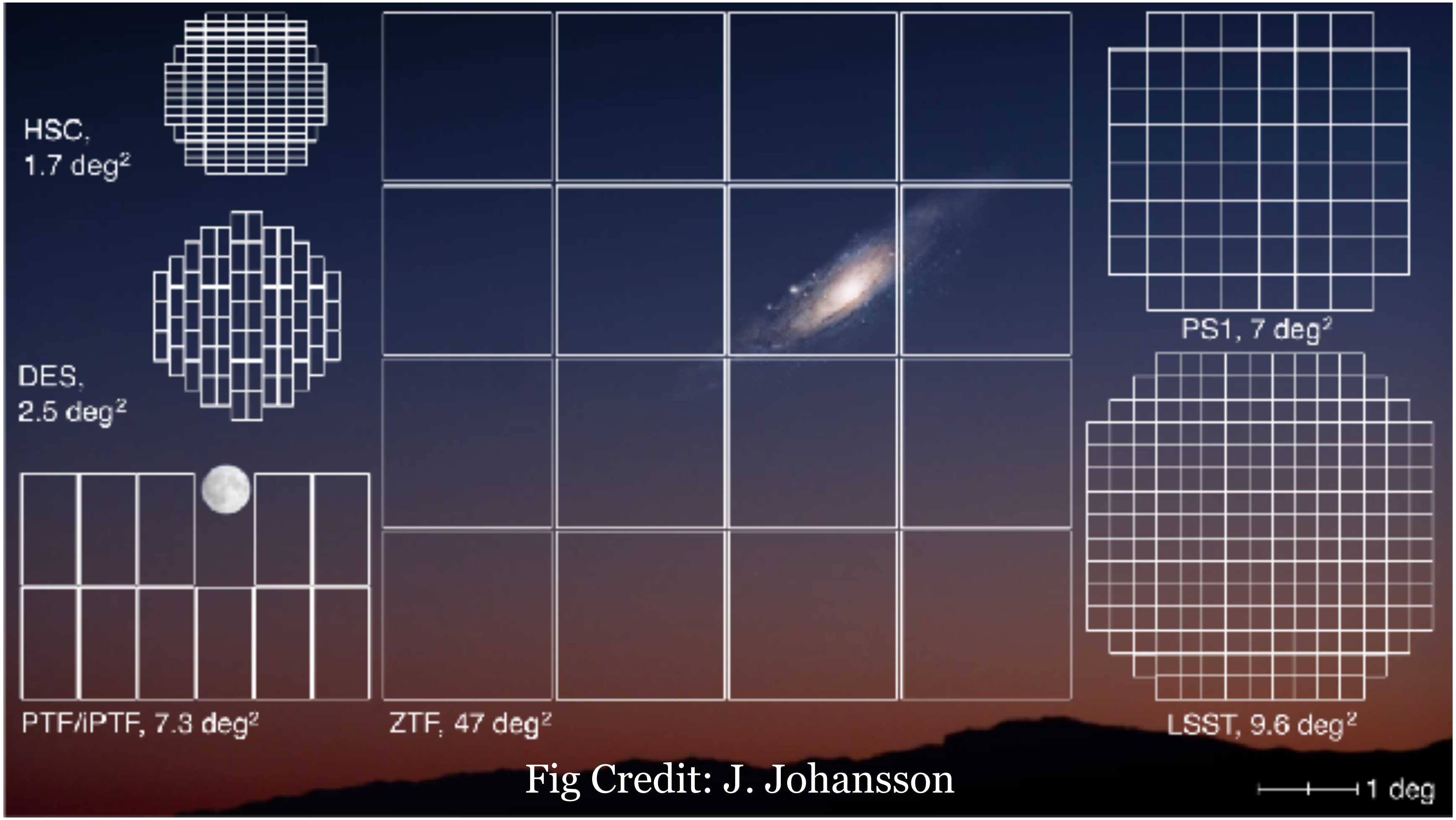
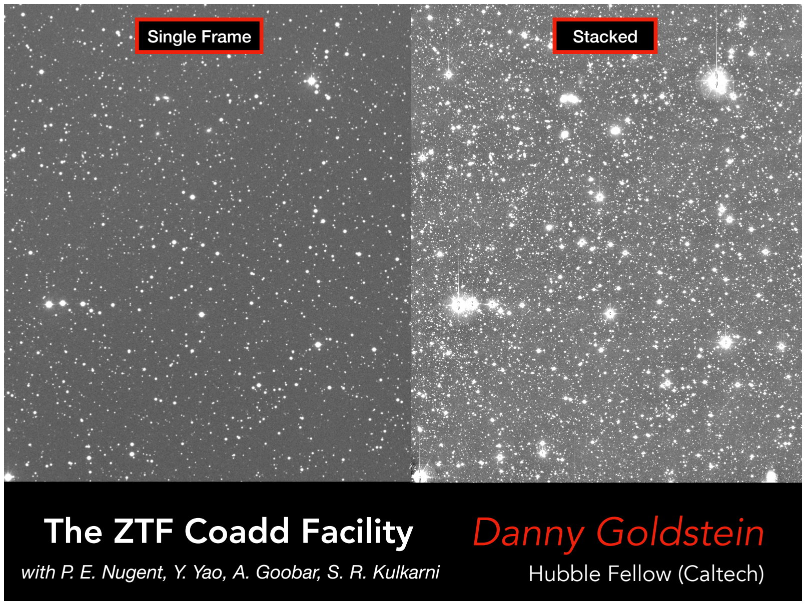
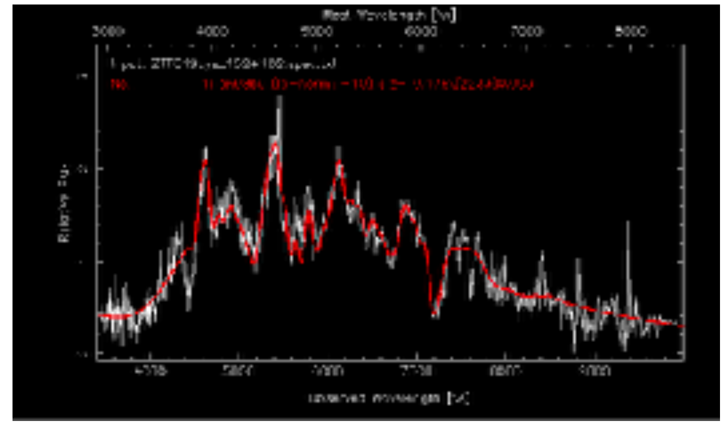


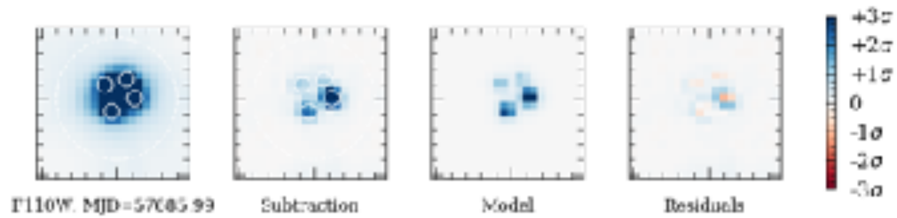
Fig Credit: J. Johansson

Image Stacking: ZTF Co-adds





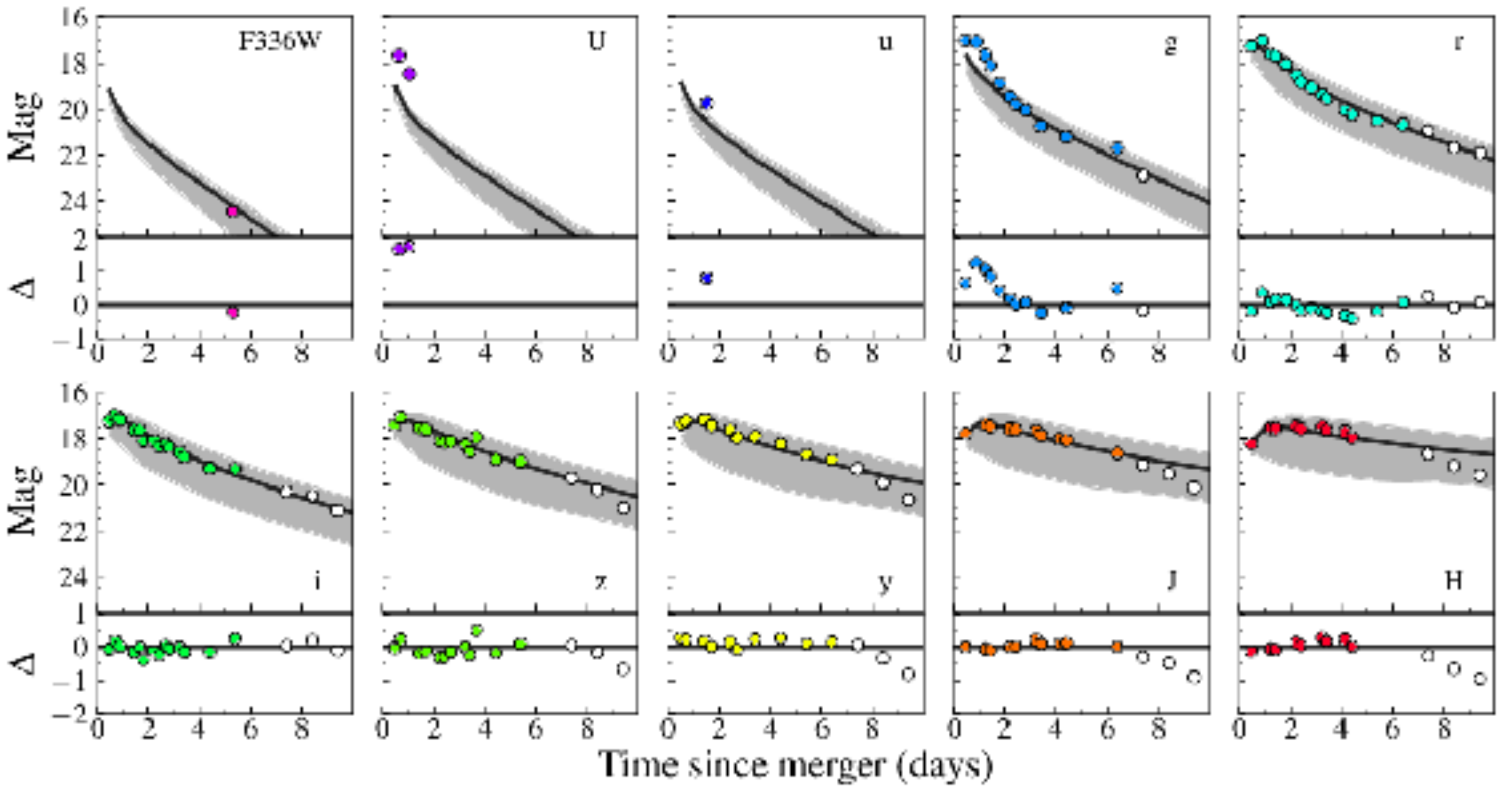
- ZTF co-add facility
- Gemini/VLT follow-up with AO



H_0 from standard sirens: Impact of kilonova constraints

Fitting GW170817/ AT2017gfo

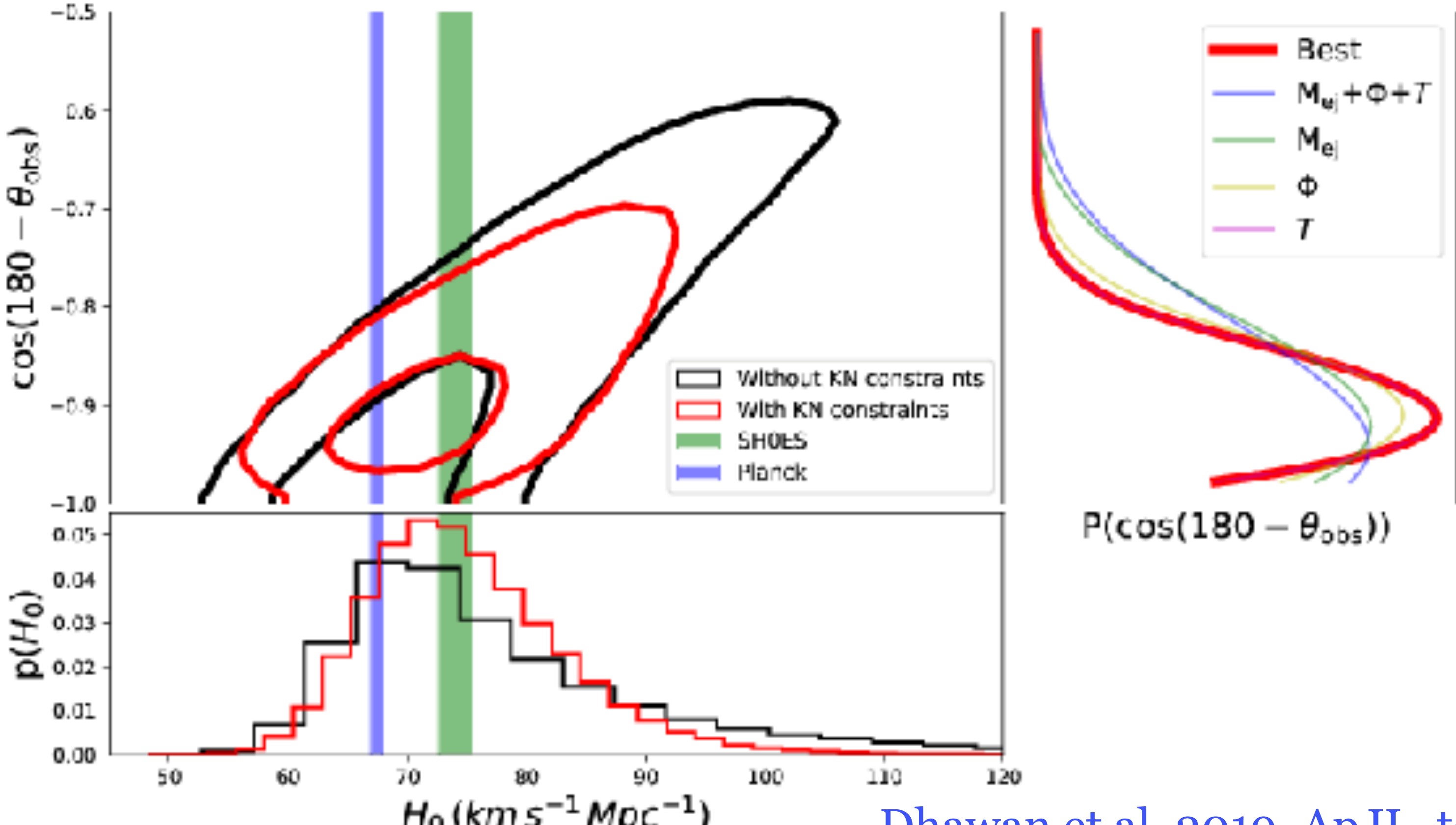
- Fitting 3-D models to data
  - UV to NIR coverage
  - Largest sensitivity in the redder filters



Dhawan et al. 2019, ApJL, to be submitted

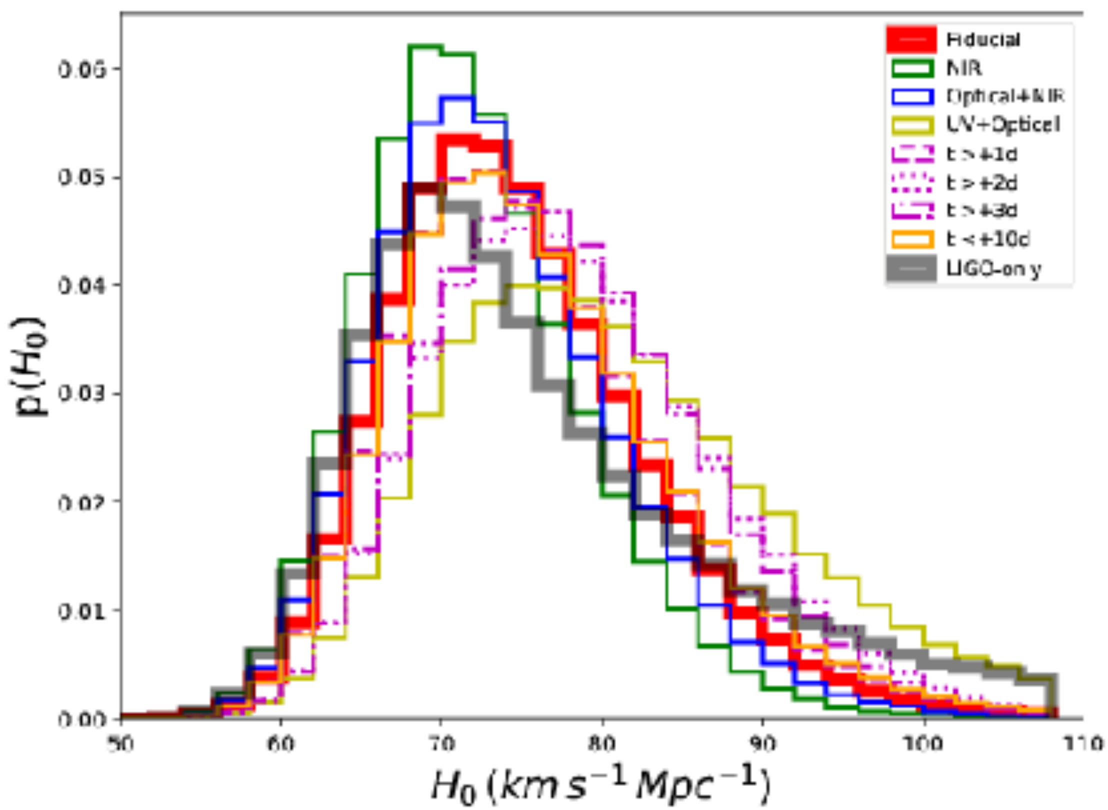
Combined EMGW H_0

- EMGW sources: Distance ladder independent H_0
  - Degeneracy with inclination
  - Independent EM constraints
  - Improvement of 25%



Dhawan et al. 2019, ApJL, to be submitted

Future kN observations



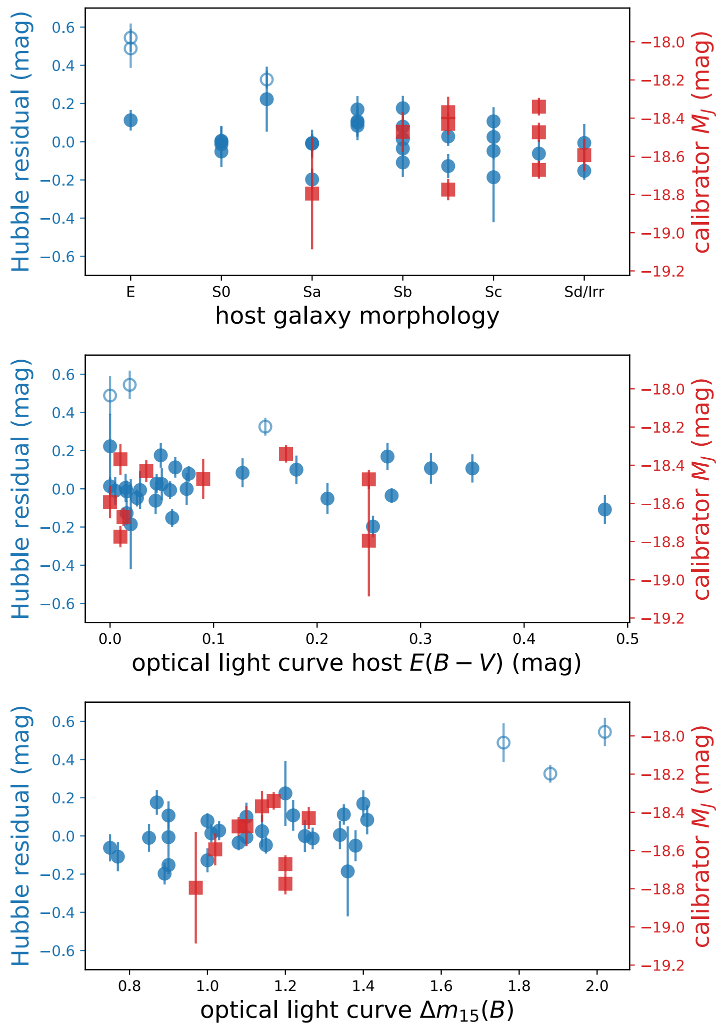
- Different wavelength ranges
  - NIR is most constraining
- Restricting phase ranges
  - t < +2 d crucial
    - Improvement drops by factor 2

Dhawan et al. 2019, ApJL, to be submitted

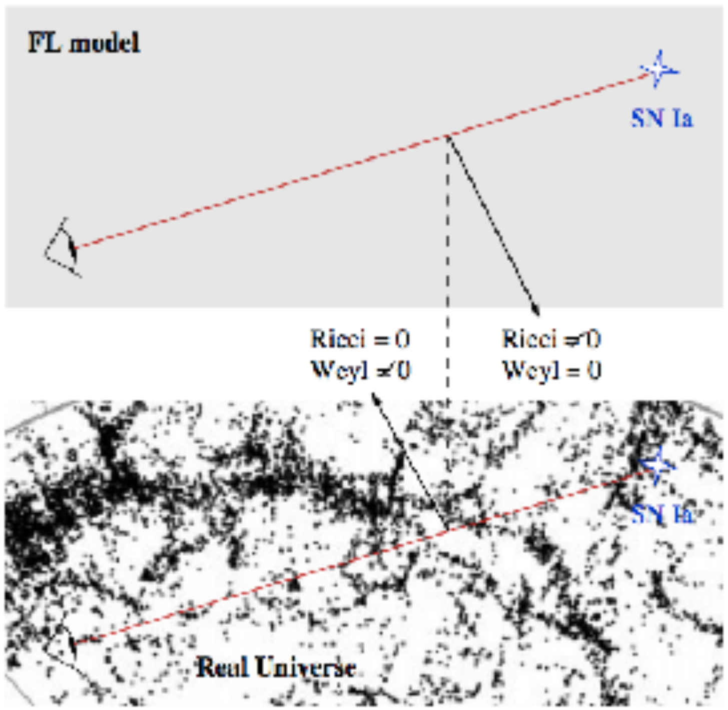
Summary + Outlook

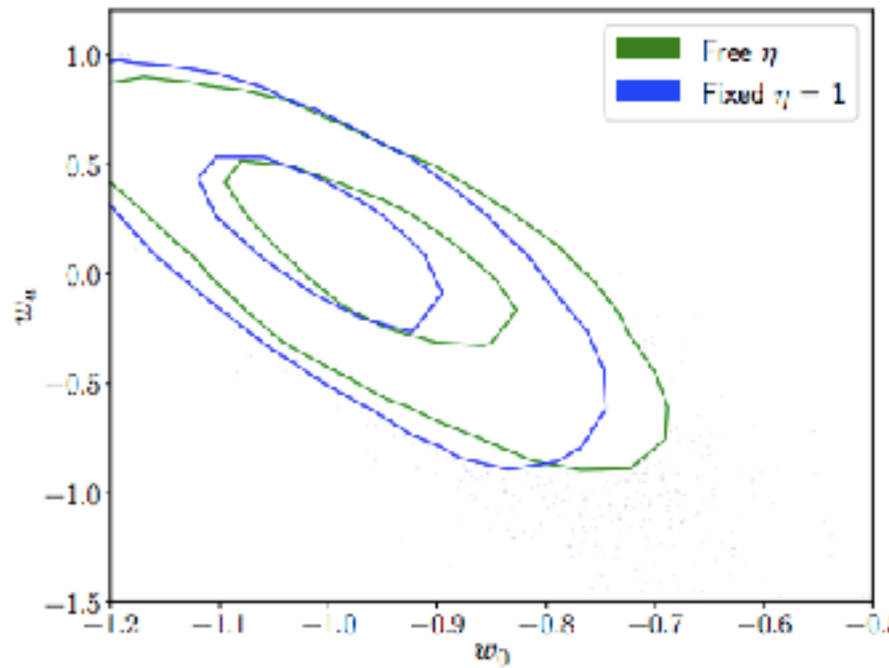
- Local distance ladder H_0 insensitive to SN systematics, e.g. dust, intrinsic scatter
  - Likely resolution of Hubble tension from early universe physics
- Moderate evidence against non-standard dark energy models
- First multiply imaged, resolved lensed SN Ia
  - Magnification insensitive to assumptions on extinction
  - Can measure extinction in each line-of-sight
  - Time-delays too small for H_0 inference
- ZTF should find more (and larger time-delay) lensed SNe
- kN constraints on inclination
  - Improve the luminosity distance inference
  - Require early-time data
  - NIR follow-up is crucial

Diagnostics



Impact of inhomogeneities





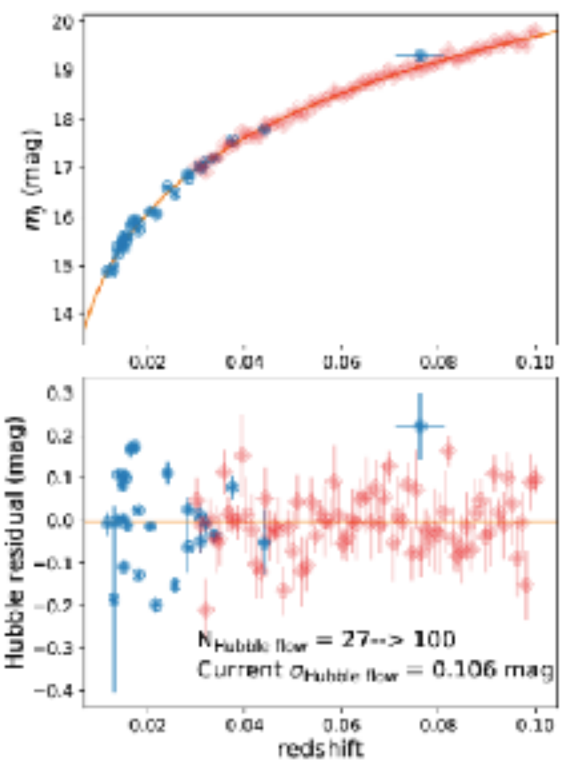
$$QD'' + \left(\frac{2Q}{1+z} + \frac{Q'}{2}\right)D' + \frac{3}{2}\eta\Omega_M(1+z)D = 0,$$

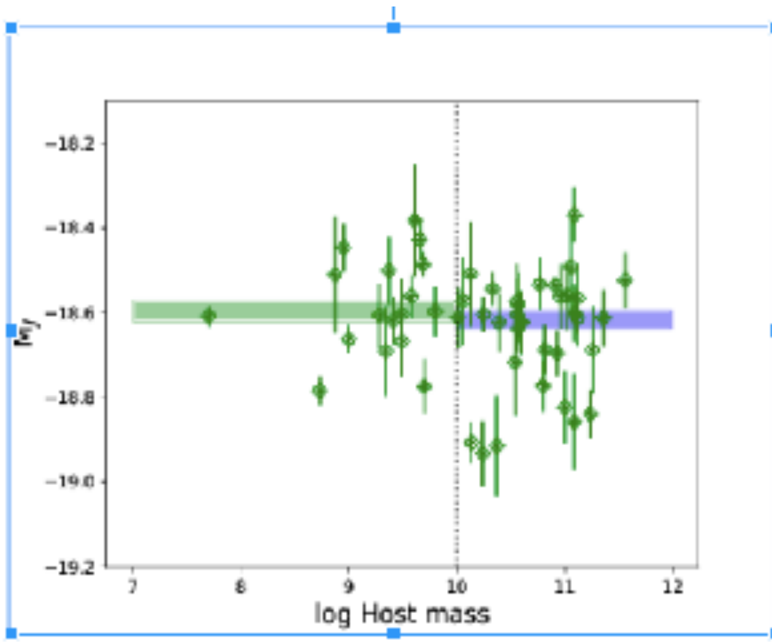
$$Q(z) = \Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_{DE}(z, w)$$

- 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?





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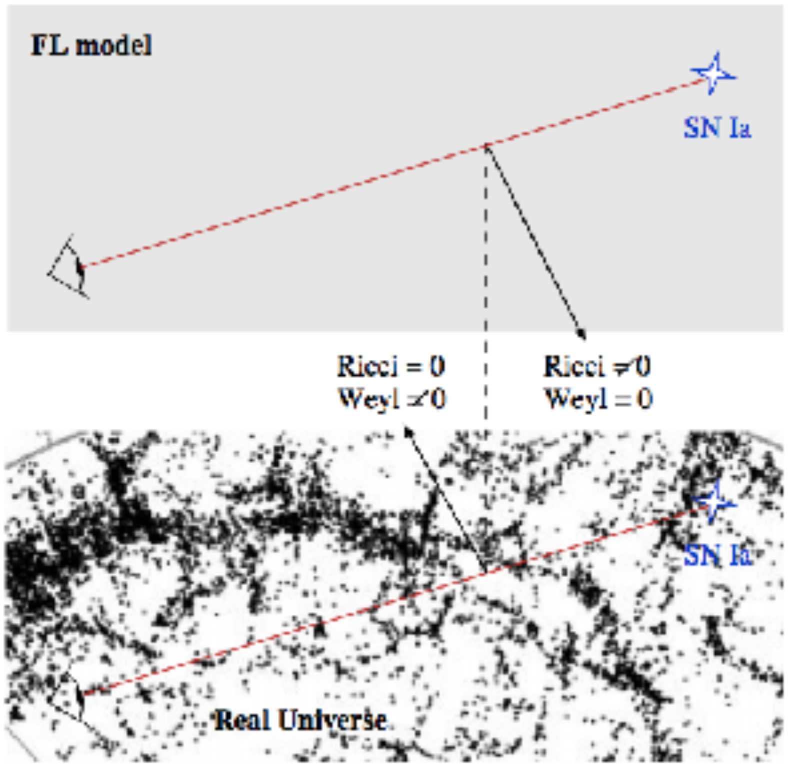


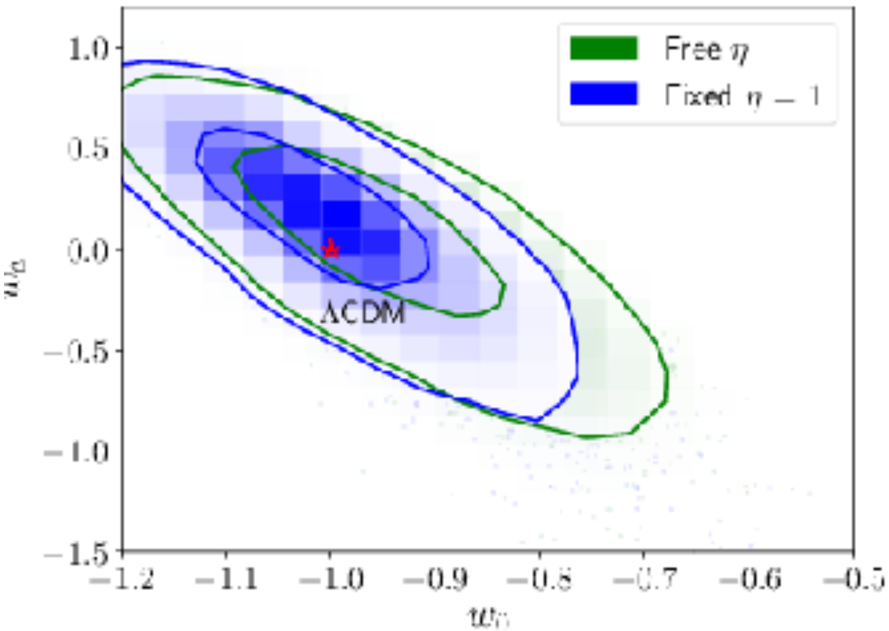
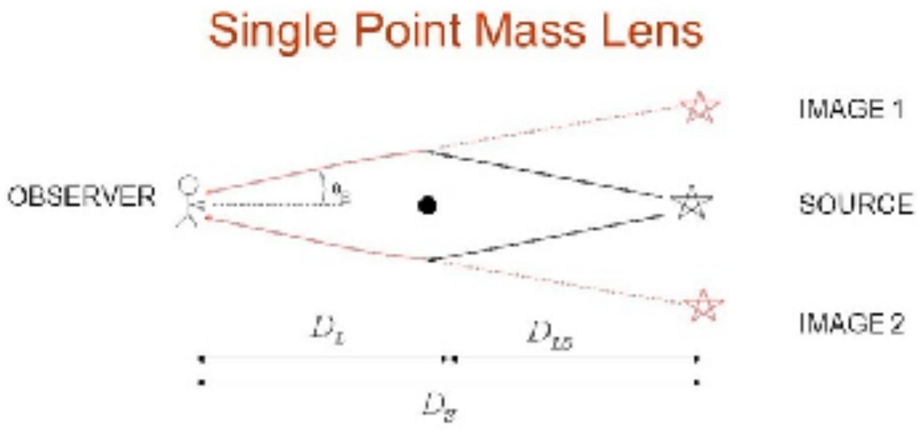


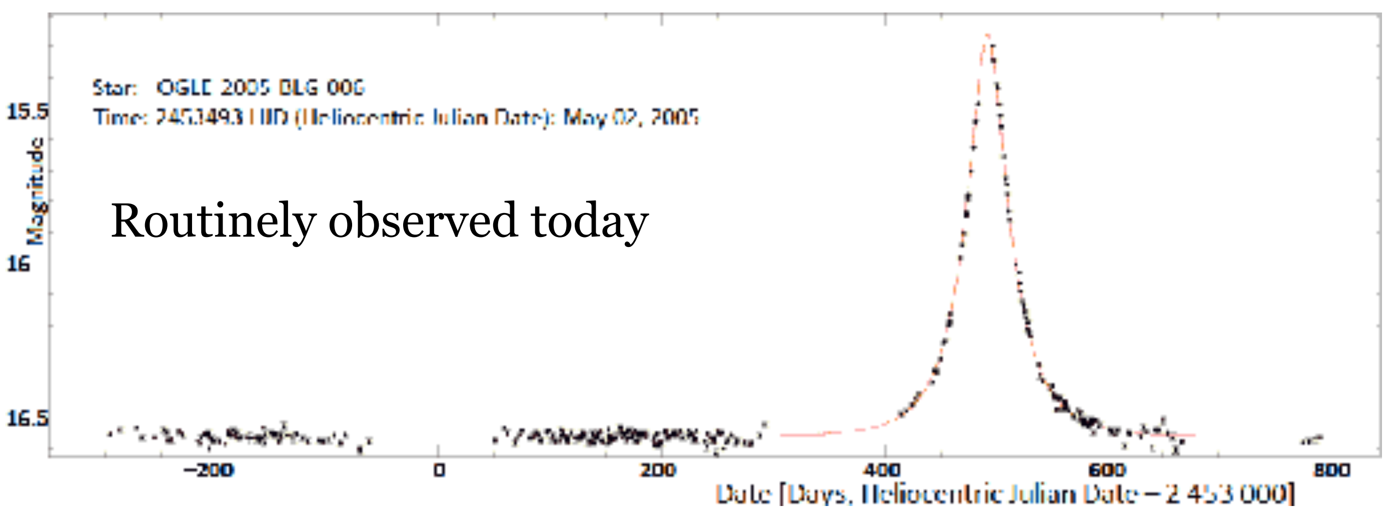
Figure: The impact of impact of departures from homogeneity on dark energy inference (**Dhawan** et al. 2018c)

Gravity in action: *micro lensing*



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

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!



Routinely observed today

Summary & Outlook

- SNIa Hubble diagram disfavors PBHs as major DM contributor over wide mass range
- Gravitational telescopes (I): can greatly enhance the depth of SN surveys. Pilot NIR survey detected 6 CC SNe up to z=1.7 (photometric typing). With sustained surveys (from space?) may be able to find first generation of SNe @z>10?
- Gravitational telescopes (II): ZTF and LSST discoveries of lensed SNIa will provide great targets for spectroscopic tests for potential evolution of "standard candle"
- Three strongly lensed SNe discovered in last few years: PS1-10afx, iPTF16geu (SN Zwicky!!) and SN Refsdal
- iPTF16geu/SN Zwicky first/only resolved Type Ia SNe, *amplification measured, without model assumptions on the lens:*

➢ *The 0.3" radius from lens among smallest systems known*. Unlike all QSO/galaxy strong lensing systems, found with low resolution imaging, thanks to standard candle nature of SNe Ia

➢ The large amplification and symmetry of the event + different brightness of images suggests that *the SN may be further lensed by substructures in the lensing galaxy, although differences for 3 images likely due to extinction in lens! Stay tuned!*

➢ *How rare? We also have PS1-10fx with large amplification. Why no smaller amplification events yet?*

➢ ZTF + LSST will tell. *If* *<u>not</u>* as rare as predicted, does this have deep implications?

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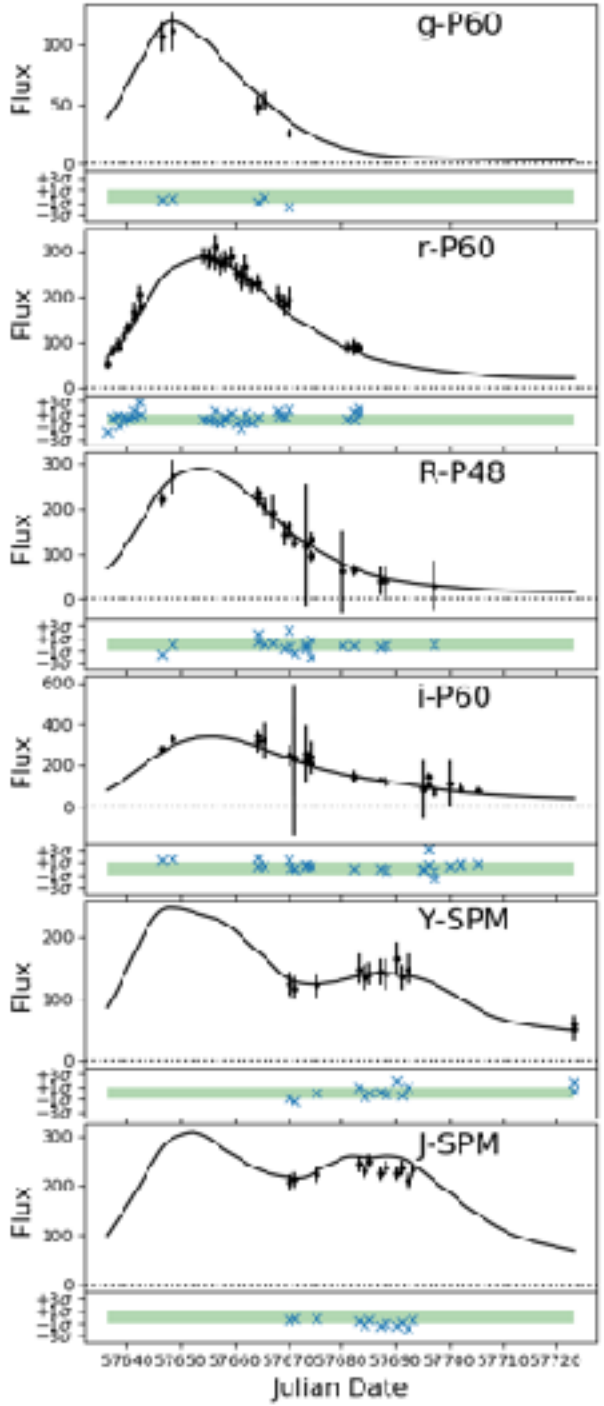
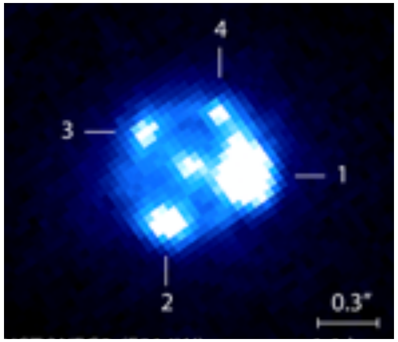
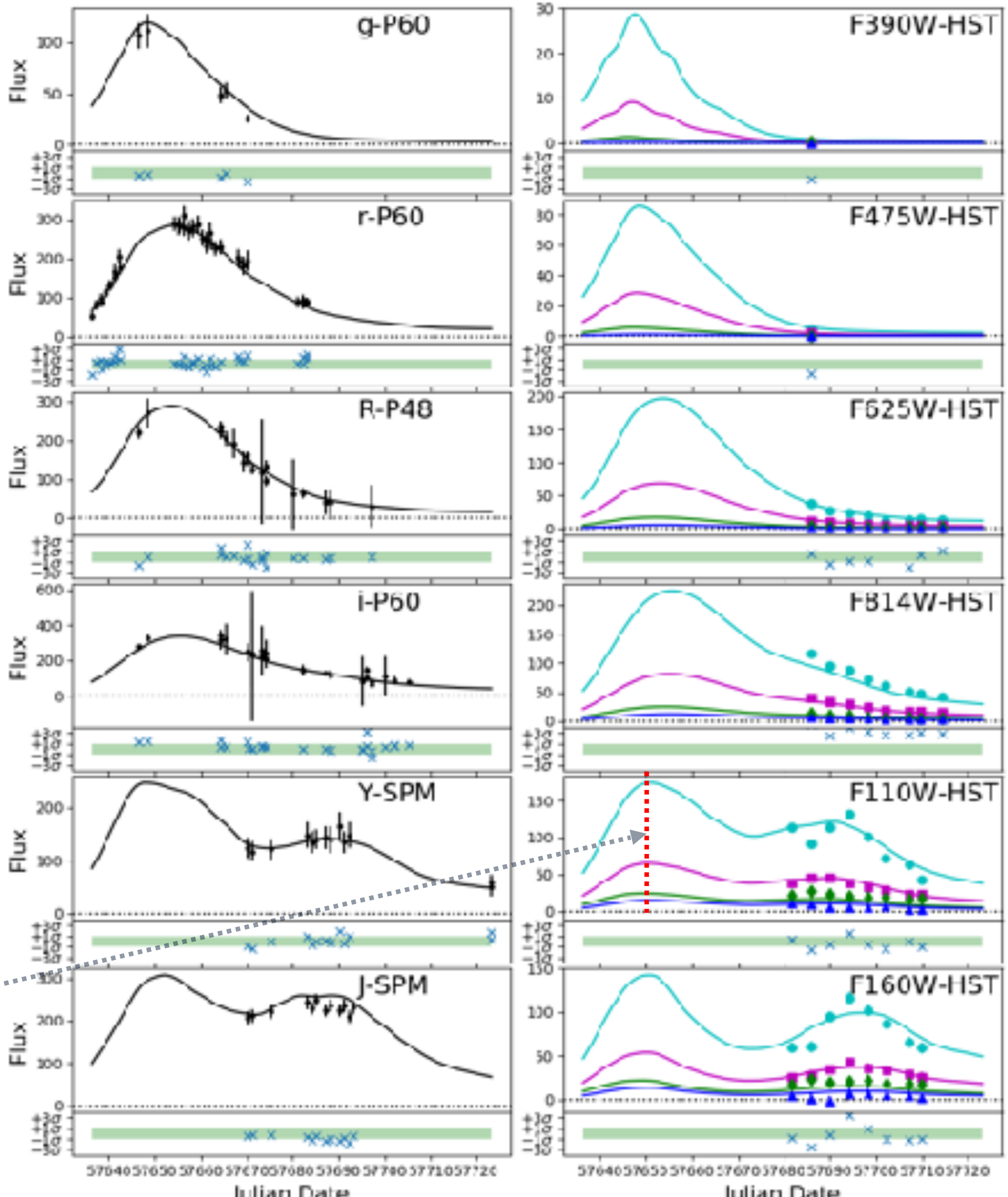




Multiband lightcurves fitted *allowing for differential extinction in lens* + common extinction in host galaxy.

Very small time-delays between images: poor constraints on H_o from this particular event!



HST

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