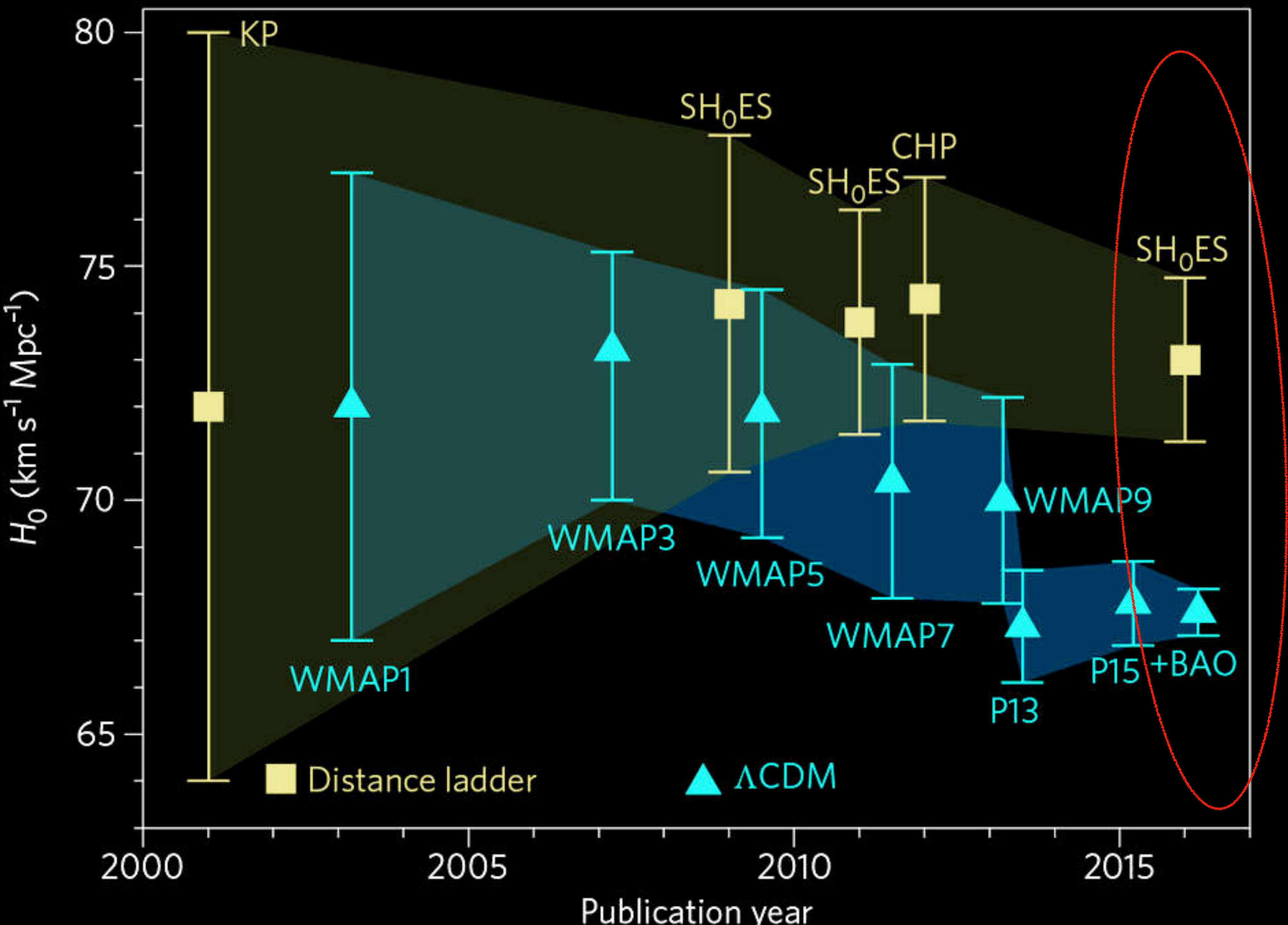
Strongly Lensed Supernovae: A New Window on Dark Energy

Danny Goldstein (Berkeley + DESC)

H_0: The Biggest Tension in Cosmology



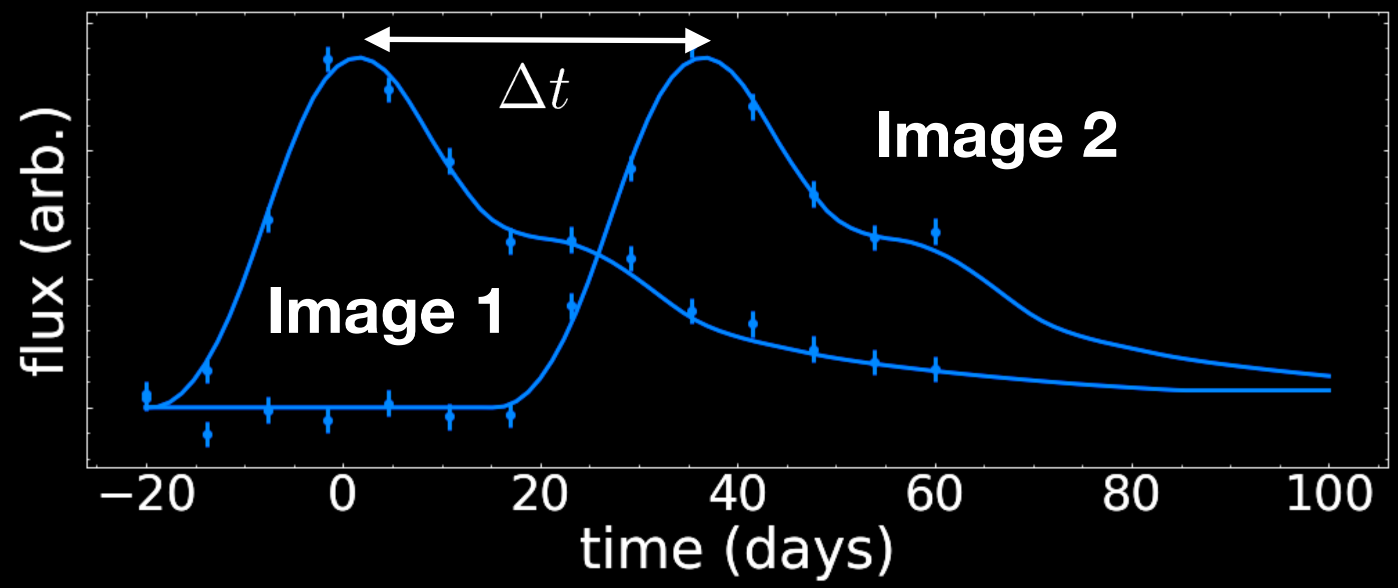
3.4σ

Need H_0 to <1% to resolve tension

Freedman 2017 (Nature Astronomy)

Time Delays: An Independent Route to H_0

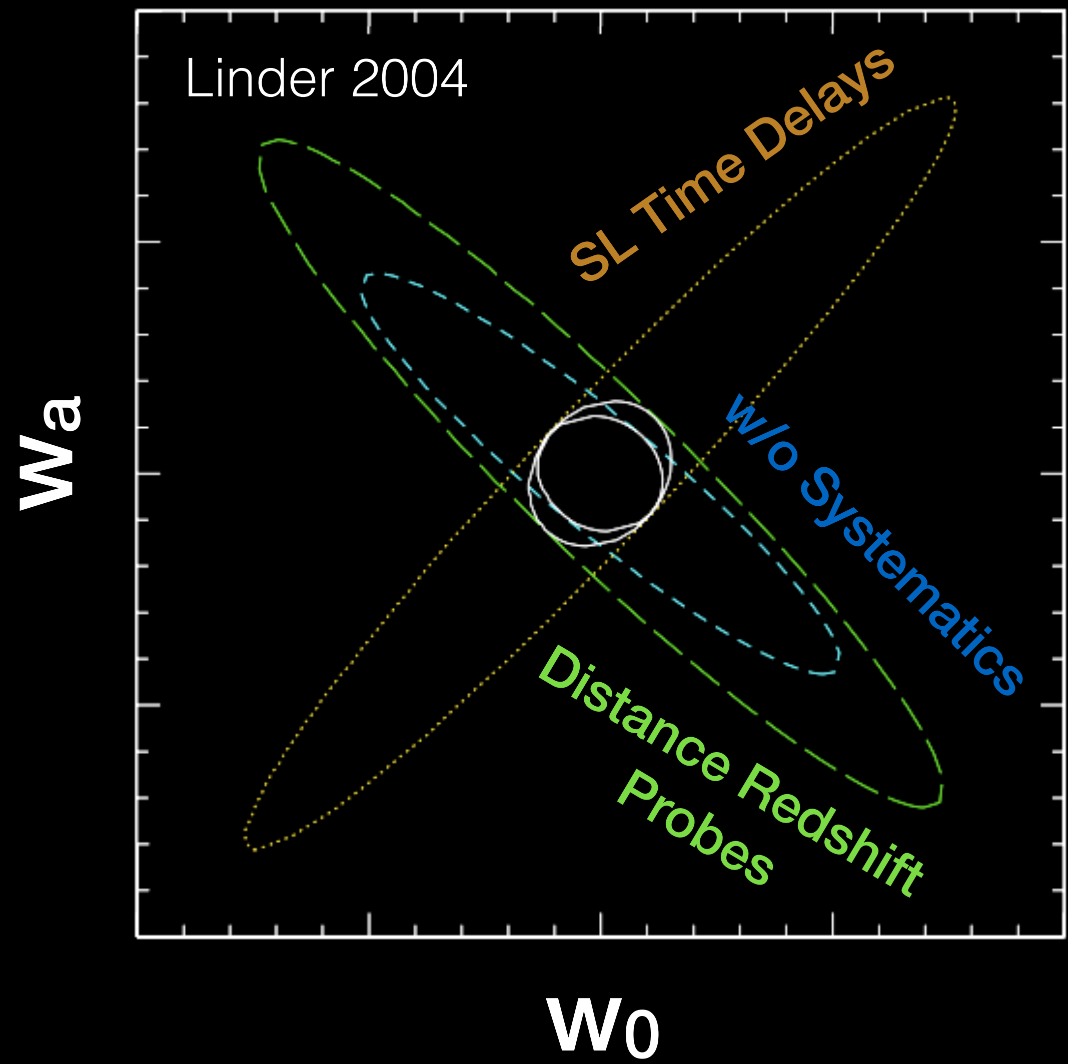
Time delays between multiple images of strongly lensed Type Ia supernovae directly constrain H_0 (Refsdal 1964) and provide leverage on dark energy (Linder 2004, 2011).



$$\Delta t \propto \boxed{\frac{D_l D_s}{D_{ls}}} \propto H_0^{-1} f(w)$$

Triple ratio of distances: a unique cosmology probe

Complementarity: The Time Delay Advantage For Dark Energy

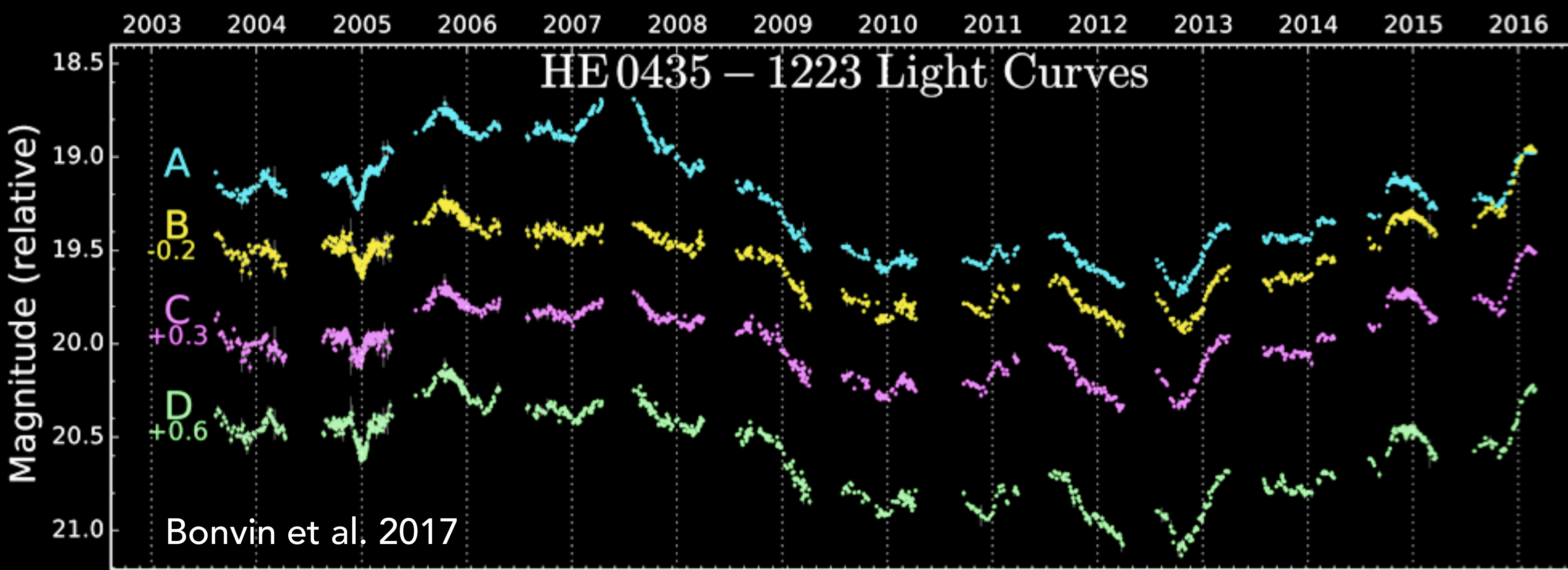


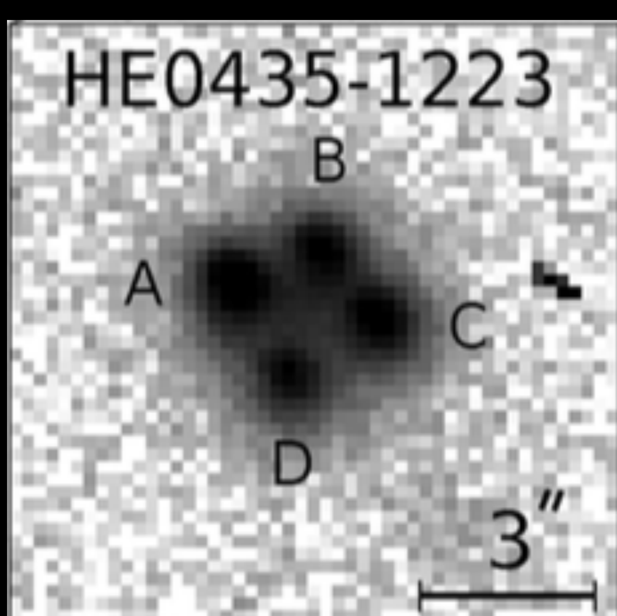
Time delays probe dark energy in a different way than standard distance-redshift and volume probes, giving them high complementarity (Linder 2004, 2011).

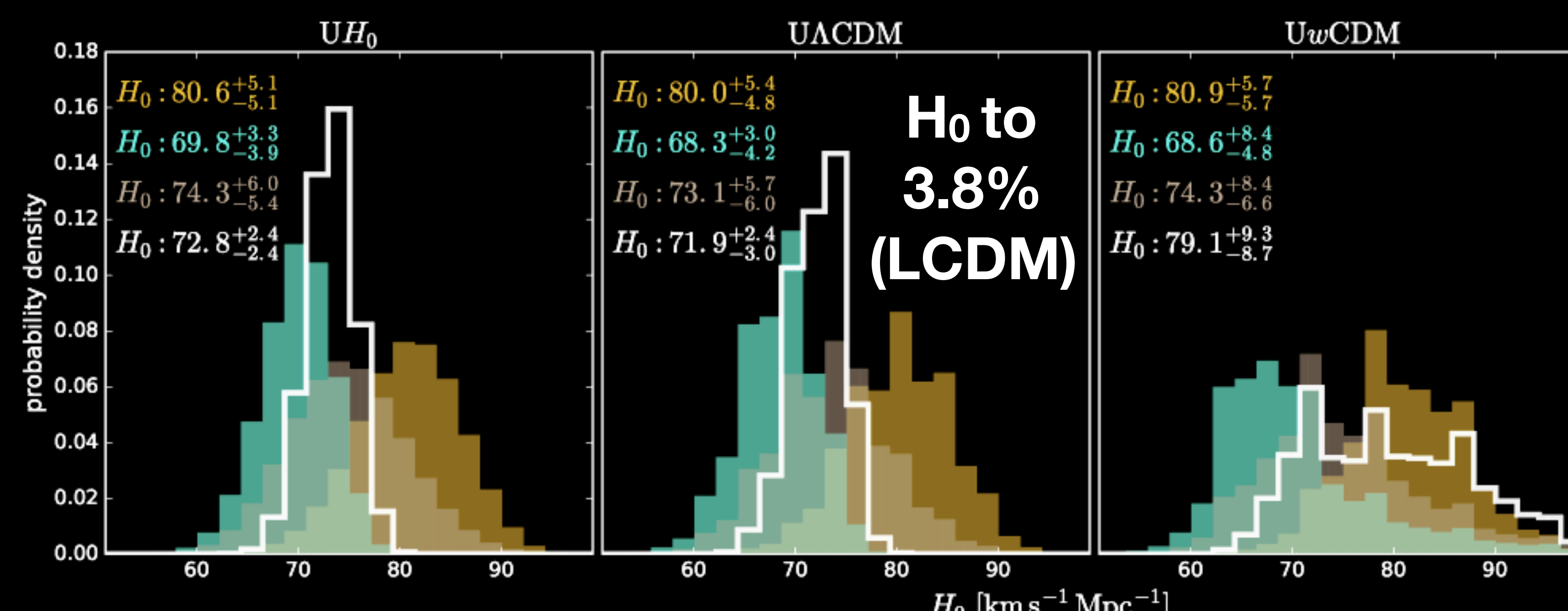
$$\Delta t \propto \boxed{\frac{D_l D_s}{D_{ls}}} \propto H_0^{-1} f(w)$$

Triple ratio of distances: a unique cosmology probe

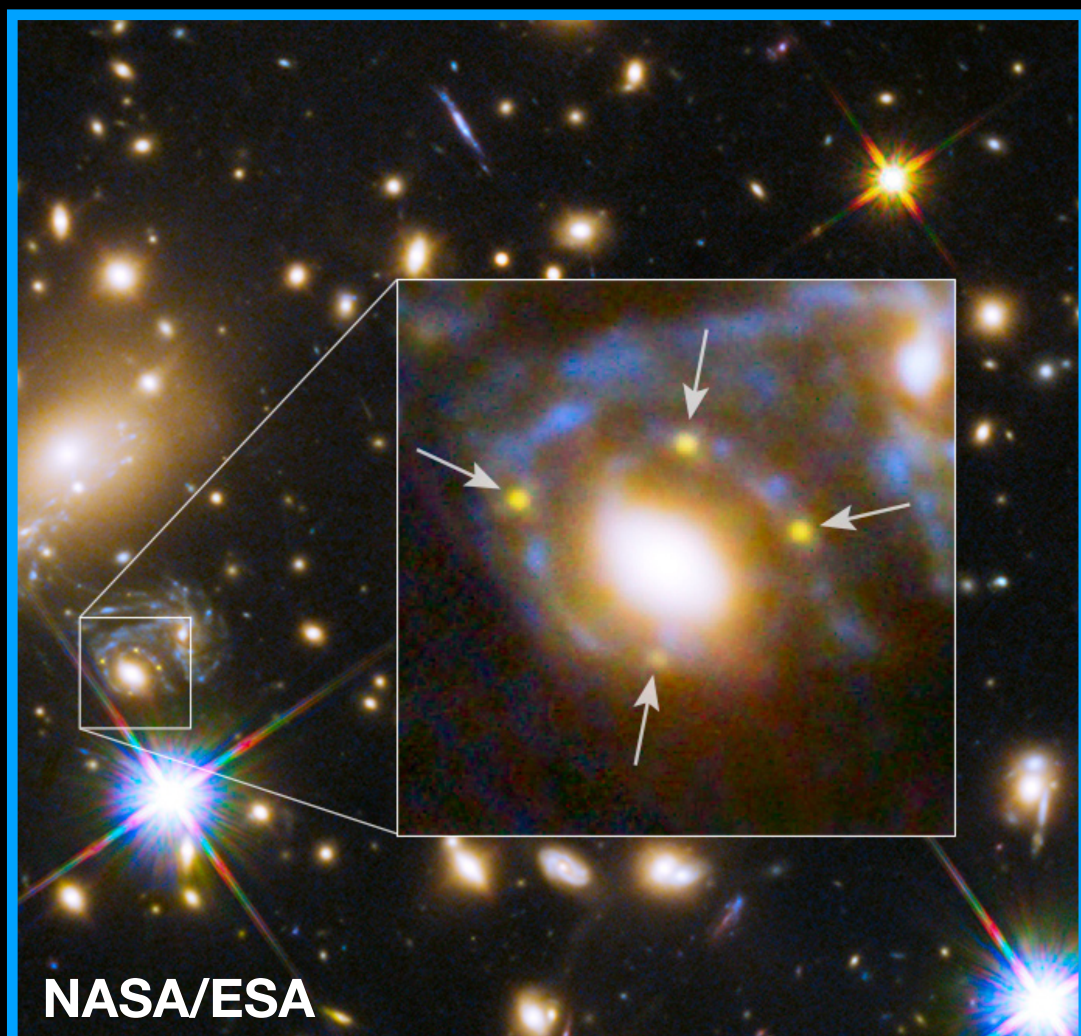
State of the art is to use strongly lensed *quasars* (see Treu talk)



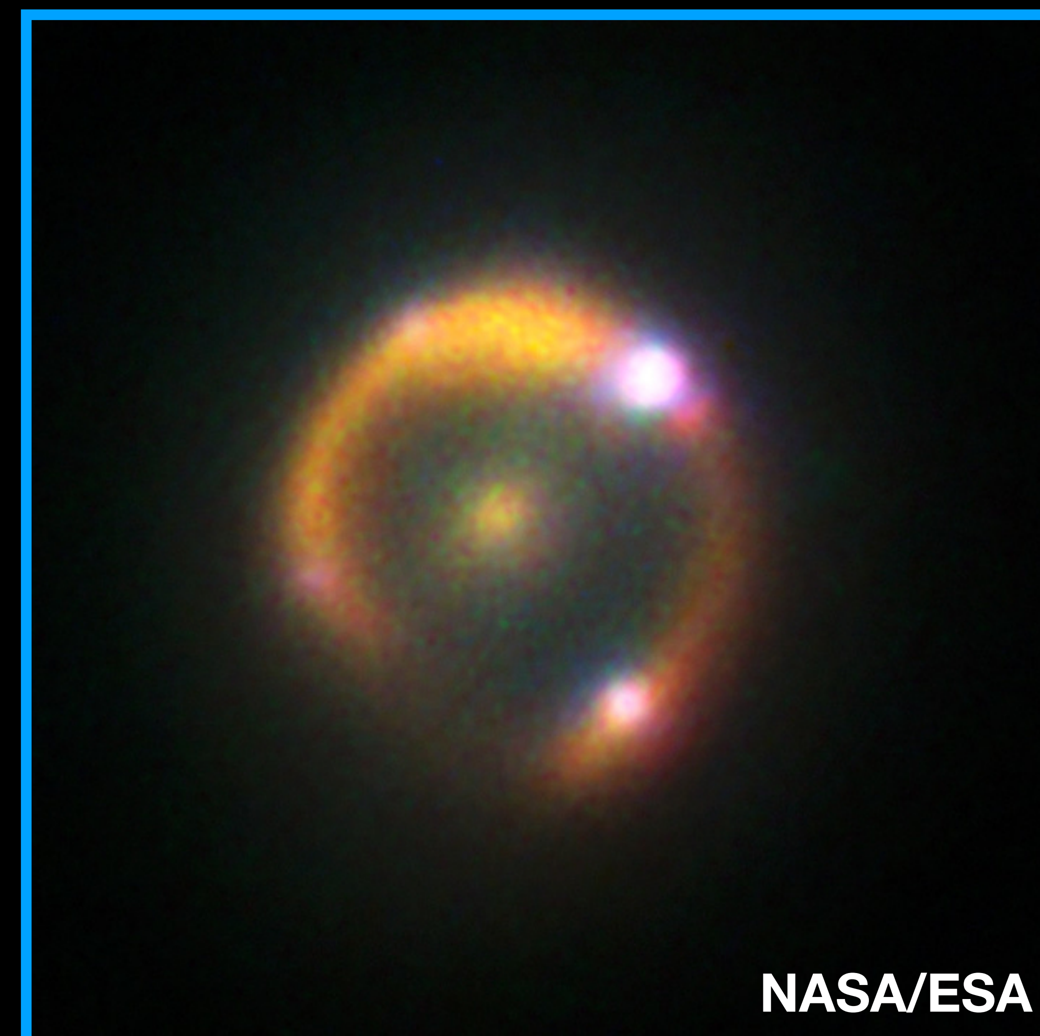




But in the past two years, the first multiply imaged supernovae were discovered!



SN “Refsdal” (SN 1987A-like) z=1.49
Kelly et al. 2015 (*Science*)
discovered w/*HST*, μ~ 10,
J~24.2 (AB)

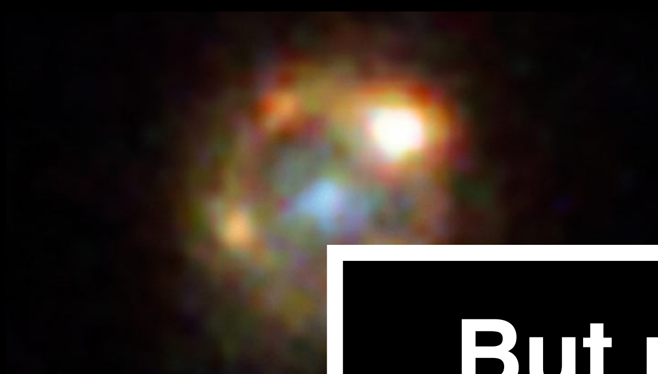


iPTF16geu (SN Ia) z=0.41
Goobar et al. 2017 (*Science*)
discovered w/ P48, μ ~ 52,
i ~ 19 (AB)

Advantages of Lensed SNe

Lensed Type Ia Supernovae	Lensed Quasars / AGNs
Require ~weeks of monitoring	Require 10+ years of monitoring
SED modeled precisely	SED not known
Need only S/N ~ 10 - 20 per LC point	Need S/N ~ 100 per LC point
Time delays unaffected by microlensing at early times	Time delays affected by microlensing at all times

Advantages of Lensed SNe



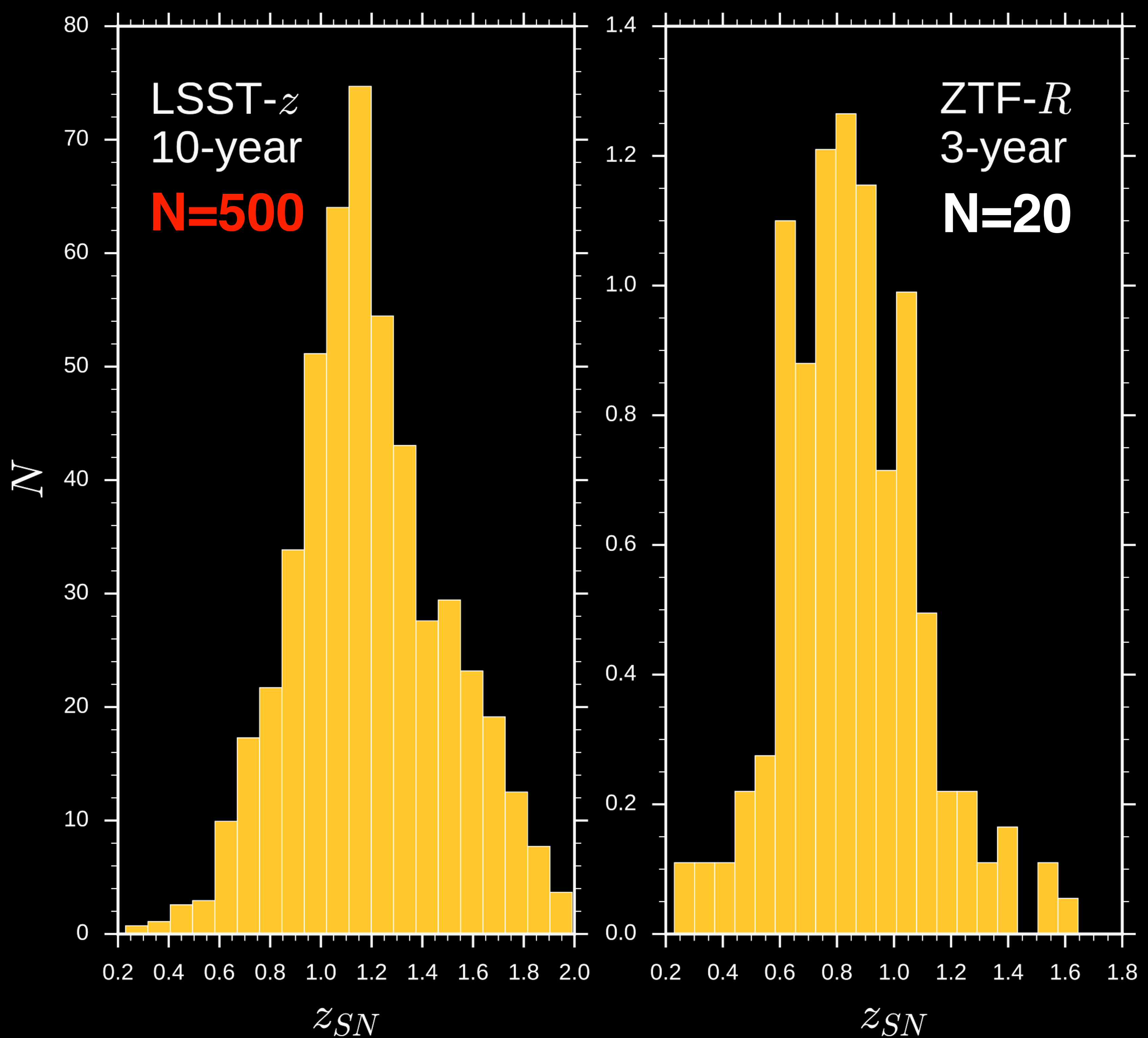
Lensed Type Ia	Lensed Quasars /
Rec	ring
Need only S/N ~ 10 - 20 per LC point	Need S/N ~ 100 per LC point
Time delays unaffected by microlensing at early times	Time delays affected by microlensing at all times

But most strongly lensed SNe are unresolvable by wide-field surveys (including LSST!), making them hard to discover.

HOW TO FIND GRAVITATIONALLY LENSED TYPE Ia SUPERNOVAE

Daniel A. Goldstein[1,2] and Peter E. Nugent[1,2]

published in ApJL (Jan 2017)



Thanks to new glSN hunting techniques, we are now expecting ~10x as many glSNe from LSST than predictions of Oguri+Marshall (2010), which required resolved images.

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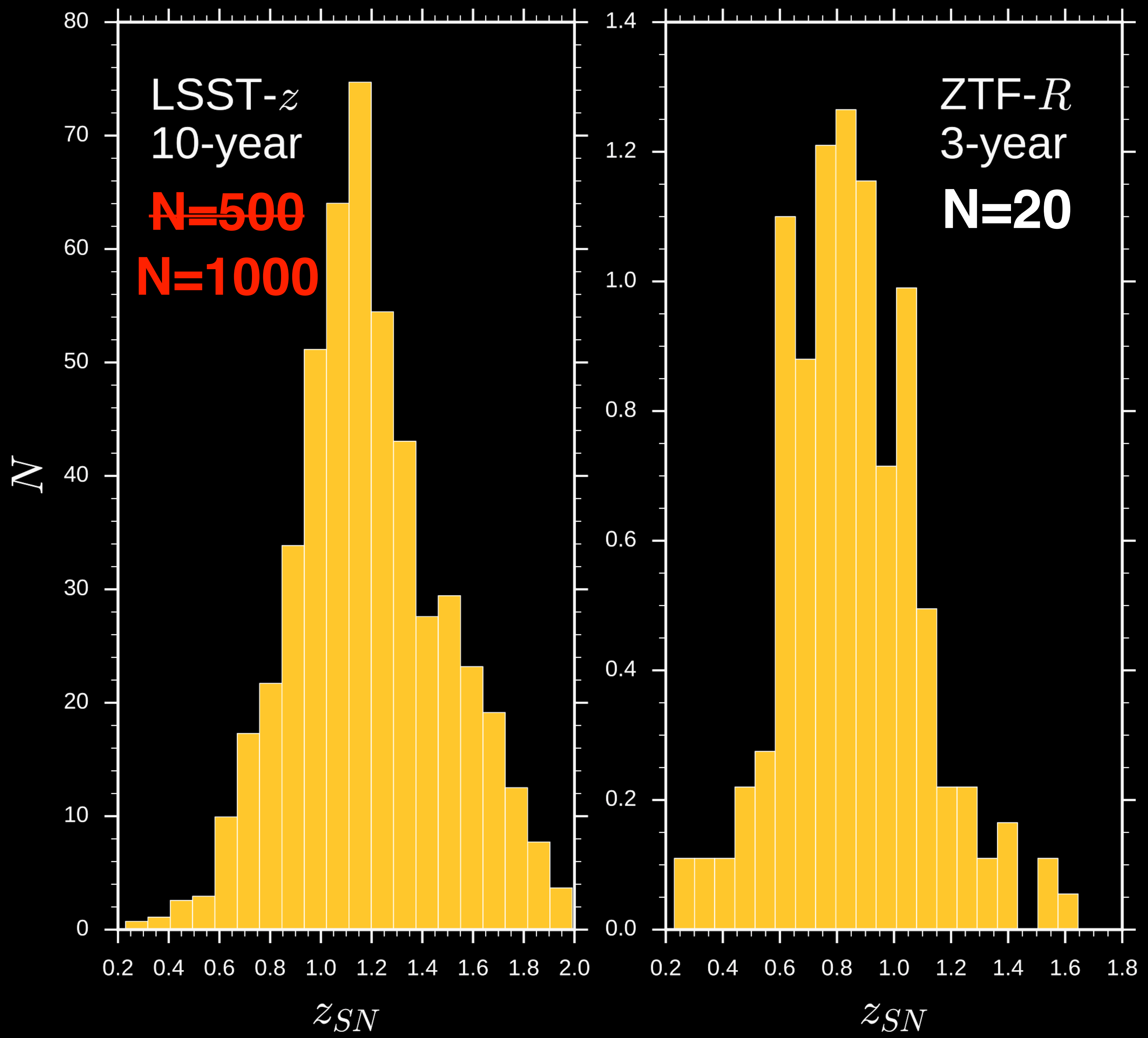
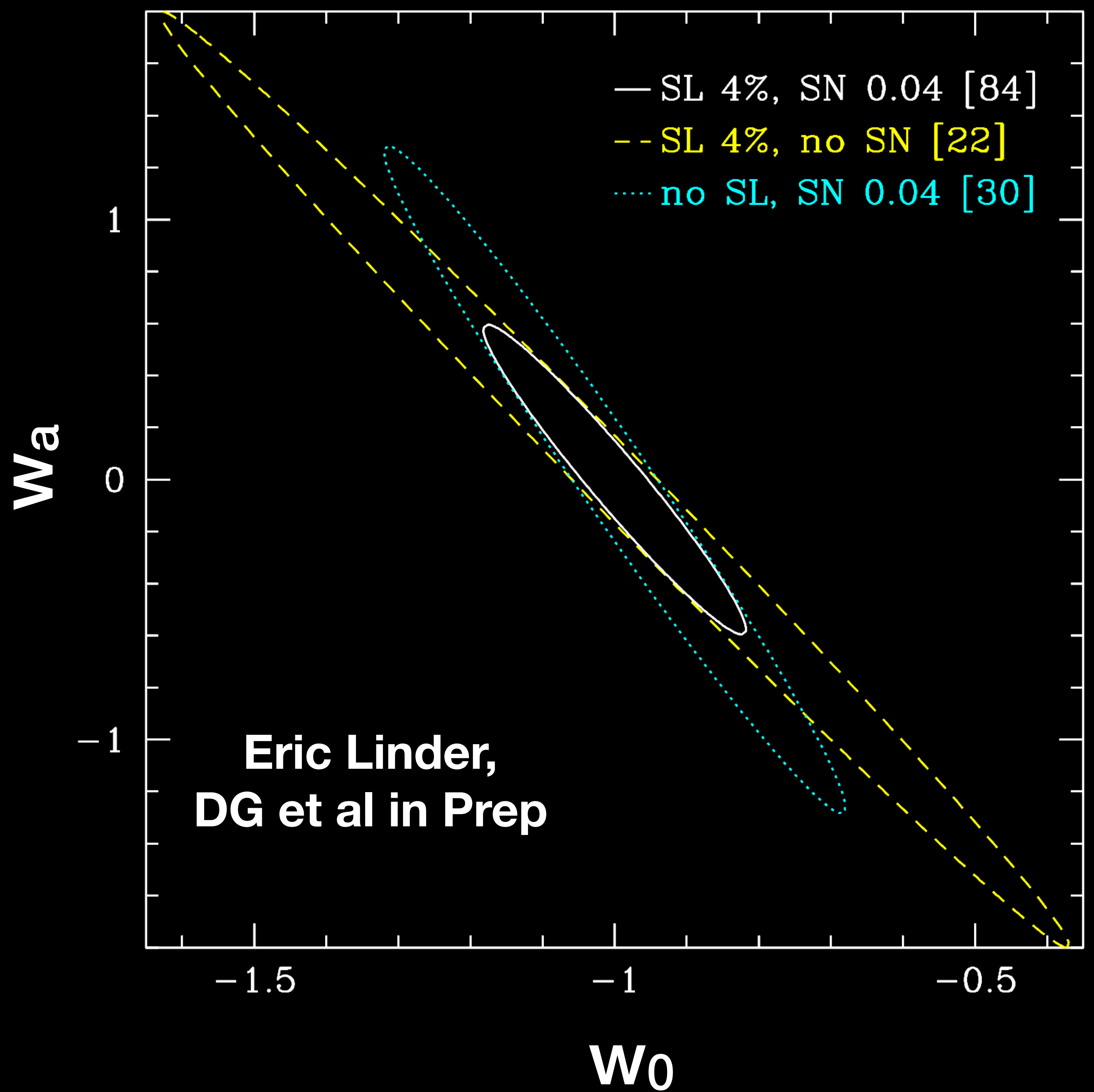


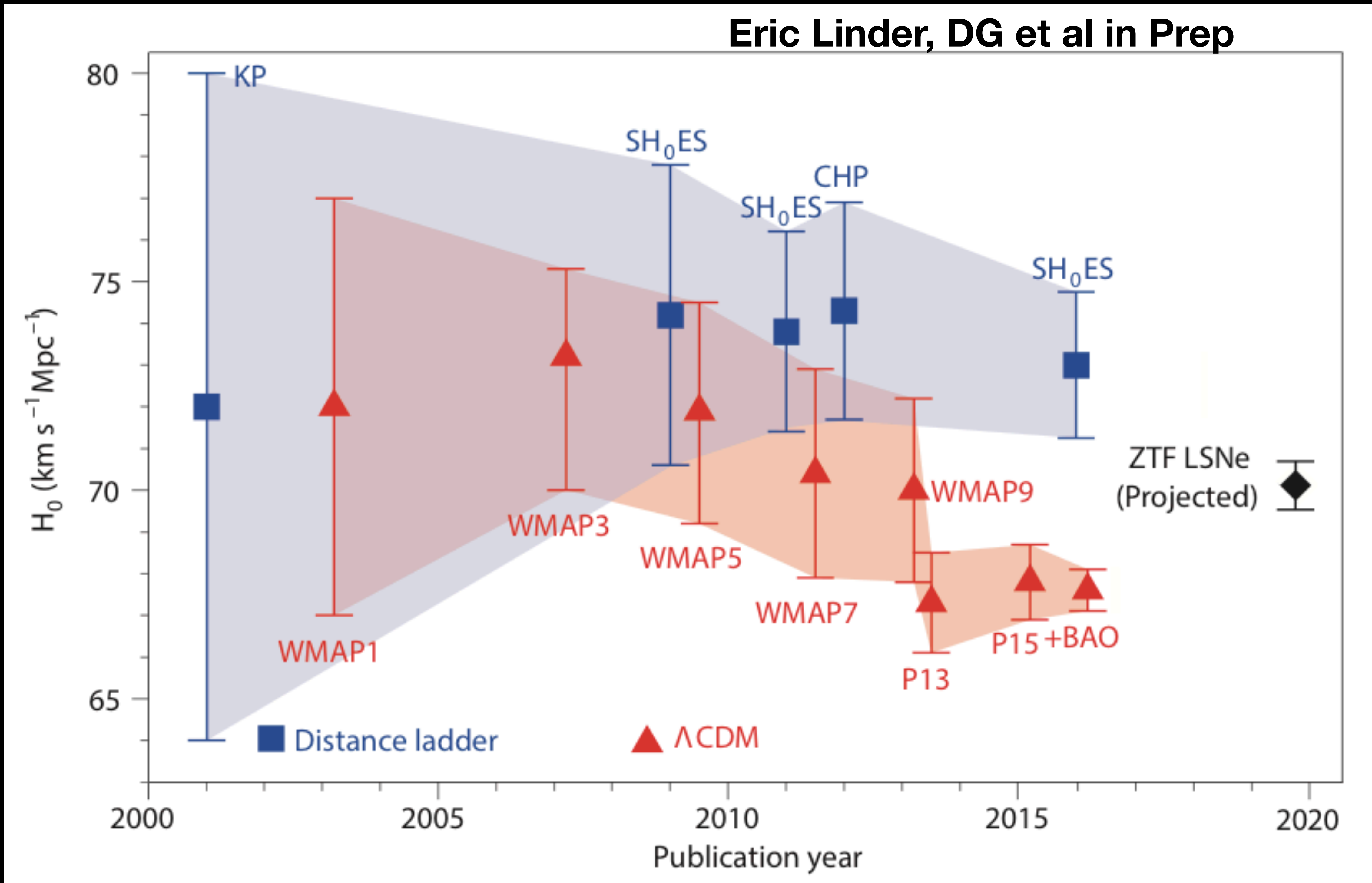
Thanks to new glSN hunting techniques, we are now expecting ~20x as many glSNe from LSST than predictions of Oguri+Marshall (2010), which required resolved images.

Dark Energy Expectations for ZTF glSNe



Time delays from ZTF glSNe can increase DE FOM by ~3-4x over SN Ia distances alone

H_0 Expectations for ZTF glSNe



Expectations for LSST?

Expectations for LSST?

Contingent on follow-up!

LSST is an excellent discovery machine—but it can't deliver SN cosmology on its own. glSNe have three specific follow-up needs:

- Need spectroscopic follow up for transient typing, source / lens redshift acquisition, and lens velocity dispersions
- Need high-spatial resolution imaging (space based or AO) for lens modeling
- Need high-cadence monitoring in multiple filters to extract precise time delays (Goldstein et al. 2017)

the “easy" part:

glSN Monitoring: AO+Non-AO

need monitoring of images to S/N ~ 20, ~8 *grizy* visits per image @ 4 day cadence = ~few % time delays (incl. systematics)

- Given 500 time delay glSNe…
- ~300 have image separation greater than 0.6’’, could be monitored with 4m-class telescope (no AO), ~few hours total per system, can pick these off in concert with QSO team
- ~200 need AO monitoring, could use a 2m telescope for ~1 day total per system with RoboAO

4m uncorrected

+

2m AO

glSN Spectroscopy

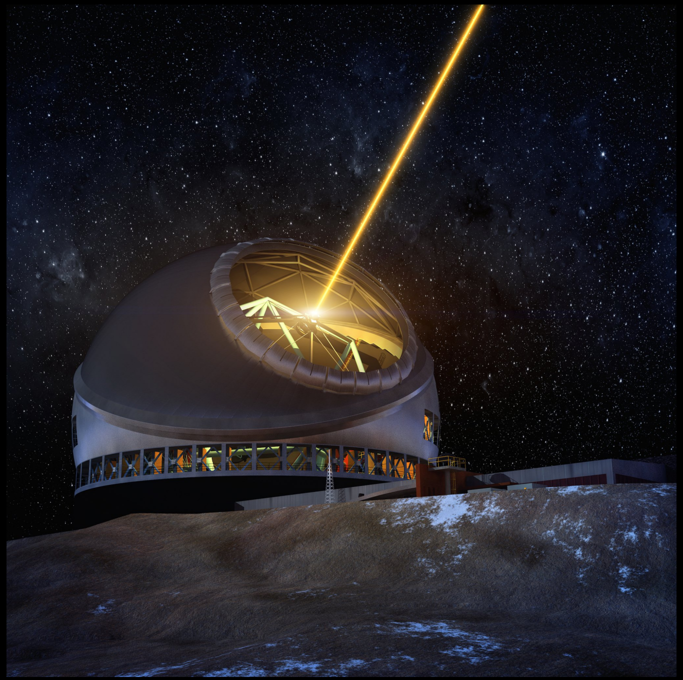
need source redshift (z~1), lens redshift (z~0.5), and lens σ (to ~20km/s)
same needs as lensed QSOs, plus transient classification

- Half of lens redshifts will be provided by DESI (to z~1), more from 4MOST
- Velocity dispersions – R ~ 2000+: nearby – long (6-8hr) integrations on 4m class, ~few hr per lens on 10m class, z~1 must go to Keck, TMT
- For source redshifts, could do everything with ~2 weeks of Keck; a few days of TMT.
- Bright transient classification can be done with low-resolution (R~100) spectra on a small (~2m) telescope with long integrations
- Fainter transients: can obtain classification and redshifts from 4m, 8m, Keck, and later TMT

glSN Hi-res Imaging / AO

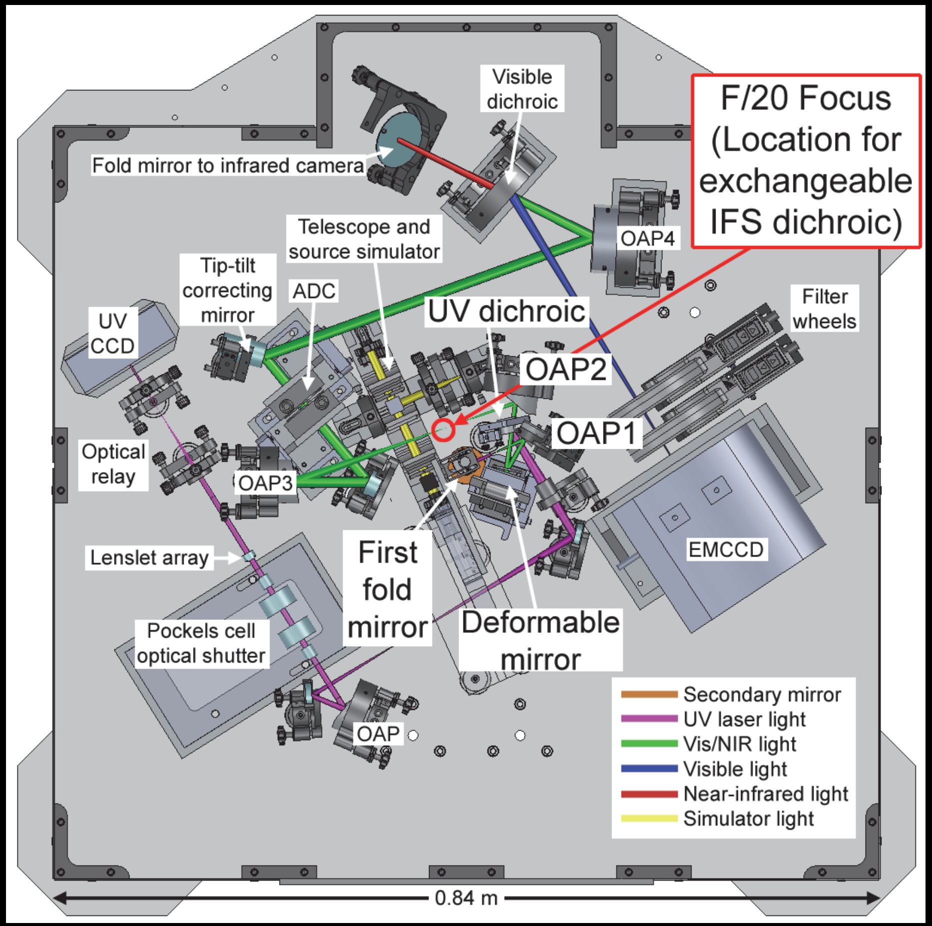
need high angular resolution imaging (0.1″) of lensed SN and host galaxy to model potential

- Current state of the art is HST imaging: ~few % measurements of the lens potential with ~few hr of integration (but fate of HST past 2021 is uncertain)
- WFIRST will be able to provide sufficient resolution to model the brighter systems – with an IFC, can also get transient typing, photometric redshifts of nearby galaxies, possibly redshifts



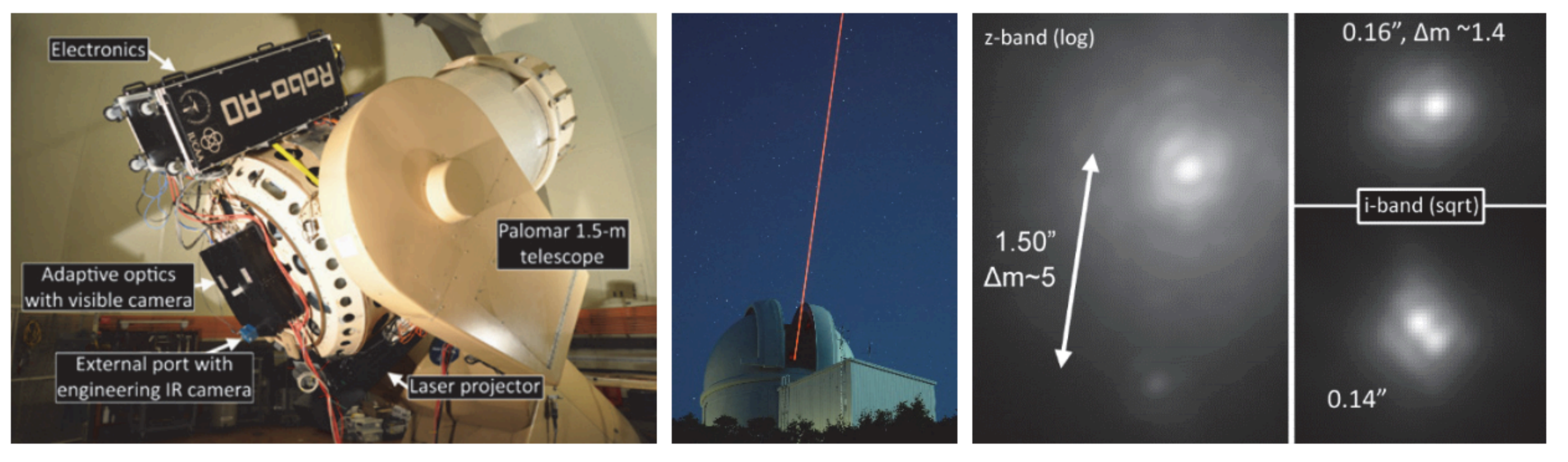
- ELTs: ~10x resolution of HST, can easily pick off targets with 15-30 minutes of integration

Baranec+16

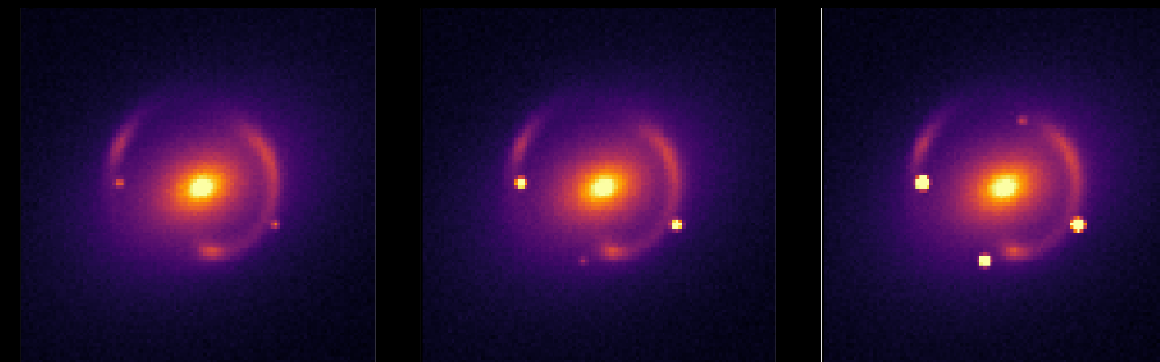


Rapid Transient Surveyor: a solution for resolved image monitoring (and transient typing?)

- AO Acuity 0.1” (Vis) 0.16” (IR)
- Designed for rapid response, cadence
- R~24 in 2-3hr on UH 2.2m
- IFU w/ R ~100 over 650-1700nm



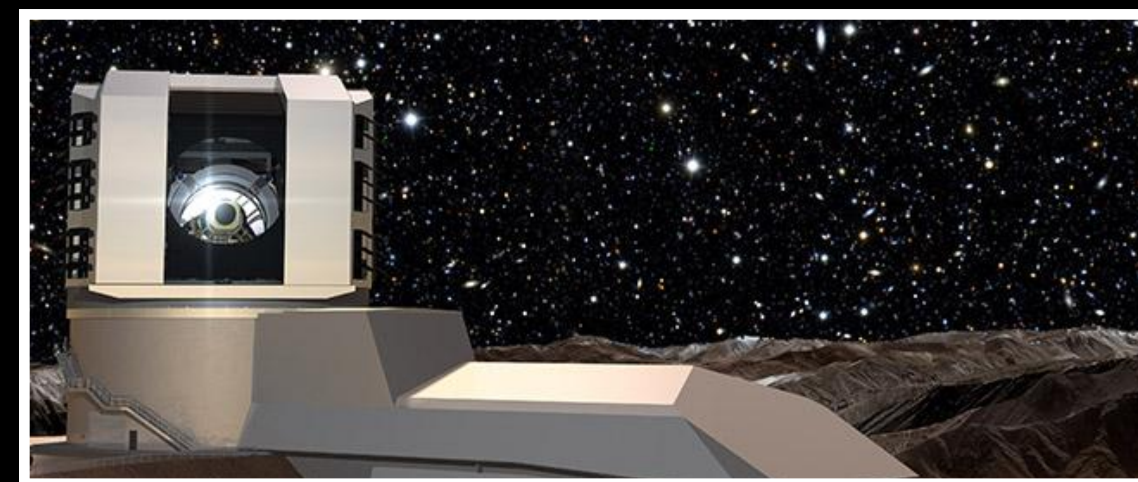
Summary



- LSST should find ~1,000 strongly lensed SNe Ia. ZTF (starting April) should find 10-20.

- Time delays from these systems can provide sub-percent constraints on H_0 independent of the local distance ladder and CMB, and leverage on dark energy when combined with other probes.

- To extract cosmology from these objects, follow-up resources for monitoring, high-res imaging, and spectroscopy are needed. Much of this could be accomplished with 4-meters.



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CVDE: 5 Questions

- ***How will this effort enhance our current knowledge of dark energy?***
  - Can deliver sub-percent constraints on H0 independent of the local distance ladder and CMB, and leverage on dark energy when combined with other probes.
- ***How does the idea complement other efforts?***
  - Dark energy constraints from time delays have high complementarity with essentially every other probe (Linder 2011); this effort can share resources with lensed QSOs
- ***Cost estimate***
  - $1.2M / yr for operations, $2M to finish RTS as the AO system is already funded (NSF). Assuming we can make use of SNAP/JDEM IR chips.
- ***Timeline***
  - ZTF (2018-2020) will be the pathfinder for this analysis, laying the groundwork for LSST which will come immediately after.
- ***What are the key technical and logistical obstacles (if any)?***
  - Organizing an array of follow-up resources (spectroscopy, monitoring) that can respond rapidly to new glSNe