Snowmass2021 - Letter of Interest

[Measuring H_0 in the 2020s]

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Rachael L. Beaton/Princeton
Collaboration (optional):
Contact Email: rachael.l.beaton@gmail.com

Abstract: Many of the fundamental physical constants in Physics, as a discipline, are measured to exquisite levels of precision. The fundamental constants that define Cosmology, however, are largely determined via a handful of independent techniques that are applied to even fewer datasets. The history of the measurement of the Hubble Constant (H_0), which serves to anchor the expansion history of the Universe to its current value, is an exemplar of the difficulties of cosmological measurement; indeed, as we approach the centennial of its first measurement, the quest for H_0 still consumes a great number of resources. In this LOI, we discuss how the approaching era of Extremely Large Telescopes (ELTs) could transform the astrophysical measure of H_0 from the limited and few into a fundamentally new regime where (i) multiple, independent techniques are employed with modest use of large aperture facilities and (ii) 1% or better precision is readily attainable. This quantum leap in how we approach H_0 is due to the unparalleled sensitivity and spatial resolution of ELT's and the ability to use integral field observations for simultaneous spectroscopy and photometry, which together permit both familiar and new techniques to effectively by-pass the conventional "ladder" framework to minimize total uncertainty. Three independent techniques are discussed – (i) *standard candles* via a two-step distance ladder applied to metal, poor stellar populations, (ii) *standard clocks* via gravitational lens cosmography, and (iii) *standard sirens* via gravitational wave sources – each of which can reach 1% with relatively modest investments from 30-m class facilities. These measurements, however, require a range of facilities and we further emphasize the importance of community access to a diverse range of facilities in both hemispheres.

H_0 and the Cosmic Frontier:

Since its theoretical prediction[1] and experimental discovery[2], the Hubble constant (H_0) has been a critical parameter for cosmological models. The history of its measurement is demonstrative of its importance, as the resolution of controversy in its measured or inferred value from independent lines of evidence has led to fundamental discoveries in cosmology, including most recently Dark Energy. Moreover, the pursuit of ever more robust measurements of H_0 has motivated facilities and refinements of instrumentation and technique that have broad influence.

Since the HST Key Project in 2001[3], the landscape for measuring H_0 has culminated in its measure at $\sim$2%[4;5;6;7;8] via the traditional Cepheid-based distance ladder. Likewise, via modeling of the anisotropies of the Cosmic Microwave Background (CMB) has improved from WMAP[9] in 2013 to a 0.6% measure from Planck in 2018.[10;11] The past decade has also seen the realization of long proposed techniques[12;13] to measure H_0, including gravitational lens cosmography[14;15;16;17] and gravitational waves[18], both of which are delivering comparable accuracy and precision to the traditional methods.

As we look toward the 2020's, we do so at yet another conflict in the value of H_0[19;20]. Recent investigations have shown that, if calibrated either locally or to the CMB, the two tracers of evolution of the expansion, the Baryon Acoustic Oscillations (BAO) and Supernovae Ia, produce results that are largely in agreement.[21] Thus, while the middle-ages of the Universe are well probed by current techniques, how they are anchored – either in the Universe's youth or at its current age, result in different cosmologies due to the strong degeneracy between H_0 and other cosmological parameters. Model-independent probes of H_0 are critical.

Theoretical means to resolve the tension require "new physics."[22;23;24;25] Proposed modifications to the standard model include evolving dark energy[22], interacting dark matter[23;24], and interacting neutrinos [25], among others. Moreover, despite an ever-increasing volume of work presenting detailed tests, debate continues regarding if there are lingering *instrumental systematic effects* or if there are nefarious *astrophysical systematic effects* impacting the techniques as they claim unprecedented precision and accuracy. [11;26;27;28;29;30]

While on-going studies may indeed provide resolution to the current H_0 controversy, the community is still, effectively, limited to two high-precision techniques for measuring H_0. Because H_0 is a fundamental quantity, it must be measured rigorously by independent techniques, independent teams, and independent datasets. **In this LOI, we highlight the key science contributions that Extremely Large Telescopes (ELT's) will provide to enable three independent and fundamentally different measurements of H_0 at the 1% uncertainty level.** The different means of measuring H_0 with ELT's are:[31] (i) using *standard candles* via luminosity distances (§ 1), (ii) using *standard clocks* via gravitational lens time delays (§ 2), and (iii) using *standard sirens* via gravitational wave sources (§ 3).

1 H_0 via Standard Candles

The modern distance ladder,[32] combines geometric calibrations of stellar standard candles to calibrate the SNe Ia and then determinate H_0 from SNe Ia in the Hubble Flow. While the traditional distance ladder uses Cepheid-type variables, recent work has demonstrated the tip of the red giant branch (TRGB) is a powerful distance indicator.[27;28;33] Major advantages of the TRGB-method[33;34] are that RGB stars can be found in low-stellar density, low-reddening, and low-metallicity stellar halos of galaxies; RGB stars are present for all Hubble types; RGB stars are non-variable such that only a single set of imaging in two bands are required to make the measurement and in the IR. Taken together, the IR-TRGB requires $<$ 1/10th the observing time of Cepheids and is free from the bulk of its systematics.[33;35]

Working together with time-domain imaging on 8-m class facilities, ELT's enable the time-domain spectroscopy necessary to extend 1% geometric distances with eclipsing binaries from 50 kpc[36;37] to 1 Mpc to expand the number "anchor" systems for the distance scale.[38] The IR-TRGB can measure distances to galaxies directly in the Hubble Flow (e.g., $D \sim 100$ Mpc) on 30-m class facilities.[39;40;41;42;43] For a galaxy at 100 Mpc ($m - M = 35$ mag), the apparent magnitude of the TRGB is m_H=29 mag – as an example, this corresponds to a ∼1 hour integration with TMT+IRIS for photometry at 20σ (∼0.05 mag uncertainty per star). At this distance, each galaxy is an independent, 5% measurement of H_0 and reaching 1% precision in H_0 would naively require ∼25 galaxies.

2 H_0 via Standard Clocks

Gravitational lensing time-delay cosmography can also determine H_0. If a multiply-imaged, lensed object has intrinsic variability, then the same variable behavior will appear in each of the individual lensed images at delayed times due to different light travel paths. The time-delay, or difference in travel time, depends on the space-time curvature and the distances involved in the lensing system with the result that with the time delays measured, we can infer absolute distance ratios and measure H_0.

The lensing systems will be discovered by current and future deep imaging surveys on 8-m class telescopes[44;45] and from space with the Euclid and Roman Observatories. Follow-up confirmation requires 8-m class telescopes, while subsequent monitoring can be conducted on smaller aperture facilities.[46] High spatial resolution imaging and spectroscopy data are required to produce a precise mass model for the primary lensing galaxy and to account for the mass distribution along the line-of-sight.[17;47;48;49] Only a 30-m class facility, however, can provide the integral field spectroscopy at sufficient spatial resolution and sensitivity to produce the precision cosmographic measurements – reducing the distance uncertainties from $\sim 20\%$ to $\sim 7 - 8\%$ per system.[49;50] Using current error-budgets, a 1% precision measurement of H_0 requires gravitational time-delay measurements for 40 systems.

3 H_0 via Standard Sirens

Gravitational Wave (GW) signals act as *standard sirens* and provide a third independent route to H_0.[13] The observable quantities from a GW signal are: the amplitude, h, the GW frequency, and the chirp rate and these correspond to three physical parameters of chirp mass, frequency, and the distance.[51] With source localization (either with a third GW detection or electromagnetic counterpart), the only other data required to measure H_0 is the redshift of the host galaxy. Sufficient sources for a 5% measure of H_0 are anticipated within 5 years of sustained LIGO/VIRGO operation.[52] The first kilonova event provided a 10% estimate of H_0, with much of the uncertainty coming from the inclination;[18] thus, achieving a 1% H_0 measurement will require redshifts of ∼25 GW host galaxies.

4 Recommendations

A 1% measure of H_0 with the CMB provides constraints on the nature of dark energy, the physics of neutrinos, the spatial curvature of the Universe, and has the potential to reveal "new physics" with confidence. While great progress has occurred, the community still lacks sufficient clarity from cosmological model-independent measurements of H_0. We have described how ELTs have the potential to change how H_0 is measured, providing three CMB-independent paths at 1% precision[31], and, given the longevity of such facilities, providing sustained, long-term improvements for cosmological measurements. Coordinated dual-hemisphere programs are best able to deliver these measurements.[53] The critical capabilities are:

- 30-m class telescopes with high-resolution, high-sensitivity integral field spectrographs.
- Community access to 4-m, 8-m, and 30-m class facilities in both hemispheres.[53]
- Open access transient broker services like ANTARES.[54]

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Authors: (names and institutions)
Simon Birrer, Stanford University, sibirrer@stanford.edu;
Mark Dickinson, NOIRLab, ed@noao.edu;
Chris Fassnacht, UCDavis, cdfassnacht@ucdavis.edu;
Tommaso Treu, UCLA, tt@astro.ucla.edu;
Francis-Yan Cyr-Racine, University of New Mexico, fycr@unm.edu;
Peter Nugent, LBNL, penugent@lbl.gov;
Michael Pierce, U.Wyoming, mpierce@uwyo.edu;
Yu-Dai Tsai, Fermilab, ytsai@fnal.gov'