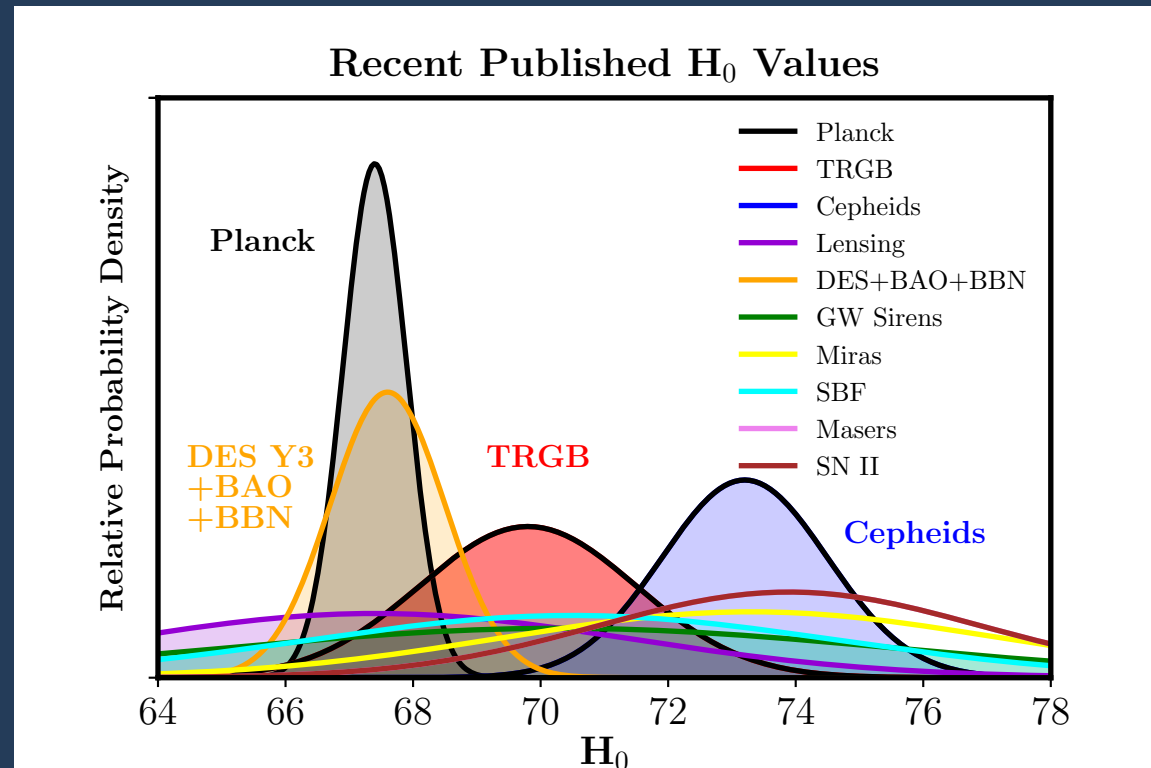


Summary

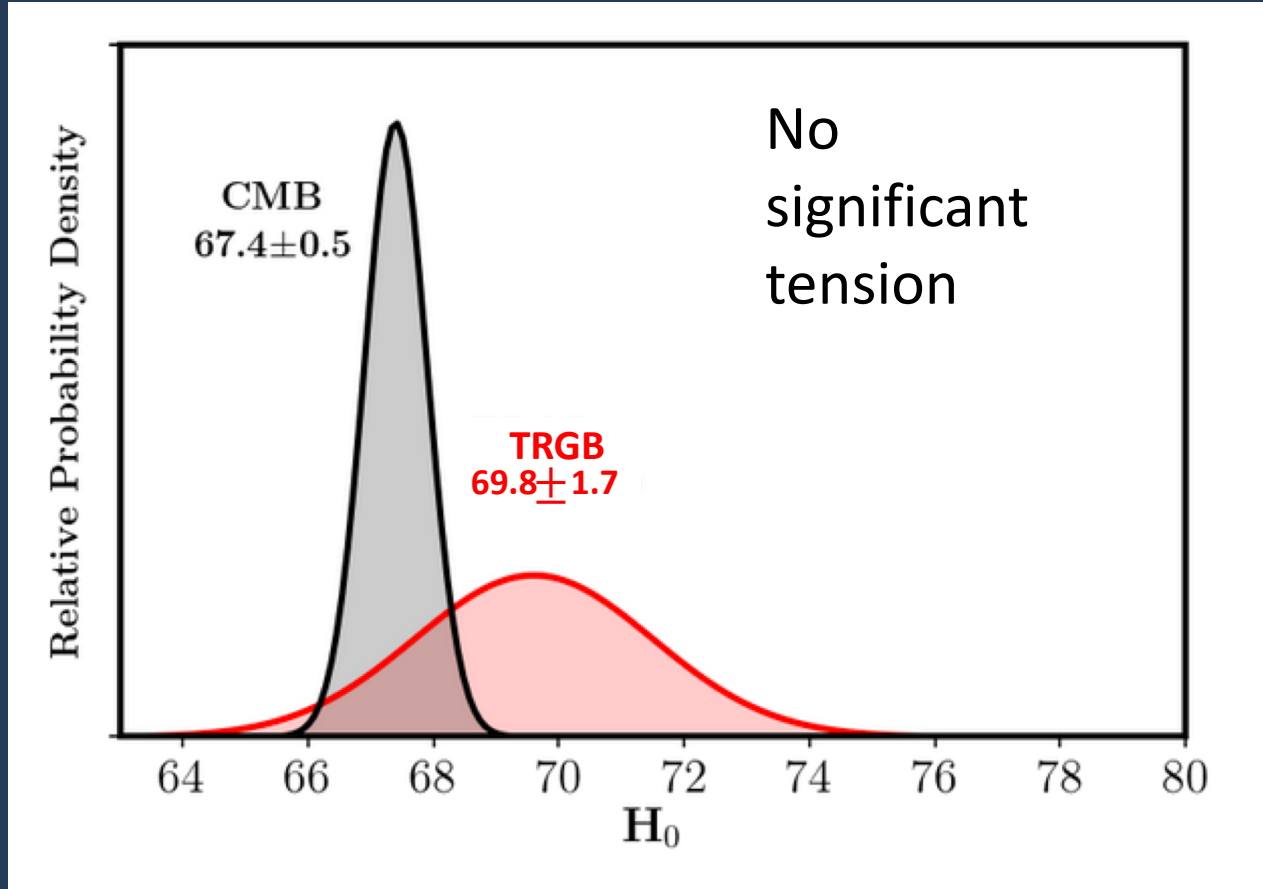
- Astrophysical Distance Indicators (e.g., the TRGB) provide an increasingly accurate means of measuring distances in the local universe.
- Three decades ago, the distances to nearby galaxies were not known to better than a factor of two. **Including systematic errors**, we now have accuracies of
 - 2% percent for galaxies < 5 Mpc [ground-based observations]
 - 3% percent for galaxies < 30 Mpc [with HST]
- The TRGB and Cepheid calibrations of SN_{Ia} and H_0 differ by 4.6%

Recent Published Values of the Hubble Constant



WLF (2021)

TRGB Compared to CMB



1.3 sigma tension with Planck

WLF+ (2019); WLF (2021) ApJ, 919, 16

The Current Status of H_0

Toward a New Geometric Distance to the Active Galaxy NGC 4258. III.

3D Disk-Fitting Model

Input Data

10,000 maser
 $X, Y, v_{\text{LOS}}, a_{\text{LOS}}$
 Binned in velocity

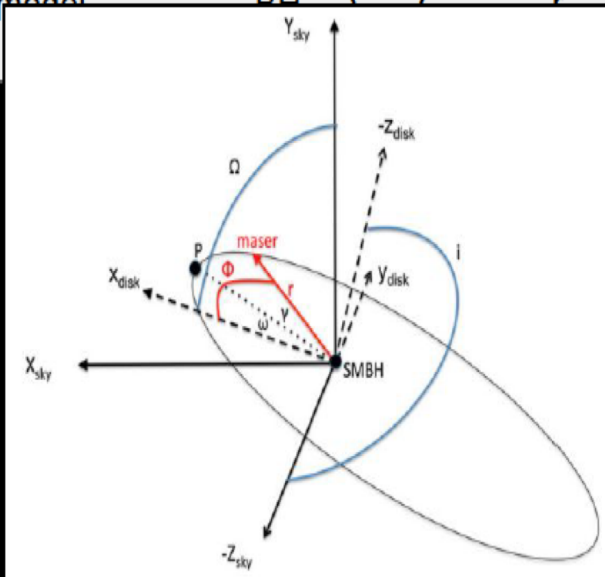


3D Disk-Fitting Model

Goal: determine maser disk geometry
 + estimate distance.

$$v_{\text{LOS,model}} = v_r \sin i_r \sin \phi + v_y \sin i_r \cos \phi + v_0$$

$$a_{\text{LOS,model}} = -G M_{\text{BH}} / (rD)^2 \sin i_r \sin \phi$$

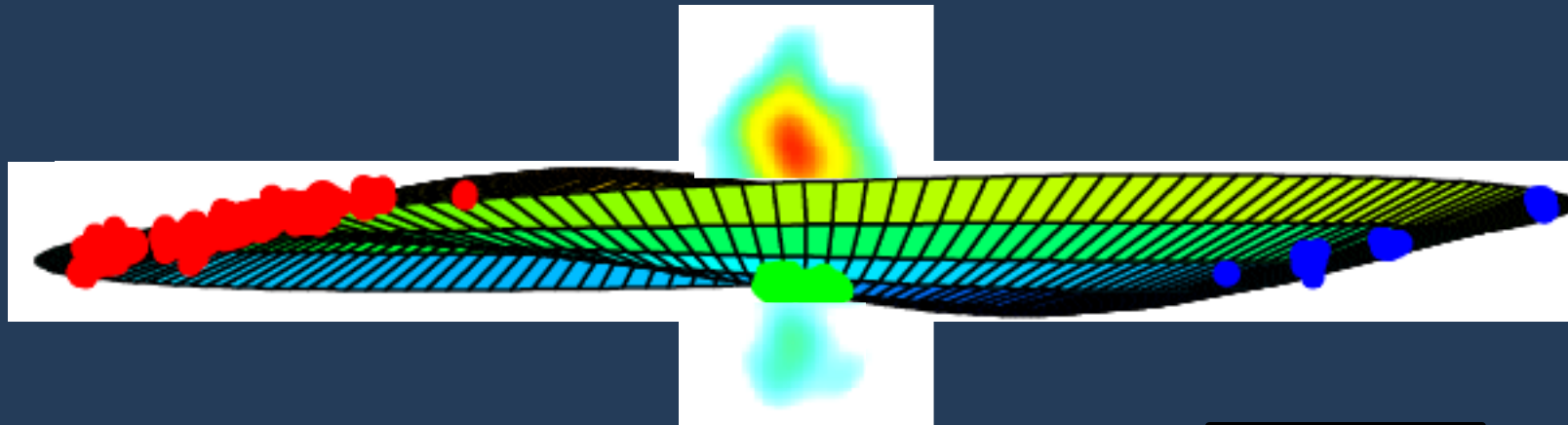
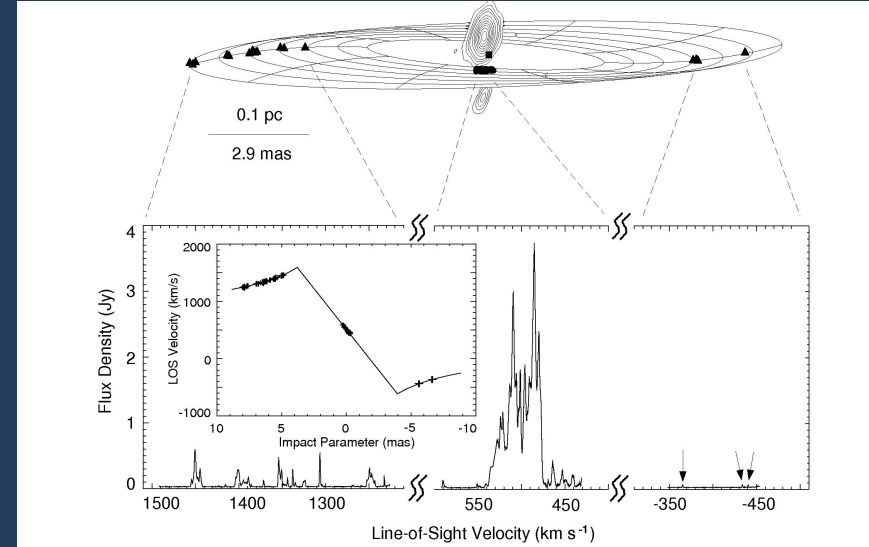
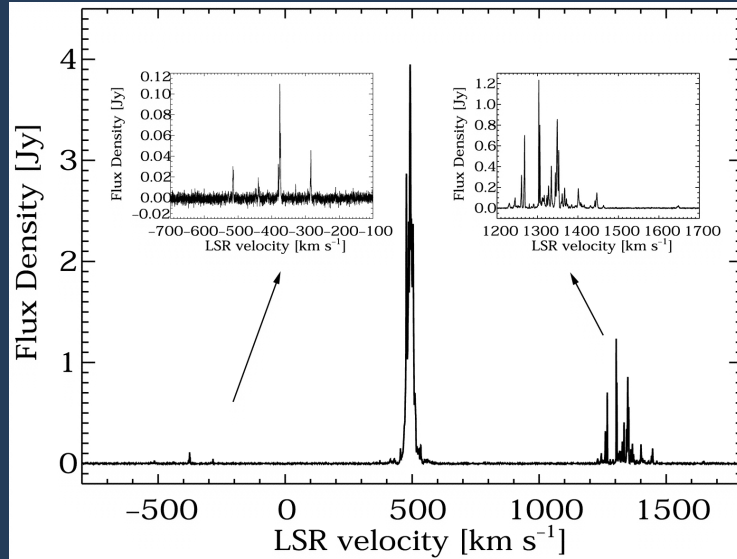


Results

Rotation curves constrain
 $M^{1/2} \sin i_r \dots (M = M_{\text{BH}} / D)$

Accelerations provide distance
 $D = -(G M / r^2 a_{\text{LOS,model}}) \sin i_r \sin \phi$

The Ideal Case: NGC 4258 Megamaser disk



Moran, Reid

A distance to the Large Magellanic Cloud that is precise to one per cent

G. Pietrzyński^{1,2*}, D. Graczyk^{1,2,3}, A. Gallenne^{4,5}, W. Gieren², I. B. Thompson⁶, B. Pilecki¹, P. Karczmarek⁷, M. Górski², K. Suchomska⁷, M. Taormina¹, B. Zgirski¹, P. Wielgórski¹, Z. Kołaczowski^{1,8}, P. Konorski⁷, S. Villanova², N. Nardetto⁵, P. Kervella⁹, F. Bresolin¹⁰, R. P. Kudritzki^{10,11}, J. Storm¹², R. Smolec¹ & W. Narloch¹

- NIR photometry from South African Astronomical Observatory, angular diameters from ESO VLT and PIONIER
- Main advance of this paper is a more precise surface-brightness color relation
- Apply this to previously obtained catalog of DEBs from the Araucaria project

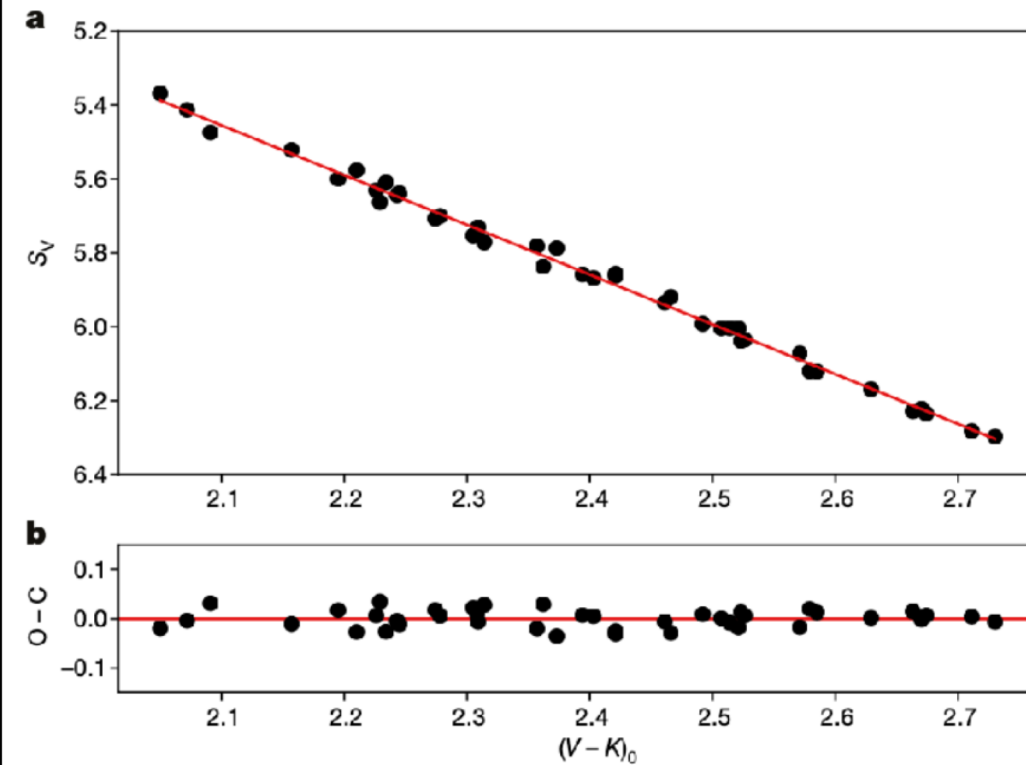


Fig. 1 | New relation between surface brightness S_V and $(V - K)_0$ colour. **a**, Plot of S_V versus $(V - K)_0$ (data points) and fitted line. The r.m.s. scatter on this relation is 0.018 mag, which means an 0.8% precision in stellar angular diameters. The precision of this relationship is fundamental for measuring precise cosmic distances. **b**, Residuals (observed minus calculated) for the fit. Both S_V and $(V - K)_0$ are in magnitudes.

$$d_{LMC} = 49.59 \pm 0.09(\text{stat}) \pm 0.54(\text{sys}) \text{ kpc}$$

$$d = 9.2985 \frac{R}{\phi}$$

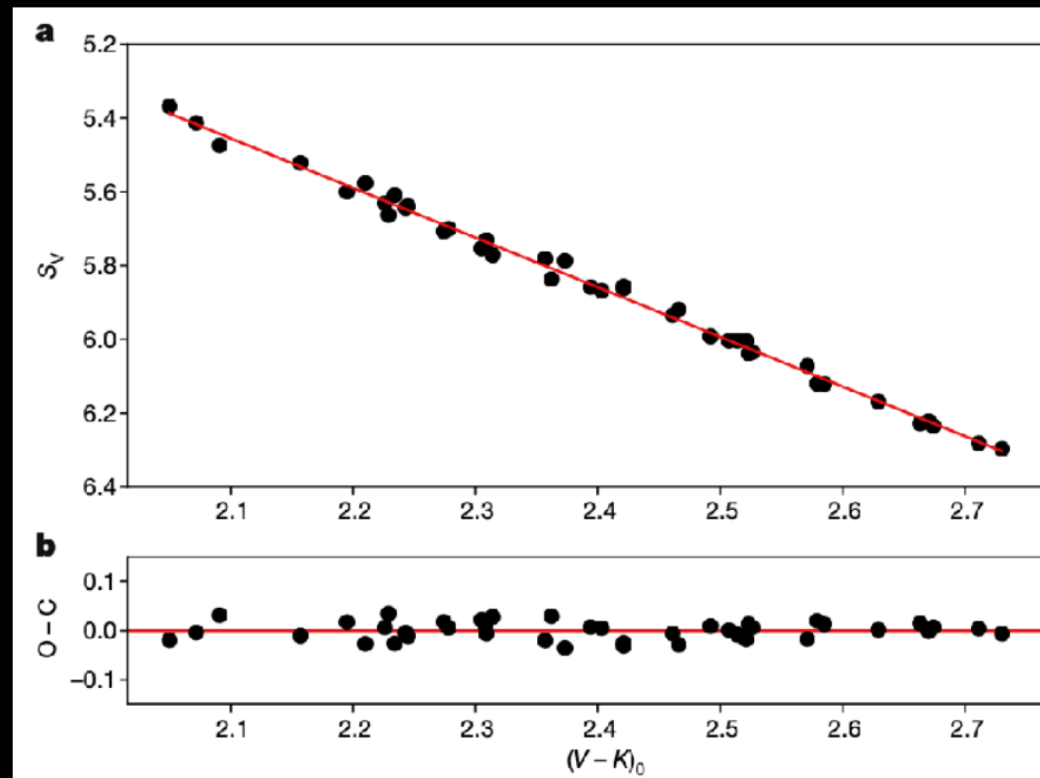
INDIVIDUAL FLUXES

- **Surface brightness-color relation (SBCR)**
 - Theoretical relation between photometry surface brightness
 - Verified empirically
 - Definition of surface brightness: $S_V = V_0 + 5 \log \phi$

$$\Rightarrow \phi = 10^{(S_V - V_0)/5}$$

(reminder: ϕ = angular radius)

- Can also use model atmospheres, but those are less precise



$$d = 9.2985 \frac{R}{\phi}$$

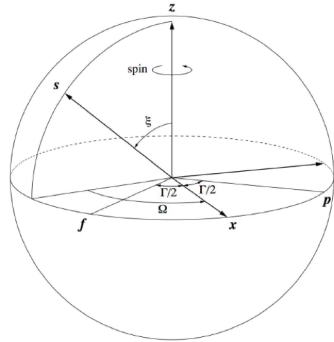
Basic Angle Differences

- Changes in the basic angle difference manifest map to changes in the parallax estimations for sources

Substituting Eq. (14) into Eq. (7) we readily obtain a relation between the change in parallax and the corresponding changes in basic angle and attitude:

$$\left. \begin{aligned} \delta_x &= 0 \\ \delta_y &= \cos \xi \sec(\Gamma_c/2) R \delta\varpi \\ \delta_z &= \sin \Omega \sin \xi \cos(\Gamma_c/2) R \delta\varpi \\ \delta\Gamma &= 2 \cos \Omega \sin \xi \sin(\Gamma_c/2) R \delta\varpi \end{aligned} \right\} \quad (15)$$

Basic angle change Parallax change



Disclaimer

As recipes for the systematic correction of the EDR3 parallaxes, these functions should be regarded as provisional and indicative. While we have reason to believe that their application will in general reduce systematics in the parallaxes, this may not always be the case. Users are urged to make their own judgement concerning the relevance of the indicated bias correction for their specific applications. Whenever possible, depending on the type and number of sources under consideration, users of EDR3 should try to derive more targeted bias estimates for their specific use cases.

Applying Gaia Zero-Point Calibration: Cepheids

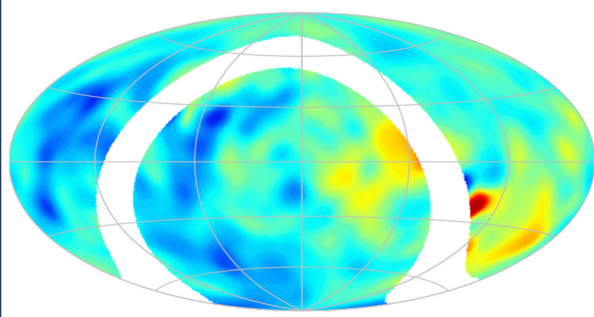
Major Concerns:

- Measurements bright compared to bulk of data ($G < 12$)
- Cepheid color varies over time
 - Gaia catalogue assumes constant color over all observations
- Zero-point offset is degenerate with metallicity effects

Status: Gaia Early Data Release 3 (EDR3)

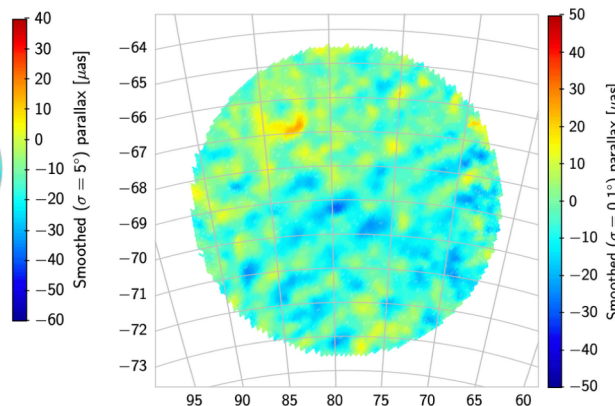
Parallax bias - spatial variations on large and small scales

5° smoothed EDR3 parallaxes of QSOs
(RMS = 9.4 μas)



Lindgren et al. (2021), A&A 649, A2 [LKH]

0.1° smoothed EDR3 parallaxes in LMC (G=16-18)
(RMS = 6.9 μas)



“The biases related to angular covariance are likely to be hard to eliminate. The hope there is that DR4 will significantly reduce them. “

A cautionary note:

- Corrections for very bright sources are significantly more uncertain - a problem for the Milky Way Cepheids ($4 < G < 12$ mag)
- Parallax offset is degenerate with Cepheid metallicity
- There is a minimum systematic error floor of 10 μas in the parallax distance to *any given* cluster (Lindgren et al. 2020; Maíz Apellániz et al. 2021; Cerny et al. 2021)

Improvement in Parallaxes



Hipparcos

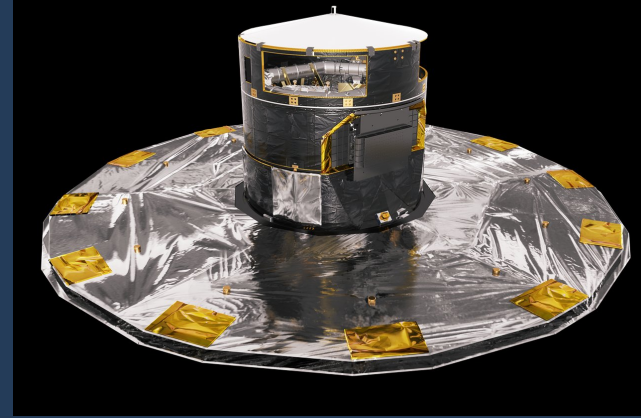
120,000 stars

600-1000 μas

DR1

2,000,000 stars

300 μas



Gaia

DR2

1,300,000,000 stars

30-40 μas

EDR3

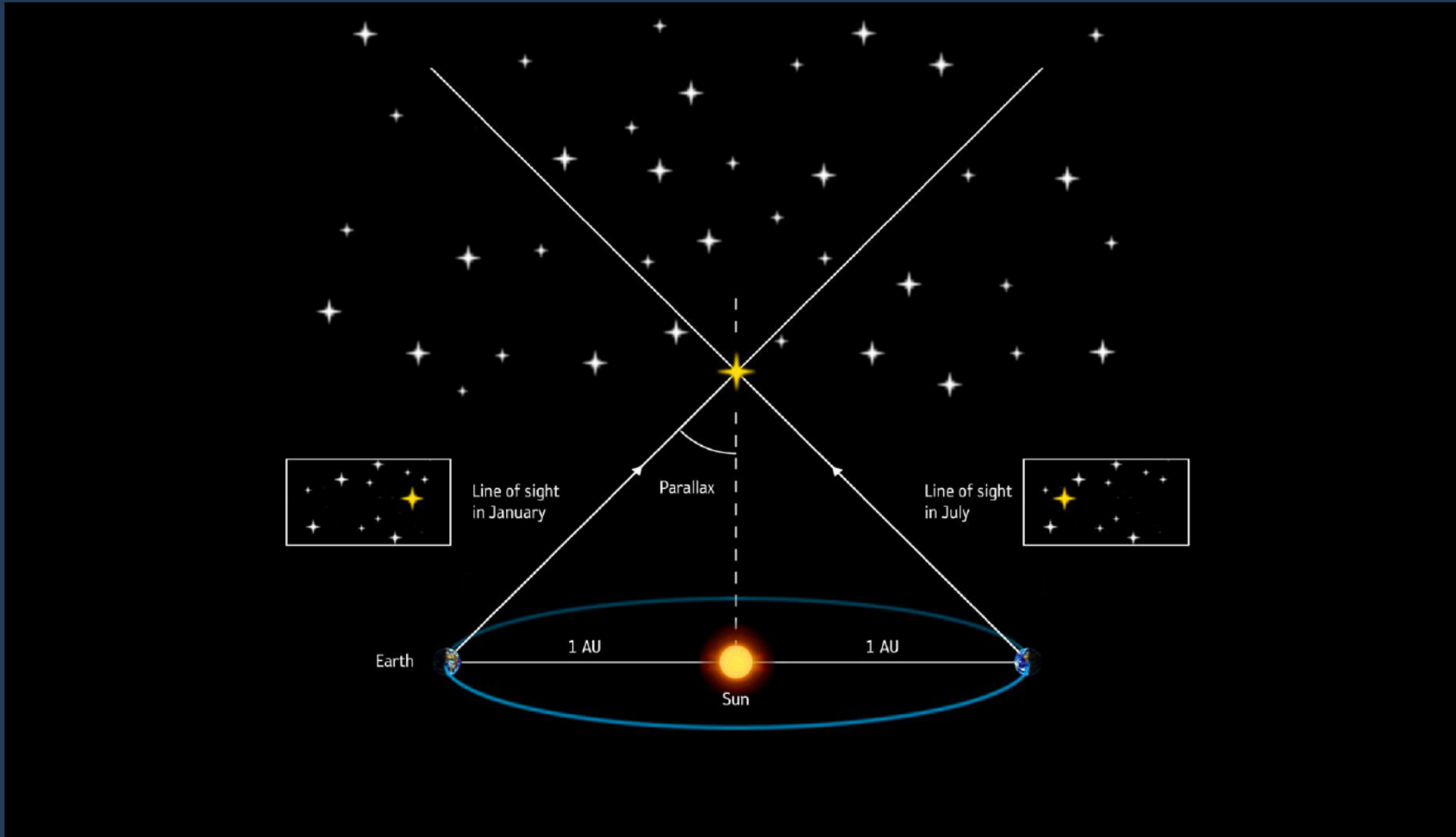
1,500,000,000 stars

10 μas !!

Global ZP offset
 $\sim 30 \mu\text{as}$

Multi-parameter
ZP offset

1. Milky Way Parallaxes from Gaia



Absolute Calibration of the Distance Scale

1. Milky Way

2. LMC

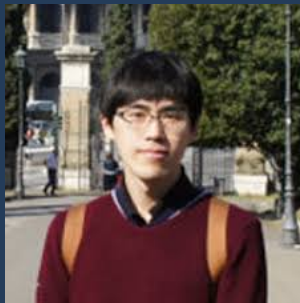
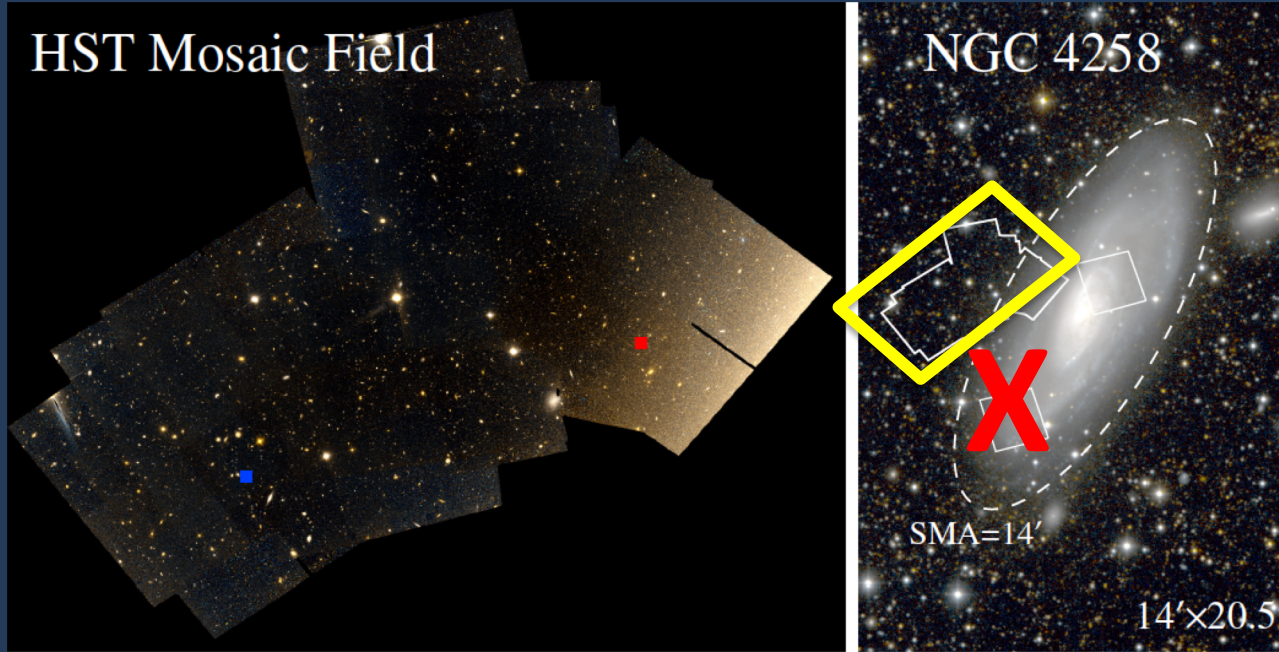
3. NGC 4258

Gaia Parallaxes

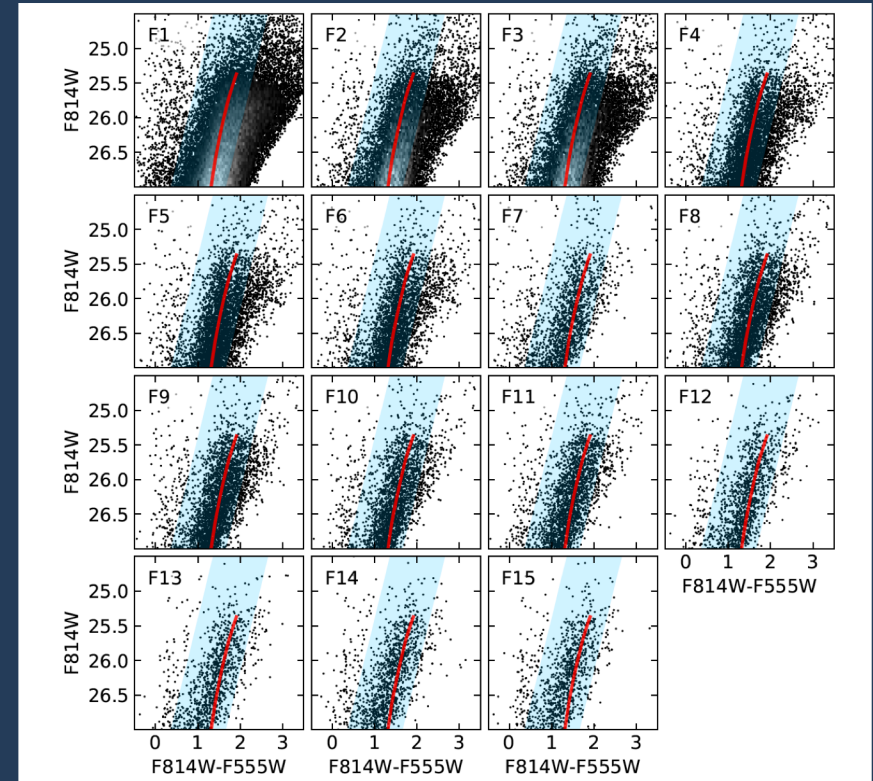
Detached Eclipsing Binaries

H₂O Megamasers

Recent NGC 4258 TRGB Measurements



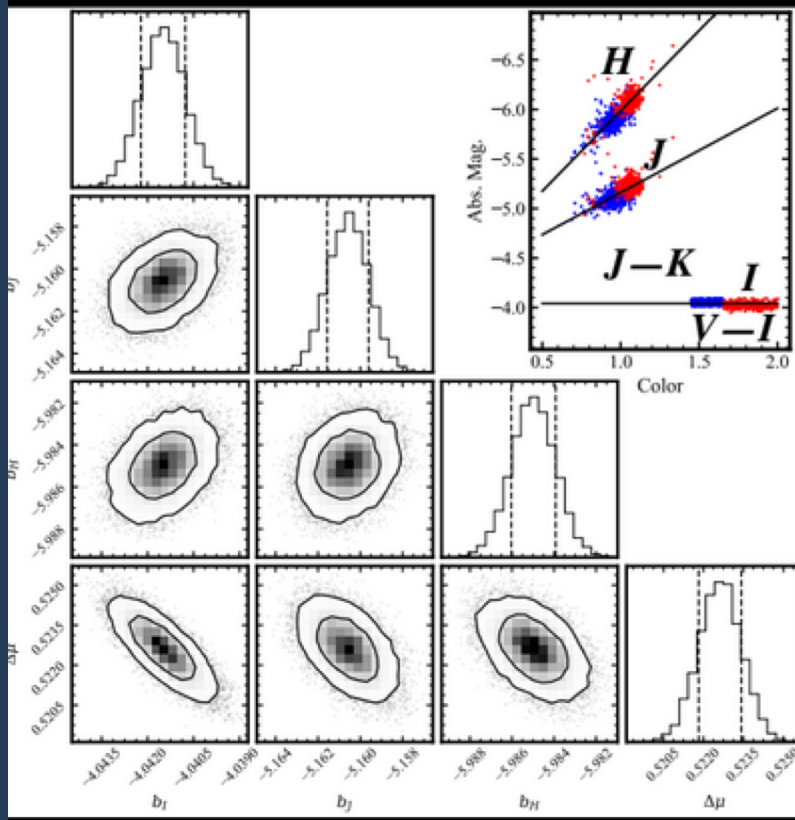
In Sung Jang



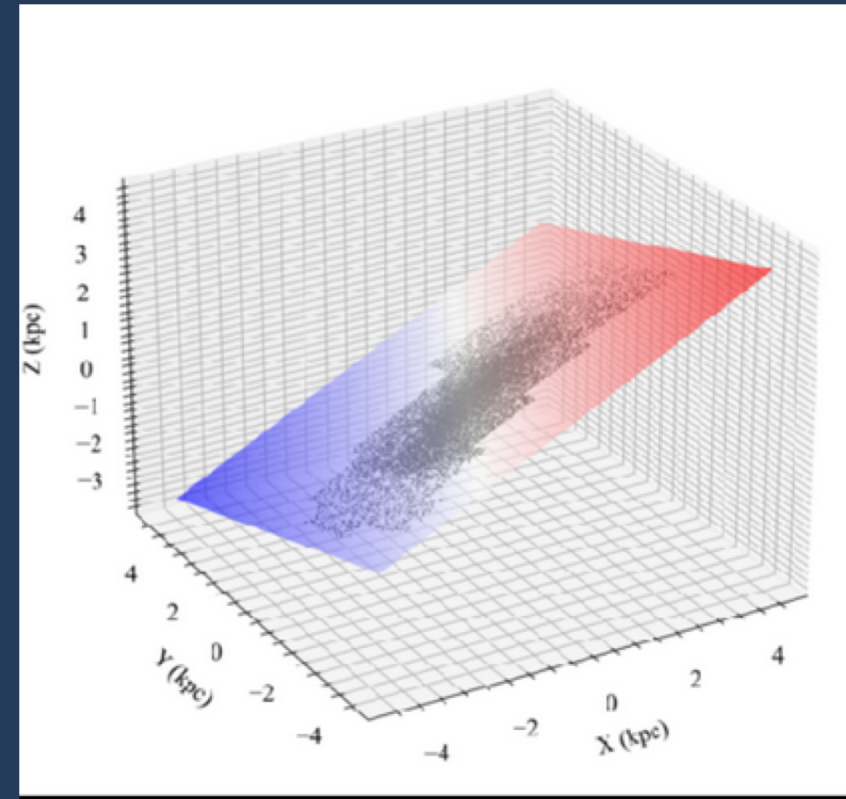
Jang et al, ApJ, 2021

Additional Tests of the TRGB:

Hoyt (2022) PhD Thesis

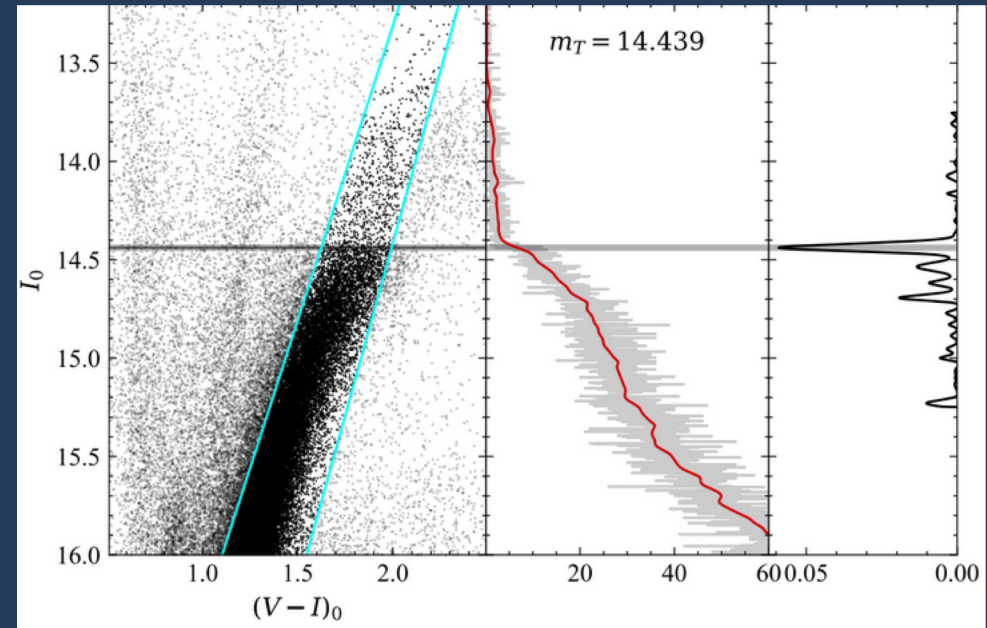
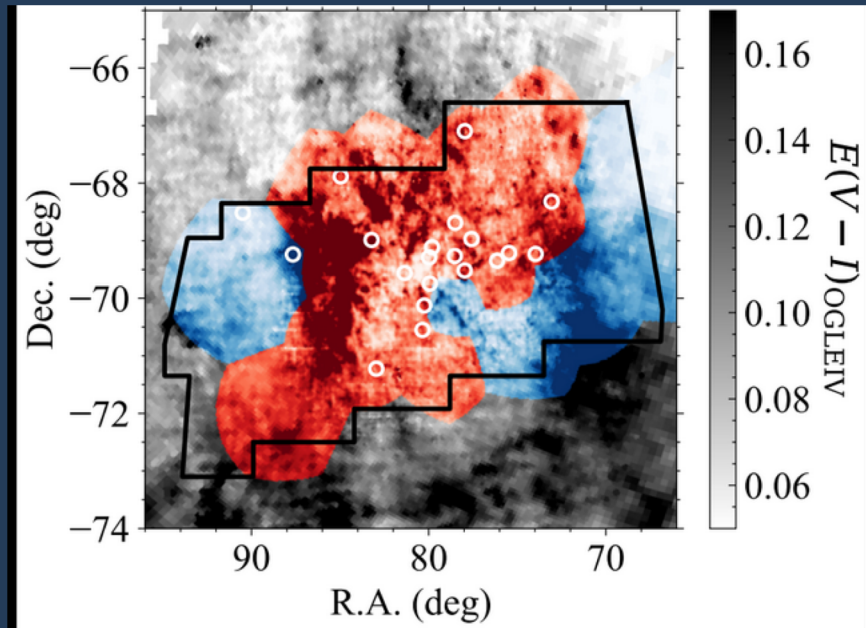


Multiwavelength (VIJHK) measurements of TRGB results in differential LMC/SMC distance modulus consistent with DEBs at 2% level



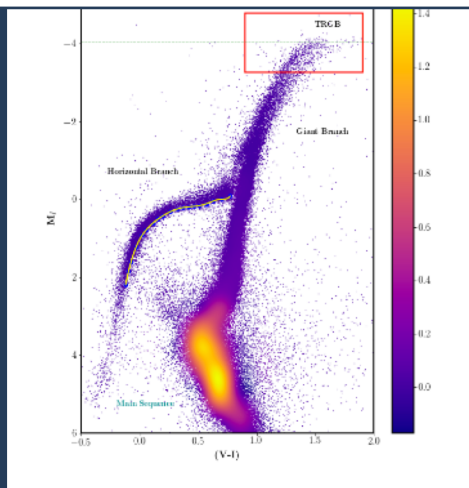
3D tilt of LMC measured using TRGB, consistent with Cepheid measurements.

New LMC TRGB Measurements: Hoyt (2022) PhD Thesis



Recent Tests of the TRGB Calibration

Milky Way globular clusters

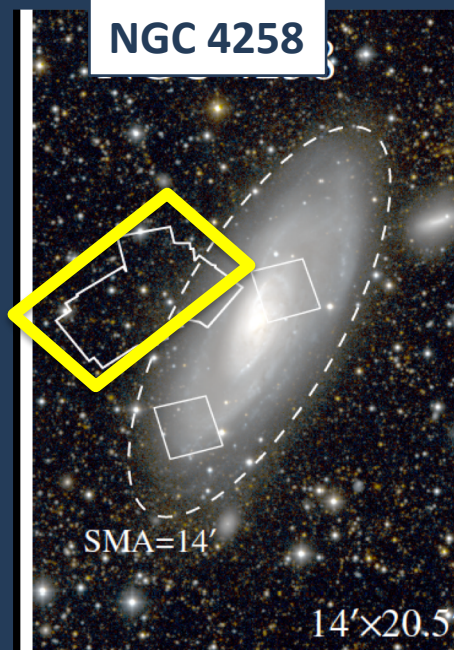


Cerny et al. 2021, arXiv:2012.09701

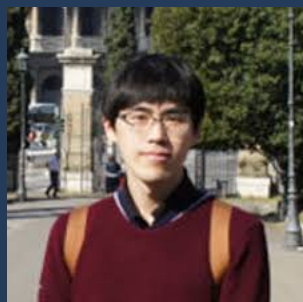


Will Cerny

NGC 4258

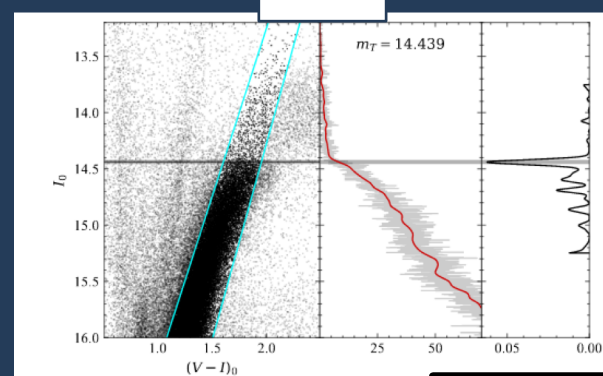


Jang et al. 2021

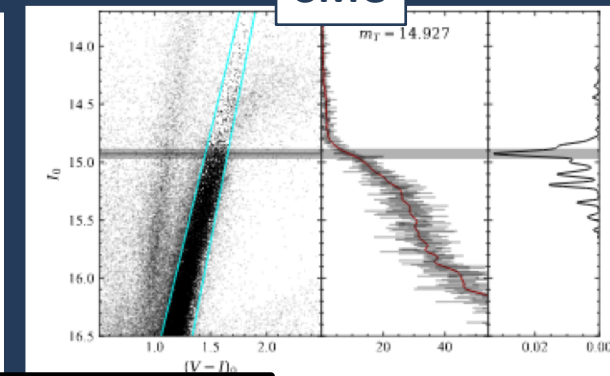


In Sung Jang

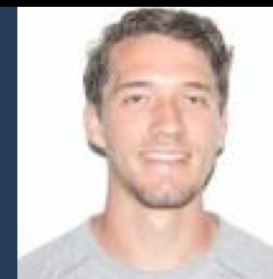
LMC



SMC



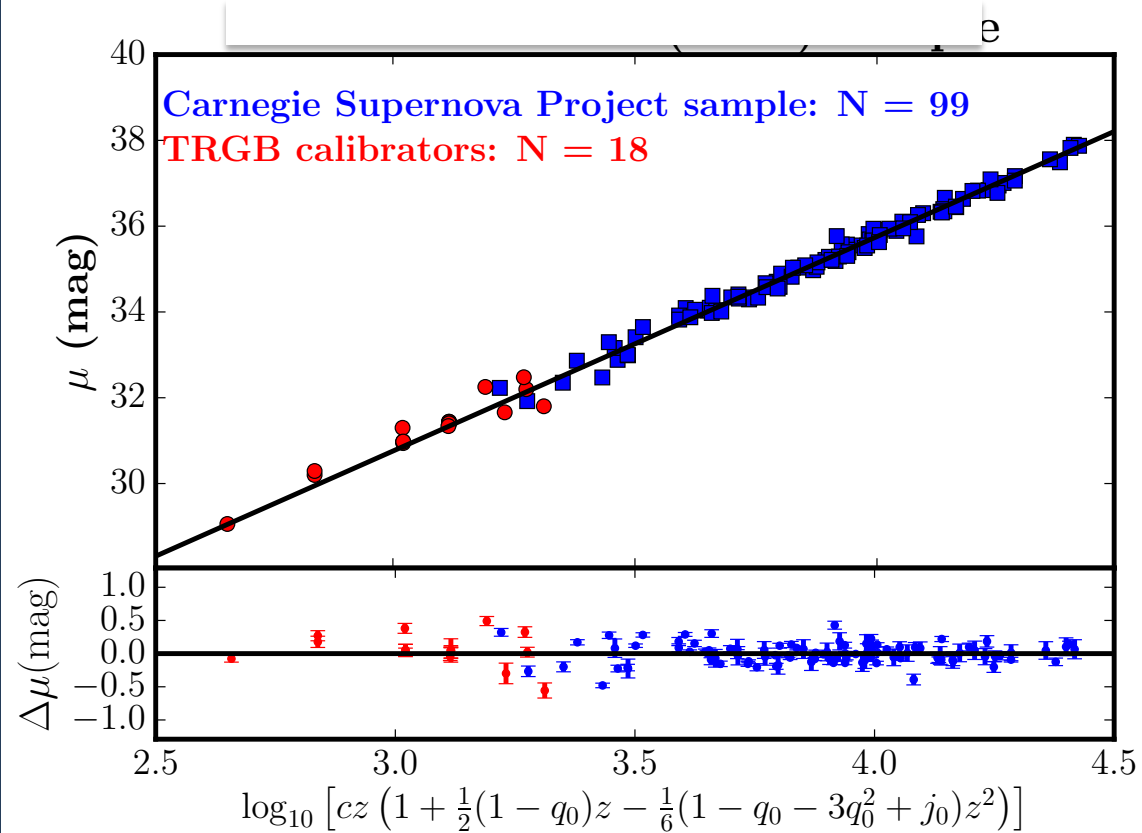
Hoyt 2021, 2022



Taylor Hoyt

Independent zero points in agreement at the $\pm 1\%$ level. [WLF (2021), ApJ, 919, 16]

CCHP TRGB Calibration of H_0



MCMC analysis:

$$H_0 = 69.6 \pm 0.8 \text{ (stat) [1.1\%]} \\ \pm 1.7 \text{ (sys) [2.4\%] km s}^{-1} \text{ Mpc}^{-1}$$

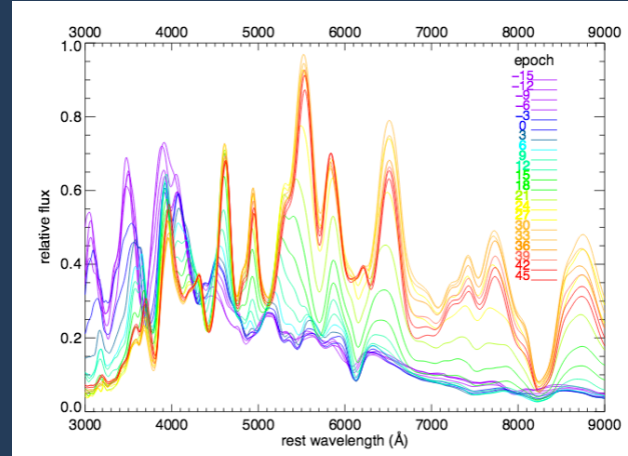
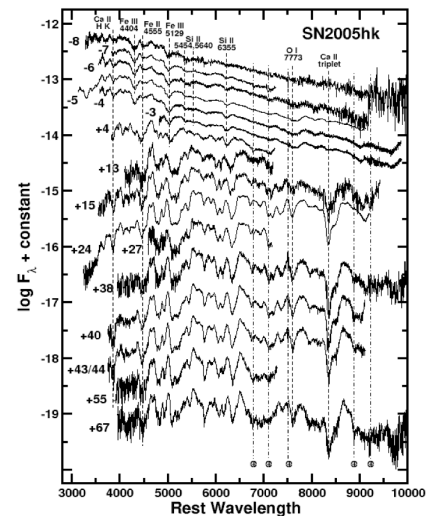
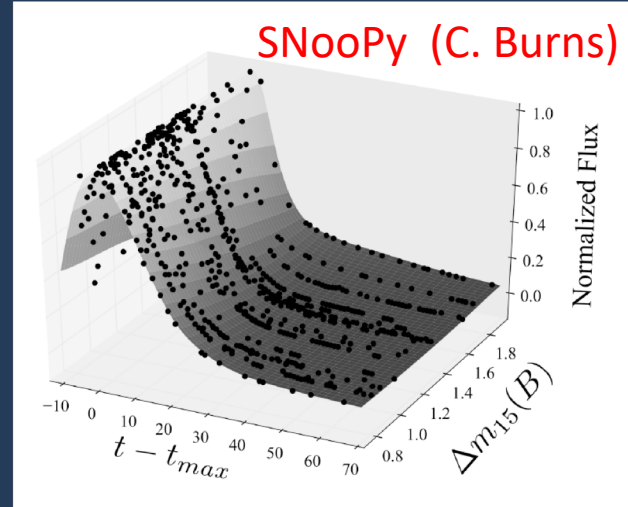
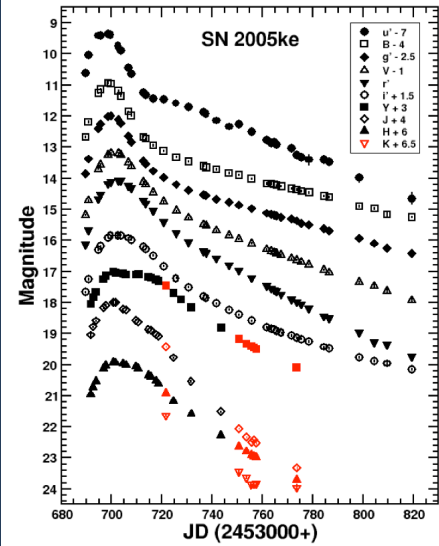
LMC as the anchor galaxy **

Distance modulus:

$$\mu_0 = m - M = 5 \log d_L + 25 \quad \text{where } d_L \text{ is in Mpc}$$

WLF et al. (2019, 2020)

CSP: Dealing With Systematics



Well-sampled photometry and spectra

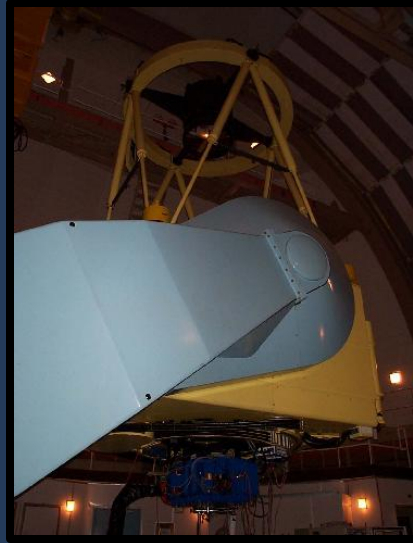
Most extensive, self-consistent data set
for dealing with systematics

Input to MCMC analysis

Carnegie Supernova Project-I (CSP)



Swope 1-meter



du Pont 2.5-meter



Magellan 6.5-meter

M. Phillips, W. Freedman co- PIs