The role of the LMC in the Extragalactic Distance Scale: Cepheids and Miras

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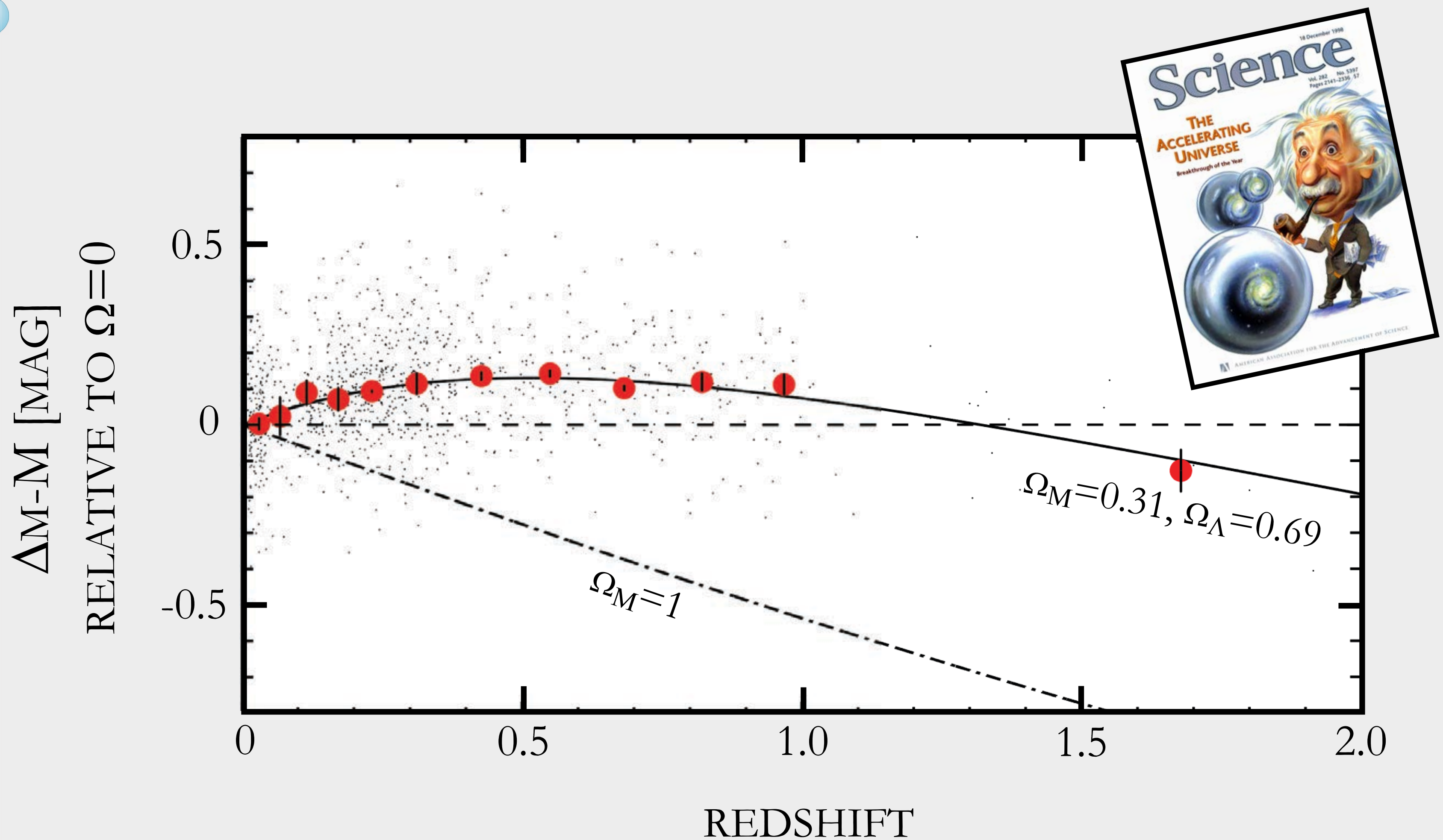
OUTLINE

- Introduction & motivation
- Results on Cepheids
- Results on Miras
- Recent developments and future work

SNe Ia: Universe dominated by dark energy & dark matter



Riess+ (1998); Perlmutter+ (1999)

Scolnic+ (2018)

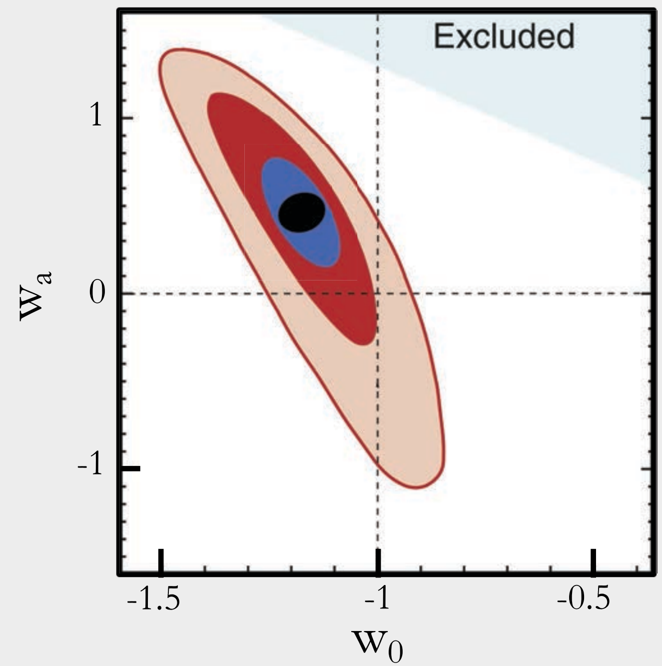
WHAT IS DARK ENERGY?

- Equation of state of dark energy & "figure of merit":

$$w = P/\rho c^2$$

$$w(a)=w_0+w_a(1\text{-}a)$$

$$\mathrm{FoM}=[\boldsymbol{\sigma}(w_0)\times\boldsymbol{\sigma}(w_a)]^{-1}$$

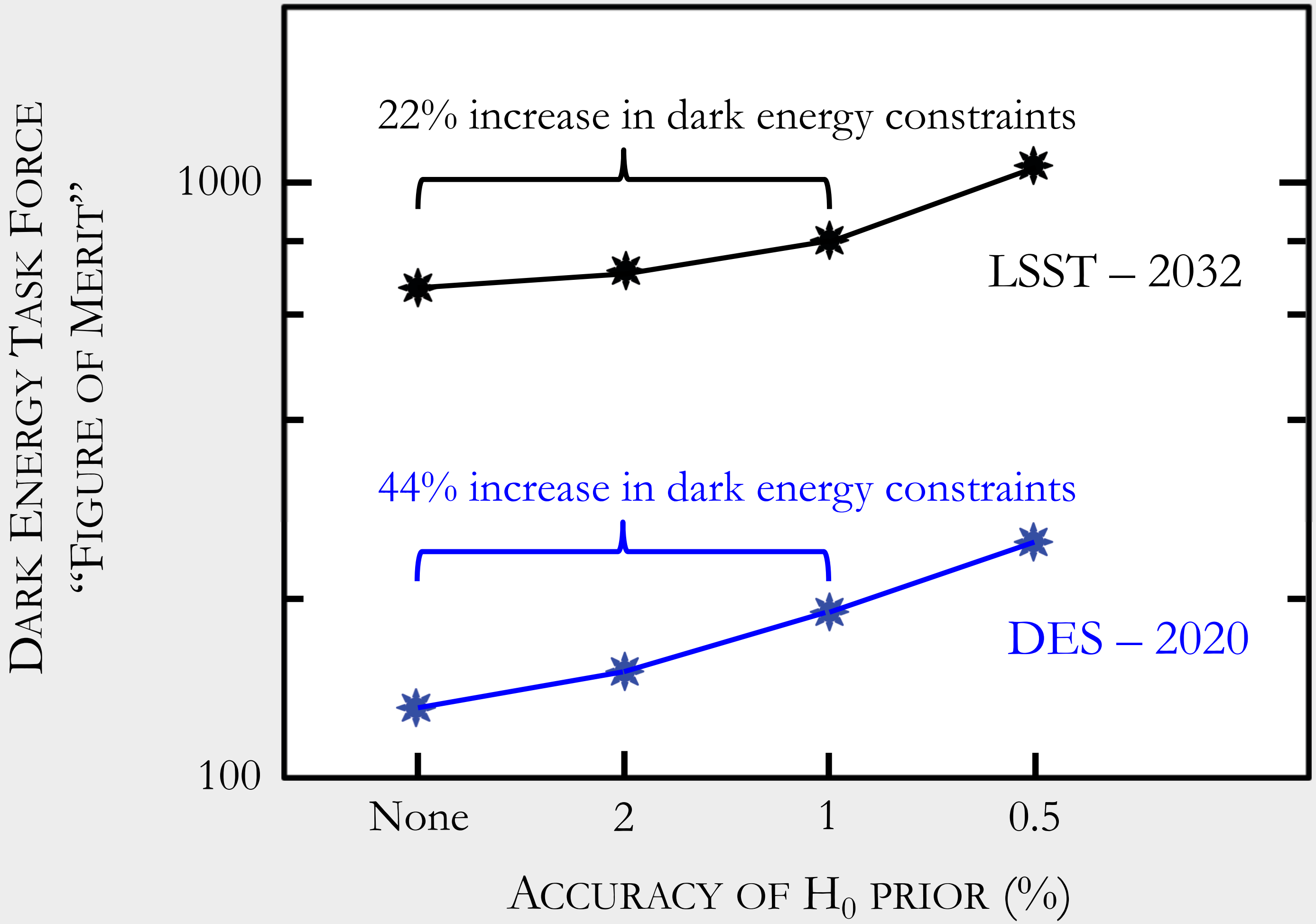


Coupled with additional priors (such as H_0)

- Hinshaw+'13: $w_0 \pm 0.09$; $w_a \pm 0.5$
- DES ('20): $w_0 \pm 0.08$; $w_a \pm 0.3$
- LSST ('32): $w_0 \pm 0.05$; $w_a \pm 0.1$

HINSHAW+ (2013)

Initial motivation for further improvement in H_0



Based on Weinberg+ (2013)

THE "CLASSICAL" DISTANCE SCALE

- First "rung": independent geometrical methods
  - Milky Way: π's from *Hubble*; eventually *Gaia* (systematics…)
  - LMC: eclipsing binaries (previous talk)
  - N4258: Masers orbiting central supermassive black hole
- Second "rung": different stellar populations
  - Cepheids (Leavitt Law)
  - Miras
  - Tip of the Red Giant Branch
  - RR Lyrae, Red Clump, Blue supergiants, …
- Hubble flow
  - SNe Ia; others? (SBF, Tully-Fisher, FP…)

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100+ YEARS OF THE LEAVITT LAW

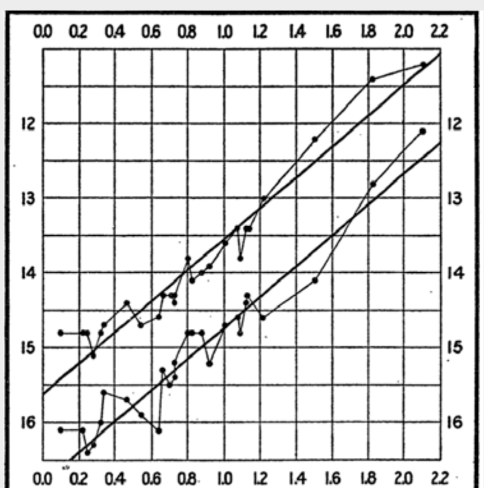
PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

A SPIRAL NEBULA AS A STELLAR SYSTEM MESSIER 33[1]

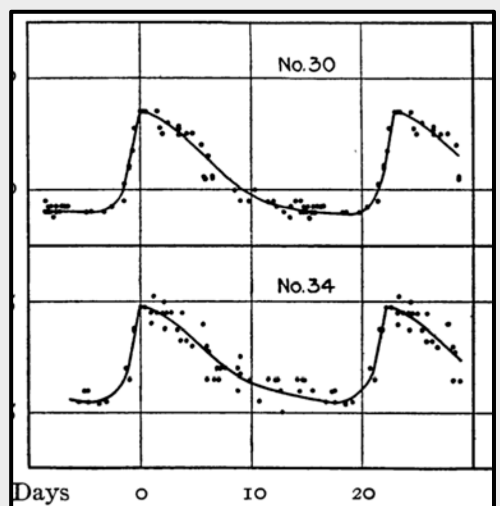
Leavitt (1912)

Hubble (1926)

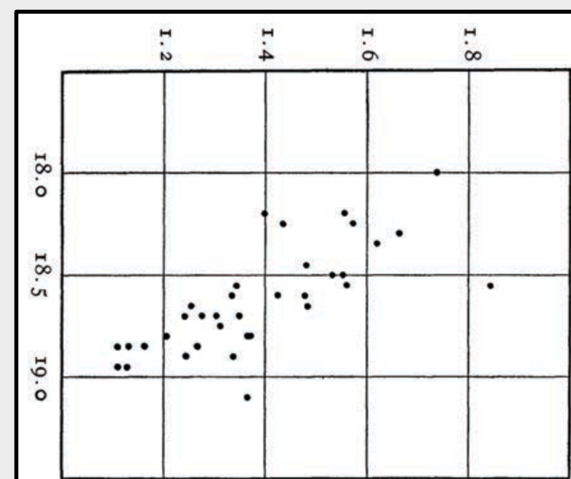
MAGNITUDE



LOG PERIOD [DAYS]



TIME [DAYS]

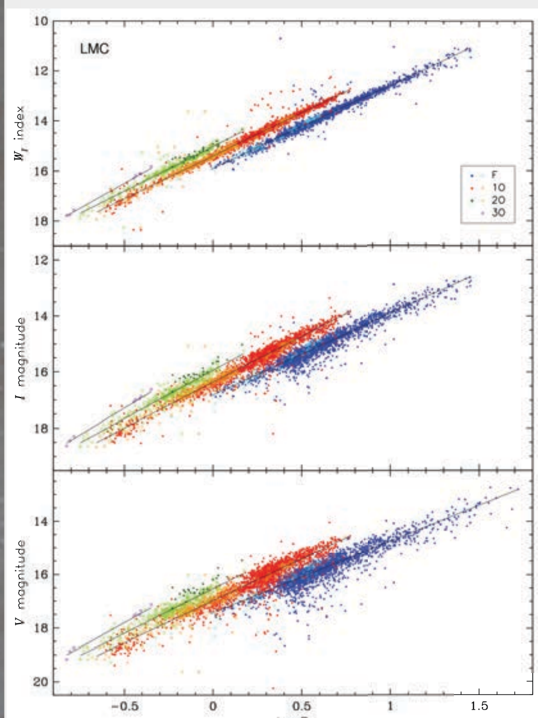


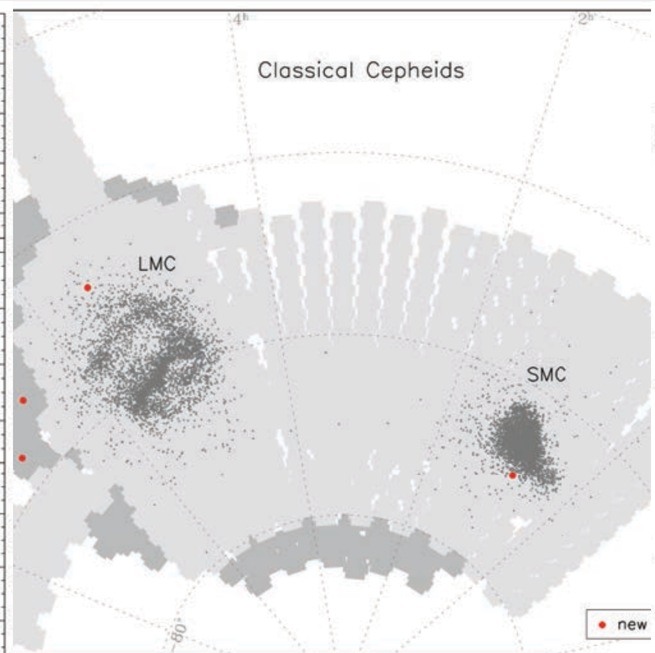
LOG PERIOD [DAYS]

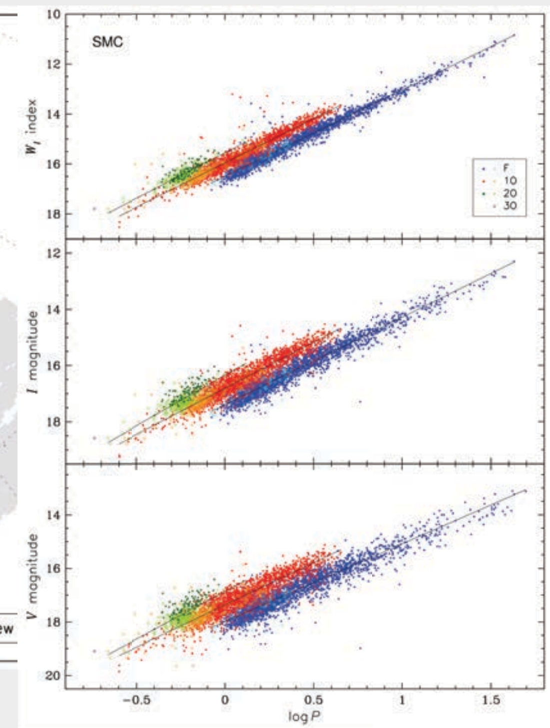
100+ YEARS OF THE LEAVITT LAW

$$W_I = I - 1.55(V - I) = \alpha \log P + \beta$$

pulsation		α	β	σ
F	LMC	-3.314 ± 0.008	15.888 ± 0.005	0.077
1O	LMC	-3.431 ± 0.007	15.393 ± 0.002	0.081
2O	LMC	-3.548 ± 0.027	15.025 ± 0.008	0.087
3O	LMC	-4.000 ± 0.134	14.486 ± 0.077	0.071
F	SMC	-3.460 ± 0.011	16.493 ± 0.005	0.155
1O	SMC	-3.548 ± 0.017	15.961 ± 0.004	0.169
2O	SMC	-3.651 ± 0.098	15.545 ± 0.025	0.154







Soszynski+ (2017, 2019)

The LMC Near-Infrared Synoptic Survey

- Early 2006: Wonderful OGLE-II PLRs in BVI

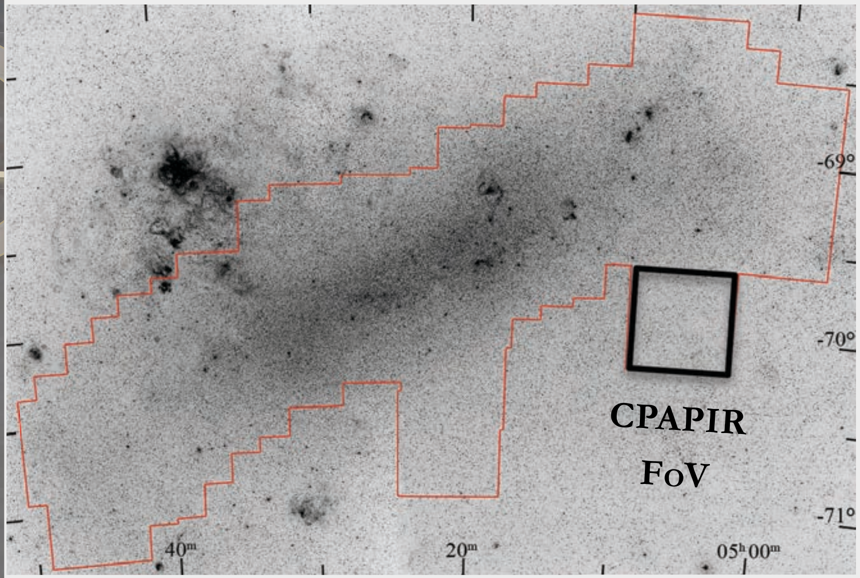
- Nothing comparable at NIR wavelengths
  - Largest sample: 92 Cepheids with JHK_S observations (Persson+ 04)

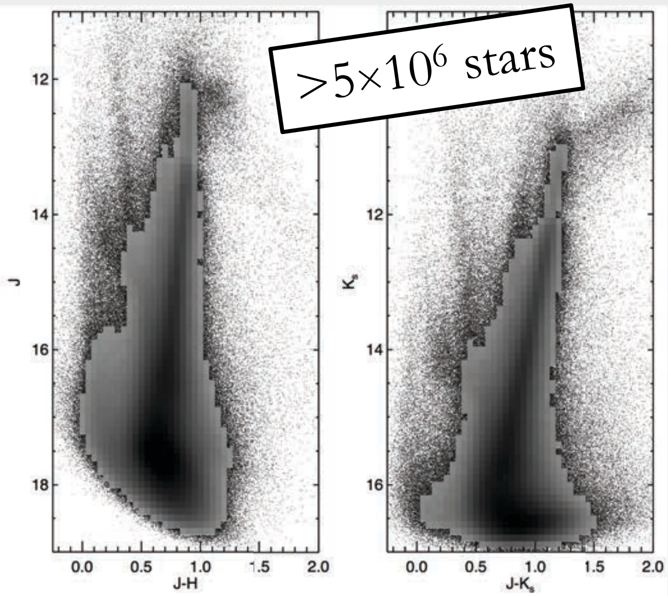
- Advantages of NIR Cepheid PLRs were already known:
  - Reduced sensitivity to dust, metallicity: lower systematic uncertainties
  - Narrower intrinsic width (from instability strip): lower statistical unc.

- Large-format NIR camera coming to CTIO 1.5-m for a few years → let's seize this opportunity!

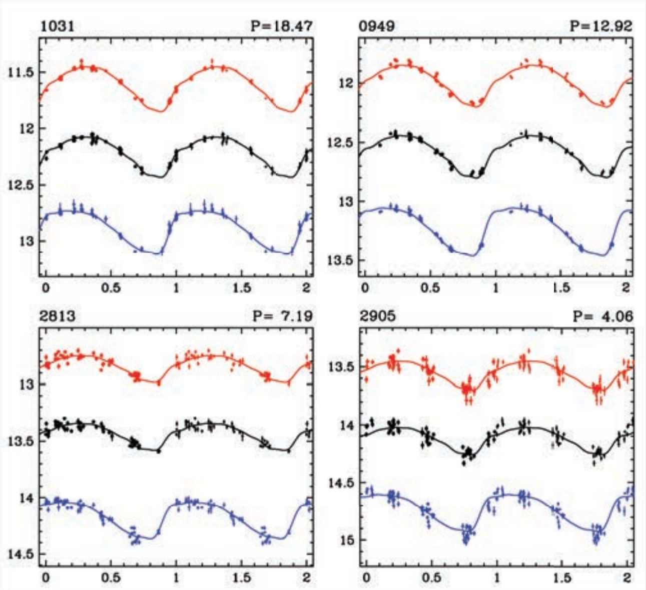
(Shashi Kanbur, Chow-Choong Ngeow, Lucas Macri)

LMCNISS PAPER 1 RESULTS



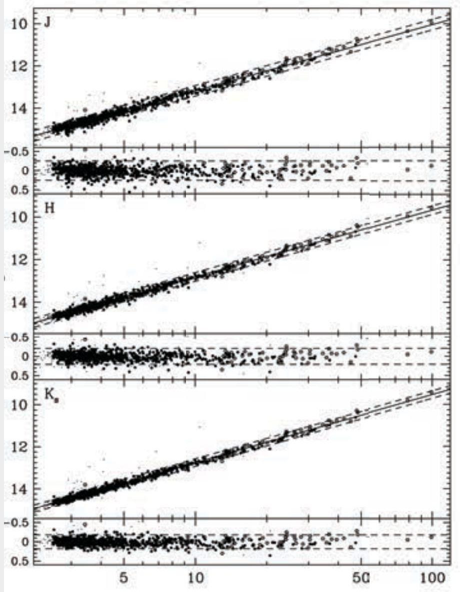


JHKs MAGNITUDES



PHASE

EXTINCTION-CORRECTED MAGNITUDES



PERIOD [DAYS]

MACRI, NGEOW, KANBUR+ (2015)

Impact on Distance Scale

- OGLE-III Cepheids (Periods, V & I magnitudes) and NIR magnitudes from LMCNISS
(Soszyński, Poleski, Udalski+ 2008; Macri, Ngeow, Kanbur+ 2015)

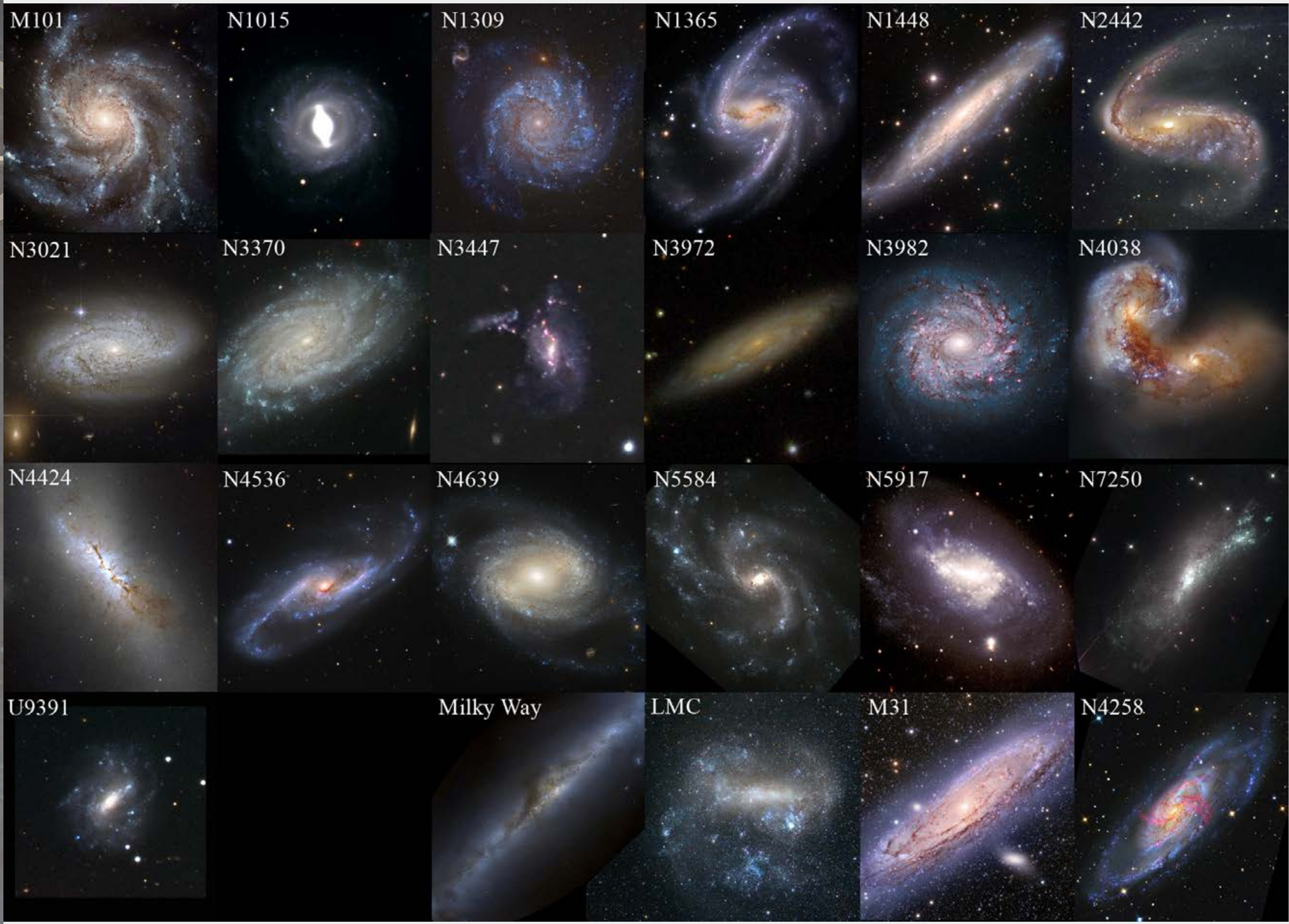
+

- Extremely precise and accurate LMC distance based on OGLE detached eclipsing binaries
(Pietrzyński, Graczyk, Gieren+ 2013)

=

- One of the three "anchors" of the Extragalactic Distance Scale used to measure H_0 with σ=2.4% by the SH0ES project (Riess, Macri, Hoffmann+ 2016)

SH0ES ANCHORS & SN HOST GALAXIES

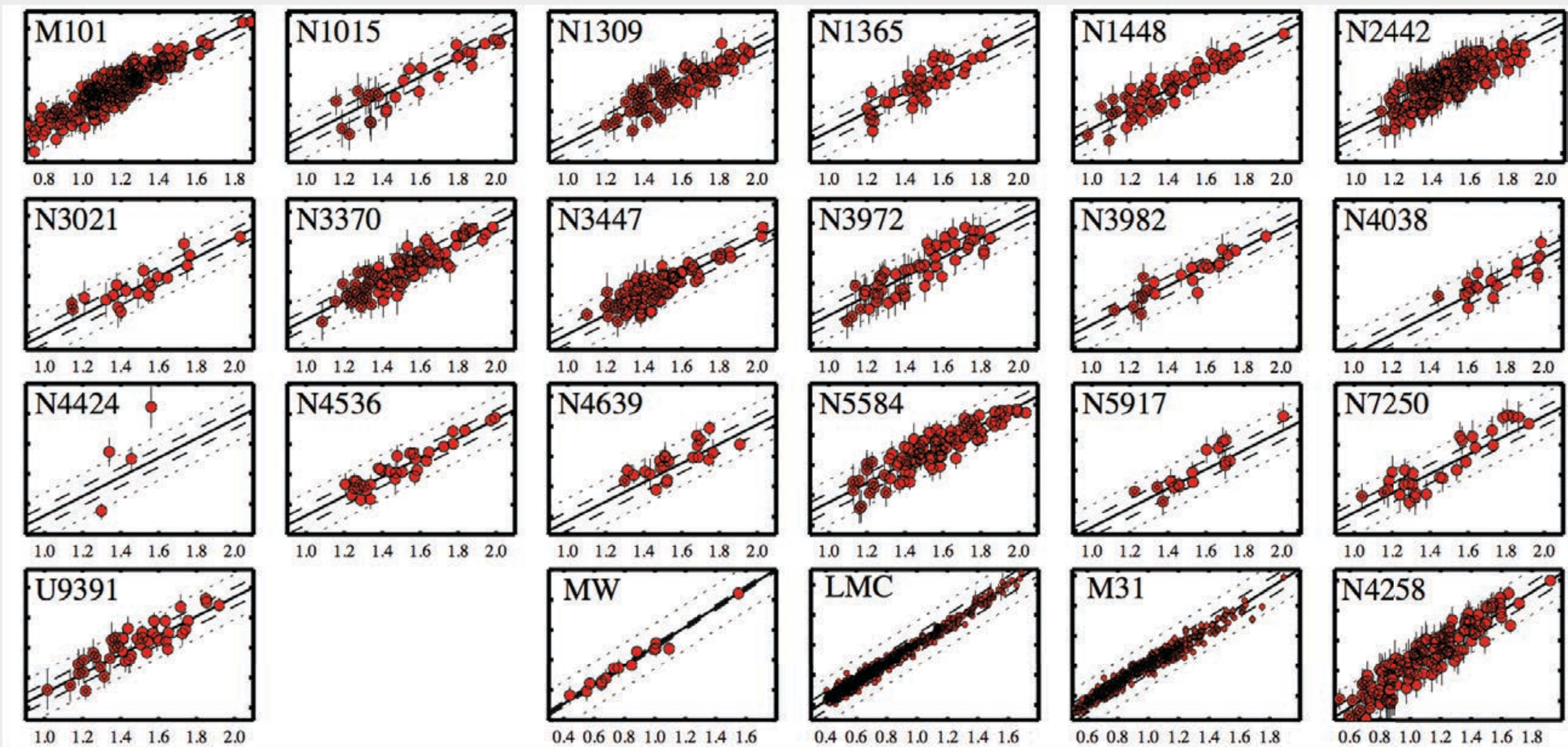


RIESS, MACRI, HOFFMANN+ (2016)

SH0ES CEPHEID P-L RELATIONS

2300 Cepheids with homogeneous H-band photometry enable a 2.4% determination of H_0

H MAG

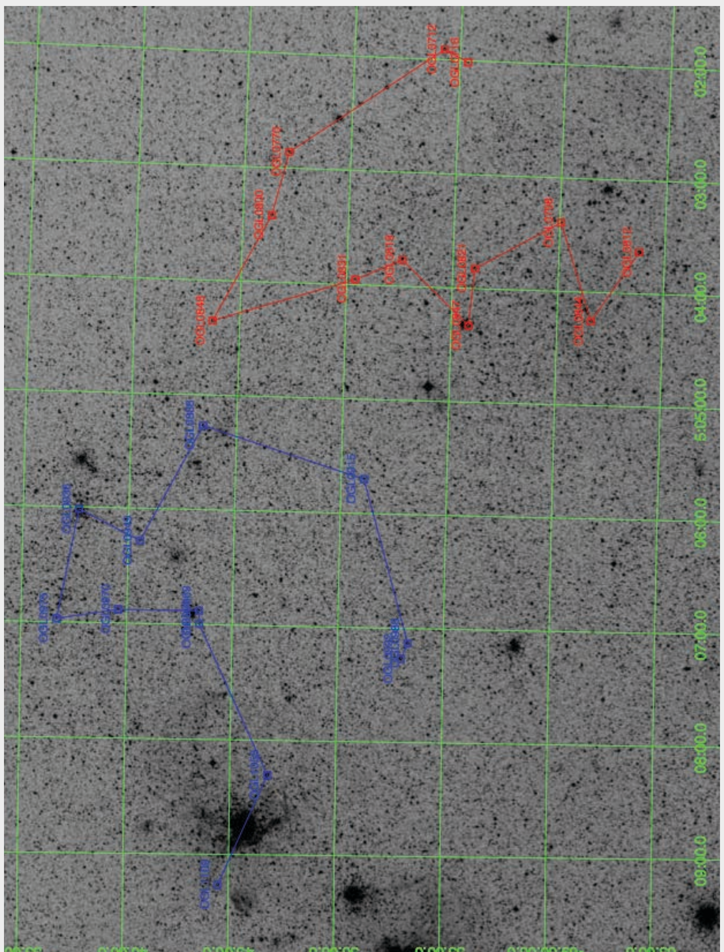


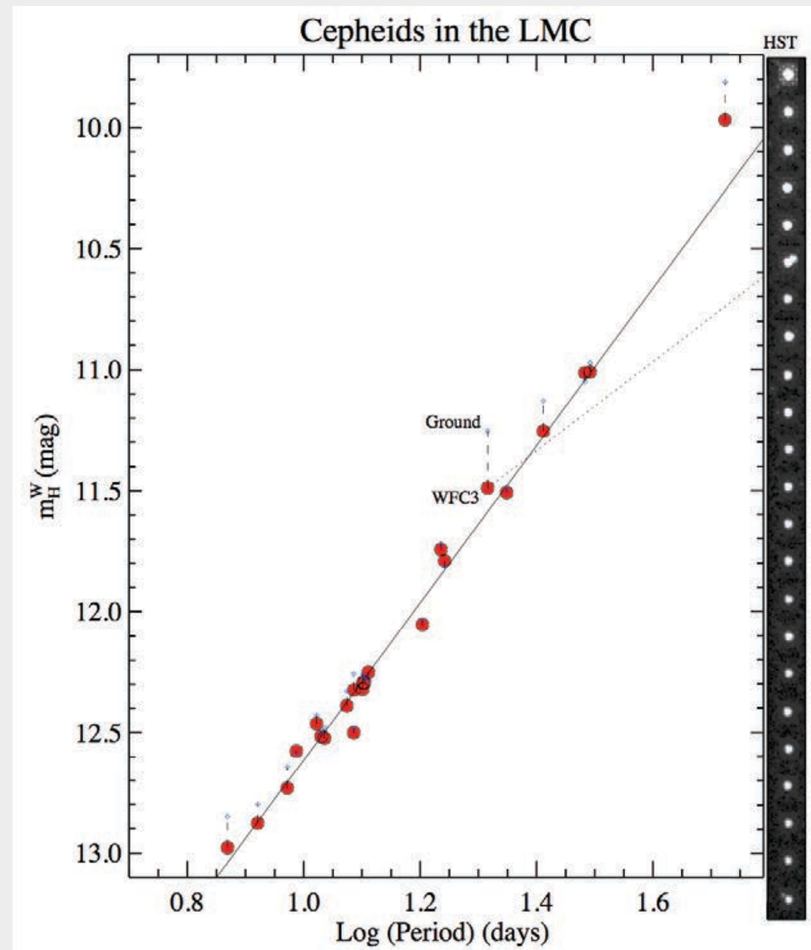
LOG PERIOD [DAYS]

RIESS, MACRI, HOFFMANN+ (2016)

HST IMAGING OF 70 LMC CEPHEIDS

- Take advantage of new observing mode (DASH) to efficiently image many Cepheids at VIH in one orbit





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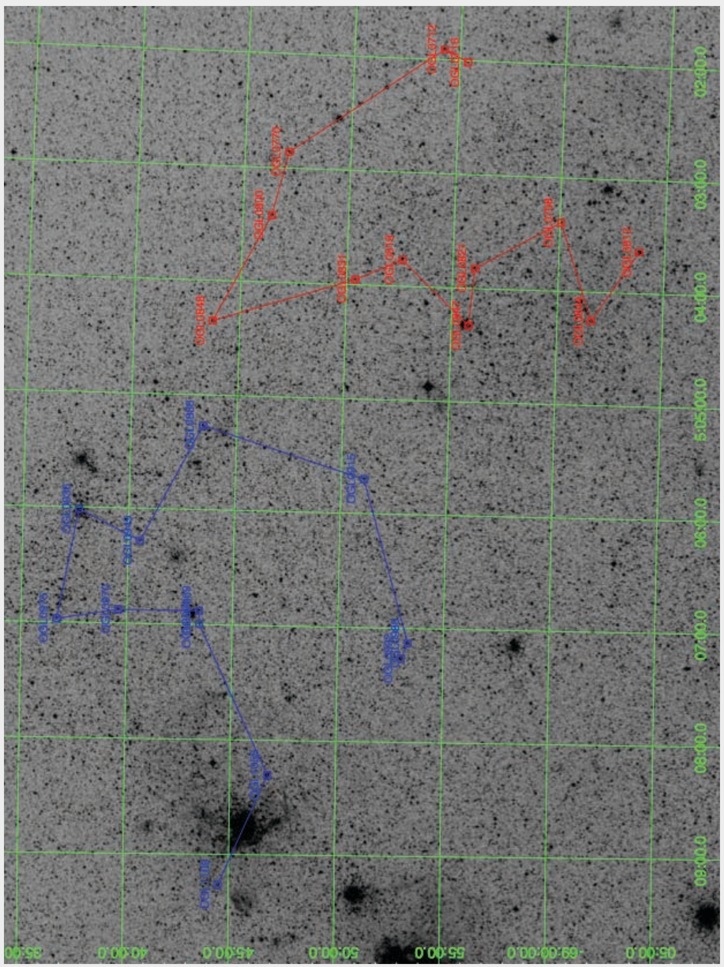
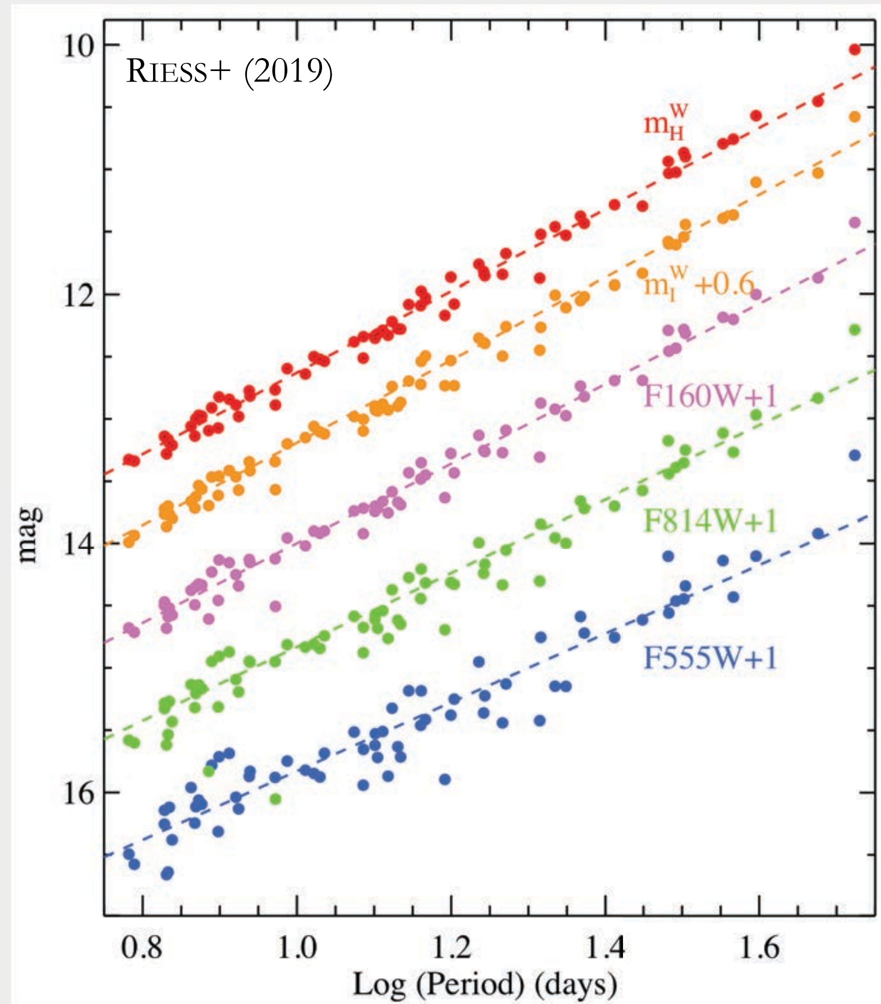




HST IMAGING OF 70 LMC CEPHEIDS

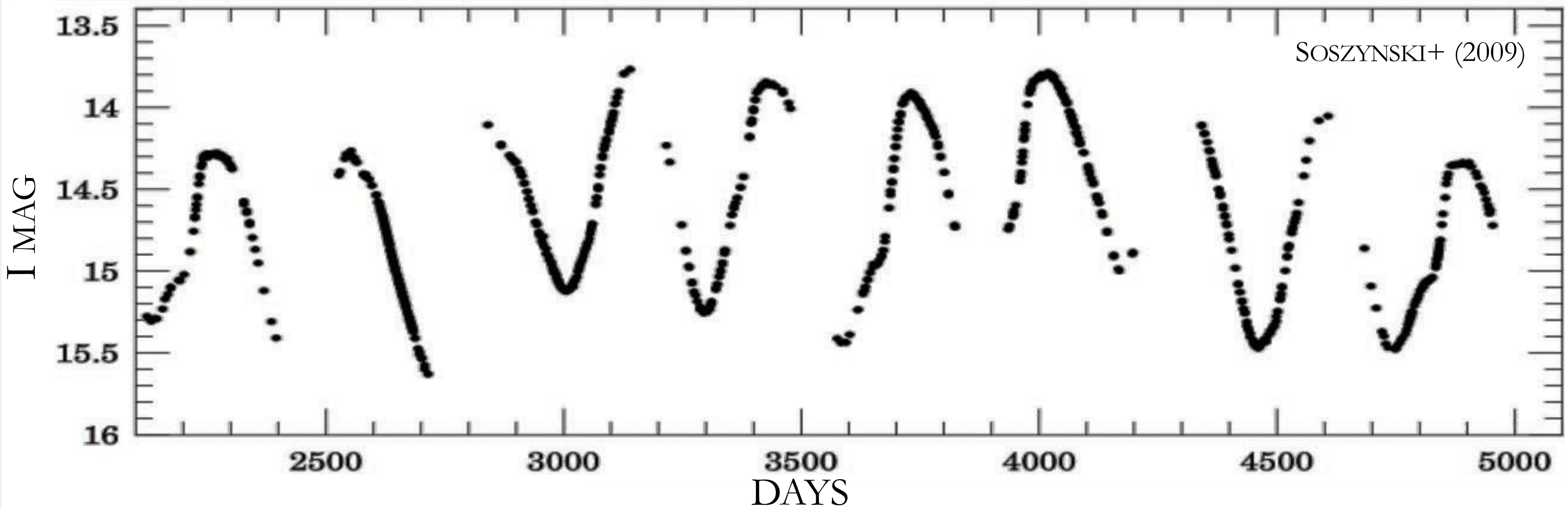
- Correct single-phase VIH observations to mean mags using OGLE and LMCNISS light curves
  - Even tighter PLRs (zero crowding), σ=0.075 mag
  - Same photometric system (HST) as all other Cepheids negates one source of systematic uncertainty
- Calibrate using improved DEB distance (previous talk) to obtain LMC-based H_0 with σ=2.5% (1.3% sys)
  - Pietrzynski+2019, Riess+2019
- 3 anchors, all with HST photometry, yield $\sigma(H_0)$=1.9%
  - Includes new maser distance to N4258 (Reid+2019)

Outline

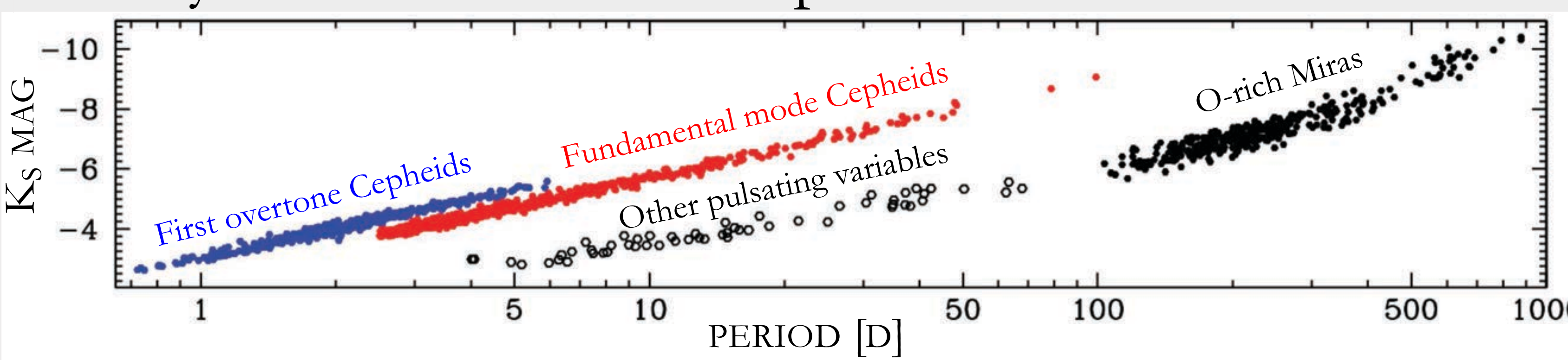
- ✓ Introduction & motivation
- ✓ Results on Cepheids
- ➢ Results on Miras
- Recent developments and future work

WHY MIRAS?

- Plentiful in all galaxies → go beyond face-on spirals
- Large amplitudes in I-band → relatively easy to detect



- Very luminous in NIR → powerful distance indicator



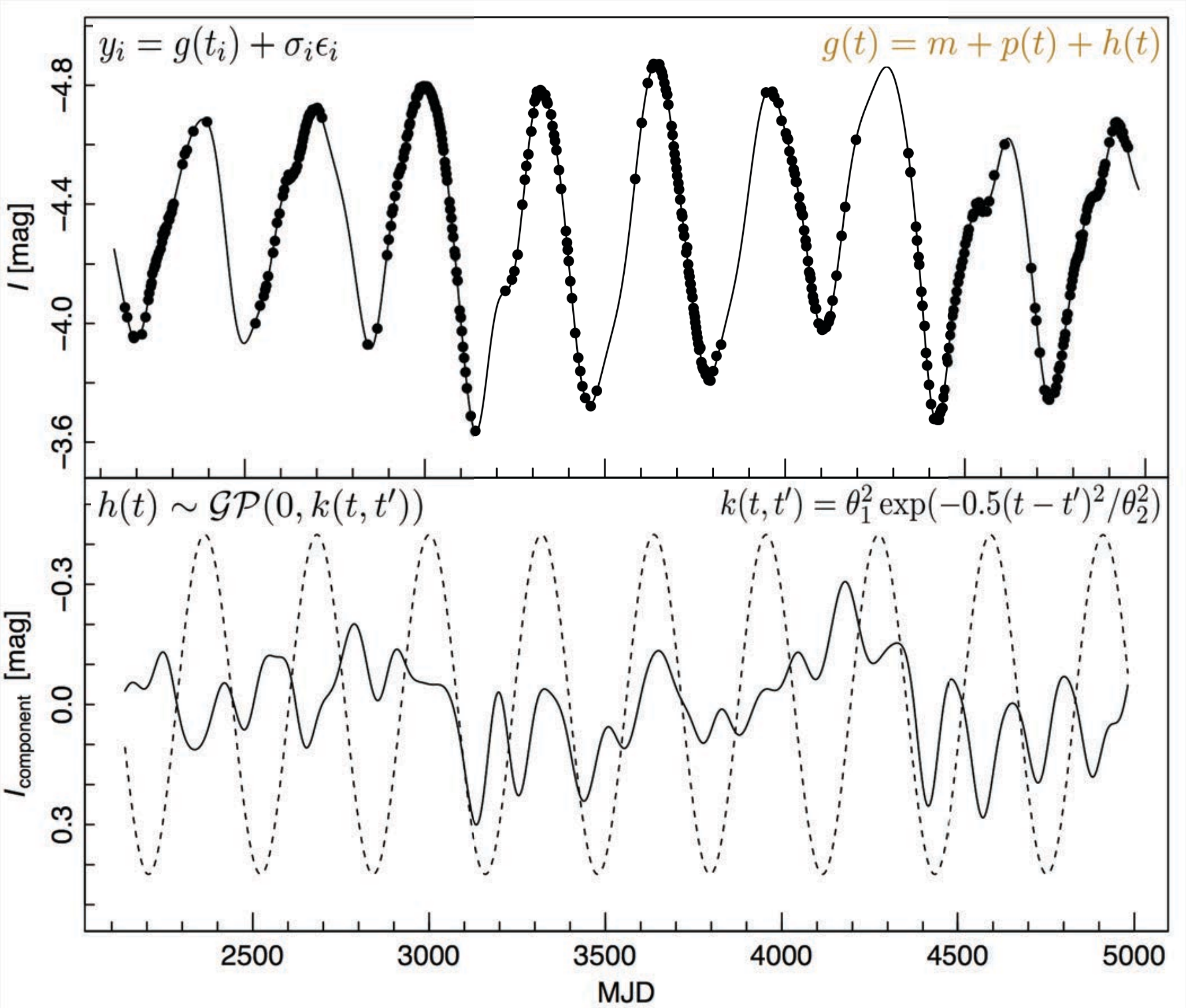
MACRI+(2015); BHARDWAJ+(2016); YUAN+(2017A)

LMCNISS Mira sample

- 690 Miras from Soszyński, Udalski, Szymański+ 2009
  - 668 with observations in all of JHK_S
- Issue: NIR observations concentrated at just three epochs for a given variable, due to long periods
- Solution: Use OGLE I-band light curves to generate JHK_S templates through regression techniques
- Derive PLRs for O- and C-rich Miras

Gaussian Process Template

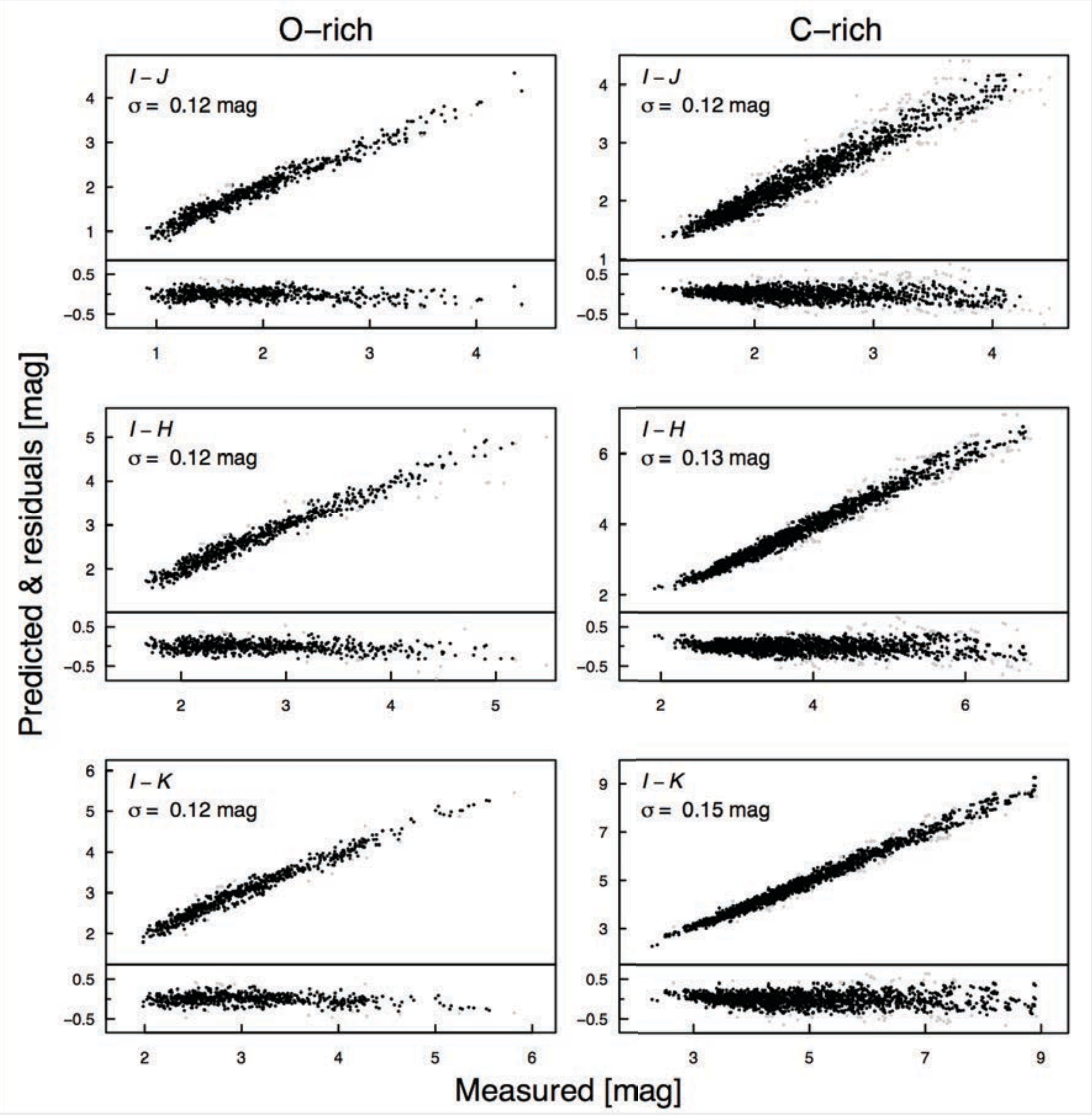
Decomposition of Mira light curve (OGLE/LMC)



He, Yuan+(2016)

Regression model

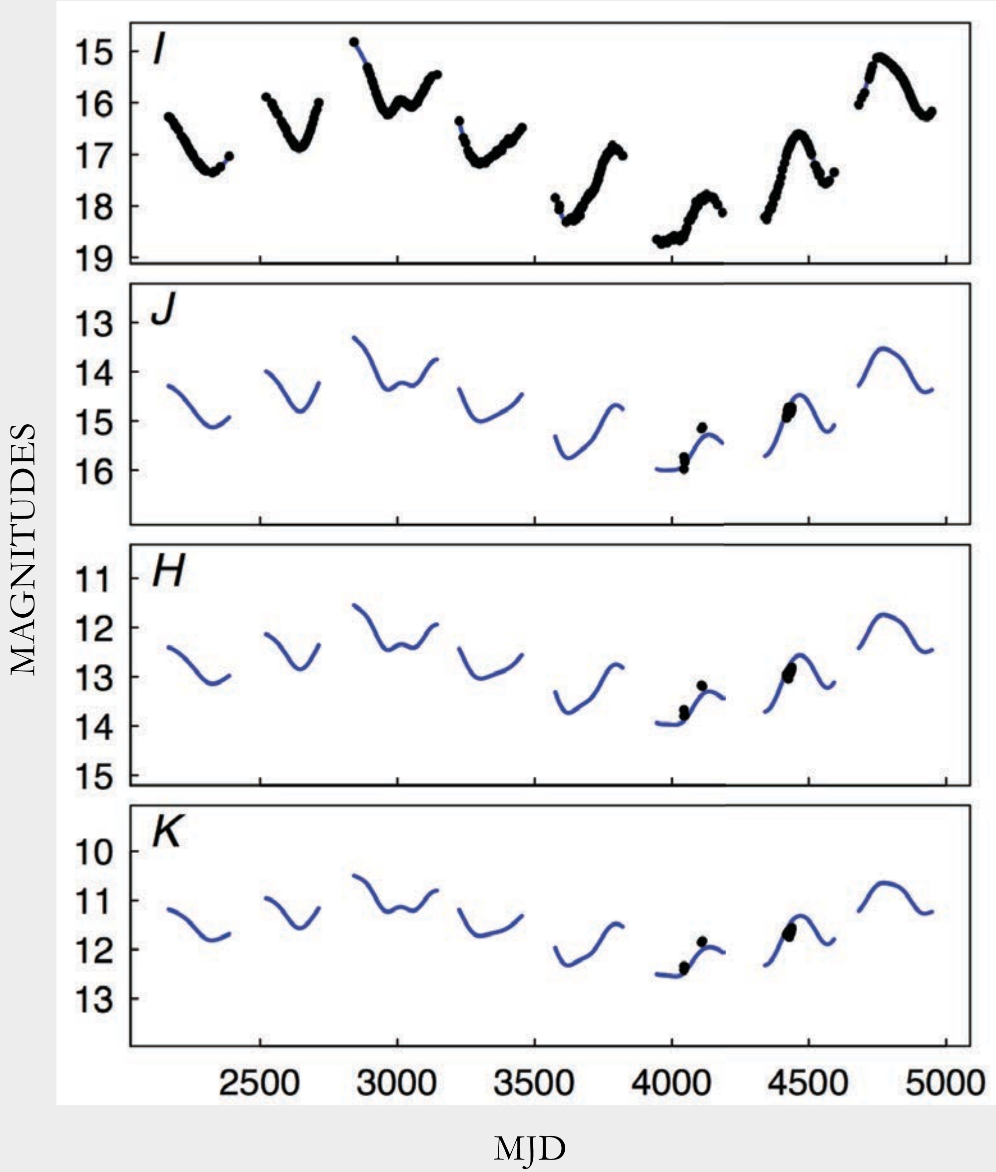
Based on ~82,000 individual JHK_S measurements + OGLE light curves



Yuan+(2017a)

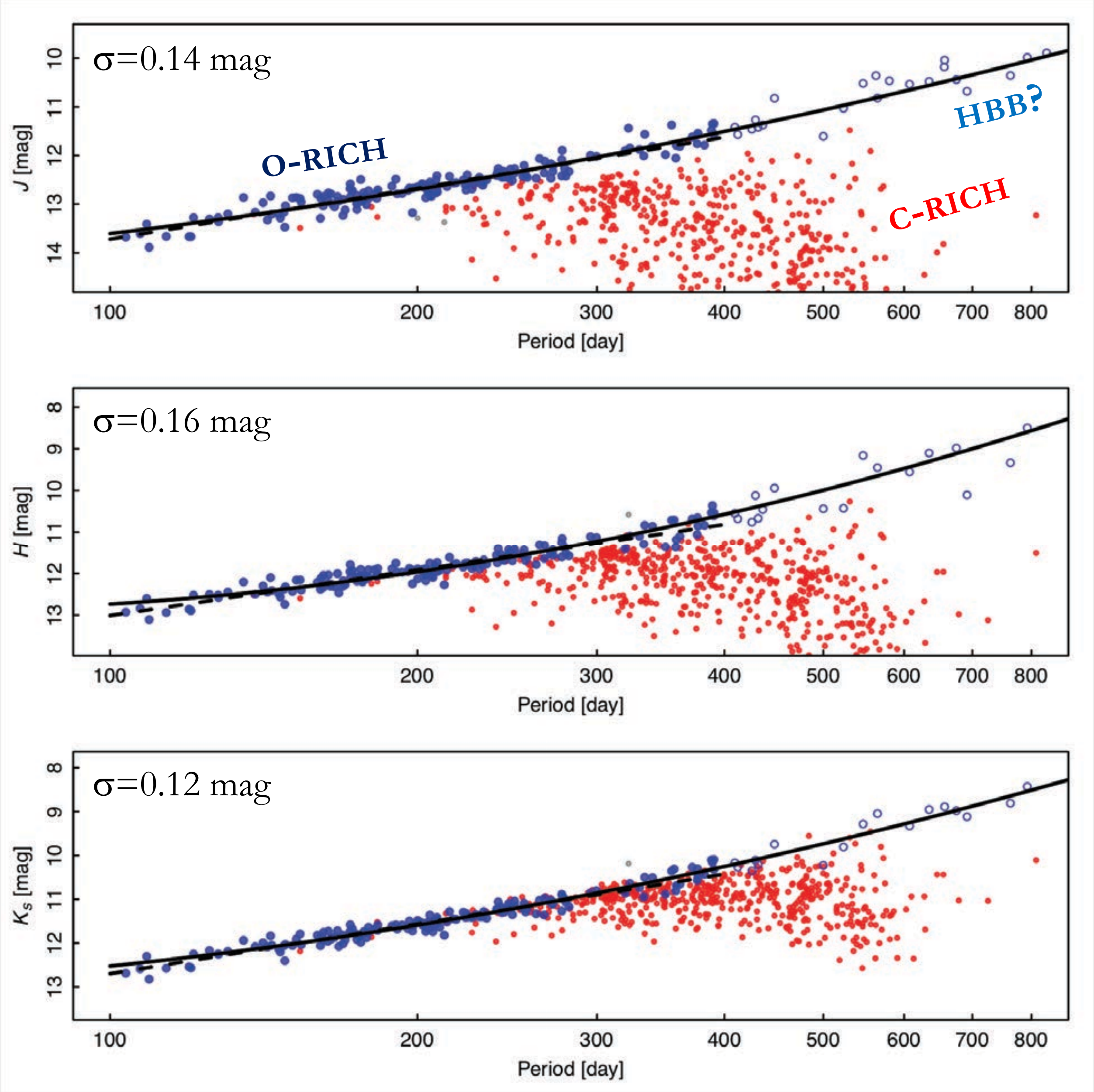
Mira template light curves

Use 3 NIR phase points + template to estimate max, mean, min



Yuan+(2017a)

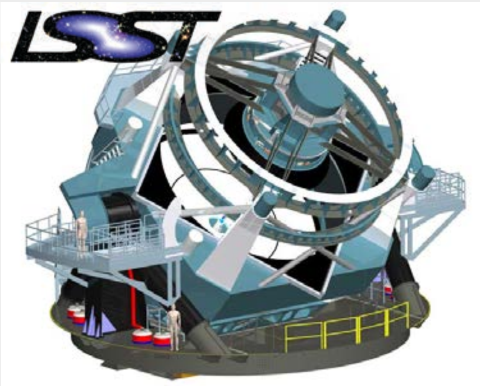
LMC MIRA PLRs



YUAN+(2017A)

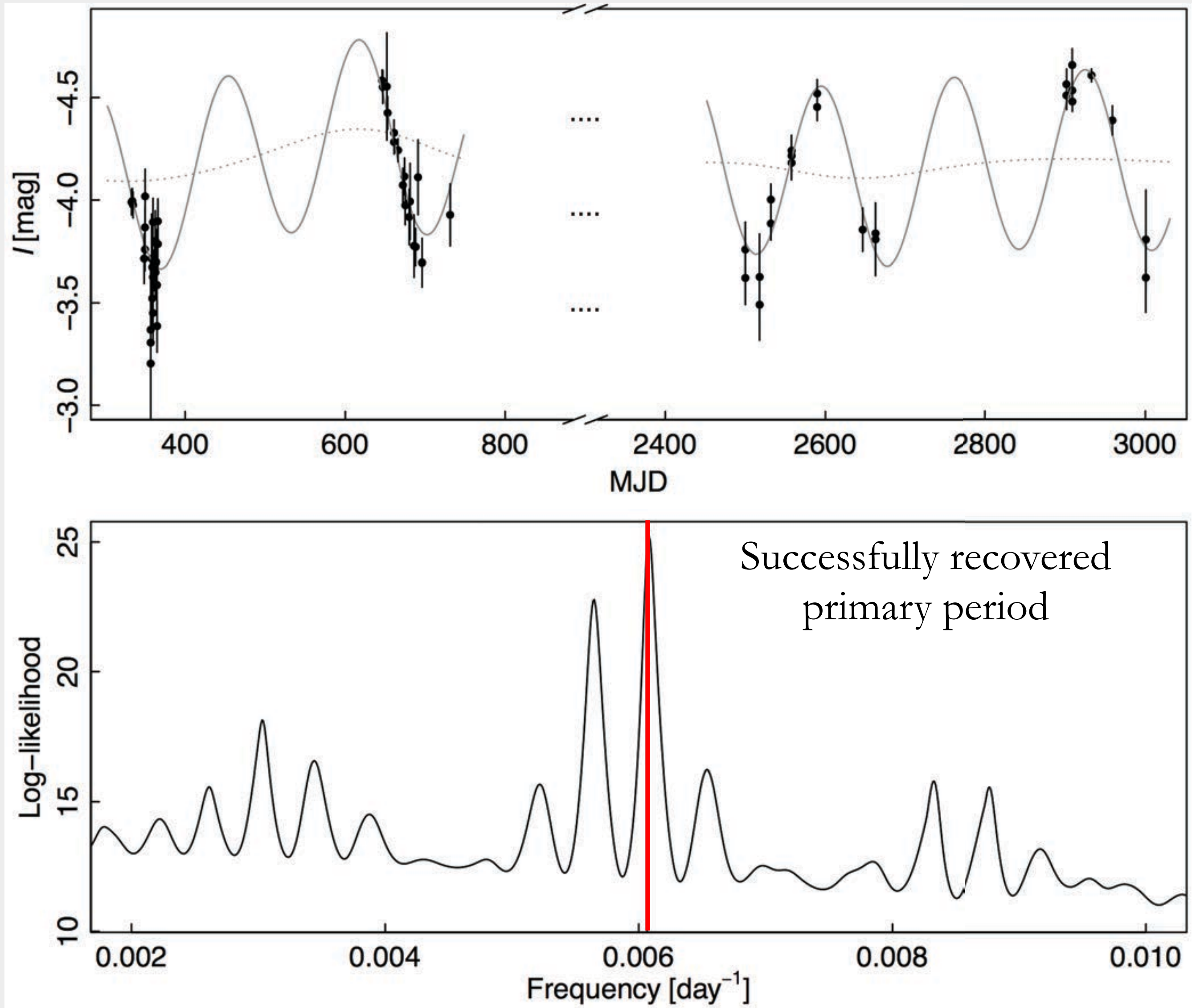
Beyond the LMC

- LSST will be sensitive enough to detect over 10^5 Miras in ~200 galaxies with D < 15 Mpc
- How to detect periodic but irregular variables using sparsely-sampled light curves?
- Develop & test novel periodogram technique with existing high-cadence observations (OGLE)
- Apply to sparser observations of M33 (Pellerin & Macri 2011)



GAUSSIAN PROCESS PERIODOGRAM

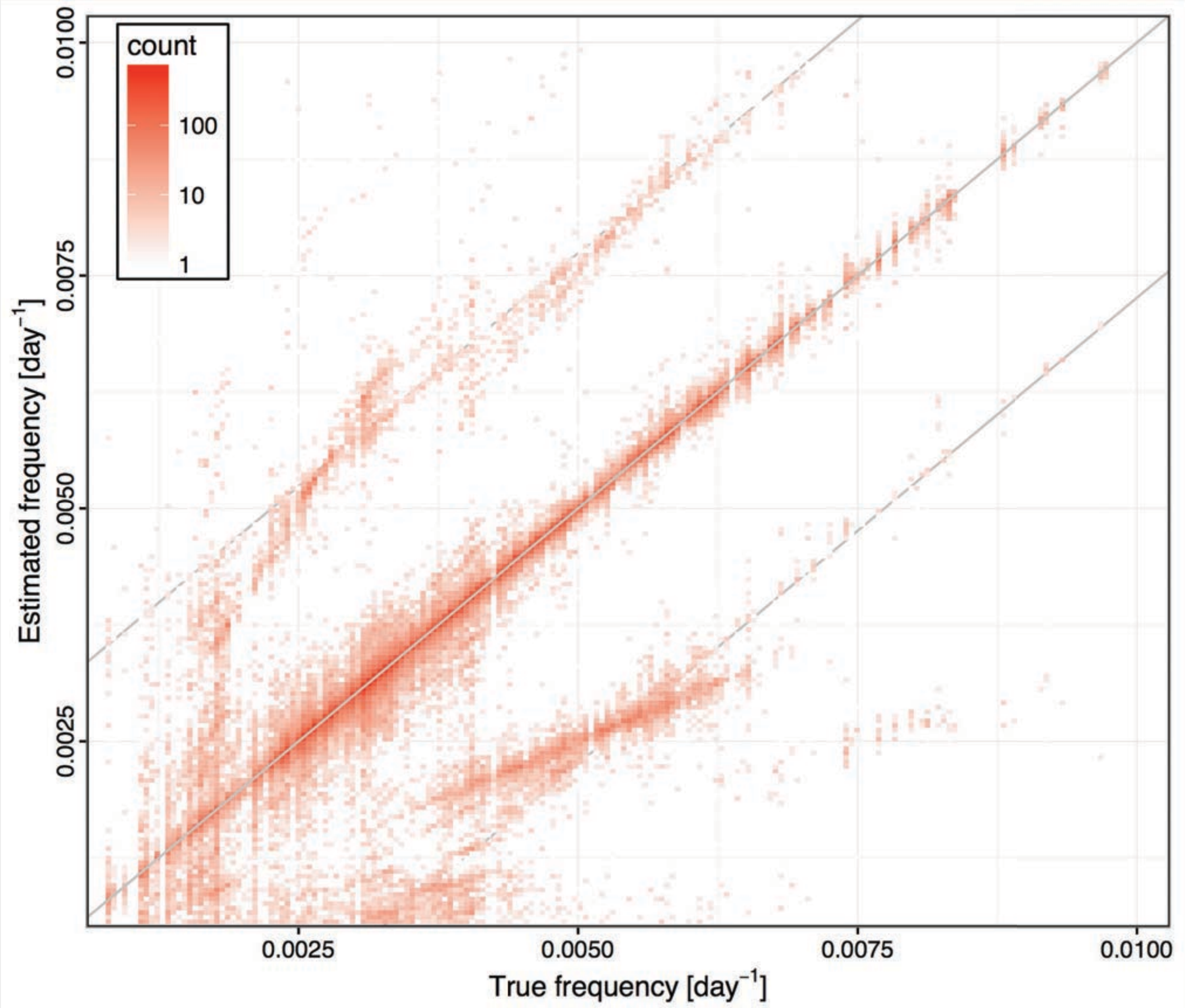
APPLIED TO NOISIER & SPARSER SIMULATED LIGHT CURVE (OGLE)



HE, YUAN+(2016)

Gaussian Process Periodogram

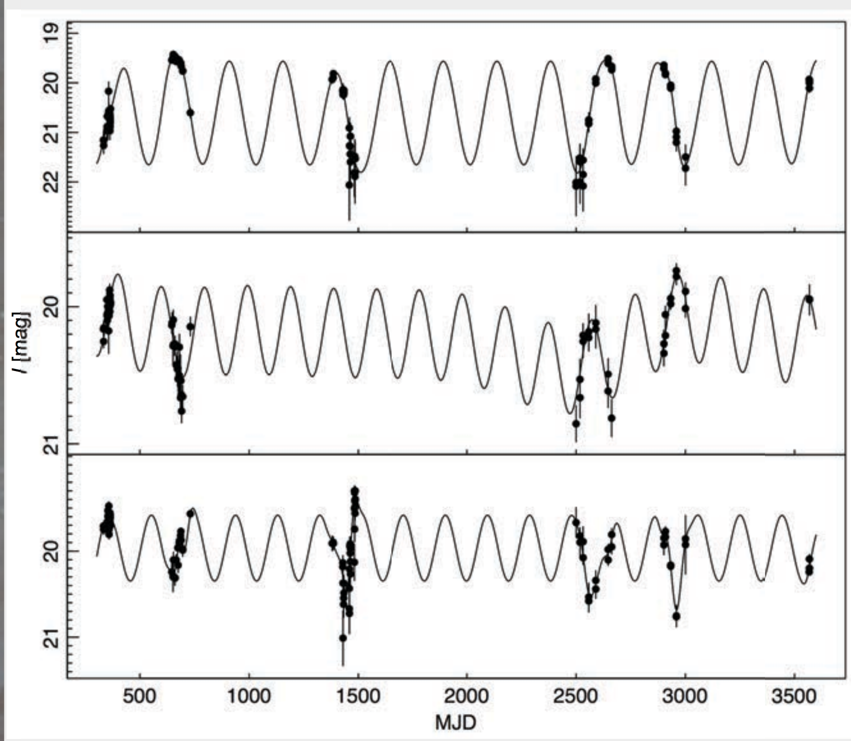
Successfully recovered primary period for 74% of simulated light curves

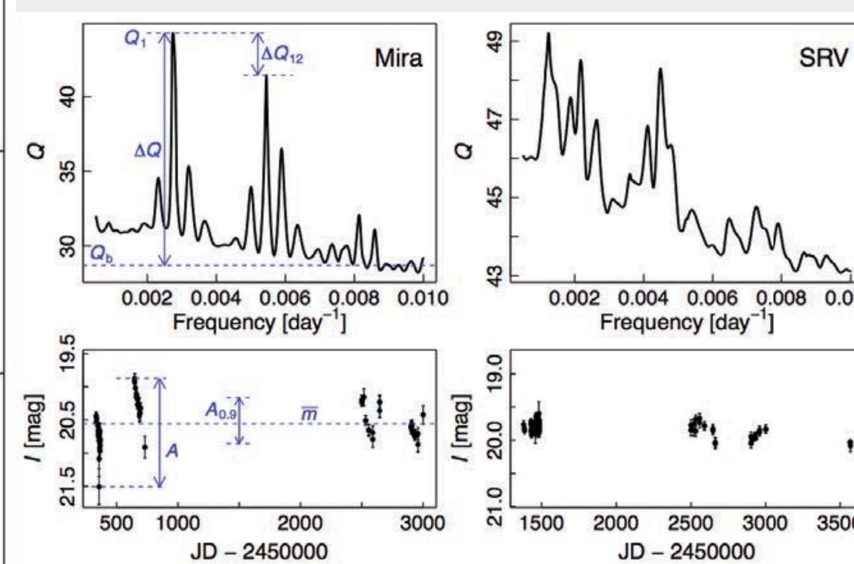


He, Yuan+(2016)

First results from M33

- Searched for Miras among 2.4×10^5 stars in M33
  - Based on I-band data only, spanning ~7 years
  - Used Random Forest classifier trained on 18 features
- Discovered >1800 Mira candidates



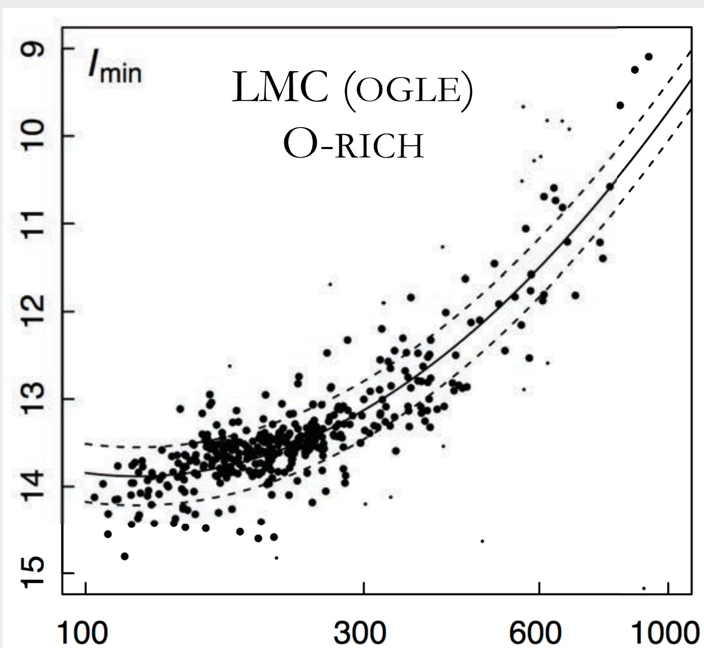


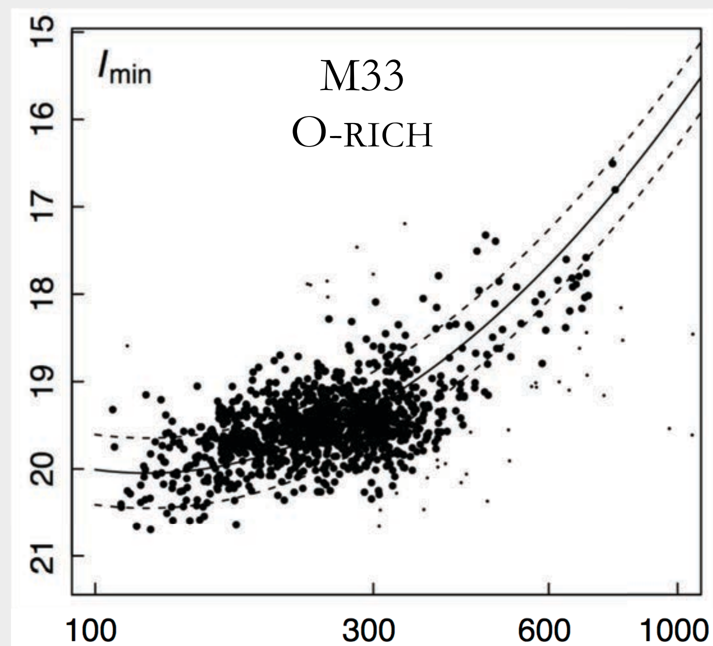
Yuan+ (2017b)

First results from M33

- Searched for Miras among 2.4×10⁵ stars in M33
  - Based on I-band data only, spanning ~7 years
  - Used Random Forest classifier trained on 18 features
- Discovered >1800 Mira candidates

MAGNITUDE





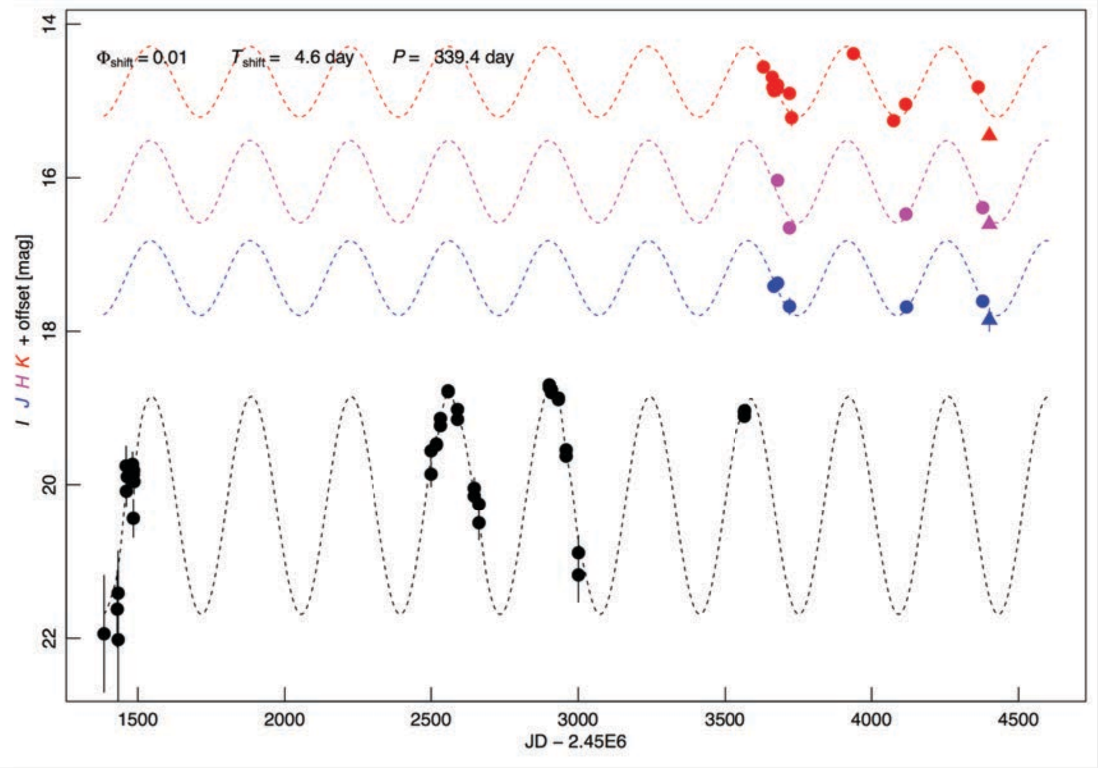
PERIOD

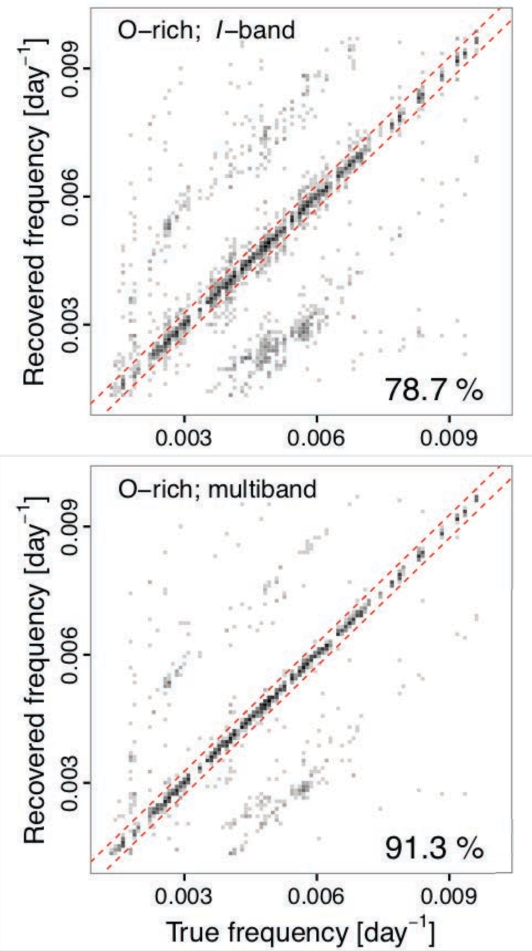
Yuan+ (2017b)

M33 MIRAS IN NEAR-INFRARED

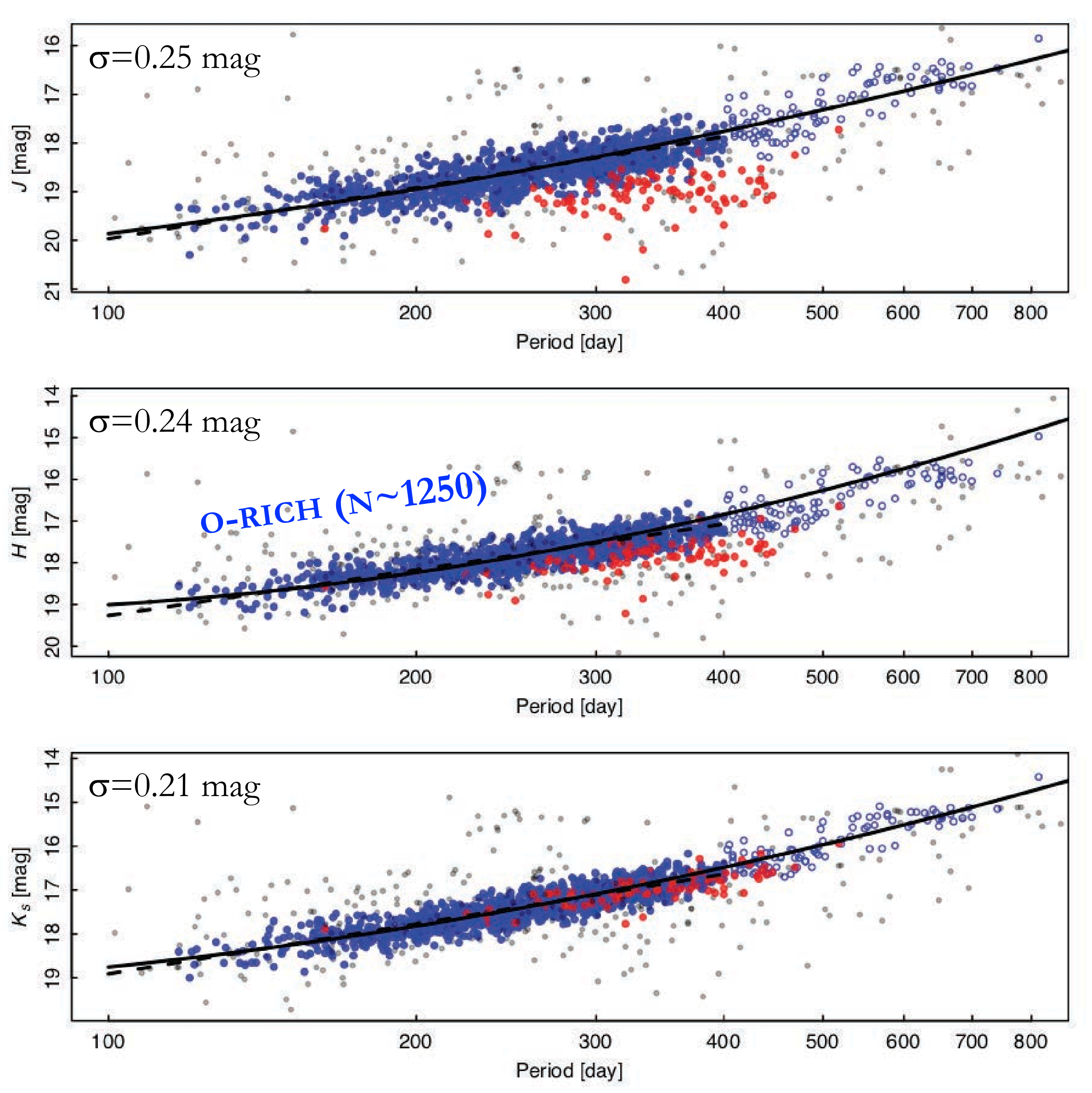
- Fit multi-band model to our JHK_S magnitudes (Gemini N, KPNO) and Javadi+2015 (UKIRT)
  - Significantly improved period recovery!

YUAN, MACRI+ (2018)





LEAVITT LAWS FOR M33 MIRAS



YUAN, MACRI+ (2018)

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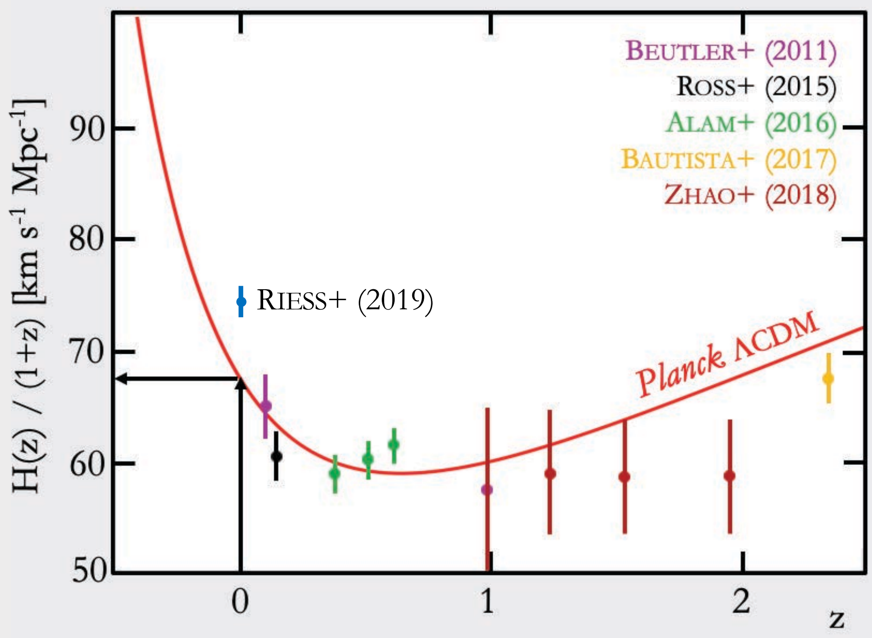
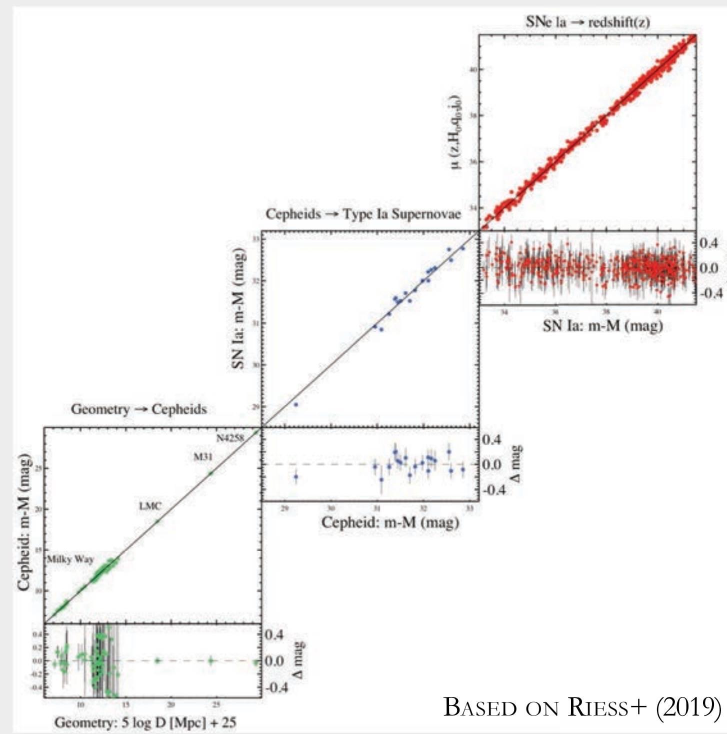
“HUBBLE TENSION”

- Compare measurement of H_0 with <u>prediction</u> based on CMB+BAO (assuming ΛCDM): >4σ discrepancy





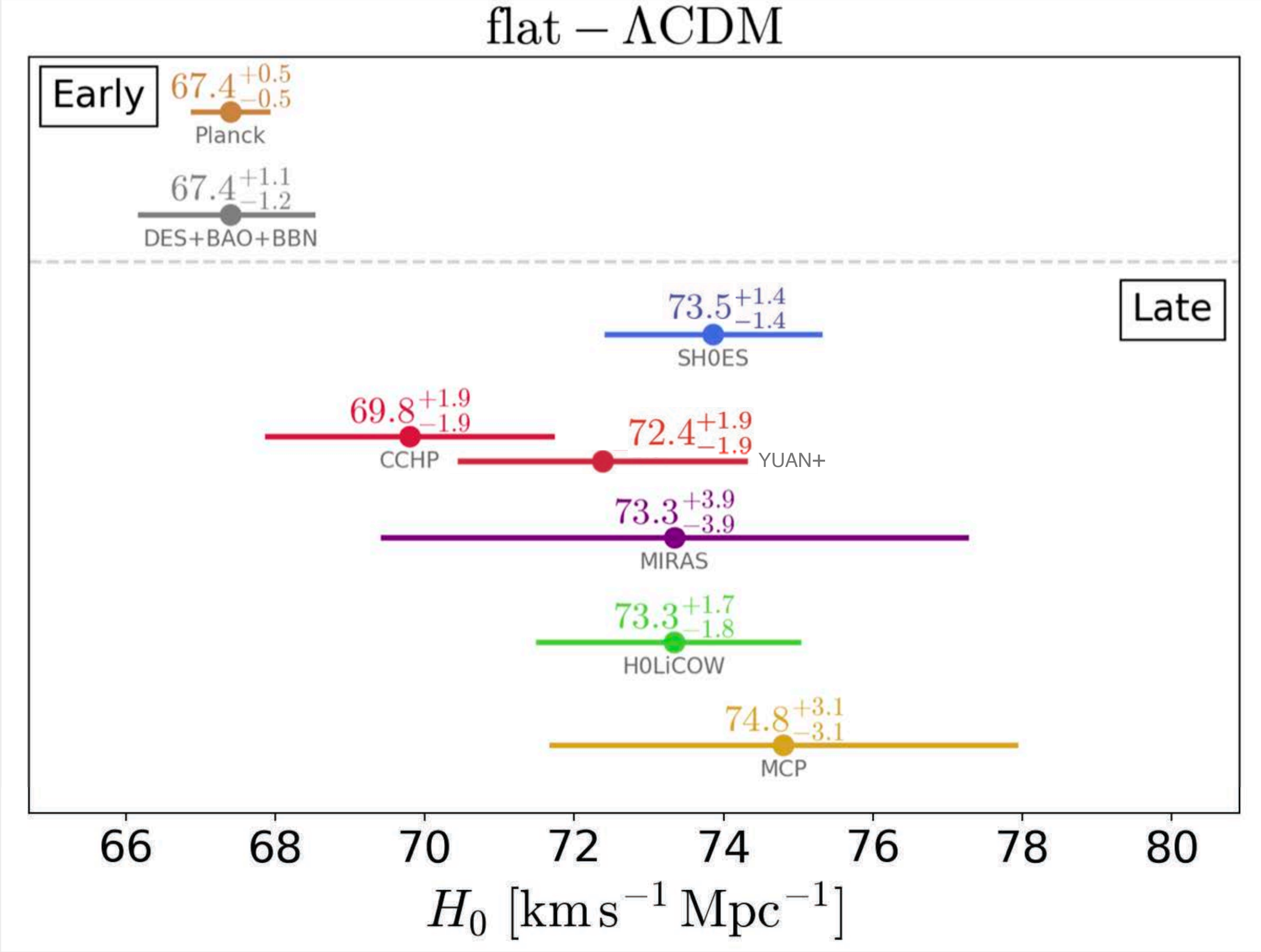
BASED ON RIESS+ (2019)

VERY RECENT DEVELOPMENTS

online.kitp.ucsb.edu/online/enervac-c19/

- Gravitational time-delays (H0LICOW, STRIDES)
  - 6 lenses, blinded analysis: H_0=73.3±1.7 km s^{-1} Mpc^{-1} (Wong+, arXiv:1907.04869)
- Maser-based distances (MCP)
  - 4 hosts beyond N4258: H_0=74.8±3.1 km s^{-1} Mpc^{-1} (Reid, KITP workshop)
- Cepheids (improved LMC & N4258 distances)
  - H_0=73.5±1.4 km s^{-1} Mpc^{-1} (Reid, Pesce & Riess, arXiv:1908.05625)
- Other indicators (share some “rungs” with Cepheids)
  - Miras: H_0=73.3±3.9 km s^{-1} Mpc^{-1} (Huang+, arXiv:1908.10883)
  - TRGB: H_0=69.8±1.9 km s^{-1} Mpc^{-1} (Freedman+, arXiv:1907.05922)
    → 72.4±1.9 w/blending corr. (Yuan+, arXiv:1908.00993)

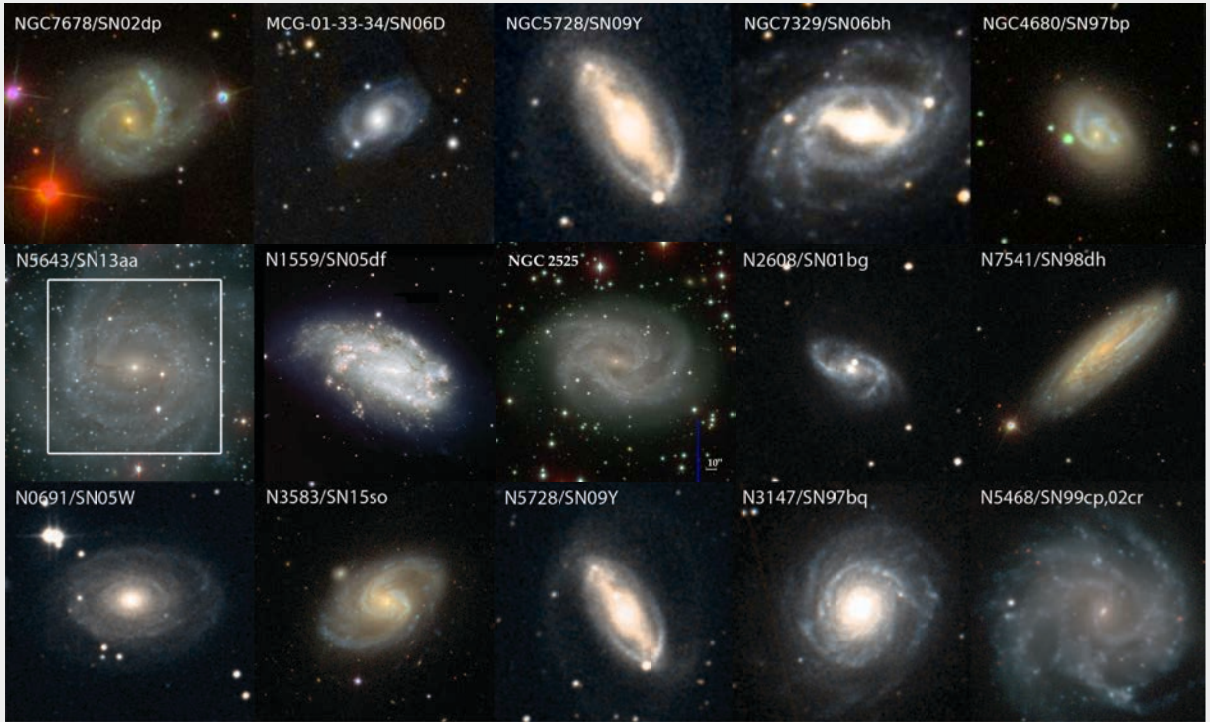
RECENT DEVELOPMENTS



Adapted from Fig 1 of Verde, Treu & Riess (arXiv:1907.10625)

ONGOING SH0ES EFFORTS

- Cepheid search in 15 additional hosts of SNe Ia
  - Increase calibrator sample to 38; should yield $\sigma(H_0)$=1.6%
  - Mira search in nearest 4 (check Cepheid distances)
- HST observations of MW Cepheids (resolve *Gaia* sys.)

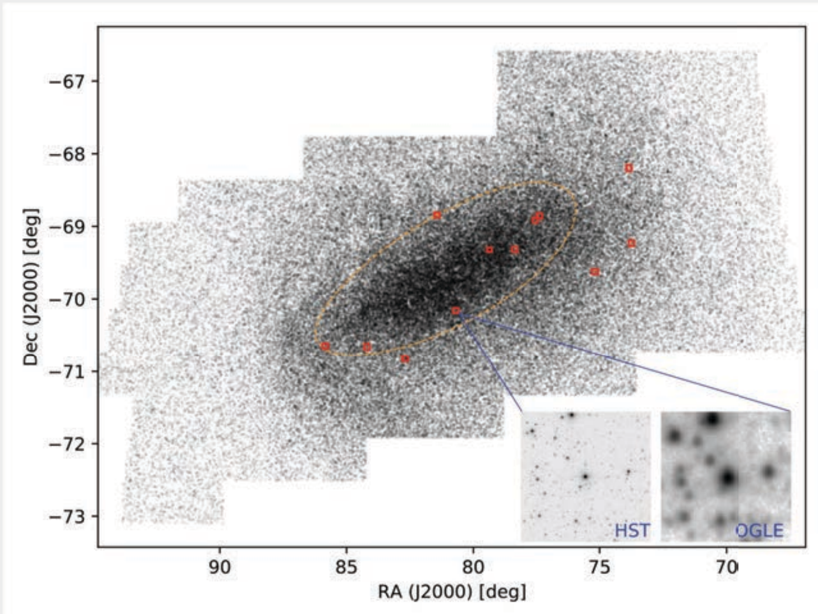


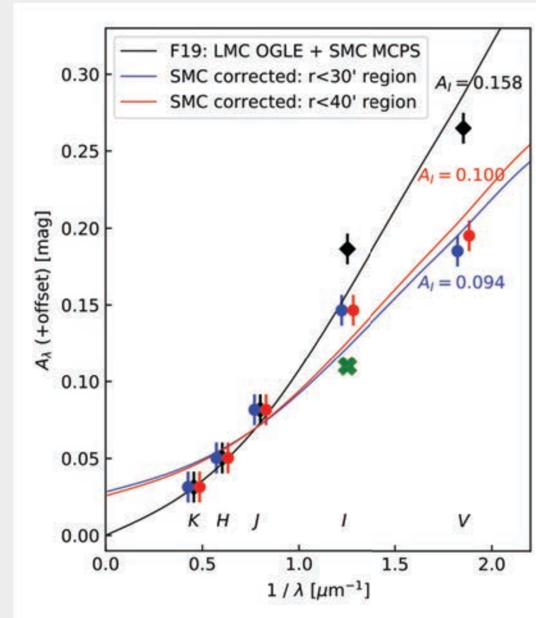
Summary

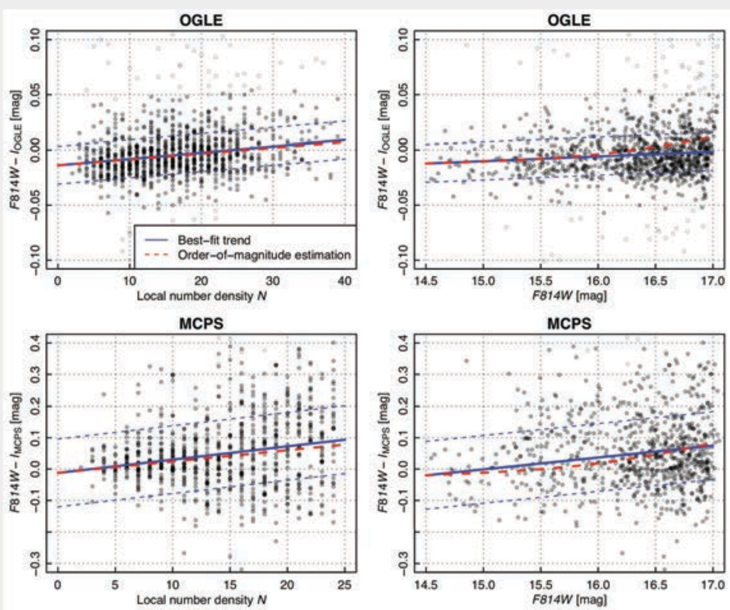
- SH$_0$ES project: calibration of modern, high-quality SNe Ia using Cepheids in the near-infrared
  - H_0=73.5±1.4 km s^{-1} Mpc^{-1} → $\sigma(H_0)$=1.9%
  - >4σ tension wrt *Planck*+BAO → New Physics in dark sector?
- Goal: $\sigma(H_0)$=1.3% by early 2020s
  - *HST, Gaia* parallaxes to Milky Way Cepheids
  - 50 Cepheid distances to nearby SNe Ia
- Miras as "first rung" of an independent ladder
  - Absolute calibration via LMC and N4258
  - Gaussian process periodogram in M33 bodes well for LSST

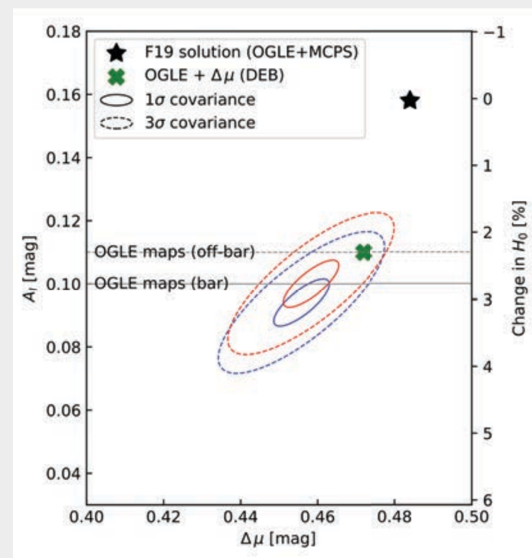
Backup slides

TRGB in LMC





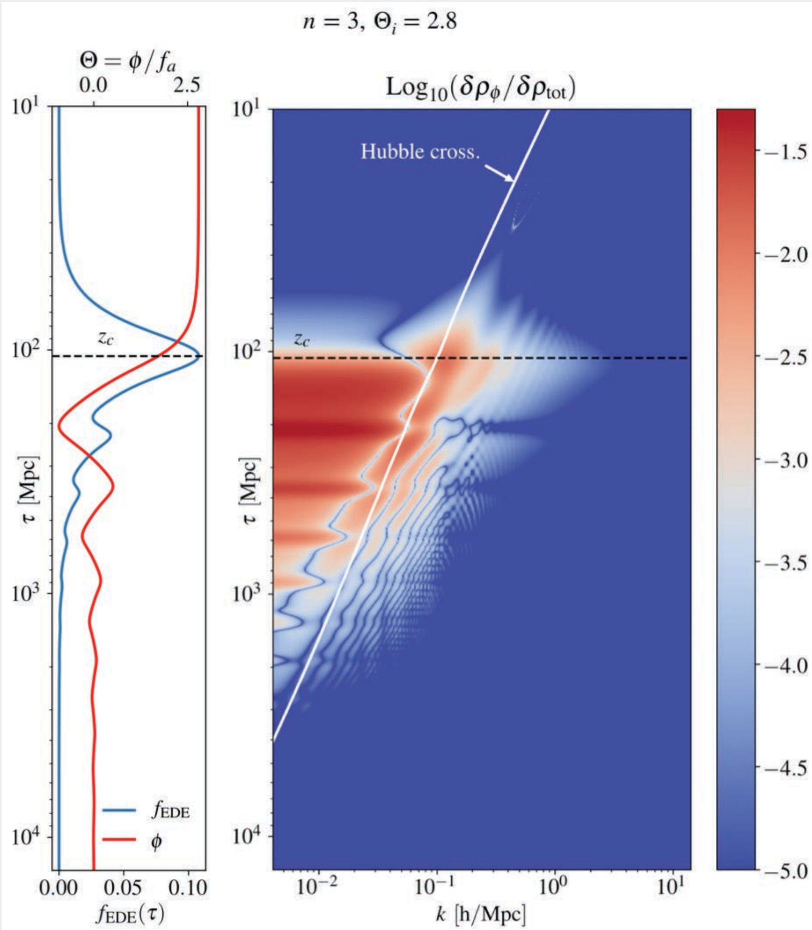


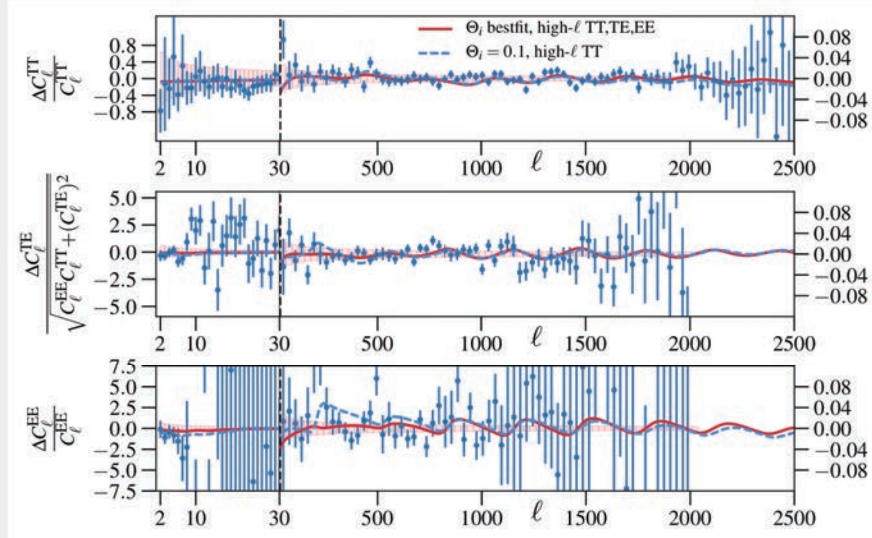


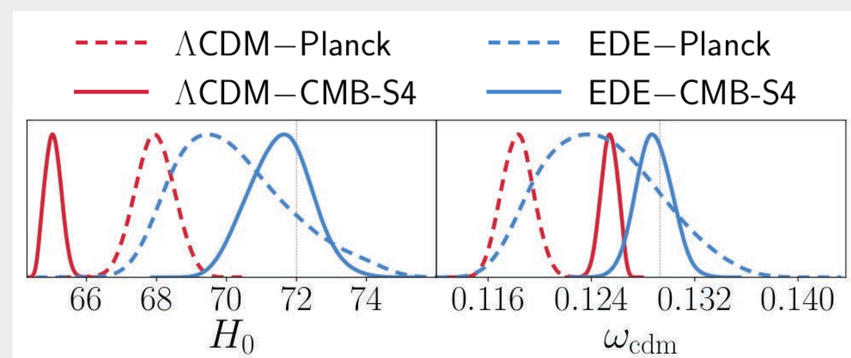
Yuan+(arXiv:1908.00993)

RESOLUTION: EARLY DARK ENERGY?

Poulin+18, Smith+19: oscillating scalar field with ρ_{EDE}/ρ_{TOT}~10% at z~3500
Slightly better fit to *Planck* data; 27σ with CMB-S4!! (DoE CD-0)







arXiv:1908.06995; 1811.04083