Cepheids and other stellar populations

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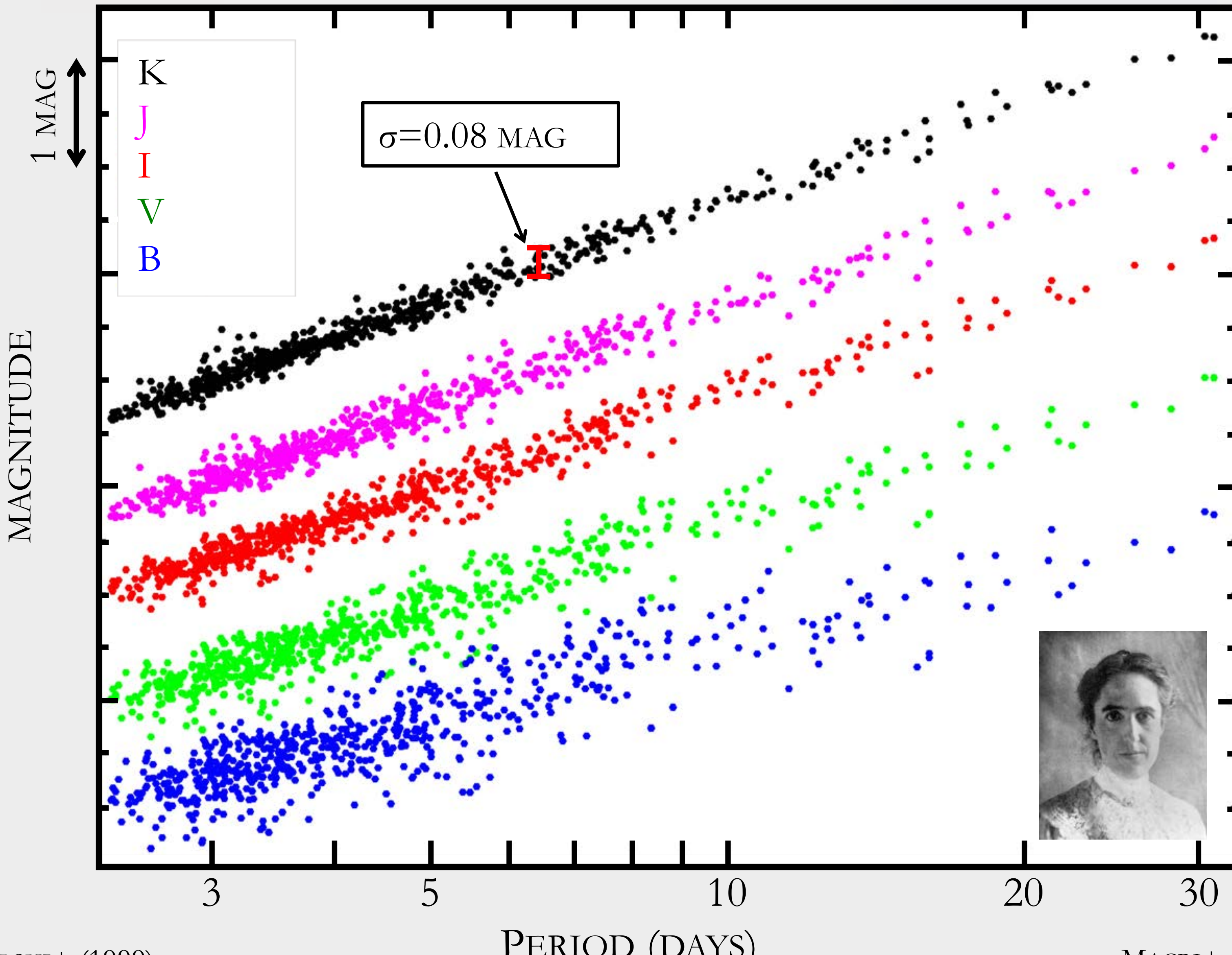
ADVANTAGES OF SH0ES CEPHEIDS

- 3 independent absolute calibrations:
  - 50+ Milky Way parallaxes (*Hipparcos*, HST/FGS, HST/WFC3)
  - Maser distance to NGC 4258 (today's talk by Mark Reid)
  - Detached eclipsing binaries in the LMC (Pietrzyniski+18)
- Primary measurements made at H-band (1.6μm)
  - Impact of dust reduced by >3× relative to I-band
  - Used in reddening-free Wesenheit index (Madore 1982)
  - Minimal sensitivity to metallicity (Wielgorski+ 2017)
  - No Ceph.-SN residuals vs. distance: crowding under control
- Matrix-based formalism
  - Allows unbiased quantification of "analysis systematics"

LEAVITT LAWS IN THE LMC

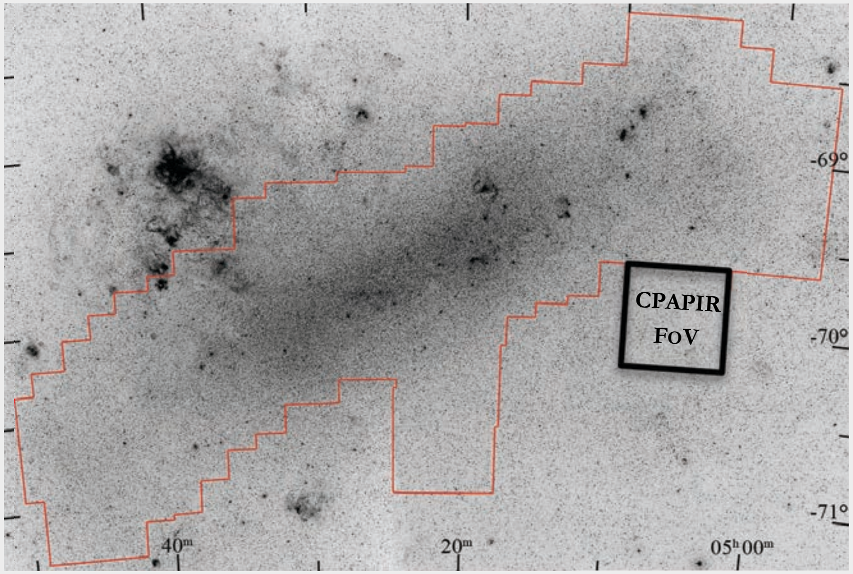


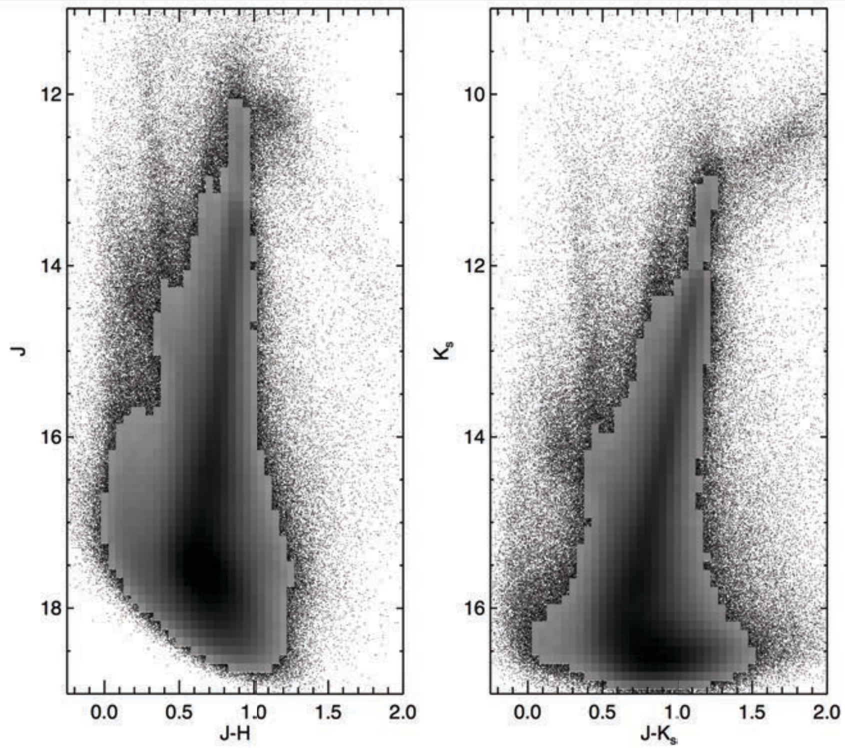
UDALSKI+ (1999)

MACRI+ (2015)

SH0ES Anchor #2 of 5: LMC

- CTIO 1.5-m, 18 sq deg synoptic survey (Macri+ 2015)
  - >1400 OGLE Cepheids, P=2-100d, tied to 2MASS
  - **70 P~6-60d observed with HST/WFC3**
- 1.1% DEB distance (Pietrzynski+ 2018)
- Fully-propagated uncertainty: σ(anchor)=1.3%





Macri+ (2015)

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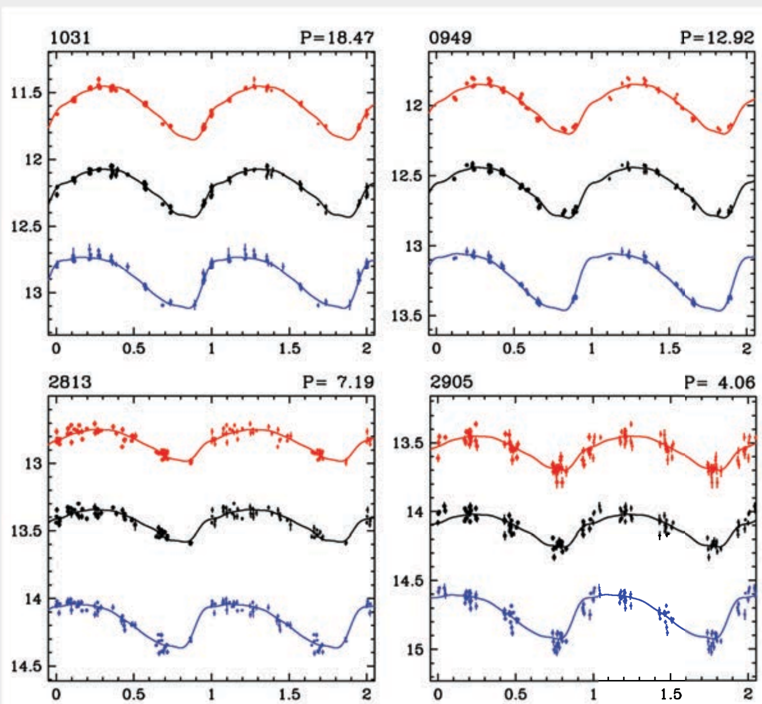
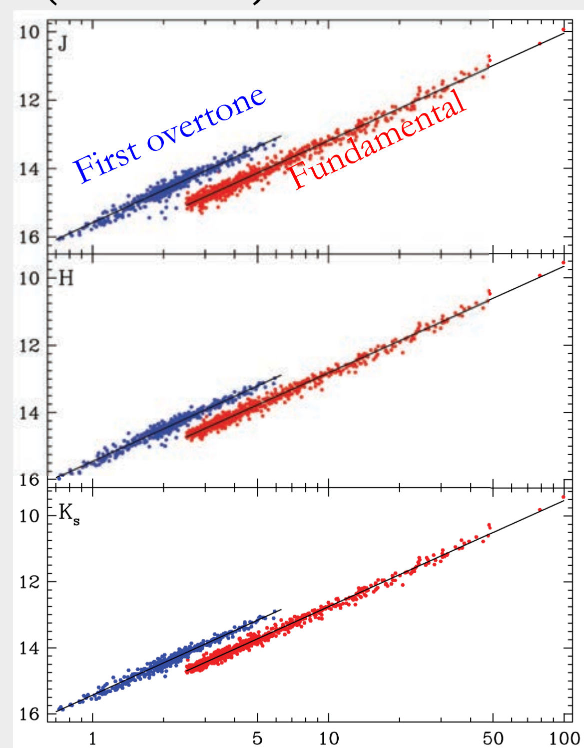


JHK$_S$ MAGNITUDES

PHASE

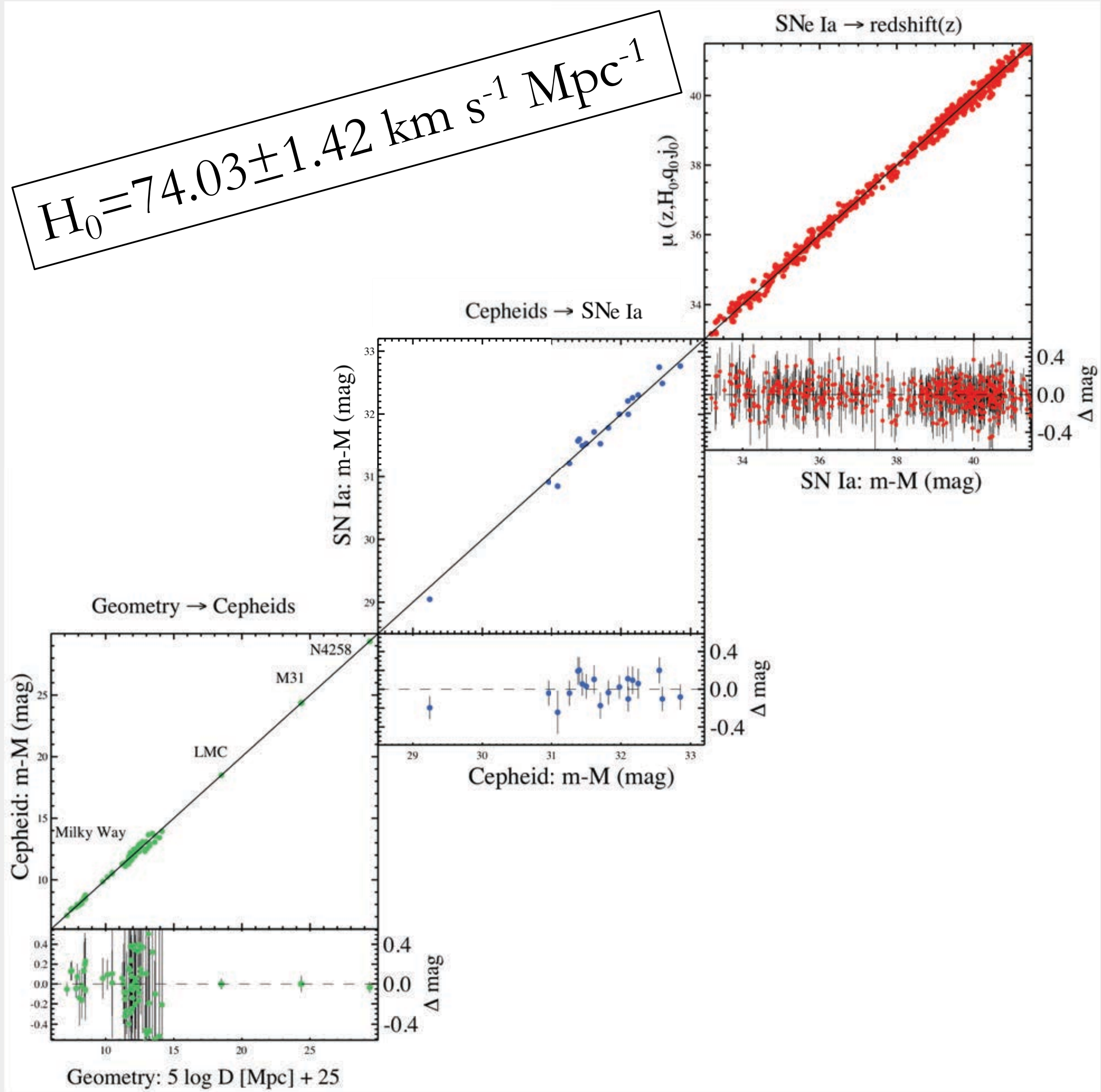


MAGNITUDE

PERIOD (DAYS)

MACRI+ (2015)

SH$_0$ES DISTANCE LADDER

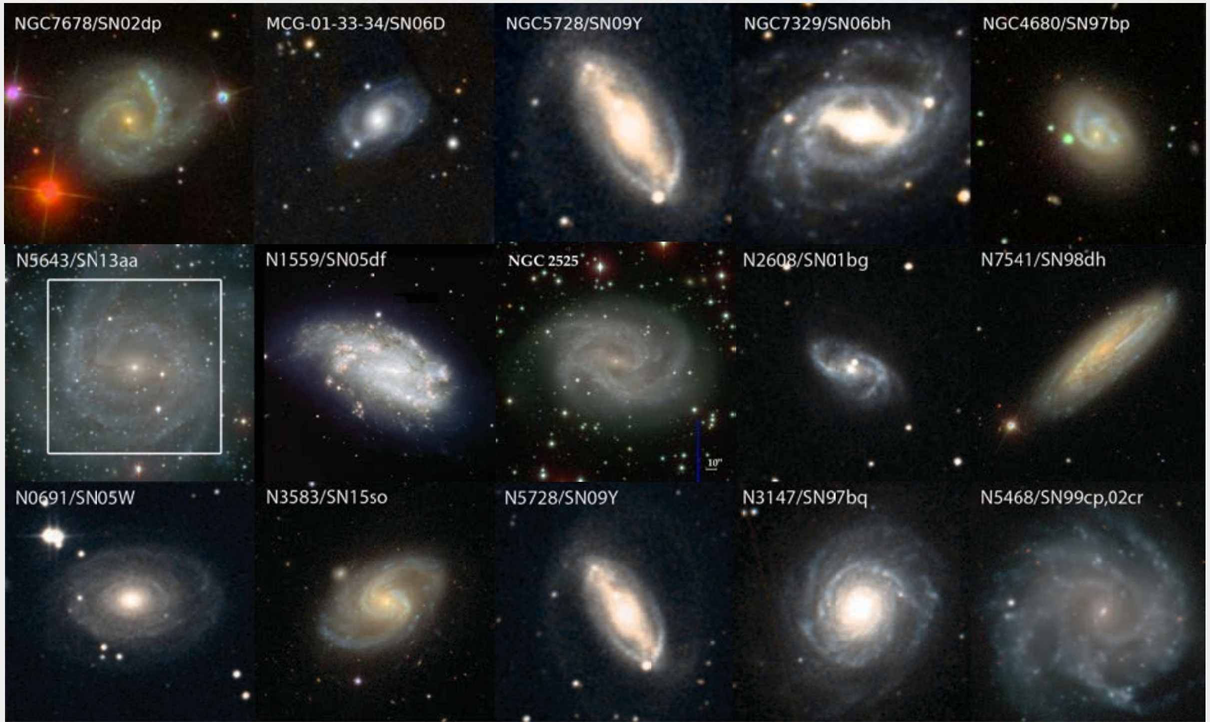


RIESS+ (2019)

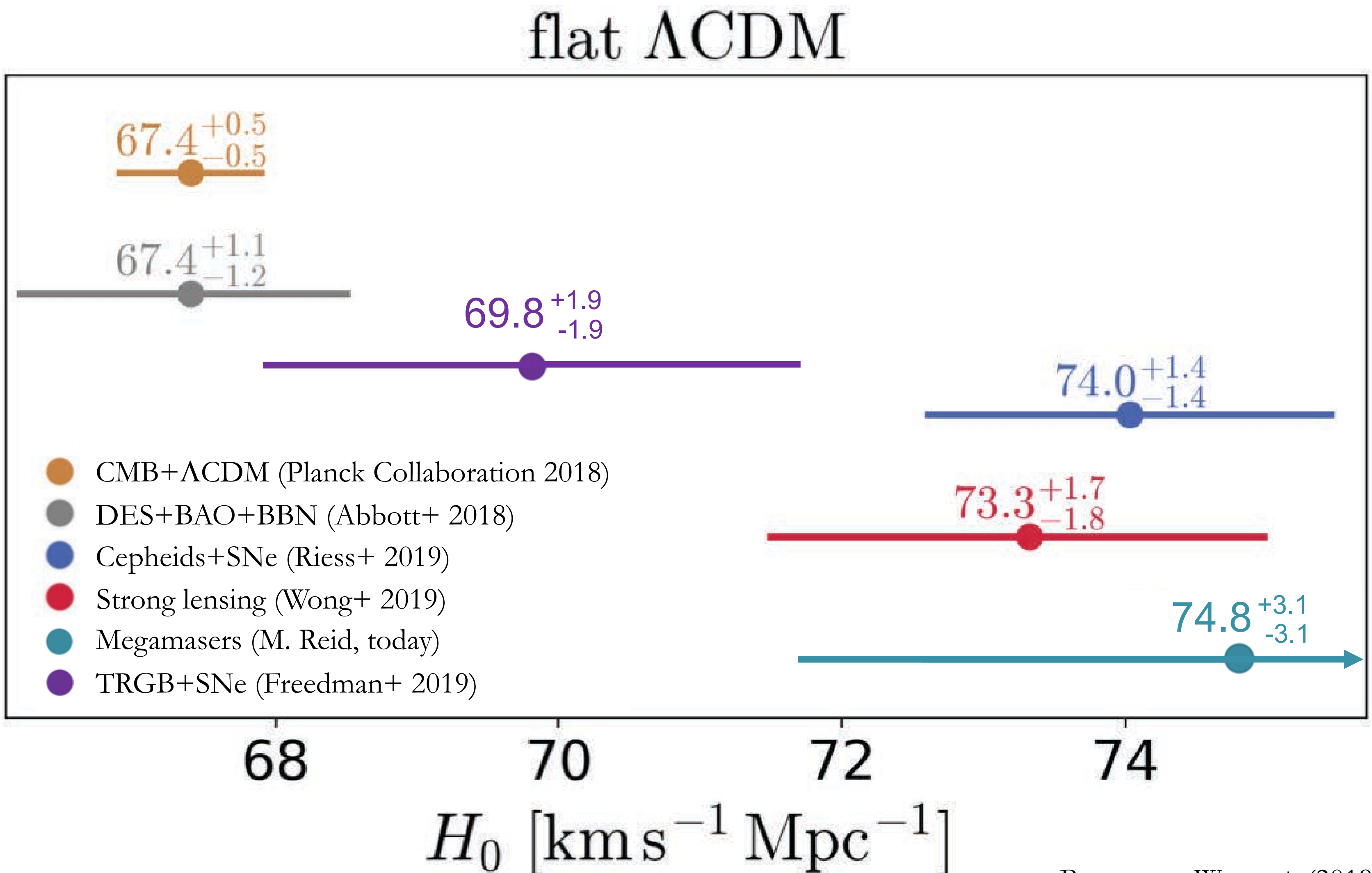
HST Cycles 25 & 26

- 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 of those hosts
  - Consistency check of Cepheid Distance Scale



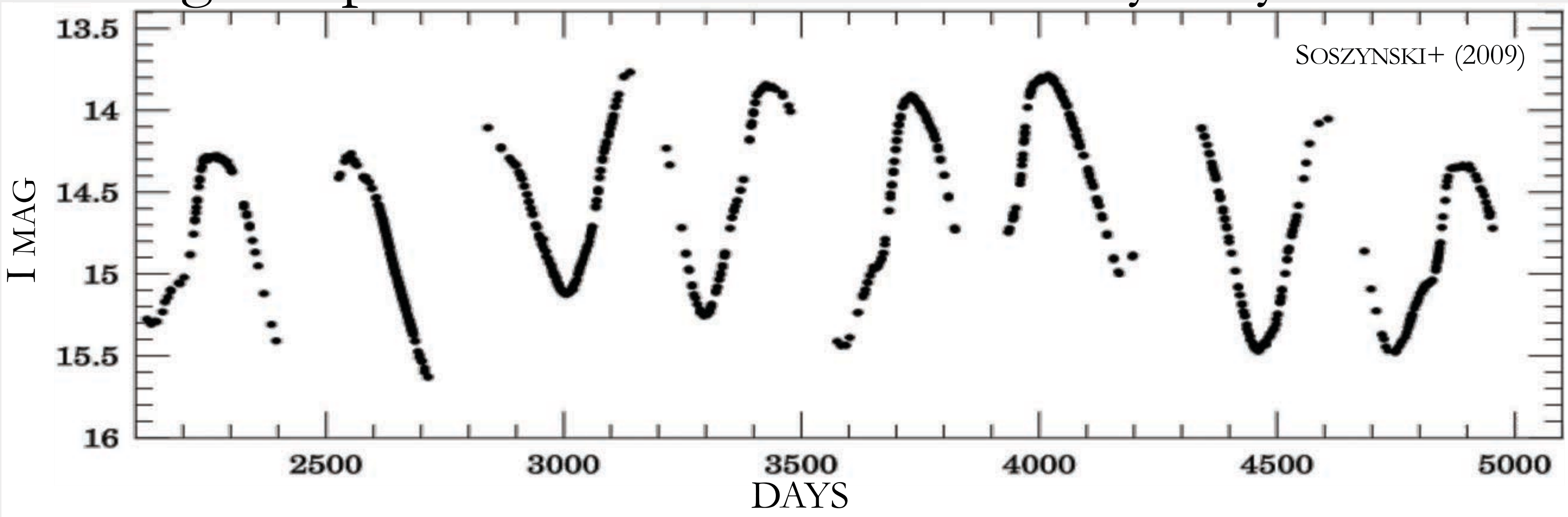
Independent H_0 estimates



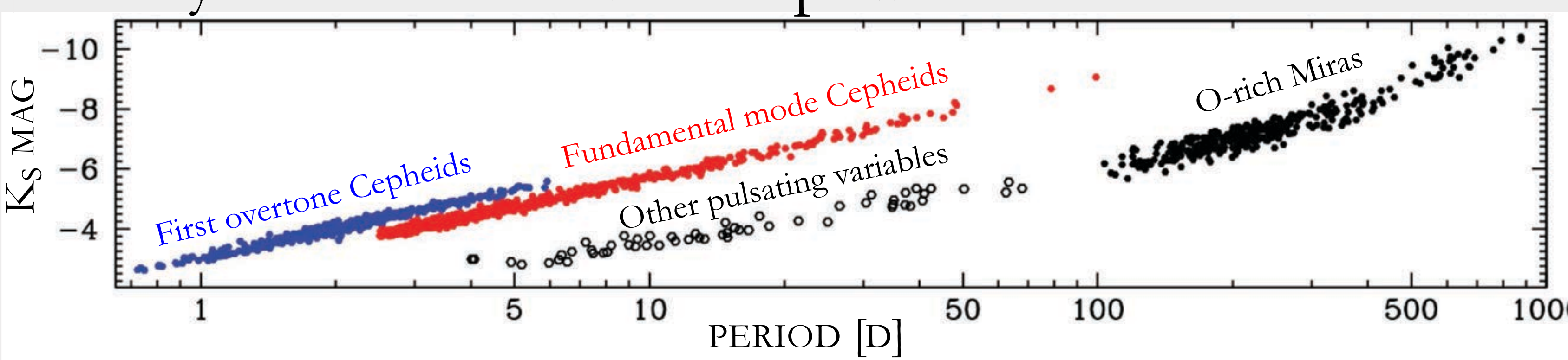
Based on Wong+ (2019)

Why Miras?

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



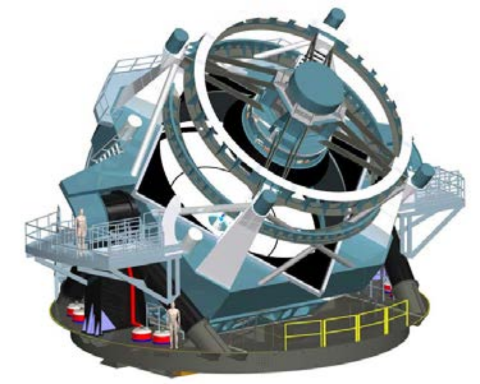
- Very luminous in NIR → powerful distance indicator



Macri+(2015); Bhardwaj+(2016); Yuan+(2017)

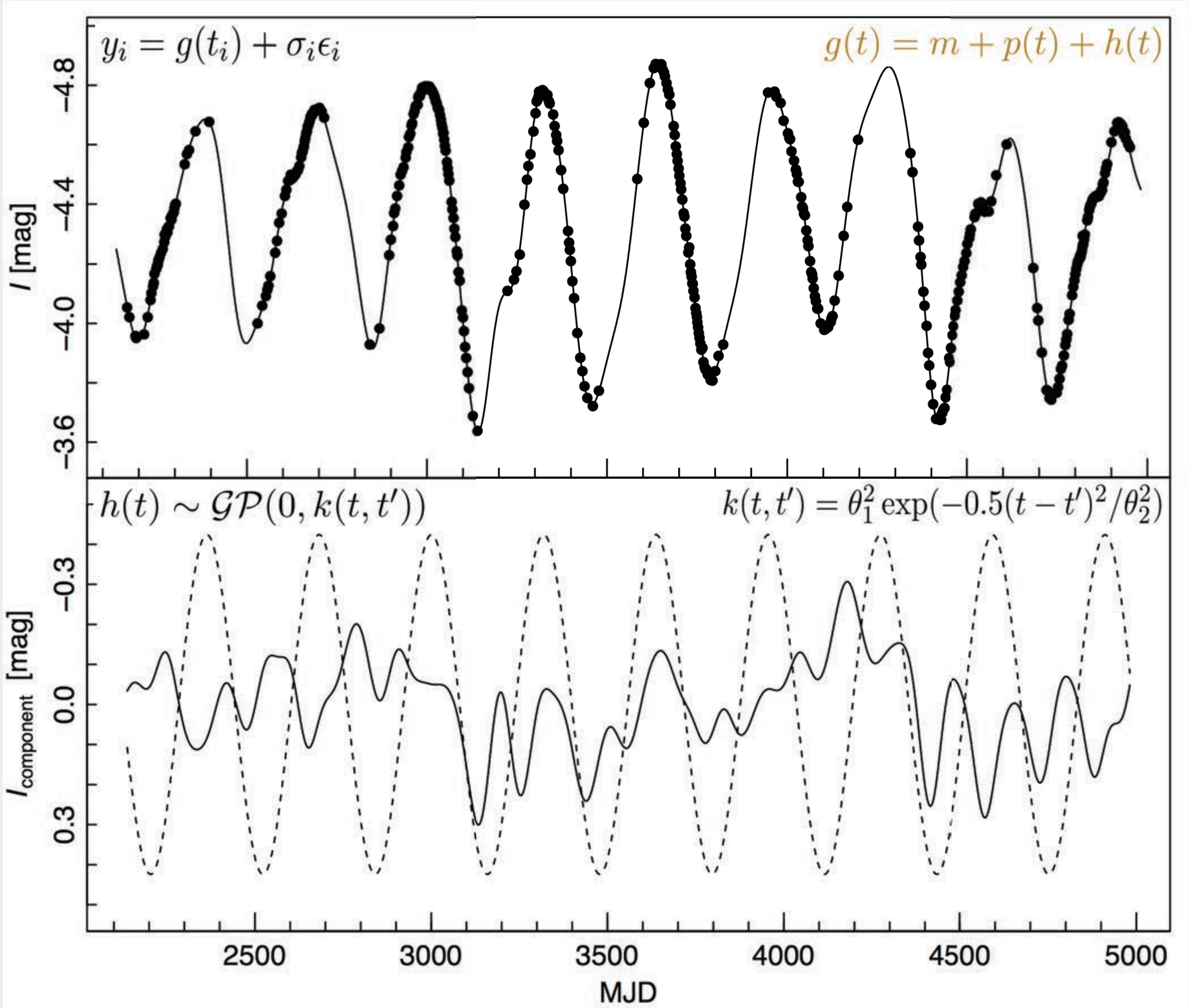
Why Miras?

- 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

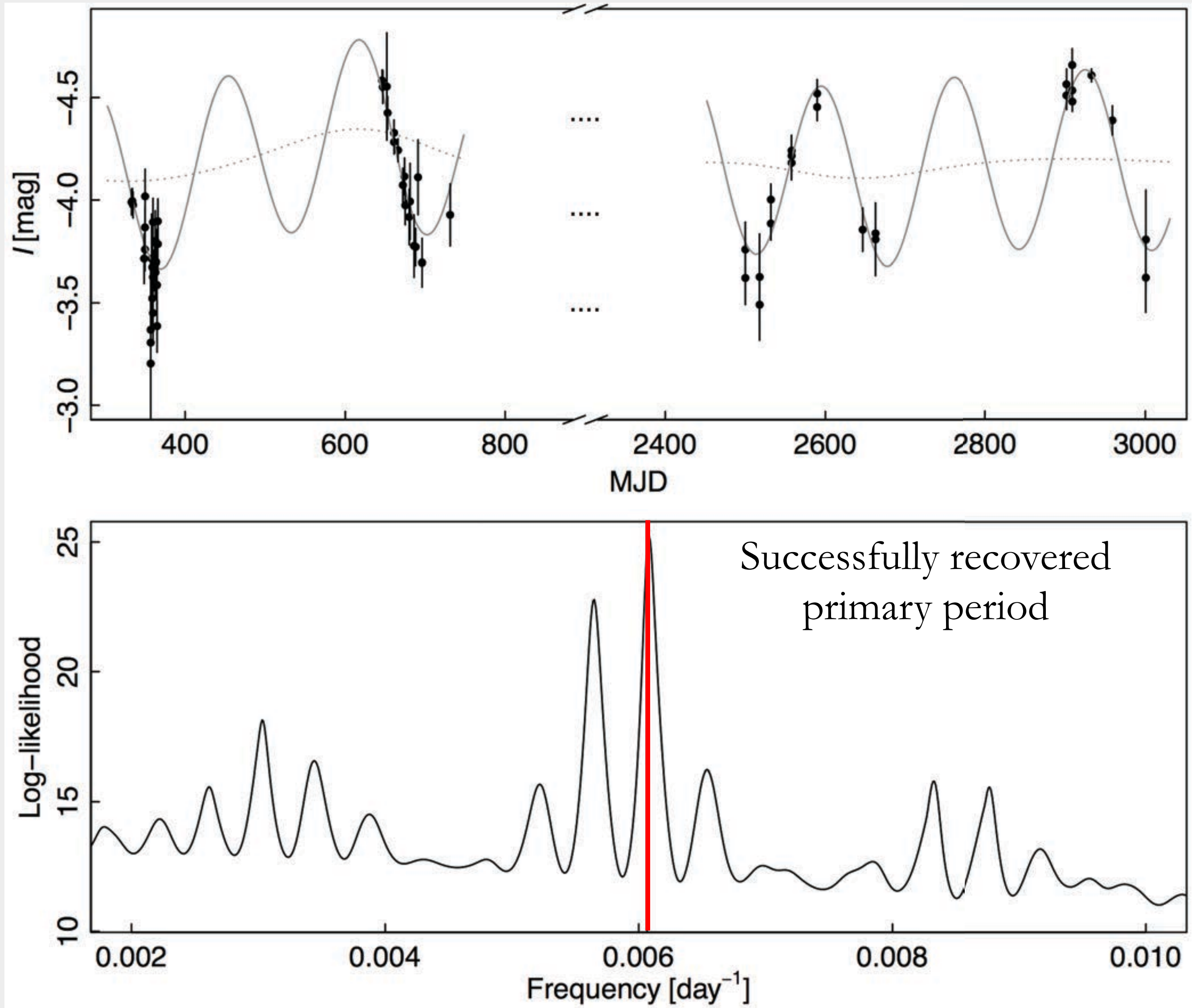
Decomposition of Mira light curve (ogle lmc)



He, Yuan+(2016)

Gaussian Process Periodogram

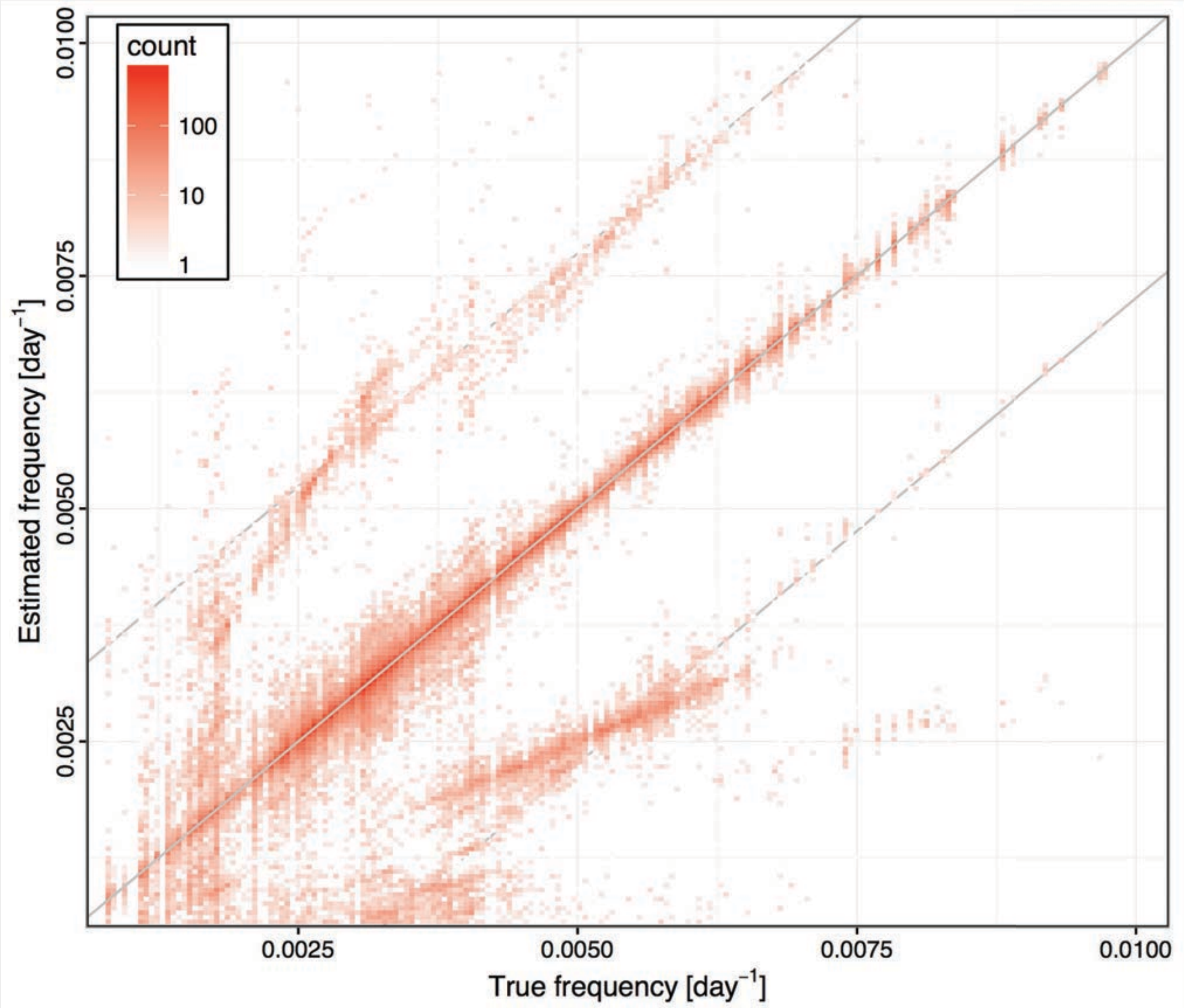
Applied to noisier & sparser simulated light curve



He, Yuan+(2016)

Gaussian Process Periodogram

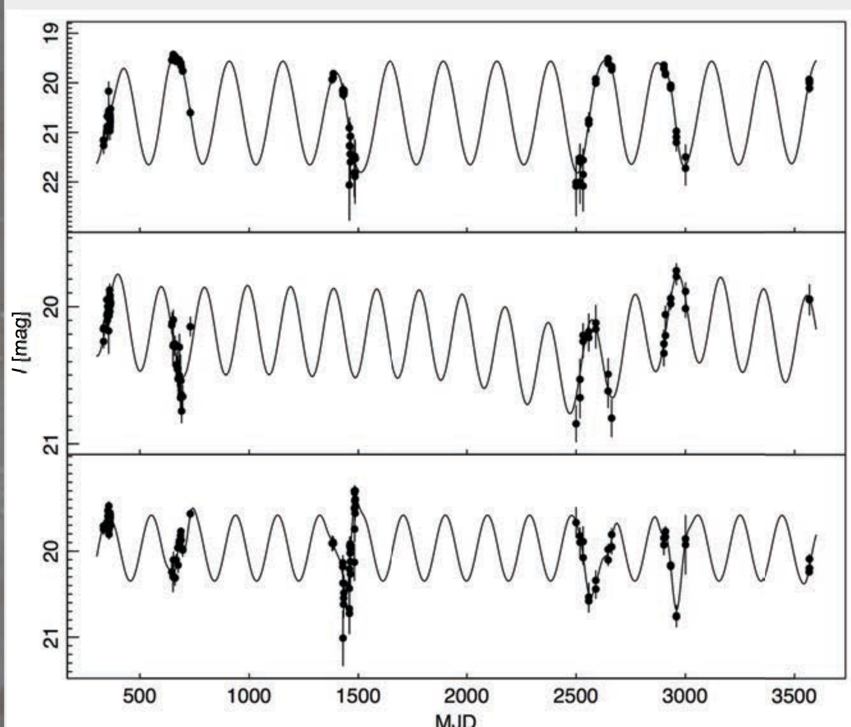
Successfully recovered primary period for 74% of simulated light curves

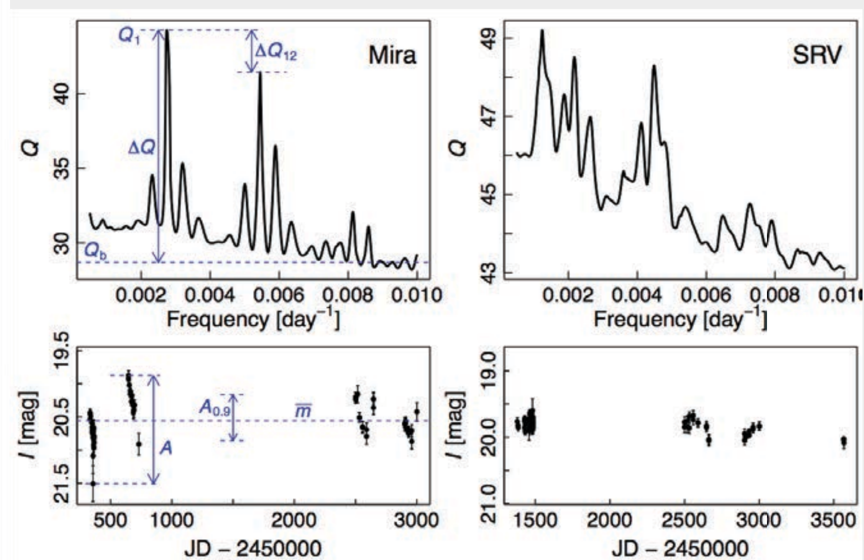


He, Yuan+(2016)

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+ (2017A)

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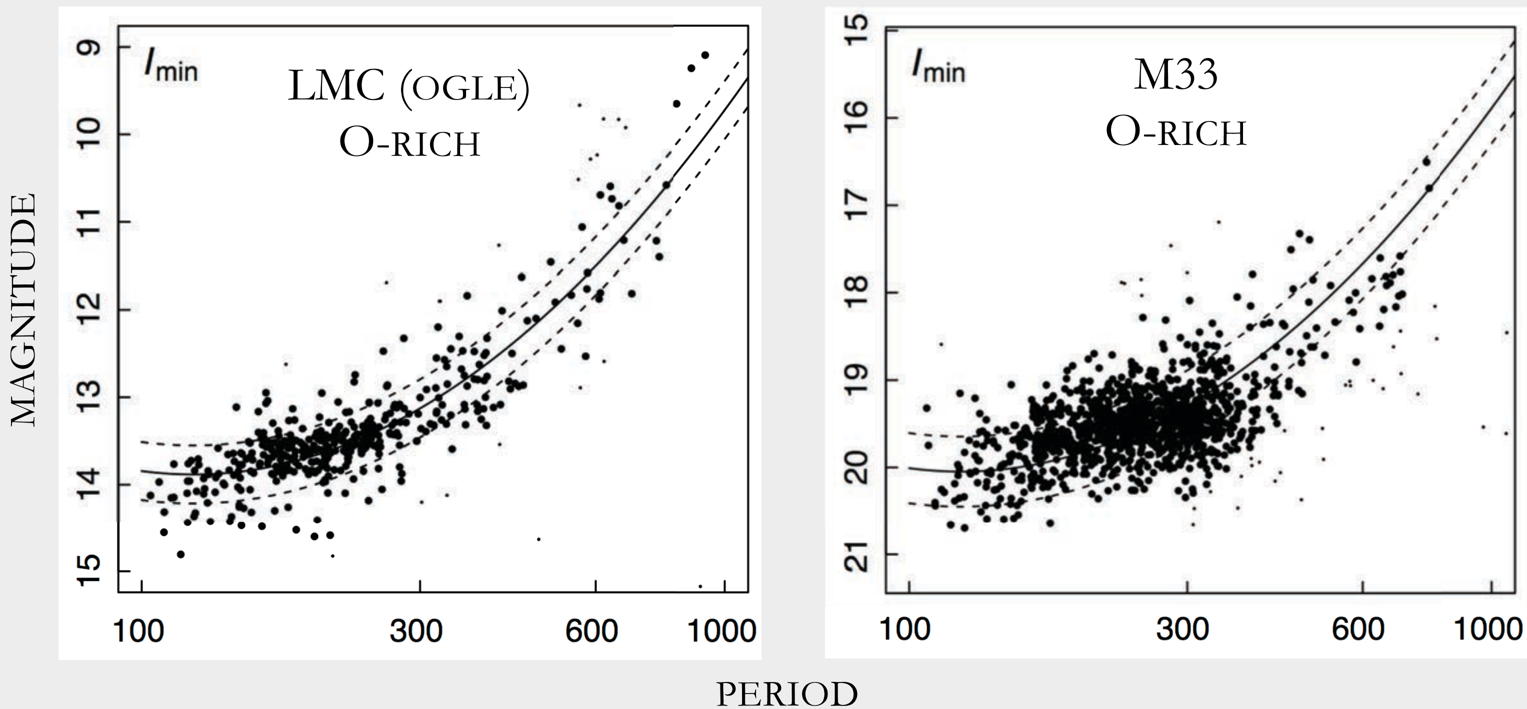


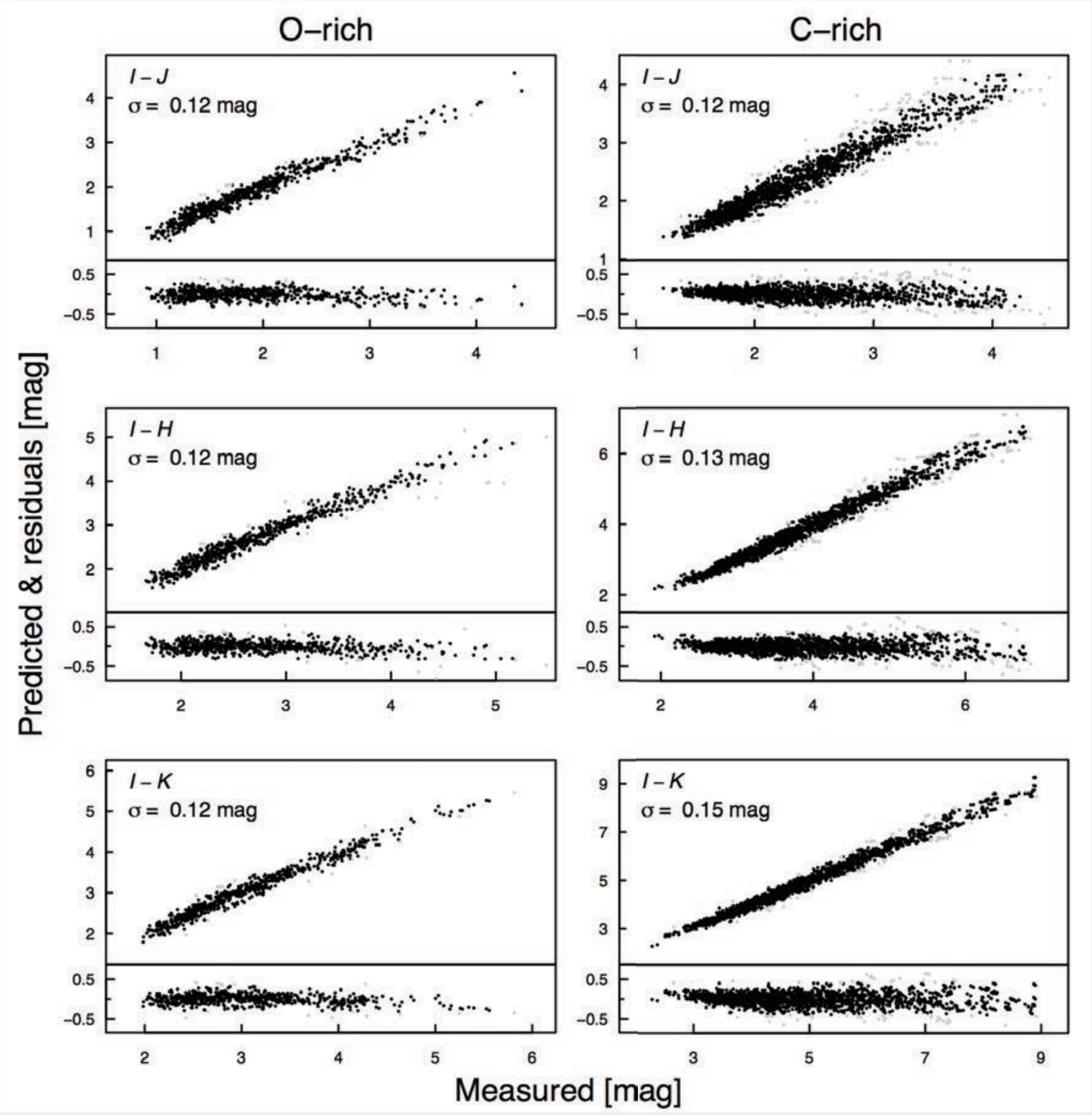
Yuan+ (2017A)

LMC Mira sample

- 690 Miras from Soszyński, Udalski, Szymański+ 2009
  - O/C-rich classification
  - 668 with JHKs magnitudes from our observations
- Issue: NIR observations concentrated at just three phases 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

Regression model

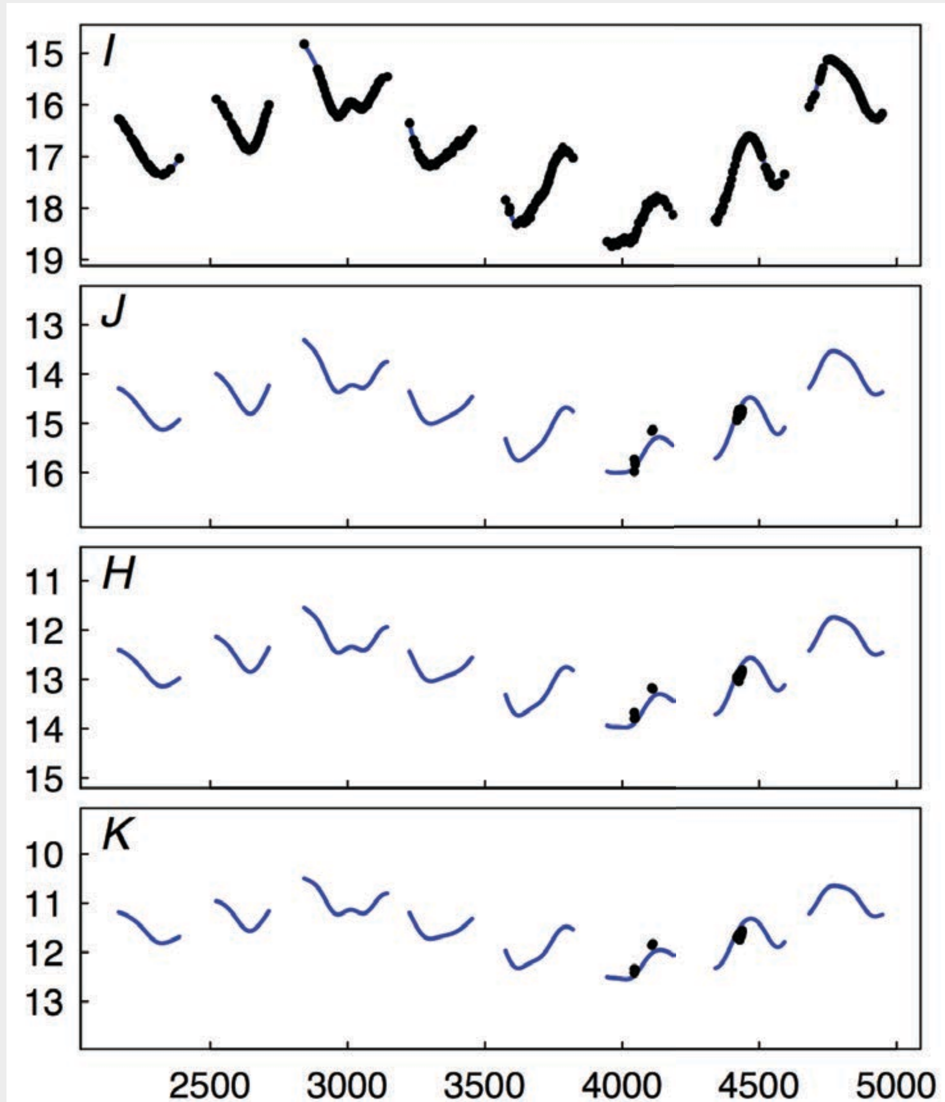
Based on ~82,000 individual JHK_S measurements + OGLE light curves



Yuan+ (2017B)

Mira template light curves

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

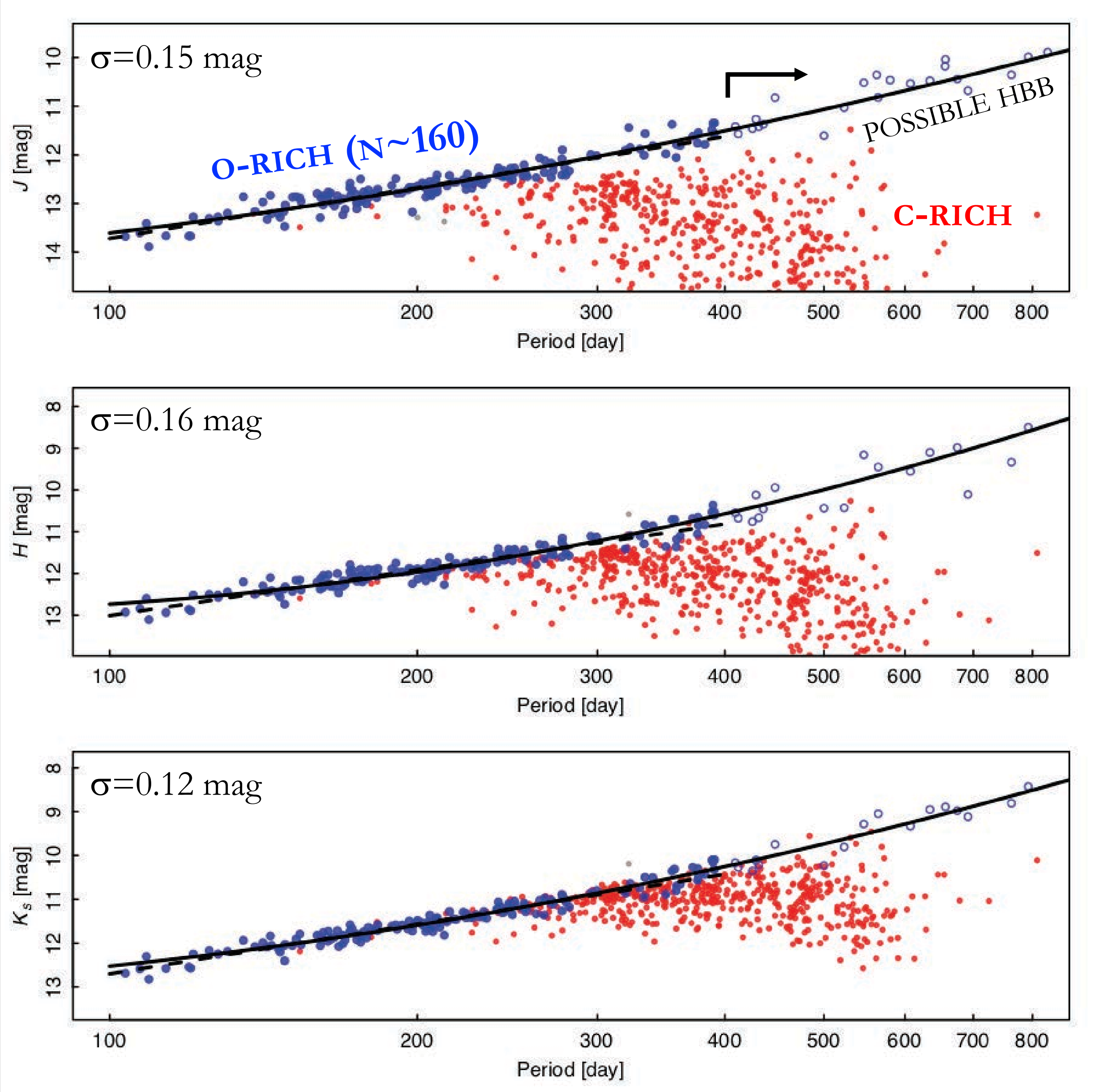


Magnitudes

MJD

Yuan+ (2017b)

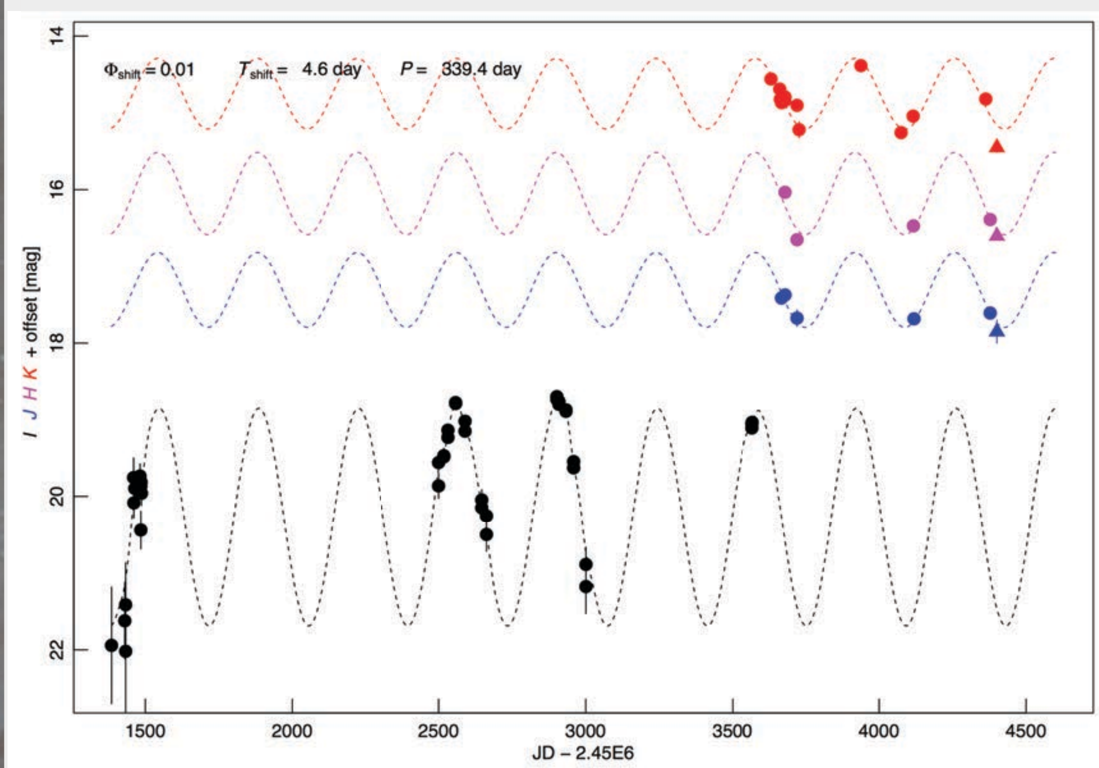
LEAVITT LAWS FOR LMC MIRAS

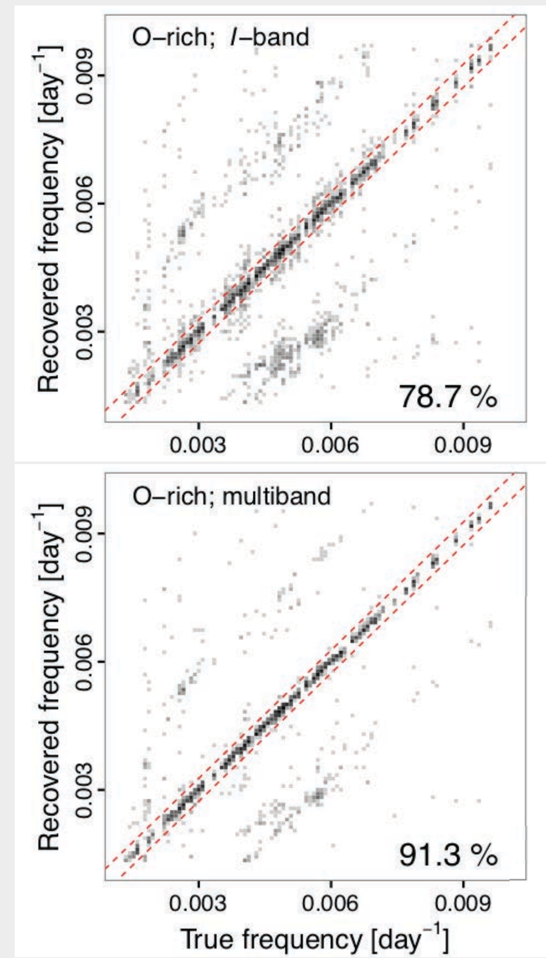


YUAN+ (2017B)

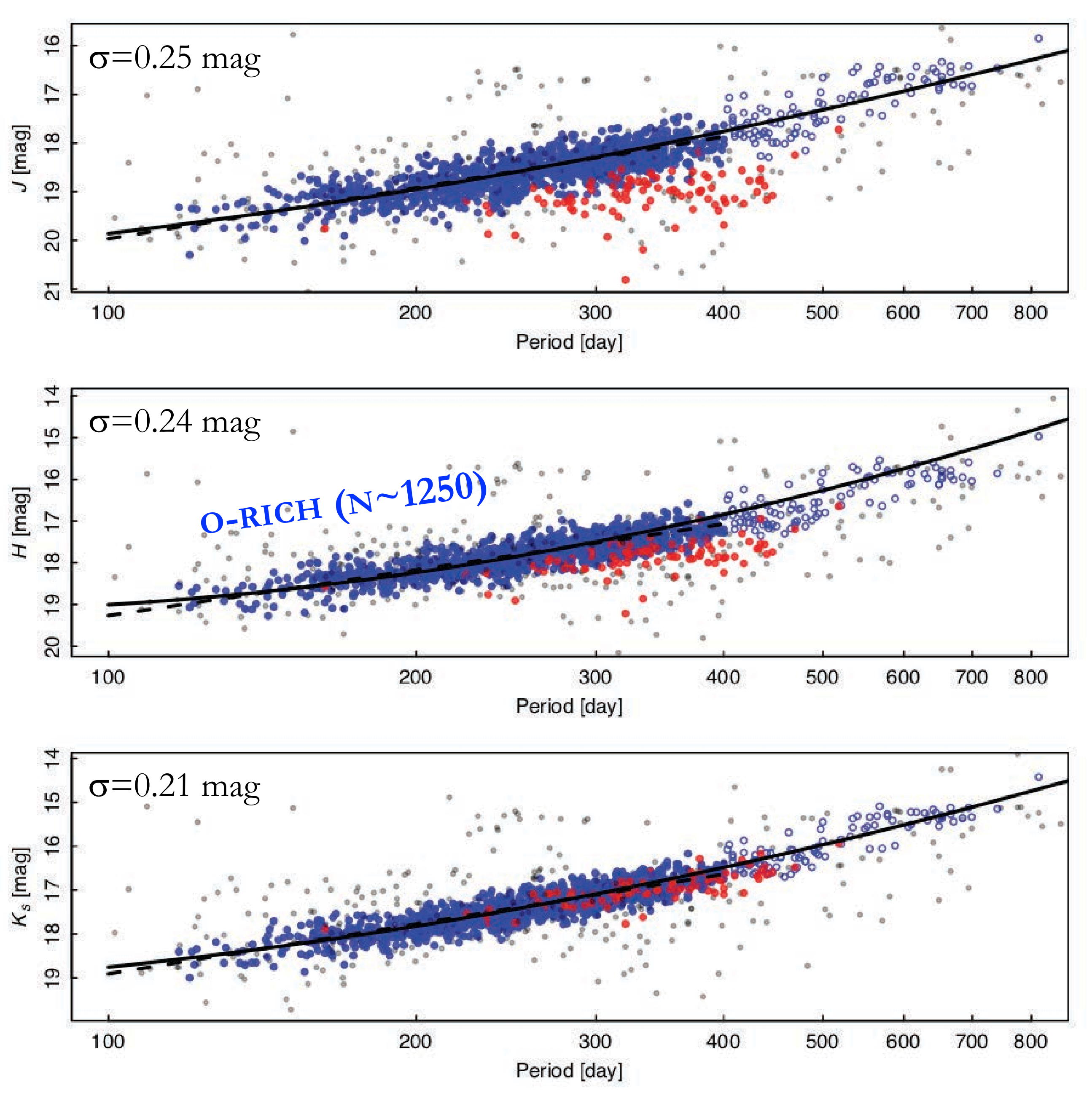
Back to M33

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





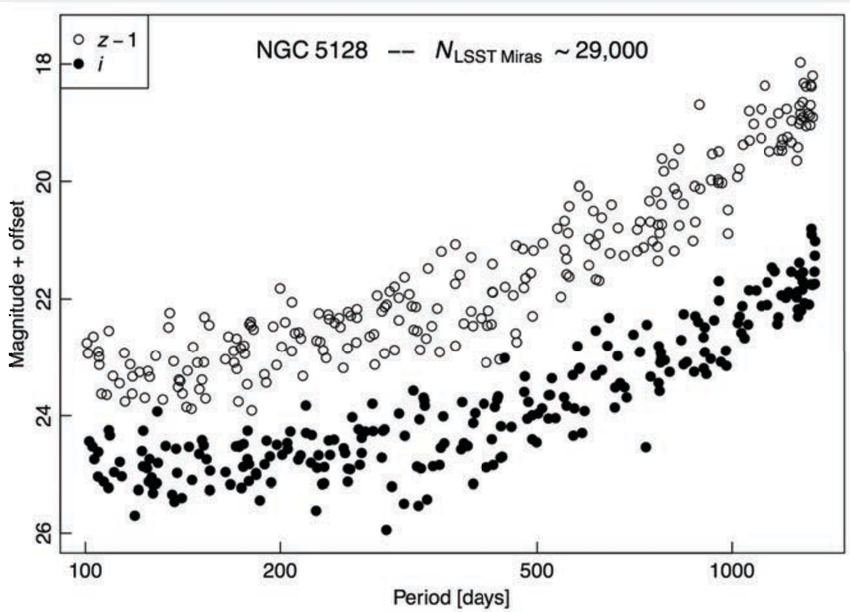
LEAVITT LAWS FOR M33 MIRAS

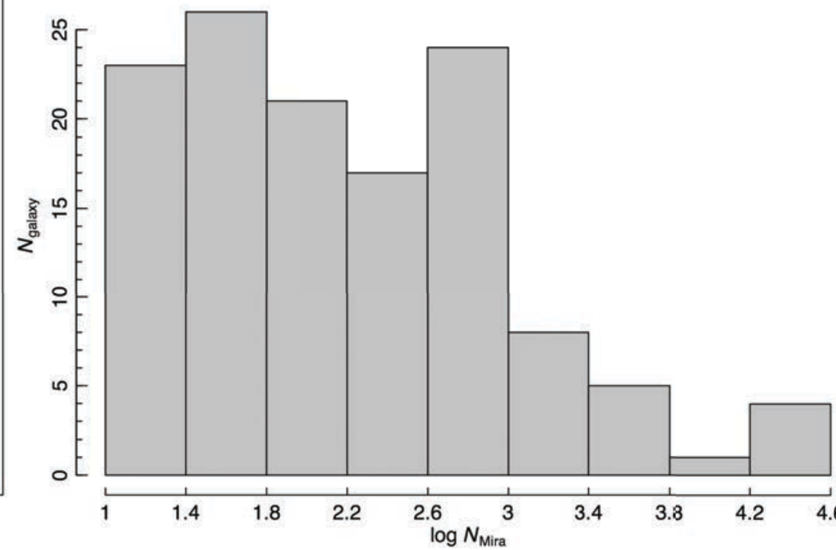


YUAN+ (2017A & 2018)

PROSPECTS FOR LSST

- Next: extension of Gaussian Process periodogram to *griz* bands, test on simulated LSST light curves
- LSST: ≳ 70 galaxies with ≳ 100 Miras within 4 years





YUAN, PHD THESIS, TEXAS A&M UNIVERSITY (2017)

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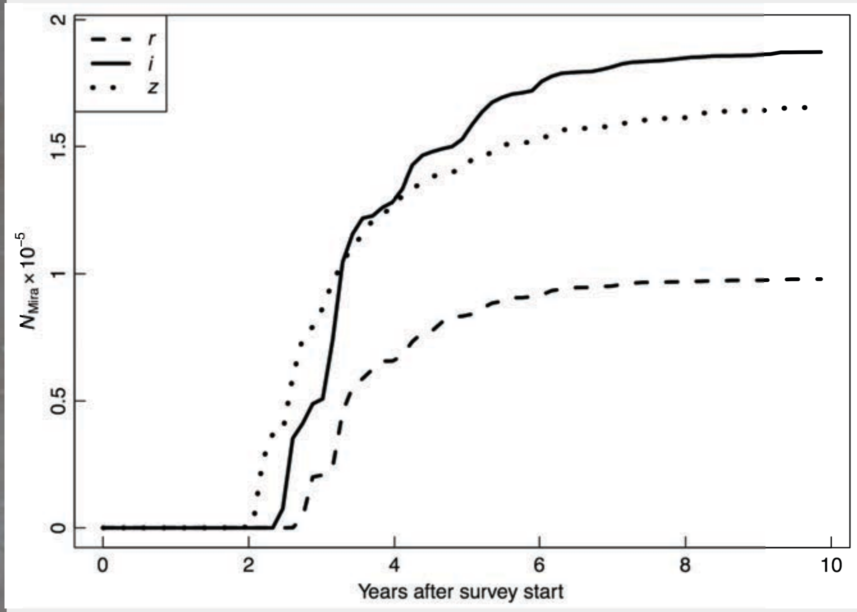

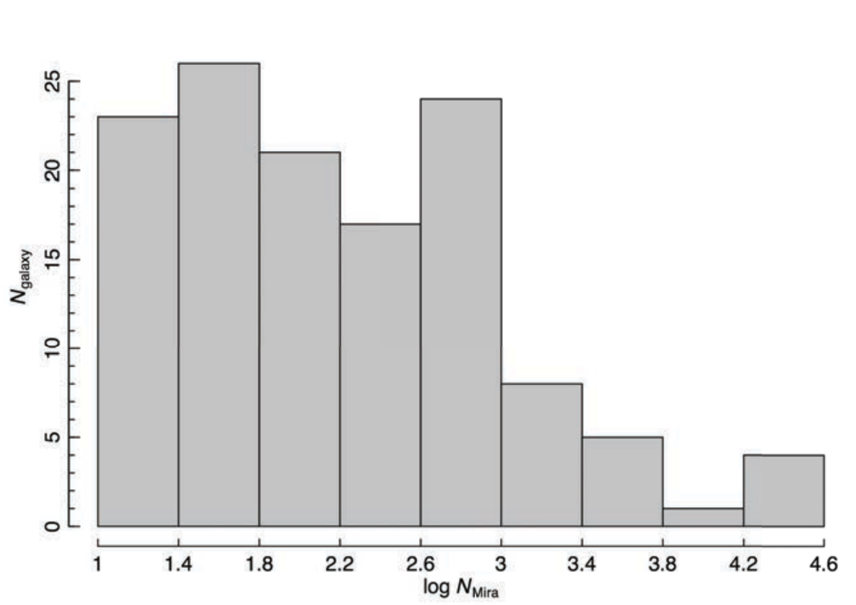

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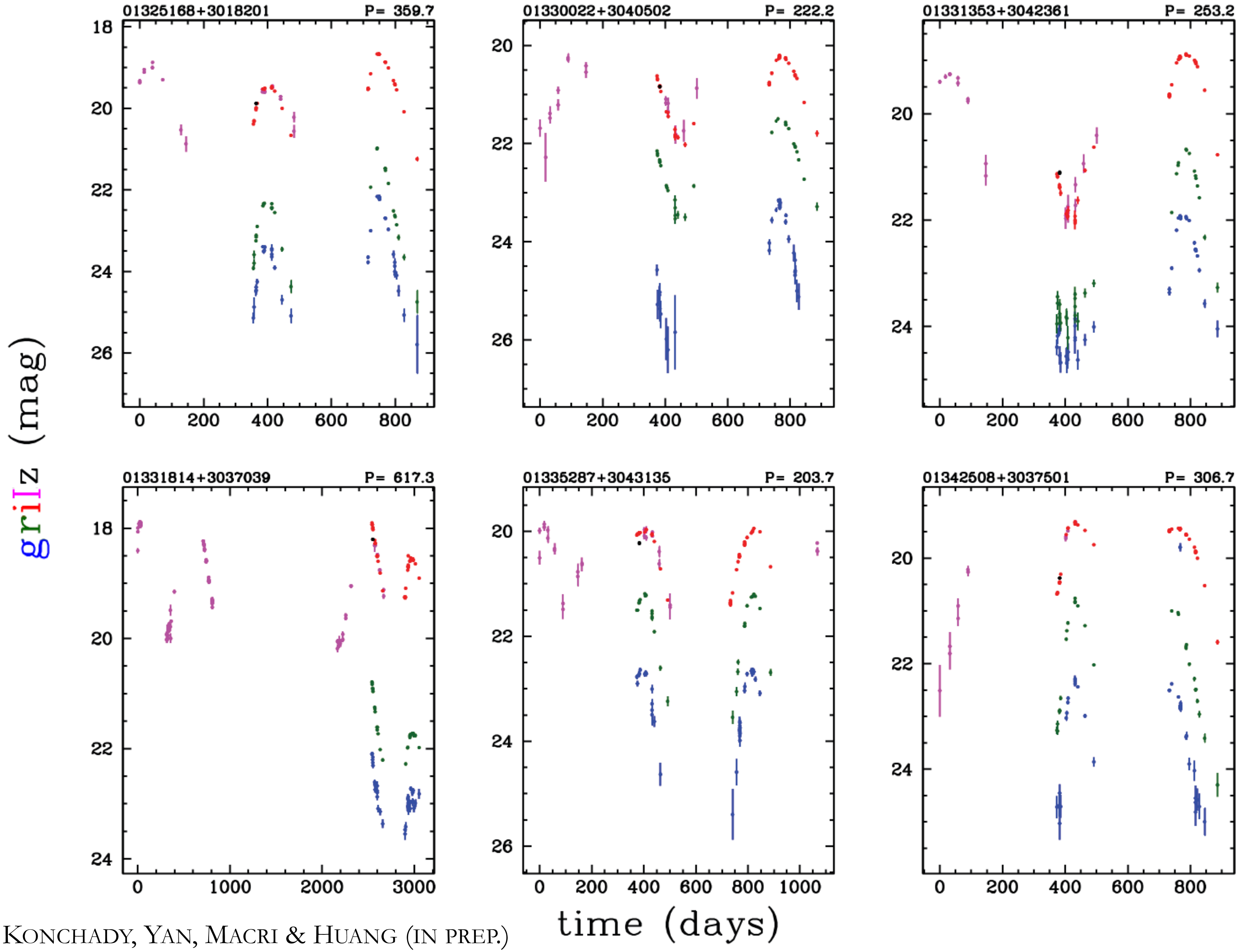
M33 MIRAS IN LSST BANDS



Konchady, Yan, Macri & Huang (in prep.)

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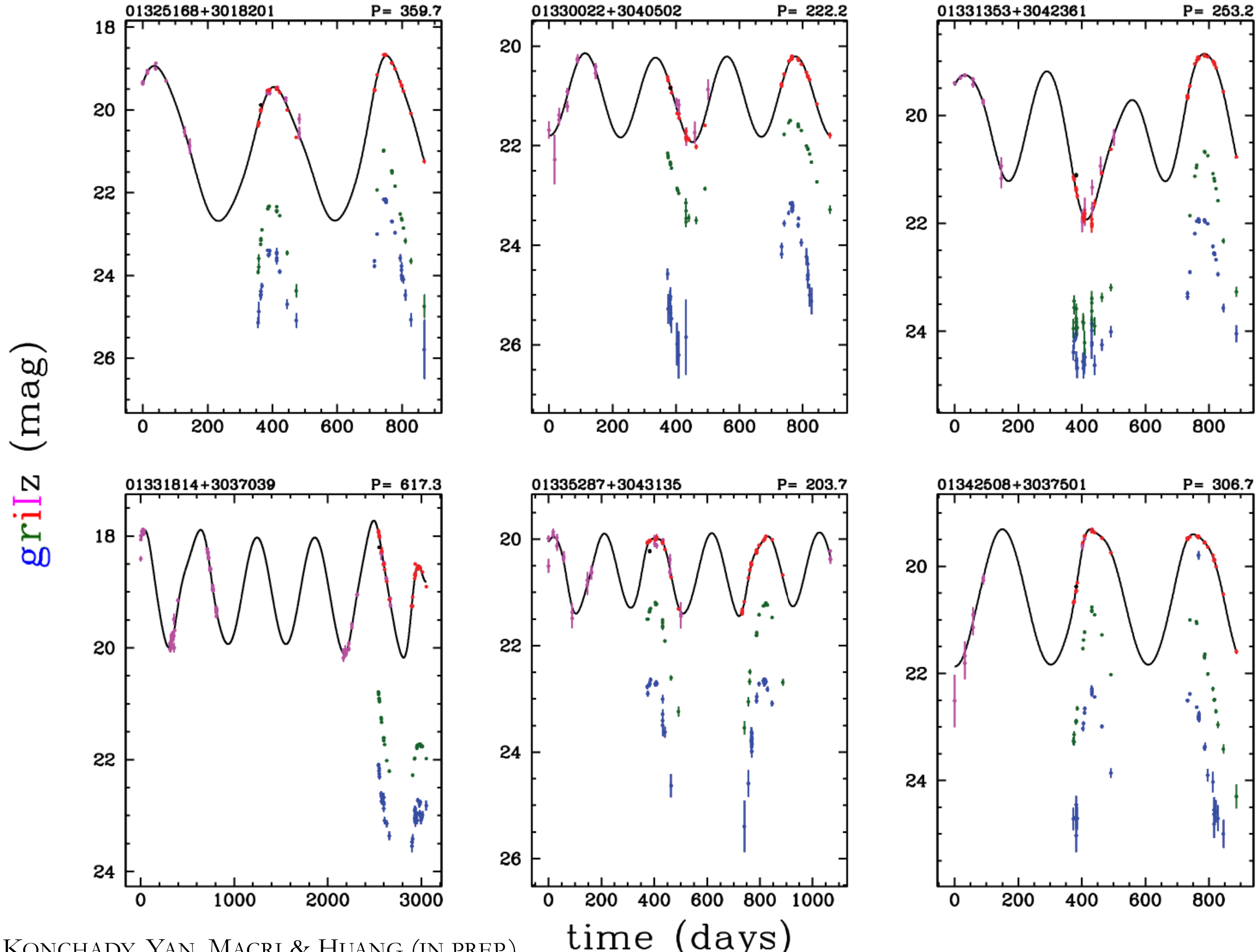


Konchady, Yan, Macri & Huang (in prep.)

CEPHEIDS VS. TRGB

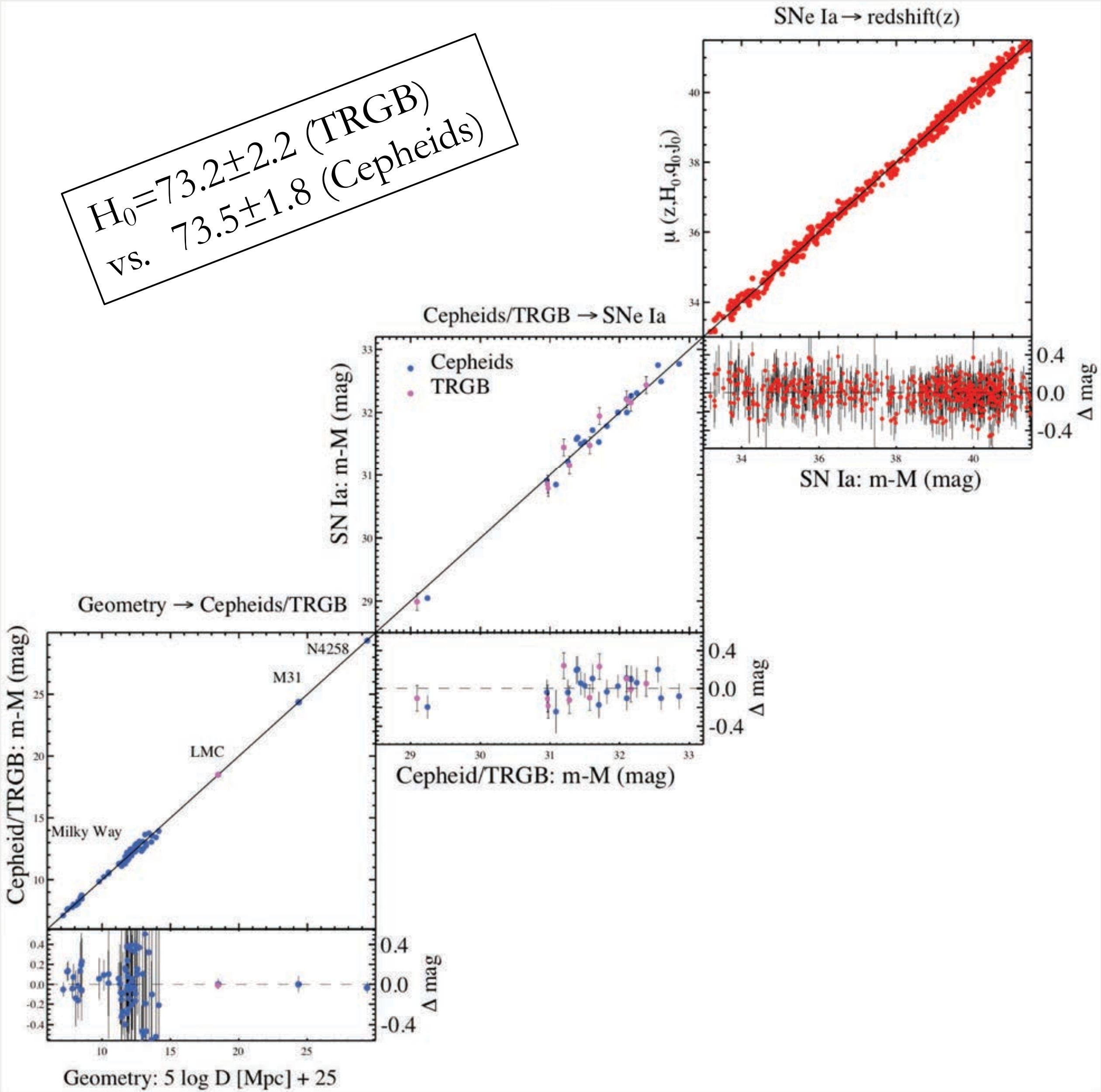
- Distances to 10 SNe Ia hosts using Cepheids vs. TRGB, anchored to LMC (D=49.6 kpc ± 1.1%, Pietrzynski+2019)

- Cepheids: HST/WFC3 F160W
  - LMC: Riess+2019; SN hosts: Riess+2016

- TRGB: HST/ACS F814W
  - SN hosts: Jang & Lee 2017, Hatt+2018
  - LMC: I_0=14.52±0.04 mag, A_I=0.10±0.02 mag (Jang & Lee 2017, OGLE-III) -0.01±0.02 mag (ground-to-HST transformation) yields M_{TRGB}=-3.97±0.04 mag (Yuan+, in prep.; see poster)

- H_0=73.2±2.2 (TRGB) vs 73.5±1.8 (Cepheids)

CEPHEIDS VS TRGB



YUAN+ (IN PREP.)

Do Cepheids & TRGB agree?

Depends on which LMC TRGB calibration you adopt…
(μ=18.477 mag in all cases below)

A_I (mag)	Extinction method	I_{obs}	M_I	H_0	Source
0.10±0.02*	OGLE red clump	14.62	-3.97±0.03*	73.2	Jang & Lee 17
0.05±0.05	NIR colors within LMC	14.59±0.02	-3.95±0.03	73.9	Hatt+18, Hoyt+17
0.16±0.02	hosts w/diff. [Fe/H]	14.60±0.02	-4.05±0.02	69.8	Freedman+19

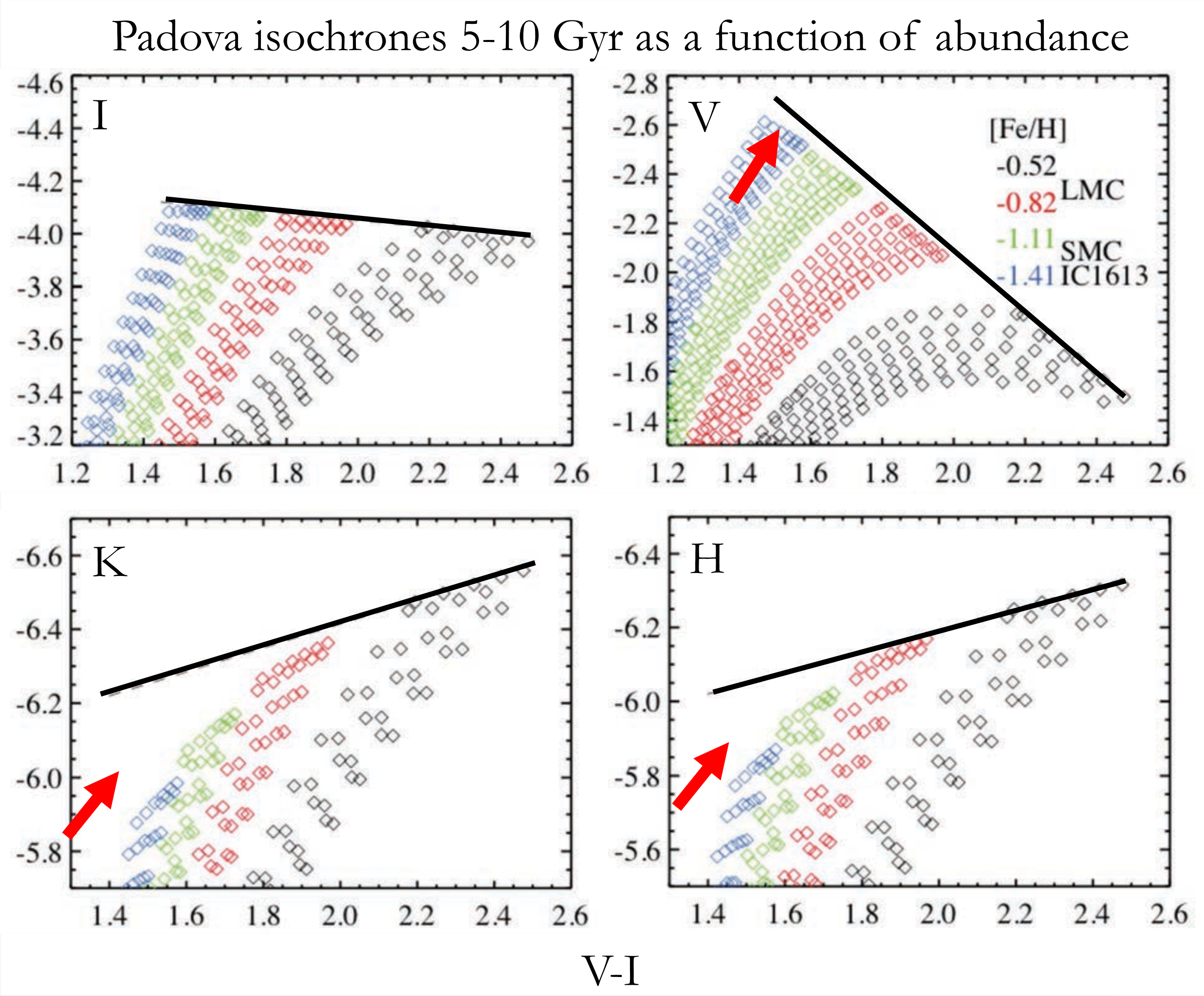
*: provided by Jang & Lee

3 different methods for estimating extinction → 5% changes in H_0
There are 3σ differences among these…could [Fe/H] explain?

Slide provided by A. Riess

TRGB COLORS TO INFER EXTINCTION

Freedman+2019 estimate LMC extinction using linear color slope, but TRGB depends on age *and* metallicity



LMC too bright relative to lower [Fe/H] SMC, IC 1613

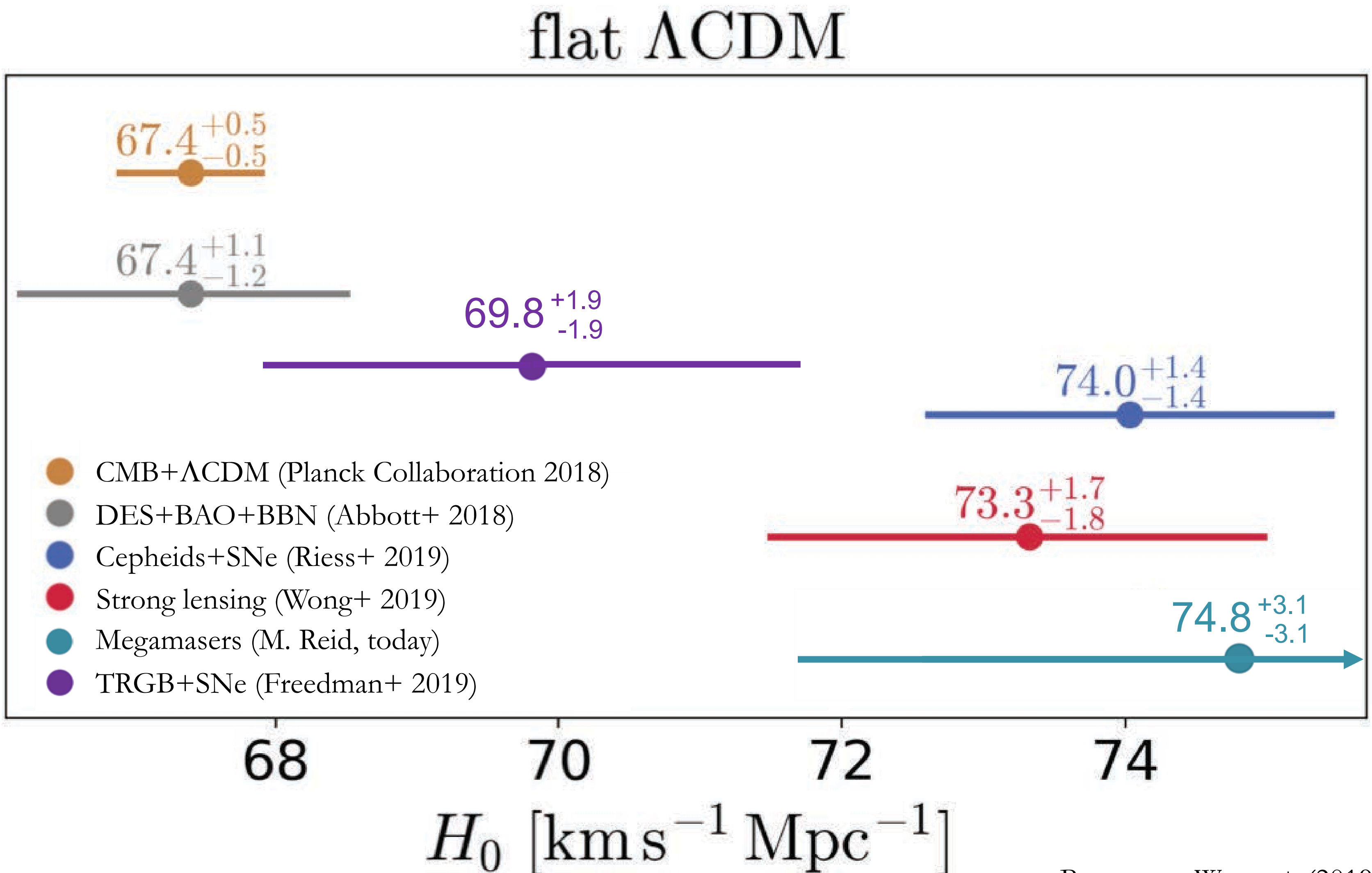
Stellar models indicate extinction overestimated by A_I~0.1 mag; 5% lower H_0

see also McQuinn+2019

RGB [Fe/H]: LMC~-0.6, SMC~-1.2 (Nidever+ 2019); IC 1613 ~-1.4 (Sibbons+2015)

SLIDE PROVIDED BY A. RIESS

INDEPENDENT H_0 ESTIMATES



BASED ON WONG+ (2019)