Status and prospects for the Extragalactic Distance Scale with ELTs

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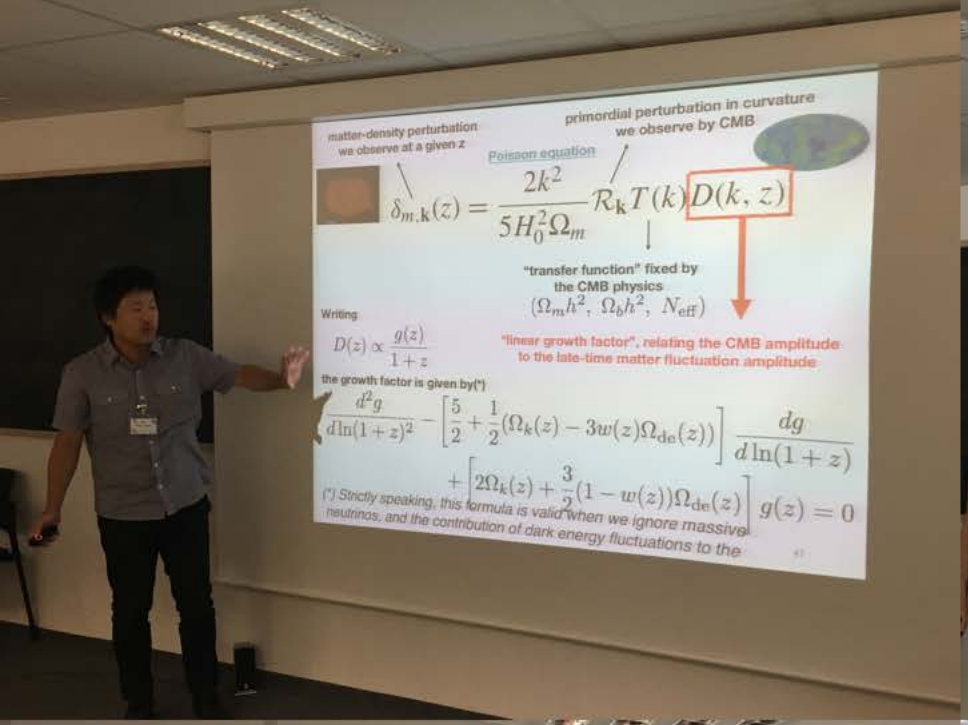
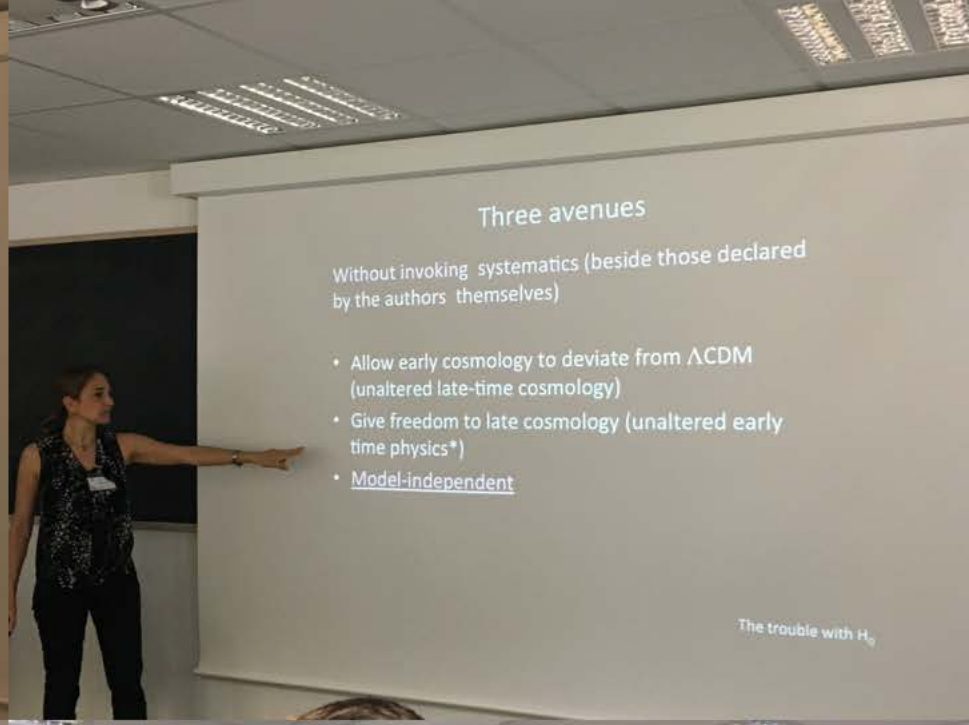
Thank you and apologies…

- Thank you to the organizers for inviting me, and apologies for only being able to attend today…
- We're in the middle of a month-long workshop on the Extragalactic Distance Scale in Garching
- Check out our website for very interesting talks, including ideas for ELT-enabled science
  - www.munich-iapp.de/programmes-topical-workshops/2018
- A great place to host a long meeting, check it out!


matter-density perturbation we observe at a given z
primordial perturbation in curvature we observe by CMB
Poisson equation
$\delta_{m,\mathbf{k}}(z) = \frac{2k^2}{5H_0^2\Omega_m}\mathcal{R}_{\mathbf{k}}T(k)D(k,z)$
"transfer function" fixed by the CMB physics
$(\Omega_m h^2,\ \Omega_b h^2,\ N_{\rm eff})$
Writing
$D(z) \propto \frac{g(z)}{1+z}$
"linear growth factor", relating the CMB amplitude to the late-time matter fluctuation amplitude
the growth factor is given by(*)
$\frac{d^2g}{d\ln(1+z)^2} - \left[\frac{5}{2} + \frac{1}{2}(\Omega_k(z) - 3w(z)\Omega_{\rm de}(z))\right]\frac{dg}{d\ln(1+z)} + \left[2\Omega_k(z) + \frac{3}{2}(1-w(z))\Omega_{\rm de}(z)\right]g(z) = 0$
(*) Strictly speaking, this formula is valid when we ignore massive neutrinos, and the contribution of dark energy fluctuations to the

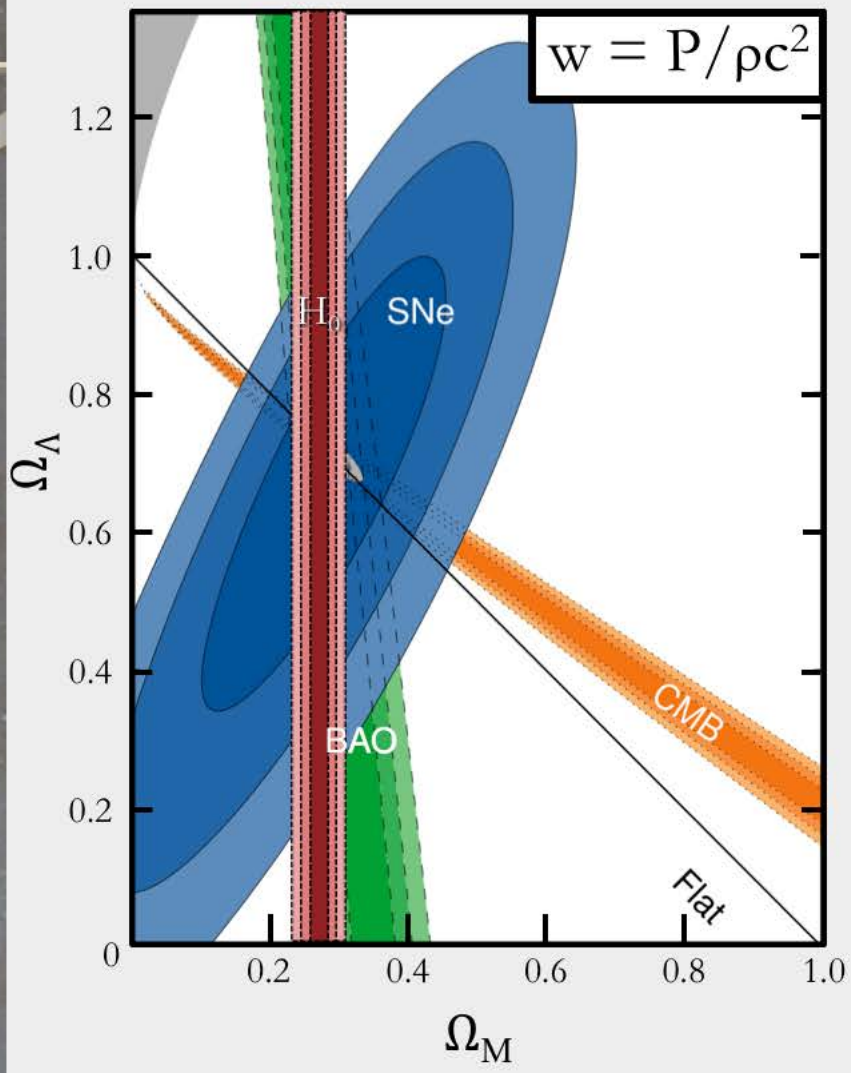

Three avenues
Without invoking systematics (beside those declared by the authors themselves)
• Allow early cosmology to deviate from ΛCDM (unaltered late-time cosmology)
• Give freedom to late cosmology (unaltered early time physics*)
• Model-independent
The trouble with H_0


Tests of Local H_0 since SH_0ES (Riess et al. 2016)
EARLY UNIVERSE
LATE UNIVERSE
66.9 +/- 0.6, CMB, Planck 2016
66.98 +/- 1.2, BAO+BBN ^{2}H Addison et al. 2018
68 +/- 0.8, BAO+ACTPol,SPT,WMAP Addison et al. 2018
73.24 +/- 1.74, Riess et al. 2016
Reanalyses
73.6 +/- 1.5, Cardona et al. 2016, 73.3 +/- 1.7 Follin and Knox 2017, 73.0 +/- 1.8, Feeney, Mortlock 2018
SN Ia NIR only 72.8 +/- 3.1, Dhawan, Jha, Leibundgut 2017
WFC3 Parallax only 76.7 +/- 2.1, Riess, Casertano et al. 2018a
Gaia DR2 (48 MW Cepheids) 73.7 +/- 2.7, Riess, Casertano et al 2018b
HOLICOW-3 lenses 72.8 +/- 2.4 ($\beta_{\rm int}$=0.3), Bonvin et al. 2017
65
70
75
80
H_0 (km s^{-1} Mpc^{-1})

Outline

- **Motivation**
- The Extragalactic Distance Scale today
- The landscape in 2023
- Possible ELT programs

Motivation: what is the nature of dark energy?



Suzuki+ (2012); Riess, Macri+ (2016)

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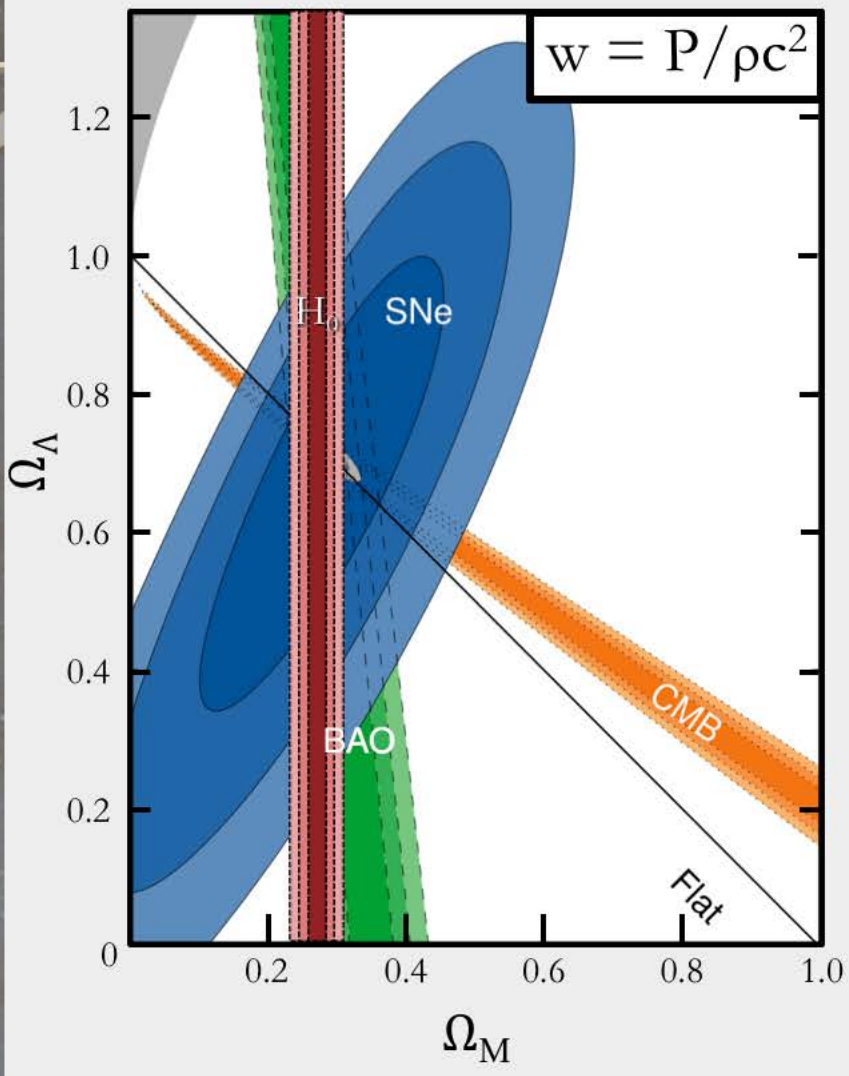

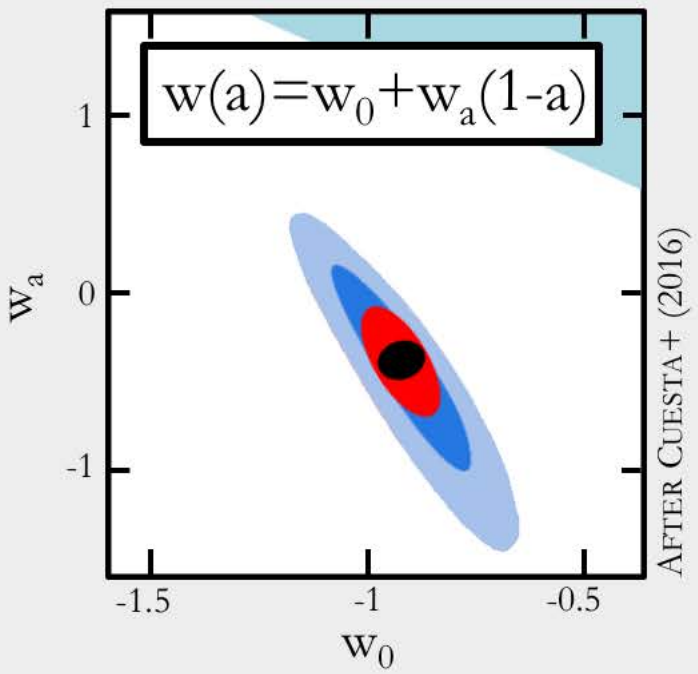

Coupled with additional priors (such as H_0)

- C16: w_0 ±0.18; w_a ±0.6
- DES: w_0 ±0.08; w_a ±0.3
- LSST: w_0 ±0.05; w_a ±0.1

Suzuki+ (2012); Riess, Macri+ (2016)

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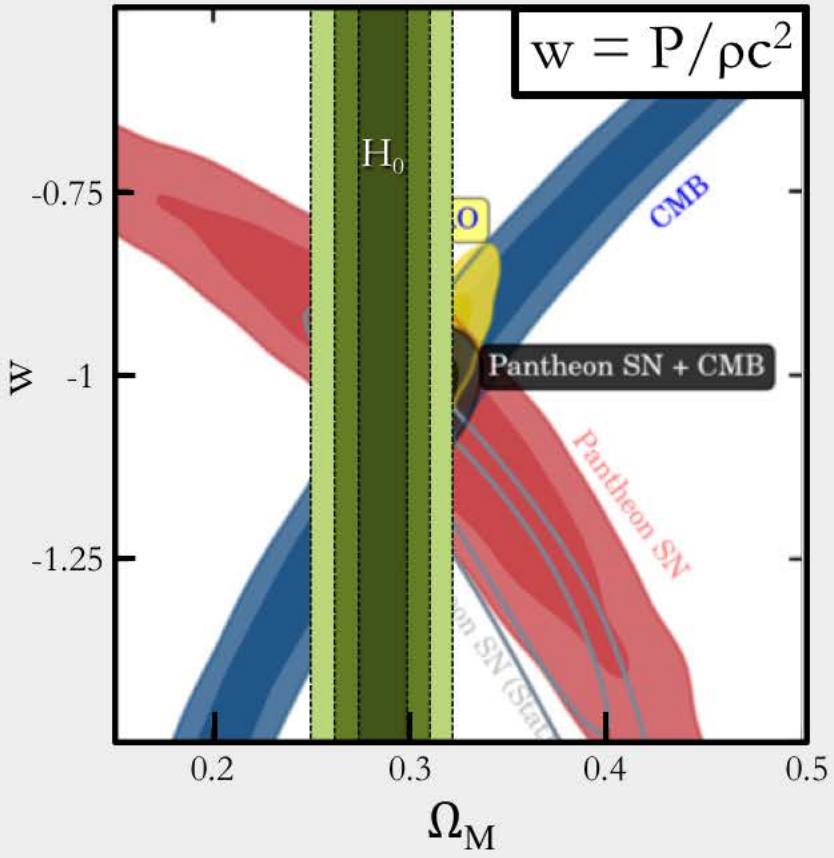

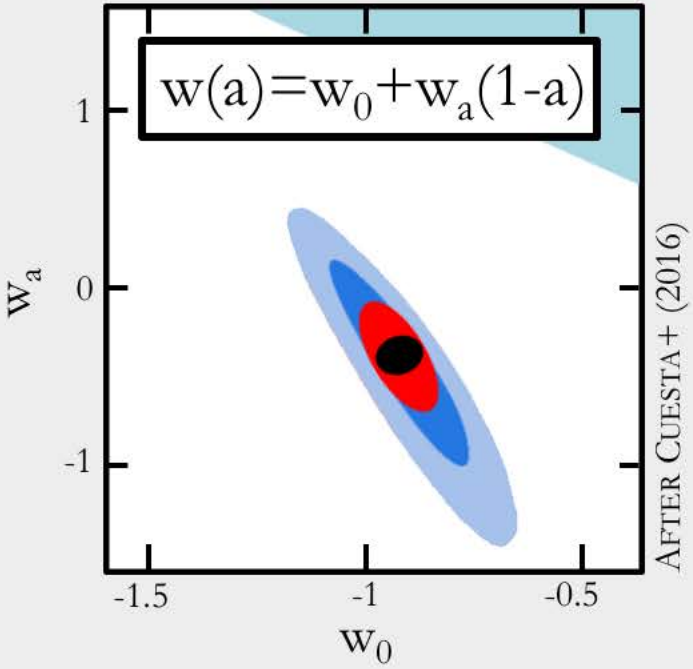

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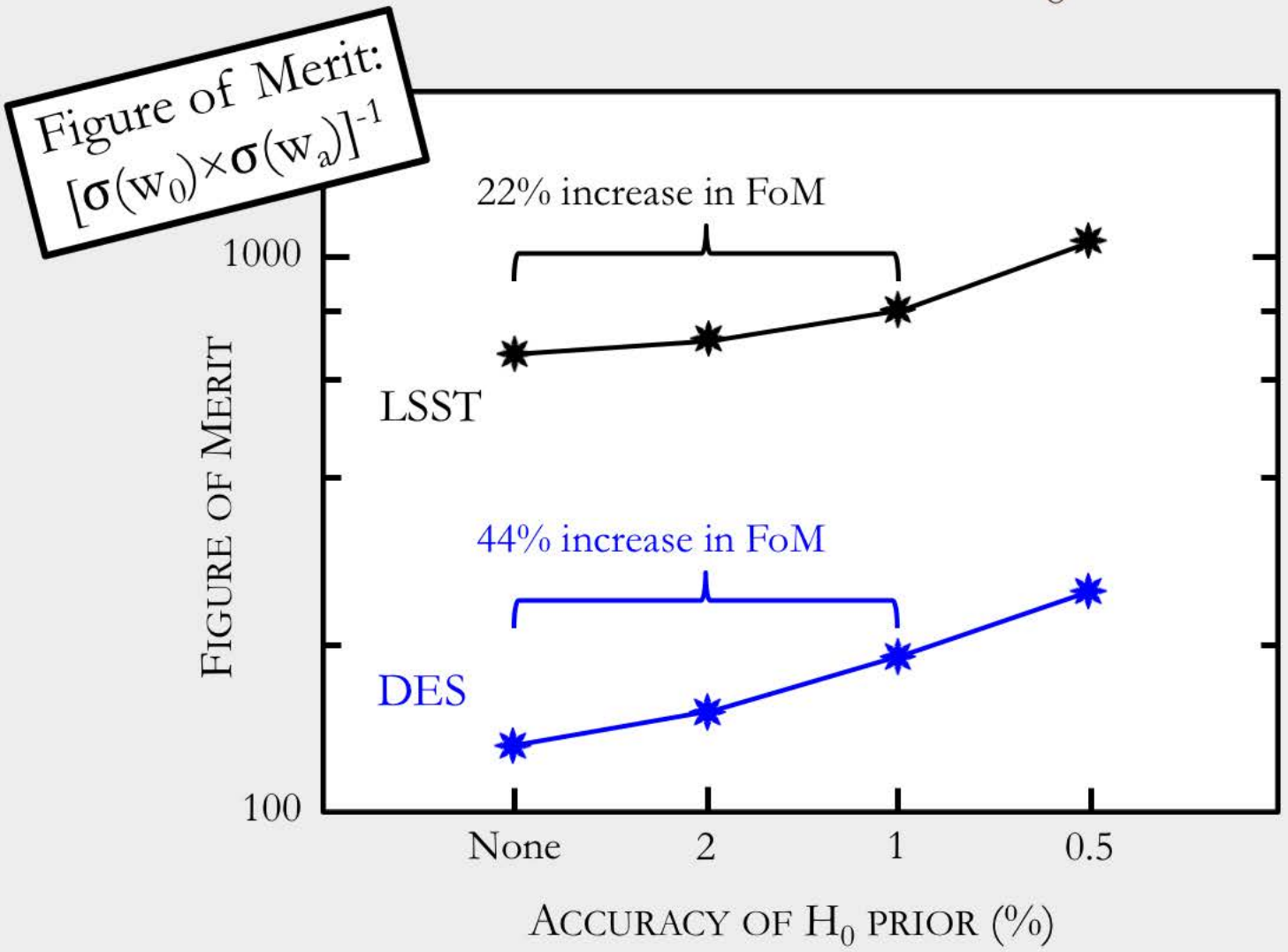
Scolnic+ (2017); Riess, Macri+ (2016)

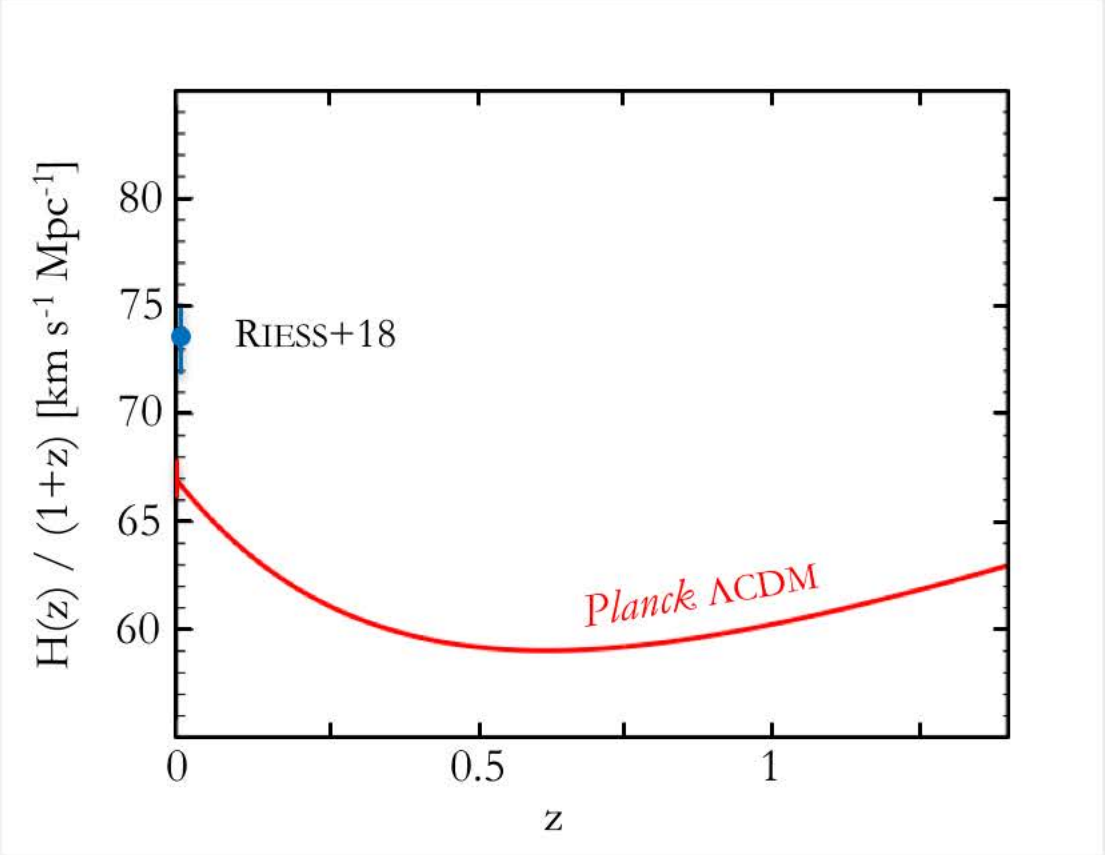
Motivation for further improvement in H_0



Based on Weinberg+ (2012)

H(z) vs. H_0

- Compare <u>predicted</u> H_0 for an *assumed* cosmology, fit to CMB+BAO data, against local measurement
- 3.7σ difference: systematic error(s) or "New Physics"?



After Busca+ (2012); Riess+ (2018)

H(z) vs. H_0

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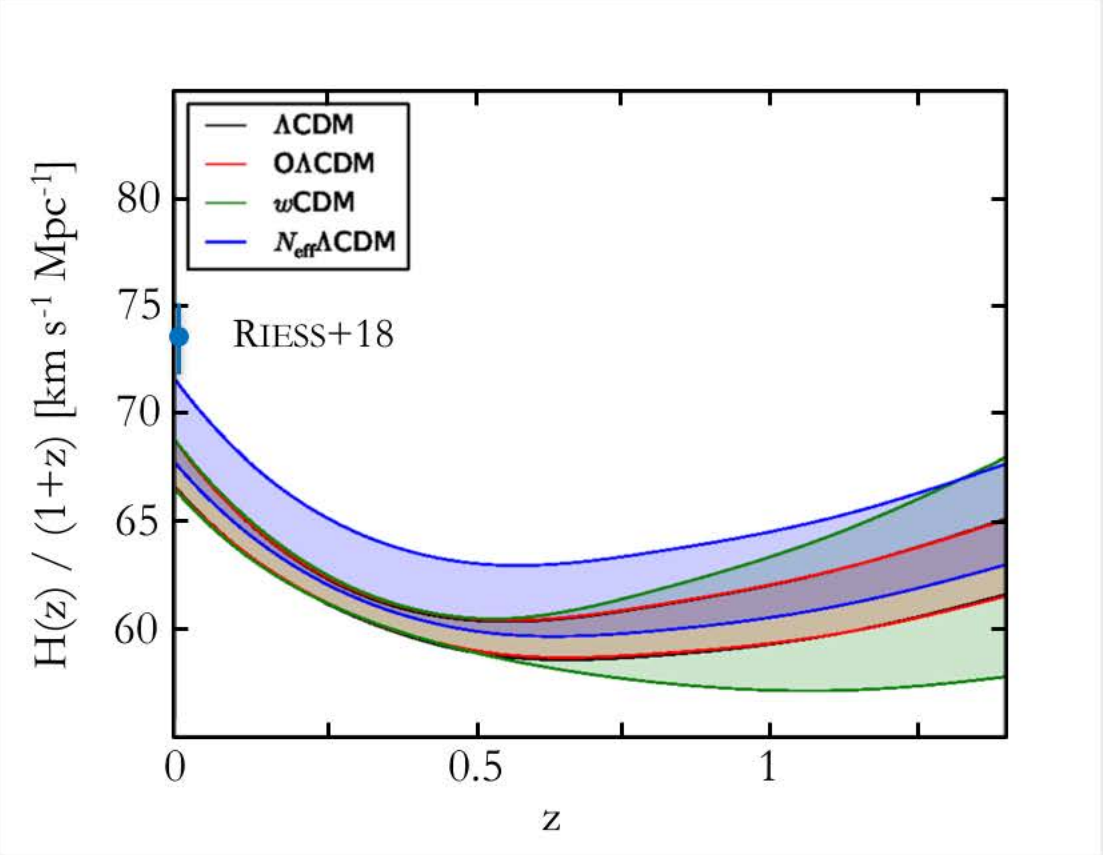
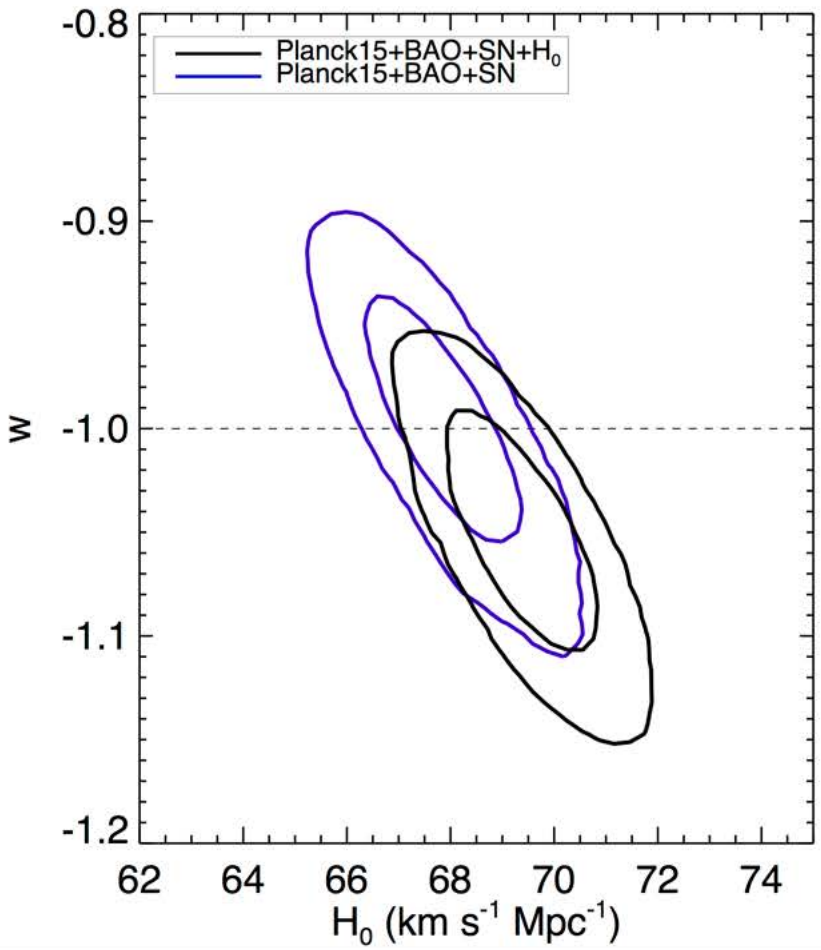
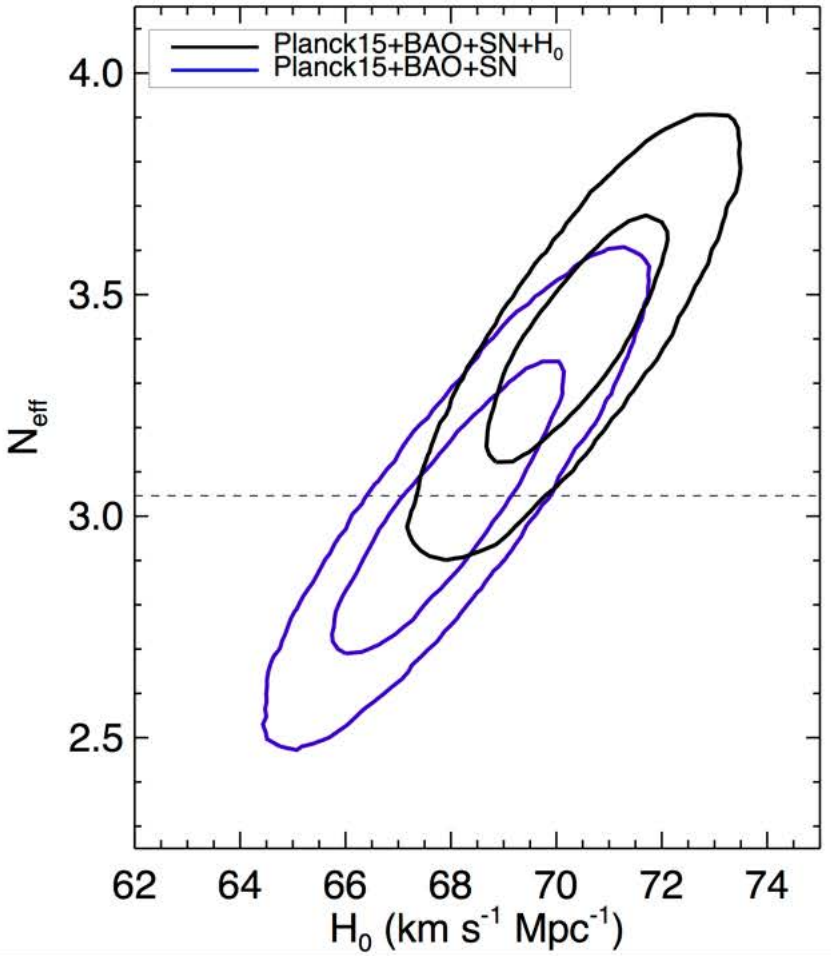


CUESTA+ (2015); RIESS+ (2018)

EXPLORING THE DARK SECTOR

- "Dark photons" in early Universe?
- Late-time evolution of dark energy?





RIESS, MACRI+ (2016)

Outline

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- ➢ **The Extragalactic Distance Scale today**
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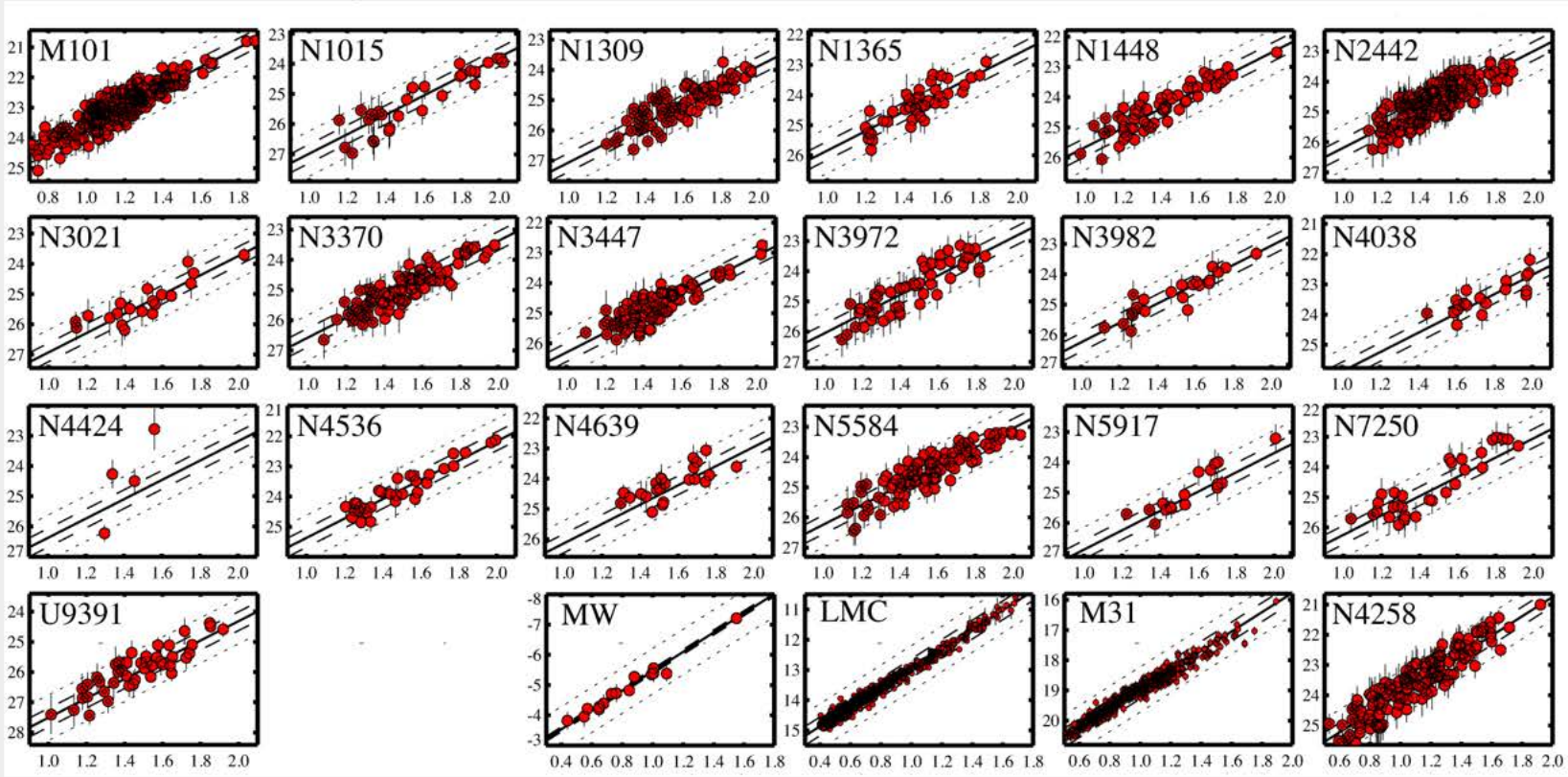
The Distance Scale today

- Cepheids
  - $0 \lesssim \log P(d) \lesssim 2$; $-2 \lesssim M_I \lesssim -8$; $-3 \lesssim M_K \lesssim -9$
  - Exhibit very tight P-L relation in near-infrared ($\sigma \sim 0.1$ mag)
  - Absolute calibration via parallax (MW) or other geometric methods (LMC, N4258)

  - Can be efficiently discovered using 8-m telescopes out to ~10 Mpc (Fassnaugh+'15; Hoffmann & Macri '15)
  - "Easily" observable with HST out to ~50 Mpc
  - Used to calibrate SNe Ia & determine H_0 to 2.4% (Riess, Macri+ 2016) → 2.3% (Riess+2018)

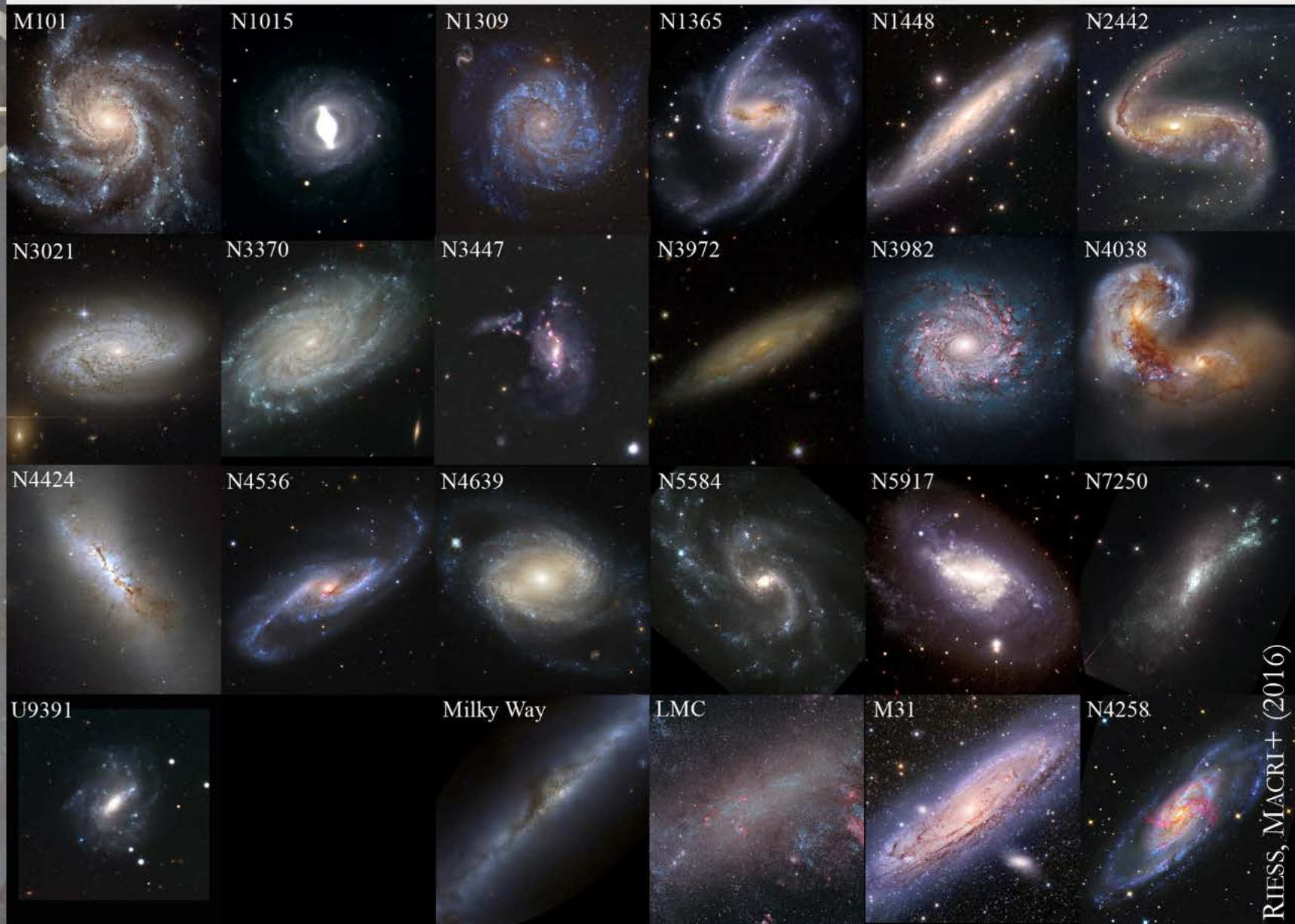
Cepheids to 40 Mpc with HST

- Cepheids in 19 hosts of modern SNe Ia + 4 calibrators
- >1500 with homogeneous HST photometry
  - +800 with ground-based observations



Riess, Macri+ (2016)

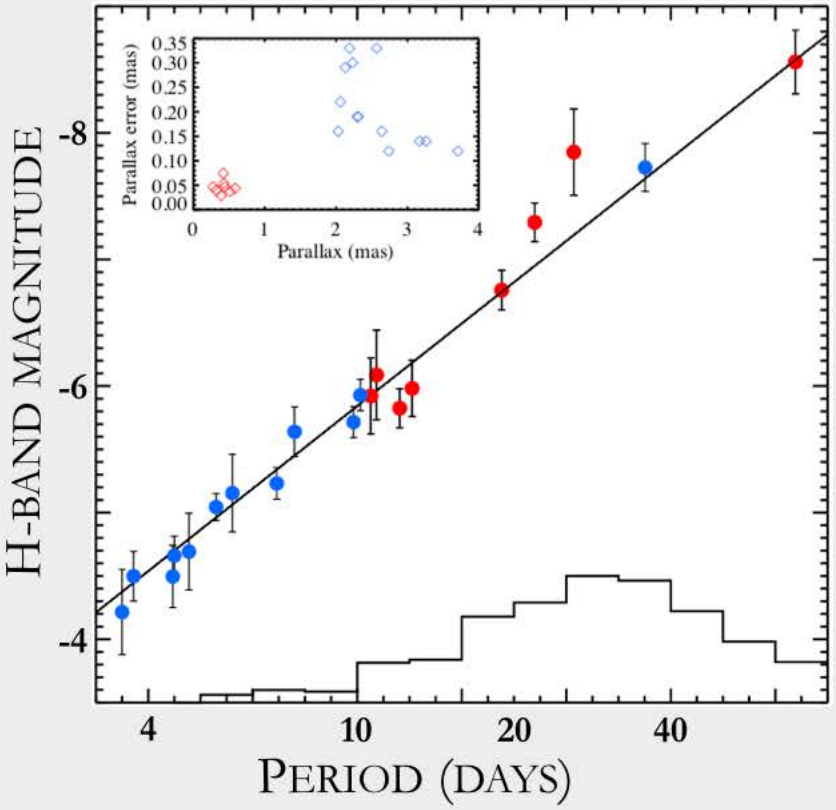
Cepheids to 40 Mpc with HST

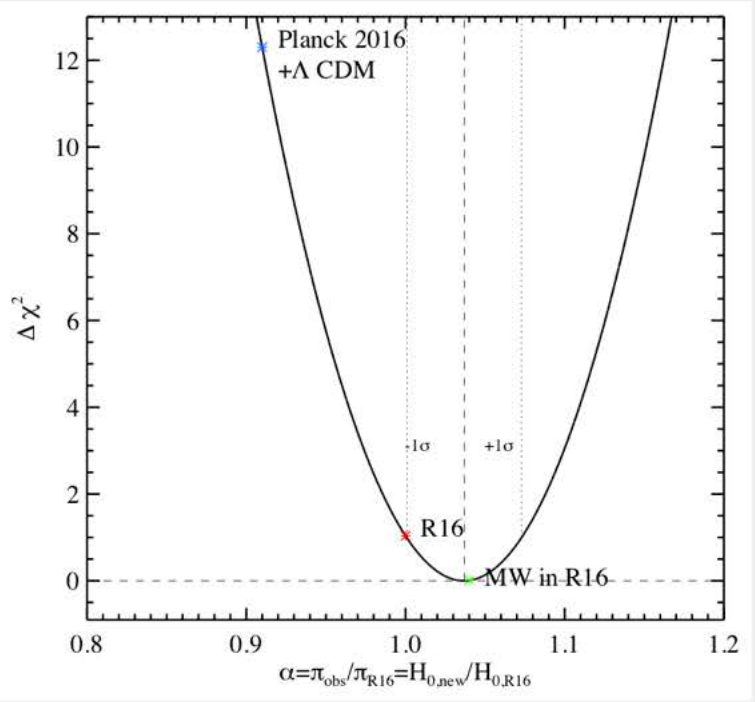


Riess, Macri+ (2016)

MW CEPHEID PARALLAXES

- HST parallaxes for 8 long-period Cepheids
  - Using novel scanning technique with WFC3 (Riess+2014, Casertano+2016, Riess+2018)
  - Confirms (and slightly improves) 2016 H_0 results





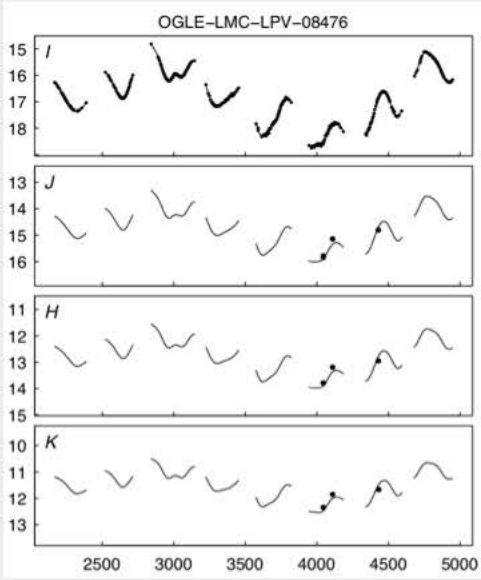
RIESS+ (2018)

The Distance Scale today

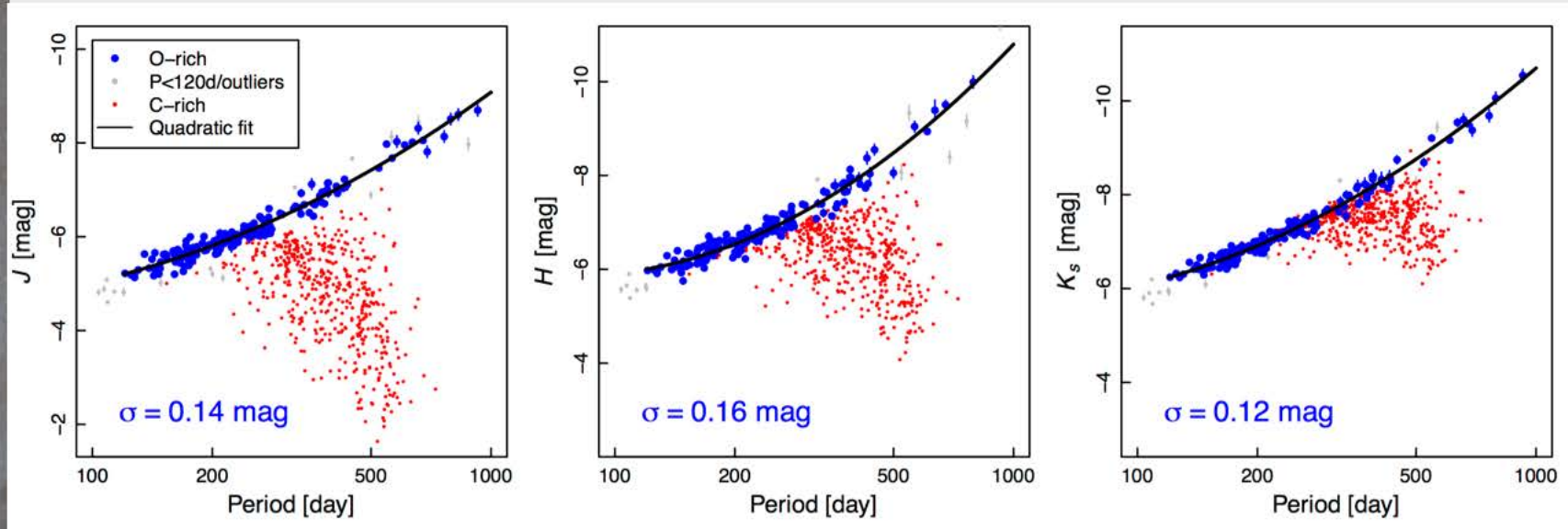
- Miras
  - $2 \lesssim \log P(d) \lesssim 3$; $-6 \lesssim M_K \lesssim -11$
  - Low/Intermediate-mass stars: present in any galaxy type
    - And in much greater numbers than Cepheids
  - O-rich Miras exhibit tight P-L relation ($\sigma \sim 0.15$ mag)
  - Absolute calibration in LMC & N4258
  - New techniques for robust detection, period determination and mean magnitude estimation for extremely sparse data

MIRA P-L RELATIONS IN LMC

- Mean JHK_s magnitudes derived from template fitting based on exquisite I light curves from OGLE

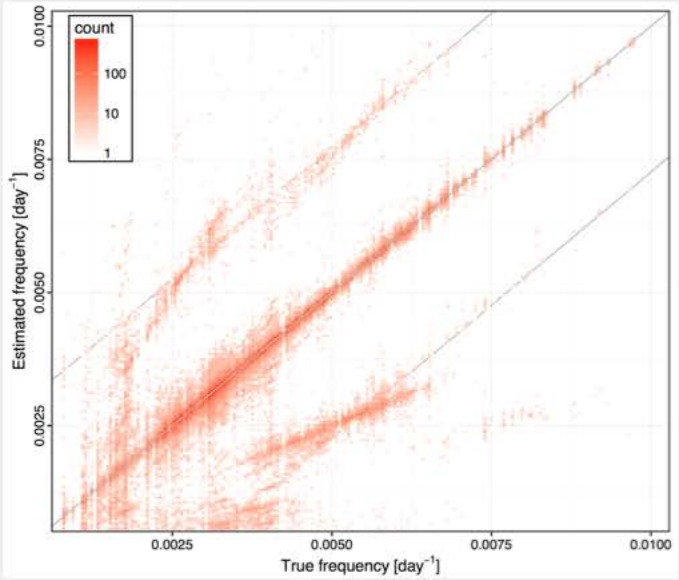


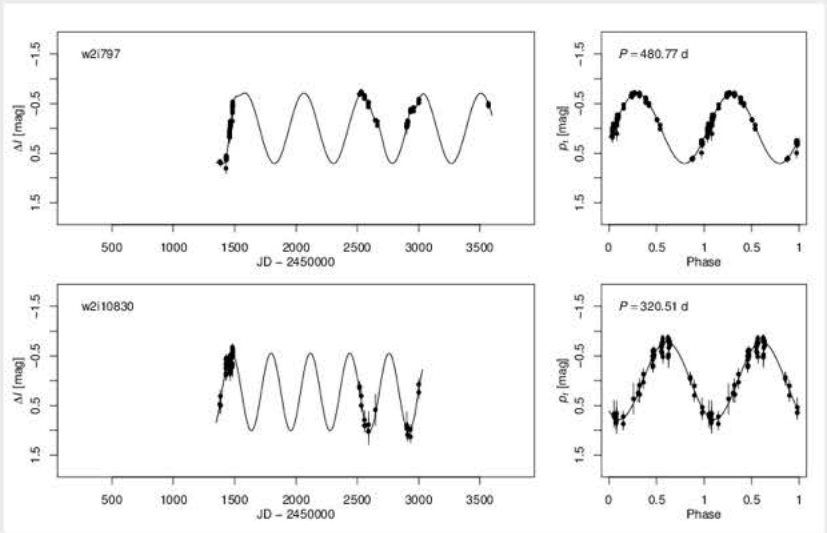
YUAN+ (2017A)



Discovering Miras with sparse data

- Gaussian Process Periodogram technique successfully recovers 74% of Miras in I band, even in the limit of very sparse light curves





He+ (2016), Yuan+ (2017b,)

Discovering Miras with sparse data

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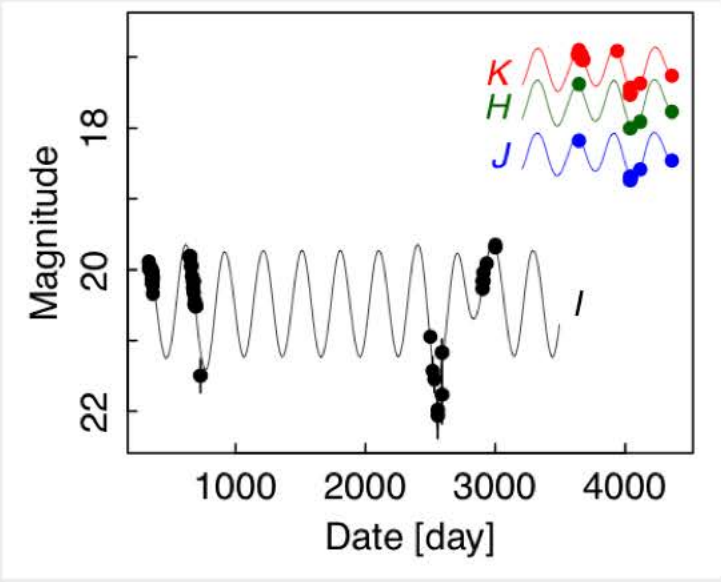
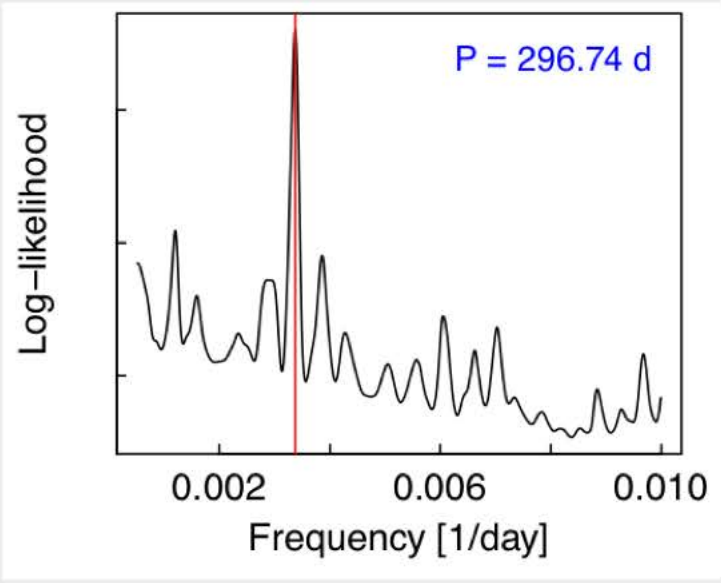
- Efficiency improves significantly adding just a few NIR data points

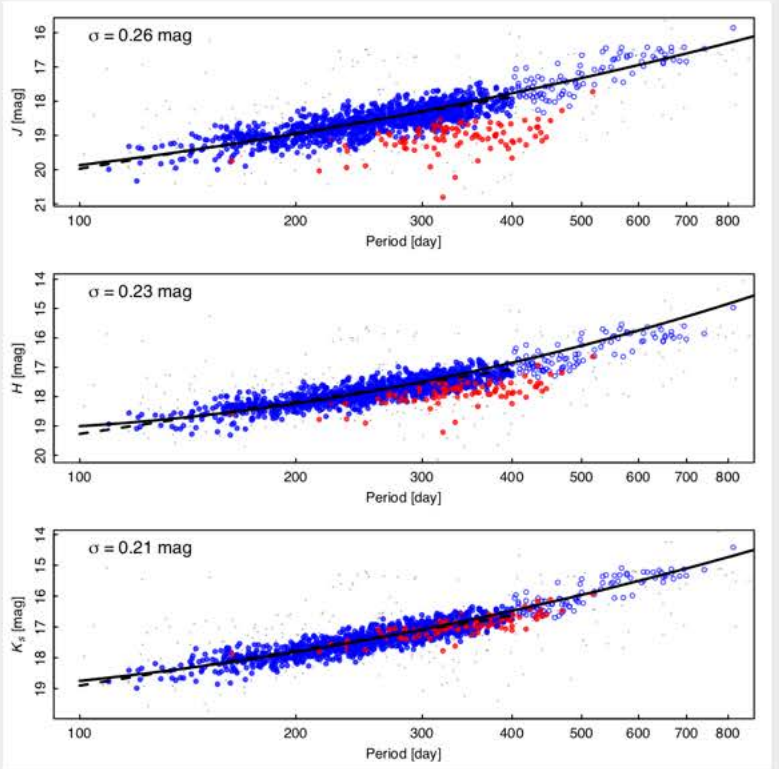


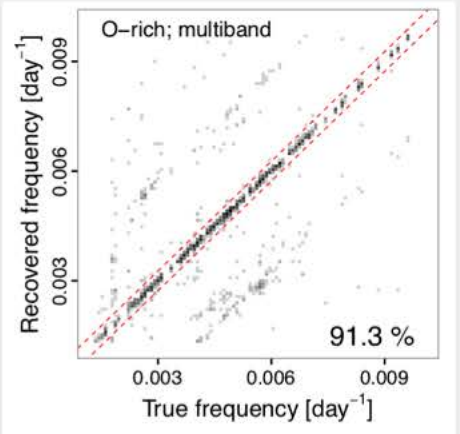


Yuan, Macri+ (2018)

Discovering Miras with sparse data

- Gaussian Process Periodogram technique successfully recovers 74% of Miras in I band, even in the limit of very sparse light curves
- Efficiency improves significantly adding just a few NIR data points
- Promising results in M33



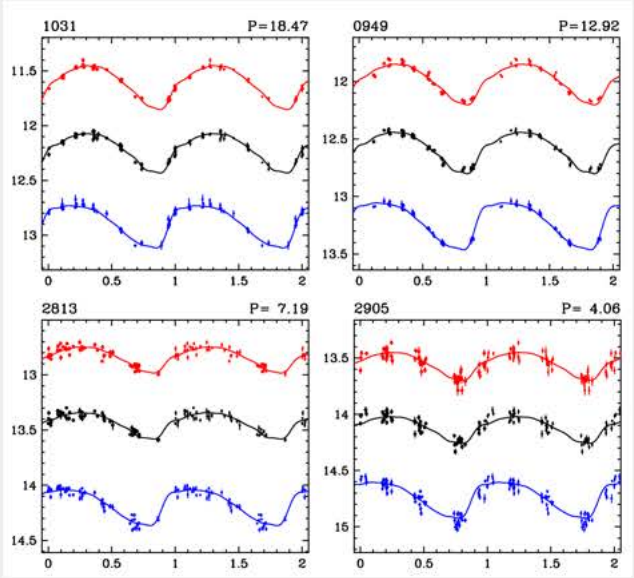


Yuan, Macri+ (2018)

LMC-BASED CALIBRATIONS

- Many distance indicators can be calibrated in LMC
  - 2% distance via eclipsing binaries (Pietrzynski+ '13) – 1% soon!
  - Discovered by OGLE surveys (Soszynski+ '08ab, '09ab)
  - NIR light curves from LMCNISS, VMC, others
  - Spectroscopic abundances for metallicity dependence

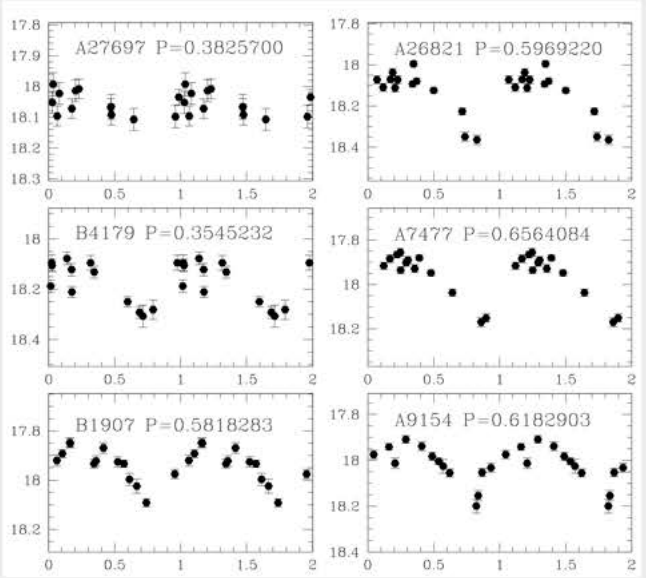
Cepheids



JHK$_S$ MAGNITUDES

MACRI+ (2015)

RR Lyrae

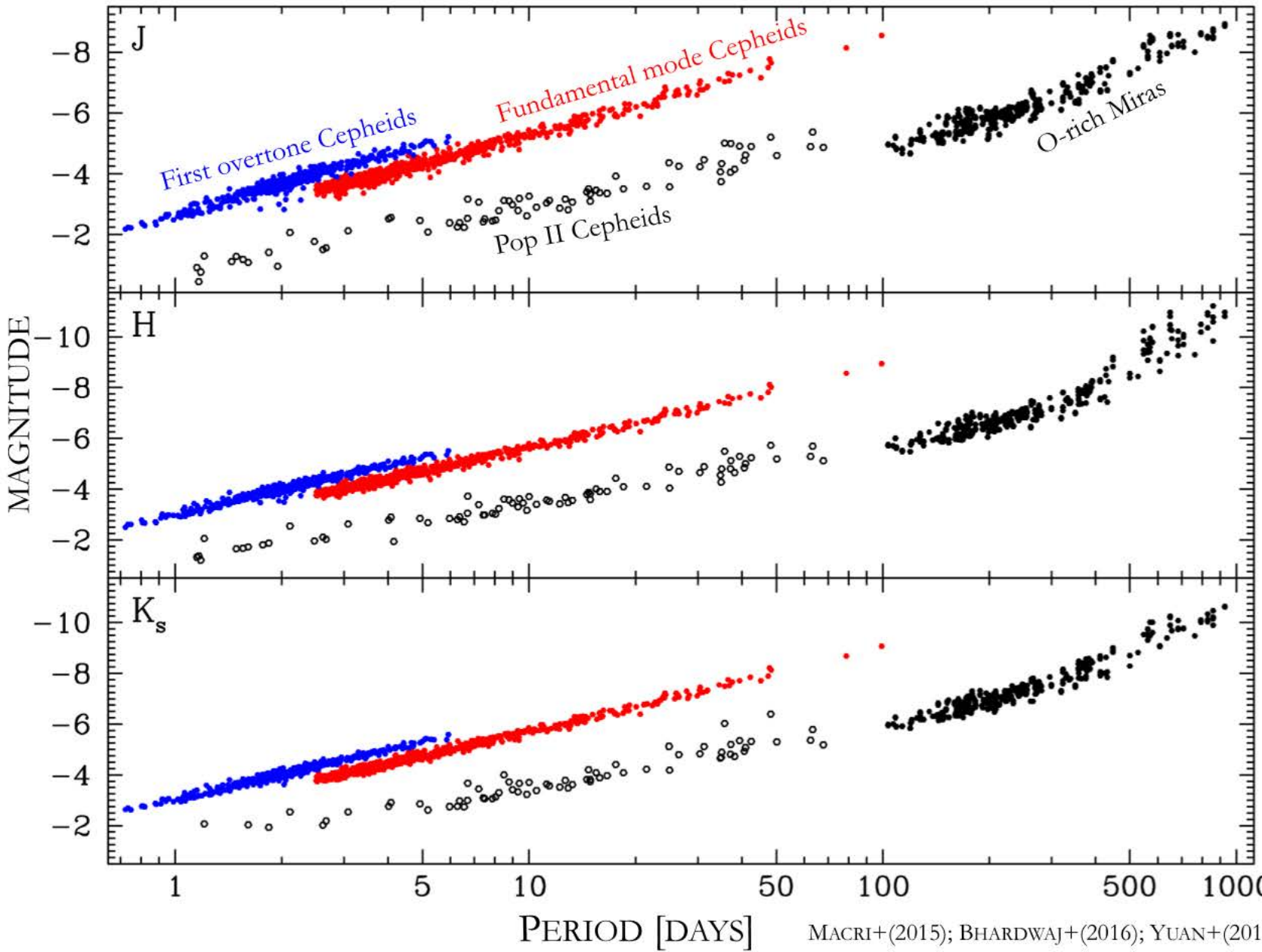


K$_S$ MAGNITUDE

PHASE

MURAVEVA+ (2015)

LMC-BASED CALIBRATIONS



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

Outline

- ✓ Motivation
- ✓ The Extragalactic Distance Scale today
- ➢ **The landscape in 2023**
- • Possible TMT programs

The Landscape in 2023

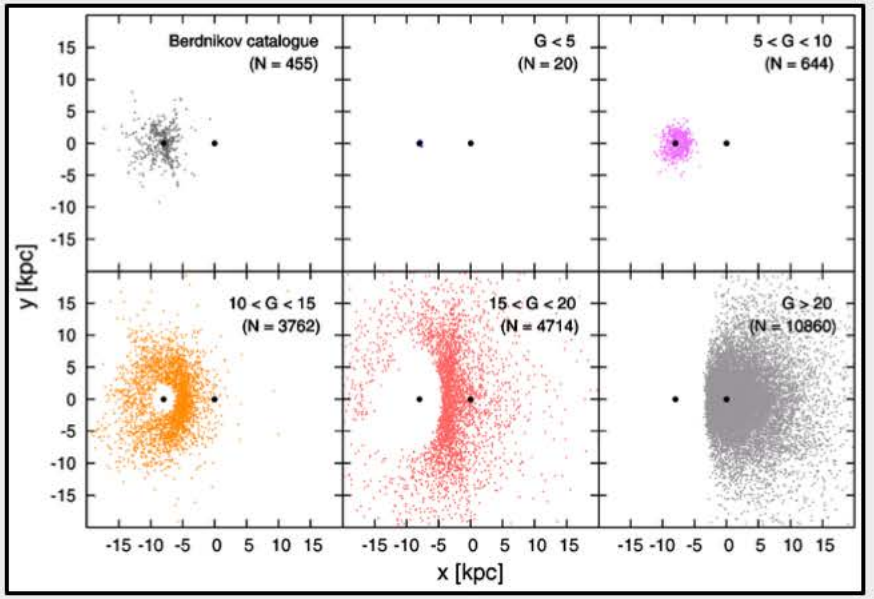
- *Gaia*
  - Data Release 4
- LSST
  - Start of survey operations
- ELTs
  - Approaching first light!
- *JWST*
  - Cycle 2(?) under way

The Landscape in 2023

- *Gaia*
  - Cepheid P-L zeropoint to 0.3-0.6%
- LSST
  - Cepheid/Mira PLRs in ~80 galaxies ($D \lesssim 10$ Mpc)
- ELTs
  - NIR AO time-series photometry of Cepheids & Miras
  - Detailed chemical abundances of Cepheids
- *JWST*
  - Precise photometry of LSST & ELT sources

Gaia discovery of & parallaxes to Milky Way Cepheids by 2023

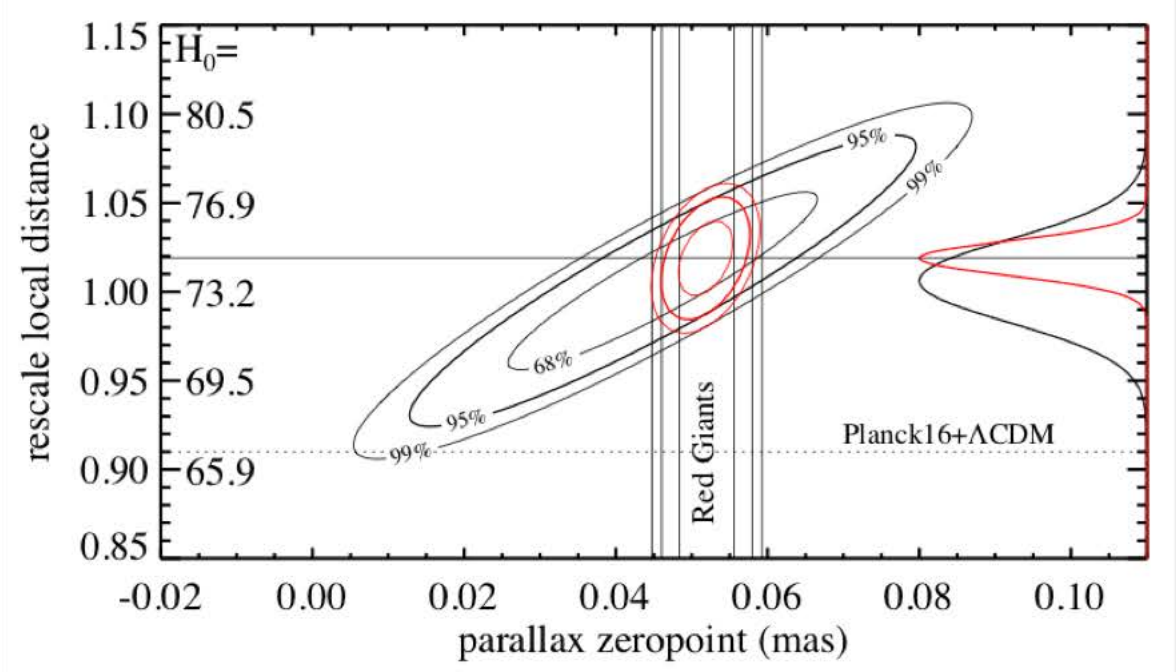
- Cepheid population of Milky Way:
  - N_{TOT}~ 20,000; N_{Gaia}~ 9,000
- Uncertainty in Period-Luminosity relation parameters:
  - Slope: 0.1-0.2%
  - Zeropoint: 0.3-0.6%
    - Range reflects uncertainties due to dust corrections



Windmark, Lindegren & Hobbs (2011)

GAIA DATA RELEASE 2: A PROMISING START

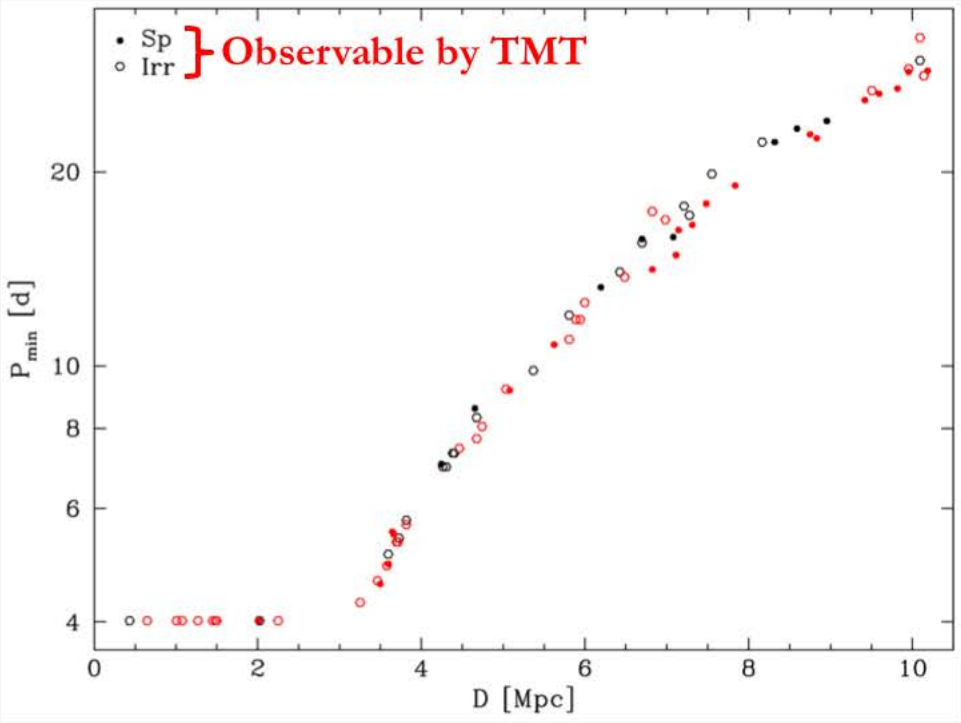
- Parallaxes to 50 Cepheids with HST NIR photometry
  - Ad-hoc correction for small parallax systematic error (to be solved by time of final *Gaia* data release)
  - Would yield 2% determination of H_0 today (4.3σ tension)



RIESS, MACRI+ (2018)

LSST SENSITIVITY TO CEPHEIDS

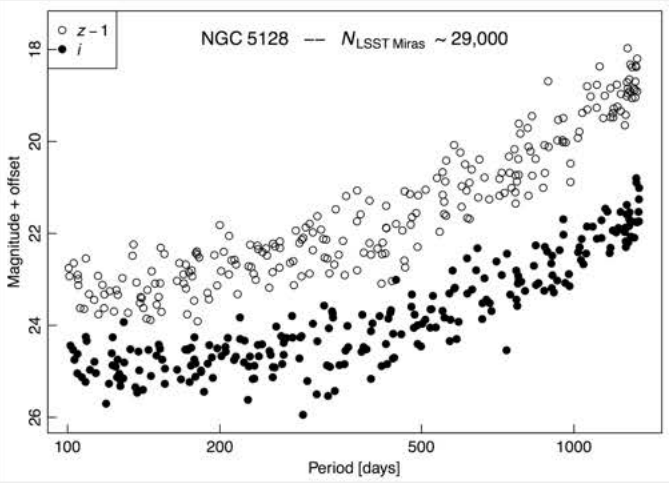
- LSST point-source sensitivity and baseline cadence suitable for detecting Cepheids at least out to 10 Mpc
- Follow-up with all ELTs possible



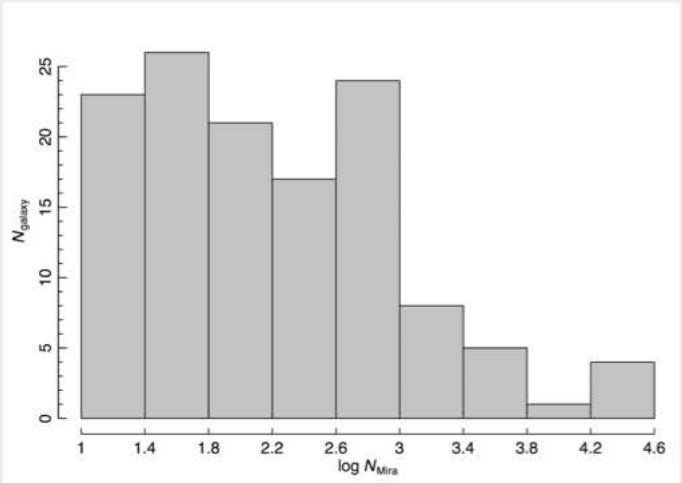
HOFFMANN & MACRI (2015)

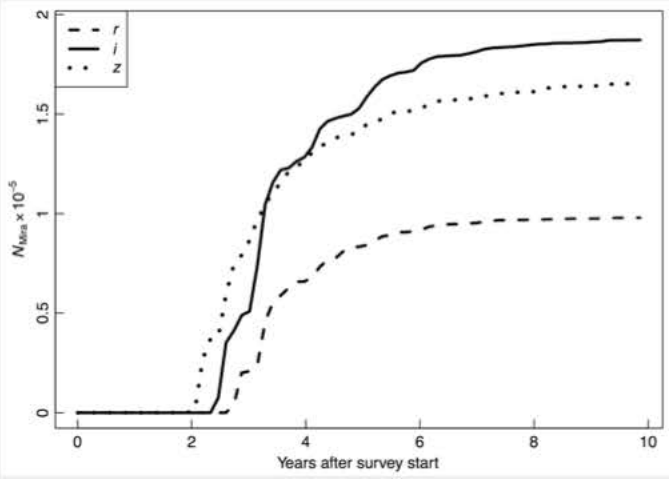
LSST SENSITIVITY TO MIRAS

- Newly developed Gaussian-process periodogram bodes well for searches with better-quality LSST data!
  - Should find > 2×10^5 Miras across 200 galaxies
- NIR follow-up critical for accurate distances, population studies



YUAN, PHD THESIS (2017)





JWST OBSERVATIONS

- JWST+NIRCam improves over HST+WFC3
  - 4× finer sampling & 3× resolution
  - Similar FoVs (123" vs 130")
- But it's still a modest aperture telescope…
  - 3hr to SNR~10 for P=20d Cepheid @ 50 Mpc in J+K
  - At least 10 epochs needed to obtain periods
    - Very expensive overheads…
- Better suited for single-epoch observations to provide exquisite photometric calibration (critical for 1% H_0)
  - Euclid might be better suited for this

Outline

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- ✓ The Extragalactic Distance Scale today
- ✓ The landscape in 2023
- ➢ **Possible ELT programs**

ELT OBSERVATIONS

- TMT+IRIS improves over JWST+NIRCam
  - ~9× finer sampling, ~5× better resolution
    → greatly reduce impact of crowding & blending
  - Small overheads well suited for time-series programs
- FoV considerably smaller…
  - 34" vs 123"
- But much larger aperture!
  - 5, 15 min to SNR~10 for P=20d Cepheid @ 50 Mpc in J&K
  - 1, 2 hr for same object @ 100 Mpc

Possible ELT programs

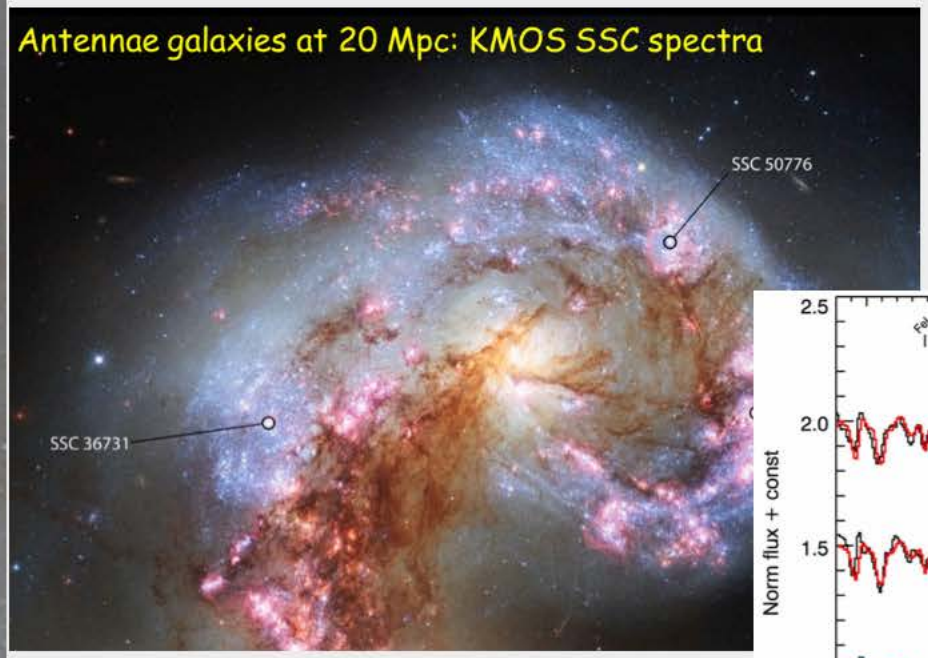
- Cepheid/Mira distances
  - Increase calibrator sample of SNe Ia hosts
  - Hosts of rare/interesting objects from ZTF/LSST for which precise luminosity calibration is desired
  - Next-gen bulge lum. vs. black hole mass relations

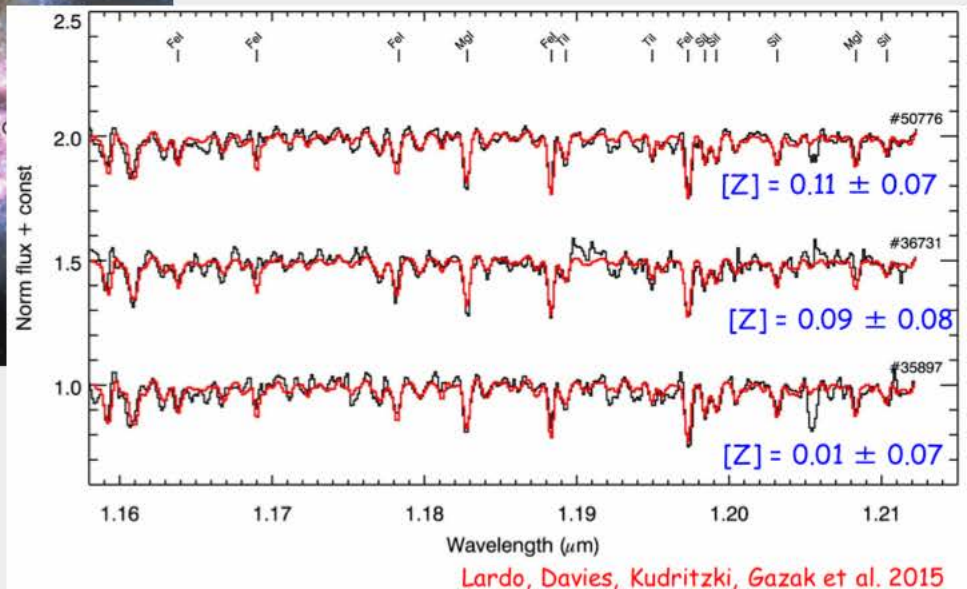
POSSIBLE ELT PROGRAMS

- Metallicity dependence of indicators
  - Spectroscopic stellar abundances beyond the Virgo Cluster using blue & red supergiants
- NIR follow-up of LSST extragalactic variables
  - Population studies of Miras
- MCAO Surface Brightness Fluctuations
  - Alternative "Pop II only" distance scale, tied to TRGB (calibrated with *Gaia*)

STELLAR ABUNDANCES OUT TO 20MPC

- Slides from Rolf-Peter Kudritzki (UH & LMU) presentation last week at MIAPP



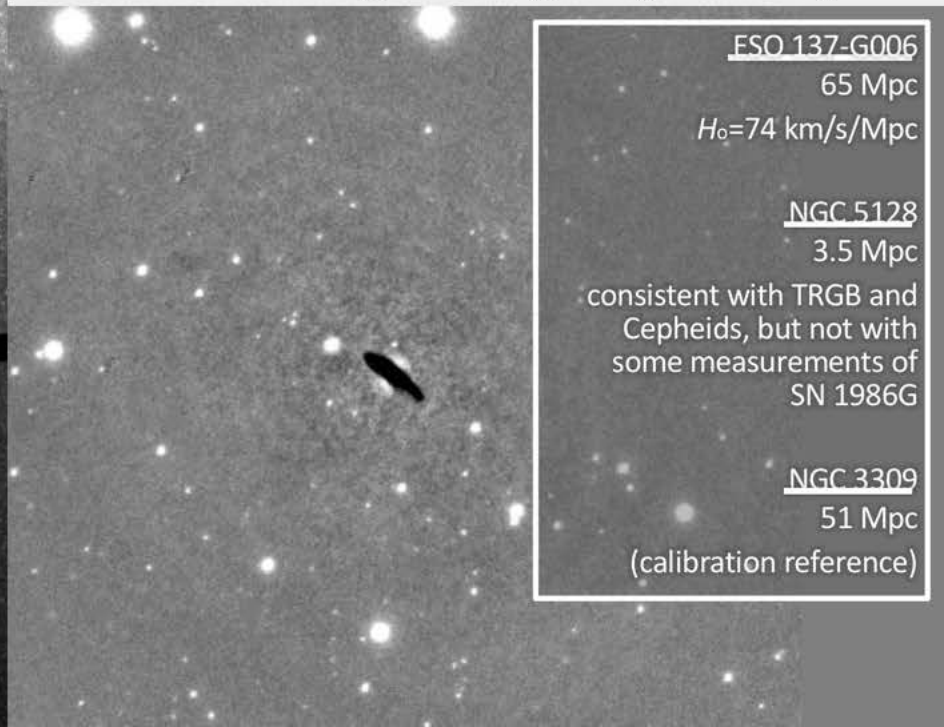


AO Surface Brightness Fluctuations

- Slides from Joe Jensen's (Utah Valley Univ.) presentation last week at MIAPP

K-band imaging of Cen A with Gemini AO

AO SBF signal for galaxy at 65 Mpc



Thank you!