# Cepheid Calibration and Gaia parallaxes (the best shot at 1%)

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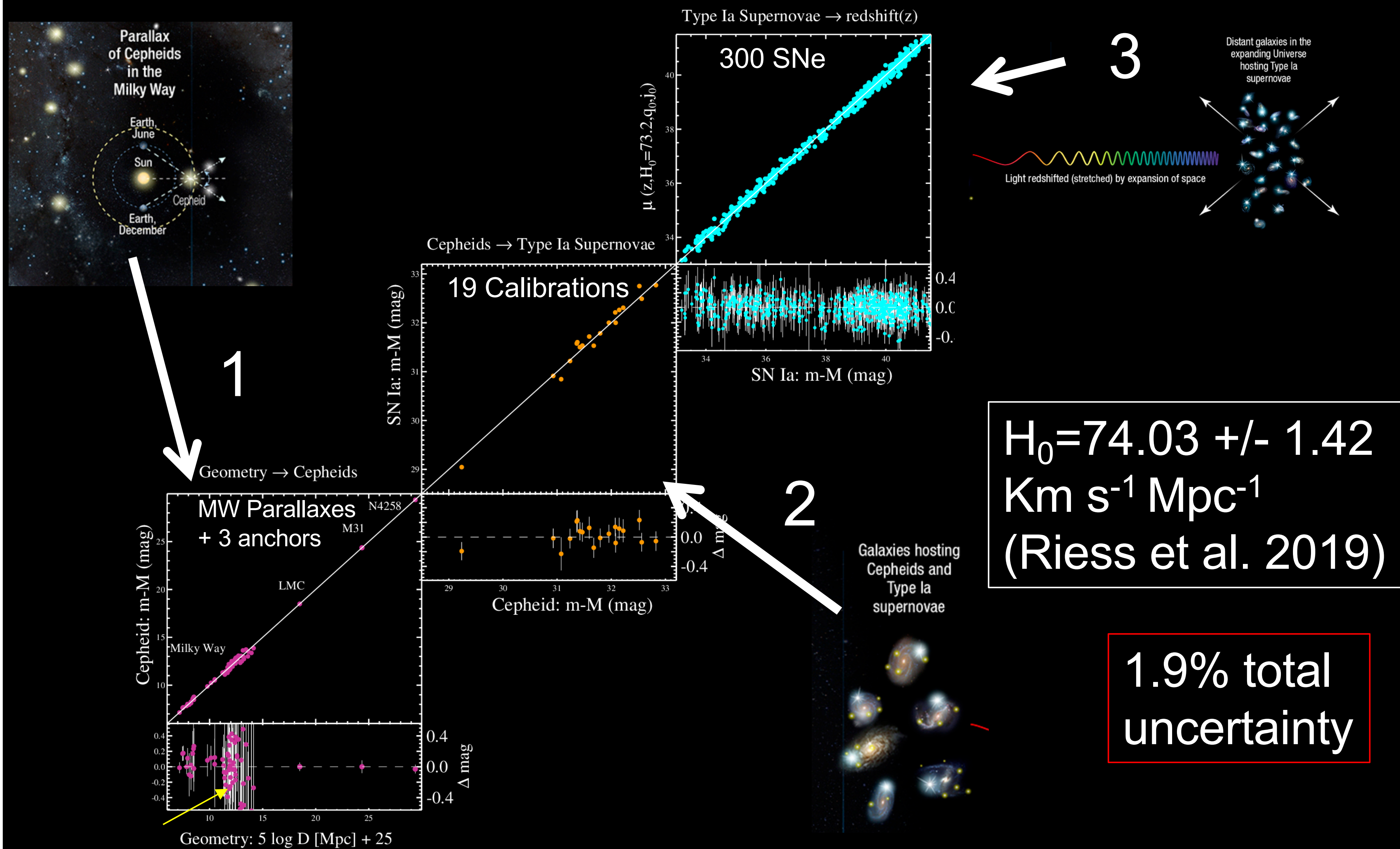
and the SH0ES Team

# The Hubble Constant in 3 Steps: SH0ES Today




$H_0$=74.03 +/- 1.42 Km $s^{-1}$ $Mpc^{-1}$ (Riess et al. 2019)

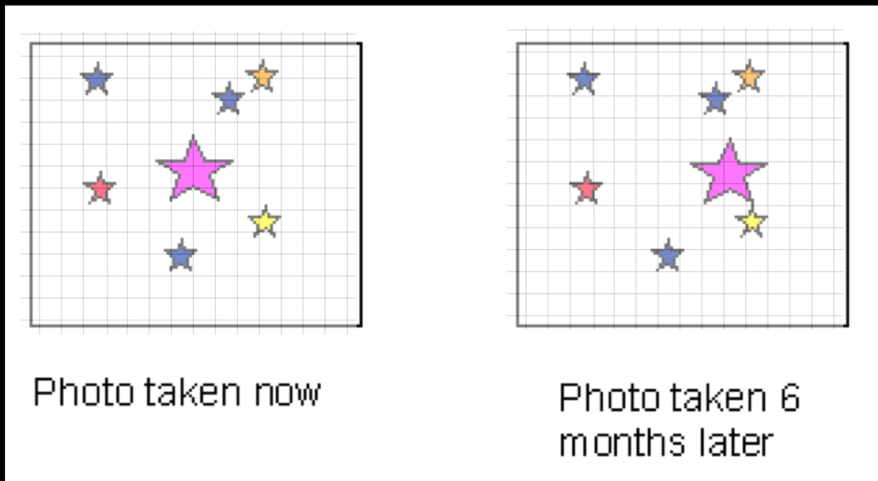
1.9% total uncertainty

# Five Independent Sources of Geometric Cepheid Calibrations

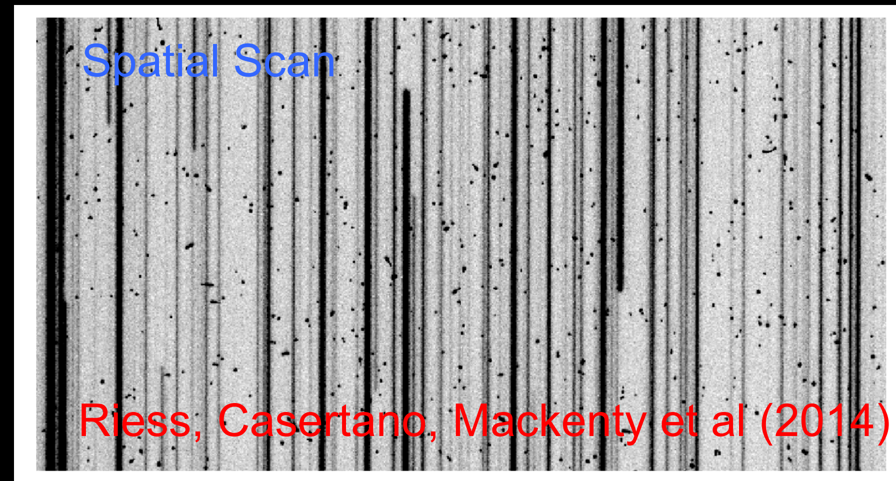
| Independent Geometric Source | | $H_0$ |
|---|---|---|
| NGC 4258 $H_20$ Masers: Humphreys et al 2013, Riess et al 2016 (2.6%) [7.58+/- 0.08 +/- 0.08 Mpc, Reid talk yesterday -> 72.0] | | 72.3 |
| LMC 8 Late Detached Eclipsing Binaries: Pietrzyński et al. 2019 (1.5%) | | 74.2 |
| Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van Leeuwen et al 2007) (2.2%) | | 76.2 |
| Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess et al. 2018 (3.3%) | | 75.7 |
| Milky Way 50 Gaia DR2+HST, Long P Parallaxes: Riess et al. 2018 (3.3%) | | 73.7 |

Three different parallax calibrations for MW Cepheids
Different methods and systematics, consistent results

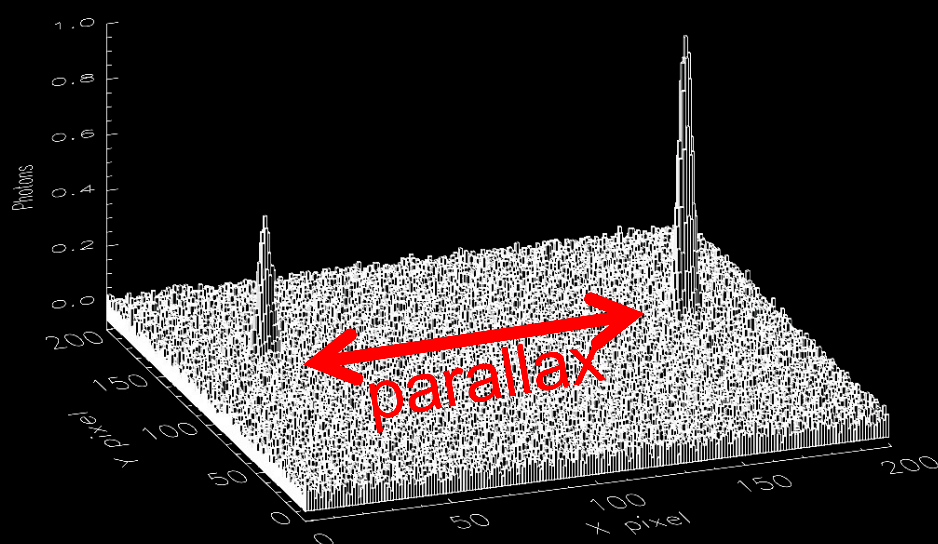
# Precision astrometry with HST WFC3 Spatial Scanning

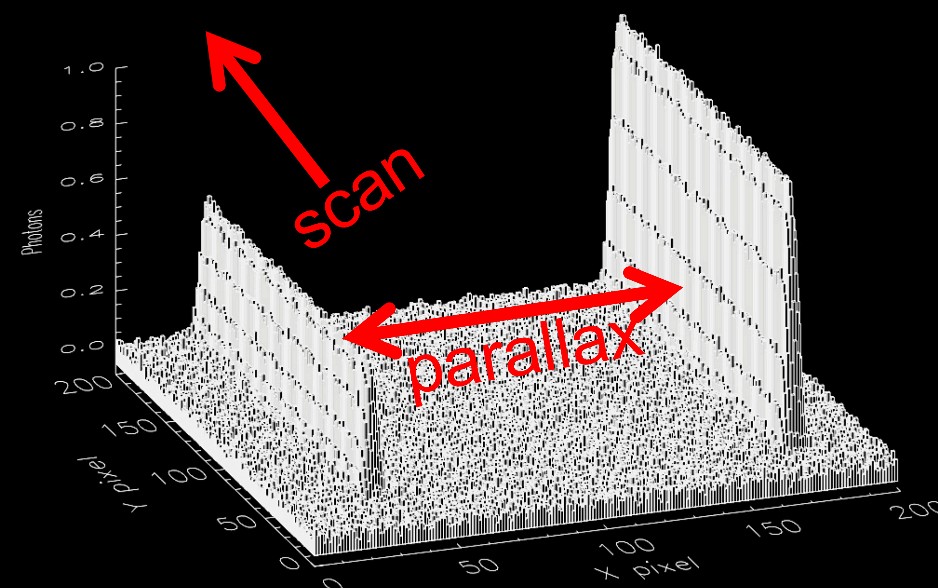



Imaging: astrometry $\sigma_\theta$=0.01 pix
HST: 0.4mas, ~1$\sigma$ @ 2 kpc



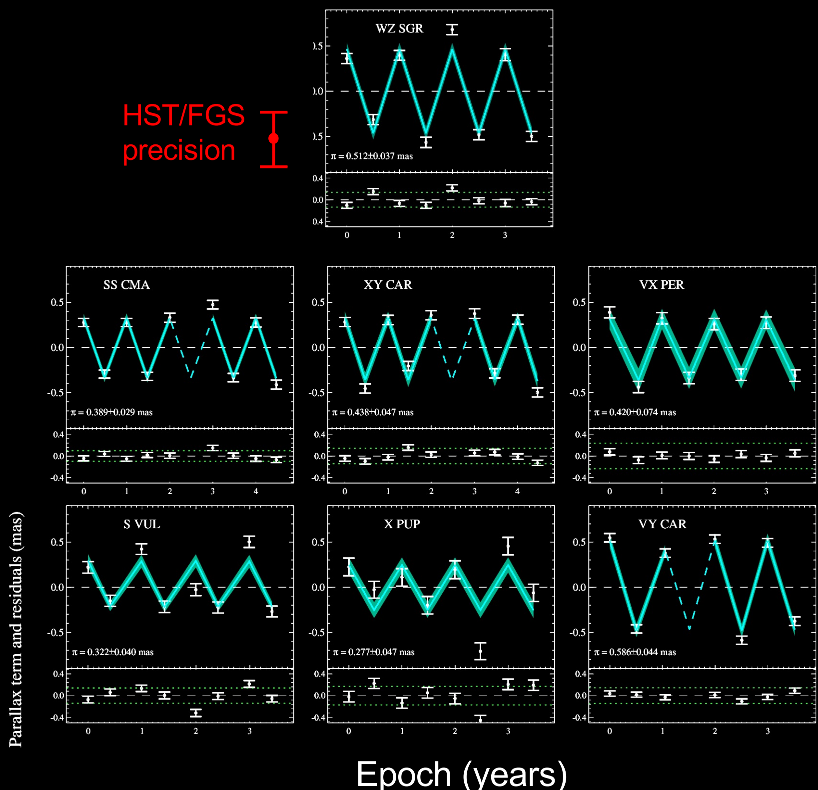

Scanning, $\sigma_\theta=0.01/\sqrt{N}$ samples pix
(20-40 $\mu$as/epoch)



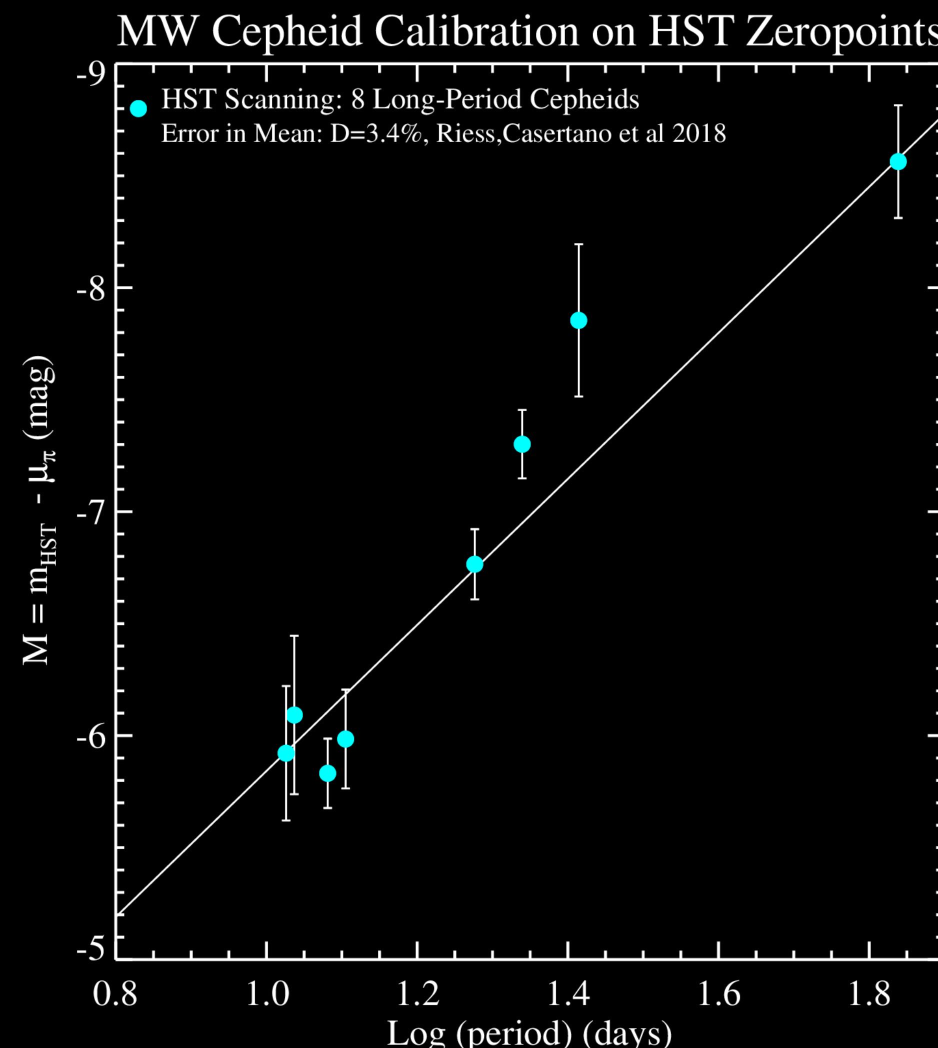



# HST spatial scanning parallaxes (> 4 years of data)

8 MW Cepheid Parallax measurements
1.7<D<3.6 Kpc, error in mean=3.3%

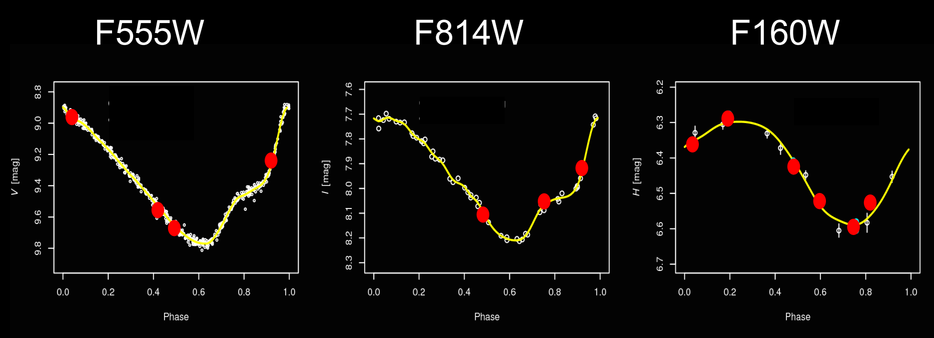


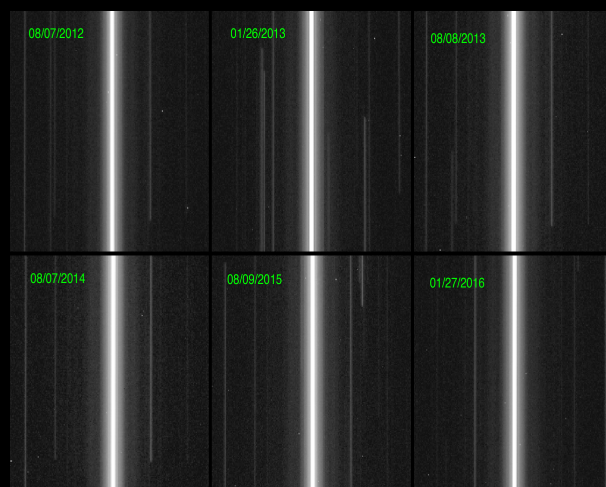

Riess et al. (2018)
Casertano et al (2016)



# Milky Way Cepheids in Gaia DR2

- 50 *Benchmark* long-period MW Cepheids
- Spatial scanning HST Photometry

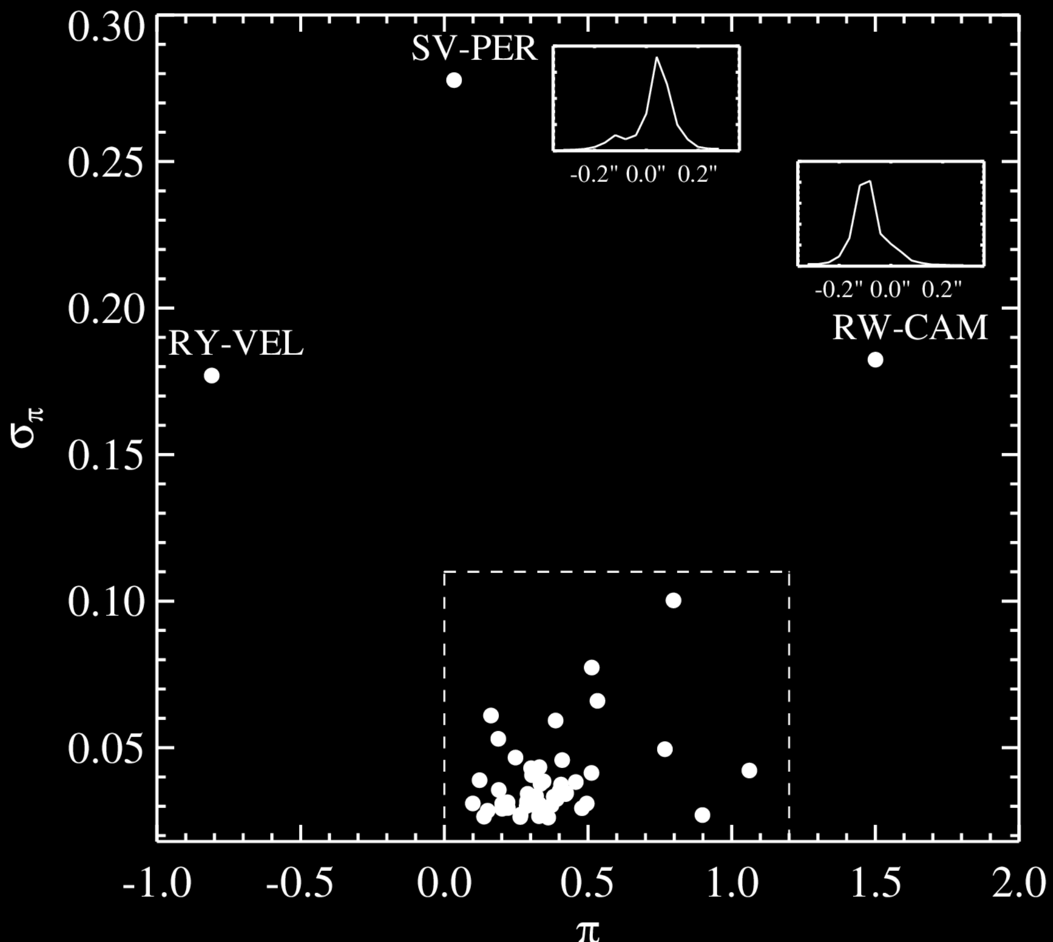



Fast Scans 7.5"/s $\Rightarrow$ exposure time ~ 0.01 s / pixel
Median DR2 parallax error 40 $\mu$as (4% @ 1kpc)
Expected combined calibration error < 1% (~0.5% at mission end)

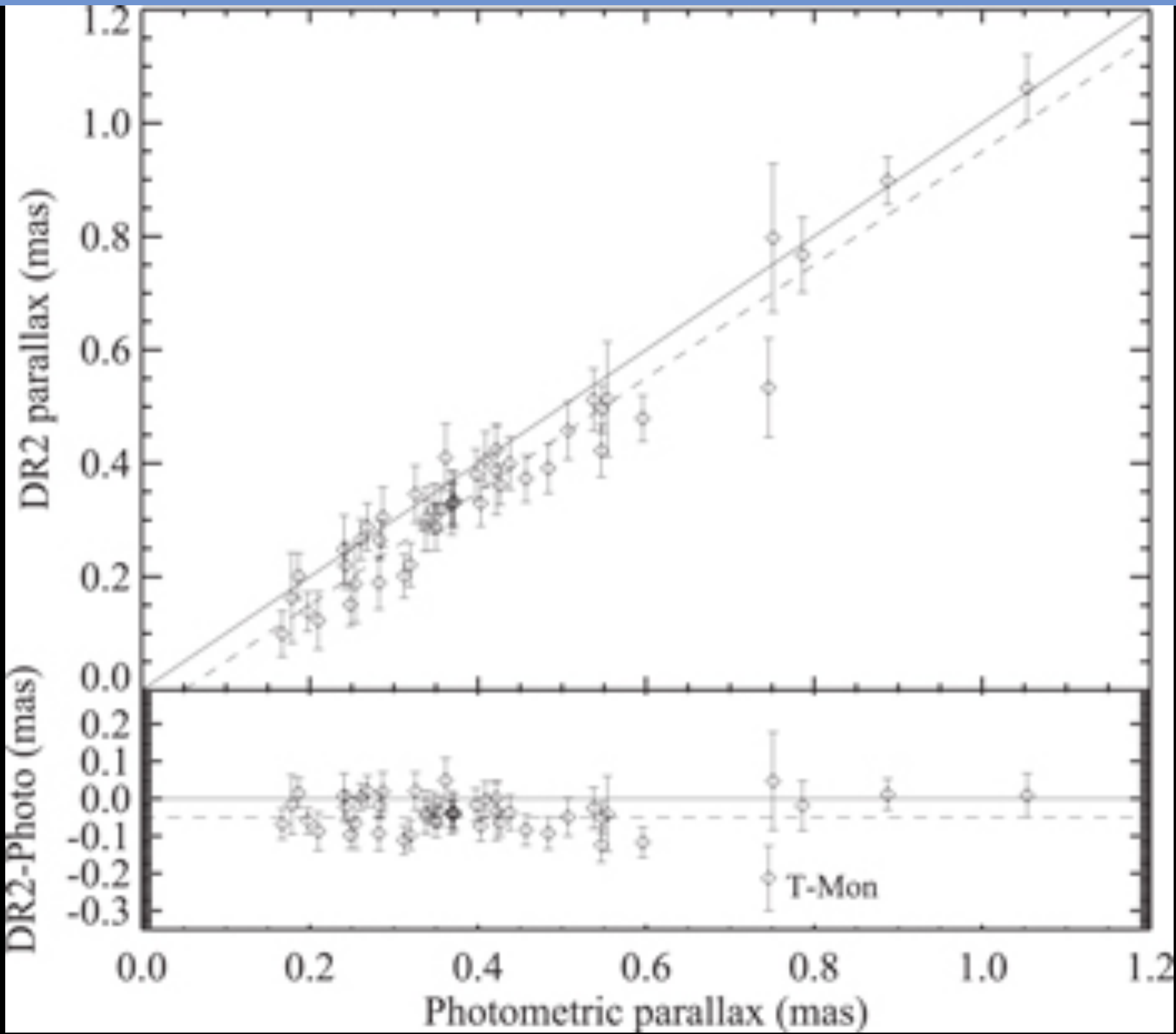
# Gaia DR2 Parallaxes and Errors

Some Cepheids have large/anomalous errors or G < 6




We rejected these 3 plus T Mon (G=6.1 but often G<6))

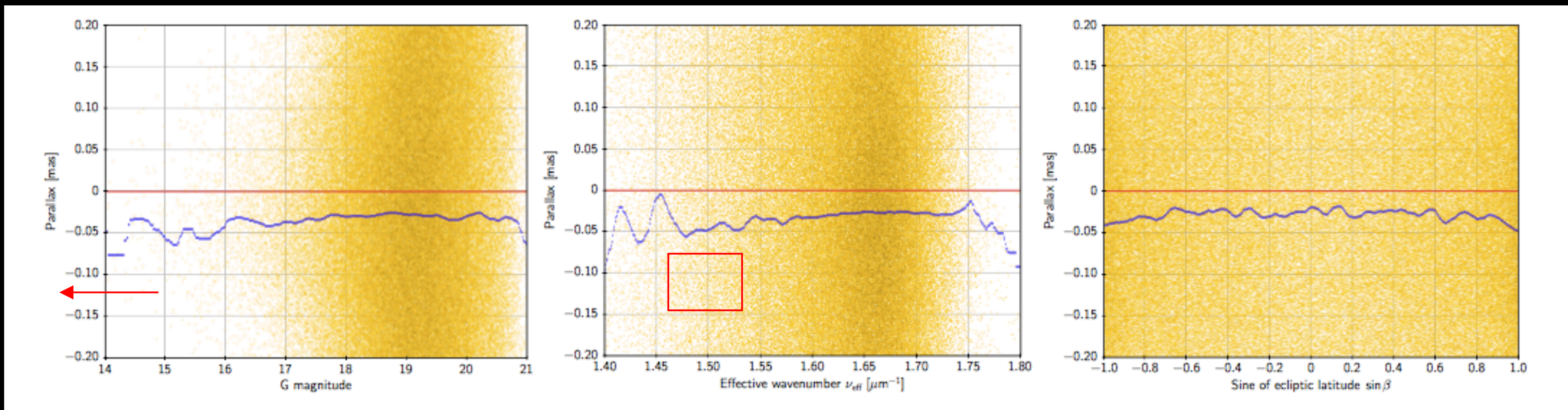
# Parallax offset!



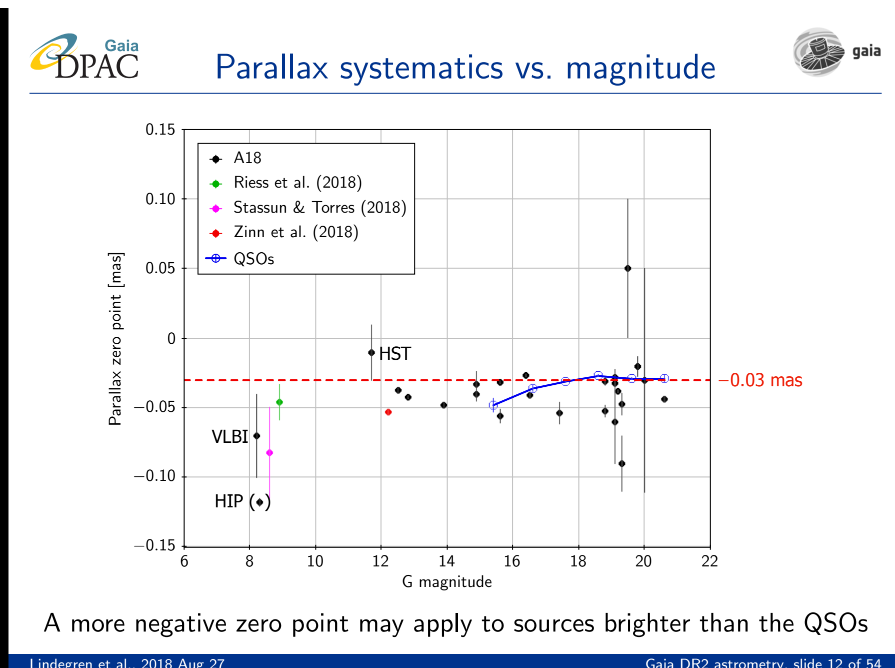

DR2 results have a parallax offset in DR2 (see Brown talk)
Likely due to Basic Angle variation
Appears to depend on magnitude, color, position of source

# DR2 parallax offset (an additive term)

Quasars parallaxes suggest that offset, varies with mag, color, possibly location (Lindegren 2018). Cepheids are brighter and redder than quasars



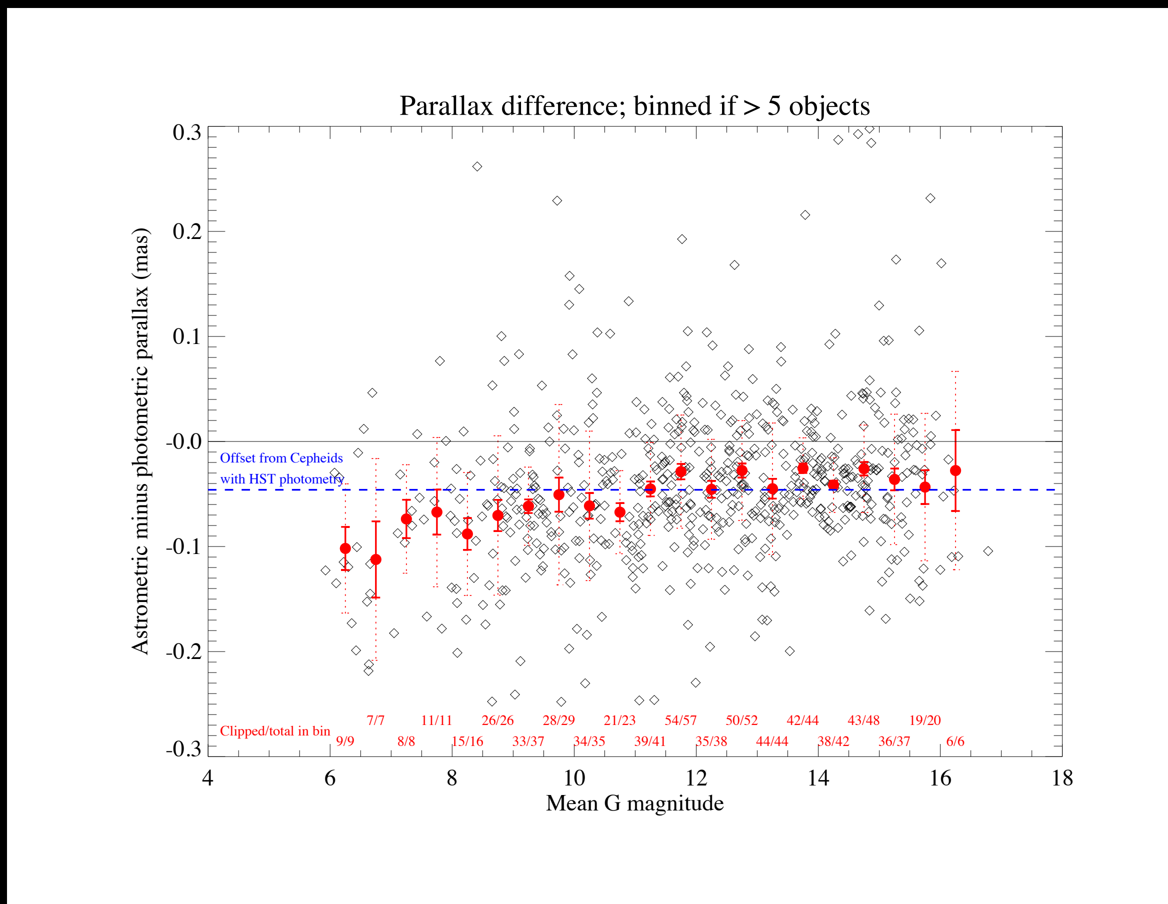

Lindegren et al 2018




Lindegren, IAU 348

# Another test on unbiased set of Gaia Cepheids

600 MW Fundamental Mode Cepheids (VarCepheid DR2 catalog)
Parallax and photometry from DR2

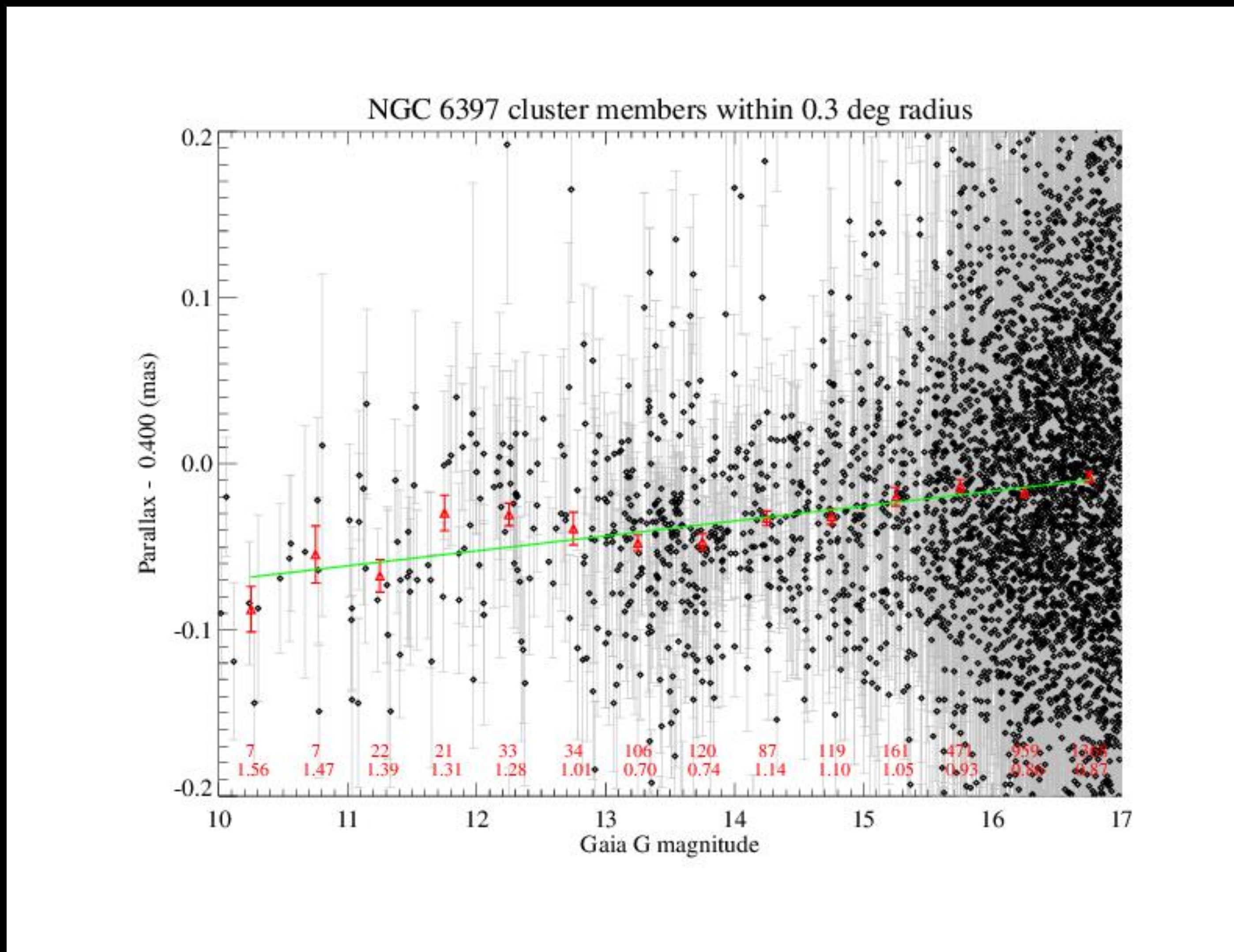



Parallax bias increases with apparent luminosity

NOTE: saturated stars (G < 6) should NOT be used

# Another test on unbiased set of Gaia Cepheids

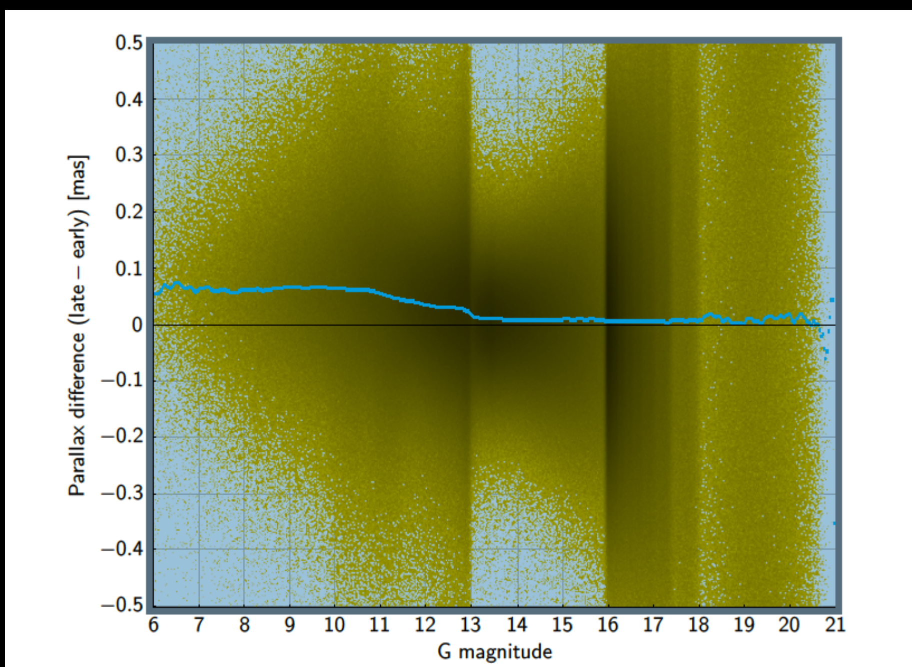
## Magnitude effect also seen in some globular clusters (e.g., NGC 6397) – but not in all

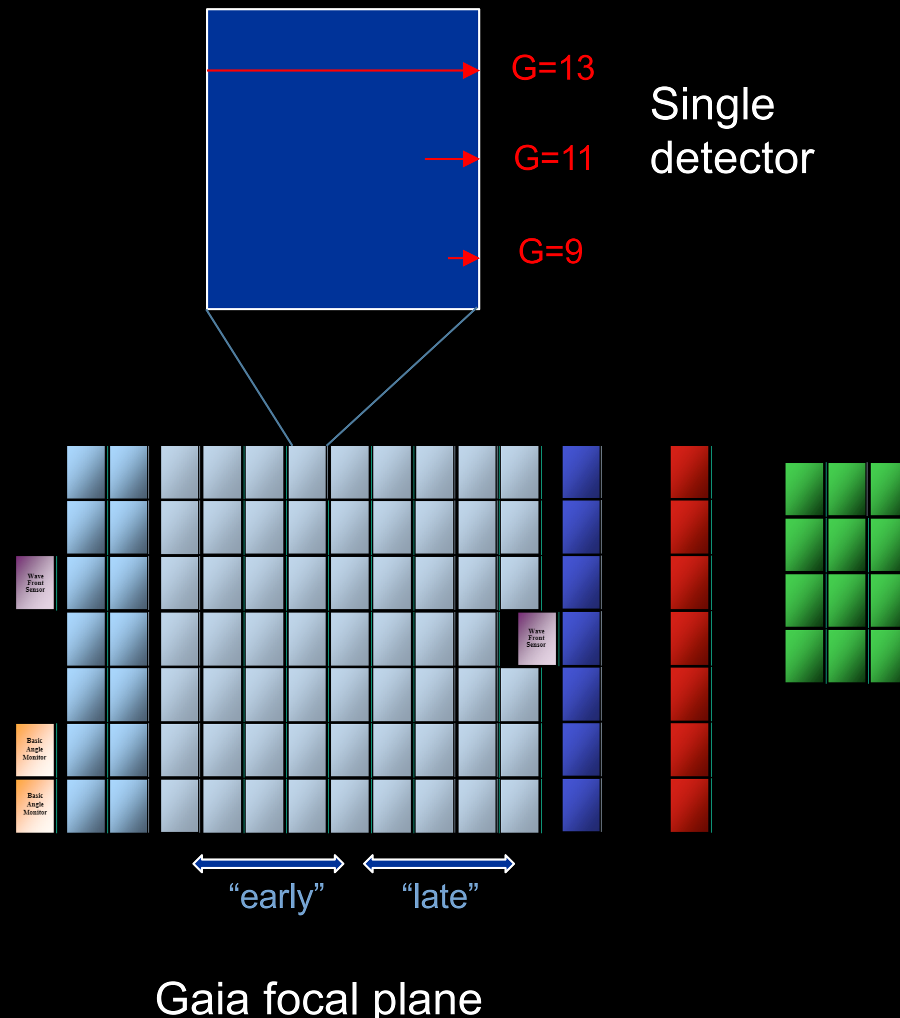


# Why a magnitude-dependent offset?

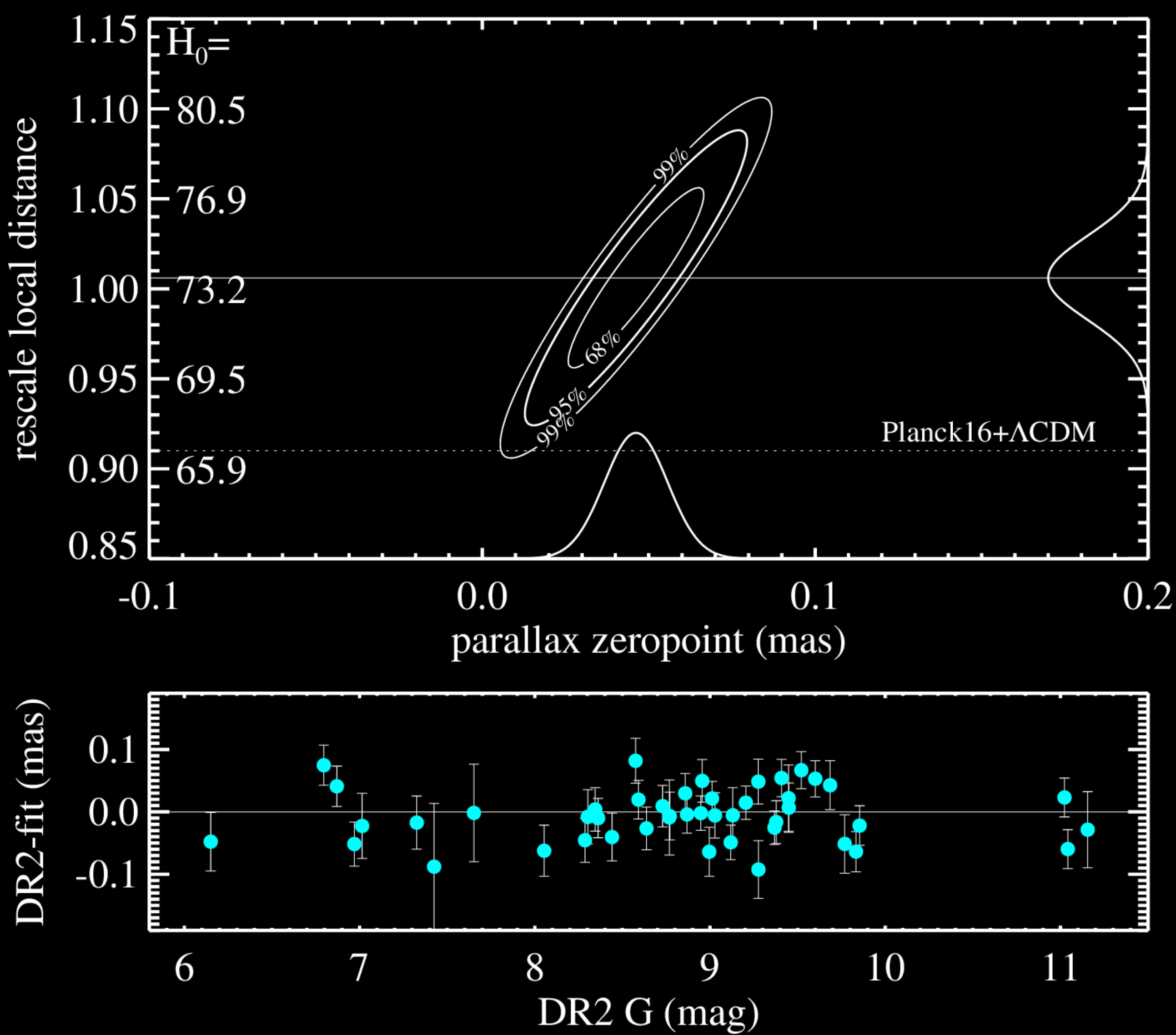
- Some parallax issues arise at G < 13
- G < 13 stars need gating to avoid saturation - sampling a subset of the focal plane

  Could this contribute to the offset?
- Parallax derived from “early” and “late” focal plane differs at G < 13 (Lidegren 2018)
- Note: in current AGIS solution, only global calibration parameters are adjusted



# Determine the parallax offset for our Cepheid sample




Assume constant offset (similar mag, color)

Solve for additive and multiplicative term

Additive = parallax offset (-46 +/- 13 $\mu$as)

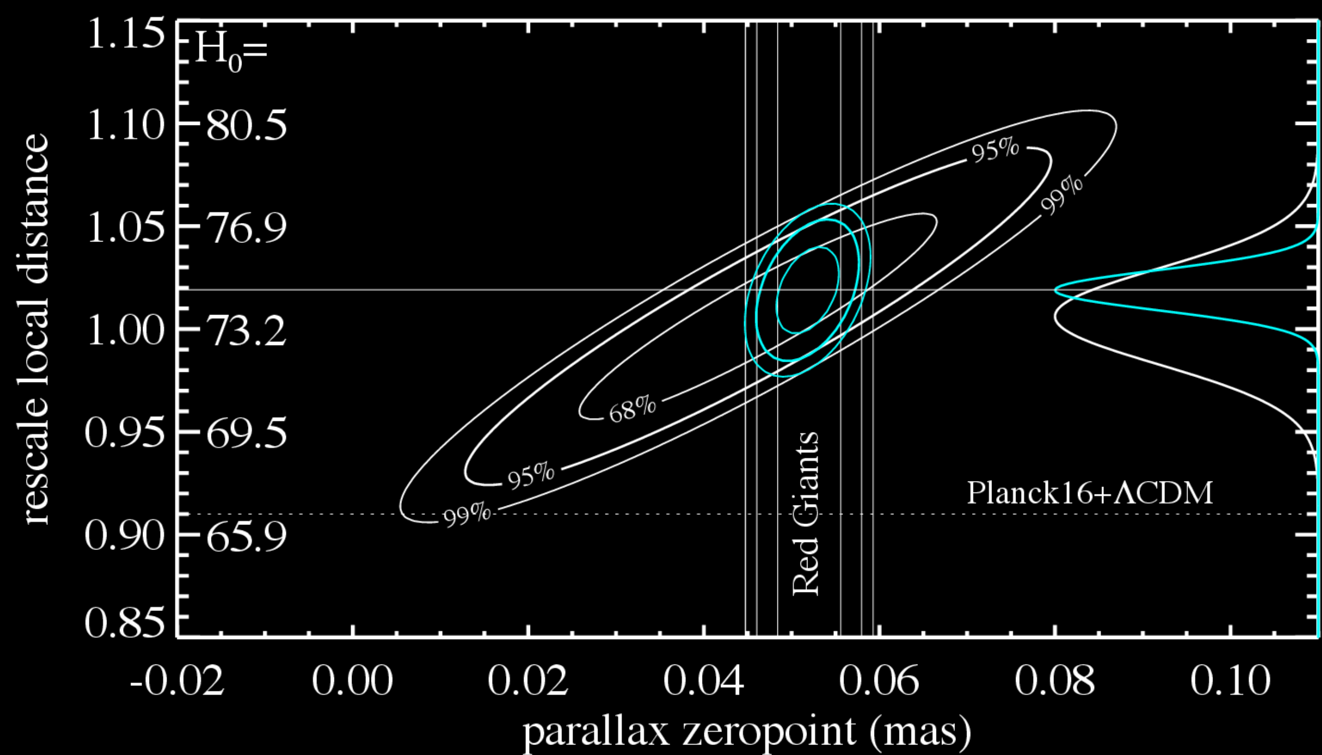
Multiplicative =change in Cepheid calibration (1.008 +/- 0.033; 2.9 $\sigma$ from Planck+ΛCDM)

Covariance due to small parallax range!

Some evidence errors are underestimated by ~ 20% (might include position-dependent offset)

# The Impact of Constraining the Gaia DR2 Parallax offset

Using Zinn et al. 2018 prior on DR2 Parallax offset (Kepler astero-seismology to measure radii for 3000+ Red Giants→ good match to Cepheids



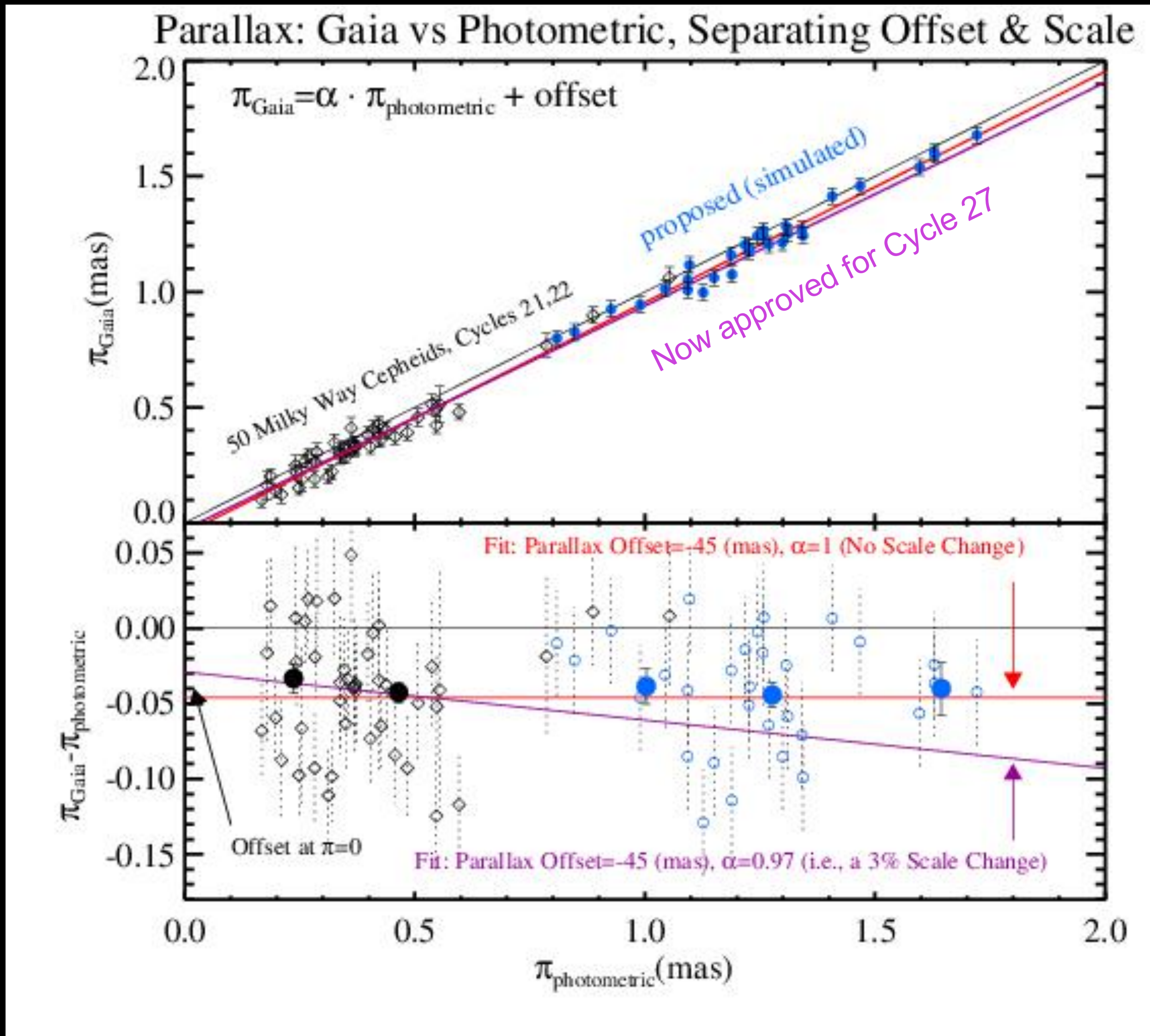

$\alpha$=1.017 +/- 0.013

Full distance ladder
$H_0$=73.83 +/- 1.48

-4.3 $\sigma$ tension with Planck16

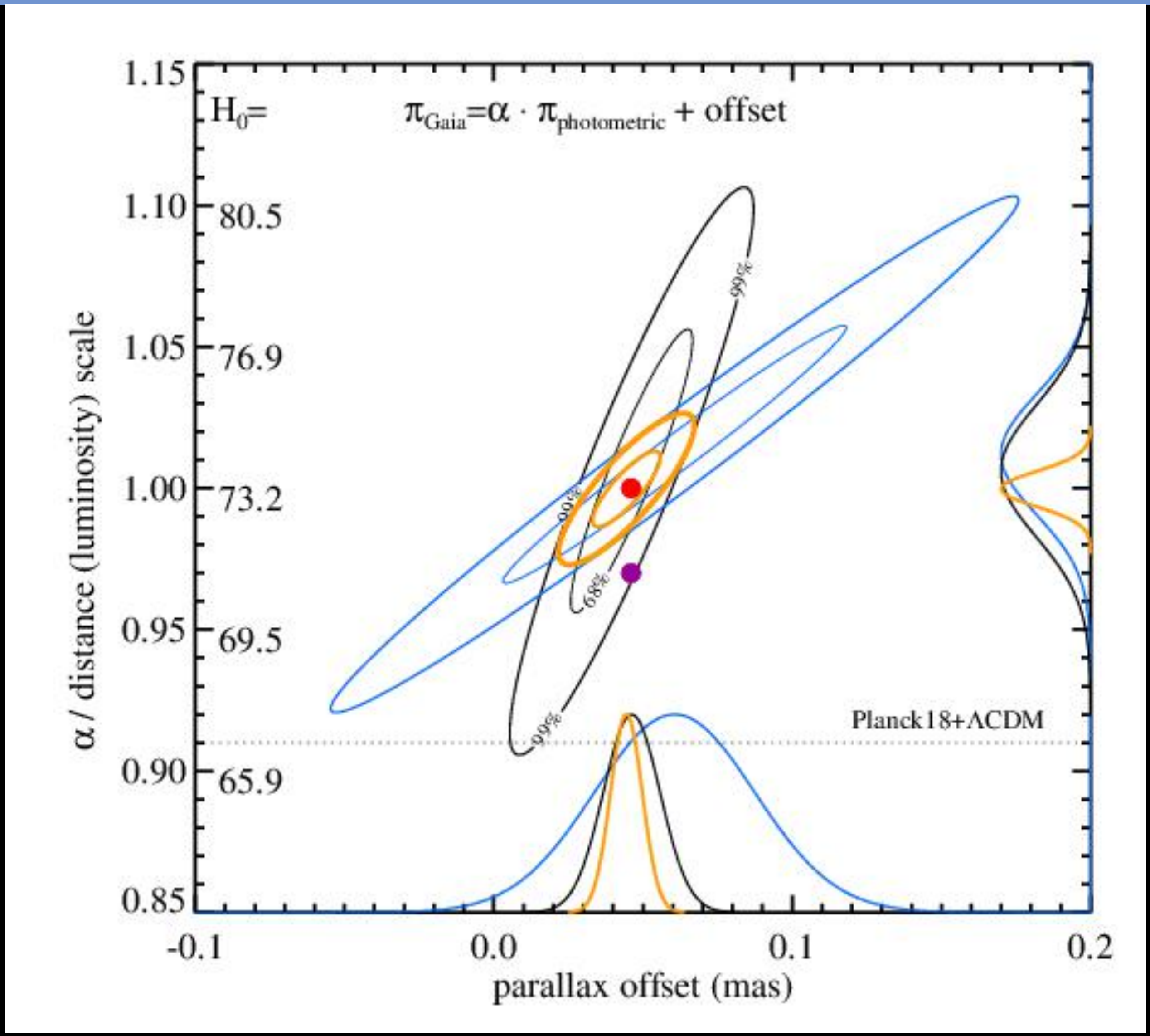
(if you double Zinn et al errors →
4.2 $\sigma$ tension )

# Improving parallaxes: a new HST sample




A new sample of 40 Cepheids at much larger parallaxes (greatly improves separation between offset and scale)

# Expected results with new MW Cepheid sample




Simulated results with 50+40 Cepheids, fitting for offset and scale
Expect <~ 1% calibration using DR2 errors, better with DR3

# Summary

- Multiple paths to Cepheid calibration yield strong agreement, consistent values for H0
  - LMC (currently most precise)
  - NGC 4258
  - MW parallaxes (three methods: FGS, WFC3, Gaia)
    - Need HST photometry to avoid systematics
- Status of Gaia parallaxes
  - Currently affected by the DR2 offset issue
  - We determine offset directly from Cepheid sample
  - Reduces effective accuracy by ~ 2.5 (from 1.3% to 3.3%)
- New HST observations, DR3 improvements are coming
  - In about a year, Gaia will yield the best Cepheid calibration
  - 1% is well within reach

[Added bonus: crosschecks between HST photometry and DR3]