

Gaia parallaxes of Galactic open clusters
calibrate Cepheid luminosity to 0.9% and
raise H_0 tension with Planck+ Λ CDM to 5.3σ

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with Mauricio Cruz Reyes, Adam Riess, Stefano Casertano, and Louise Breuval

Please see arXiv IDs:

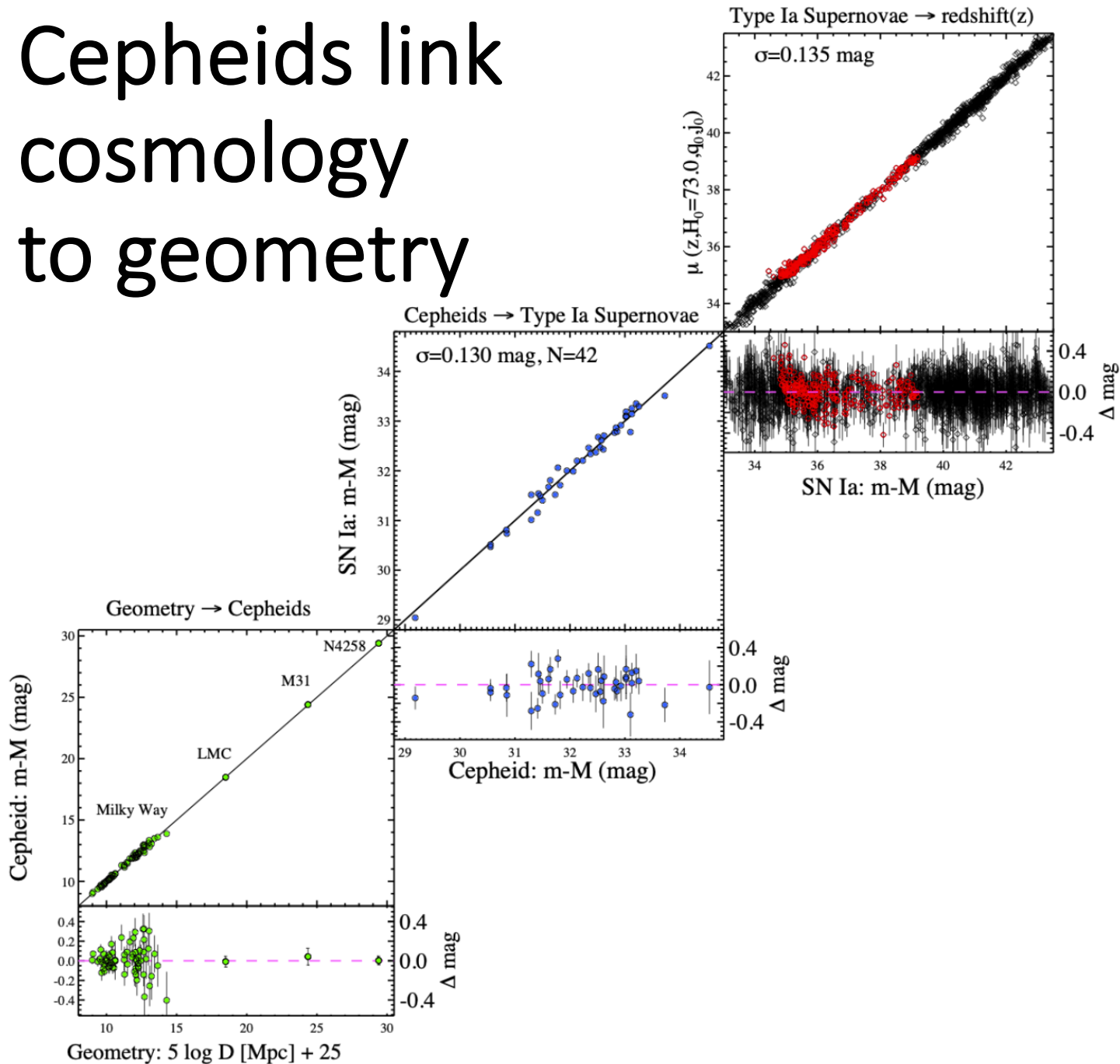
2208.01045 : Riess et al., ApJ accepted

2208.09403 : Cruz Reyes & Anderson, A&A submitted

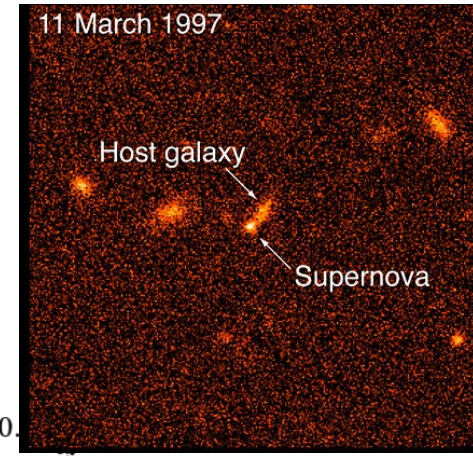
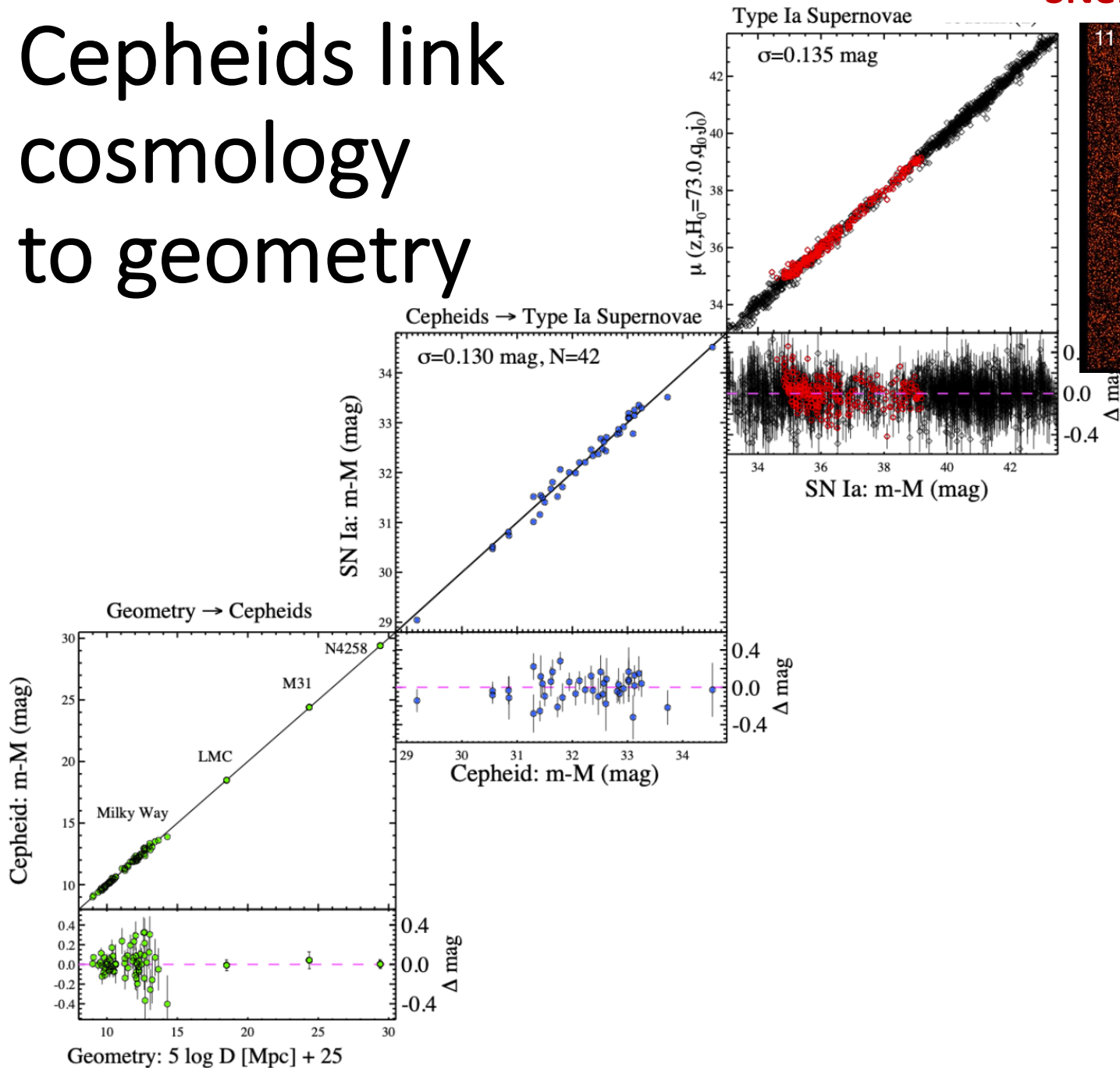


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Cepheids link cosmology to geometry

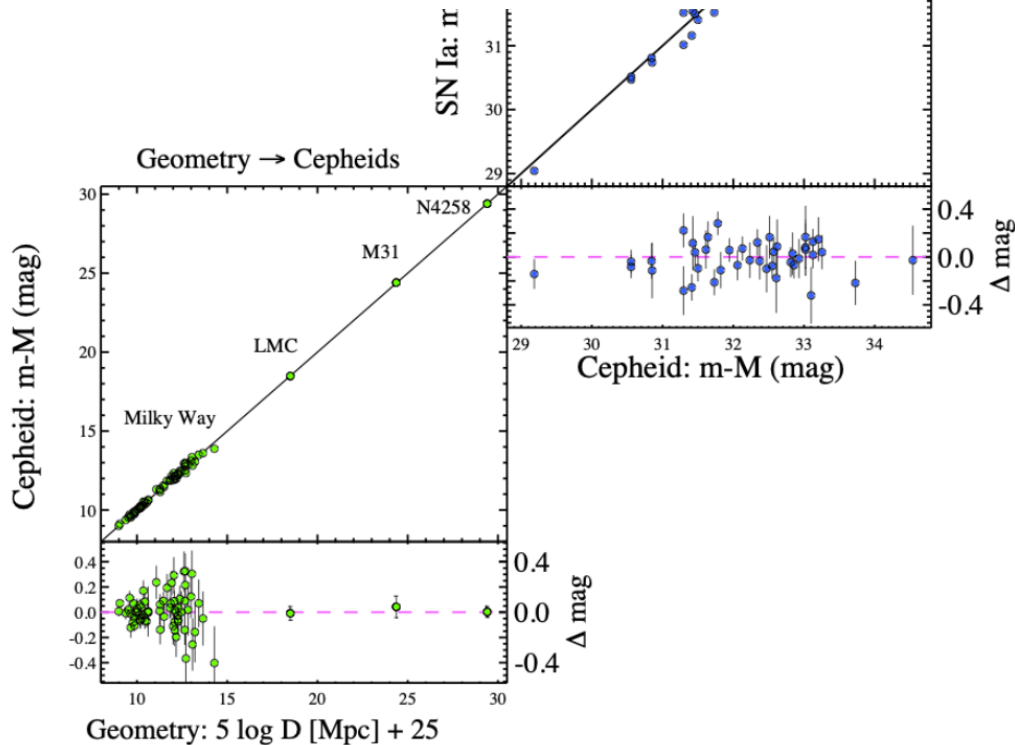


Cepheids link cosmology to geometry

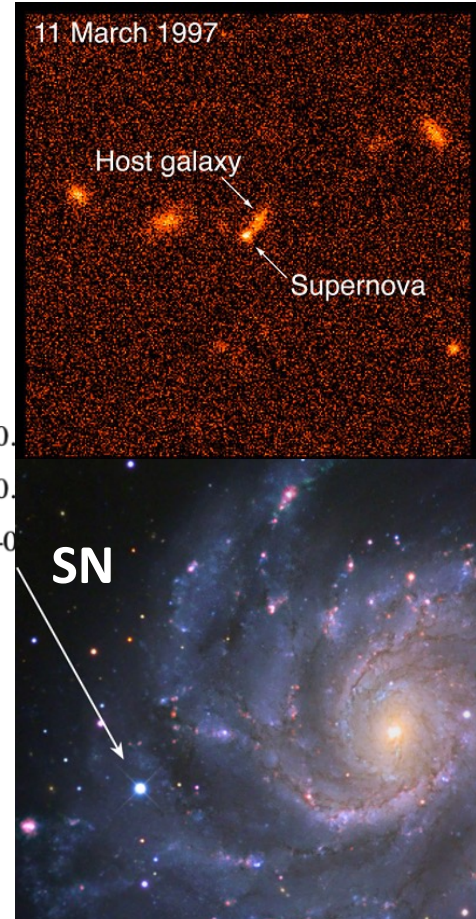
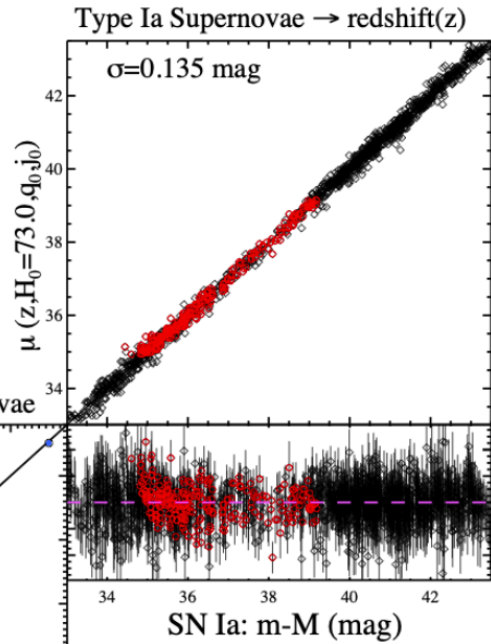


Cepheids link cosmology to geometry

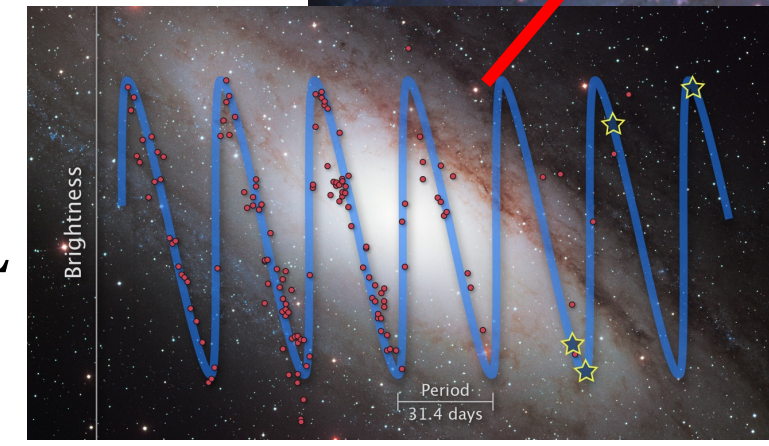
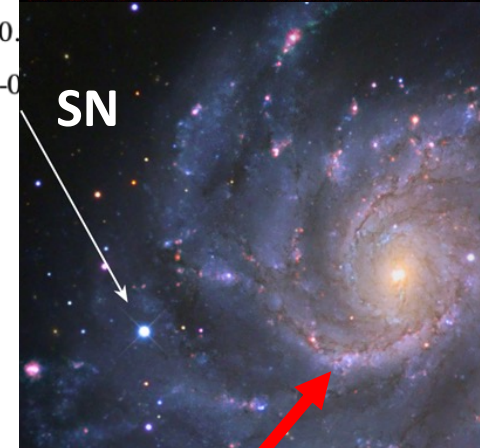
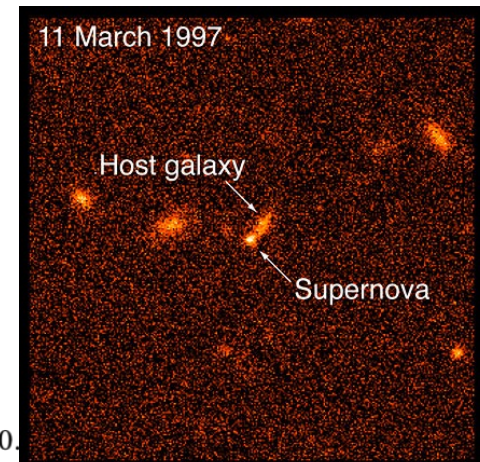
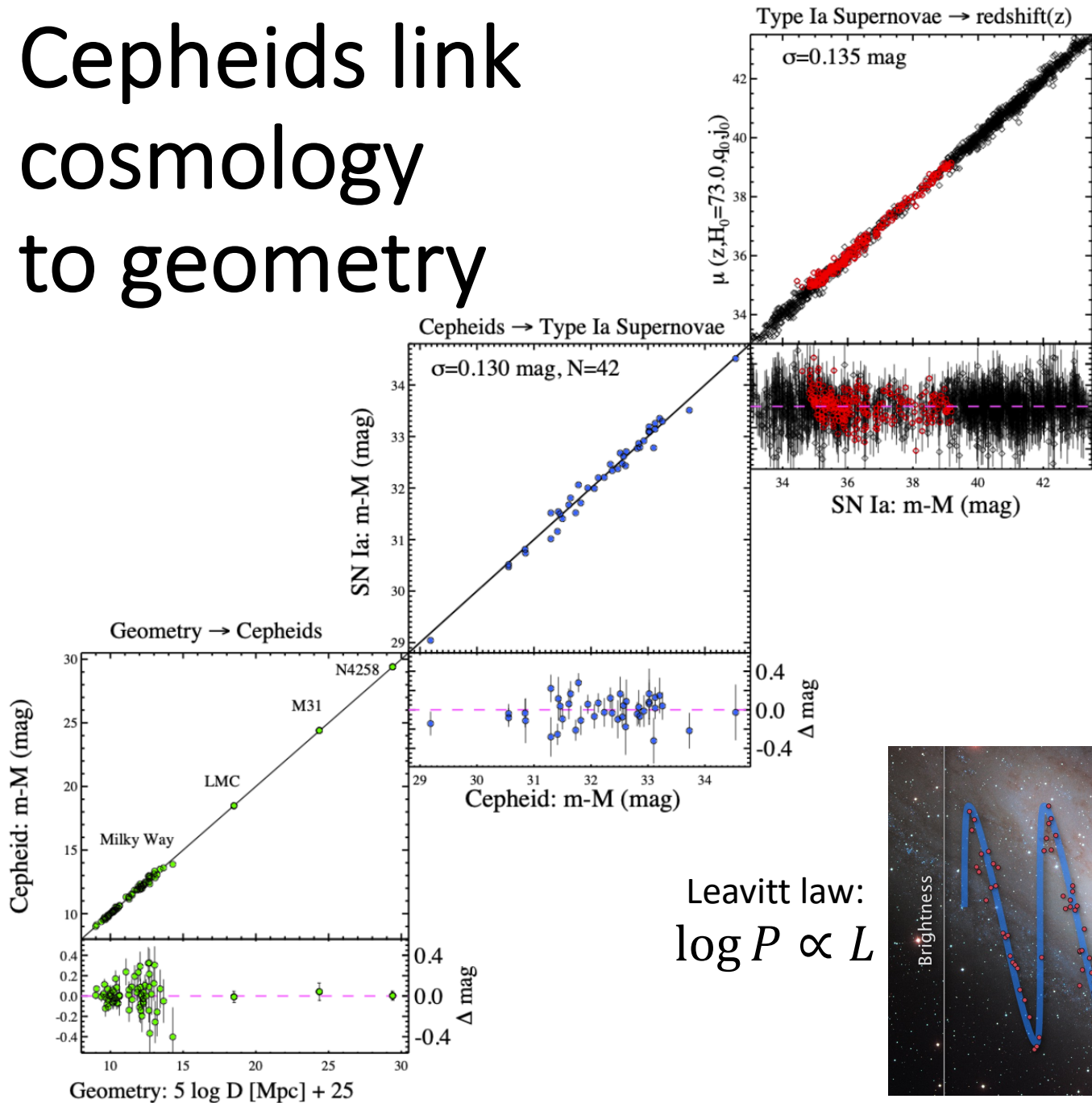
**Close enough for Cepheids
far enough for SNeIa**



Cepheids \rightarrow Type Ia Supernovae
 $\sigma=0.130$ mag, $N=42$



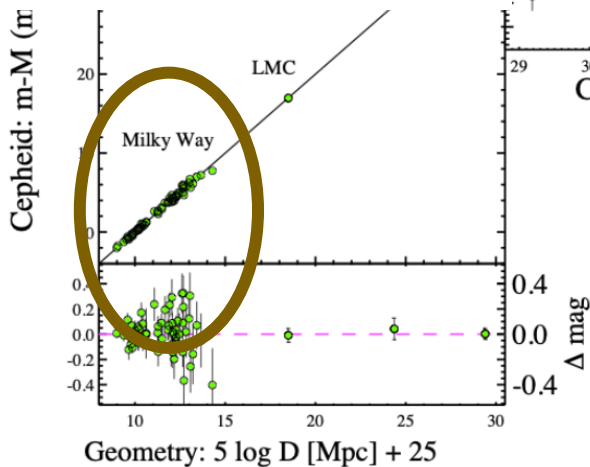
Cepheids link cosmology to geometry



Leavitt law:
 $\log P \propto L$

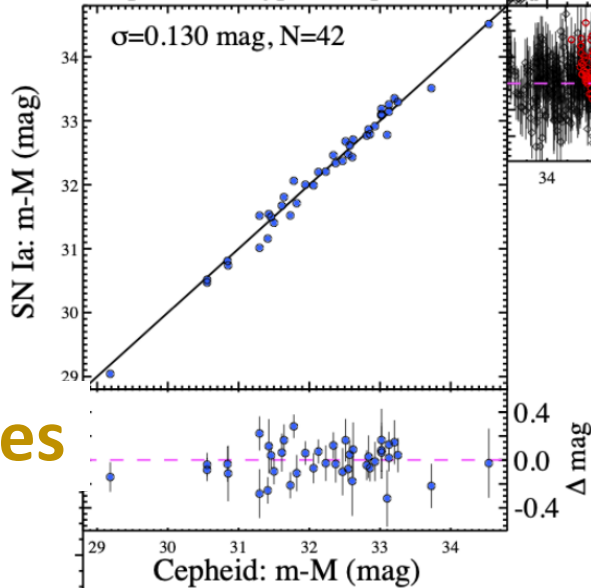
Cepheids link cosmology to geometry

Gaia Parallaxes



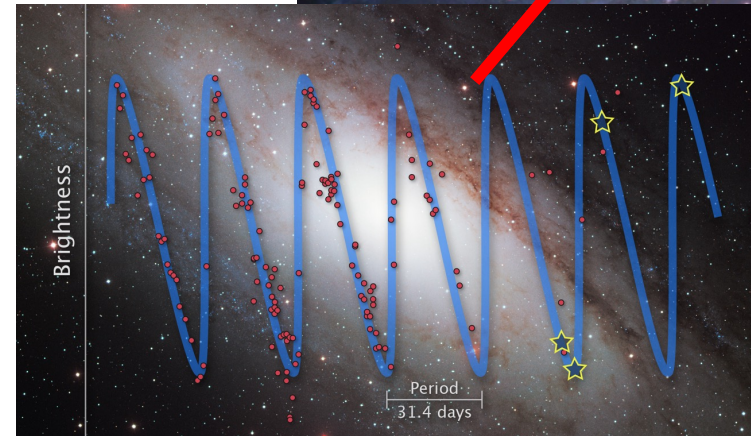
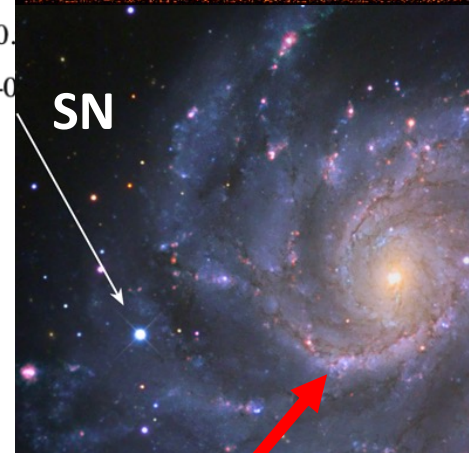
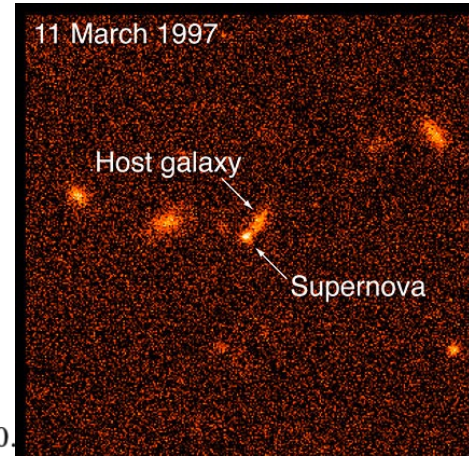
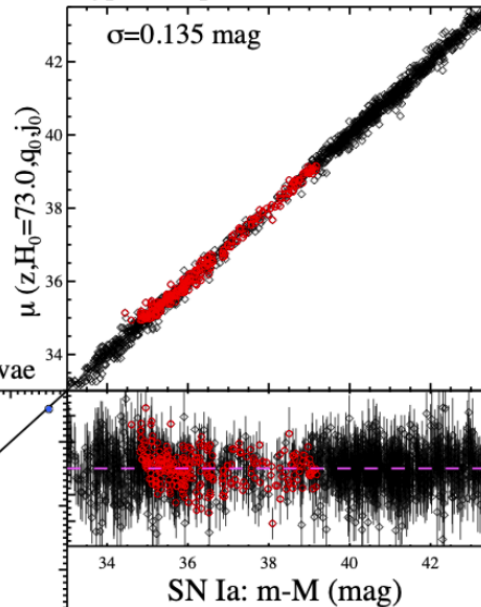
Geometry → Cepheids

Cepheids → Type Ia Supernovae



Leavitt law:
 $\log P \propto L$

Type Ia Supernovae → redshift(z)



Classical Cepheids are great for this!

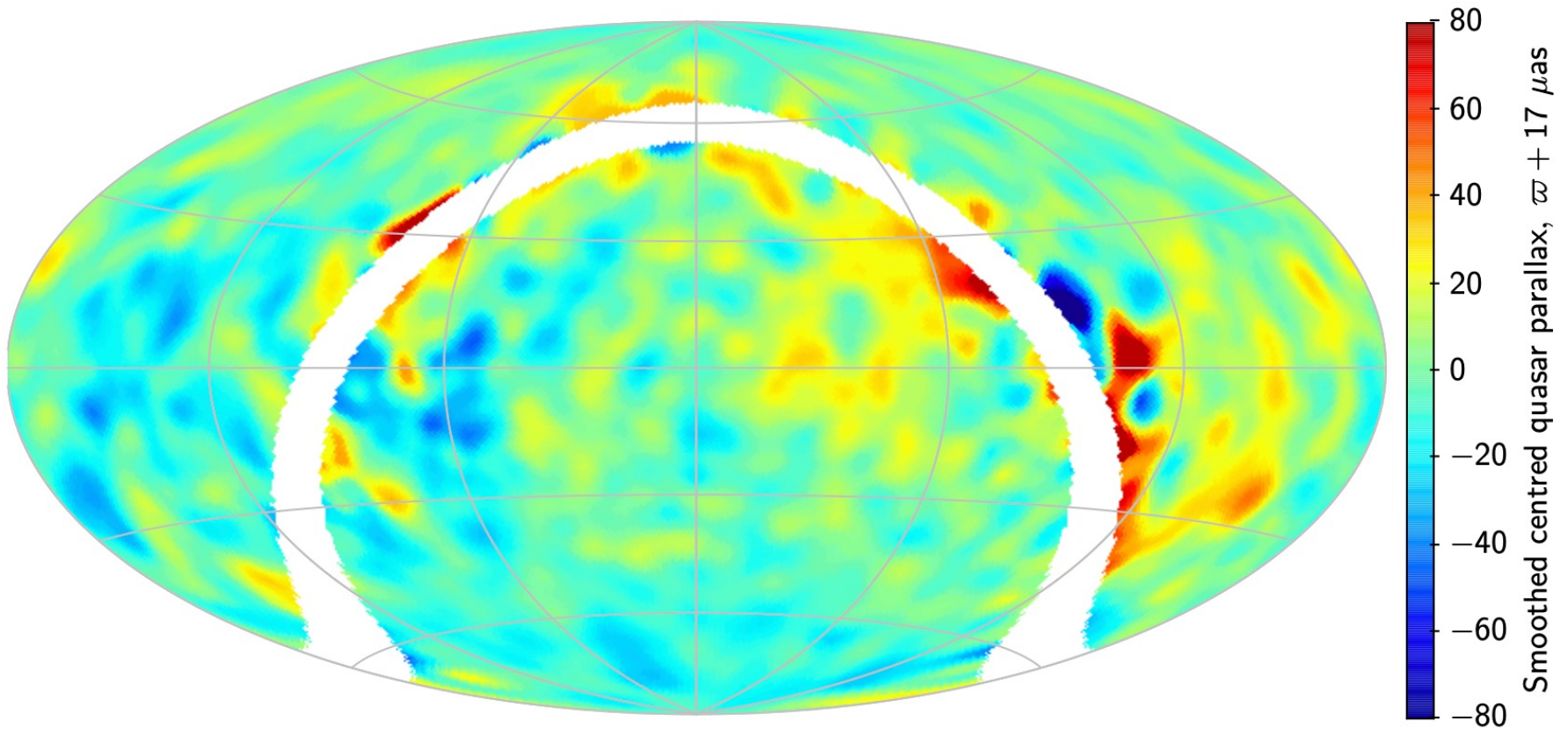
- **Each Cepheid a standard candle**
- **Characteristic variability** identifies Cepheids
- observed PL-sequences
 - **Minimal contamination** by non-Cepheids
 - Observed **scatter constrains uncertainties**
- **Well understood by stellar evolution**
(e.g. RIA+2016, A&A **591**, A8)

Cepheids improved a lot since 2016

- Improved geometric anchors
- Doubled SN-hosts with identified Cepheids
- Homogeneous HST photometry
- Metallicity effect measured by high-res spectroscopy
- Systematics checked extensively
- **Gaia parallaxes : gold standard**
- **Precision & systematics improved : tension grows**

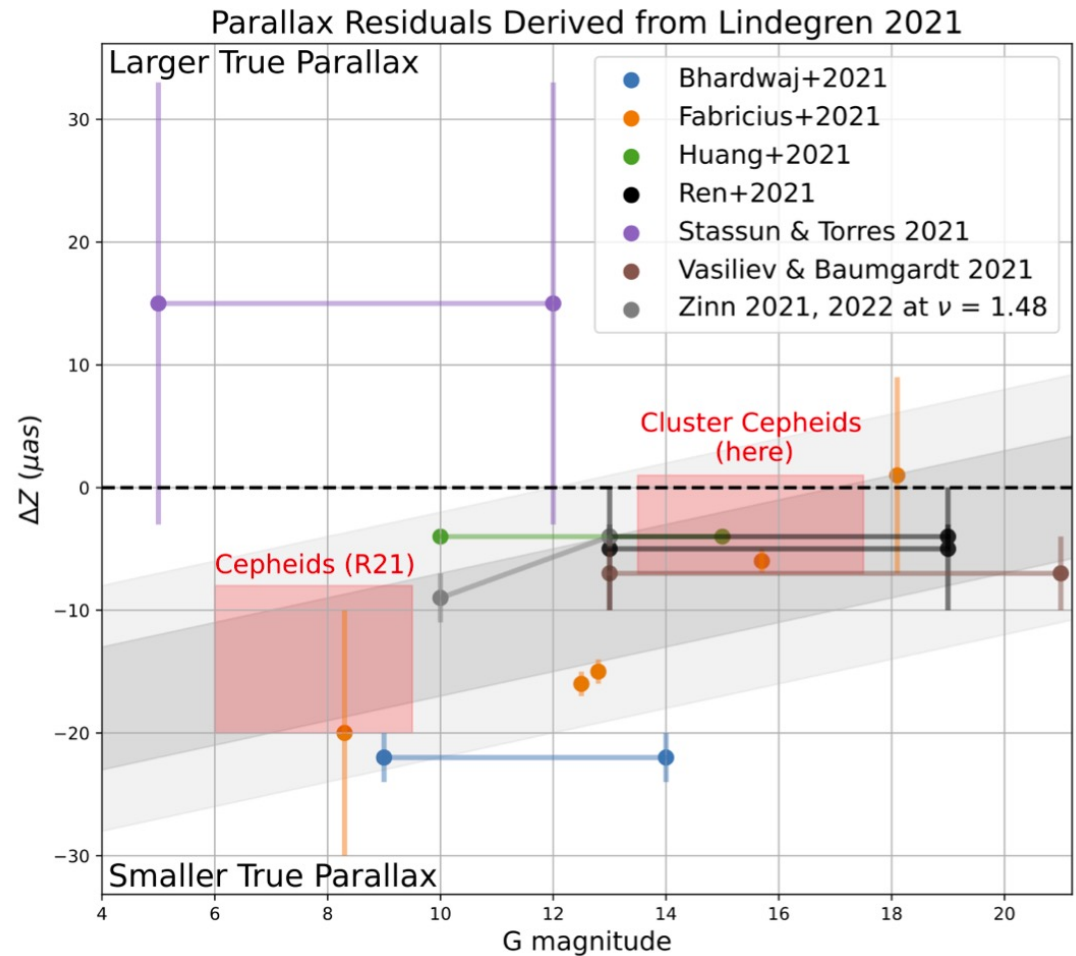
cf. Louise Breuval's talk
on Saturday @ 10:20

Gaia parallax systematics by magnitude, color, position

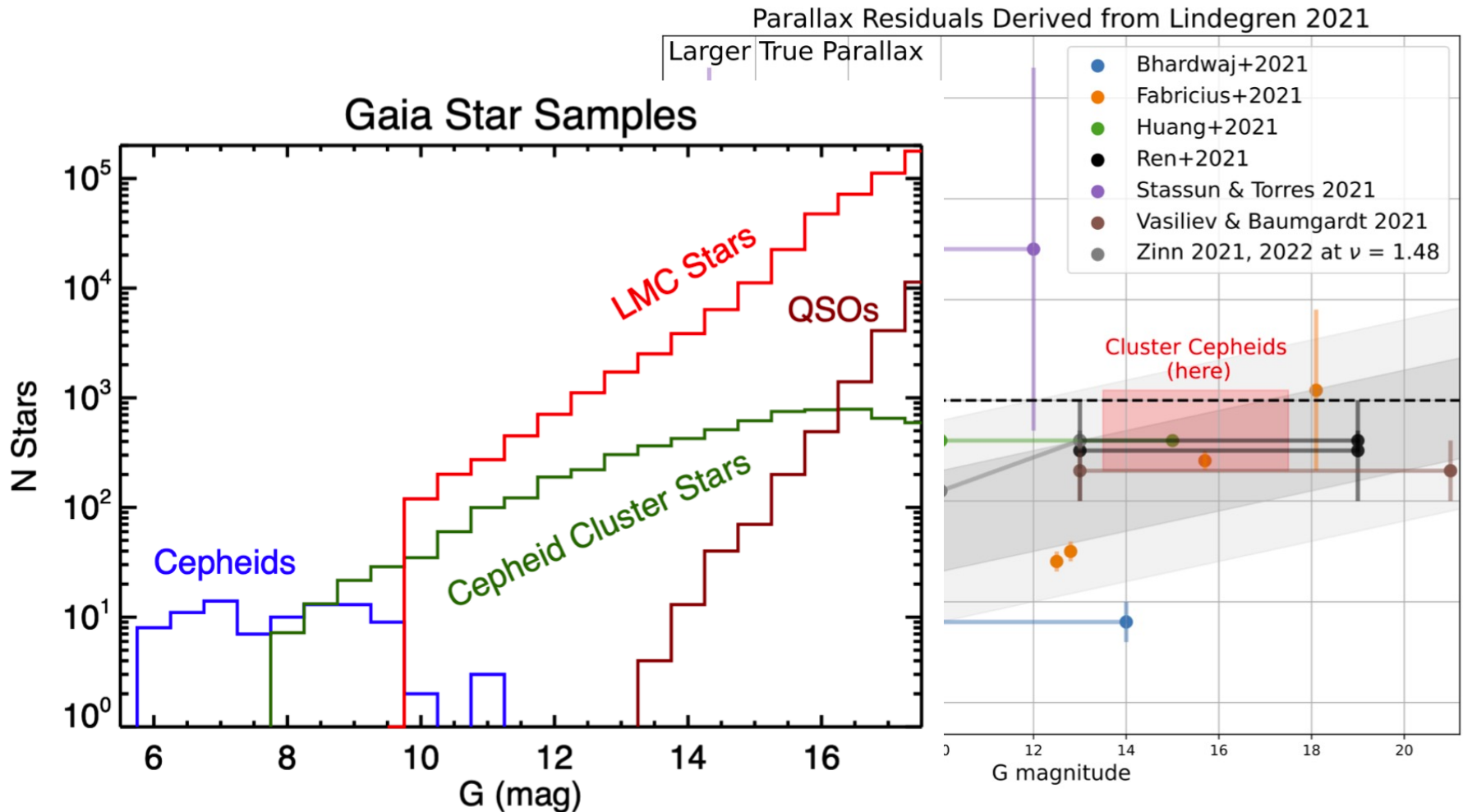


Lindegren+2021, A&A 649, A4

Systematics correction adequate at magnitudes where it is constrained



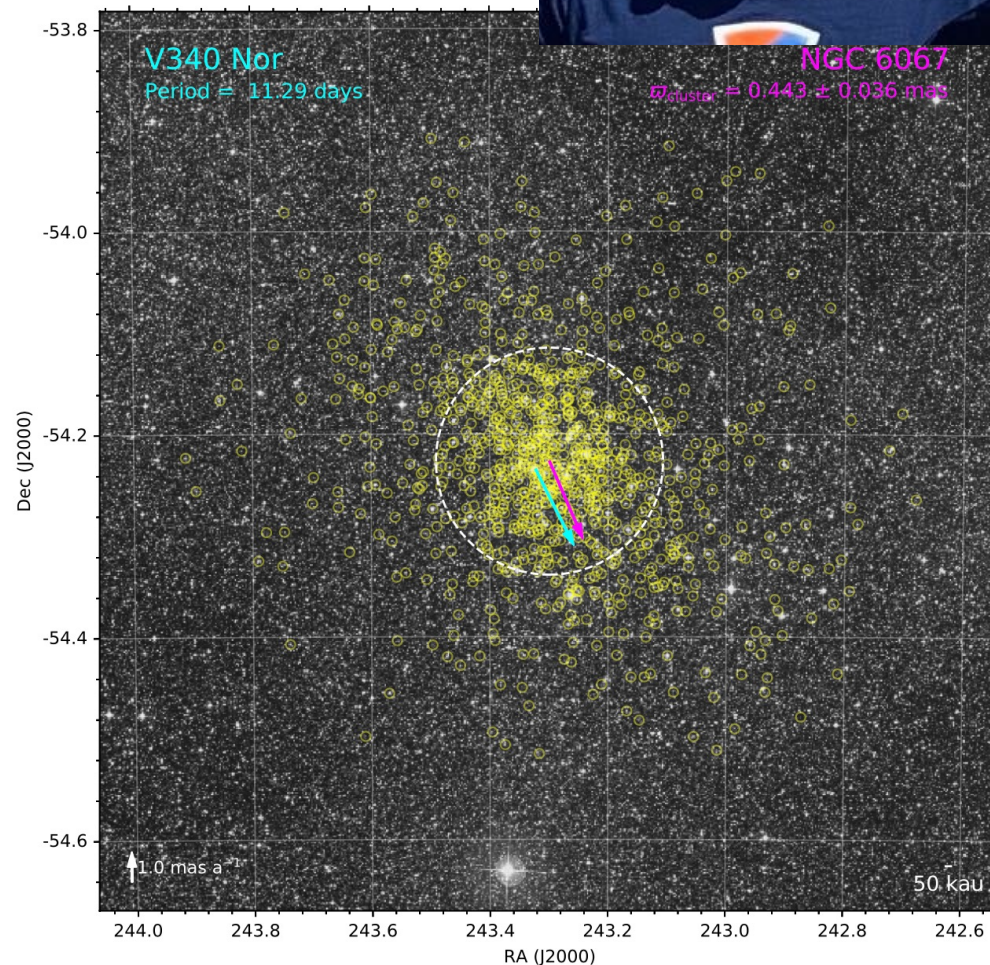
Systematics correction adequate at magnitudes where it is constrained



New census of Cluster Cepheids establishes Gold sample of 34

2208.09403 : Cruz Reyes & RIA

- **Details: Mauricio Cruz Reyes, Friday 16:30 PS A**
- New approach: **find open clusters near Cepheids** using Gaia DR3 data
- Typical total uncertainty : $\sim 7 \mu\text{as}$

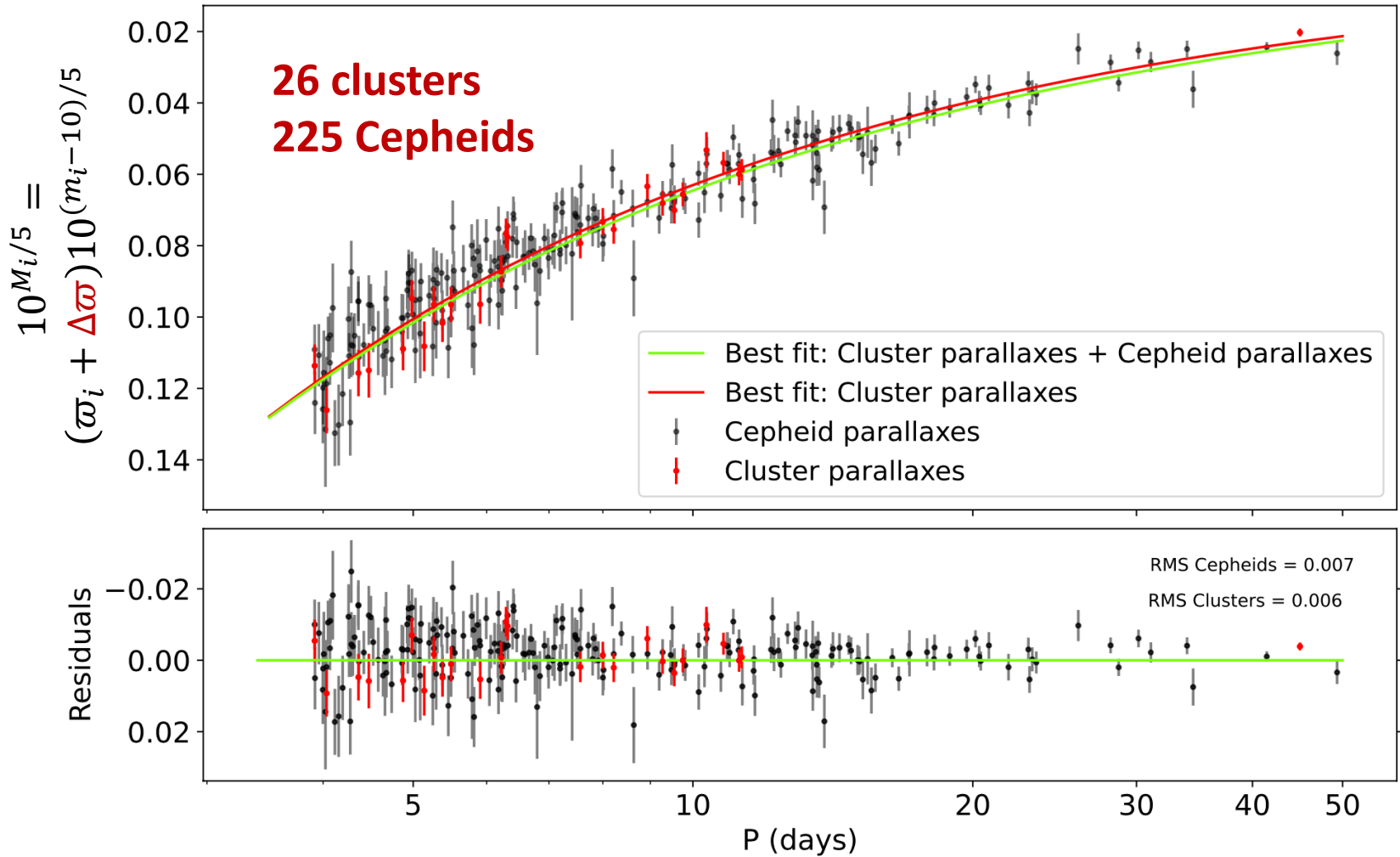


Gaia-only Cepheid luminosity calibration (no HST!)

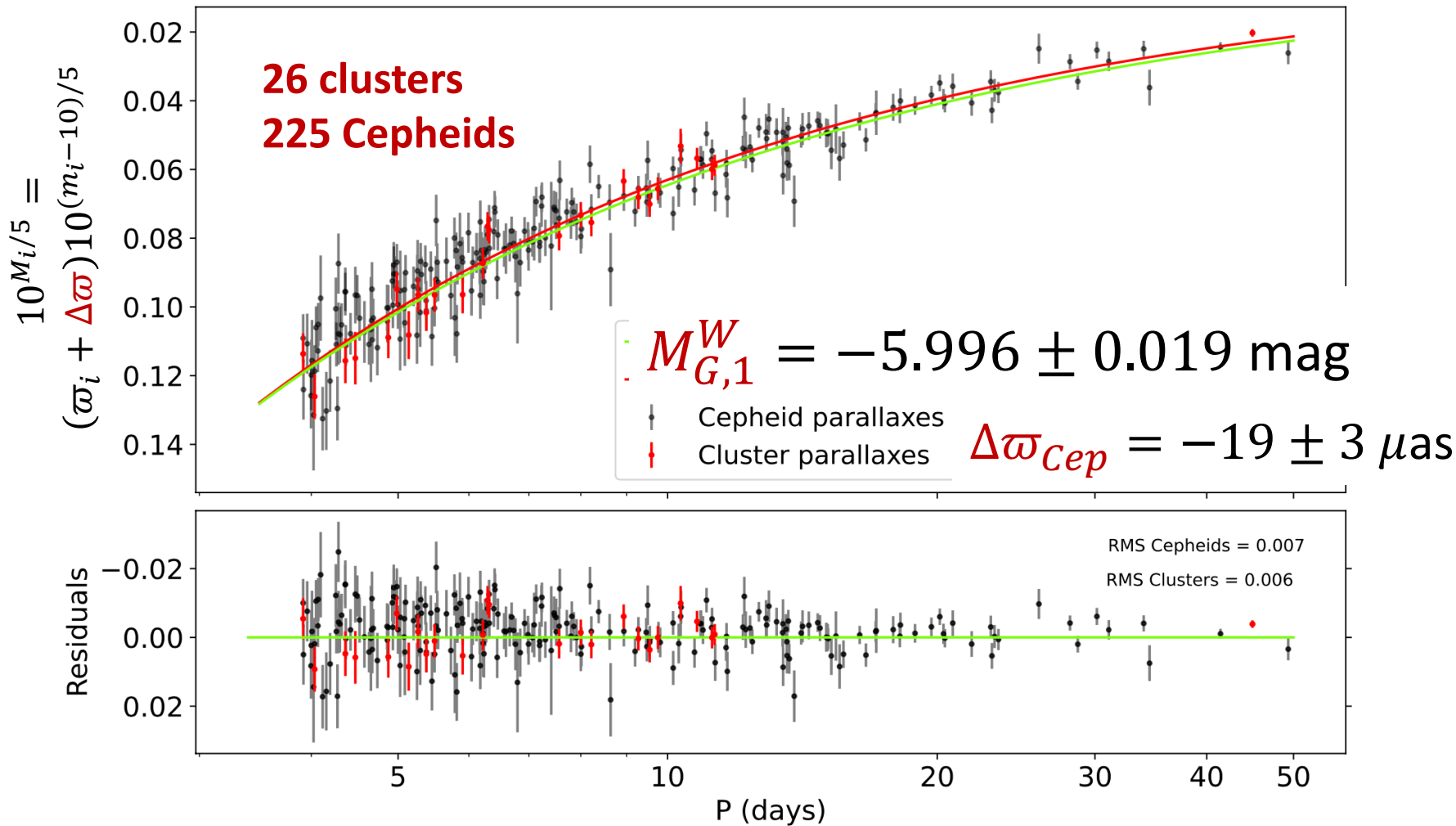
2208.09403 :
Cruz Reyes & RIA

- $M_i^W = \alpha (\log P - 1) + M_1^W + \gamma \left[\frac{\text{Fe}}{\text{H}} \right]$
- $10^{M_i/5} = (\varpi_i + \Delta\varpi) 10^{(m_i - 10)/5}$
- $\Delta\varpi_{Cl} = 0, \Delta\varpi_{Cep} \neq 0$
(Lindegren+2021, Flynn+2022, Maiz Apellaniz 2022)
- L21 corrections applied to all parallaxes
- New Cepheid photometry from Gaia DR3 SOS (Ripepi+22)
- **Combined 3-param fit to 26 cluster and 225 field Cepheids**

0.9% calibration of Cepheid luminosity



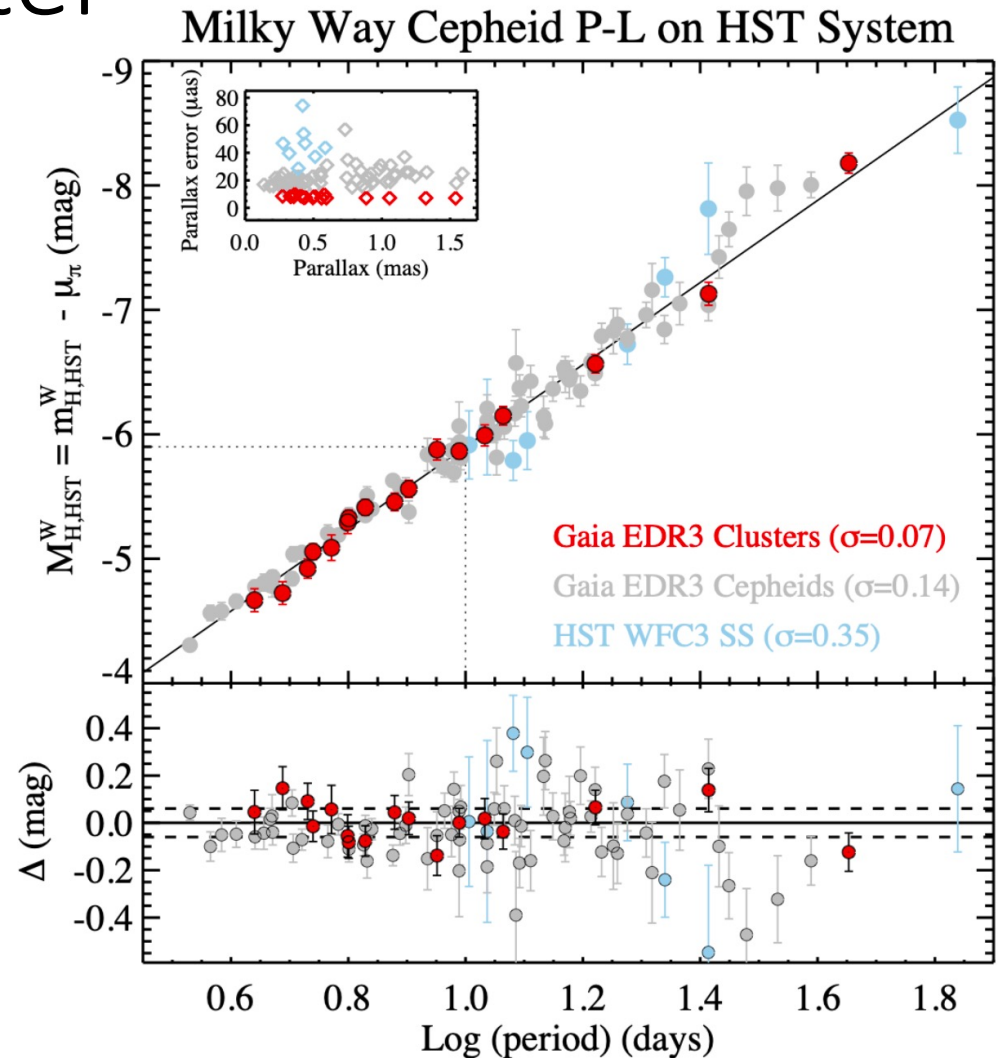
0.9% calibration of Cepheid luminosity



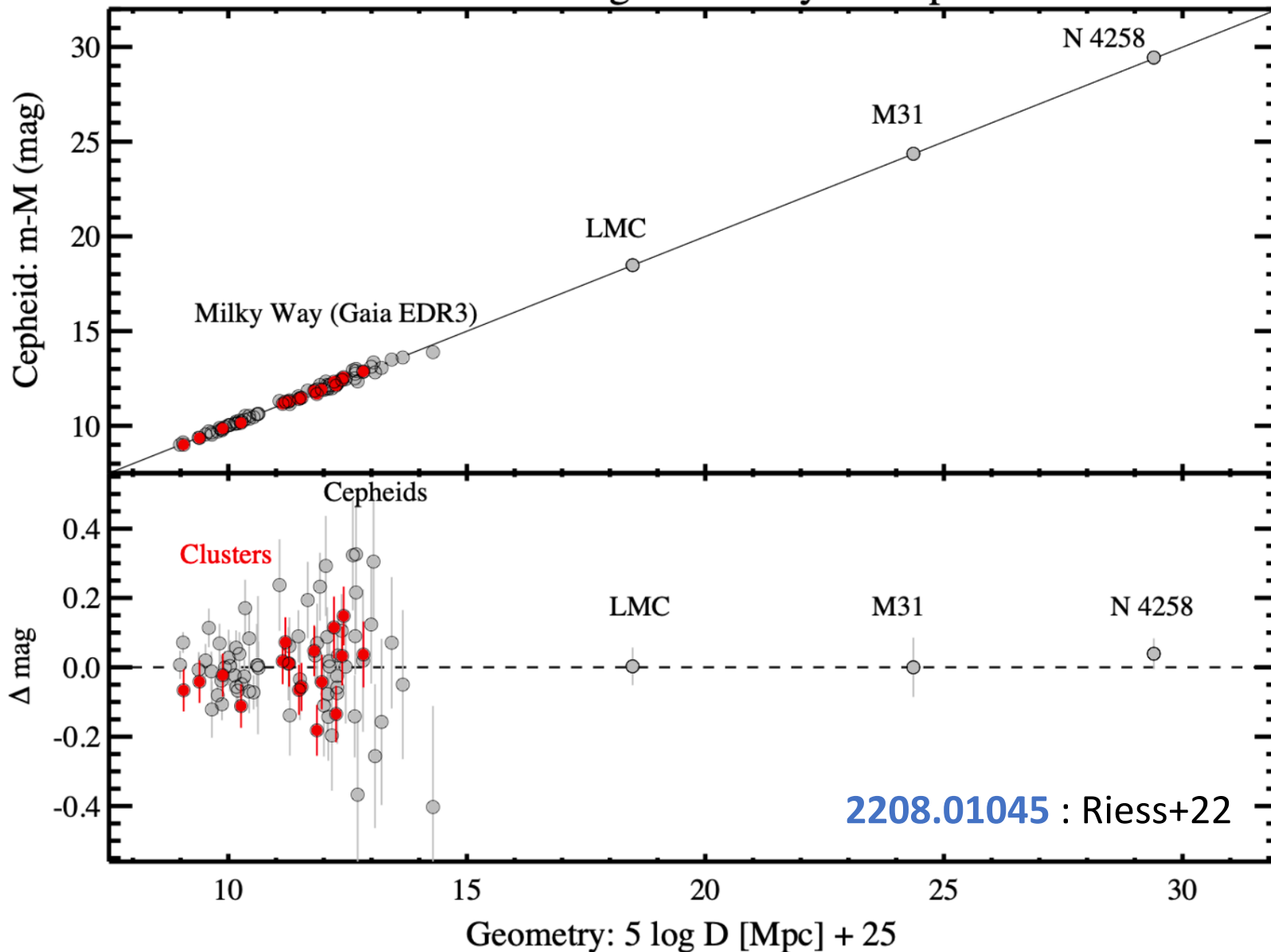
New HST photometry: LMC-like LL scatter

2208.01045 : Riess+22

- 17 cluster Cepheids with 3-band HST photometry
- 3x better parallax errors = 9x the weight for LL calibration
- 0.06 – 0.045 mag scatter constrains parallax & reddening systematics
- 0.9% calibration of $M_{H,1}^W$



First rung: Geometry \rightarrow Cepheids



Constraining $M_{H,1}^W$ for SHOES H_0 analysis

- $\chi^2 = \left(\varpi_{EDR3,i} - \varpi_{phot,i} + \Delta\varpi_{cl} \right)^2 \sigma_i^{-2}$

- $\varpi_{phot,i} = 10^{-0.2(\mu_{o,i}-10)}$

- $\mu_{o,i} = m_{i,H}^W - \left(M_{H,1}^W + \alpha (\log P - 1) + \gamma \Delta \left[\frac{O}{H} \right]_i \right)$

- σ_i combines photometric & astrometric uncertainties, PLR intrinsic width, uncertainty for offset if needed
- Free parameters: $M_{H,1}^W$ and (optionally) $\Delta\varpi_{cl}$
- α, γ fixed to SHOES baseline values : use $M_{H,1}^W$ as constraint for SHOES H_0

$H_0 = 73.15 \pm 0.97 \text{ km s}^{-1} \text{ Mpc}^{-1}$
differs by **5.3 σ** from *Planck*+ Λ CDM

- 5-7% improvement on H_0 from cluster parallaxes
- $M_{H,1}^W$ and $\Delta\varpi_{Cl}$ fully consistent MCR & RIA (2022)
- MW alone : $H_0 = 73.3 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Fit ^a	N	$M_{H,1}^W$ [mag]	zp [μas]	b_W [mag/dex]	Z_W	σ_{IS} [mag]	H_0 CC only [$\text{km s}^{-1} \text{ Mpc}^{-1}$]	H_0 all anchors
2, G+S	17	-5.902 ± 0.026	-3 ± 4	-3.299 ± 0.015^b	-0.217 ± 0.046^b	0.060	72.9 ± 1.3	73.04 ± 0.99
2, G	14	-5.907 ± 0.024	-4 ± 4	-3.299 ± 0.015^b	-0.217 ± 0.046^b	0.047	72.7 ± 1.3	72.98 ± 0.99
2, G+S ^c	17	-5.893 ± 0.018	0^d	-3.36 ± 0.07	-0.217 ± 0.046^b	0.060	—	—
2, G ^c	14	-5.907 ± 0.018	0^d	-3.44 ± 0.08	-0.217 ± 0.046^b	0.047	—	—
1, G+S	17	-5.890 ± 0.018	0^d	-3.299 ± 0.015^b	-0.217 ± 0.046^b	0.060	73.3 ± 1.1	73.16 ± 0.97
1, G	14	-5.892 ± 0.017	0^d	-3.299 ± 0.015^b	-0.217 ± 0.045^b	0.047	73.2 ± 1.1	73.14 ± 0.97

$H_0 = 73.15 \pm 0.97 \text{ km s}^{-1} \text{ Mpc}^{-1}$
differs by **5.3 σ** from *Planck*+ Λ CDM

MCR & RIA 22, fixed α, γ :

$$M_{H,1}^W = -5.915 \pm 0.017 \text{ mag}$$

$$\Delta\varpi_{cep} = -13 \pm 5 \mu\text{as}$$

- 5-7% improvement on H_0 from cluster parallaxes
- $M_{H,1}^W$ and $\Delta\varpi_{cl}$ fully consistent MCR & RIA (2022)
- MW alone : $H_0 = 73.3 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Fit ^a	N	$M_{H,1}^W$ [mag]	zp [μas]	b_W [mag/dex]	Z_W	σ_{IS} [mag]	H_0 CC only [$\text{km s}^{-1} \text{ Mpc}^{-1}$]	H_0 all anchors
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Conclusions

[2208.01045](#) : Riess et al., ApJ accepted

[2208.09403](#) : Cruz Reyes & Anderson, A&A submitted

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- New cluster parallaxes *combine statistical precision* (more stars) *and accuracy* (systematics adequately corrected by Lindegren+2021)
- Cepheid luminosity scale calibrated to 0.9%, *with or without HST*
- Consistent $\Delta\varpi_{Cep}$ for both (Gaia only, Gaia+HST)
- *Two independently determined sets of Gaia EDR3 cluster parallaxes yield close agreement for $M_{H,1}^W$ and $\Delta\varpi_{Cep}$*
- Tight LL scatter severely limits margin for parallax uncertainties
- New HST photometry plus cluster parallaxes improves H_0 by 5-7%
- $H_0 = 73.15 \pm 0.97 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is 5.3σ from Planck+ Λ CDM
- **Exciting times: the tension rises as systematics improve**