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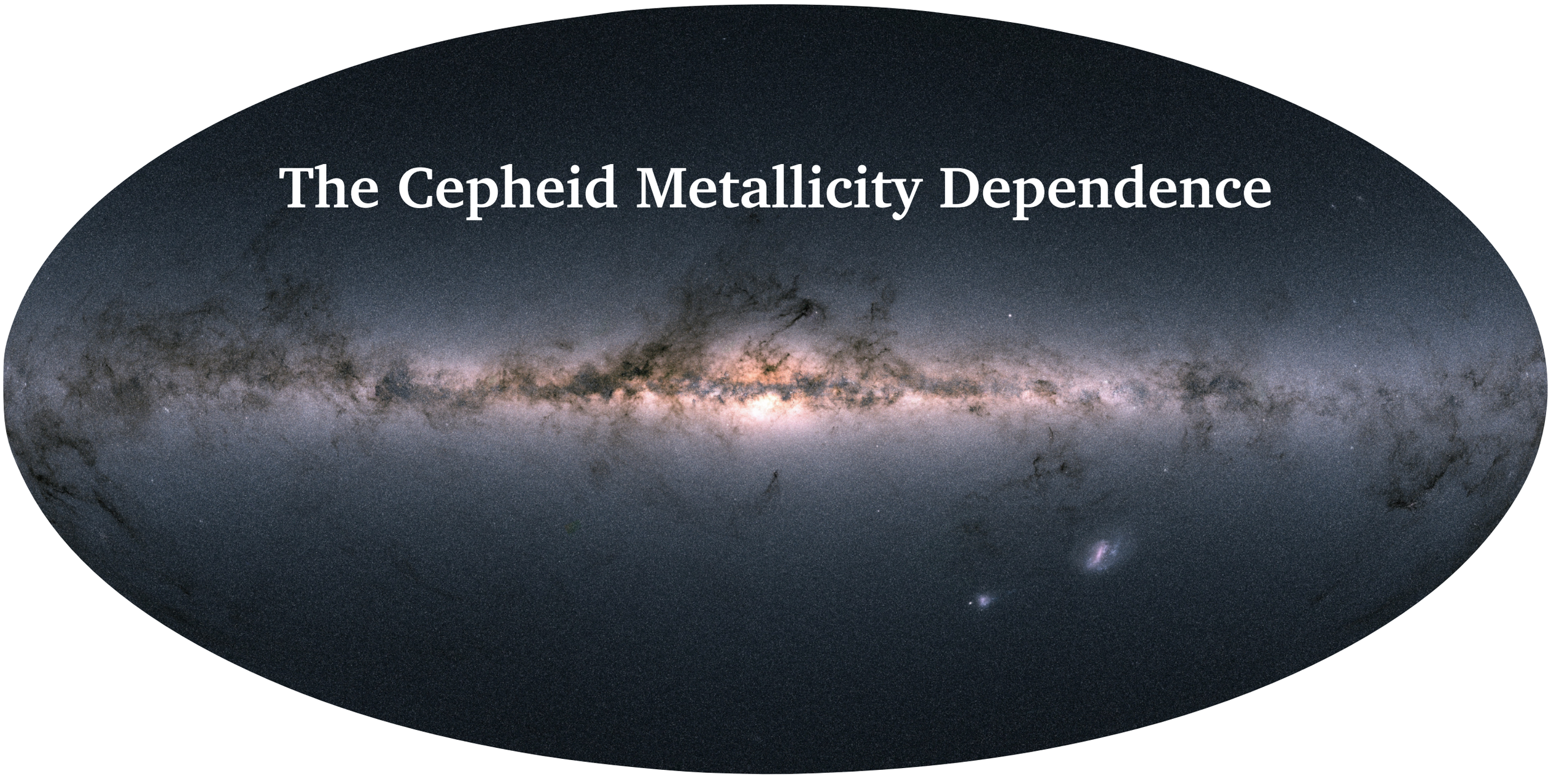
The Cepheid Metallicity Dependence



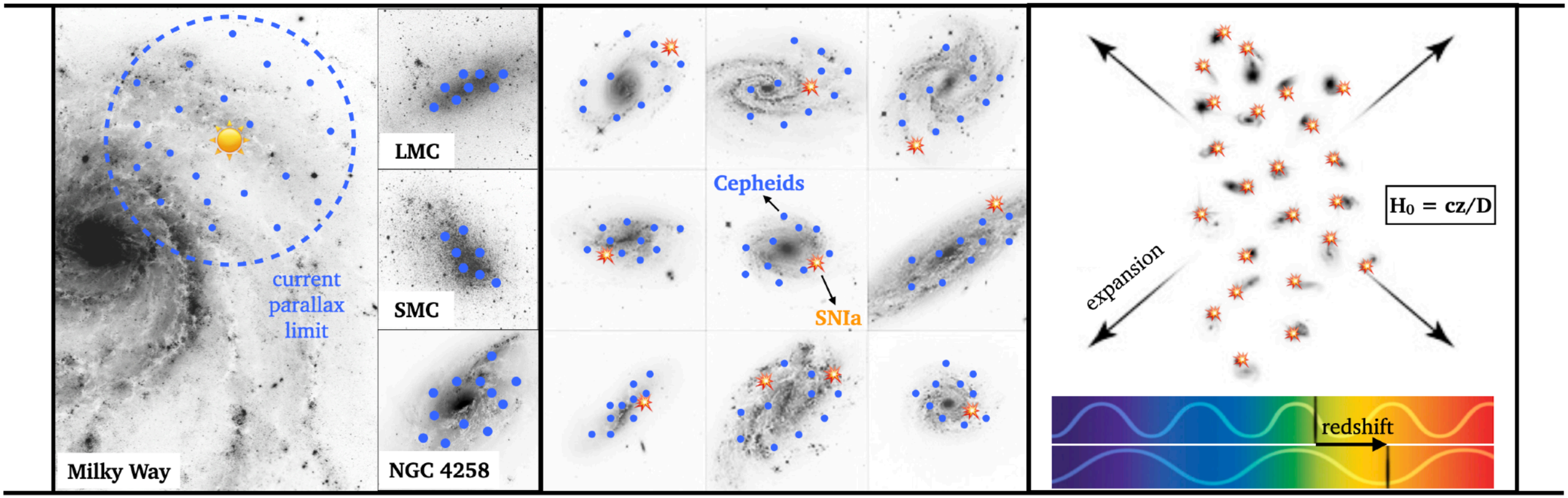
CosmoVerse School – Sofia – 25 May 2026

Are we really observing the same objects everywhere?

1st rung
Geometry → Cepheids in 4 anchor galaxies

2nd rung
Cepheids → 42 SNIa in 37 host galaxies

3rd rung
277 SNIa → redshifts



Local Group: distance < 10 Mpc

10 Mpc < distance < 60 Mpc

0.02 < redshift (z) < 0.20 (Hubble Flow)

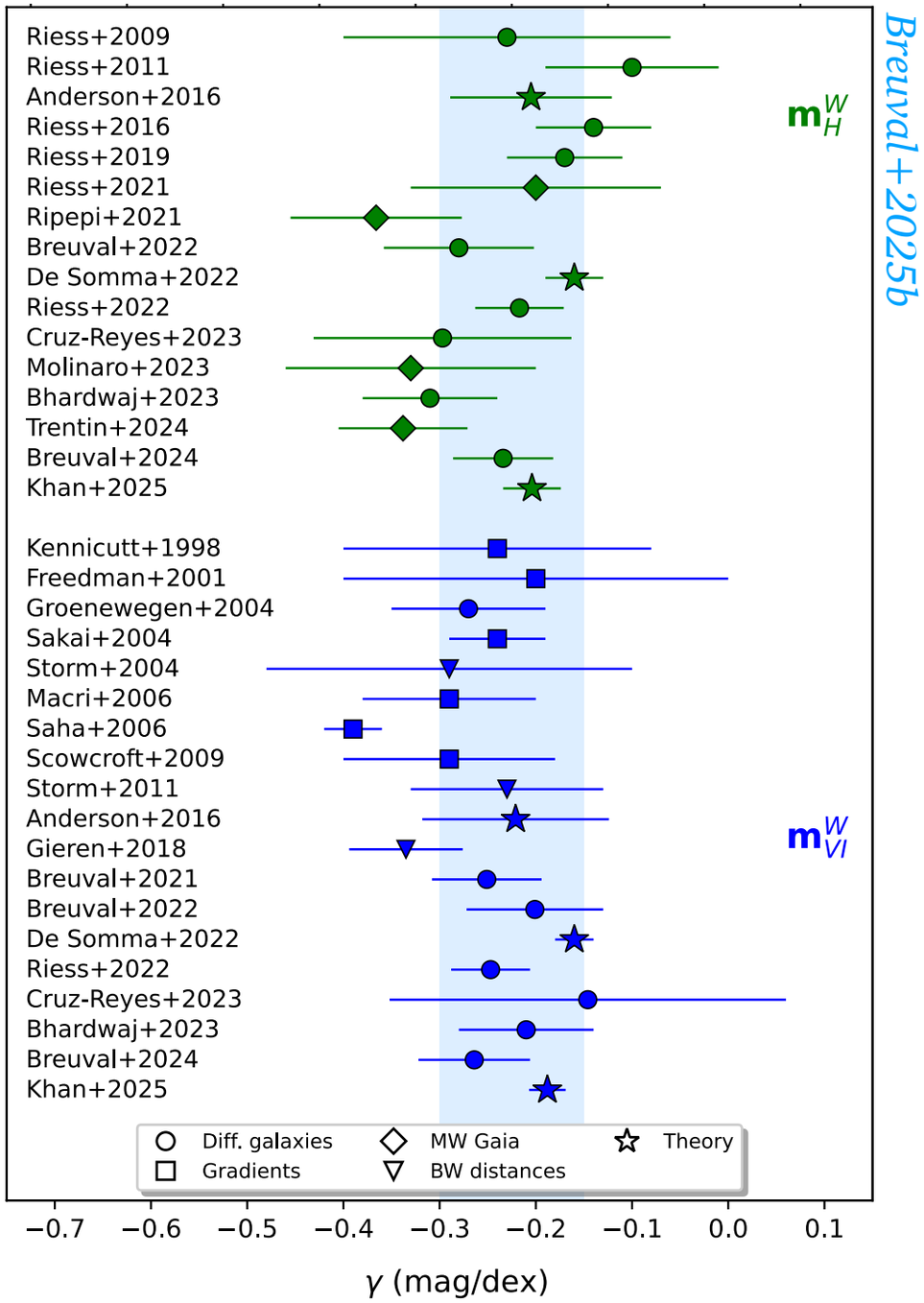
The Cepheid Metallicity Dependence γ

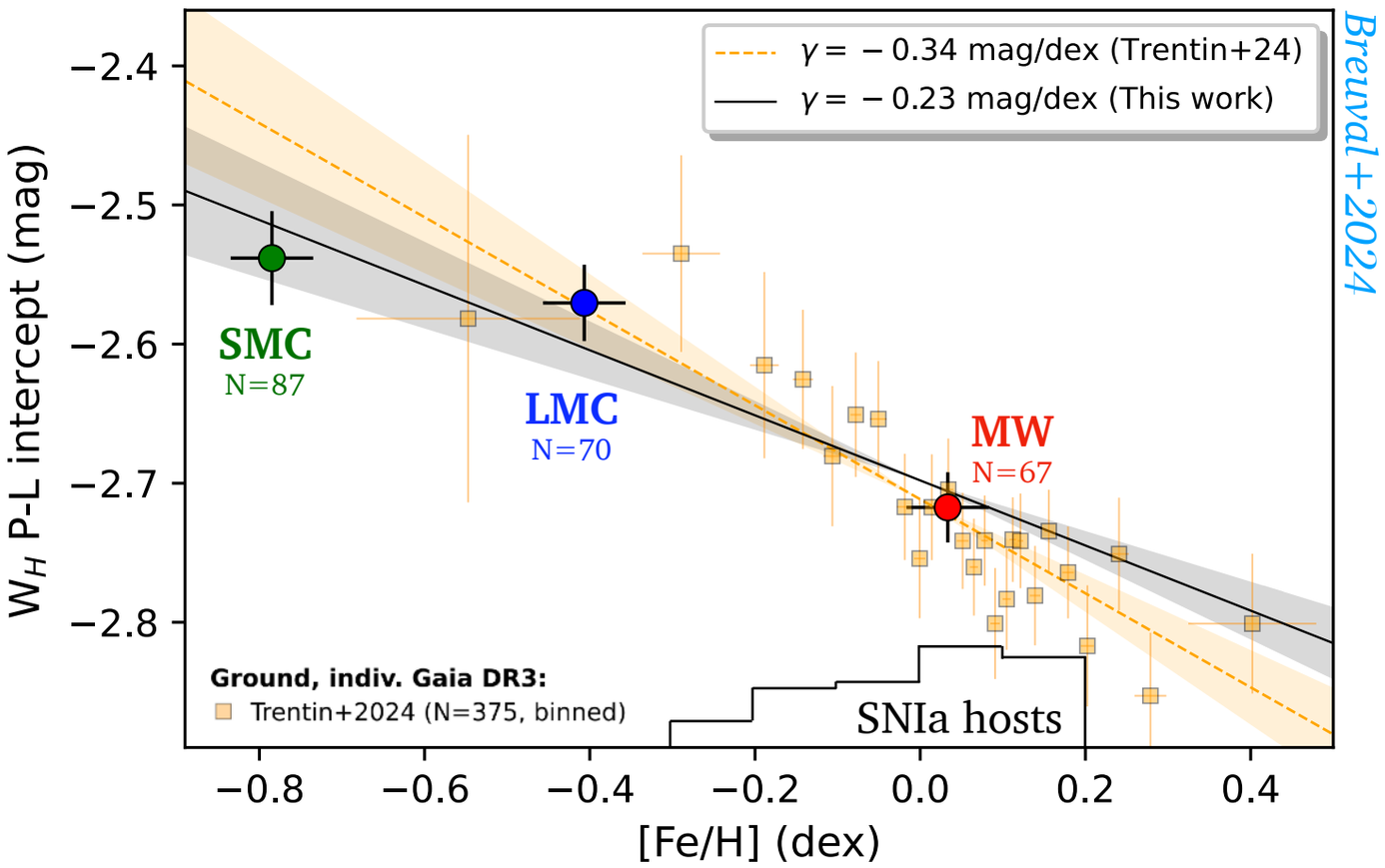
- Metal-rich Cepheids are brighter than metal-poor ones.

$$\mathbf{Mag = a\ logP + b + \gamma\ [Fe/H]}$$

$\gamma > 0$ → metal-rich Cepheids are fainter
$\gamma < 0$ → metal-rich Cepheids are brighter

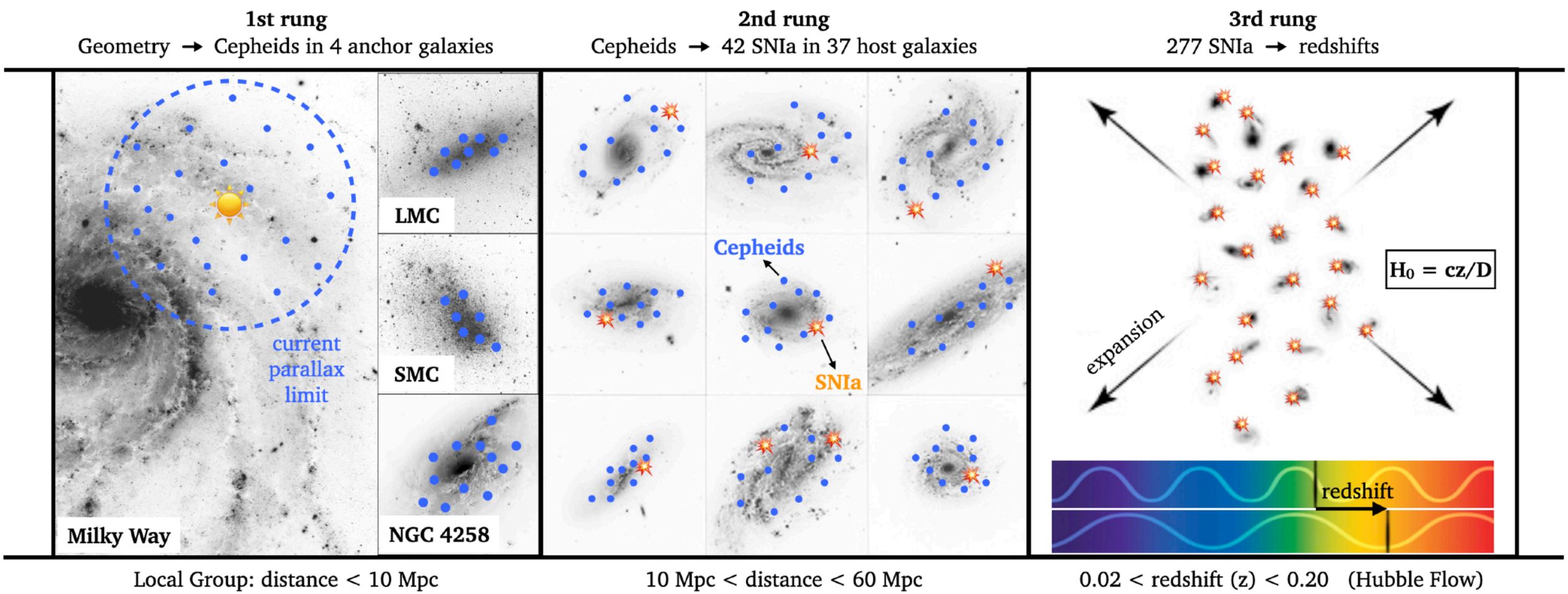
- Two main methods to measure γ empirically:
  - using metallicity gradient within a galaxy (MW, M33)
  - comparing P-L intercepts between different galaxies





Impact of γ for H_0 is <0.8 km/s/Mpc because SNIa hosts and Cepheid anchors share similar metallicities

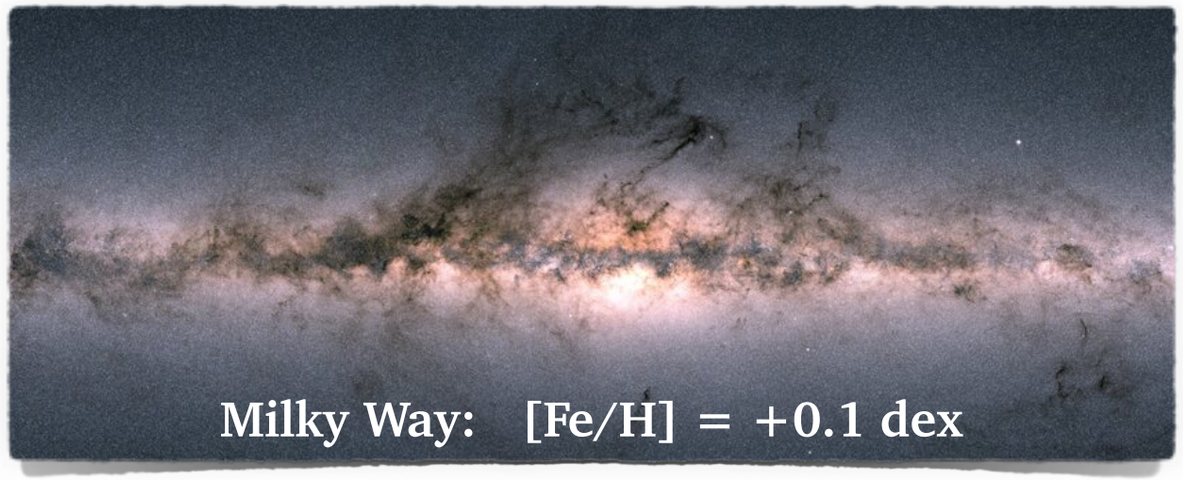
Why should we care about the metallicity dependence?



- **In the distance ladder, for H_0:** make Cepheids in anchor galaxies **<u>consistent</u>** (LMC and SMC more metal-poor than MW and NGC 4258)

- **For distance measurements**: the PL relation in the LMC is often used as reference for measuring distances

Importance of the metallicity correction



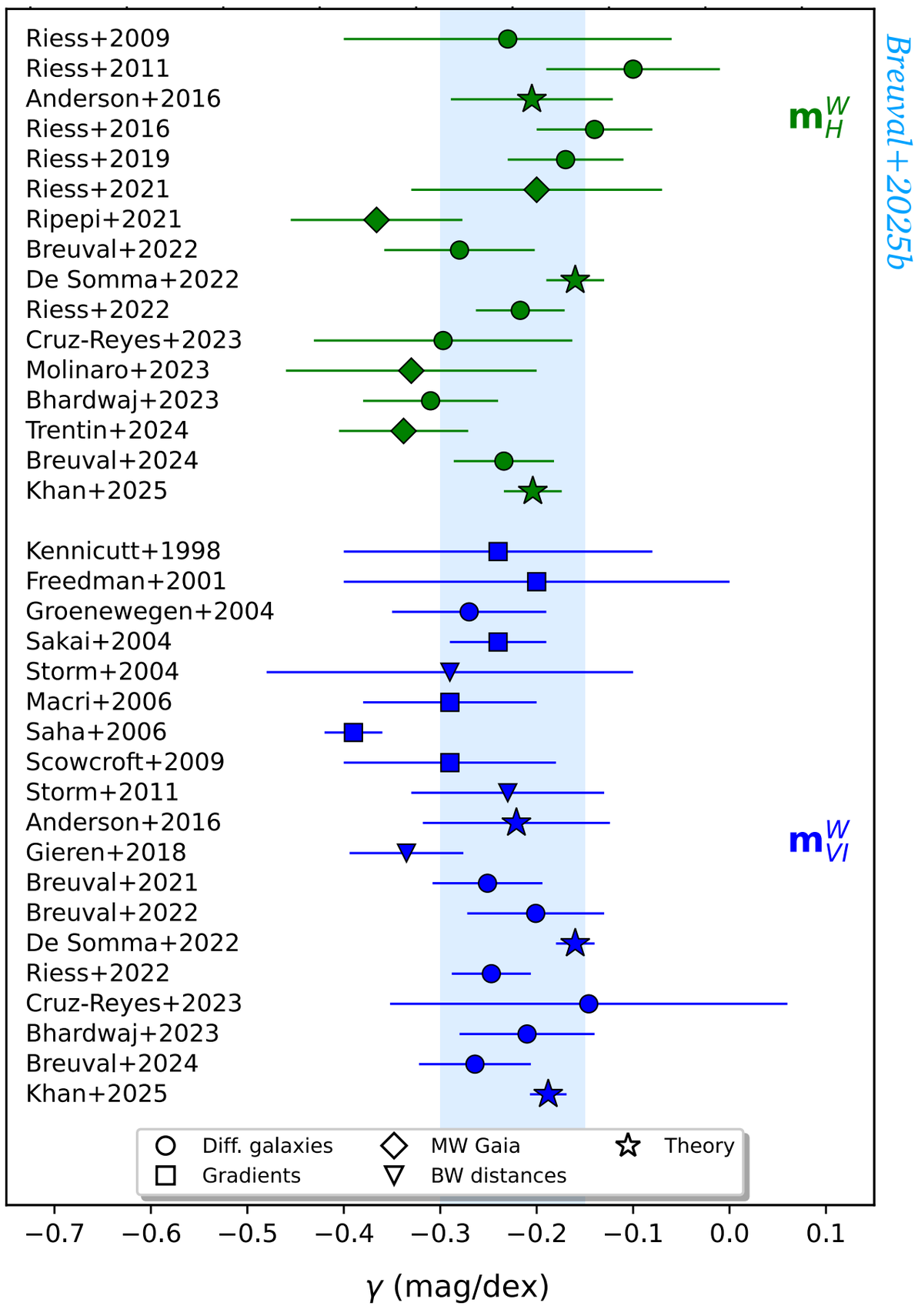
Measuring the distance to M33 with respect to:

Milky Way: **d = 880 kpc**
LMC: **d = 850 kpc** ⚠

Prediction of the metallicity effect from models

	Nonlinear convecting models	**Geneva linear models including rotation**
	Marconi et al. (2005) *Bono et al. (2008)*	*Anderson et al. (2016)* *Khan et al. (2025)*
Individual filters ***H, V, I***	$\gamma > 0$	$\gamma < 0$
	De Somma et al. (2022)	*Anderson et al. (2016)* *Khan et al. (2025)*
Wesenheit indices W_H, W_{VI}, W_G	$\gamma < 0$	$\gamma < 0$

Empirical measurements of the metallicity effect



- Full list of references for model predictions and empirical measurements in Breuval et al. (2022, 2025b).

- Most values are between **-0.15** and **-0.30** mag/dex, using various methods:

  - comparing galaxies where Cepheids have different abundances (e.g. MW, LMC, SMC)

  - using metallicity gradients in a spiral galaxy (e.g. NGC 4258, M101, M33)

  - spread of Cepheid metallicities in MW with Gaia parallaxes

Past measurements of the metallicity effect and their limits

[Wielgorski et al. (2017)](#)

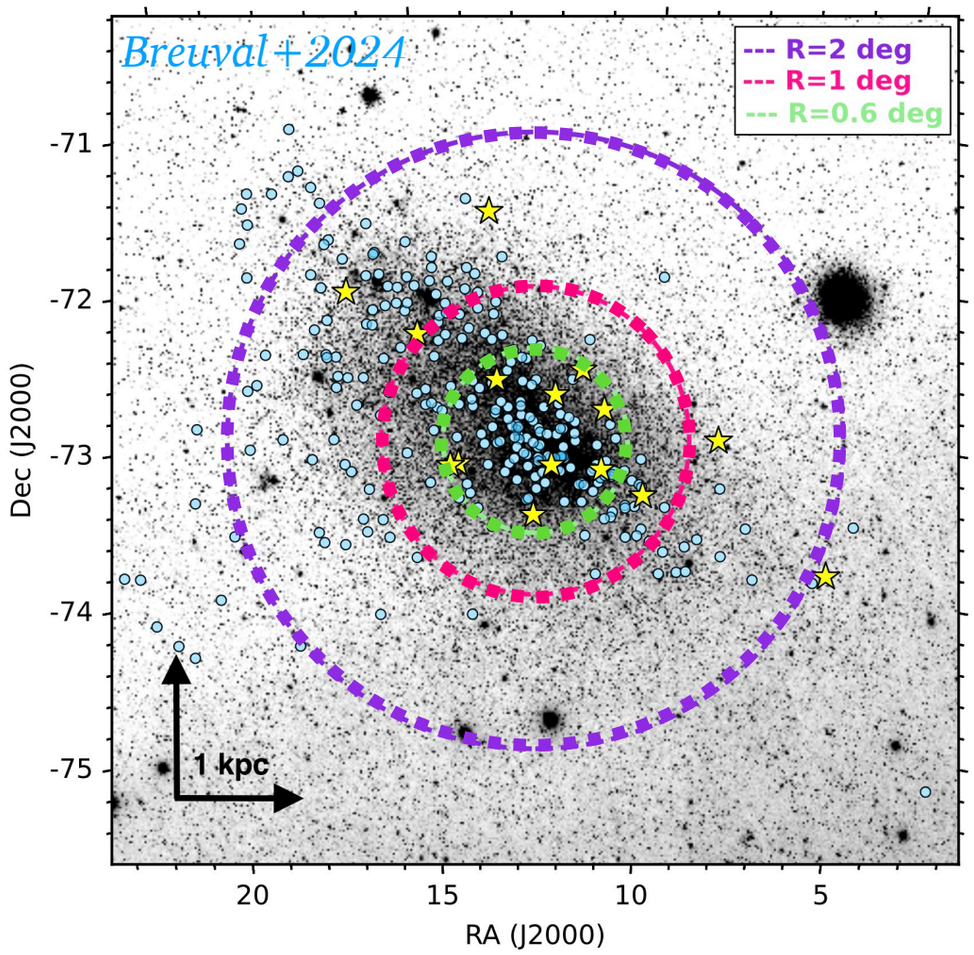
$\gamma = 0$

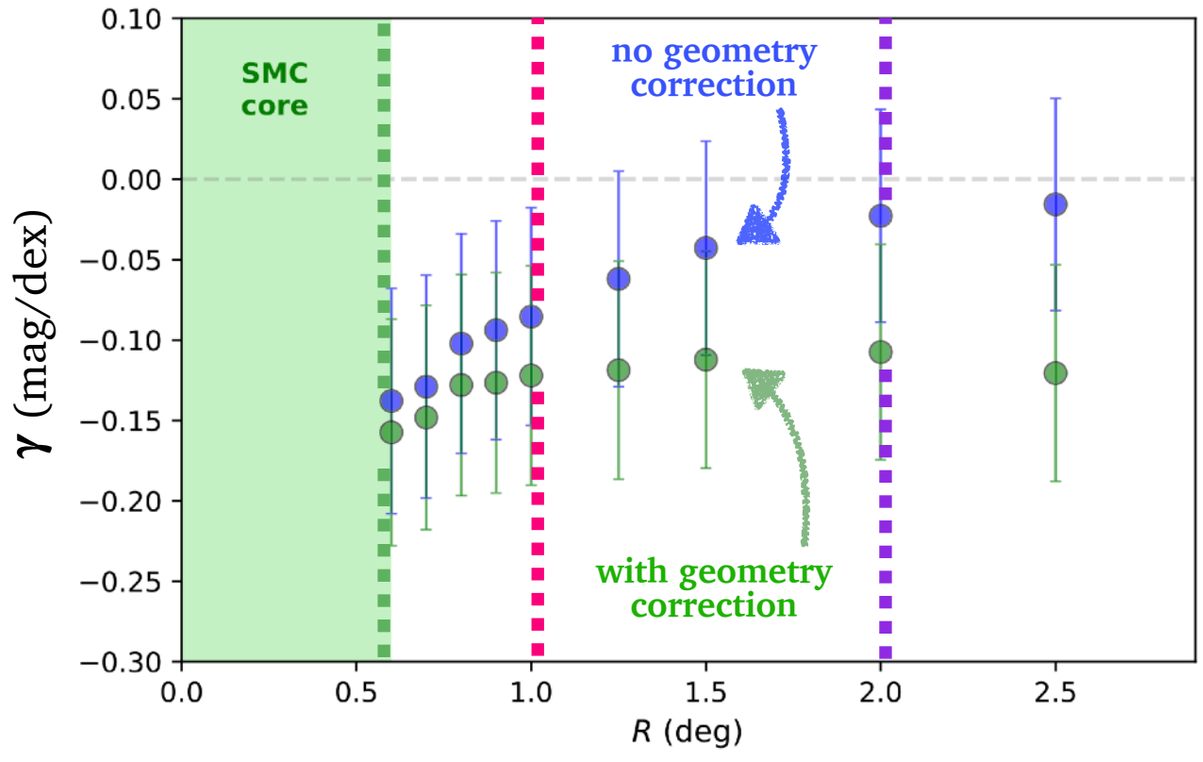
- **Sample**: LMC + SMC Cepheids
- **Method**: compare PL intercepts with fixed slope.
- **Issues**:

- limited metallicity range & mean metallicities (LMC = -0.4 dex, SMC = -0.75 dex)

- **depth** of the Magellanic Clouds introduces **dispersion** and biases the metallicity effect (see discussion in Breuval et al. 2022)

⚠ need to use SMC core-region





Past measurements of the metallicity effect and their limits

$\gamma < 0$ and $\gamma > 0$
(depending on filter)

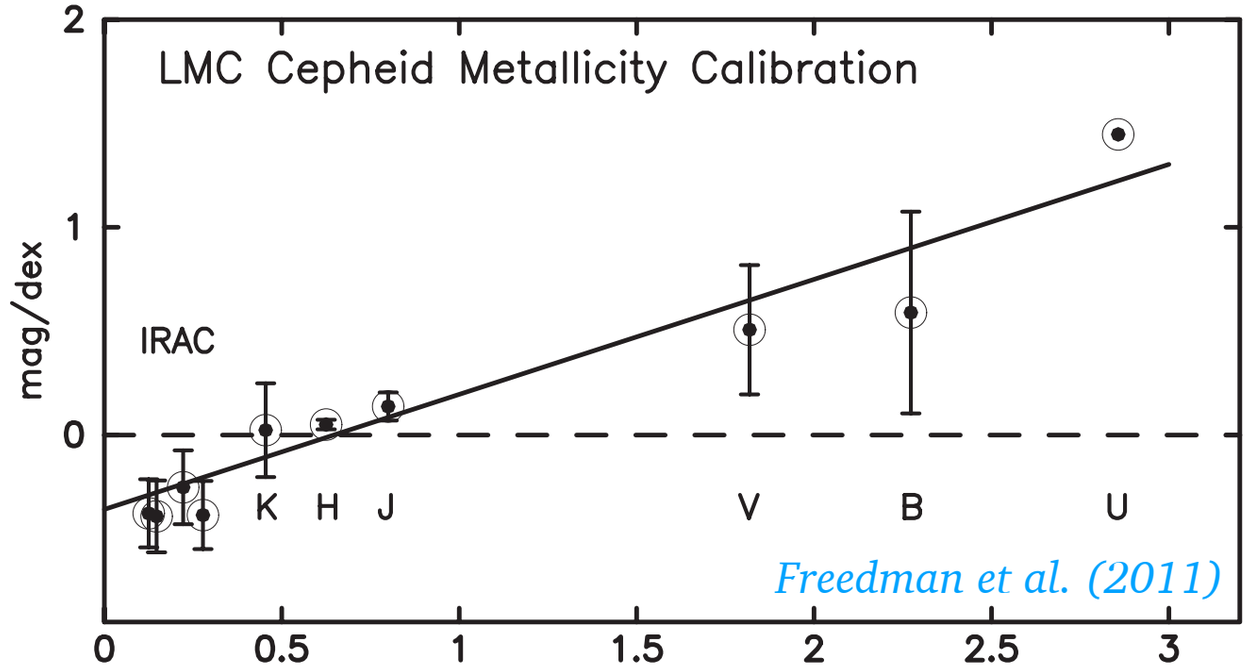
[Freedman et al. (2011)](#)

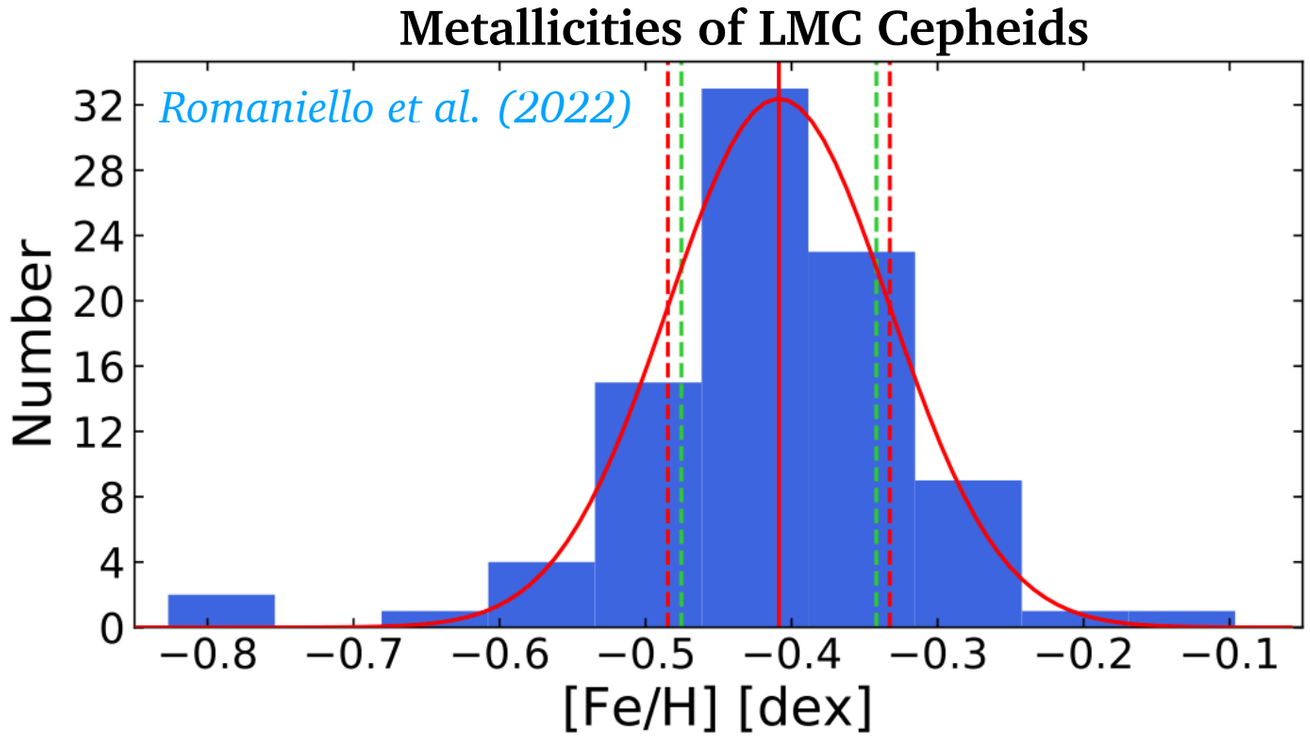
- **Sample**: LMC Cepheids
- **Method**: PL residuals, individual metallicities for each LMC Cepheid
- **Issues**:
  - LMC Cepheid metallicity: narrow distribution (Romaniello et al. 2022)

    Δ [Fe/H] $\sim$ 0.3 dex

  - error bars likely underestimated

⛔ **Should not be done** ⚠️



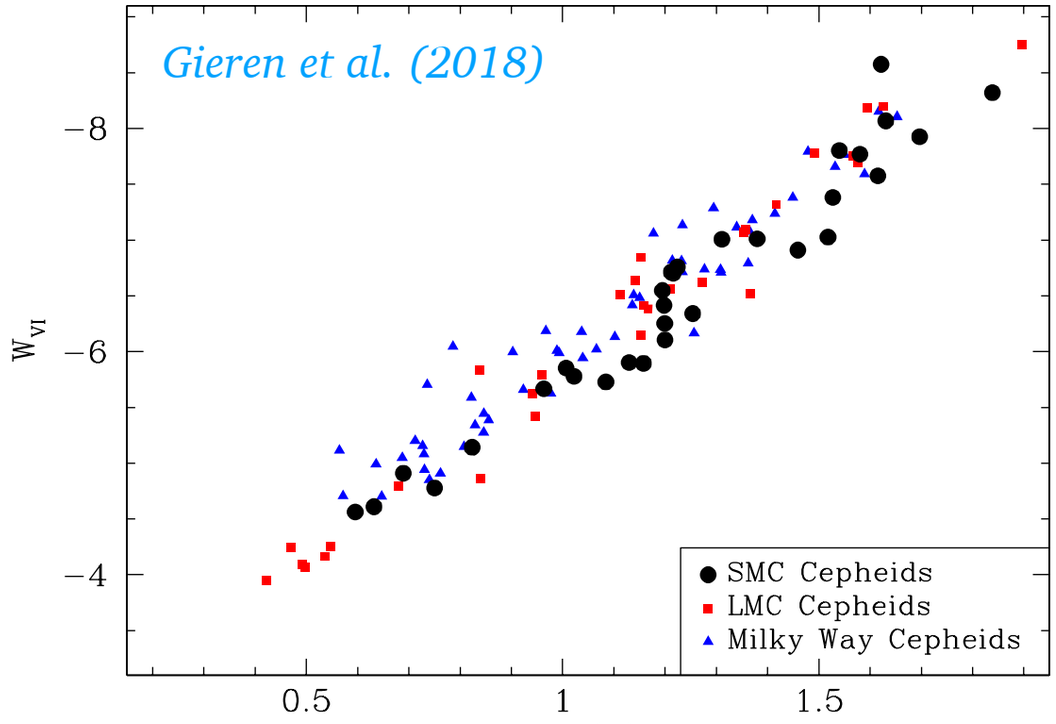


Past measurements of the metallicity effect and their limits

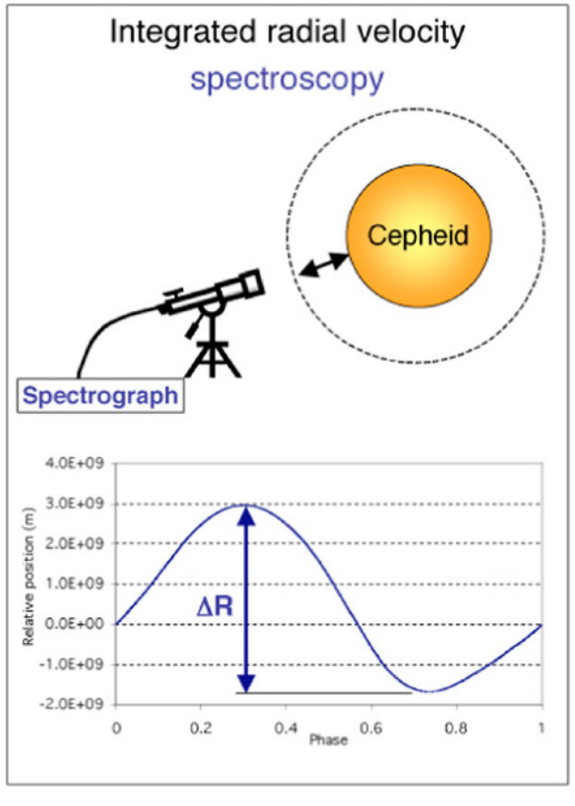
$\gamma = -0.2$ mag/dex

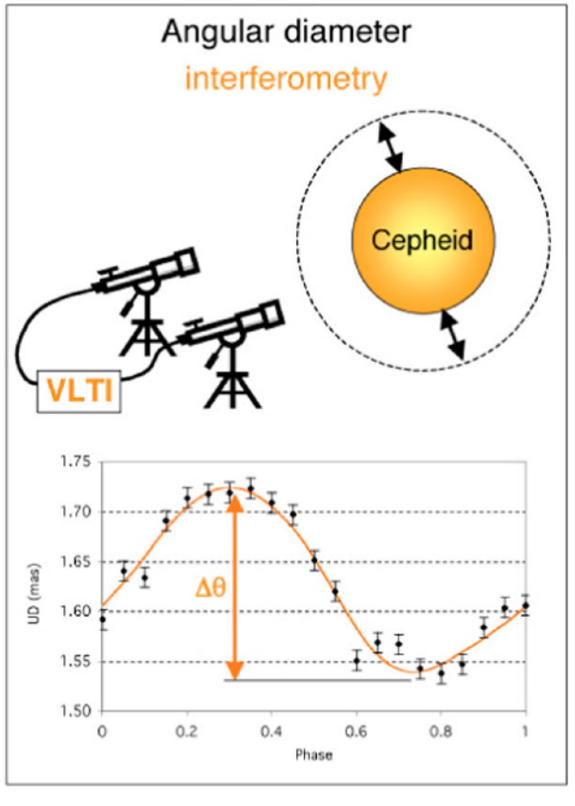
[Gieren et al. (2018)]

- **Sample**: MW + LMC + SMC Cepheids
- **Method**: PL intercepts with fixed slope, distances from Baade-Wesselink method
- **Issues**:
  - small sample (~30 Cepheids in each galaxy)
  - uncertainty on value of the "*projection factor*"



⚠ **Distances are highly unreliable** ⚠



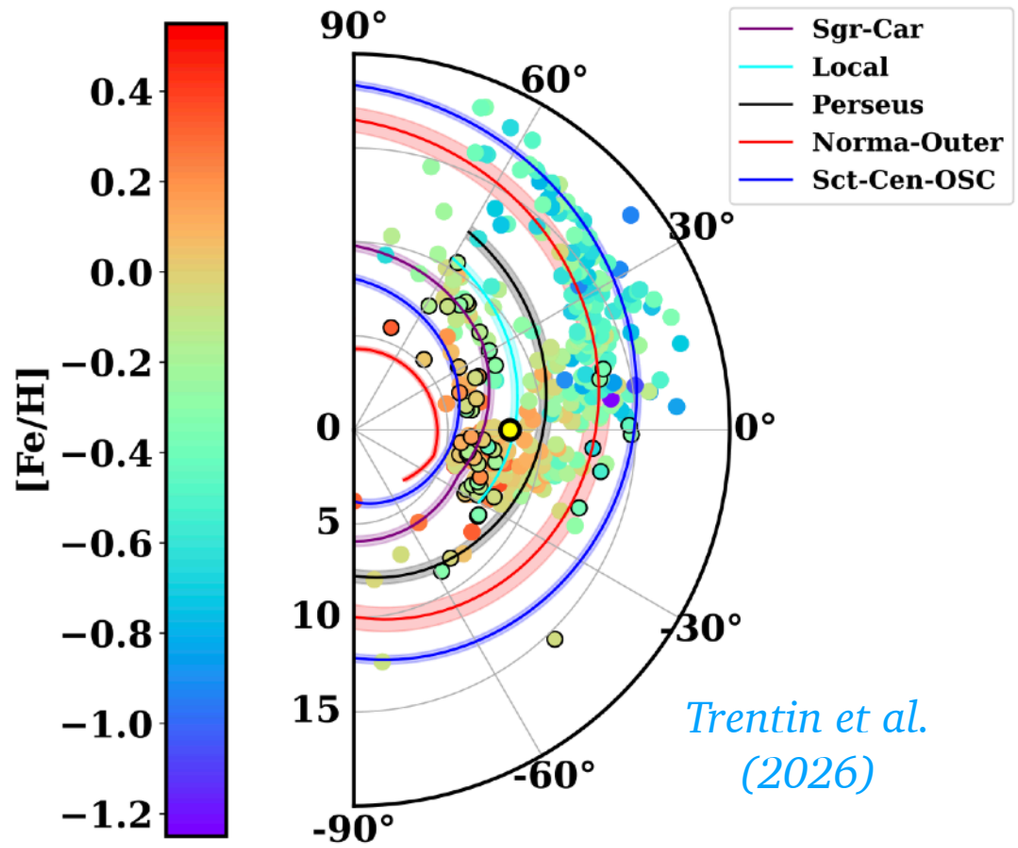


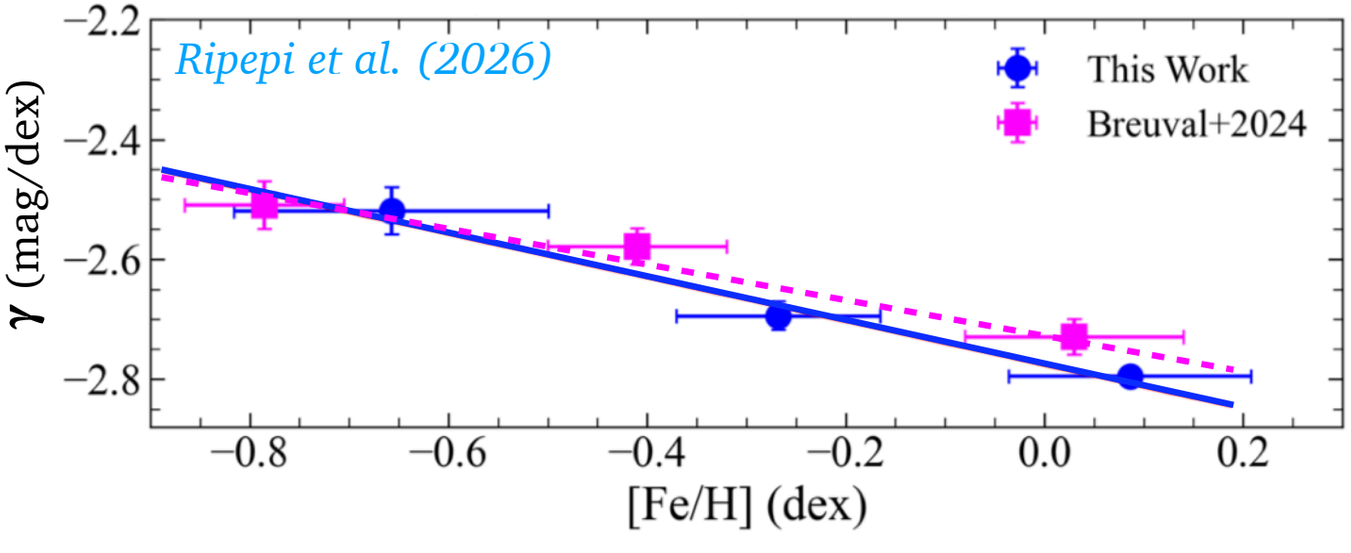
Past measurements of the metallicity effect and their limits

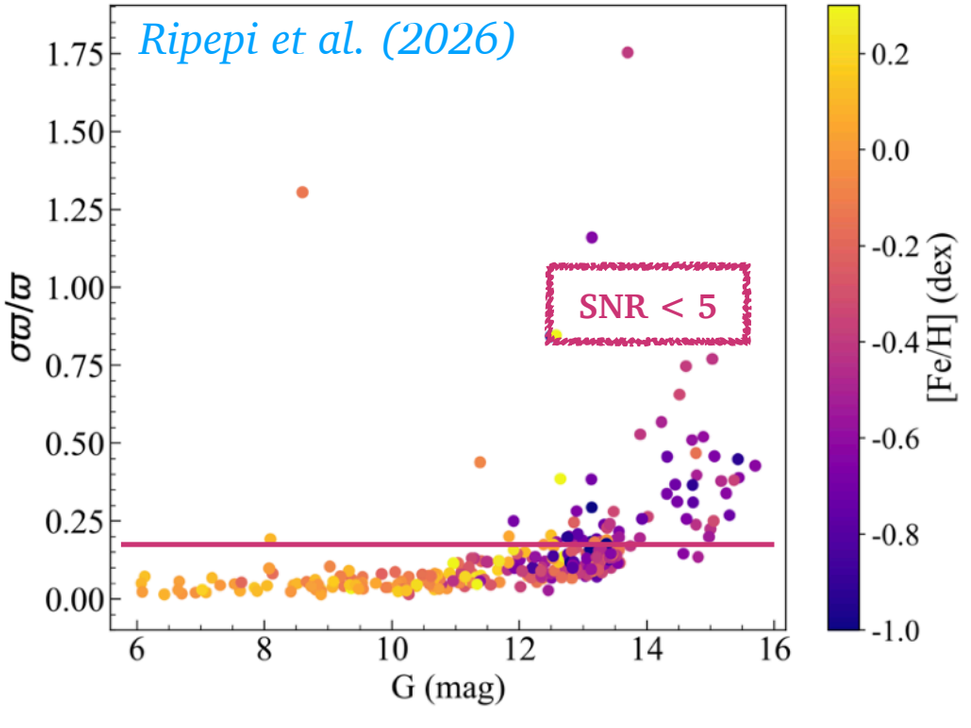
$\gamma \sim -0.36$ mag/dex

[Ripepi et al. (2026)](#)

- **Sample**: MW Cepheids with Gaia DR3 parallaxes
- **Method**: fit PLZ relation in Milky Way (3 free parameters)
- **Issues**:
  - few Cepheids with very high/low metallicity
  - lower parallax SNR for low metallicity Cepheids because at larger distances





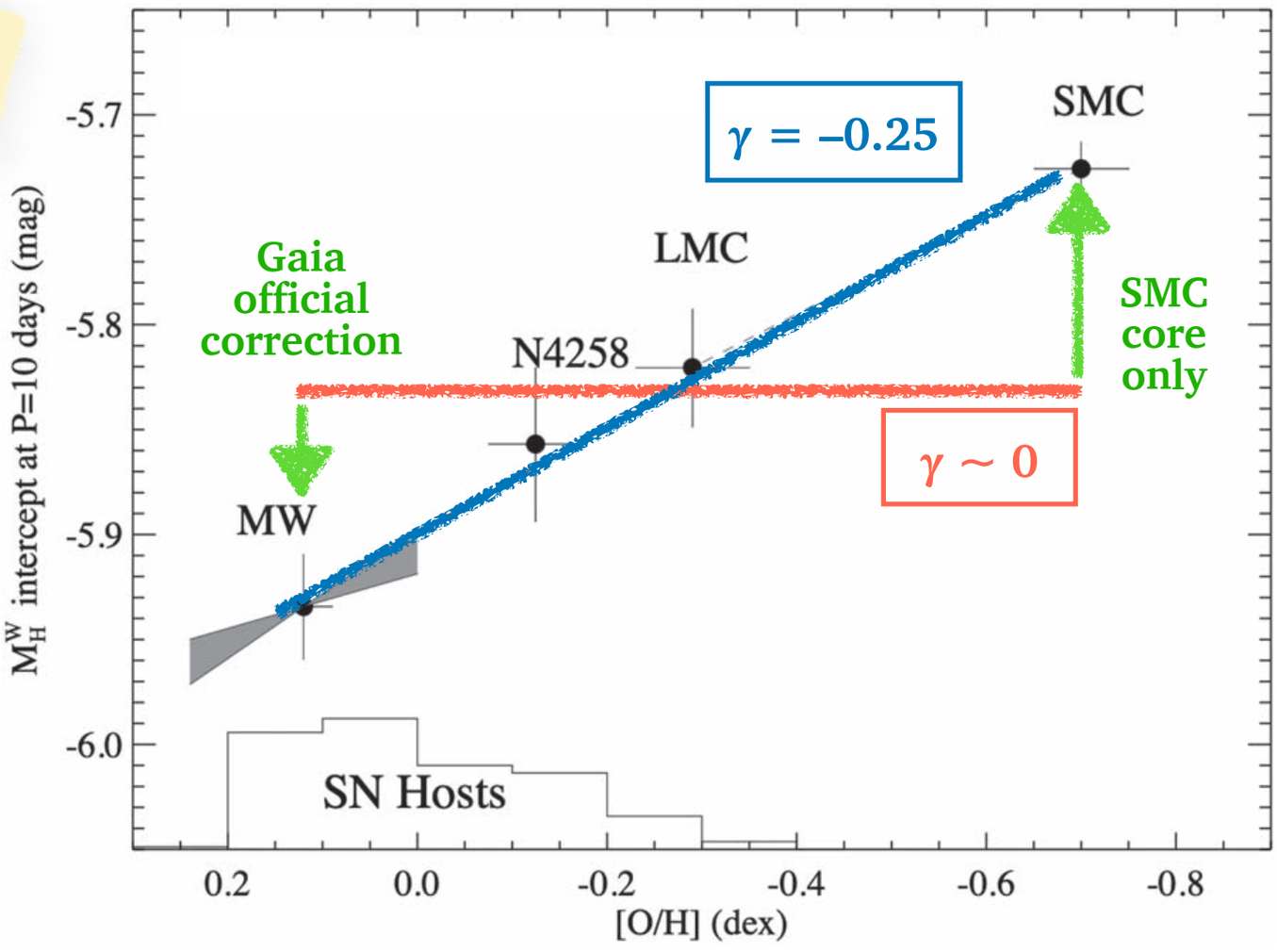


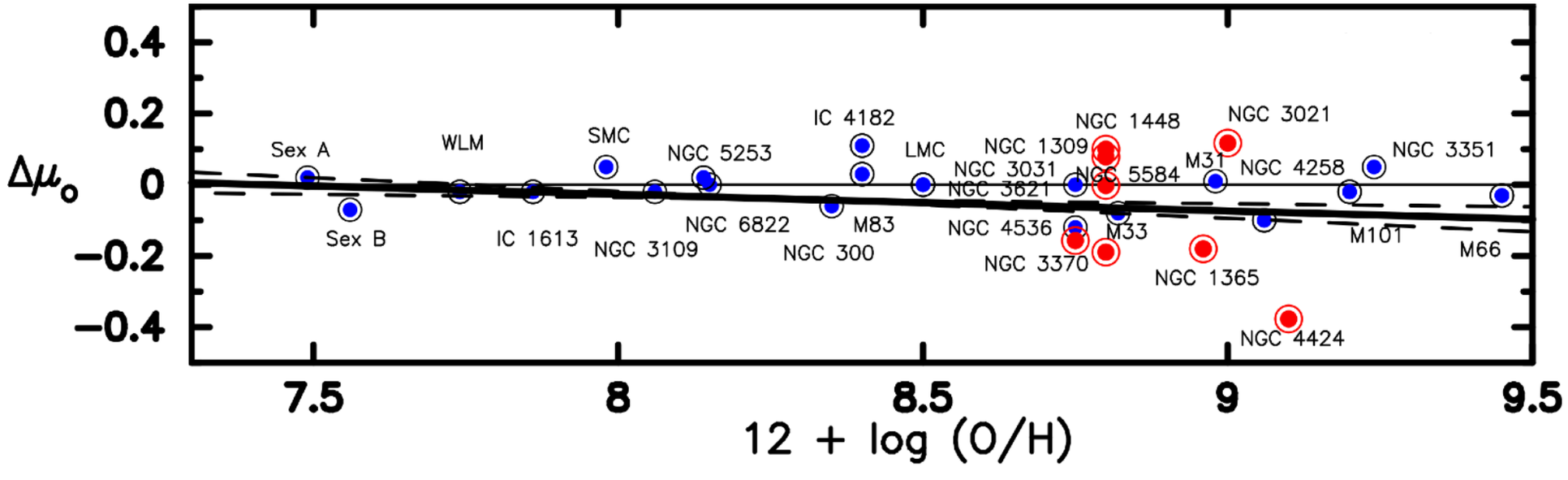
Past measurements of the metallicity effect and their limits

$\gamma = 0$

[Madore & Freedman (2023, 2025)]

- **Sample/Method**: Cepheid and TRGB distances to ~30 nearby galaxies
- **Issues**:
  - old & inhomogeneous data
  - assumes that TRGB method does not depend on metallicity
- unusual treatment of Gaia parallaxes
- SMC full sample (depth effect)





Metallicity effect: lessons & requirements for a precise calibration

MAIN LIMITATIONS:

→ narrow metallicity range (Δ [Fe/H] > 0.5 dex is preferred)

✅ use the largest metallicity range available by combining MW, LMC and SMC Cepheids

→ imprecise distances (BW technique, Gaia DR2)

✅ use Gaia DR3 parallaxes with Lindegren et al. (2021) zero-point and additional -14 µas correction recommended for Cepheids (Riess et al. 2021)

→ Magellanic Clouds geometry

✅ apply geometry correction in LMC and SMC to reduce PL scatter

✅ avoid the use of Cepheids too far from the center (make a cut of the central region)

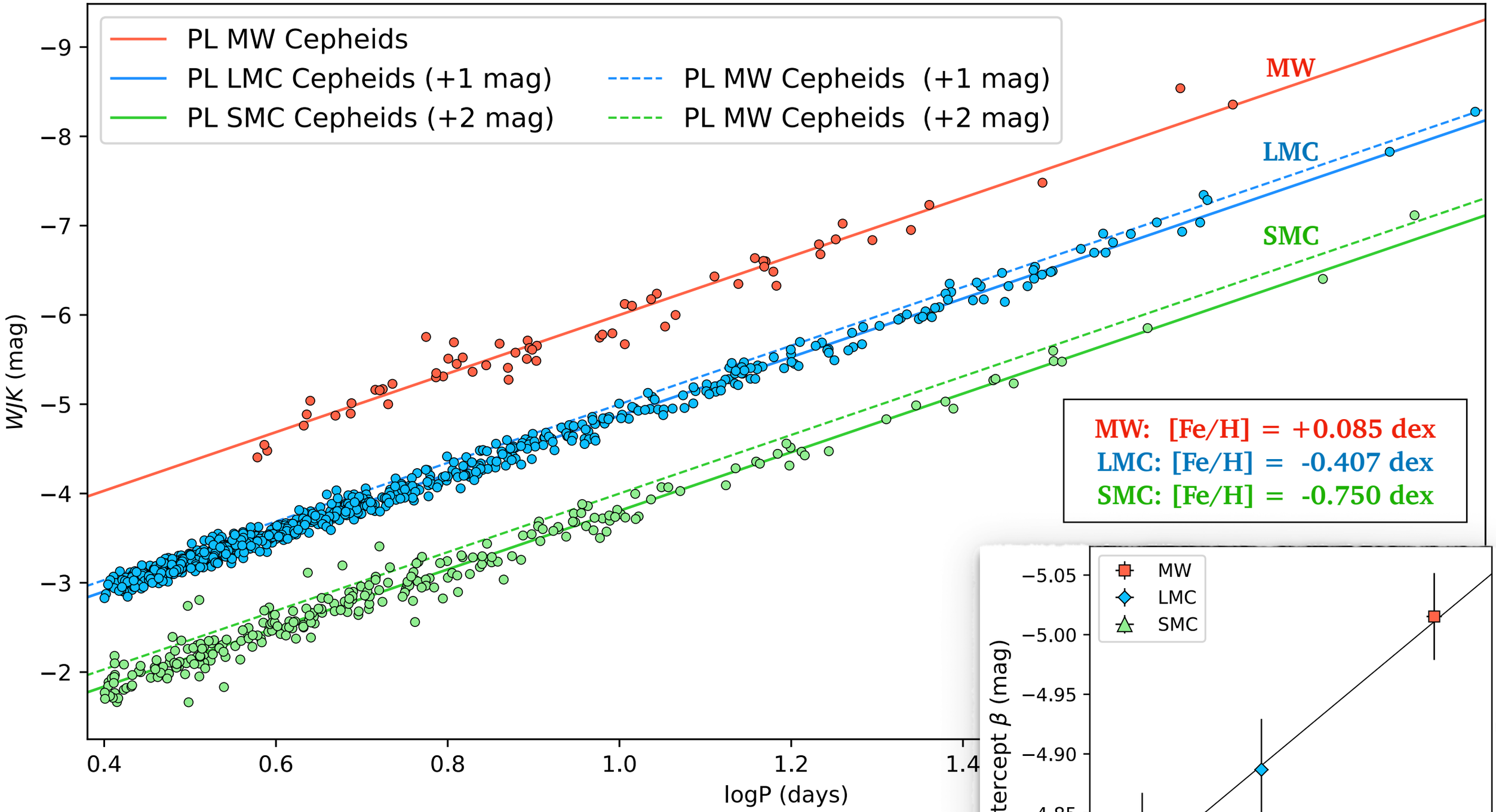
TO PERFORM THE BEST CALIBRATION:

→ use full light curves instead of random epoch magnitudes (true average magnitudes)

→ avoid to combine different photometric systems (photometric ZP)

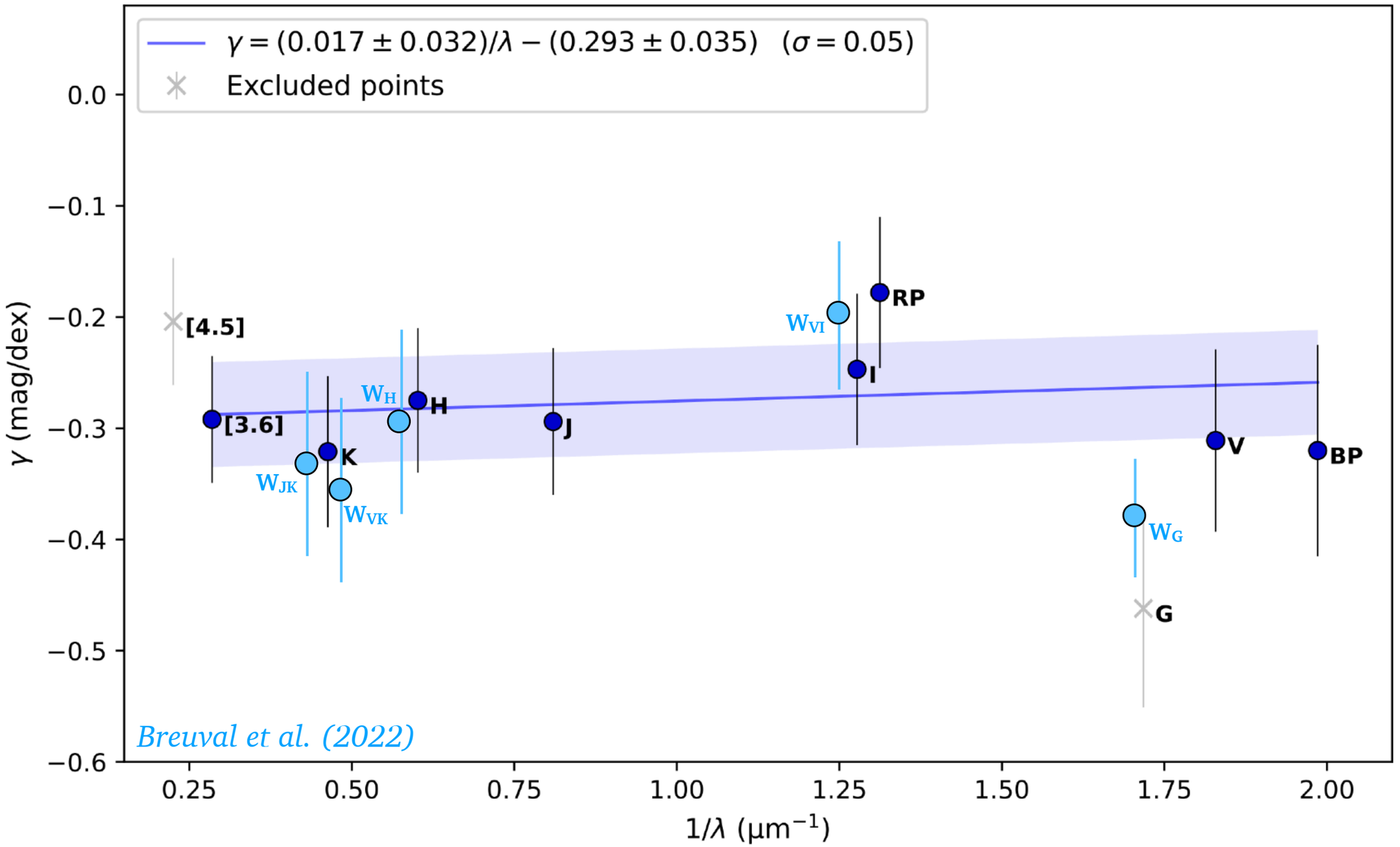
→ use recent and consistent metallicities ([Fe/H] or [O/H]) and photometry

Using the largest metallicity range: the MW–LMC–SMC sample



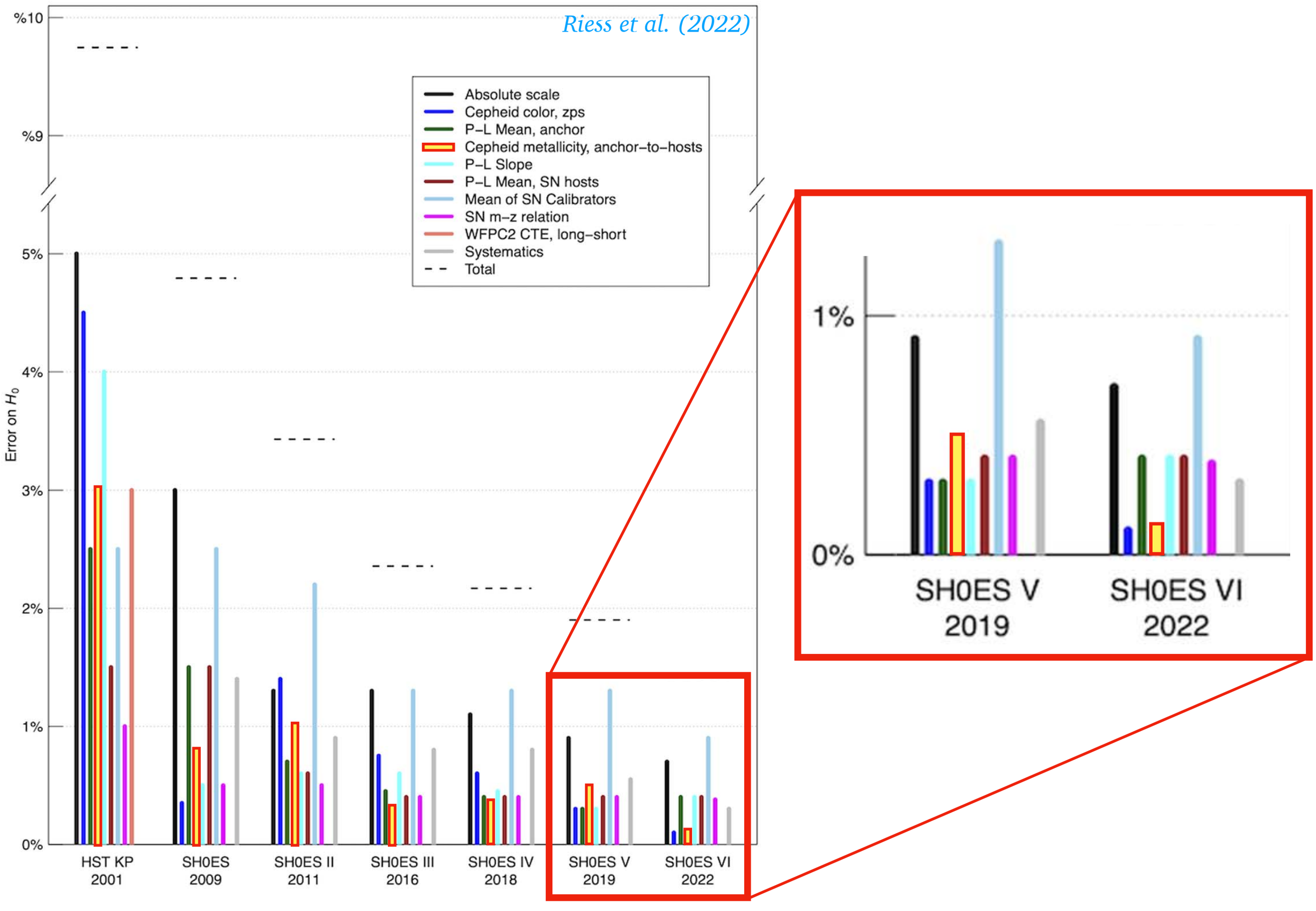
Cepheid Period-Luminosity (P-L) relation in three galaxies of different chemical composition (Breuval et al. 2021)

A Dependence with Wavelength?



- 10 filters (*Gaia*, *Spitzer*, ground NIR and optical) + 5 reddening-free Wesenheit magnitudes
- No wavelength dependence

The Cepheid Metallicity Dependence in the H_0 Error Budget



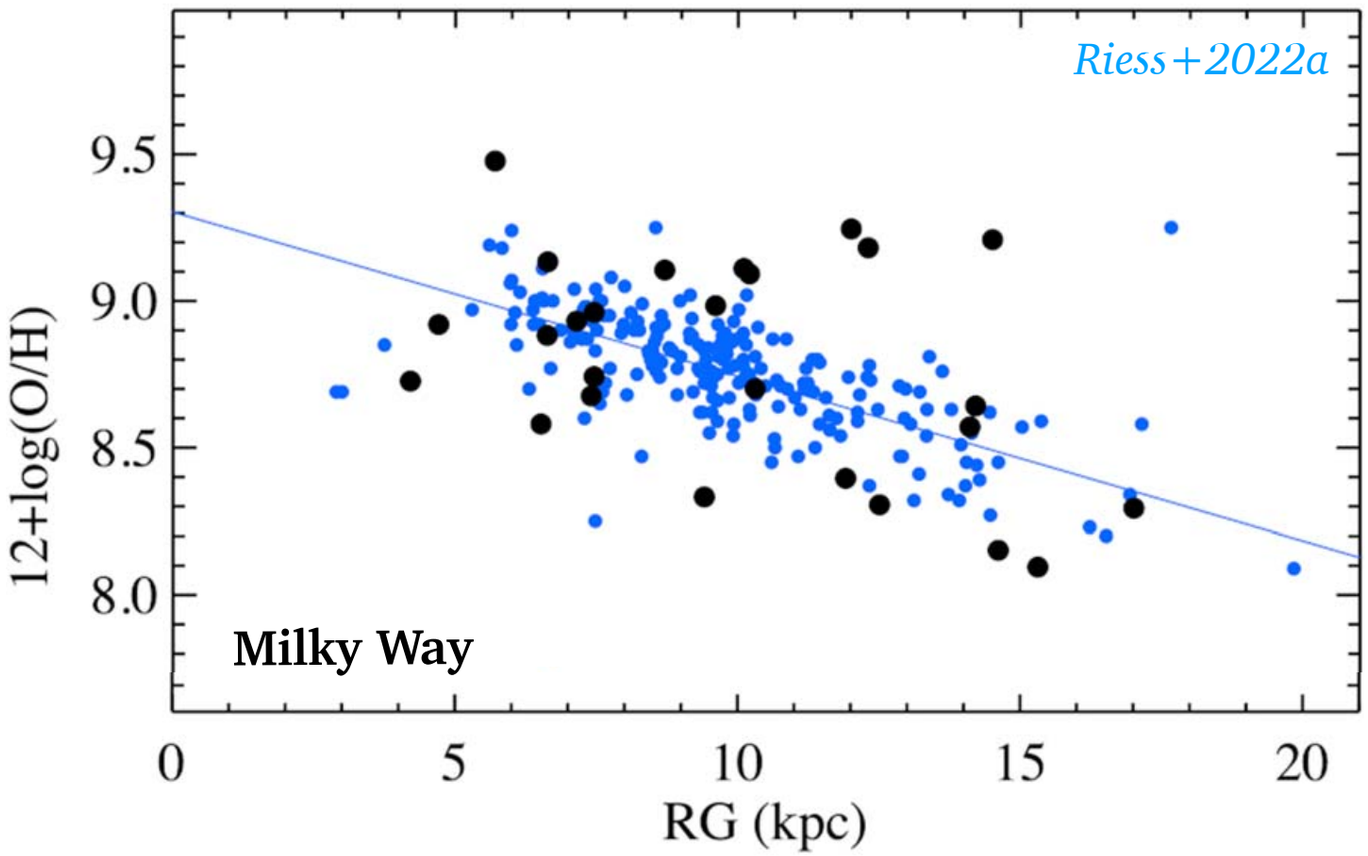
How to measure Cepheid metallicities across the Distance Ladder?

Nearby Cepheids:
[Fe/H] or [O/H] from direct spectra measurements (individually)

Distant Cepheids:
[O/H] from HII regions

→ Excellent agreement between Cepheid spectra and HII regions

Comparison between the two methods for Milky Way Cepheids:



Conclusion on the metallicity dependence:

- → Was the main systematic for decades because early H_0 measurements relied on LMC as only anchor.
- → The exact value of γ has very little impact for H_0 (< 0.8 km/s/Mpc when using the most extreme γ).
- → **Consensus** on the value and sign of γ, confirmed with models.