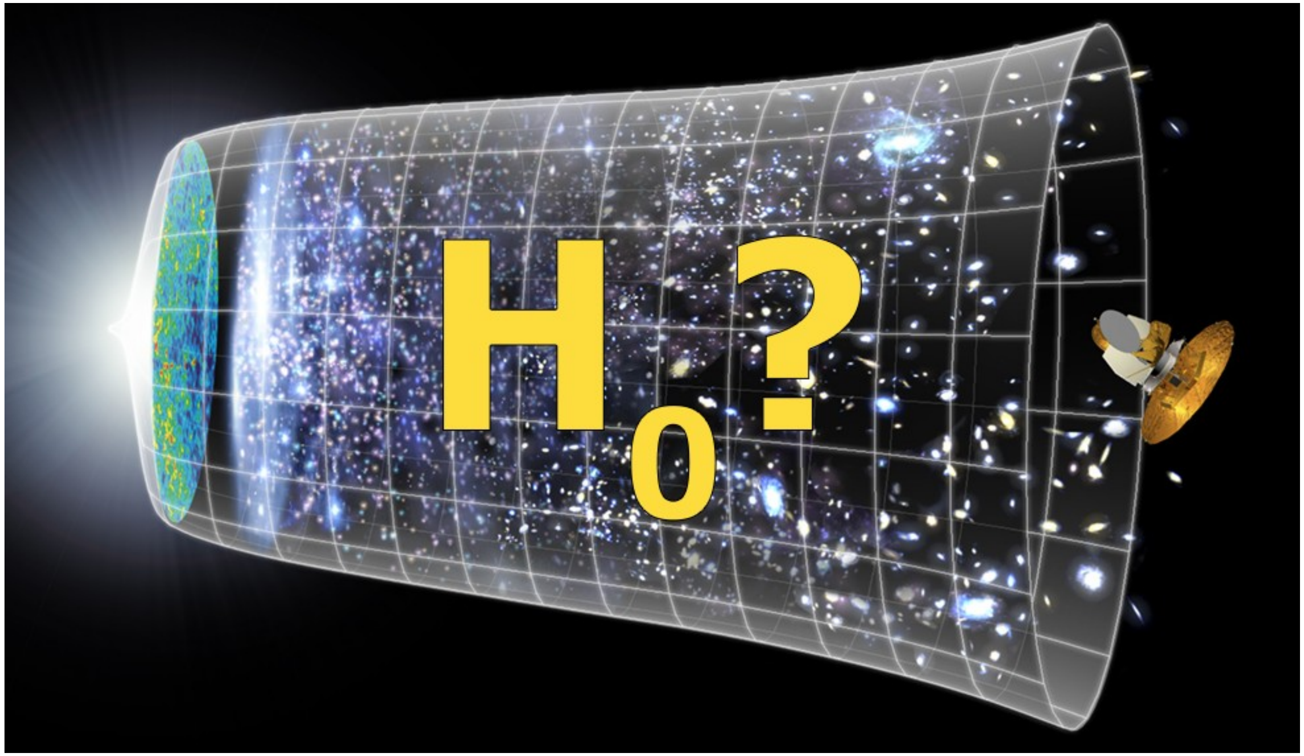


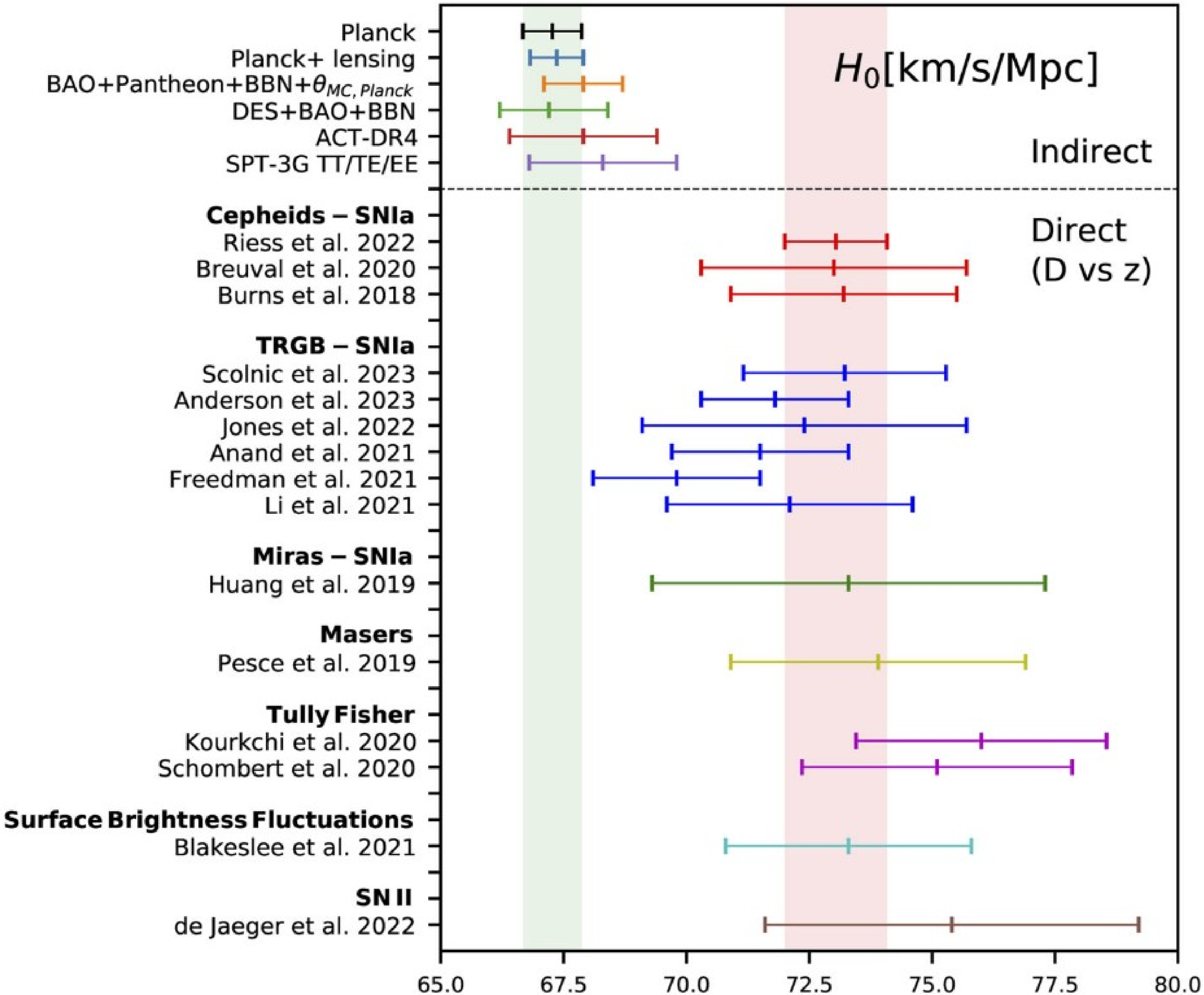
The Hubble tension

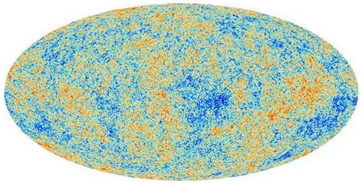
Dariusz Graczyk
CAMK, Toruń

Araucaria PROJECT

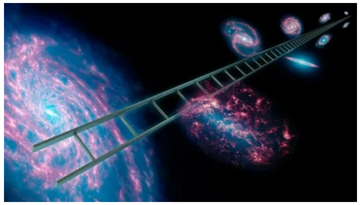
CAMK PAN

“Early” versus “late” H_0



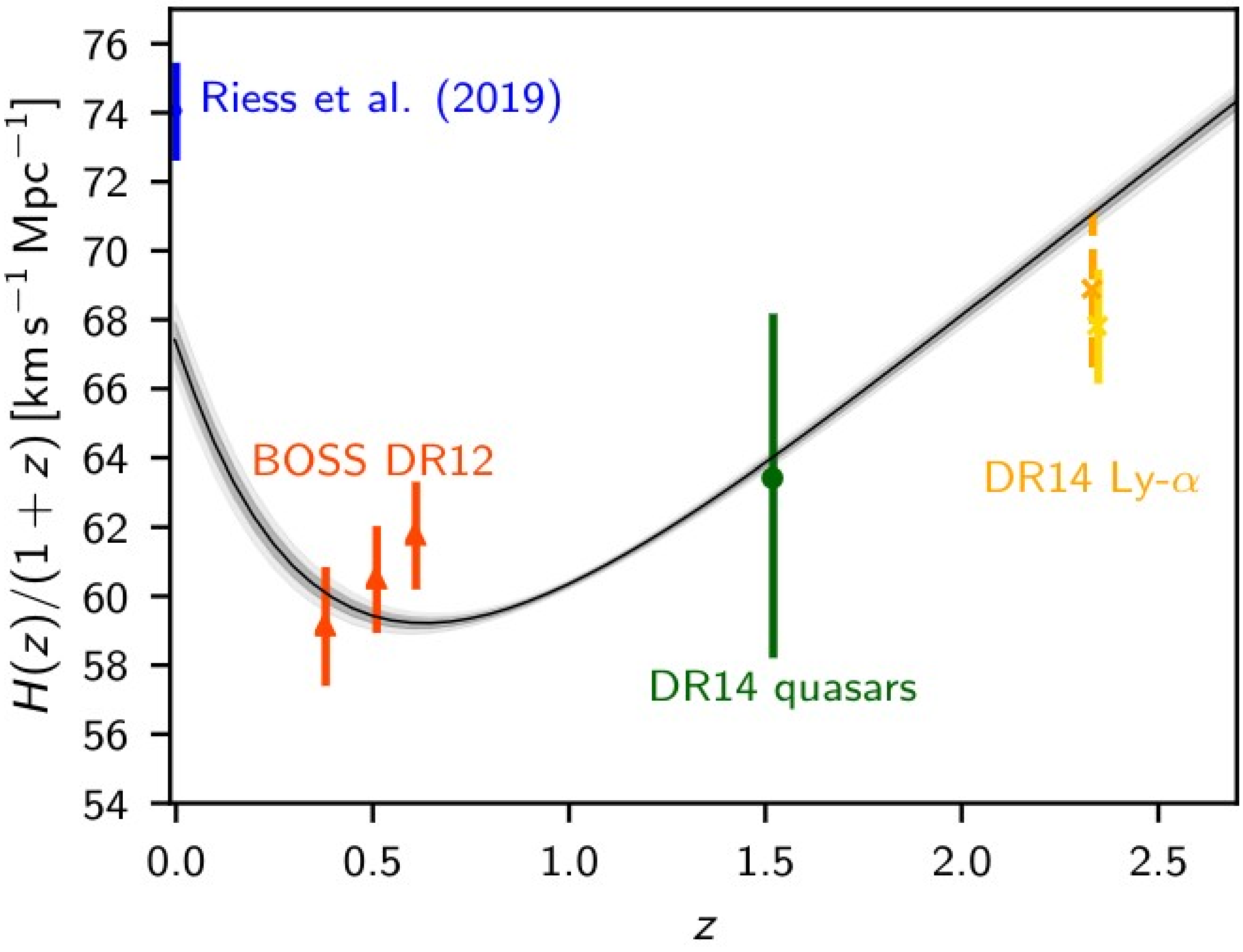


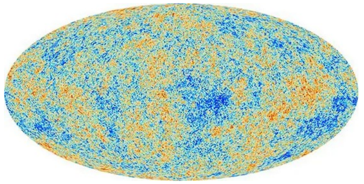
Planck 2018 results
H_0=67.4 ± 0.5 km/s
(Planck Collaboration 2020)



Local measurement
H_0=73.0 ± 1.0 km/s
(Riess+2022)

“Early” versus “late” H_0





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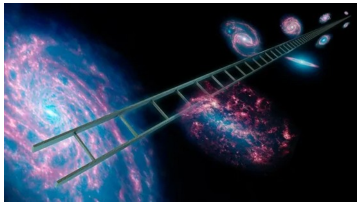


Local measurement
H_0=73.0 ± 1.0 km/s
(Riess+2022)

Ways to resolve the tension

Real tension:
Cosmology
is precise
and accurate

"New physics":
an extension to the base ΛCDM model,
new "species", interactions

→ A "favorite" option

Our "special" place in the universe:
we live in a big void
or
The universe is not isotropic

→ Not excluded

Apparent tension:
Cosmology
is precise,
but not accurate

Systematics in CMB data
or
Error in CMB analysis

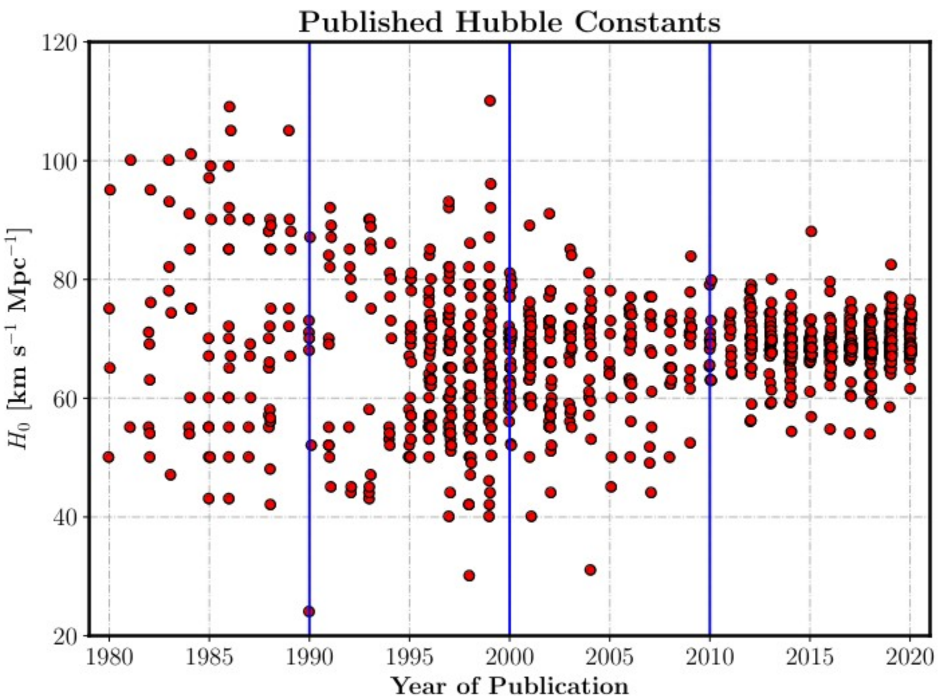
→ Not excluded

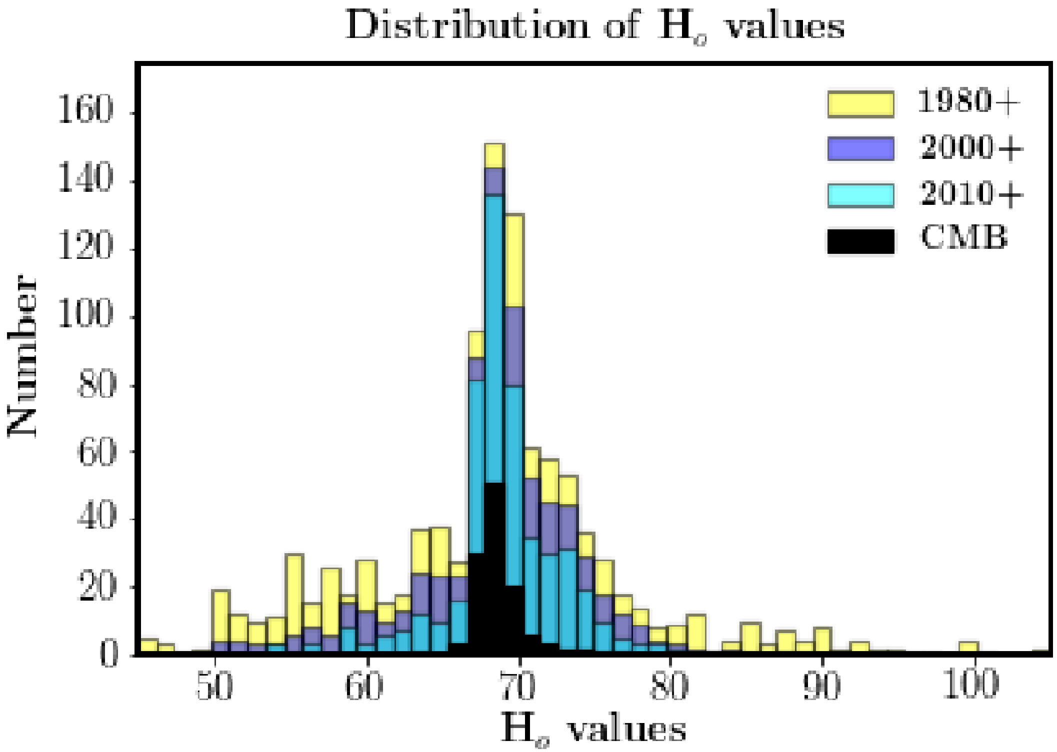
Systematics in data used to construct
the extragalactic distance ladder,
underestimated errors

→ A likely option

Ways to resolve the tension

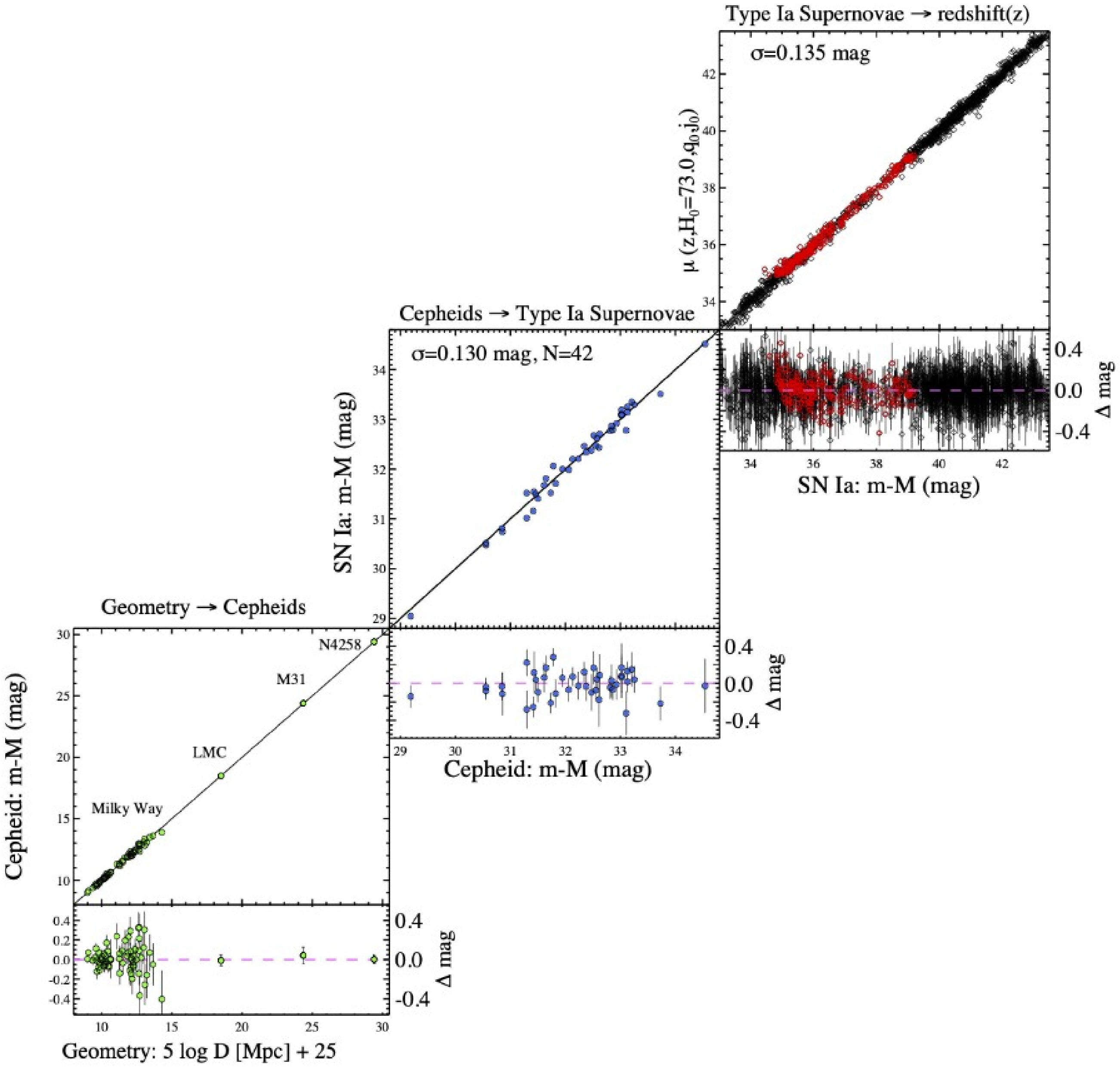
Apparent tension:
Cosmology is precise, but not accurate



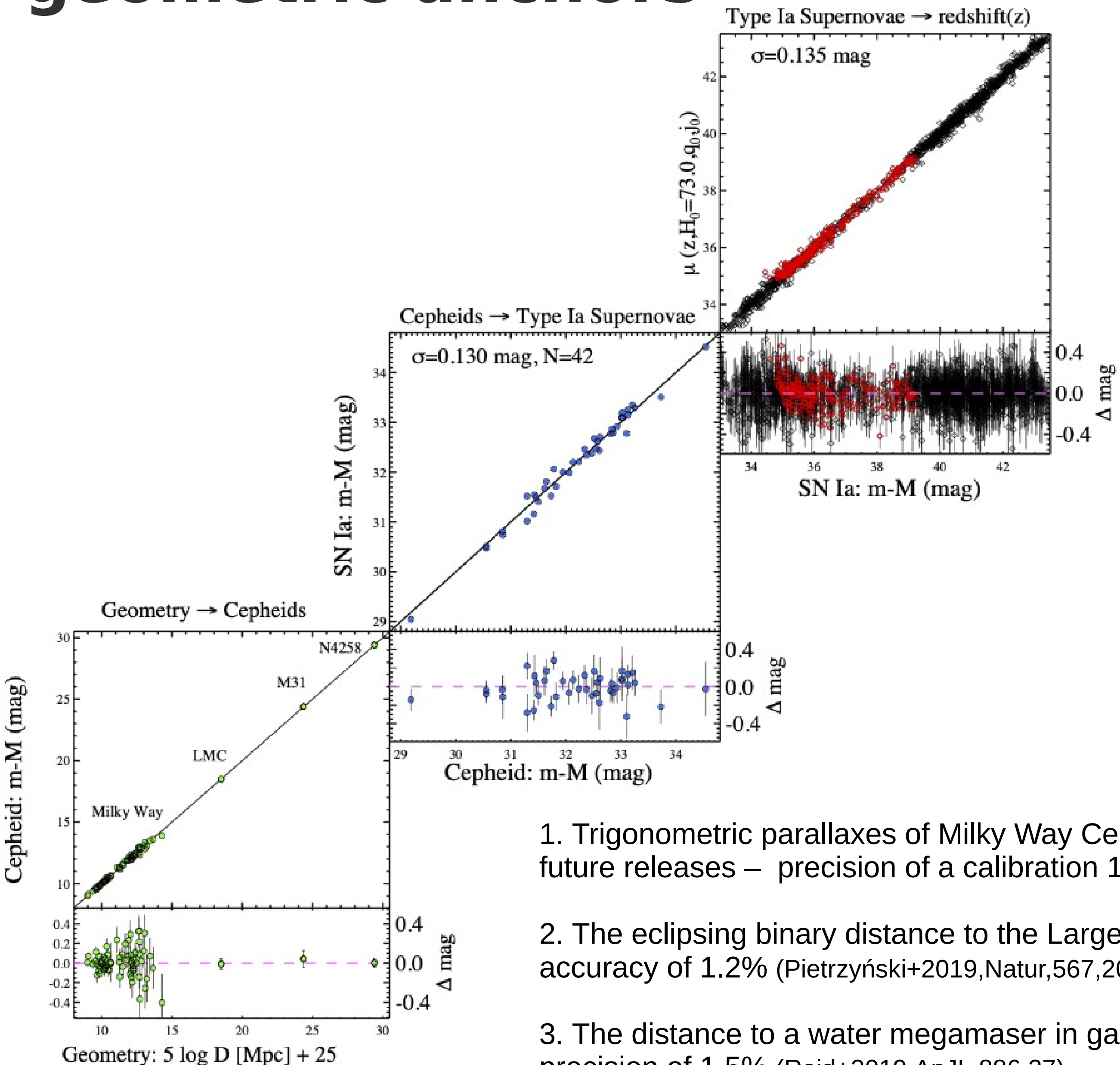


After Freedman(2021,ApJ,919,16)

The extragalactic distance ladder



The extragalactic distance ladder – geometric anchors



1. Trigonometric parallaxes of Milky Way Cepheids provided by Gaia DR3 and future releases – precision of a calibration 1.0% (e.g. Riess+2021,ApJL,908,6; SH0ES)

2. The eclipsing binary distance to the Large Magellanic cloud – precision and accuracy of 1.2% (Pietrzyński+2019,Natur,567,200; Araucaria project)

3. The distance to a water megamaser in galaxy NGC 4258 (Messier 106) – precision of 1.5% (Reid+2019,ApJL,886,27)

The extragalactic distance ladder : geometric anchors – LMC

The eclipsing binary distance to the Large Magellanic cloud (Pietrzyński+2019,Natur,567,200; Araucaria project)

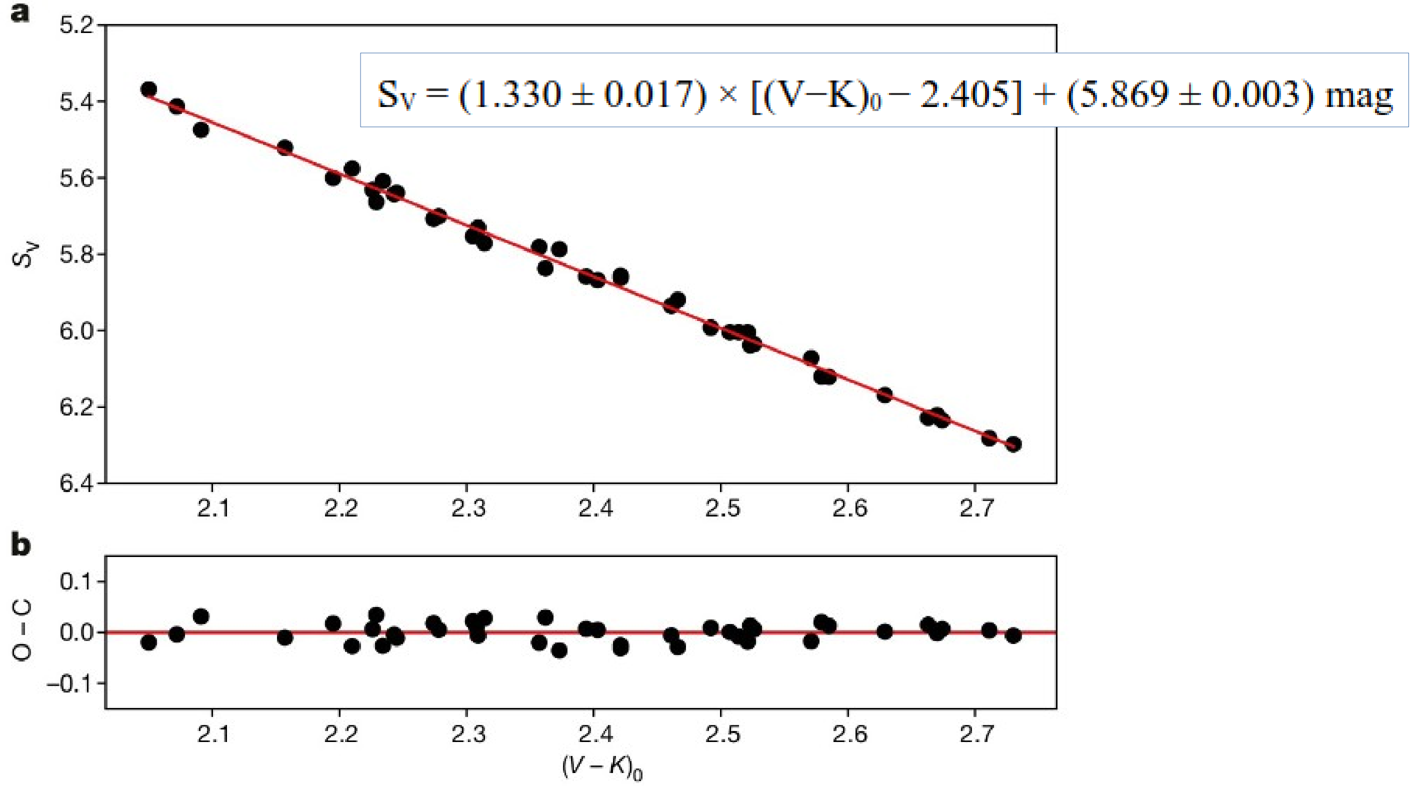


Fig. 1. New relation between surface brightness S_V and $(V-K)_0$ colour. a, Plot of S_V versus $(V-K)_0$ (data points) and fitted line. The r.m.s. scatter on this relation is 0.018

The extragalactic distance ladder : geometric anchors – calibration of Cepheids

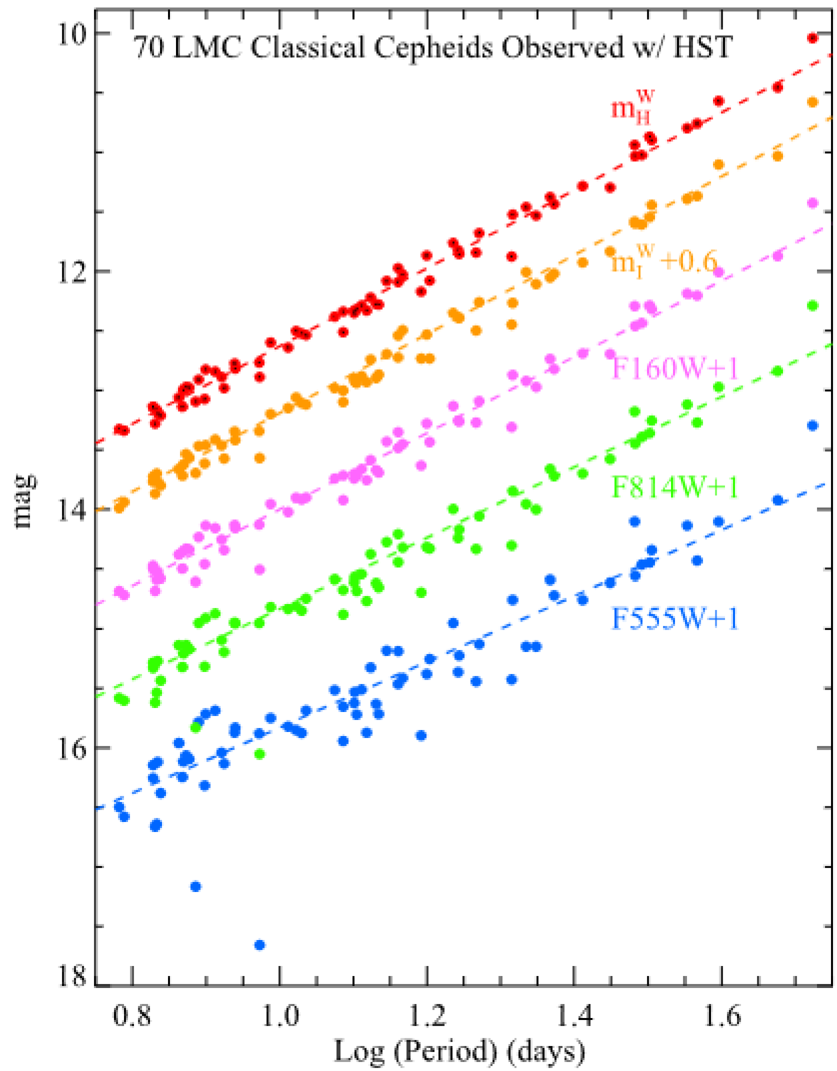


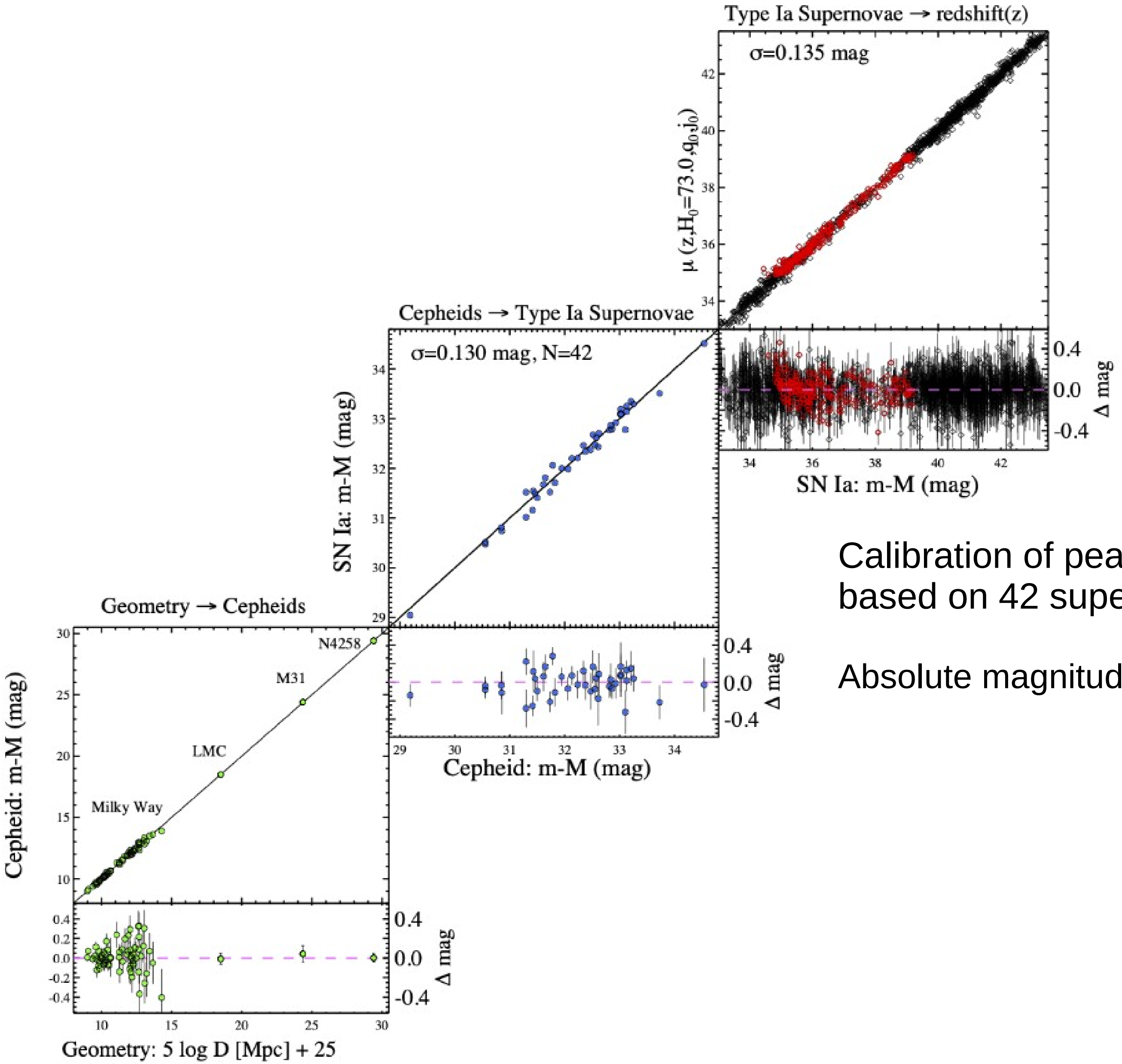
Figure 3. Period–mean magnitude relation for the 70 LMC Cepheids with slopes and statistics given in Table 3.

after Riess+(2019,ApJ,876,85; SH0ES)

Period–Mean magnitude Relations from *HST* LMC Cepheids

Band	Slope[a]	Intercept[b]	Scatter[b]
F555W	−2.76	17.638	0.312
F814W	−2.96	16.854	0.202
F160W	−3.20	16.209	0.104
$m_I^{W,c}$	−3.31	15.935	0.085
m_H^W	−3.26	15.898[d]	0.075

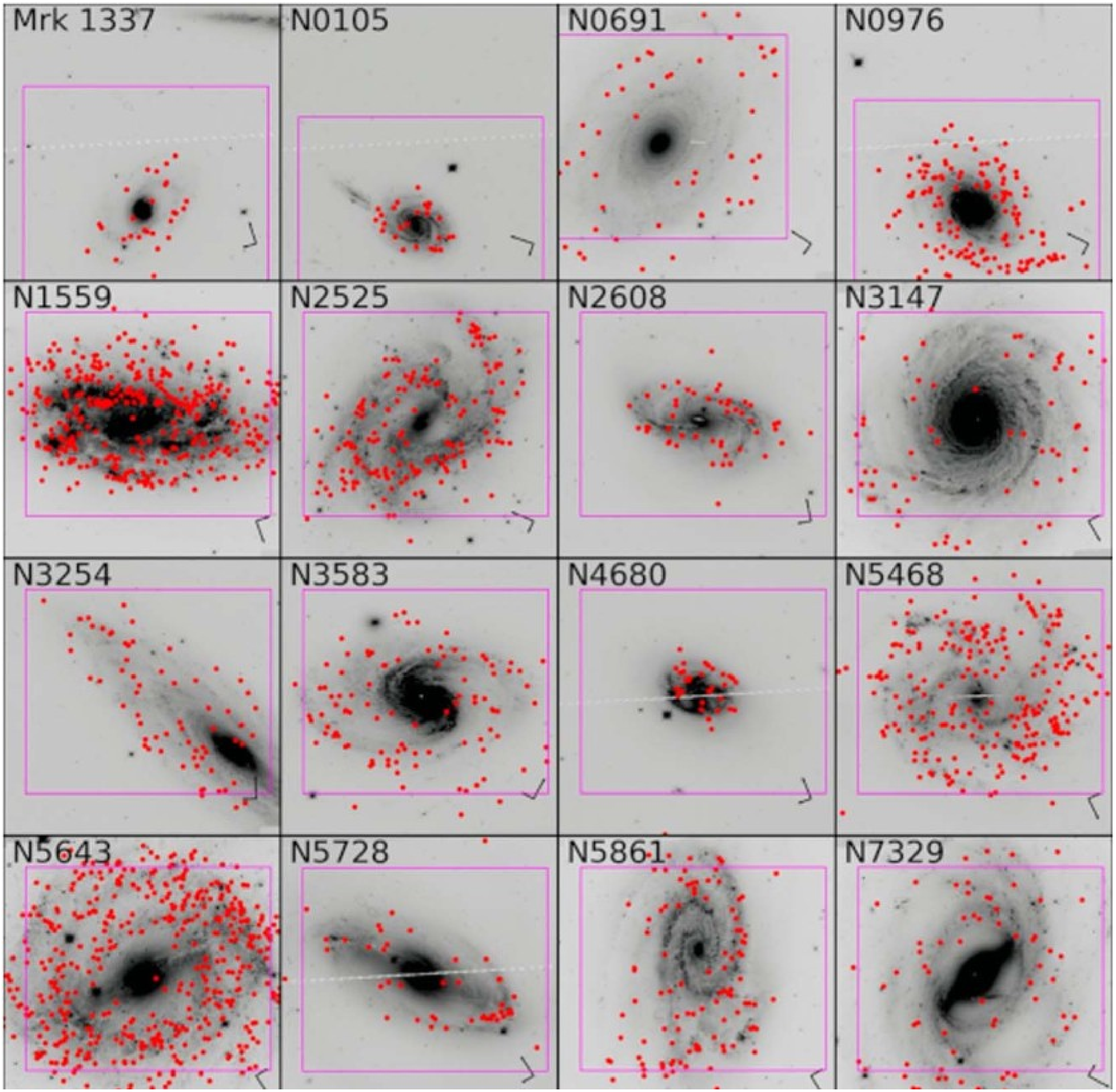
The extragalactic distance ladder – calibration of SN Ia



Calibration of peak brightness of SN Ia based on 42 supernovae in 37 host galaxies

Absolute magnitude: –19.2 mag in B band

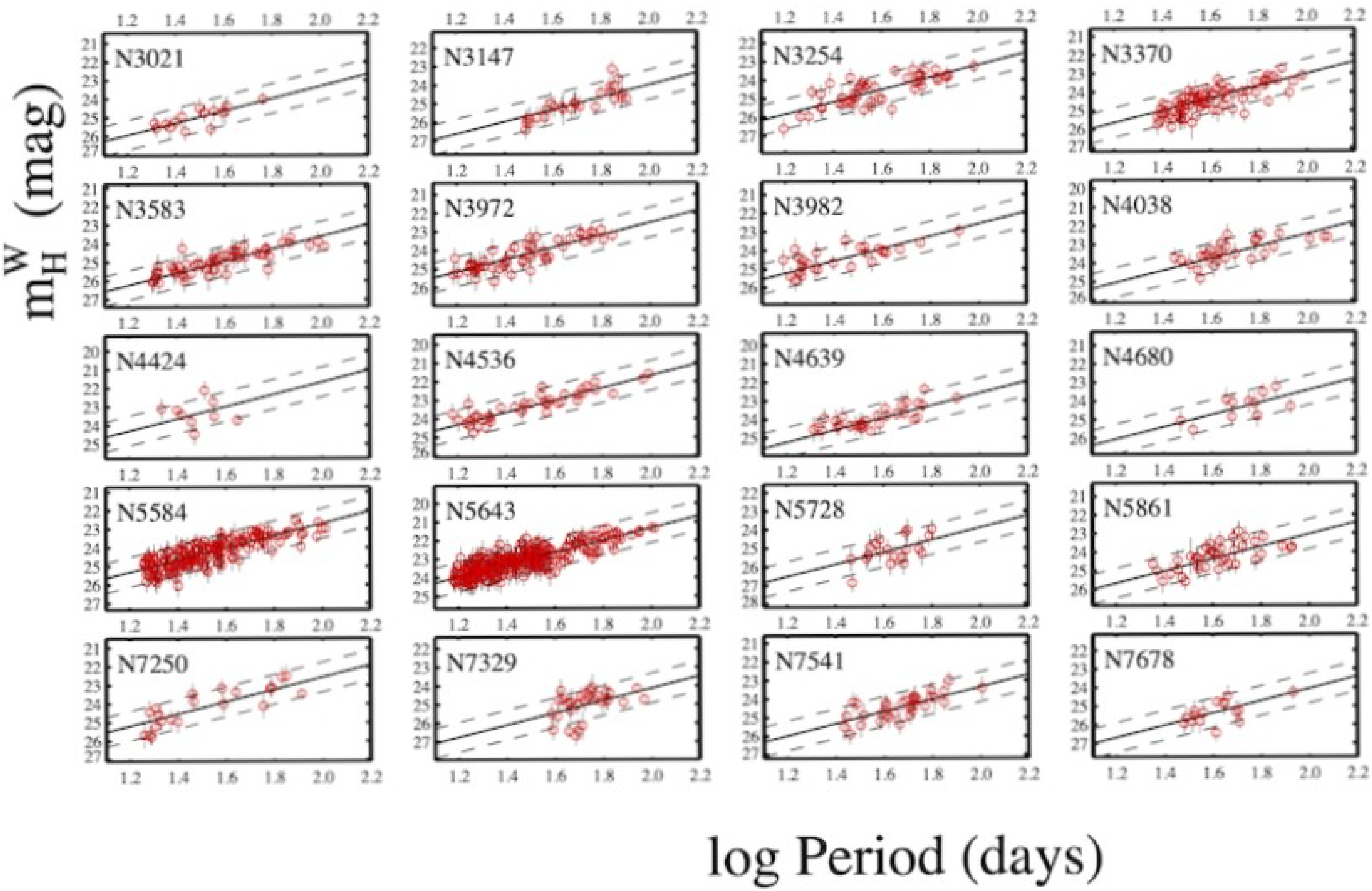
The extragalactic distance ladder – calibration of SN Ia



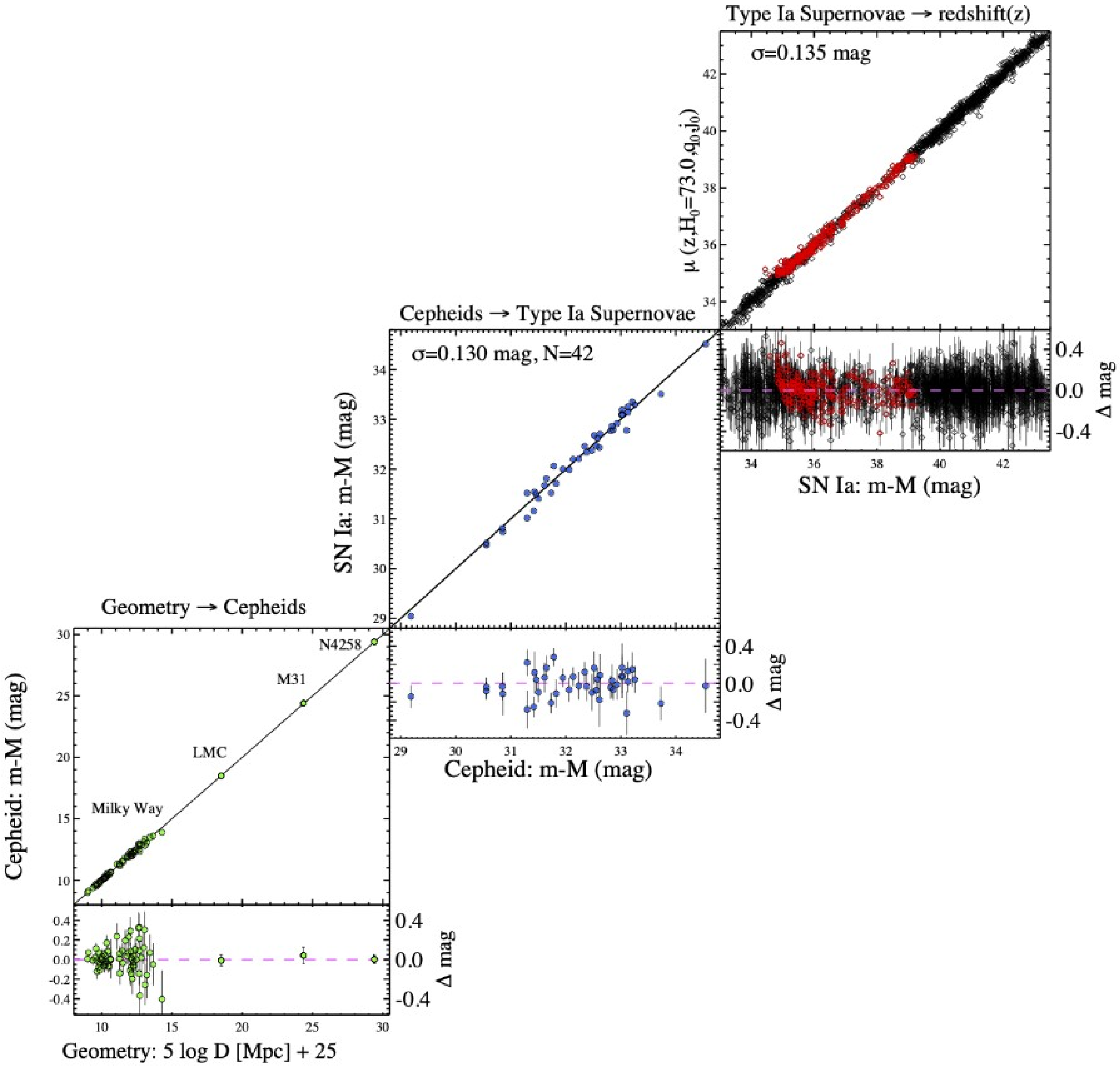
Riess+(2022,ApJL,934,7)

The extragalactic distance ladder – calibration of SN Ia

Riess+(2022,ApJL,934,7)



The extragalactic distance ladder

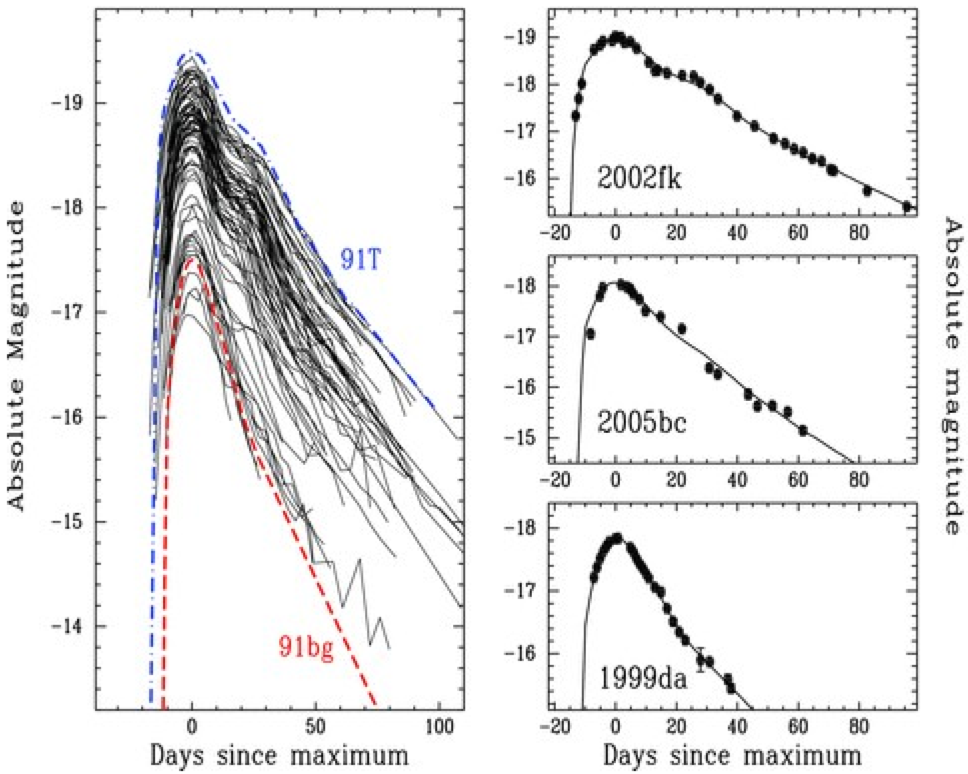


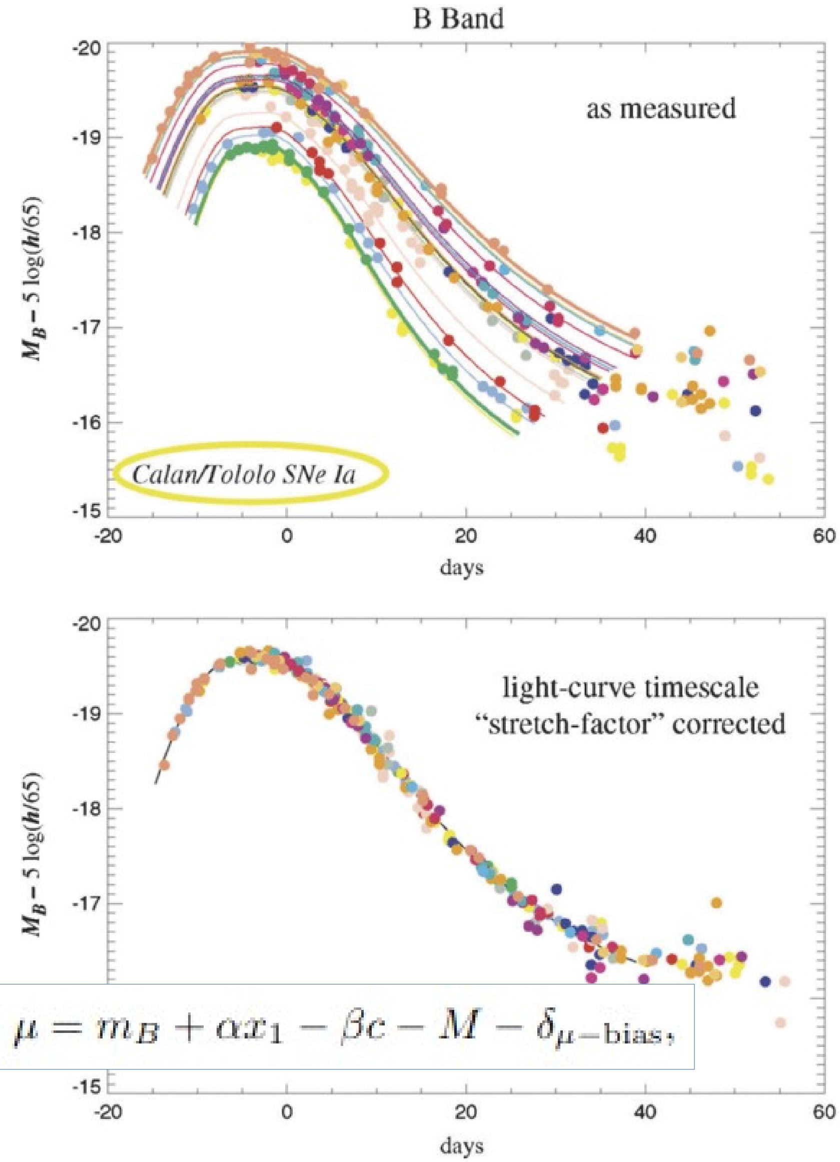
SNe Ia:
Pantheon+ sample of 1550 SN Ia

Fiducial absolute magnitude after the *standarization:*
$M_B^0 = -19.253 \pm 0.027\, mag$

Calibration sample z < 0.02
Hubble flow 0.023<z<0.15
Cosmology sample z > 0.15

The extragalactic distance ladder: standardization of SN Ia

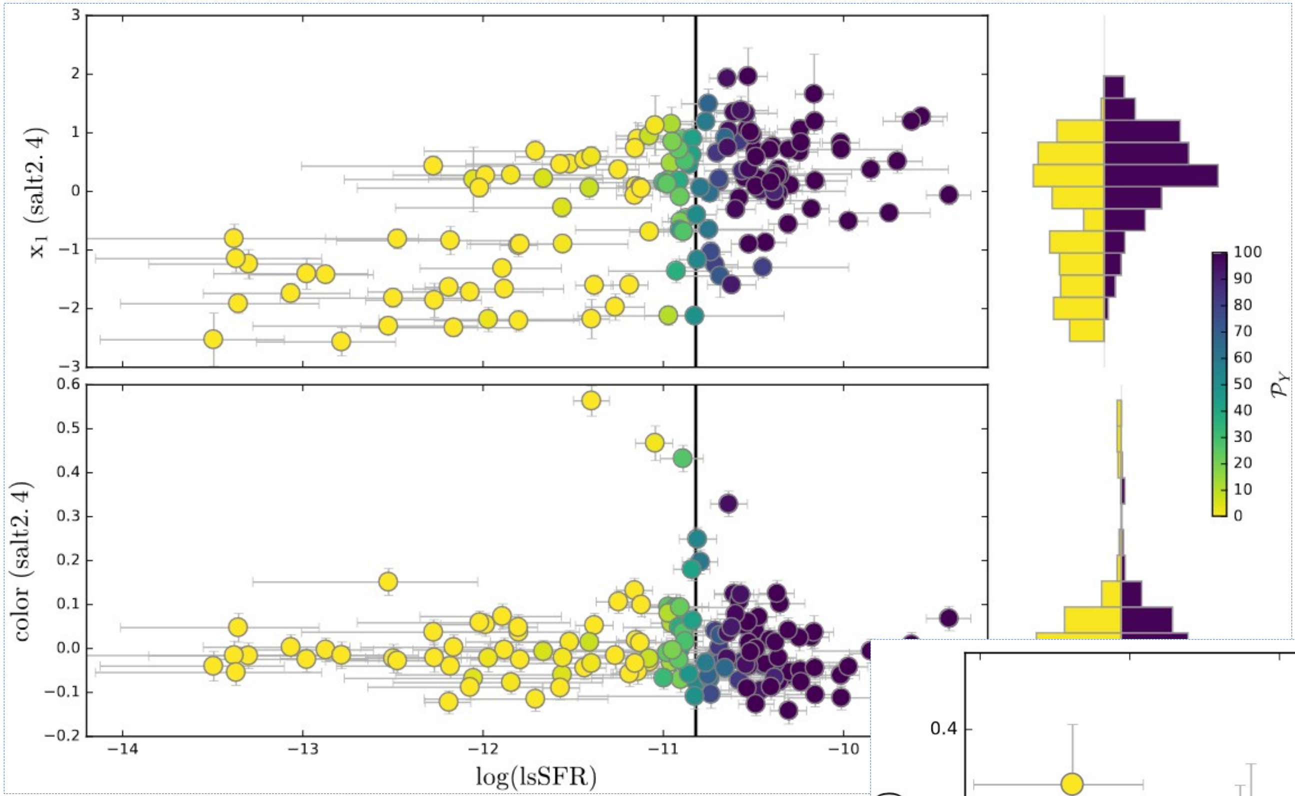


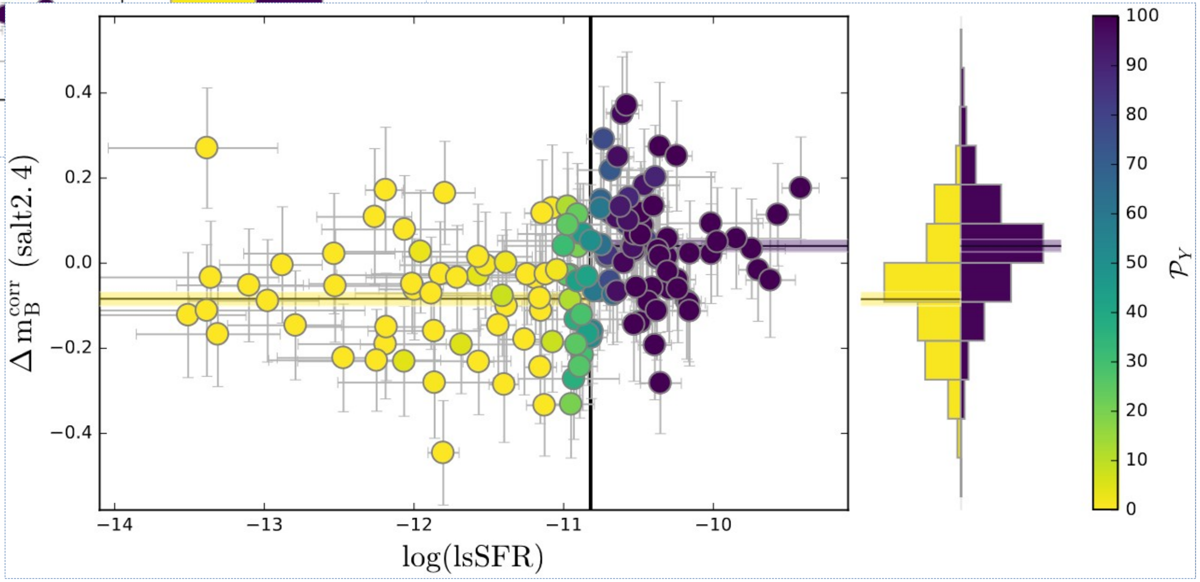


$$\mu = m_B + \alpha x_1 - \beta c - M - \delta_{\mu-\text{bias}},$$

Raw peak magnitudes: σ=0.65 mag
After standardization: σ=0.13 mag
Sibling SNe Ia: σ=0.08 mag

The extragalactic distance ladder: standardization of SN Ia





The extragalactic distance ladder: summary

Magnitude of ***possible*** systematic effects present in different rungs of the distance scale

1st step: Anchor calibrators of Cepheids	2nd step: Calibration and standardization of Cepheids	3rd step: Calibration and standardization of SNe Ia
Physics: well understood	Physics: not fully understood	Physics: still debated, no progenitor known
↓	↓	↓
Smaller than 1%	2-3%	4-5%

The extragalactic distance ladder: update – JWST

Riess & Breuval (2023)