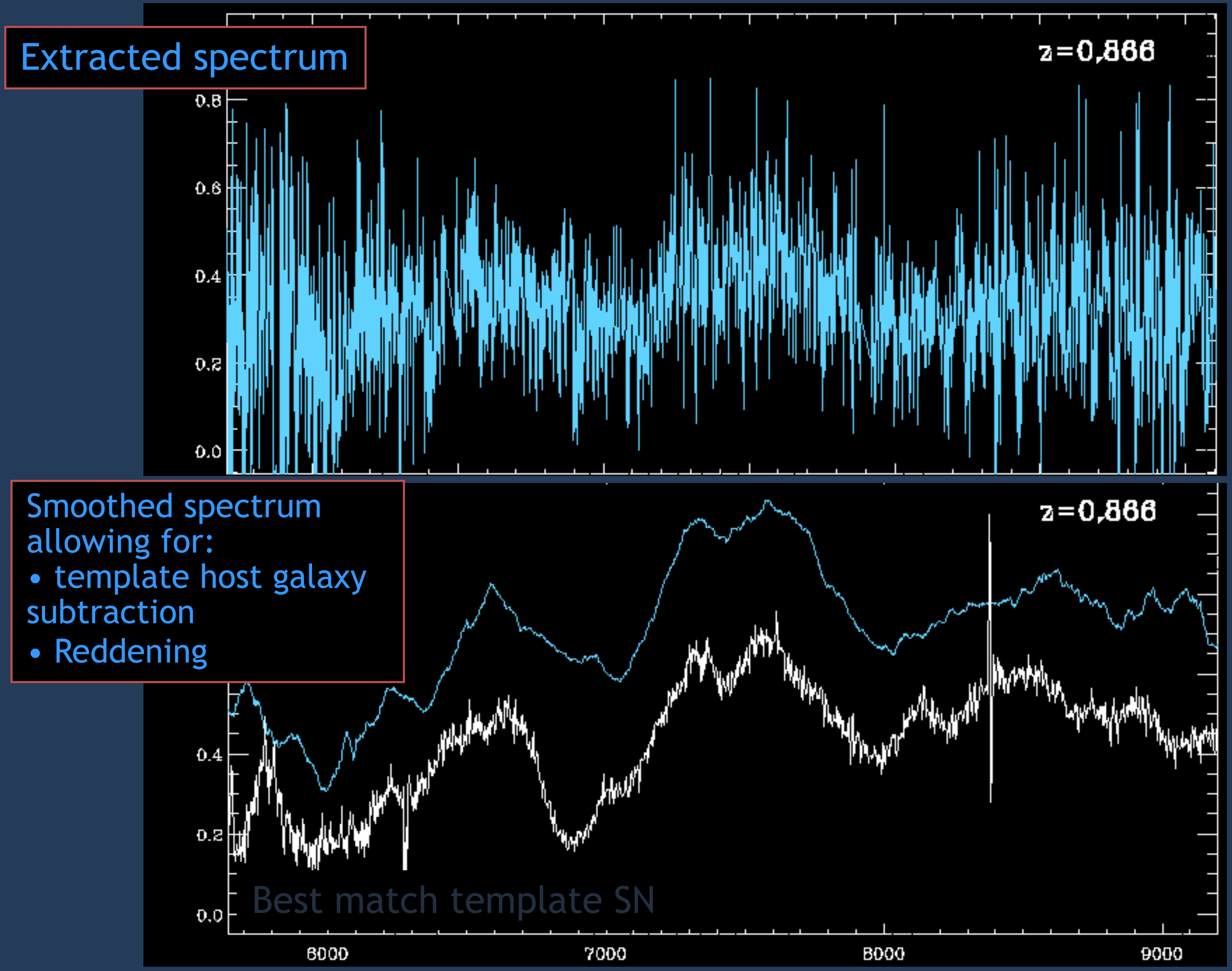
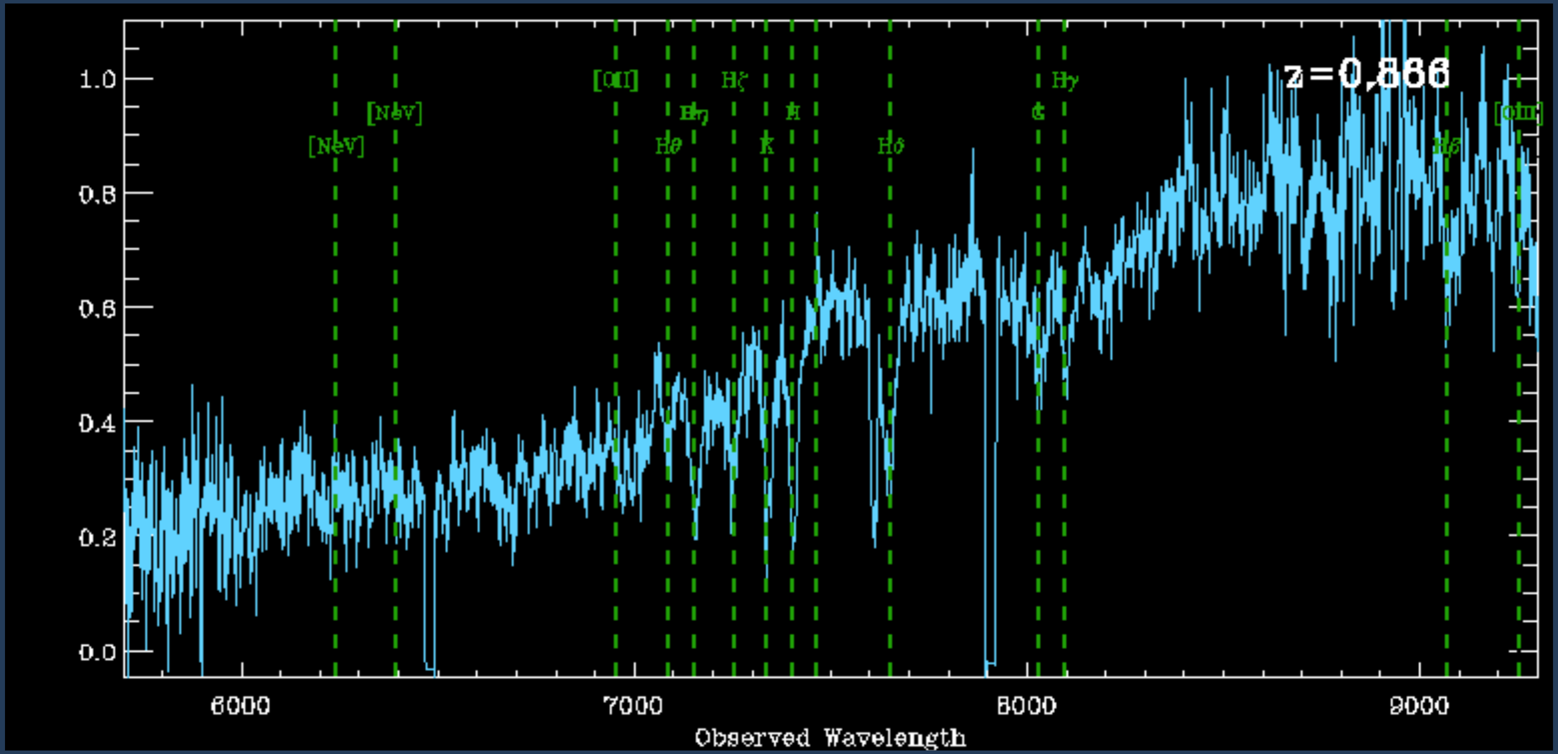
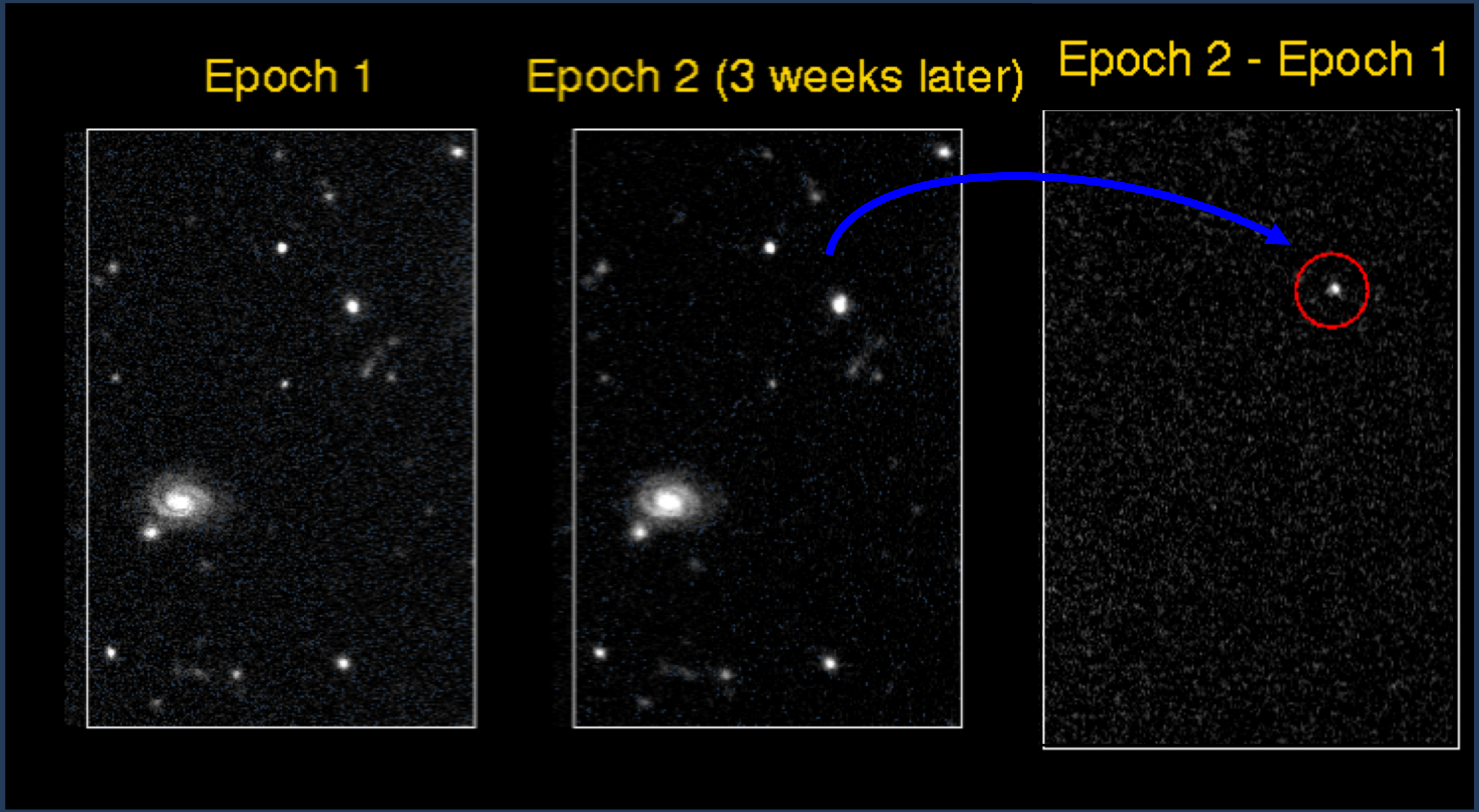

Extracted spectrum
z=0.866
0.8
0.6
0.4
0.2
0.0
Smoothed spectrum
allowing for:
• template host galaxy
subtraction
• Reddening
z=0.866
0.4
0.2
0.0
Best match template SN
6000
7000
8000
9000

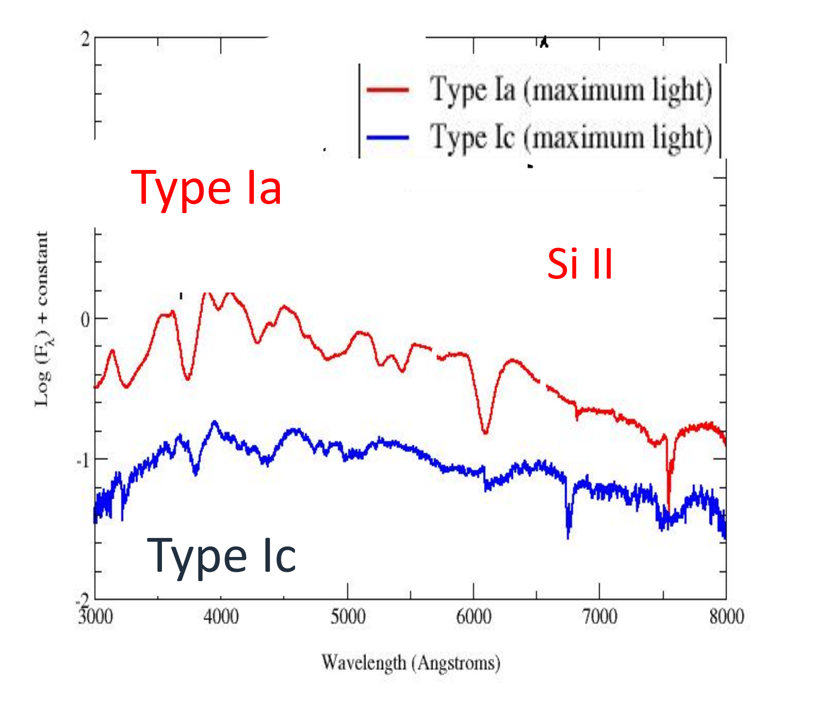
Host Galaxy spectrum



Finding Distant Supernovae



Type-Ia Supernovae



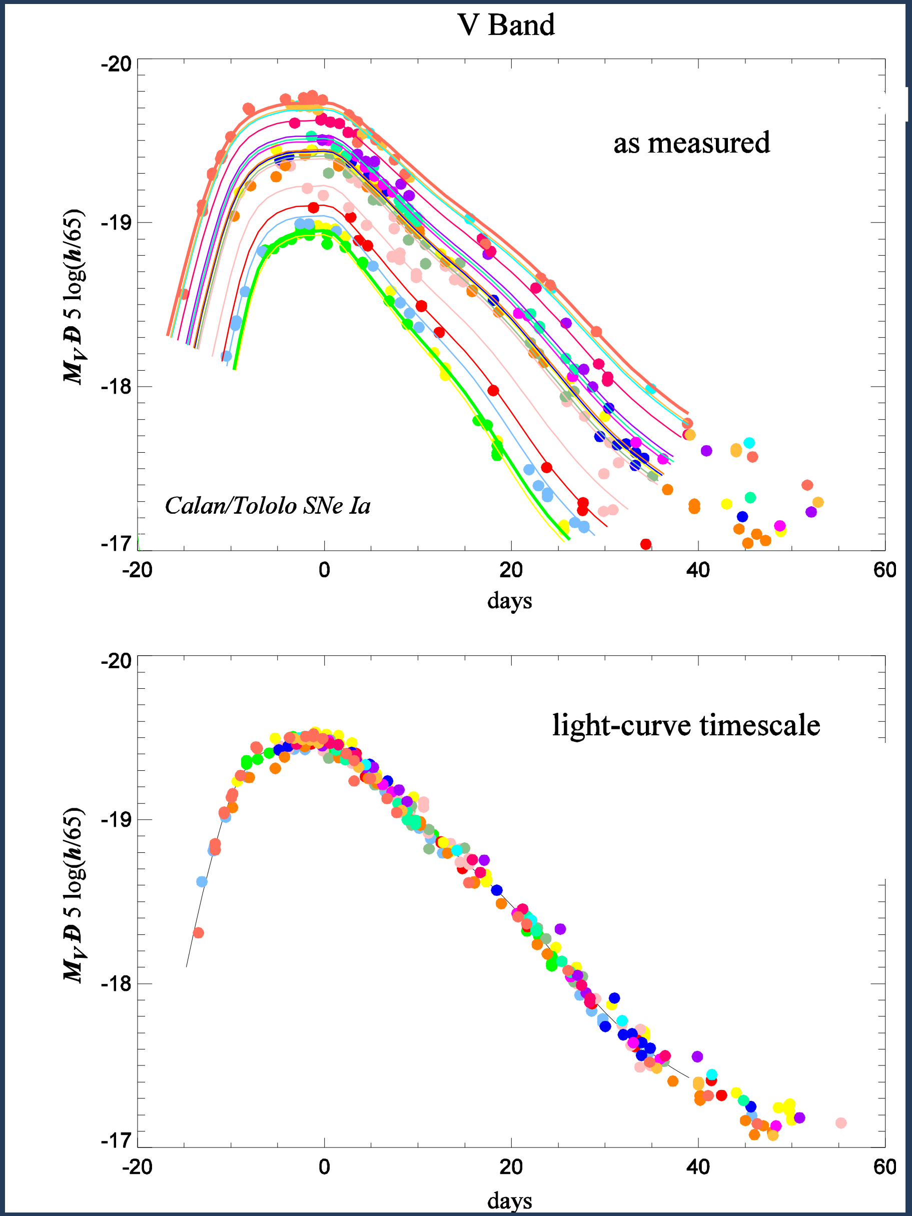
Spectral Classification:

- No hydrogen in the spectra
- Early spectra: Si, Ca, Mg (absorption features)
- Si II feature at 6150 Å
- Late spectra: Fe, Ni (emission features)

Type Ia SNe as Standard Candles

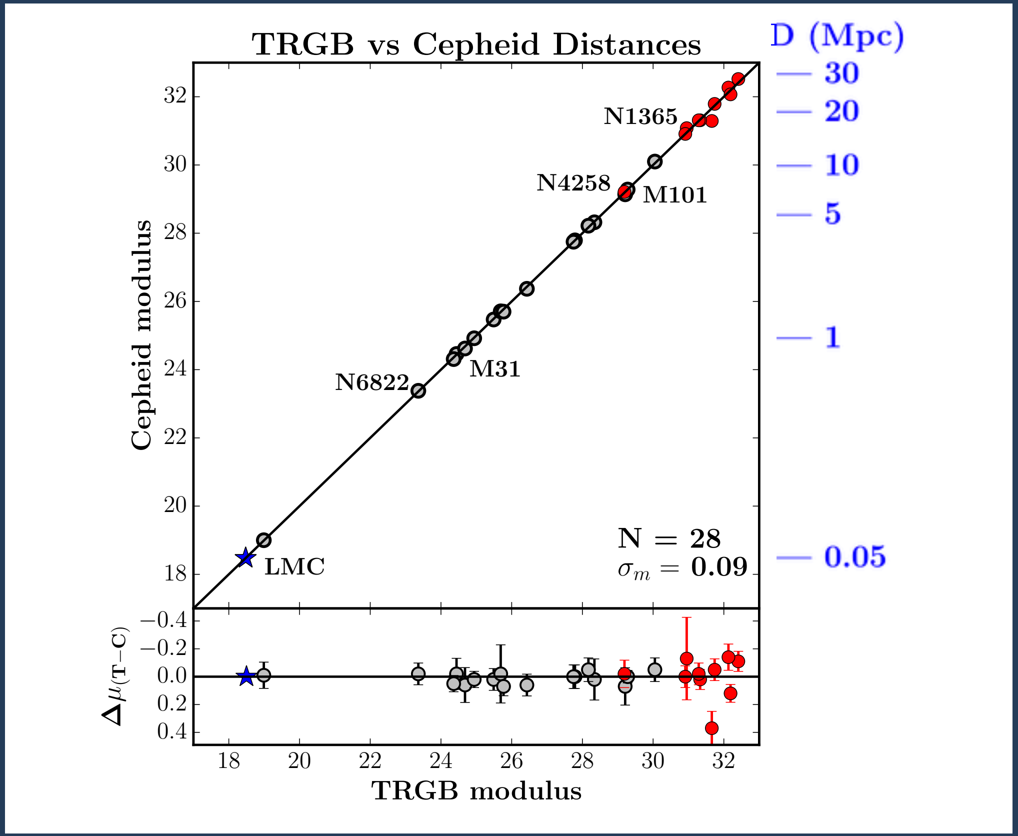
- SNe Ia are bright; visible at high-z
- Identified spectroscopically
- Small dispersion in peak luminosity
- Standardize using width-brightness relation

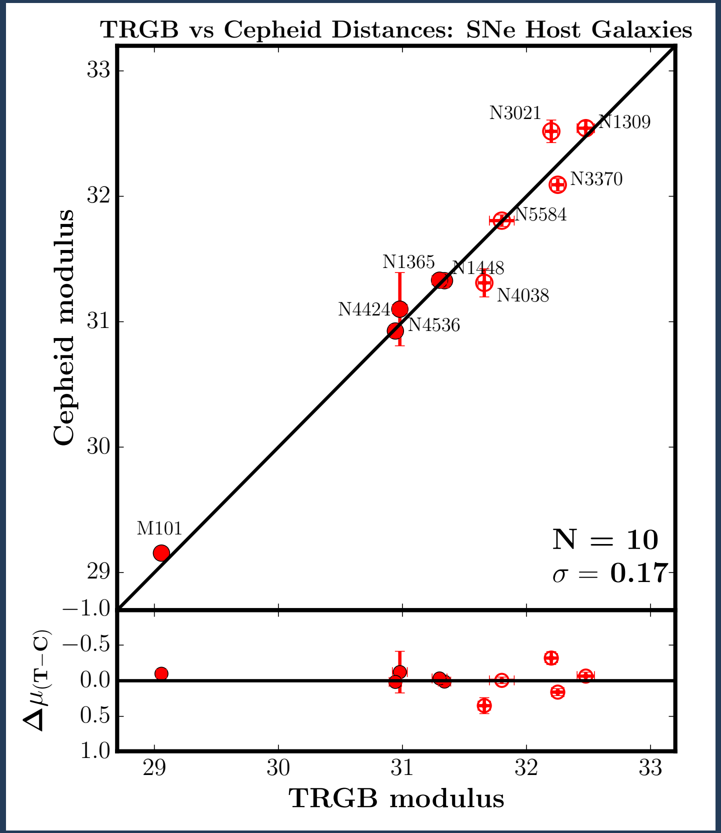
- Rise time: ~ 20 days
- Decay time: ~ 2 months
- Brightness: M_B ~ –19.5 at peak



Type Ia
Supernovae

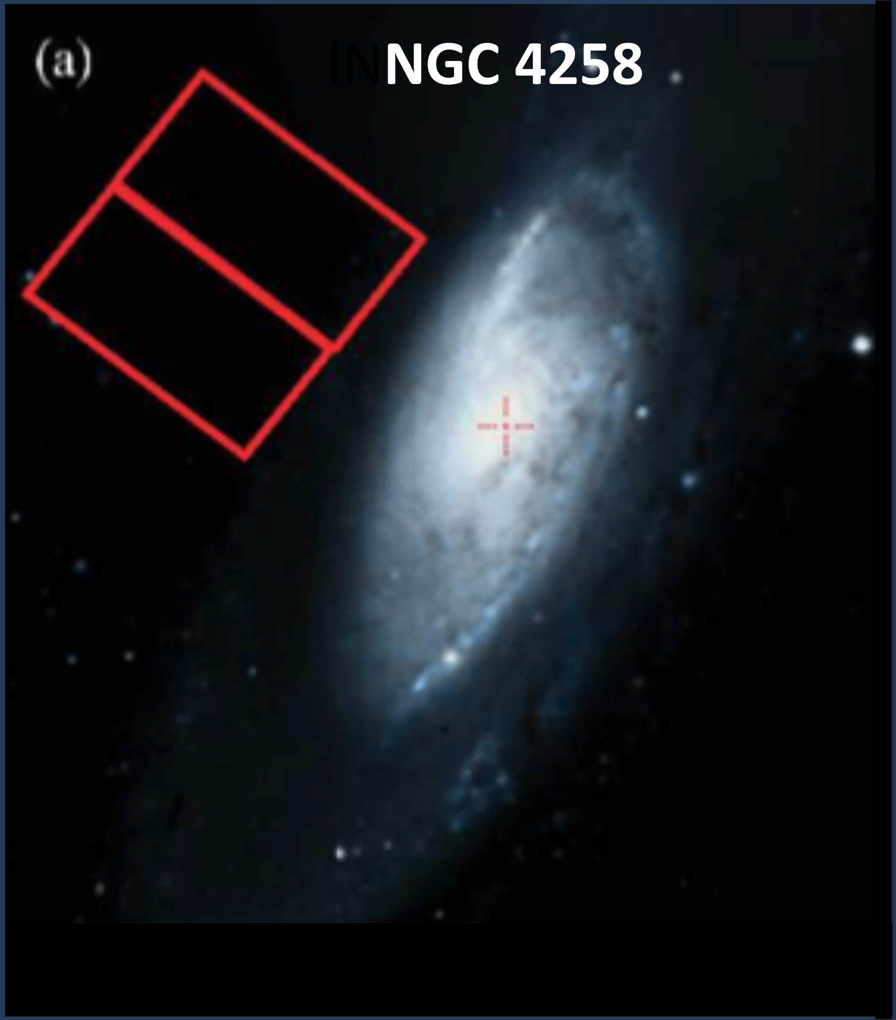
Comparison of Published TRGB and Cepheid Distances

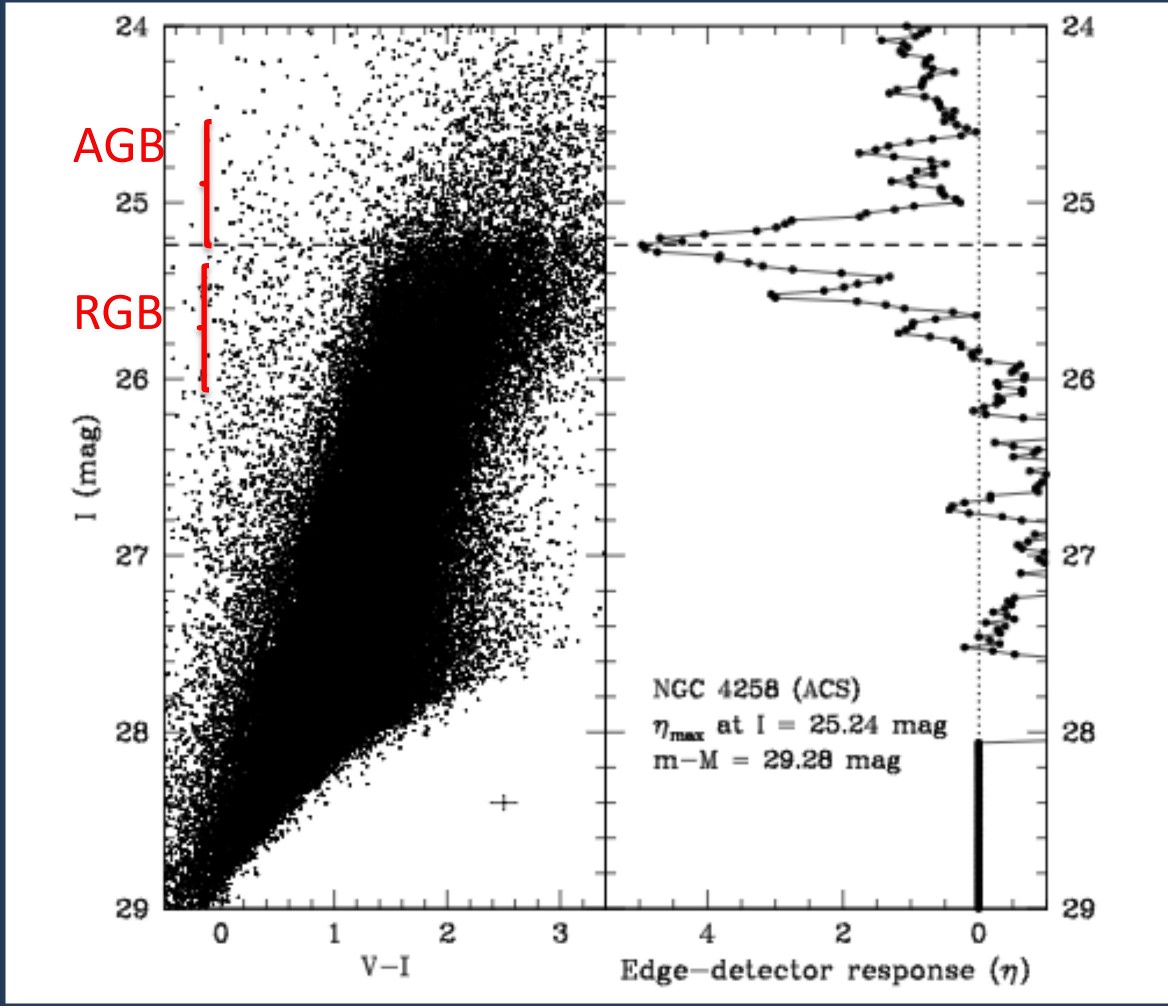




WLF et al. (2019)

The Tip of the Red Giant Branch



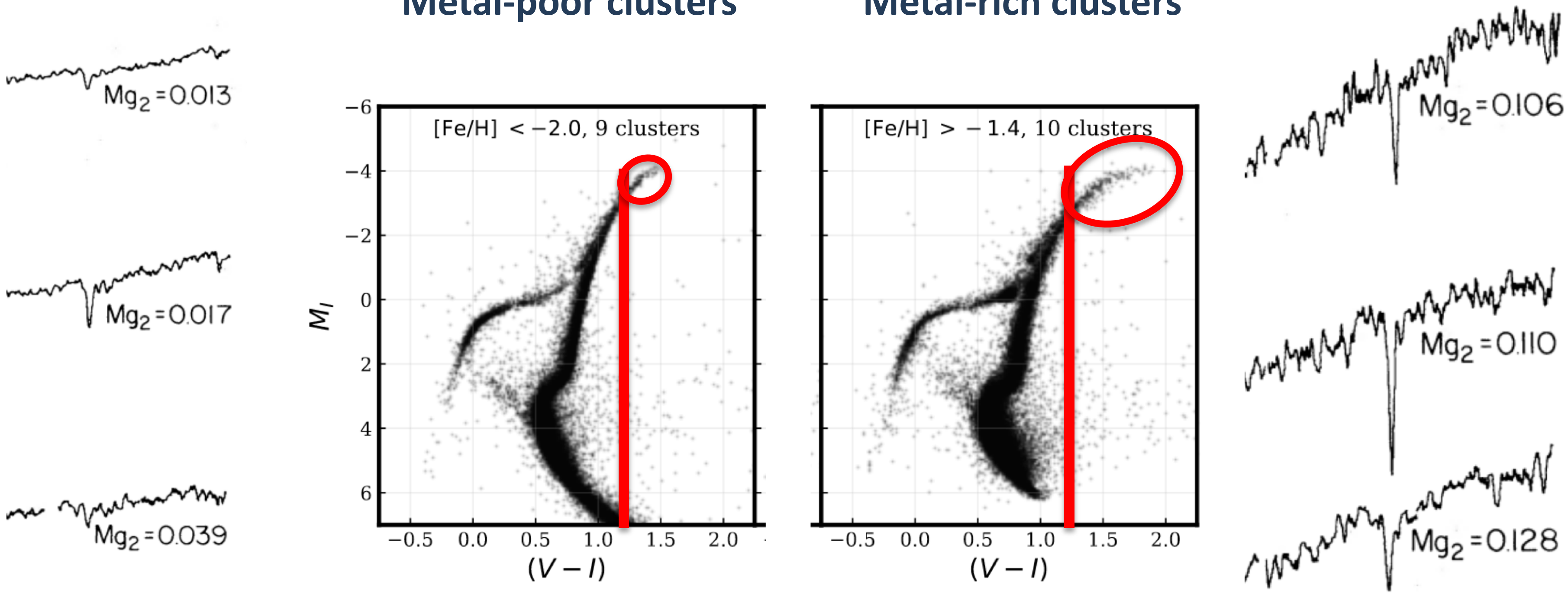


Measure 1st derivative of luminosity function

Mager, Madore & WLF (2008)

Empirical Calibration of the TRGB: Metallicity Effects

Metal-poor clusters **Metal-rich clusters**

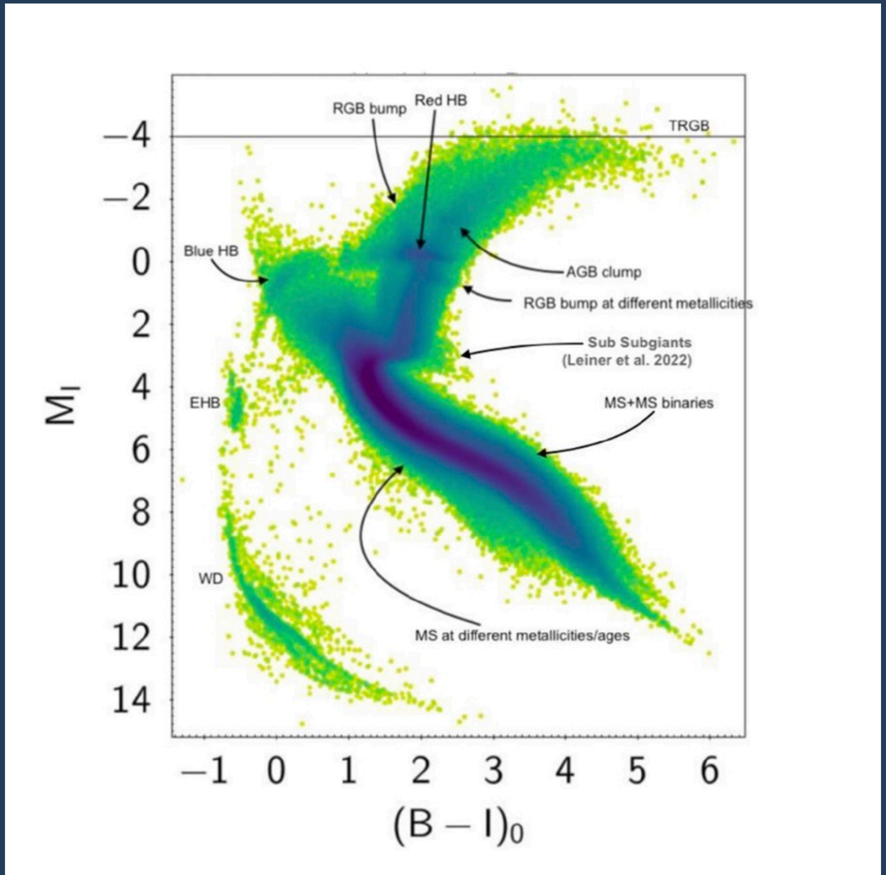


← Temperature

Spectroscopy from Burstein & Faber (1984)

CMDs adapted from Cerny et al. 2020

Milky Way CMD from Gaia

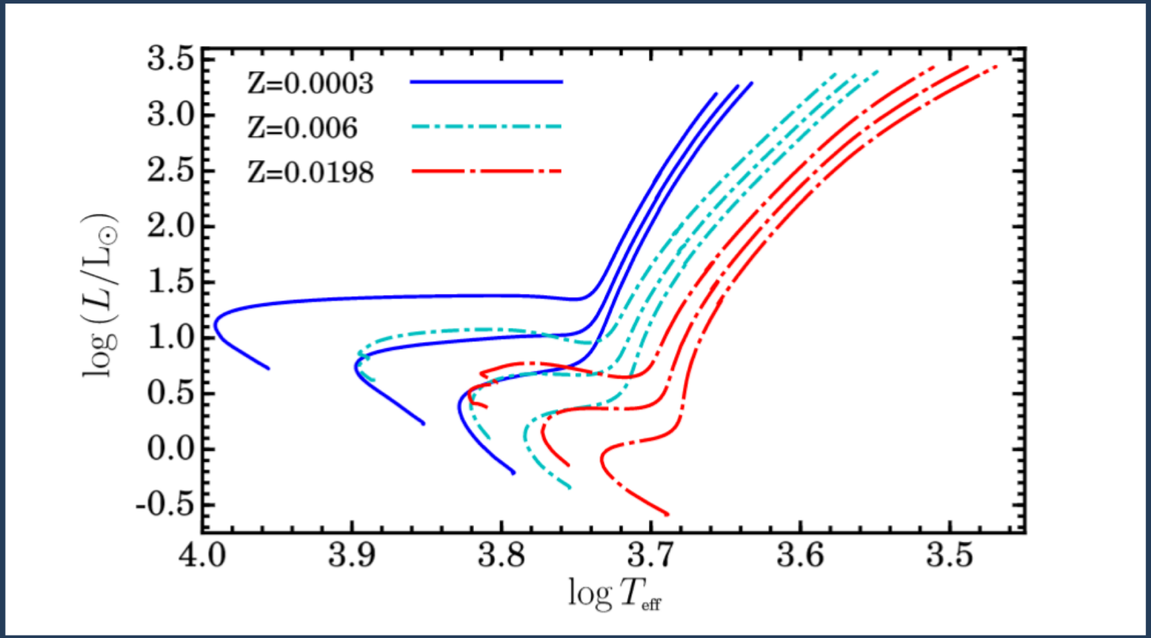


4 million stars |b| > 50º

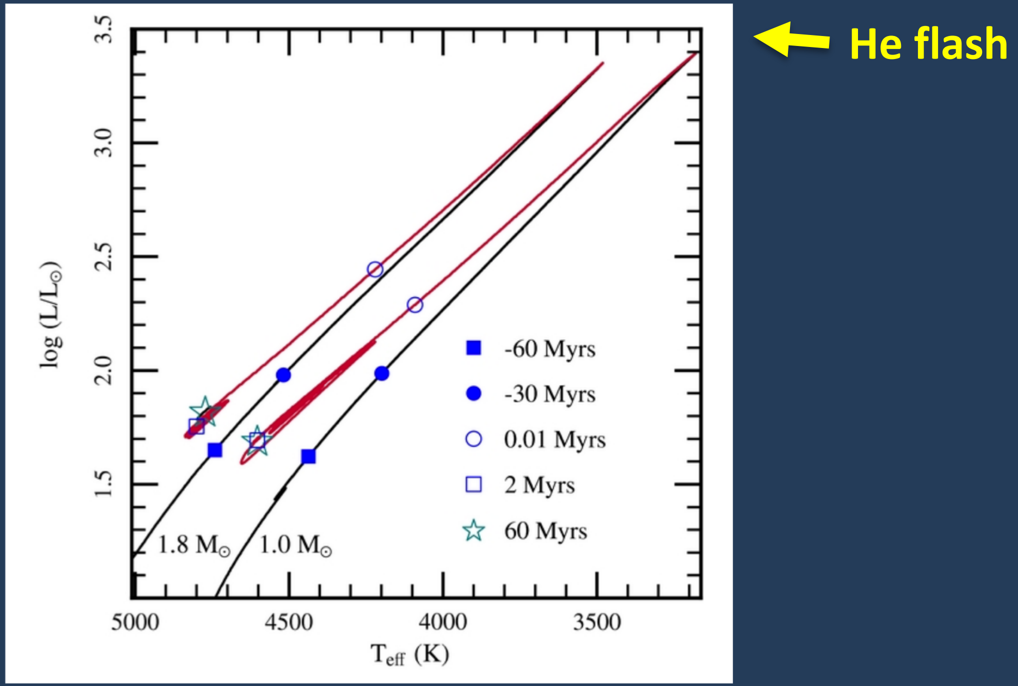
CMD generated by combining Johnson-Kron-Cousins (B-I) from the Gaia parallax and XP spectra using synthetic photometry

M. Bellazini

Tip of the Red Giant Branch (TRGB)

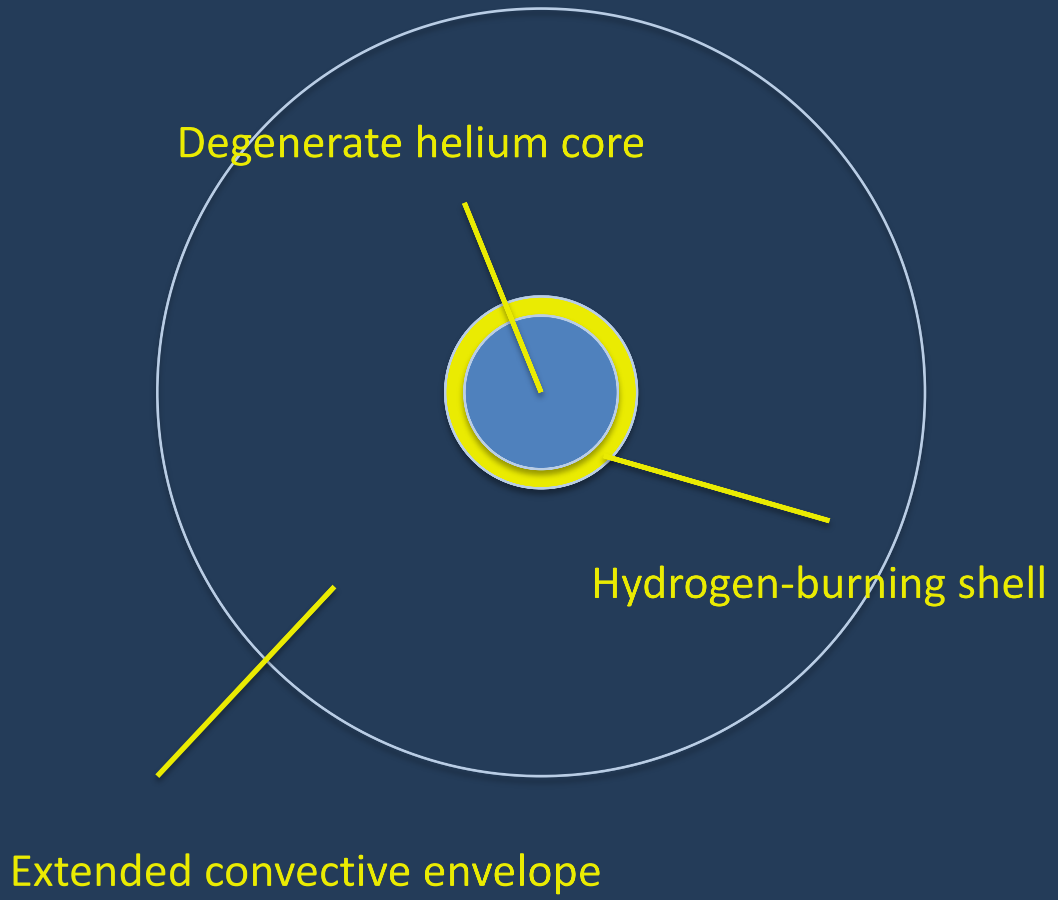


Serenelli et al. (2017)



Bildsten et al. 2012 (MESA)

Stellar Astrophysical Distance Methods: Lifting Degeneracy in Helium Core for Low-mass Stars (TRGB)



- Well-understood nuclear physics determines the temperature at which the electron degeneracy in the core is lifted, followed by helium core ignition
- $T_c \sim 10^8$ K, $M_c = 0.47\ M_\odot$
- Because of the degeneracy, the helium ignition happens at almost constant core mass. Thus the ignition occurs at a predictable luminosity.

The Challenge for H_o Measurements

$$T = \frac{\Delta H}{\sqrt{\sigma_P^2 + \sigma_C^2}}$$

$H_{Planck} = 67.4$
$\sigma_{Planck} = 0.5$

$H_{Ceph} = 73.0$
$\sigma_{Ceph} = ??$

For the tension in H_o to be at a level of 5σ, H_0 has to be measured to a TOTAL (statistical precision + systematic accuracy of) 1.0%

If, say, $H_0 = 72$ and the errors were a factor of 2 (1.5) larger than currently estimated, the tension would be only 1σ (3σ).

γ (mag / dex)

Gaia EDR3 parallax measurements:
Effect in near-infrared as large as in optical, contrary to previous studies.

The Optical Gravitational Lensing Experiment.
Cepheids in the Galaxy IC1613:
No Dependence of the Period–Luminosity Relation on Metallicity*

Ripepi et al. 2021
Best estimates:

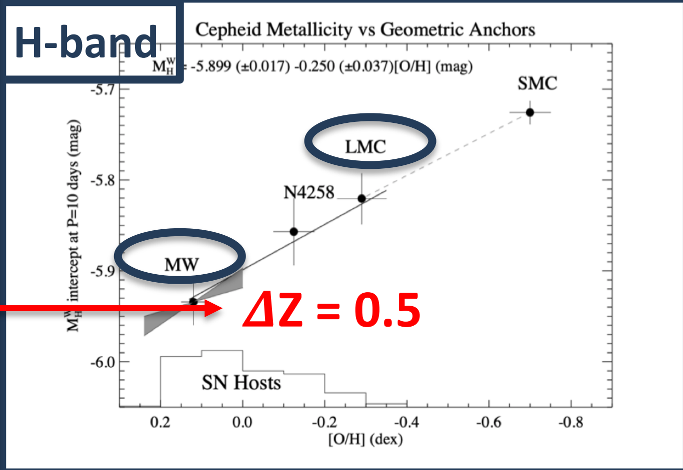
Breuval + Riess et al. 2021
$-0.048 < \gamma < -0.251$

Udalski et al. 2001
$\gamma = 0$

Implications:

- ΔZ (MW – LMC) = 0.5 dex
- For = -0.2 mag/dex ⇨ 0.1 mag or 5% in distance
- For = -0.4 mag/dex ⇨ 0.2 mag or 10% in distance

Given these uncertainties, it is not yet possible to rule out a systematic effect due to metallicity at the > 1% level.



Gieren et al. 2021
$-0.221 < \gamma < -0.335$

Riess et al. 2016
$\gamma = -0.13 \pm 0.07$

Riess et al. 2021
$\gamma = -0.217 \pm 0.046$

What Should We Next Understand to Take Cepheid Measurements to Next Level of Accuracy?

The Cepheid **Period-Luminosity-Color-Metallicity** Relation (Leavitt Law)

$$M_{\lambda_1} = \alpha \, logP + \beta(m_{\lambda_1} - m_{\lambda_2})_o + \gamma[O/H] + \delta$$

Luminosity	Period	Color term	'Metallicity'	Zero point

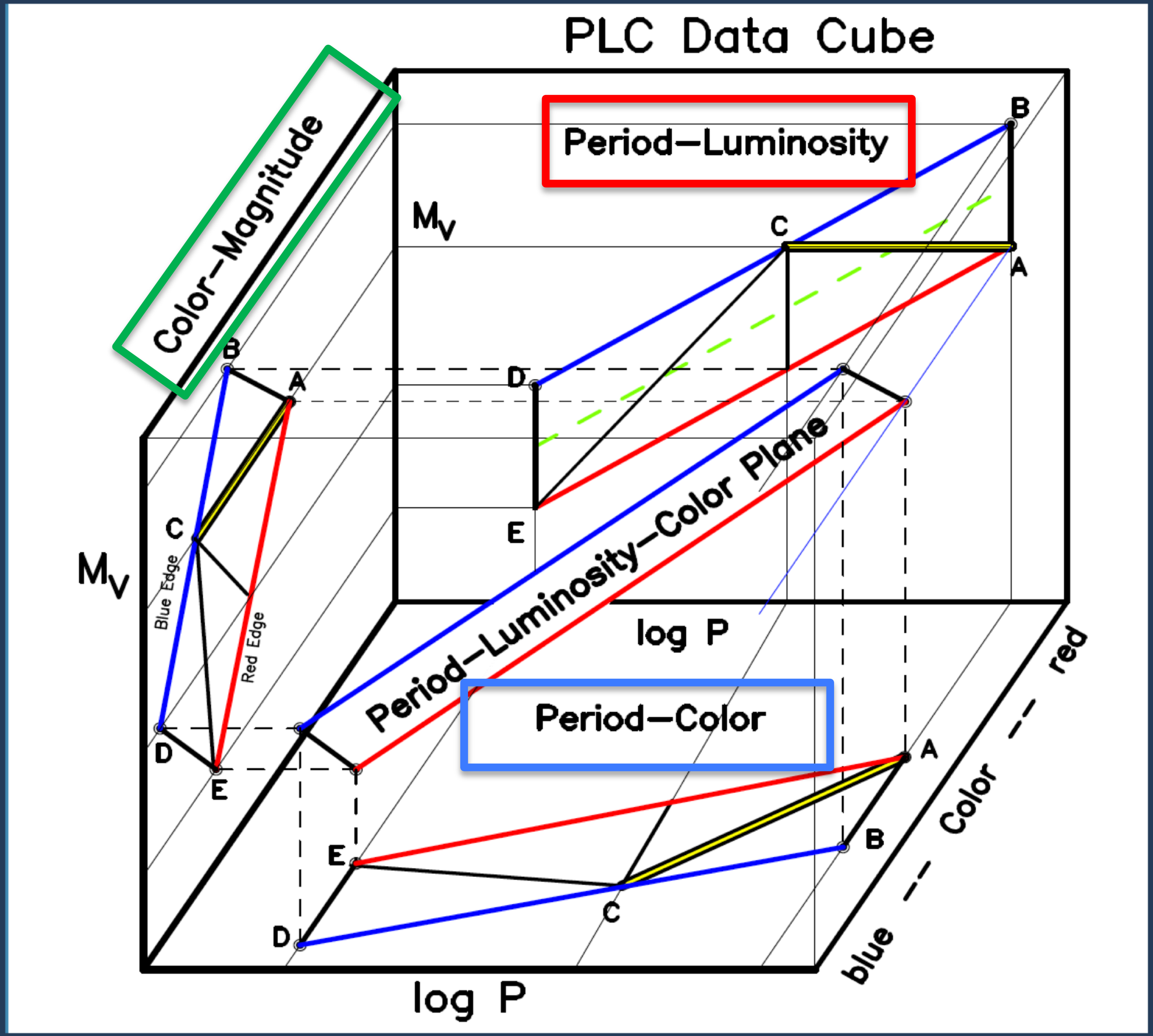
Important tests of the Cepheids:

1. the metallicity coefficient*
2. image resolution*

* JWST

Current Challenges to 1% ***Accuracy:***

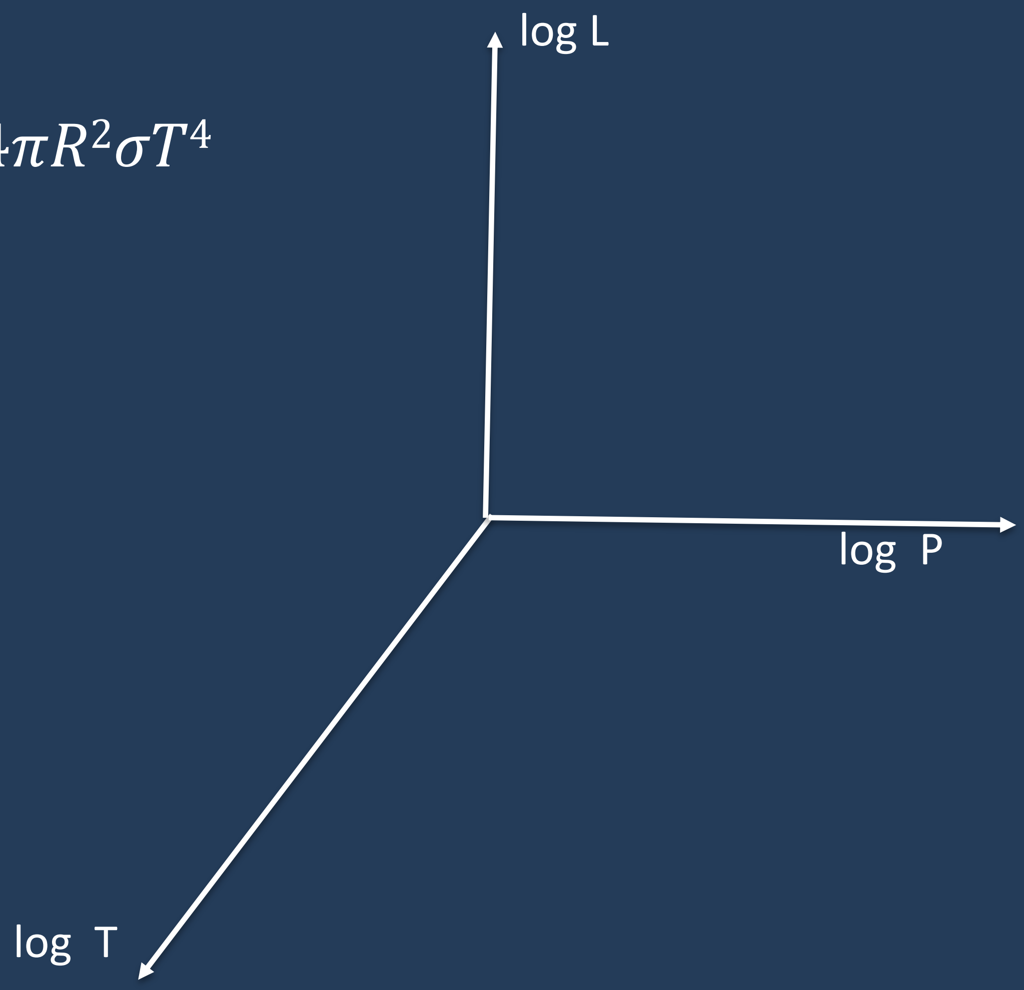
Astrophysical Distance Methods: Cepheids



Madore & WLF 1991

Astrophysical Distance Methods: Cepheids

$$L = 4\pi R^2 \sigma T^4$$



Cepheid Calibration of the Hubble Constant

Key Project: $H_0 = 72 \pm 3$ (stat.) $\pm$ 7 (sys.) km/sec/Mpc

Spitzer: $H_0 = 74.3 \pm 2.1$ (stat.) $\pm$ 4 (sys.) km/sec/Mpc

SHoES: $H_0 = 73.04 \pm 1.04$ (total) km/sec/Mpc

Can we conclude that these Cepheid results are now definitive?

Advantages & Disadvantages of Cepheids and TRGB for Measuring Distances

Cepheids

Advantages

1 Bright (M_V ~-6 mag)
2 Easily Identifiable
3 Potentially small dispersion in PL

Disadvantages

1 Metallicity dependence
2 Late-type galaxies only
3 Crowding/blending
4 Need many epochs
5 In regions of high extinction

TRGB

Advantages

1 In all types of galaxies
2 In regions of low to no extinction
3 Crowding negligible
4 Non-variable
5 Easily calibrated metallicity
6 Small dispersion in tip luminosity

Disadvantages

1 Fainter (M_I~-4 mag)

Freedman (2021) ApJ, 919, 16