The (Physics of the)Cosmic Distance Ladder

Cosmology and fundamental physics with current and future ESO facilities

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On behalf of G. Bono, G. Fiorentino, M. Monelli, C. Martinez-Vazquez, P.B. Stetson, M.T. Botticella, M. Della Valle, C. Barbarino and many other colleagues

An astrophysical view on the distance ladder

OUTLINE

→ **Impact of the distances on Ho**

→ **Classical Cepheids (by contract)**

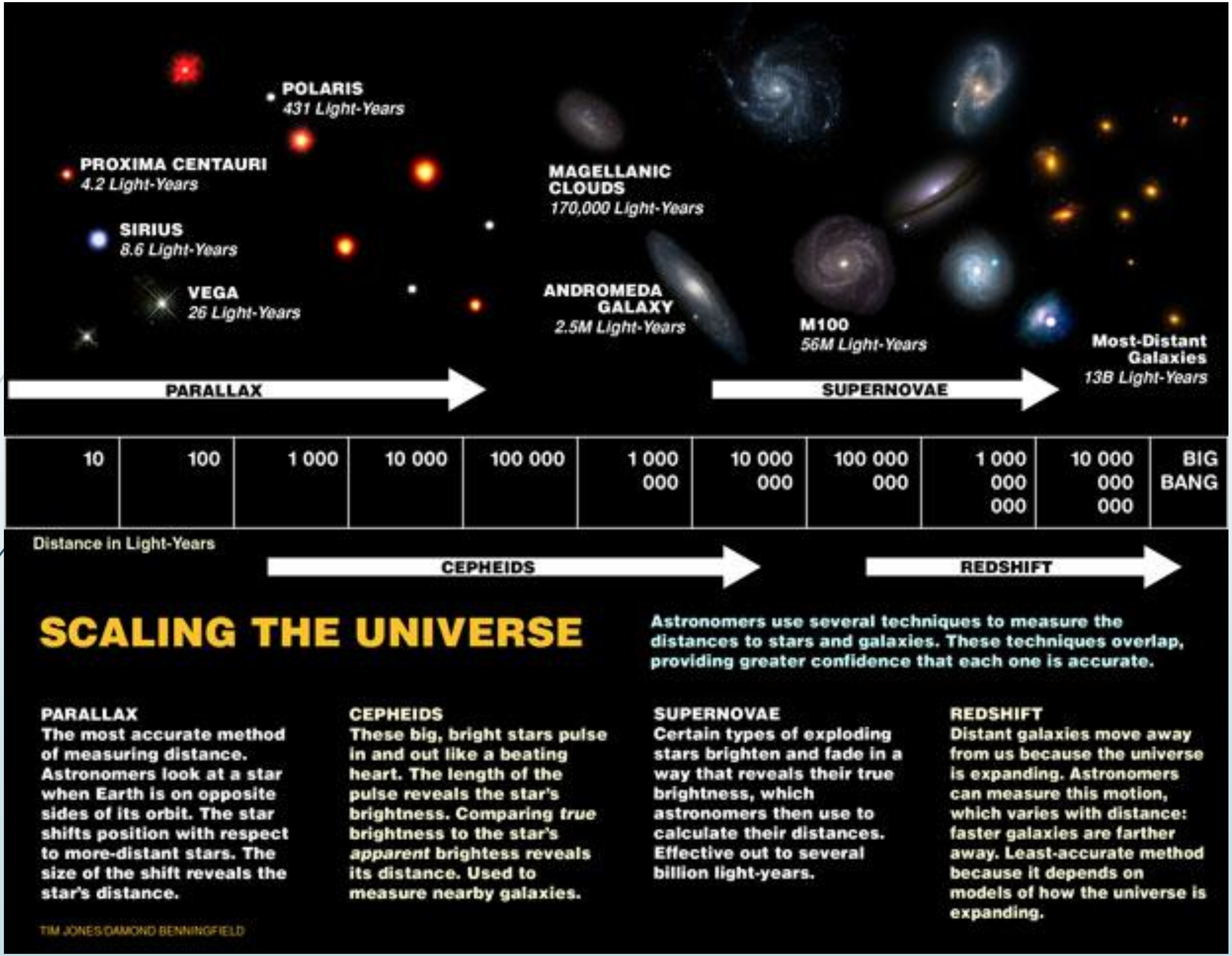
→ **RR Lyrae (& TRGB)**

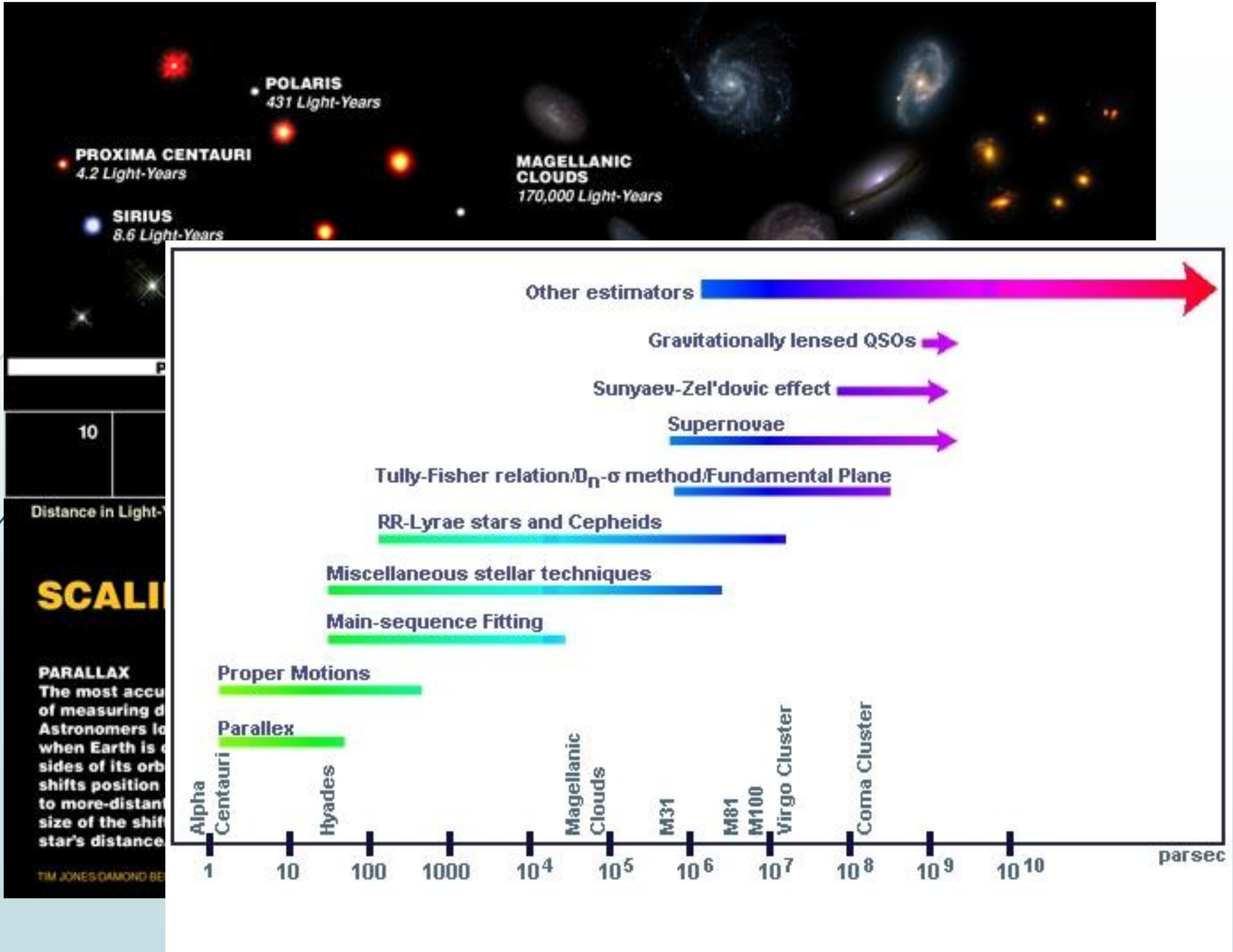
→ **(some) Core-Collapse Supernovae**

→ **The near future (Gaia, JWST, LSST, E-ELT)**

Why Variable Stars and Transients?

- Tracers of different stellar populations
- Physics Labs
- Standard Candles:
  - RR Lyrae → Old (≥ 10 Gyr) → all galaxies; distances within the LG
  - Cepheids → Young → disks, late type irregulars; distances up to ~ 25 Mpc
  - Type Ia SNe → ubiquitous; cosmological distances
  - Type IIP SNe (yes, type IIP SNe!) → young progenitors; current distances up to z ~ 0.4 (but we will go cosmological with E-ELT)
  - Type Ib, Ic and superluminous SNe as Standardizable Candles


POLARIS
431 Light-Years
PROXIMA CENTAURI
4.2 Light-Years
SIRIUS
8.6 Light-Years
VEGA
26 Light-Years
MAGELLANIC CLOUDS
170,000 Light-Years
ANDROMEDA GALAXY
2.5M Light-Years
M100
56M Light-Years
Most-Distant Galaxies
13B Light-Years
PARALLAX
SUPERNOVAE
10
100
1 000
10 000
100 000
1 000 000
10 000 000
100 000 000
1 000 000 000
10 000 000 000
BIG BANG
Distance in Light-Years
CEPHEIDS
REDSHIFT
SCALING THE UNIVERSE
Astronomers use several techniques to measure the distances to stars and galaxies. These techniques overlap, providing greater confidence that each one is accurate.
PARALLAX
The most accurate method of measuring distance. Astronomers look at a star when Earth is on opposite sides of its orbit. The star shifts position with respect to more-distant stars. The size of the shift reveals the star's distance.
CEPHEIDS
These big, bright stars pulse in and out like a beating heart. The length of the pulse reveals the star's brightness. Comparing true brightness to the star's apparent brightess reveals its distance. Used to measure nearby galaxies.
SUPERNOVAE
Certain types of exploding stars brighten and fade in a way that reveals their true brightness, which astronomers then use to calculate their distances. Effective out to several billion light-years.
REDSHIFT
Distant galaxies move away from us because the universe is expanding. Astronomers can measure this motion, which varies with distance: faster galaxies are farther away. Least-accurate method because it depends on models of how the universe is expanding.
TIM JONES/DAMOND BENNINGFIELD


POLARIS
431 Light-Years
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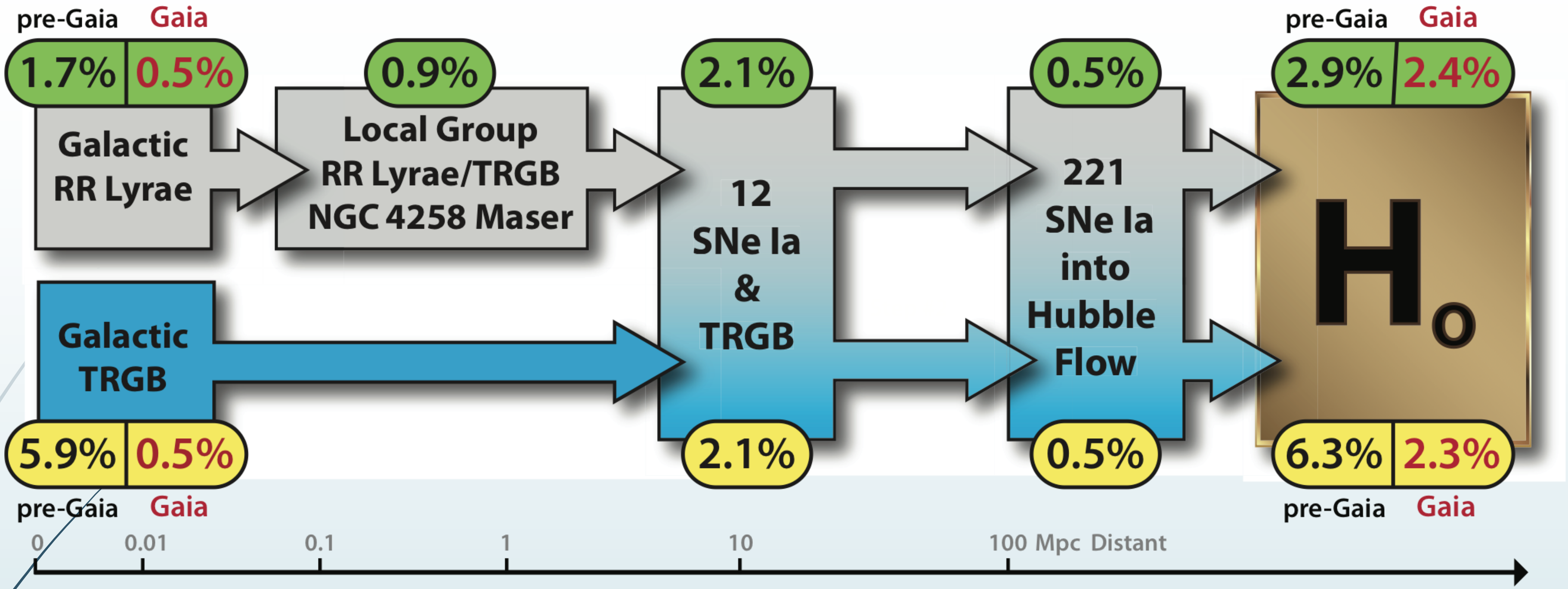
170,000 Light-Years
10
Distance in Light-
SCALI
PARALLAX
The most accu
of measuring d
Astronomers lo
when Earth is o
sides of its orb
shifts position
to more-distant
size of the shif
star's distance
Other estimators
Gravitationally lensed QSOs
Sunyaev-Zel'dovic effect
Supernovae
Tully-Fisher relation/D_n-σ method/Fundamental Plane
RR-Lyrae stars and Cepheids
Miscellaneous stellar techniques
Main-sequence Fitting
Proper Motions
Parallex
Alpha Centauri
Hyades
Magellanic Clouds
M31
M81
M100
Virgo Cluster
Coma Cluster
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
parsec

The CCHP Pathways to a 3% Determination of the Hubble Constant



There is evidence that Type II Cepheids

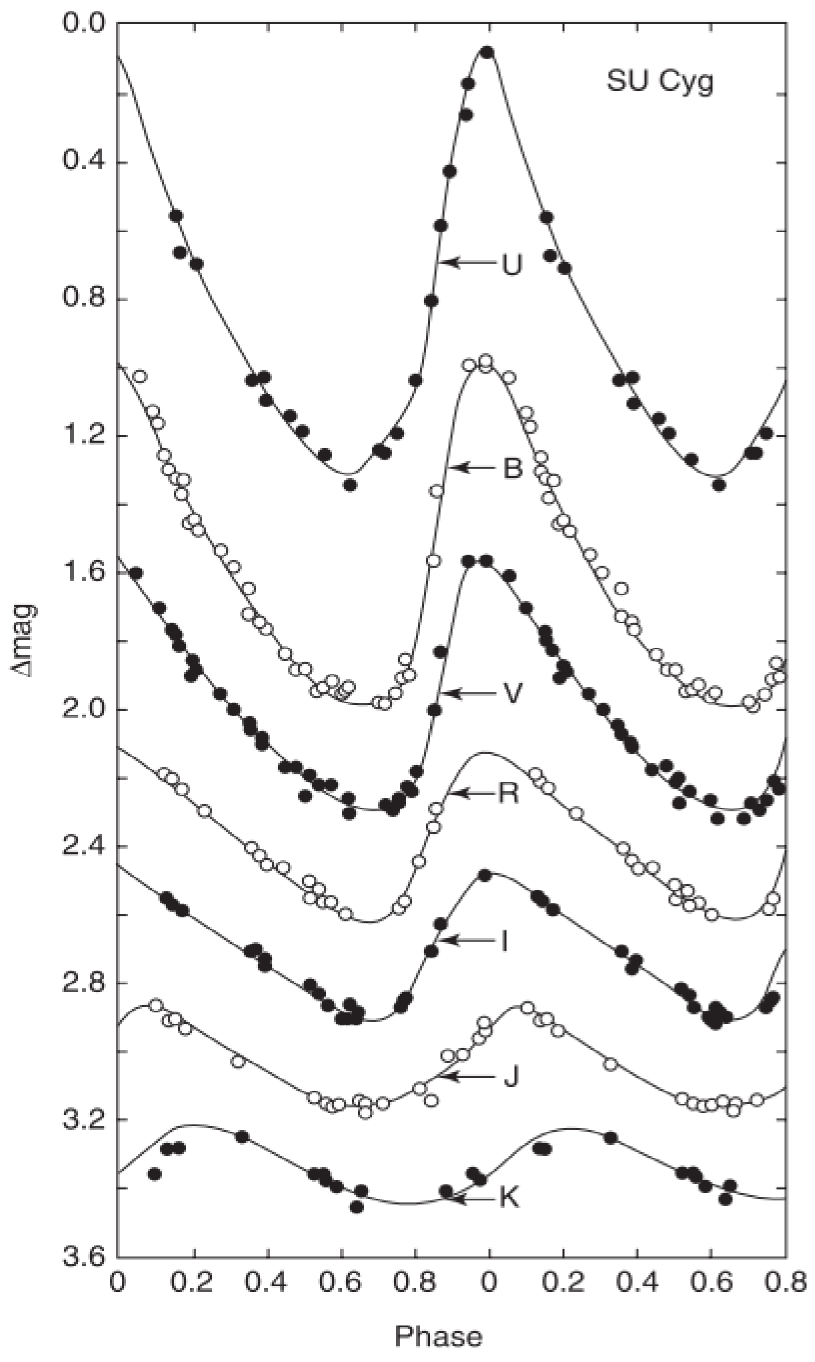
(2-3 mag brighter than RR Lyrae)

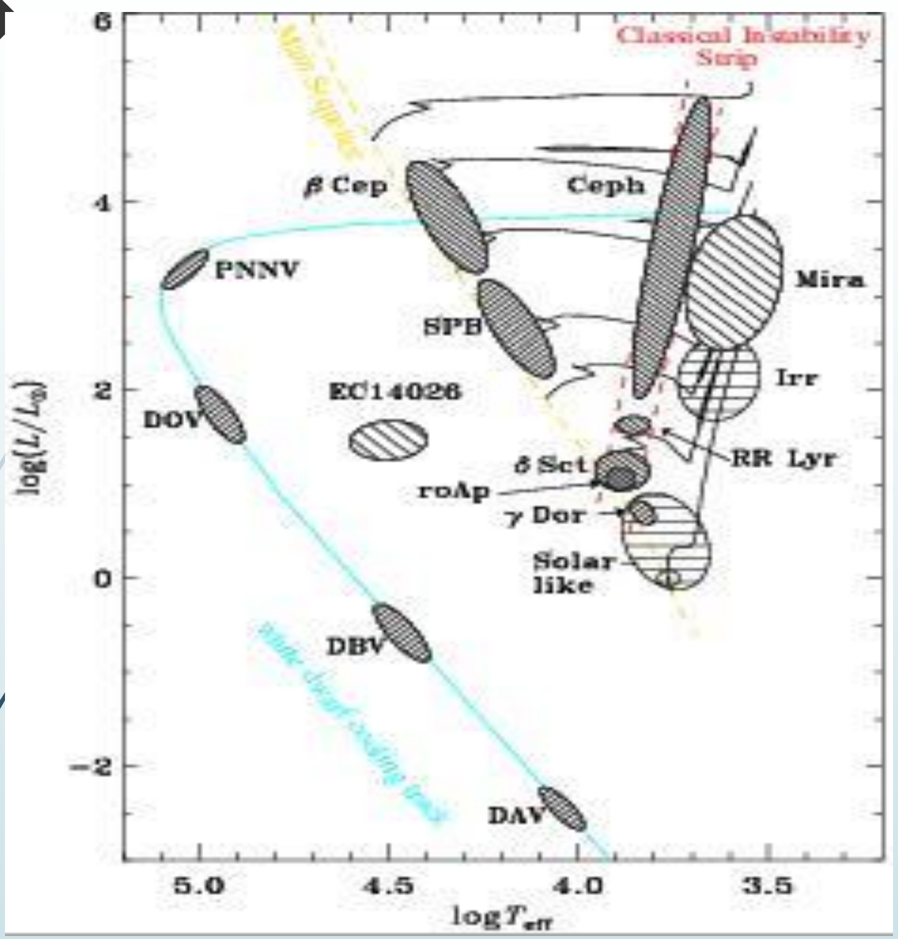
are also going to play a crucial role

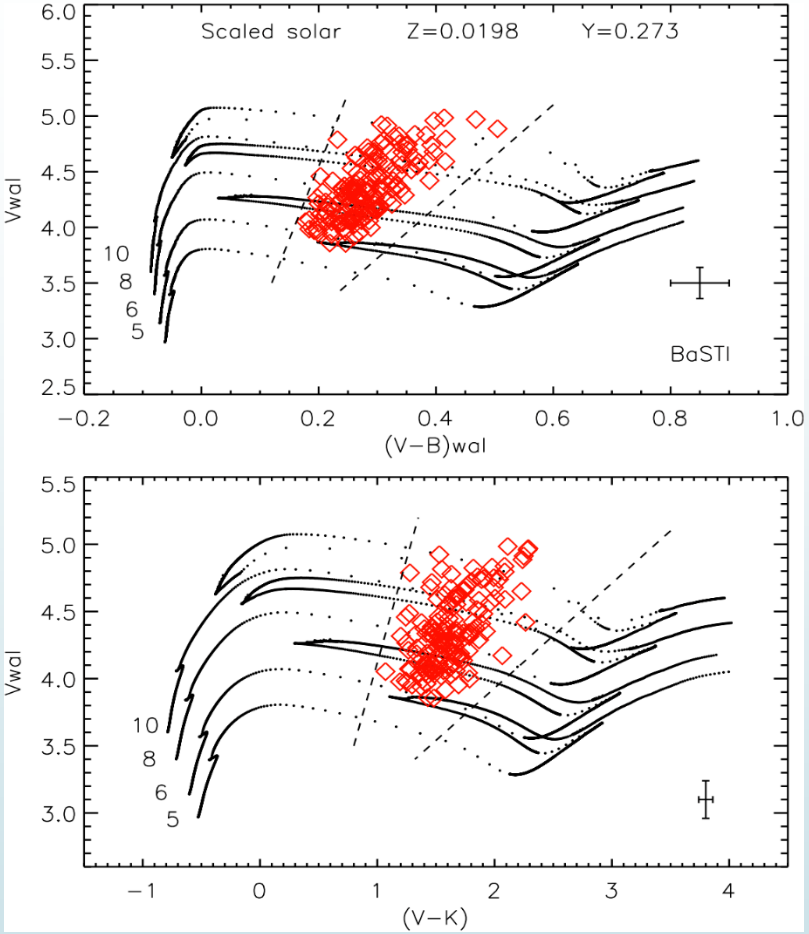
Classical Cepheids

Classical Cepheids in a nutshell

- **Radially pulsating variable stars**
- **Main Sequence progenitors between 2 and 20 $M_\odot$ (some of them will explode as Supernovae!), but most of the MW Cepheids are in the mass range 4-9 $M_\odot$**
- **Periods between 1 and 100 days (but Cepheids with longer periods have been detected**
- **Absolute magnitudes between $M_V \approx -2$ mag and $M_V \approx -6$ mag → *bright* objects → visible at large distances**
- **The absolute magnitude depends (basically) on the period → distances!!**





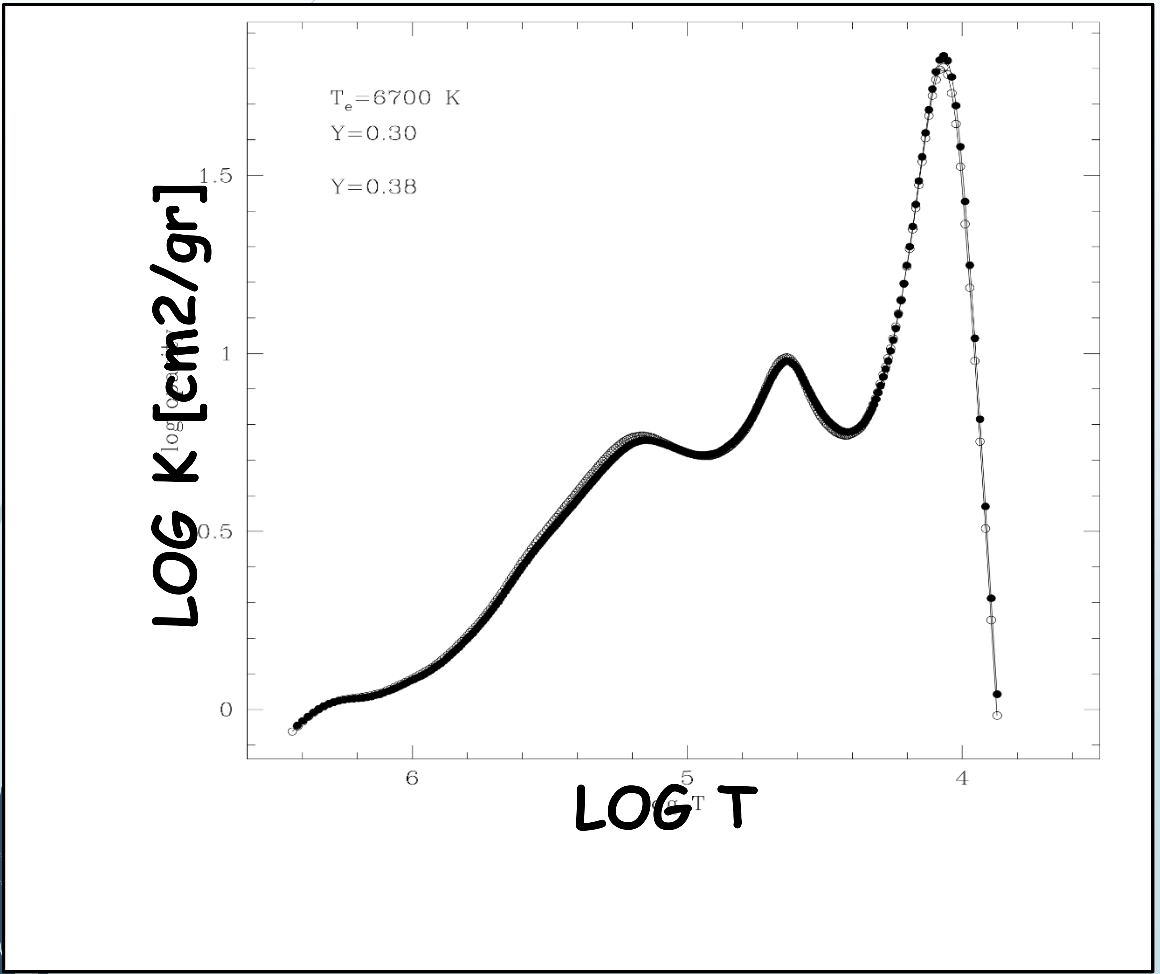


Cepheid Instability Strip

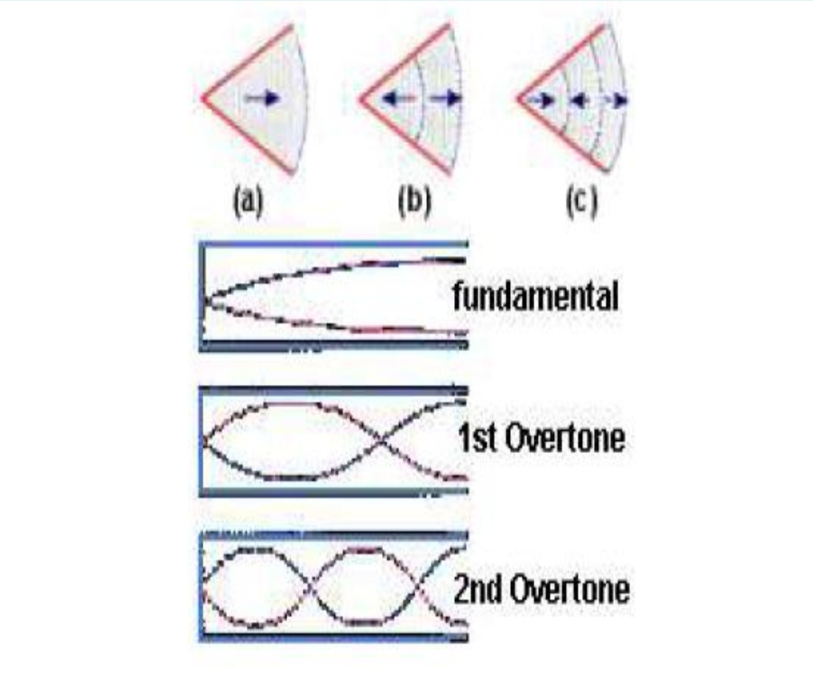
Intermediate-mass stars central He-burning phase

Why stars pulsate?

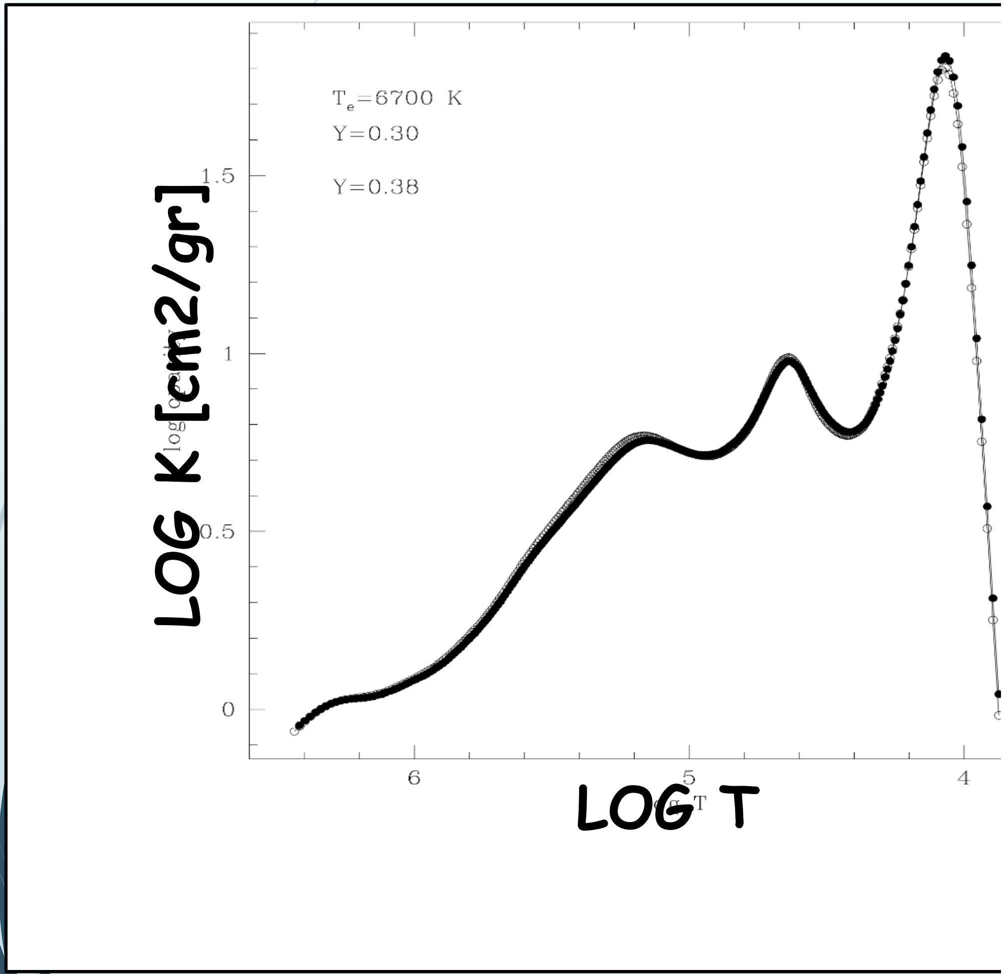
K & Y mechanisms



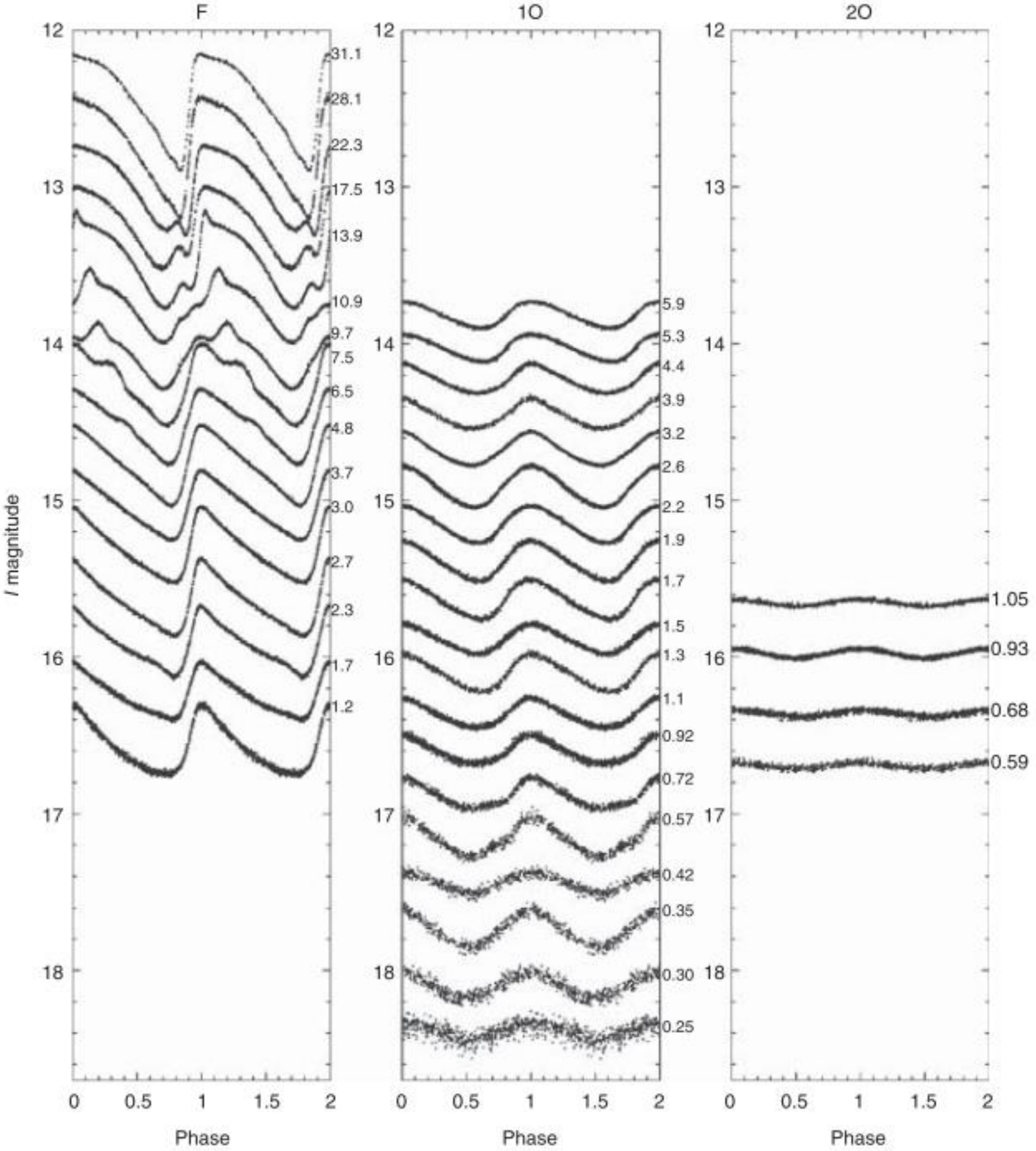
Radial Modes



Why sta

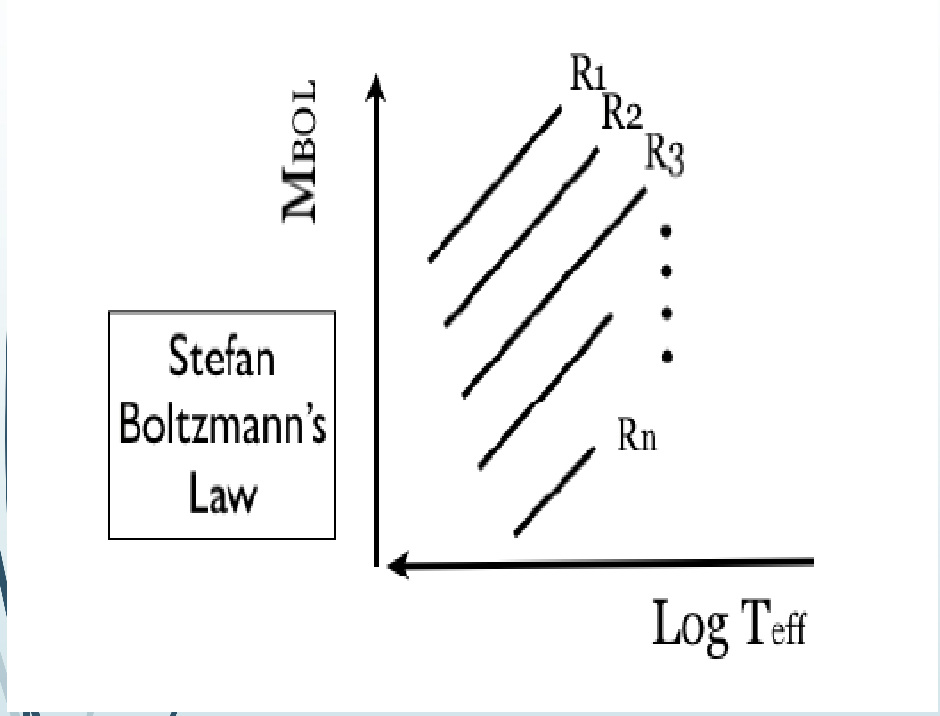


T_e=6700 K
Y=0.30
Y=0.38
LOG K [cm2/gr]
LOG T
1.5
1
0.5
0
6
5
4



F
1O
2O
I magnitude
Phase
12
13
14
15
16
17
18
0
0.5
1
1.5
2
31.1
28.1
22.3
17.5
13.9
10.9
9.7
7.5
6.5
4.8
3.7
3.0
2.7
2.3
1.7
1.2
5.9
5.3
4.4
3.9
3.2
2.6
2.2
1.9
1.7
1.5
1.3
1.1
0.92
0.72
0.57
0.42
0.35
0.30
0.25
1.05
0.93
0.68
0.59

Basic leading physical arguments



Mbol = const + 5log R + 10log Teff
Stefan-Boltzmann

P = √(R/g) *von Ritter relation*

g=surface gravity

P = Q / √ρ

Period-Luminosity-Color

Mbol = α + β*log P + γ*log Teff

M_X = α + β*log P + γ* CI

Warning!
The Period brings in the Stellar mass ….

This means that PLC & PL implicitly include the Mass-luminosity relation.

… but the pulsation models are envelope models!!

This opens the path to the marriage of convenience between stellar evolution and stellar pulsation

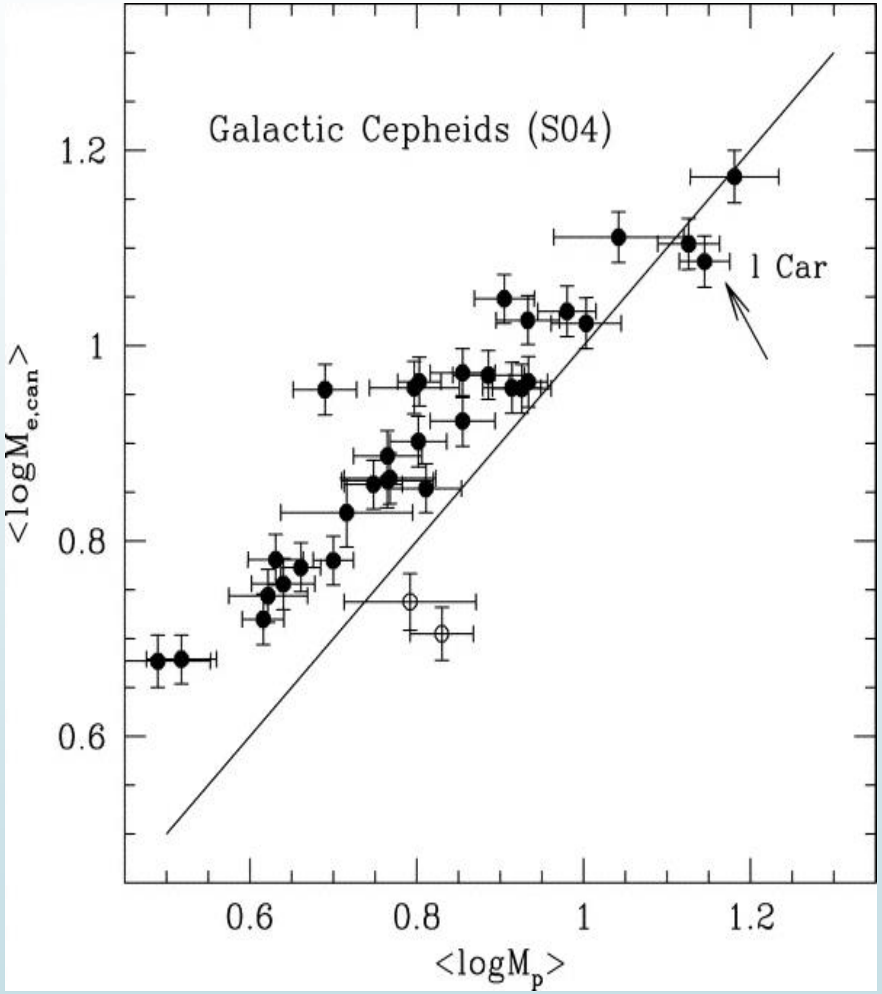
The ML relation and the metallicity dependence are fundamental ingredients ….

We were facing a stark discrepancy between evolutionary & pulsation masses (Christy 1968)

The former ones 30-40% larger than the latter ones

Discrepancy alleviated by the "new" opacities [Livermore & OP] → at the 10-20% level

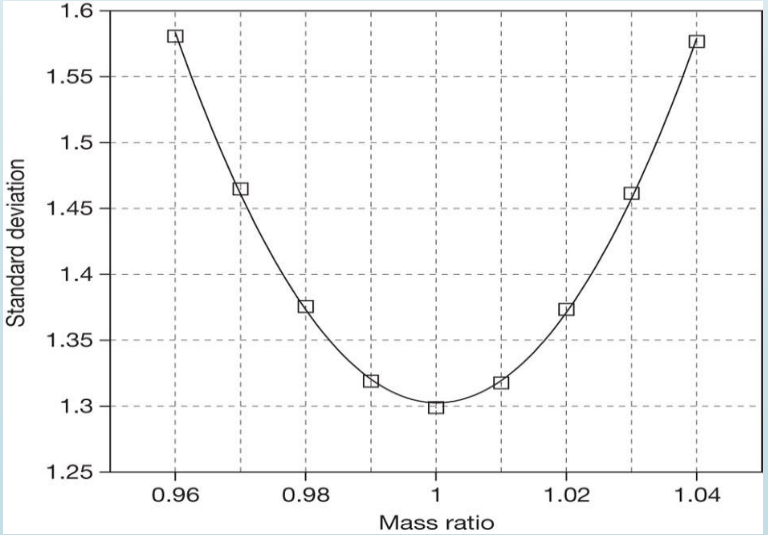
NO ACCURATE MEASUREMENTS OF THE DYNAMICAL MASS OF A CEPHEID!!



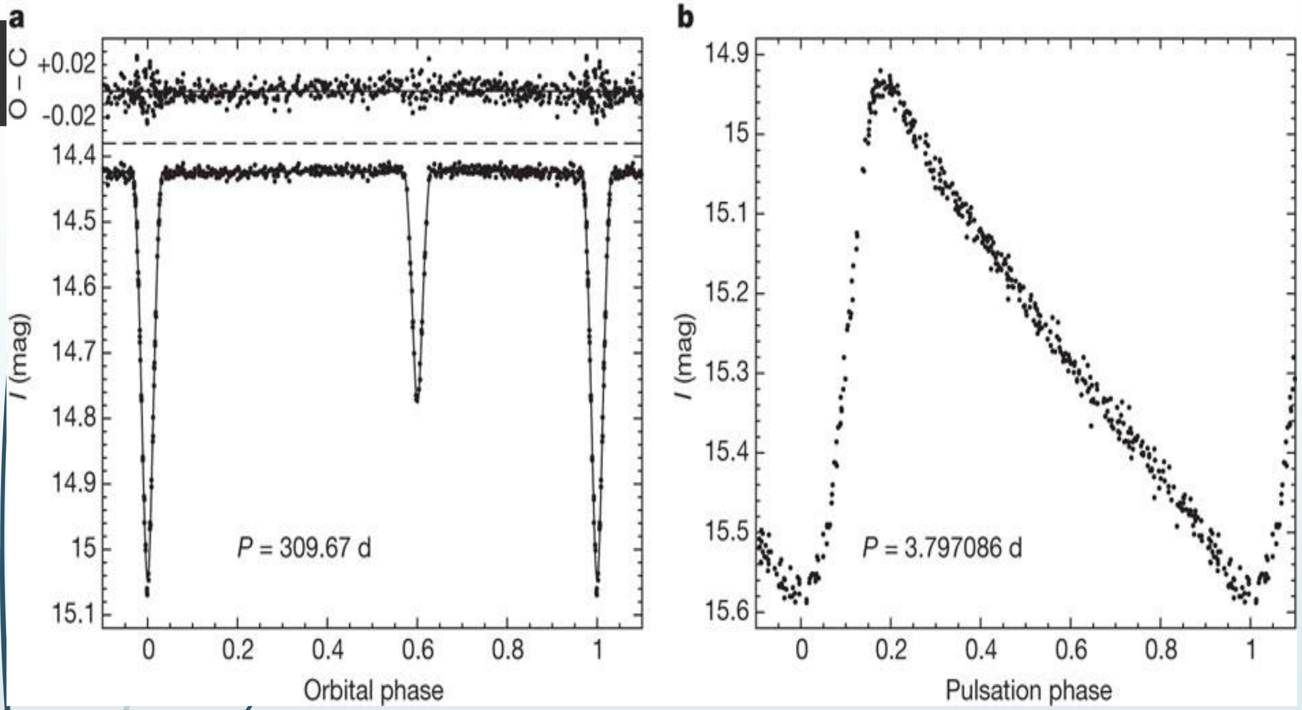
Caputo et al. (2005)

Double-lined, well detached eclipsing binary (OGLE) in the Large Magellanic Cloud

Pietrzyński + Nature 468, 542-544 (2010)
+ ESO Press Release



The procedure adopted to separate Pulsation & orbital motion of the Cepheid



Change of brightness of the binary system caused by the mutual eclipses, and the intrinsic change of the brightness of the Cepheid

The pulsational masses based on period & mean radius provide masses that, within theoretical and the empirical uncertainties, agree quite well with dynamical mass.

Mdyn=4.14±0.05 Mo
Mpul =3.98±0.29 Mo

Cepheid Pulsation & Evolutionary Properties

Cepheid do obey to a PLC relations
(consequence of a Mass-Luminosity relation)

$$\mathrm{Log}L/L_o = \alpha + \beta \,\mathrm{Log}\, P + \gamma \,\mathrm{Log}\, T_e$$

$$M_V = \alpha + \beta \,\mathrm{Log}\, P + \gamma \, CI$$

The PL neglects the width in temperature of the IS
This assumption is valid in the NIR, but not in the optical
[σ (V)=0.2-0.3 mag]

Why we use PL instead of PLC relation?

Observations: sensitivity to reddening uncertainties

Theory: sensitivity to color-temperature relations

Lack of homogeneous metallicity scale for MW and MC Cepheids

Reddening law: MW + external gal.

Metallicity gradients based on Oxygen abundances:

→O is an α-element …

→Strong nebular emission lines in HII regions

→Blue & Red supergiants → Kudritzki et al. (2015)

Recipe for Ho 1.5-1.8%

→Calibrating SNIa

→Zero-point of PL relation

→Metallicity dependence of zero-point and slope

Cepheids allow us to calibrate SNIa in spirals but not in ellipticals → RR Lyrae + TRGB

How can we settle the zero-point and the metallicity dependence?

1) Spectroscopic Route

HR spectra Galactic & Magellanic Cepheids

2) Period-Wesenheit relations

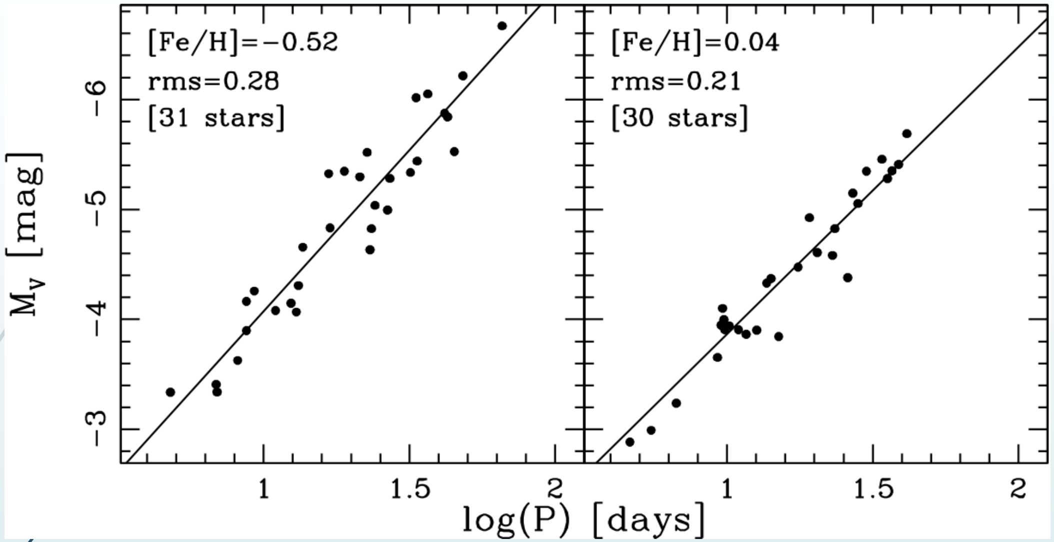
Galactic & Magellanic Cepheids

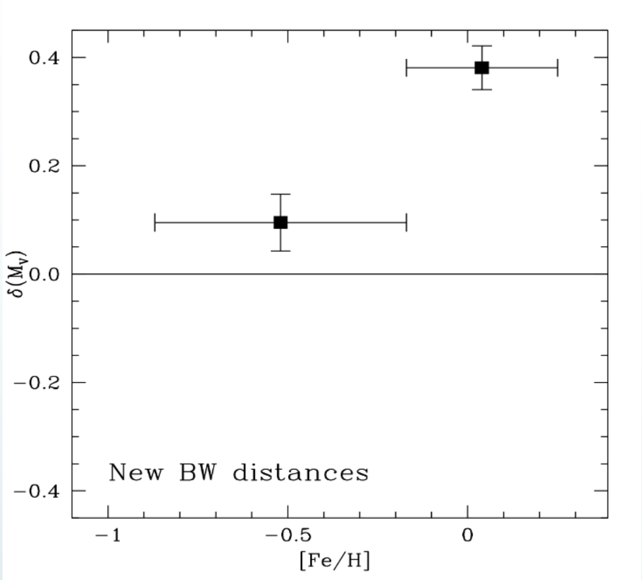
3) Extragalactic Route

Homogeneous analysis of all available data

4) LMC depth effects

1) Metallicity dependence: V-band



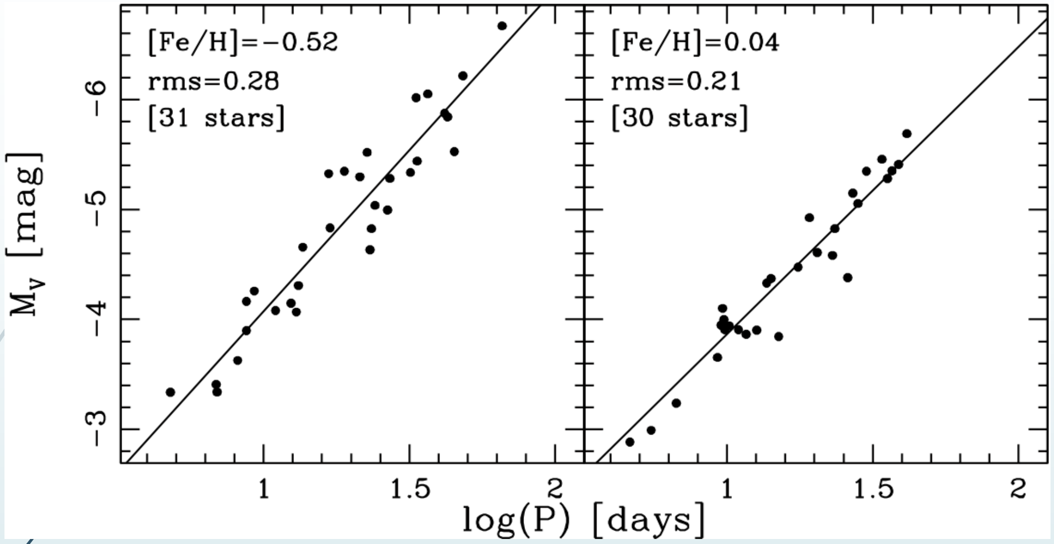


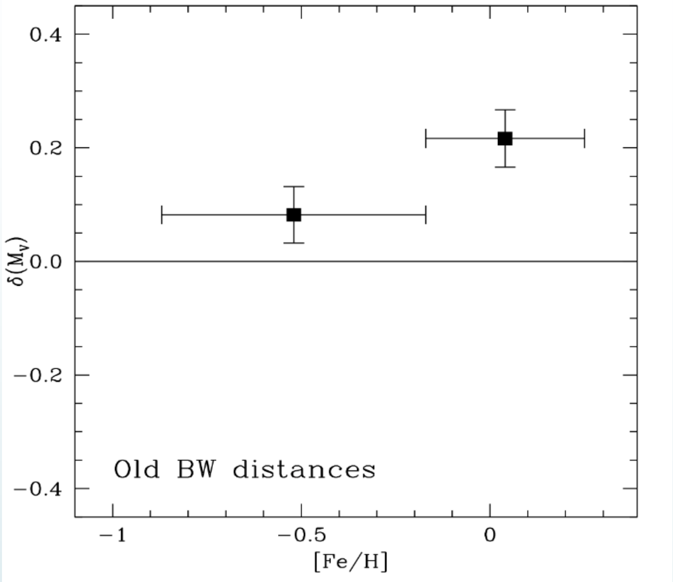
The PLV relation is not Universal (95% confidence level)

Not affected by LMC distance

MP & MR Cepheids are located at 2 and 9 σ from zero. The difference bewteen MP & MR is at 3σ

1) Metallicity dependence: V-band



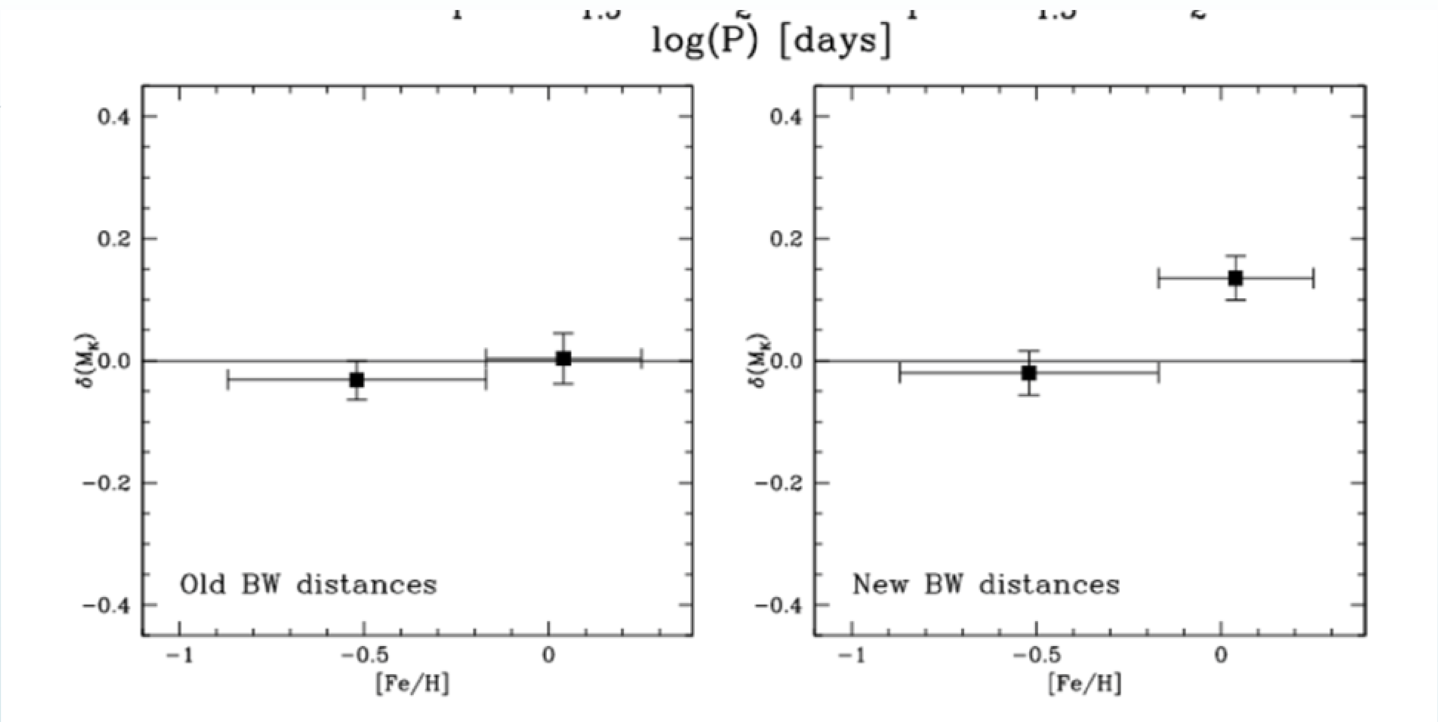


The PLV relation is not Universal (95% confidence level)

Not affected by LMC distance

MP & MR Cepheids are located at 2 and 9 σ from zero. The difference bewteen MP & MR is at 3σ

1) Metallicity dependence: K-band



NIR bands are much less sensible to metallicity effects, but still we have a problem with solar-metallicities

2) Wesenheit relations

$$W(BV) = V - A_V/E(B-V) * (B-V)$$

PROS

Reddening free

Linear over the entire period range

<<Mimic a PLC relation>>

Theory marginally dependent on mixing-length & on Y

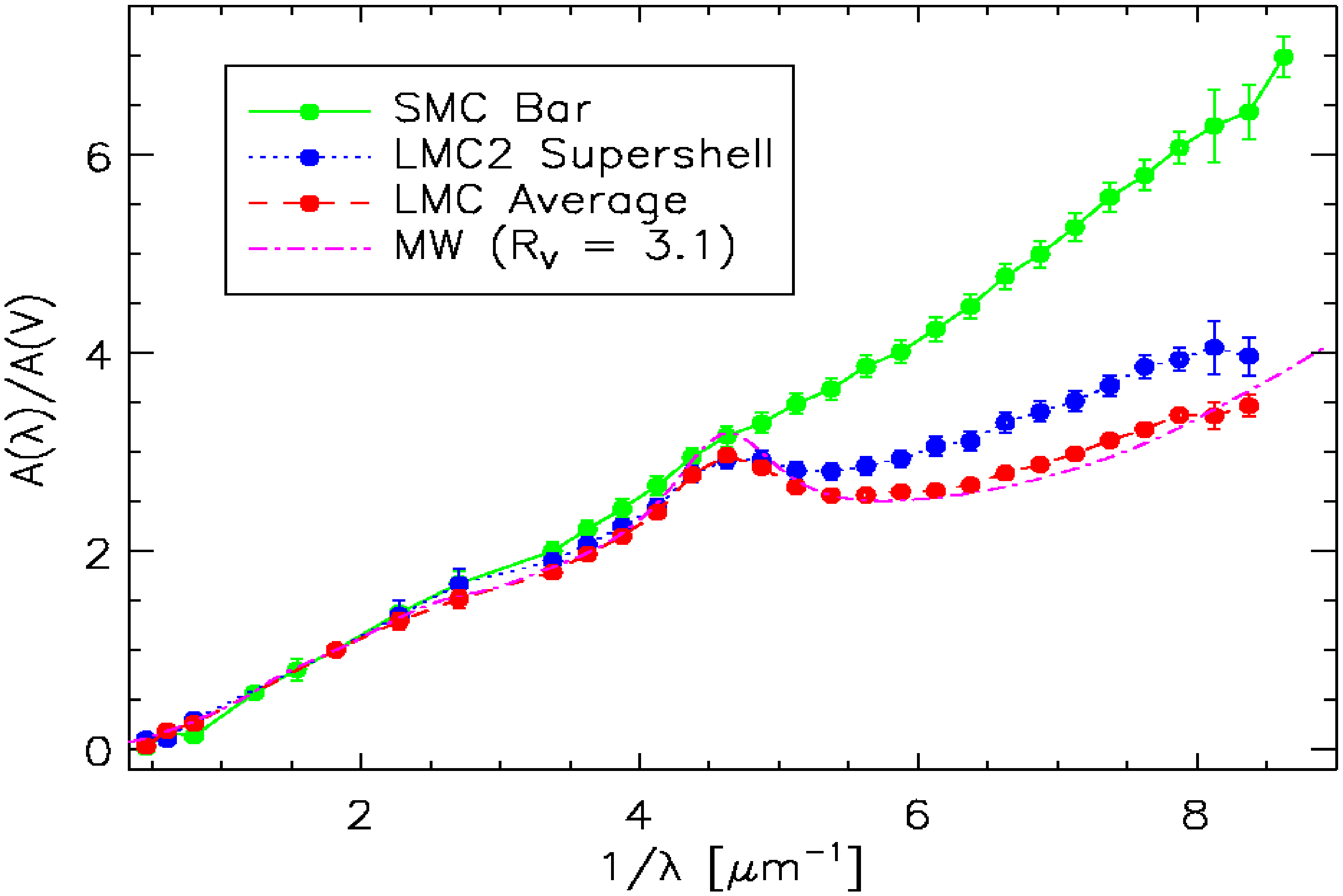
CONS

Uncertainties in the reddening law (Cardelli like)

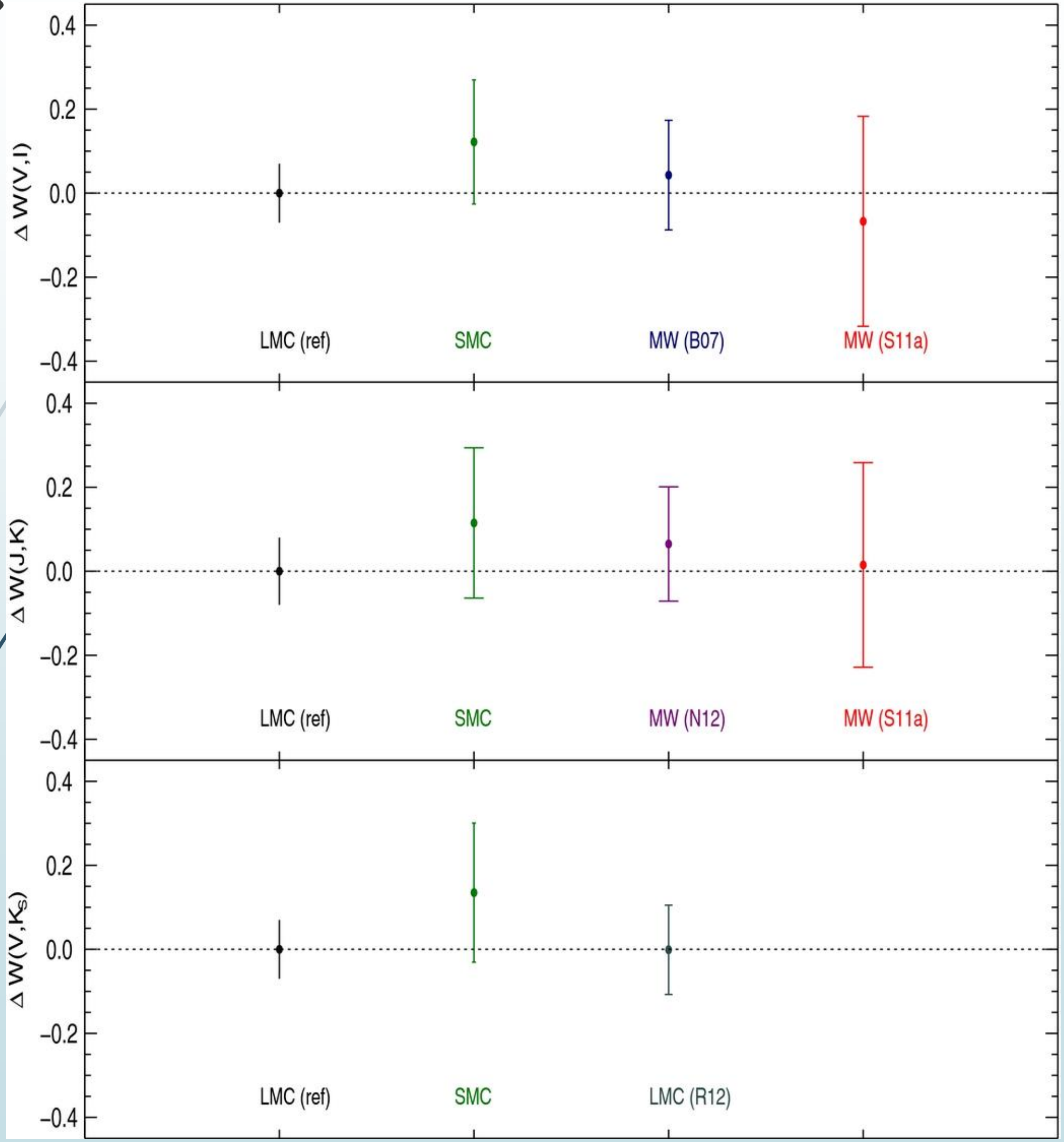
Is the reddening law universal ?

Accurate mean B,V,I or JHK magnitudes

Reddening laws (MW + Magellanic Clouds)



Very-similar slopes



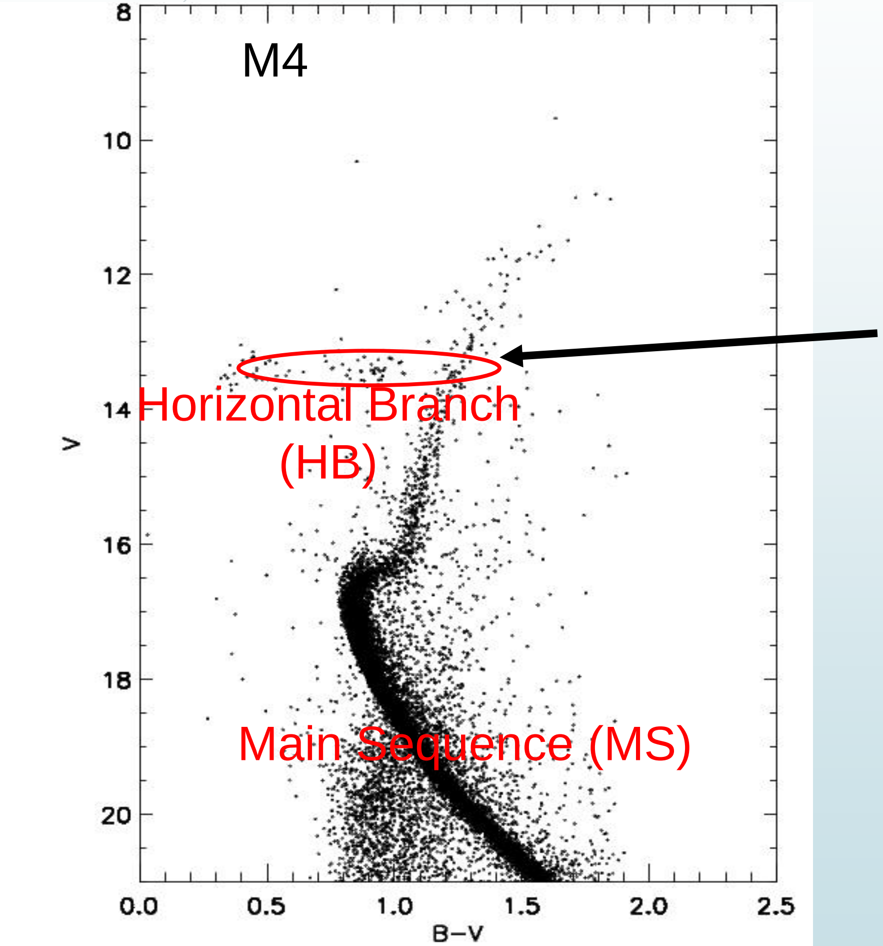
Benedict et al. (2007)
Ngeow (2012)
Storm et al. (2011a,b)
Ripepi et al. (2012)

VI & NIR PW relations slopes & ZPs are minimally affected by metallicity

Lack of homogeneous Optical & NIR data sets!

RR Lyrae stars

RR Lyrae variables

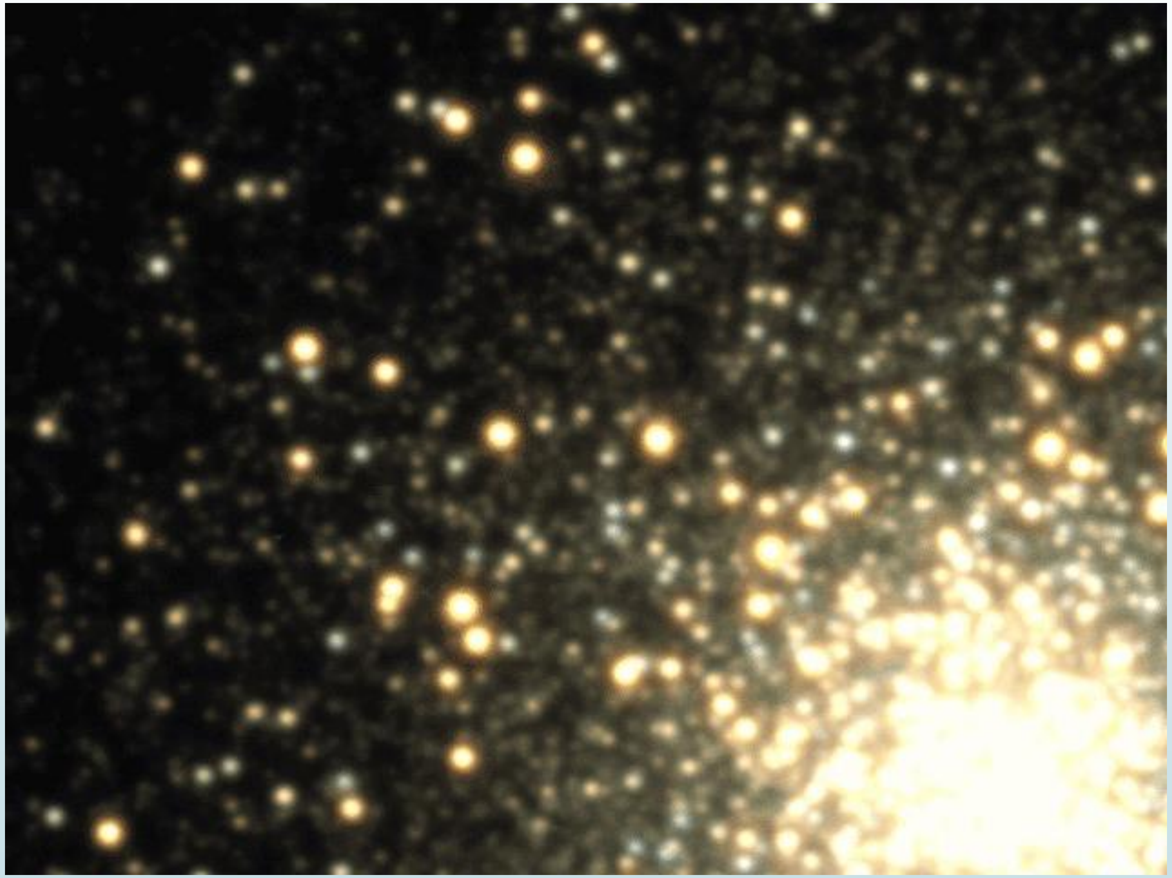


Stetson + (2014)

- Initial mass (MS): ~0.8-0.9 M_{sun}
- Mass (HB): ~0.6-0.8 M_{sun}
- Core He + Shell H burning
- [Fe/H] ~ -2.5 – 0.5 (*Smith 2005)*
- Old: >10 Gyr (GCs, halo, bulge)

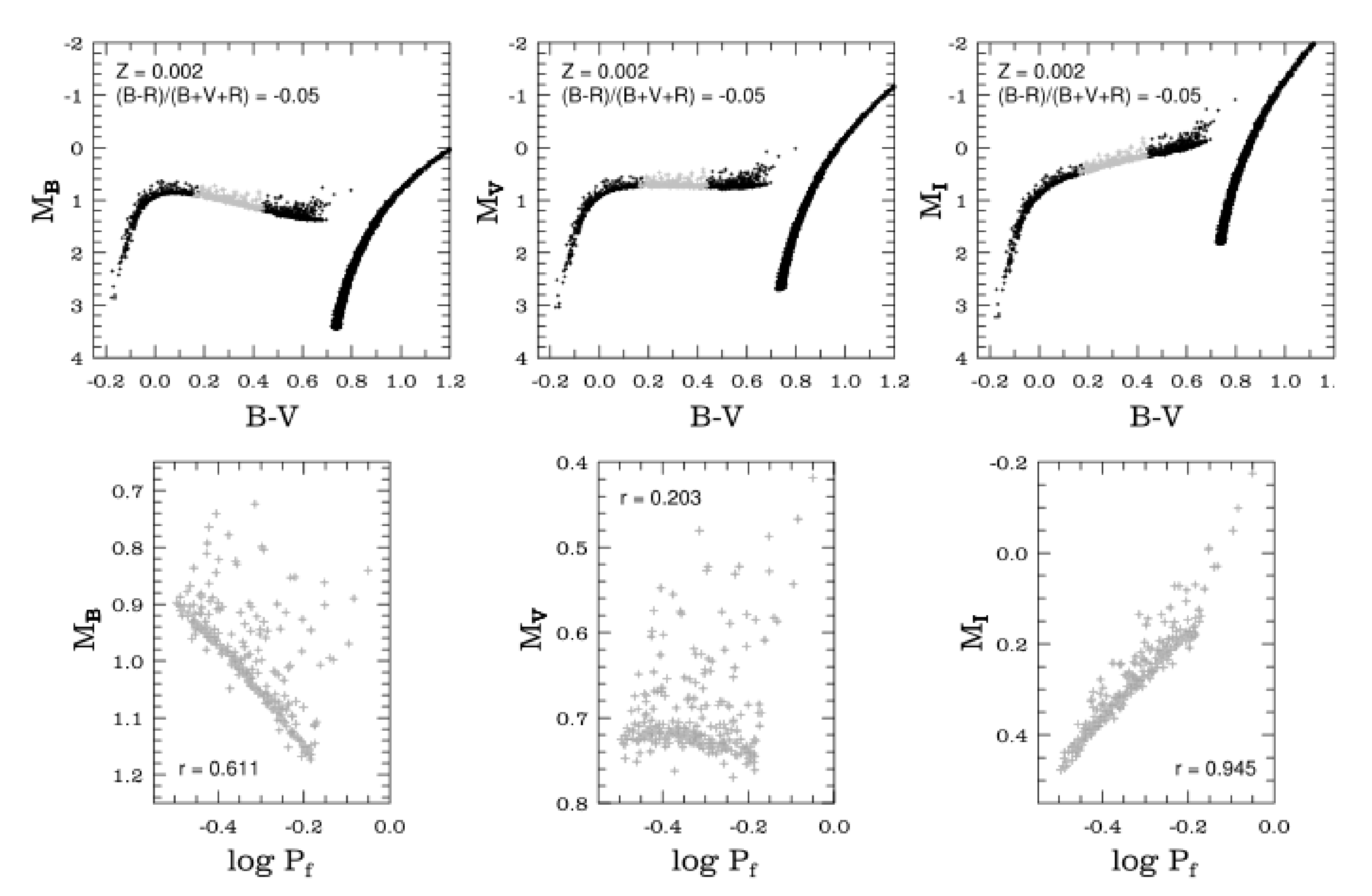
RR Lyrae Stars observational properties

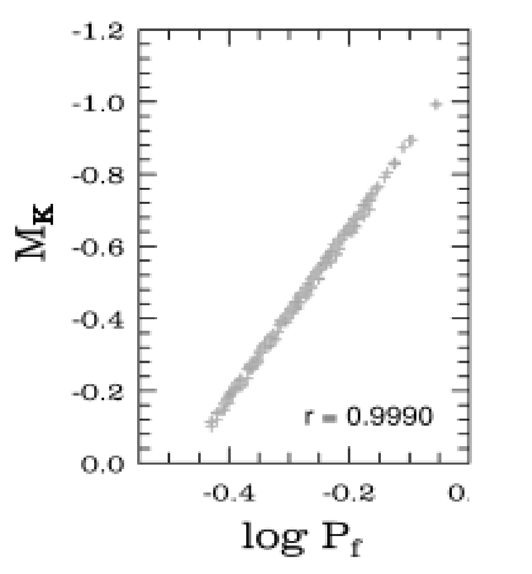
- Almost constant luminosity in the *V*-band, since their luminosity depends on the core mass (almost constant for the low-mass stars, due to degeneracy)
- Intrinsic brigthness *V* ~ 0.6 mag (some dependence on the metallicity)
- Magically, a Period-Luminosity relation appears in the *IJHK* bands, due to bolometric correction effects, with some dependence on the metallicity



M3, APOD, 2004 October 12

Effect of the bolometric correction when viewing the HB



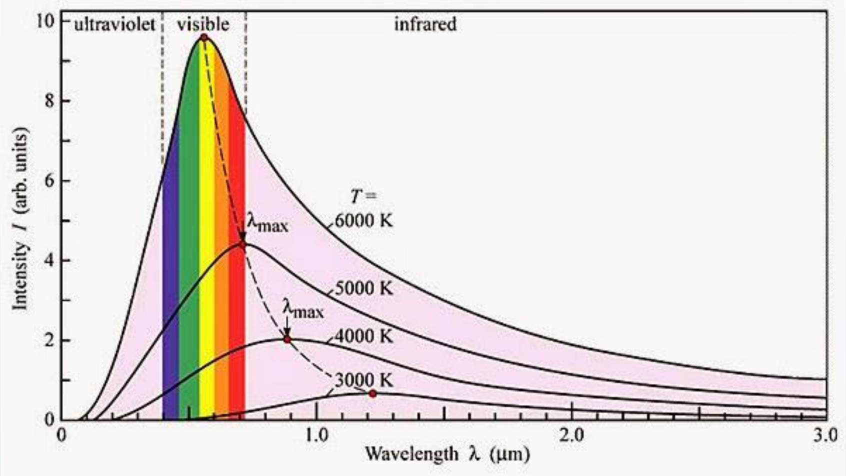


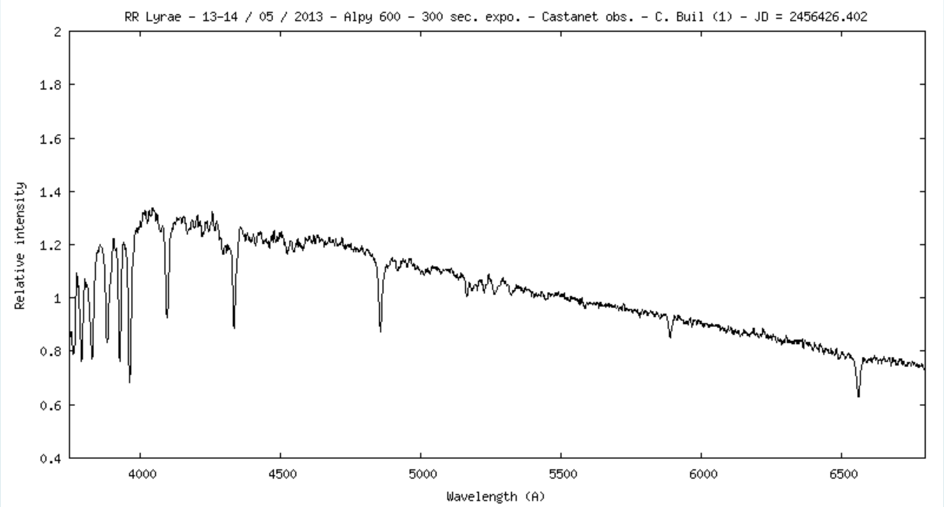
Catelan et al. 2004

The RR Lyrae *K*-band Period-Luminosity relation

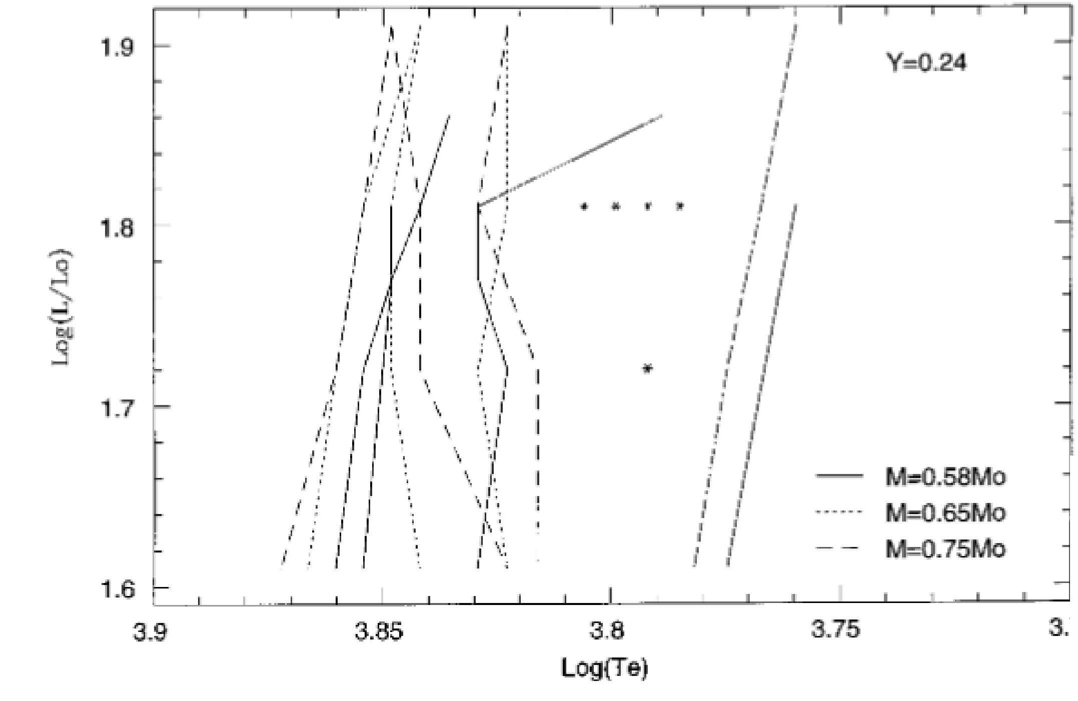
- **In the optical bands we observe a horizontal distribution (wow, the Horizontal Branch!), since the luminosity level is set by the mass of the core. The *V*-band nicely follows the peak of the BB curve, according to Wien**

- **In the near-infrared things go wild, since in the *K*-band RRLs are on their Rayleigh tail → the bolometric correction is the dominant effect**

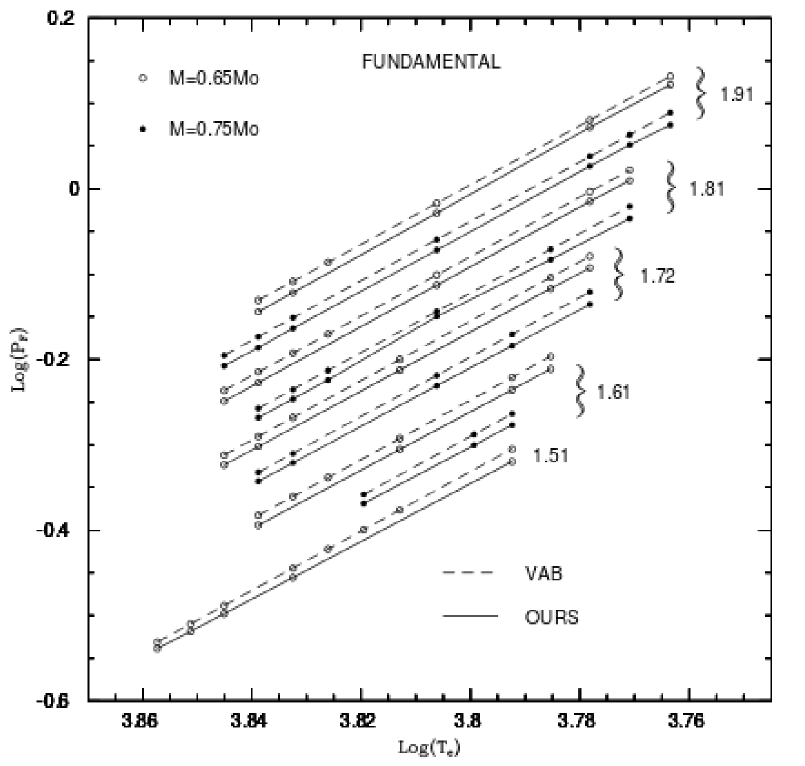




Credits: C. Buil



$$M_K = -0.766 - 2.071 \log P + 0.167[Fe/H]$$



The trick is that, moving to cooler temperatures:

The bolometric correction steadily decreases from hotter to cooler RRLs

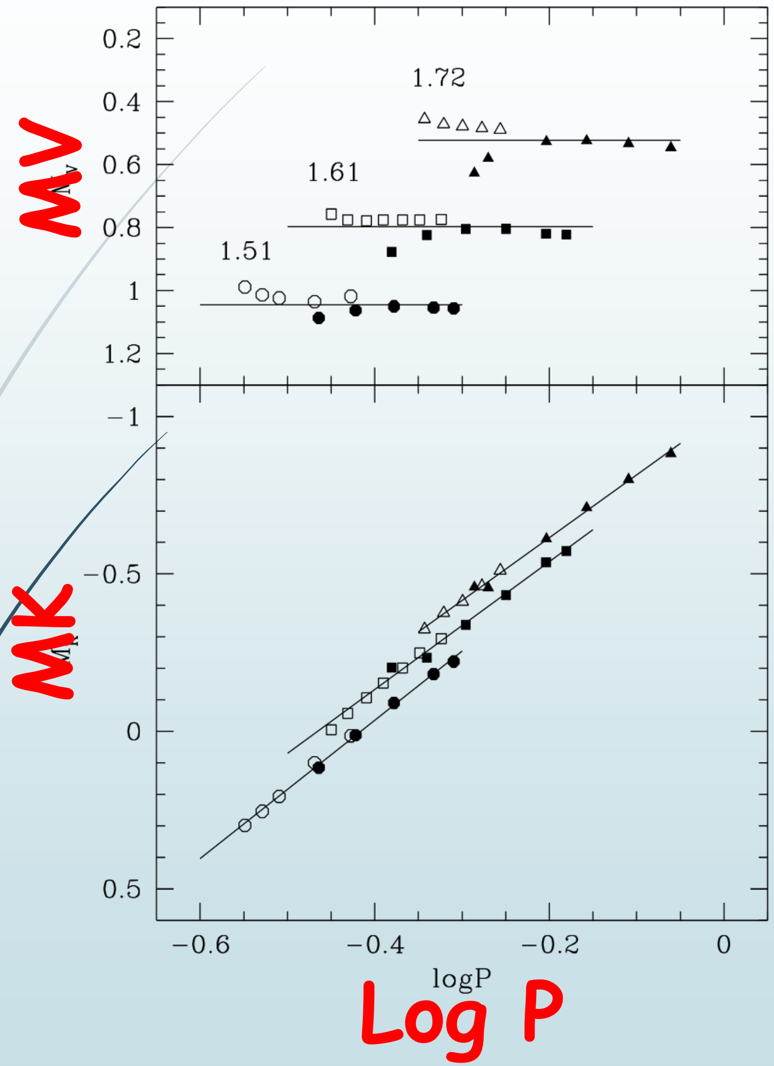
Hence RRLs become brighter (in the *K*-band) as they become cooler

Periods become longer with decreasing temperatures

$$\log P^F = 11.066(\pm 0.002) + 0.832 \log L - 0.650 \log M - 3.363 \log T_e$$

Bono et al. 1997

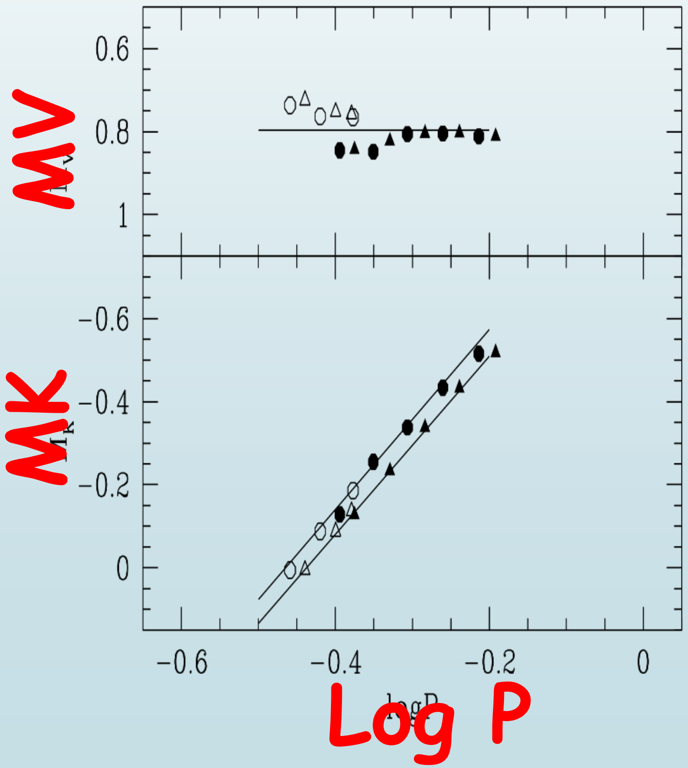
Why NIR is better than optical?



Bono et al. (2001)

Mv(RR) = α + β [Fe/H]

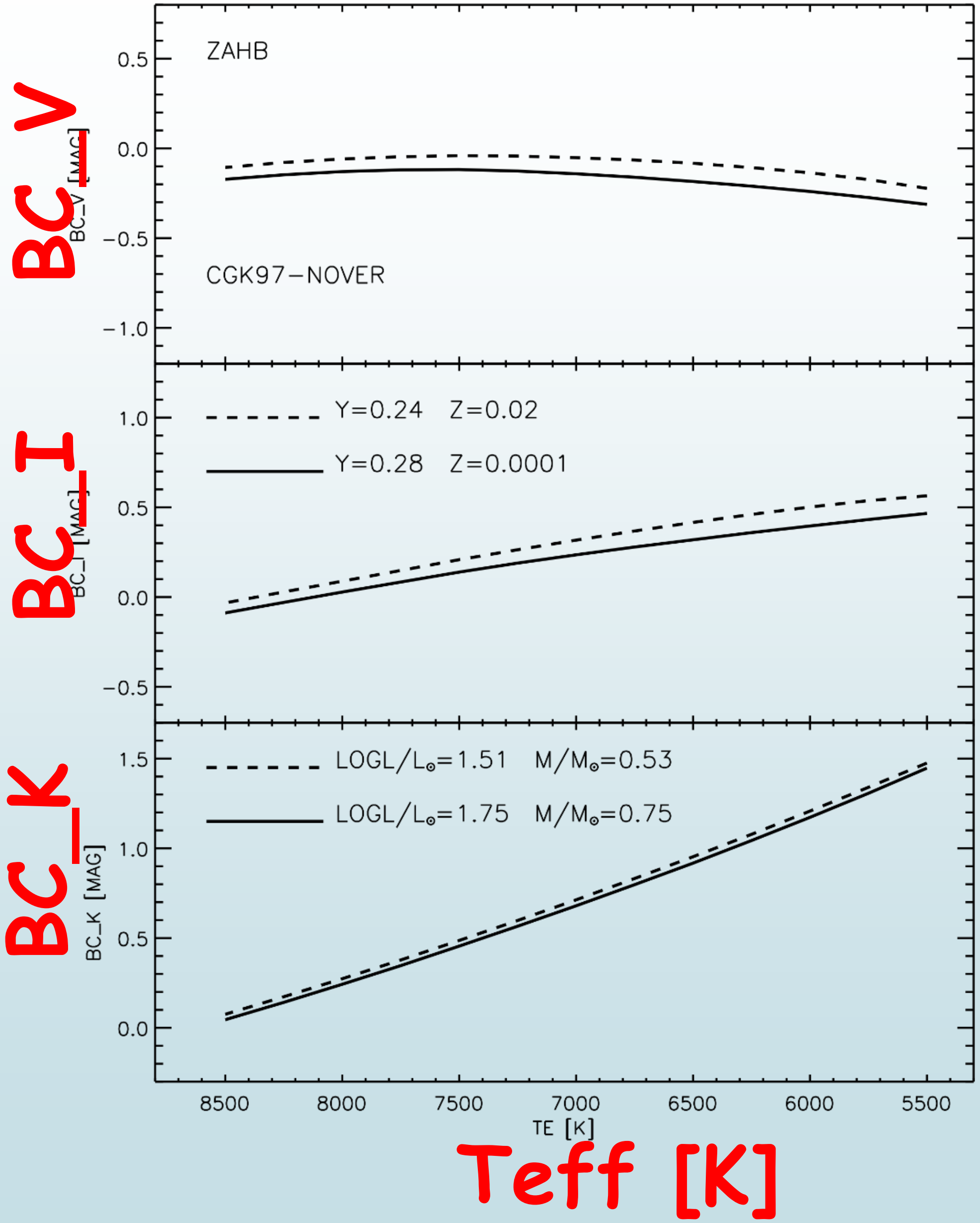
Affected by evolutionary effects!



Why NIR is better than optical?

In the B-band the hottest are the brightest!!

In the NIR the coolest are the brightest!!



PL/PLC in RR Lyrae & Cepheids

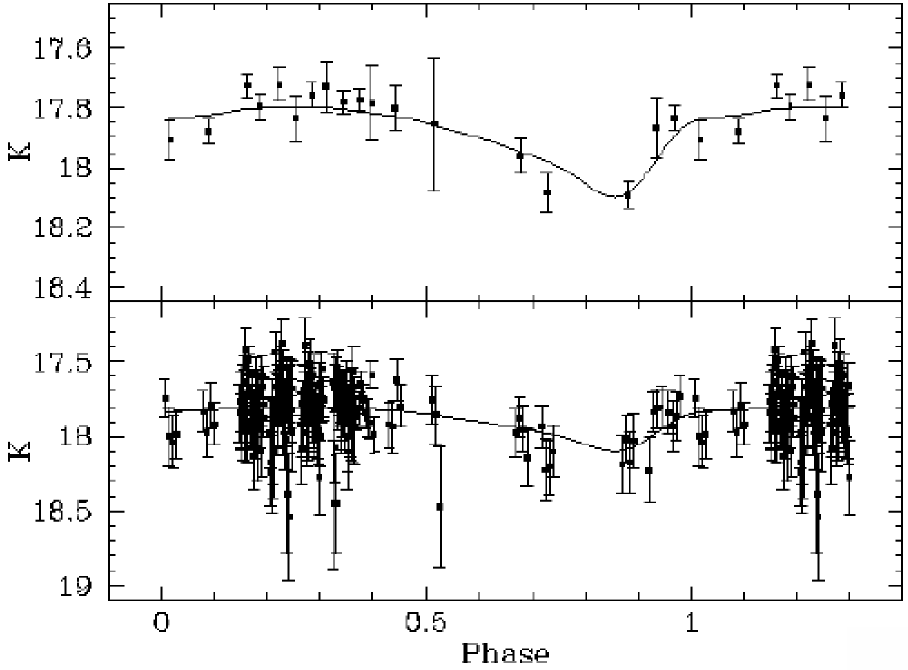
In Cepheids the PL/PLC is a direct consequence of the ML relation → more massive stars are, at fixed Teff, brighter

→ lower gravities → longer periods → optical/NIR

The difference in mass for RR Lyrae stars is at most of the order of 20%. The PL/PLC is the Consequence of the BC →

This is the reason why it shows up with R/I-band ….

The LMC old cluster Reticulum: the first PLK outside the Galaxy

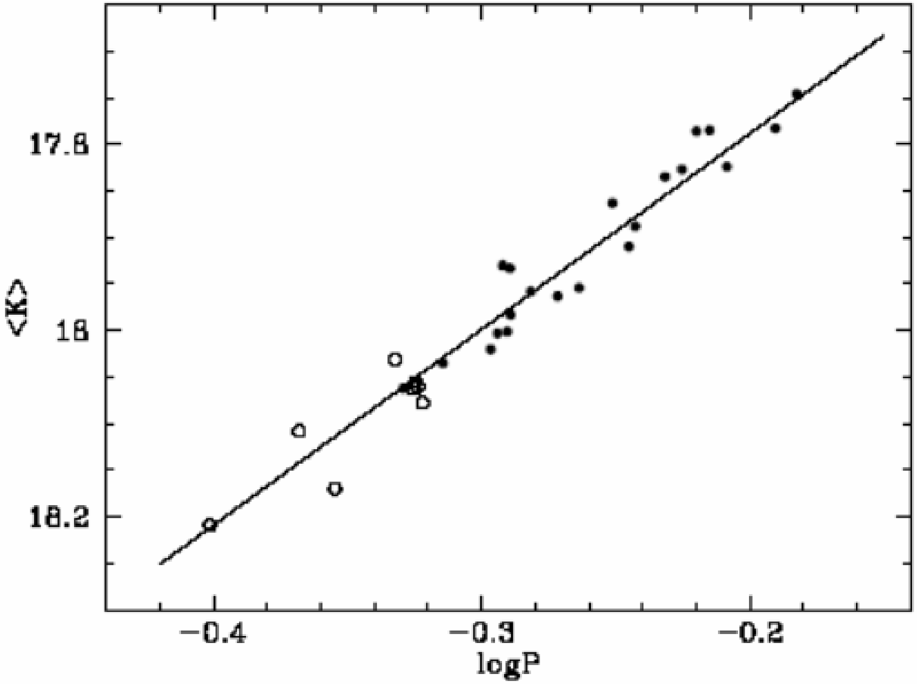


Dall'Ora et al. 2004

$$< K > = -2.16(\pm 0.09)\log P + 17.352(\pm 0.025)$$

$$DM_0 = 18.523 \pm 0.005$$

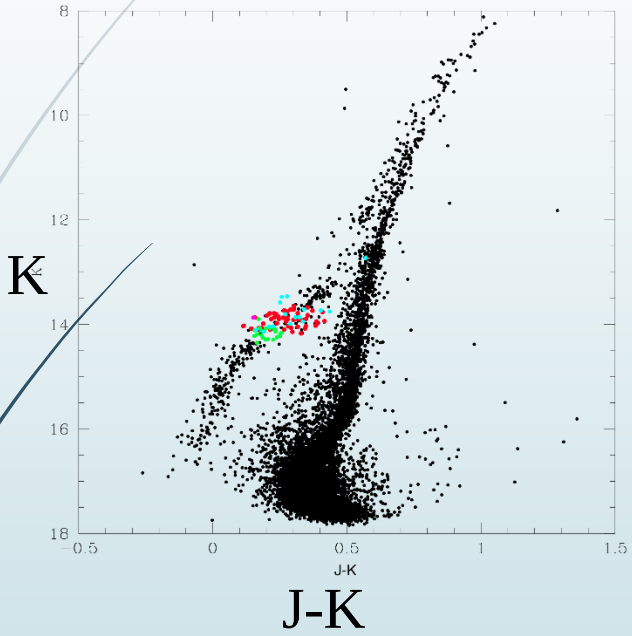
(intrinsic spread only)

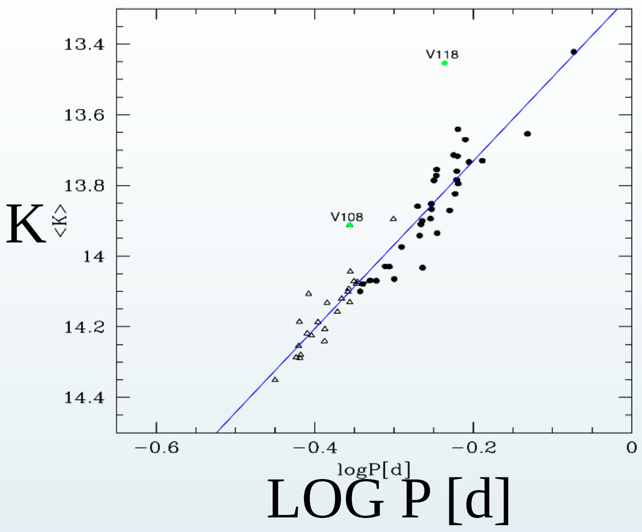


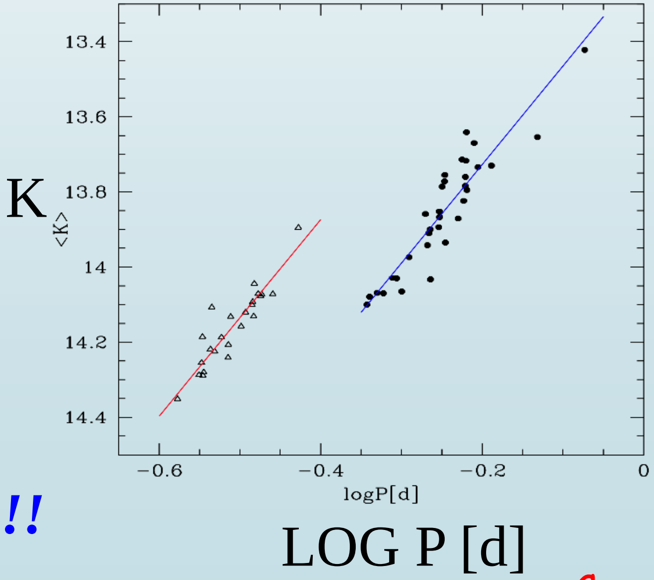
RR Lyrae in M5

33 RRab + 24 RRc

J, (71), K (120) with SOFI@NTT
J, (25), K (22) with NICS@TNG





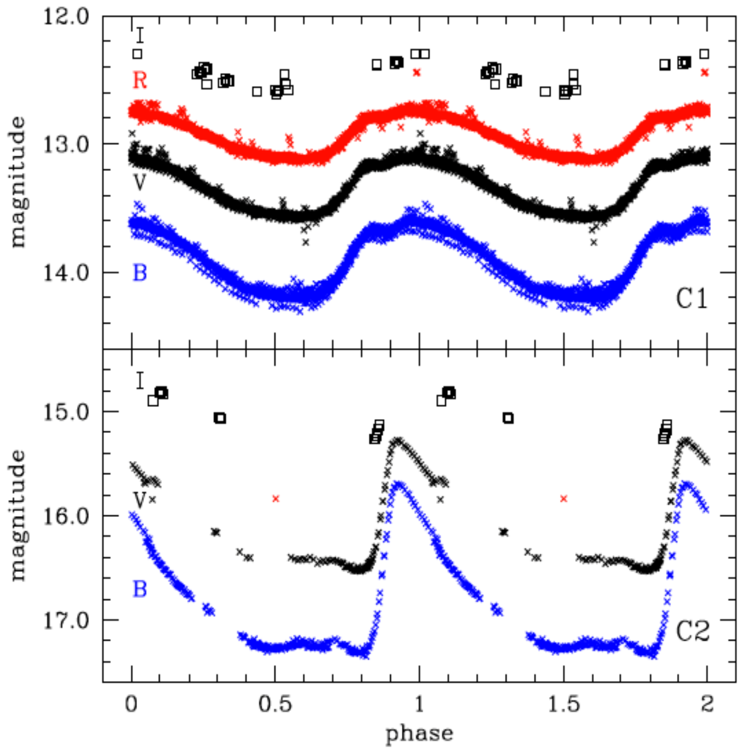


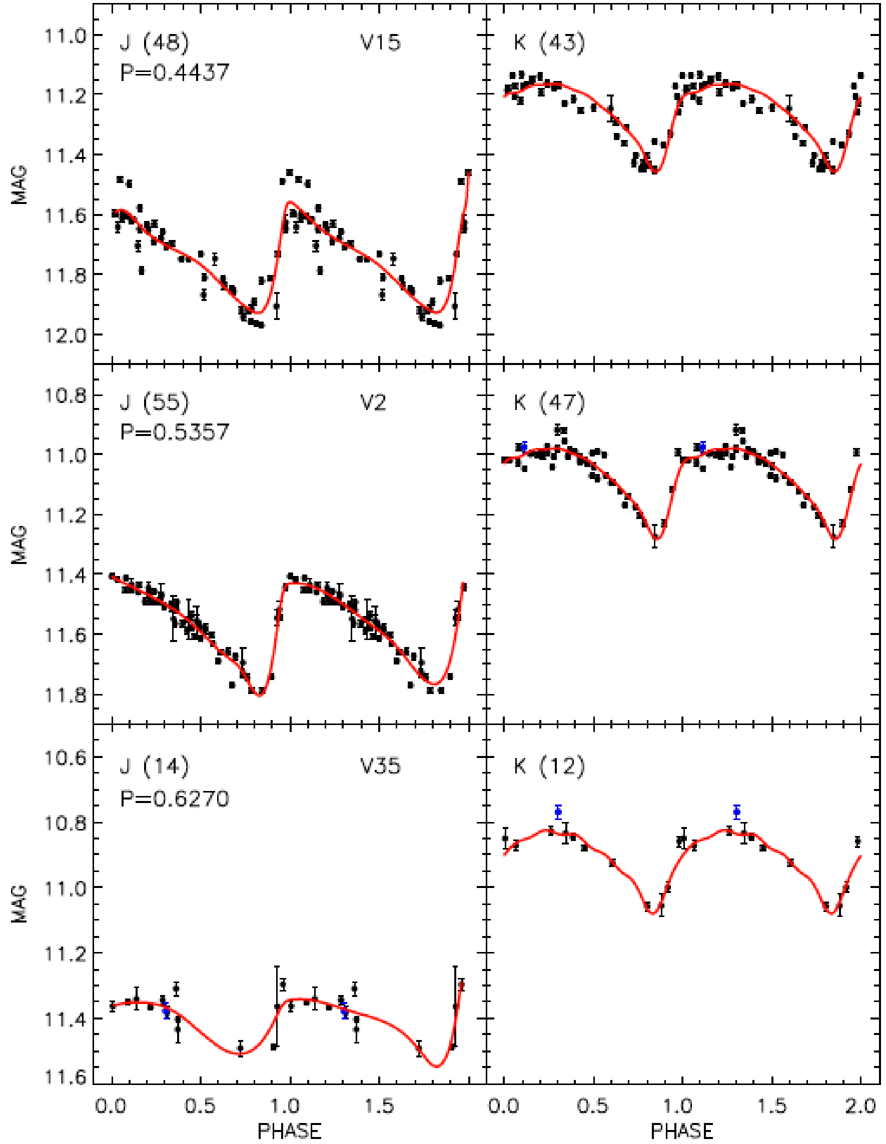
μ=14.44 ± 0.02 mag

Astrometric distance μ=14.44 ± 0.05 mag!!
Rees (1993, 1996)

Coppola, Dall'Ora + (2011)

M4 a new spin on GC distance scale

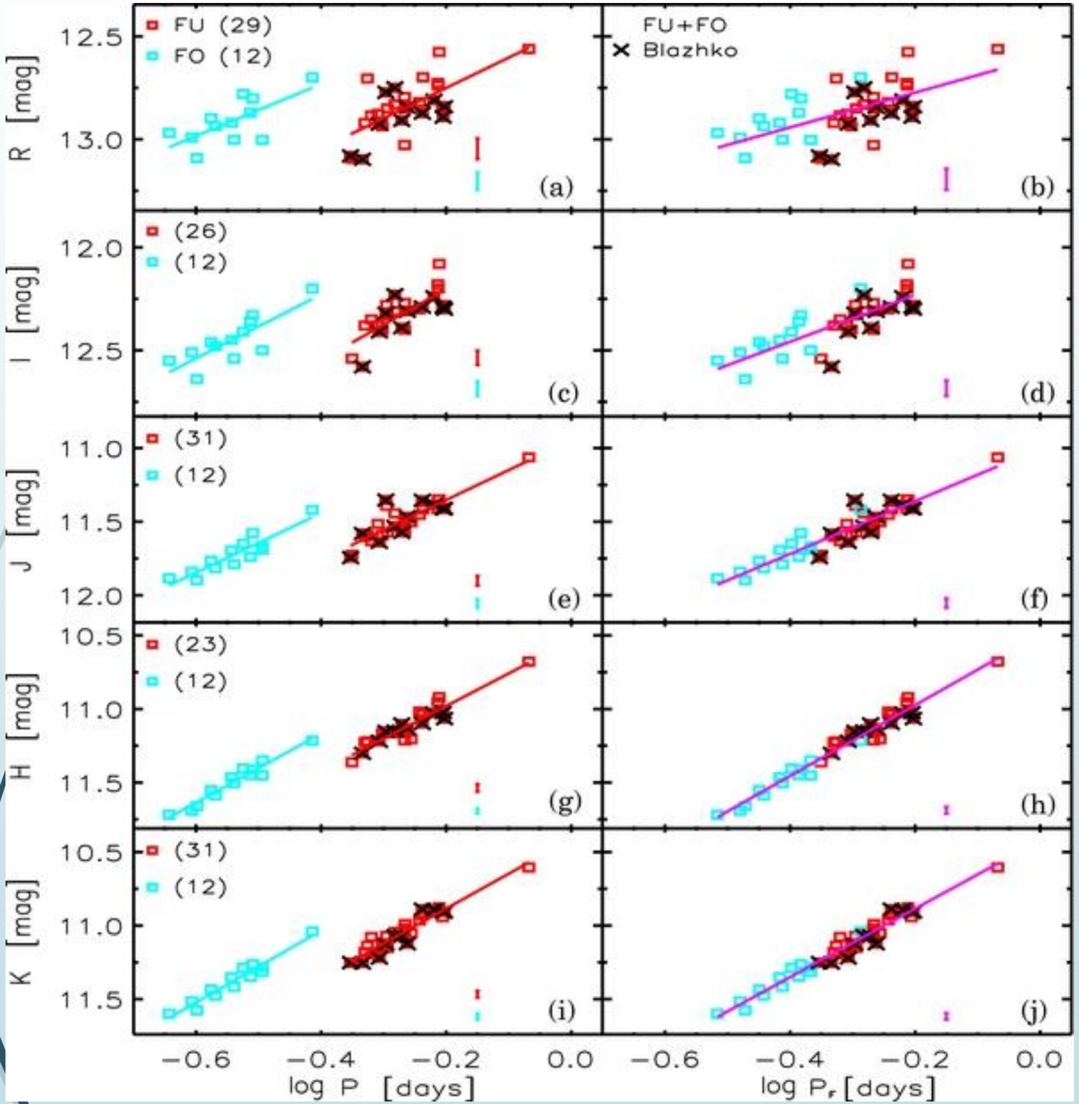


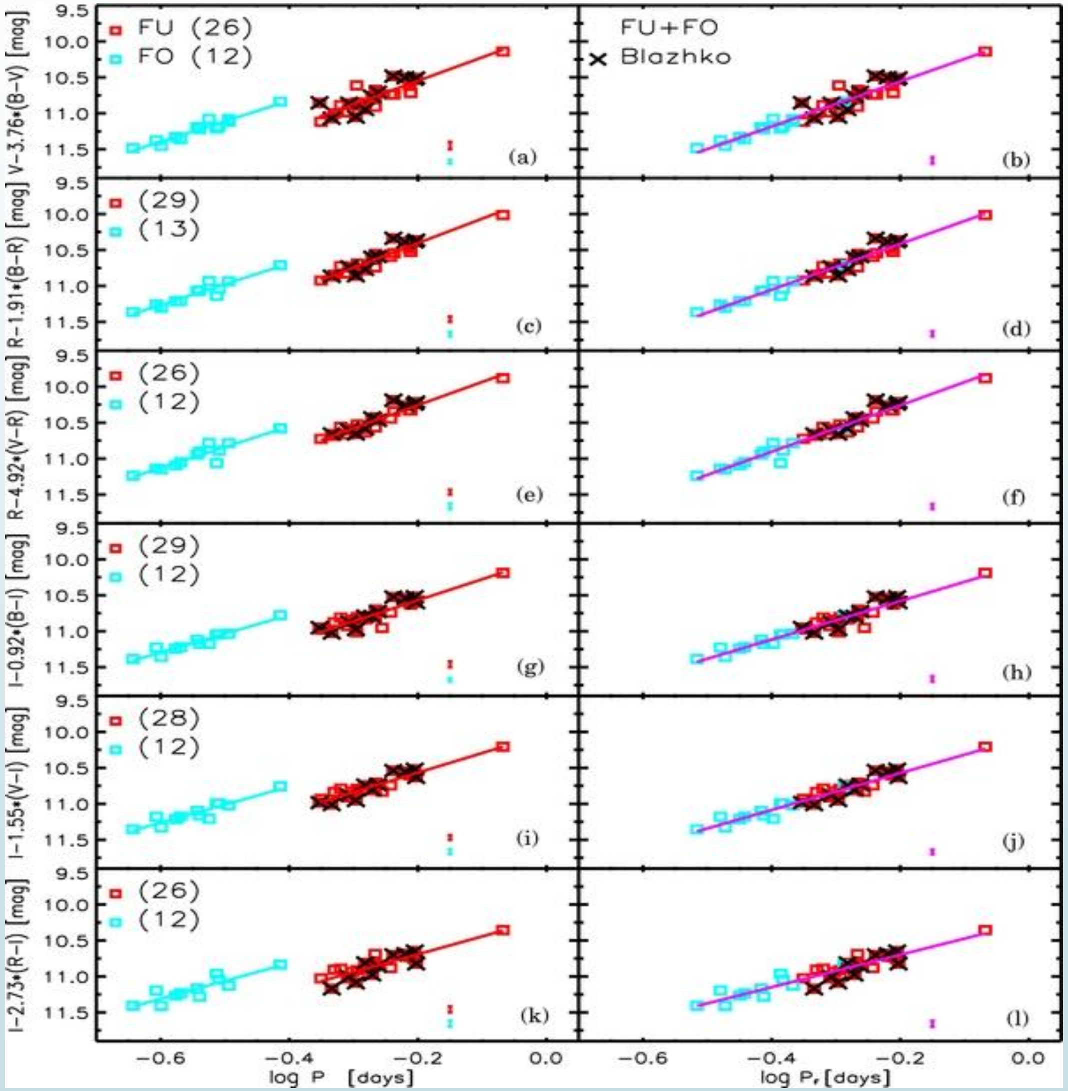


Selected optical/NIR light curves

Stetson et al. (2014)

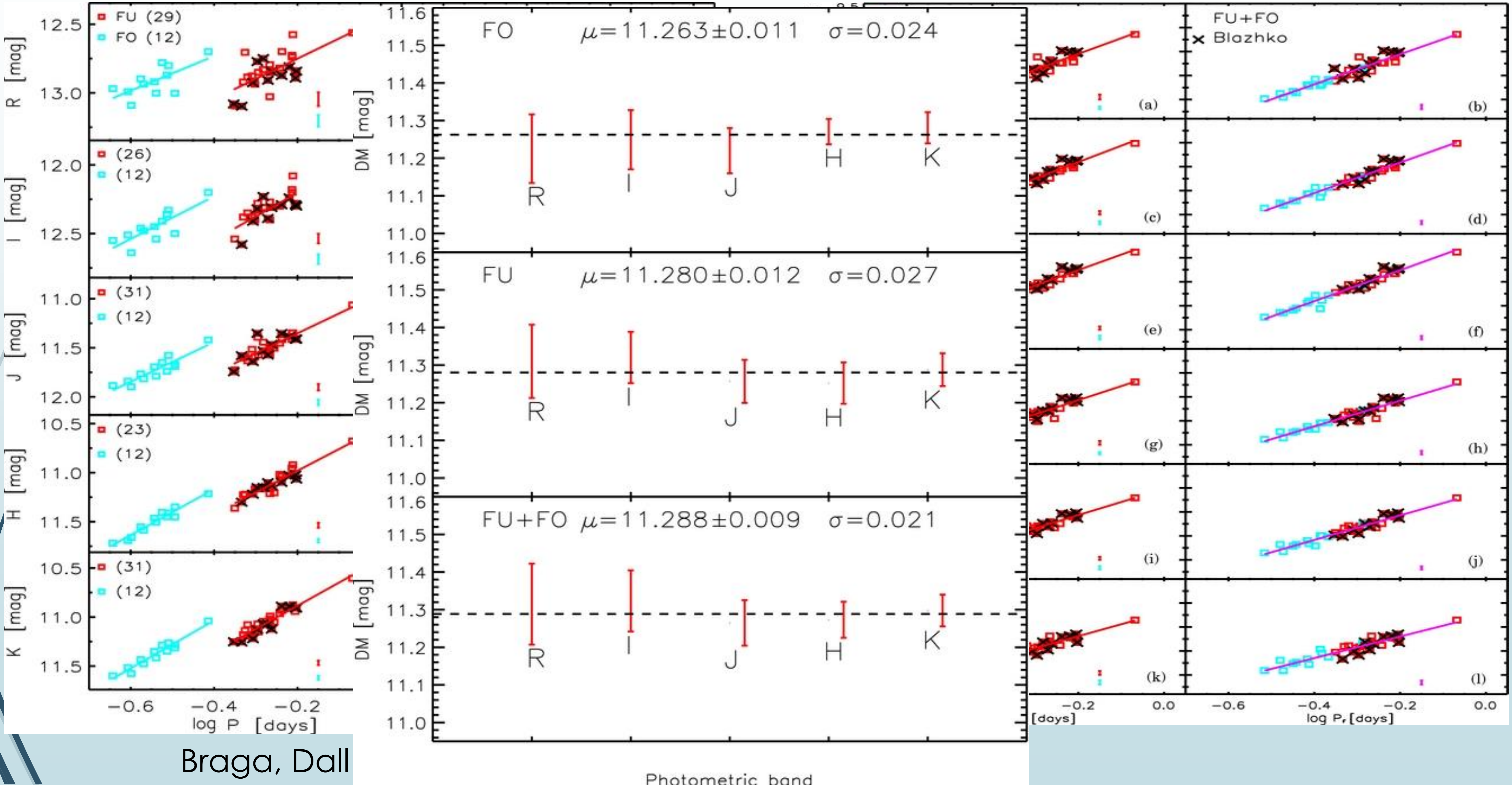
M4 a new spin on GC distance scale





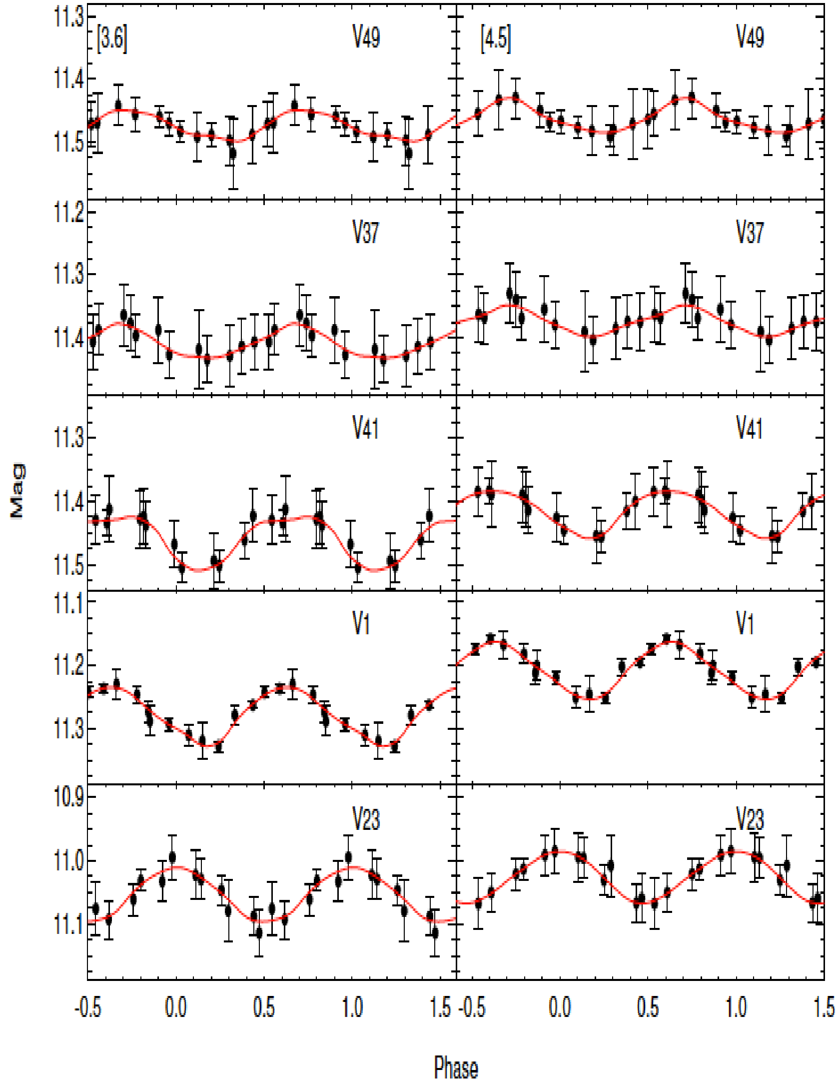
Braga, Dall'Ora et al. 2015

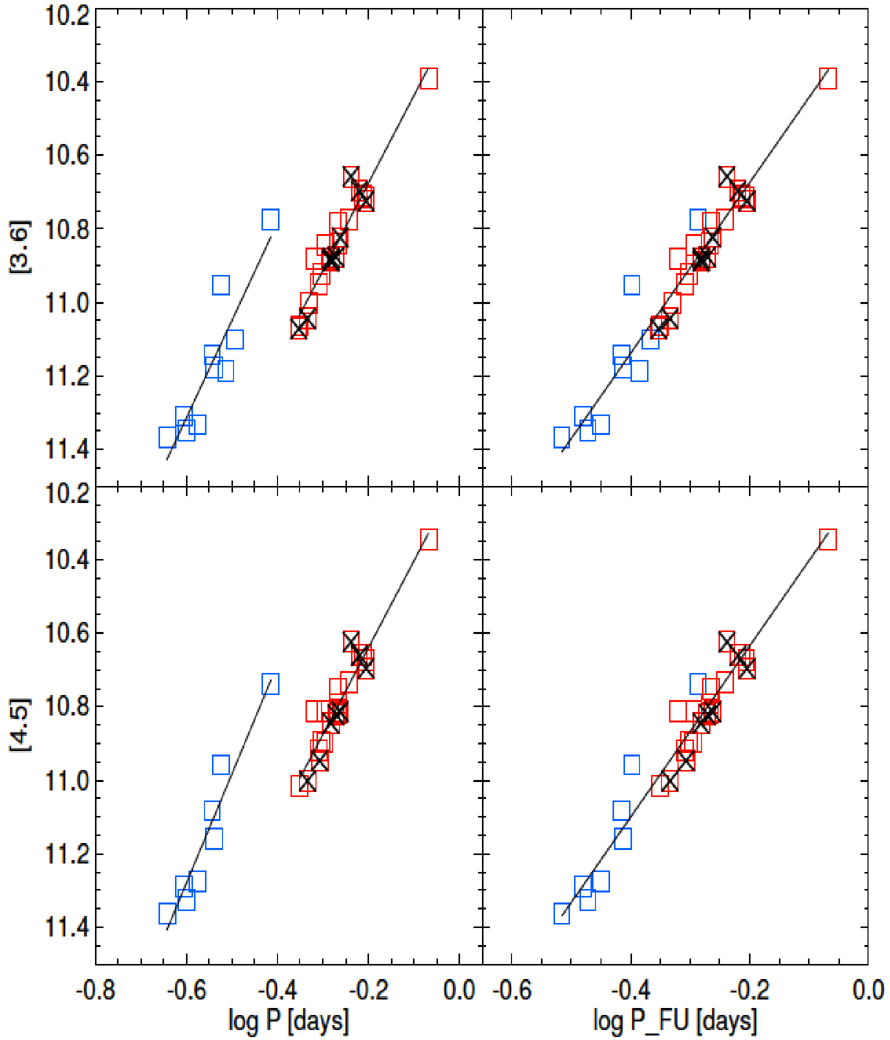
M4 a new spin on GC distance scale



Braga, Dall

New accurate M4 distances
Spitzer data (Neeley et al. 2015, 2017)





M4 DM measure

TABLE 1
TRUE DISTANCE MODULI AND REDDENINGS FOR M4 AVAILABLE IN THE LITERATURE.

μ[a] mag	R_V[b] mag	E(B-V)[c] mag	Ref.[d]	Notes[e]
11.28±0.06	3.62±0.07	0.37±0.01	H12	(1)
11.18±0.18	…	…	P95	(2)
11.19±0.01	3.8	0.34±0.03	LJ	(3)
11.22±0.11	4	0.37±0.01	DL	(4)
11.28±0.06	4	0.37	L90	(5)
11.48	3.8	0.32	B09	(6)
11.18±0.18	3.8	0.33±0.01	H04	(7)
11.30±0.05	3.62±0.07	0.399±0.010	K13	(8)
11.37±0.08	…	…	B03	(9)

[a]True distance modulus and its error when estimated by the authors.
[b]The ratio between absolute and selective extinction.
[c]Mean reddening.
[d]References: H12, Hendricks et al. (2012); P95: Peterson et al. (1995); LJ: Liu& Janes (1990b); DL: Dixon & Longmore (1993); L90: Longmore et al. (1990); B09: Bedin et al. (2009); H04: Hansen et al. (2004); K13: Kaluzny et al. (2013); B03: Bono et al. (2003).

Braga, Dall'Ora et al. (2015)

Agreement with literature

$DM_{(PLZ\text{-}Glob)}=11.296\pm0.003\pm0.026$

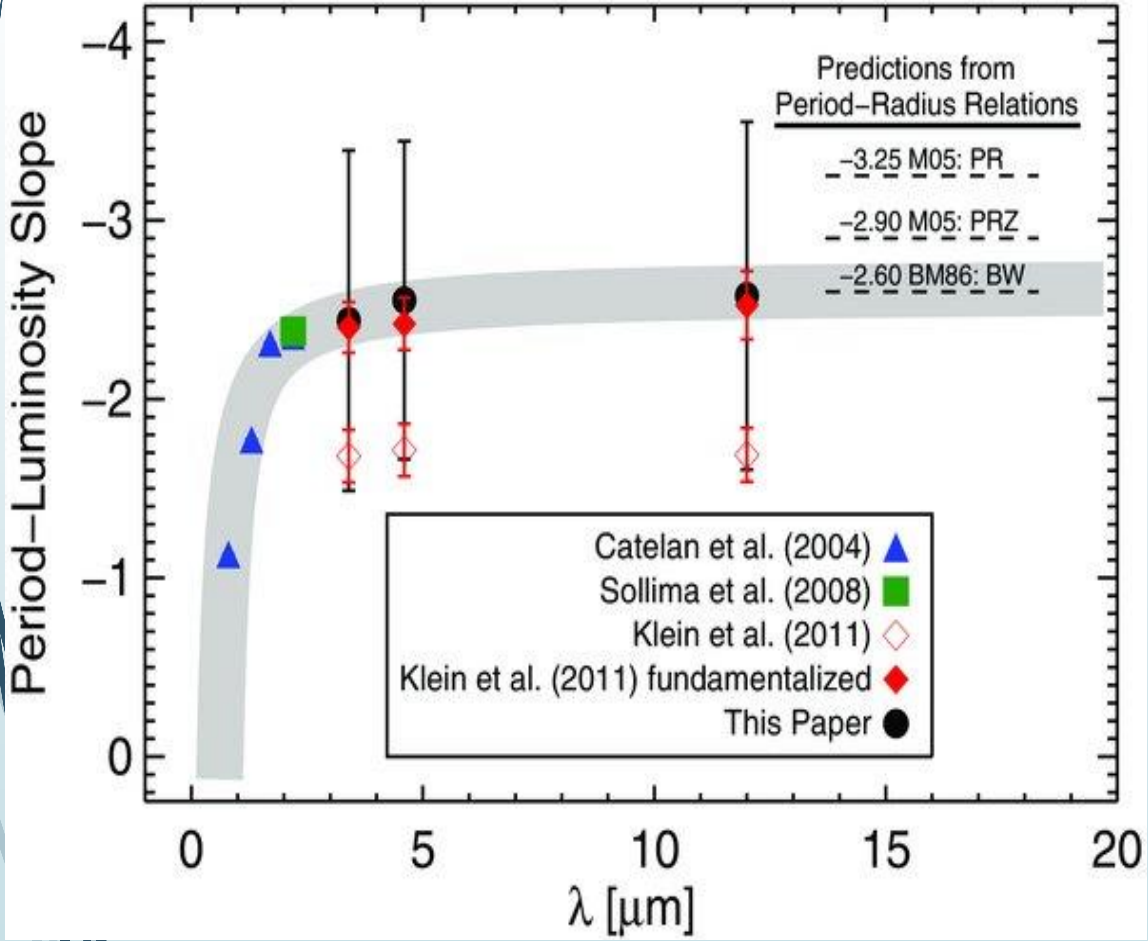
$DM_{(PWZ\text{-}Glob)}=11.267\pm0.011\pm0.035$

Without optical bands…

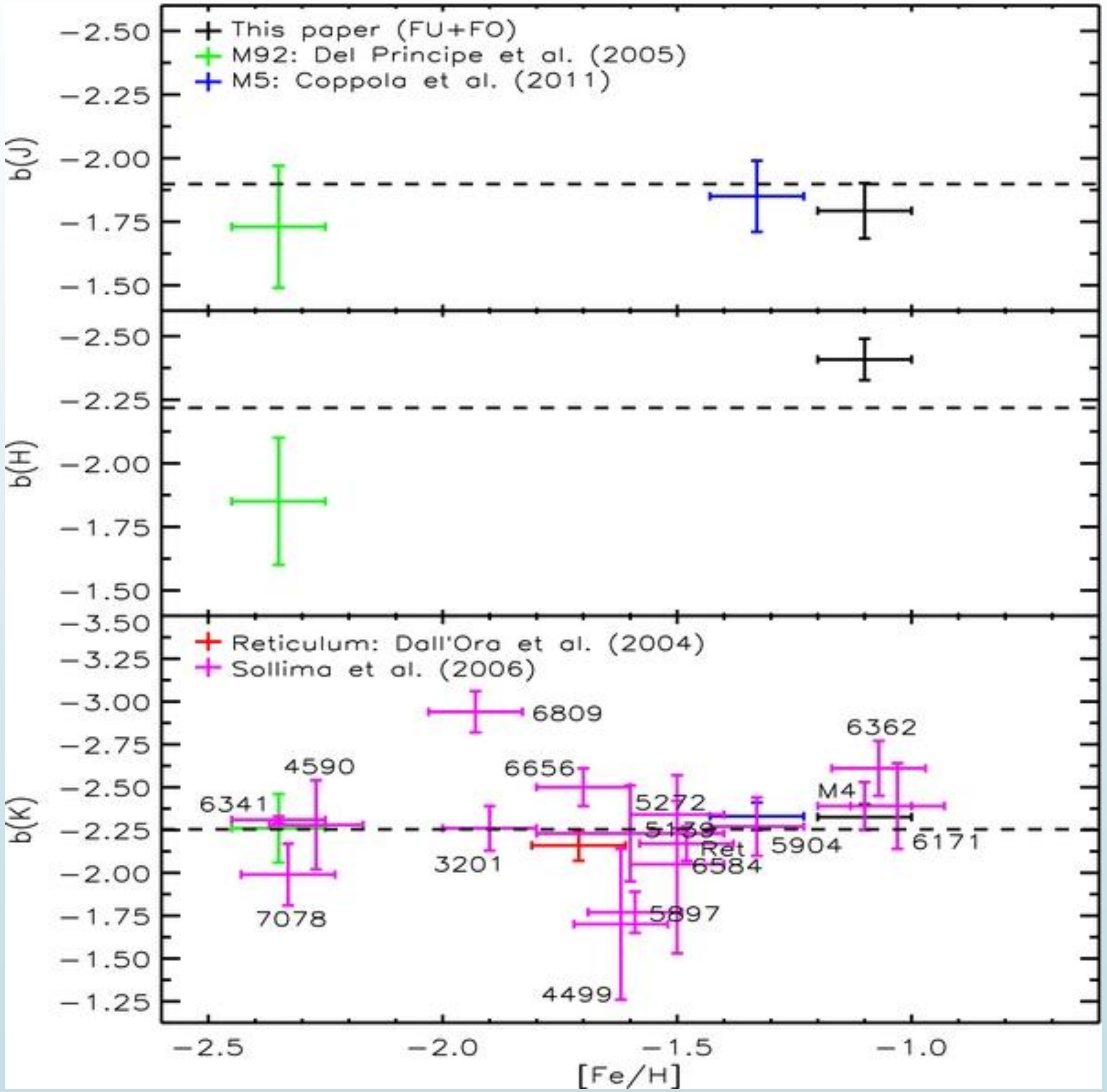
$DM_{(PLZ\text{-}Glob)}=11.282\pm0.003\pm0.015$

$DM_{(PWZ\text{-}Glob)}=11.267\pm0.012\pm0.019$

What is the slope of the PLK relation?



Madore et al. 2013



Braga, Dall'Ora et al. 2015

Playing with E-ELT

Why we want to use RRLs to measure distances with E-ELT?

All in all, we would go *local, and not cosmological*....

The reasons are:

RRLs Gaia distances → sound calibration of the PLK relation:

anchor the Cepheids distances

distances for early-type structures

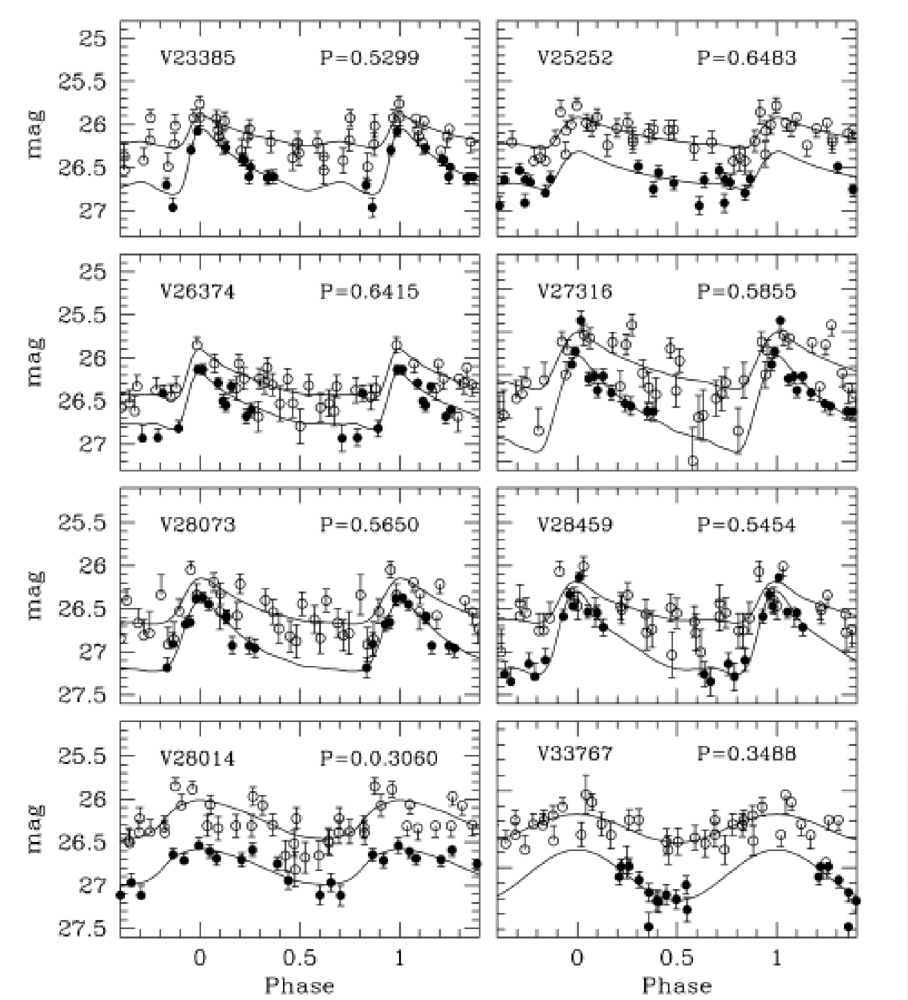
MICADO expected performances tell us that we can reach *K* ~ 29 mag with one hour integration

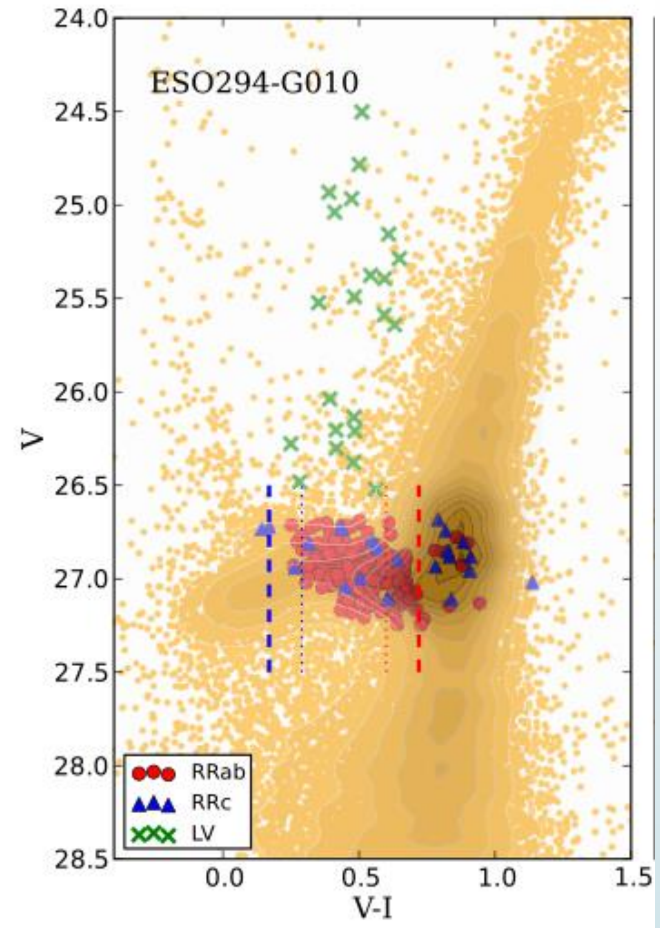
In principle, we could explore up to μ ~ 29.5 mag (~ 25 Mly)

But...

Remember that we need optical-based ephemerids (HST)

RRLs have been reported in the optical up to the Sculptor Group (~ 6.2 Mly, Yang+, 2014)



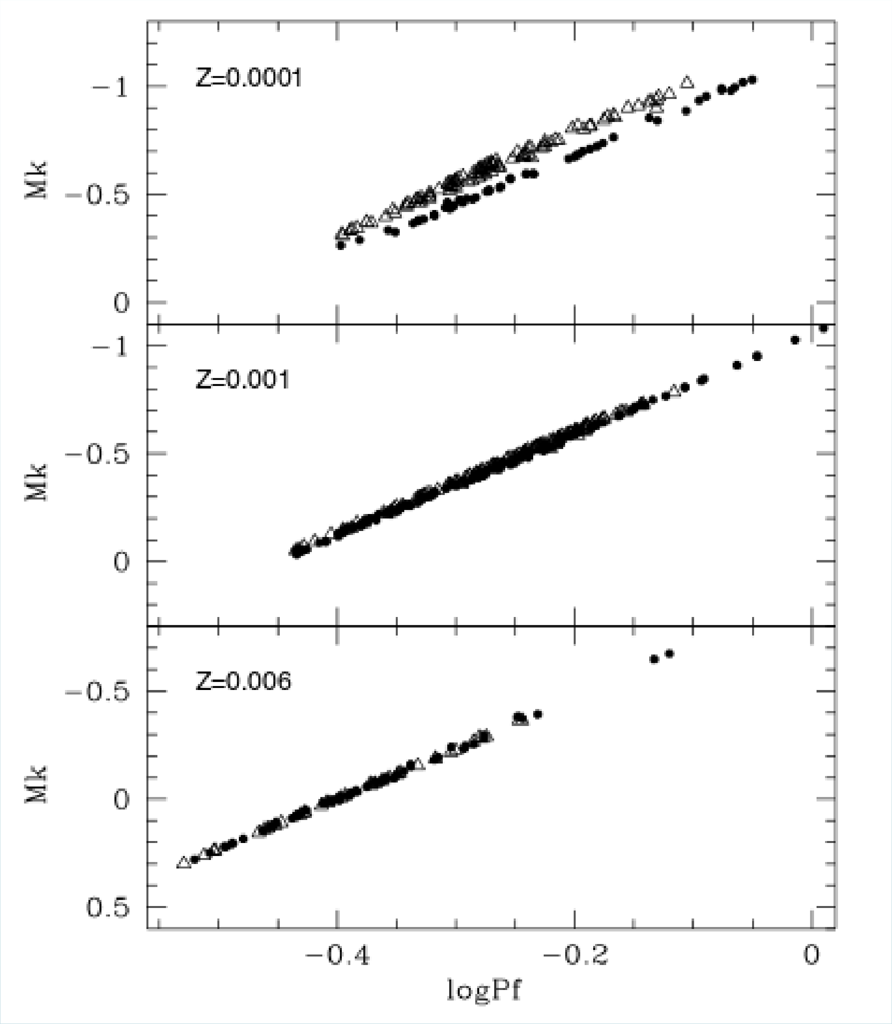


Yang et al. ApJ, 2014

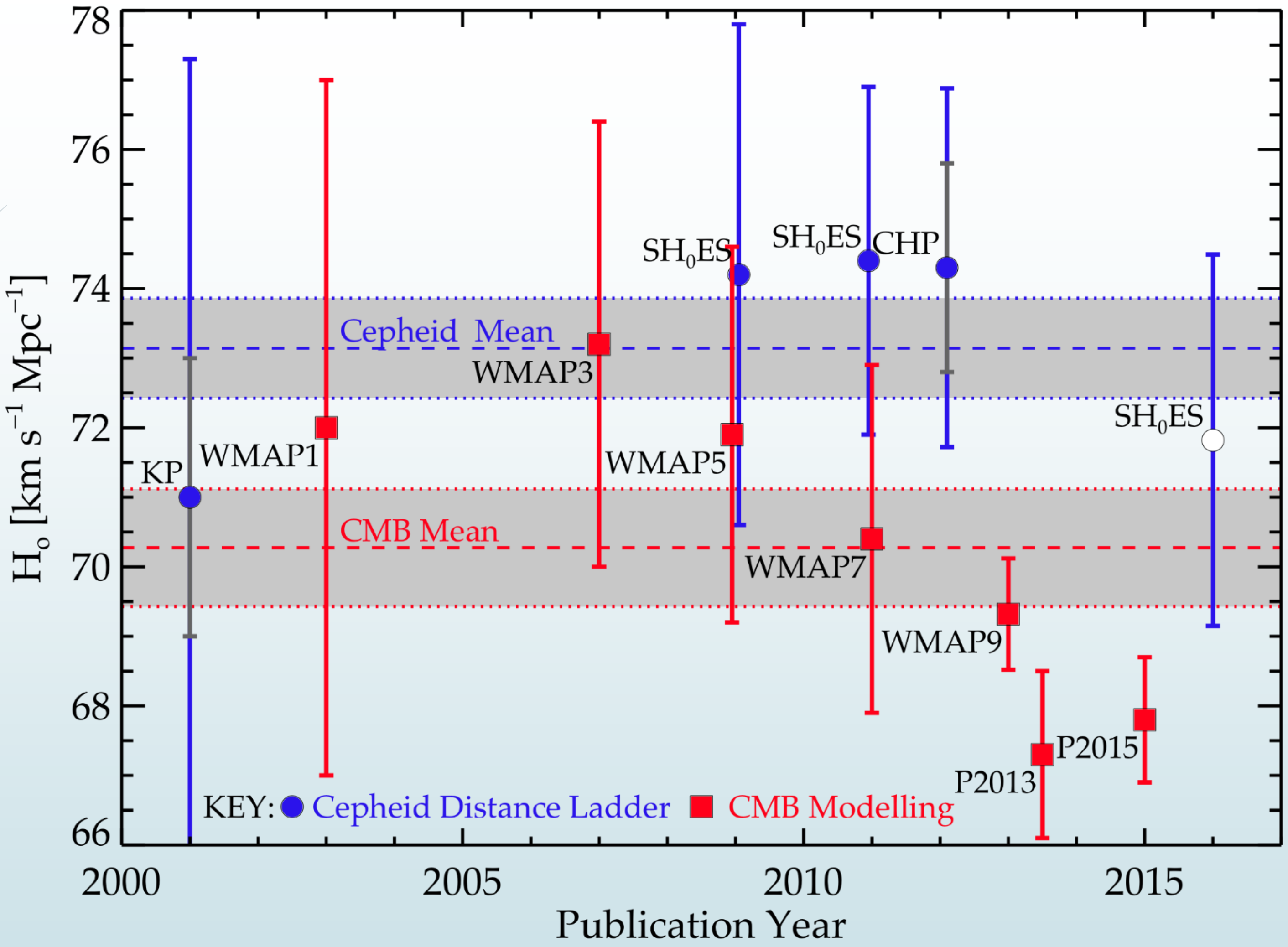
Can we go farther than the optical limit?

The PLK relation is basically due to the bolometric correction, that is *intrinsically* a temperature-luminosity relation

This means that we can adopt synthetic HB and pick up the observed *bona-fide* variable stars in the *expected* Instability Strip...



Cassisi et al. 2004



Beaton + (2016) → An independent approach to the extragalactic distance scale: RR Lyrae + tip RGB

Tip of the Red Giant Branch

Same evolutionary channel of RR Lyrae stars:
e-degenerate Helium core affected by thermal neutrinos!!!

Therefore, the luminosity is roughly the same, with populations effects depending on the metallicity

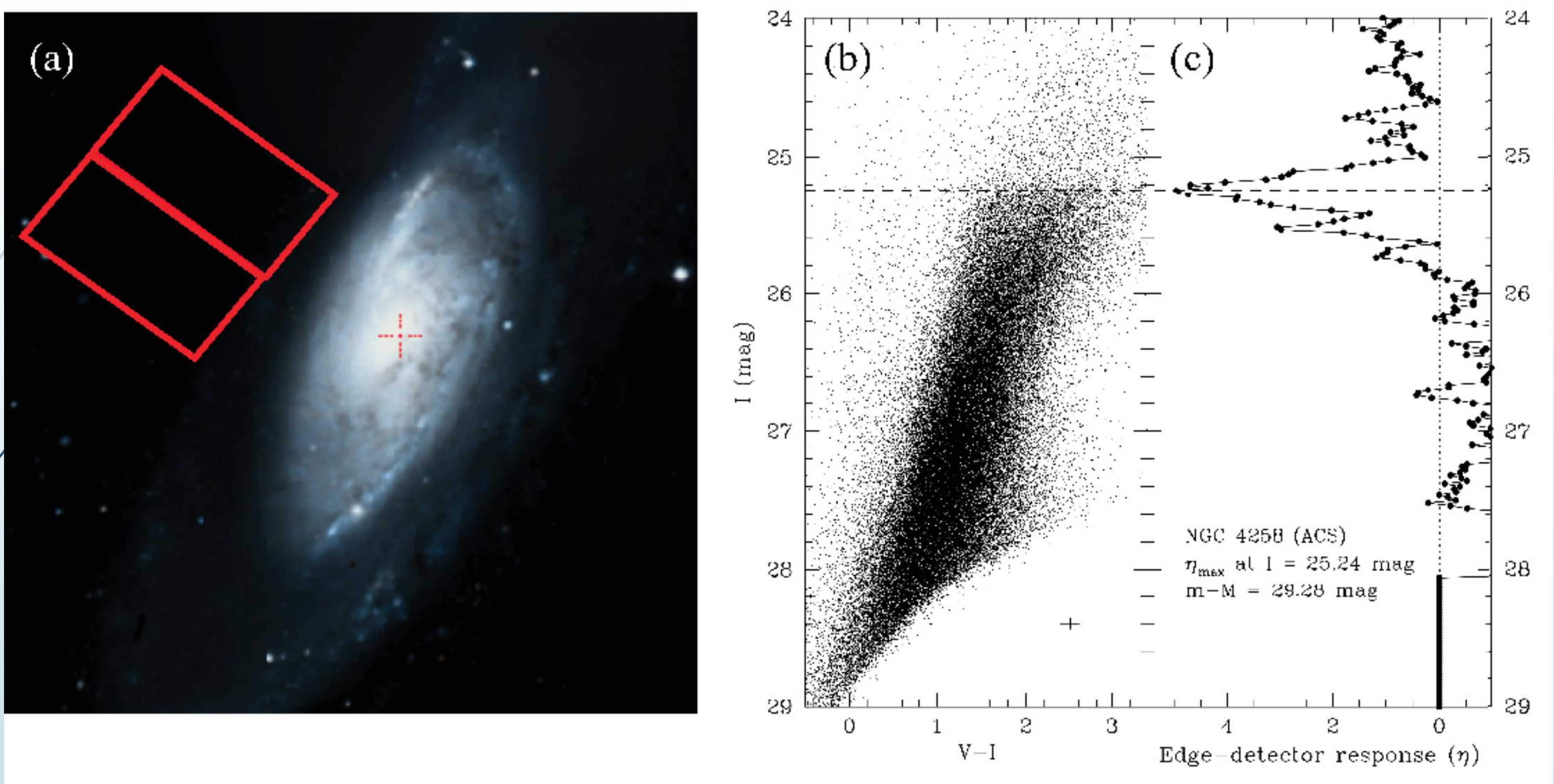
TRGB is brighter than RR Lyrae, and can be observed at larger distances.

Moreover, it does not need time-series observations to be detected

$$M_I^{\mathrm{TRGB}} \sim -4.1 \pm 0.1$$

$$M_K^{TRGB} = -6.92 - 0.62[Fe/H]$$

Tip of the Red Giant Branch



Example of TRGB detection in NGC 4258

A Check-Point

→ Facing a golden age for constraining systematics young vs old standard candles

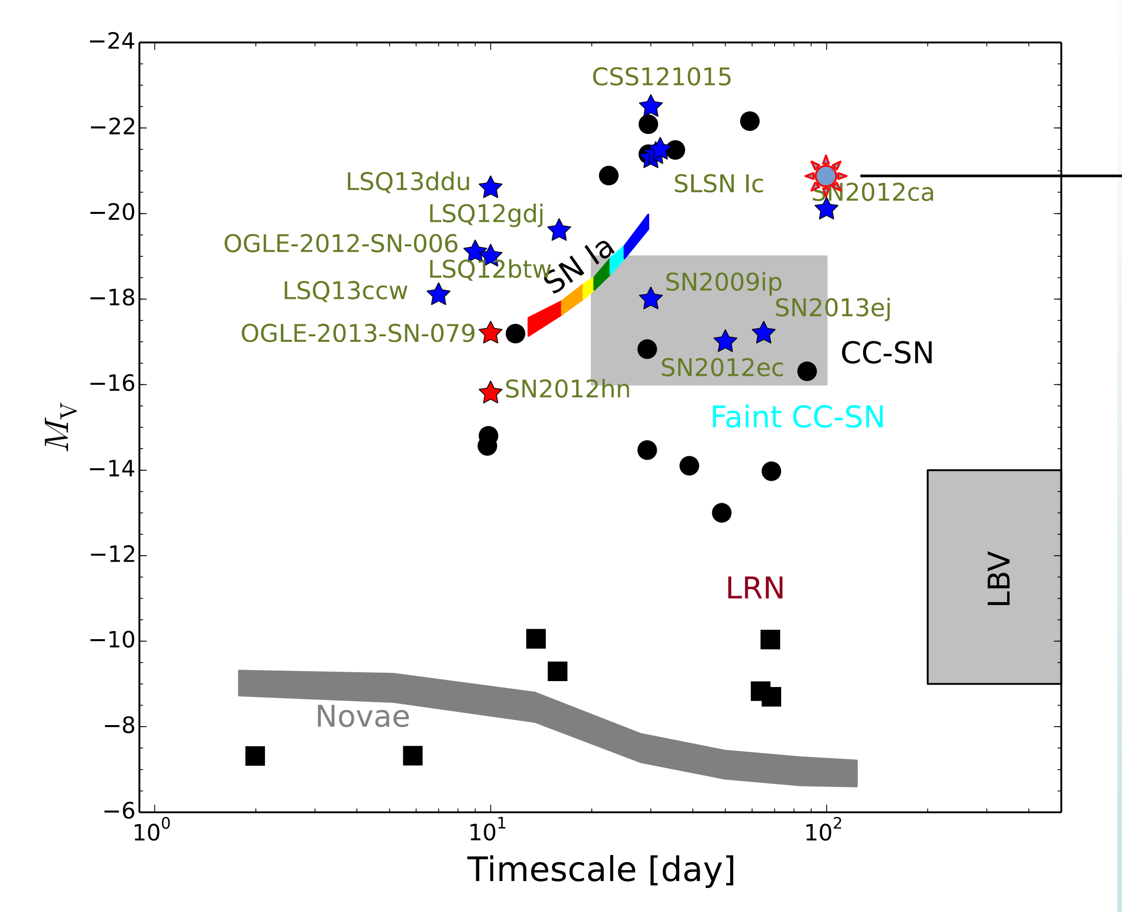
→ Environmental effects: complete census across Local Group and Local Volume galaxies

→Spectroscopic characterization

→Change in the paradigm: from observing facilities to experiment driven

Core-Collapse Supernovae

Transients : current science



SN 2013dn
Dall'Ora et al, in prep.

Smartt et al. 2015

What are the limits of physical explosions and transients?
Can we use cosmological distance indicators other than Ia SNe?

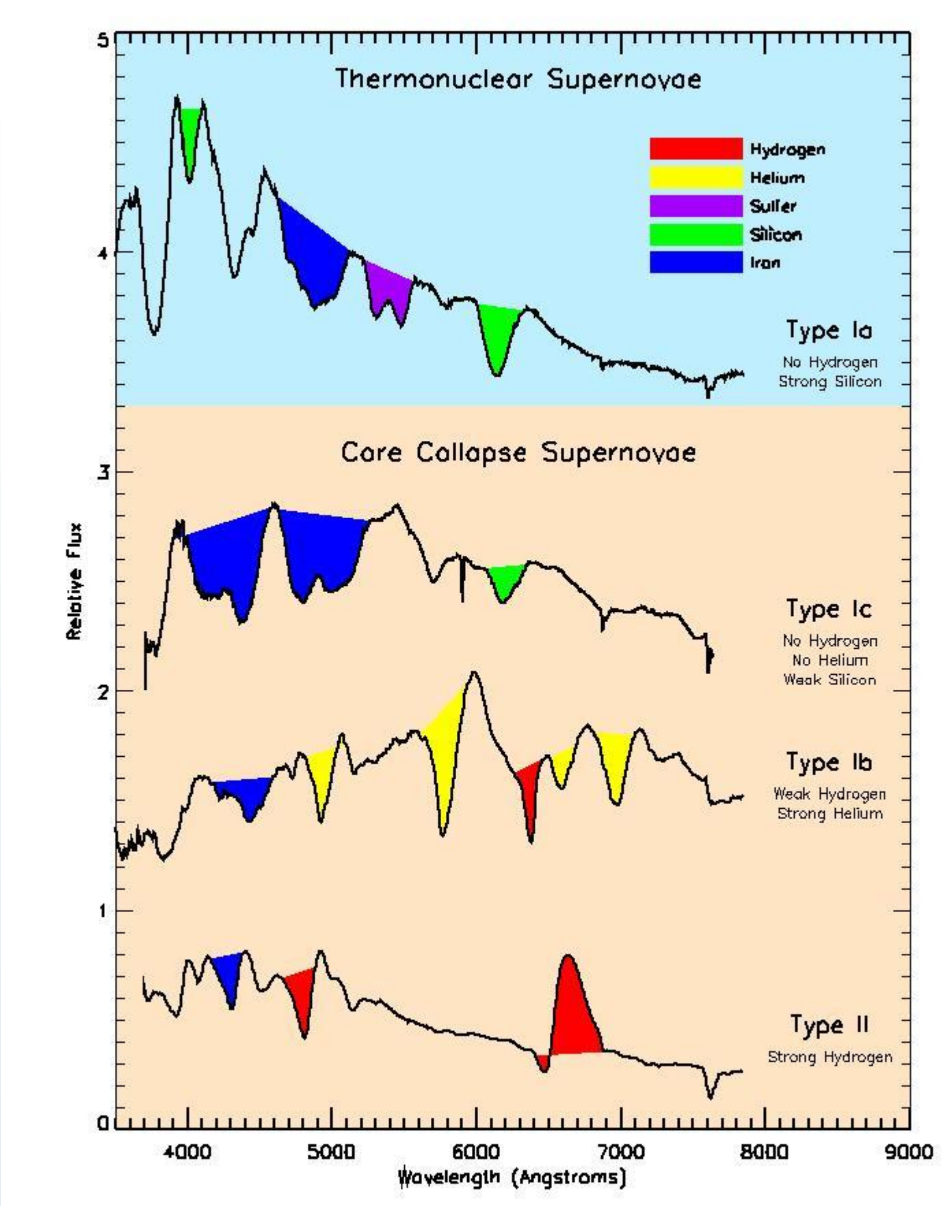
Credits: S. Smartt

A quick reminder

- SNe are primarily classified on the basis of their spectra:

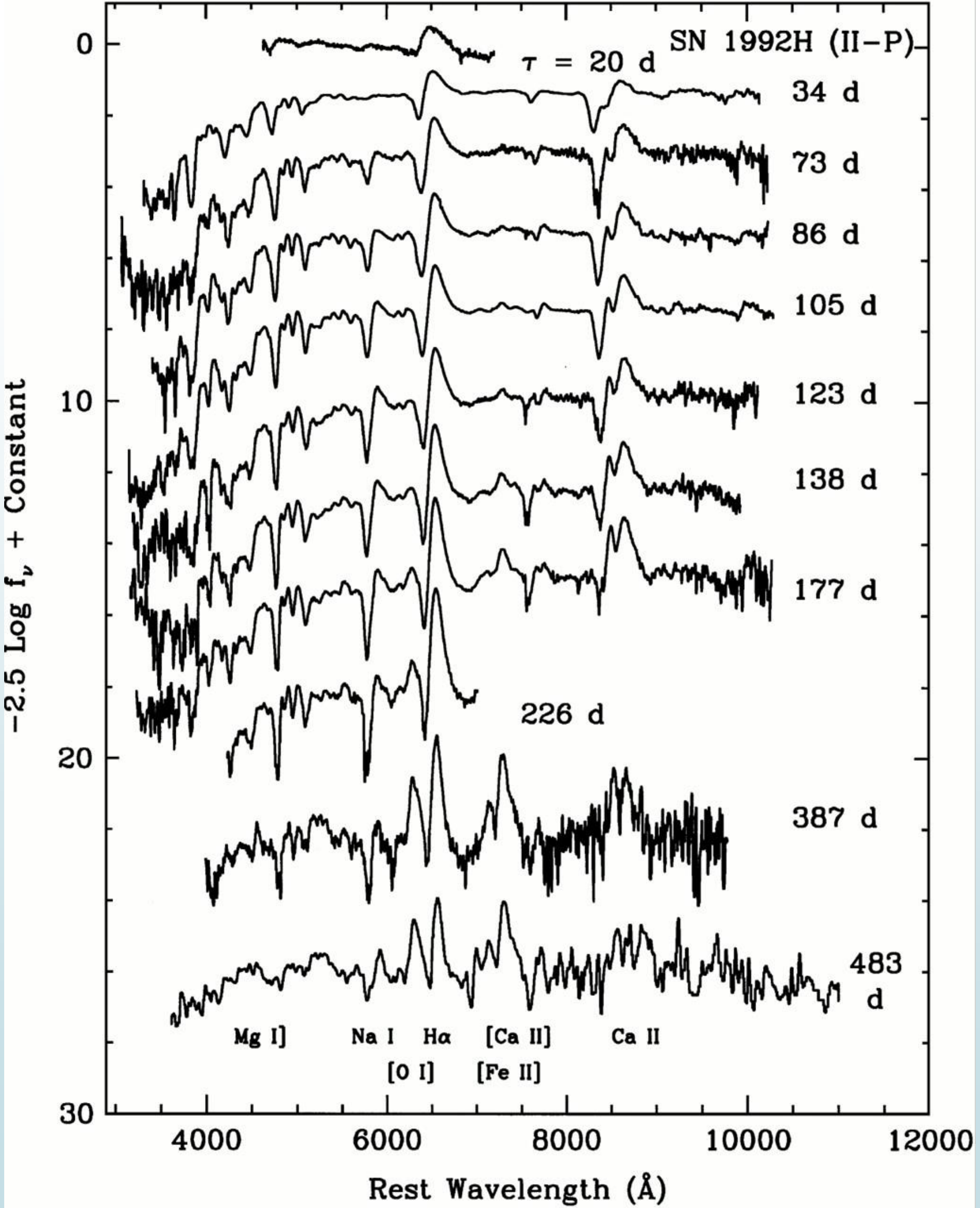
- Type I → no Hydrogen
  - Ia → strong Silicon
  - Ib → strong Helium (but a little Hydrogen)
  - Ic → no Helium, weak Silicon

- Type II → yes Hydrogen



Phenomenology of IIP SNe

- Strong Hydrogen lines --> Type II classification
- A long plateau in their lightcurve
- A sharp fall
- A radioactive tail



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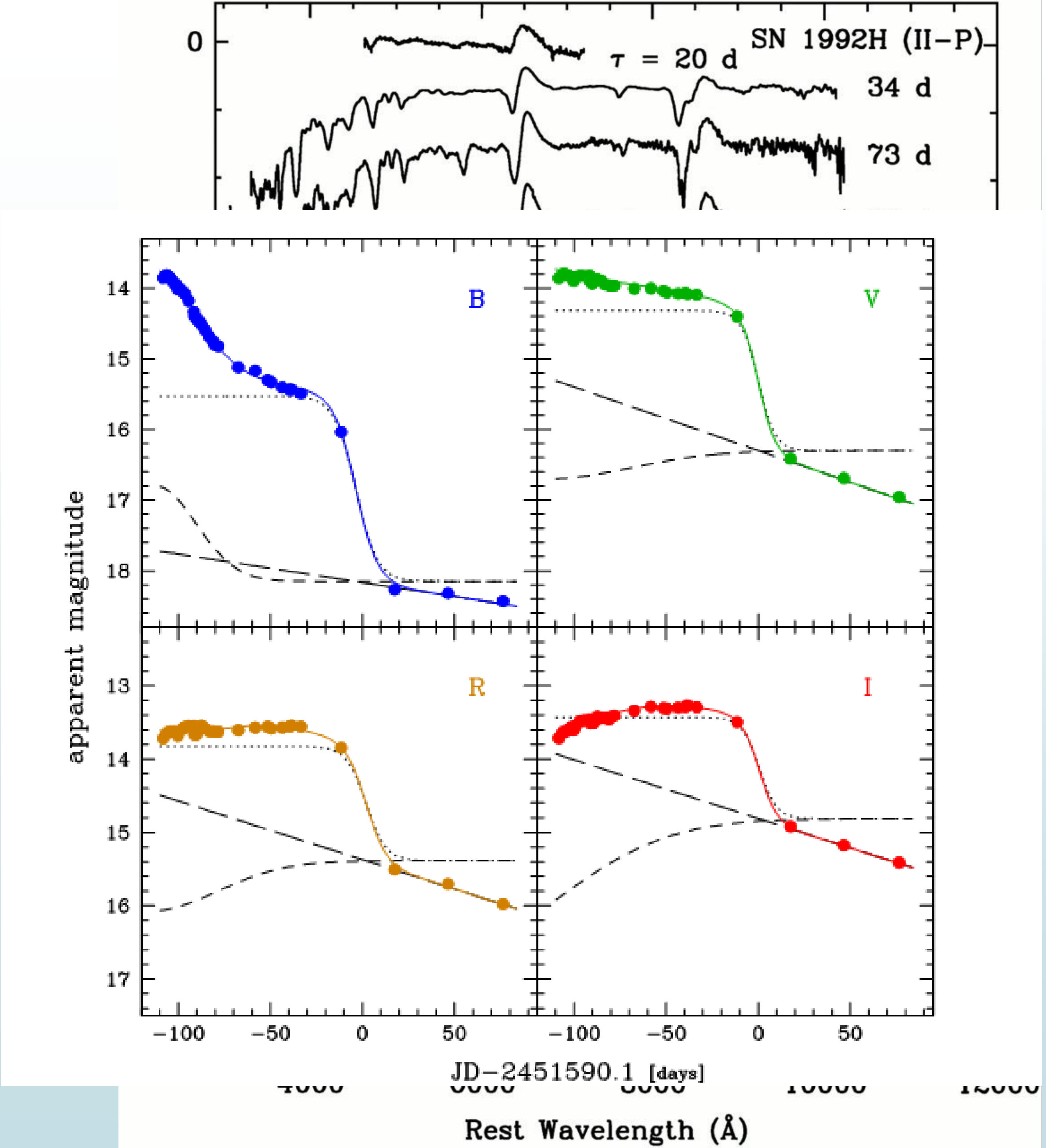
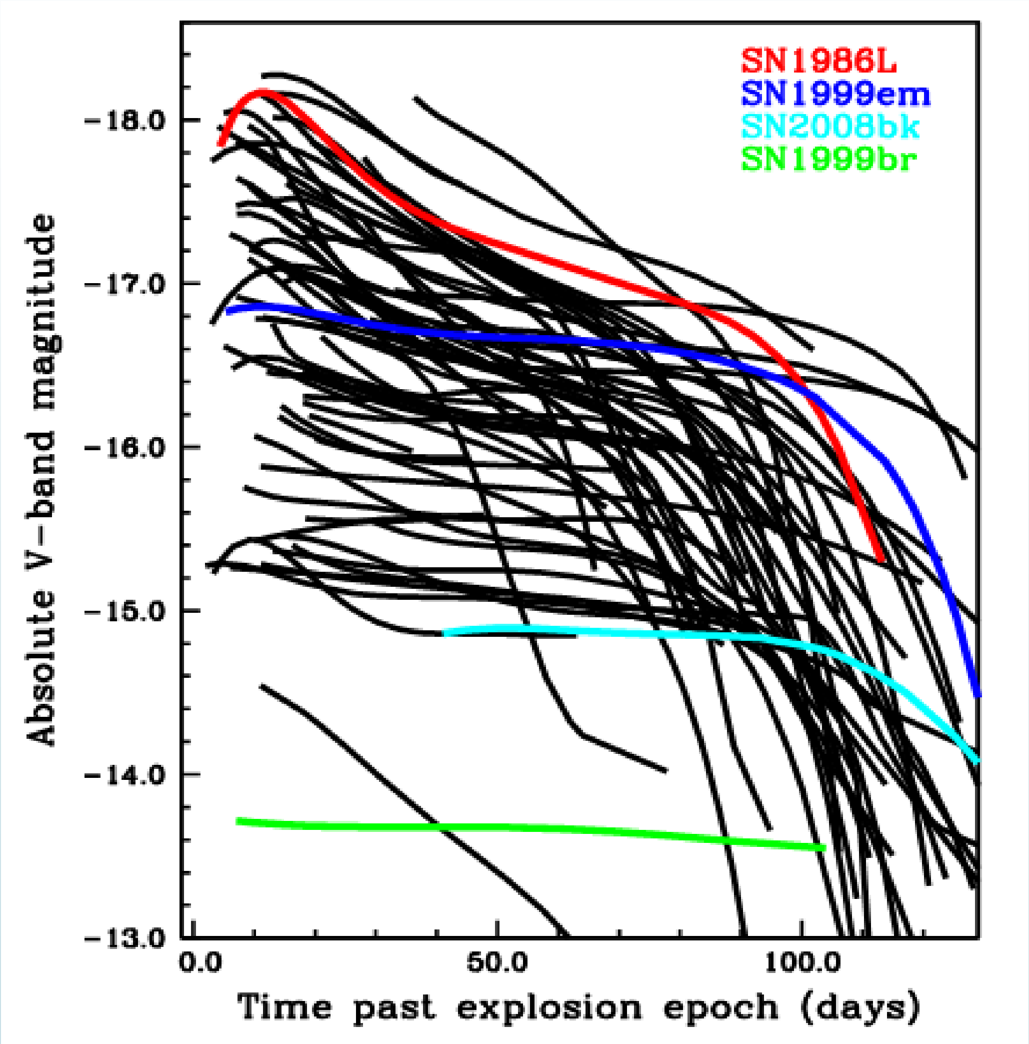


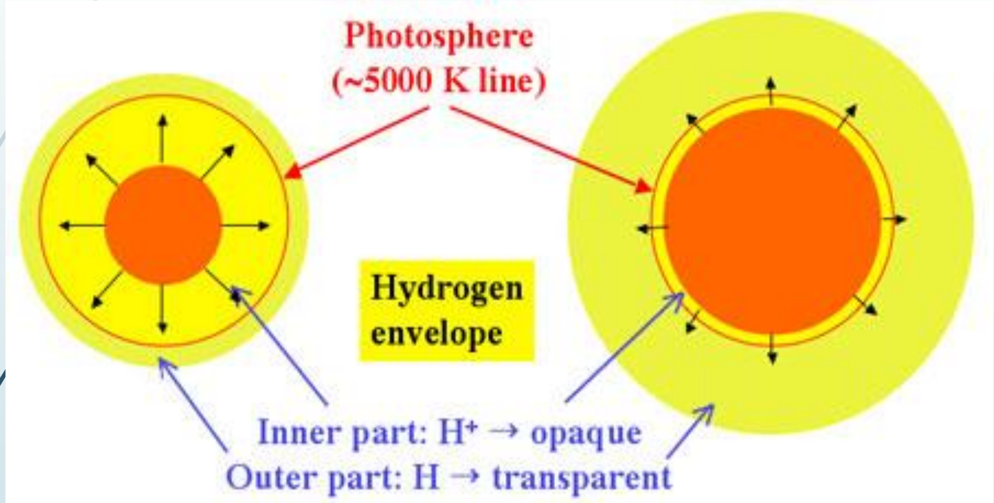
Mesured features of IIP SNe

- The duration of the plateau is usually of the order of ~100 days, ranging between 80 and 120 days
- The initial velocity of the ejecta is of the order of 1-2 x 10^4 km/s
- The initial temperature is of the order of 1-2 x 10^4 K
- Peak luminosities commonly range between Mv = -15.5 and Mv = -18.5 mag --> how can we use them as distance indicators?



Anderson et al. 2014

A few crucial points



In a Type IIP supernova, the position of the photosphere corresponds to where **hydrogen recombination** is taking place.

Since the temperature of recombination is constant, as the supernova expands and cools, the photosphere receeds in mass and a plateau is created in the light

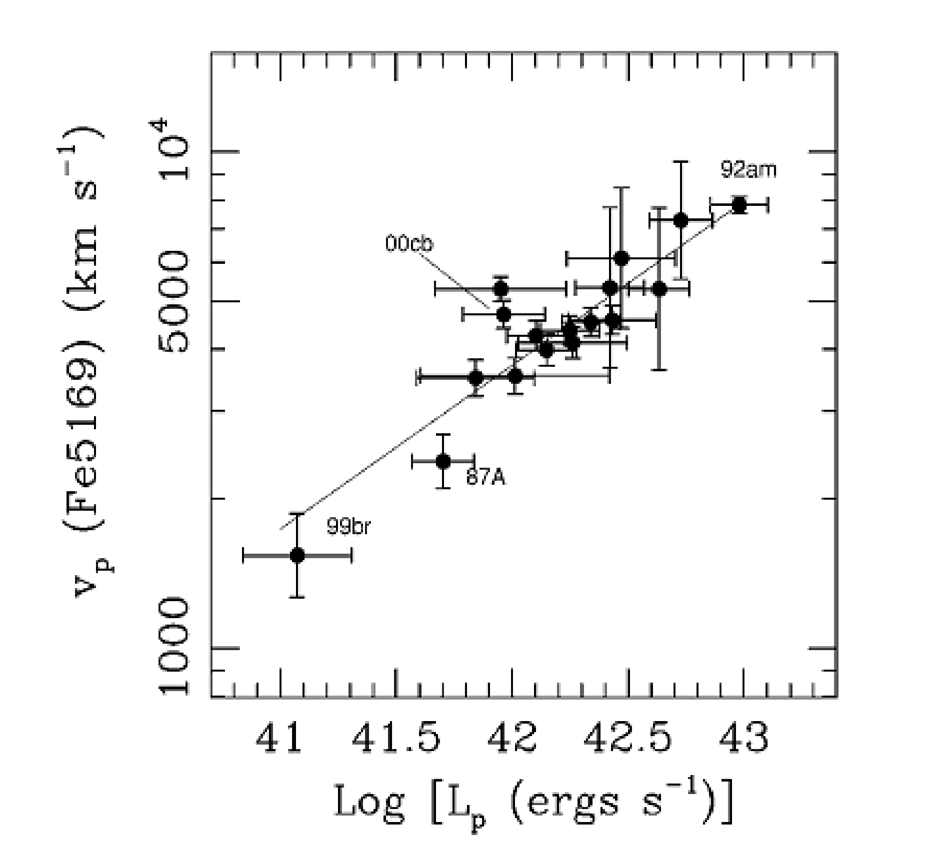
The length of the plateau is dependent on the depth of the hydrogen envelope

The expansion is **homologous -->** the velocity is proportional to the radius

The Standardized Candle Method (SCM)

A recasting of the EPM or of the Baade-Wesselink relation

$$L = 4\pi v_{ph}^2 t^2 \zeta^2 T_{ph}^4$$



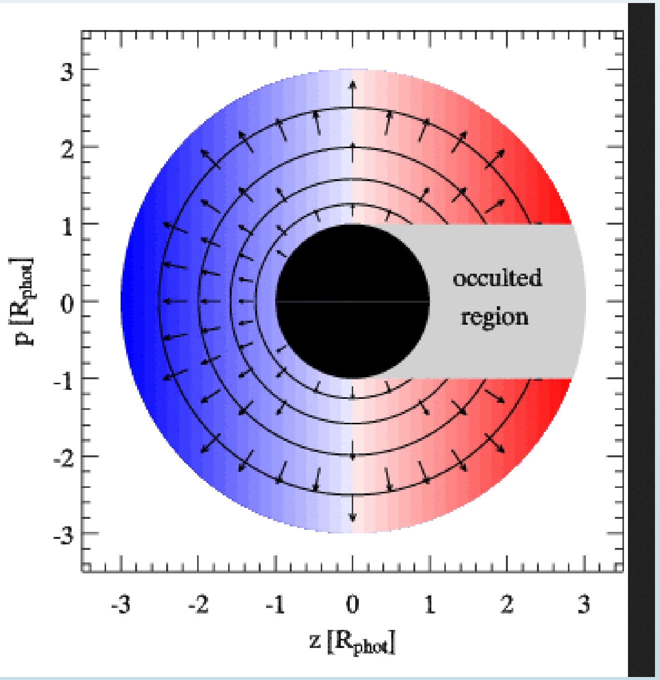
Hamuy & Pinto 2002

Why does the SCM exist?

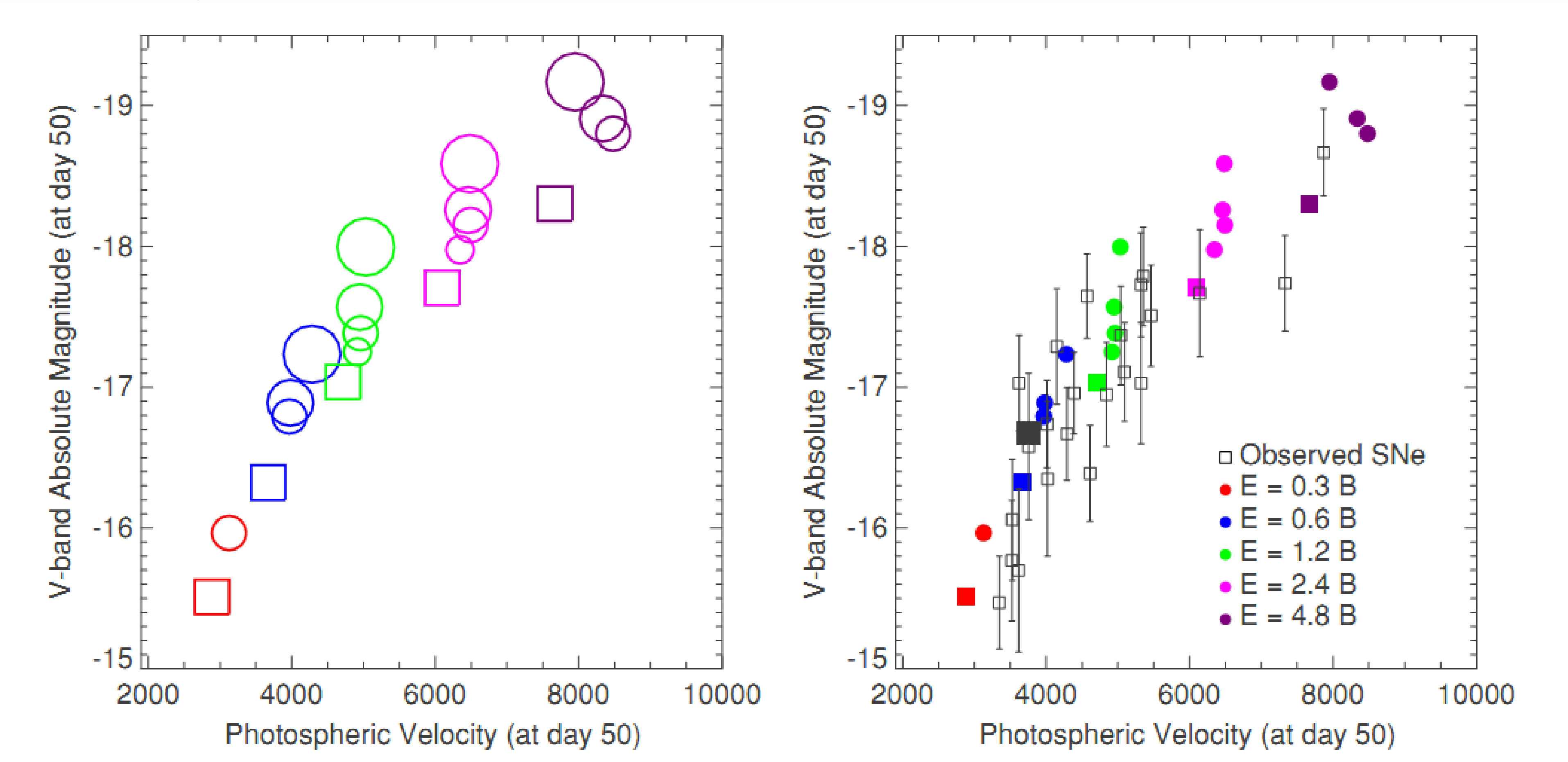
- A higher luminosity implies a larger hydrogen recombination front
- ... but it also implies a higher photospheric velocity (homologous expansion)

$$L_p = 4\pi R^2 \sigma T_{\mathrm{I}}^4$$

$$v_{\mathrm{sn}} \approx (2E/M_{\mathrm{ej}})^{1/2}$$

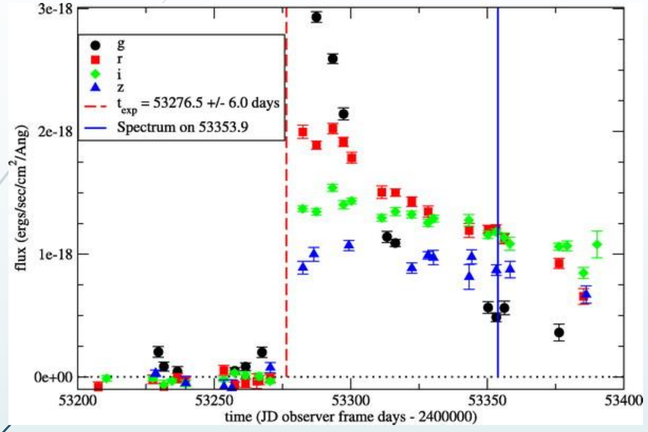


Theoretical Predictions



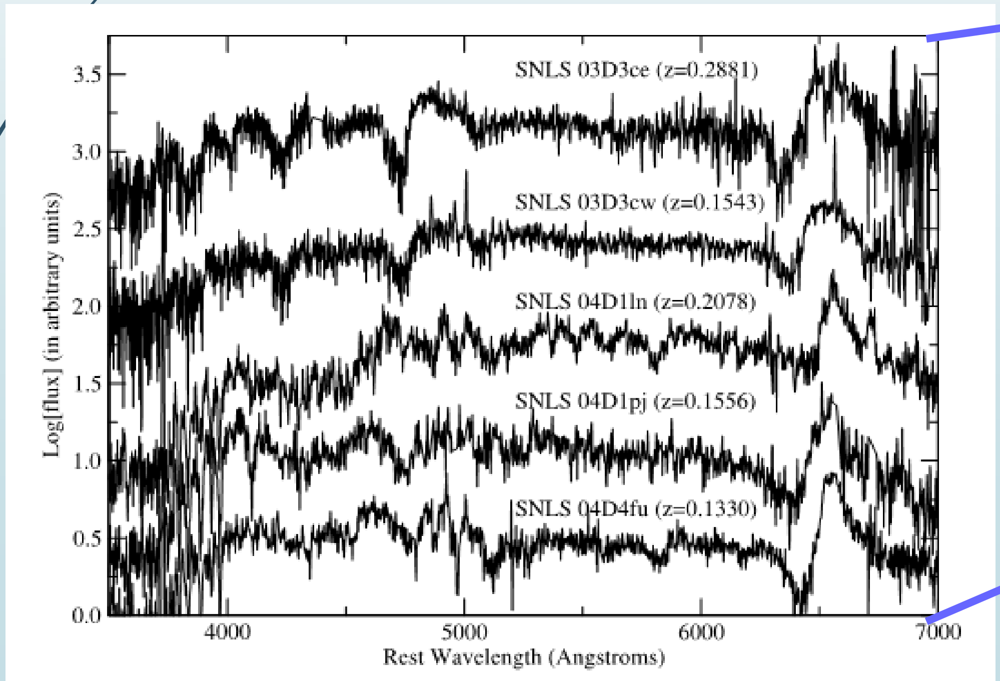
Kasen & Woosley 2009

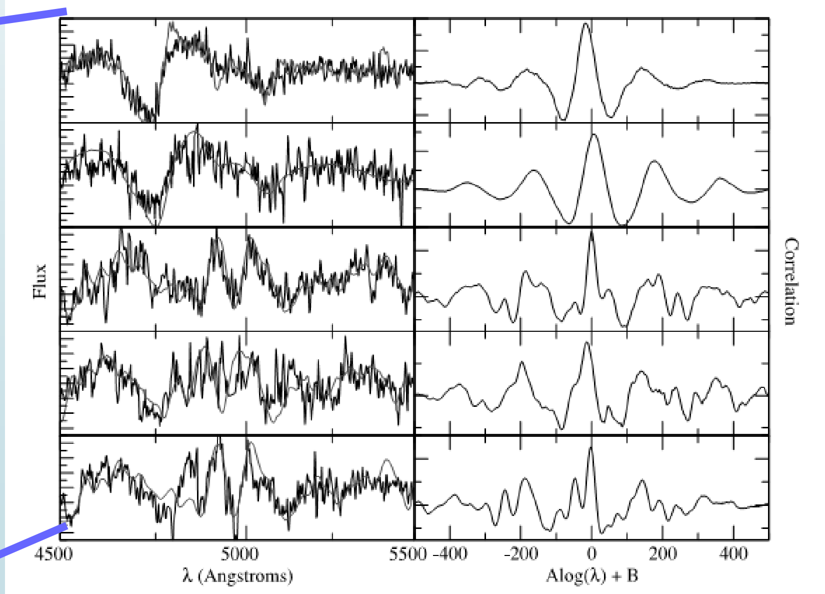
But... can we really measure distant IIP SNe?



CFHT

Nugent et al. 2006





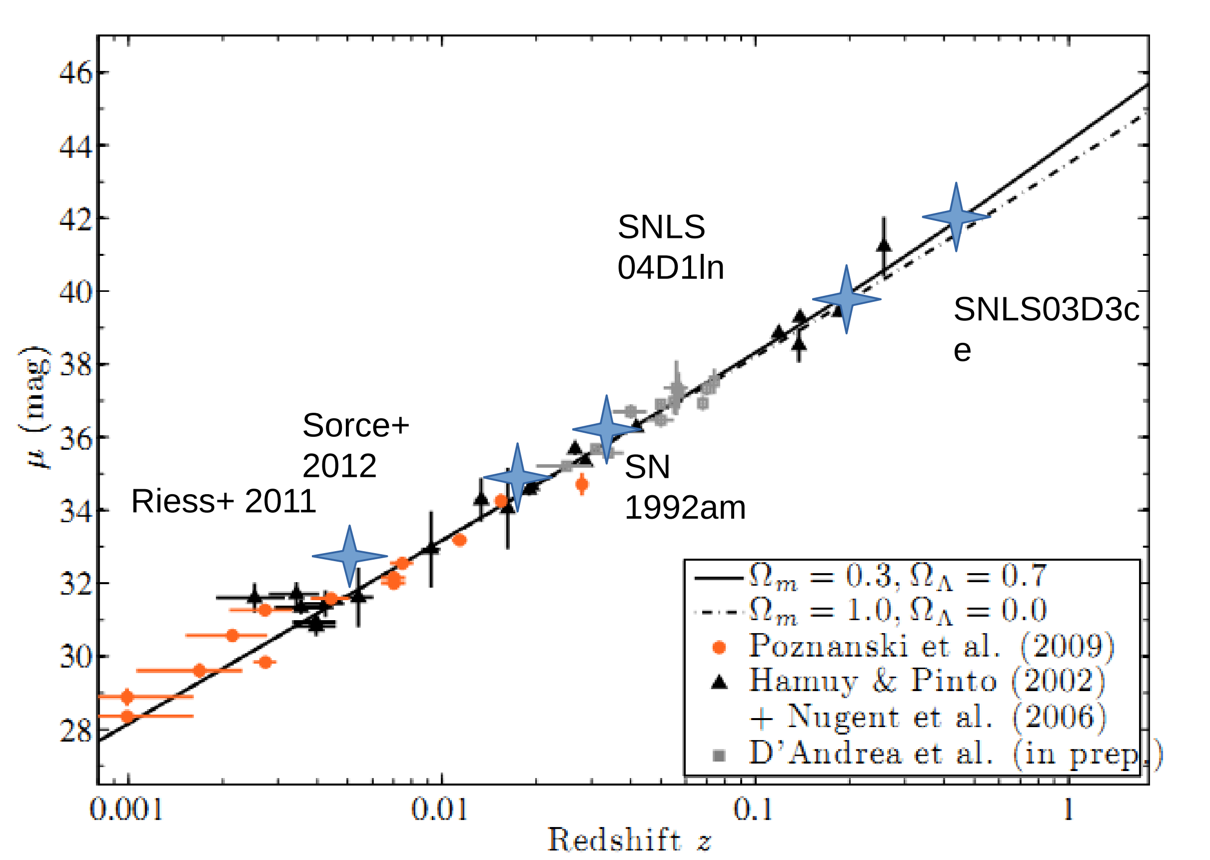
Keck

But... what does SCM really add?

Strictly speaking, this is not an independent calibration of the SN Ia distance scale

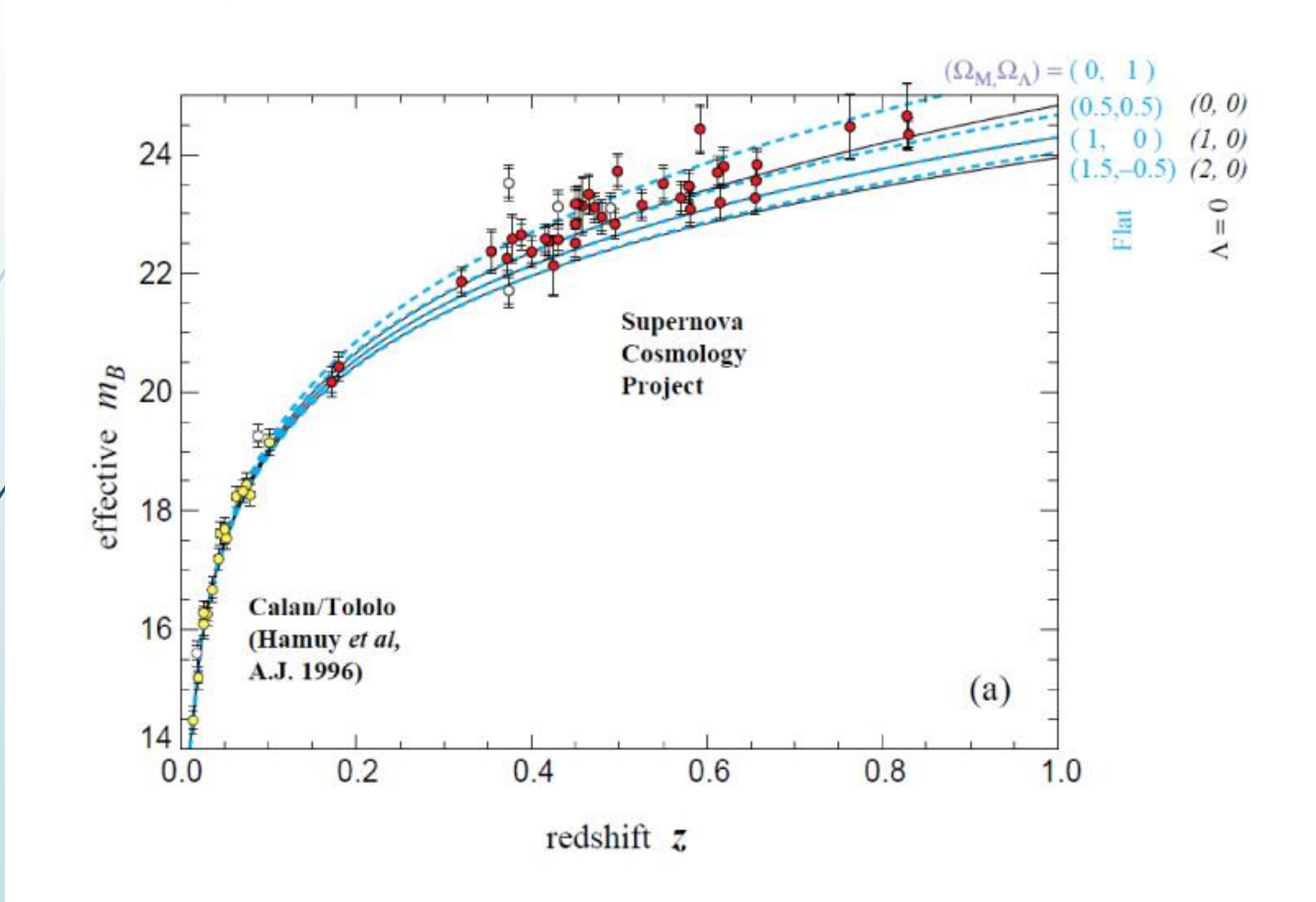
But it can be pushed far away, up to cosmological distances

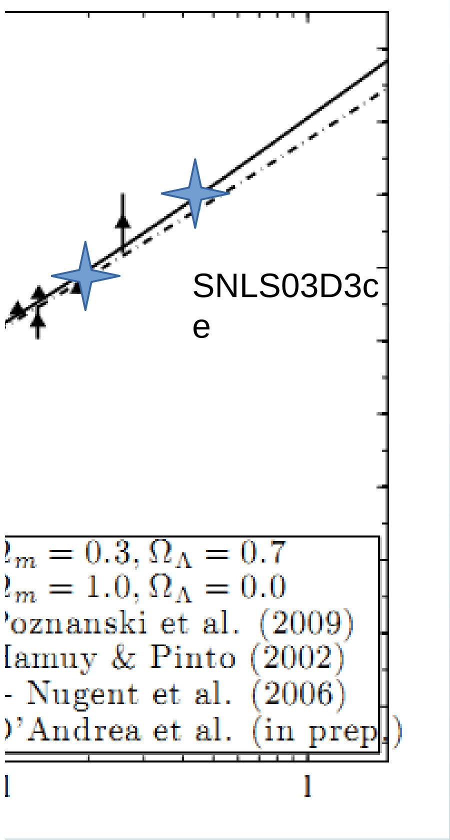
Therefore, it can be used as healthy check of the SNe Ia results



Poznanski et al. 2009

But... what does SCM really add?





Poznanski et al. 2009

Current Calibrations

$$I_p - A_I + 5.820(\pm 0.764)\log\left(\frac{v_p}{5000}\right) = 5\log(cz) - 1.797(\pm 0.103).$$

Hamuy & Pinto 2002
rms = 0.29 mag

→ 8 SNe, heliocentric corrected redshifts, "color" extinction, *adopted* H0 = 65 km/s/Mpc

$$M_I = -\alpha\log_{10}(V_{\mathrm{Fe\,II}}/5000) - 1.36[(V-I)-(V-I)_0] + M_{I_0}$$

rms = 0.26 mag

Nugent et al. 2006 → 24 SNe with mixed distances, mainly based on z-SBF, and "color" extinction at day 50, with a fixed extinction law, *adopted* H0 = 68

$$M_I = M_{I_0} - \alpha\log_{10}(v_{\mathrm{Fe\,II}}/5000) + R_I\,[(V-I)-(V-I)_0]$$

rms = 0.22 mag

Poznanski et al. 2009, 19 SNe z-SBF distances, extinction law as a free parameter, *adopted* Ho = 70

$$m + \alpha\log(v_{\mathrm{FeII}}/5000) - \beta(V-I) = 5\log cz + zp.$$

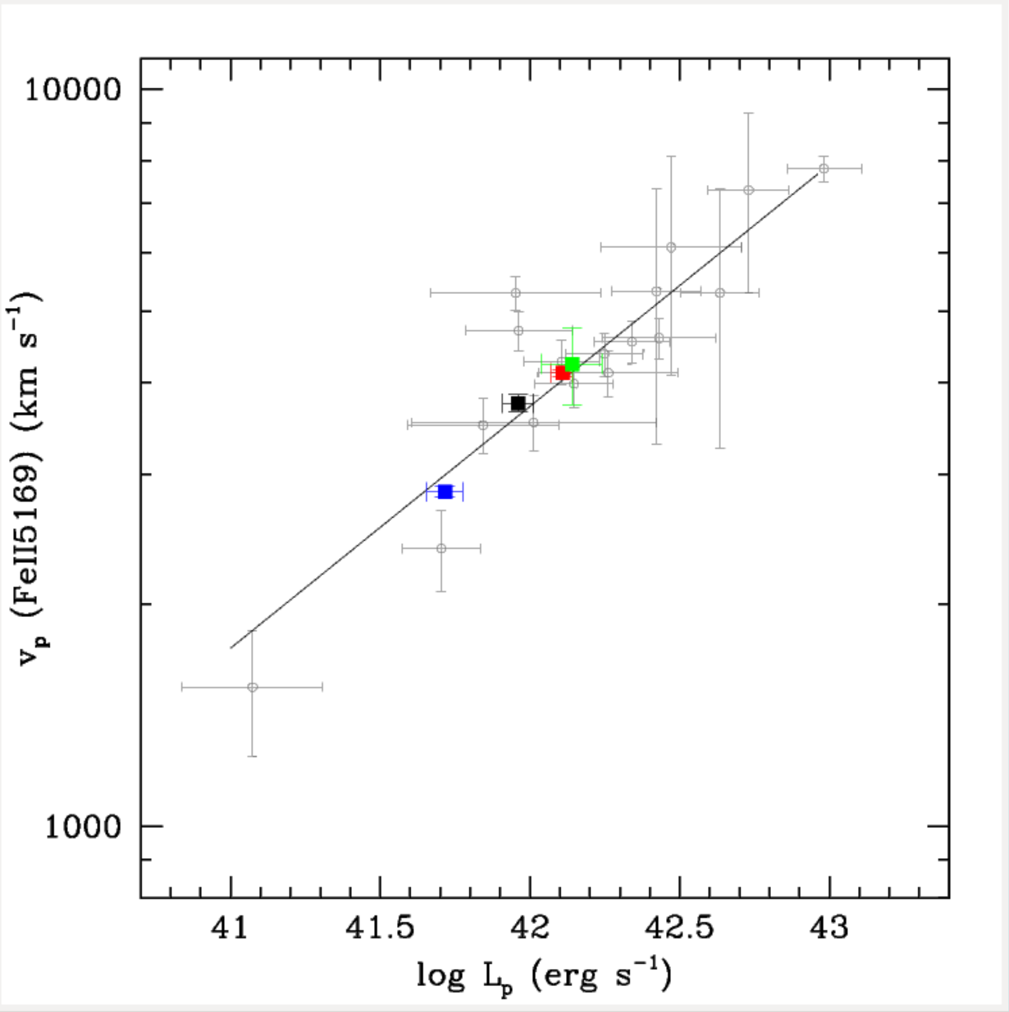
rms = 0.19 mag

Olivares et al. 2010, 37 nearby SNe, heliocentric corrected redshifts, Cepheids calibrated, "custom" reference phase, local extinction law

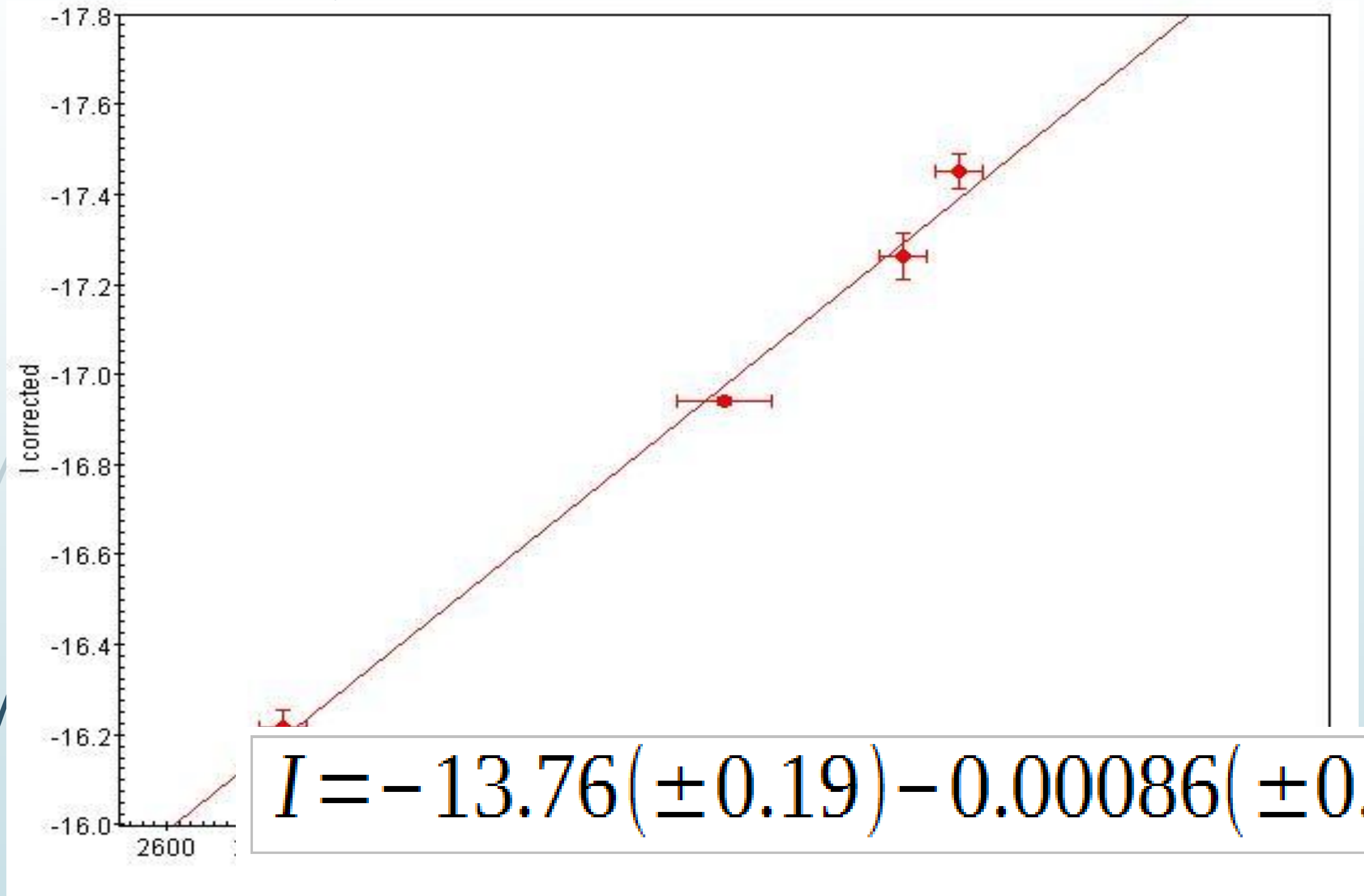
A simple exercise

What happens if we put in the HP diagram four **nearby** IIPs, studied with a homogenous data reduction and with a homogenous treatment of the reddening of the host galaxy?

- SN 2012aw (M95), Dall'Ora+14
- SN 2012ec (NGC 1084), Barbarino, Dall'Ora+15
- SN 2012A (NGC 3239), Tomasella+13
- SN 2013ej (M74), Yuan+16



Again a simple exercise



- A simple fit of the I-band dereddened absolute magnitudes, as a function of the velocity (not log v) gives...

$$I = -13.76(\pm 0.19) - 0.00086(\pm 0.00005) \times v_{exp} (50)$$

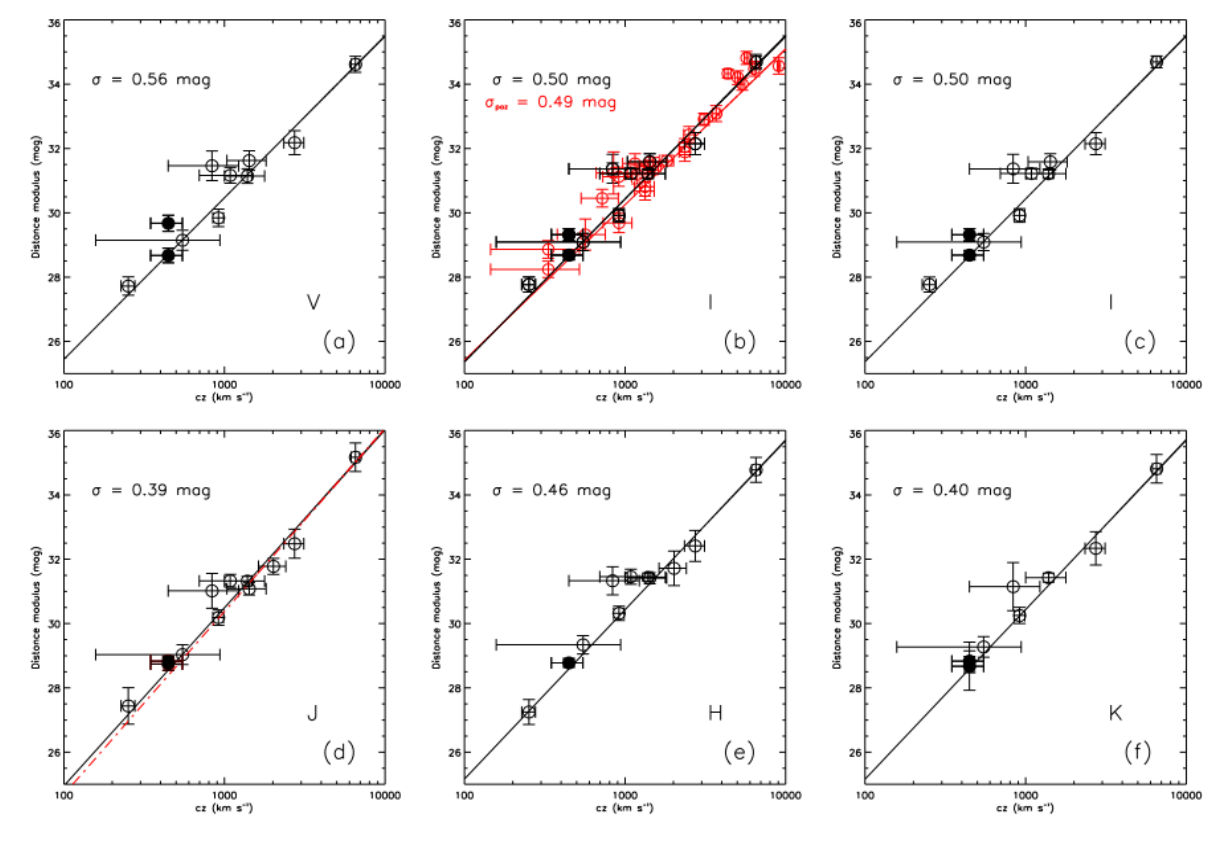
$$\sigma = 0.054\, mag$$

The Role of E-ELT

- To calibrate the SCM with Primary Distance Indicators we need to increase the number of host galaxies where IIP SNe have exploded, and also we have detected Cepheids and TRGB
- Currently, only a very few objects are available
- This means that we can either:
  - Wait for other IIP SNe to explode in nearby galaxies... 😂
  - Or... observe Cepheids and TRGB in more distant galaxies (yes, E-ELT), where IIP SNe have been already exploded...

The Role of E-ELT

- However, E-ELT will observe in the NIR bands
- Can we apply the SCM in the NIR?…

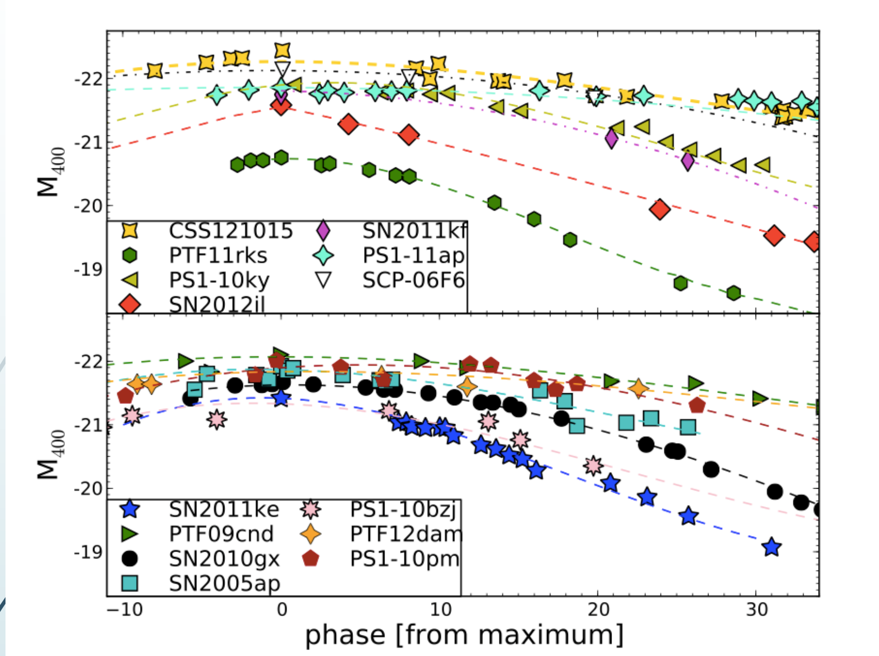


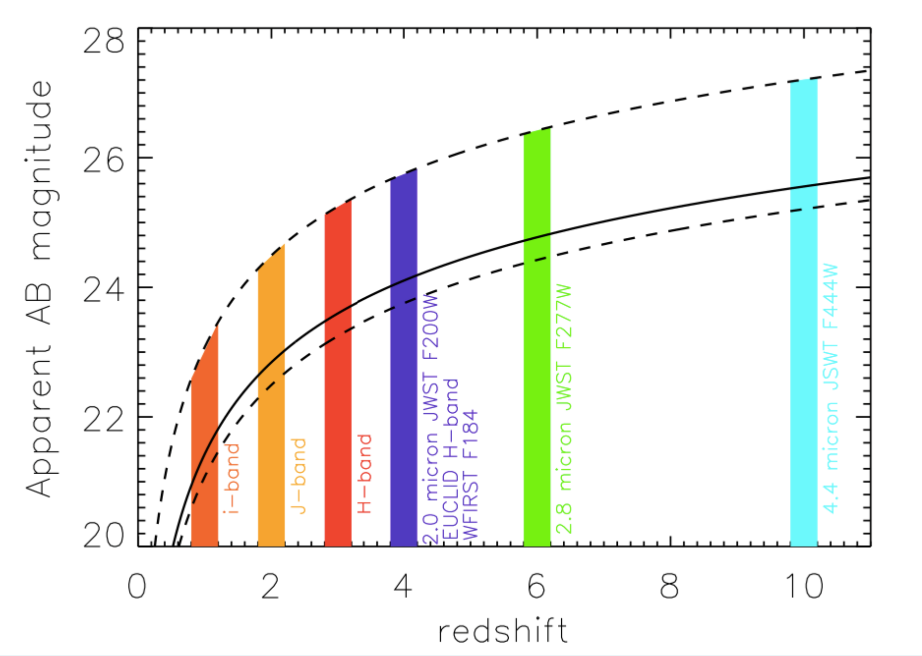
Maguire et al. 2010

Why is SCM appealing?

- SCM is a fast and simple method, with a good accuracy (10-15%), with a known physics behind
- It can be used up to cosmological distances and it can provide a healthy check of the Ia SNe calibration
- IIP SNe rates could provide a higher statistics than Ia SNe (Hopkins & Beacon 2006)
- They are a homogeneous sample with respect to the age of the stellar population
- BUT.... we still lack a calibration on Primary Distance Indicators (Cepheids, TRGB)...

Another application: SLSNe as standardizable candles





Inserra & Smartt 2014, ApJ, 796, 18

- Super-luminous SNe : hot, UV bright sources, M_{UV} ~ -22 mag
- Peak magnitude is (potentially) standardizable to ± 0.2 mag
- Already shown to be exclusively produced in low metallicity dwarf galaxies ($Z < 0.2Z_{\odot}$)
- Ideal high redshift probes : cosmology, star formation, beyond z > 6 with LSST, JWST, VLT and E-ELT

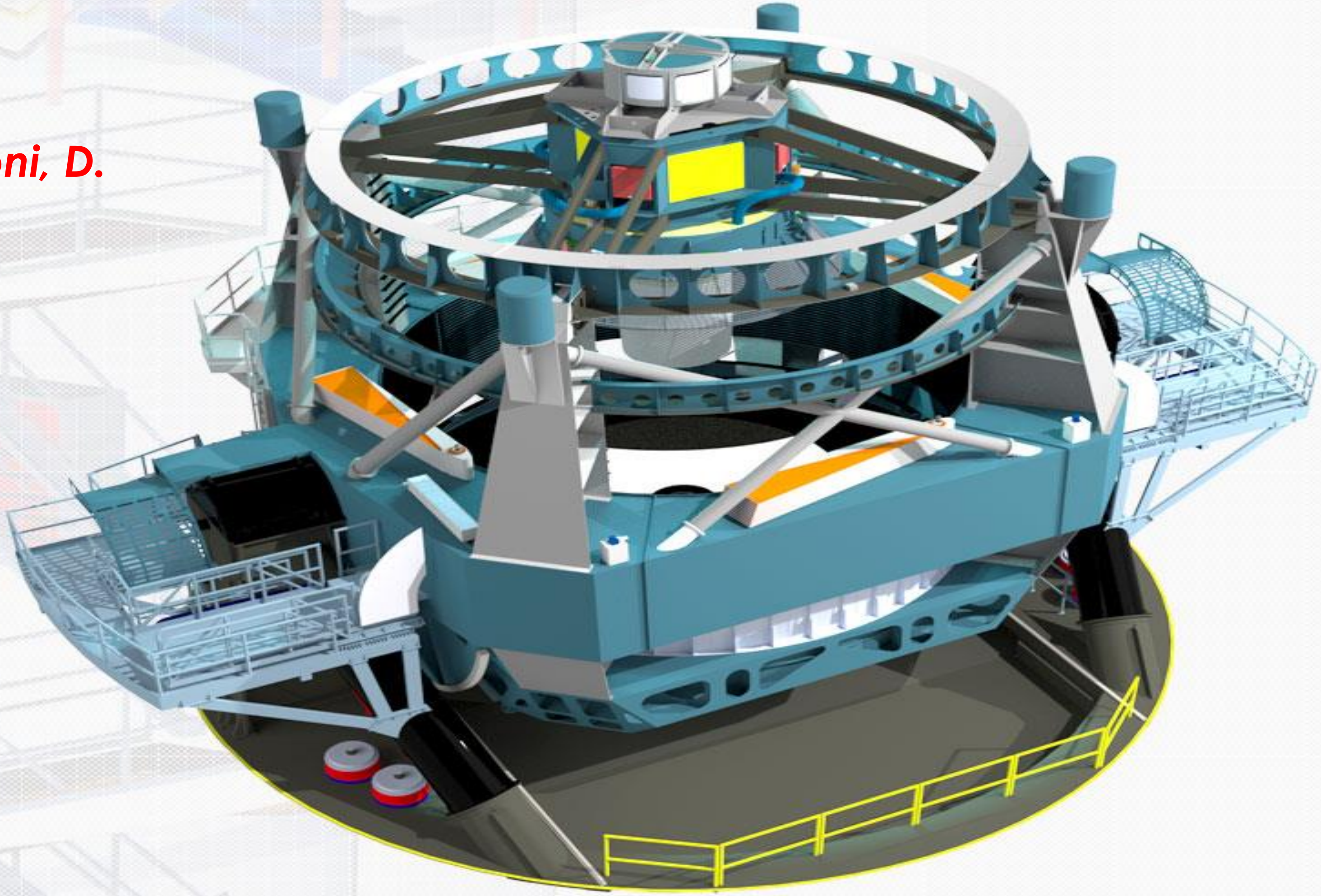
Credits: S. Smartt

What’s cooking?

LSST: a new spin

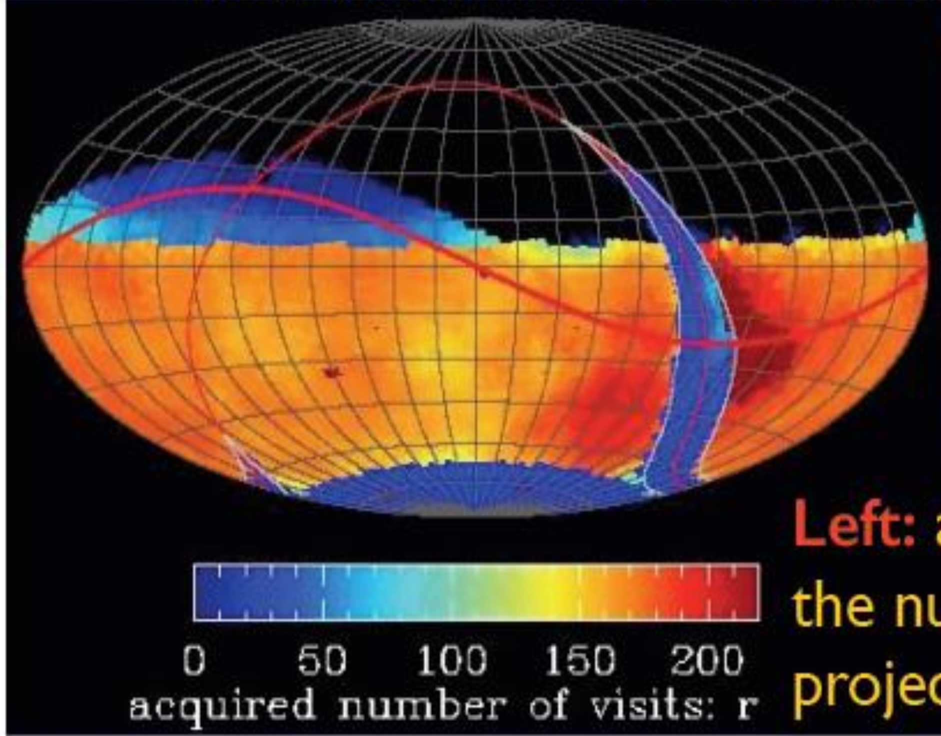
G. Bono, M. Dall'Ora, G. Fiorentino, S. Marinoni, D. Magurno

PI-ship supported by INAF



Basic idea behind LSST: a uniform sky survey

- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- after 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky
- ~100 PB of data: about a billion 16 Mpix images, enabling measurements for 40 billion objects!



LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

LSST: the numbers

Single epoch (5σ) measurements

u=23.9 -- g=25.0 -- r=24.7 -- i=24.0 –- z=23.3 – y=22.1

Final mean magnitudes

u=26.1 -- g=27.4 -- r=27.5 -- i=26.8 –- z=26.1 – y=24.9

Number of visits x band

u=56 – g=80 – r=184 – i=184 –- z=160 – y=160

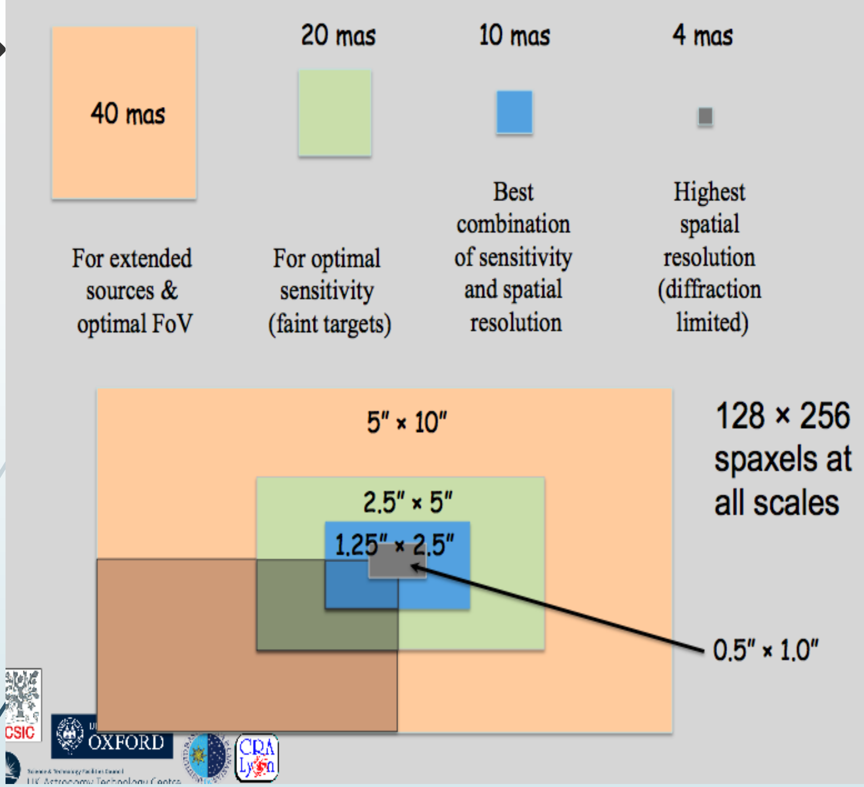
Median number of visits x field in all bands → 824

Two 15 sec exposures x visit

90% survey + 10% special programs

E-ELT: the near future

E-ELT Integral Field Spectrograph: HARMONI



Plus SCAO + **LTAO**

33,000 spaxels per exposure!

LSST & ELT at least five years in common

Wavelength Ranges & Resolving Powers

Bands	R
V+R, I+z+J, H+K	~4000
V, R, I+z, J, H, K	~10000
Z, J_high, H_high, K_high	~20000

→ ❖ Exploring adding simultaneous V-K coverage at R~500-1000 ←

❖ Re-assessing the need for high spectral resolving power at visible wavelengths (< 0.8 micron)

NIRSPEC@JWST

FoV ~3′ X 3′ for MOS

Slit width ~200 mas

Slits Micro Shutter Array
Fixed slits
IFU (3″″ X 3″)

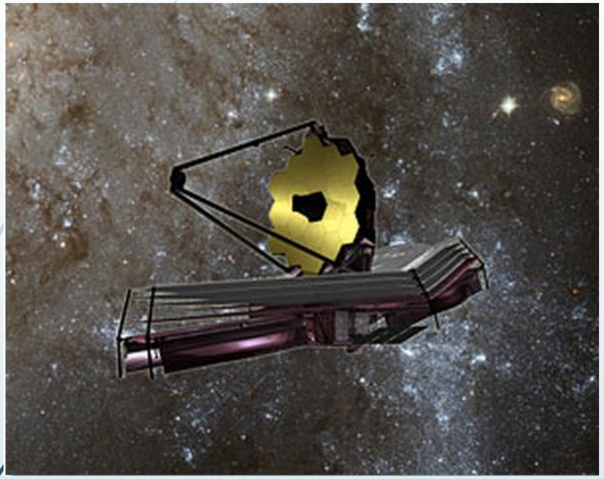
Spectral Resolution
R~100 → 0.7 -- 5 μm (single prism)
R~1000 → 1 -- 5 μm (3 gratings)
R~2700 → 1 -- 5 μm (3 gratings)

R=100 → t_exp ~ 10,000 sec point source continuum at 3 μm

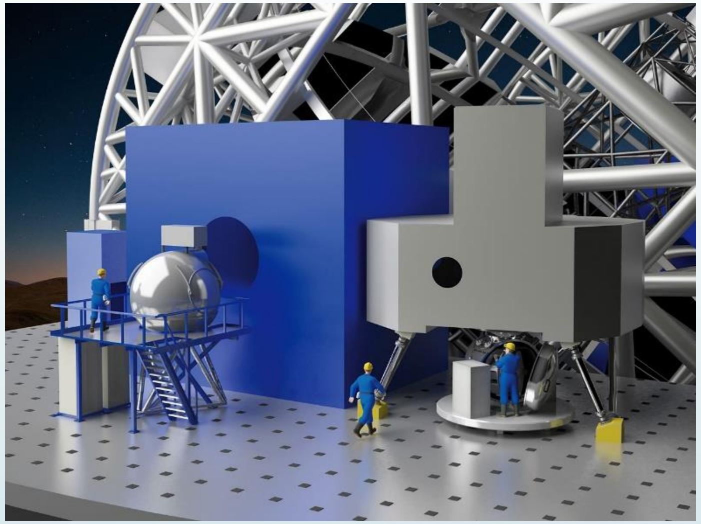
S/N=10 is AB~26 mag

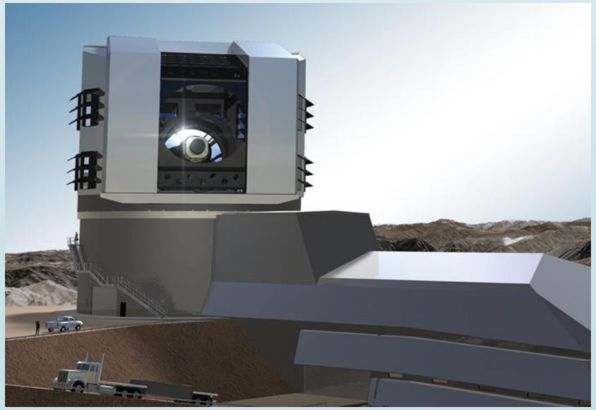
Synergies between JWST & ELTs

High-z : JWST, LSST and E-ELT



NIRSPEC
Surveys
$H_{AB} > 25$



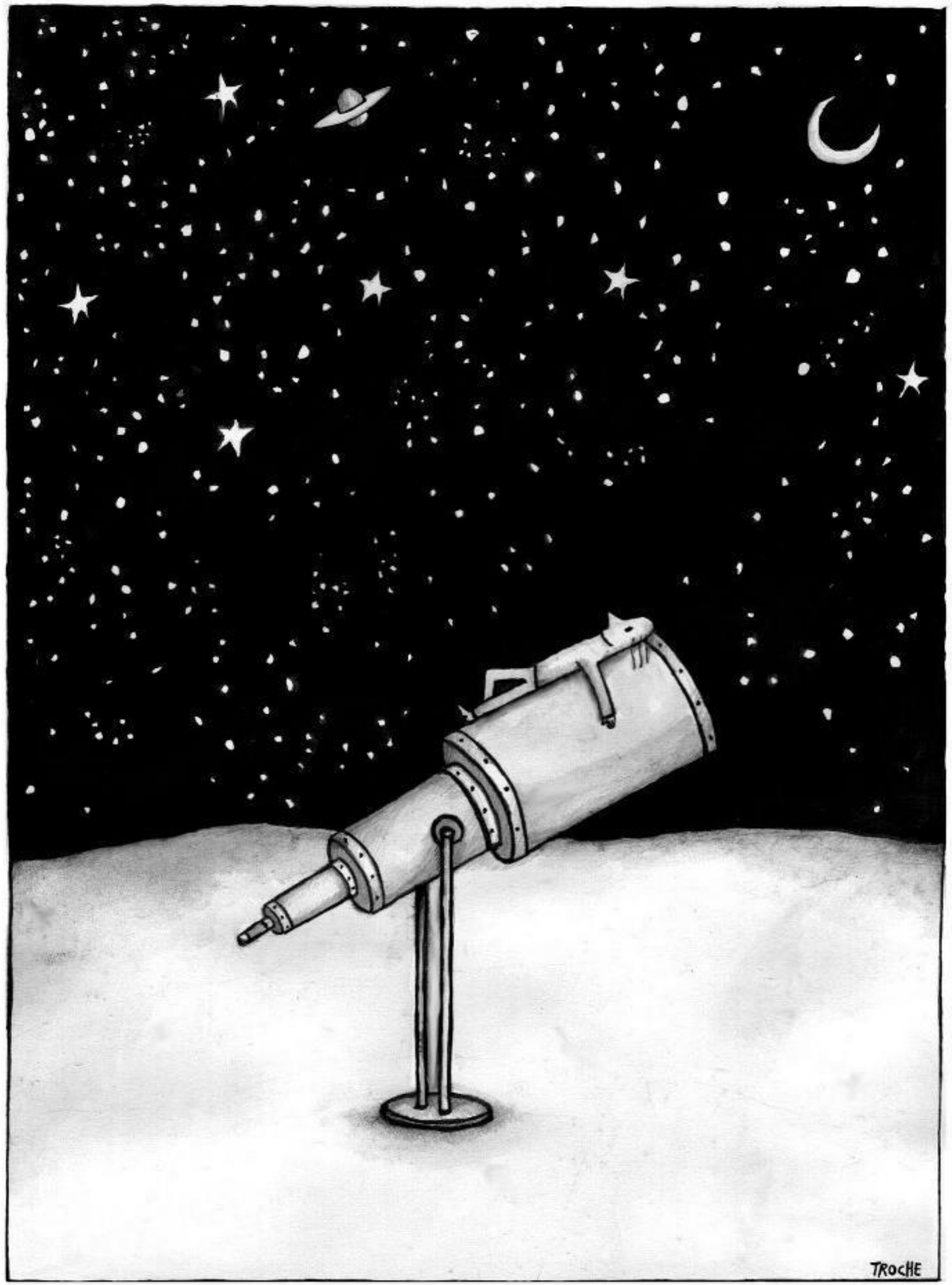


LSST
Surveys
$z_{AB} > 25$

- Feed for ELT spectra
- ELT + HARMONI
- 4hrs gets H_{AB}=25 at S/N~20 (R~500)
- SLSNe at *z = 6-10*

Credits: S. Smartt

Thank you



“Mirar el Cielo es un sentimiento”