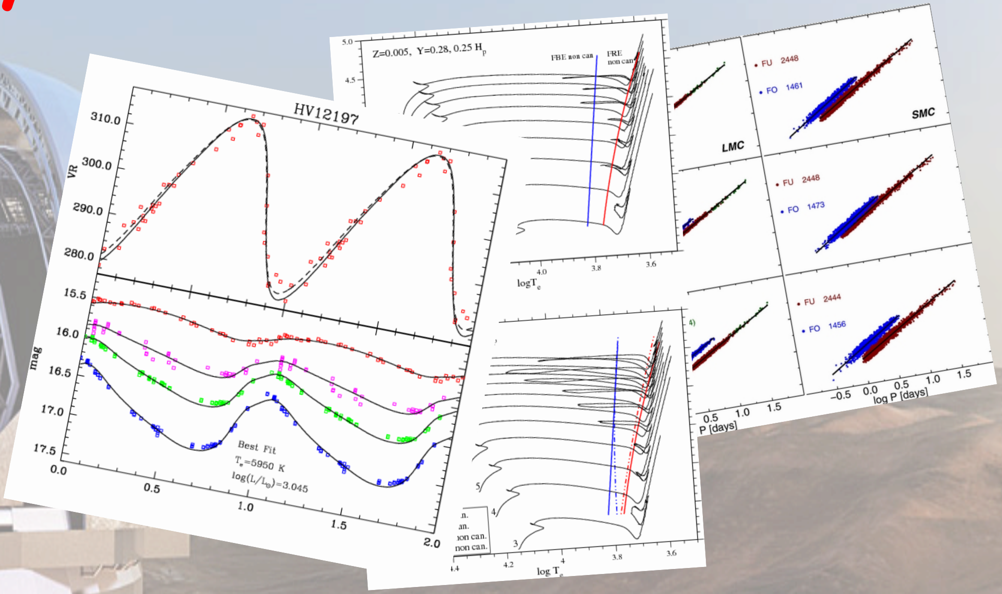
Erice, Sicily, 8-20 October, 2015
International PhD School "F. Lucchin": Science and Technology with E-ELT
- XIV Cycle II Course

Stellar variability in the E-ELT era



Marcella Marconi

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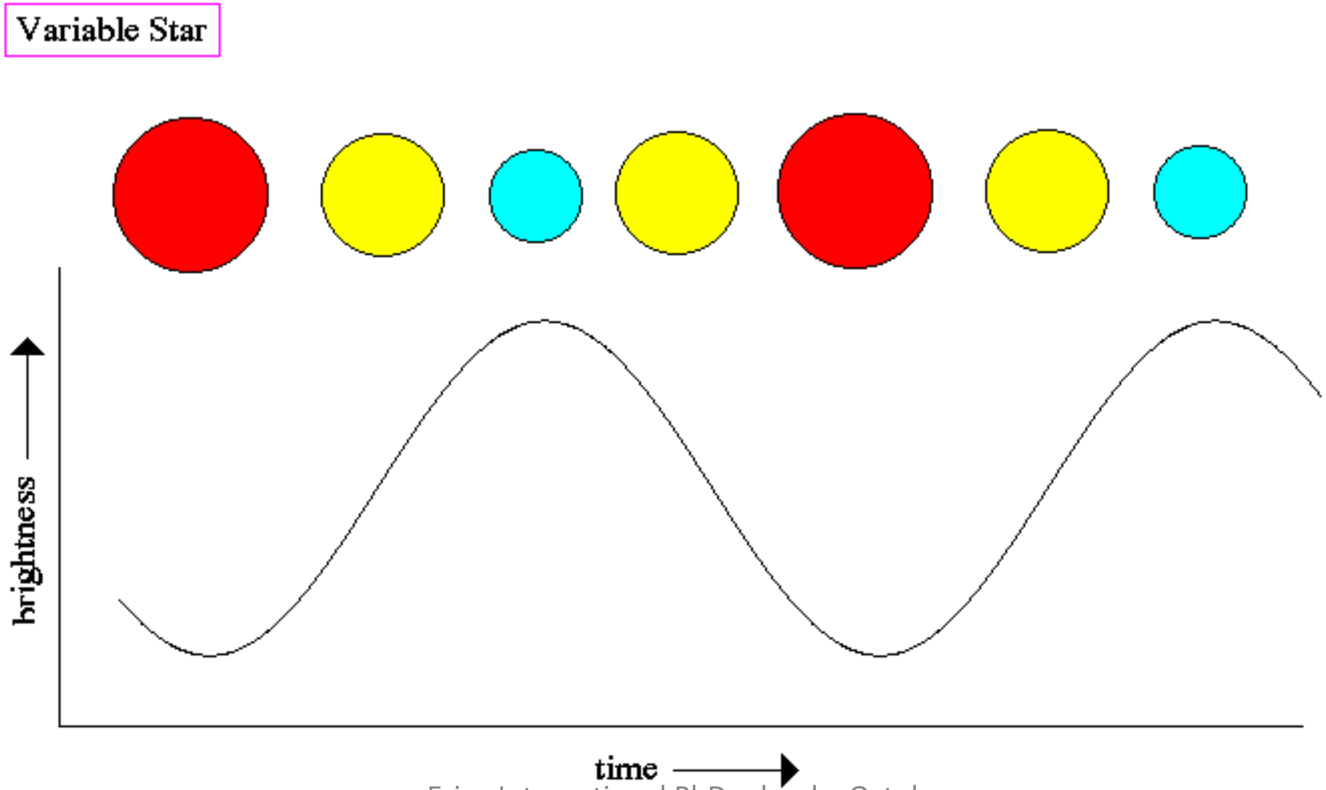
Outline

- Properties of pulsating stars
- Why to study pulsating stars
- The pulsation mechanisms
- Theoretical approach to the study of pulsating stars
- **Cepheids**: properties, open problems, results and perspectives in the E-ELT era
- **RR Lyrae**: properties, open problems, results and perspectives in the E-ELT era

Pulsating Variable stars

Pulsating stars are intrinsic variables showing cyclic or periodic variations on a time scale of the order of the *free fall* time.
In the simplest case they are radial pulsators.

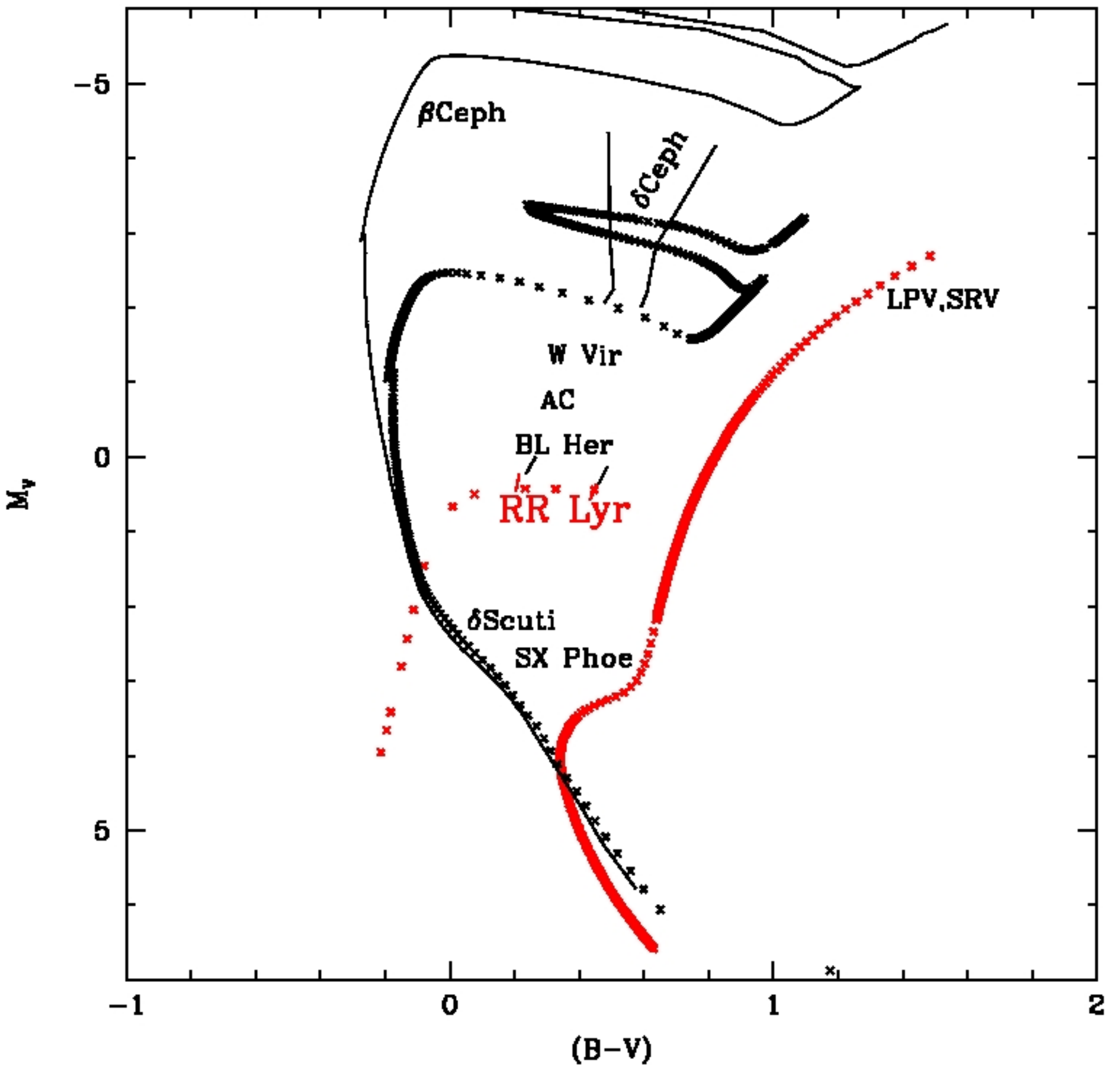


Properties of pulsating stars

Class	Period (days)	M_V	Pop	Evo. Phase
δ Cephei (CC)	1 – 100(?)	-7(-8) ÷ -2	I	Blue Loop
δ Scuti (δSc)	< 0.5	2 ÷ 3	I	MS-PMS
β Cephei	< 0.3	-4.5 ÷ -3.5	I	MS
RV Tauri	30 – 100	-2 ÷ -1	I, II	post-AGB
Miras	> 100	-2 ÷ 1	I, II	AGB
Semiregulars (SR)	> 50	-3 ÷ 1	I, II	AGB
RR Lyrae (RRL)	0.2 – 1	~0.5 ÷ 0.6	II	HB
W Virginis (Type2C)	10 – 50	-3 ÷ -1	II	post-HB
BL Herculis (Type2C)	< 10	-1 ÷ 0	II	post-HB
SX Phoenicis (SXPhe)	< 0.1	2 ÷ 3	II	MS
ACs	0.3 - 2.5	-2 ÷ 0	?	HB-turnover
SP Cepheids (SPC)	< 2	≤ 0.0	I	Blue Loop
LL Cepheids (LLC)	0.55 – 0.65	≤ 0.4	?	?

Properties of pulsating stars

Location of pulsating stars in the HR diagram



Properties of pulsating stars

The time scale of pulsation

- As for an acoustic wave, pulsation period ≈ time required to propagate through the diameter of the star:

$$\Pi \sim 2R/\langle v_s\rangle$$

$\langle v_s\rangle$ = adiabatic sound velocity over the whole star in its equilibrium state.

- For a self gravitating structure in hydrostatic equilibrium, (no rotation, no magnetic fields) for which pressure vanishes on the surface:

$$\boxed{-\Omega = 3\int P\,dV} = 3\int P/\rho\,dm = 3\int \langle v_s{}^2\rangle/\Gamma_1\,dm = 3\,\langle v_s{}^2/\,\Gamma_1\rangle M$$

$$\Rightarrow \langle v_s\rangle \approx (-\Omega/\,3\,\Gamma_1 M)^{1/2}$$

Virial theorem

$$\Rightarrow \Pi \approx (I/-\Omega)^{1/2} \qquad (I=\int r^2 dm)$$

Properties of pulsating stars

⇒ for given mass and radius, Π decreases as $|\Omega|$ increases

⇒ by replacing $M=4/3\pi R^3\rho$ we obtain

$$\Pi \sim 2/\sqrt{(4/3\ \pi G\ \rho)} \Rightarrow \quad \Pi\sqrt{\rho} = \text{costant}$$

$\uparrow$

Period-density law

For known stars $10^6 \geq \rho/\rho_\odot \geq 10^{-9}$

$\uparrow$ $\uparrow$

white dwarfs red supergiants

$$\Rightarrow \quad 3\ \text{s} \leq \Pi \leq 1000\ \text{d}$$

Why to study pulsating stars

On the basis of a simple theoretical approach

$$P\sqrt{\rho} = cost$$

but for Stephan-Boltzman law $L = 4\pi\sigma R^2 T_e^4$

$$\Downarrow$$

$$\boldsymbol{P=P(L,M,Te)}$$

Period-Luminosity-Color-Mass (PLCM) relation

Observed P and colors $\Rightarrow$ constraints on L and/or M

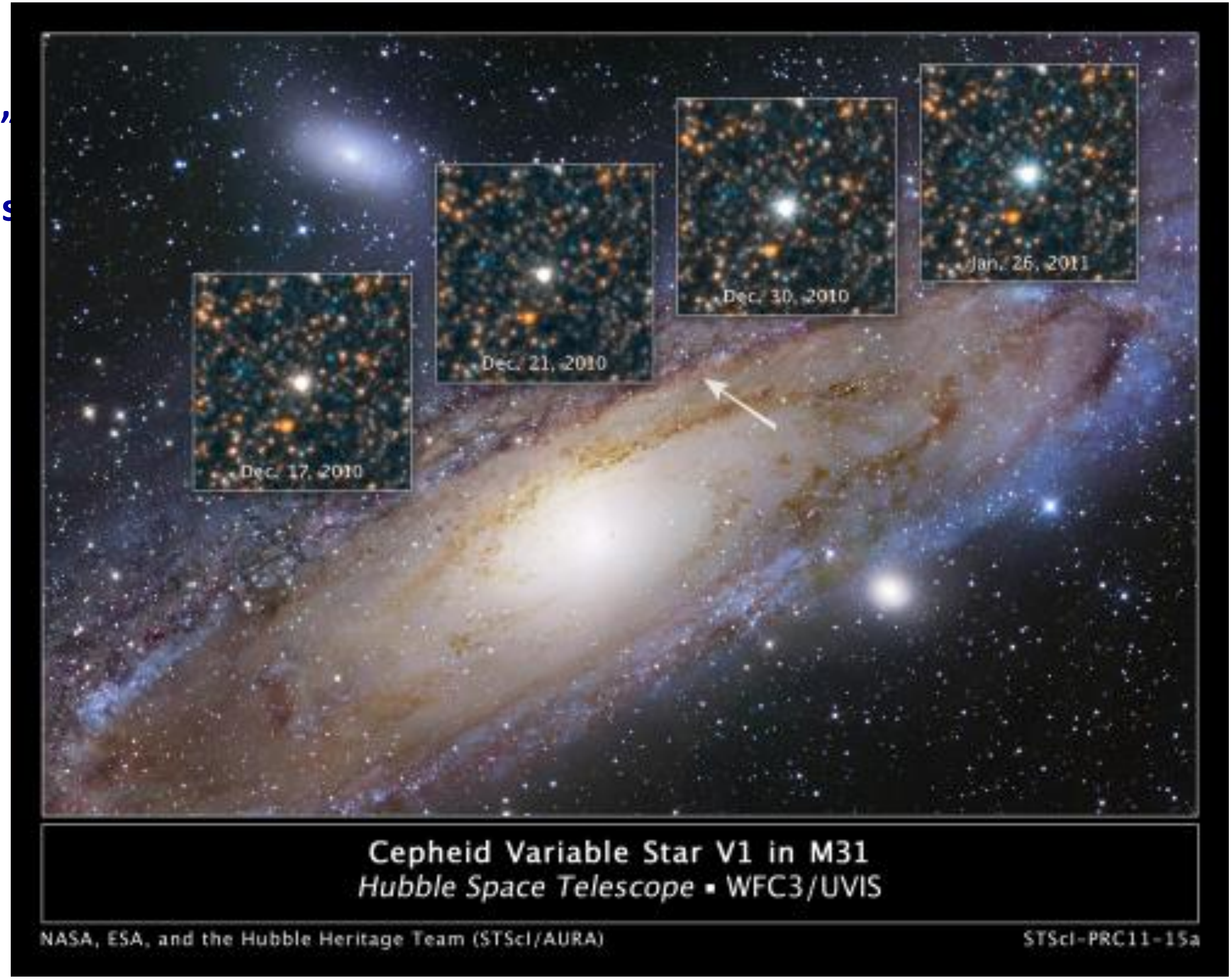
Why to study pulsating stars

- "easily" recognized thanks to the light variations
- Periods and amplitudes are unaffected by distance and reddening

Why to study pulsating stars

- “easily’

- Periods



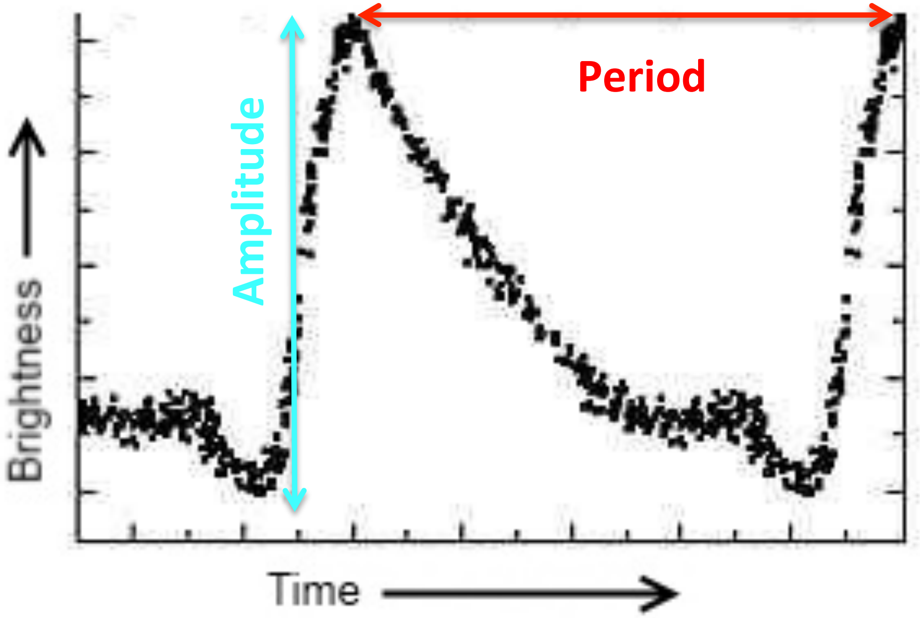
Cepheid Variable Star V1 in M31
Hubble Space Telescope ▪ WFC3/UVIS

NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

STScI-PRC11-15a

Why to study pulsating stars

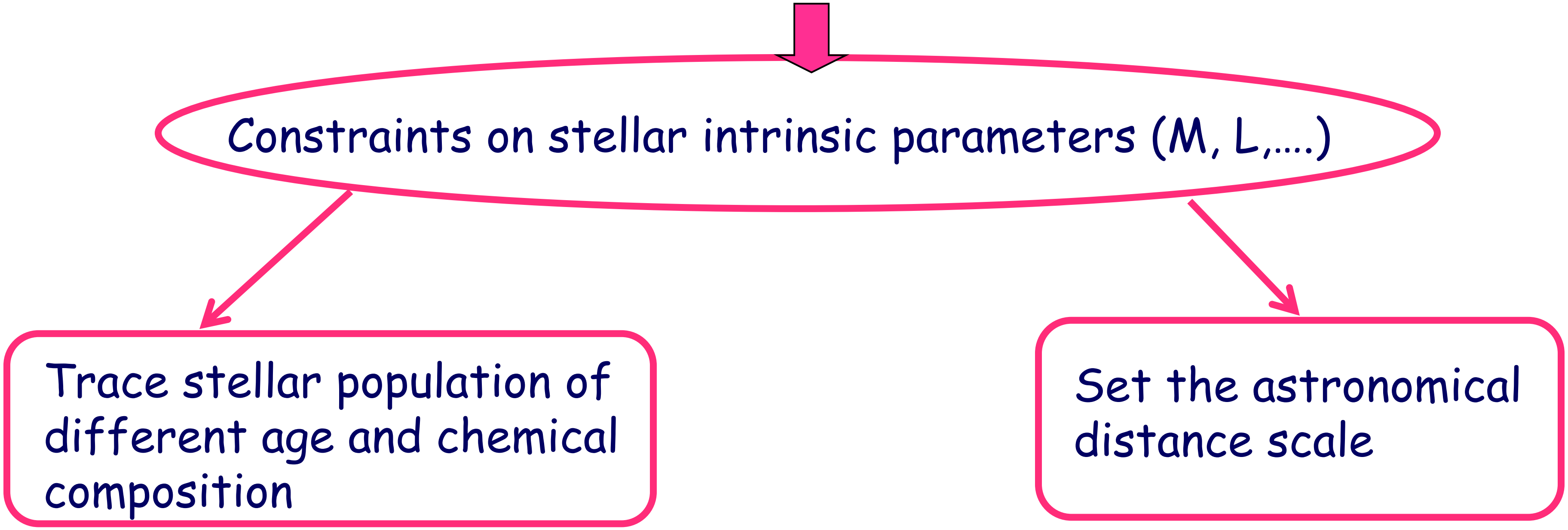
- **“easily” recognized thanks to the light variations**
- **Periods and amplitudes are unaffected by distance and reddening**



Why to study pulsating stars

- **"easily" recognized thanks to the light variations**
- **Periods and amplitudes are unaffected by distance and reddening**
- **Period-density relation ⇒ period (and amplitude) related to M,L,Te (Y,Z)**

A theoretical and observational study of the pulsating stars properties

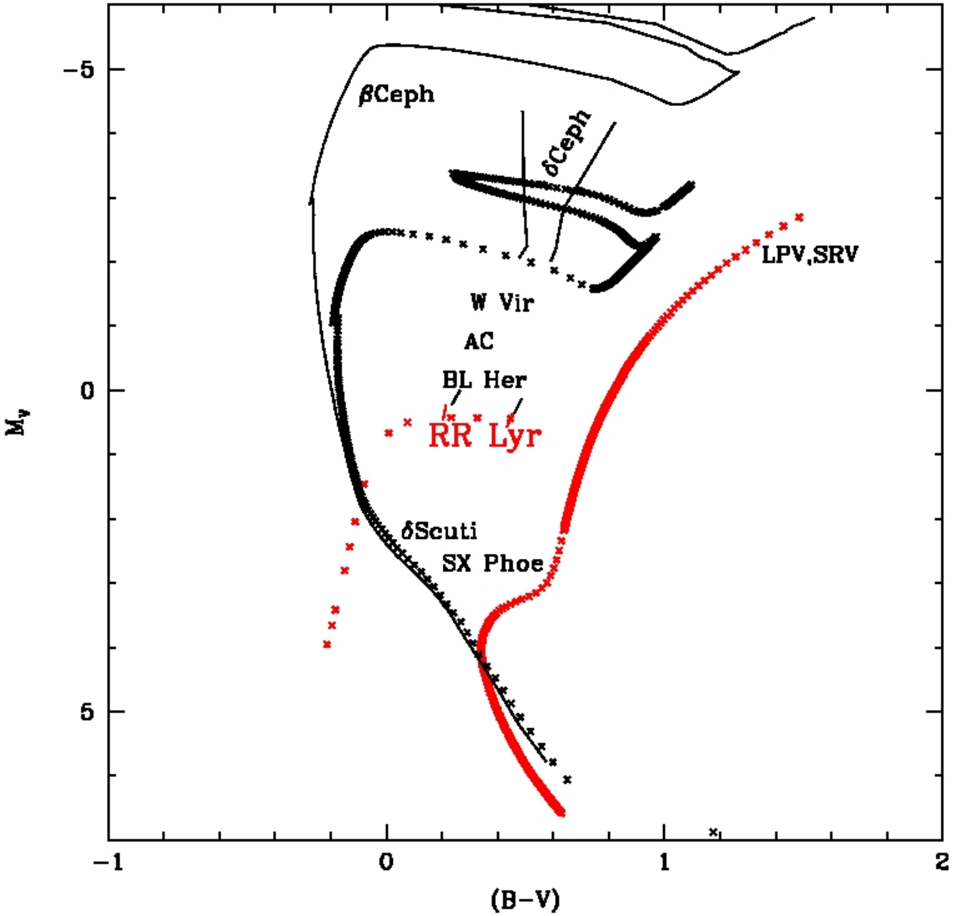


Constraints on stellar intrinsic parameters (M, L,….)

Trace stellar population of different age and chemical composition

Set the astronomical distance scale

Pulsating stars in the instability strip



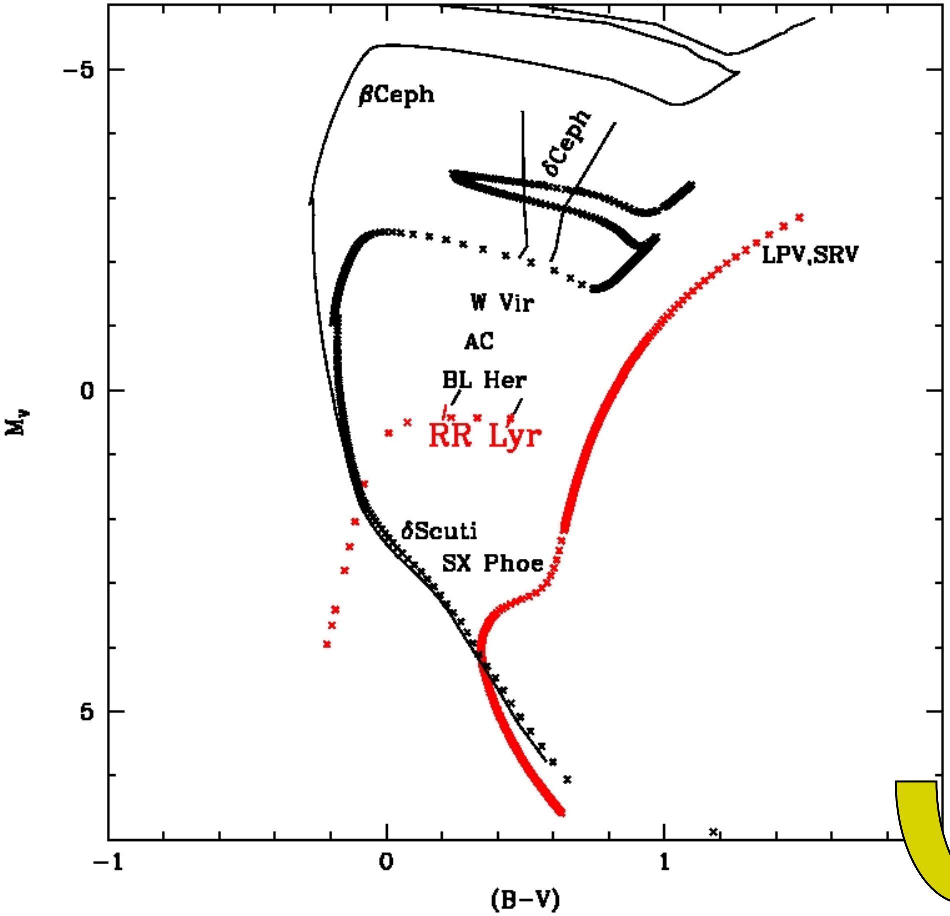
The various classes of pulsating stars map a wide range of periods and different evolutionary phases

⬇

They can trace stellar populations of different age in the same system

Why to study pulsating stars

Pulsating stars in the instability strip



Tracers of stellar populations in galaxies

- **old (> 10 Gyr)**

RR Lyrae, Pop II Cepheids, SX Phoenicis

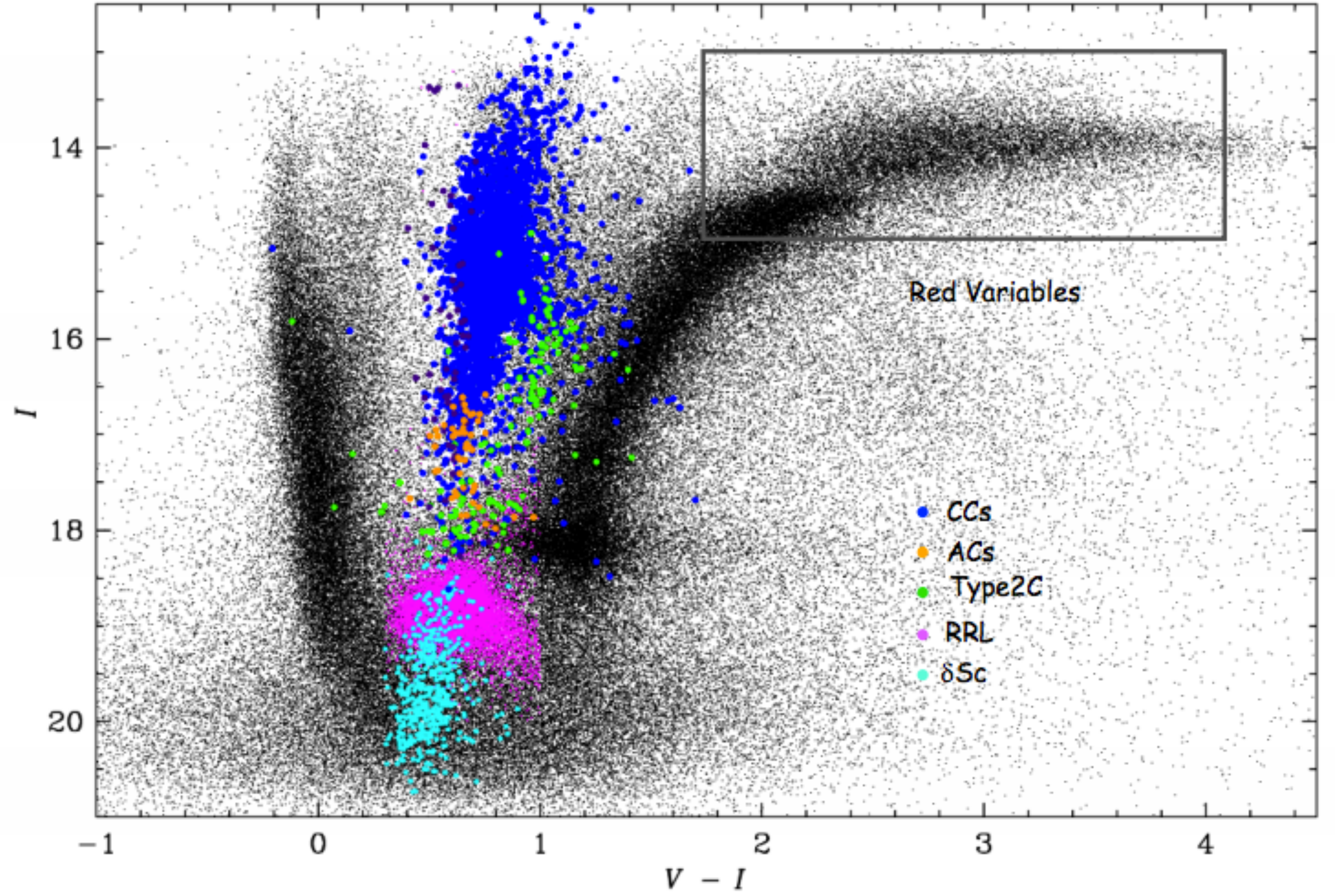
- **intermediate age (1-5 Gy)**

Anomalous Cepheids

- **young (t< 100 Myr)**

Classical Cepheids

LMC variables from OGLE III

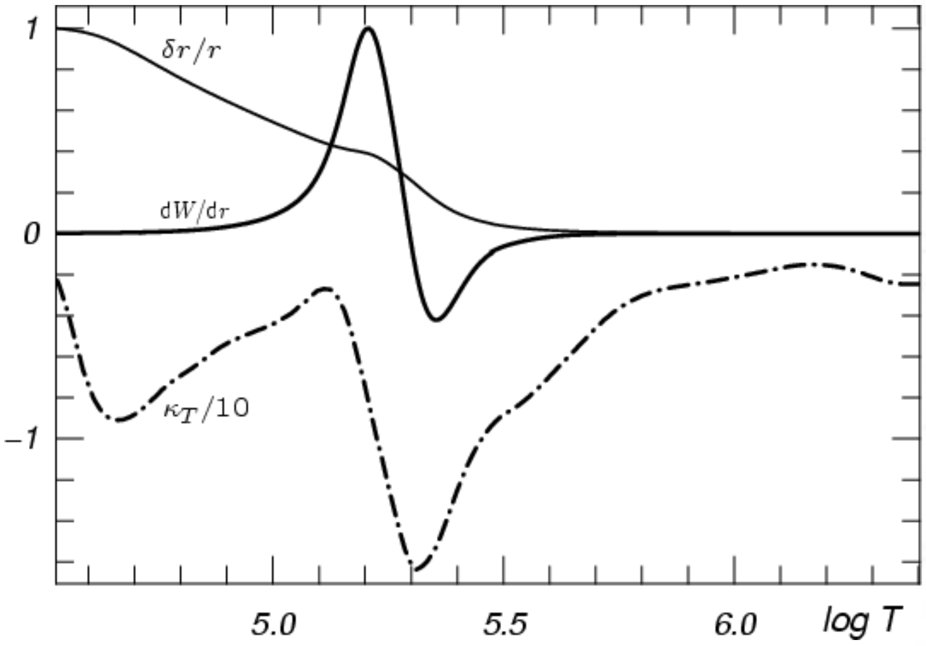


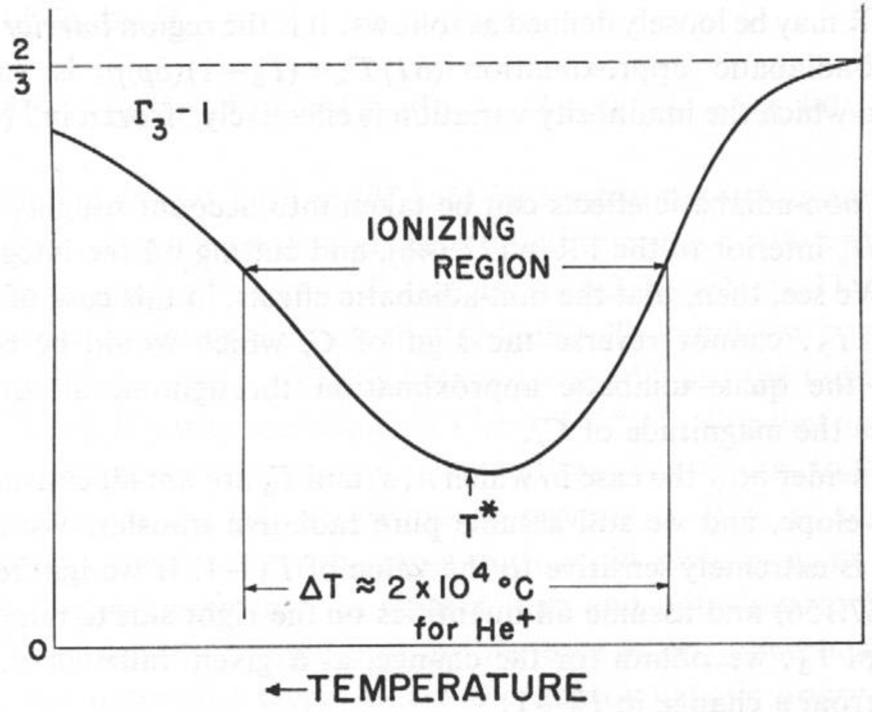
Soszynski et al. 2009

Driving mechanisms

In the classical instability pulsation mechanisms expected to be connected with the position in the HR diagram, i.e. related to L, T_e (R)

Valve effect: variation of opacity (κ mechanism) and Γ_3 -1 (γ mechanism) in the ionization regions of the most abundant elements of stellar envelopes: H, He and He^+ (Zhevakin 1953, 1954)



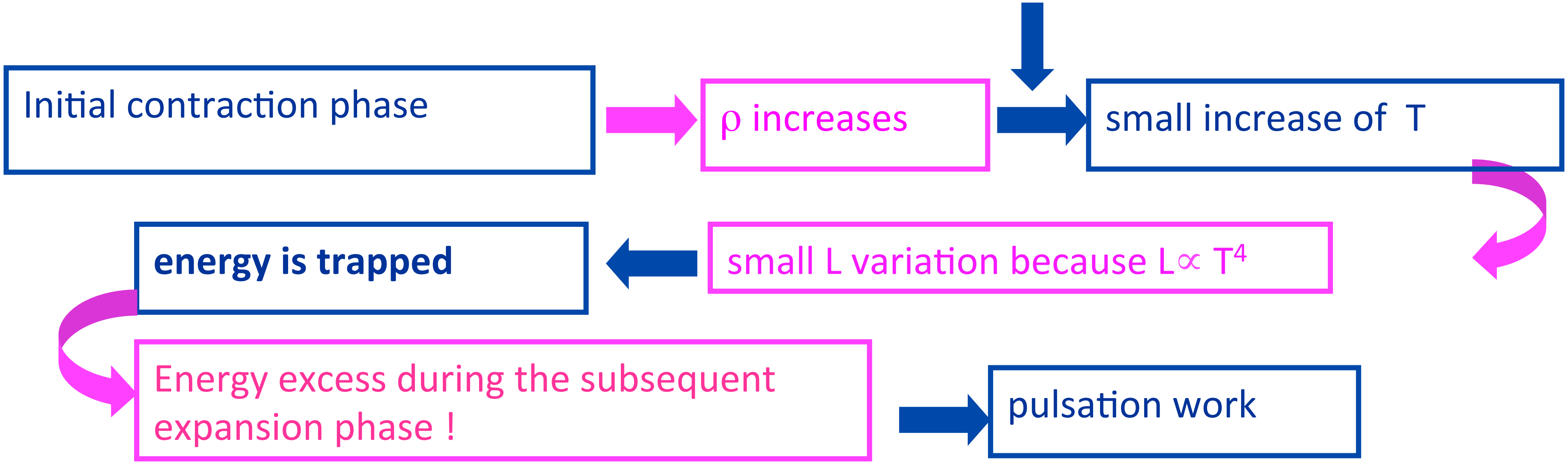


The pulsation mechanisms

γ mechanism

The adiabatic exponent $\Gamma_3-1 = (d\log T/d\log\rho)$ decreases in the ionization regions.

Most of the released energy during the phases of contraction goes into ionization:



Initial contraction phase

ρ increases

small increase of T

small L variation because $L \propto T^4$

energy is trapped

Energy excess during the subsequent expansion phase !

pulsation work

The pulsation mechanisms

k mechanism

Opacity variations in the H, HeI, HeII ionization regions:

$(k\rho = 1/\lambda)$ $k \propto \rho^n T^{-s}$

stellar interior ⇒ positive n and s: opacity decreases during contraction of the stellar envelope producing heat loss

ionization regions ⇒ s becomes large and negative: small temperature variations cause an increase of κ during contraction

⇒ further radiation trapping ⇒ energy excess ⇒ pulsation work

The pulsation mechanisms

γ mechanism : **effect of T variations on L variations**

k mechanism: **effect of *k* variations on L variations**

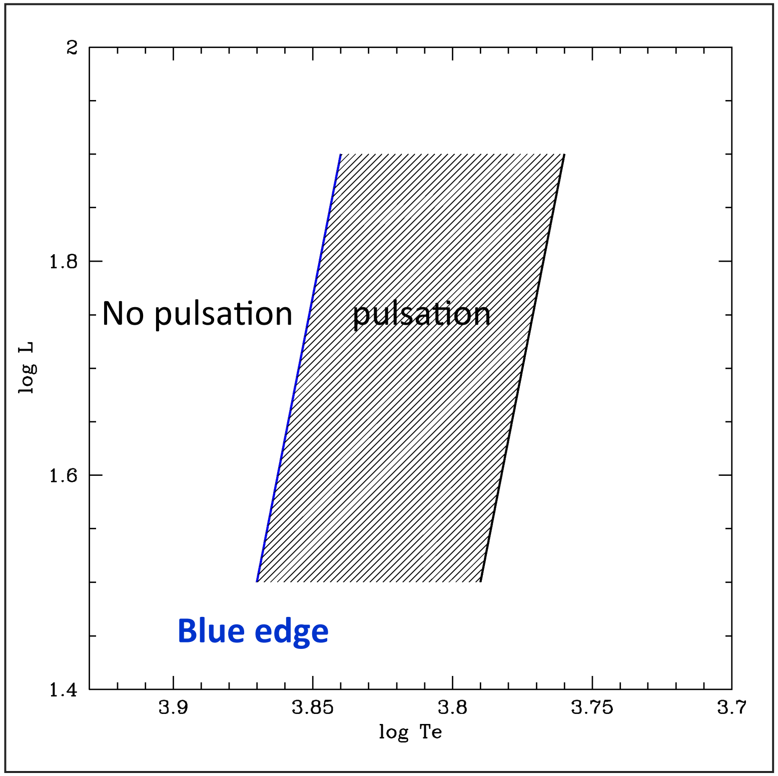
Both the ***k*** and ***γ mechanisms*** are efficient in driving the pulsation but the phenomenon is started by a *stochastic fluctuation* of the external layer properties (e.g. contraction)

The pulsation mechanisms

*Why the instability strip has a **BLUE** boundary?*

If the model effective temperature is too high the H and He ionization regions are very external ⇒ low density, small mass takes part in the pulsation driving through the k and γ mechanisms ⇒ damping prevails ⇒ no pulsation

Only when the ionization regions are deep enough the mass involved in the pulsation driving mechanisms prevails ⇒ pulsation



The pulsation mechanisms

Why the instability strip has a RED boundary?

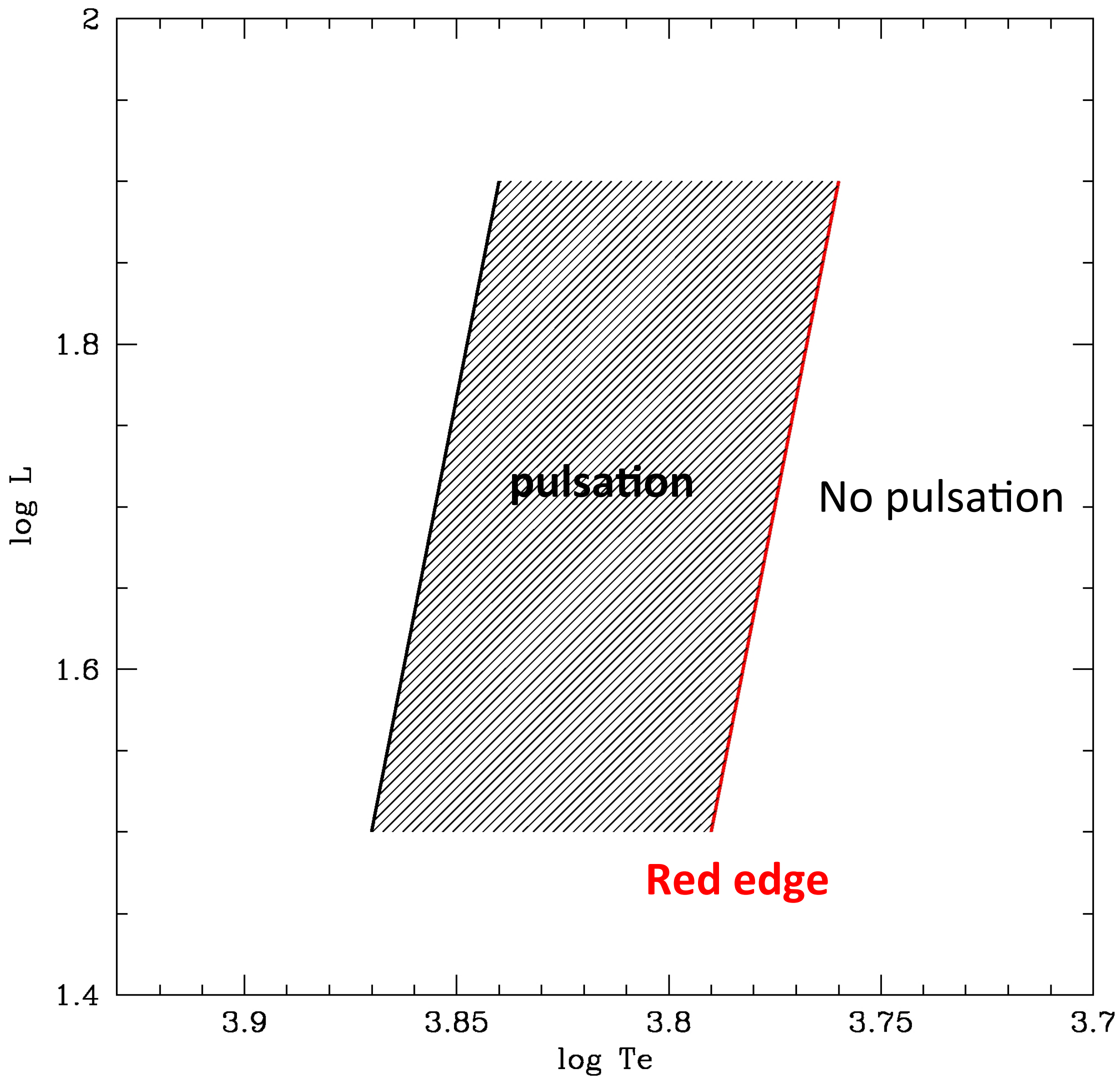
Moving toward lower effective temperature the depth of the driving ionization regions increases and the mass taking part in the phenomenon is larger ⇒ increasing pulsation efficiency

But convection also becomes more efficient at lower effective temperatures
⇒ k and γ gradients are reduced
⇒ quenching of pulsation (Baker & Kippenhahn 1965)

The pulsation mechanisms

When the quenching effect due to convection prevails pulsation is no more efficient

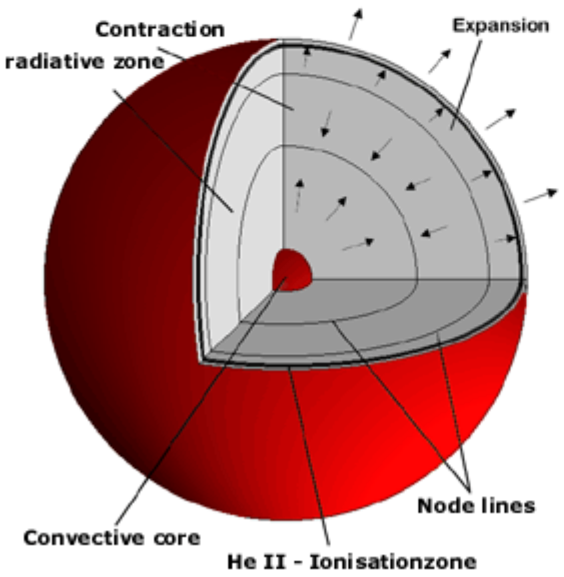
⇒ **red boundary** of the instability strip



Theoretical approach to the study of pulsating stars

Radially pulsating envelope models

- Spherical simmetry: the star varies its volume and luminosity on the pulsation time scale but the shape remains spherical.
- No rotation, no magnetic fields.



- The core is excluded (nuclear reactions evolve on much longer time scales, pulsation mechanisms excited in the envelopes)
- The envelope is divided in~150-250 mass zones.

The Hydrodynamical equations

To study the pulsation properties of the variable stars we need to adopt hydrodynamical models solving the hydrodynamical equations in the stellar Envelope (the core is excluded):

Mass conservation equation

Momentum equation

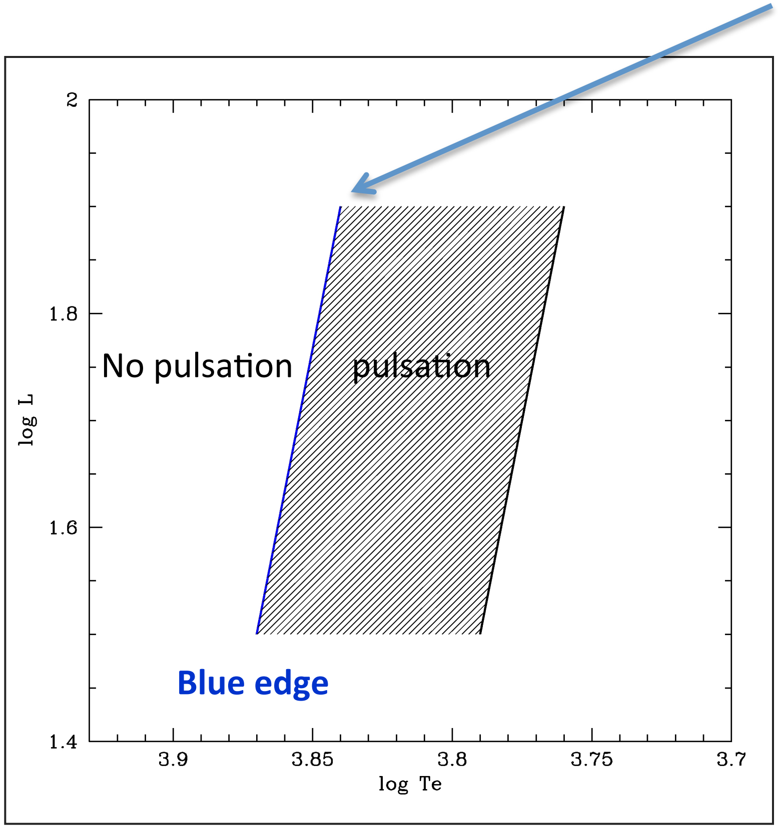
Energy equation

+ heat transfer equation

Theoretical approach to the study of pulsating stars

Theoretical analysis by steps: the linear approach

- ***Linear adiabatic*** analysis (Eddington 1918) ⇒ **Periods**
- ***Linear NONadiabatic*** analysis (Baker & Kippenhahn 1962, Cox 1963, Castor 1971, Iben 1971….) ⇒ **Periods, blue boundary**



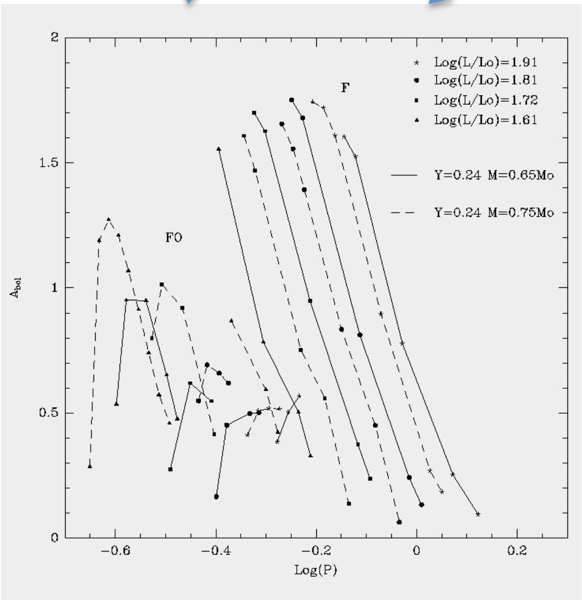
Theoretical approach to the study of pulsating stars

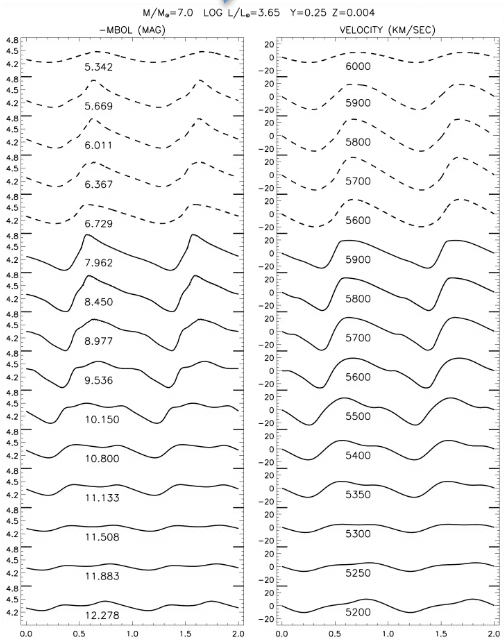
Theoretical analysis by steps:the nonlinear approach

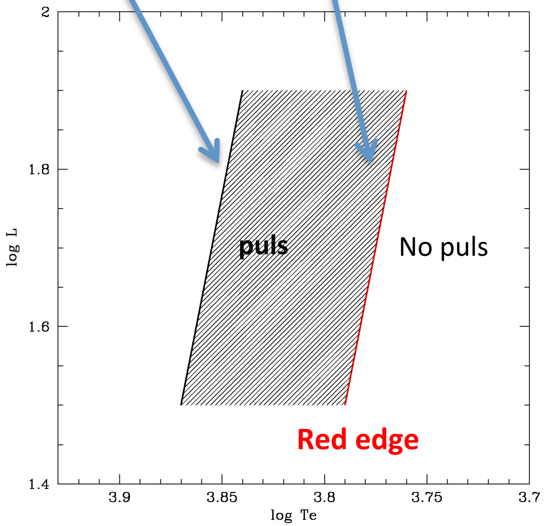
- ***NONlinear radiative*** analysis (Christy 1966, Stellingwerf 1974…..)

  ⇒ **Periods, amplitudes (max-min), blue boundary**

- ***NONlinear convective*** analysis (*Gehmeyr et al. 1990, Bono & Stelingwerf 1994, Bono, Marconi Stellingwerf 1999, Szabo et al. 2000, 2004*)
- ⇒ **Periods, amplitudes, lightcurves, blue and red edges**







Theoretical approach to the study of pulsating stars

➡ Need for nonlinear convective models

Since the first 80's several authors included convection in their nonlinear hydrocodes:

Stellingwerf 1982,1984 ApJ

Gehmeyer 1992, 1993 ApJ

Bono & Stellingwerf 1994 ApJS

Feuchtinger 1999 ApJ

Szabò, Kollath & Buchler 2004 A&A

Theoretical approach to the study of pulsating stars

Most important applications of non-linear convective pulsation codes

Classical Cepheids	e.g. Bono, Marconi & Stellingwerf 1999 ApJS, 2008 ApJ, 2010 ApJ; Fiorentino et al. 2002 ApJ, 2013 MNRAS Marconi et al. 2005 ApJ, 2010 ApJ, 2013 ApJ; Wood et al. 1997 ApJ, Keller & Wood 2006 ApJ; Smolec & Moskalik 2010 A&A
RR Lyrae	e.g. Bono & Stellingwerf 1994, Bono et al. 1995 ApJ, 1997 ApJ, Marconi et al. 2003 ApJ, Di Criscienzo et al. 2004 ApJ, Marconi et al. 2011 ApJ, 2015 ApJ, Gehmeyr et al. 1993 ApJ, Feuchtinger et al. 1999 A&A, Szabo et al. 2004, A&A, Dékány et al. 2008 MNRAS,
Anomalous Cepheids	e.g. Marconi, Fiorentino, Caputo 2004 A&A; Caputo et al. 20054 A&A, 2005 ApJ;
Type II Cepheids	e.g. Marconi & Di Criscienzo 2007 A&A; Di Criscienzo et al. 2007 A&A; Smolec 2015 AAS
δ Scuti and SX Phoenicis stars	e.g. Bono et al. 1997 ApJ; 2002 ASPC; Fiorentino et al. 2015 ApJ; Smolec 2015 AAS

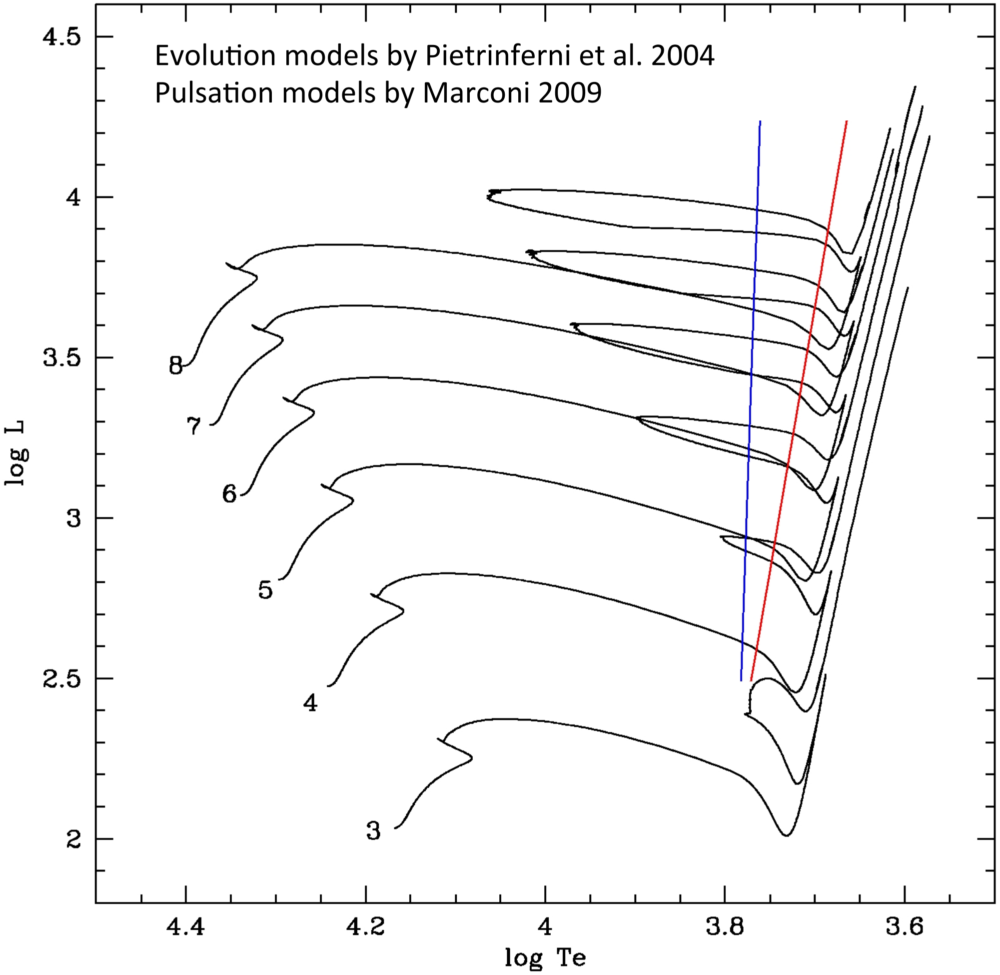
Classical Cepheids: general properties

Classical Cepheids are yellow supergiant stars

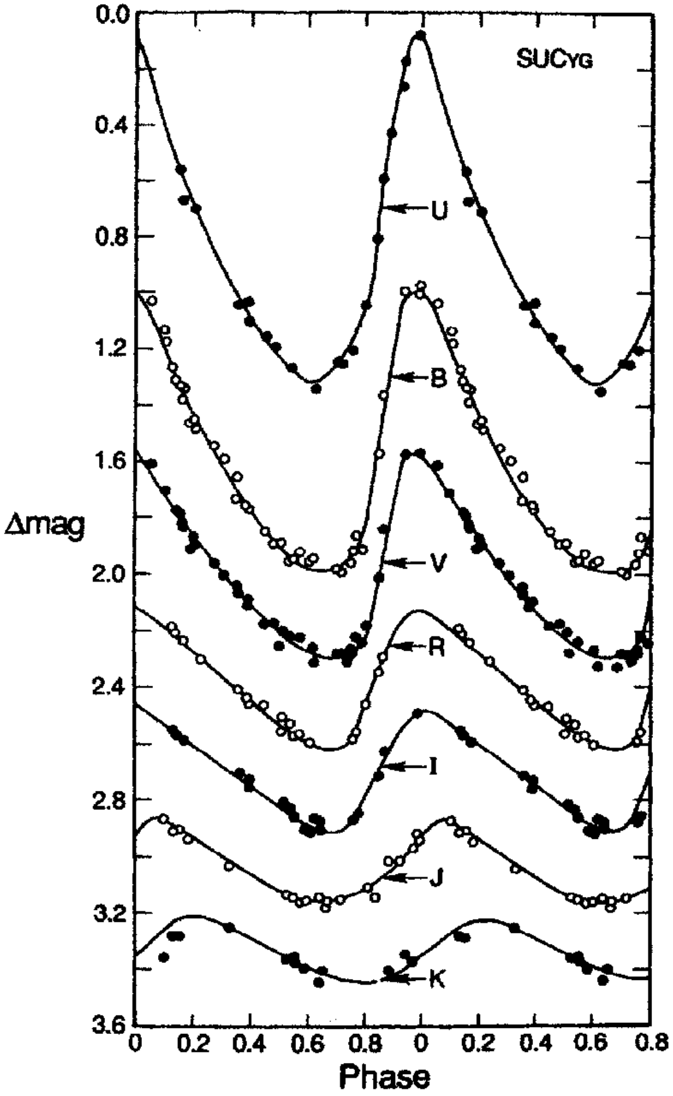
1d ≤ P ≤ 100d
M_V from -2 to -7 mag.

Pulsation in three radial modes: Fundamental (F), First Overtone (FO) and Second Overtone (SO)

Associated to the so called ***blue loop*** evolutionary phase of intermediate mass stars corresponding to their central Helium burning.



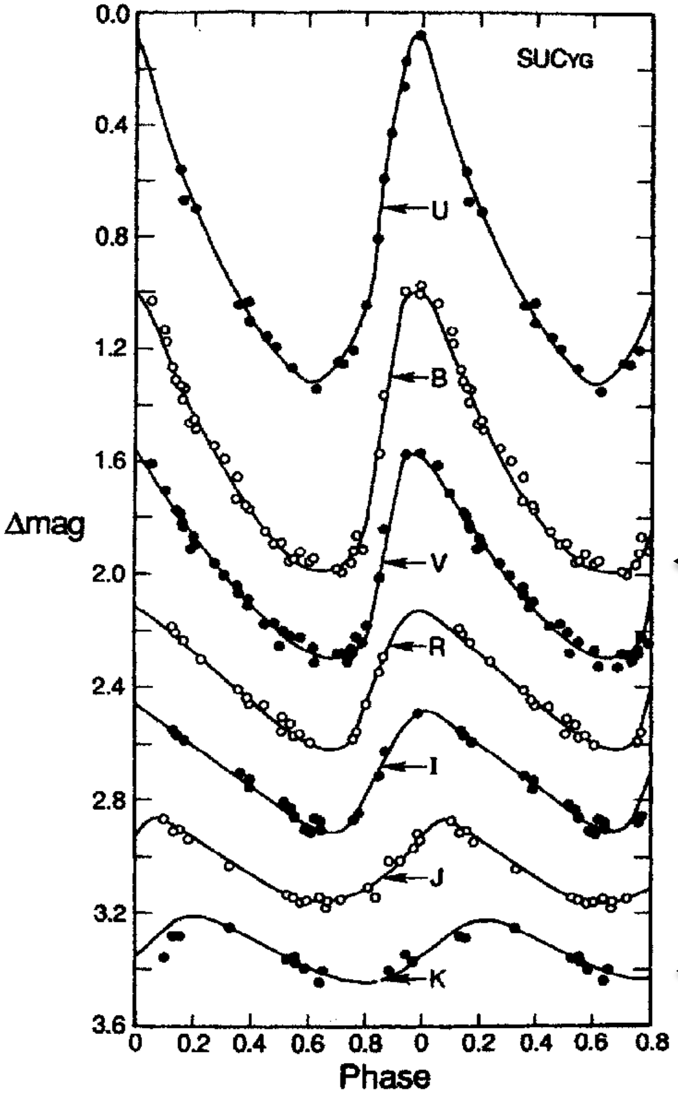
Cepheids light curves



From the light-curves, we derive the mean magnitude (intensity weighted)

Phase = $(JD - JD_{max})/P$

The light curve depends on the wavelenght



The amplitude decrease moving from optical to NIR bands

Pro Optical	Con Optical
Easy to detect thanks to large amplitudes	Need many phase points (telescope time consuming)

Pro NIR	Con NIR
Few observations allow mean magnitudes with small errors	Very difficult to detect

The Cepheid Mass-Luminosity relation

The theory of stellar evolution predicts that in this evolutionary phase the mass and luminosity are related: $\log L/L_\odot = \alpha + \beta \log M/M_\odot + \gamma \log Z + \delta \log Y$

- Canonical ML: no core overshooting during the H burning phase.
- Non canonical ML: mild or full core overshooting is assumed.

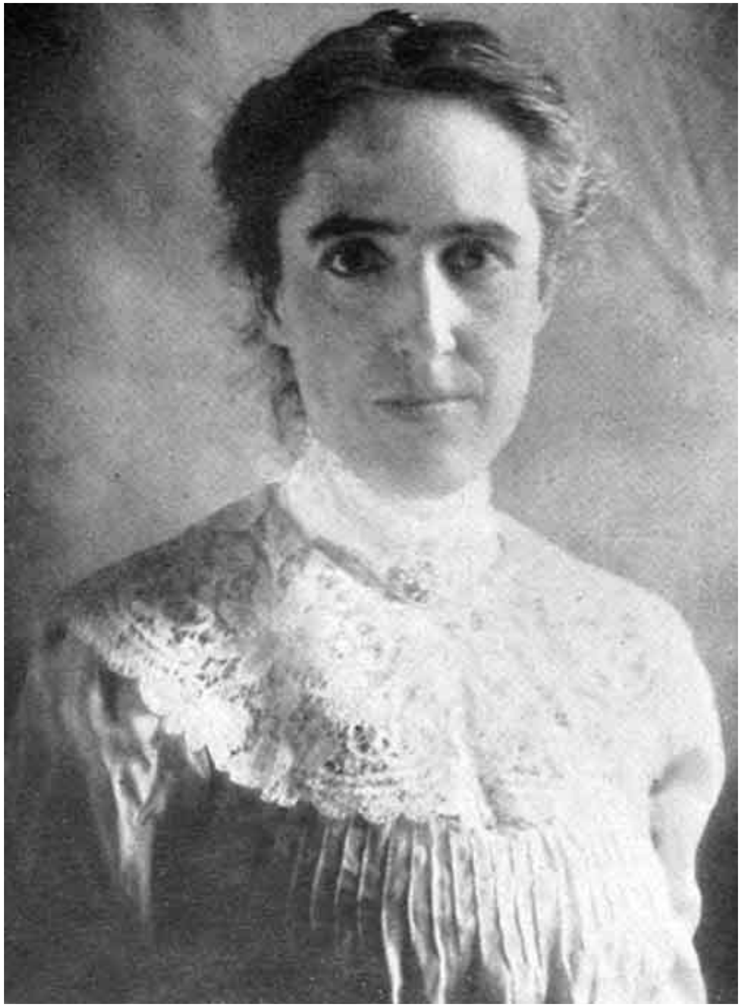
canonical	$\log L_{can} = a + b \log M + c \log Y + d \log Z$
mild overshooting	$\log L_{mild} = a + b \log M + c \log Y + d \log Z + 0.25$
full overshooting	$\log L_{full} = a + b \log M + c \log Y + d \log Z + 0.5$

(Chiosi, Wood & Capitanio 1993)

Overshooting $\Rightarrow$ $\not\Leftarrow$ smaller mass at fixed L than the canonical one

Mass loss produces the same effect !

Cepheids as distance indicators



Since the discovery by Miss Leavitt (1908, 1912) in the Small Magellanic Cloud, Classical Cepheids are known to obey to a Period-Luminosity (P-L) relation.

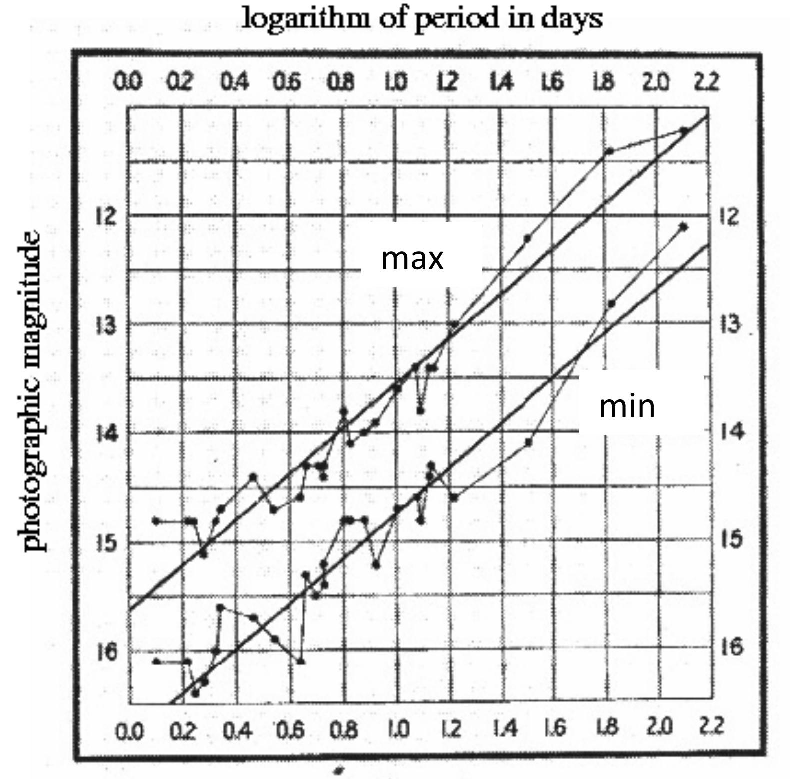
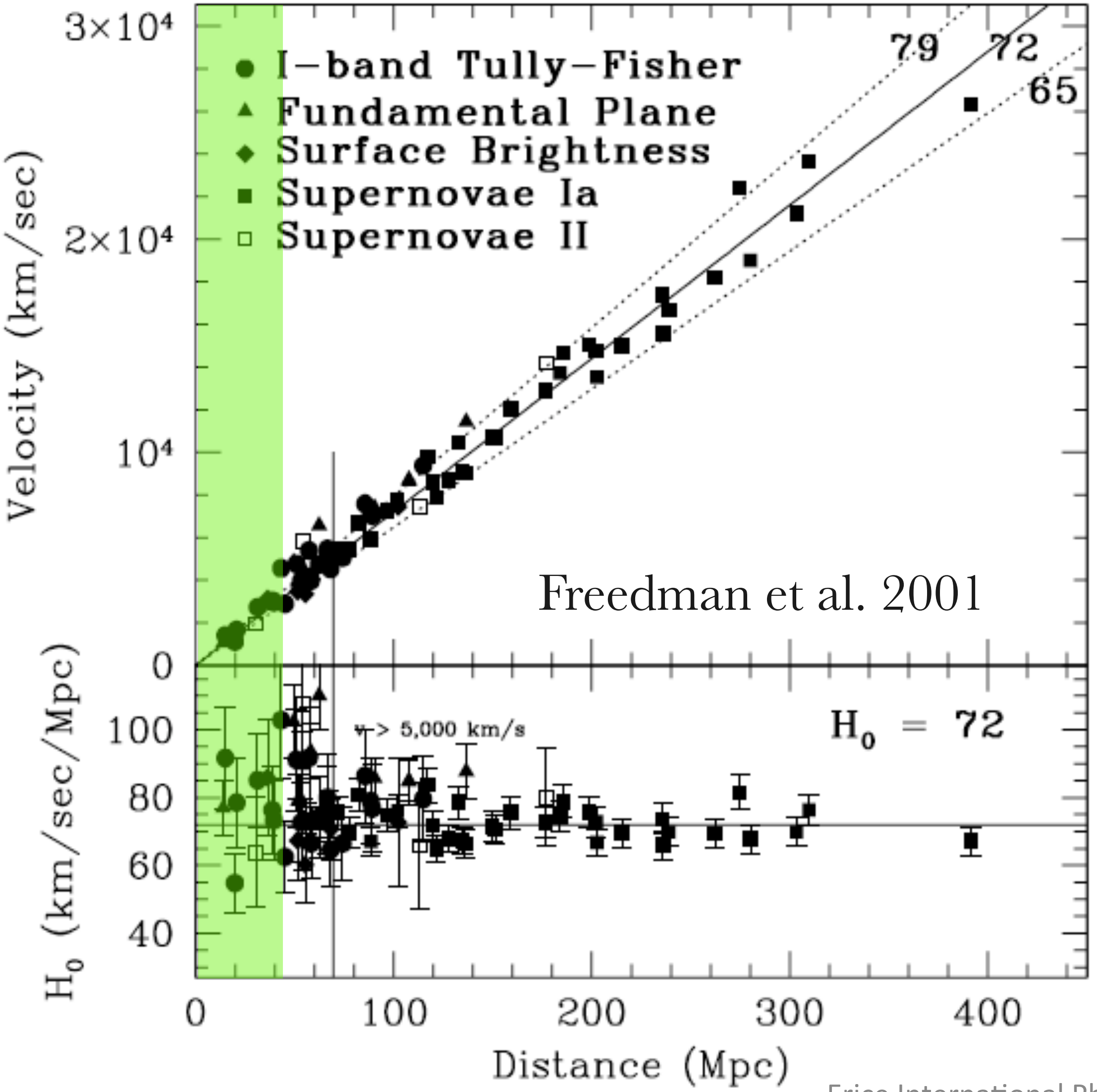


FIG. 2.

Classical Cepheids as calibrators:

The secondary distance indicators are typically calibrated with the Cepheid PL



Freedman et al. 2001

Physical basis of PLC and PL relations

$P\sqrt{\rho}$= costant → Period is a function of mass, luminosity, effective temperature

e.g. $\log P = 10.557 - 3.28 \log T_e + 0.93 \log L - 0.79 \log M$

(Bono, Castellani, Marconi 2000 ApJ) for LMC Cepheids (F mode)

For classical Cepheids Mass-Luminosity relation

$$\log L = a + b \log M + c \log Z + d \log Y$$

predicted by stellar evolution

⬇

Period-Luminosity-Color (PLC) relations.

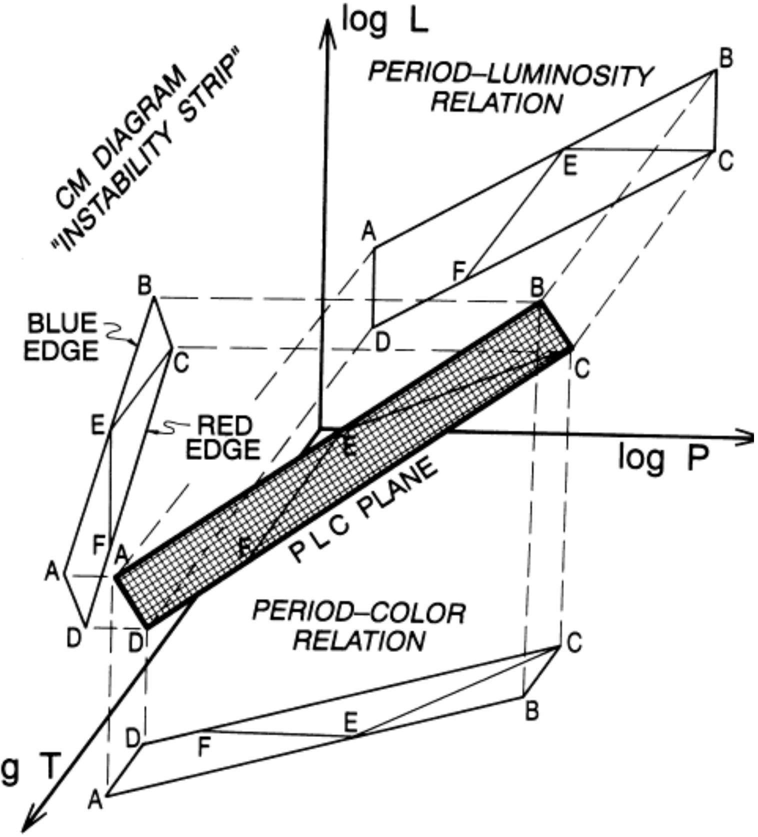
From the PLC to the PL relation

For Classical Cepheids $L=L(M,Y,Z) \Rightarrow$ ***PLC*** *(!)*

projecting on the PL plane → ↓

PL

MADORE AND FREEDMAN



The PLC relation holds for each individual Cepheids: measuring the period and the color, one infers the absolute magnitude and in turn the distance.

The PL relation is obtained averaging over the color extension of the instability strip:
It is a statistical relation !!

The double role of Classical Cepheids

Relevant role for the ***extragalactic distance scale*** and ***stellar evolution***

They obey to a PL relation

Calibration of the extragalactic distance scale (up to 30 Mpc with HST)

H_0 estimate
(e.g. Freedman et al. 2001)

Important to construct an accurate extragalactic distance scale

ML relations predicted by evolutionary calculations

Input to pulsation models

Theory versus observations

Insight into evolutionary and pulsational physics

Classical Cepheids: open problems

1) Dependence of Cepheid properties and PL on chemical composition

2) Linearity of the PL over the whole observed period range

3) Origin of the *mass discrepancy* between evolutionary and pulsational estimates

Classical Cepheids: open problems

1) **Dependence of Cepheid properties and PL on chemical composition**

Implications of the dependence of Cepheid PL relation on chemical composition…

The Cepheid PL relation was often assumed to be universal:
LMC PL applied to extragalactic Cepheids often independently of their chemical composition (see e.g. the HST Key Project)

Dependence on chemical composition ⇒systematic effects on the extragalactic distance scale (and H_0)!!

A general consensus on the "universality" of the P-L relations has not been achieved yet !

Some of the results on the metallicity dependence of Cepheid distances (in the optical bands)

Gould 1994	$\Delta\mu/\Delta\log Z = -0.44\ (+0.1\ -0.2)$ mag dex^{-1}
Kochanek 1997	$\Delta\mu/\Delta[O/H] = -0.32 \pm 0.2$ mag dex^{-1}
Sasselov et al. 1997	$\Delta\mu/\Delta\log Z = -0.4 \pm 0.2$ mag dex^{-1}
Kennicutt et al. 1998	$\Delta\mu/\Delta[O/H] = -0.24$ mag dex^{-1}
Caputo et al. 2000	$\Delta\mu/\Delta[O/H] = 0.27$ mag dex^{-1}
Freedman et al. 2001	$\Delta\mu/\Delta[O/H] = -0.2 \pm 0.2$ mag dex^{-1}
Sakai et al. 2004	$\Delta\mu/\Delta[O/H] = -0.24 \pm 0.05$ mag dex^{-1}.
Macri et al. 2006	$\Delta\mu/\Delta[O/H] = -0.29$ mag dex^{-1}
Mager et al. 2013	$\Delta\mu/\Delta[O/H] = -0.33 \pm 0.12$ mag dex^{-1}
Fausnaugh et al. 2015	$\Delta\mu/\Delta[O/H]$ up to -0.61 ± 0.21 mag dex^{-1}

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NO GENERAL CONSENSUS YET

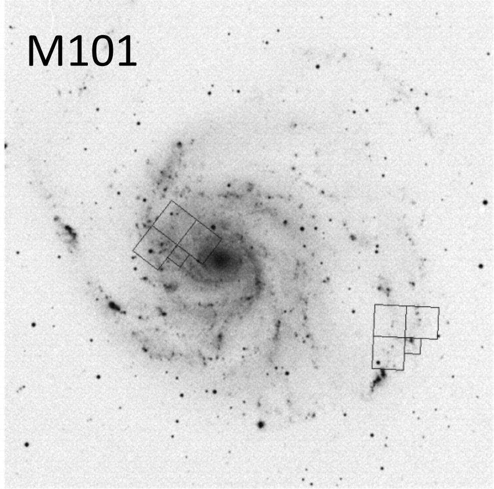
Empirical tests for metallicity effect

Several tests of the metallicity effect based on:

1) the comparison between Cepheids belonging to 2 fields of different metallicity (?) in the same galaxy

$$\Delta \log Z = \Delta[O/H]$$

Kennicutt et al. 1998 : $\Delta\mu/\Delta[O/H] = -0.24$ mag dex^{-1}



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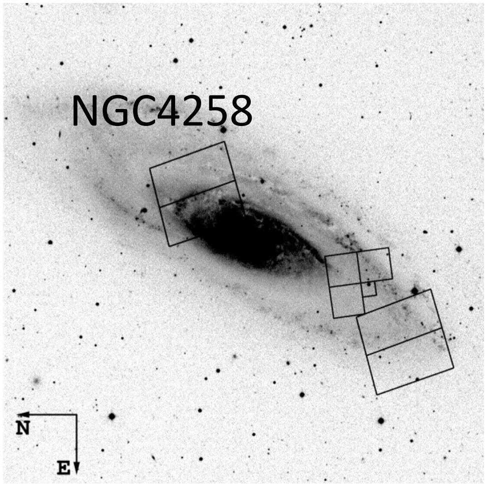
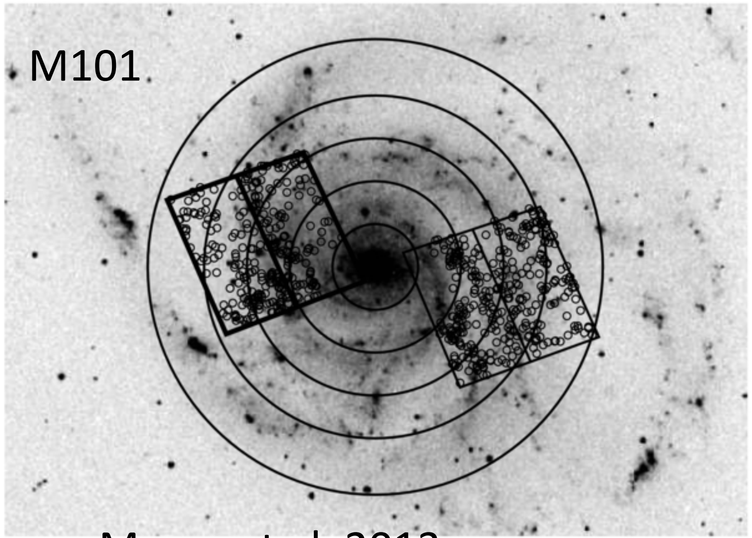
KP metallicity correction
$\Delta\mu/\Delta[O/H] = -0.2\pm0.2$ mag dex^{-1}



Macri et al. 2006:
$\Delta\mu/\Delta[O/H] = -0.29$ mag dex^{-1}

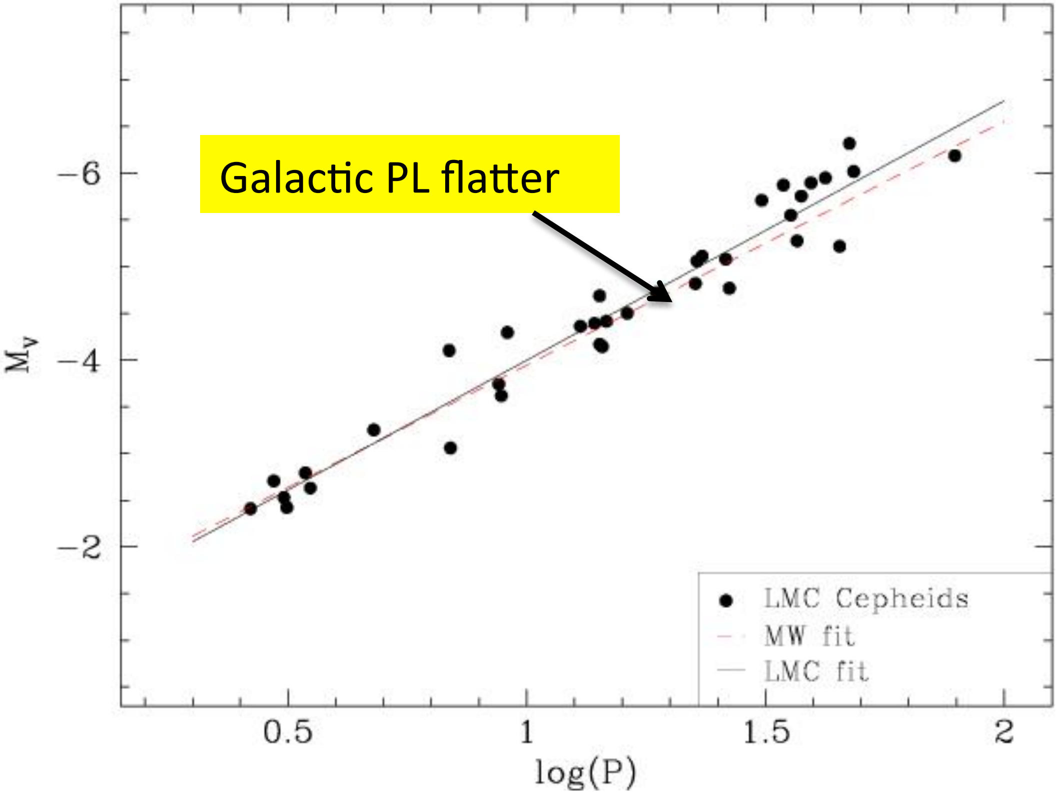


Mager et al. 2013:
$\Delta\mu/\Delta[O/H] = -0.33$ mag dex^{-1}

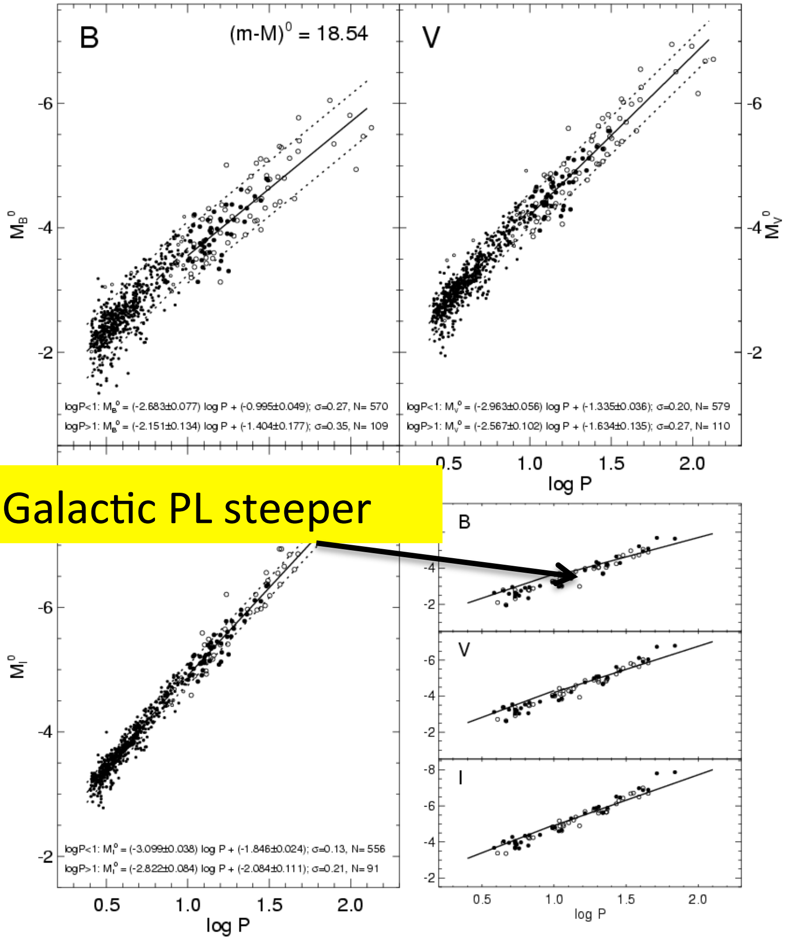
Empirical tests for metallicity effect

Several tests of the metallicity effect based on:

2) the comparison between Cepheids in the two MCs (see e.g. Sasselov et al. 1997) or between the Magellanic and Galactic pulsators (see e.g. Kanbur et al. 2003; Storm et al. 2004, 2011; Groenewegen et al. 2004; Sandage et al. 2004)



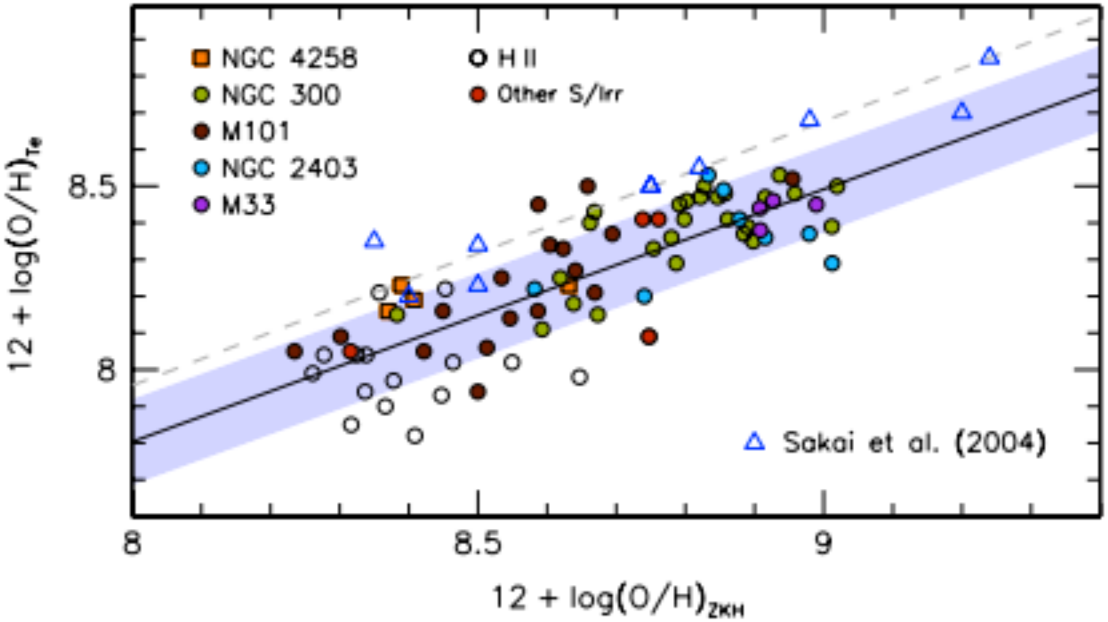
Galactic PL flatter



Galactic PL steeper

Caveats:

Metallicity gradients in galaxies containing Cepheids are often poorly known.



Caveats:

Metallicity gradients in galaxies containing Cepheids are often poorly known.

Blended Cepheids could be responsible for a large fraction of the difference in distance modulus between different fields (see M101 case, *Macri et al. 2006*).

The metallicity difference between the two MCs is small but MC Cepheids show a non-negligible metallicity dispersion.

The period range covered by Galactic Cepheids does not coincide with the ones of the MCs.

Reddening differences can simulate metallicity differences.

How to reduce these uncertainties?

1) Change the anchor ?

→ To minimize the uncertainties in the zero-point due to the metallicity difference among LMC and metal-rich HST galaxies, **Riess et al. (2011) chose NGC 4258 as anchor** for the Cepheid PL relation.

Riess Cepheid sample

Macri et al. 2006, Riess et al. 2009a,b, Riess et al. 2011

- ACS and WFC3-IR camera (Riess 2011) on board HST Cepheid in 8 SNIa hosting galaxies.

- The zero point anchored to NGC4258 ($Z=0.02$, $d=7.2\pm0.5$ Mpc, Maser geometrical distance)

⋆**Cepheids + SNIa:** 73.8 ± 2.4 Km s^{-1} Mpc^{-1} (Riess et al. 2011)

How to reduce these uncertainties?

1) **Change the anchor ?**

→ To minimize the uncertainties in the zero-point due to the metallicity difference among LMC and metal-rich HST galaxies, **Riess et al. (2011) chose NGC 4258 as anchor** for the Cepheid PL relation.

2) **Remove the reddening contribution** by using the **Wesenheit relations** that are **reddening free by definition** and found to be **less affected by metallicity.**

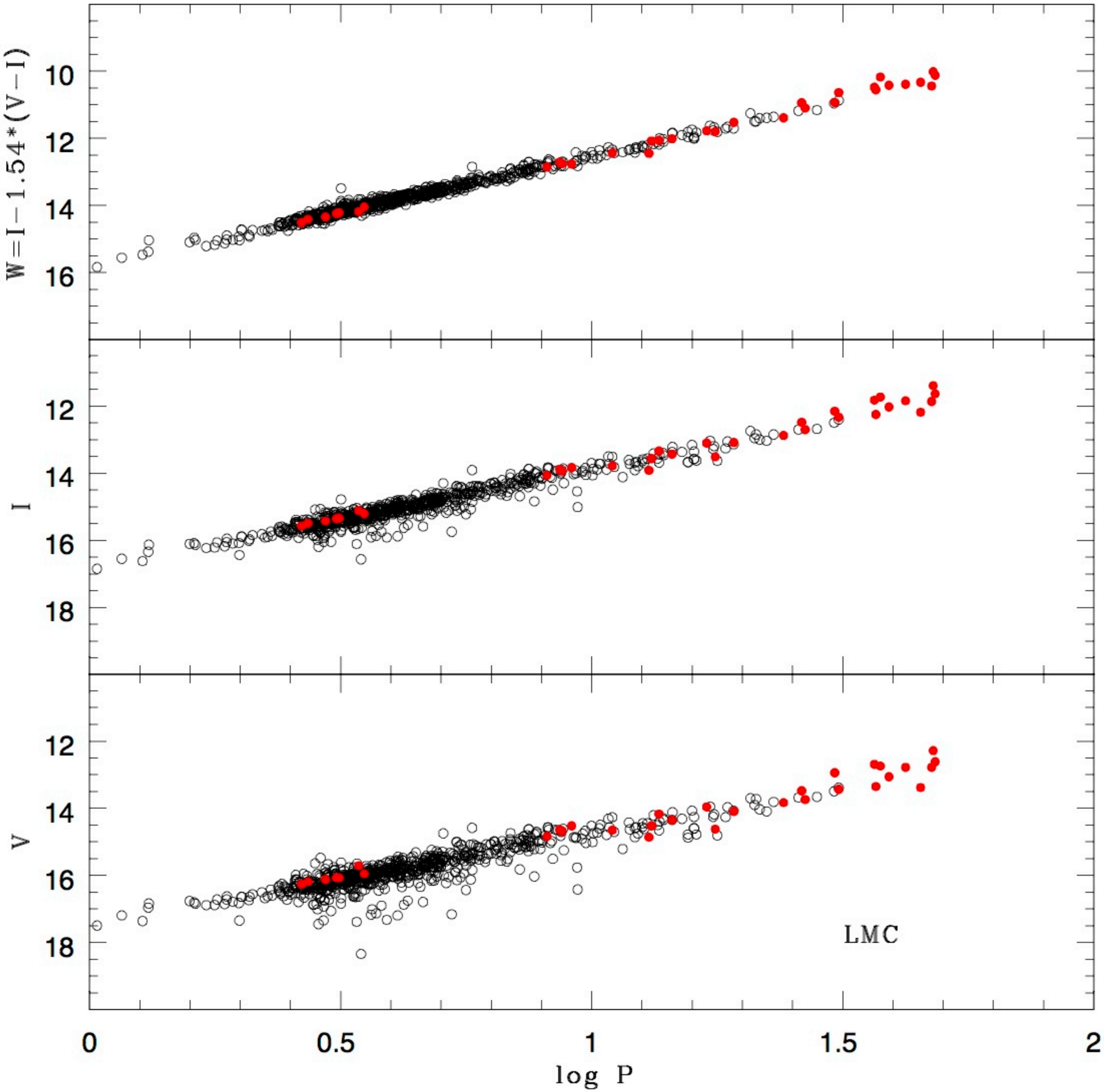
e.g.

$W(B,V) = a + b\times \log P$

Where $W(B,V)=M_V-R_V\times(B-V)$ **and** $\underline{R_V = A_V/E(B-V)}$

And similarly for the other filters combinations: W(V,R), W(V, I)….W(J,K)….ecc…

Cepheids: T era



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2) **Rem** e

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e.g.

W(B,V

Where

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Classical Cepheids: open problems

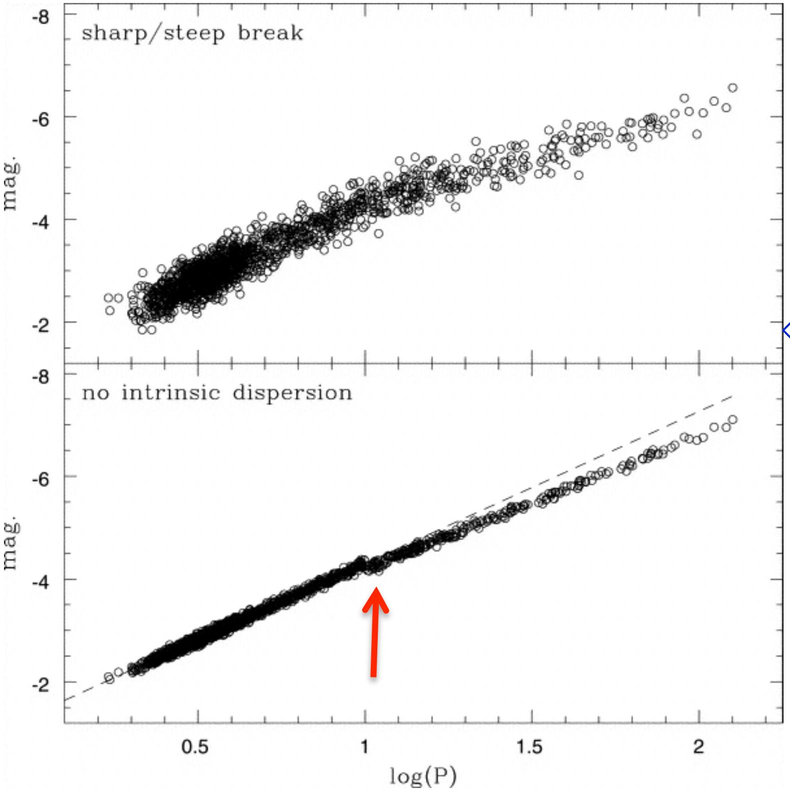
2) Linearity of the PL over the whole observed period range

Linearity of PL relations

The Cepheid PL relation has long been considered to be linear over the range $0.3 \leq \log(P) \leq 2.0$. (Madore & Freedman 1991, Tanvir 1997, Gieren et al. 1998, Udalski et al. 1999, Persson et al. 2004)

Usually represented as $M_i = a + b \log P$ **where *i* is the phot. band**

Several investigations *(e.g. Caputo et al. 2000; Tammann et al. 2003; Ngeow et al. 2005; Ngeow & Kanbur 2006)* **disclosed the nonlinearity of the PL in BVRI.**

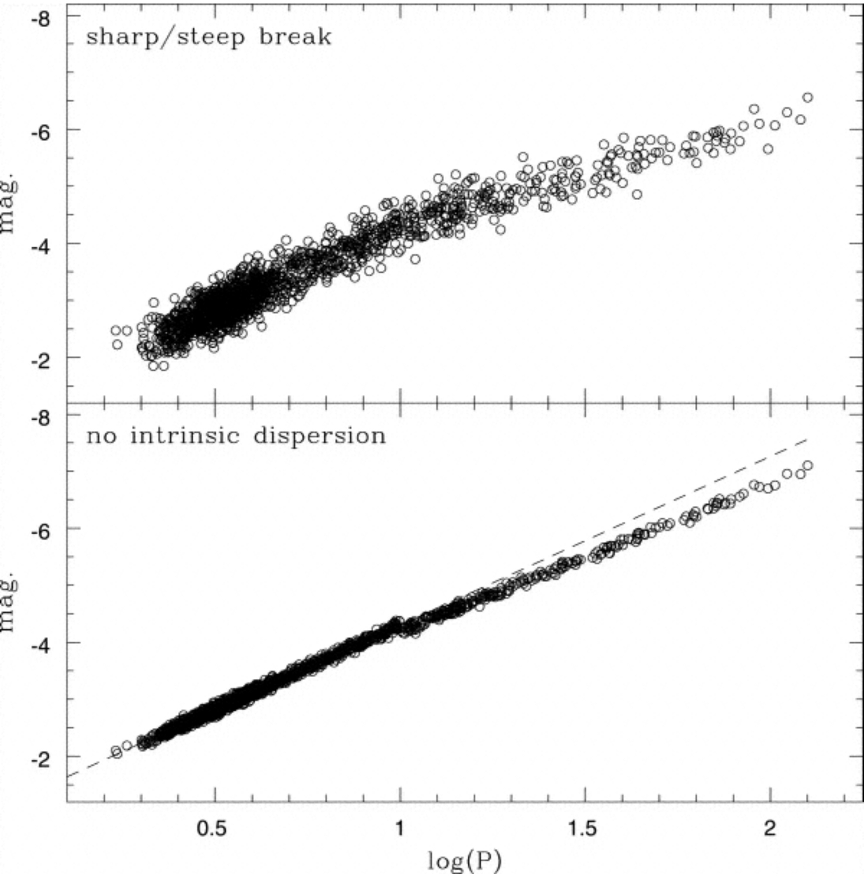


Simulated nonlinear PL relation in the LMC, based on MACHO and OGLE data by *Ngeow & Kanbur 2006*

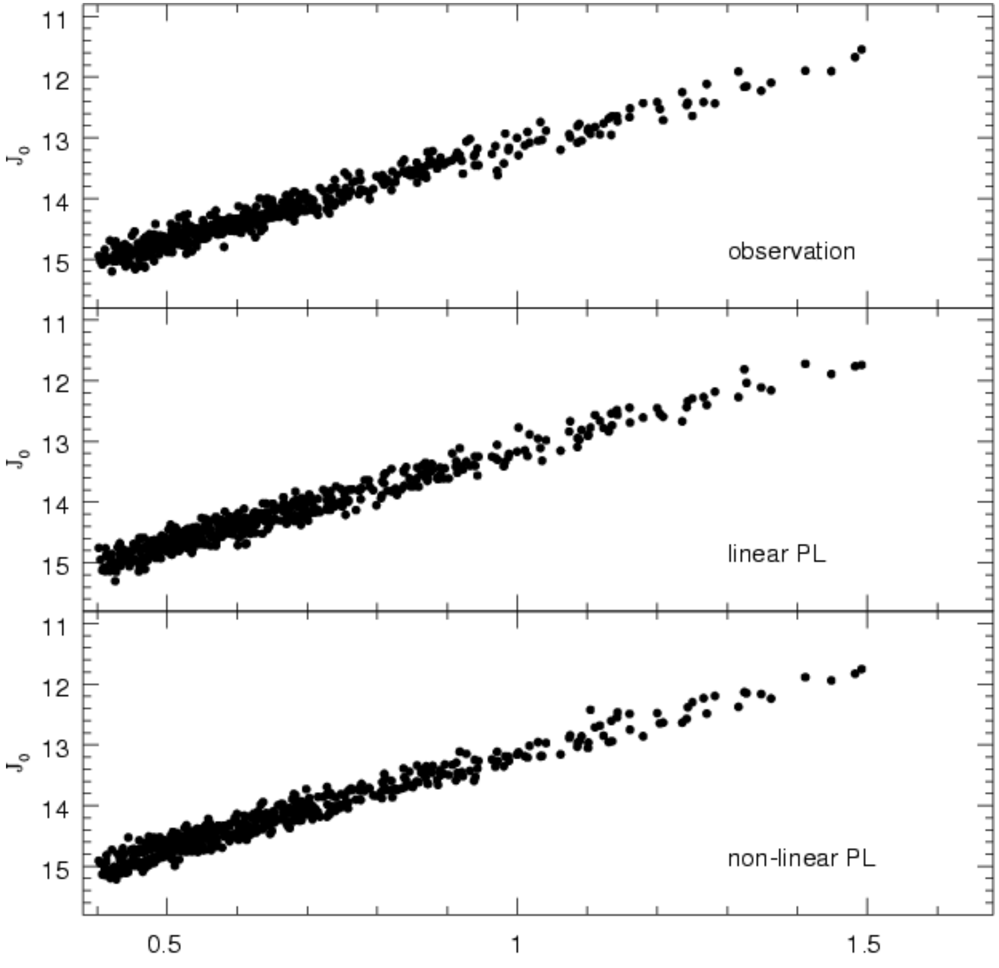
Evidence of a cut off at 10 days

The proposed mechanism that may cause the nonlinear PL relation is the interaction between the hydrogen ionization front and the stellar photosphere (Kanbur & Ngeow 2006)

It will only affect the temperature variation and not the radius variation➔NIR bands are less affected !



Ngeow & Kanbur 2006



Kanbur et al. 2008

Classical Cepheids: open problems

3) Origin of the *mass discrepancy* between evolutionary and pulsational estimates

The *mass discrepancy* problem between evolutionary and pulsational estimates

Pulsation models *versus* observations → *Pulsational* mass

Evolutionary models *versus* observations → *Evolutionary* mass

Stobie (1969), Cogan (1970), and Rodgers (1970) discovered that these two independent mass estimates did not agree, the pulsational masses being smaller by 20%-40%.

New radiative opacities in stellar models → Discrepancy reduced to about 10%-15% in mass (see e.g. Keller & Wood 2002, 2006; Caputo et al. 2005; Evans et al. 2007, and references therein)

Mass loss and core overshooting often invoked to further reduce the discrepancy (see e.g. Bono et al. 2006, Keller 2008)

A *dynamical* mass estimate

Pietrzyński et al. (2010) ➔ first accurate determination of the dynamical mass of a classical Cepheid in a well-detached, double-lined, eclipsing binary in the LMC (OGLE-LMC-CEP0227).

High-quality photometric data set + spectroscopic follow-up + near-perfect system

Cepheid mass of the pulsator to an unprecedented 1% precision.

Physical Parameter	Primary (A)	Secondary (B)
Mass ($M/M_\odot$)	4.14 ± 0.05	4.14 ± 0.07
Radius ($R/R_\odot$)	32.4 ± 1.5	44.9 ± 1.5
Teff(K)	5900 ± 250	5080 ± 270

In agreement with the *pulsational* mass based on the Period-Mass-Radius relation (Pietrzyński et al. (2010)

In agreement with the *evolutionary* estimates based on updated stellar models (see discussion in Cassisi & Salaris 2011)

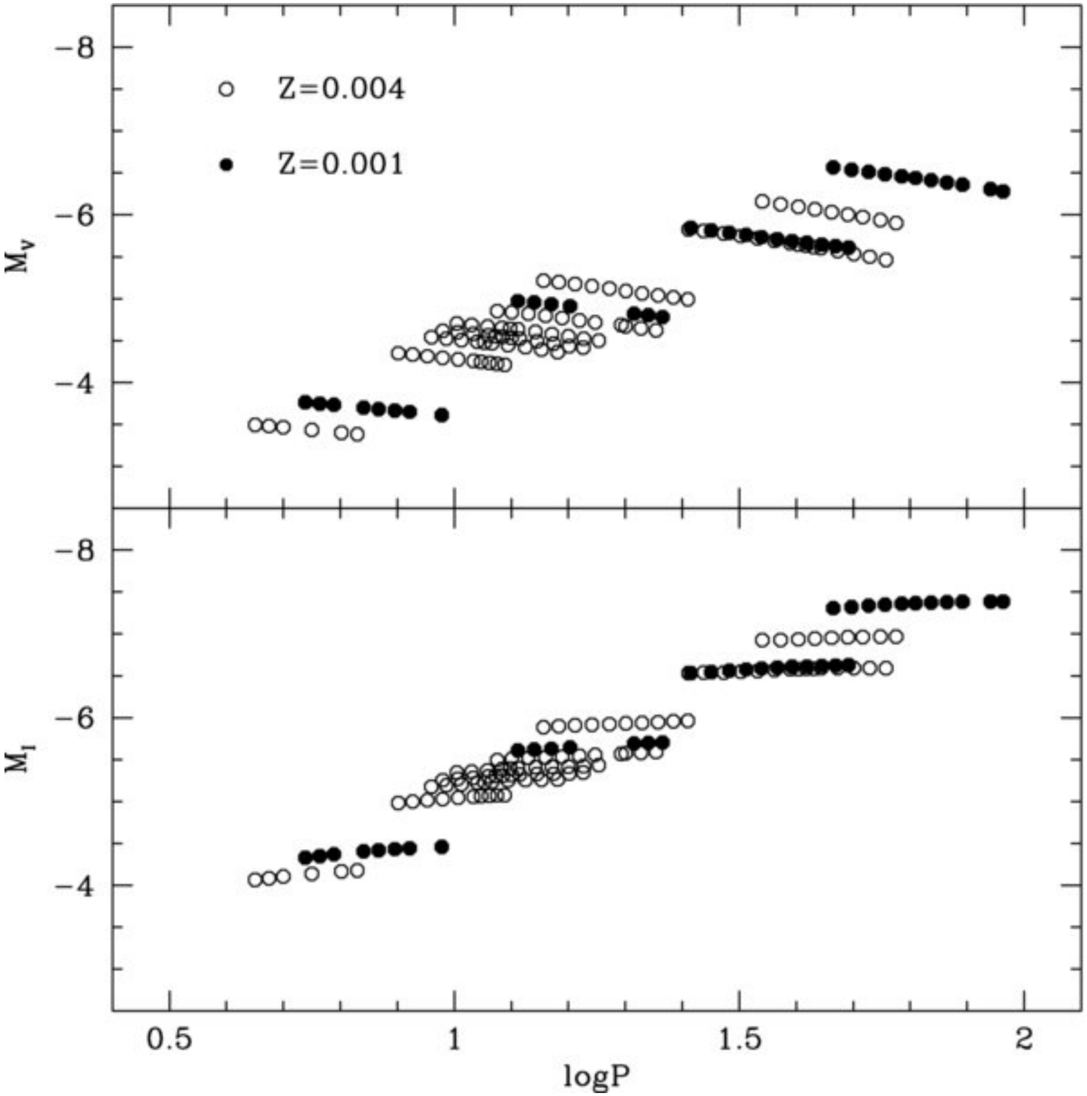
The theoretical approach to the Cepheid open problems

Nonlinear pulsation models with a nonlocal time-dependent treatment of convection (Stellingwerf 1982; Bono & Stellingerf 1994; Bono, Marconi, Stellingwerf 1999; Marconi et al. 2005, 2010, Marconi 2009)

↓

Unique opportunity of predicting all the relevant observables of pulsation (periods, topology of the instability strip, amplitudes, morphology of light and radial velocity curves) varying the input stellar parameters (mass, luminosity, effective temperature, abundances).

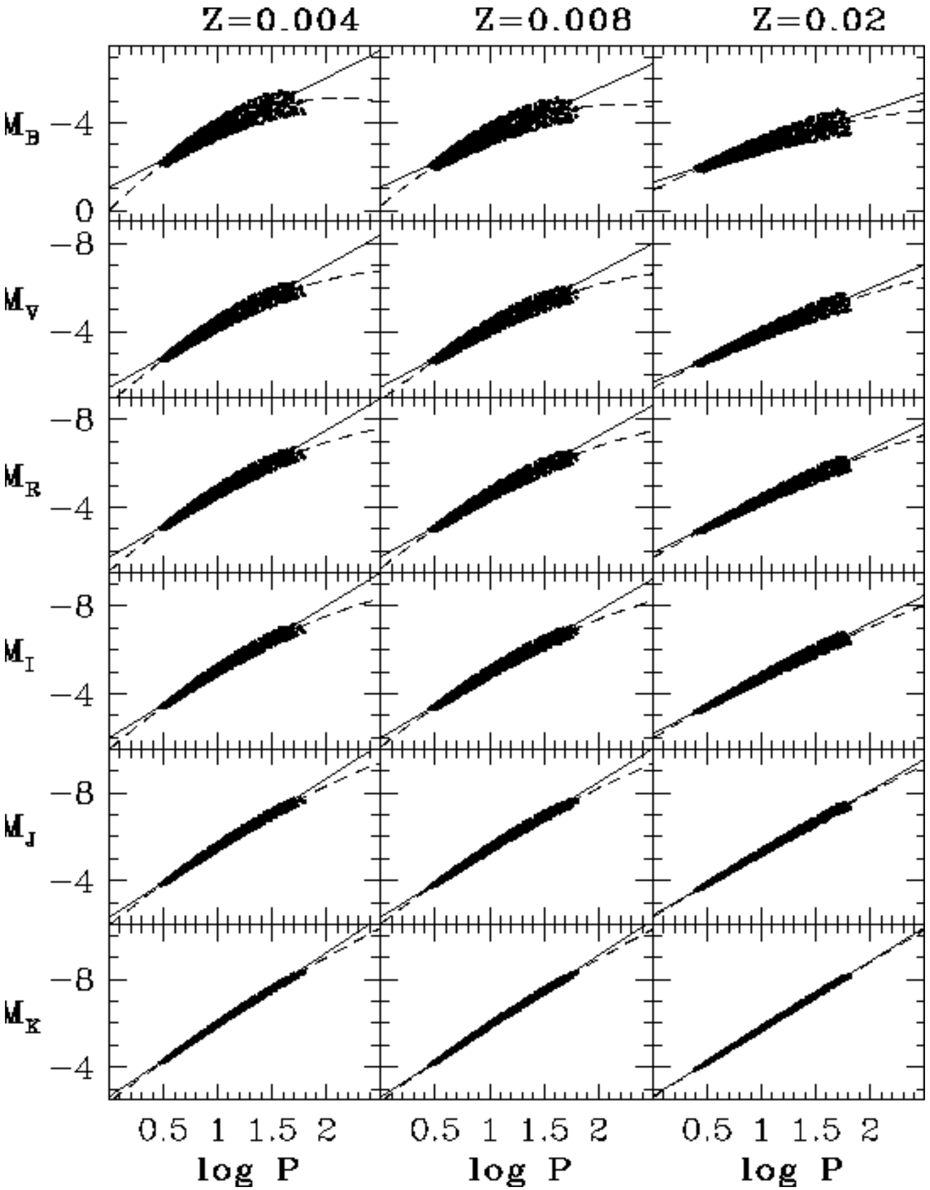
Predicted PL relations have a statistical nature



Bono et al. 2010 ApJ

As the width of the instability strip is finite, the dispersion of PL relations is significant, expecIallly in the optical bands.

PL are obtained by averaging the Cepheid distribution over the instability strip color range, deriving an average luminosity for each fixed period.

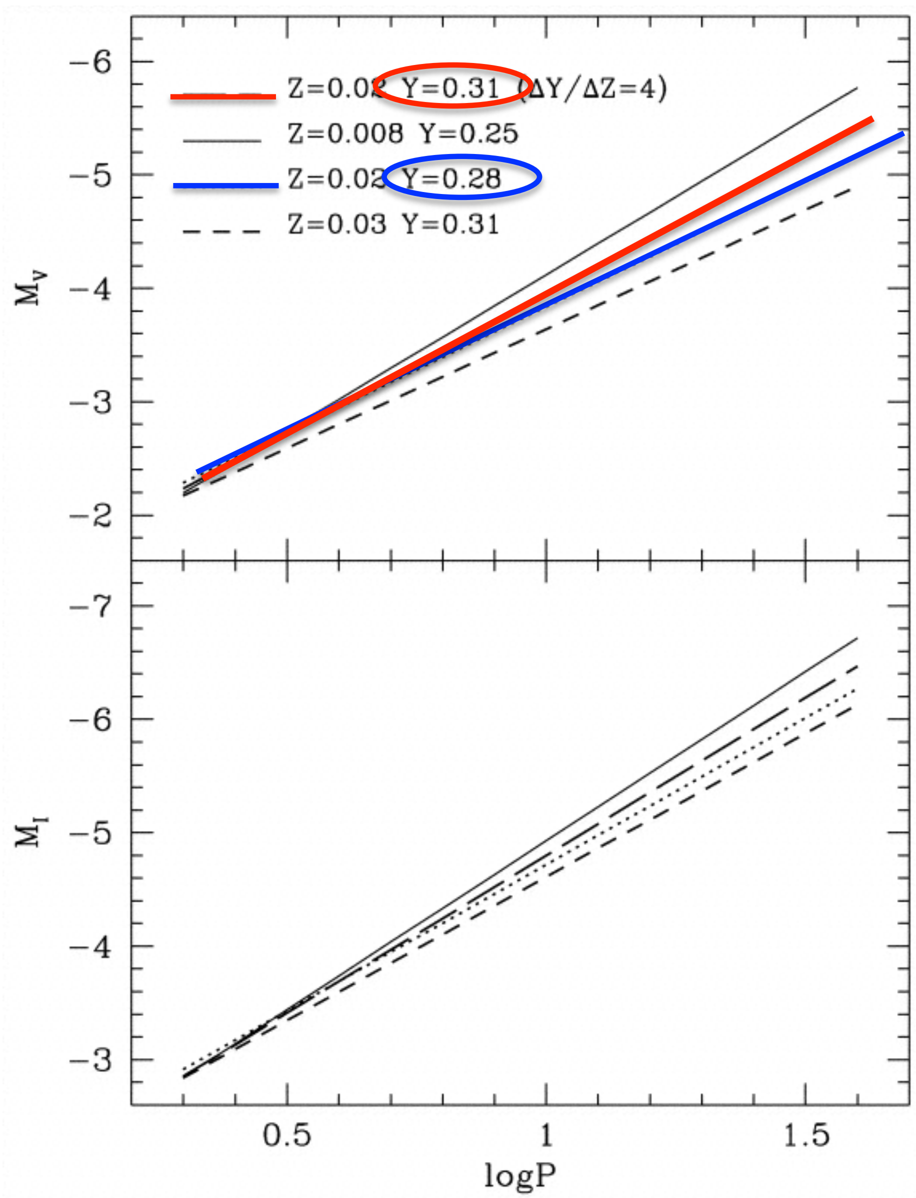


Caputo, Marconi, Musella 2000, A&A

Nonlinear convective models predict both the metallicity dependence and the nonlinearity of optical PL relations !

As Z increases the PL gets flatter !!

Y also affects the predicted PL relations



The slope decreases as Z increases at fixed ΔY/ΔZ

The slope increases as Y increases at fixed Z

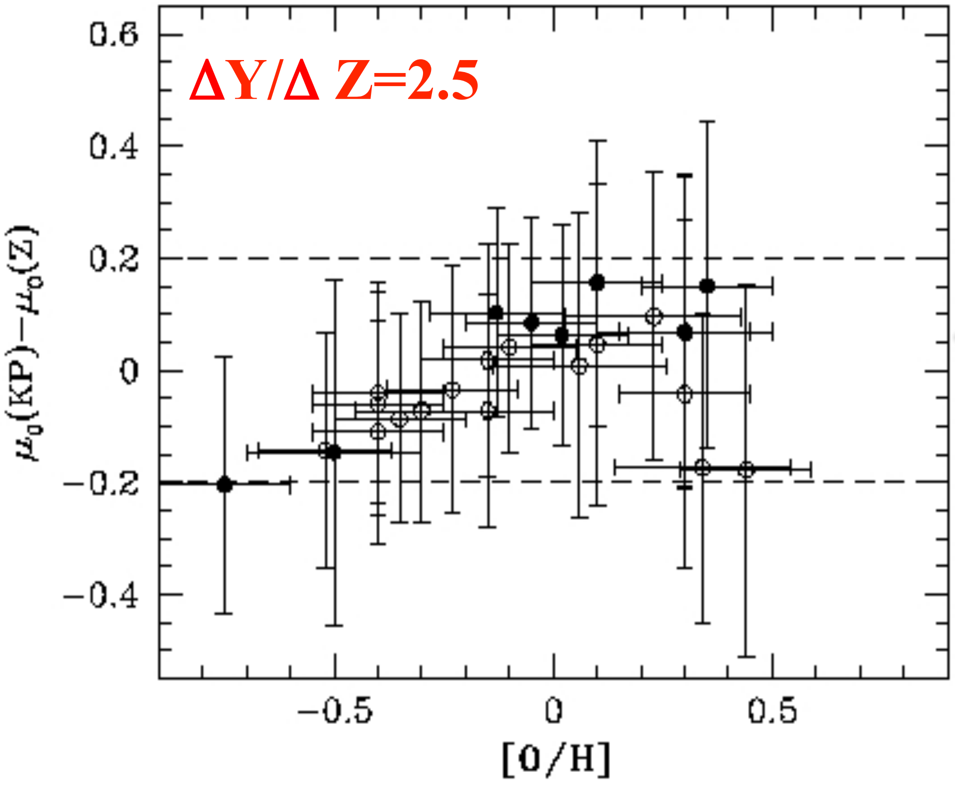
As Y increases the PL gets steeper !!

Fiorentino et al. 2002 ApJ, Marconi et al. 2005 ApJ

Theorical test for metallicity effect

μ_0(KP) = KP distance modulus adopting LMC slope

μ_0(Z) = distance modulus adopting the theoretical slope corresponding to the host galaxy

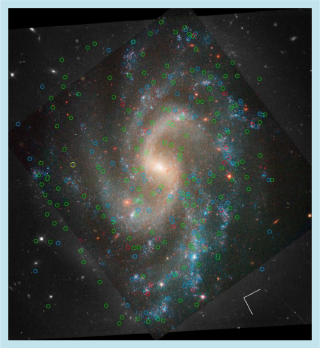


→ Distance modulus correction when the true metallicity is taken into account

Marconi, Musella & Fiorentino, 2005

Theoretical test following Riess approach

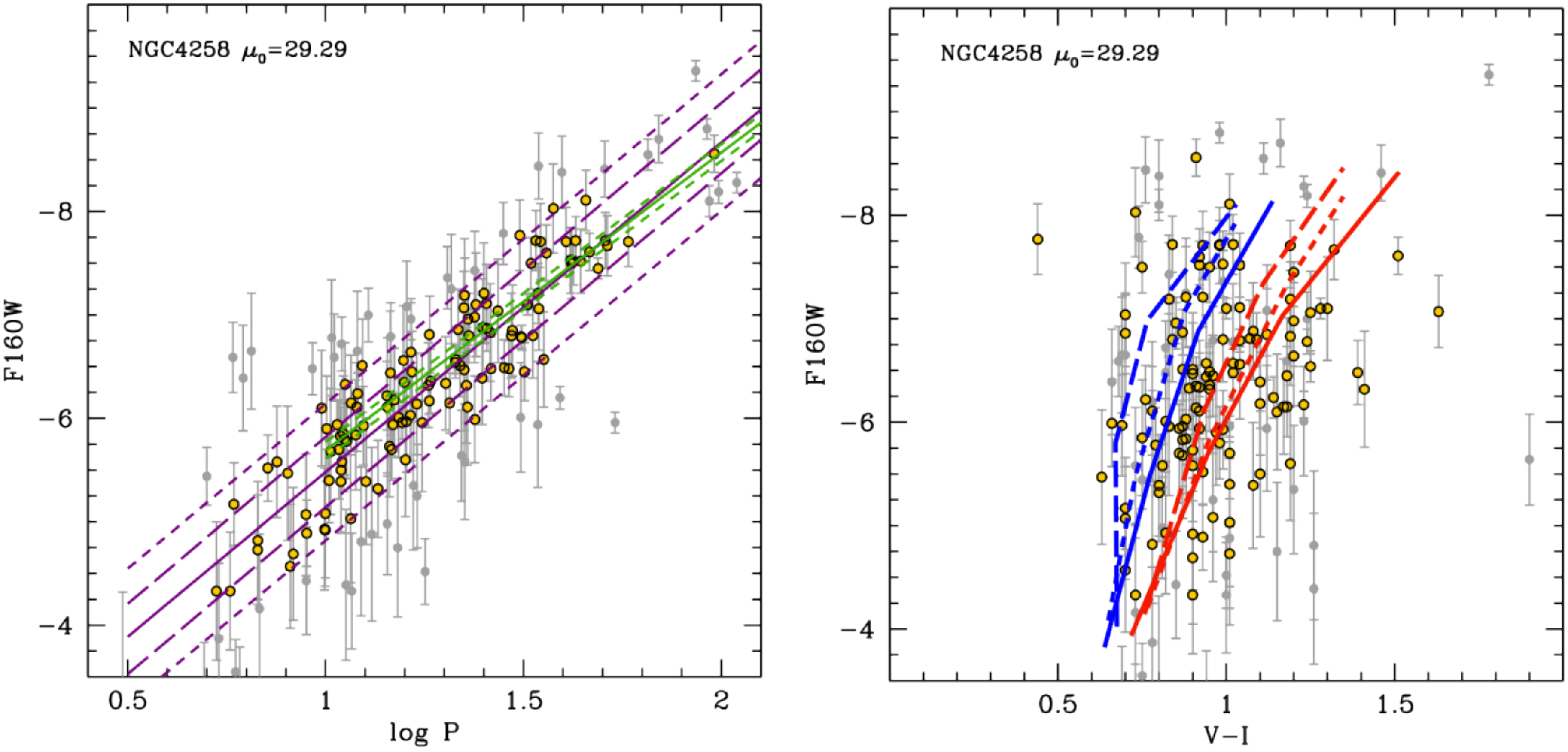
Macri et al. 2006, Riess et al. 2009a,b, Riess et al. 2011



The zero point anchored to NGC4258 (Z=0.02, d=7.2±0.5 Mpc, Maser geometrical distance)

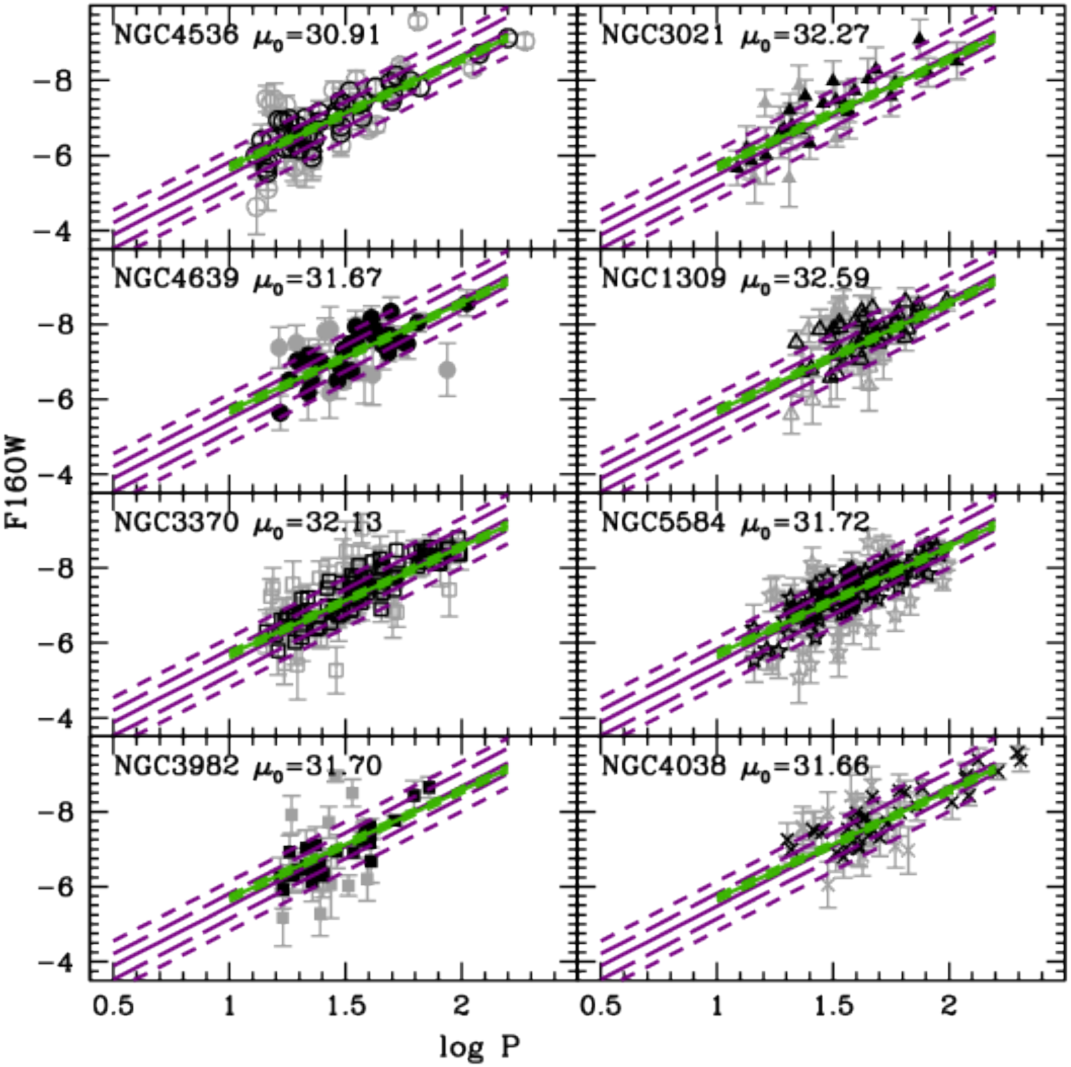
→ Use the theoretical PL relations for the metallicity of NGC4258 as calibrators

NGC4258

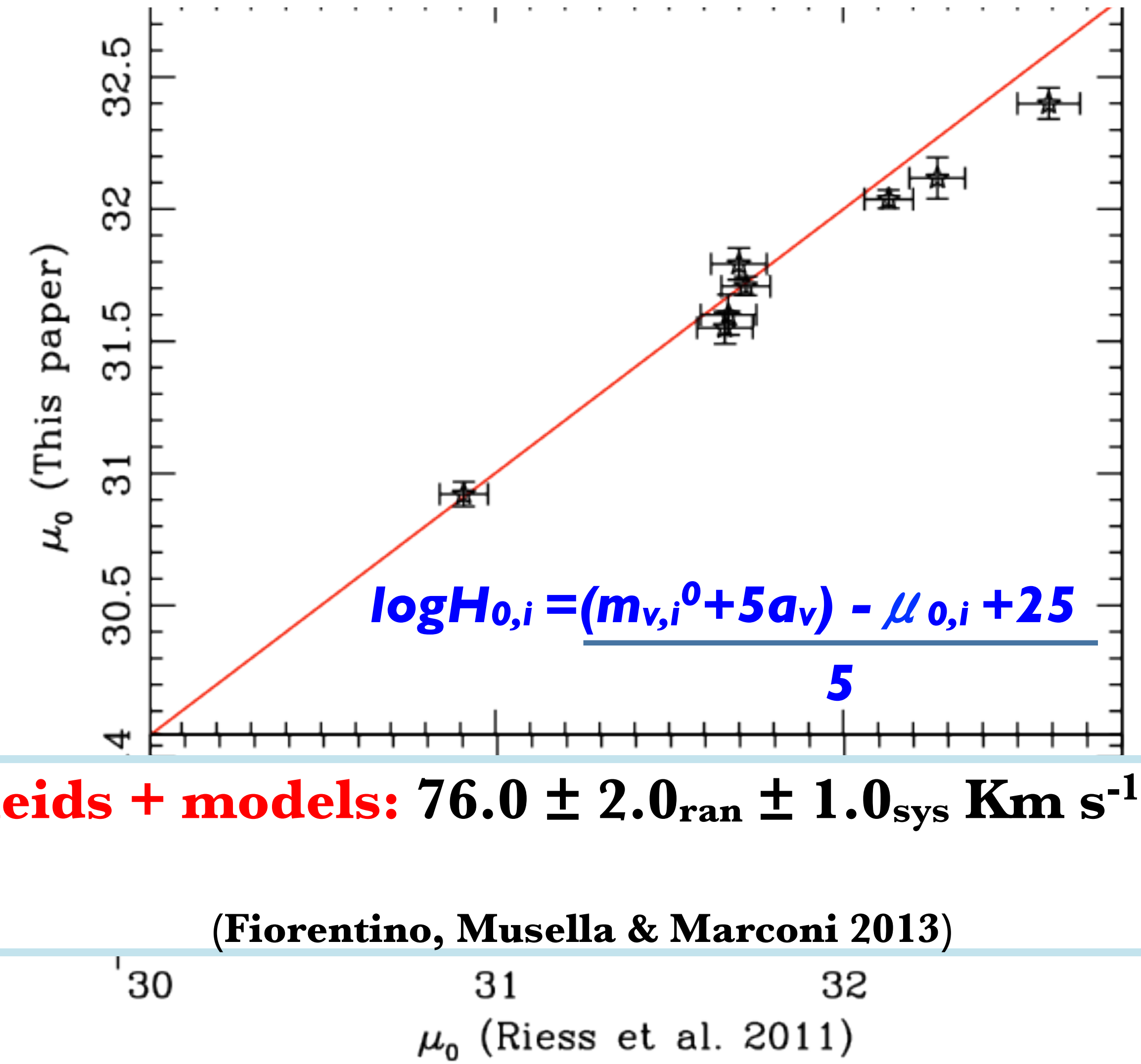


Fiorentino, Musella, Marconi 2013 MNRAS

F160W-PL relations



Extragalactic Cepheids



$$\log H_{0,i} = \frac{(m_{V,i}^{0} + 5a_V) - \mu_{0,i} + 25}{5}$$

Cepheids + models: 76.0 ± 2.0_{ran} ± 1.0_{sys} Km s^{-1} Mpc^{-1}

(Fiorentino, Musella & Marconi 2013)

Recent evaluation of H0

- **Cepheids + TRGB:** $63.7\pm2.3_{ran}\pm3.6_{sys}$ Km $s^{-1}Mpc^{-1}$ (Tammann et al. 2013)

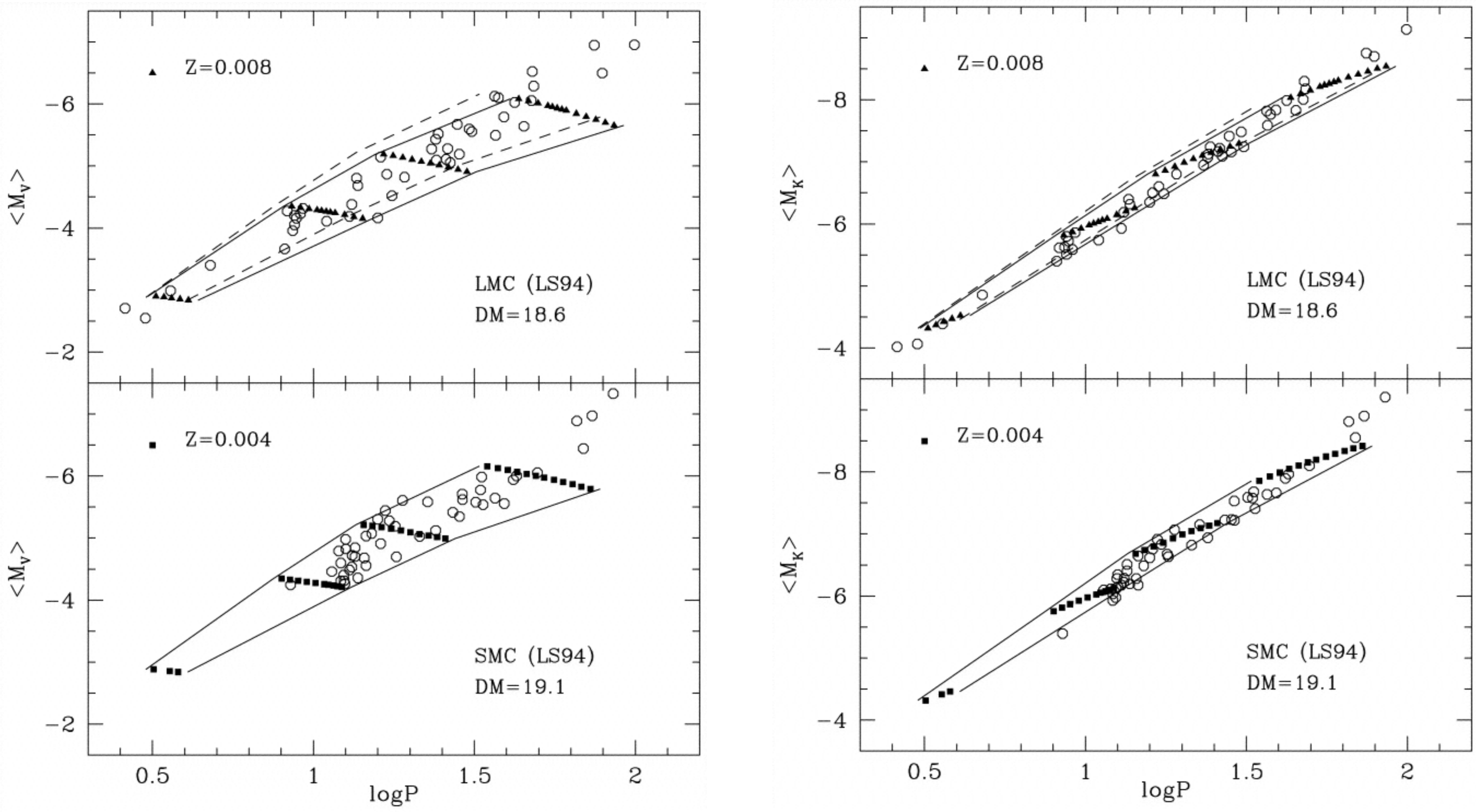
- **TRGB:** 73 ± 5 Km s^{-1} Mpc^{-1} (Mould & Sakai 2008)

- **Cepheids + SNIa:** 73.8 ± 2.4 Km s^{-1} Mpc^{-1} (Riess et al. 2011)

- **Cepheids + secondary indicators:** 74.3 ± 2.1 Km s^{-1} Mpc^{-1} (Freedman et al. 2012)

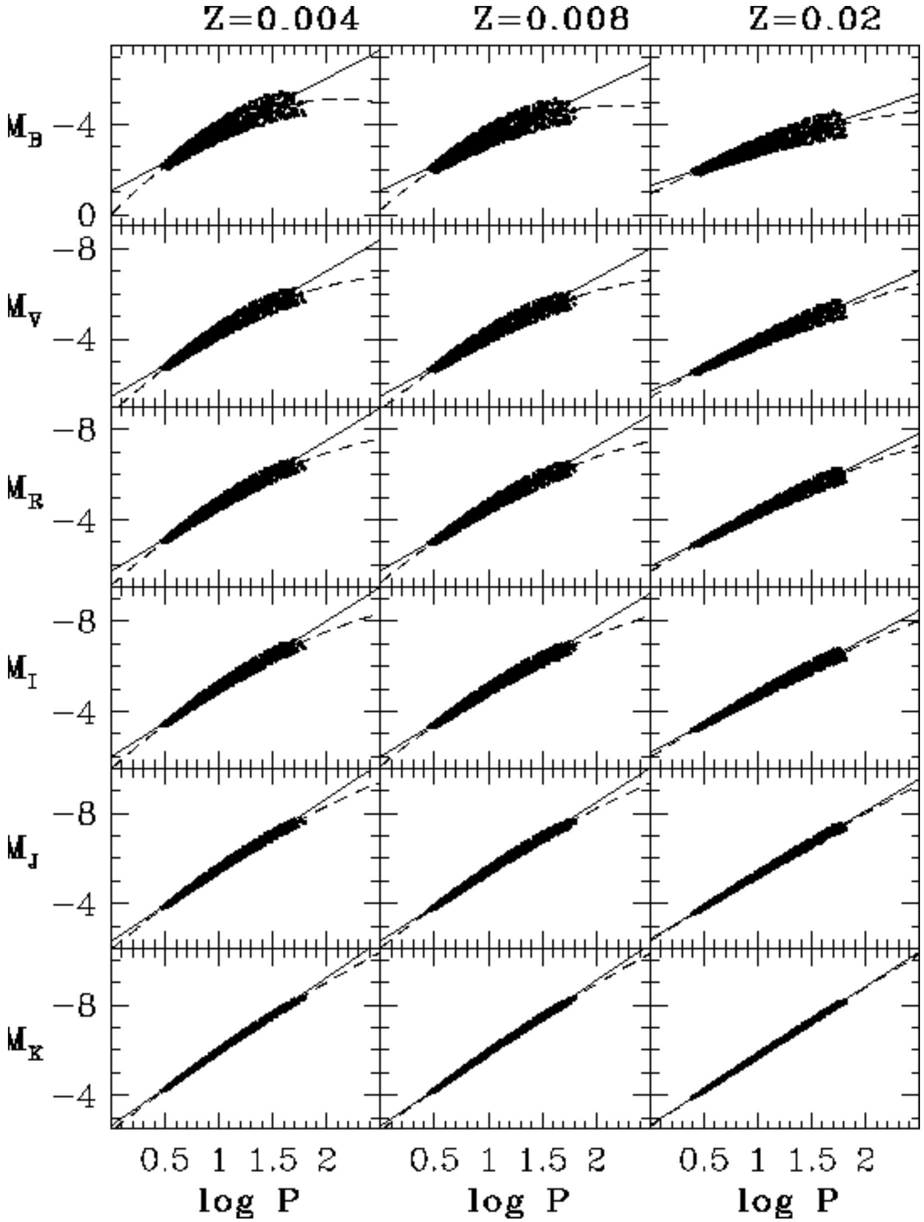
- **Cepheids + models:** $76.0 \pm 2.0_{ran} \pm 1.0_{sys}$ Km s^{-1} Mpc^{-1}

Model constraints on the *linearity* of the PL relation: Optical *versus* Near Infrared



Bono et al. 1999 ApJ

Simulated PLs show the same trend



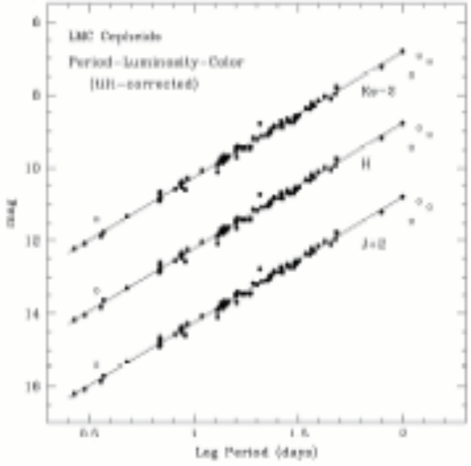
The *non*linearity effect decreases from optical to NIR bands.

Cepheids at solar metallicity show a more linear trend in agreement with observations (see e.g. *Tammann, Reindl & Sandage 2011*)

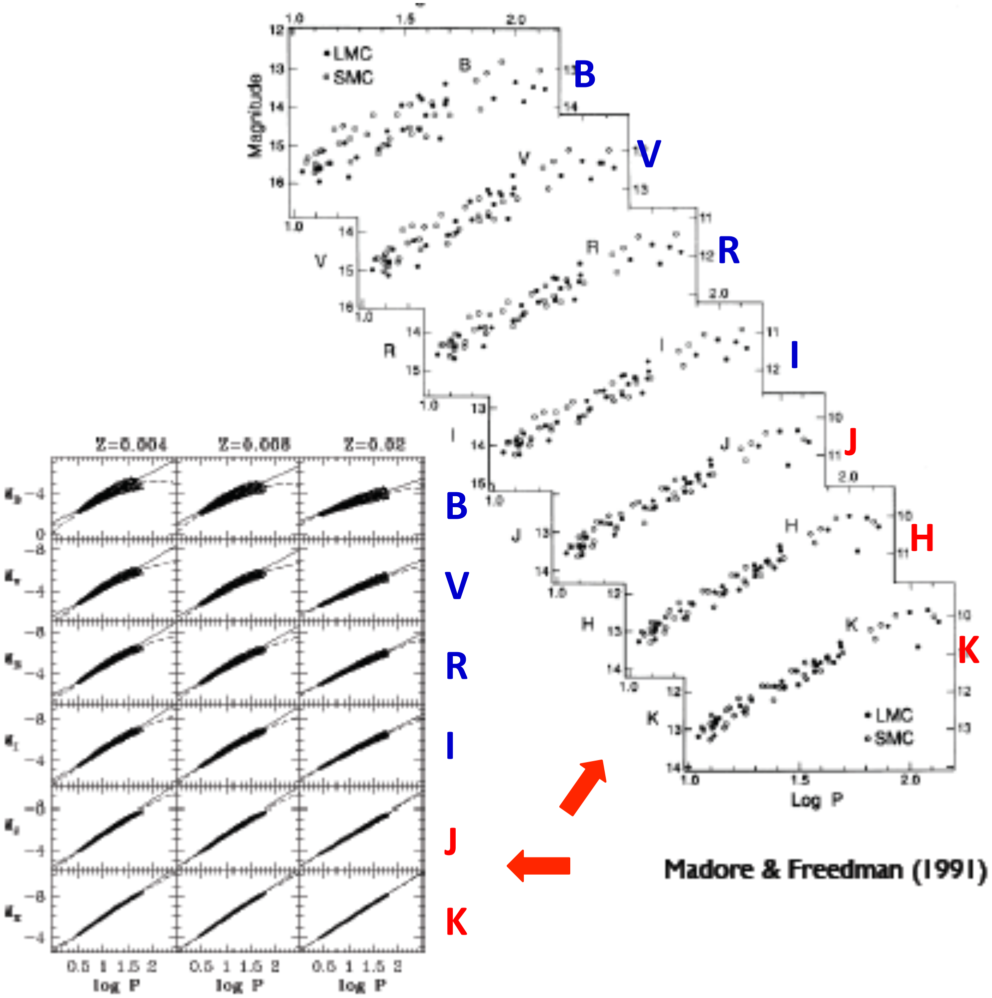
Better working in the NIR bands

ADVANTAGES

- **Low-amplitude light curves**
- **Low dependence on reddening**
- **PL in J and K linear**
- **Low dependence on metallicity**
- **Low dispersion (< 0.1 mag)**



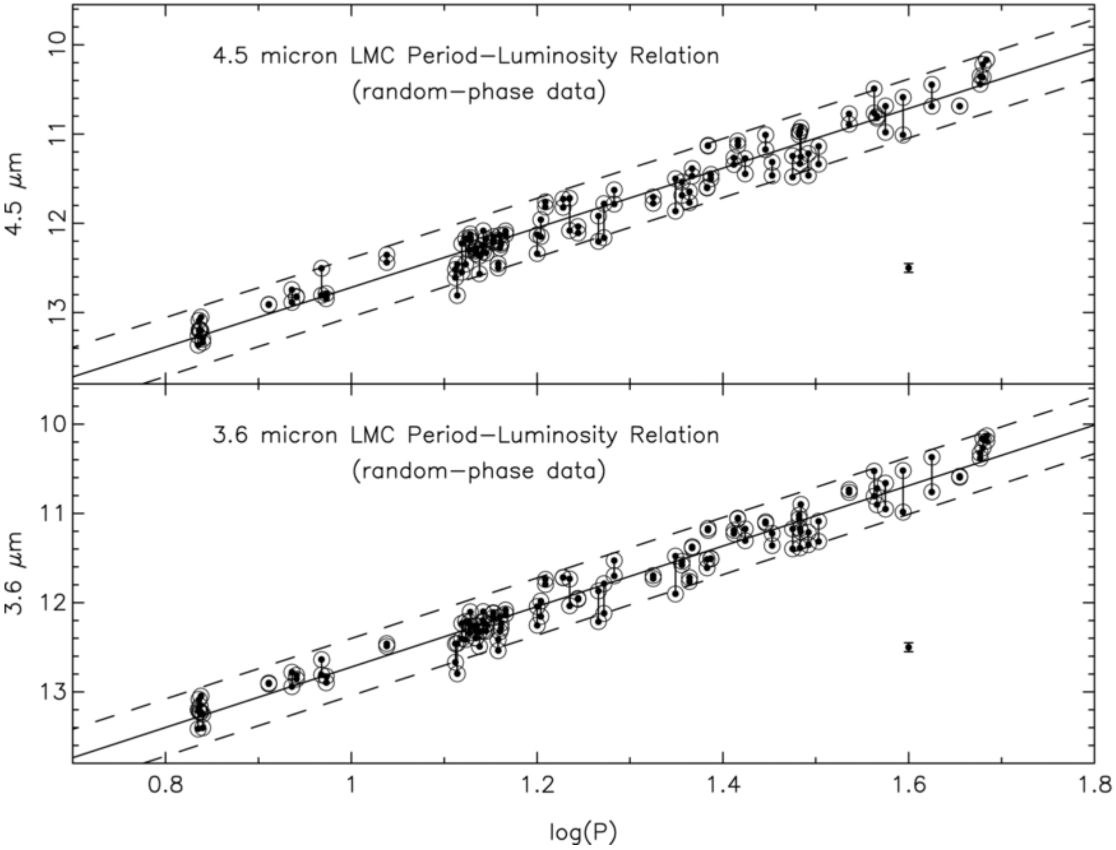
Persson et al. (2004)



Madore & Freedman (1991)

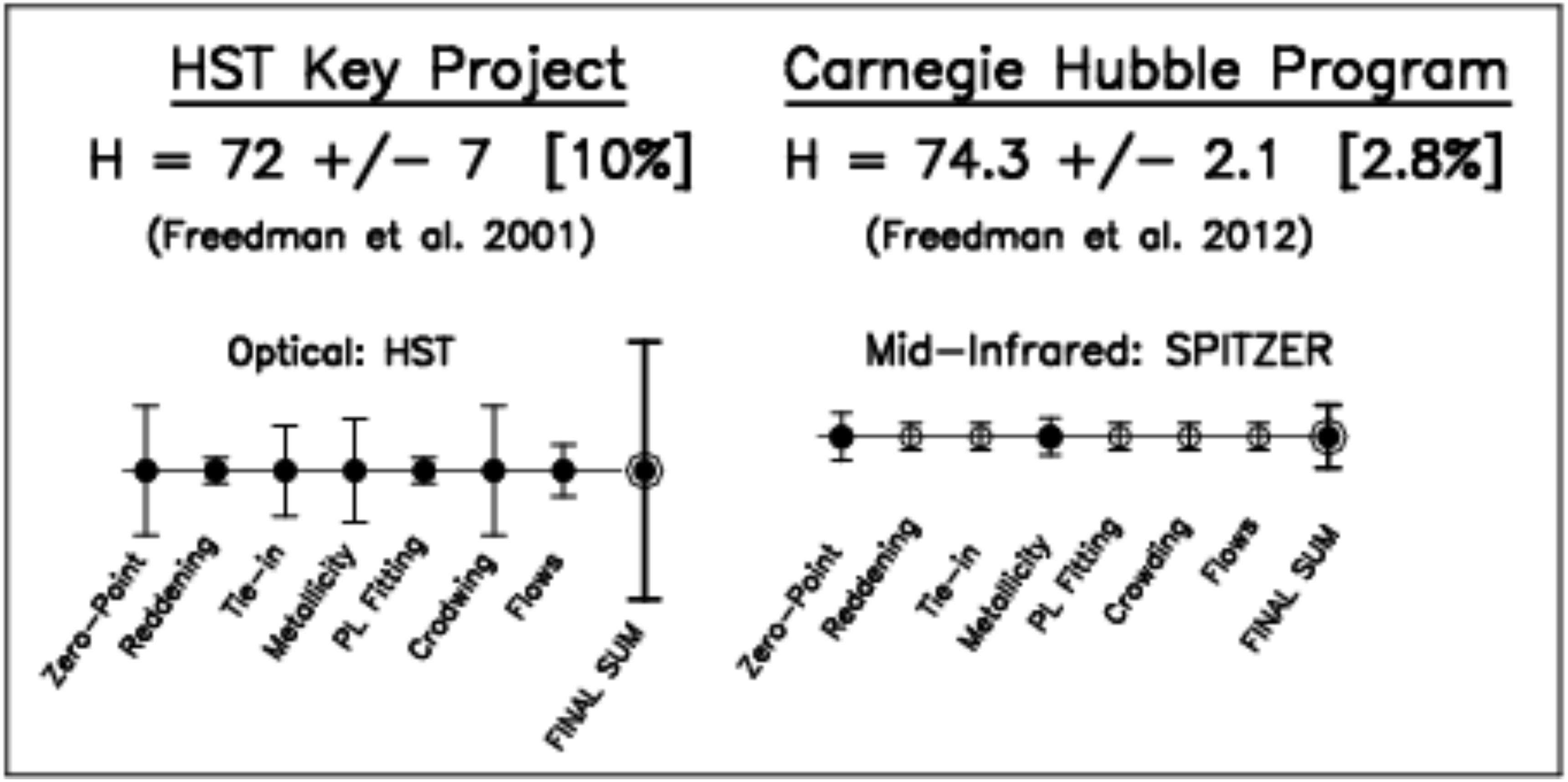
MIDinfrared PL relations

The mid-infrared Cepheid PL relation will be important in the JWST (James Webb Space Telescope) era, as it holds the promise of deriving the Hubble constant at the 2% level (Freedman & Madore 2010).

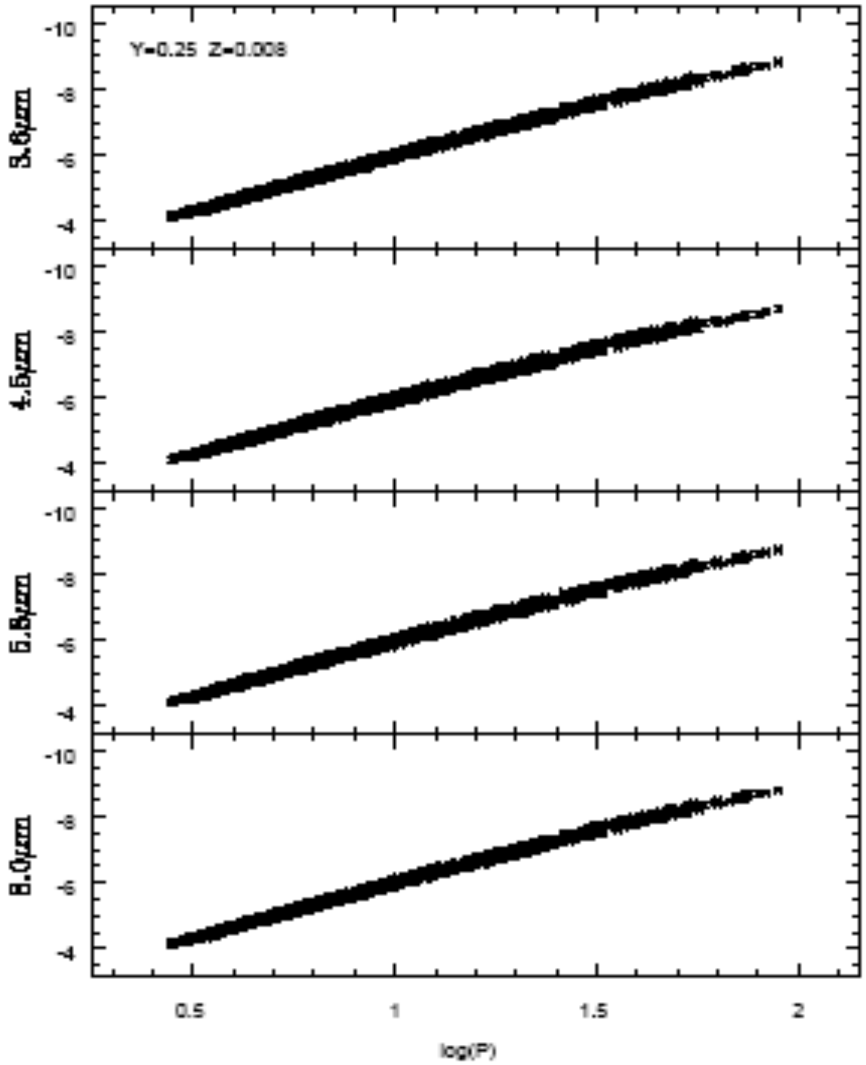


→ the Spitzer's IRAC band (3.6μm, 4.5μm, 5.8μm & 8.0μm) P-L relations were derived for Cepheids in our Galaxy (*Marengo et al. 2010*), in the LMC (*Freedman et al. 2008; Ngeow & Kanbur 2008; Madore et al. 2009; Ngeow et al. 2009*) and in the SMC (*Ngeow & Kanbur 2010*).

Expected improvements in the MIR filters



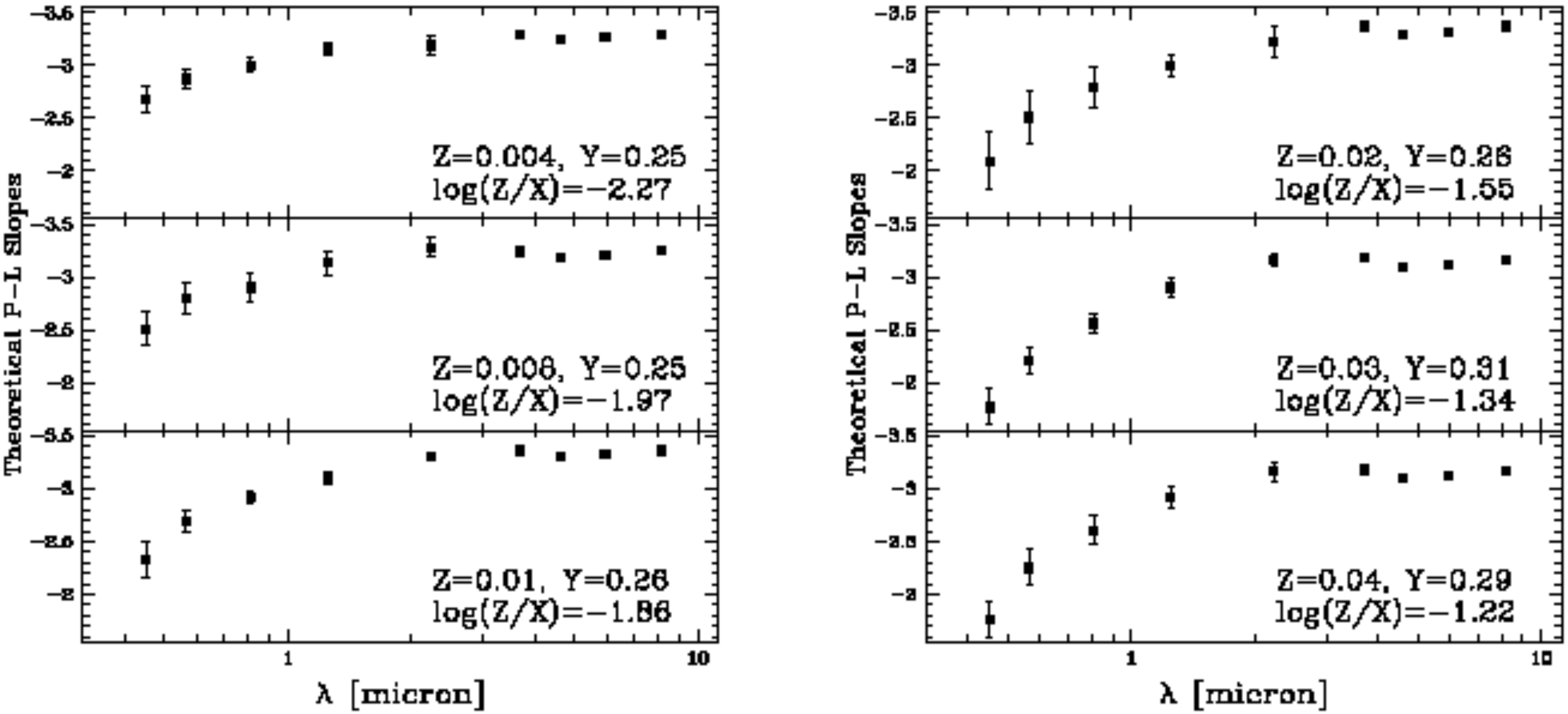
Theoretical MIDinfrared PL relations



The dispersions of the PLs in these bands are negligible

Ngeow et al, 2012, ApJ

Theoretical PL slope as a function of the wavelenght



Ngeow et al. 2012

If NIR or MIR filters are not available it is better to rely on the Wesenheit relations.

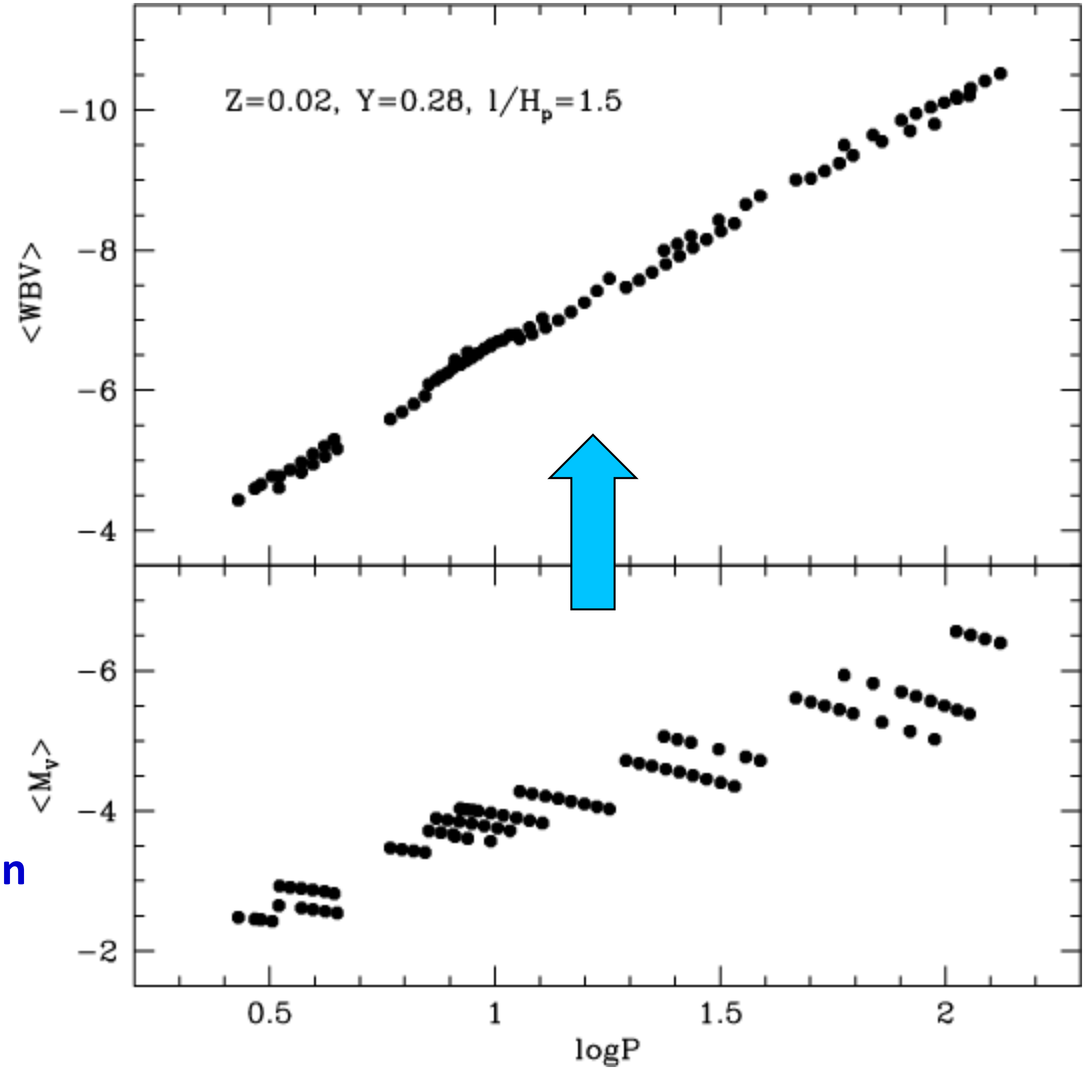
The Wesenheit relations: reddening free by definition!

$W(B,V)=V-\Upsilon * (B-V)$

$\Upsilon=A_V/E(B-V)$

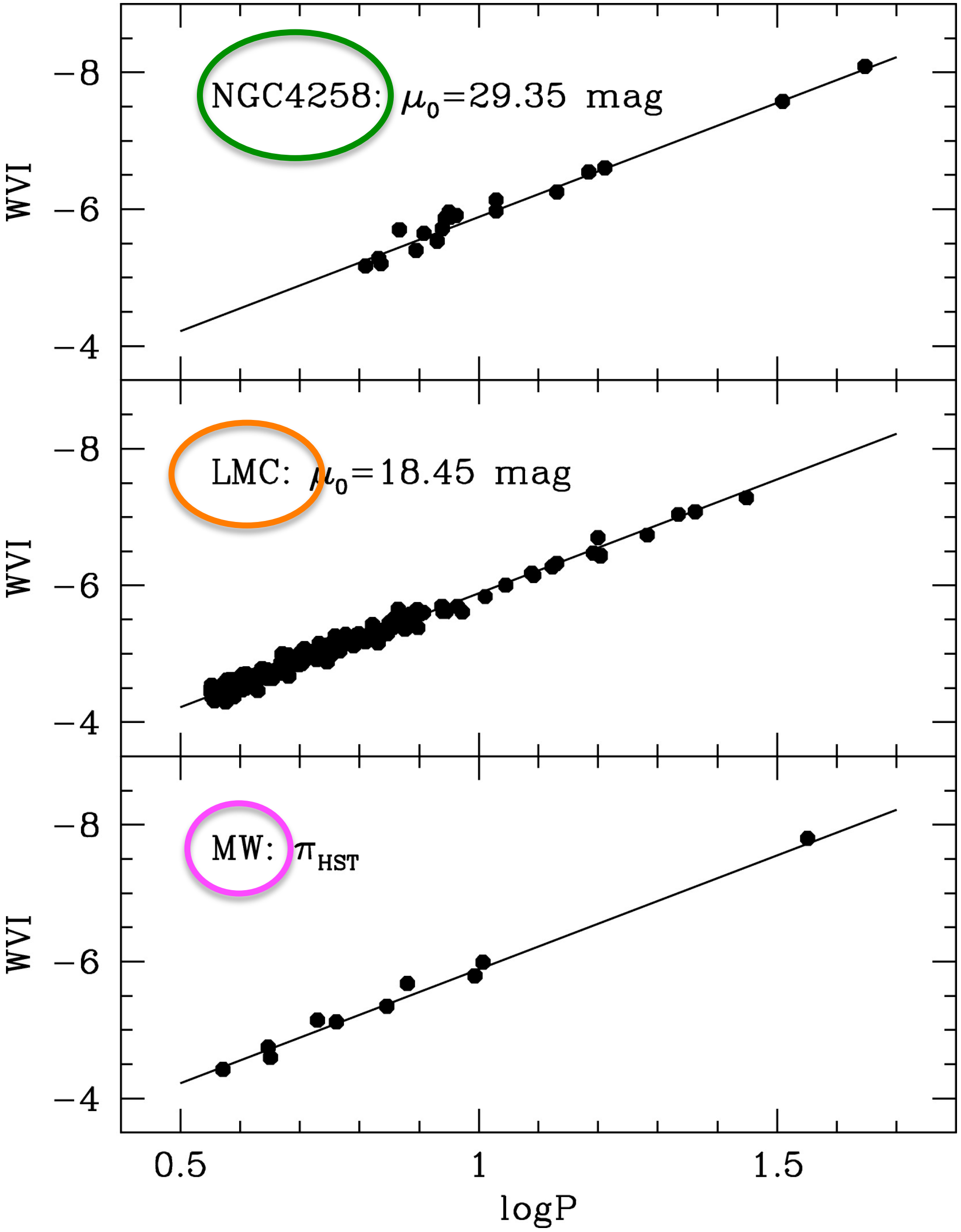
$[V-\Upsilon * (B-V)]$ vs **logP**

Also defined in the other bands typically relying on Cardelli's extinction law (Cardelli et al. 1989)



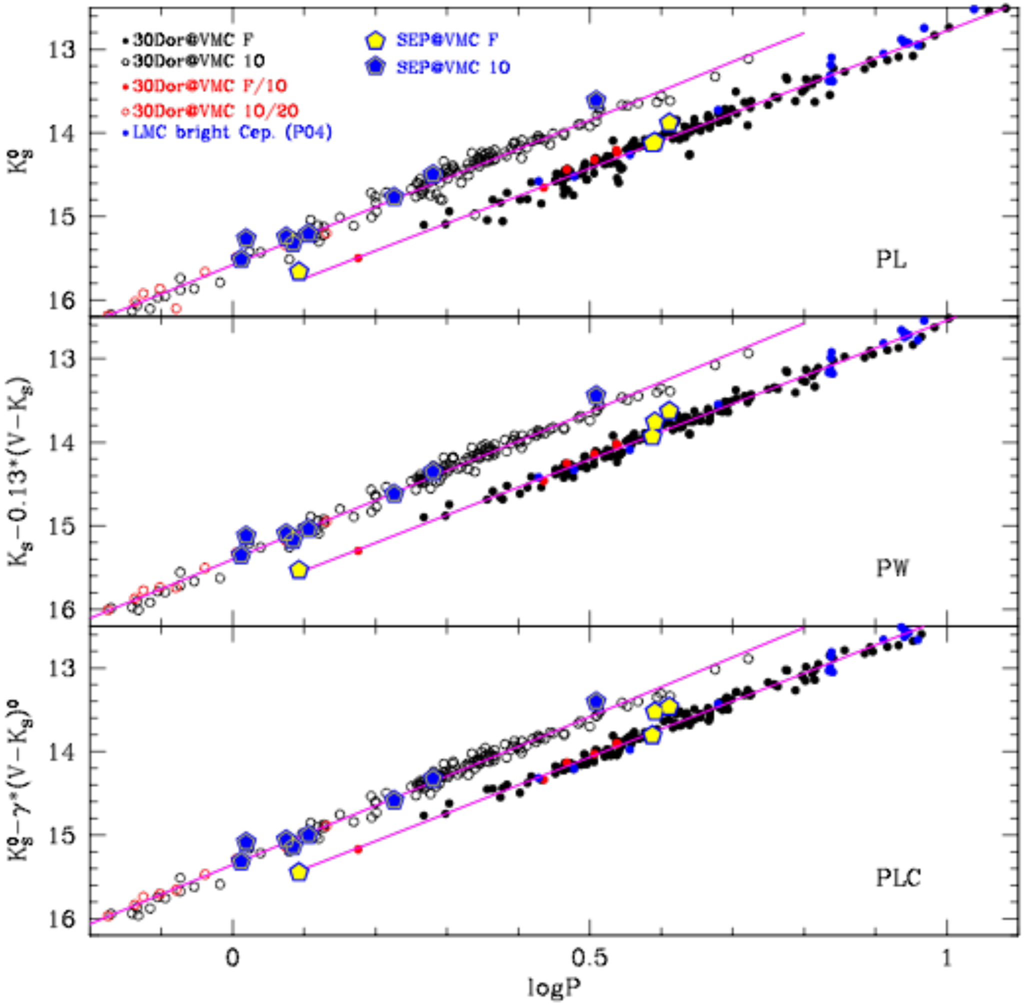
Fiorentino, Marconi et al. 2007, A&A

Very good agreement with the behaviour of observed Cepheids in the Milky Way, in the LMC and in the maser galaxy NGC4258



Still more accurate results if NIR Wesenheit relations can be applied .

30 Dor and Gaia fields: Cepheid analysis comparison



Ripepi et al. 2012 MNRAS

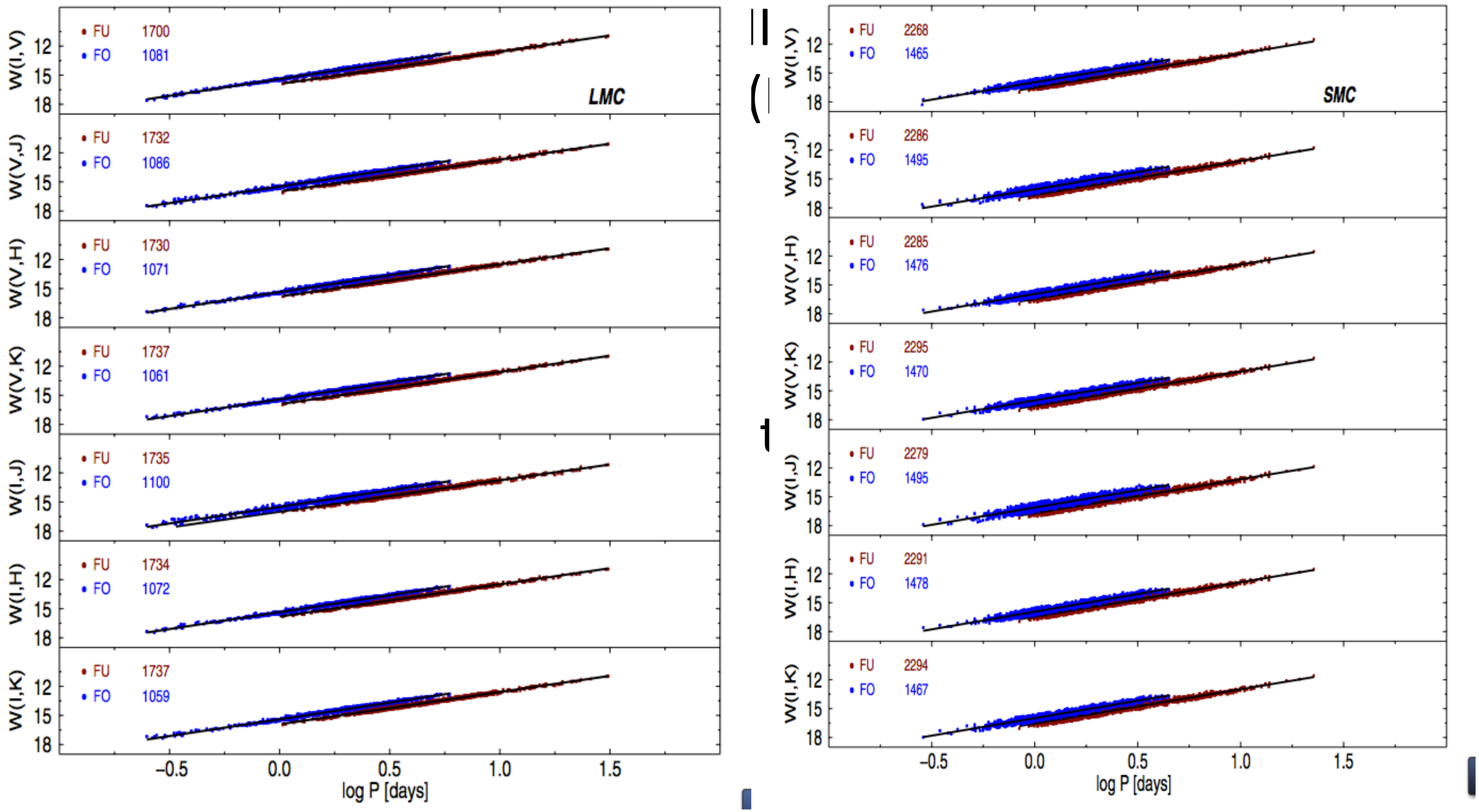
Wesenheit (V,K)

↓

Ideal to do a 3D map of the MCs

The MCs largest NIR (JHK) data set

Inno et al. 2013



Distances in agreement with literature → 3D map of the MCs

But the Cepheid distance scale is at a benchmark: GAIA parallaxes are coming soon !!

Cepheids in Gaia

Gaia is and astrometrical Satellite to measure star parallaxes

d(pc) = 1/π (arcsec)

Milky Way:

~ 800 Cefeidi known in the MW (ASAS catalogue, as in Pojmanski, 2011), mainly near the SUN

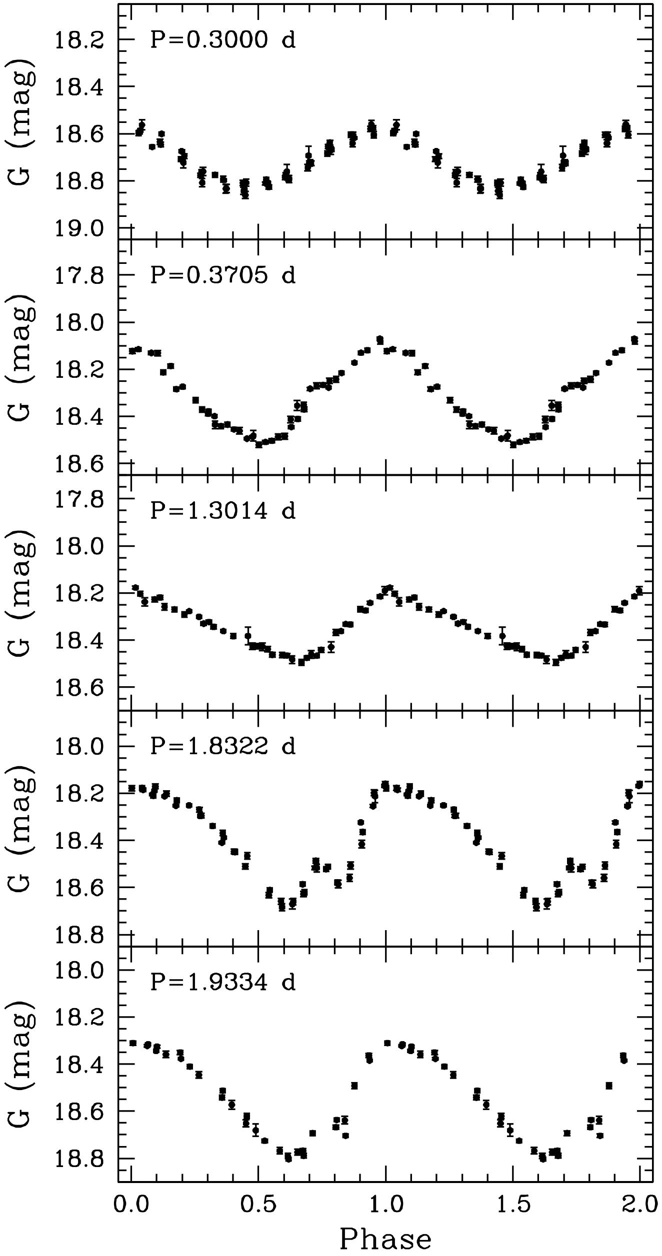
up to ~ 9000 estimated for Gaia !! About 7000 with an error on the parallaxes less than 3%

LMC: 3361 known Cepheids from OGLE III

SMC: 4630 known Cepheids from OGLE III

Soszynki et al (2008-2010)

up to ~ 400 parallaxes for these Cepheids will have an error less than 7-8%



GAIA IMAGE OF THE WEEK
(May 28, 2015)

SHORT PERIOD/FAINT CEPHEIDS
IN THE LMC OBSERVED BY GAIA

We expect to fix the zero point of the Cepheid distance scale at an unprecedented accuracy.

Coupling direct trigonometric distances and accurate spectroscopic metallicities → metallicity dependence

What pulsation models say about the mass discrepancy problem ?

The dynamical mass estimate by Pietrzyñski et al. represents an important constraint to pulsation models !!!

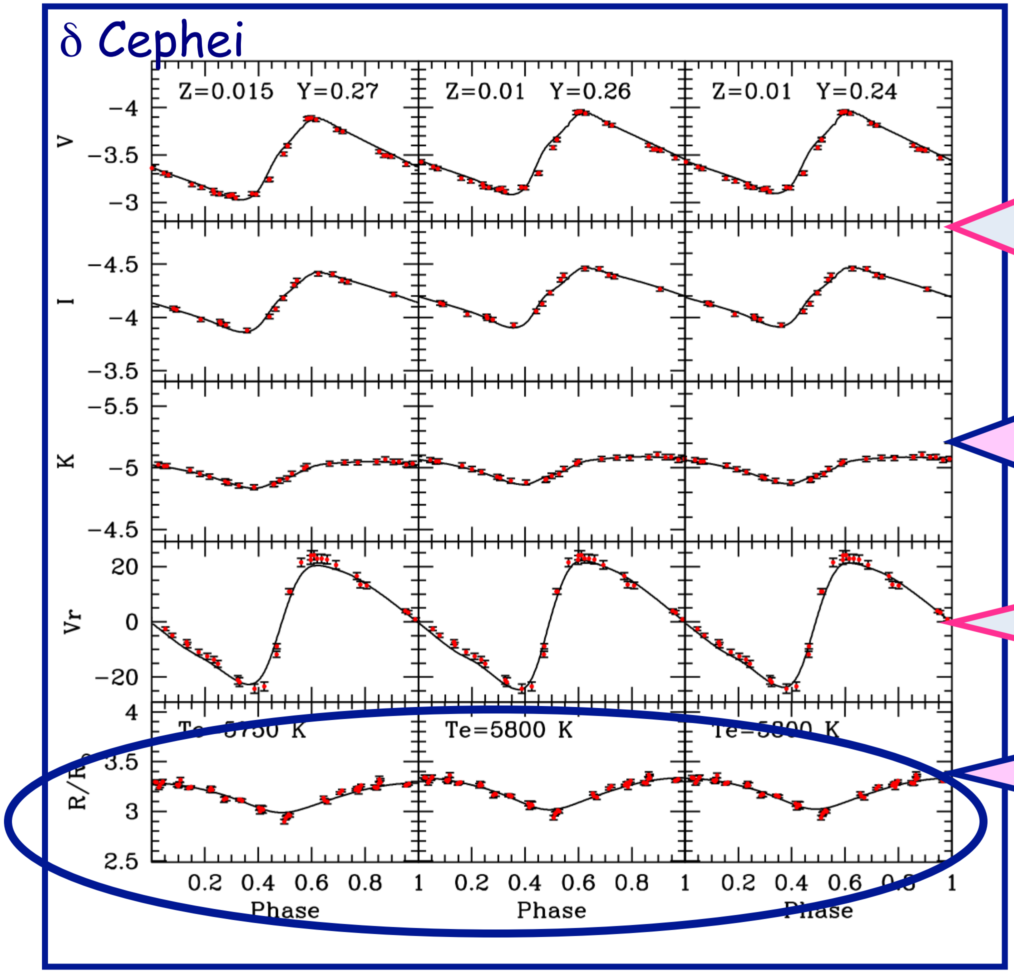
How to use this result to test the pulsation theory scenario?

Physical Parameter	Primary (A)	Secondary (B)
Mass ($M/M_\odot$)	4.14 ± 0.05	4.14 ± 0.07
Radius ($R/R_\odot$)	32.4 ± 1.5	44.9 ± 1.5
Teff(K)	5900 ± 250	5080 ± 270

One of the prediction of nonlinear convective models are light and radial velocity curves that can be directly compared with the observed ones.

The case of δ Cephei

(Natale, Marconi, Bono 2008 ApJL)



the shape and the amplitude in the optical bands depend on surface temperature and radius variation,

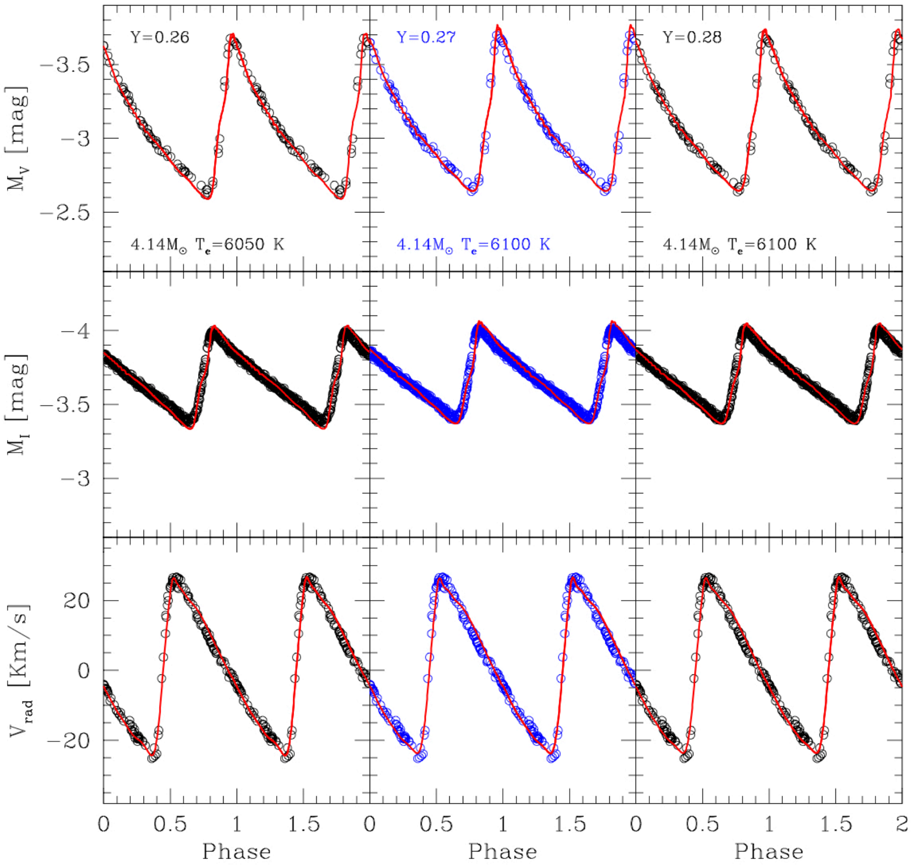
the dependence on temperature is significantly reduced in the K band

Vrad independent of reddening, but dependent on p factor

Independent of reddening and p-factor

Laurea thesis at University Federico II of Naples in 2007

The model fitting of OGLE-LMC-CEP0227



	Model fitting	Dynamical estimate
M/M$_\odot$	4.14	4.14±0.05
R/R$_\odot$	34.3	33.7±1.5
T_e(K)	6100	5900±250

$M_{0(LMC)}$=18.50 mag E(B-V) = 0.1 mag

Cepheids are not only distance indicators…..

Cepheids as age indicators

Mass-Luminosity relation + stellar ages predicted by evolutionary models (Kippenhahn & Smith 1969; Meyer-Hofmeister 1969):

increase in the pulsation period → increase in the stellar mass → decrease in the Cepheid age

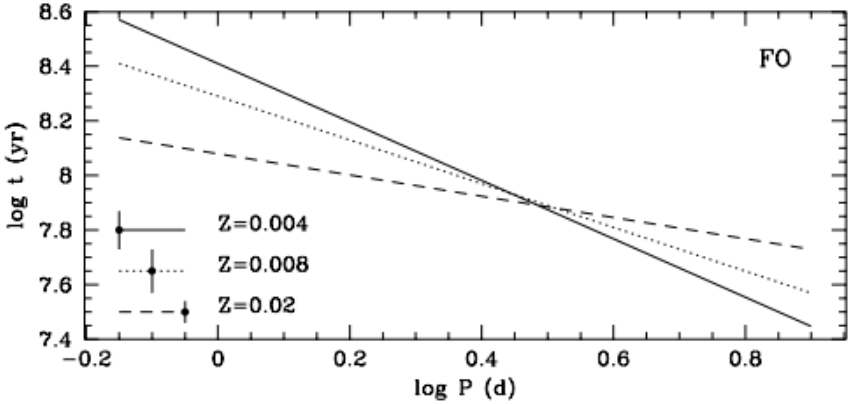
Efremov (1978) → empirical PA relation for Cepheids in Galactic, M31, and LMC clusters, whose age was independently estimated

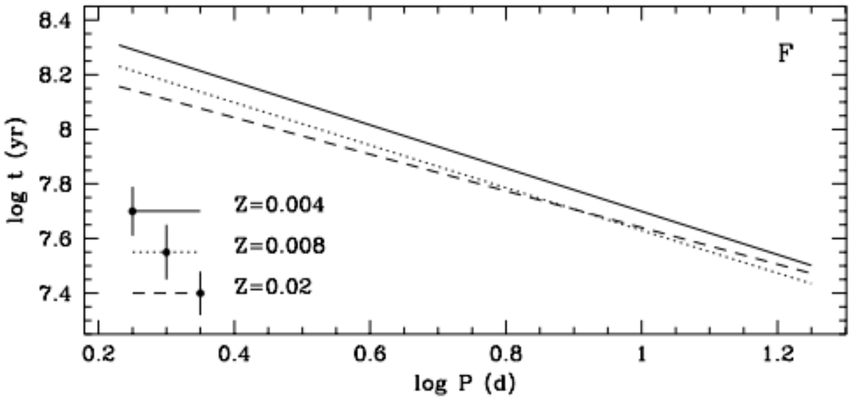
Magnier et al. (1997) → semi-empirical PA relation and used Cepheids in NGC206, the super-association in M31 →**age distribution, star formation history**

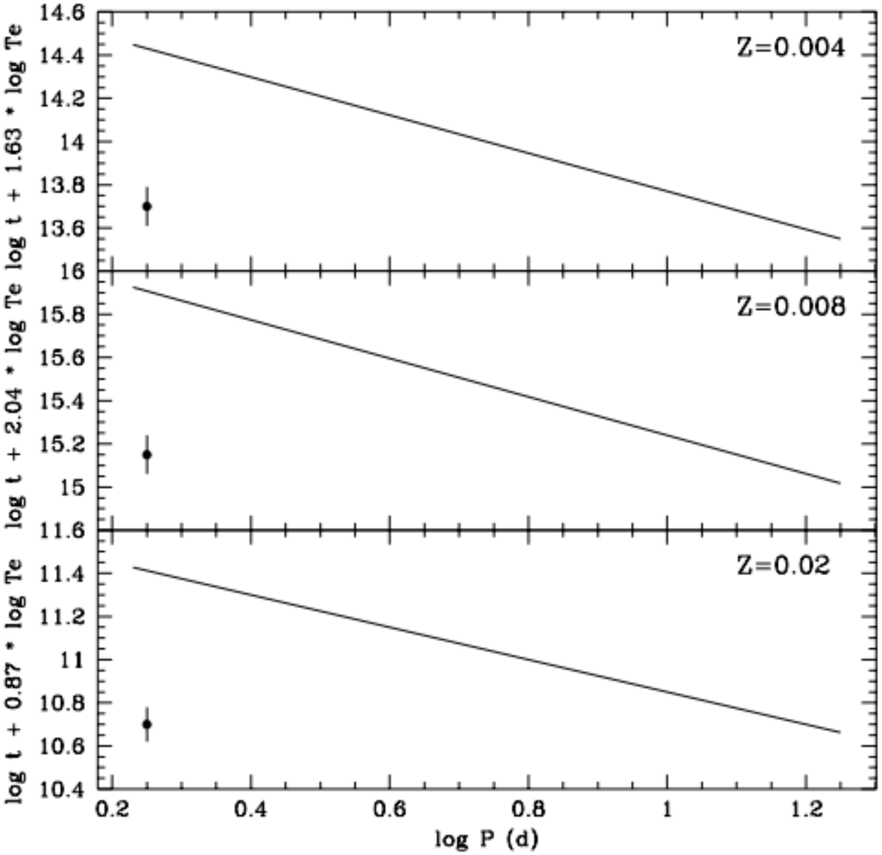
Efremov & Elmegreen (1998) Grebel & Brandner(1998) → PA relations for cluster Cepheids →**star formation history of LMC over the last 200 Myr**

Bono et al. (2005); Marconi et al. (2006); Inno et al. (2015) → theoretical Period-Age and Period-Age-Color relations → age distribution in the MCs

Predicted Period-Age and Period-Color-Age relations: Bono et al. 2005

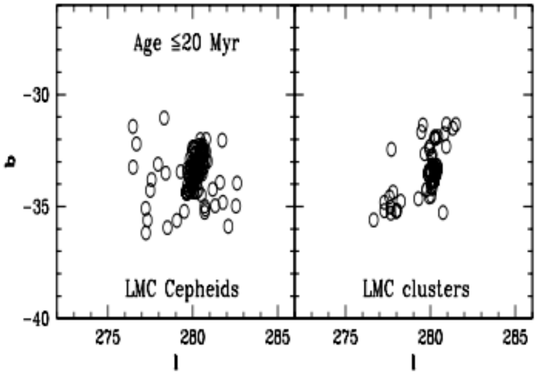


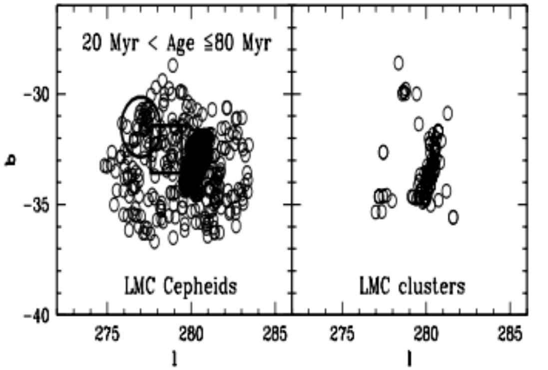


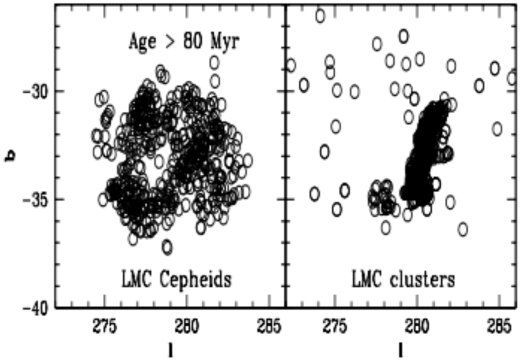


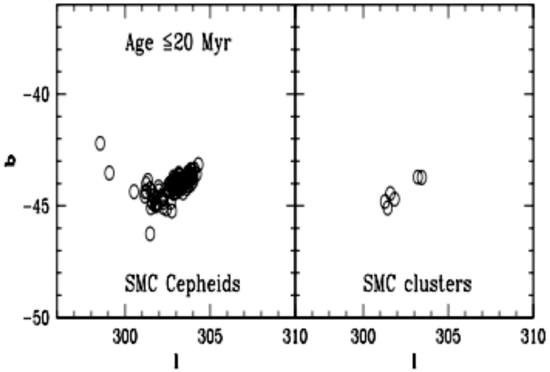
Application to Magellanic Cepheids

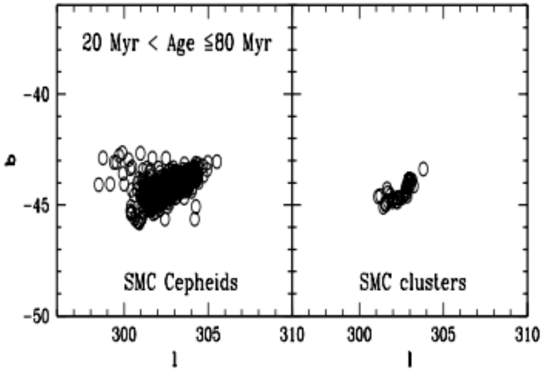
- Applying theoretical PA and PAC to SMC and LMC Cepheids (Marconi et al. 2006) , we obtain

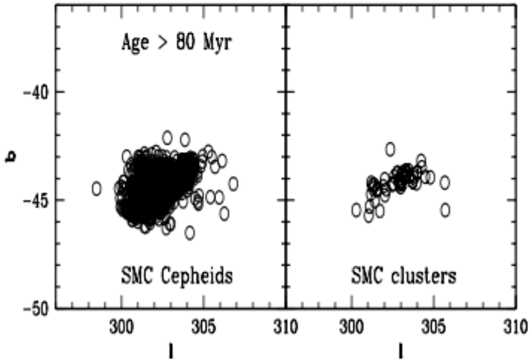










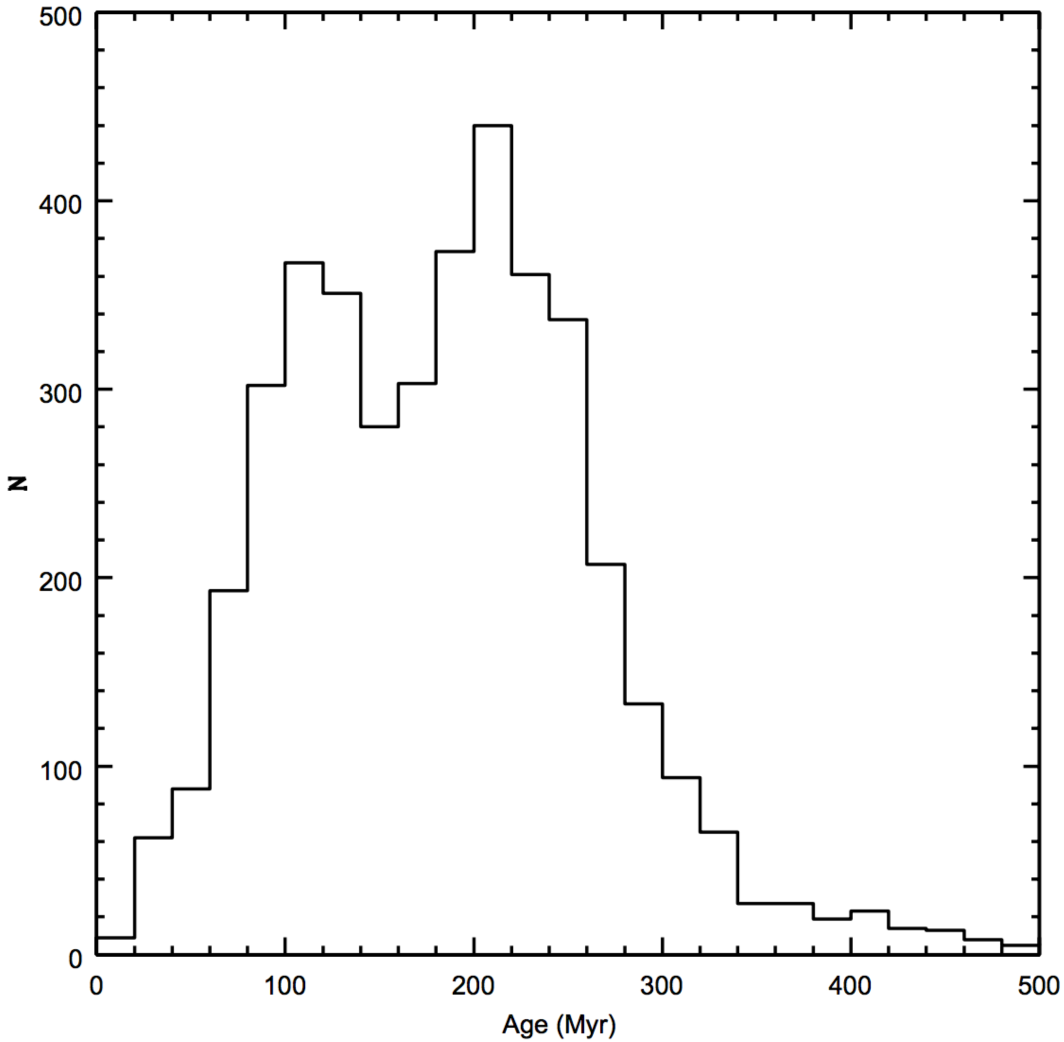


- ➢ Cluster ages estimate with independent method
- ➢ Cepheid age estimates may provide a more detailed picture (with an high spatial resolution) of recent star formation episodes in the MCs.

Age of SMC Cepheids

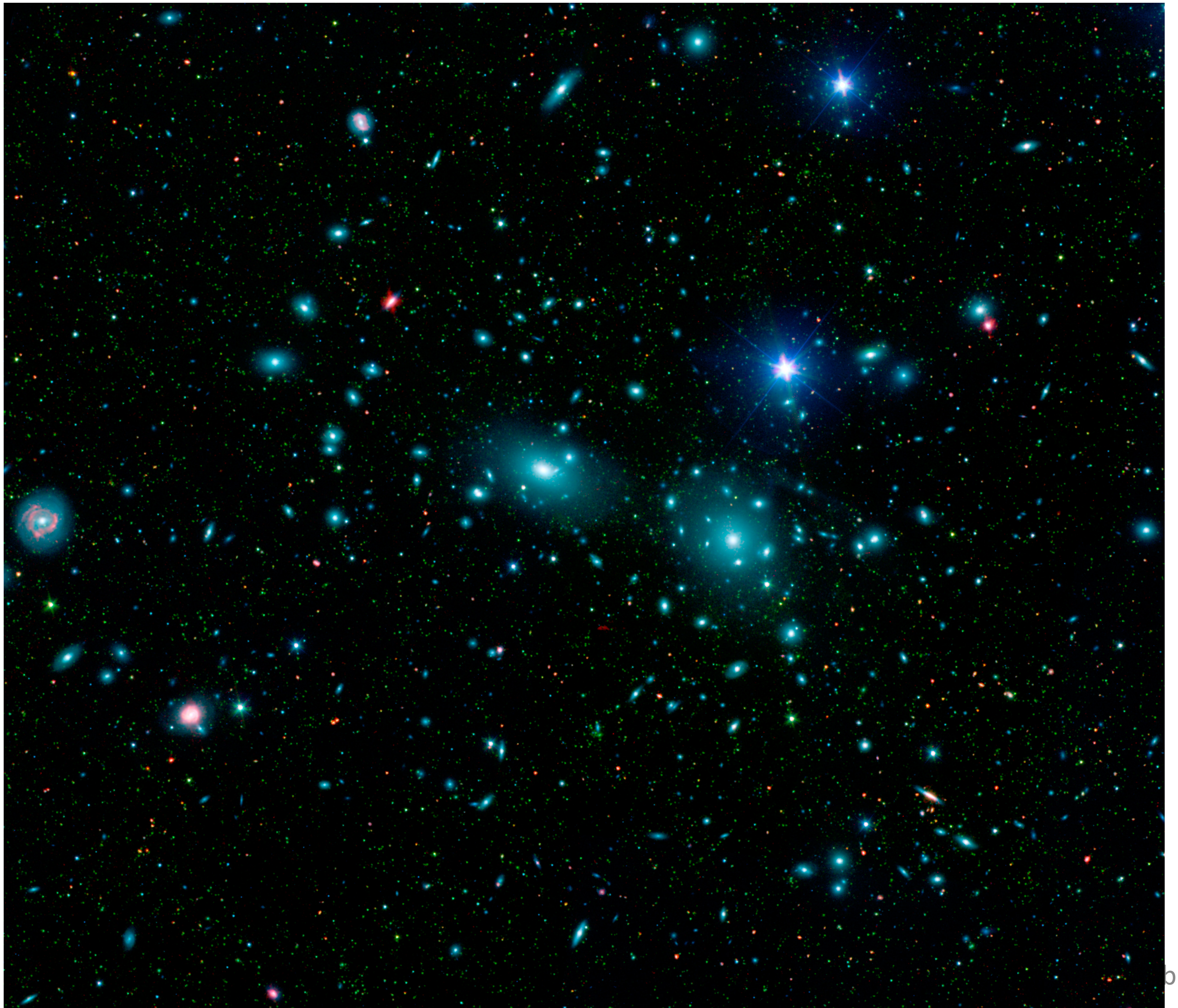
Application of theoretical
Period-Age-Color relations
to the SMC Cepheids
(Bono et al. 2005)

Subramanian &
Subramaniam 2015, A&A



Perspectives for Cepheids with E-ELT

- Reaching COMA in one step



Perspectives for Cepheids with E-ELT

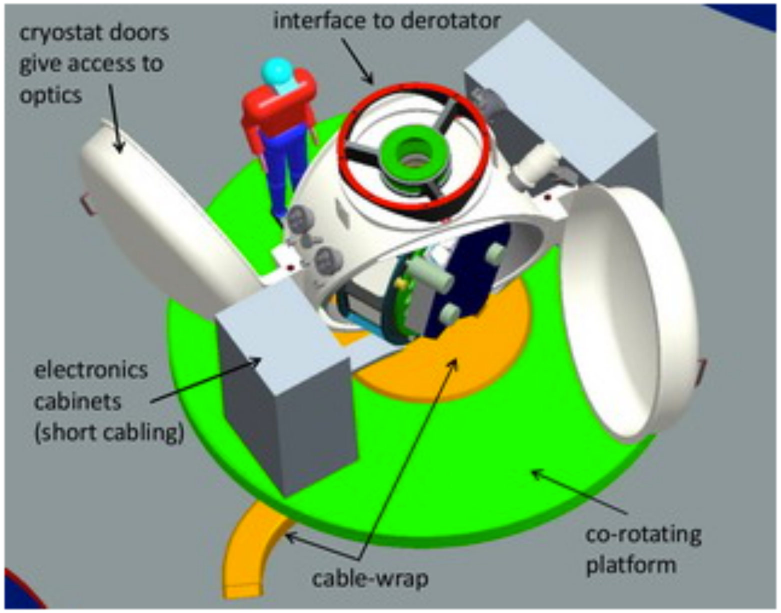
- Reaching COMA in one step

E-ELT CAM (MICADO) →even in crowded fields, opportunity to identify classical Cepheids in the Coma Cluster, and in turn the **opportunity to estimate the Hubble constant only using primary distance indicators!!**

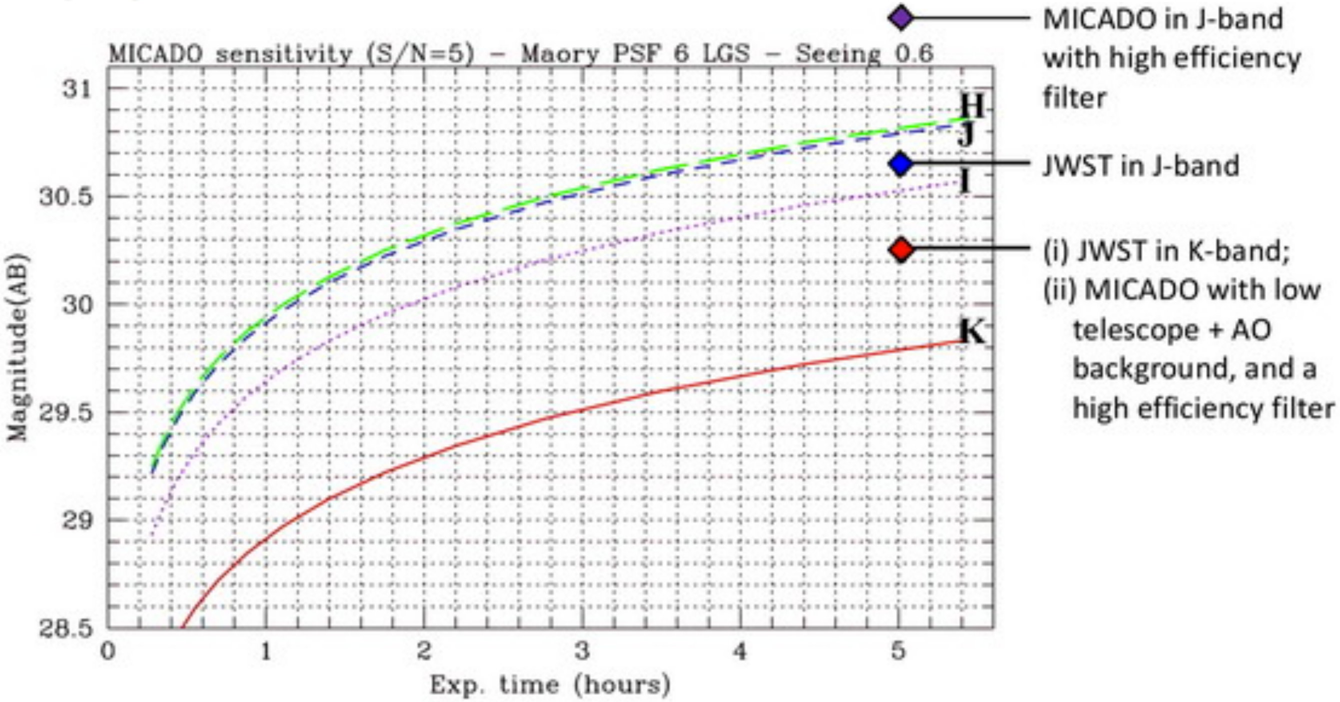
The Coma cluster not affected by peculiar motions, typical of the local Universe ➔estimate of the Hubble constant only using a primary distance indicator

E-ELT CAM: MICADO

Plus SCAO + MAO+MCAO



Overview of MICADO



Broadband imaging sensitivity of MICADO as a function of integration time

Perspectives for Cepheids with ELT

- Fix the metallicity issue

ELT high resolution MOS → spectroscopic characterization (abundances) of large extragalactic Cepheid samples → metallicity effect on the PL outside the MW

Population II pulsating stars

1) They trace the ancient stellar populations and can be used to determine their intrinsic properties.

➔ They allow to identify the oldest stellar populations in a galaxy

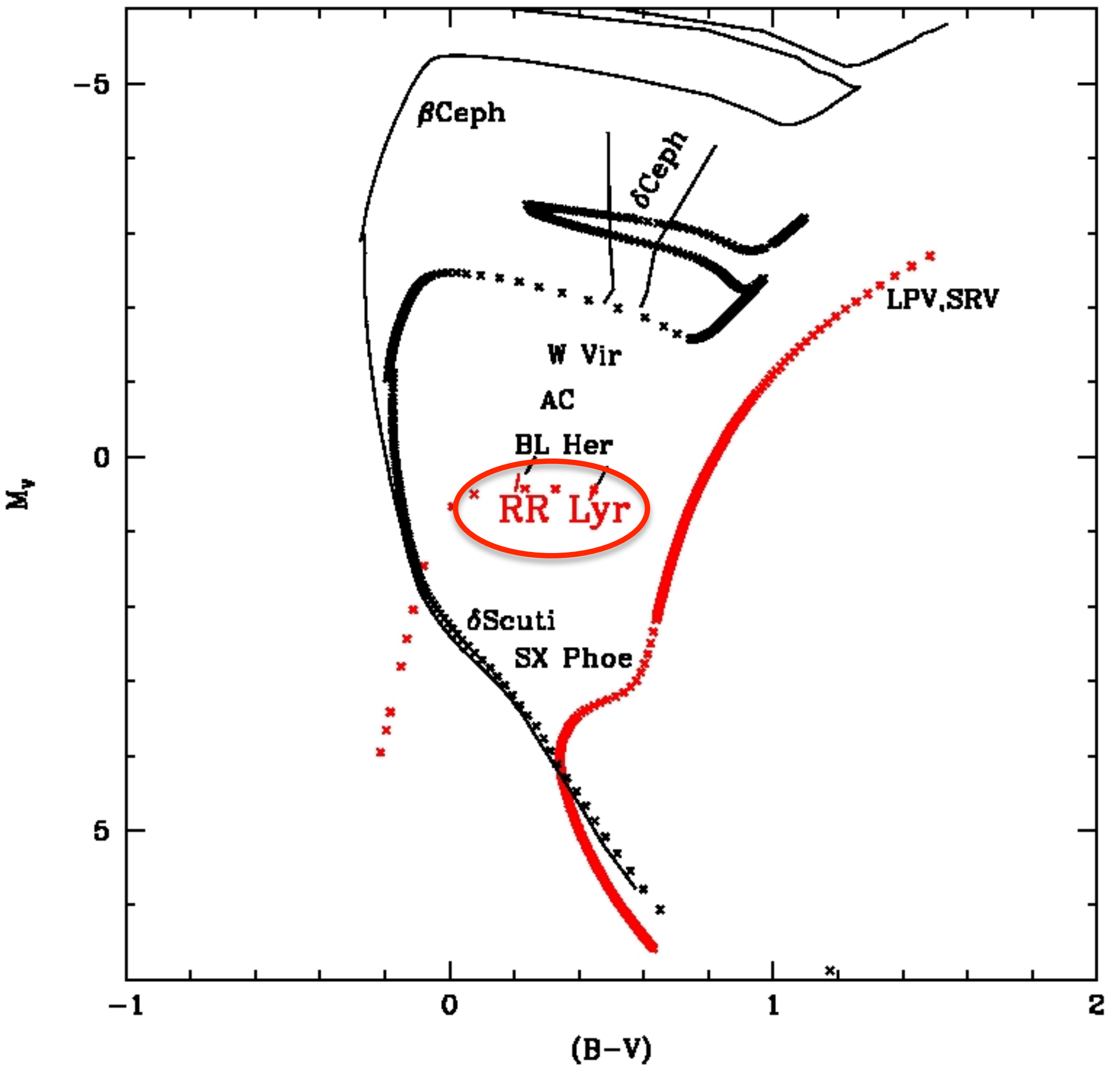
➔ they provide information on the dynamical and chemical properties of the Galactic halo, can be used to trace streams….

2) They represent fundamental standard candles for globular clusters, the Galactic centre, the Milky Way and M31 satellite dwarf galaxies.

➔They can provide an independent estimates of distances to crucial systems: e.g. the LMC…

➔They can in principle be used as alternative calibrators of secondary distance indicators (e.g. the GCLF)

RR Lyrae: general properties



RR Lyrae are low mass Helium burning stars, on the so called ***Horizontal Branch (HB)*** in the HR diagram.

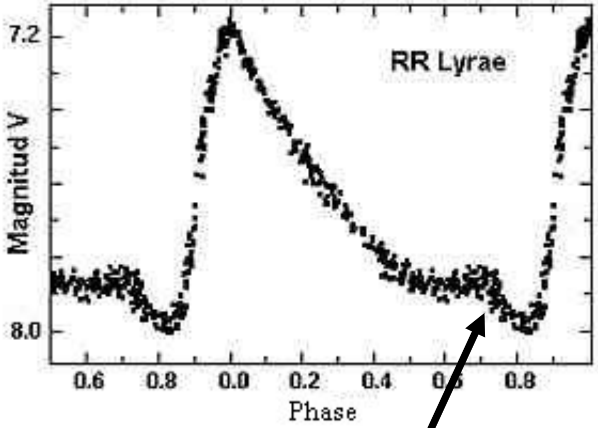
Most abundant class of pulsating stars in the Milky Way
found both in the field and in GCs

P ranges from ~ 0.3 d to ~ 1.0 d

A_V ranges from ~ 0.2 to ~ 1.8 mag

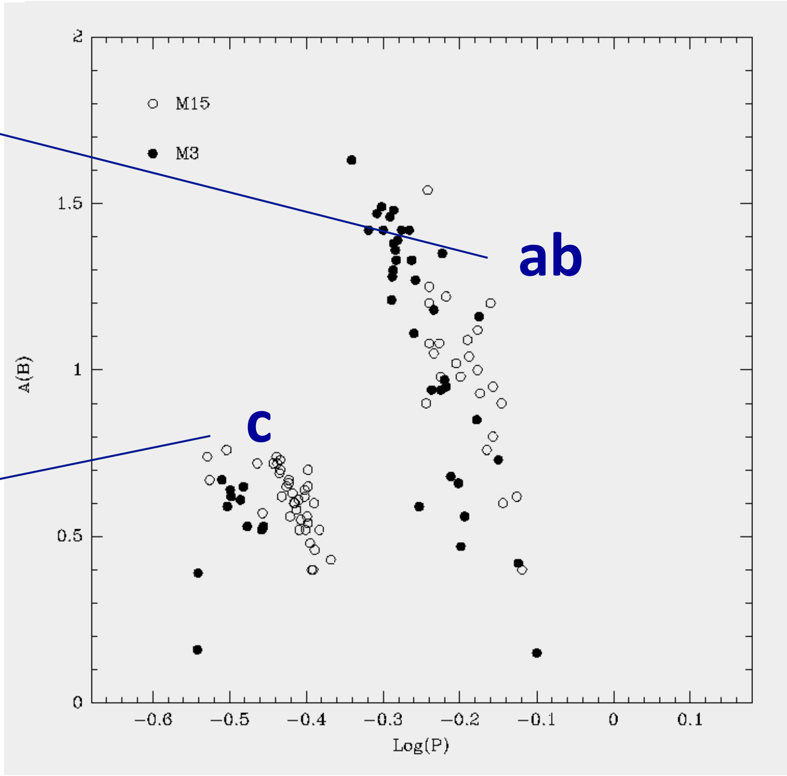
Tracers of the chemical and dynamical properties of old stellar populations

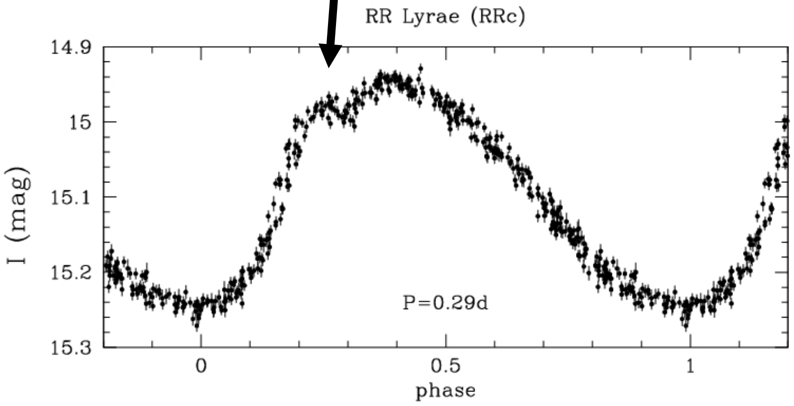
Observed properties of RR Lyrae



Light curve morphology

Bailey diagram

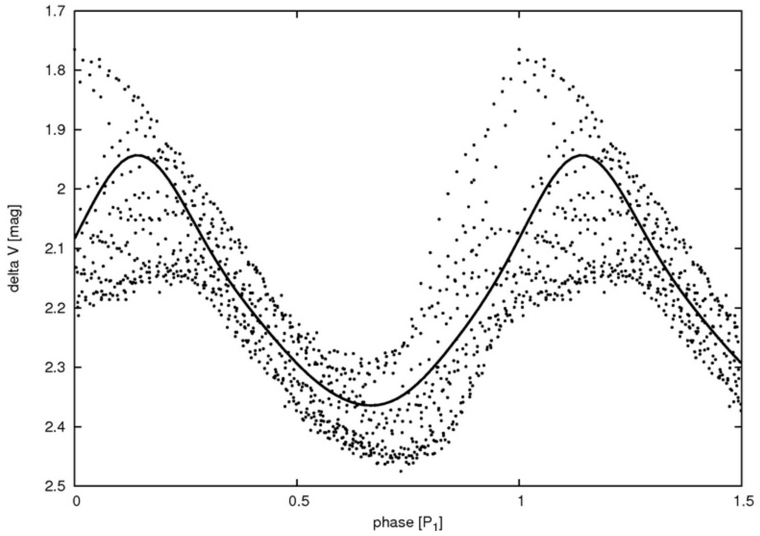




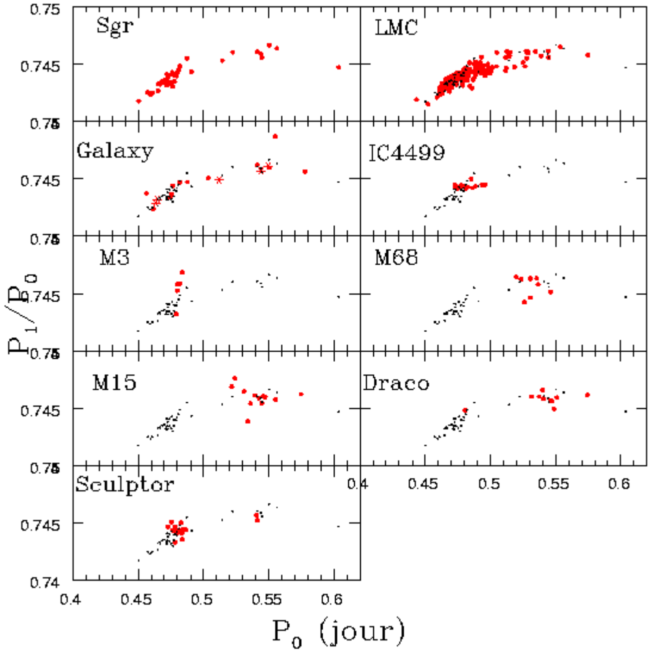
$P < 1$ d $A_V < 2$ mag   ST = A2-F2

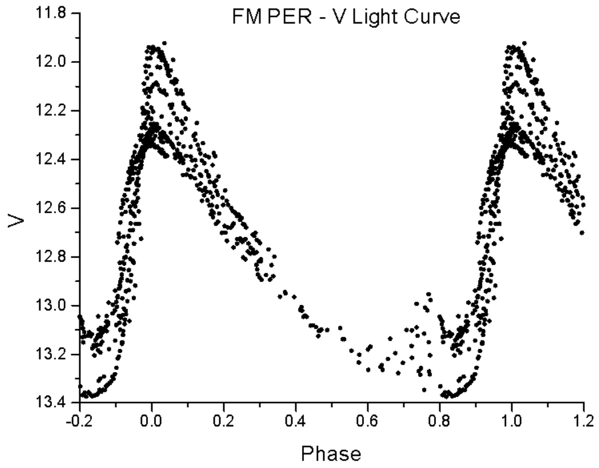
Pop.II, HB phase $M_V = 0\text{-}1$ mag

RRd pulsator



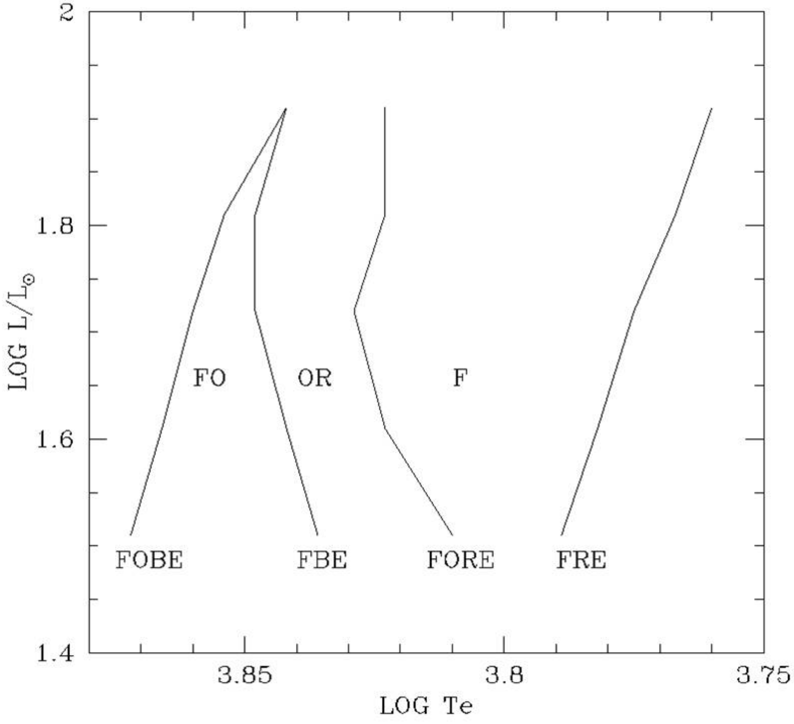
Petersen diagram➔pulsation mass

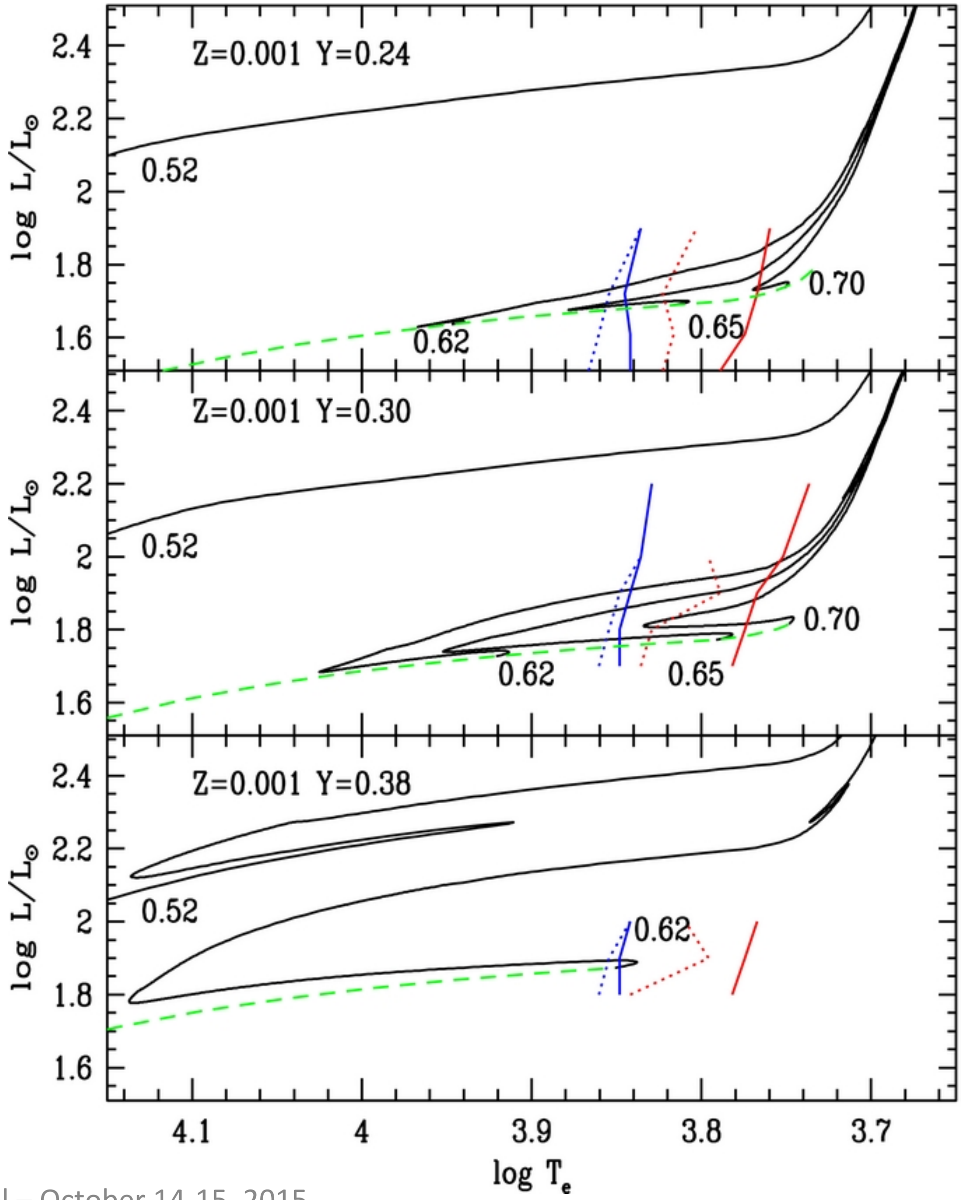




Blazhko effect: modulation on a longer time-scale

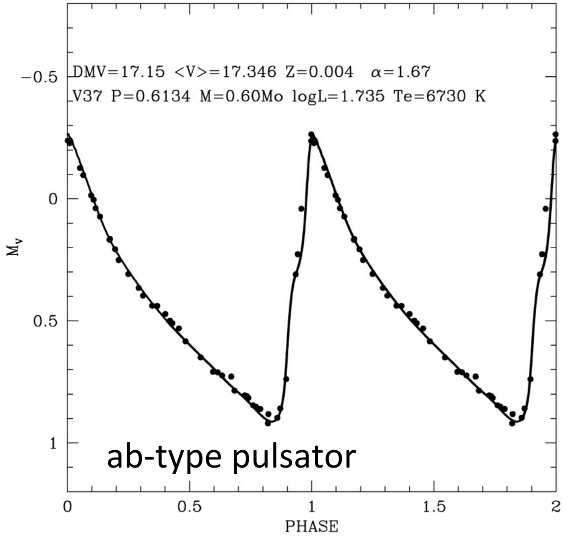
Results of nonlinear convective pulsation models: the strip

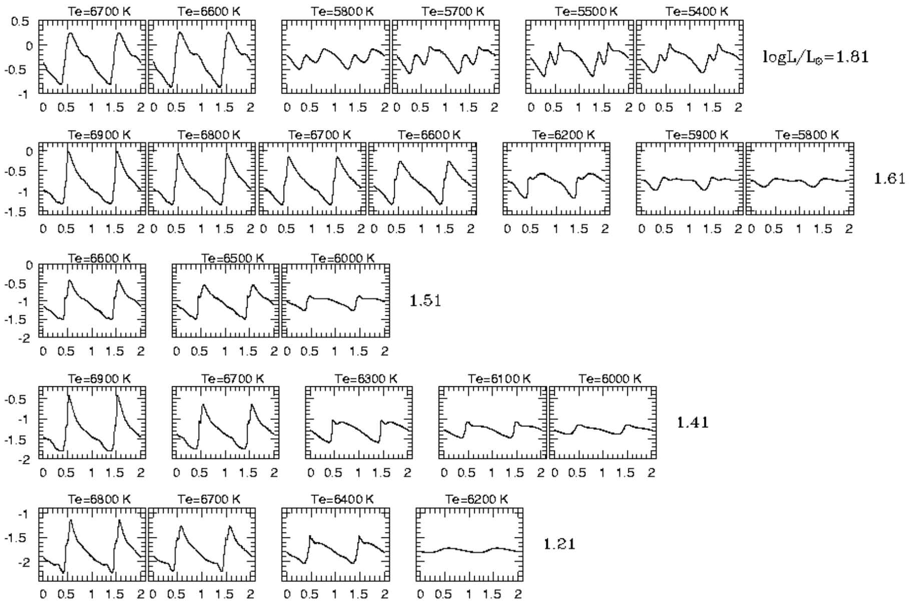


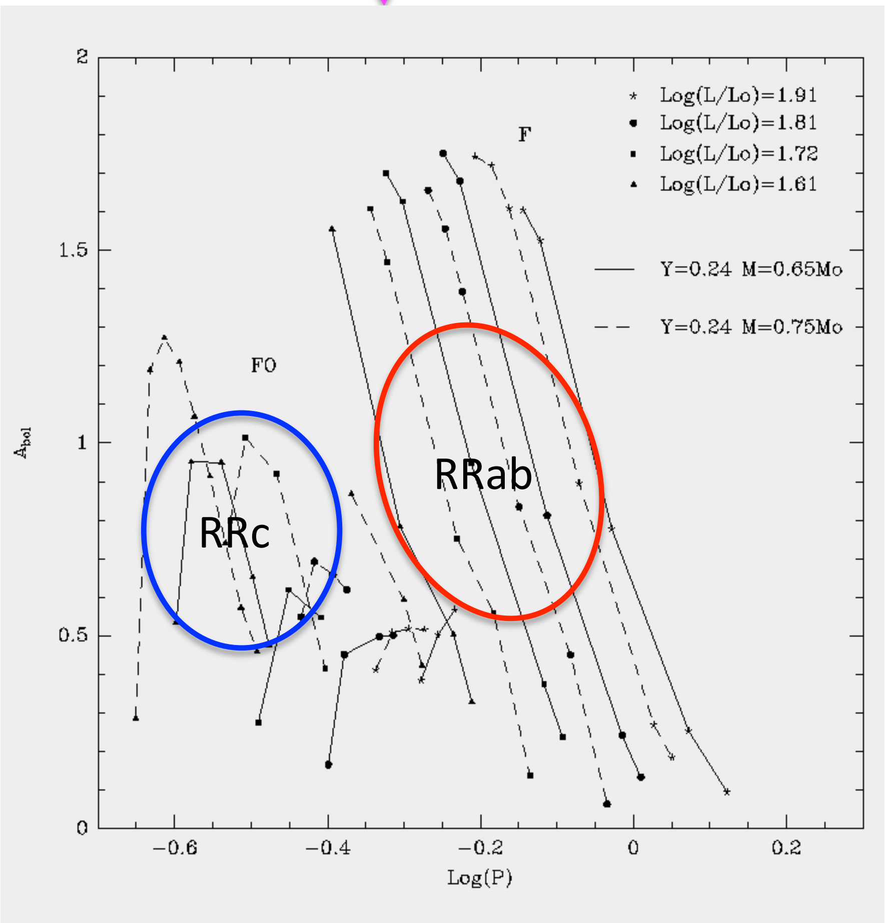


Bono, Caputo & Marconi 1995 ApJL
Bono et al. 1997 A&AS,
Marconi et al. 2003 ApJ
Di Criscienzo et al. 2004 ApJ
Marconi et al. 2011 ApJ

Results of nonlinear convective pulsation models: the light curves and the Bailey diagram

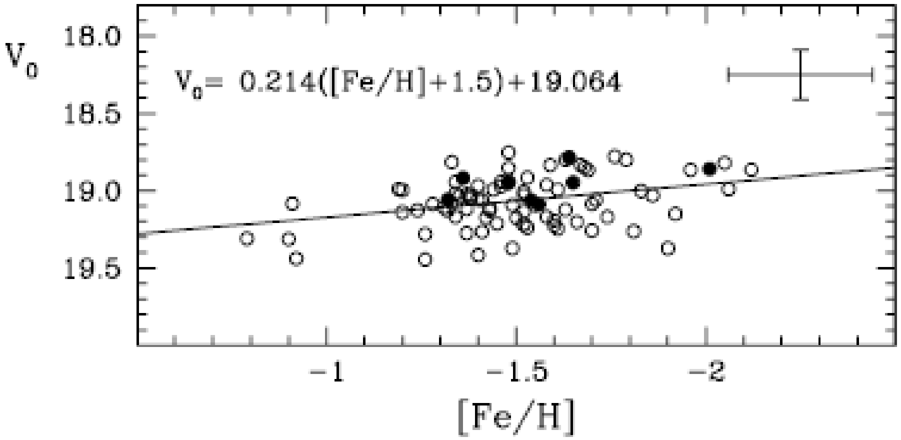




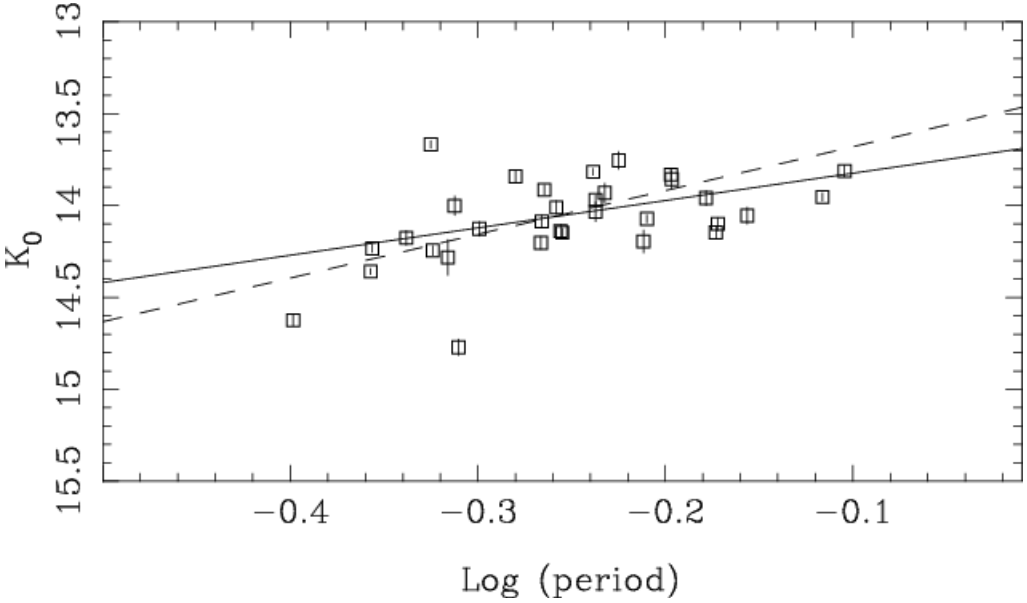


RR Lyrae as primary distance indicators

V-[Fe/H] relation



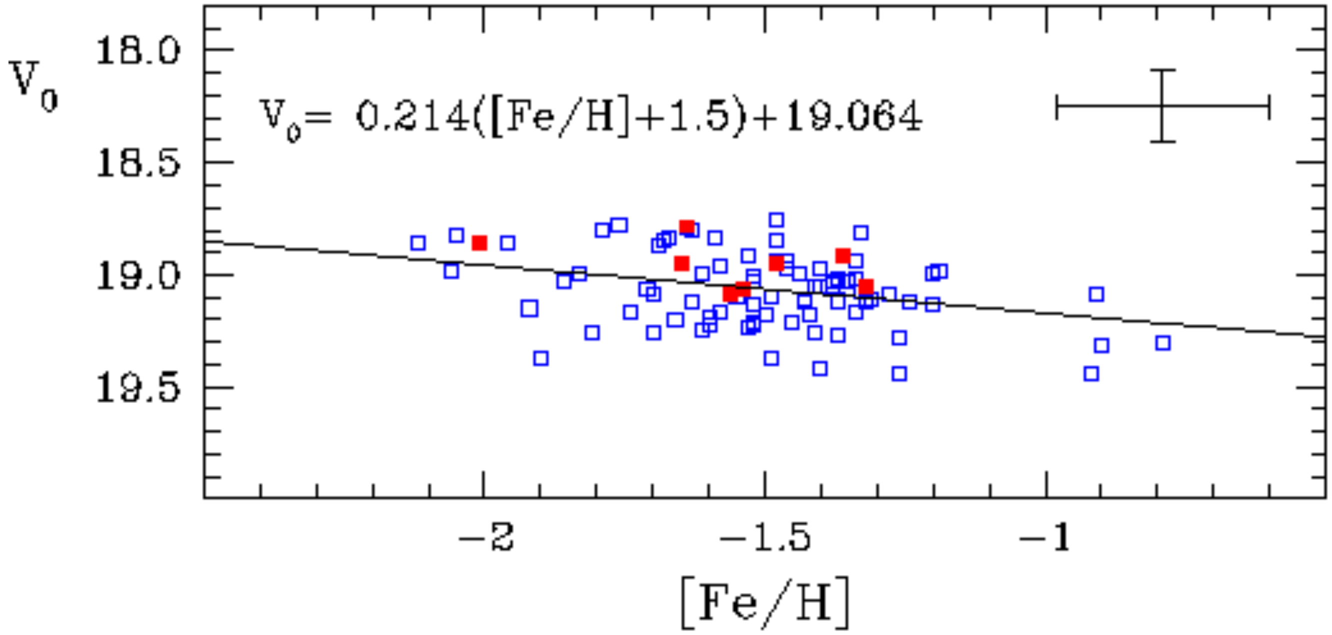
K-logP relation



The M_V-[Fe/H] relation

Usually linear $M_V(RR) = a\,[Fe/H] + b$

$0.13 < a < 0.30$ $0.5 < b < 1.0$



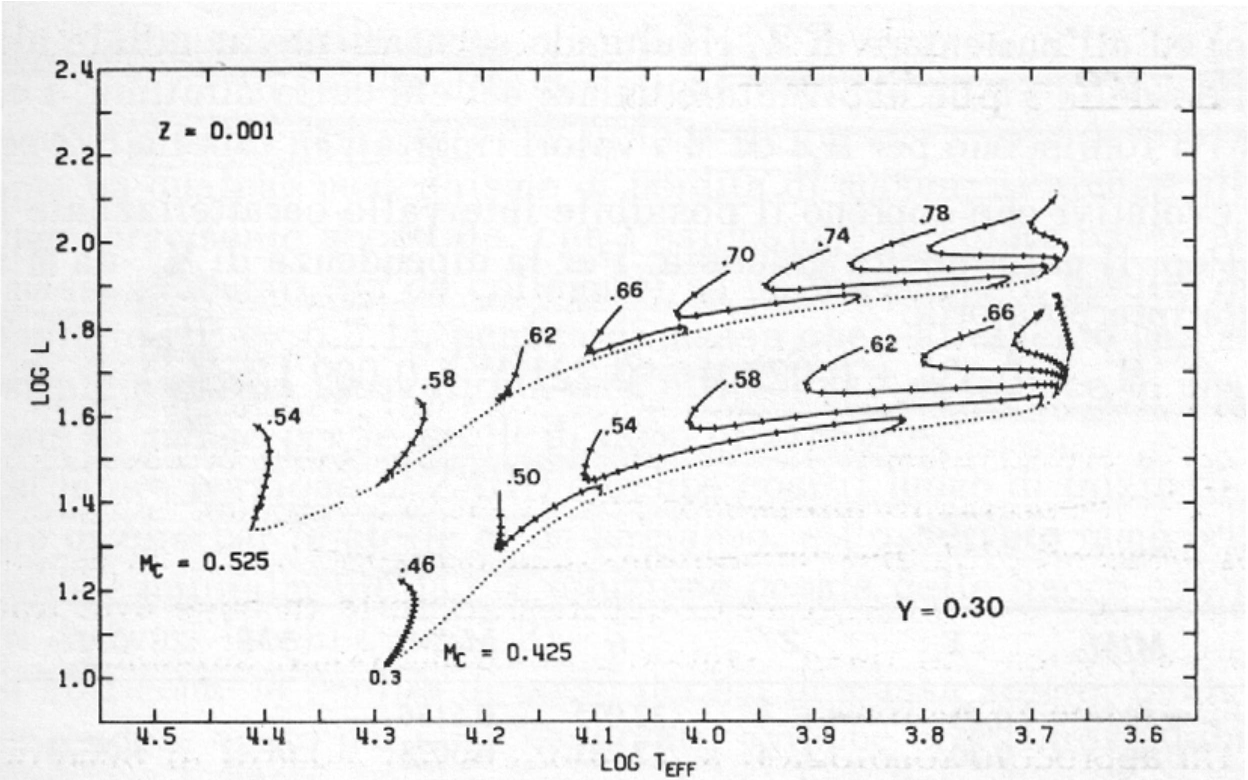
Of particular interest for RR Lyrae in globular clusters

(b → absolute ages a → relative ages)

Problems of the M_V(RR)-[Fe/H] relation

Definition of M_V(RR): lower envelope of RR Lyrae distribution?
average magnitude of RR Lyrae?
any other?

Please remember that evolutionary effects are at work !!



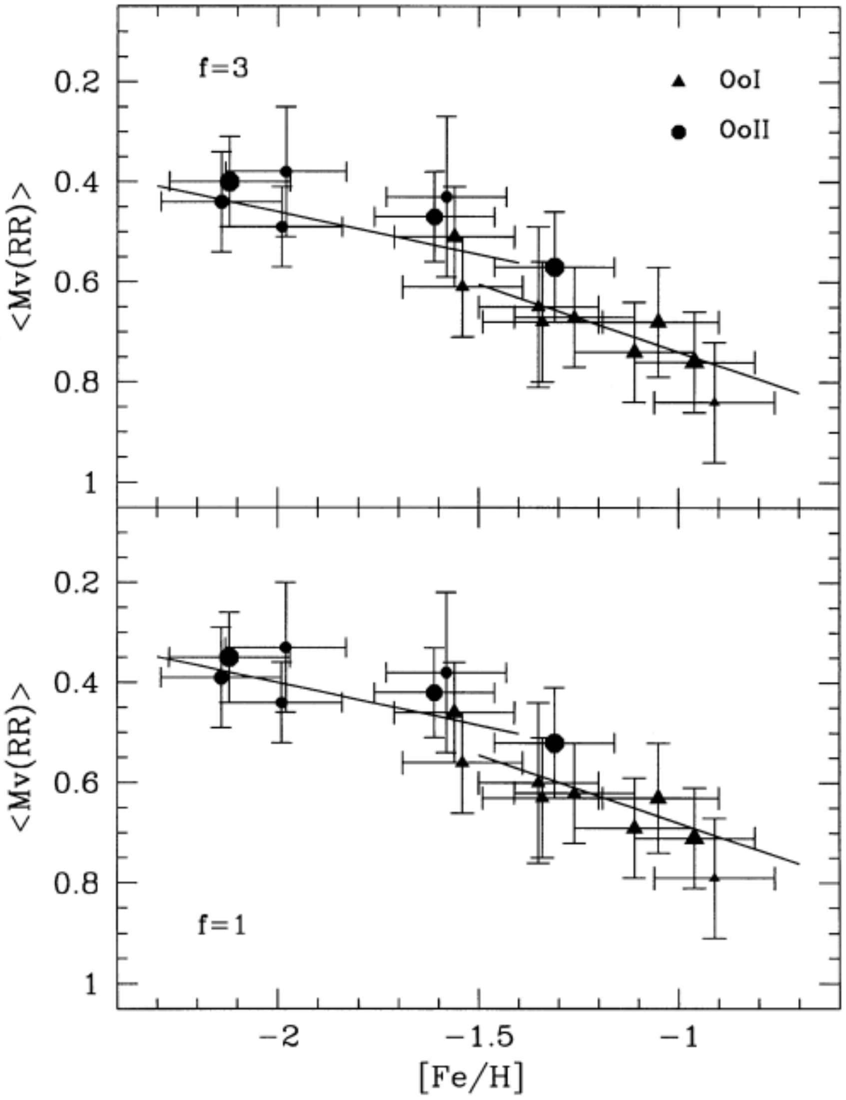
Problems of the M_V(RR)-[Fe/H] relation

The individual M_V(RR) are mean magnitudes different from static ones   (be careful when comparing with M_V(ZAHB) or M_V(HB))

As for the metallicity term the α element enhancement has to be taken into account and there is a non negligible dependence on the adopted metallicity scale.

Results of stellar evolution and pulsation models suggest a NON linear relation when the whole observed metallicity range is considered

The theoretical M_V(RR)-[Fe/H] relation



For Fe/H]<−1.5 and [Fe/H]>−1.5

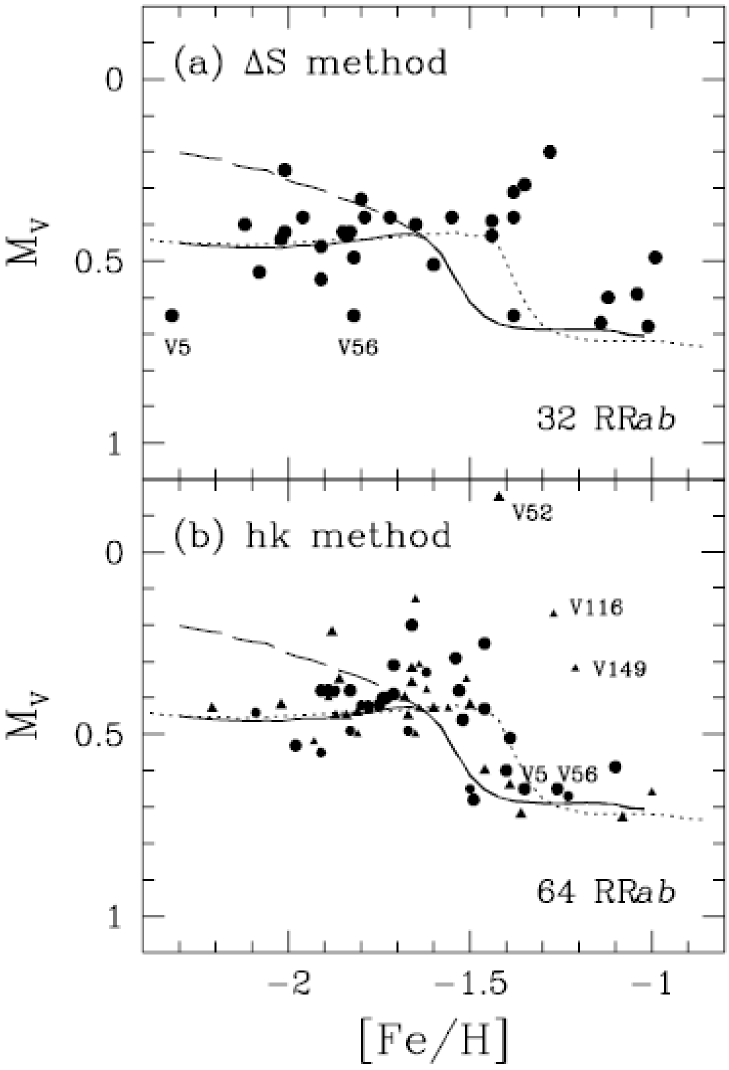
$\langle MV(RR)\rangle=0.71(\pm0.10)+(0.17\pm0.04)[Fe/H]+0.03f$

and

$\langle MV(RR)\rangle=0.92(\pm0.12)+(0.27\pm0.06)[Fe/H]+0.03f$

respectively

(Caputo, Castellani, Marconi, Ripepi 2000 MNRAS)



Rey et al. 2000 AJ

Some empirical results support the cut off at [Fe/H]=1.5 dex

Problems of the M_V(RR)-[Fe/H] relation

The individual M_V(RR) are mean magnitudes different from static ones (be careful when comparing with M_V(ZAHB) or M_V(HB))

As for the metallicity term the α element enhancement has to be taken into account and there is a non negligible dependence on the adopted metallicity scale.

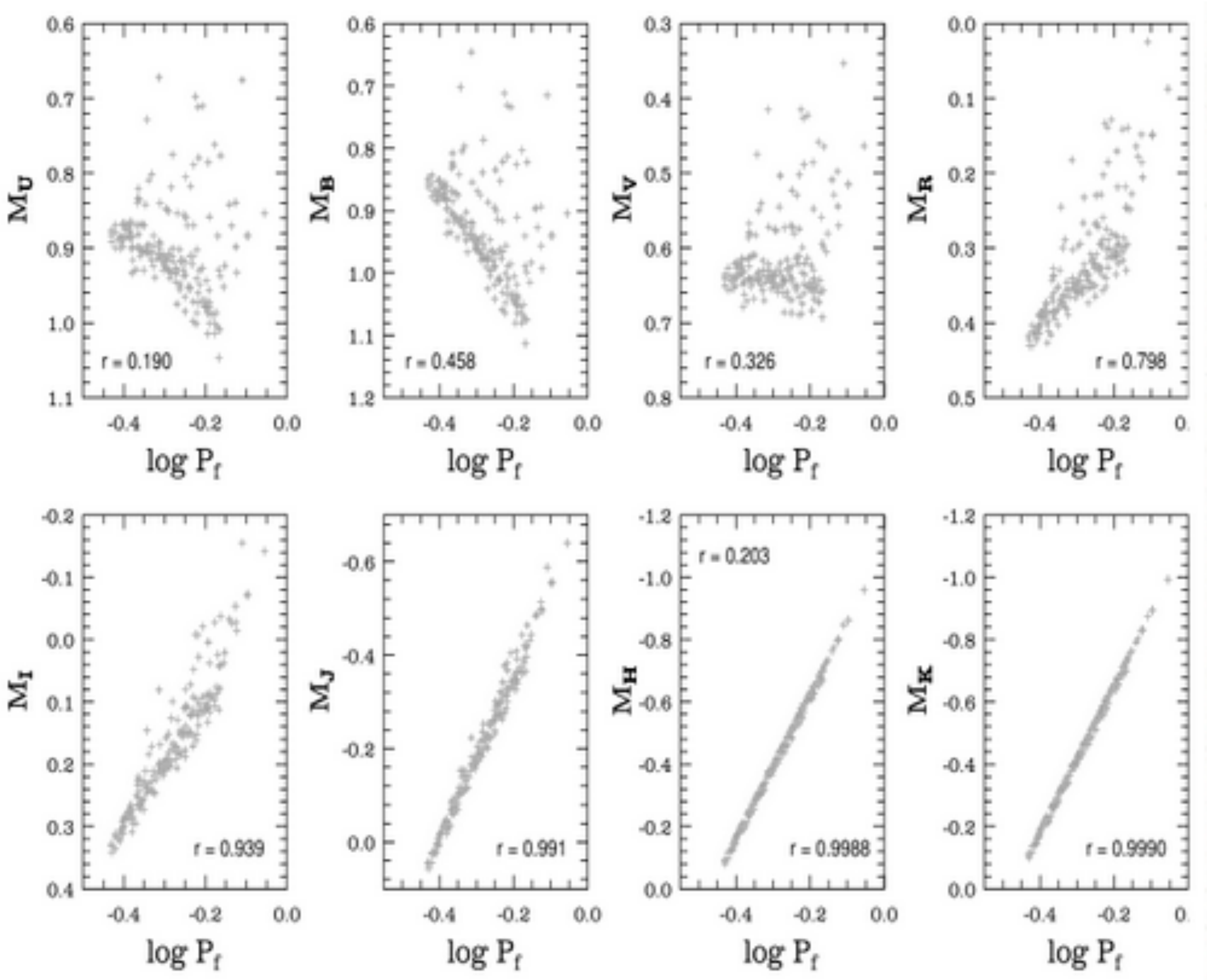
Results of stellar evolution and pulsation models suggest a NON linear relation when the whole observed metallicity range is considered

Note also that M_V(RR) is affected by the He content.
If Y increases from 0.24 to 0.38 at Z=0.001 the predicted logL/$L_{/}$ increases by about 0.2 dex

In the NIR bands and in particular in K (2.2 µm) RR Lyrae obey to a PL relation

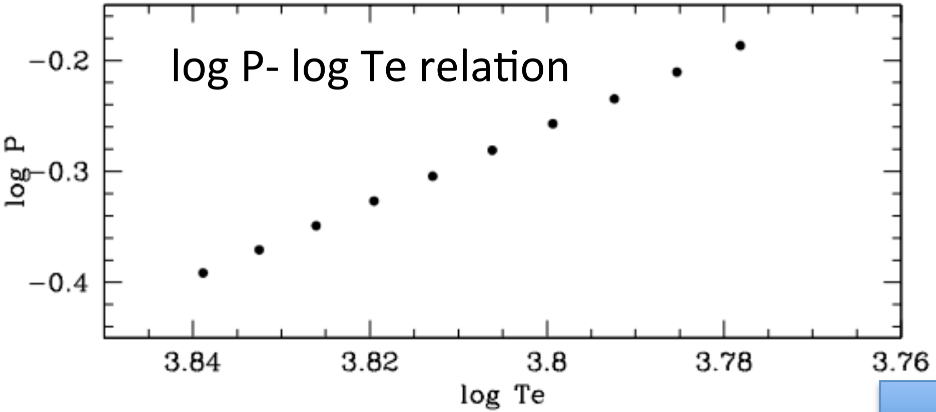
(since the pioneering investigations by Longmore et al. 1986, 1990 MNRAS)

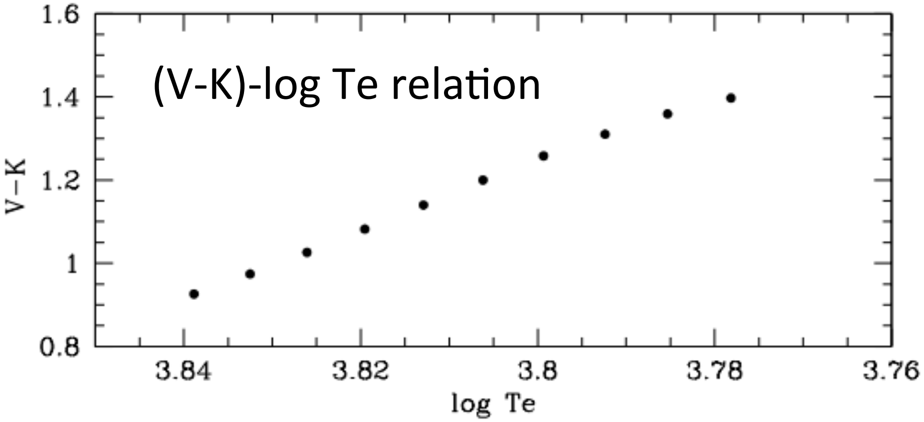
RR Lyrae PL relation

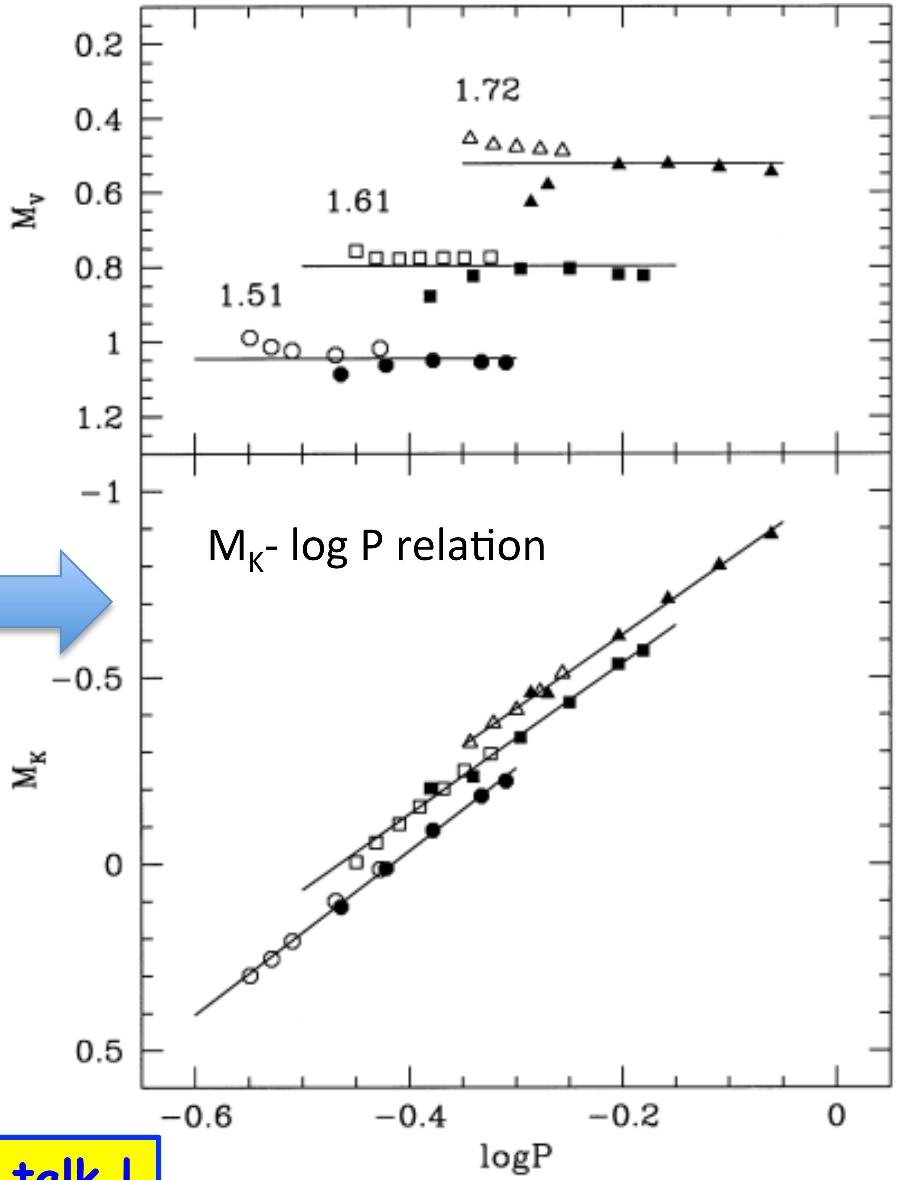


Catelan 2004

Why a PL(K)? The theoretical answer

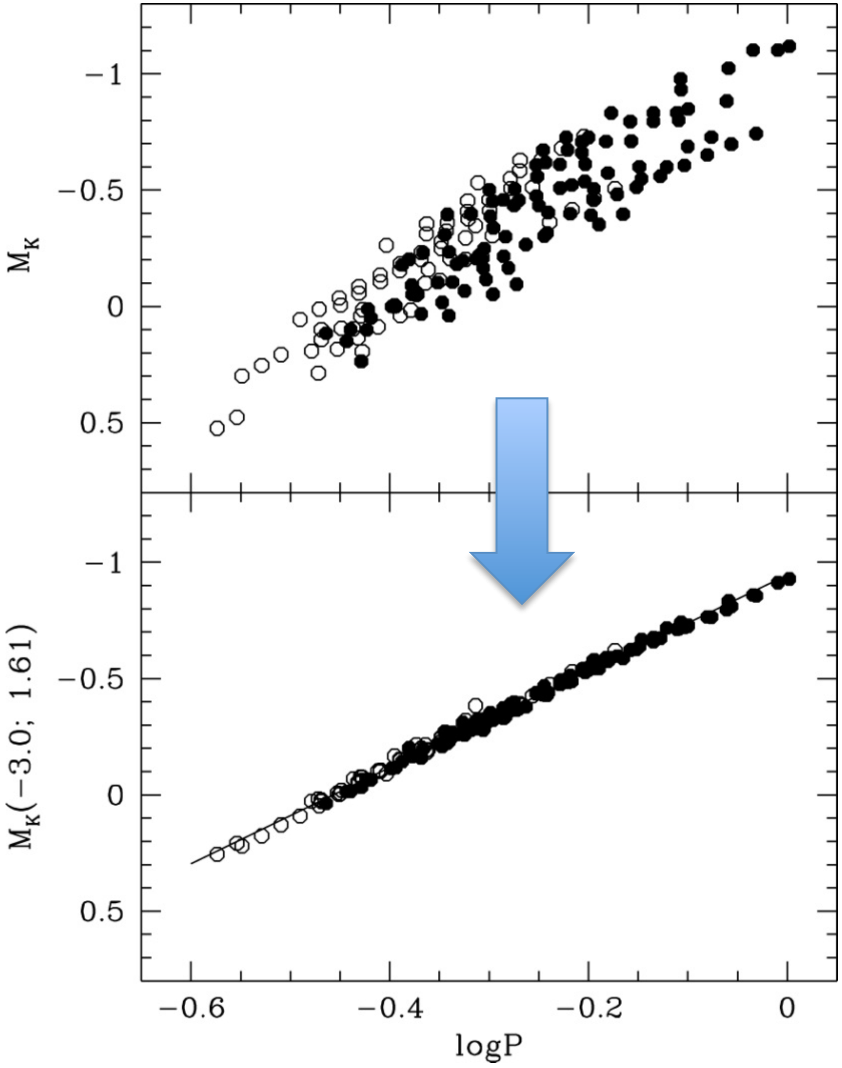






See also M. Dall'Ora's talk !

Theory predicts a metallicity term



Bono et al. 2001 MNRAS

Correcting for metallicity differences and evolutionary effects the dispersion is significantly decreased !

The true relation is of the form

$M_K = a + b \log P + c\,[Fe/H]$

Derivations of the PL_KZ relation

Tight PLZ_K relation (σ~0.05 mag) but…..

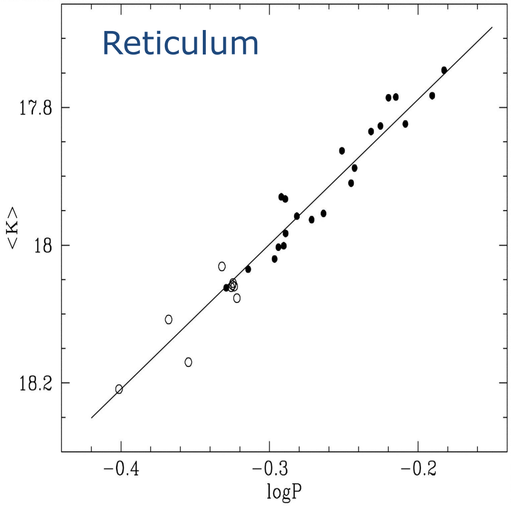
M_K=-2.101 logP+0.231[Fe/H] – 0.77 (Bono et al. 2003)

M_K=-2.353 logP+0.175logZ – 0.597 (Catelan et al. 2004)

M_K=-2.38 logP+0.08[Fe/H] – 1.07 (Sollima et al. 2008)

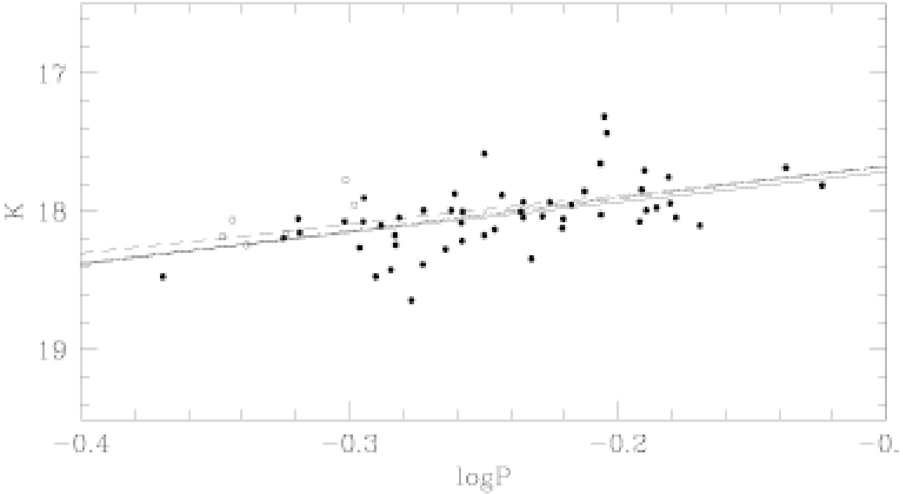
➔Significant uncertainty on the coefficients and in particular on the metallicity term (!)

Some calibrations of the LMC distance scale based on the PL_KZ relation



$\mu_{\mathrm{Reticulum}} = 18.52 \pm 0.005(\mathrm{rand}) \pm 0.117(\mathrm{sys})$

Dall'Ora et al. 2004



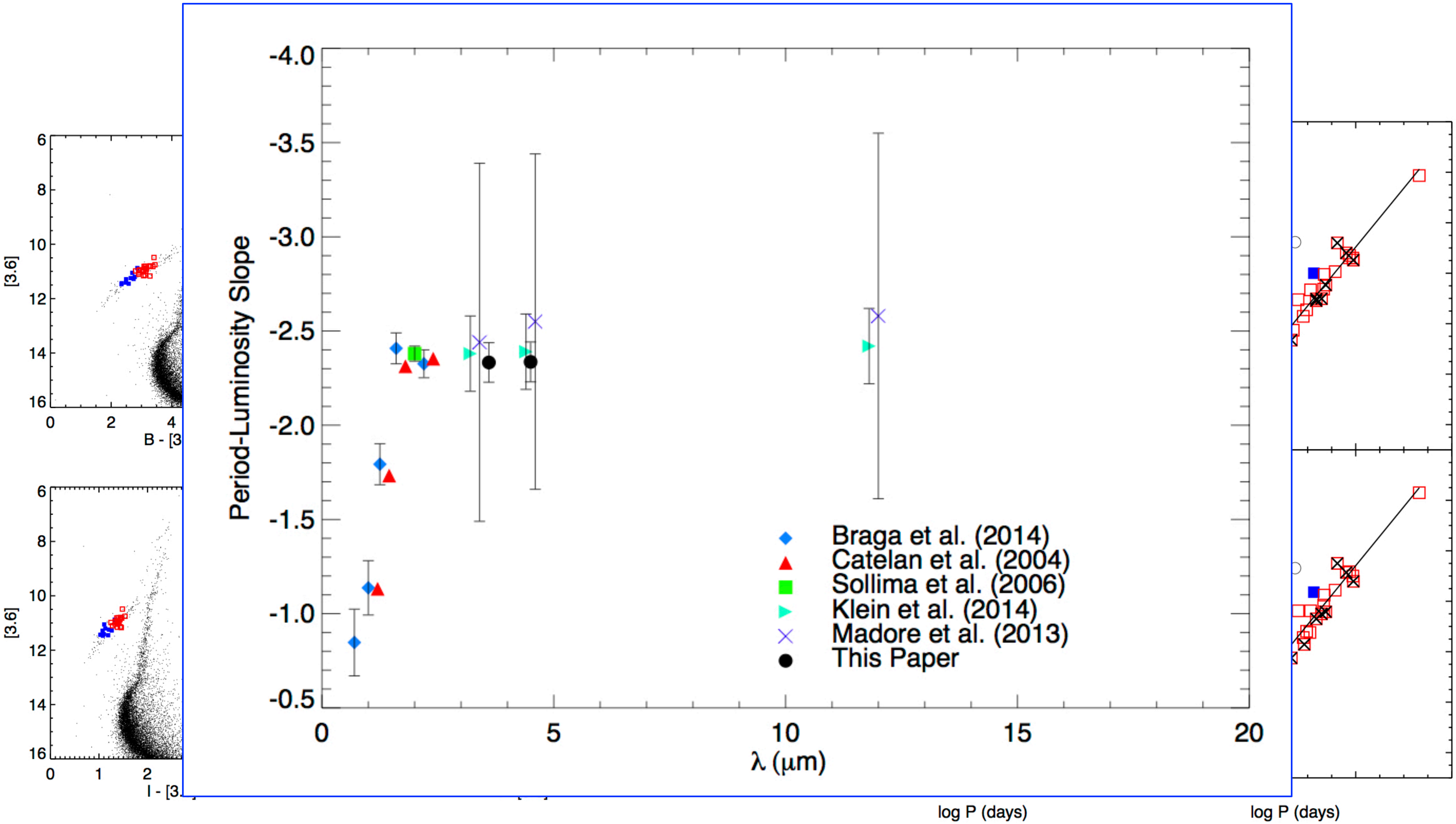
$\mu_{\mathrm{LMC}} = 18.58 \pm 0.03(\mathrm{stat})\ \mathrm{mag} \pm 0.11(\mathrm{sys})$

Szewczyk et al.2008

From the PLKZ relation based on the Magellanic Cloud Survey with VISTA (see T. Muraveva talk) ➔ 18.6-18.7 mag !! (compared with the 18.46±0.03 mag obtained from Cepheids !!)

What happens in the MIR ?

RR Lyrae PL relations in the MIR filters



Neeley et al. 2015 ApJ

Do RR Lyrae obey to Wesenheit relations?

The new metal-dependent PL and WESENHEIT relations for RR Lyrae:
model predictions and applications to observations

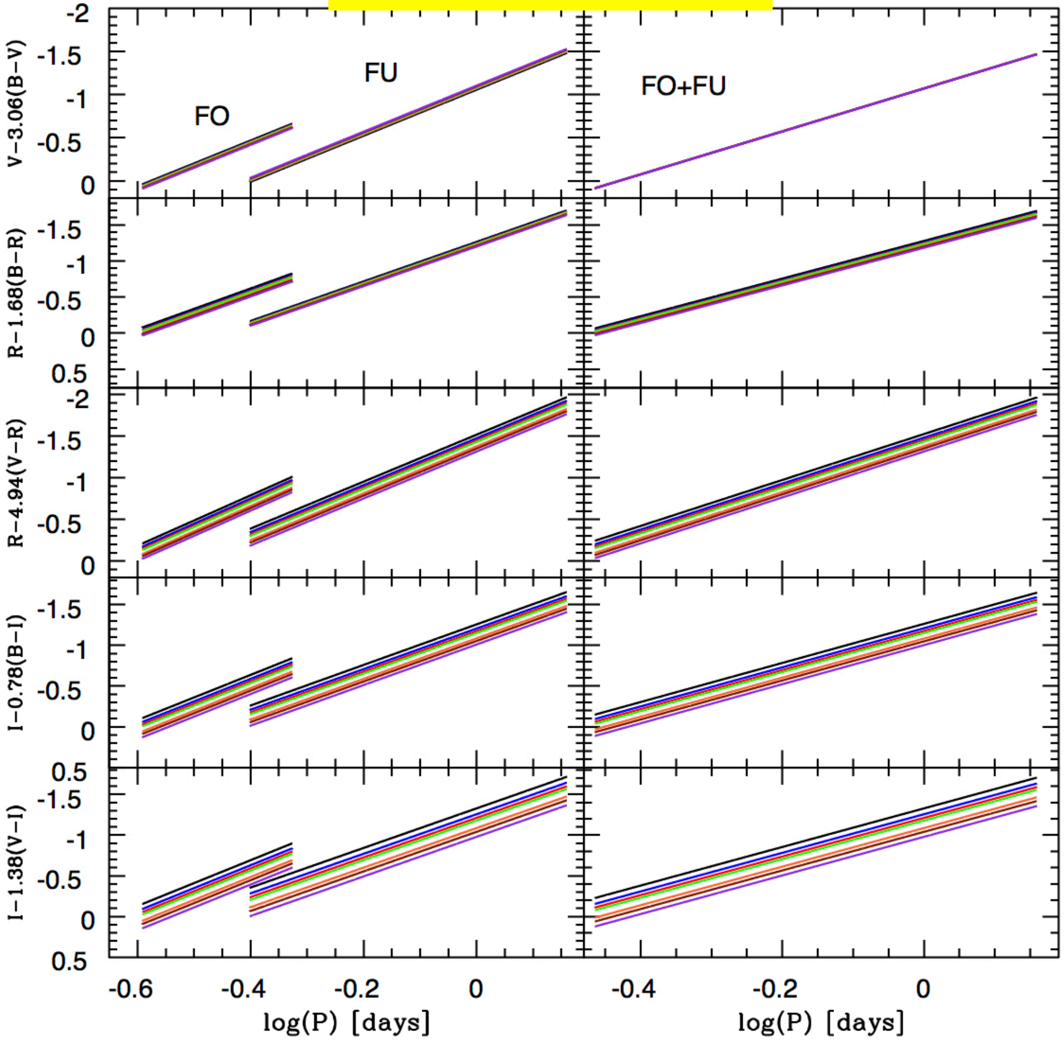
Z=0.0001, 0.0003, 0.0006, 0.001, 0.004, 0.008, 0.02

M_{ZAHB} $\log L_A = \log L_{ZAHB}$
$\log L_B = \log L_{ZAHB} + 0.1$ dex
$\log L_D = \log L_{exhaustion}$

M lower by 10%
$\log L_C = LOG_{LZAHB} + 0.2$ dex

Marconi et al. 2015 ApJ

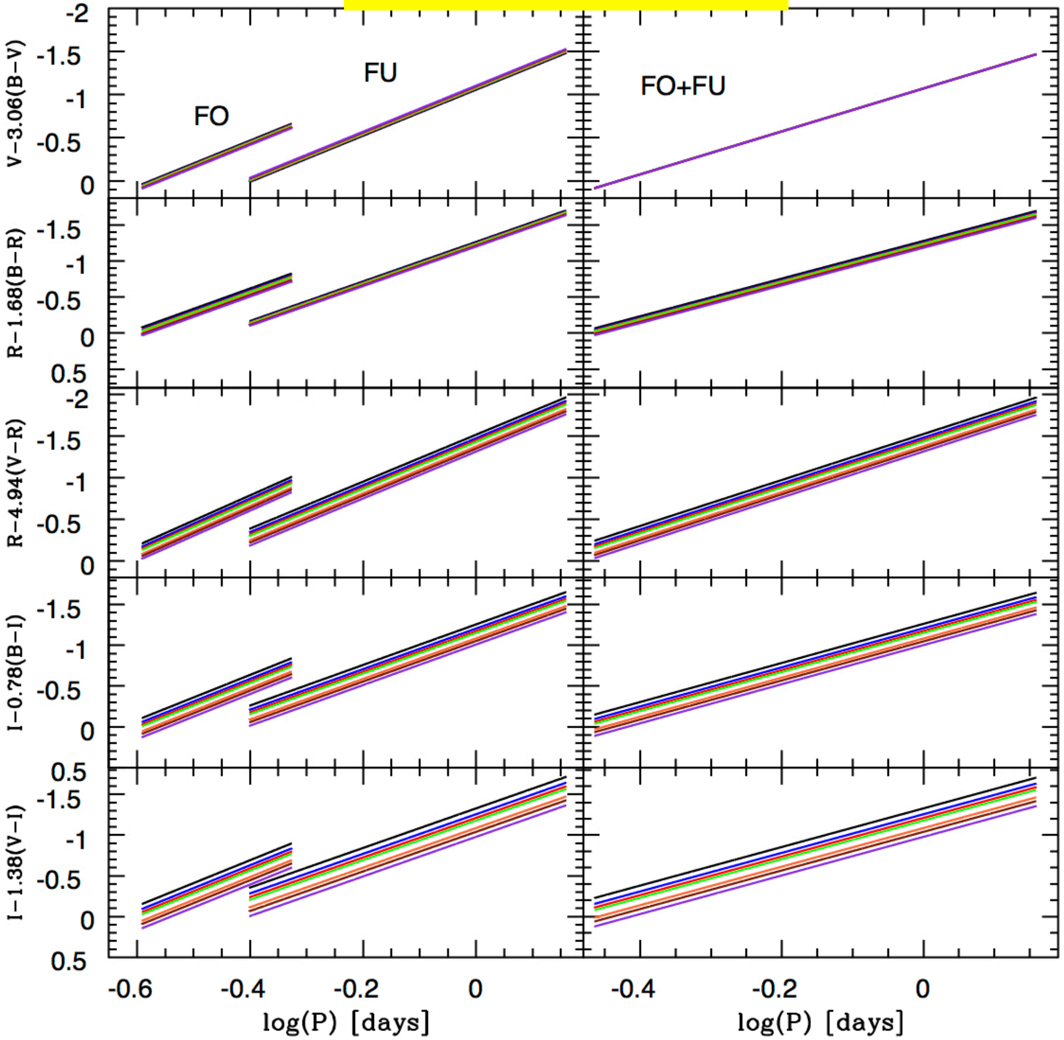
Wesenheit relations



The new metal-dependent PL and WESENHEIT relations for RR Lyrae:
model predictions and applications to observations

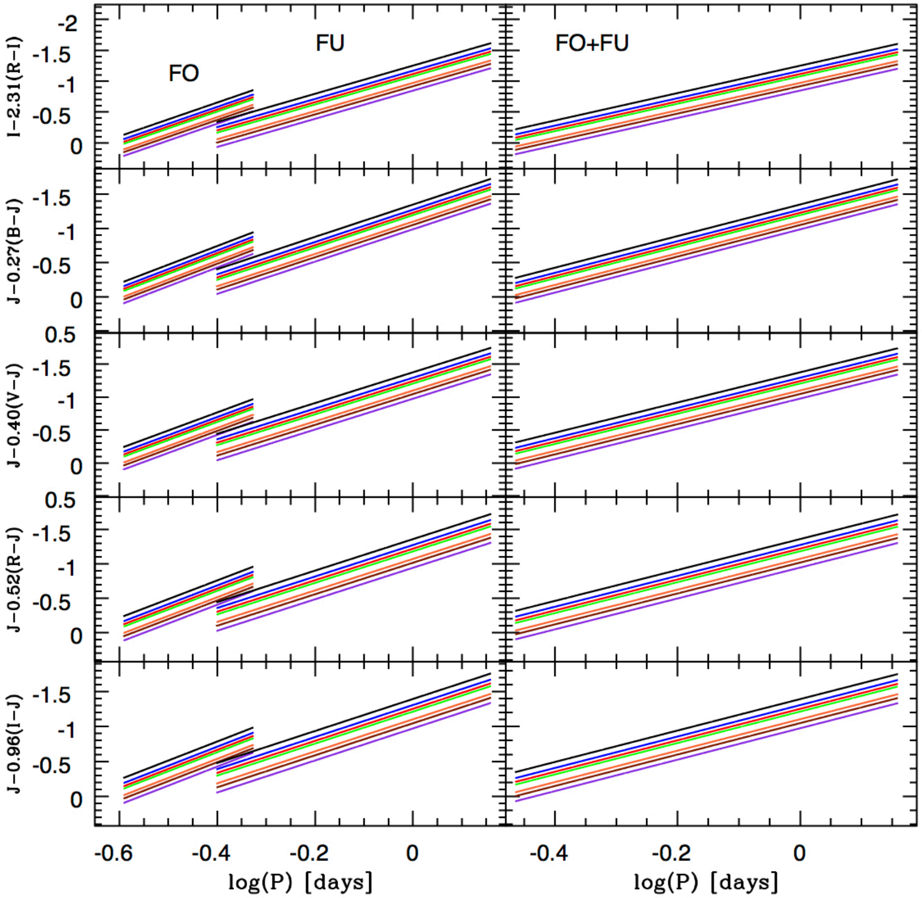
Wesenheit relations

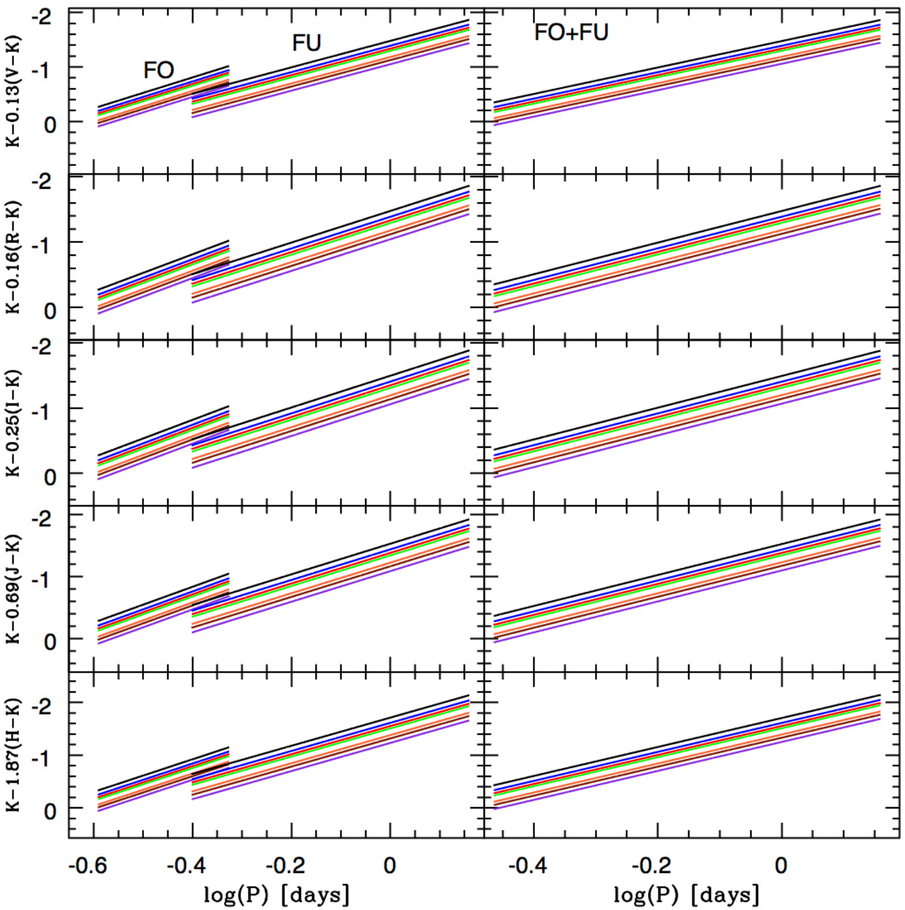
B,B-V Wesenheit is **not** sensitive to metallicity !!!



Marconi et al. 2015 ApJ

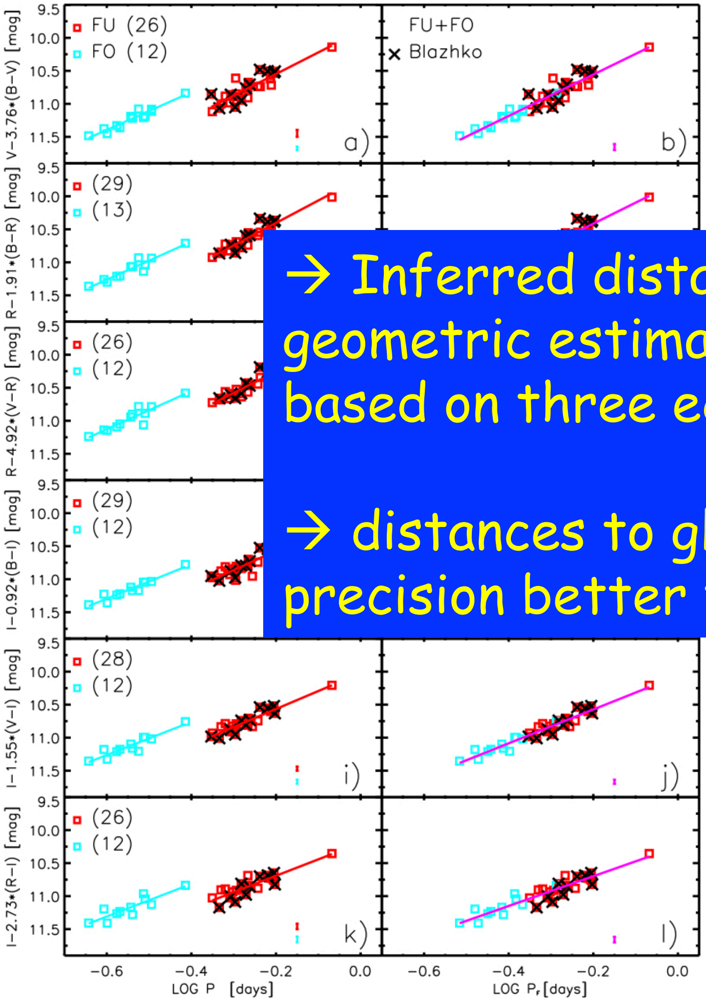
Wesenheit relations

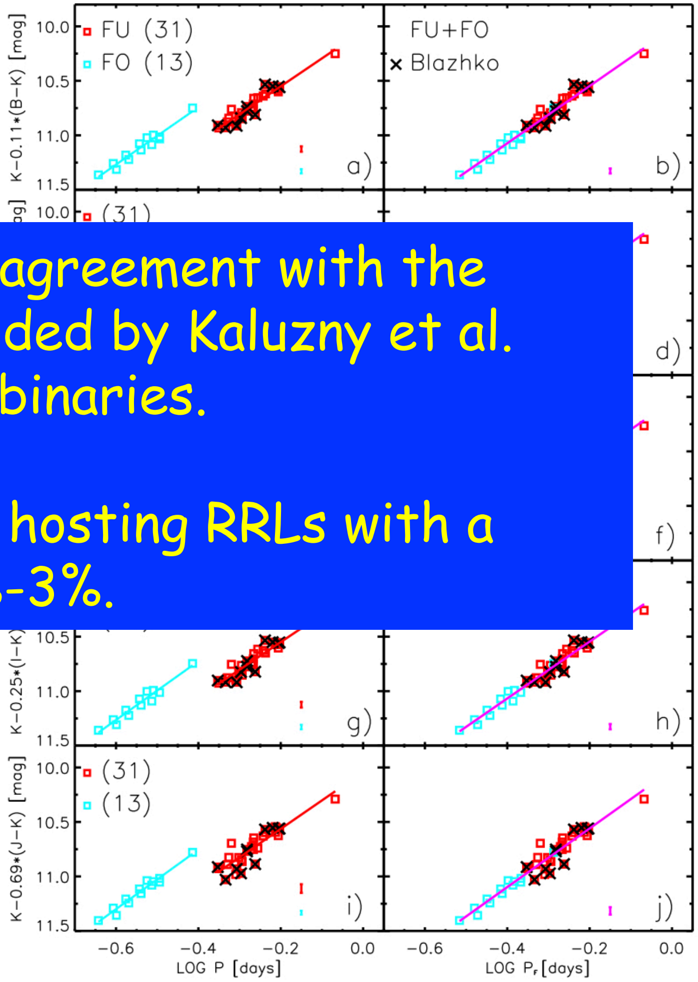




Marconi et al. 2015 ApJ

The case of M4



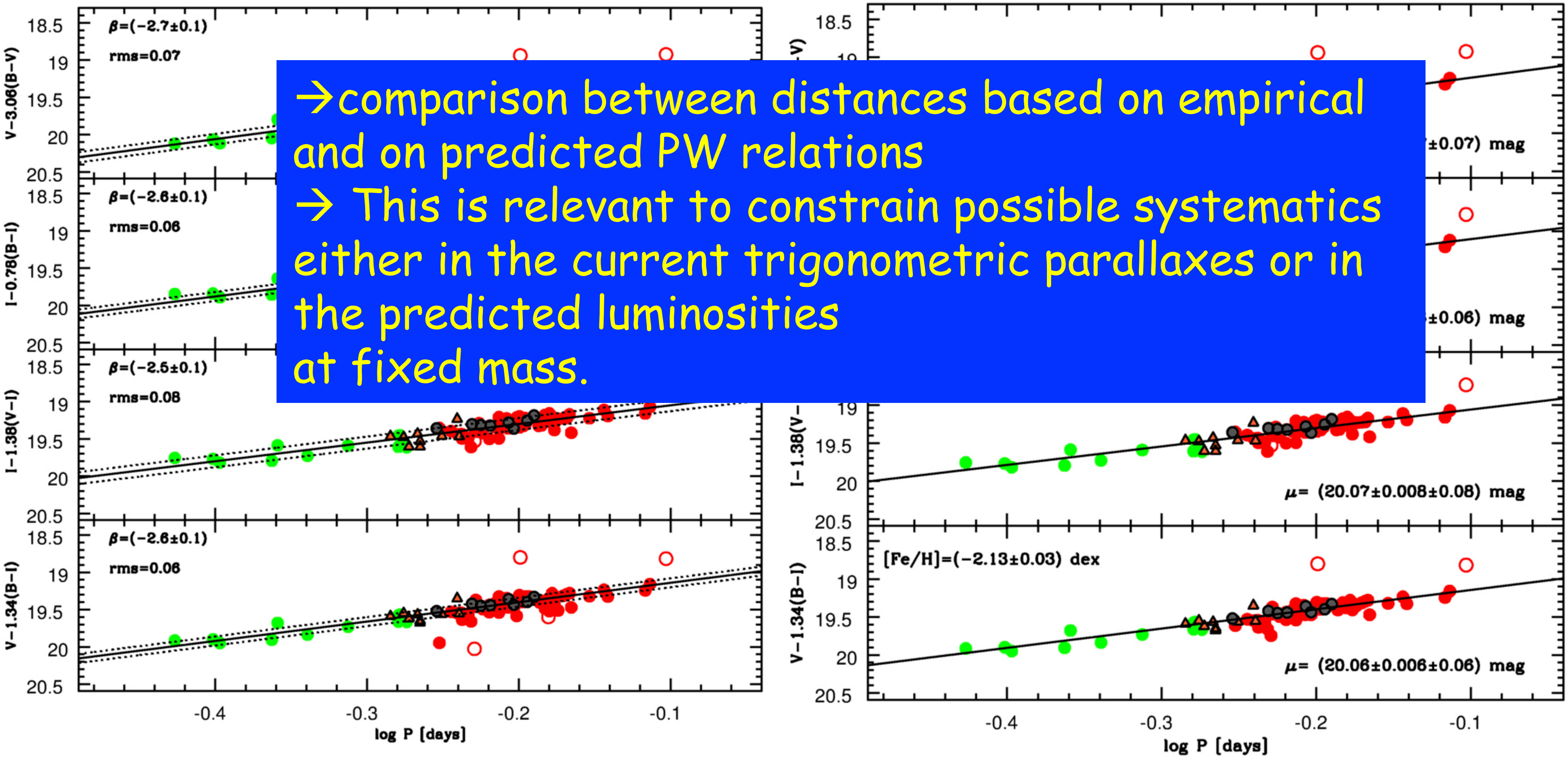


→ Inferred distances in agreement with the geometric estimate provided by Kaluzny et al. based on three eclipsing binaries.

→ distances to globulars hosting RRLs with a precision better than 2%-3%.

Braga et al. 2015 ApJ

The case of Carina



→comparison between distances based on empirical and on predicted PW relations
→ This is relevant to constrain possible systematics either in the current trigonometric parallaxes or in the predicted luminosities
at fixed mass.

Coppola et al. 2015 ApJ in press

RR Lyrae as stellar population tracers

van Albada & Baker (1971, ApJ, 169, 311) were the first to derive the pulsation relations for RR Lyrae stars on the basis of an extensive set of linear non adiabatic models:

$$\log P_0 = -1.772 - 0.68 \log(M/Mo) + 0.84 \log(L/Lo) + 3.48 \log(6500/T_e)$$

$$\log(P_0/P_1) = 0.095 - 0.032 \log(M/Mo) + 0.014 \log(L/Lo) + 0.09 \log(6500/T_e)$$

Fundamental link between pulsational and evolutionary parameters

RR Lyrae as stellar population tracers ➔stellar masses

RR Lyrae mass determinations

1) Use of double mode RR Lyrae in the Petersen diagram

2) Model fitting of observed light (and radial velocity) curves

Use of double mode RR Lyrae in the Petersen diagram theory versus observations

Original paper by Petersen (1978 A&A) based on linear adiabatic theory

Historical papers by Cox, King & Hodson (1980 ApJ) and Cox, Hodson & Clancy (1983, ApJ) based on linear nonadiabatic models

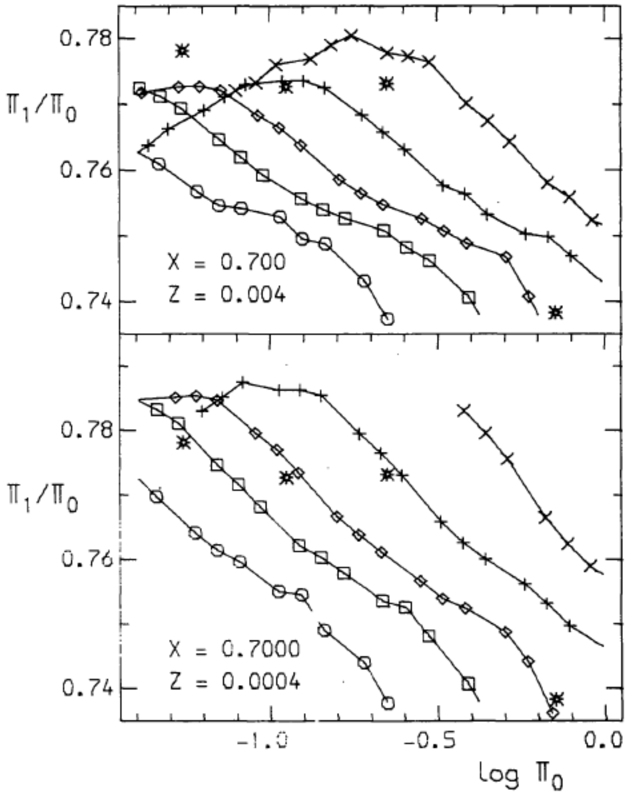


Fig. 7. Calibration of the (log Π_0, Π_1/Π_0) diagram in tern mass for two Population II compositions ($X = 0.70$, $Z =$ (and 0.0004). Three RRs variables and the RR Lyrae type star AC And are plotted in the diagram

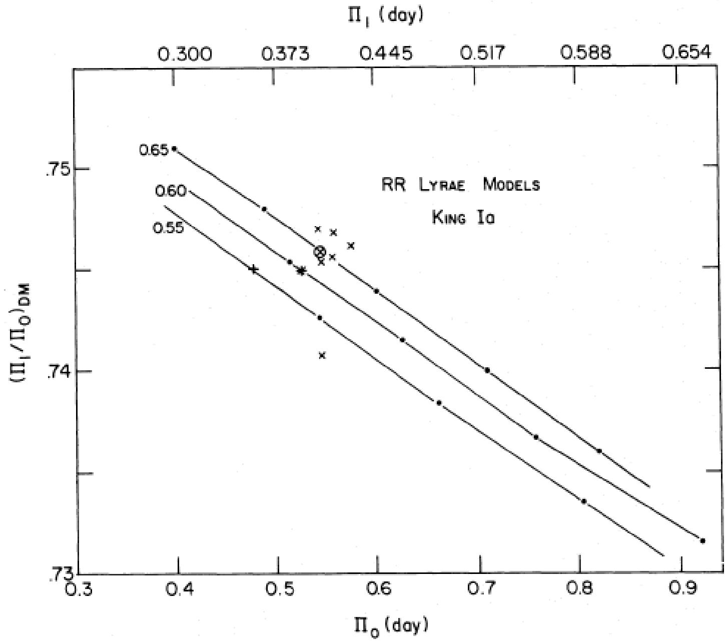
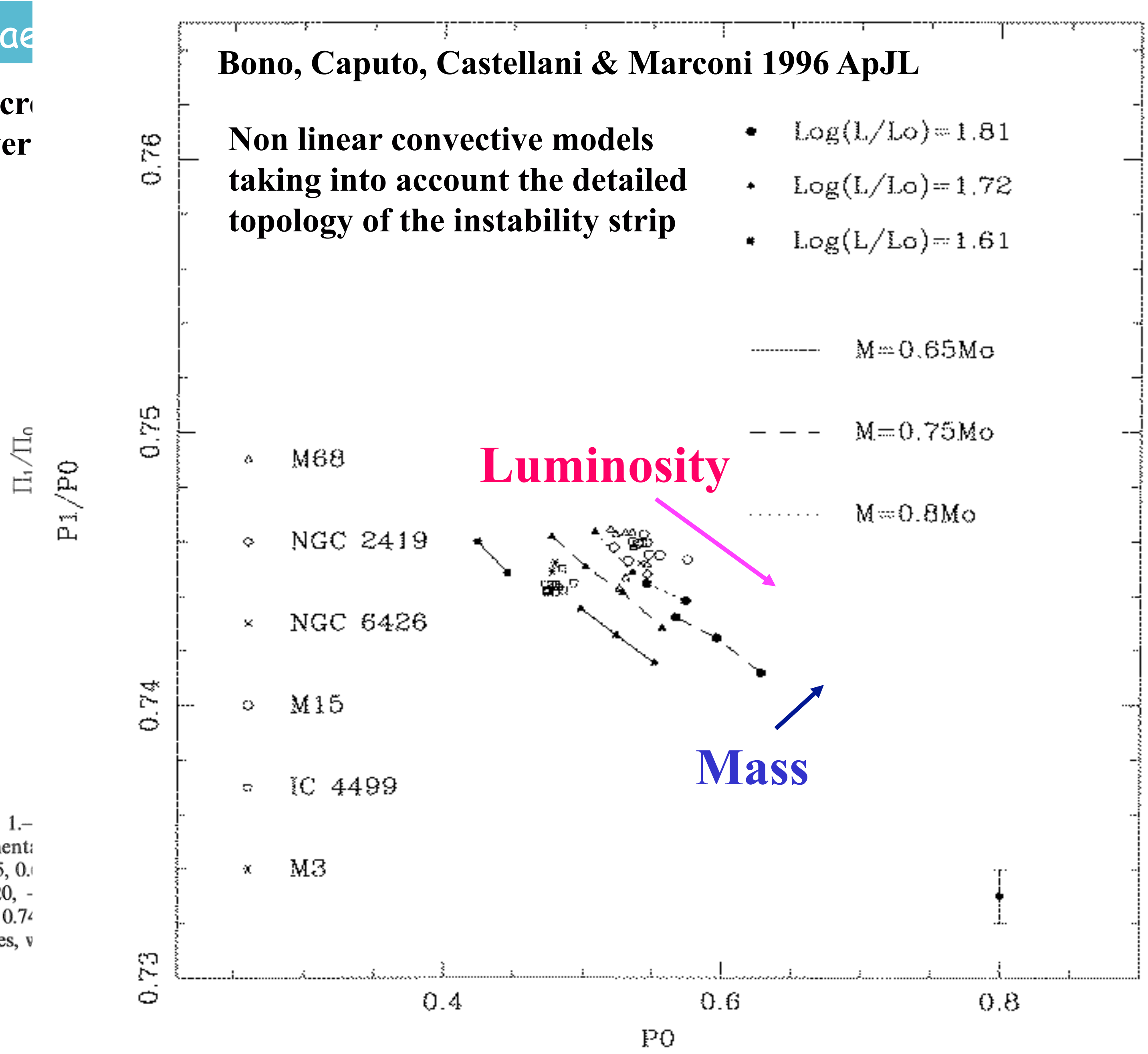


FIG. 2.—The ratio of the overtone to fundamental periods in the color and period range of the double-mode RR Lyrae variables is plotted vs. the fundamental and overtone periods. Masses of 0.55, 0.60, and 0.65 $M_\odot$ and the King Ia composition are used. The x points are from M15 with V31 circled. The + sign at $0\overset{d}{.}48$ is for the two M3 variables and the other + sign at $0\overset{d}{.}53$ is for the variable in M68.

Pulsation masses based on the Petersen diagram systematically smaller than the evolutionary ones

Discr
Liver



Bono, Caputo, Castellani & Marconi 1996 ApJL

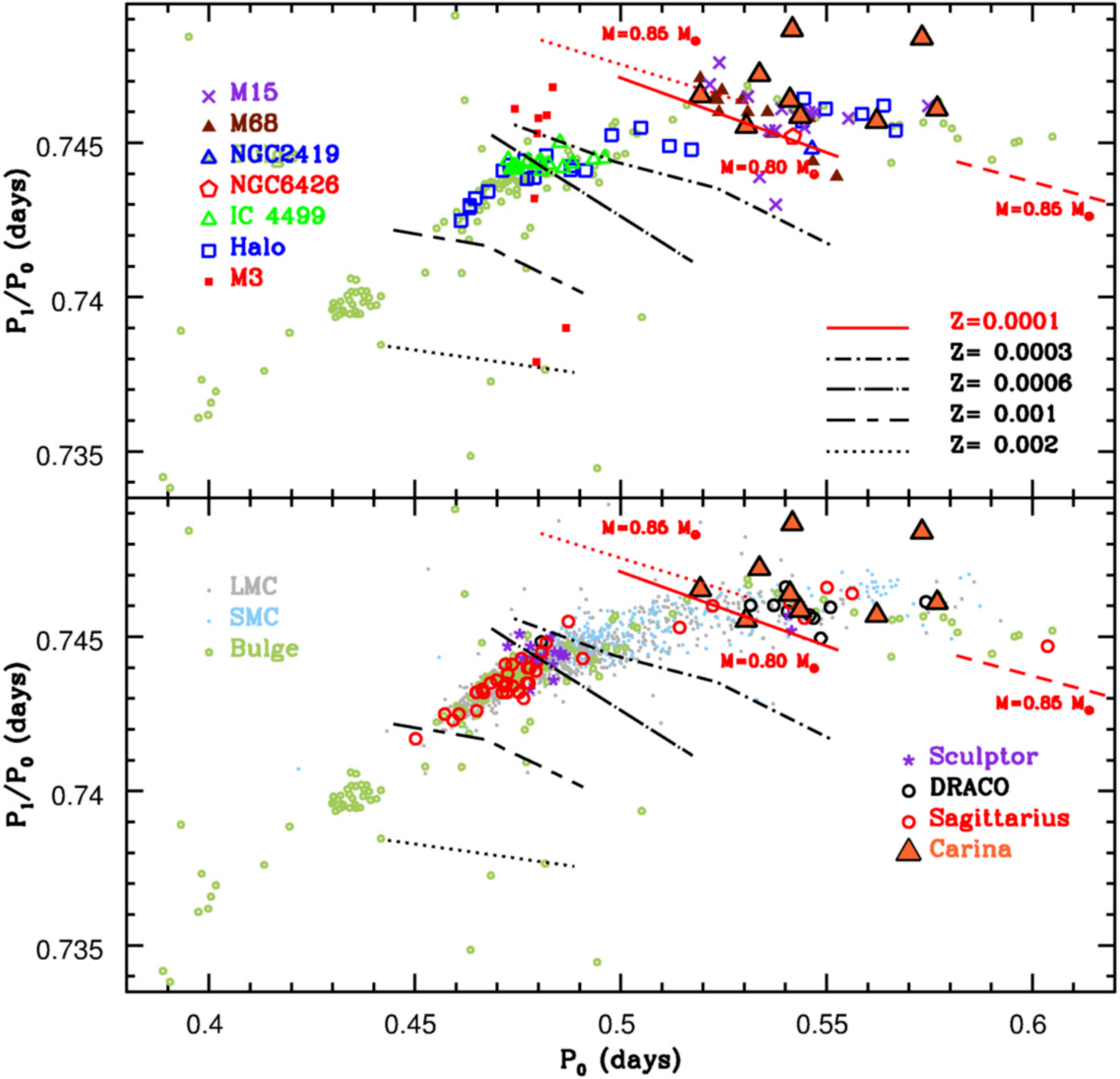
Non linear convective models taking into account the detailed topology of the instability strip

Luminosity

Mass

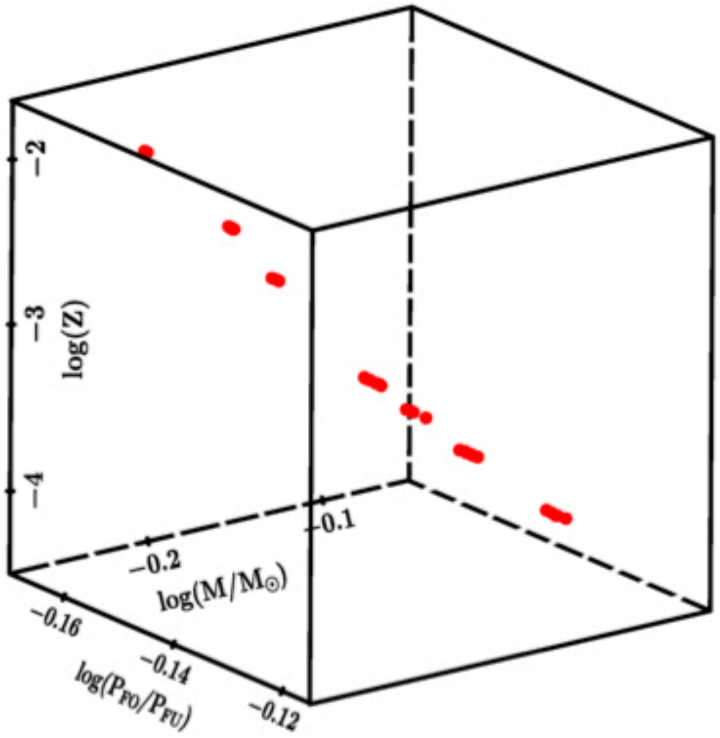
FIG. 1.–
fundament
the 0.55, 0.
−0.0420, -
0.7400, 0.74
variables, v
ables.

RR Lyrae : properties, open problems, results and perspectives in the E-ELT era



Coppola et al. 2015 ApJ

A new prediction of pulsation models → an anlytical relation to infer the masses as a function of both the period ratio and the metallicity



$$\log M/M_\odot = -0.85\ (\pm 0.05)\ -2.8\ (\pm 0.3) \log P_{FO}/P_F\ -\ 0.097\ (\pm 0.003) \log Z$$

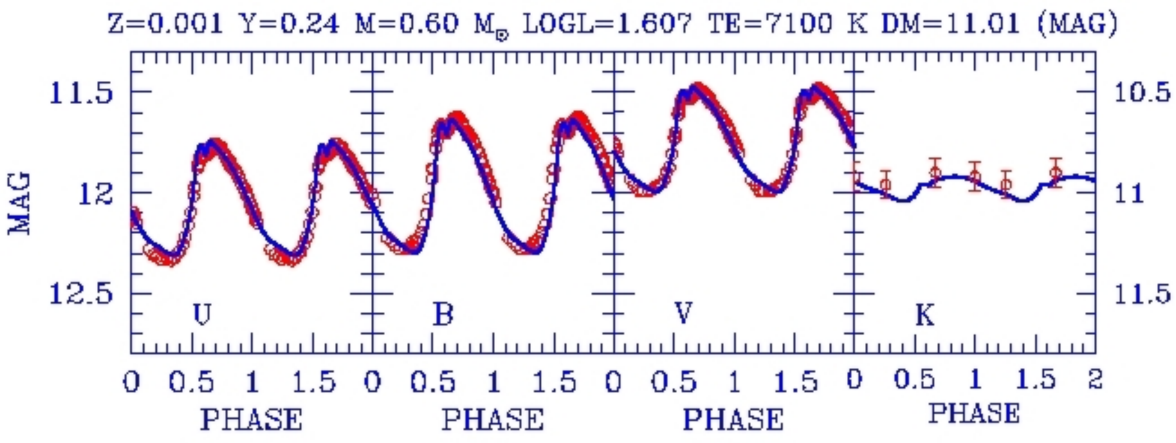
Marconi et al. 2015 ApJ

Model fitting of observed curves

Nonlinear convective models predict accurate variations of relevant quantities along a pulsation cycle

⬇

Comparison with observed RR Lyrae curves



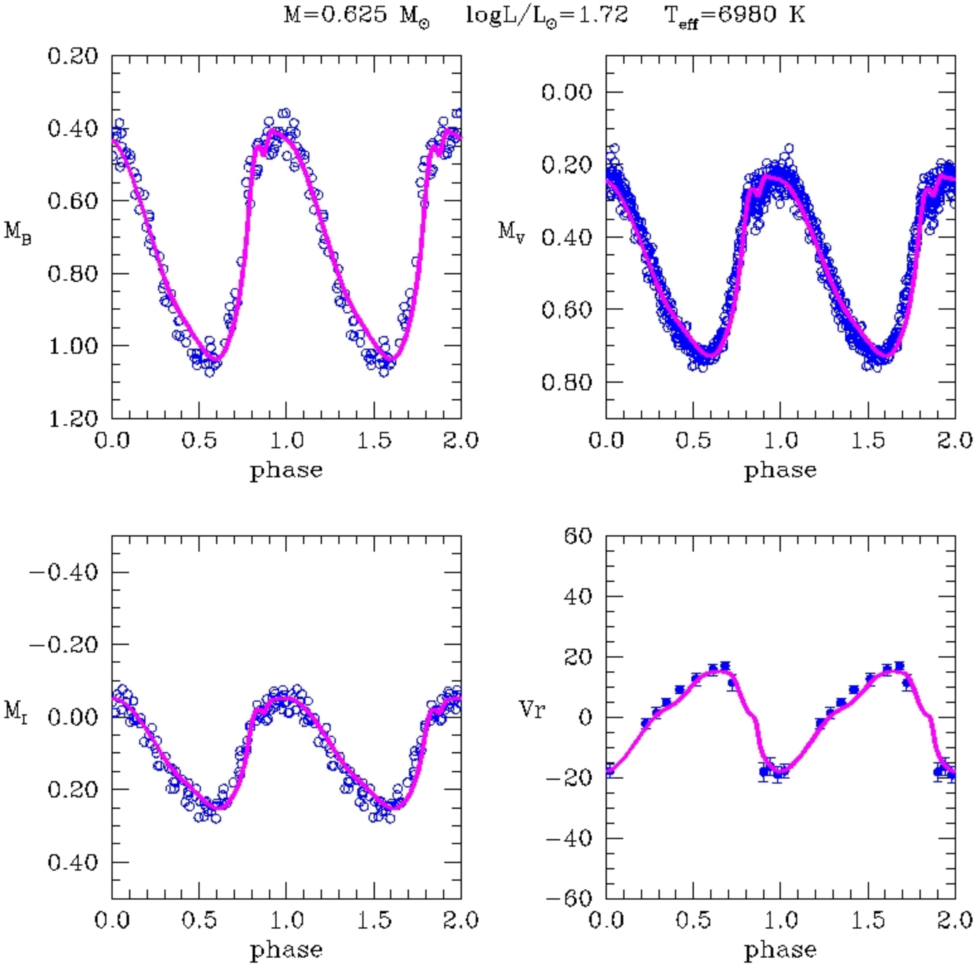
Mass, L, Te, Z in agreement with evolution

First application to RR Lyrae: Bono, Castellani, Marconi 2000 ApJL

If the radial velocity curve is available too→

Simultaneous fit of light and radial velocity curves

The case of CM Leo: Di Fabrizio, Clementini, Marconi et al. MNRAS 2002



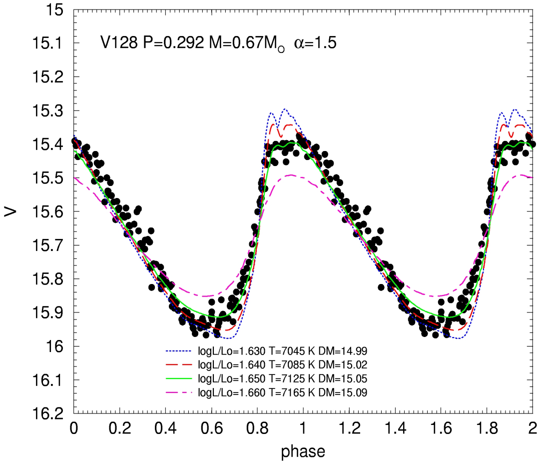
B light curve→

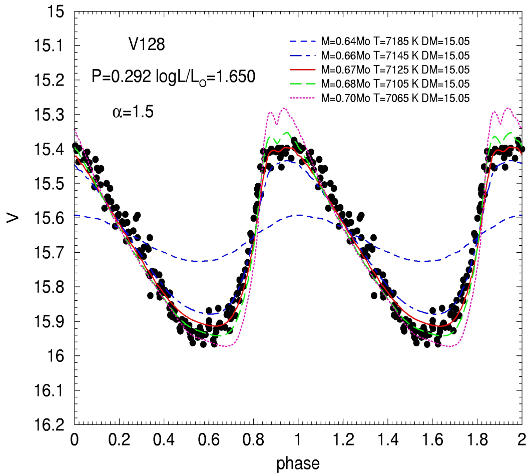
←V light curve

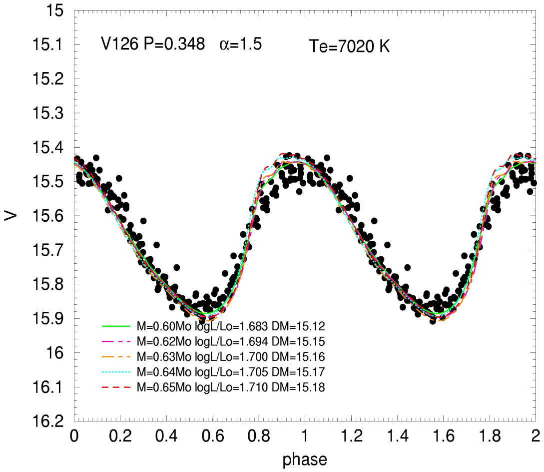
I light curve→

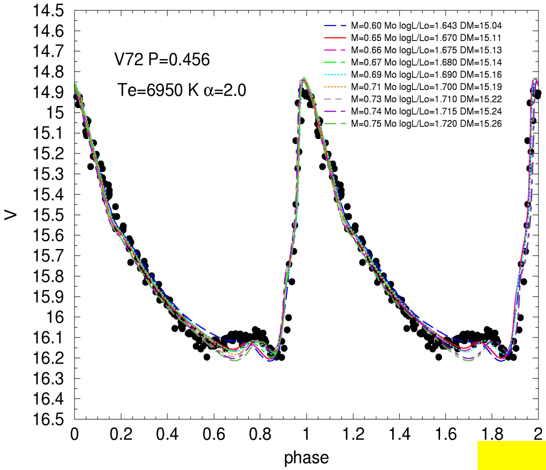
←Radial velocity curve

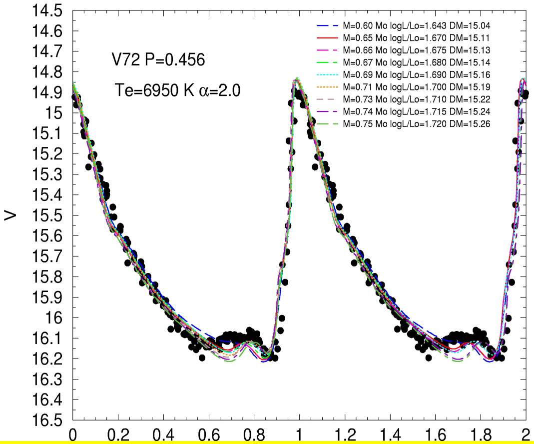
Recent results on the model fitting of light curves: the case of M3 (Marconi & Degl'Innocenti 2007 A&A)

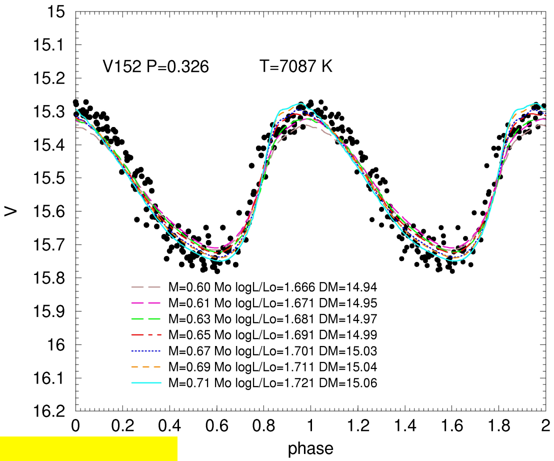








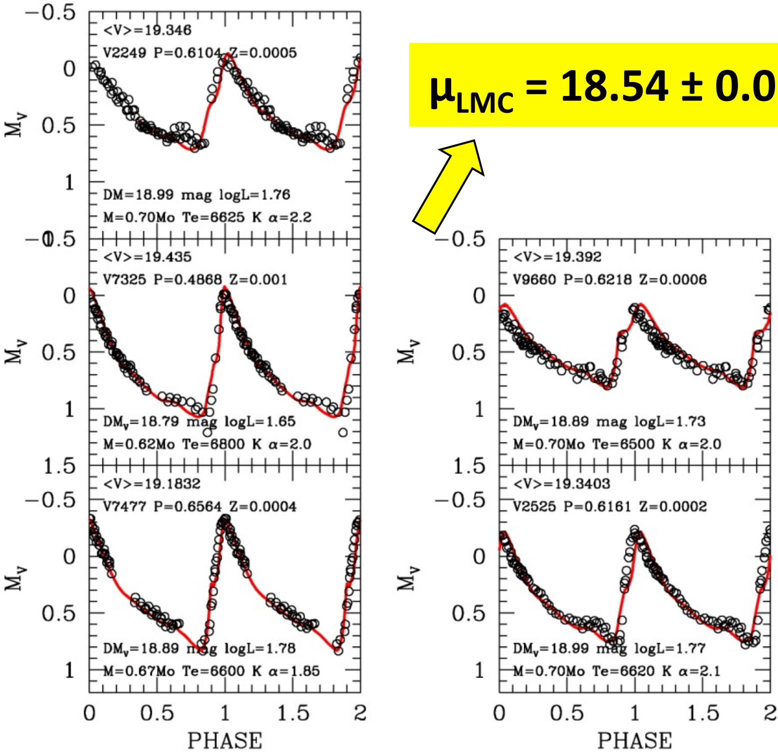




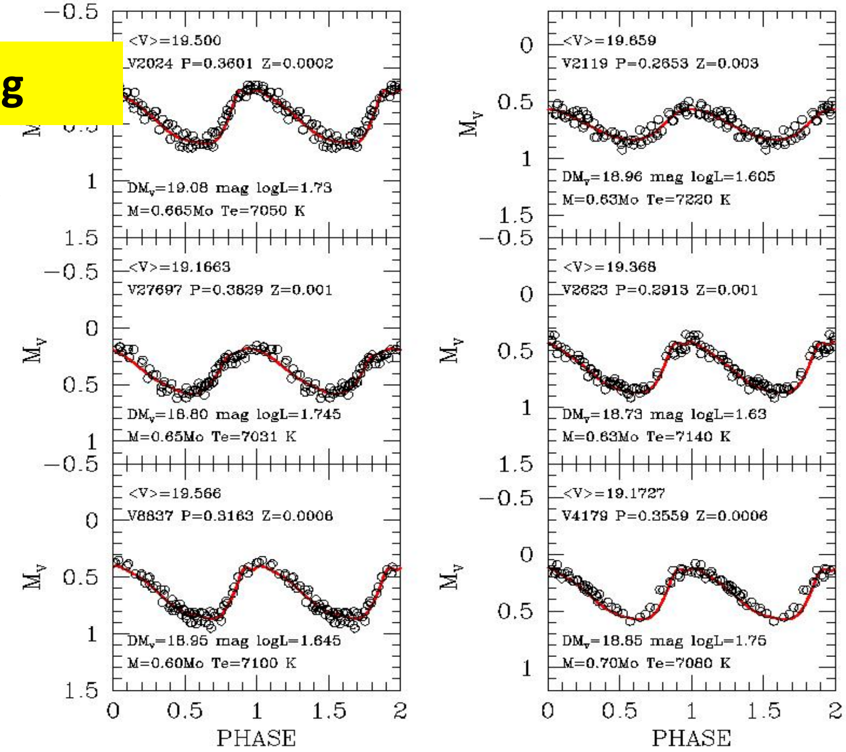
Resulting distance modulus
μ=15.10 ± 0.1 mag

Light curve model fitting of RR Lyrae in the LMC

Fundamental pulsators



First overtone pulsators



μ_{LMC} = 18.54 ± 0.02 mag

Marconi & Clementini AJ 2005

Application to LMC variables: a check of consistency

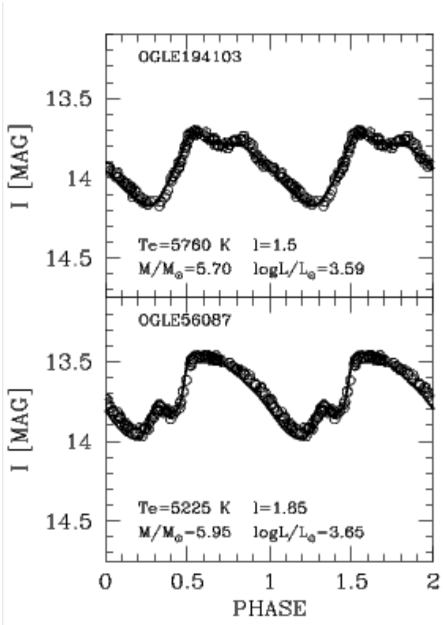
Model fitting of LMC Cepheids, RR Lyrae and δ Scuti stars

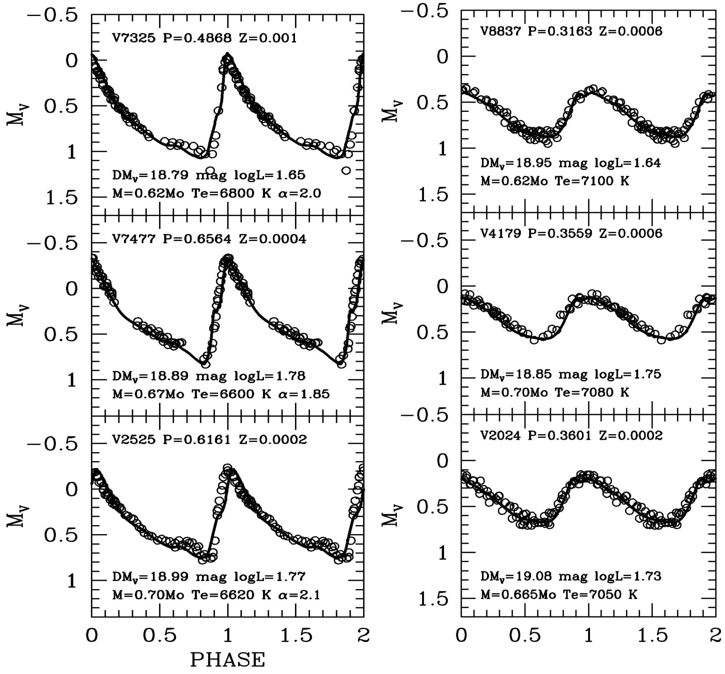
Assuming E(B-V)=0.08 mag

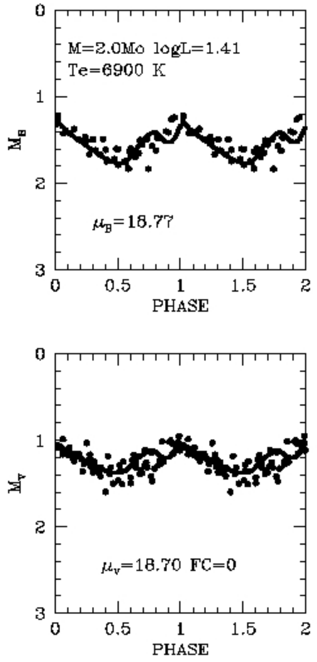
Cepheids μ=18.53±0.02 mag
Bono, Castellani, Marconi (2002)

RRLyrae μ=18.49±0.06 mag
Marconi & Clementini (2005)

δ Scuti μ=18.48±0.02 mag
McNamara, Clementini, Marconi (2005)







in agreement with results by Keller & Wood (2002, 2006) based on model fitting of MACHO Cepheids

RR Lyrae in Gaia

Milky Way:

16836 RR Lyrae known in the MW from OGLE III (Soszynsky et al. 2011)

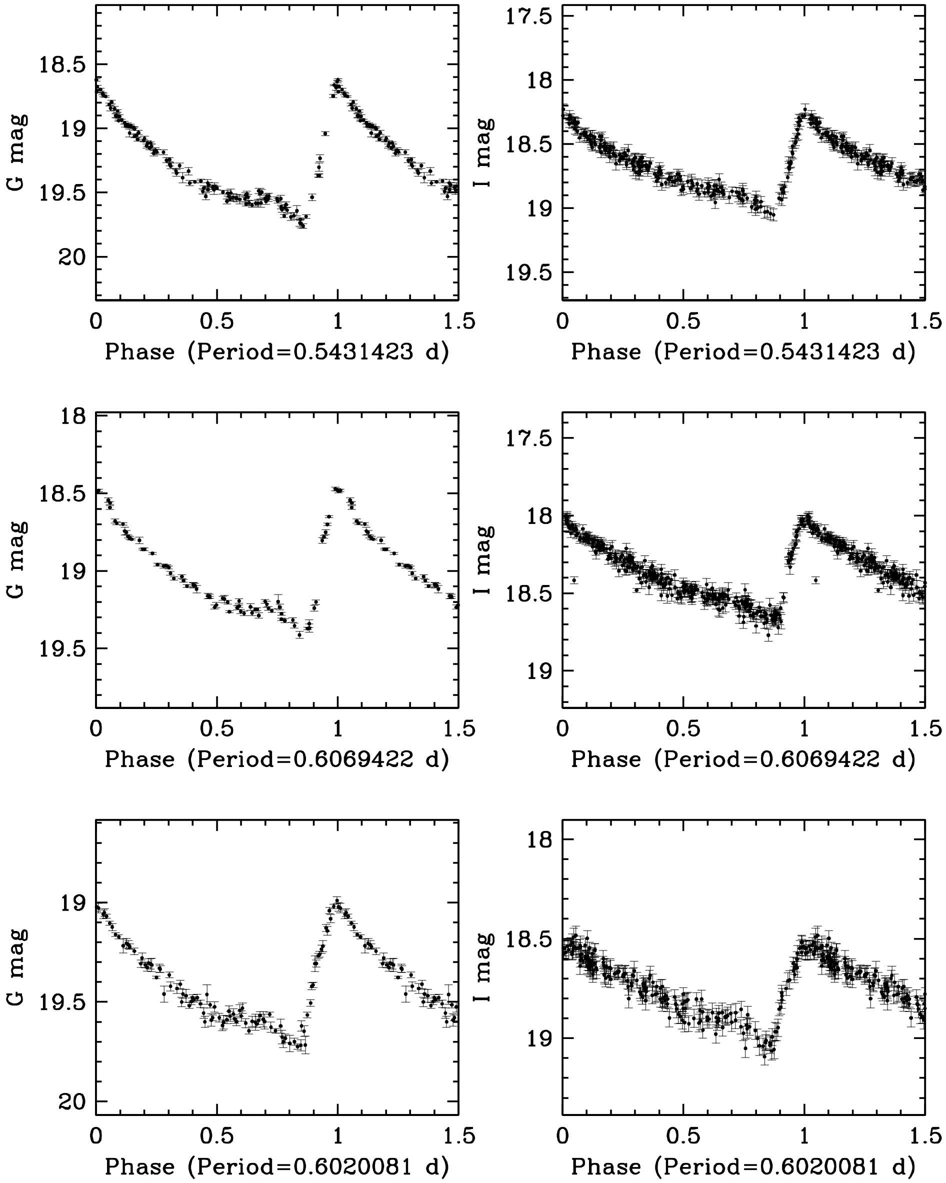
up to 40000 RRL estimated in the bulge and 70000 in the Halo!!! Almost decuplicate the number of known galactic RRL

LMC: 24906 known RR Lyrae from OGLE III

SMC: 2475 known Lyrae from OGLE III
Soszynki et al (2010)

Within 1.5 kpc $\sigma\pi/\pi<1\%$, within 3 kpc $\sigma\pi/\pi<2.5\%$, $\sigma\pi/\pi\approx25\text{-}30\%$ at 10 kpc

RR Lyrae in Globular Cluster with $\sigma\pi/\pi<1\%$



GAIA IMAGE OF THE WEEK (March 5, 2015)

RR LYRAE IN THE LMC OBSERVED BY GAIA

RR Lyrae : properties, open problems, results and perspectives in the E-ELT era

We expect to fix the zero point of the RR Lyrae distance scale at an unprecedented accuracy.

Coupling direct trigonometric distances and accurate spectroscopic metallicities → metallicity dependence of PLK, M_V-[Fe/H] relations

Perspectives for RR Lyrae with E-ELT

E-ELT → measure the brightness of HB stars with accuracy ~10% within 31-32 mag in the V band, and 28-29 mag in the K band in spiral galaxies and ~36/33 mag (V/K band) in elliptical Galaxies

➔detection of HB stars and RR Lyrae variables in several giant spiral and elliptical galaxies in the Virgo cluster

➔check of the accuracy of type Ia Supernovae as secondary distance indicators

Presence of RR Lyrae stars in both elliptical & spiral galaxies
➔unique opportunity to constrain quantitatively the dependence of the peak luminosity of SN Ia on the host galaxy

But E-ELT will not perform time-series observations

→ Need for specific techniques to use empirical and or theoretical templates, to reconstruct the light curves for both Cepheids and RR Lyrae

Laura's contribution to this lesson

Thank you !!