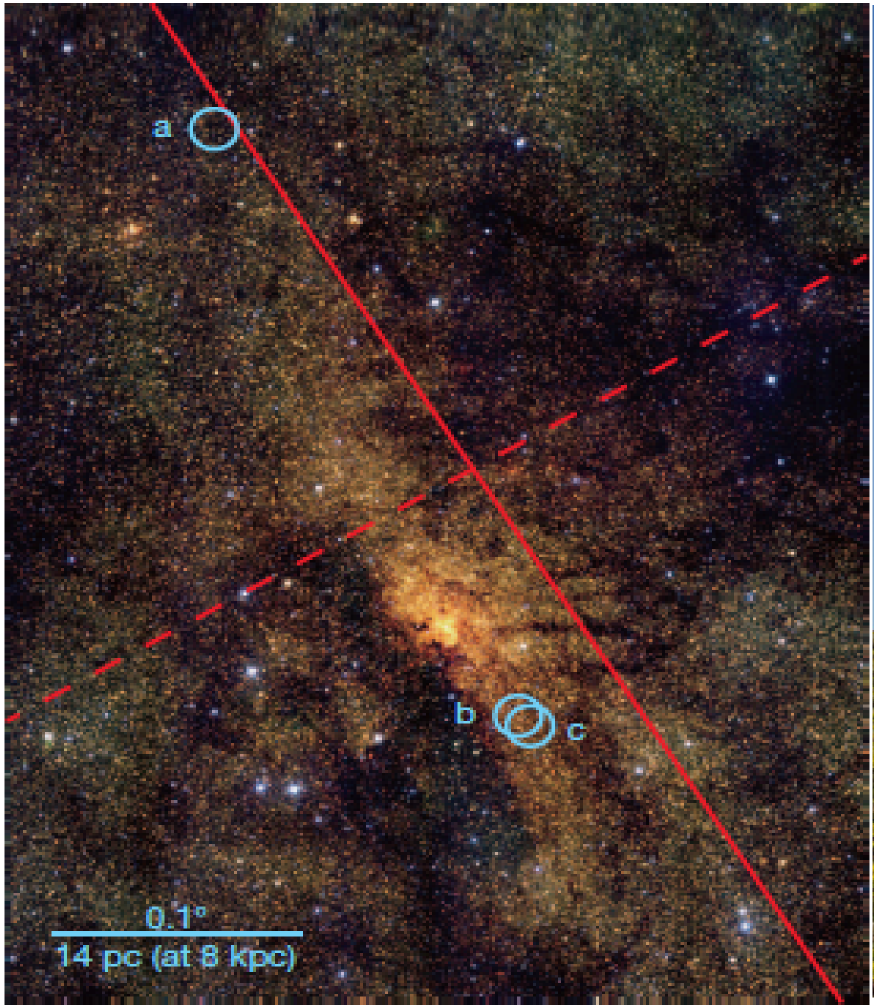
Near infrared high resolution spectroscopy of variable stars

G. Bono, Univ. Of Rome ToV + D. Magurno, M. Urbaneja + many others



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OUTLINE OF THE LECTURES

ONE

- → Why variable stars?
- → Distance indicators
- → Stellar tracers
- → Physics laboratories

TWO

- → Validating the machinery
- → Pulsation cycle
- → Telluric subtraction
- →Metallicity gradients

THREE

- → WINERED + others
- → NIR diagnostics
- → Near Future: ELT

Near infrared high resolution spectroscopy of variable stars

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OUTLINE OF THE LECTURE

ONE

→ Why variable stars: Cepheids, Miras, RR Lyrae?

→ Distance indicators: cosmology

→ Stellar tracers: Galactic spheroid

→ Physics laboratories: helium abundance

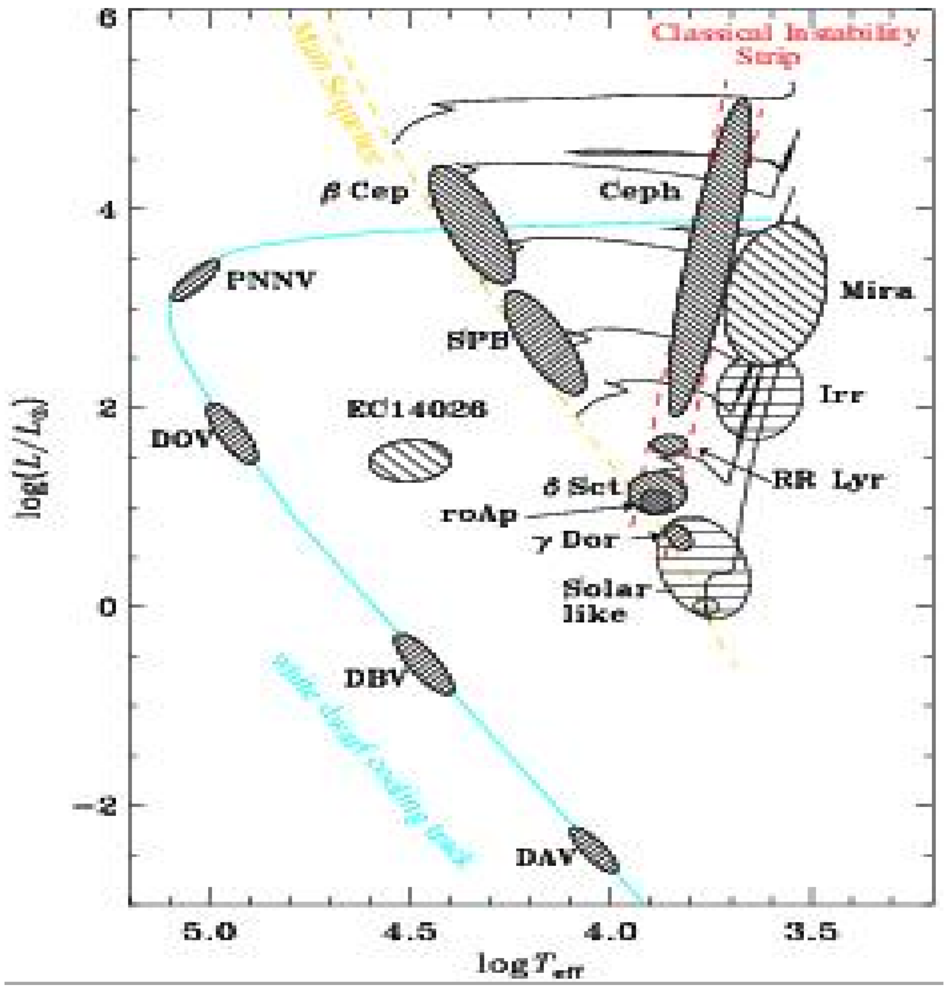
Cepheids, Mira & RR Lyrae

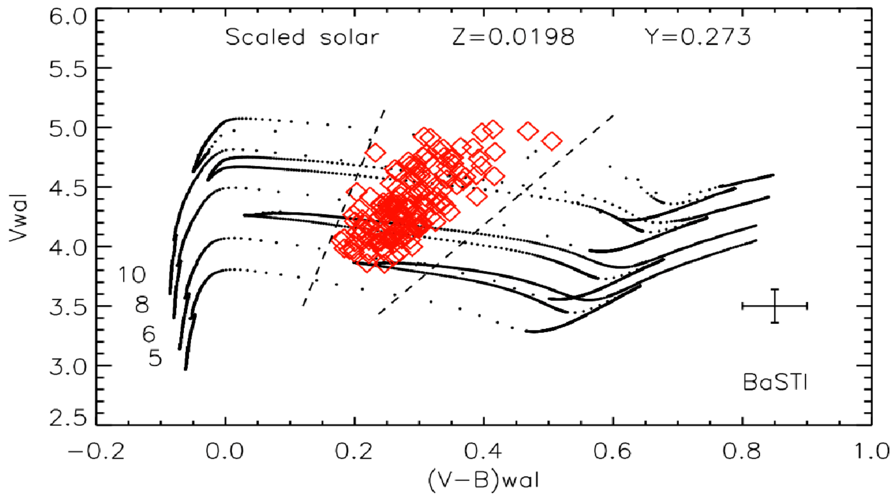
→ They can be easily identified
→ Distance better than ~3-5%
→ Age constraints

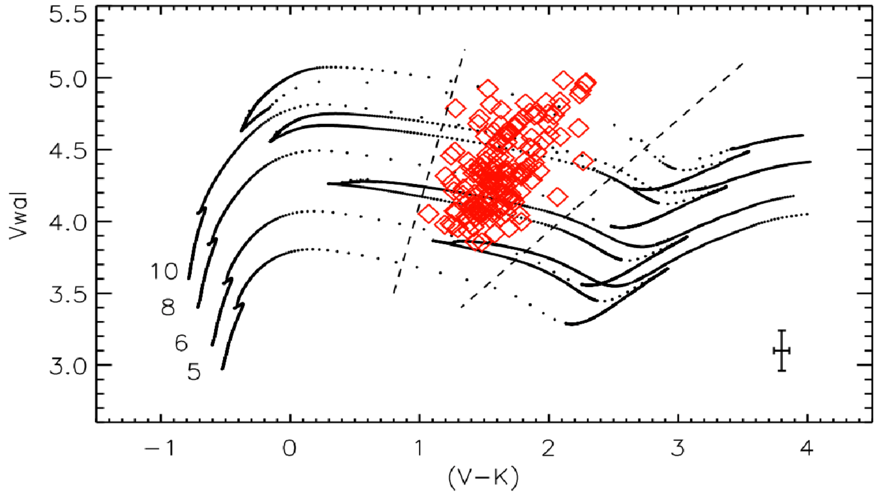
Cepheids → young [5-300 Myr]
Mira→ Intermediate [0.5-10 Gyr]
RR Lyrae → old [> 10 Gyr]

→ Demanding targets!

Pulsation & Evolutionary Properties



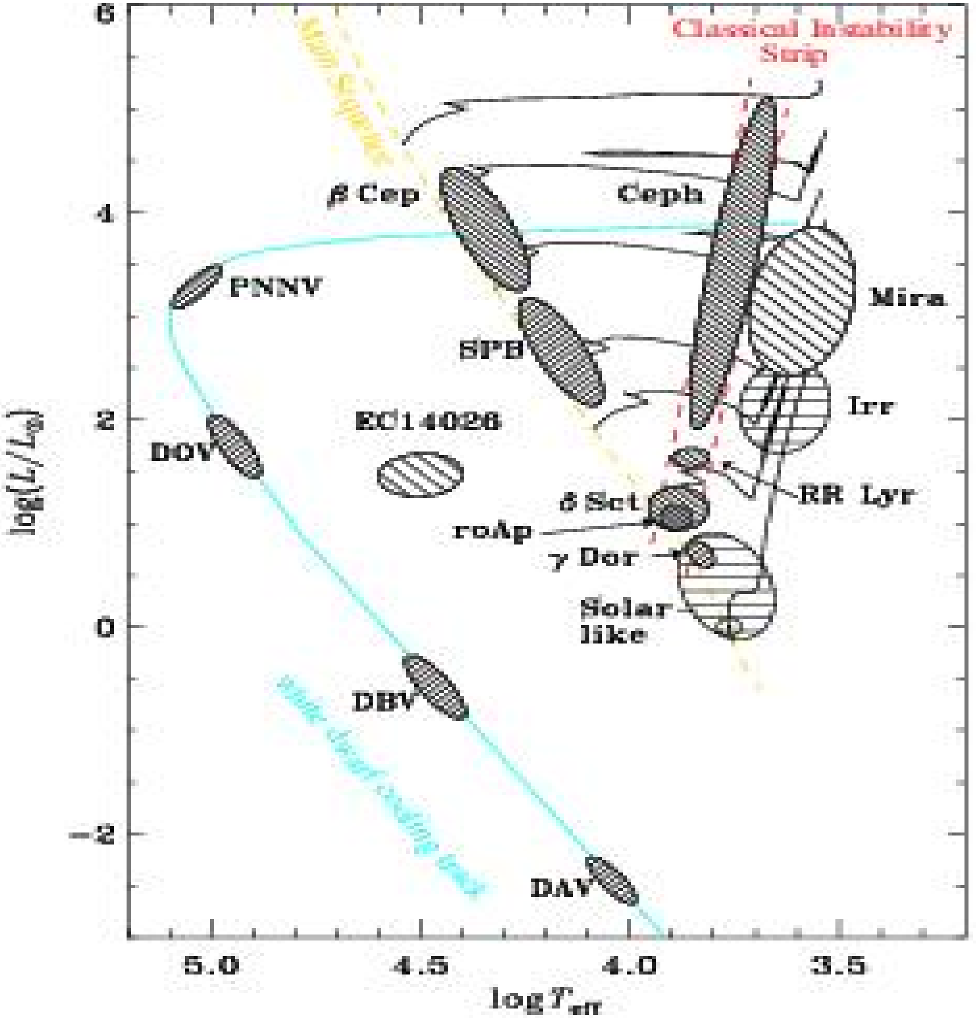


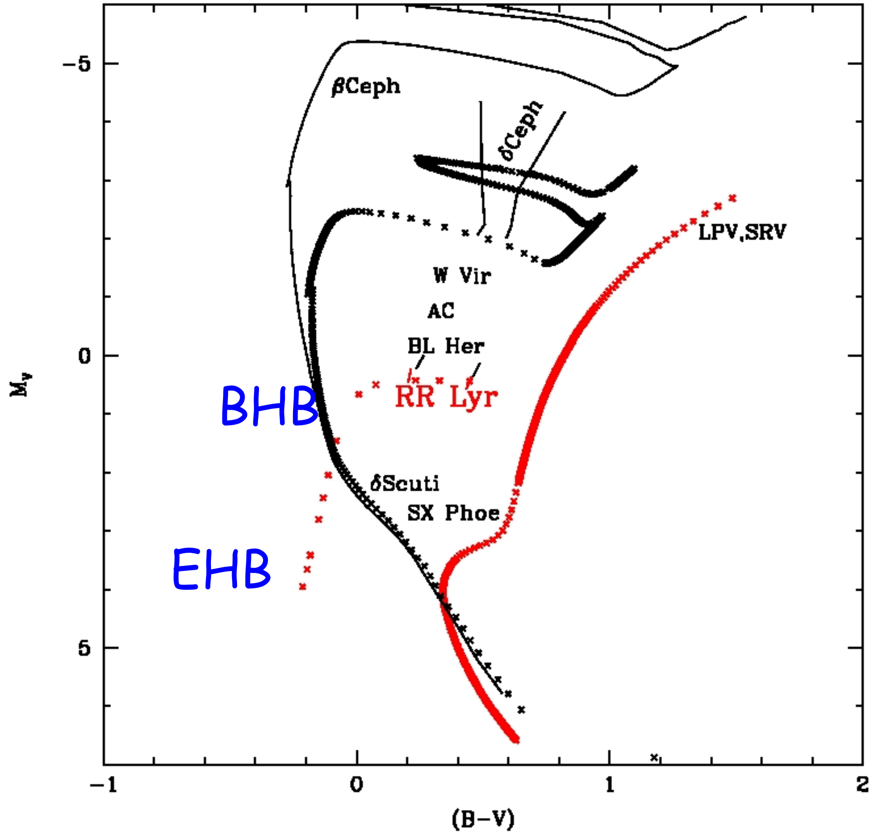


Cepheids: Intermediate-mass, central He-burning, blue loop, Thin disk

Mira: mainly intermediate-mass, double shell burning, AGB ubiquitous

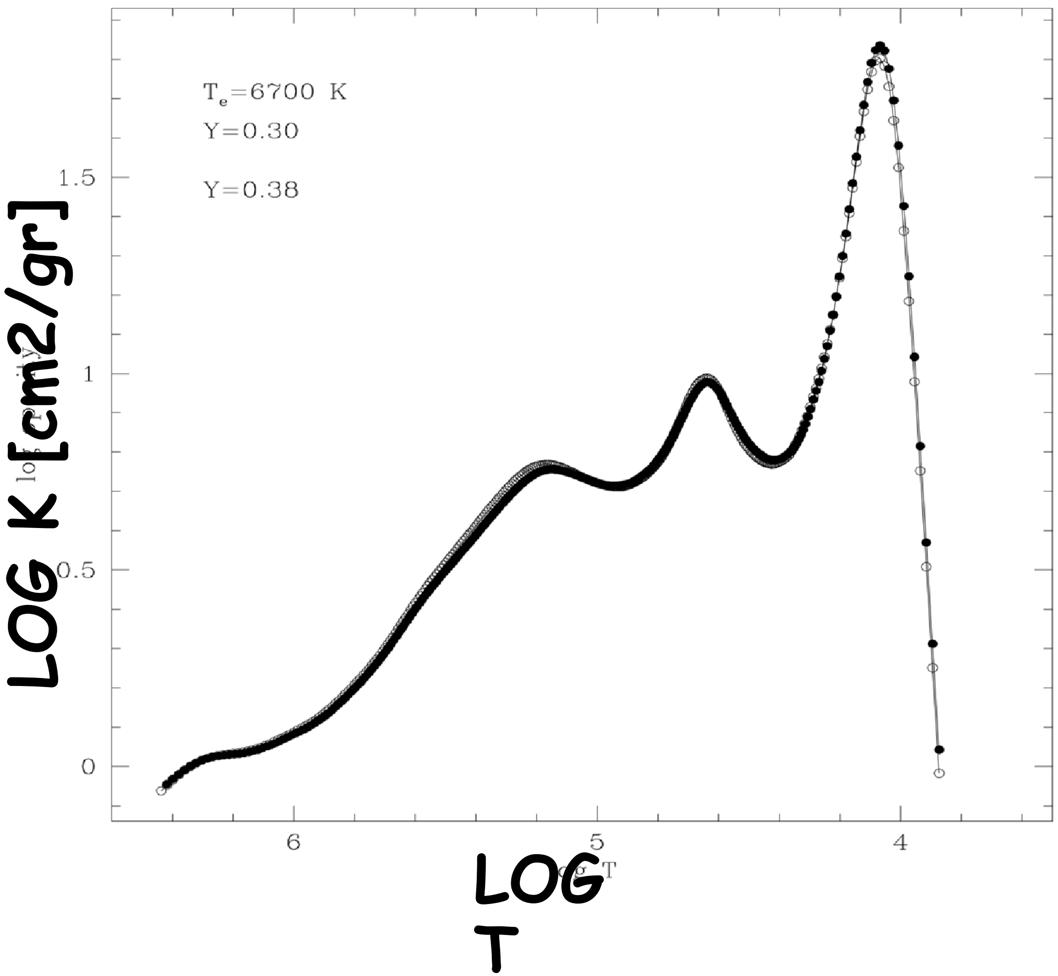
Pulsation & Evolutionary Properties





RR Lyrae: low-mass, central He burning, Horizontal Branch
Halo, Bulge, no Thin disk

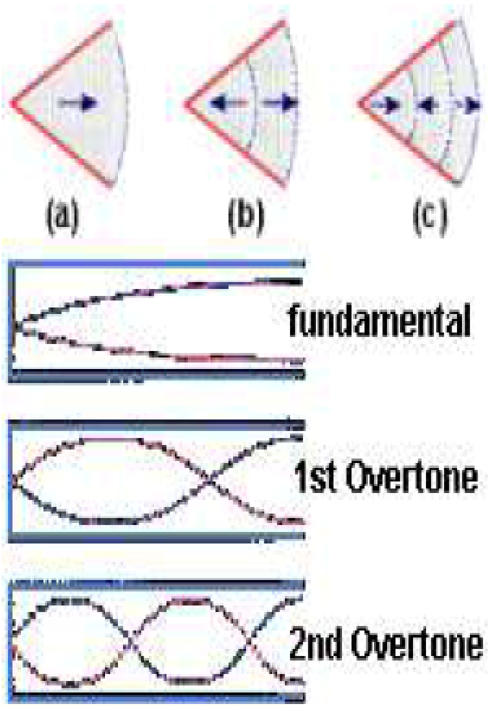
Why stars pulsate?



K & Y mechanisms
Eddington docet!

The main culprit is Cp!

Radial Modes



FU

FO

SO

Why they do not pulsate?

Non-linear non-local time dependent convective models …. + …. PdV

Stellingwerf RR Lyrae pulsation models

$$\frac{D\varpi}{Dt} = \nabla\cdot[\lambda_{ovs}\sqrt{\varpi}\nabla\varpi] + \frac{\sqrt{\varpi}}{\lambda_{ovs}}(\varpi_0 - \varpi) - 2\varpi\nabla \boldsymbol{u}\,, \quad (8)$$

where $\varpi \equiv \langle (u')^2 \rangle = 2E_t$ is the velocity of the convective field, λ_{ovs} is the diffusion scale length, and

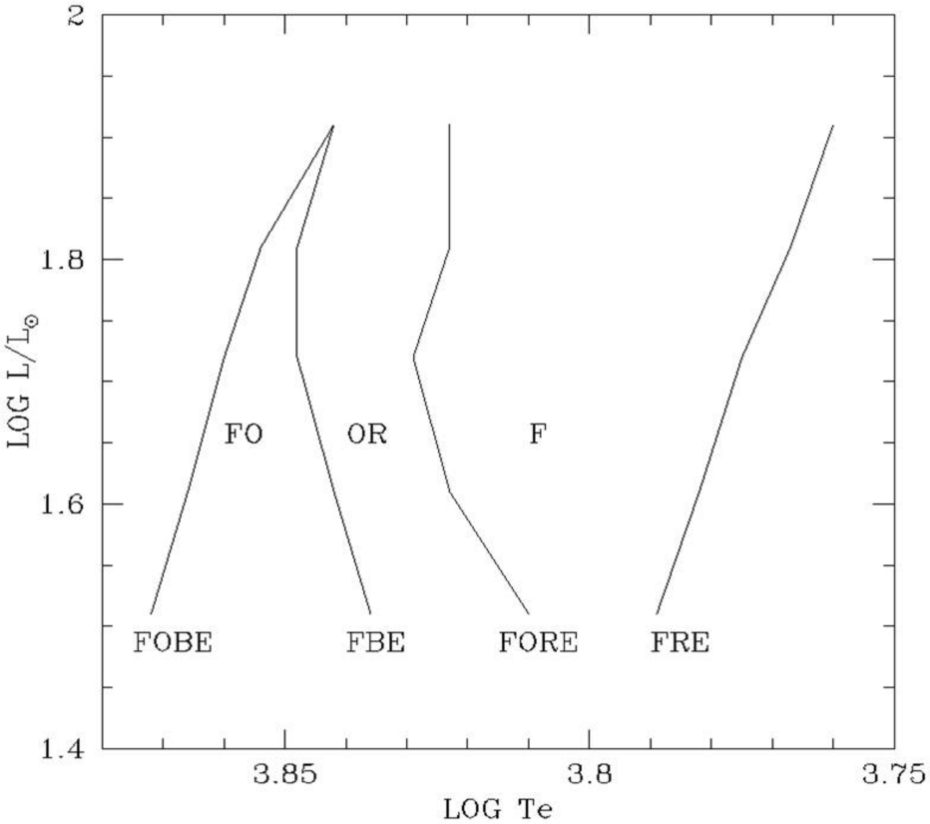
$$\varpi_0 \equiv -2Q\lambda_{ovs}\nabla P\left(\frac{\langle \boldsymbol{u}'T' \rangle}{\sqrt{\varpi}}\right). \quad (9)$$

Based on updates of Stellingwerf's original code followed extensive and detailed investigations of RR Lyrae properties.

(Bono & Stellingwerf 1994 ApJS, Bono et al. 1997 A&AS, ApJ, Bono et al. 2000, 2003 MNRAS, Marconi et al. 2003 ApJ, Di Criscienzo et al.2004 ApJ, Marconi & Clementini 2005, Marconi & Degl'Innocenti 2007, Marconi et al. 2009)

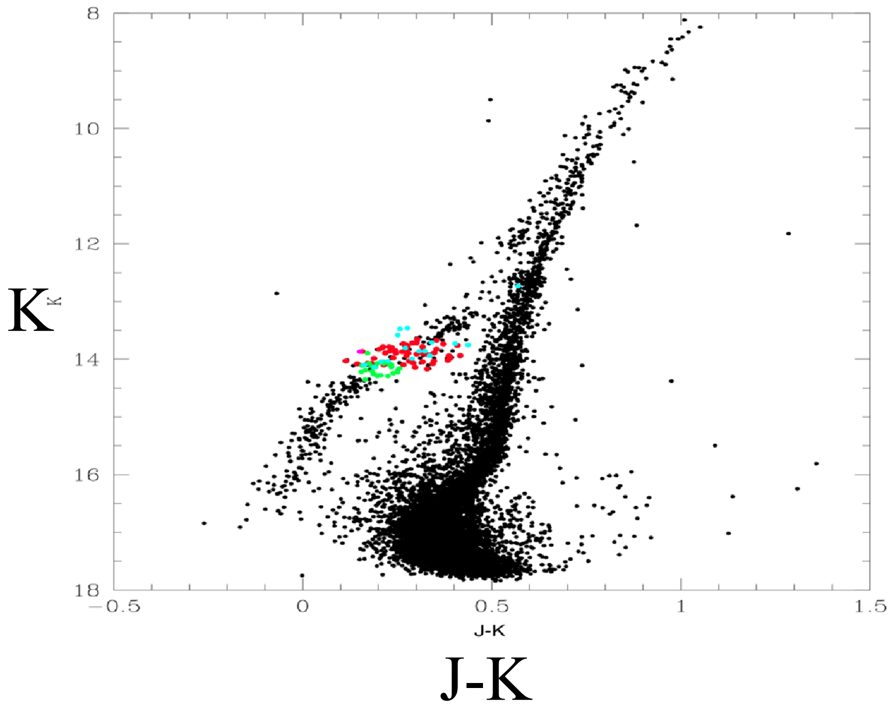
Basic facts

Topology of the instability strip



Bono et al. 1995, 1997

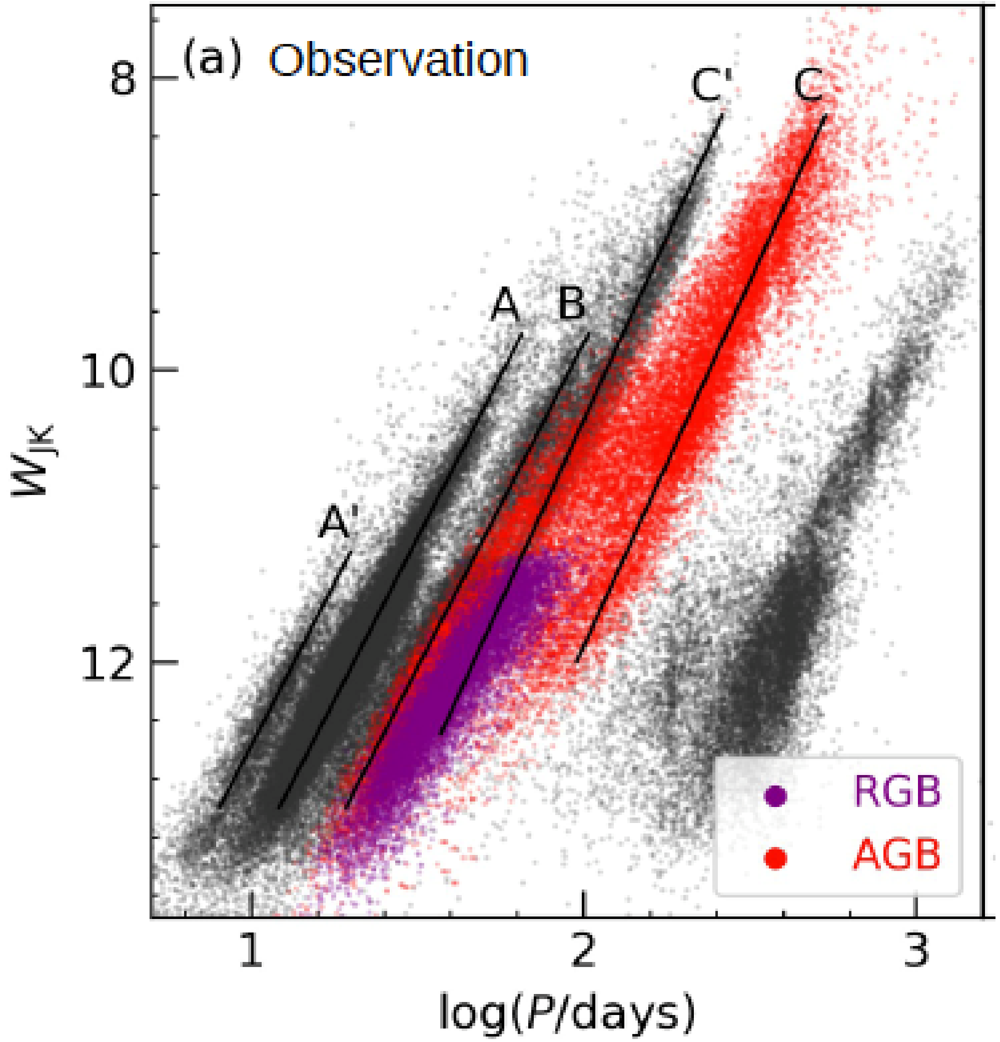
RR Lyrae in M5



Coppola + (2011)

Cepheids & RR Lyrae: FU, FO, Mixed mode

Miras in the Large Magellanic Cloud



FU plus several several overtones

Secondary modulation [binarity]

Mix between AGB and RGB stars

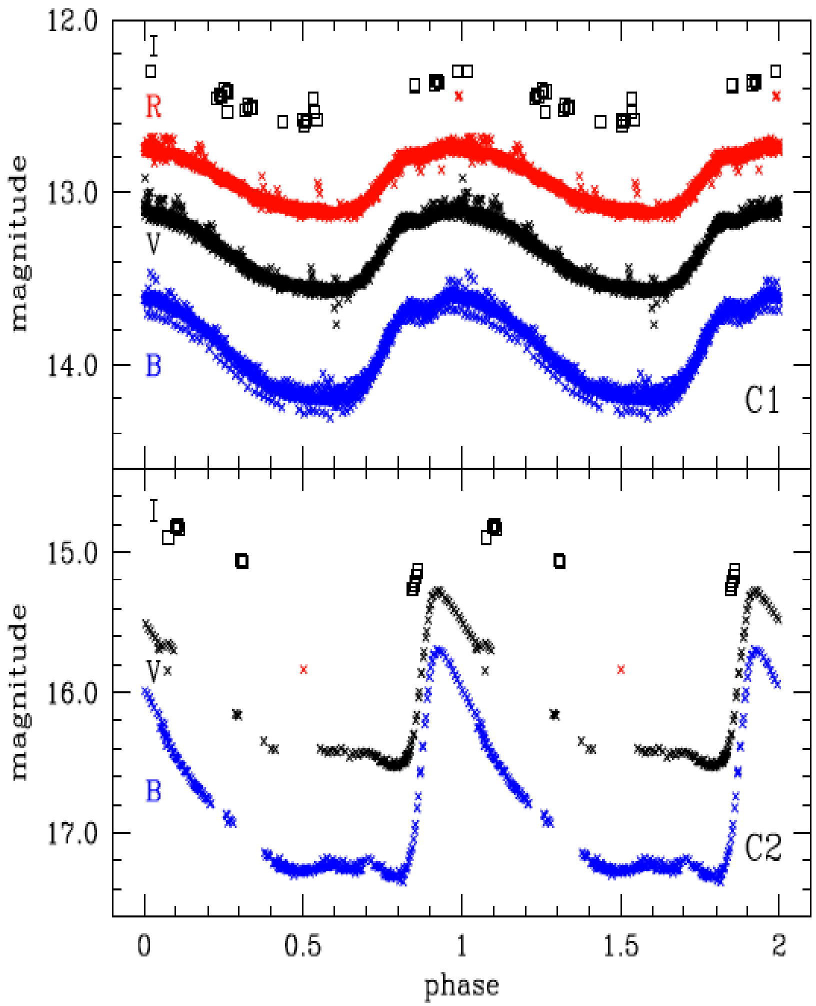
No general consensus on the number of sequences
Optical vs NIR

Wood diagram

Basic facts

Intrinsic variability

Optical bands



Stetson et al. (2014)

Luminosity amplitude:
a few tenths to ~1.5 mag

Light curve:
FOs → sinusoidal FUs → sawtooth

Radial velocity variations:
Several tens of km/s

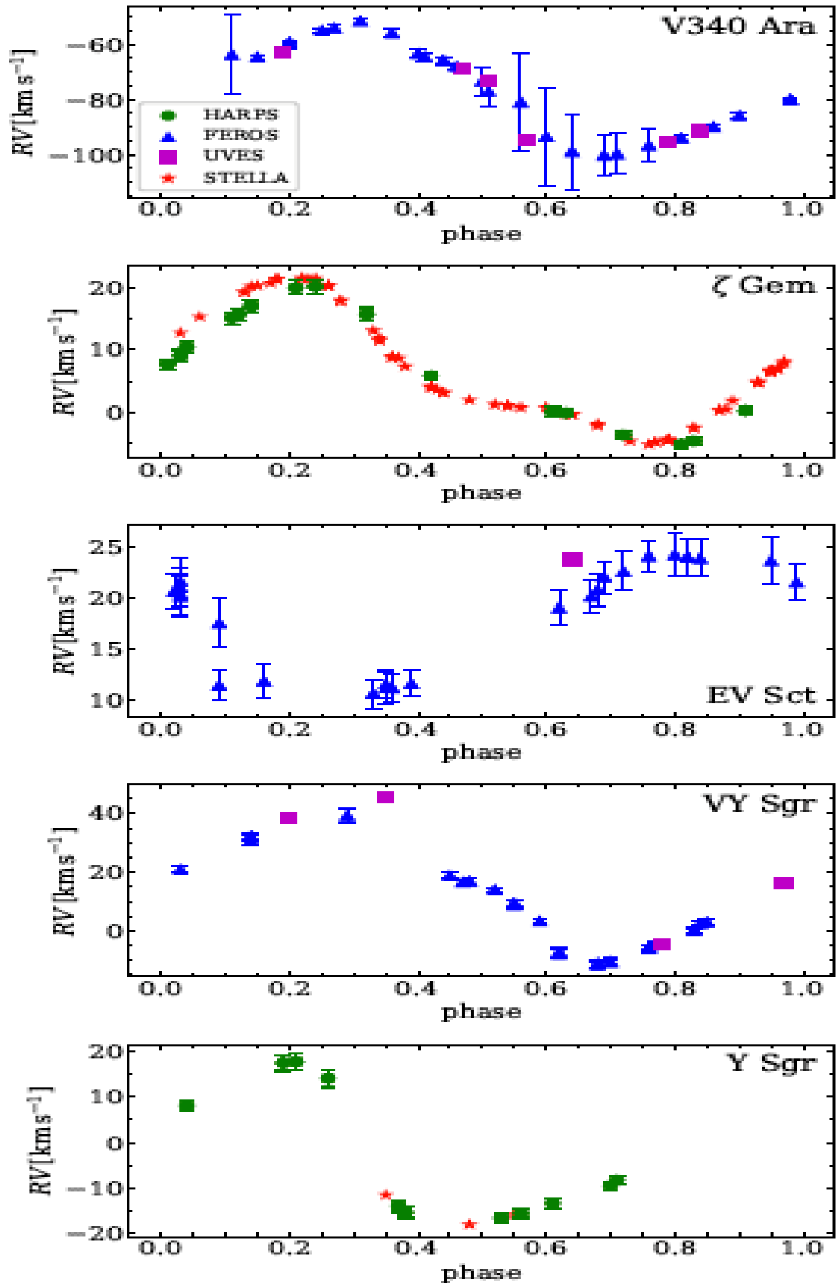
Period variations (free fall time):

RR Lyrae: 0.25 to less than 1 day

Cepheids: a few to > 100 days

Mira: from tens of days to years

Basic facts



Proxauf et al. (2017)

Intrinsic variability

Surface gravity variations: of the order of 0.5 dex

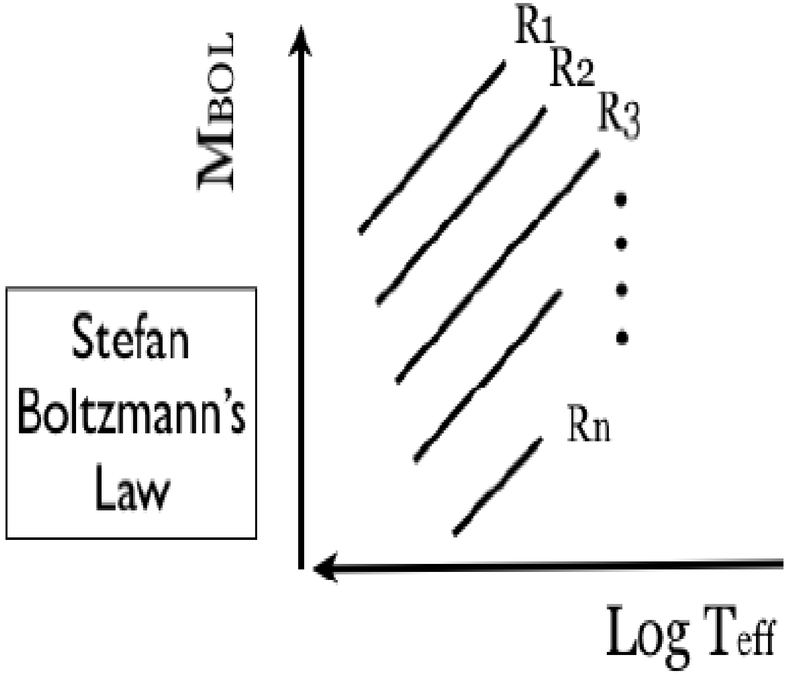
Effective temperature variations: few hundreds to more than 1000 K

Micro-turbulence Vel. variations: of the order of a few km

Continuous variation in spectral type along the pulsation cycle

Cepheids, Miras & RR Lyrae as distance indicators

Circumstantial evidence



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 ….

Cepheid Pulsation & Evolutionary Properties

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

$$LogL/Lo = \alpha + \beta \, Log \, P + \gamma \, Log \, Te$$

$$Mv = \alpha + \beta \, Log \, P + \gamma \, CI$$

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

Why we use PL instead of PLC relation?

Observations: sensitivity to reddening uncertainties

Theory: sensitivity to color-temperature relations

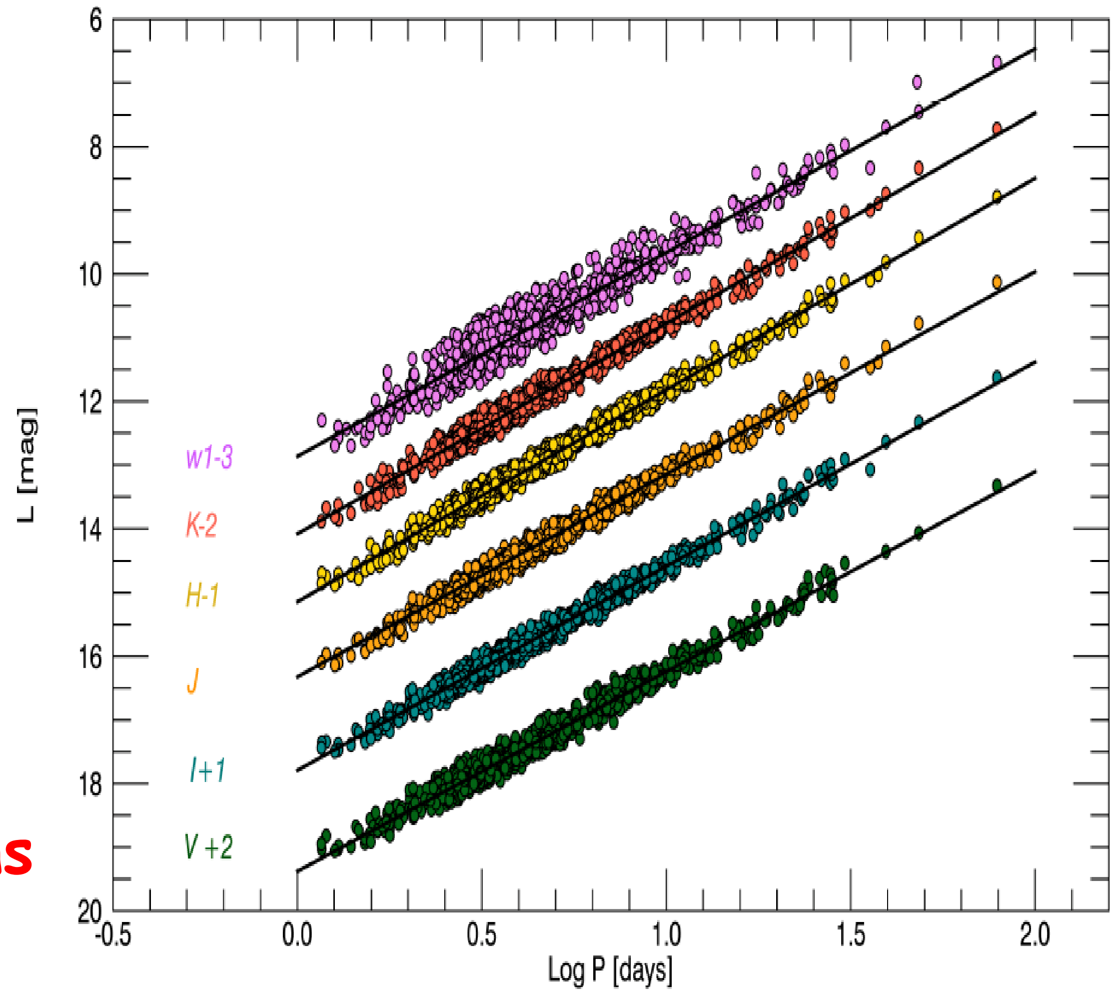
The largest NIR+MIR data set ever collected for LMC Cepheids

Inno + (2013,2016 + IRSF survey)

Optical-NIR PL relations
Absolute calibration
HST Galactic Cepheids
(9 Benedict + new
by Riess + 2016)

Empirical/theoretical
evidence indicates
PL relations are not
universal

They obey to PLZ relations



WMAP + PLANCK

$H_o = 67.8 \pm 0.9$ km / (s Mpc)

Resolved sources → 2.5σ level

Re-analysis by Efstathiou (2014) using a new maser distance to NGC4258 → 1.9σ

Tension or not tension?

New calibration by Riess + (2016)

Using new optical & NIR photometry WFC3@HST for Cepheids in 10 new galaxies hosting Sne Ia (18 calibrators) + 300 SN Ia at a redshift z ≤0.15

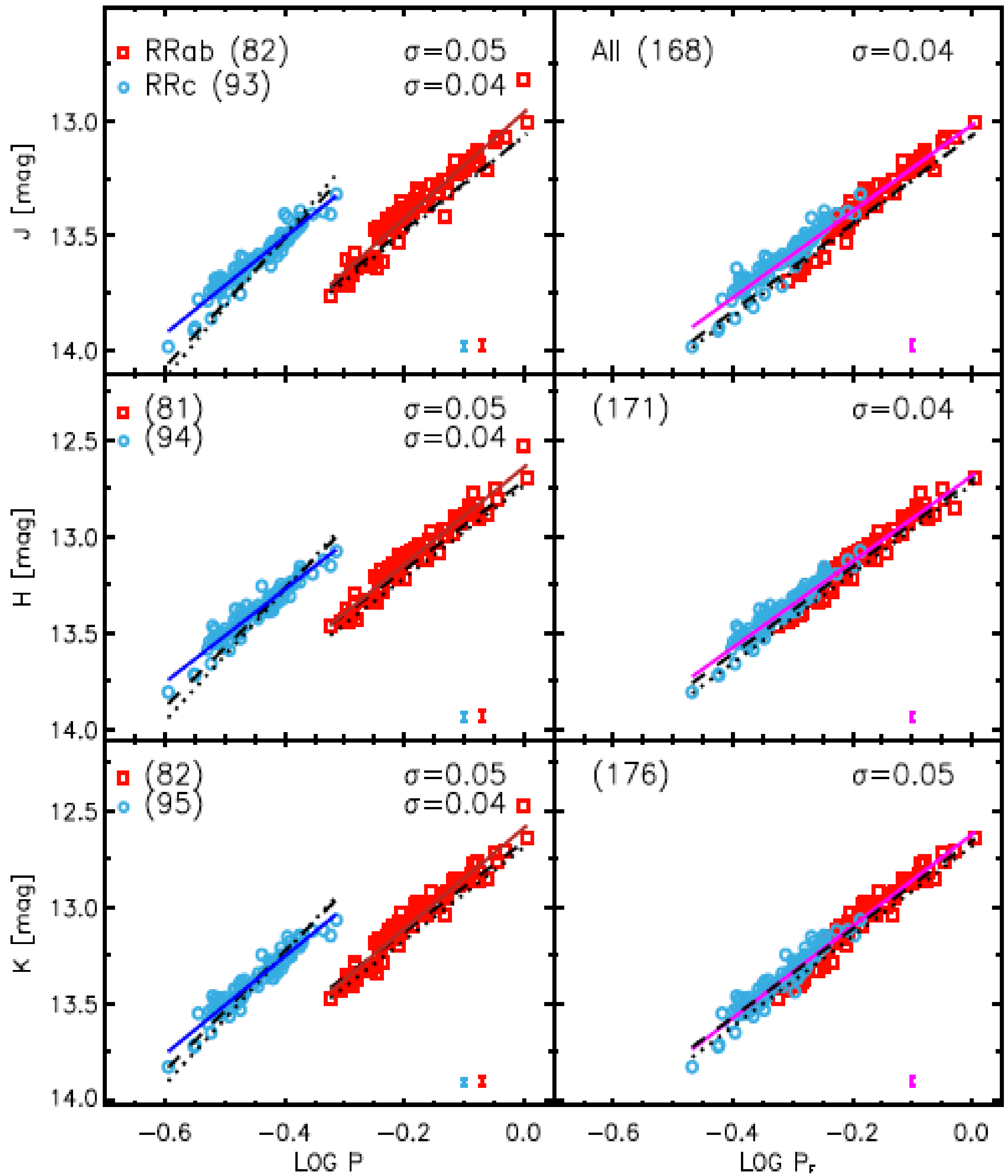
Geometrical calibrators

→Maser galaxy NGC4258 (33% improvement)
→Larger sample of LMC Cepheids + 8 double eclipsing binary
→Larger sample of M31 Cepheids + 2 double eclipsing binary
→HST rigonometric parallaxes from 9 to 15

Ho=73.02 ± 1.79 km / (s Mpc)
final uncertainties from 3.3% to 2.4%

Worth an independent approach (M. Monelli) …..

RR Lyrae as distance

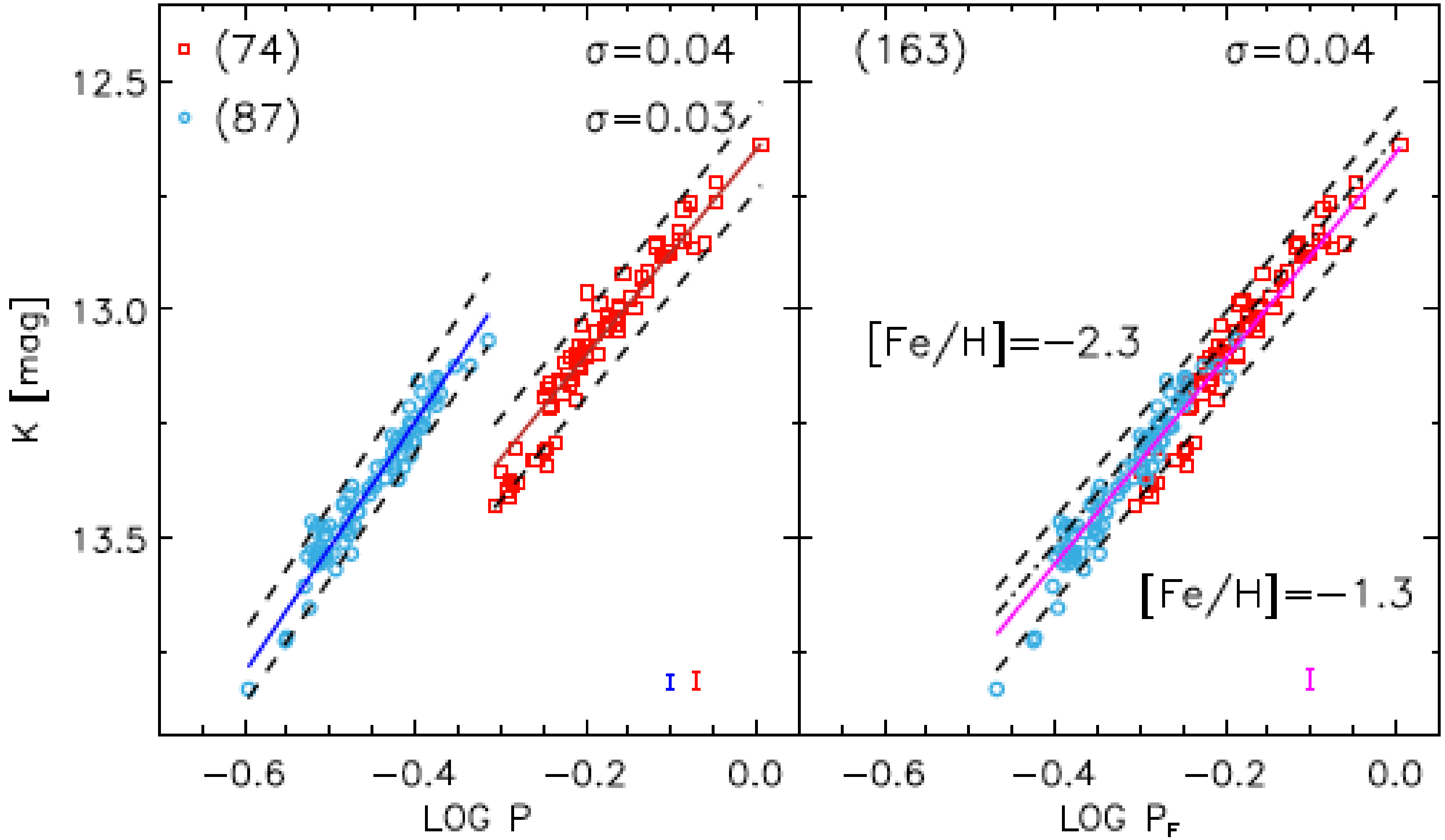


They obey to NIR PL relations due to variations in BCs

The spread at fixed period is intrinsic, it is not caused by photometric error

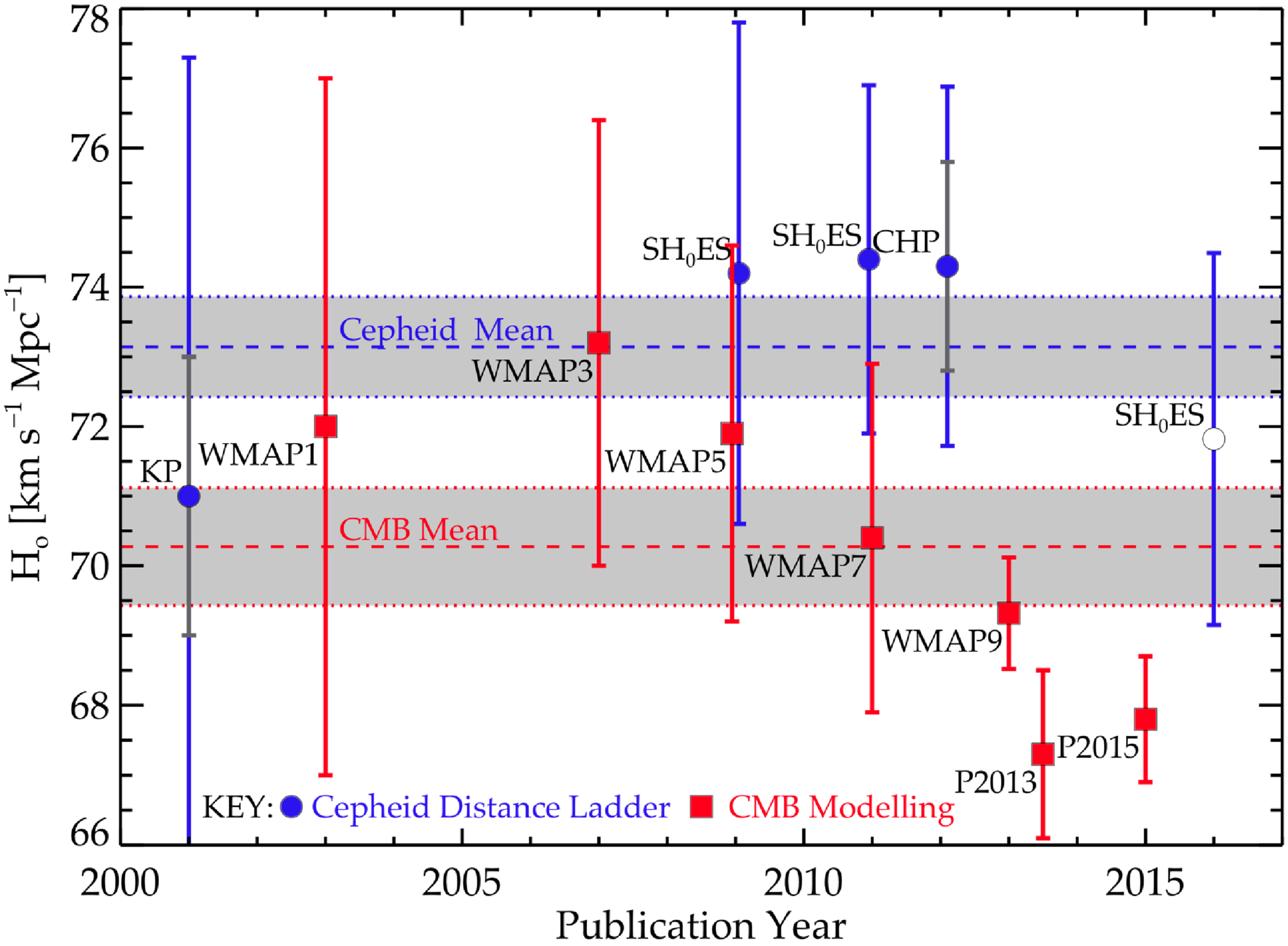
RR Lyrae in ω Cen by Braga + 2017

RR Lyrae as distance indicators



RR Lyrae in ω Cen cover more than 1 dex in iron abundance

Braga + 2017



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

We are approaching Gaia era

	B1V	G2V	M6V
$V-I_C$ [mag]	-0.22	0.75	3.85
Bright stars	5-16 µas (3 mag < V < 12 mag)	5-16 µas (3 mag < V < 12 mag)	5-16 µas (5 mag < V < 14 mag)
V = 15 mag	26 µas	24 µas	9 µas
V = 20 mag	600 µas	540 µas	130 µas

Very accurate geometrical distances and proper motions for primary distance indicators [spring 2018]

Shallower limits for radial velocities & metallicities

Running different large programmes for optical/nir Photometry + Spectroscopy → M. Monelli

Metallicities for variable stars

Are a crucial ingredient to fully exploit Gaia Trig. Parallaxes their impact on the cosmic distance scale and on cosmological parameters

This appears a trivial problem, and indeed …

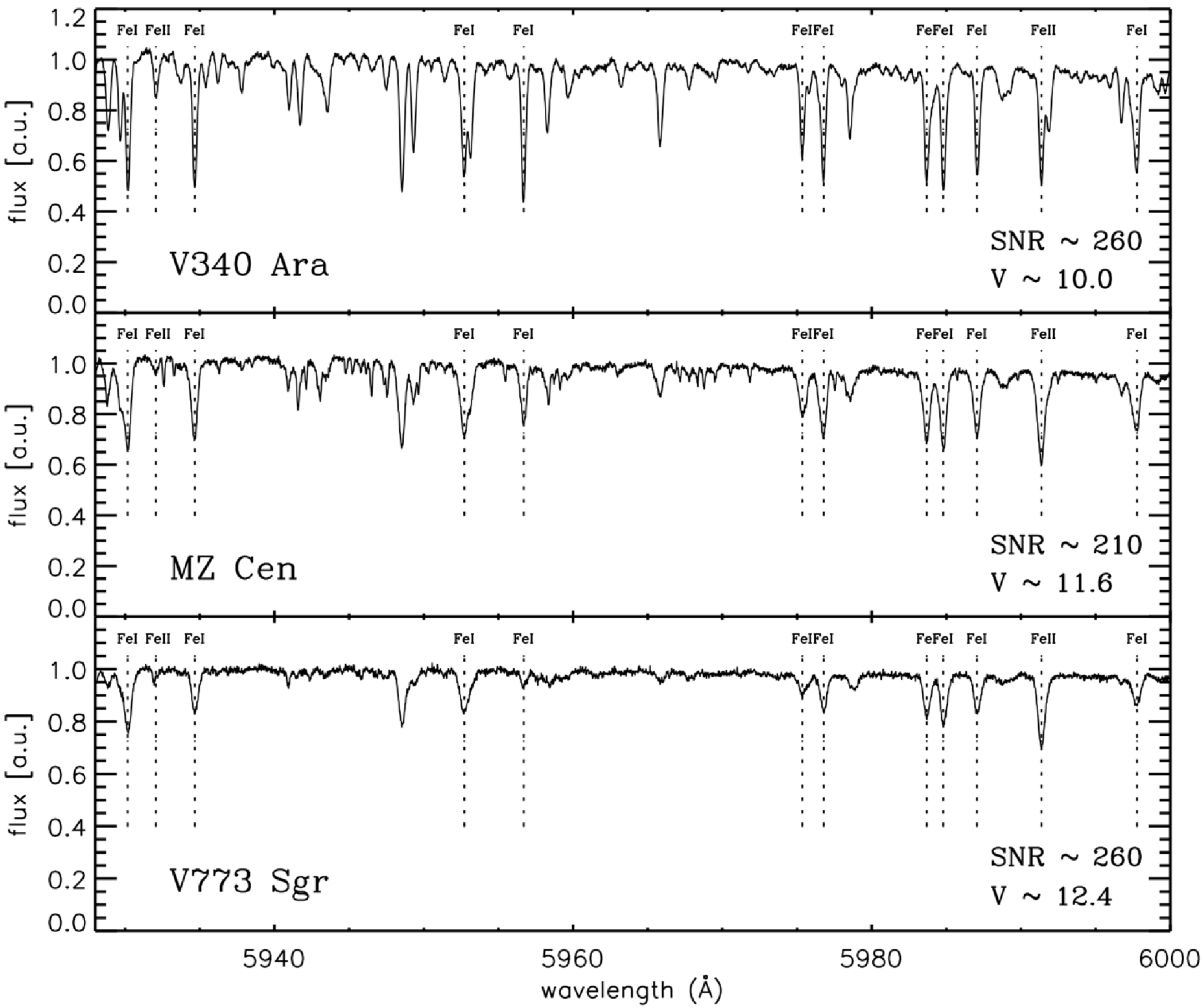
UVES@VLT spectra for ~115 Cepheids

R~38,000
Red & blue arm
Δλ=3750—9500A
t~80—2000 s
S/N > 100-200

From several tens to hundreds of weak FeI lines (EW<120mA)

From several to tens of FeII lines

Multiple spectra for Calibrating Cepheids (~12)



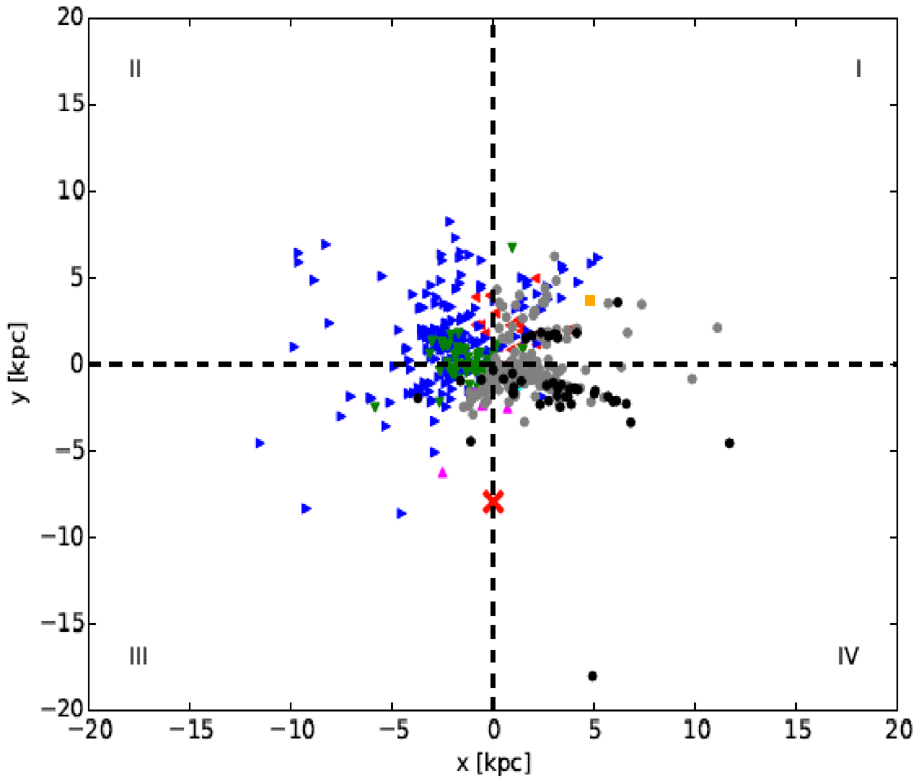
Genovali et al. (2013;2014)

Spectrograph	FEROS	HARPS	UVES	All	
No. of objects	169	9	76	205	~250
Nometal cepheids	8	1	0	8	
Cluster cepheids	11	10	8	14	
Calibrators (>2 spectra)	77	9	17	108	
No. of spectra	486	199	152	837	~1000

A new spin

50% of known Cepheids

10% new



Homogenous temperature & metallicity scale based on EWs → LTE

R≥35,000 - SNR ≥ 100

Approaching a complete census of known Cepheids

Master Thesis by B. Proxauf

…but life is never a bed of roses!!!

RR Lyrae experience nonlinear phenomena:
shock formation & propagation

Solid empirical & theoretical evidence:

UV emission, line doubling, P Cygni

Steeper is the rising branch → stronger the nonlinear phenomena
Well known dating back to Preston & Paczynski (60s)

Observing strategy: short exposures → 4-8m telescopes

possibly avoiding rising branch

Metal abundances for RR Lyrae based on HR optical spectra are only available for ~70 field stars!!!

…This is not a trivial issue!

The cosmic conspiracy concerning the measurement of primordial He abundance (Yp)

Whenever He can be measured (absorption lines) it is useless!!

Early spectral types → already enriched

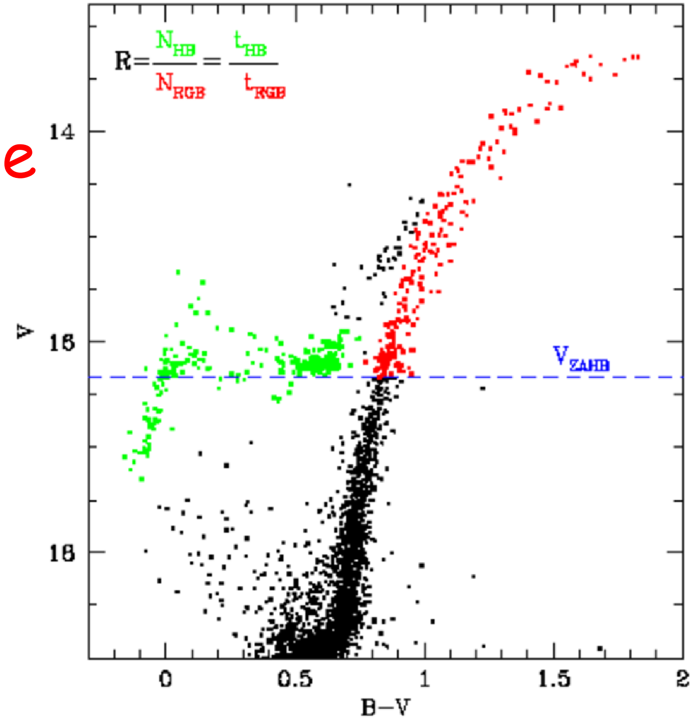
Hot & Extreme HB stars → affected by grav. settling, radiative levitation, evolutionary effects

STELLAR PARAMETERS TO ESTIMATE Yp

R - Parameter (Iben 1968)

A-parameter, RR Lyrae pulsation equation
(Caputo 1983)

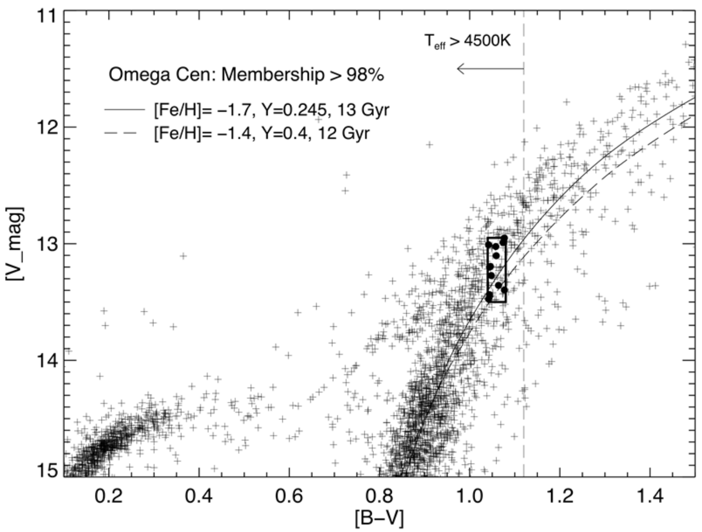
Δ-parameter, difference in V magnitude
Between ZAHB & LMS (Carney 90s)



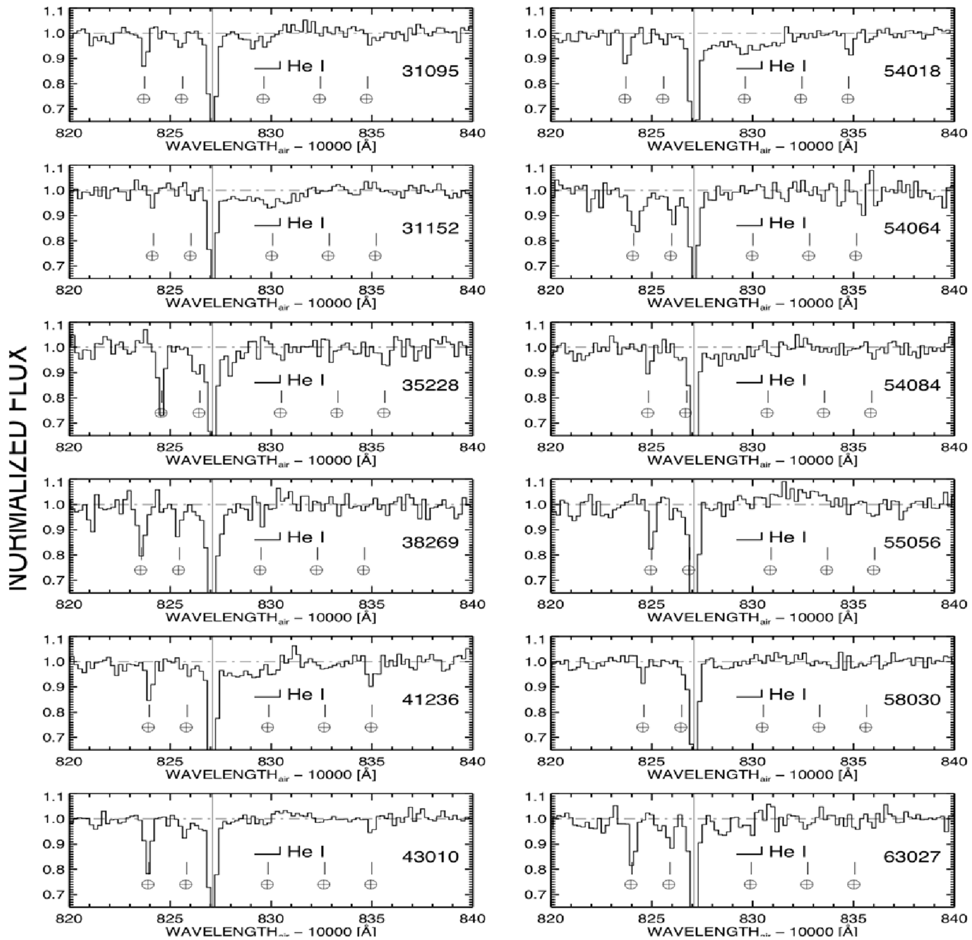
See Sandquist 2000, Zoccali + 2002,
Salaris + 2004, Catelan 2009

….but we should do better ….

He abundance (NIR HeI line at 10830A) for 12 RGs in ω Cen by Dupree et al. (2010)



Teff > 4500 K

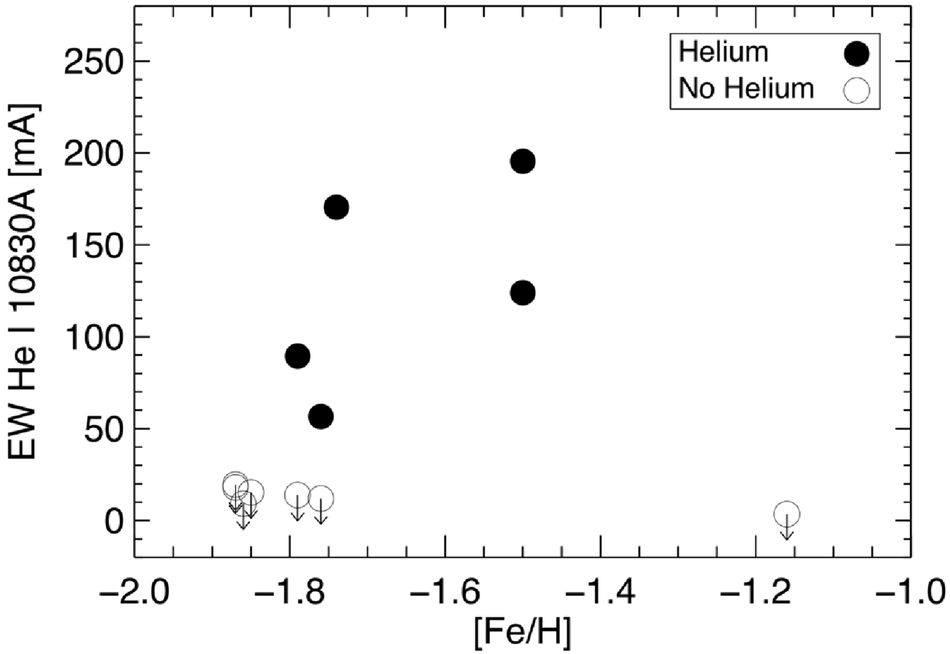


WHY NIR?

Detection of HeI lines in 5 out of 12 RGs

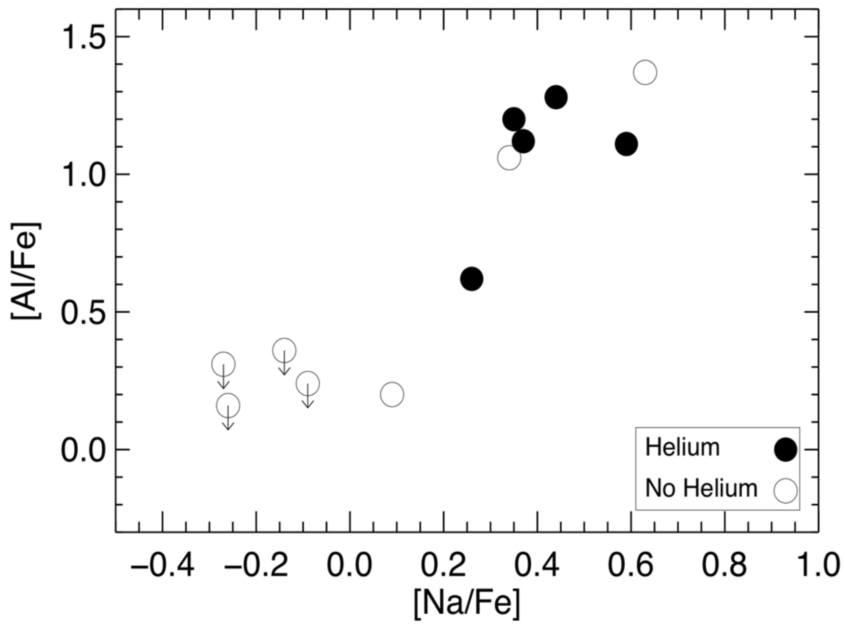
He abundance (NIR HeI line at 10830A) for 12 RGs in ω Cen by Dupree et al. (2010)

WHY NIR?



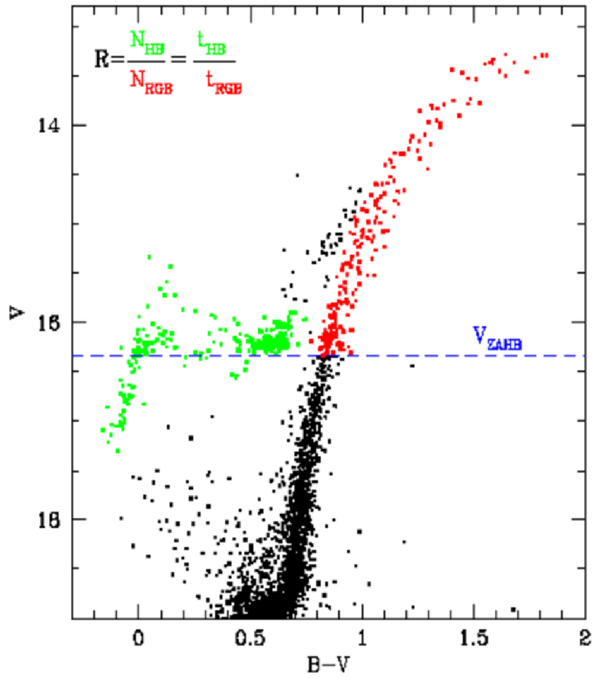
No correlation with [Fe/H]

Correlation with [Al/Fe] & [Na/Fe]



Small number statistics
Solid cromospheric models

RR Lyrae are very promising concerning He content



Hot &Extreme HB stars affected by gravitational settling & radiative levitation [Behr et al. 2000; Behr 2003]

Warm HB stars might not be affected by gravitational settling & radiative levitation, the temperature range is very limited [Villanova et al. 2009]

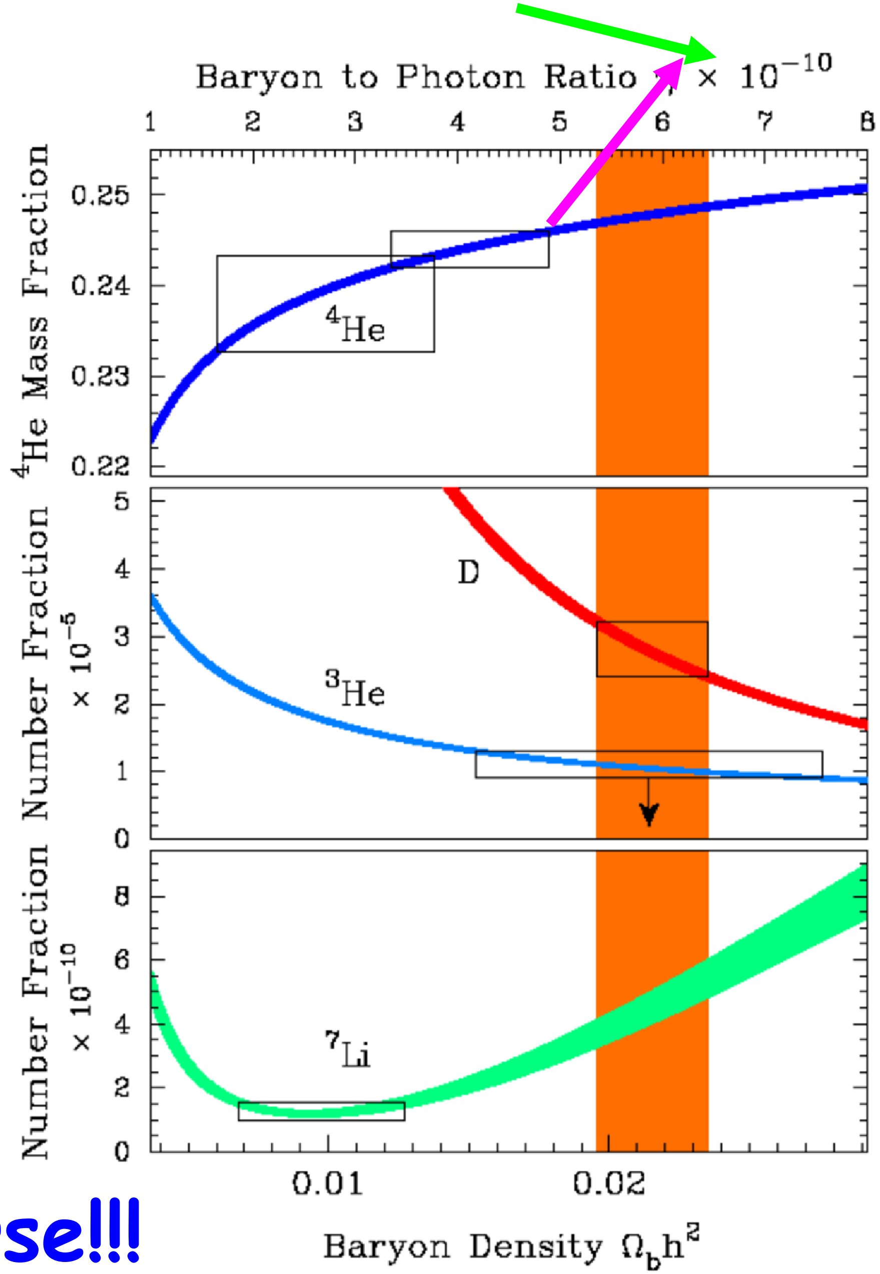
RR Lyrae are not (minimally) affected by gravitational settling & radiative levitation, since a significant fraction of their envelope is convective

Measurements of Yp quite rewarding

Boxes → He recomb. Lines from metal-poor HII regions
Izotov et al. 0.244±0.002
Olive et al. 0.234±0.002

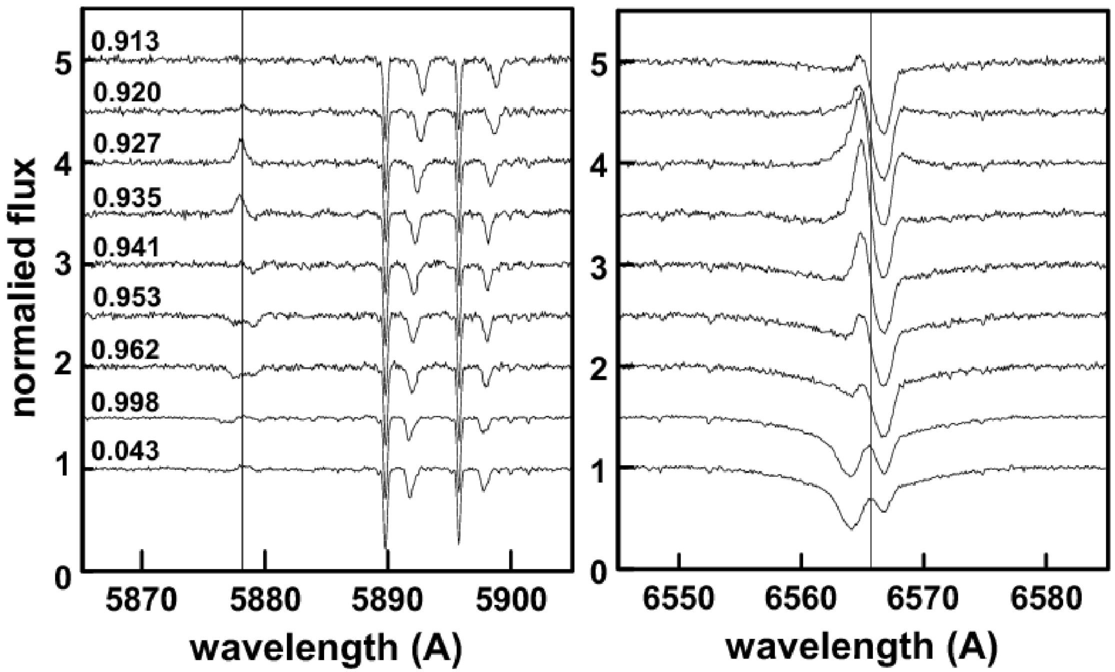
A serious discrepancy only with neutral Li
Charbonnel & Primas 2005)
Boesgaard et al (2005)

But systematics …..



¼ of the mass in the Universe!!!

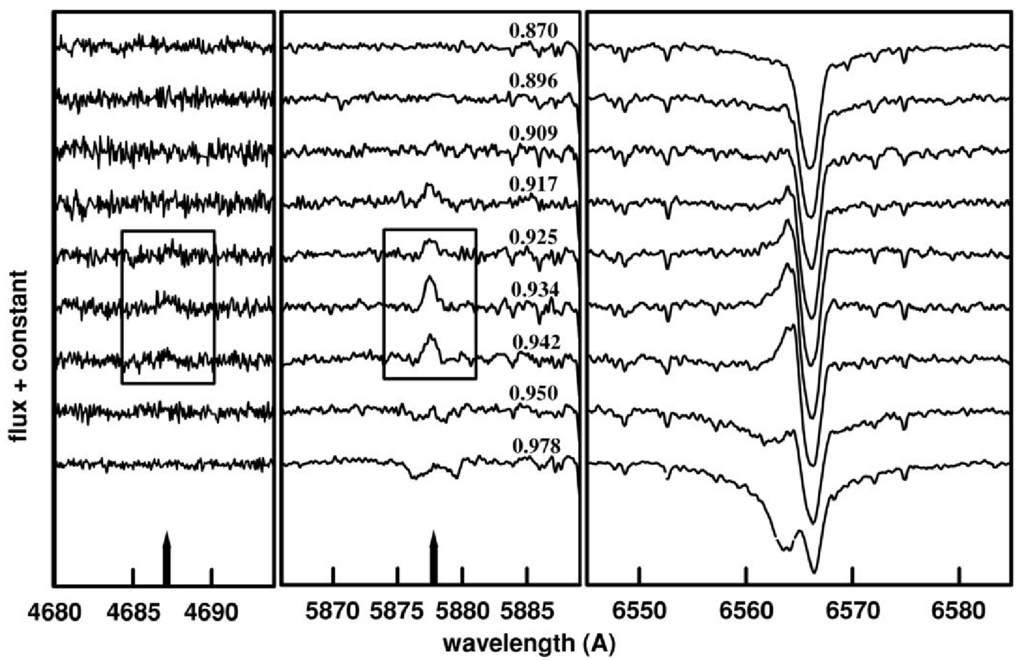
New paths in RR LYRAE He abundance



Preston (2009,2010)

He lines show up at specific phases and then disappear

They are driven by shocks!

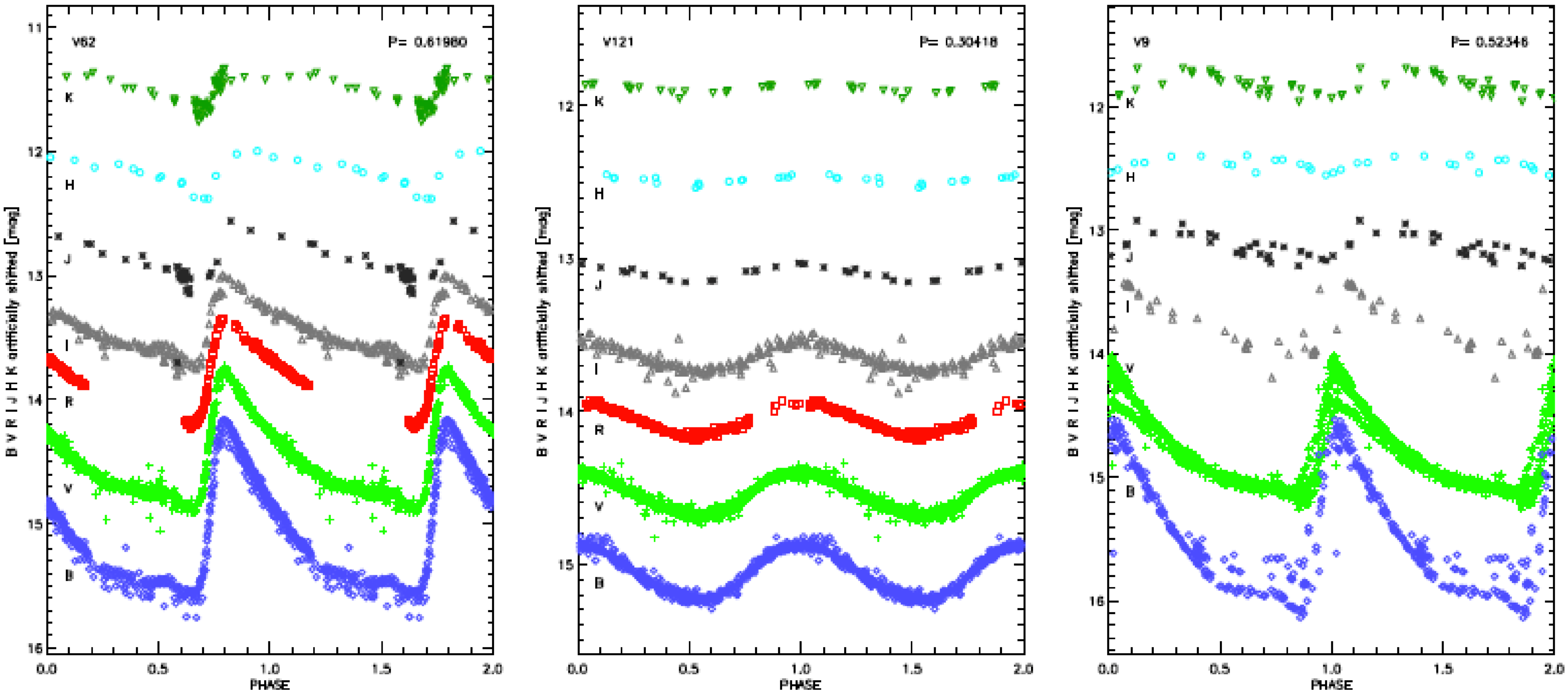


I am desperately looking for atmosphere models that can allow us to measure He abundance in RR Lyrae

New ideas to overcome the problem

Circumstantial empirical evidence

Luminosity amplitudes steadily decrease when moving from optical to NIR bands by a factor 3/4

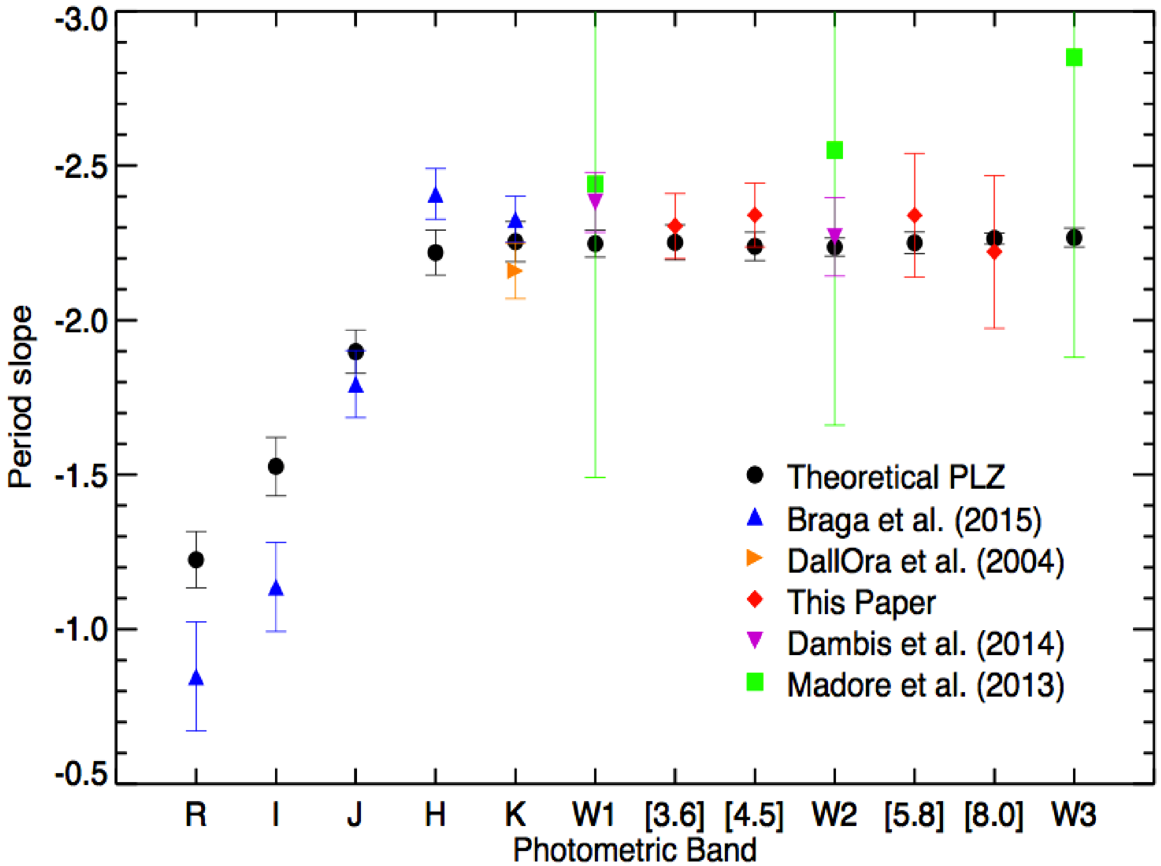


Braga + (2016,2017)

New ideas to overcome the problem

Circumstantial empirical evidence

The slope of the PL relation approaches an almost constant value when moving from optical to NIR



WHY??

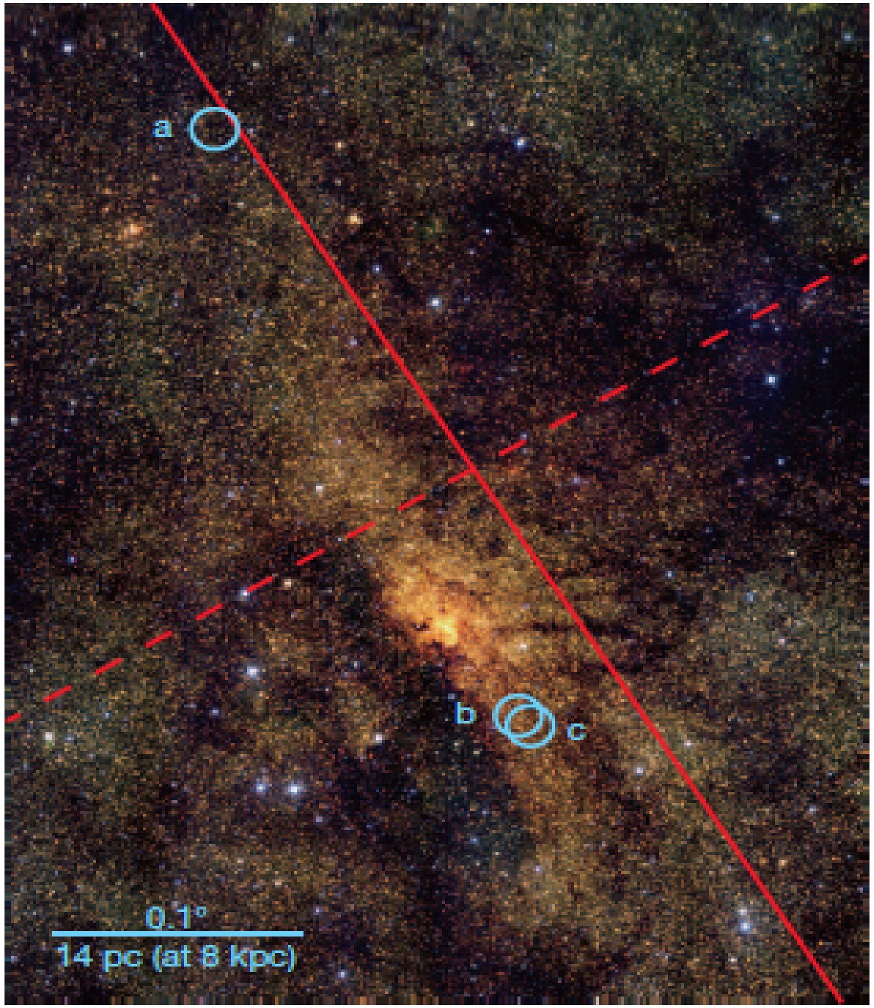
Optical is dominated by temperature variations

NIR is dominated by radius variations

Nonlinear phenomena are mitigated in NIR regime

Neeley + (2016,2017)

Deep into the crowd!



5 Cepheids in the Nuclear Bulge!

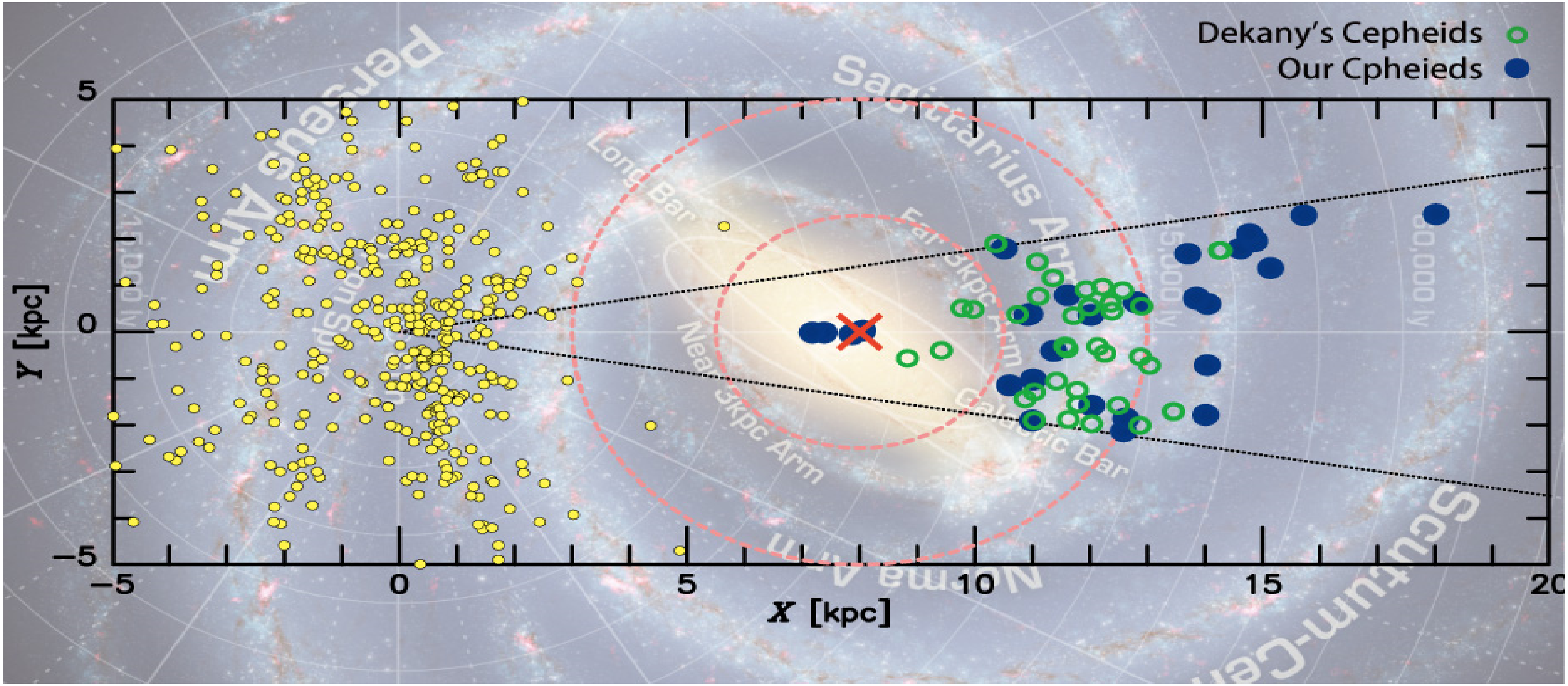
Selective absorption in K-band is
Of the order of Ak~3

This means 30 magnitudes in the
optical

Gaia & LSST are not going to be
killing machines in these environments

Matsunaga + 2011, nature

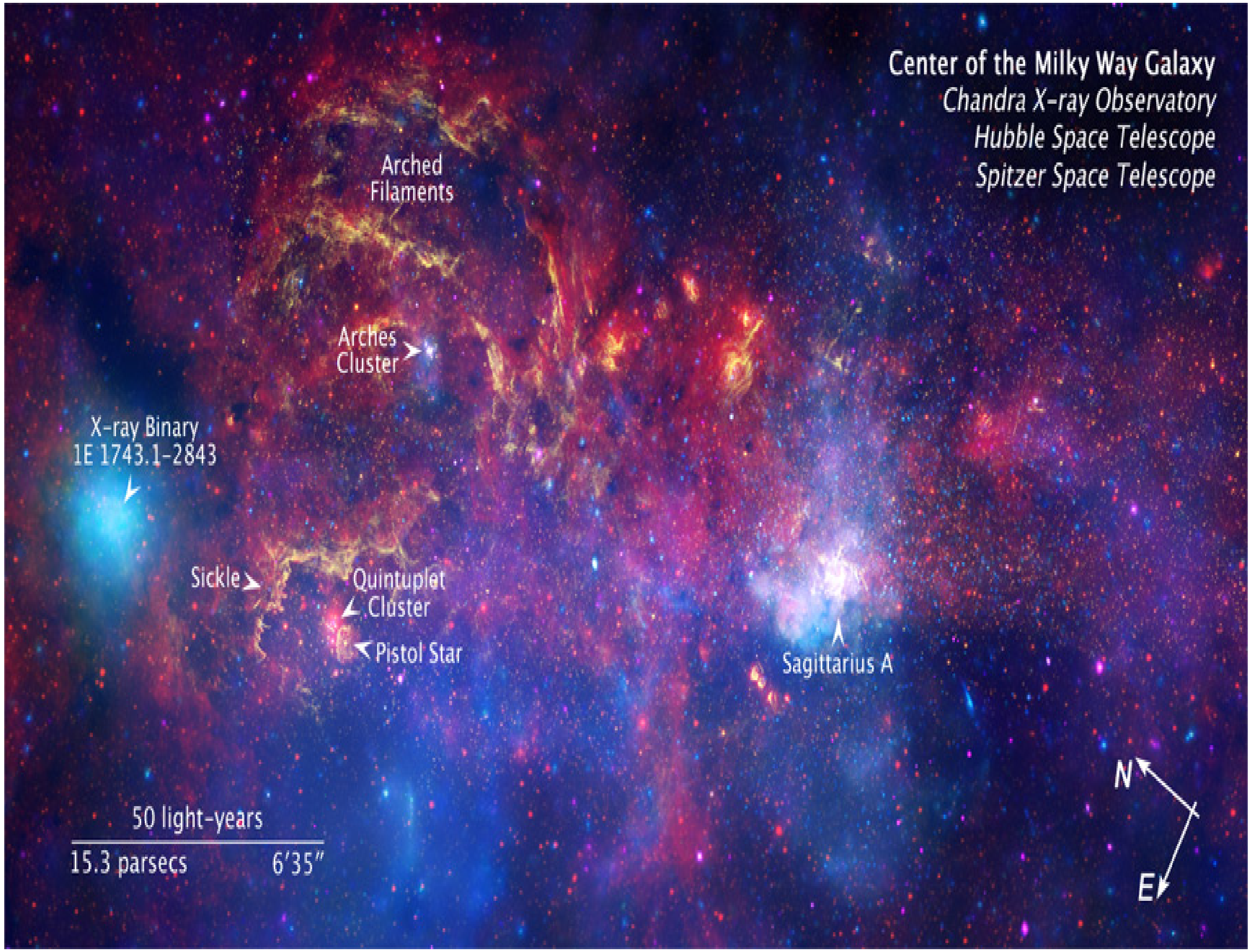
Beyond The Galactic Centre: classical Cepheids



New constraints on stellar populations & Kinematics beyond the Nuclear bulge

Matsunaga + (2016)

Pseudo bulge or classical bulge



RR Lyrae excellent to trace 3D structure of the Galactic bulge

Galaxy formation & Evolution

The role played by the Bar

Zoccali & Valenti 2017

The transition between inner & outer Bulge
metallicity gradients [?] → abundances & kinematics

Conclusions I: (preliminary)

Metal abundances (α, Fe) are fundamental ingredients

to make sense of Gaia & primary distance indicators

Added values in moving from optical to NIR spectroscopy:

Less affected by nonlinear phenomena

Exploring crucial regions of the Galactic spheroid

Yp abundance: cosmic conspiracy … still in act!!!

Continue …. Stay with us the best has to come!!!