Stellar associations: Age scales

How far can we go estimating stellar ages?

David Barrado

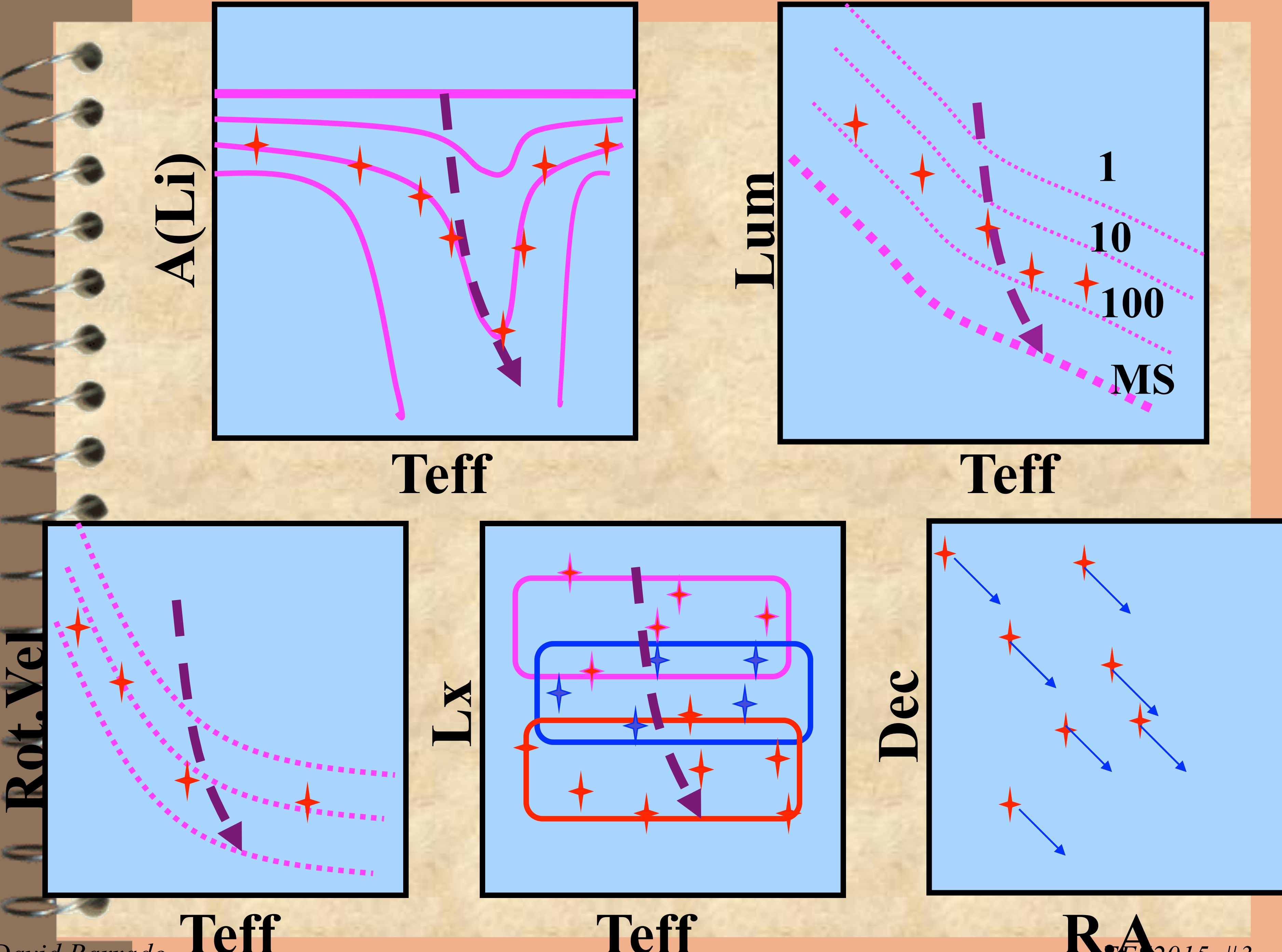
Ecole Evry Schatzman 2015

Les amas d'étoiles : jalons de la physique stellaire et de l'évolution galactique
Stellar Clusters: benchmarks of stellar physics and galactic evolution

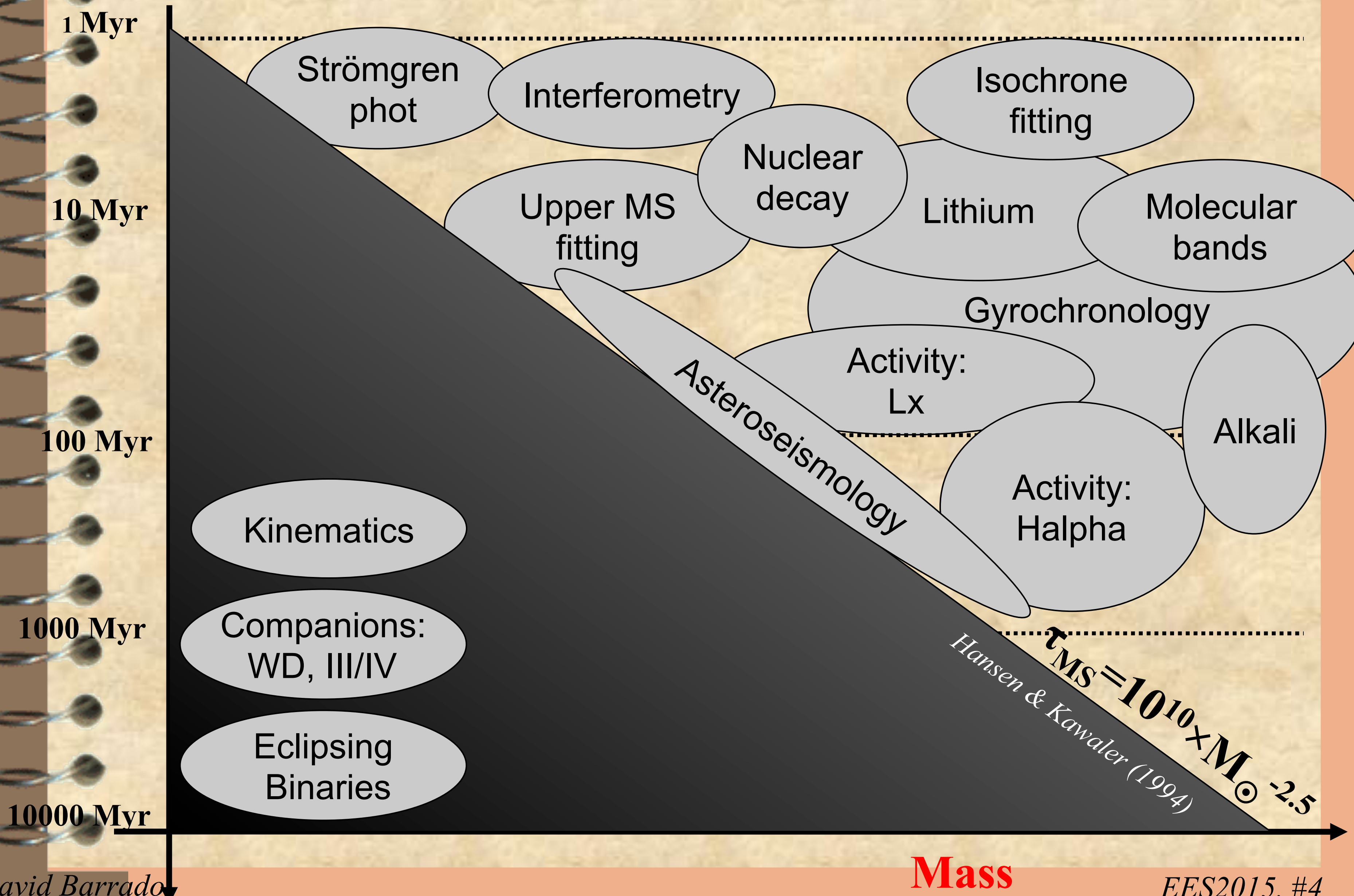
4-9 Oct 2015 Banyuls sur Mer, France

Summary
- The problems we face
-The indicators we use: Lithium, Isochrone fitting
- Examples


Science is a puzzle
But in the case of stellar ages,
we are missing many, many pieces


A(Li)
Teff
Lum
1
10
100
MS
Teff
Rot. Vel
Teff
Lx
Teff
Dec
R.A

The dependence on mass and the age range



Science is also a historical process. We build upon knowledge acquired previously, it is not *ex novo*. Sometimes, a reshuffle is needed in order to get it right.

But we have to keep intact the whole structure (sometimes we do not have to)

Some key issues

Models:
- Intrinsic problems (A.Boden, B. Chaboyer, D. Terndrup)
- Different sets of models, with different answers

Comparing theory with observational properties
- From (Teff,Lum) to (mag,colors): BC, Temp scales
- Stars are **individuals**: spots, accretion, disks, the effect of the initial conditions, rotation/activity (K. Stassun), reddening, metallicity, individual distances (a cluster has a size and a shape)
- HR uncertainties (L. Hillenbrand)

Other problems
- The star formation: instantaneous or not?
- Can we assume coevality for star clusters and MGs?

From the **Cool Stars, Stellar Systems, and the Sun** meeting in 2006, CS14

Stellar Model cocktail: ingredients

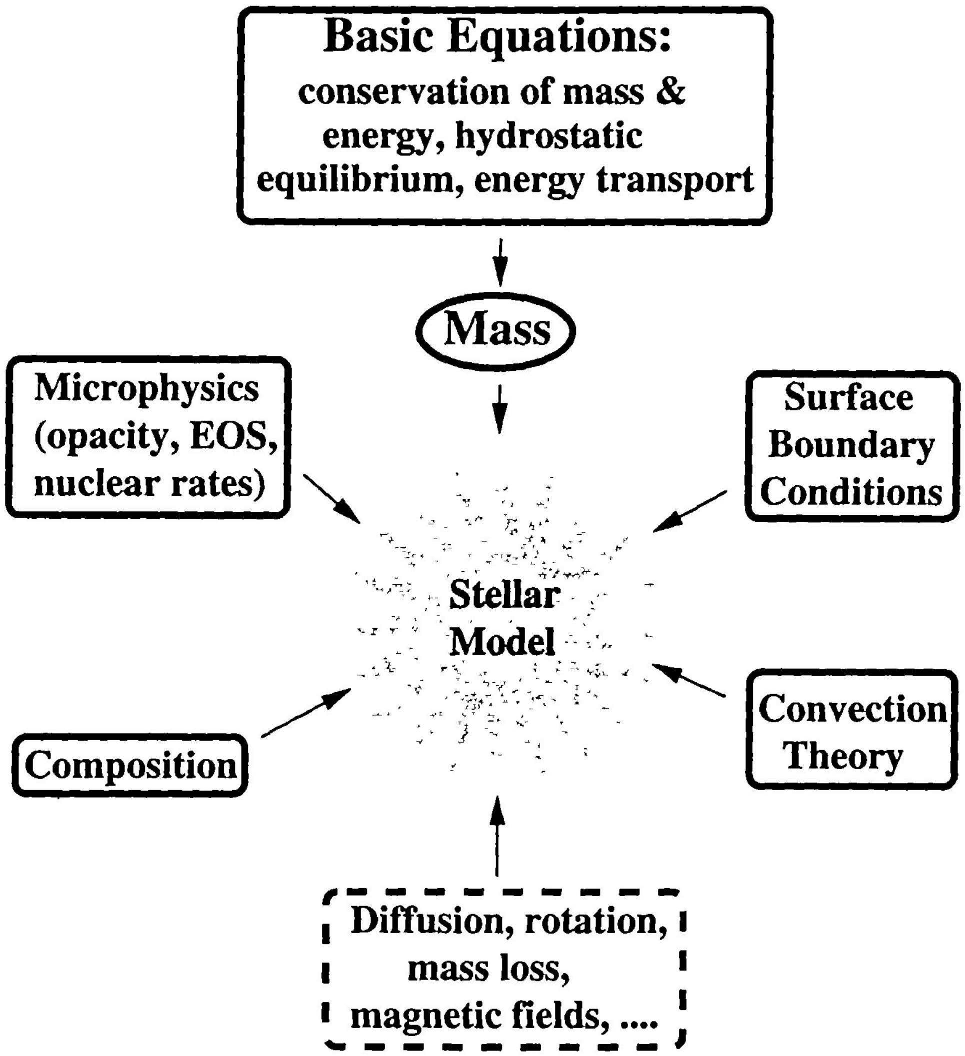
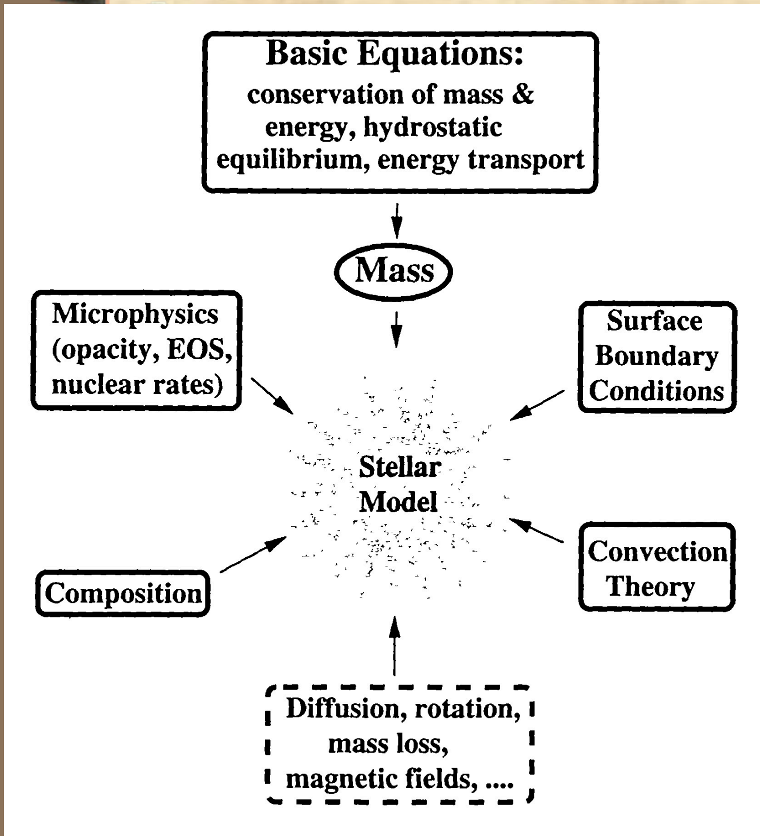


Figure 2. Overview of the important ingredients needed to create a theoretical stellar model.

Chaboyer (2001)

The "perfect" cocktail: stellar models



Chaboyer 2001

- Uncertainties
- Confronting theory with observations

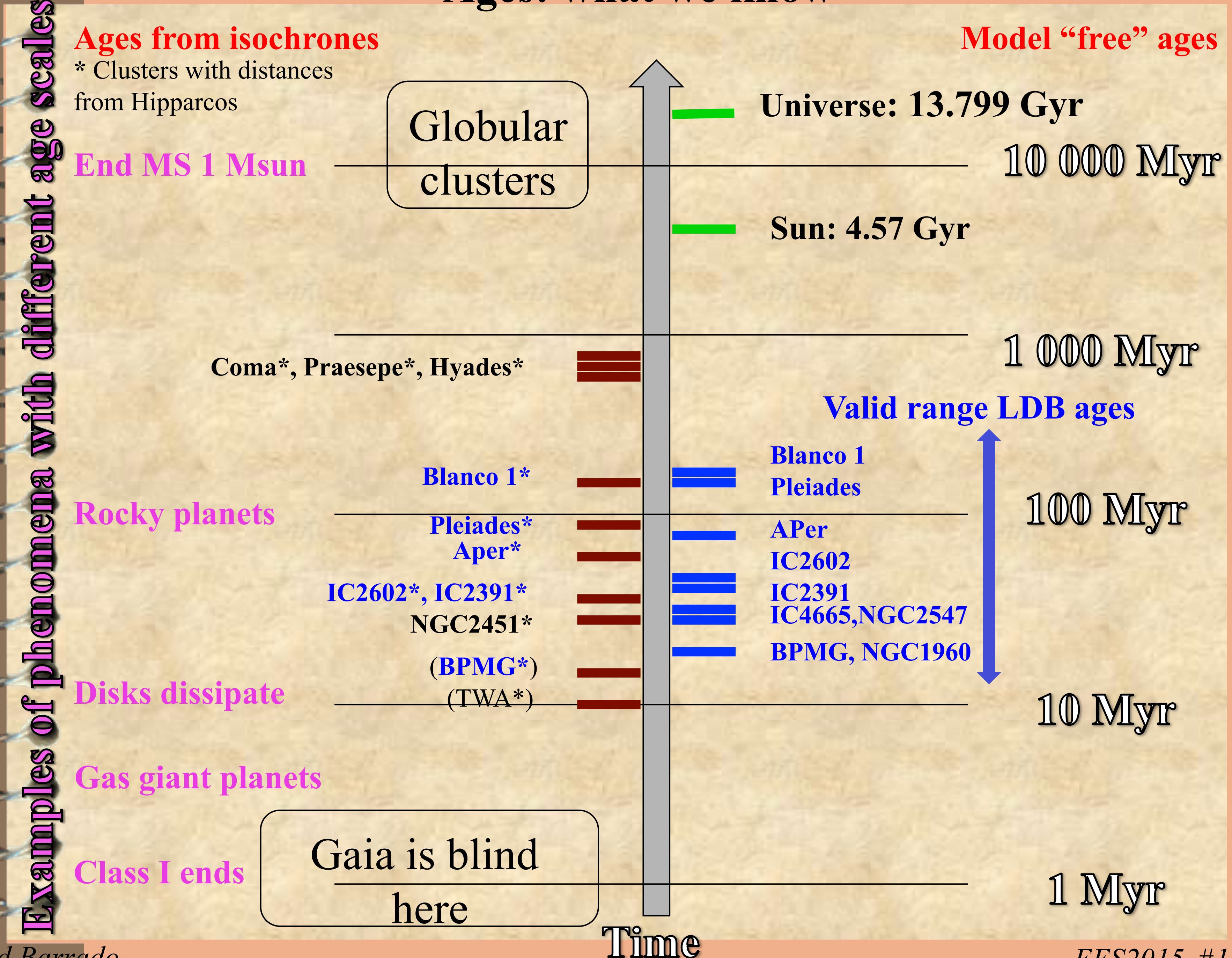
Different age scales: epistemology

(the study or a theory of the nature and grounds of knowledge especially with reference to its limits and validity)

Absolute anchors

- **13.799±0.021 billion years** within the Lambda-CDM concordance **model** (Planck Collaboration (2015), arXiv: 1502.01589.
- The Sun and its age of **4.57 Gyr**. Specifically the remnants of the formation of the Solar System. i) computer **models** of stellar evolution and through nucleocosmochronology (Bonanno et al. (2002), A&A 390, 1115), ii) **radiometric date** of the oldest Solar System material, at 4.567 billion years ago (Amelin et al. (2002), Science 297, 1678; Baker et al. (2005), Nature 436, 1127).

Ages: what we know



Age-determination methods for clusters

"*Basically age estimations of open clusters are based on:*

(1) the turn-off colours or earliest spectral types,

(2) morphological parameters,

(3) isochrone fitting,

(4) synthetic diagrams,

(5) the pre-main sequence stars and turn-on point,

(6) the Lithium transition in substellar objects.

The latter method is very recent and has been applied so far to only three open clusters. All methods are essentially based on ages given by models: evolutionary models for the upper main sequence, contraction models for pre-main-sequence stars and models of fully convective objects for very-low-mass stars and brown dwarfs".

J.-C. Mermilliod (2000)

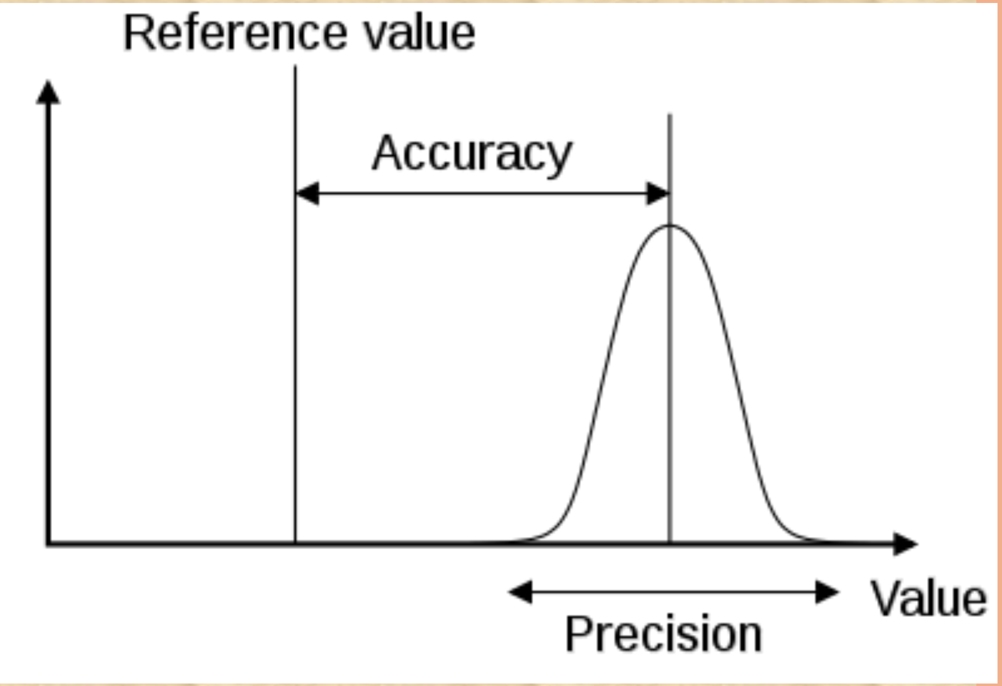
Methods: classification

I) Fundamental

II) Semi-fundamental

III) Model dependent

IV) Empirical



Many times only intrinsic errors are taken in to account. Beware!

Soderblom (2010); Soderblom et al. (2013)

Some historical perspective: the meter and the size of Earth

- After the French revolution, the directory ask the Academy of Science to provide a standard distance measurement: the meter.
- P. F. Méchain and J.-B. Delambre measured by triangulation the meridian from Dunkirk (*Dunkerque)* to Barcelona during several years
- The computations were tied to the determination of the latitudes of the extremes. Several stars were used and a very **precise** new instrument, the circle of repetition by J.-C. de Borda.
- Unfortunately the methodology itself was **not so accurate**.
- Méchain knew there was a problem (essentially in his several measurements of the latitude of Barcelona). but was unable to understand the origin and to correct it. He struggled for years and tried not to publish his data.
- The total length of the meridian is 10,002,290 meter.

As a curiosity, France and Spain were at war then, but both governments agreed to continue with the scientific operations.

How to estimate the age of star?

My own practical scale:

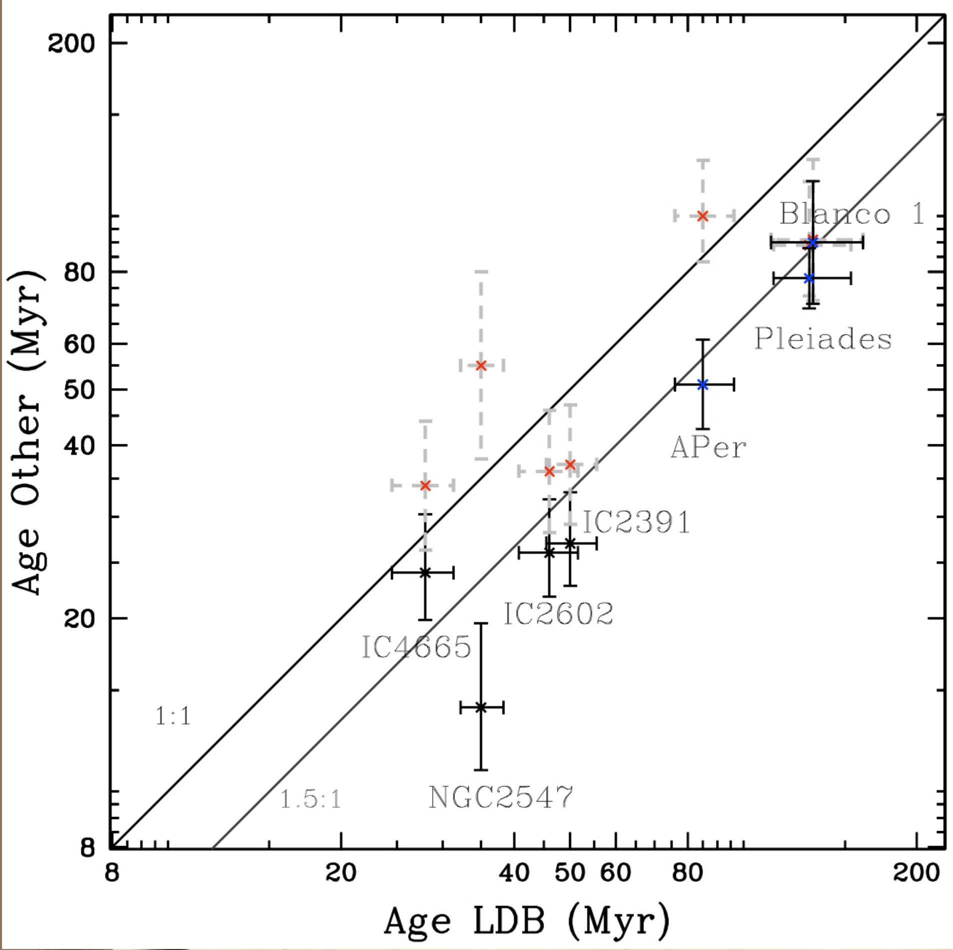
<u>Primary indicators</u>.-

- Upper Main Sequence Fitting
- Isochrone fitting
- Eclipsing binaries and related methods
- Spectral features (gravity)
- Lithium abundance
- ……..

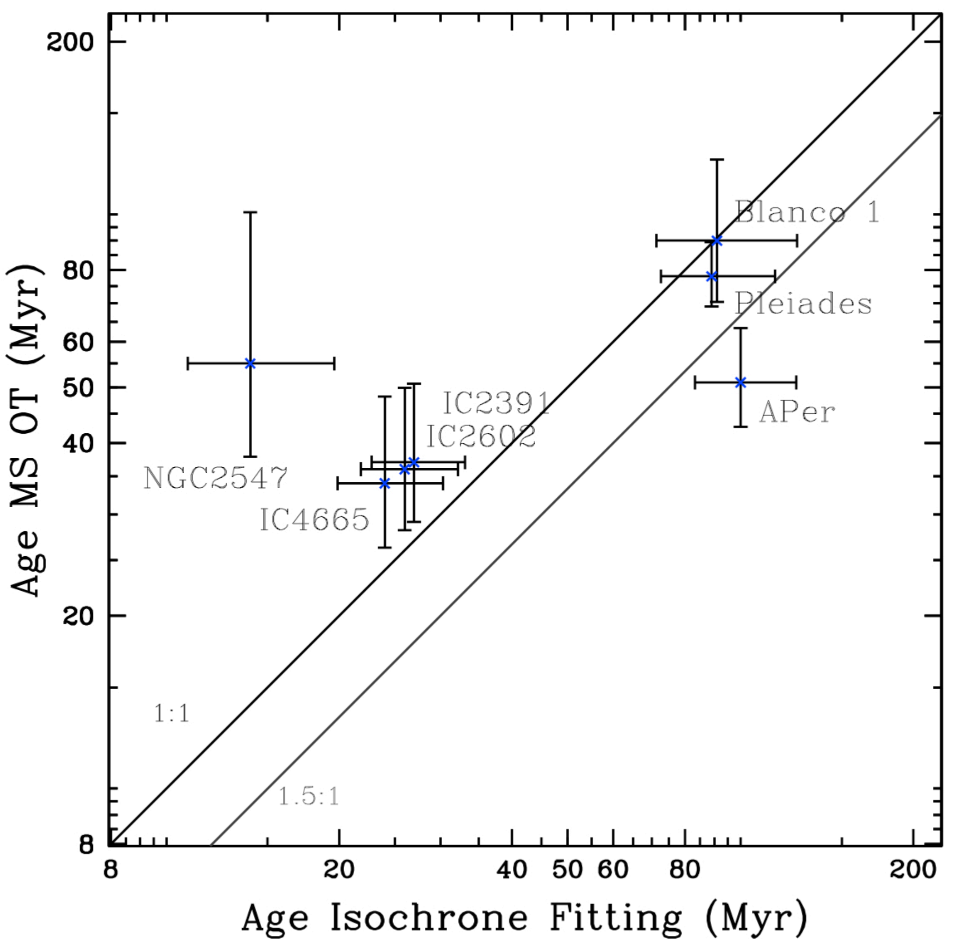
<u>Secondary indicators (additional uncertainties)</u>.-

- Stellar activity (X-ray, Halpha)
- Rotation
- Physical association to an association, to another star or to Moving Group
- ……..

Age scales

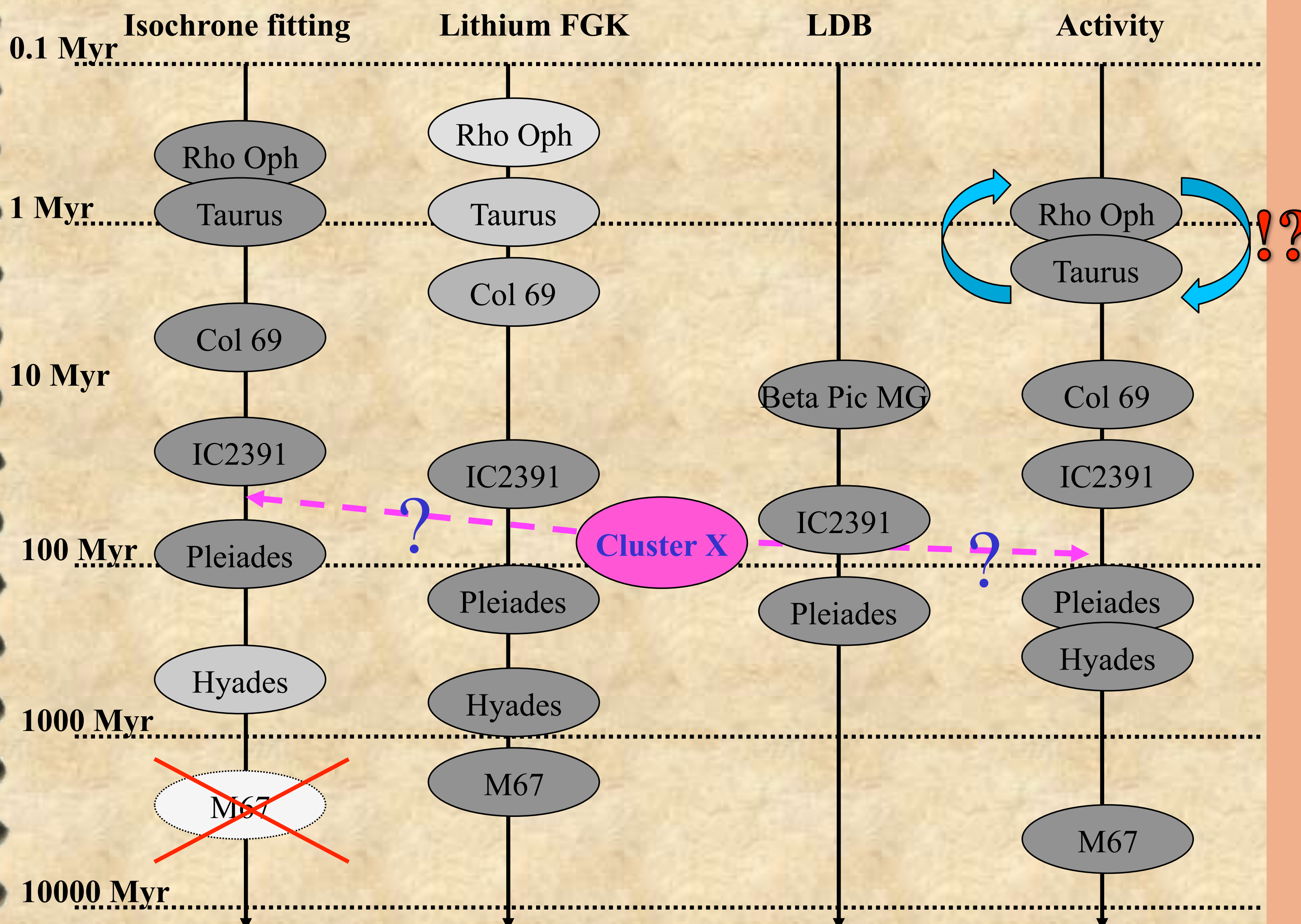


Age Other (Myr)
Age LDB (Myr)
200
80
60
50
40
20
8
20
40
50
60
80
200
Blanco 1
Pleiades
APer
IC2391
IC2602
IC4665
NGC2547
1:1
1.5:1



Age MS OT (Myr)
Age Isochrone Fitting (Myr)
200
80
60
50
40
20
8
20
40
50
60
80
200
Blanco 1
Pleiades
APer
IC2391
IC2602
IC4665
NGC2547
1:1
1.5:1

Age scales and autoconsistancy



Methods

Isochrone fitting: open clusters

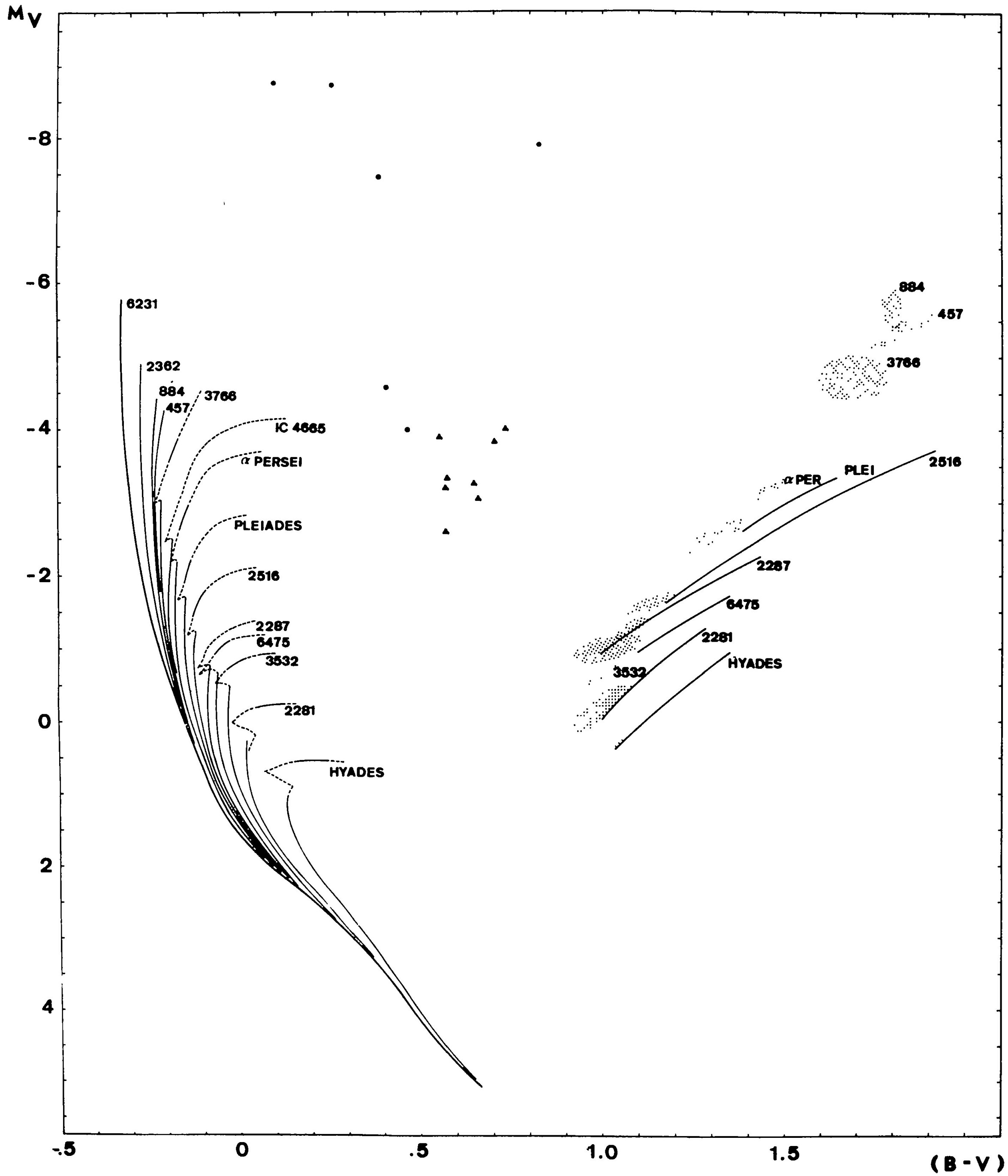


Fig. 1. Composite HR diagram presenting the sequences deduced from 14 pairs of composite diagrams (Mermilliod, 1980a). The age groups are designated by the name of the most representative cluster. The darkened areas show the positions of the red giant concentrations. Triangles stand for Cepheids and dots for non-Cepheid stars in the Hertzsprung gap. The dashed lines have been adapted from models by Maeder.

Mermilliod et al. (1981)

Please, **read old papers**. Do no re-invent the wheel: you will save a lot of time and learn many useful facts

Beta Pic MG: CMD and age

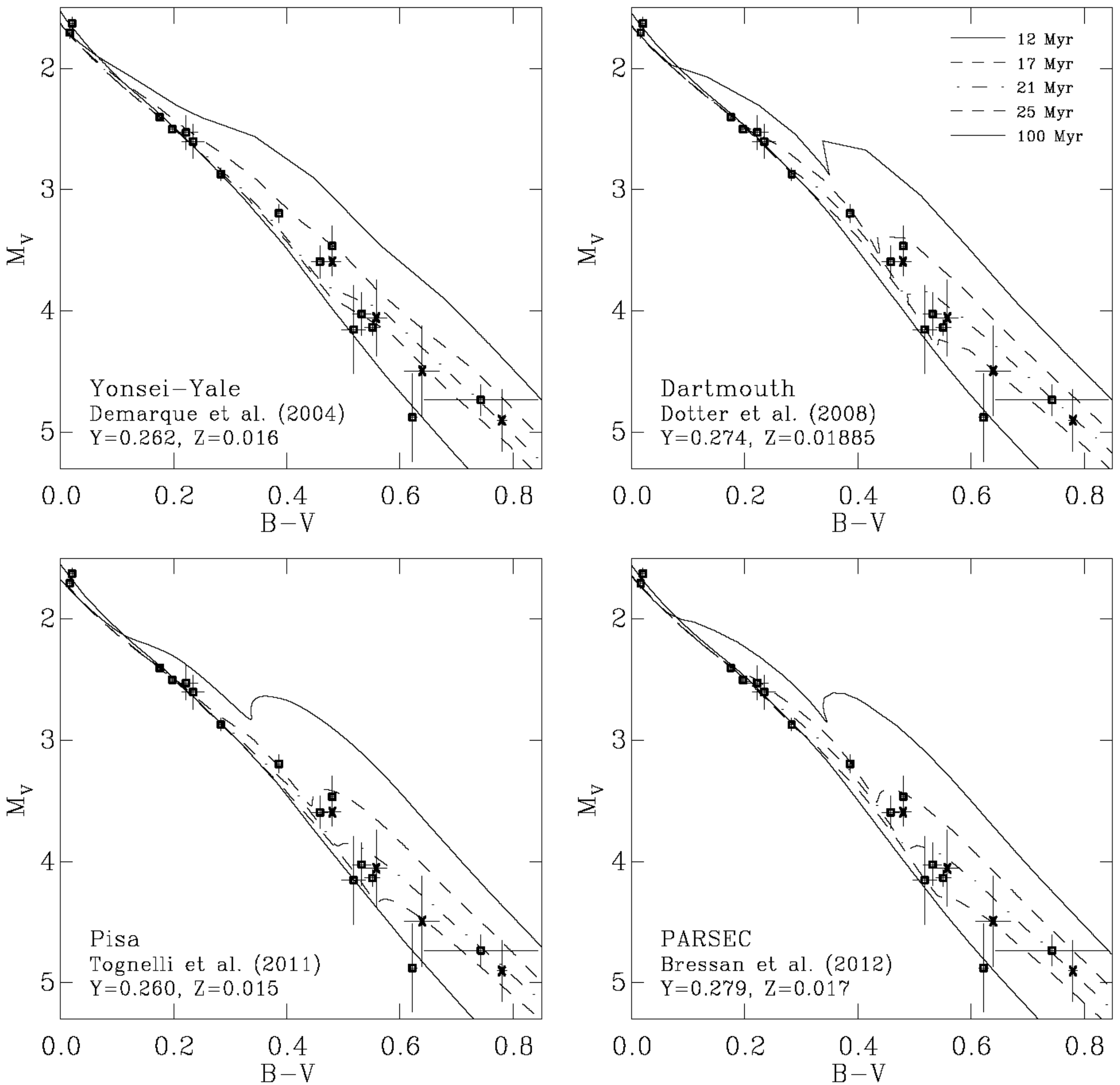
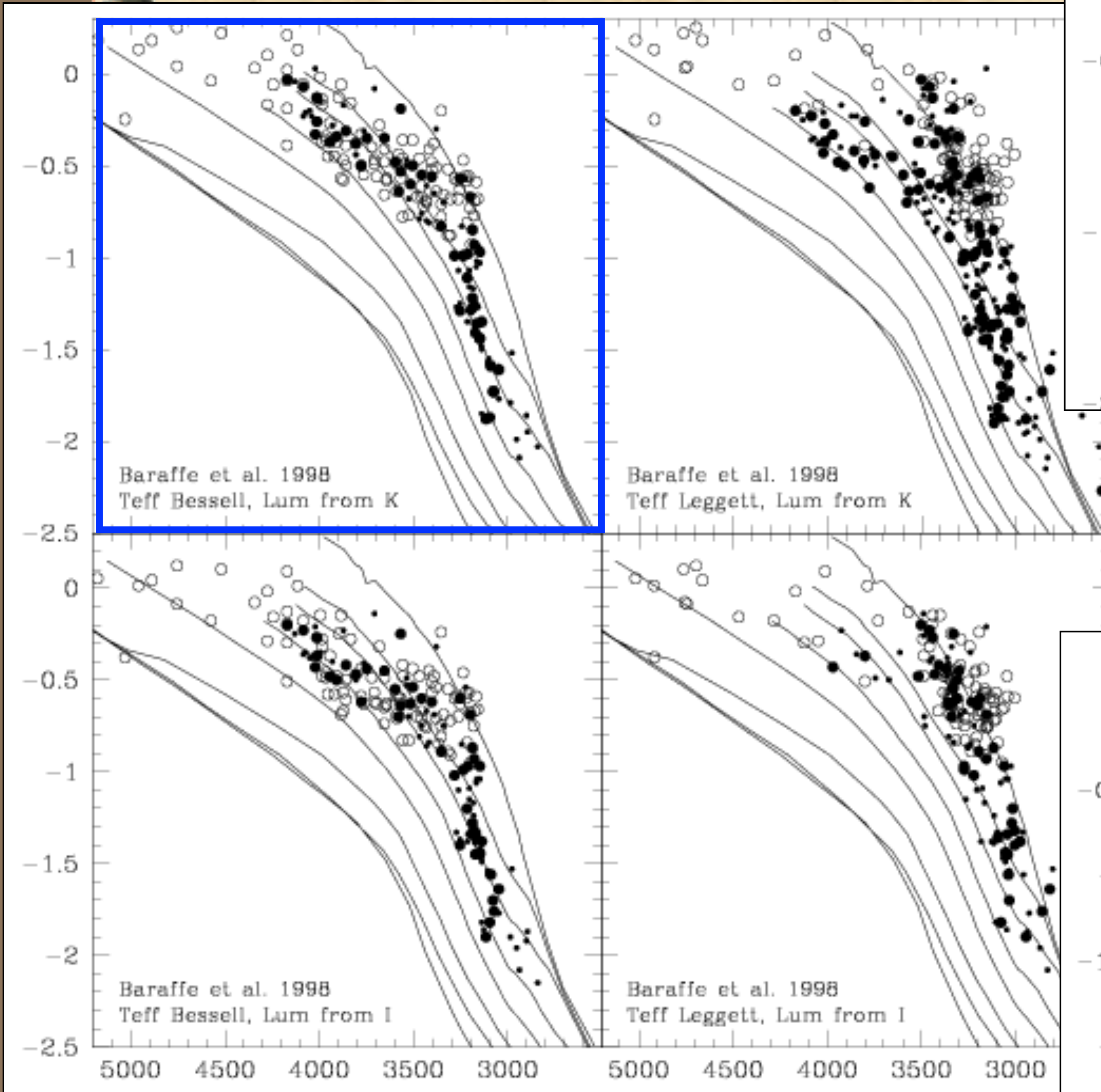
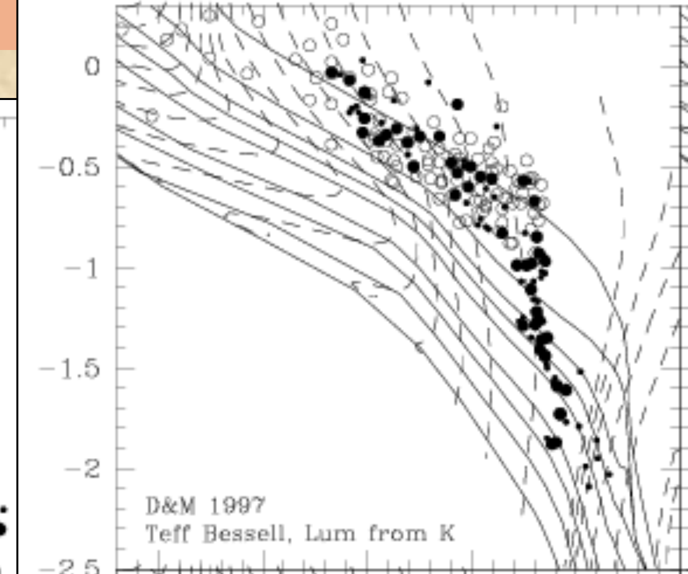


Figure 6. $M_V, B-V$ CMDs of the A-, F- and G-type BPMG members compared against the Yonsei-Yale (Y^2; Demarque et al. 2004) (*top left*), Dartmouth (Dotter et al. 2008) (*top right*), Pisa (Tognelli et al. 2011) (*bottom left*) and PARSEC (Bressan et al. 2012) (*bottom right*) model isochrones. In all panels the upper continuous line represents the position of the single-star sequence for the oft-quoted age of 12 Myr. Below this, the dot-dash and bounding dashed isochrones represent the position based on the LDB age of 21 ± 4 Myr according to Binks & Jeffries (2014). Finally, the lower continuous line denotes the position for an age of 100 Myr. The squares represent the "classic" sample of members as defined by Zuckerman & Song (2004) whereas the crosses denote additional members from Malo et al. (2013).

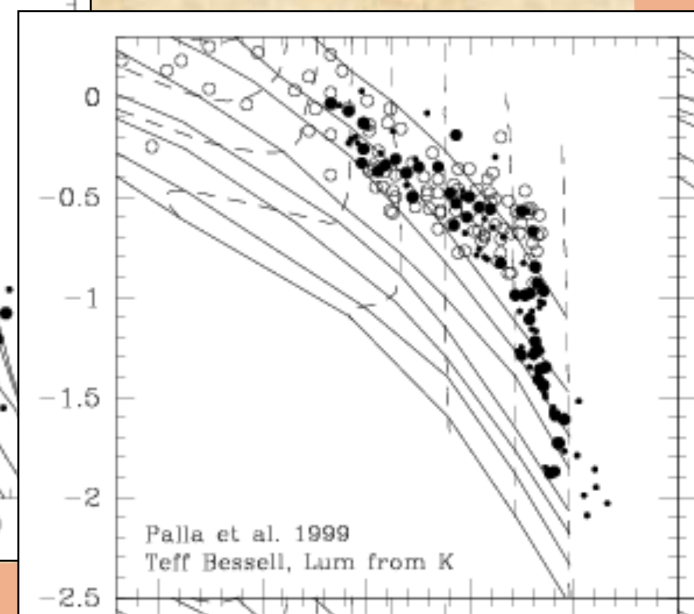
Mamajek et al. (2014)

F- and G-type isochronal age **22** Myr (±3 Myr statistical, ±1 Myr systematic)



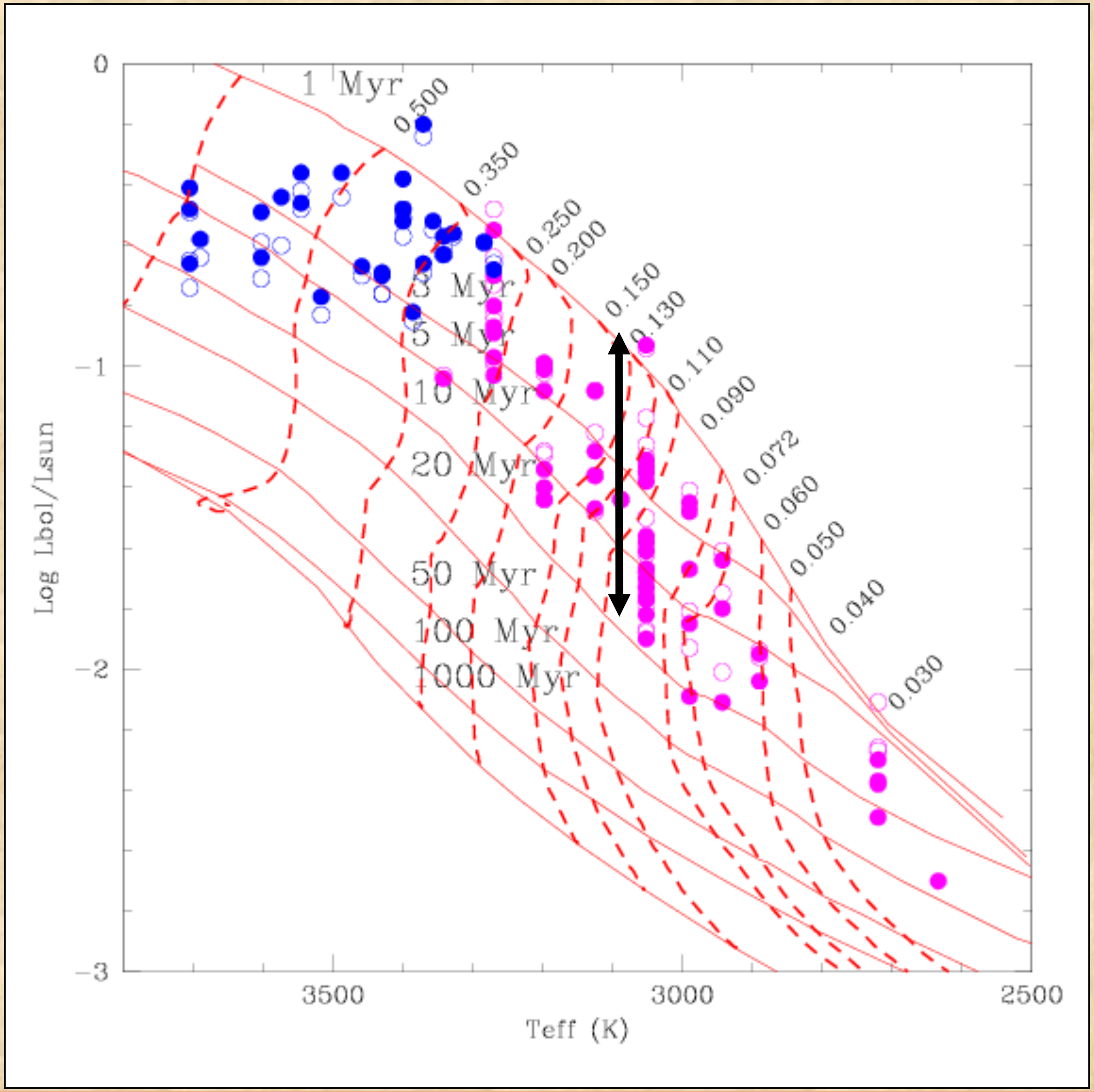


- From mag to Lum,Teff
- Which model?



David Barrado

The HR diagram and isochrone fitting: Intrinsic spread? Can we assume **coevality**?



Even if we have the perfect models, and the perfect conversion …

1-10 Myr for the same dataset, and binarity cannot take care of this.

Barrado y Navascués et al. (2004)

Novel techniques to get optimal values

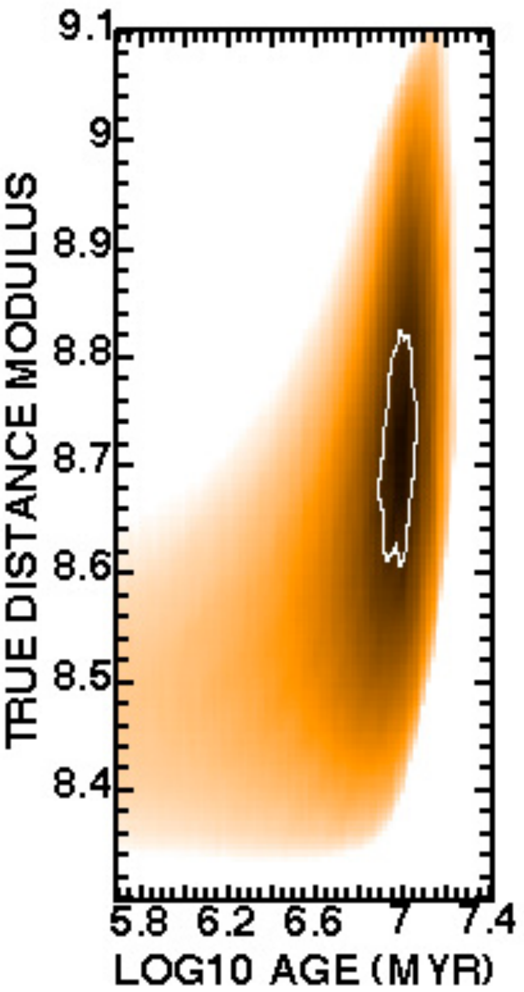


Figure 2. The τ^2 grid for Cep OB3b. The contour is at the 68 percent confidence level.

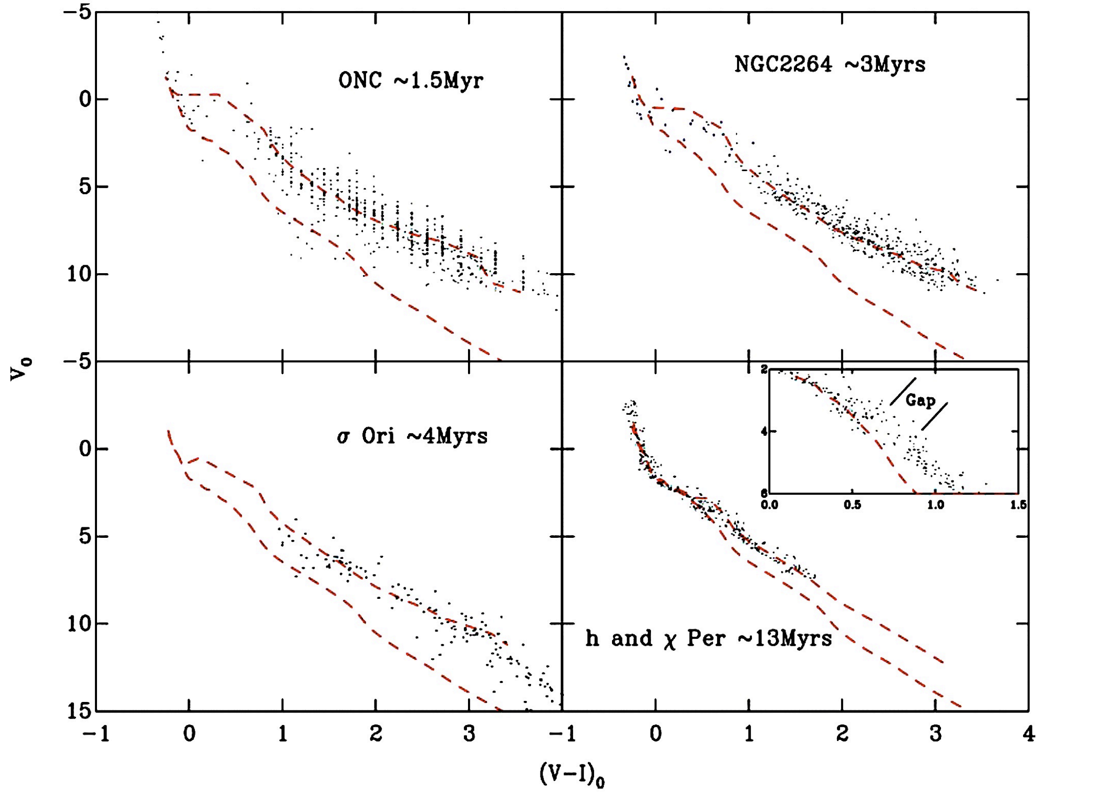


Figure 1. The CMDs for a selection of young groups in absolute magnitude and intrinsic colour. In each case the lower red dotted line is the position of the MS, the upper an appropriate Siess et al (2000) isochrone.

Table 1. The Empirical Isochrone Age Ladder.

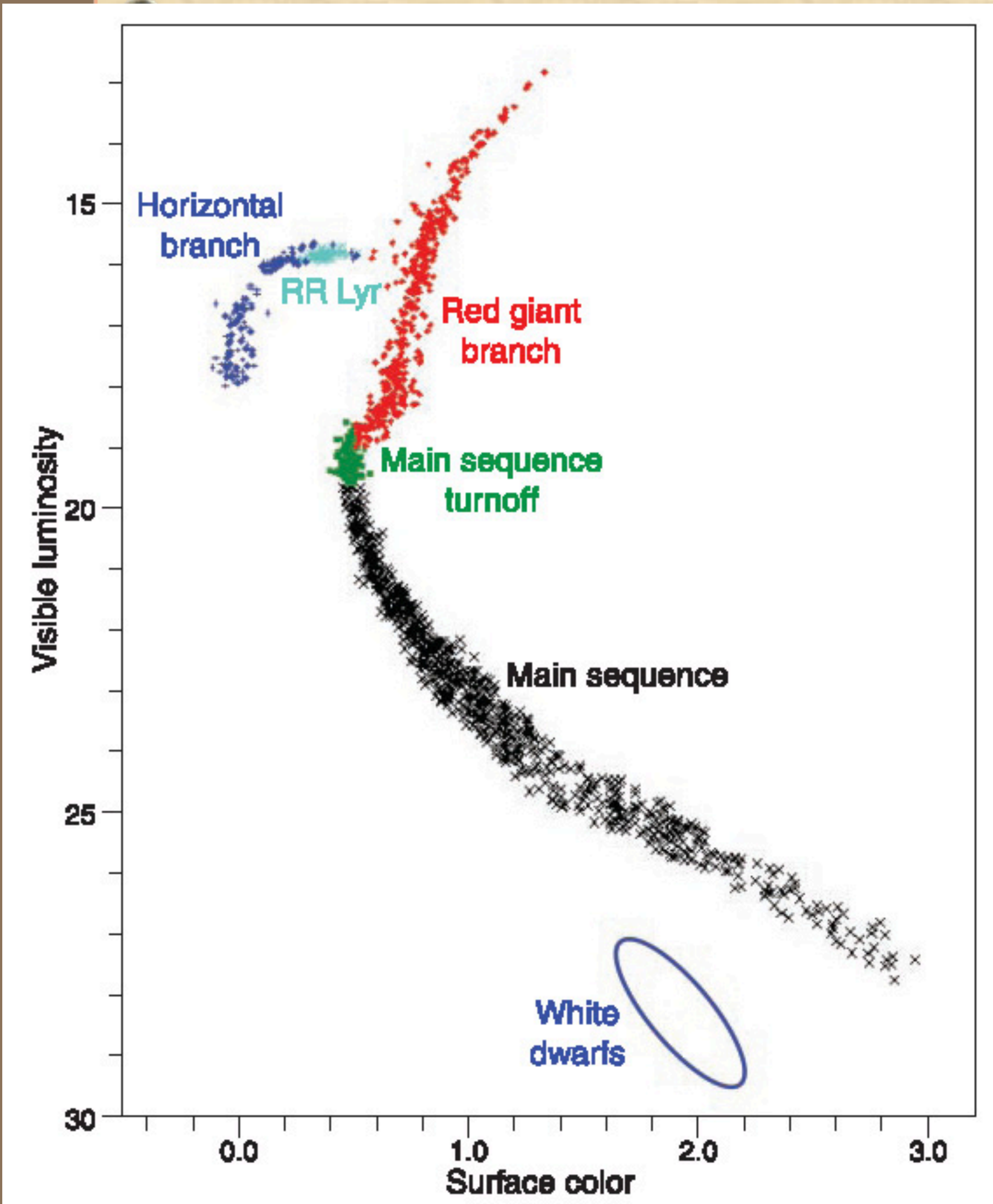
Age	Groups
1Myr	IC 5146
2Myr	ONC, NGC 6530
3Myr	λ Ori, σ Ori, NGC 2264
4-5Myr	IC 348, Cep OB3b[1], NGC 2362
5-10Myr	γ Vel[2]
10Myr	NGC 7160
13Myr	h and & χ Per
40Myr	NGC 2547

Notes: From Mayne & Naylor (2008), except for: [1]Littlefair (in prep); [2]Jeffries et al (2008)

Naylor 2009,
Naylor et al. 2009

Isochrone fitting: Globular clusters

Globular clusters: the CMD of M5



"A schematic color-magnitude diagram for a typical globular cluster showing the location of the principal stellar evolutionary sequences. This diagram plots the visible luminosity of the star (measured in magnitudes) as a function of the surface color of the star (measured in B-V magnitude). Hydrogen-burning stars on the ***main sequence*** *eventually exhaust the hydrogen in their cores (main sequence turnoff). After this, stars generate energy through hydrogen fusion in a shell surrounding an inert hydrogen core. The surface of the star expands and cools (****red giant branch****). Eventually the helium core becomes so hot and dense that the star ignites helium fusion in its core (****horizontal branch****). A subclass is unstable to radial pulsations (****RR Lyrae****). When a typical globular cluster star exhausts its supply of helium, and fusion processes cease, it evolves to become a* ***white dwarf****."*

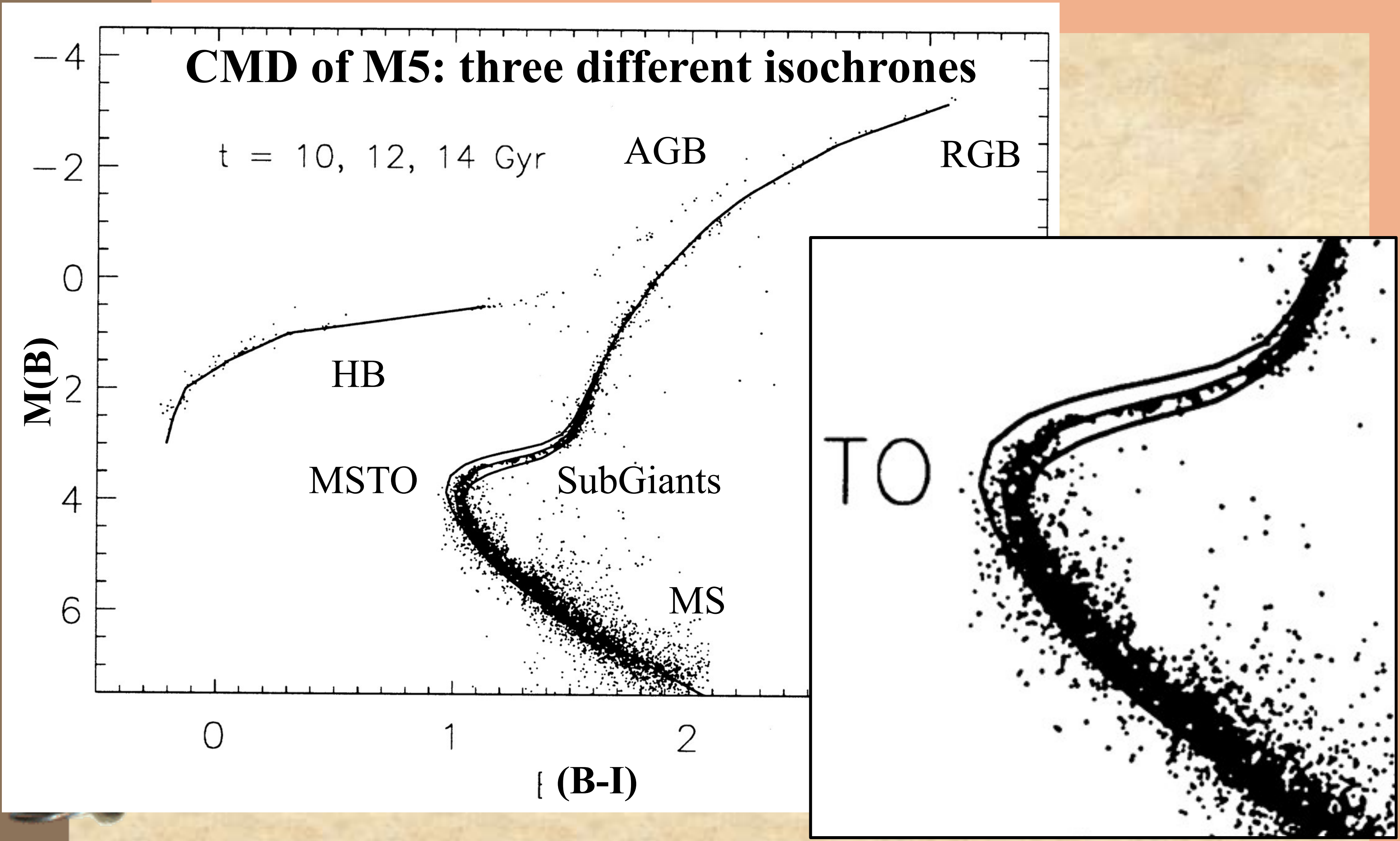
Krauss & Chaboyer (2003)

GC: summary of age determination techniques

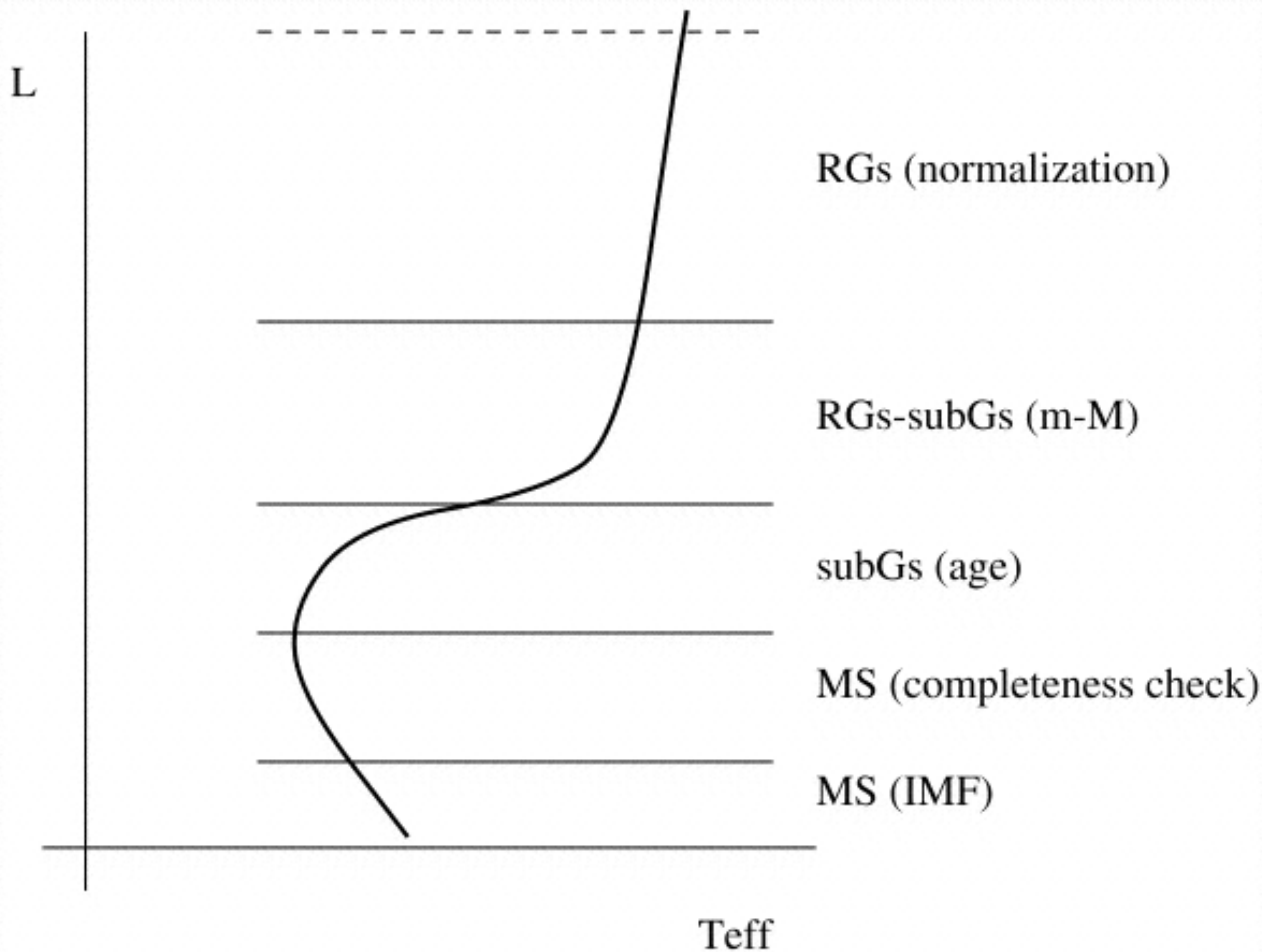
- Isochrone Fitting
- Relative MS-fitting Method.- version of first, using age-insensitive regions (MG and RGB).
- ΔColor.- The color of the MSTO is a strong function of age, while the color of the RGB is relatively insensitive to age. Thus, ΔColor (MSTO - RGB) is sensitive to the age of a globular cluster (Sarajedini & Demarque 1990; VandenBerg, Bolte, & Stetson 1990).
- ΔMagnitude.- It uses the difference in magnitude between the MSTO (or the SGB) and the HB as an age diagnostic (e.g., Renzini 1991).

- Comparison of the Spectral Energy Distribution with theoretical synthesis models (extragalactic method, starburst, etc).

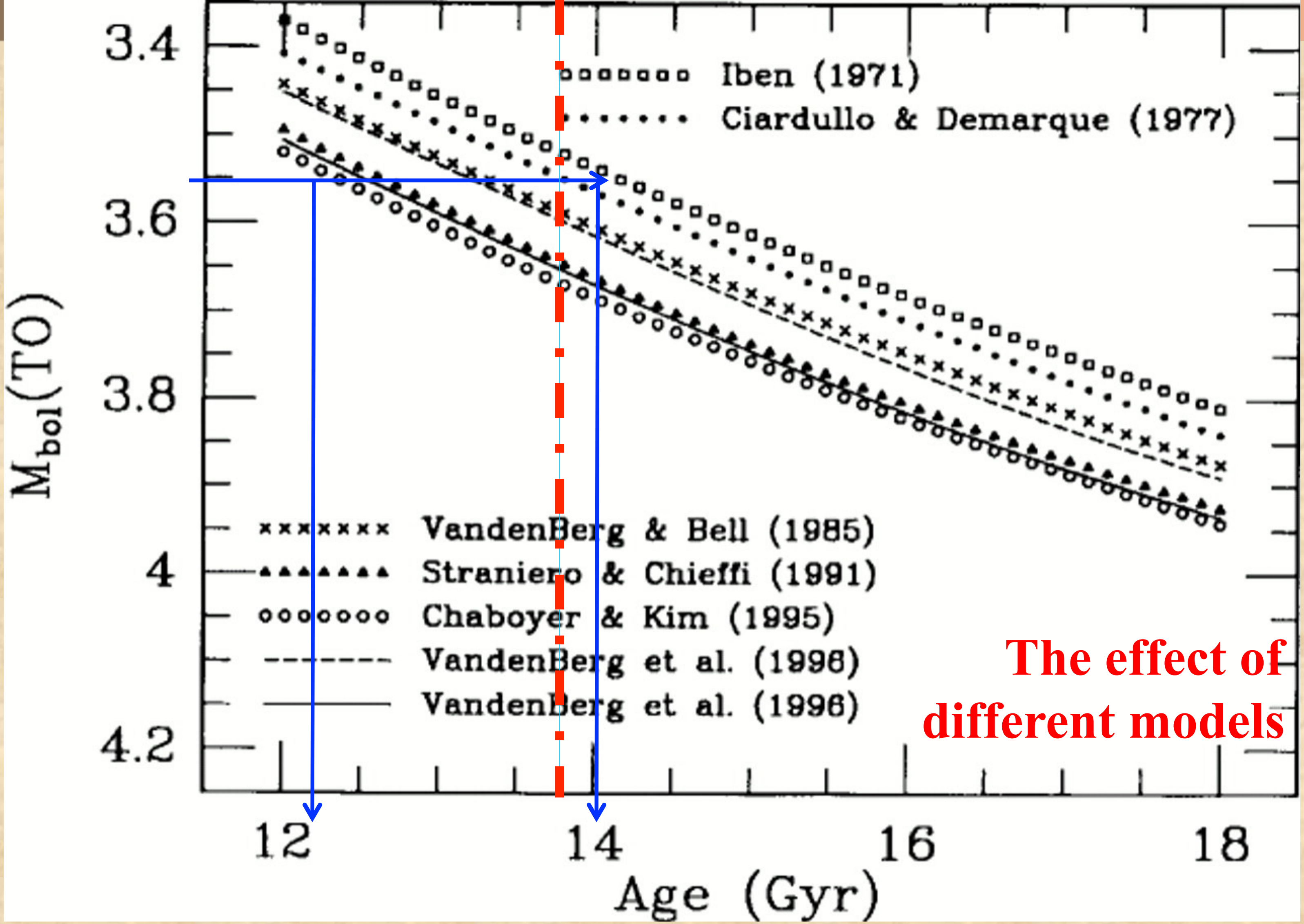
Vandenberg et al. (1990); Chaboyer (2001); Bruzual & Charlot 2003; Marín-Franch et al. (2009); Wang et al. (2010)



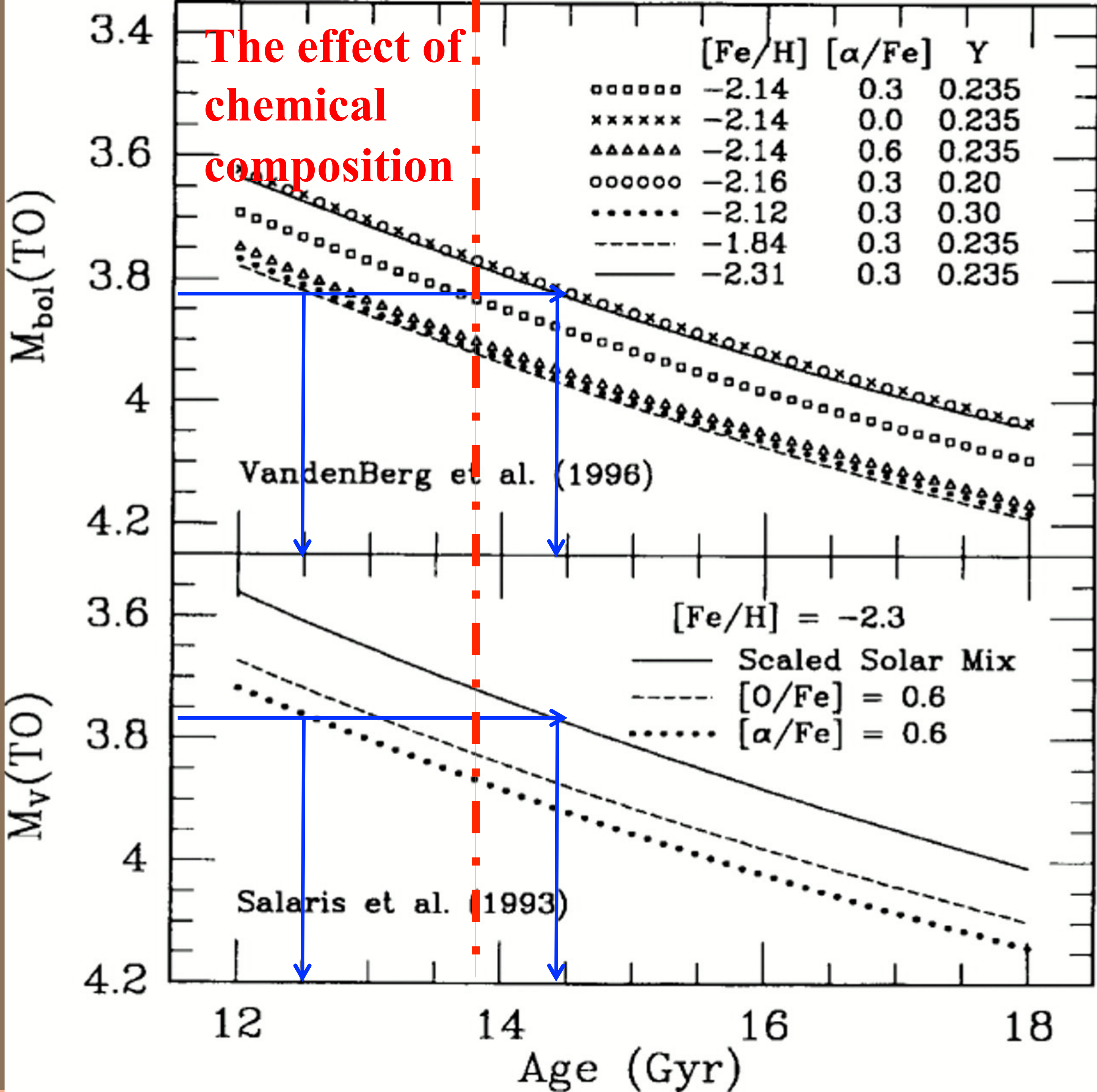
"*The CMD of M5 and three different isochrones. Notice that a vertical shift in any of the non-fitting isochrones (10 and 14 Gyr) will make them fit the observed CMD perfectly well. This is equivalent to a change in the distance modulus*". Jimenez (1998)



The bins used in the LF method to determine age and distance of a GC.
Jimenez & Padoan (1998)

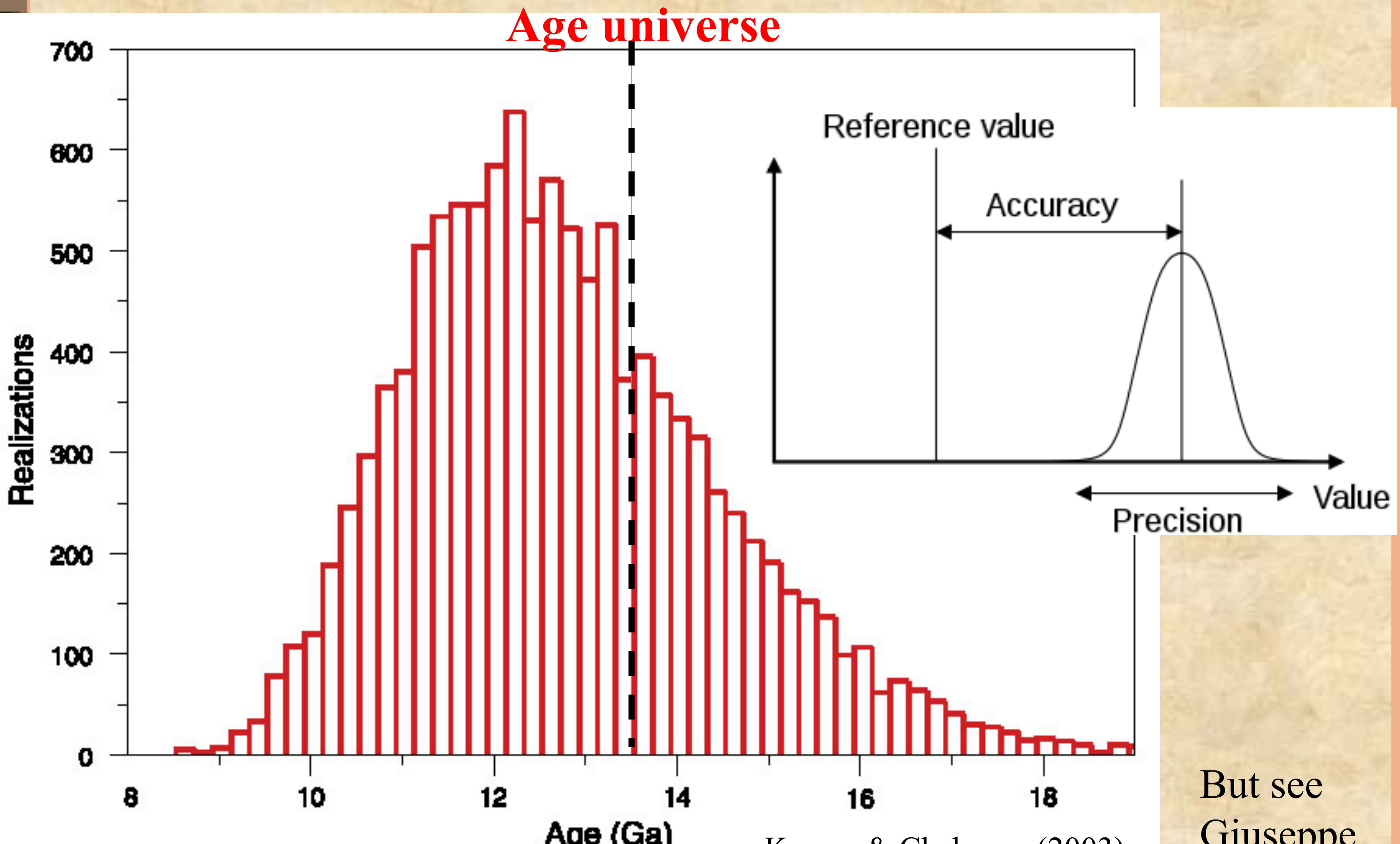


"Turnoff luminosity vs age relations from the indicated investigations for the particular choice of Y=0.20 and Z=0.0001 for the mass-fraction abundances of helium and the heavier elements, respectively. The M_{bol}(TO) values were calculated on the assumption that the solar value is 4.72 mag." Vandenberg et al. (1996)



"Turnoff luminosity vs age relations from the indicated investigations for the particular choice of Y=0.20 and Z=0.0001 for the mass-fraction abundances of helium and the heavier elements, respectively. The $M_{bol}(TO)$ values were calculated on the assumption that the solar value is 4.72mag." Vandenberg et al. (1996)

The limits of the precision



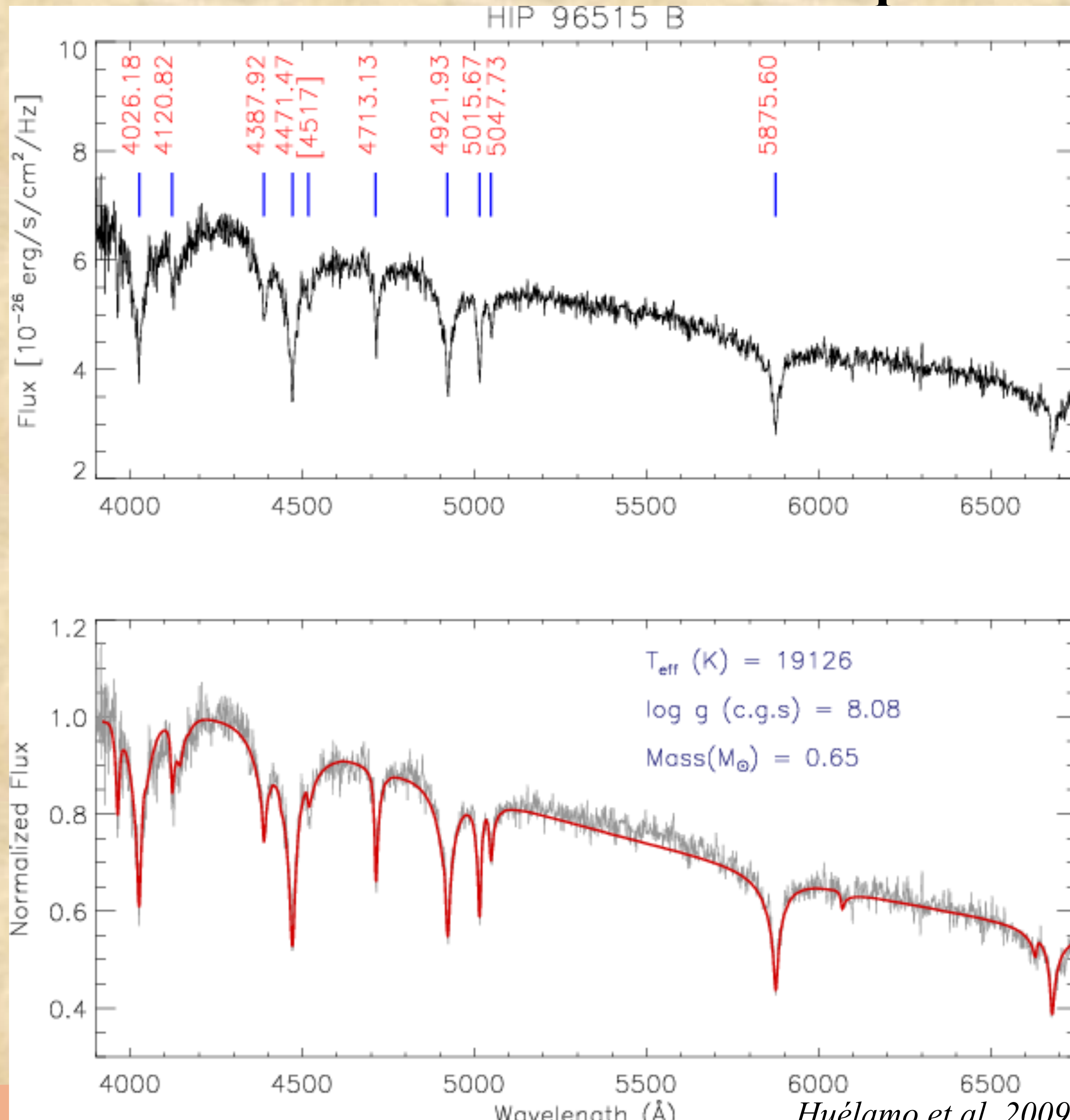
Krauss & Chaboyer (2003)

Fig. 3. Histogram representing results of Monte Carlo presenting 10,000 fits of predicted isochrones for differing input parameters to observed isochrones to determine the age of the oldest globular clusters.

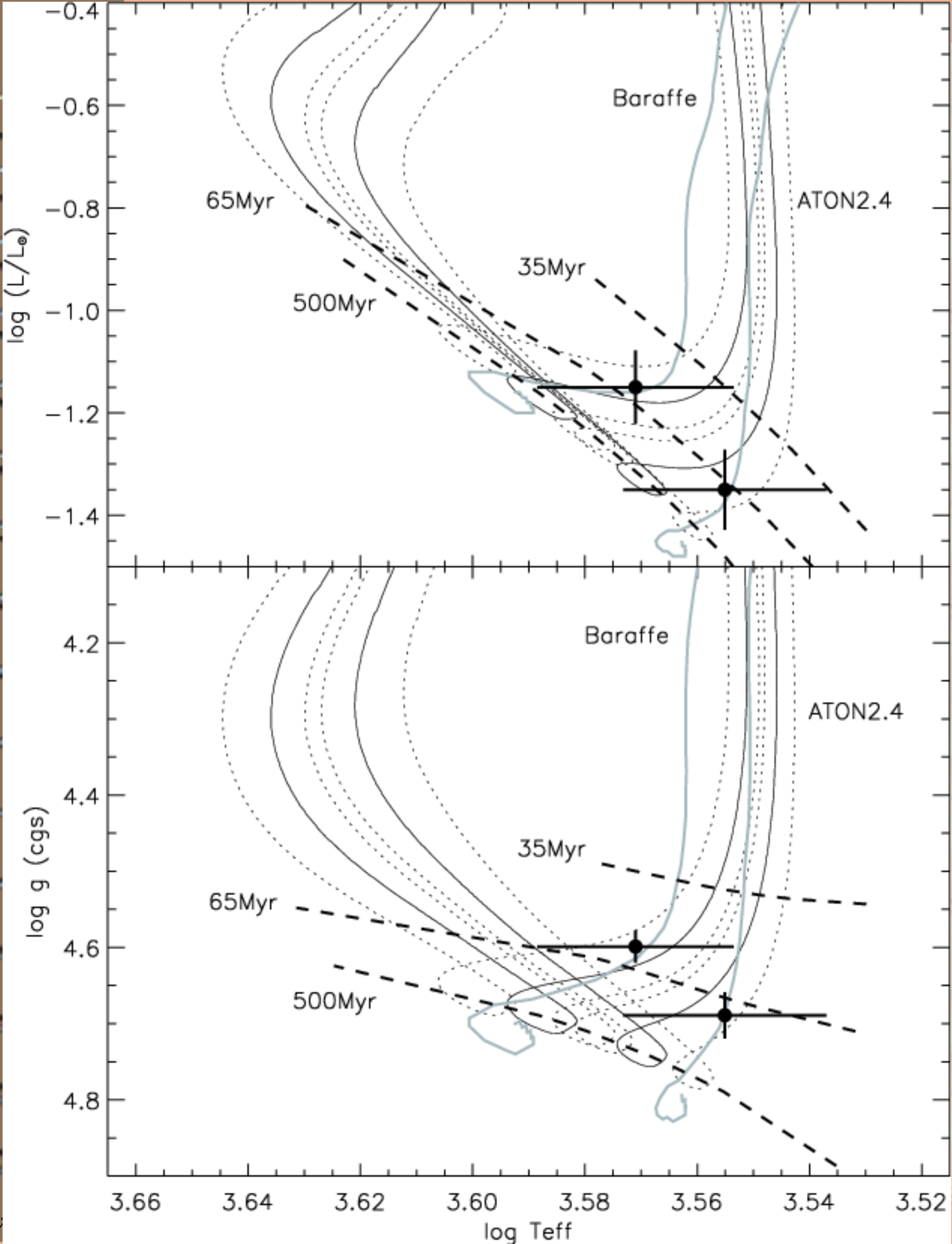
But see Giuseppe Bono talk

Isochrone fitting: White Dwarfs

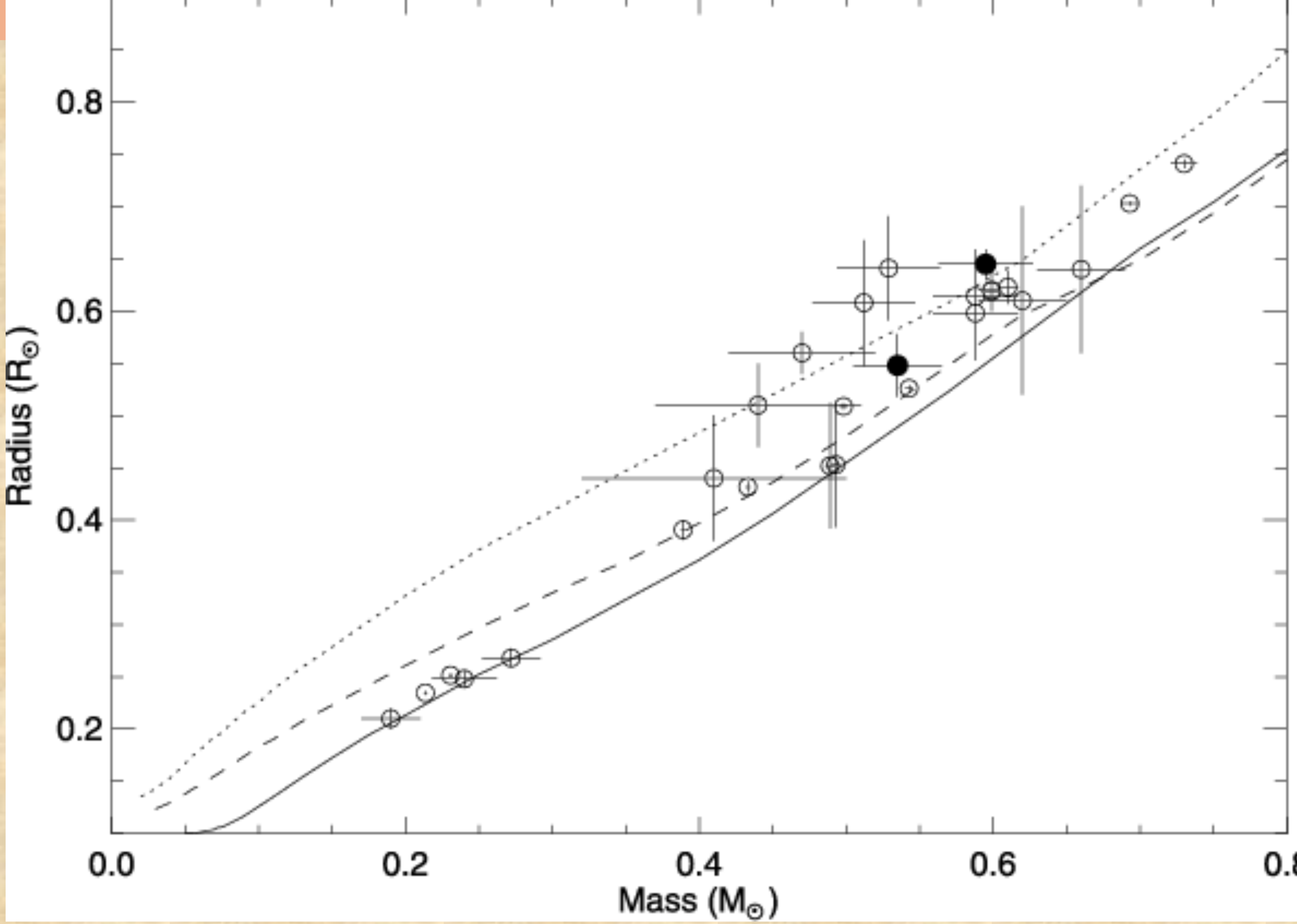
The triple system HIP 96515: a low-mass eclipsing binary with a DB white dwarf companion



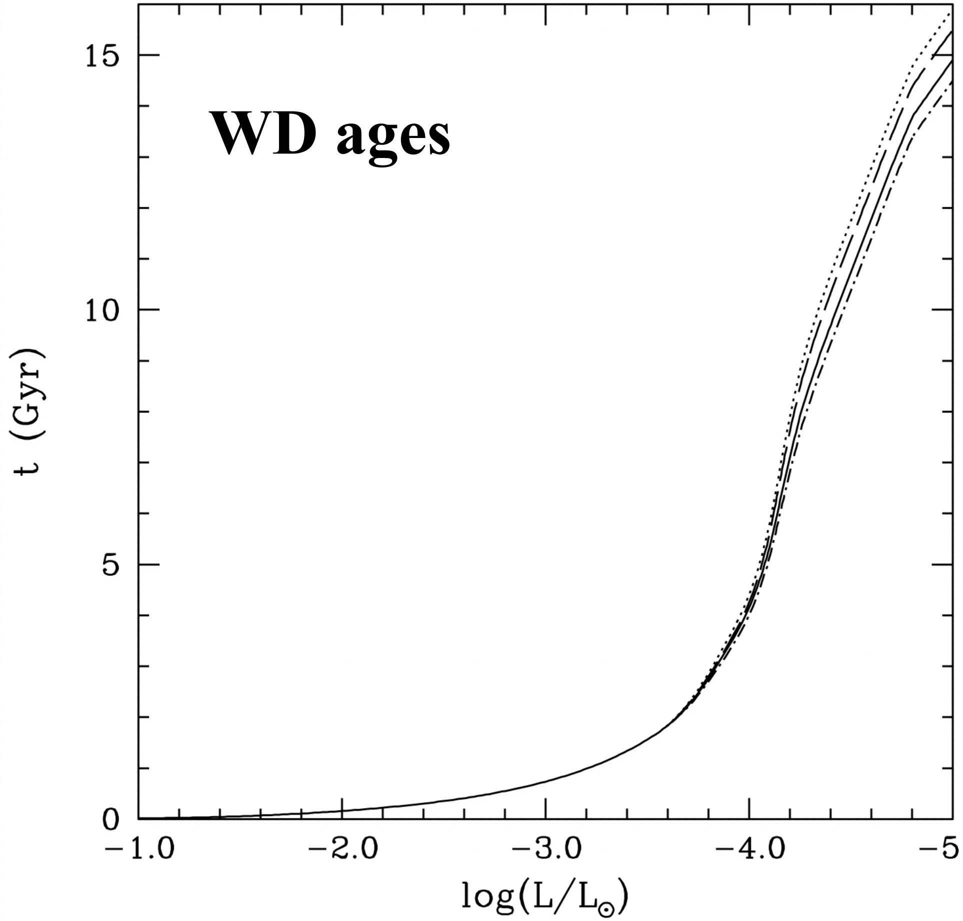
Huélamo et al. 2009

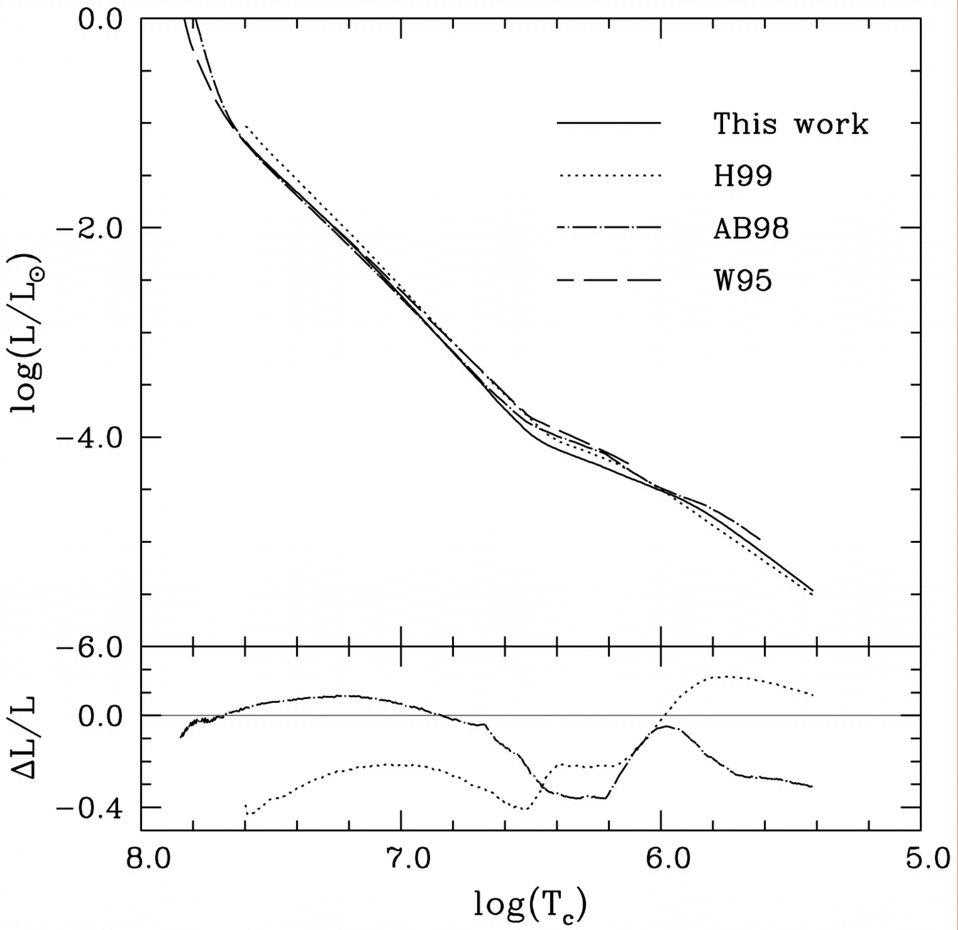


*"Stellar luminosity (top panel) and surface gravity (bottom panel) versus effective temperature. HIP 96515 Aa and Ab are represented by filled circles. The grey and black solid lines represent evolutionary tracks by Baraffe et al. (1998) and Landin et al. (2006), respectively, for 0.6 and 0.5 stellar masses. The dotted lines represent the uncertainties in the stellar masses for the ATON models. The comparison of HIP 96515 A with the two sets of evolutionary tracks provides an age of 60 Myr, that is, places the eclipsing binary members on the pre-main sequence, although with **large uncertainties**."*
Huélamo et al. (2009)



"*Mass-luminosity relation for all known eclipsing binaries with masses M < 0.7 (see Shkolnik et al. 2008, and references therein). HIP 96515 Aa and Ab are represented by filled circles. The dotted, dashed, and solid lines represent evolutionary tracks by Baraffe et al. (1998) for 50, 100, and 500 Myr, respectively.*". Huélamo et al. (2009)



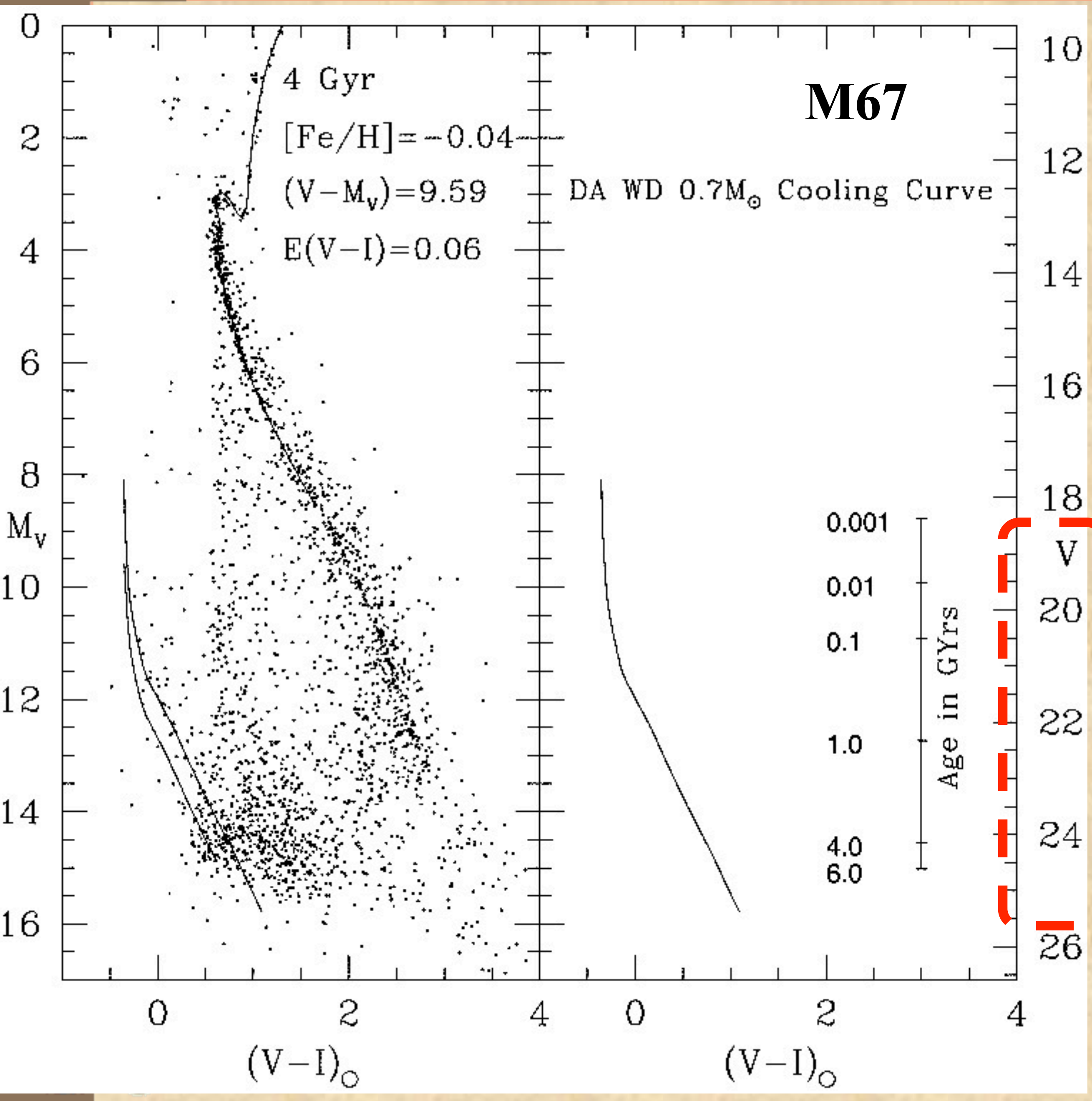


"Cooling sequences for a 0.606 M white dwarf neglecting phase separation (solid line) and taking into account phase separation (dotted line) computed assuming $l = k_B T$ per particle."

"T_c-L relationship for the three cooling sequences of a 0.6 M white dwarf discussed in this paper (upper panel). Also Hansen (1999), Althaus & Benvenuto (1998)."

Salaris et al. (2000)

WD ages

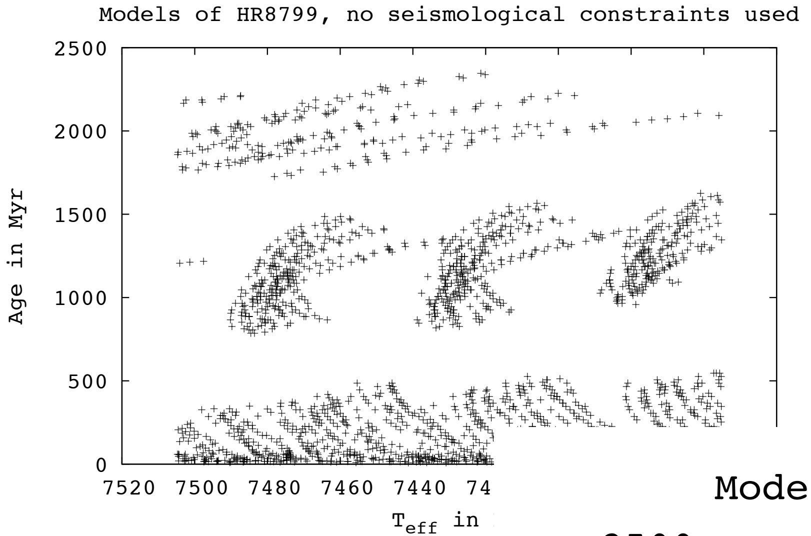


"Left.- M67 M_V, (V-I) CMD for the entire cluster is shown. Only objects passing a shape test, indicating that they were likely to be stars are included in these diagrams except that theoretical cooling curves for 0.7 (upper) and 1.0 Msun DA WDs are included. Also shown is an isochrone for 4 Gyr for a metallicity of [Fe/H] = -0.04, which is appropriate to M67. Right.- Replot of the 0.7 M cooling curve, indicating along it cooling times to various magnitudes."

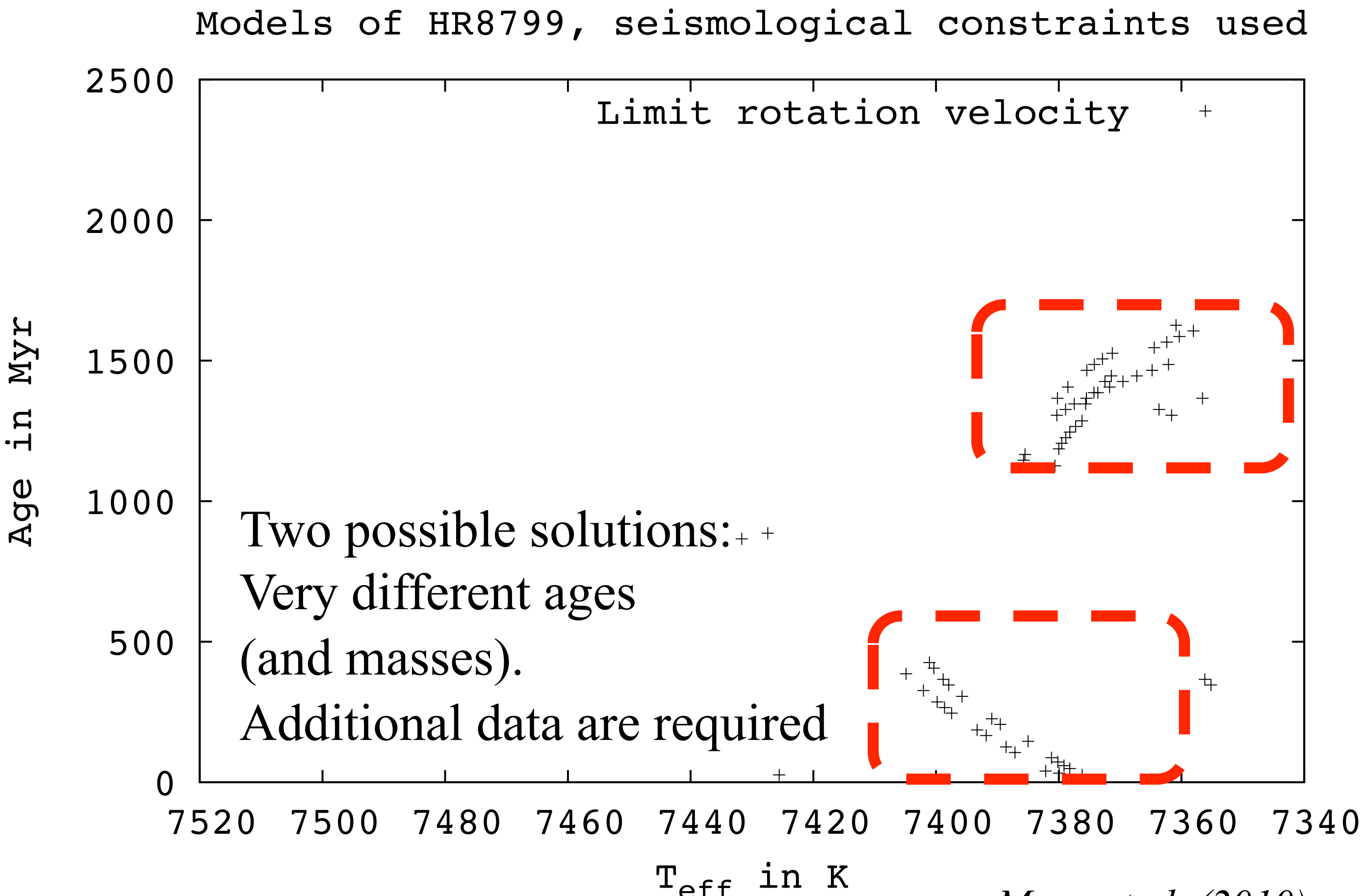
Richer et al. (1998)

Problem: by definition, it cannot be absolute

Asterosismology



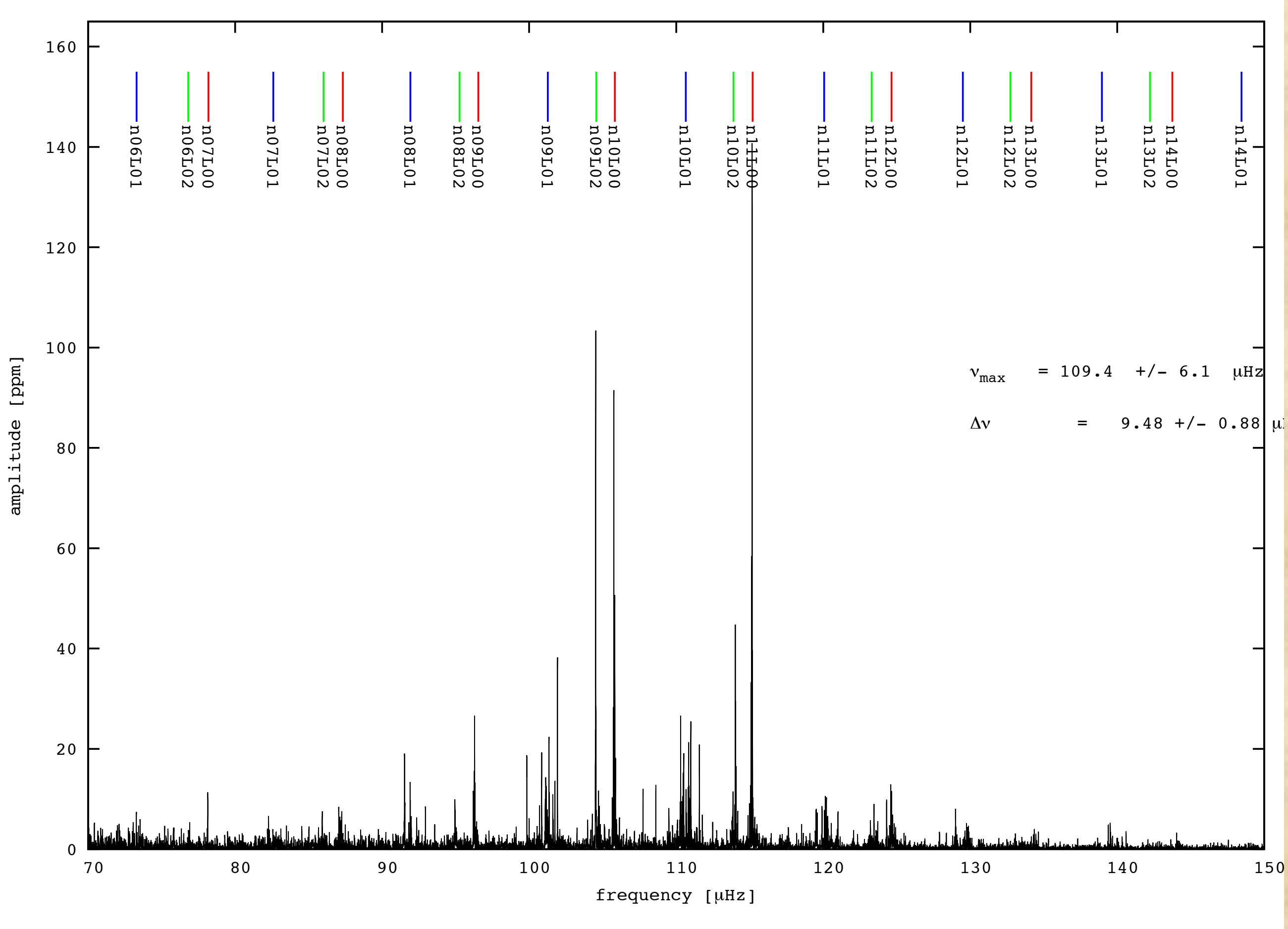
Asterosismology:
The example of HR8799



Moya et al. (2010)

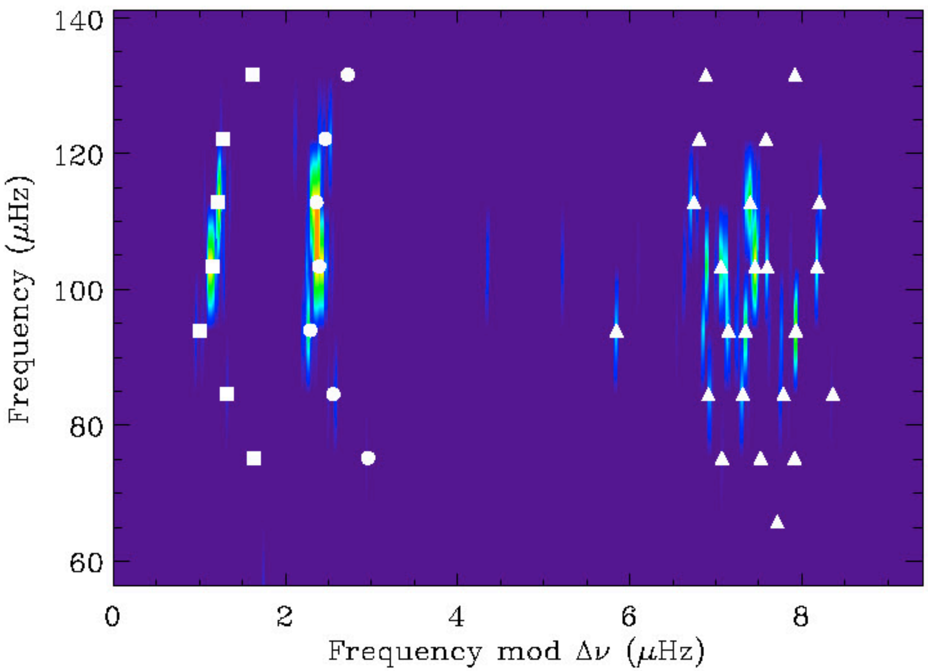
David Barrado

Kepler 91



"*Power spectrum of the light curve, in a region centred on the maximum of the oscillations. The upper part of the figure shows the various modes identified for increasing value of n: in red the modes with l = 0, green l = 2, blue l = 1. The black dotted line represents the heavy smoothed power spectrum.*", Lillo-Box et al. (2014)

Kepler 91



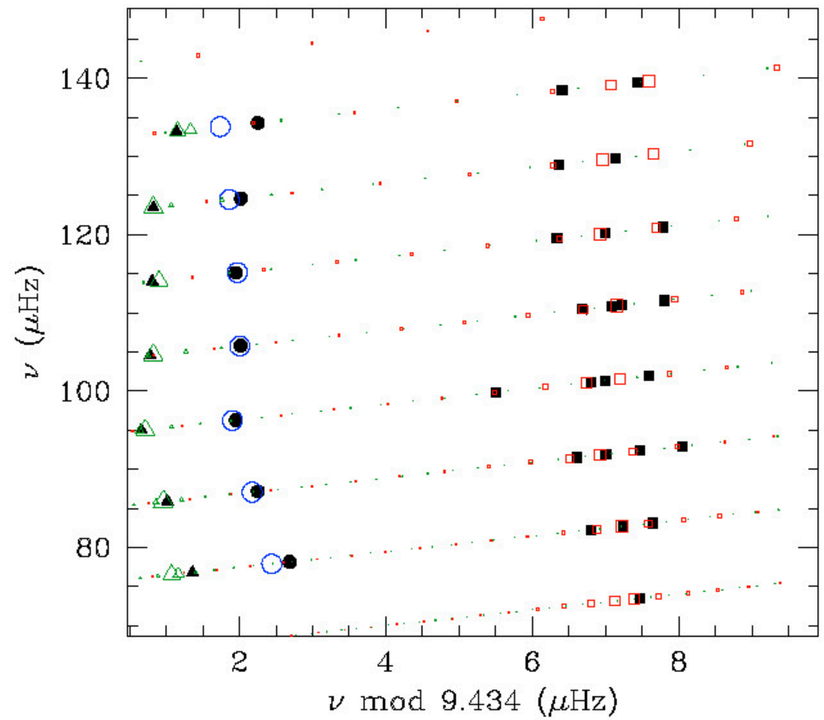


Fig. 5. Left: Échelle diagram of the power spectrum of the data with the fitted modes overplotted. Circles for l = 0, triangles for l = 1 and squares for l = 2. The power spectrum is fitted using Maximum Likelihood Estimation (see section § 3.5.2). **Right:** Comparison between observational (black solid dots and white symbols in the left panel) and theoretical (open symbols) frequencies in the échelle diagram for a typical good fitting of radial and non-radial modes. Circles correspond to radial modes, squares to dipole modes and triangles to quadrupole ones. The size of the theoretical symbols is an indication of the expected amplitude based on the value of the inertia mode (Houdek et al. 1999). The asymptotic period spacing for this model is 76s.

Lillo-Box et al. (2014)

Kepler 91

Table 2. Summary of the results for the host star properties from the different methods explained in Sect. 3.

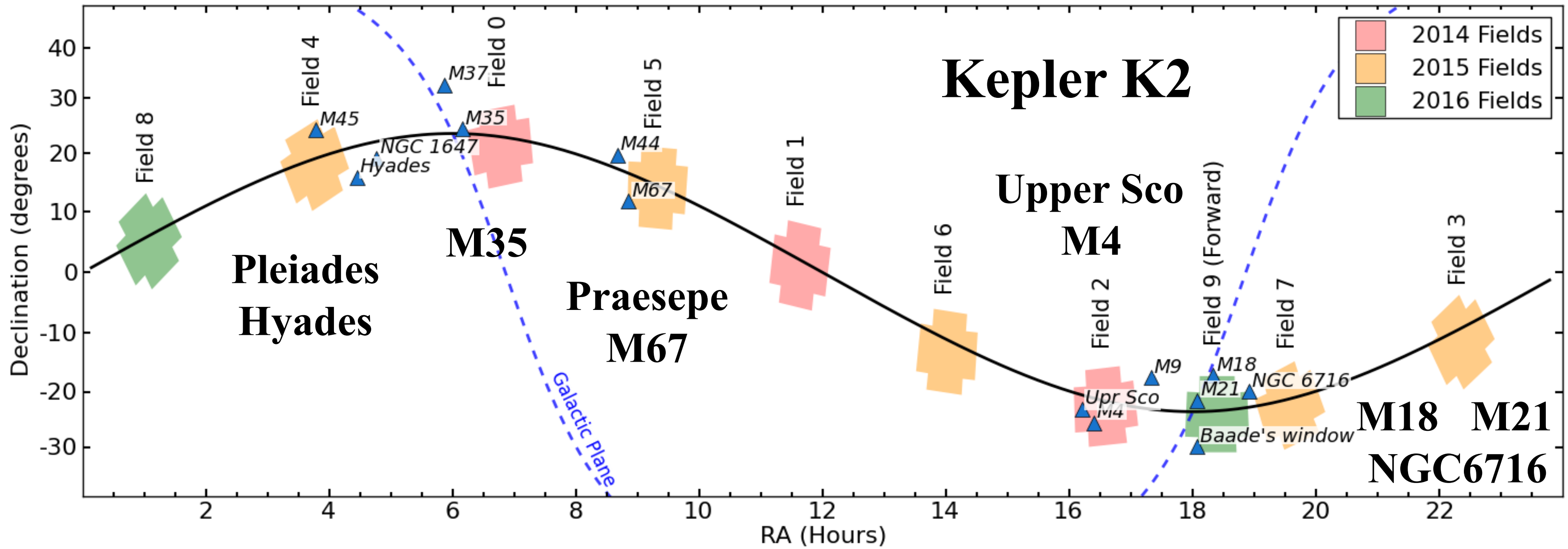
Method (section)	$M_*(M_\odot)$	$R_*(R_\odot)$	$\log g$	ρ (kg/m^3)	[Fe/H][b]	$T_{\rm eff}$	Age (Gyr)	L_* ($L_\odot$)
KIC10 (Sect. 3.1)	1.45	7.488	**2.852 ± 0.5**	4.86	**0.509 ± 0.5**	**4712 ± 200**	N/A	N/A
TCE (Sect. 3.1)	1.49	7.59	**2.85**	4.80	(−0.2)[a]	**4837**	2.66 ± 0.83	N/A
Huber13 (Sect. 3.1)	1.344 ± 0.169	6.528 ± 0.352	2.94 ± 0.17	6.80	**0.29 ± 0.16**	**4605 ± 97**	N/A	N/A
SED (Sect. 3.3)	N/A	N/A	<3.5	N/A	**0.4 ± 0.2**	**4790 ± 110**	N/A	N/A
Spec. (Sect. 3.4)	N/A	N/A	**3.0 ± 0.3**	N/A	**0.11 ± 0.07**	**4550 ± 75**	N/A	N/A
Sc.Rel. (Sect. 3.5.1)	$1.19^{+0.27}_{-0.22}$	$6.20^{+0.57}_{-0.51}$	2.93 ± 0.17	**7.0 ± 0.4**	N/A	(4550 ± 75)[a]	N/A	$14.8^{+3.9}_{-3.3}$
Freq. (Sect. 3.5.3)	**1.31 ± 0.10**	**6.30 ± 0.16**	**2.953 ± 0.007**	**7.3 ± 0.1**	(0.11 ± 0.07)[a]	(4550 ± 75)[a]	**4.86 ± 2.13**	**16.8 ± 1.7**

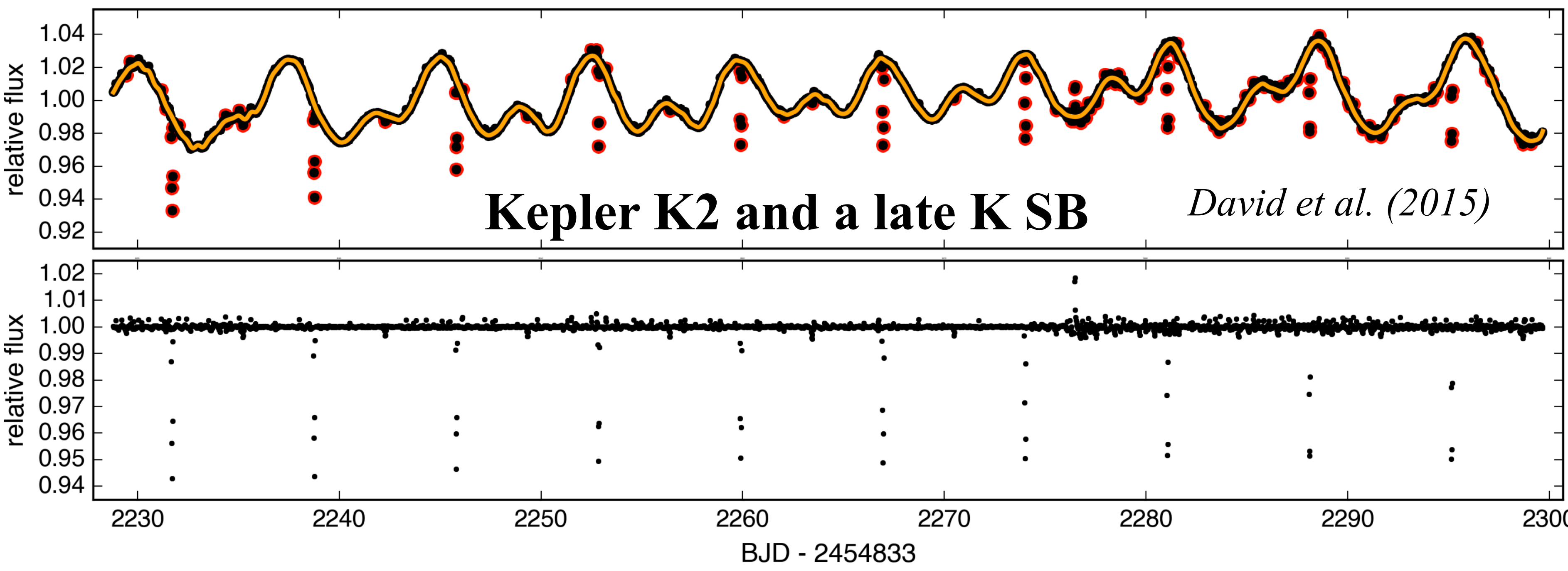
Notes. Parameters in bold represent primary values (i.e. a directly determined parameter by this method). Values in neither bold nor brackets have been calculated based on other previously determined or assumed parameters. The expression N/A reflects parameters that cannot be determined by the corresponding method. [a] Assumed (input) parameter, also in parenthesis. [b] Note that [M/H] ≈ log($Z/Z_\odot$).

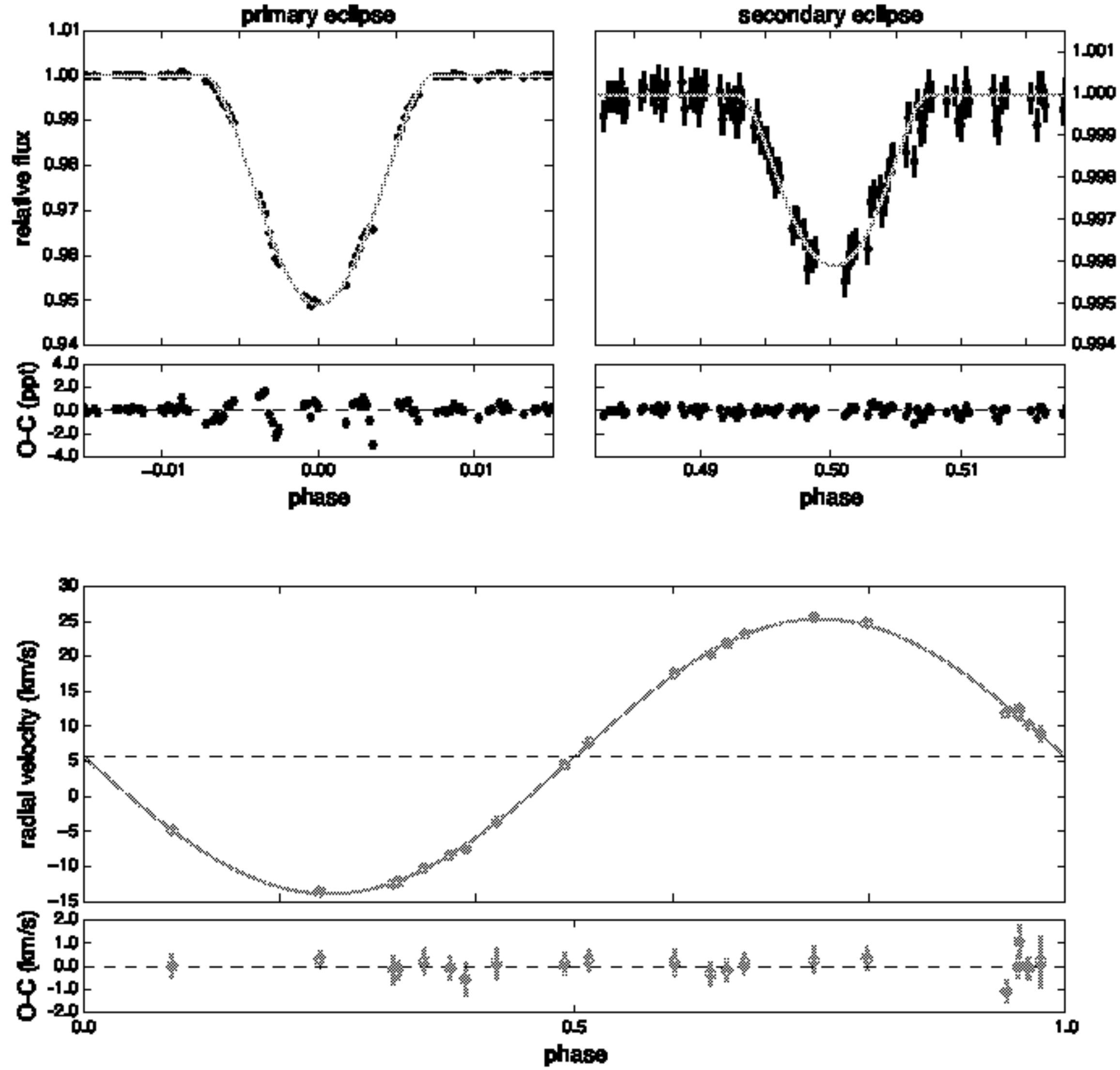
Compare the different results with several techniques. Even 3.5.1 and 3.5.3, both based on asterosismology, produce different values. From Lillo-Box et al. (2014)

Lillo-Box et al. (2014)

The cornerstone:
The Pleiades
I.- Eclipsing binaries


Kepler K2
2014 Fields
2015 Fields
2016 Fields
Declination (degrees)
RA (Hours)
Field 8
Field 4
Field 0
Field 5
Field 1
Field 6
Field 2
Field 9 (Forward)
Field 7
Field 3
M45
M37
M35
NGC 1647
Hyades
M44
M67
M9
M18
M21
NGC 6716
Upr Sco
M4
Baade's window
Galactic Plane
Pleiades
Hyades
M35
Praesepe
M67
Upper Sco
M4
M18 M21
NGC6716


relative flux
Kepler K2 and a late K SB
David et al. (2015)
relative flux
BJD - 2454833



Light curve

RV curve

Figure 3. Best-fit JKTEBOP model to the $K2$ photometry (top panels) and the Mermilliod et al. (1992) radial velocities (bottom panel). For each panel the residuals of the best fit model are plotted below. Measurement uncertainties in the top left and bottom panels are smaller than the points themselves. The horizontal dashed line indicates the best-fit systemic radial velocity.

David et al. 2015

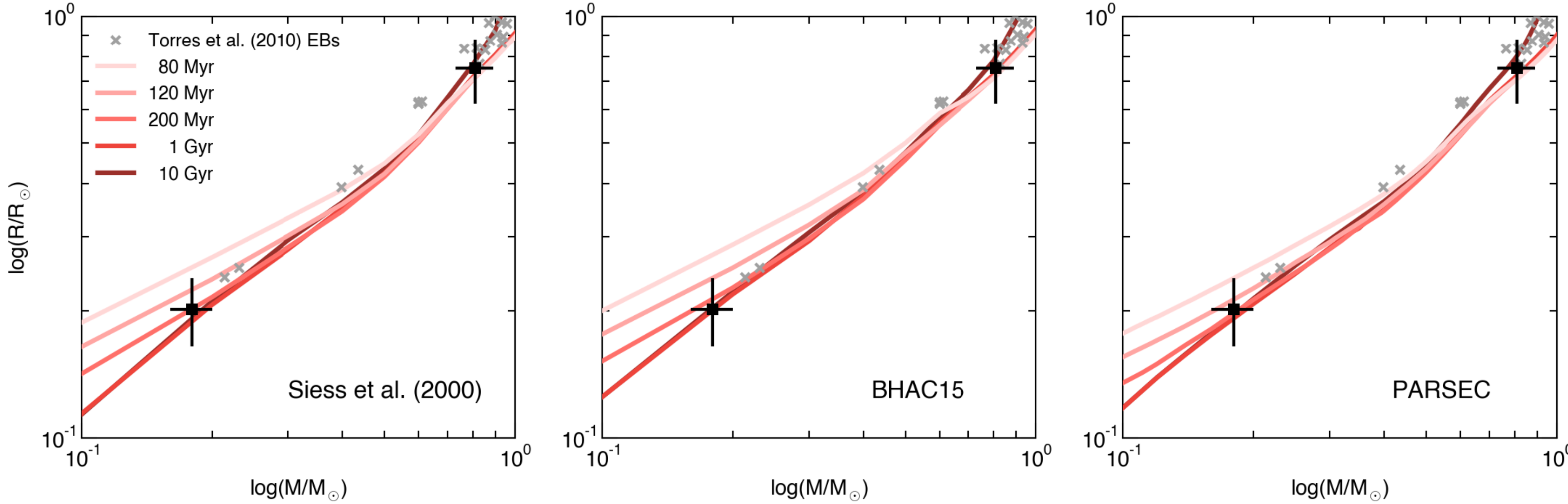


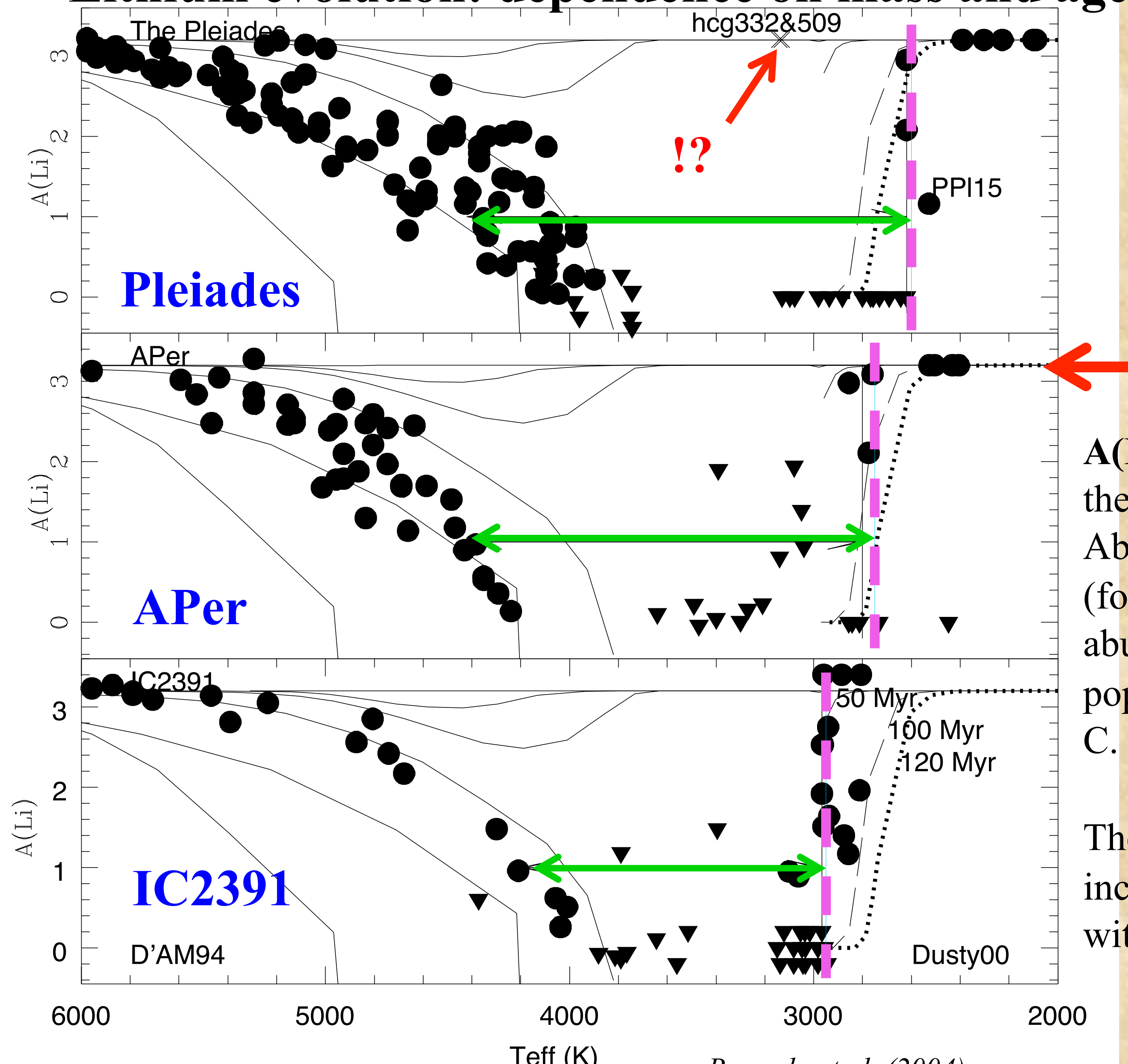
Figure 4. Isochrones in the mass-radius plane with the components of HII 2407 and benchmark EBs from Torres et al. (2010) overplotted. From left to right, the evolutionary models depicted are from Siess et al. (2000), Baraffe et al. (2015), and Bressan et al. (2012). All models plotted are for solar metallicity (Z=0.02).

David et al. 2015

Masses and radii do not fit in the isochrones, even for objects with known ages (such as eclipsing binaries in clusters)

Lithium (I)
LDB in mid M

Lithium evolution: dependence on mass and age



Barrado et al. (2004)

A(Li)=3.1-3.2, the meteoritic Abundance (for cosmological abundance and population II, see C. Charbonnel)

The lithium abyss increases its width with age

LBD in the Pleiades

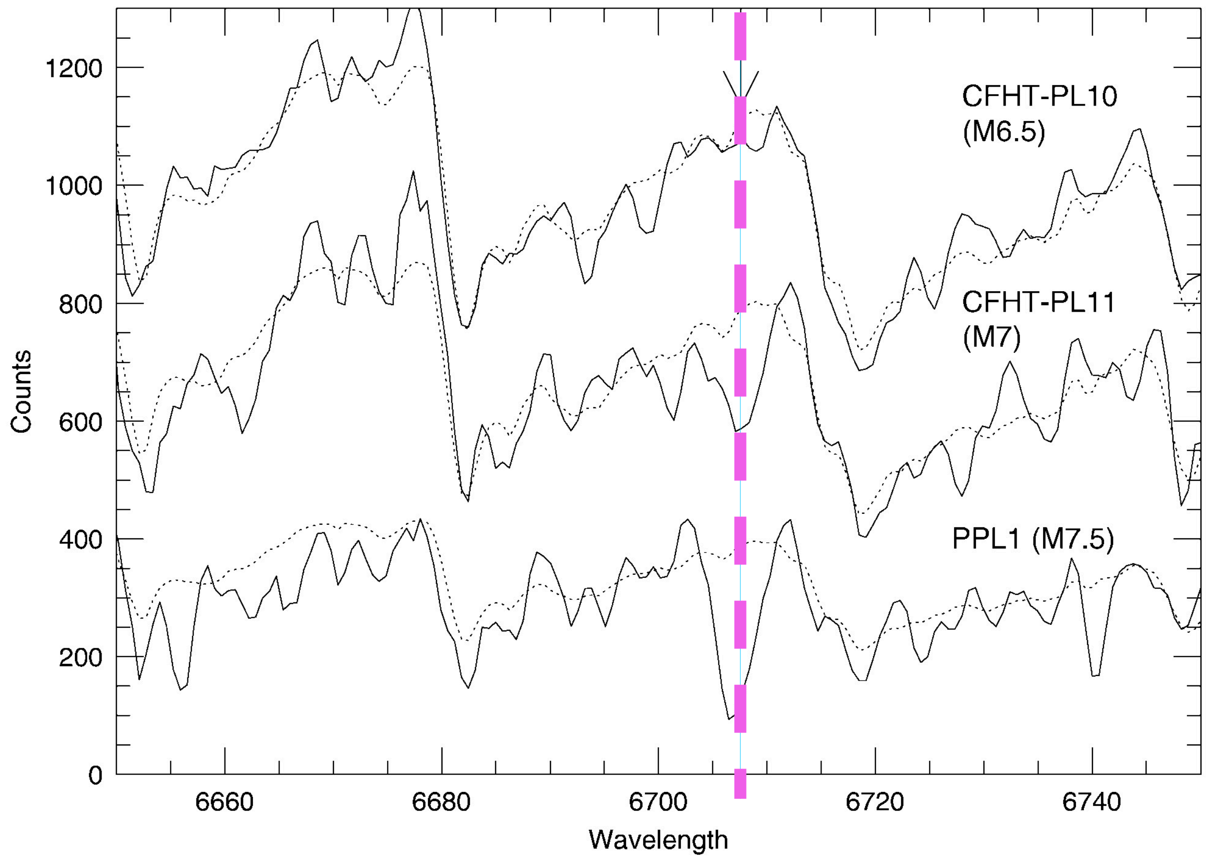
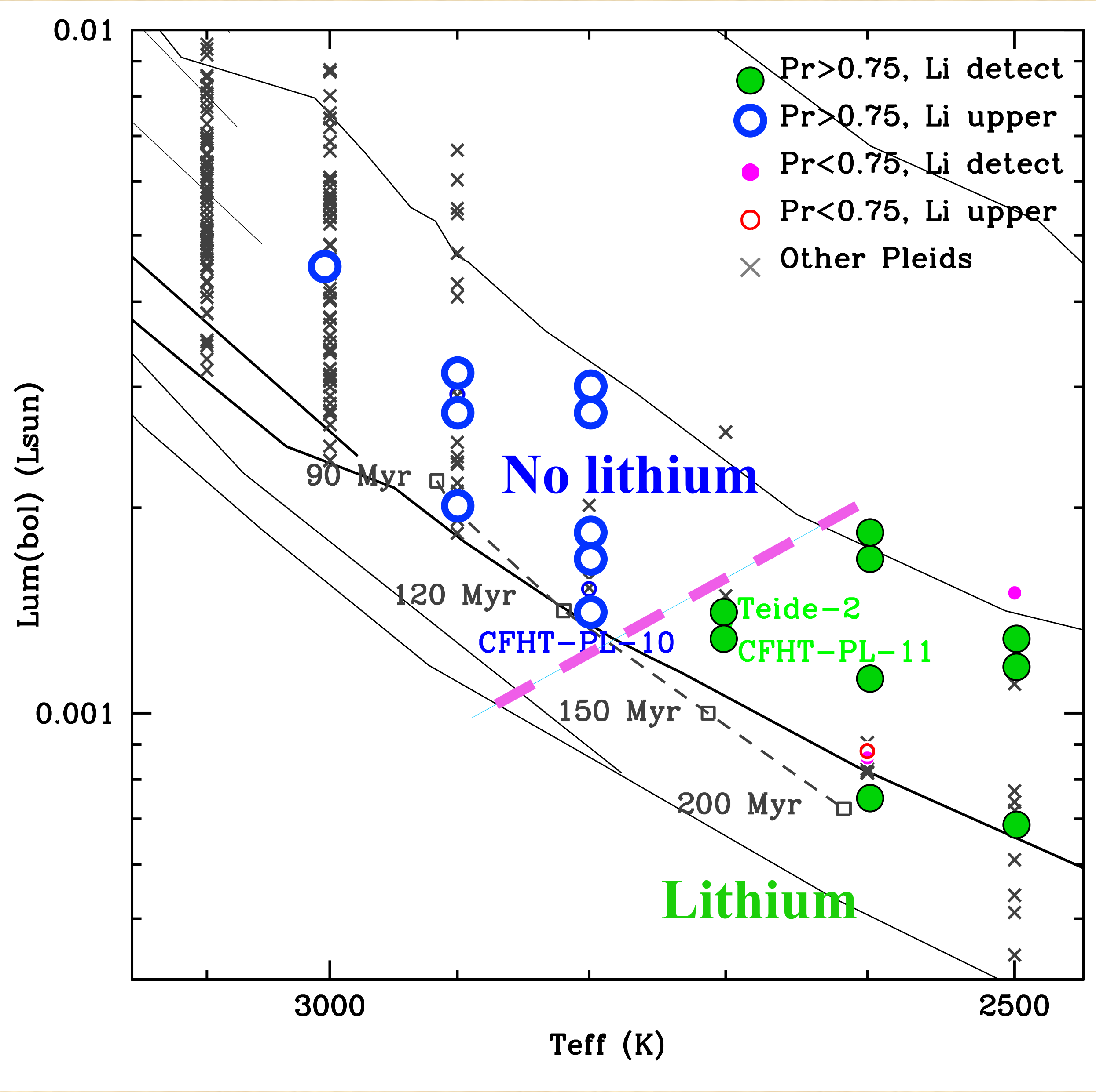


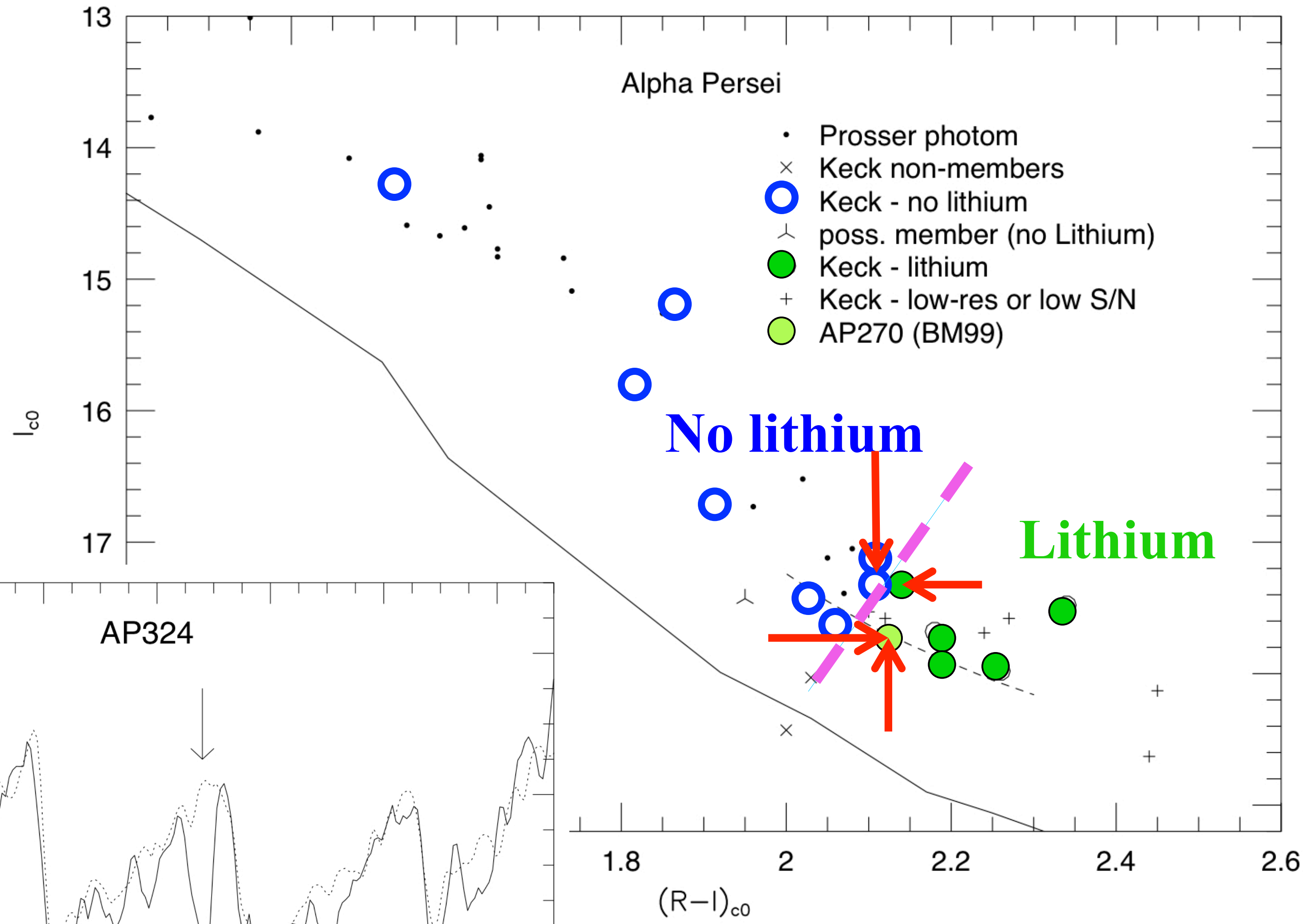
FIG. 1.—Sample spectra of Pleiades brown dwarf candidates obtained with the Keck II LRIS. The displayed wavelength region is only a small portion of the full spectrum, selected in order to highlight the lithium 6708 Å region. The *y*-axis is correct for CFHT PL 10, while the spectra of the other two stars are offset relative to CFHT PL 10 to avoid having the spectra overlap. The dashed line is a spectrum of GL 65AB, a field M6–M6.5 binary, assumed to have entirely depleted its initial lithium.

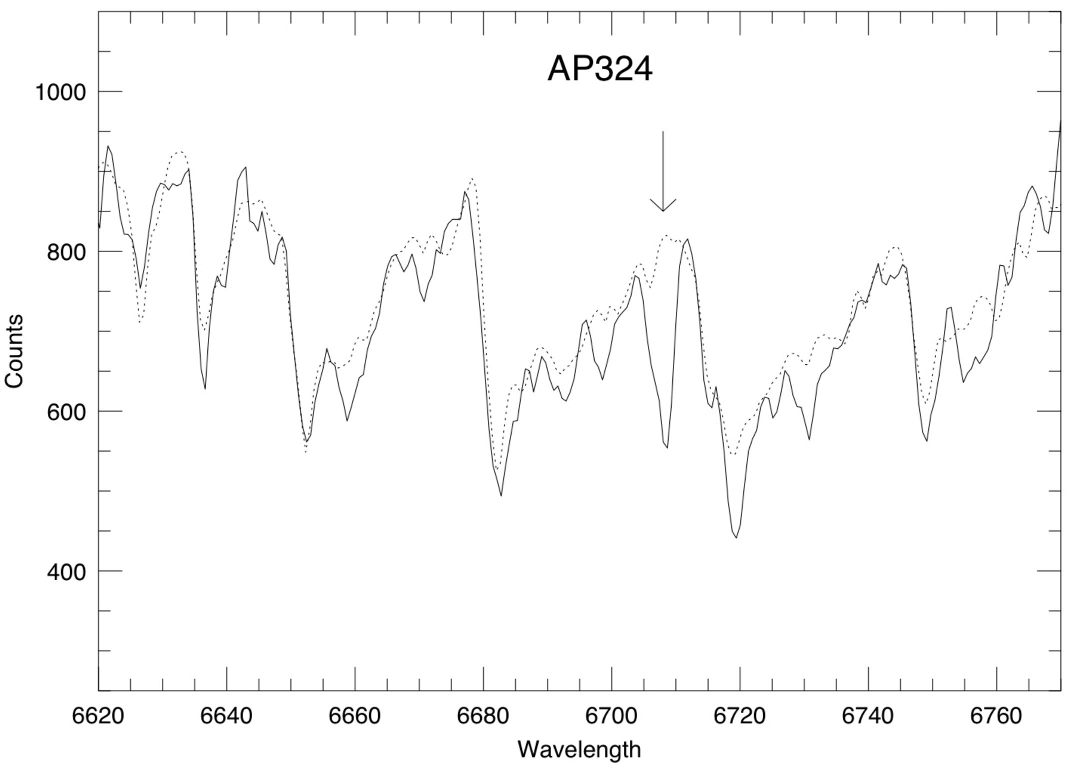
Stauffer et al. (1998)

DANCE: LBD in the Pleiades



Sarro et al. 2014), Bouy et al. (2014); Barrado et al. (2015)

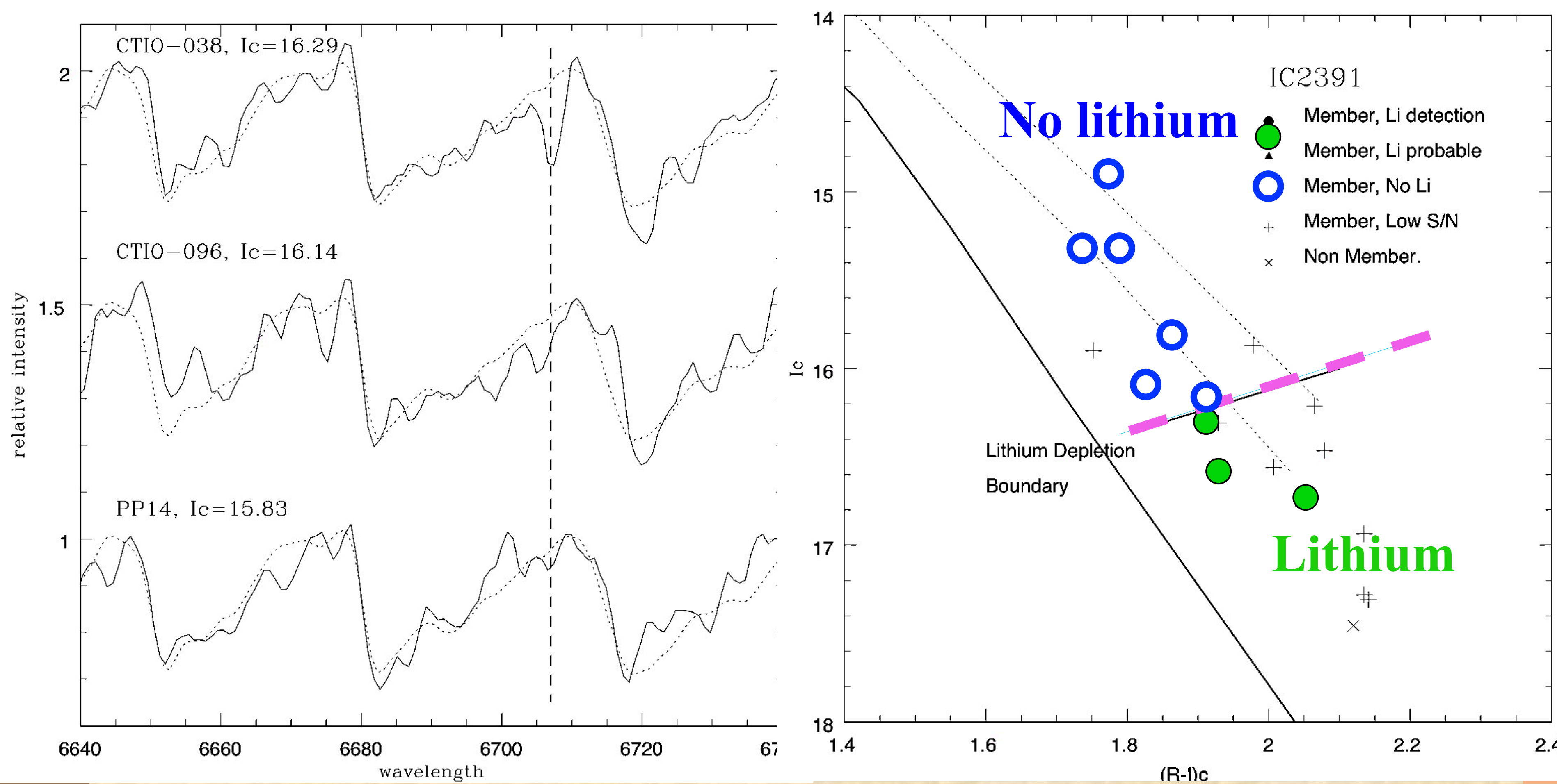




Which value should we use?

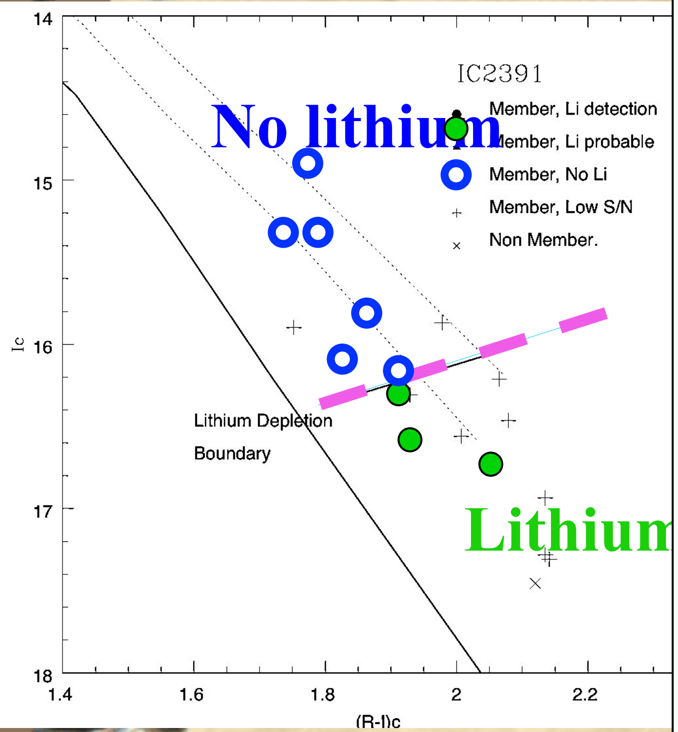
Stauffer et al. (1999)

LDB IC2391

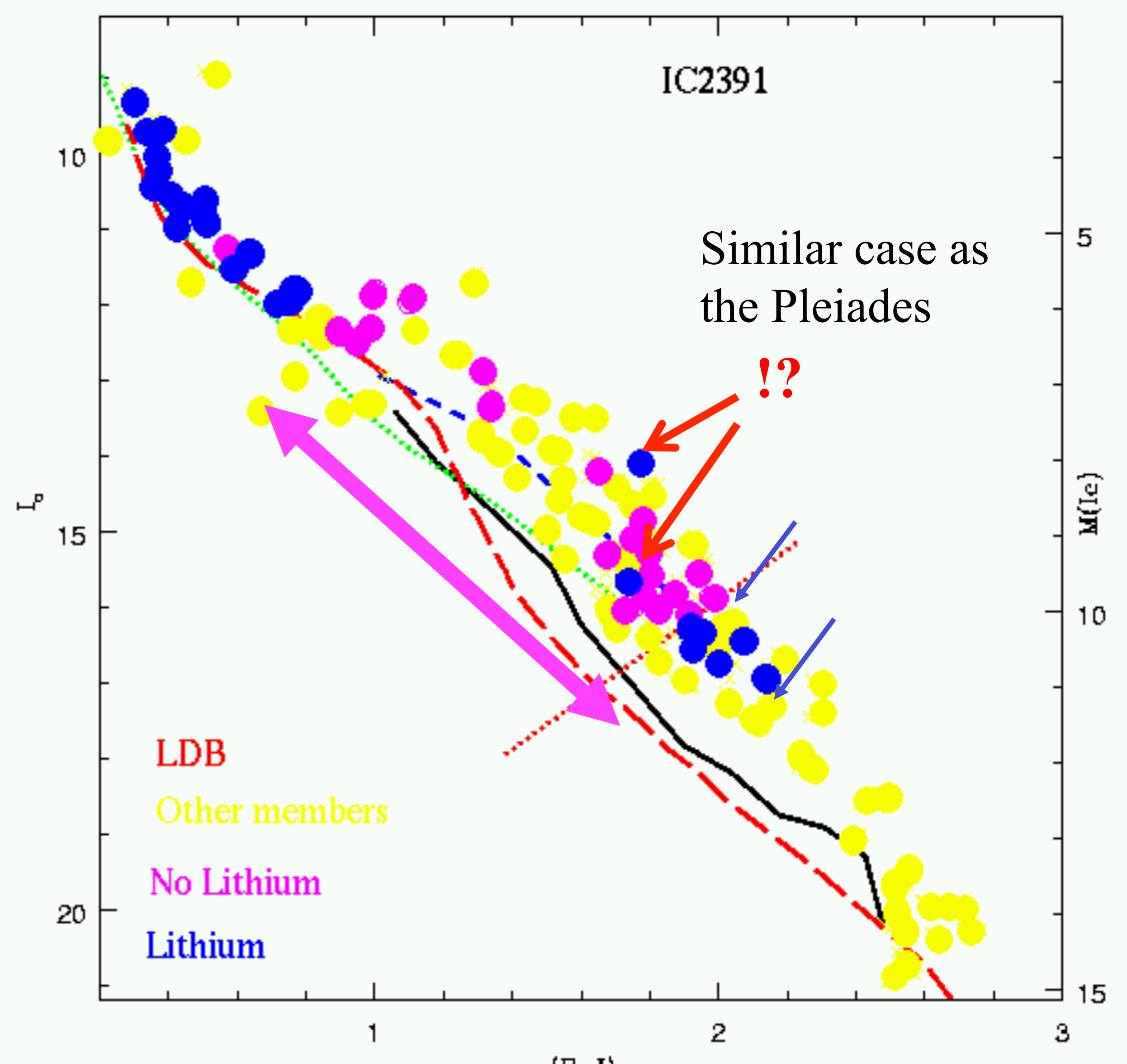


CTIO−038, Ic=16.29
CTIO−096, Ic=16.14
PP14, Ic=15.83
relative intensity
wavelength
2
1.5
1
6640
6660
6680
6700
6720
IC2391
No lithium
Lithium
Member, Li detection
Member, Li probable
Member, No Li
Member, Low S/N
Non Member.
Lithium Depletion
Boundary
Ic
(R-I)c
14
15
16
17
18
1.4
1.6
1.8
2
2.2
2.4

LDB IC2391

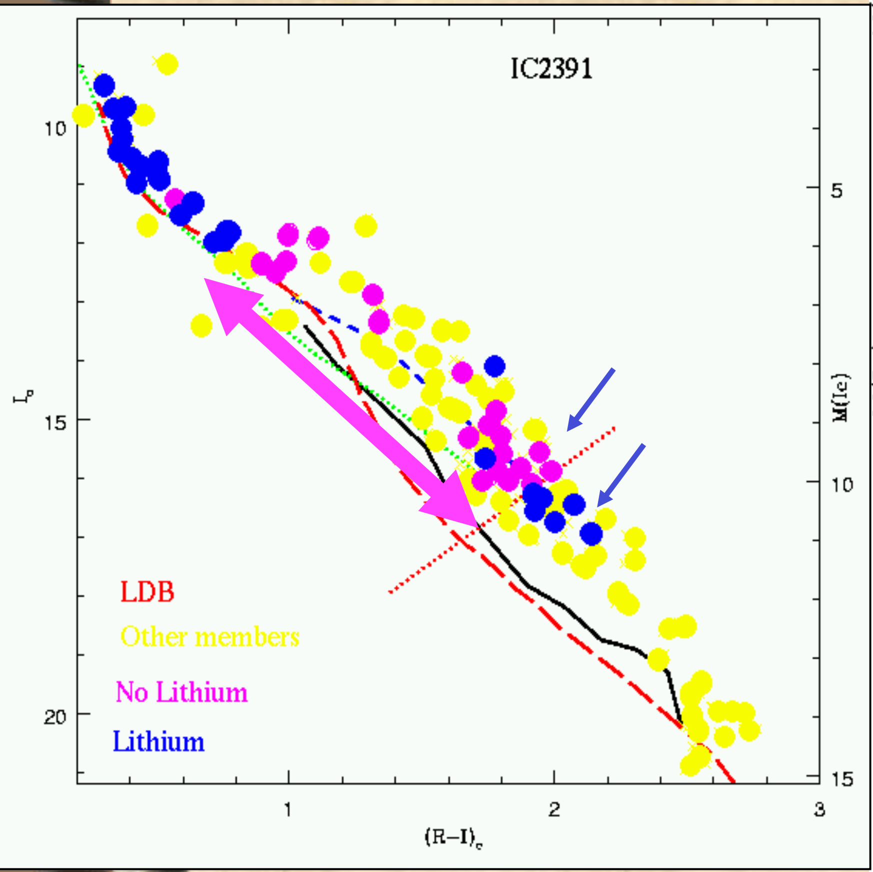


Barrado et al. (1999)

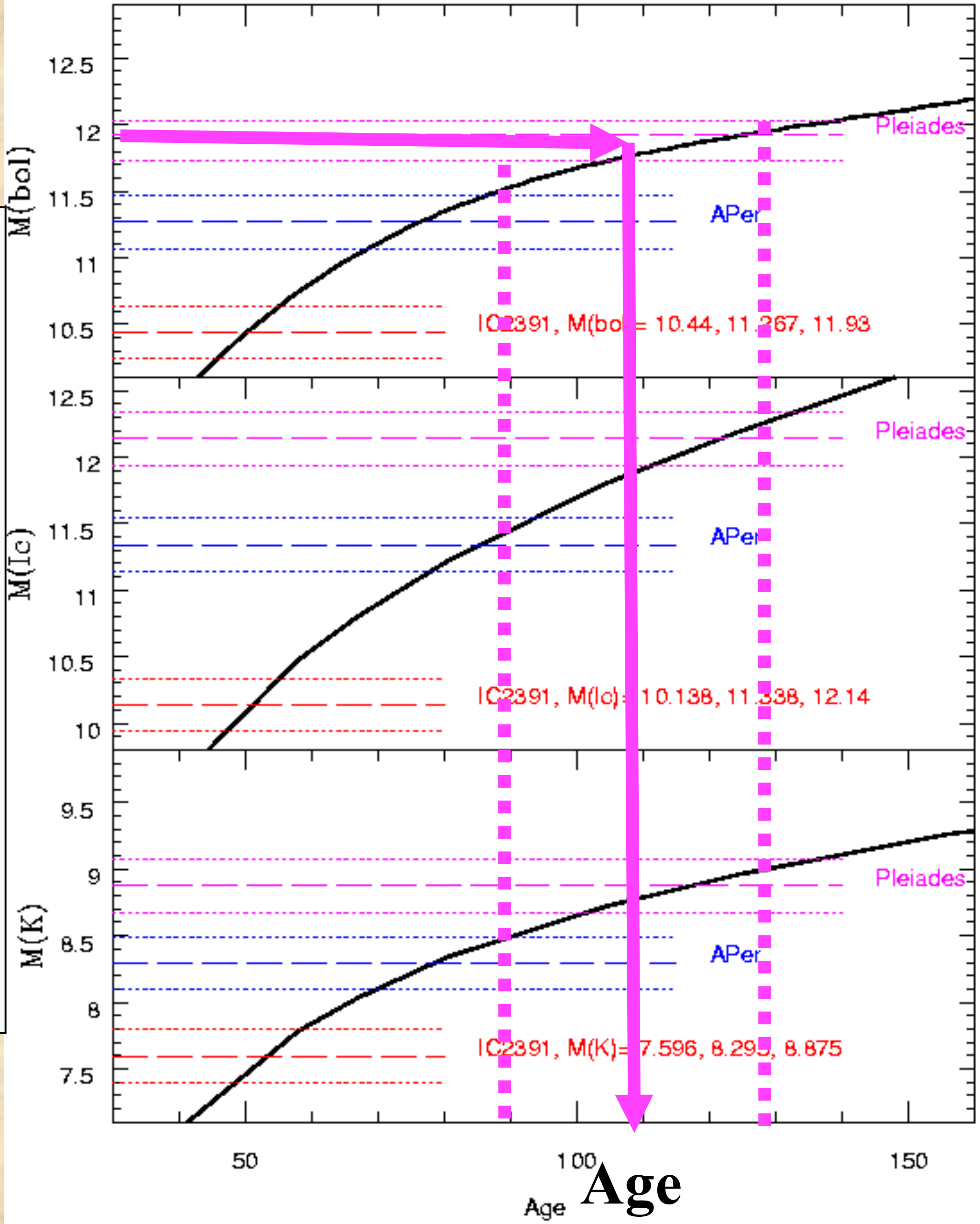


Barrado et al. (2004)

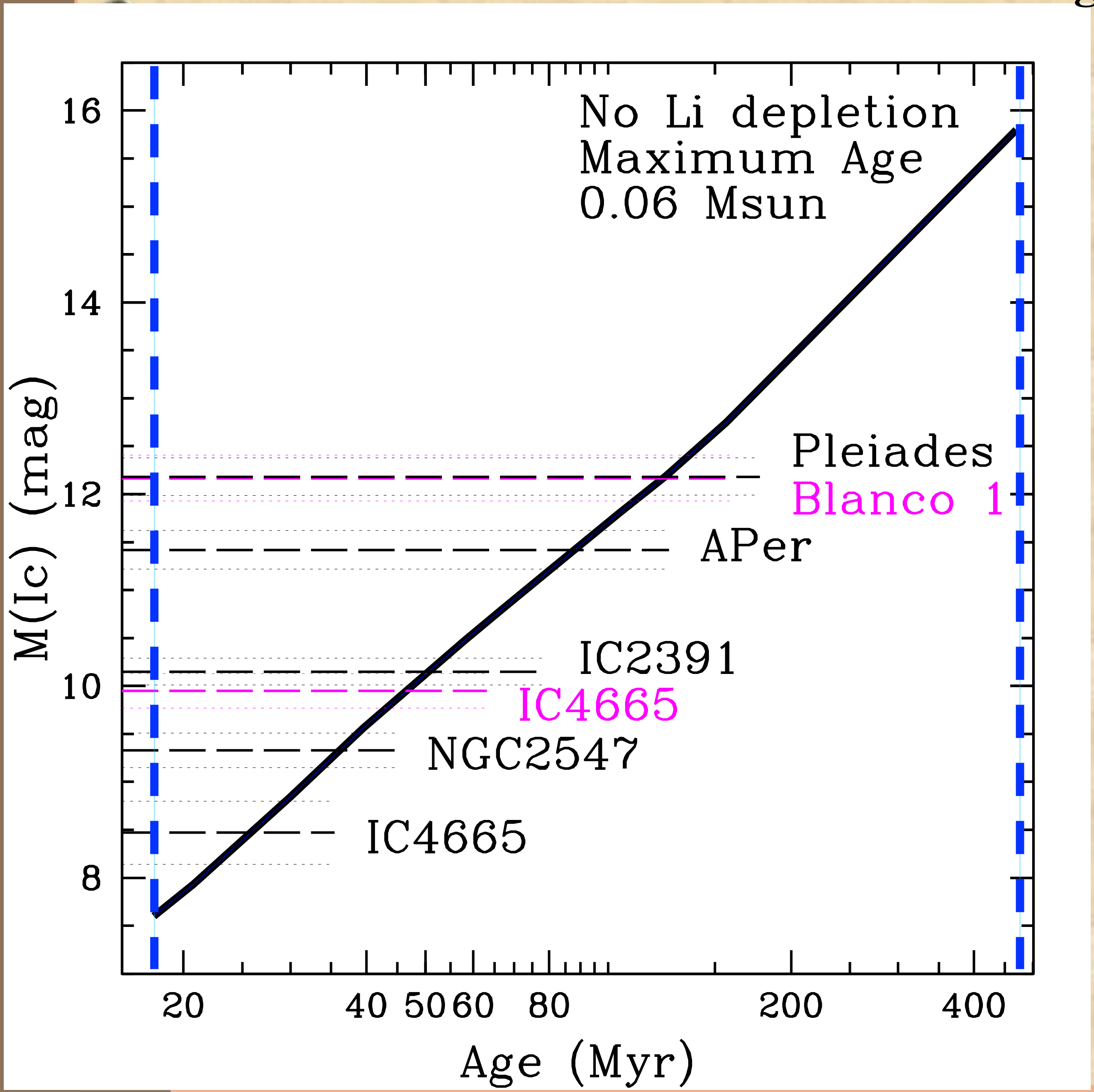
Lithium Depletion Boundary



Barrado et al. (2004)



LDB: from CMD to ages



Valid for
15 < age < 450 Myr
(model dependant)

Cluster	I_{LDB} (mag)	LDB Age (Myr)	Ref.	M_{bol} (mag)	Homogeneous LDB Age (Myr)	Mermilliod MS Age (Myr)	Overshoot MS Age (Myr)	Ref.
β Pic MG		21 ± 4	a	8.28 ± 0.54	$20.3 \pm 3.4 \pm 1.7$			b
NGC 1960	18.95 ± 0.30	22 ± 4	c	8.57 ± 0.33	$23.2 \pm 3.3 \pm 1.9$	< 20	$26.3^{+3.2}_{-5.2}$	k
IC 4665	16.64 ± 0.10	28 ± 5	d	8.78 ± 0.34	$25.4 \pm 3.8 \pm 1.9$	36 ± 5	41 ± 12	l
NGC 2547	17.54 ± 0.14	35 ± 3	e	9.58 ± 0.20	$35.4 \pm 3.3 \pm 2.2$		48^{+14}_{-21}	m
IC 2602	15.64 ± 0.08	46^{+6}_{-5}	f	9.88 ± 0.17	$40.0 \pm 3.7 \pm 2.5$	36 ± 5	44^{+18}_{-16}	m
IC 2391	16.21 ± 0.07	50 ± 5	g	10.31 ± 0.16	$48.6 \pm 4.3 \pm 3.0$	36 ± 5	45 ± 5	n
α Per	17.70 ± 0.15	90 ± 10	h	11.27 ± 0.21	$80 \pm 11 \pm 4$	51 ± 7	80	o
Pleiades	17.86 ± 0.10	125 ± 8	i	12.01 ± 0.16	$126 \pm 16 \pm 4$	78 ± 9	120	o
Blanco 1	18.78 ± 0.24	132 ± 24	j	12.01 ± 0.29	$126 \pm 23 \pm 4$		115 ± 16	j

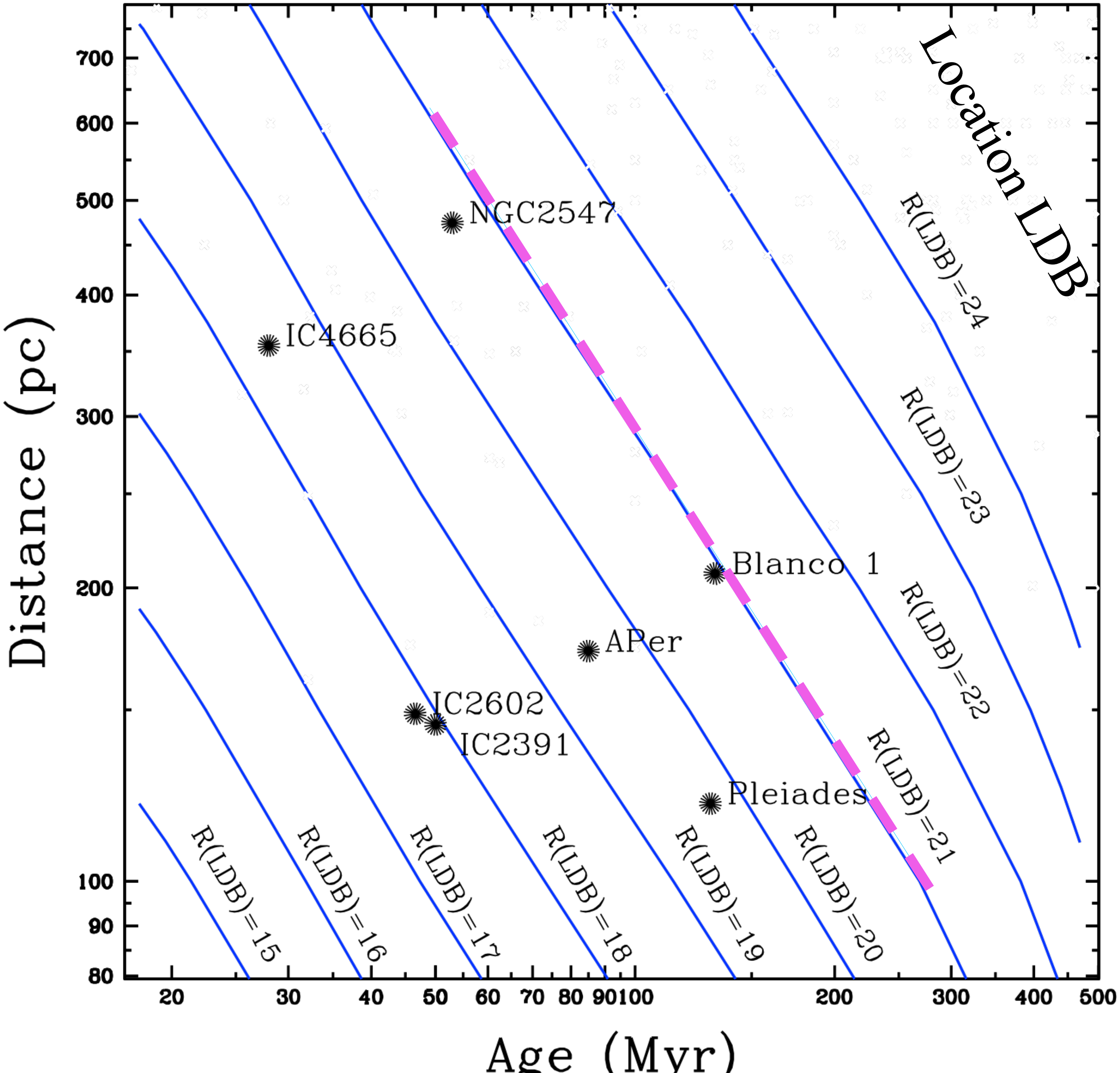
Table 1: LDB ages compared with ages determined from upper main sequence fitting using models both with and without convective overshoot. Columns 2-4 list the apparent I magnitude of the LDB, the published LDB age and the source paper. Columns 5 and 6 give a bolometric magnitude and LDB age that have been homogeneously reevaluated using the locations of the LDB from the original papers, the evolutionary models of *Chabrier and Baraffe* (1997) and bolometric corrections used in *Jeffries and Oliveira* (2005). The error estimates include uncertainty in the LDB location, distance modulus, a calibration error of 0.1 mag and then separately, a physical absolute uncertainty estimated from *Burke et al.* (2004). The last three columns give an upper main sequence age from *Mermilliod* (1981) using models with no convective overshoot, followed by literature age estimate using models with moderate convective overshoot. References: (a) *Binks and Jeffries* (2013); I mag. not available; M_{bol} calculated from K_{LDB}. (b) most massive member is A6V, hence no UMS age. (c) *Jeffries et al.* (2013), (d) *Manzi et al.* (2008), (e) *Jeffries and Oliveira* (2005), (f) *Dobbie et al.* (2010), (g) *Barrado y Navascués et al.* (2004), (h) *Stauffer et al.* (1999), (i) *Stauffer et al.* (1998), (j) *Cargile et al.* (2010), (k) *Bell et al.* (2013), (l) *Cargile and James* (2010), (m) *Naylor et al.* (2009), (n) derived by E. Mamajek using data from *Hauck and Mermilliod* (1998) and isochrones from *Bertelli et al.* (2009), (o) *Ventura et al.* (1998).

Soderblom et al. (2013)

Measured LDB ages from 20 to 130 Myr

Valid range: **15 < age < 450 Myr** approx

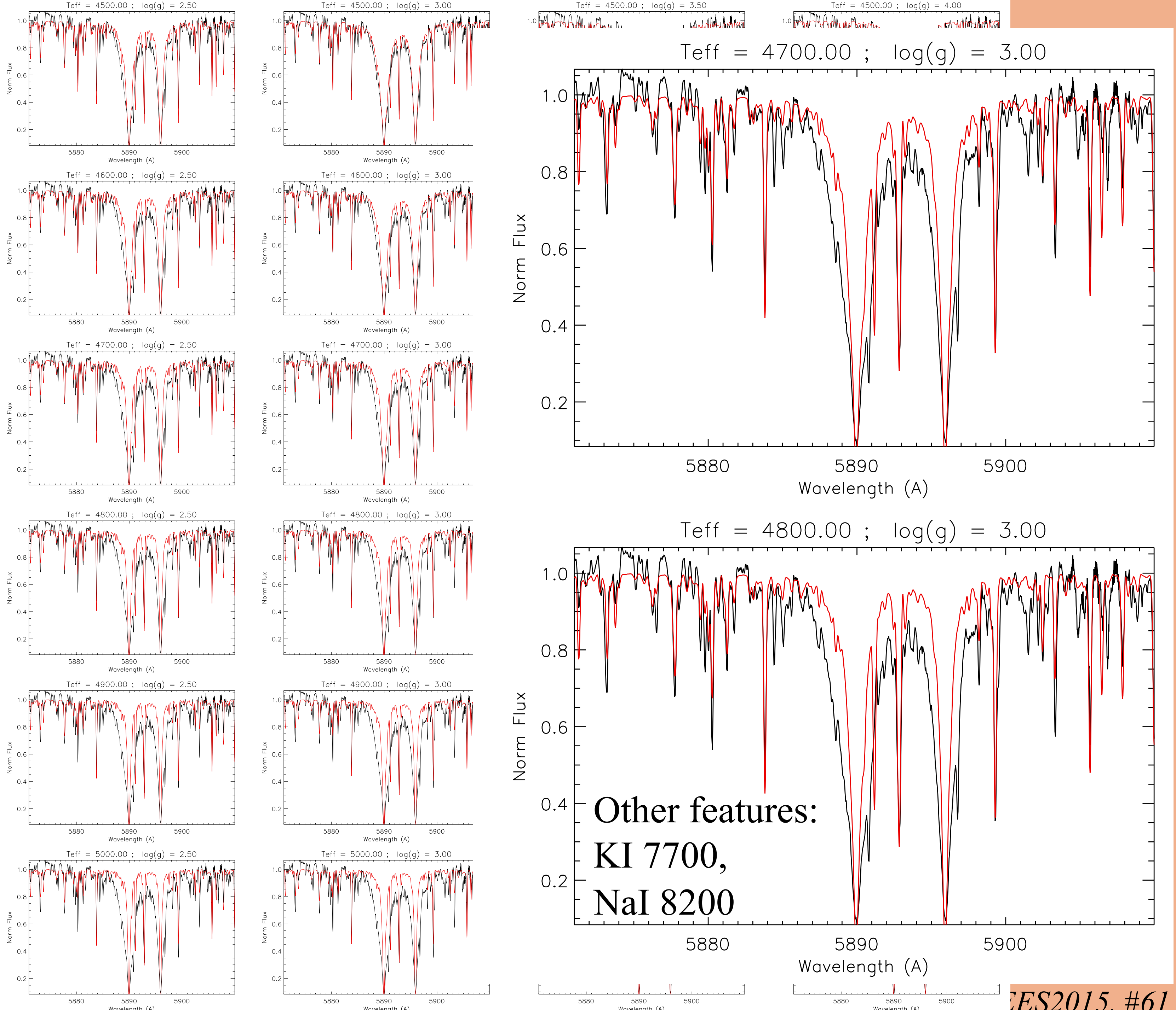
Clusters and the LDB



Good quality spectra is needed with a 8-class telescope

Spectral resolution:
1500 minimum
2500 common
3500 best
SNR≈50

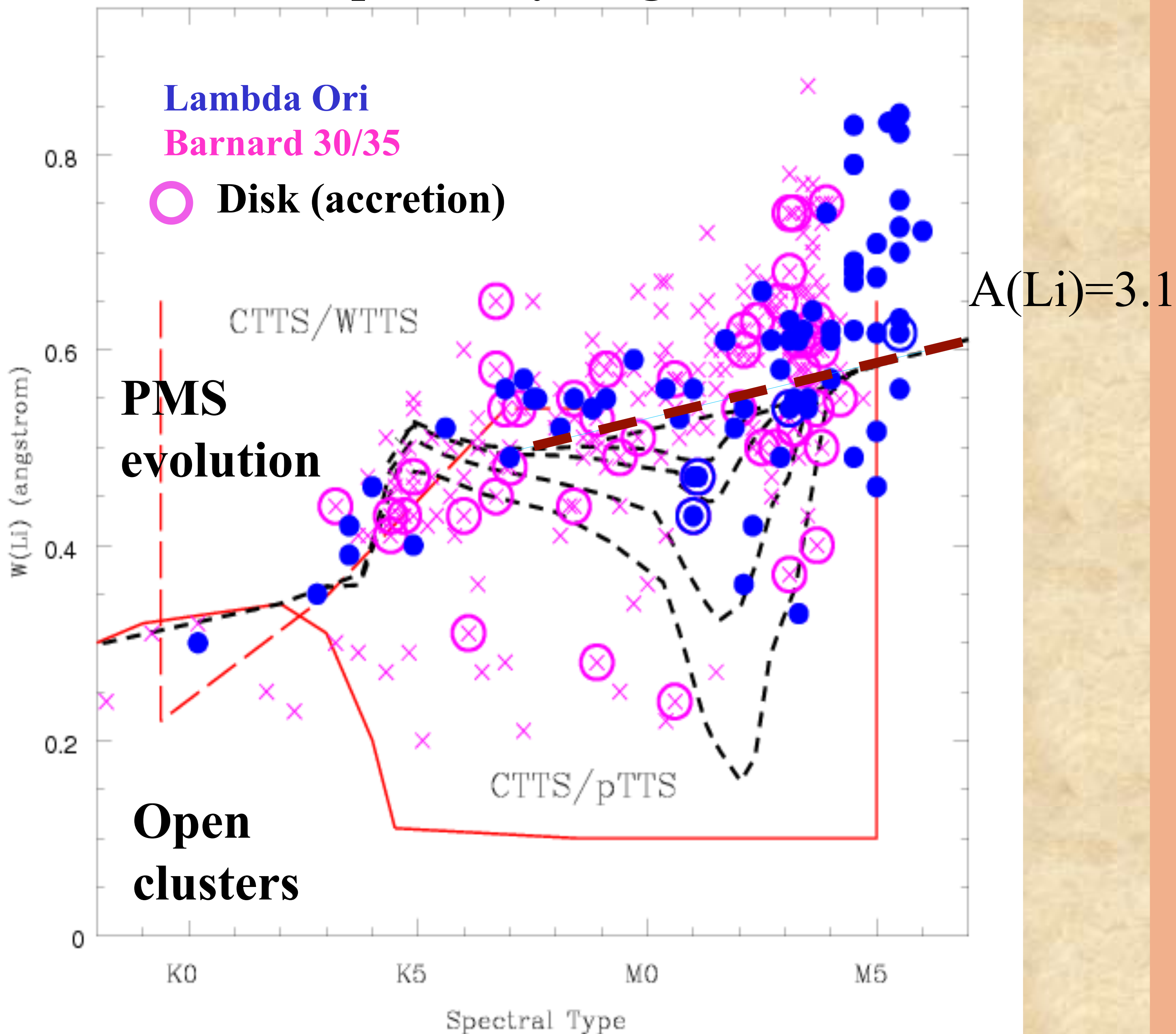
Gravity
via alkali spectral features



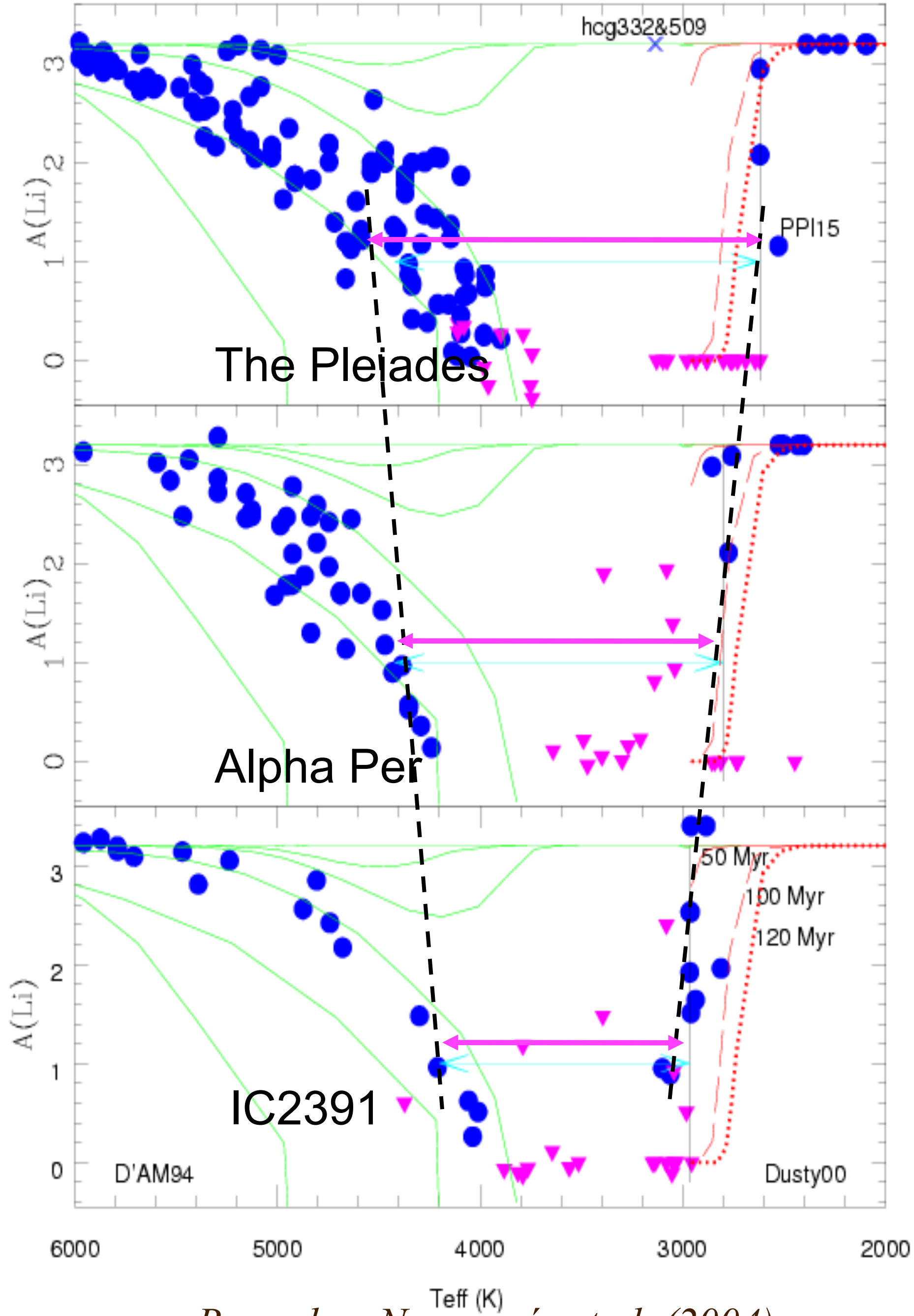
Other features:
KI 7700,
NaI 8200

Lithium (II)
FGK(M)

Lithium depletion: young associations



Lithium depletion: clusters



Barrado y Navascués et al. (2004)

Lithium spread:
The role of rotation
(and activity)

See:
Soderblom et al. (1993)

Standard models predict that the depletion happens during the Pre-Main Sequence evolution. However, the observations shows that it continues beyond the arrival to the ZAMS, so additional**, non-standard mixing** has to take place.

Moreover, for clusters older than the Pleiades there is a narrow effective temperature range (6400-6900 K) which shows a large depletion of lithium abundance due to non-standard mixing, the so called **lithium gap, dip or chasm** (Boesgaard & Tripicco (1986a); Michaud & Charbonneau (1991); Balachandran (1995)). Pilachowski et al. (1984), Pilachowski (1986), Pilachowski et al. (1987), Pilachowski et al. (1988), for **NGC7789, the Pleiades, NGC752, and M67**; Boesgaard & Tripicco (1986b), Boesgaard (1987b), Boesgaard (1987a), Boesgaard et al. (1988), Boesgaard & Budge (1988), Boesgaard & Budge (1989), Barrado y Navascués et al. (1996) for **the Hyades**, **Coma, the Pleiades and Alpha Per, and Praesepe**; Soderblom et al. (1993a), Soderblom et al. (1993b), Soderblom et al. (1993c) for **Praesepe, the Pleiades and Ursa Majoris moving group**.

More recently, additional observations for clusters, generally younger, have been studied. Again, just to provide some references: **NGC2516 and M35**, almost Pleiades twins (Jeffries et al. (1998); Barrado y Navascués et al. (2001a))**, IC2602 and IC2391** (Barrado y Navascués et al. (1999); Randich (2001); Randich et al. (2001); Barrado y Navascués et al. (2004)), **NGC2547** (Jeffries et al. (2003)), **IC4665** (Jeffries et al. (2009)), and **Collinder 69** (Dolan & Mathieu (1999), Bayo et al. (2012)).

Real change in abundance:

- Bouvier et al.(2008) & Eggenberger et al. (2012).- disk life-time, rotation evolution and extramixing at the bottom of the convective envelope.

- Sommers & Pinsonneault (2014).- radius dispersion for a fixed mass and age (*this is against the possibility of using isochrone fitting to derive ages*).

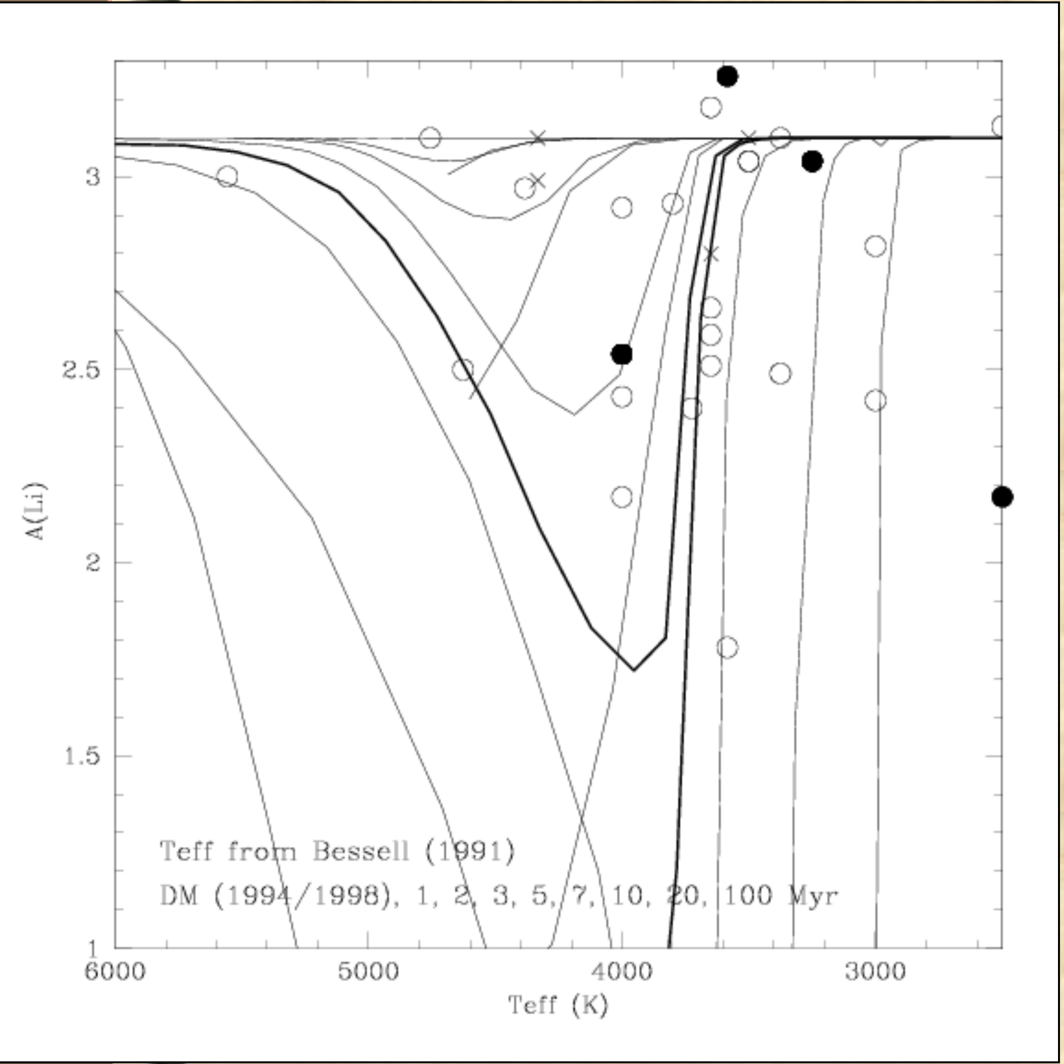
- Jackson & Jeffries (2013, 2014).- active Pre-Main Sequence stars have an expanded radius due to the presence of spot.

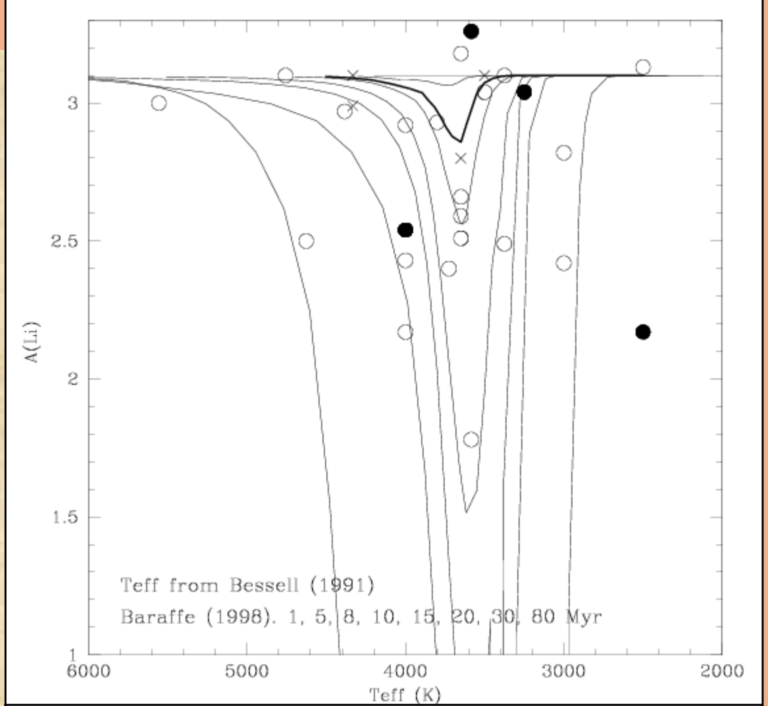
Apparent effect:

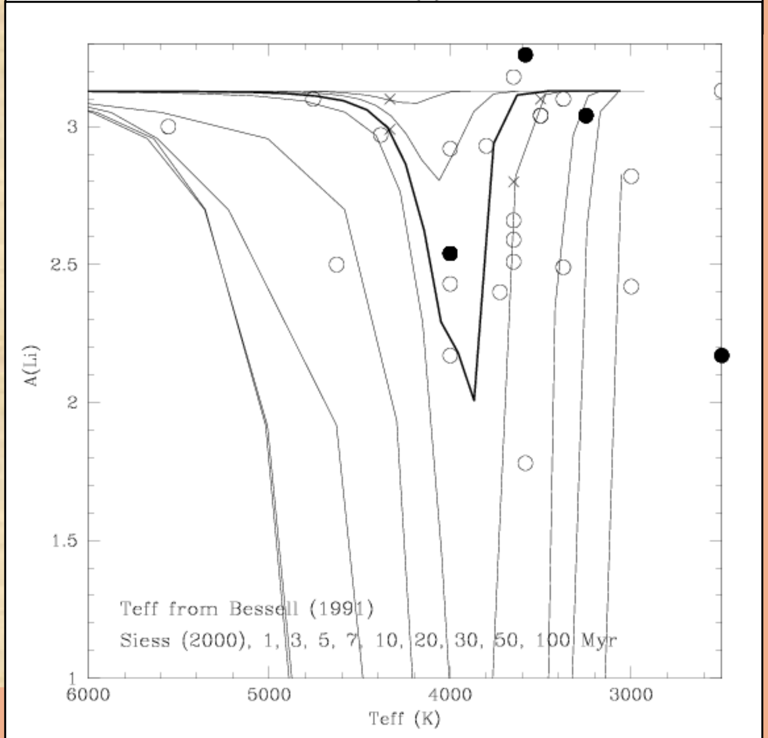
- A number of works dealing with **the effect of activity**: Stuik et al. (1997), Jeffries (1999), King et al. (2000), Barrado y Navascués et al. (2001b), King & Schuler (2004), King et al. (2010).

Lithium depletion:

The effect of different models



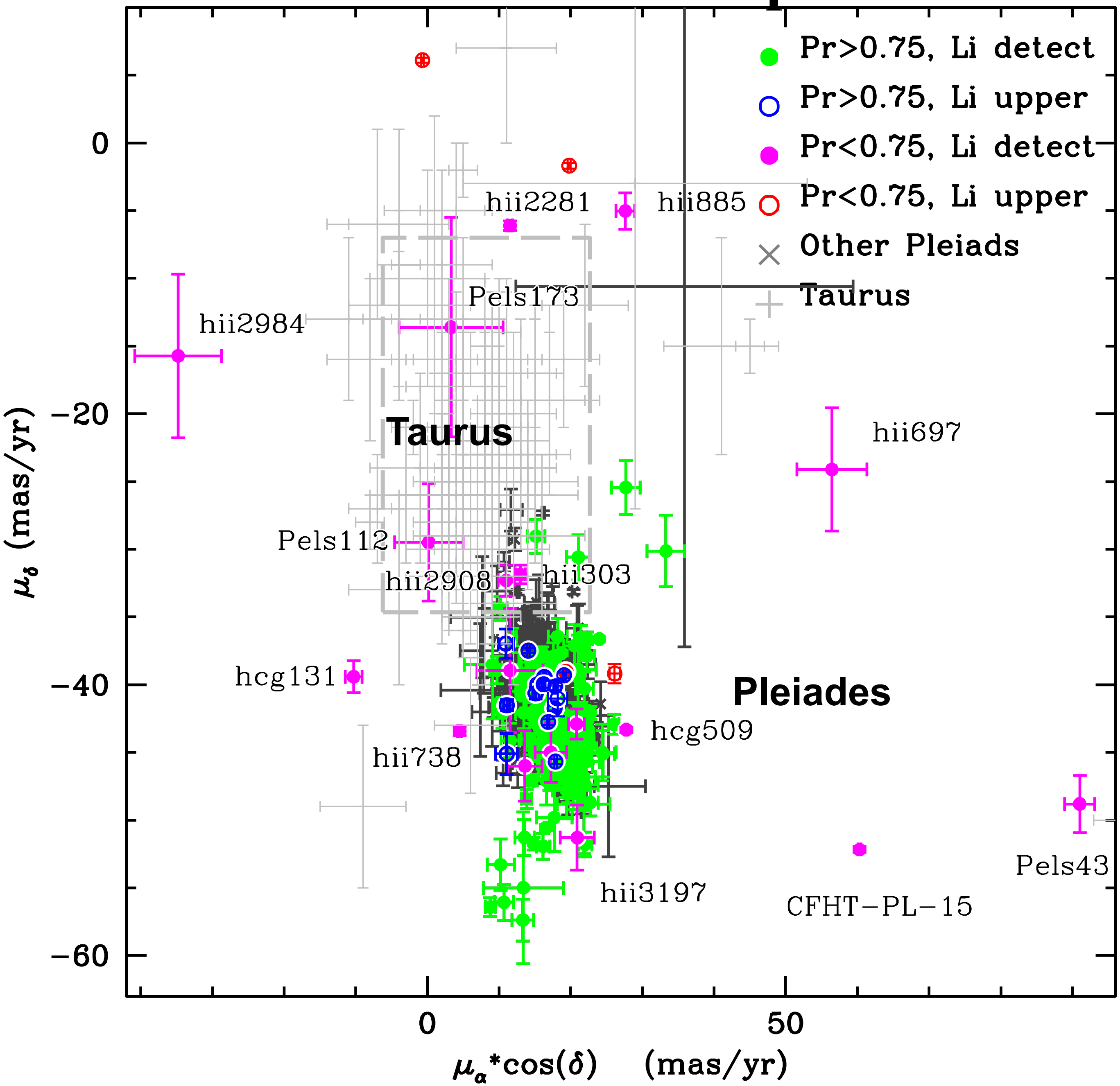




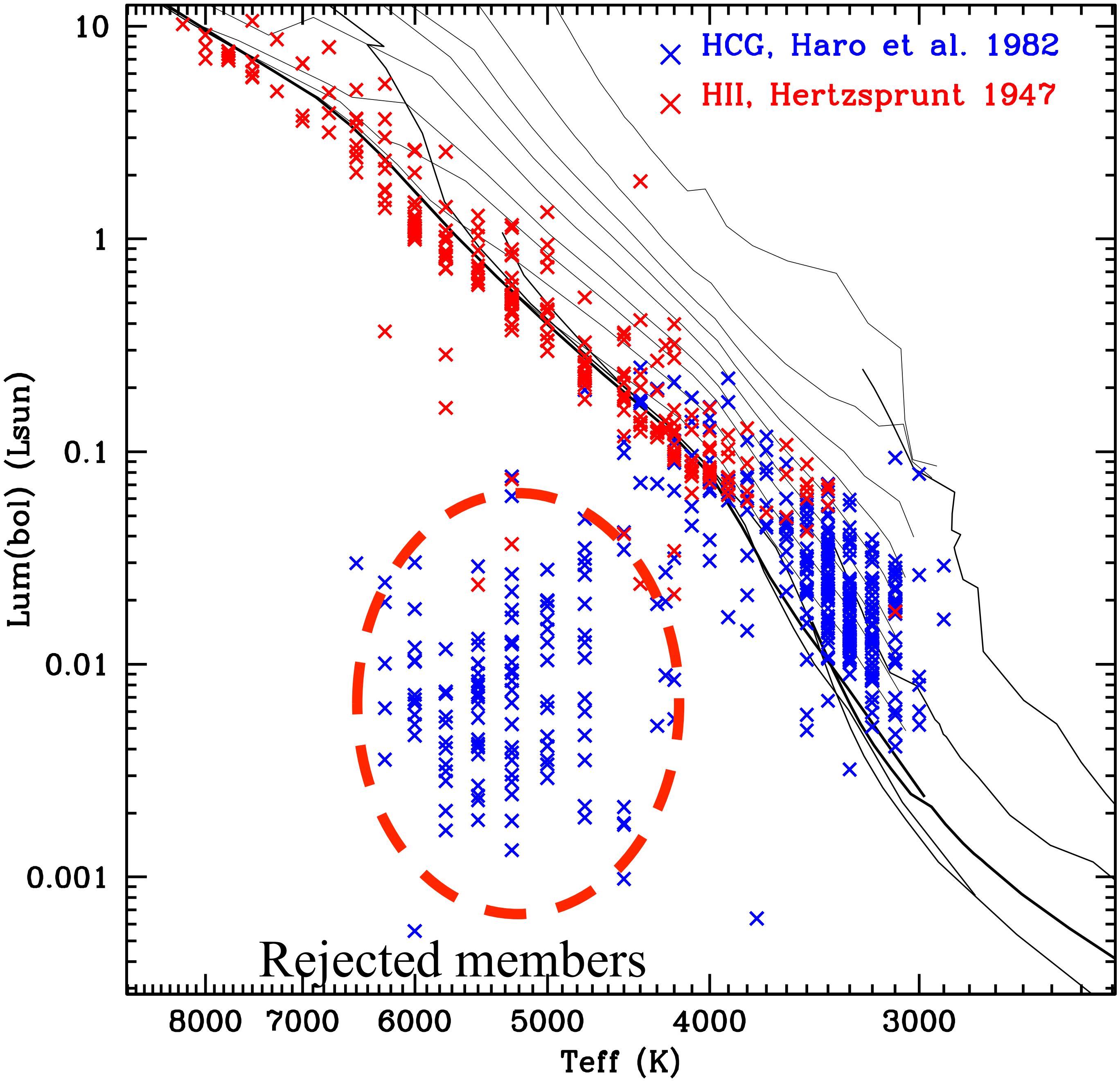
David Barrado

The cornerstone: The Pleiades (II)

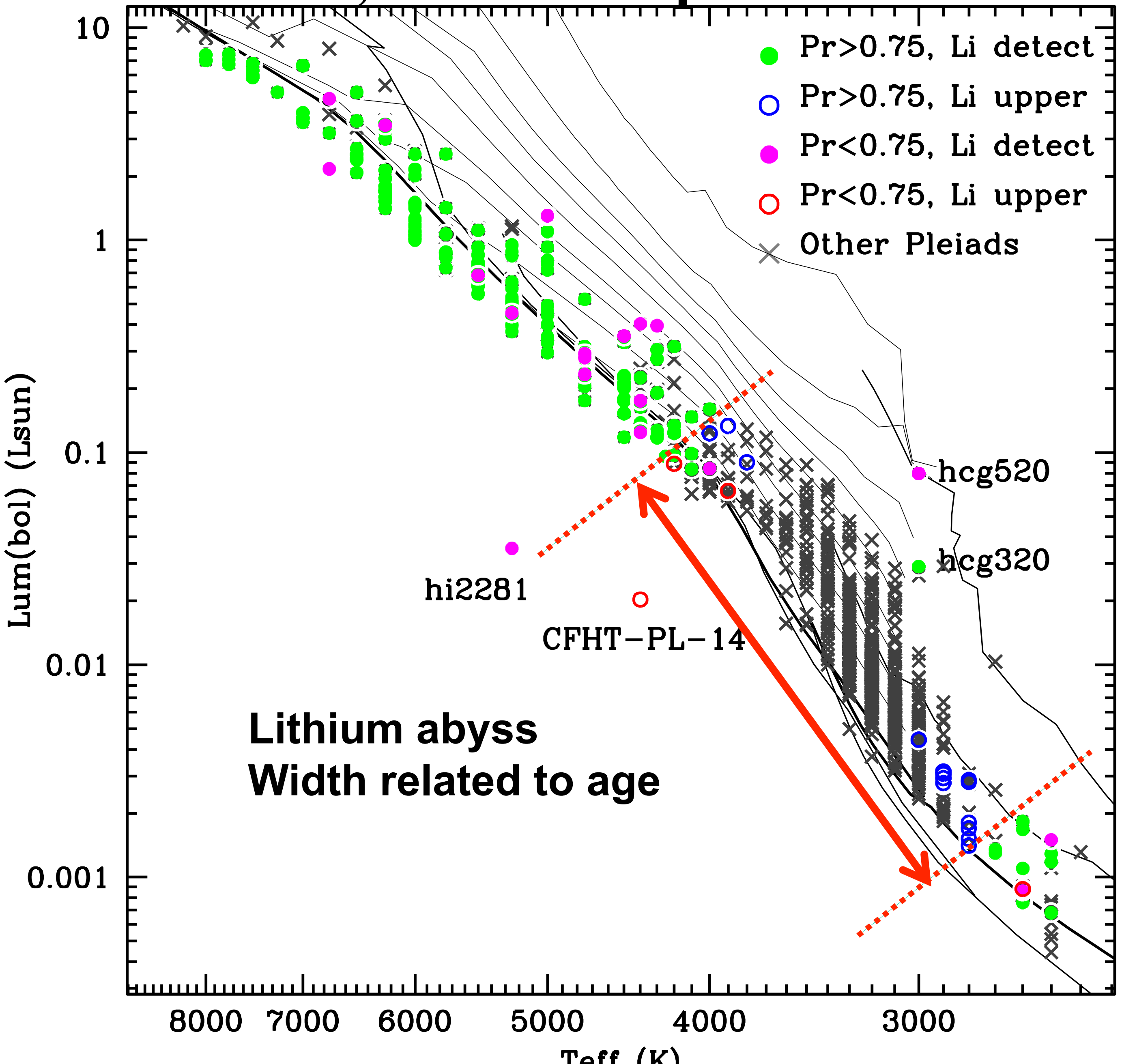
DANCe: membership



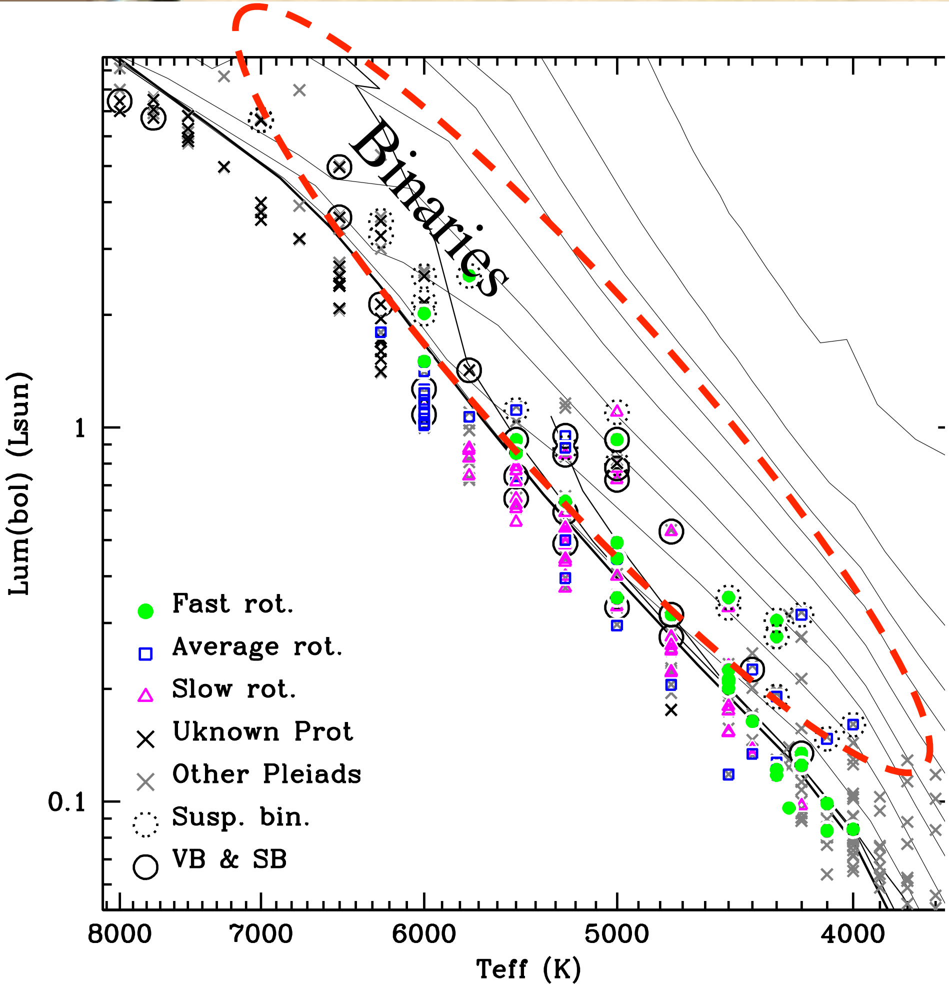
- Bouy et al. 2013, 2015;
- Sarro et al. 2014

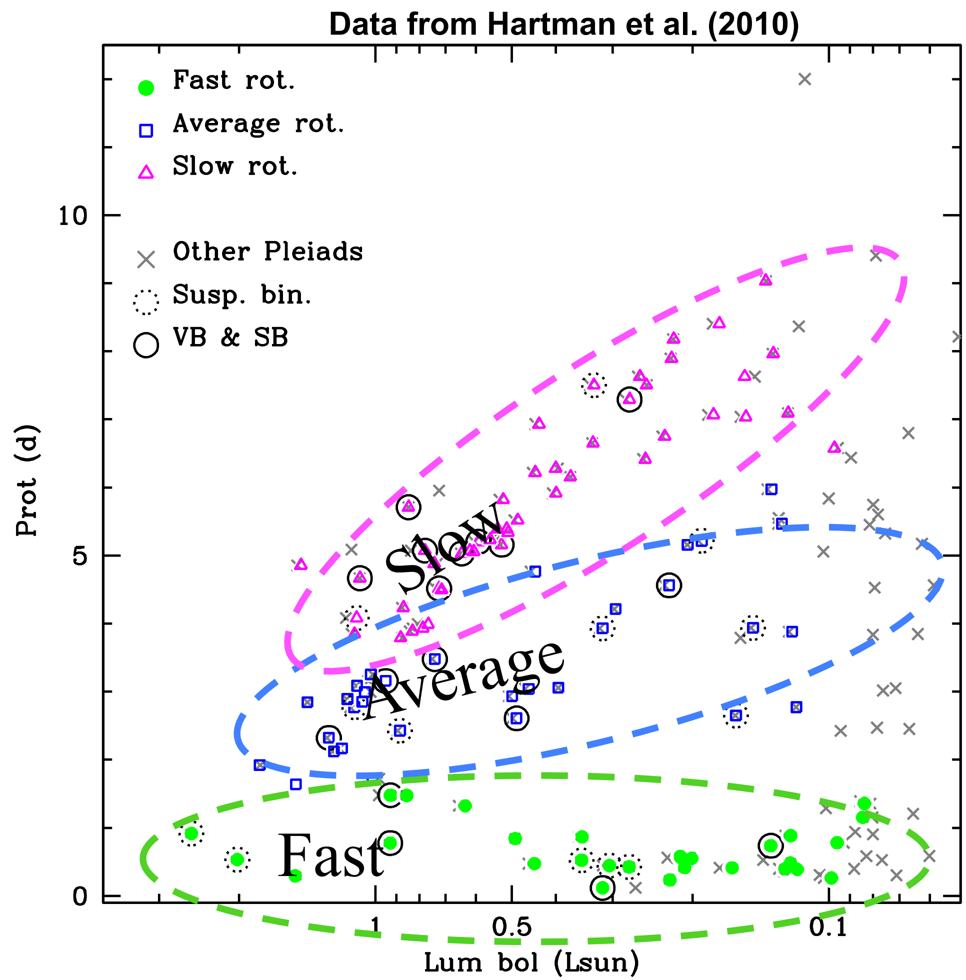

HCG, Haro et al. 1982
HII, Hertzsprunt 1947
Lum(bol) (Lsun)
10
1
0.1
0.01
0.001
8000
7000
6000
5000
4000
3000
Teff (K)
Rejected members

HRD, membership & lithium



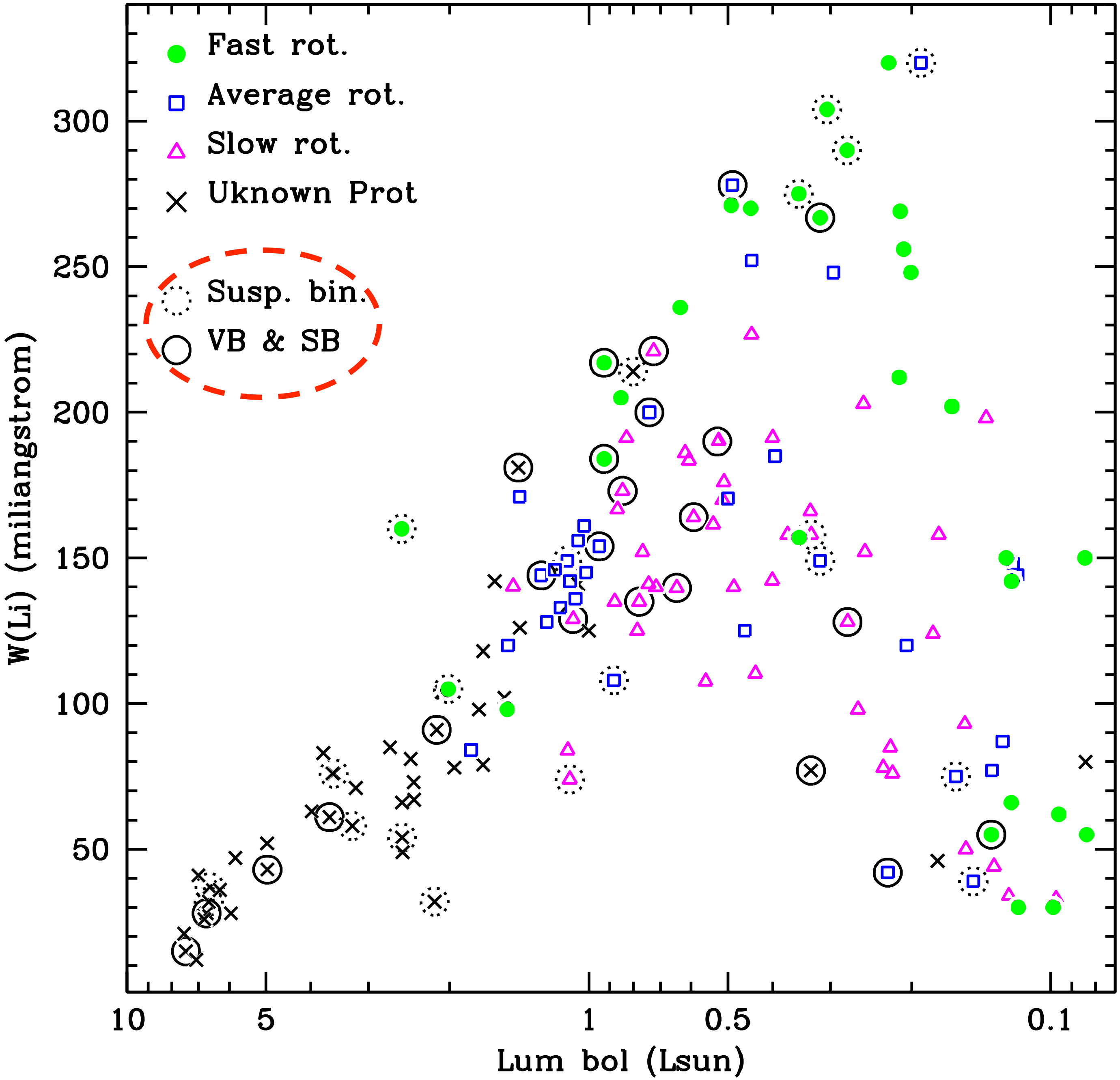
Binaries and rotation



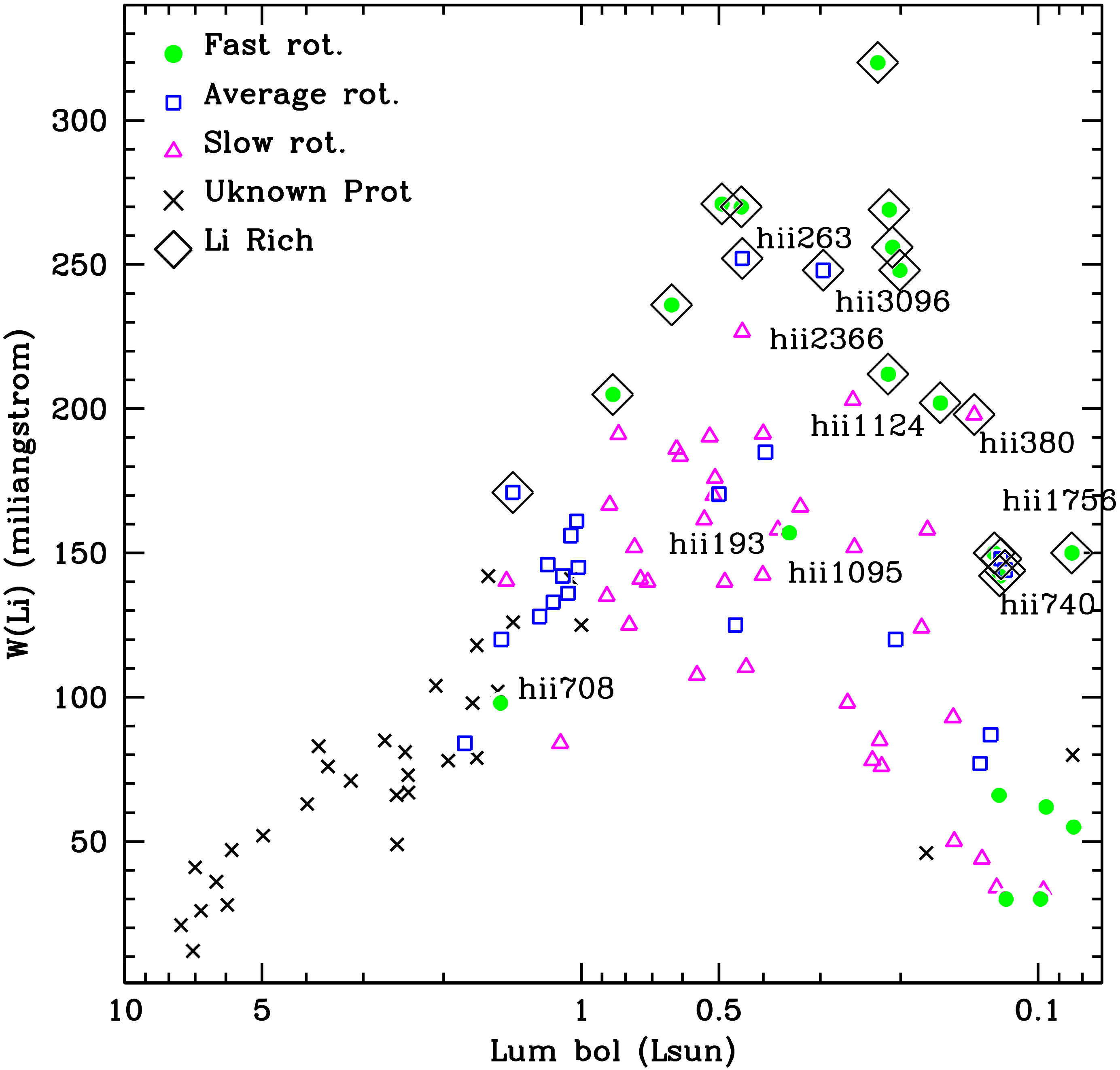


Gyrochronology? Depends…

Lithium in binaries



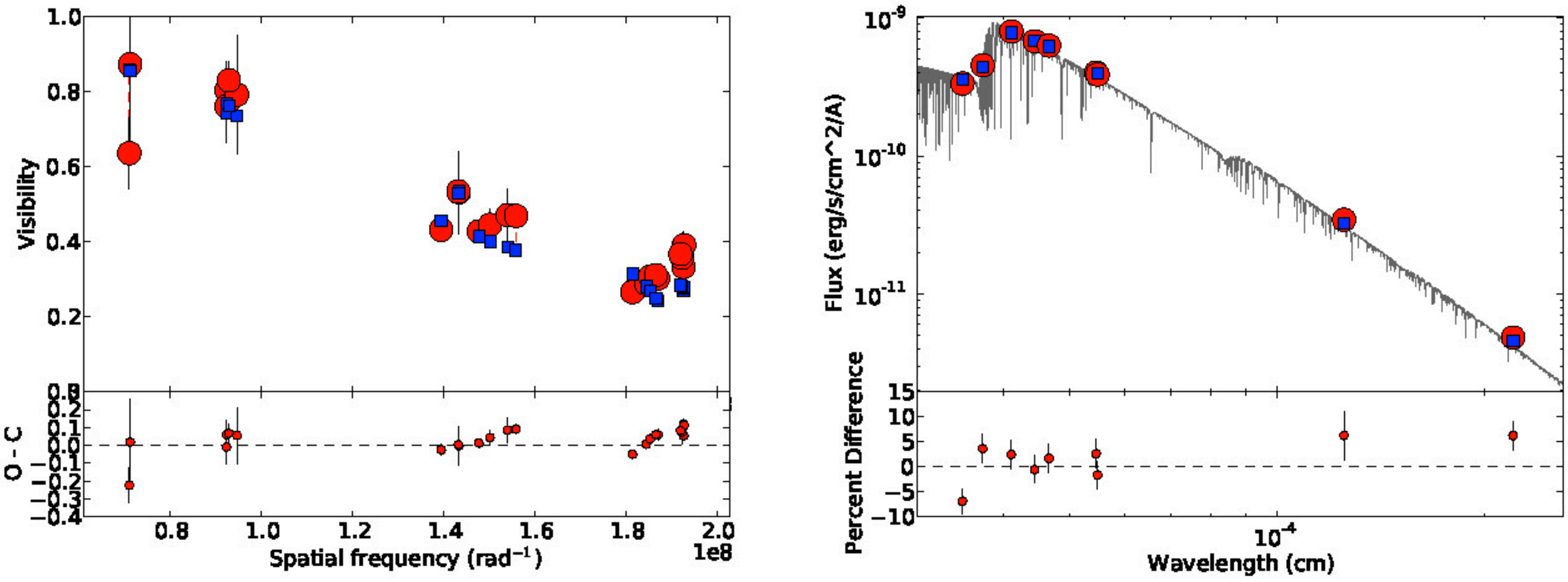
Only single stars



Interferometry

Ursa Majoris Group

Defined in 1949 by Roman. The assumed age og UMaG is 300 Myr



(c) (d)

Figure 4. Top Left - Visibility measurements (red circles) for Phecda (HD 103287) are compared to the best fit model visibilities (blue squares) assuming the ELR prescription for gravity darkening. Dashed lines connect individual model and measured values and solid lines are the error bars. Top Right - Photometric measurements (red circles) for Phecda (HD 103287) are compared to the best fit model photometry (blue squares) assuming the ELR prescription for gravity darkening. The spectral energy distribution from which the PED is calculated is plotted in grey for comparison. Bottom Left - Same as Top Left, but for the vZ gravity darkening law. Bottom Right - Same as Top Right, but for the vZ gravity darkening law.

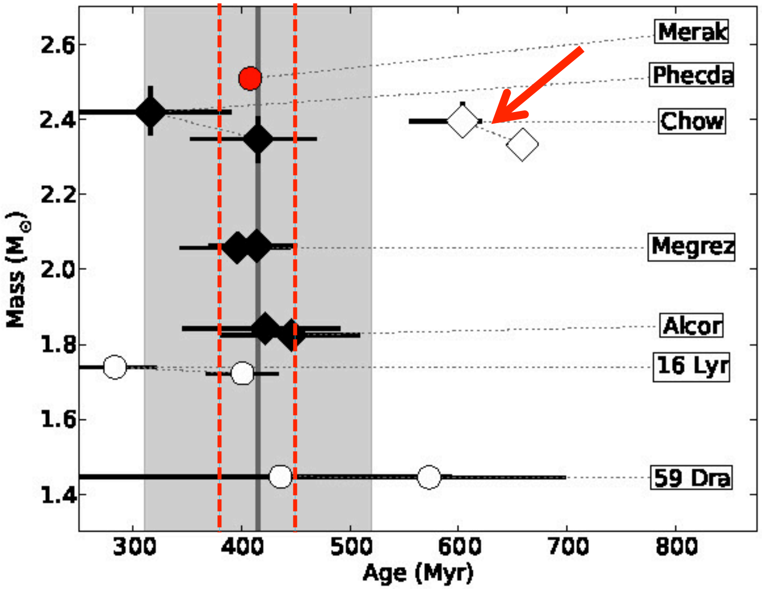
Jones et al. 2015

*"MESA **evolutionary code** for rapidly rotating stars. …combine these age estimates and determine the age of the moving group to be **414±28** Myr"*

Ursa Majoris Group

Final errors

Rejected



(c)

Figure 10. Distribution of stellar masses versus age for 7 stars in the Ursa Major moving group as determined using the vZ gravity darkening law (10a), ELR law (10b), and both (10c) with the model described in Section 4.1. The circles are slowly rotating stars ($V_e < 170$ km s^{-1}) and the diamonds are rapidly rotating ($V_e > 170$ km s^{-1}). The black points are nucleus members and the white points are stream members. The red point shows the mass and age of the nucleus member, Merak, that was previously observed by Boyajian et al. (2012) and is discussed here in Section 4.3. In some cases, the size of the statistical error bar is smaller than the size of the symbol. The dark vertical lines represent the median in the ages, the shaded regions represent the gapper scale (the standard deviation equivalent discussed in Section 5.4). The dotted lines in 10c connect the age and mass estimates from the two different laws.

ABSTRACT:

"*MESA evolutionary code for rapidly rotating stars. …combine these age estimates and determine the age of the moving group to be* ***414±28*** *Myr*"

Jones et al. 2015

Kinematics

Kinematics and age: Beta Pic MG

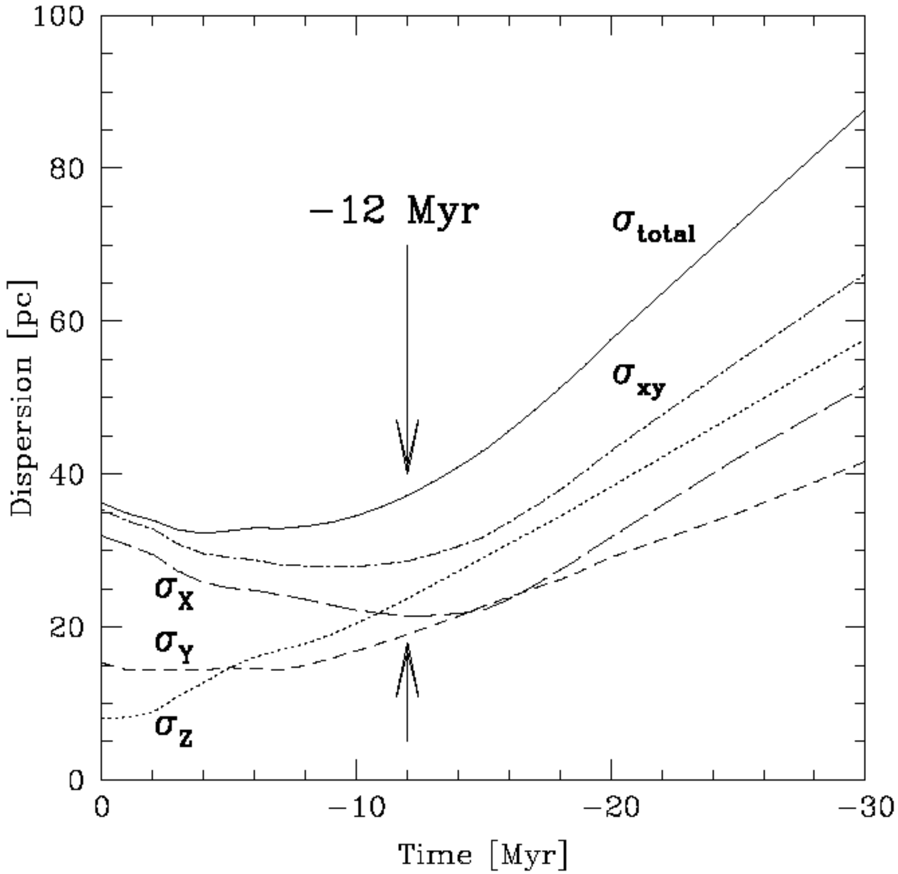


Figure 2. 1σ dispersions in X, Y, Z coordinates (σ_X, σ_Y, σ_Z) as a function of time in the past, assuming linear trajectories. The quadrature sums of the X- and Y- dispersions (σ_{XY}) and X-, Y- and Z- dispersions ($\sigma_{\rm total}$) are also plotted. Linear trajectories in Z are obviously the poorest approximation (contrast with dispersion measured for epicyclic orbit in Fig. 4). The σ_{XY} dispersion may be the most useful overall metric of the group's size using the linear trajectory technique.

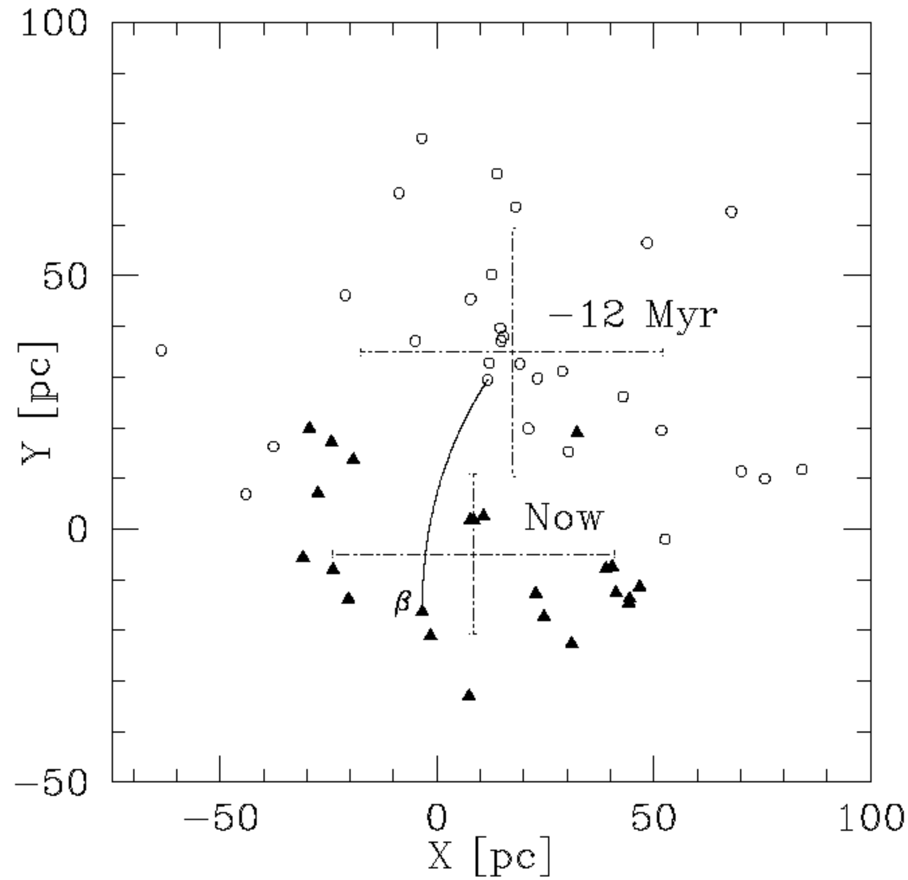
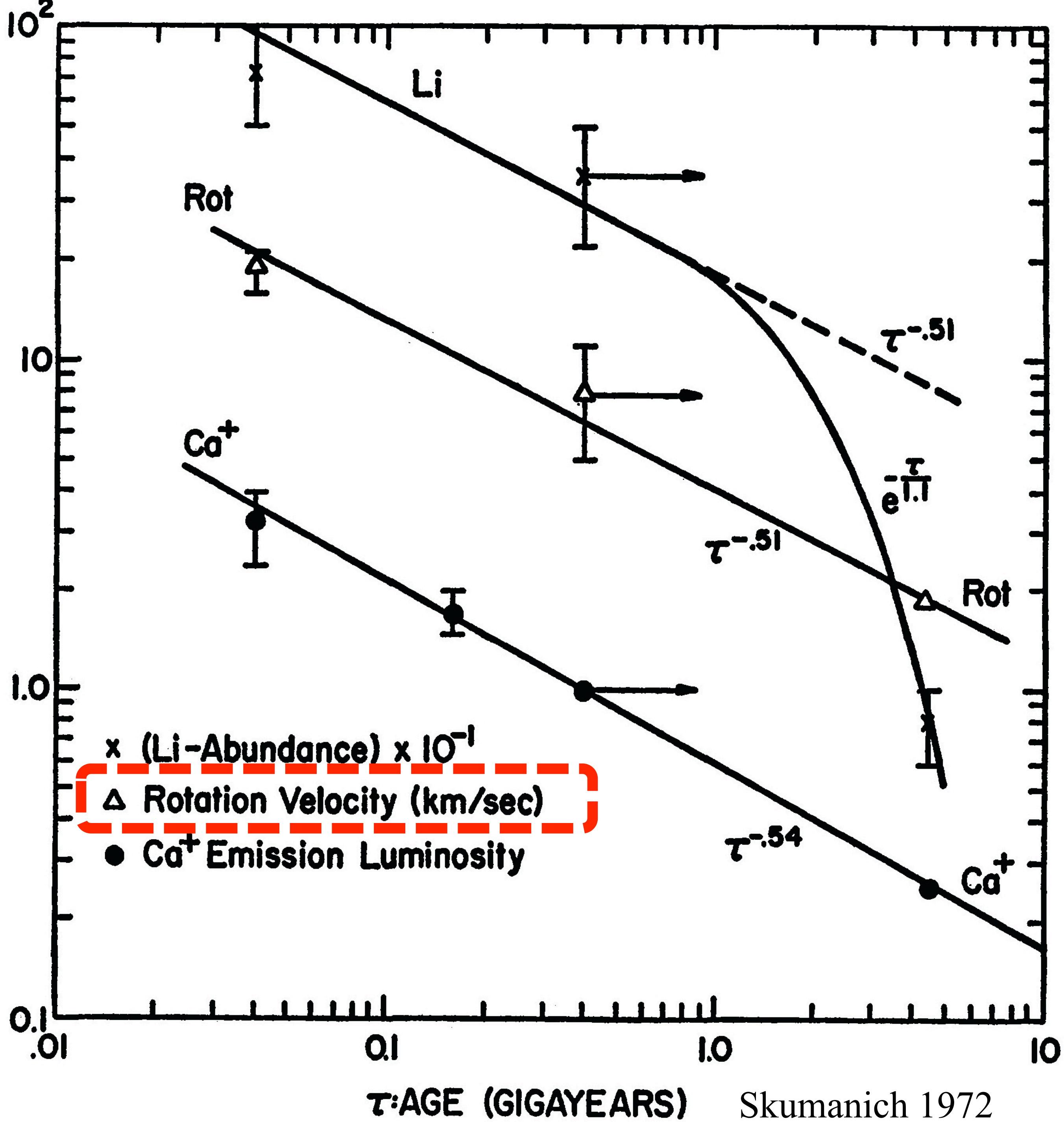


Figure 3. Distribution of BPMG members in the XY plane now (*filled triangles*) and 12 Myr ago (*open circles*) using epicycle orbit approximation. The dispersion in the X and Y directions are plotted now and 12 Myr ago. The trajectory for the star β Pic itself is plotted as a solid arc, and labelled with a "β". The reference frame has its origin at the Sun's current position, but is co-moving with the LSR of Schönrich et al. (2010).

Mamajek et al. (2014)

Gyrochronology



Skumanich 1972

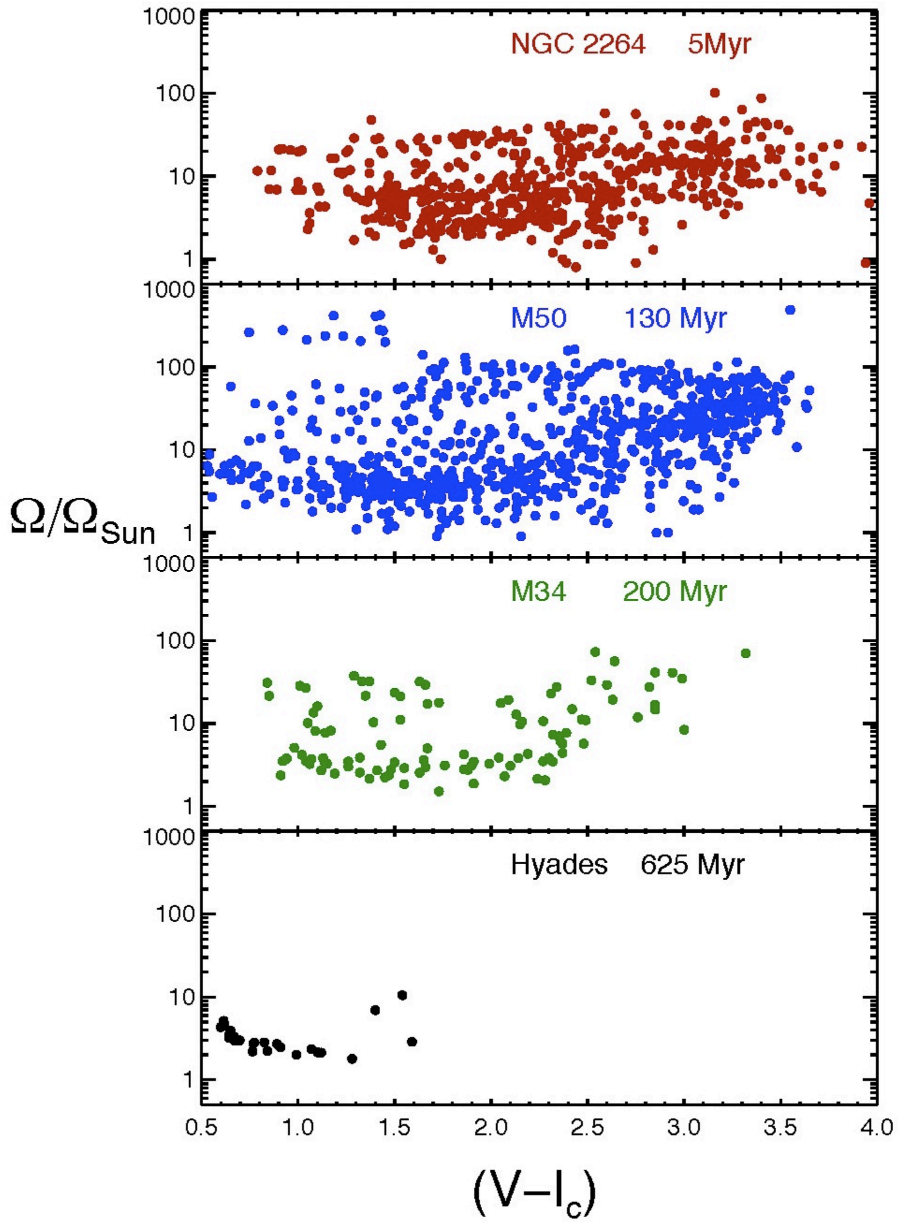
"Gyrochronology"

Using rotation to determine age

Overall decline of rotation with age for solar-type stars studied for 40+ years (Kraft 1967).

Note >20x scatter at ZAMS but almost none in Hyades; the convergence takes place in ~300 Myr, but then AM loss slows down.

Recent work by Barnes (2007) and Mamajek & Hillenbrand (2008).



D. Soderblom

Seems to work for old stars

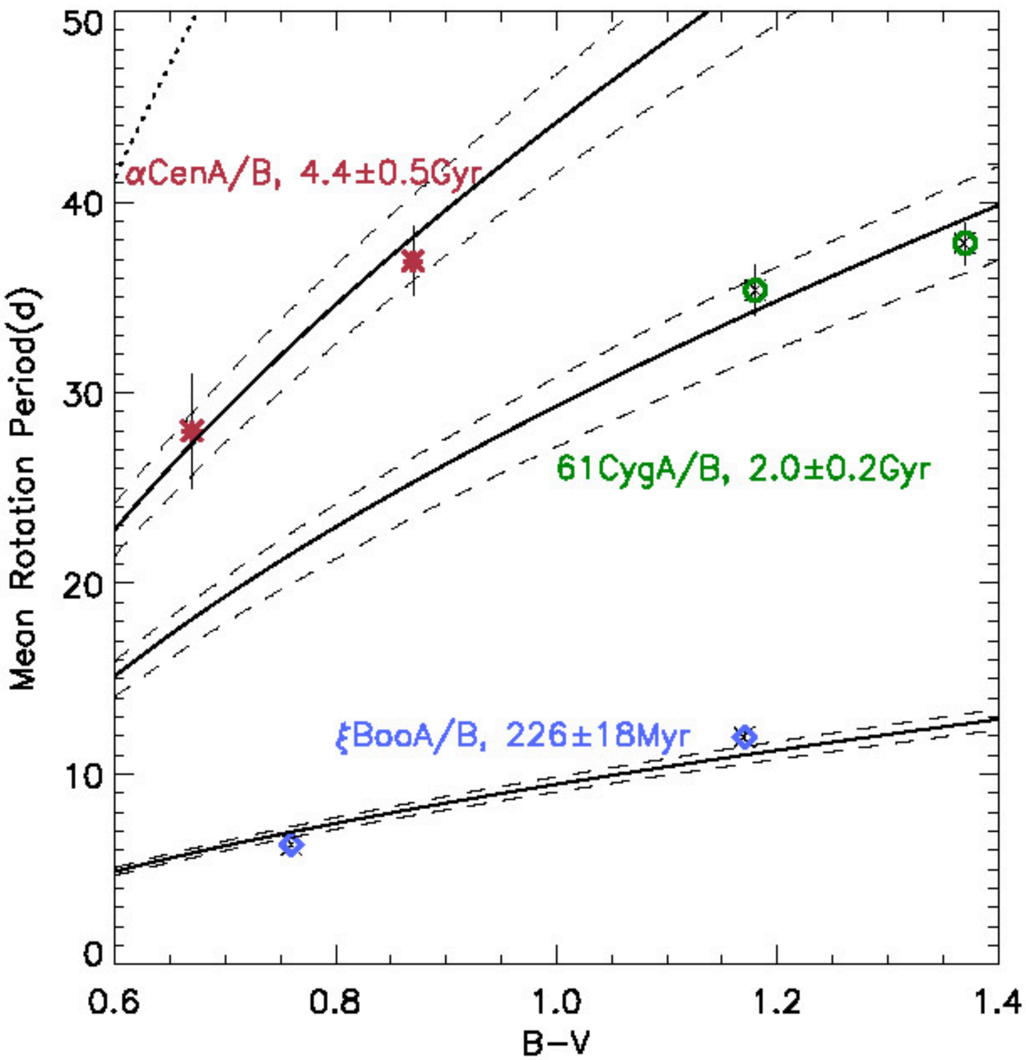


Figure 8. The components of the wide binaries ξ Boo, 61 Cyg, and α Cen appear to give the same gyro ages. (Figure from Barnes, 2007)

D. Soderblom

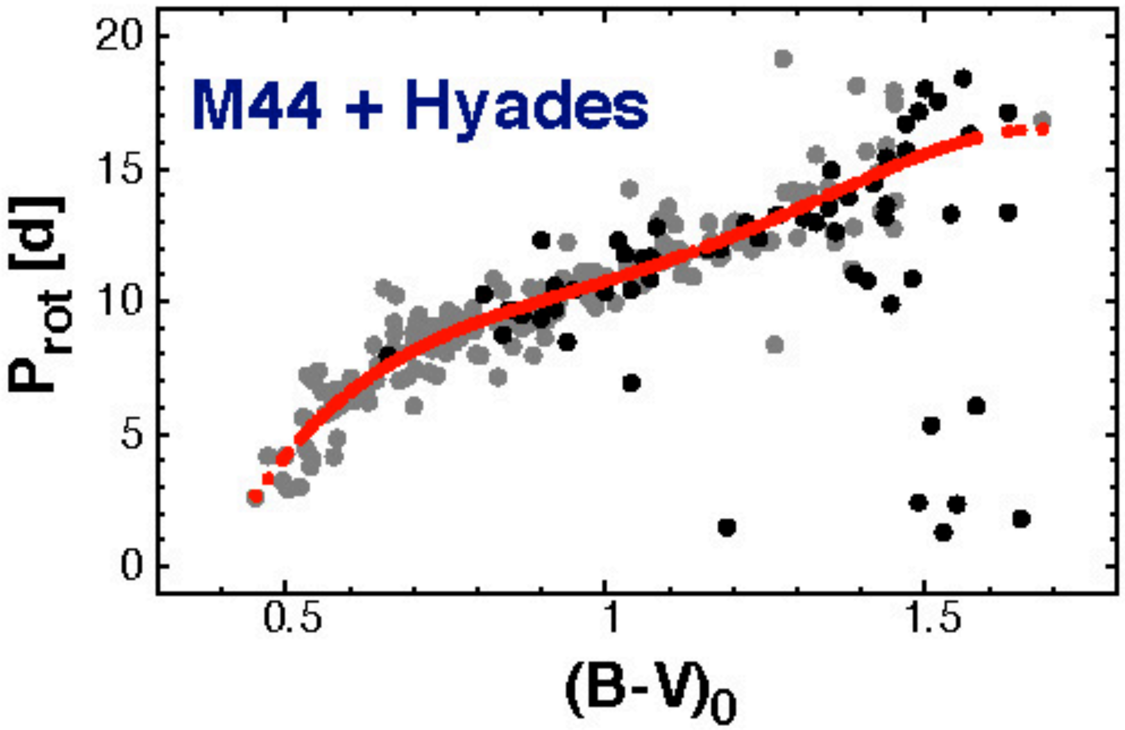
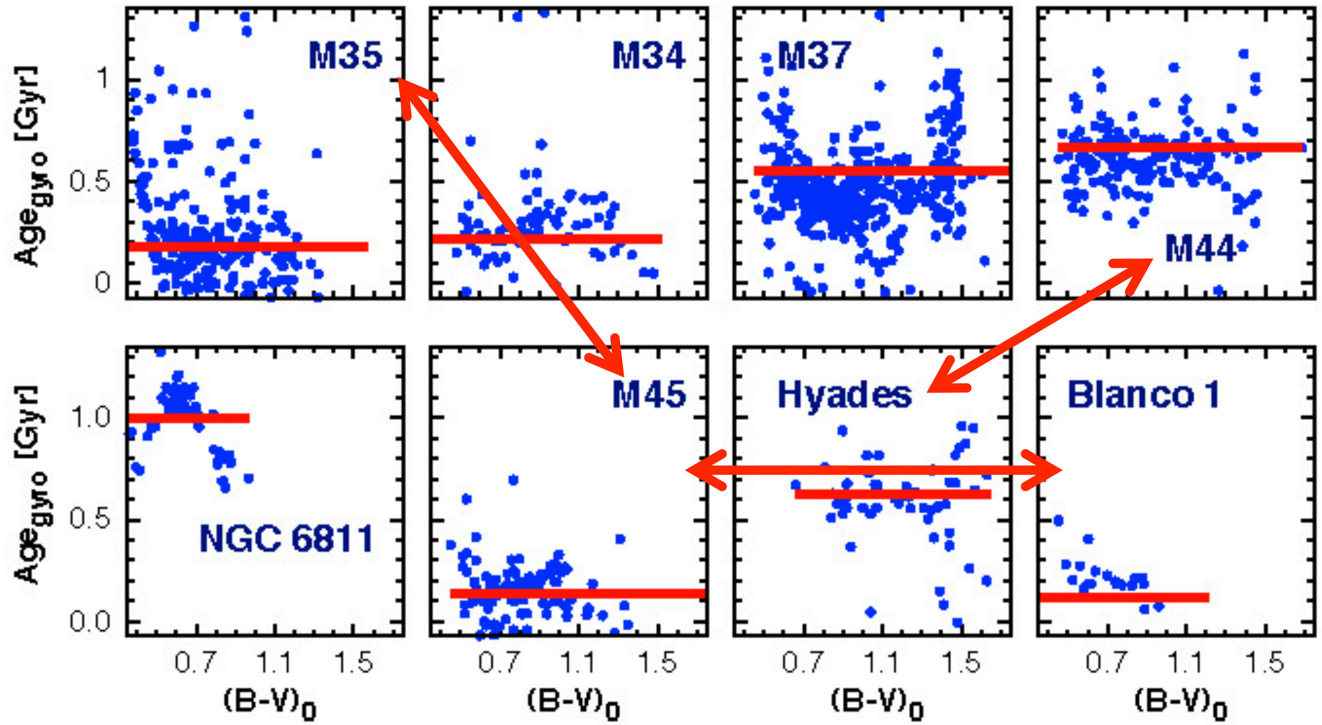
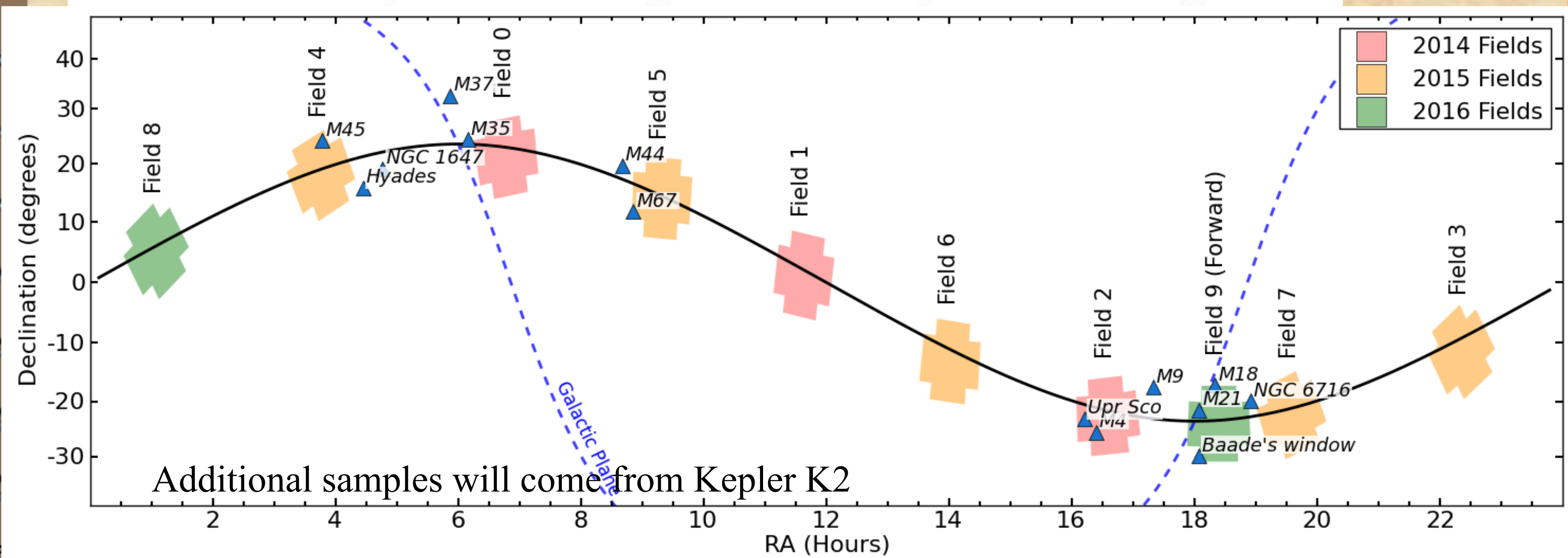


Fig. A.2. Fourth-order polynomial fit to the combined data of M44 (Praesepe, gray points) and the Hyades (black points). The fit (red dots) is sampled at the same $(B-V)_0$ values as the data. All data are plotted, including the 13 outliers mentioned in the text.

D. Soderblom

Kovacs (2015)



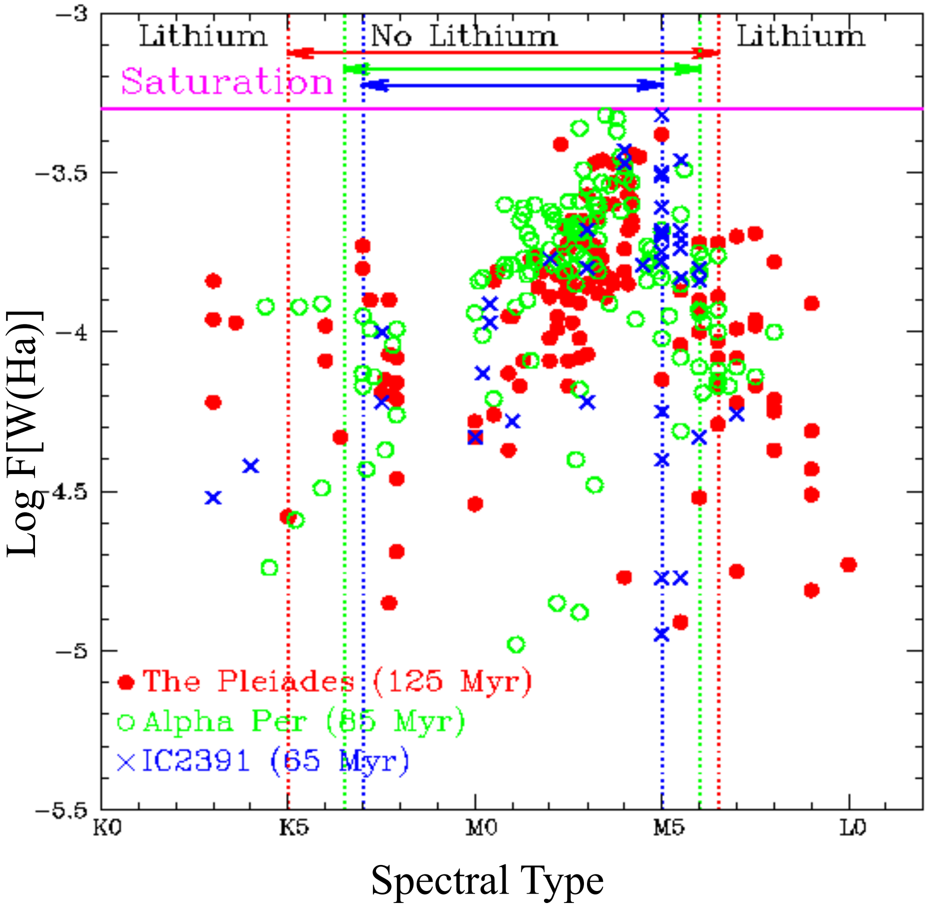


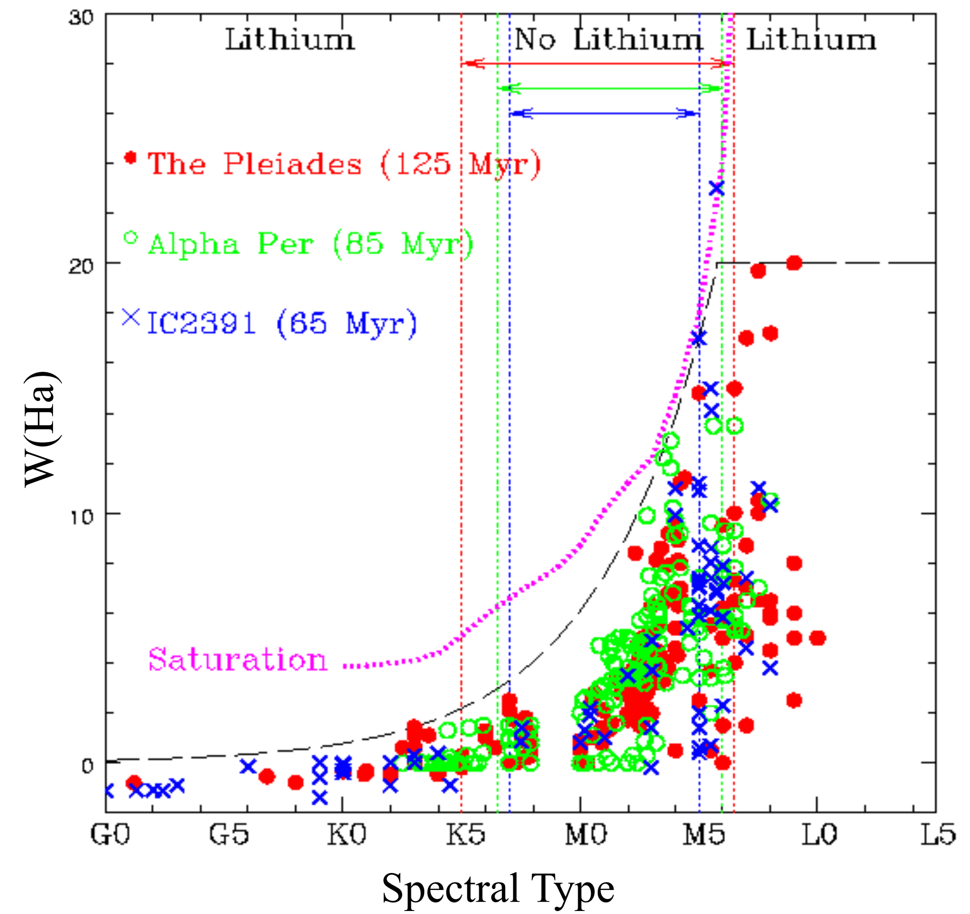
Additional samples will come from Kepler K2

Stellar activity

Stellar activity: H(alpha) emission

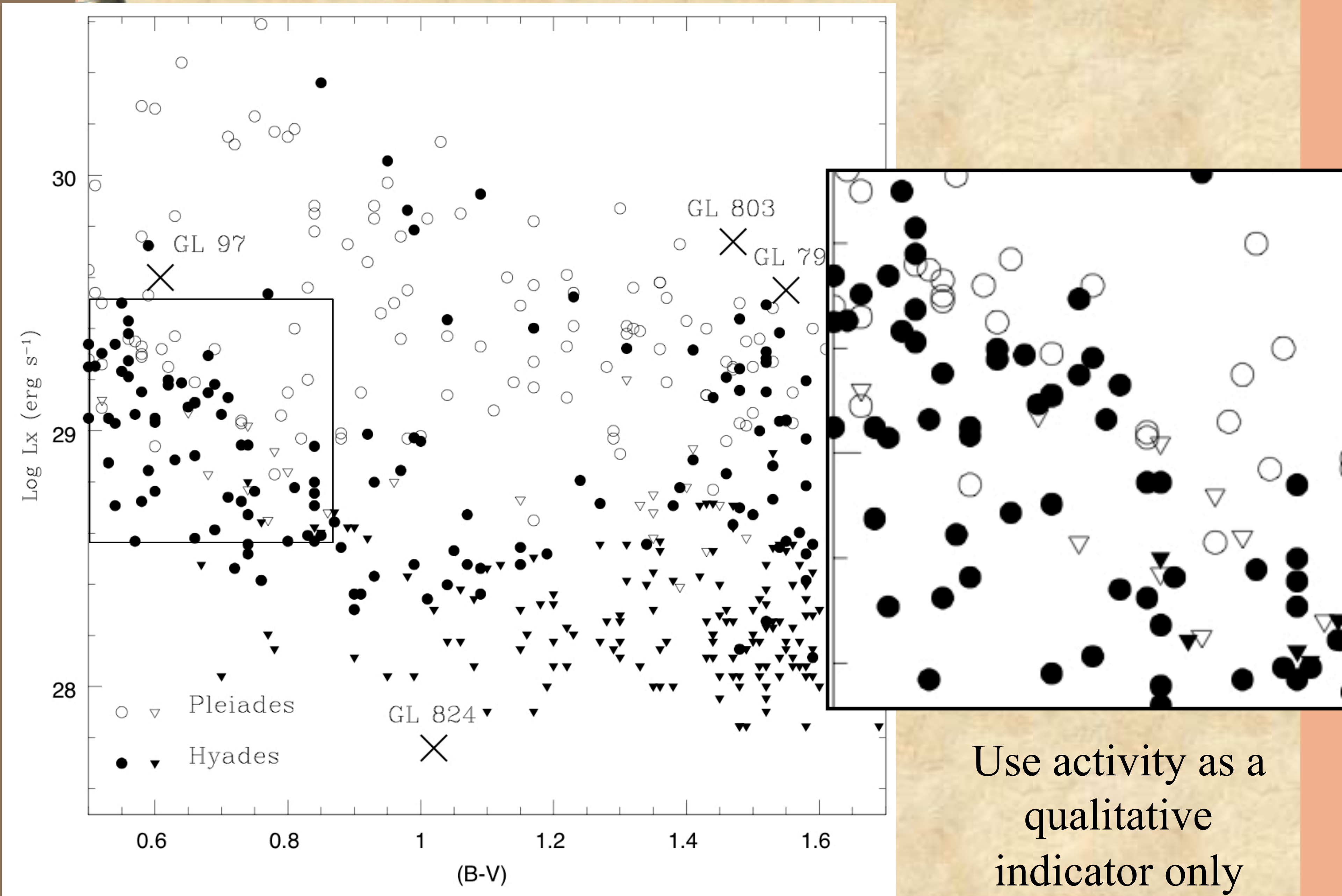
Do we really understand stellar activity and other properties we use?





Barrado y Navascués & Martín 2003

Activity: X-rays



Use activity as a qualitative indicator only

Barrado et al. (1999) BPMG

The Beta Pic moving group

The Beta Pic MG age

Table 1. Literature age estimates for the BPMG. We adopt the terms "traceback age" and "expansion age" generically for any age estimate trying to infer when an unbound group of stars was at its minimum size in the past.

Reference ...	Age (Myr)	Method ...
Barrado y Navascués et al. (1999)	20 ± 10 Myr	CMD isochronal age (KM stars)
Zuckerman et al. (2001)	12^{+8}_{-4} Myr	H-R diagram isochronal age (GKM stars) + Li depletion
Ortega et al. (2002)	11.5 Myr	Traceback age
Song et al. (2003)	12 Myr	Traceback age
Ortega et al. (2004)	10.8 ± 0.3 Myr	Traceback age
Torres et al. (2006)	~ 18 Myr	Expansion age
Makarov (2007)	22 ± 12 Myr	Traceback age
Mentuch et al. (2008)	21 ± 9 Myr	Li depletion
Macdonald & Mullan (2010)	~ 40 Myr	Li depletion (magneto-convection models)
Binks & Jeffries (2014)	21 ± 4 Myr	Li depletion boundary
Malo et al. (2014b)	26 ± 3 Myr	Li depletion boundary
Malo et al. (2014b)	21.5 ± 6.5 Myr (15 – 28 Myr)	H-R diagram isochronal age (KM stars)
This work	22 ± 3 Myr	CMD isochronal age (FG stars)
Final	**23 ± 3 Myr (1σ)** **[± 2 Myr (stat.), ± 2 Myr (sys.)]**	Li depletion bounday & isochronal age (FGKM stars)

Mamajek et al. (2014)

The Beta Pic MG age

20 ± 10 Myr	CMD isochronal age (KM stars)
12^{+8}_{-4} Myr	H-R diagram isochronal age (GKM stars) +
11.5 Myr	Traceback age
12 Myr	Traceback age
10.8 ± 0.3 Myr	Traceback age
~ 18 Myr	Expansion age
22 ± 12 Myr	Traceback age
21 ± 9 Myr	Li depletion
~ 40 Myr	Li depletion (magneto-convection models)
21 ± 4 Myr	Li depletion boundary
26 ± 3 Myr	Li depletion boundary
21.5 ± 6.5 Myr ($15 - 28$ Myr)	H-R diagram isochronal age (KM stars)
22 ± 3 Myr	CMD isochronal age (FG stars)
23 ± 3 Myr (1σ) **2 Myr (stat.), ± 2 Myr (sys.)]**	Li depletion bounday & isochronal age (FGKM stars)

Mamajek et al. (2014)

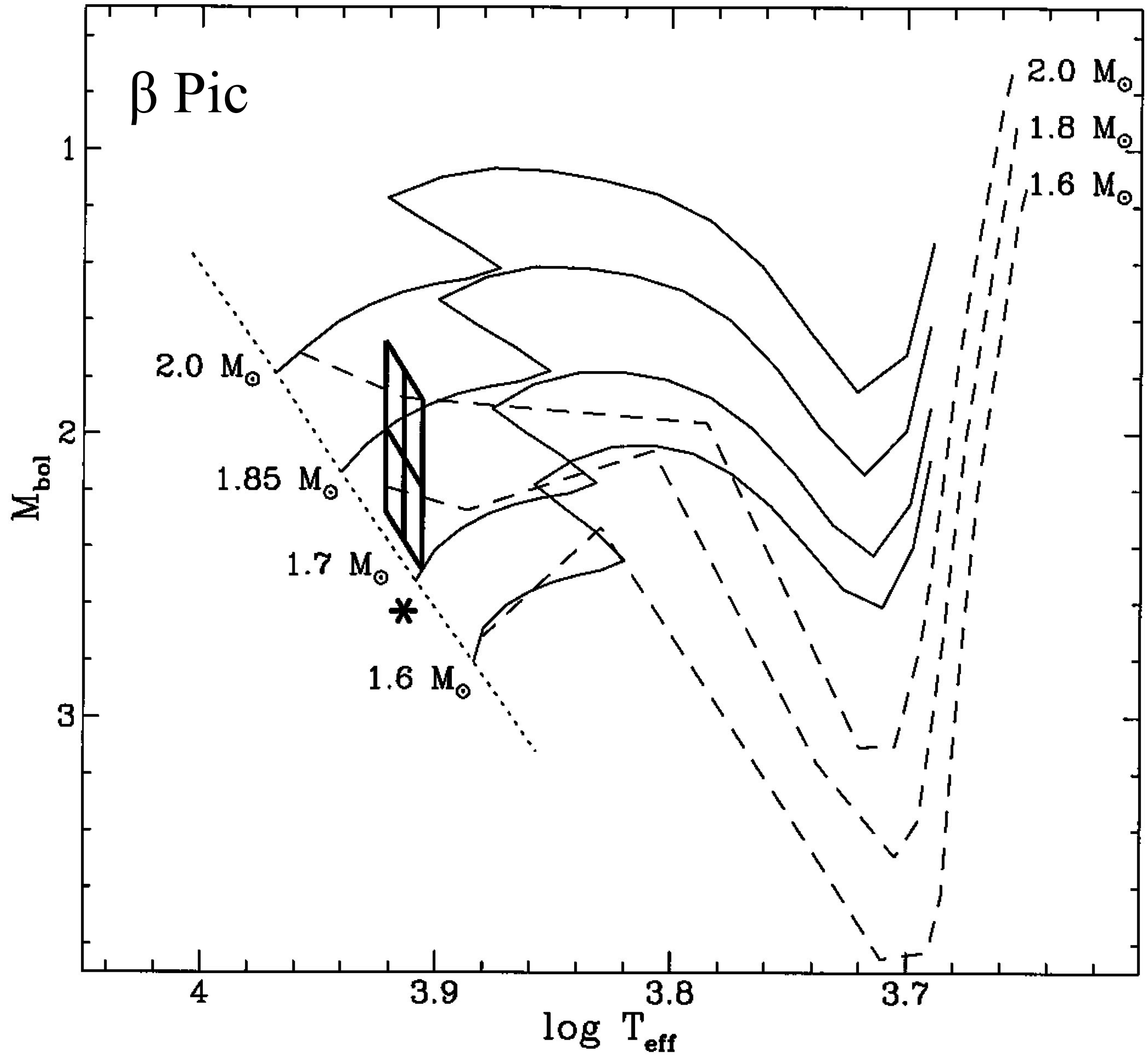
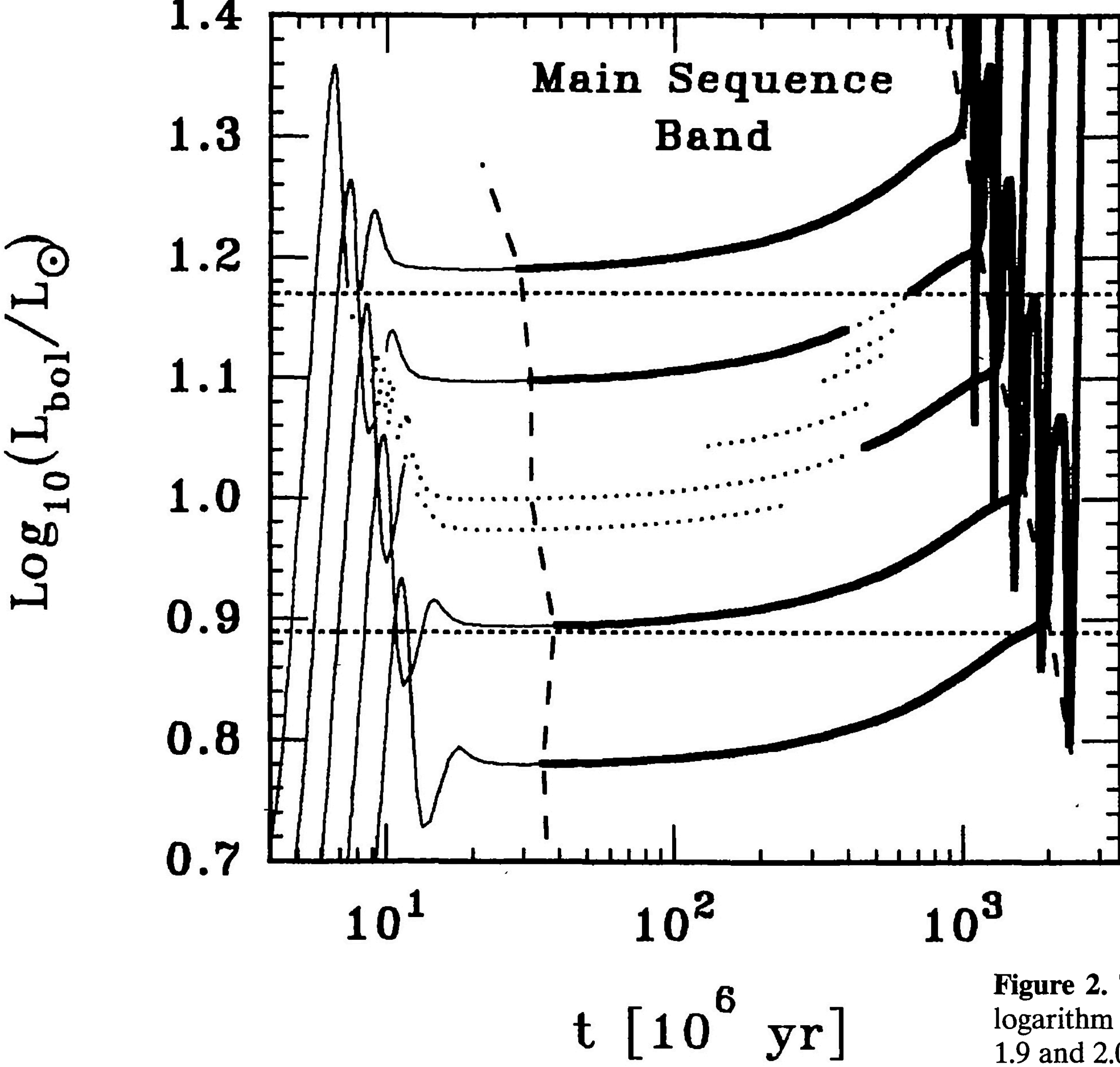


FIG. 4.—H-R diagram showing the position of β Pic to $Z = Z_\odot$ evolutionary tracks. The asterisk shows the apparent position of the star, while the trapezoid shows the best estimate. *Dashed lines*, pre–main-sequence tracks (D'Antona & Mazzitelli 1994); *solid lines*, tracks for evolution from the ZAMS to the red giant branch (Vanden Berg 1985).

Lanz et al. (1995)

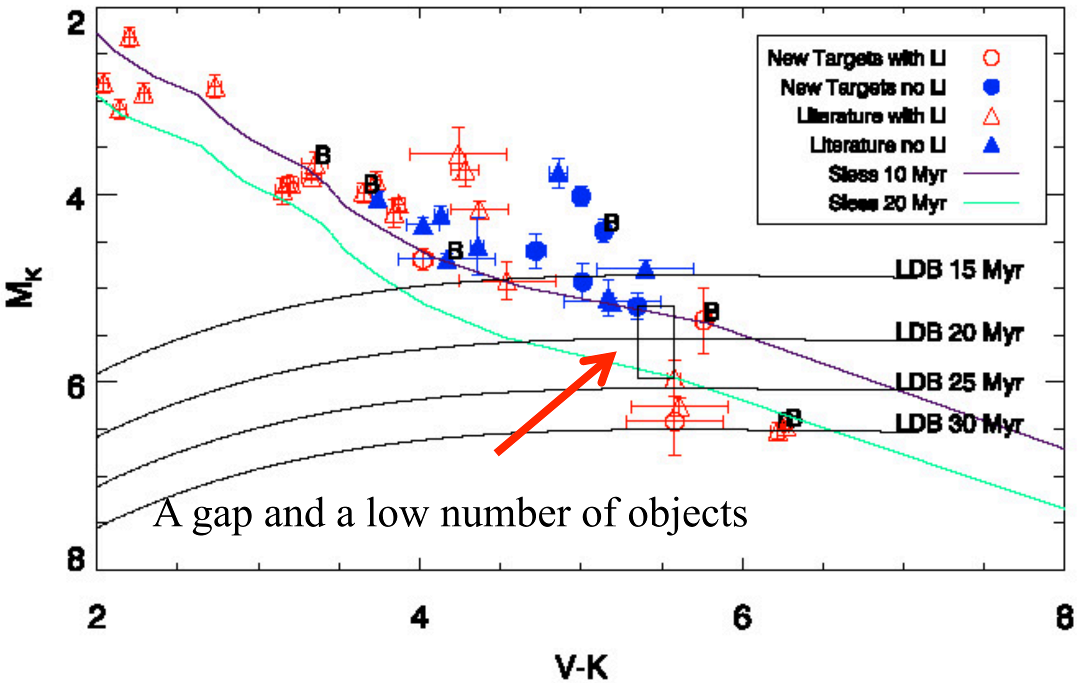


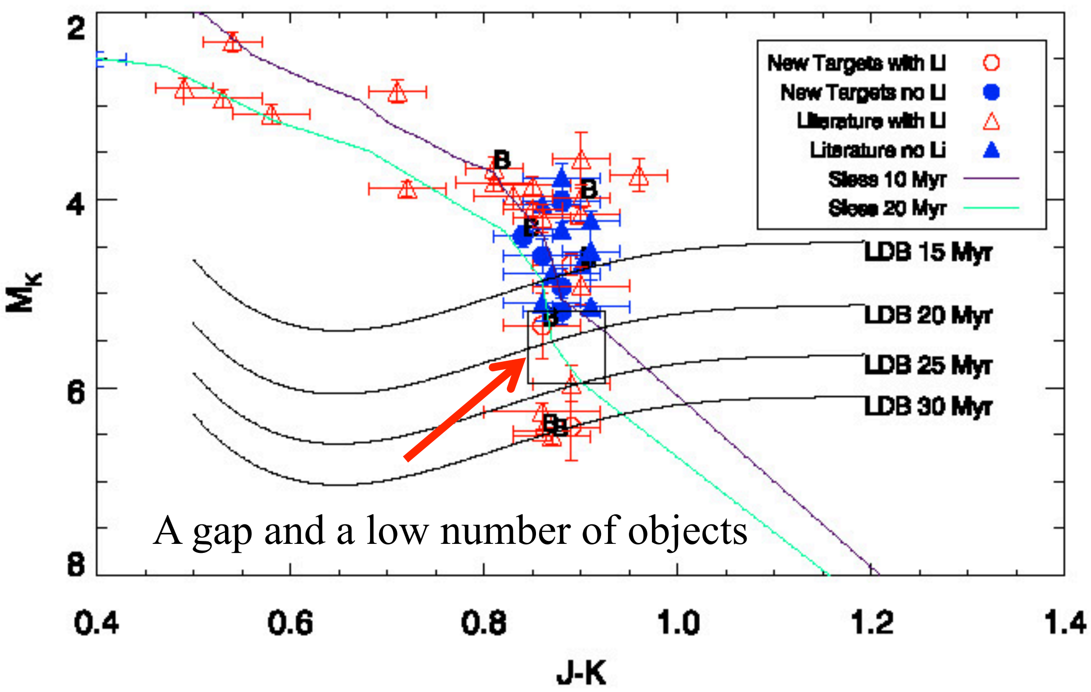
β Pic

Figure 2. The logarithm of the bolometric luminosity versus the logarithm of the age for stars (from bottom to top) of 1.6, 1.7, 1.8, 1.9 and 2.0 $M_\odot$. Solid thin and thick lines correspond to PMS and subsequent evolution, respectively, whereas long-dashed lines indicate the main-sequence boundaries. Horizontal short-dashed lines indicate the luminosities of the edges of the *β* Pic error box. Dotted lines represent evolutionary stages inside *β* Pic's error box, and thus are consistent with observations. In order to define this region better, we have also included results corresponding to objects of 1.766, 1.833, 1.866, 1.880 and 1.925 $M_\odot$. For the last of these masses we have found no main-sequence evolutionary stage inside *β* Pic's error box.

Brunini & Benvenutto (1996)

David Barrado





BPMG 21±4 Myr

"Locating the LDB in 3 separate colour (or spectral-type) vs. magnitude diagrams. New members from Table 1 and objects from the literature are indicated. Absolute magnitudes are calculated from 2MASS K and a trigonometric parallax where available or a kinematic distance otherwise. Known, unresolved binaries are marked with 'B'. Black lines represent constant luminosity loci from Chabrier & Baraffe (1997) where Li is predicted to be 99% depleted at the ages indicated. The green and maroon lines are 10 and 20 Myr isochrones from Siess et al. (2000). The rectangle in each diagram represents the estimated LDB location and its uncertainty, based on the faintest Li-depleted member and the brightest Li-rich member (but excluding the unresolved binary at MK ≃ 5.3)"

Binks & Jeffries (2014)

Lanz et al. (1995): "*... the star is either a pre-main-sequence (PMS) star* ***nearing the zero-age main sequence*** *(ZAMS), or it is a main-sequence star older than* ***0.3 Gyr***."

Brunini & Benvenutto (1996): "*... argues in favour of a* ***large age*** *for β Pic. However, the estimation of stellar ages employing cometary fluxes should be* ***treated with caution****, on account of the diversity of possible planetary systems*".

Barrado y Navascués (1999, 2001): "*The estimated age for b Pic is then* ***20±10 Myr****, where the uncertainty in the age arises primarily from possible errors in the pre–main-sequence isochrones and in the conversion from color to effective temperature.*"

Malo et al. (2014): "*We find that the inclusion of the magnetic field in evolutionary models increase the isochronal age estimates for the K5V-M5V stars. Using these models and field strengths, we derive an average isochronal age between 15 and 28 Myr and we confirm a clear Lithium Depletion Boundary from which an age of* ***26±3 Myr*** *is derived, consistent with previous age estimates based on this method.*"

Binks & Jeffries (2014): "*The LDB age of the BPMG is* ***21±4 Myr*** *and insensitive to the choice of low-mass evolutionary models. This age is more precise, likely to be more accurate, and much older than that commonly assumed for the BPMG*"

ABSTRACT
Jeffries & Binks (2014) and Malo et al. (2014) have recently reported Li depletion boundary (LDB) ages for the β Pictoris moving group (BPMG) which are twice as old as the oft-cited kinematic age of $\sim$ 12 Myr. In this study we present (1) a new evaluation of the internal kinematics of the BPMG using the revised *Hipparcos* astrometry and best available published radial velocities, and assess whether a useful kinematic age can be derived, and (2) derive an isochronal age based on the placement of the A-, F- and G-type stars in the colour-magnitude diagram (CMD). We explore the kinematics of the BPMG looking at velocity trends along Galactic axes, and conducting traceback analyses assuming linear trajectories, epicyclic orbit approximation, and orbit integration using a realistic gravitational potential. None of the methodologies yield a kinematic age with small uncertainties using modern velocity data. Expansion in the Galactic X and Y directions is significant only at the 1.7σ and 2.7σ levels, and together yields an overall kinematic age with a wide range (13 – 58 Myr; 95 per cent CL). The A-type members are all on the zero age-main-sequence, suggestive of an age of > 20 Myr, and the loci of the CMD positions for the late-F- and G-type pre-main-sequence BPMG members have a median isochronal age of 22 Myr ($\pm$ 3 Myr stat., $\pm$ 1 Myr sys.) when considering four sets of modern theoretical isochrones. The results from recent LDB and isochronal age analyses are now in agreement with a median BPMG age of 23 $\pm$ 3 Myr (overall 1σ uncertainty, including $\pm$2 Myr statistical and $\pm$2 Myr systematic uncertainties).

Mamajek et al. (2014)

Impact on planets and IPMOs

Archimedes and Eratosthenes

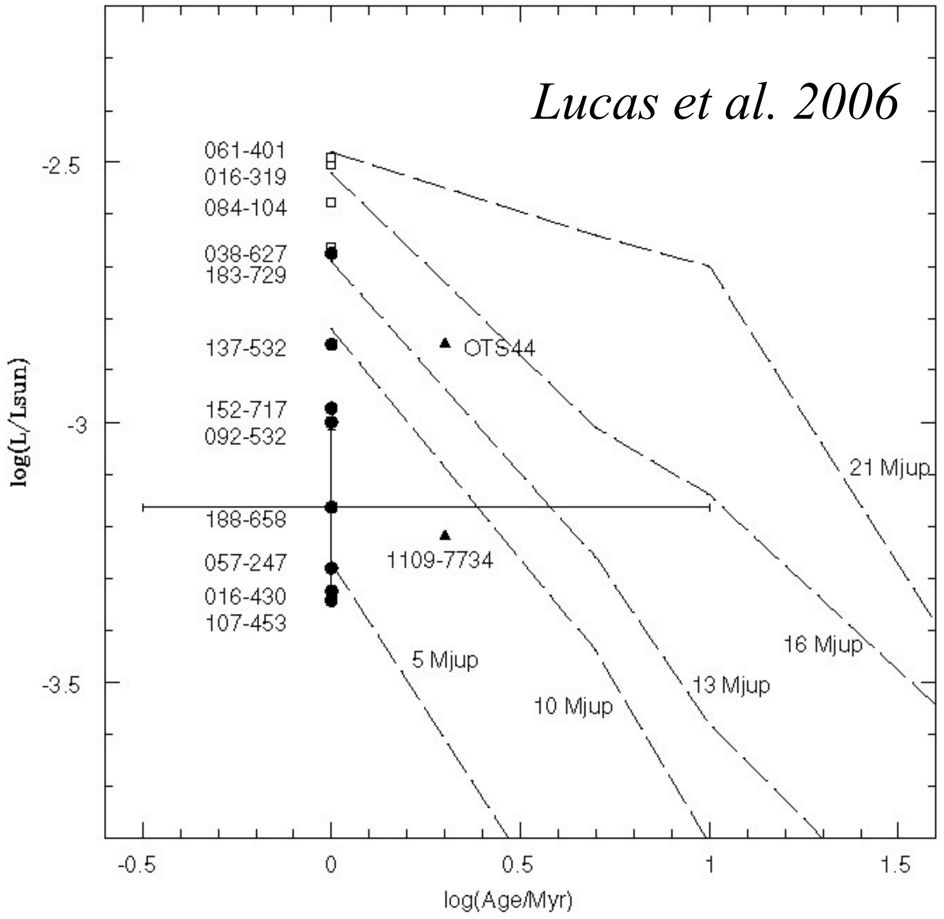
«… quienes afirman el descubrimiento de algo, pero no producen pruebas, serán reprobados por haber pretendido descubrir lo imposible».

*«… **Those who claim to discover everything but produce no proofs of the same may be confuted as having actually pretended to discover the impossible**».*

Archimedes of Syracuse, III BCE

Candidate "cluster-planets" and "free-floating" planets
(Sorted by increasing mass)

NAME click for more	MASS Jup. mass	TEMPERATURE (K)	RADIUS R_J	DISTANCE pc	Update [*: published]
rho Oph 4450	2-3	1400	-	-	06/01/10
S Ori 68	5	-	-	440	31/08/06
S Ori 70	3	1,100	1.6	440	29/10/04
Cha 110913	8	1,350	1.8	50	30/11/04
CAHA Tau 1	10	2080			11/11/09
CAHA Tau 2	11.5	2280			11/11/09



Trapezium.- Lucas et al. 2000, Weight et al. 2009

SOri.- Zapatero-Osorio et al. 2000, 2002, Barrado et al. 2001

C69.- Barrado et al. 2004, 2007

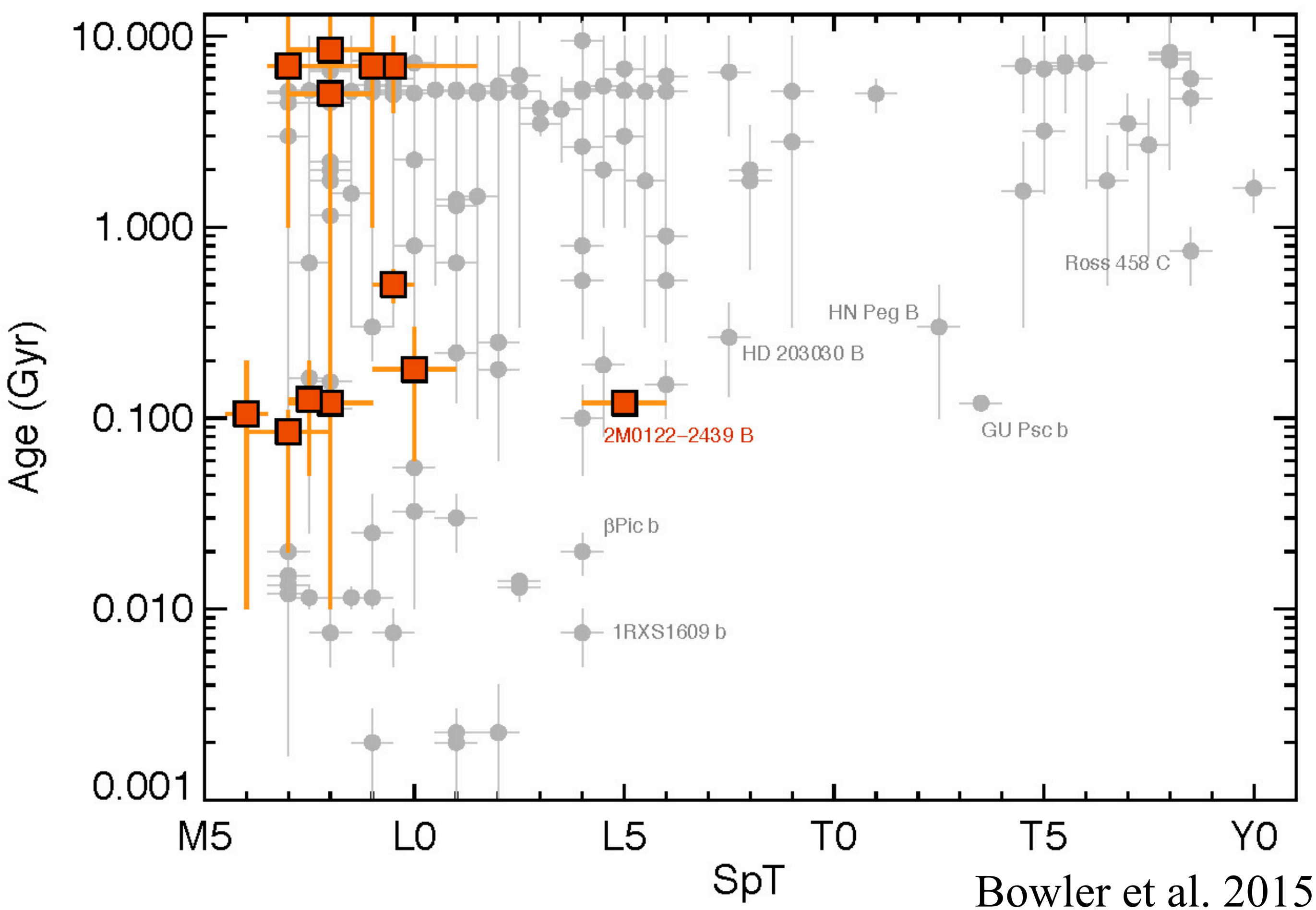
Taurus.- Quanz et al. 2009

UpperSco.- Leffreniere et al. 2008

TWA.- Chauvier et al. 2004

RhoOph.- Marsh et al. 2009

Low-Mass Companions to Members and Interlopers of Young Moving Groups



Bowler et al. 2015

Fig. 35.— The known ultracool companions to stars. Systems analyzed in this work are denoted with red squares and mostly have late-M spectral types. The dearth of young ($\lesssim$100 Myr) companions later than ~L5 reflects the paucity of young planets discovered via direct imaging. Note that we have excluded the HR 8799 planets (Marois et al. 2008; Marois et al. 2010), GJ 504 b (Kuzuhara et al. 2013), and HD 95086 b (Rameau et al. 2013) because their spectral types are either poorly constrained or may defy conventional classification schemes. Known companions (grey circles) are from Deacon et al. (2014) and are supplemented with our own compilation.

Transiting exoplanets

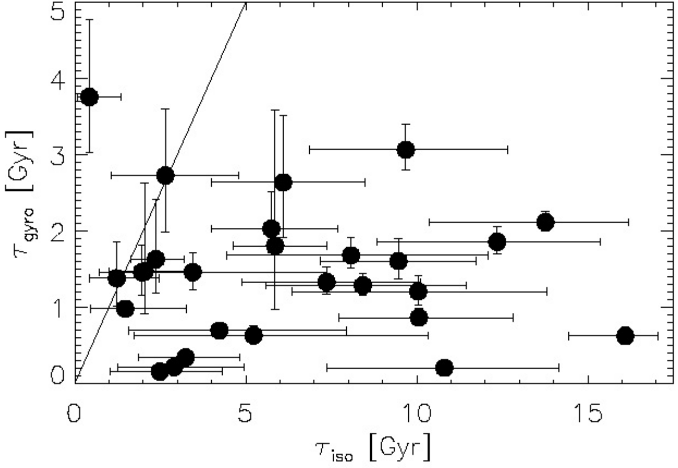


Fig. 4. Comparison of gyrochronological ages (τ_{gyro}) to isochronal ages (τ_{iso}) for planet host stars with measured rotation periods. Points with error bars indicate the mean and standard deviation of the posterior age distribution. The straight line is the relation $\tau_{gyro} = \tau_{iso}$.

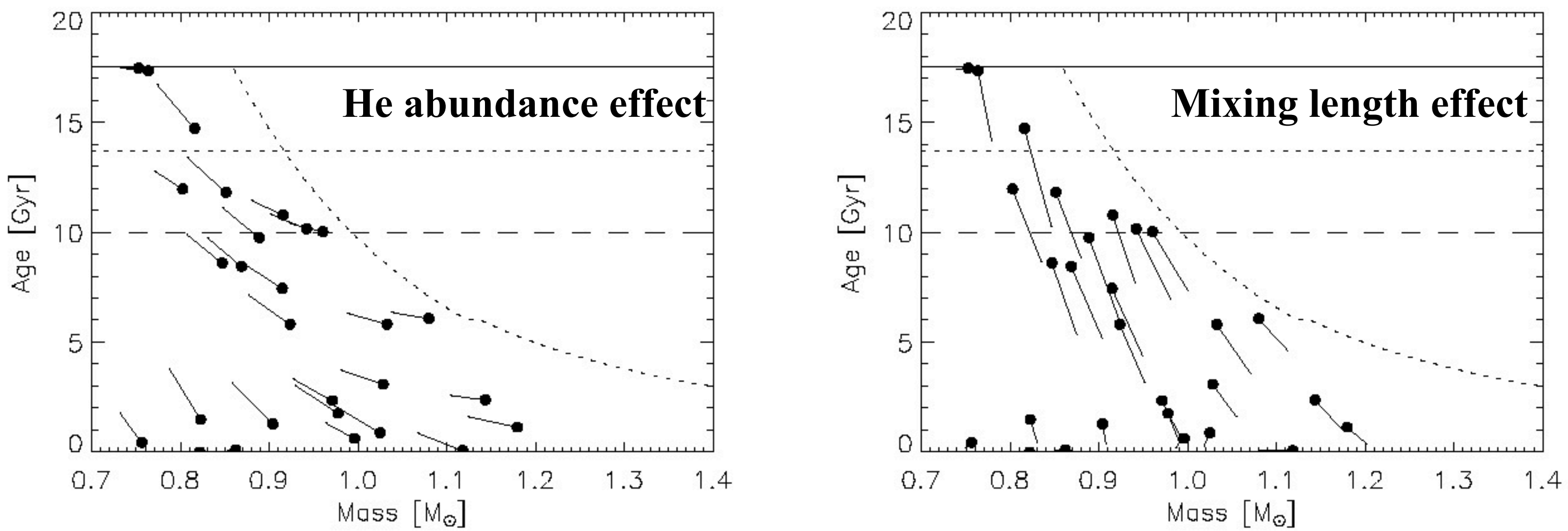
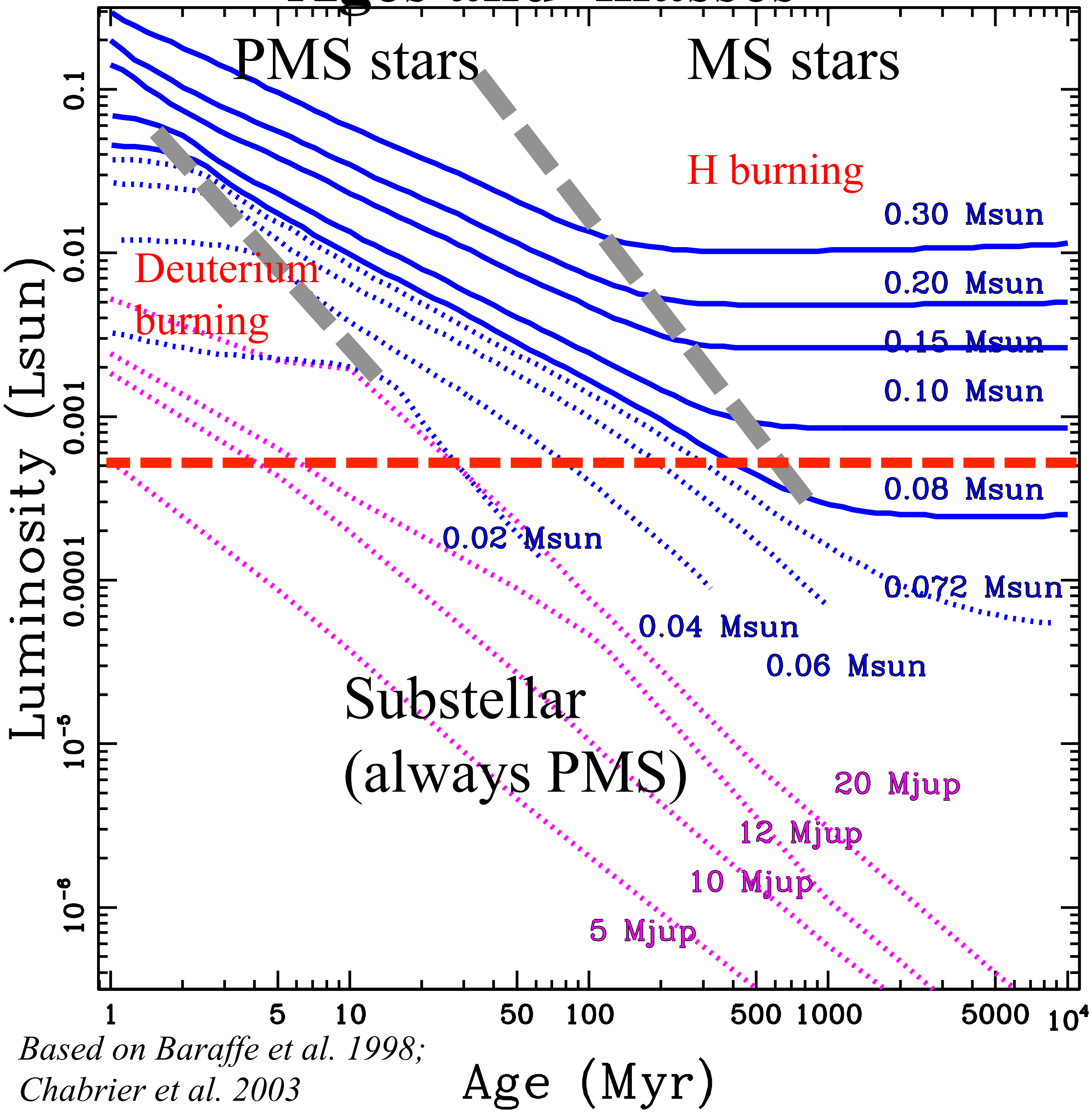


Fig. 2. Change in the best-fitting masses and ages of transiting exoplanet host stars due to a change in the assumed helium abundance or mixing length parameter. Dots show the best-fitting mass and age for the default values of Y and α_{MLT} and lines show the change in mass and age due to an increase in helium abundance $\Delta Y = +0.02$ (left panel) or a change in mixing length parameter $\Delta\alpha_{MLT} = -0.2$ (right panel). Horizontal lines indicate the age of the Galactic disc (dashed), the age of the Universe (dotted) and the largest age in our grid of stellar models (solid). The curved dotted line shows the terminal age main sequence (TAMS) for stars with solar composition.

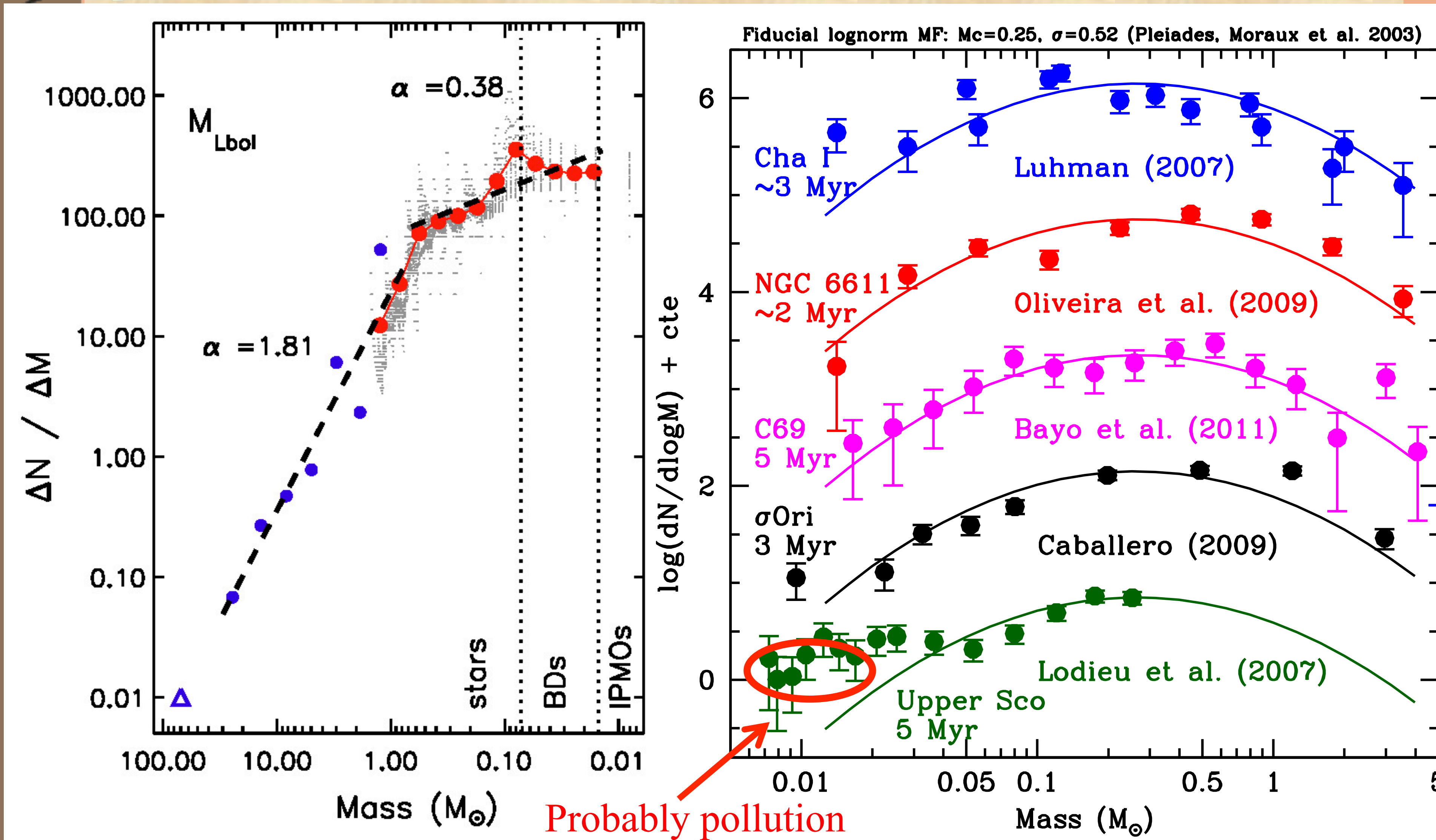
Maxted et al. 2015

Ages and masses



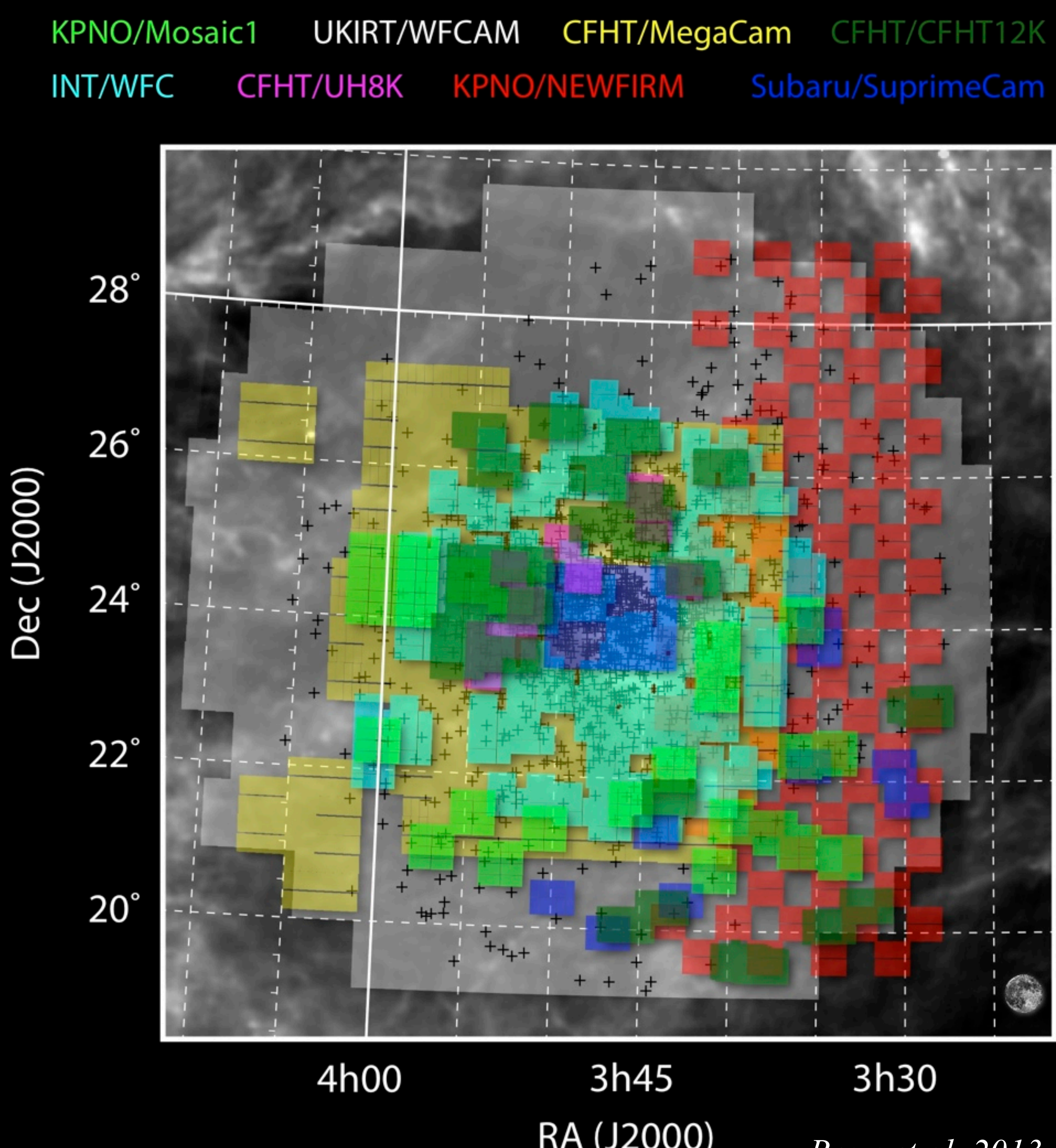
Based on Baraffe et al. 1998; Chabrier et al. 2003

C69: a 100% spectroscopic IMF



See detail in Bayo 2009; Bayo et al. 2011, 2012

Searching for complete, unbiased census



Bouy et al. 2013

Dancefloor: The Pleiades

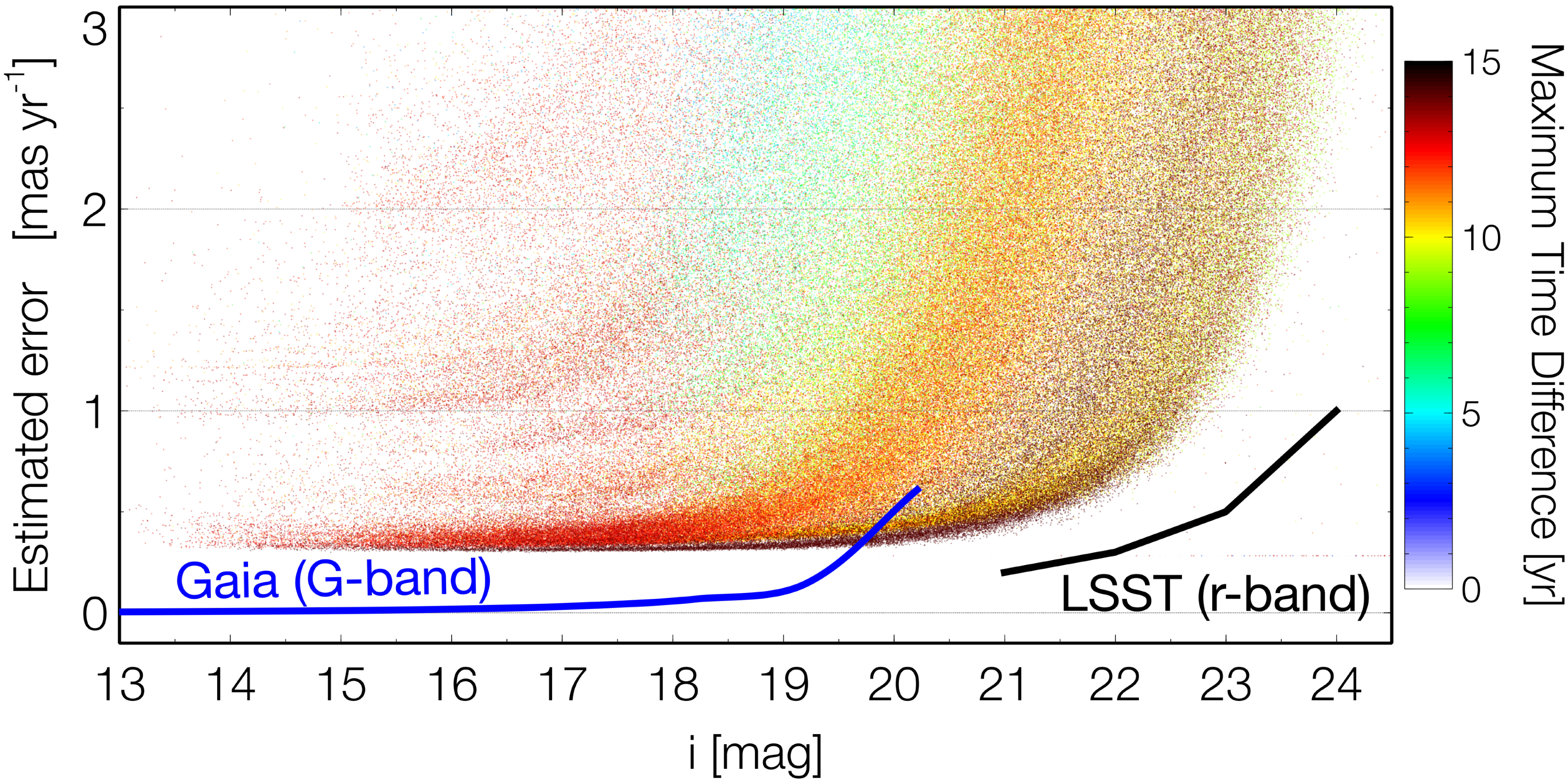
14784 individual images

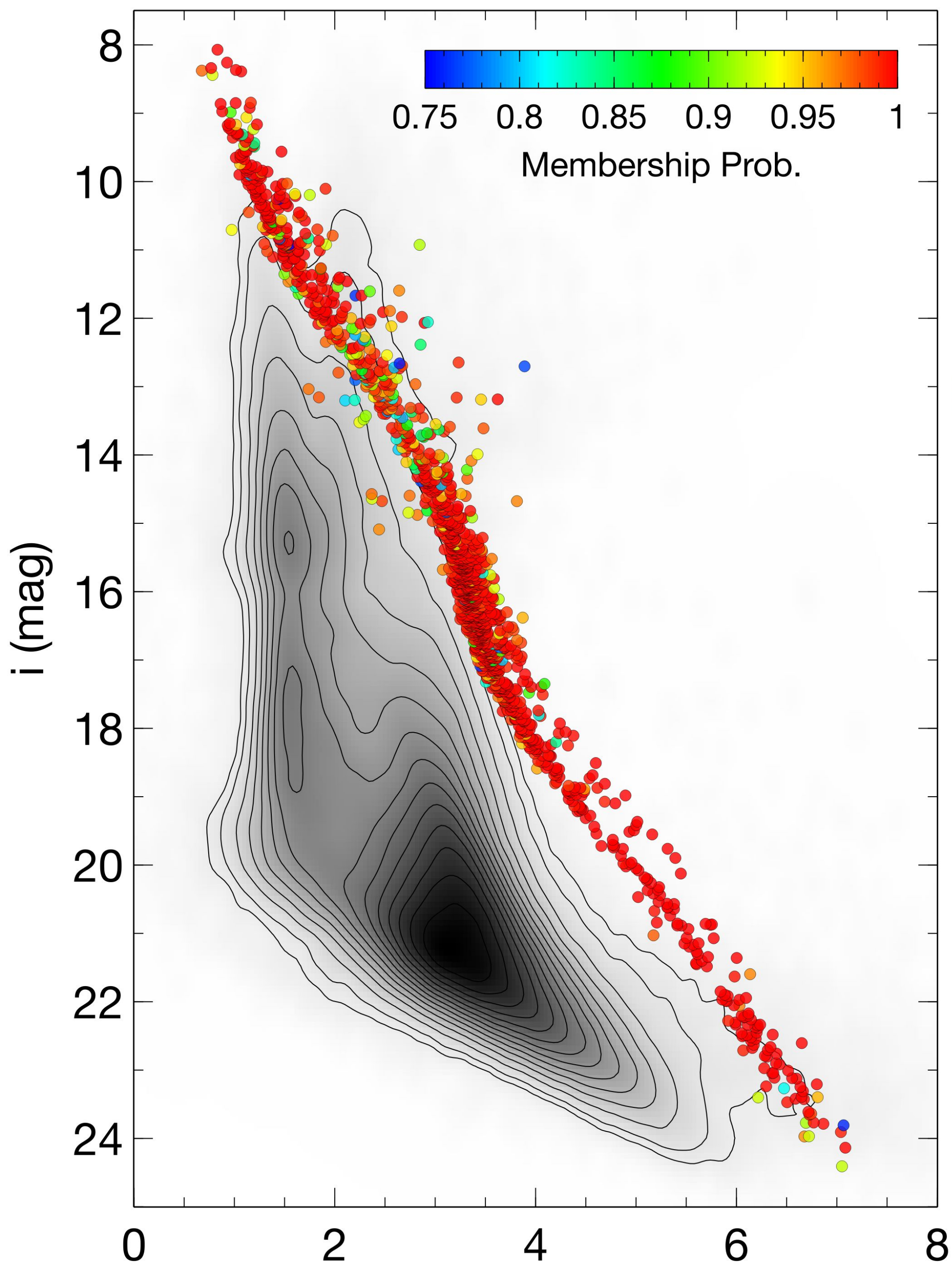
Details in:
Bouy et al. 2013, 2014
Sarro et al. 2013

Moon at scale

H. Bouy

Astrometry from the ground



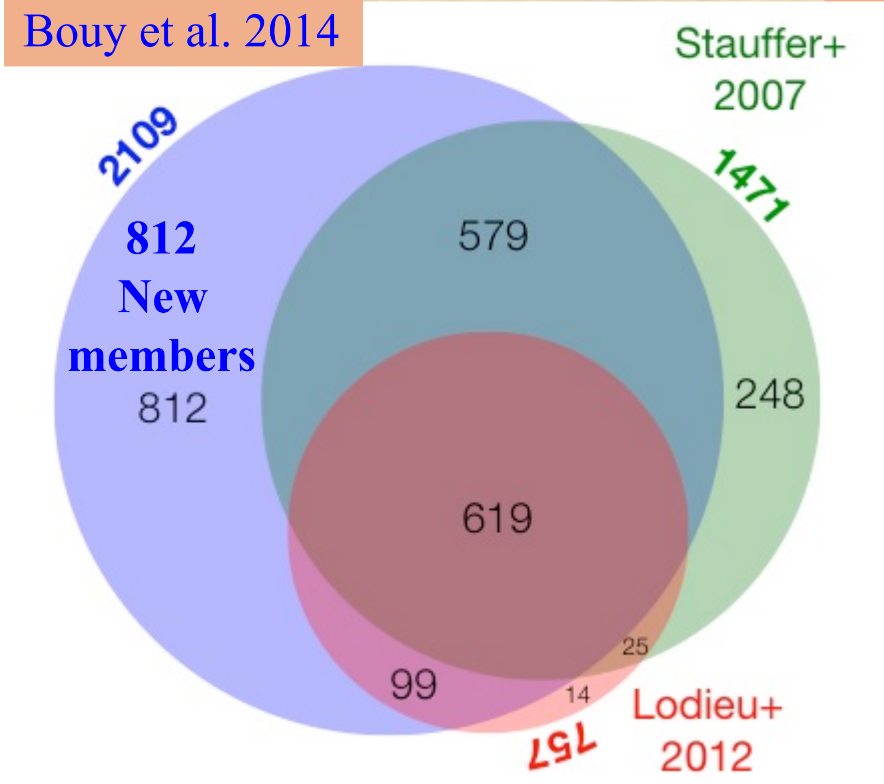


Bouy et al. 2014

Tycho catalog and the bright end

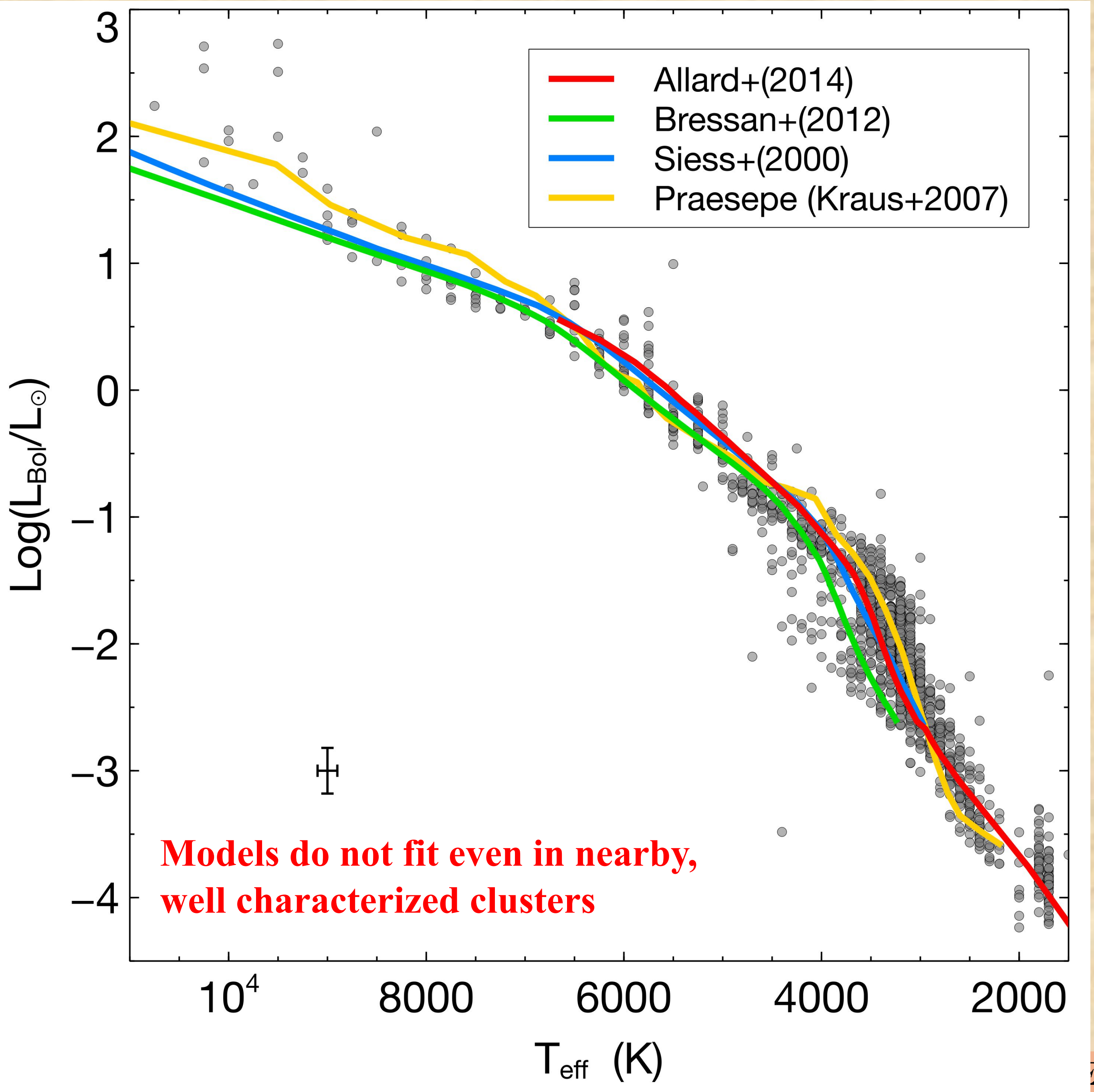
83 of the 207 candidate members were not present in Stauffer et al. (2007) list

Bouy et al. 2014

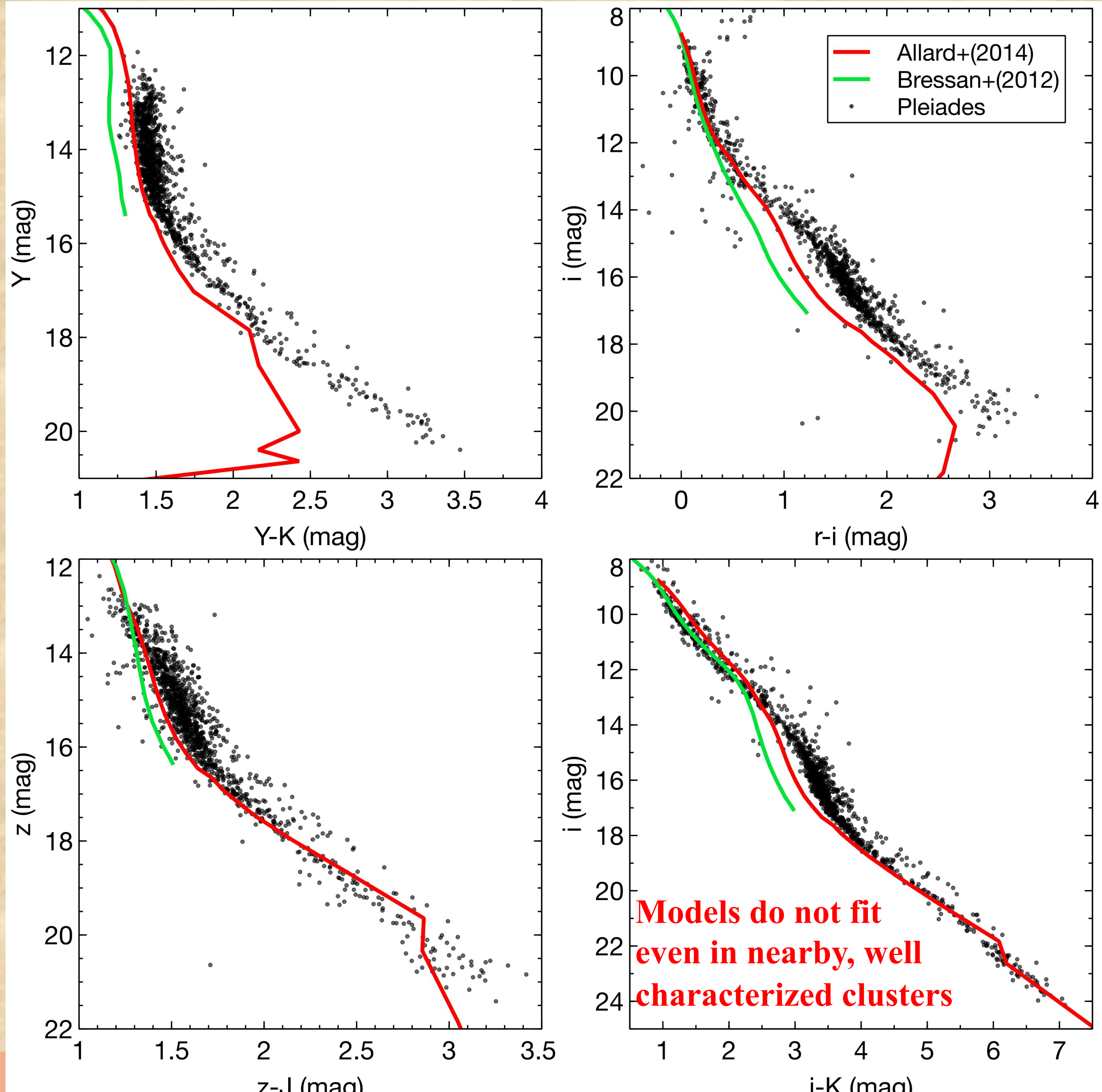


The best studied open cluster and we are discovering new things

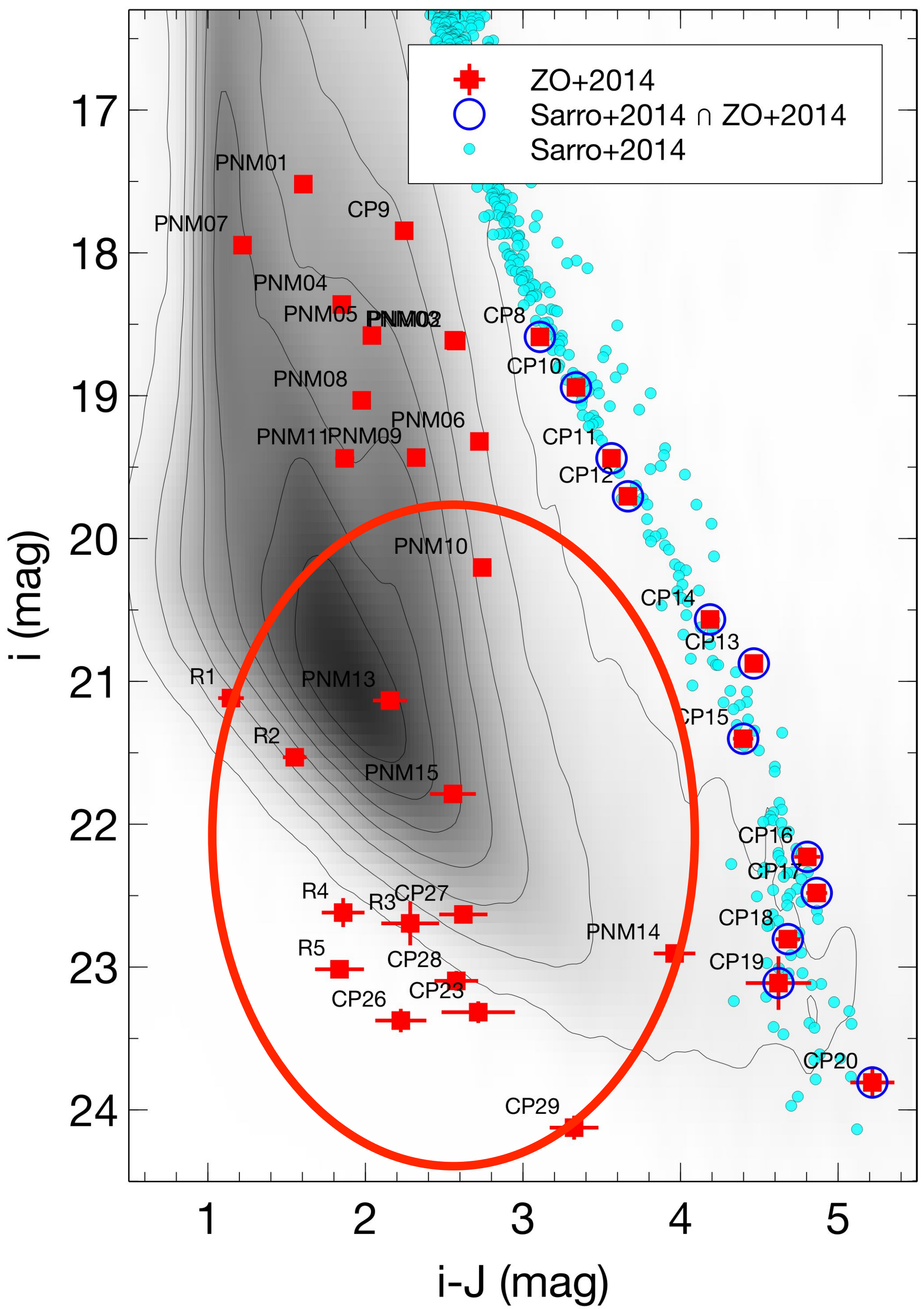
Data and models



Data and models



Check public databases



Effect of contaminants on the MF

“*L'historien ne doit aux morts que la vérité*”

“***The historian owns nothing to the dead except the truth***”

“*El historiador debe a los muertos nada salvo la verdad*”

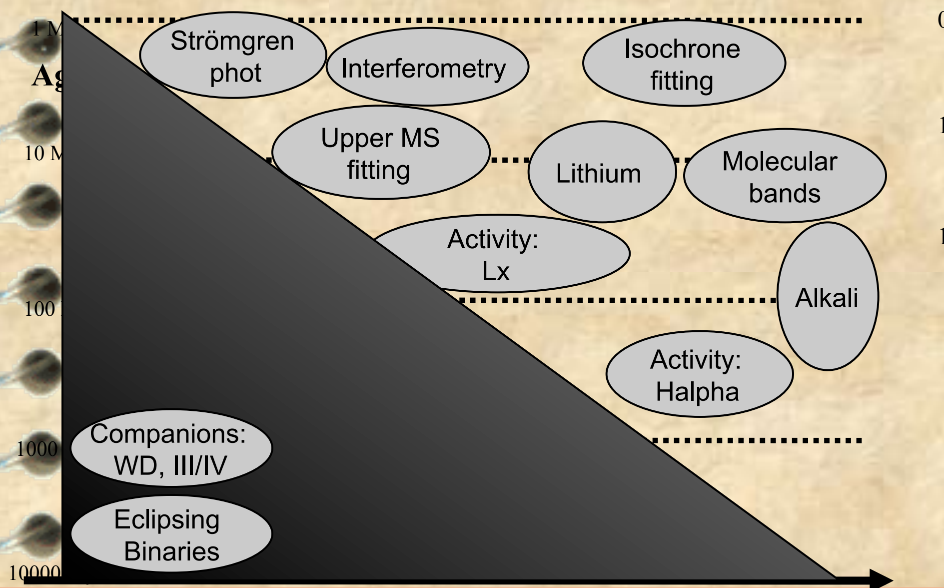
Jean-Baptiste Delambre, “*Historie de l´astronomie moderne*”, 1821

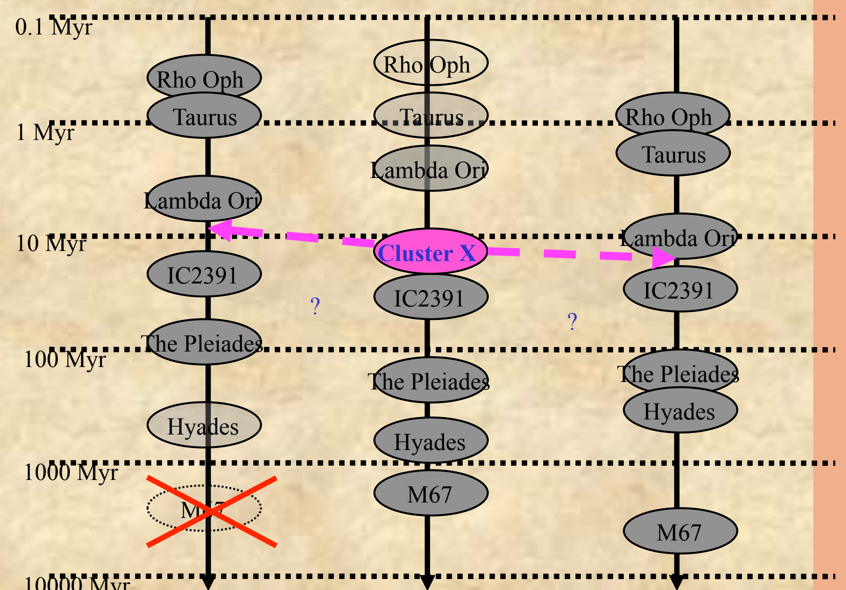
Summary (I)

Primary indicators
- Different models
- Conversions observations-theory
- Can we assume coevality?

Secondary indicators
- Do we really know the ages of the "well-known" SFR and clusters?
- Do we really understand the properties we use, such as activity?
- Again, coevality

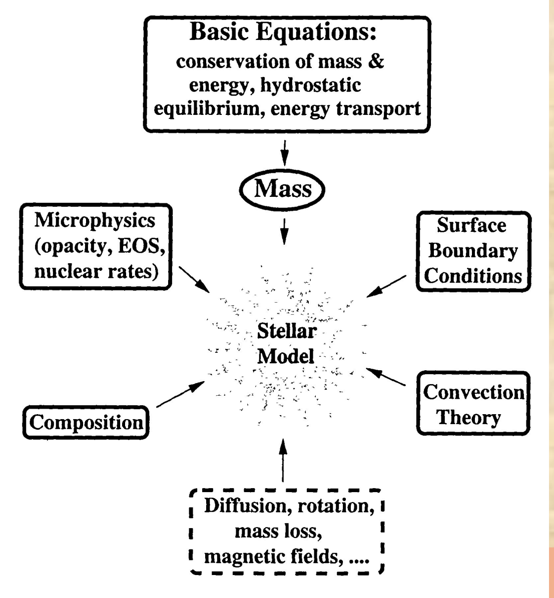
Consistency
- Different masses and ages, different methods
- Each age value is linked to models and to specific scales.

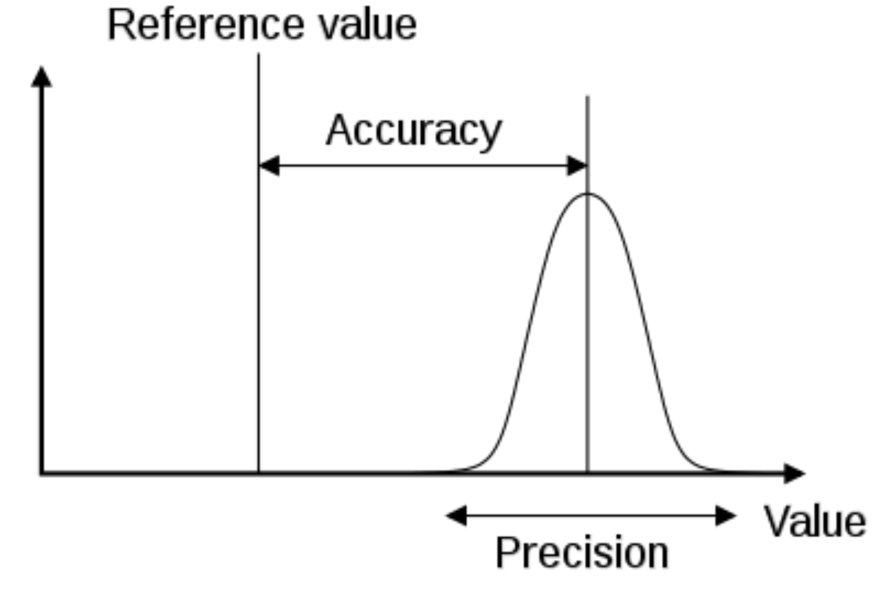




Summary (II)

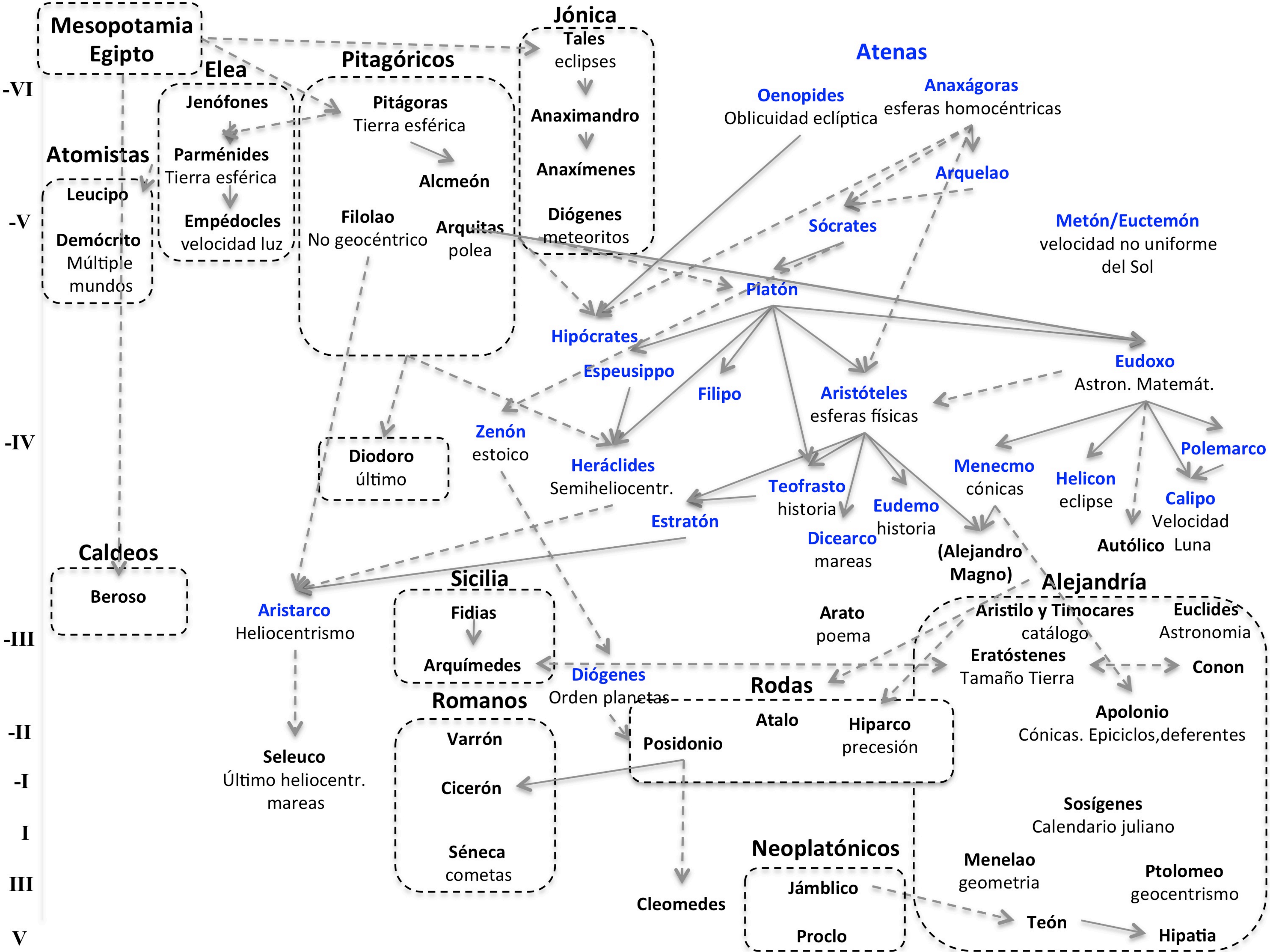
- Models are complex beast with a lot of physics behind
- Search “below the carpet”
- Read papers, specially old ones
- Give credit to previous results
- Be sceptical
- Be realistic with errorbars
- Precision versus accuracy





Concerning the hommage to Jean-Paul Zahn

There is a chain of **knowledge** transmitted over the generations. And in the case of PhD students and supervisors, a line of **questions**



Mesopotamia
Egipto
Jónica
Tales
eclipses
Anaximandro
Anaxímenes
Diógenes
meteoritos
Elea
Jenófones
Parménides
Tierra esférica
Empédocles
velocidad luz
Pitagóricos
Pitágoras
Tierra esférica
Alcmeón
Filolao
No geocéntrico
Arquitas
polea
Atomistas
Leucipo
Demócrito
Múltiple
mundos
-VI
-V
-IV
-III
-II
-I
I
III
V
Atenas
Oenopides
Oblicuidad eclíptica
Anaxágoras
esferas homocéntricas
Arquelao
Sócrates
Metón/Euctemón
velocidad no uniforme
del Sol
Platón
Hipócrates
Espeusippo
Filipo
Aristóteles
esferas físicas
Eudoxo
Astron. Matemát.
Zenón
estoico
Heráclides
Semiheliocentr.
Teofrasto
historia
Estratón
Eudemo
historia
Dicearco
mareas
Menecmo
cónicas
Helicon
eclipse
Polemarco
Calipo
Velocidad
Luna
Autólico
(Alejandro
Magno)
Diodoro
último
Caldeos
Beroso
Aristarco
Heliocentrismo
Sicilia
Fidias
Arquímedes
Diógenes
Orden planetas
Arato
poema
Alejandría
Aristilo y Timocares
catálogo
Euclides
Astronomia
Eratóstenes
Tamaño Tierra
Conon
Apolonio
Cónicas. Epiciclos,deferentes
Rodas
Atalo
Posidonio
Hiparco
precesión
Romanos
Varrón
Cicerón
Séneca
cometas
Seleuco
Último heliocentr.
mareas
Cleomedes
Sosígenes
Calendario juliano
Neoplatónicos
Jámblico
Proclo
Menelao
geometria
Ptolomeo
geocentrismo
Teón
Hipatia

Two sides of reality:
Thales of Miletus

The absentminded philosopher.- thinking about the stars, fell down in a ditch

The investor who had the knowledge.- knowing the olive crop was going to be excellent, he rented all mills around Miletus and made a huge amount of money with his monopoly.

Many thanks to:

SOC

E. Moraux (IPAG, chair)

C. Charbonnel (IRAP/Observatoire de Genève)

Y. Lebreton (GEPI Obs. de Paris/IPR Univ. de Rennes 1)

F. Martins (LUPM, Université de Montpellier)

A. Robin (UTINAM, Besançon)

LOC

E. Moraux (IPAG, chair)

M.-H. Sztefek (IPAG, gestionnaire)

F. Maia (IPAG)

I. Joncour (IPAG)

Y. Lebreton (GEPI Obs. de Paris/IPR Univ. de Rennes 1)

B. Dintrans (IRAP)

I hope you have enjoyed these talks

and

thanks for your attention!!!