Tests of stellar physics with high-precision data from eclipsing binary stars

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Eclipsing binary systems

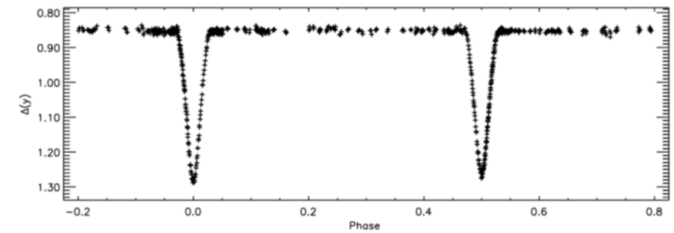
Eclipsing binaries are powerful tools for stellar astrophysics…

- Binaries contain stars in all evolutionary stages
- They provide empirical and model-independent measurements of stellar properties
- Information is maximized when eclipses are present
  ⇨ Masses and radii with accuracy ~1%
- Assumption that detached binary components resemble and evolve like single stars

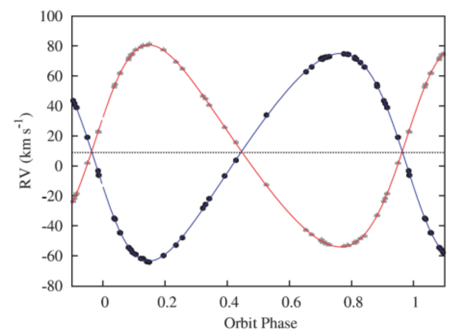
⬇

Precision astrophysics

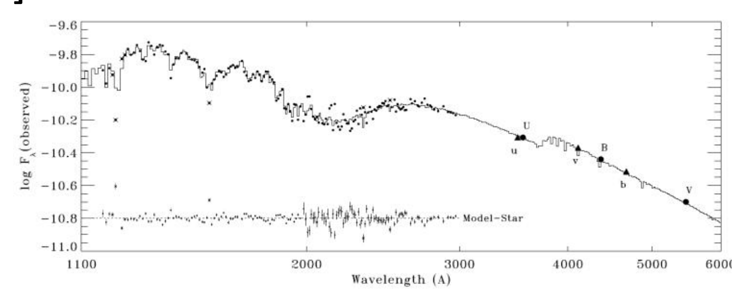
- Light curve:
  - Physical properties
    - $r_A = R_A/a$
    - $r_B = R_B/a$
    - T_{effB}/T_{effA}
    - L_B/L_A
  - Orbital properties
    - P
    - i
    - e
    - w



- Rad. Vel. curve:
  - Physical properties
    - $M_A \sin^3 i$
    - $M_B \sin^3 i$
  - Orbital properties
    - a sin i
    - γ
    - (P,e,w)



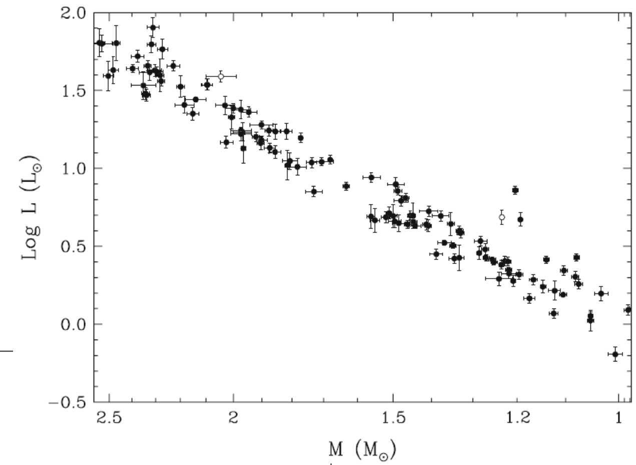
- Multi-band photometry or spectrophotometry:
  - T_{effA}
  - [m/H]
  - A_λ

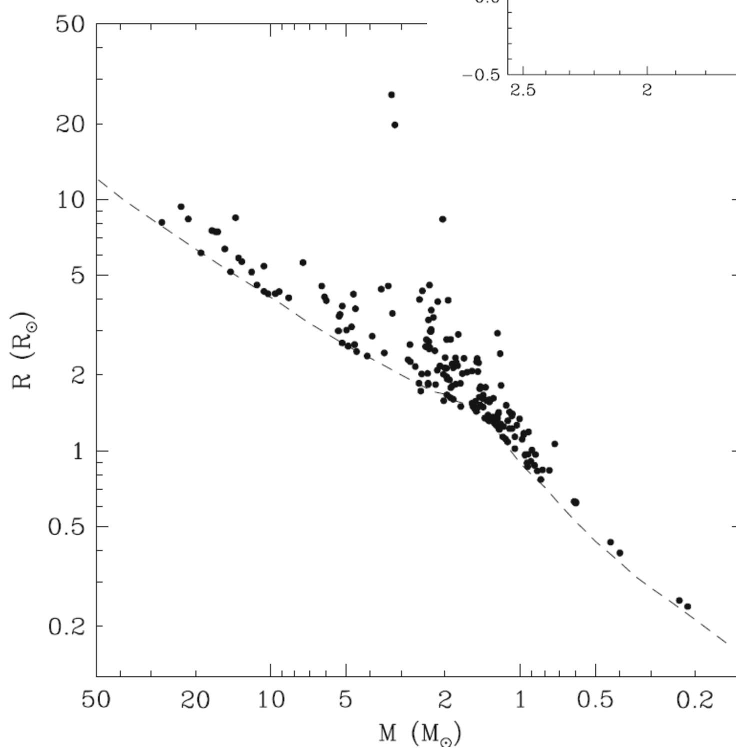


- Indirect indicators:
  - age
  - [m/H]

Precise stellar masses and radii

- Very nice review by Torres et al. (2010, A&ARv)
- 188 stars (94 eclipsing systems) with masses and radii better than 3%
- Lots of astrophysical insight
- Stellar evolution:
  rotation, convection, diffusion
- Tidal evolution:
  synchronization, circularization, apsidal motion





Eclipsing binaries as tools

Stellar models have made great strides during the last decades thanks to improvements in :

- Opacities
- Equations of state
- Nuclear reaction rates
- Convection

Crucial: **iterative process of comparison of model predictions with observations ⇨ only relevant when the number of free parameters is small or null**

Good description of models in the main sequence for stars of intermediate mass 1-5 $M_{\odot}$

Eclipsing binaries have greatly contributed to this!

But theory still presents shortcomings when describing some physical processes and their consequences…

- Convection
- Mass loss

… and it is also time to further sophisticate models by including other effects…

- Rotation
- Magnetic fields
- …

What is the role of eclipsing binaries in this context?

What kind of relevant tests can they provide?

What important physical mecanishms arise?

Model testing with eclipsing binaries

- Need to be very strict about measurement accuracy
- Expected model differences in the few % level ⇨ only measurements better than 2-3% provide meaningful tests
- BUT, in some evolutionary stages changes are much faster, i.e., poorer accuracy may be fine
- Typical EB analysis results:

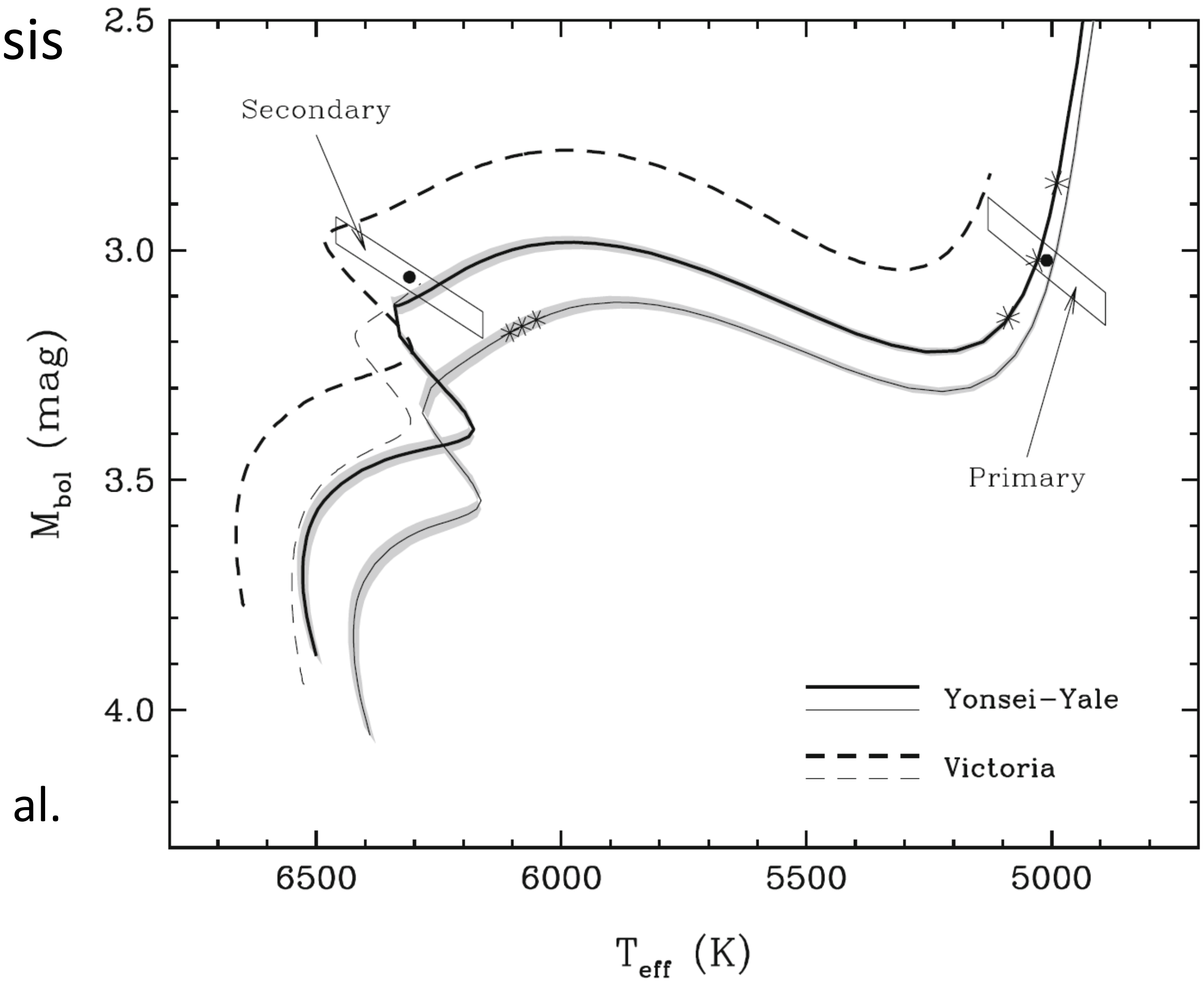
	Primary	Secondary
Absolute dimensions:		
$M/M_\odot$	1.414 ± 0.007	1.257 ± 0.005
$R/R_\odot$	1.988 ± 0.008	1.474 ± 0.017
$\log g$ (cgs)	3.992 ± 0.004	4.201 ± 0.010
$v \sin i^a$ (km s^{-1})	16.6 ± 0.2	13.4 ± 0.2
$v_{sync}{}^b$ (km s^{-1})	18.3 ± 0.1	13.6 ± 0.2
$v_{psync}{}^c$ (km s^{-1})	18.3 ± 0.1	13.6 ± 0.2
$v_{peri}{}^d$ (km s^{-1})	18.5 ± 0.1	13.7 ± 0.2
Photometric data:		
V^e	10.473 ± 0.009	11.080 ± 0.014
$(b-y)^e$	0.363 ± 0.007	0.360 ± 0.008
$m_1{}^e$	0.144 ± 0.013	0.139 ± 0.016
$c_1{}^e$	0.466 ± 0.014	0.436 ± 0.017
$E(b-y)$	0.044 ± 0.015	
T_{eff}	6265 ± 85	6320 ± 90
M_{bol}	2.90 ± 0.06	3.51 ± 0.07
$\log L/L_\odot$	0.74 ± 0.02	0.49 ± 0.03
$B.C.$	-0.01	-0.01
M_V	2.91 ± 0.06	3.52 ± 0.07
$V_0 - M_V$	7.37 ± 0.09	7.37 ± 0.10
Distance (pc)	298 ± 12	298 ± 13
Abundance:		
[Fe/H]	-0.12 ± 0.07	

BK Peg (Clausen et al. 2010, A&A)

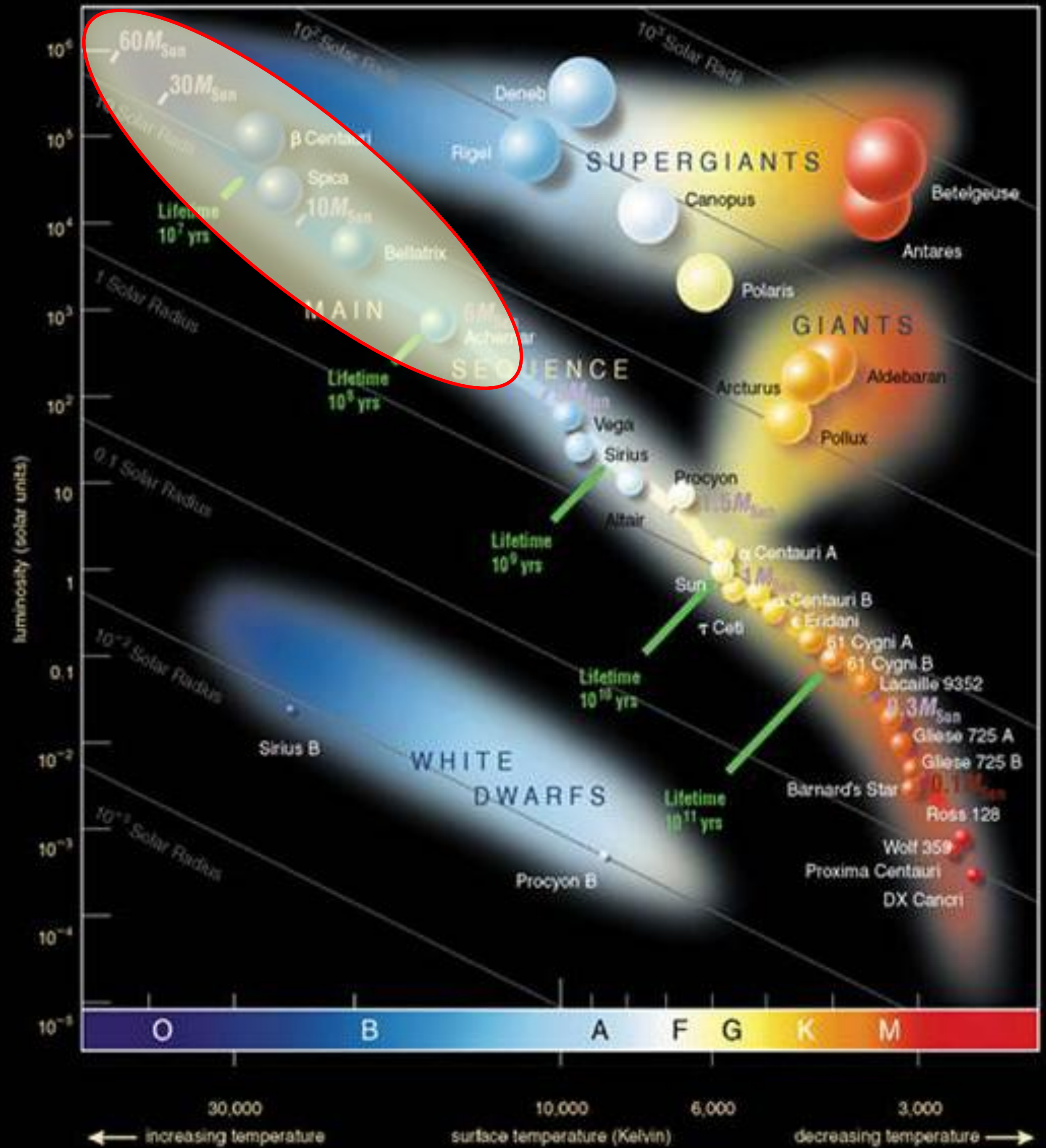
Model testing with eclipsing binaries

Nearly all physical parameters well known (M, R, Teff, L, Mbol) and possible constraints for others ([Fe/H], age)

Coevality hypothesis
⇨ isochrone

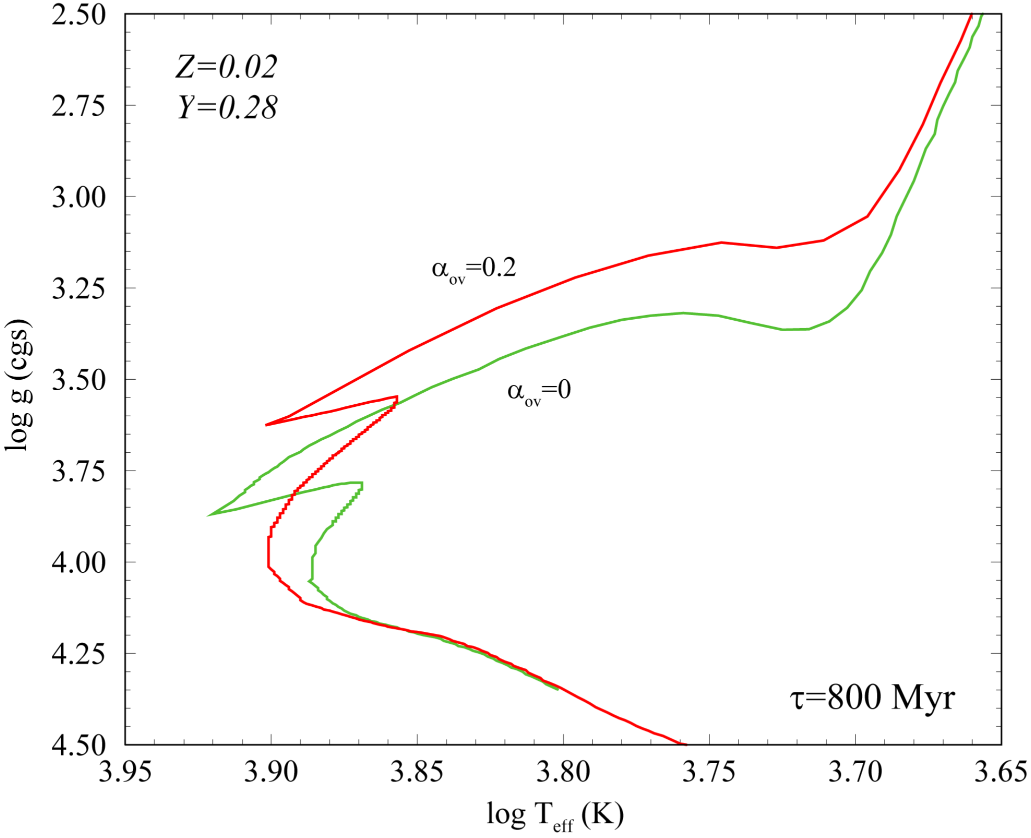


AI Phe (Torres et al. 2010, A&ARv)


SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
β Centauri
Spica
Bellatrix
Achernar
Deneb
Rigel
Canopus
Betelgeuse
Antares
Polaris
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
0.3 M_{Sun}
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

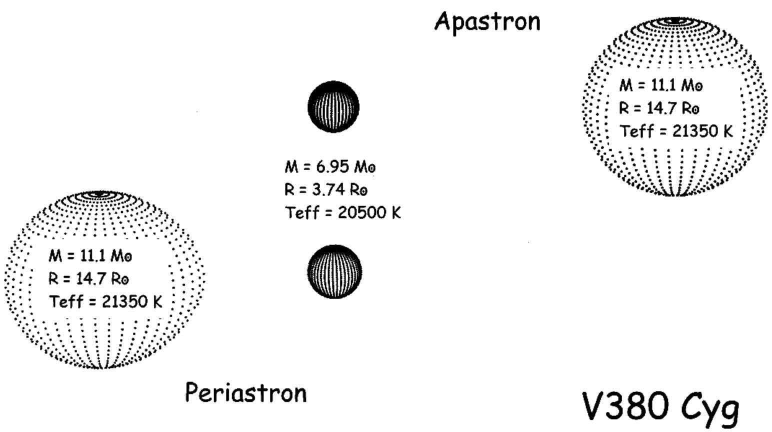
Open problems in high-mass stars

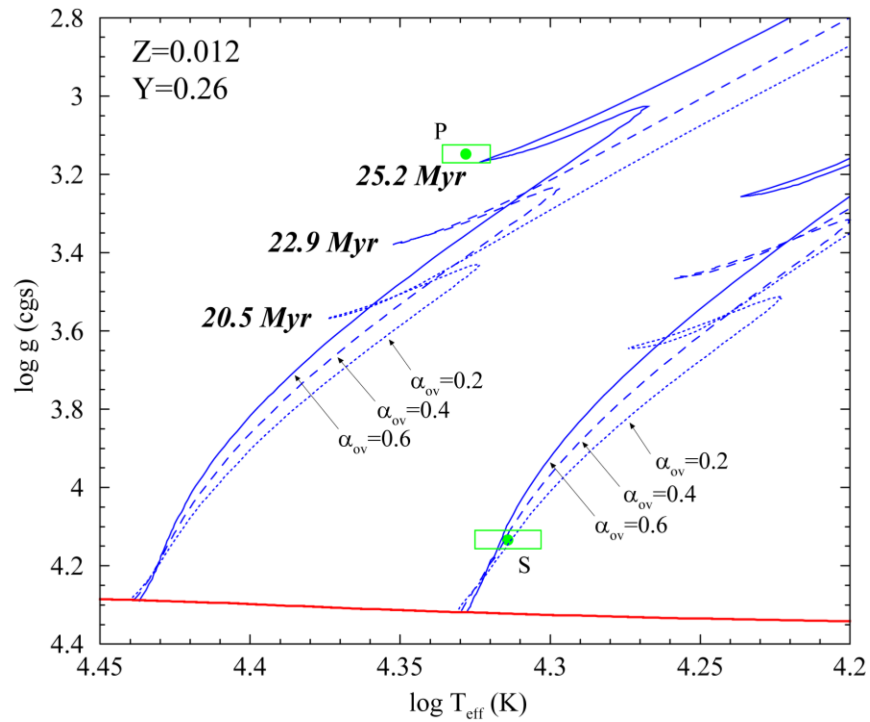
- Binaries provide macroscopic parameter measurements and can thus probe the size of the convective core
  - Convective energy transport
  - Mass loss
  - Rotation?



V380 Cyg: a test case

- Guinan et al. (2000, ApJ)
- Full analysis with precise values of M, R, Teff, [Fe/H] and apsidal motion rate





Observations:

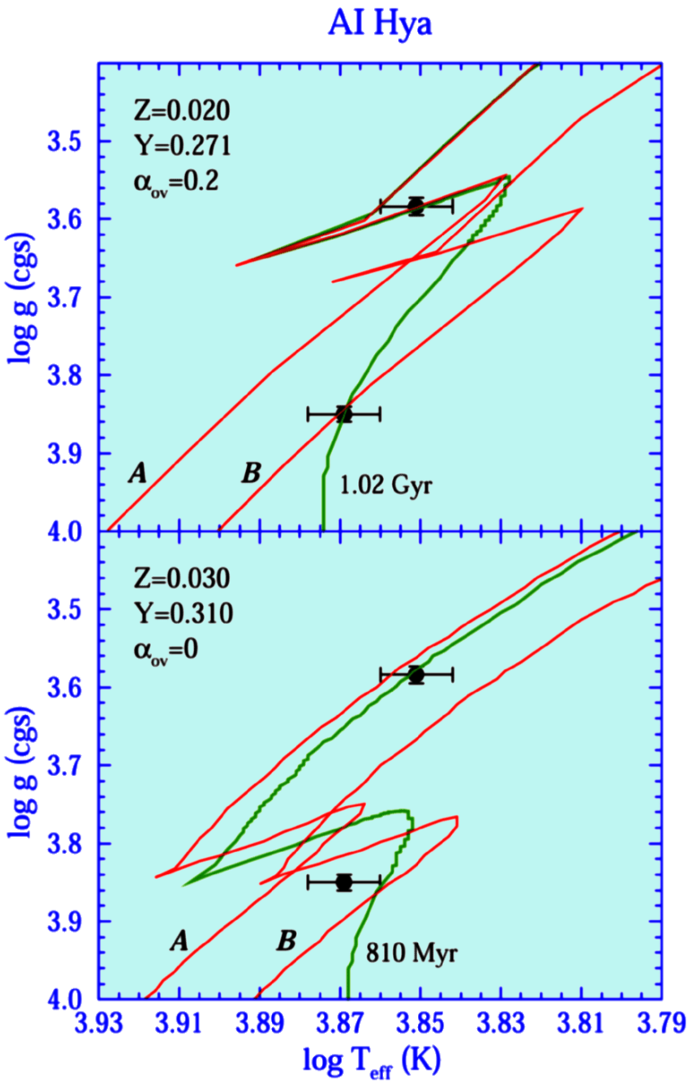
- log k_2A = −2.89 0.04
- log T_{eff}A = 4.329 0.008
- log T_{eff}B = 4.312 0.011

Model Predictions with Different Amounts of Overshooting for the Components of V380 Cygni

	Primary Component			Secondary Component		
α_{ov}	Age (Myr)	log T_{eff}	log k_2	Age (Myr)	log T_{eff}	log k_2
0.2......	20.5 ± 1.5	4.267 ± 0.010	−2.66 ± 0.03	20 ± 3	4.311 ± 0.009	−2.10 ± 0.02
0.4......	22.9 ± 1.5	4.282 ± 0.010	−2.75 ± 0.03	23 ± 3	4.313 ± 0.009	−2.11 ± 0.02
0.6......	25.2 ± 1.5	4.324 ± 0.010	−2.91 ± 0.03	26 ± 3	4.314 ± 0.009	−2.11 ± 0.02

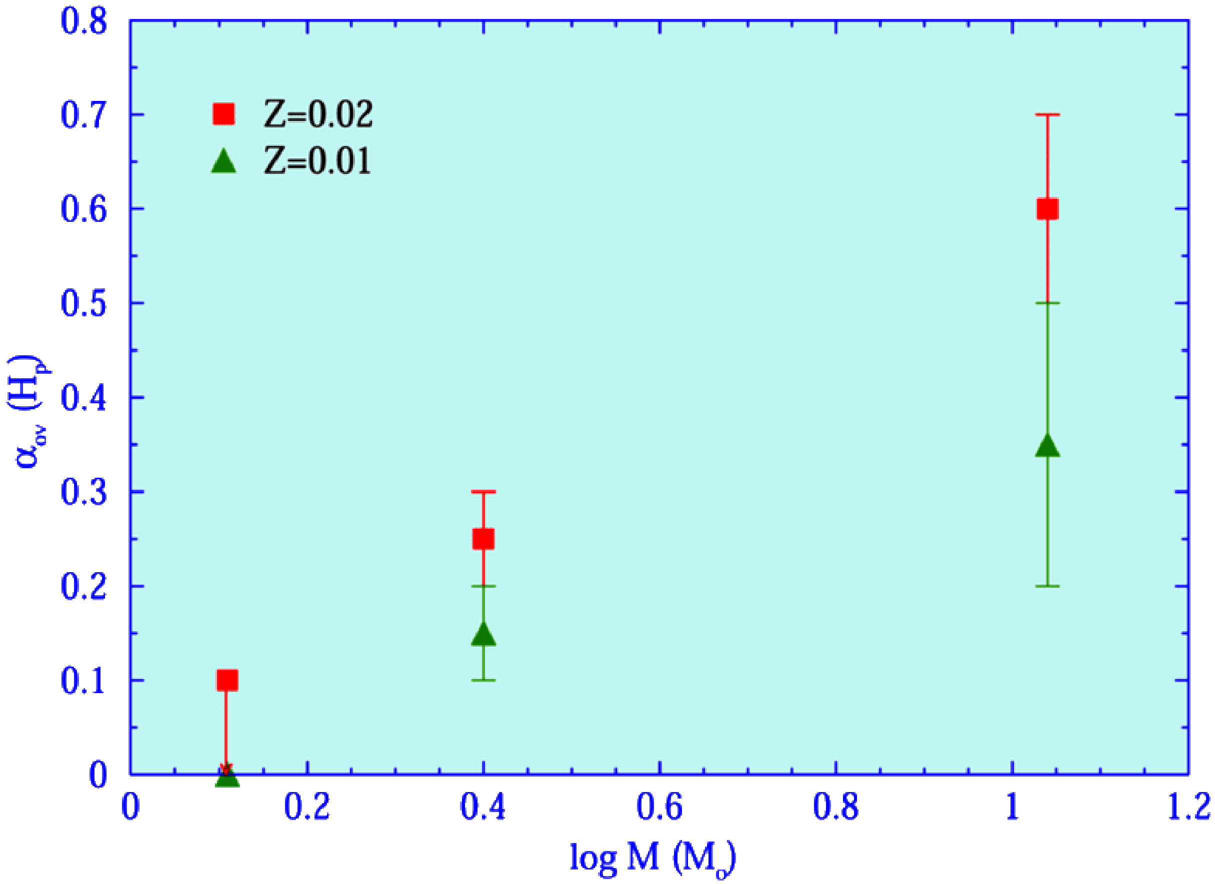
Constraining α_{ov}

- Other studies of V380 Cyg find essentially compatible parameters
  - Pavlovski et al. (2009, MNRAS): No CNO abundance anomalies
  - Tkatcheko et al. (2012, A&A): Kepler LC
- The case for a high overshooting parameter (>0.4) is quite strong
- At the same time, HV2274, in the LMC and with metallicity 1/3 solar, yields equivalent results (Ribas et al. 2000, ApJ):
  - H-R diagram: $\alpha_{ov} > 0.2$
  - Apsidal motion: $0.1 < \alpha_{ov} < 0.5$
- And constraints are also obtained from less massive systems



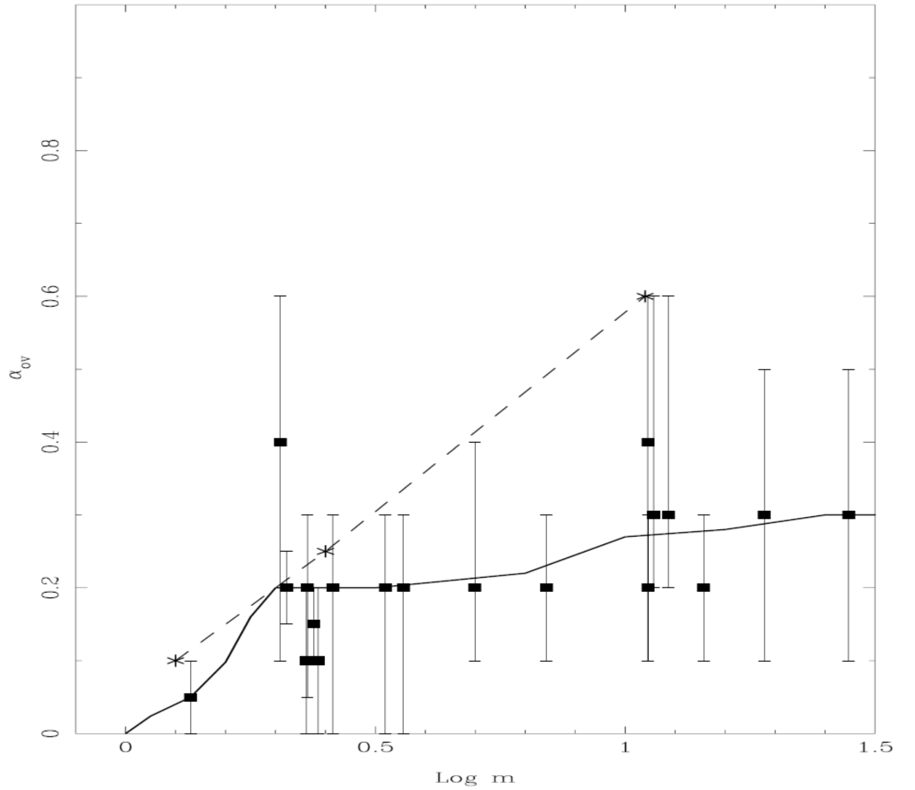
Mass dependence of α_{ov}?

- Ribas et al (2000, MNRAS) propose a dependence with mass using EBs and clusters
- (+ a tentative metallicity dependence)



Mass dependence of α_{ov}?

- Claret (2007, A&A) carried out a reanalysis of EB data
- BUT, did not consider T_{eff} & it is based on less constraining systems
- The resulting relationship is shallower
- But, Fernandes et al. (2012, MNRAS) find it even steeper...

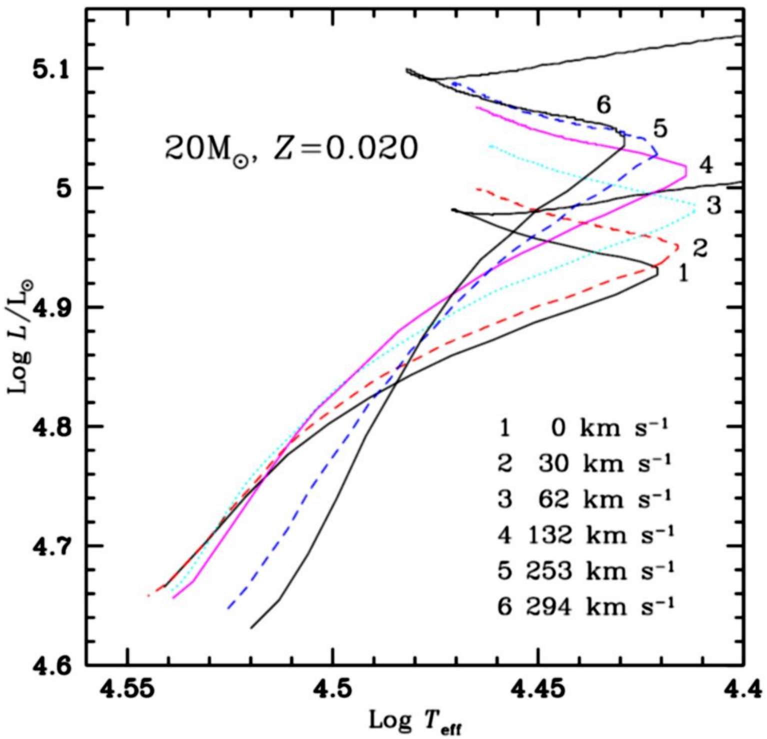


- Asteroseismology also provides information on convective overshooting for stars with 10-14 $M_\odot$:
  - Aerts et al. 2003: α_{ov}=0.10±0.05
  - Ausseloos et al. 2004: α_{ov}=0.3
  - Aerts et al. 2006: α_{ov}=0.20±0.05
  - Mazumdar et al. 2006: α_{ov}=0.20±0.05

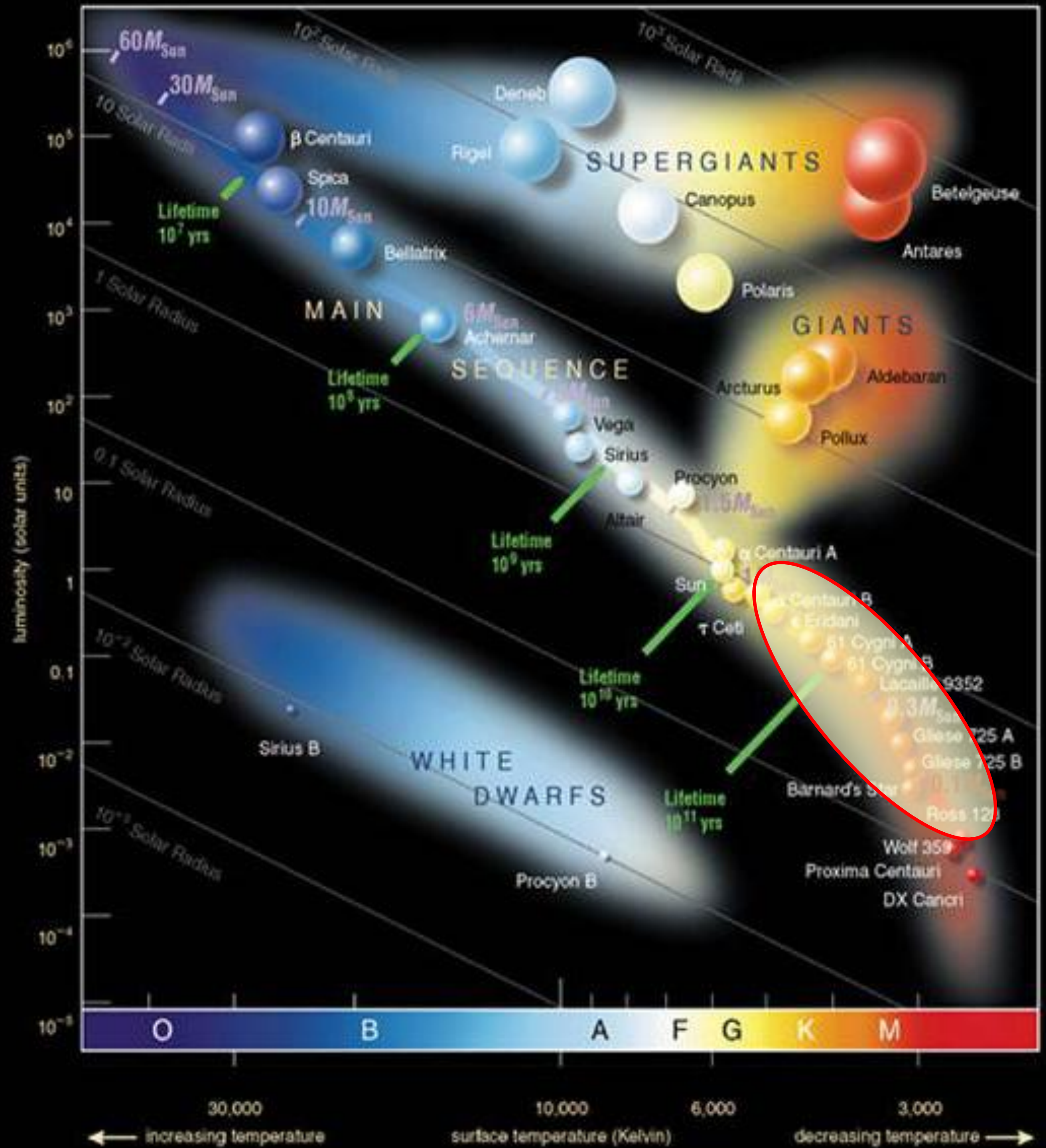
Some thoughts…

- EBs vs. single stars (v sin i):
  - V380 Cyg ⇨ 100 km/s
  - Asteroseismology ⇨ 10-20 km/s
- The situation is definitely NOT resolved

Meynet & Maeder (2000, A&A)



- EB analyses are mostly sensitive to convective size core (i.e., longer MS evolution & different internal density profile)
- Caution needs to be taken because of degeneracy: convective overshooting, rotation and mass loss have similar observational signatures for binaries
- How about magnetic fields? (Maeder & Meynet 2005, A&A)
- And helium abundance?



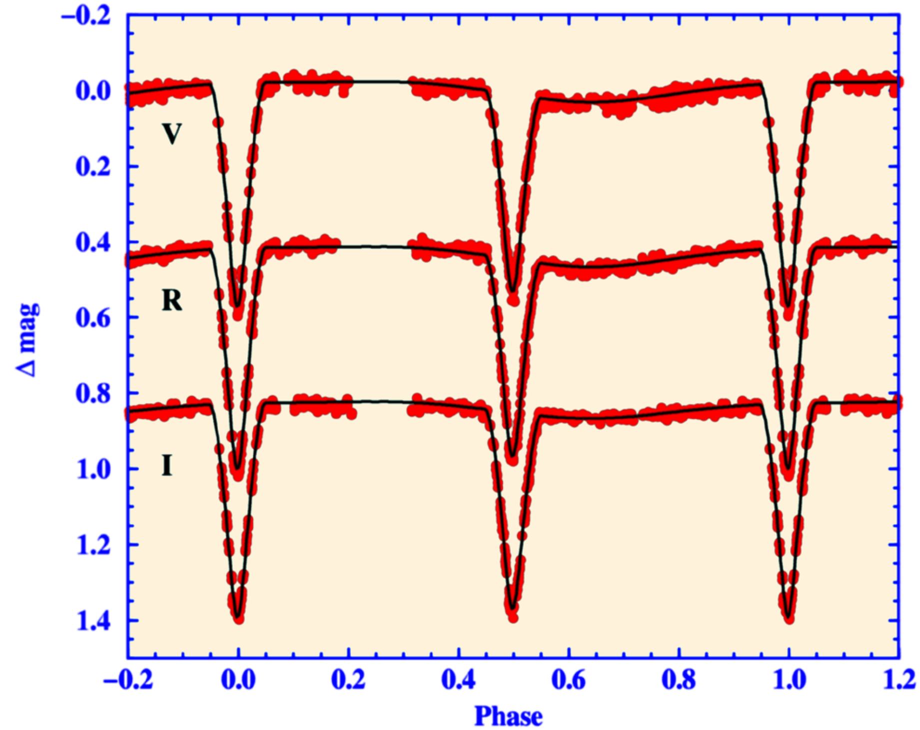
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
Canopus
Betelgeuse
Antares
Polaris
β Centauri
Spica
Bellatrix
Achernar
Aldebaran
Arcturus
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
τ Ceti
Barnard's Star
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
$60M_{Sun}$
$30M_{Sun}$
$10M_{Sun}$
luminosity (solar units)
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

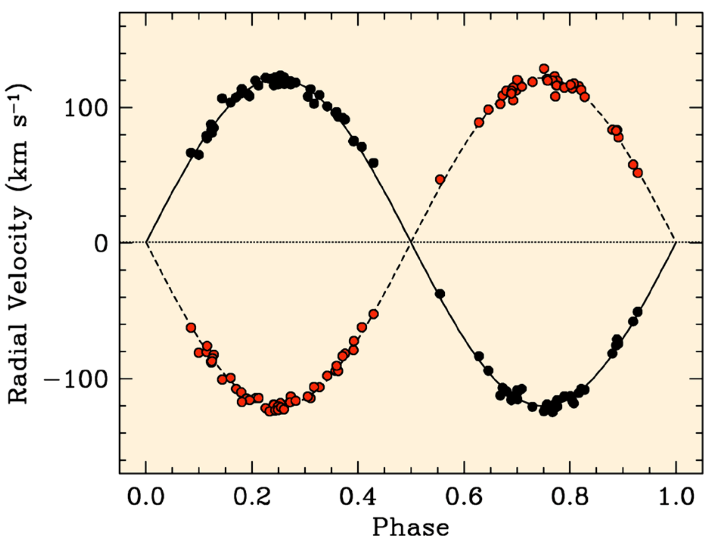
YY Gem: a benchmark

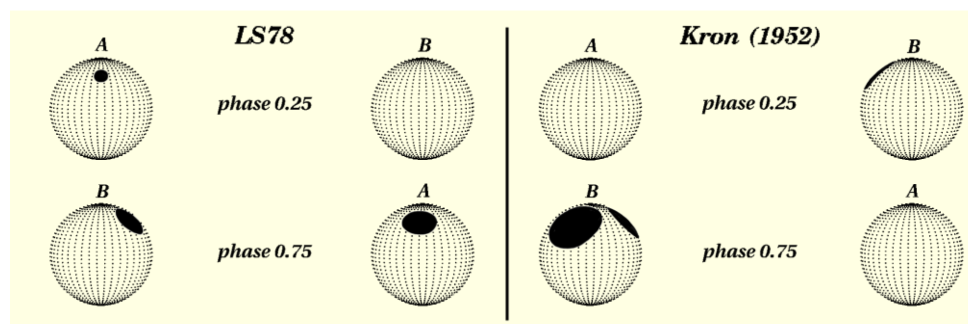
Torres & Ribas (2002, ApJ)

PHYSICAL PROPERTIES OF THE MEAN COMPONENT OF YY GEM

Parameter	Value
Mass ($M_\odot$)	0.5992 ± 0.0047
Radius ($R_\odot$)	0.6191 ± 0.0057
$\log g$ (cgs)	4.6317 ± 0.0083
$\bar{\rho}$ (g cm^{-3})	3.56 ± 0.10
$v \sin i$ (km s^{-1})	37 ± 2
$v_{sync} \sin i$ (km s^{-1})	38.5 ± 0.4
T_{eff} (K)	3820 ± 100
$L/L_\odot$	0.0733 ± 0.0015
M_{bol} (mag)	7.569 ± 0.020
M_V (mag)	8.950 ± 0.029



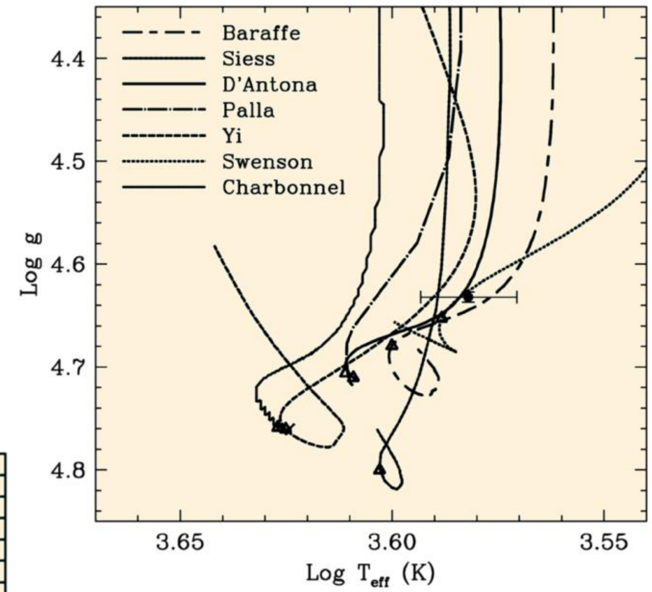


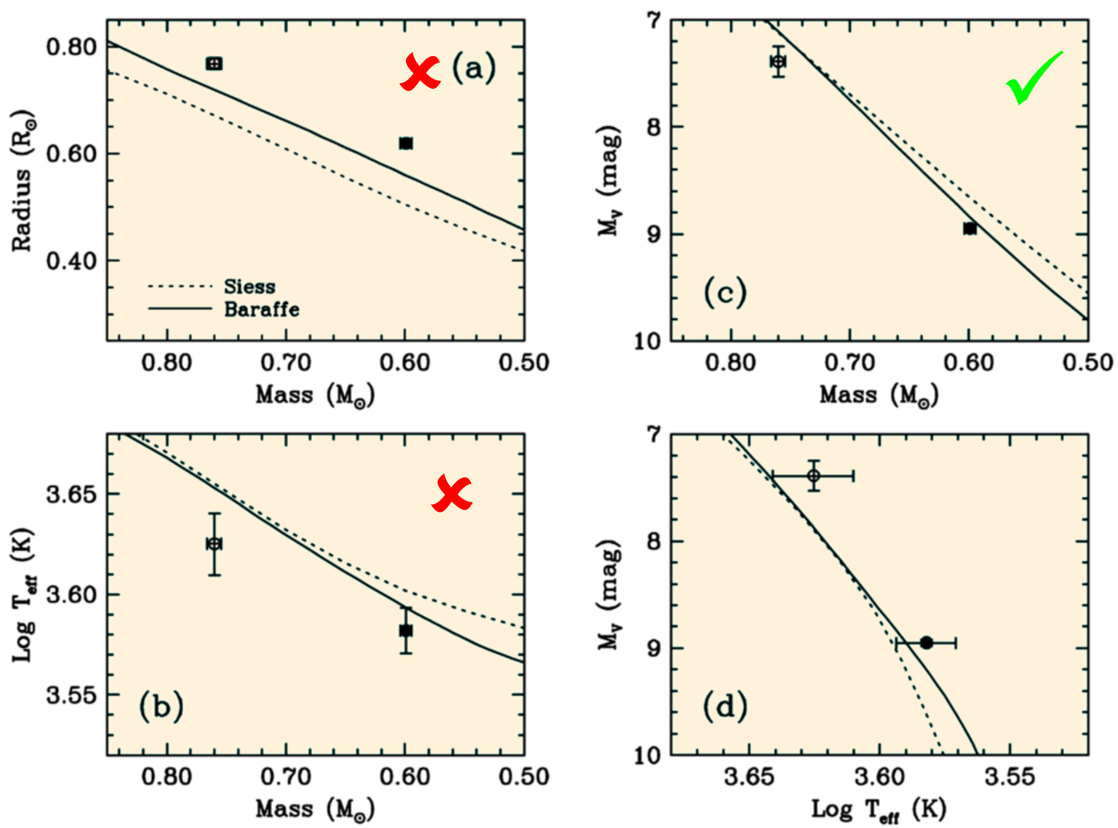


Member of the Castor sextuple system ⇨~370 Myr & metallicity ~ solar

YY Gem & evolution models

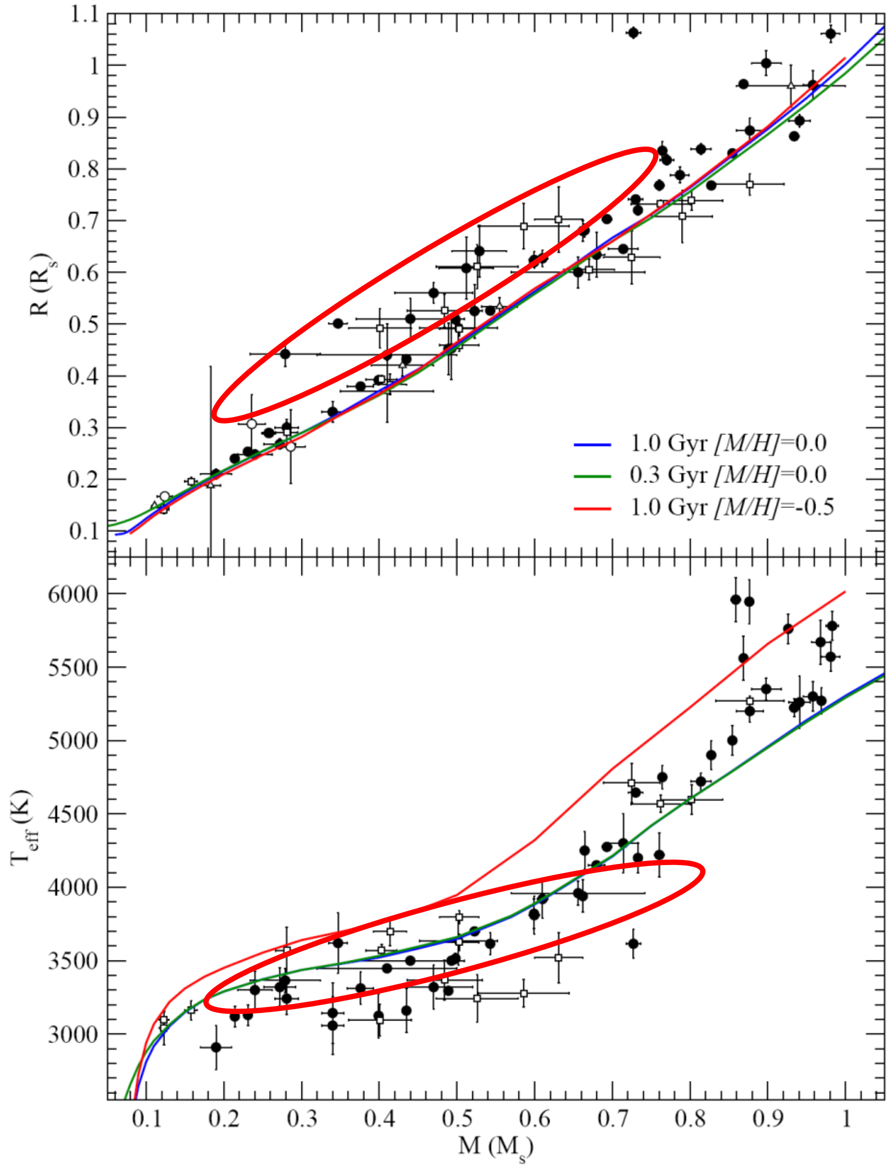
- Clearly "above" the MS in all cases
- Models suggest that YY Gem is a PMS star (we know it's not!)

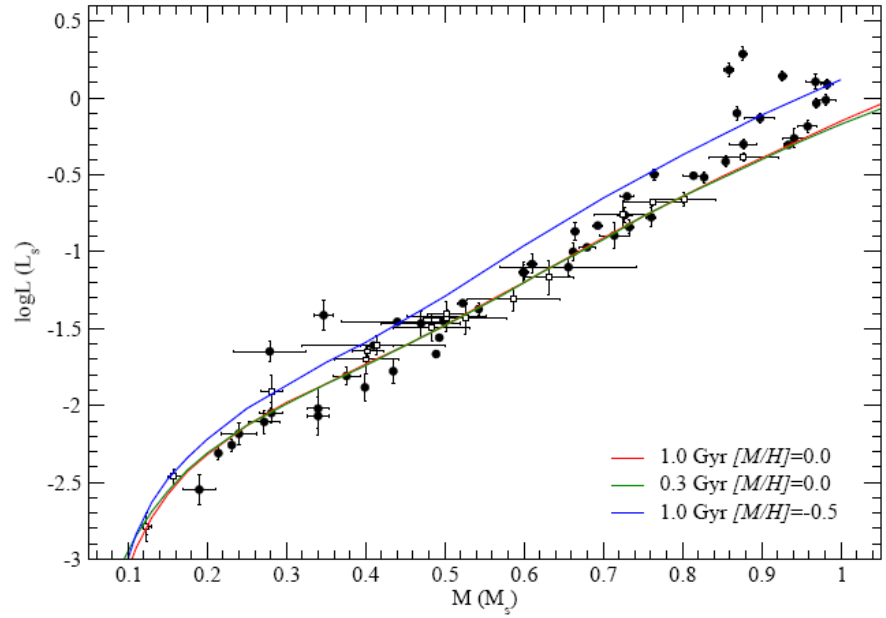




- V818 Tau B & YY Gem AB
- M_v plots OK
- Radius > models! (10-20%)
- T_{eff} < models (5%)

10 years (and 10s of papers) later…

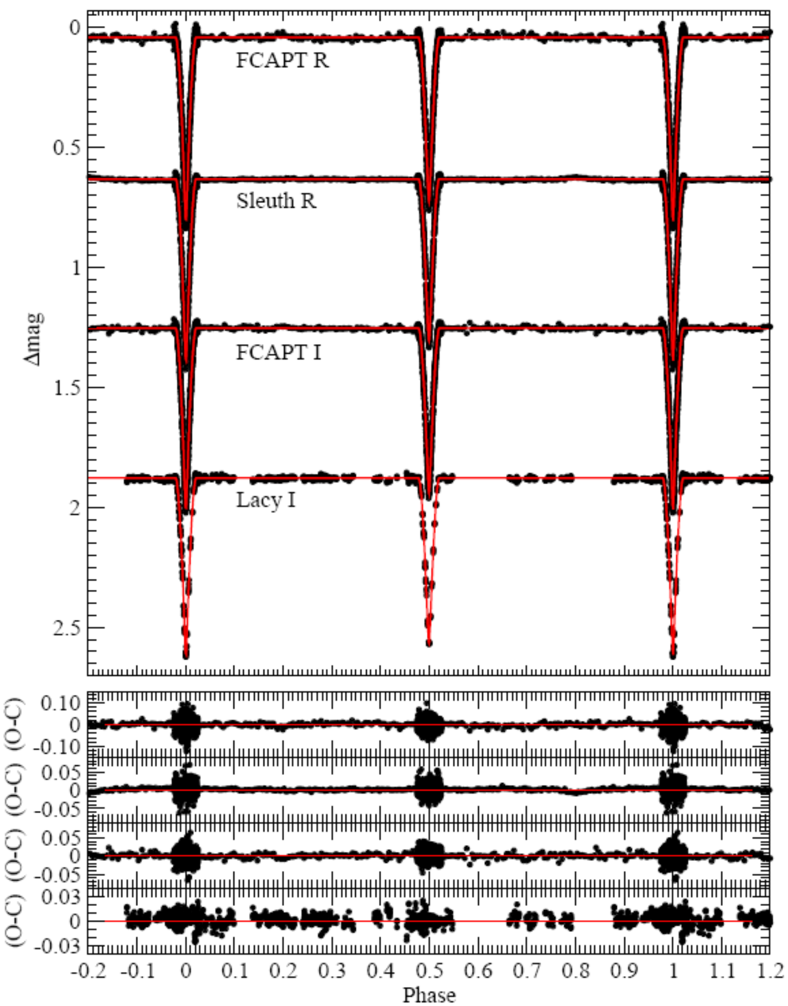


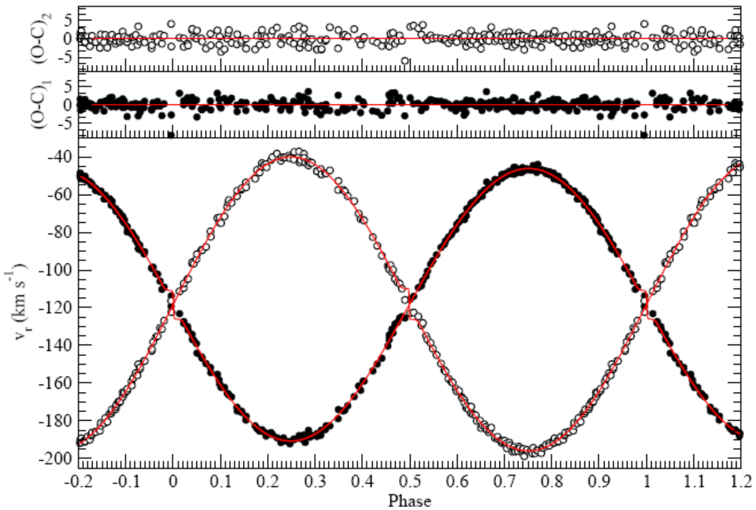


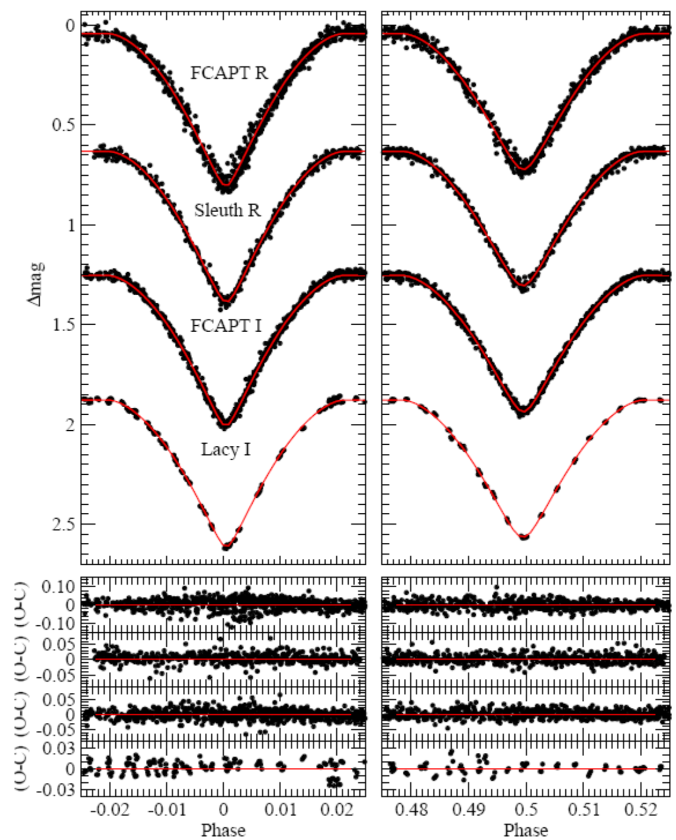
- *R* ~10% underestimated by models
- T_{eff} ~5% overestimated by models
- *L* correctly predicted

CM Dra: a little jewel

EB: M4.5V + M4.5V

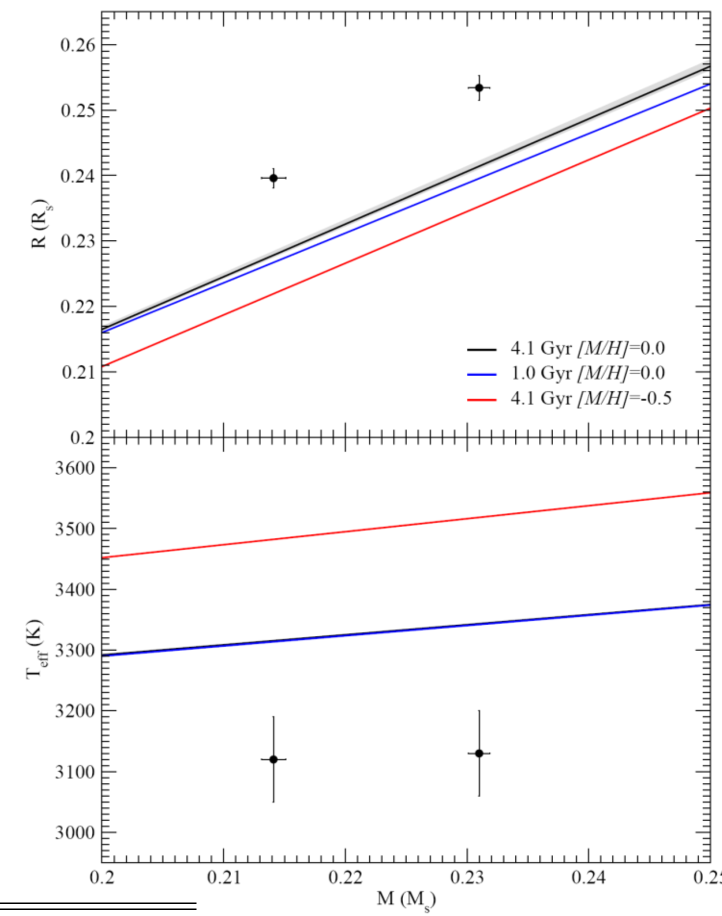






Morales et al. (2009, ApJ)

CM Dra & evolution models



Stars with most precise properties besides the Sun!

⇨0.5% error in mass

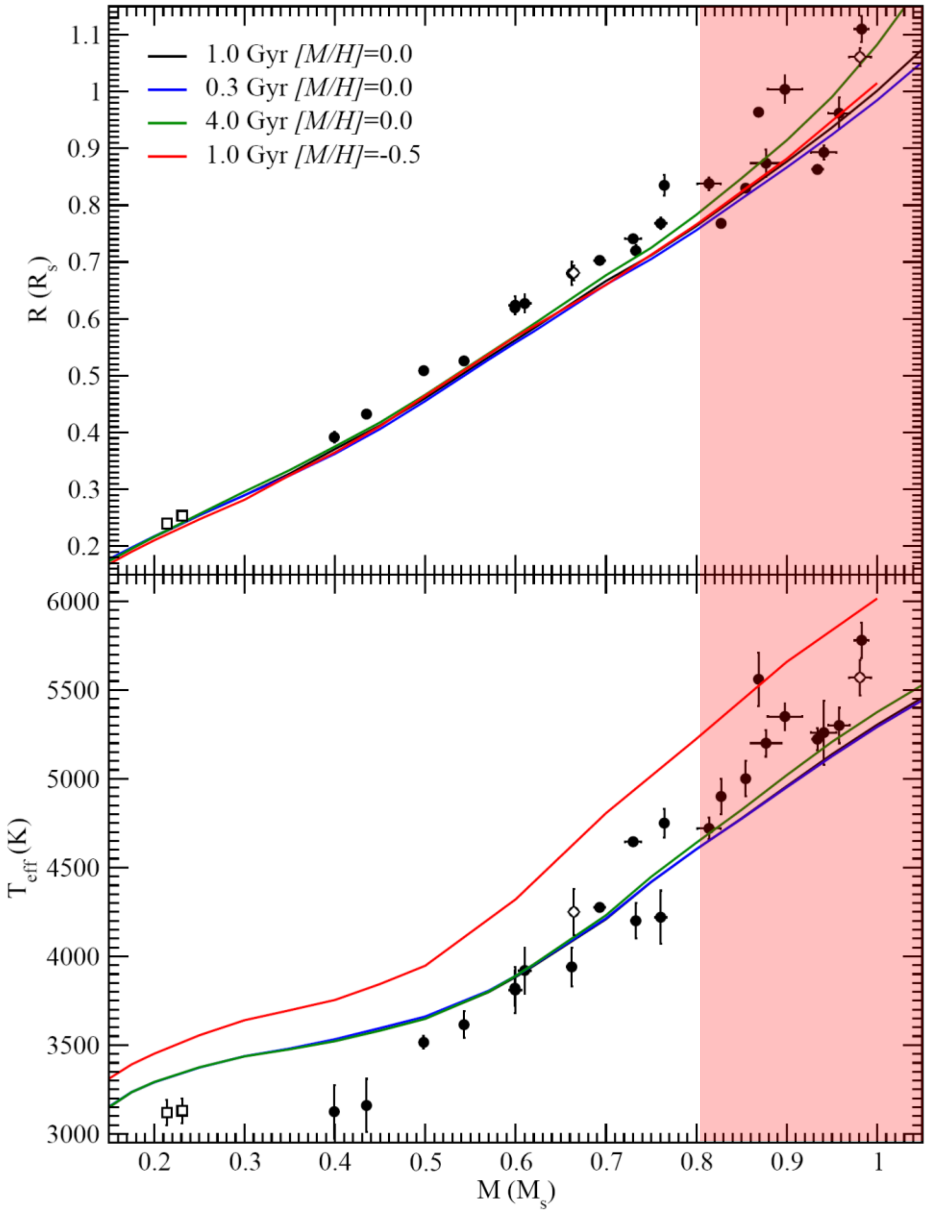
⇨0.6% error in radius

$\Delta R/R$ ~ 5% - 5.2%

$\Delta T_{eff}/T_{eff}$ ~ –6.4% - –5.9%

Properties	Component 1	Component 2
$M\ (M_\odot)$	0.2310 ± 0.0009	0.2141 ± 0.0010
$R\ (R_\odot)$	0.2534 ± 0.0019	0.2396 ± 0.0015
$\log g$ (cgs)	4.994 ± 0.007	5.009 ± 0.006
$T_{\rm eff}$ (K)	3130 ± 70	3120 ± 70
$\log(L/L_\odot)$	-2.258 ± 0.038	-2.313 ± 0.056
Age (Gyr)	4.1 ± 0.8 (*Main sequence*)	
$[M/H]$	$-1 < [M/H] < -0.6$	

Comparison between models and EBs



EBs with masses and radii accurate to the 3% level

Below 0.8 $M_{\odot}$:

- Larger radii
- Cooler eff. temp.

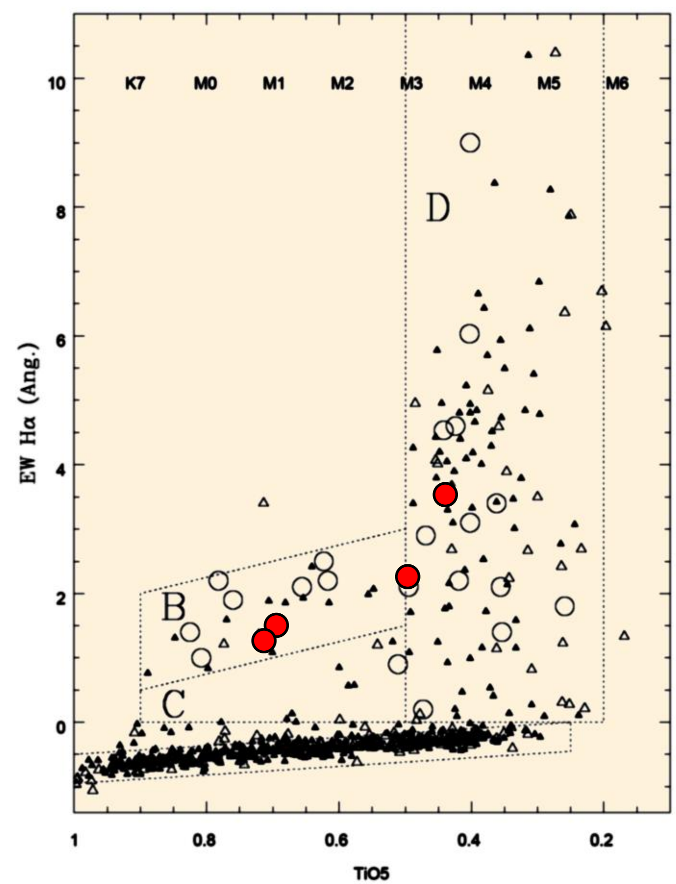
Above 0.8 $M_{\odot}$ the radius differences due to MS evolution exceed 2%

No PMS objects for now

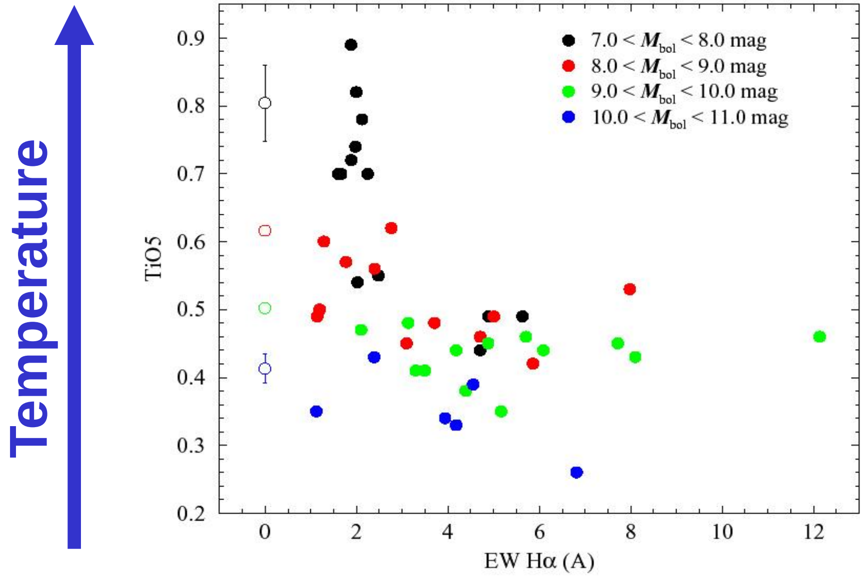
Looking for answers…

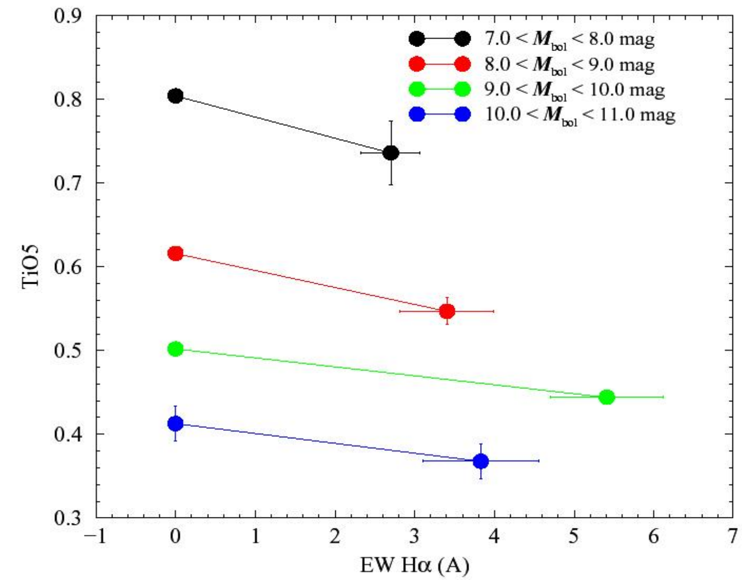
- Metallicity or missing opacities in models (Berger et al. 2006; Casagrande et al. 2008):
  - ⇨ Tests yield unrealistically high metallicities or opacities
  - ⇨ Isolated stars agree with models (Demory et al. 2009)
- Are M stars in EBs intrinsically different from field stars in any way?
  - ⇨ Close binaries are forced to spin up in orbital sync
  - ⇨ More magnetically active than average field stars!
  - ⇨ Any M star with Prot < 10 days has saturated activity
  - ⇨ Current period range in EBs: 0.5 – 2.8 d

Gizis et al. (2002, ApJ)

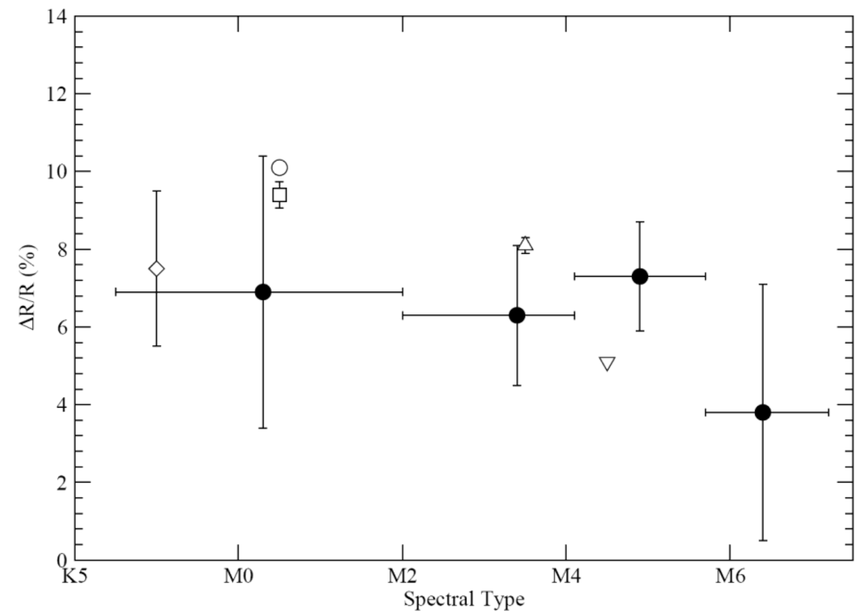


What about isolated field stars?





- PMSU + 2MASS: 647 inactive + 48 active
- They should show the same systematics ⇨ They do!
- If $L_{act} \approx L_{inact}$ ⇨ Active stars cooler… ⇨ …and therefore larger!



Morales et al. (2008, ApJ)

Hypothesis

- Differences with models related to the high magnetic activity of EBs (Ribas 2006; Torres et al. 2006; López-Morales 2007)?

- Two possible scenarios:

  - ➢ Energy conservation (López-Morales & Ribas 2005):
    - Spots lower the overall photospheric temperature…
    - …the star compensates by increasing radius to conserve the total flux

    ⇨ $L' = (1-\beta)\, 4\, \pi\, R'^2\, \sigma\, T_{eff}'^4$

  - ➢ Different interior physics because of B (Mullan & MacDonald 2001,2009, 2011, 2012; Chabrier et al. 2007):
    - Onset of convection + hydrostatic equilibrium

    ⇨ $\nabla_{ad} + \delta' < \nabla_{rad}$

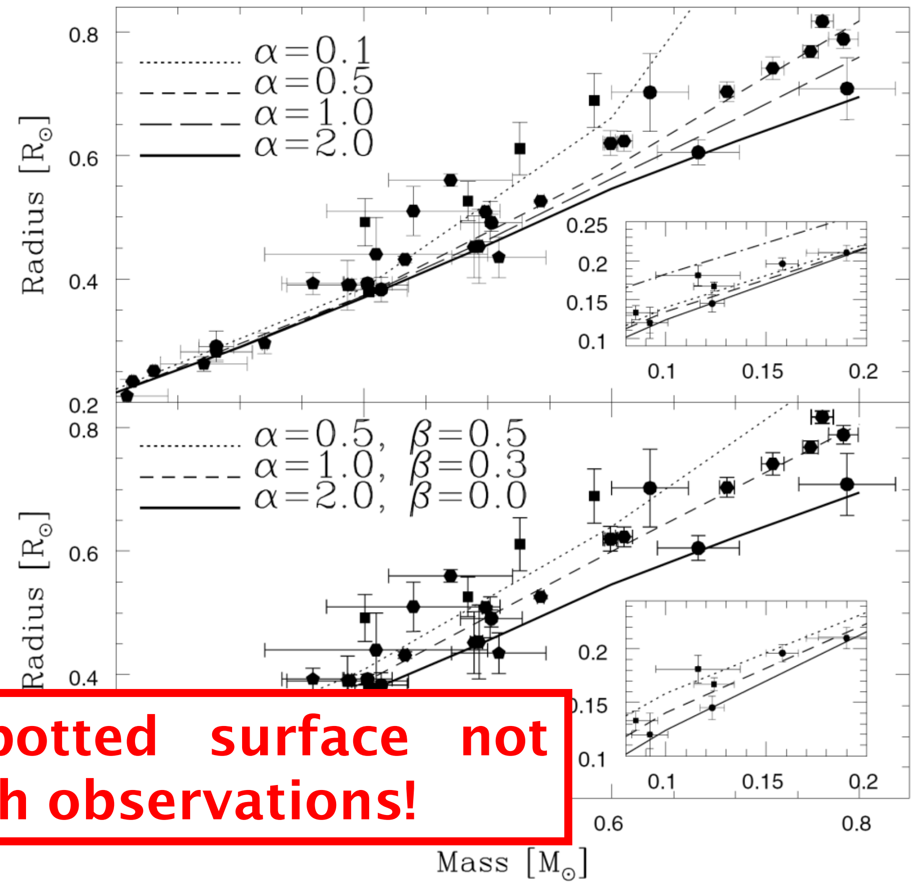
    - Or lower convection efficiency ($\alpha\downarrow$)

Chabrier et al. (2007)

Inhibition of convection: *α*↓

α ~ 0.5

Little effect for fully convective stars such as CM Dra!



Very large spotted surface not compatible with observations!

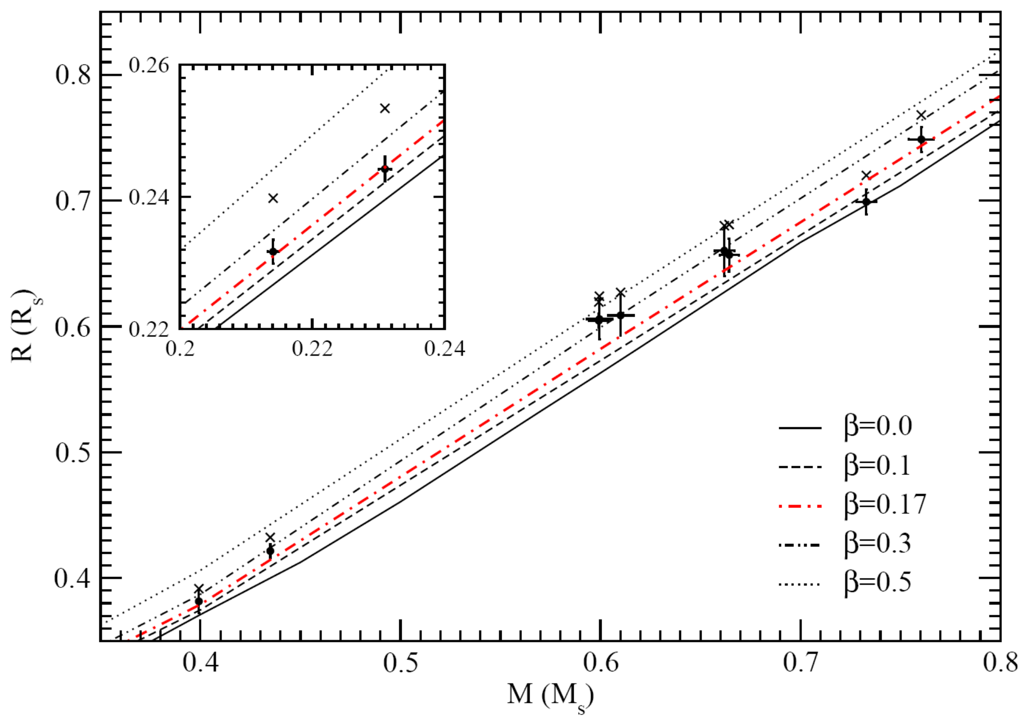
Surface spots: spot coverage β

β ~ 0.3-0.5

$$\beta = \frac{S_s}{S}\left[1-\left(\frac{T_{eff,s}}{T_{eff}}\right)^4\right]$$

- 30-50% of pitch black spots!
- 65%-100% of spots with 15% temp. contrast

Making sense of all this…



CM Dra (fully convect.) used to separate α and β effects.

Assuming polar spots, observations consistent with models if:

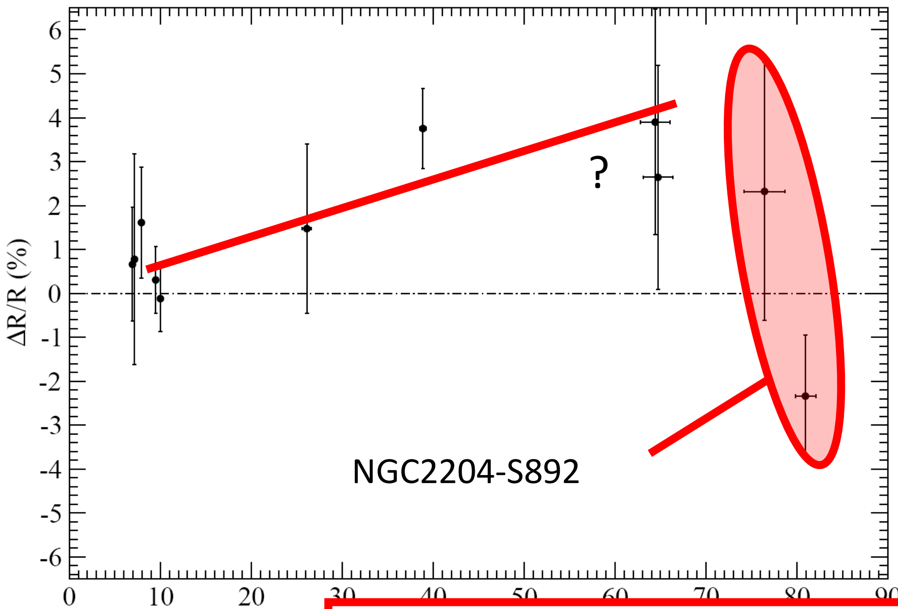
$$\beta = 0.17 \pm 0.03$$

(~35% spot coverage)

Radius correction ~ 3%

Other systems are roughly reproduced if:

- spots on EBs are mostly polar (compatible with Doppler tomography; Strassmeier 2009)
- saturated systems have similar spot coverages

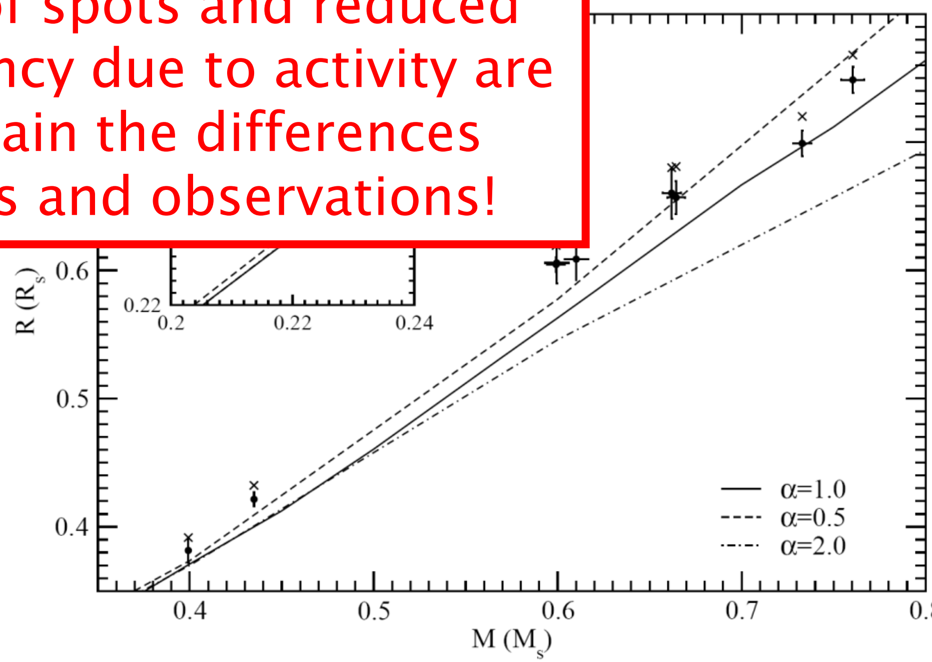


Effect of magnetic fields and rotation on convective motion may be also present!

Stronger B, i.e., smaller conv. efficiency, for faster rotation?

Both the effect of spots and reduced convective efficiency due to activity are needed to explain the differences between models and observations!

It can be reproduced reducing the mixing length parameter α



Morales et al. (2010, ApJ)

Wrapping up

- Magnetic activity responsible for the discrepancies:
  - Metallicities or opacities have to be increased to unrealistic values to explain the discrepancies
  - Isolated main sequence active stars show same pattern
- Spots have a significant effect on the determination of the radii of EBs if distributed close to the poles

- Assuming mostly polar spots and activity-saturated systems to have similar spot coverages, all works if:
  - Systematic ~3% overestimation of the radii from light curves
  - ~2% increase of the radius to compensate the loss of radiative efficiency due to spots (β)
  - Increase of up to 4% of the radius from the lower convective efficiency in fast rotating magnetically active stars (α)

Is this it?

- We have assumed "universality" in the effects determining M-star properties (from 0.1 to 0.8 $M_{\odot}$) ⇨ is this the case? ⇨ do fully- and partly-convective stars behave the same?

- Not clear that polar spots are ubiquitous on low-mass stars ⇨ very few cases studied and some degeneracies present (see Morin et al. 2008, 2010) ⇨ have dipolar fields (see Donati & Landstreet 2008)

- Testable predictions:
  - Near-IR light curves ⇨ less radius discrepancy (3% ⇨ 1-2%) (TBC)
  - Long period binaries ⇨ less activity & less discrepancy

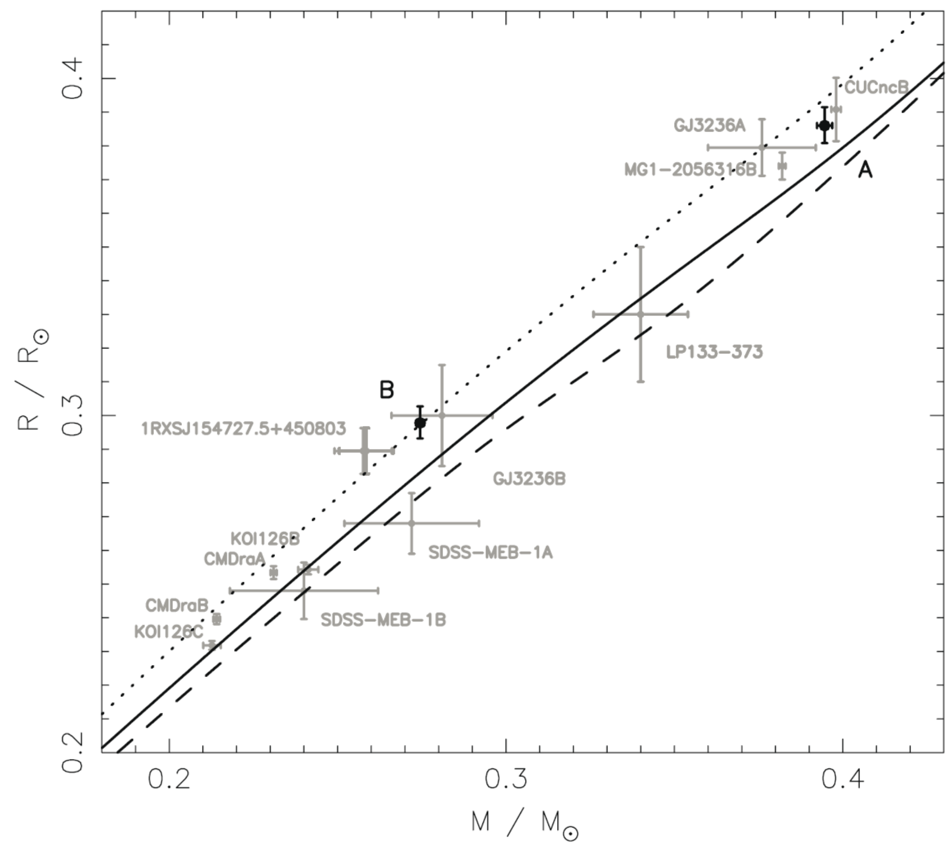
- There are alternatives to the Chabrier et al. (2007) approach ⇨ Mullan & MacDonald (2001, 2009, 2010, 2012) ⇨ Later onset of convection instead of lower efficiency

- Seems to work fine for some objects (2M0535-05, HD 130948, CM Dra)

- BUT: (1) magnetic field strength is a free parameter and the resulting central field is very (too?) strong: ~10 MG; (2) Is L conserved?

No… still an open problem

- Irwin et al. (2011) report eclipsing binary from MEarth with P = 41 d and rotating at natural rate (65 days) ⇨ quite inactive?
- But their radii are 3.8 ± 0.8% larger than model predictions!
- So the activity scenario (namely convection + spot light blocking) may not be the whole story…
- In any case, it is clear that magnetic fields can be relevant for convection and models should account for them!



Irwin et al. (2011, ApJ)