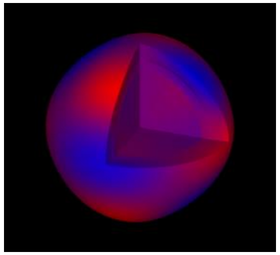
The Impact of Asteroseismology across Stellar Astrophysics
KITP October 2011



The Empirical Mass Distribution of Hot B Subdwarfs derived by asteroseismology and other means

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1. Introduction to sdB stars

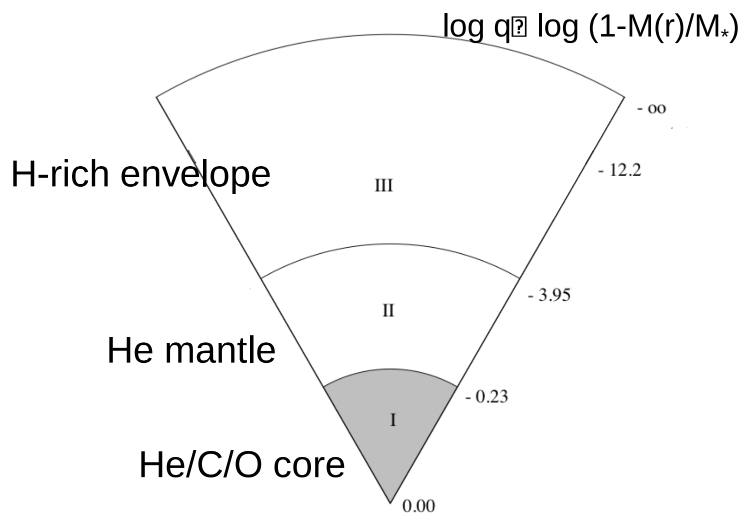
Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars belonging to Extreme Horizontal Branch (EHB)

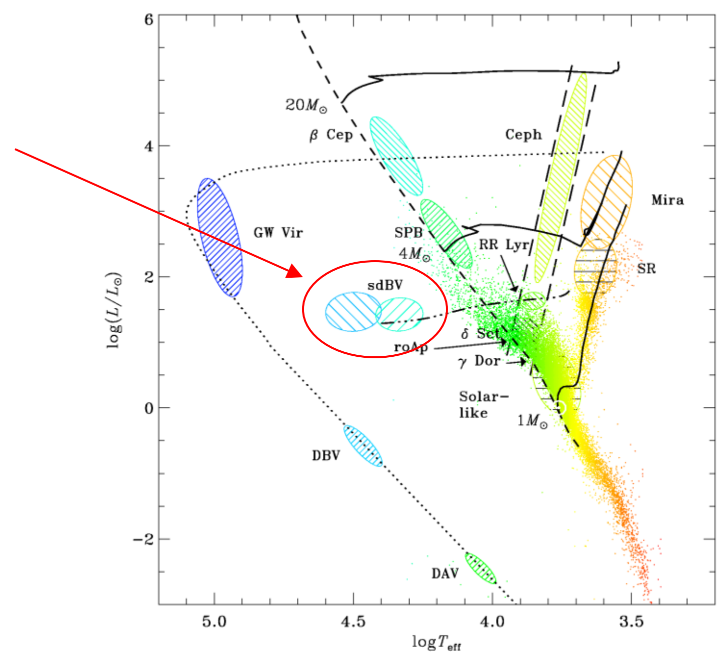
- convective He-burning core (I), radiative He mantle (II) and very thin H-rich envelope (III)
- lifetime of ~ 10^8 yr (100 Myr) on EHB, then evolve as low-mass white dwarfs
- At least 50% of sdB stars reside in binary systems, generally in close orbit (P_{orb} ≤ 10 days)

Two classes of multi-periodic sdB pulsators:

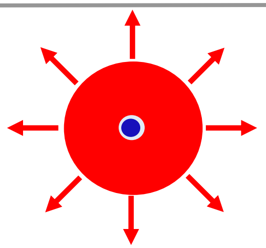
> short-periods (P ~ 80 - 600 s), A ≤ 1%, p-modes (envelope)

> long-periods (P ~ 45 min - 2 h), A ≤ 0.1%, g-modes (core). Space observations required !





2. Single and binary formation scenarios

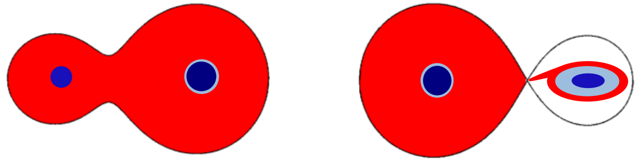


- Single star evolution (enhanced mass loss at tip of RGB)

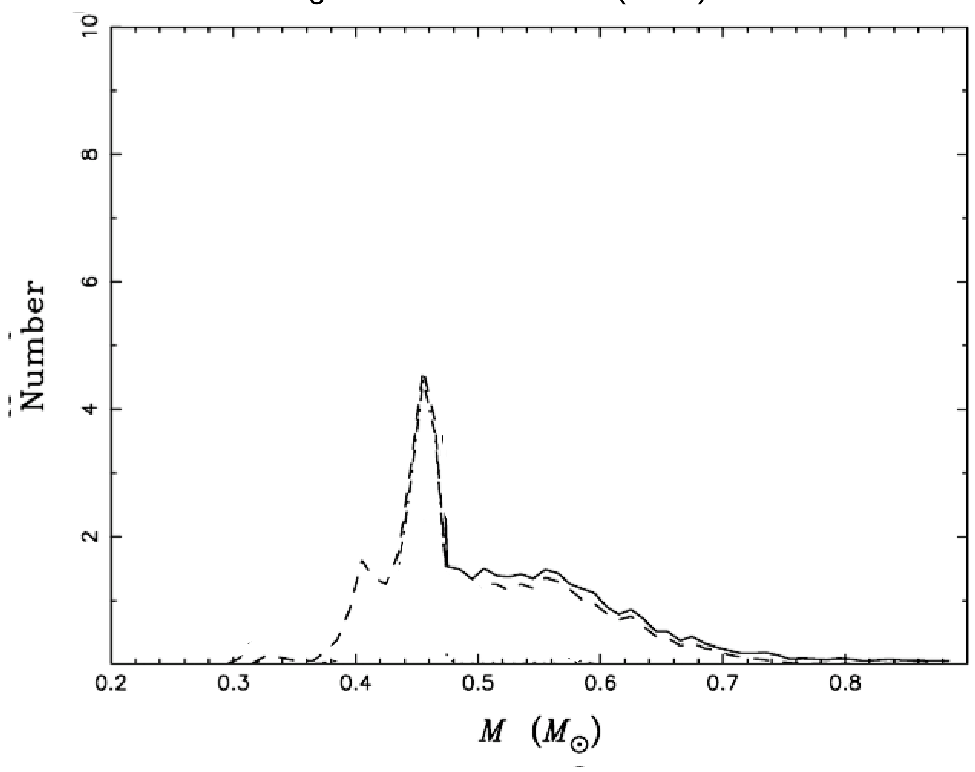
  Mass range in 0.40 - 0.43 $\leq M_*/M_s \leq$ 0.52 (Dorman et al. 1993)

- Binary star evolution (Han et al. 2002, 2003)

  Common envelope ejection (CE), stable mass transfer by Roche lobe overflow (RLOF), and He-white dwarf mergers



Figures from Han et al. (2003)



Weighted mean distribution for binary evolution:

(including selection effects)

0.30 $\leq M_*/M_s \leq$ 0.70

peak ~ 0.46 Ms (CE, RLOF)

high masses (mergers)

3. Method for sdB asteroseismology

Search the star model(s) whose theoretical periods best fit all the observed ones, in order to minimize

$$S^2 = \sum \frac{1}{\sigma}(P_{\rm obs} - P_{\rm th})^2$$

- Static models including detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- Efficient optimization codes (based on *Genetic Algorithms*) are used to find the minima of S^2, i.e. the potential asteroseismic solutions

> Example: PG 1336-018, pulsating sdB + dM eclipsing binary

✓ Light curve modeling (Vuckovic et al. 2007):

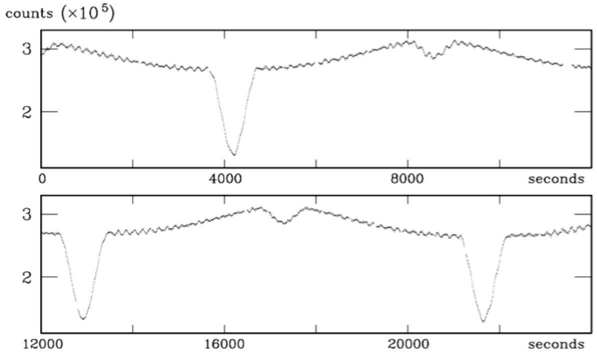
I. $M_{tot} = 0.389 \pm 0.005\ M_s$ et $R = 0.14 \pm 0.01\ R_s$

II. $M_{tot} = 0.466 \pm 0.006\ M_s$ et $R = 0.15 \pm 0.01\ R_s$

III. $M_{tot} = 0.530 \pm 0.007\ M_s$ et $R = 0.15 \pm 0.01\ R_s$

✓ Seismic analysis (Charpinet et al. 2008):

$M_{tot} = 0.459 \pm 0.005\ M_s$ et $R = 0.151 \pm 0.001\ R_s$



⇒ Our asteroseismic method is sound and free of significant systematic effects

4. Available samples (of sdBs with known masses)

I. The asteroseismic sample

Name	log g (cm s^{-2})	$T_{\rm eff}$ (K)	M ($M_\odot$)	log $M_{\rm env}/M$	References
PG 0014+067	5.780±0.008	33550±380	0.490±0.019	−4.31±0.22	Brassard et al. (2001)
	5.775±0.009	34130±370	0.477±0.024	−4.32±0.23	Charpinet et al. (2005a)
	5.772	34130±370	0.478	−4.13	Brassard & Fontaine (2008)
PG 1047+003	5.800±0.006	33150±200	0.490±0.014	−3.72±0.11	Charpinet et al. (2003)
PG 1219+534	5.807±0.006	33600±370	0.457±0.012	−4.25±0.15	Charpinet et al. (2005b)
Feige 48	5.437±0.006	29580±370	0.460±0.008	−2.97±0.09	Charpinet et al. (2005c)
	5.462±0.006	29580±370	0.519±0.009	−2.52±0.06	Van Grootel et al. (2008a)
EC 05217−3914	5.730	32000	0.490	−3.00	Billères & Fontaine (2005)
PG 1325+101	5.811±0.004	35050±220	0.499±0.011	−4.18±0.10	Charpinet et al. (2006a)
PG 0048+092	5.711±0.010	33300±1700	0.447±0.027	−4.92±0.20	Charpinet et al. (2006b)
EC 20117−4014	5.856±0.008	34800±2000	0.540±0.040	−4.17±0.08	Randall et al. (2006b)
PG 0911+456	5.777±0.002	31940±220	0.390±0.010	−4.69±0.07	Randall et al. (2007)
BAL 090100001	5.383±0.004	28000±1200	0.432±0.015	−4.89±0.14	Van Grootel et al. (2008b)
PG 1336−018	5.739±0.002	32780±200	0.459±0.005	−4.54±0.07	Charpinet et al. (2008)
PG 1605+072	5.248	32300±300	0.707	−5.78	van Spaandonk et al. (2008)
	5.217	32300±300	0.561	−6.22	
	5.226±0.004	32300±300	0.528±0.002	−5.88±0.04	Van Grootel (2008)
	5.276	32630±600	0.731	−2.83	Van Grootel et al. (2010a)
	5.278	32630±600	0.769	−2.71	
EC 09582−1137	5.788±0.004	34805±230	0.485±0.011	−4.39±0.10	Randall et al. (2009)
KPD 1943+4058	5.520±0.030	27730±270	0.496±0.002	−2.55±0.07	Van Grootel et al. (2010b)
KPD 0629−0016	5.450±0.034	26485±195	0.471±0.002	−2.42±0.07	Van Grootel et al. (2010c)
KIC02697388	5.489±0.033	25395±225	0.463±0.009	−2.30±0.05	Charpinet et al. (2011)
	5.499±0.049	25395±225	0.452±0.012	−2.35±0.05	

15 sdB stars modeled by asteroseismology

(we took the most recent value in case of several analyses)

4. Available samples

II. The extended sample (sdB + WD or dM star)

Name	log g (cm s^{-2})	T_{eff} (K)	M_1 ($M_\odot$)	Nature	Eclipses	References
KPD 0422+5421	5.565±0.009	25000±1500	0.511±0.049	sdB+WD	yes	Orosz & Wade (1999)
PG 1241−084	5.63±0.03	28490±210	0.48±0.09	sdB+dM	yes	Wood & Saffer (1999)
	5.60±0.12	28490±210	0.485±0.013			Lee et al. (2009)
HS 0705+6700	5.40±0.10	28800±900	0.48	sdB+dM	yes	Drechsel et al. (2001)
HS 2333+3927	5.70±0.10	36500±1000	0.38	sdB+dM	no	Heber et al. (2005)
NSVS 14256825	5.50±0.02	35000±5000	0.46	sdB+dM	yes	Wils et al. (2007)
PG 1336−018	5.74±0.05	31300±300	0.389±0.005	sdB+dM	yes	Vuckovic et al. (2007)
	5.77±0.06	31300±300	0.466±0.006			
	5.79±0.07	31300±300	0.530±0.007			
2M 1533+3759	5.57±0.07	29230±125	0.376±0.055	sdB+dM	yes	For et al. (2010)
2M 1938+4603	5.425±0.009	29565±105	0.48±0.03	sdB+dM	yes	Østensen et al. (2010)
KPD 1946+4340	5.452±0.006	34500±400	0.47±0.03	sdB+WD	yes	Bloemen et al. (2011)

Light curve modeling + spectroscopy ⇒ mass of the sdB component

Need uncertainties to build a mass distribution

⇒ 5 sdB stars retained in this subsample

Extended sample: 15+5 = 20 sdB stars with accurate mass estimates

- 11 (apparently) single stars
- 9 in binaries (including 4 pulsators)

I. Assumption of a normal distribution

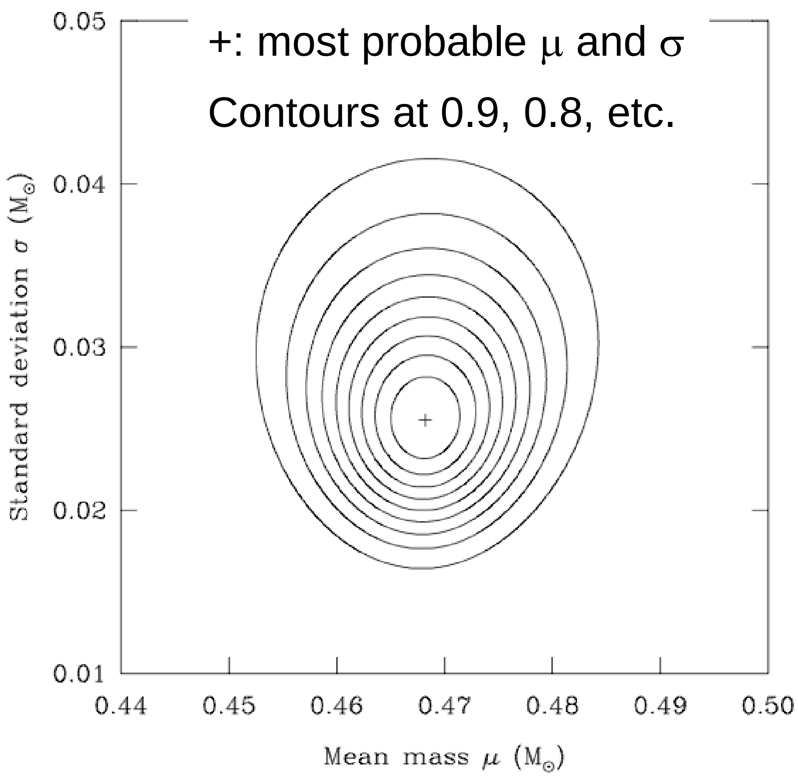
$$L(\mu, \sigma) = \prod_{i=1}^{N} [2\pi(\sigma^2 + \sigma_i^2)]^{-1/2} \exp\{-\frac{(m_i - \mu)^2}{2(\sigma^2 + \sigma_i^2)}\}$$

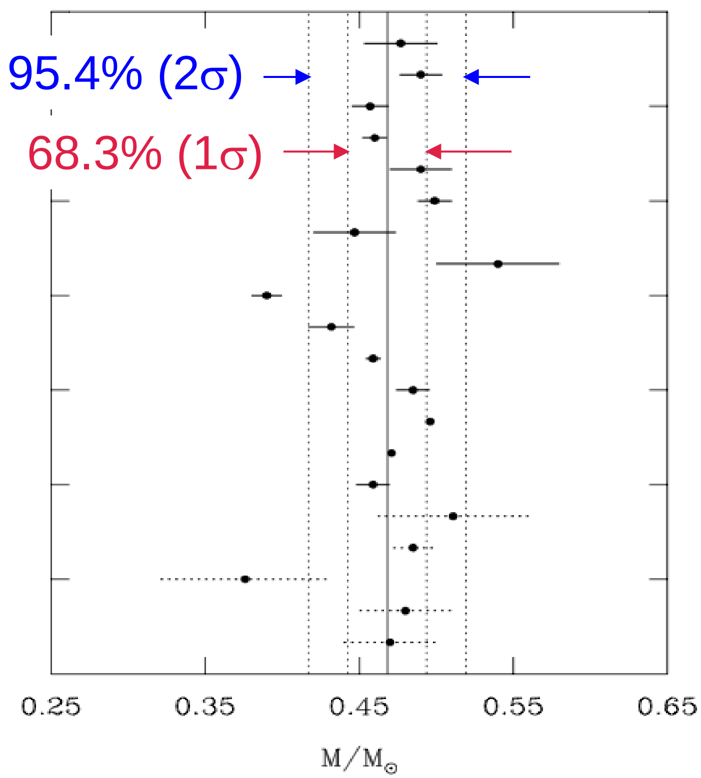
μ: mean mass

σ: standard deviation

Extended sample: $\mu = 0.468$ Ms and $\sigma = 0.026$ Ms

Asteroseismic sample: $\mu = 0.467$ Ms and $\sigma = 0.027$ Ms



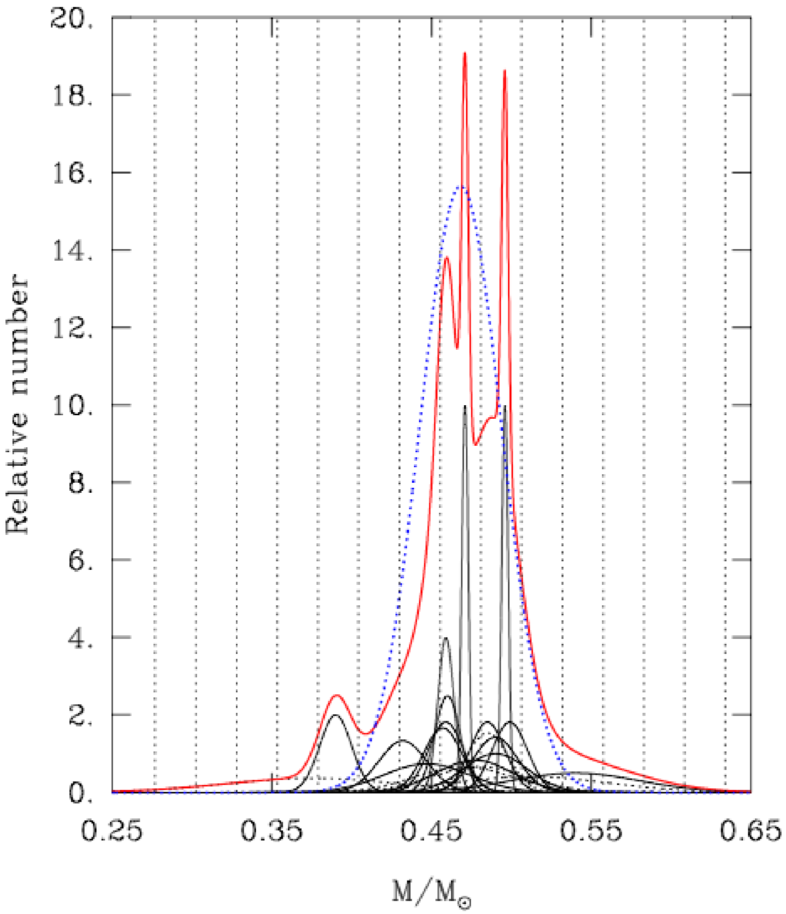


II. Model-free distribution

(only σ_i's are assumed to obey normal distribution law)

Red curve: addition of all sdBs (mass with uncertainties) in extended sample

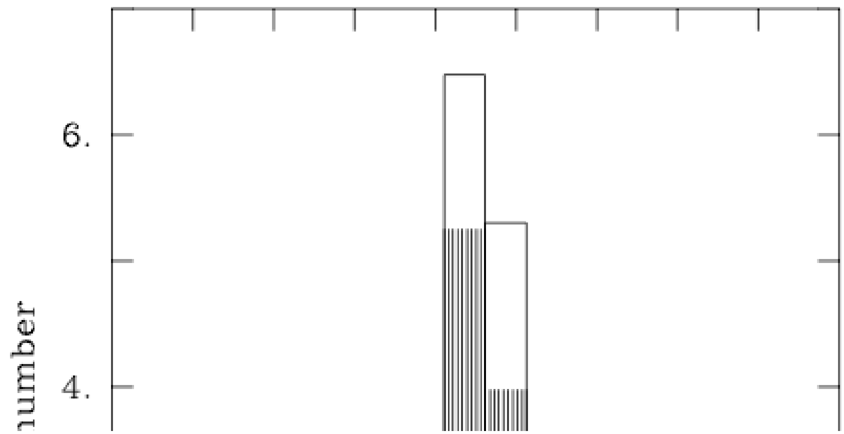
Blue curve: normal distribution ($\mu = 0.468$ Ms and $\sigma = 0.026$ Ms)



5. Mass distributions

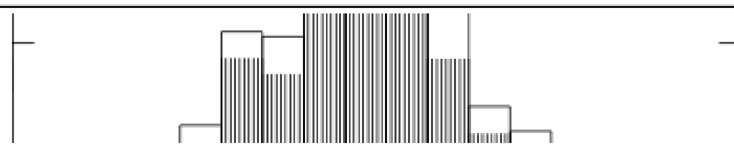
Binning the distribution in the form of an histogram (bin width = σ = 0.026 Ms)

Extended sample:
(white)
Mean mass: 0.469 Ms
Median mass: 0.471 Ms
Range of 68.3% of stars:
0.436-0.501 Ms



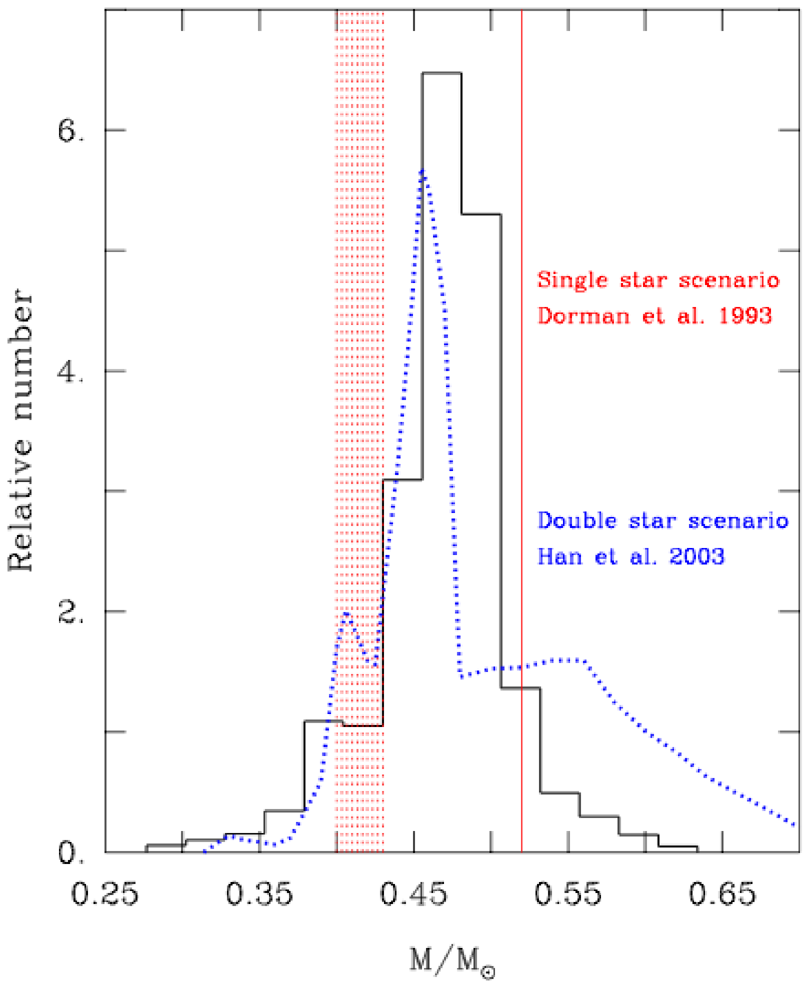
Asteroseismic sample:
(shaded)
Mean mass: 0.470 Ms
Median mass: 0.471 Ms
Range of 68.3% of stars:
0.441-0.499 Ms

Sample	Mean mass ($M_\odot$)	Median mass ($M_\odot$)	Range of mass (68.3%; $M_\odot$)
extended (20 stars)	0.469	0.471	0.436–0.501
15 pulsators	0.470	0.471	0.441–0.499
5 binaries (orbits)	0.464	0.476	0.411–0.510
9 binaries (total)	0.470	0.466	0.435–0.515
11 singles	0.468	0.473	0.437–0.498



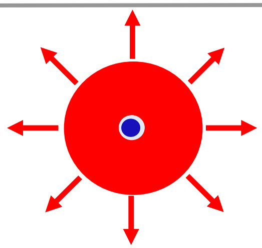
No detectable significant differences between distributions
(especially between singles and binaries)

6. Comparison with theoretical distributions



Empirical distribution agrees well with expectations of stellar evolution theory...but still small-number statistics !

2. Single and binary formation scenarios

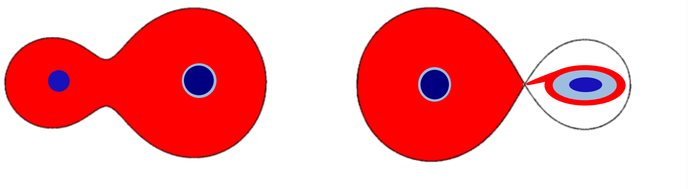


- Single star evolution (enhanced mass loss at tip of RGB)

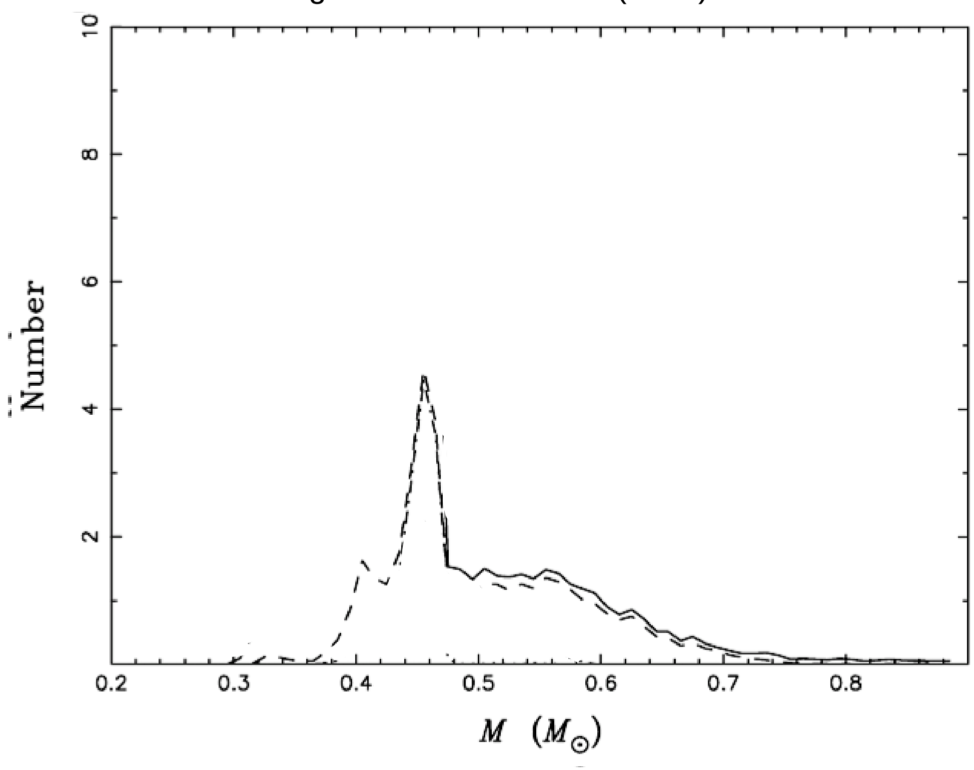
  Mass range in 0.40 - 0.43 ≤ M_*/Ms ≤ 0.52 (Dorman et al. 1993)

- Binary star evolution (Han et al. 2002, 2003)

  Common envelope ejection (CE), stable mass transfer by Roche lobe overflow (RLOF), and He-white dwarf mergers



Figures from Han et al. (2003)



Weighted mean distribution for binary evolution:

(including selection effects)

0.30 ≤ M_*/Ms ≤ 0.70

peak ~ 0.46 Ms (CE, RLOF)

high masses (mergers)

Conclusions and room for improvement

✓ No significant differences between distributions of various samples (asteroseismic, light curve modeling, single, binaries, etc.)

✓ Single star evolution scenario does exist

✓ Importance of the merger scenario ? (single stars with fast rotation)

✓Our empirical mass distribution agrees well with theoretical expectations...

But:

✓ Currently only 20 objects: 11 (apparently) single stars and 9 binaries

✓ Among $>$ 2000 known sdB, ~100 pulsators are now known (e.g. thanks to *Kepler*)

✓ Both light curve modeling and asteroseismology are a challenge (accurate spectroscopic and photometric observations, stellar models, etc.)