Tópicos

Close binary stars

Mónica Zorotovic

Lecture 3

18/08

Parameter distribution for binaries

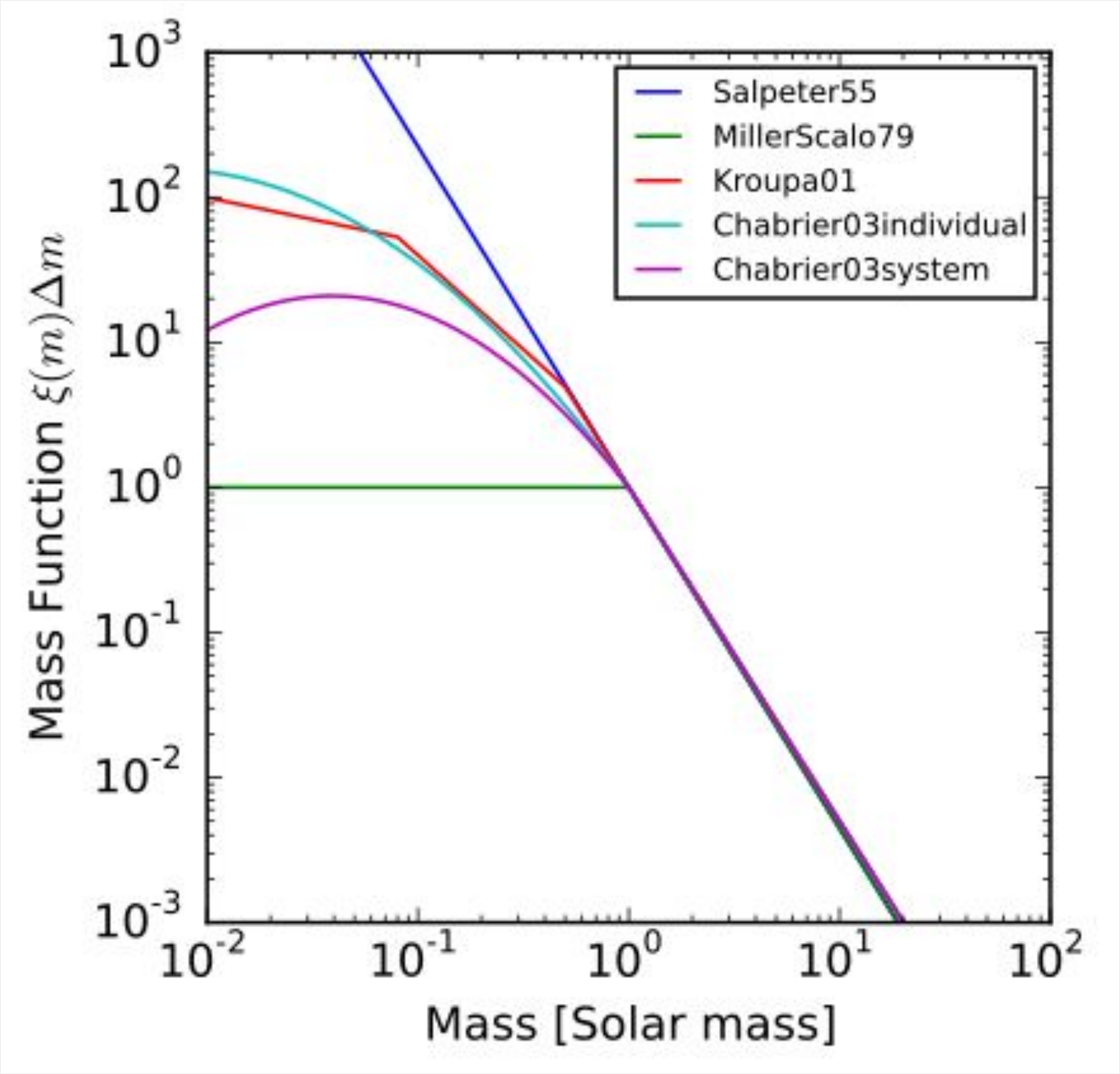
Parameter distribution for binaries

How many binaries have a given
– Primary mass M_1
– Secondary mass M_2 (or mass ratio q)
– Orbital period P (or separation a)
– Eccentricity e

Very important for statistical comparisons between models and observational data.

Also give us clues on the binary formation channels.

Primary Mass M1: IMF



Mass ratio

Widely discrepant conclusions (difficult detection of low-mass companions).

It has been proposed that the mass ratio distribution of solar-type binaries is:

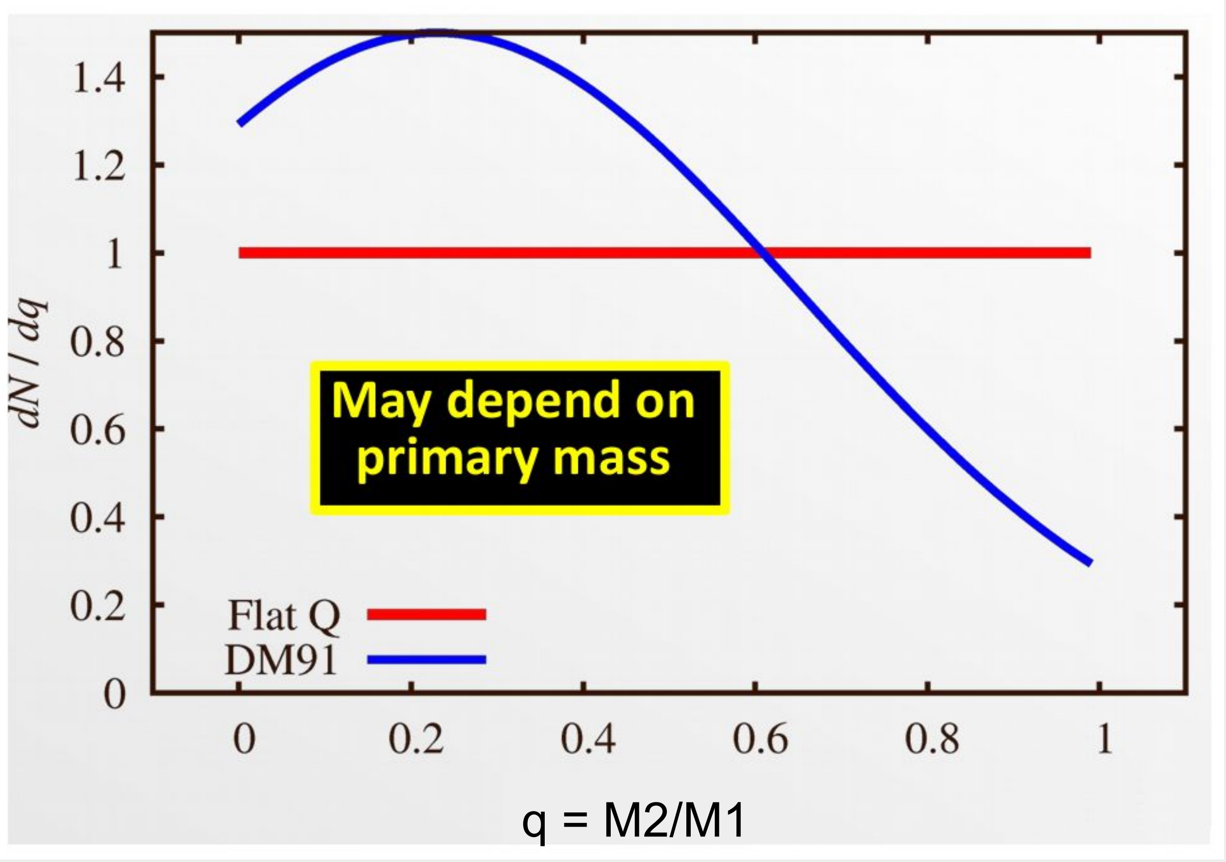
- flat
- single peaked
- bimodal
- monotonically decreasing with q (i.e. $f(q) \propto q^x$ with $x<0$)
- increasing with q (i.e. $f(q) \propto q^x$ with $x>0$)
- …

?

Mass ratio

Example:
Duquennoy & Mayor (1991), solar type primaries

Single peak around q ~ 0.3

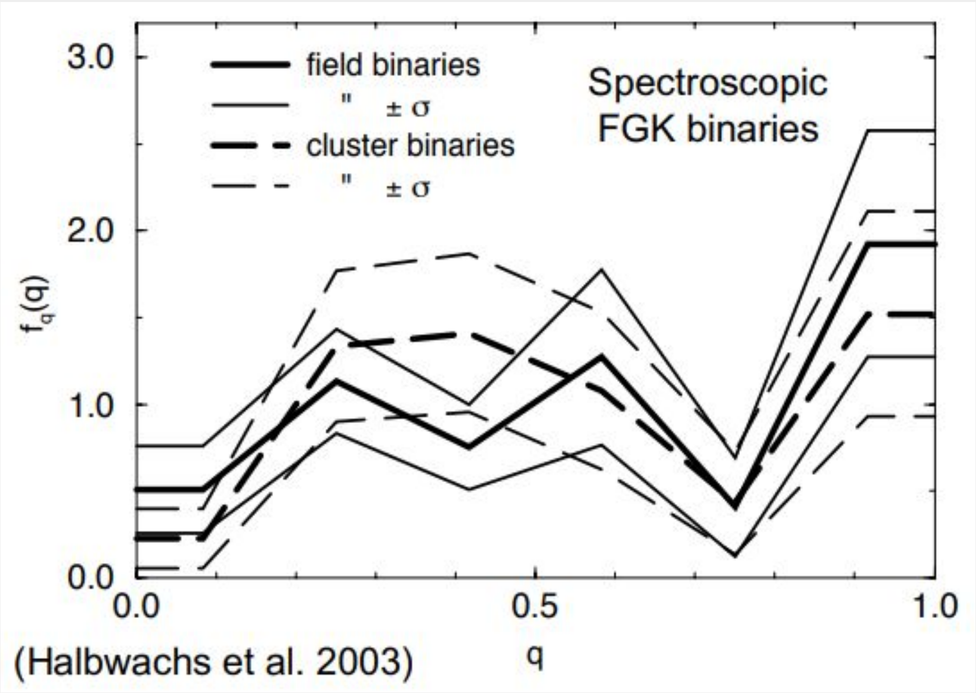


Mass ratio

Example
Hallwachs et al (2003), FGK primaries

2 power laws + peak at q ~ 1

A single-component power-law model $f(q) \propto q^x$ does NOT adequately describe the data.



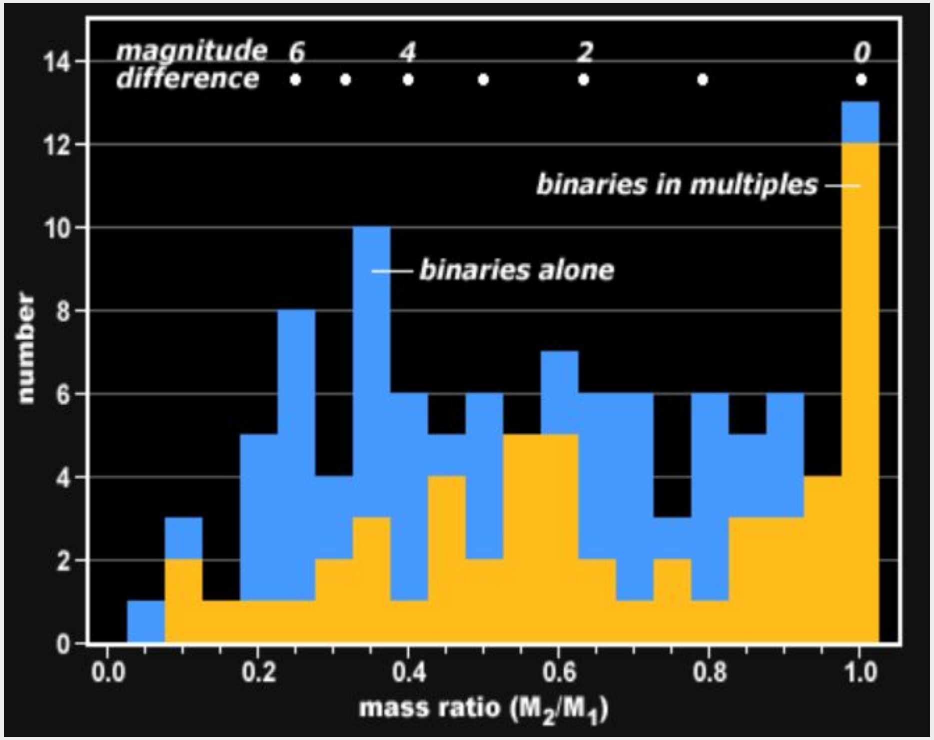
power-law slope across q = 0.1 - 0.3
power-law slope across q = 0.3 - 1.0
excess fraction of twins with q ≈ 1.0

Mass ratio

Example
Raghavan et al. (2010), solar type

Flat down to $q \sim 0.1$-0.2 with a marginally significant peak at $q \gtrsim 0.95$.

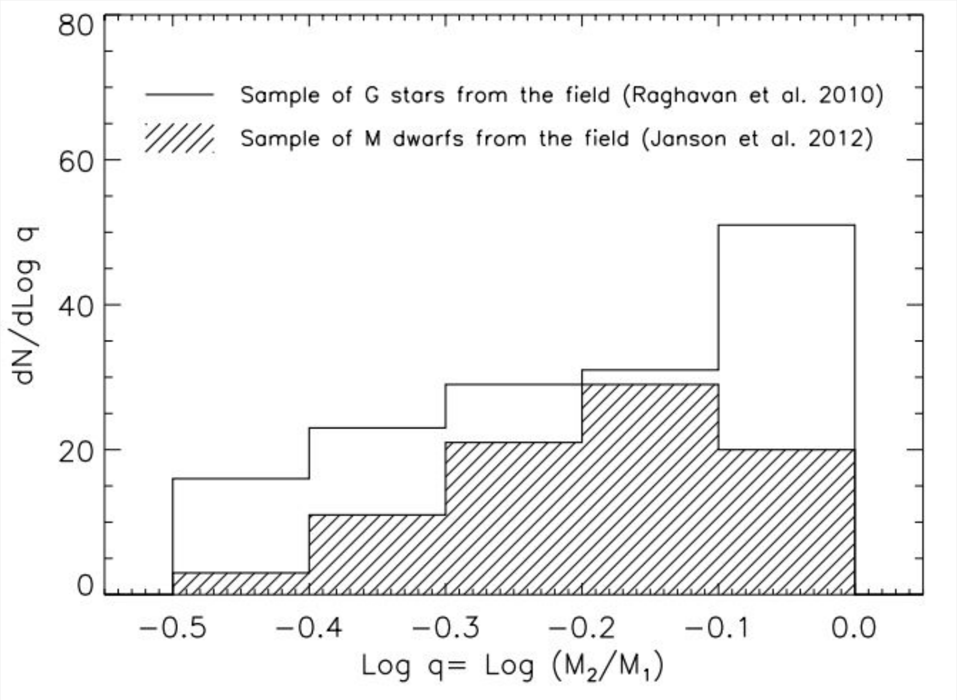
Divided the sample distinguishing binaries that are known to have at least a third companion: 3 features

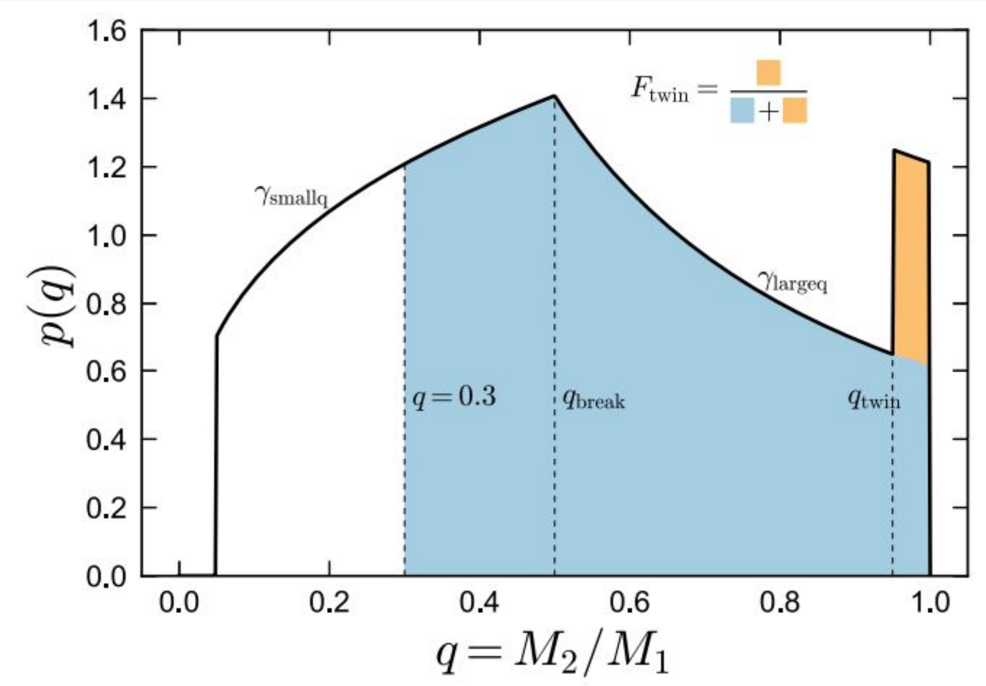


- The spike at $q \sim 1$ (two equal mass stars) comes especially from binary stars that are components of multiple systems.
- Broad flat distribution that may have a secondary peak at $q \sim 0.3$-0.4 (more apparent in isolated binary systems) as noted by DM91.
- Lack of systems with $q \lesssim 0.2$ (Brown dwarf desert?)

Mass ratio

More recent examples





Reggiani & Meyer (2013):

Cummulative distribution for solar-type (G) and M-dwarf primaries in the field.

Less twins in M-dwarf

El-Badry et al. (2019):

42 000 MS wide binaries from Gaia with
$50 < a/AU < 50000$
$0.1 M_\odot < M_1 < 2.5\ M_\odot$

peak at q ~ 0.5
Large incidence of twins (q=1)

Summary: mass ratio not clear!

Different surveys produce different q distributions.

One remarkable feature of the mass ratio distribution for solar-type binaries is the dearth of substellar companions, the so-called “**BD desert**”.
Is it real?

Theoretical computer simulations of star formation predict there should be a large number of systems with $q \lesssim 0.2$ and few that actually reach $q = 1.0$.

Is this an observational bias?

- Low mass (K - M) stars and BDs are faint and difficult to detect.
- Twin binaries are the easiest to discover

Summary: mass ratio not clear!

Current evidence shows that the mass ratio distribution differs significantly between short- and long-period binaries.

Short-period binaries (members of triple systems??):

- slowly declining $f(q)$ function towards high q (i.e. $f(q) \propto q^x$ with $x<0$)
- But strong peak at $q \approx 1$

Long-period (isolated) binaries:

- single peak around $q \approx 0.3$ (similar to DM91)

Multiplicity Statistics: Diagnostics for Binary Star Formation

(Abt+ 90; Kroupa 95a,b; Bate+ 95,02; Tokovinin 00,06; Tohline 02; Goodwin & Kroupa 05; Sana+ 12; Kratter+ 06,10; Raghavan+ 10; Offner+ 12; Duchene & Krause 13; Tobin+ 16a,b; **Moe & Di Stefano 17**

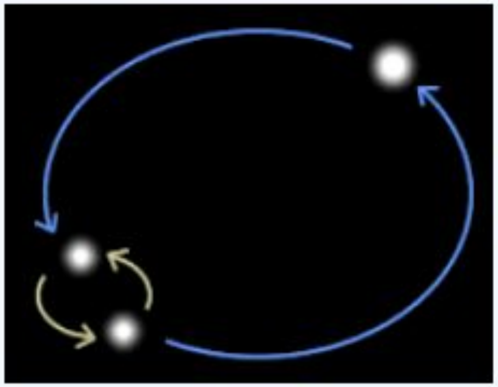
Wide Companions:
log P (days) = 5 - 9;
a = 100 - 30,000 AU;
Core Fragmentation

- f_{wide} = 0.5, initially independent of M_1
- f(q) initially consistent with random pairings drawn from IMF
- Subsequent dynamical ejections: systems with smaller M_1 and q are preferentially disrupted by ZAMS

Intermediate-Period Companions:
log P (days) = 1 - 5;
a = 0.1 - 100 AU;
Disk Fragmentation

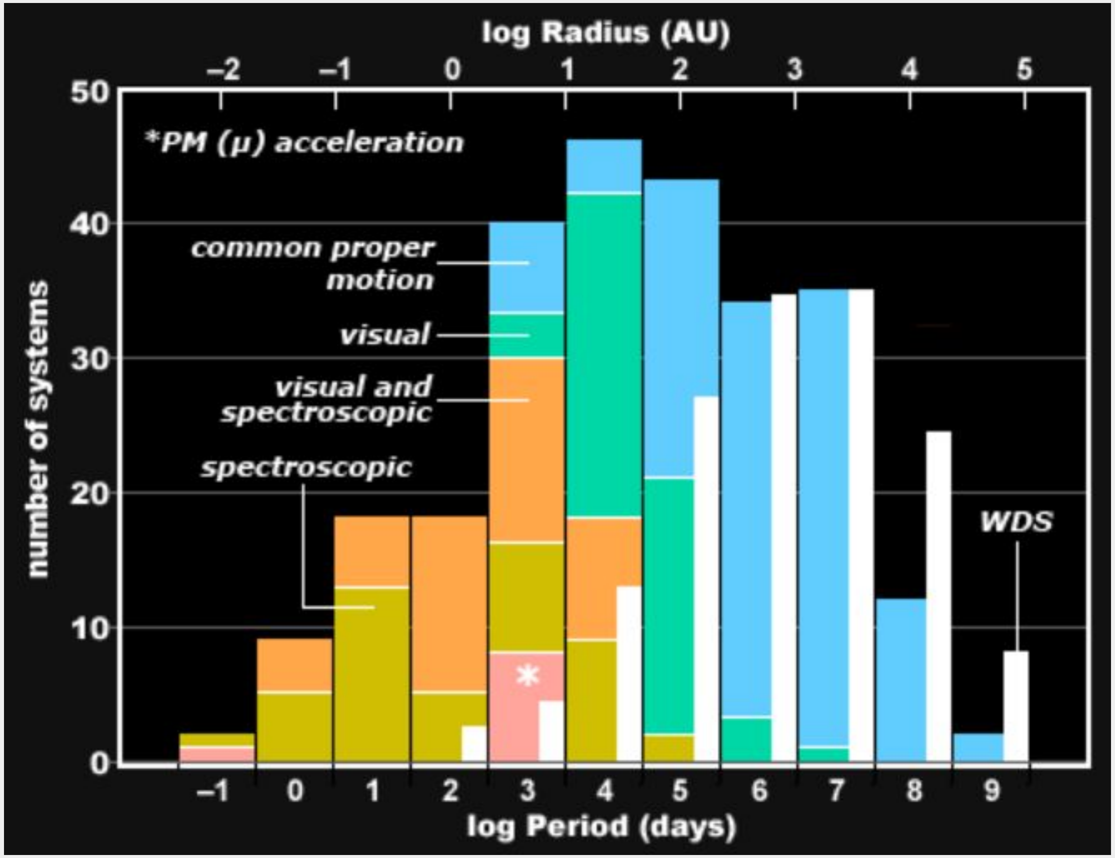
- f_{mid} = 0.4 (M_1 = 1$M_\odot$) - 1.5 (30$M_\odot$)
- f(q) correlated due to co-evolution / shared accretion in the disk
- M_1 = 1$M_\odot$: uniform f(q)
- M_1 > 5$M_\odot$: weighted toward q = 0.2

Very Close Binaries
log P (days) < 1;
a < 0.1 AU;
Dynamical Hardening in Triples during Pre-MS



- f_{close} = 0.02 (M_1 = 1$M_\odot$) - 0.2 (30$M_\odot$)
- Most have outer tertiaries
- Uniform f(q) with excess twin fraction

Orbital Period: different techniques needed

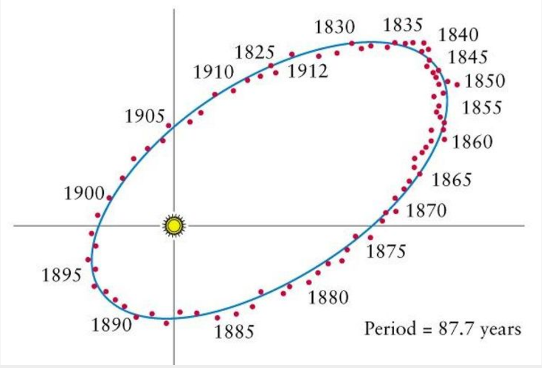


Systems which have orbits smaller than the orbit of Saturn predominantly identified by:

- spectroscopy (doppler → RV)
- interferometric imaging
- astrometry (wobble in proper motion)

Systems with logP[d] $\gtrsim$ 6 (~3000 yr, a $\gtrsim$ 250 AU) are almost entirely identified by common proper motion.

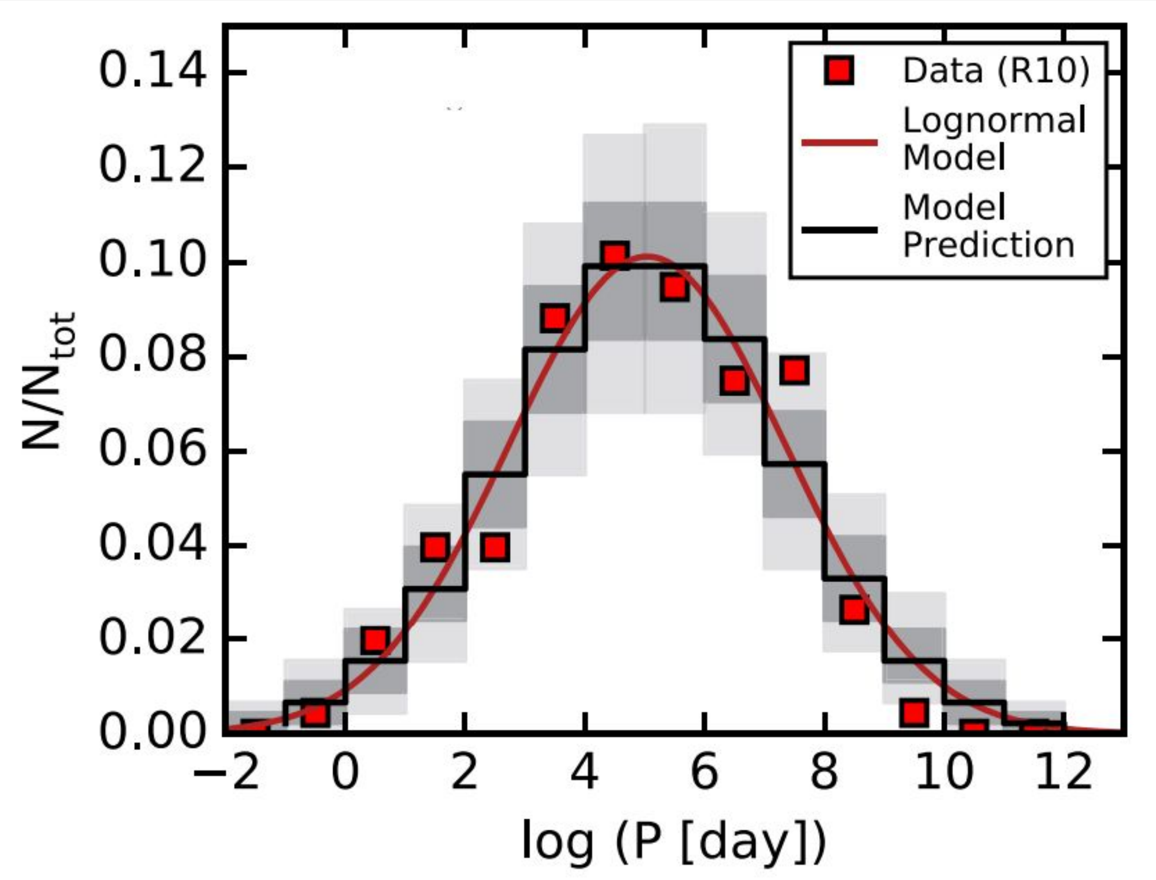
Systems with logP[d] ~ 4.0 to 4.9 comprise the largest number of double stars that can be resolved by visual observations.
Larger periods need longer baseline (only ~200 years of binary studies)



Orbital Period: log normal

A distribution normal in logP was first proposed by Gerard Kuiper in 1935

Most reliable multiplicity surveys: orbital periods form a "bell shaped" distribution on log period (log normal), currently believed to best represent the distribution of binary orbits.



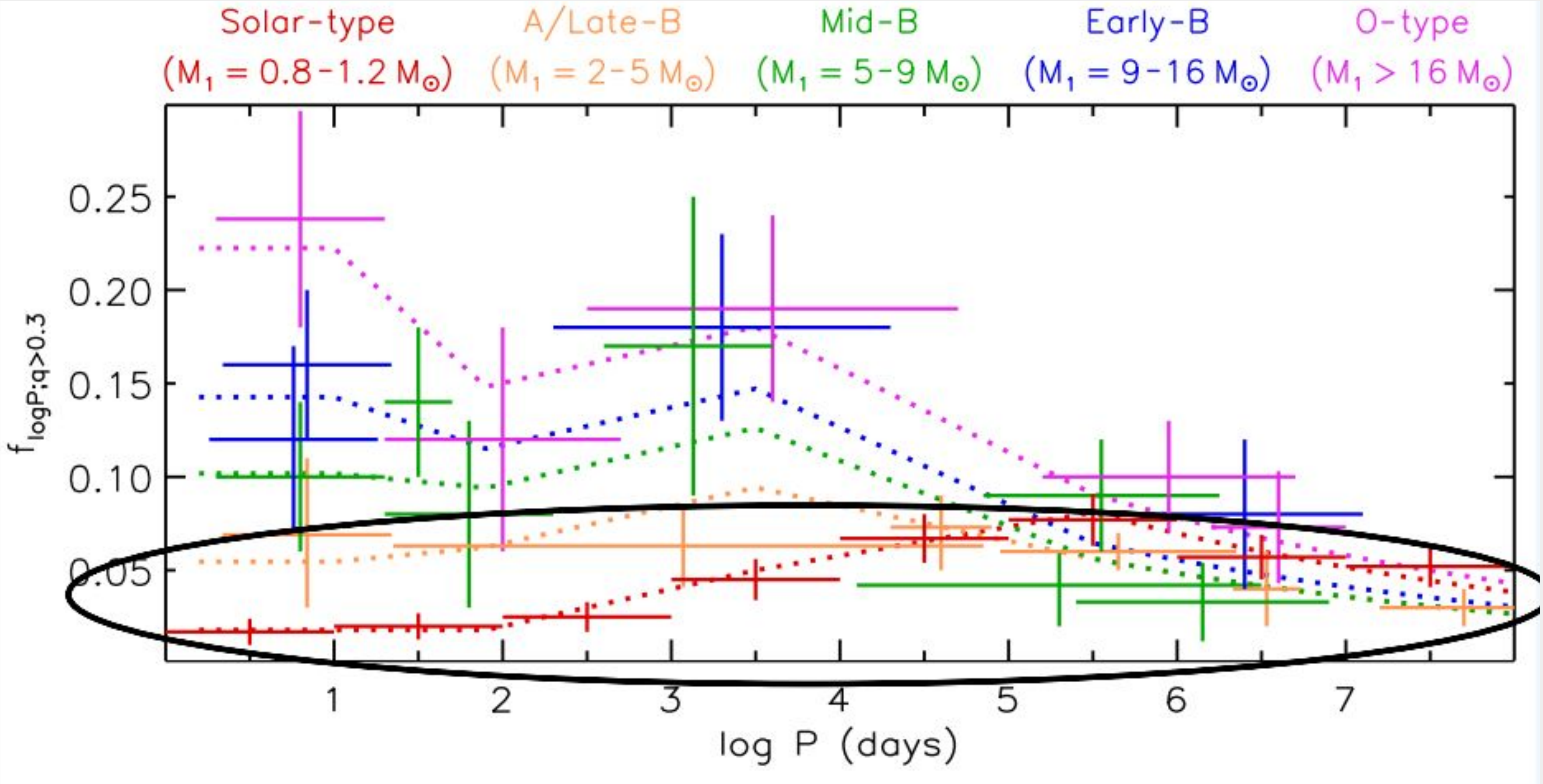
Period distribution for the Sun-like MS stars in Raghavan et al. 2010 (R10, red squares): log normal distribution with median P~260 years (logP[d] ~ 4.98)

Black: distribution predicted by simulations with the log normal model with the median from R10, based on the observations (red).

DM91: was similar, but with median P~180 years (logP[d] ~ 4.82)

Dependence of P on M_1

Moe & Di Stefano (2017) for binaries with q>03

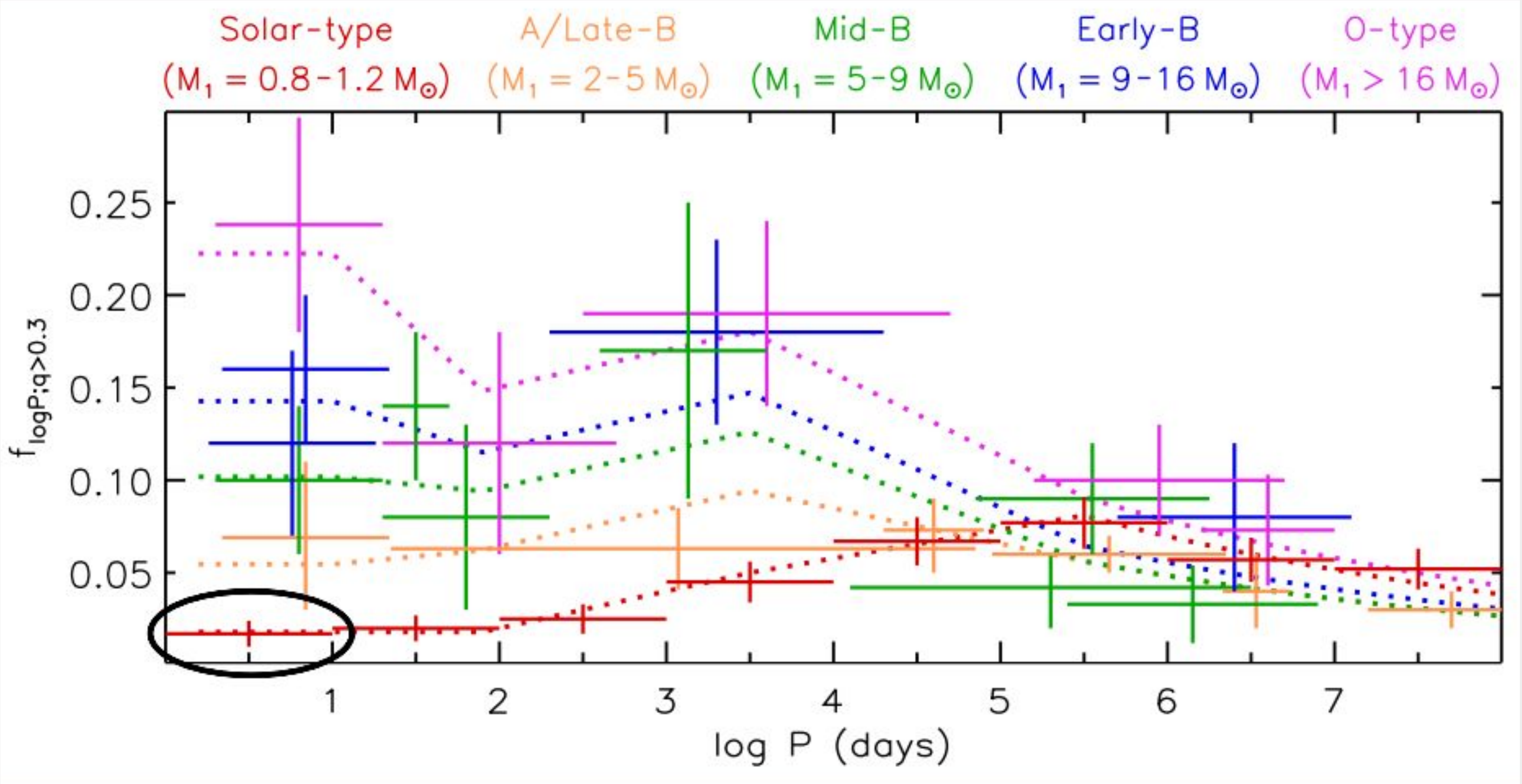


Companions to solar-type MS stars: log-normal period distribution as found by Duquennoy & Mayor (1991) and Raghavan et al. (2010)

but peak at larger logP (5-6)

Dependence of P on M_1

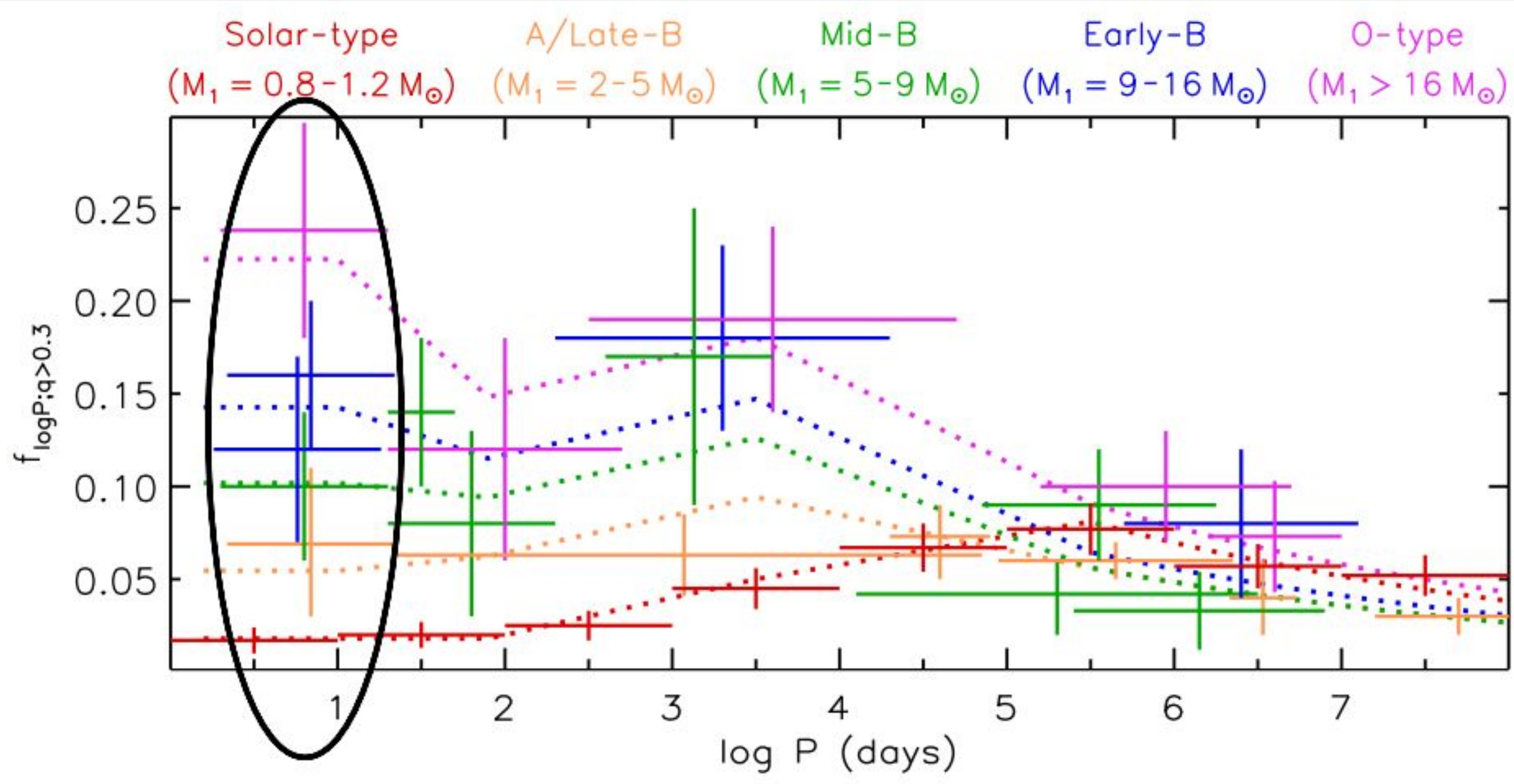
Moe & Di Stefano (2017) for binaries with q>03



~2% of solar-type MS primaries have companions with q > 0.3 and P = 1 - 10 days.

Dependence of P on M_1

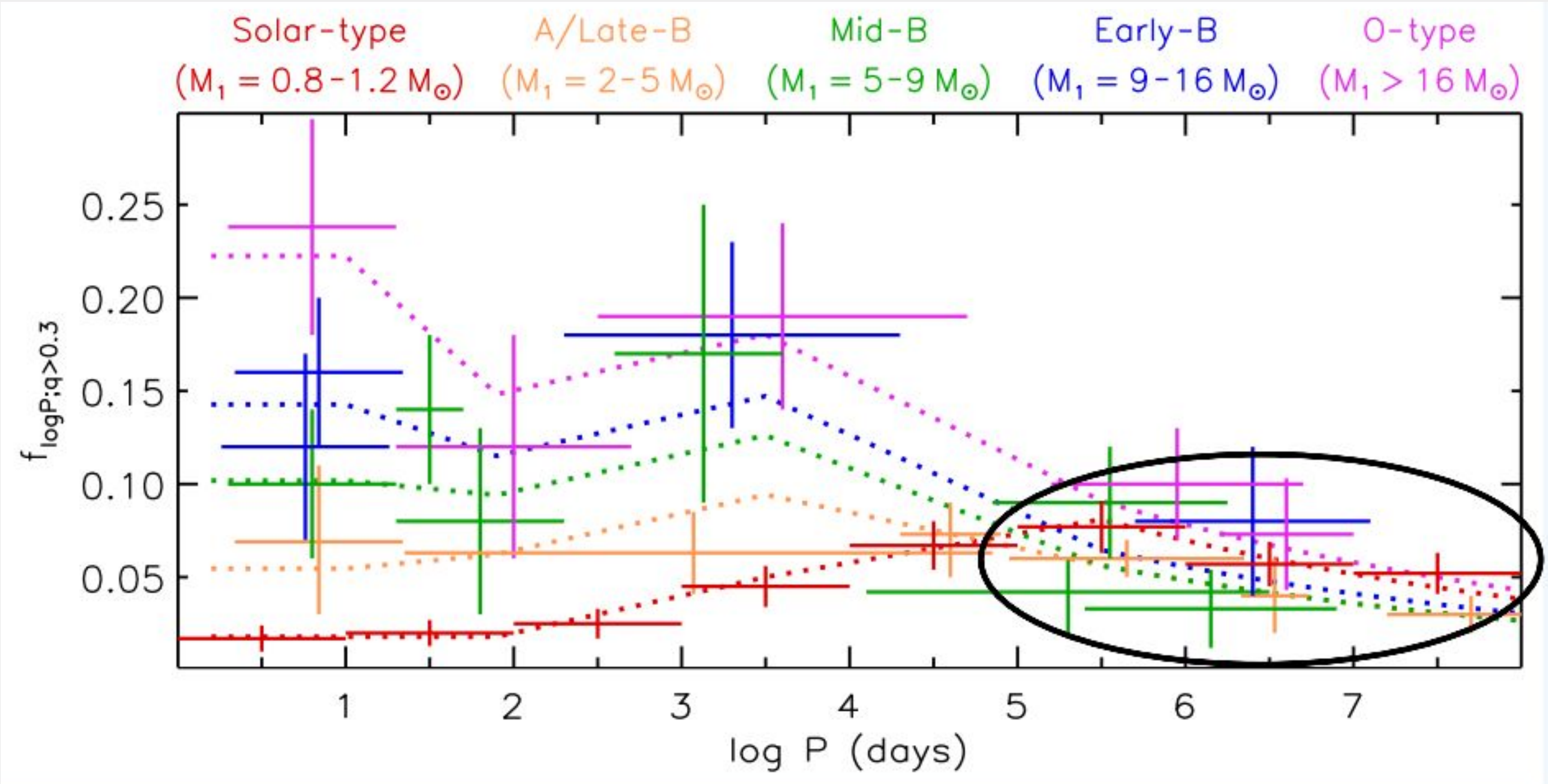
Moe & Di Stefano (2017) for binaries with q>03



Very close binary fraction increases dramatically with M_1
(Abt et al. 1990; Sana et al. 2012; Chini et al. 2012; Kobulnicky et al. 2014)

Dependence of P on M_1

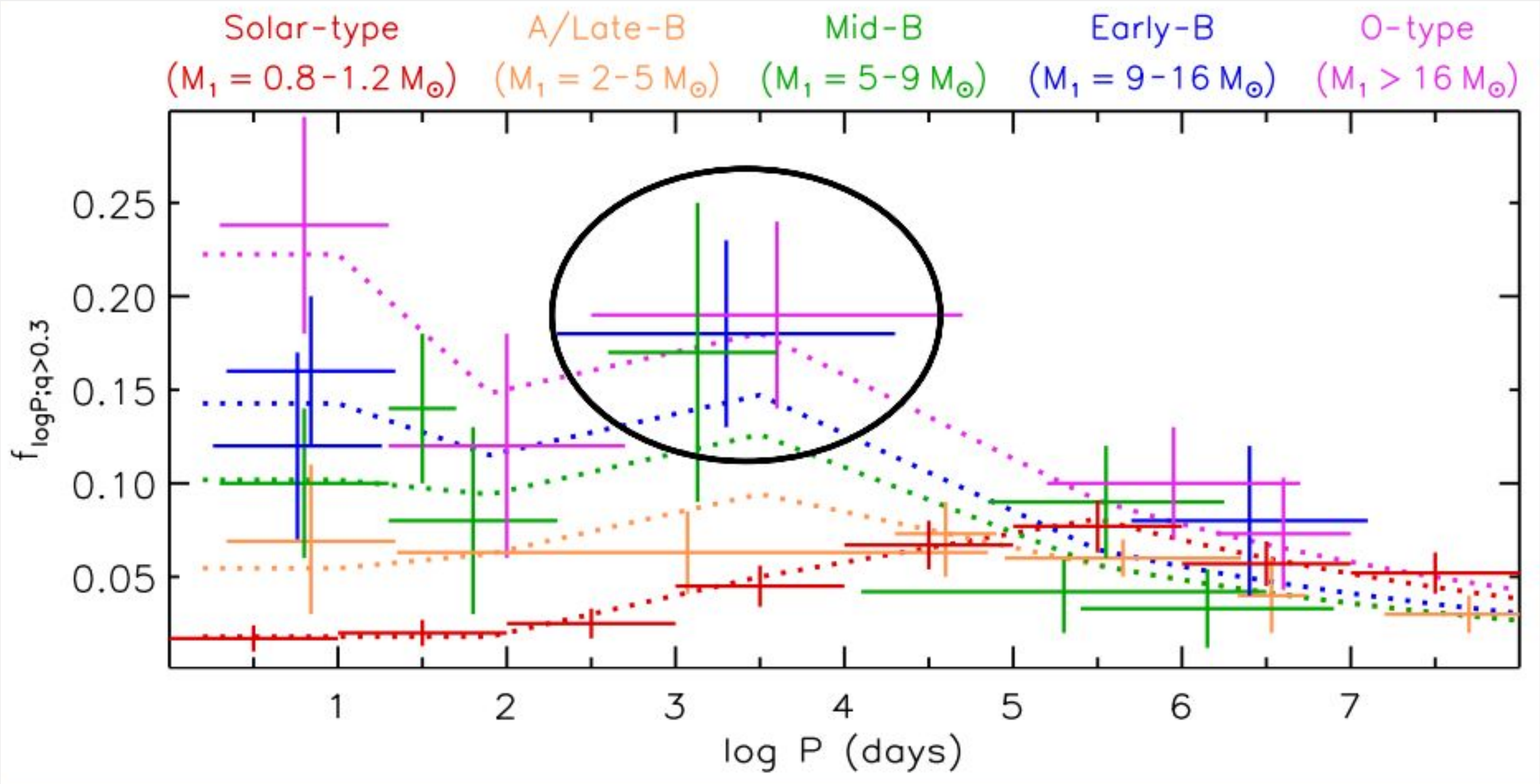
Moe & Di Stefano (2017) for binaries with q>03



Frequency of wide companions with q > 0.3 relatively independent of M_1, consistent with theories of core fragmentation (Goodwin & Kroupa 2005; Offner et al. 2012; Thies et al. 2015)

Dependence of P on M_1

Moe & Di Stefano (2017) for binaries with q>03



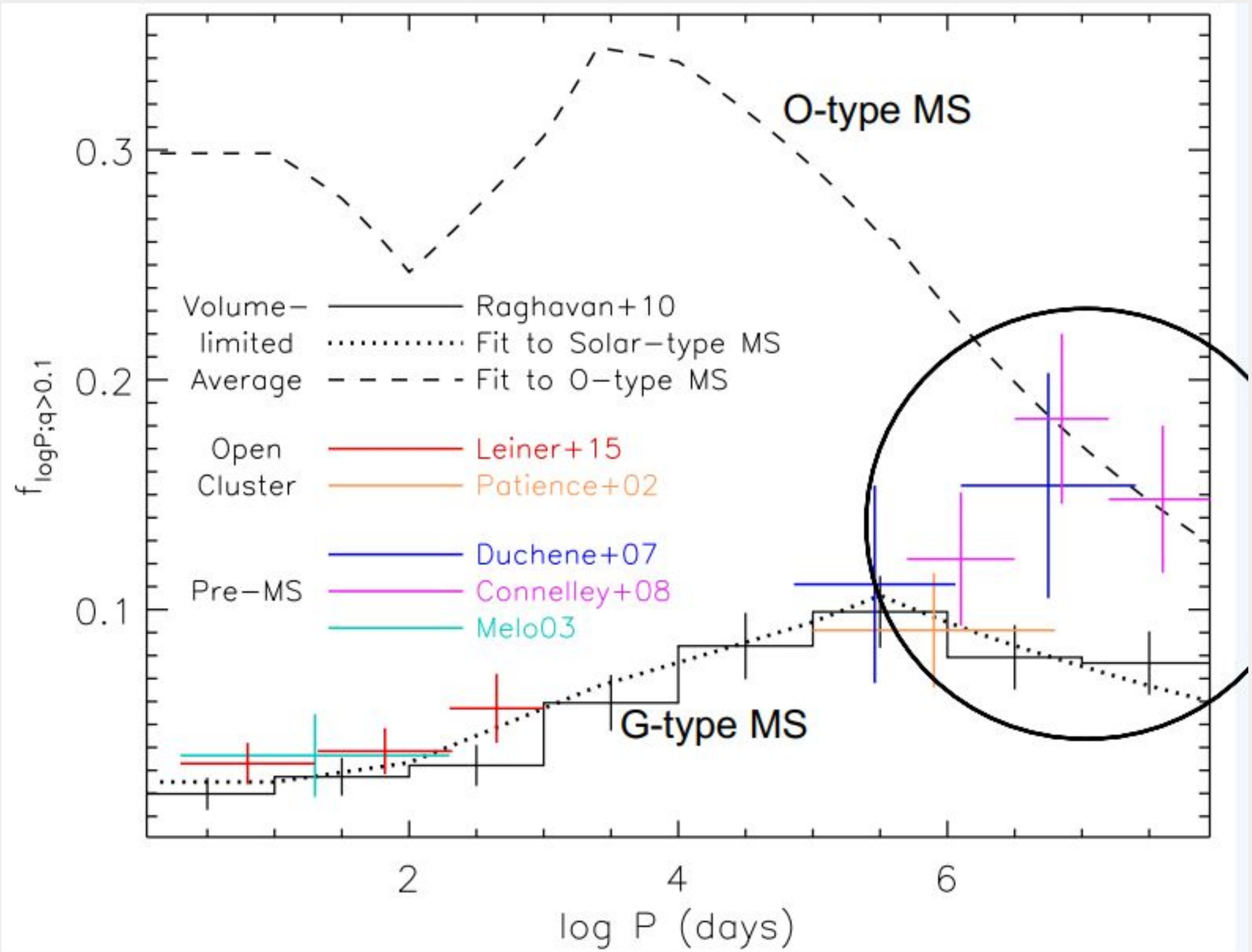
Early-type MS stars also have a large companion frequency at intermediate P;
Rizzuto+2013, LBI, early-B; Sana+2014, LBI, O-type; Evans+2015, SB2s, Cepheids

Disks around massive protostars are more prone to fragmentation

(Kratter et al. 2006, 2011)

Dependence of P on age

When pre-MS stars are included:

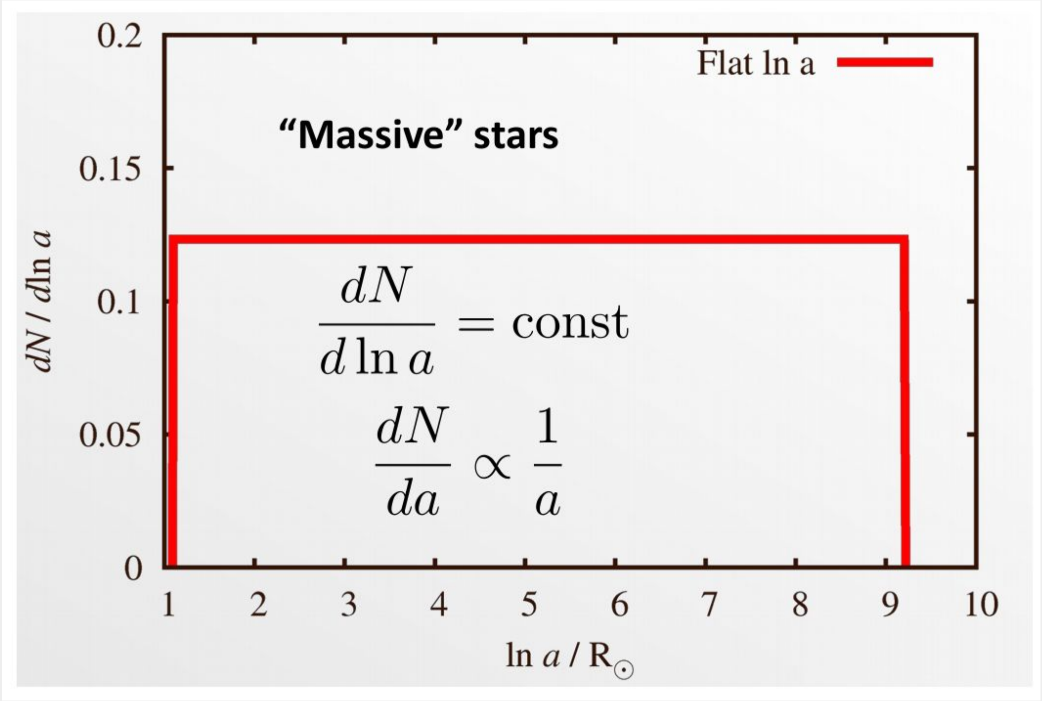


Systems with q>0.1

Frequency of wide companions (a > 100 AU) to so solar-type pre-MS primaries is 2 - 3 times larger than that measured for solar-type MS stars, and consistent with that measured for O-type MS primaries.
(Duchene+07, Connelley+08)

Suggests that the wider binaries are almost equally likely to form, regardless of primary mass, but do not remain bound for long if M1 is small

Initial Orbital Separation: flat in ln(a)?



Opik’s law

$$dn \propto d\log a = \frac{da}{a}$$

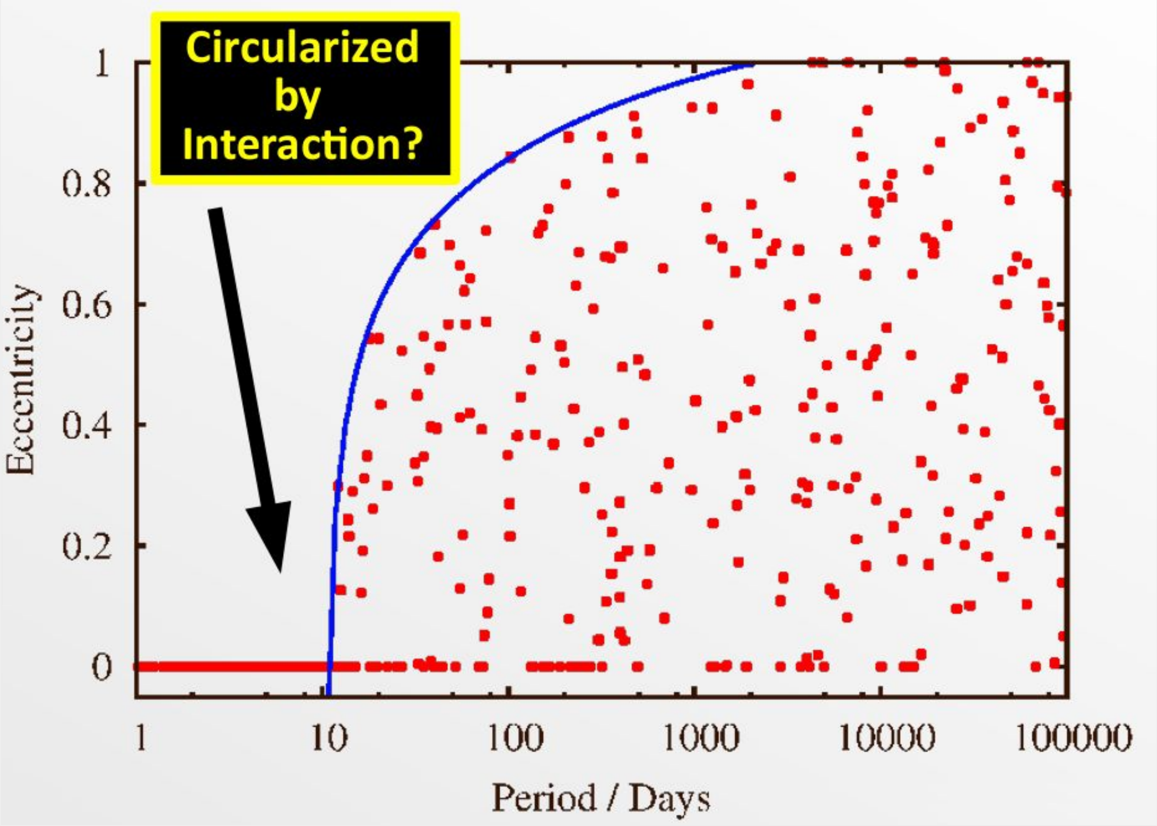
The initial orbital separation is usually assumed to be flat in ln(a)
(e.g., Opik 1924, Popova, Tutukov & Yungelson 1982).

But it is also not clear:
- For a $\lesssim 3\times10^3$ AU, the distribution of separations of binaries in the disc is approximated well by Opik’s law.
- At larger separations, the number of binaries falls more steeply, roughly as $dn \propto da/a^{1.6}$ for 3×10^3 AU $\lesssim a \lesssim 10^5$ AU (Lepine & Bongiorno 2007)

Eccentricity

J. H. Jeans (1919) predicted no correlation between period and eccentricity, and that e would be distributed according to the law: 2ede, i.e. all values of e^2 would be equally likely (called a **thermal distribution**).

BUT, Jeans compared with samples and found e is not thermallized.

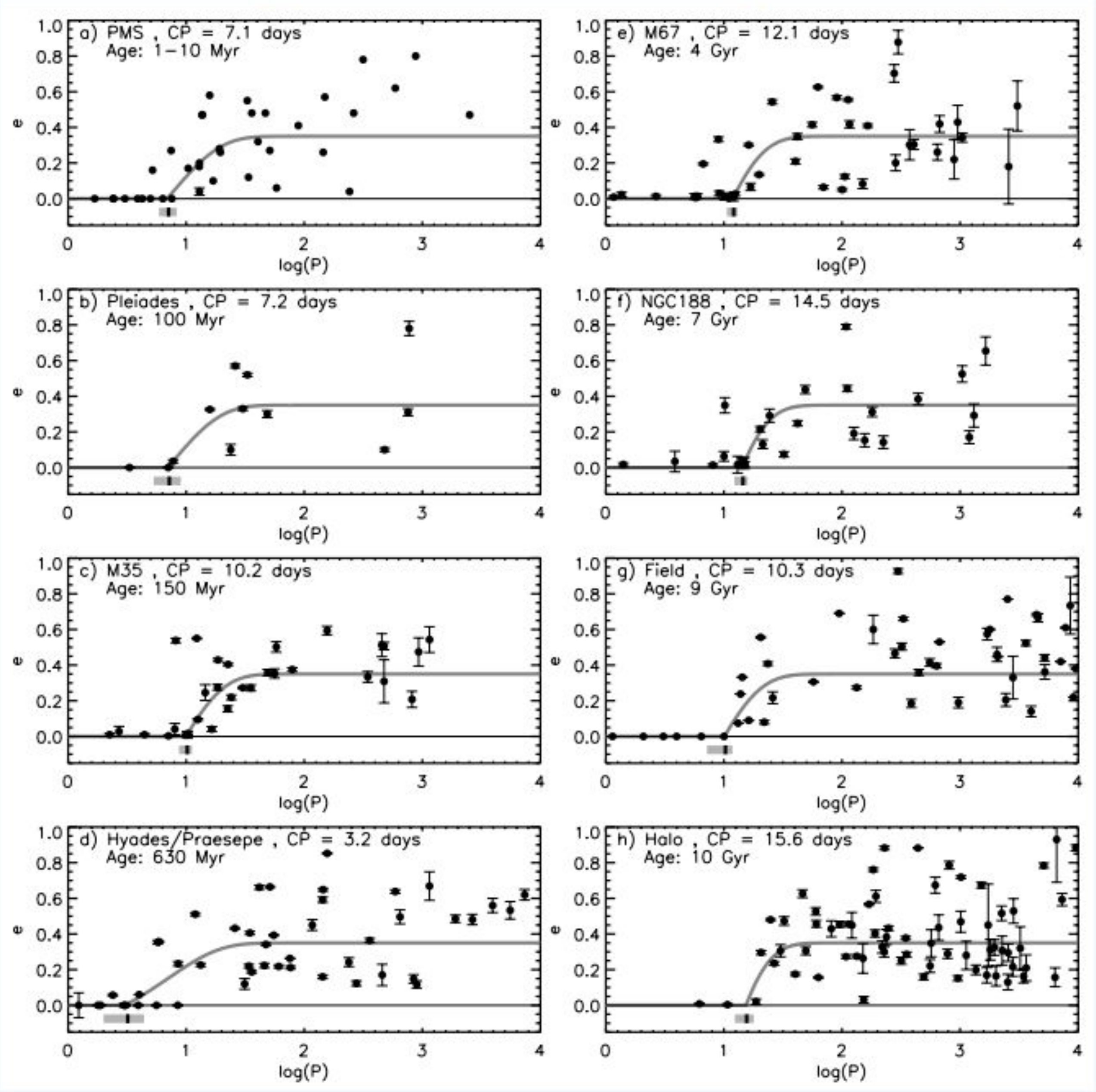


Modern samples confirm Jeans's original observation that binaries in the field do not appear to be thermalized, but the prediction of no correlation between e and P seems to be true, except for very short period binaries (get circularized).

Blue line from DM91 (maximum eccentricity without filling Roche lobe).
Fast circularization of orbits with P $\lesssim$ 12 d (circularization period)

Eccentricity

Solar-type binaries (Meibom & Mathieu 2005)

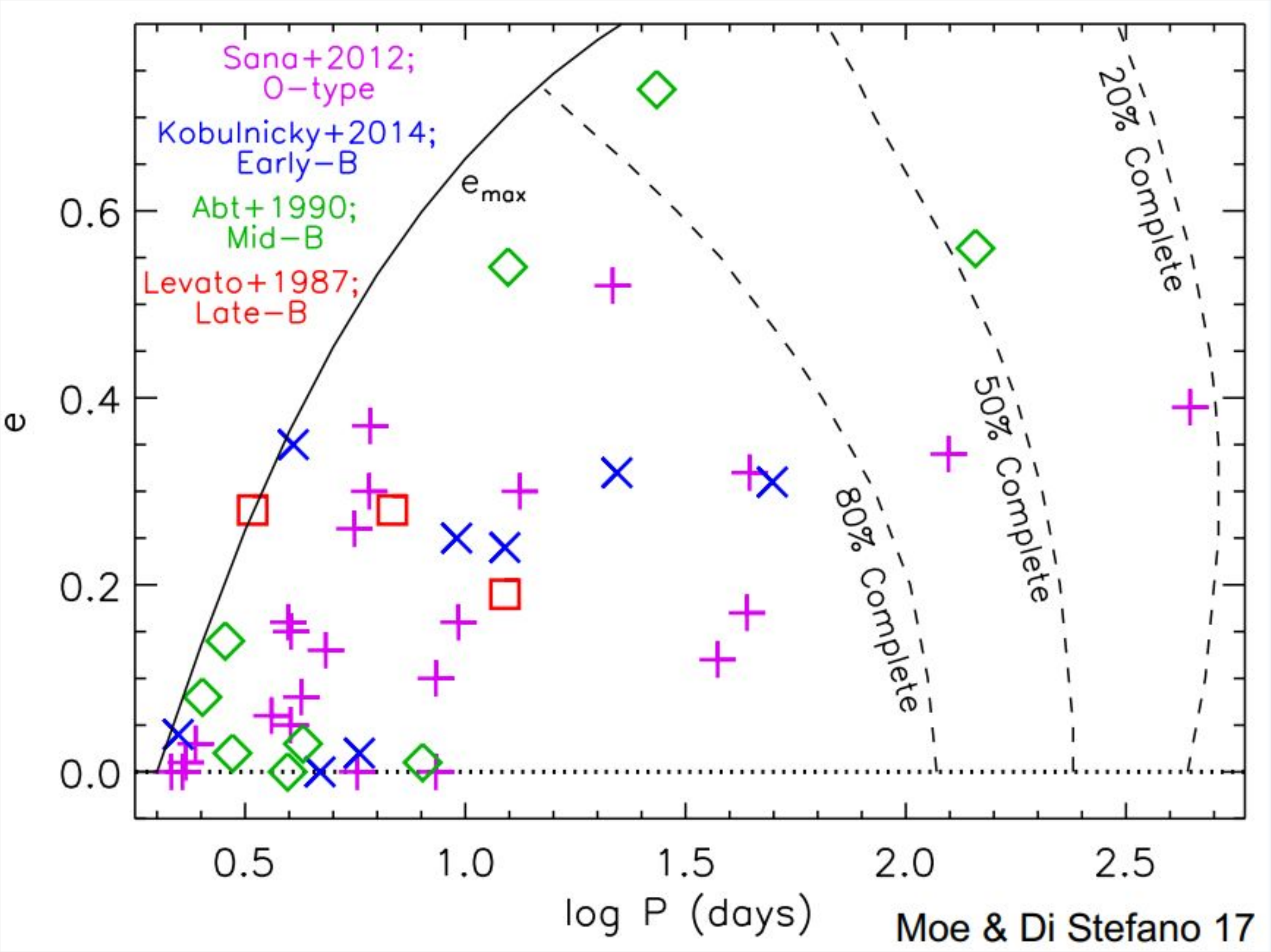


Tidal circularization period increases from P_{circ} = 6 days (pre-MS) to P_{circ} = 15 days (halo)

Beyond P > 100 days, $f_e \propto e^{\eta}$ with $\eta = 0.4$

Eccentricity
Massive stars

Circularization less efficient in massive stars (tides less efficient).



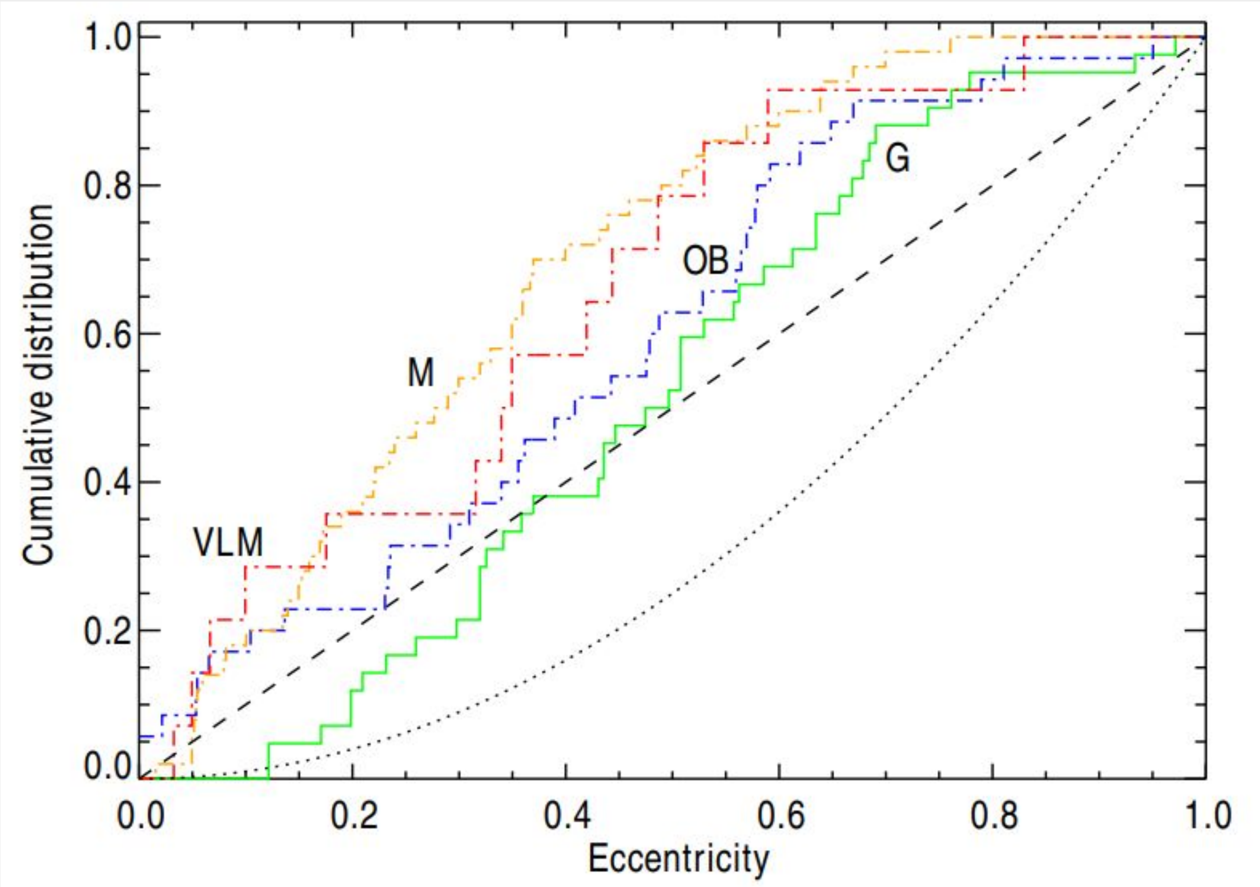
O and B stars:

P_{circ} = 2 days

For P > 20 d, early type binaries are consistent with a thermal distribution, indicating dynamical interactions play a role in their formation.

Eccentricity
Flat v/s thermal

Duchêne & Kraus 2013: Cumulative distribution of eccentricities for field multiple systems with $2 \leq \log P \leq 4$ among:



Solar-type (G) stars
(Raghavan et al. 2010),

Low-mass (M) stars
(Pourbaix et al. 2004)

Very low-mass stars and BDs
(Dupuy & Liu 2011)

High-mass stars (OB)
(Abt 2005, Sana et al. 2012a).

The dot-dashed curves (all samples except solar type) indicate incomplete samples (i.e. potentially biased).
Black dashed/dotted curves: expected for flat/thermal distribution.

Evolutionary effects

Binary evolution affects your multiplicity statistics (Moe & Di Stefano 2017)

For a volume-limited sample:

30% ± 10% of massive stars are the products of binary evolution (de Mink+ 2014)
mass transfer and mergers

20% ± 10% of early-type "primaries" are actually the secondaries in which the true primaries have already evolved into compact remnants

11% ± 4% of solar-type "primaries" have WD companions

30% ± 10% of SB1s contain compact remnant companions

SB1 = spectroscopic binaries where only 1 star is clearly detected

Next: Classification of binary stars

(Based on observational techniques)