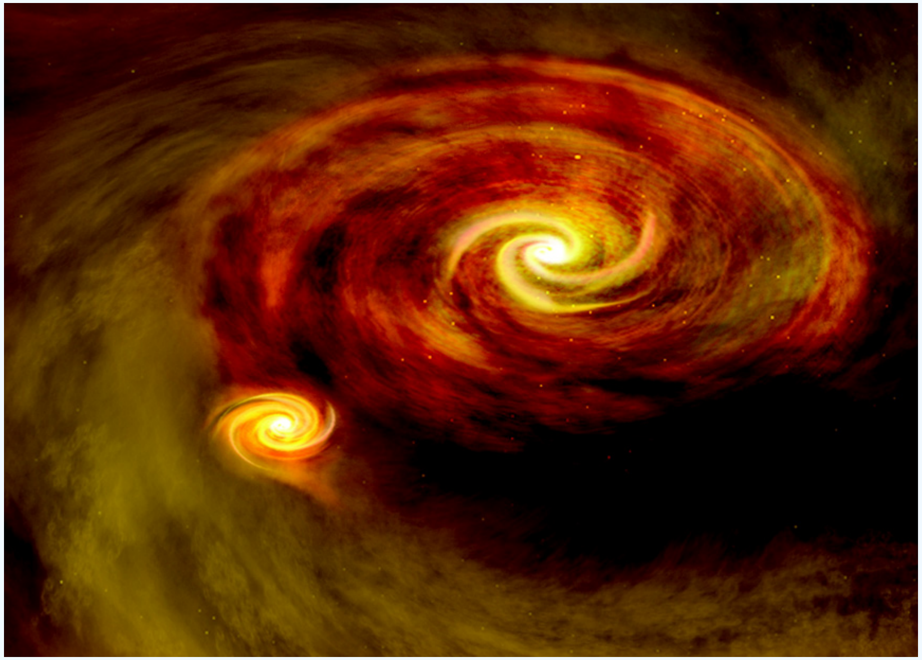
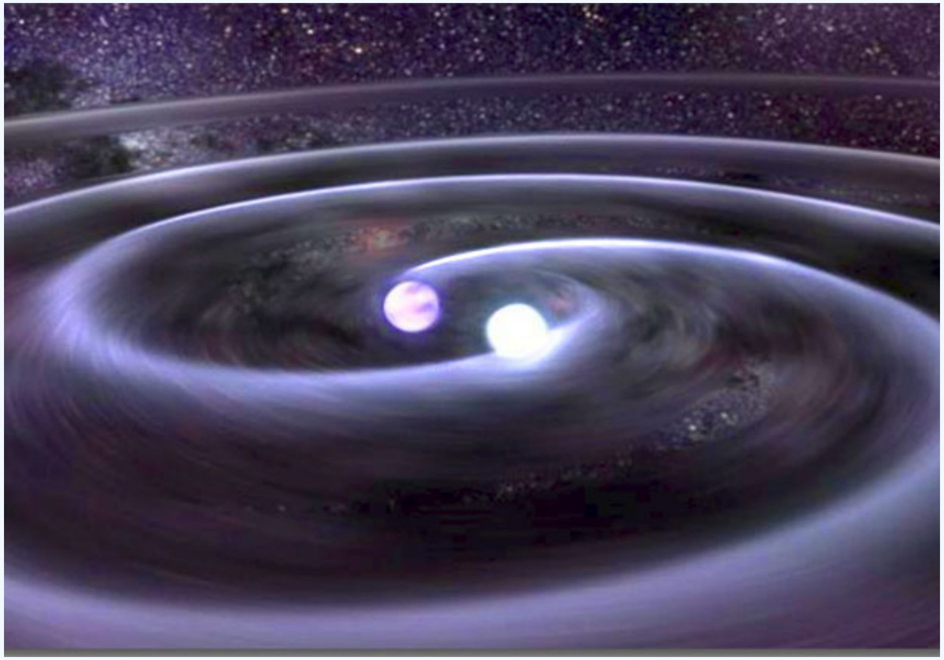
Statistics of Binary & Multiple Stars: Implications for Formation & Evolution





Max Moe (University of Arizona)

The Impact of Binaries on Stellar Evolution

ESO Garching – July 3, 2017

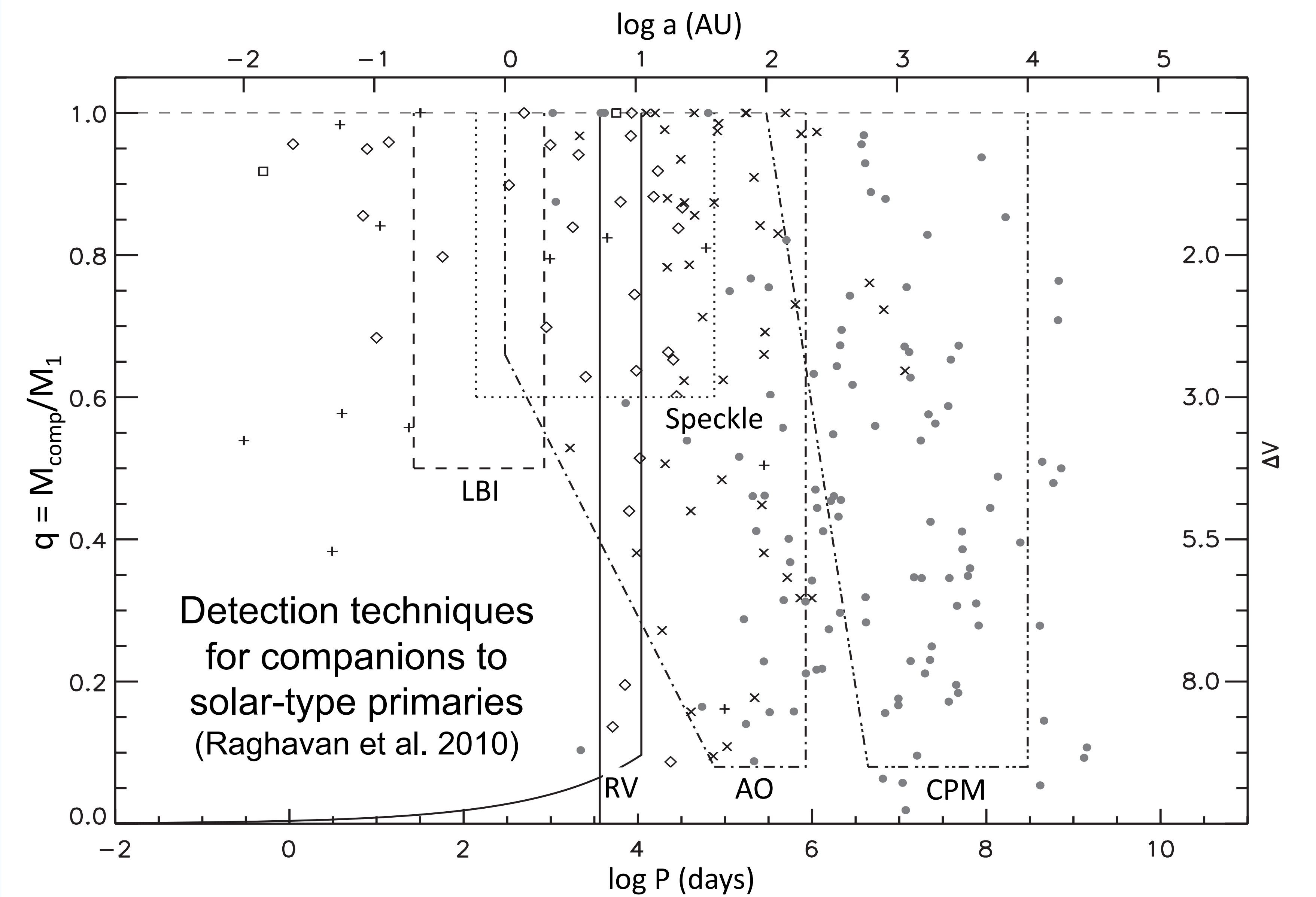
Topics:

- Detection methods and selection effects
- Corrected joint pdf $f(M_1, P, q, e) \neq f(M_1) \times f(P) \times f(q) \times f(e)$ for systems near ZAMS ($\tau \sim 5$ Myr) and $Z = Z_\odot$
- Variations as a function of τ, Z, and environment
- Implications for binary star formation and evolution

Main Resources:

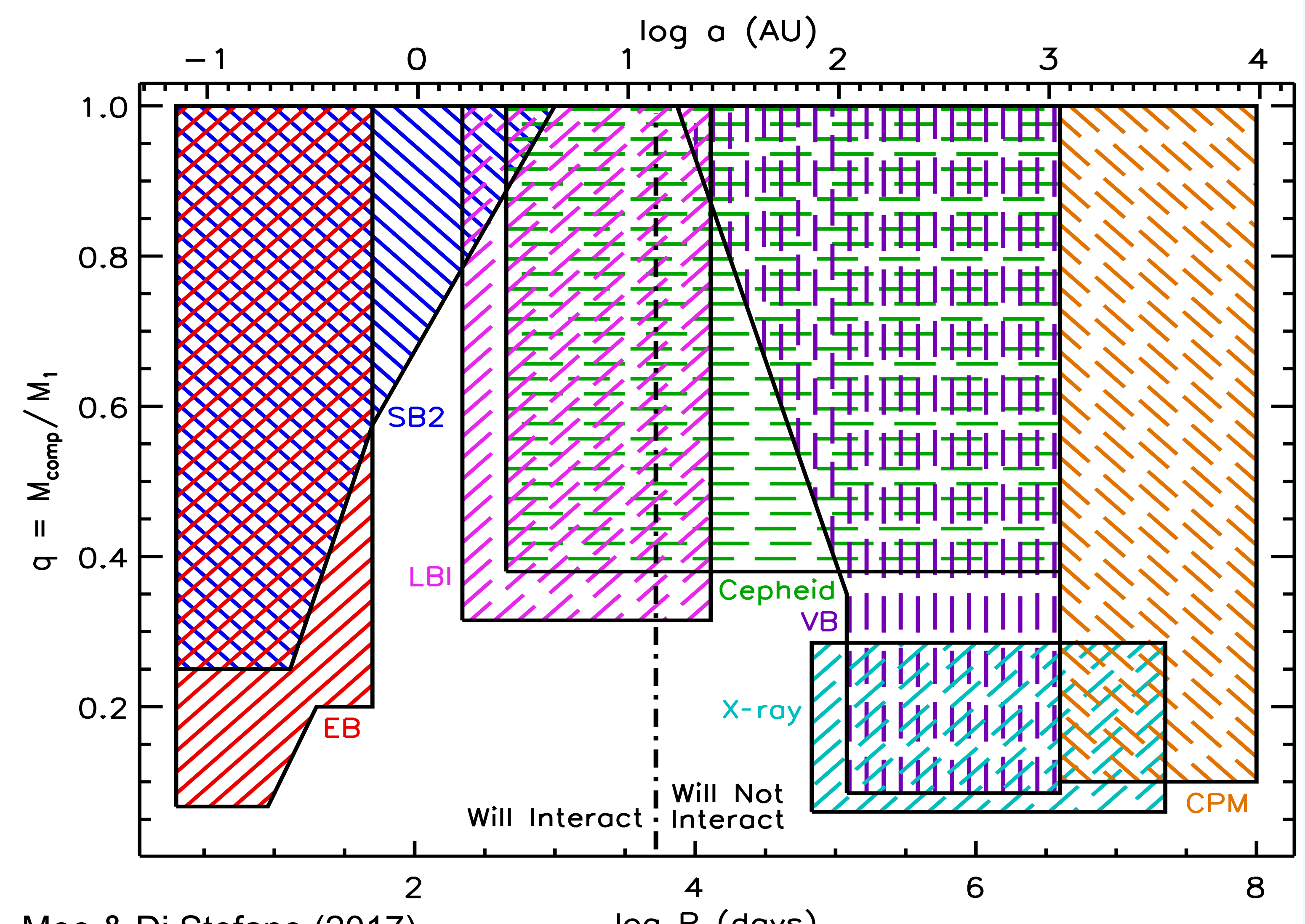
- Review by Duchene & Kraus (2013)
- Meta-analysis by Moe & Di Stefano (2017)

Mind your Ps and Qs: $f(P, q) \neq f(P) \times f(q)$



Relatively complete across $q = M_{comp}/M_1 = 0.1 - 1.0$ and log P (days) = 0 - 8

Detection Techniques for Companions to OB-type MS Primaries ($M_1 > 3\ M_\odot$)



Moe & Di Stefano (2017)

Insensitive across small q & intermediate P – must correct for incompleteness!

Cannot directly measure multiplicity fractions F_{bin}, F_{trip}, or F_{quad}.

But can measure **multiplicity frequency** $f_{mult} = F_{bin} + 2F_{trip} + 3F_{quad}$.

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

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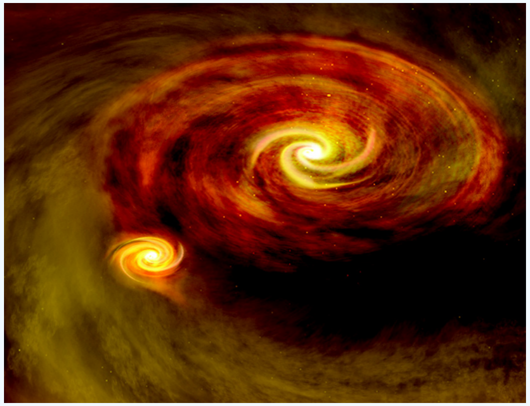
Intermediate-Period Companions:
log P (days) = 1 - 5;
a = 0.1 - 100 AU;
Disk Fragmentation



- 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

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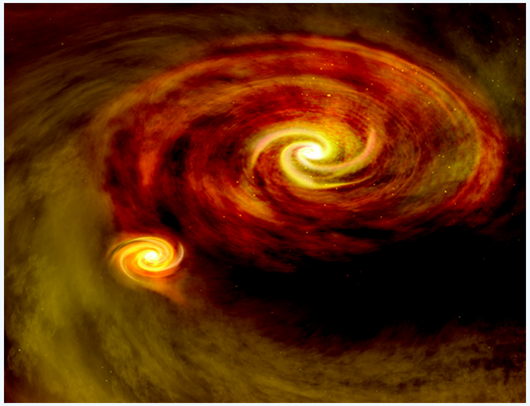

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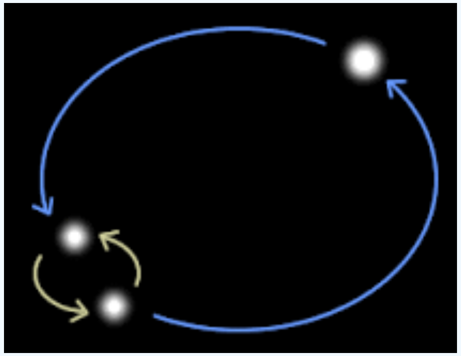
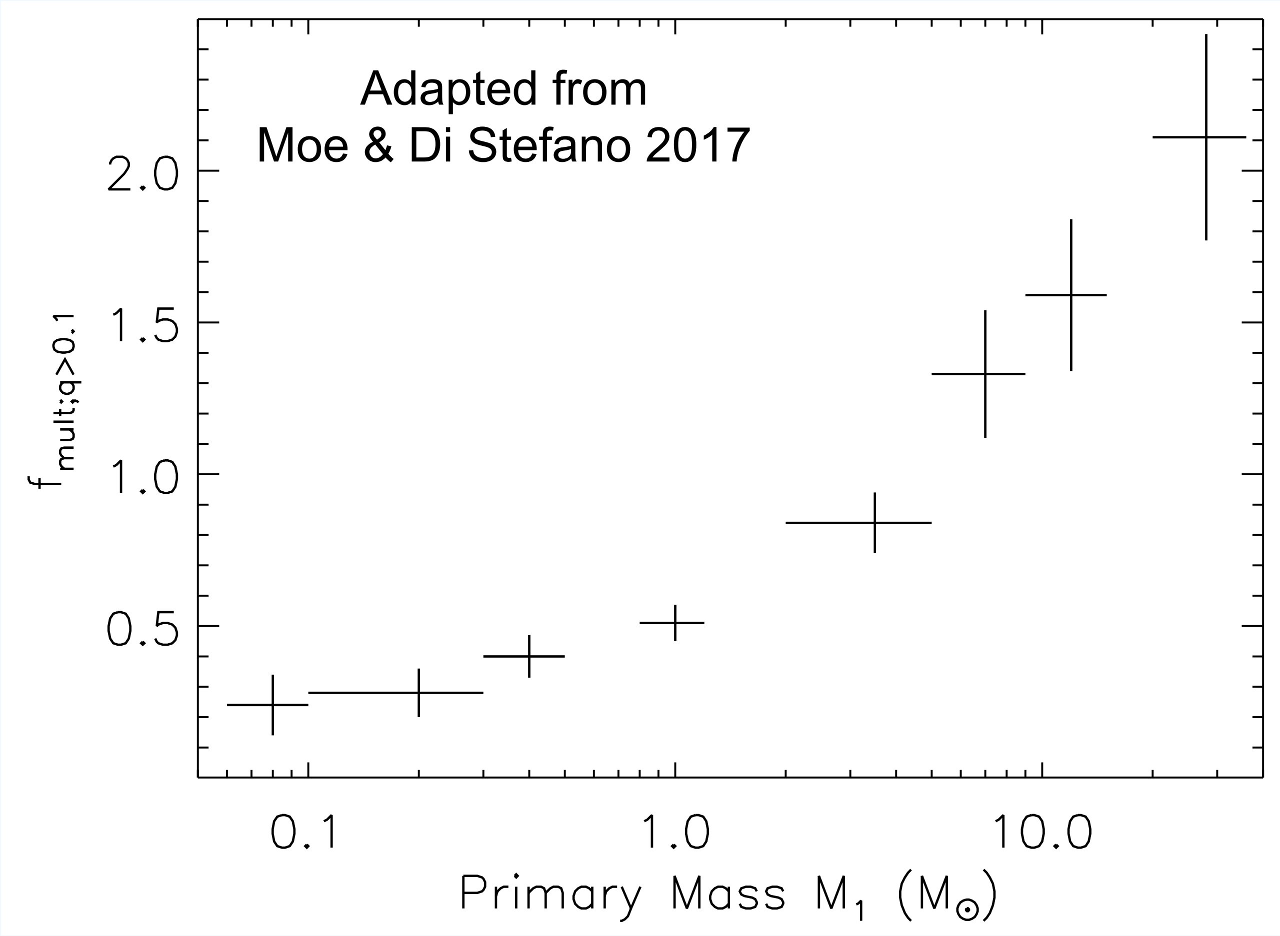
Very Close Binaries
log P (days) < 1;
a < 0.1 AU;
Dynamical Hardening in Triples during Pre-MS



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

Multiplicity Frequency

Corrected frequency of companions with $q > 0.1$ and $\log P$ (days) < 8 ($a <$ 10,000 AU) per primary near ZAMS

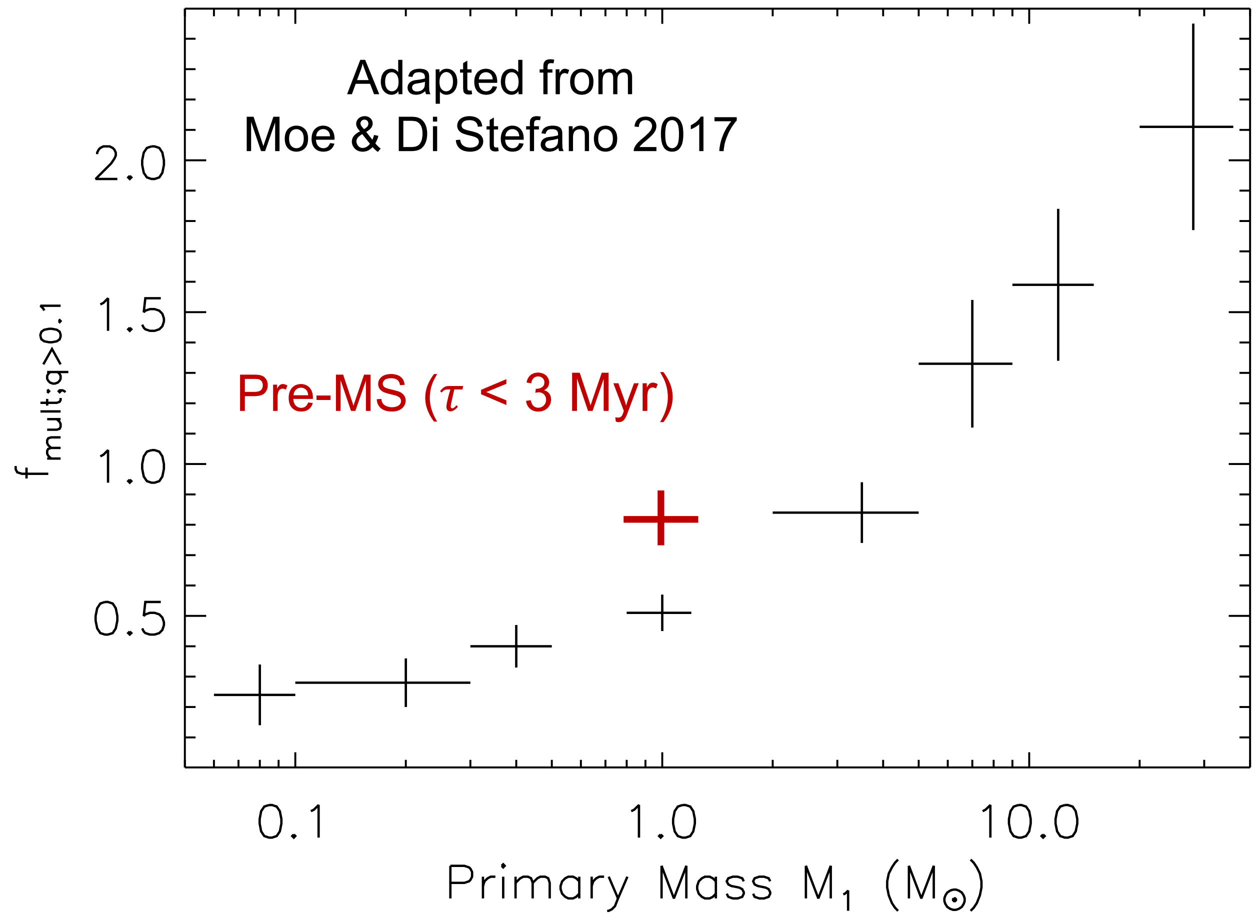


Solar-type MS ($M_1 = 1M_\odot$): $f_{mult} = 0.50 \pm 0.04$;
F_{single} = 60%, F_{bin} = 30%, $F_{trip/quad}$ = 10%

O-type MS ($M_1 = 28M_\odot$): $f_{mult} = 2.1 \pm 0.3$;
F_{single} < 5%, F_{bin} = 20%, $F_{trip/quad}$ = 75%

Multiplicity Frequency

Corrected frequency of companions with $q > 0.1$ and log P (days) < 8 (a < 10,000 AU) per primary near ZAMS

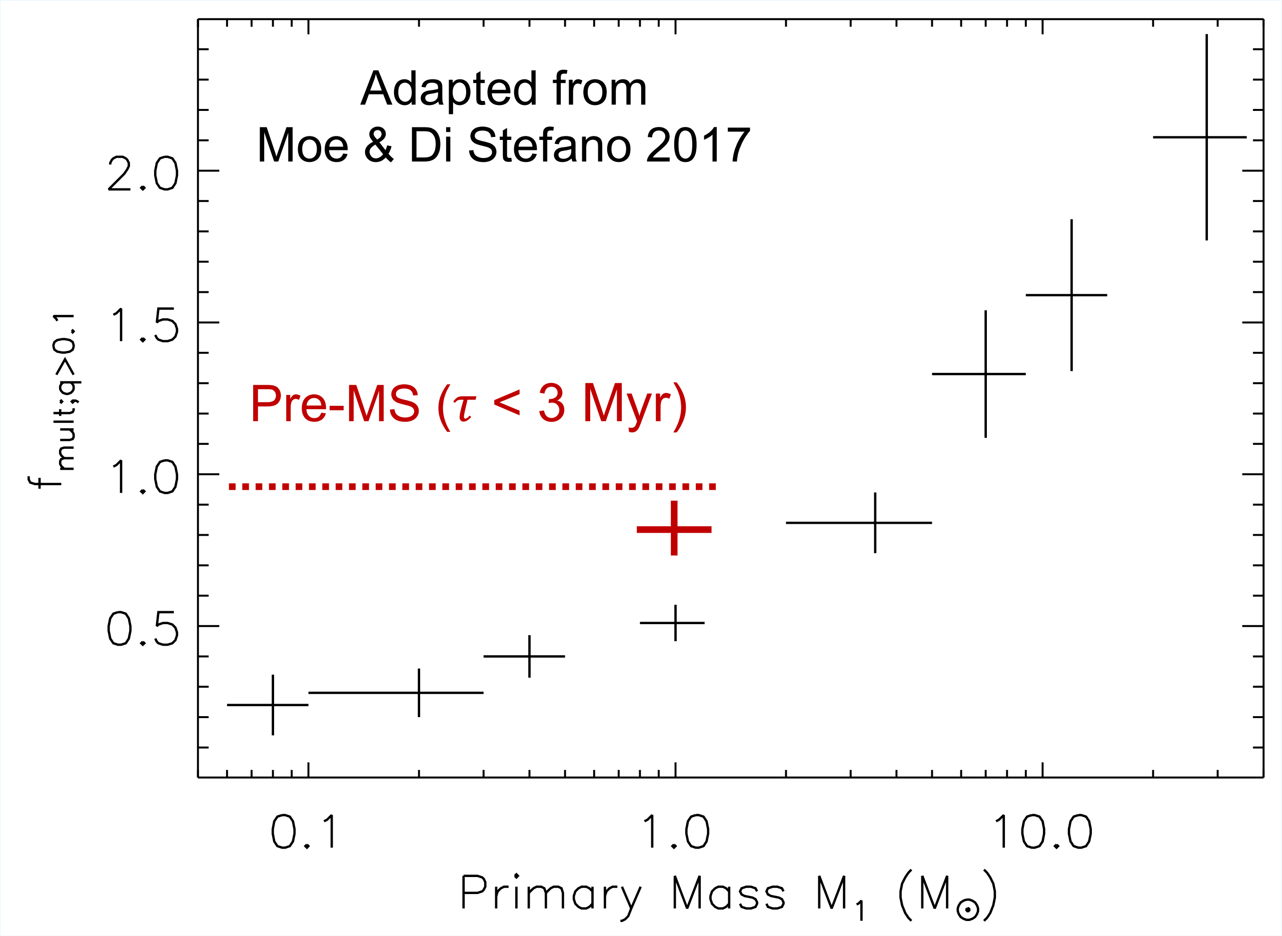


For $M_1 = 1\ M_\odot$, frequency of **wide** companions (**a > 100 AU**) is 2 - 3 times larger during the early pre-MS phase (τ < 3 Myr) (Ghez et al. 1993; Duchene et al. 2007; Connelley et al. 2008; Tobin et al. 2016)

Overall multiplicity frequency: $f_{mult} = 0.5 \rightarrow 0.8$

Multiplicity Frequency

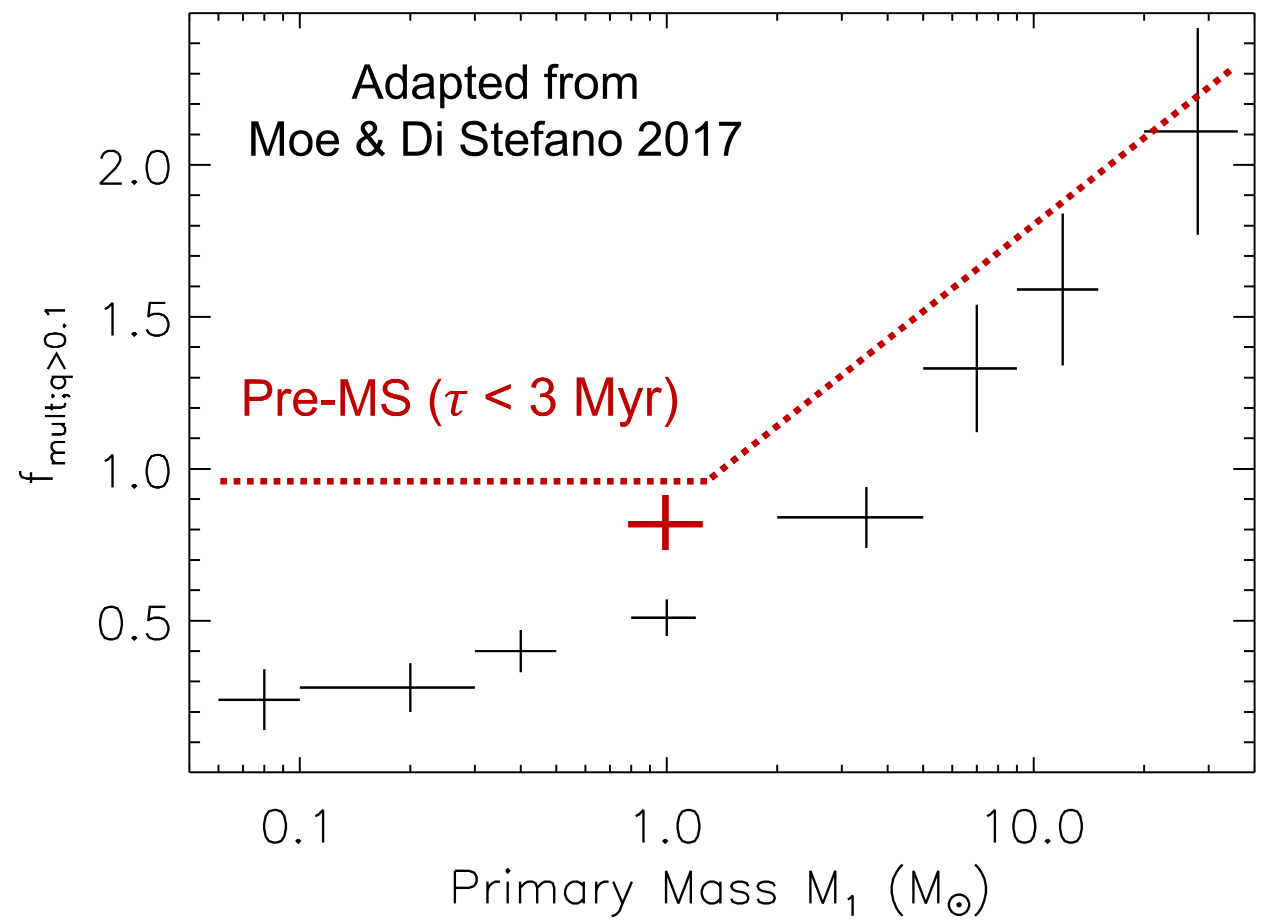
Corrected frequency of companions with $q > 0.1$ and log P (days) < 8 (a < 10,000 AU) per primary near ZAMS



$f_{mult} \approx 1.0$ for all $M_1 < 1M_\odot$ during pre-MS, but disruption of wide binaries with smaller binding energies (smaller M_1 and q) reduces f_{mult} by ZAMS (Goodwin & Kroupa 2005; Marks & Kroupa 2011; Thies et al. 2015)

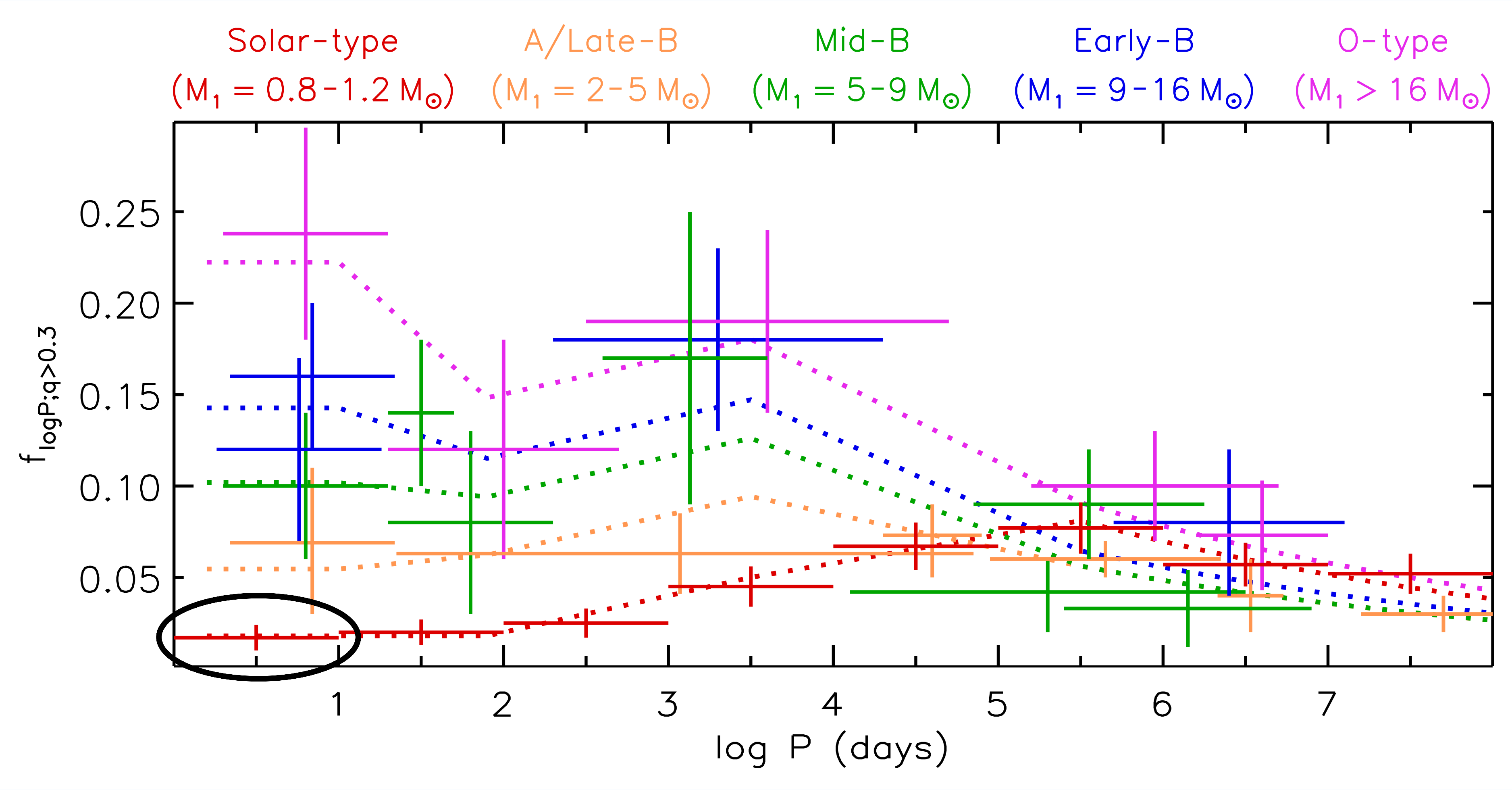
Multiplicity Frequency

Corrected frequency of companions with $q > 0.1$ and log P (days) < 8 (a < 10,000 AU) per primary near ZAMS



For $M_1 > 1M_\odot$, disk fragmentation is progressively more likely with increasing primary mass (Kratter et al. 2006, 2011)

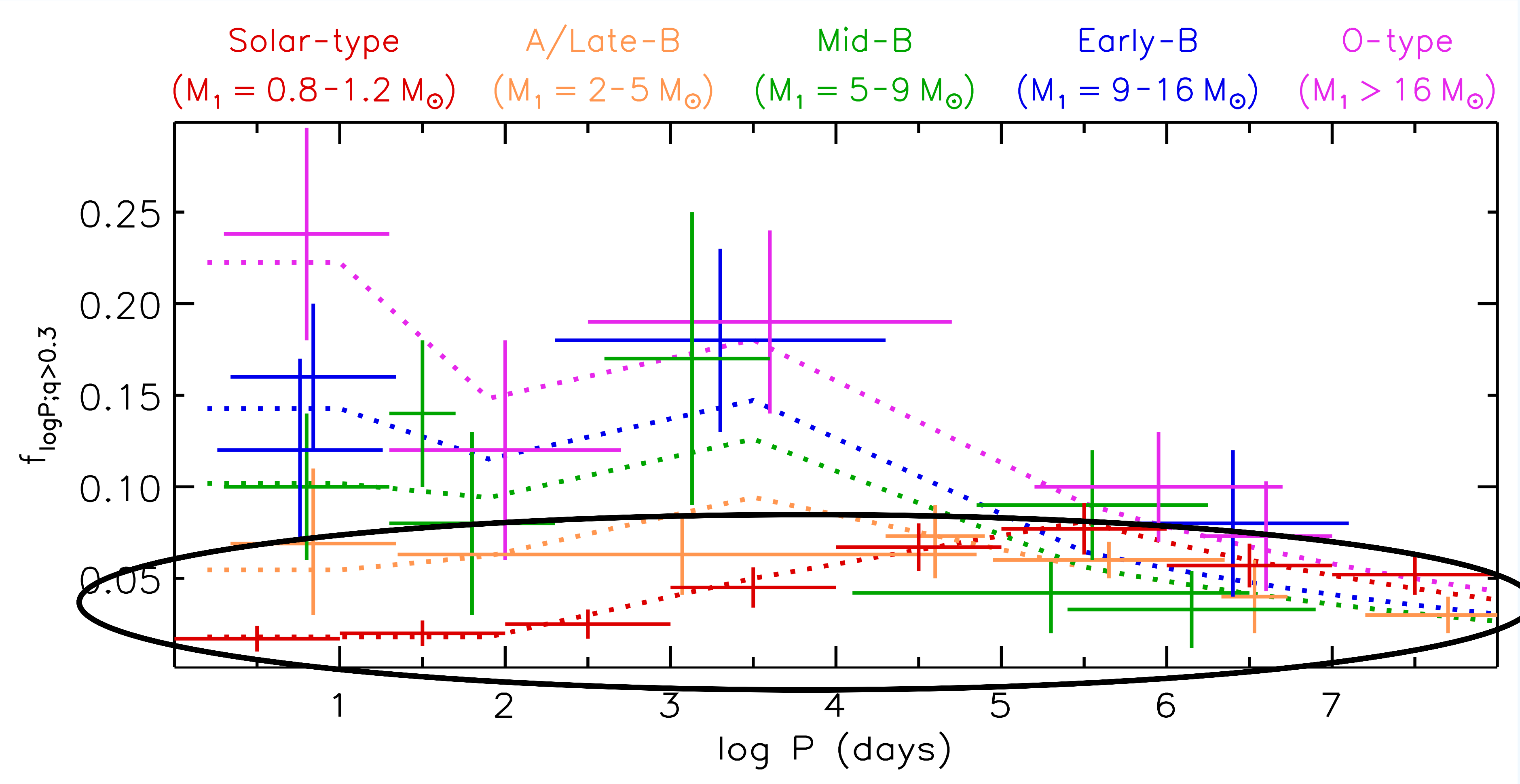
Period distribution $f_{logP;q>0.3}(M_1, P)$ from Moe & Di Stefano (2017)



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

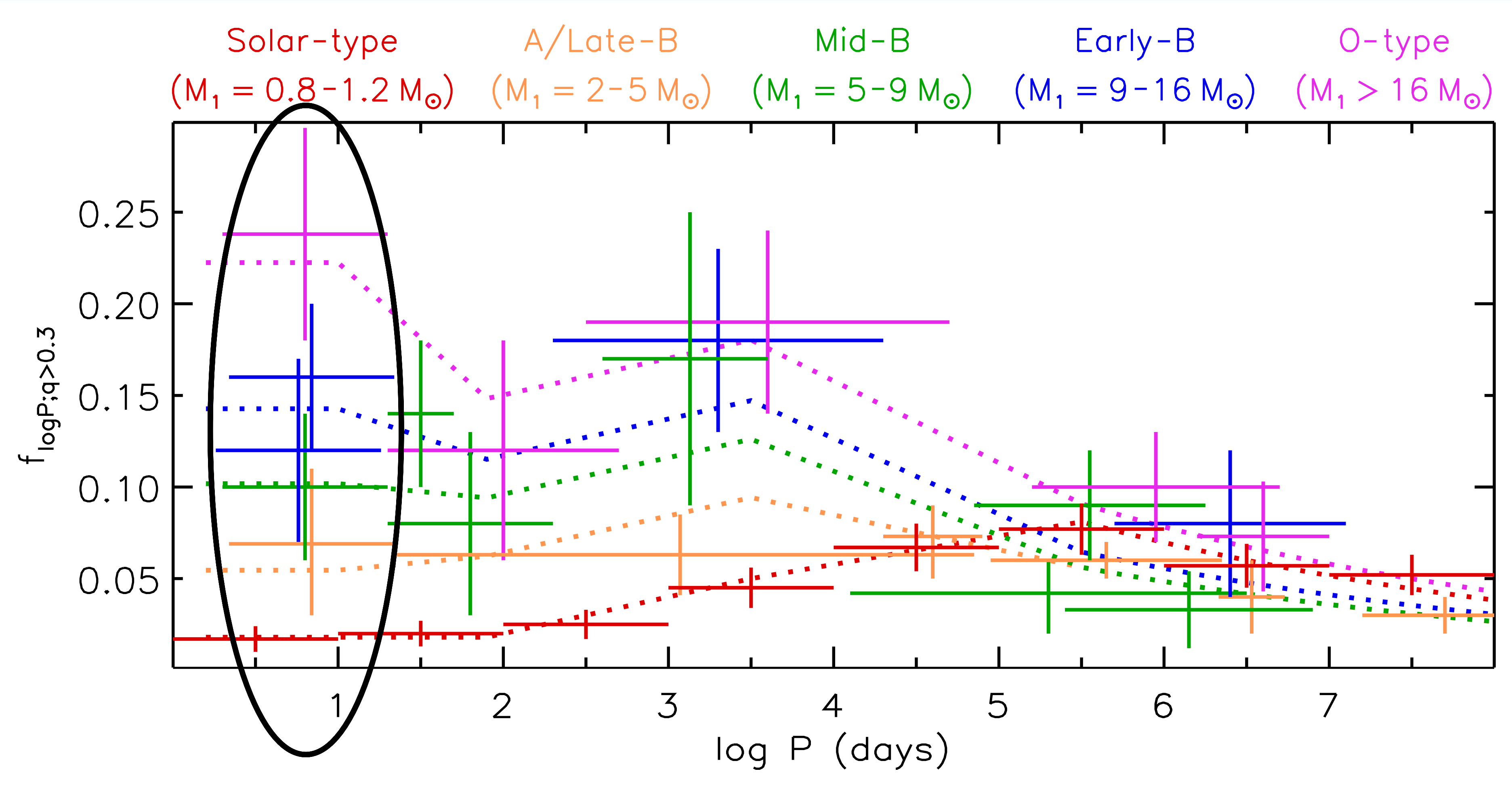
Integral under dotted lines yields the MS multiplicity frequency $f_{mult;q>0.3}(M_1)$.

Period distribution $f_{logP;q>0.3}(M_1, P)$ from Moe & Di Stefano (2017)



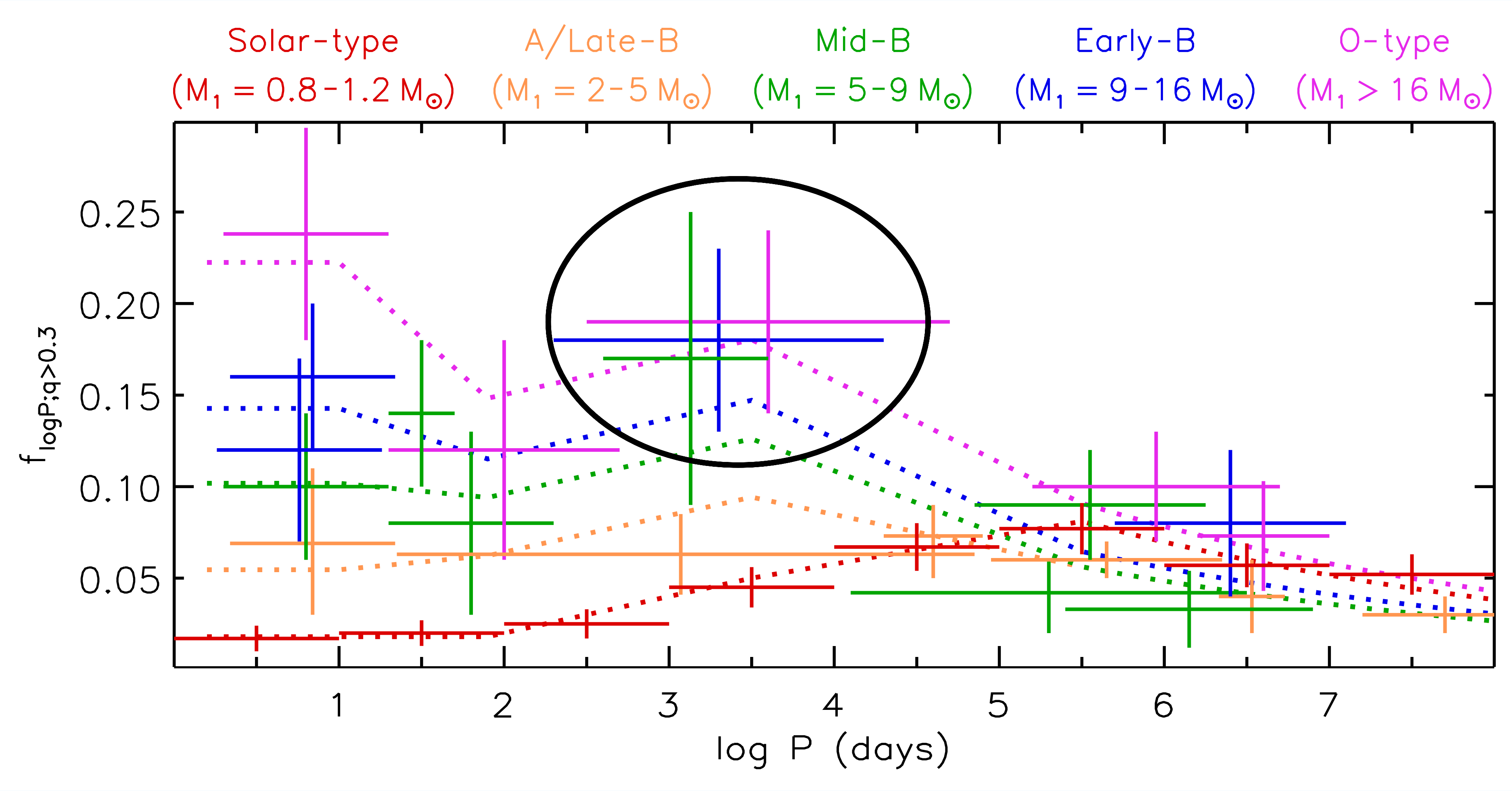
Companions to solar-type MS stars: log-normal period distribution as found by Duquennoy & Mayor (1991) and Raghavan et al. (2010)

Period distribution $f_{logP;q>0.3}(M_1, P)$ from Moe & Di Stefano (2017)



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)

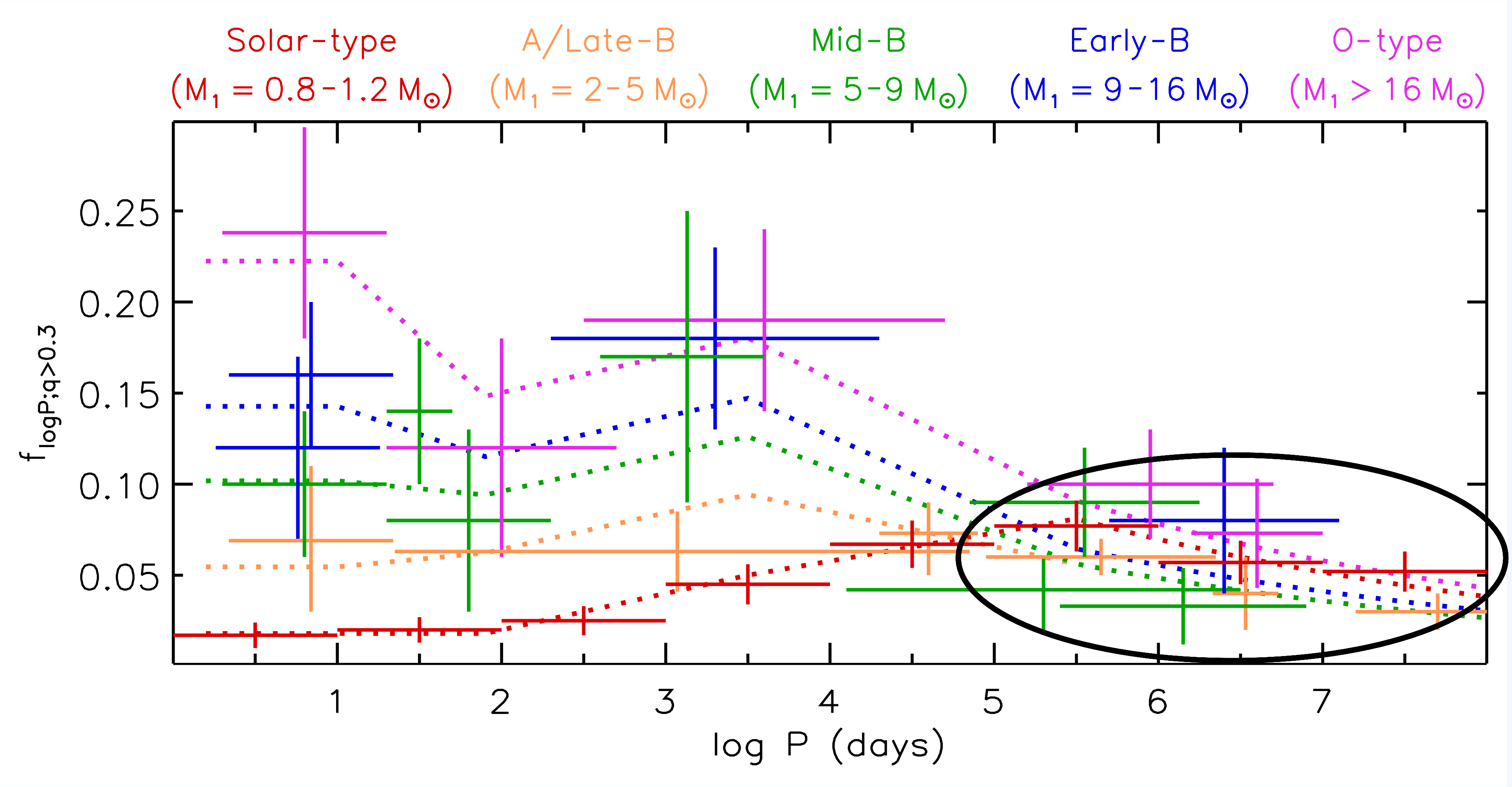
Period distribution $f_{logP;q>0.3}(M_1, P)$ from Moe & Di Stefano (2017)



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)

Period distribution $f_{logP;q>0.3}(M_1, P)$ from Moe & Di Stefano (2017)



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)

Distribution $f_q(M_1,P)$ of mass ratios $q = M_{comp}/M_1$

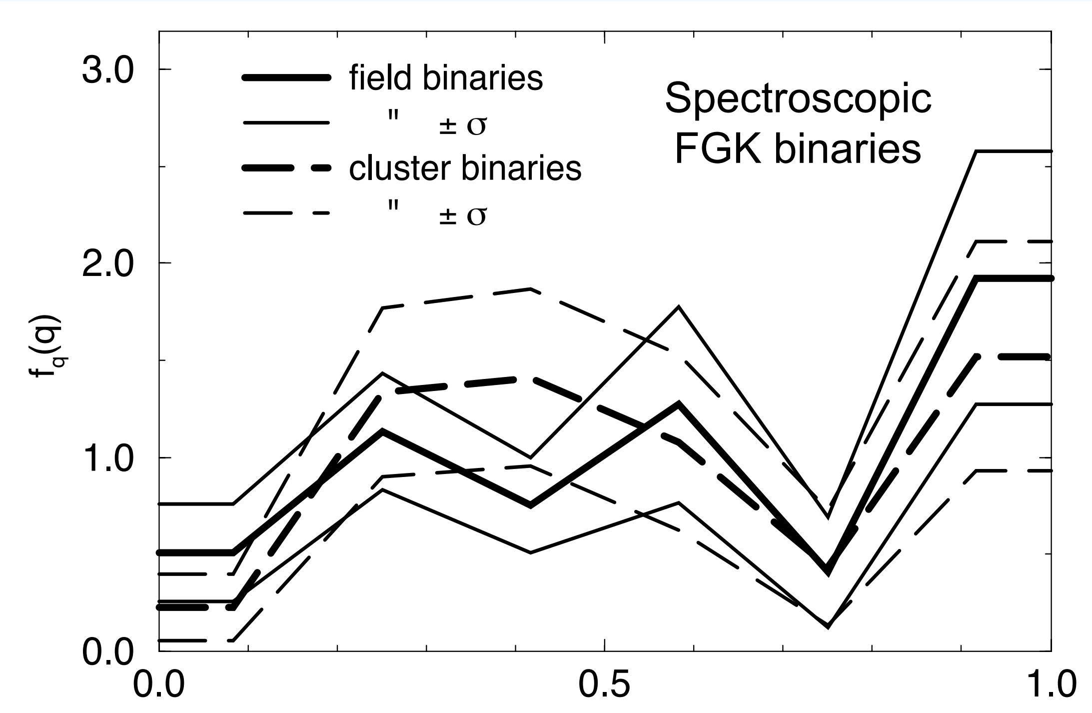
A single-component power-law model $f_q \propto q^{\gamma}$ does **NOT** adequately describe the data.

Need 3 parameters:

$\gamma_{smallq}(M_1,P)$: power-law slope across q = 0.1 - 0.3

$\gamma_{largeq}(M_1,P)$: power-law slope across q = 0.3 - 1.0

$F_{twin}(M_1,P)$: excess fraction of twins with q ≈ 1.0

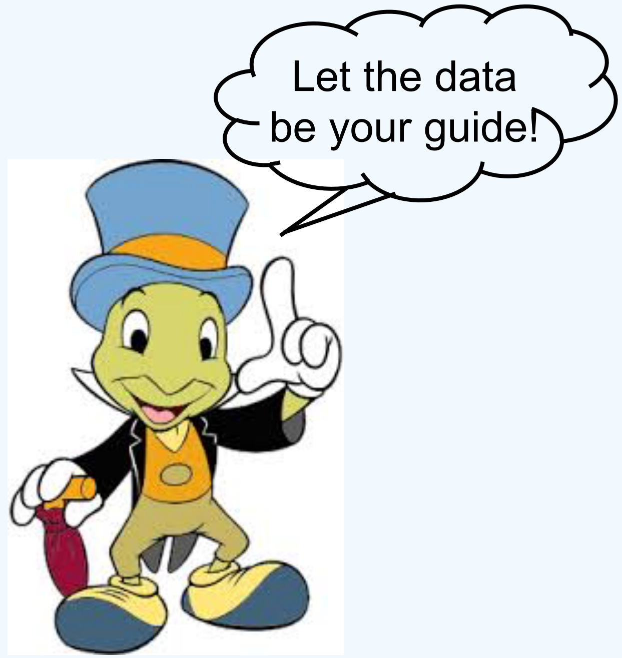


(Halbwachs et al. 2003)

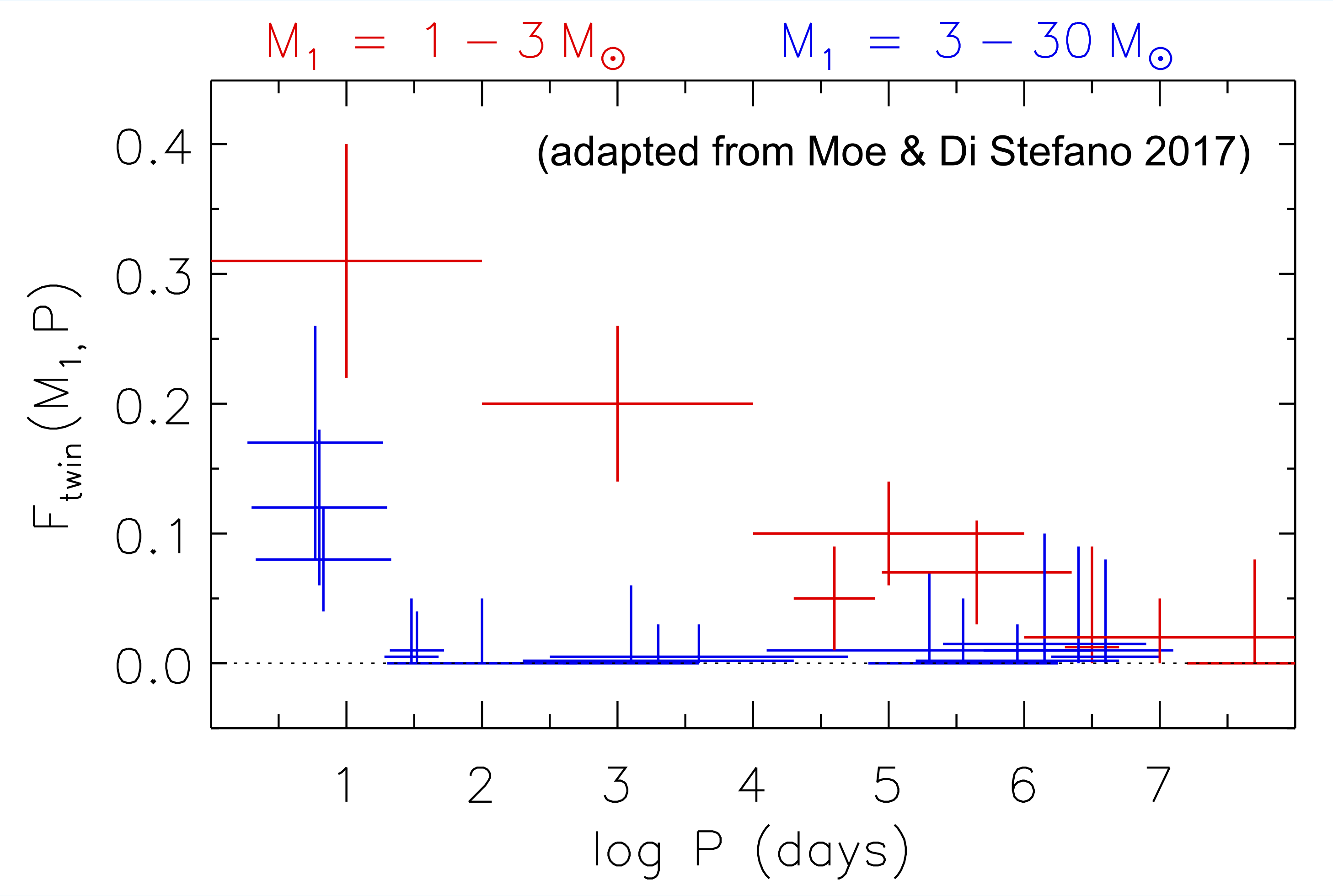
$\gamma_{smallq} = 0.5$

$\gamma_{largeq} = -0.5$

$F_{twin} = 25\%$



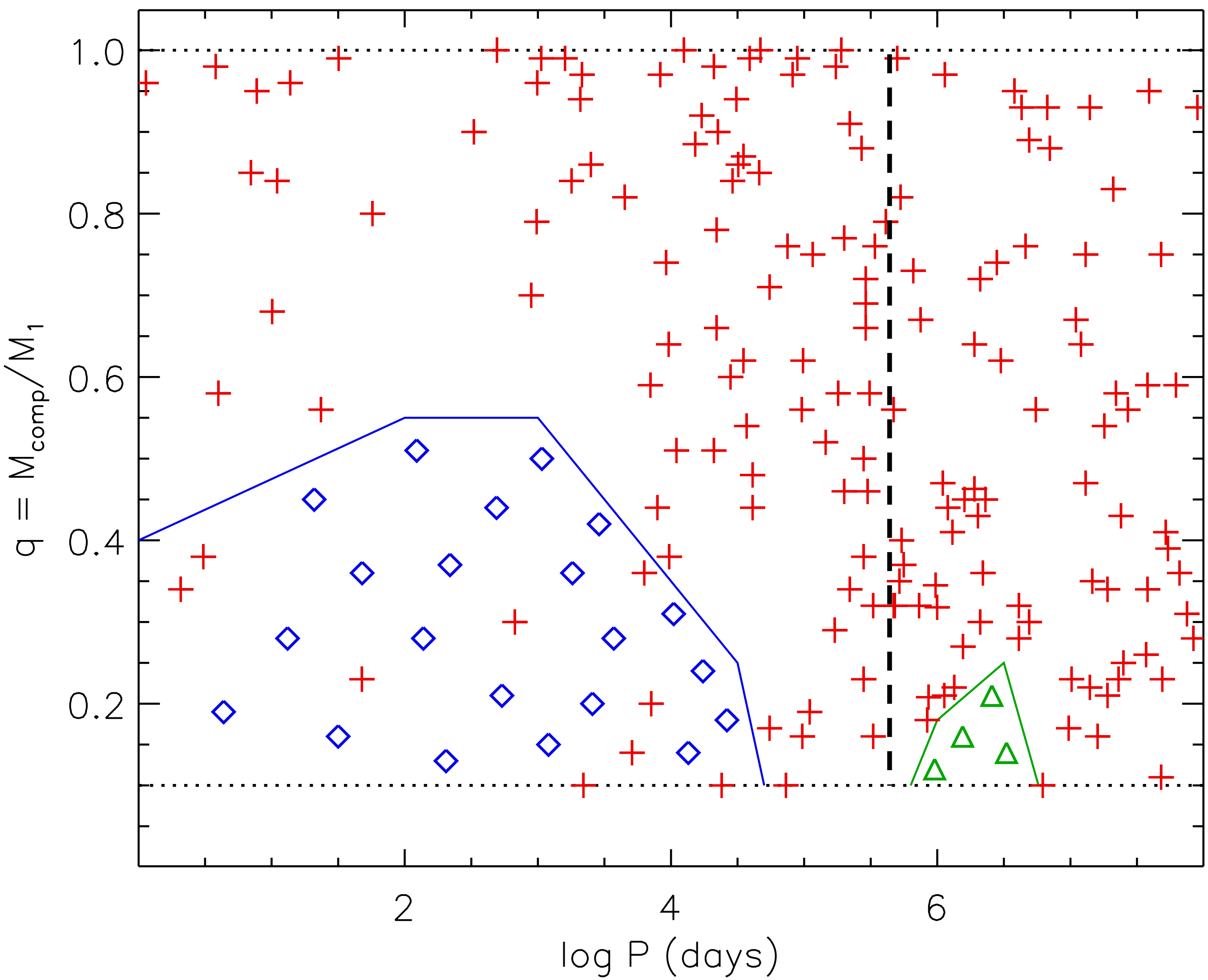
Excess Twin Fraction $F_{twin}(M_1,P)$



Solar-type binaries: larger F_{twin} due to pre-MS RLOF and/or shared accretion in longer-lived disks (Kroupa 1995; Tokovinin 2000; Halbwachs et al. 2003)

Massive protostars have rapid contraction timescales and shorter disk lifetimes

Mass-ratio distribution $f_q(P)$ for solar-type primaries $M_1 = 1M_\odot$

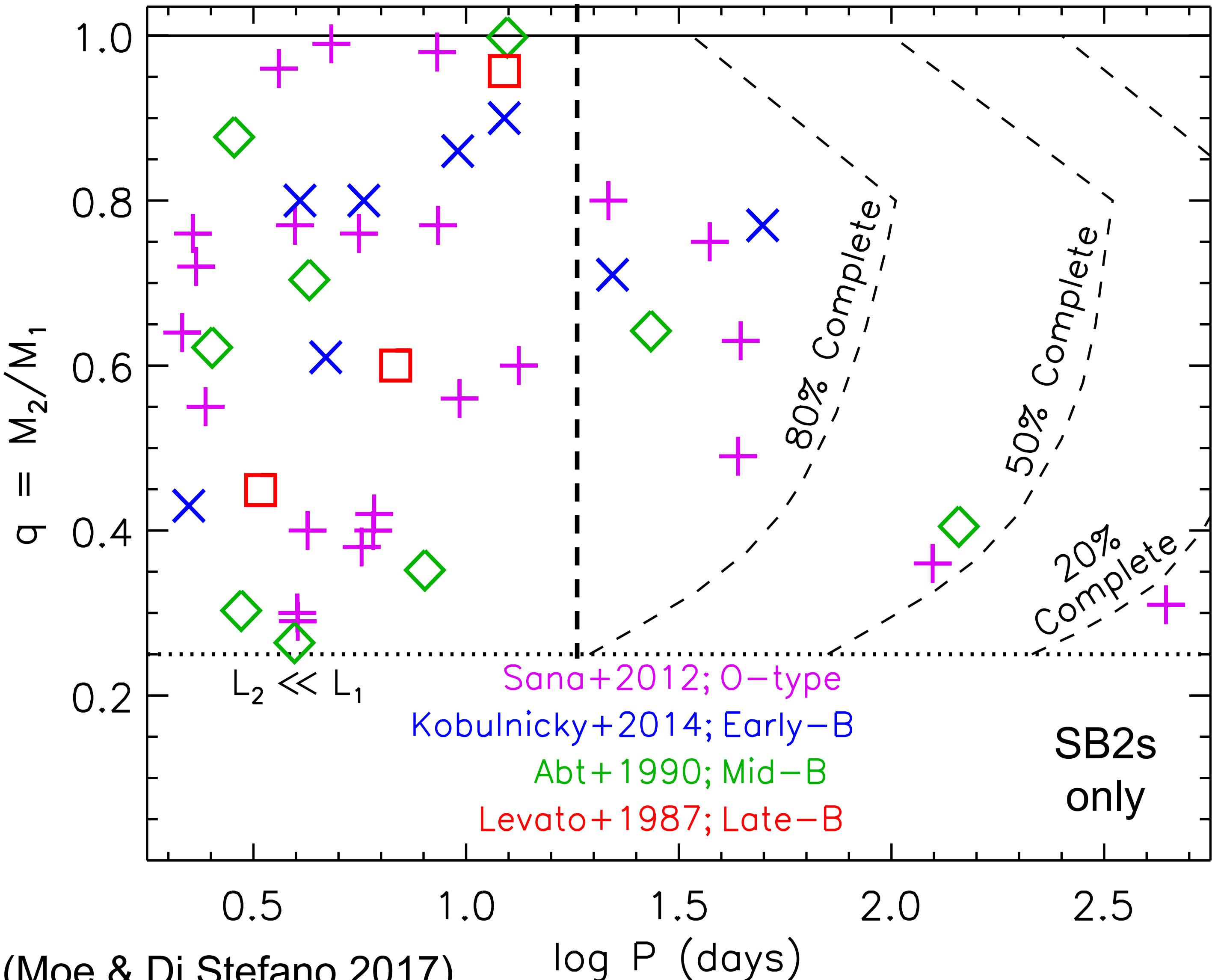


a < 100 AU:
uniform f_q with
excess twins
(fragmentation &
co-evolution in disk)

a > 100 AU:
weighted toward
small q = 0.2 - 0.4
(core fragmentation +
dynamical ejections)

Data (Raghavan et al. 2010); corrections for selection biases & missing stellar companions ◇ and △ (Moe & Di Stefano 2017)

Mass-ratio distribution $f_q(P)$ for OB-type MS primaries $M_1 > 3M_\odot$



(Moe & Di Stefano 2017)

P < 20 days:

γ_{largeq} = –0.4;

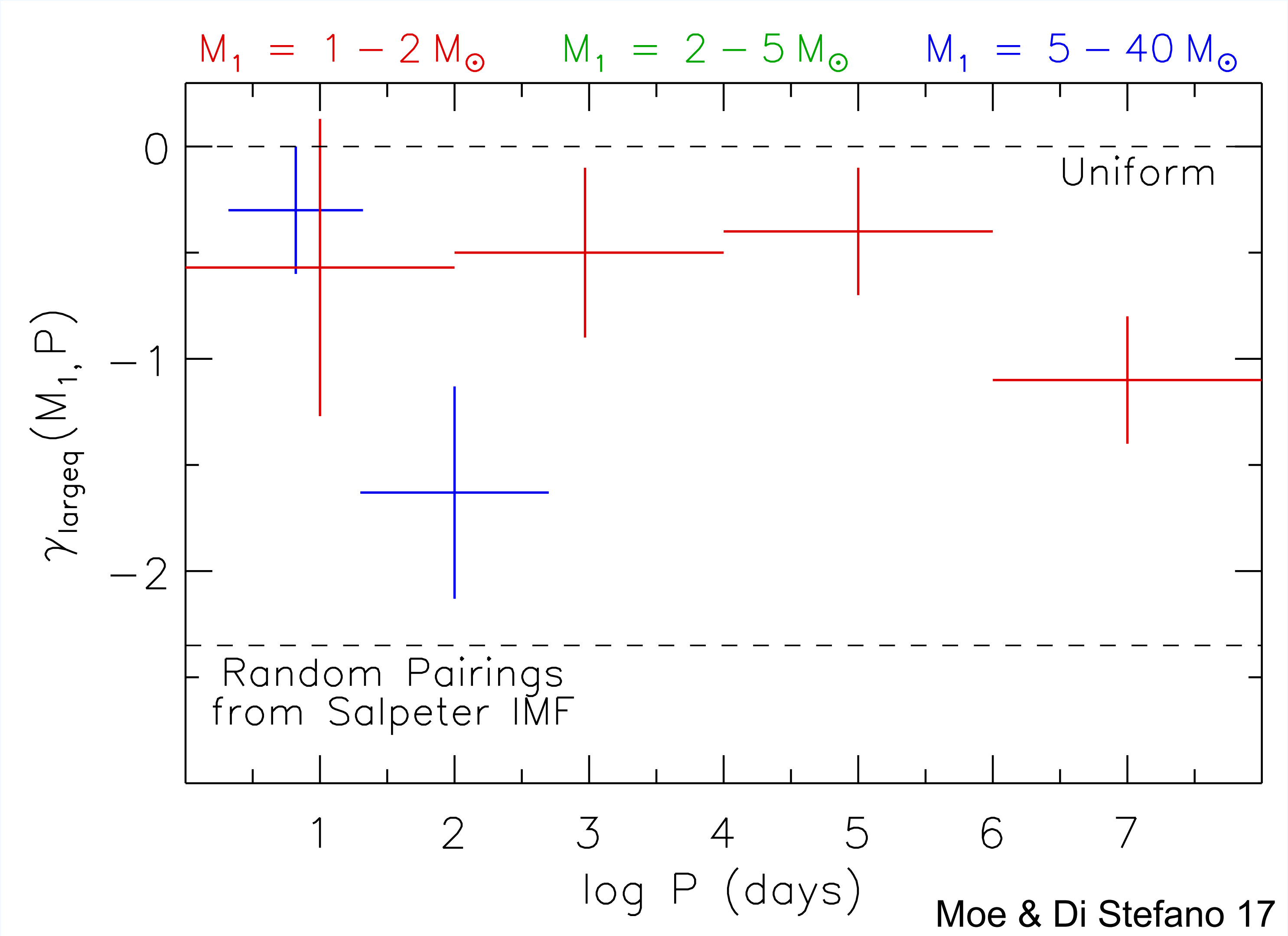
F_{twin} = 10 - 20%

P = 20 - 500 days:

γ_{largeq} = –1.6;

F_{twin} < 5%

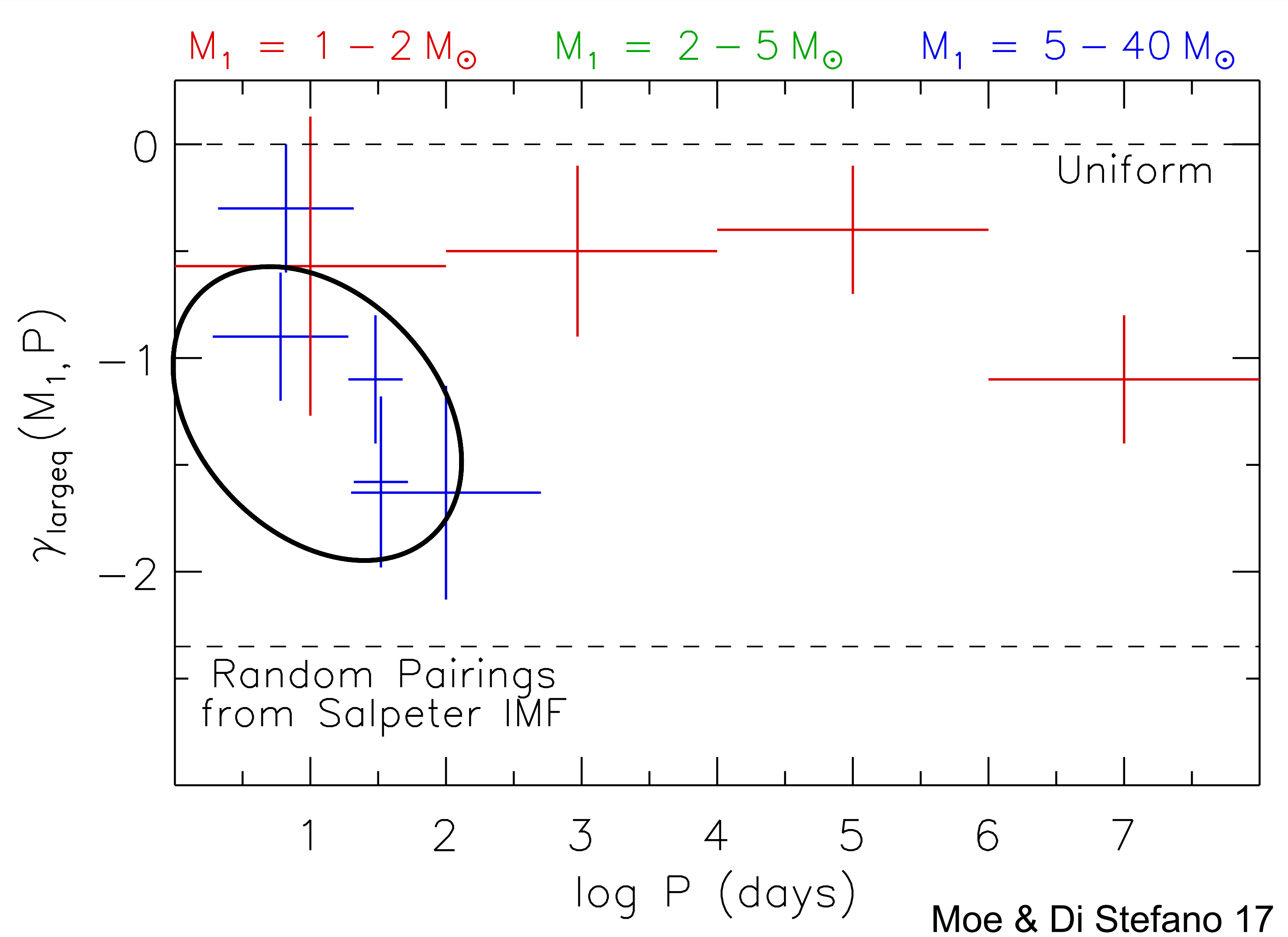
Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



Solar-type MS binaries (Raghavan et al. 2010);

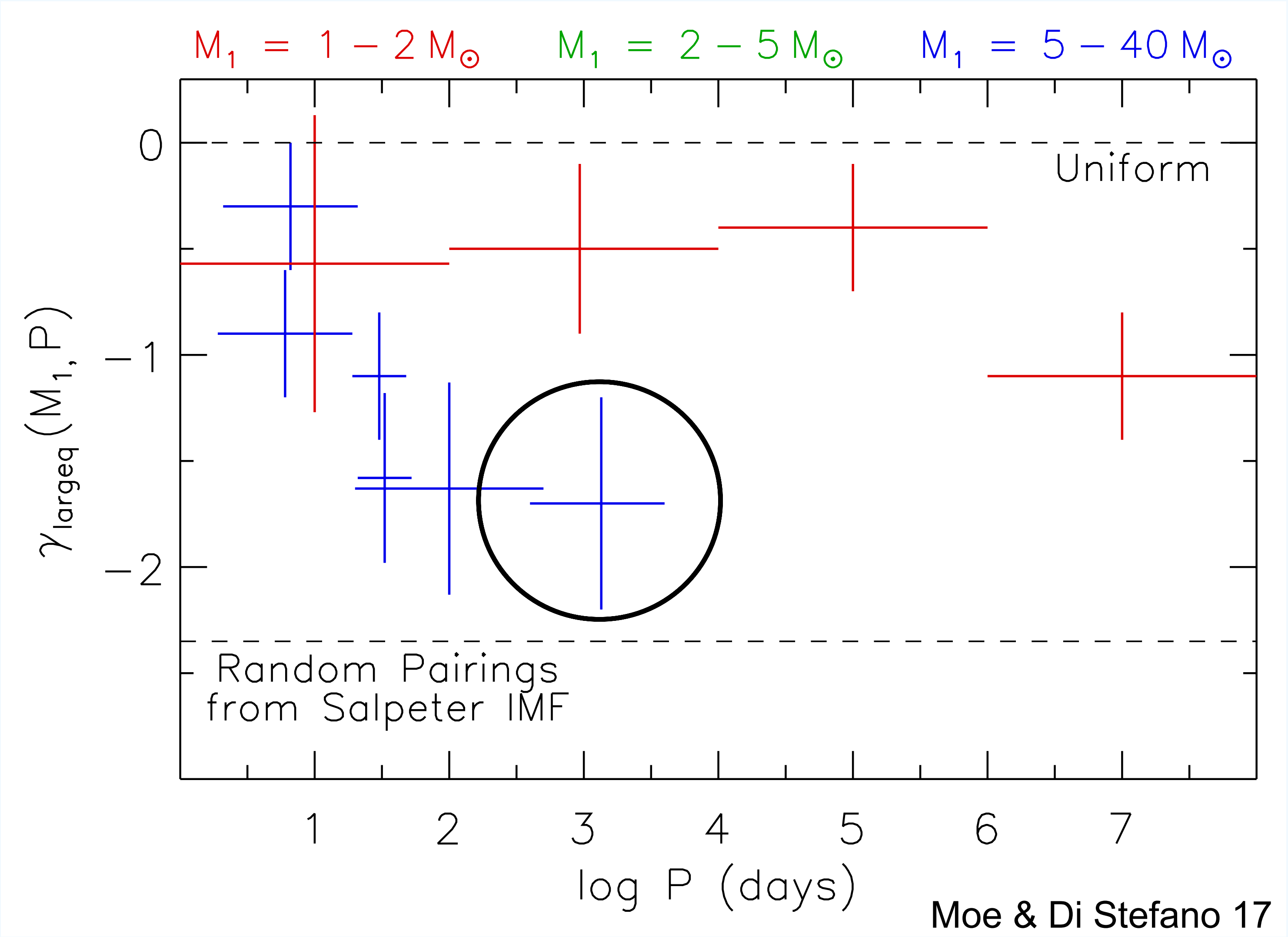
SB2 companions to O / early-B MS primaries (Abt+90; Sana+12; Kobulnicky+14)

Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



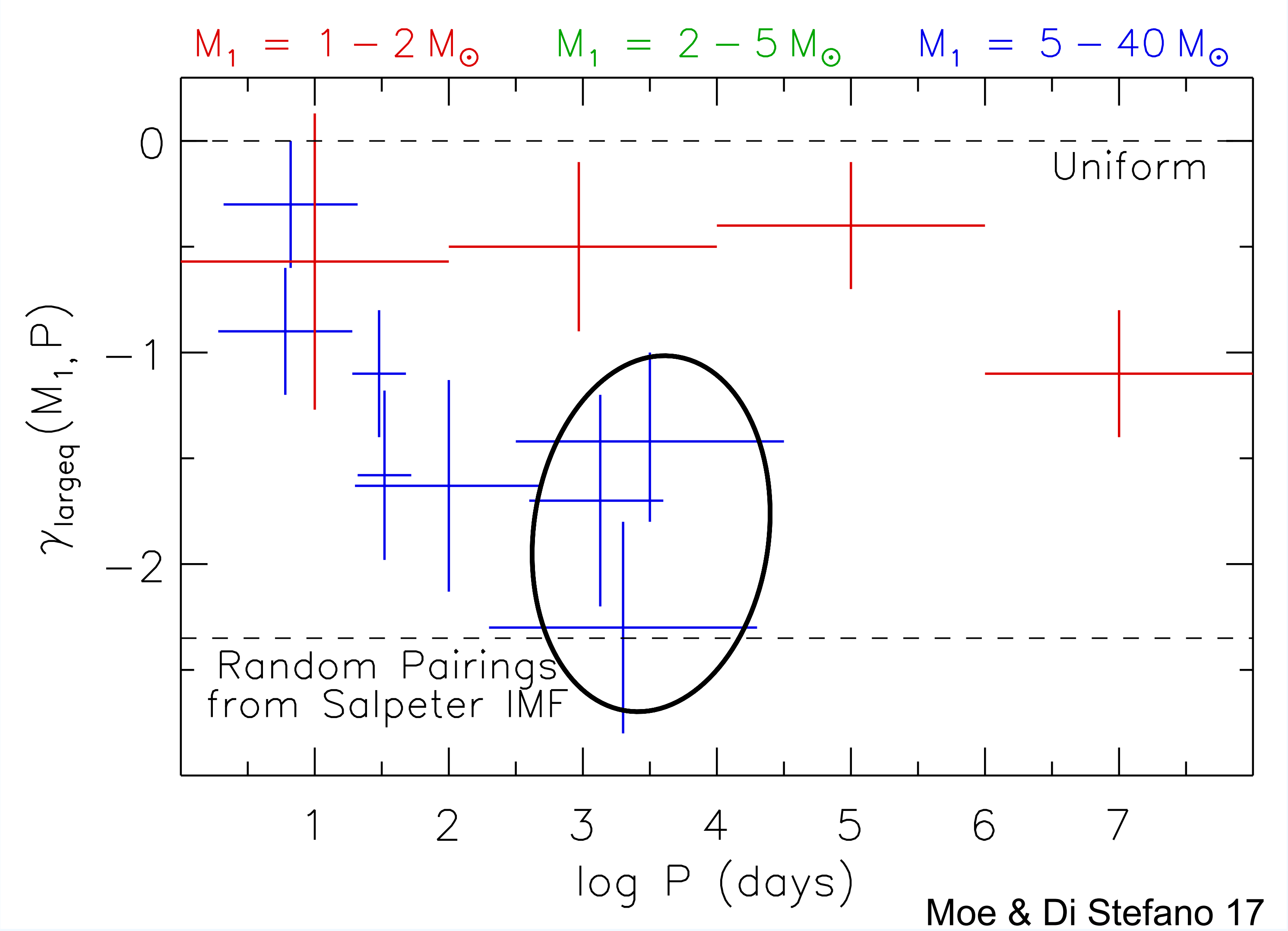
Eclipsing binaries with early-B primaries
(Moe+ 2013; 2015)

Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



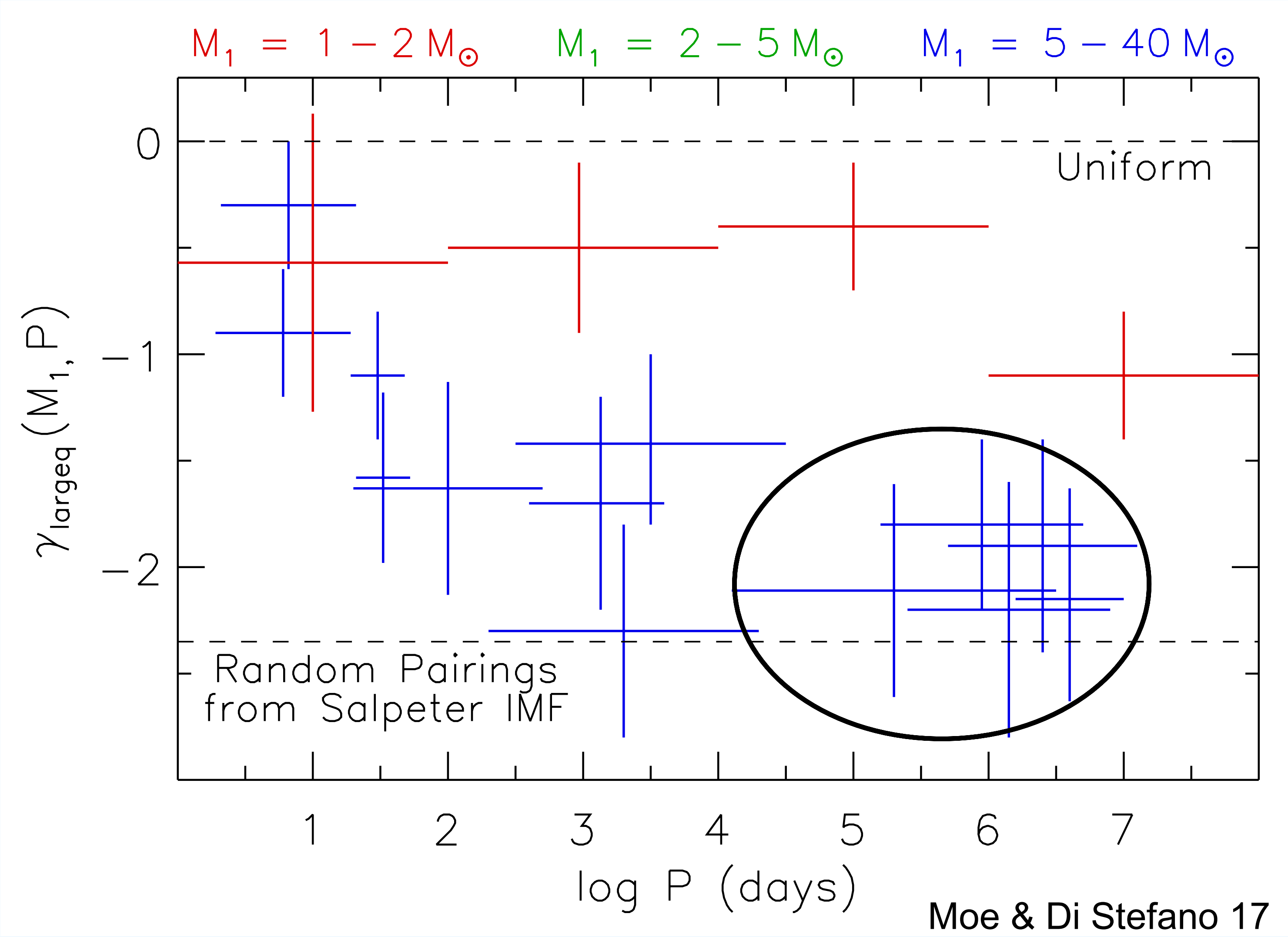
Radial velocity companions to Cepheid primaries
(Evans+ 2015)

Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



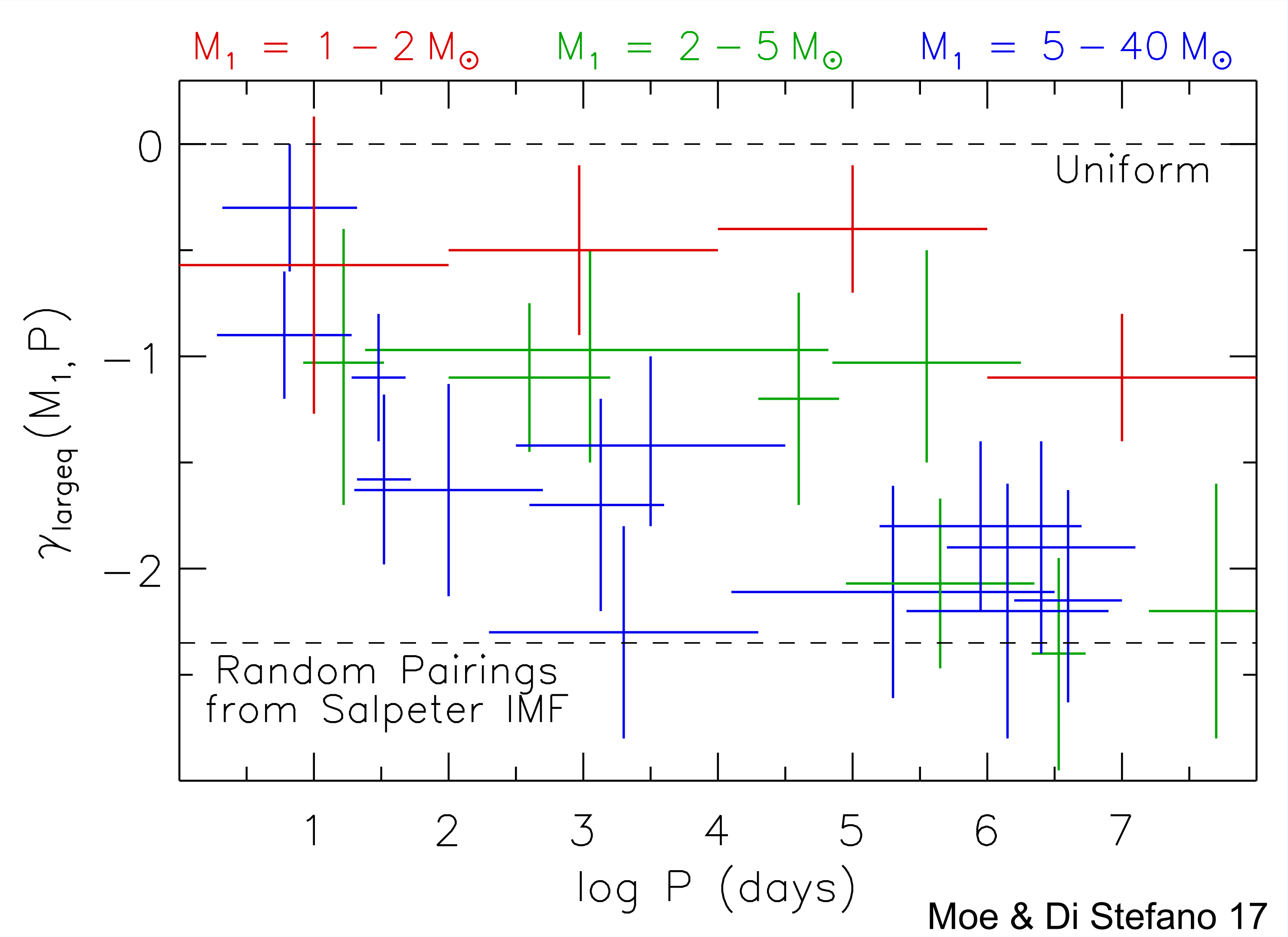
Long-baseline interferometry of
early-B (Rizzuto+ 2013) and O-type (Sana+ 2014) MS primaries

Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



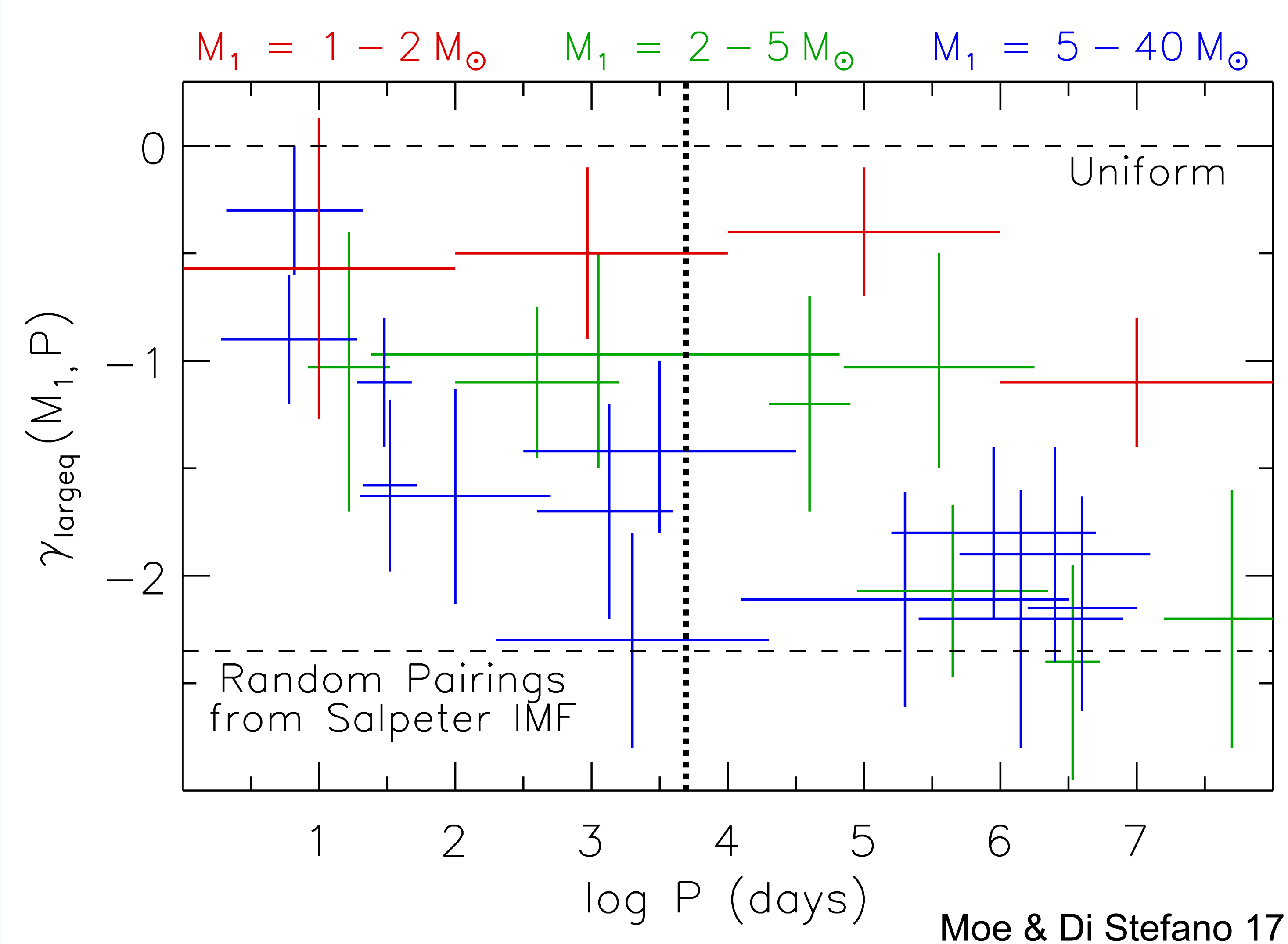
Visual companions to early-type MS primaries, including CPM (Abt+ 1990), AO (Duchene+ 2011; Sana+ 2014), lucky imaging (Peter+ 2012), and HST imaging (Aldoretta+ 2015)

Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



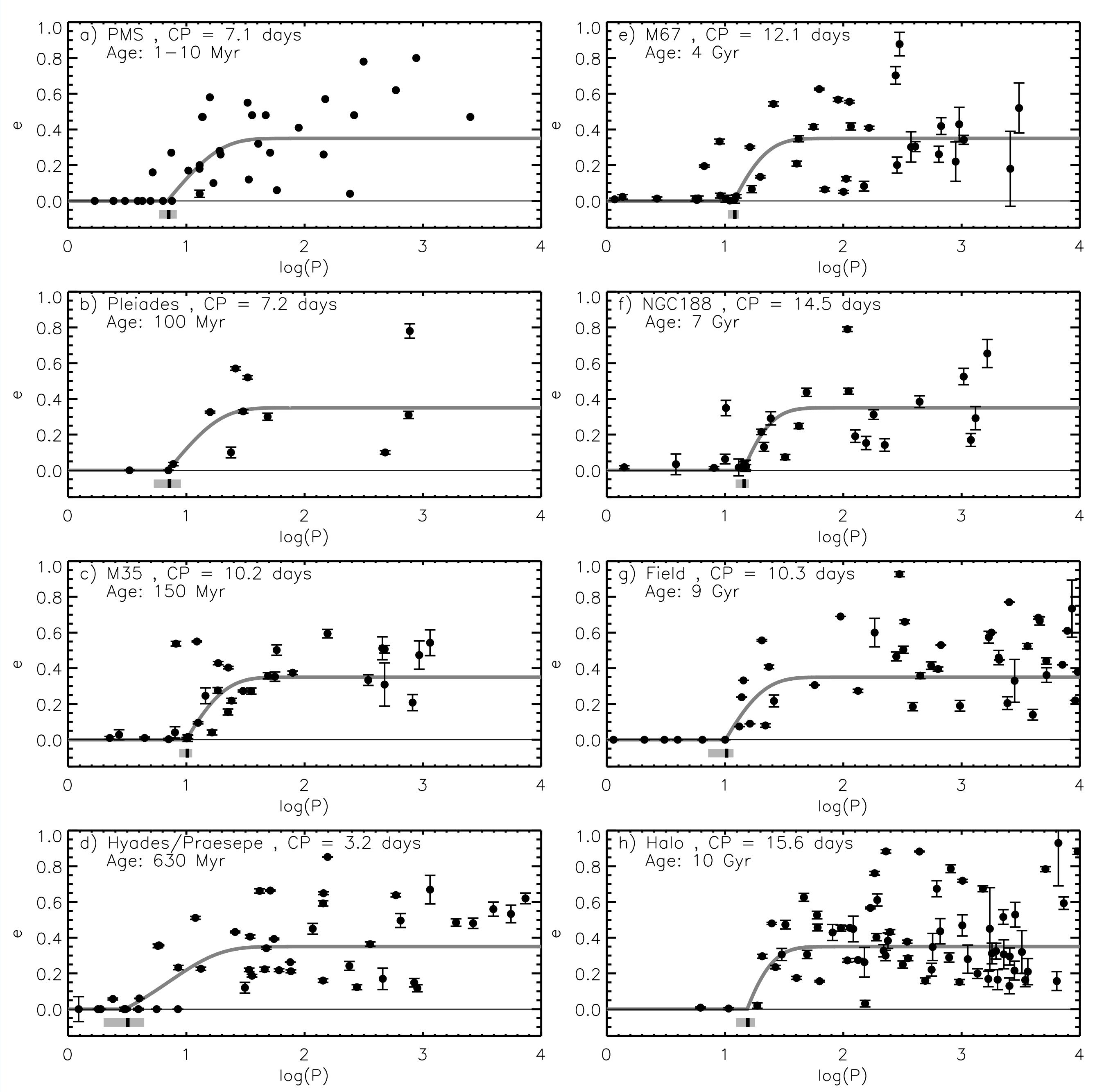
Very close binaries (a < 0.1 AU): uniform f_q with excess twin fraction.
Wide binaries (a > 100 AU): initially consistent with random pairings from IMF.
Transition occurs at shorter separations for more massive binaries.

Power-law component $\gamma_{largeq}(M_1,P)$ of mass-ratio distribution f_q



The mass-ratio distribution f_q of binaries that will interact
(a < 10 AU; left of dotted line) depends critically on M_1 and P

Eccentricity distribution for solar-type binaries (Meibom & Mathieu 2005)



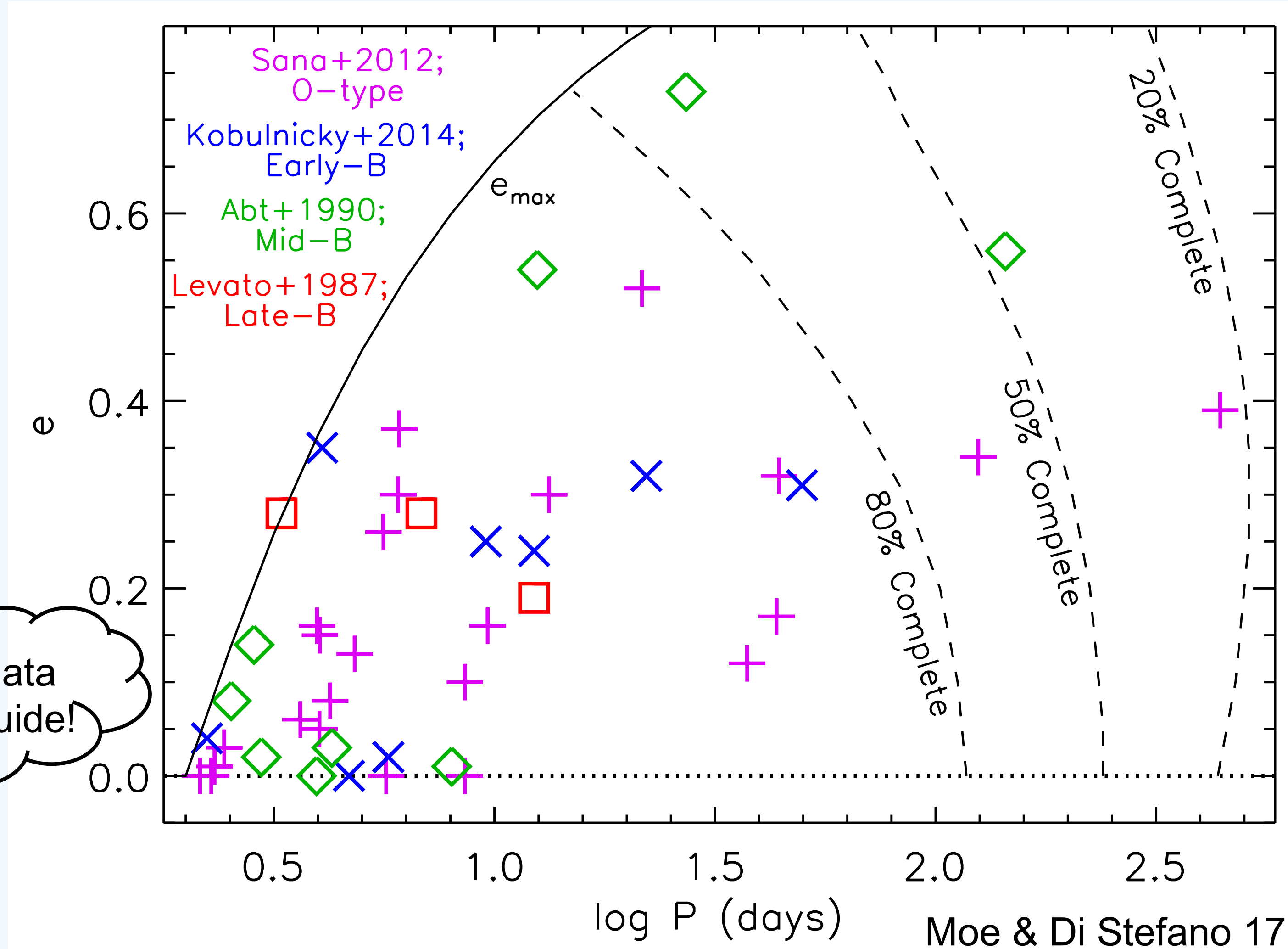
Tidal circularization period increases from P_{circ} = 6 days (pre-MS) to P_{circ} = 15 days (halo)

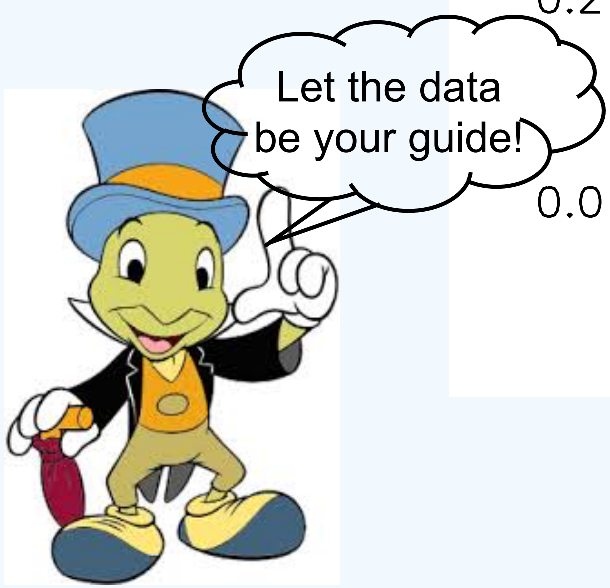
Beyond P > 100 days, $f_e \propto e^{\eta}$ with $\eta = 0.4$

Eccentricity distribution for early-type binaries

P_{circ} = 2 days
(tides less efficient in early-type stars)

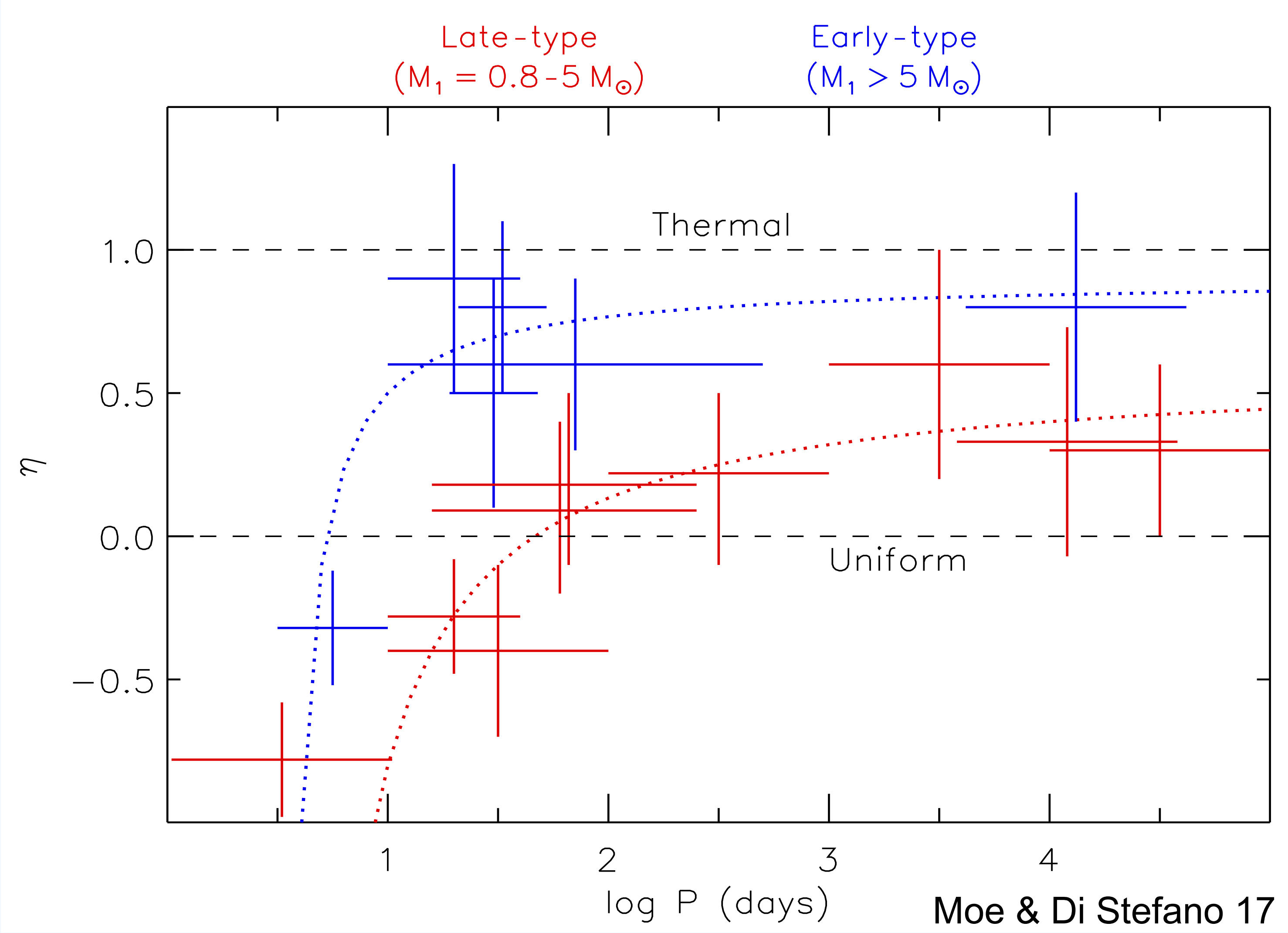
$e_{max}(P)$: maximum eccentricity without filling Roche-lobe at periastron





Eccentricity distribution f_e (M_1,P)

$f_e \propto e^\eta$
across domain
$0 < e < e_{max}(P)$

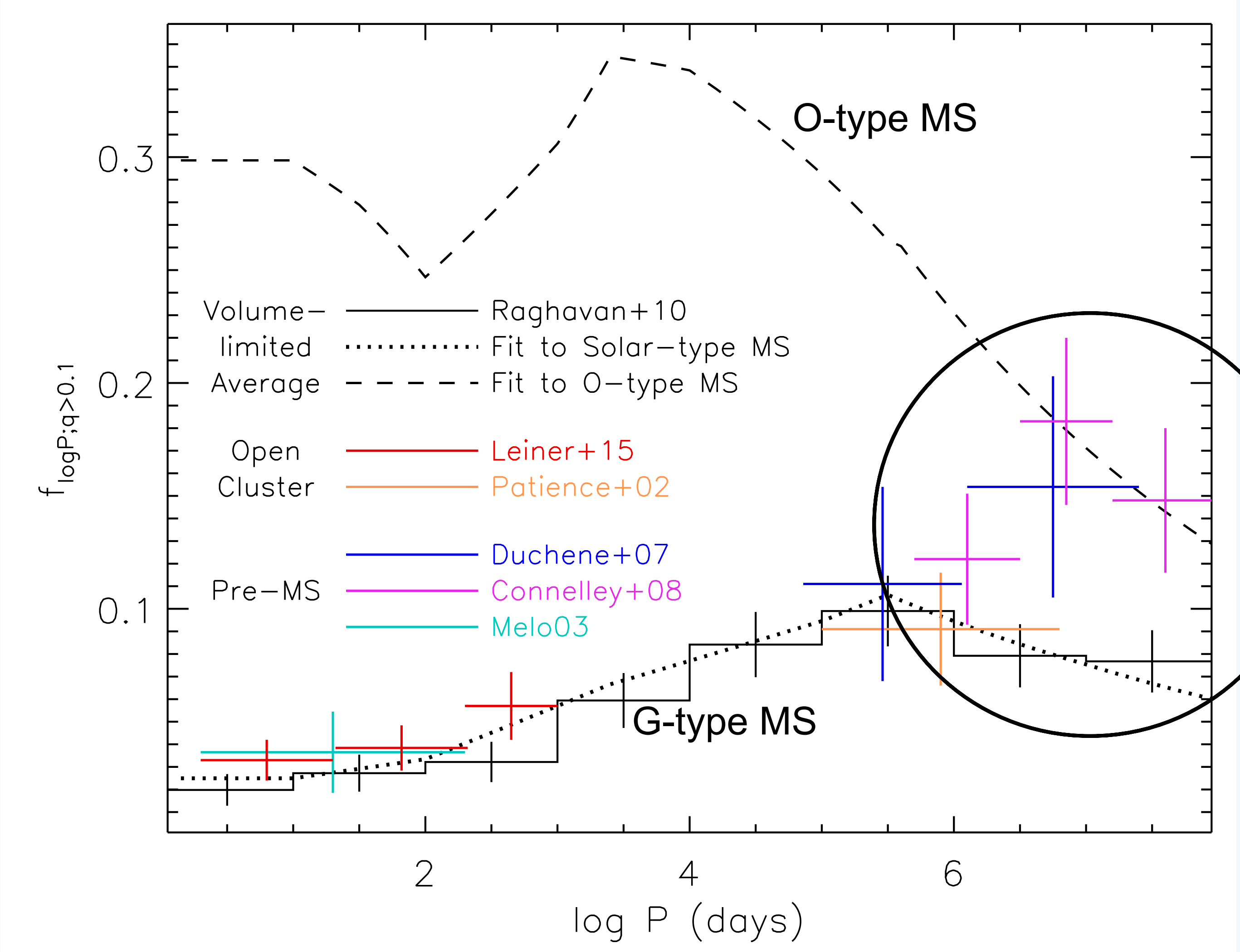


Tidal circularization dominates at P < 20 days

For P > 20 days, early-type binaries are consistent with a thermal distribution (η = 1; Ambartsumian 1937), indicating dynamical interactions play a role in their formation

Period distribution $f_{logP;q>0.1}(M_1, P, \tau)$ from Moe & Di Stefano (2017)

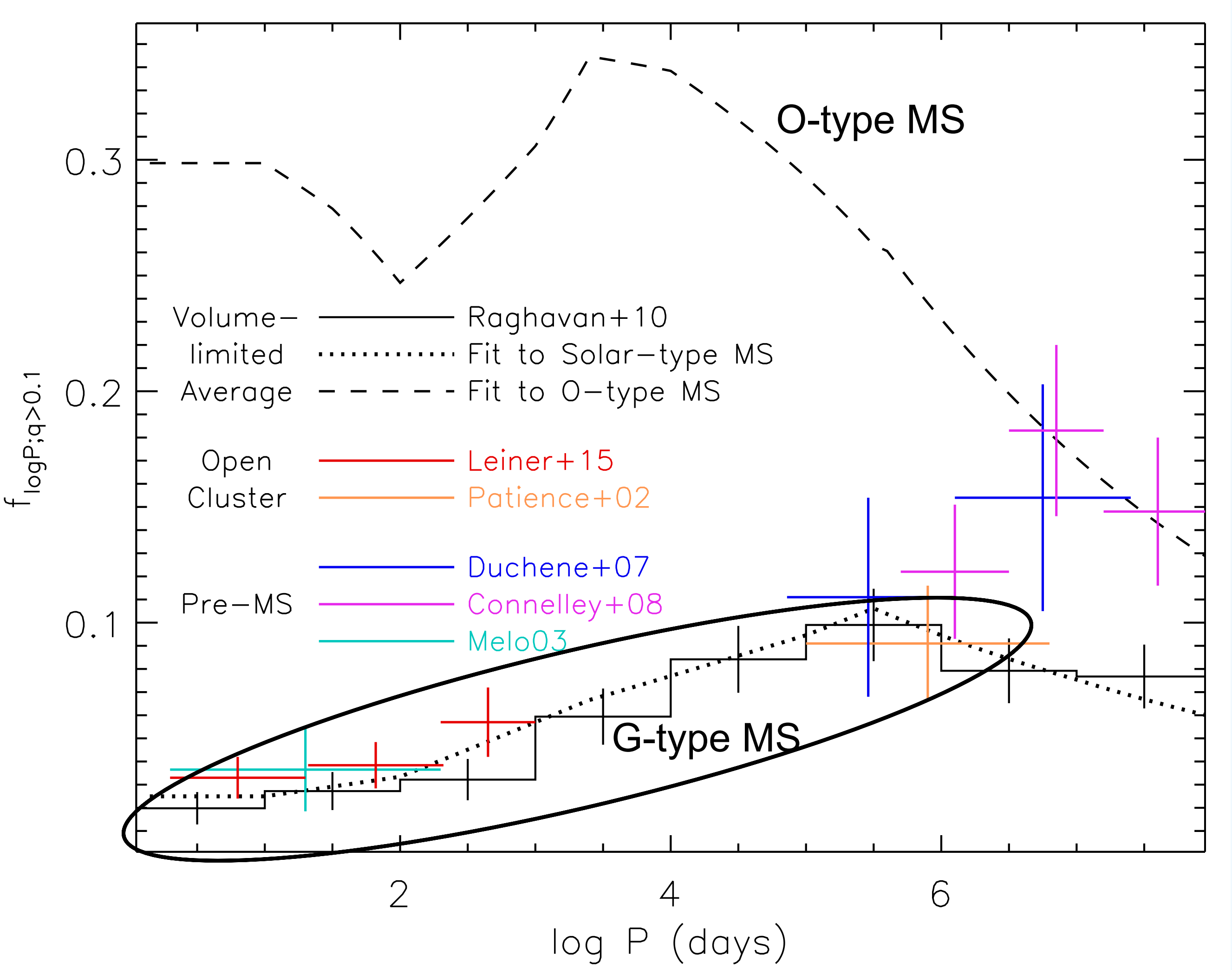
Frequency of companions with q > 0.1 per decade of period



Frequency of wide companions (a > 100 AU) to $M_1 = 1M_\odot$ pre-MS primaries is 2 - 3 times larger than that measured for $M_1 = 1M_\odot$ MS stars (Duchene+07, Connelley+08) and consistent with that measured for O-type MS primaries

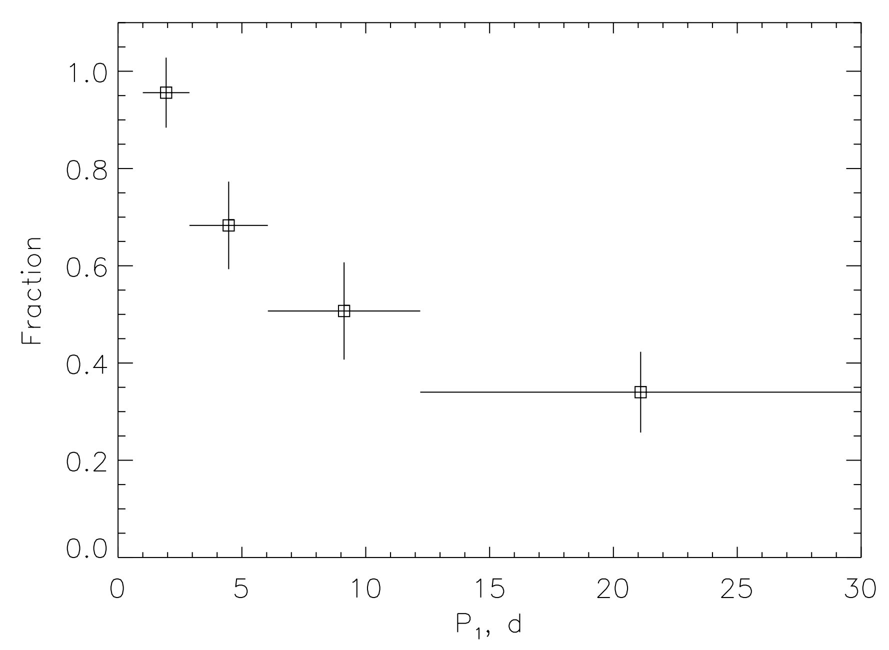
Period distribution $f_{logP;q>0.1}(M_1, P, \tau)$ from Moe & Di Stefano (2017)

Frequency of companions with q > 0.1 per decade of period

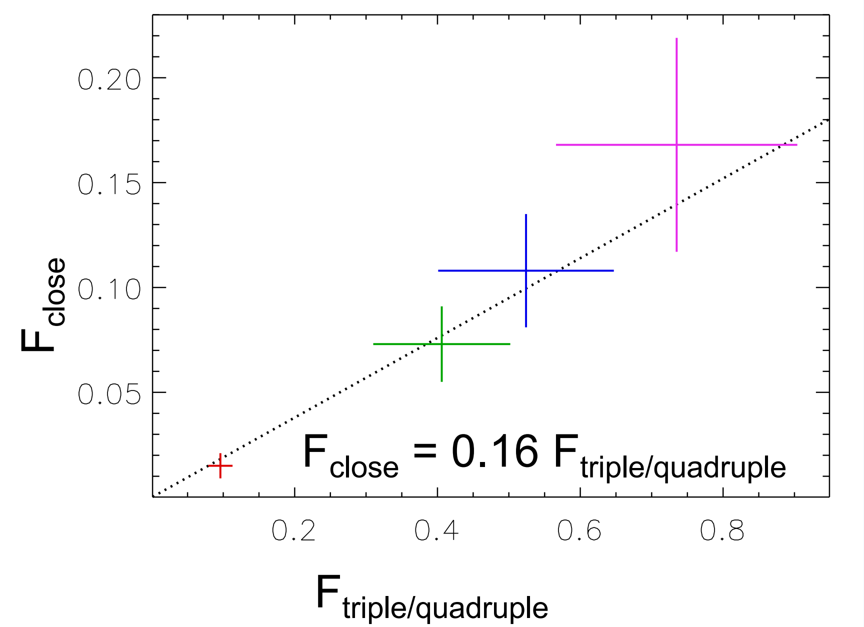


For pre-MS (Mathieu 94; Melo 03) and solar-type MS primaries in open clusters (Patience+03; Geller+12; Leiner+15), the companion frequency across a < 100 AU matches that for field solar-type MS stars, which is substantially smaller than that measured for O-type MS stars.

Very close binaries derive from dynamical interactions in triples



~80% of solar-type binaries with P_{inner} < 7 days have tertiary companions, while only ~30% of slightly wider binaries with P_{inner} > 20 days have such tertiary components (Tokovinin+ 2006)



The very close binary fraction (P < 7 days) is directly proportional to the overall triple/quadruple star fraction, independent of M_1 (Moe & Di Stefano 2017)

Very close binaries derive from dynamical interactions in triples **BUT mostly during the early pre-MS phase**

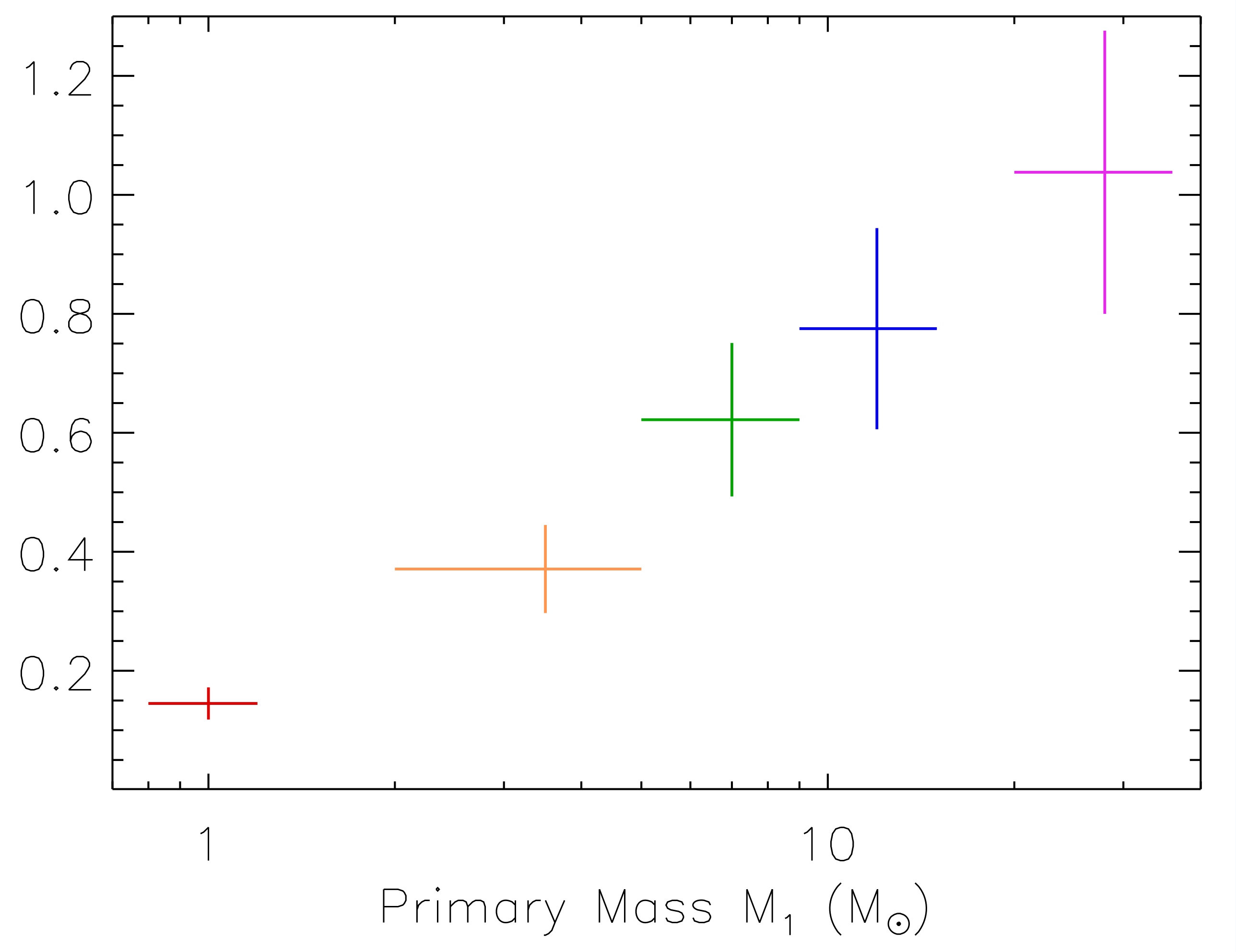
Two mechanisms:

Moe & Kratter 2017 (on arXiv today)

1) Kozai-Lidov oscillations in stable triples coupled with tidal friction (Kiseleva+ 98; Fabrycky & Tremaine 07)	20% MS	Inclined tertiaries with a_{outer} = 500 - 5,000 AU
	20% pre-MS	Inclined tertiaries with a_{outer} = 20 - 1,000 AU
2) Dynamical unfolding of unstable triples combined with significant energy dissipation in disk (Bate+ 02, 09)	60% pre-MS	Coplanar tertiaries with a_{outer} = 0.5 - 50 AU

Binary Star Evolution via RLOF (Moe and Di Stefano 2017)

Frequency of companions with log P (days) < 3.7 (a < 10 AU) and q > 0.1



- Only 15% of M_1 = 1 $M_\odot$ primaries will interact via RLOF
- 80 - 90% of O-type primaries will experience RLOF (consistent with Sana+ 2012)
- 10 - 20% of O-type primaries are in compact triples with a_{outer} < 10 AU

Binary Star Evolution via RLOF (Moe and Di Stefano 2017)

Even for a < 10 AU, the distribution of ZAMS binary properties are highly correlated (see also Abt+ 1990 and Duchene & Kraus 2013):

$$f(M_1, P, q, e) \neq f(M_1) \times f(P) \times f(q) \times f(e)$$

The density of binaries in certain pockets of the $f(M_1, P, q, e)$ parameter space differs by up to a factor of **~50** compared to canonical initial conditions adopted in many binary population synthesis studies

Separately adjusting the individual distributions f(P), f(q), and f(e) to the extremes will still not encompass the true nature of the binary population

Monte Carlo code that generates population of binaries based on observed $f(M_1, P, q, e)$ is available

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)

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

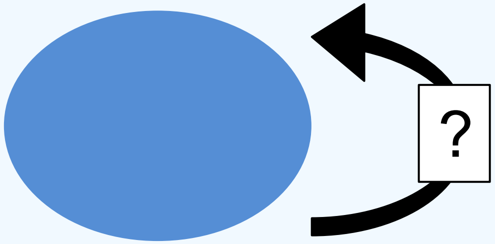
30% ± 10% of SB1s contain compact remnant companions

Solar-type SB1s:
1) Sirius-like binaries with hot WDs
2) Barium stars

Early-type SB1s:
1) EBs vs. SB1s
2) N(SB1s)/N(SB2s) increases with age

Malachi **Regulus** Moe

Regulus (α Leonis - the heart of the lion):
- SB1 with P = 40 days
- Rapidly rotating B-type star
- Companion either K-dwarf or WD



30 ± 10% of SB1s have compact remnant companions
(Moe & Di Stefano 2017)

How the close binary fraction changes with decreasing metallicity Z

Reference	Spectral Type	Minimum $\log(Z/Z_\odot)$	As Z↓, $\Delta F/F$
Carney+ 2005	G	−2.4	<|30%|
Gao+ 2014	G	−1.5	+50%
Hettinger+ 2015	F	−1.7	−25%
Moe+ 2013	B	−0.7	<|20%|
Dunstall+ 2015	B	−0.4	<|30%|

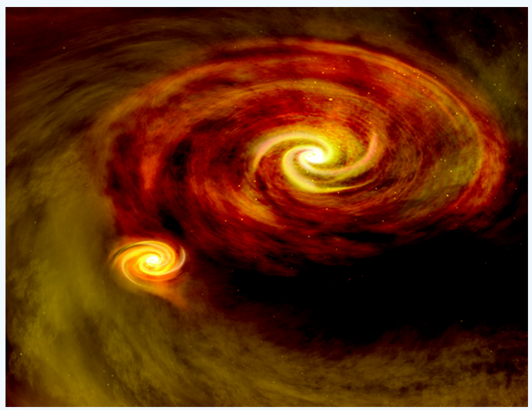
Variations with respect to Z are small and possibly due to sensitivity and selection biases, e.g., lower-metallicity stars are systematically older and more likely to contain WD companions

Multiplicity Statistics: Diagnostics for Binary Star Formation and Initial Conditions for Binary Star Evolution (Moe & Di Stefano 2017)

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

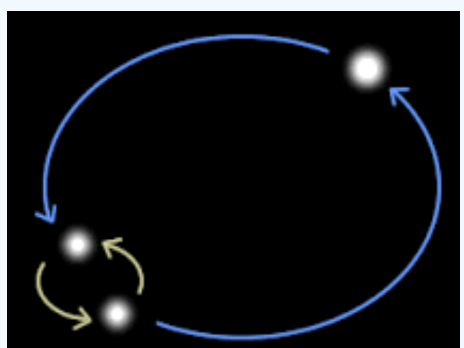
- f_{wide} = 0.5, initially independent of M_1
- f(q) initially consistent with random pairings drawn from IMF
- Subsequent dynamical ejections: systems with smaller M_1 and q are preferentially disrupted by ZAMS

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



- f_{mid} = 0.4 ($M_1 = 1M_\odot$) - 1.5 ($30M_\odot$)
- f(q) correlated due to co-evolution / shared accretion in the disk
- $M_1 = 1M_\odot$: uniform f(q)
- $M_1 > 5M_\odot$: 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 ($M_1 = 1M_\odot$) - 0.2 ($30M_\odot$)
- Most have outer tertiaries
- Uniform f(q) with excess twin fraction