Pre-Main-Sequence Binaries

Multiplicity Statistics → Fragmentation, Accretion, & Migration

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In Colloboration With

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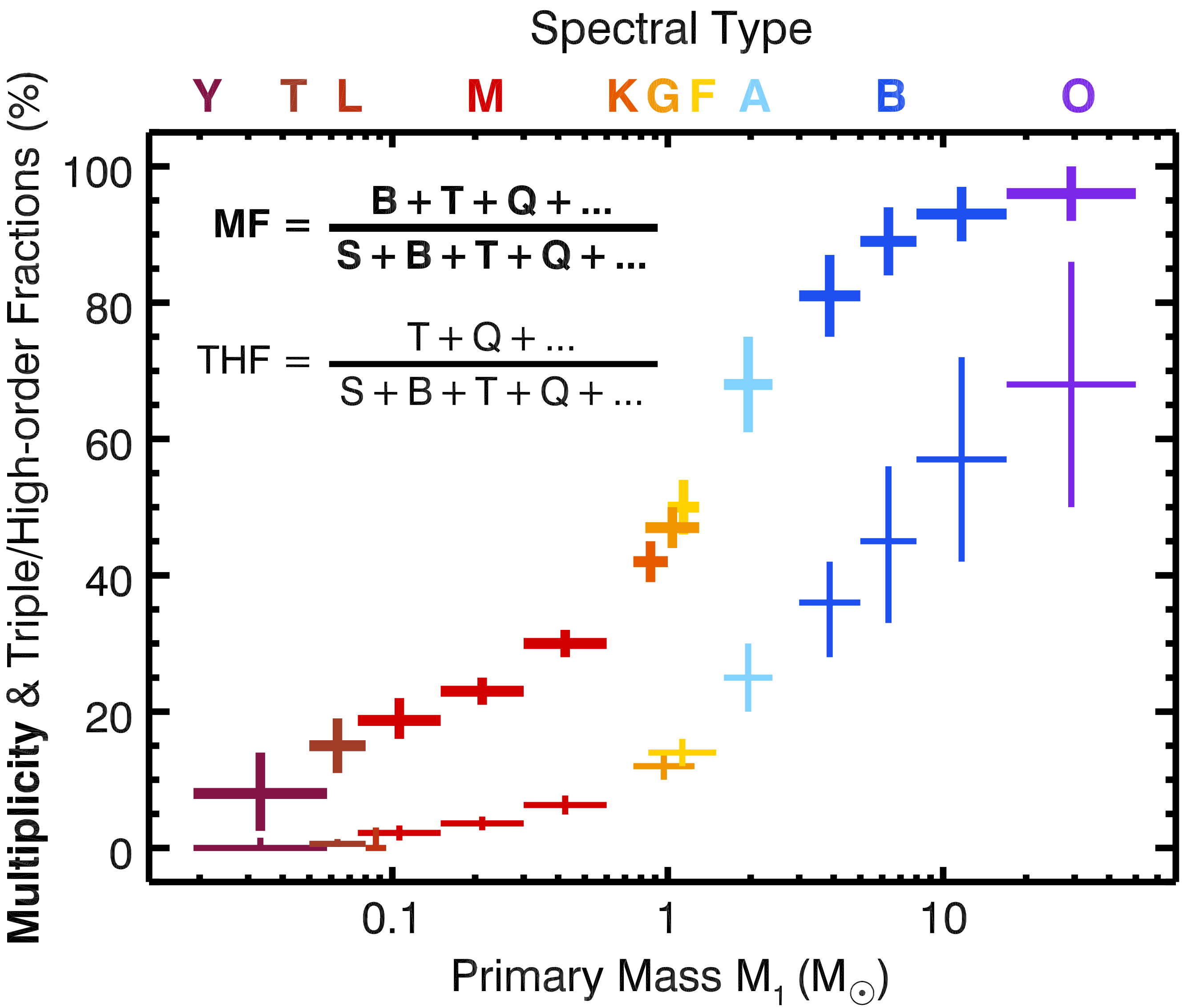
Thank You Organizers Dan, Zoltan, Yan-Fei, & Kaitlin!

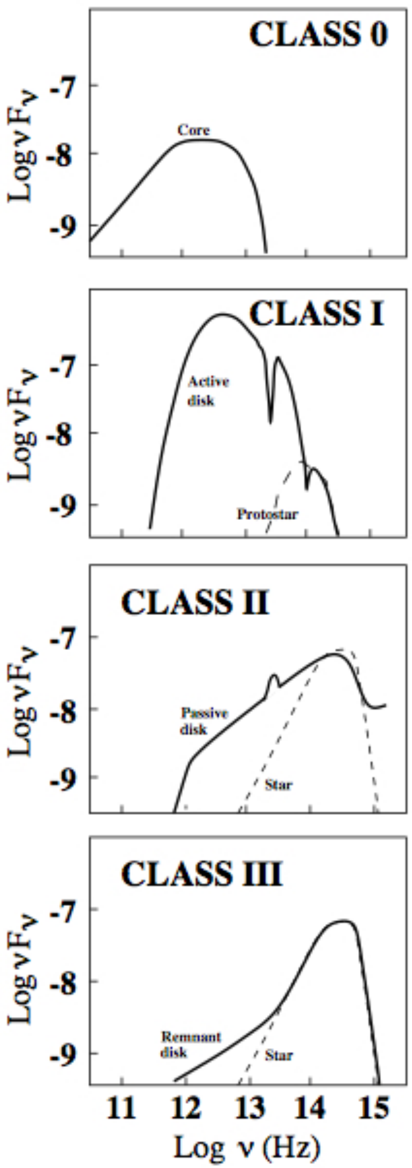
Multiplicity Statistics of Main-Sequence (MS) Stars

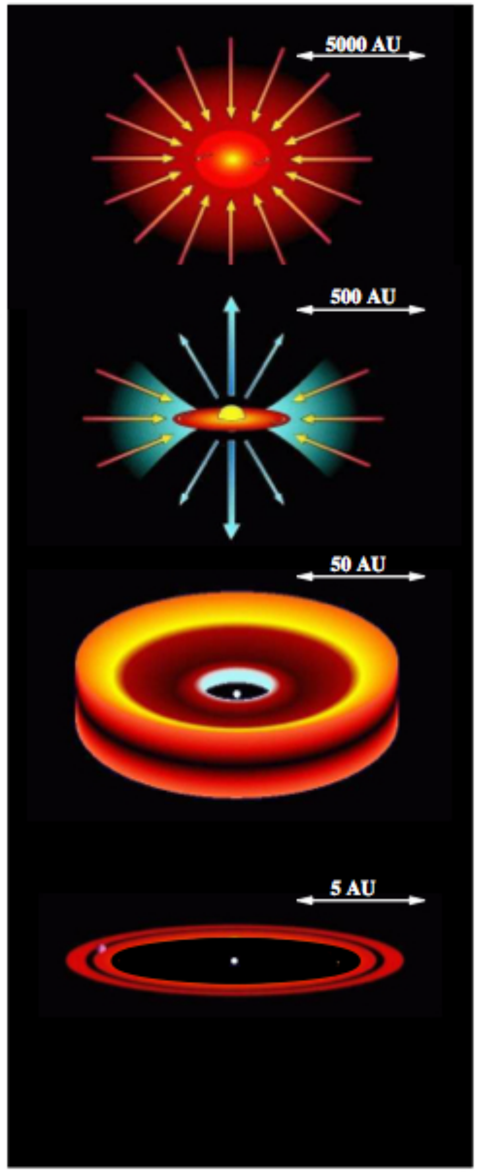


Offner, Moe, Kratter, et al.

(review chapter for Protostars & Planets VII)

Classification of Young Stellar Objects (YSOs)





$M_{gas} \approx 1 - 100\ M_*$
$\tau \approx 0.05$ Myr

$M_{gas} \approx 0.2\ M_*$
$\tau \approx 0.5$ Myr

$M_{gas} \approx 10^{-2}\ M_*$
$\tau \approx 3$ Myr

$M_{gas} \approx 10^{-4}\ M_*$
$\tau \approx 10$ Myr

Embedded Protostars

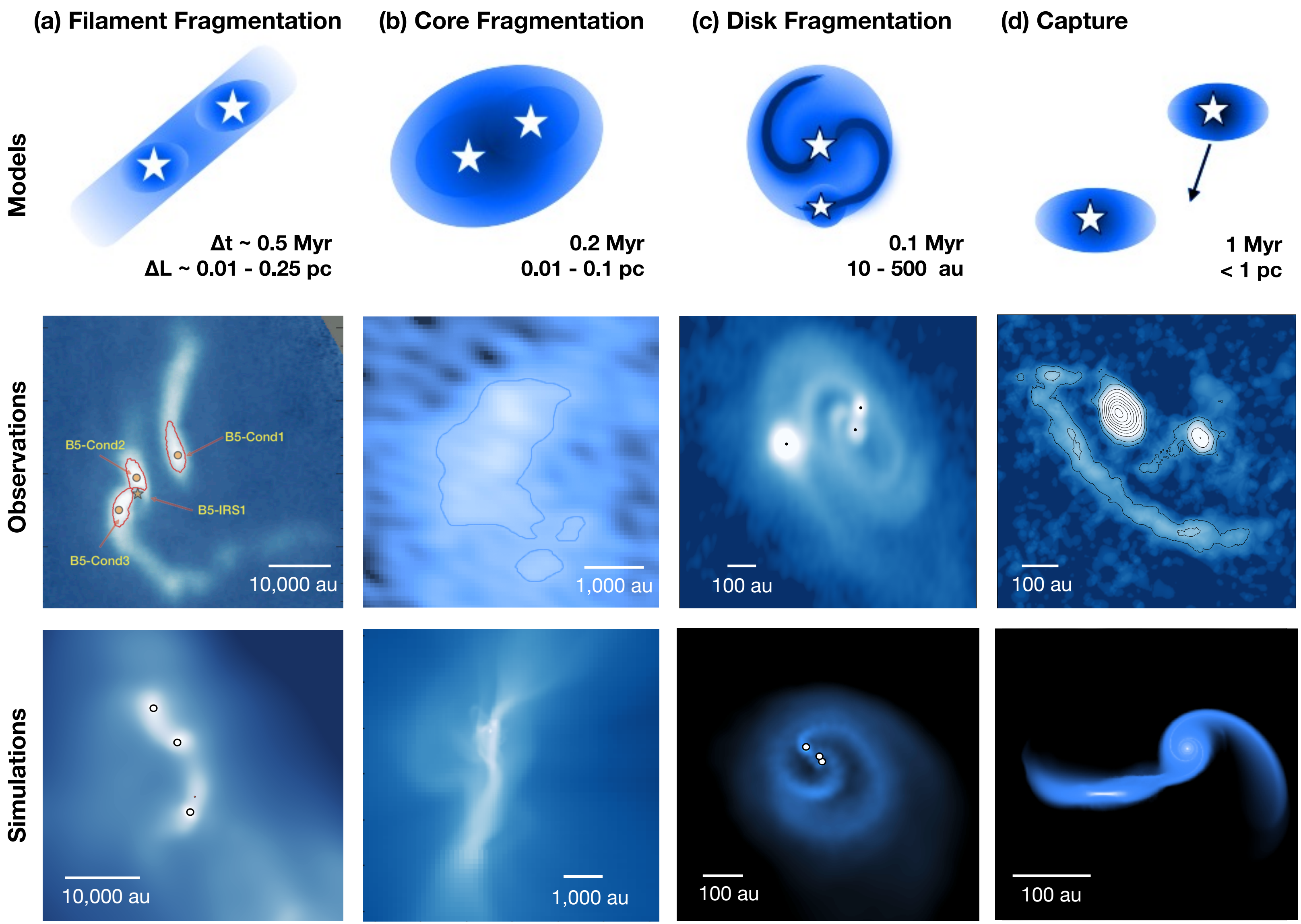
Pre-MS Stars:

T Tauri ($M_* < 2\ M_\odot$)
Herbig Ae/Be (2-16 $M_\odot$)

Isella (2006)

Williams & Cieza (2011)

Binary Star Formation Channels



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Close Binary Stars (a < 10 AU) Cannot Form *In Situ*

Core Fragmentation?: First hydrostatic core has radius r ≈ 5 - 10 AU (Larson 1969)

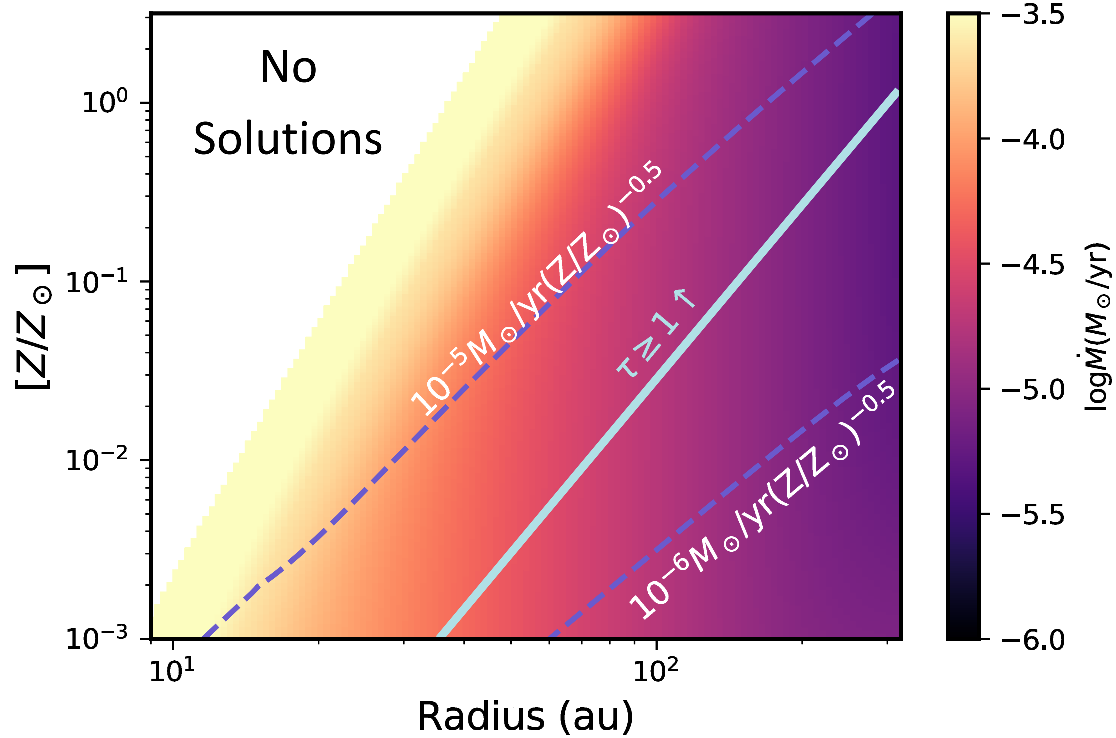
Core fragmentation during secondary collapse stage extremely unlikely (Boss 1986; Bate 1998, 2011)

Disk Fragmentation?:

Inner disk too hot to fragment:

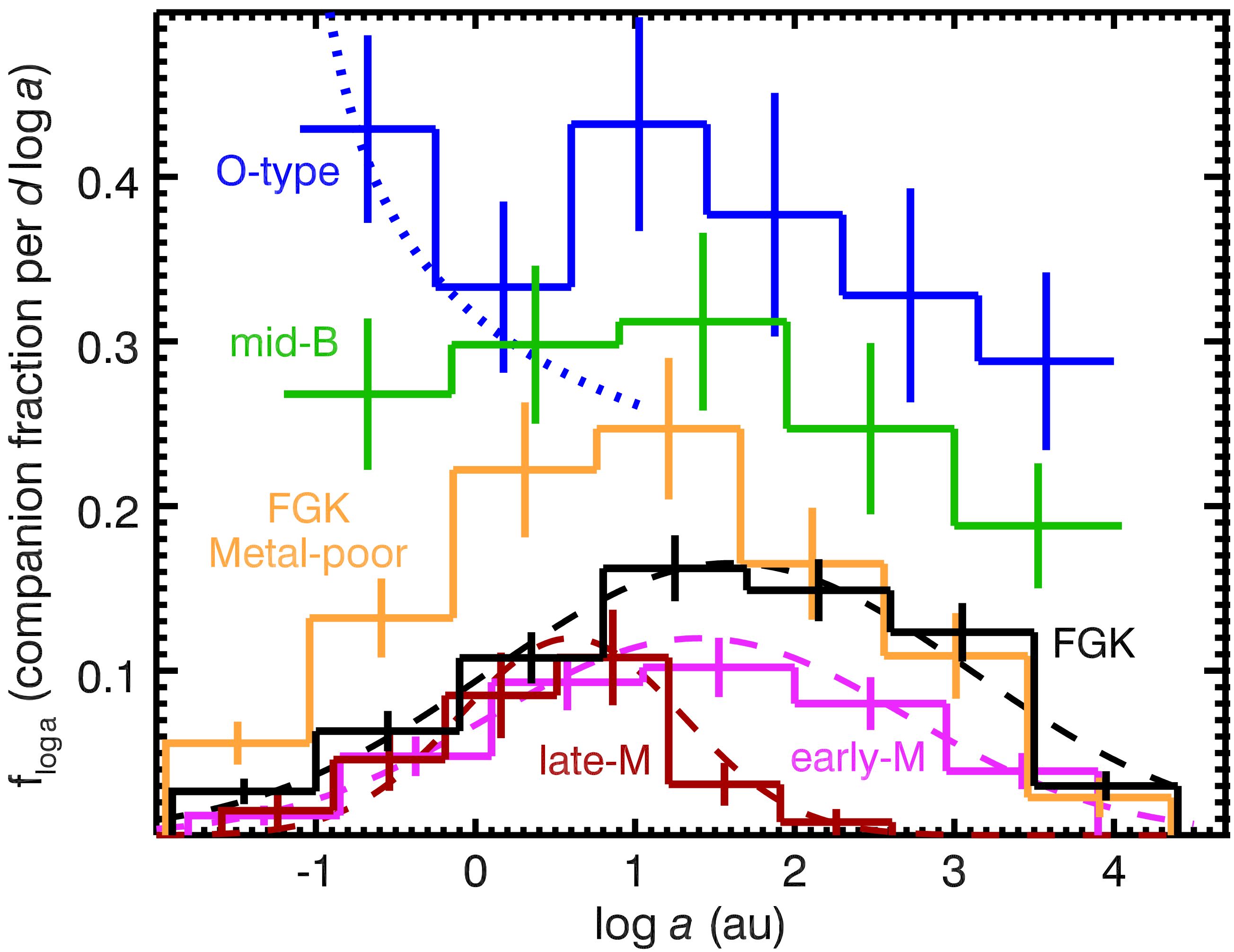
$$Q_{Toomre} = c_s \kappa / \pi G \Sigma < 1$$

$$t_{cool}\, \Omega < 1$$



Moe, Kratter, & Badenes (2019)

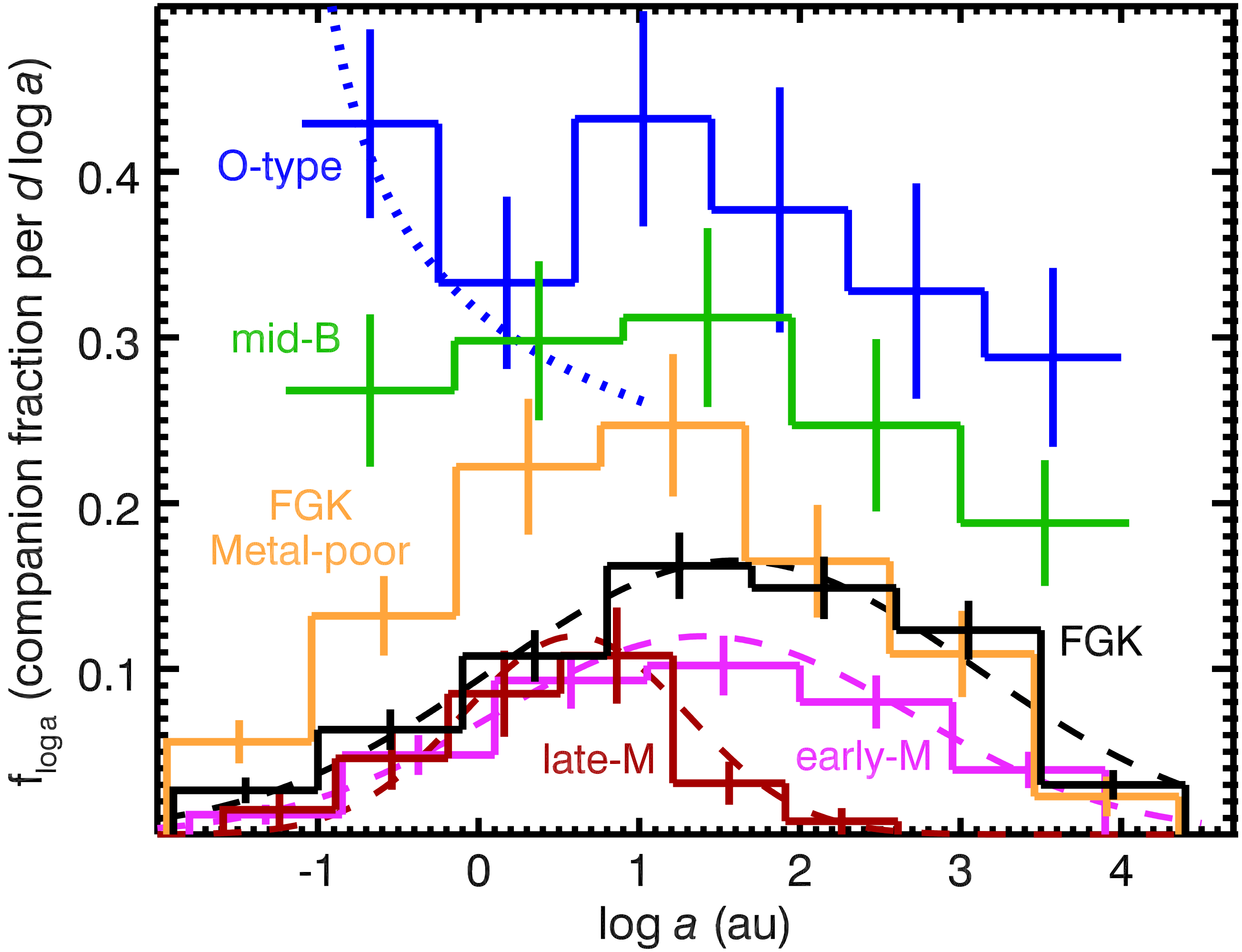
Orbital Separation Distribution of MS Binaries



Offner, Moe, Kratter, et al. (review chapter for Protostars & Planets VII)

Solar-type binaries follow log-normal distribution, peaking near 50 AU; $F_{a<10au} \approx 20\%$ (Duquennoy & Mayor 1991; Raghavan et al. 2010; Tokovinin 2014)

Orbital Separation Distribution of MS Binaries



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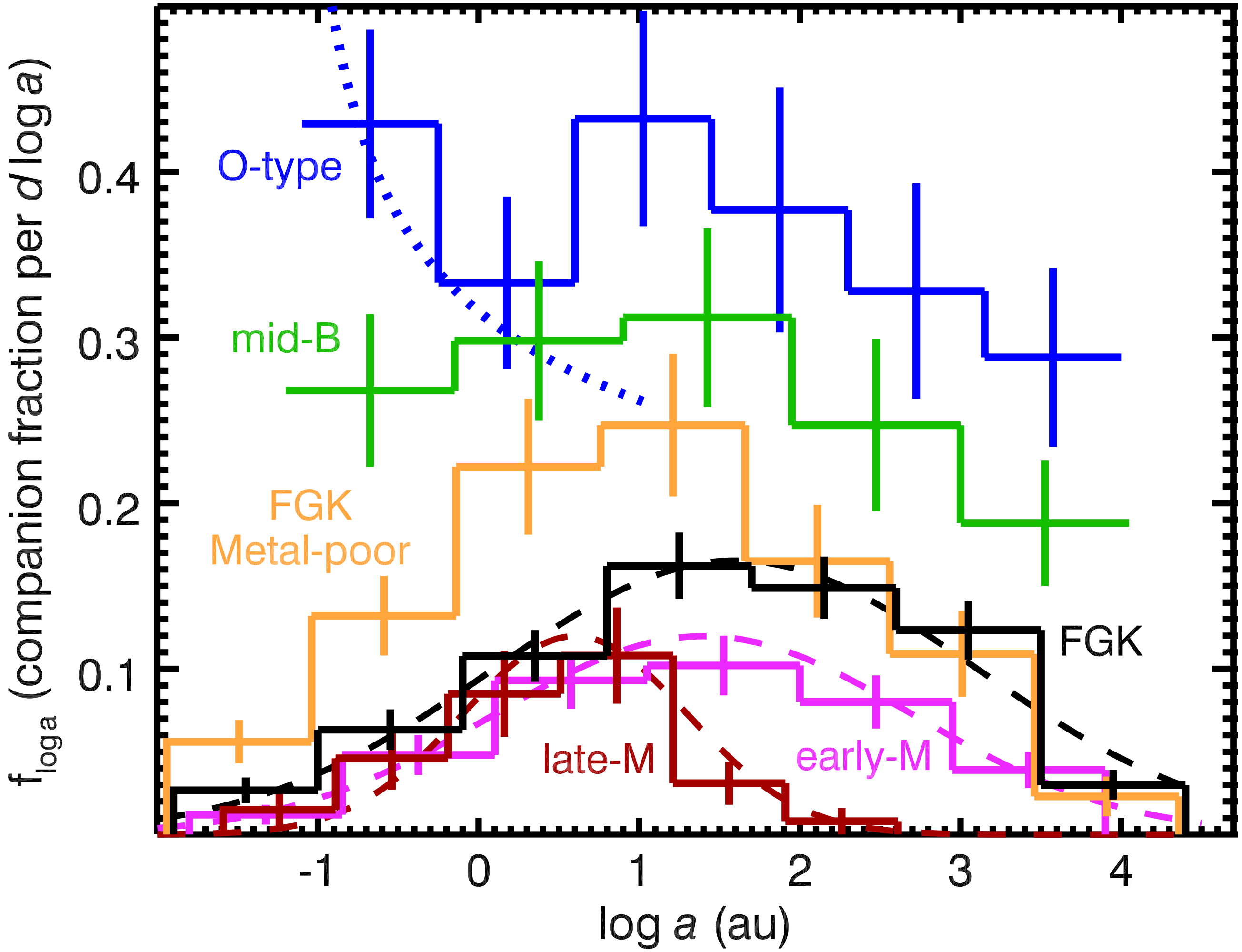
Low-mass binaries peak at shorter separations; $F_{a<10au} \approx 15\%$
(Fischer & Marcy 1992; Janson et al. 2012,2014; Winters et al. 2019)

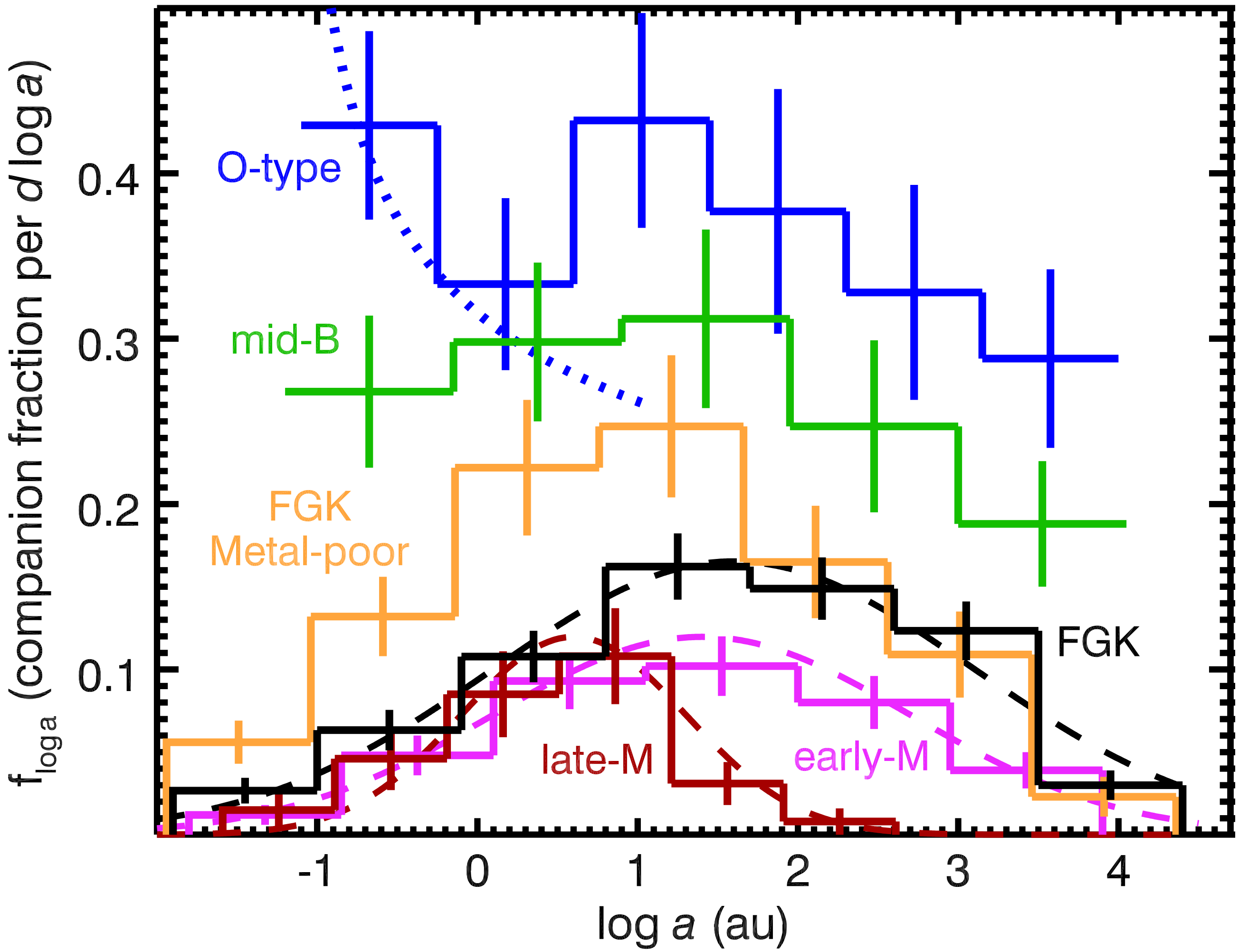
Orbital Separation Distribution of MS Binaries



Offner, Moe, Kratter, et al. (review chapter for Protostars & Planets VII)

Close binary fraction of solar-type stars decreases from $F_{a<10au}$ ≈ 40% at [Fe/H] = –1.0 to $F_{a<10au}$ ≈ 10% at [Fe/H] = 0.5, but wide binary fraction is metallicity invariant (Badenes et al. 2018; Moe et al. 2019; El-Badry & Rix 2019)

Orbital Separation Distribution of MS Binaries



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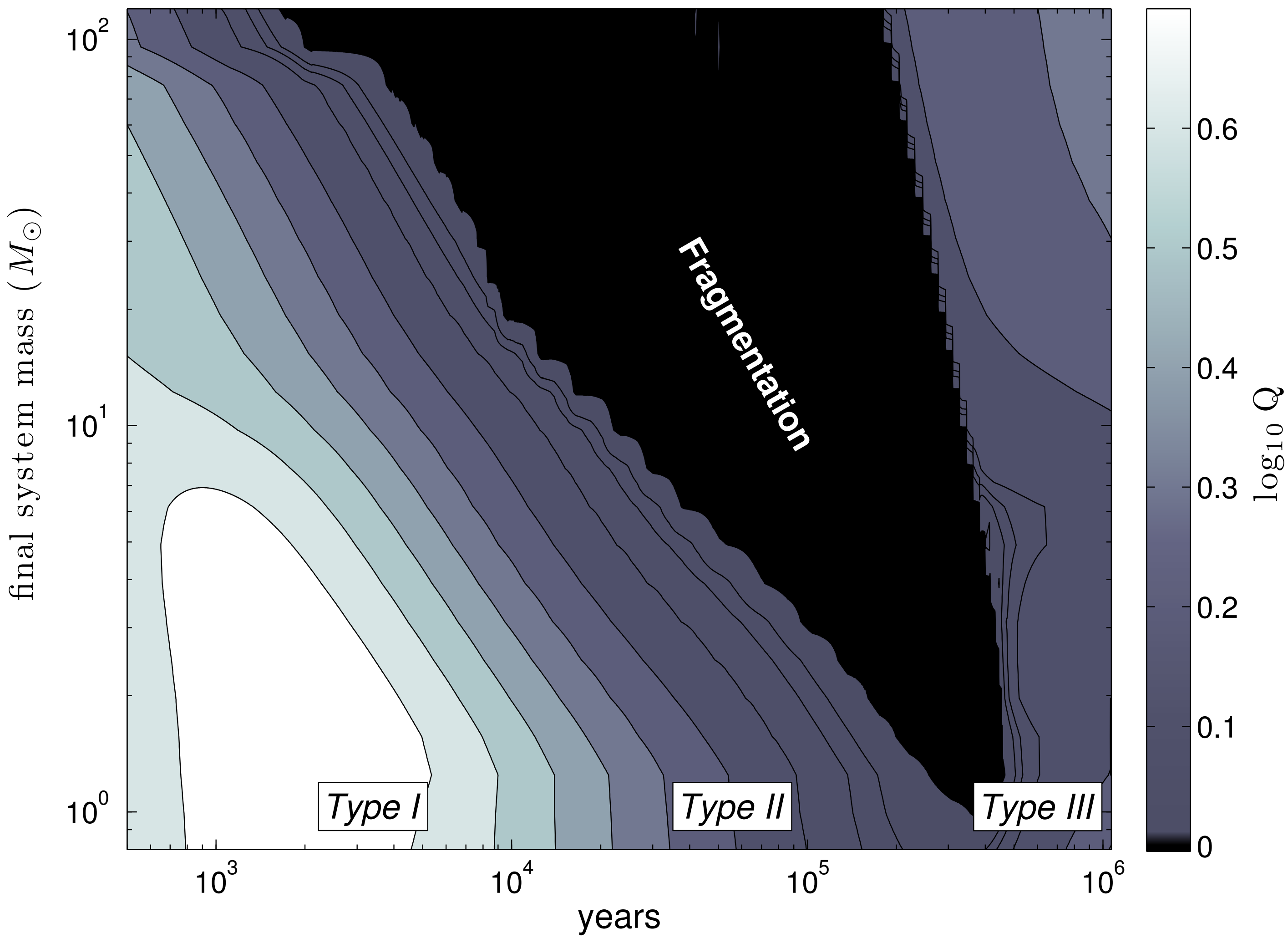
Protostars & Planets VII)

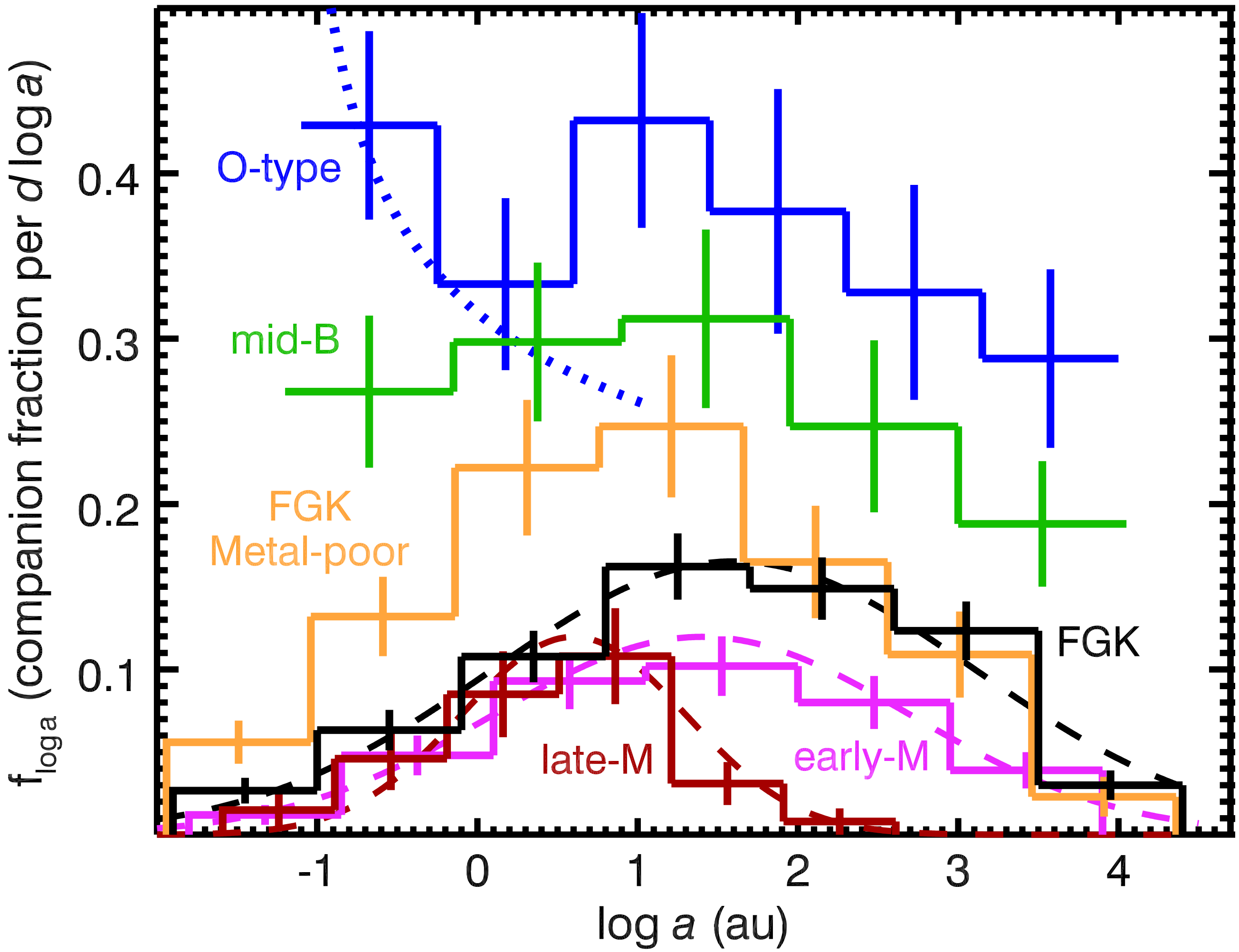
Companions to OB stars follow Öpik's law (Abt et al. 1990; Moe & Di Stefano 2017), but *inner* binary companions to O stars are skewed toward short separations (Sana et al. 2012; dotted blue; $F_{a<10au} \approx 70\%$)

More Massive Disks are More Prone to Fragmentation



Kratter, Matzner, & Krumholz (2008)

Orbital Separation Distribution of MS Binaries



Offner, Moe, Kratter, et al.

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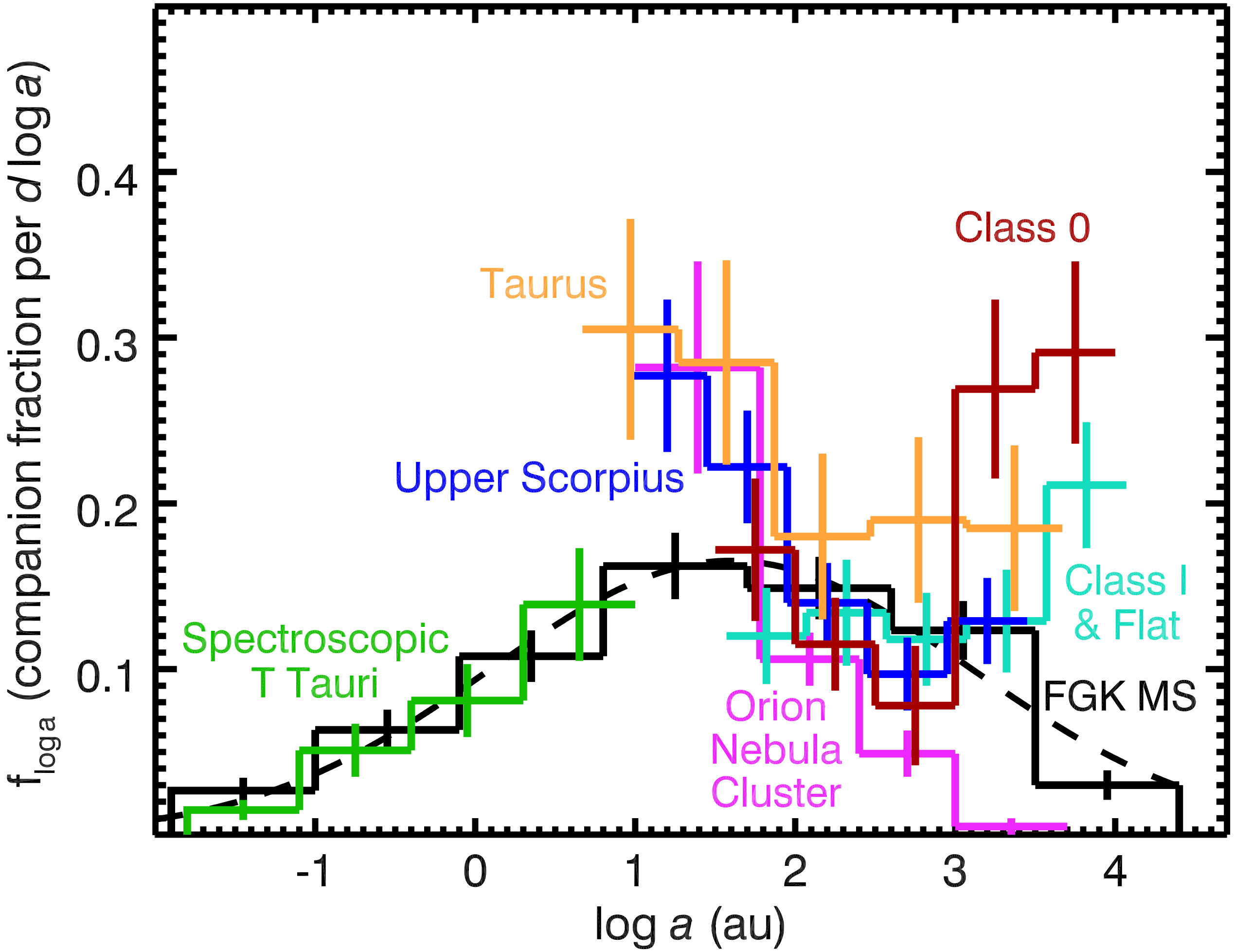
Increasing probability of disk fragmentation with mass explains observed trend in close binary fraction, but *not separation distribution*

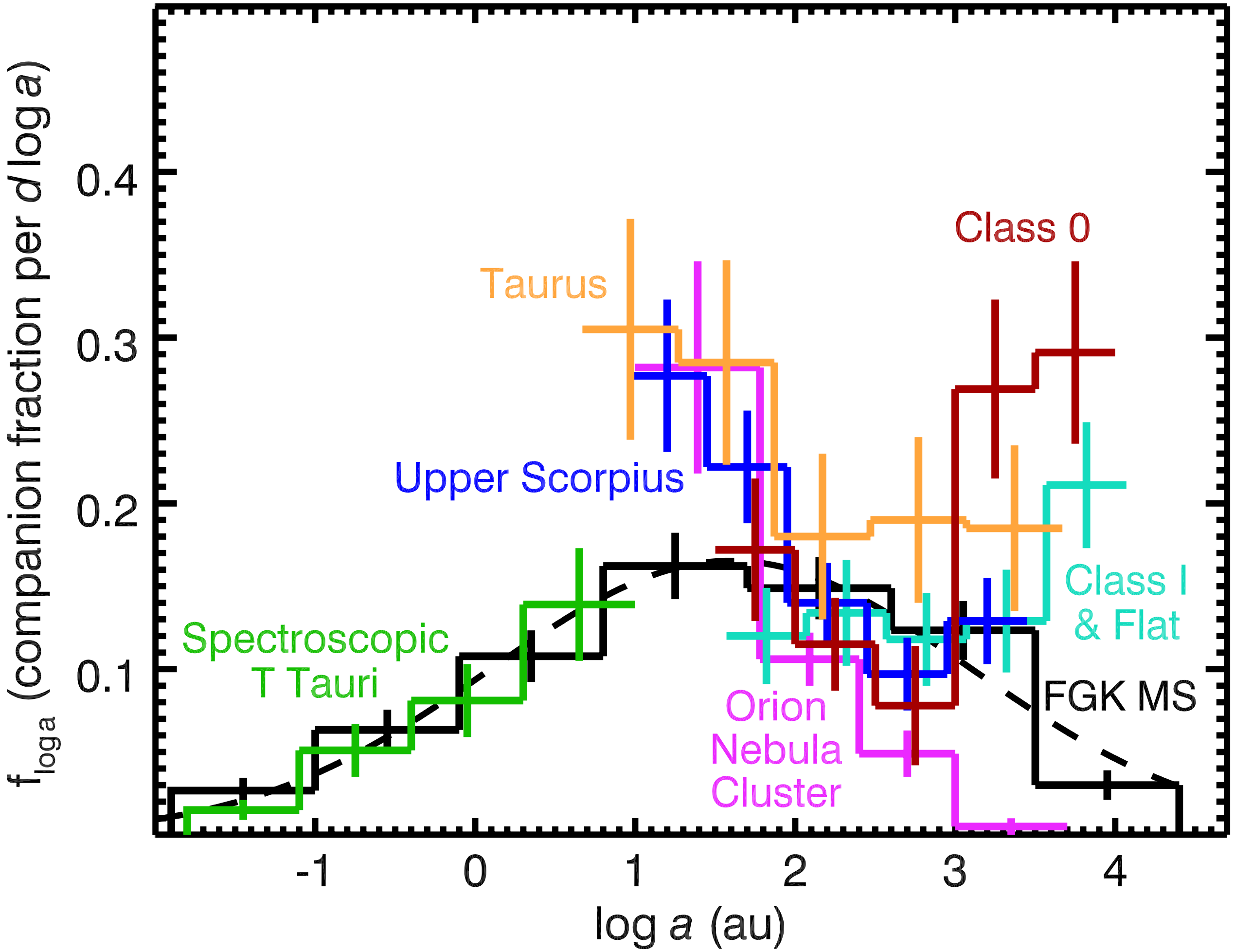
Orbital Separation Distribution of Solar-type Pre-MS Binaries



Offner, Moe, Kratter, et al. (review chapter for Protostars & Planets VII)

Wide binary fraction of pre-MS stars depends on age and stellar density, but close pre-MS binaries are consistent across all environments, matching the MS distribution (Kounkel, Covey, Moe, et al. 2019)

Orbital Separation Distribution of Solar-type Pre-MS Binaries



Offner, Moe, Kratter, et al.
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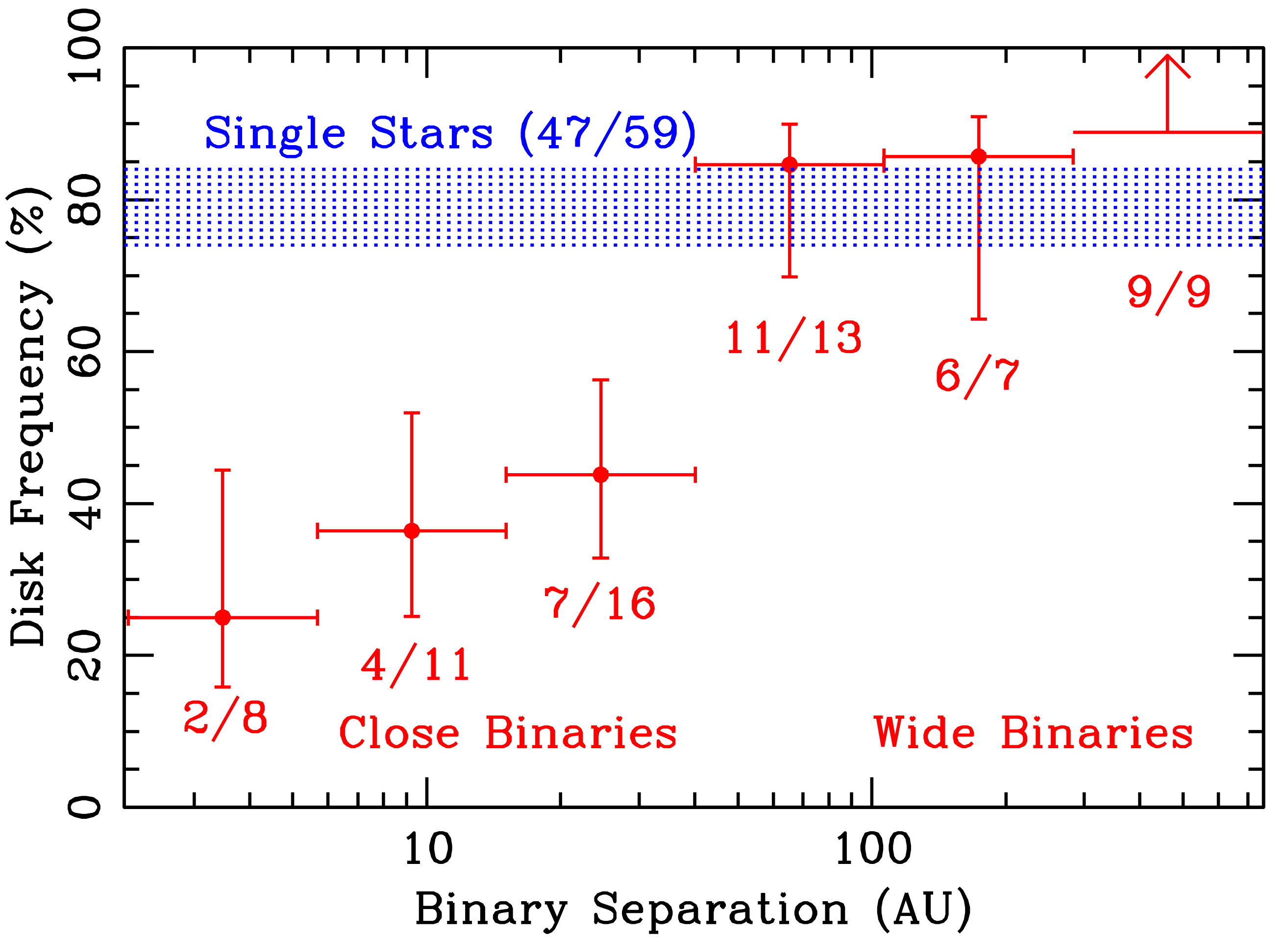
Close binaries originally migrated from
a > 50 AU to a = 0.1 - 10 AU
during embedded Class 0/I phase within τ < 1 Myr

Close Companions Truncate Circumprimary Disk Mass / Lifetime

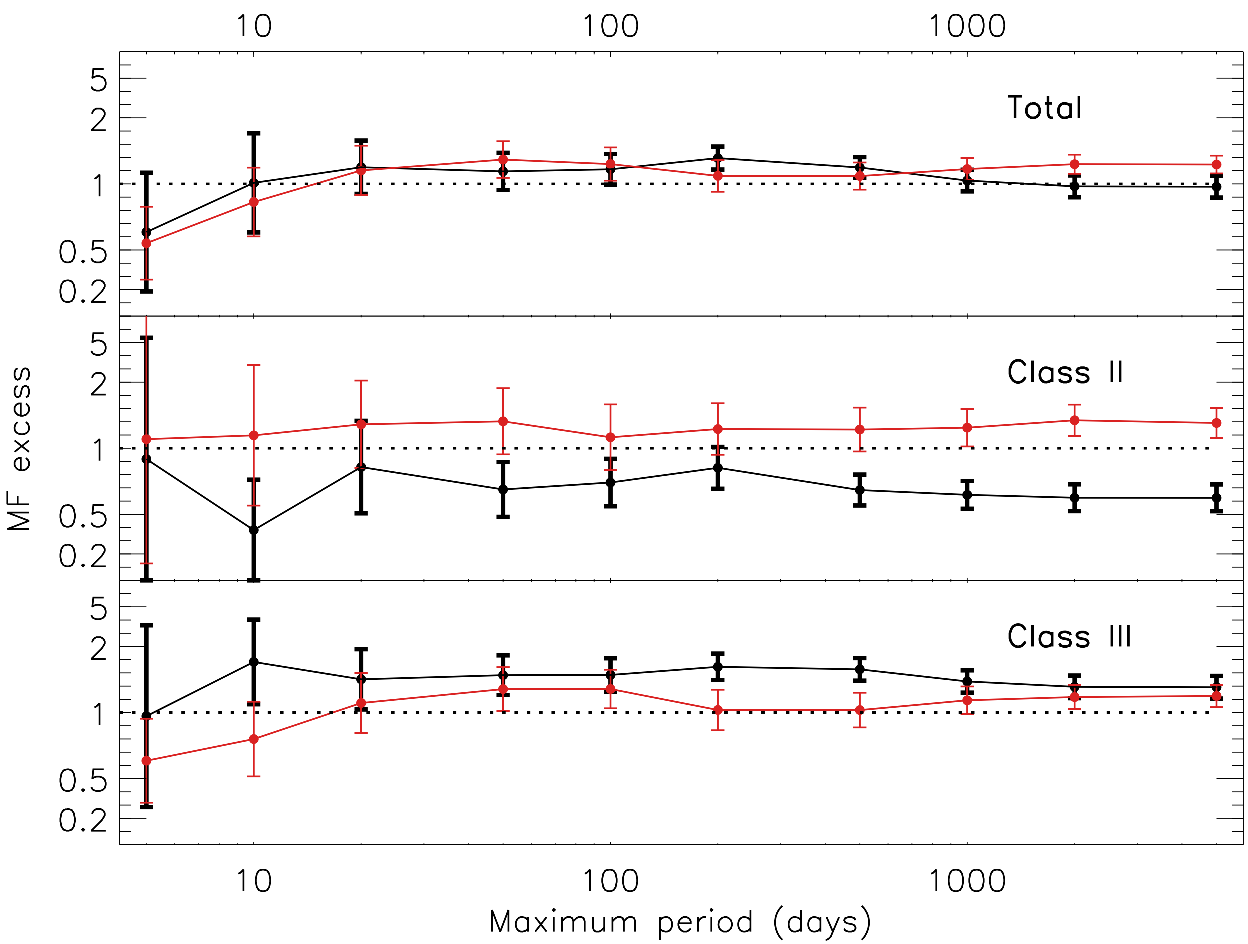
Binaries with a < 50 AU have smaller disk frequency
(Jensen et al. 1996; Kraus et al. 2012; Harris et al. 2012; Cheetham et al. 2015)



Taurus-Auriga:
τ ≈ 1 - 2 Myr
(Kraus et al. 2012)

Close Companions Truncate Circumprimary Disk Mass / Lifetime

Class II (Classical T Tauri): Deficit of Close Binaries
Class III (Weak-lined T Tauri): Surplus of Close Binaries
Class II + Class III: Matches Field MS Distribution



Kounkel et al. 2019

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Three Key Parameters:

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

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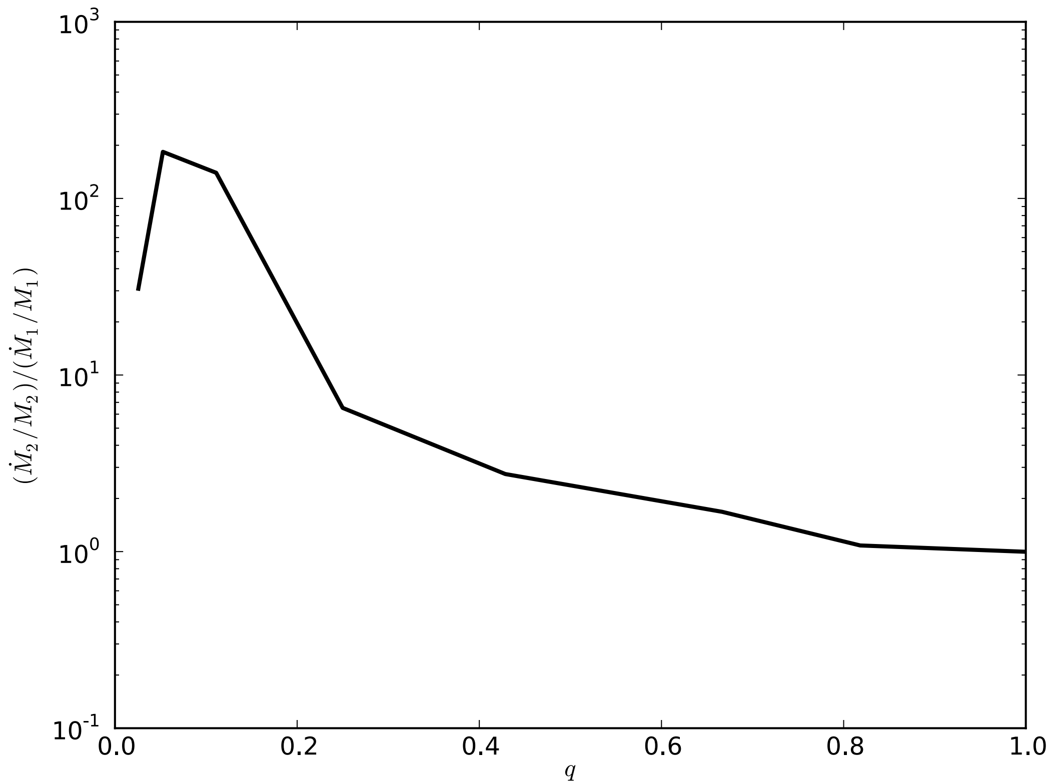
1) Preferential Accretion onto Secondary
(Bate & Bonnell 1997; Farris et al. 2014; Young & Clarke 2015)



Farris et al. 2014

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$f_2 = \Delta M_2 / \Delta M = 0.5 + 0.5x(1\text{-}q)^{0.7}$ where $x = [0, 1]$

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2) Orbital Migration scales with Accreted Mass onto Secondary

$$\frac{\mathrm{d}a}{a} = -\eta \frac{\mathrm{d}M_2}{M_2}$$

Tang et al. (2017) slow sinks: $\eta = 3.2$
Muñoz et al. (2019) $q = 1.0$: $\eta = -2.1$
Muñoz et al. (2020) $q < 0.2$: $\eta > 0$
Duffell et al. (2020) $q < 0.05$: $\eta > 0$

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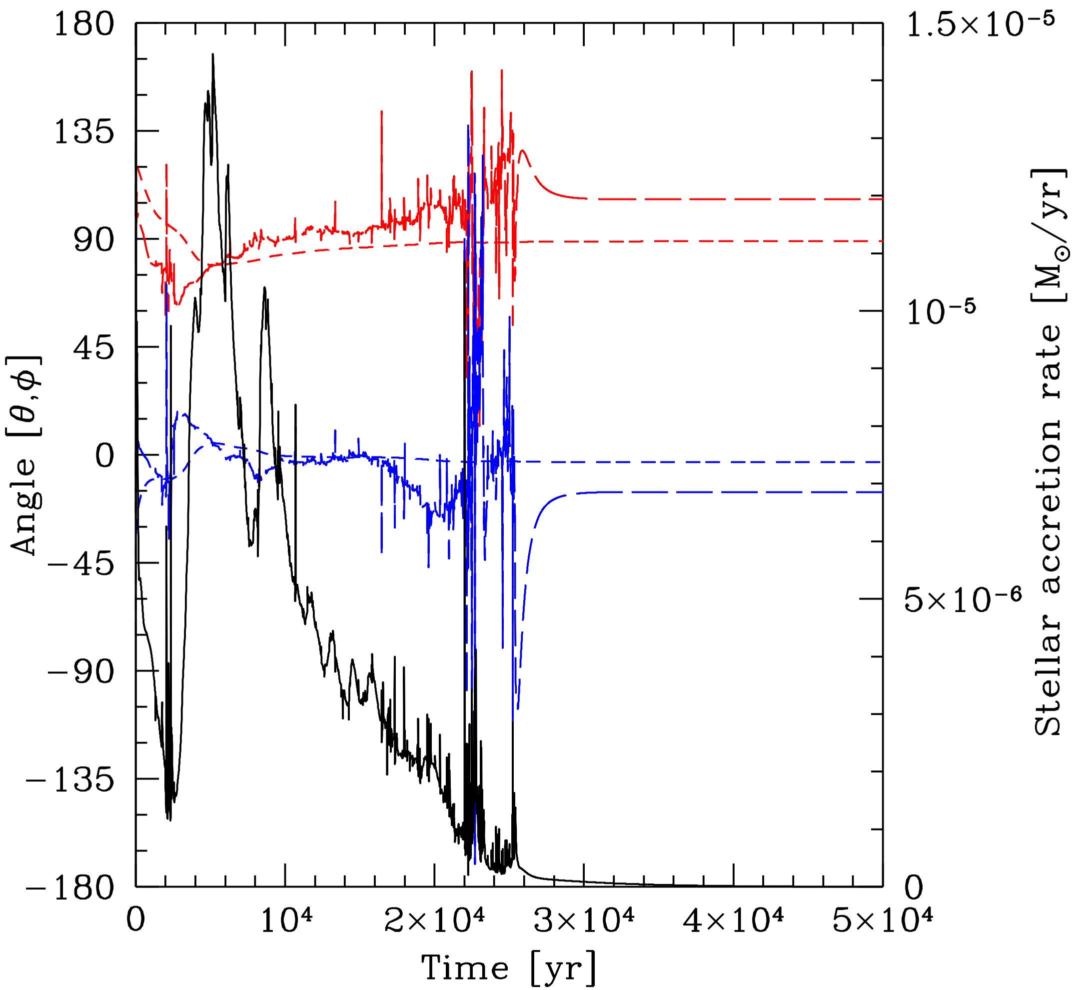
3) Stochastic / Variable $\dot{M}$ and $\dot{J}$

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

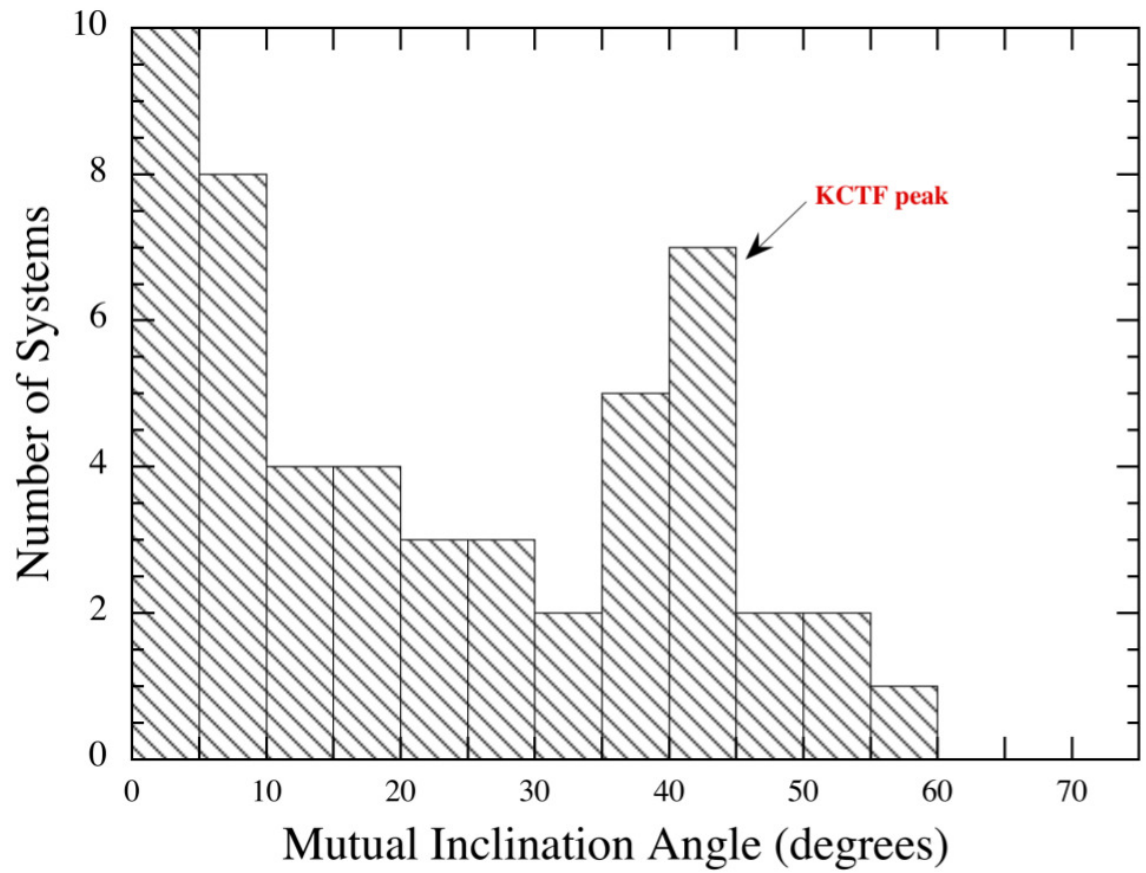
Bate, Lodato, & Pringle (2010)



Mass infall rate (and direction of infall) onto protostellar disks varies on timescales of 10^3 yr (10s to 100s of orbits)

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

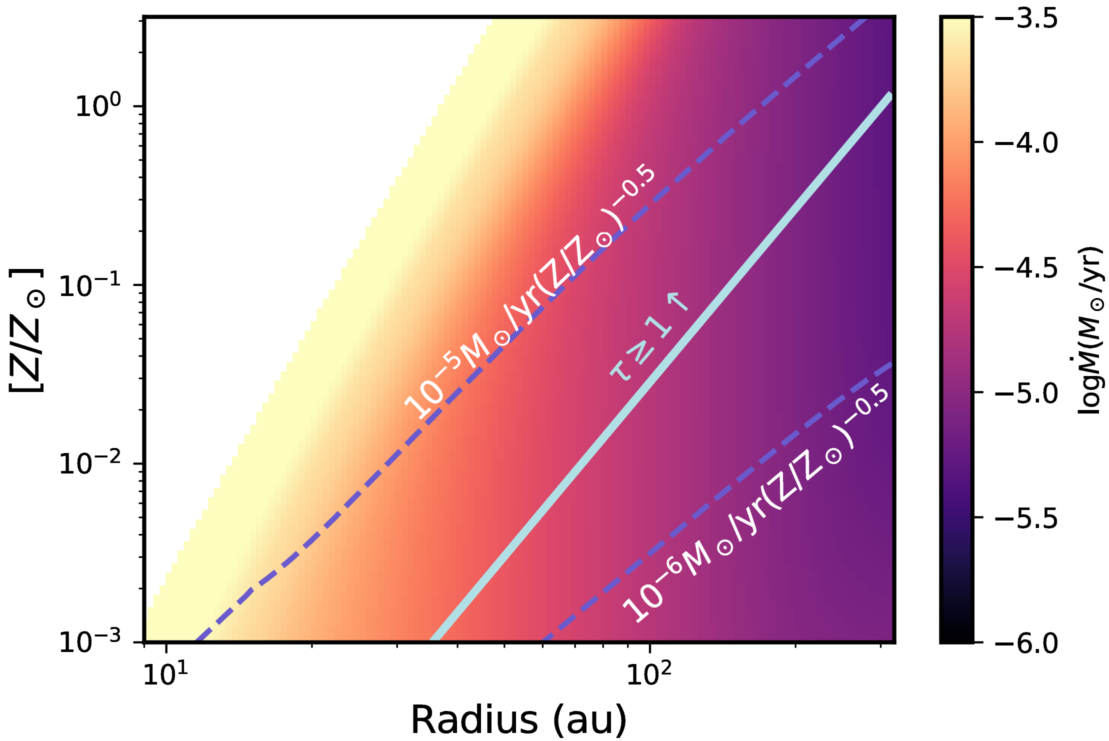
Modest misalignment among compact triples with a_{out} < 10 AU (Borkovits et al. 2016)



Similar degree of misalignment among circumbinary disks (Czekala et al. 2019)

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Moe, Kratter, & Badenes (2019)



For solar-type stars with $Z = Z_\odot$, not all protostellar disks fragment. Only the ~20% that achieve stochastic excursions up to $\dot{M} = 10\ \langle\dot{M}_{infall}\rangle$ can drive a gravitational disk instability.

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Three Key Parameters:

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(Bate & Bonnell 1997; Farris et al. 2014; Young & Clarke 2015)

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3) Stochastic / Variable $\dot{M}$ and $\dot{J}$

Divide mass assemblage into N = 20 accretion episodes, each with:

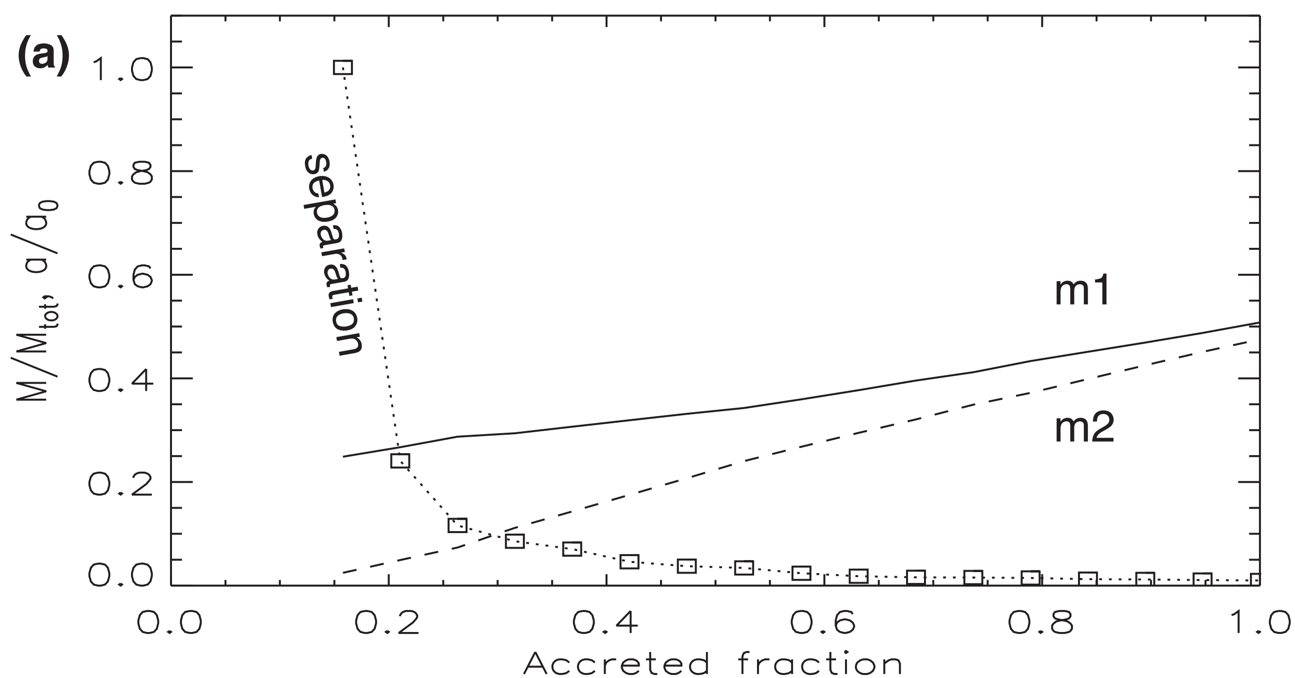
Random $x = [0, 1]$
Random $\eta = [0, 3]$

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Disk Fragmentation:

1) Occurs at random accretion episode N = [1, 20]
2) Initial separation across a = 50 - 500 AU
3) Initial companion mass (Kratter et al. 2008): 0.01 $M_\odot$ for solar-type primaries
   0.1 $M_\odot$ for OB primaries
   $q_{init} \approx 0.05$

Example Evolution:



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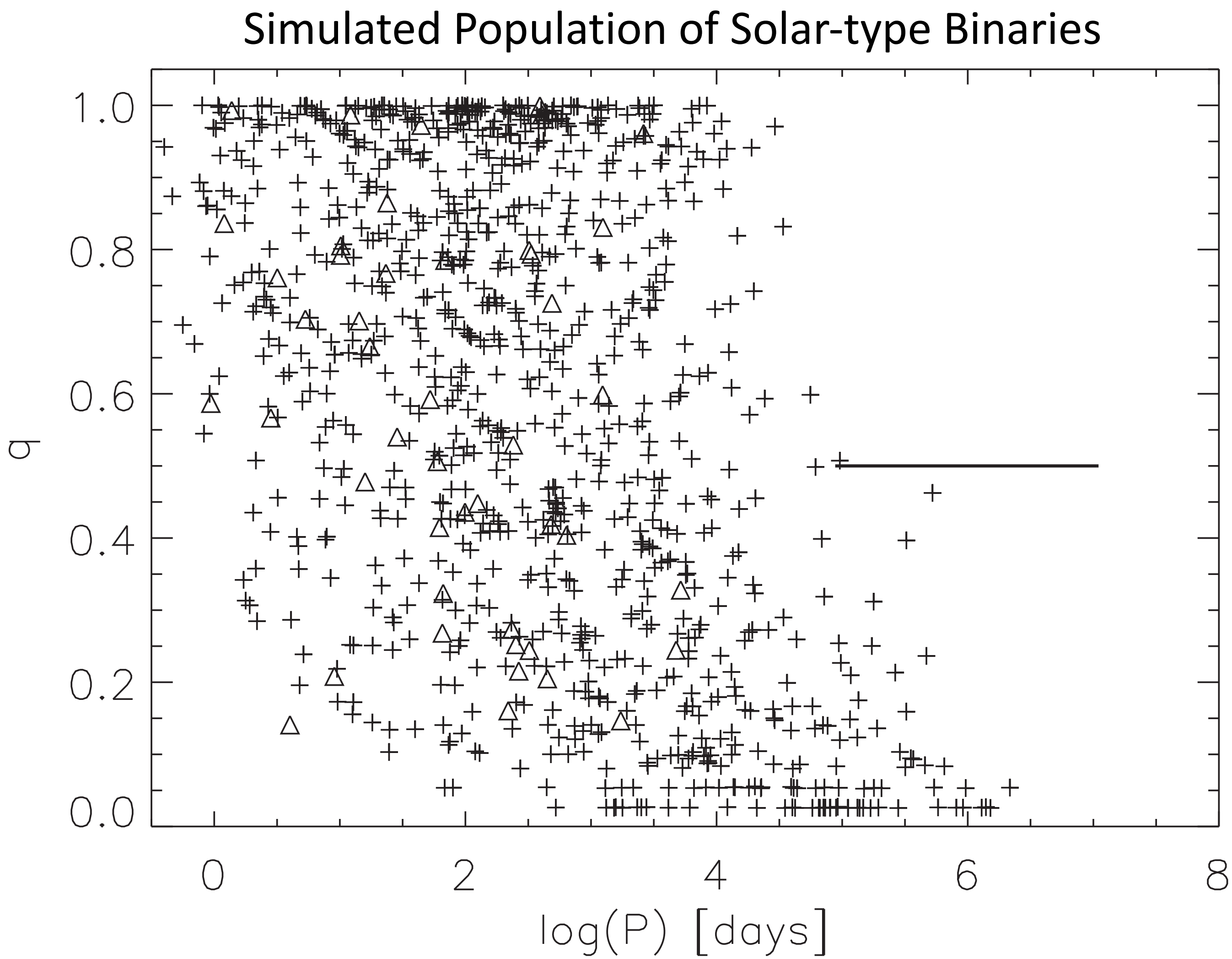

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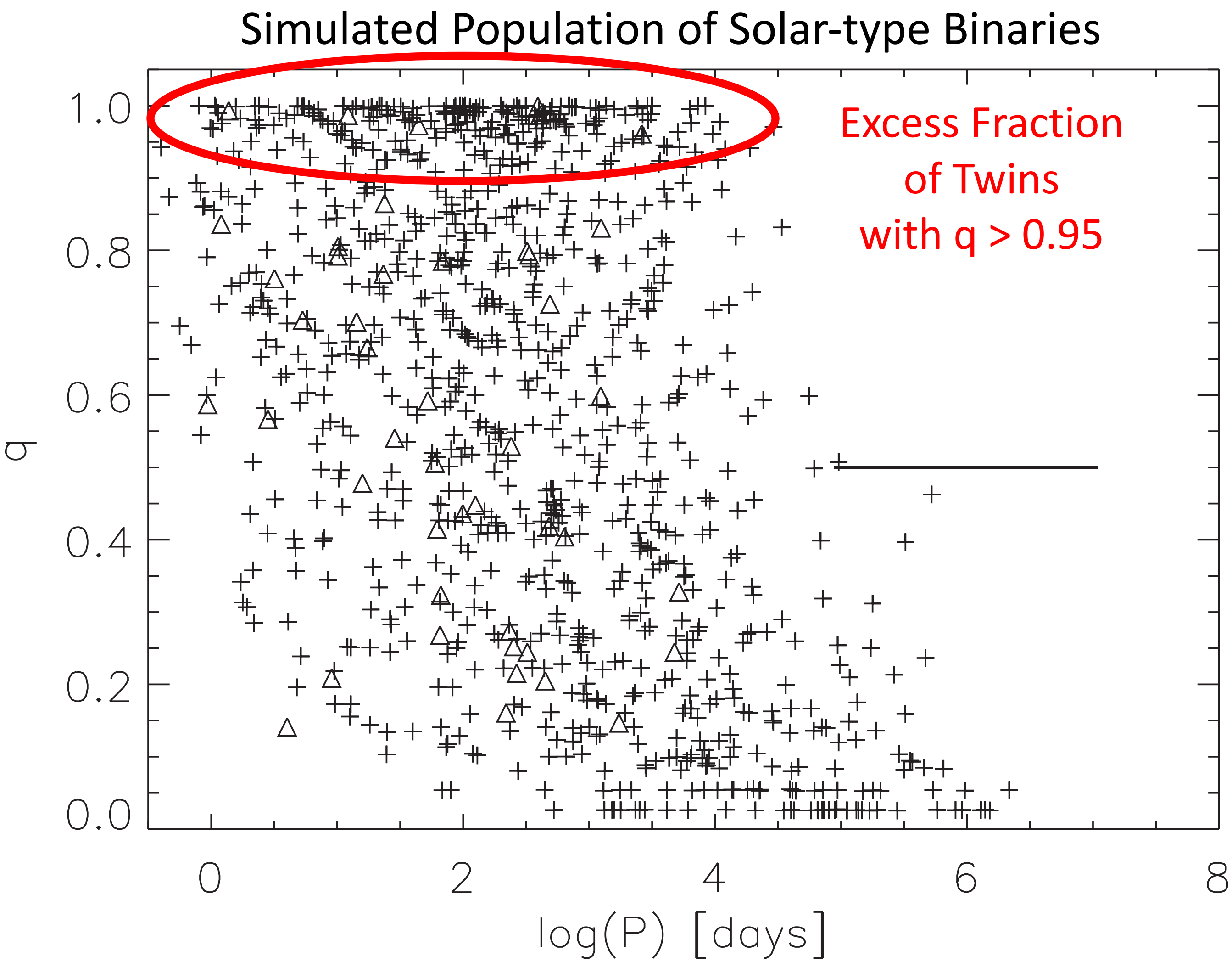
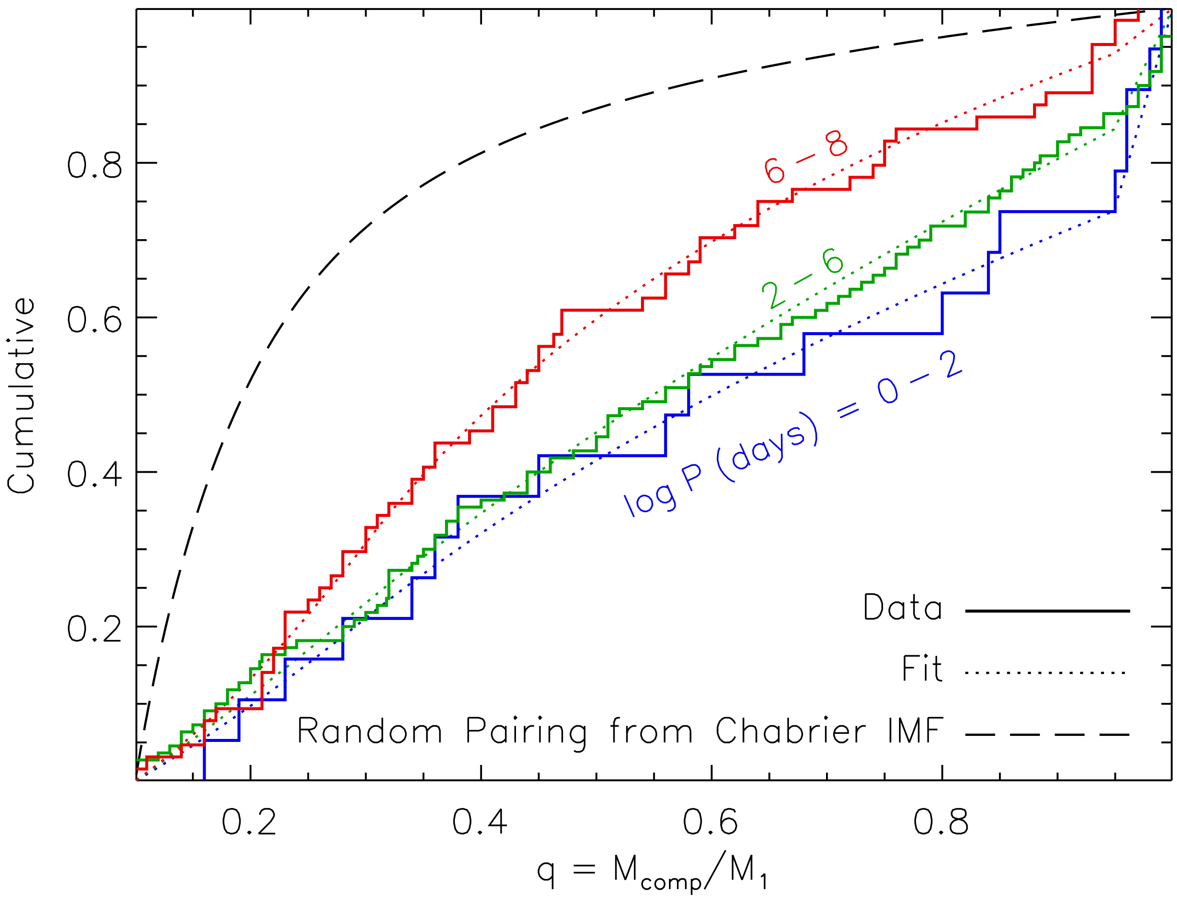


Mind your Ps and Qs: f(P,q) ≠ f(P) × f(q) (Moe & Di Stefano 2017)



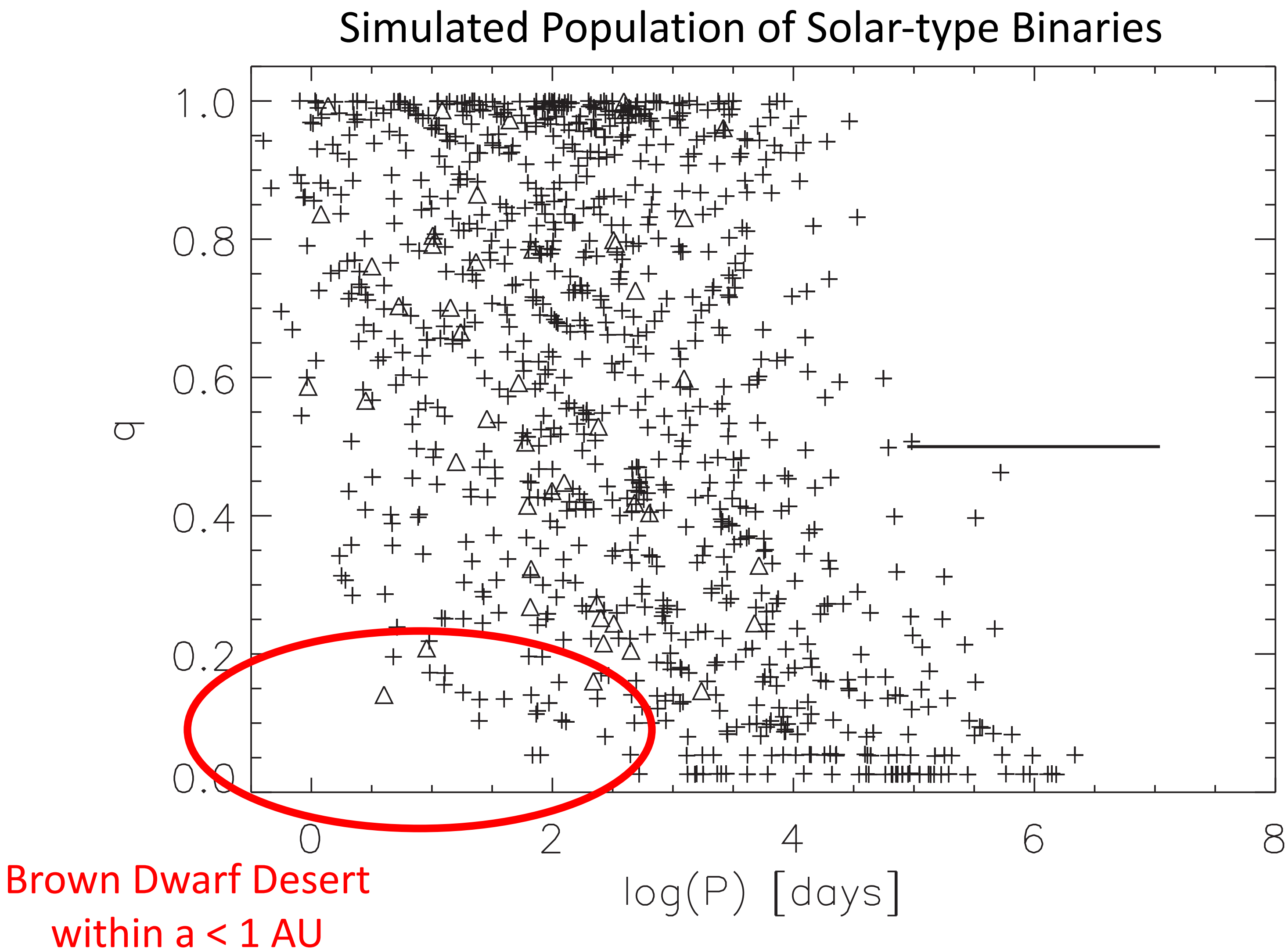
For solar-type binaries, excess twin fraction is:

F_{twin} = 30% near a = 0.1 AU (Tokovinin 2000)

F_{twin} = 10% near a = 100 AU (Moe & Di Stefano 2017)

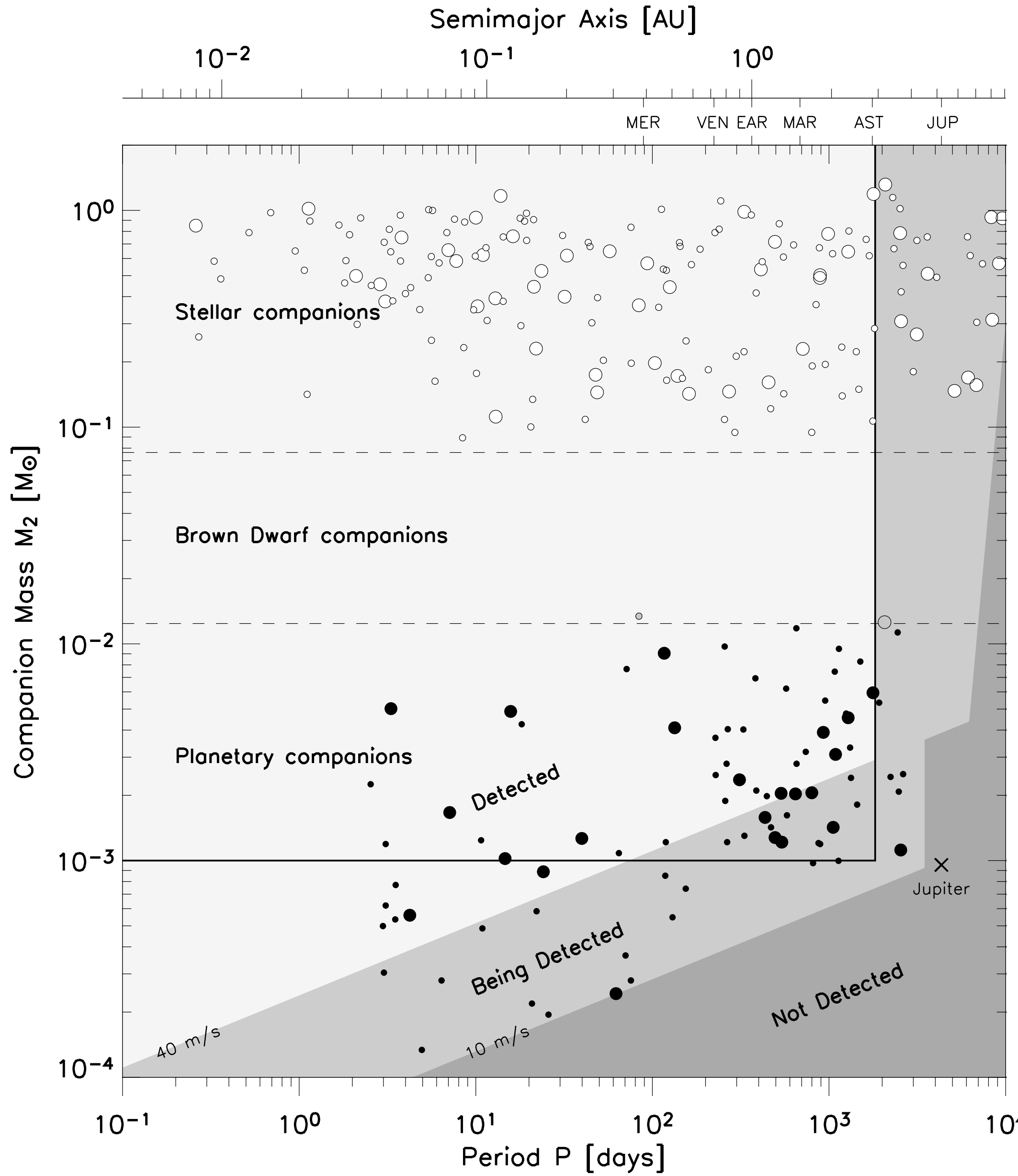
F_{twin} = 2% near a = 1,000 AU (El-Badry et al. 2020)

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)



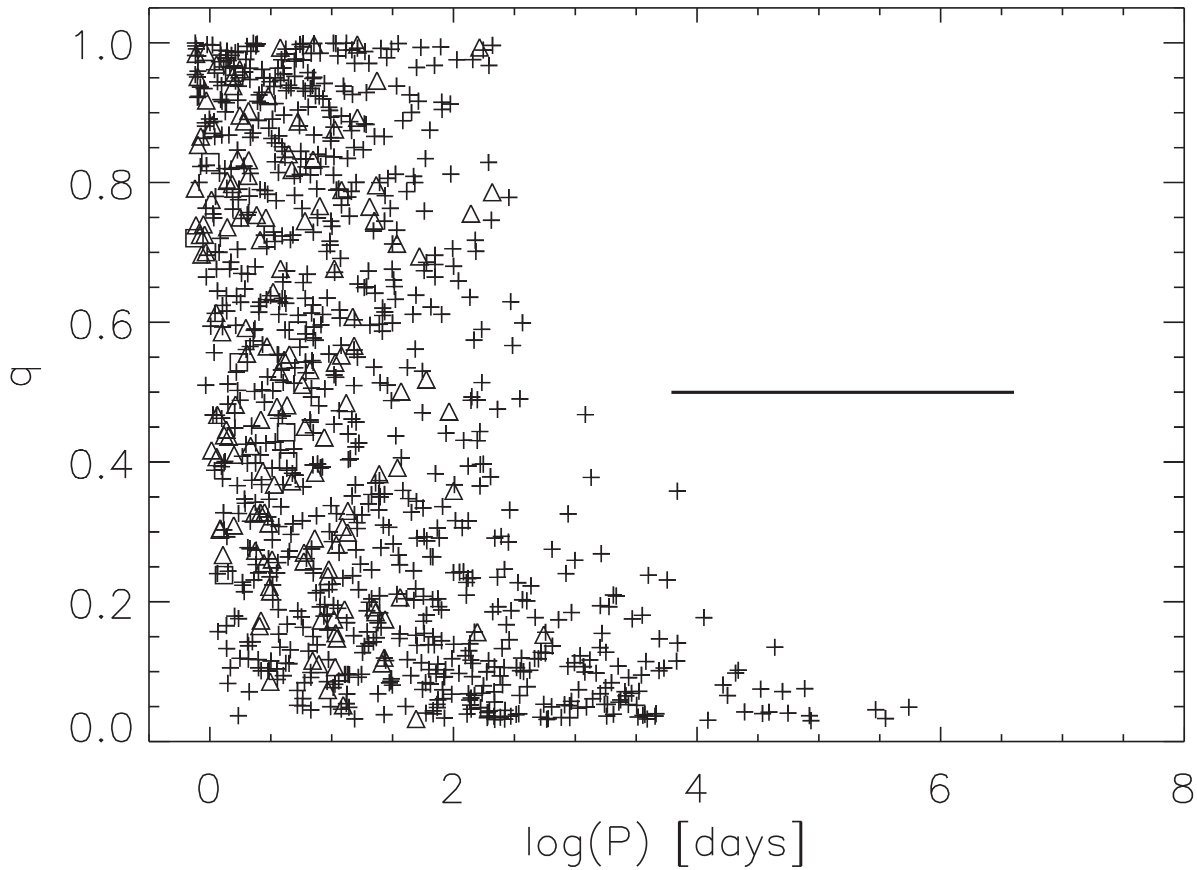
Brown Dwarf Desert

Deficit of q = 0.01 - 0.1 companions within a < 1 AU (Grether & Lineweaver 2006; Csizmadia et al. 2015; Shahaf & Mazeh 2019)



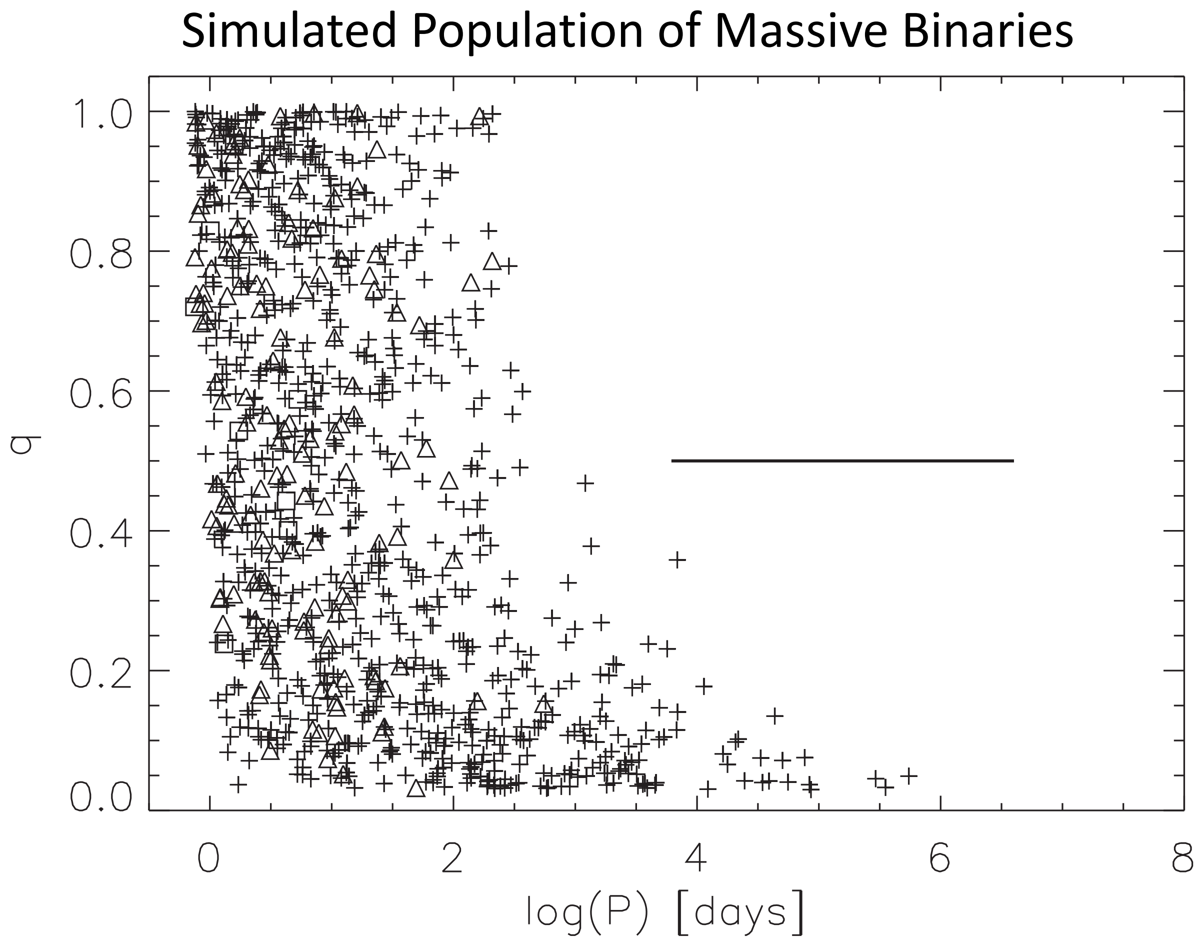
Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Simulated Population of Massive Binaries



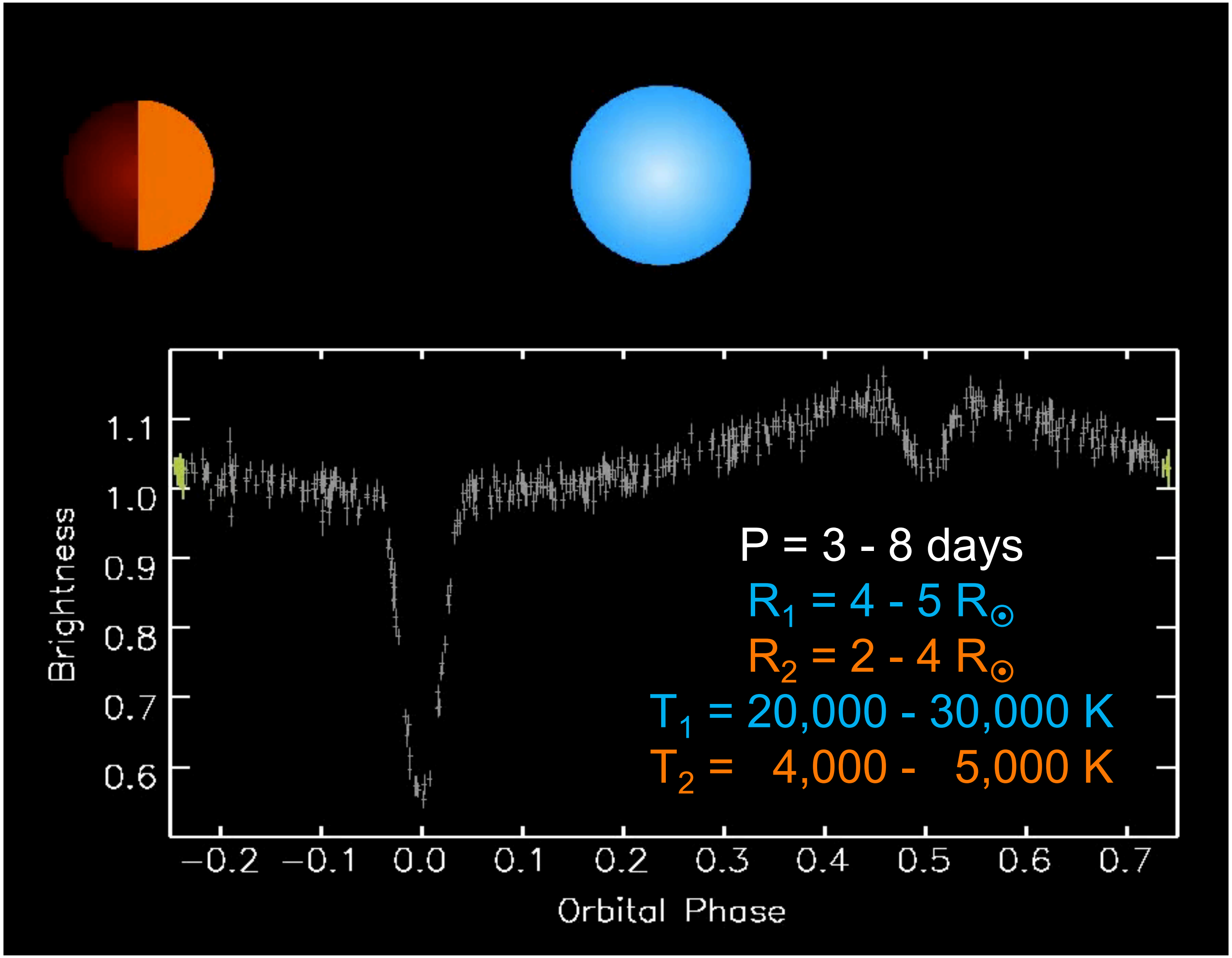
Uniform q distribution with smaller excess twin fraction (F_{twin} = 10% at a = 0.1 AU), consistent with observations (Moe & Di Stefano 2017)

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)



Existence of close, extreme mass-ratio binaries with q = 0.05

A New Class of Nascent EBs with Extreme Mass Ratios (Moe & Di Stefano 2015)

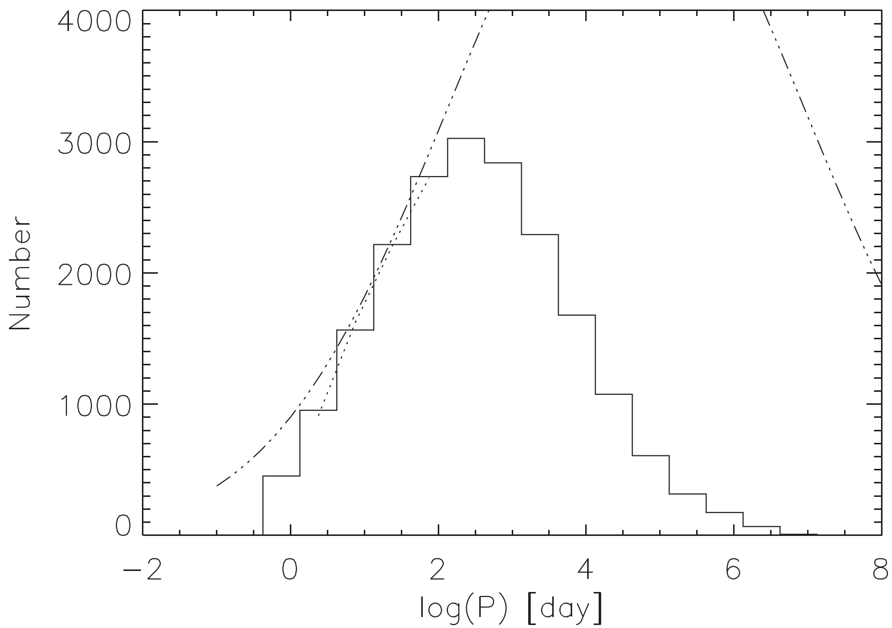


OB-type MS primaries (M_1 = 7 - 20 $M_\odot$) irradiating very close pre-MS companions (M_2 = 0.8 - 2.0 $M_\odot$; q = 0.05 - 0.2) with very young ages τ = 0.6 - 2 Myr

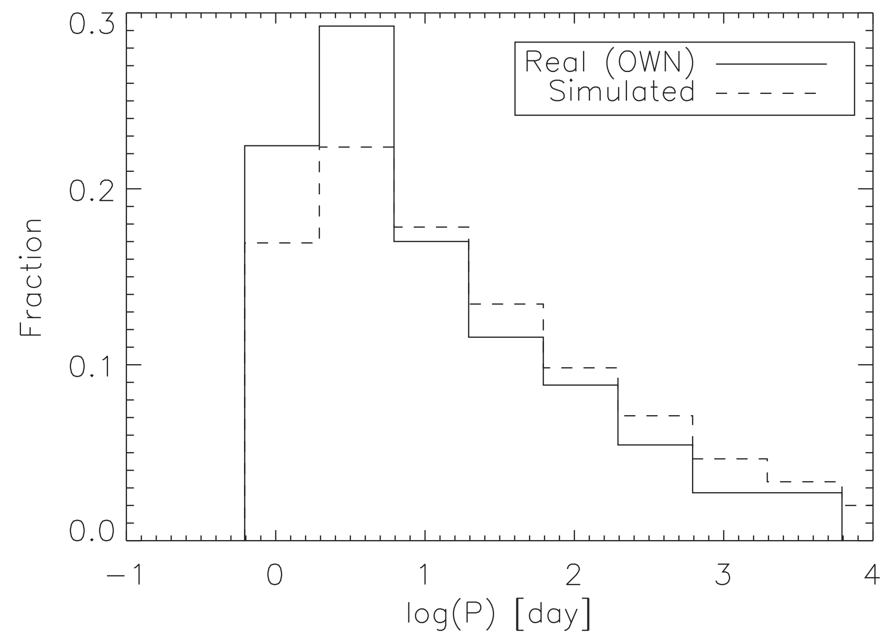
Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Simulated Period Distributions

Solar-type Binaries:
skewed toward long periods



Massive Binaries:
skewed toward short periods



More Massive Disk → **More Prone to Fragmentation**

More Massive Disk → **More Inward Orbital Migration**

Toy Model of Disk Fragmentation, Accretion, & Migration (Tokovinin & Moe 2020)

Simulated Period Distributions

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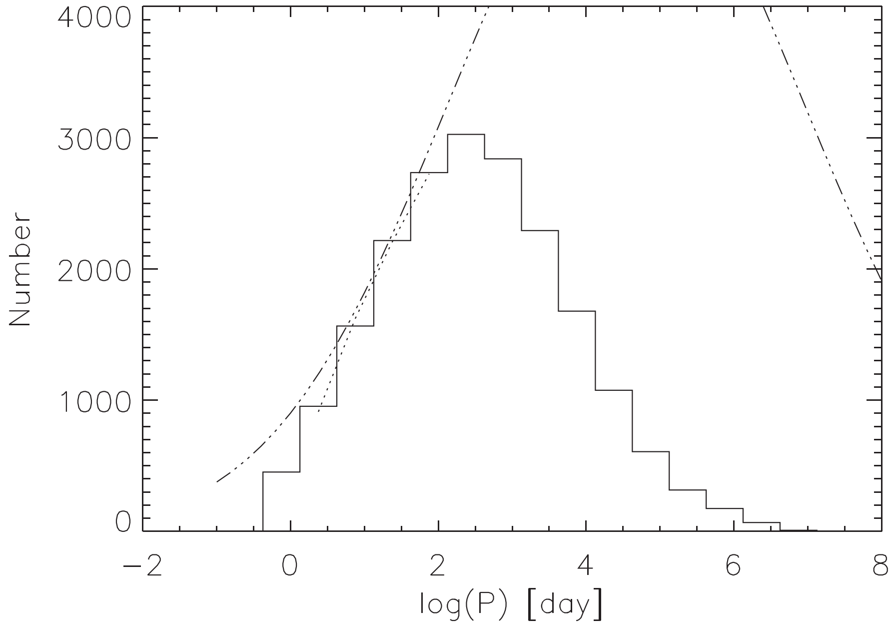

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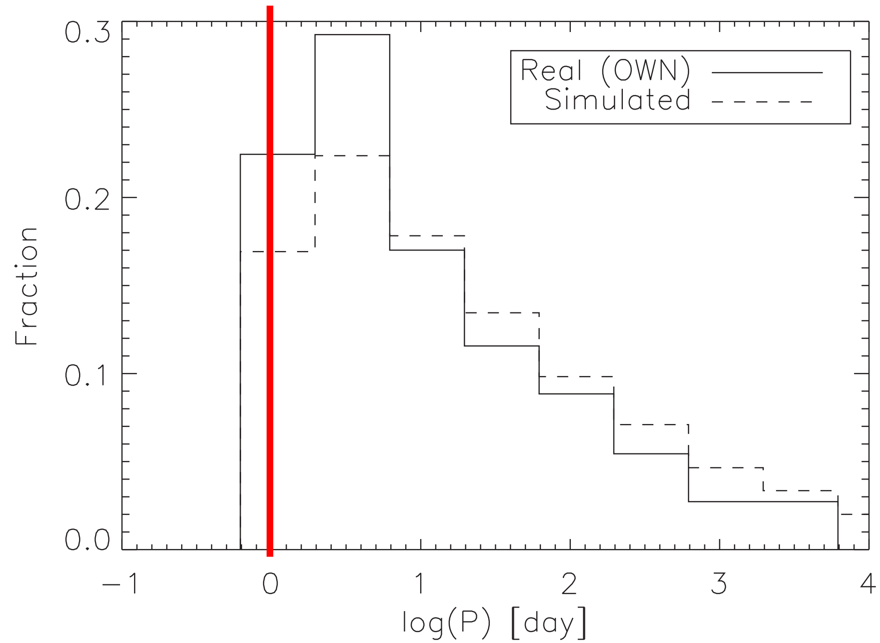
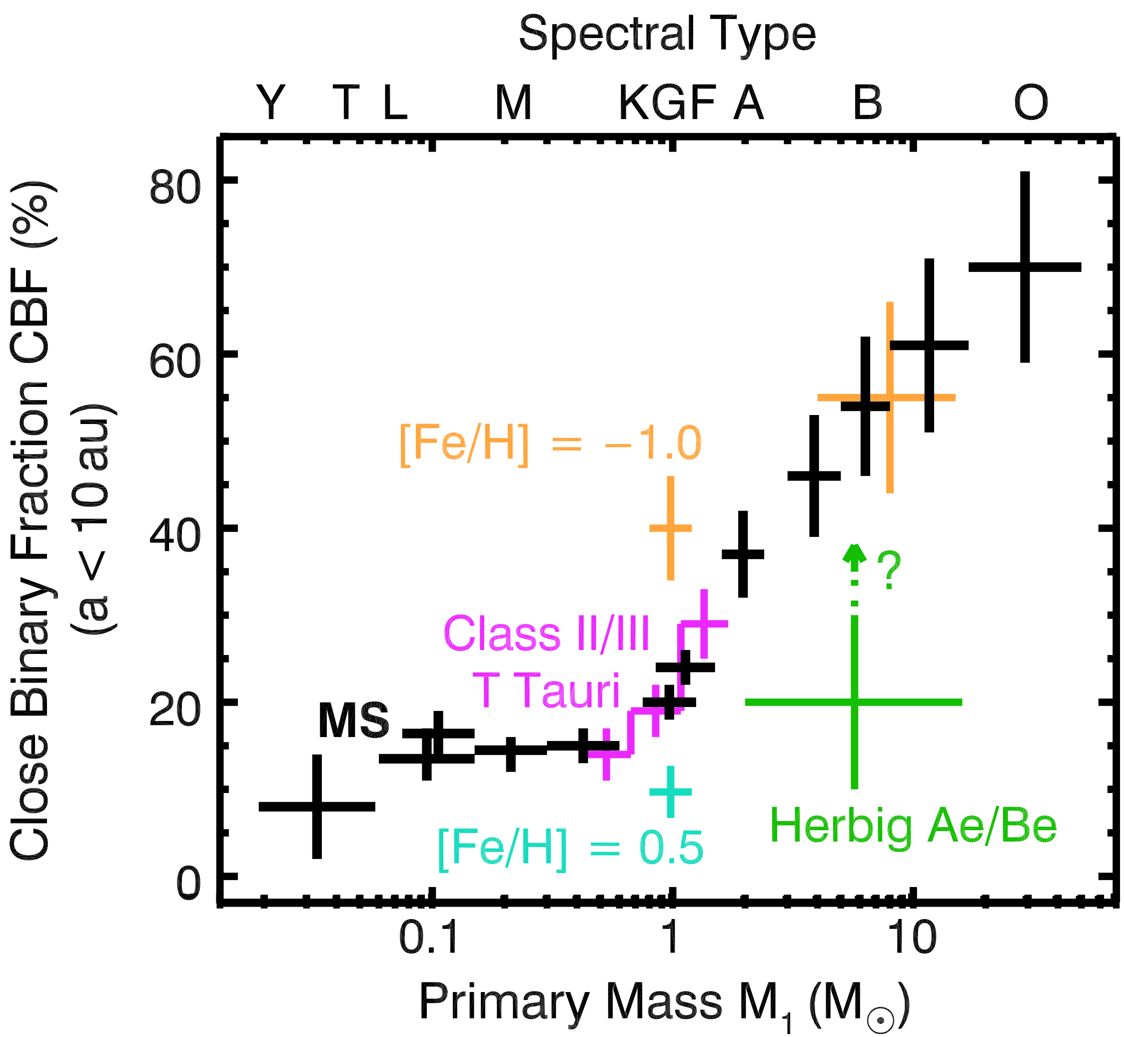


Cliff near P = 1 day in massive binary period distribution (Roche lobe filling on pre-MS).

In our simulations, ~30% of B-type stars are pre-MS mergers.

Most massive stars ($M > 100\ M_\odot$) derive from mergers of twin $q \approx 1$ pre-MS binaries.

Final Comments on Close Massive Binaries



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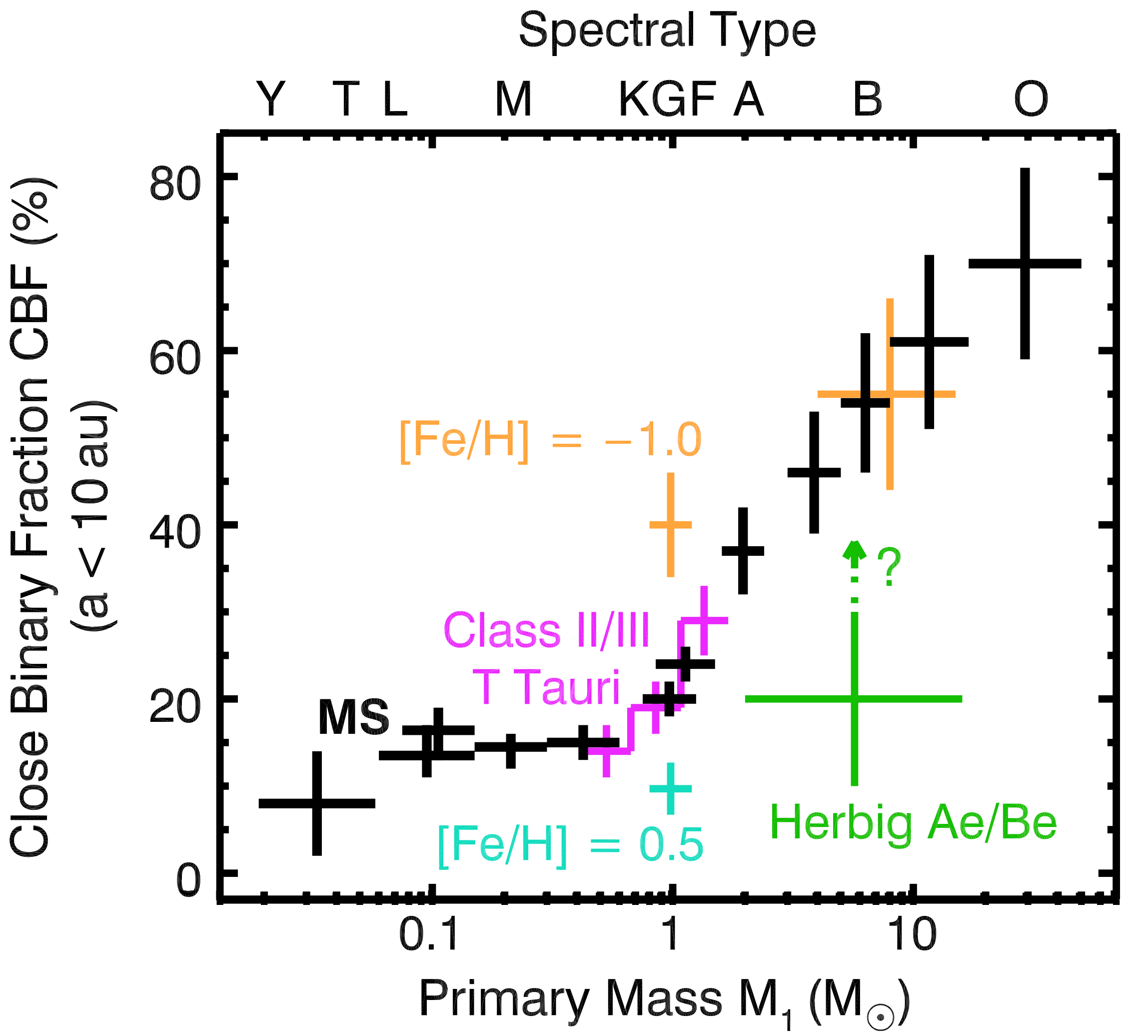
Unlike solar-type stars, close binary fraction of massive stars is relatively metallicity invariant (Moe & Di Stefano 2013; Almeida et al. 2017)

Final Comments on Close Massive Binaries



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Measured close binary fraction of Herbig Ae/Be pre-MS stars

is *smaller* than their A/B MS counterparts

(Corporon & Lagrange 1999; Apai et al. 2007; Sana et al. 2017; Ramírez-Tannus et al. 2021)

Final Comments on Close Massive Binaries

In M17 (Swan Nebula; τ ≈ 1 Myr),
there are ≈60 B-type stars.

Only 11 are Herbig Be stars
with signs of active disk accretion.

None of these 11 have
close companions (Sana et al. 2017).

But B-type stars in slightly
older clusters (τ ≈ 3 Myr)
have large close binary fraction.


(ESO)

Interpretation #1: Close companions to B-type stars
migrate inward between τ ≈ 1 Myr and 3 Myr
after most of the disk has dissipated
(no theoretical explanation yet).

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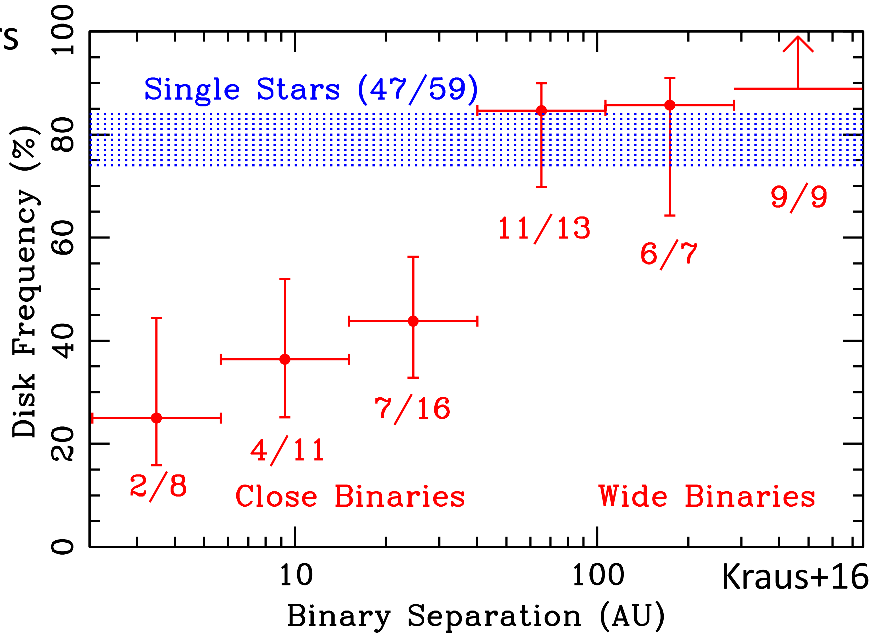
Interpretation #1: Close companions to B-type stars migrate inward between τ ≈ 1 Myr and 3 Myr *after most of the disk has dissipated (no theoretical explanation yet).*

Interpretation #2: Selection Effect – subset of B-types stars with disks are biased against close binaries (similar to observed T Tauri sample).



Summary

Close binaries initially fragmented on large scales ($a \approx 50 - 500$ AU), migrated inward ($\eta \approx 1.5$) with preferential accretion onto secondary ($q \rightarrow 1$) during the embedded Class 0/I phase ($\tau < 1$ Myr)

More massive disks are more prone to fragmentation and provide more dissipation for inward binary orbital migration, but the process is stochastic.