Multiplicity Statistics & Properties across the HR Diagram

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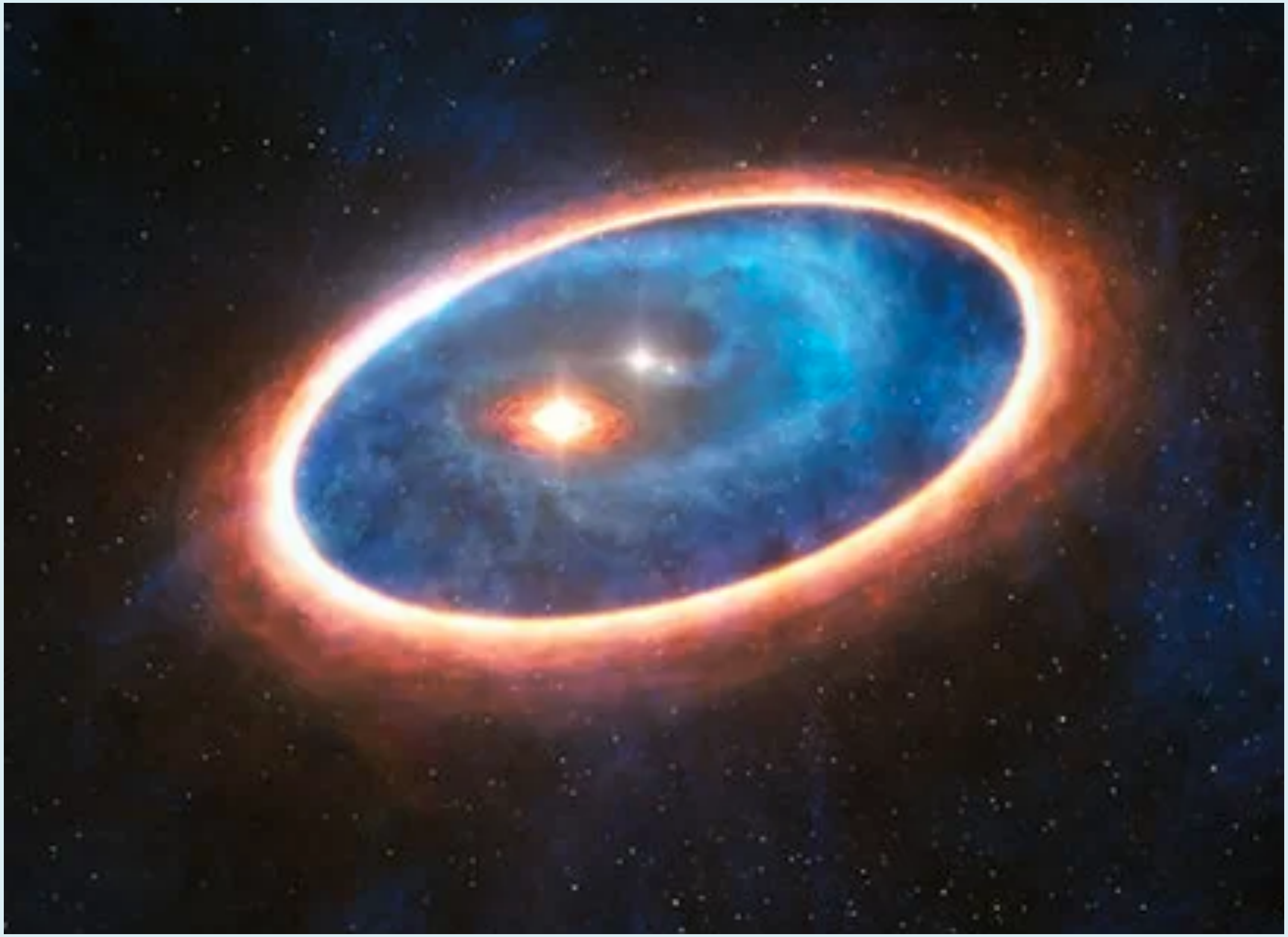


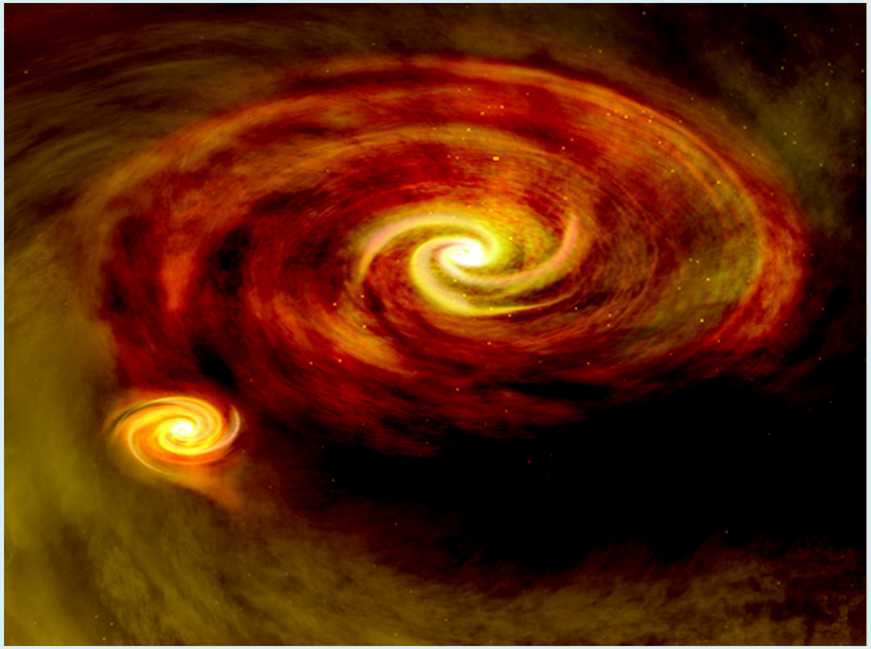
Overall Theme:

Two Modes of Binary Star Formation

(Kroupa et al. 1995; Bate et al. 1995, 2002; Kratter et al. 2002, 2006; Clarke 2009; Offner et al. 2010; Lee et al. 2017; **Moe & Di Stefano 2017; Moe et al. 2019**)

Gravitational Instability and Fragmentation within **Disk**:

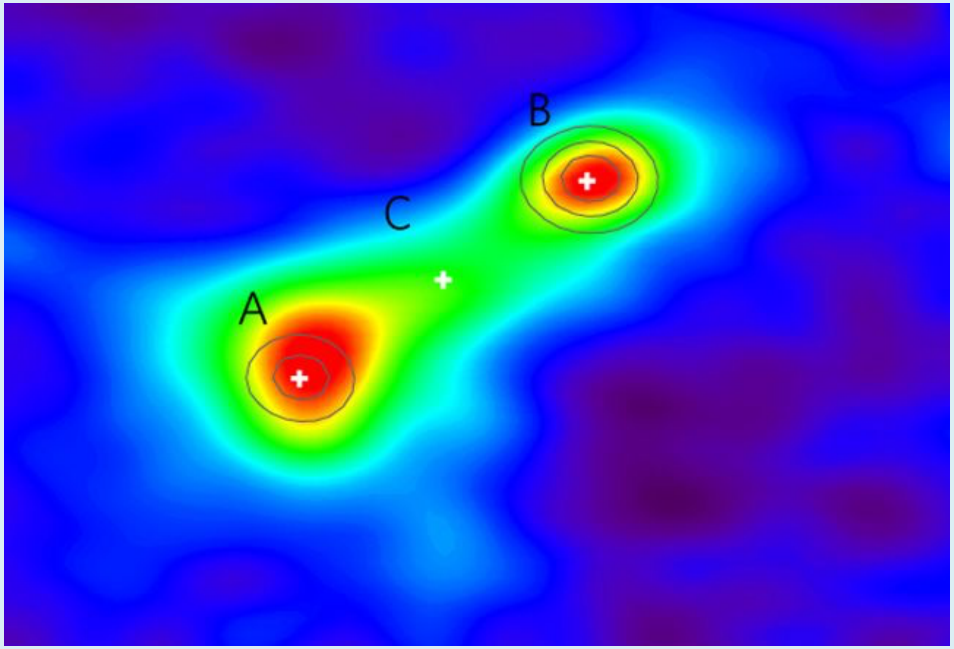
$Q_{Toomre} = c_s^2\Omega/\pi G\Sigma = 3\alpha c_s^3/G\dot{M} < 1$



Close Binaries:
a < 100 AU

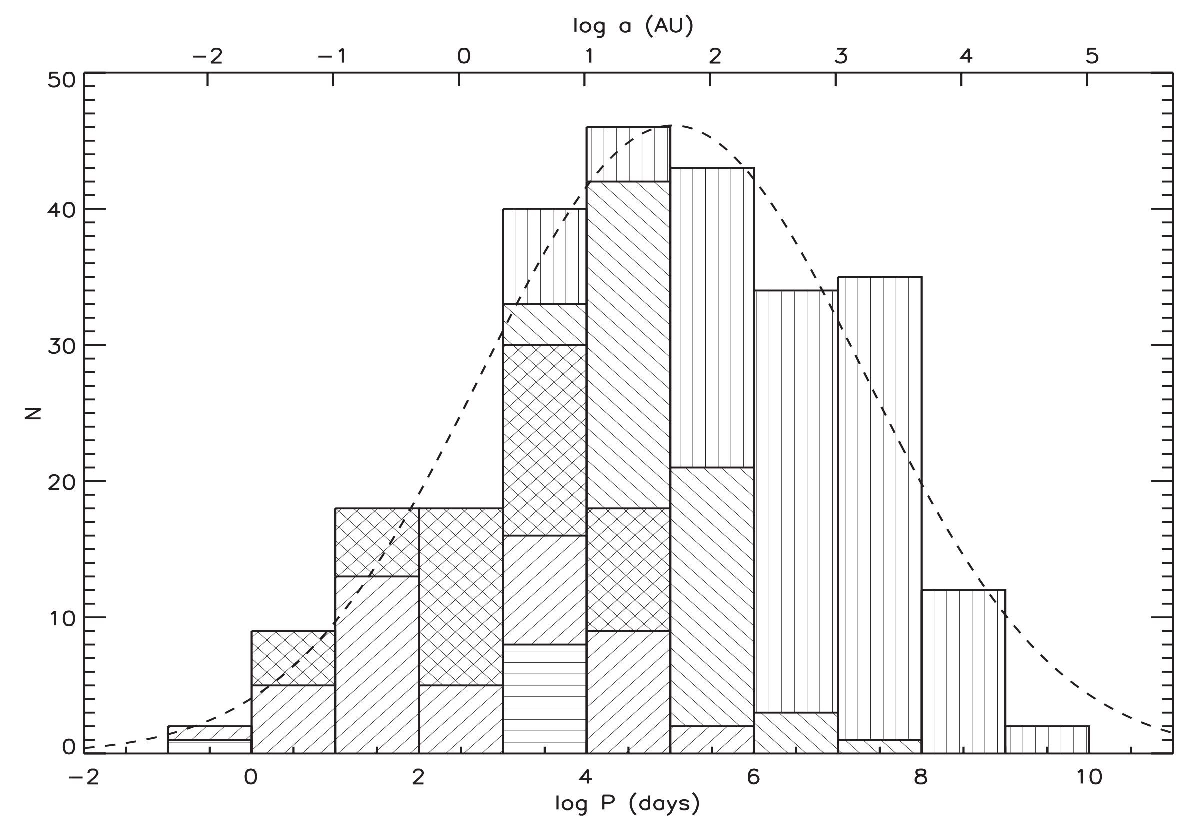
Turbulent Fragmentation of Molecular **Cores**:

Mach $= \sigma_v/c_s > 1$



Wide Binaries:
a > 100 AU

Field Solar-type Primaries



Duquennoy & Mayor 1991:
F7-G9 IV/V/VI, ~15 pc

Raghavan et al. 2010:
F6-K3 IV/V, 25 pc

Tokovinin 2014:
F0-G9 IV/V, 67 pc

Log-normal period distribution peaking at a ~ 50 AU

DM91 measured F_{bin} = 57% binary fraction, while R10 and T14 found F_{bin} = 44%

Reasons for ΔF_{bin} = 13% discrepancy:

~3% due to missing late-M companions in R10 (Chini+ 2014; Moe & Di Stefano 2017)

~2% due to sample selection (spectral types, luminosity classes)

~8% due to WD companions added in DM91 (Moe & Di Stefano 2017)

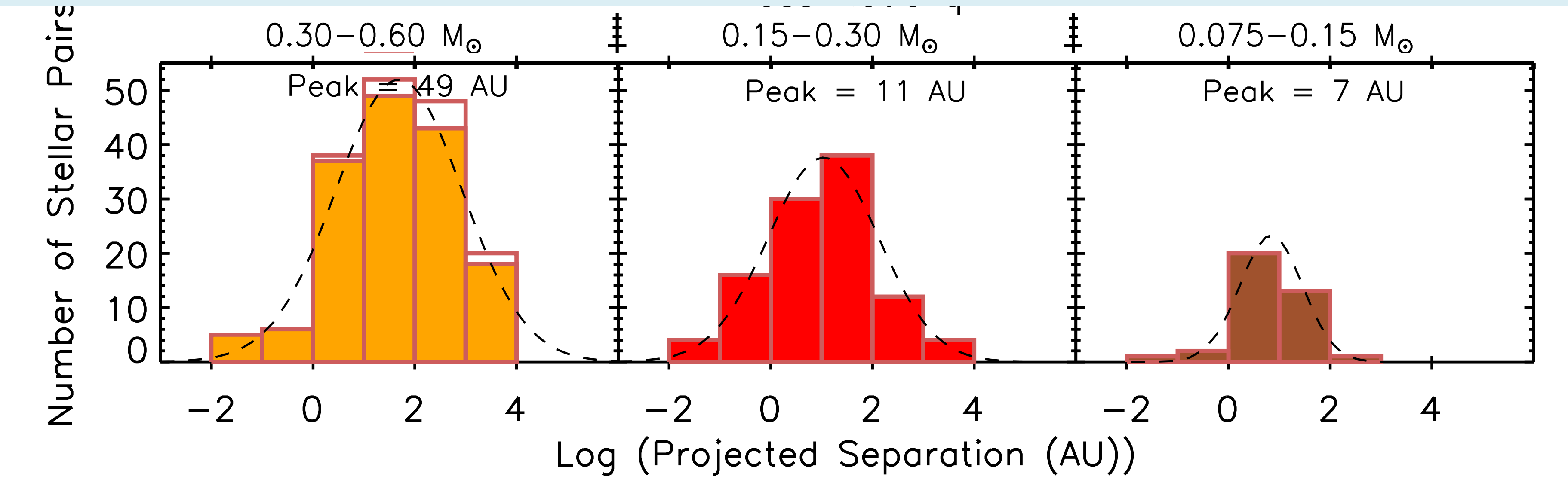
Gaia will find new WD companions to nearby stars as astrometric binaries.

Field M-dwarf Primaries

Fischer & Marcy 1992; Basri et al. 2006; Law et al. 2008; Bergfors et al. 2010; Janson et al. 2012; Dieterich et al. 2012; Ward-Duong et al. 2015;
Winters et al. 2019, 25 pc, $M_1 = 0.075 – 0.6\ M_\odot$

Corrected binary fraction of F_{bin} = 27% ± 2% for all M-dwarfs, increasing from $F_{bin} \approx 20\%$ for late-M to $F_{bin} \approx 35\%$ for early-M (lower than $F_{bin} \approx 45\%$ for G-dwarfs)

Log-normal period distribution, peaking at a = 50 AU for early-M (similar to G-dwarfs) and a = 7 AU for late-M

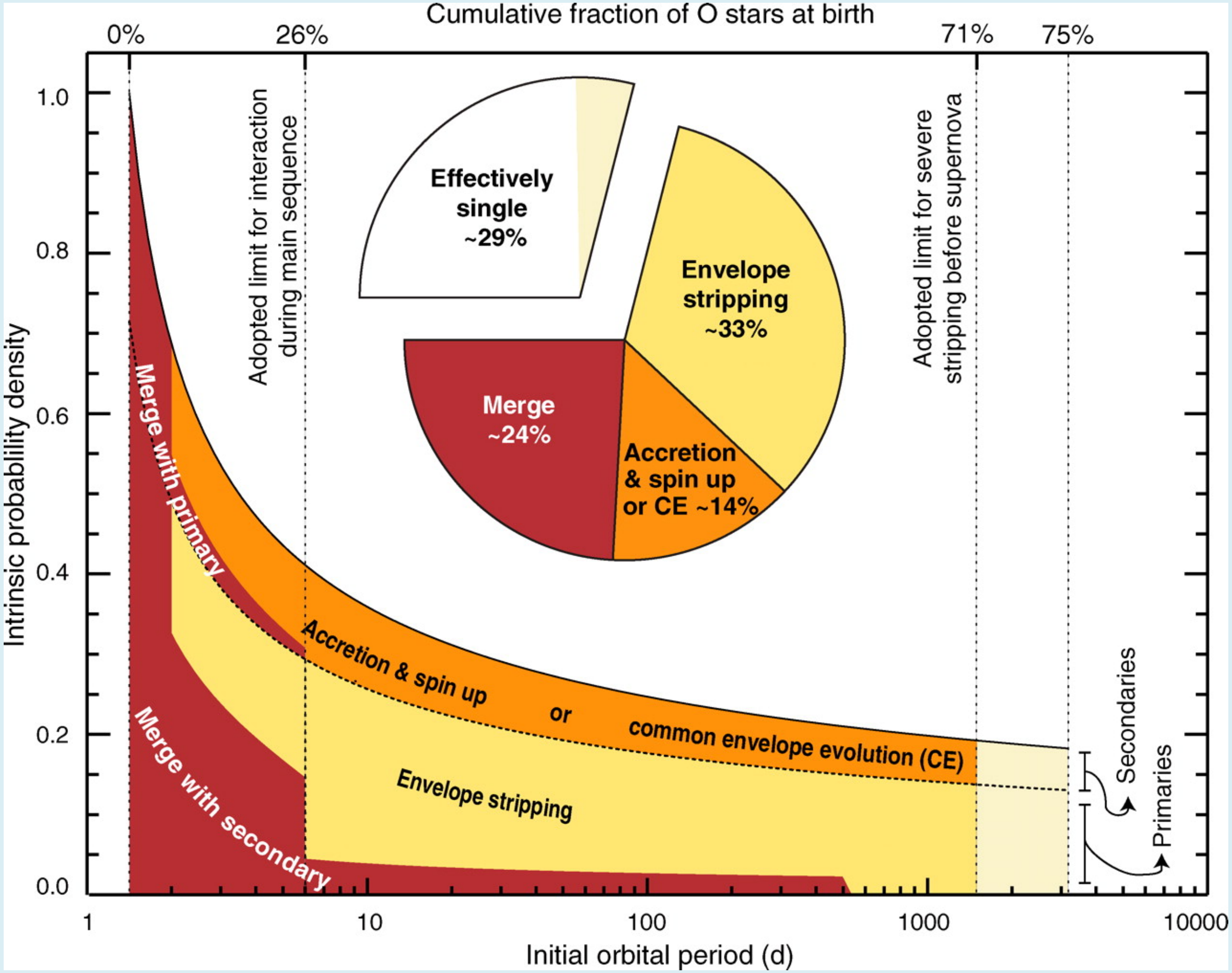


O-type Primaries

Binary interactions dominate the lives of massive stars (Sana et al. 2012).

~70% of O stars have companions with q > 0.1 within a < 10 AU.

~100% of O stars in clusters (non-runaways) have companions within a < 100 au (Sana et al. 2014; Moe & Di Stefano 2017).

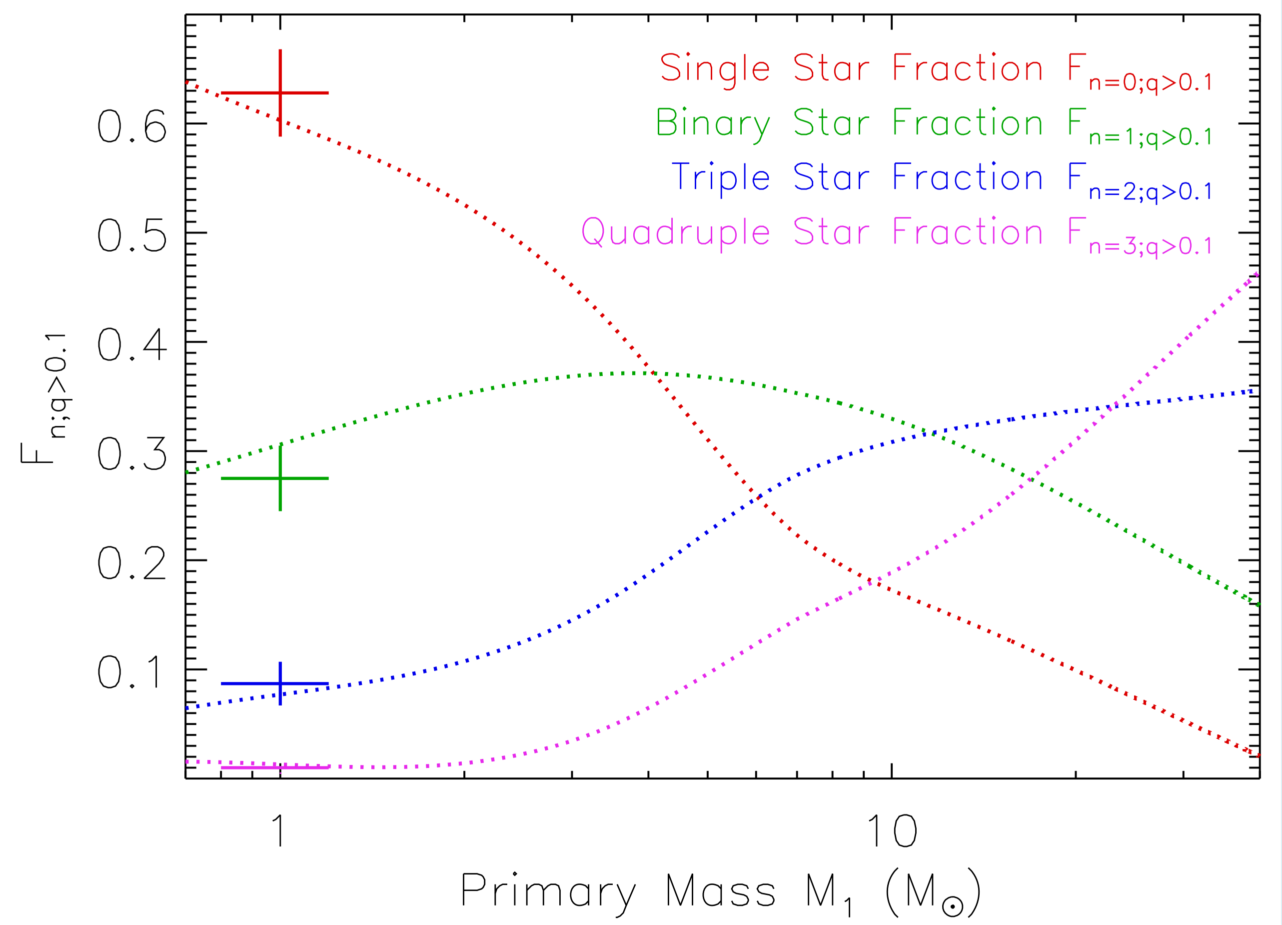


Gaia can detect q < 0.1 companions to massive stars, and will constrain massive binary properties as a function of age & environment

Triple Star Fractions

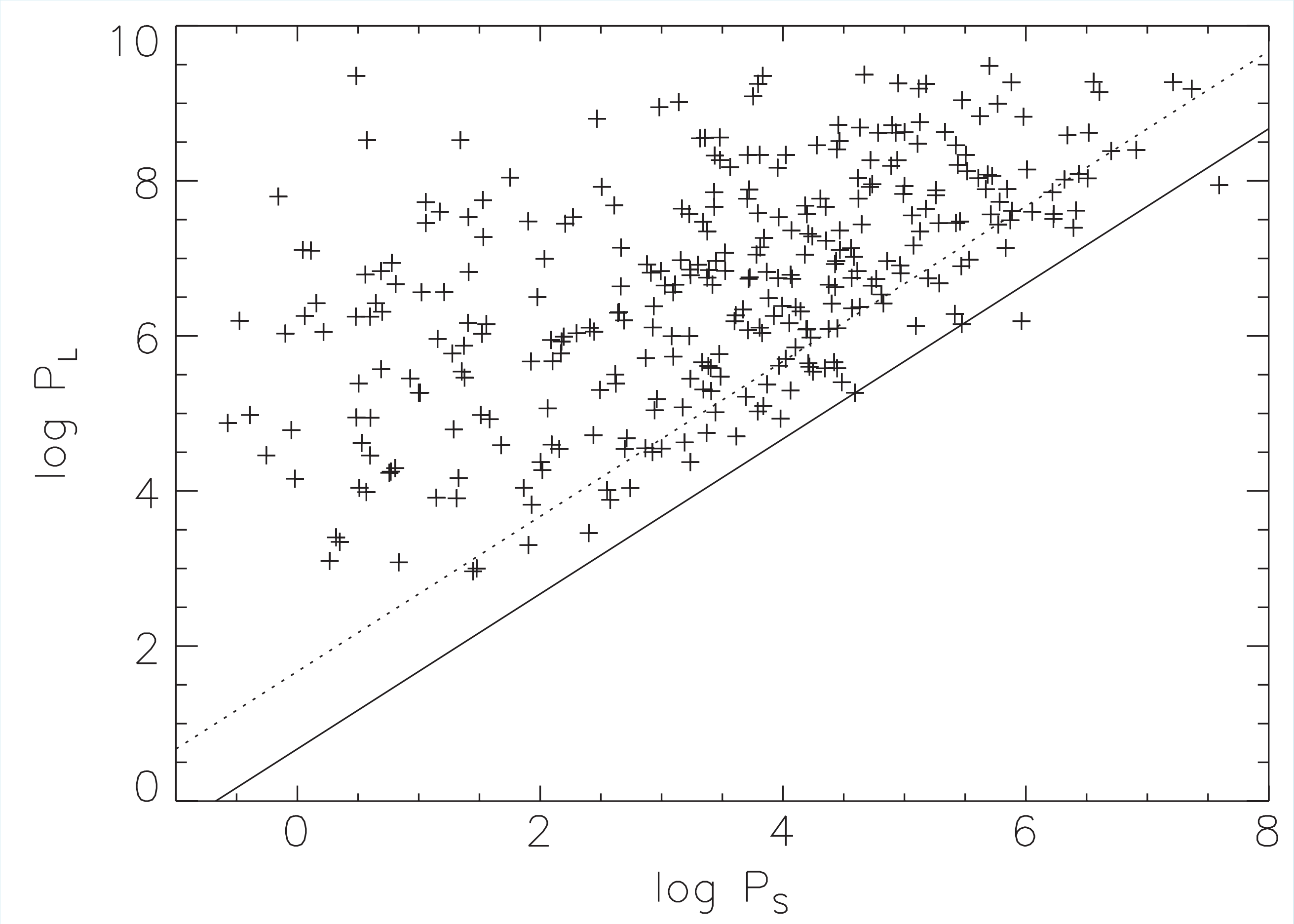
While only 10%-15% of solar-type primaries are in triples (Raghavan et al. 2010; Tokovinin 2014), most massive stars are in triples & higher-ordered multiples (Sana et al. 2014; Moe & Di Stefano 2017)

Every O-type primary has 2.1 ± 0.3 companions with q > 0.1



Triple Star Hierarchies

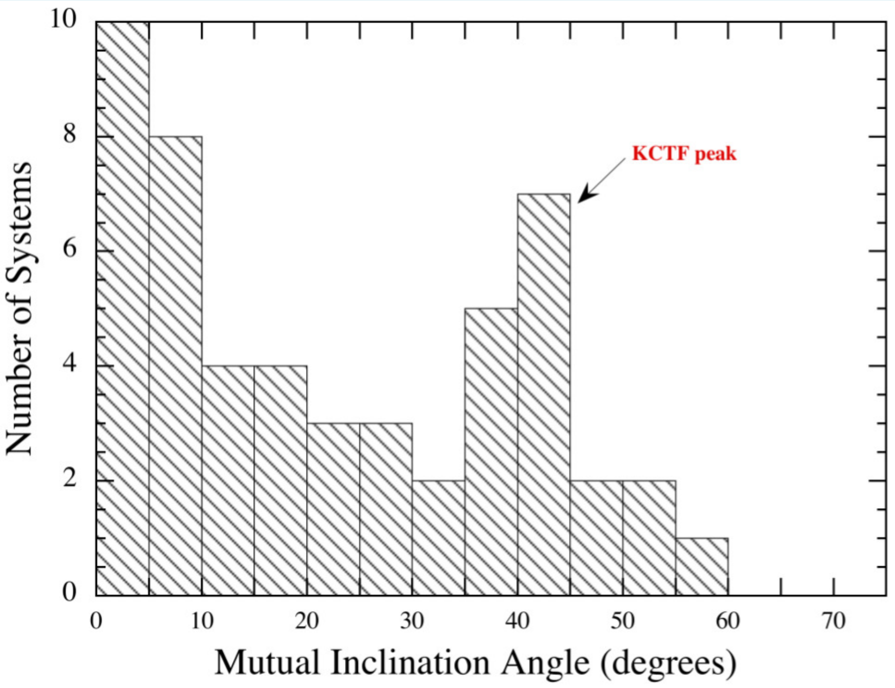
Solar-type triples occupy the full parameter space of dynamically stable hierarchies $f(P_{in}, P_{out} > 5\,P_{in})$, *nearly* consistent with random drawings from overall log-normal period distribution (Tokovinin 2014)

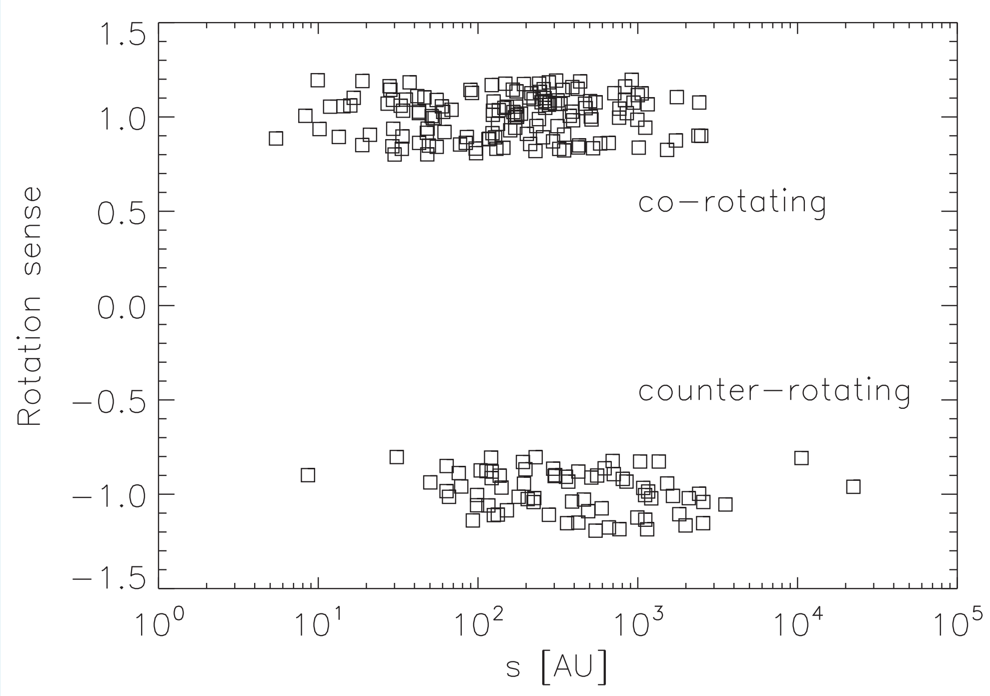


Gaia will be first to fully measure $f(P_{in}, P_{out})$ for OBA primaries

Triple Star Mutual Inclinations

Most compact solar-type triples with a_{out} < 50 AU are coplanar (i < 40°), while wide tertiaries with a_{out} > 1,000 AU have random orientations with respect to inner binary (Borkovits et al. 2016; Tokovinin 2017)

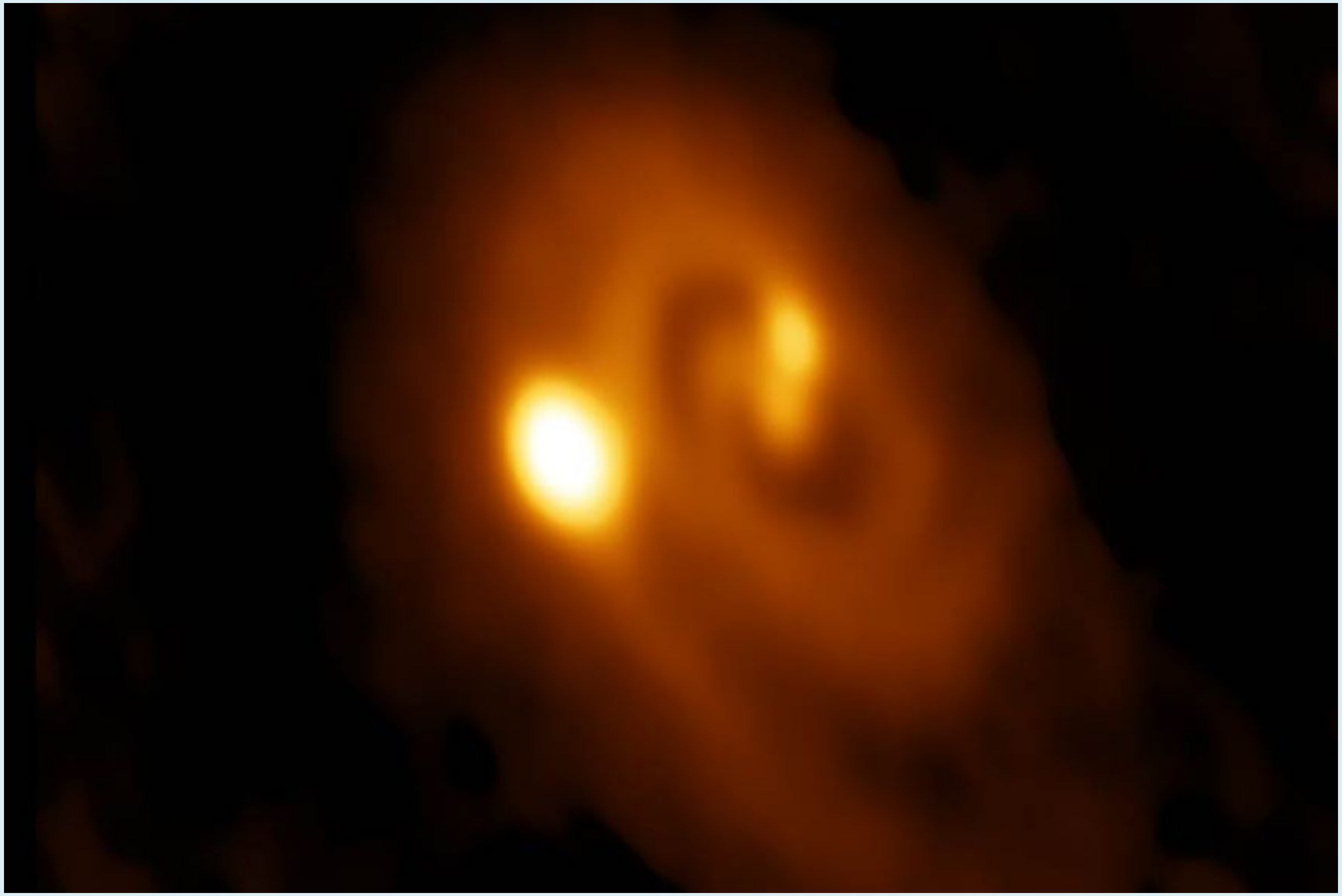




Gaia will help constrain $i_{mutual}(a_{in}, a_{out})$ for massive triples

Close Companions – Disk Fragmentation

"A triple protostar system formed via fragmentation of a gravitationally unstable disk" (Tobin et al. 2016)

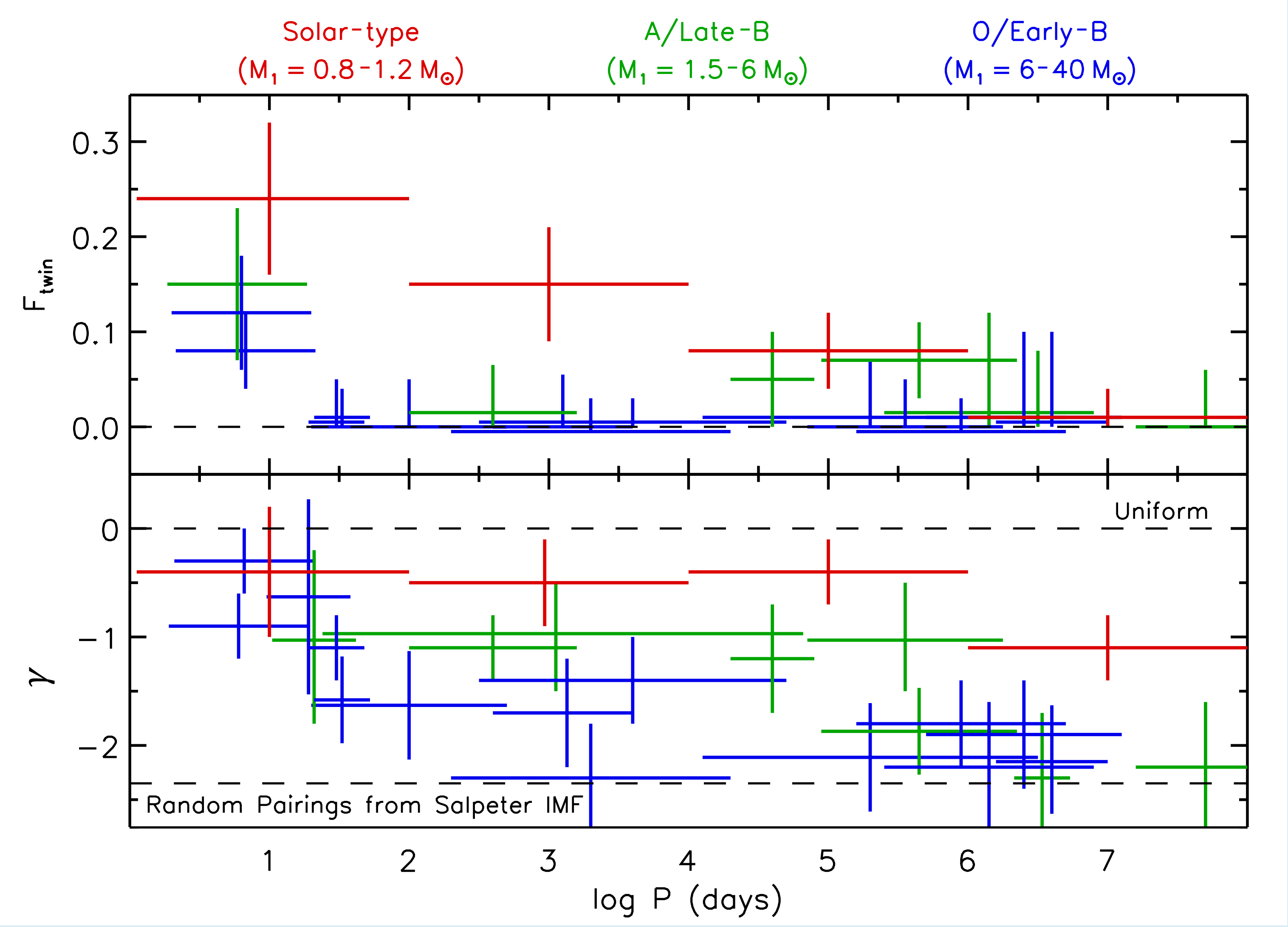


ALMA observations of L1448 IRS3B reveal coplanar tertiary accreting from disk at a_{out} ~ 100 AU

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

Excess fraction of twins with q > 0.95

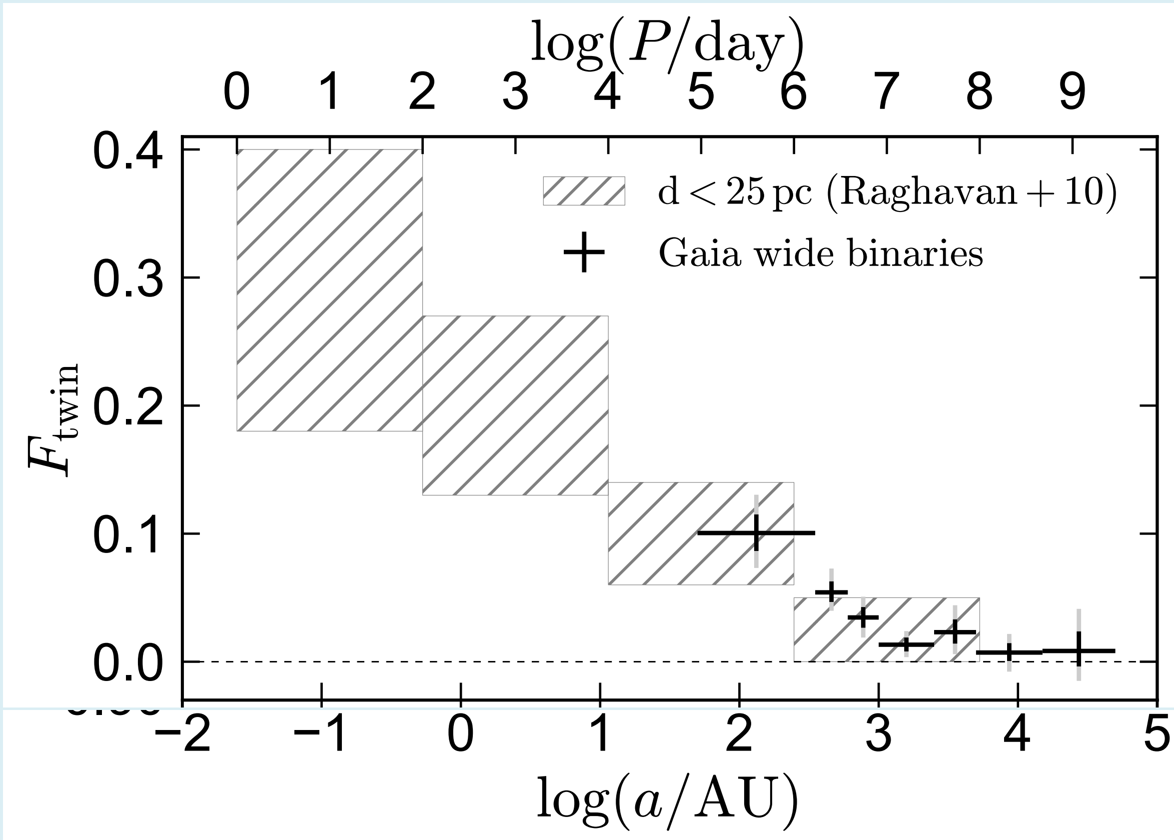
Power-law slope $f \propto q^{\gamma}$



Very close binaries have uniform q distribution with excess twin fraction (disk fragmentation and accretion), wide binaries are weighted toward small q (core fragmentation), and there is an M_1 dependent transition between these regimes.

Based on Gaia 200-pc sample of CPM binaries, El-Badry et al. (submitted; arXiv:1906.10128) confirmed wide binaries are weighted toward small q, but also found a small but statistically significant excess twin fraction extending out to a ~ 5,000 AU.

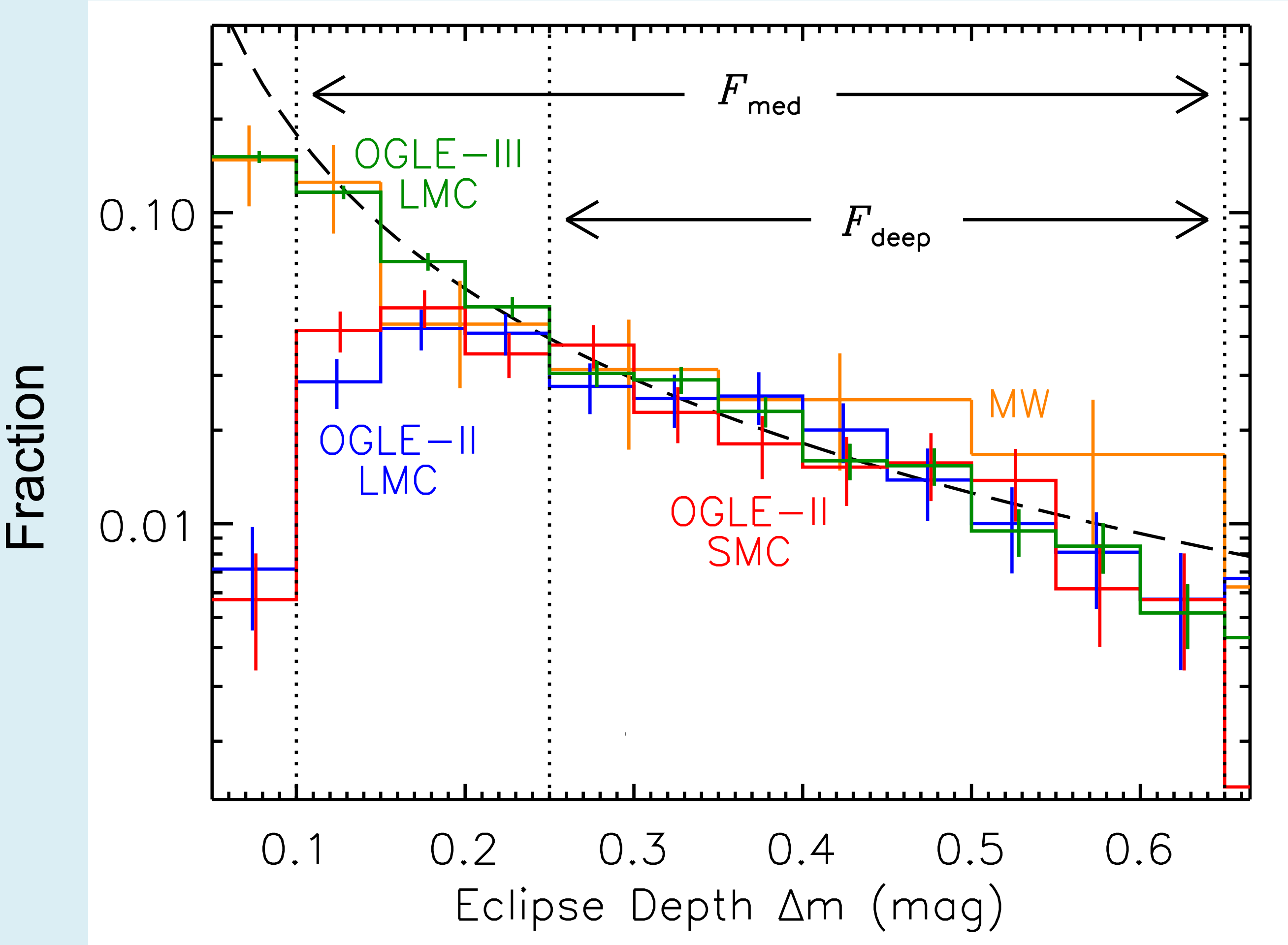
We concluded very wide twins initially formed in the disk within a < 200 AU, but then were dynamically widened to a > 200 AU in their dense birth clusters.



Gaia DR3 spectroscopic and astrometric binaries will better constrain $f_q(M_1,P)$.

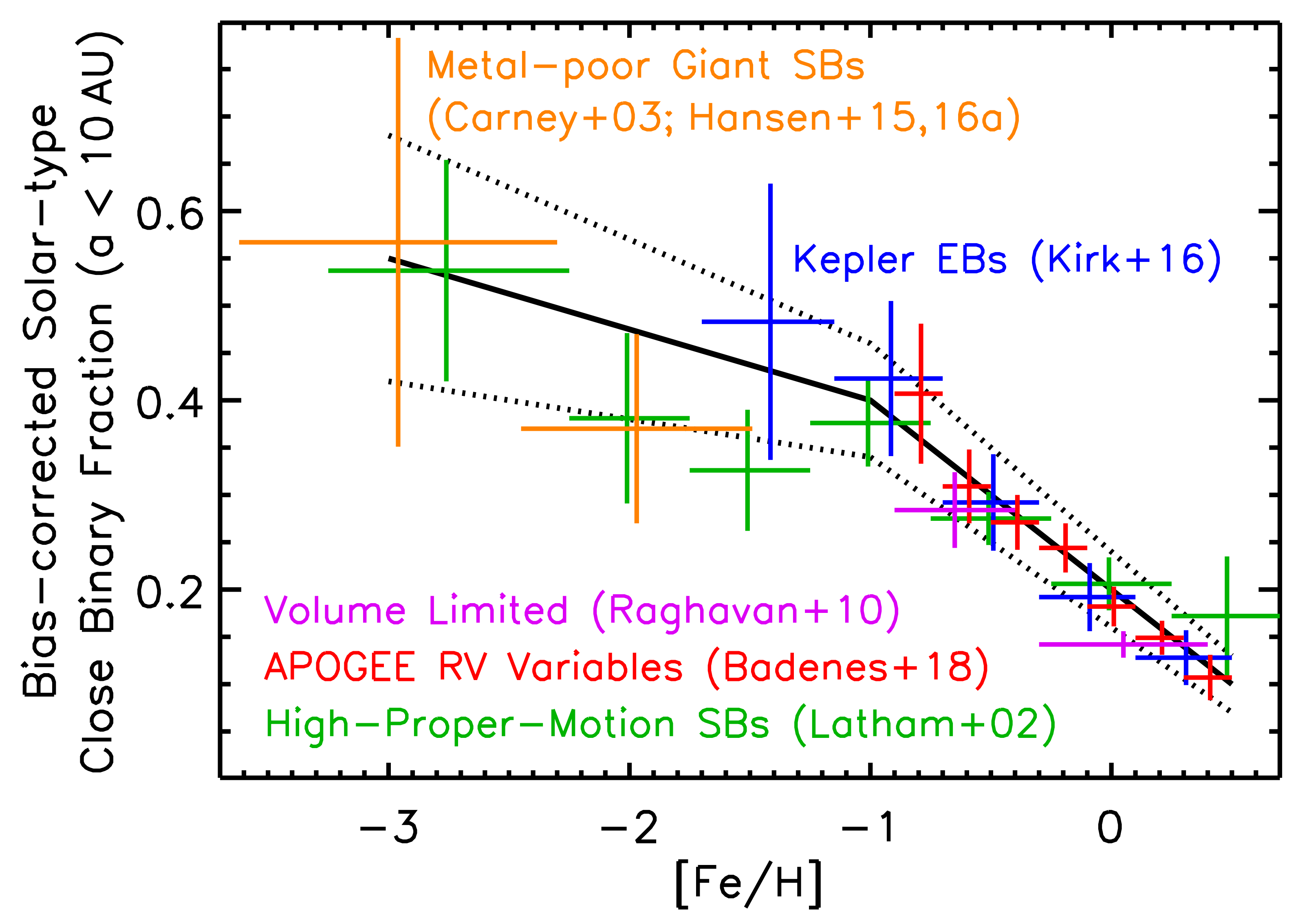
Dependence on Metallicity

B-type EBs in the SMC, LMC, and MW (Moe & Di Stefano 2013)



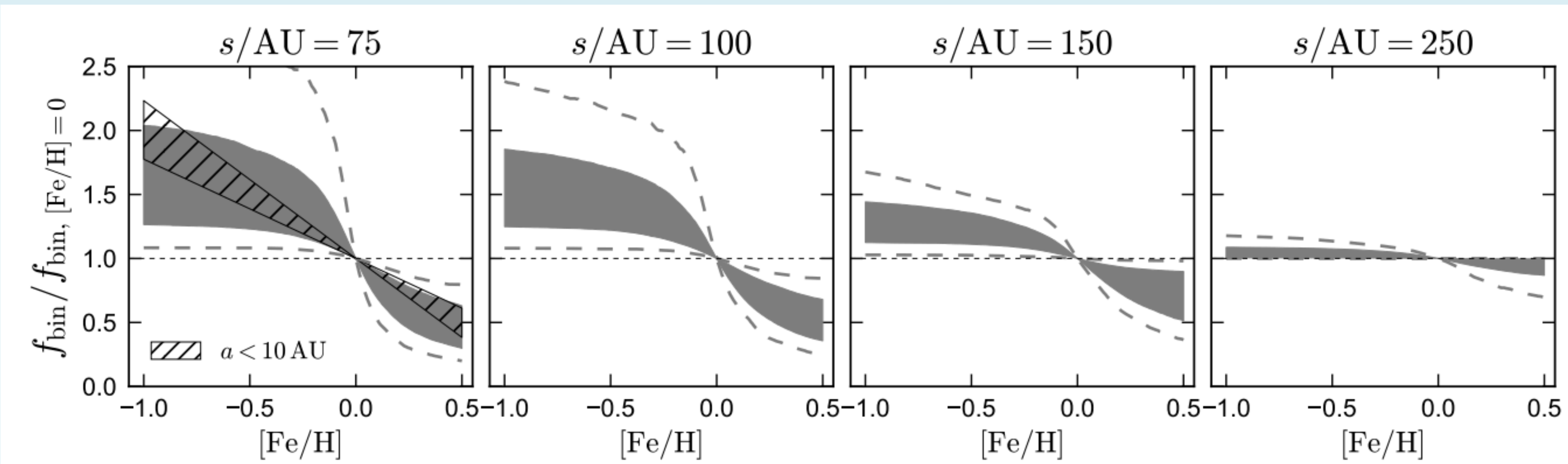
Properties of close massive binaries are invariant across –0.8 < [Fe/H] < 0.2.

Close binary fraction of solar-type stars decreases significantly with metallicity (Moe et al. 2019).



All five samples/methods provide consistent trend!

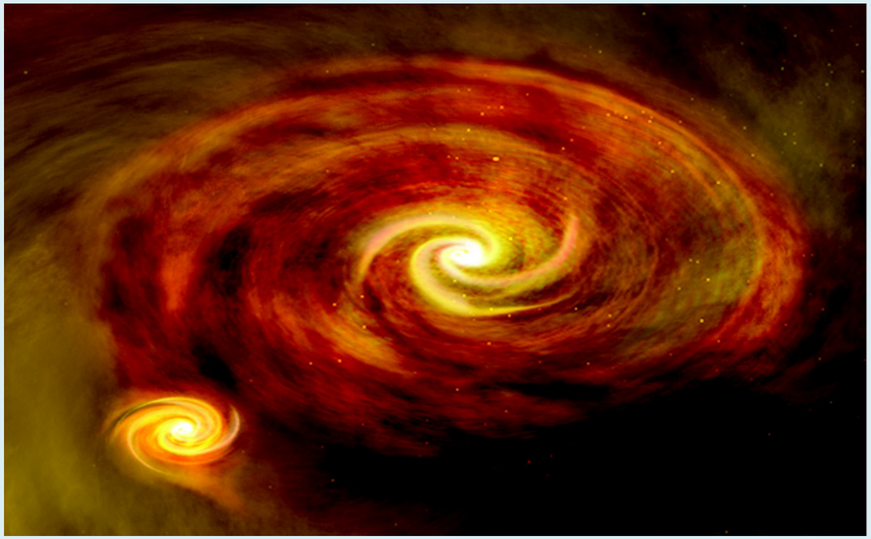
But imaging reveals the wide (a > 200 AU) binary fraction of solar-type stars is metallicity invariant (Moe et al. 2019).



Utilizing Gaia common-proper-motion binaries with [Fe/H] measurements from wide-field spectroscopic surveys, El-Badry & Rix (2019) confirmed the metallicity dependence emerges below a < 200 AU.

Two Modes of Binary Star Formation (Moe et al. 2019)

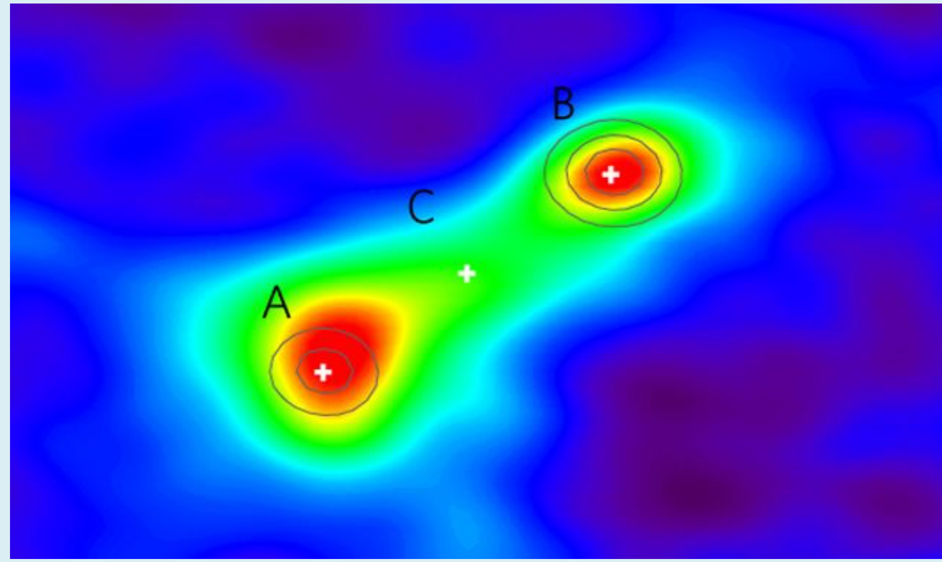
Gravitational Instability and Fragmentation of **Optically Thick Disks**:
$Q_{Toomre} = c_s^2\Omega/\pi G\Sigma = 3\alpha c_s^3/G\dot{M} < 1$;
$a < 100$ AU



With decreasing [Fe/H], disks become less optically thick, become cooler, and fragment.

Massive disks of OB protostars have high accretion rates and always fragment, even at [Fe/H] = 0

Turbulent Fragmentation of **Optically Thin Molecular Cores**:
Mach = $\sigma_v/c_s > 1$; $a > 100$ AU

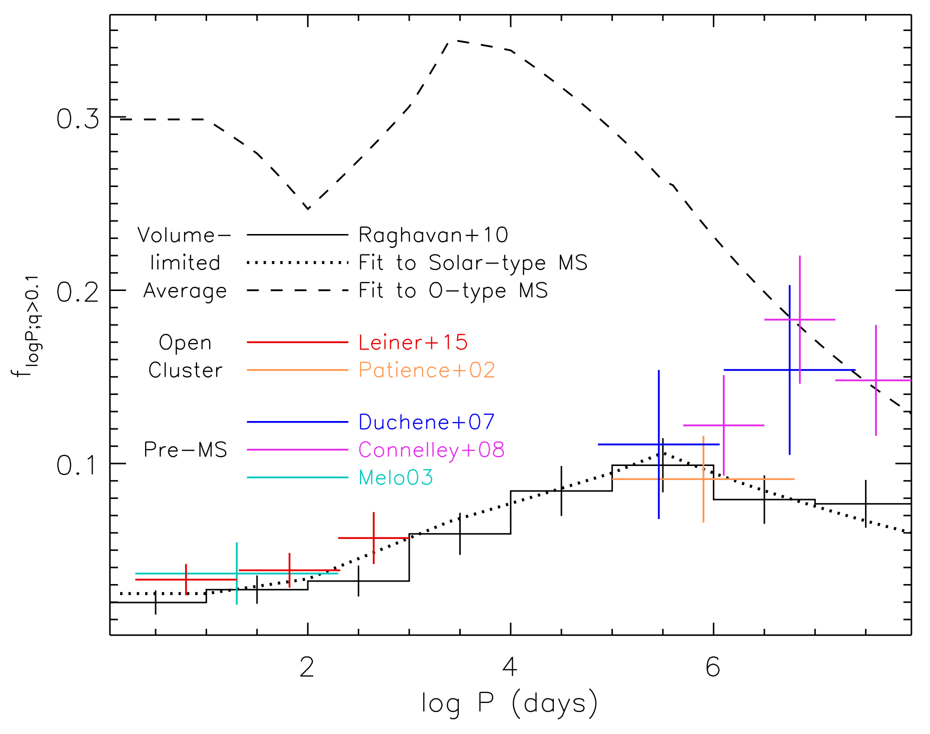


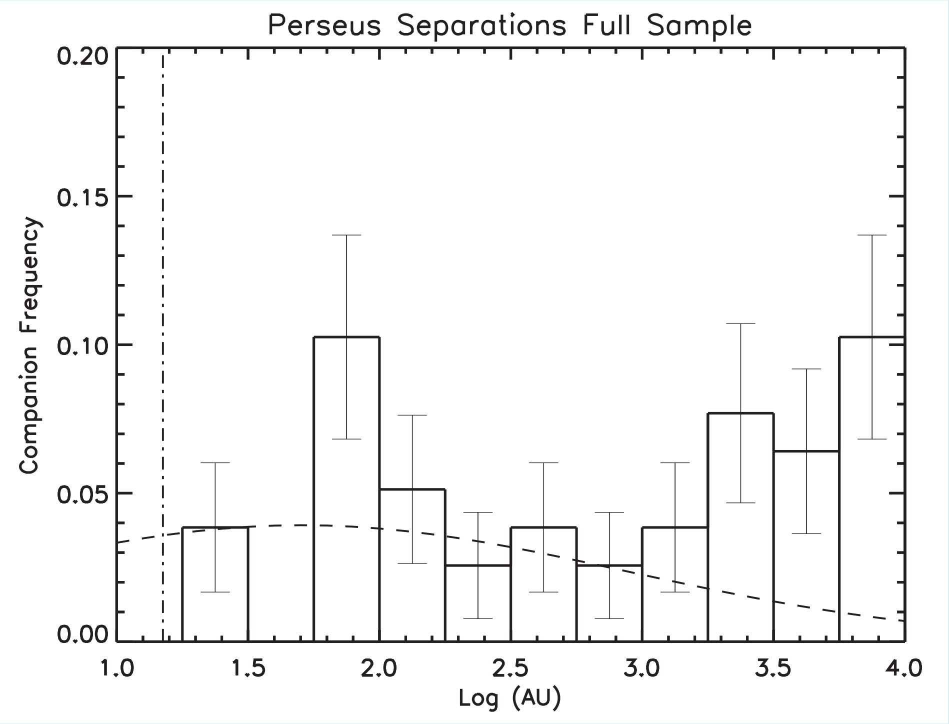
Independent of opacity (Bate+ 2019): wide binary fraction and IMF are metallicity invariant across $-1.5 < [Fe/H] < 0.5$

Gaia DR3 will fill in gaps within $f(M_1, P, Z)$ and explore dependence on X_i

Pre-MS Binaries

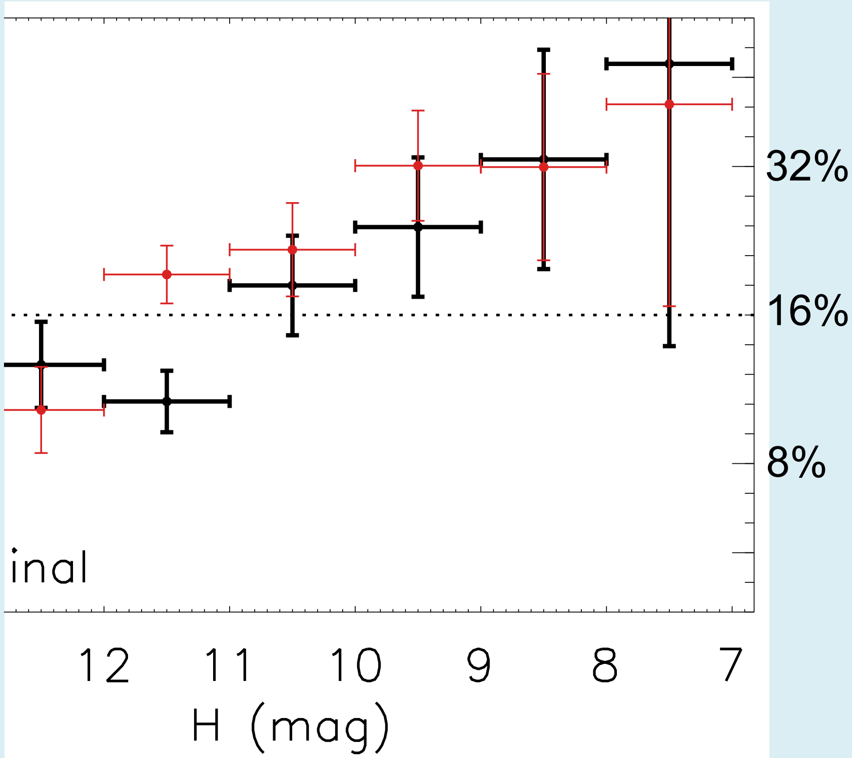
IR / radio observations of embedded class 0/I protostars reveal an excess of companions beyond a > 500 AU, suggesting core fragmentation on large scales is efficient but then wide low-mass binaries are disrupted within ~0.5 Myr (Duchene et al. 2007; Connelley et al. 2008; Tobin et al. 2016; Moe & Di Stefano 2017)



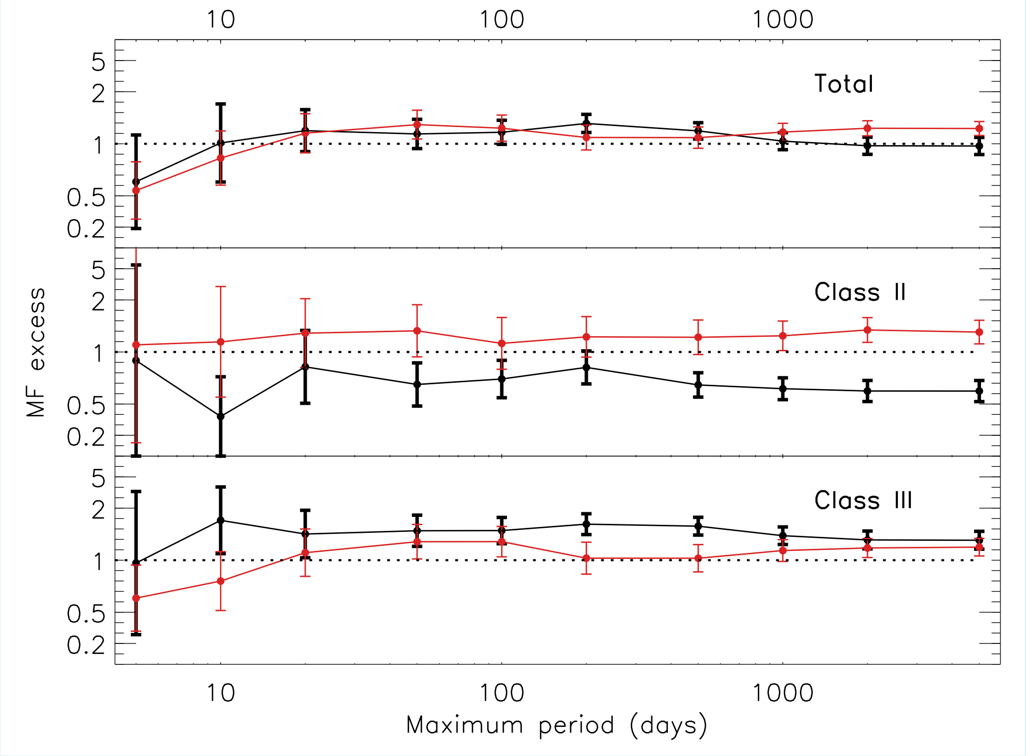


Kounkel et al. (2019) analyzed APOGEE spectra of ~5,000 T Tauri stars, and discovered ~400 binaries (SB2s from CCF and SB1s from RV variability).

Close binary fraction (a < 10 AU) increases with luminosity (i.e., M_1), consistent with the field.



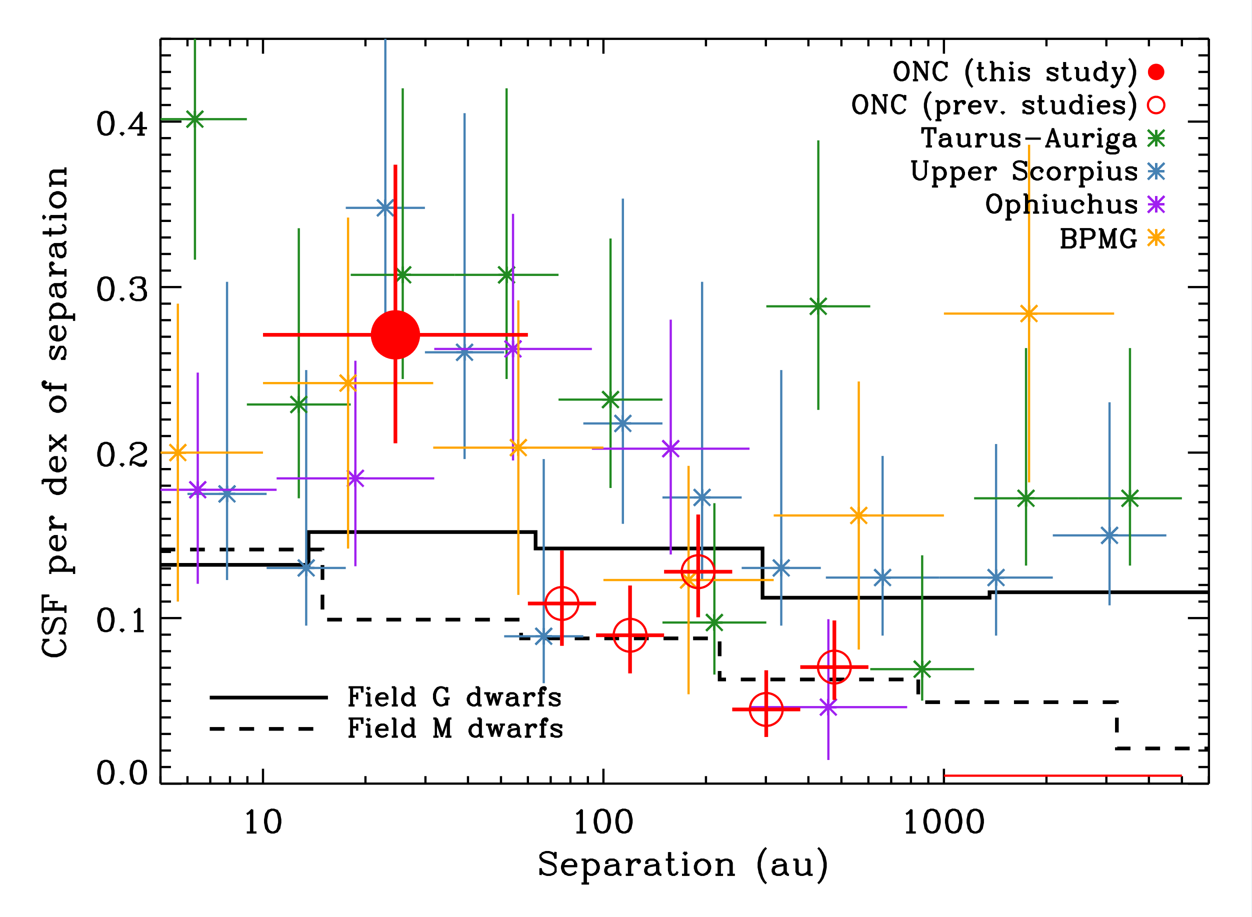
Separation distribution across a = 0.1 - 10 AU matches field distribution.



Close binary properties of M_1 = 0.3 – 3 $M_\odot$ primaries set by ~1 Myr!

AO and sparse aperture masking reveal an excess of young T Tauri binaries across a = 10 – 60 AU compared to the field (Duchene et al. 2018).

The consistency below a < 10 AU and across a = 60 – 500 AU but large excess across a = 10 – 60 AU, even in Orion, is a major mystery!



Perhaps Gaia can help resolve discrepancy / discontinuity in f(P, τ, n)?

Compact Remnant Companions to MS Stars

Regulus: a rapidly rotating B8IV star;
P = 40 day SB1, likely a WD companion

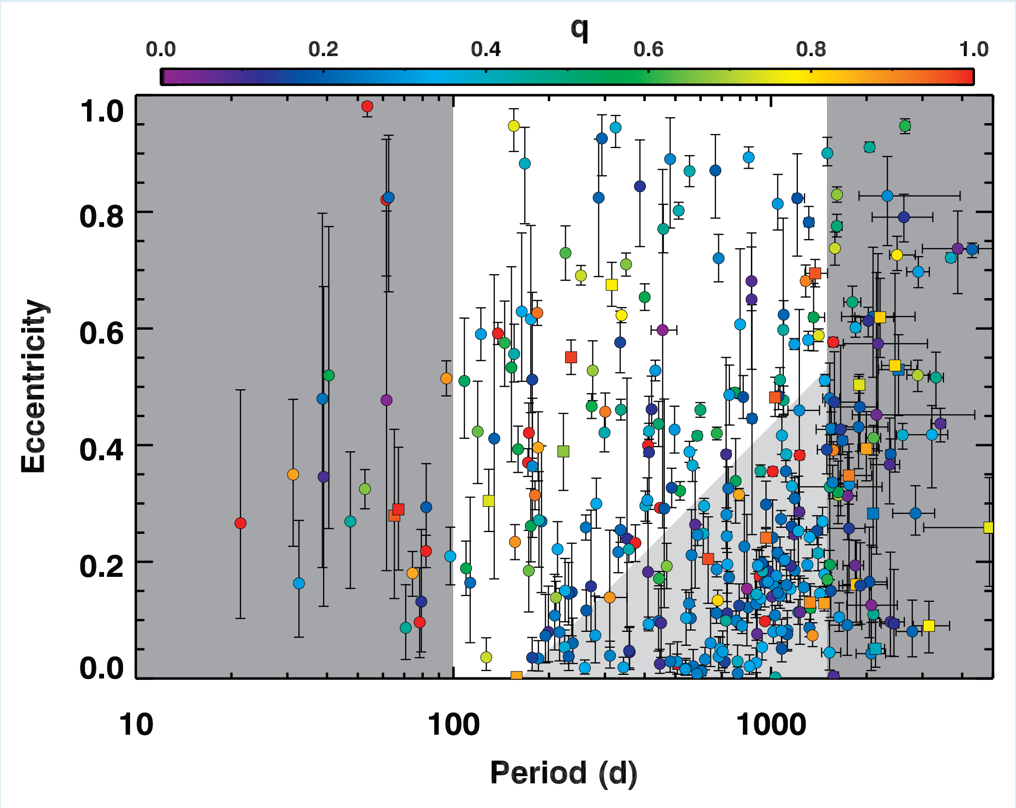
Census of confirmed WD companions closely orbiting BAFG stars incomplete beyond d > 10 pc (Holberg et al. 2016); **Gaia will help**

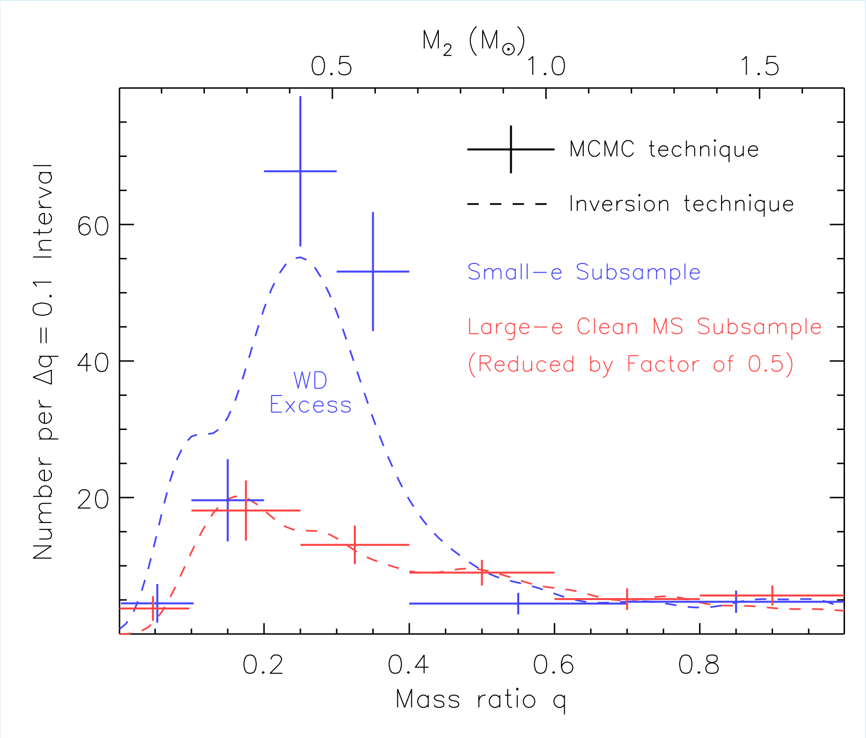
After correcting for incompleteness, 11% ± 3% of field solar-type stars have WD companions, i.e., ~20% of companions are WDs, and 30% ± 10% of SB1s have WD companions (Moe & Di Stefano 2017)

Malachi Regulus Moe

~30% of O stars are the products of binary evolution (de Mink et al. 2015), and ~20% of OB "primaries" are actually the companions in which the true primaries have already evolved into NSs or BHs (Moe & Di Stefano 2017)

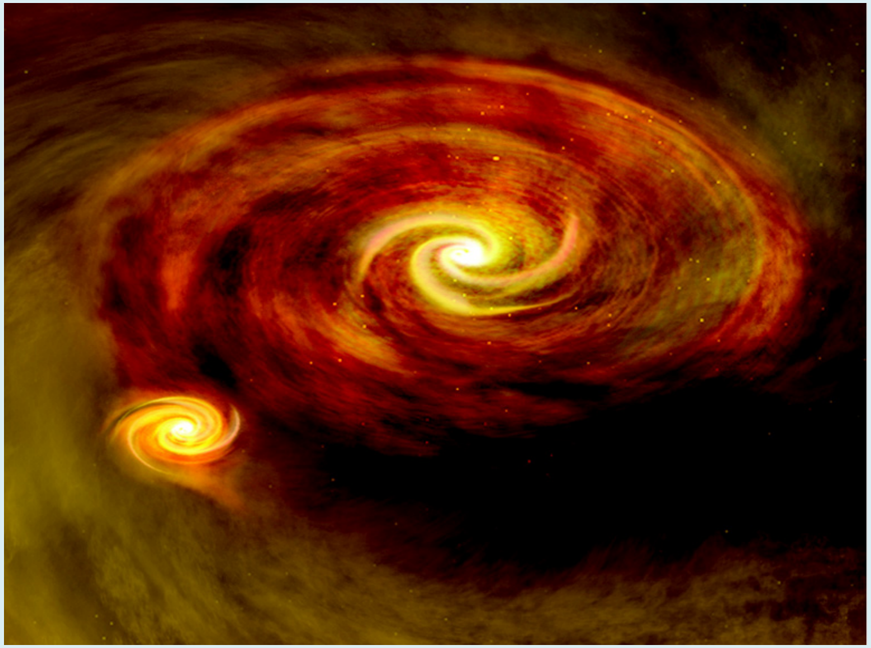
Phase modulation of Kepler pulsating δ Scuti stars (older A/F dwarfs) reveal binary companions across a = 0.5 – 5 AU, 22% ± 6% of which are WDs with small eccentricities (Murphy, Moe et al. 2018)





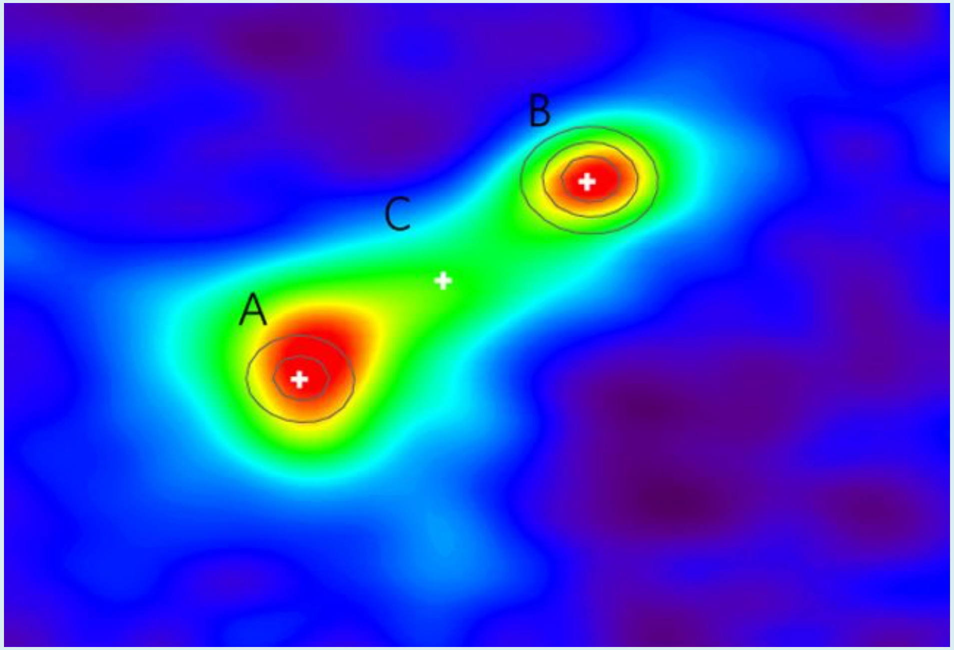
Overall Theme

Disk Fragmentation:
Close binaries with a < 100 AU



Increases with M_1.
Compact coplanar triples.
Uniform q & excess twins.
Decreases with [Fe/H].
Independent of τ and n.

Core Fragmentation:
Wide binaries with a > 100 AU



Independent of M_1.
Wide tertiaries randomly oriented.
Weighted toward q = 0.3 & few twins.
Independent of [Fe/H].
Decreases with τ and n.

Conclusion

Multiplicity statistics constitute a complicated parameter space:

$f(M_1, M_2, P, e, [MS, BD, WD, NS, BH], [M_3, P_{out}, i_{mut}], [Z, X_i], [\tau, n])$

Gaia will explore new regions of this parameter space, providing new insights into binary star formation and evolution.