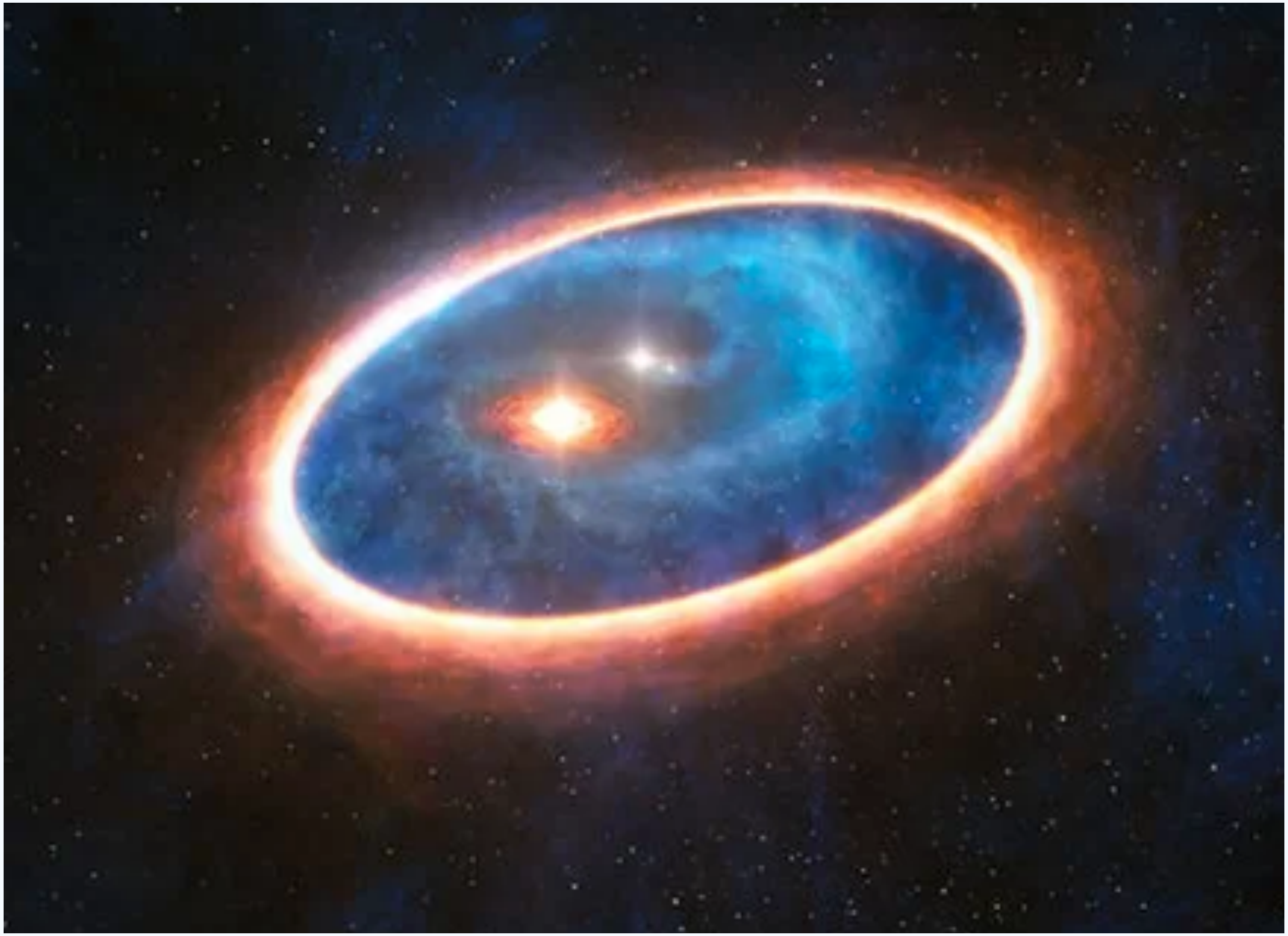
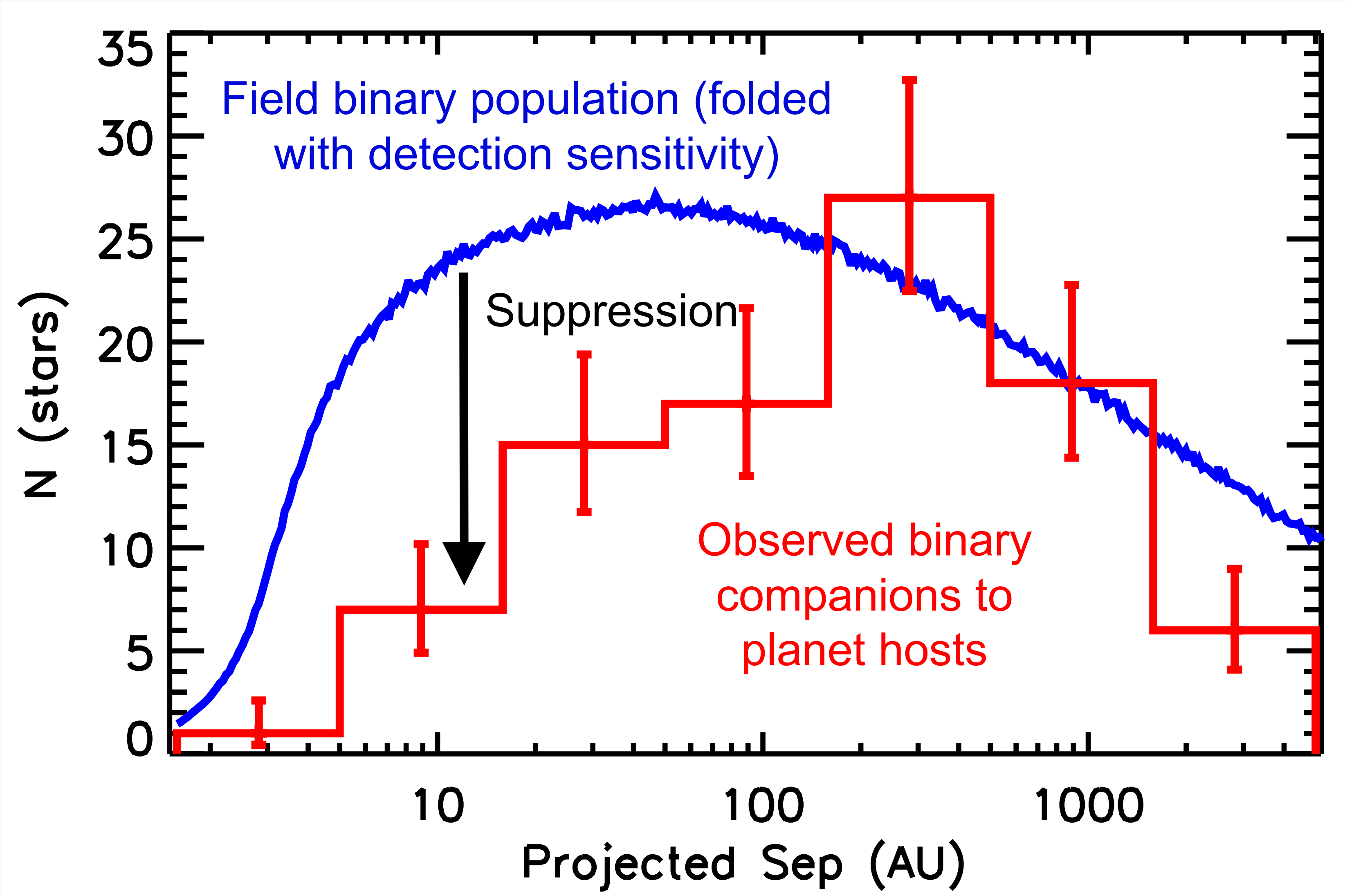
Impact of Binary Stars on Planet Formation and Statistics

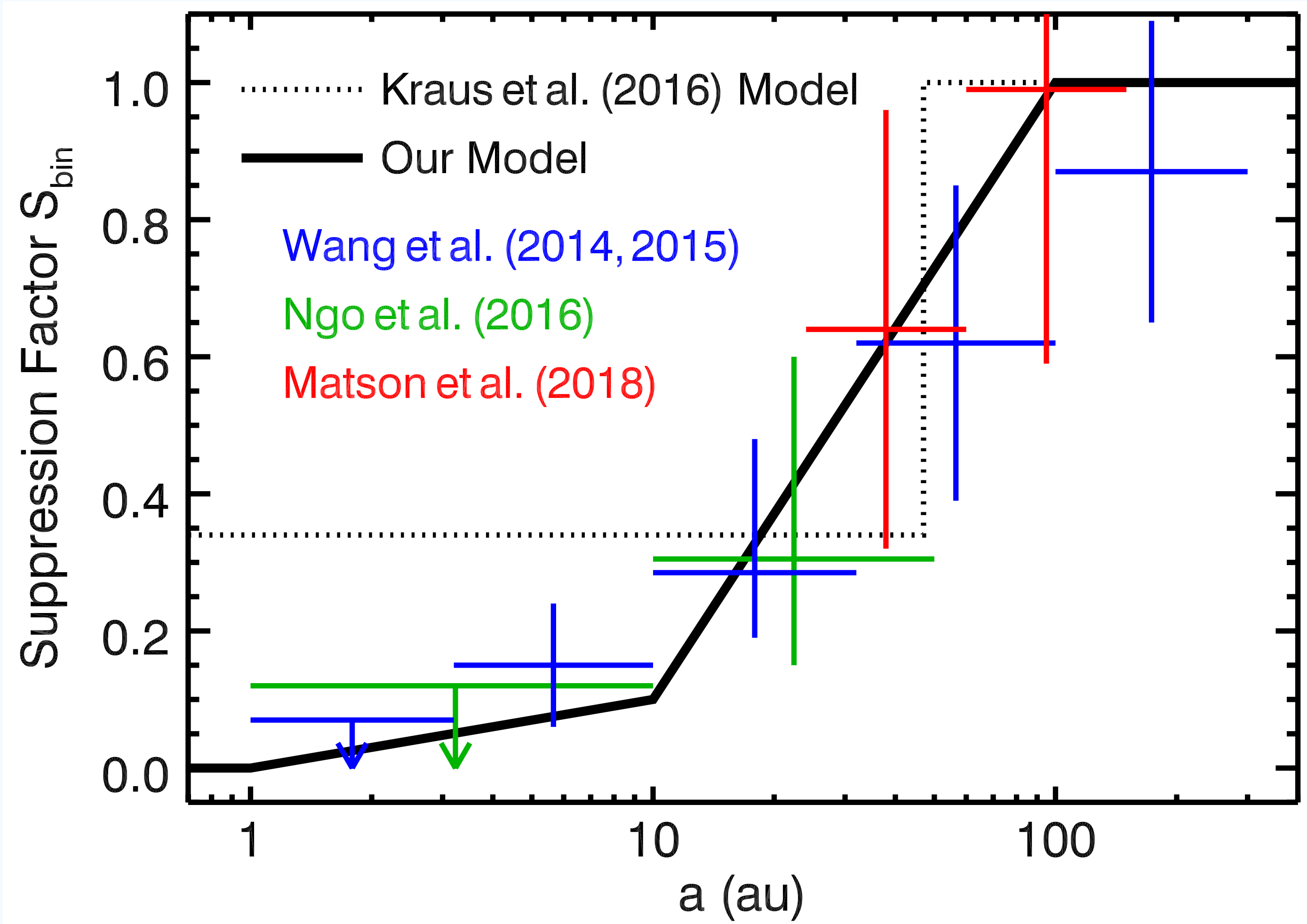
Maxwell Moe (University of Arizona)



Although close binaries can harbor circumbinary (P-type) planets, binaries with a < 50 AU suppress formation of circumstellar (S-type) planets (Wang et al. 2014, 2015; Kraus et al. 2016; Ngo et al. 2016)

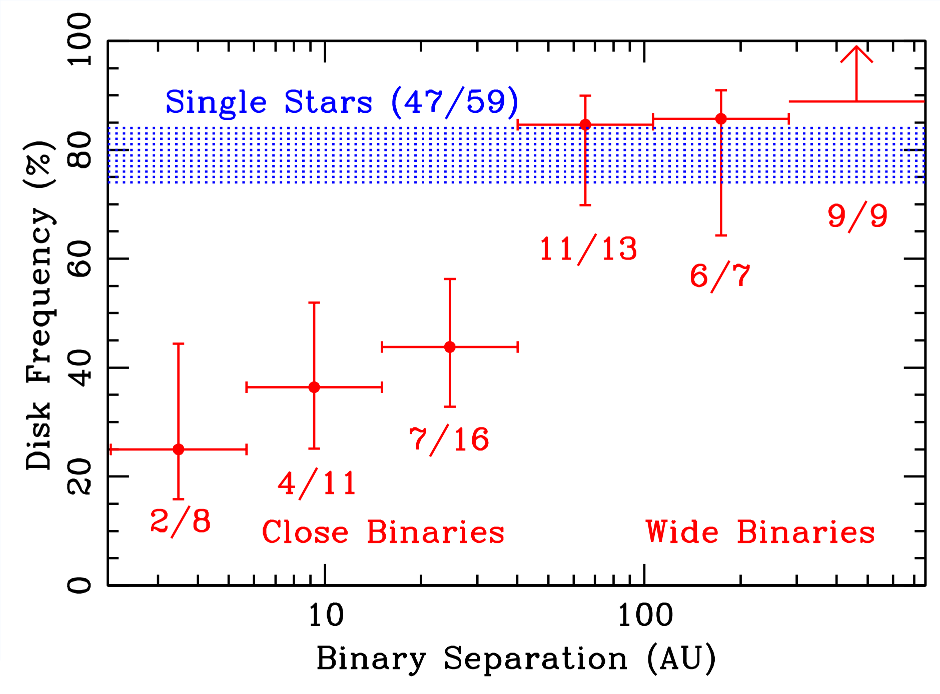


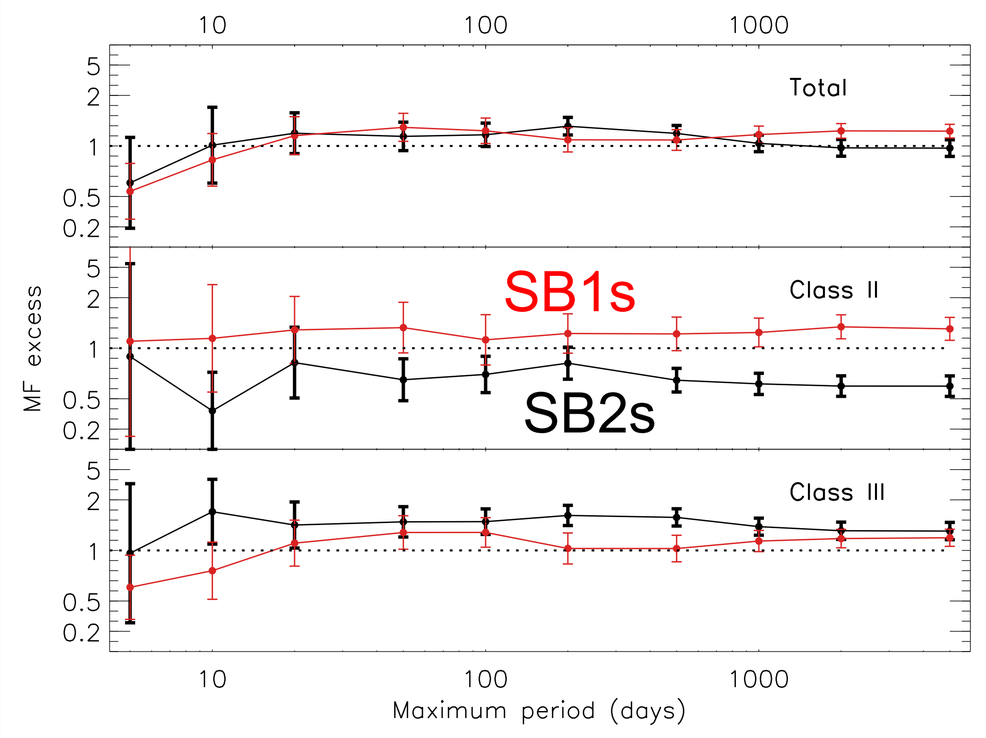
Suppression factor is a continuous function of binary separation



Planet suppression by close binaries is **NOT** just due to dynamical stability: a binary companion increases turbulence in the disk, truncates the disk, and accretes disk material on rapid timescales (Artymowicz & Lubow 1994; Haghighipour & Raymond 2007; Rafikov & Silsbee 2015)

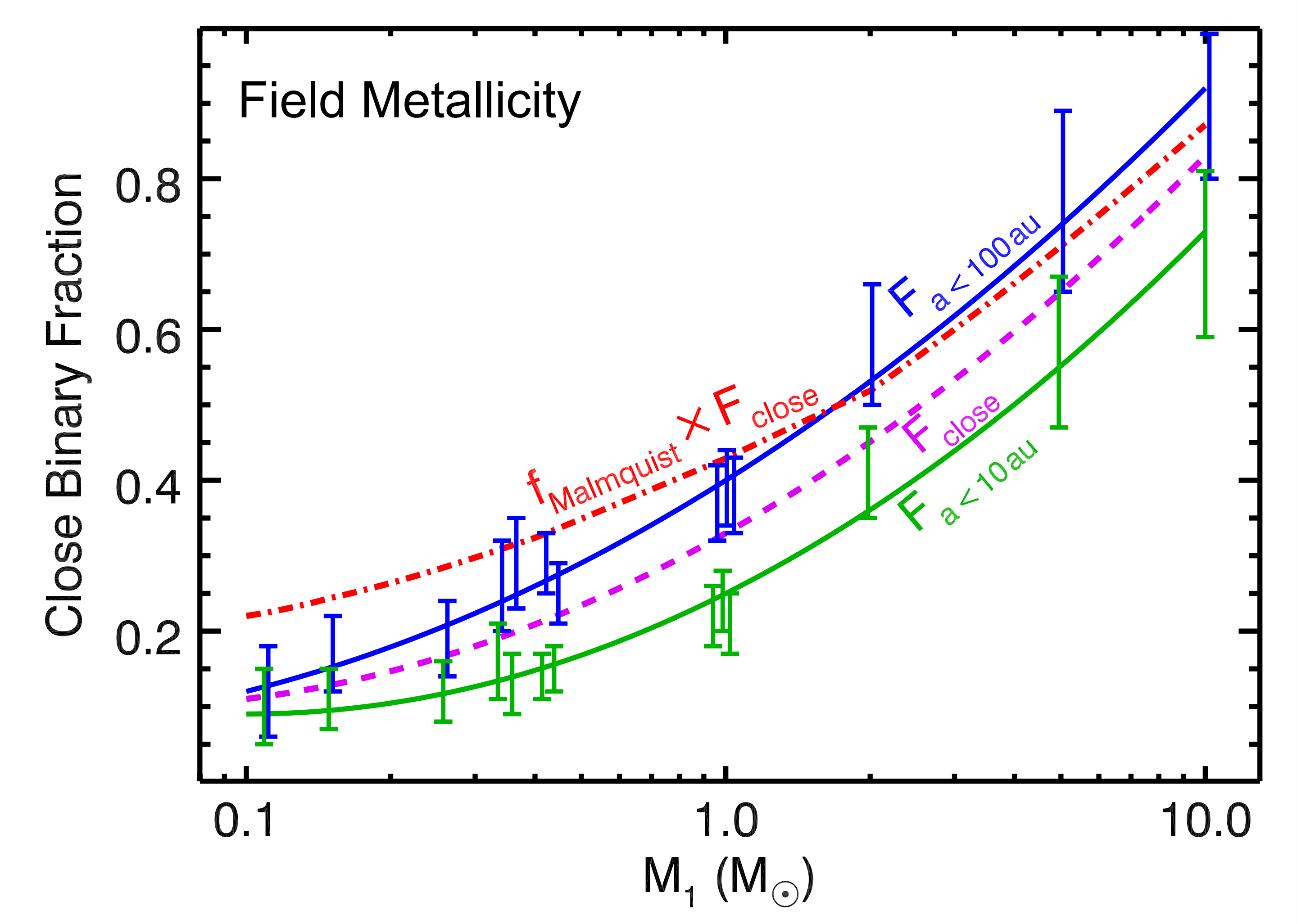
Binaries with a < 50 AU have **shorter disk lifetimes** (Kraus et al. 2012)





Especially SB2s with q > 0.7 (Kounkel, Covey, Moe et al. 2019)

Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)



In magnitude-limited samples, **43% ± 6%** of G-type stars cannot host planets due to presence of close binaries

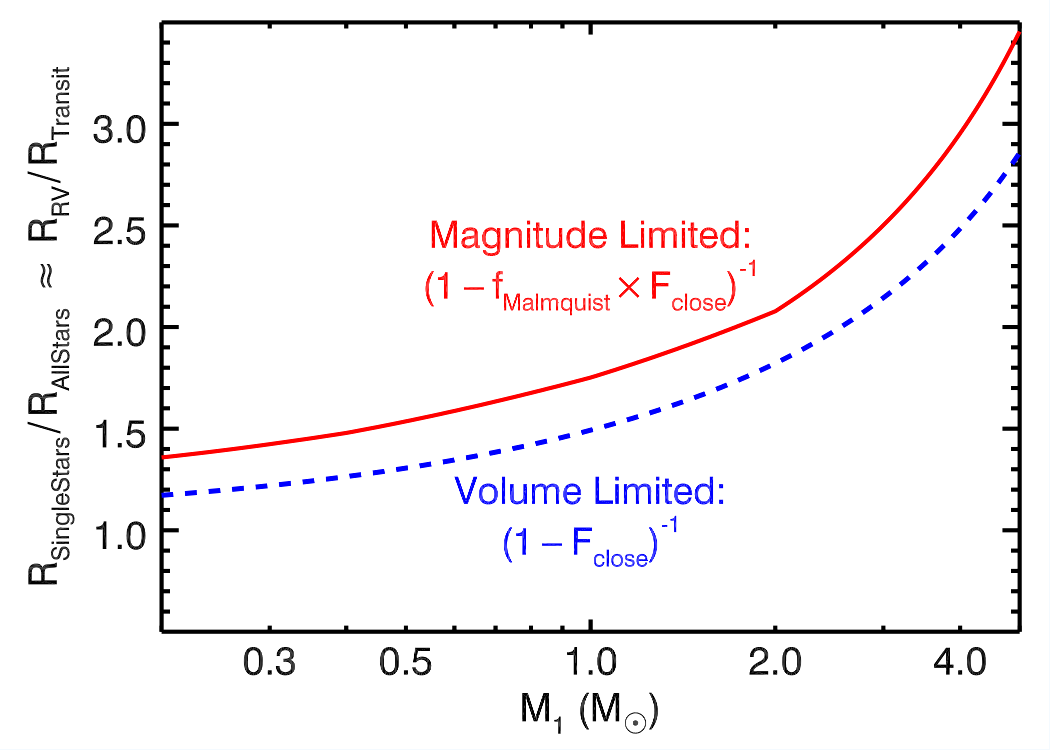
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

Well-known ~4σ discrepancy in hot Jupiter occurrence rates between RV surveys and *Kepler*:

$R_{HJ;RV}$ = 0.9% - 1.2% (Mayor et al. 2011; Wright et al. 2012)

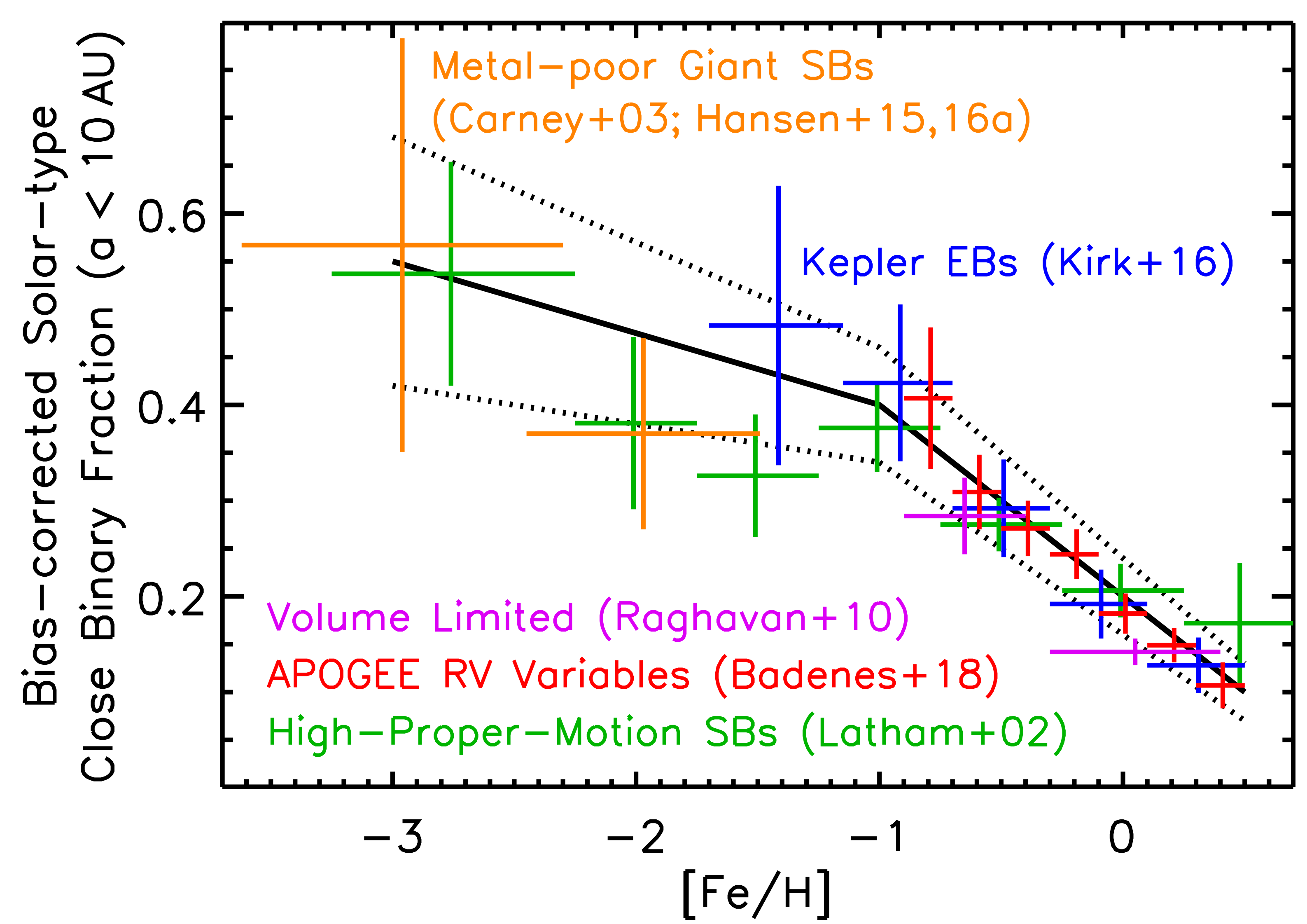
$R_{HJ;Transit}$ = 0.4% - 0.6% (Fressin et al. 2013; Petigura et al. 2017)

Neither transit dilution by binary companion (Wang et al. 2015; Teske et al. 2018) nor differences in [Fe/H] (Guo et al. 2017) can explain factor of ~2 discrepancy



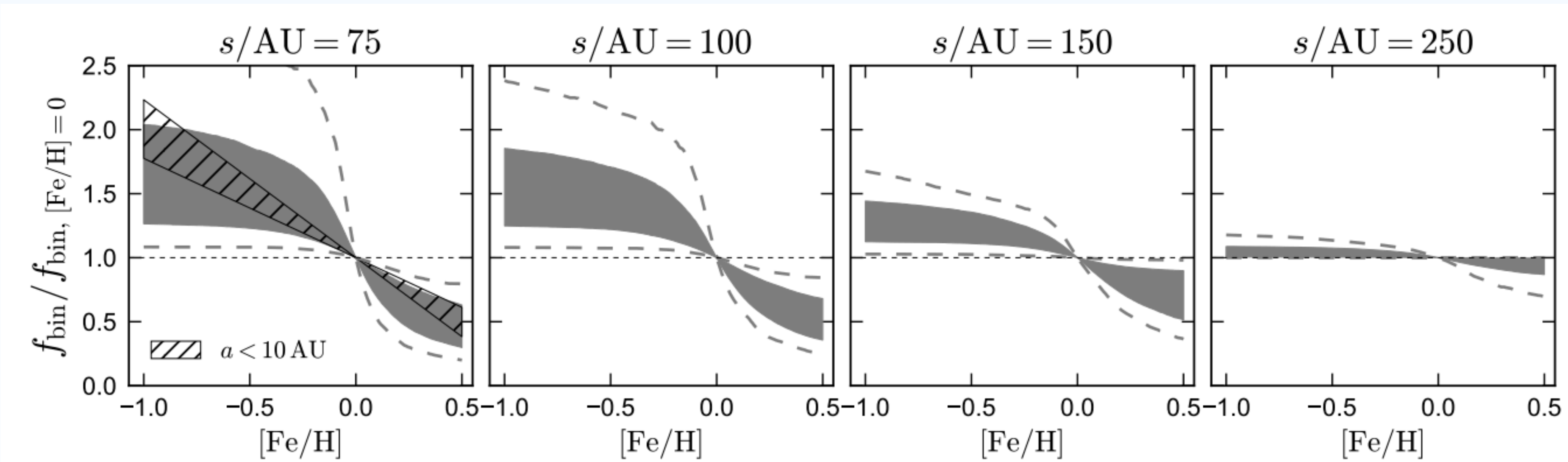
By removing spectroscopic binaries from their samples, RV surveys for Jovian planets orbiting G-type stars boost their detection rate by a factor of 1/(1-0.43) = 1.8

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).

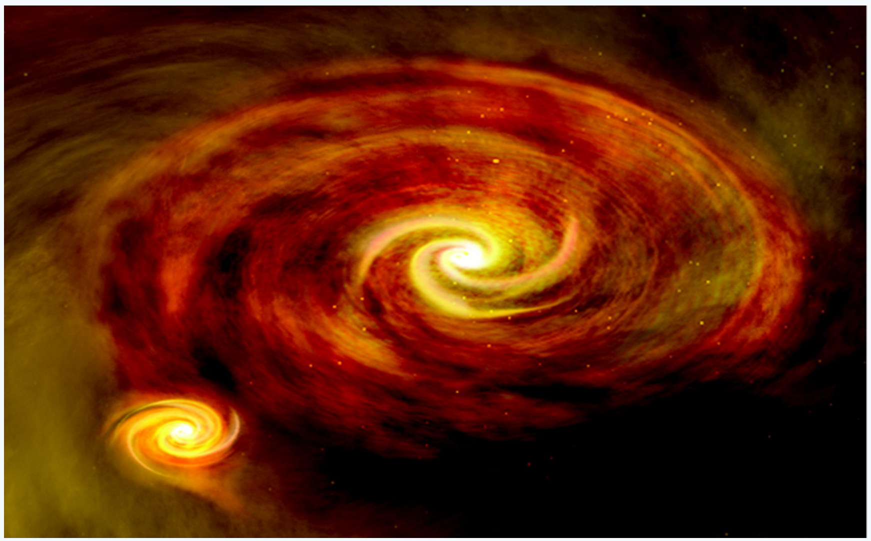


Utilizing Gaia common-proper-motion binaries with [Fe/H] measurements from wide-field spectroscopic surveys, El-Badry & Rix (2019) confirmed the metallicity dependence emerges below a < 200 AU.

Two Modes of Binary Star Formation

(Kroupa et al. 1995; Bate et al. 1995,2002; Kratter et al. 2002, 2006; Offner et al. 2010; Tobin et al. 2016; Lee et al. 2017; **Moe & Di Stefano 2017; Moe et al. 2019**)

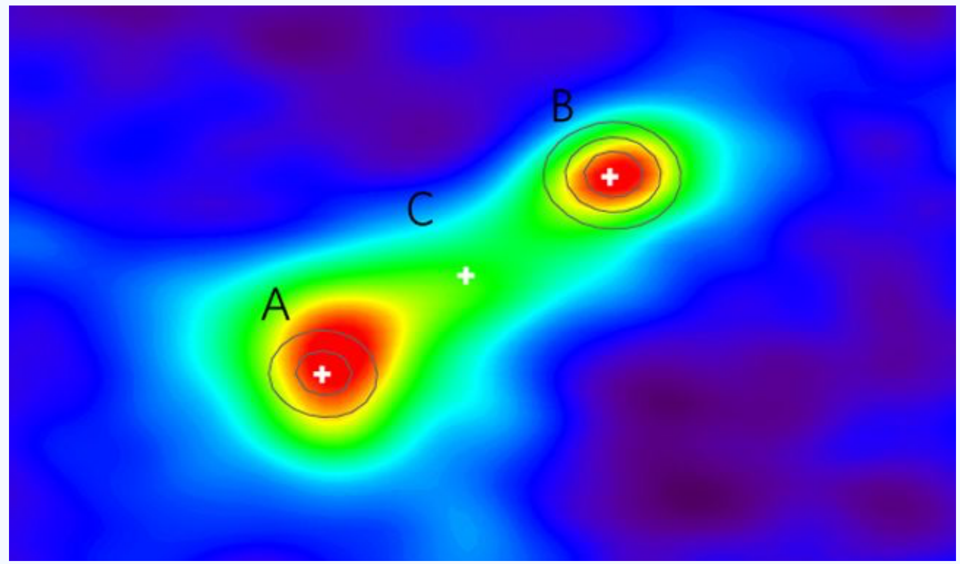
Gravitational Instability and Fragmentation of **Optically Thick Disks**:
$Q_{Toomre} = c_s^2\Omega/\pi G\Sigma = 3\alpha c_s^3/G\dot{M} < 1$;
$a < 200$ AU



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

massive disks of OB protostars always fragment, even at [Fe/H] = 0

Turbulent Fragmentation of **Optically Thin Molecular Cores**:
Mach = $\sigma_v/c_s > 1$; $a > 200$ AU



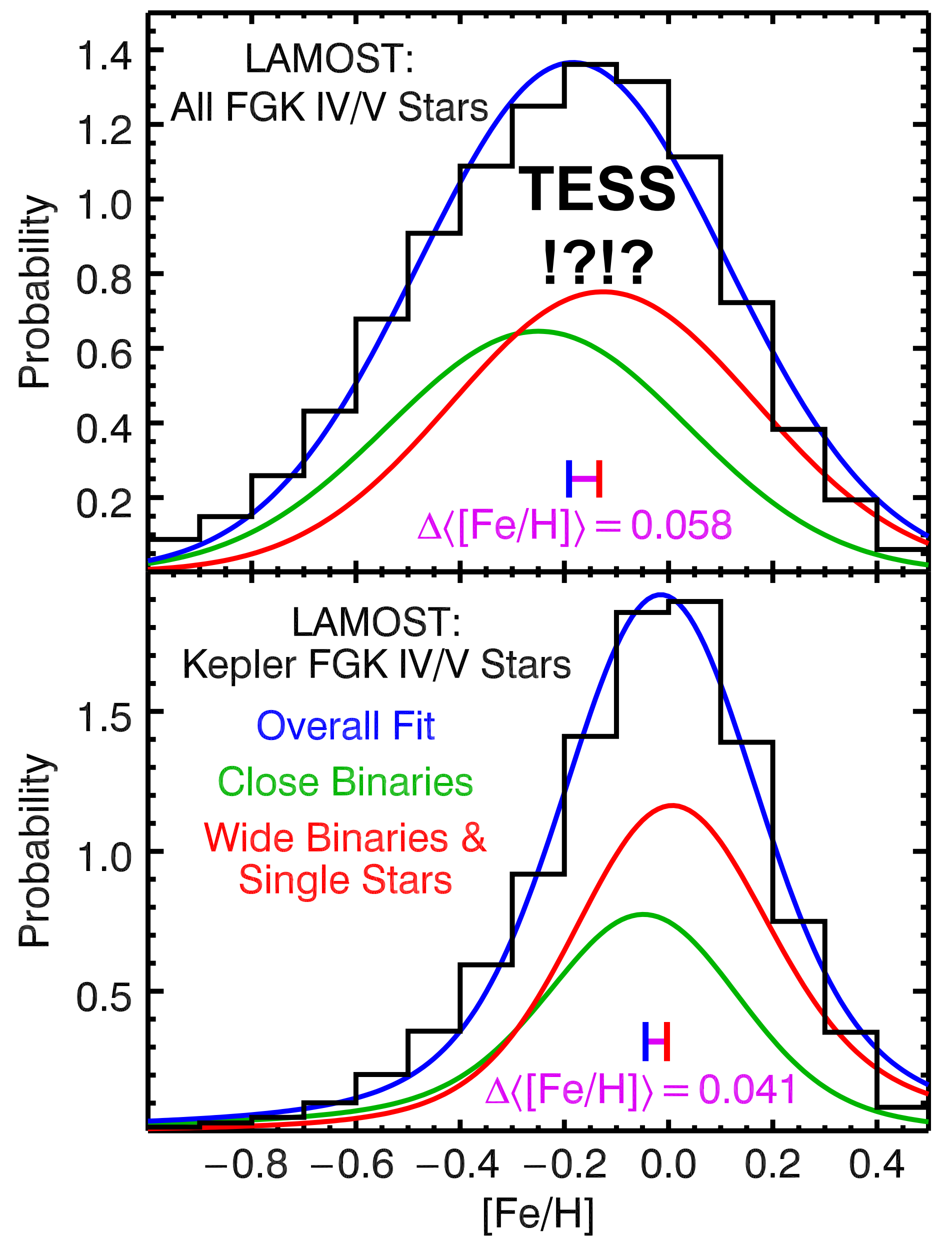
Independent of opacity (wide binary fraction and IMF are metallicity invariant)

Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

LAMOST measured metallicities of ~5 million field stars and ~40% of Kepler stars (Dong et al. 2014; Ren et al. 2016; Zong et al. 2018).

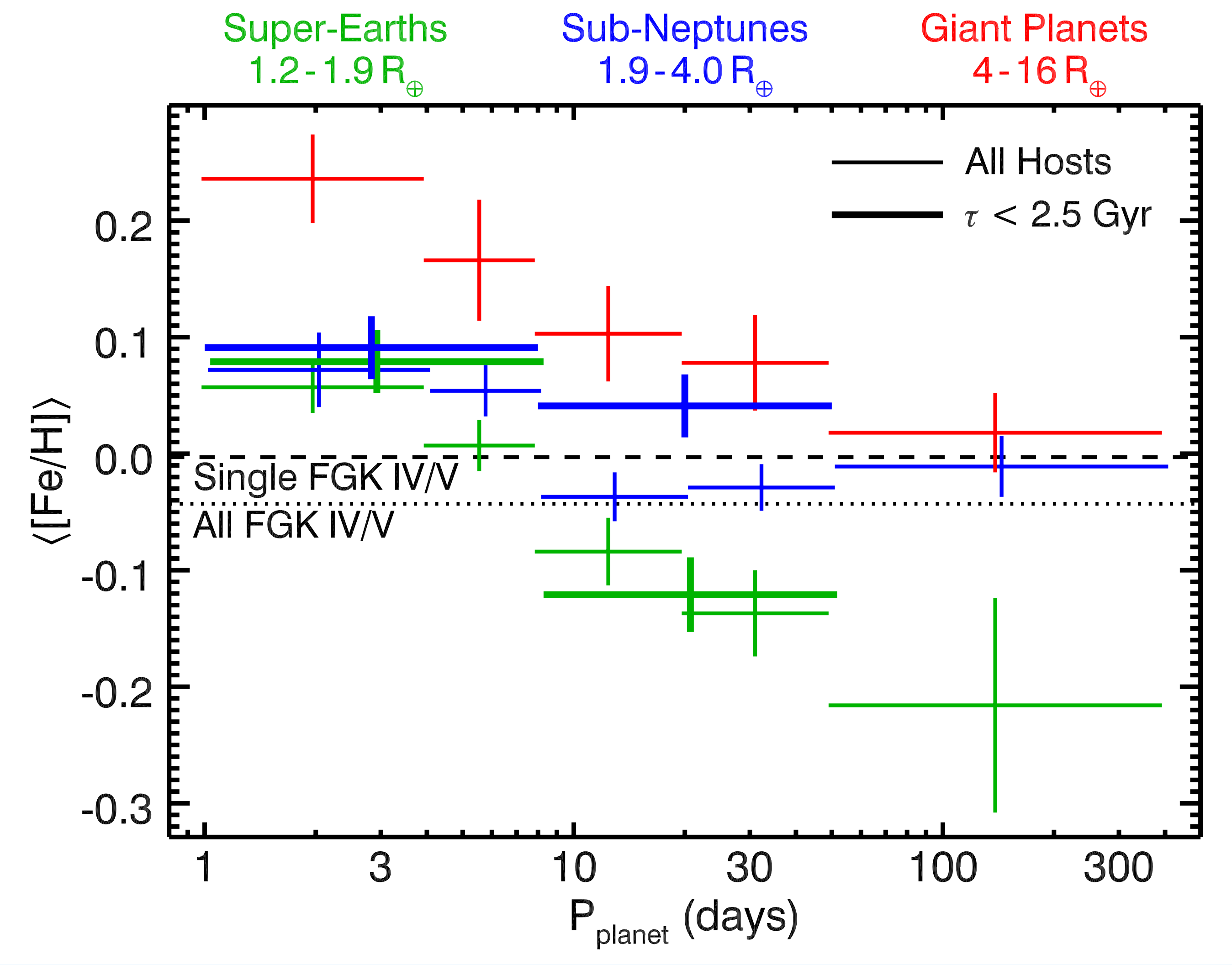
Kepler FGK IV/V stars are more metal rich than field counterparts.

Single stars and wide binaries, which can host close planets, are Δ⟨[Fe/H]⟩ = 0.05 dex more metal rich than the parent population.



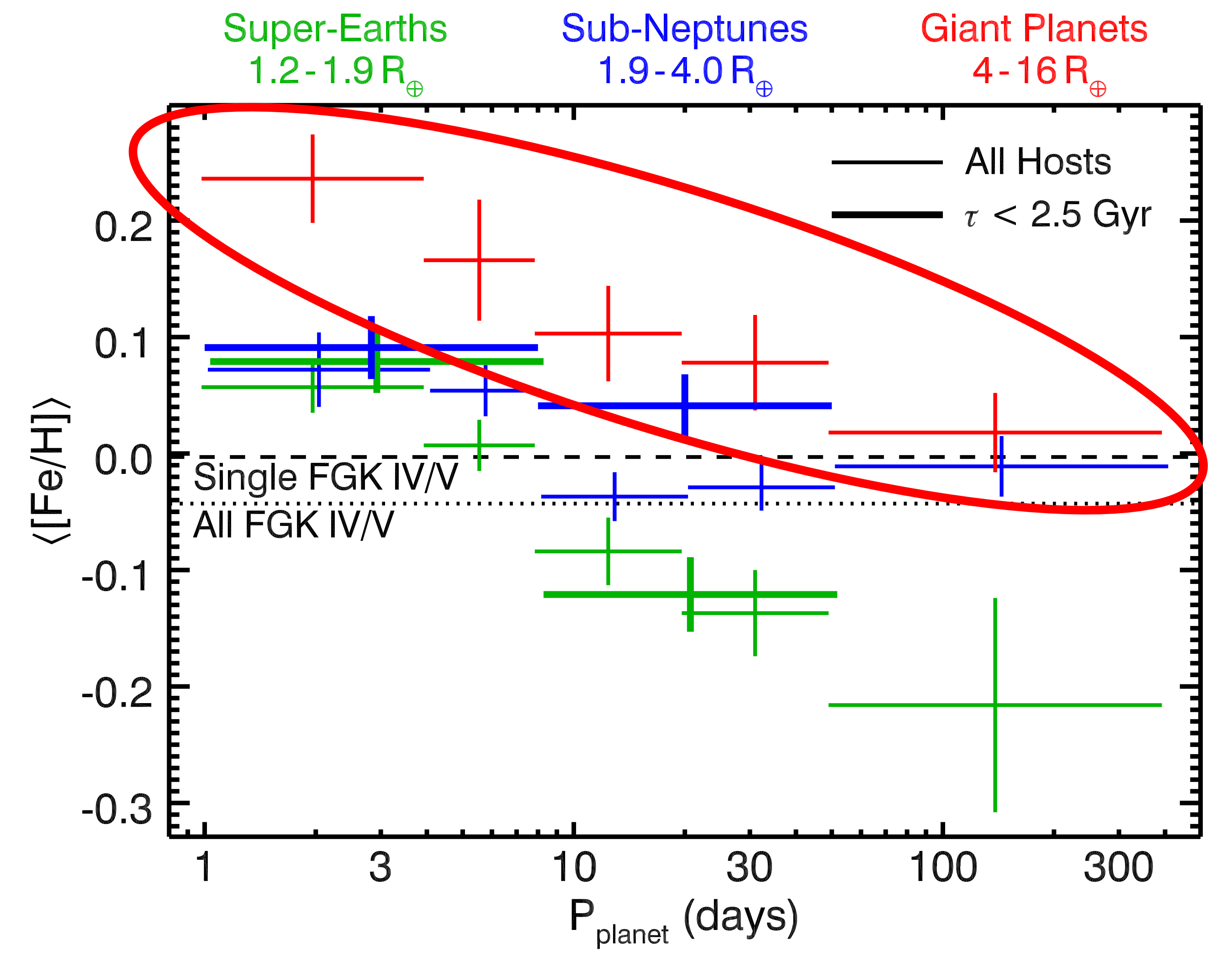
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

LAMOST metallicities of Kepler FGK IV/V stars (Zong et al. 2018)
+ radii of confirmed planets from Gaia DR2 (Berger et al. 2018)
+ ages from gyrochronology (Walkowicz et al. 2013)



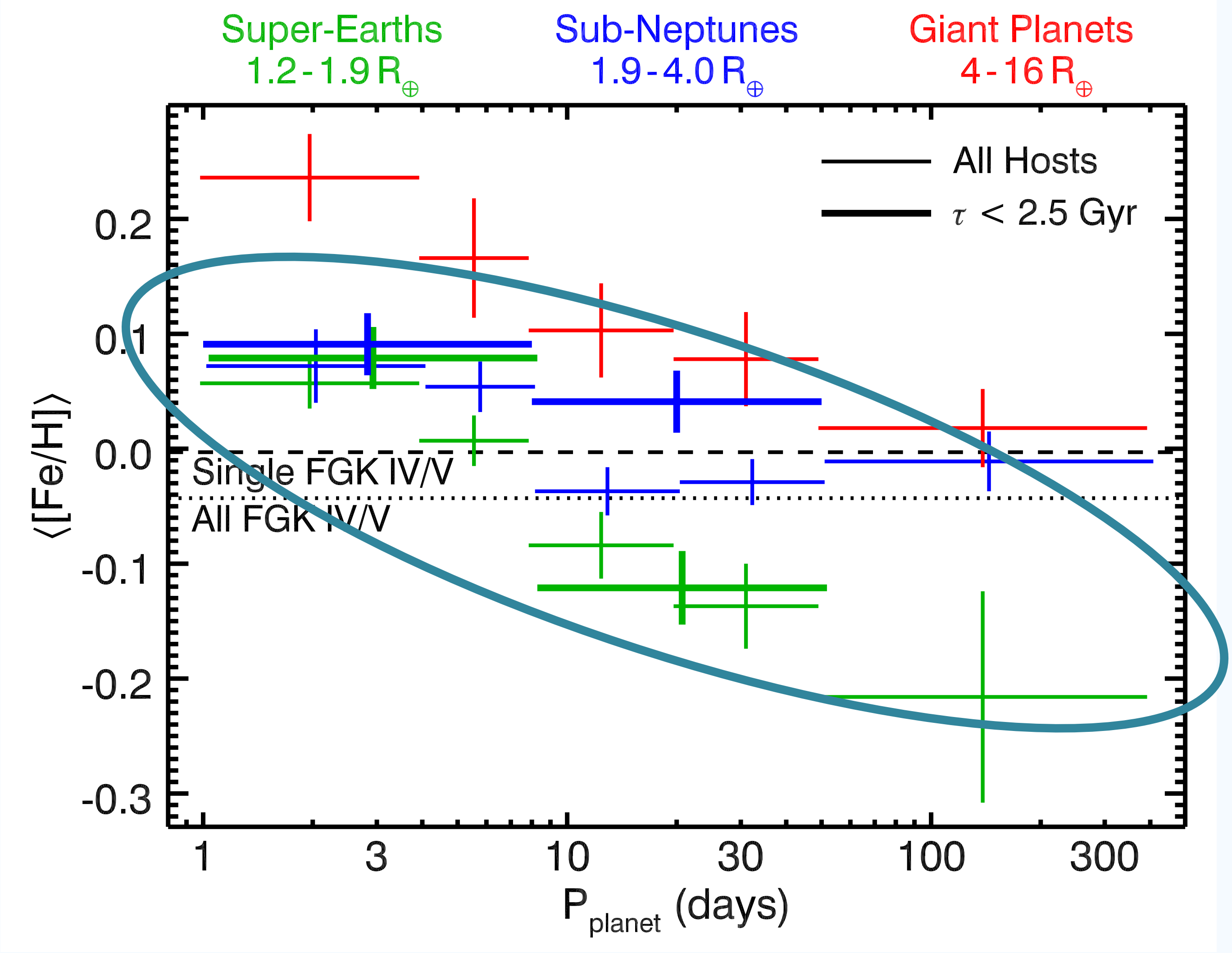
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

Kepler giant planet metallicity vs. period correlation consistent with RV results from Buchhave et al. (2018), who found hot Jupiters have ⟨[Fe/H]⟩ = 0.23 ± 0.03 while cool Jovian analogs have ⟨[Fe/H]⟩ = −0.07 ± 0.05.



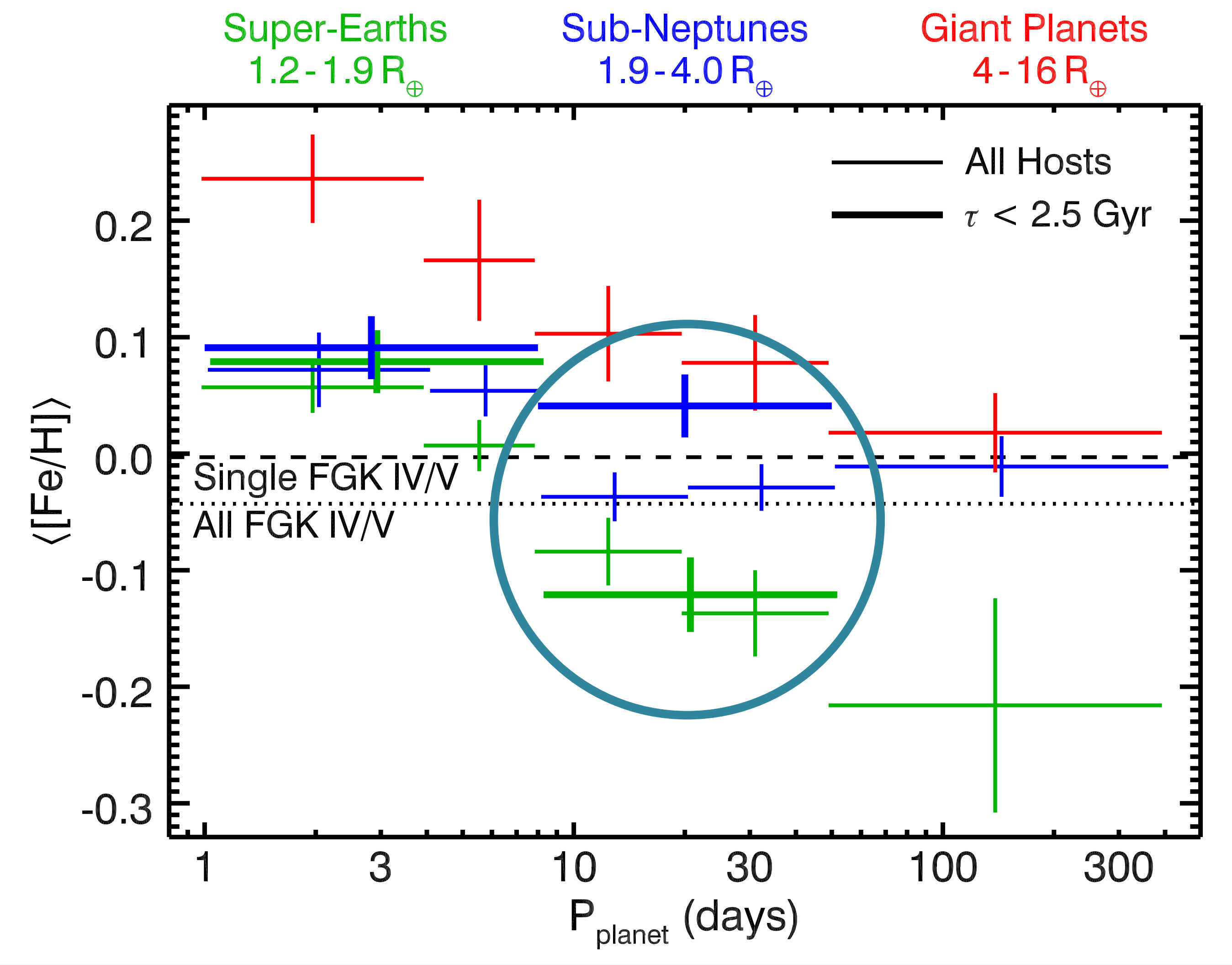
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

Hot small planets are metal rich compared to warm small planets, similar to trend found by Mulders et al. 2016, Wilson et al. 2018, and Petigura et al. 2018



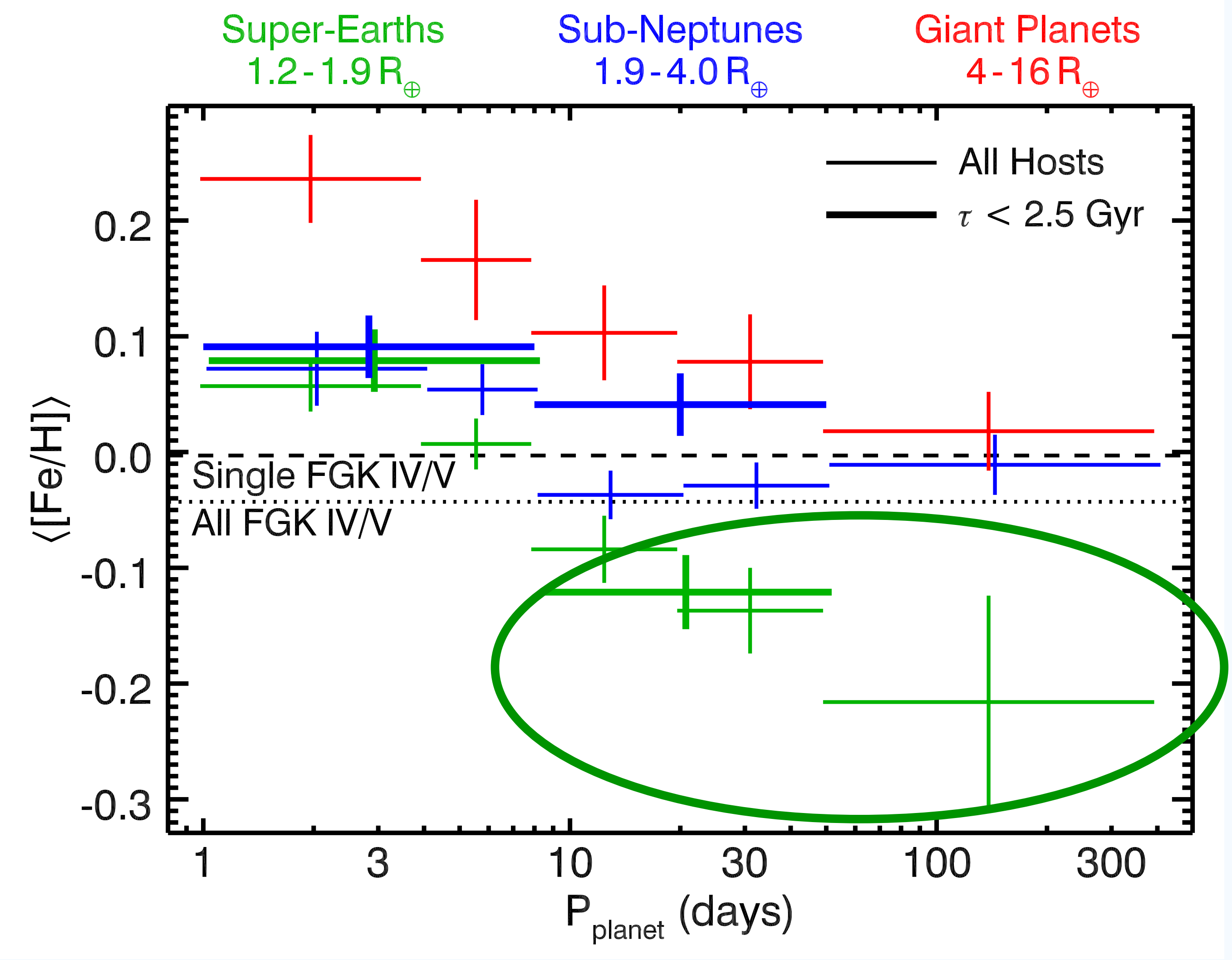
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

Warm super-Earths have distinctly lower metallicities than warm sub-Neptunes (especially at young ages).
Similar to trend found by Owen & Murray-Clay (2018), but now ~5σ result!



Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

Warm and cool super-Earths have ⟨[Fe/H]⟩ = −0.15:
if protoplanetary disk is too metal rich, then more likely to form a sub-Neptune



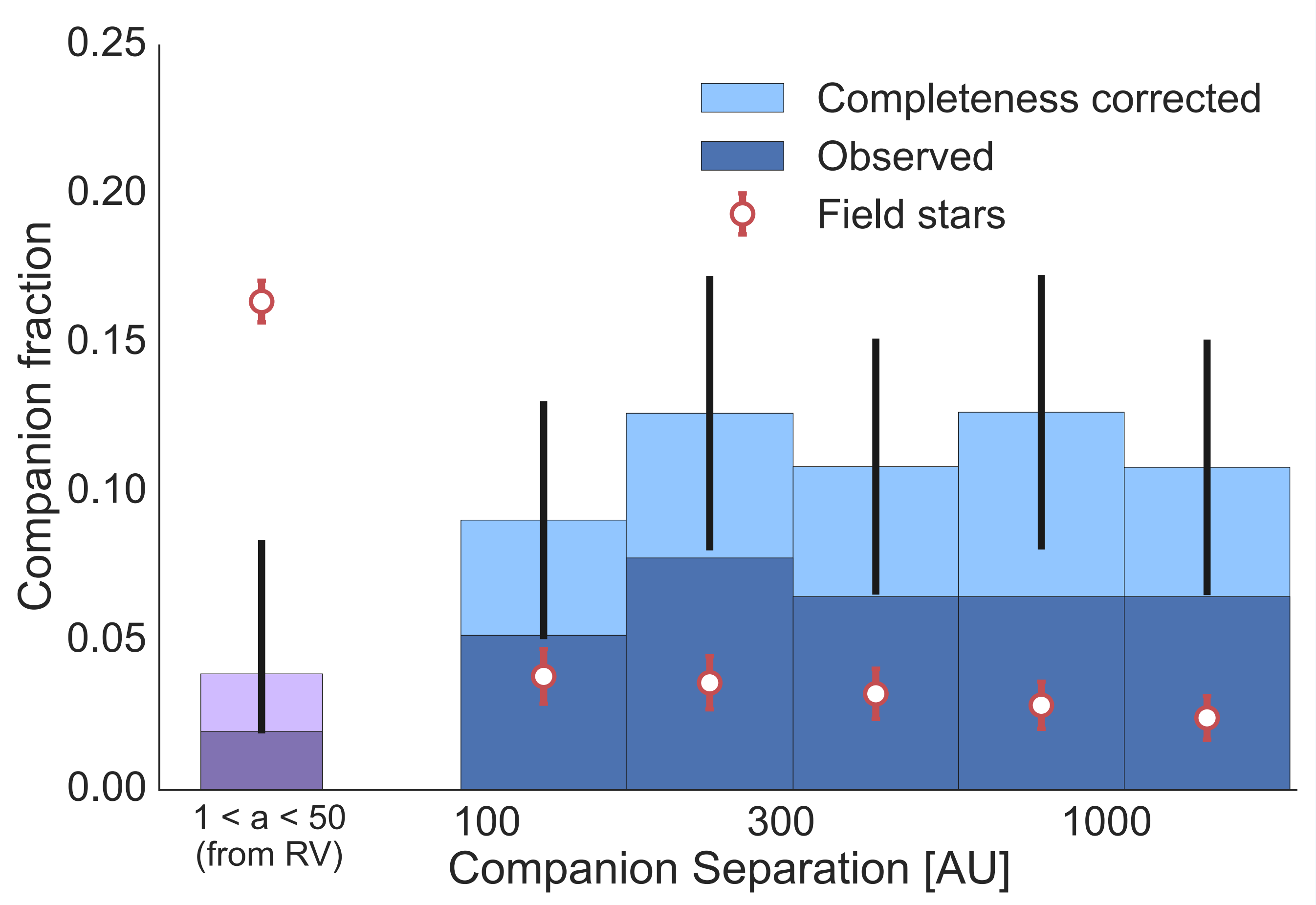
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

Suppose η_{Earth} = 0.2 for all Kepler FGK stars
(assuming we can measure this accurately: Petigura et al. 2013,
Silburt et al. 2015, Barbato et al. 2018, Zink & Hansen 2019)

Then η_{Earth} = 0.8 for single Kepler FGK stars
with $-0.3 < [Fe/H] < 0.0$

Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

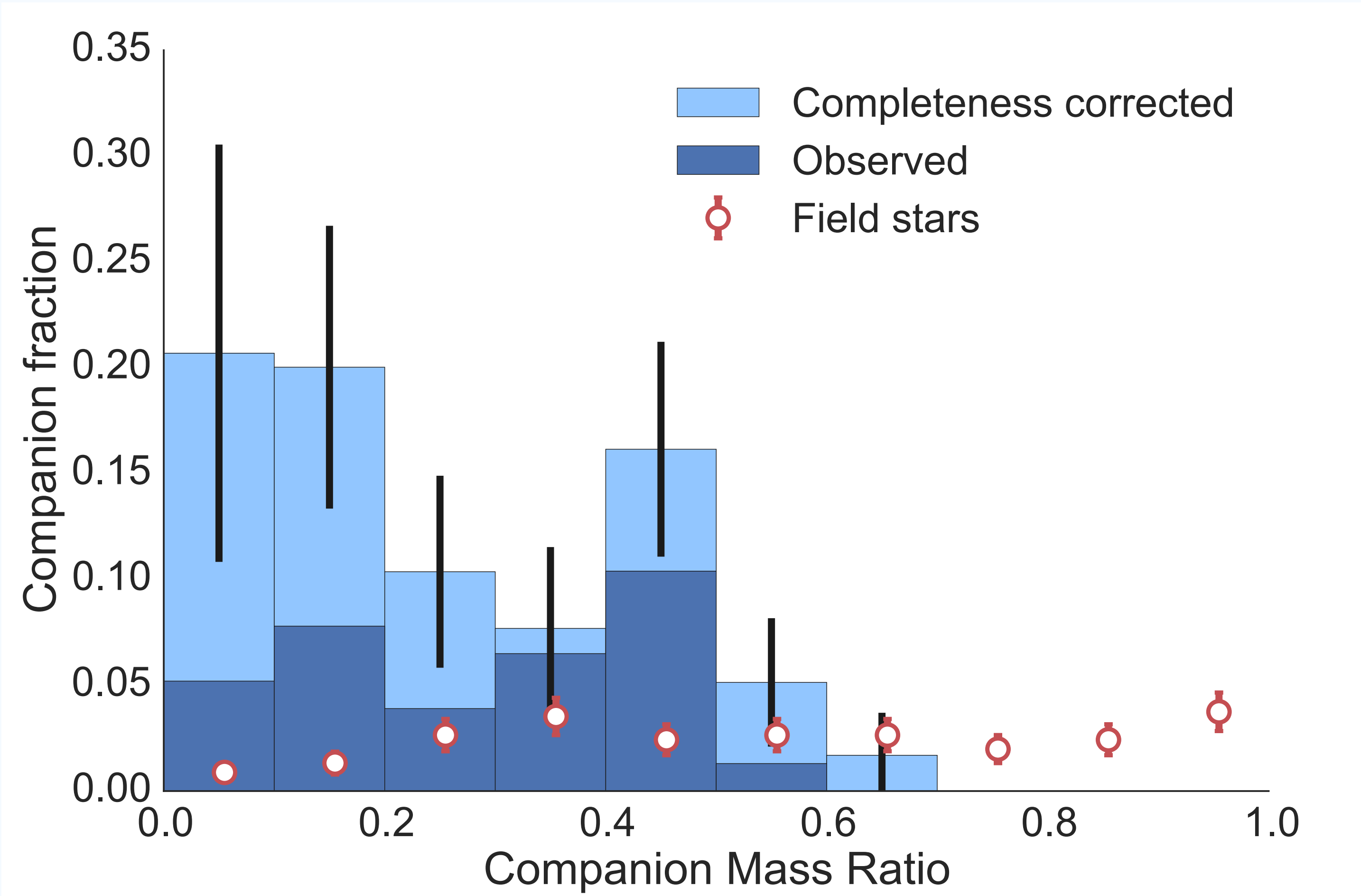
Ngo et al. (2016) discovered 47% ± 7% of hot Jupiter hosts have wide stellar companions (a = 50 – 2000 AU), a **4.4σ excess** relative to the field



Majority too wide for Kozai-Lidov cycles, and so they concluded excess mass facilitates both formation of hot Jupiters and wide binaries (see also Fontanive et al. 2019)

Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

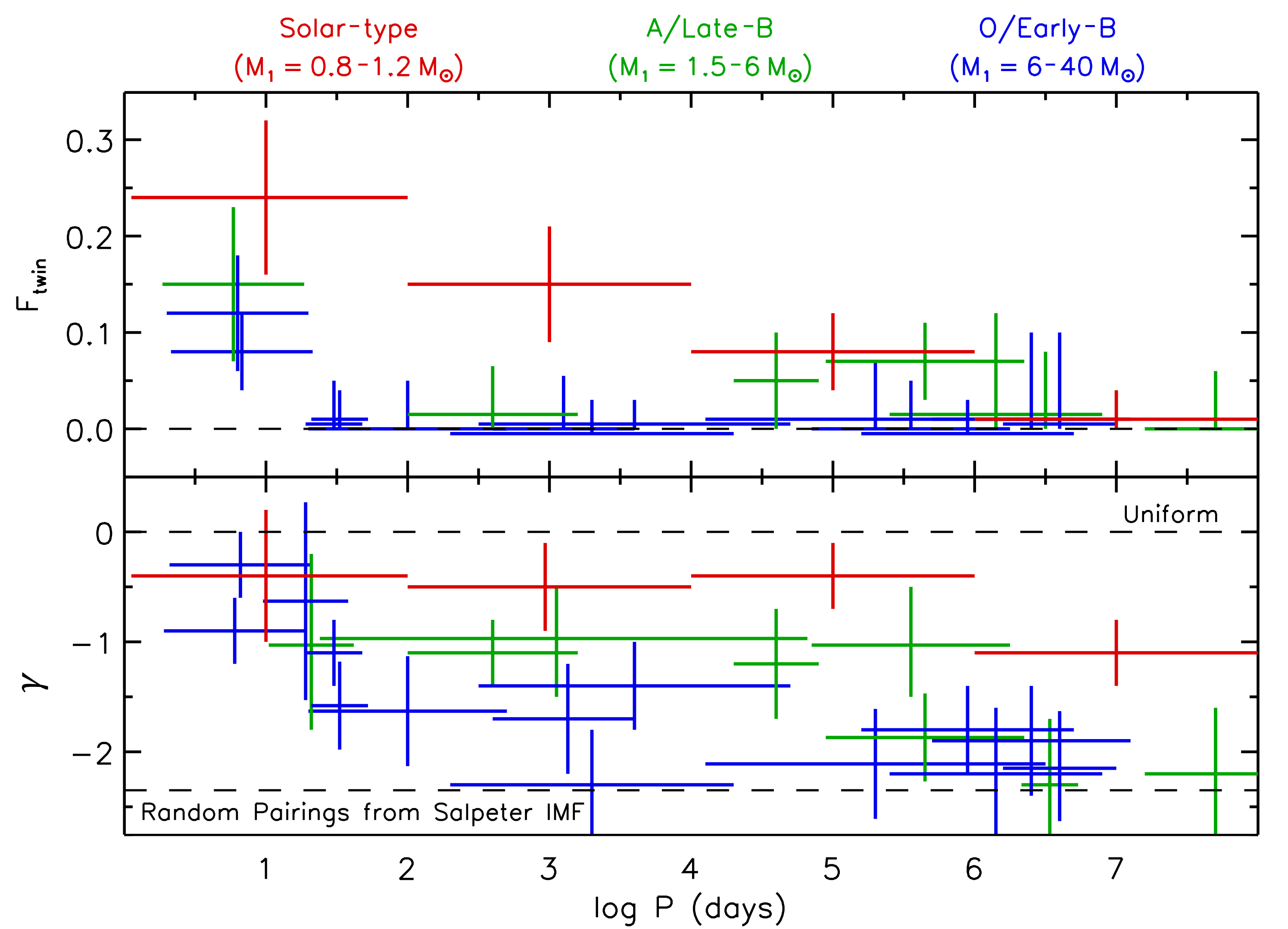
Ngo et al. (2016) also found wide companions to hot Jupiter hosts are weighted toward small binary mass ratios



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

Excess fraction of twins with $q > 0.95$

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



Wide field binaries and **wide** companions to hot Jupiter hosts have **consistent** mass-ratio distributions.

See Winters et al. (2019) and poster for multiplicity statistics of M-dwarfs

Are you a frequentist or a Bayesian?

If wide binaries *do not* influence planet formation, what do you expect the wide binary fraction of hot Jupiter hosts to be relative to the field?

	Close Binaries	Wide Binaries	Single Stars
Field	~40%	~20%	~40%
Hot Jupiters	~0%	~33%	~67%

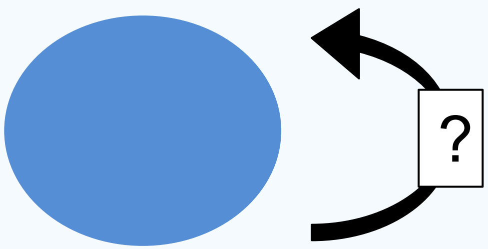
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)

	Close Binaries (a < 50 au)	Wide Companions (a = 50 - 2,000 au)	Effectively Single (No Companions below a < 2,000 au)
Field Population for $M_1 = 1.2M_\odot$ and [Fe/H] = 0.15	40% ± 6% (**Not** 21% ± 1%)	21% ± 4% Binary 7% ± 2% Outer Tertiary 28% ± 5% Total (**Not** 16% ± 1%)	39% ± 6%
Expectation for Hot Jupiters given F(a < 50 au) = 4%	4%	**37% ± 7%**	59% ± 7%
Observed Hot Jupiters	$4\%^{+4\%}_{-2\%}$	**47% ± 7%**	49% ± 7%

After accounting for selection biases,
there is **no statistically significant excess**
of wide stellar companions to hot Jupiter hosts.

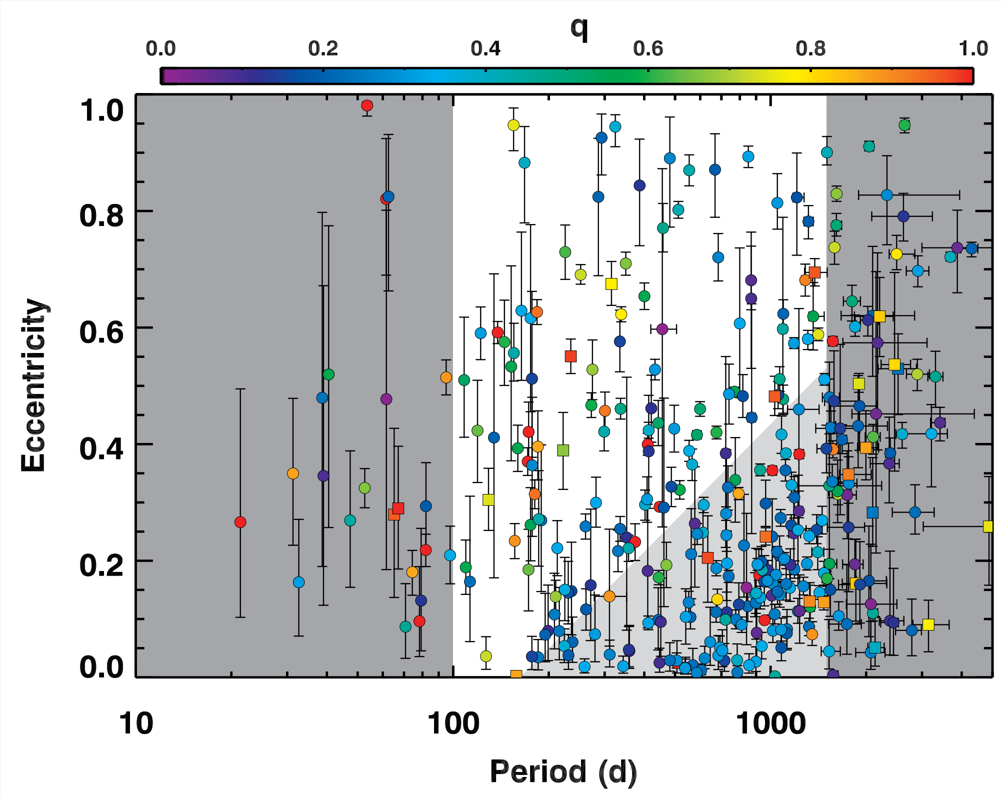
WD Companions to MS Stars

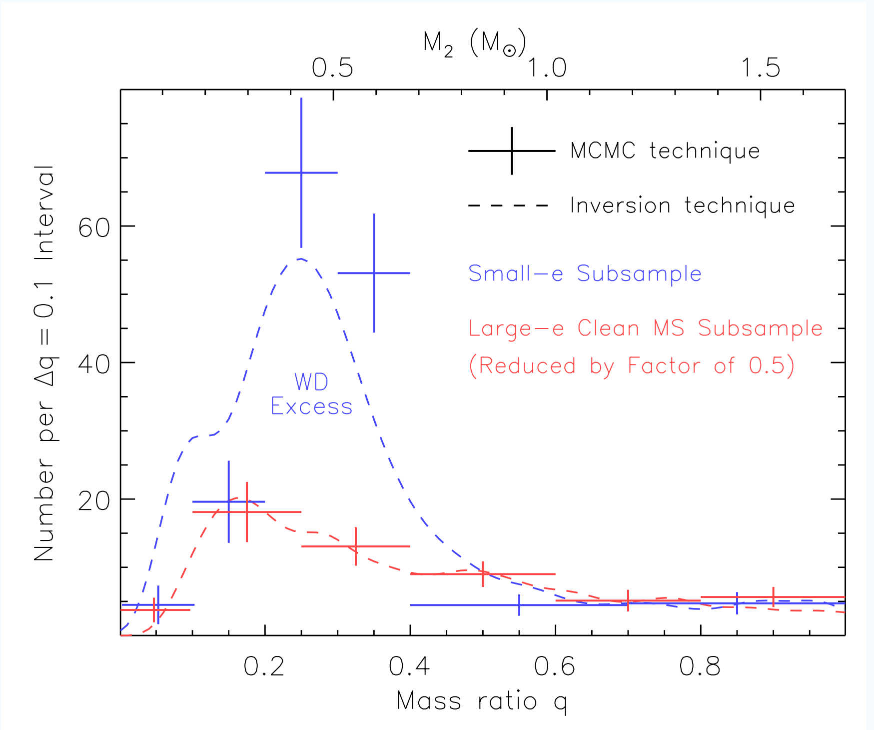
Regulus: a rapidly rotating B8IV star;
P = 40 day SB1, likely a WD companion



Malachi Regulus Moe

For solar-type primaries, ~30% of SB1s (20% of close binaries) have WD companions (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)

~10% of transiting Earth Kepler/TESS candidates are actually transiting WDs. Need multi-epoch RVs to validate!

Conclusions:

In magnitude-limited samples, 43% ± 6% of G-type stars cannot have close planets because they are already in close binaries

Close binaries account for apparent discrepancy in hot Jupiter occurrence rates.

Close binary fraction decreases significantly with metallicity.

Hot/warm Jupiters have host ⟨[Fe/H]⟩ = +0.2,
sub-Neptunes and Jovian analogs have ⟨[Fe/H]⟩ = 0.0,
and Earth analogs have ⟨[Fe/H]⟩ = −0.2.

η_{Earth} is ~4 times larger for single FGK stars with [Fe/H] = −0.2 compared to all FGK stars

There is no significant excess of wide stellar companions to hot Jupiters.

~10% of transiting Earth candidates are actually WDs.