Fruitful returns from cadenced RV observations with SDSS

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SDSS-V + ZTF
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Framework

- Goal: find as many short-period binaries as possible, in order to
  - Constrain multiplicity statistics in the field.
  - Identify interesting systems for follow-up.
- Radial Velocities from SDSS-IV and SDSS-V: cadences, errors, and challenges.
- Main results so far: multiplicity statistics for binary WDs and field stars, discovery of a detached BH binary.
- Synergies with other data sets: Gaia, ASASS-SN, ZTF, ...

Open Questions

- **Multiplicity Statistics** only known at all P in the MS and in the Solar Neighborhood [Duchene & Kraus 13, Moe & DiStefano 17].

- Studies in stellar clusters (small samples) [Carney+ 03; Geller+ 08; Matijevic+ 11; Sana+ 12; Merle+ 17], but **no panoramic view of the interplay between multiplicity, stellar evolution, and stellar properties in the field**. Open questions:

  - Are our ideas about RLOF basically correct?

  - Stellar multiplicity vs. stellar properties and environment: Mass, age, metallicity, disk/halo... ⇔ SF theory [Machida+ 09, Bate 14], dynamics [Kroupa & Petr-Gotzens 11].

  - Rate of CE events in the MW? Rate of stellar mergers? Formation rate of short P systems? Can we help constrain BPS models for SNe, GW sources, etc.?

What are we looking for?

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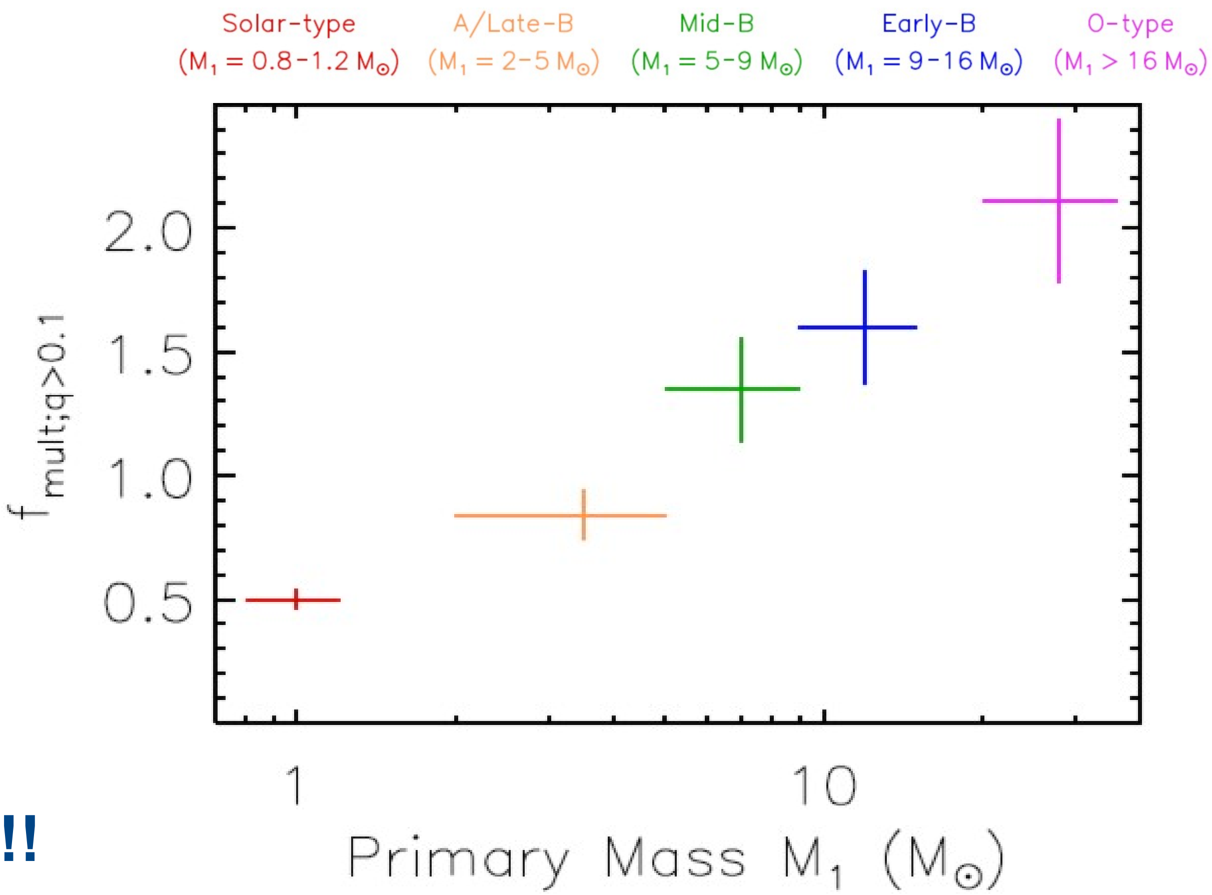
- **Stellar Multiplicity Statistics** (well measured for Sun-like MS stars, D<25 pc) [Raghavan+ 10, Duchene & Kraus 13, Moe & DiStefano 17 (MD17)]:
  - Multiplicity frequency (f_m): dominated by M_1.
  - Period (P): ~lognormal.
  - Mass Ratio (q): ~flat, F_{twin}.
  - Eccentricity (e): tidal circularization, ~uniform.
- **These statistics are not independent of each other!!!!** [Sana+ 12, MD17].

$$f_m = \int f(P)dP$$

MD 17



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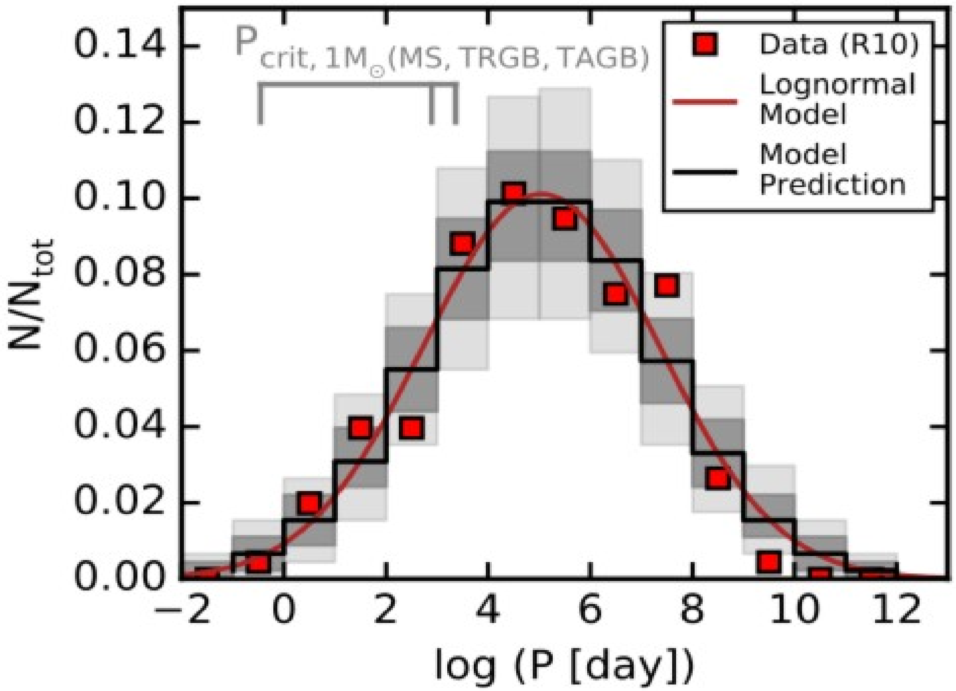
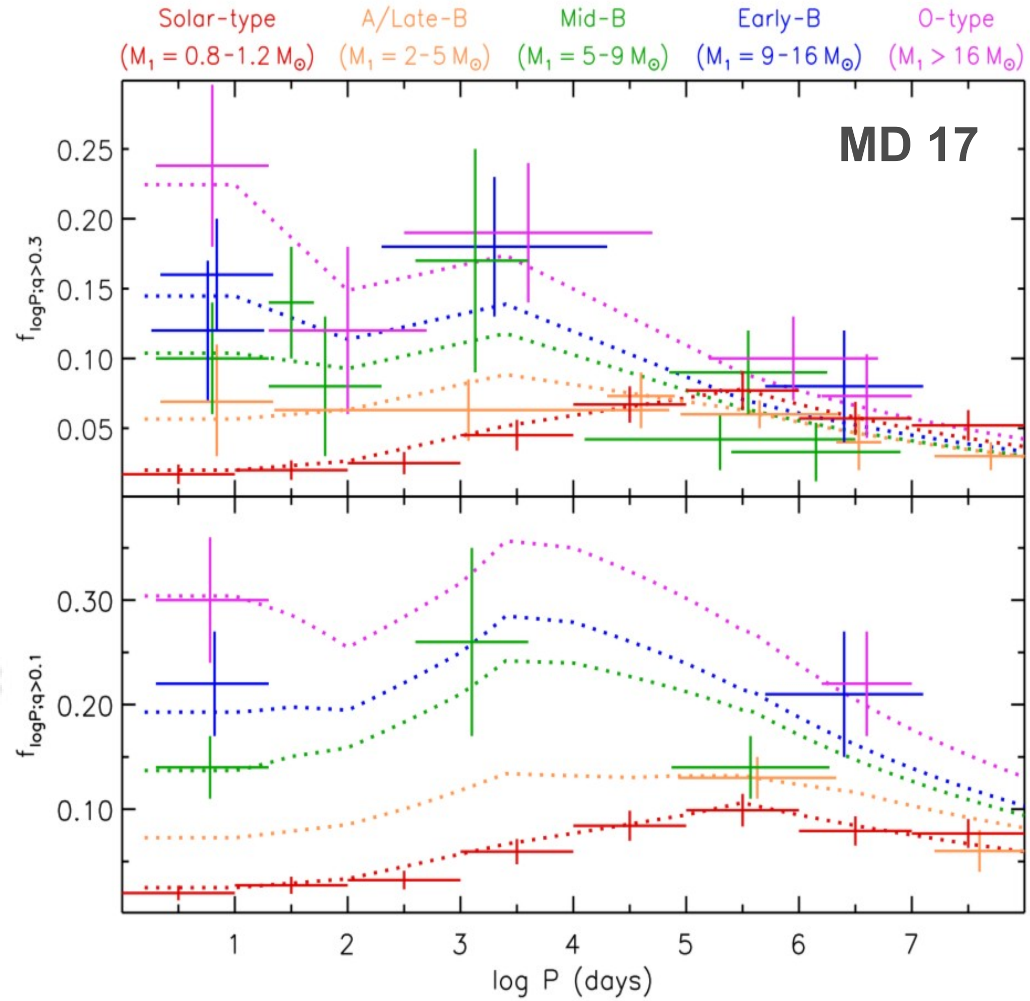
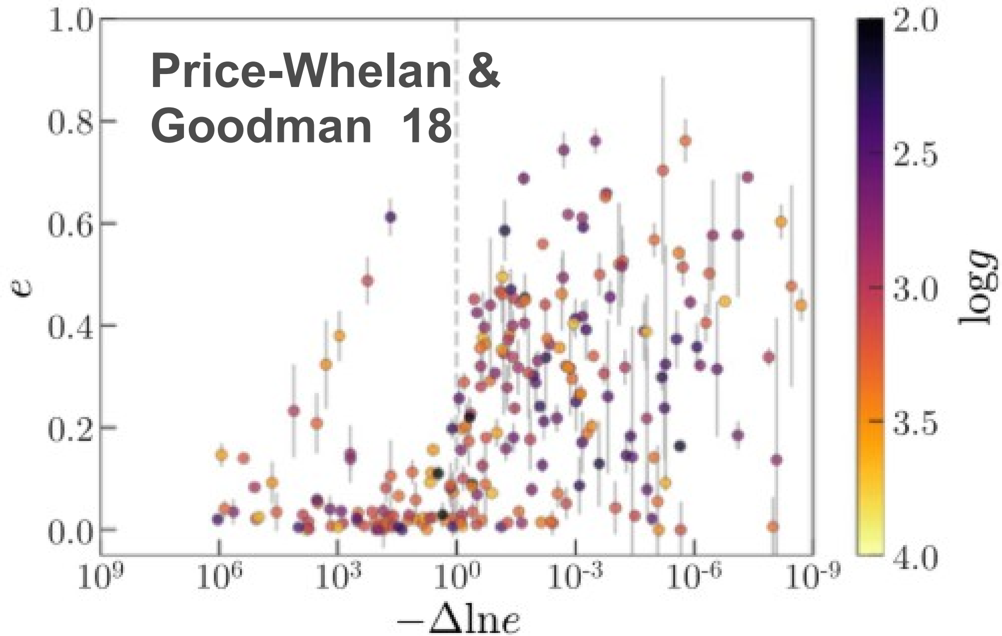


$$f(P, q, e) \neq f(P)f(q)f(e)$$





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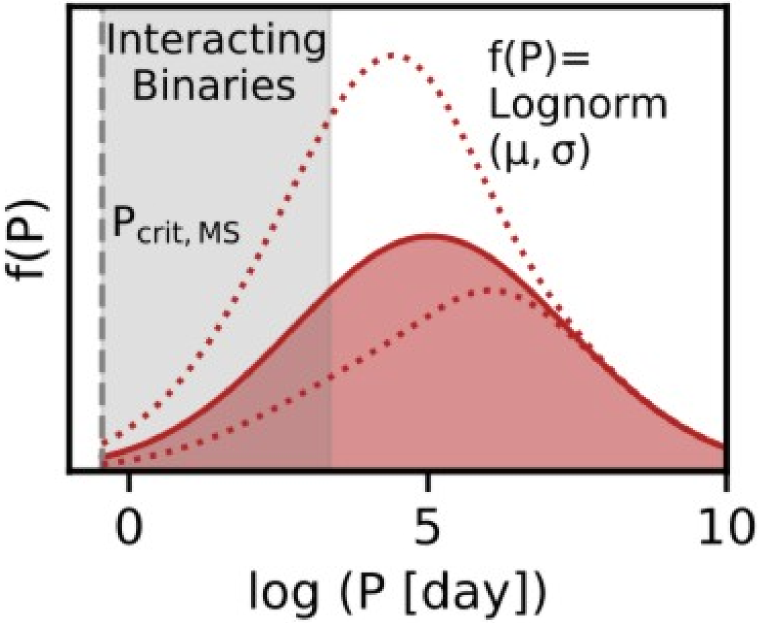

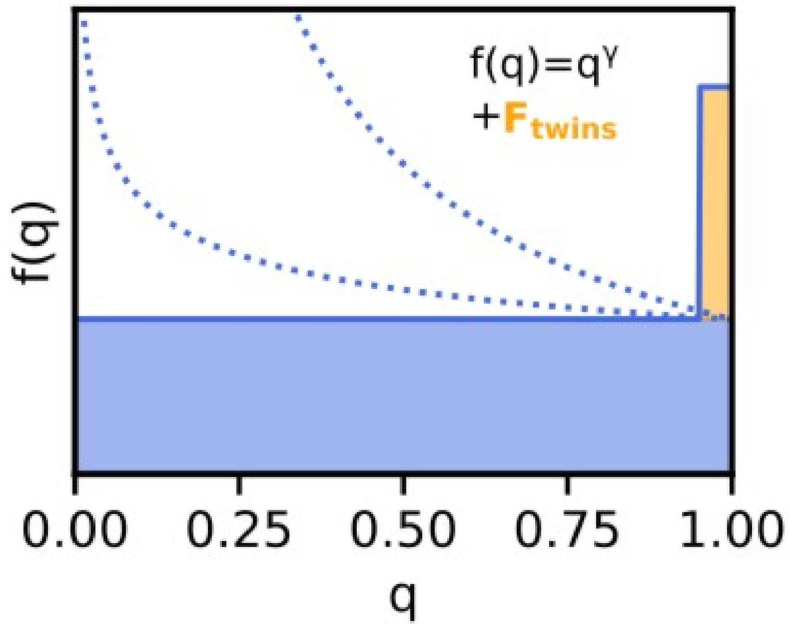

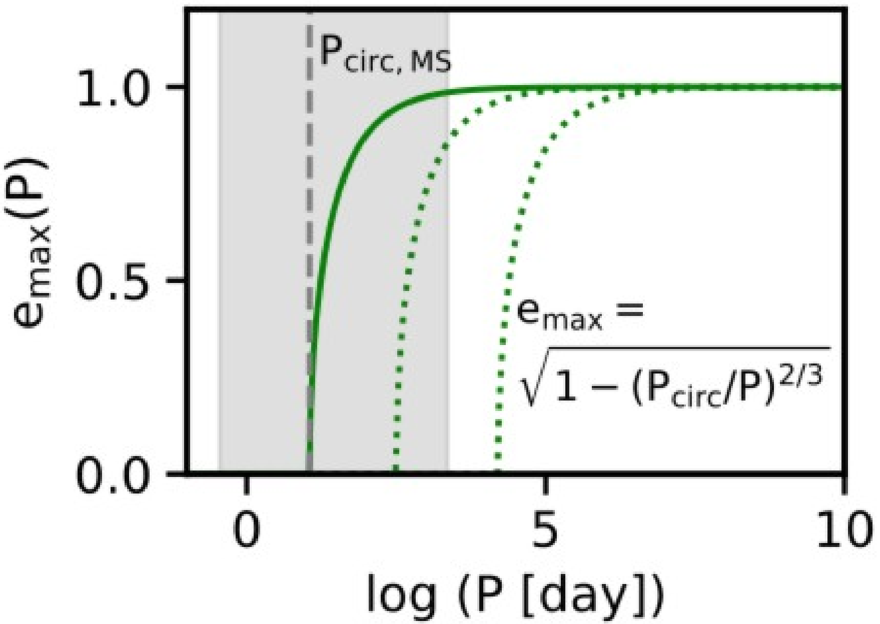

Multiplicity and Stellar Evolution

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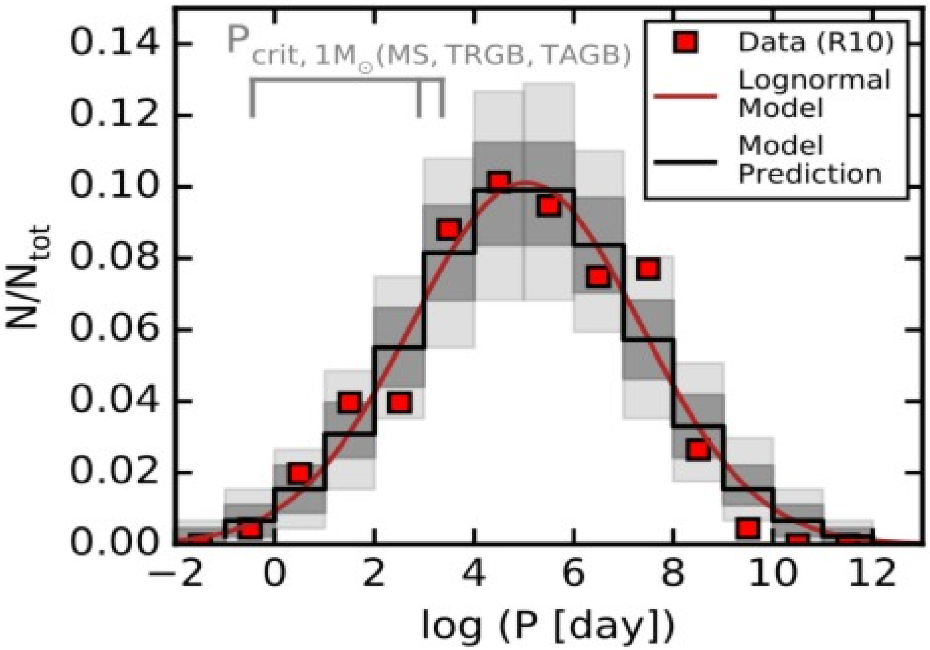
- Critical P for RLOF (q=1):

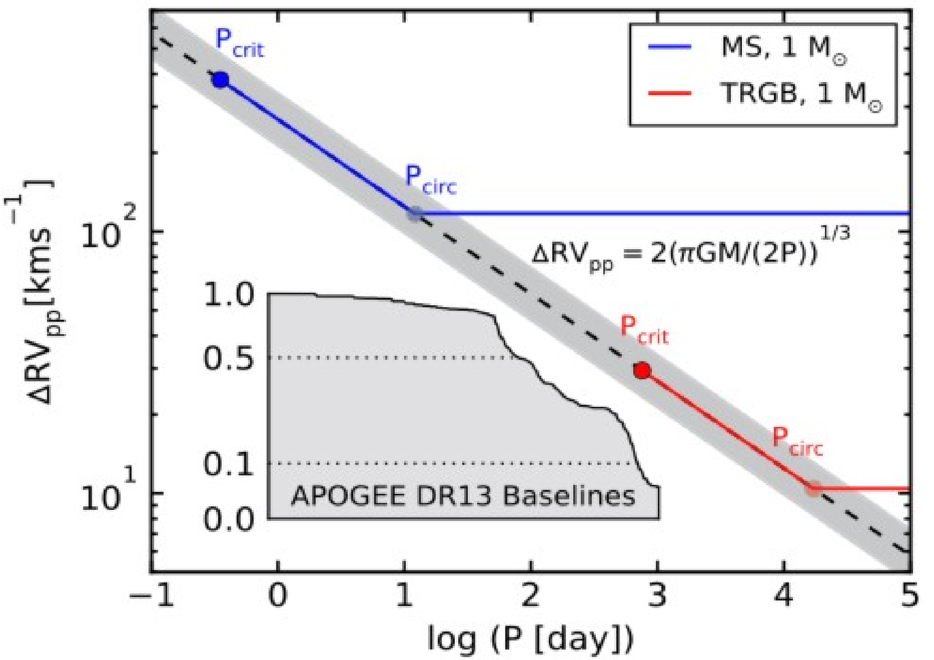
$$P_{crit} = 0.76(R^3/(GM))^{1/2}$$

- Core H exhaustion ⇒ R↑ (RGB) ⇒ P_{crit}↑. log P_{crit} : -0.35 (MS) ⇒ 2.9 (TRGB) ⇒ 3.4 (TAGB).

- Case A (MS), B (RGB) and C (AGB) mass transfer. RGB (Case B) ⇒ Unstable [Pavloskii & Ivanova 15] ⇒ Common Envelope ⇒ merger or short P system.

- P_{crit} translates to maximum peak-to-peak RV: $\Delta RV_{PP}=2(\pi GM/(2P))^{1/3}$





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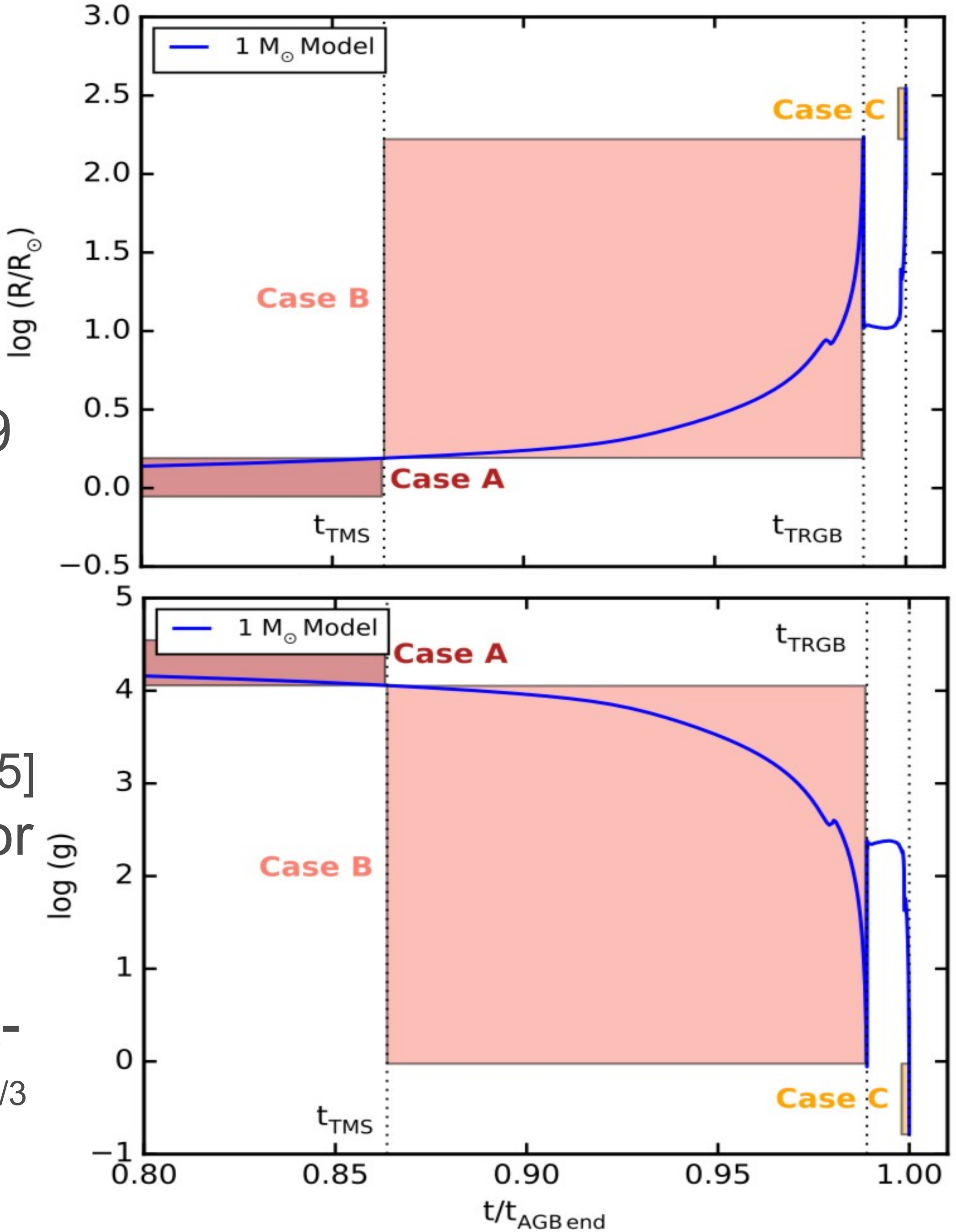

RVs in Large Spectroscopic Surveys

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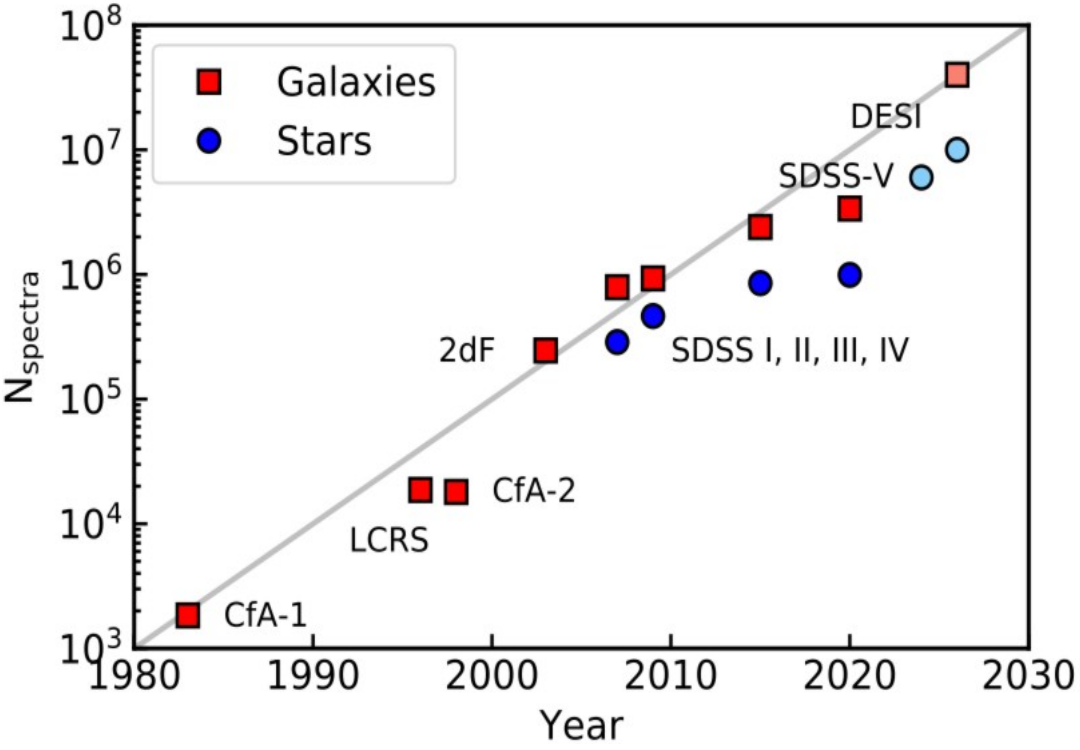
- **RVs**: most efficient probe of multiplicity for log P<4 ⇒ spectra.
- **Large spectroscopic surveys**: SDSS/SEGUE [Yanni+ 09], SDSS/APOGEE [Majewski+ 17], RAVE [Steinmetz+ 06], WEAVE [Dalton+ 14], MSE [Szeto+ 18].
- Well characterized (pipelines) ⇒ stellar parameters.
- Caveat: Orbital fitting requires ~10 RVs, good phase sampling ⇒ not for most targets.



We don't need to fit the orbits to answer many of the open questions about stellar multiplicity!

RVs in Large Spectroscopic Surveys

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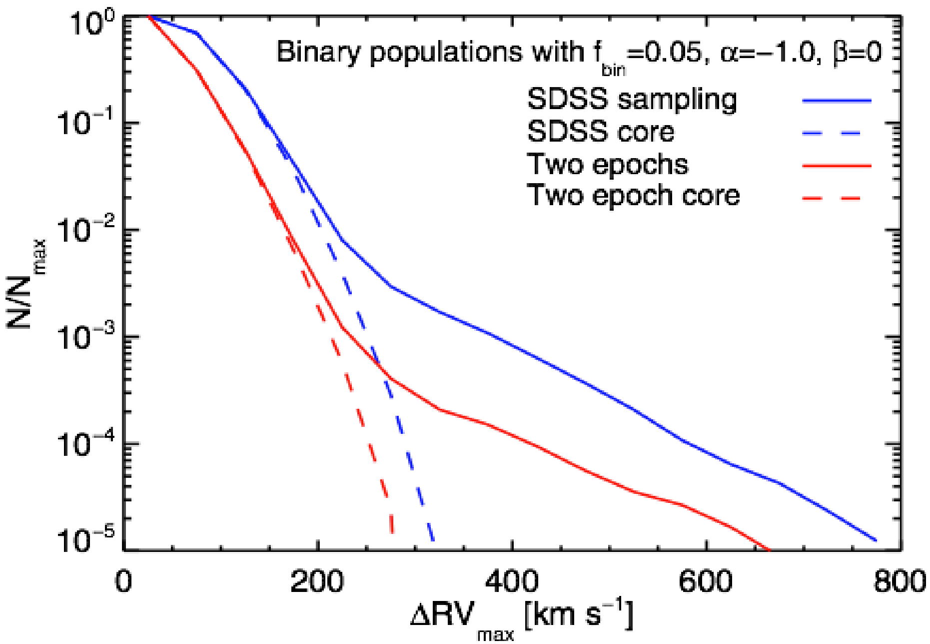
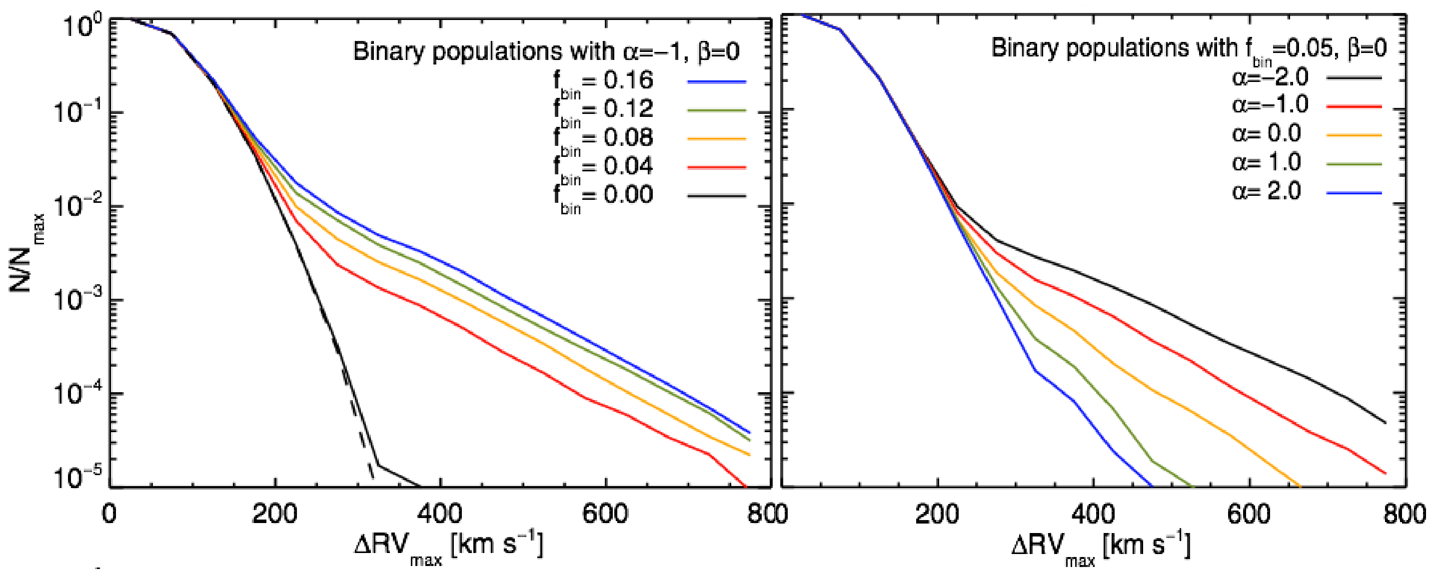
- Few epochs (4 or less) ⇒ ΔRV_{max} = Max(RV_i) - Min(RV_i)
- RV errors ⇒ core of ΔRV_{max} distribution. Binaries ⇒ tail.
- Shape and height of tail ⇒ multiplicity statistics.
- Searches for RV variability ⇒ clear transition between core and tail.

[Maoz, CB & Bickerton 12 – WD binaries]





WD Binaries

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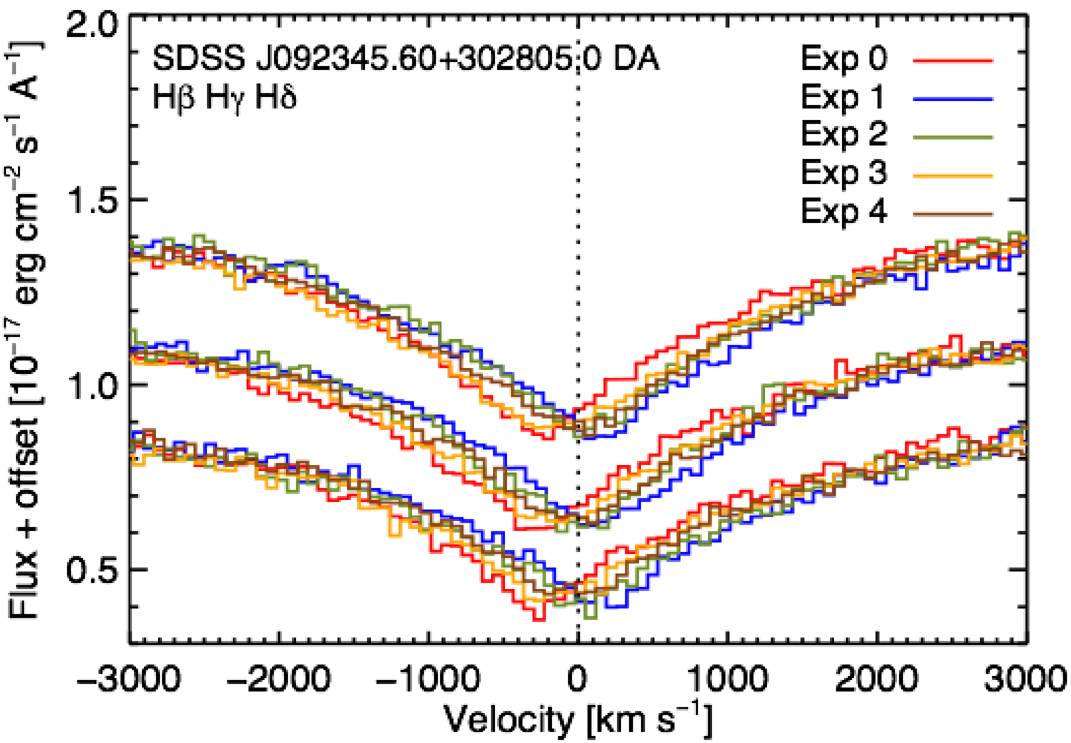
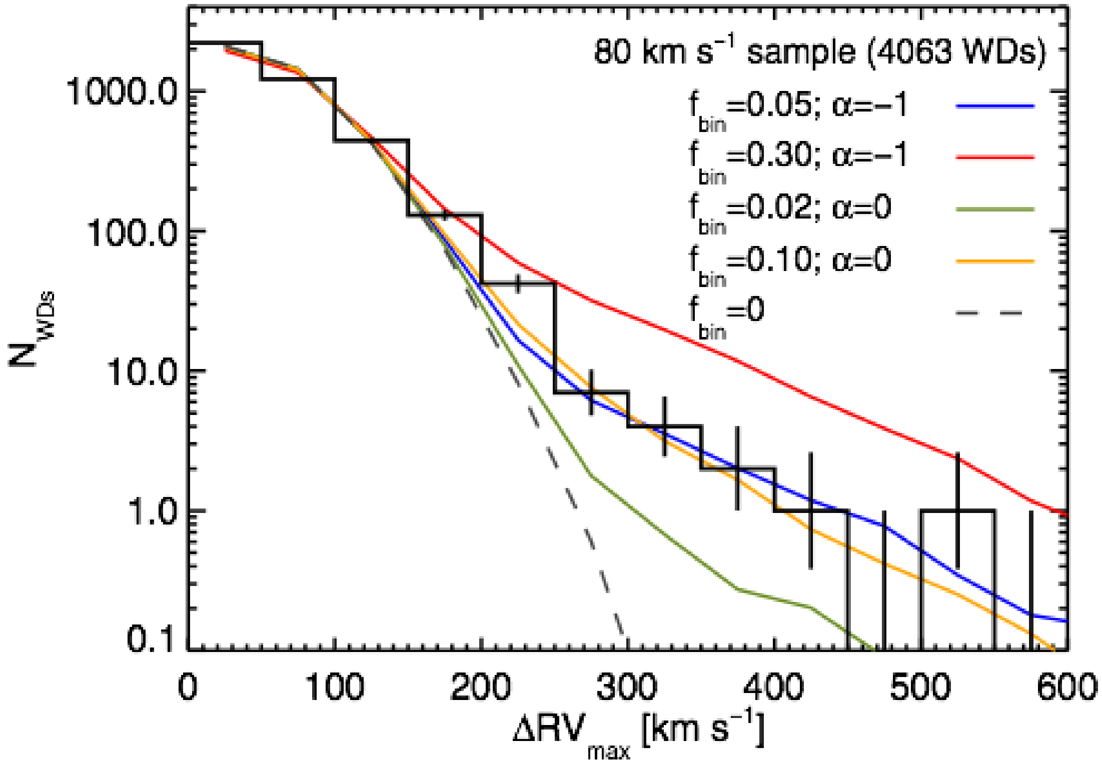
- Pre-merger WDs ⇒ P~hrs, RV~500 km/s, detectable at SDSS resolution (70 km/s/pixel) [Badenes+ 09, Mullally+ 09].
- ~4000 WDs in DR7 ⇒ ΔRV_{max} distribution ⇒ f_{bin}, f(P)⇒ WD merger rate.
- Complement w/ SPY survey (fewer WDs, higher R) [Maoz & Hallakoun 17].
- Enough WD mergers to explain SN Ia [Badenes & Maoz 12, Maoz+ 18]. LISA foreground!

WD binary 'caught' by SDSS [Badenes+ 09]

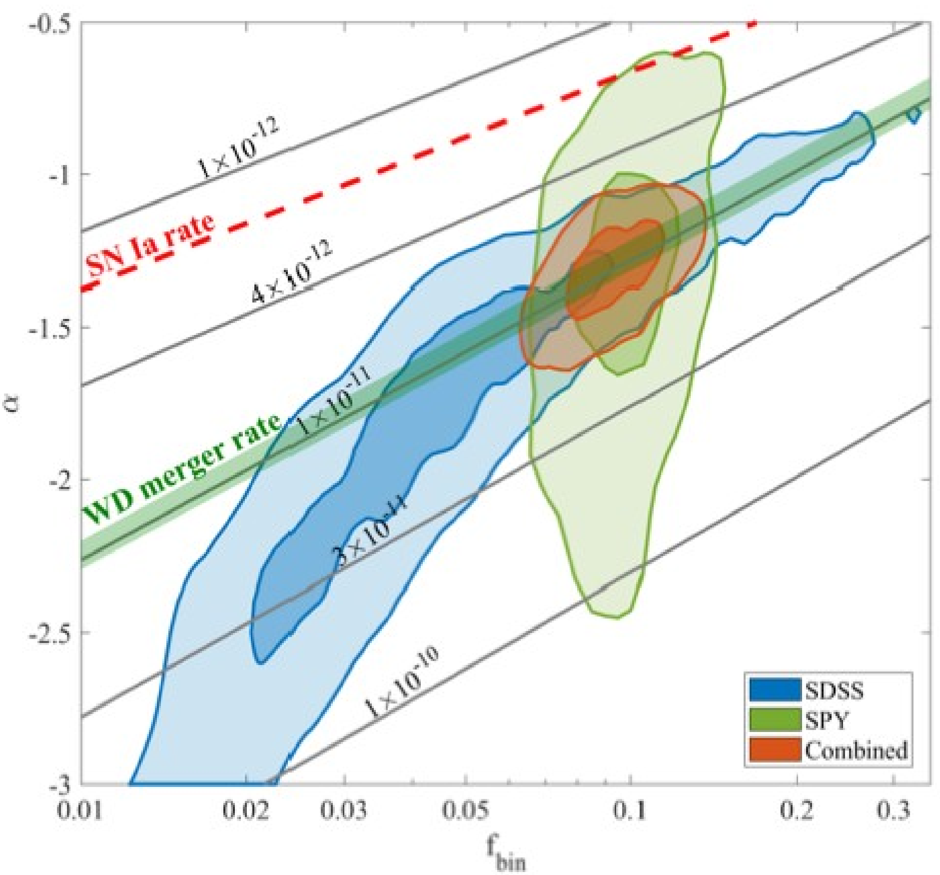


WD Binaries

[Badenes & Maoz 12]



[Maoz, Hallakoun & CB 18]



APOGEE

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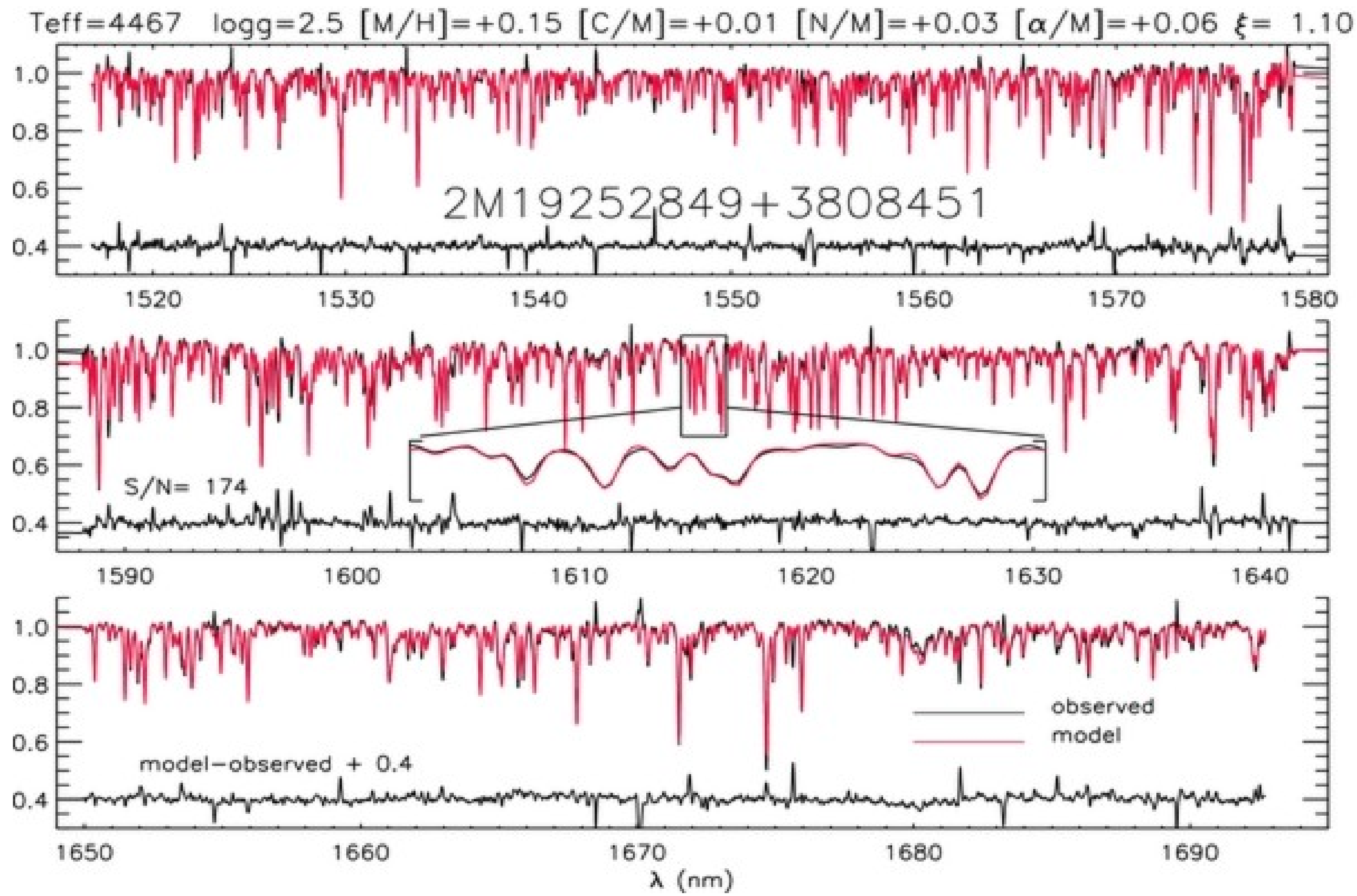
- Galactic evolution: Multi-epoch IR spectra R~20,000, ~10^5 stars, high S/N [Majewski+ 17].
- MS, RG and RC stars, M~1 M_{Sun}, most of MW disk [Zasowski+ 13].
- ASPCAP [Perez+ 16] ⇒ T_{eff}, log(g), [Fe/H], **RVs**. RC catalog [Bovy+ 14]. The Cannon [Ness+ 15,16].

SDSS DR 10



APOGEE: ΔRV_{max} vs. log(g)

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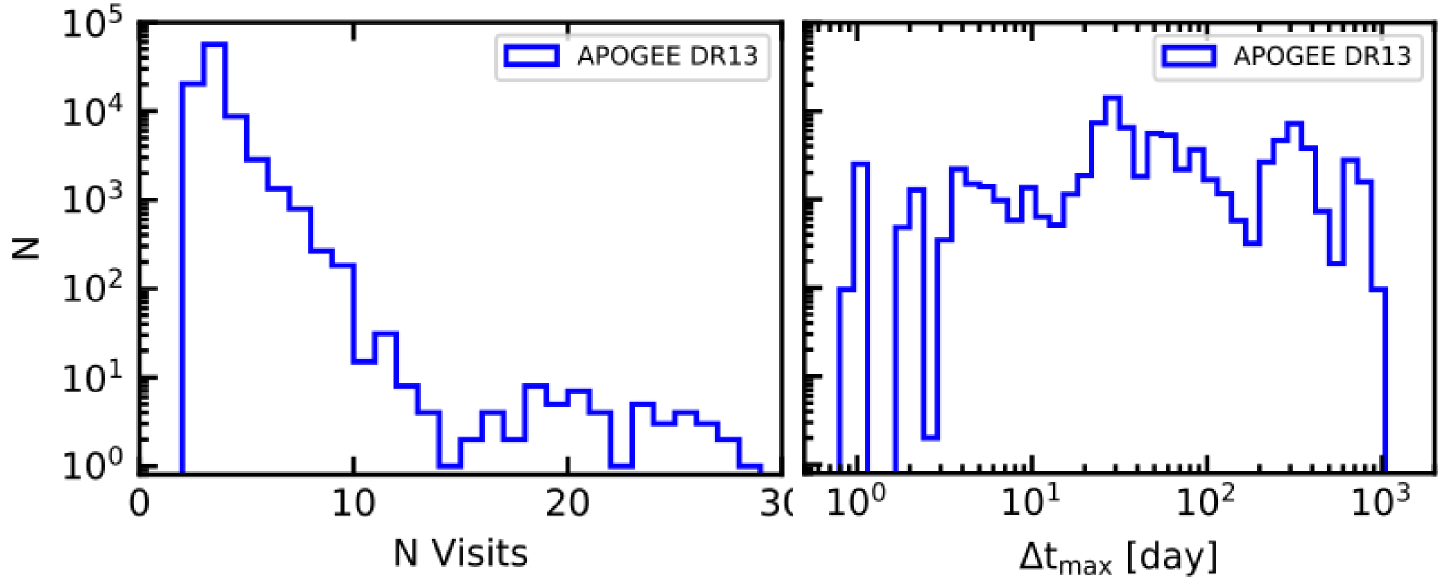
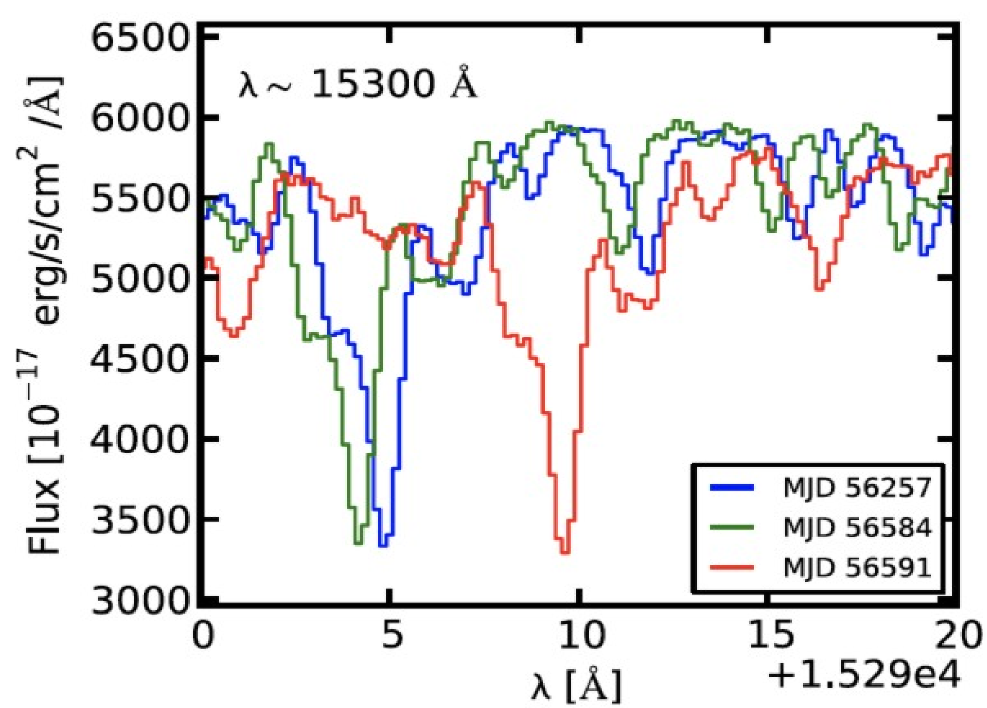
- Few RVs/star (median is 3) ⇒ no orbits! [but Troup+ 16]
- Figure of merit: **ΔRV_{max}**. Multiple systems ⇒ ΔRV_{max} > 10 km/s (> 2,000).
- Clear trend of ΔRV_{max} with log(g): stellar multiplicity meets stellar evolution.





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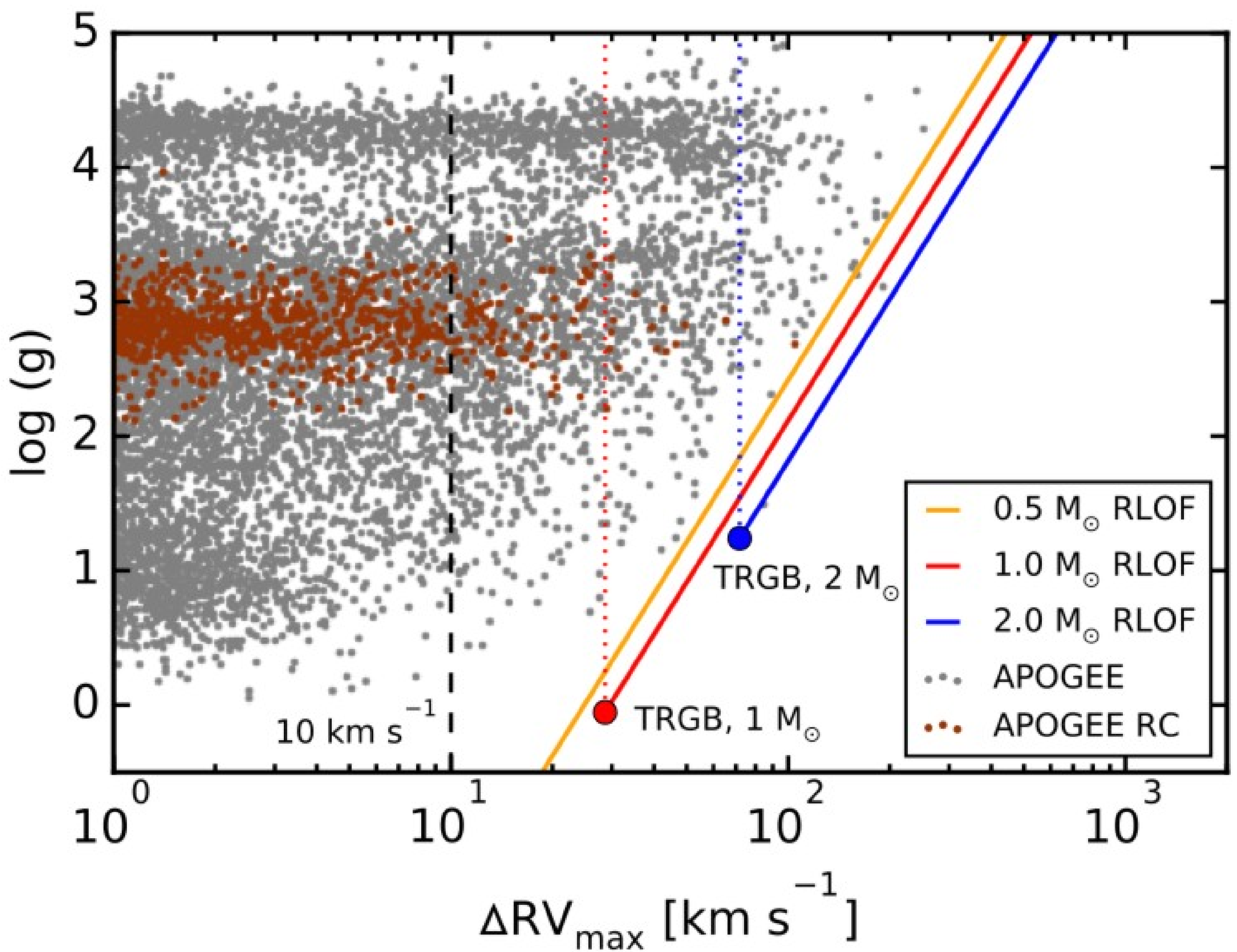

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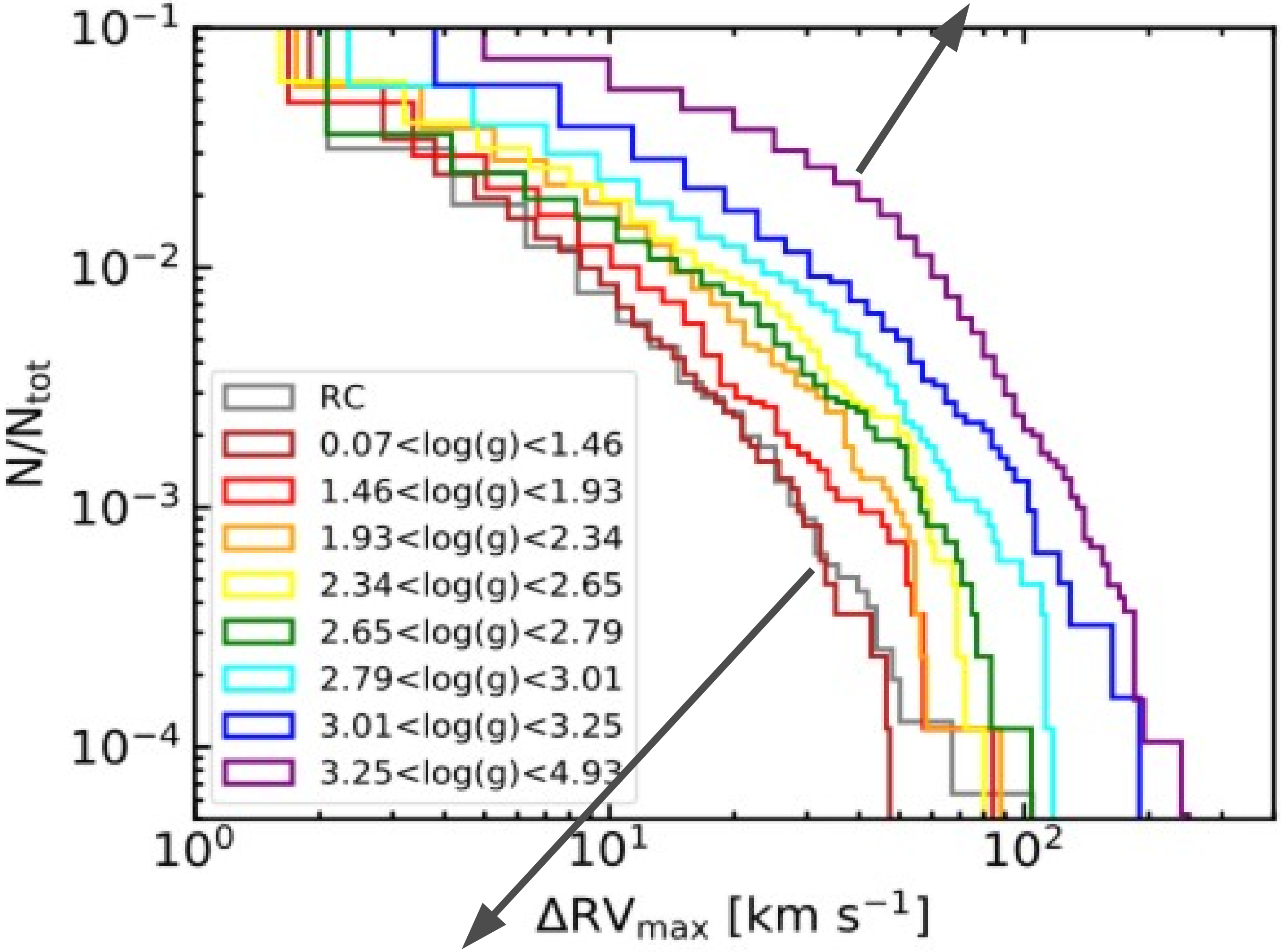
MS & subgiants: higher ΔRV_{max}



TRGB & RC: similar ΔRV_{max} distributions

APOGEE: Models for ΔRV_{max}

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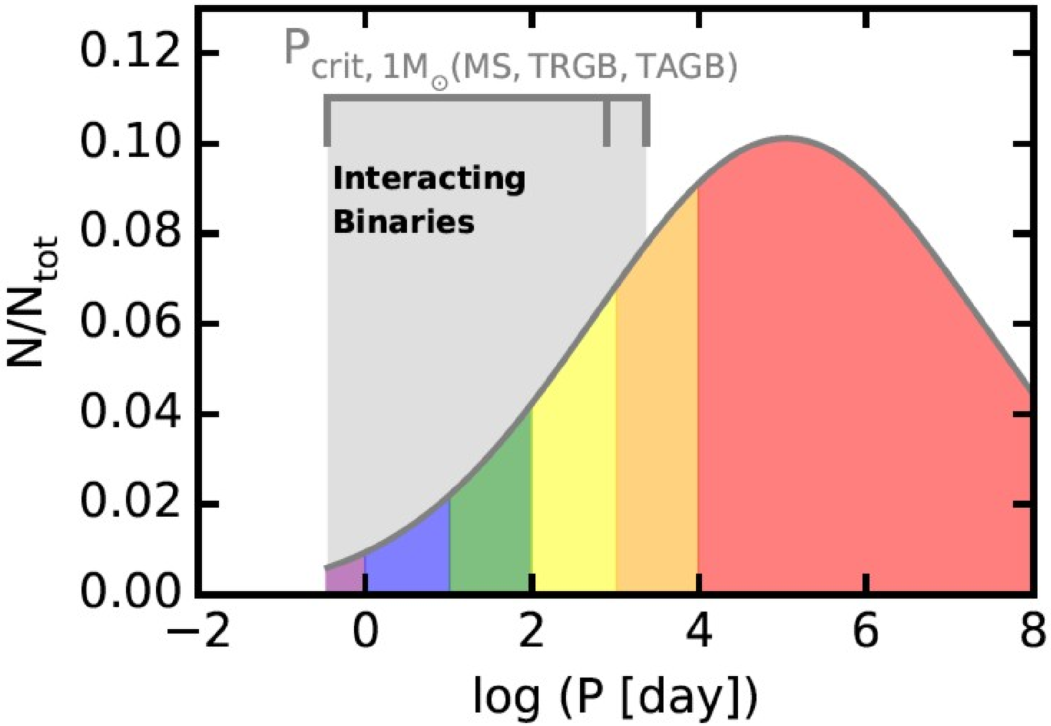

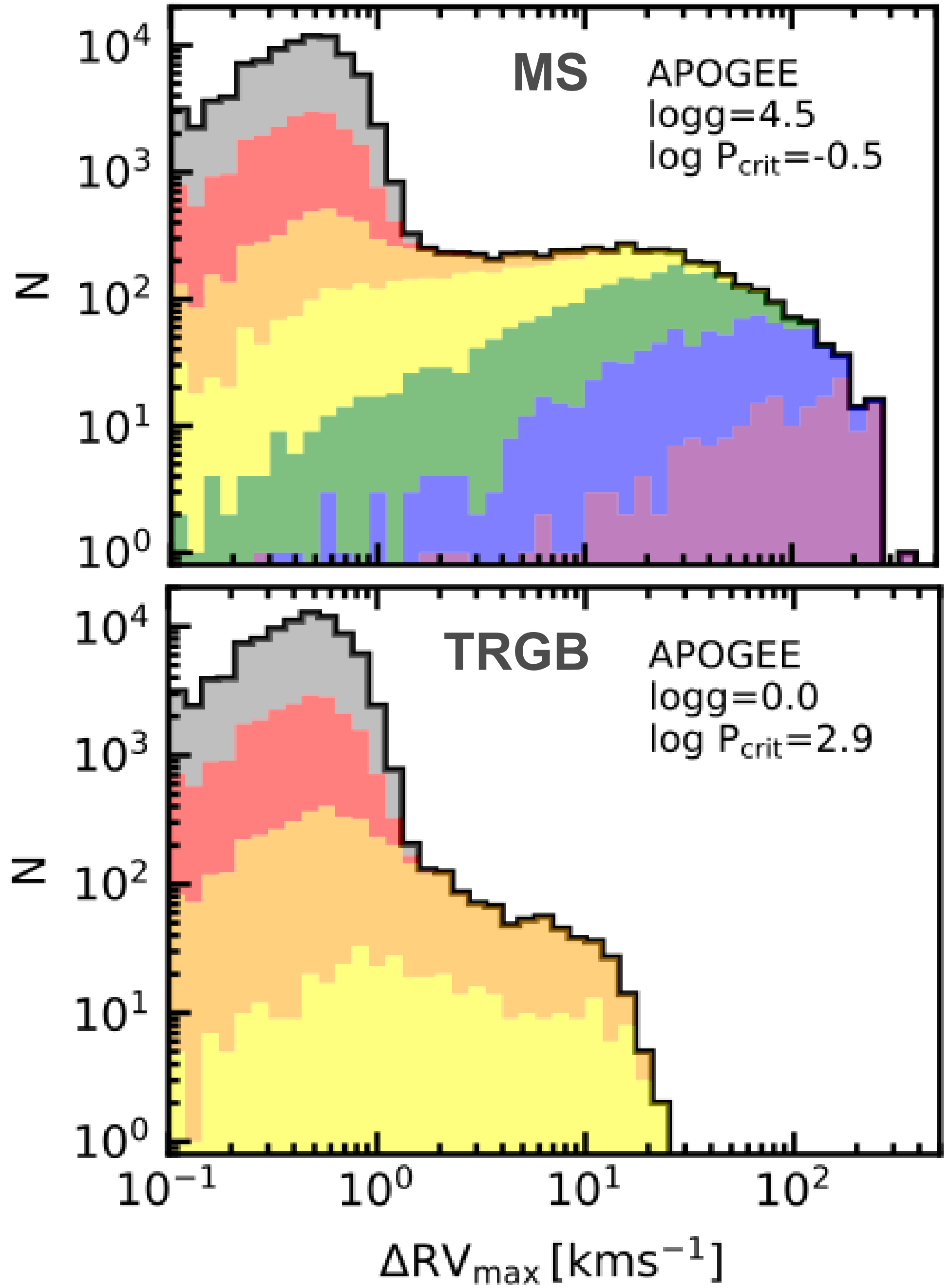

- Monte Carlo models for ΔRV_{max} [Badenes & Maoz 12, Maoz+ 12].
- Assume M = 1 $M_{Sun,}$ lognormal P, flat q, tidal circularization [Verbunt & Phinney 95]. Parameters: f_m, log(g) (⇒ P_{crit}), N.

APOGEE: ΔRV_{max} vs. log(g)

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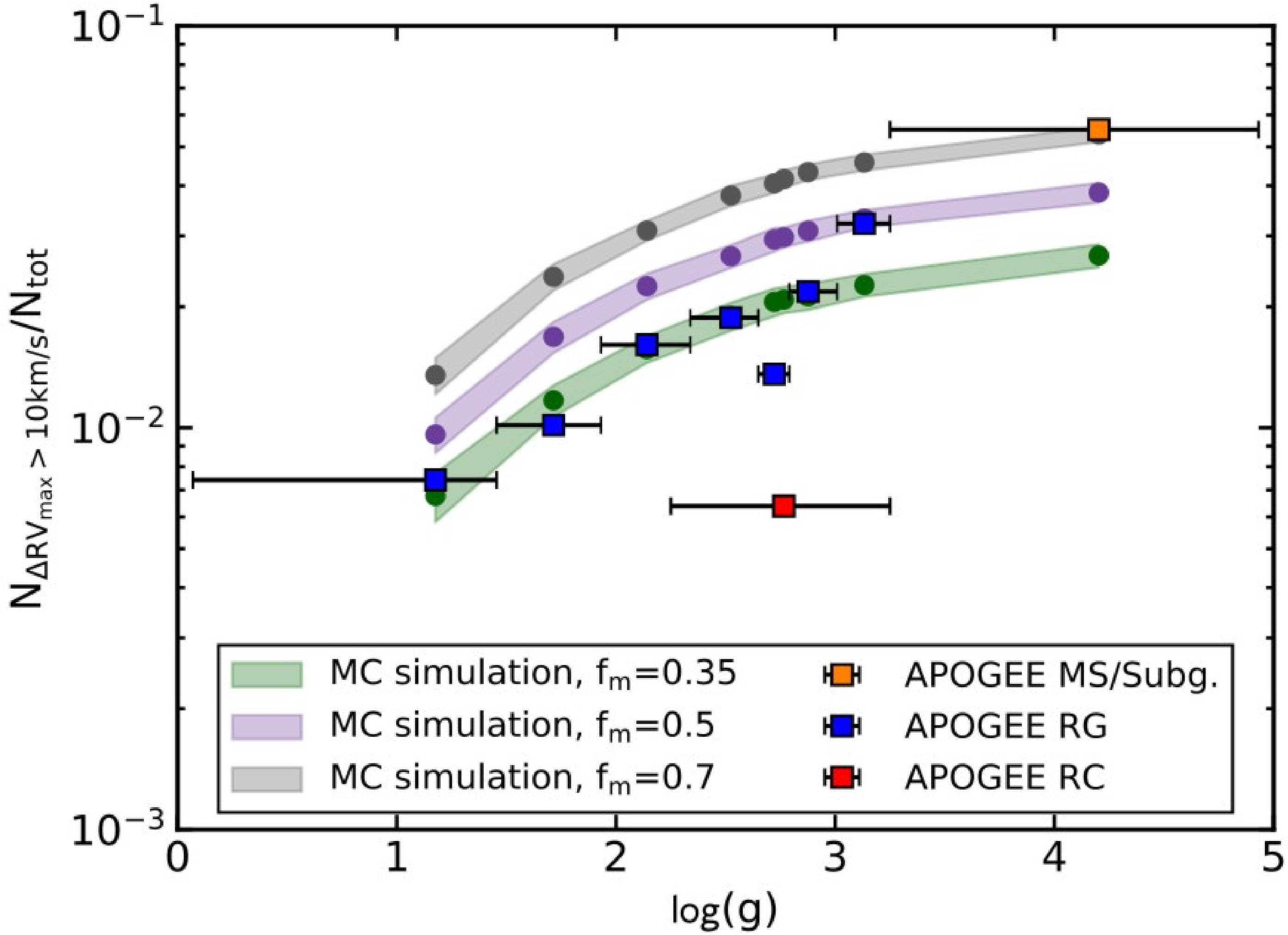
- Fraction of systems with ΔRV_{max} > 10 km/s.
- MC models work well in the RGB, but not at high log(g).
- Support for **lognormal P dist, truncated at P_{crit}.**
- Best-fit MC model in the RGB has f_m=0.35. Caveats: log P < 3.3, simple models, WD+RGB [MD 17].



APOGEE: ΔRV_{max} vs. [Fe/H]

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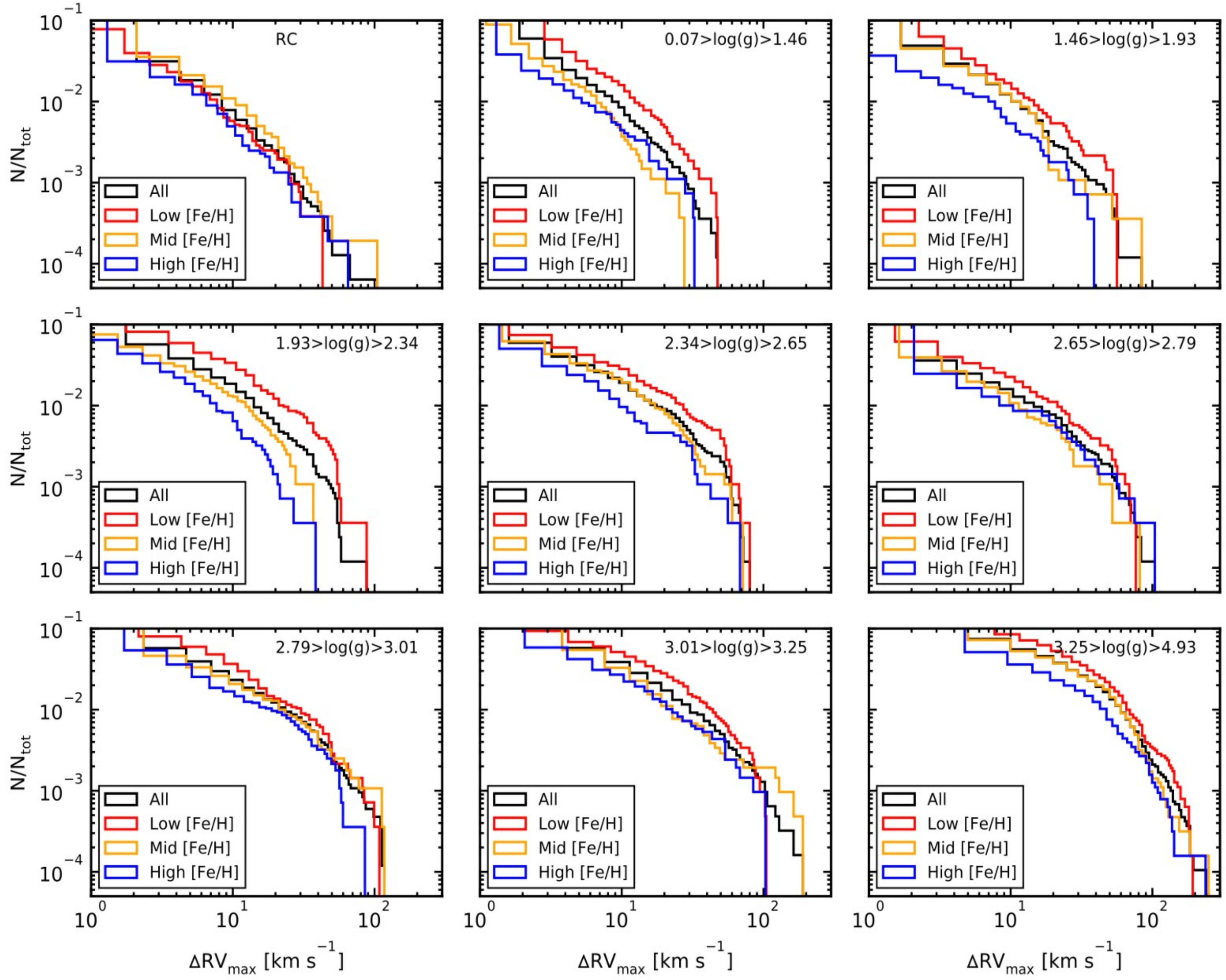
NYU 4/16/19

- APOGEE view of MW disk ⇒ [Fe/H].
- ΔRV_{max} distribution in [Fe/H] terciles: low ~ -0.5; high ~0.0.
- ΔRV_{max} in low [Fe/H] clearly above high [Fe/H] in all non-RC samples.
- Consistent with **f_m a factor 2-3 higher at low [Fe/H]** for close (log P < 3.3) binaries.



APOGEE: ΔRV$_{max}$ vs. [Fe/H]

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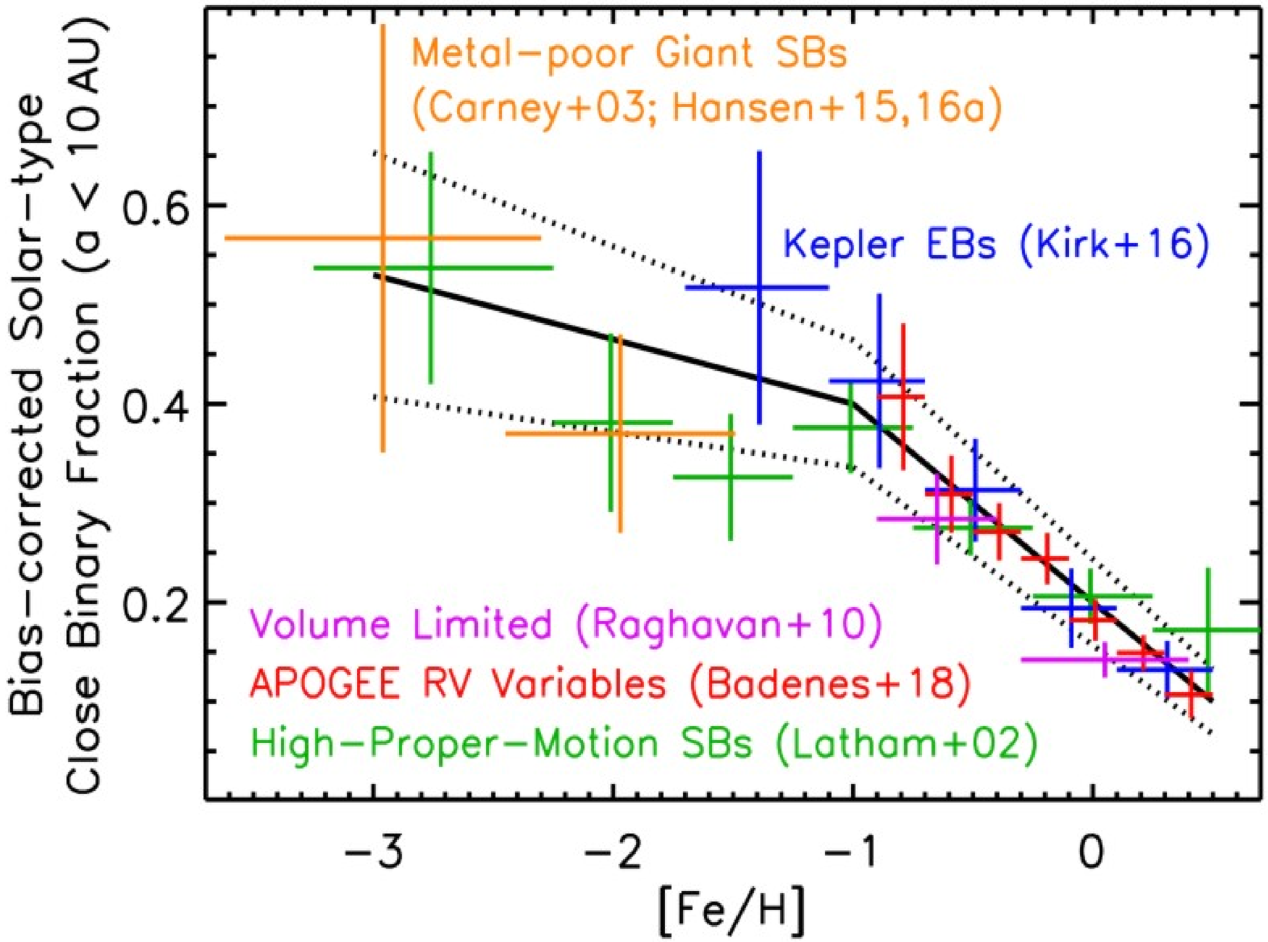
- Previous RV surveys did not find this effect!!!!
- Moe, Kratter & CB 18: explained by uncorrected biases.
- Bias-corrected meta-analysis: consistent picture: **f_m increase by a factor 6 across [Fe/H] range**.

Moe, Kratter & CB 18



Discovery of TAT-1

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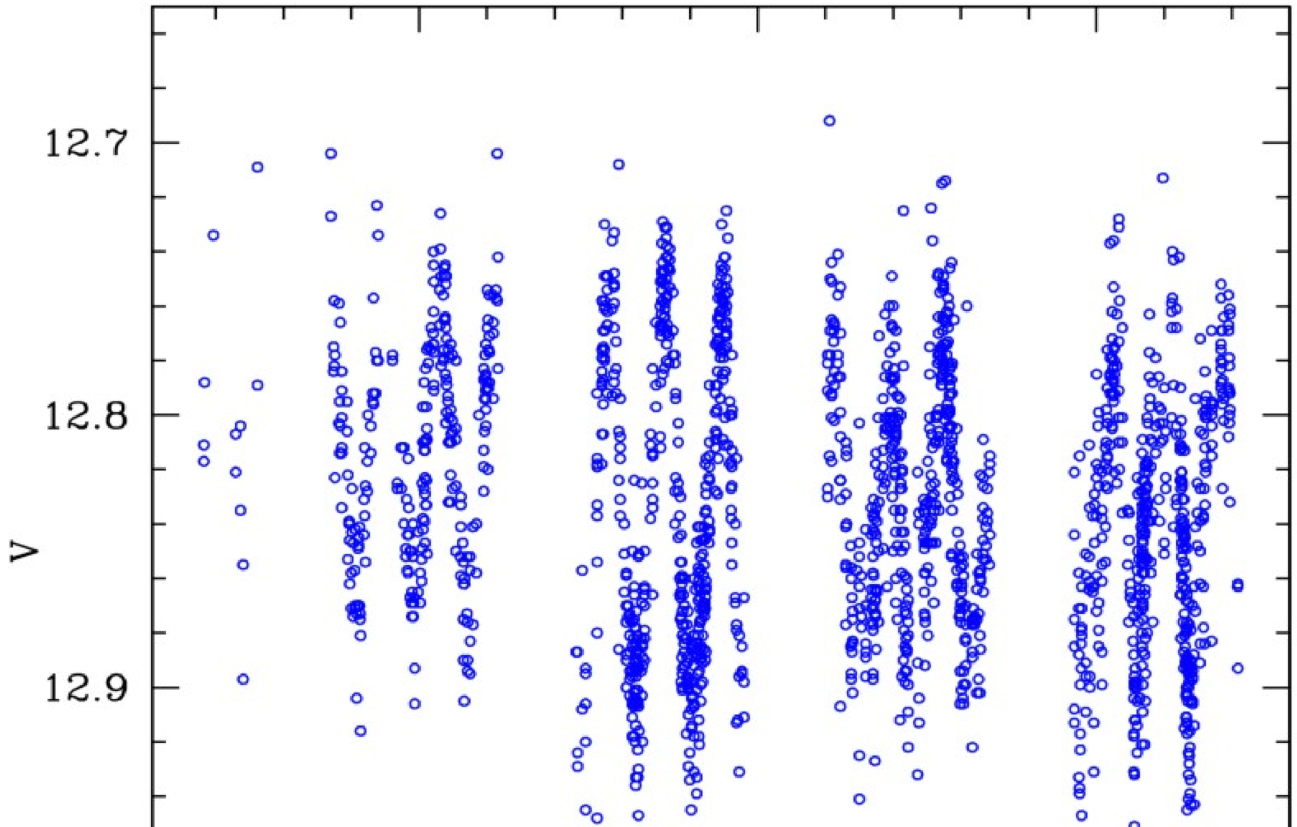
- Use APOGEE RVs to select systems with high mass function.

- TAT-1: photometric variable, P=83 days. Starspots. K = 45 km/s SB1.

- GAIA parallax: D>2.5 kpc, L>200 $L_{Sun} \Rightarrow M_1 > 2\ M_{Sun} \Rightarrow M_2 > 2.5\ M_{Sun}$.

- **Probably a BH!**



Thompson+ 19

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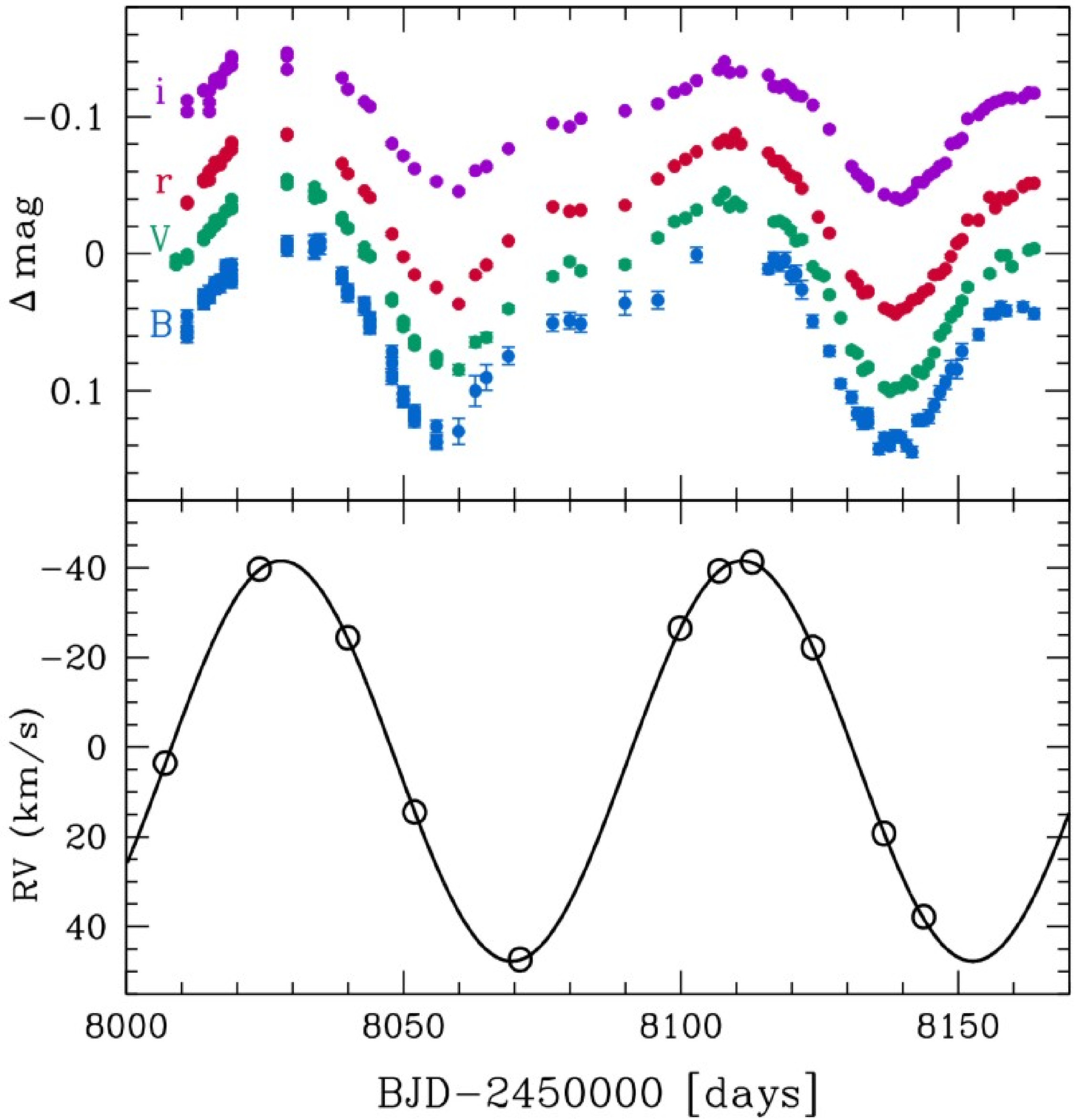

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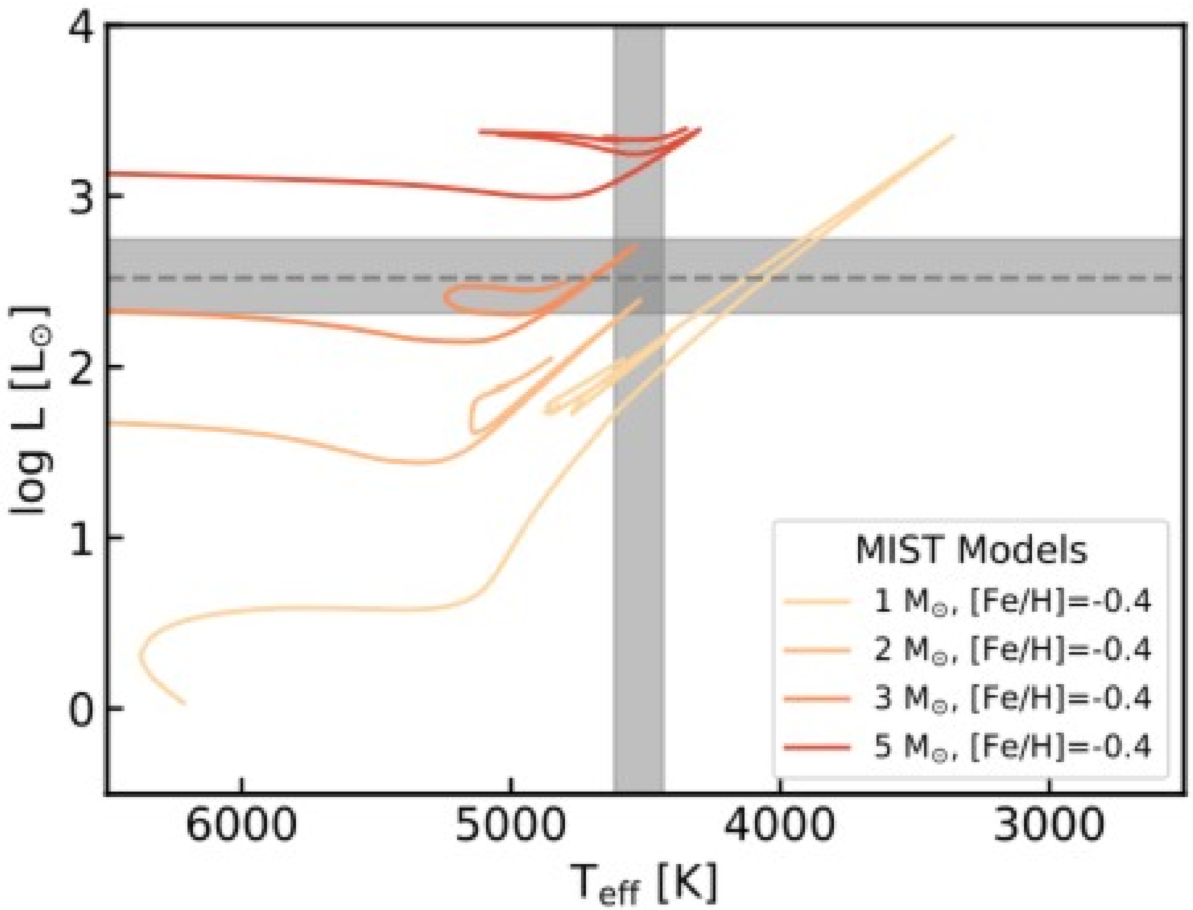

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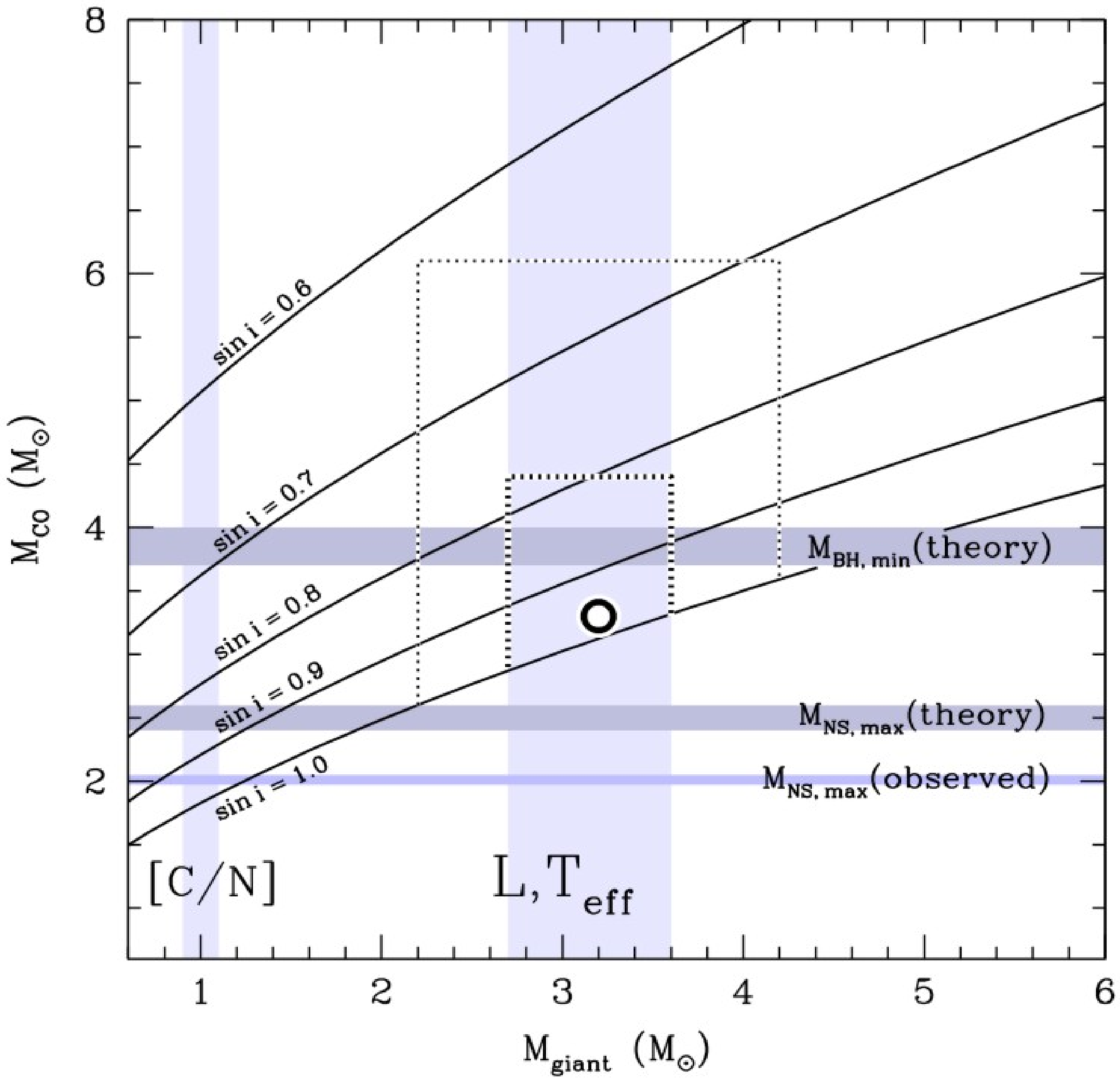

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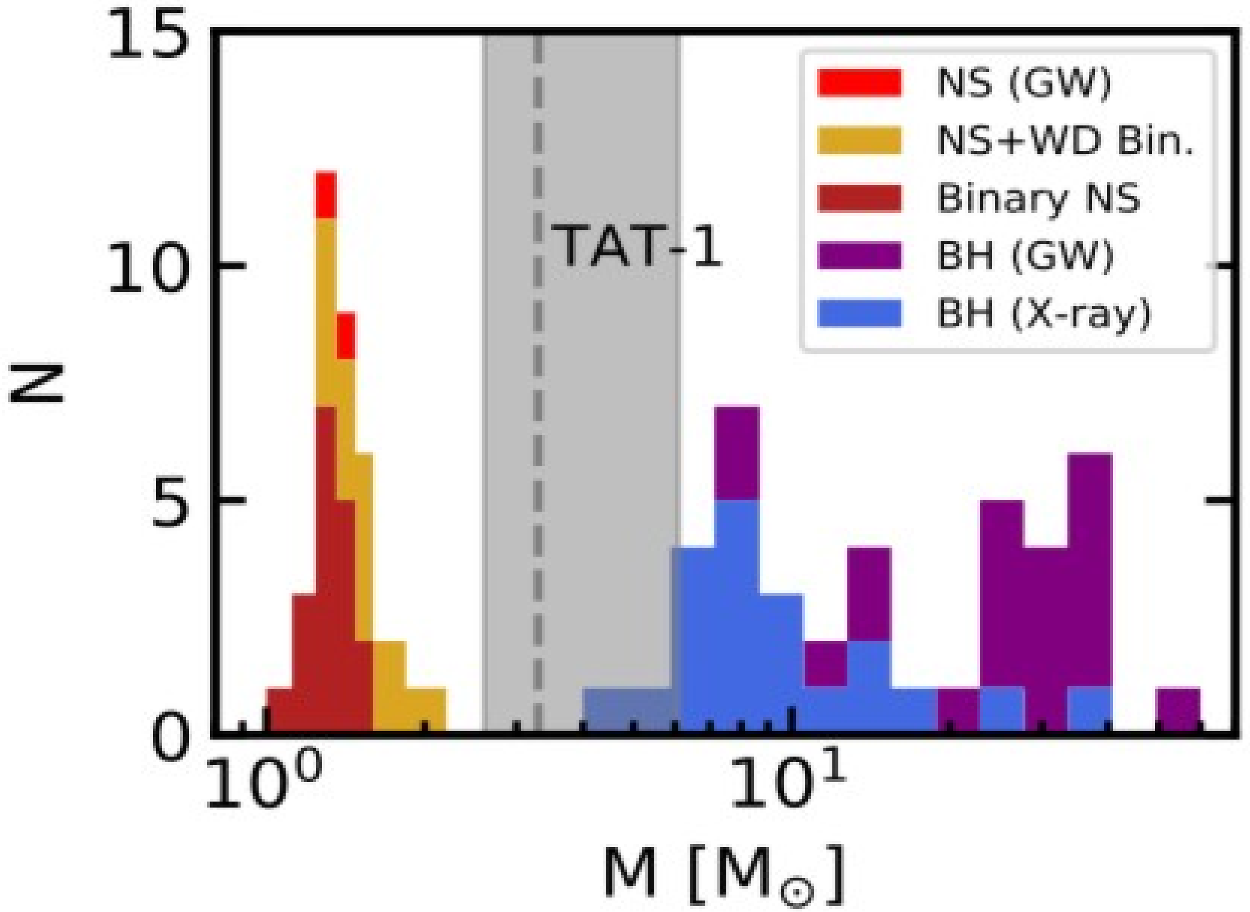

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Implications

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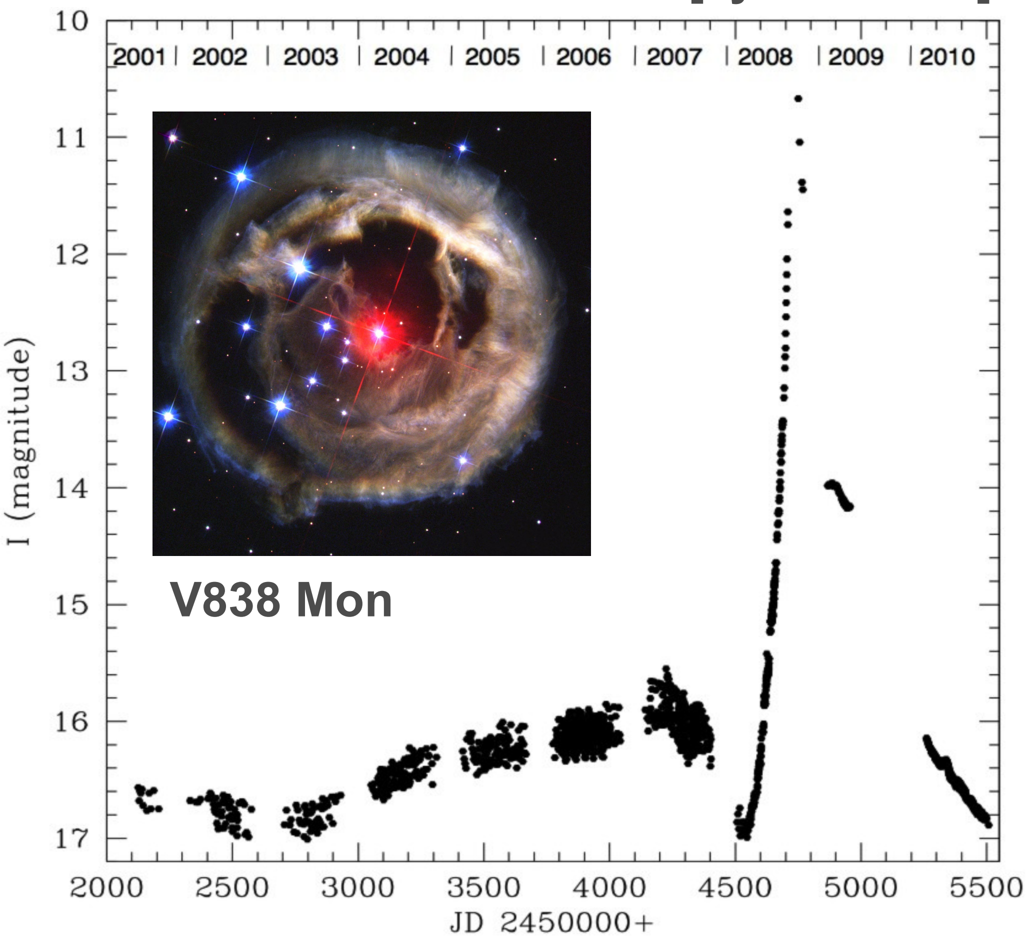
- Case B mass transfer rate ⇒ CE events, stellar mergers (LRNe), birth rate of short P systems? [Tylenda+ 13, Kochanek+ 14].
- More close binaries at low [Fe/H] ⇔ SF theory [Machida+ 09, Bate 14].
- What about BPS models in different environments, redshift evolution? [de Mink & Belczynski 15]?
- Planet host metallicities ⇒ habitability [Johnson 10, Howard+ 12, Thompson+ 17, Guo+ 17].



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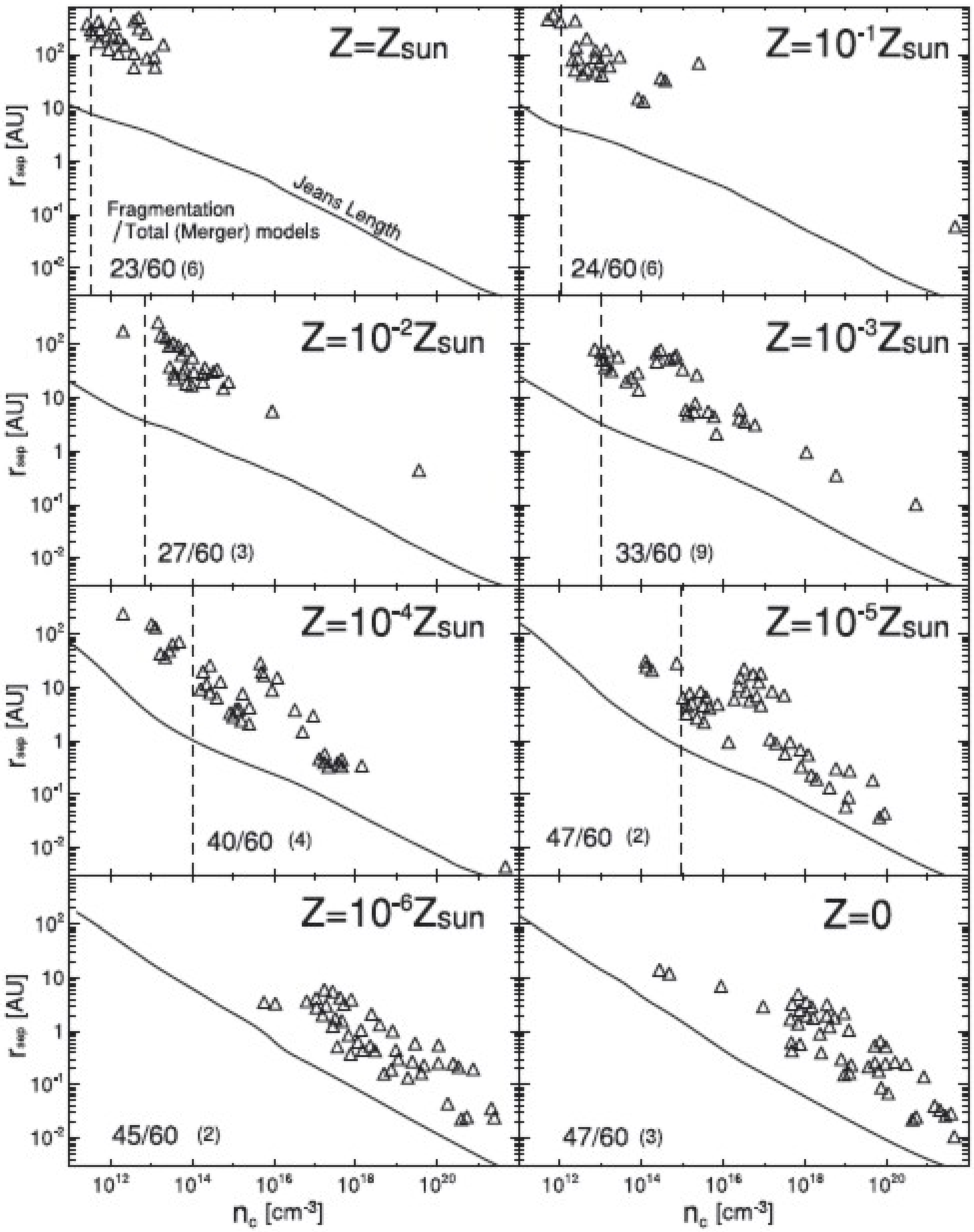
Machida+ 09



Summary

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- APOGEE: high resolution, multi-epoch IR spectra of ~100,000 stars (Galactic archeology).
- Unique view of stellar multiplicity in the field, from the MS to the RC. Few-epoch spectra: no orbits ⇒ ΔRV_{max}.
- Attrition of high ΔRV_{max} (short P) systems as stars climb the RGB, consistent with lognormal P dist., truncated at P_{crit} ⇒ Case B mass transfer. ΔRV_{max} in RC stars ~ TRGB.
- Clear trend with [Fe/H]: lower [Fe/H] stars have higher ΔRV_{max} distributions ⇒ higher f_m at lower [Fe/H].
- Discovery of the first stellar mass non-accretting BH.
- Future work: Hierarchical Bayesian models, multiplicity statistics w/ age & Galactic location, GAIA, BPS, follow-up of interesting systems.

Hierarchical Bayesian Models

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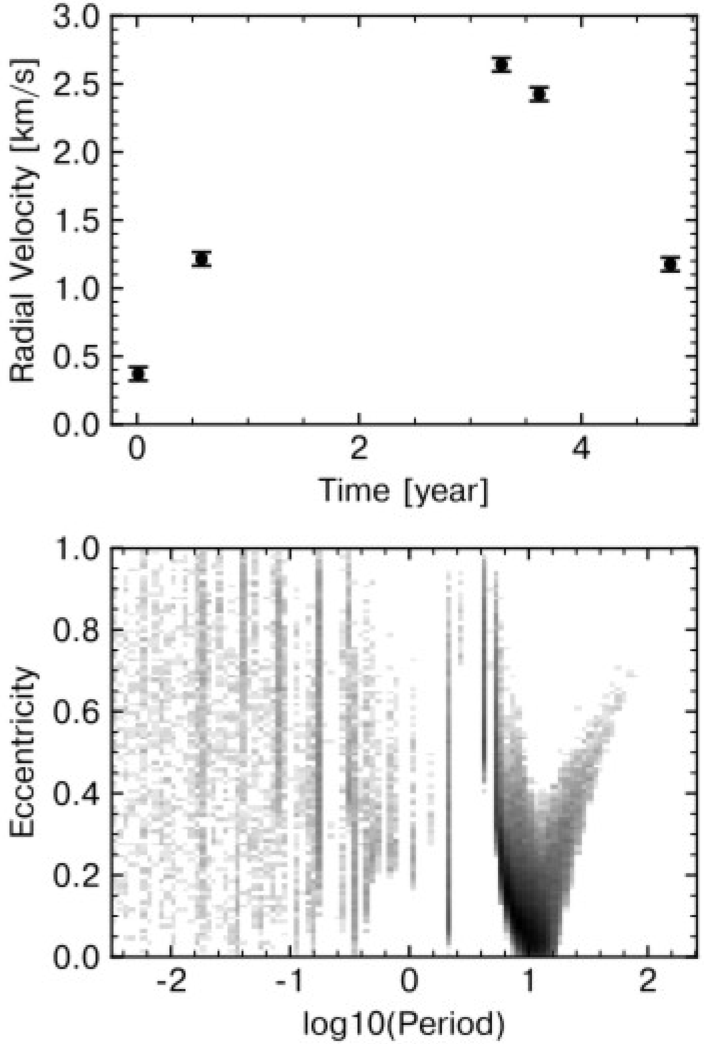
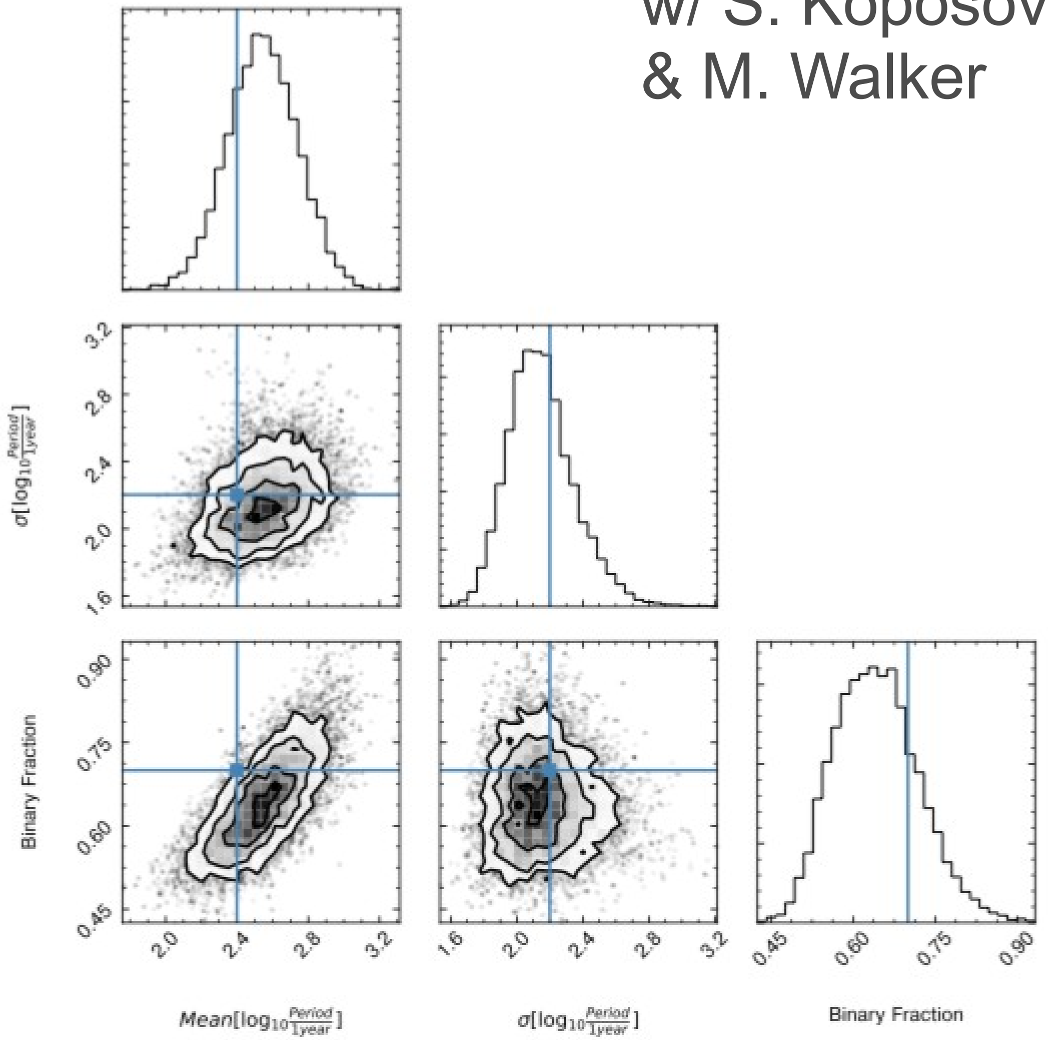


w/ S. Koposov
& M. Walker



GAIA

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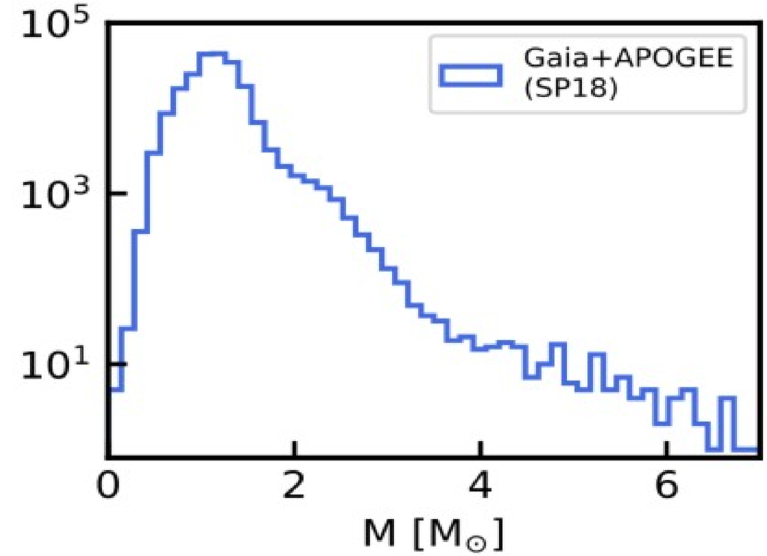

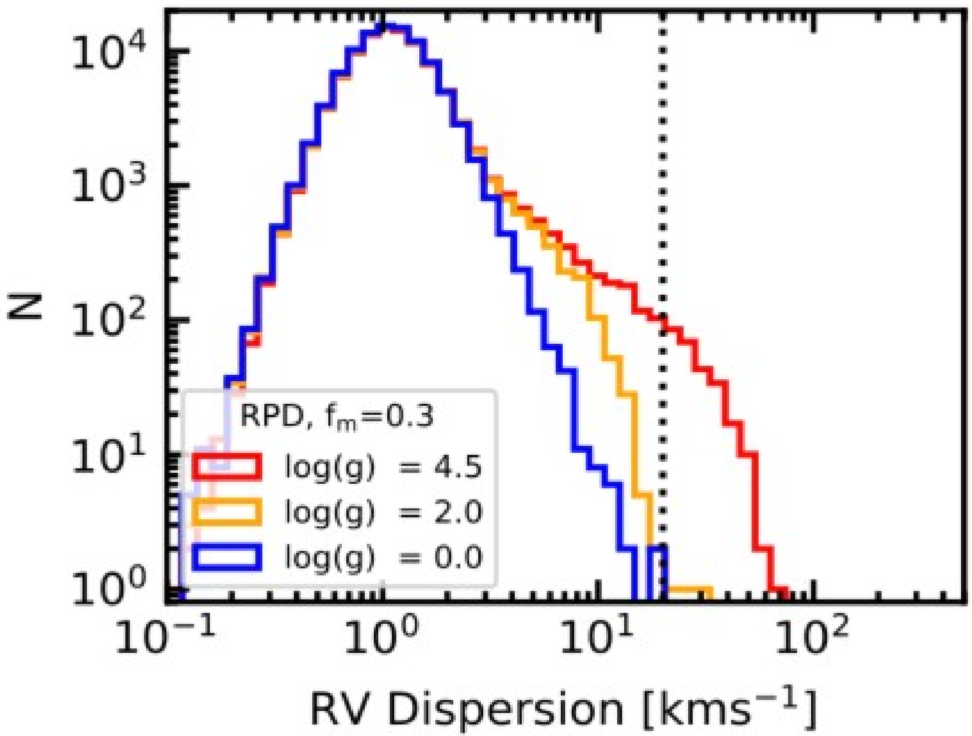

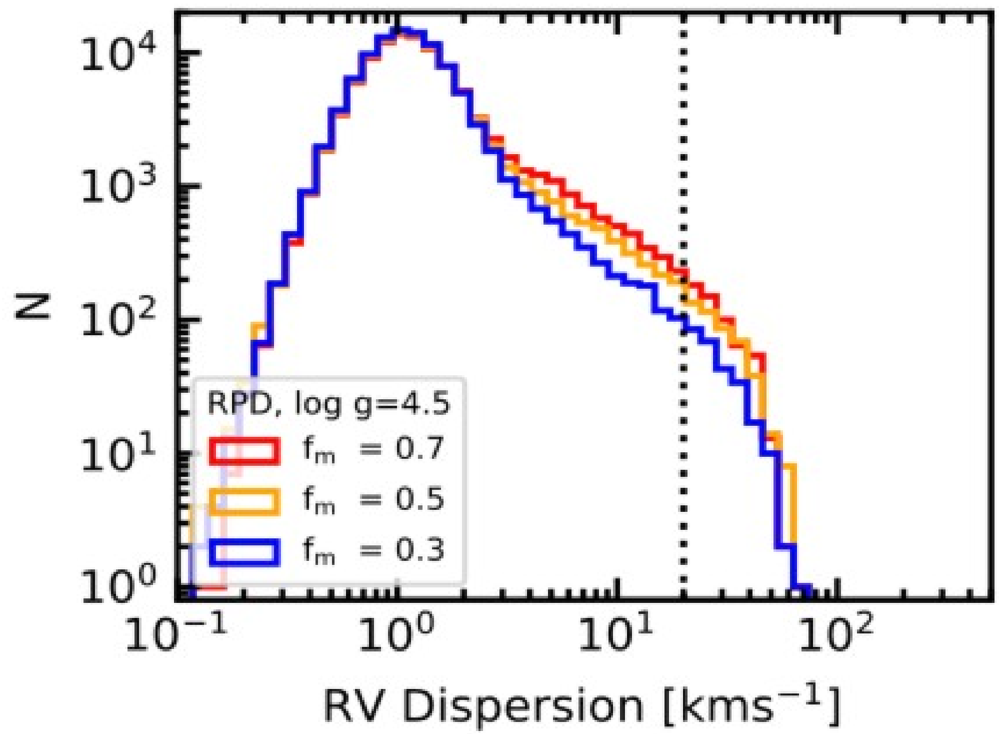

Additional Plots

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