Finding the double sunsets: close binaries and spectroscopic surveys

Carles Badenes
University of Pittsburgh / PITT PACC

IAC, La Laguna
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Research Group @ U Pitt:

- Graduate Students: Sumit Sarbadhicary, Héctor Martínez-Rodríguez, **Christine Mazzola**.
- Postdocs: Brett Andrews, Lluís Galbany

Main Collaborators (on this research):

- Todd Thompson (OSU), Kevin Covey (UWW), Peter Freeman (CMU/Statistics), Matthew Walker (CMU/Physics), Maxwell Moe (UofA).
- The APOGEE RVvar group: Nick Troup (UVa), David Nidever (NOAO), Nathan De Lee (NKU), and many others.
- GAIA, WEAVE: Teresa Antoja (UB), Sara Lucatello (Padova).

Funding:

The twin suns of Tatooine slowly disappear
behind a distant dune range...

Star Wars. George Lucas, 1977.

Outline

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- **Introduction:** Close Binaries, Why do we care and what are we looking for?
- **Data:** Radial Velocities from large spectroscopic surveys.
- **Results:** WD binaries. Multiplicity statistics vs. stellar evolution and metallicity in SDSS/APOGEE.
- **Conclusions:** Implications. Future directions: GAIA, WEAVE.

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- **Close binaries** (will interact) ⇒ deviations from single stellar evolution.
- **Unresolved systems** ⇒ healthy skepticism.
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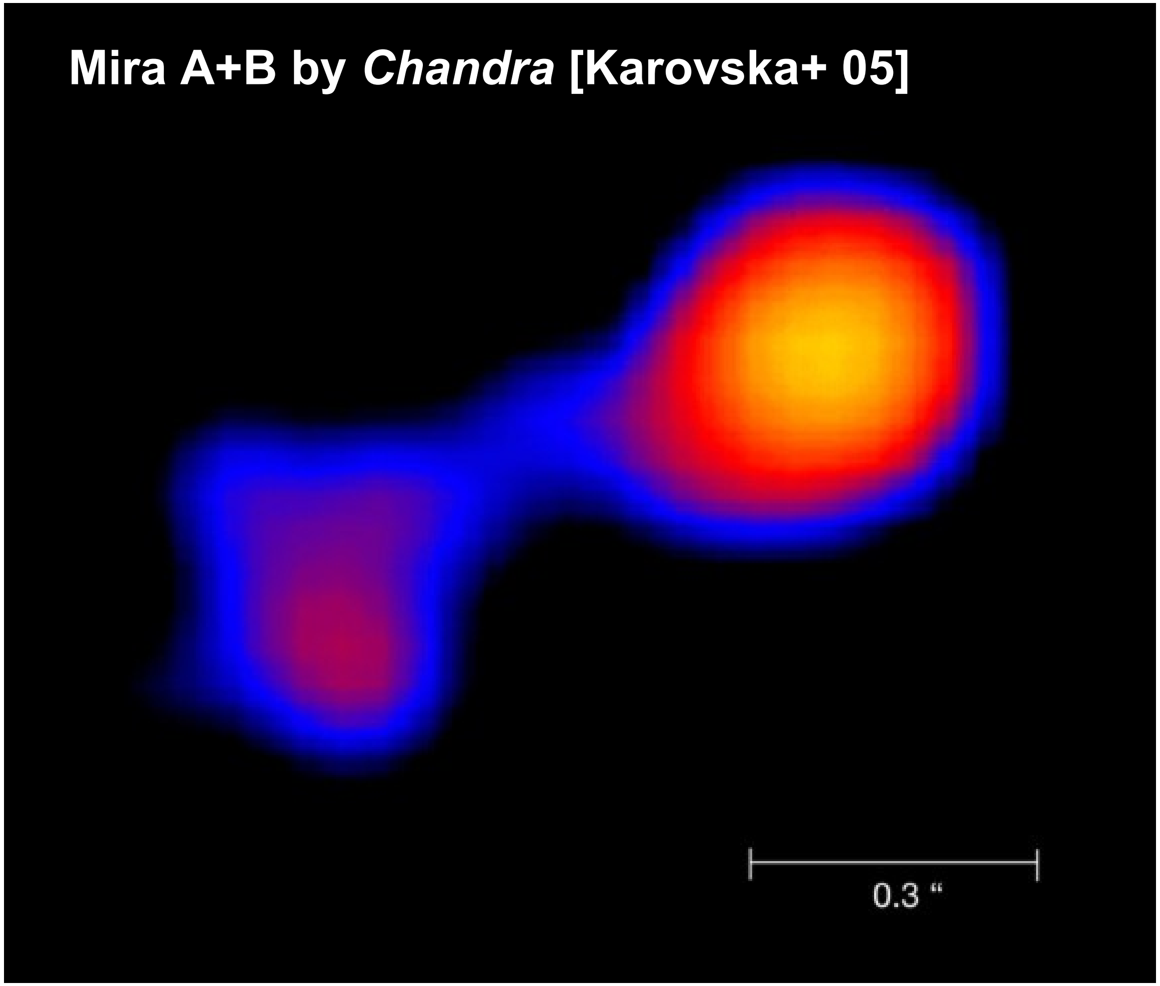

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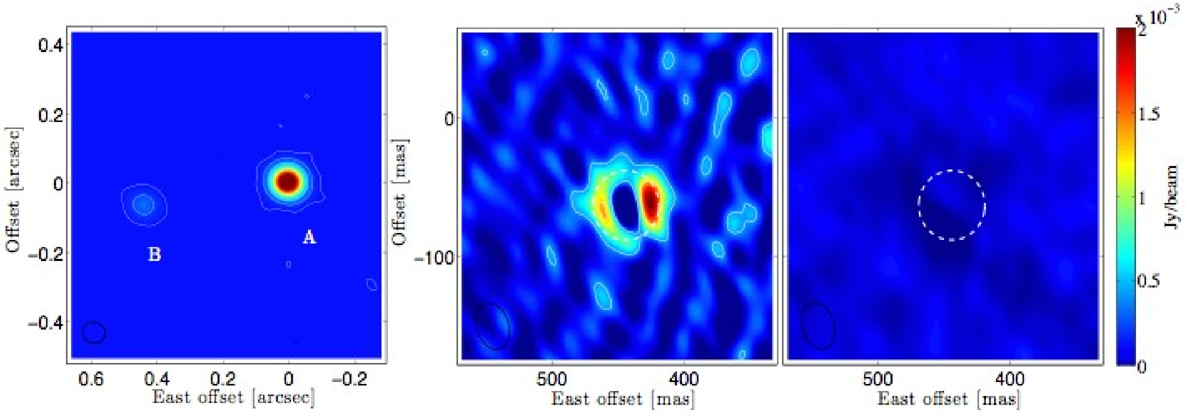
Mira A+B by *ALMA* [Vlemmings+ 15]



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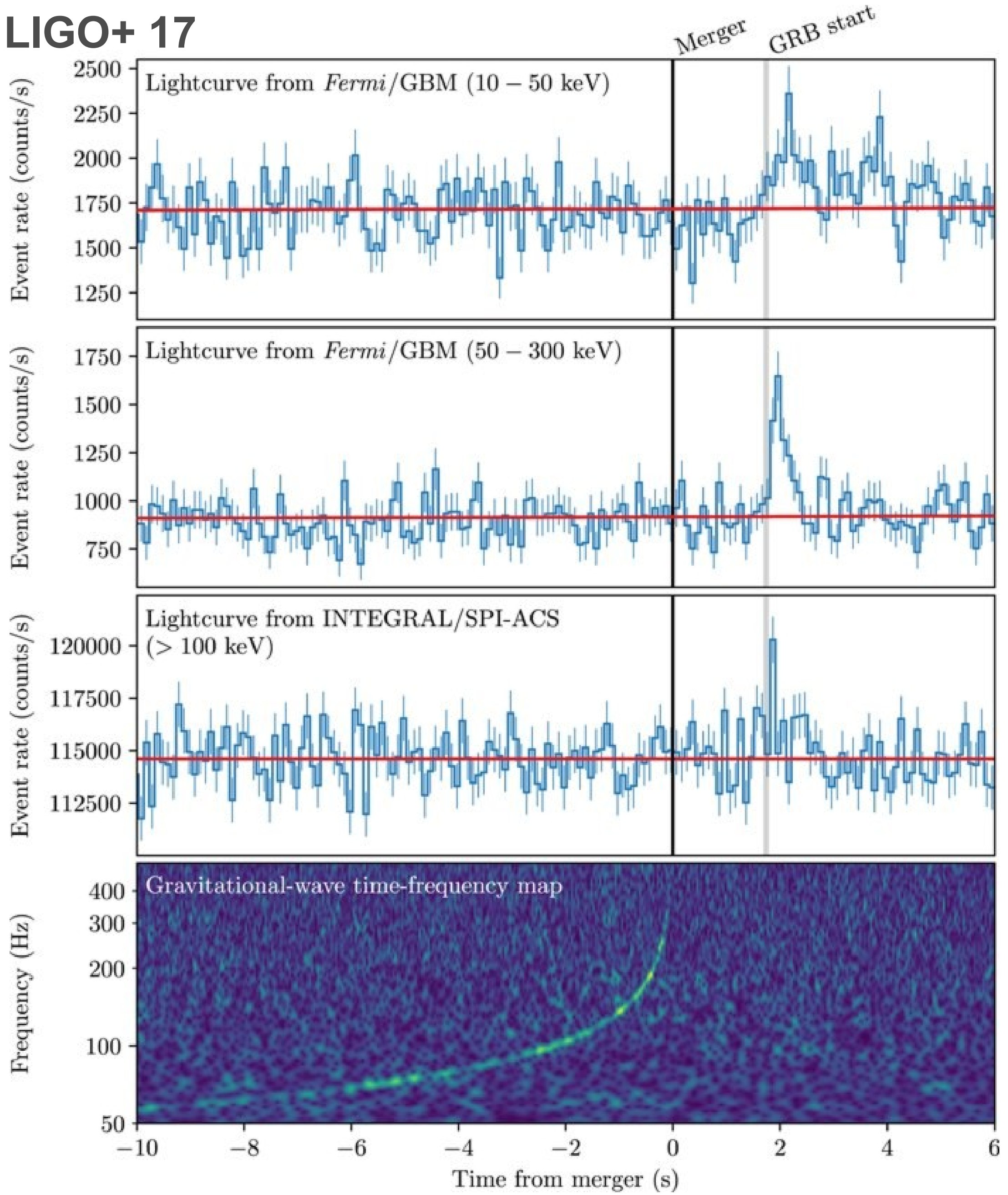
LIGO+ 17



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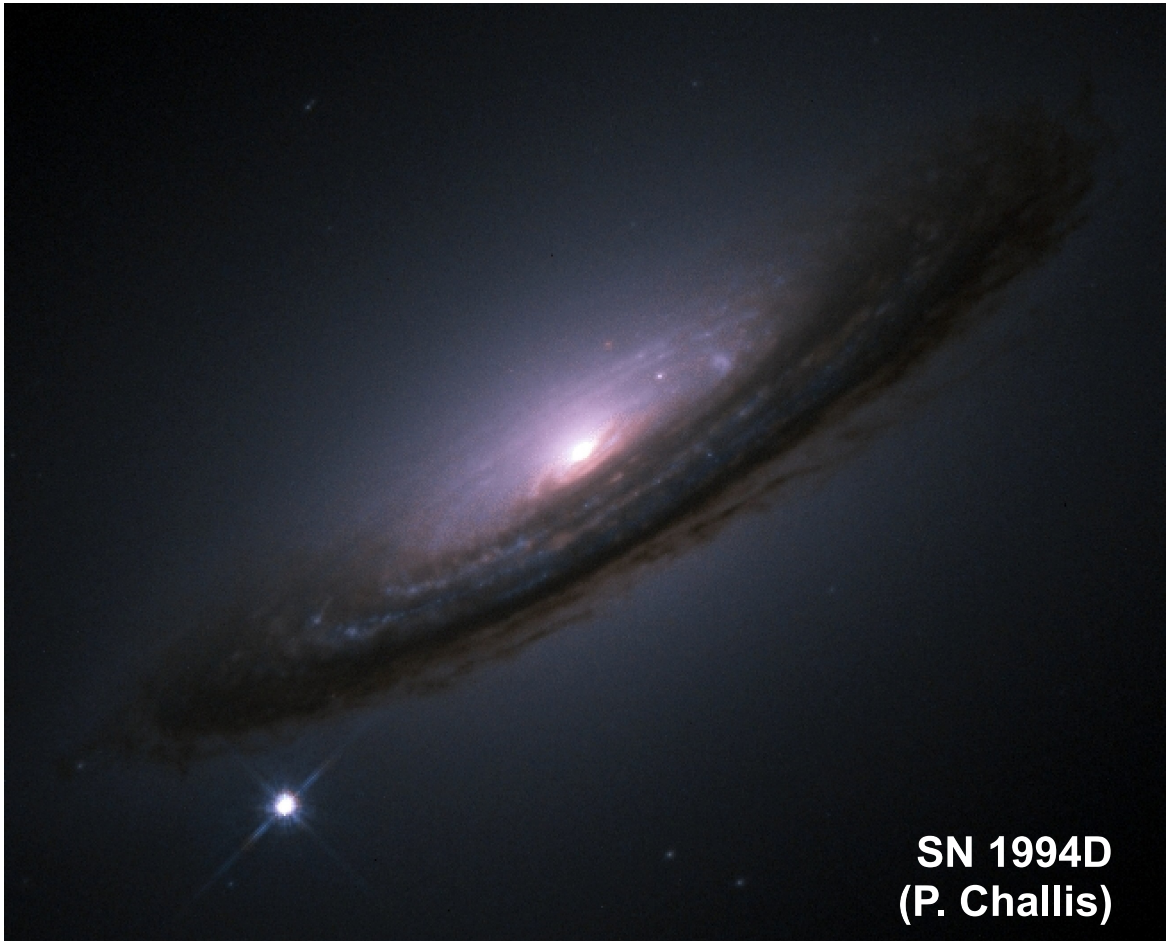

SN 1994D
(P. Challis)

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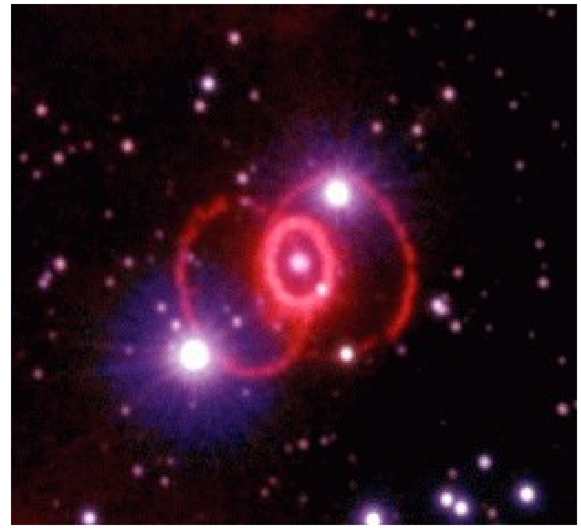

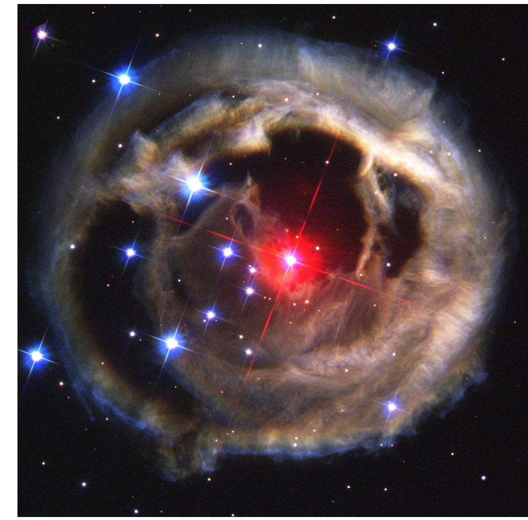

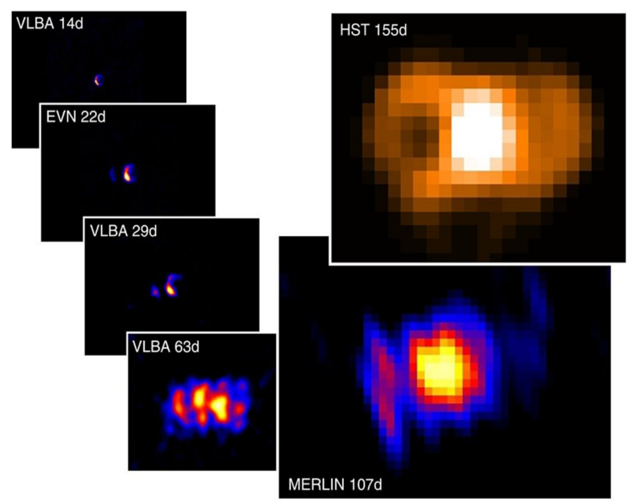

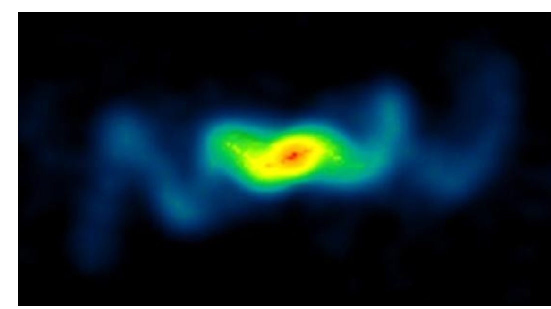

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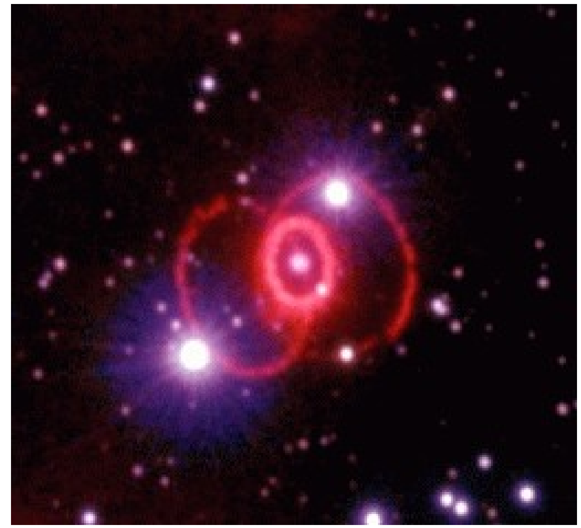
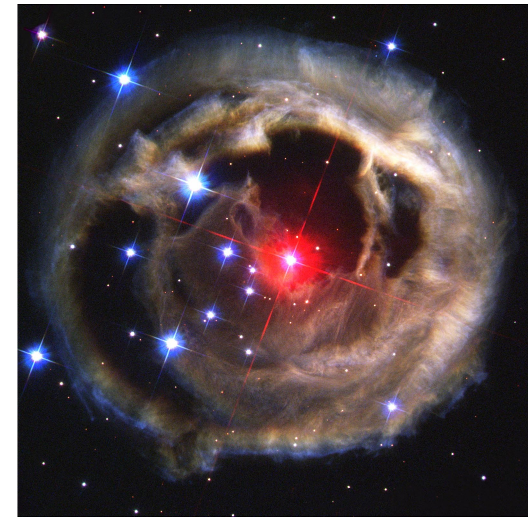
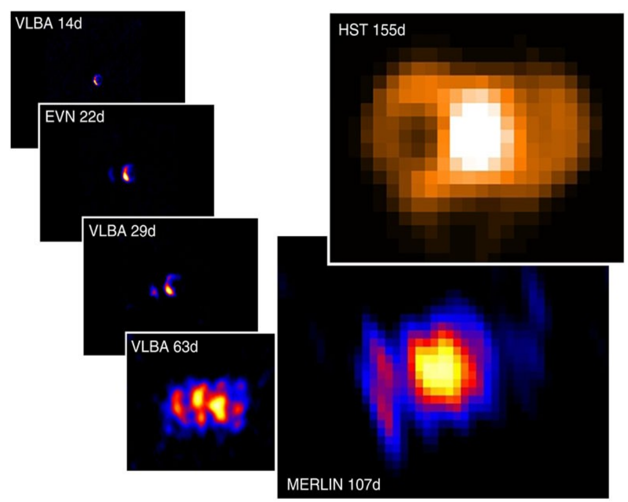
SN 1987A

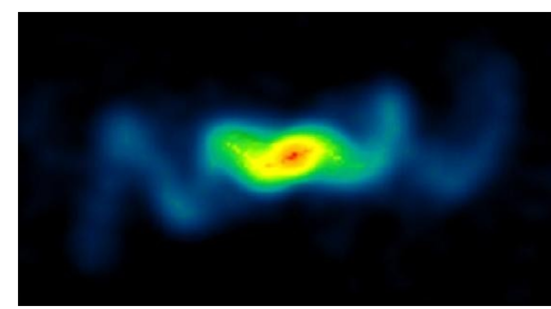


V838 Mon





RS Oph



SS 433

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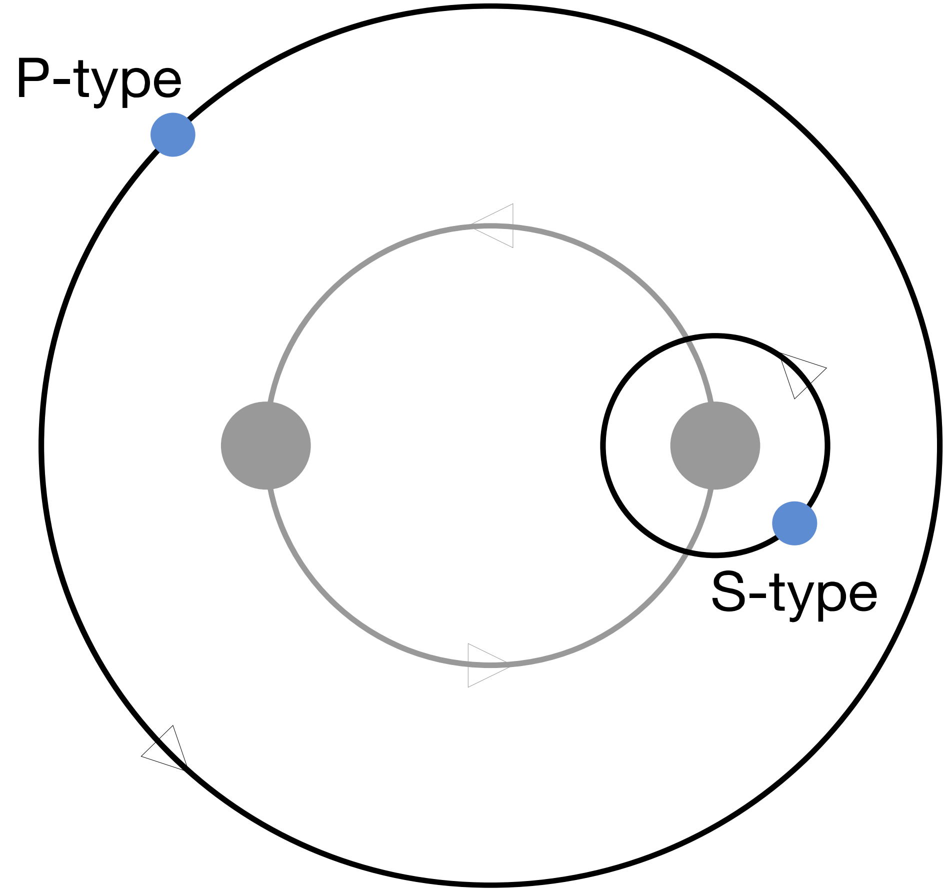

Wikipedia

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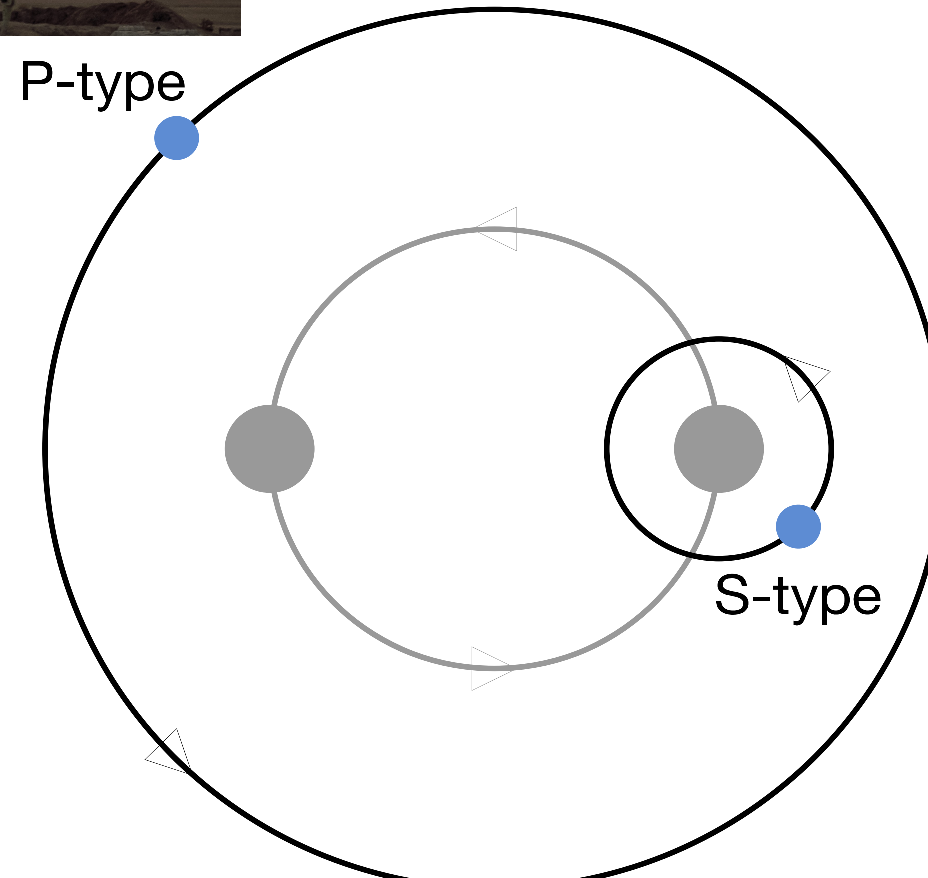

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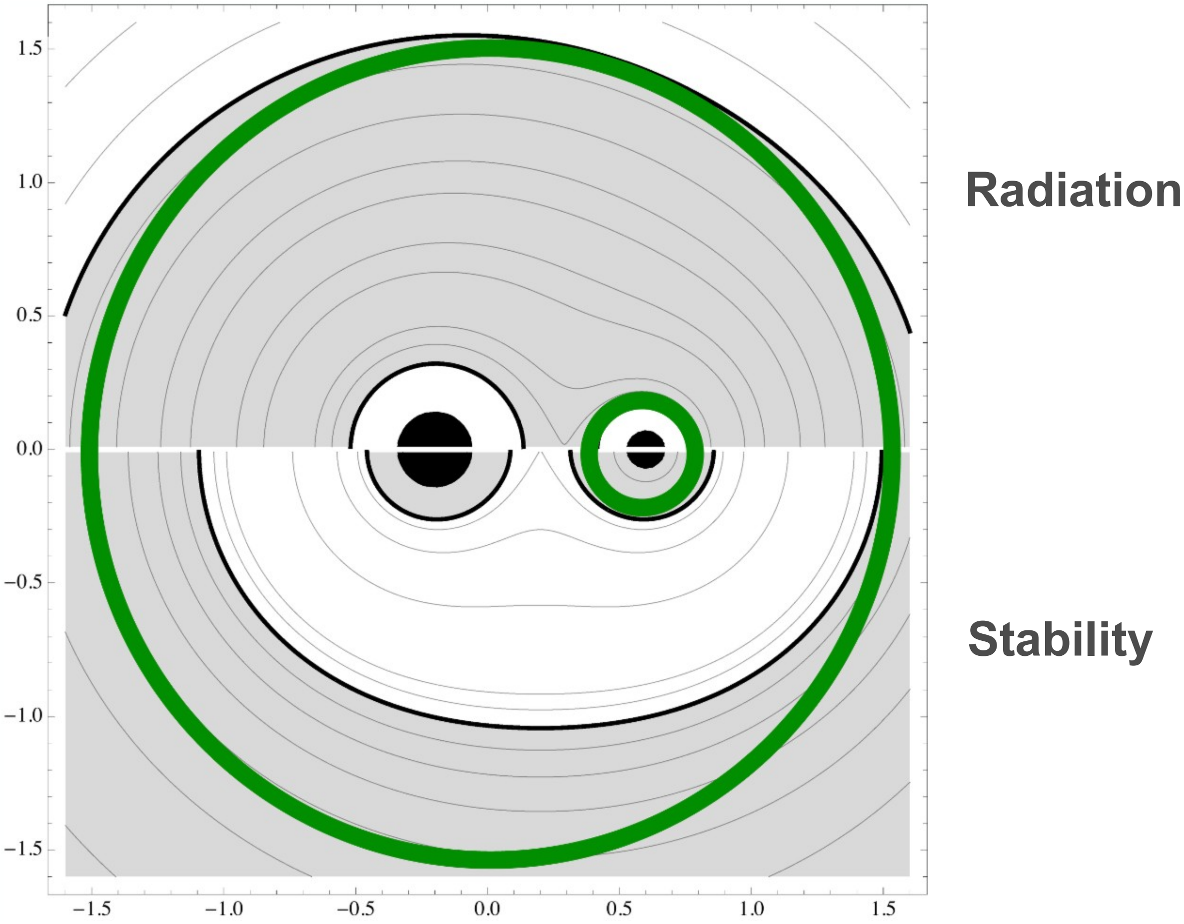
Circumbinary Habitability [Jamie+ 14]



What are we looking for?

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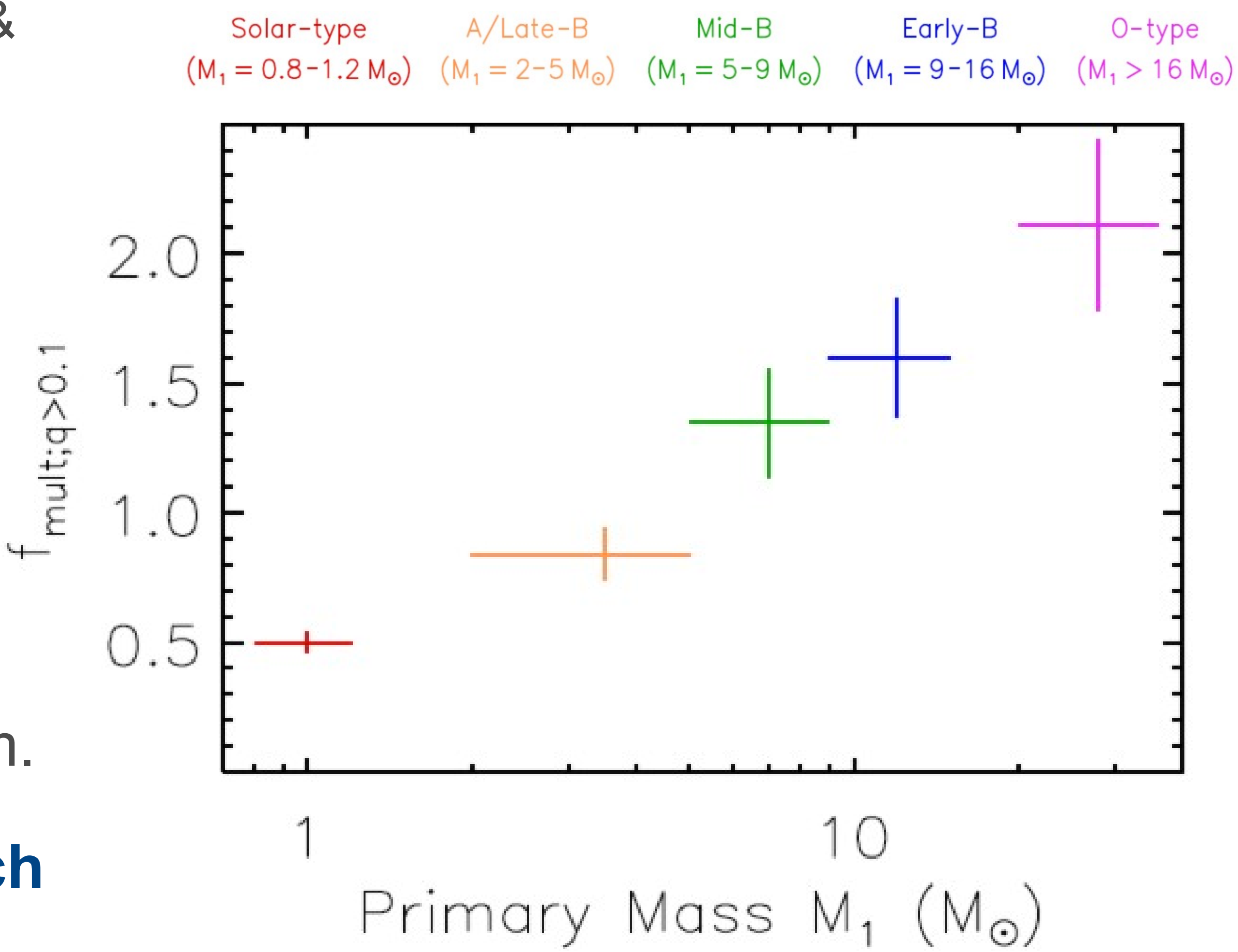
- **Stellar Multiplicity** (Sun-like MS stars, D<25 pc) [Raghavan+ 10, Duchene & Kraus 13, Moe & DiStefano 17 (MD17)]:
  - Multiplicity fraction (f_m): dominated by M_1.
  - Period (P): ~lognormal.
  - Mass Ratio (q): ~flat.
  - Eccentricity (e): tidal circularization, ~uniform.
- **Not independent of each other!!!!** [Sana+ 12, MD17].

MD 17



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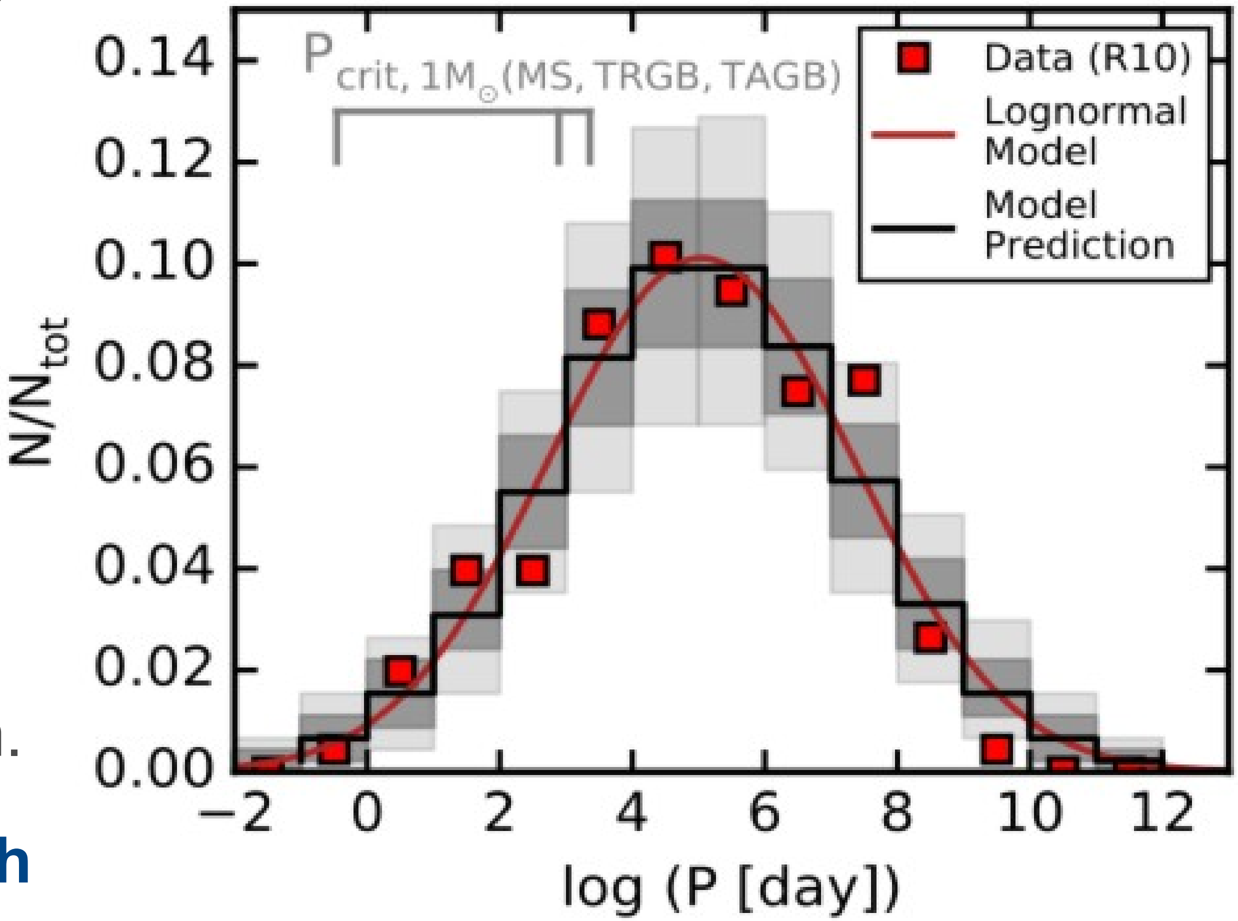

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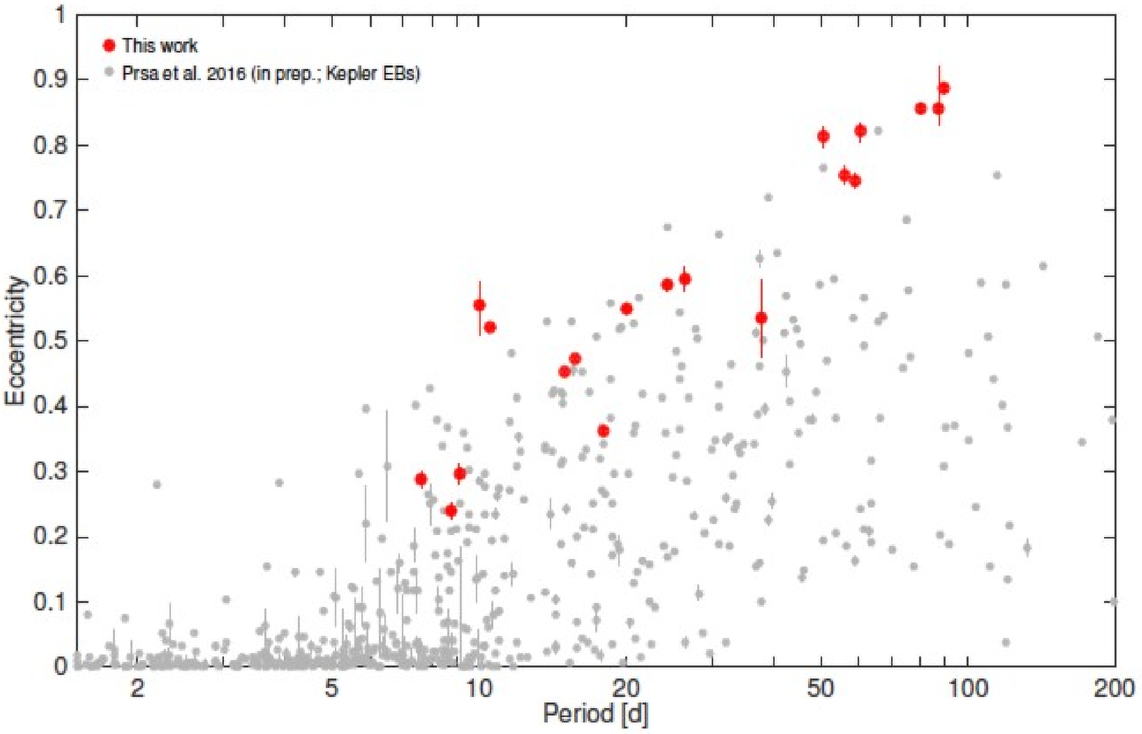
Shporer+ 16



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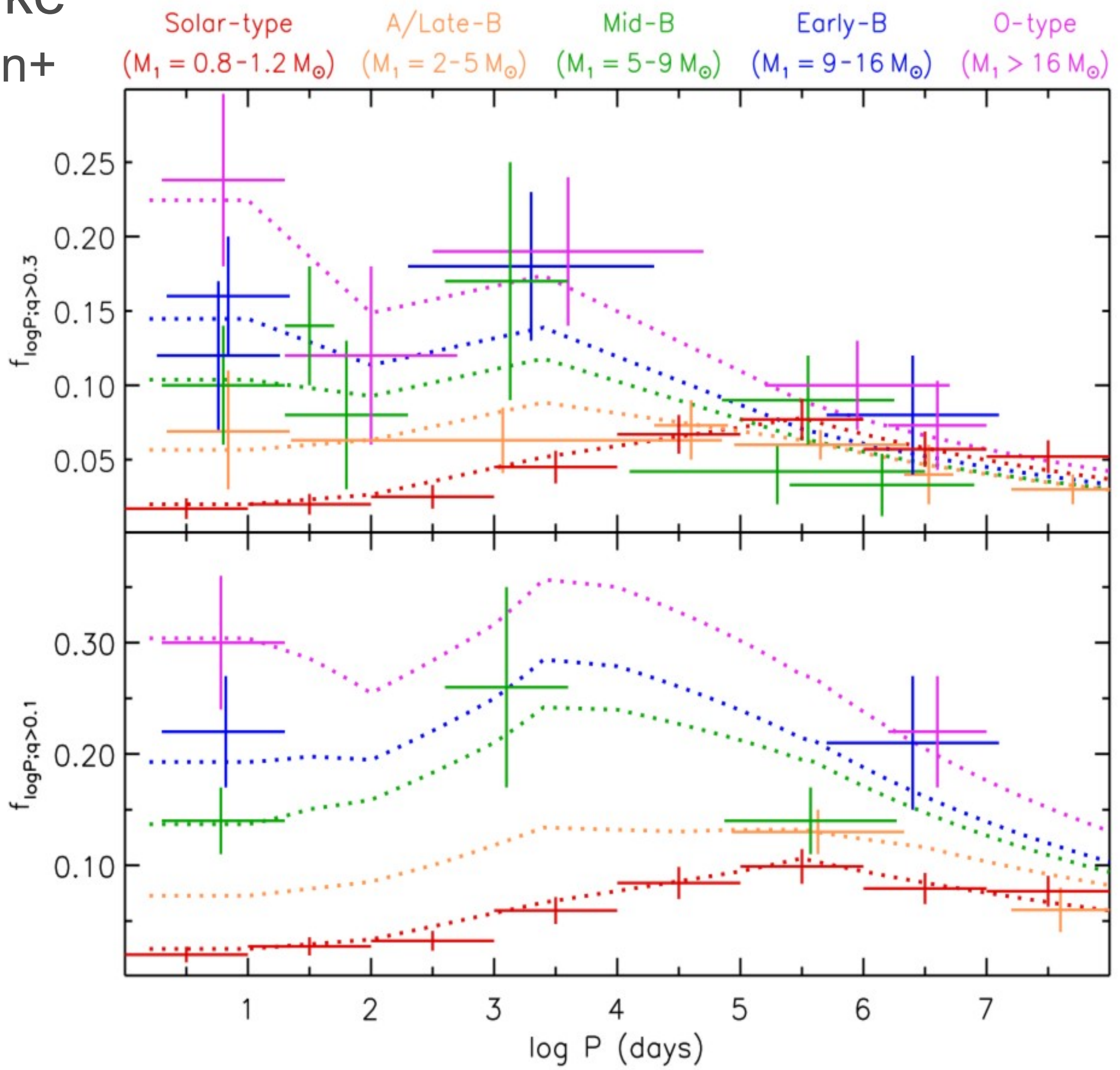

Multiplicity and Stellar Evolution

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- Critical P for RLOF (q=1):

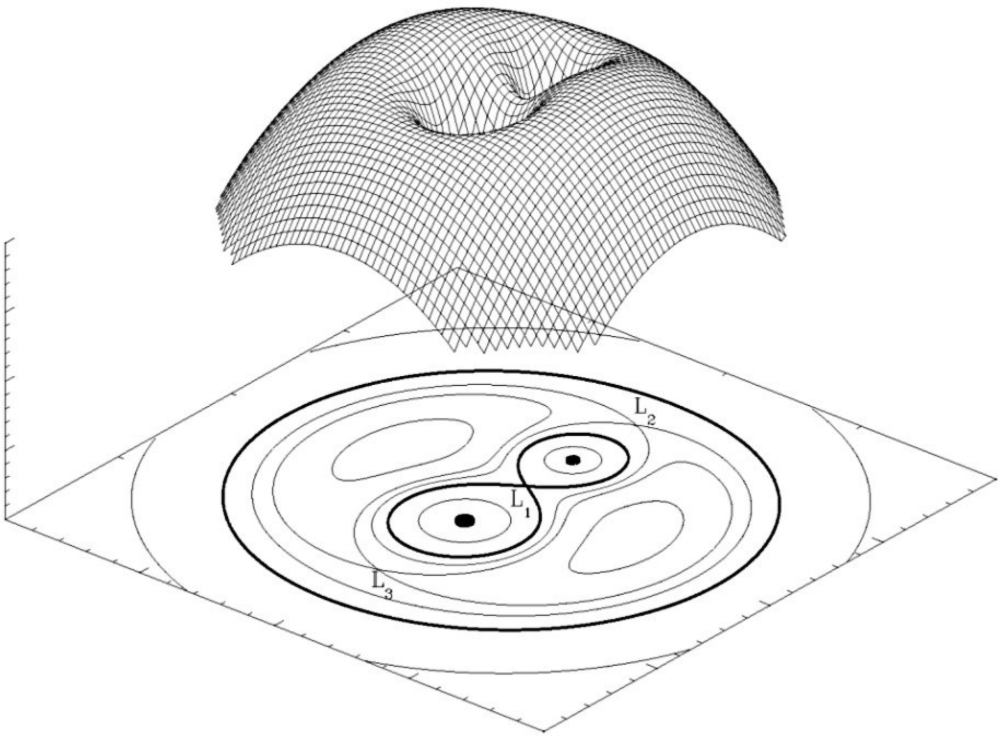
$$P_{crit} = 0.76(R^3/(GM))^{1/2}$$

- 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 mass transfer [Pavloskii & Ivanova 15] ⇒ Common Envelope ⇒ merger or short P system.



Roche Potential [Wikipedia]

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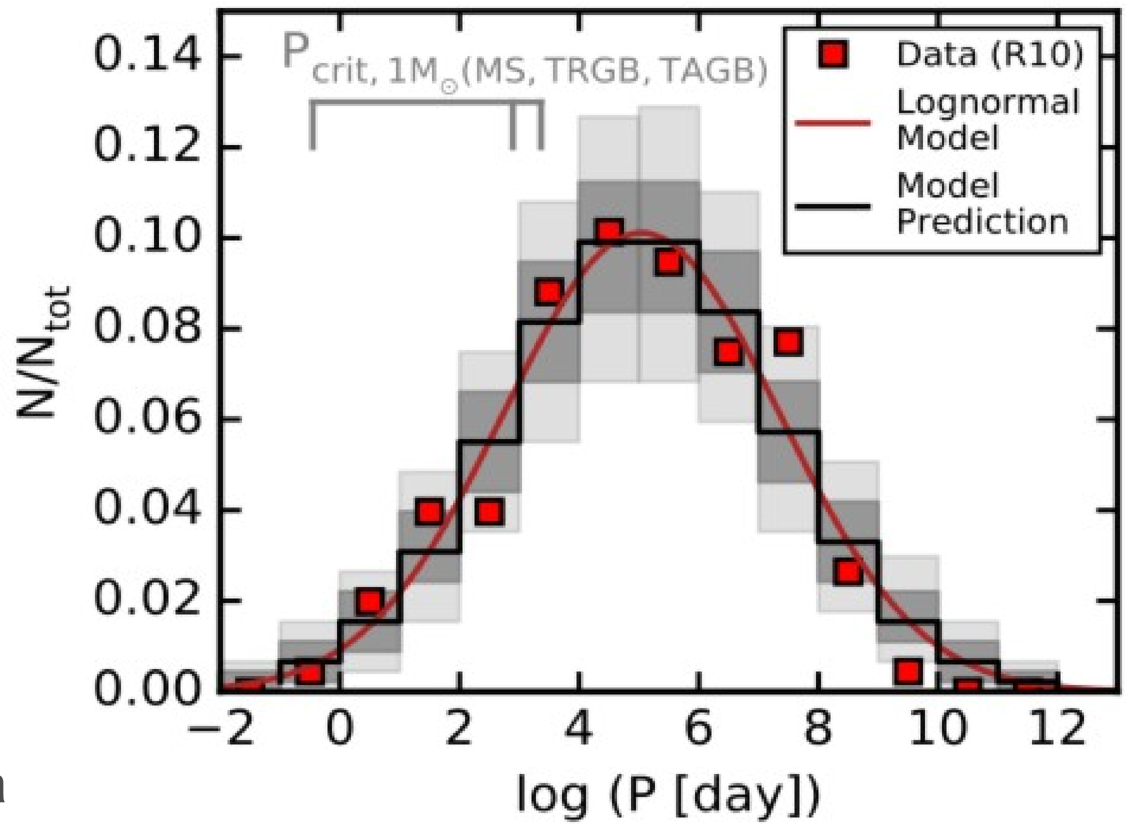

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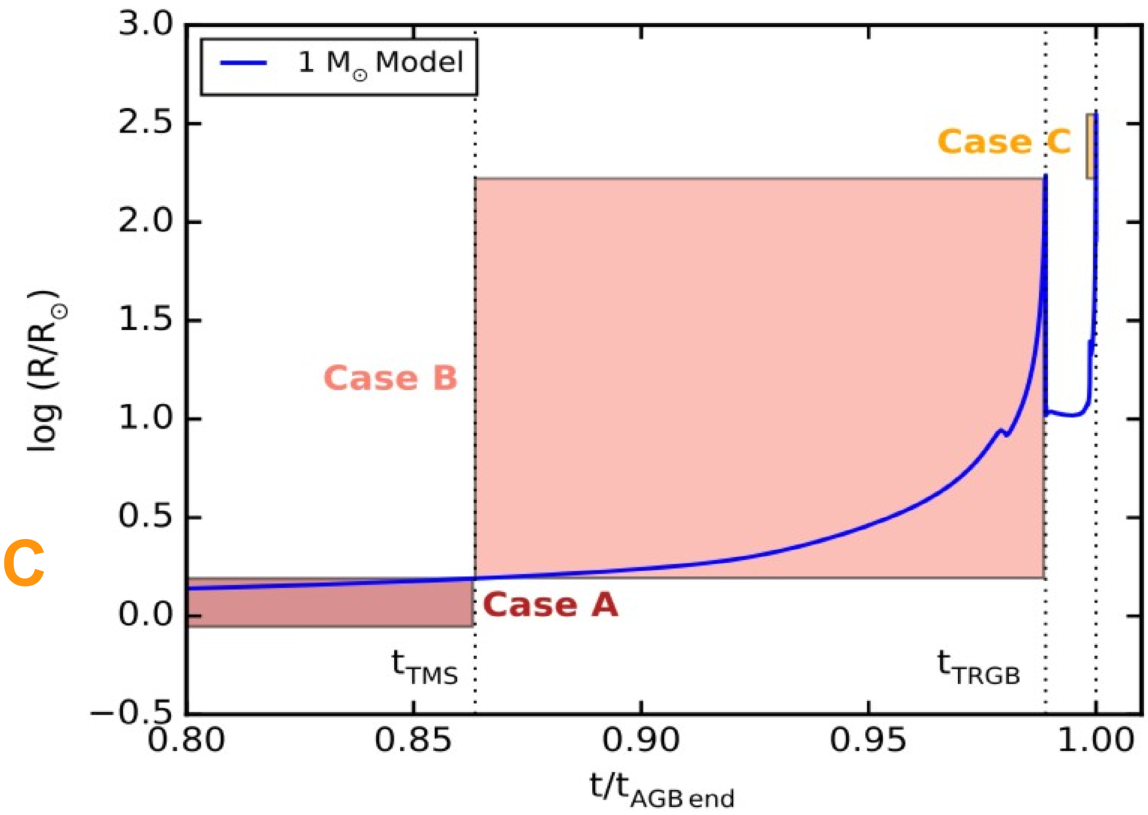

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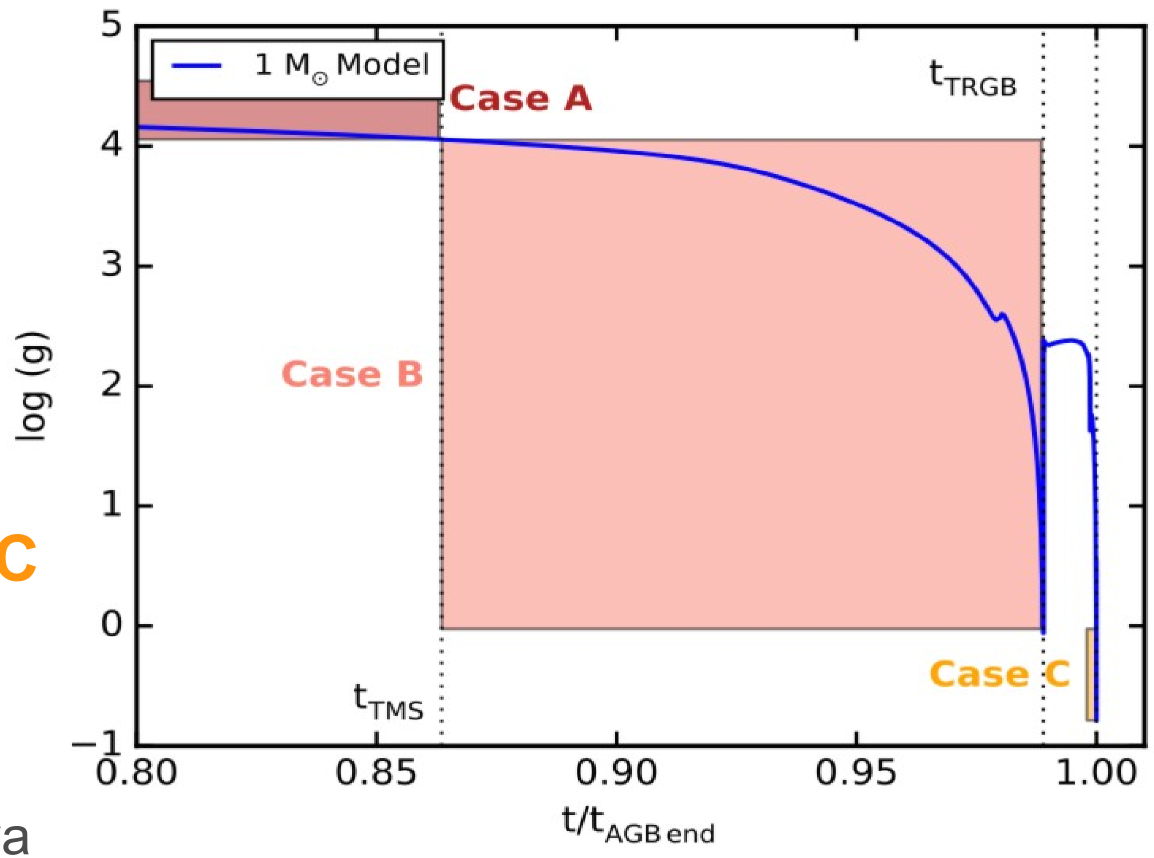
log g = log(M/R²)



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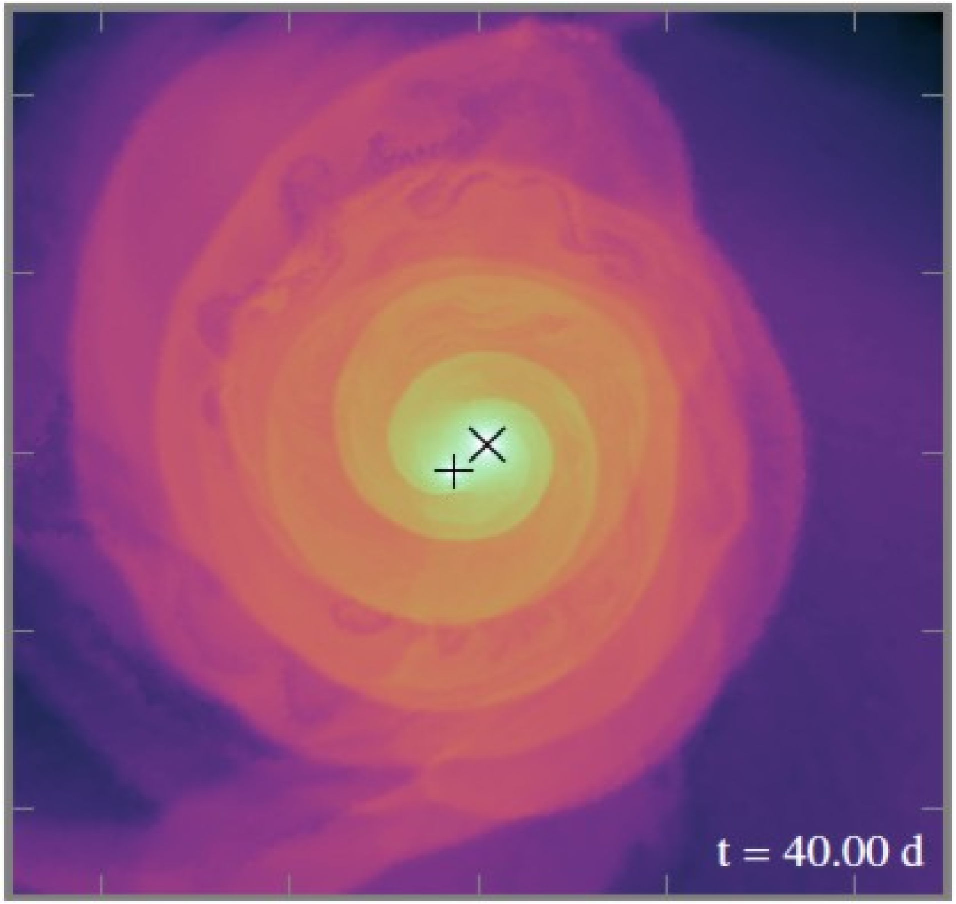

Ohlmann+ 15

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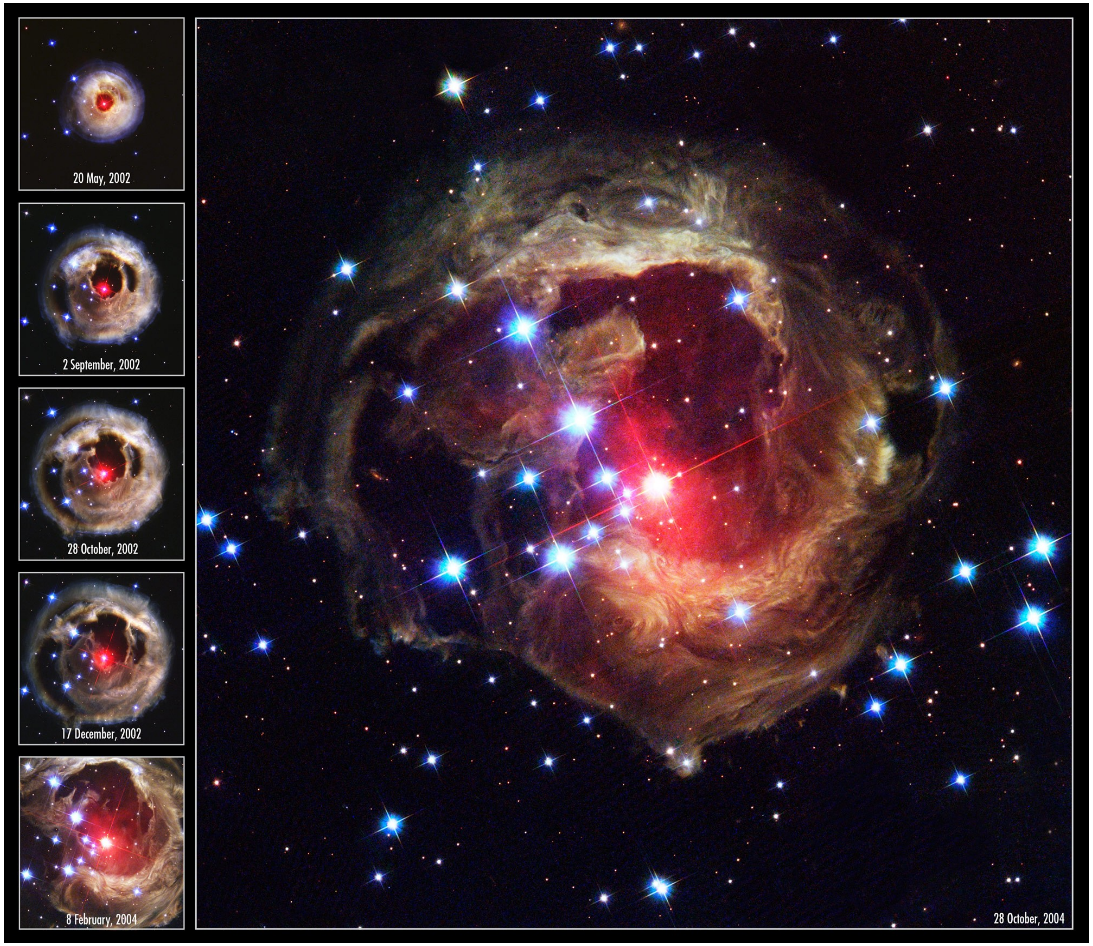

V838 Mon [Bond+ 03]

Open Questions

- Multiplicity Statistics only known accurately at all P in the MS and in the Solar Neighborhood [Duchene & Kraus 13].

- 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 age/metallicity in the field. Open questions:

  - Are our ideas about RLOF basically correct?

  - Stellar multiplicity vs. environment: age? metallicity? ⇔ 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.?

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RVs in Large Spectroscopic Surveys

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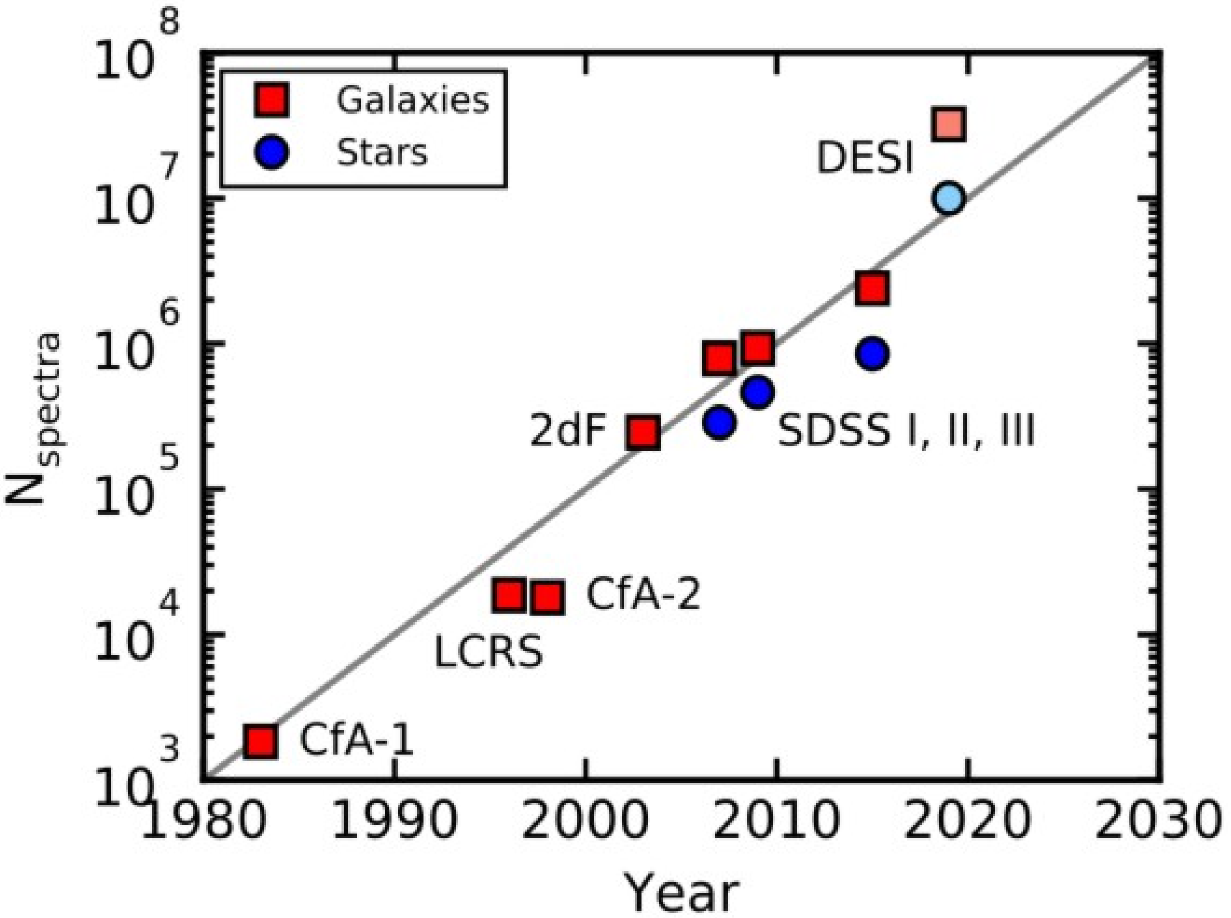
- **RVs**: most efficient probe of multiplicity for log P<4 ⇒ spectra.
- **Large spectroscopic surveys**: SDSS/SEGUE [Yanni+ 09], SDSS/APOGEE [Majewski+ 17], RAVE [Steinmetz+ 06], WEAVE [Dalton+ 14].
- Well characterized (pipelines) ⇒ stellar parameters.
- Caveat: Orbital fitting requires ~10 RVs, good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



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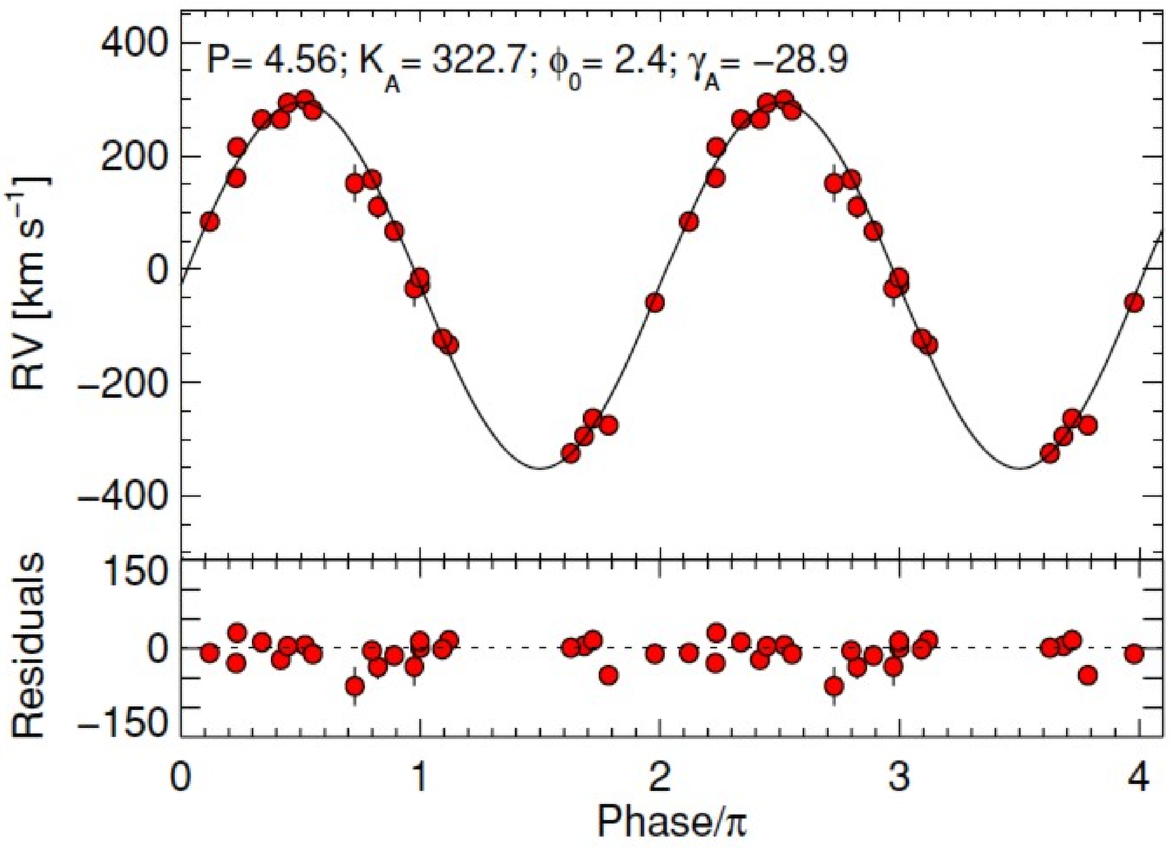

Badenes+ 09

RVs in Large Spectroscopic Surveys

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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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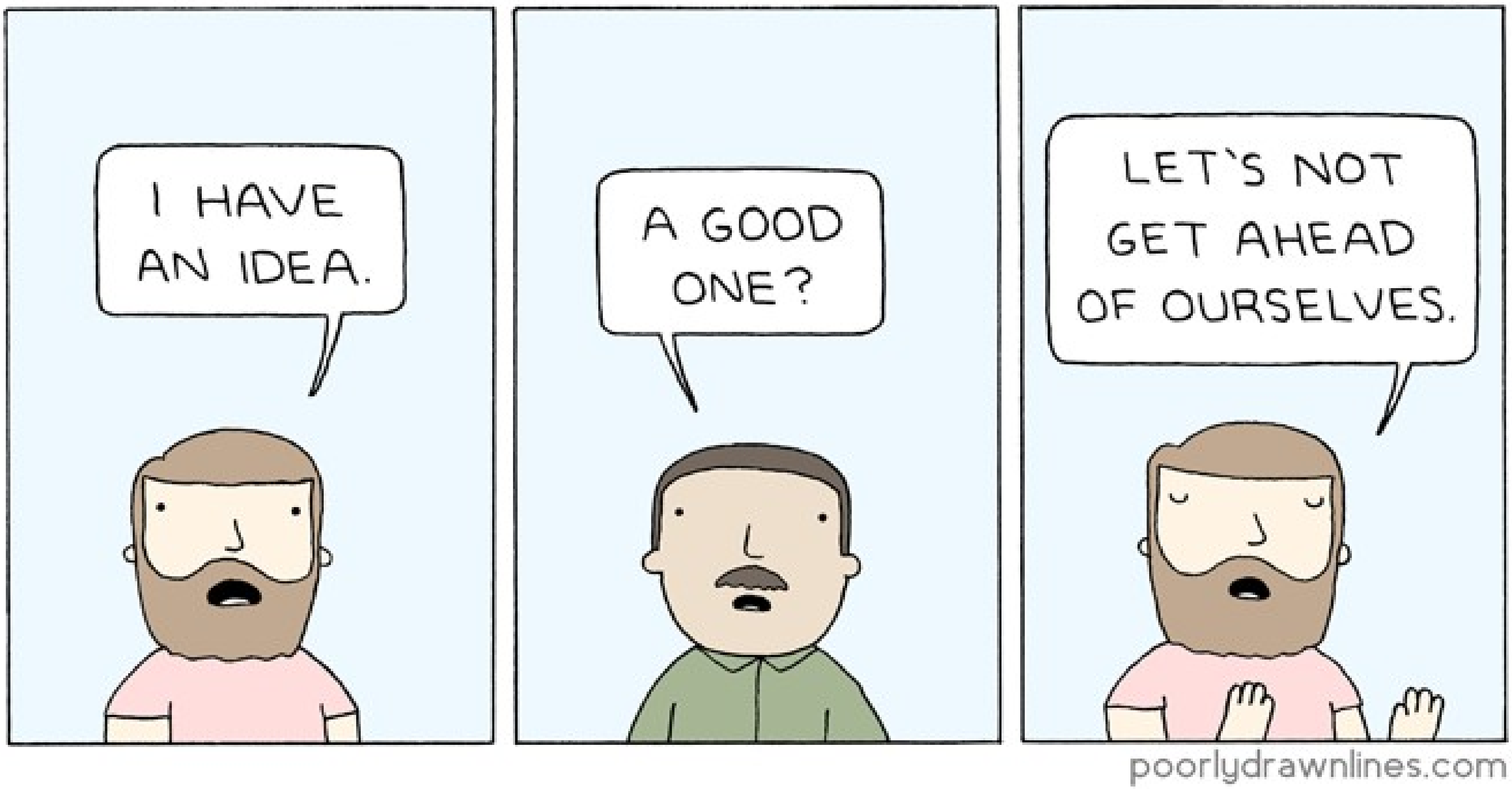

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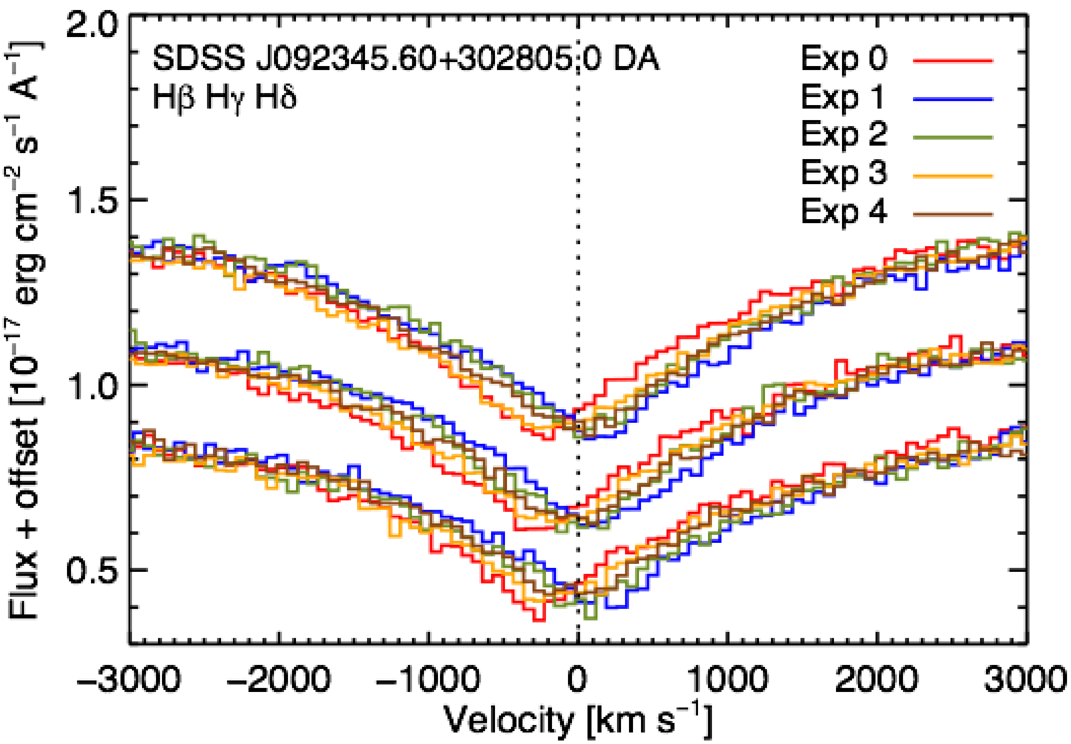
Interlude: WD Binaries

- Sparsely sampled RV curves ⇔ **WD binaries**.
- Pre-merger WDs ⇒ P~hrs, RV~500 km/s [Badenes+ 09, Mullally+ 09].
- **ΔRV_{max}** = $Max(RV_i) - Min(RV_i)$ ⇒ f_{bin}, P distribution ⇒ WD merger rate.
- Enough WD mergers to explain Type Ia SNe [Badenes & Maoz 12, Maoz+ 18]. LISA foreground!

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



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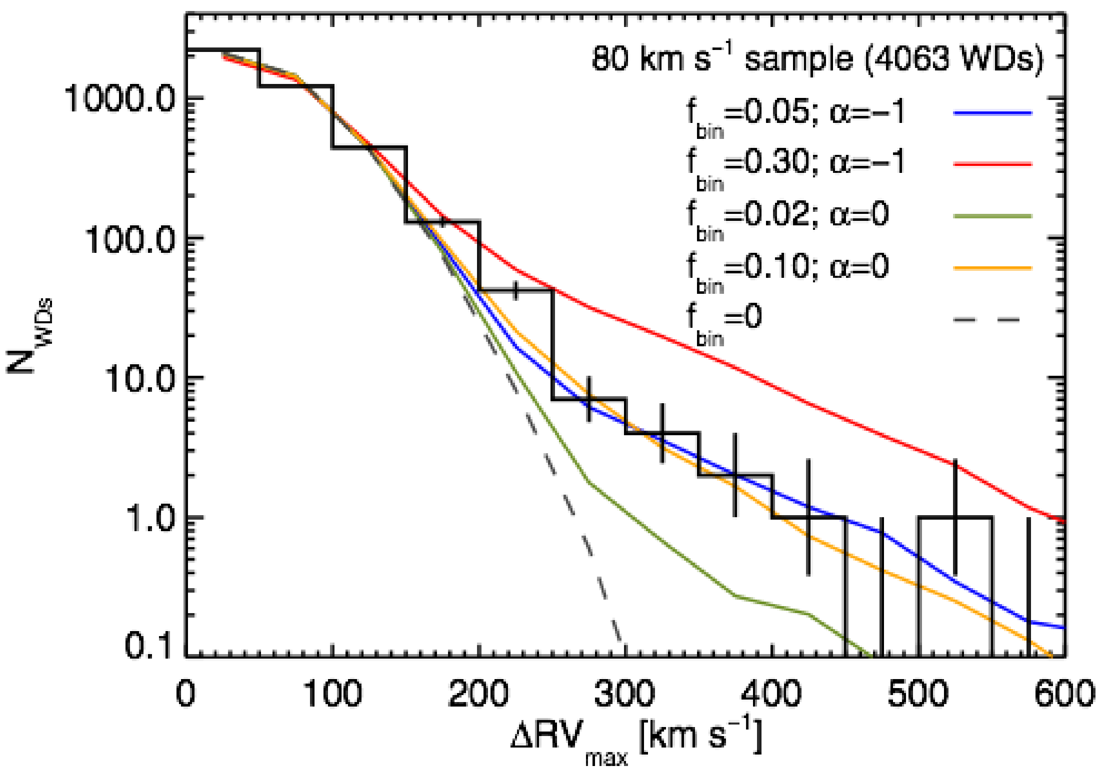
[Badenes & Maoz 12]



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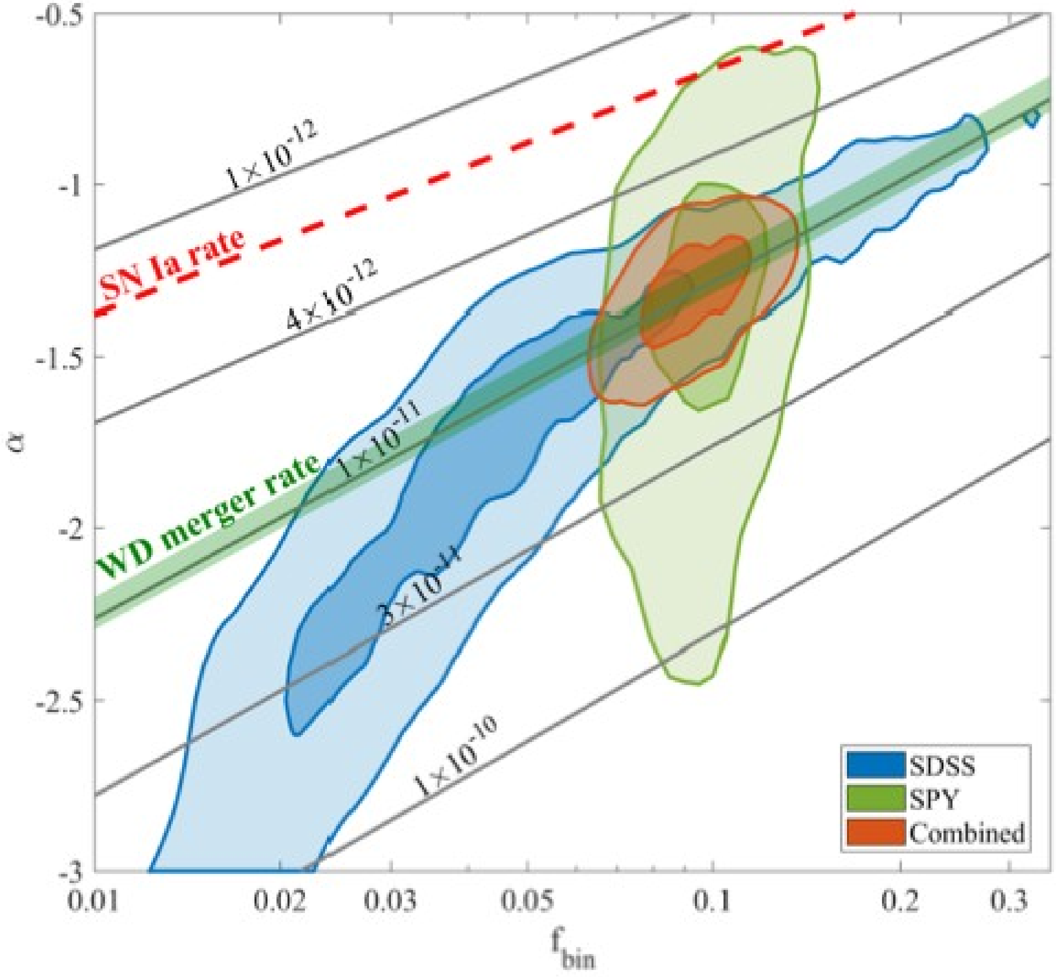
[Maoz, Hallakoun & CB 18]



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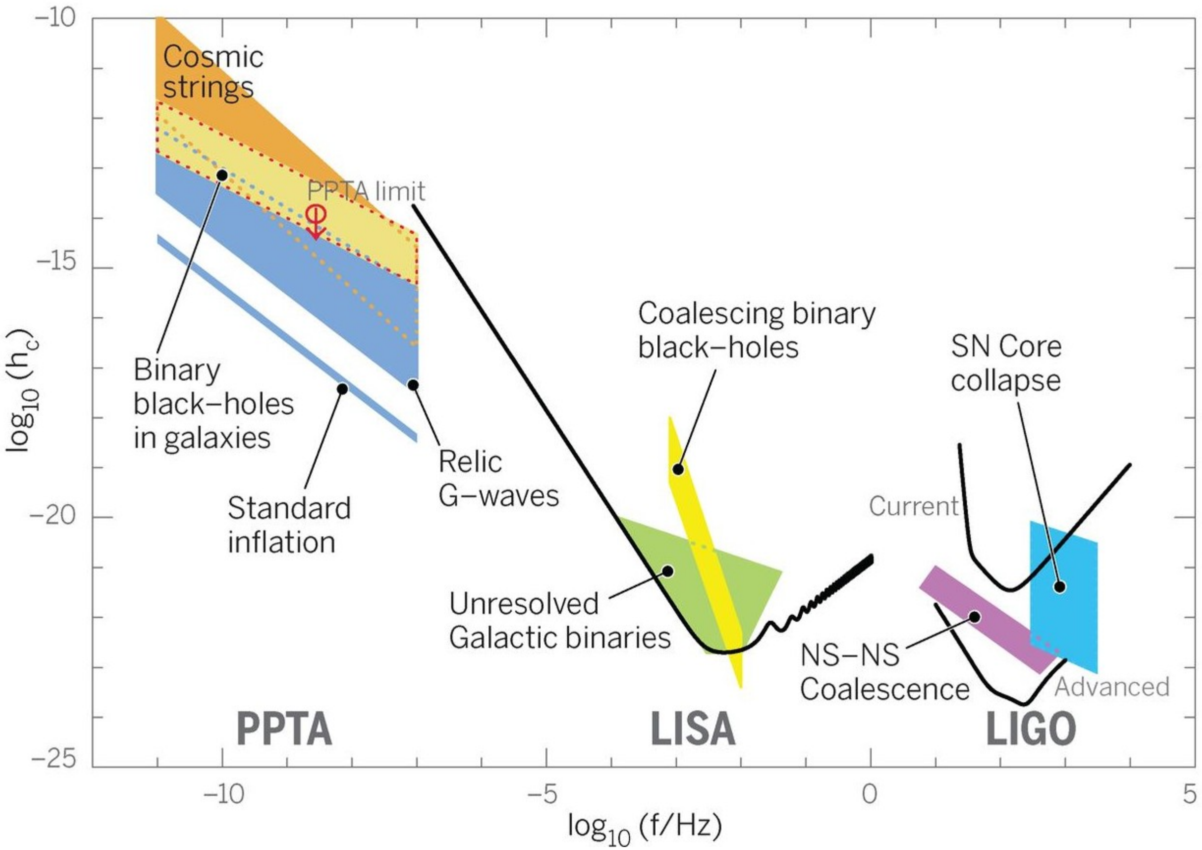
[Blandford 15]



APOGEE

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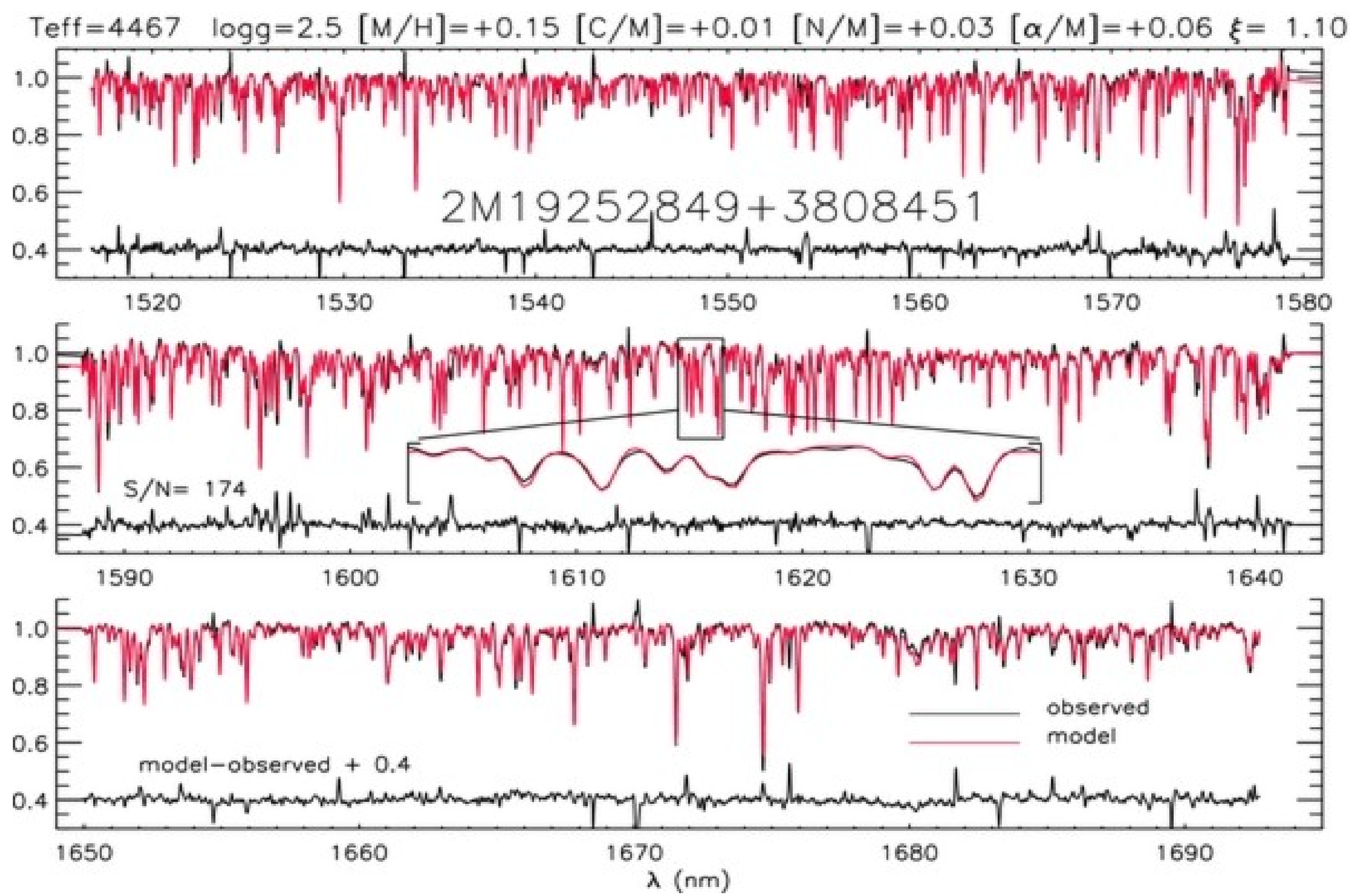
- Galactic evolution: Multi-epoch IR spectra R~20,000, ~10^5 stars, high S/N [Majewski+ 17].
- MS, RG and RC stars, M~1 M_{Sun}, most of MW disk [Zasowski+ 13].
- ASPCAP [Perez+ 16] ⇒ T_{eff}, log(g), [Fe/H], **RVs**. RC catalog [Bovy+ 14]. The Cannon [Ness+ 15,16].

SDSS DR 10



APOGEE

- Galactic evolution: Multi-epoch IR spectra R~20,000, $\sim 10^5$ stars, high S/N [Majewski+ 17].
- MS, RG and RC stars, $M \sim 1\ M_{Sun}$, most of MW disk [Zasowski+ 13].
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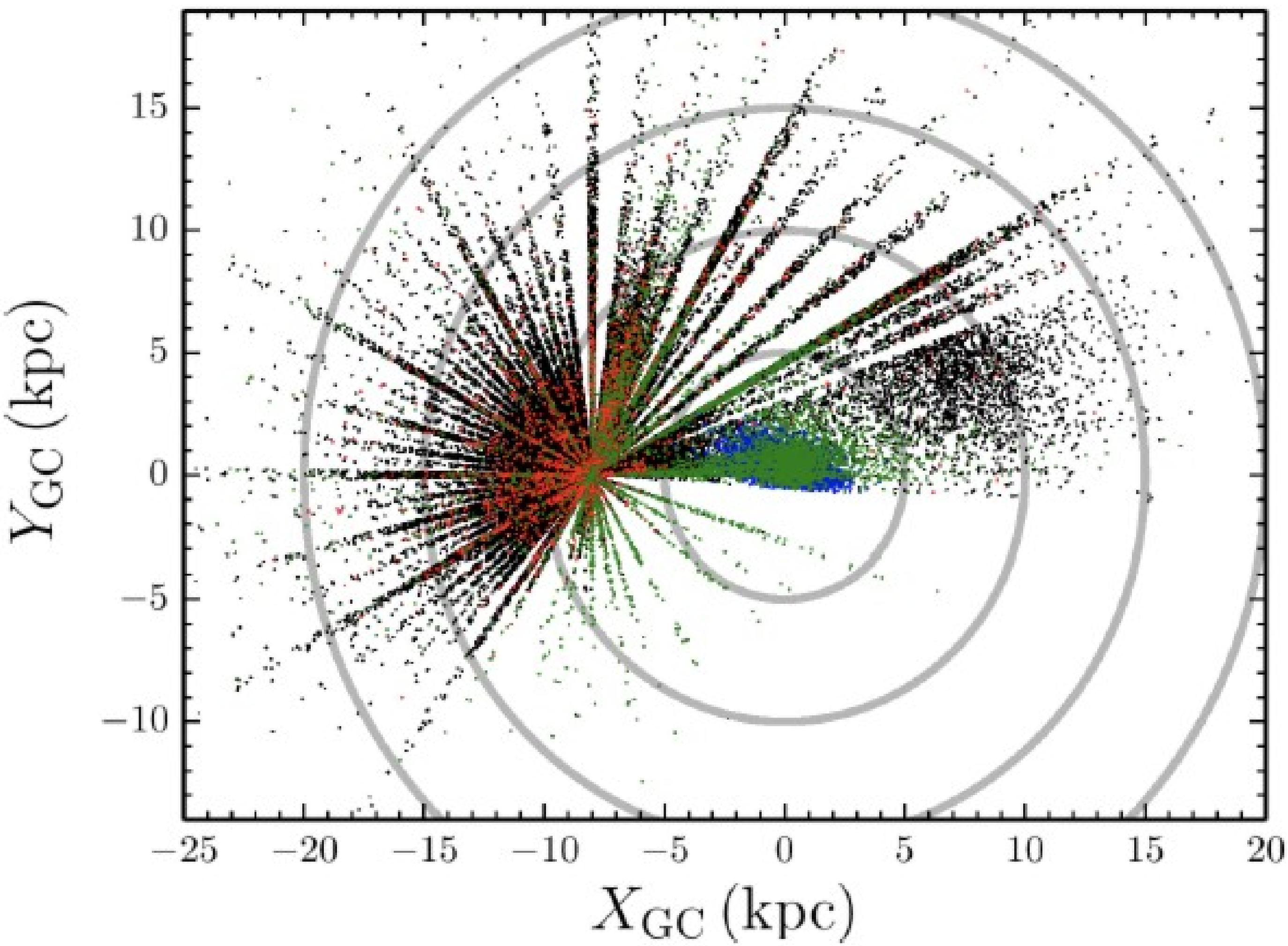
Majewski+ 17



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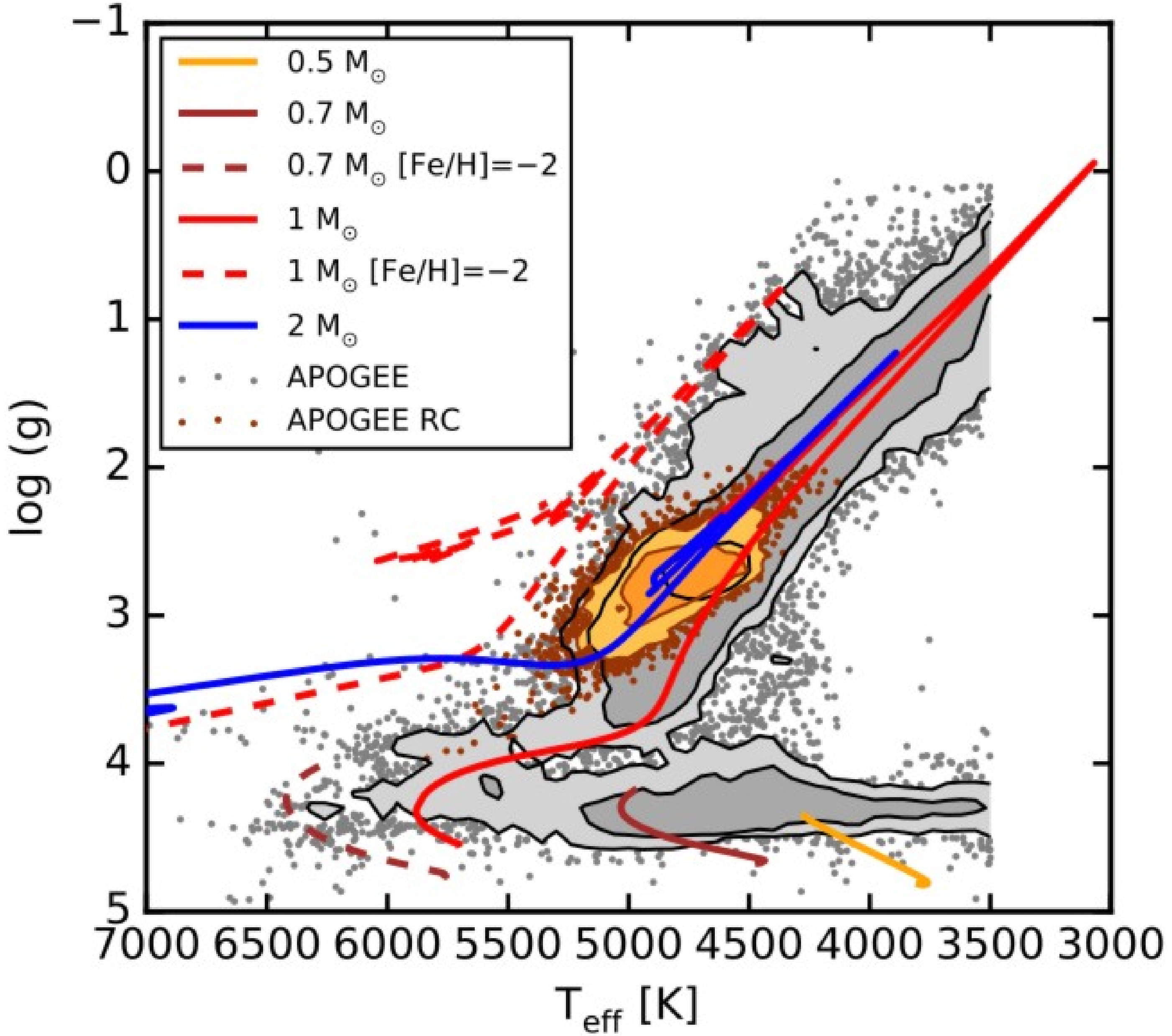


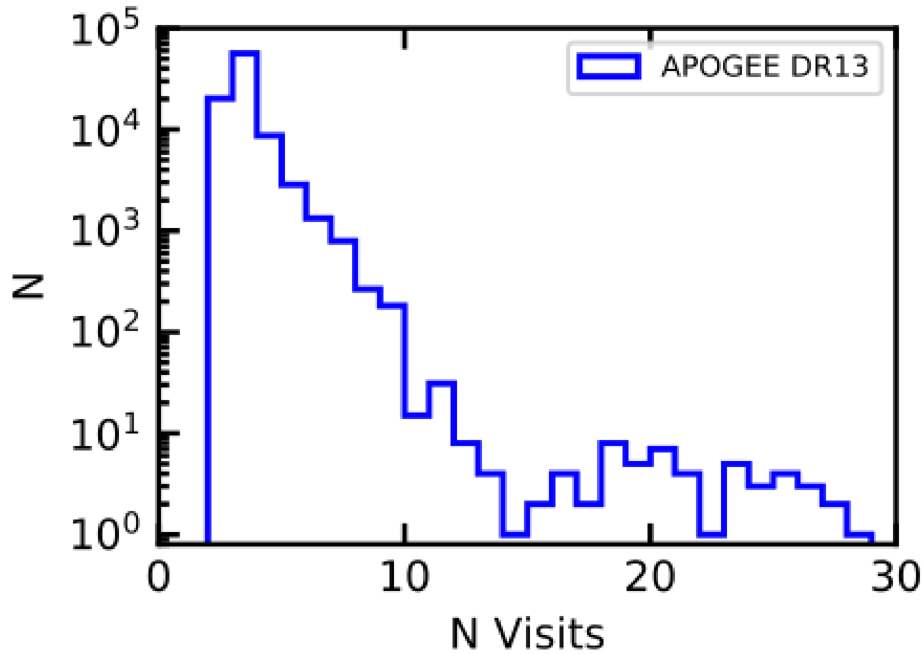
APOGEE: ΔRV_{max} vs. log(g)

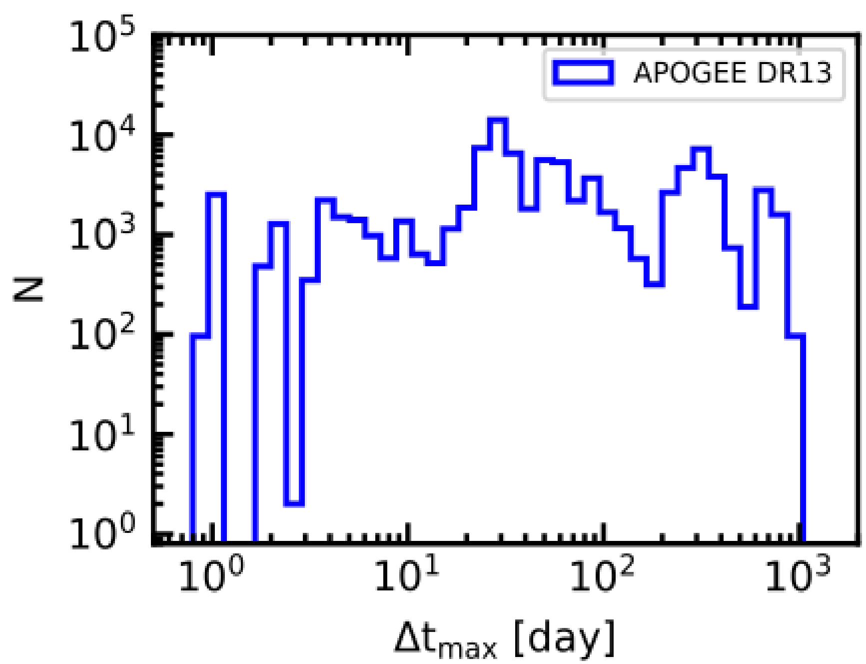
Carles Badenes
IAC 2/5/18

- 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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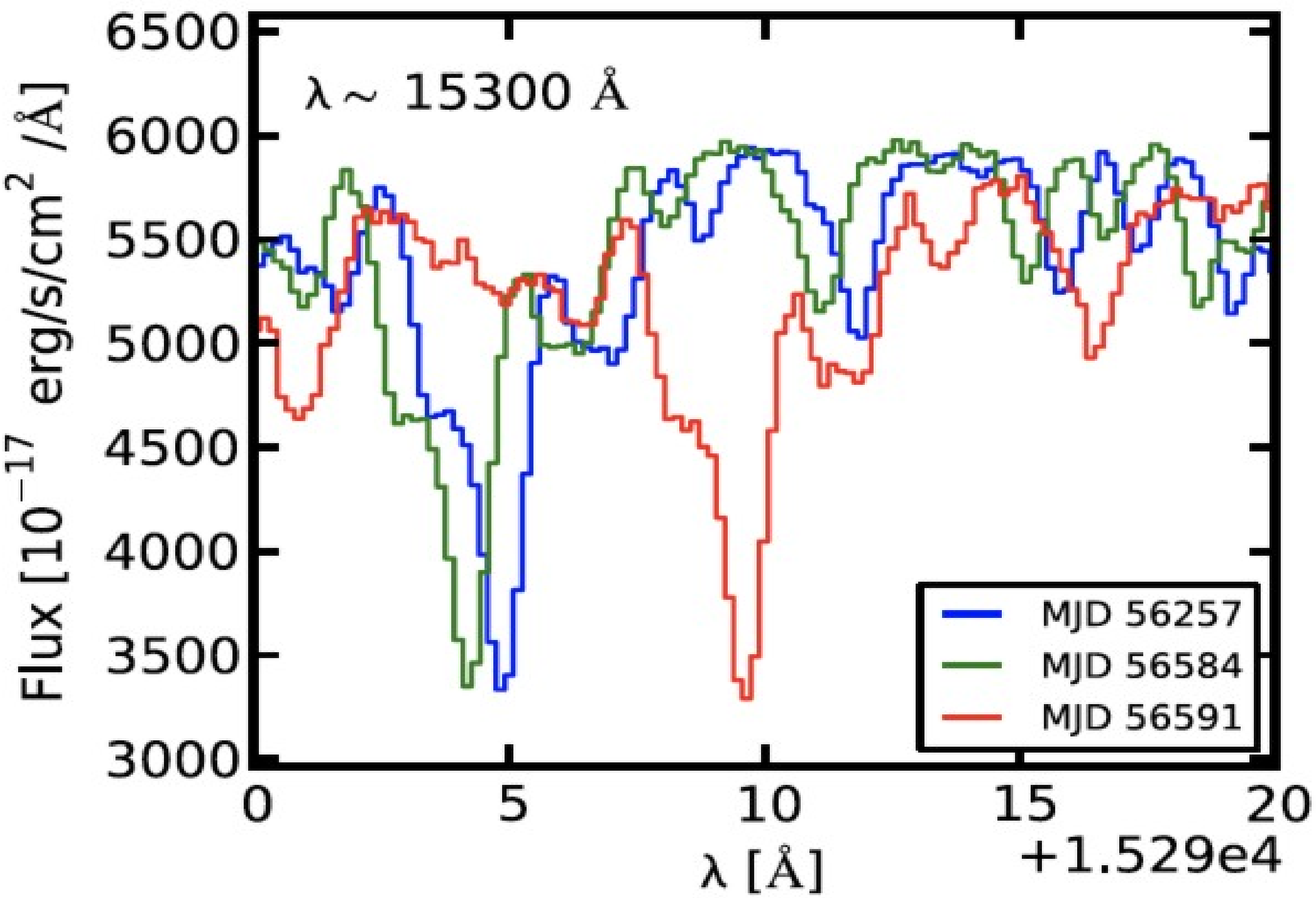

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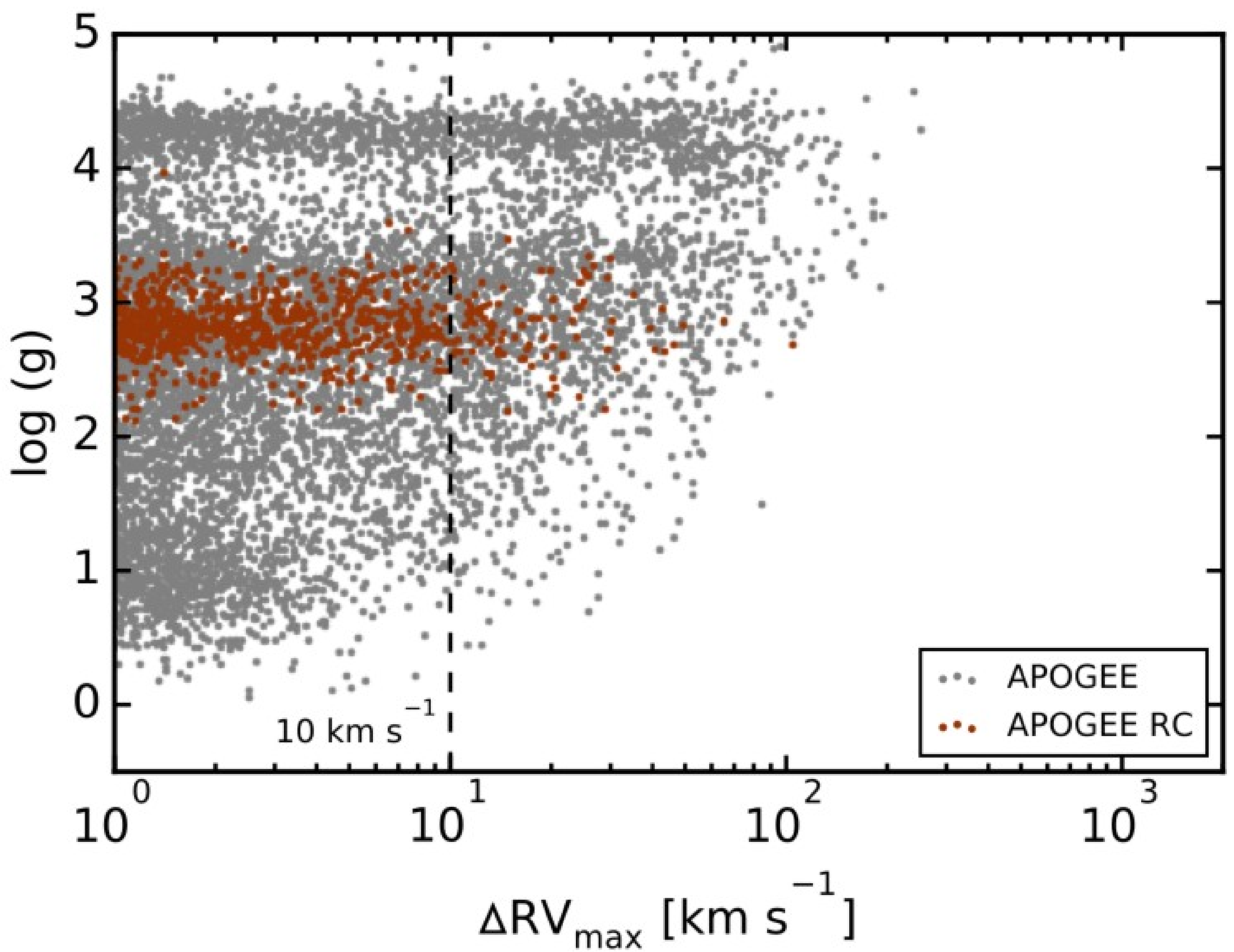

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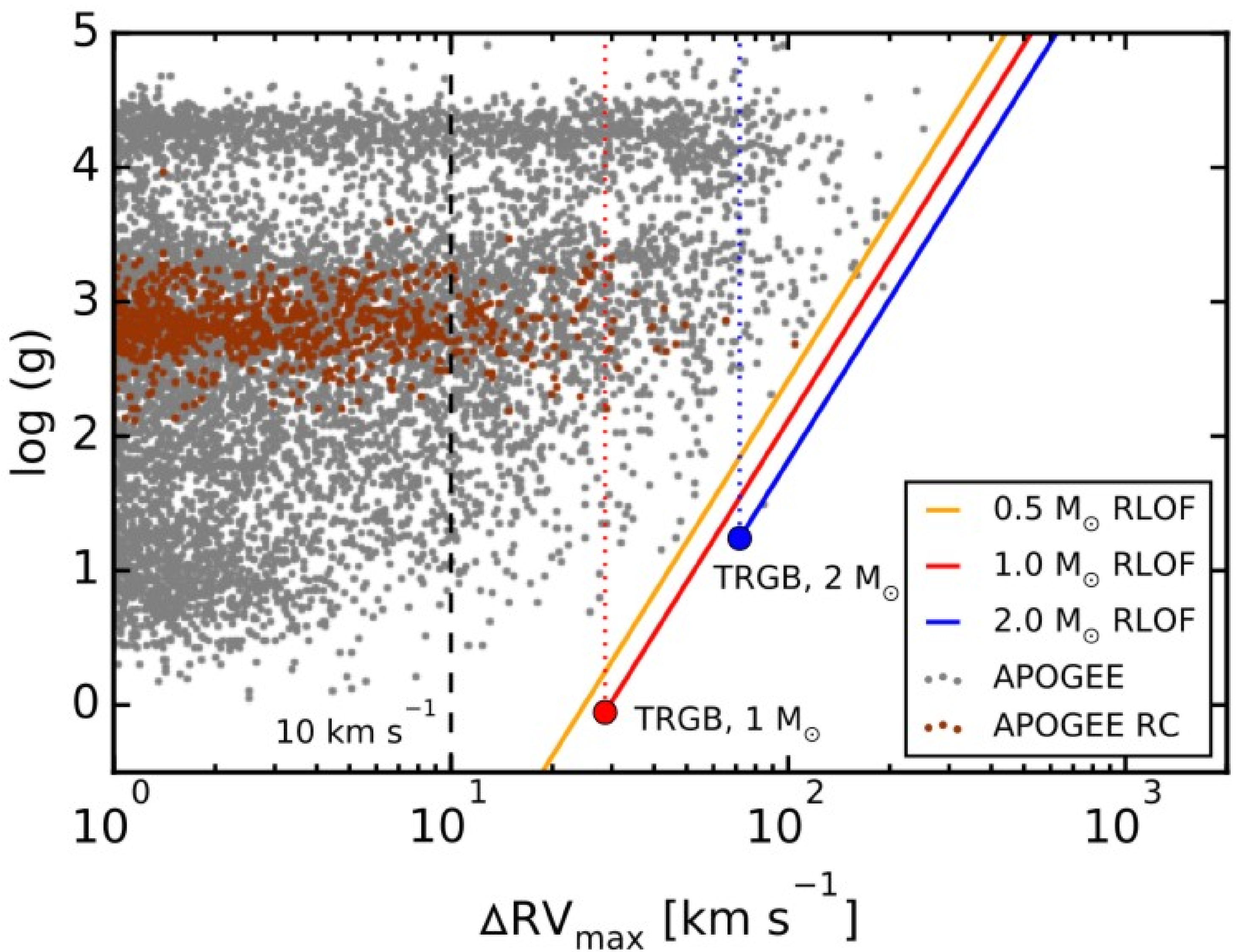

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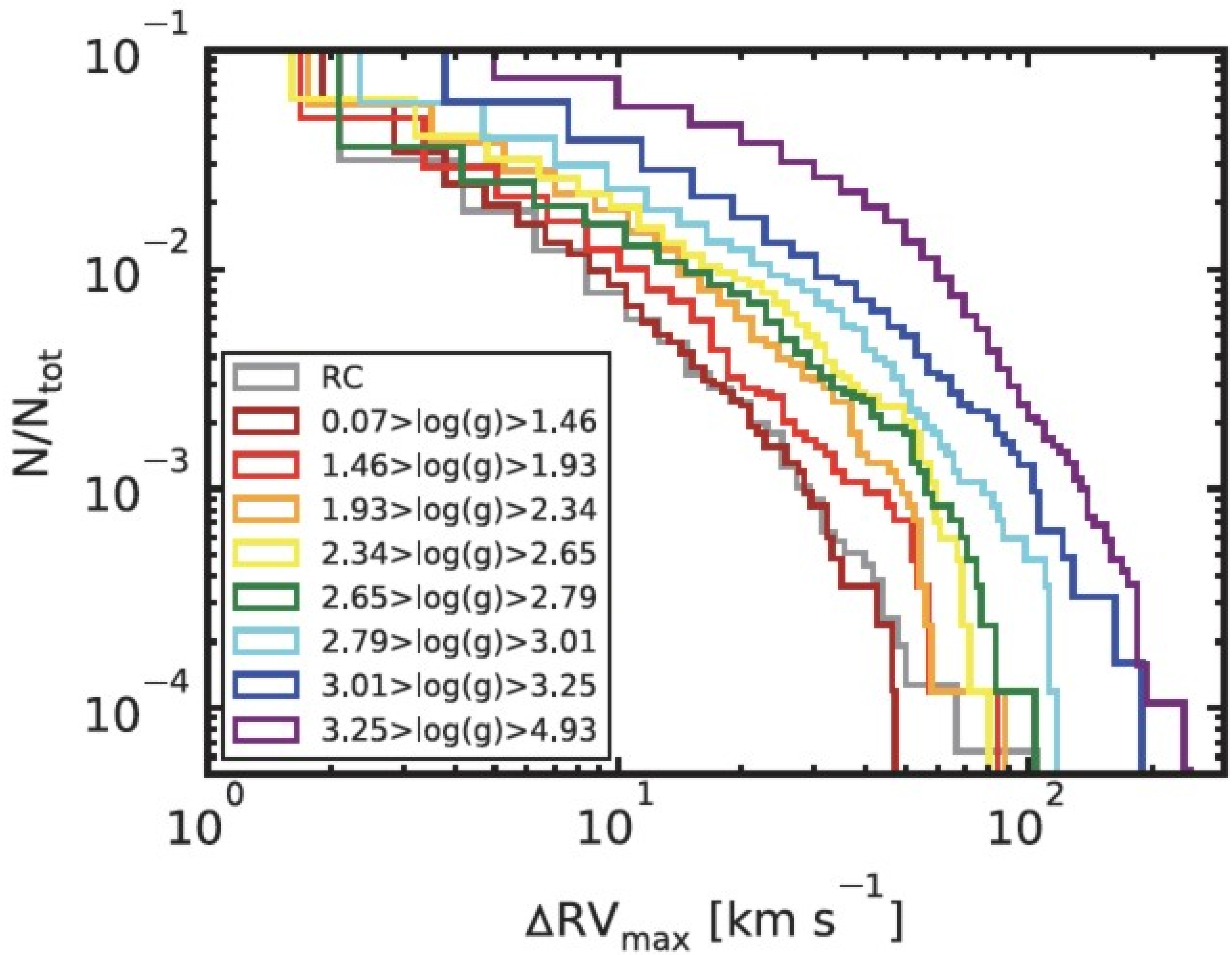

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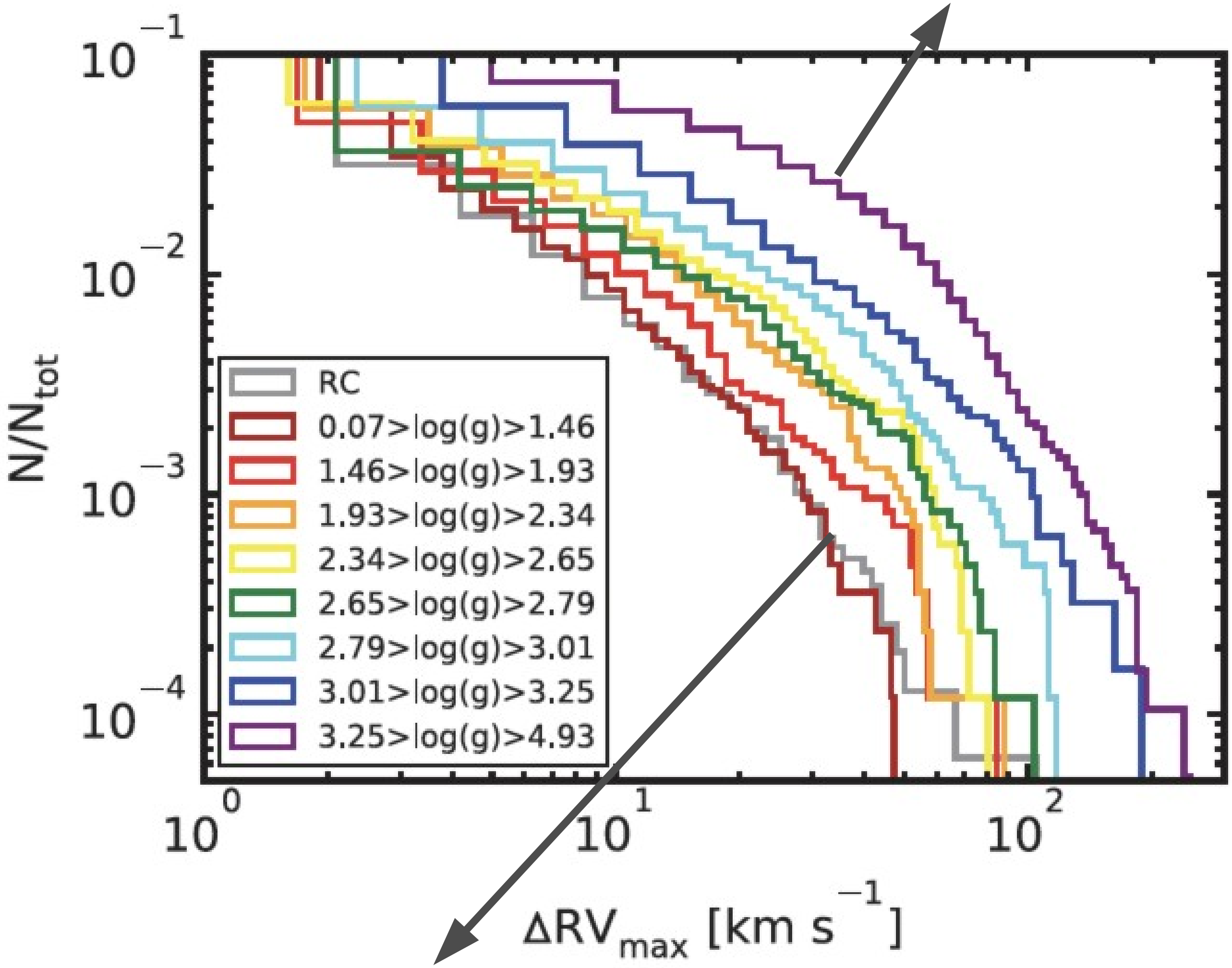
MS & subgiants: higher ΔRV_{max}



TRGB and RC have similar ΔRV_{max} distributions

APOGEE: ΔRV_{max} vs. log(g)

Carles Badenes
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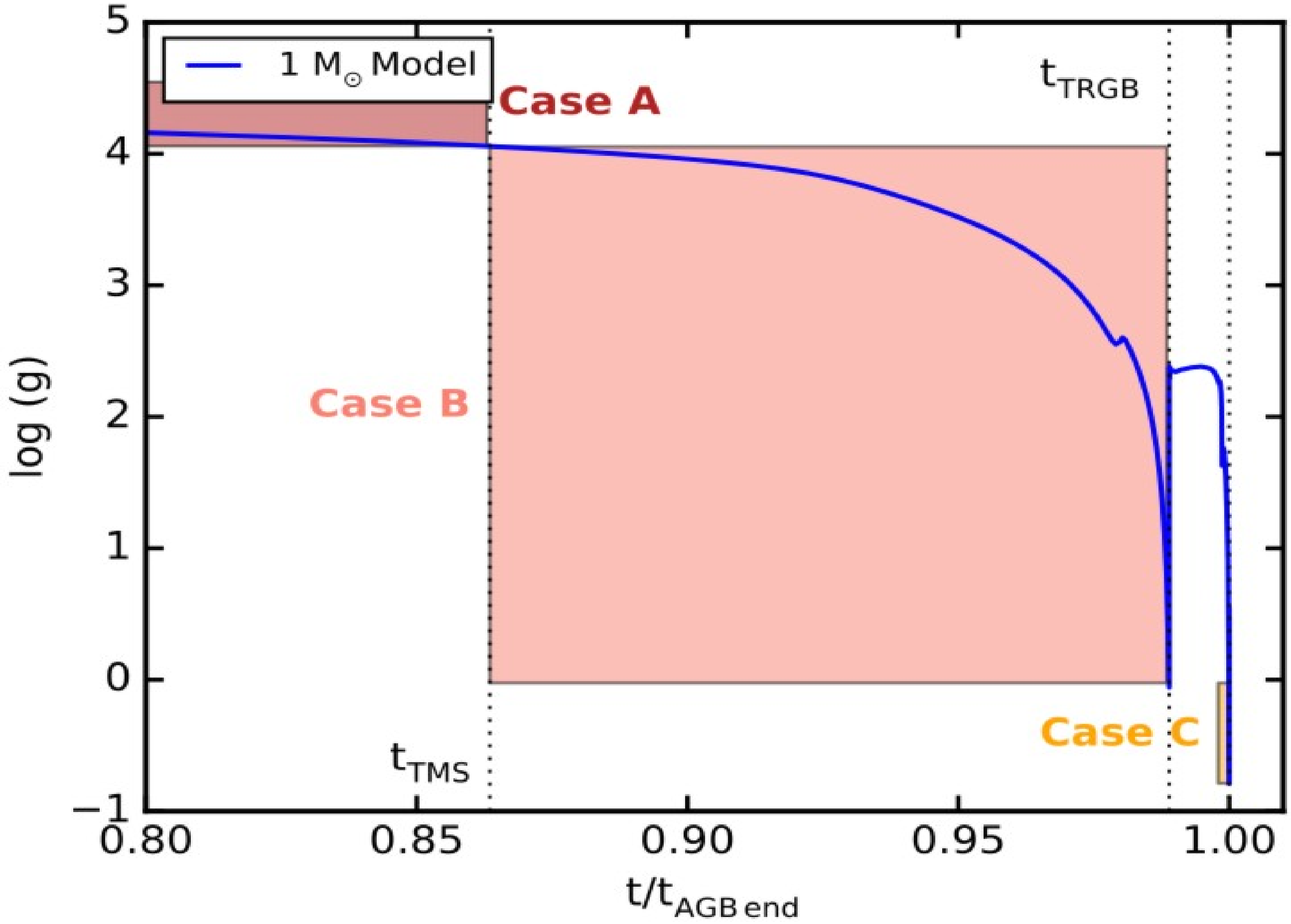

TRGB and RC have similar ΔRV_{max} distributions

APOGEE: ΔRV_{max} vs. log(g)

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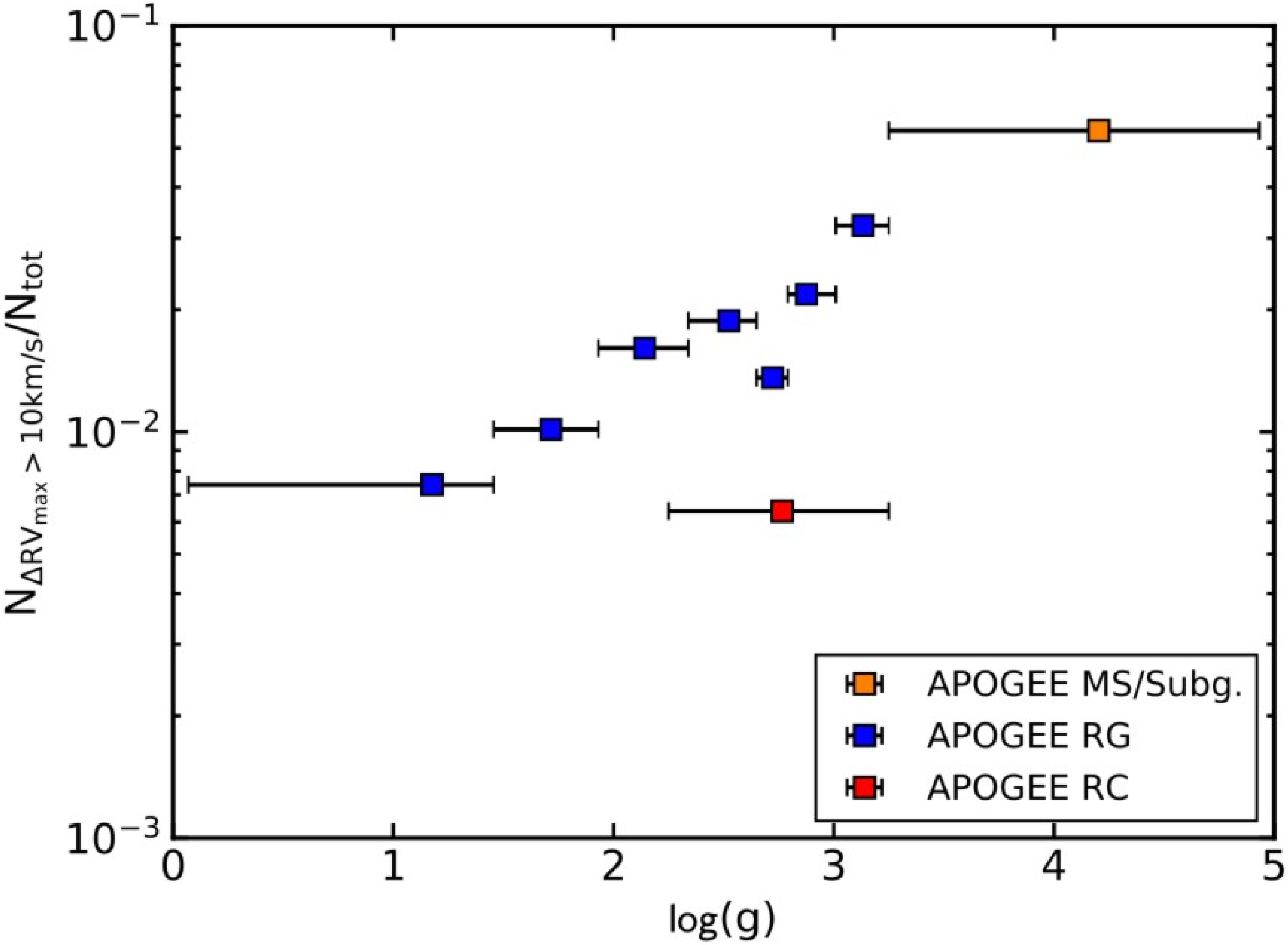
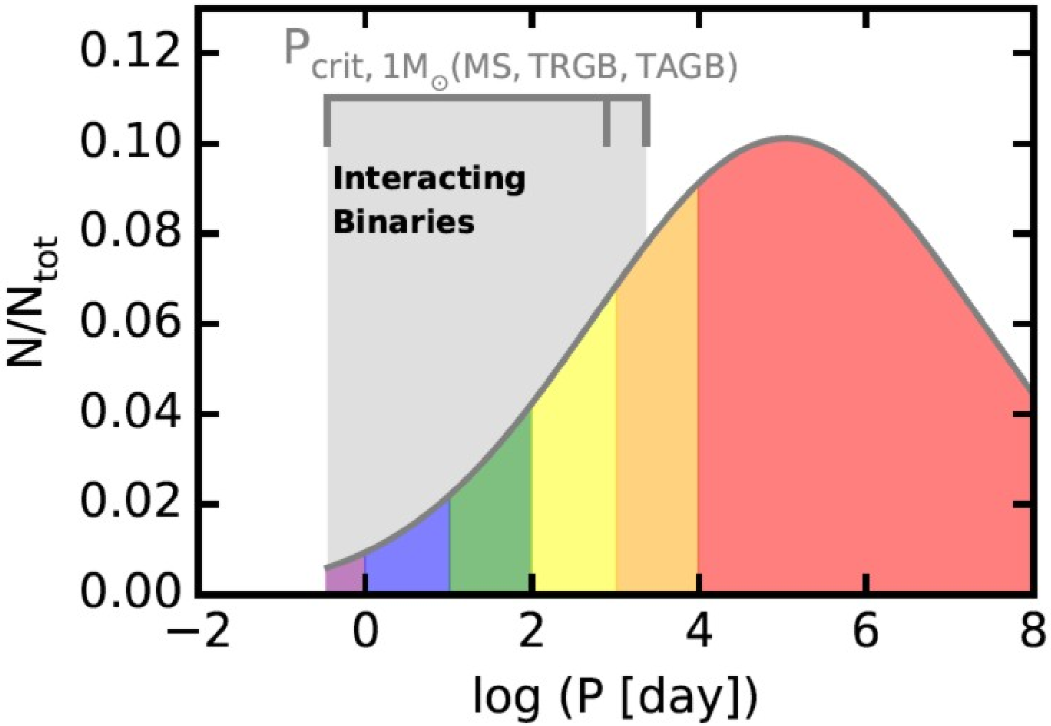
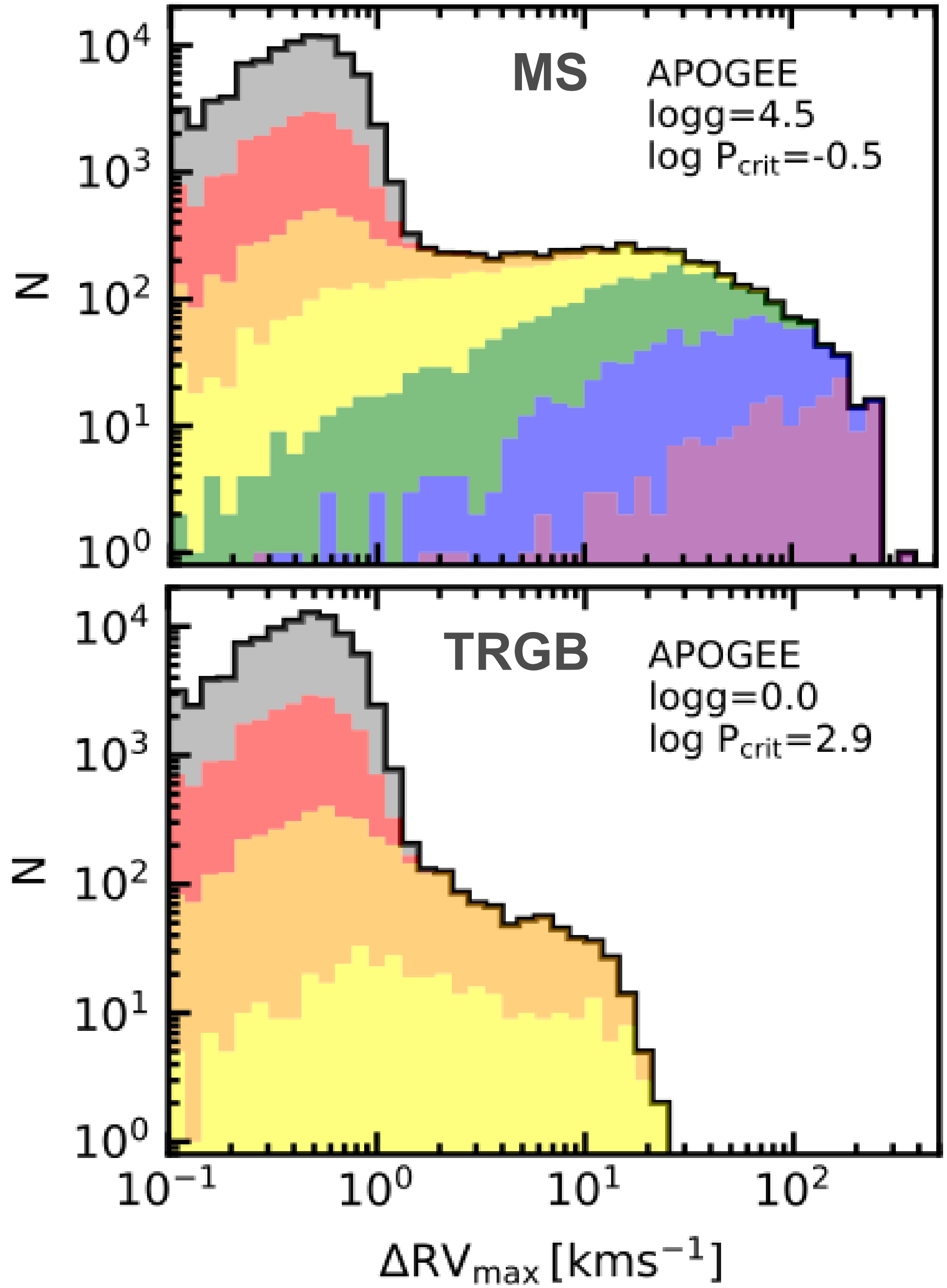
- Fraction of systems with ΔRV_{max} > 10 km/s.
- Clear descending trend, but contamination from RC at log(g)~2.8.
- Attrition of high ΔRV_{max} (short P) systems: 88% systems in the MS are gone in the RC.
- Observational constraint on **Case B mass transfer**.



APOGEE: Models for ΔRV_{max}

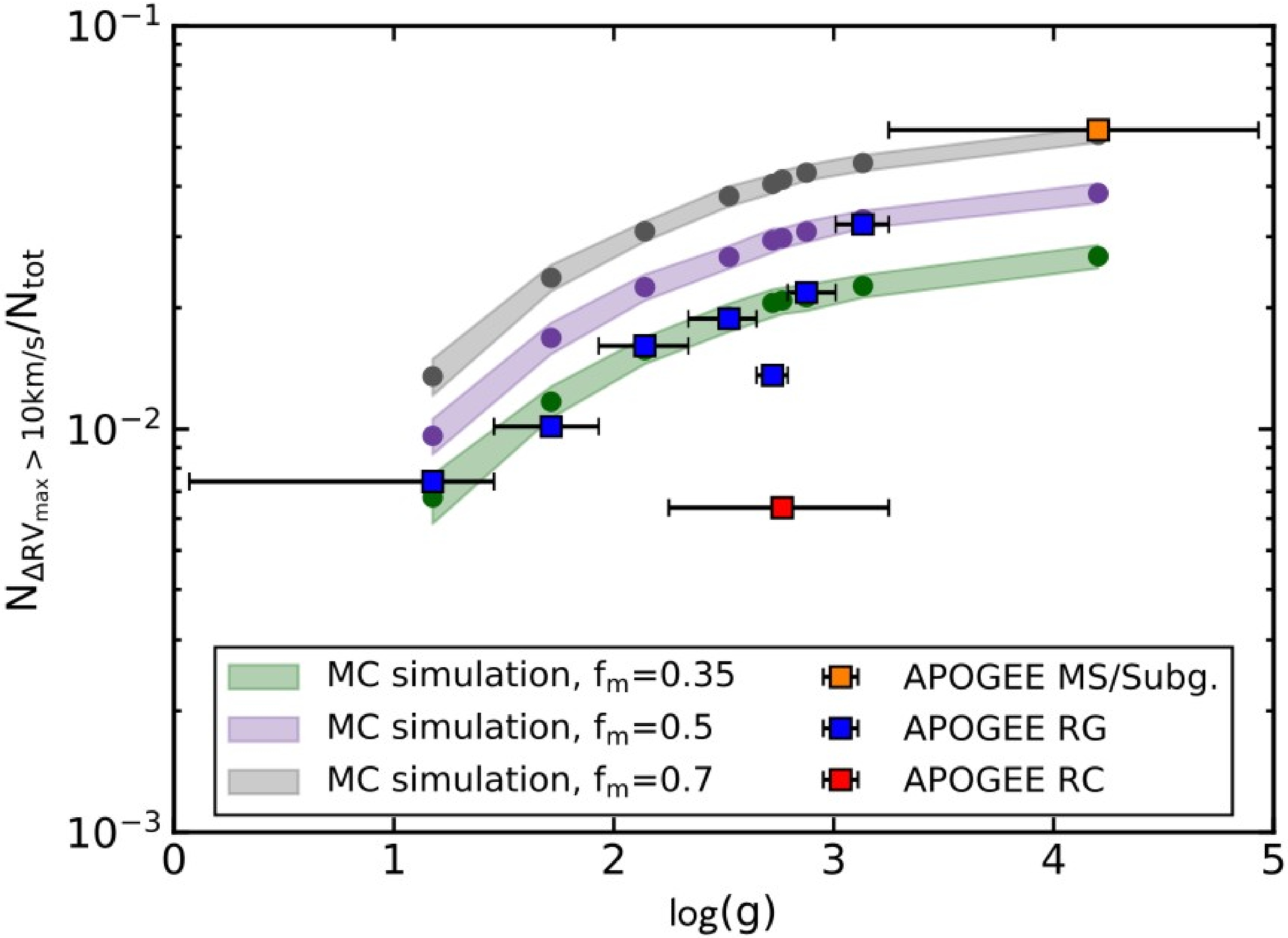


- Monte Carlo models for ΔRV_{max} [Badenes & Maoz 12, Maoz+ 12].
- Assume M = 1 $M_{Sun,}$ lognormal P, flat q, tidal circularization [Verbunt & Phinney 95]. Parameters: f_m, log(g) (⇒ P_{crit}), N.



APOGEE: ΔRV_{max} vs. log(g)

- 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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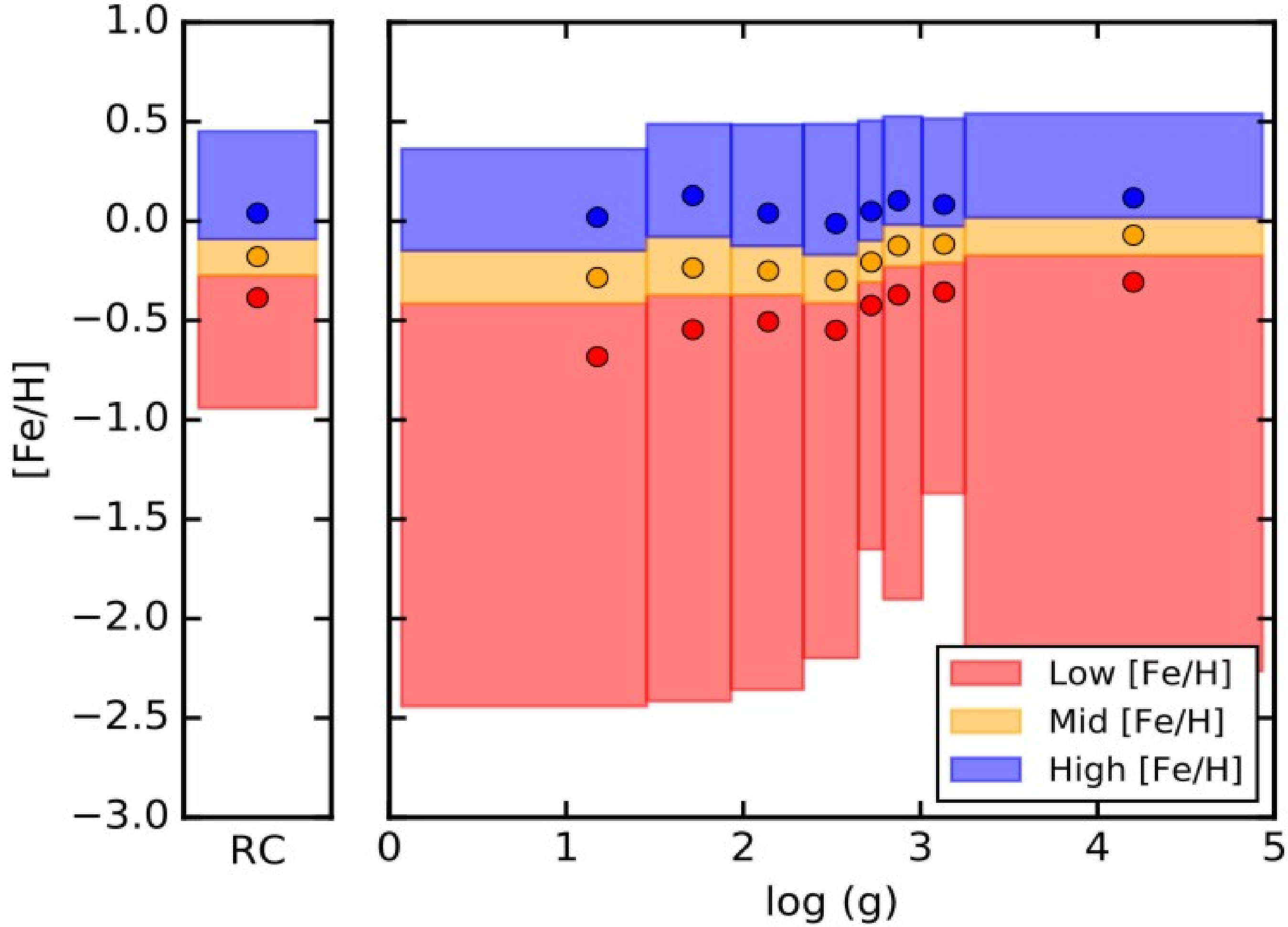
- APOGEE view of MW disk ⇒ [Fe/H].
- ΔRV_{max} distribution in [Fe/H] terciles: low ~ -0.5; high ~0.0.



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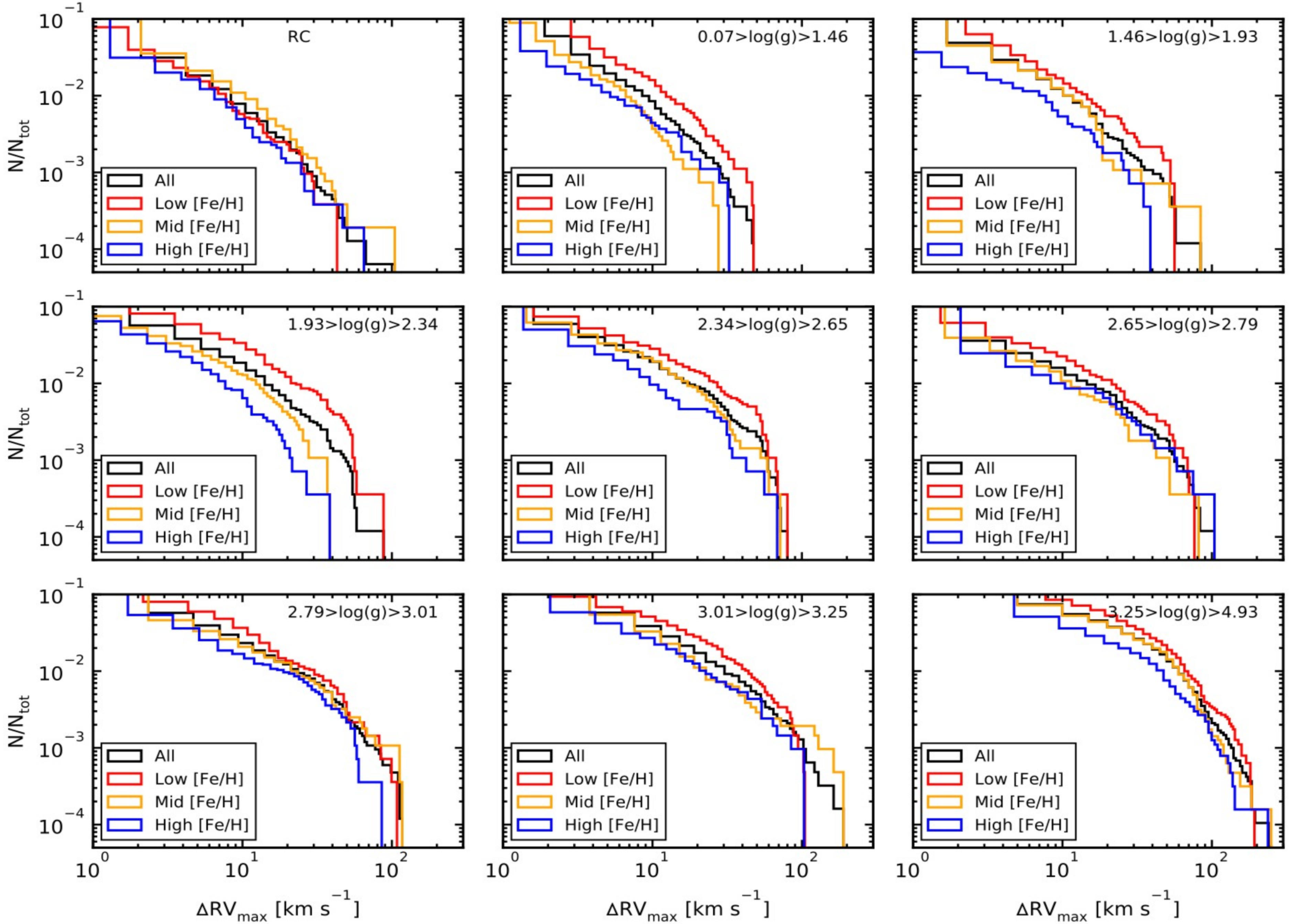
IAC 2/5/18



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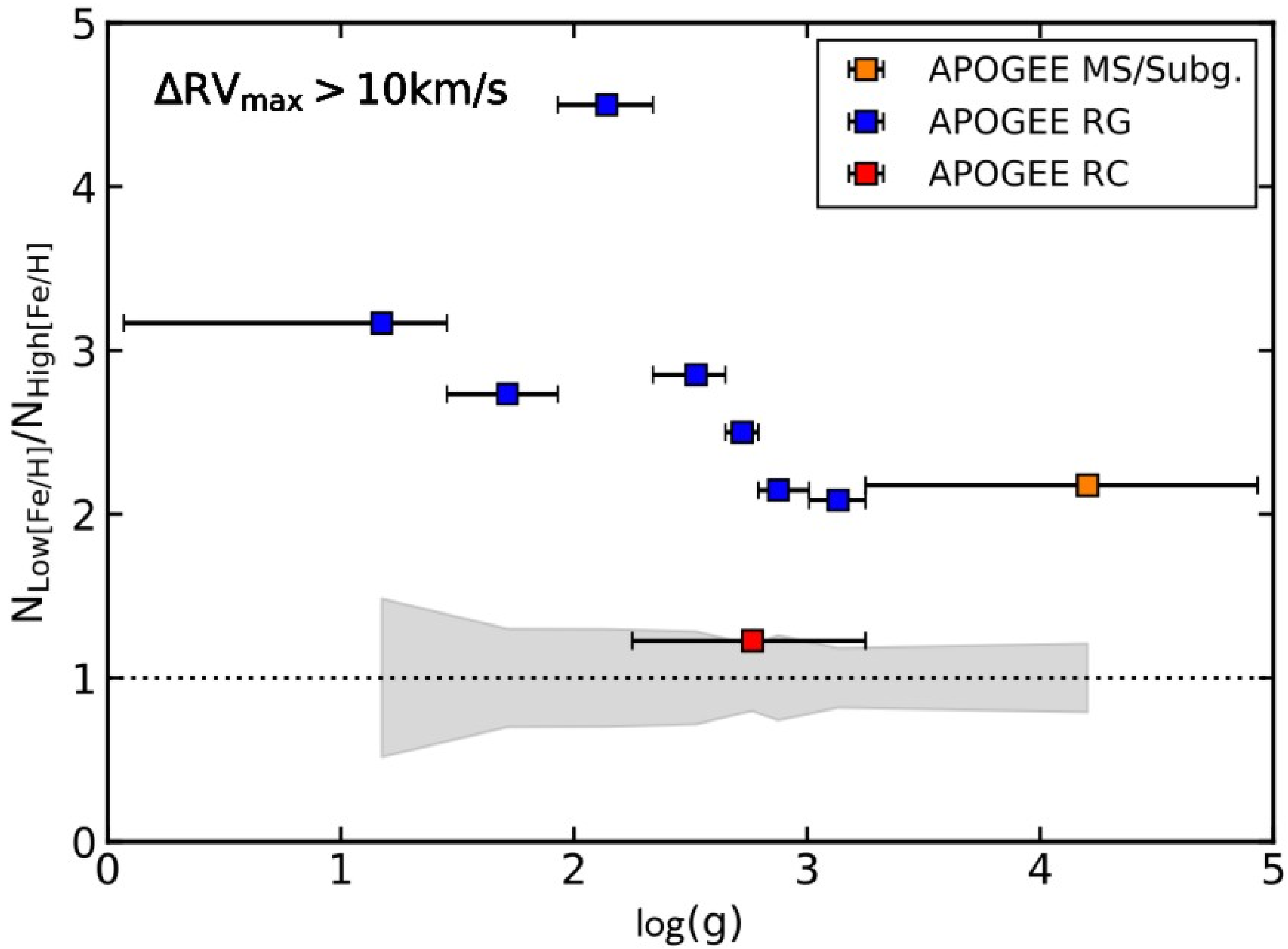
- APOGEE view of MW disk ⇒ [Fe/H].
- ΔRV_{max} distribution in [Fe/H] terciles: low ~ -0.5; high ~0.0.
- ΔRV_{max} in low [Fe/H] clearly above high [Fe/H] in all non-RC samples.
- Consistent with **f_m a factor 2-3 higher at low [Fe/H]** for close (log P < 3.3) binaries.



Outline

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- **Introduction:** Close Binaries, Why do we care and what are we looking for?
- **Data:** Radial Velocities from large spectroscopic surveys.
- **Results:** WD binaries. Multiplicity statistics vs. stellar evolution and metallicity in SDSS/APOGEE.
- **Conclusions:** Implications. Future directions: GAIA, WEAVE.

Implications

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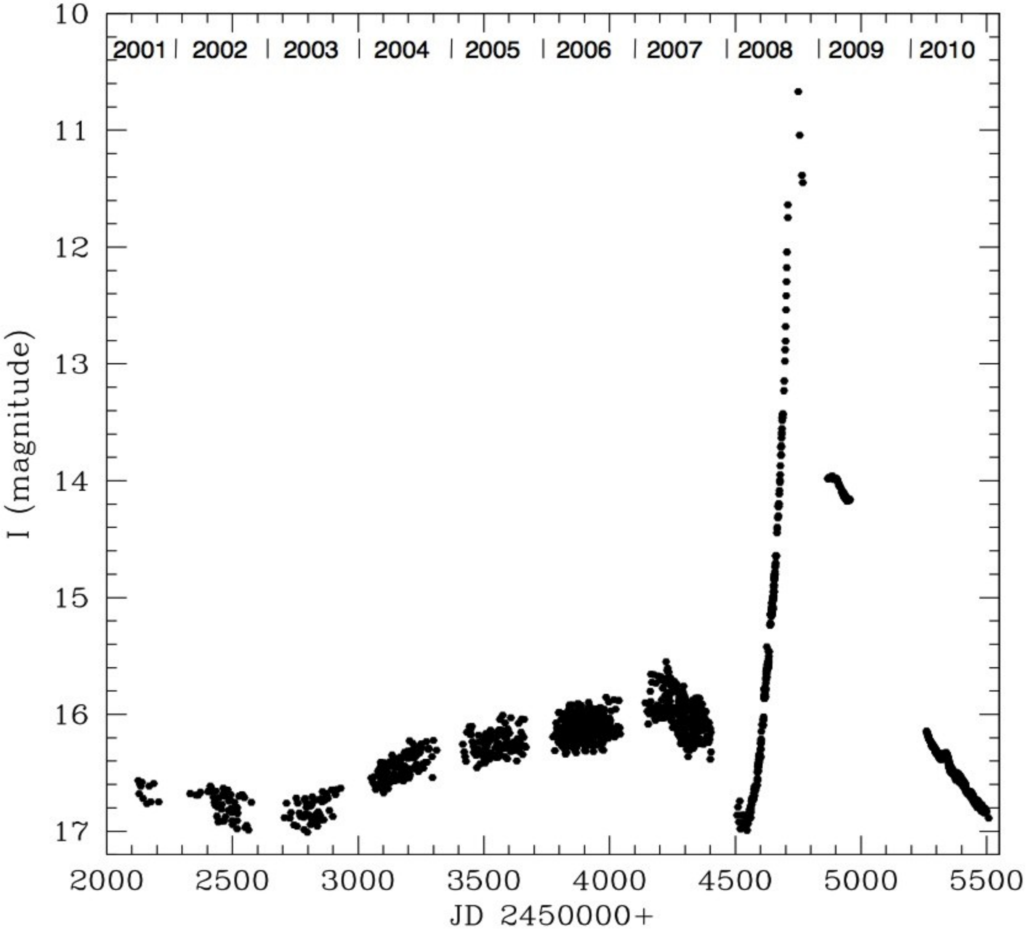
- Case B mass transfer rate ⇒ CE events, stellar mergers (LRNe), birth rate of short P systems? [Tylenda+ 13, Kochanek+ 14].
- More close binaries at low [Fe/H] ⇔ SF theory [Machida+ 09, Bate 14].
- What about BPS models in different environments, redshift evolution? [de Mink & Belczynski 15]?
- Planet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

V1309 Sco [Tylenda+ 13]



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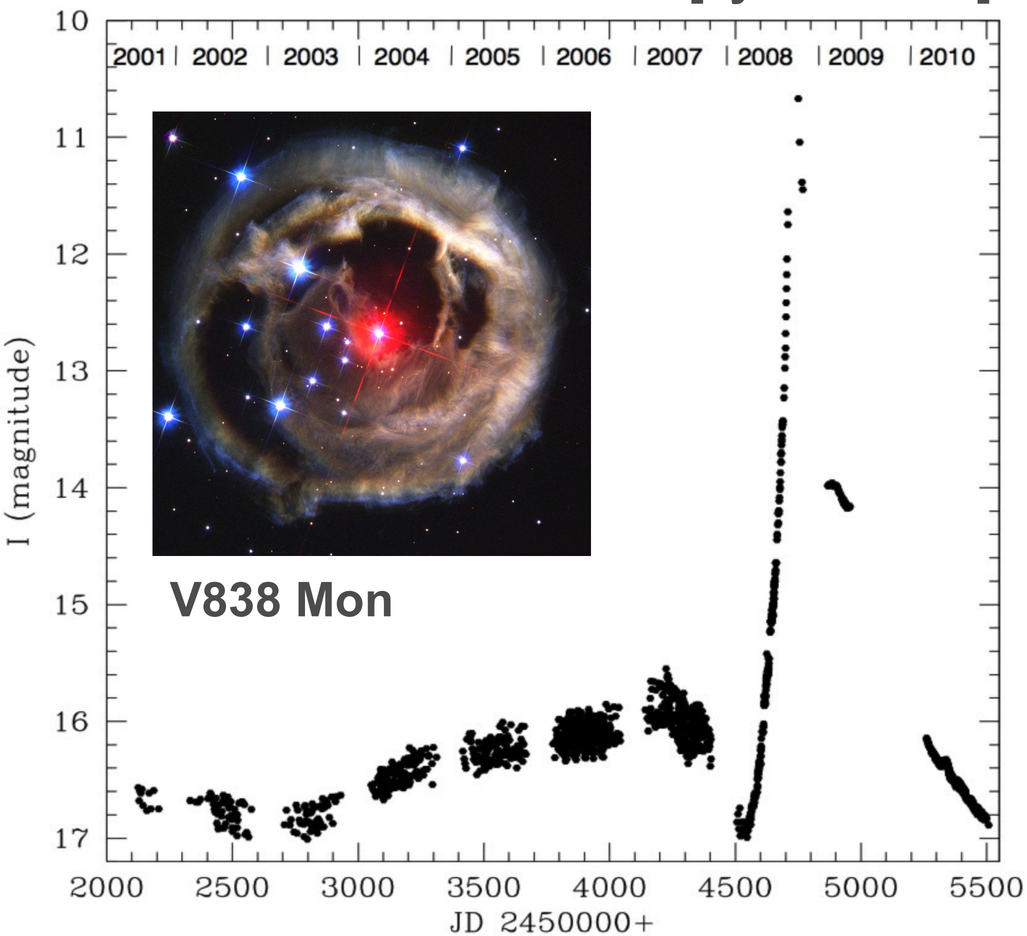

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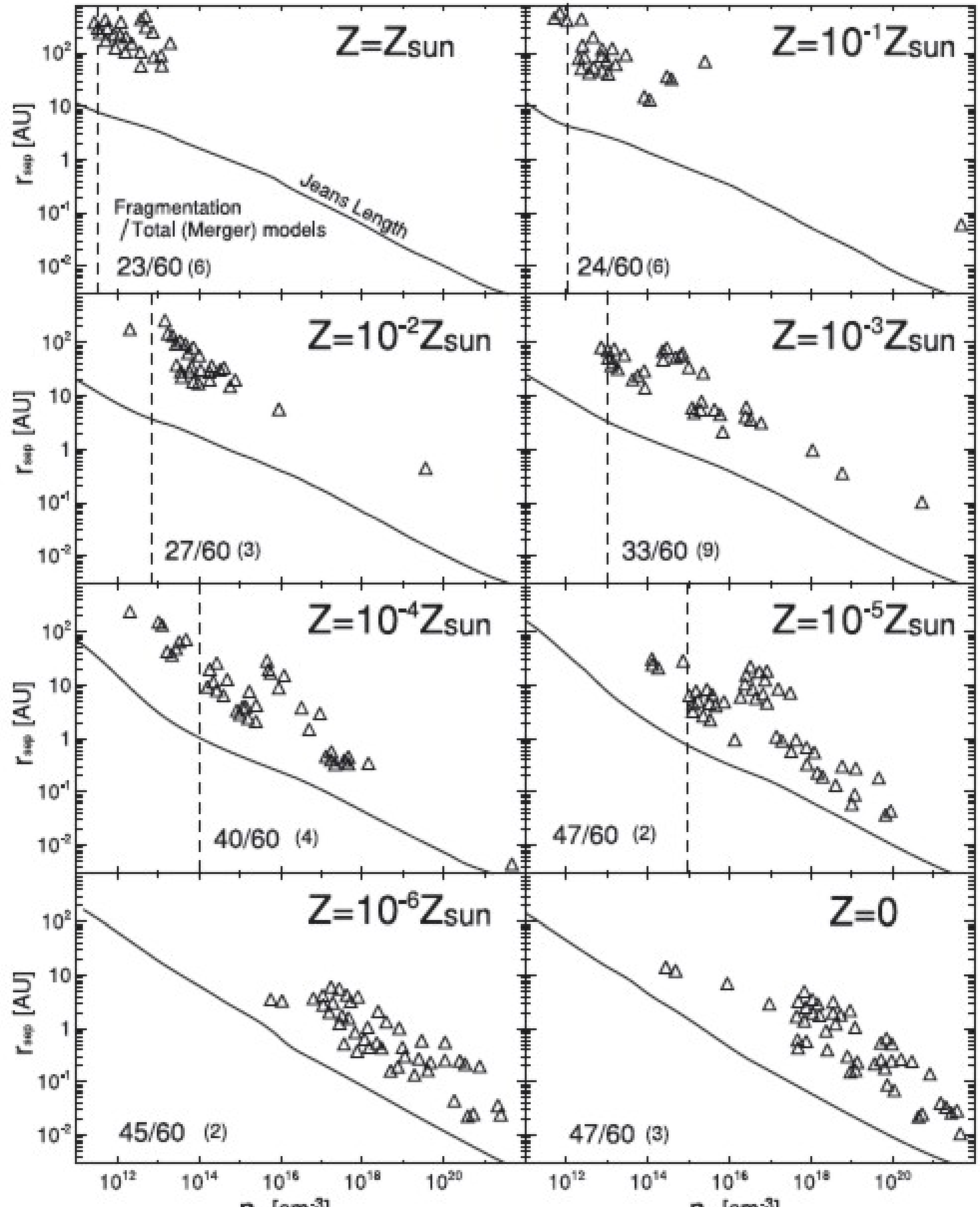
Machida+ 09



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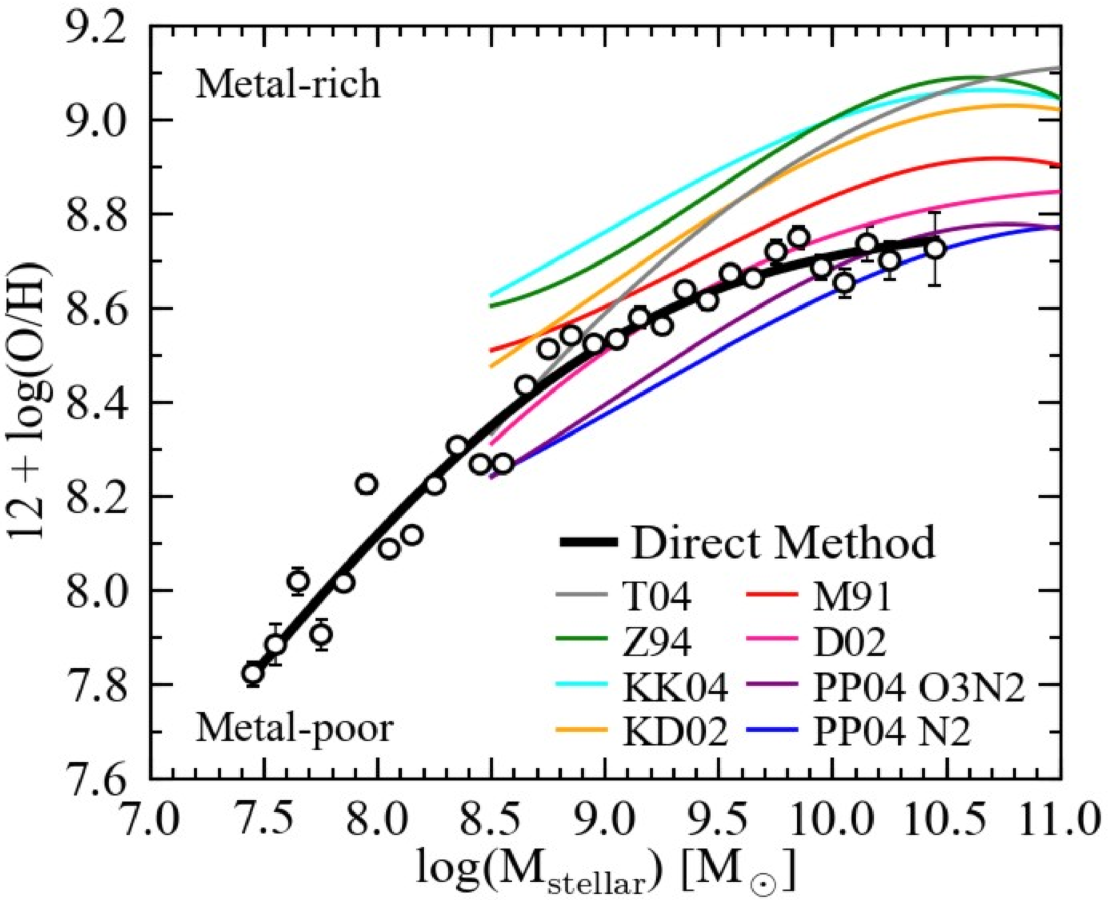
Andrews & Martini 13



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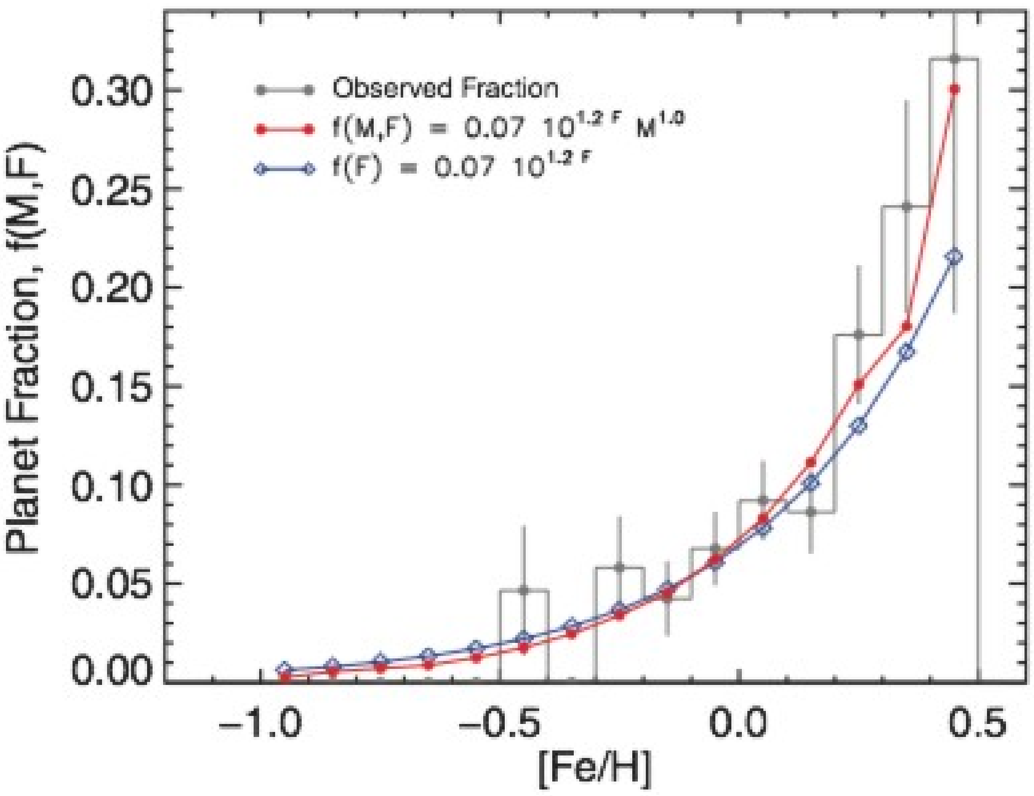
Johnson 10



Follow Up

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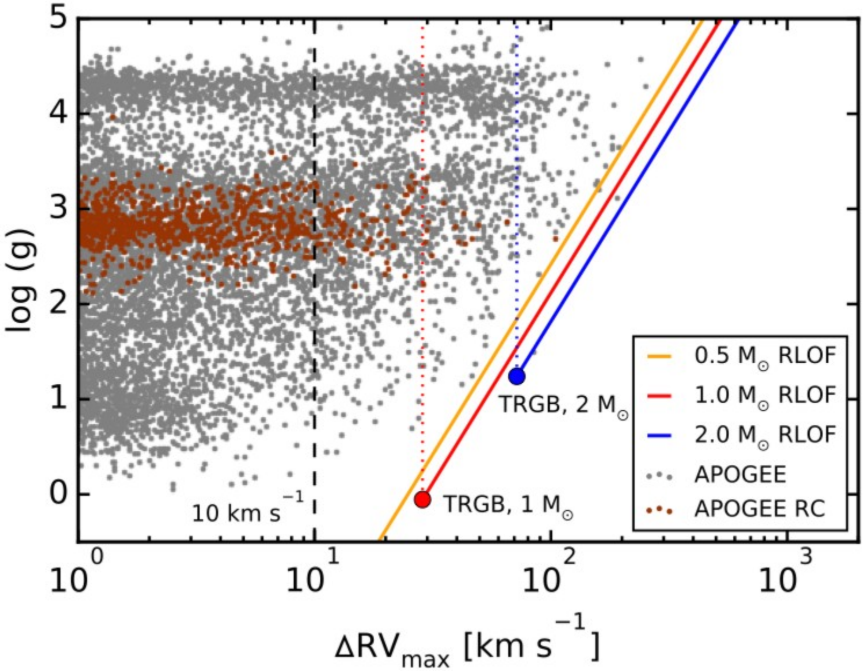
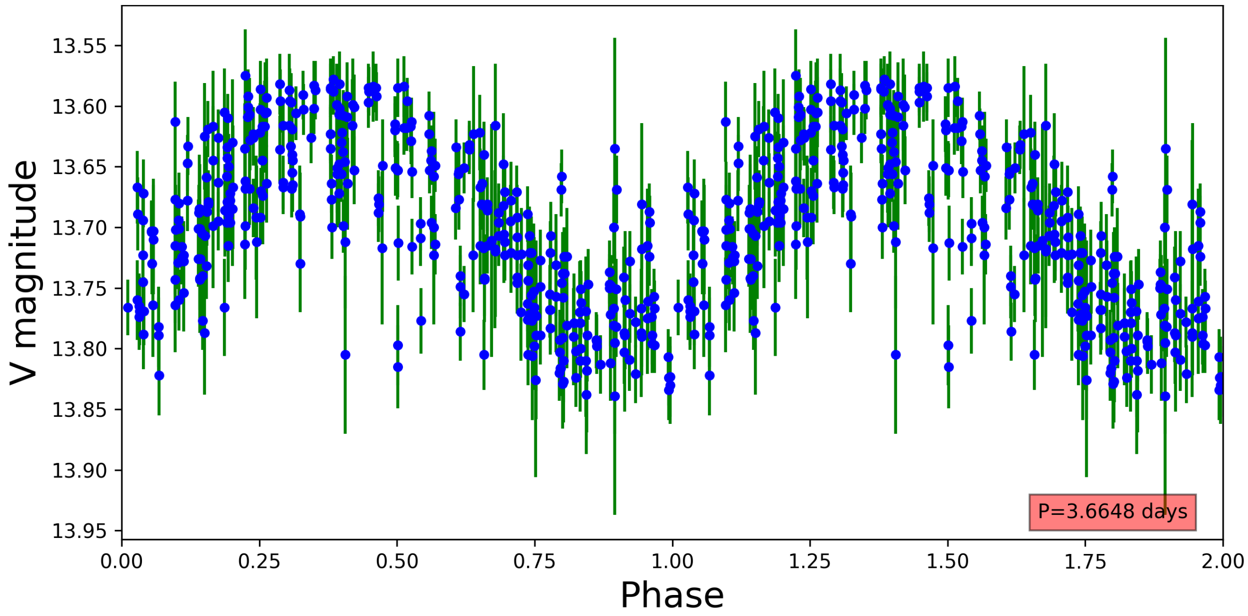


ASAS-SN



GAIA DR2

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	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	**> 1,500,000,000**	**1,142,679,769**
Number of 5-parameter sources	> 1,300,000,000	2,057,050
Number of 2-parameter sources	> 200,000,000	1,140,622,719
Sources with mean G magnitude	> 1,500,000,000	1,142,679,769
Sources with three-band photometry (G, G_{BP}, G_{RP})	> 1,100,000,000	-
Sources with radial velocities	> 6,000,000	-
Lightcurves for variable sources	> 500,000	3,194
Known asteroids with epoch data	> 13,000	-
Additional astrophysical parameters	> 150,000,000	-

GAIA

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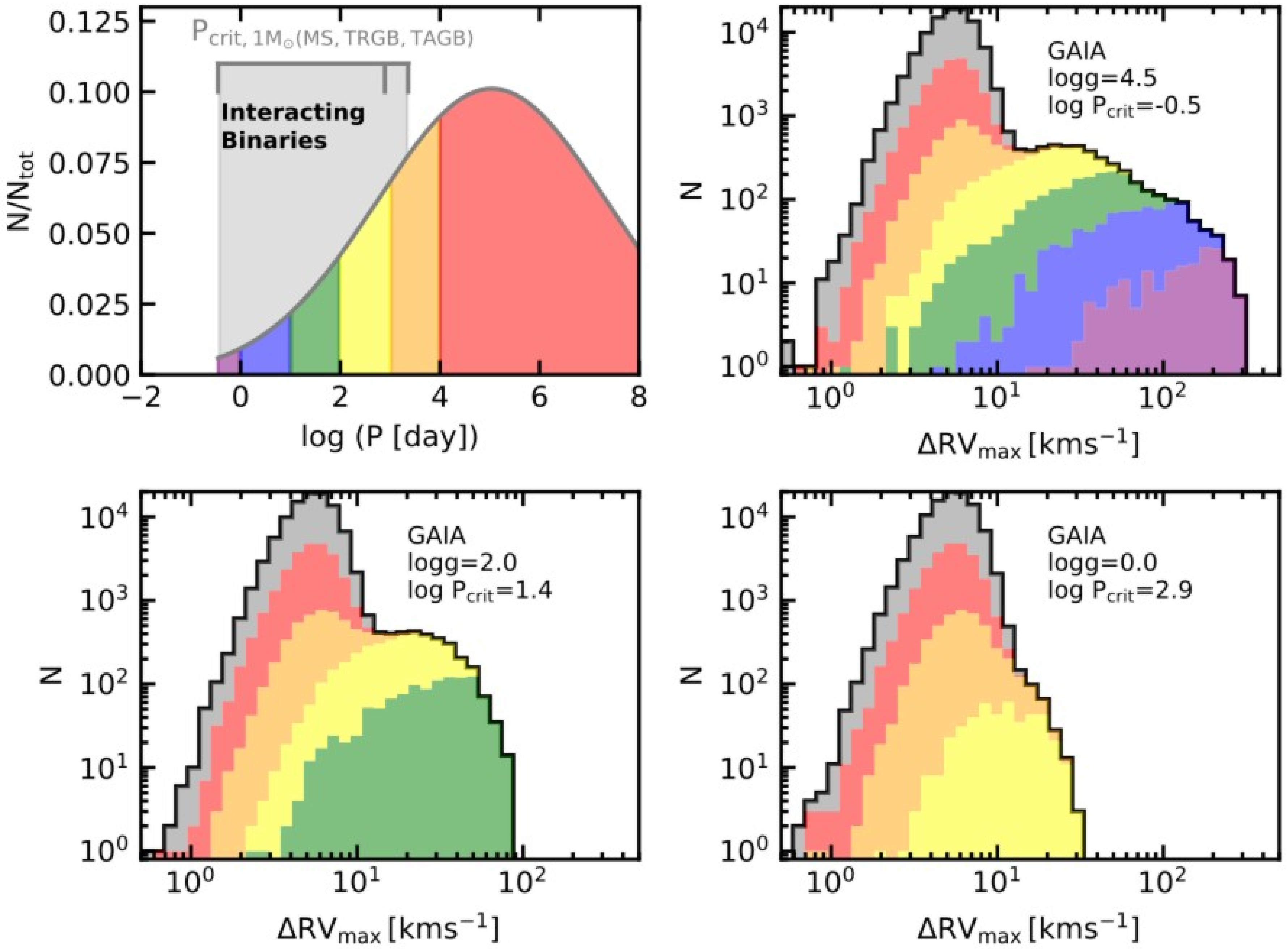

GAIA

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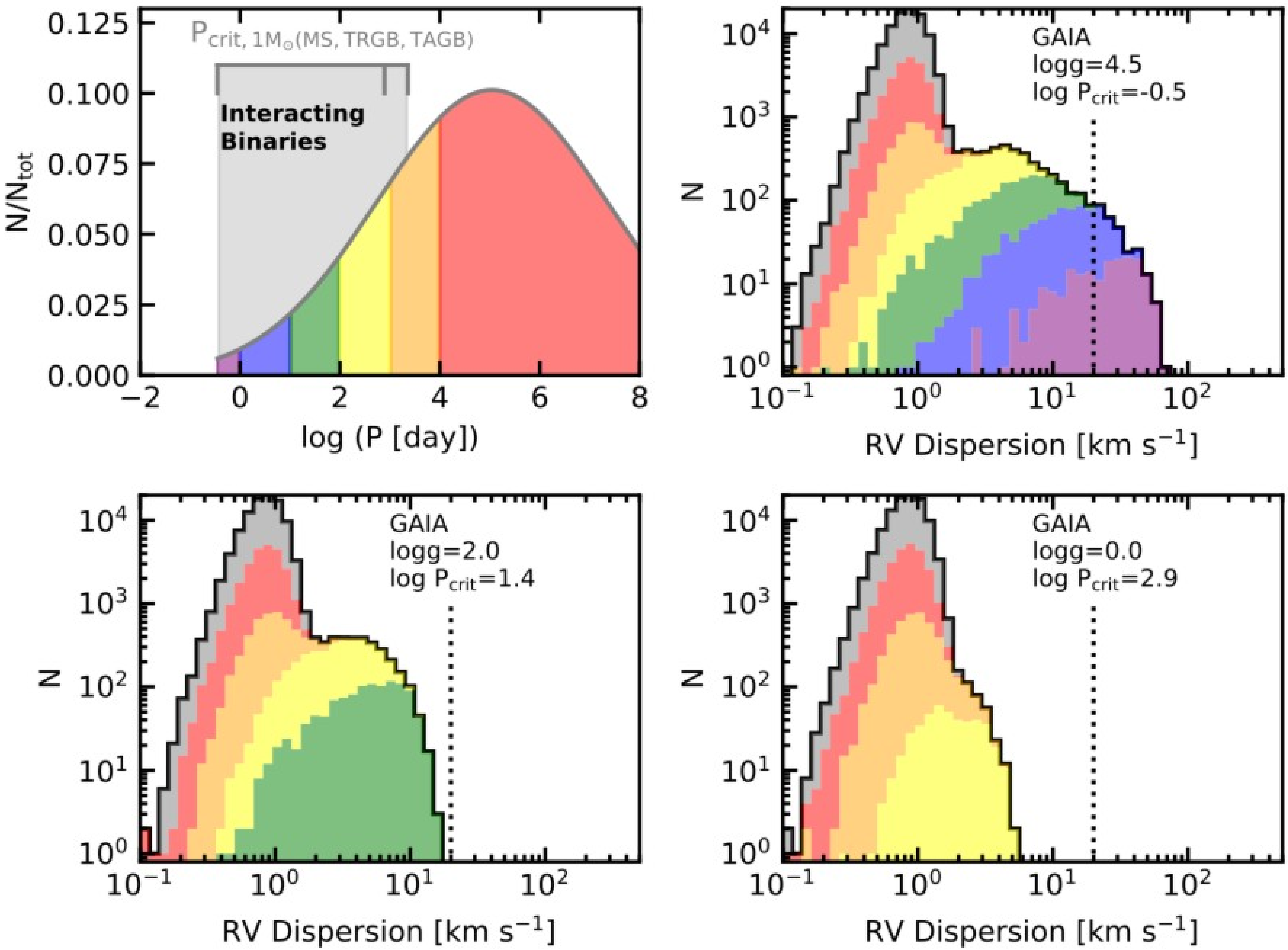

GAIA

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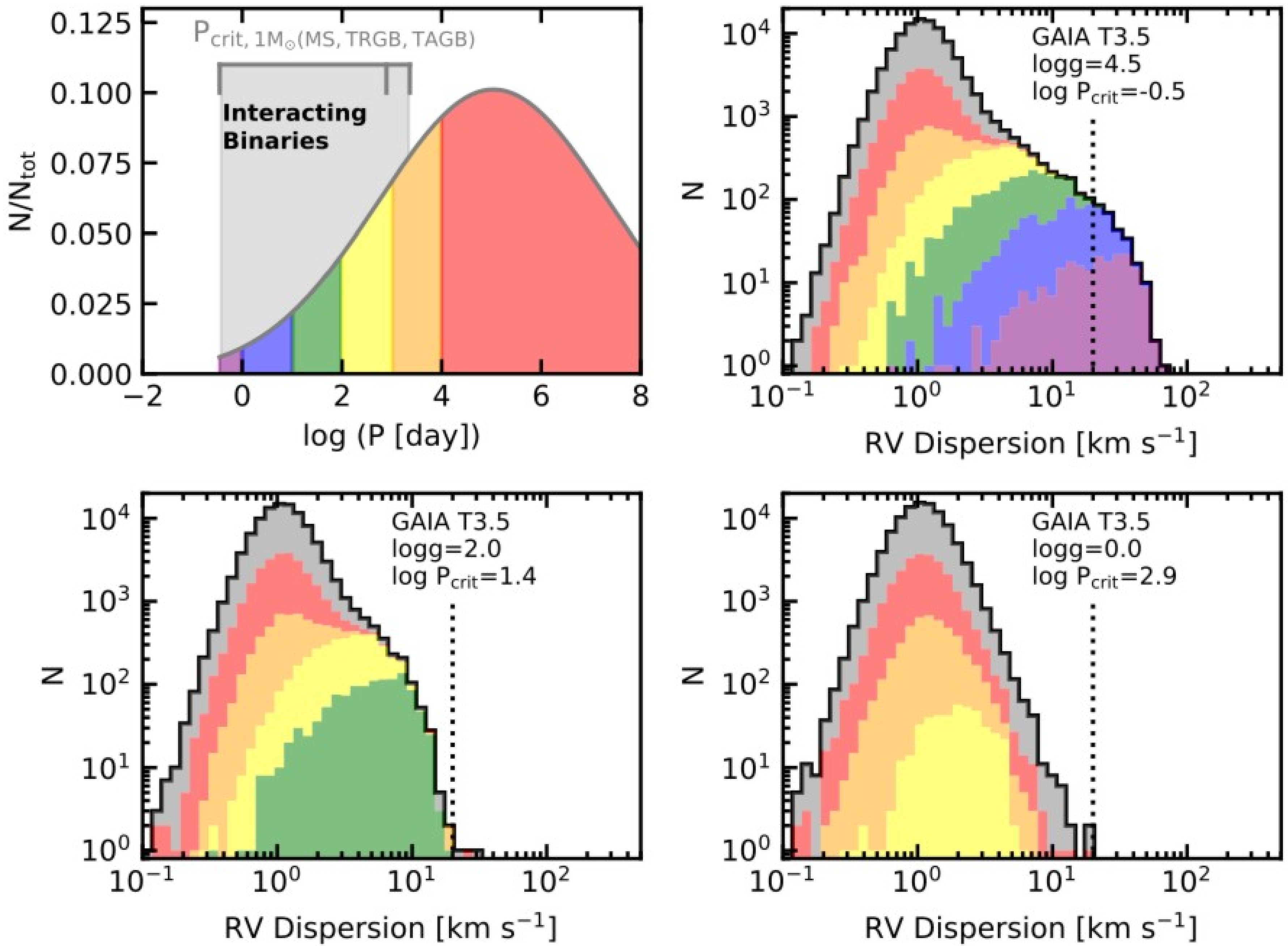

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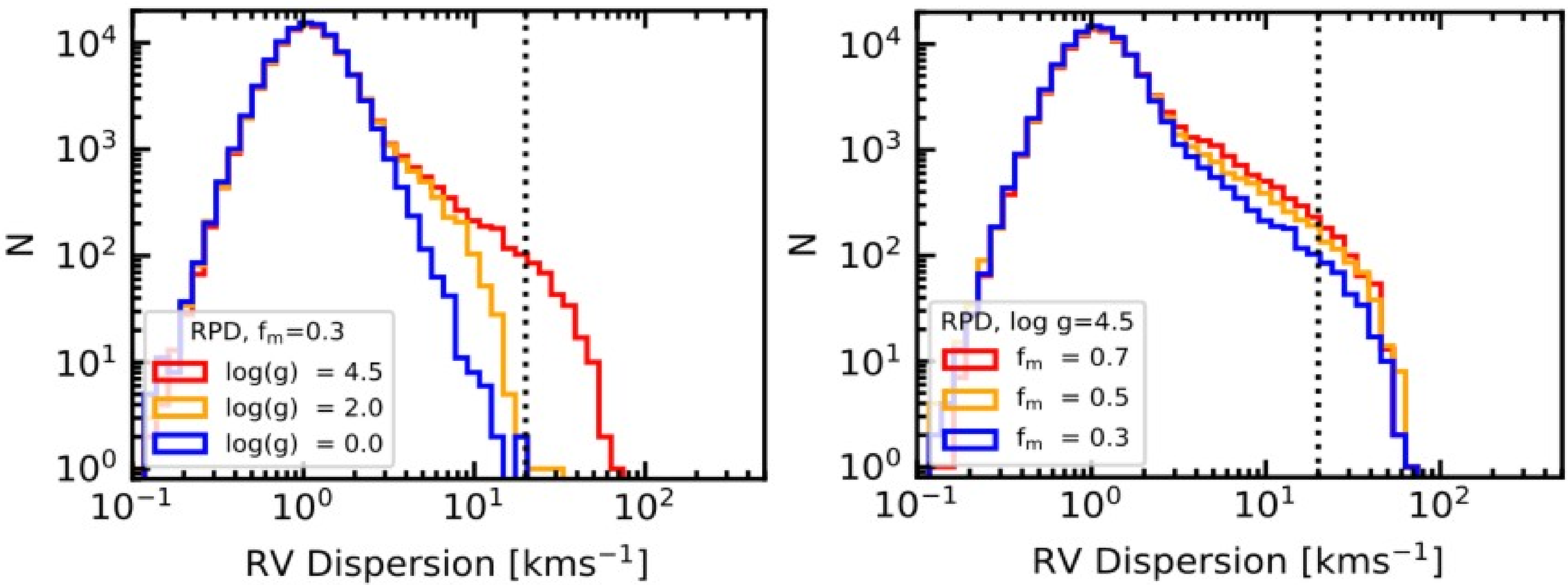

WEAVE

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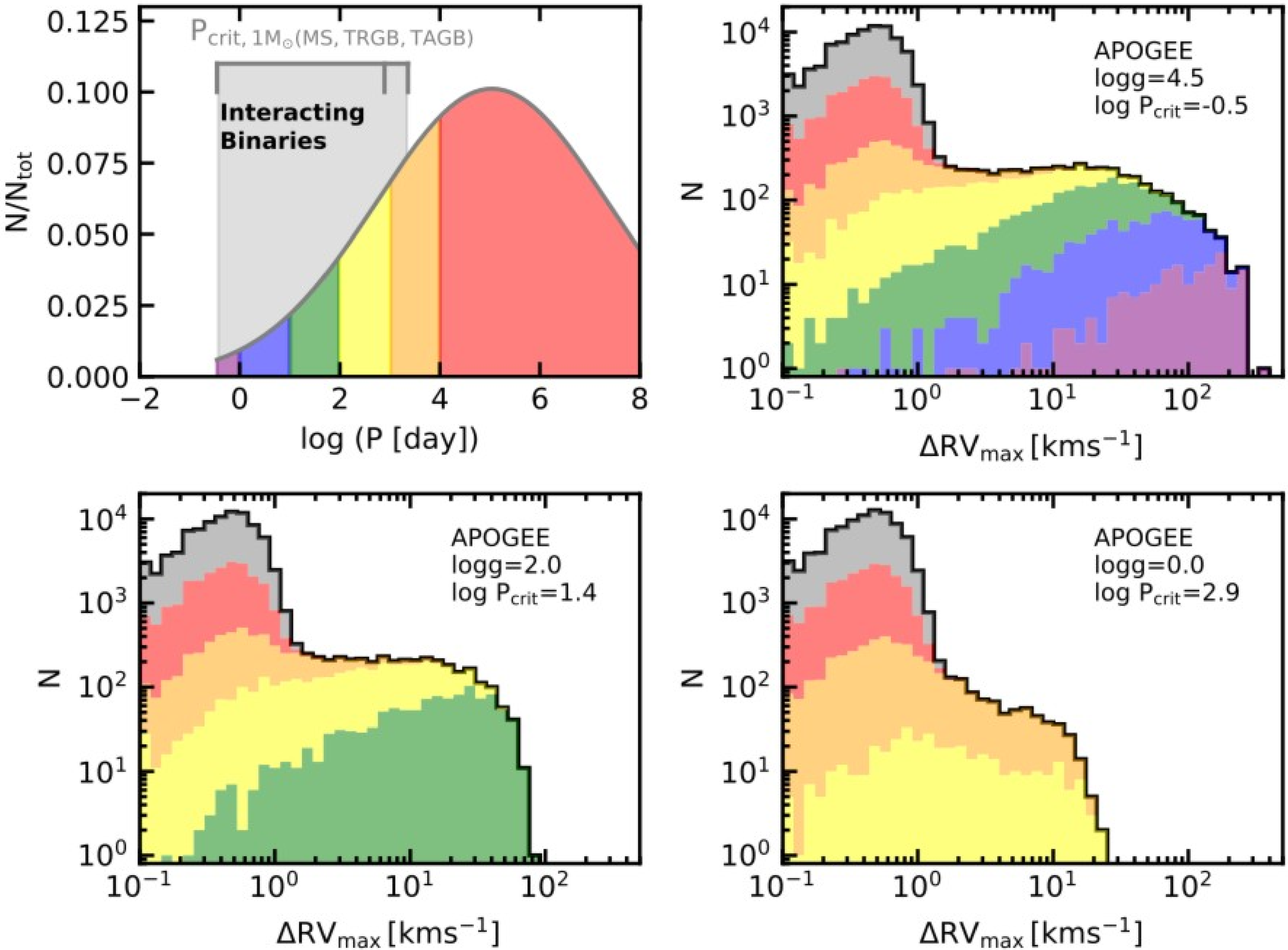

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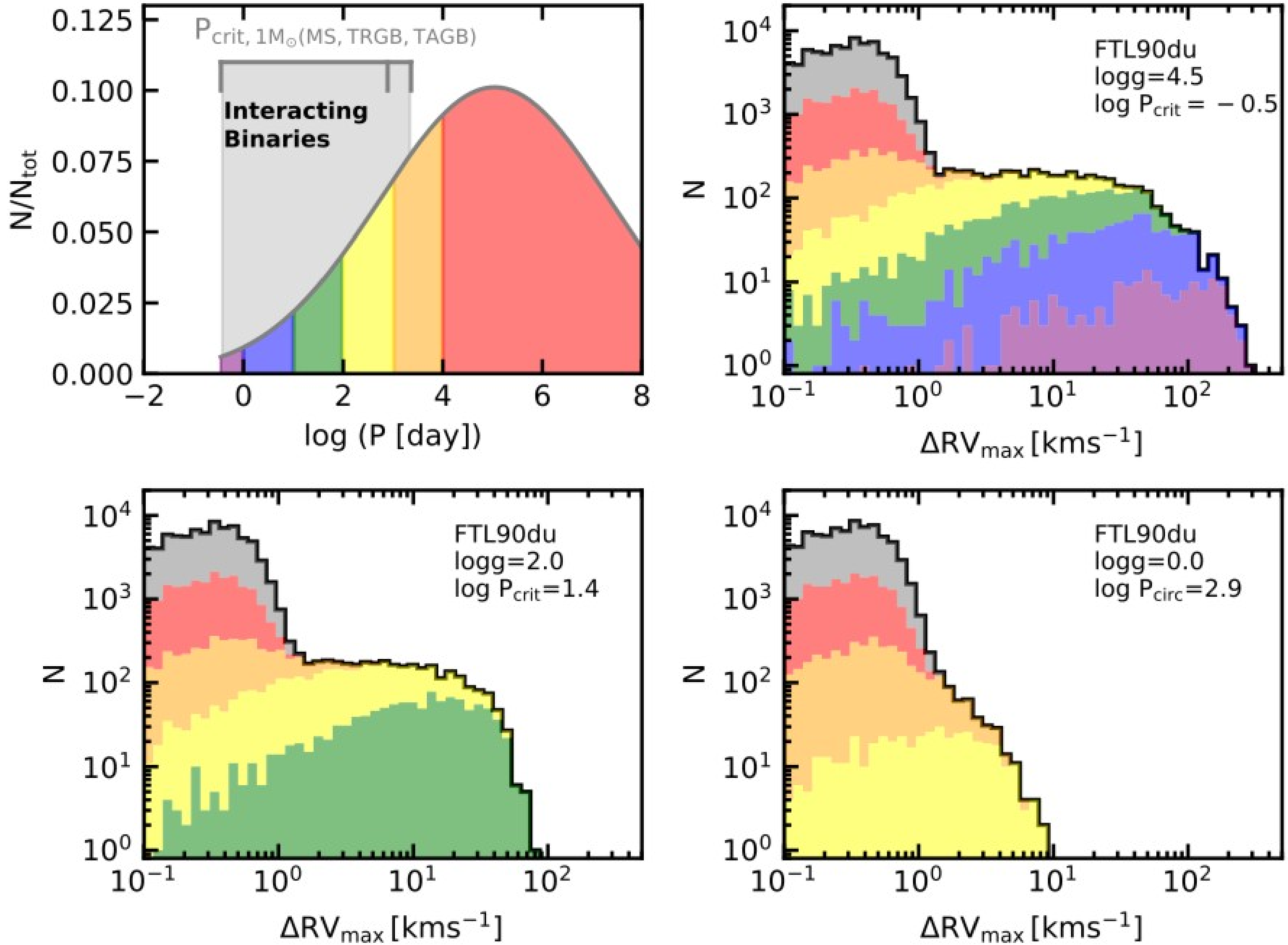

WEAVE

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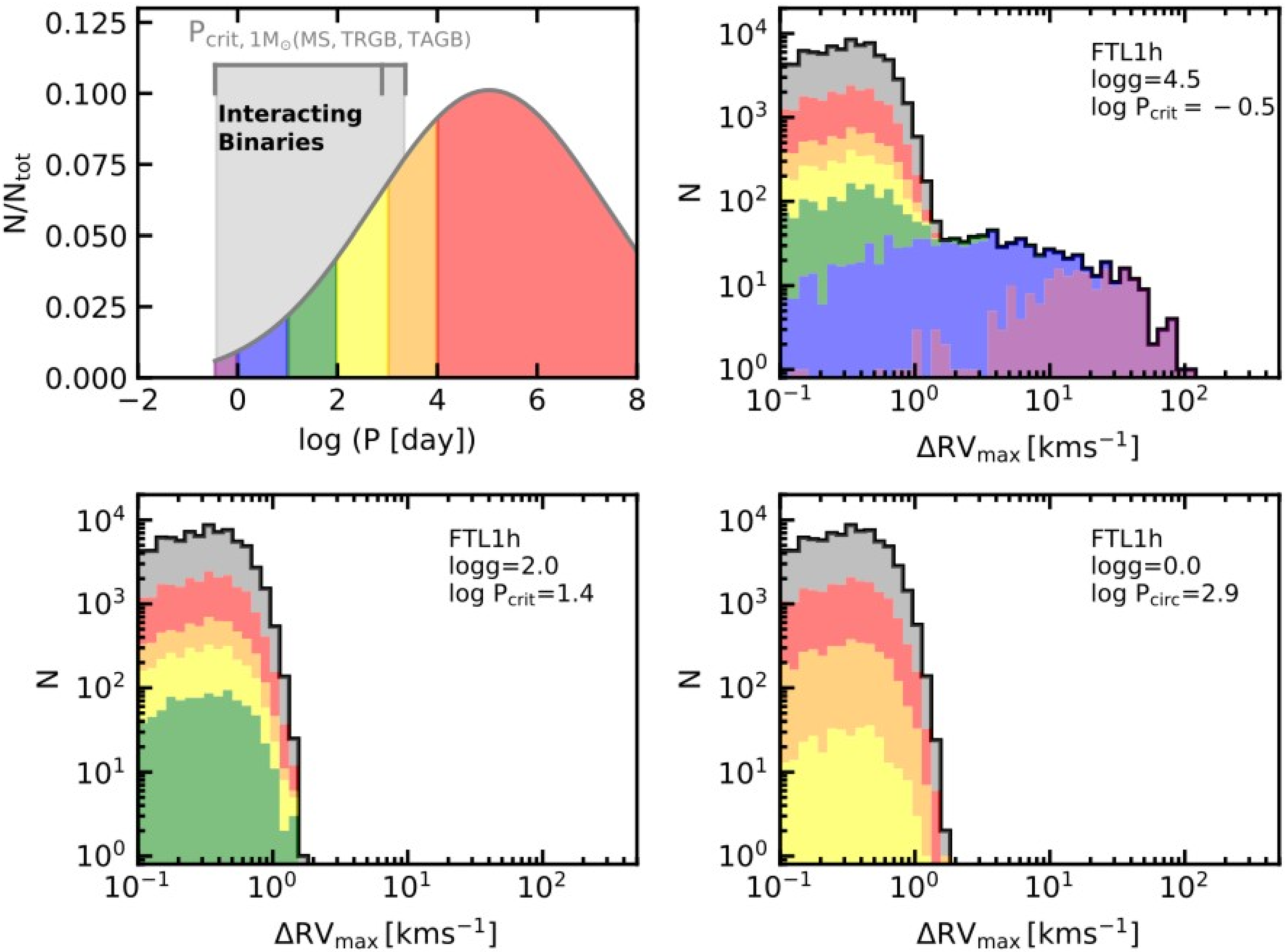

Now on arXiv

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STELLAR MULTIPLICITY MEETS STELLAR EVOLUTION AND METALLICITY: THE APOGEE VIEW

Carles Badenes[1,2], Christine Mazzola[1], Todd A. Thompson[3], Kevin Covey[4], Peter E. Freeman[5], Matthew G. Walker[6], Maxwell Moe[7,8], Nicholas Troup[9], David Nidever[10], Carlos Allende Prieto[11], Brett Andrews[1], Rodolfo H. Barbá[12], Timothy C. Beers[13], Jo Bovy[14,15], Joleen K. Carlberg[16] Nathan De Lee[17,18], Jennifer Johnson[3], Hannah Lewis[9], Steven R. Majewski[9], Marc Pinsonneault[3], Jennifer Sobeck[19], Keivan G. Stassun[18], Gail Zasowski[20]

Draft version November 3, 2017

ABSTRACT

We use the multi-epoch radial velocities acquired by the APOGEE survey to perform a large scale statistical study of stellar multiplicity for field stars in the Milky Way, spanning the evolutionary phases between the main sequence and the red clump. We show that the distribution of maximum radial velocity shifts (ΔRV_{max}) for APOGEE targets is a strong function of $\log(g)$, with main sequence stars showing ΔRV_{max} as high as $\sim$300 km s^{-1}, and steadily dropping down to $\sim$30 km s^{-1} for $\log(g)\sim 0$, as stars climb up the Red Giant Branch (RGB). Red clump stars show a distribution of ΔRV_{max} values comparable to that of stars at the tip of the RGB, implying they have similar multiplicity characteristics. The observed attrition of high ΔRV_{max} systems in the RGB is consistent with a lognormal period distribution in the main sequence and a multiplicity fraction of 0.35, which is truncated at an increasing period as stars become physically larger and undergo Case B mass transfer after Roche Lobe Overflow. The ΔRV_{max} distributions also show that the multiplicity characteristics of field stars are metallicity dependent, with metal-poor ([Fe/H]$\lesssim -0.5$) stars having a multiplicity fraction a factor 2-3 higher than metal-rich ([Fe/H]$\gtrsim 0.0$) stars. This has profound implications for the formation rates of interacting binaries observed by astronomical transient surveys and gravitational wave detectors, as well as the habitability of circumbinary planets.

Summary

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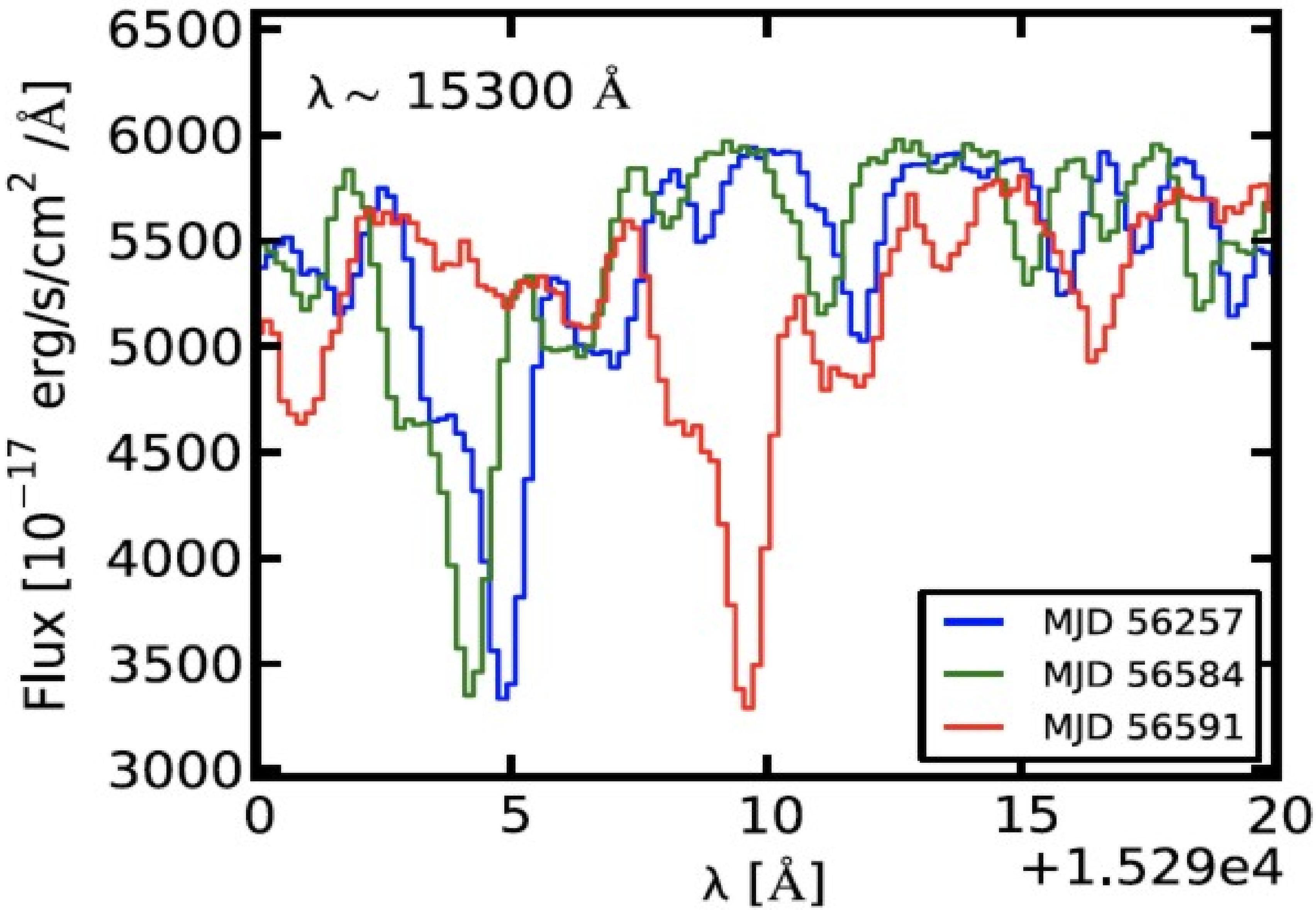
- APOGEE: high resolution, multi-epoch IR spectra of ~100,000 stars (Galactic archeology).
- Unique view of stellar multiplicity, from the MS to the RC. Few-epoch spectra: no orbits ⇒ ΔRV_{max}.
- Attrition of high ΔRV_{max} (short P) systems as stars climb the RGB, consistent with lognormal P dist., truncated at P_{crit} ⇒ Case B mass transfer. ΔRVmax in RC stars ~ TRGB.
- Clear trend with [Fe/H]: lower [Fe/H] stars have higher ΔRV_{max} distributions ⇒ consistent with higher f_m at lower [Fe/H] [Gao+ 14, 17, but Hettinger+ 15].
- Future work: Hierarchical Bayesian models, multiplicity statistics w/ age & Galactic location, BPS, follow-up of interesting systems.

Additional Plots



Additional Plots

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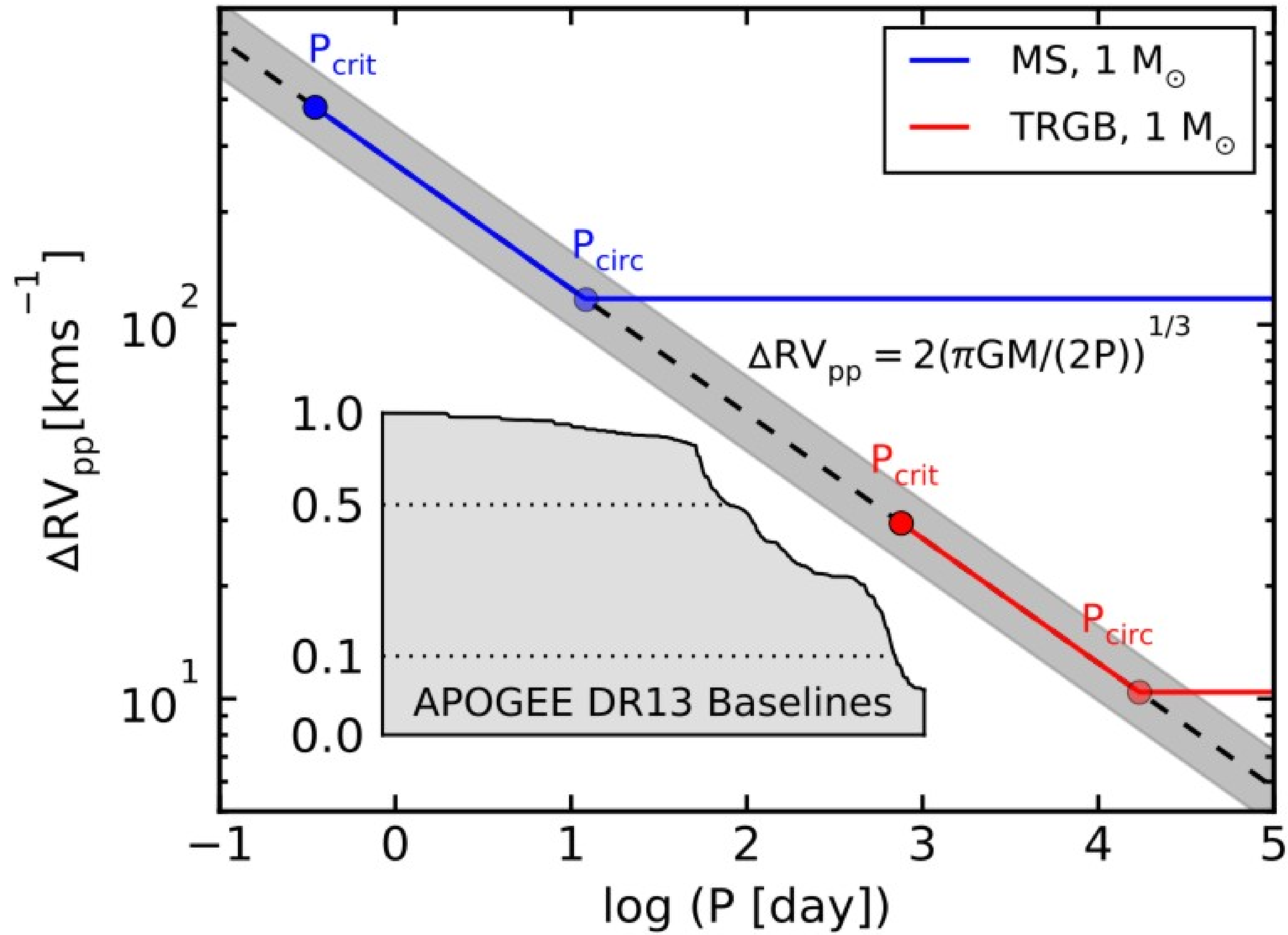

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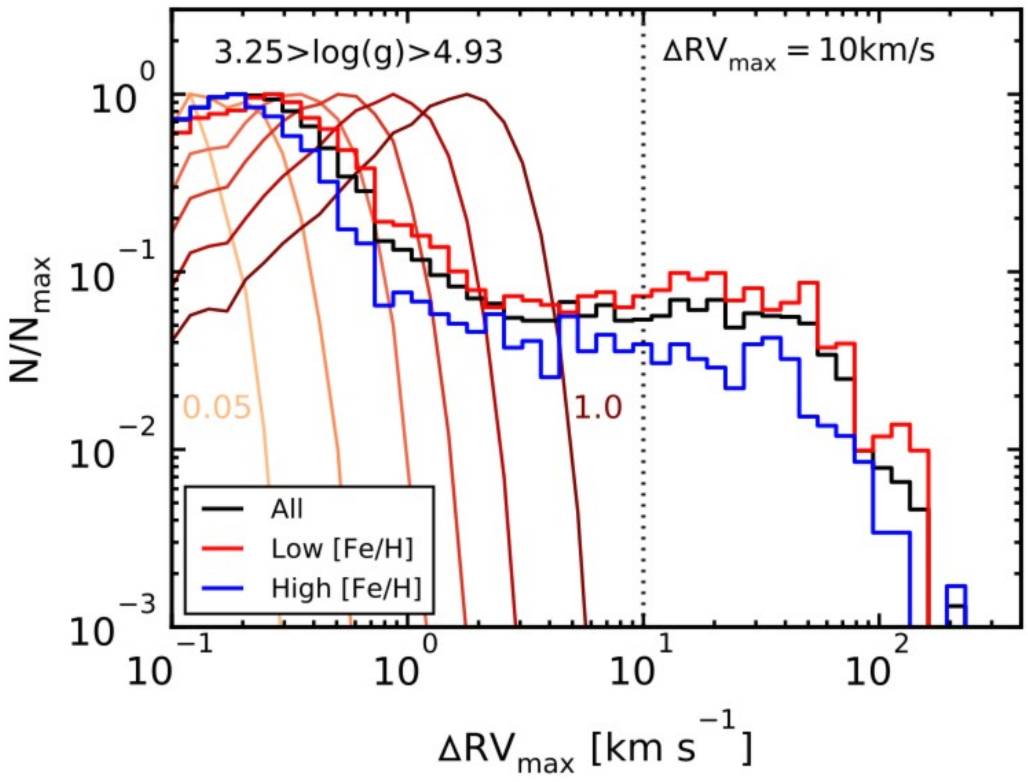

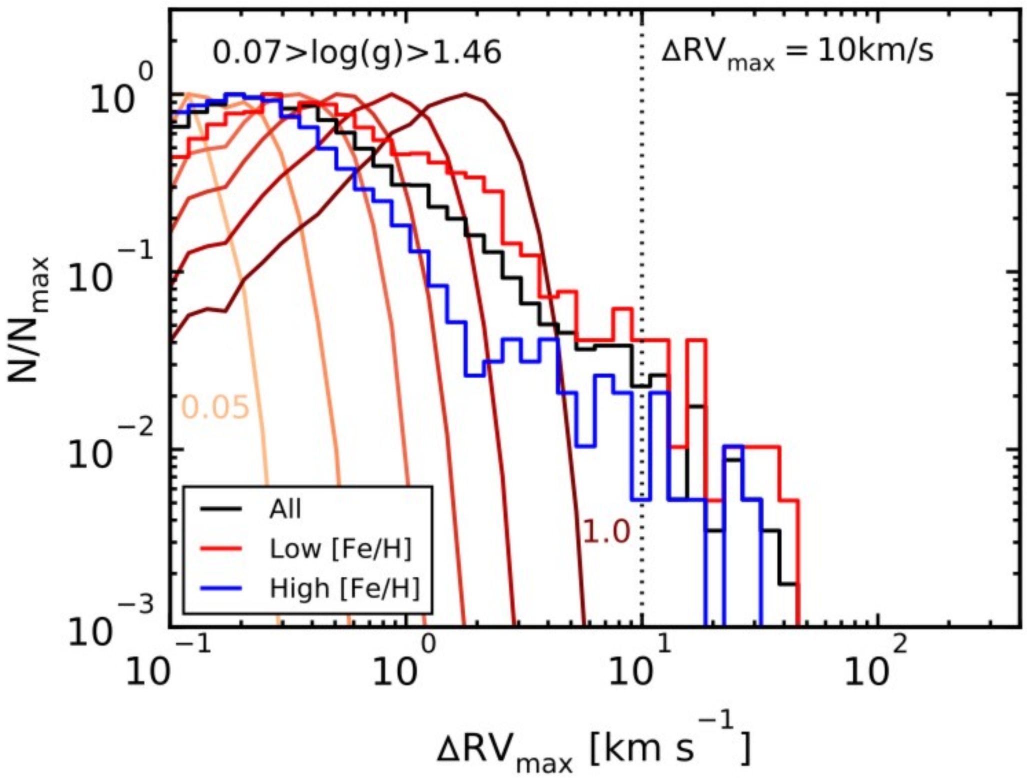

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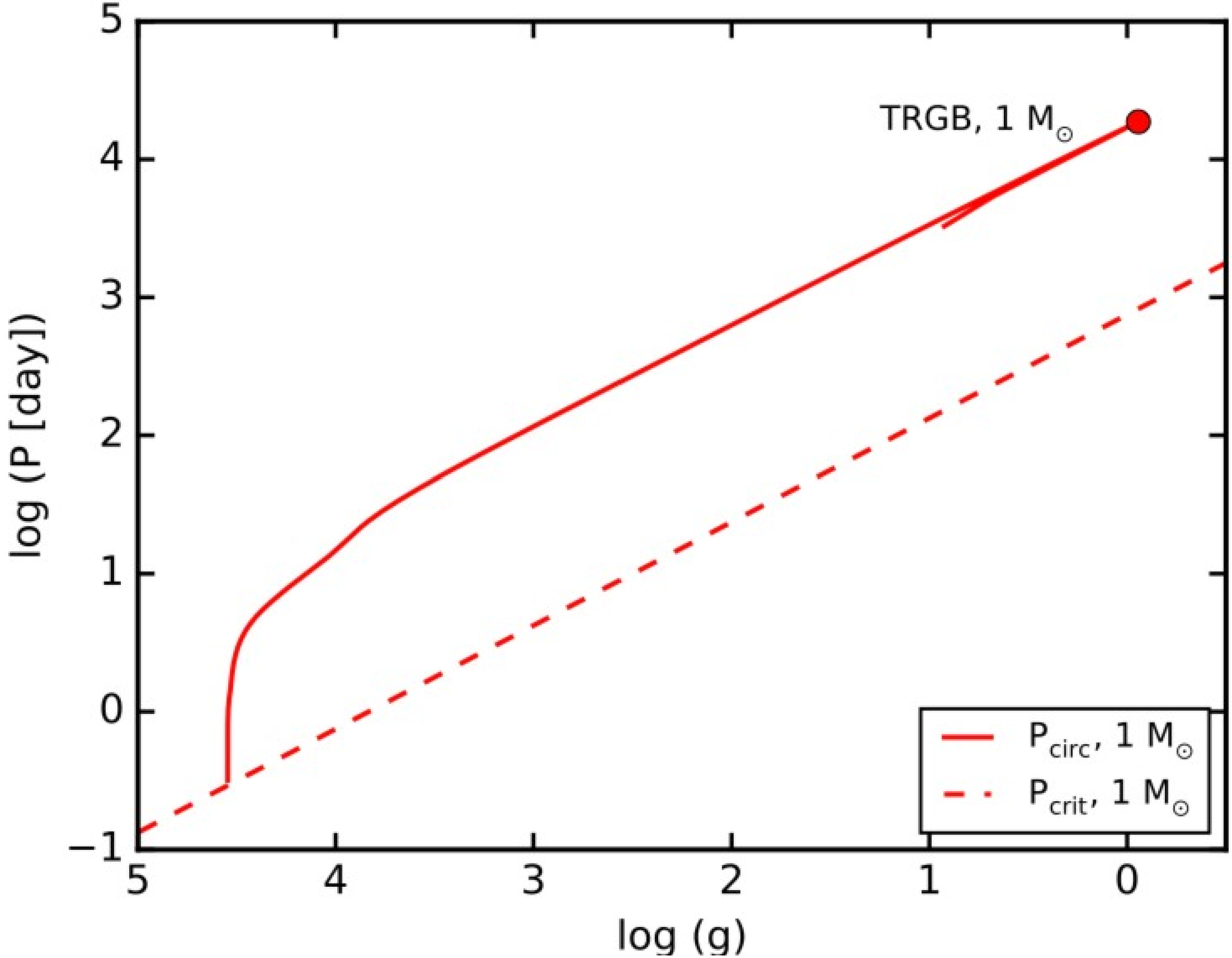

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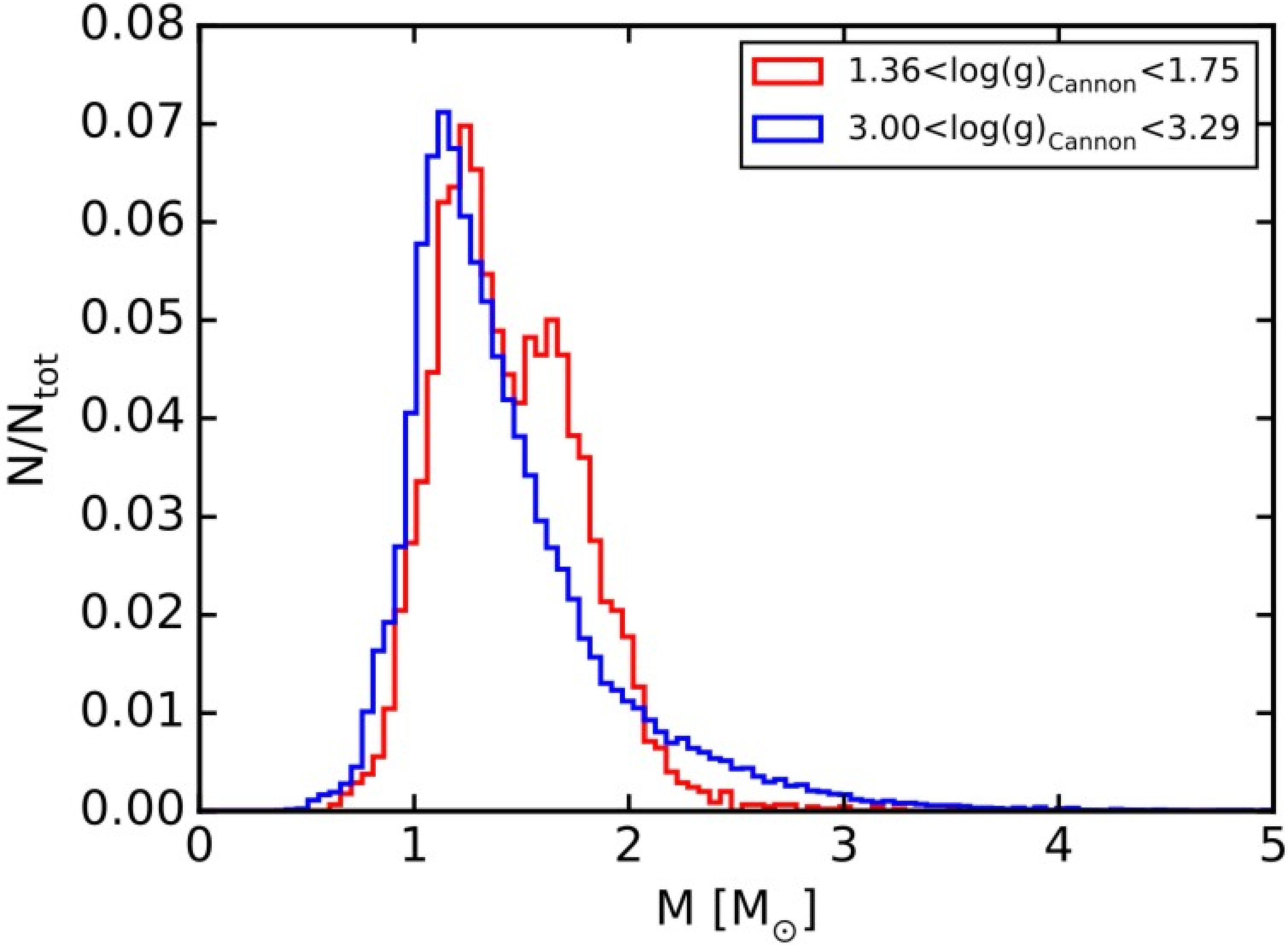

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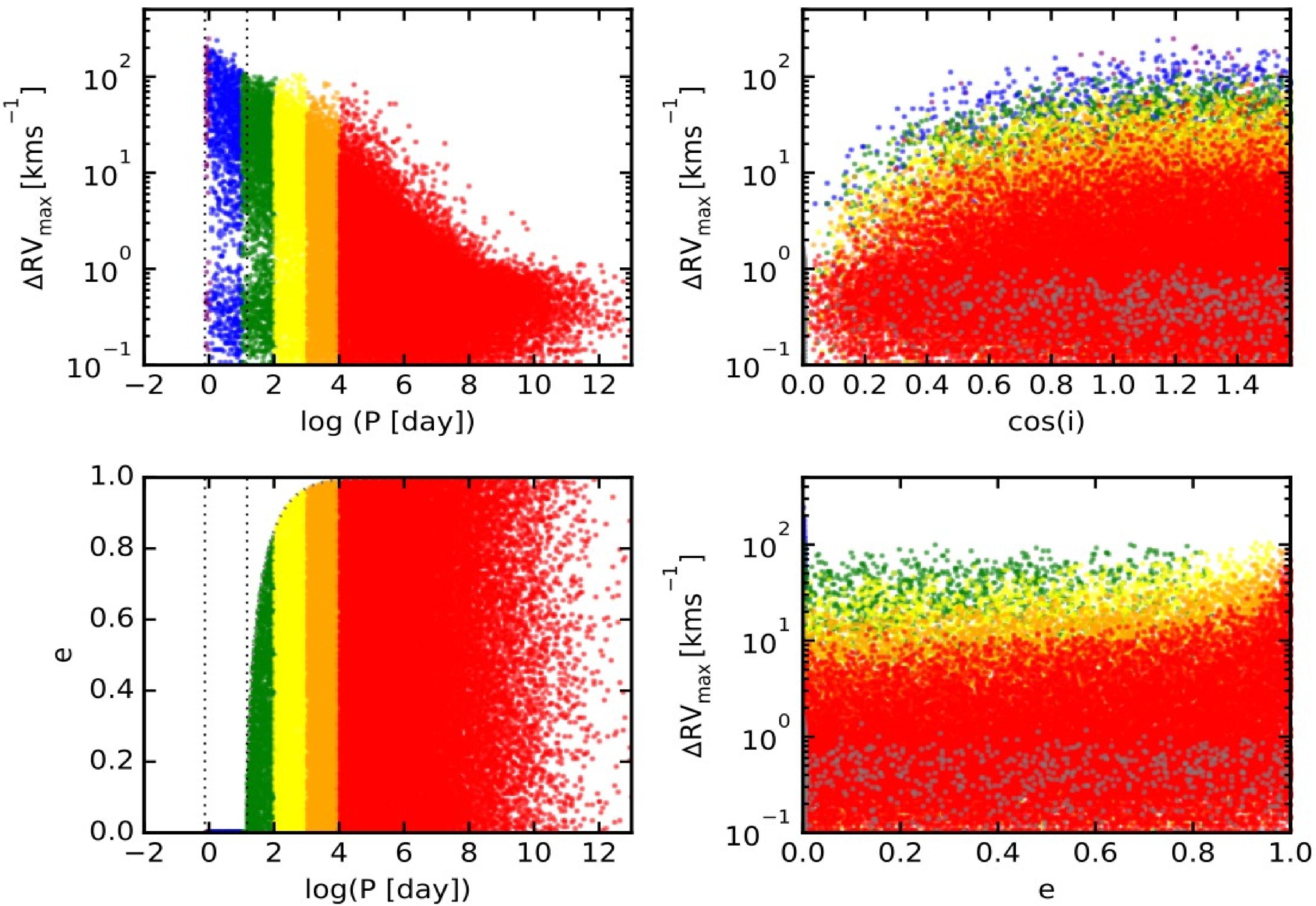

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