A Closer Look at $v\sin(i)$ and the CBF through APOGEE

Christine Mazzola Daher

ImBaSE Workshop
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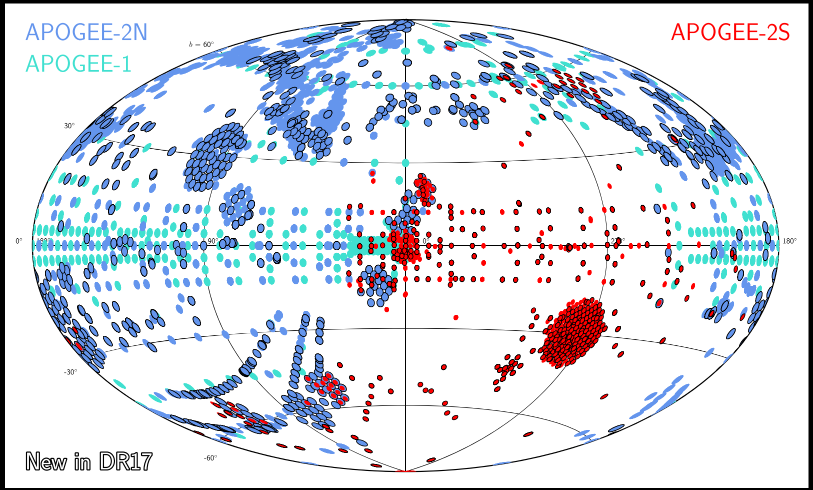
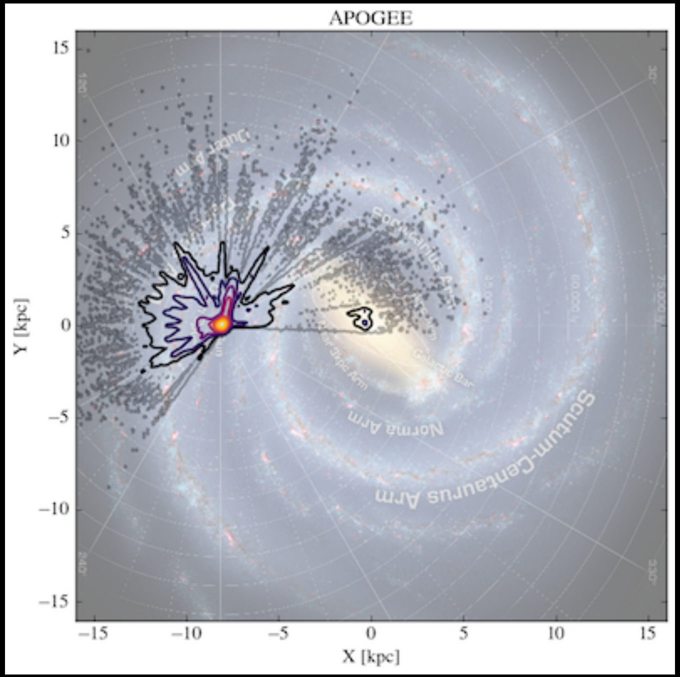
Jamie Tayar, Carles Badenes, Marc Pinsonneault,
Sergey Koposov, Kaitlin Kratter, Max Moe, *and* APOGEE

SDSS-IV: APOGEE-2 – *Overview*

- Infrared: H band accesses all major populations of the Milky Way
- High-resolution spectra: R ~ 22,500
- Public: well-documented and available for all!
- Multi-epoch: signs of unseen companions?



SDSS DR17 Release Paper *(Abdurro'uf+2022)*

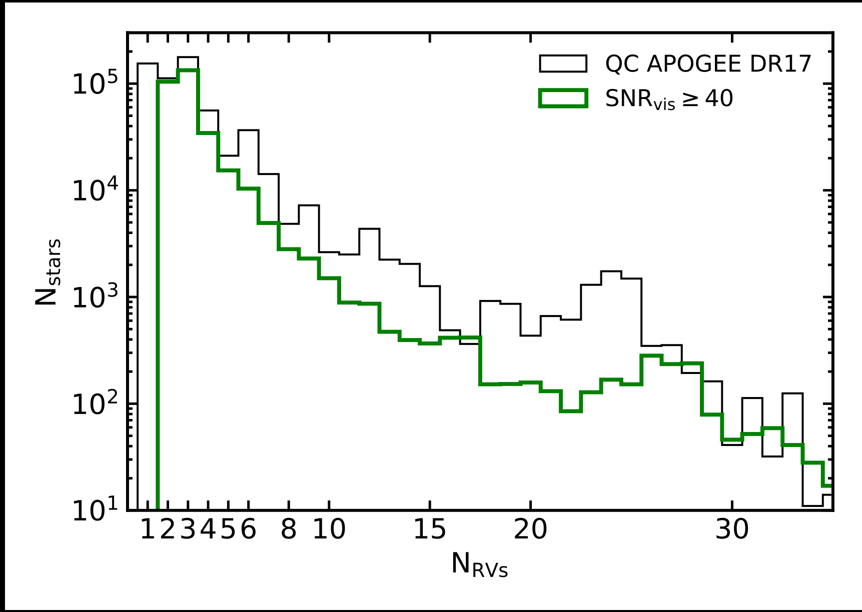


Kollmeier+2017

RV Curves – *Sparsely-Sampled* + ΔRV_{max}

Problem: Survey Planning

Getting spectra for hundreds of thousands of stars means you can't get targeted RVs for most of them.



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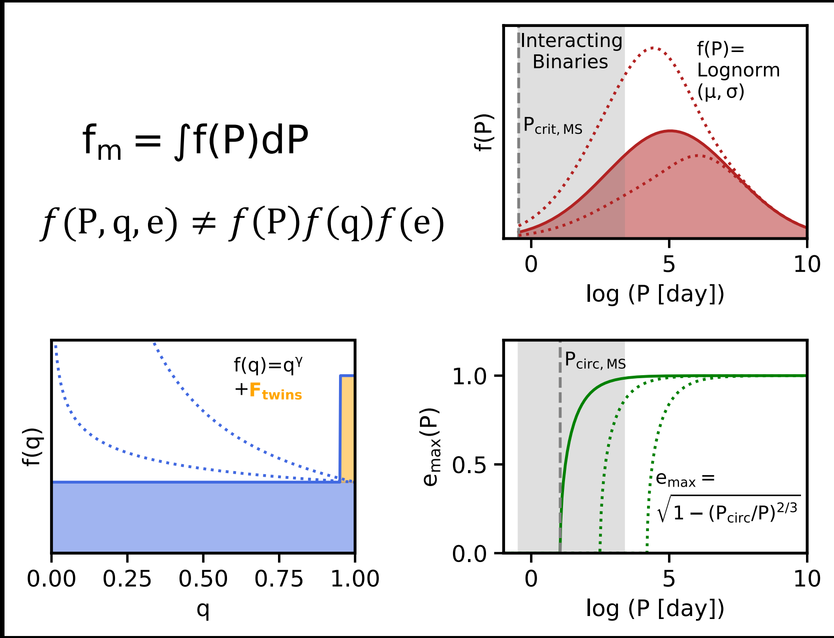
Problem: It's Complicated…

Multiplicity statistics are strong functions of the intrinsic and evolutionary properties of stars…and they are not independent of each other.



NSF Grant AST-1909022

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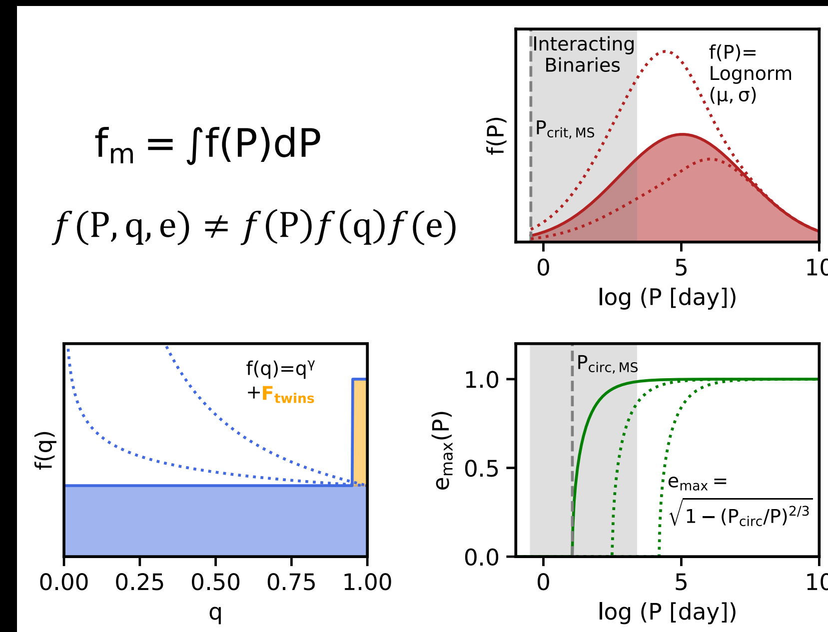

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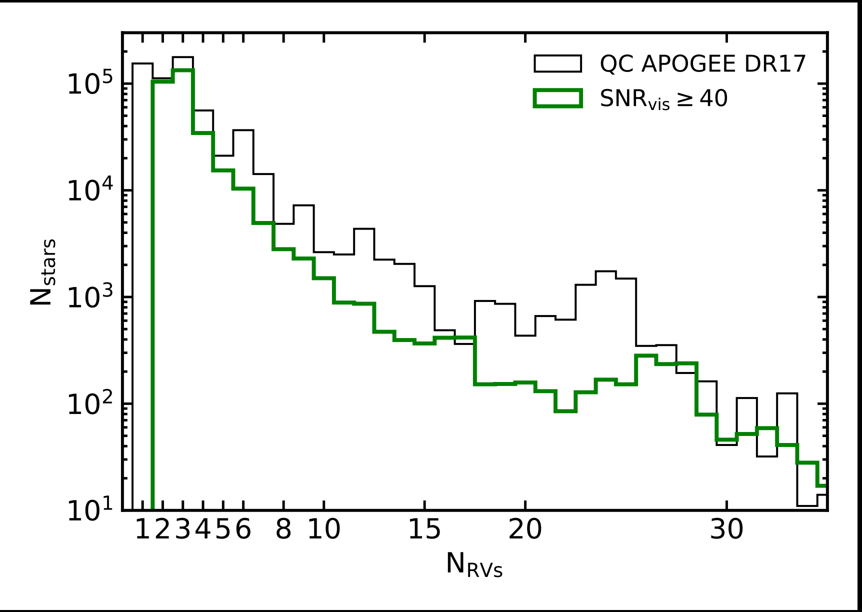
To constrain multiplicity in a complex multivariate space of stellar properties, we need large samples of well-measured stars.

RV Curves – *Sparsely-Sampled* + ΔRV_{max}

Our Solution: Don't fit RV curves — just use the data you have!

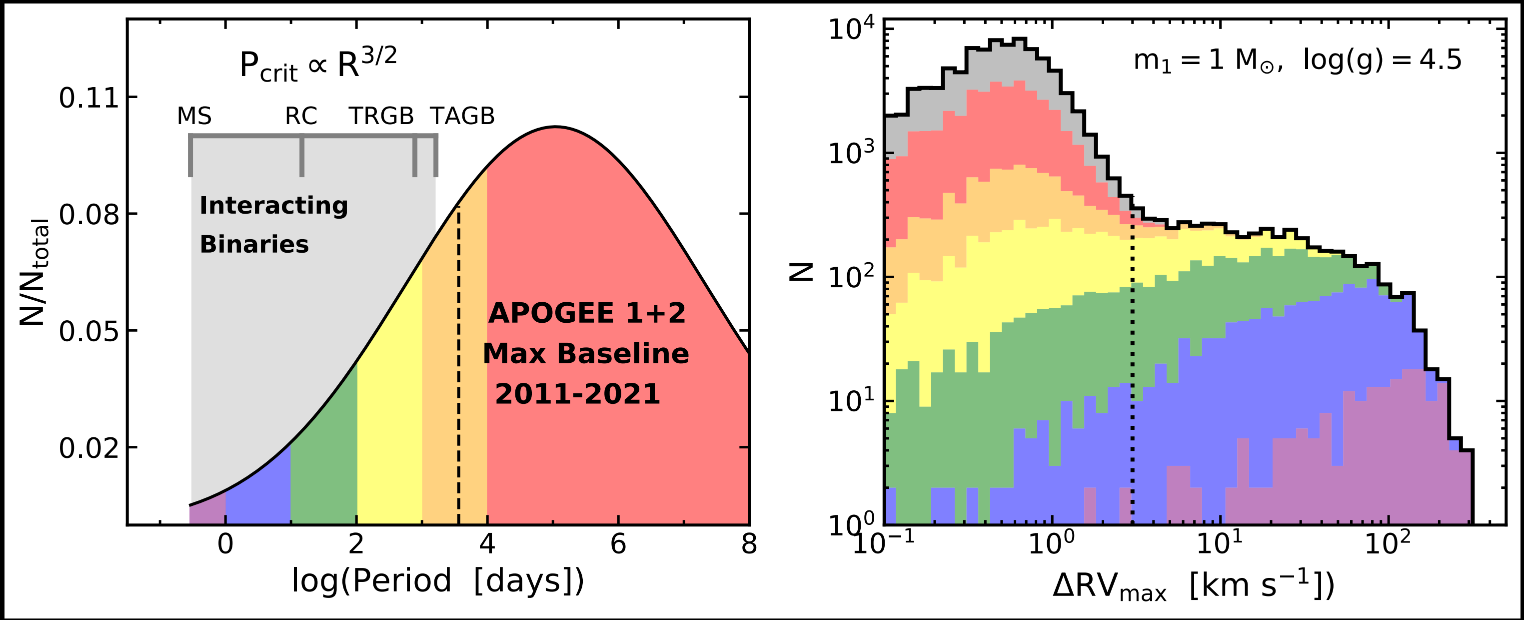
$$\Delta \mathrm{RV}_{\mathrm{max}} = |\mathrm{RV}_{\mathrm{max}} - \mathrm{RV}_{\mathrm{min}}|$$



$$f_{\mathrm{RVvar}} = \frac{\mathrm{N}_{\Delta \mathrm{RV}_{\mathrm{max}} \geq X\ \mathrm{km\ s^{-1}}}}{\mathrm{N}_{\mathrm{total}}}$$

$$\sigma_{f_{\mathrm{RVvar}}} = \sqrt{\frac{f_{\mathrm{RVvar}}\,(1 - f_{\mathrm{RVvar}})}{\mathrm{N}_{\mathrm{total}}}}$$

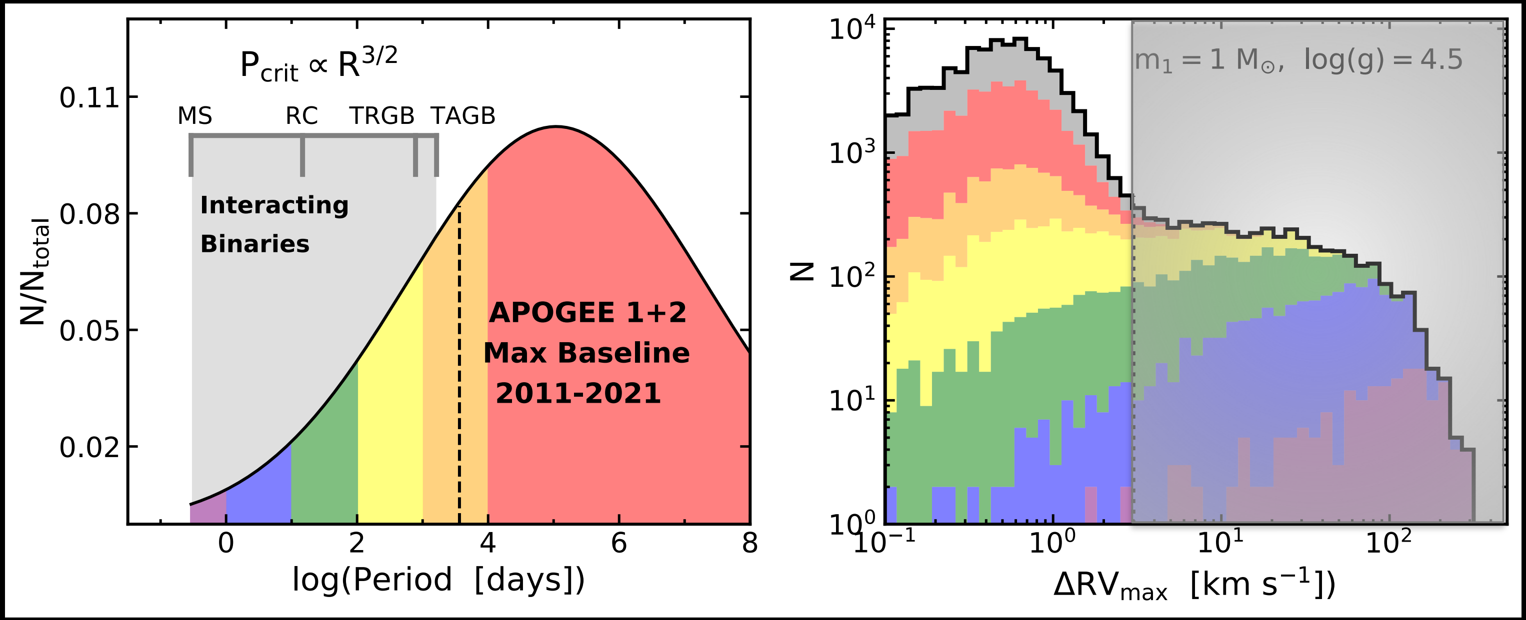
RV Curves – *Sparsely-Sampled* + ΔRV_{max}



→ Simulate a sample of single and binary stars using observational distributions

→ Sample their RV curves based on real APOGEE visit cadences

RV Curves – *Sparsely-Sampled* + ΔRV_{max}



- Low ΔRV_{max} "core" dominated by single stars (gray) + long-period binaries

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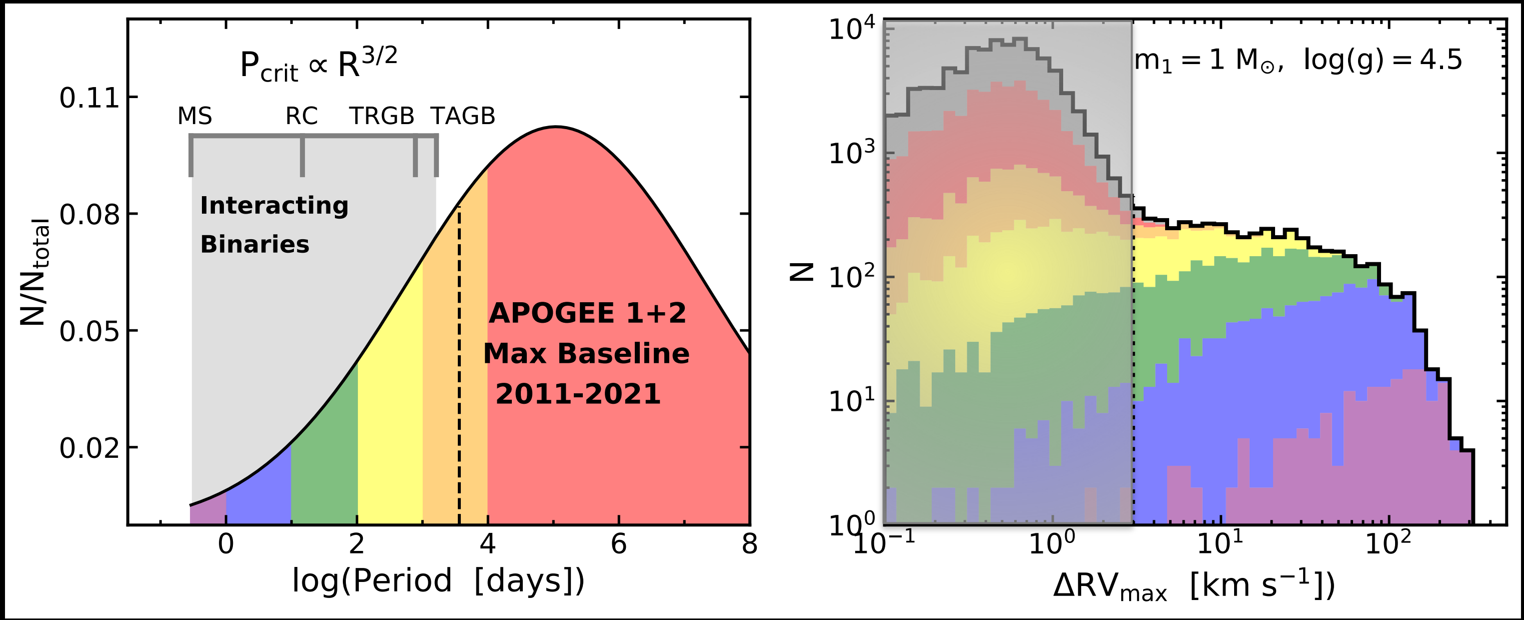

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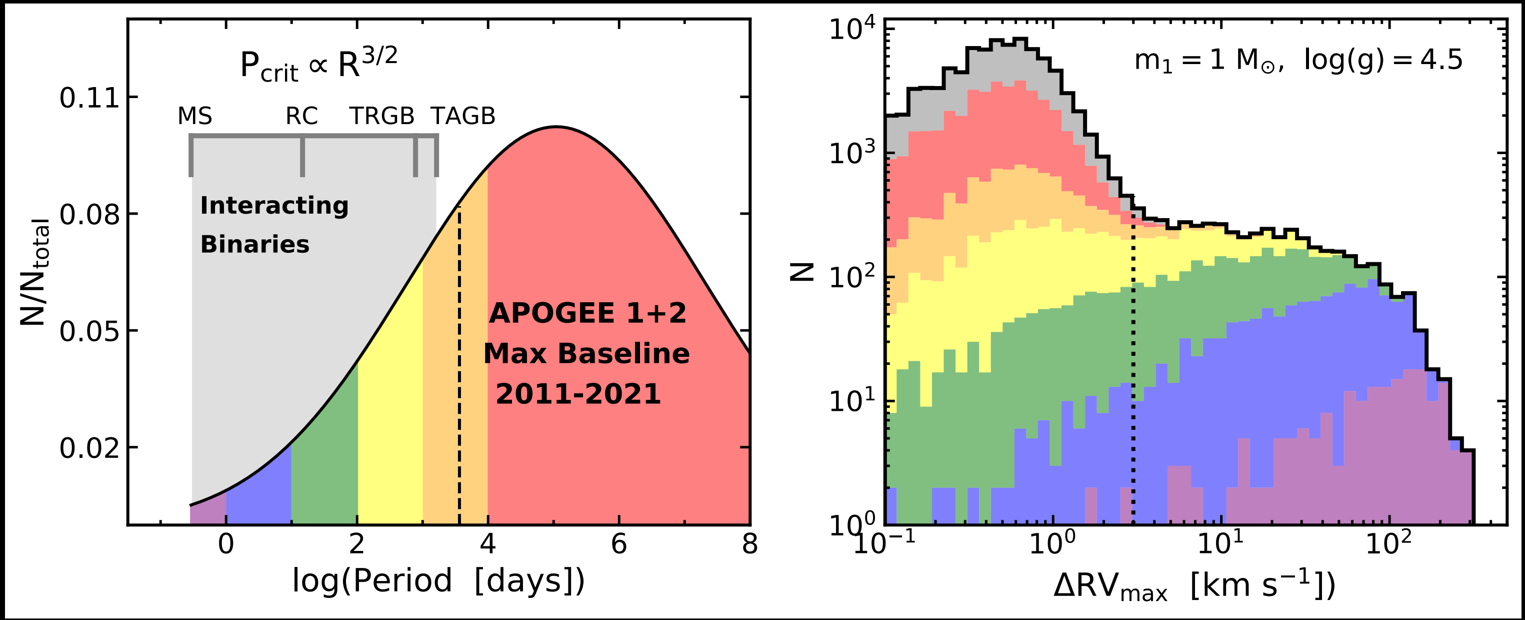

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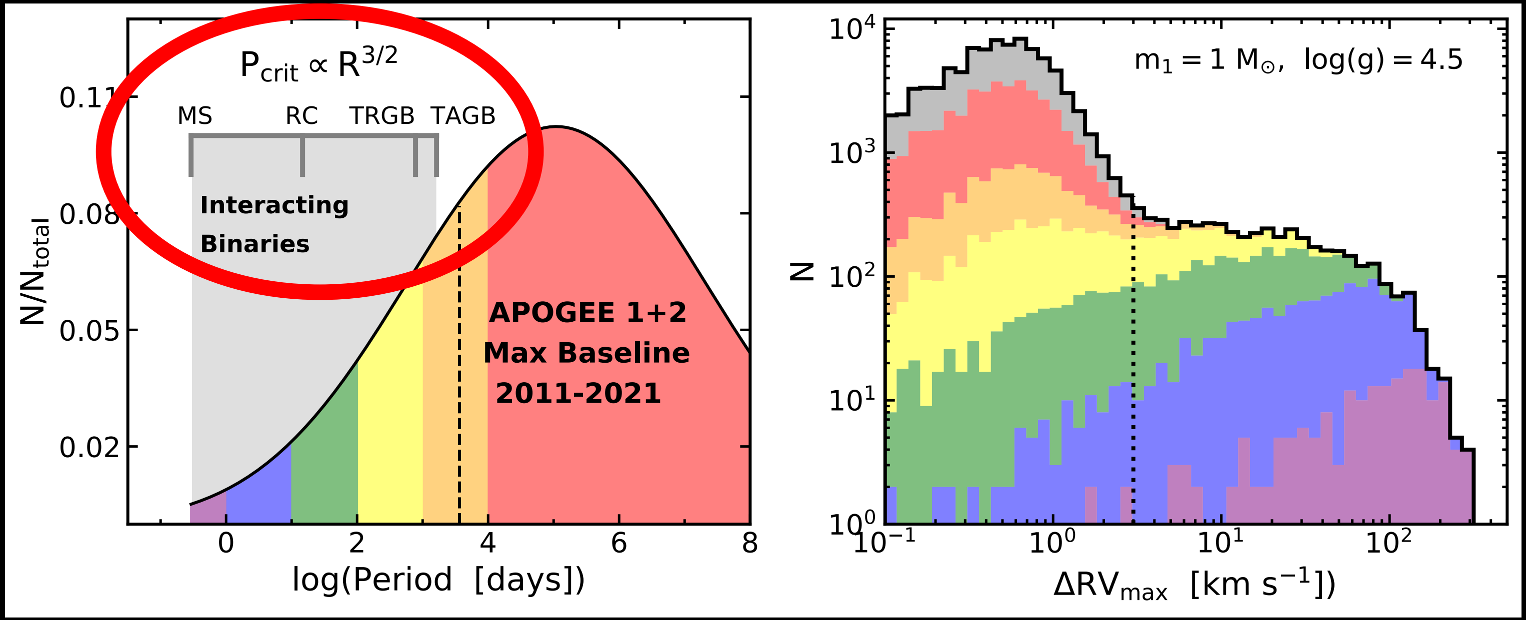

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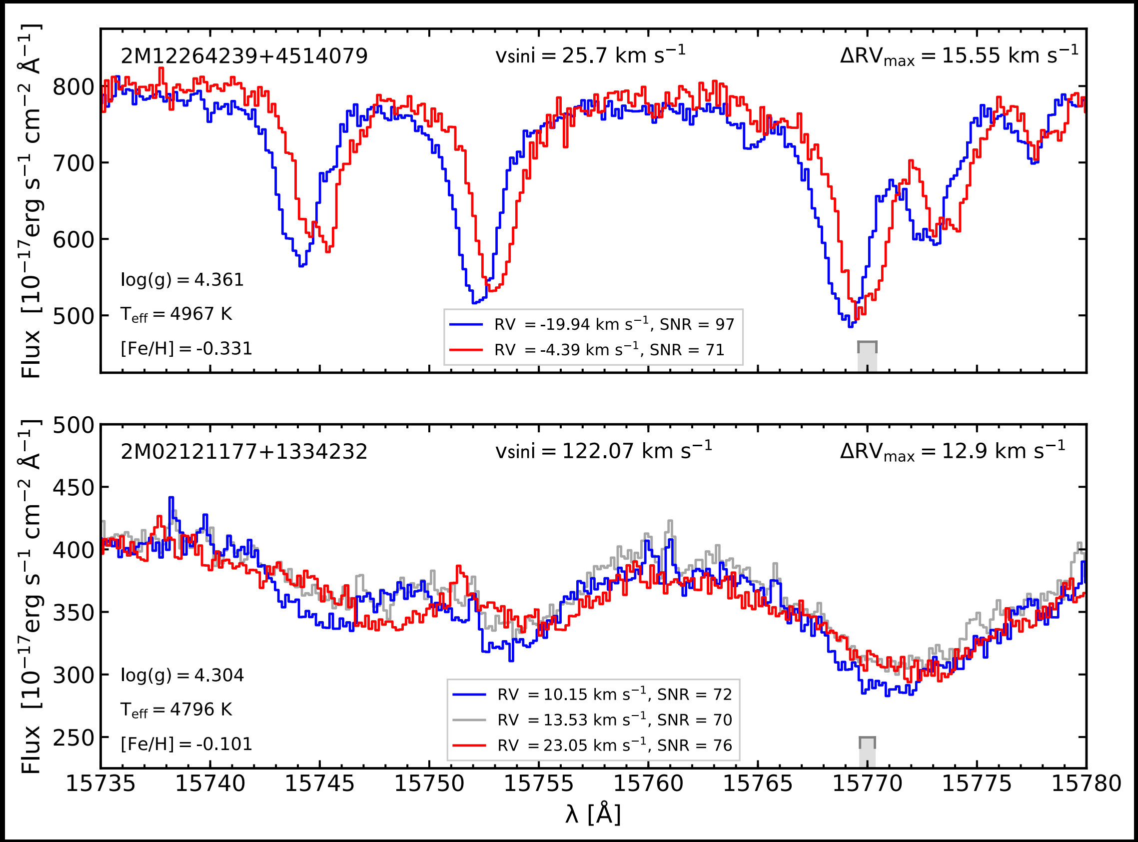
SDSS-IV: APOGEE-2 – *Data*

APOGEE RVs, T_{eff}, log(g)

v sin(i) : ASPCAP value + extra rotation fit by Jamie's pipeline

[Tayar+2015, Dixon+2020]



Daher+22

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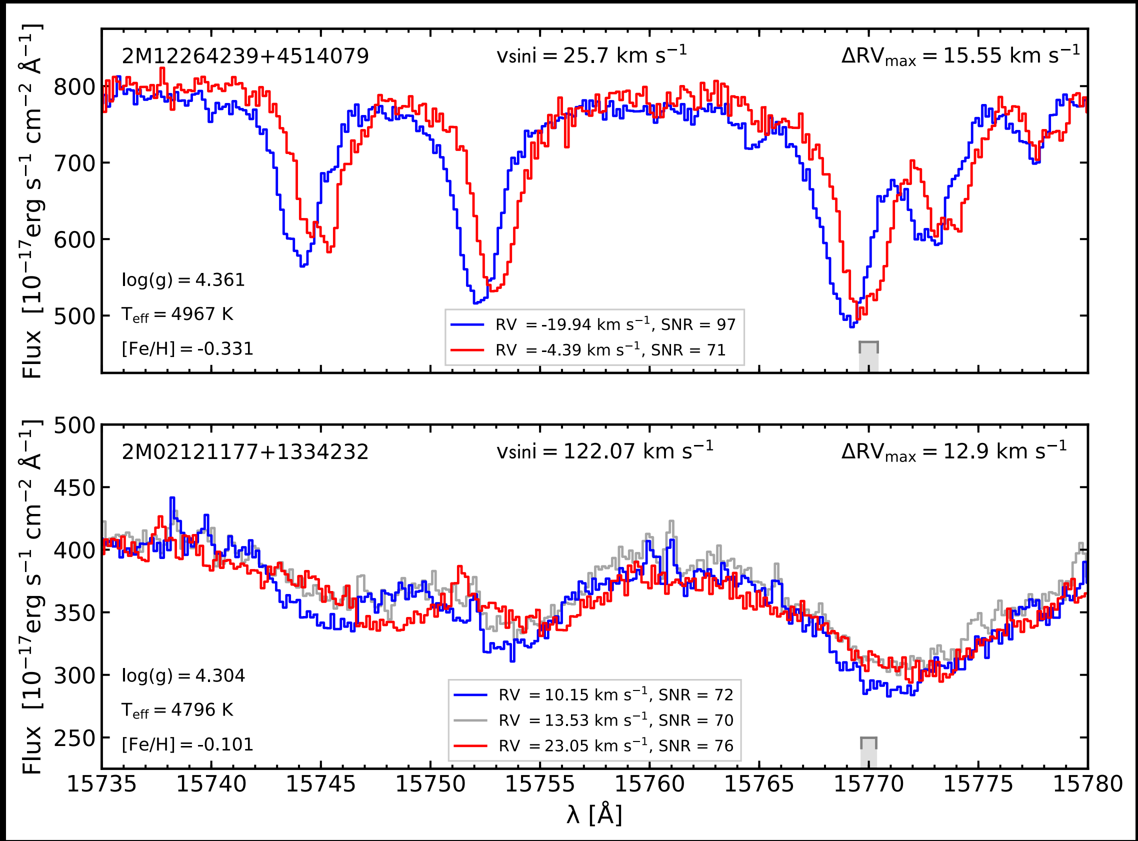
Masses, distances, and ages from isochrone fits

[Sanders & Das 2018]



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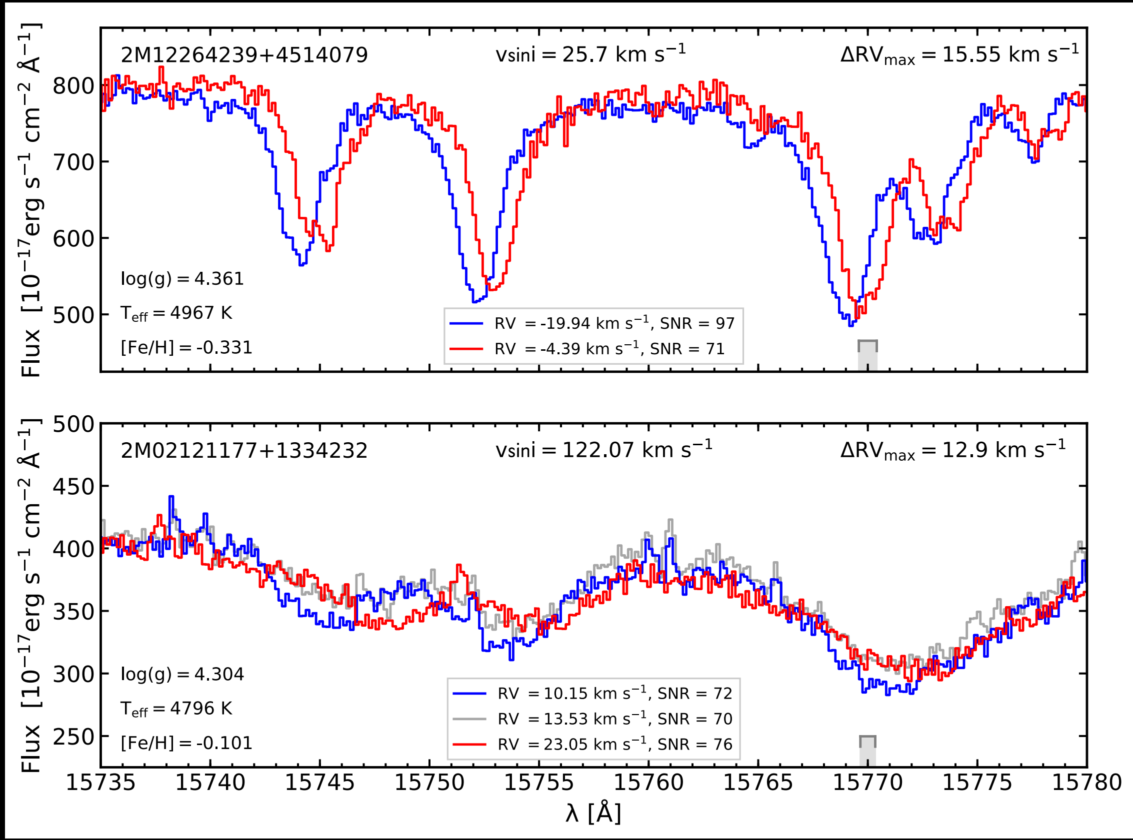

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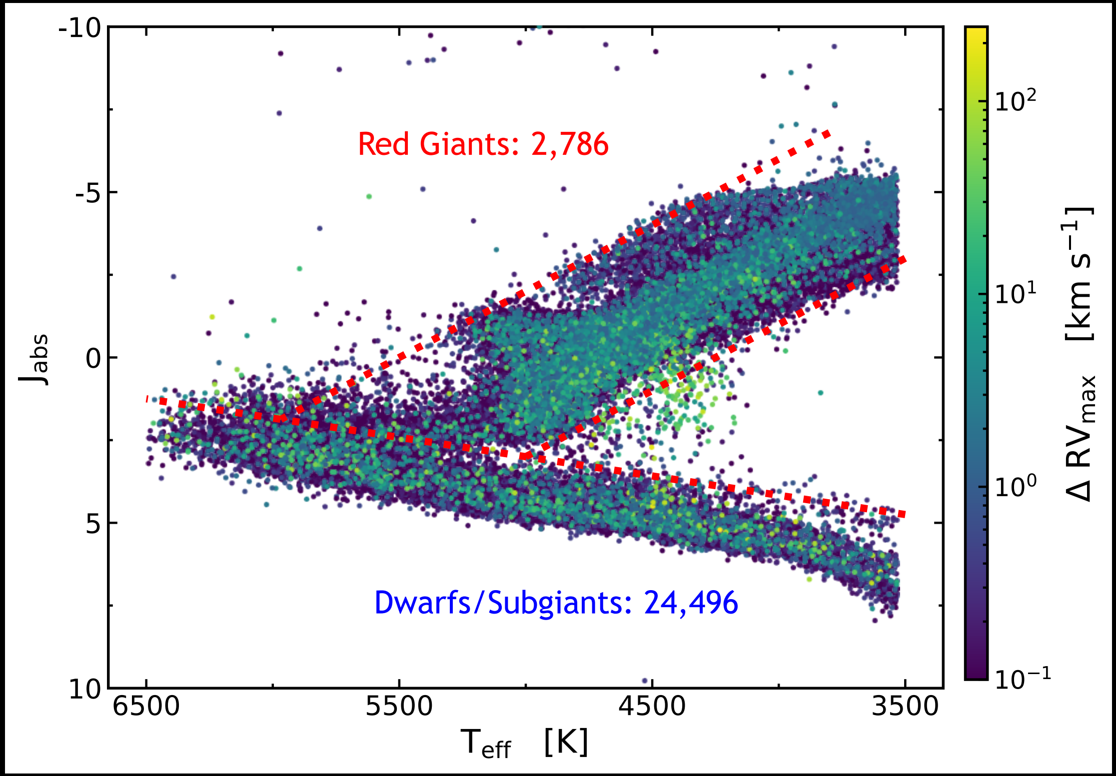


Daher+22

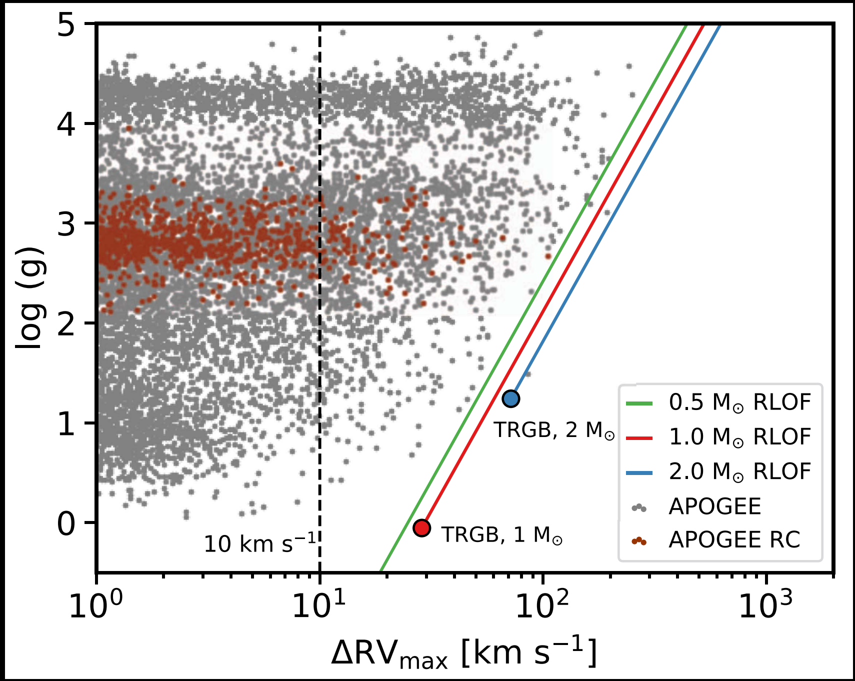
Results – *Evolution*

Compare observed ΔRV_{max} to the max peak-to-peak shift of the RV curve,

$$\Delta RV_{pp} \propto \left(\frac{M}{P_{crit}}\right)^{1/3}$$

$$P_{crit} \propto \left(\frac{GM}{g^3}\right)^{1/4}$$

- **Dwarfs and subgiants:** smaller P_{crit} → larger max ΔRV_{max} values



Badenes, Mazzola+18

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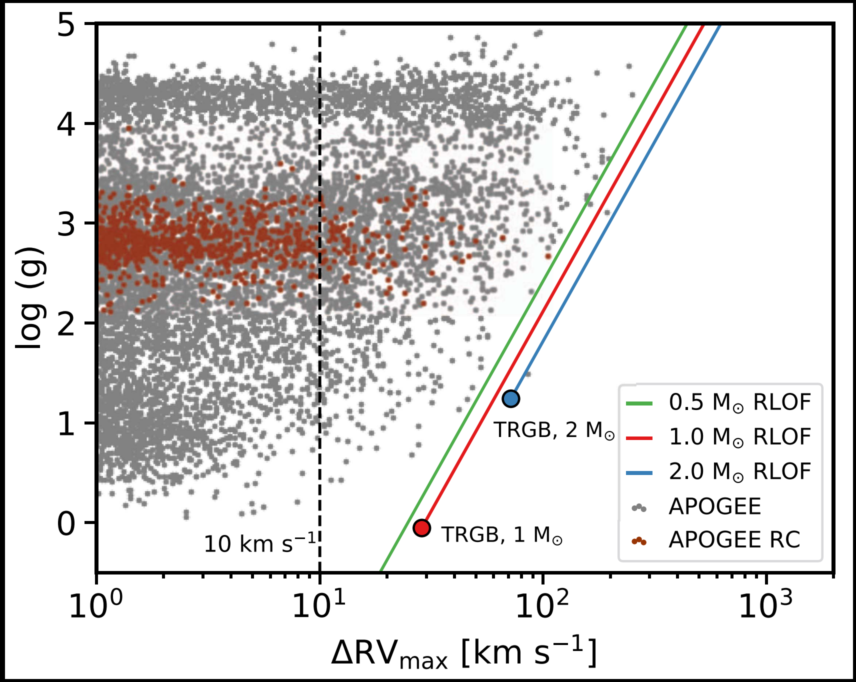
- **Dwarfs and subgiants:** smaller P_{crit} → larger max ΔRV_{max} values
- **Red clump (He-burning):** similar ΔRV_{max} to stars at the Tip of the Red Giant Branch, reminiscent of their time spent there before He fusion



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Results – *Evolution + Synchronization*

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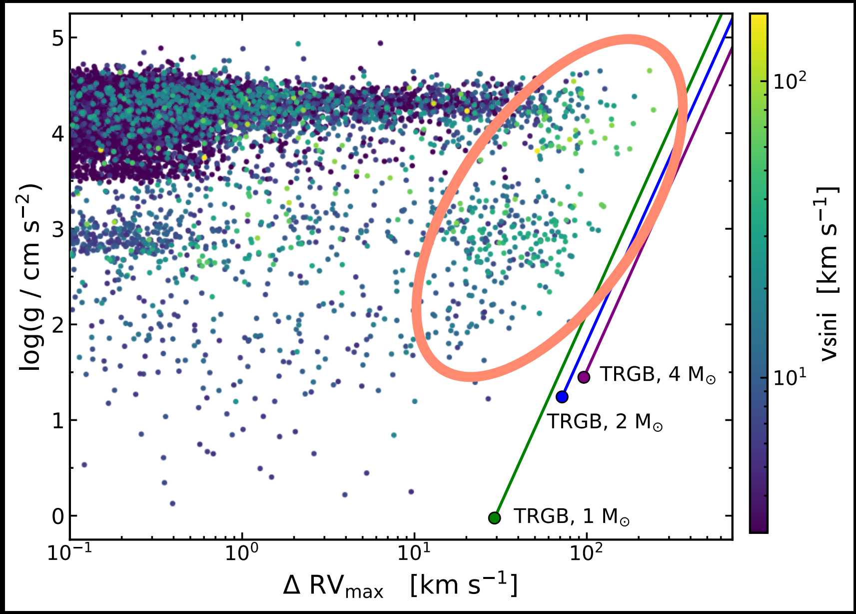

Daher+22

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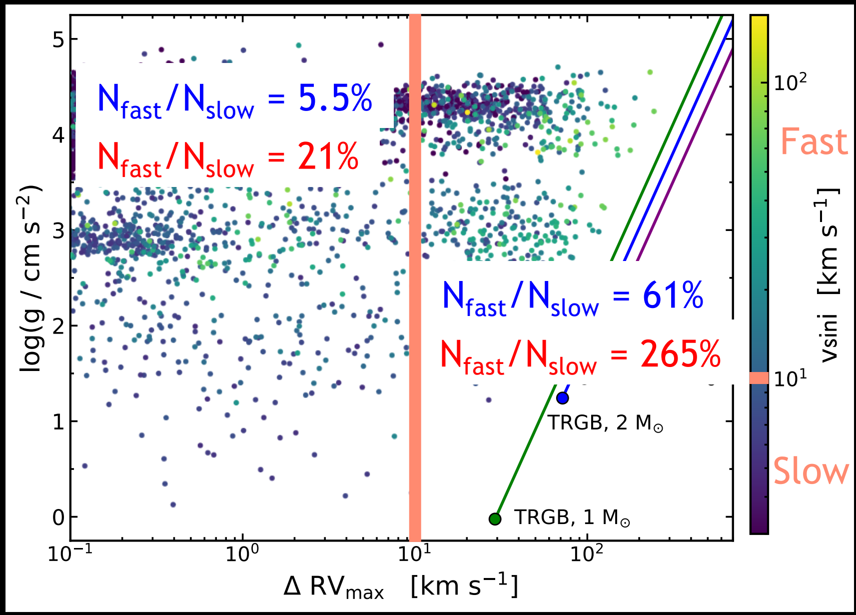


Daher+22

Hints of tidal interactions in close binaries?

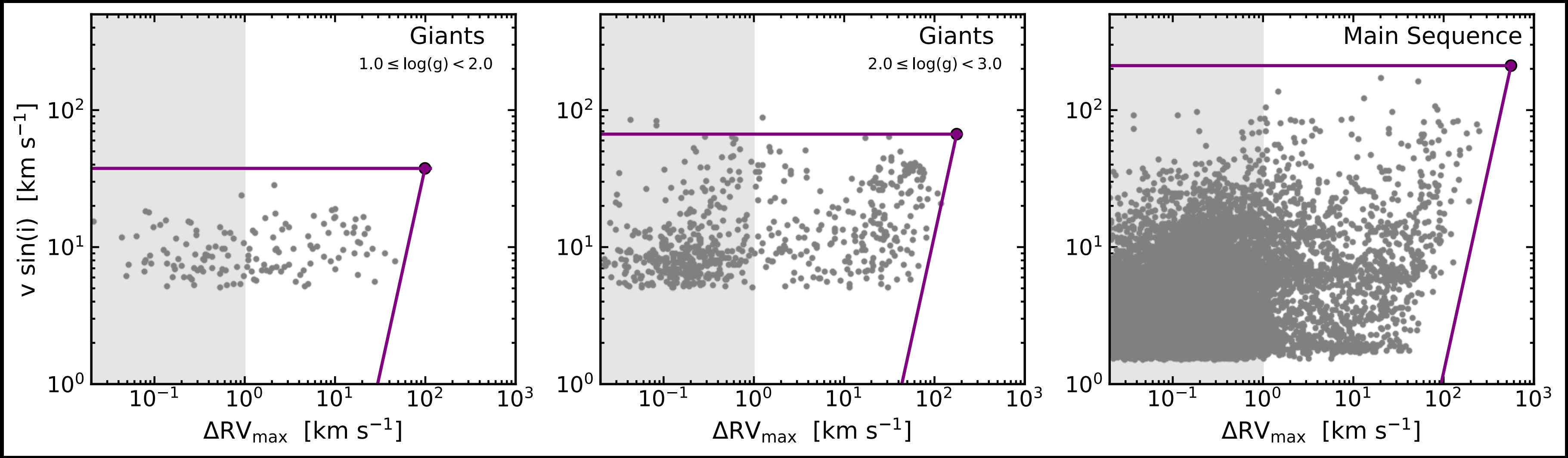
Results – *Evolution + Synchronization*

$$v\sin(i) \propto \frac{1}{P_{rot}}\sqrt{\frac{GM}{g}}$$

$$\Delta RV_{pp} \propto \left(\frac{M}{P_{crit}}\right)^{1/3}$$

$$P_{crit} \propto \left(\frac{GM}{g^3}\right)^{1/4}$$

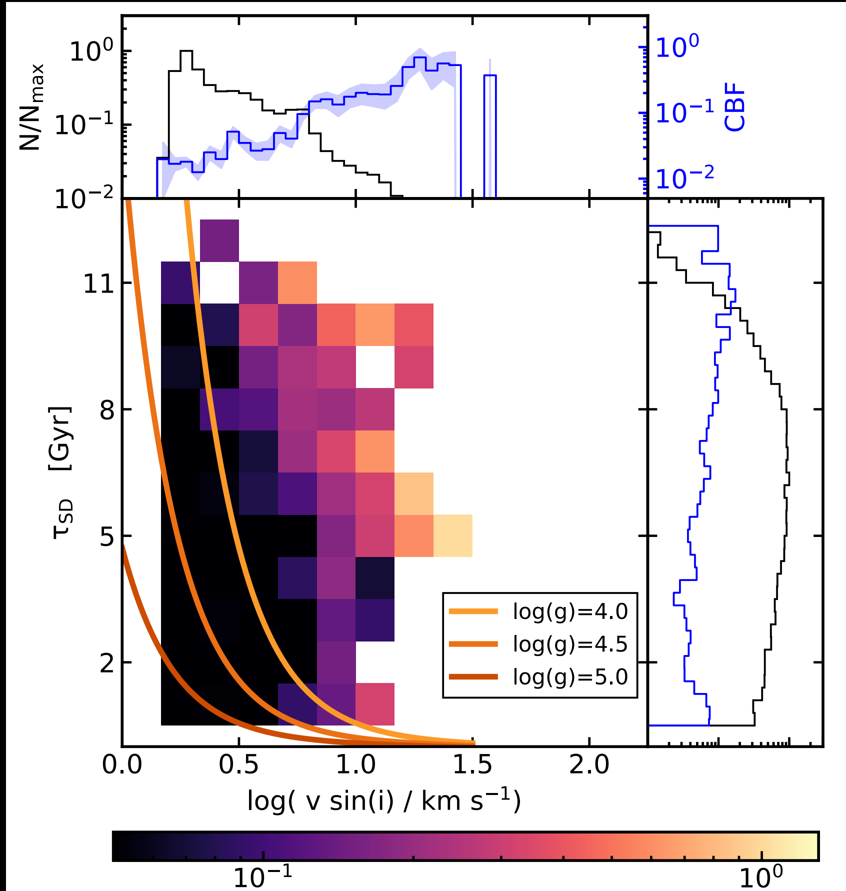
Assume rotational synchronization -- upper limits on *v* sin(i) *and* ΔRV_{max}!



Adapted from Daher+2022

Predictions from Gyrochronology

- Young stars can rotate at a range of speeds due to leftover angular momentum from birth.



Daher+2022

Predictions from Gyrochronology

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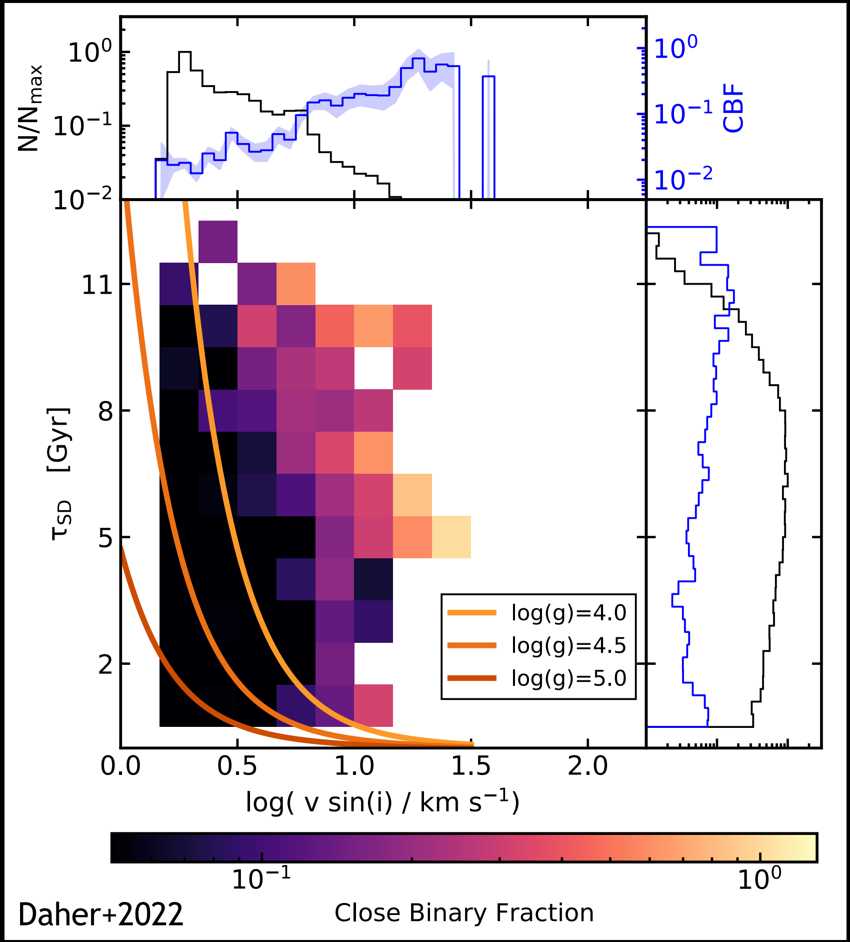
- In isolation, older MS stars below the Kraft break will naturally spin down over time.



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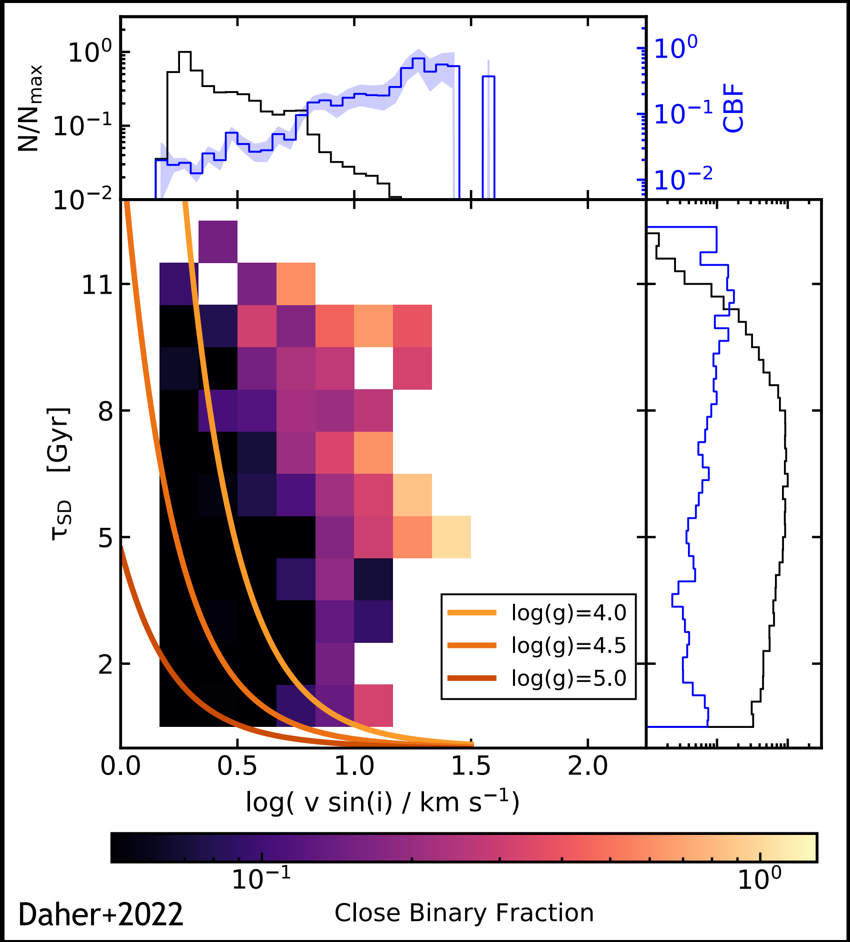
- Rotationally synchronized MS binaries rapidly rotate regardless of age.



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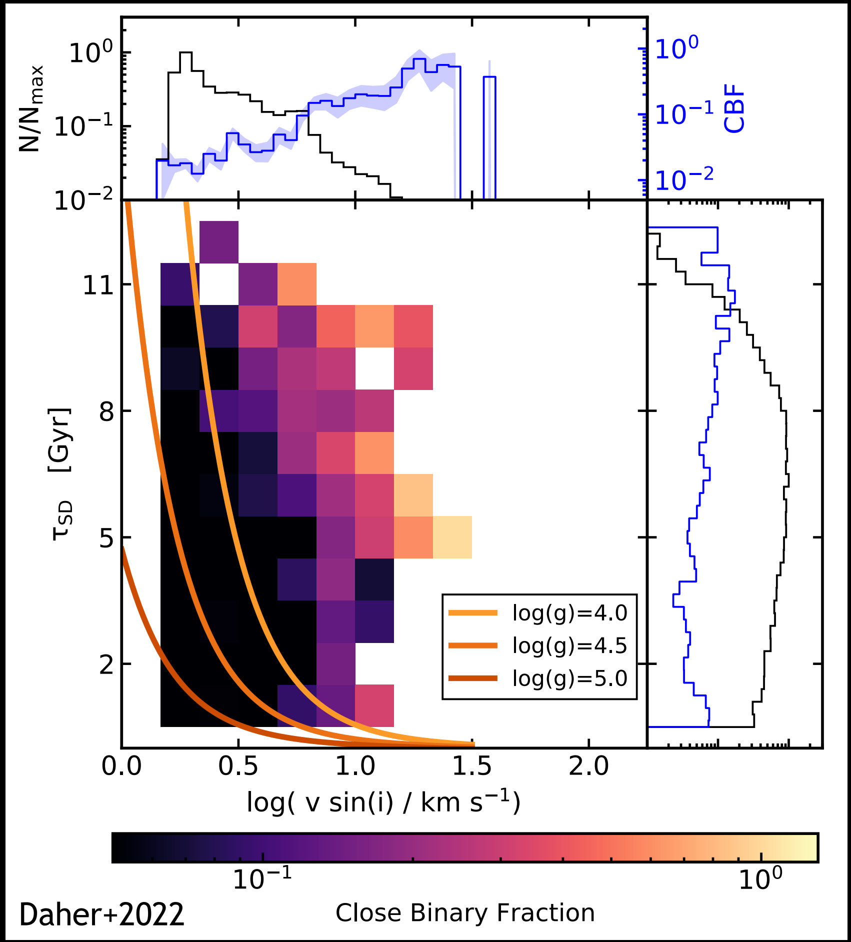
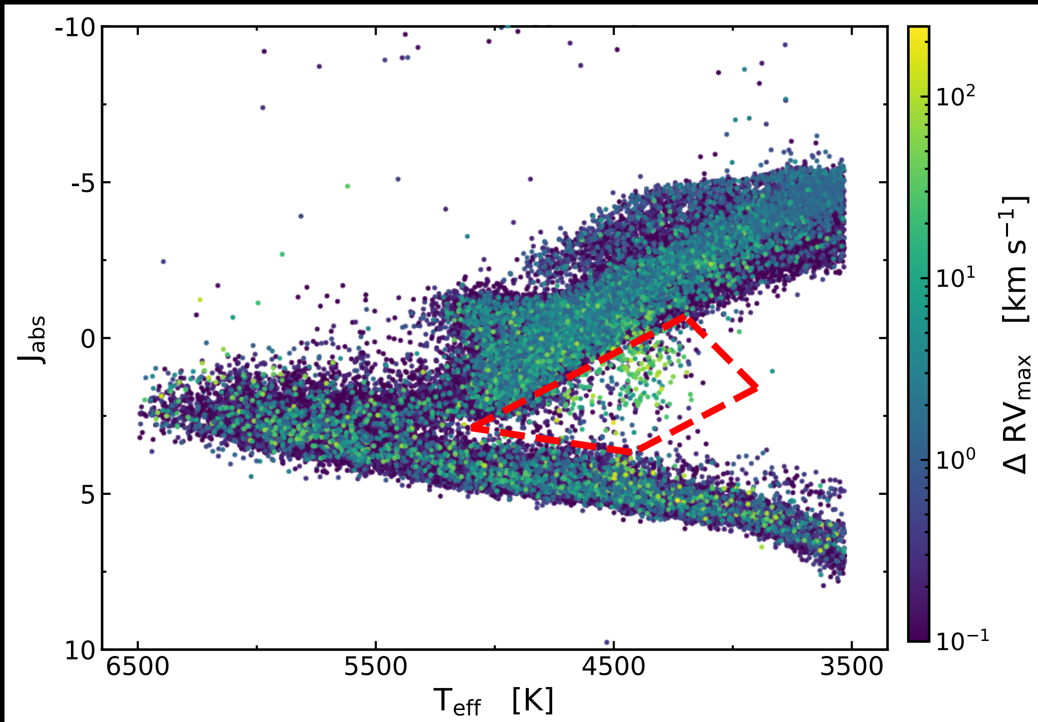
We both expect and observe an age-dependent correlation between *v* sin(i) and the CBF!



Future Work – *Rapid Rotators*



Possibly sub-subgiants [Geller+17a, Leiner+17, Geller+17b]

Don Dixon is looking at their TESS lightcurves in more detail!

Or…poor fits by APOGEE, leading to anomalously cool T_{eff}??

See Rachel Patton's poster and forthcoming paper for more!

Summary

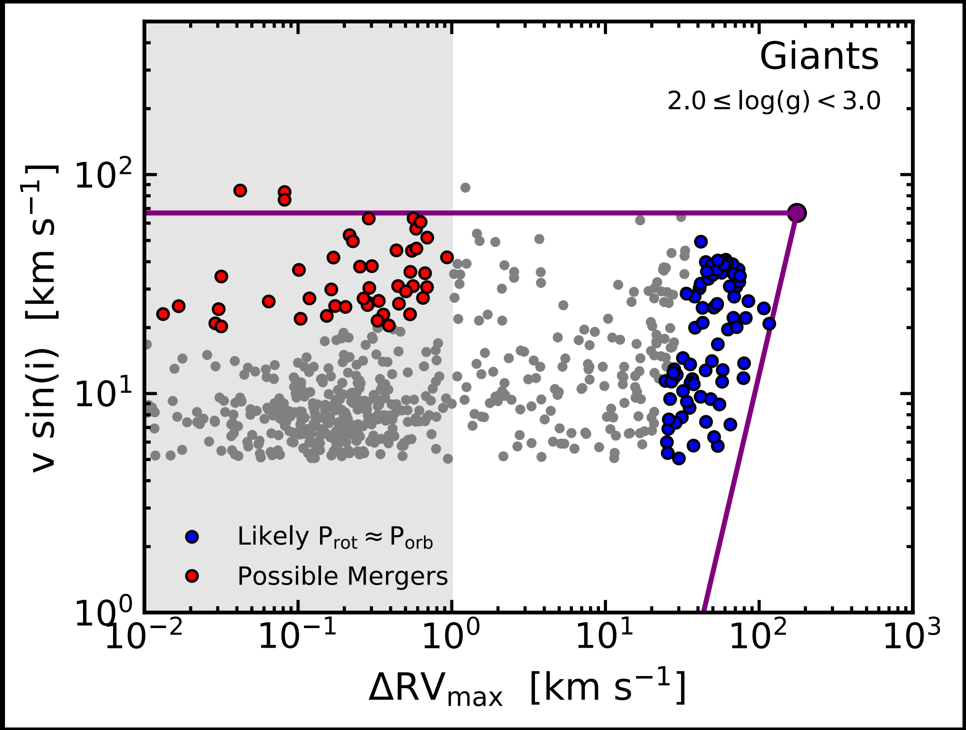
- APOGEE's formula for success:
  (high-res spectra + multi-epoch RV curves) x ~10^5 Milky Way field stars
  = large, statistical sample to study stellar multiplicity

- Sparse RV curves? No problem! Just use ΔRV_{max} to infer the presence of close companions up to $\log(P/\mathrm{d}) \leq 4$.

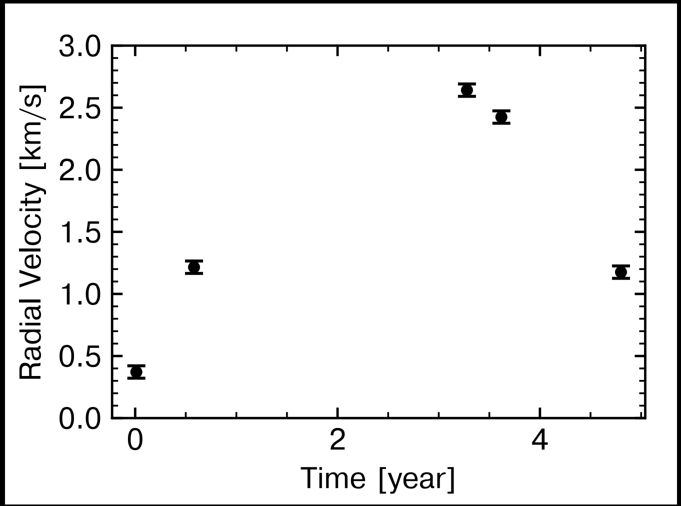
- With this, we've found:
  - Hints of tidal interactions via rotation: trends in data agree with simple rotational synchronization limits + attrition of short period systems as stars evolve
  - Link between age, rotation, and binarity: age-dependent correlation between rotation and CBF agree with expectations from gyrochronology

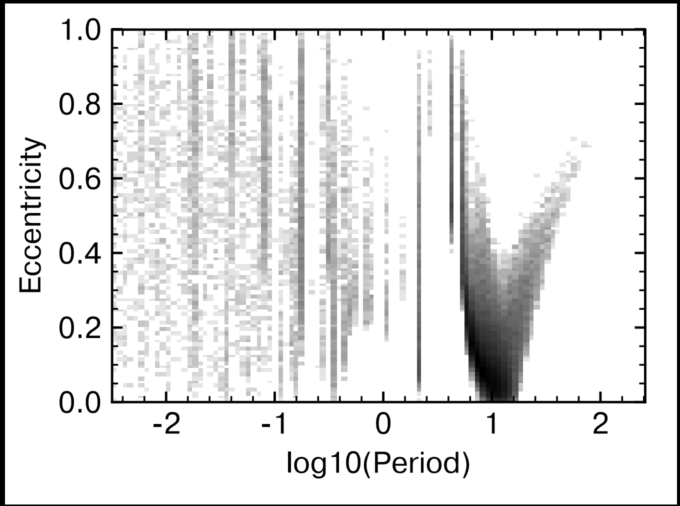
EX: Future Work – *Rapid Rotators*

- Likely to be synchronized: tightly constrain P_{orb} and compare with P_{rot}
  - Seek follow-up RVs with MWM when needed
  - *Gaia* DR3 should be able to help constrain radius and sin(i), improving P_{rot} from v sin(i)
- Likely to be interacting: search light curves for signs of active interactions
  - Can come from ASAS-SN, TESS, ZTF, *Kepler*, and in the future, LSST/VRO
- Unusually fast rotation: hyper-rotating when dwarfs, true binaries but unlucky RVs, *or* merger remnants??



EX: Future Work – *Bayesian Inference* + P_{orb}





NSF Grant AST-1909022

It may be impossible to tightly constrain a given binary's P_{orb} with 2-3 RVs…

But we can constrain P_{orb} as a function of Fe and α abundances using the weak constraints of 100,000s of APOGEE/MWM stars!

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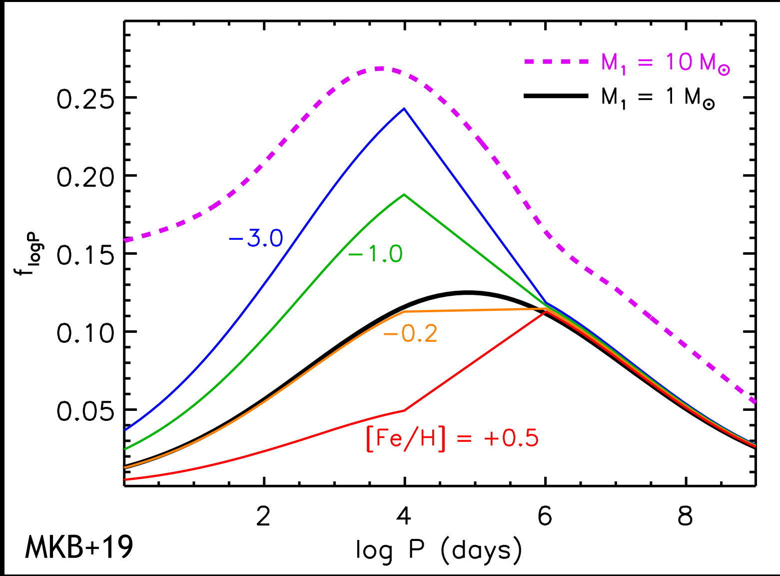
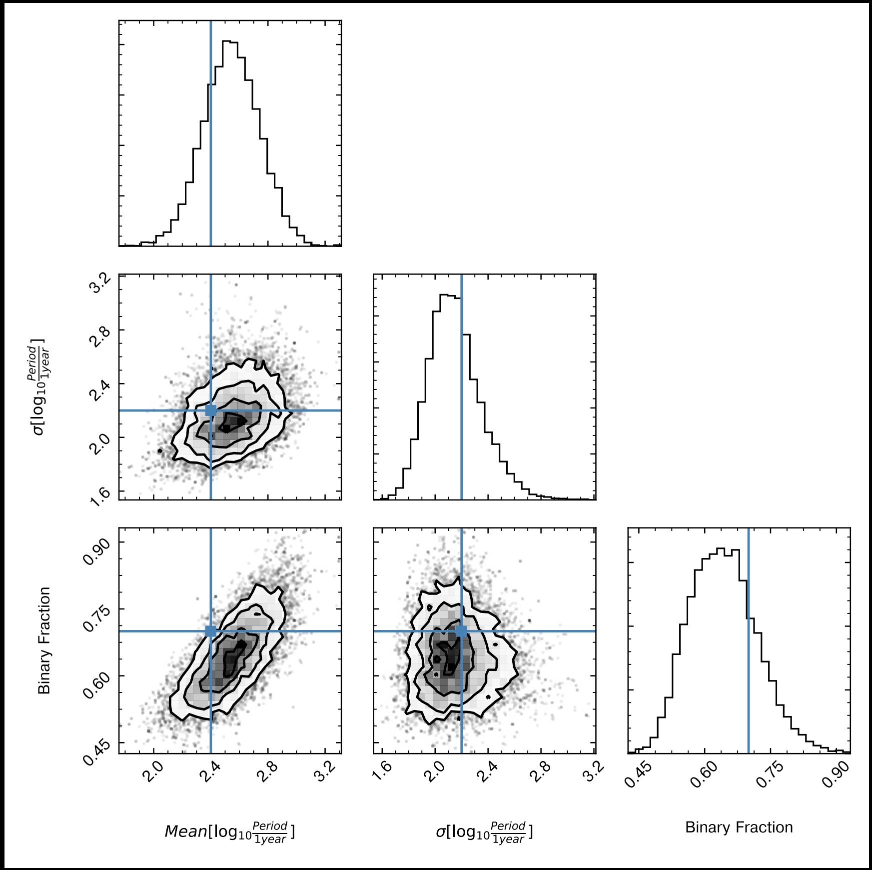
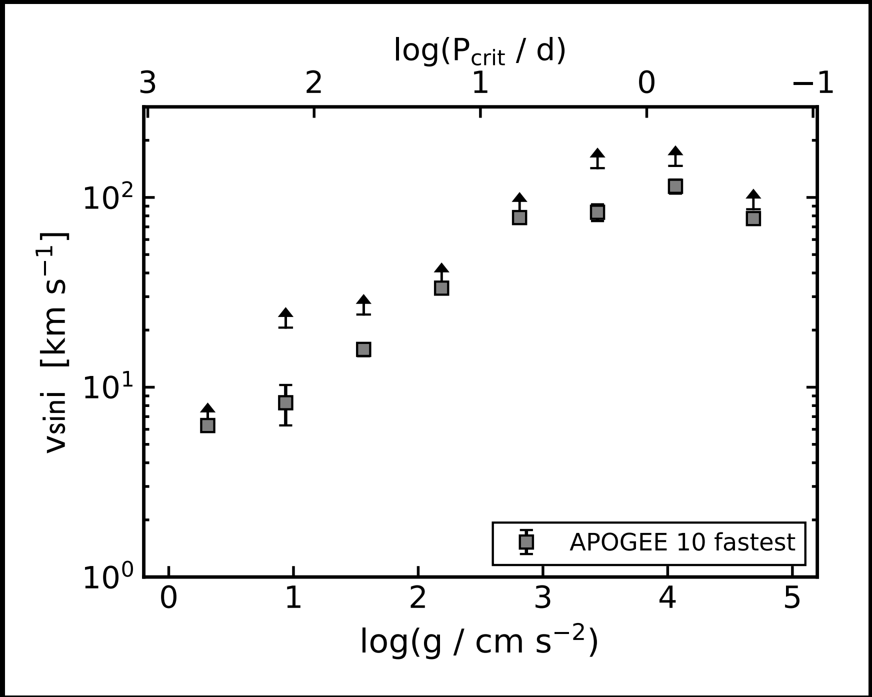




EX: Results – *Evolution + Synchronization*

Compare the fastest rotators as a function of log(g):

- Gray squares: median $v\sin(i)$ of the 10 fastest rotators
- Black arrows: $v\sin(i)$ of fastest rotator



Daher+22

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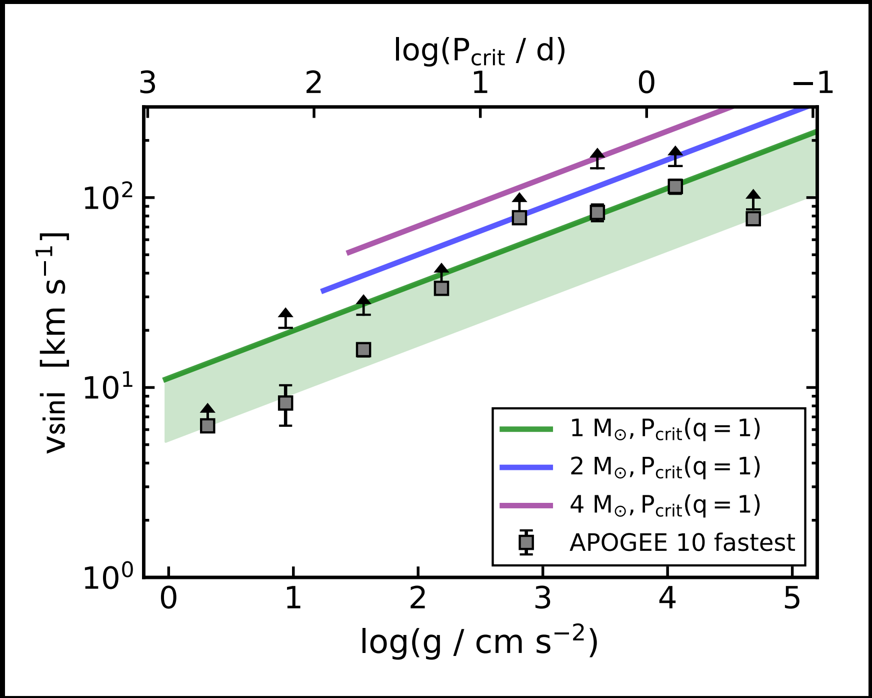
- Black arrows: v sin(i) of fastest rotator

Compare them against the max v sin(i) we expect from rotational synchronization, $P_{rot} \approx P_{crit}$:

$$v \sin(i) \propto \frac{1}{P_{rot}} \sqrt{\frac{GM}{g}}$$

$$P_{crit} \propto \left(\frac{GM}{g^3}\right)^{1/4}$$



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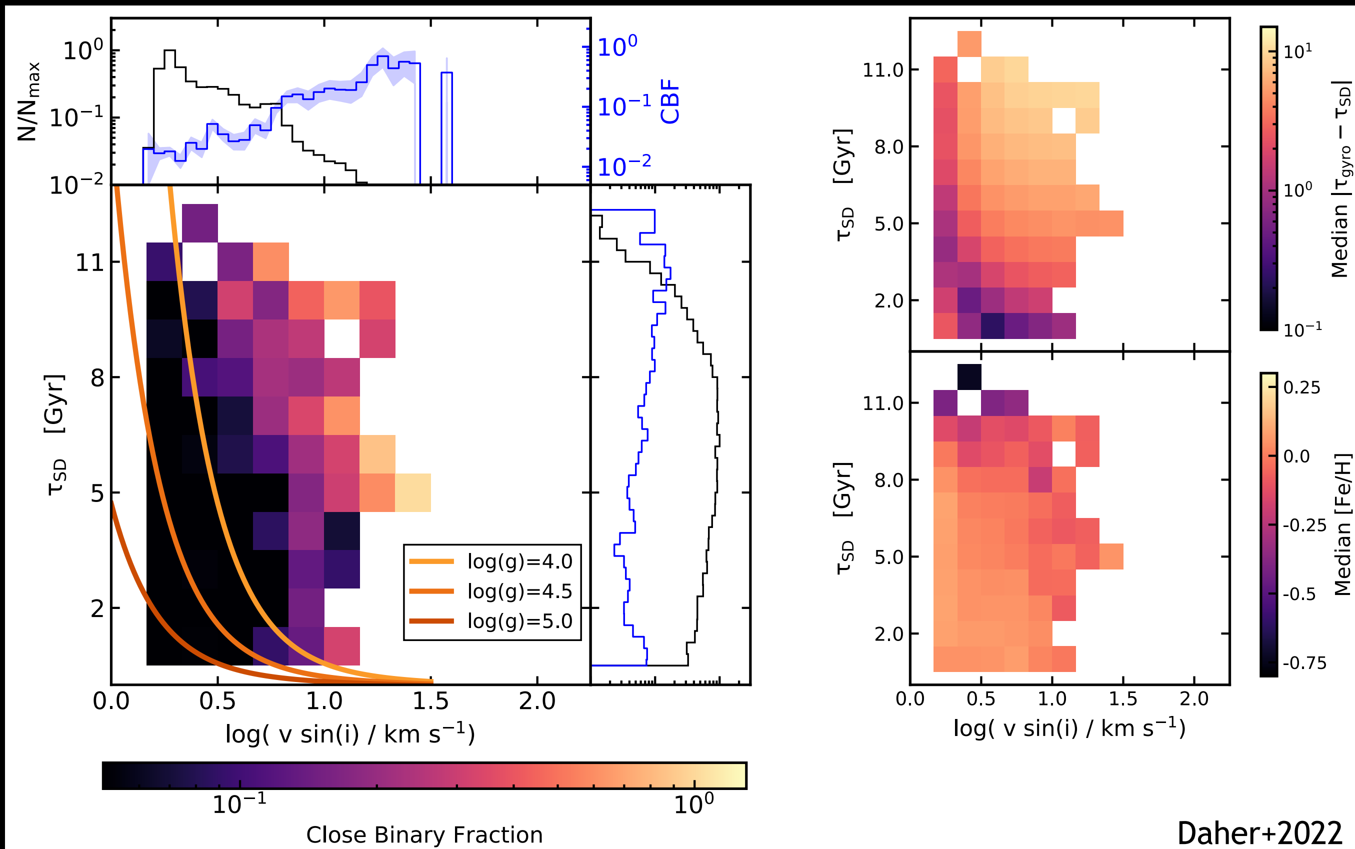
EX: Results – *Gyrochronology*



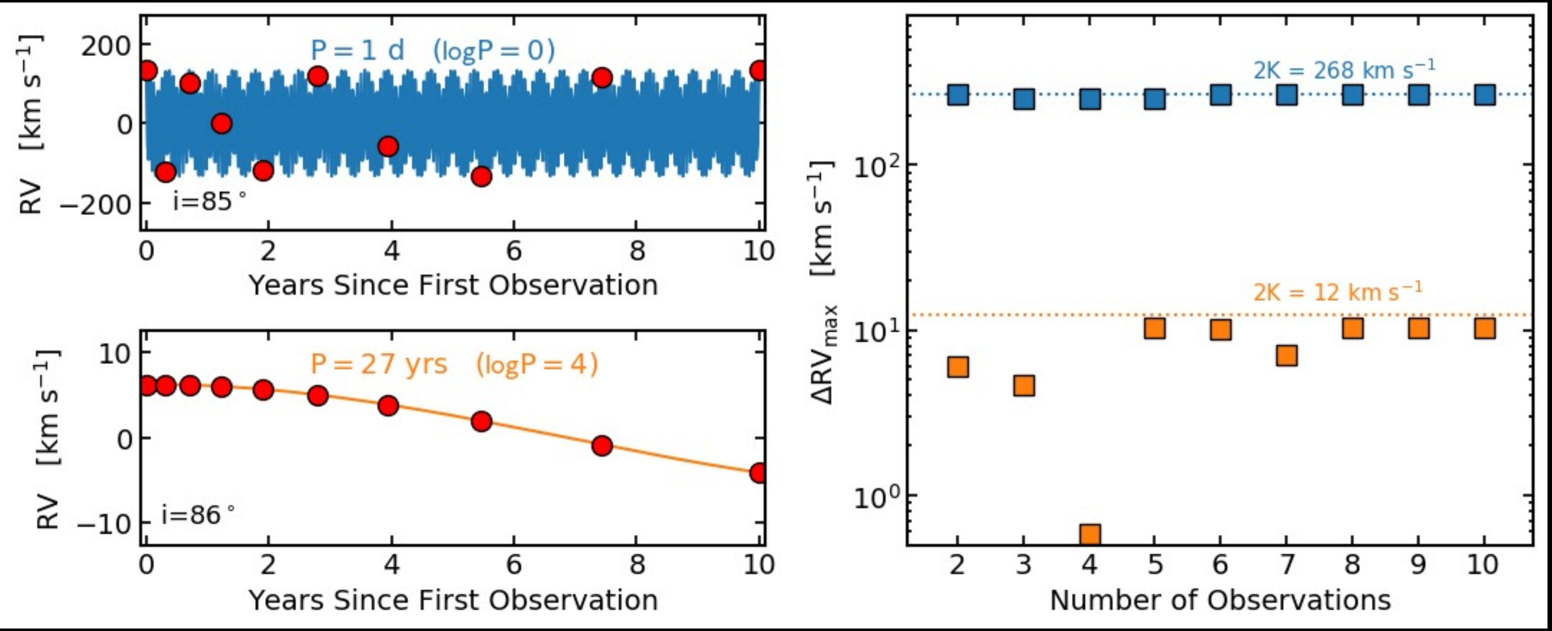
Huge discrepancies between isochronal and gyro ages, and not explainable by [Fe/H] differences!

EX: RV Curves – *Sparsely-Sampled* + ΔRV_{max}

How well does ΔRV_{max} capture the true RV variability of a

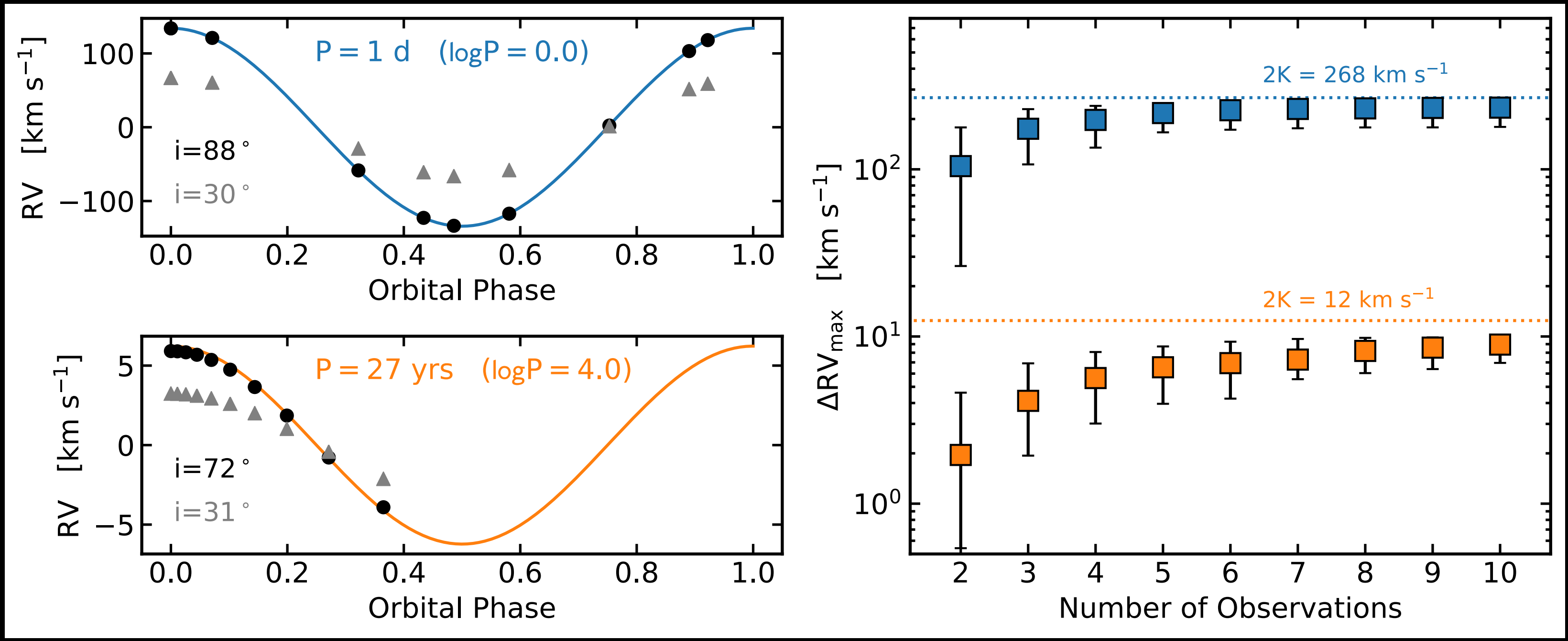
(i) a very close binary: P = 1 day (a ≈ 0.02 AU)

(ii) a bit wider binary: P ≈ 27 years (a ≈ 11 AU)



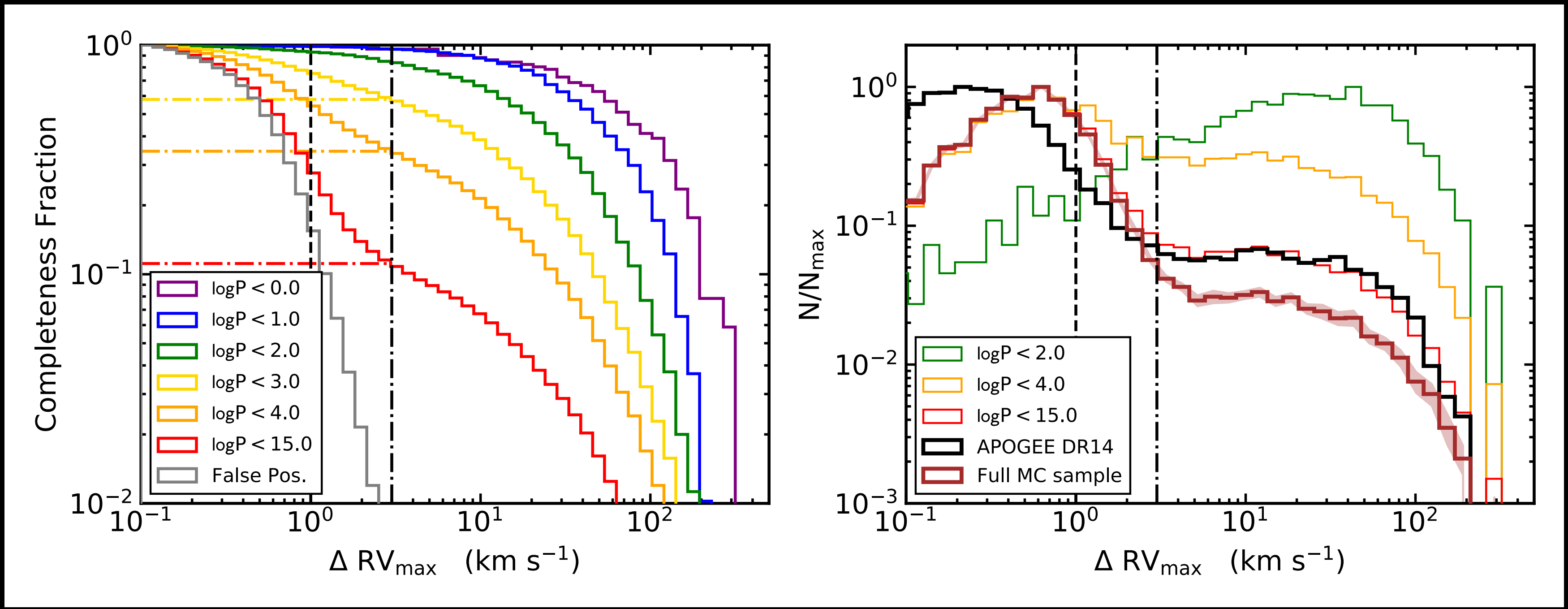
EX: RV Curves – ΔRV_{max} + *Marginalize Over Inclination*

Simulate 1000 systems with inclinations randomly sampled from a uniform distribution



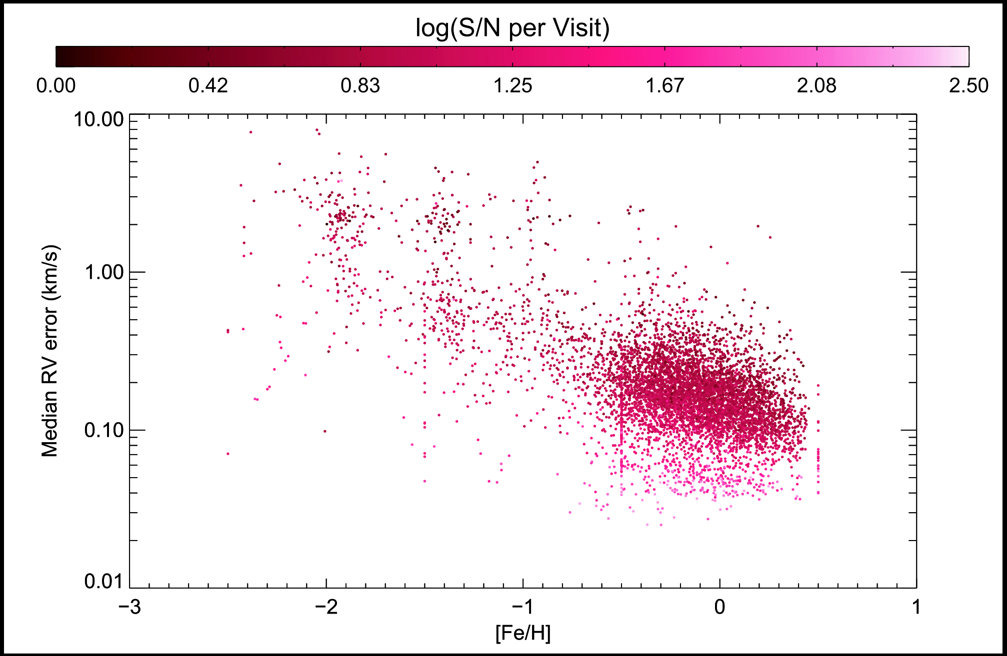
EX: RV Curves – f_{RVvar} -> *CBF*

Convert f_{RVvar} into a completeness-corrected close binary fraction based upon simulated binaries and our chosen $\Delta\mathrm{RV}_{\mathrm{max}}$ threshold!



Adapted from Mazzola+2020

EX: RV Errors – *Observed*



Troup+2016

APOGEE reports ~100 m/s

Milky Way Mapper (SDSS-V) hopes for 10 m/s!

EX: RV Errors – *Observed*

APOGEE reports ~100 m/s

Milky Way Mapper (SDSS-V) hopes for 10 m/s!

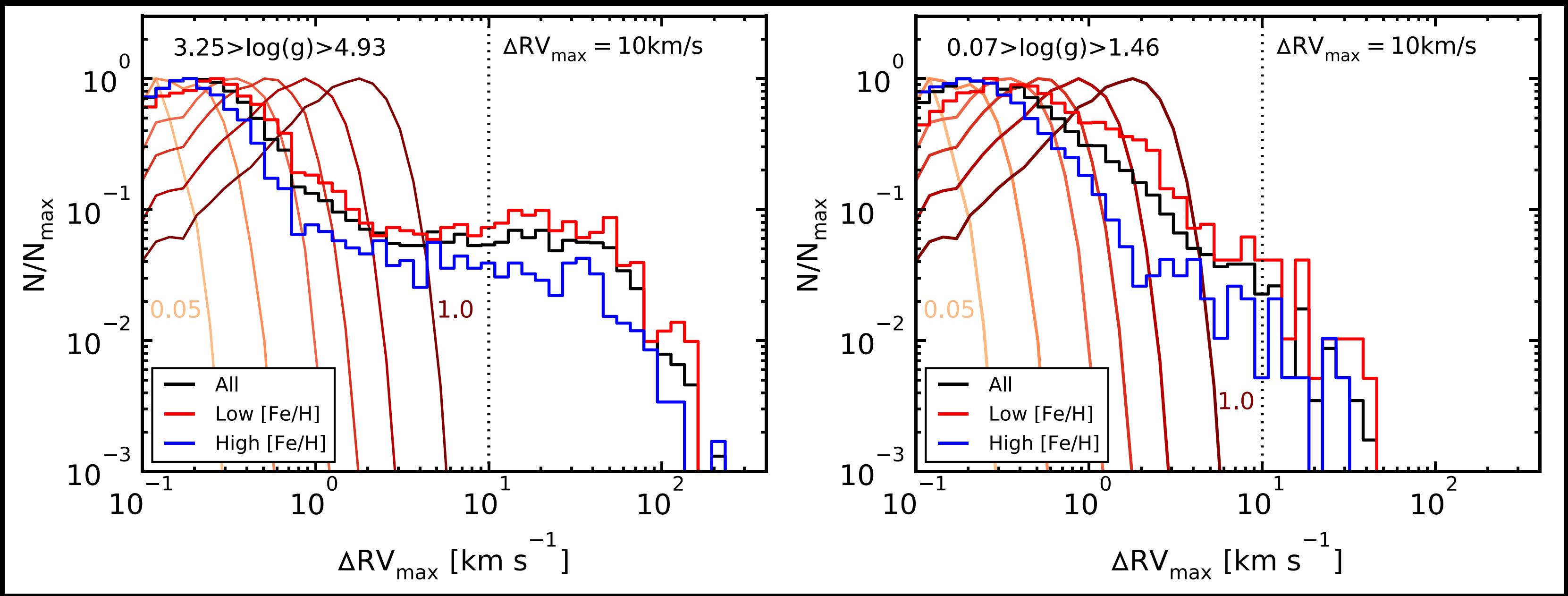
Truthfully, RV errors are hard...

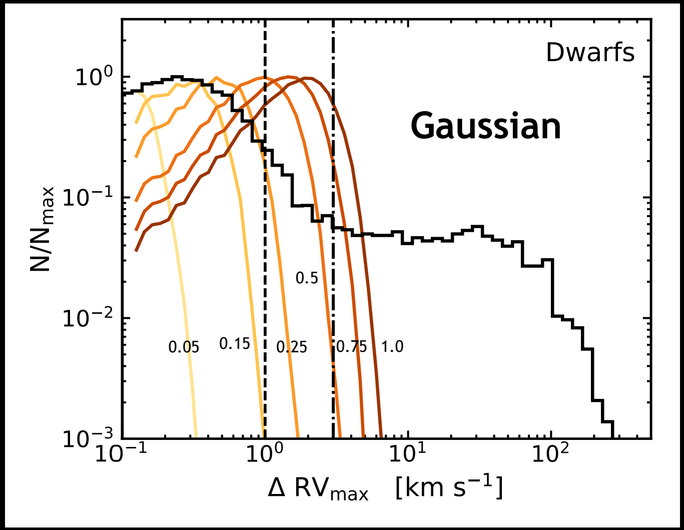
EX: RV Errors – *Observed*

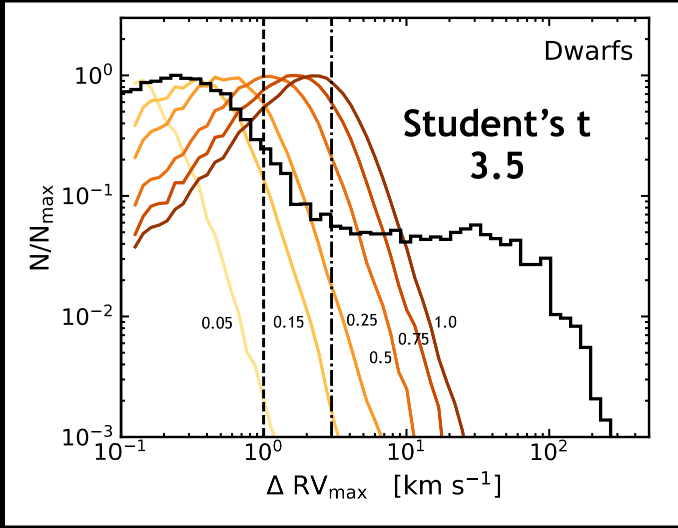
RV errors, and thus the ΔRV_{max} core, increase based on sample properties

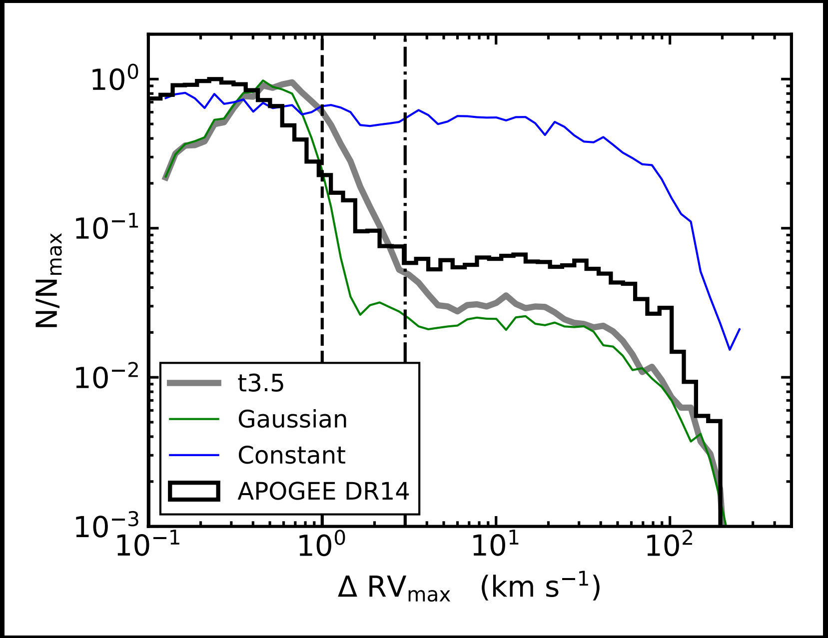
- lower log(g) (RV jitter)
- lower [Fe/H] (weaker lines)

Badenes, CMD+2018





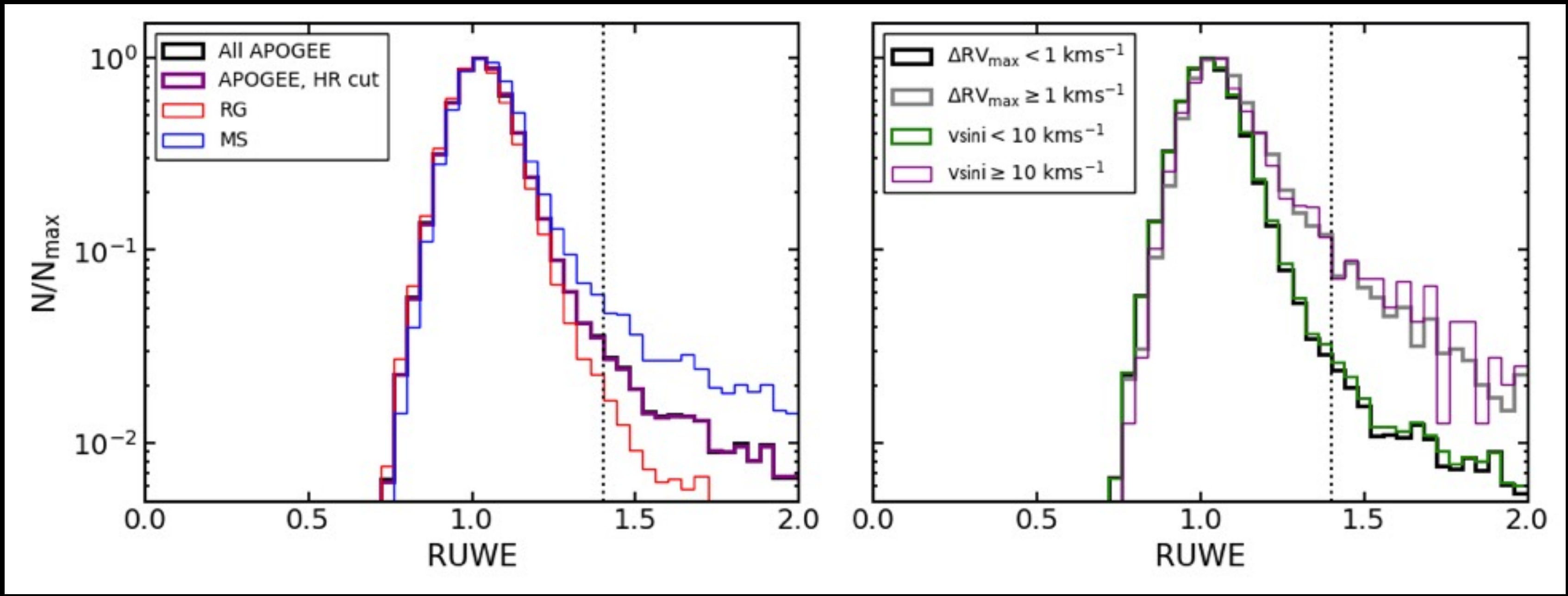




Mazzola+2020

Some success modeling with a Student's t distribution as compared to Gaussian

EX: CBF and Rotation – *Gaia RUWEs*



- RUWEs are larger for MS than for RG
- RUWEs are larger for RV variables and rapid rotators