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Uncovering Binary Formation Channels Using APOGEE

Christine Mazzola Daher

CCAPP Fellows Symposium
Sept. 30, 2022

Carles Badenes, Max Moe, Kaitlin Kratter

Why study binaries?

Because stellar multiplicity affects or is tied to practically every area of astronomy!

Astro2020 Science White Paper

Stellar multiplicity: an interdisciplinary nexus

Thematic Areas: ☑ Planetary Systems ☑ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

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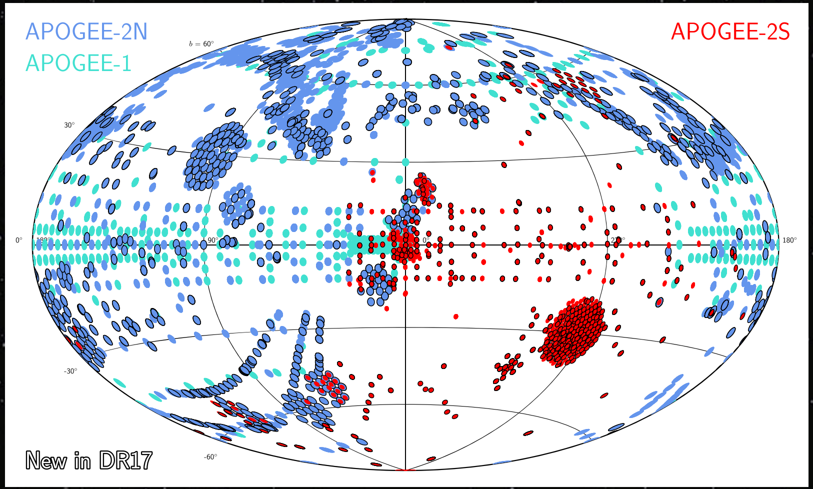
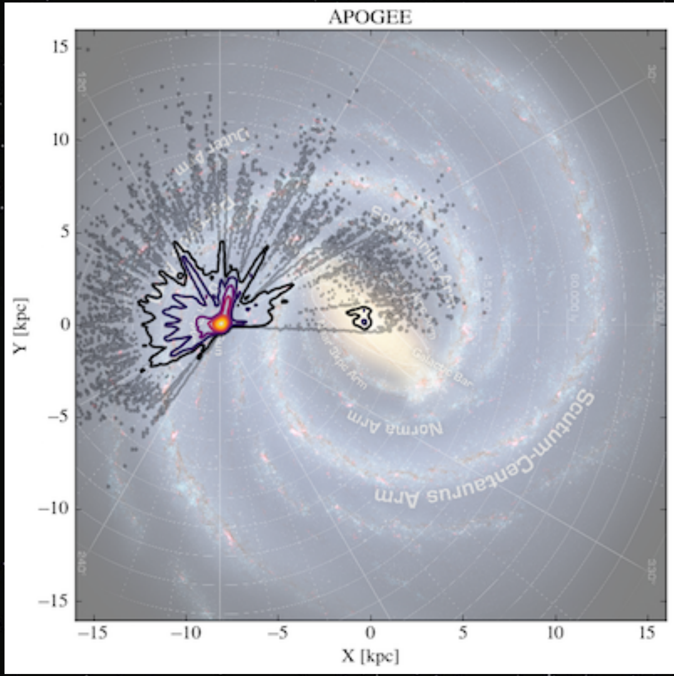
SDSS-IV: APOGEE-2 – *Overview*

- 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)*

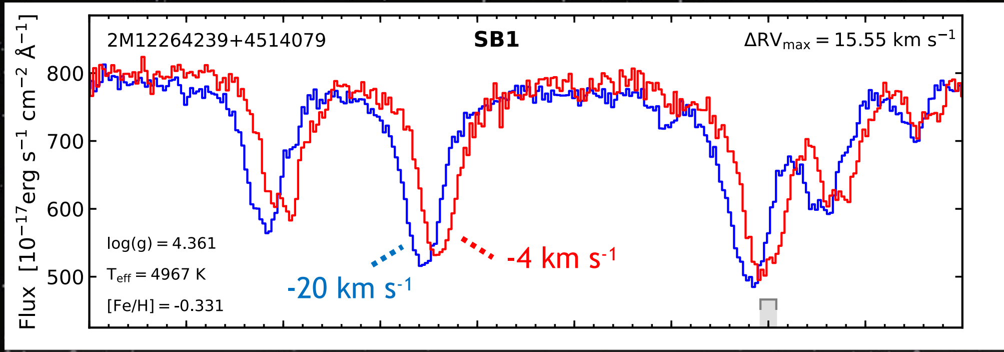


Kollmeier+2017

SDSS-IV: APOGEE-2 – *Spectra*

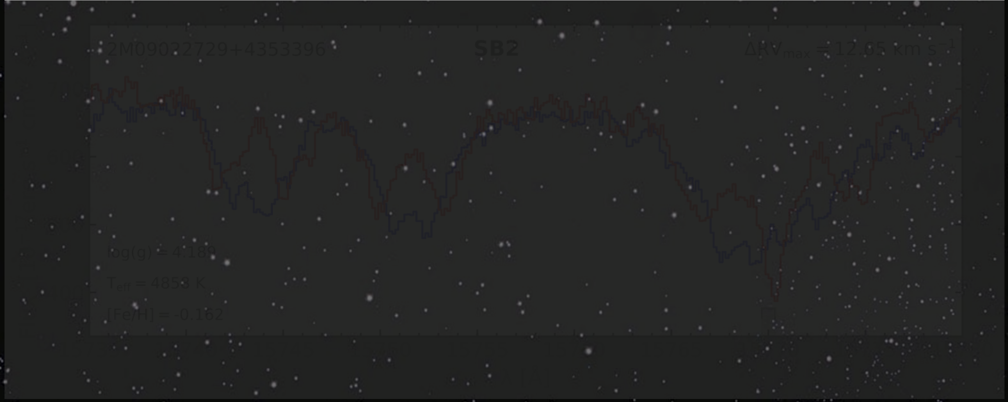
Spectroscopic Binary 1 (SB1)

- Only see clear spectral features from the photometric primary
- Lines Doppler shifted periodically due to orbital motion
- Convert those shifts into radial velocities (RVs)



Spectroscopic Binary 2 (SB2)

- See clear spectral features from both primary and secondary
- Line blending and inconsistent RV determination can confound the APOGEE pipeline



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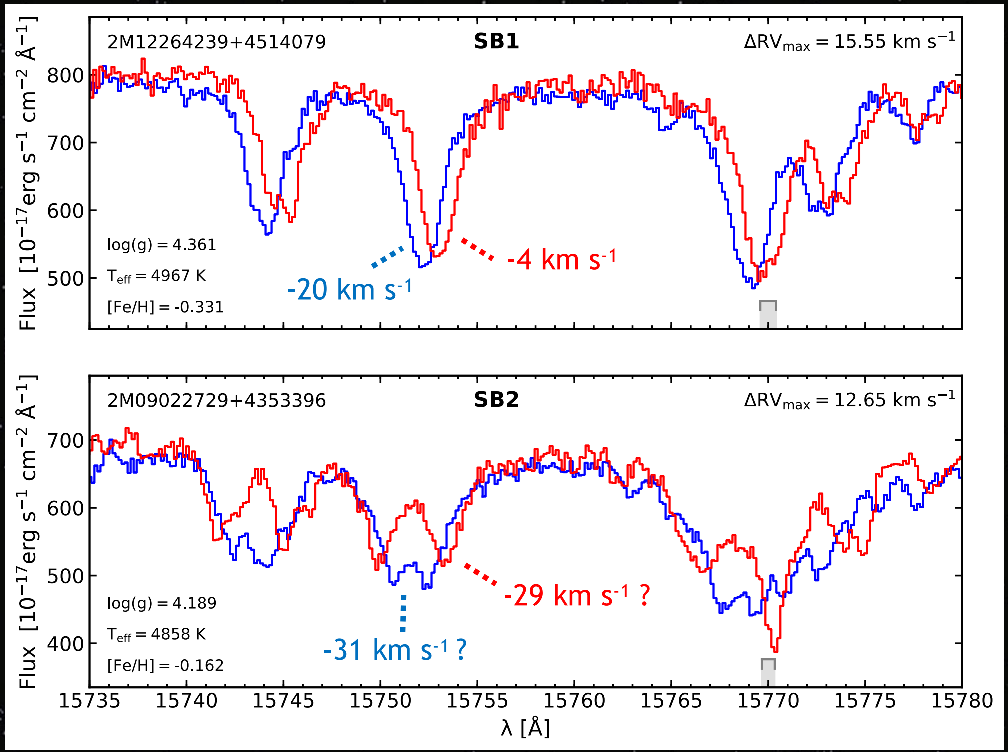


RV Curves – *Theory*

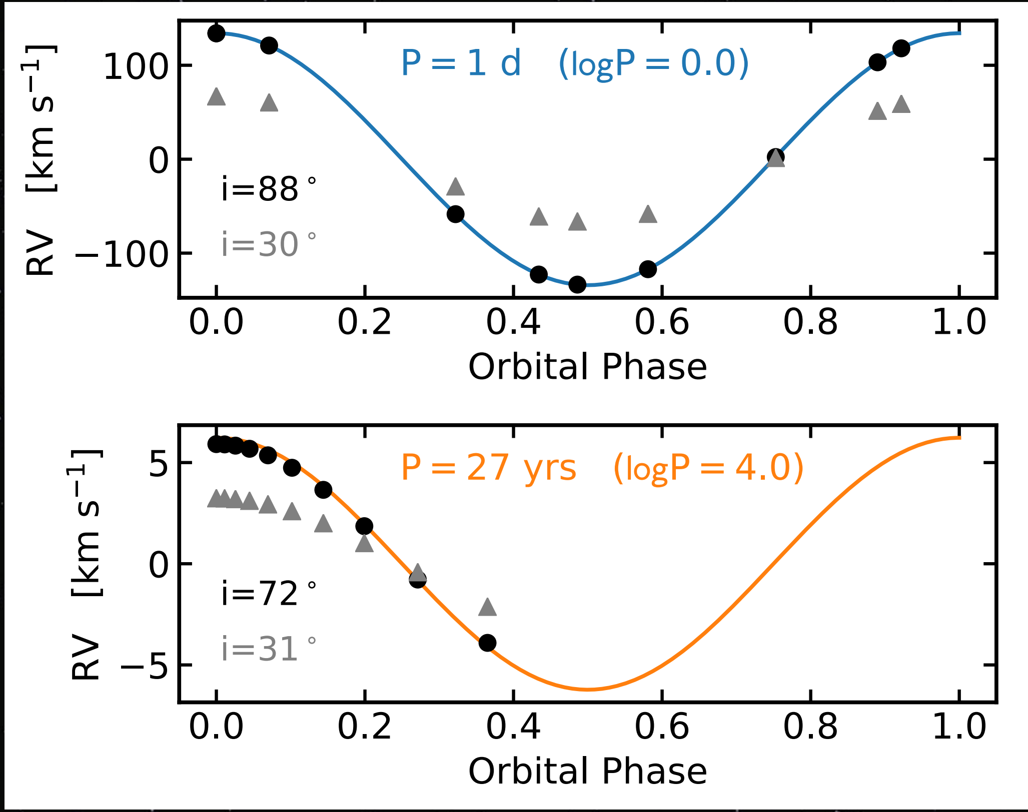
$$\mathrm{RV}_1(t) = K\ \sin i\ \left(\cos(\nu(t)+\omega) + e\cos\omega\right)$$

- *K* : semi-amplitude
- *i* : inclination
- *e* : eccentricity

Maximum possible RV shift = 2*K*

$$K = \frac{2\pi}{\sqrt{1-e^2}}\ \frac{a}{P}\ \frac{q}{1+q}$$

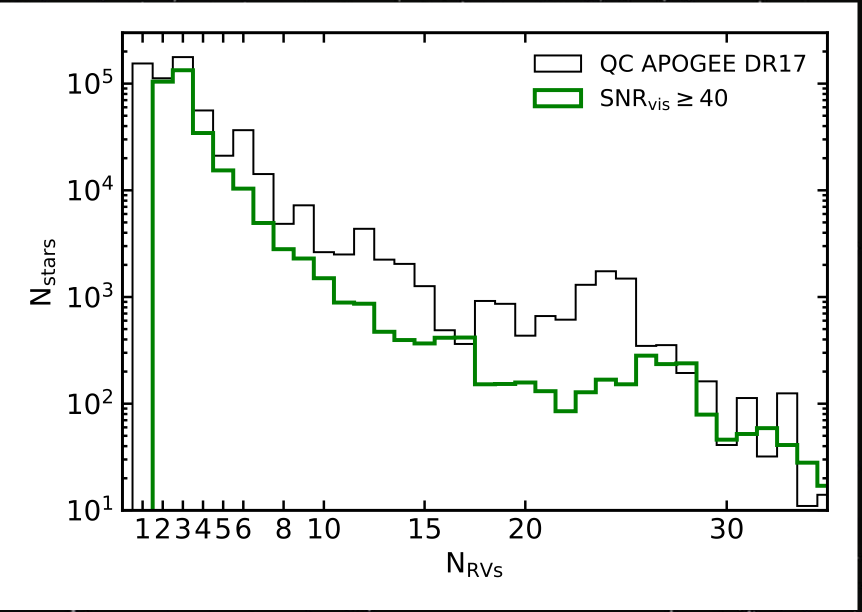
- *P* : period
- *q* : mass ratio, m_2/m_1
- *a* : orbital separation



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.



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.

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

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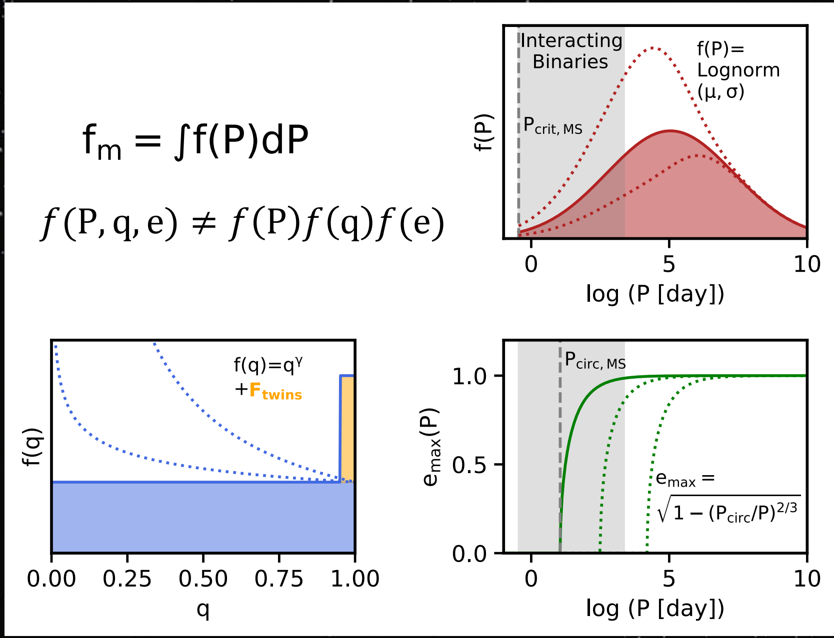

NSF Grant AST-1909022

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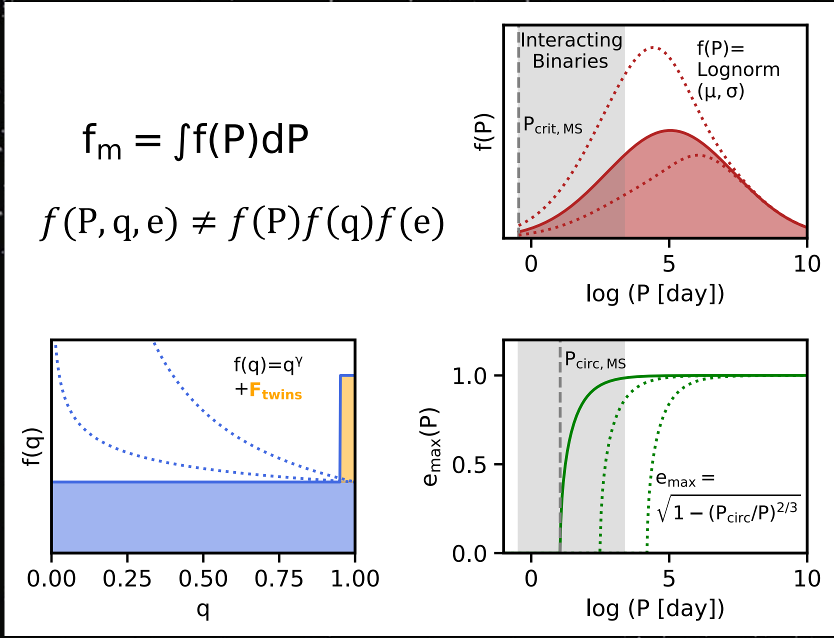

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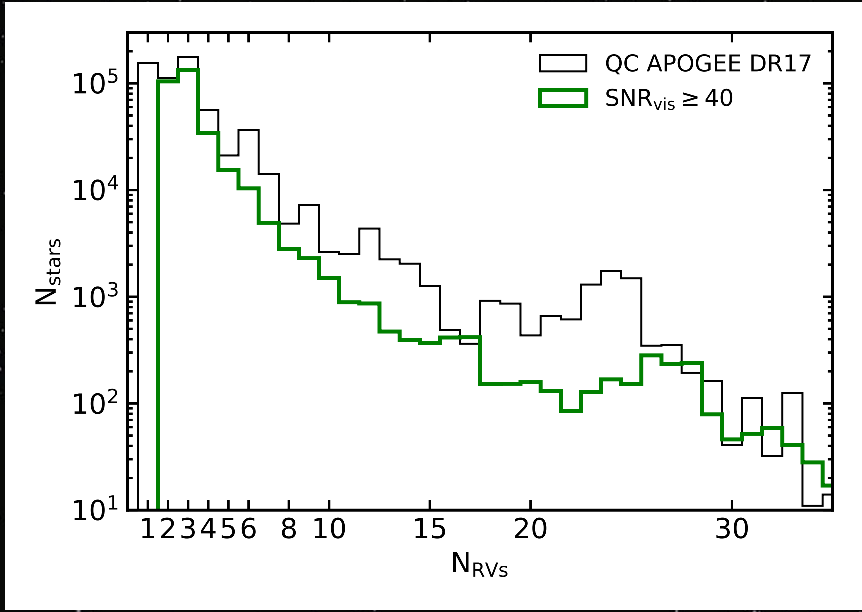
RV Curves – *Sparsely-Sampled* + ΔRV_{max}

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



$$\Delta RV_{max} = |RV_{max} - RV_{min}|$$

$$f_{RVvar} = \frac{N_{\Delta RV_{max} \geq X \text{ km s}^{-1}}}{N_{total}}$$

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

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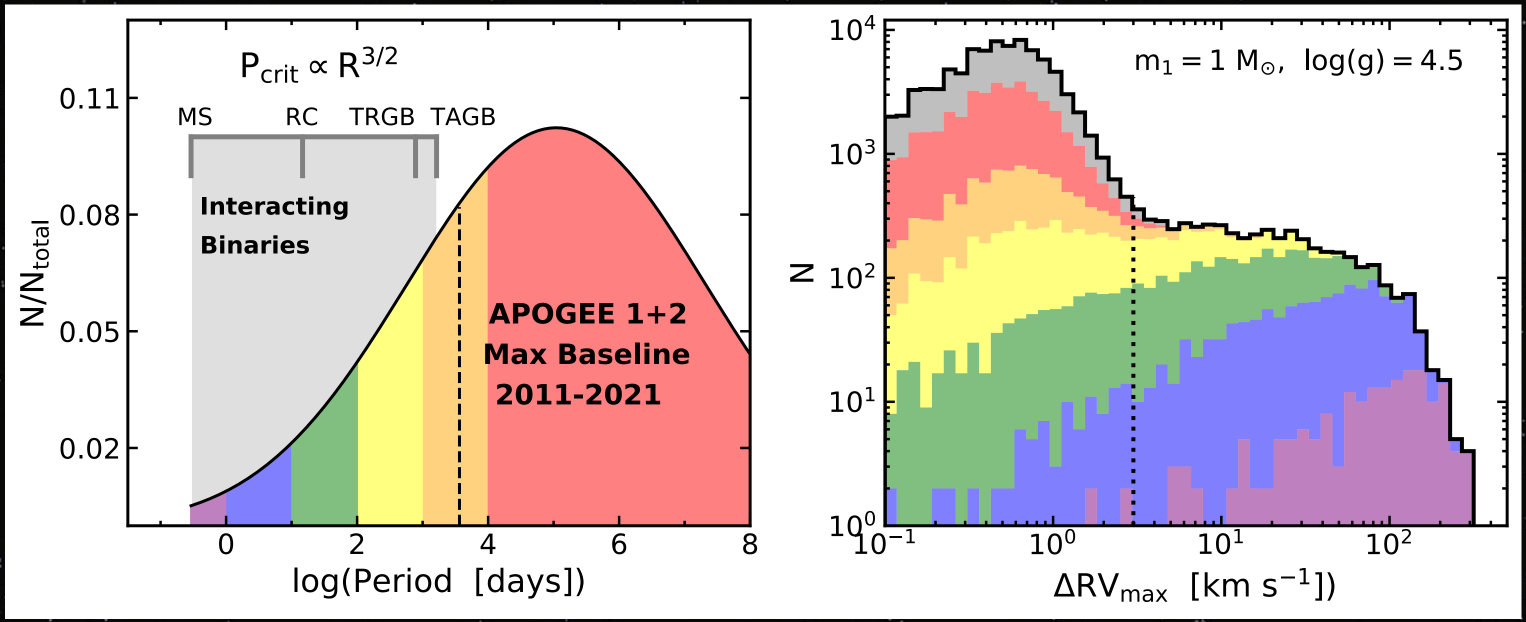

- Low ΔRV_{max} "core" dominated by single stars (gray) + long-period binaries
- High-ΔRV_{max} "tail" dominated by short-period binaries
- Choose a threshold ΔRV_{max} value to define RV variability

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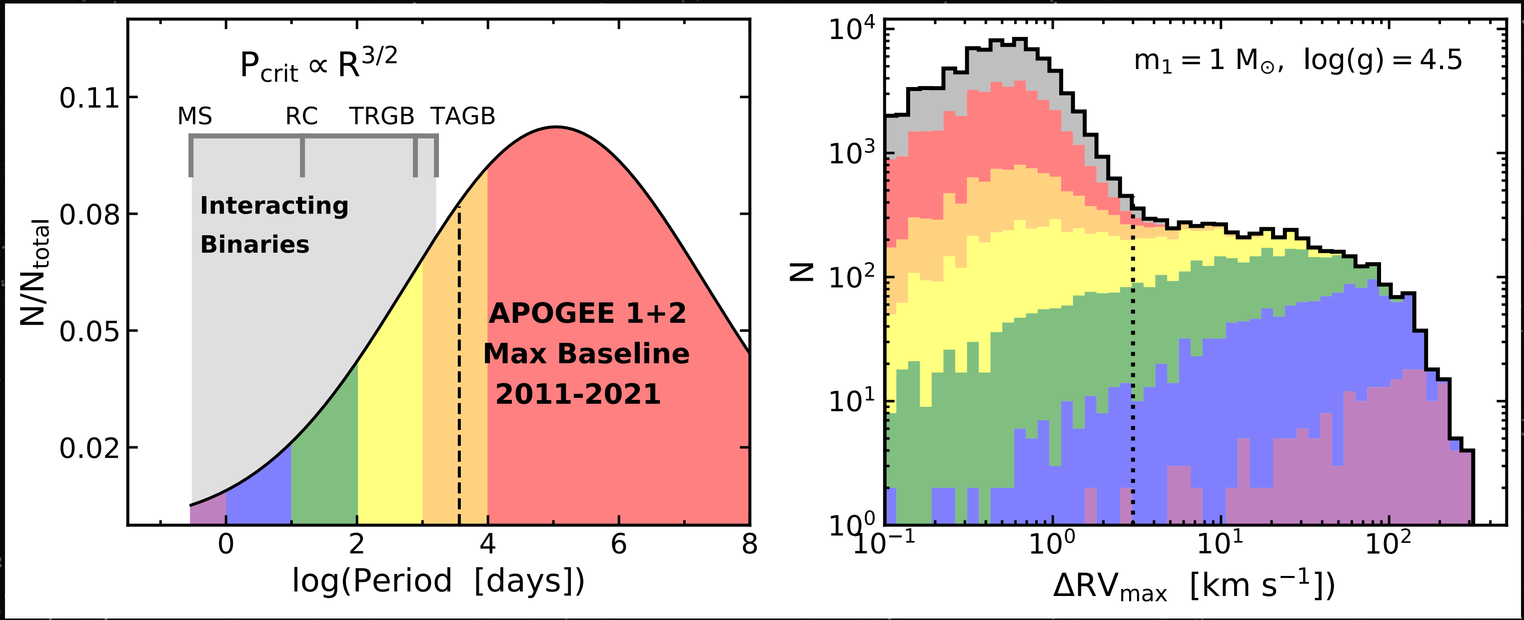

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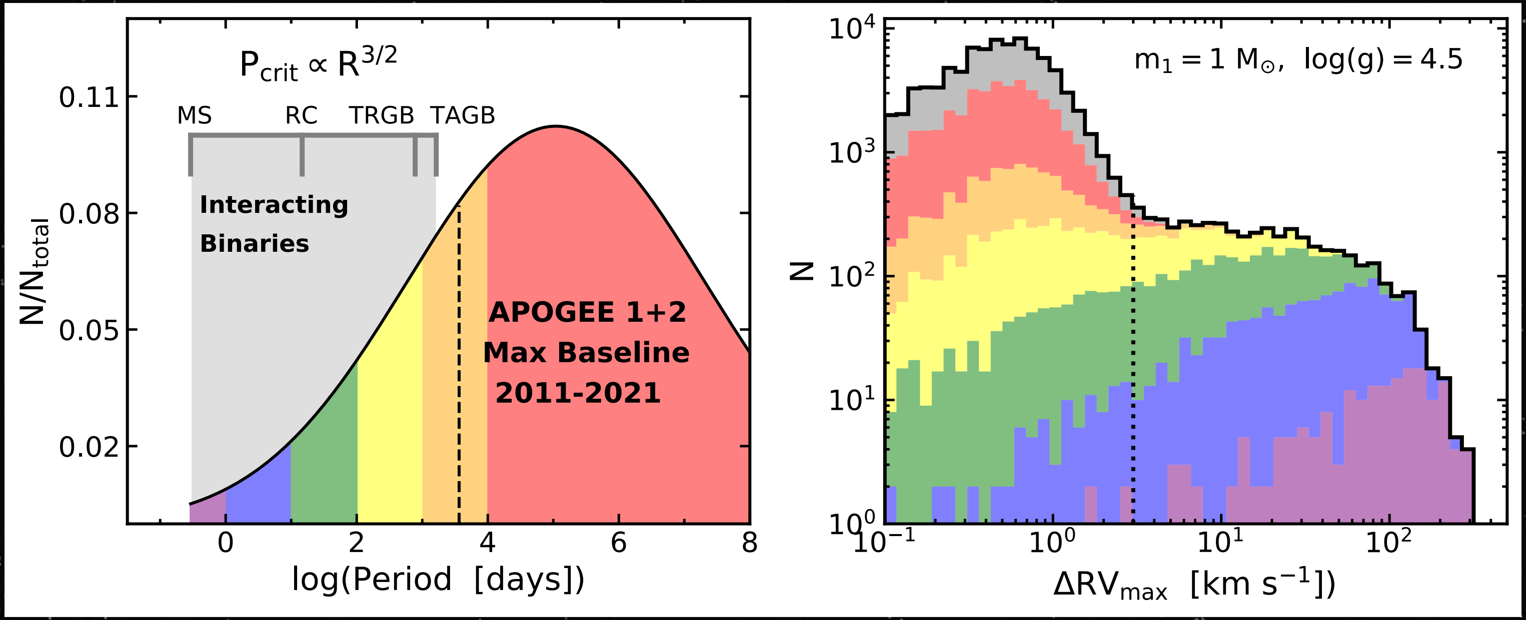

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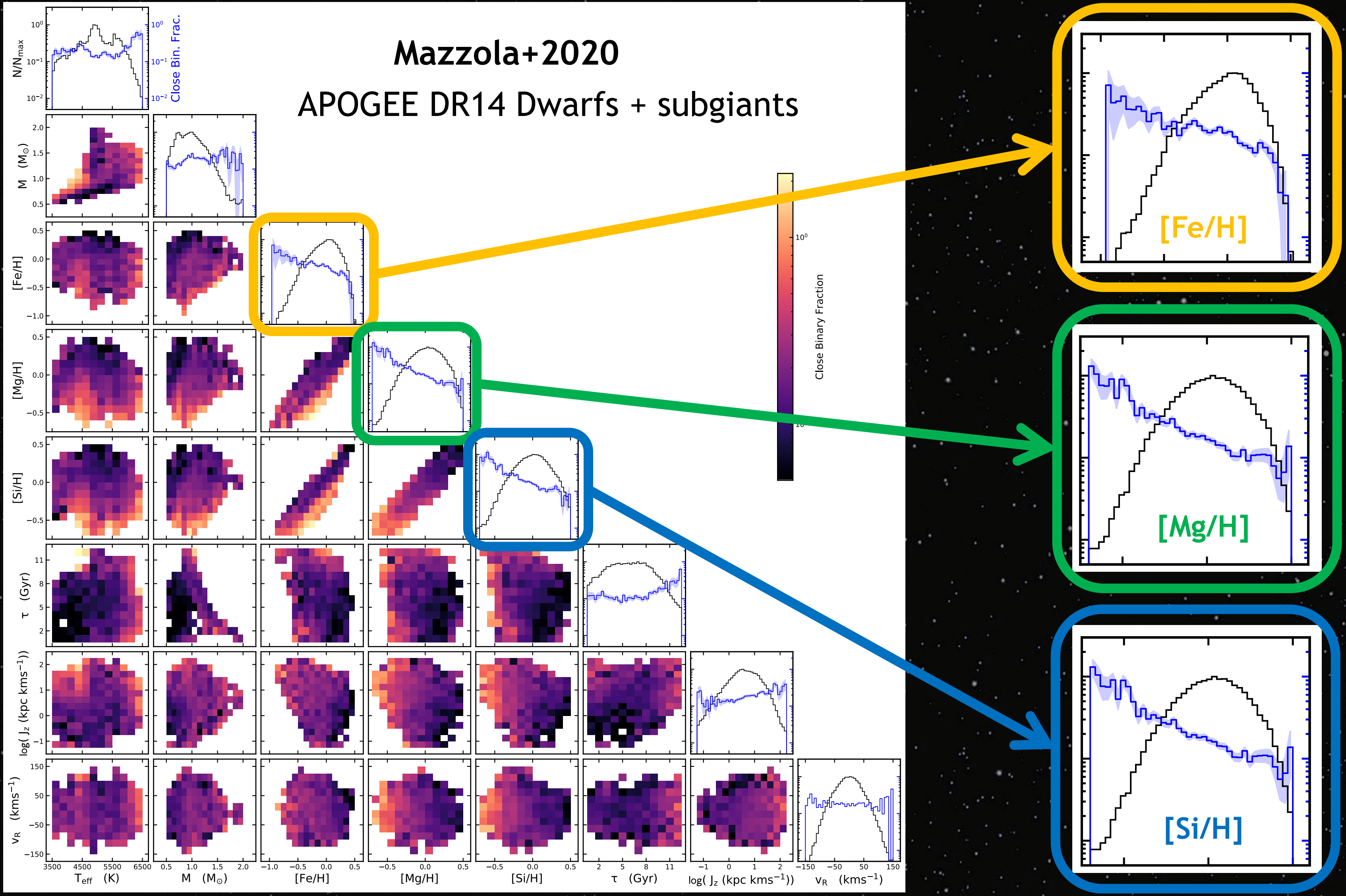
Mazzola+2020

APOGEE DR14 Dwarfs + subgiants

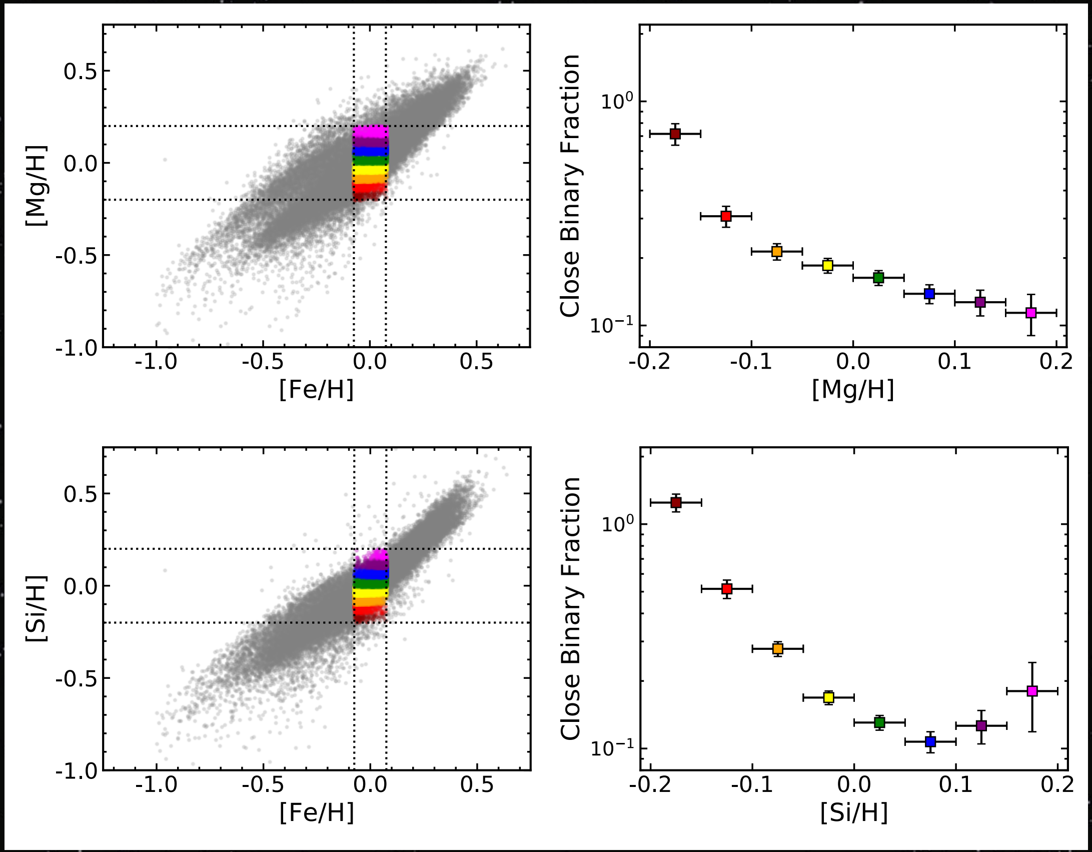


CBF and Chemistry – *Results*

Stronger anti-correlation between CBF and α than with Fe,

but…

Strongly non-monotonic at solar [Fe/H]!

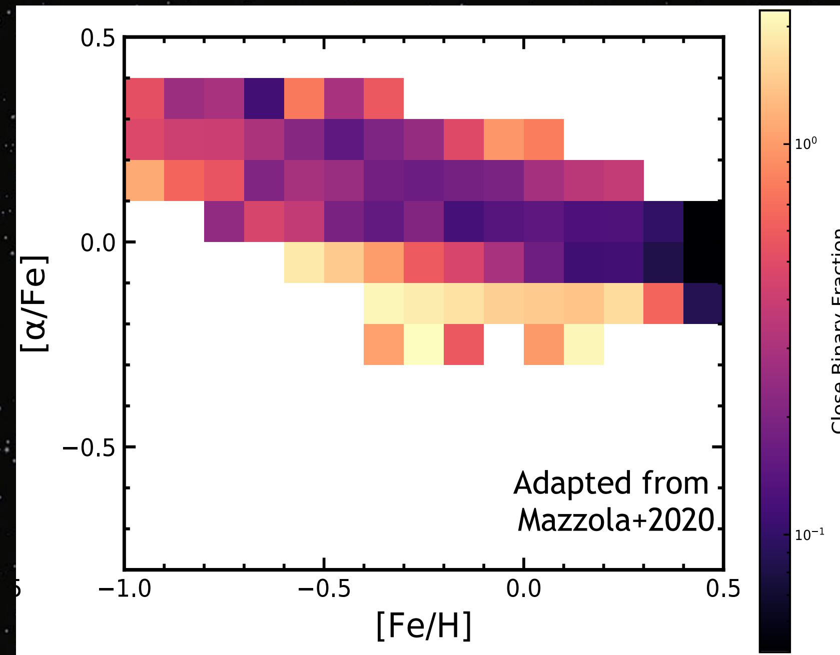


Adapted from Mazzola+2020

CBF and Chemistry – *Interpretation*

Models predict an anti-correlation between [Fe/H] and protostellar disk fragmentation.

- Metal-poor cores are hotter, larger, and more gravitationally unstable.
- Metal-poor disks have lower optical depths, promoting cooling and fragmentation.



So what about α abundances?

For [α/Fe] < 0.05, these effects produce an even stronger anti-correlation with α abundance than with Fe!

For [α/Fe] > 0.05, a chemistry-independent floor of CBF ~ 10% emerges.

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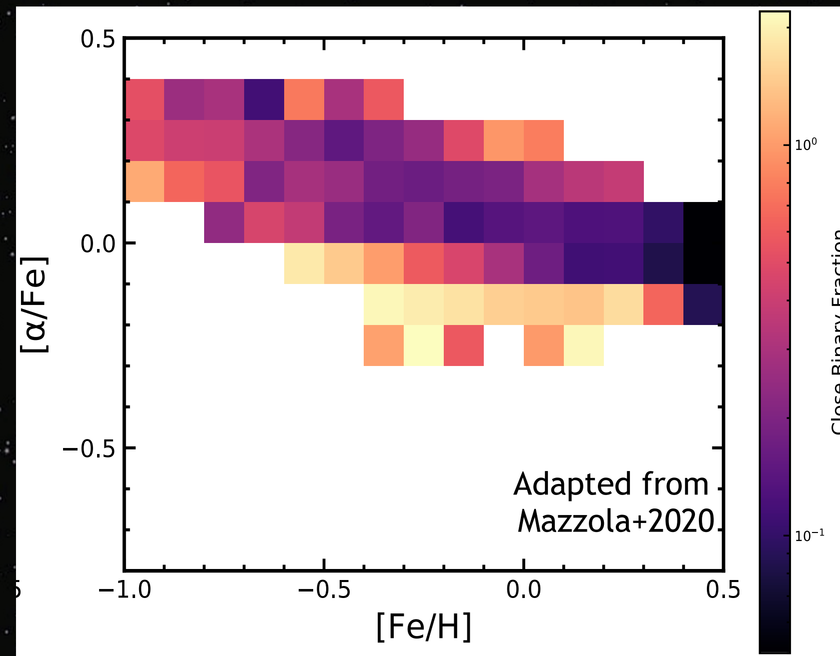

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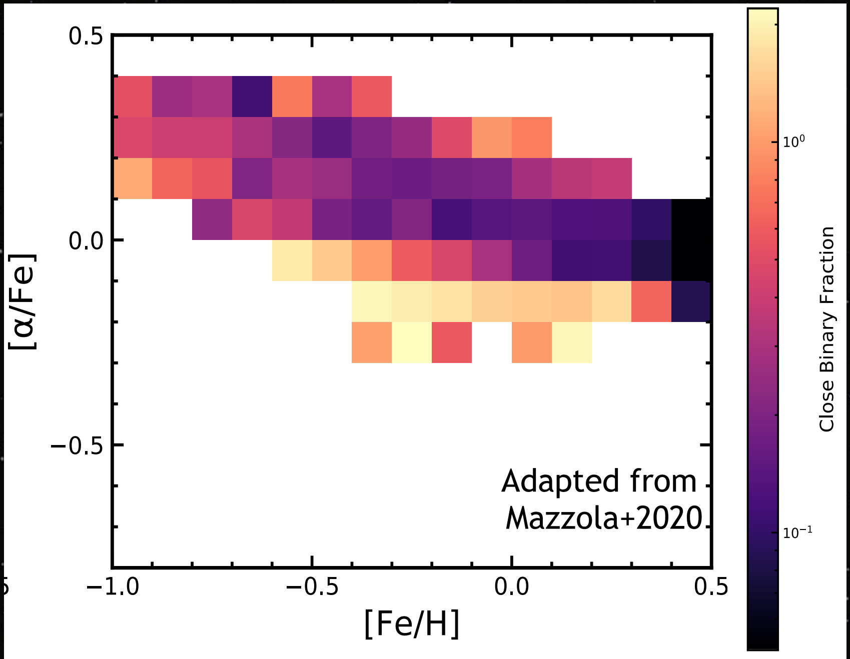

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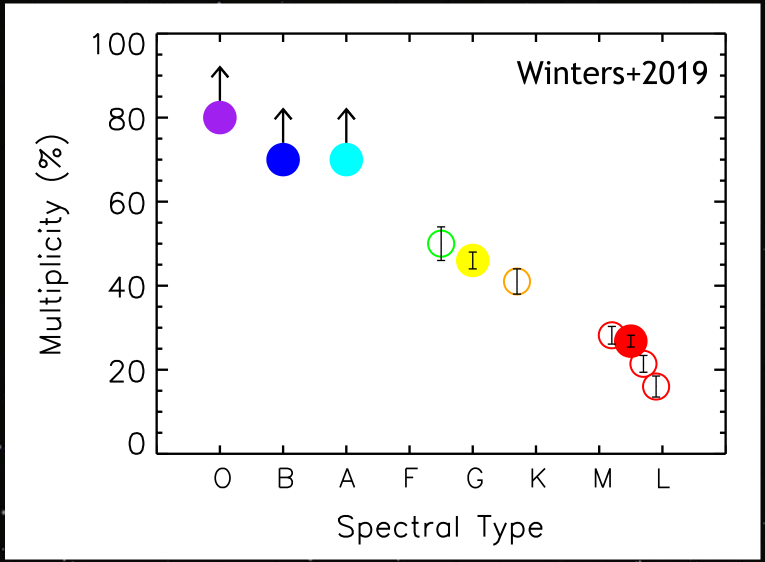
CBF and M dwarfs – *Motivation*

A floor of CBF ~ 10% has emerged elsewhere too—M/brown dwarfs!

Perhaps this floor is universal. But *why*?
Two leading explanations:

1) At least 10% of protostellar discs fragment early on, regardless of their chemistry or final m_1

2) Metal-rich and/or low-mass discs can't fragment, *but* a small fraction of cores fragment on larger scales and decay into closer binaries, leading to CBF ~ 10%



How the M-dwarf CBF varies with chemistry can distinguish between these two possibilities.

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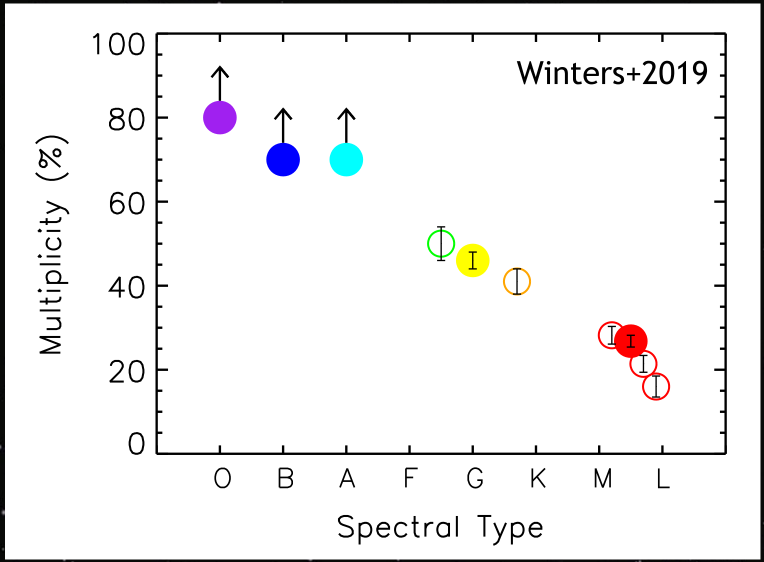

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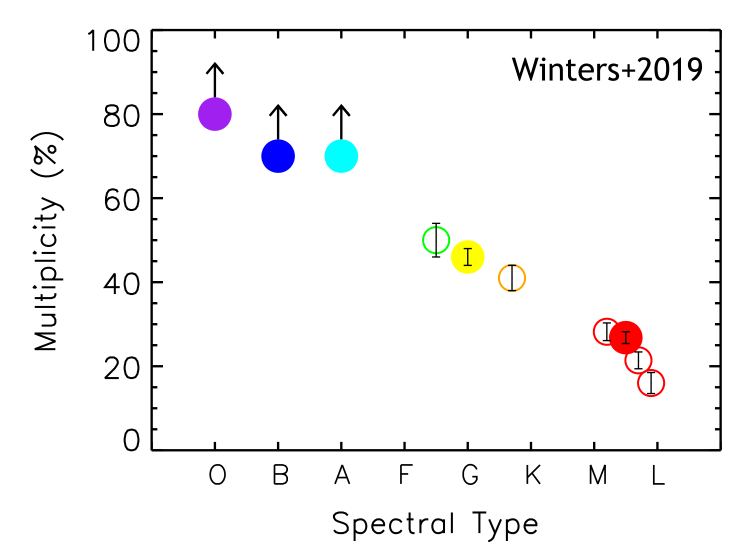

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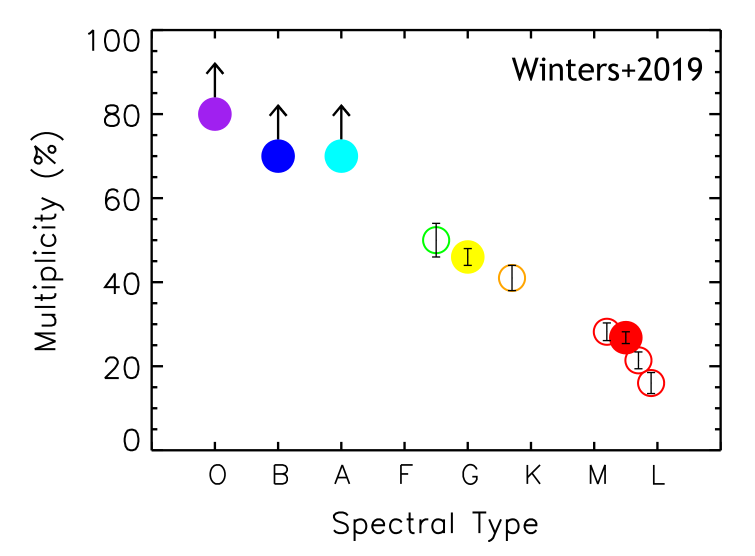

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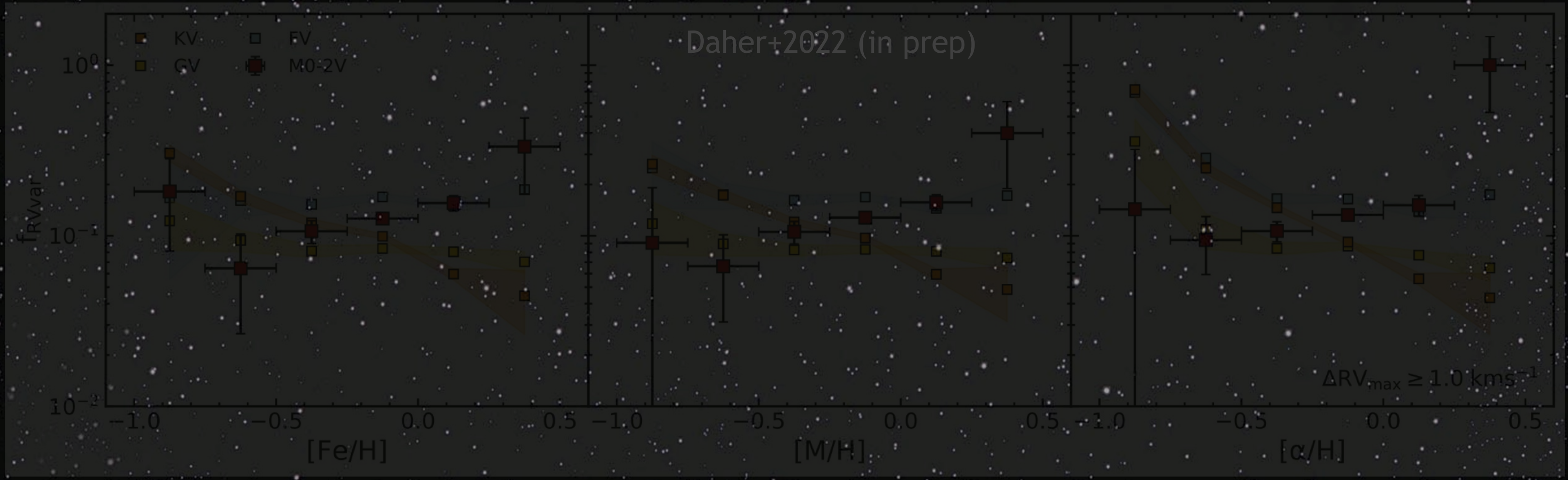
CBF and M dwarfs – *Preliminary Data*

- APOGEE DR17 RVs, T_{eff}, log(g), chemical abundances
- Gaia EDR3 Bailer-Jones distances
- HR-select dwarfs, T_{eff}-assign M K G F

Spectral Type	$T_{\rm eff}$ Range	$\log(g)$ Range	N	$N_{\rm RVvar}$
F	5960 – 7220	3.39 – 4.69	8125	1304
G	5325 – 5960	3.56 – 5.39	21776	2050
K	3890 – 5325	4.12 – 5.81	25041	2404
M0-5	3000 – 3890	4.36 – 6.10	4127	492



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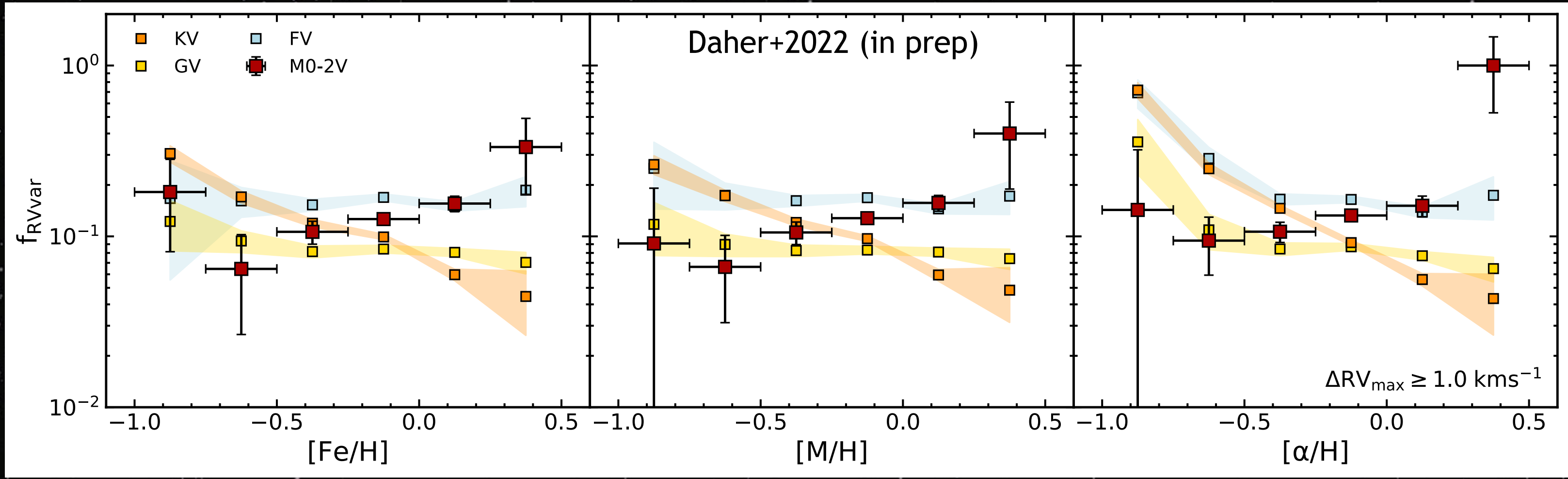
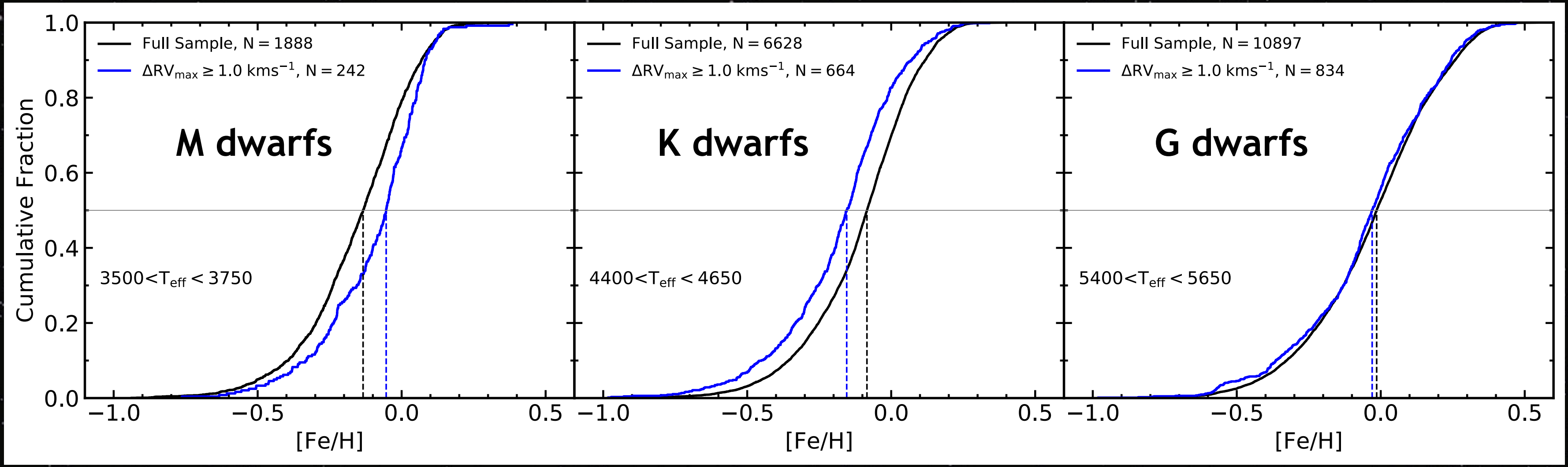


CBF and M dwarfs – *Preliminary Results*

Compare the cumulative distributions of [Fe/H] for RV variables vs. the full population of M vs. K vs. G dwarfs.



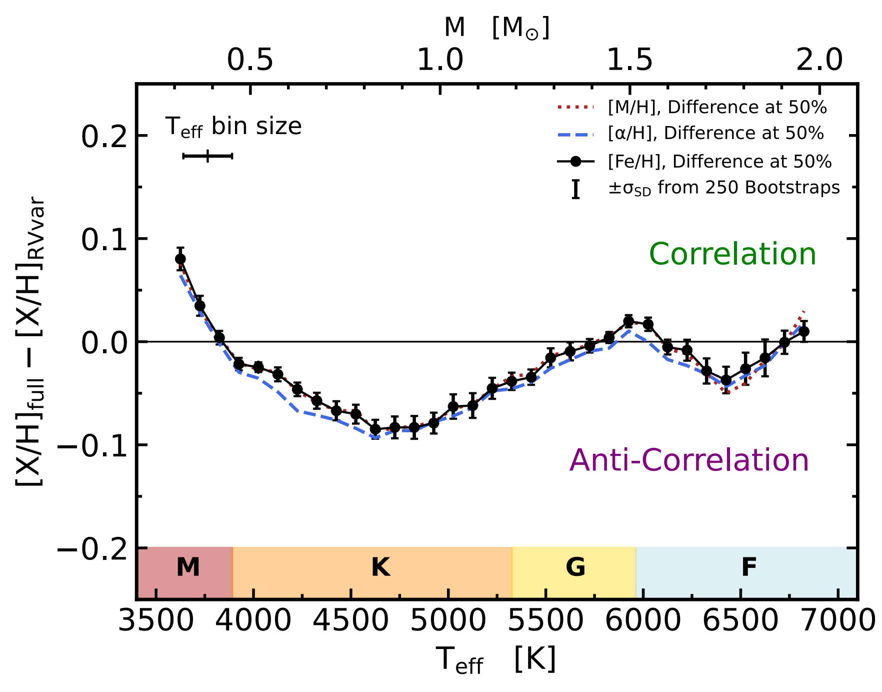
Daher+2022 (in prep)

CBF and M dwarfs – *Preliminary Results*

Shift the T_{eff} bin center slowly and measure the difference between the cumulative histograms each time.

- Transition seems to occur around T_{eff} ~ 3800 K (0.45 $M_{\odot}$)
- The differences reach an inflection point around 4750 K (0.8 $M_{\odot}$)
- For G/F, the difference flattens out and gets noisy

No matter the bin width or shift, and for all ΔRV_{max} thresholds of 1,2,3,10



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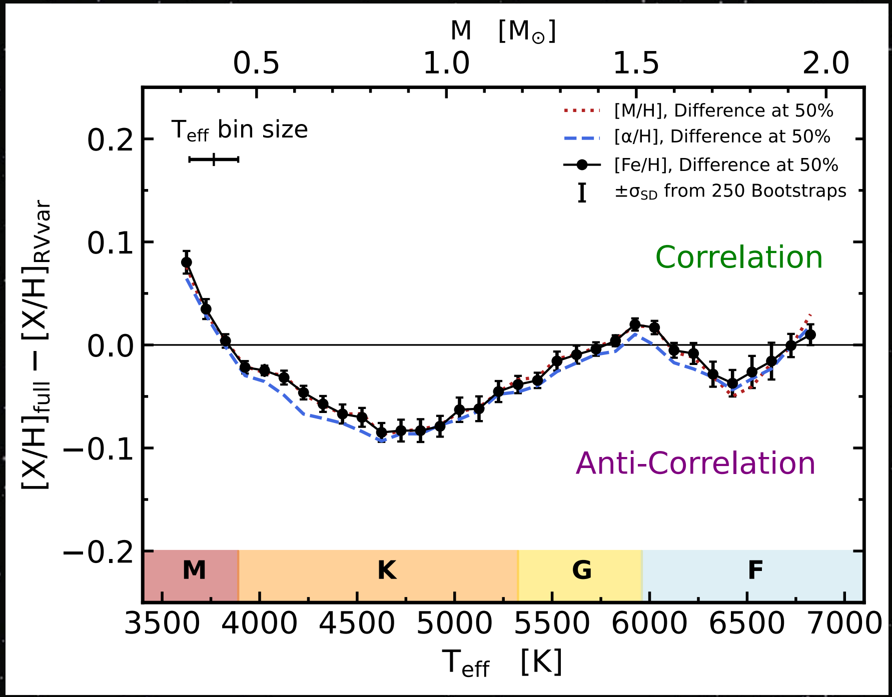

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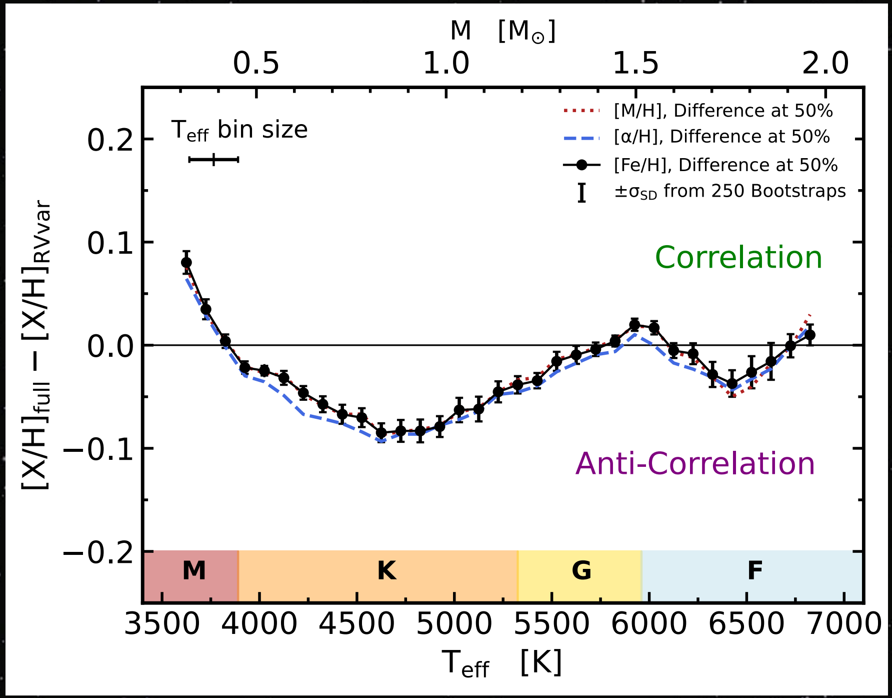

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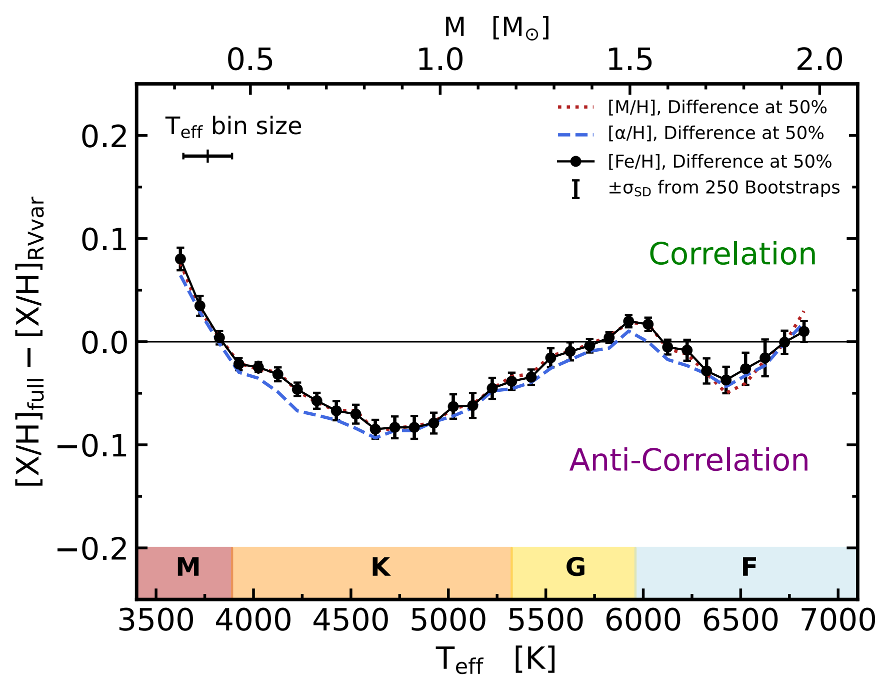

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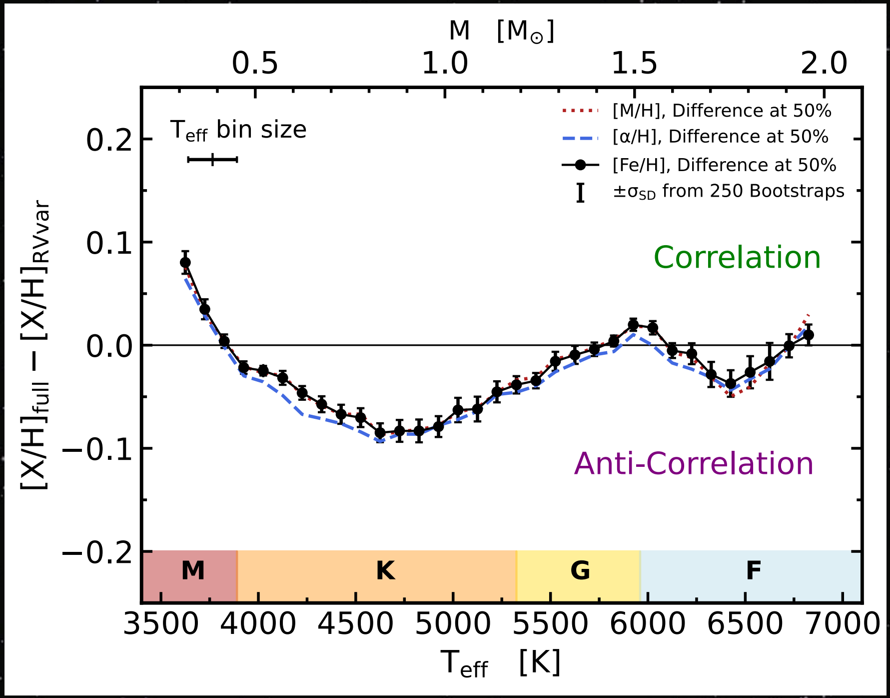

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Maybe a slow hand-off between metallicity-driven fragmentation and mass-driven fragmentation?

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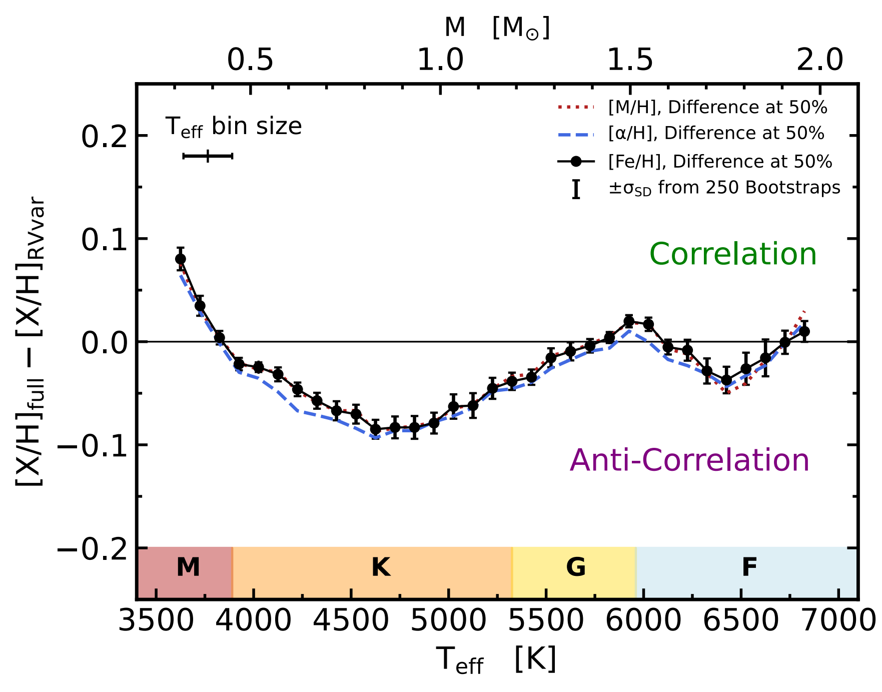

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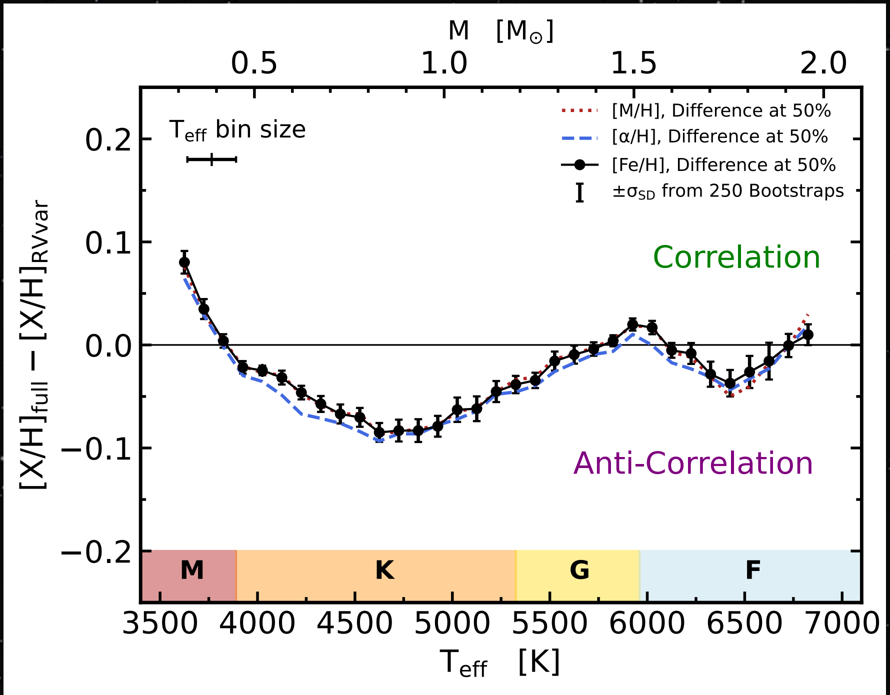

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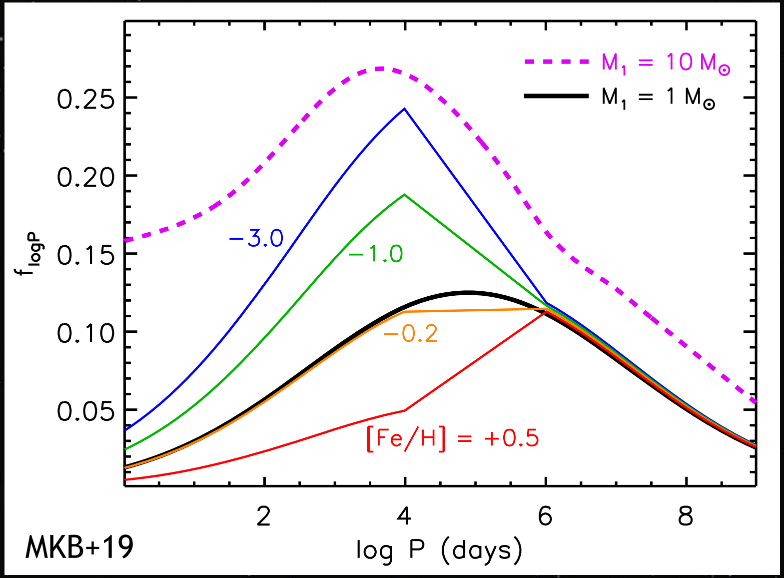
Summary

- Binaries are fundamental to our understanding of astrophysics
- Large samples of binaries are needed to disentangle various correlations from one another
- Chemistry + CBF = clues to the formation of close binaries

Future Work - *Bayesian Inference* + P_{orb}

Another consequence of these theories is that companions should be skewed towards shorter periods.

This leads to an increase in high-ΔRV_{max} stars, which to our method is degenerate with an increased close binary fraction.



Adapted from Jayasinghe+21

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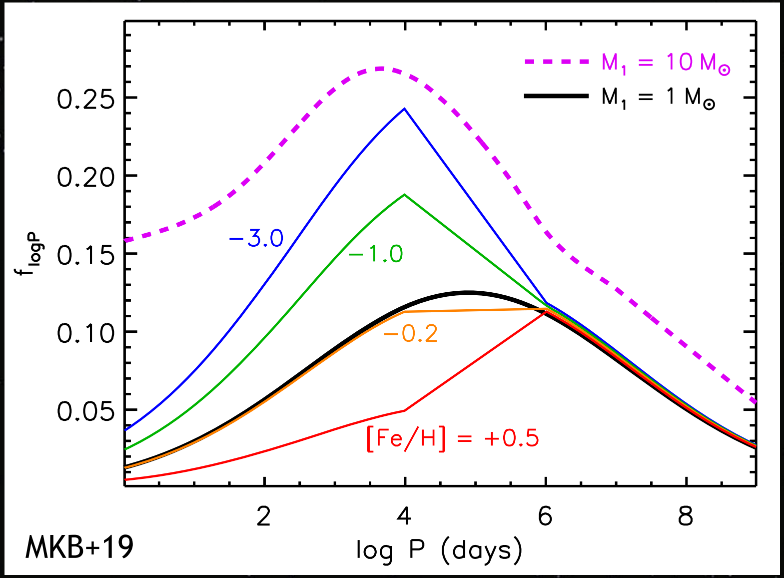

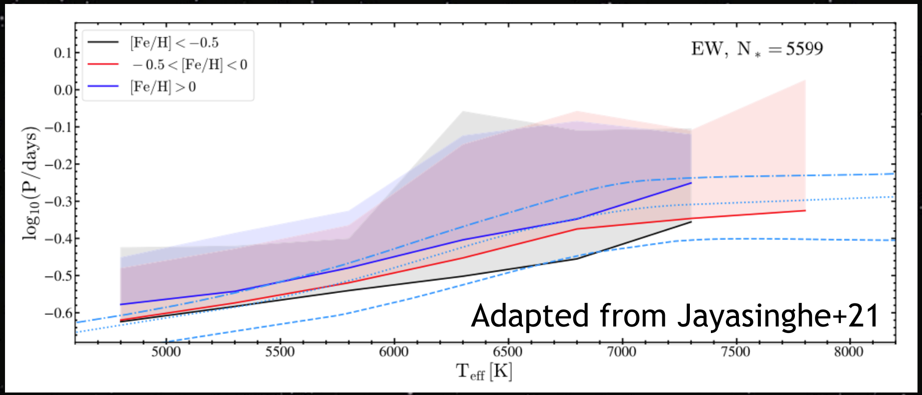

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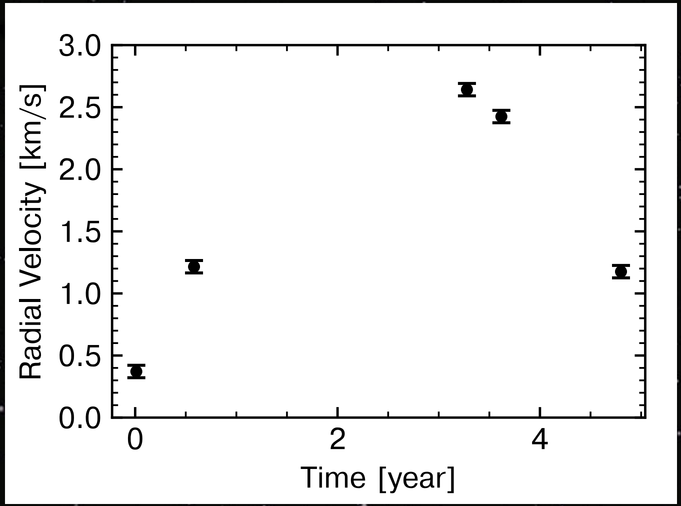
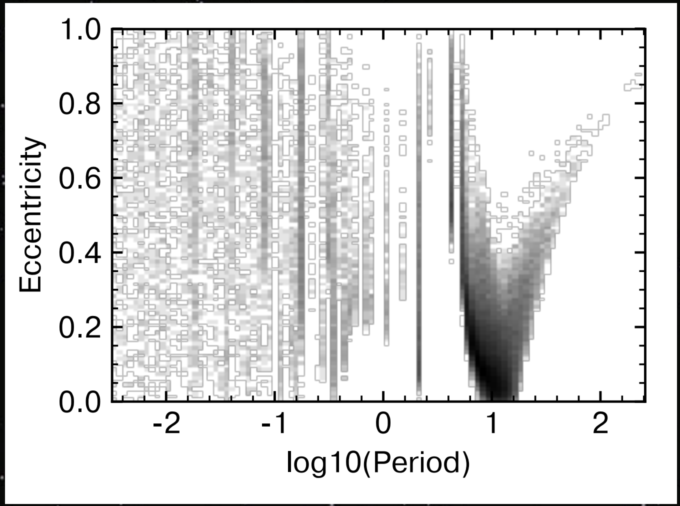


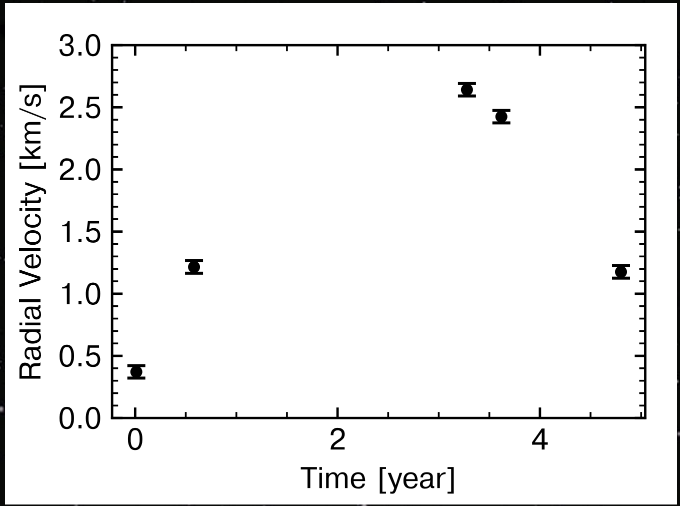


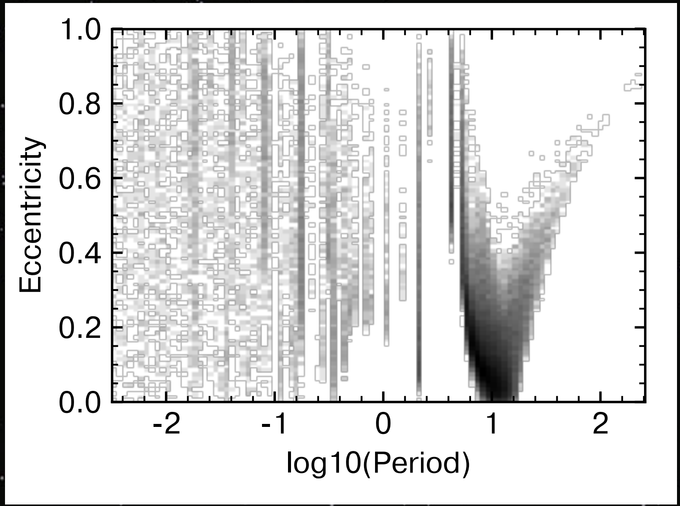
NSF Grant AST-1909022

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!

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



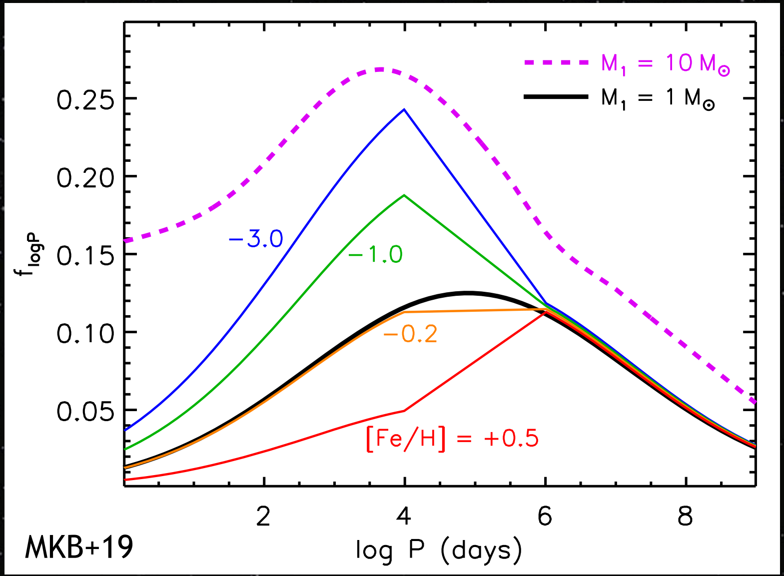


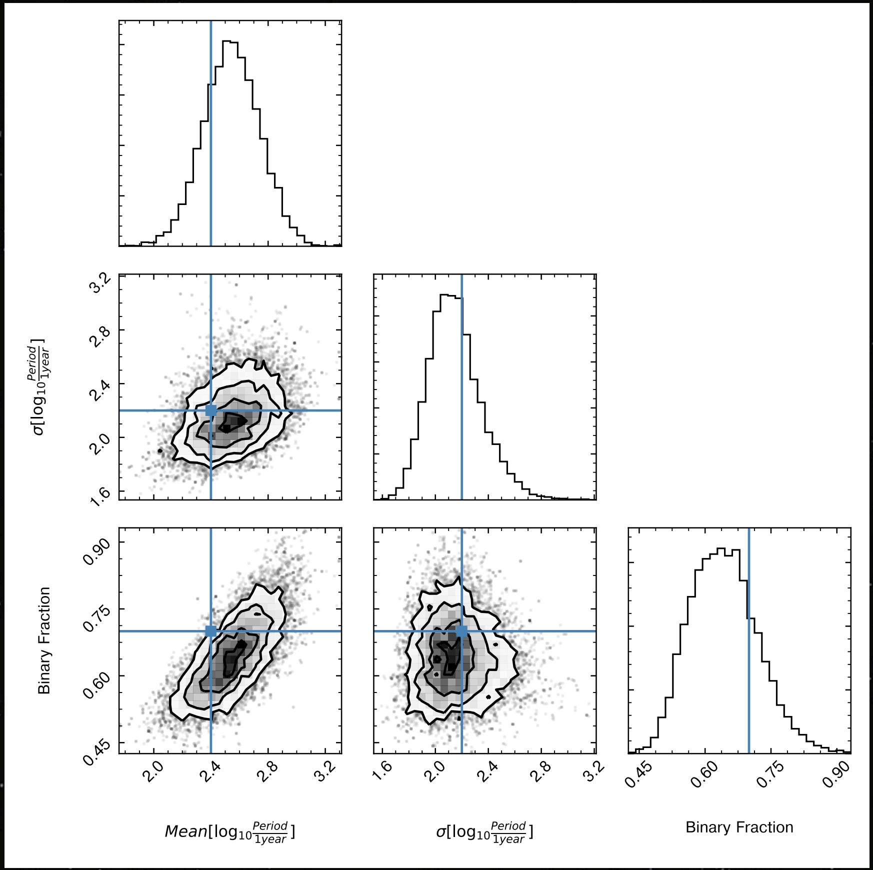
NSF Grant AST-1909022

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

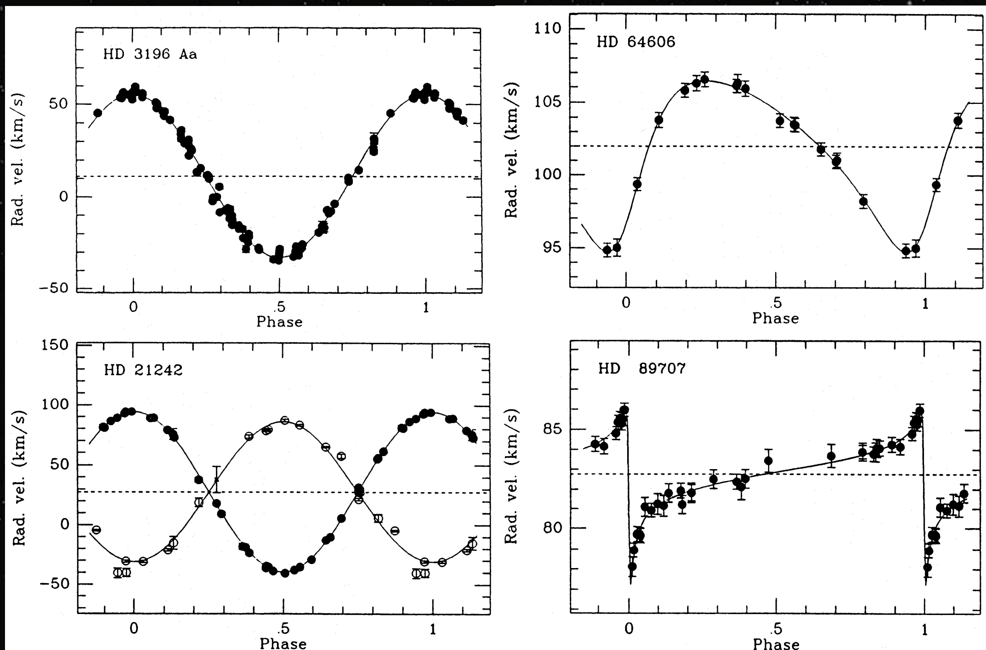
But we can constrain P_{orb} as a function of Fe and α abundances using the weak constraints of 100,000s of APOGEE/MWM stars!

Future Work - *Bayesian Inference* + P_{orb}

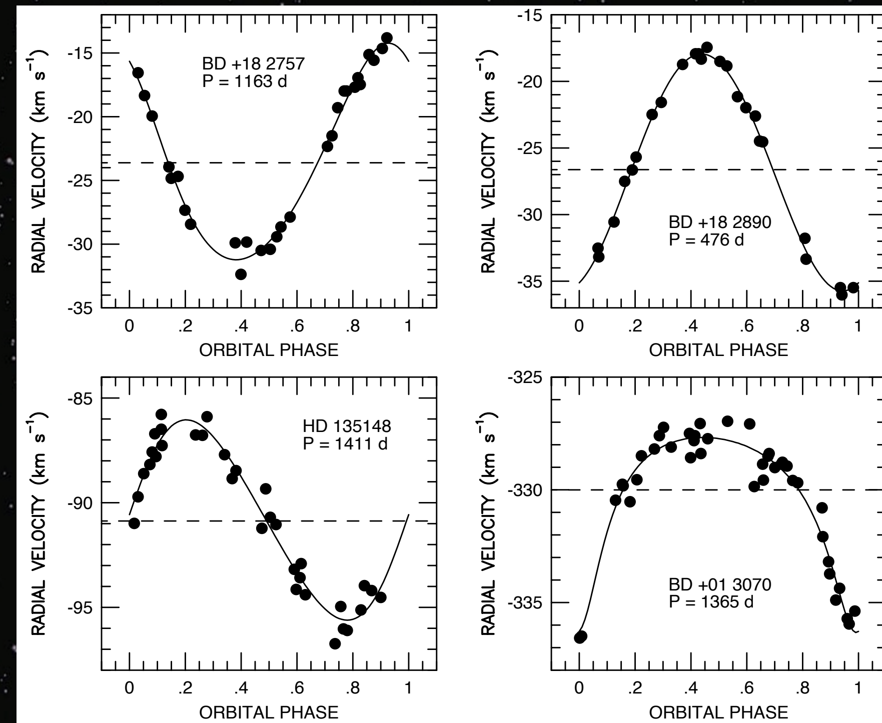




EX: RV Curves – *Historical Approach*



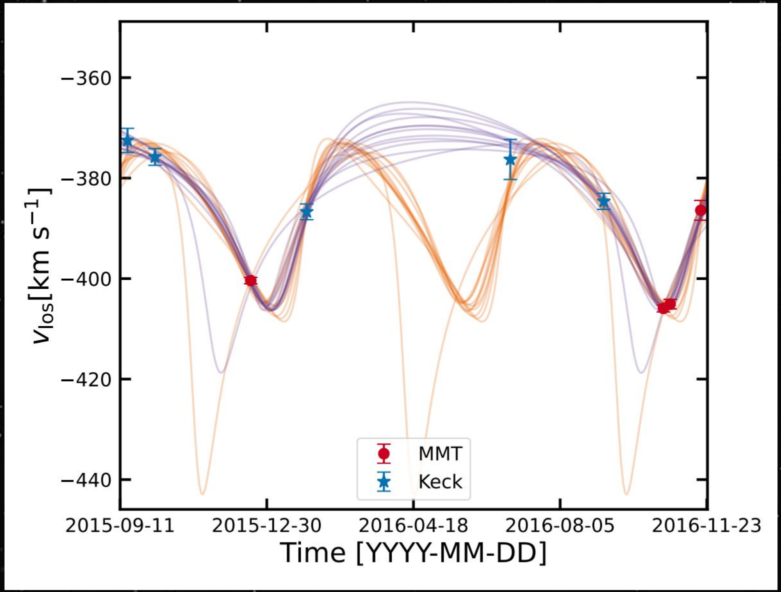
Duquennoy & Mayor 1991



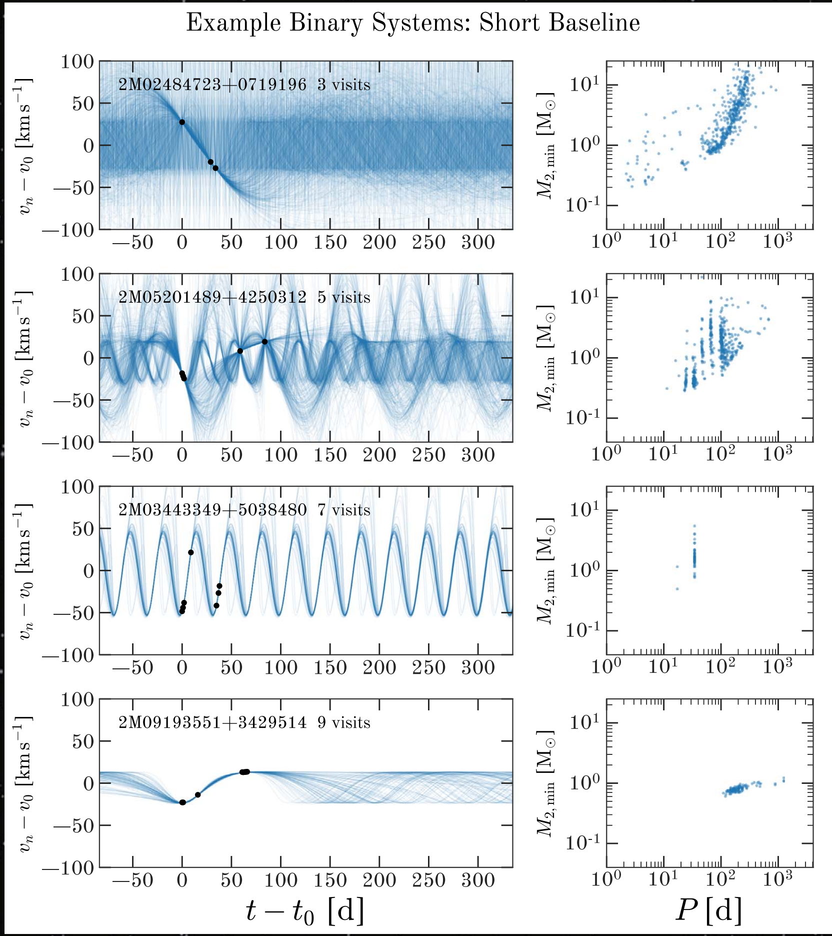
Carney+2003

EX: RV Curves – *Modern Approach*

Use the data you have + the leaps in computing of the last few decades!



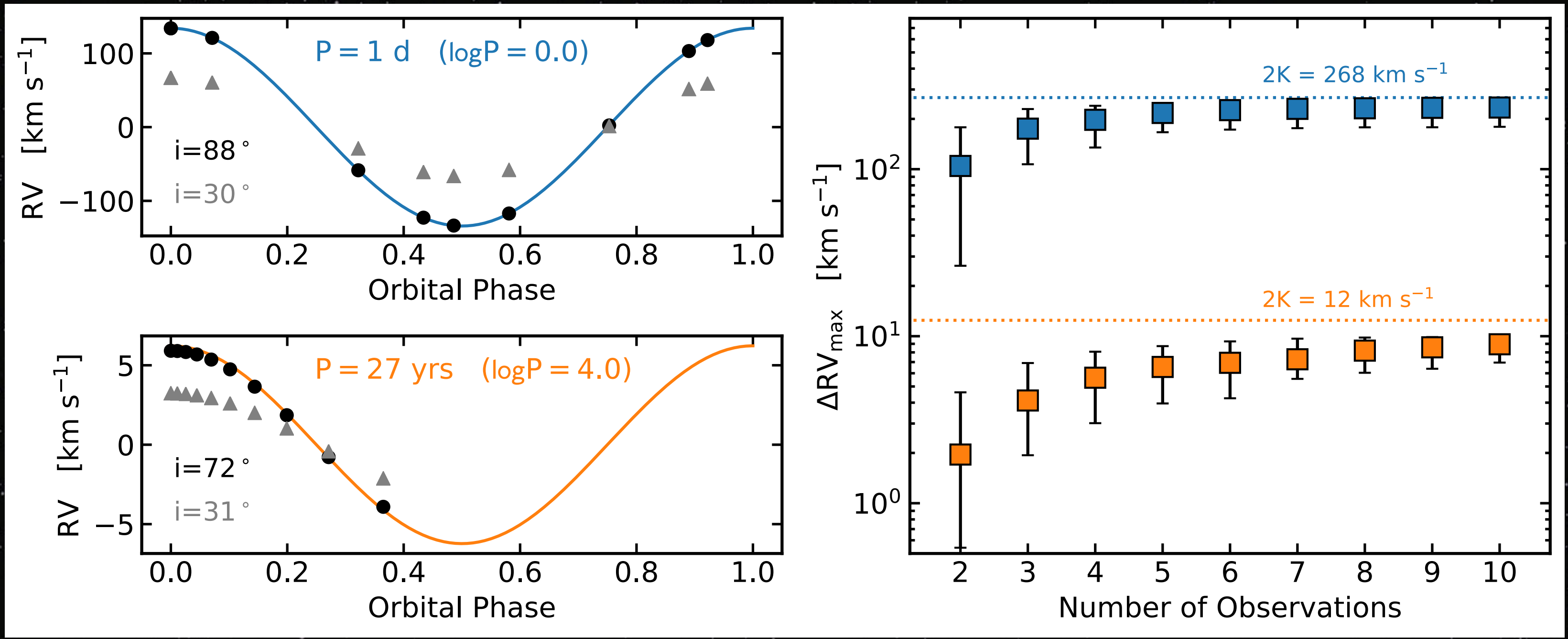
Buttry+2022



Price-Whelan+2020

EX: Marginalize Over Inclination

Simulate 1000 systems with inclinations randomly sampled from a uniform distribution



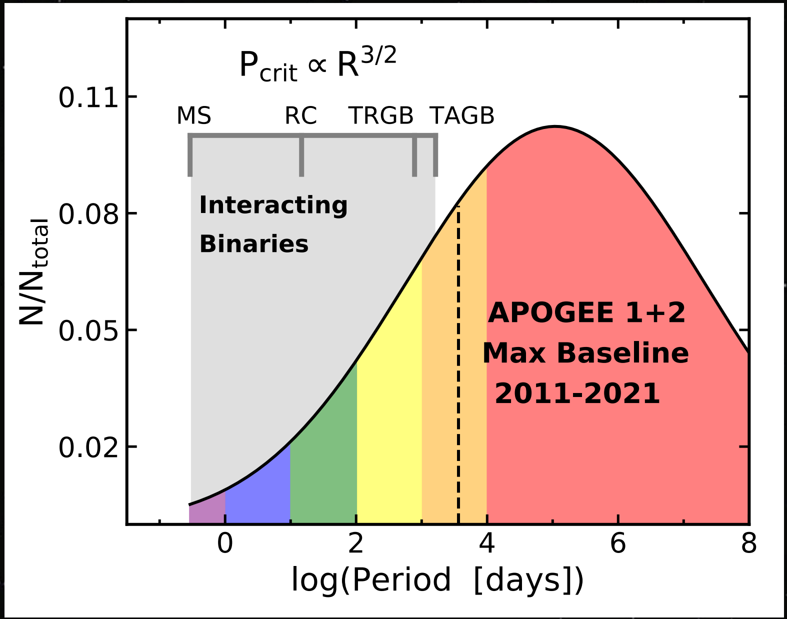
EX: RV Curves – *Sparsely-Sampled* + *ΔRV_{max}*

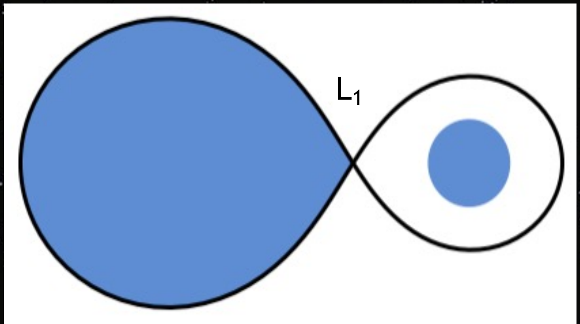
Raghavan+2010: lognormal *P* distribution
for Sun-like stars in the Solar neighborhood

Mass transfer can occur when the
primary overflows its Roche lobe!

Critical period for RLOF
to occur at $q = M_2/M = 1$:

$$P_{crit} \propto \sqrt{\frac{R^3}{GM}}$$



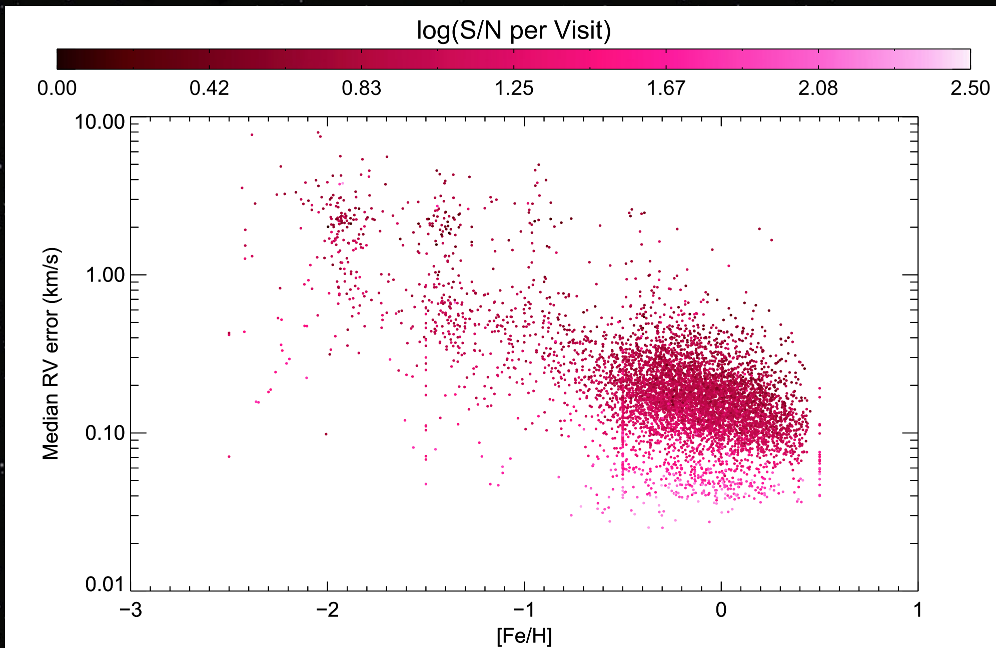


Binary Star [Wikipedia]

P_{crit} changes as the primary evolves:

- Increases as the star expands (ascends RGB)
- Decreases once the star shrinks (He fusion)

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!

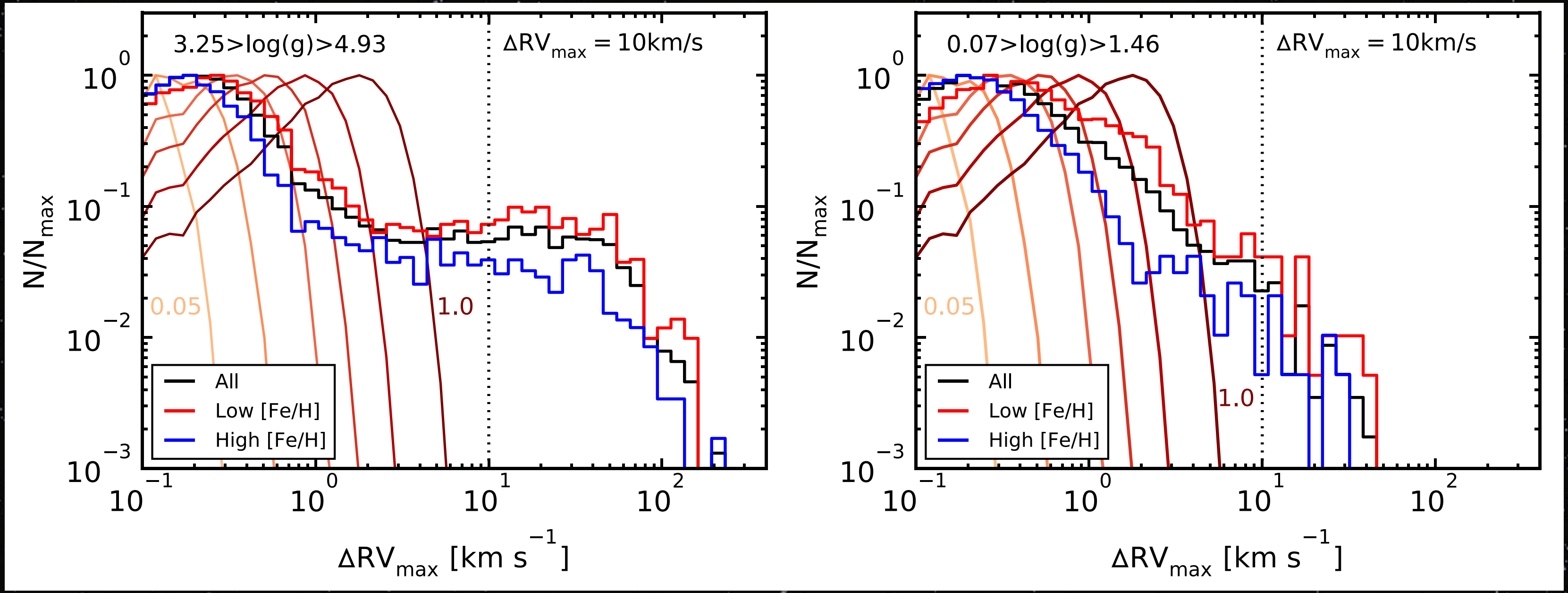
Truthfully, RV errors are hard…

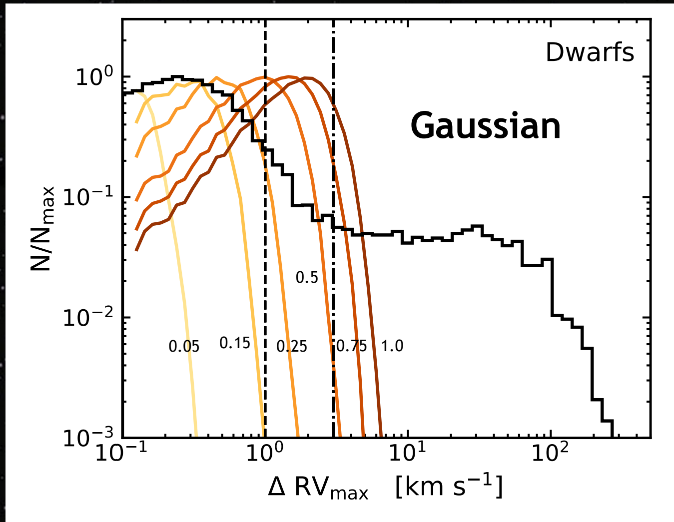
EX: RV Errors – *Observed*

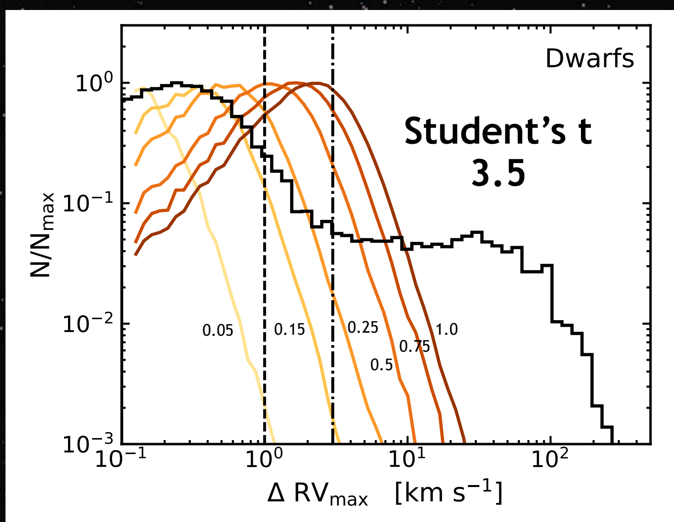
RV errors, and thus the ΔRV_{max} core, increase based on sample properties

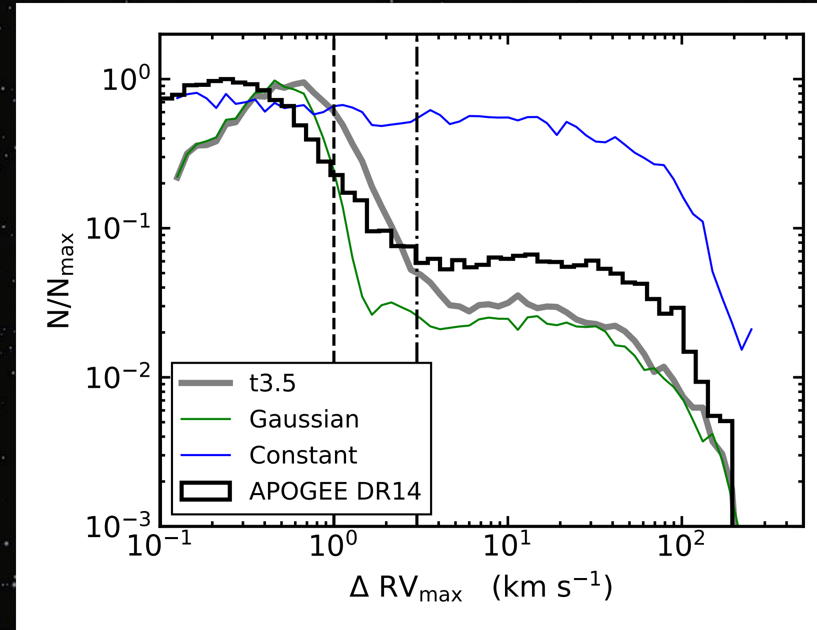
- lower log(g) (RV jitter)
- lower [Fe/H] (weaker lines)

Badenes, CMD+2018







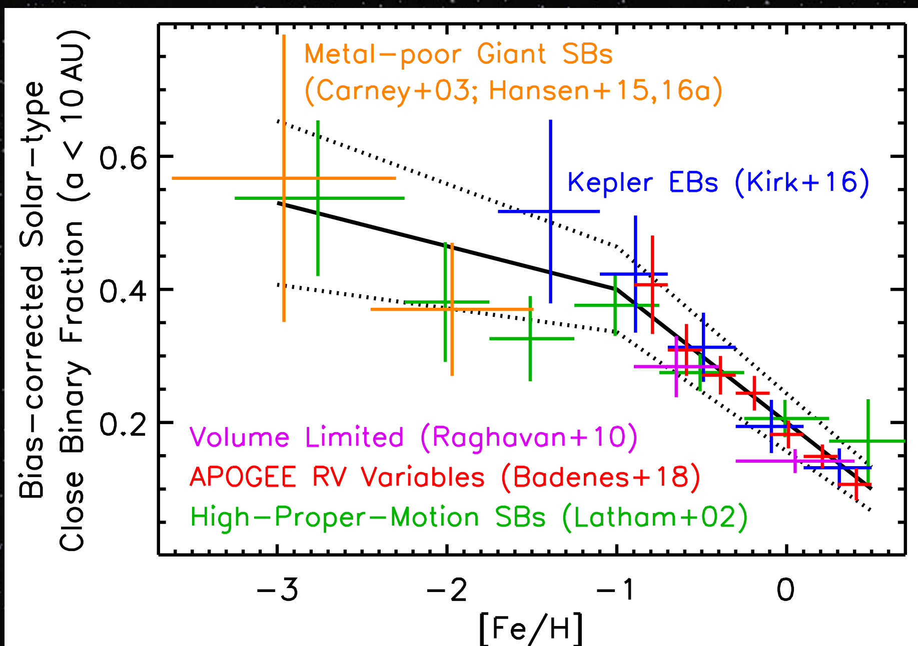


Mazzola+2020

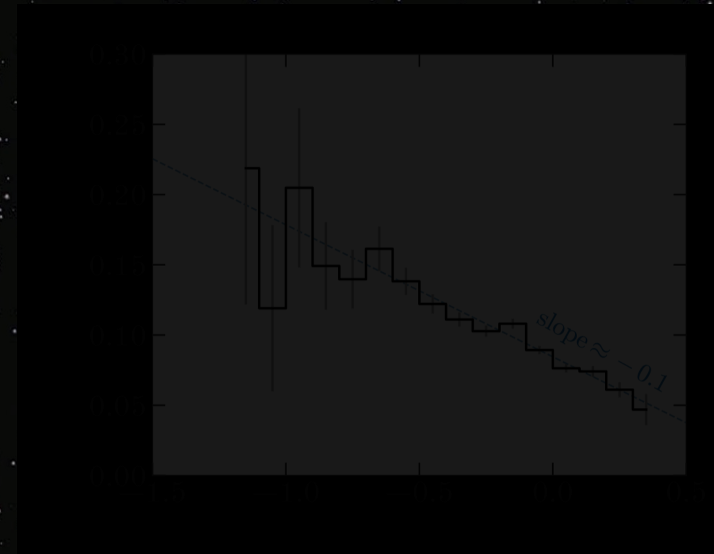
Some success modeling with a Student's t distribution as compared to Gaussian

EX: CBF and Chemistry – *Previous Studies*

In APOGEE DR16, Price-Whelan+2020 found an anti-correlation between f_{bin} and [M/H].



Moe, Kratter, & Badenes 2019



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Meta-analysis by Moe, Kratter, & Badenes 2019 found that the CBF increased by a factor ~ 6 across their [Fe/H] range after correcting for biases.

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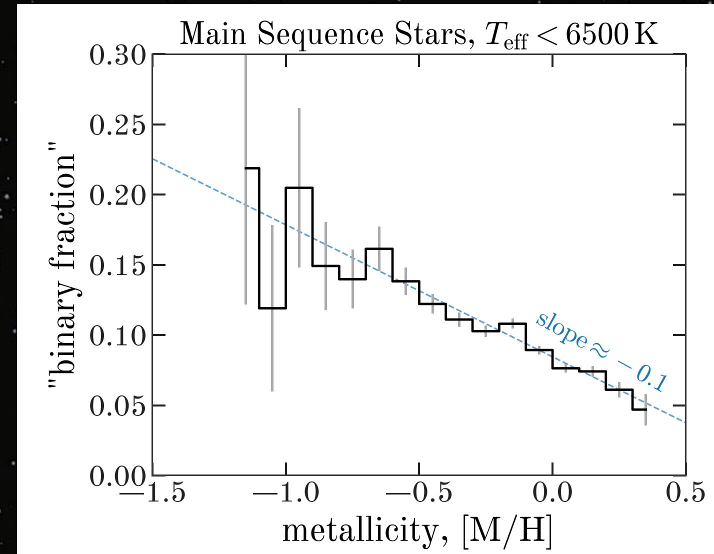
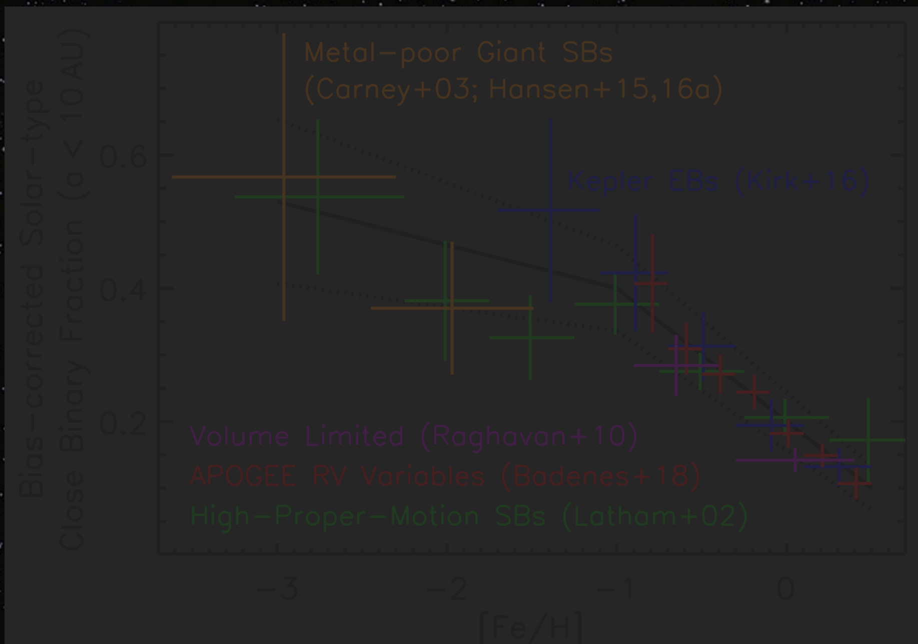


Price-Whelan+2020



Moe, Kratter, & Badenes 2019

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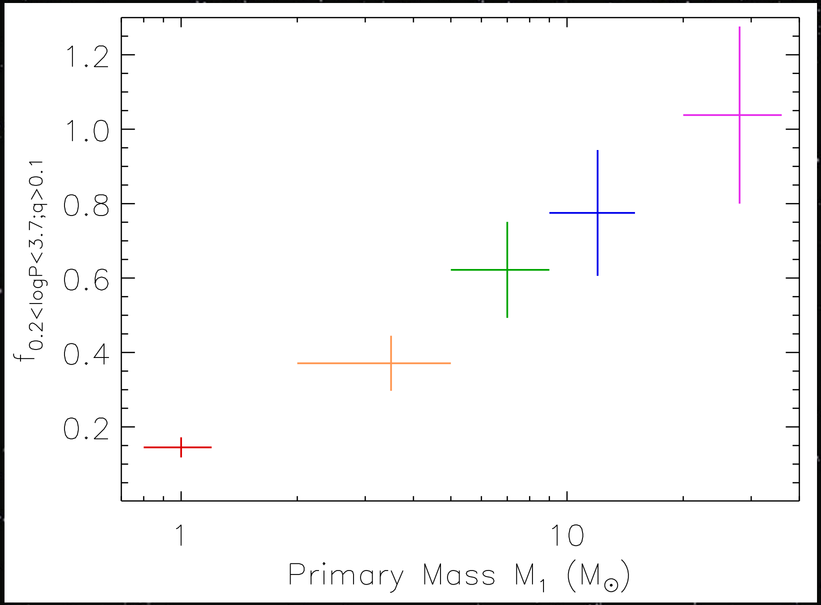
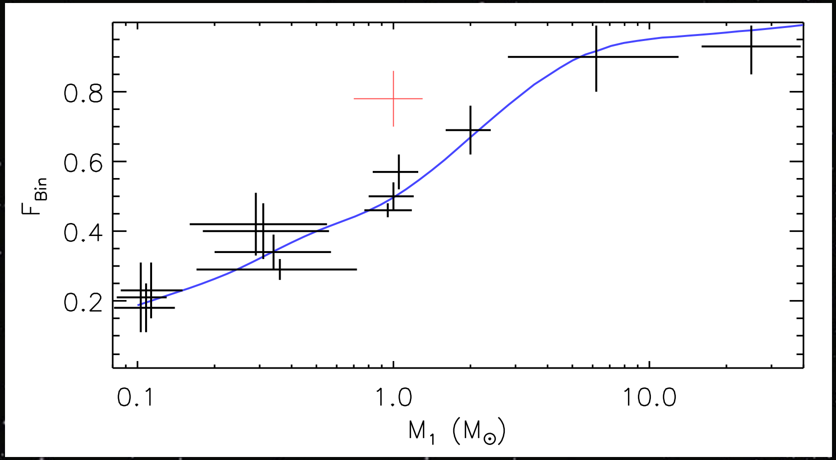
EX: CBF and Stellar Mass/T_{eff}

Primary mass is strongly correlated with the close binary fraction.



Moe & Di Stefano 2017



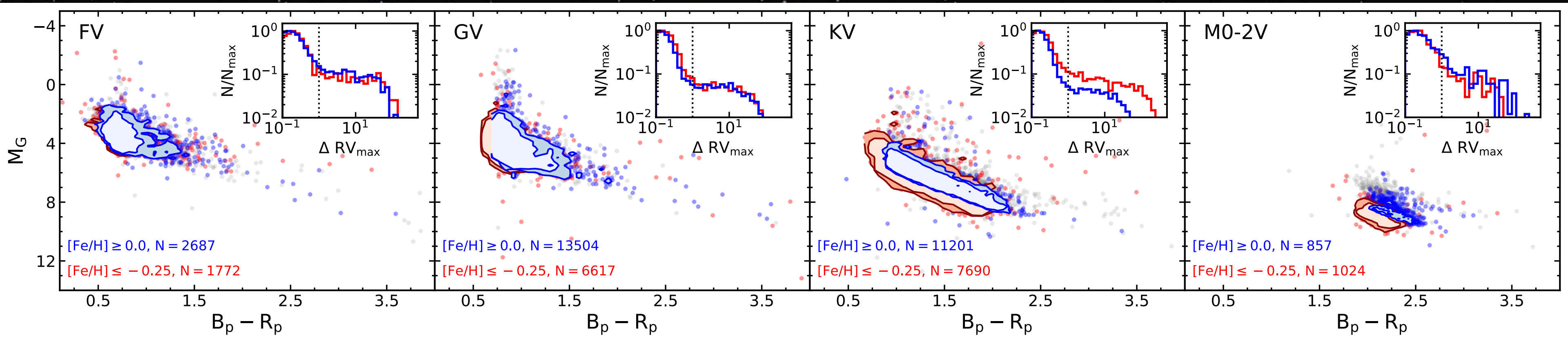
Moe 2019

red point is for solar-type pre-MS stars

EX: CBF and M dwarfs – *Preliminary Data*

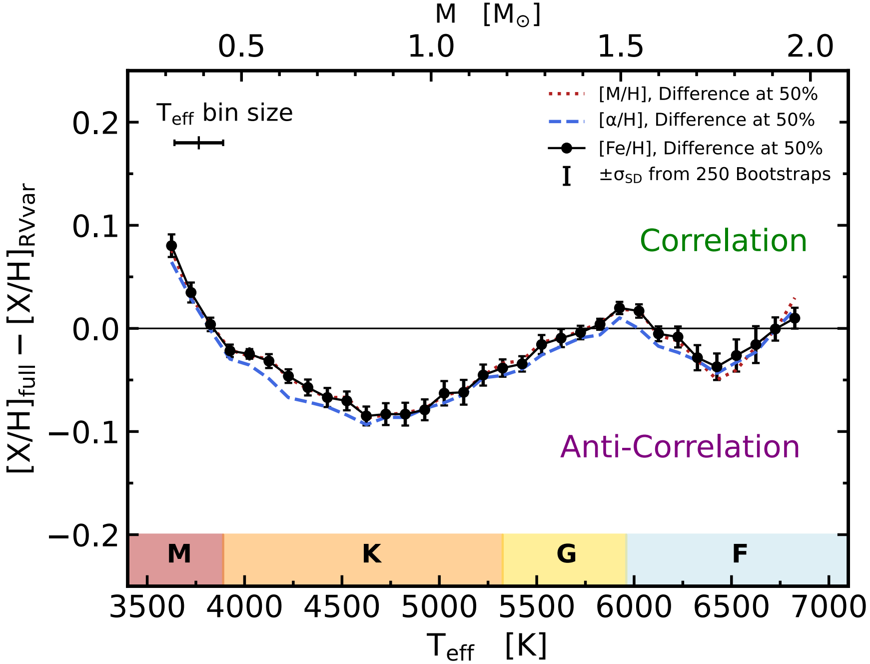
- APOGEE DR17 RVs, T_{eff}, log(g), chemical abundances
- Gaia EDR3 Bailer-Jones distances
- HR-select dwarfs, T_{eff}-assign M K G F

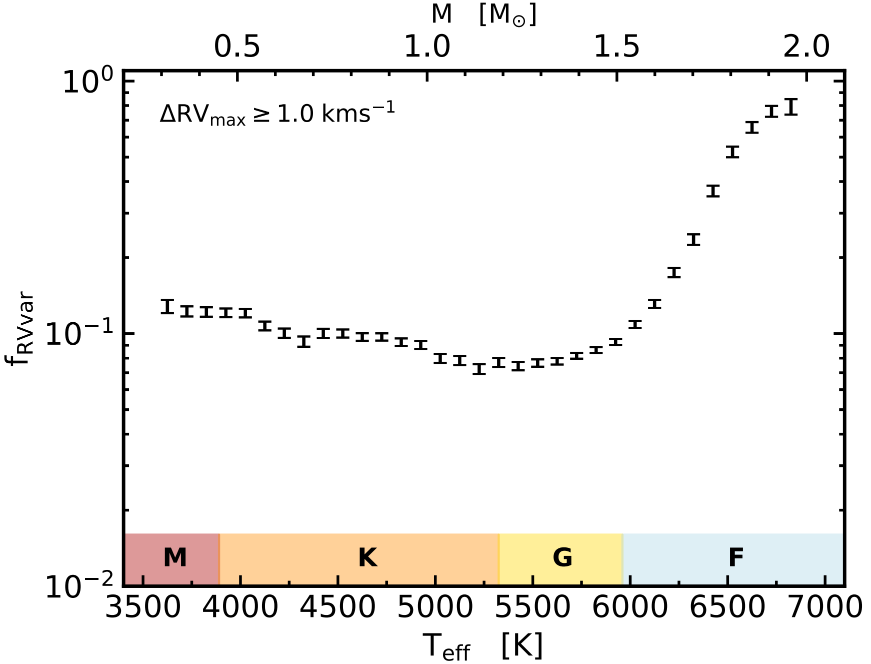
Spectral Type	T_{eff} Range	$\log(g/\mathrm{cm\ s^{-2}})$ Range	N	$N_{RV\ variable}$[1]
F	5960 – 7220	3.39 – 4.69	8125	1304
G	5325 – 5960	3.55 – 4.75	31965	2625
K	3890 – 5325	4.15 – 5.26	36540	3422
M0-2	3500 – 3890	4.36 – 5.20	4033	511



Daher+2022 (in prep)

EX: CBF and M dwarfs – *Preliminary Results*

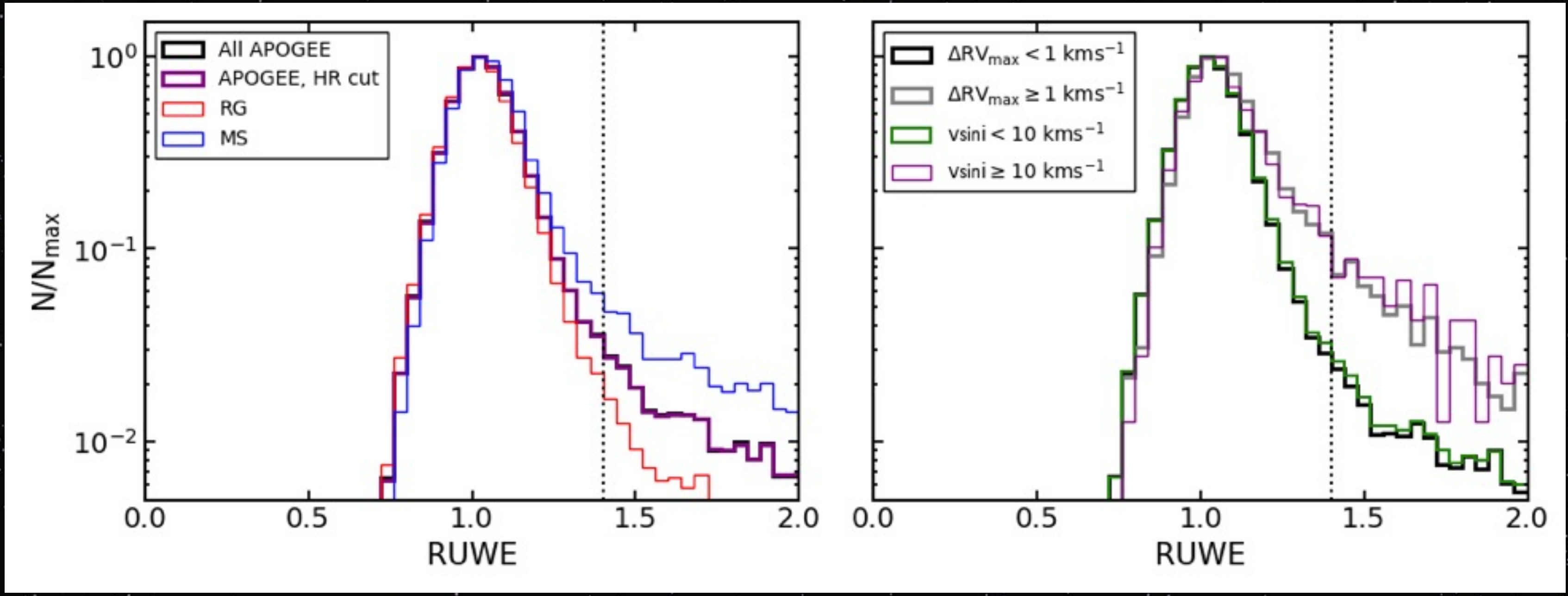




Daher+2022 (in prep)

See a very strong trend with in T_{eff} / mass!

EX: CBF and Rotation – *Gaia RUWEs*



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