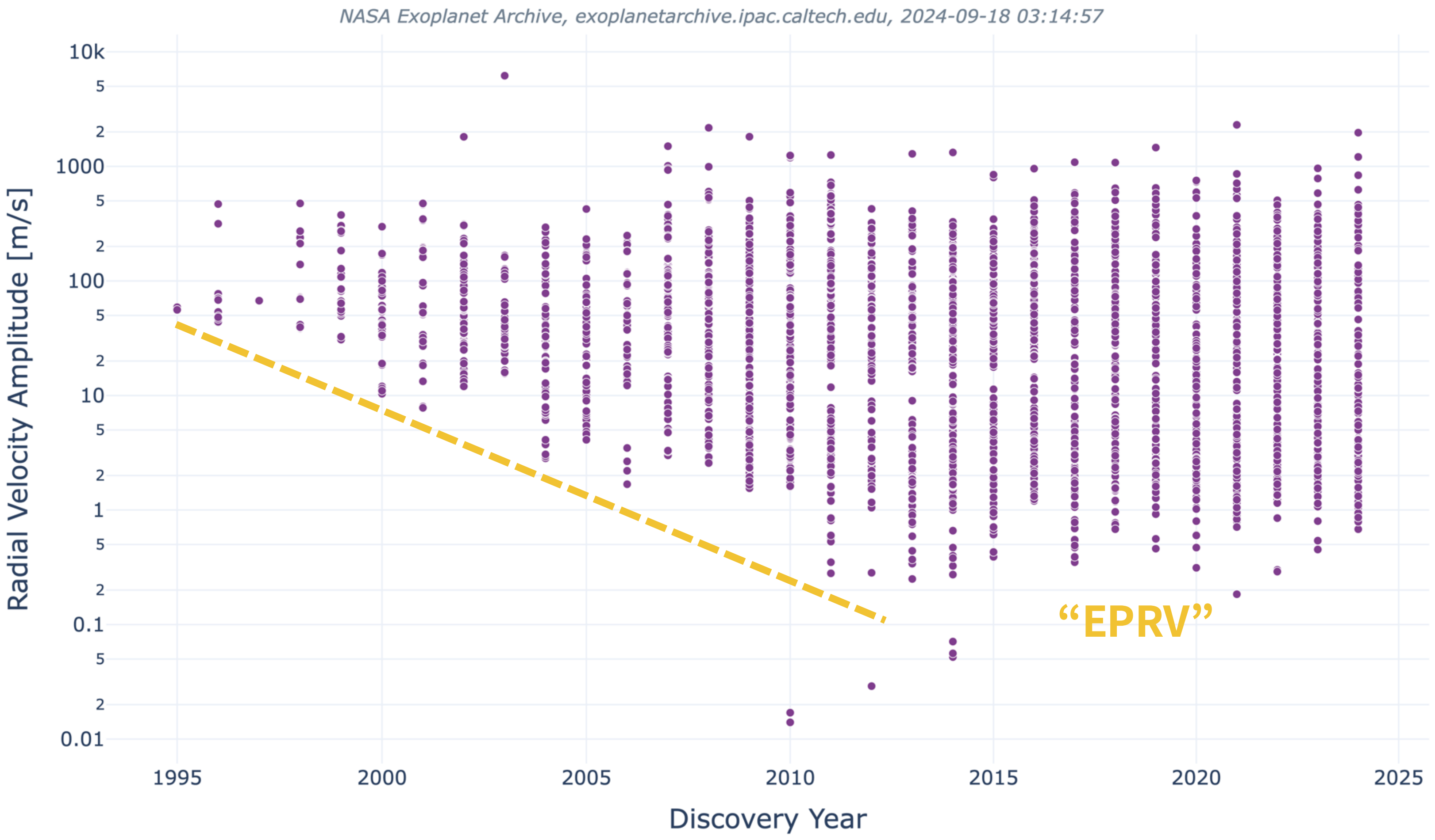
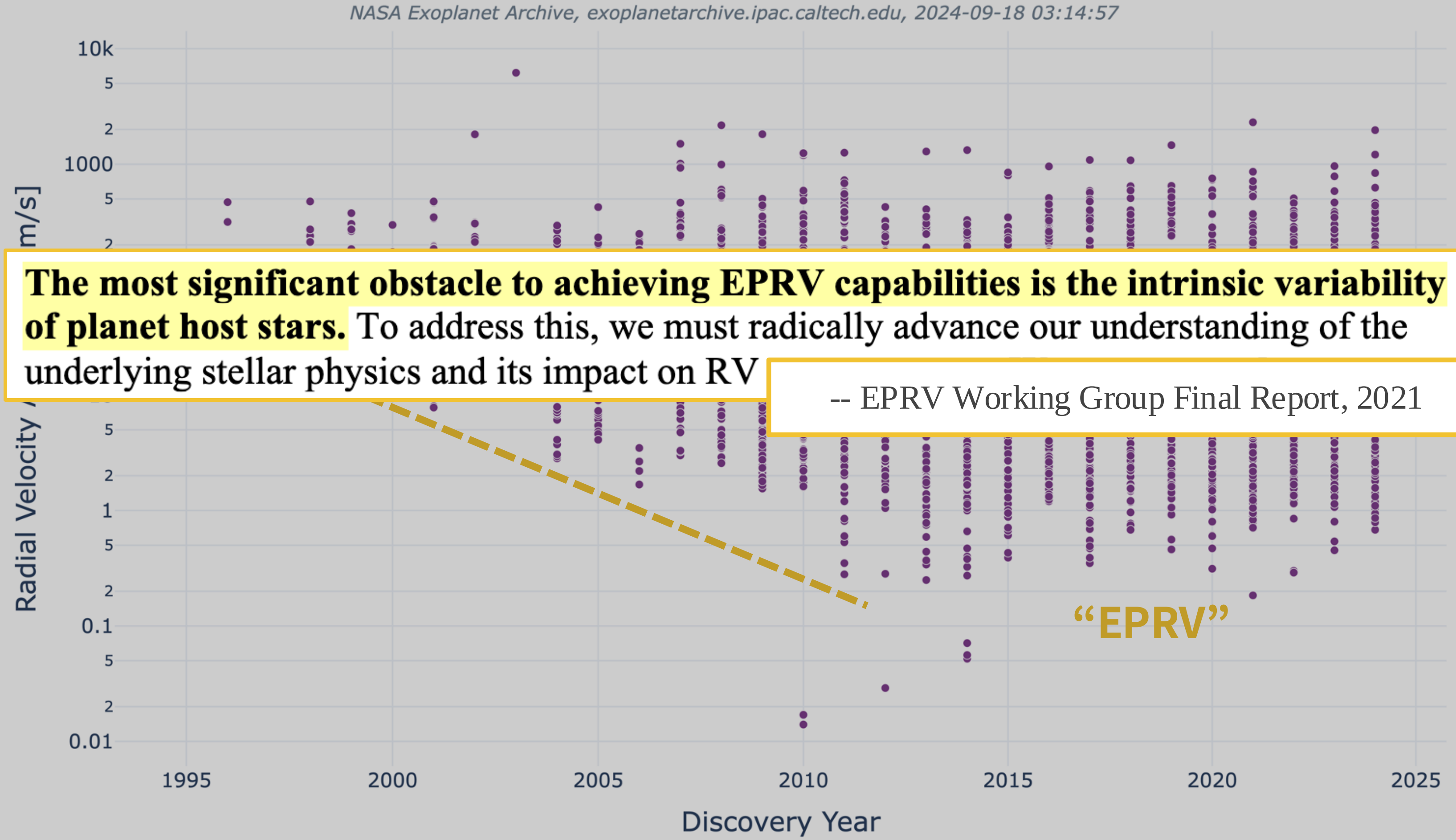
Mitigation Methods for Stellar Spectral Variability

Megan Bedell

Research Scientist
Center for Computational Astrophysics, Flatiron Institute



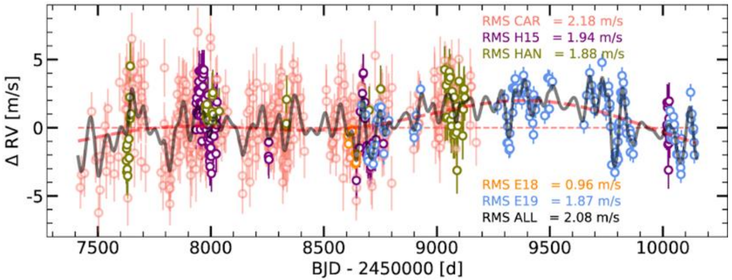
NASA Exoplanet Archive, exoplanetarchive.ipac.caltech.edu, 2024-09-18 03:14:57
Radial Velocity Amplitude [m/s]
10k
1000
100
10
1
0.1
0.01
Discovery Year
1995
2000
2005
2010
2015
2020
2025
"EPRV"



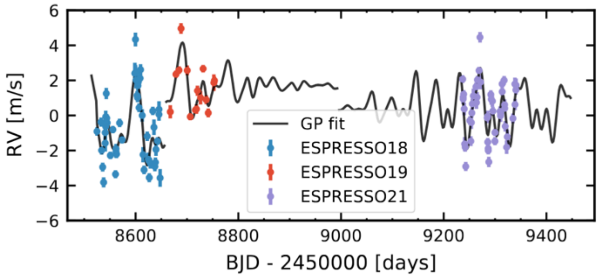
The most significant obstacle to achieving EPRV capabilities is the intrinsic variability of planet host stars. To address this, we must radically advance our understanding of the underlying stellar physics and its impact on RV

-- EPRV Working Group Final Report, 2021

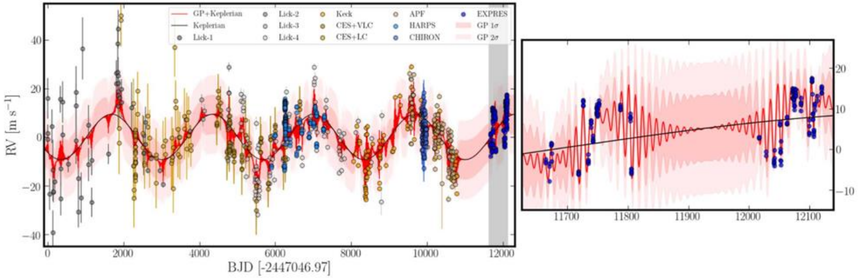
The more data we get, the more stellar signals we see…



Barnard’s star: Gonzalez Hernandez et al. (2024)

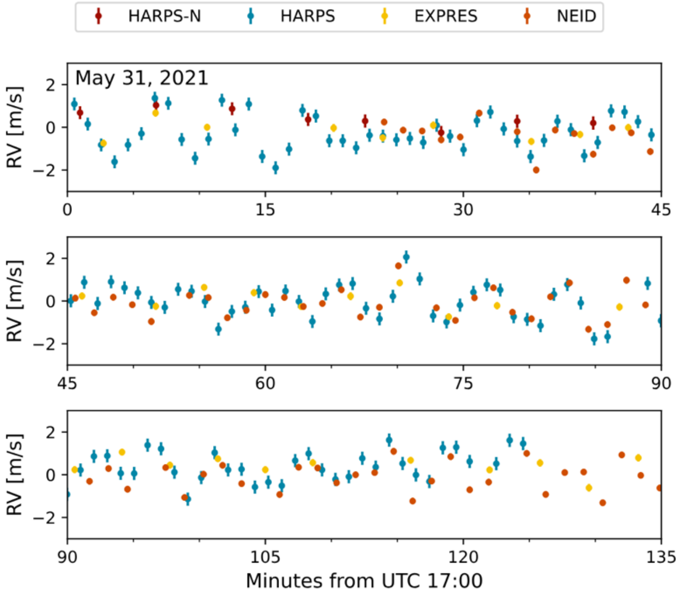


Proxima Cen: Faria et al. (2022)

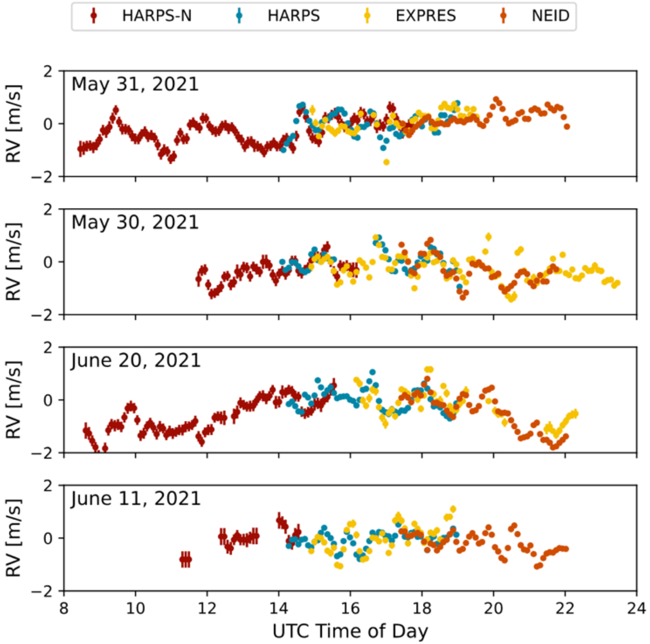


Eps Eri: Roettenbacher et al. (2022)

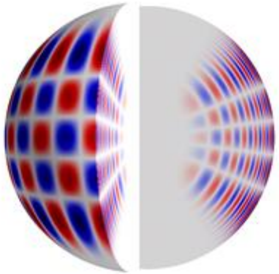
The issue persists even for the quietest & most familiar star



Sun: L. Zhao et al. (2023)

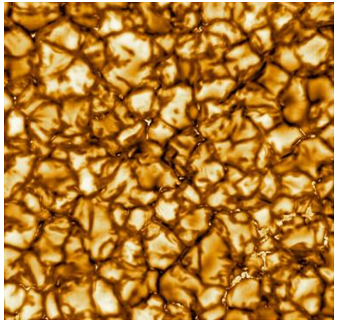


What are we really observing?



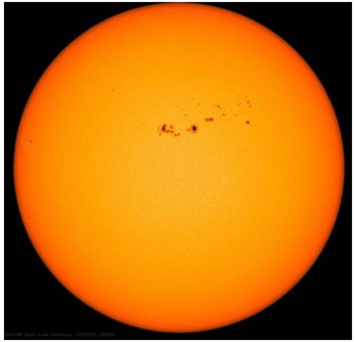
~ 10s cm/s

Oscillations



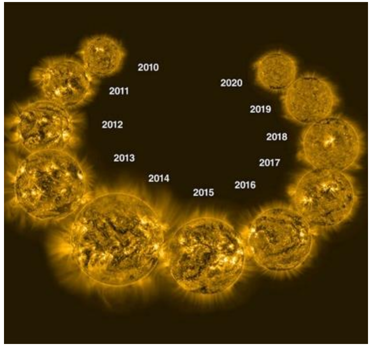
~ 1 m/s

(Super-)granulation



~ few m/s

Spots & faculae



~ 10 m/s

Activity cycles

ASTROPHYSICS!

How do we **model** stellar variability in the spectrum?

A quick overview of recently developed methods

AESTRA: Deep Learning for Precise Radial Velocity Estimation in the Presence of Stellar Activity

Yan Liang[1], Joshua N. Winn[1], and Peter Melchior[1,2]

Measuring precise radial velocities on individual spectral lines

IV. Stellar activity correlation with line formation temperature★

K. Al Moulla[1], X. Dumusque[1], and M. Cretignier[2]

A linearized approach to radial velocity extraction

S. Shahaf★ and B. Zackay

A Compact, Coherent Representation of Stellar Surface Variation in the Spectral Domain

Lily L. Zhao[1,2,6], Megan Bedell[1], David W. Hogg[1,3,4,5], and Rodrigo Luger[1]

A Gaussian process model for stellar activity in 2D line profile time-series

Haochuan Yu,[1★] Suzanne Aigrain,[1] Baptiste Klein,[1] Michael Cretignier,[1] Florian Lienhard[2] and Stephen J. Roberts[3]

Data-Driven Modeling of Telluric Features and Stellar Variability with StellarSpectraObservationFitting.jl

Christian Gilbertson,[1,2,3,4] Eric B. Ford,[2,3,5,6] Samuel Halverson,[7] Evan Fitzmaurice,[2,3,8] Cullen H. Blake,[9] Guðmundur Stefánsson,[10,11] Suvrath Mahadevan,[2,3,12] Jason T. Wright,[2,3,13] Jacob K. Luhn,[14] Joe P. Ninan,[15] Paul Robertson,[14] Arpita Roy,[16,17] Christian Schwab,[18] and Ryan C. Terrien[19]

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Separating planetary reflex Doppler shifts from stellar variability in the wavelength domain

A. Collier Cameron[1,2★] E. B. Ford[2,3,4,5] S. Shahaf[6] S. Aigrain,[7] X. Dumusque,[8] R. D. Haywood,[9,10†] A. Mortier[11,12] D. F. Phillips,[9] L. Buchhave[13] M. Cecconi,[14] H. Cegla[8,15] R. Cosentino,[14] M. Crétignier[8] A. Ghedina,[14] M. González,[14] D. W. Latham,[9] M. Lodi,[14] M. López-Morales,[9] G. Micela,[16] E. Molinari,[17] F. Pepe,[8] G. Piotto,[18] E. Poretti[14] D. Queloz,[11] J. San Juan[14] D. Ségransan,[8] A. Sozzetti[19] A. Szentgyorgyi,[9] S. Thompson,[11] S. Udry[8] and C. Watson[20]

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A Gaussian process framework for modelling stellar activity signals in radial velocity data

V. Rajpaul,[1★] S. Aigrain,[1] M. A. Osborne,[2] S. Reece[2] and S. Roberts[2]

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I. Validation of the method and application to mitigate stellar activity ★ ★★

X. Dumusque[1]

Efficient modeling of correlated noise

II. A flexible noise model with fast and scalable methods

J.-B. Delisle[1], N. Hara[1,★], and D. Ségransan[1]

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Insights on the Spectral Signatures of Stellar Activity and Planets from PCA

Allen B. Davis[1], Jessi Cisewski[2], Xavier Dumusque[3,4], Debra A. Fischer[1], and Eric B. Ford[5,6,7,8]

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Identifying activity induced RV periodicities and correlations using central line moments

J. R. Barnes,[1★] S. V. Jeffers,[2] C. A. Haswell,[1] M. Damasso,[3] F. Del Sordo,[4] F. Liebing,[2] M. Perger[4,5] and G. Anglada-Escudé[4,5]

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Stellar activity correction using PCA decomposition of shells

M. Cretignier, X. Dumusque, and F. Pepe

Identifying Exoplanets with Deep Learning. IV. Removing Stellar Activity Signals from Radial Velocity Measurements Using Neural Networks

Zoe. L. de Beurs[1,2,3,4], Andrew Vanderburg[2,3,5,24], Christopher J. Shallue[6], Xavier Dumusque[7], Andrew Collier Cameron[8], Christopher Leet[9], Lars A. Buchhave[10], Rosario Cosentino[11], Adriano Ghedina[11], Raphaëlle D. Haywood[12,25], Nicholas Langellier[6,13], David W. Latham[6], Mercedes López-Morales[6], Michel Mayor[7], Giusi Micela[14], Timothy W. Milbourne[6,13], Annelies Mortier[15,16], Emilio Molinari[17], Francesco Pepe[7], David F. Phillips[6], Matteo Pinamonti[18], Giampaolo Piotto[19,20], Ken Rice[21,22], Dimitar Sasselov[6], Alessandro Sozzetti[18], Stéphane Udry[7], and Christopher A. Watson[23]

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Spectrum radial velocity analyser (SERVAL)

High-precision radial velocities and two alternative spectral indicators

M. Zechmeister[1], A. Reiners[1], P. J. Amado[2], M. Azzaro[3], F. F. Bauer[1], V. J. S. Béjar[4,5], J. A. Caballero[6], E. W. Guenther[7], H.-J. Hagen[8], S. V. Jeffers[1], A. Kaminski[9], M. Kürster[10], R. Launhardt[10], D. Montes[11], J. C. Morales[12], A. Quirrenbach[9], S. Reffert[9], I. Ribas[12], W. Seifert[9], L. Tal-Or[1], and V. Wolthoff[9]

New Methods for Finding Activity-sensitive Spectral Lines: Combined Visual Identification and an Automated Pipeline Find a Set of 40 Activity Indicators

A. W. Wise[1], S. E. Dodson-Robinson[1,2], K. Bevenour[1], and A. Provini[1]

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Haochuan Yu[1★] Suzanne Aigrain,[1] Baptiste Klein,[1] Michael Cretignier,[1] Florian Lienhard[2] and Stephen J. Roberts[3]

...Data-Driven Mode...

StellarSpectraObservationFitting.jl

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FIESTA II. Disentangling Stellar and Instrumental Variability from Exoplanetary Doppler Shifts in the Fourier Domain

J. Zhao[1,2], Eric B. Ford[1,3,4,5], and C. G. Tinney[2,6]

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Multi-mask least-squares deconvolution: extracting RVs using tailored masks

F. Lienhard,[1★] A. Mortier,[1,2] L. Buchhave,[3] A. Collier Cameron,[4] M. López-Morales,[5] A. Sozzetti,[6] C. A. Watson[7] and R. Cosentino[8]

Improving Earth-like planet detection in radial velocity using deep learning

Yinan Zhao[1], Xavier Dumusque[1], Michael Cretignier[2], Andrew Collier Cameron[3,4], David W. Latham[5], Mercedes López-Morales[5], Michel Mayor[1], Alessandro Sozzetti[6], Rosario Cosentino[7], Isidro Gómez-Vargas[1], Francesco Pepe[1], and Stephane Udry[1]

Wapiti: A data-driven approach to correct for systematics in RV data

Application to SPIRou data of the planet-hosting M dwarf GJ 251★

M. Ould-Elhkim[1], C. Moutou[1], J.-F. Donati[1], É. Artigau[2,3], P. Fouqué[1], N. J. Cook[2], A. Carmona[4], P. I. Cristofari[1,5], E. Martioli[6,7], F. Debras[1], X. Dumusque[8], J. H. C. Martins[10], G. Hébrard[6], C. Cadieux[2], X. Delfosse[4], R. Doyon[2], B. Klein[9], J. Gomes da Silva[10], T. Forveille[4], T. Hood[1], and P. Charpentier[1]

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A linearized approach to radial velocity extraction

Quiet Please: Detrending Radial Velocity Variations from Stellar Activity with a Physically Motivated Spot Model

Jared C. Siegel[1,20], Samuel Halverson[2], Jacob K. Luhn[3], Lily L. Zhao[4], Khaled Al Moulla[5], Paul Robertson[3], Chad F. Bender[6], Ryan C. Terrien[7], Arpita Roy[8,9], Suvrath Mahadevan[10,11], Fred Hearty[10,11], Joe P. Ninan[10,11], Jason T. Wright[10,11,12], Eric B. Ford[10,11,13,14], Christian Schwab[15], Guðmundur Stefánsson[1,16,19], Cullen H. Blake[17], and Michael W. McElwain[18]

...tral Domain

Lily L. Zhao[1,2,6], Megan Bedell[1], David W. Hogg[1,3,4,5], and Rodrigo Luger[1]

Mea...

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Characterization of K2-167 b and CALM, a new stellar activity mitigation method

Zoë L. de Beurs,[1,2★†] Andrew Vanderburg,[3] Erica Thygesen,[4] Joseph E. Rodriguez,[4] Xavier Dumusque,[5] Annelies Mortier,[6] Luca Malavolta,[7,8] Lars A. Buchhave,[9] Christopher J. Shallue,[10] Sebastian Zieba,[11,12] Laura Kreidberg,[11] John H. Livingston,[13,14,15] R. D. Haywood,[16,17] David W. Latham,[10] Mercedes López-Morales[11] and André M. Silva[18,19]

...and Planets from

...her[1], and Eric B. Ford[5,6]

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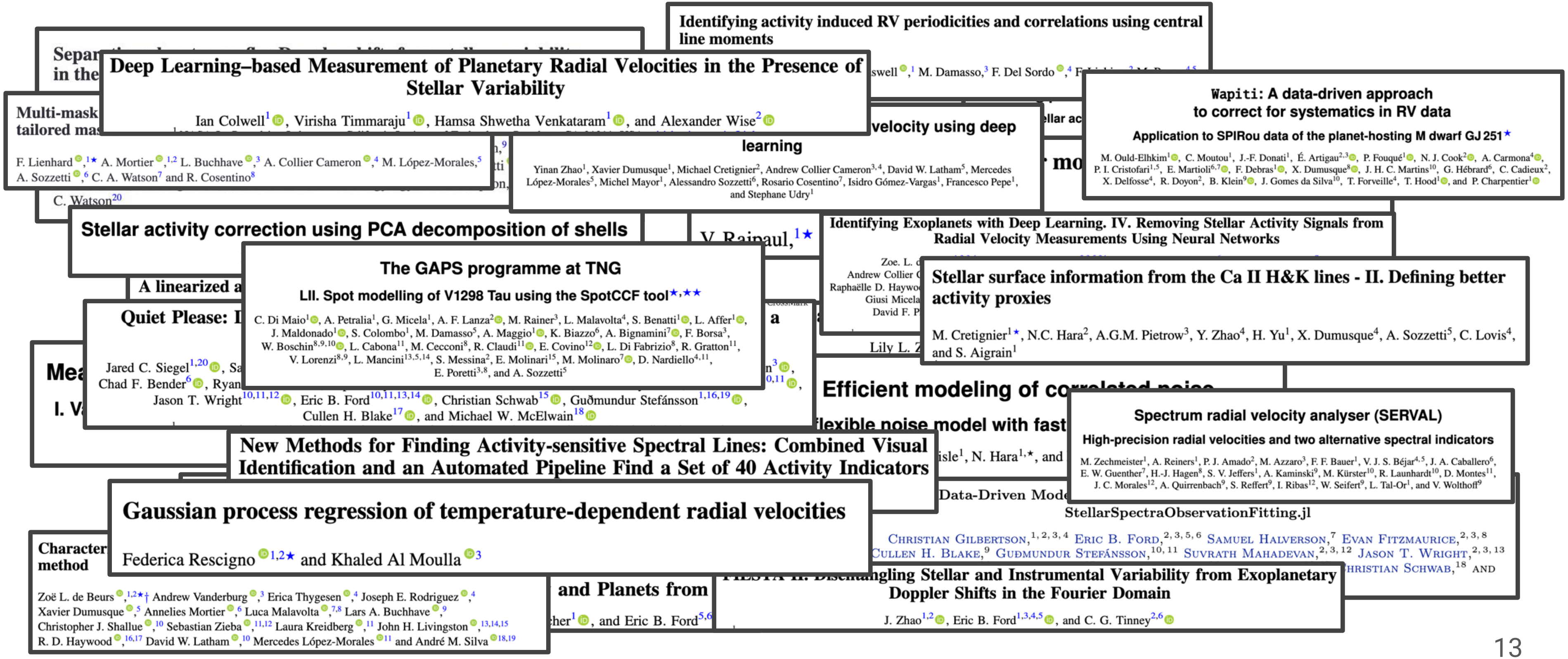
A quick overview of recently developed methods

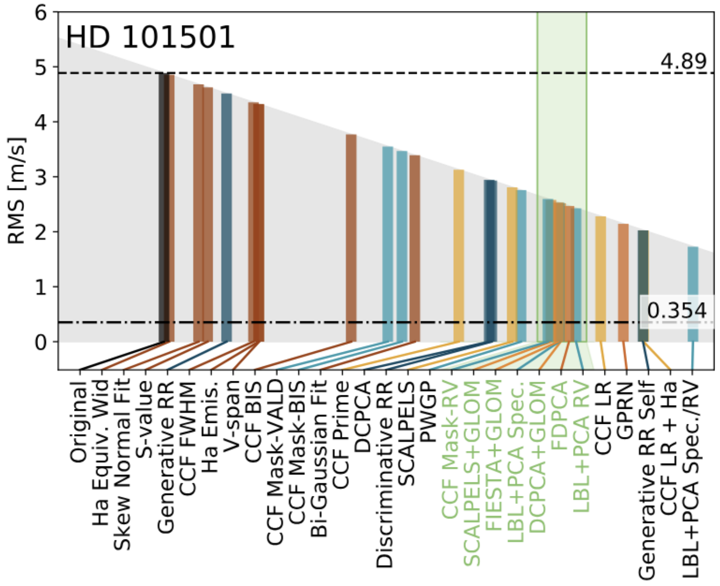


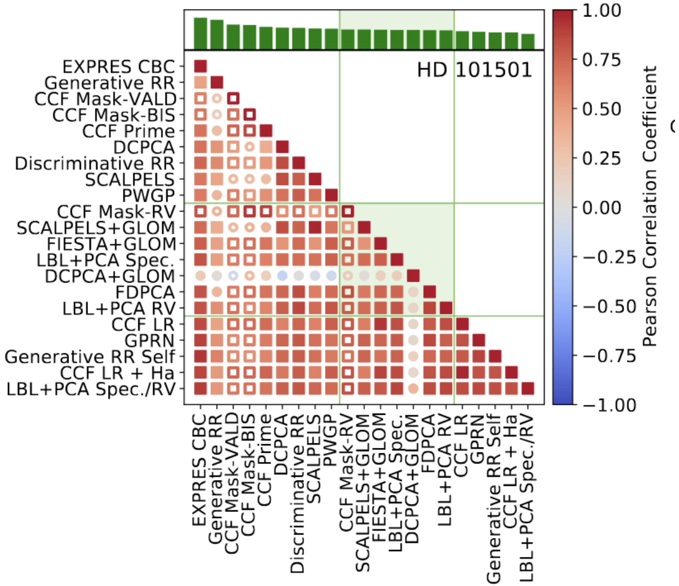
A quick overview of recently developed methods

ADS library at: https://bedell.space/mitigation

S	
A	
B	
C	
D	

Quantitative comparison of methods is hard!





L. Zhao et al. (2022)

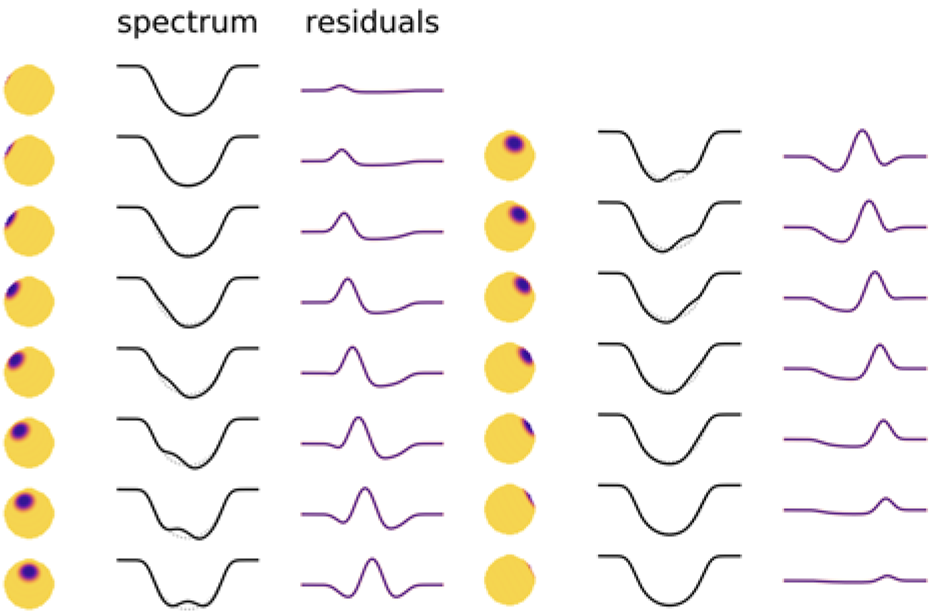
can

How ~~do~~ we model stellar variability in the spectrum?

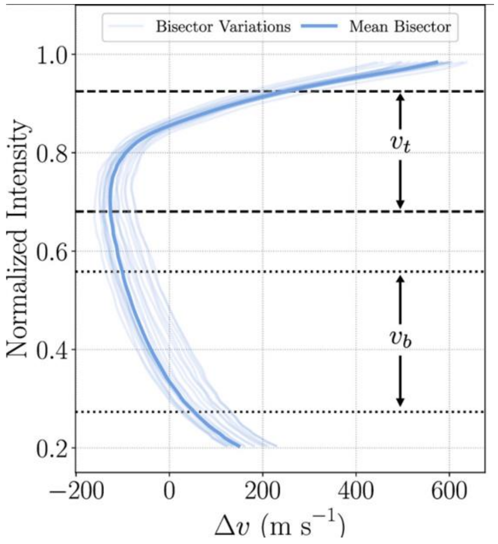
Some overarching themes in stellar signal mitigation

1. Line shape (a)symmetry
2. Wavelength (in)dependence
3. Time coherence
4. An underlying stellar surface
5. An underlying stellar atmosphere

Theme 1: Use the inherent *symmetry* of a true Doppler shift



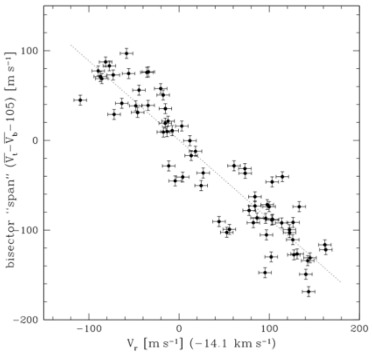
Luger, Bedell et al. (2021)



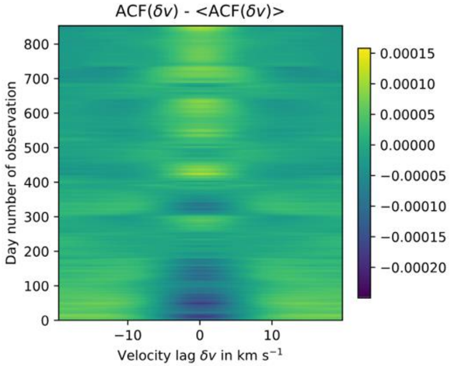
Palumbo et al. (2024)

Theme 1: Use the inherent *symmetry* of a true Doppler shift

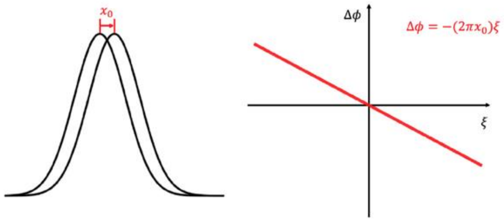
Examples:



Detrending with CCF bisector slope
(Queloz et al. 2001)



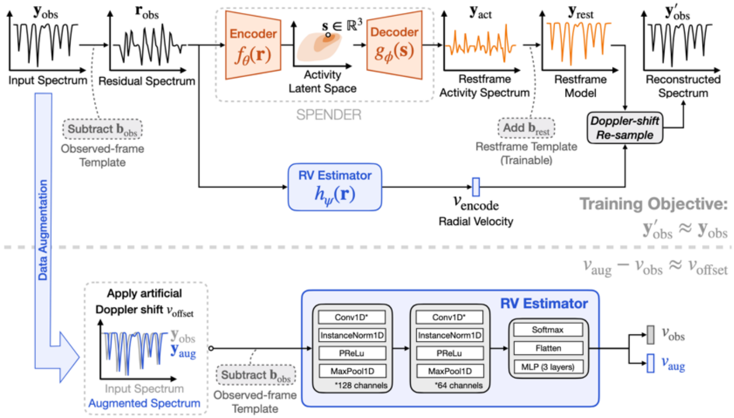
ACF shape changes with
SCALPELS model
(Collier-Cameron et al. 2021)



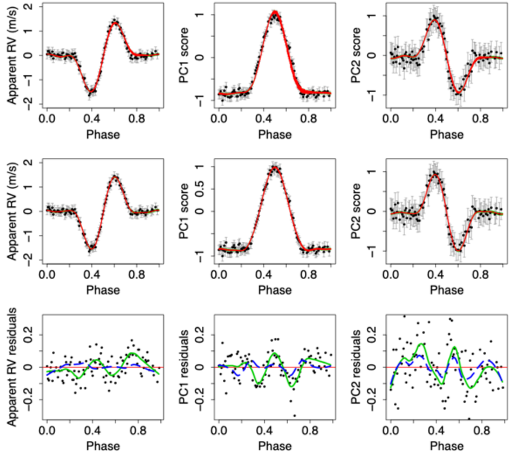
CCF Fourier phase modeling with FIESTA
(J. Zhao et al. 2020, 2022)

Theme 1: Use the inherent *symmetry* of a true Doppler shift

Or more generally: Enforce that the variability signal shouldn't be a Doppler shift

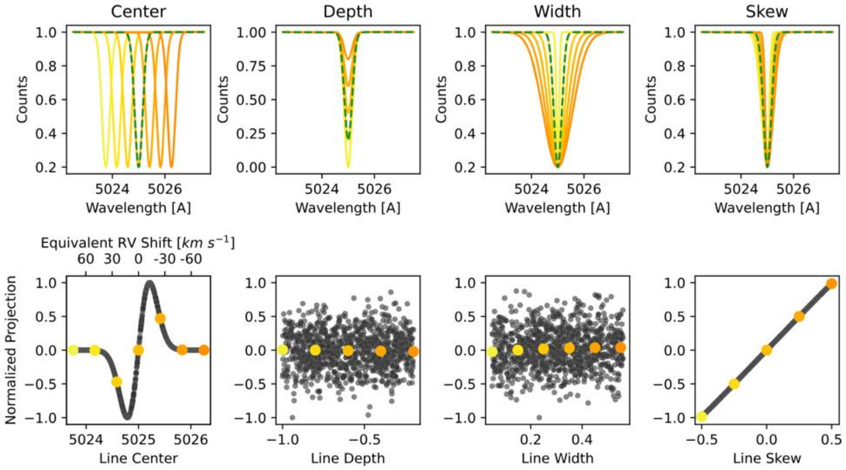


Neural network trained with augmented data in AESTRA
(Liang et al. 2023)

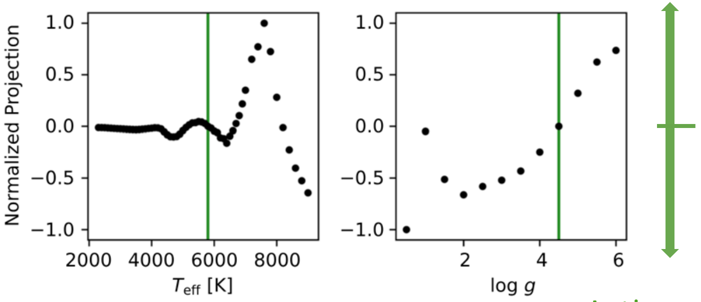


Doppler-constrained PCA
(Jones et al. 2017, 2022;
Gilbertson et al. 2024)

Note: Stellar signals are not entirely asymmetric, nor entirely orthogonal to a Doppler shift



Correlated with Doppler shift



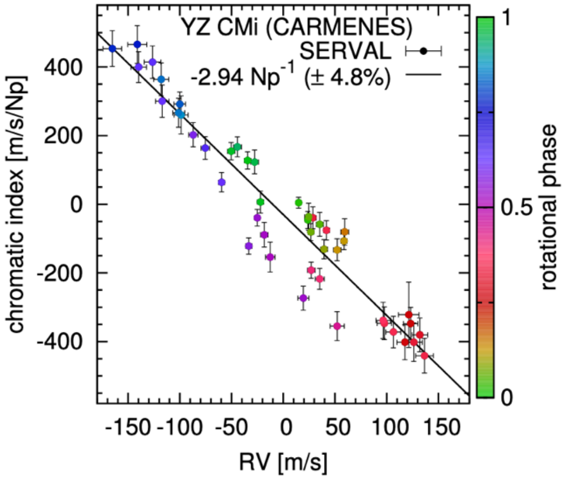
Fully independent

Anti-correlated with Doppler shift

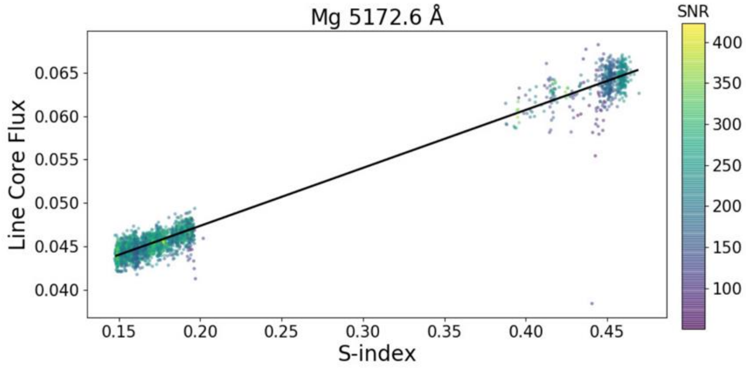
L. Zhao, Bedell et al. (2024)

Theme 2: Use the *wavelength independence* of a true Doppler shift

Examples:



Chromatic RV index from SERVAL
(Zechmeister et al. 2018)

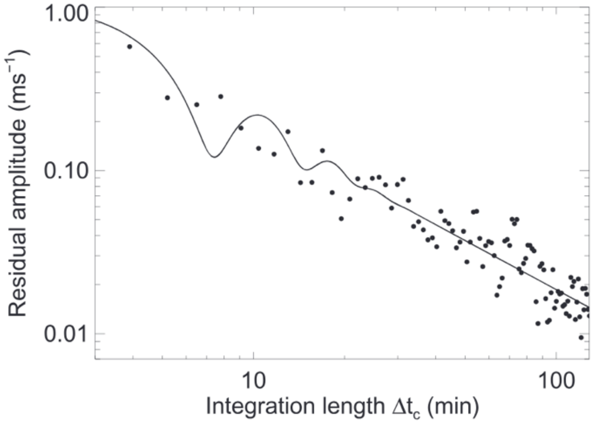


Activity indices from individual lines
(figure from Wise et al. 2018)

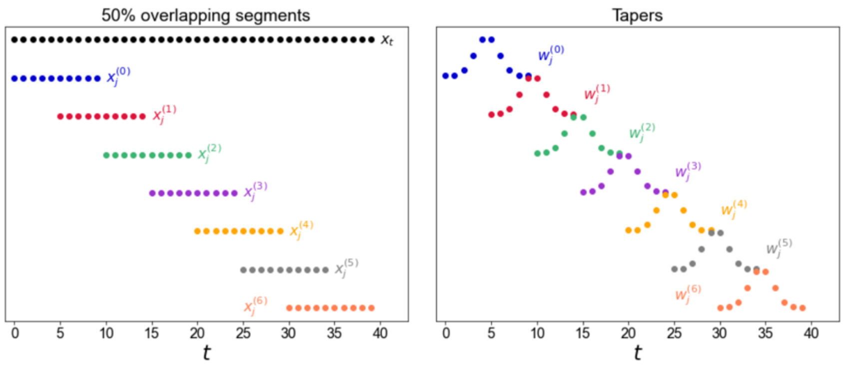
(+ general use of order-by-order / chunk-by-chunk / line-by-line RV determination)

Theme 3: Use the *time coherence* of a true Doppler shift

Average / bin over the stochastic signals…



Integrating over p-modes
(Chaplin et al. 2019)

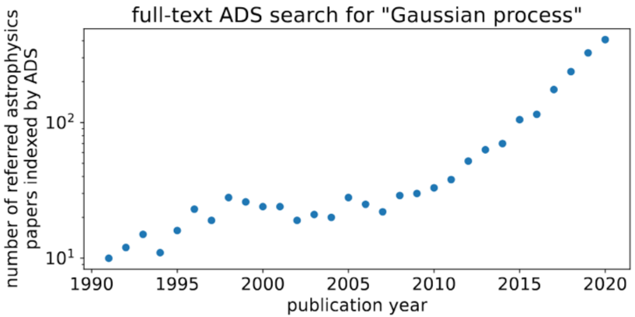


Welch's method for periodograms
(Dodson-Robinson et al. 2022)

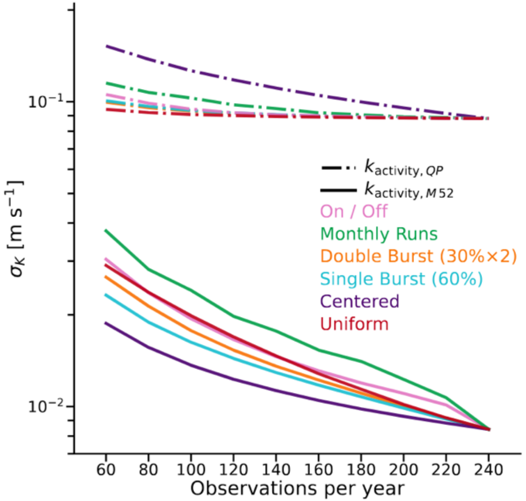
(+ generally segmenting data in time)

Theme 3: Use the *time coherence* of a true Doppler shift

Average / bin over the stochastic signals…
… or model in the time domain

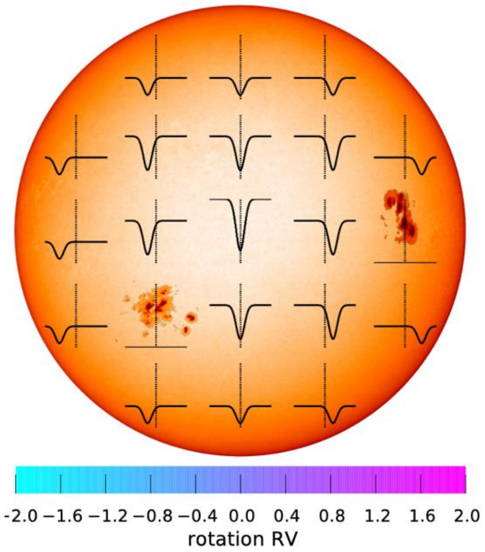


GP modeling
(Aigrain & Foreman-Mackey 2023)



Quantifying the demands on time coverage
(Gupta & Bedell 2024)

Theme 4: Use the physics of the *stellar surface*



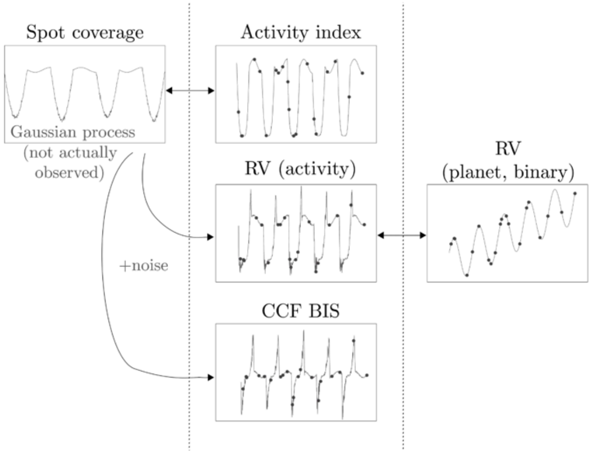
SOAP 2.0: Dumusque et al. (2014)
& SOAP-GPU: Y. Zhao & Dumusque (2023)

starry: Luger et al. (2019)
github.com/rodluger/starry

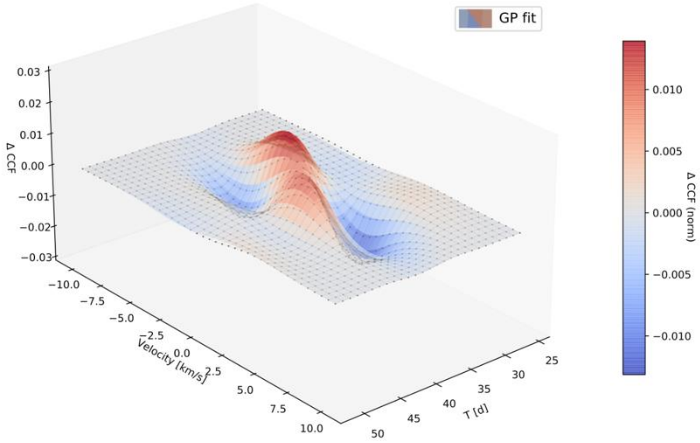
spotter: Garcia et al. (in prep)
spotter.readthedocs.io

Theme 4: Use the physics of the *stellar surface*

Ex.: the FF' method (Aigrain et al. 2012)



Rajpaul et al. (2015)

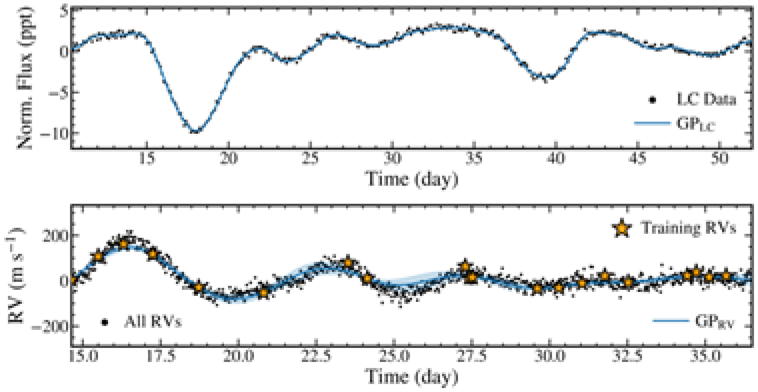


Yu et al. (2024)

Theme 4: Use the physics of the *stellar surface*

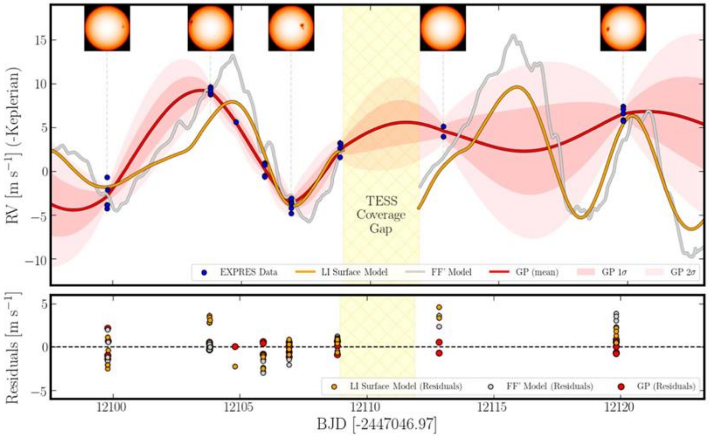
Ancillary data can be very helpful here!

Photometry:



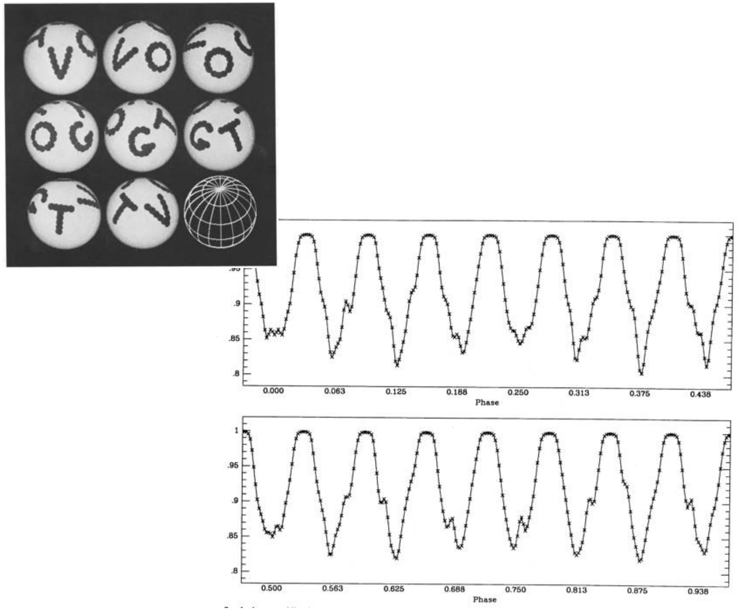
Tran, Bedell, & Foreman-Mackey (2023)

Interferometry:

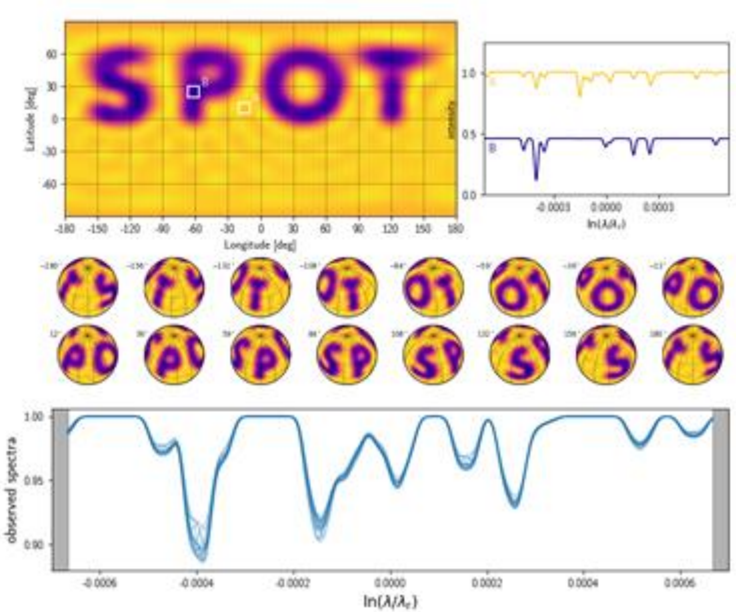


Roettenbacher et al. (2022)

Note: Explicitly mapping the star from spectra alone is **possible** but demanding

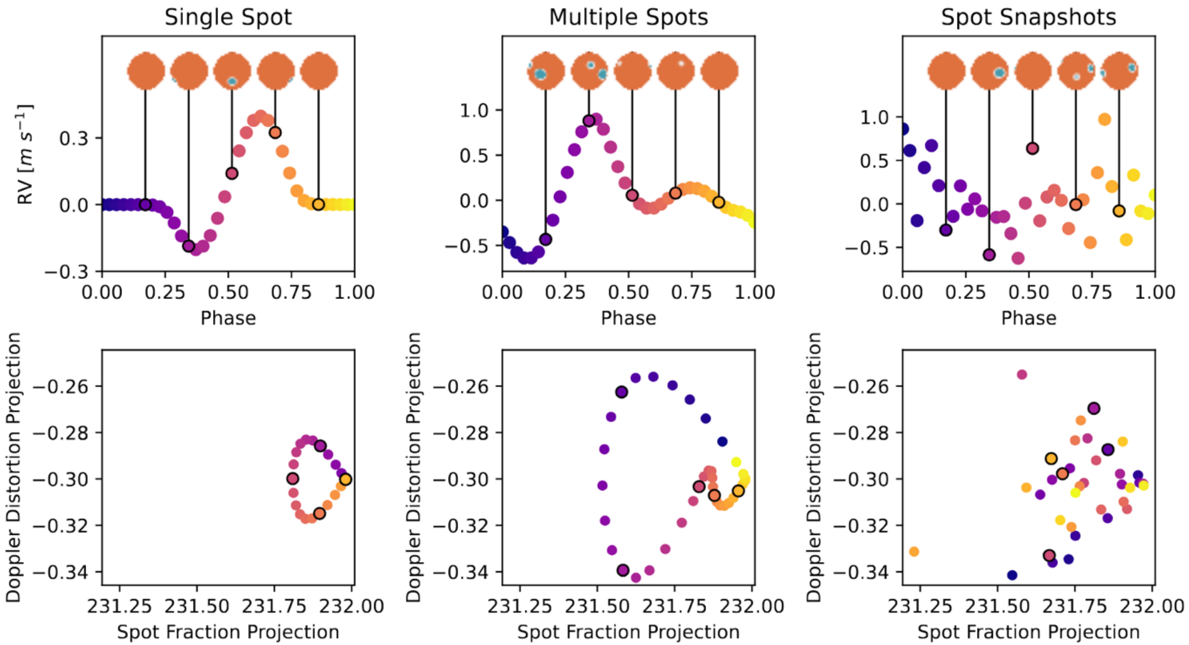


Vogt et al. (1987)



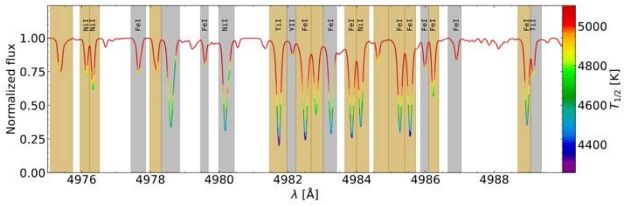
Luger, Bedell, et al. (2021)

Note: If the stellar surface can be represented compactly & coherently, so can a sufficient model.

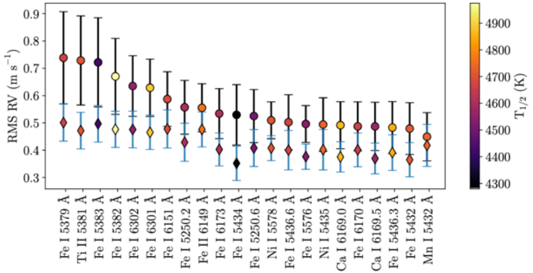


L. Zhao, Bedell et al. (2024)

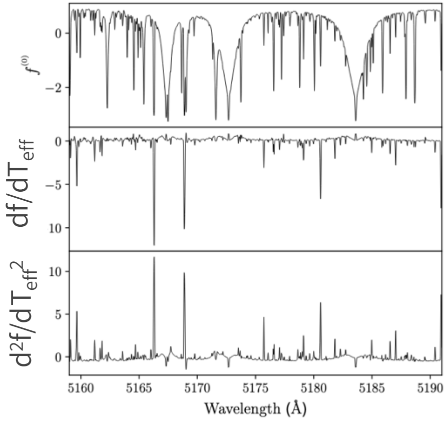
Theme 5: Use the physics of the *stellar atmosphere*



Using temperature of formation in “line-by-line” RVs (Al Moulla et al. 2022)



Tuning bisector diagnostics by line (Palumbo et al. 2024)

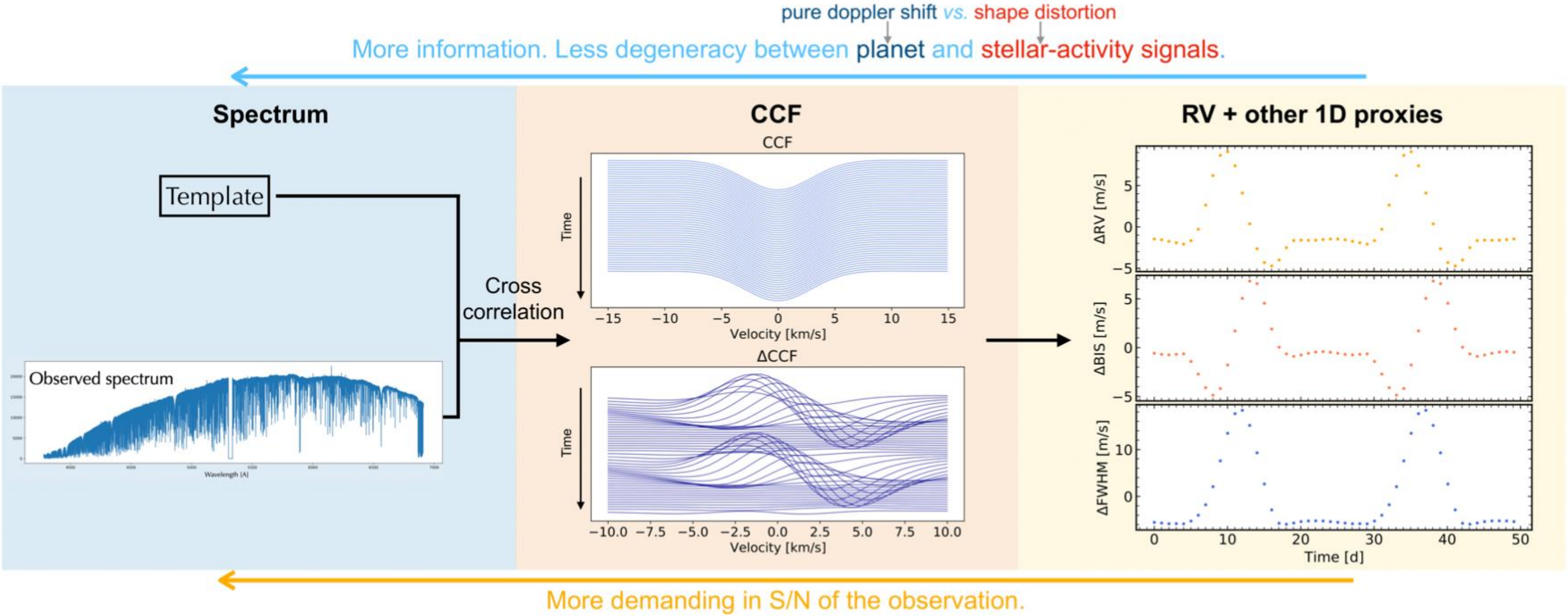


Linearized model with PHOENIX spectrum inputs (Shahaf & Zackay 2023)

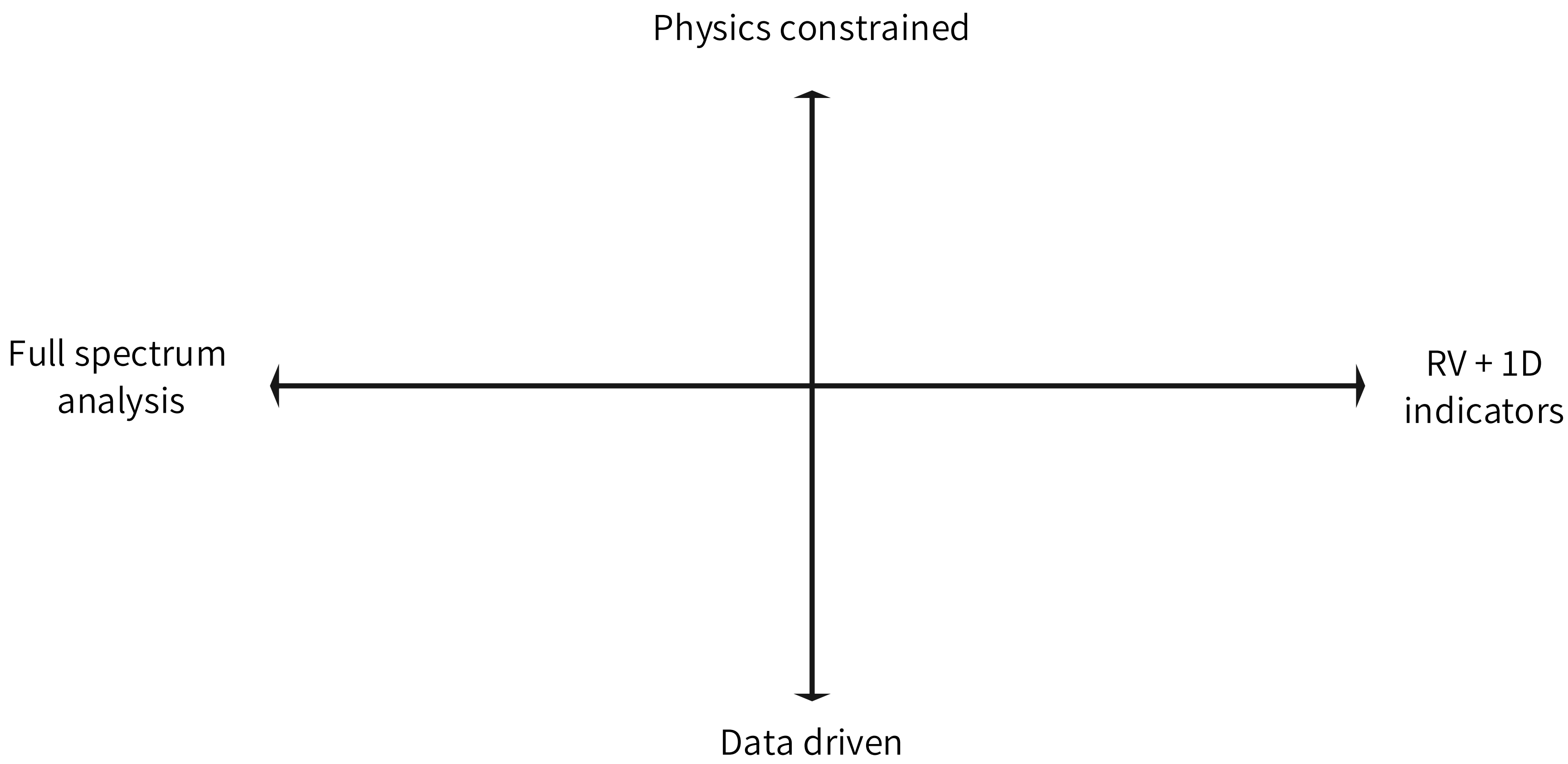
Some overarching themes in stellar signal mitigation

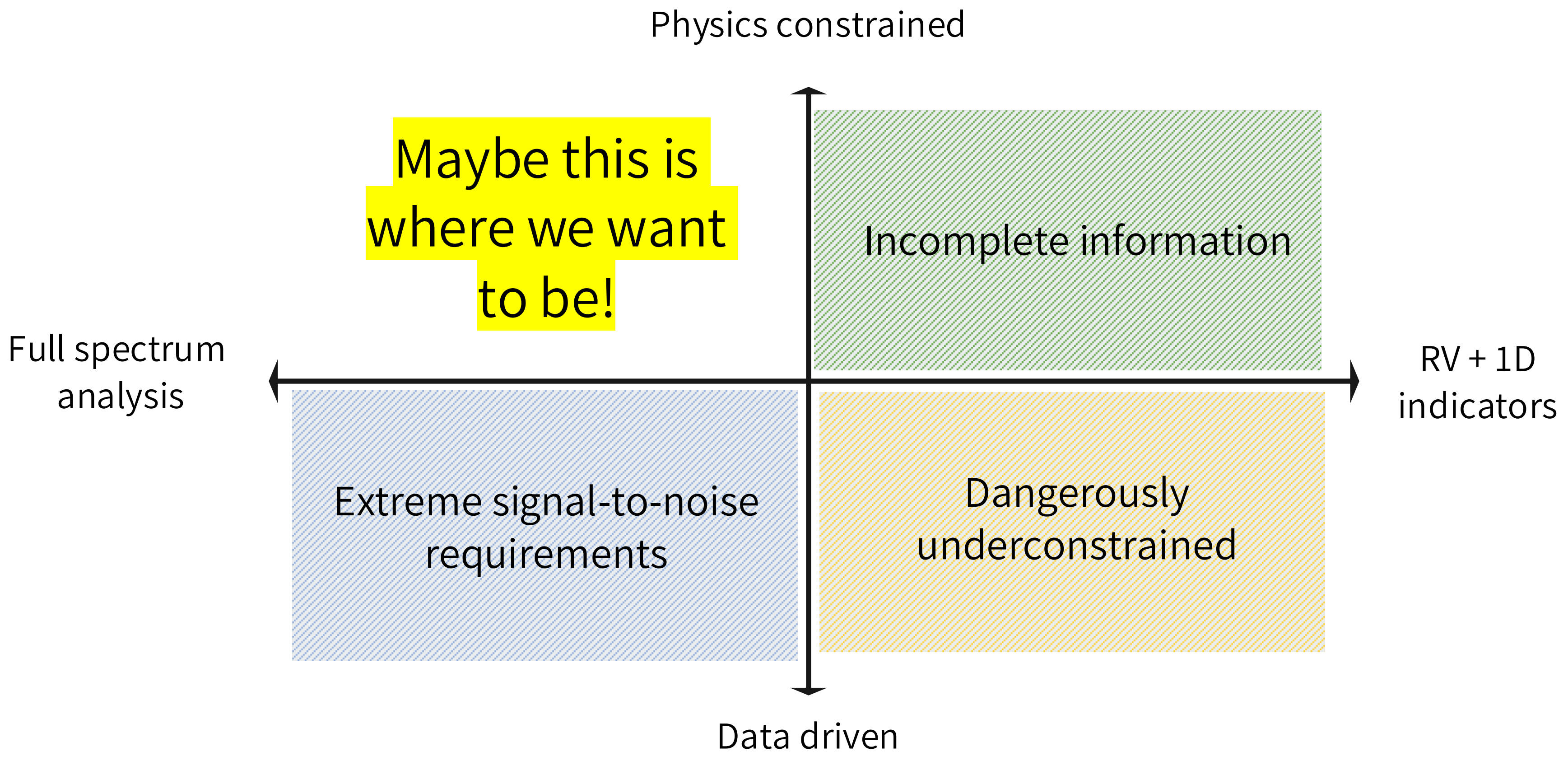
1. Line shape (a)symmetry
2. Wavelength (in)dependence
3. Time coherence
4. An underlying stellar surface
5. An underlying stellar atmosphere

One last point:



Yu et al. (2024)


Physics constrained
Full spectrum analysis
RV + 1D indicators
Data driven


Physics constrained
Maybe this is where we want to be!
Incomplete information
Full spectrum analysis
RV + 1D indicators
Extreme signal-to-noise requirements
Dangerously underconstrained
Data driven

What opportunities do we have to learn more about stellar physics?

Exoplanet searches

Asteroseismology

Keck Planet Finder

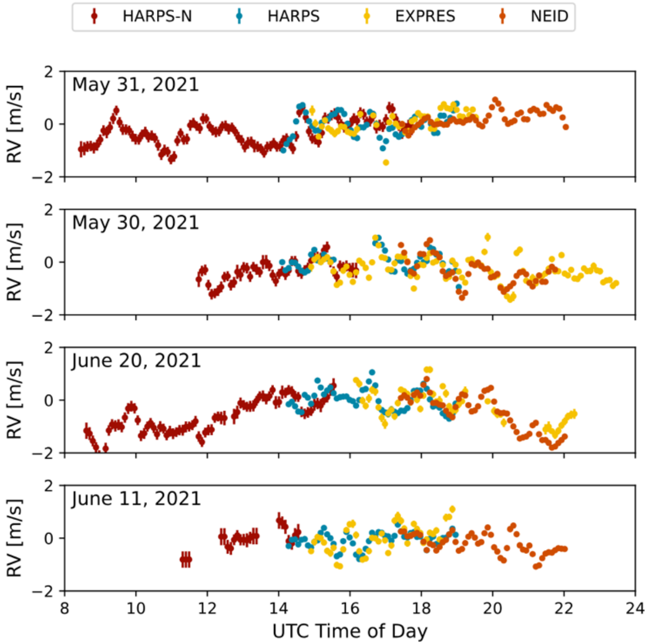
-CLEF

SONG
STELLAR OBSERVATIONS NETWORK GROUP

ANDES

See also: talks from Huber, Bedding

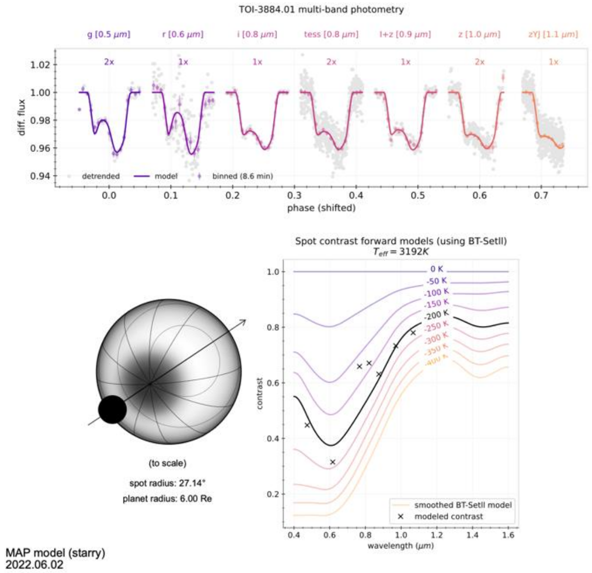
Continuous, coordinated observations shed light on (super-)granulation & more



L. Zhao et al. (2024)
See also: talks by O'Sullivan & Gupta

Better spatially resolved spectra to come

+ IAG spectral atlas (Ellwarth et al (2023))



Starspot crossing observations
(figure made by Lionel Garcia)
See also: talks tomorrow morning!

Takeaways:

- RV surveys are showing us a lot about stars, whether we like it or not!
- The community is working hard & making progress on data analysis methods to separate out planets from stellar variability
- Advances in available data & techniques will allow us to incorporate a greater degree of stellar physics in future analyses