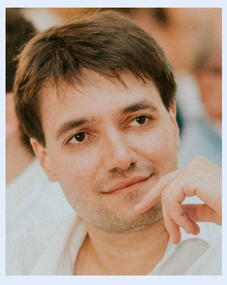
Doppler Imaging of the Sun: A proof of concept



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Can we use Doppler Imaging to model activity-induced line-shape variations in Sun-like stars?

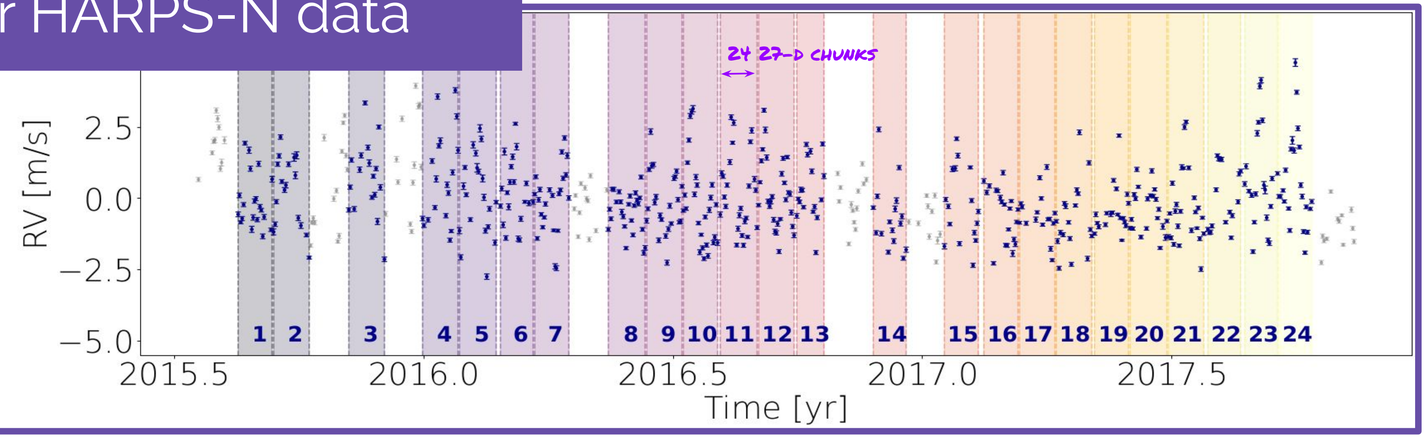
Solar HARPS-N data

3 years of public HARPS-N Solar data

- Reduced with ESPRESSO Data reduction software [1]
- Select cloud-free data with low differential extinction [2,3]
- Normalise and process spectra with YARARA [4,5]
- Divide the data into chunks of 1 P_{rot} (~27d)
- Keep chunks with at least 10 points and phase gap < 0.2

See the analysis of the full 8 yr HARPS-N Solar data set arXiv2405.12065

486 points
1.3 m/s RMS



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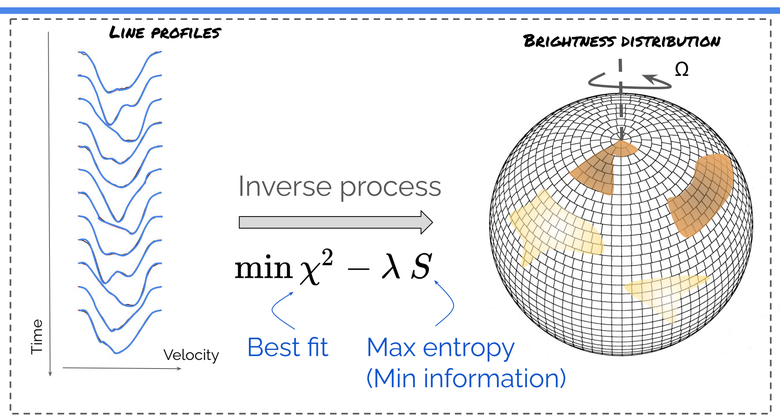
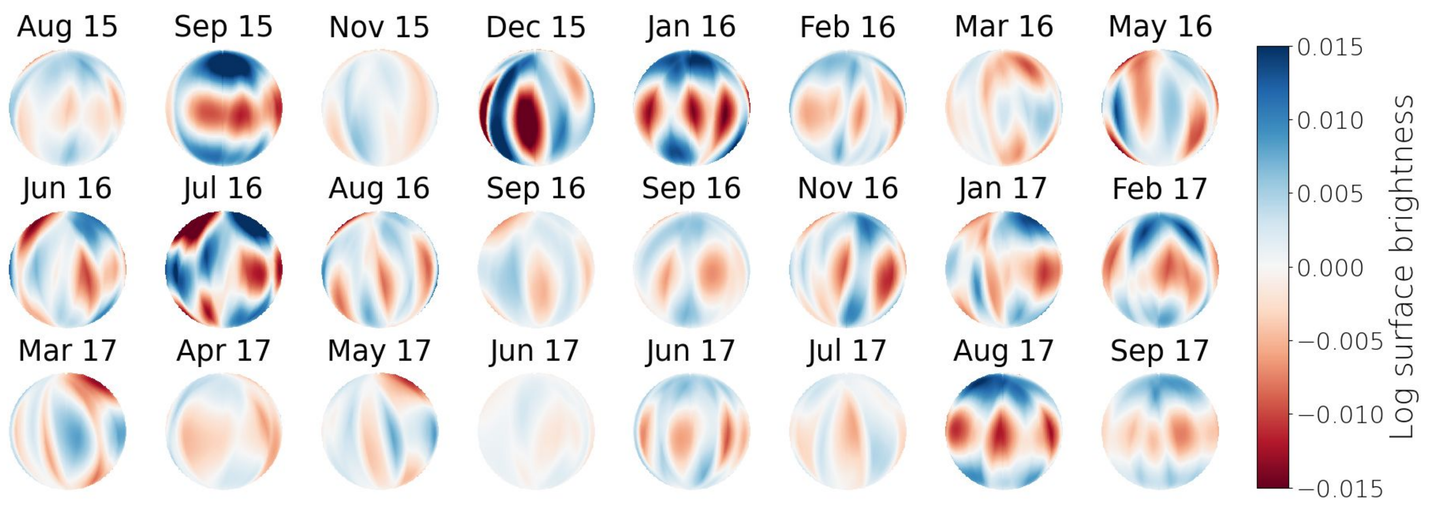


Doppler Imaging of the Solar spectra

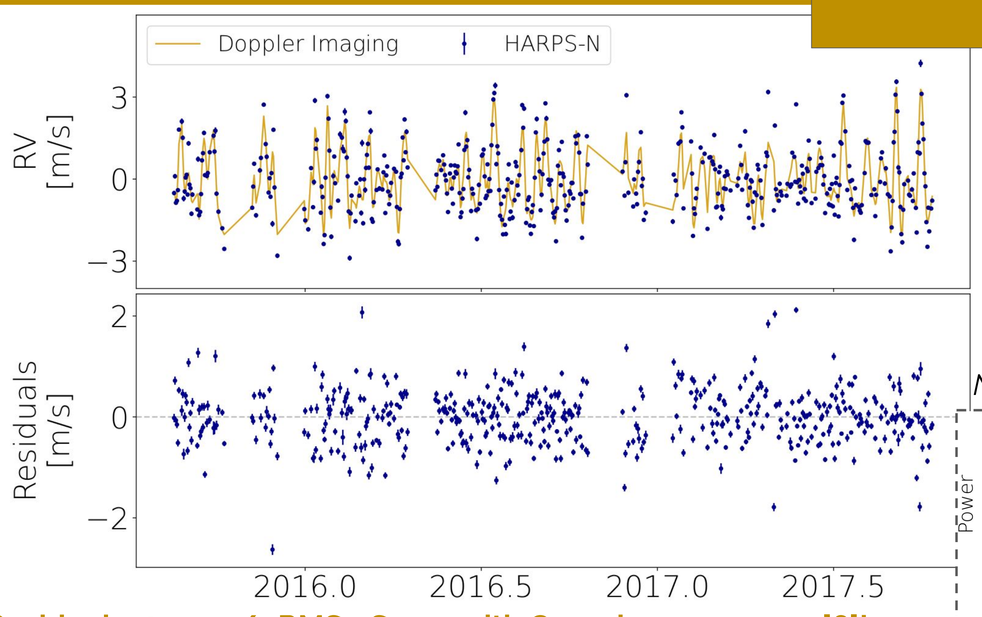
Best-fitting brightness distributions from HARPS-N Solar Spectra



Method: Doppler Imaging

Doppler Imaging inverts spectra/CCFs into brightness distribution [7,8]
Ill-posed problem (max entropy regularisation)
Designed for rapidly-rotating stars
Work with Sun as spectra precise enough and good temporal sampling

Goodness of fit

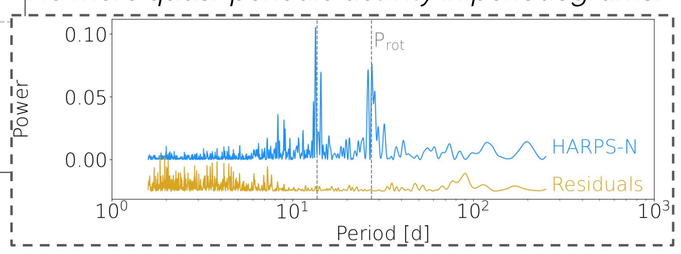


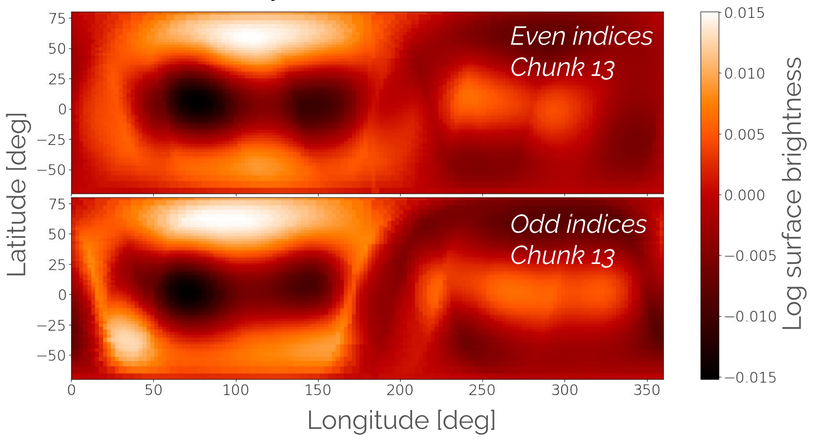
Residuals: 0.55 m/s RMS - Same with Gaussian processes [6]!
Combination of Instrument stability (0.4 m/s) and Supergranulation (0.6 m/s)

Is the fit robust?

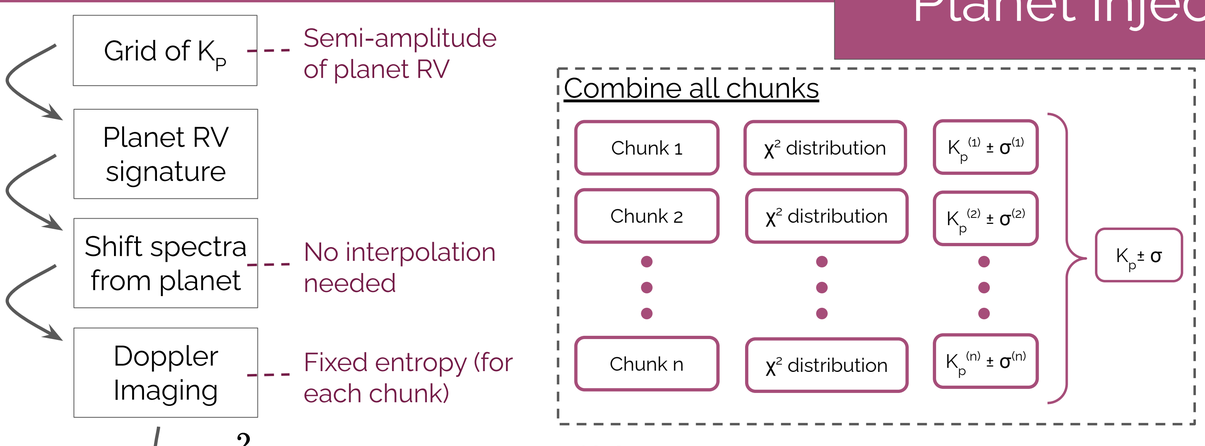
- Radial velocities (RV) extracted from best-fit spectra consistent with HARPS-N RVs
- Leave-one-out cross-validation conclusive
- Tentative evidence of differential rotation
- Similar brightness maps obtained when reconstructed only from even (or odd) indices (for a given chunk)

No more quasi-periodic activity in periodograms!





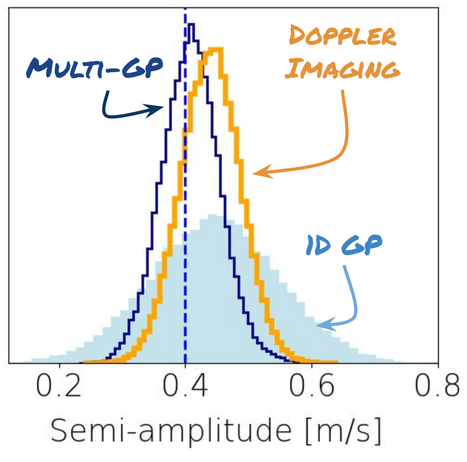
Planet injection & recovery



- Planet injected directly in HARPS-N Solar line profiles
K_P = 0.4 m/s - P_{orb} = 100 d (repeat for 3 ≠ orbital phases)

- Recover the planet RV semi-amplitude using 3 methods

1. 1D Gaussian process (GP) regression
$K_p = 0.44 \pm 0.18$ m/s *Marginal detection*
2. Multi-dimensional GP (w/ S index [10])
$K_p = 0.42 \pm 0.07$ m/s *Fair detections*
3. Doppler Imaging $K_p = 0.44 \pm 0.06$ m/s



Proof of concept completed: Convergence of the Doppler Imaging code and good preliminary performance on planet recovery → **We no longer fit the RVs!!**

Perspectives of improvement

- What are we reconstructing? Comparison with SDO HMI intensitigrams and magnetograms. Can we recover latitudinal differential rotation? Magnetic cycle?
- Need for a more robust process: Bayesian framework with Information Field Theory? Faster computation with GPUs?
- Include the intrinsic evolution of activity: Towards a joint Doppler Imaging and Gaussian Process framework? [11,12]
- Towards a more physically-realistic model: Including the inhibition of convective blueshift and the Zeeman effect in active regions

Acknowledgements: This project received funding from the European Research Council (ERC) under the H2020 research & innovation programme (grant agreements #865624 GPRV, PI: S. Aigrain). We thank the HARPS-N solar team and TNG staff for processing the solar data and maintaining the solar telescope.

References: [1] Dumusque et al. 2021, A&A, 648, 103 [2] Collier Cameron et al. 2019, MNRAS, 487, 1082 [3] Al Moulla et al. 2023, A&A, 669, A39 [4] Cretignier et al. 2020, A&A, 640, A42 [5] Cretignier et al. 2021, A&A, 653, A43 [6] **Klein** et al. 2024, MNRAS, in press (arXiv:2405.12065) [7] Donati & Landstreet 2009, ARA&A, 47, 333 [8] Kochukhov 2016, LNP, 314, 177 [9] Petit et al. 2015, A&A, 584, A84 [10] Barragán et al. 2022, MNRAS, 509, 866 [11] Luger et al. 2021, AJ, 162, 124 [12] Finociety & Donati 2022, MNRAS, 516, 5887