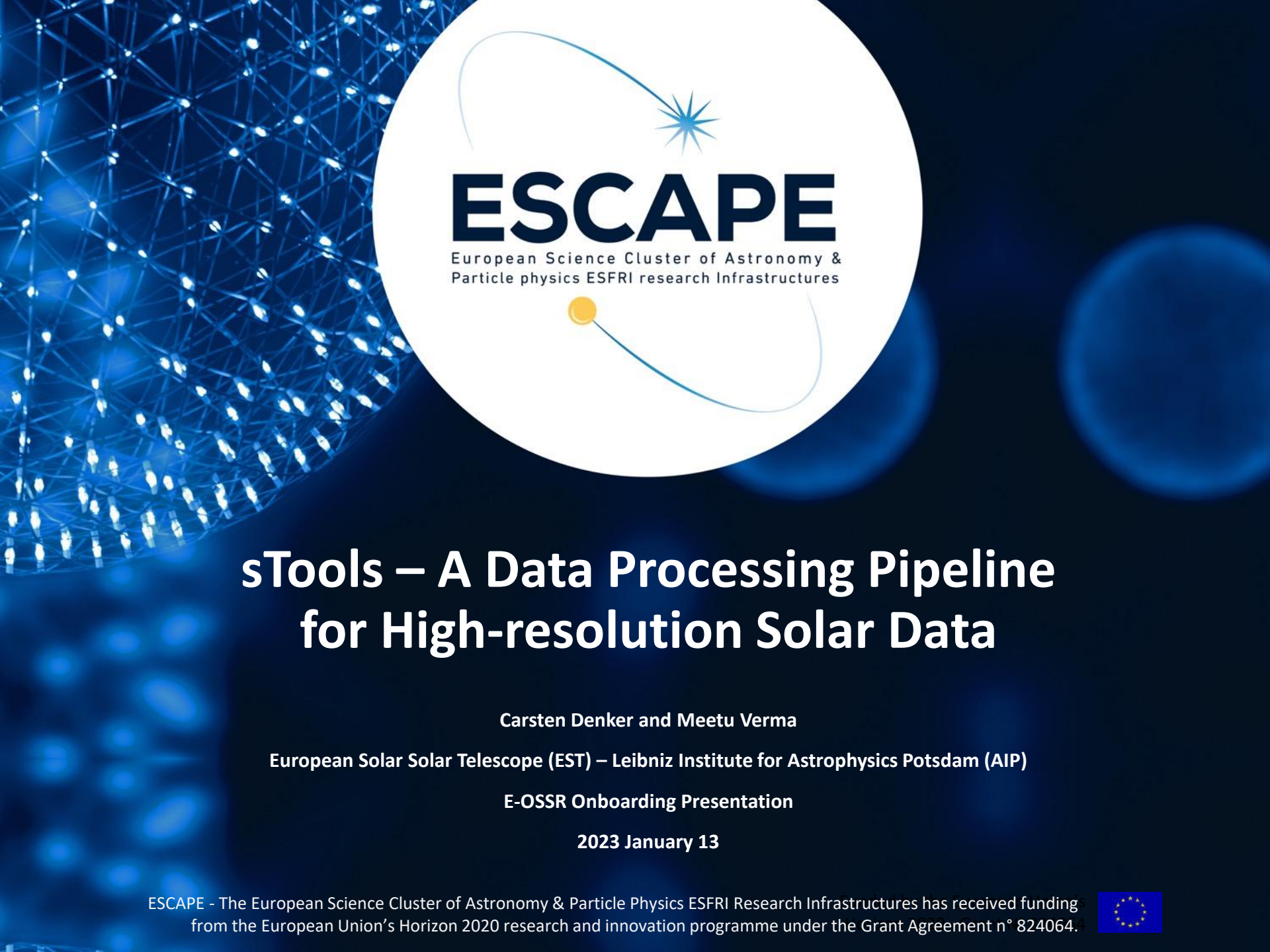

sTools – A Data Processing Pipeline for High-resolution Solar Data

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E-OSSR Onboarding Presentation

2023 January 13

ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement n° 824064.

Introduction

- Aim:
  - Introduction of the ***sTools*** data processing pipeline for high-resolution solar observations.
- Contents:
  - European Solar Telescope (EST)
  - Software/Service Development
  - Software/Service Requirements
  - “User story” HiFI+
  - OSSR Integration
  - Science cases HIFI+, FaMuLUS, and CLASSIC

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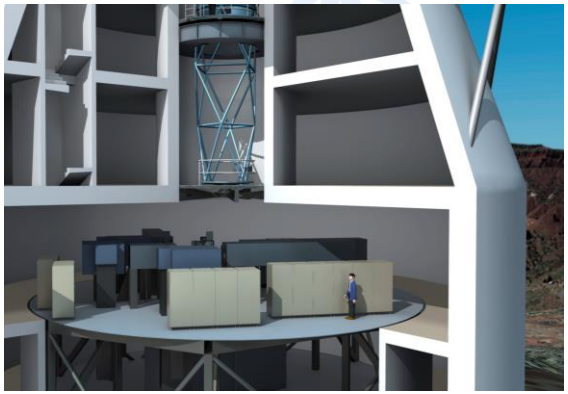
Introduction

European Solar Telescope (EST)

- The 4-meter EST is a proposed major research infrastructure for studying activity and dynamic of the Sun with high spatial, temporal, and spectral resolution and with high polarimetric sensitivity.
- Develop techniques for spectral inversions of photospheric and chromospheric absorption lines. Construct a spectral classification engine based on already existing machine learning software.
- Demonstrate science capabilities of new techniques.



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Introduction

- ***sTools*** Data Processing Pipeline
  - High-cadence imaging
  - Imaging spectropolarimetry
  - High-resolution spectroscopy
  - Data visualization
  - General methods for solar data analysis
  - GREGOR solar telescope and Vacuum Tower Telescope (VTT) as pathfinders since EST is only on the ESFRI roadmap

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Introduction

- Supported Instruments
  - Digitization of historical solar full-disk images @ Solar Observatory Einstein Tower
  - Blue Imaging Channel (BIC) @ GREGOR
  - GREGOR Fabry-Pérot Interferometer (GFPI) @ GREGOR
  - High-resolution Fast Imager (HiFI) @ GREGOR
  - Improved High-resolution Fast Imager (HiFI+) @ GREGOR
  - Fast Universal Multi-Line Spectrograph (FaMuLUS) camera system @ VTT
- Common Research Environment (CRE) and GREGOR/VTT archive @ AIP (gregor.aip.de, DOI:10.3847/1538-4365/aab773) in collaboration with AIP's E-Science Section

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Software/Service Development

- ***sTools*** (DOI:10.1017/S1743921317000114) is mainly written in the Interactive Data Language (IDL).
- IDL Coding Standard provided by ITT Visual Solutions (Article ID: 4120, released 2007-04-25).
- Development:
  - Code development of AIP's Solar Physics Section since 2012
  - Initially, Apache Subversion for version control
  - Migration to GibLab in 2023 as part of the Horizon 2022 ESCAPE project
- The code is under active development and maintained by AIP's Solar Physics Section.
- The software development is science-driven.

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Software/Service Development

- Programs, procedures, and functions are used in the routine processing of GREGOR and VTT data.
- Processed data and metadata are saved in FITS format and are partly compliant with the SOLARNET standards (arXiv:2011.12139).
- The ***sTools*** data processing pipeline is publicly available at AIP's GitLab repository (gitlab.aip.de/cdenker/stools).
- Extensive inline comments and program headers.
- Software released under GNU General Public License (GPL, Version 3, 2007 June 29).

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Software/Service Requirements

- IDL is platform independent.
- IDL Libraries:
  - IDL Astronomy Library
  - SolarSoftWare (SSW)
  - Coyote and Catalyst Libraries (https://www.idlcoyote.com/)
  - MPFIT (pages.physics.wisc.edu/~craigm/idl/idl.html)
- Hardware requirements: High-end workstations or servers
- Image restoration relies on third-party software packages:
  - KISIP (DOI:10.1117/12.788062, DOI:10.1051/0004-6361:200809894)
  - MOMFBD: (DOI:10.1117/12.451791, DOI:10.1007/s11207-005-5782-z)
- The image restoration codes are written in C and C+, respectively, and were only tested on Unix/Linux platforms.

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OSSR Integration

- What is available?
  - IDL software library
- What will be onboarded?
  - All IDL programs, procedures, and functions for the listed instruments listed above.
  - IDL programs for data visualization, data processing, and creation of high-level data products.
- Are there open points and requirements?
  - Transfer of application specific software (GREGOR/VTT instruments) to new EST instrumentation
- What is the “user story” of a EOSC user taking on the software/service?
  - Processed Level 1.0 and partly Level 2.0 GREGOR data is made publicly available with transparent data processing steps.
  - Software, CRE, and GREGOR archive documented in peer-reviewed publications.
  - Peer-reviewed articles of science cases and methods employing ***sTools***.

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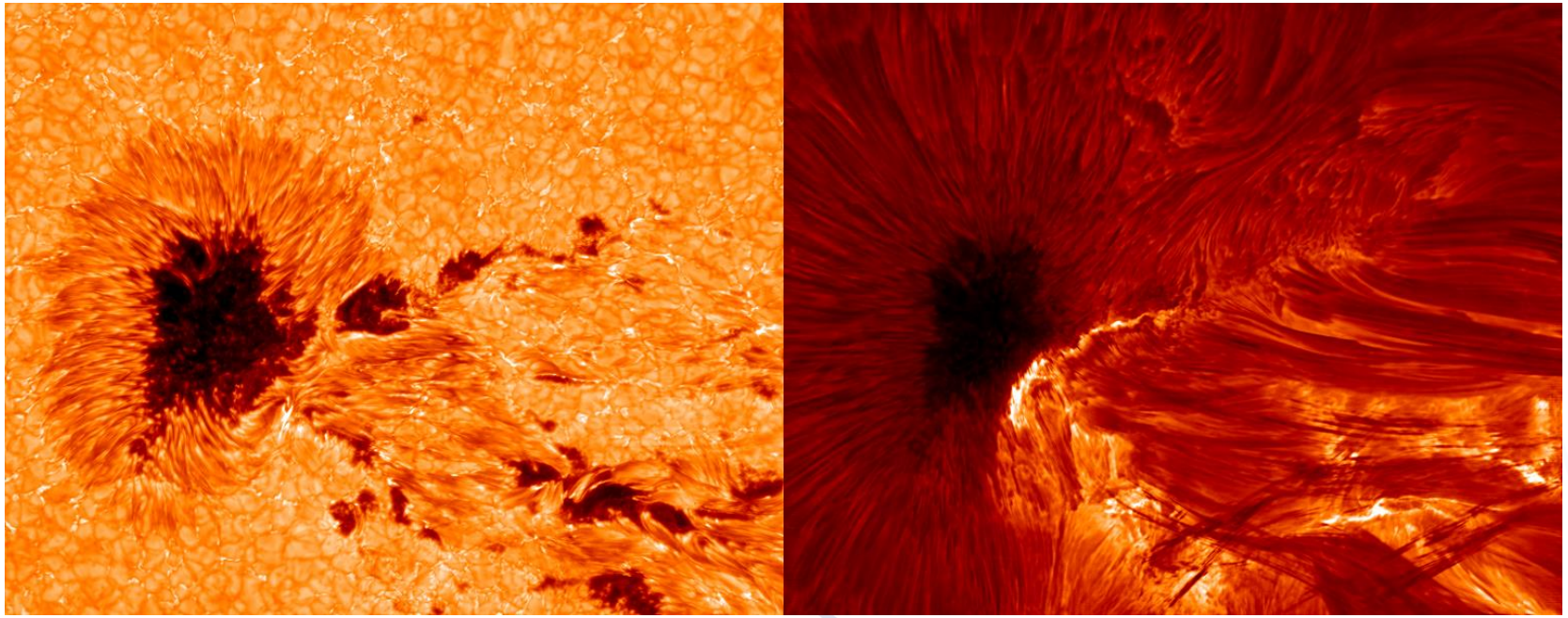
Science Cases

HIFI+ Data Processing and Image Restoration

- High cadence imaging at up to 100 Hz
- Data transfer rate of six cameras of about 2.4 GB/s
- On-site data Level 1.0 data processing → immediate feedback on data quality



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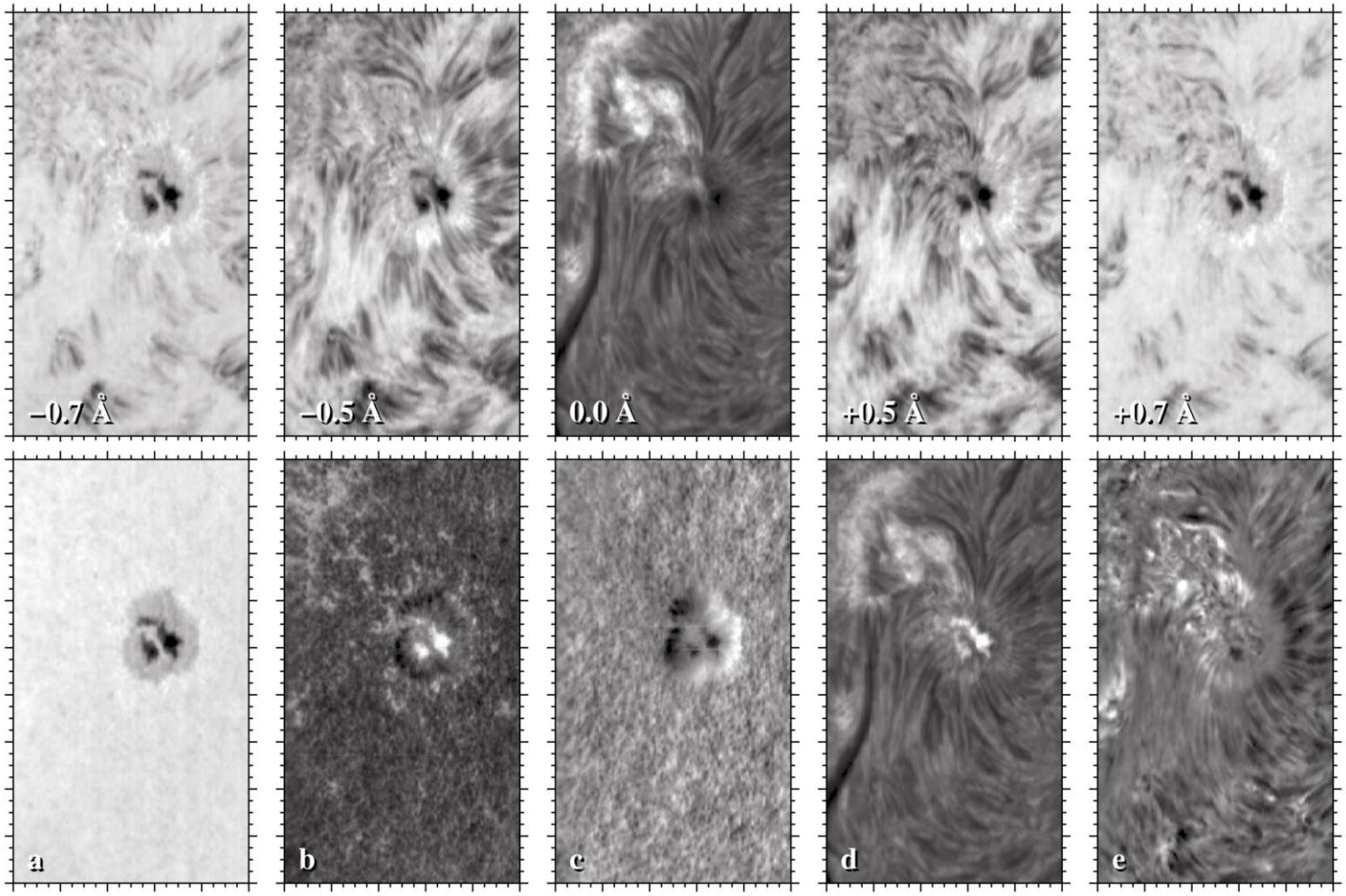
Science Cases

Efficient Processing of Echelle Spectra



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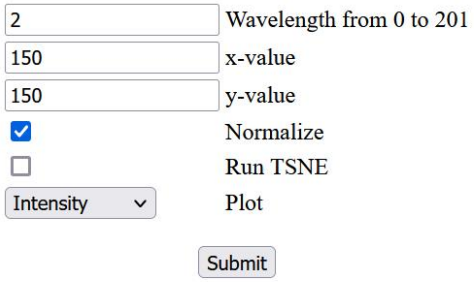
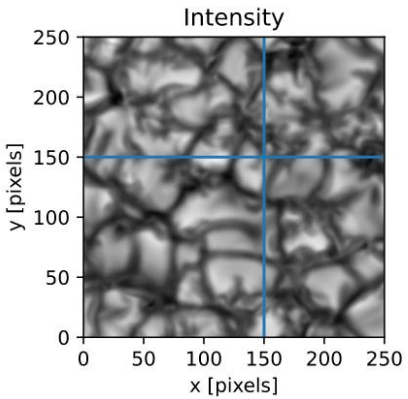
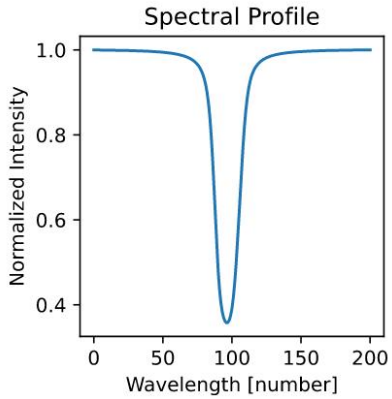
Science Cases

- ***CLAssification of Solar Spectral Information Contents*** (CLASSIC, classic.aip.de)
  - Classification based on openTSNE and HDBSCAN
  - Clusters can be identified by visual inspection and comparison with maps of observables computed from the Fe I 7090 Å line.
  - Project cluster labels back to visualize their distribution in CO^{5}BOLD (DOI:10.1016/j.jcp.2011.09.026) snapshots.
  - Prototype for data obtained with the FaMuLUS camera system for the VTT echelle spectrograph.







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Refereed Publications

- **Denker, C., Verma, M., Wiśniewska, A., Kamlah, R., Kontogiannis, I., Dineva, E., Rendtel, J., Bauer, S.-M., Dionies, M., Önel, H., Woche, M., Kuckein, C., Seelemann, T., and Pal, P.S. 2023:** *Improved High-resolution Fast Imager (HiFI+).* Journal of Astronomical Telescopes, Instruments, and Systems, in print
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- **Diercke, A., Kuckein, C., Verma, M., and Denker, C. 2021:** *Filigree in the Surroundings of Polar Crown and High-latitude Filaments.* Solar Physics **296** 35, doi:10.1007/s11207-021-01776-7
- **Kamlah, R., Verma, M., Diercke, A., and Denker, C. 2021:** *Wavelength Dependence of Image Quality Metrics and Seeing Parameters and their Relation to Adaptive Optics Performance.* Solar Physics **296** 29, doi:10.1007/s11207-021-01771-y
- **Verma, M., Matijevič, G., Denker, C., Diercke, A., Dineva, E., Balthasar, H., Kamlah, R., Kontogiannis, I., Kuckein, C., and Pal, P.S. 2021:** *Classification of High-resolution Solar Hα Spectra Using t-distributed Stochastic Neighbor Embedding.* The Astrophysical Journal **907** 54, doi:10.3847/1538-4357/abcd95
- **Kontogiannis, I., Dineva, E., Diercke, A., Verma, M., Kuckein, C., Balthasar, H., and Denker, C. 2020:** *High-resolution Spectroscopy of an Erupting Minifilament and its Impact on the Nearby Chromosphere.* The Astrophysical Journal **898** 144, doi:10.3847/1538-4357/aba117

Techniques and Methods

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- **Pal, P.S., Verma, M., Rendtel, J., González Manrique, S.J., Enke, H., and Denker, C. 2020:** *Solar Observatory Einstein Tower: Data Release of the Digitized Solar Full-disk Photographic Plate Archive.* Astronomische Nachrichten **341** 575, doi:10.1002/asna.202013791
- **Verma, M., Denker, C., Diercke, A., Kuckein, C., Balthasar, H., Dineva, E., Kontogiannis, I., Pal, P.S., and Sobotka, M. 2020:** *High-resolution Spectroscopy of a Surge in an Emerging Flux Region.* Astronomy and Astrophysics **639** A19, doi:10.1051/0004-6361/201936762
- **Palacios, J., Utz, D., Hofmeister, S., Krikova, K., Gömöry, P., Kuckein, C., Denker, C., Verma, M., González Manrique, S.J., Campos Rozo, J.I., Koza, J., Temmer, M., Veronig, A., Diercke, A., Kontogiannis, I., and Cid, C. 2020:** *Magnetic Flux Emergence in a Coronal Hole.* Solar Physics **295** 64, doi:10.1007/s11207-020-01629-9
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- **Dineva, E., Verma, M., González Manrique, S.J., Schwartz, P., and Denker, C. 2020:** *Cloud Model Inversions of Strong Chromospheric Absorption Lines Using Principal Component Analysis.* Astronomische Nachrichten **341** 64, doi:10.1002/asna.202013652
- **Kontogiannis, I., Tsiropoula, G., Tziotziou, K., Gontikakis, C., Kuckein, C., Verma, M., and Denker, C. 2020:** *Emergence of Small-scale Magnetic Flux in the Quiet Sun.* Astronomy and Astrophysics **633** A67, doi:10.1051/0004-6361/201936778
- **Diercke, A. and Denker, C. 2019:** *Chromospheric Synoptic Maps of Polar Crown Filaments.* Solar Physics **294** 152, doi:10.1007/s11207-019-1538-z
- **Denker, C. and Verma, M. 2019:** *Background-Subtracted Solar Activity Maps.* Solar Physics **294** 71, doi:10.1007/s11207-019-1459-x

Techniques and Methods

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