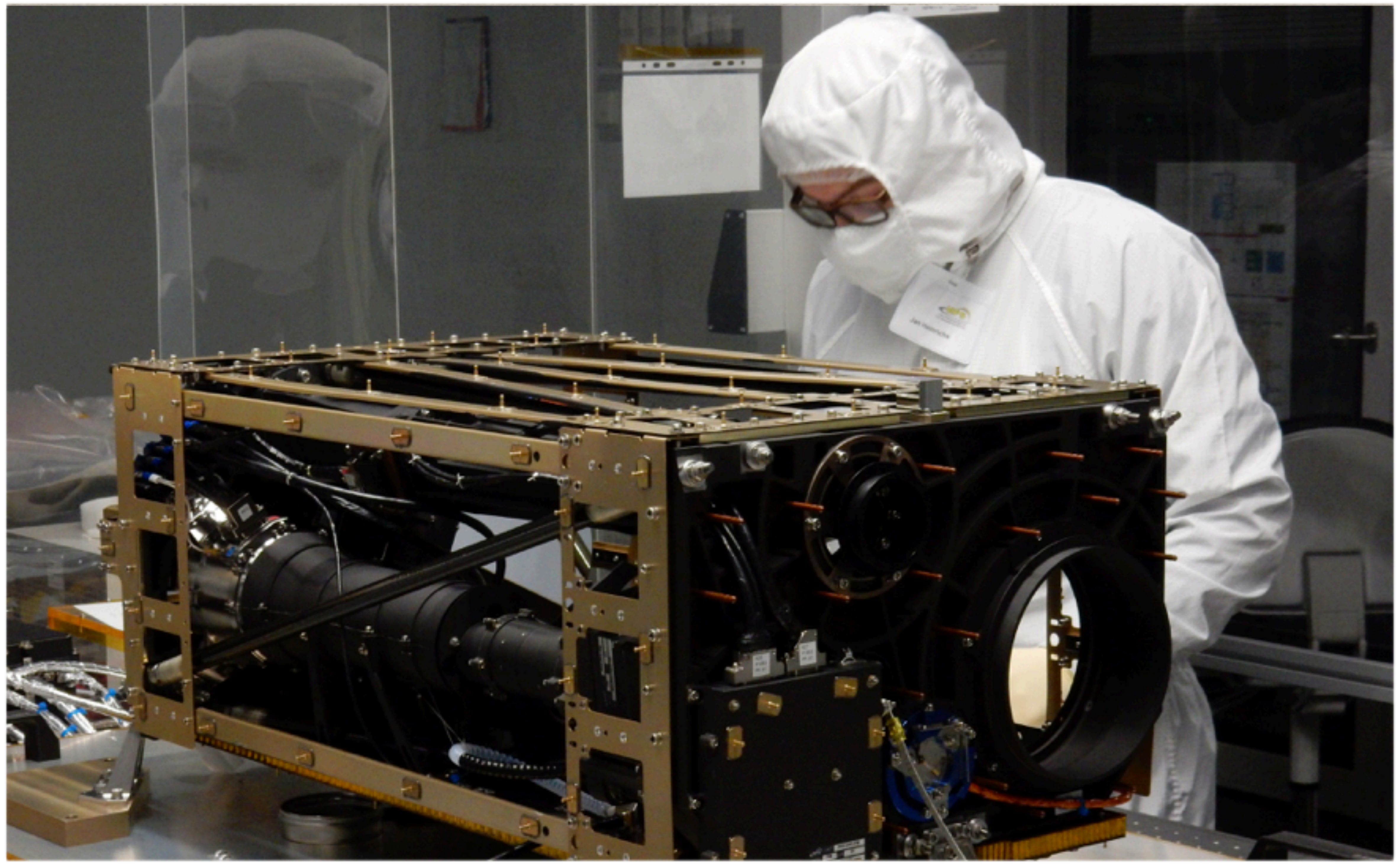
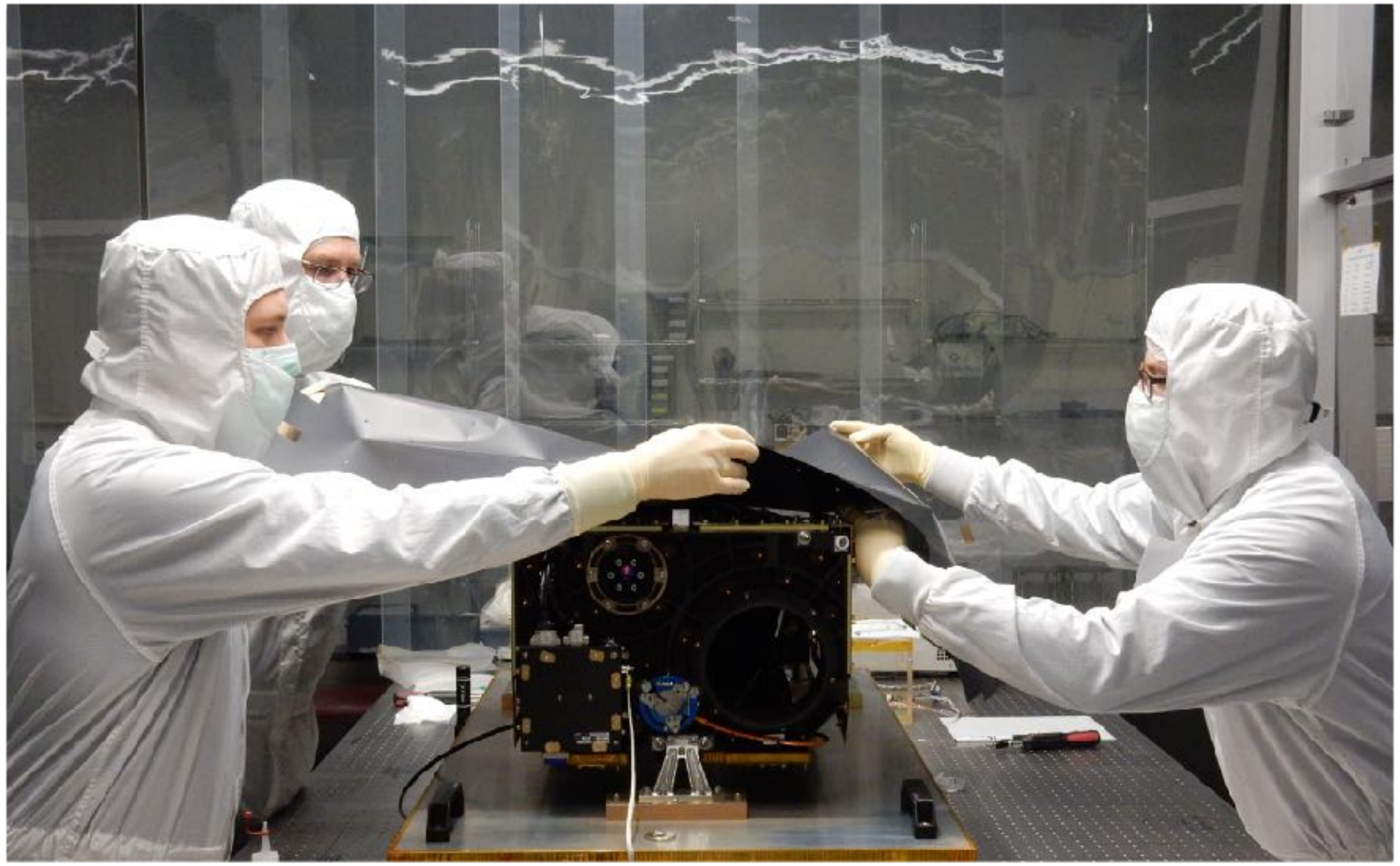




Prospects for Solar Orbiter Magnetometry

Andreas Lagg and the PHI Team

MPI for Solar System research, Göttingen

1. How and where does the solar wind plasma and magnetic field originate in the corona?
2. How do solar transients drive heliospheric variability?
3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Solar Orbiter Science Cases

1. How and where does the solar wind plasma and magnetic field originate in the corona?
2. How do solar transients drive heliospheric variability?
3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

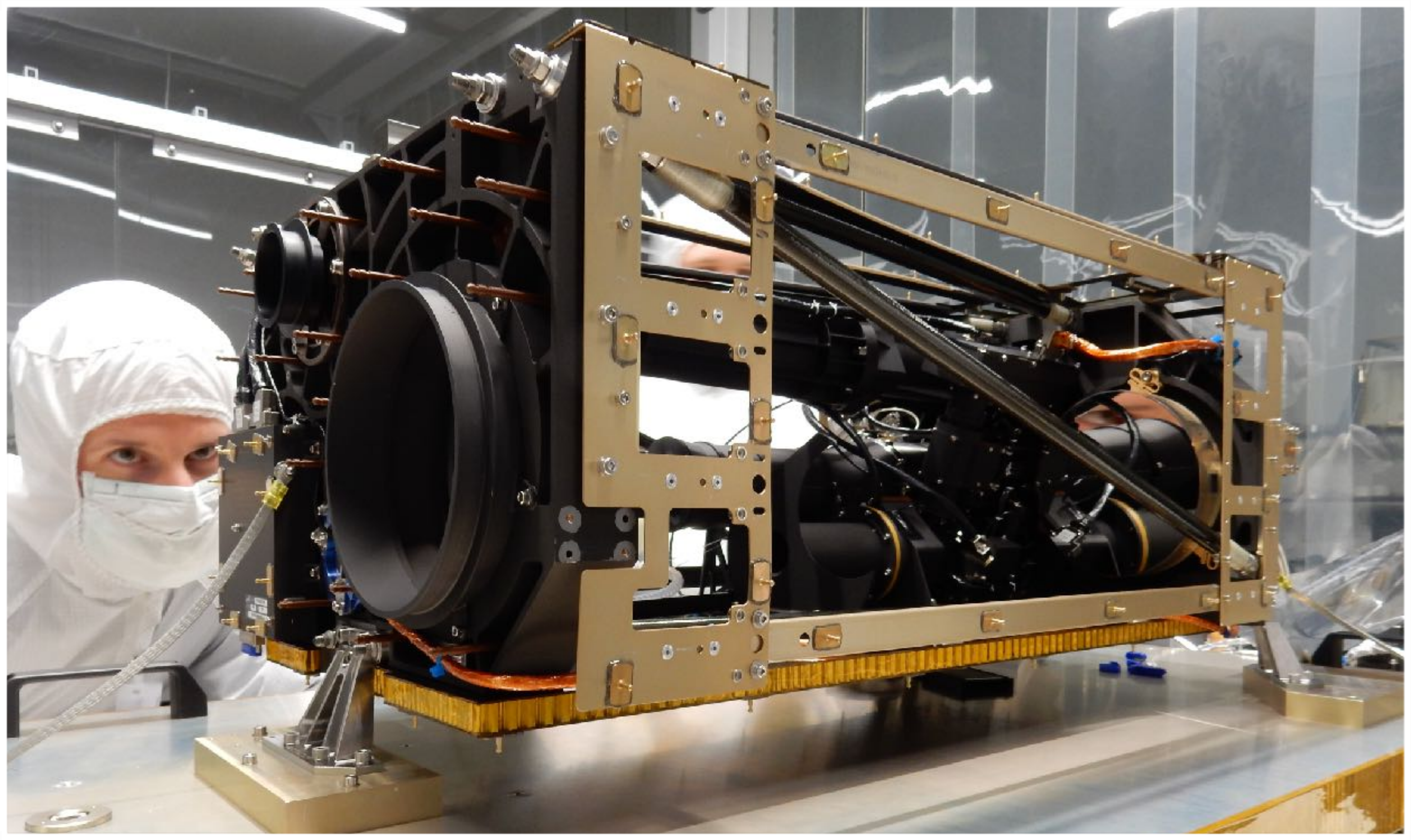
Significant PHI contribution

Magnetic field on solar surface will be measured by

POLARIMETRIC AND HELIOSEISMIC IMAGER (PHI)

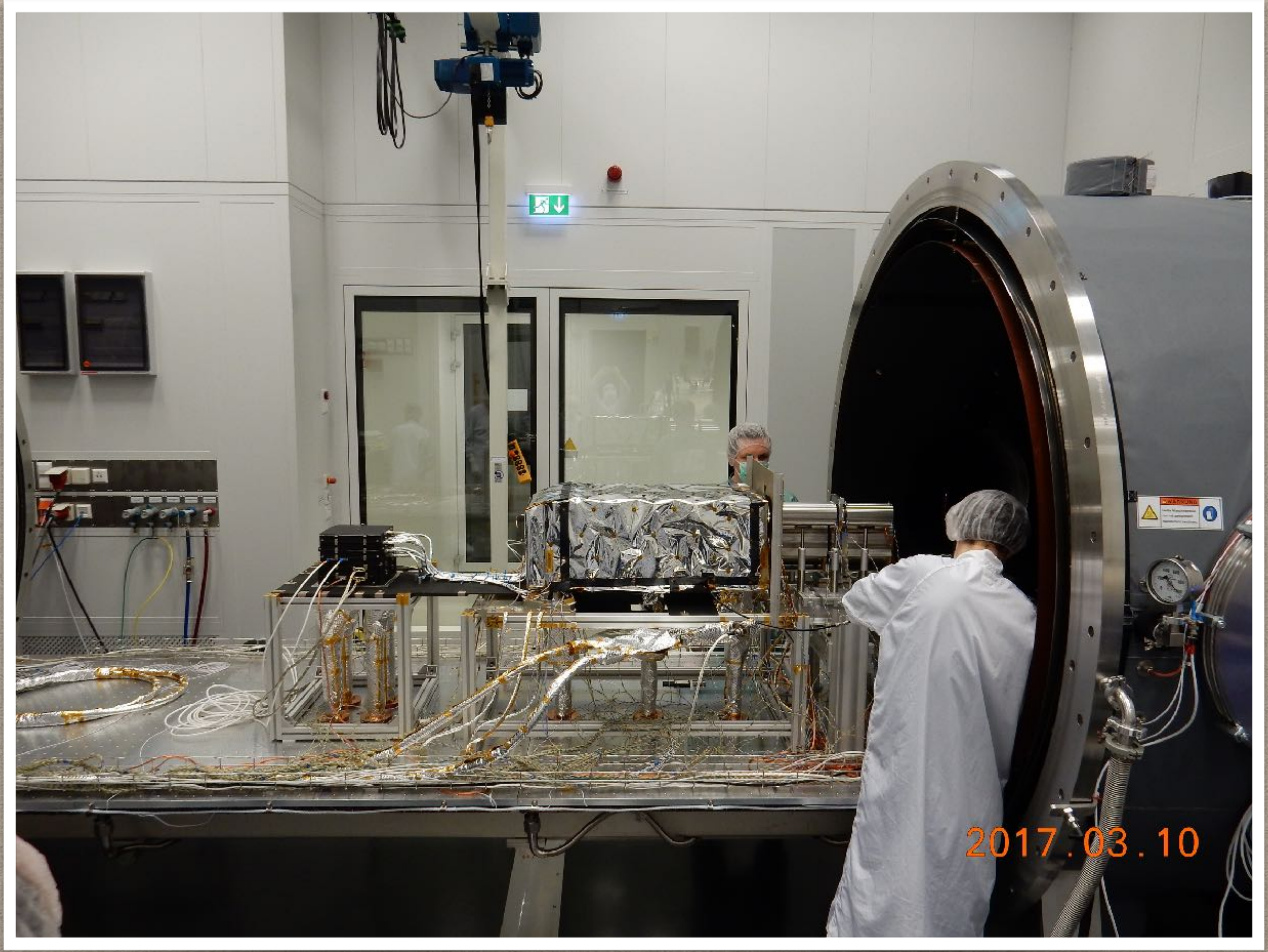
Current status:

- Flight model currently at MPS
- Polarimetric calibration done
- Final FM tests
- delivery to ESA: mid April 2017



PHI FM, Jan 21 2017

PHI End-to-end test (March 2017)



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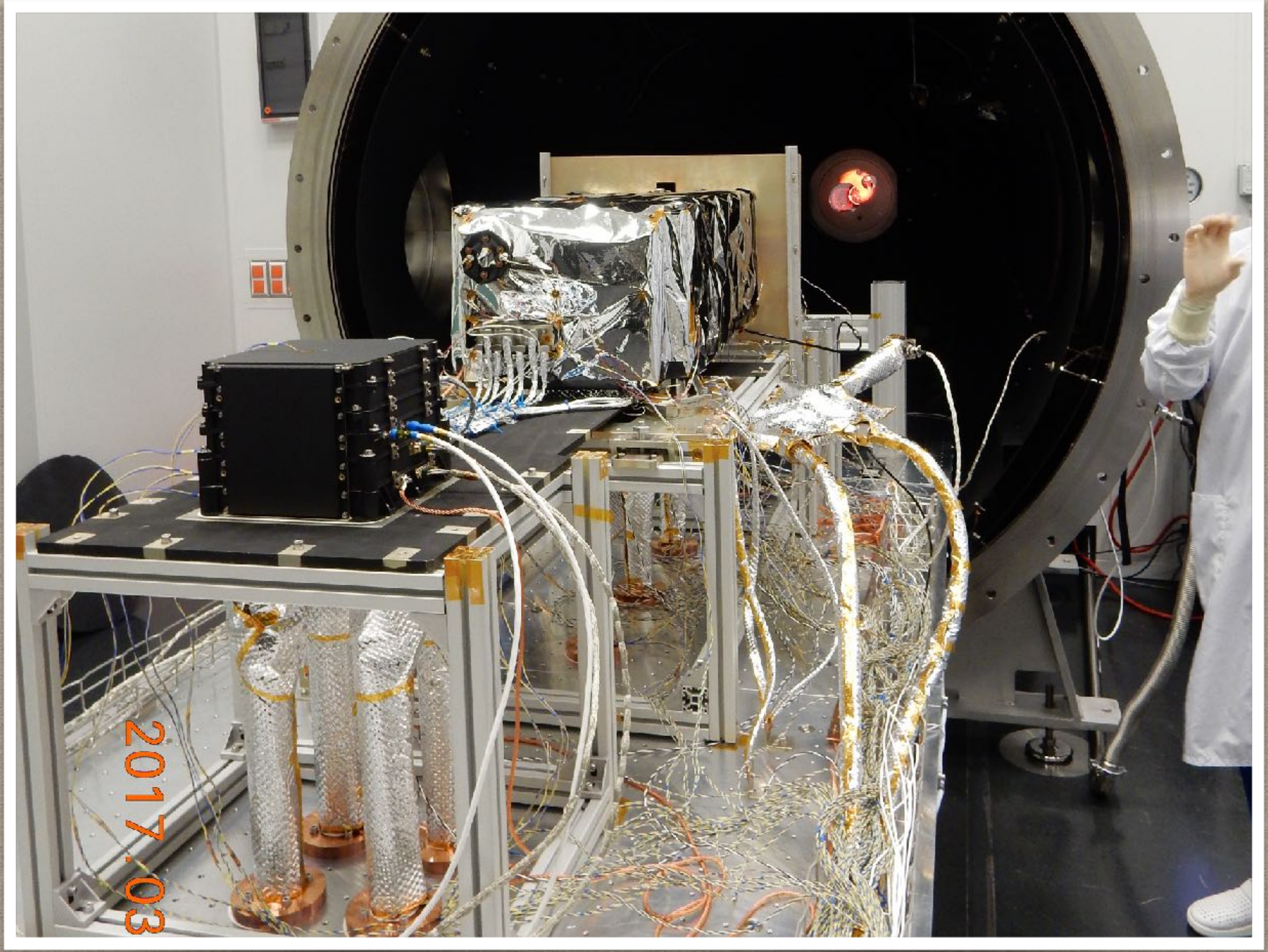
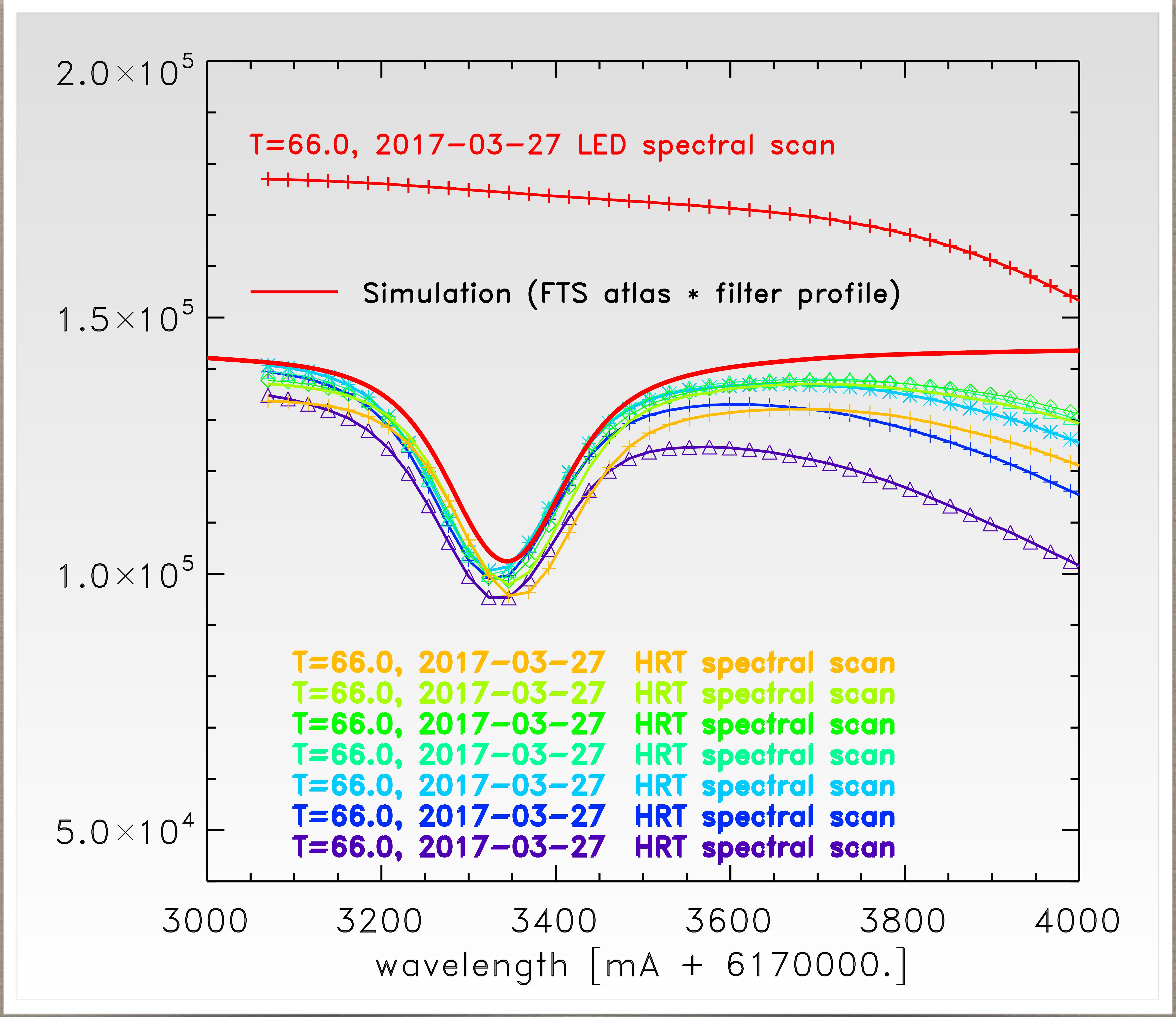


PHI HRT Spectral Scan

- Structures in the wings of the Fe line represent the cavity errors of the etalon
- LED scan yield the transmission curve of the interference prefilter
- Resulting line profiles (width, depth, position) correspond well with the reference profile (FTS atlas)



Polarimetric Calibration

Performed in MPS cleanrooms (March 2017):

- liquid crystals (modulating elements): T=45°
- including entrance window
- pol. efficiencies:
  I: 0.991
  Q: 0.585
  U: 0.573
  V: 0.556
  (HRT)
- χ^2 = 3.1e-7

Modulation Matrix

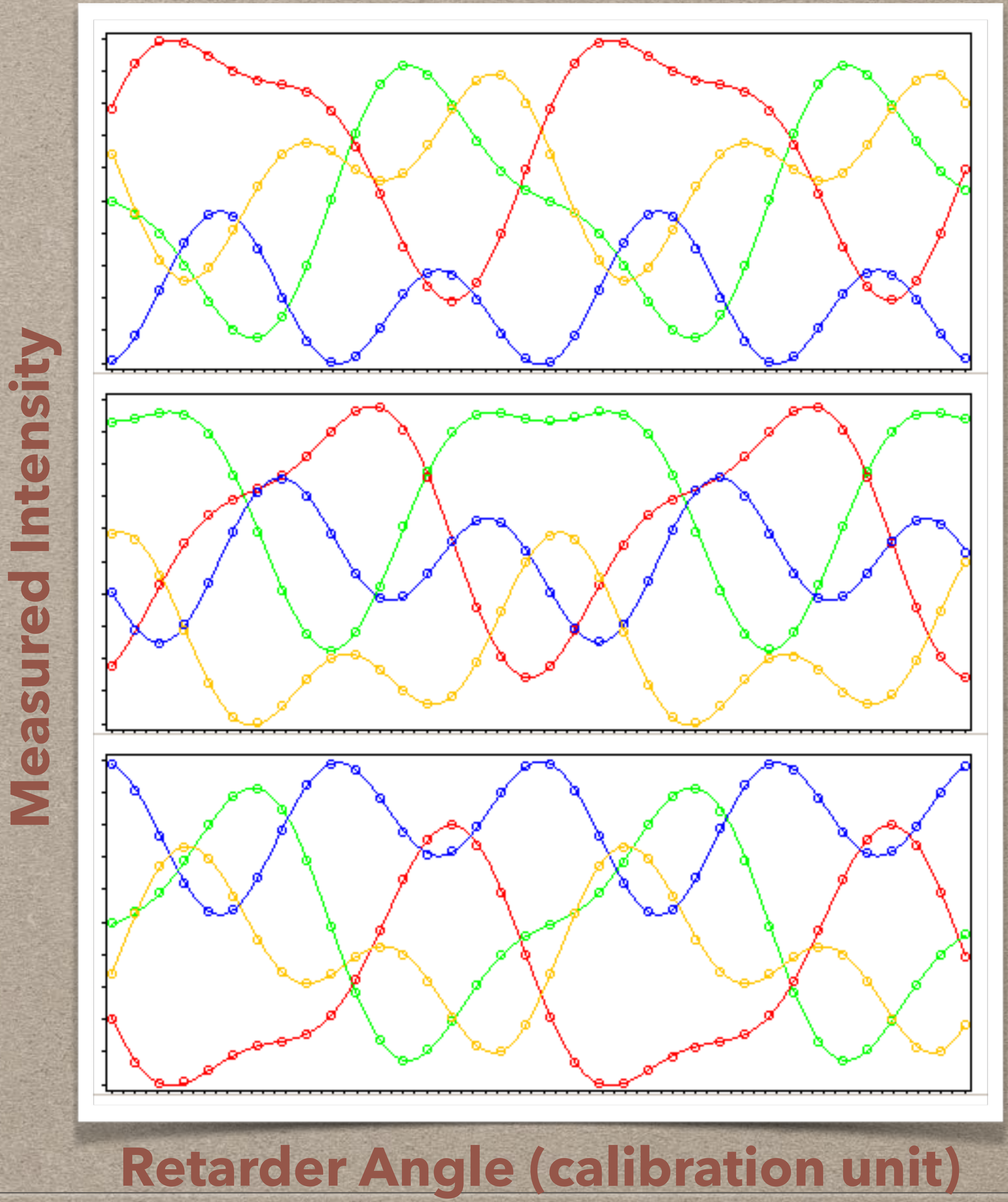
1.001	0.570	-0.347	-0.743
1.001	0.006	-0.692	0.725
1.000	-0.983	-0.032	-0.186
0.999	0.315	0.860	0.393

Demodulation Matrix

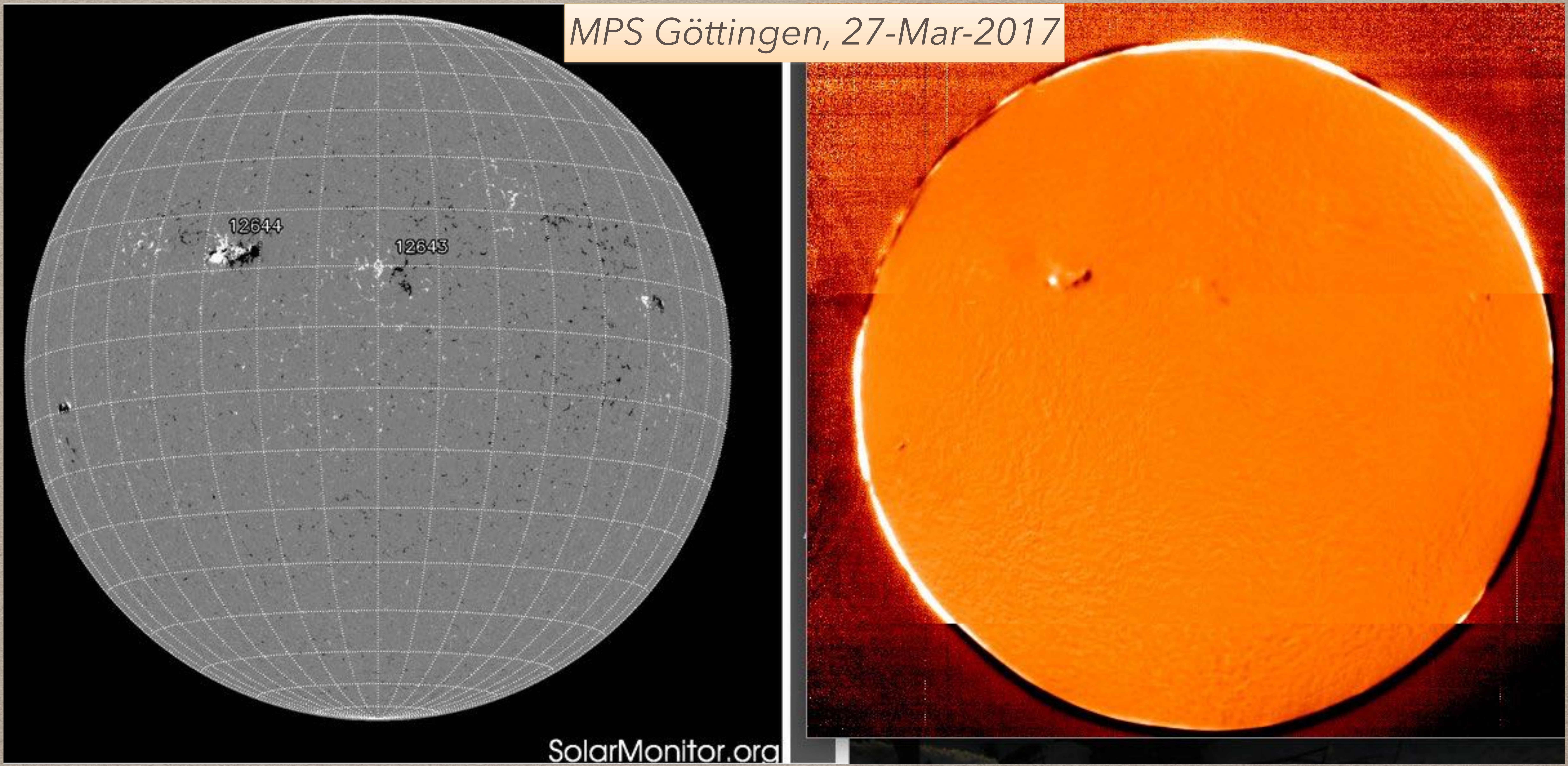
0.276	0.196	0.250	0.278
0.396	0.104	-0.717	0.217
-0.202	-0.537	0.088	0.652
-0.577	0.595	-0.254	0.237

Efficiency

0.991	0.585	0.573	0.556



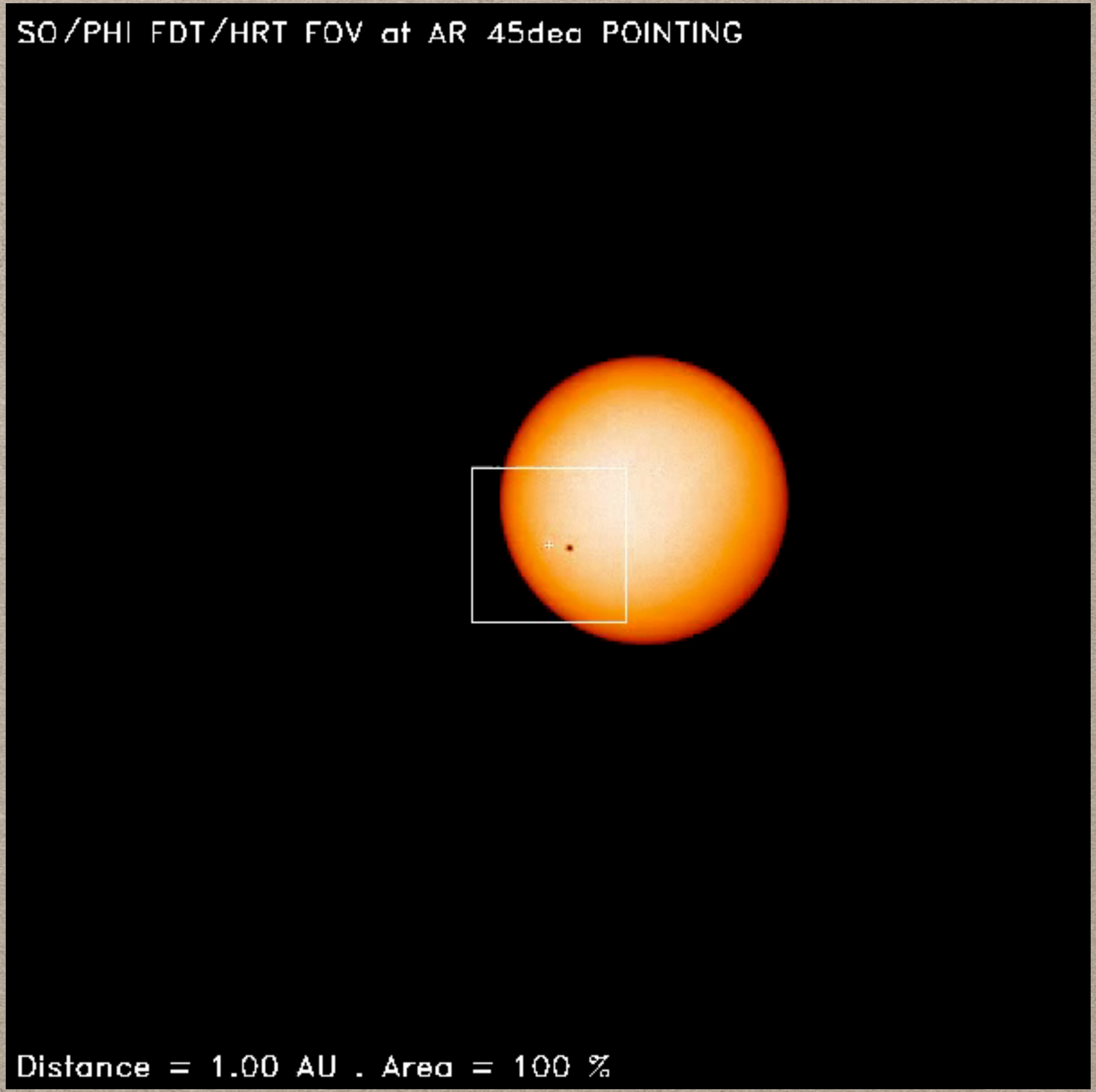
First PHI Full-disk magnetogram



SO/PHI BASIC SPECS

Two Telescopes:

1. Full Disk Telescope:
   - FoV ~ 2°
   - Resolution ~3.5 arcsec/pix
   - Full disk at all orbit positions
   - 17 mm aperture diameter
2. High Resolution Telescope:
   - FoV ~ 16 arcmin
   - Resolution: 0.5 arcsec per pixel (i.e., ~200 km at 0.28 AU)
   - 140 mm aperture diameter



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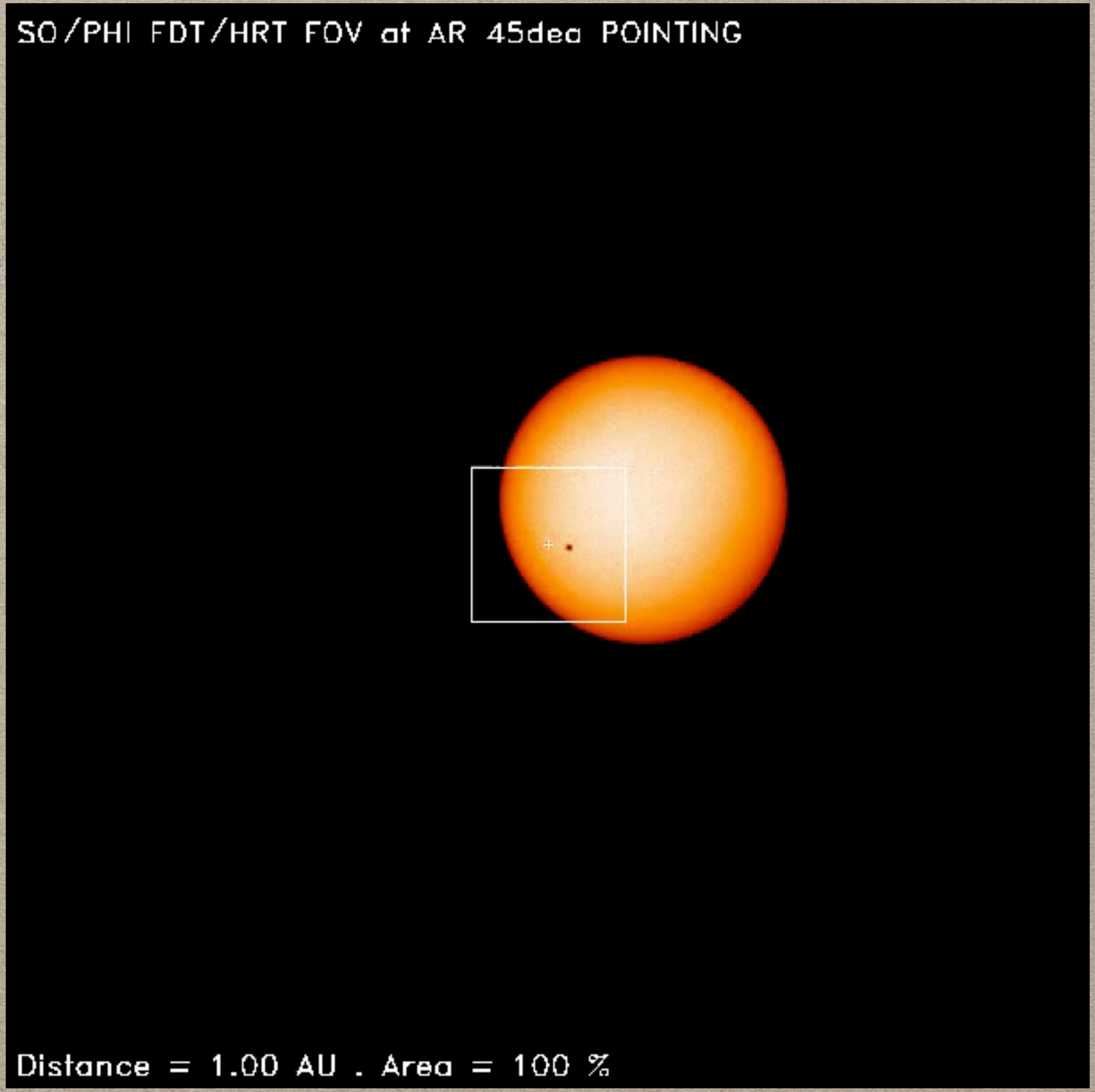


PHI at a glance:

- Scans over magnetic sensitive photospheric absorption line (FeI 617.3nm)
- Narrow-band filtergrams at 6 spectral positions, 4 polarisation states

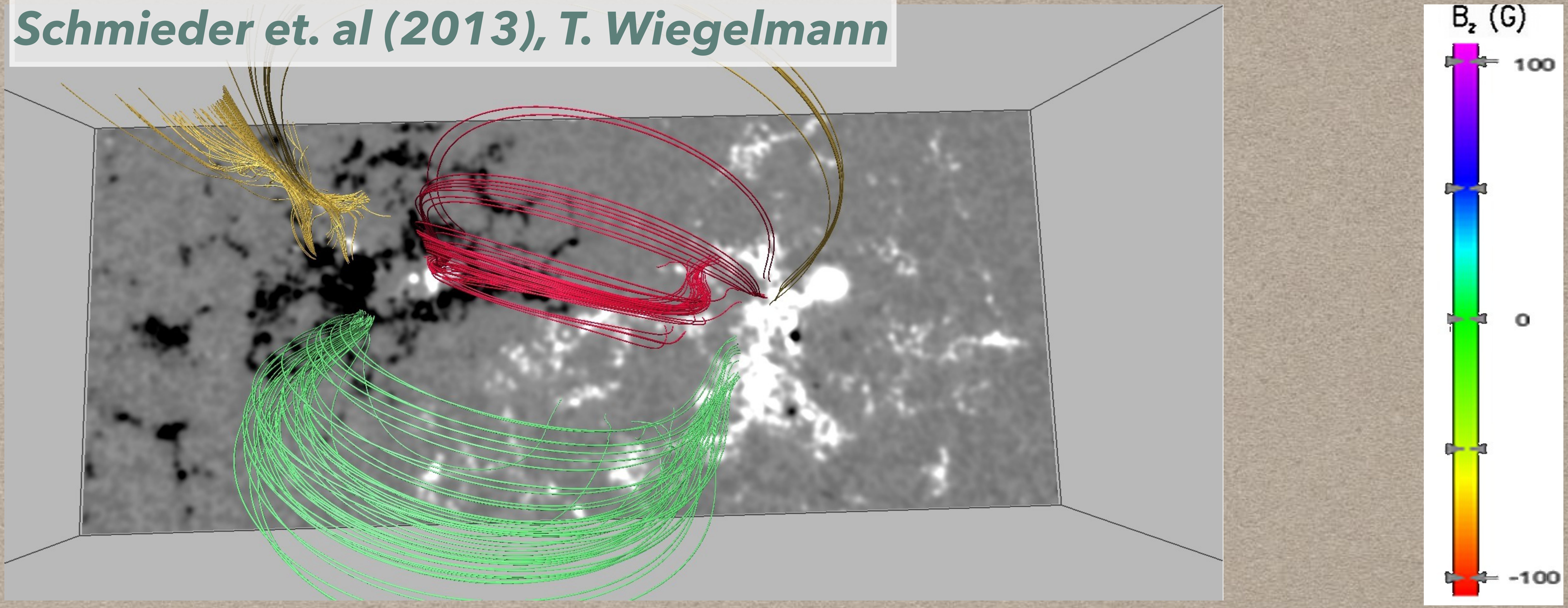
- On-board data processing:
  - data reduction (dark, flat, calibration)
  - retrieval of physical parameters (ME inversions)
  - lossless / lossy compression
  - compression factor 12-1000

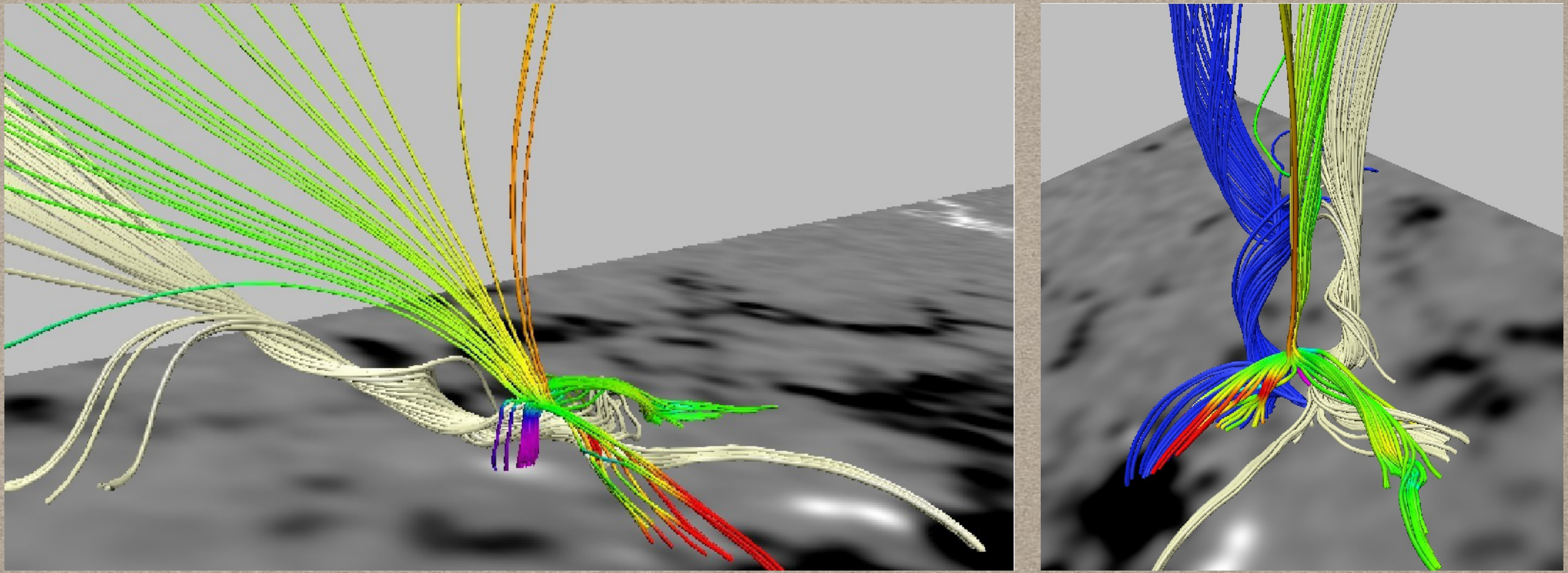
Intensity LOS-velocity B-strength B-inclination B-azimuth

SO/PHI SCIENCE: ATMOSPHERIC COUPLING

- probe all solar layers from its interior up to the heliosphere
  –> main emphasis: coupling
  (Francesca Zucarello)
- SO/PHI will provide the photospheric magnetic field structure which represents essential boundary conditions to achieve these goals.

Schmieder et. al (2013), T. Wiegelmann

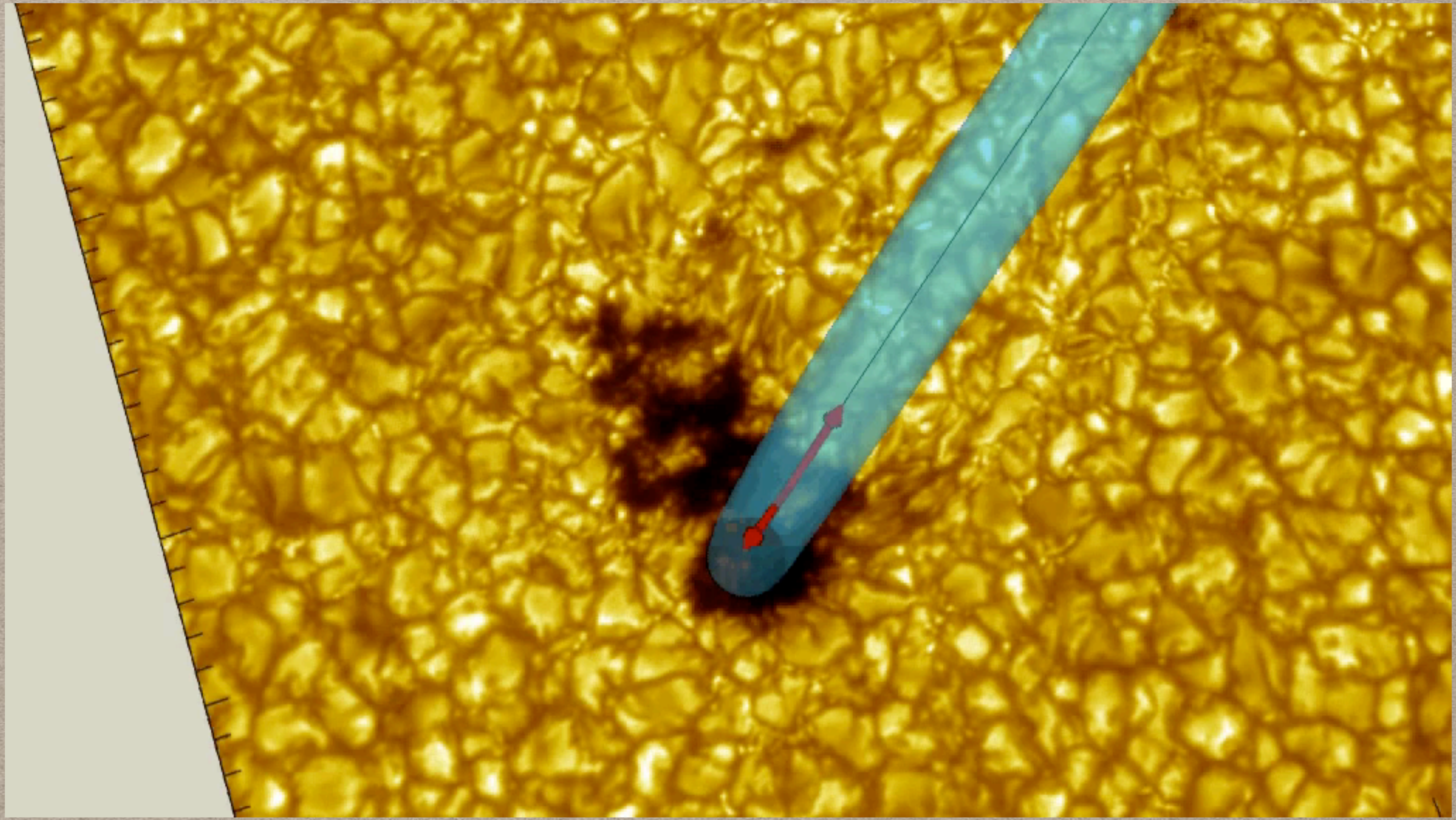




Marsch et. al (2004)

Removal of 180° ambiguity

- allows measurement of **currents, build-up of magnetic energy** in ARs
- improve boundary conditions for modelling the higher layers
- **Essential to improve understanding of energy release mechanisms**



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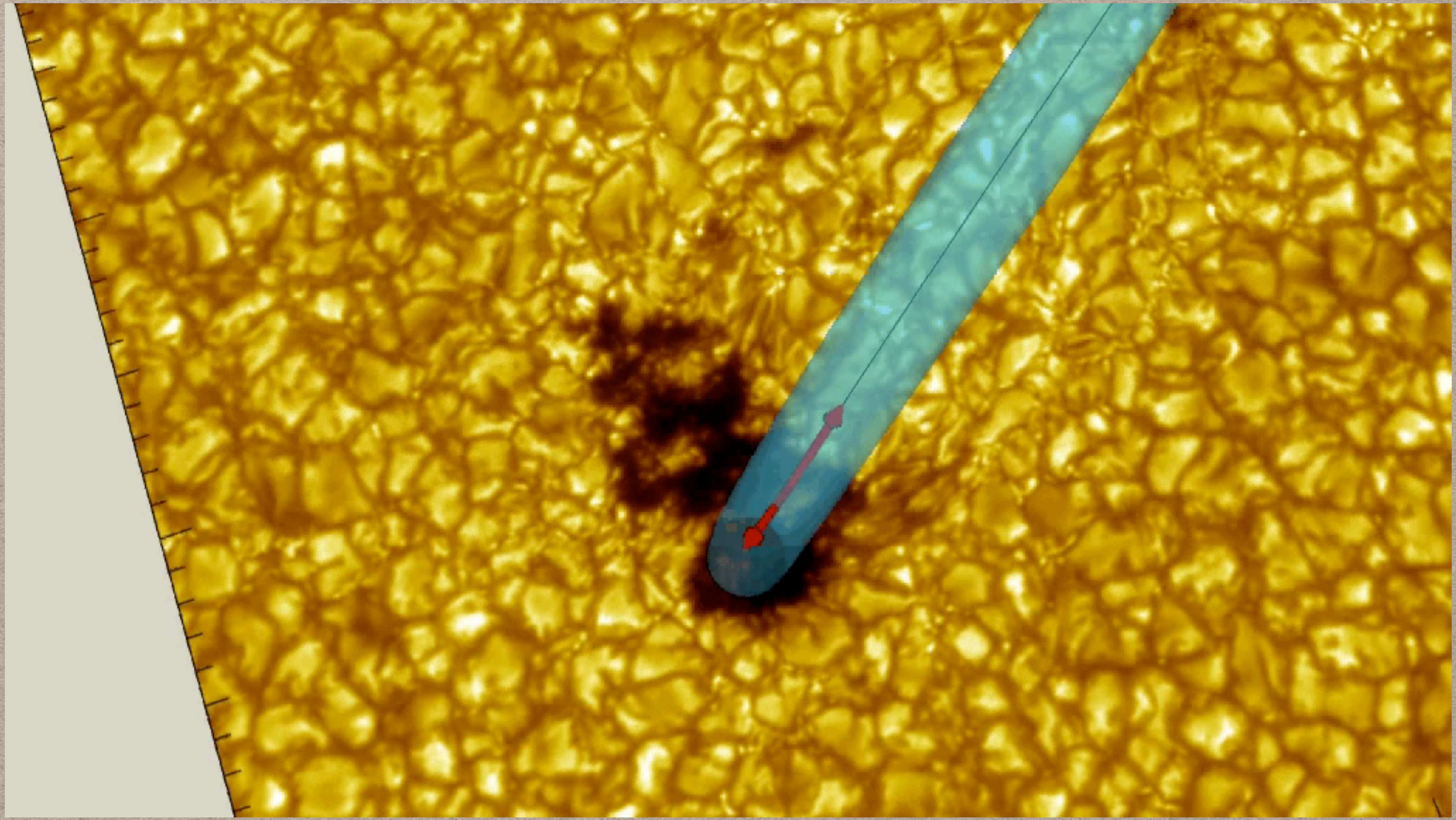
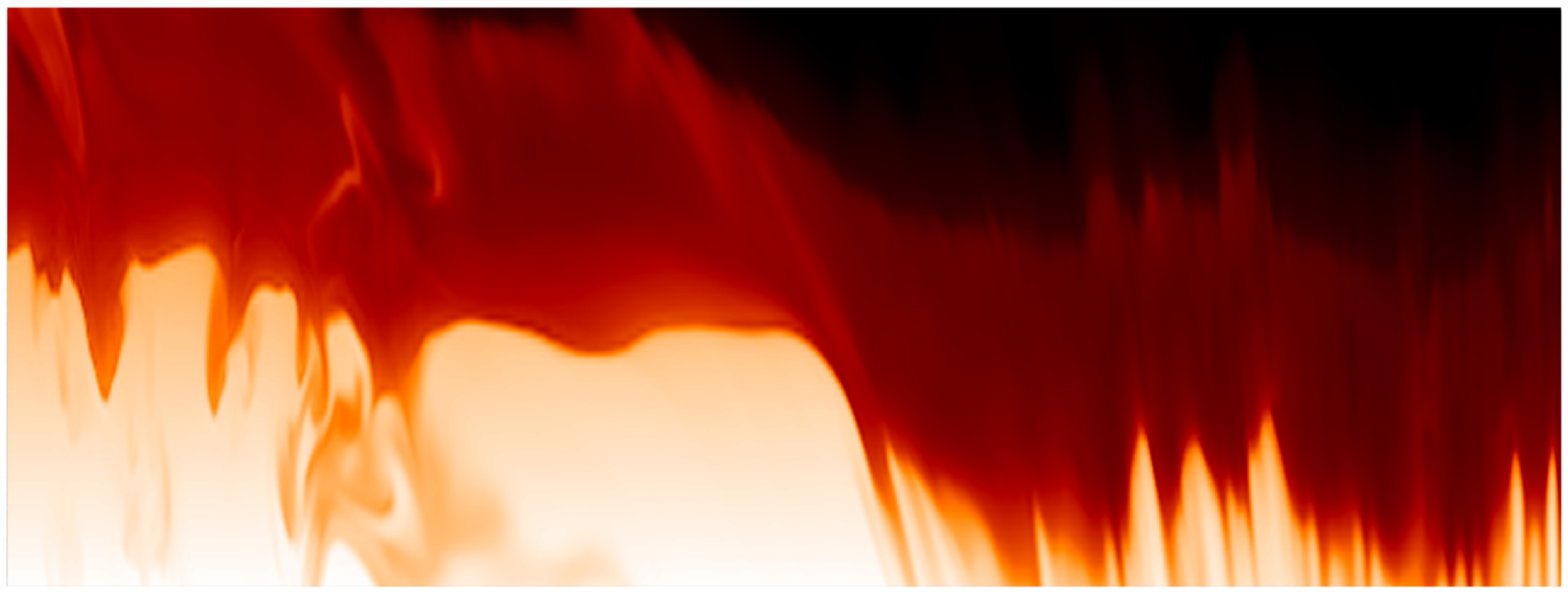
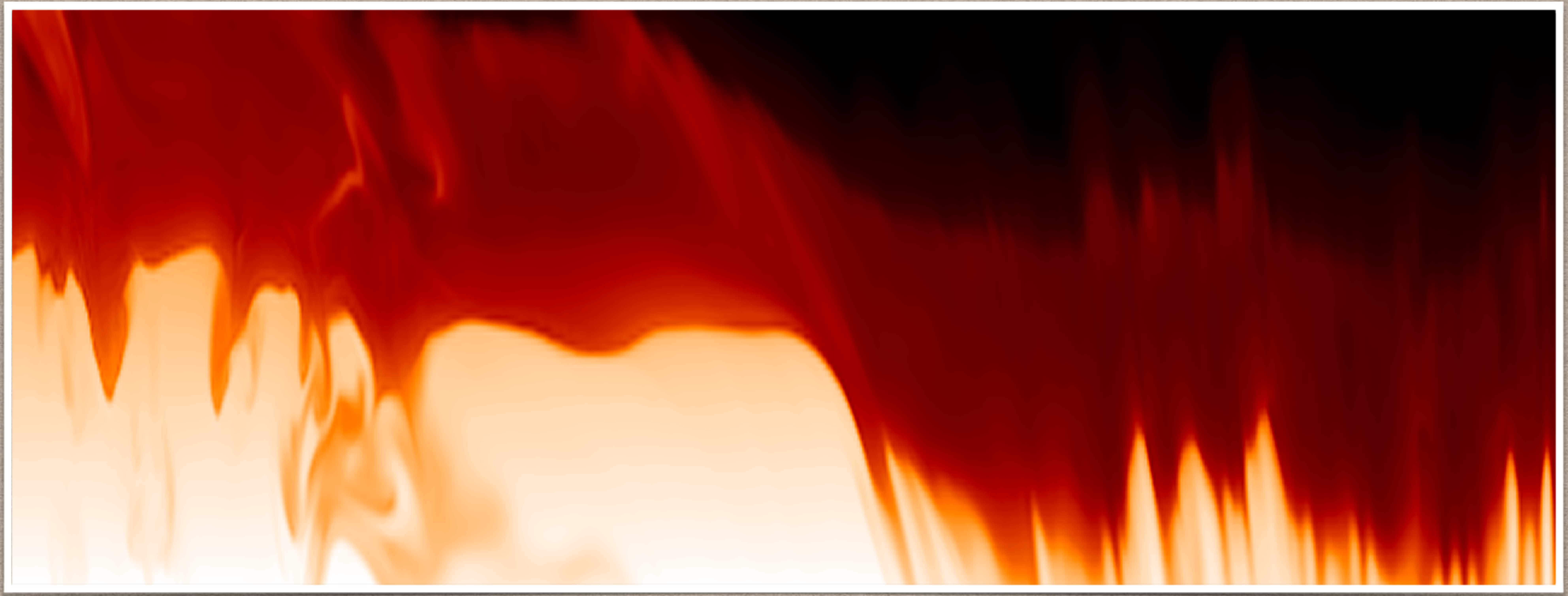


Stereoscopic B-measurements



Stereoscopic B-measurements

Magnetograms based on inversion of RTE are showing B on surfaces of equal optical depth.



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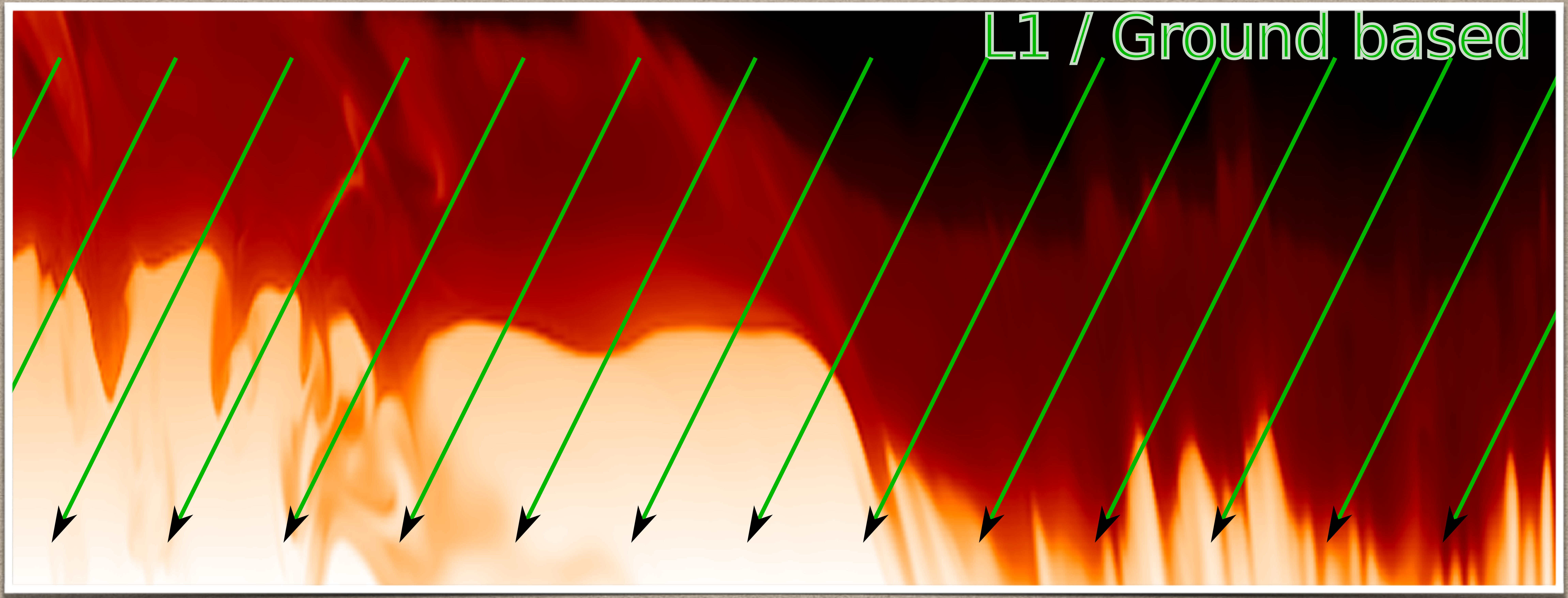
Stereoscopic measurements will allow for inversions on a geometrical height scale

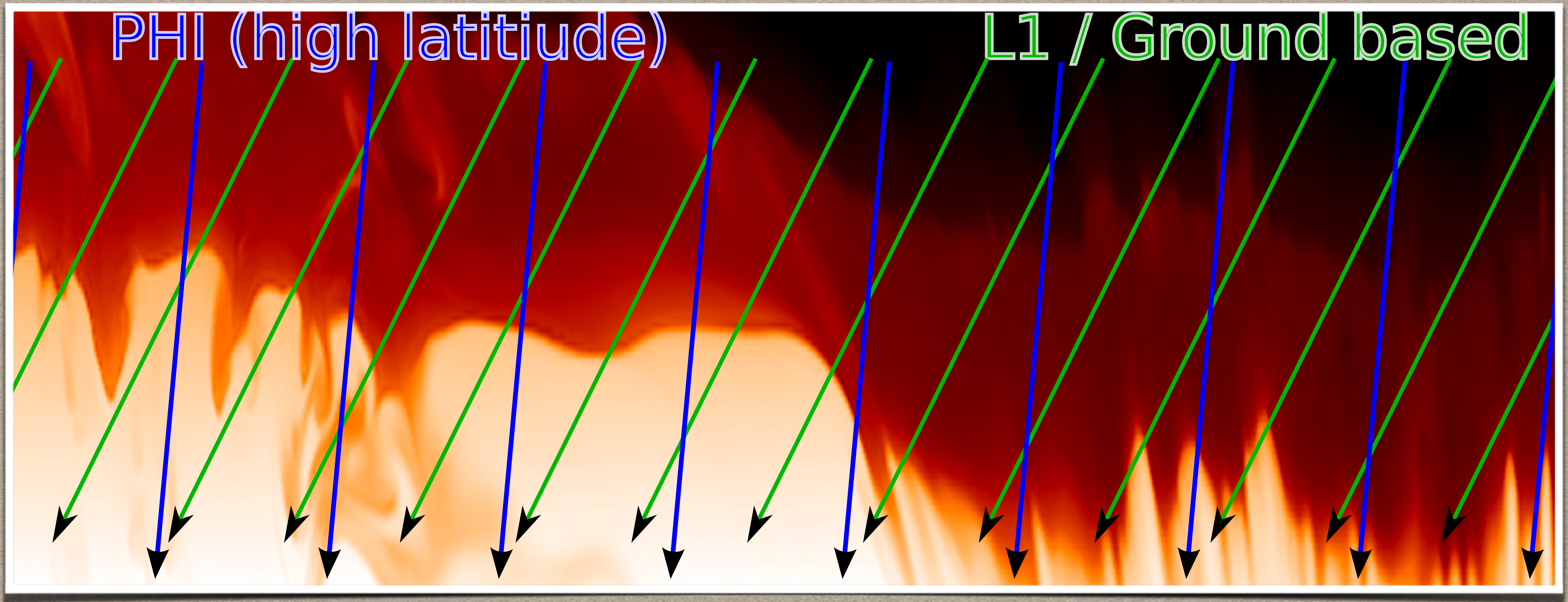


STEREOSCOPIC B-MEASUREMENTS

Magnetograms based on inversion of RTE are showing B on surfaces of equal optical depth.

Stereoscopic measurements will allow for inversions on a geometrical height scale

–> significant improvement/ simplification for B-field extrapolation



4.1 How is magnetic flux transported to and re-processed at high solar latitudes?

- 4.1.1 Study the detailed solar surface flow patterns in the polar regions, including coronal hole boundaries.
- 4.1.2 Study the subtle cancellation effects that lead to the reversal of the dominant polarity at the poles
- 4.1.3 Explore the transport processes of magnetic flux from the activity belts towards the poles and the interaction of this flux with the already present polar magnetic field.
- 4.1.4 Study the influence of cancellations at all heights in the atmosphere.

4.2 What are the properties of the magnetic field at high solar latitudes?

- 4.2.1 Probability density function (PDF) of solar high-latitude magnetic field structures.
- 4.2.2 Basic properties of solar high-latitude magnetic field structures.
- 4.2.3 Probe the structure in deep layers of the Sun.

4.3 Are there separate dynamo processes acting in the Sun?

4.4 How are coronal and heliospheric phenomena related to the solar dynamo?

Objective 4: How does the solar dynamo work and drive connections between the Sun and the heliosphere?

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Polar magnetic field measurements

- What are the difficulties?
- Why is it important?
- What do we know?
- What can we expect from PHI?
- How to operate PHI to maximize polar field information?

PROBLEMS IN MEASURING POLAR FIELDS

- foreshortening hides many details
- makes ambiguity removal tricky
- study of features with almost no change in viewing angle
- ground-based: low contrast hinders stable AO locking
- low photon flux (limb darkening)
- sampling higher layers
- highly inclined LOS wrt. solar vertical → simple inversions (ME-type) not applicable
- Zeeman effect: || vs. ⊥

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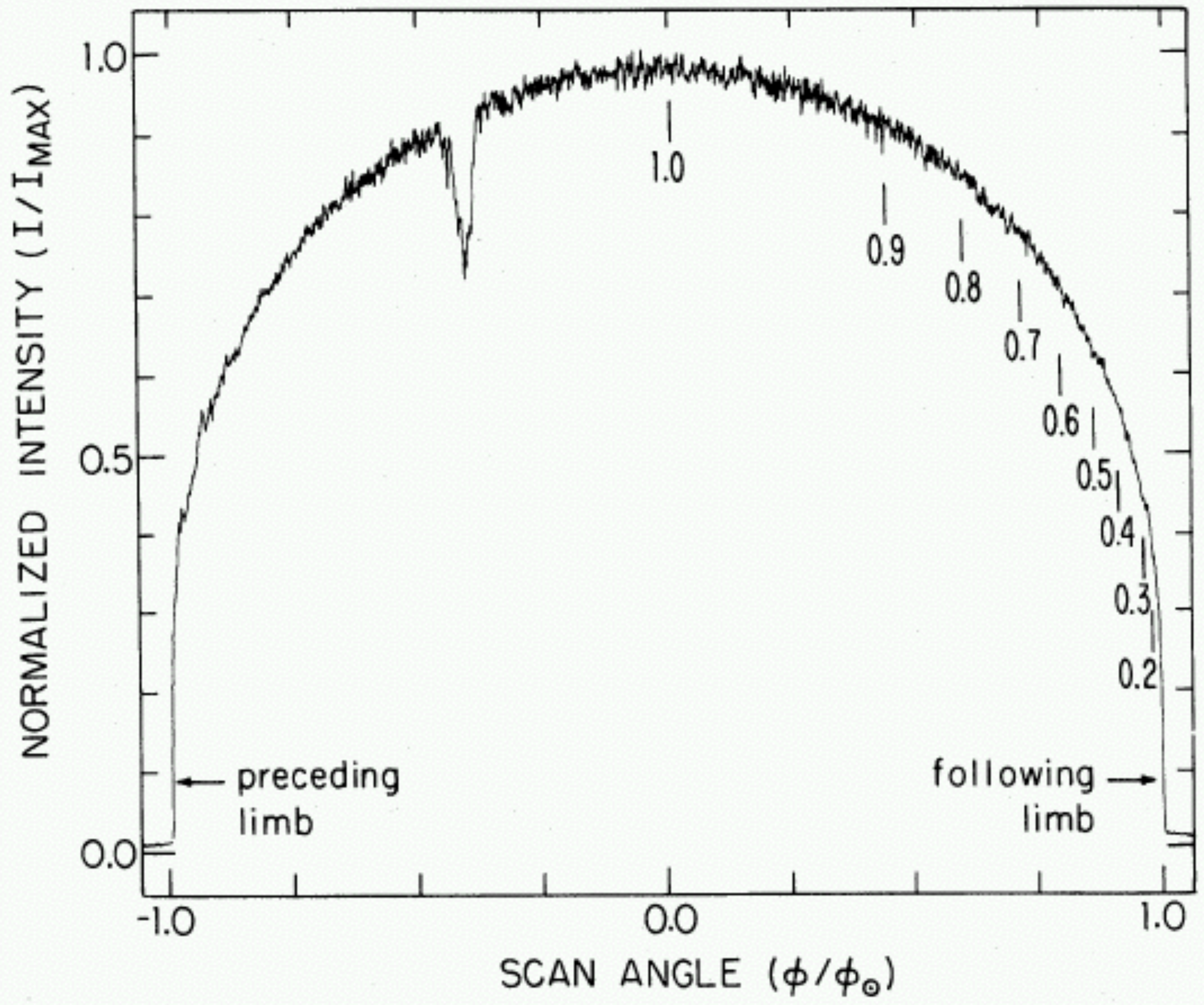

FIG. 1.—A typical drift scan plotted against scan angle $\phi/\phi_\odot$. The intensities plotted here have been corrected for zero point and normalized. Representative values of $\mu = \cos\,\theta$ are marked along the following half of the scan.

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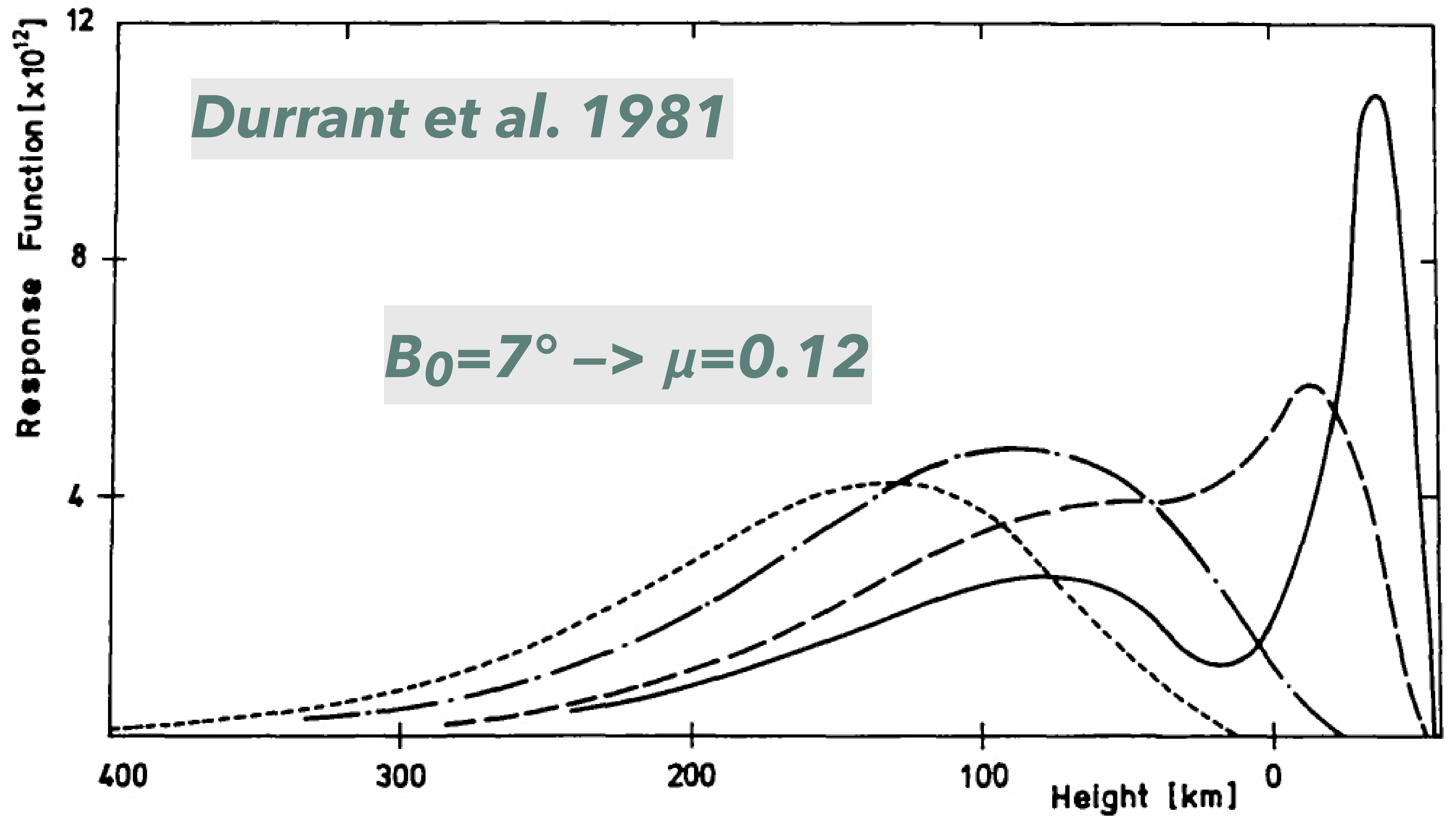
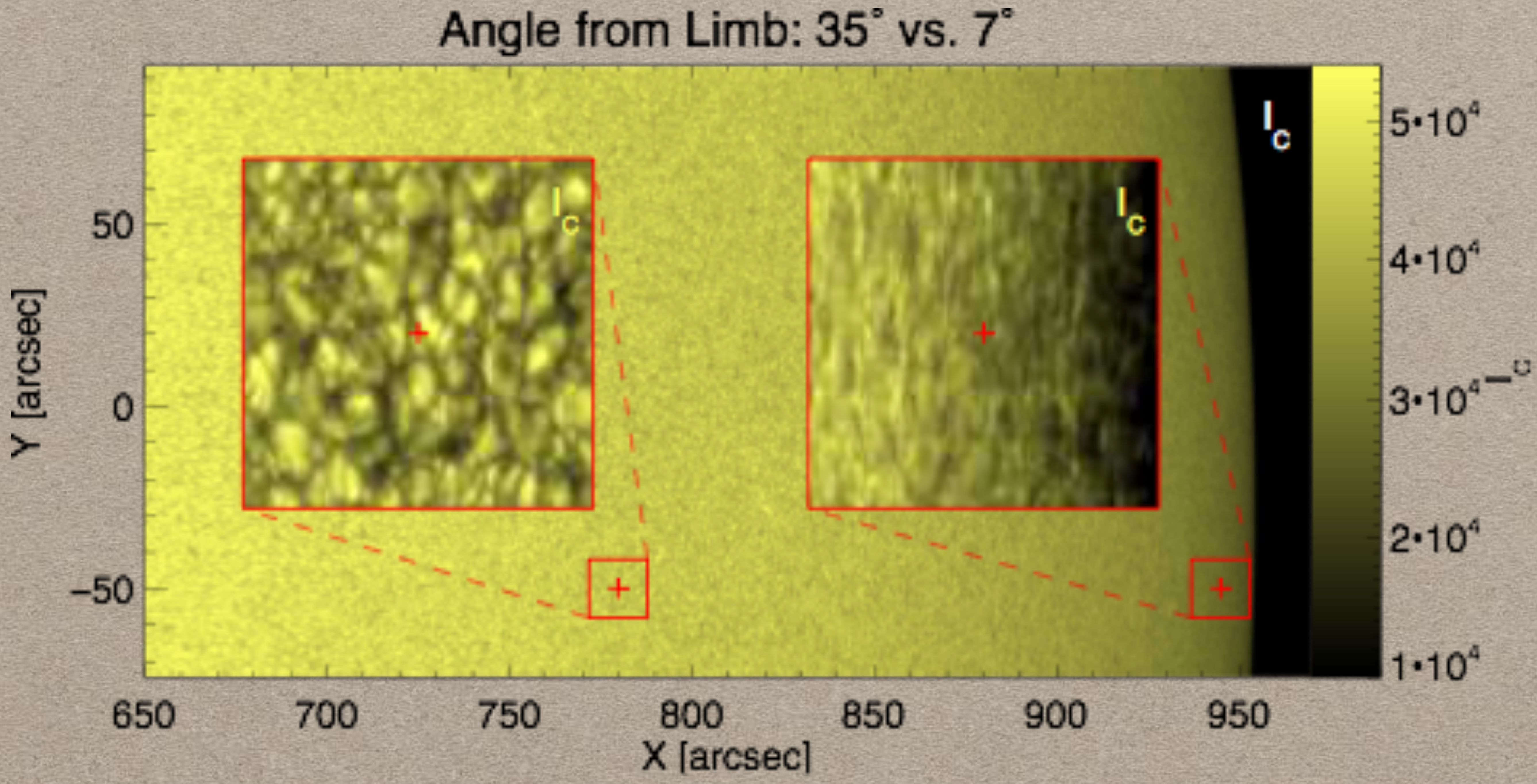
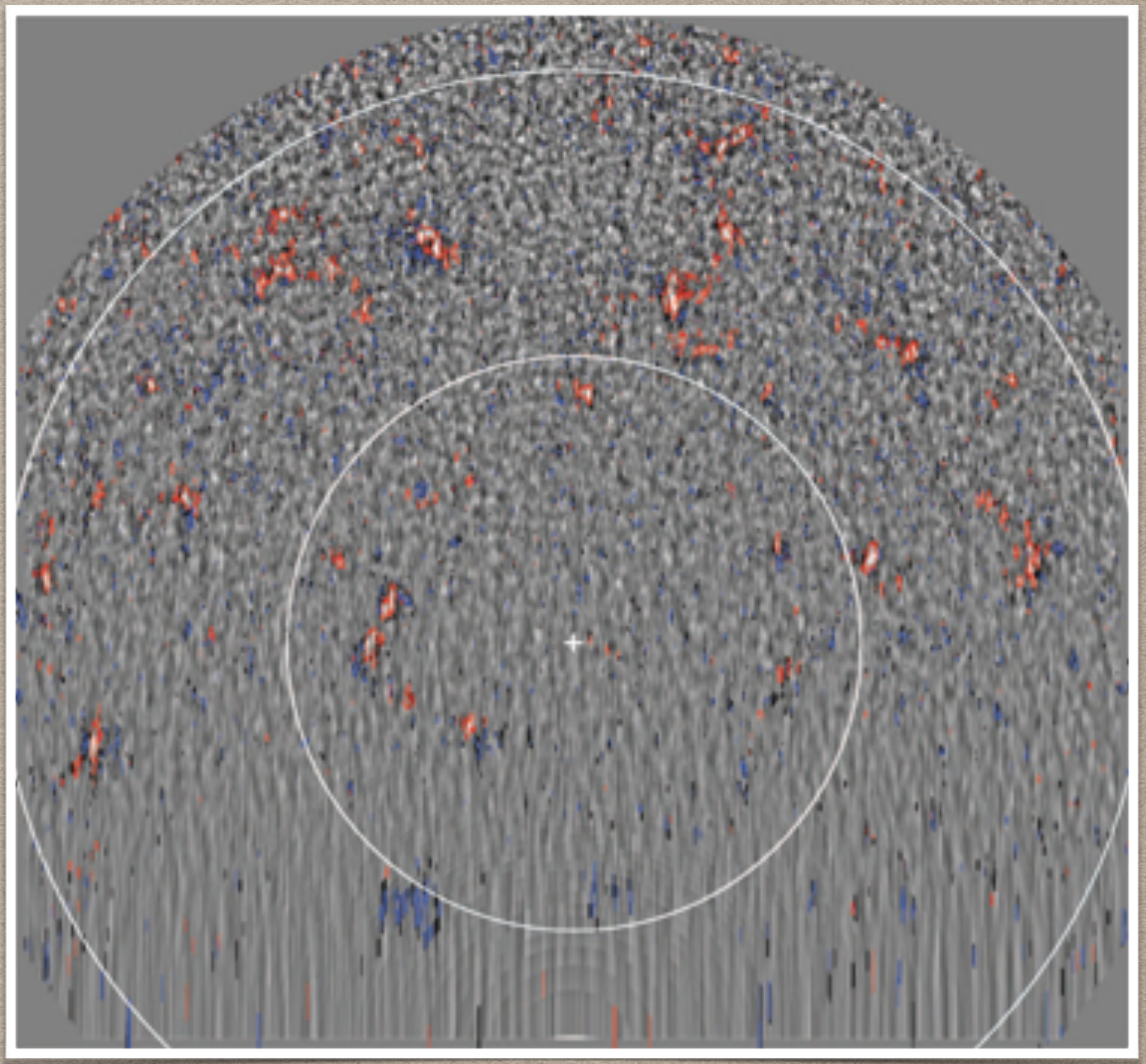


Fig.2. Temperature fluctuation response functions for continuum radiation seen at various heliocentric angles (——,μ=1.0; ---,μ=0.6; -.-.,μ=0.2; ...,μ=0.1). The abscissa gives the vertical height in the atmosphere; the optical path is 1/μ times this distance.

SO/PHI POLAR SCIENCE

- polar field is directly related to dynamo process (source of poloidal field)
- polar *B* field distribution responsible for coronal holes, polar plumes, X-ray jets, . . .
- study of **emergence / cancellation** highly relevant (Milan Gosic)



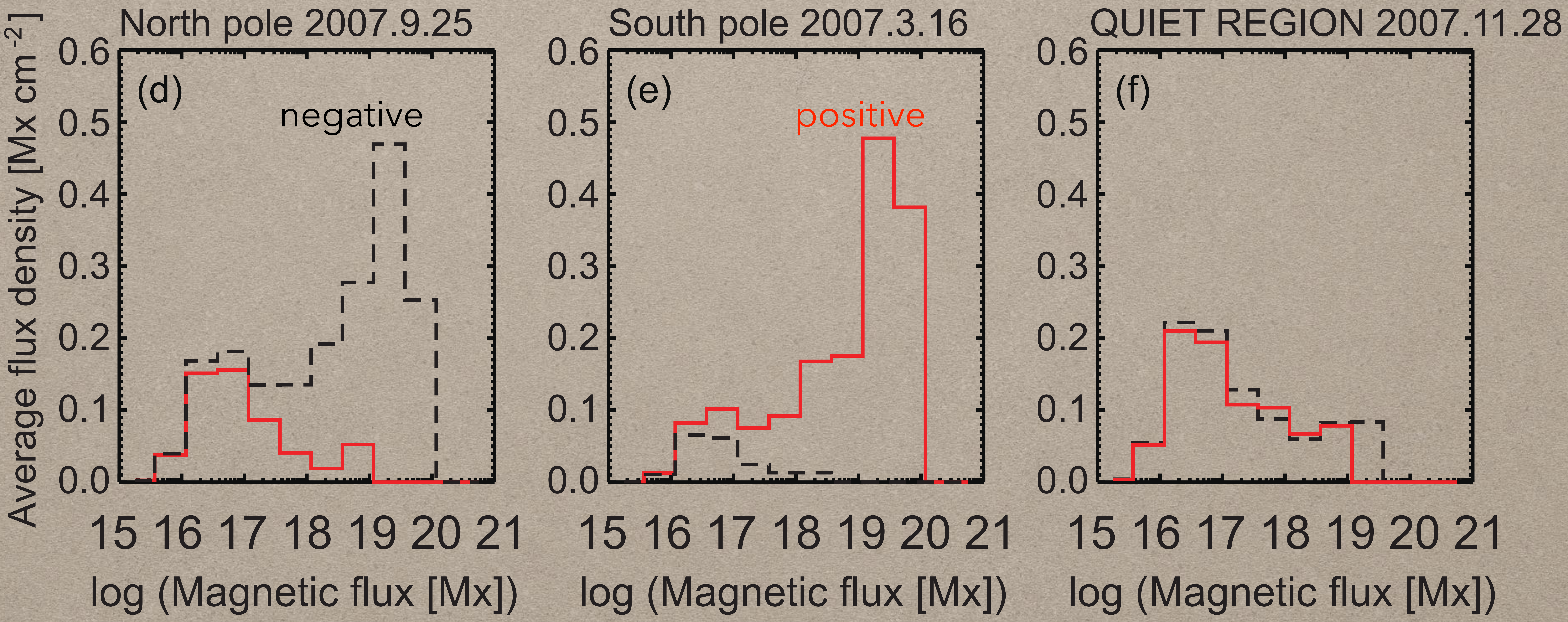


Tsuneta et. al (2008)

Polar magnetic fields: PDFs

Shiota et al. (2012)

flux patch average flux



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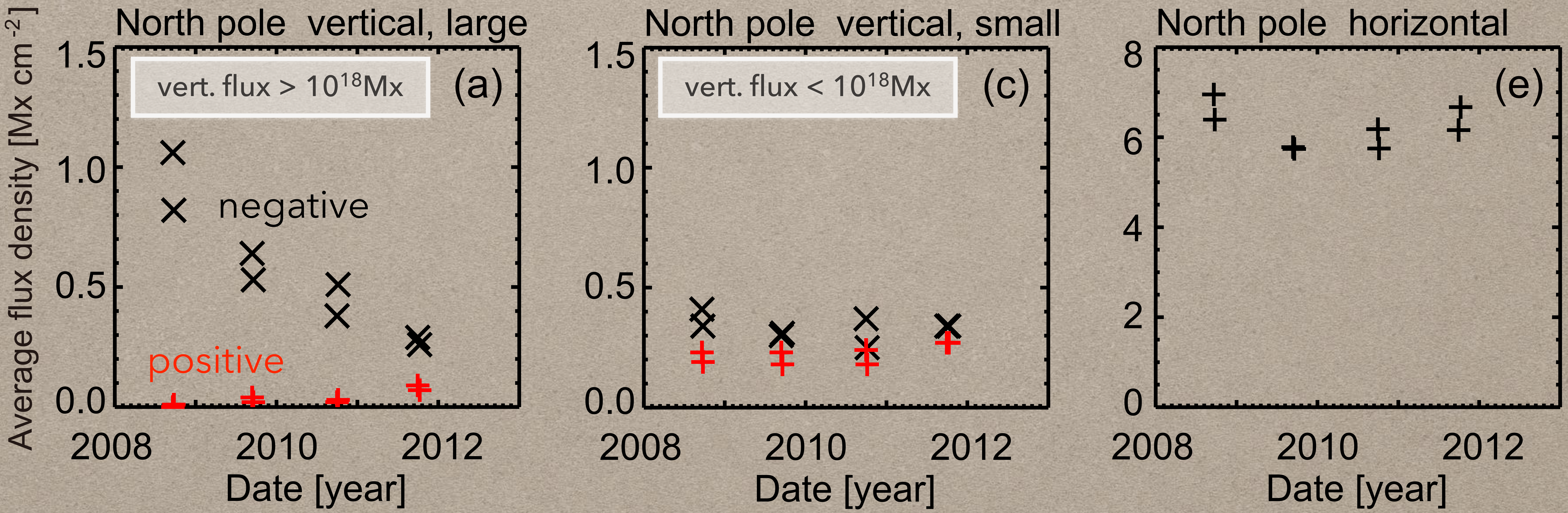


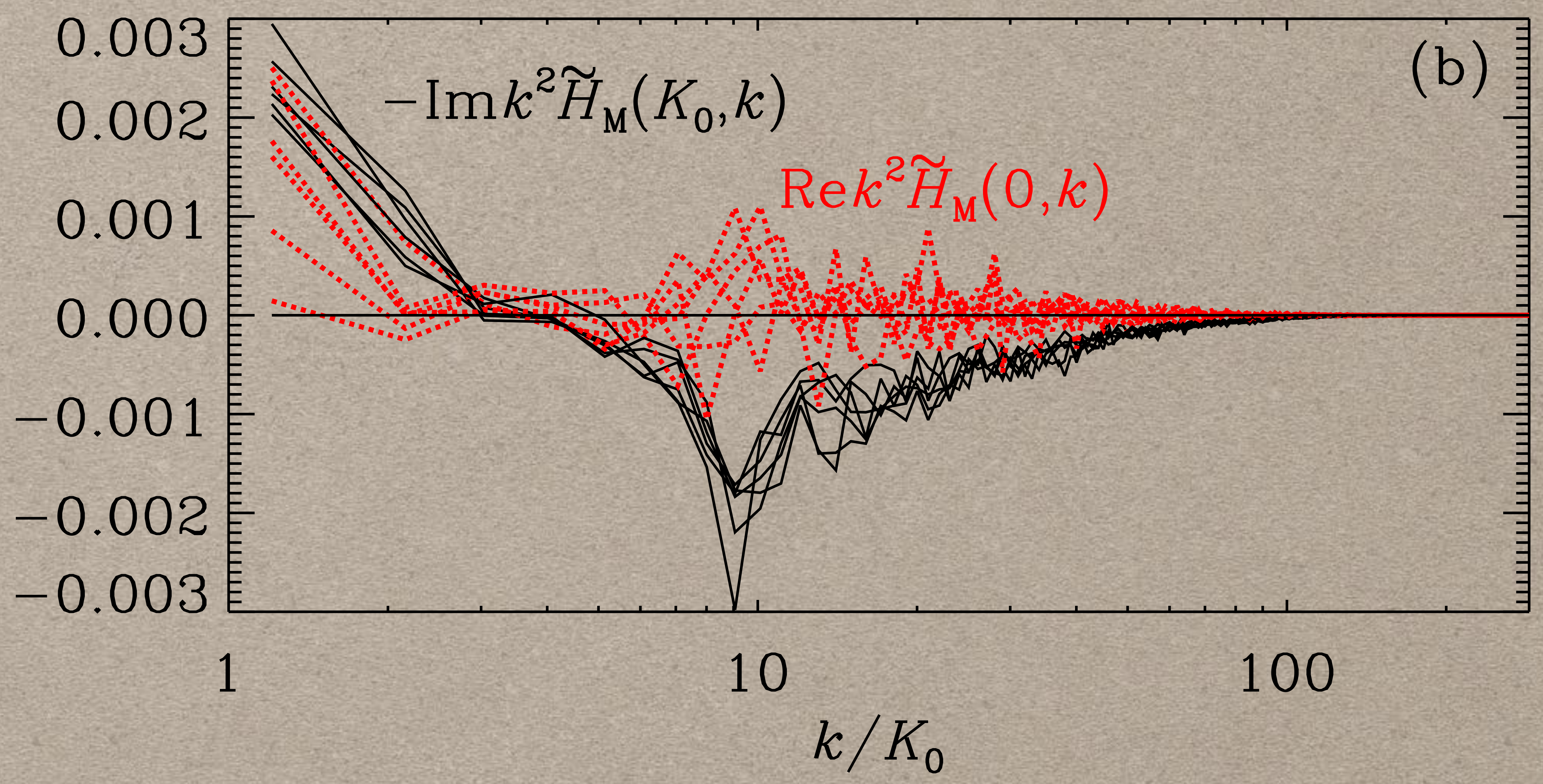
Polar small-scale flux emergence

- small-scale surface dynamo
  → **no latitudinal dependence expected**
- in-ecliptic measurements strongly biased:
  → cannot quantitatively determine the **latitudinal distribution of magnetic flux** and in particular the **emergence of small-scale magnetic features**
  (foreshortening, sampled height layer, different sensitivity for B_H, B_T, small deflections in near-vertical field)
- **evenly distributed measurements mandatory**

If PDF of properties (number, size, flux) are significantly different at high latitudes –> strong support for weak features being due to global dynamo.

SolO/PHI measurements will provide the answer.

- Magnetic helicity is a conserved quantity in highly turbulent flows
- Unless the dynamo is able to purge some small-scale helicity out of dynamo active layer, it will be catastrophically quenched
- This "escaping" helicity can be observed with PHI
- Models require a bihelical structure of magnetic helicity (different sign for small and large scale)



Dynamo-action generates bihelical magnetic helicity spectrum, a property of a realistic dynamo model, in the turbulent zone (Brandenburg et al., 2017)

HELICITY MAPPING FOR DYNAMO STUDIES

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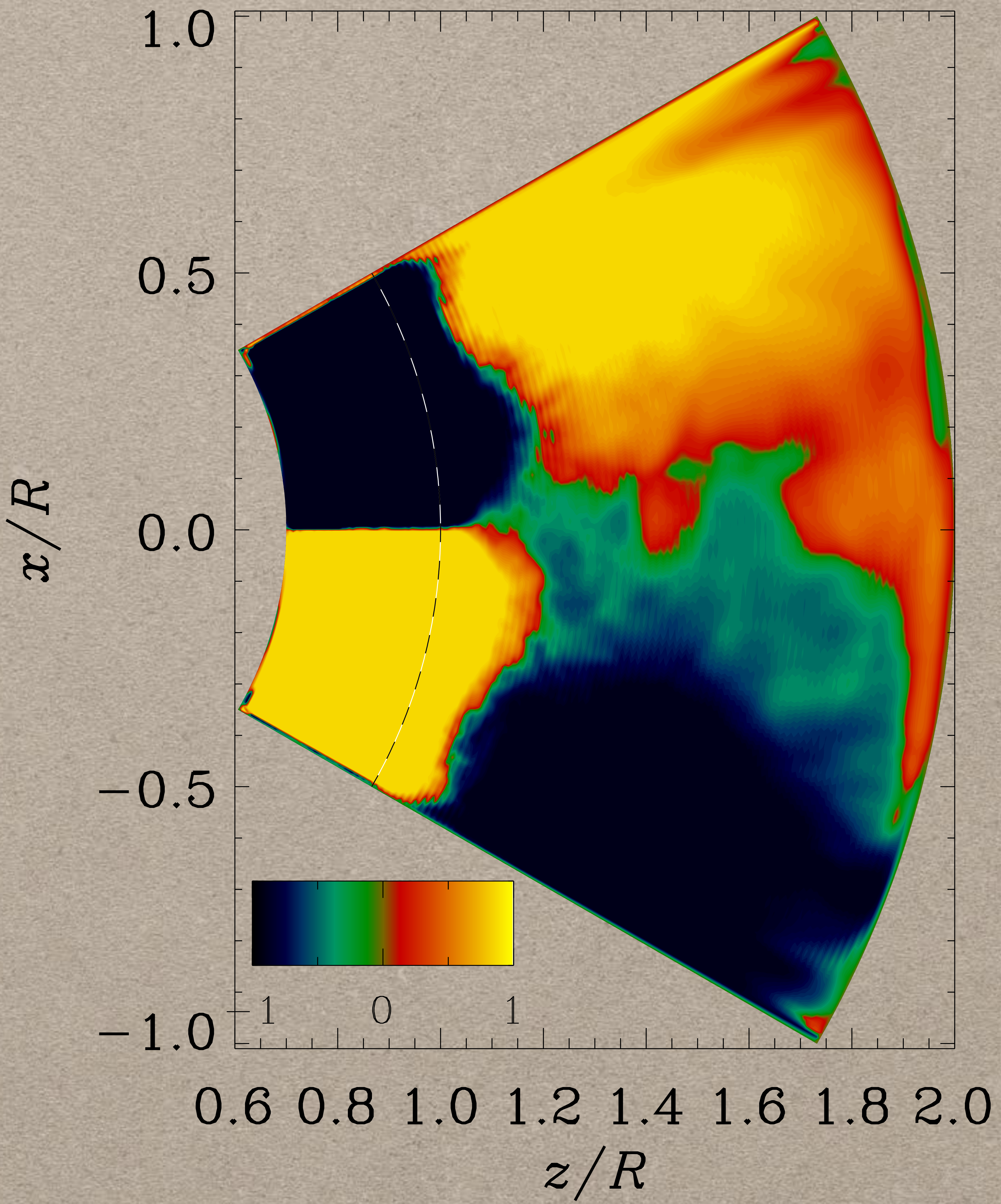

Sign change of helicity (Warnecke et al., 2011): inside the Sun and close to the surface the current helicity changes sign.

HELICITY MAPPING FOR DYNAMO STUDIES

solar orbiter PHI MPS

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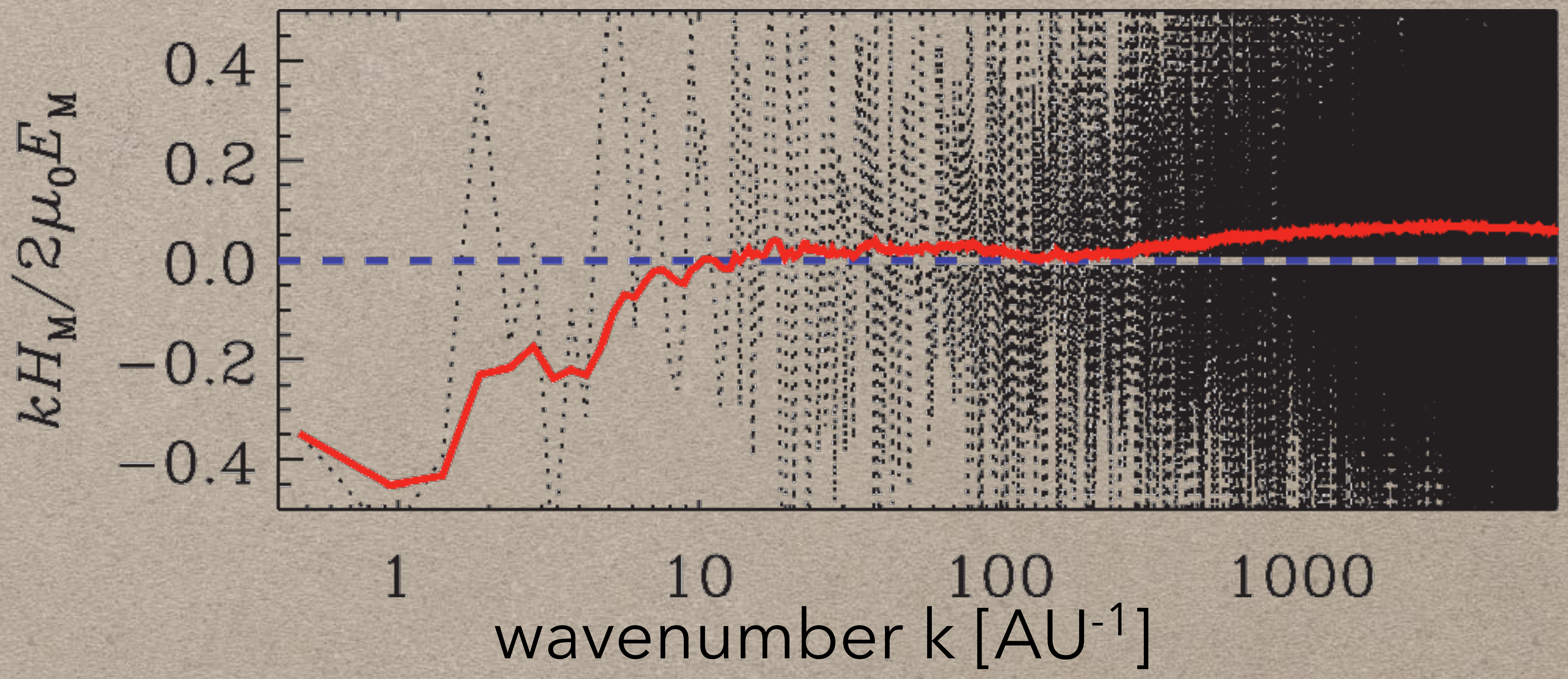
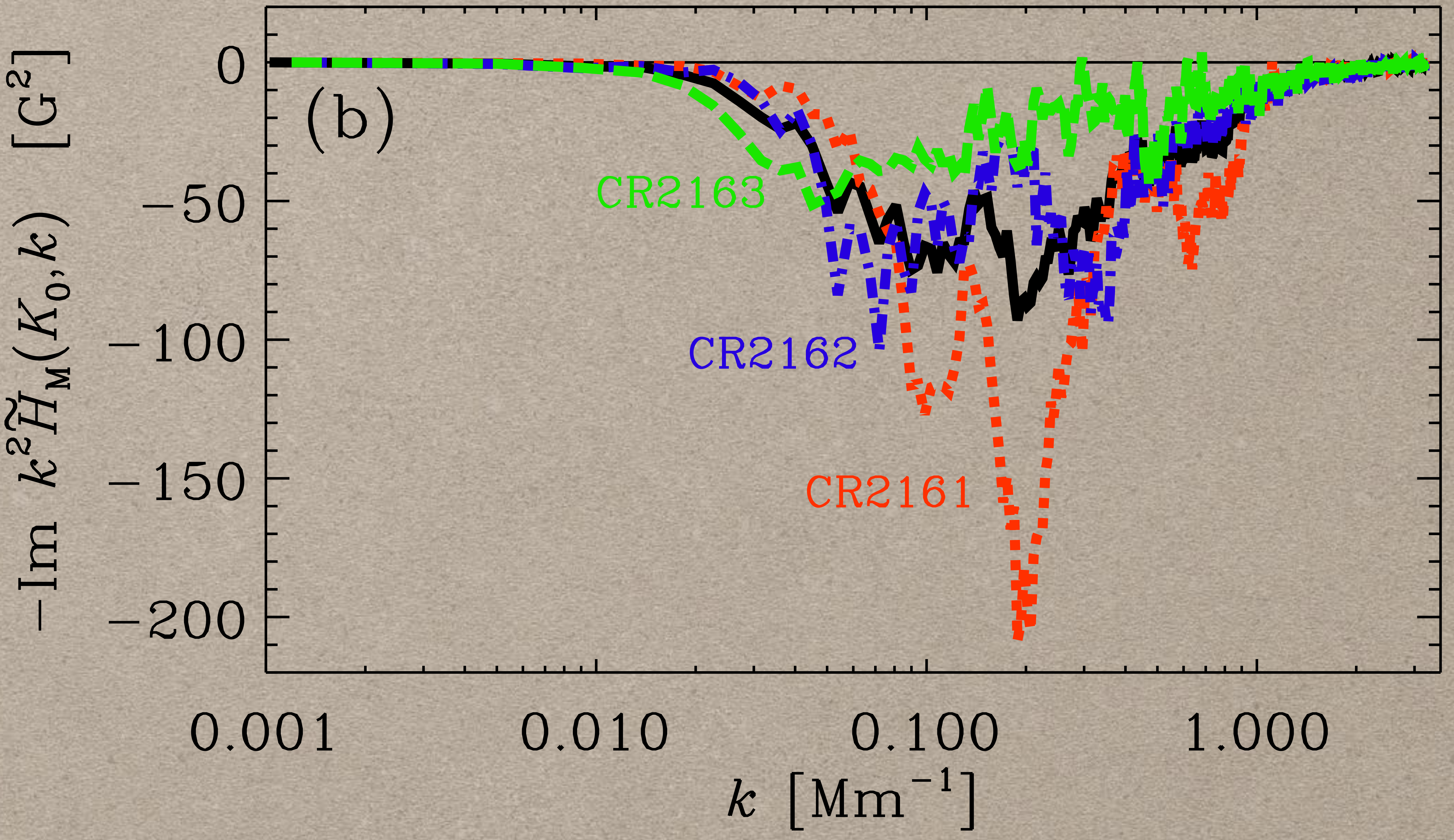


Ulysses measurements: the helicity spectrum in the solar wind. The sign change as function of distance from the Sun is here opposite to what is predicted to happen in the turbulent region within the Sun (Brandenburg et al., 2011)

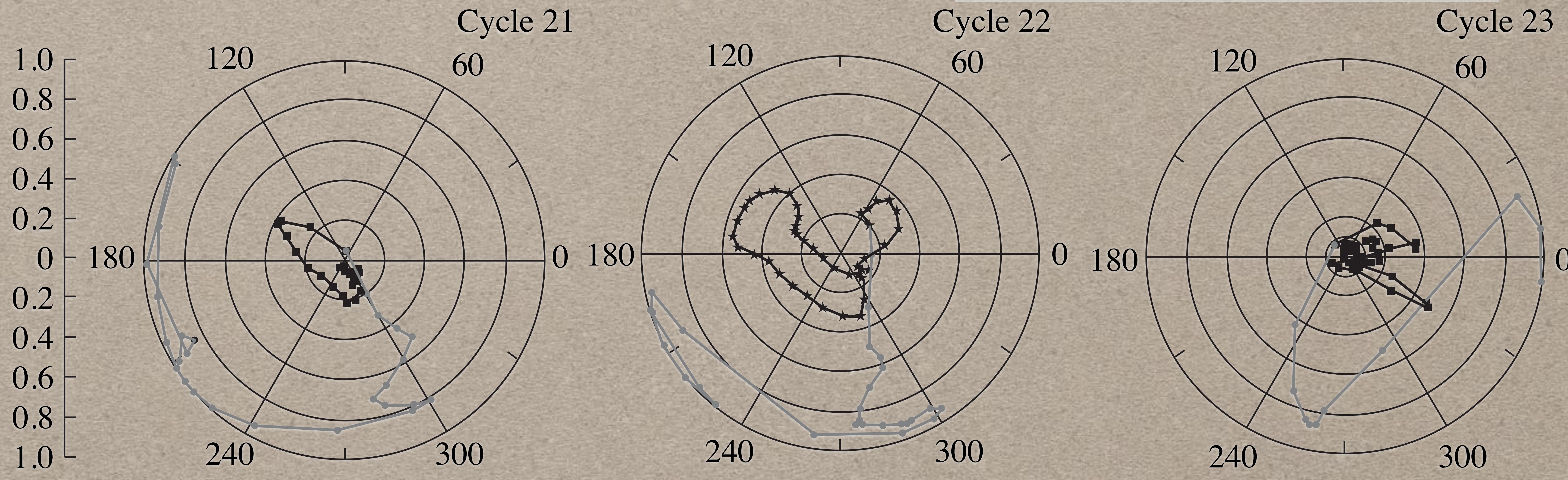
- A novel technique of Double Fourier Transform, to compute magnetic helicity spectrum, has recently been developed and applied to ground-based global synoptic vector magnetograms (Brandenburg et al., 2017).
- Due to the limited time span of the data, the evidence for bihelical spectrum remained inconclusive.



Synoptic vector magnetograms from SOLIS. Bihelical structures are not detected, the signal at the large scales is very weak. Is the timing of the measurement just unfortunate, or is solar surface a special case? This can be confirmed with PHI.

- most accepted global dynamo models assume that magnetic and rotation axes are aligned
- measurements point to misalignment
- SO/PHI to study the misalignment between the rotation and dipolar axes of the sun

Livshits & Obridko 2006



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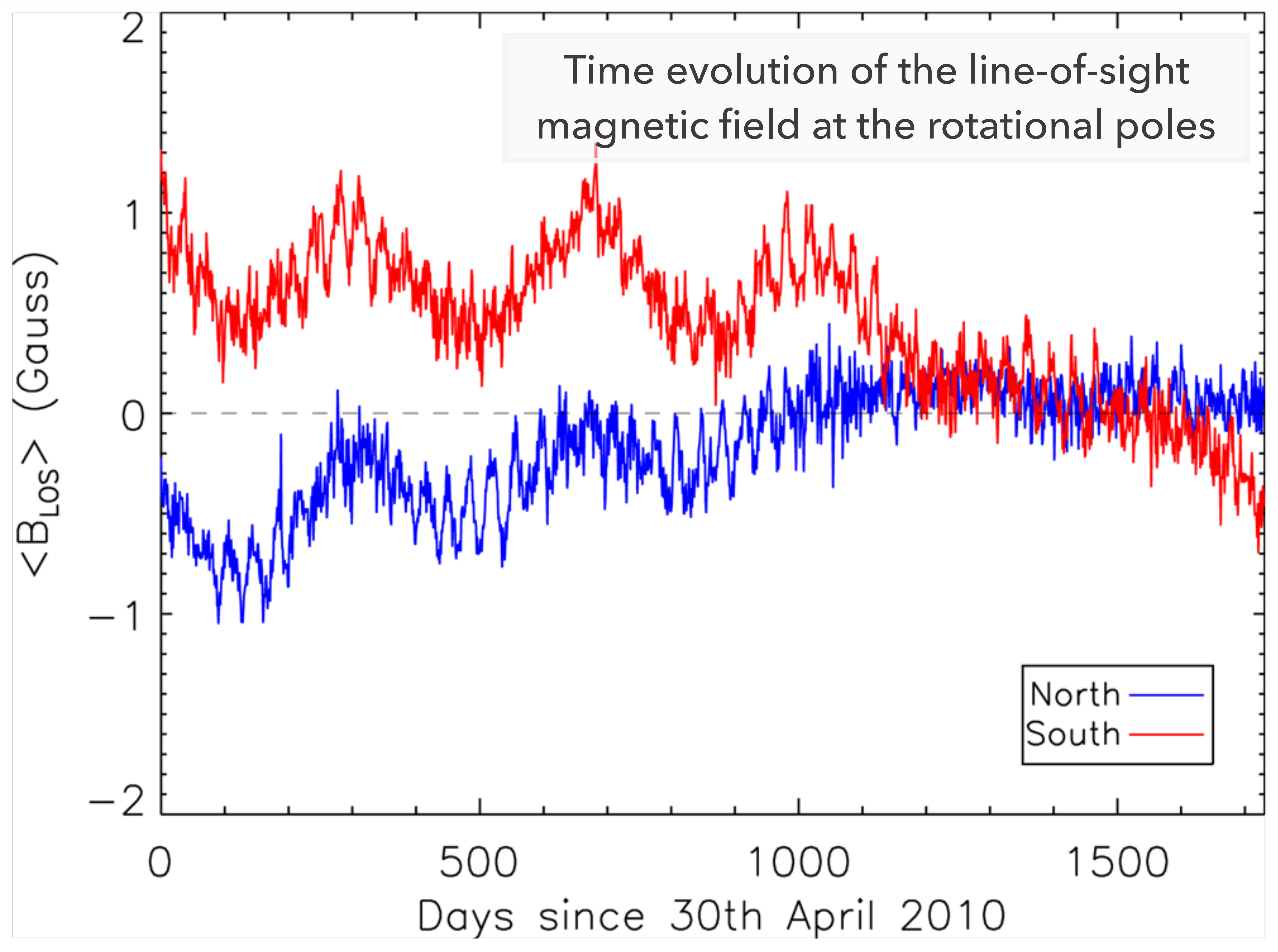
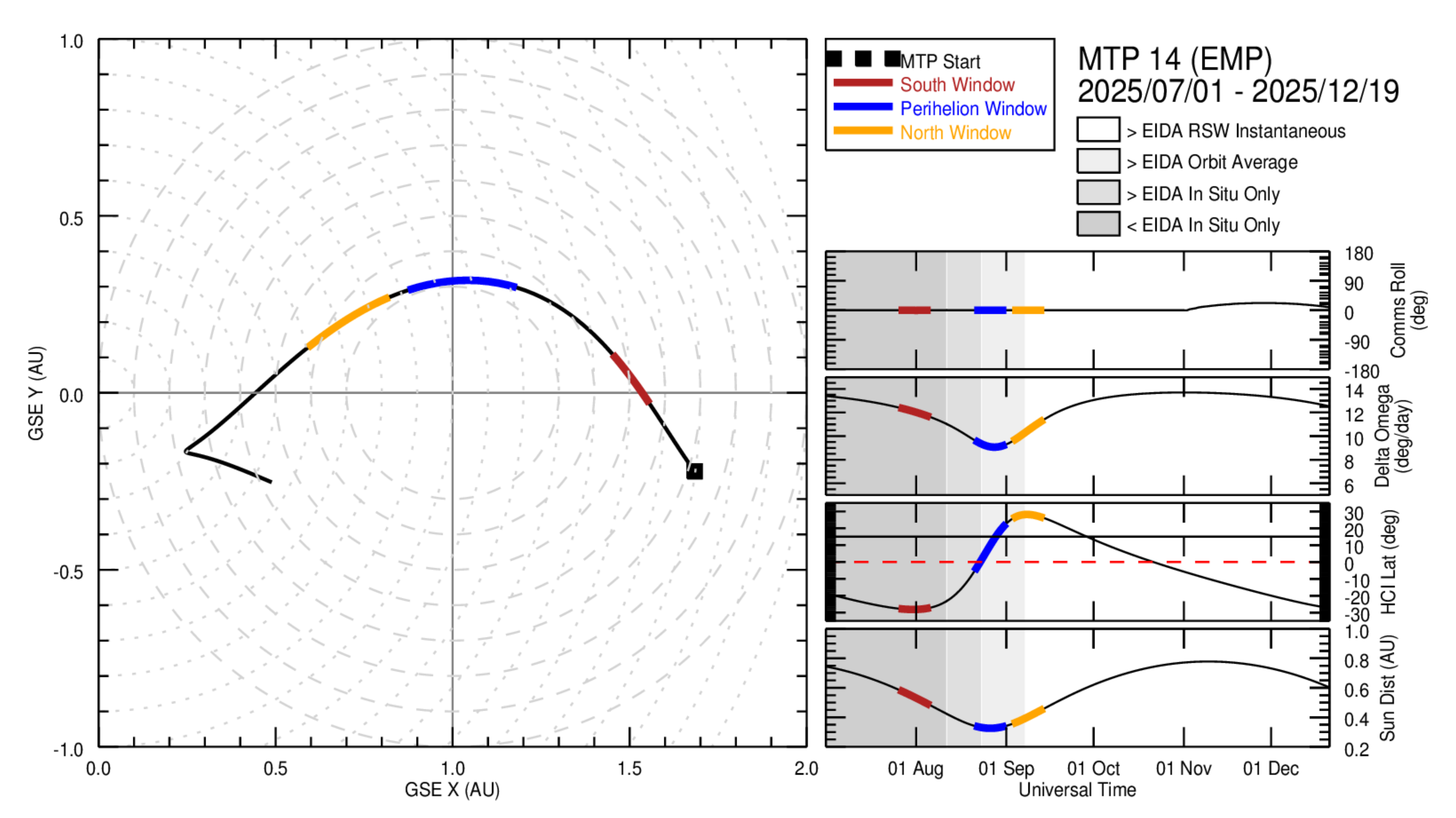


Pastor Yabar et al. 2015

OPTIMIZE POLAR SCIENCE WITH PHI

- max. solar latitude
- min. distance co-observations from Earth:
  - large B0 angle
    (8th March: South pole, 8th September: North pole)
  - ground-based support: Canary observatories September preferable; DKIST?
- HRT ME maps of all parameters + few Stokes parameter maps

Optimize Polar Science with PHI



SUMMARY

Magnetic Field measurements are essential for a majority of Solar Orbiter the science goals

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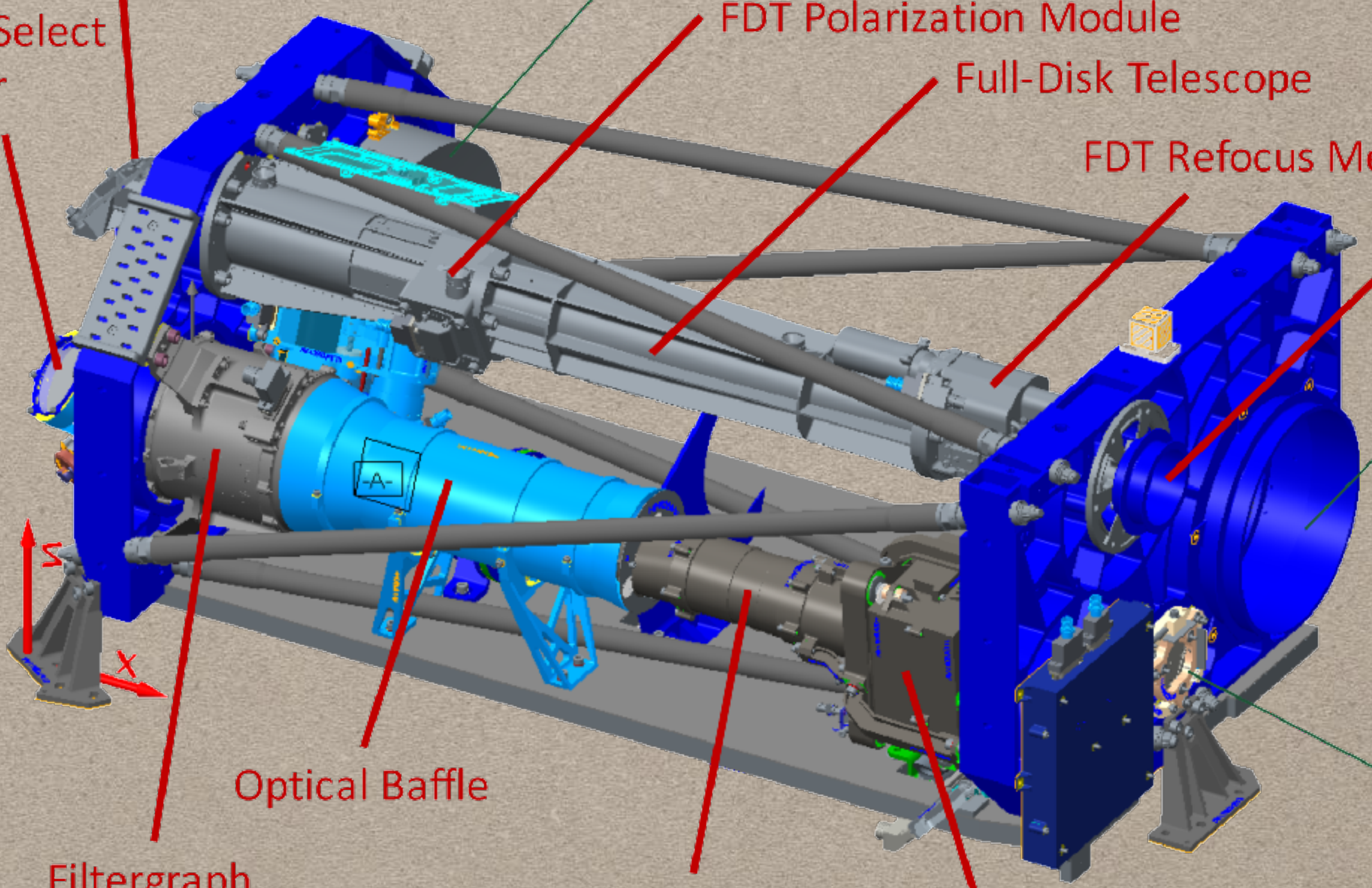
Ambiguity-free magnetic field maps for high-resolution ground based solar telescopes

Improved boundary conditions for extrapolating the photospheric field for coupling science

SO/PHI DESIGN

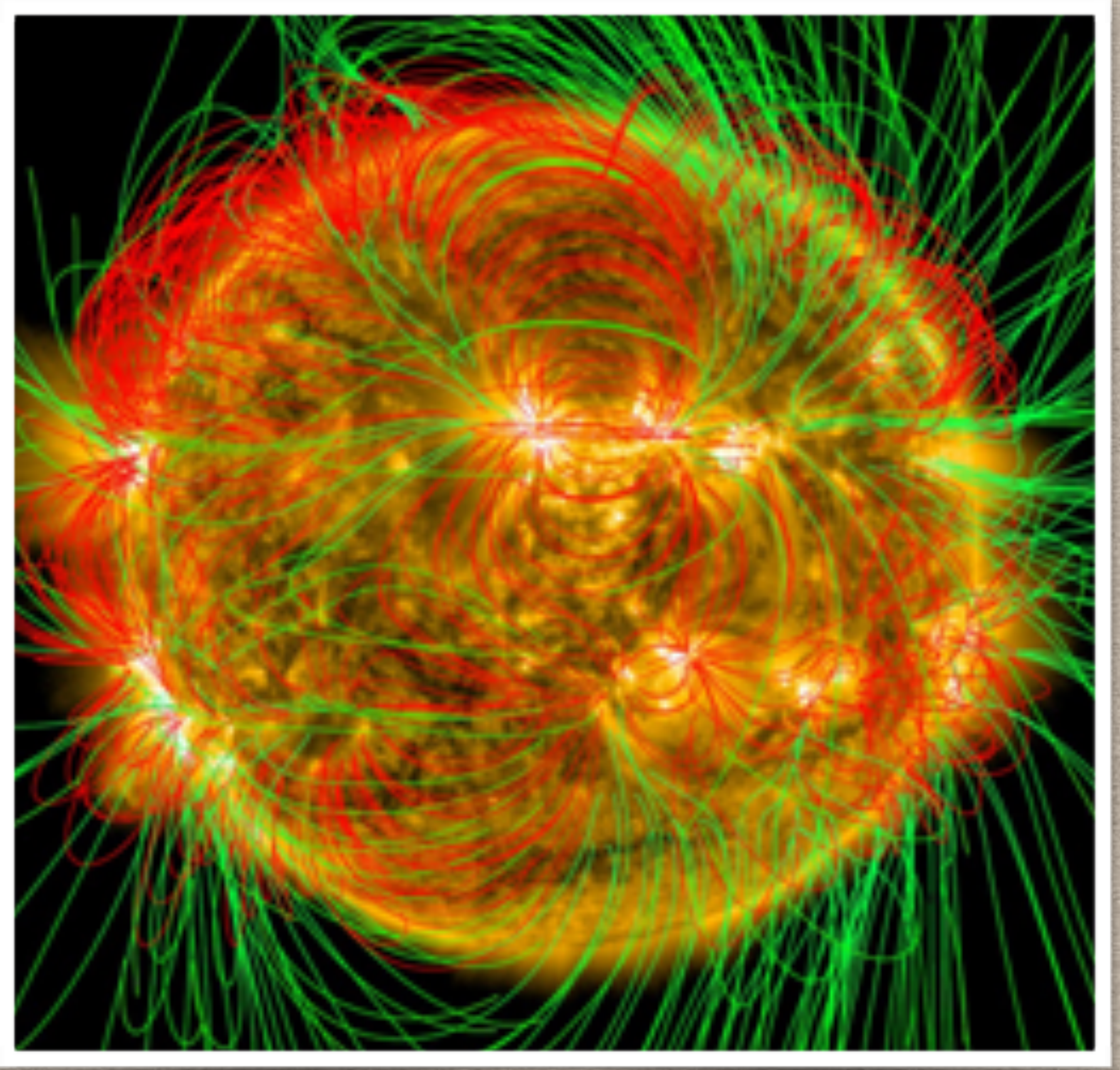
- HRT: off-axis Ritchey-Chrétien telescope
- FDT: off-axis refractor
- Polarization Packages: based on Liquid-Crystal Variable Retarders (LCVRs)
- Filtergraph: transfer-optics with solid state etalon and interference filters
- Image stabilization: 30 Hz Correlation Tracker
- Focal Plane: 2k / >10fps APS detector

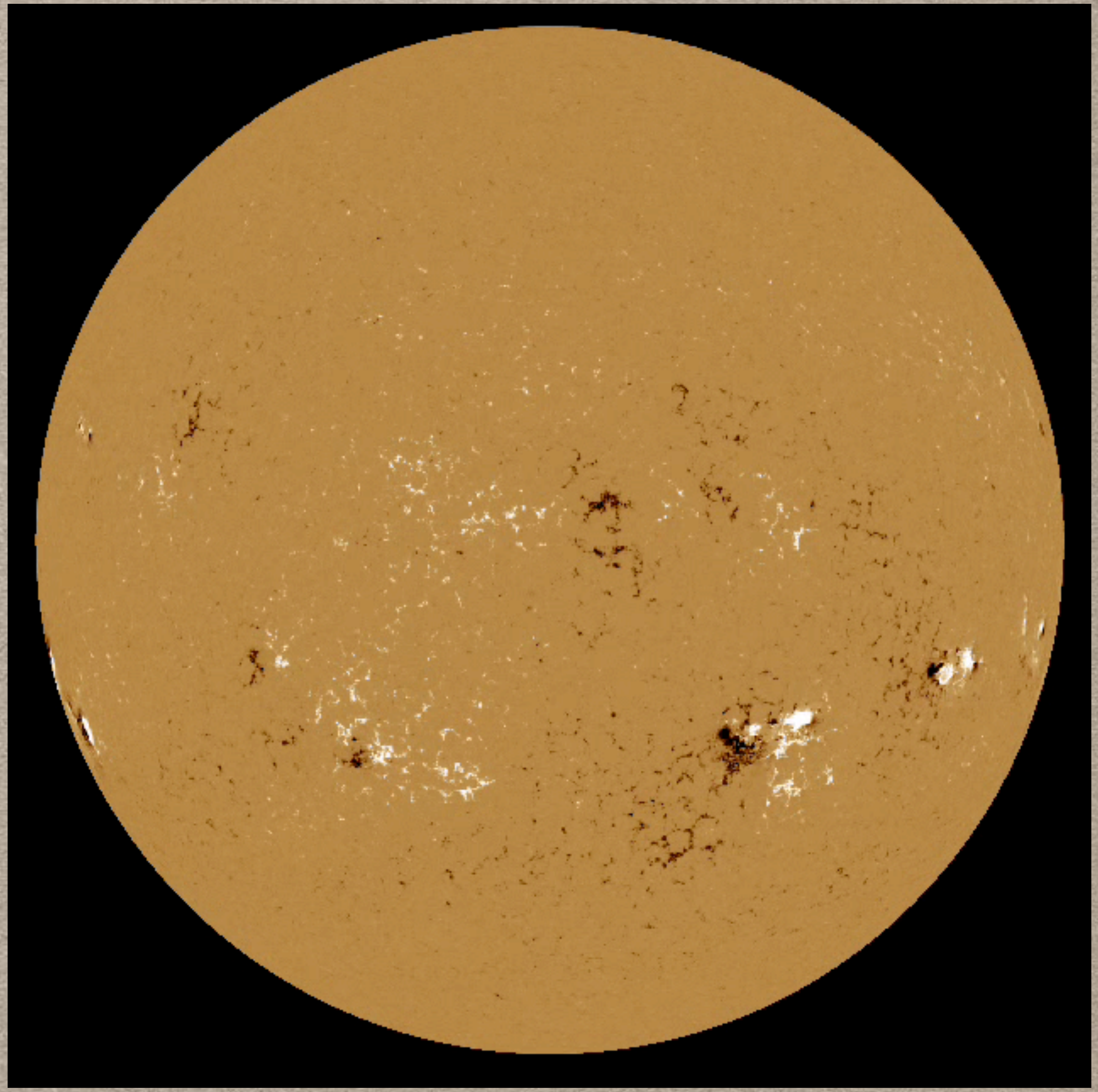


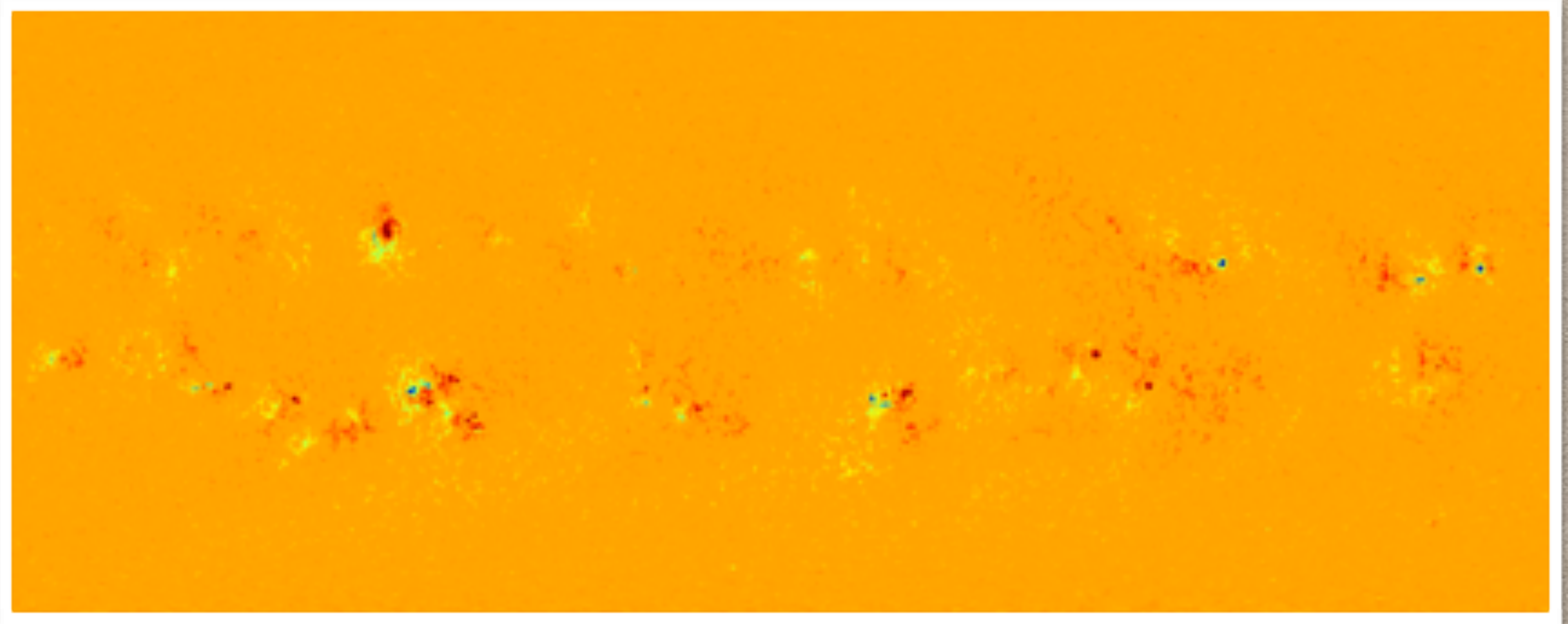
SO/PHI corona and global Sun science

SO's close perihelion transits enables to follow surface structures for more than half of a rotation period, i.e. up to 23 days.

Vantage points far from Earth allow for instantaneous 4π magnetic maps







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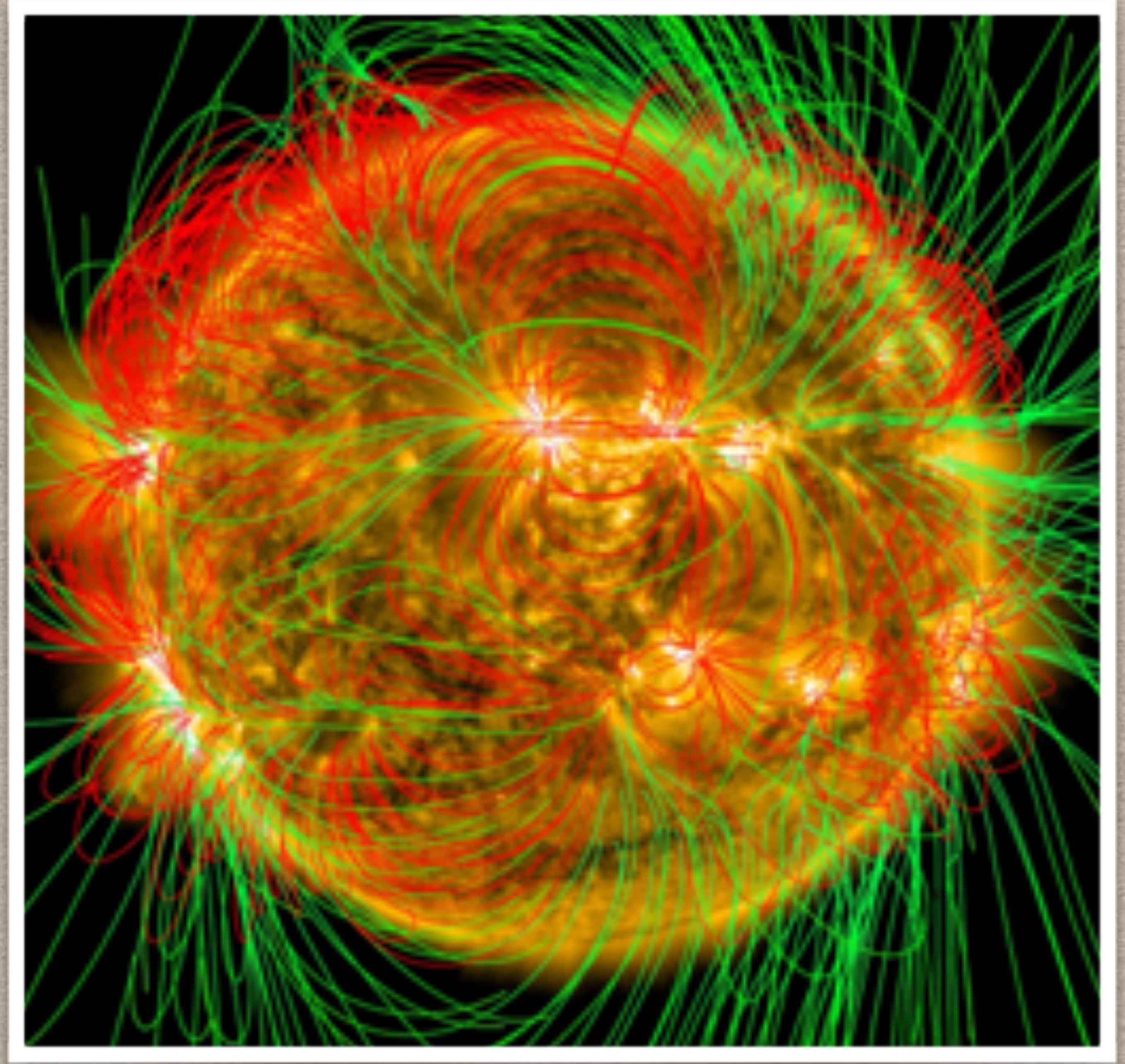
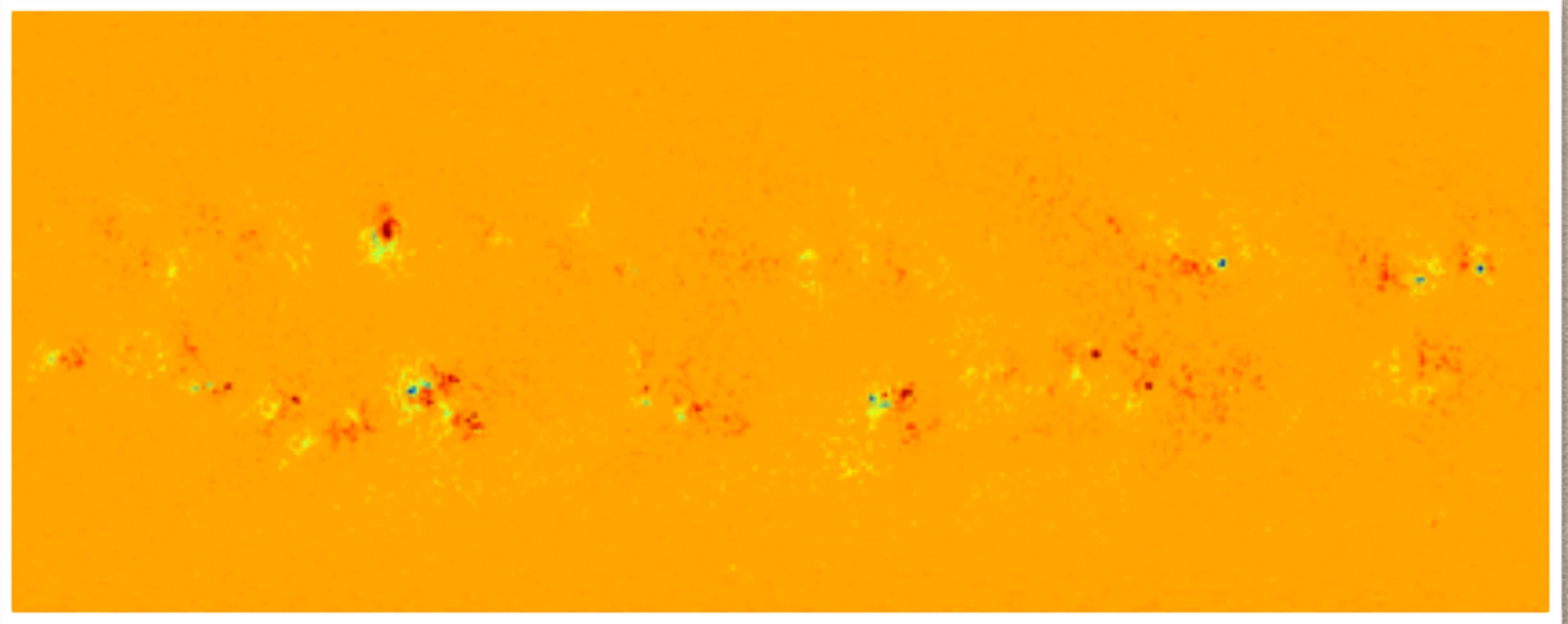
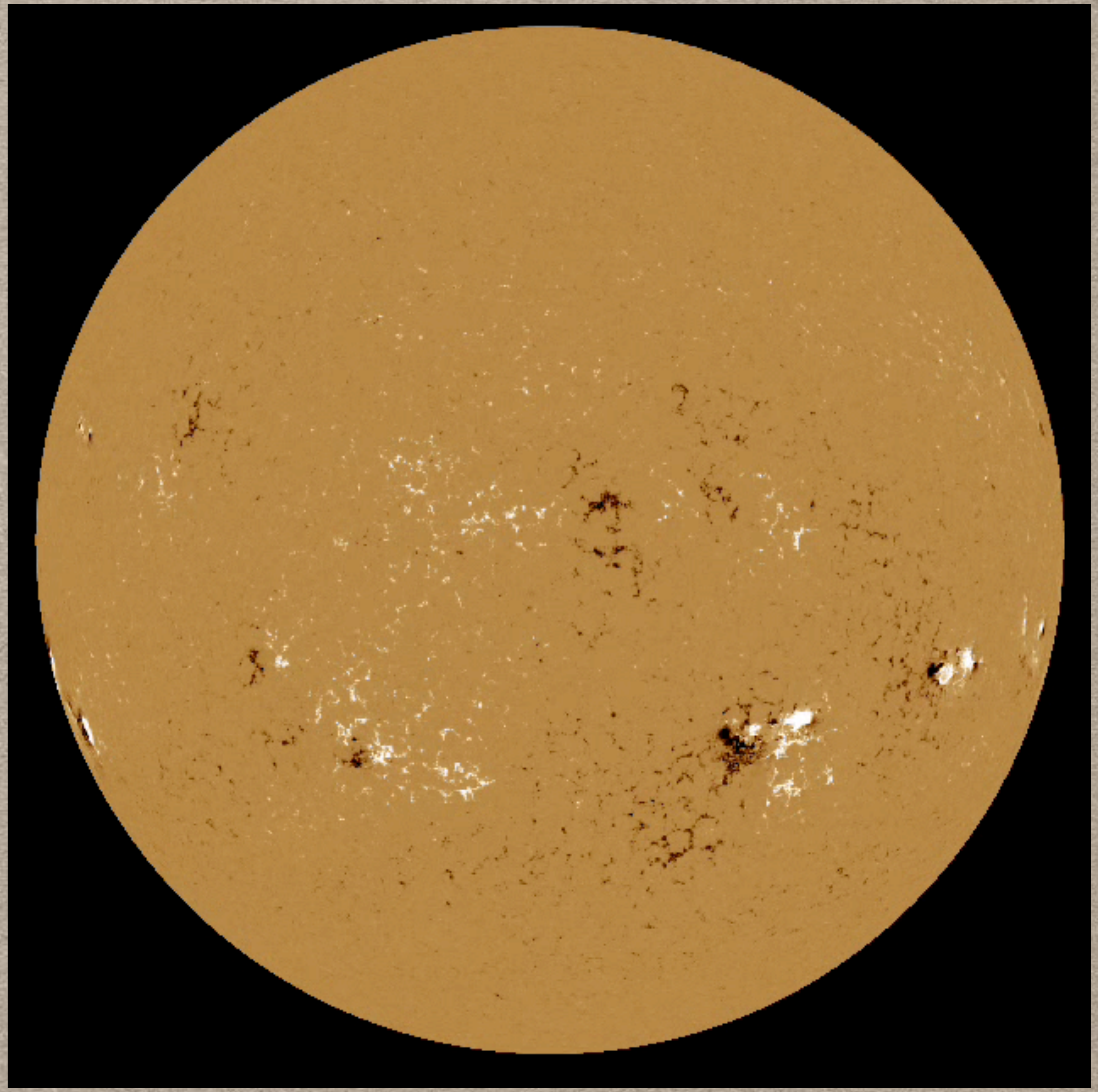


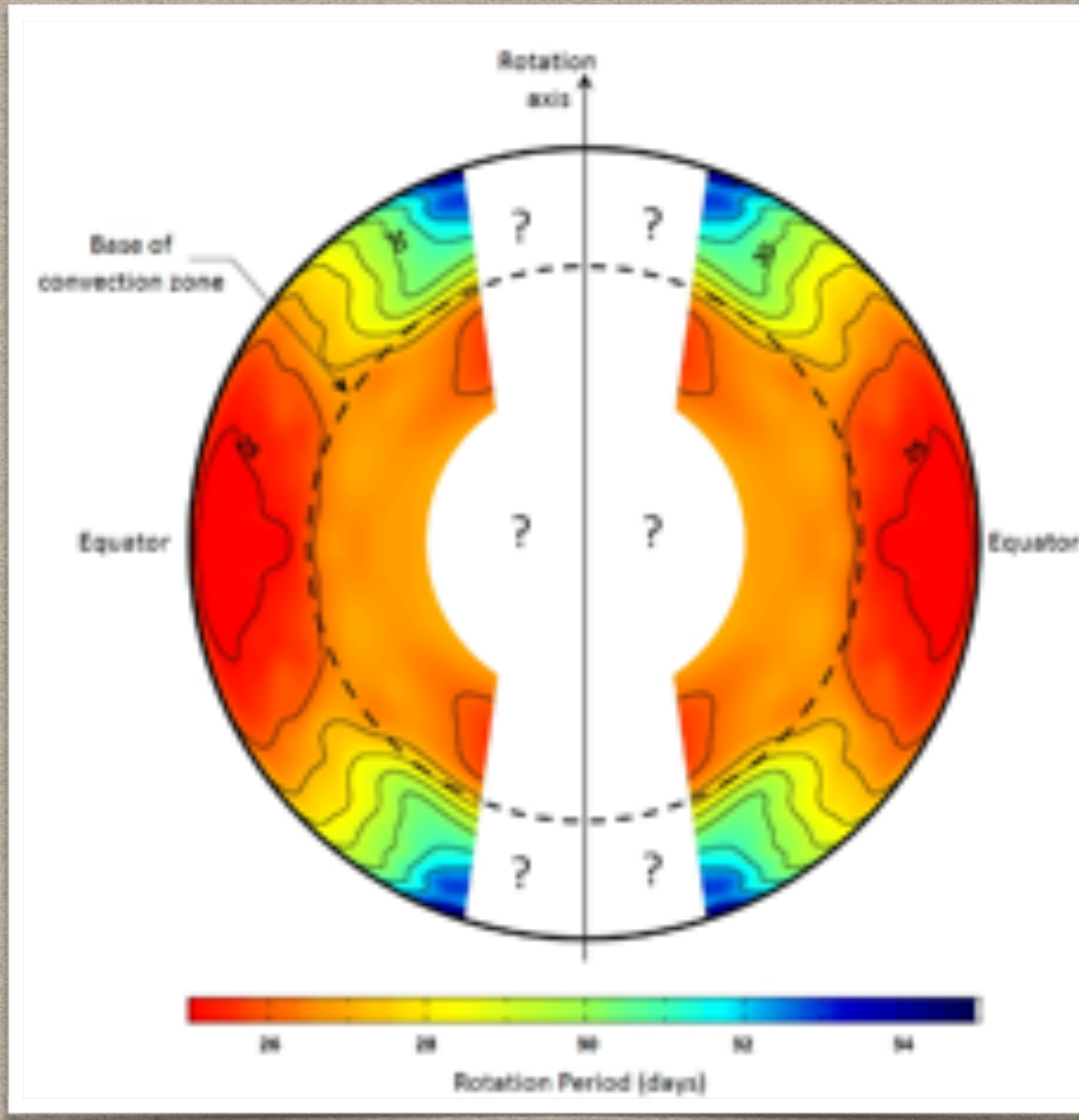


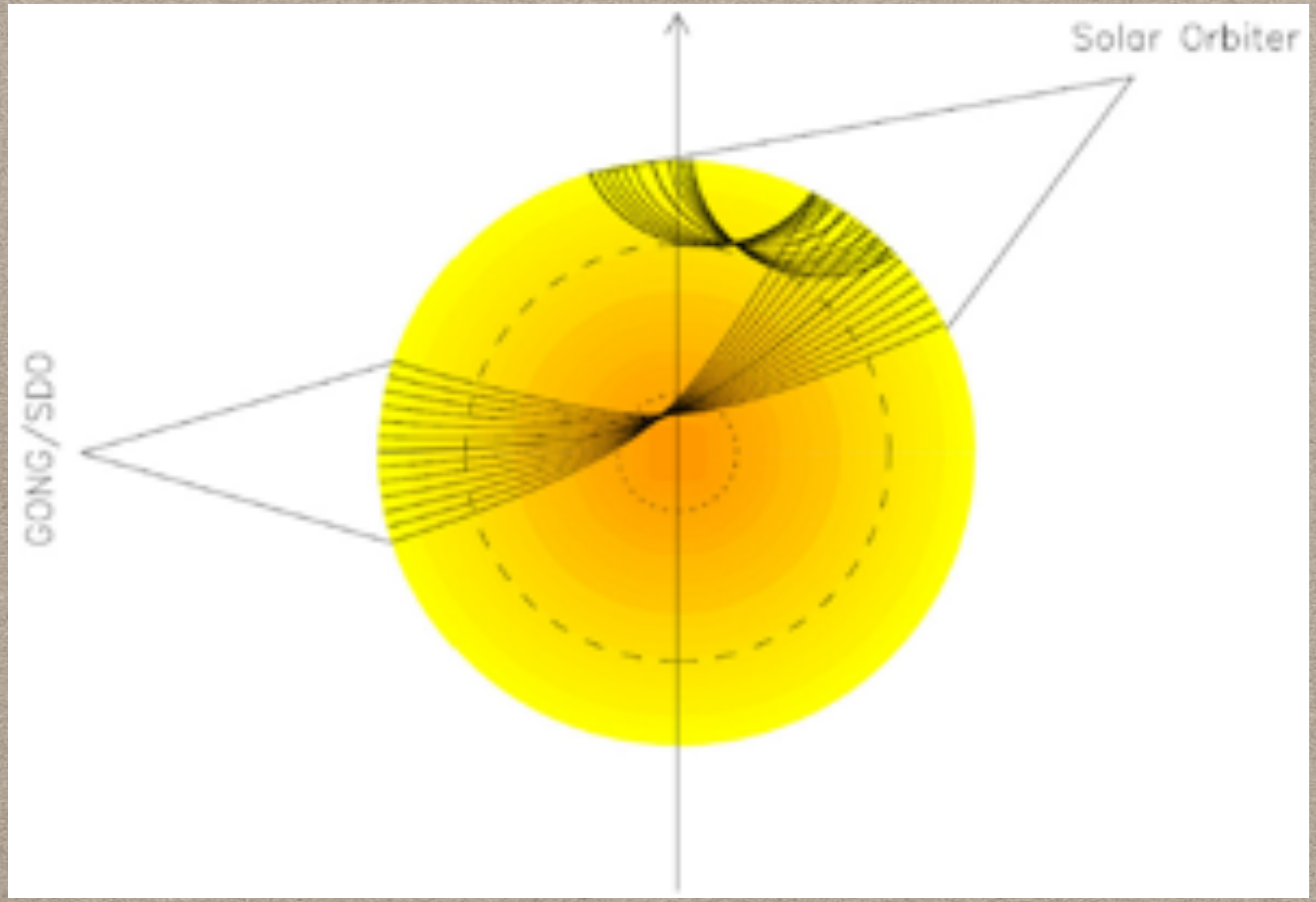


SO/PHI SCIENCE: HELIOSEISMOLOGY

Observations from a vantage point in the ecliptic does not allow probing solar latitudes higher than ~70°.

SO/PHI observations from out of the ecliptic will help to address problems of, e.g., the solar dynamo.





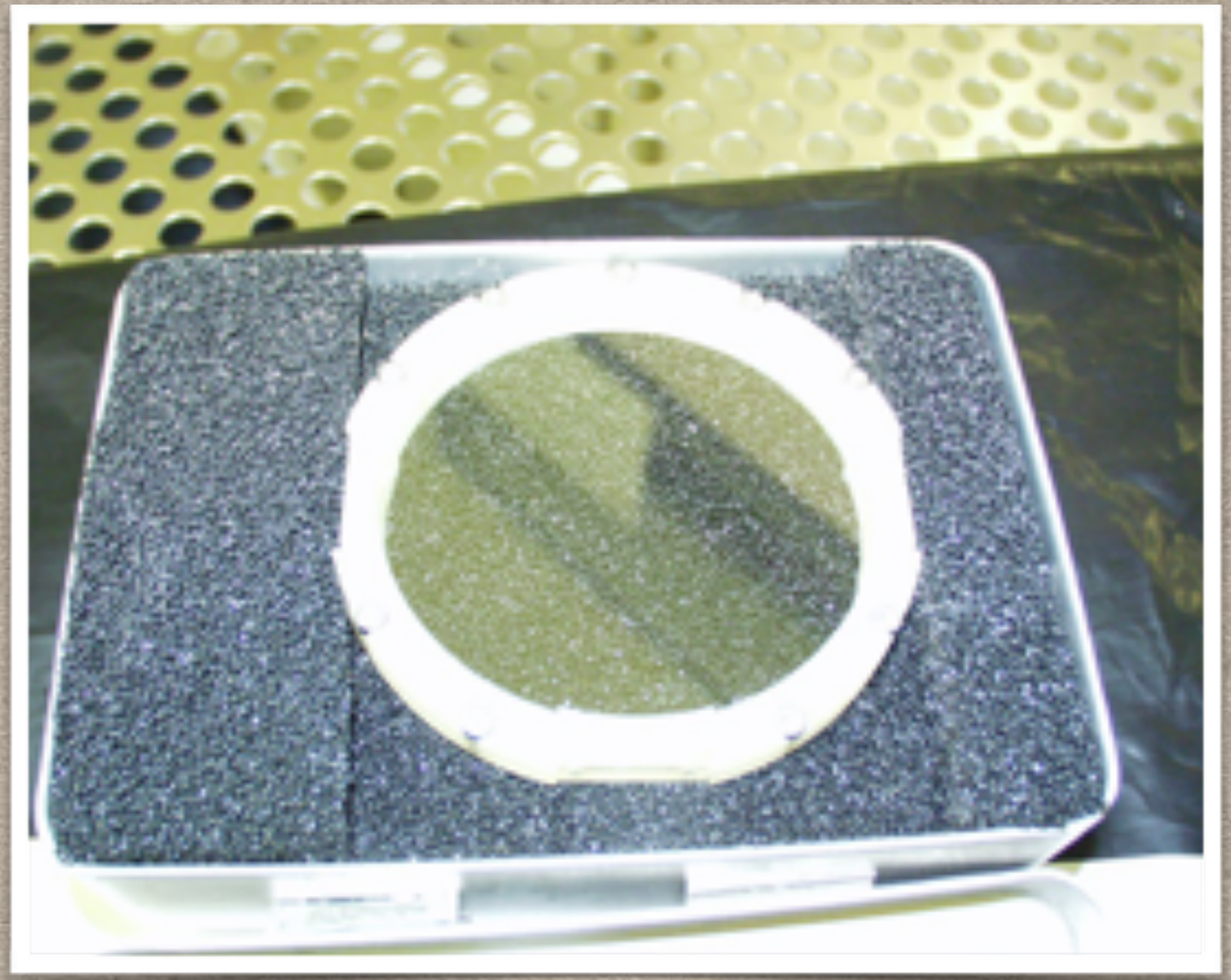
Stereoscopic Helioseismology

Probing the Sun from different vantage points may allow for probing deeper layers than what is possible with only one instrument.

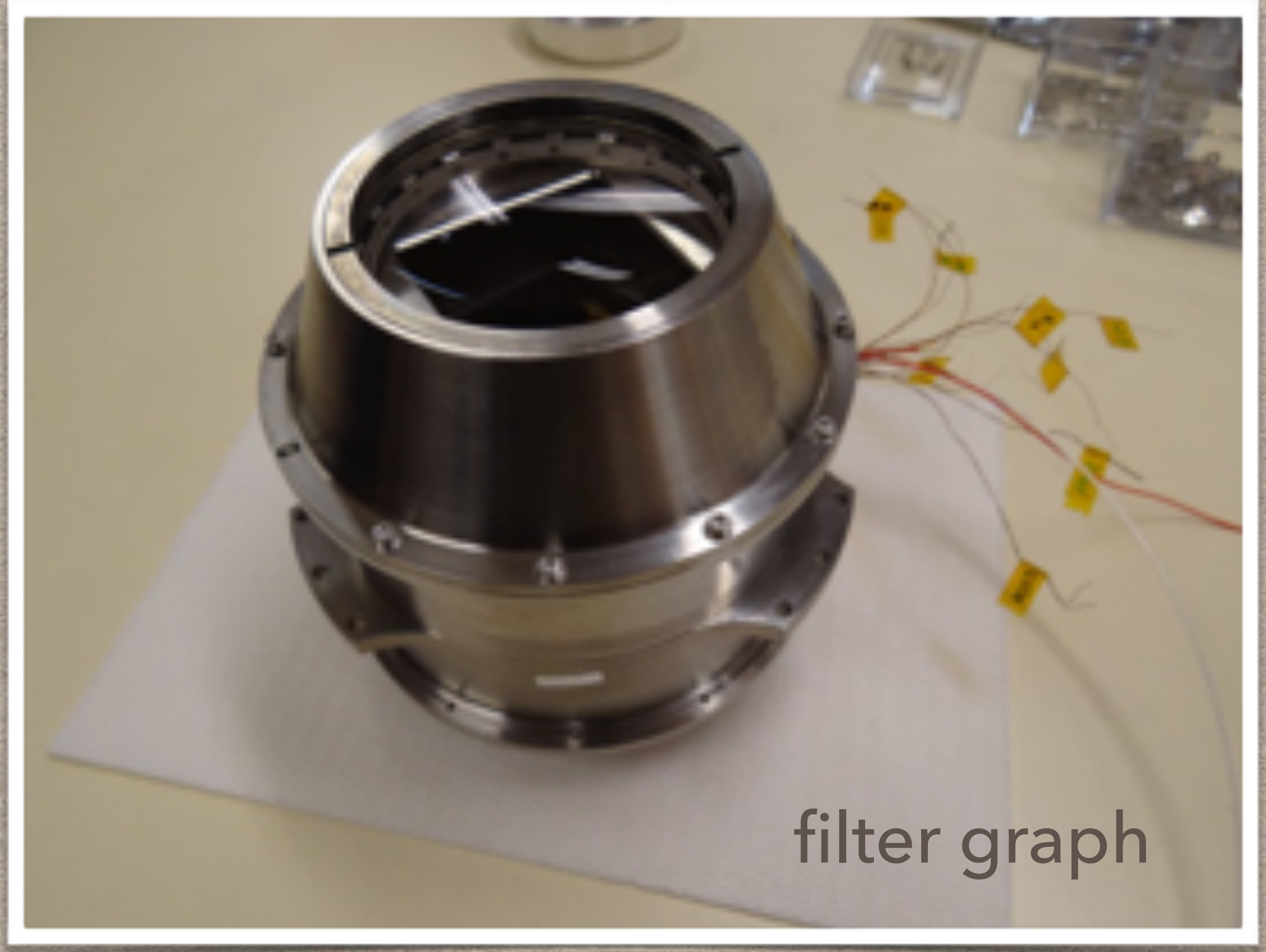
SO/PHI FILTERGRAPH

Line scanning device based on a solid state Fabry-Pérot etalon:

- FWHM = 90mÅ, free spectral range = 3.0Å
- ~ 1nm surface roughness, ~10nm abs thickness tolerance
- T-stability: <0.1K on etalon
- 66°C operating temperature
- 1.5 W heater power



250μm $LiNbO_3$ etalon



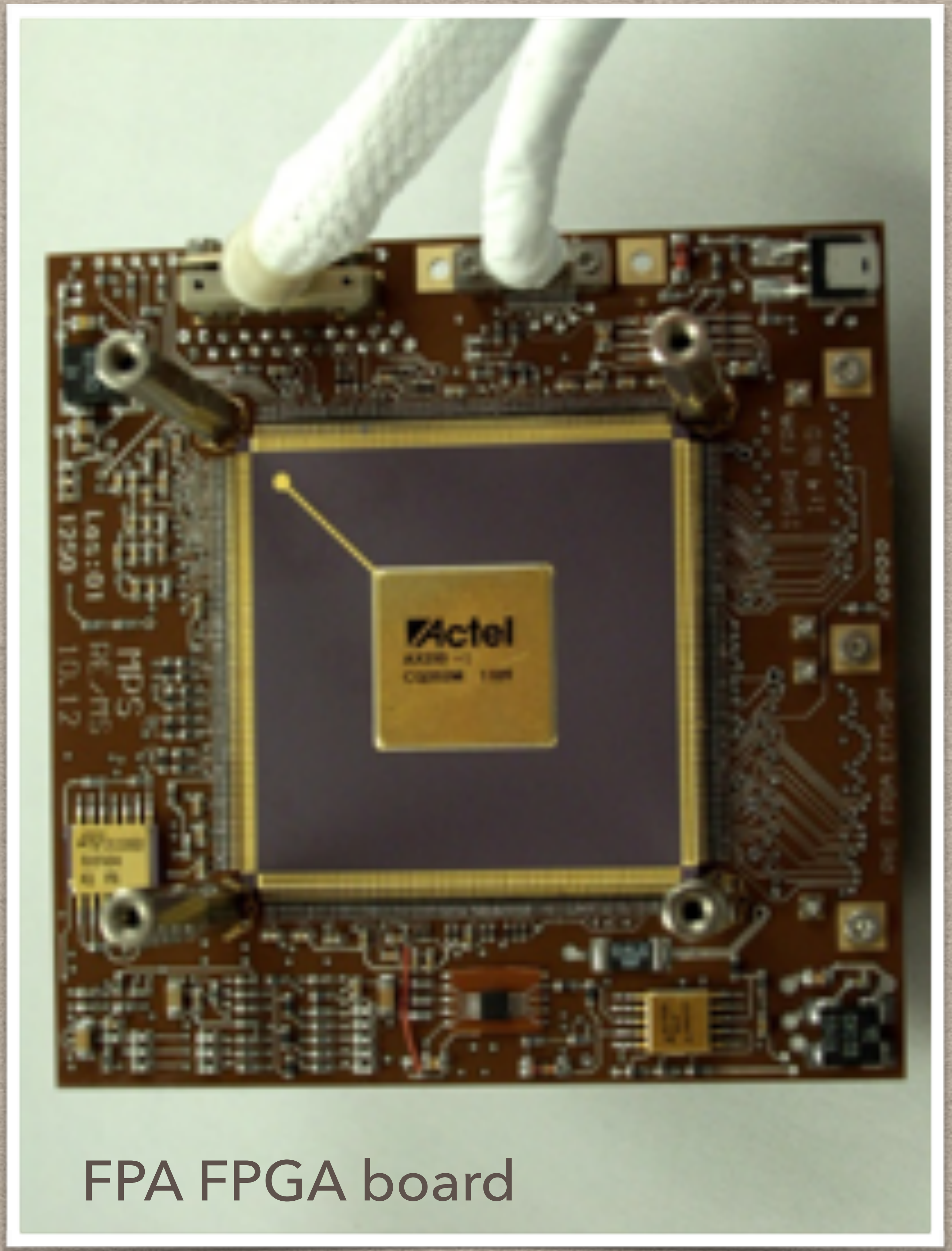
filter graph

- 2 optical windows (lenses, ITO coated)
- 2 interference filters (order sorter, IR blocker)
- 1 $LiNbO_3$ etalon
- Oven (active thermal control)
- HV connection

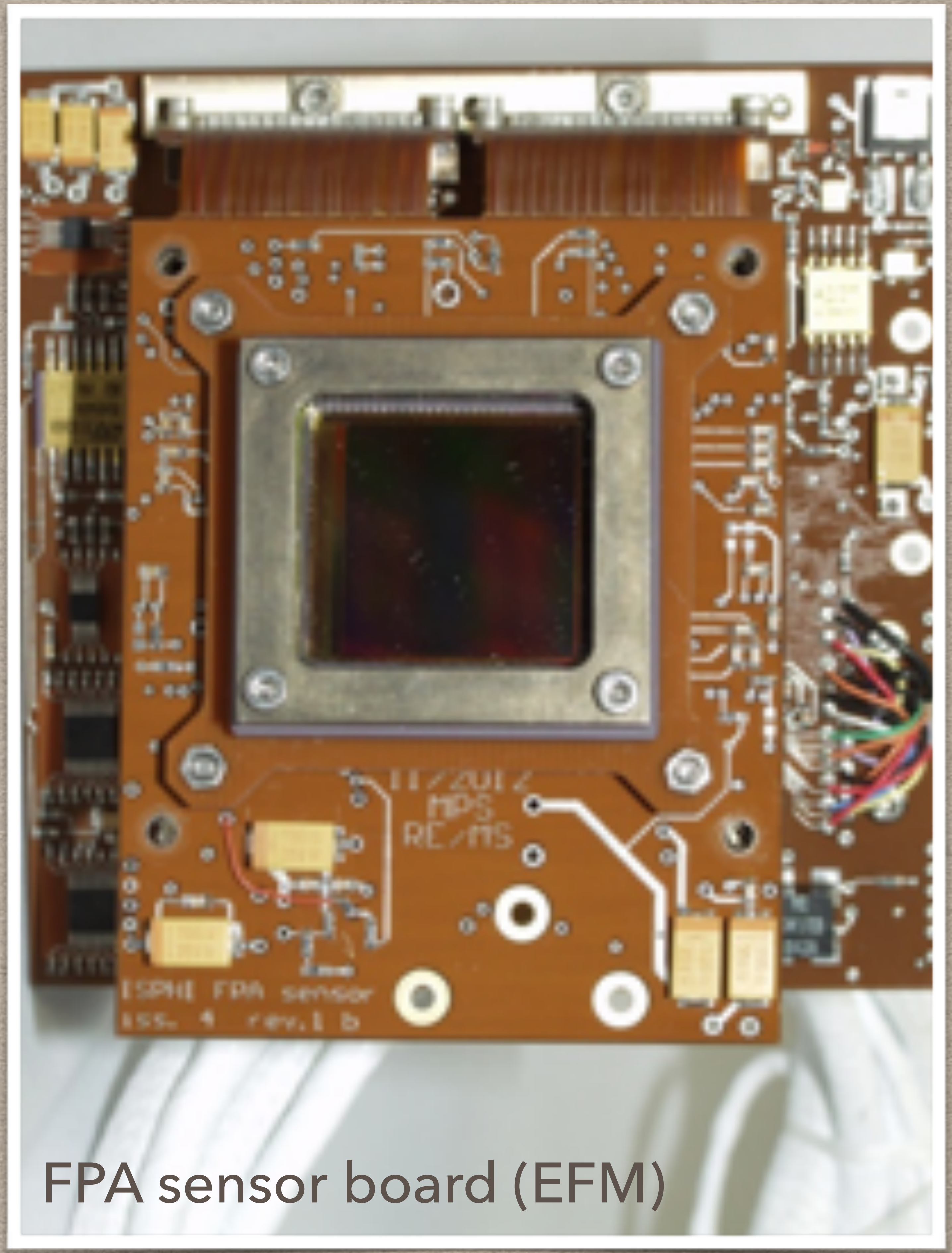
SO/PHI FOCAL PLANE ASSEMBLY

solar orbiter PHI MPS

- 2k x 2k read-out at > 10fps
- FWC: 100ke$^-$ (<1% linearity)
- Actively cooled sensor (cold element) => dark noise: ~100 e$^-$/s per pixel
- Automatic Single Event Upset (SEU) recovery
- Automatic sensor Single Event Latch-up (SEL) detection and recovery (sensor power cycle)

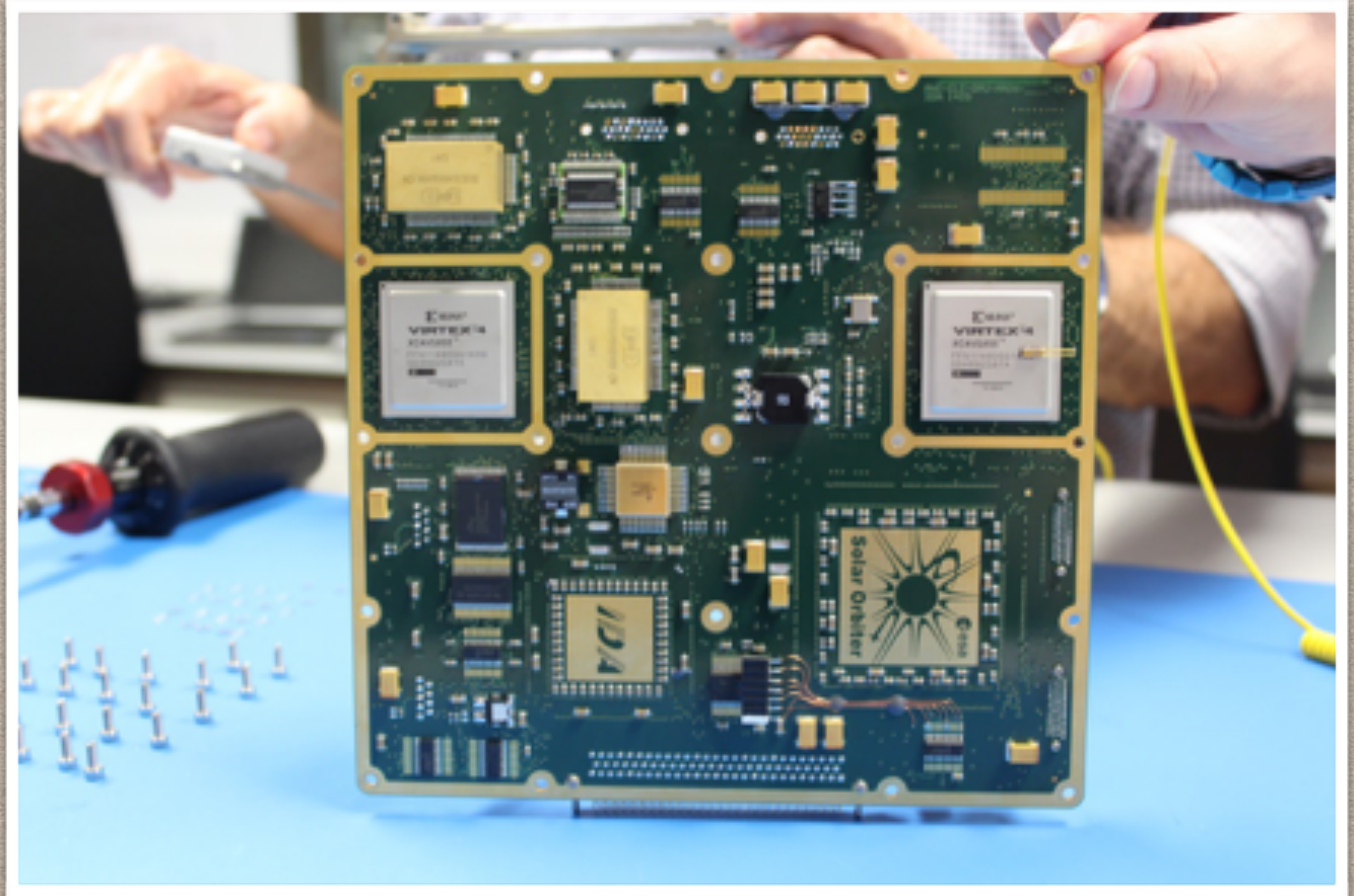


FPA FPGA board


FPA sensor board (EFM)

SO/PHI DIGITAL PROCESSING UNIT

solar orbiter PHI MPS



Tasks:

- Instrument control
- Science data Acquisition with >10 fps
- Correlation Tracker control
- Onboard data calibration
- Onboard data inversion
- 4 Tbits flash memory control
- Commanding/Telemetry

Most critical items:

2 reconfigurable FPGAs for onboard data analysis, image acquisition and CT control