

Probing the Sun's magnetic field from multiple viewpoints with the help of Solar Orbiter



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Why do we study such a boring star?



- it supplies Earth with 99.96% of all energy
- it produces space weather & negatively impacts technical systems
- it is the only star we can resolve & study in detail
- it is a gigantic plasma-physics laboratory
- it affects our climate etc. etc.



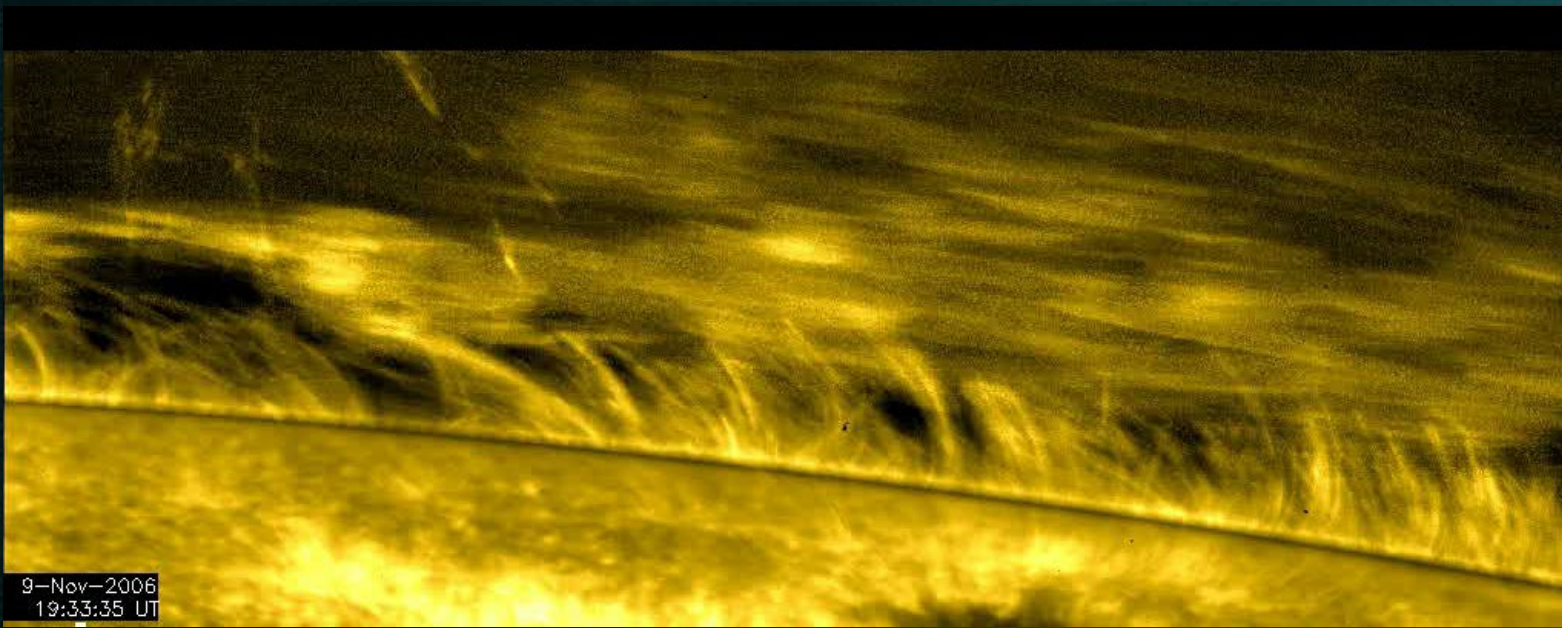


The dynamic and active Sun

SDO/AIA

Prominence (gas at 10 000 K)
Ca II K line

Hinode/SOT, Okamoto



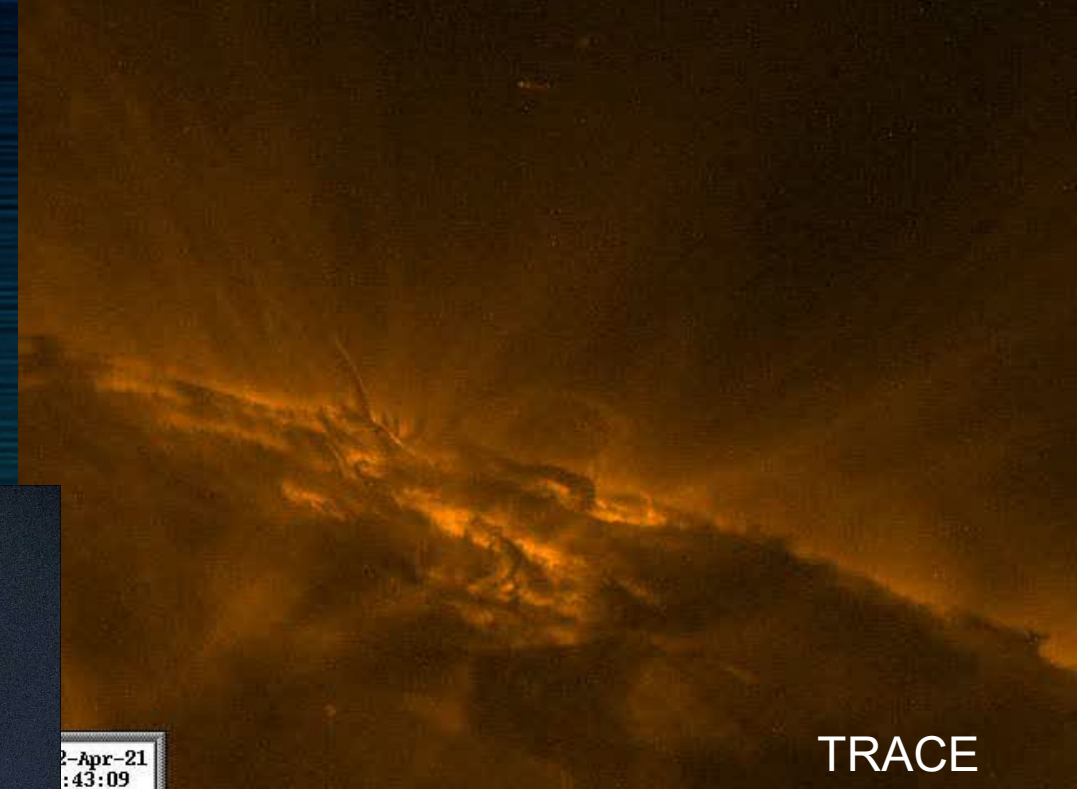
Active region dynamics
(gas around 1 million K)
AIA Fe XII 193 Å



The violent Sun

Flare

Coronal mass ejection
(gas between 80000 and 1 million K)



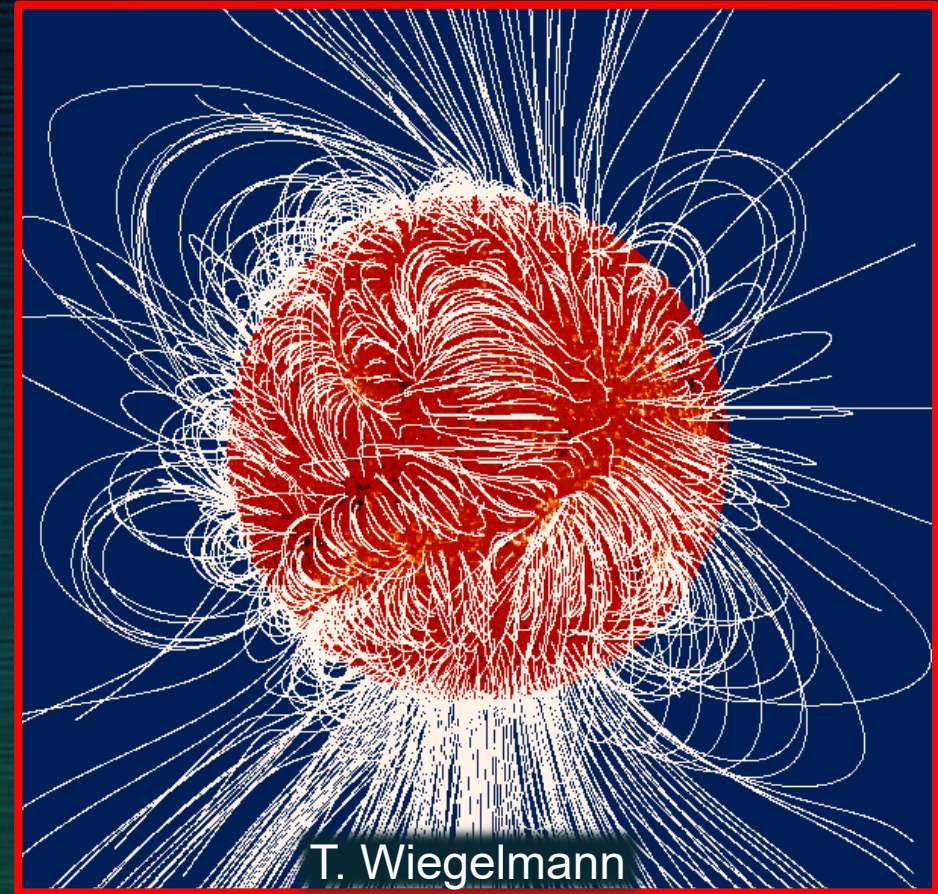
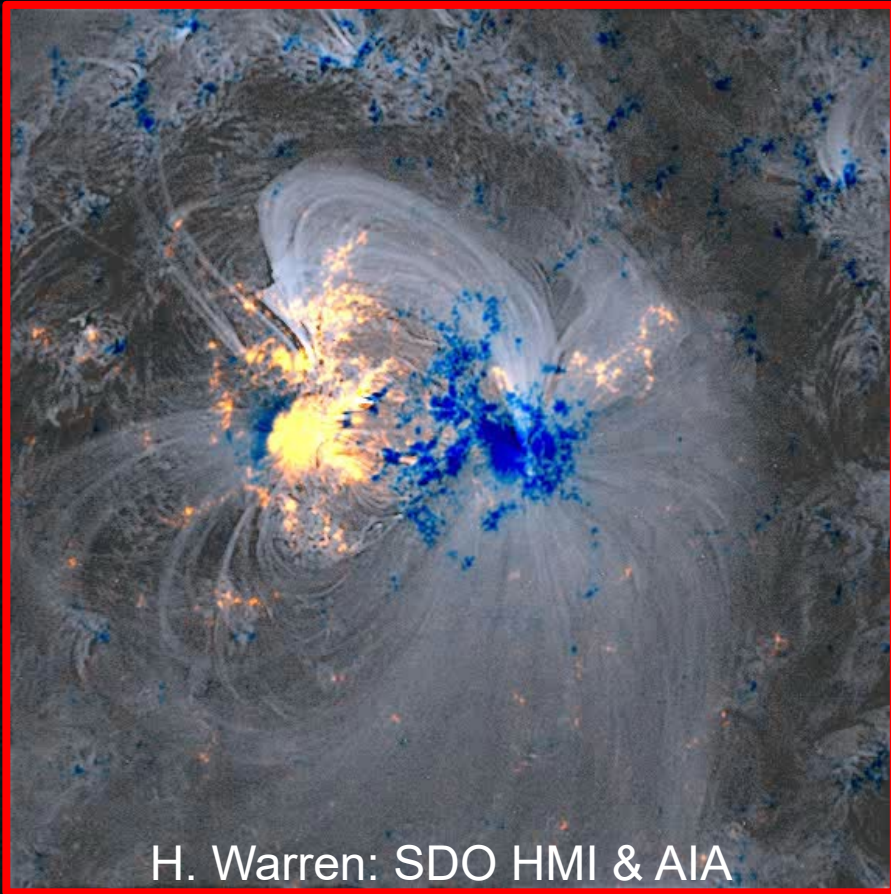
TRACE

The active phenomena of our dynamic and violent star, the Sun, are prototypical of activity throughout the Universe

SDO/AIA, M. Druckmüller



Solar dynamics and activity: driven by its Magnetic Field



- Magnetic field stores & transports energy that heats the corona & drives flares etc.
- Sun's open magnetic flux guides escaping particles and populates the solar wind

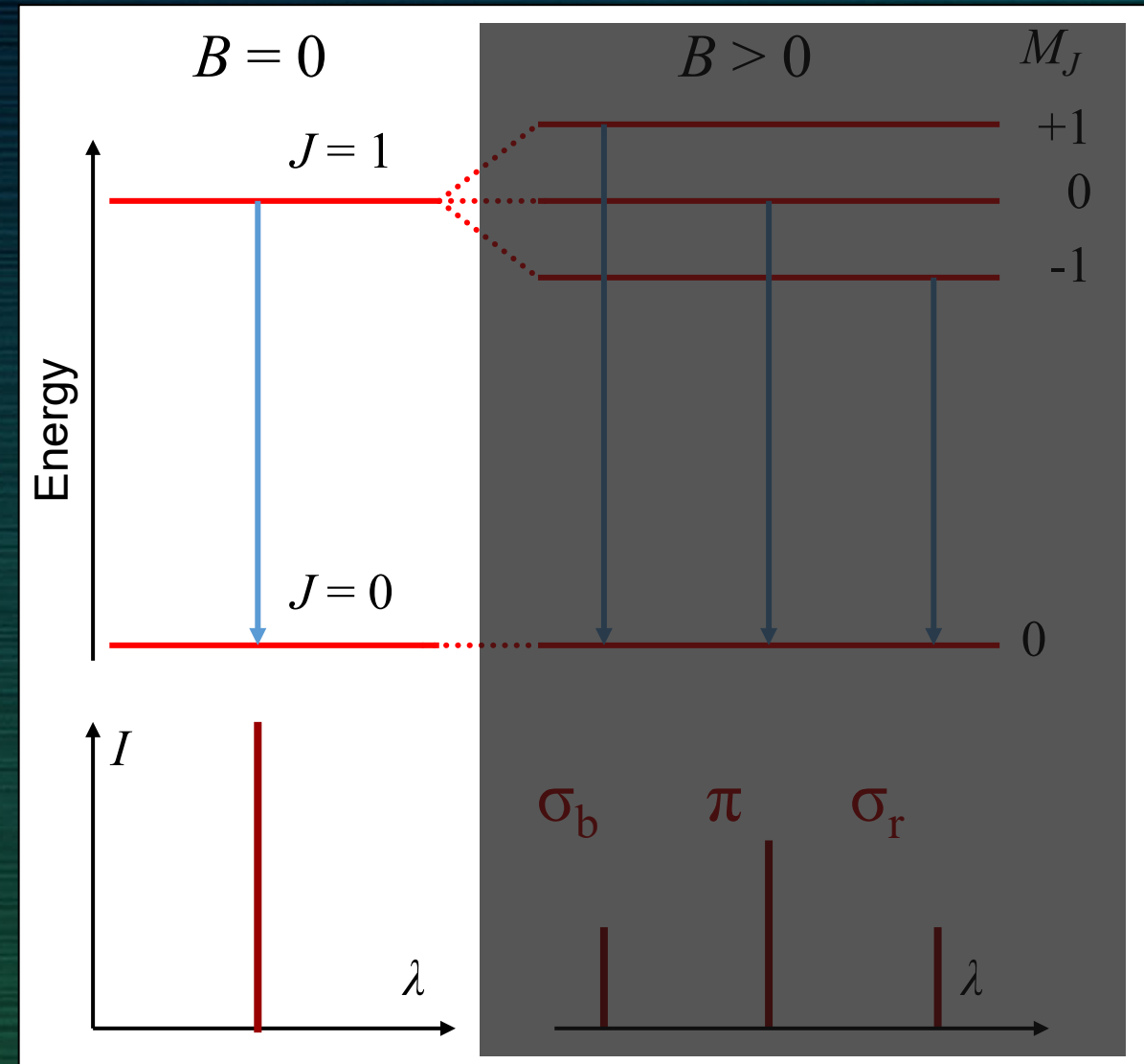


Measuring solar magnetic field: Zeeman splitting of atomic levels

- In a B -field a level with total angular momentum J splits into $2J+1$ sub-levels with different M
- $E_{J,M} = E_J + \mu_0 g M_J B$
- Transitions are allowed between levels with $\Delta J = 0, \pm 1$ & $\Delta M = 0$ (π), ± 1 (σ_b, σ_r)

- Splitting is determined by Landé factor g :

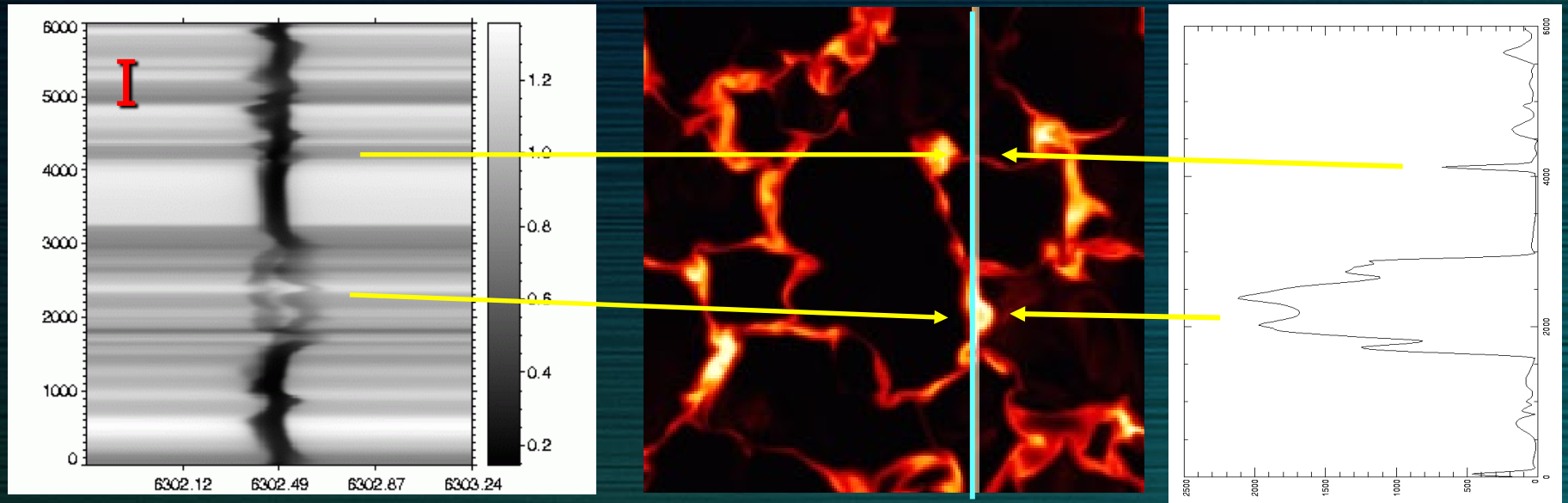
$$g(J, L, S) = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$





Zeeman effect in photospheric spectral lines

Fe I 630.2 nm

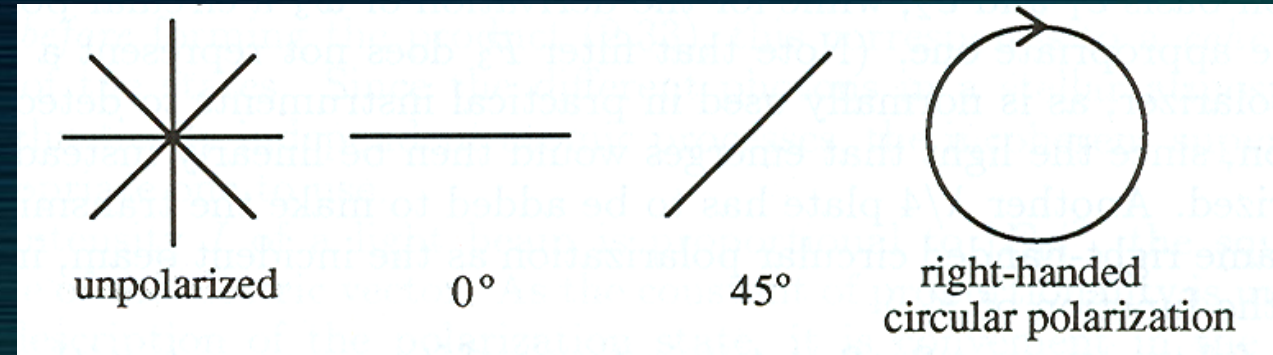


- On Sun: Complete Zeeman splitting usually only in sunspots
 - Outside spots splitting is often subtle, difficult to measure
 - Often easier to detect Zeeman effect through its **unique** polarization signature
- ➔ Measurement of polarization is central to measuring solar magnetic fields

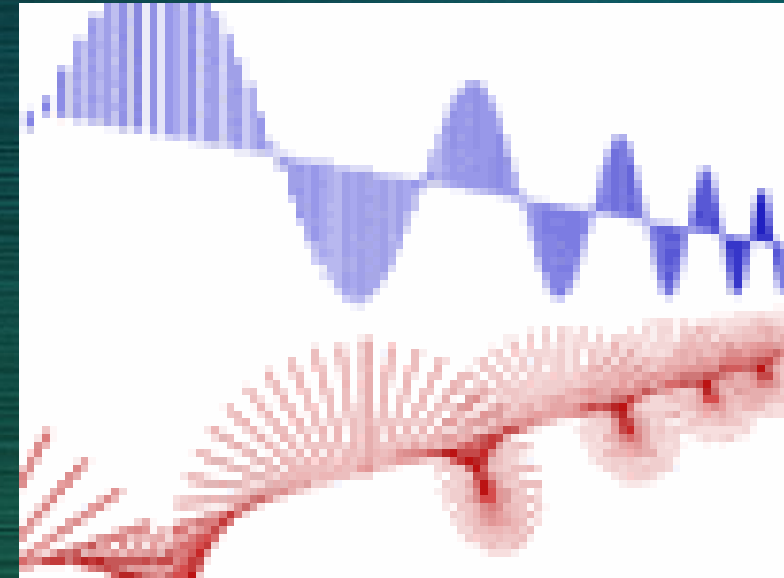


Polarized radiation

- Zeeman splitting often too small on Sun
- Main signature of B is polarisation
- Polarized radiation is described by the 4 **Stokes parameters: I , Q , U and V**



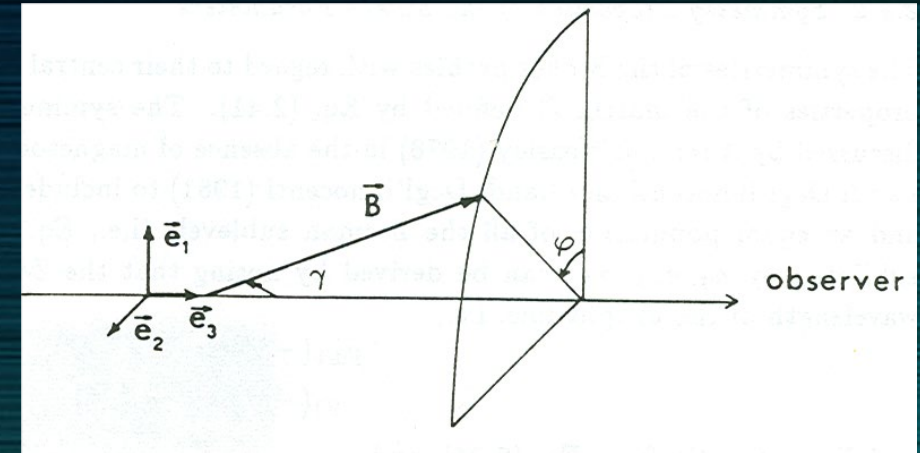
- I = total intensity = sum of all polarisations
- $Q = I_{\text{lin}}(0^\circ) - I_{\text{lin}}(90^\circ)$
- $U = I_{\text{lin}}(45^\circ) - I_{\text{lin}}(135^\circ)$
- $V = I_{\text{circ}}(\text{right}) - I_{\text{circ}}(\text{left})$
- Note: **Stokes parameters** are sums and differences of intensities, i.e. they are **directly measurable**



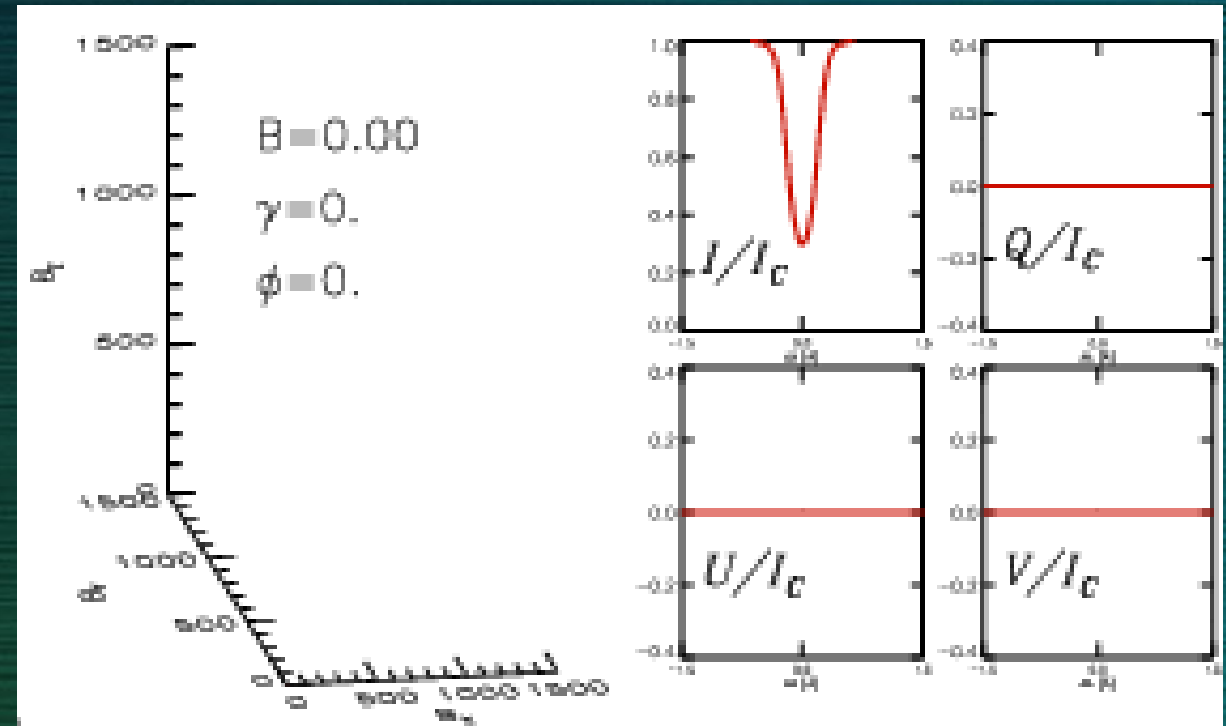


Dependence on B , γ , and φ

- $I \sim \kappa_\sigma (1 + \cos^2 \gamma) / 4 + \kappa_\pi \sin^2 \gamma / 2$
- $Q \sim B^2 \sin^2 \gamma \cos 2\varphi$ ← 180°
- $U \sim B^2 \sin^2 \gamma \sin 2\varphi$ ← ambiguity
- $V \sim B \cos \gamma$



- $V \rightarrow$ longitudinal component of B
- $Q, U \rightarrow$ transverse component of B



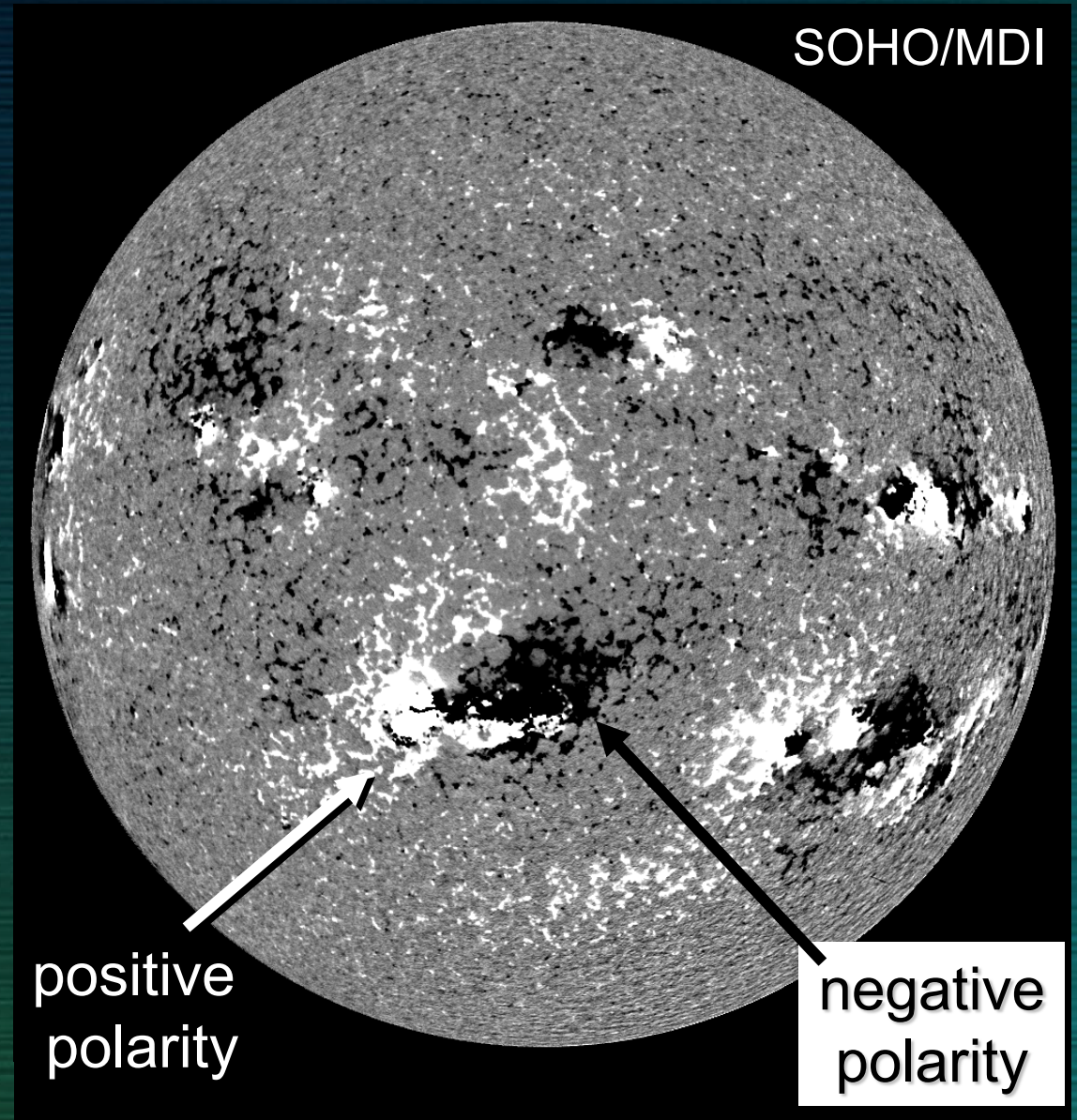
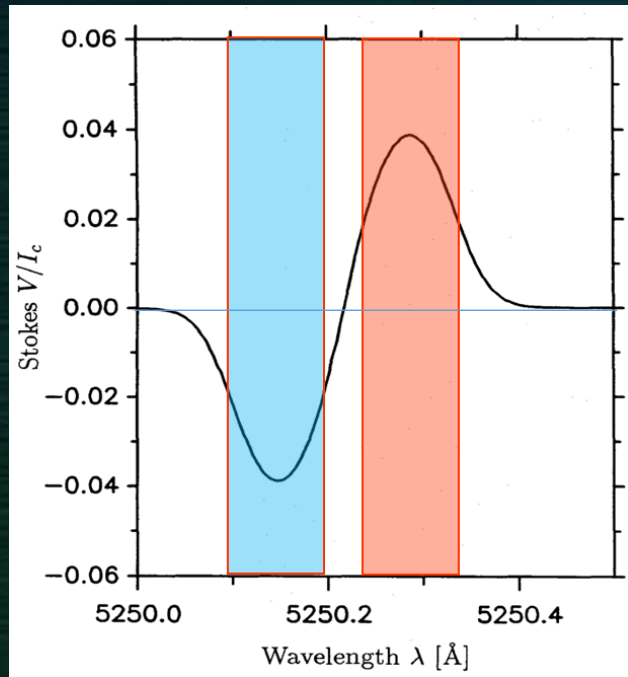
Juanma Borrero



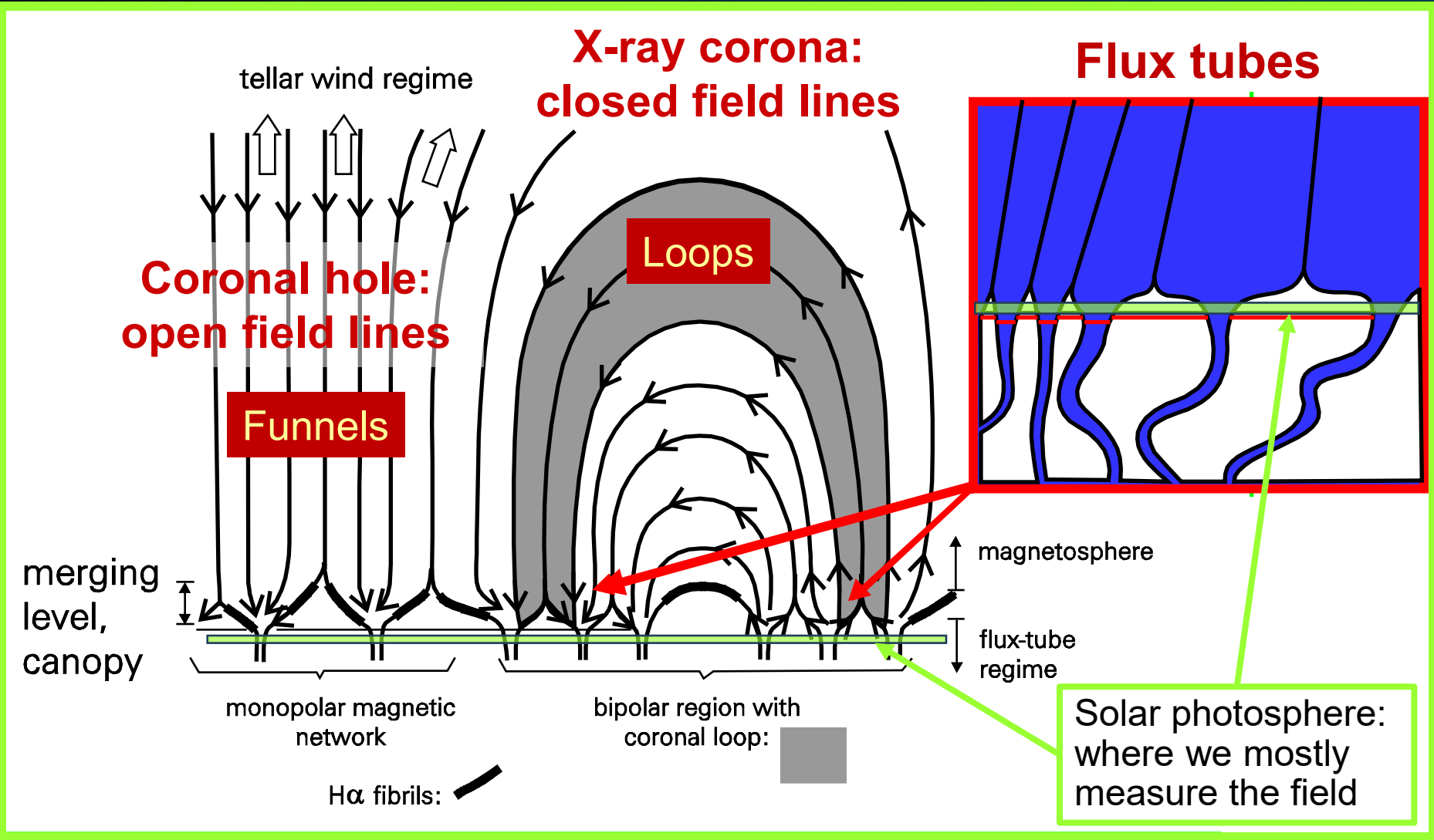
Magnetograms

- **Magnetogram:** Diff. between (net circular) polarization in the two wings of a Zeeman sensitive line, calibrated to give the LOS magnetic field

- $B_{\text{LOS}} \sim \frac{V}{dI/d\lambda}$ (weak field approximation)

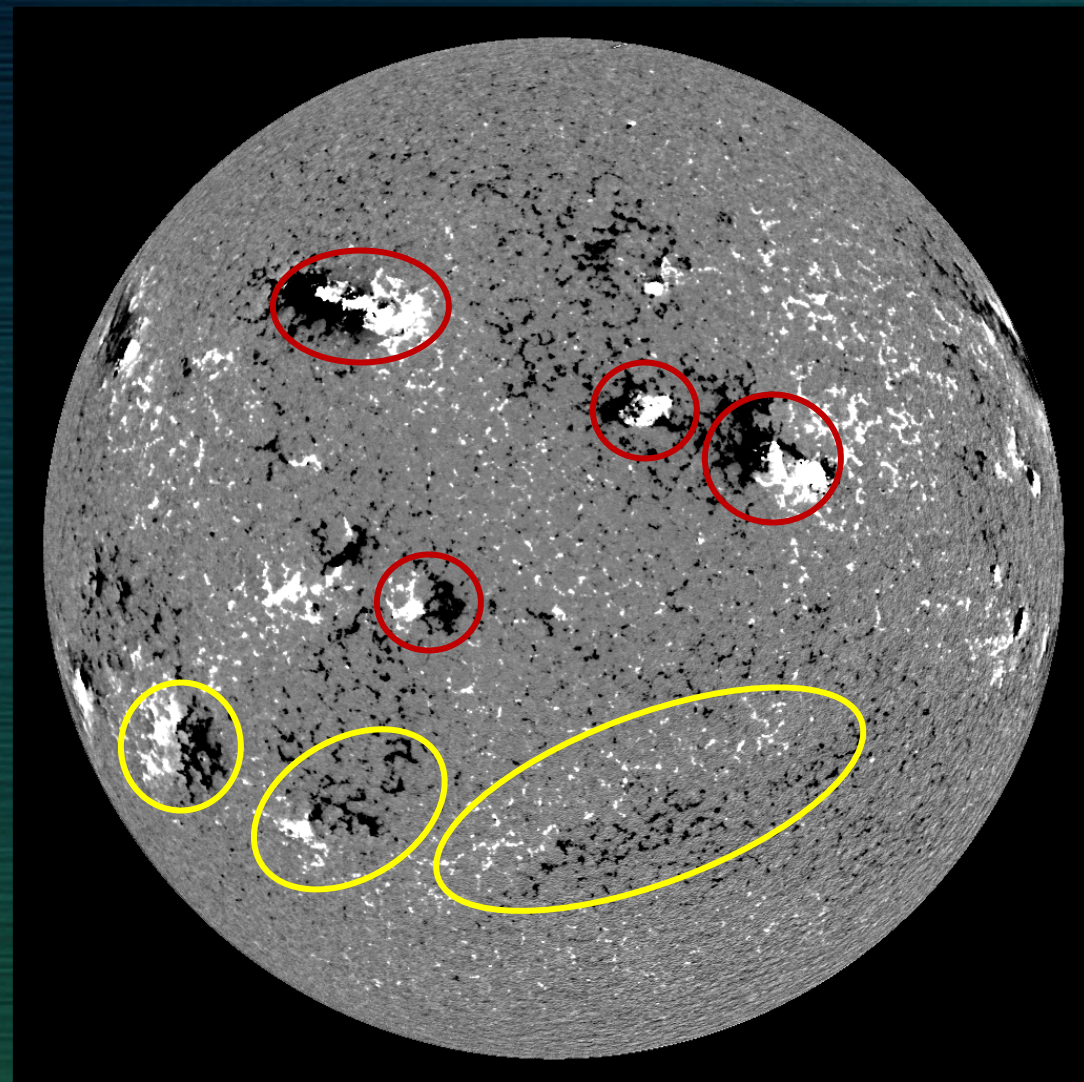


Flux tubes, canopies, loops & funnels



Life cycle of magnetic field

- Magnetic field emerges from interior as compact bipolar structures, e.g. young active regions: **red ovals**
- Convective flows cause the two polarities to diffuse & drift apart. They also cancel with time
- As active regions age, they become larger, more diffuse, weaker: **yellow circles**
- It is impossible to follow the life cycle of an active region fully from one vantage point, as they typically live more than half a solar rotation period



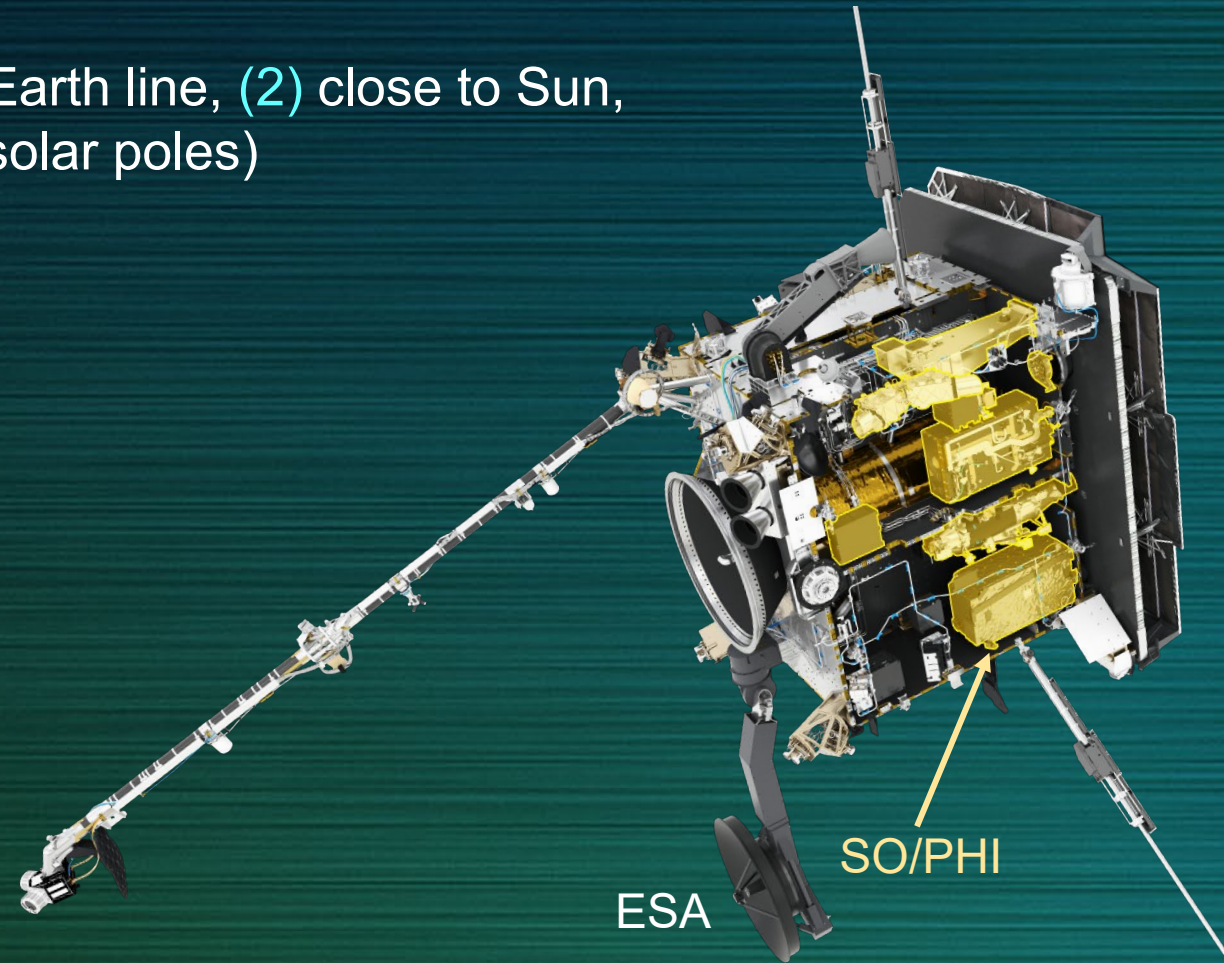


Overview Solar Orbiter

- ESA/NASA mission carrying 6 remote sensing & 4 in situ instruments
- Launched 2020, entered nominal mission phase Dec. 2021
- Highly elliptical orbit bringing it (1) far from Sun-Earth line, (2) close to Sun, and (3) out of ecliptic (i.e. giving it a view of the solar poles)



ESA



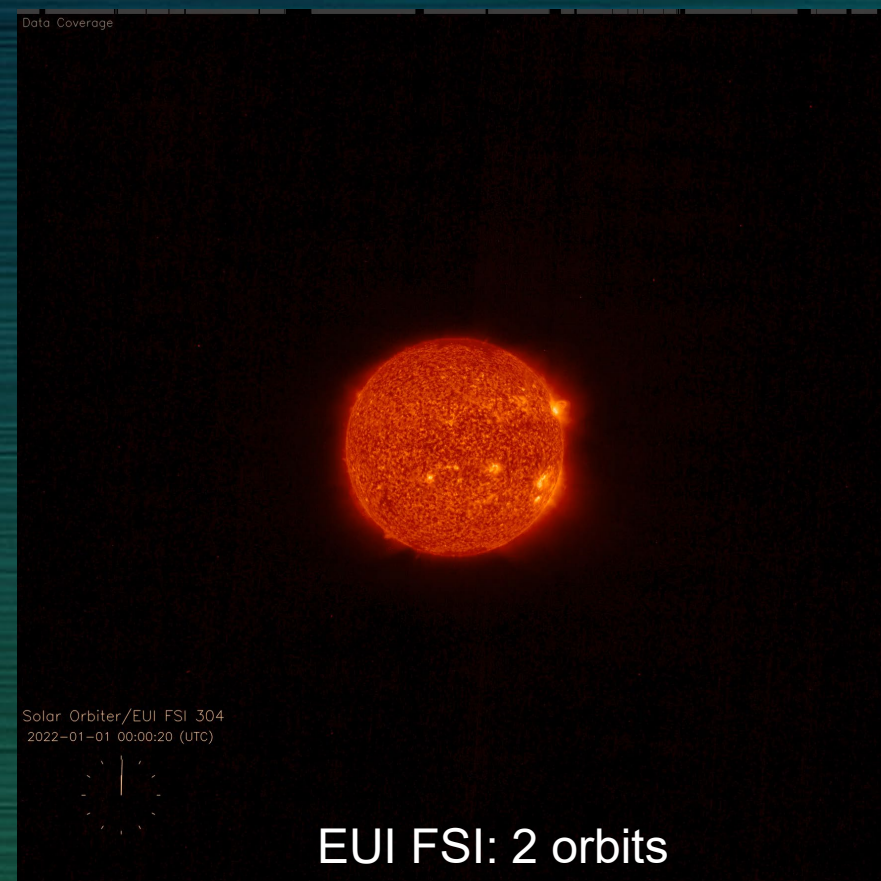
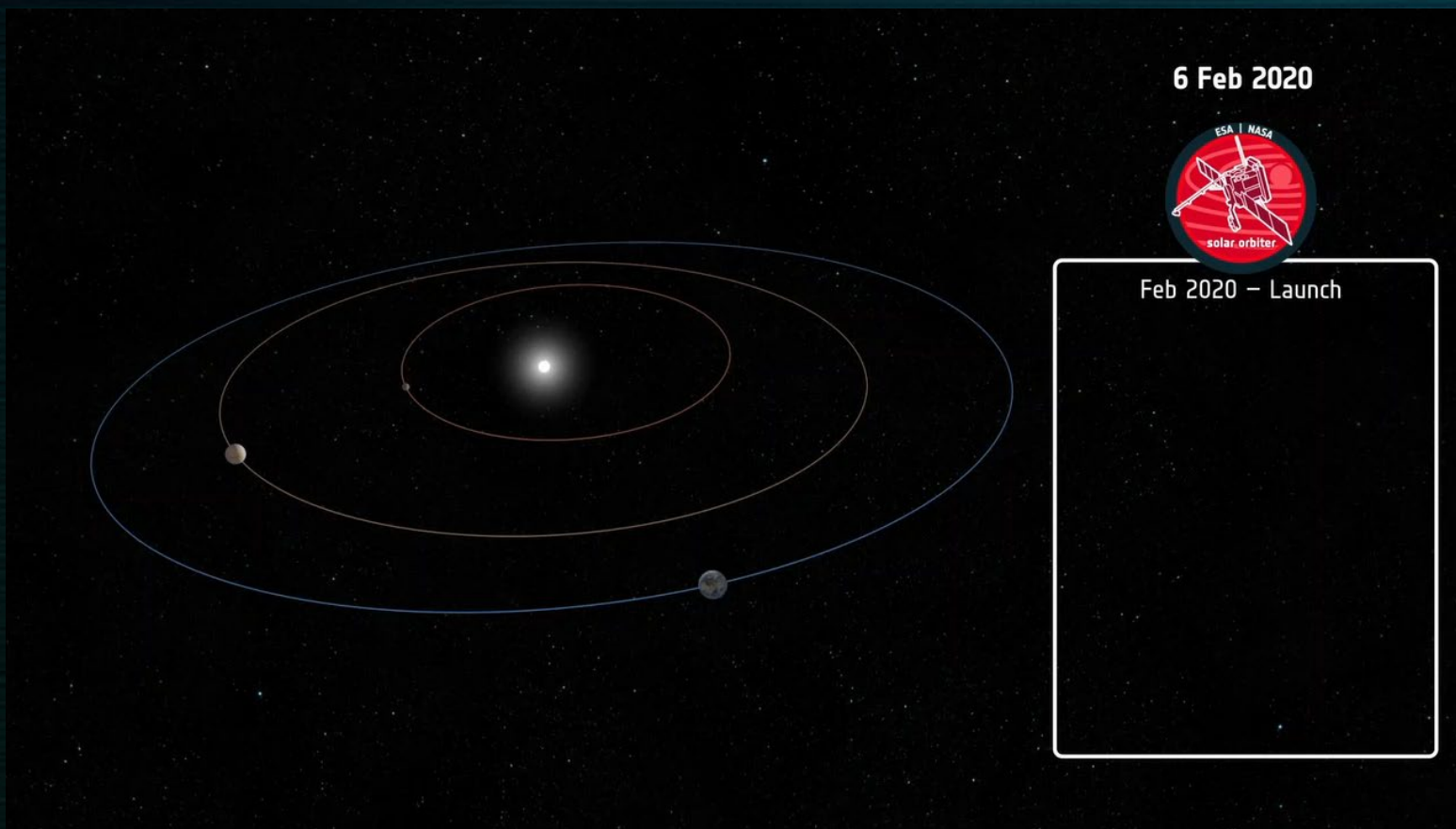
ESA

SO/PHI



Solar Orbiter's unique orbit

- Solar Orbiter's orbit brings it:
 - far from the Sun-Earth line
 - close to the Sun
 - out of the ecliptic





Overview SO/PHI: Polarimetric and Helioseismic Imager

SO/PHI is a tunable, imaging vector spectro-polarimeter with two telescopes. First magnetograph to leave Sun-Earth line

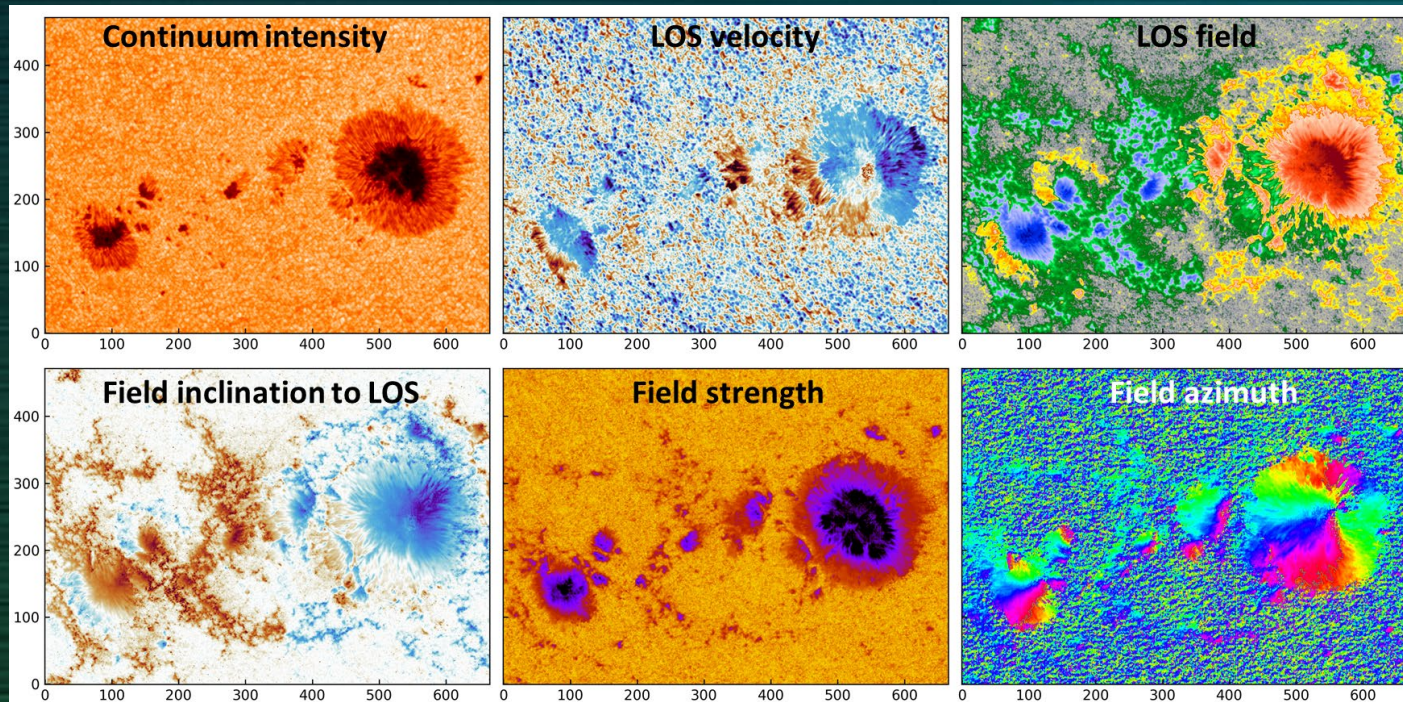
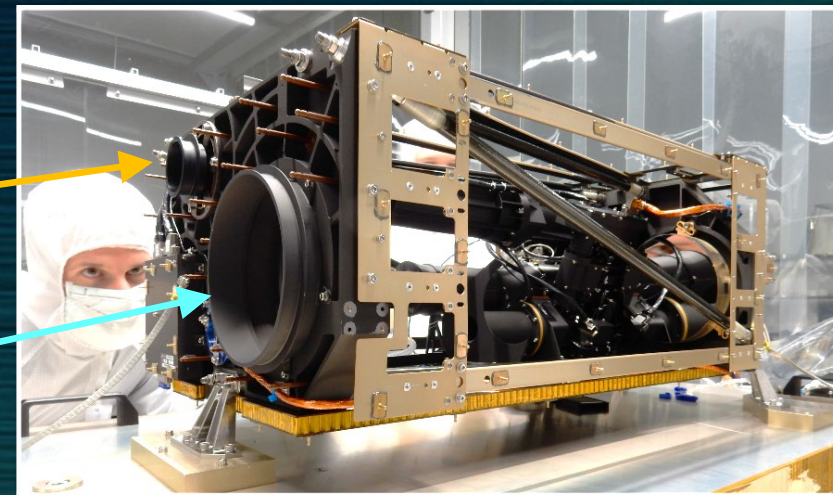
Full Disk Telescope:

- images entire solar disk at all orbital phases

High Resolution Telescope:

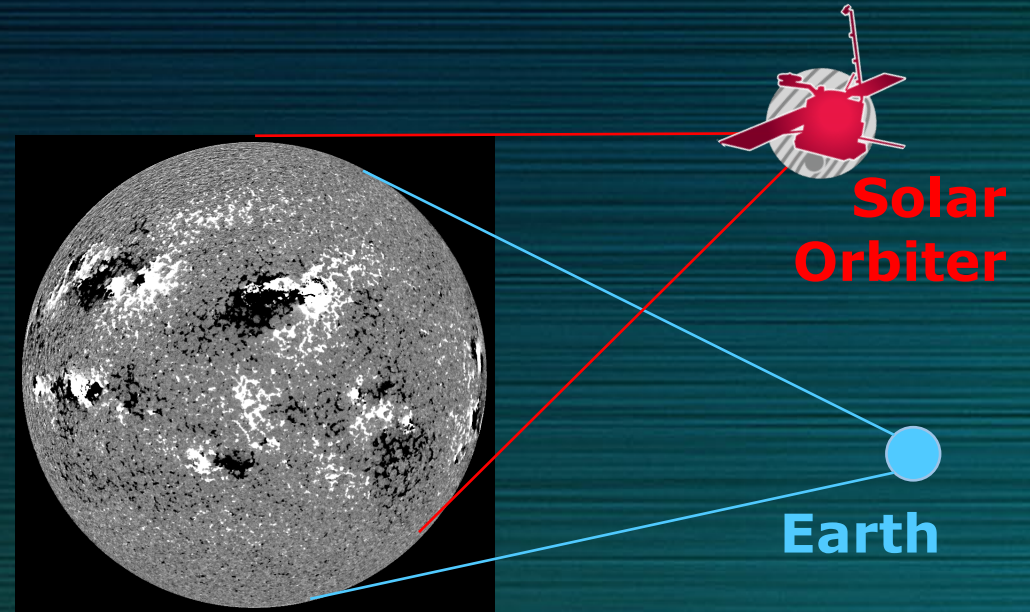
- max. resolution (at 0.28 AU): 200km
- Spectral line: Fe I 6173 Å (same as SDO/HMI)
- PHI measures magnetic vector, LOS velocity, continuum intensity

Instrument paper: Solanki et al. (2020)
A&A 642, A11



Looking at the same point on the Sun from two directions

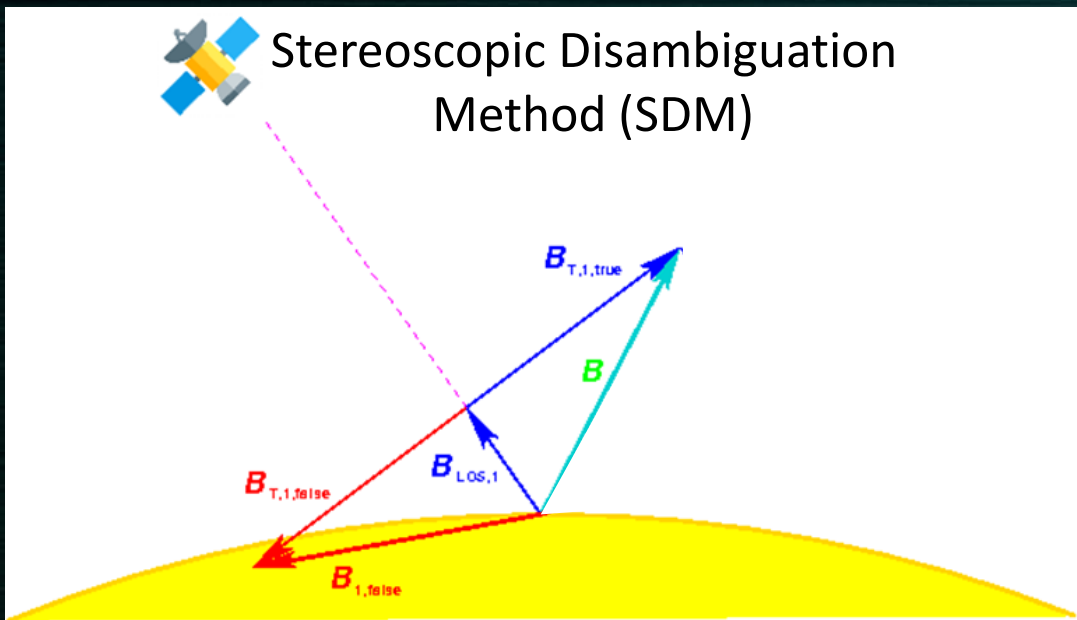
- Part of every orbit, Solar Orbiter and instruments on or around Earth can see the same features on the Sun, but from different directions
- This opens possibilities to
 - do **stereoscopy** (i.e. determine 3D structure of solar surface)
 - use the Doppler effect to determine **two components of velocity** (instead of just one)
 - **resolve the 180° ambiguity** of the transverse magnetic field introduced by the Zeeman effect



Excellent cross-calibration between PHI and other magnetographs in Earth orbit, e.g. HMI and Hinode, allows their data to be combined

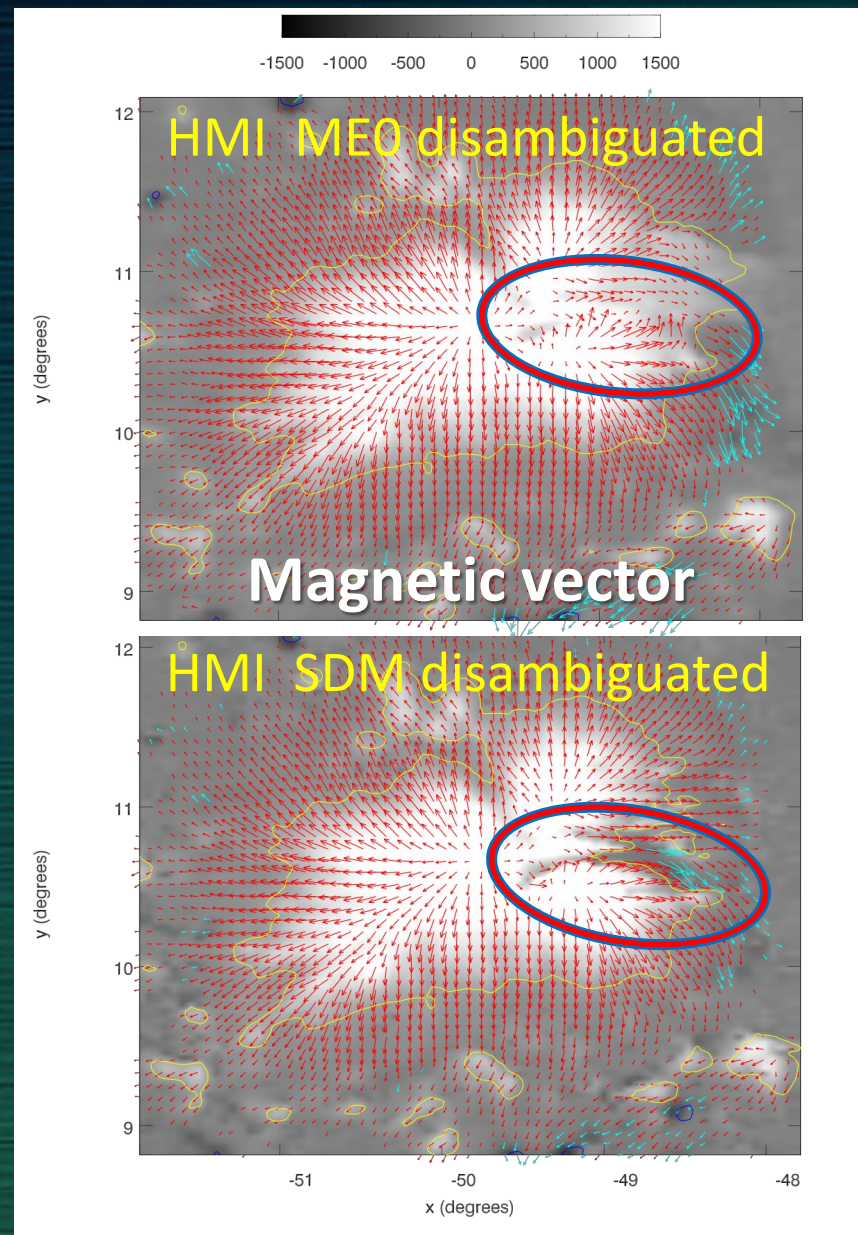
Resolving 180° ambiguity in magnetic azimuth

- Transverse field obtained from Zeeman effect has a 180° ambiguity → wrong currents, poor coronal extrapolations
- Standard techniques need assumptions about the field
- Combine PMI & HMI vector fields → better disambiguation
- Application to PHI + HMI data → improves on standard techniques in areas with excess magnetic energy



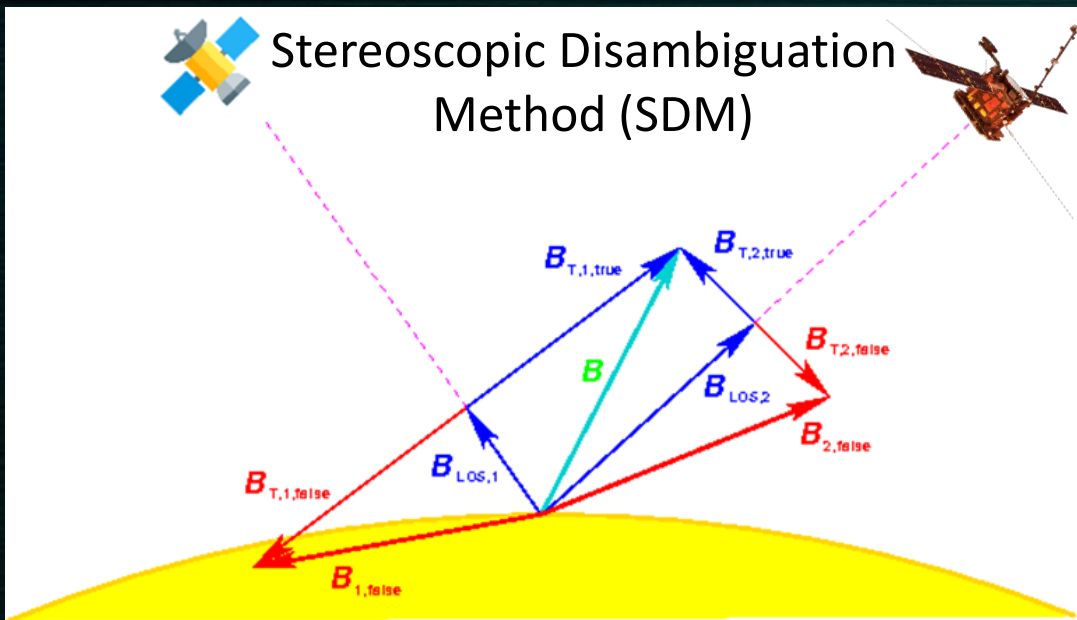
Valori et al.
2022, 2023
A&A

Xiang Li et al. in prep.



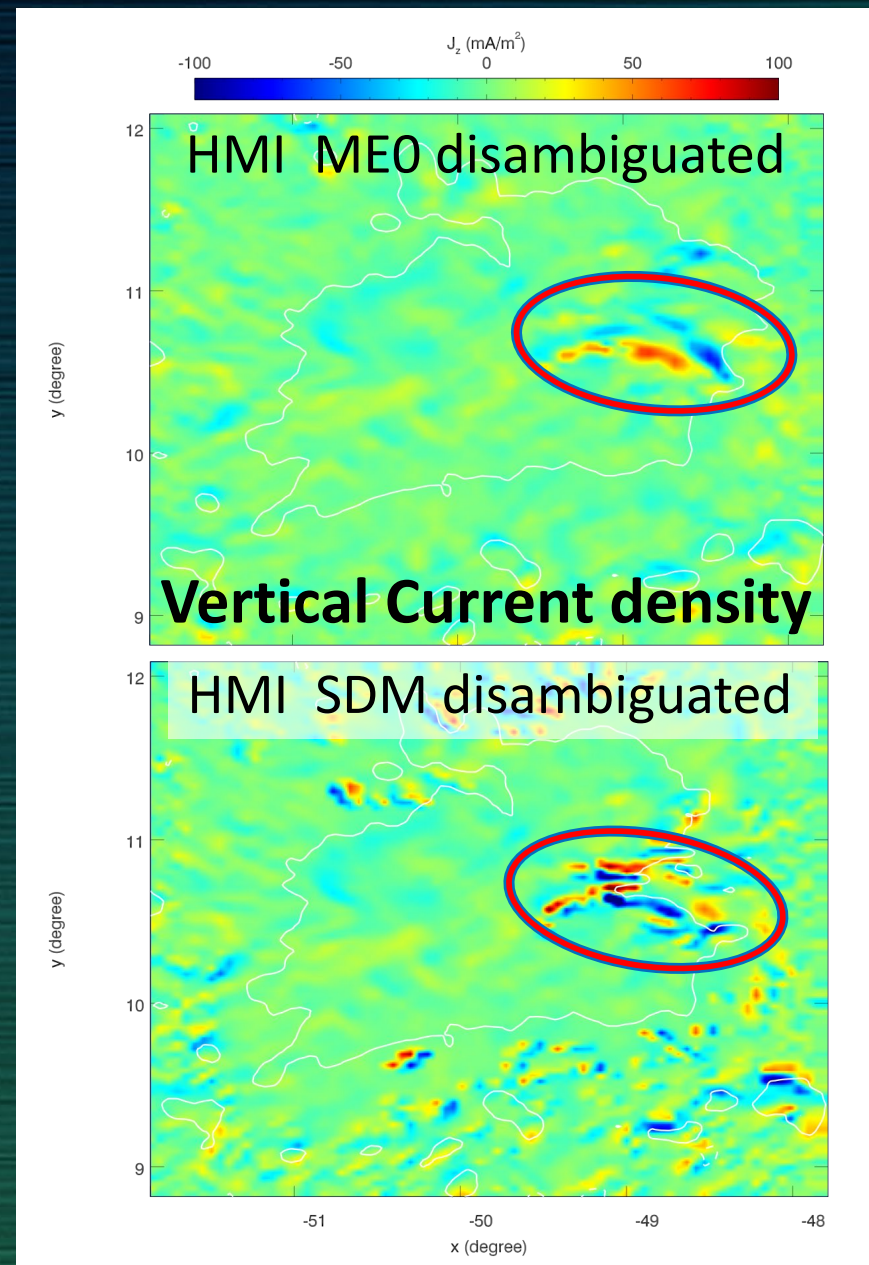
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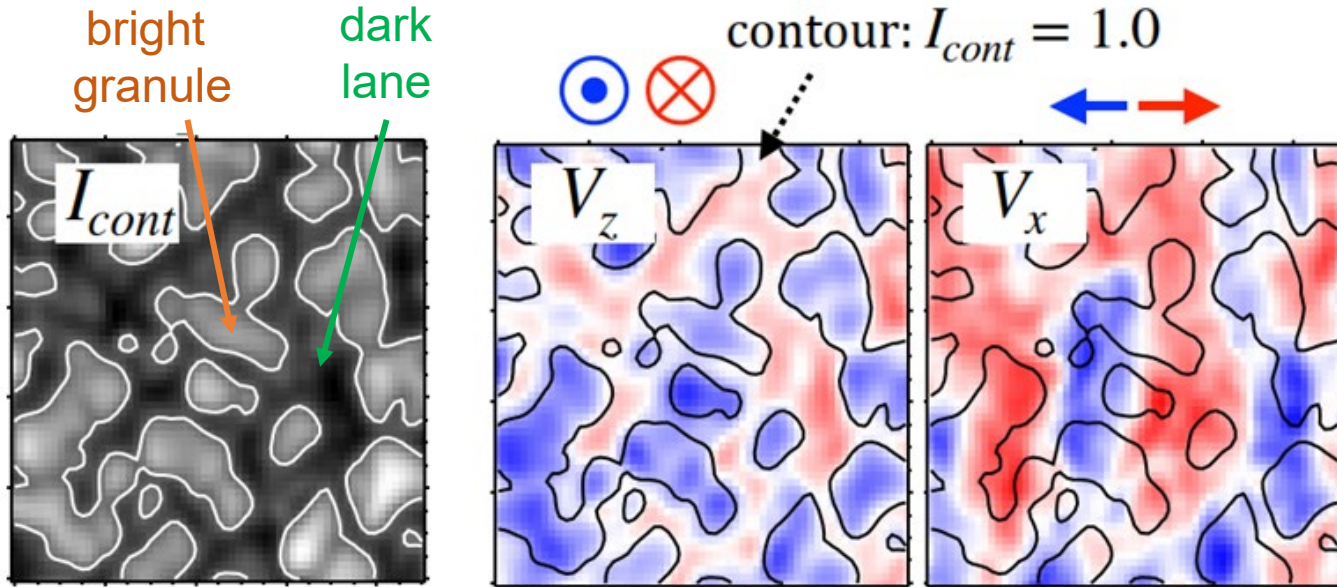


Valori et al.
2022, 2023
A&A

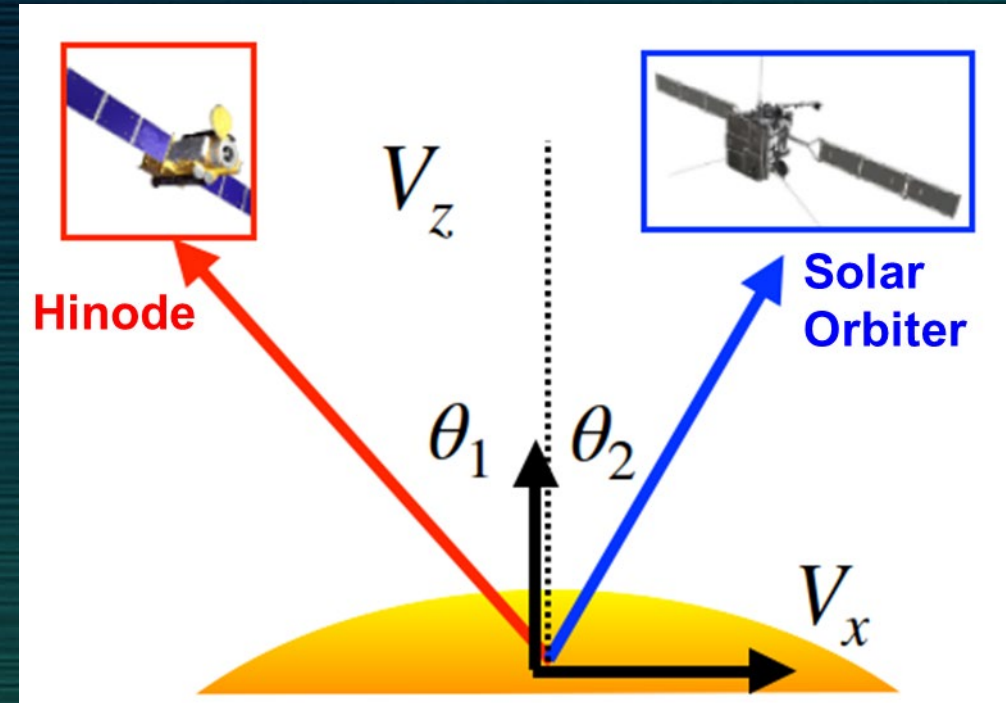
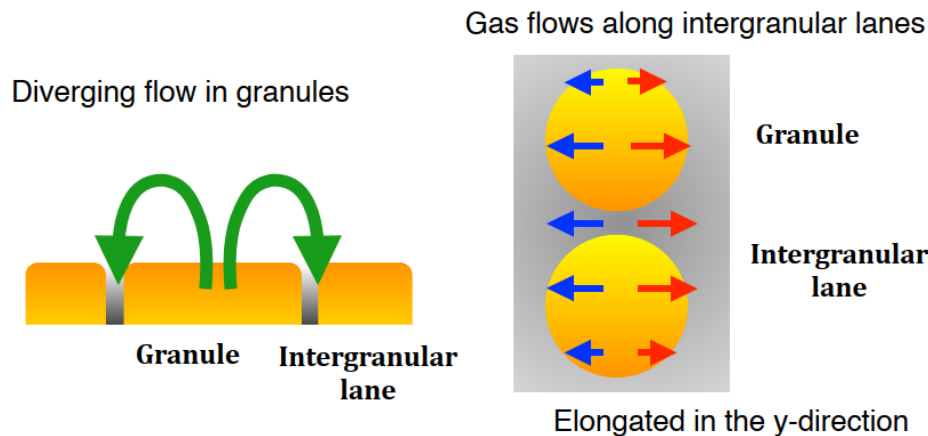
Xiang Li et al. in prep.



Vertical and horizontal velocity in granulation



Horizontal velocities at sub-granular scales are not accessible to tracking

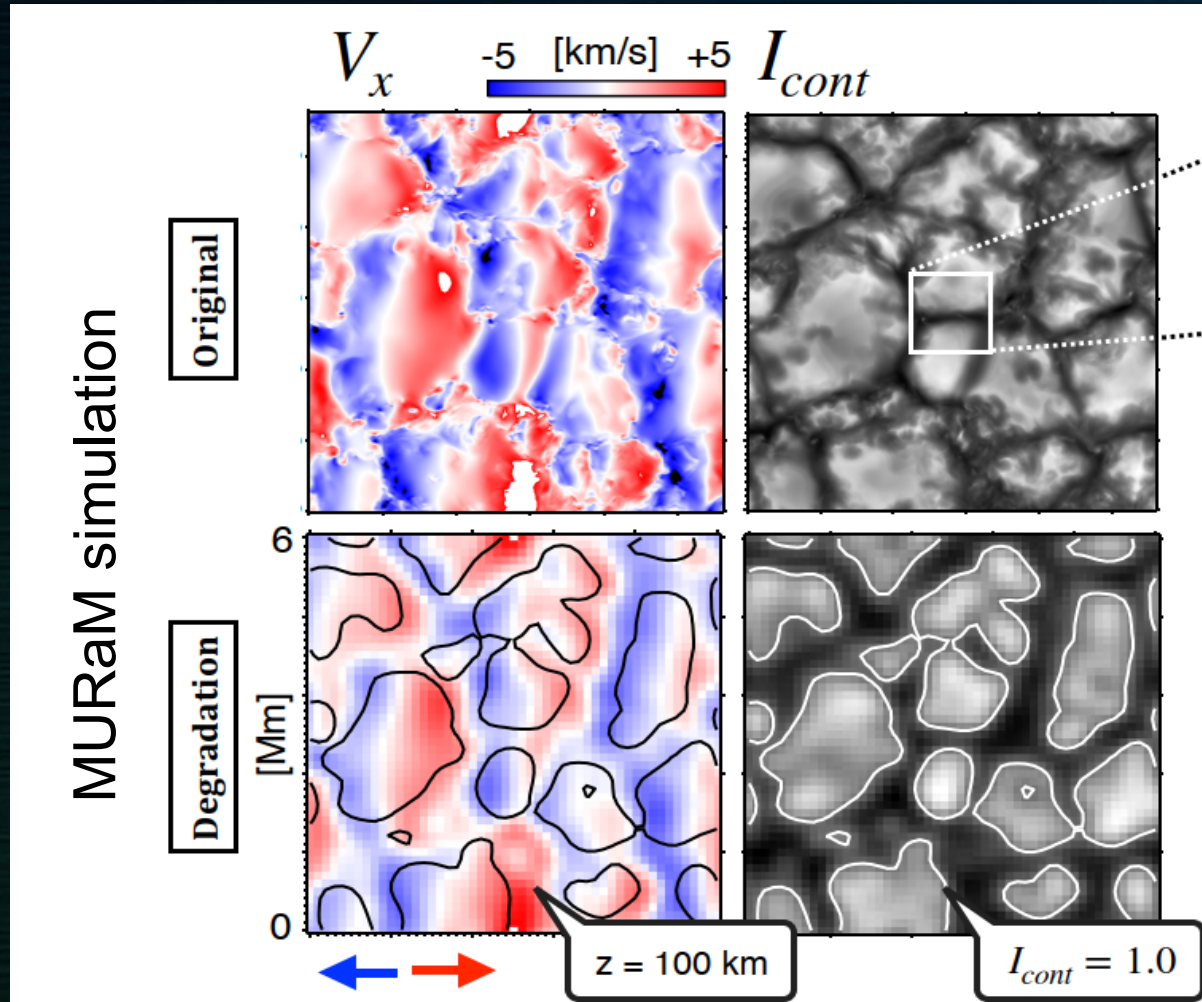


Structured on mesogranular scales: Real or artefact?

→ Check by comparing with MURaM MHD simulations

Takayoshi Oba et al. in prep

Vertical and horizontal velocity in granulation



As expected:

- Upflows in granules, downflows in lanes
- Horizontal flow diverges from centres of granules

Surprise:

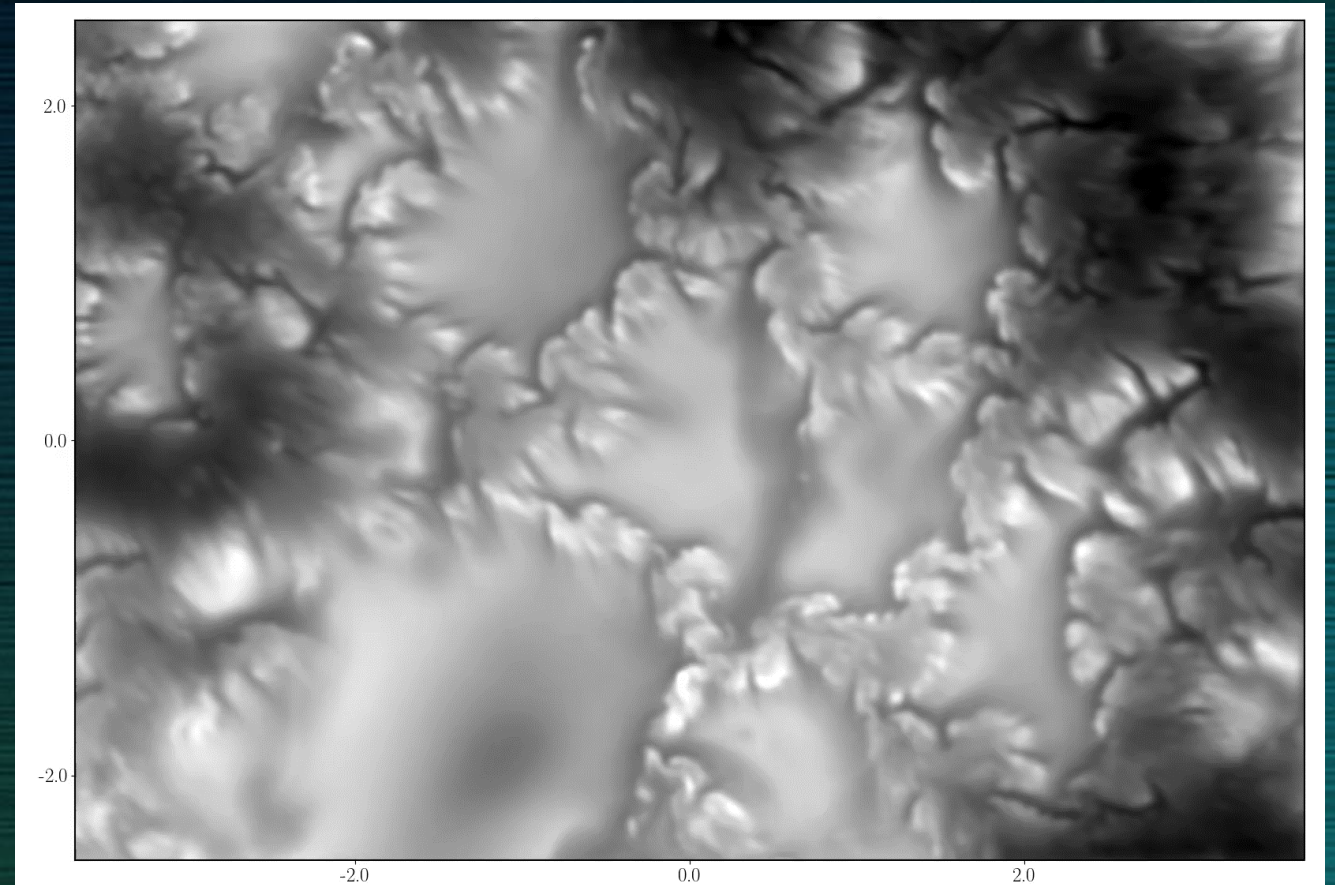
- Horizontal flow extends into intergranular lanes
 - Structured on mesogranular scales: Real or artefact?
- Supported by MHD simulations with MURaM code

Effects of horizontal flows: ubiquitous instabilities



Daniel K. Inouye Solar Telescope (DKIST) in Hawaii: largest solar telescope in world → highest resolution of 19 km on Sun

Kuridze et al. Nature, under review



Shows ubiquitous Kelvin-Helmholtz instability at edges of magnetic features: produced by horizontal flows in the intergranular lanes moving past magnetic features

Wilson depression of sunspots



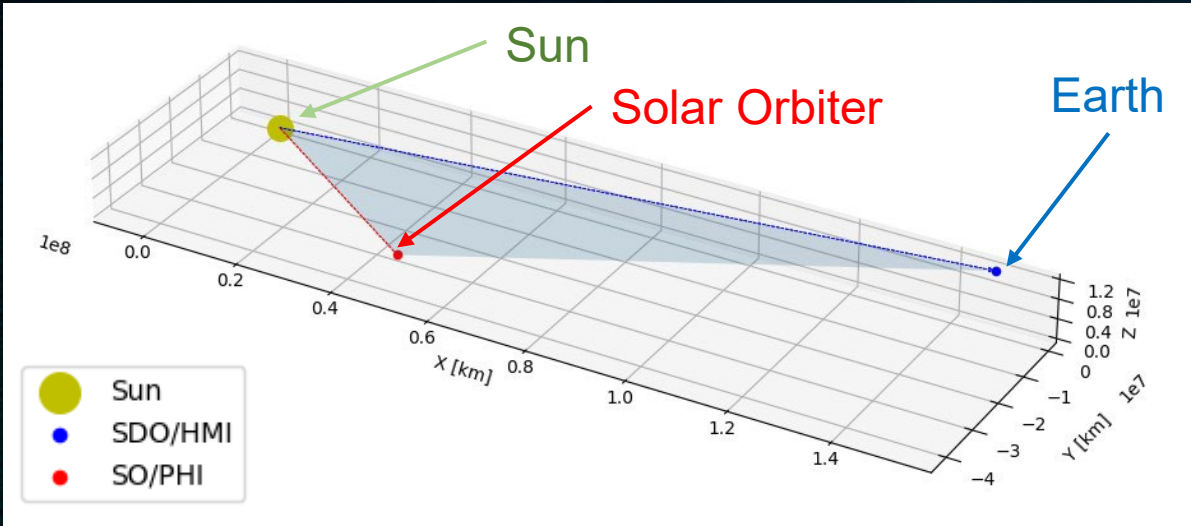
The Wilson effect shows that even very symmetric sunspots look asymmetric near the limb.

Simplest explanation: we can see deeper into sunspot umbrae than the surrounding quiet solar surface

Physical explanation: pressure balance in sunspots. Because of the pressure exerted by the strong field in the sunspot, the gas pressure and hence the gas density is lower

→ Wilson depression

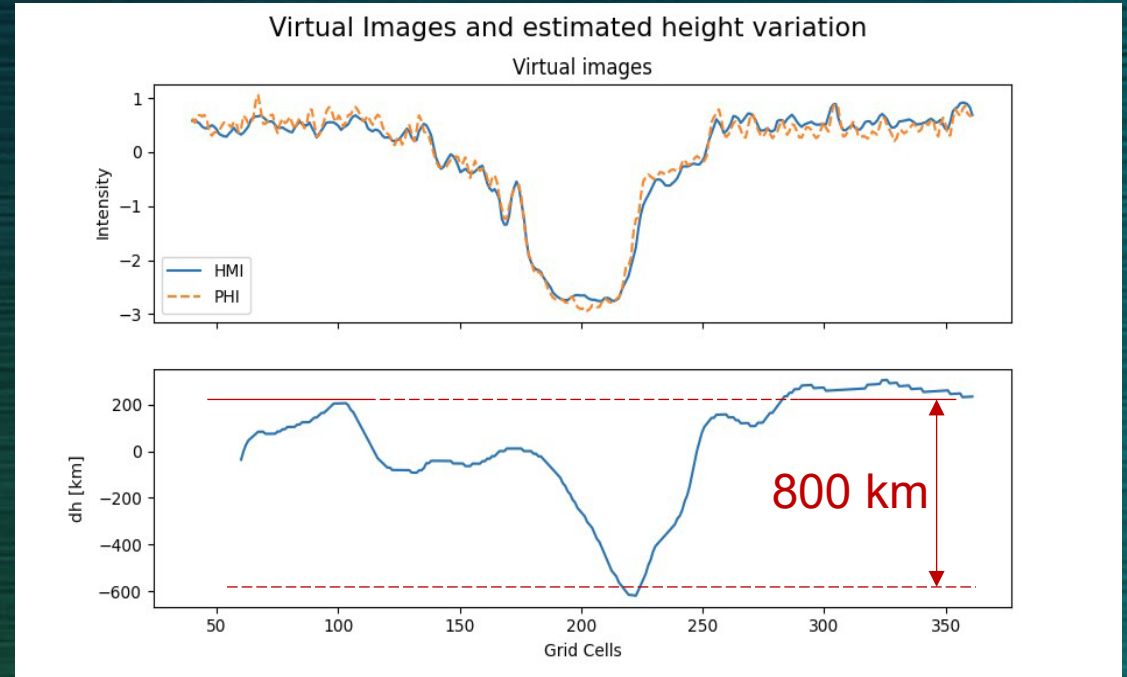
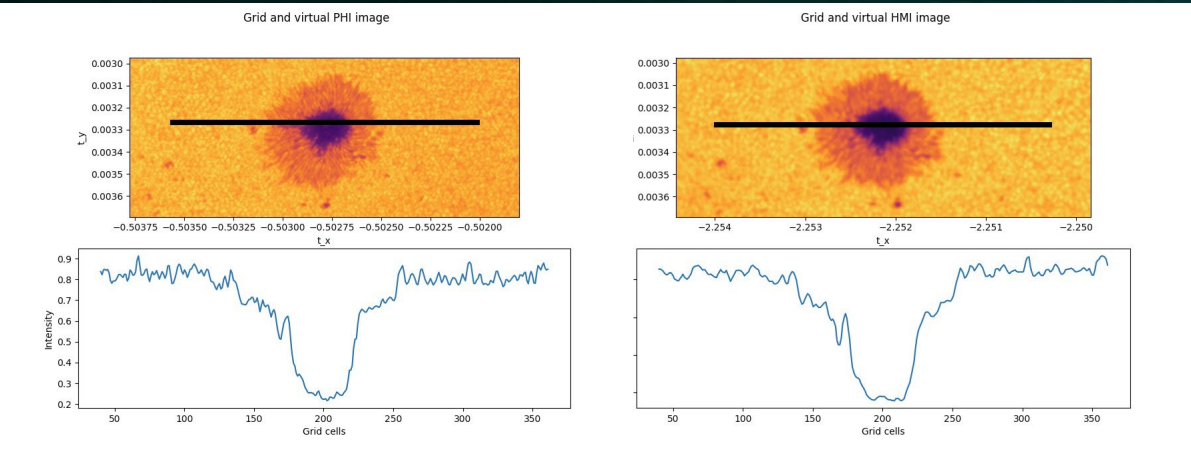
Wilson depression of sunspots



Stereoscopy of sunspots: Determine Wilson depression without extra assumptions on spot

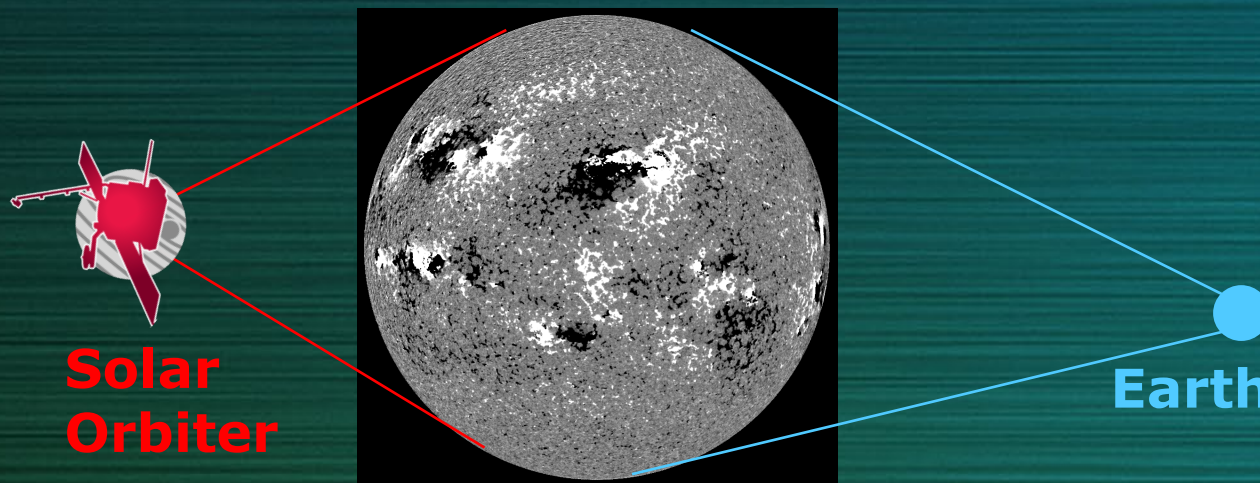
Combine SO/PHI and HMI data:

→ First ever direct measurement of the Wilson depression of a sunspot via triangulation



Looking at the solar far side

- Every orbit, Solar Orbiter spends some time on the far side of the Sun
- New science opportunities :
 - Measure the field on far side and on near side at same time → make faster, more reliable synoptic maps → improved extrapolated coronal and heliospheric magnetic field
 - Follow active regions, sunspots etc. for longer without long interruptions → better evolution studies
 - Test far-side helioseismology

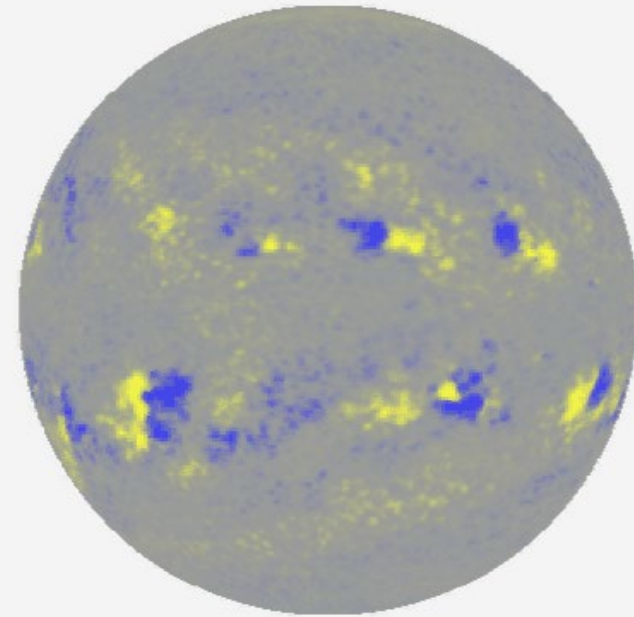


Synoptic charts and solar cycle

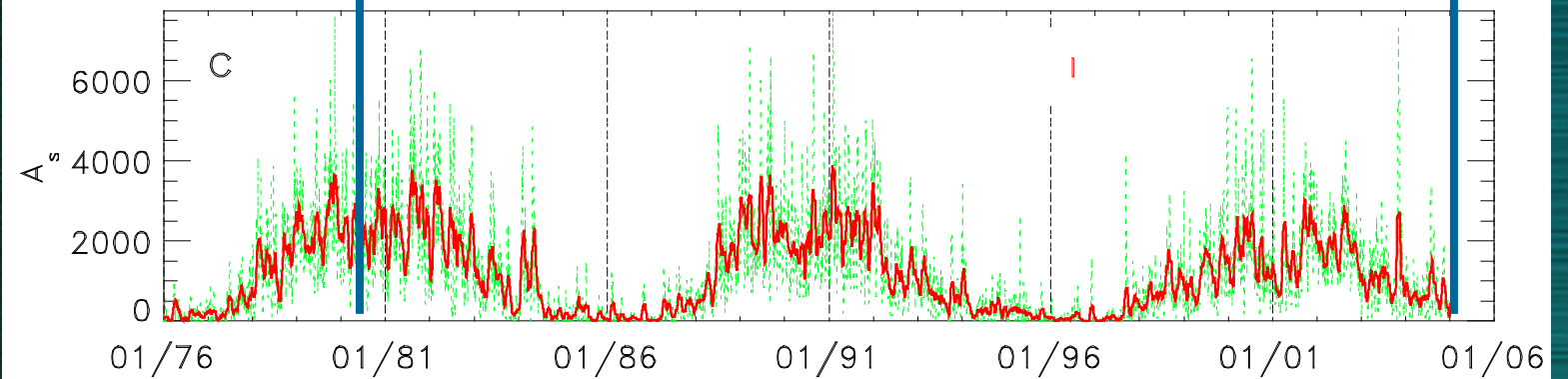
- Synoptic maps showing evolution of field over 2.5 solar cycles
- Synoptic chart is made with Sun's average rotation rate: features at small latitudes move faster, at high latitudes slower

On right: Evolution of sunspot areas over the same period of time

D. Hathaway



Sunspot areas





Multi-viewpoint: improved synoptic maps



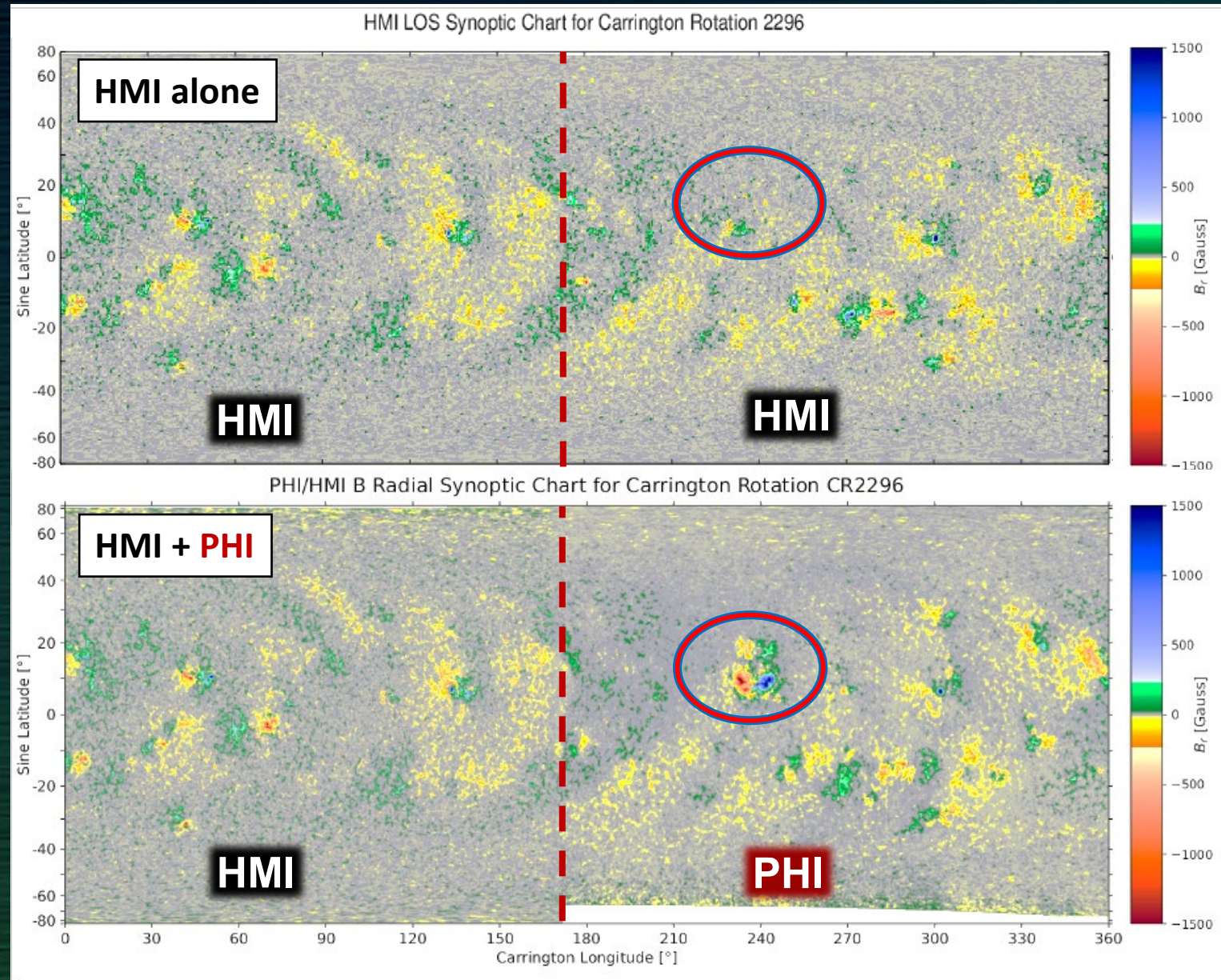
Example synoptic maps produced by HMI alone and by combining HMI + PHI

Note new AR that appeared on Sun's far side and was missed by HMI

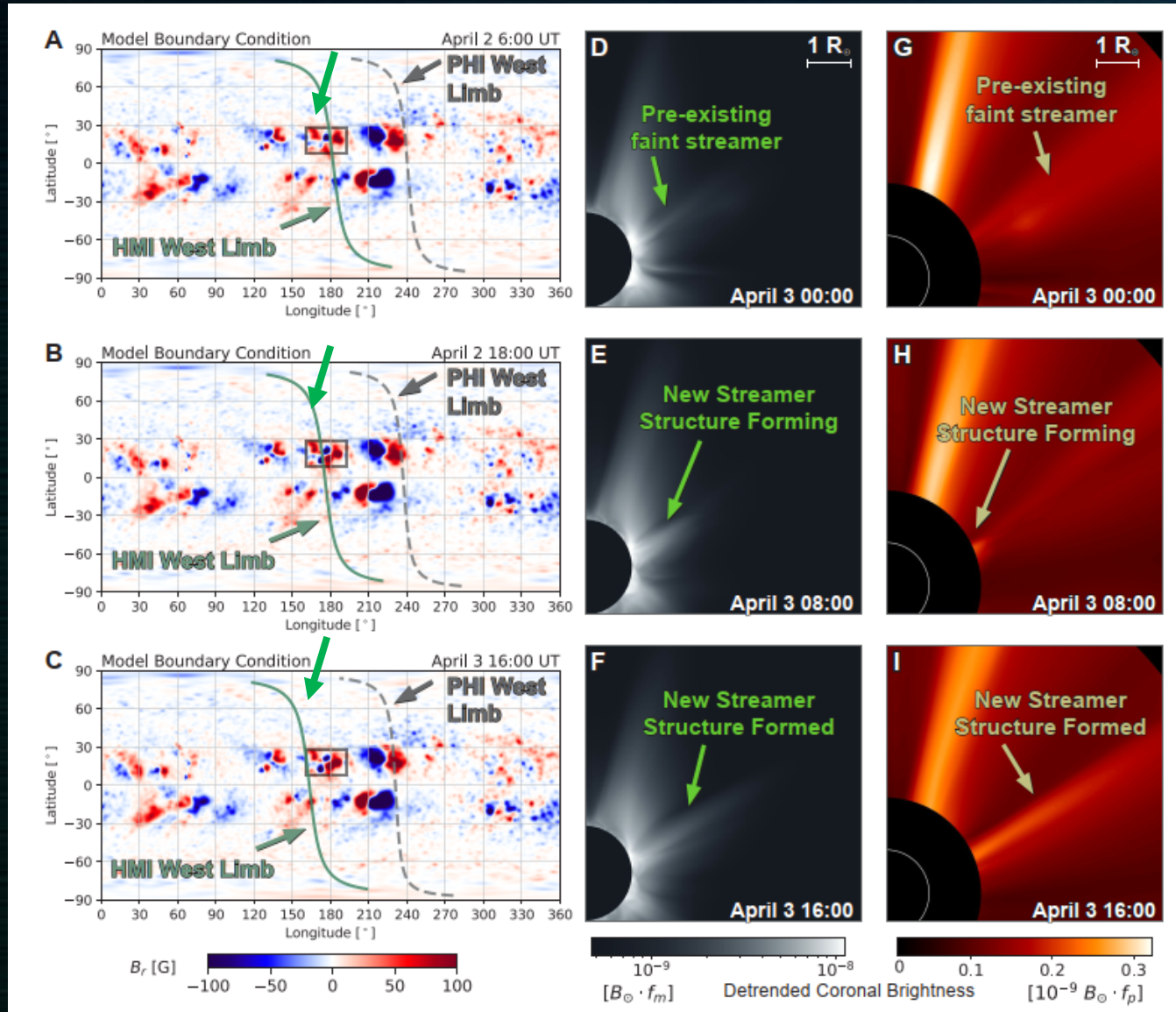
Pole filling for combined synoptic maps being worked on

CR2296 (2025-03-29 to 04-26)
took 17.9 days with HMI + PHI

Löschl et al. (2023a,b), in prep.
Francisca Ferreira Santos



SO/PHI improves predictions of coronal structure



- Predictive Science's model gave incorrect streamer structure at total solar eclipse on 2024 April 8 when using just HMI data
- PHI data taken from quadrature to Earth showed an AR had emerged just outside HMI's FOV
- Including PHI data in computations got streamer structure of the eclipse corona right

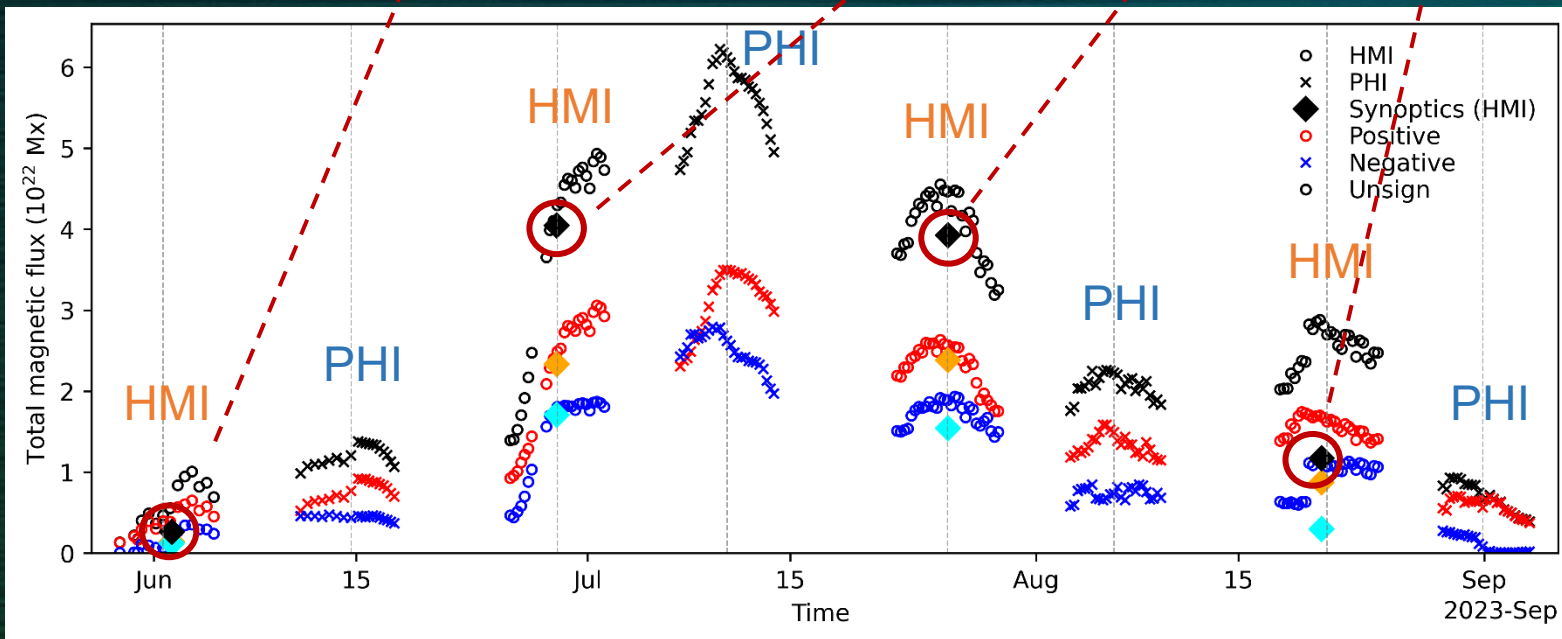
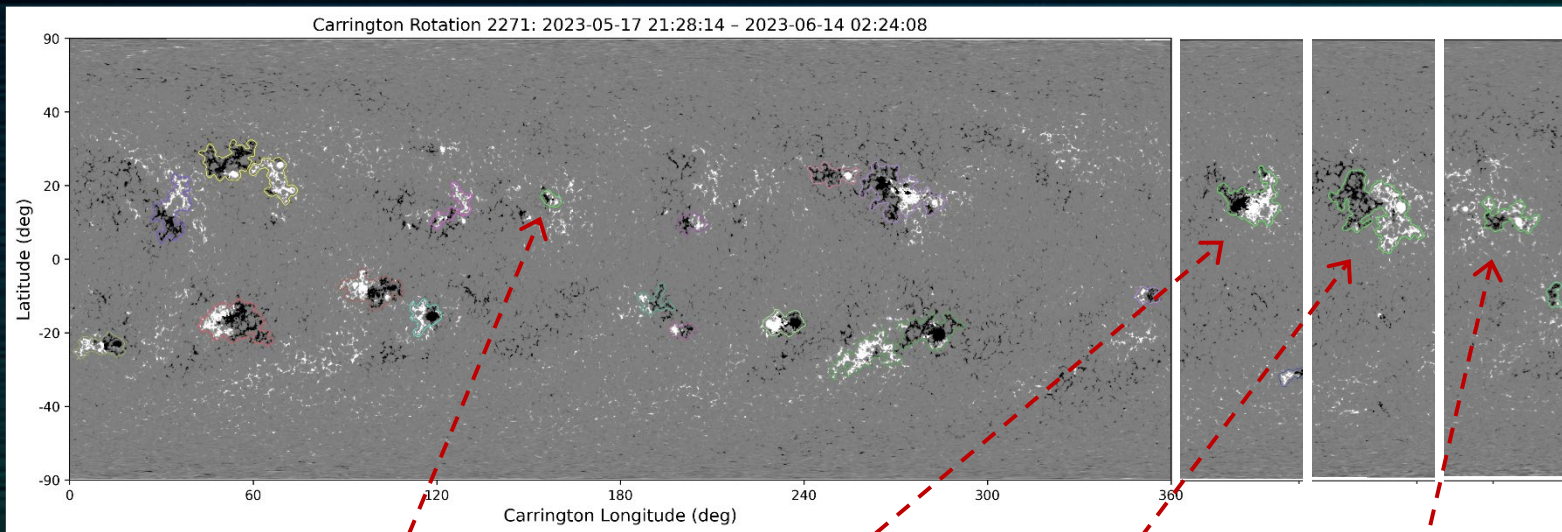
C. Downs et al. 2025 Science



Missing AR magnetic flux in synoptic charts



- Carrington maps give a lower limit of the maximum flux reached by ARs
- Nearly half of 47 studied ARs show maximum magnetic flux reached on solar far side
- → HMI Carrington maps underestimate their fluxes by up to 50%; for short-lived ARs by up to 100%

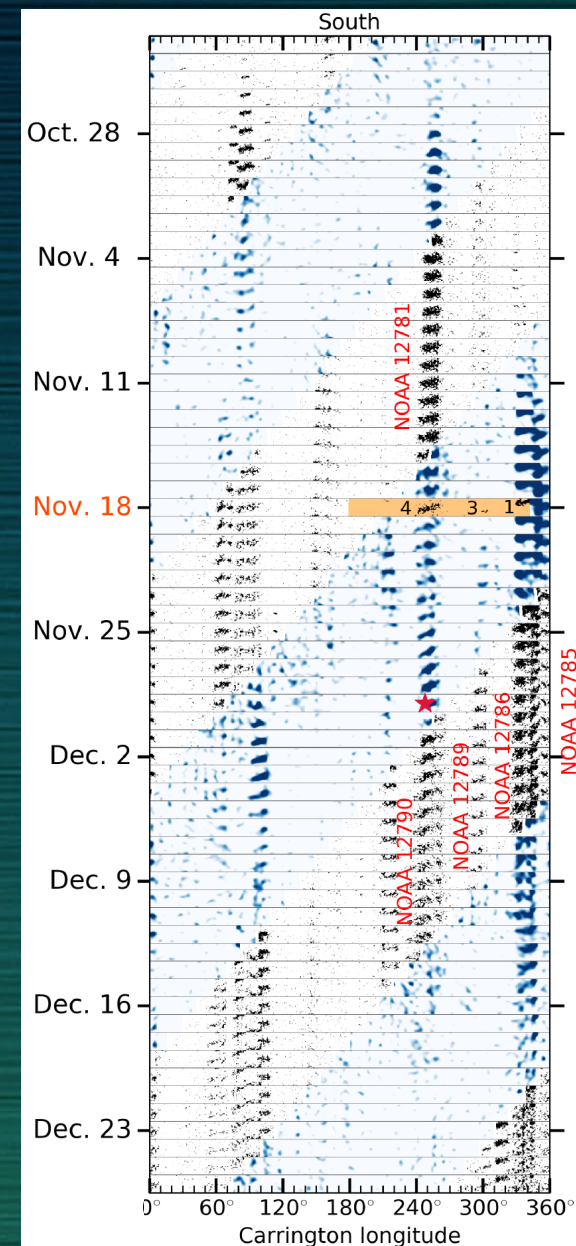
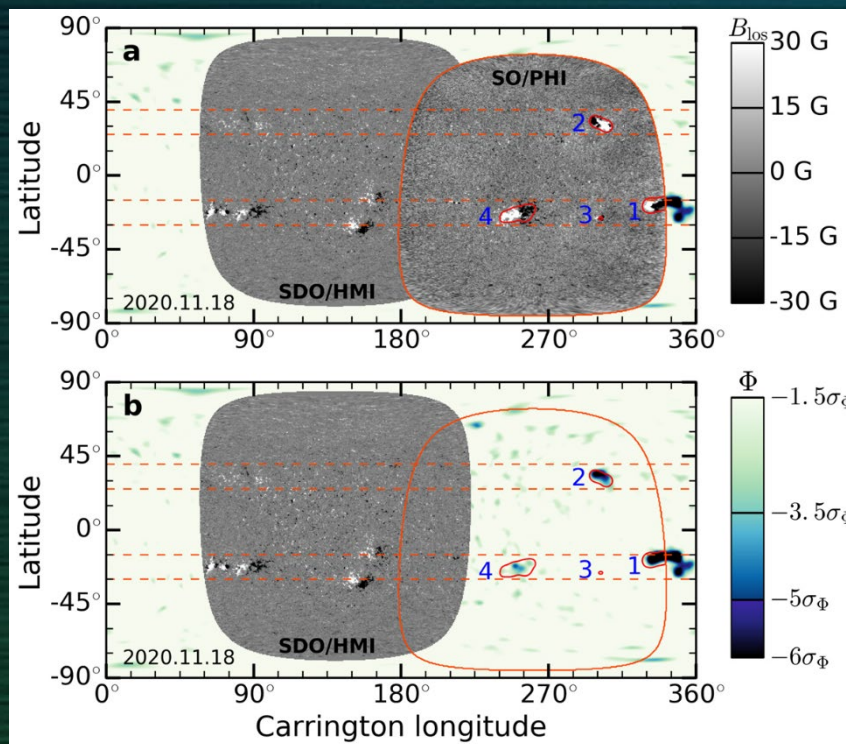
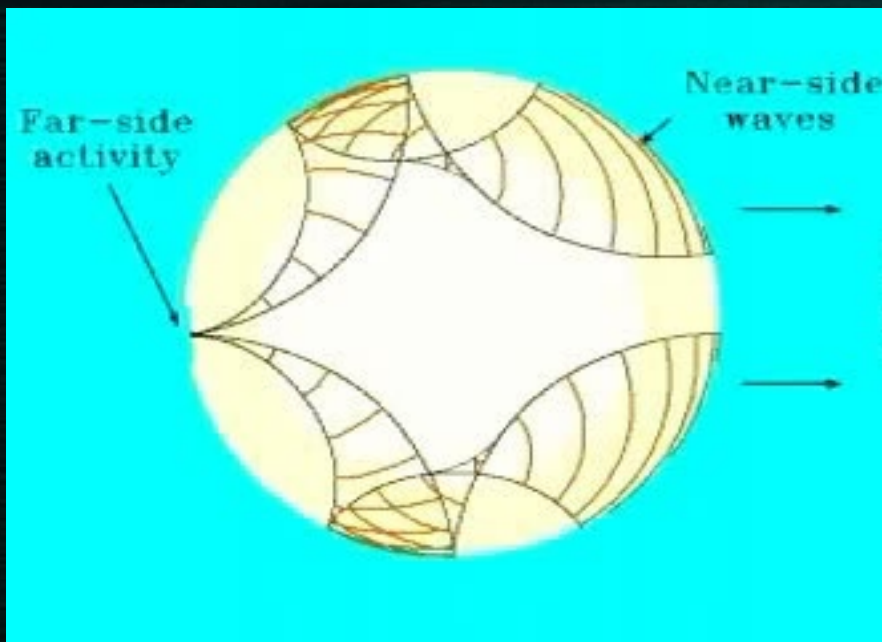


H. Strecker

Helioseismic far-side imaging

- Helioseismology can detect active regions on far side of the Sun
- SO/PHI can test and calibrate this method when on solar far side
- Result: far-side helioseismology detects all but the weakest active regions, with signal strength proportional magnetic flux of active region

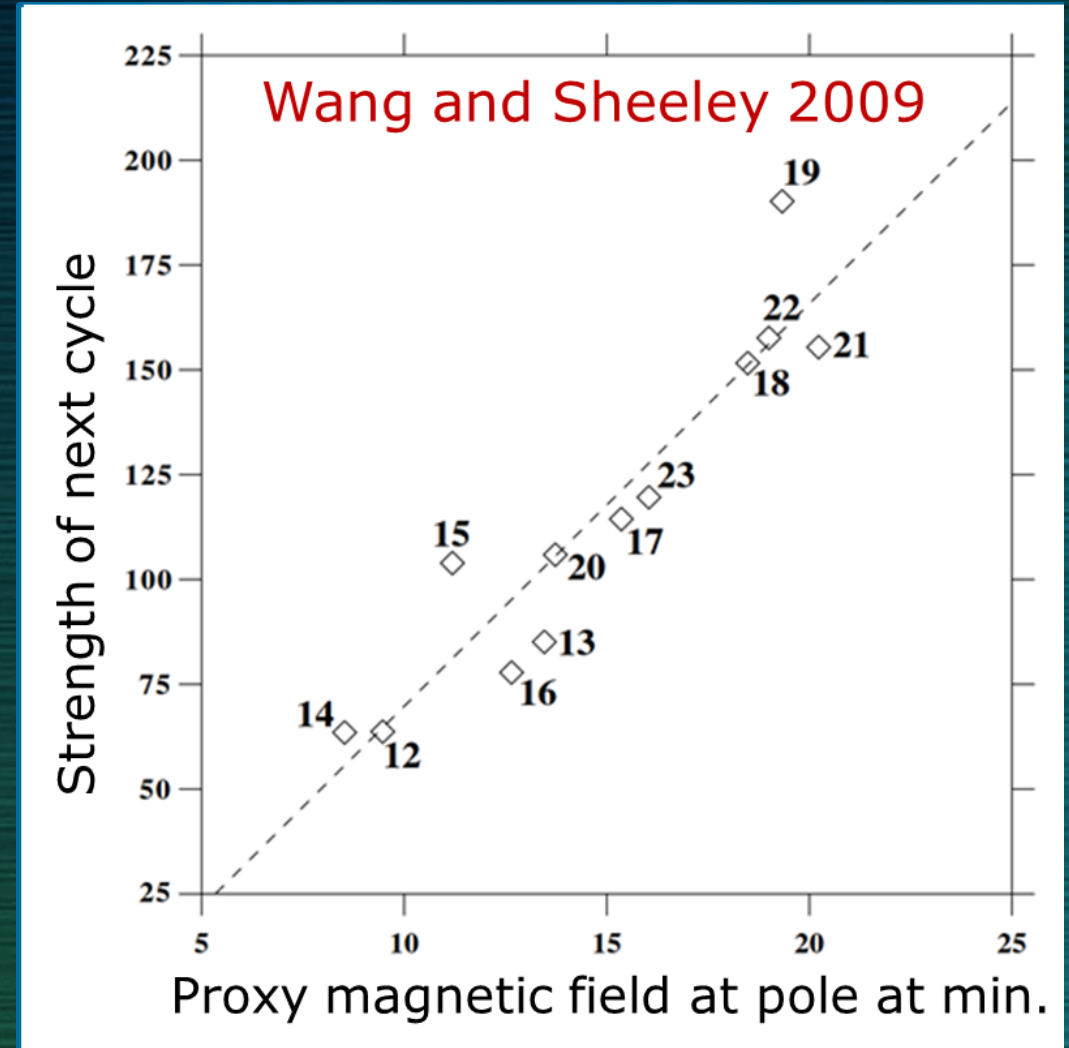
Dan Yang et al. (2023); in prep.





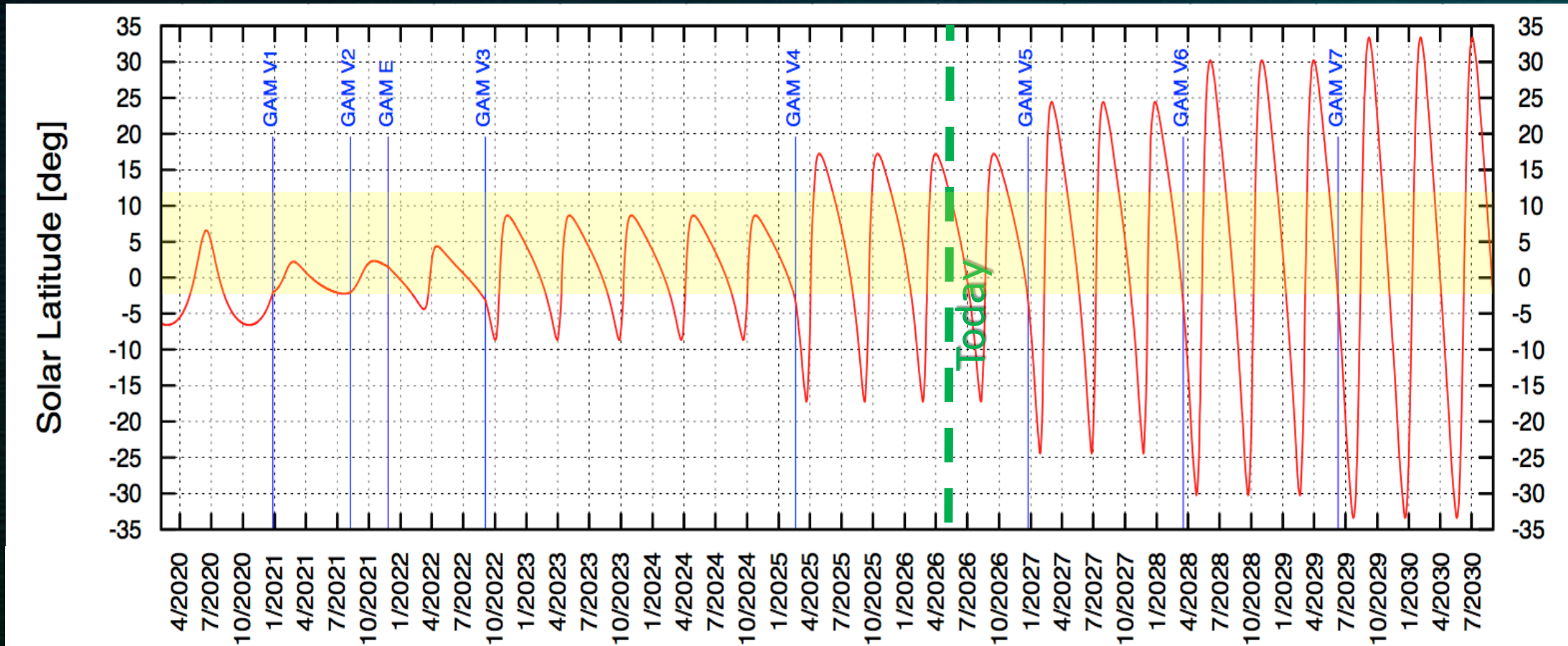
Why is it important to study the poles?

- The solar poles:
 - play a crucial role in the solar dynamo, e.g. in determining the strength of the next cycle
 - are the main source of open magnetic flux
 - are the main source of the fast solar wind
 - are where the magnetic flux is least well known (open flux problem: i.e. in situ measurements in heliosphere show 2-3 times more magnetic flux than the open flux seen on the Sun)
 - are “terra incognita”



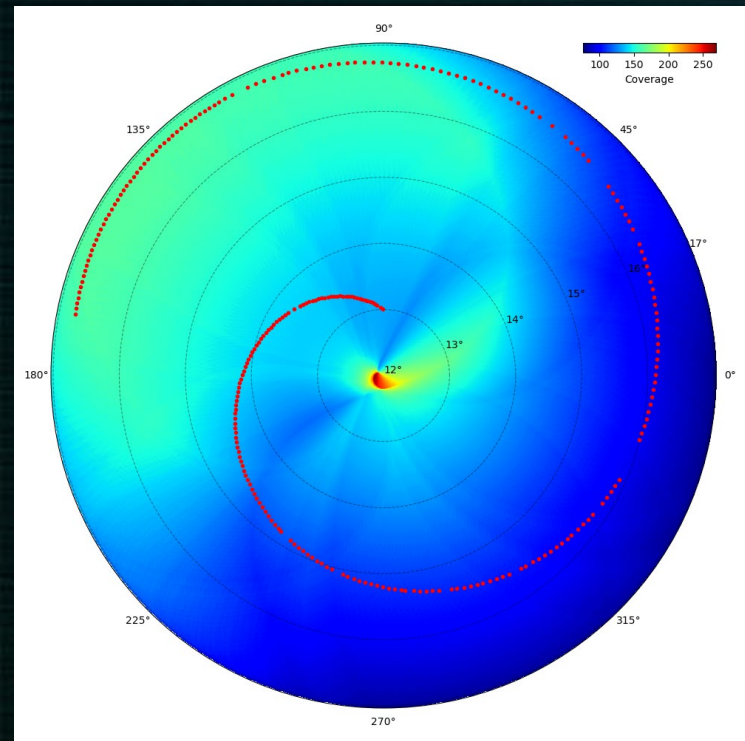
Looking at the poles of the Sun

- Solar Orbiter is the first mission to image the solar poles from outside the ecliptic plane
- Although the angle it currently sees the poles at is rather small, it provides far superior knowledge compared with, e.g., HMI



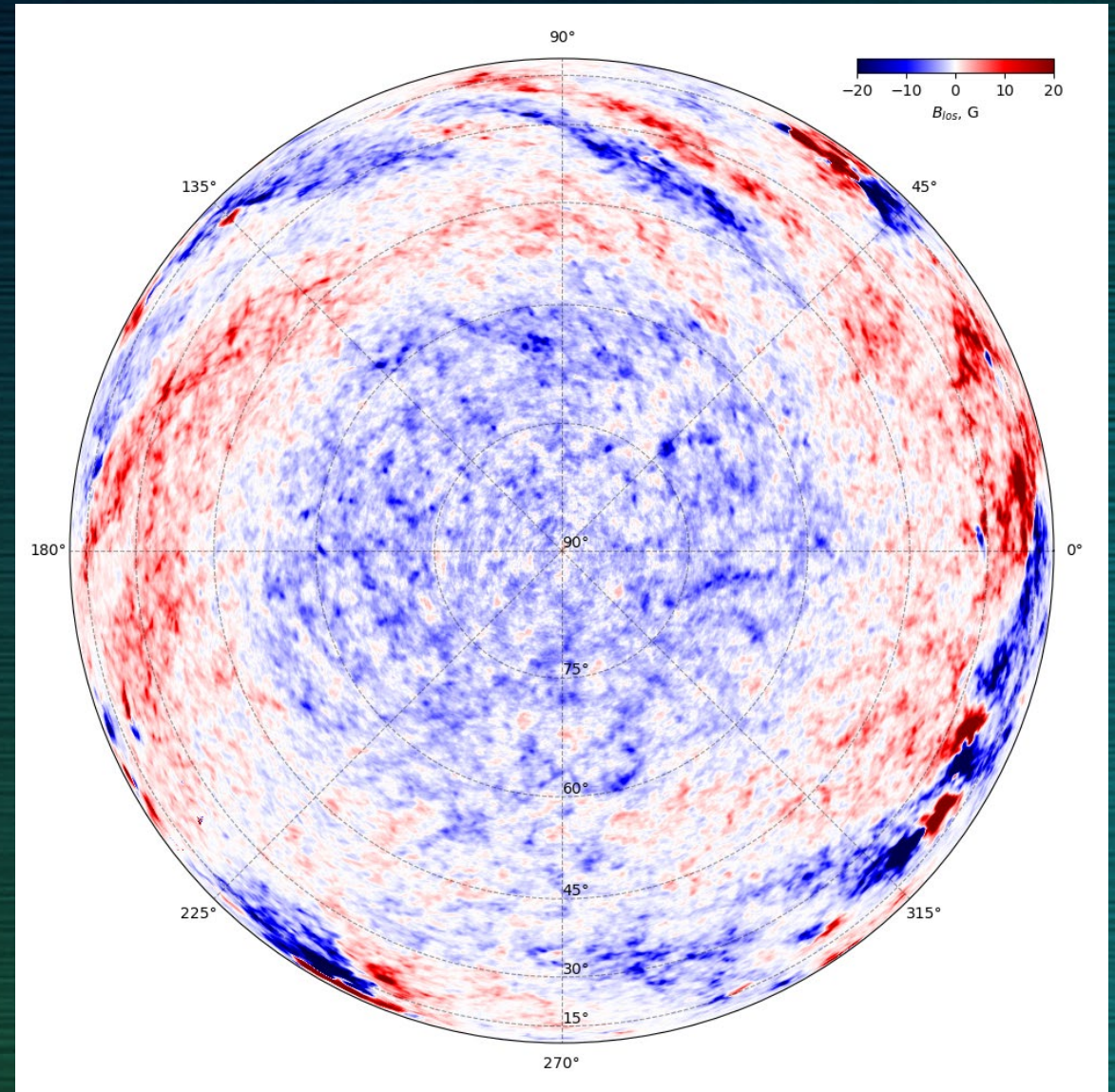
Magnetic field at the Sun's North pole with FDT

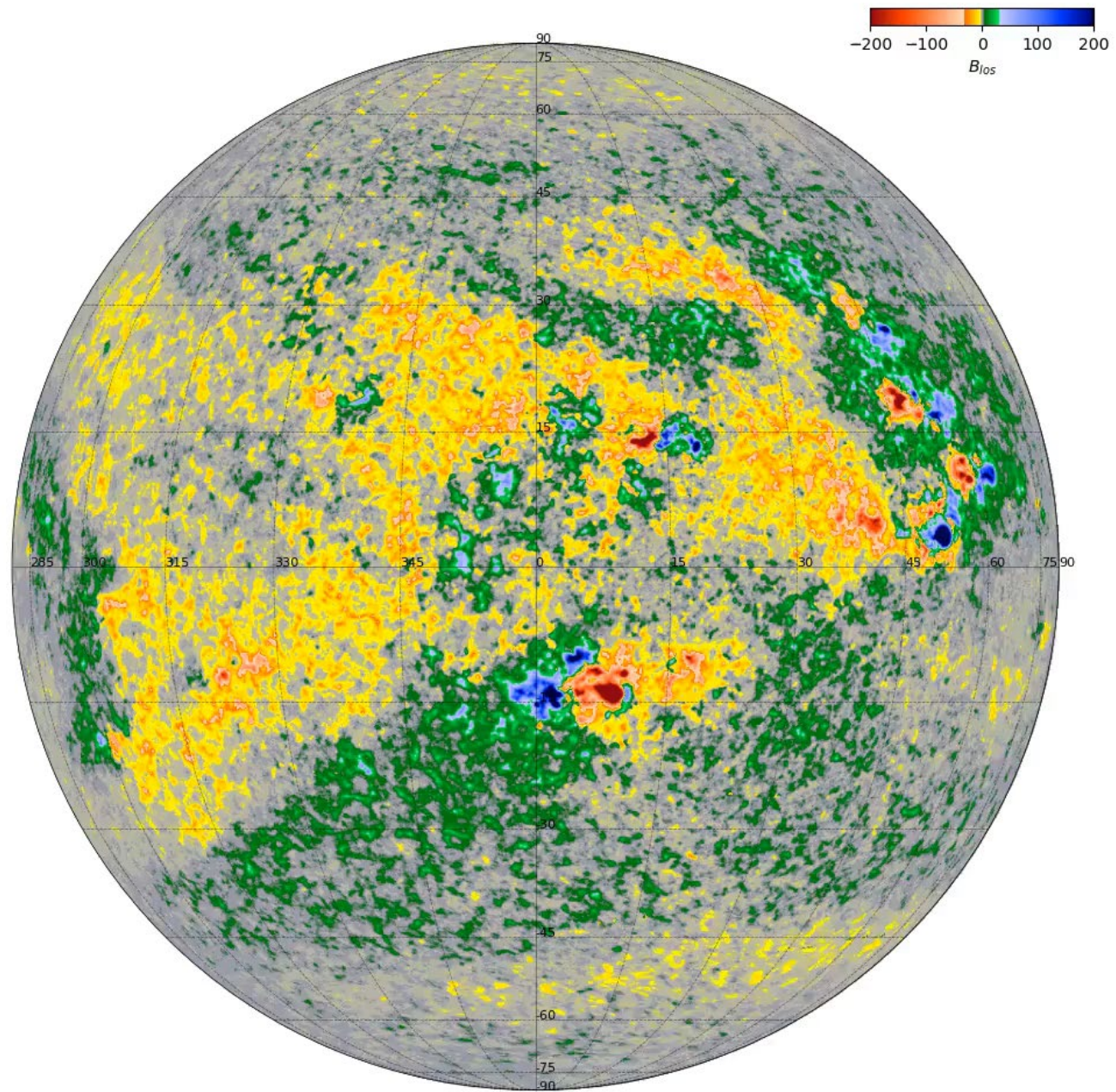
- Line of sight field, B_{LOS} , as it would be seen from directly above solar north pole
- Composite of 270 magnetograms taken over a full solar rotation



Still preliminary!

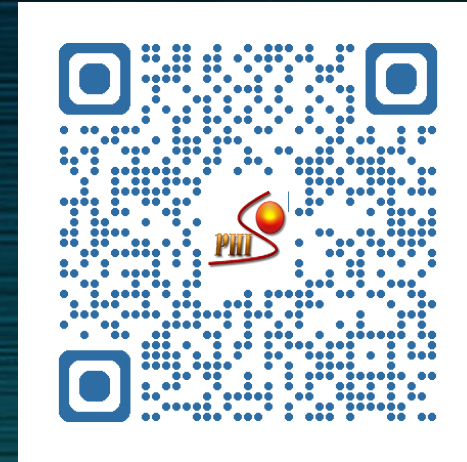
Artem Ulyanov et al. in prep





SO/PHI-FDT and HRT: Latest data releases

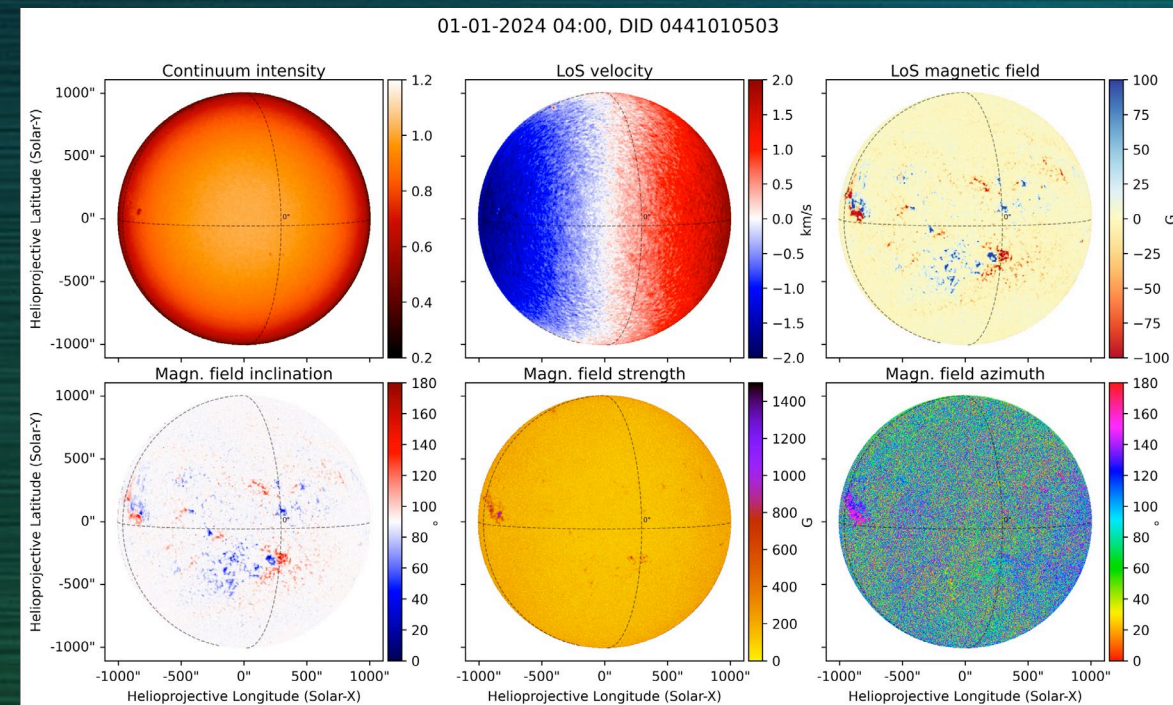
- **FDT:** Release of all physical parameters and Stokes data of 2024 – 2025
 - First release of full magnetic vector
 - Most artefacts are below noise level (but e.g. LOS velocity stil has some offsets)
 - Since 22 February 2025: on-board averages of 3 individual measurens
 - Better signal-to-noise



- **HRT:** data releases
 - Data up to spring 2025 released in January 2026
 - V02 of 2023 released. Main update: Straylight Corrected (Sinjan et al., under revision) and WCS
 - Autumn 2025 and V02 of 2024 data to be released soon

- Information about the data:
https://www.uv.es/jublanro/phidata_fdt.html

- <https://www.cosmos.esa.int/web/soar>

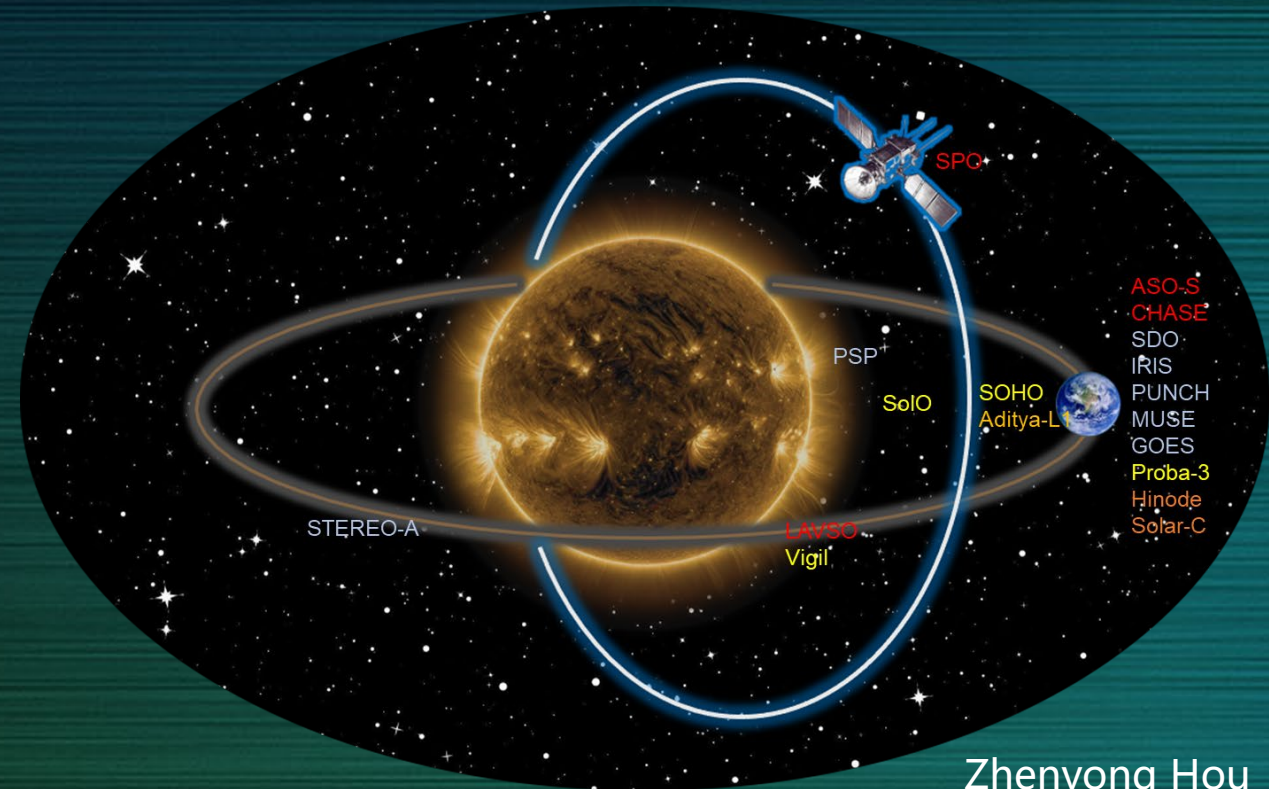


Future missions that will look at the Sun from different vantage points

- Multiple missions are currently being built to reach orbits that will allow novel views of the Sun:
- Vigil (ESA) and LAVSO/Xihe-2 (China) will be heading to the Sun-Earth Lagrange L5 point
- Solar Polar Orbit Observatory (China) will use Jupiter gravity assist to go into a nearly polar orbit, reaching heliolatitudes of 70-80 degrees

Solar Polar Orbit Observatory

- Chinese space mission. Launch: 2029
- Use Jupiter and Earth flybys to reach heliolatitudes $>80^\circ$ (similar to Ulysses, but near-circular orbit)
- Heliolatitudes $> 55^\circ$ first reached 2034
- Will carry in situ and remote sensing instruments, including a magnetograph (similar to Solar Orbiter)
- Much better view of solar poles than Solar Orbiter, but neglects high-resolution aspects



Zhenyong Hou
& Jiasheng Wang

Sun's short-term effects on Earth: CMEs and space weather

CME = Coronal Mass Ejection = Hot gas ejected from the Sun at speeds of 200-2000 km/s.
CMEs are generally associated with solar flares, localized and short brightenings on the Sun

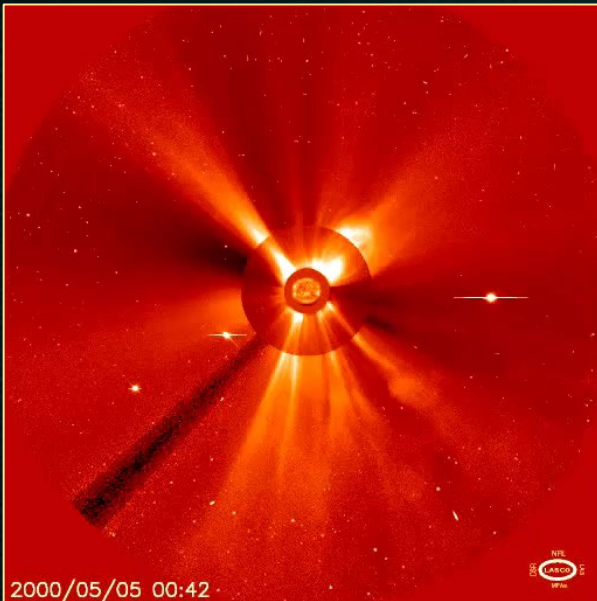
Sun produces around 500-2000 Coronal Mass Ejections (CMEs) per year

When a CME arrives at Earth it produces space weather, including aurorae. Just last week strong ones visible even at mid-latitudes

Space weather affects satellites etc.

The New York Times

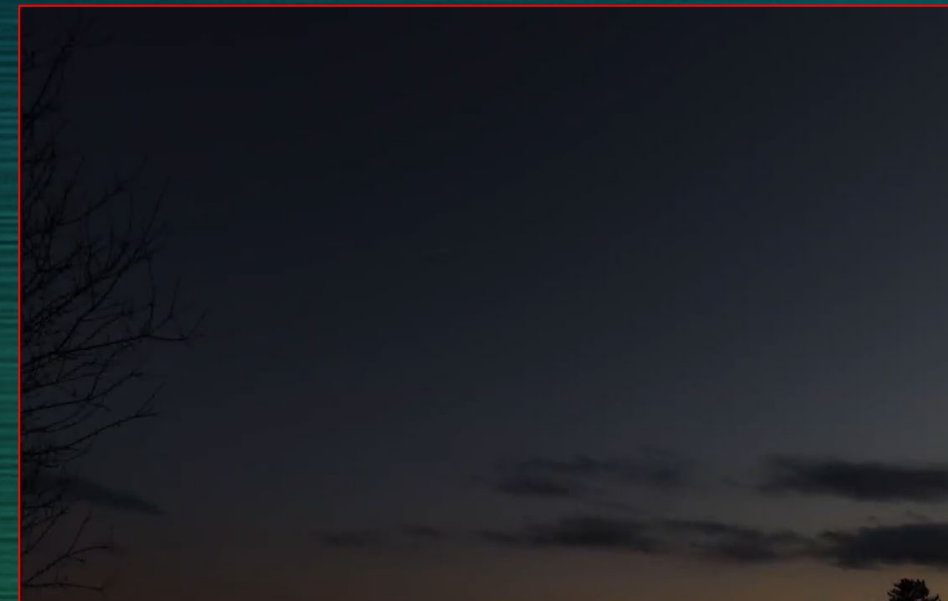
Solar Storm Destroys 40 New SpaceX Satellites in Orbit



SOHO/LASCO



Germany, 2026 Jan 18



Animation by ViralVideoLab

PMI on Vigil at Lagrange L5

- **Vigil**: ESA space weather monitoring mission to be stationed at Lagrange L5 point
- MPS contribution: **Polarimetric Magnetic-field Imager (PMI)**
- Novel science:
 - pick up active regions before they are visible from Earth and better predict flares and eruptions
 - provide unambiguous magnetic vector
 - improved helioseismology
 - stereoscopy
 - longer time series (e.g. spots), faster synoptic charts
- Instrument delivery foreseen in 2028

