THEMIS solar telescope
A new era begins

Laboratoire de Physique des Plasmas

Journées de la SF2A – S08 – Toulouse – July 3rd 2025

FSLAC International Research Lab.

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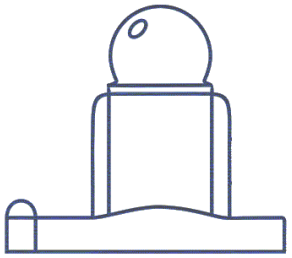
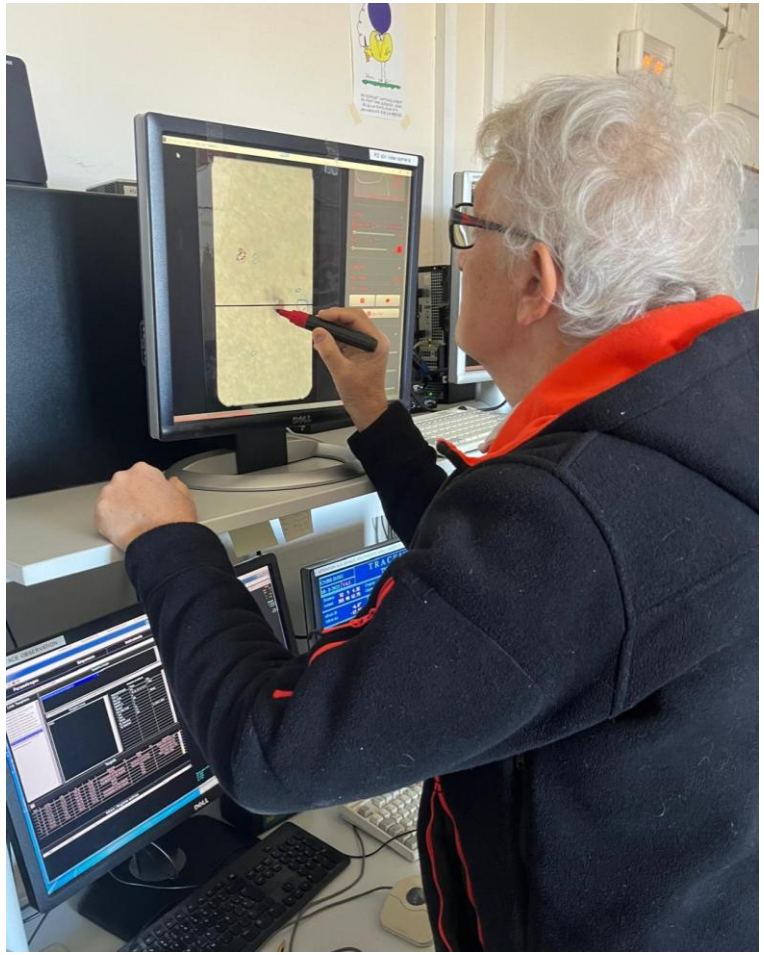
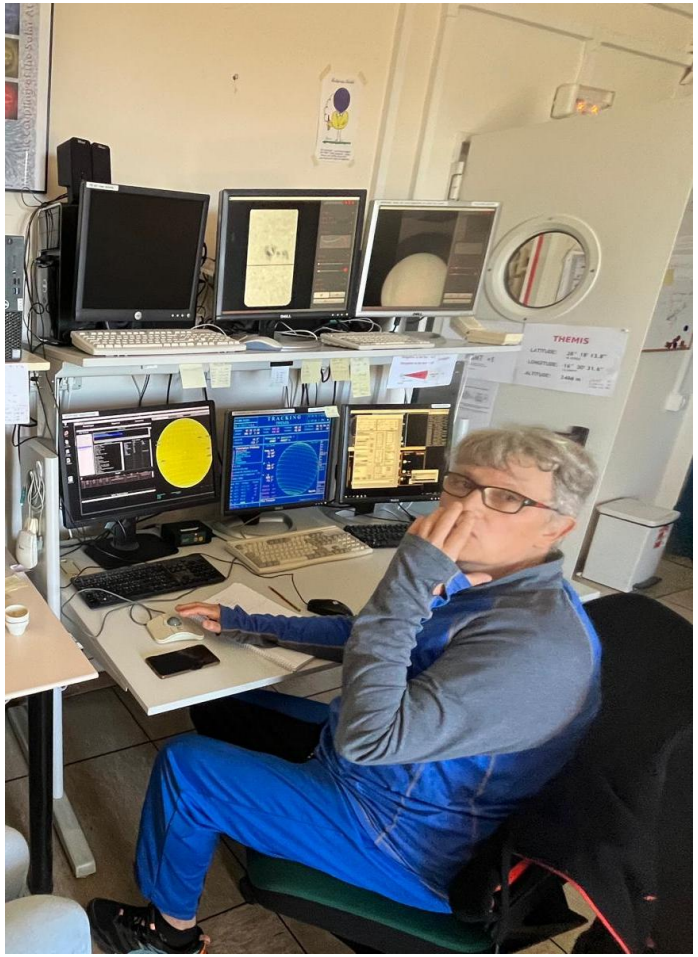
[2] Laboratoire de Physique des Plasmas, Sorbonne Université, École polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris-PSL, CNRS, Paris, France

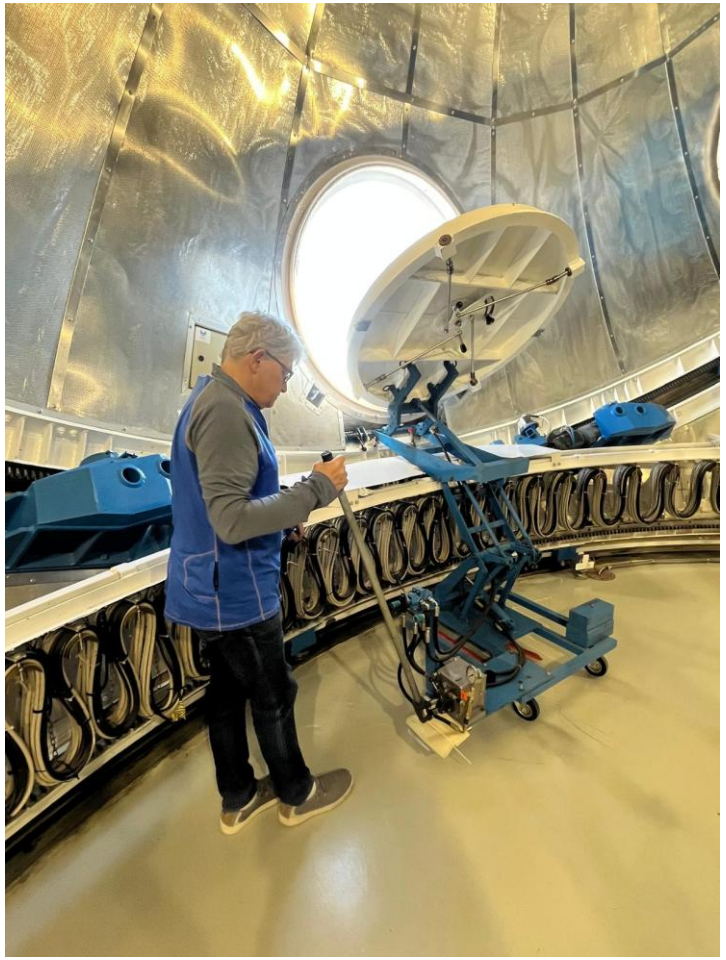


In memoria of Didier Laforgue

- Didier Laforgue passed away on June 20th 20205, after 23 years working at THEMIS as a system-instrument research engineer, and as a very appreciated observation operator.







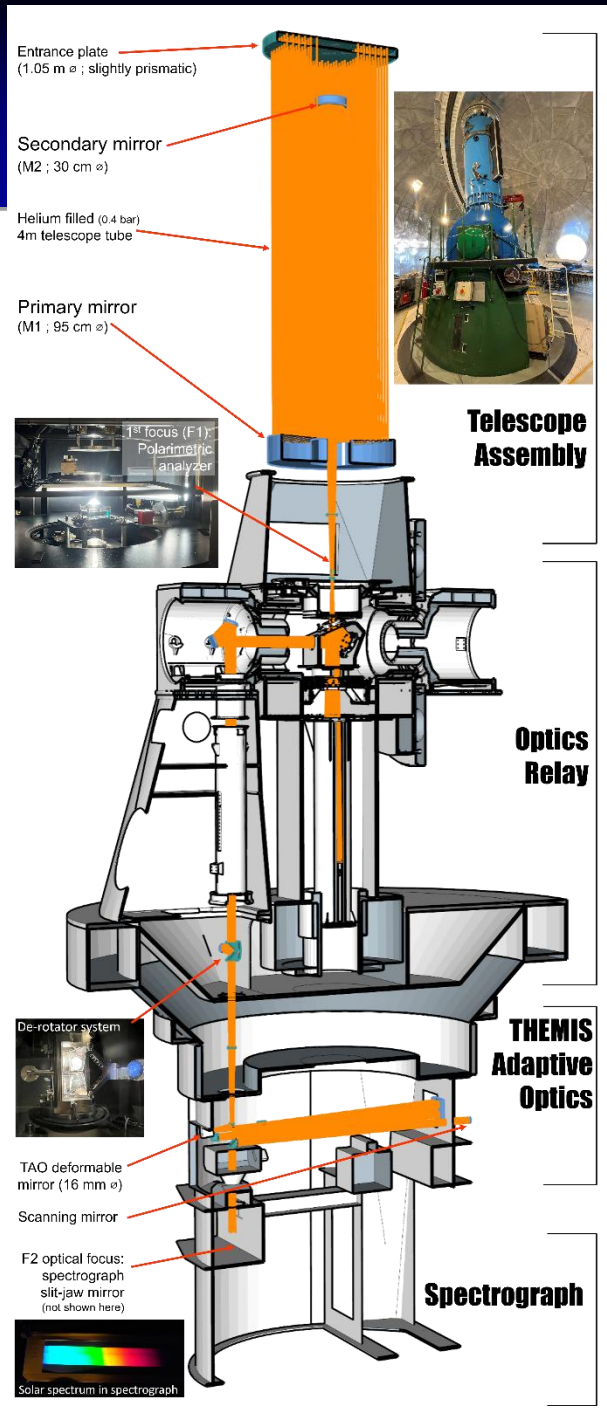
THEMIS Factsheet

Very well-maintained but,
be at that it may,
a 20th century instrument !

THEMIS @ OT in June 2025

- **Main French solar telescope**
  designed by J. Rayrole, P. Mein & M. Semel
  - Located at Teide Observatory, Tenerife, Spain
  - 1st light in March 1996, & commissioned in 99
- 1m-class solar telescope, with **one the world "slowest" optical design:**
  - Aperture: 92 cm
  - Effective focal length: 57m
  - Effective focal ratio: f/62
- **Ideal for high resolution spectropolarimetry:**
  - Ultra-high spectral resolving power:
    R ~ 200 000 to 300 000
  - Simultaneous obs. of user-defined set of up to 6 spectral lines: 6-7 Å range, 4 mÅ/pixel
- Spectrum range: 400-1100 nm
- 2'x2' square field-of-view

“Total makeover”: 2016 → 2020



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  - **Successful renovation thanks to several French teams**

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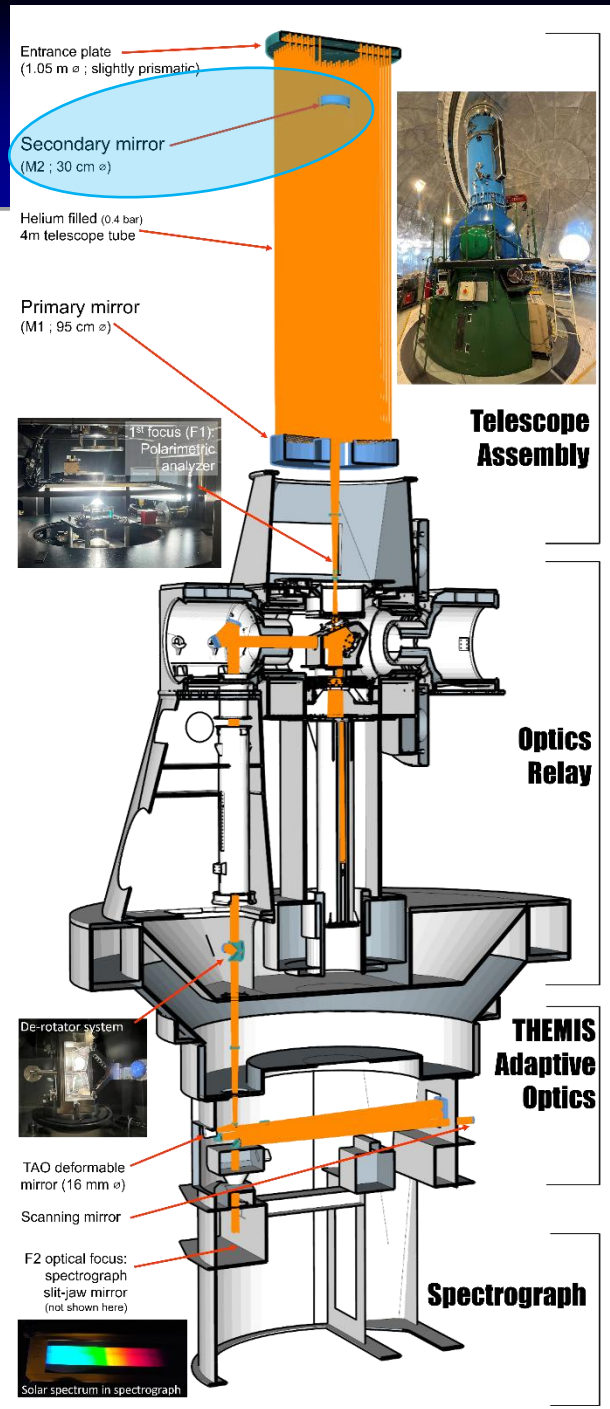

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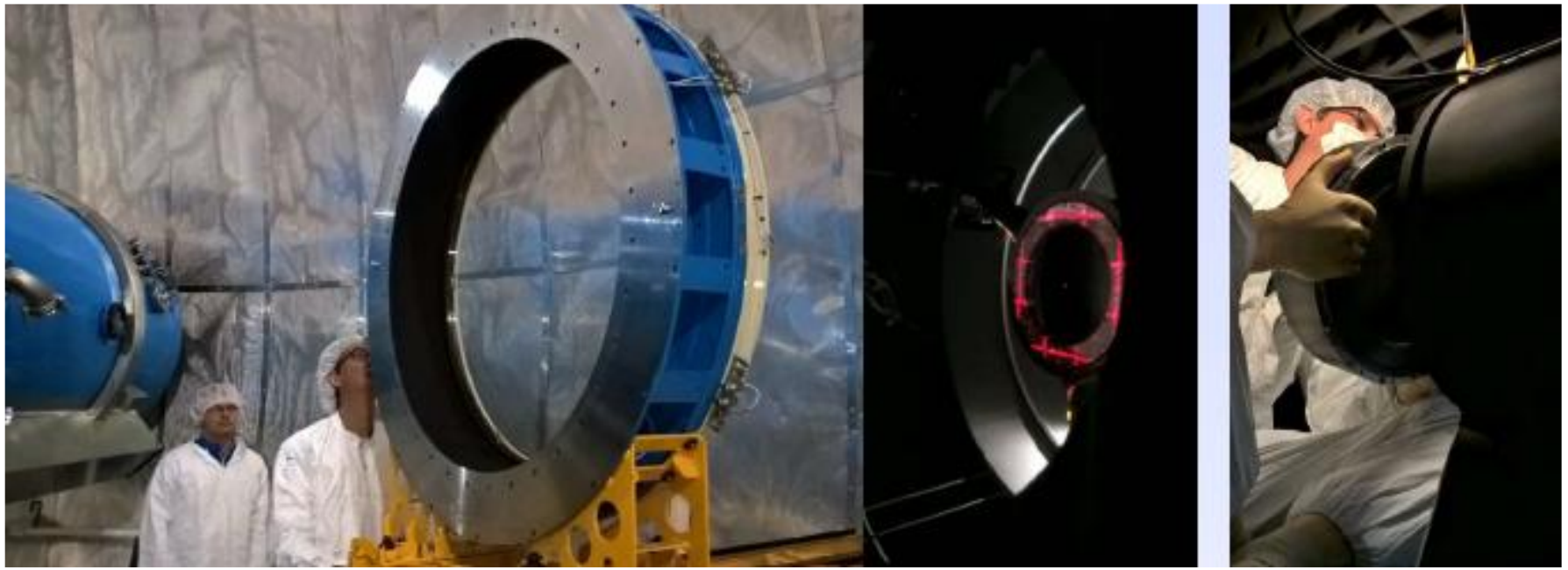

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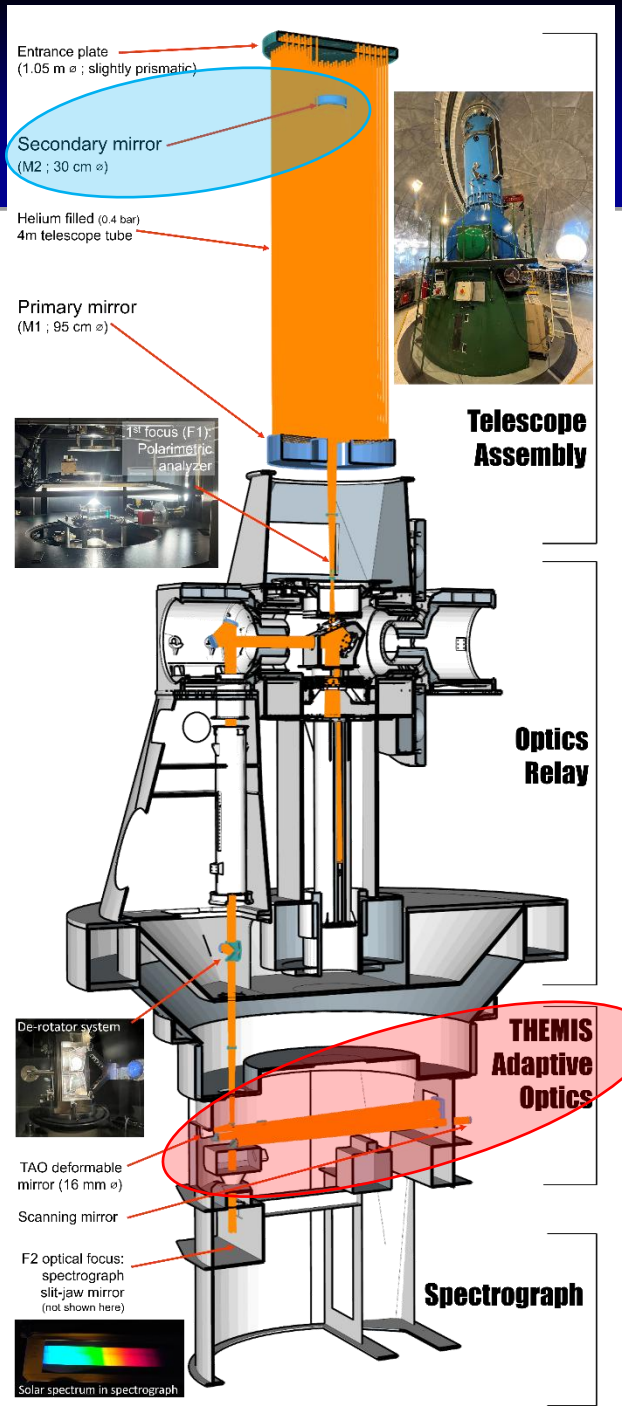

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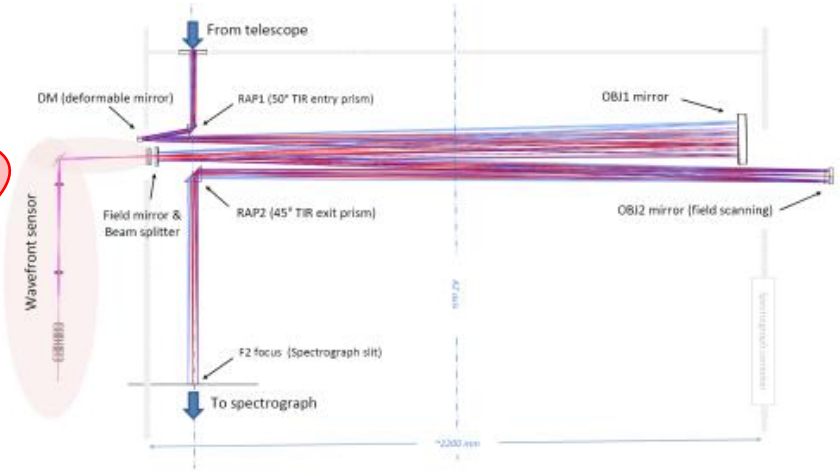

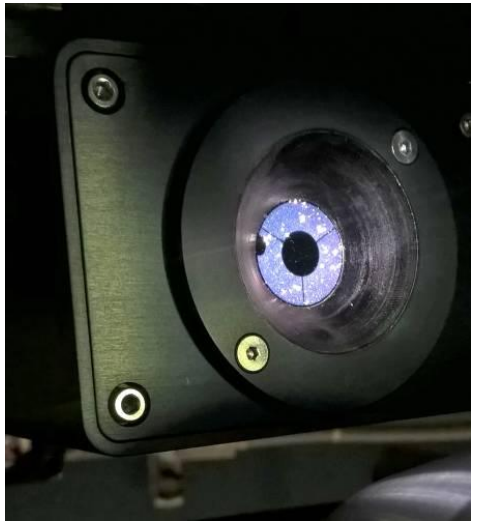

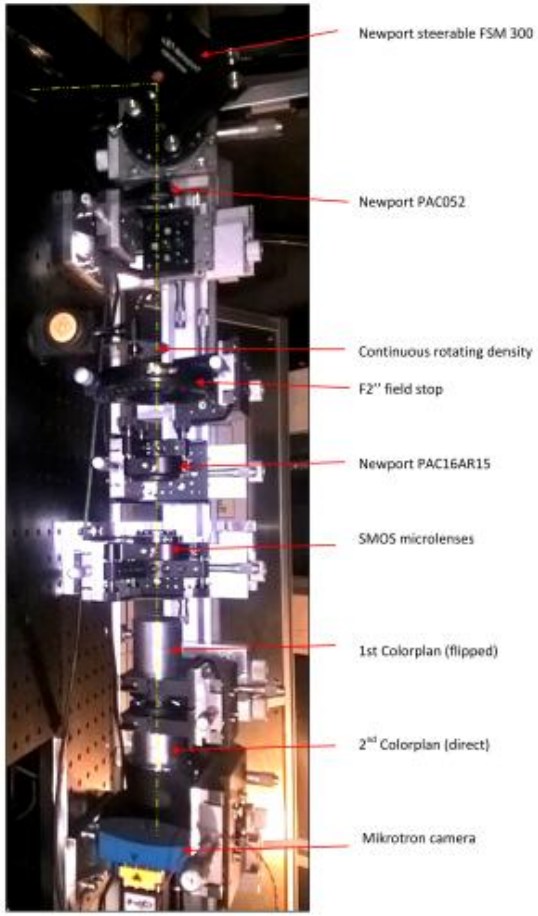

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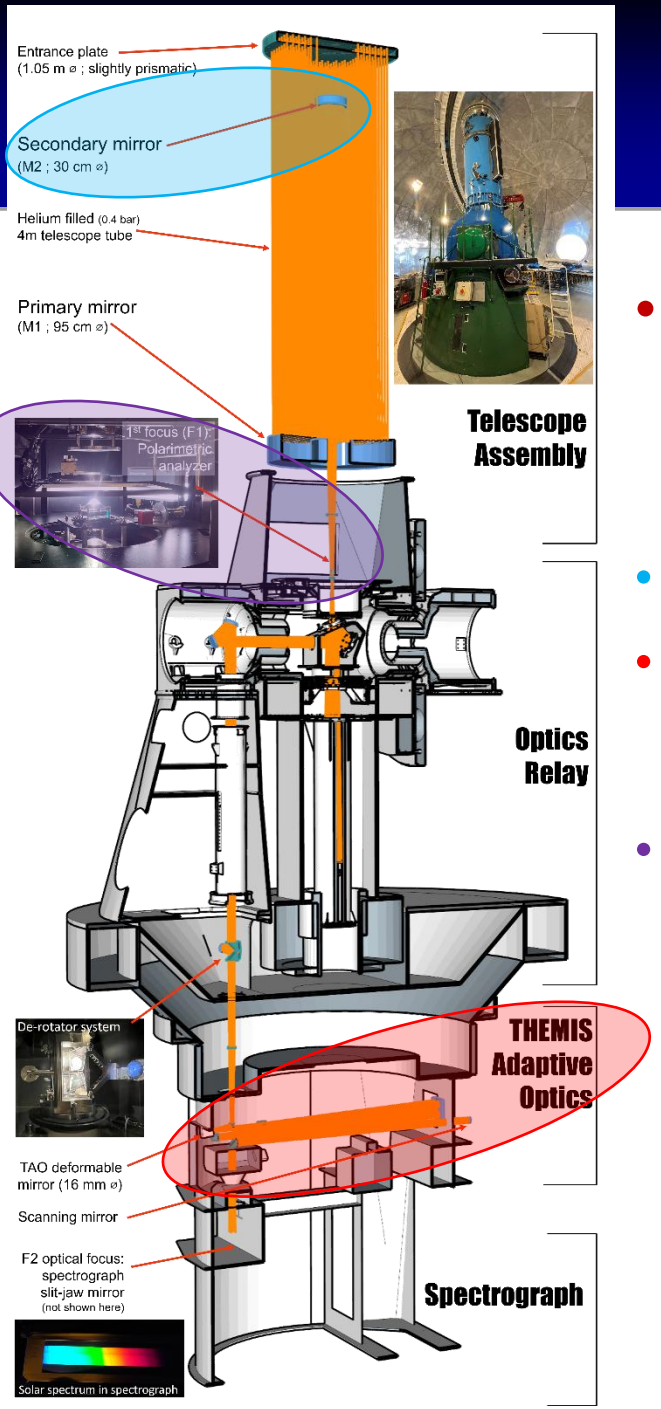

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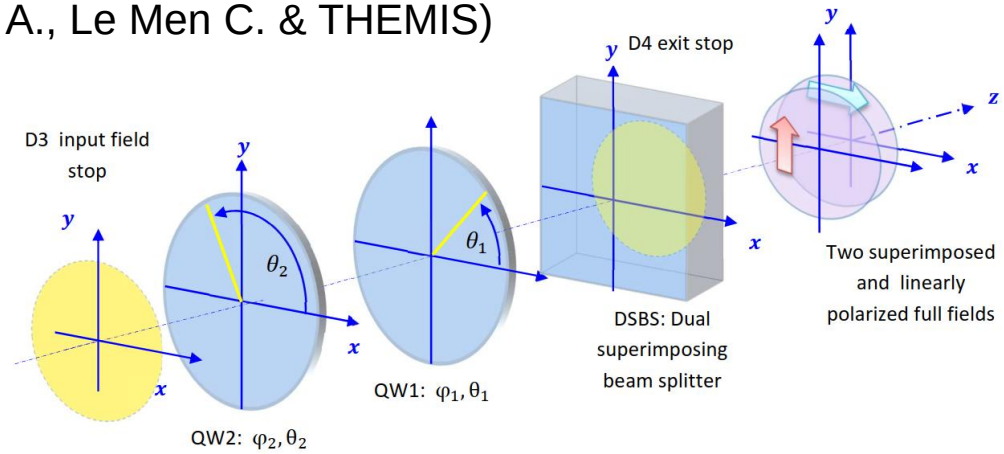
- **Superimposed dual-beam polarimetric analysis** without field limitation (Semel M., Lopez A., Le Men C. & THEMIS)



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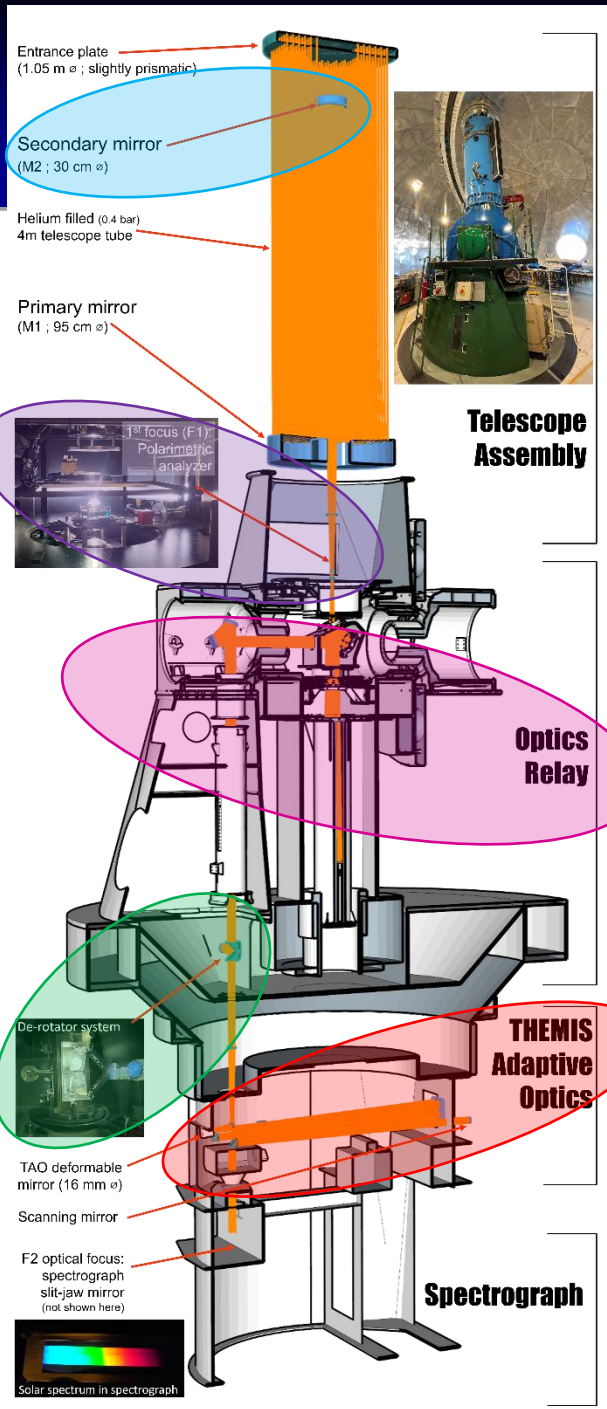

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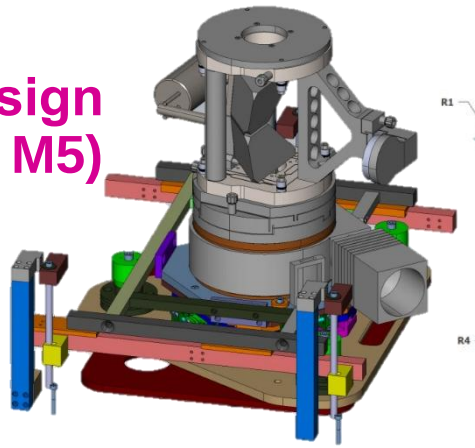
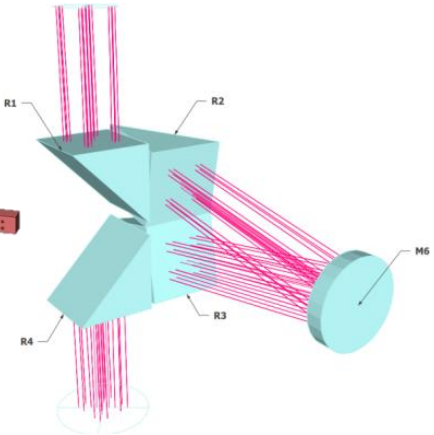
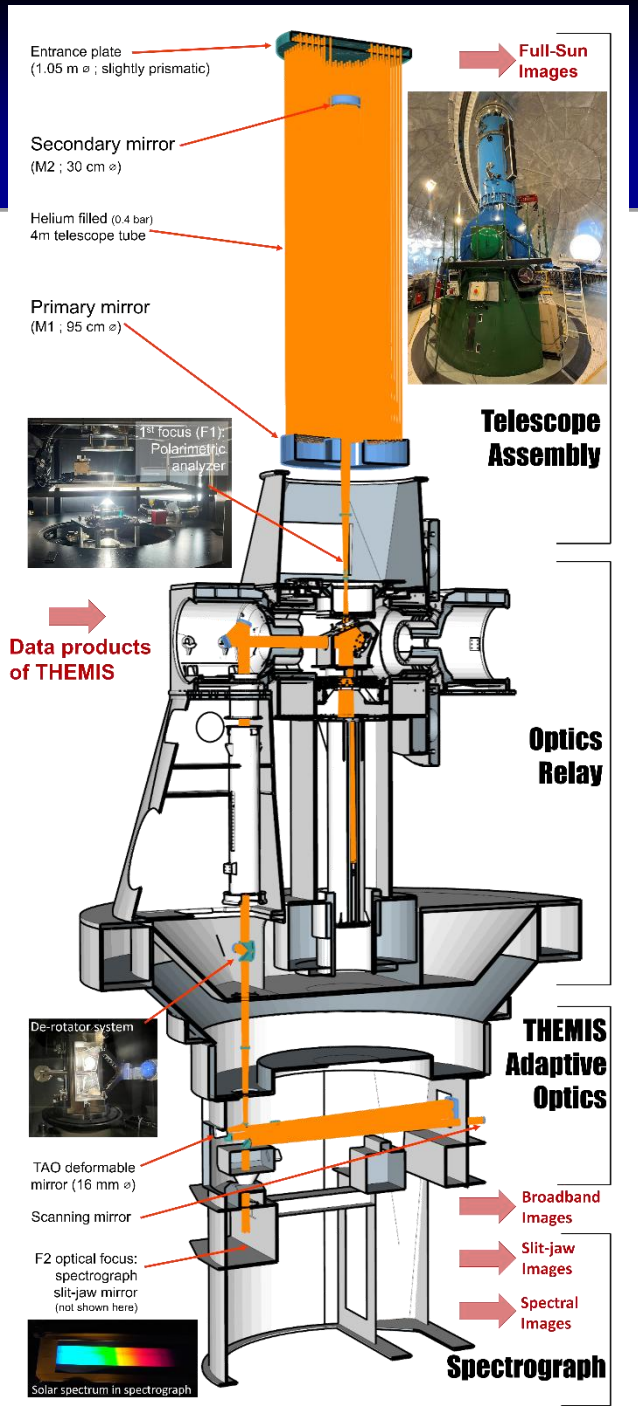
- **Superimposed dual-beam polarimetric analysis** without field limitation (Semel M., Lopez A., Le Men C. & THEMIS)
- **“Polarization- friendly” complete redesign of the whole transfer optics (M3, M4 & M5)** (Le Men, C. & THEMIS)
- **New de-rotator system** (THEMIS)
- + New context, broadband and spectral cameras.

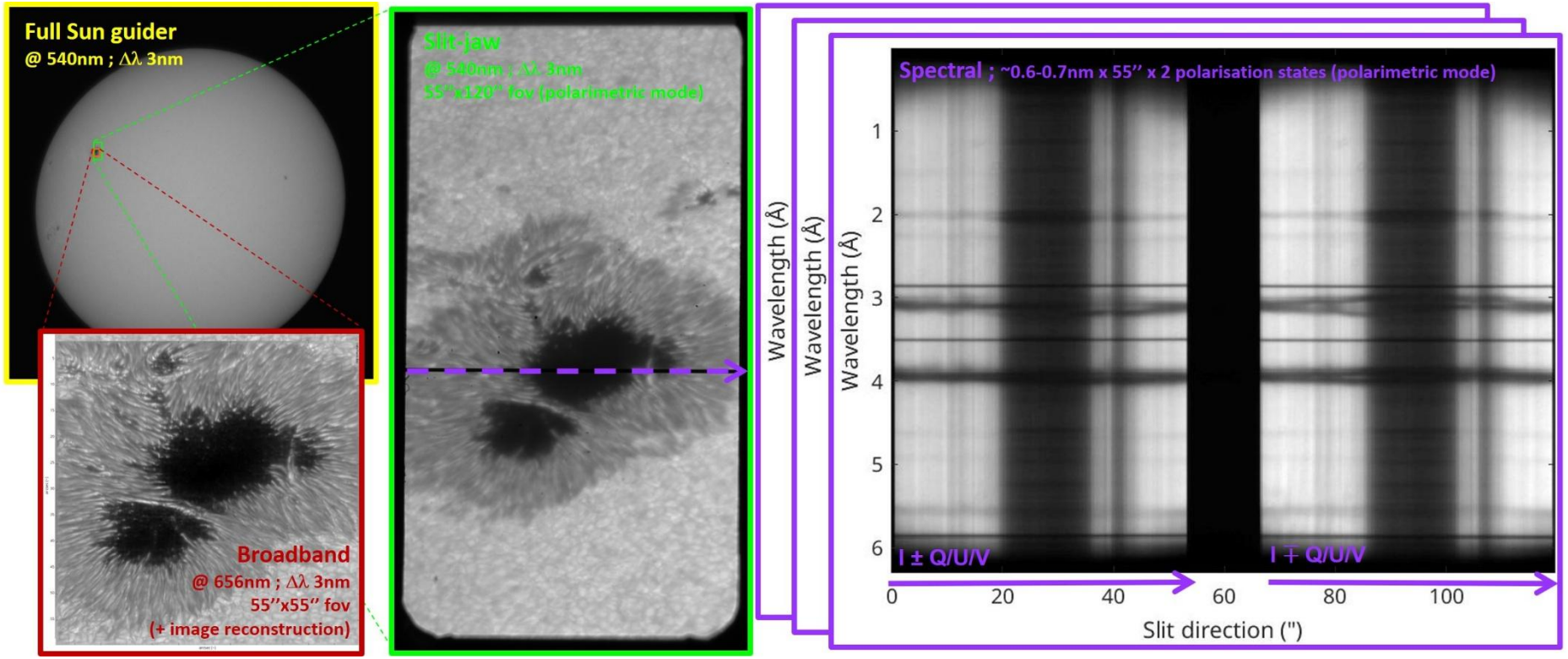




THEMIS data products



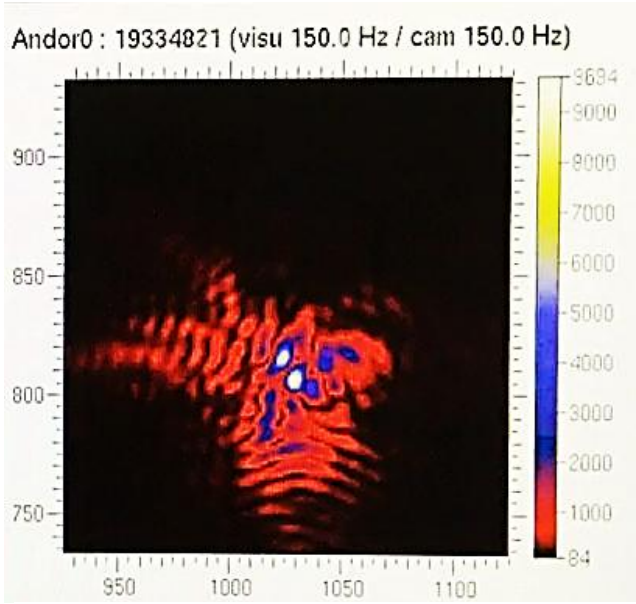
- **Full Sun Guider** & **spectrograph Slit-jaw** context images
- **BroadBand images (BBI)**
- Main science product: **MTR2 spectrograph spectral images**

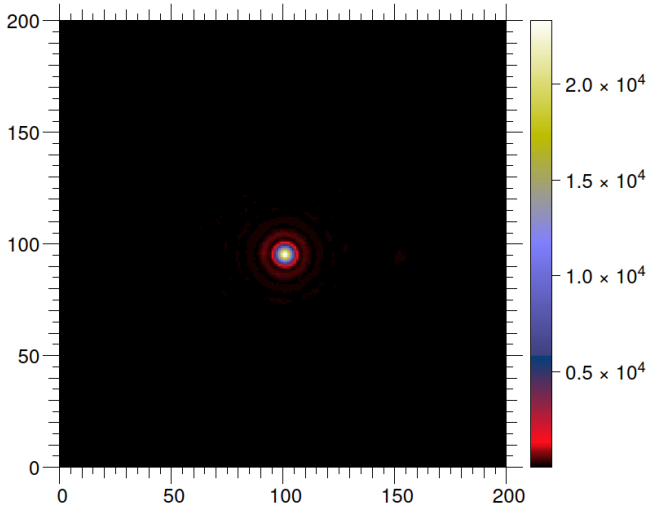


THEMIS Adaptive Optics (TAO): specifications & objectives

- Specifications
  - **76 sub-aperture Shack-Hartmann wavefront sensor** (10×10);
    - 380×380 pixel WFS images, Mikrotron EoSens 4CXP detector;
  - **THEMIS-optical-path-compatible 16 mm deformable mirror**
  - **97 actuator** on deformable mirror (11×11), from ALPAO
  - Real time correction (RTC)
    - Computer: CPU i7-4790K (Q2'14) at 4.2 GHz, 4 cores, up to 50 Gflops/core with AVX2 + FMA instructions.

- Objectives
  - ✓ **Closed AO loop on the Sun**
    - started from scratch mid-2016 → operative in December 2020
  - ✓ **RTC software running in CPU @1250 Hz** (no GPU)
    - flexible RTC software to implement and experiment new algorithms
  - **Next objective: unsupervised AO system** (optimal correction whatever the conditions)

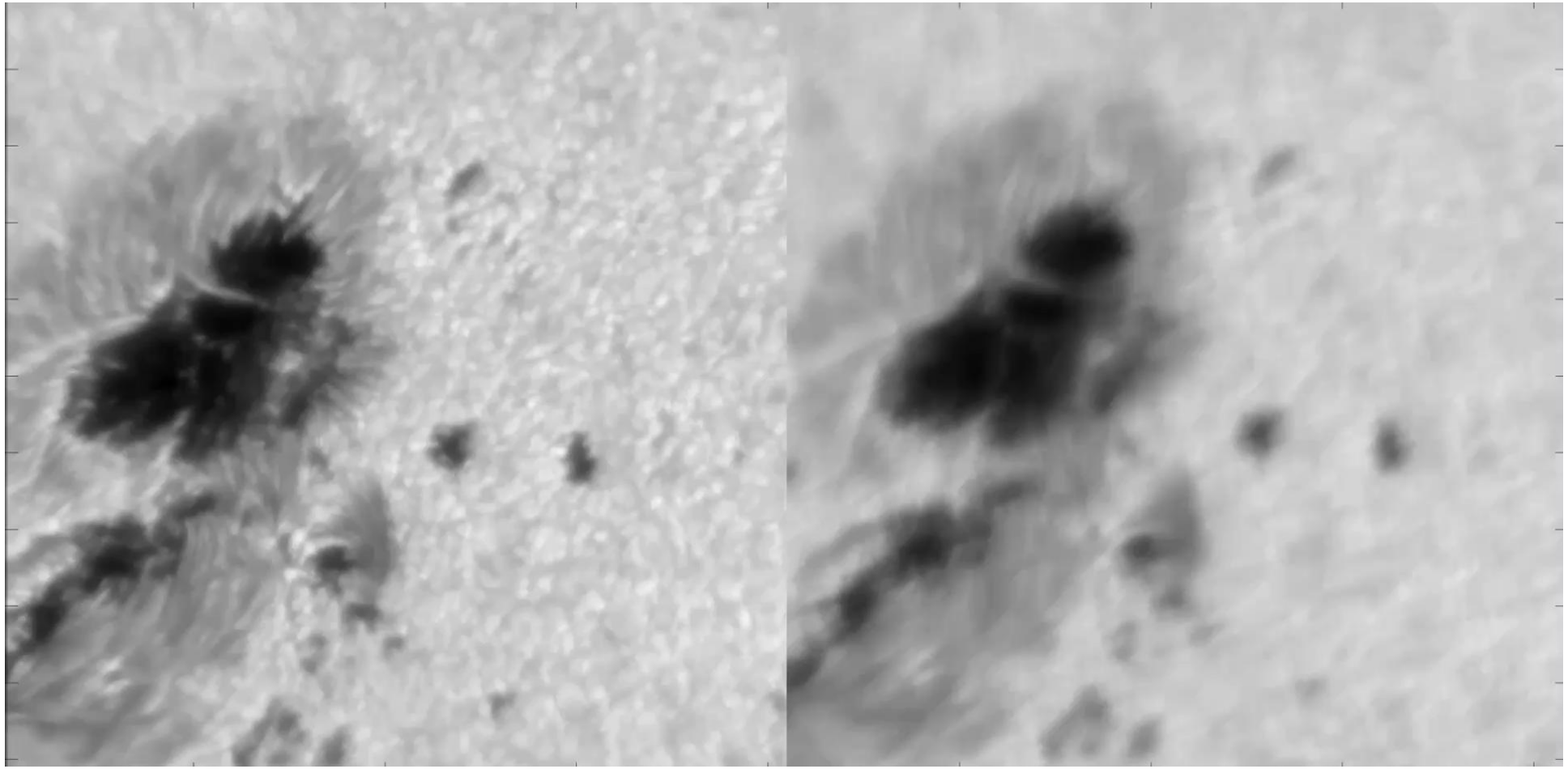




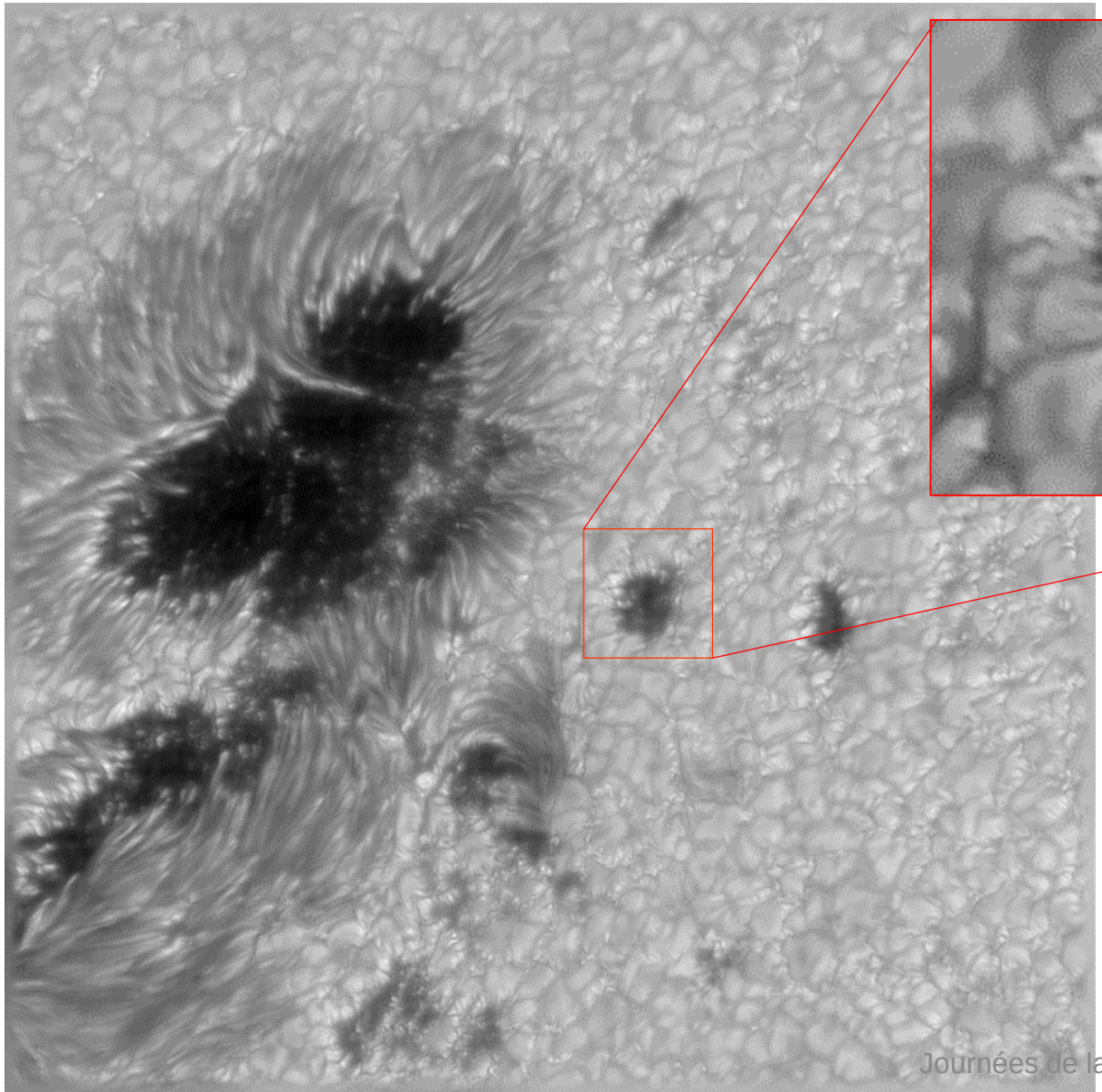
Thiebaut, E., Tallon, M. et al, SPIE proceedings 2022

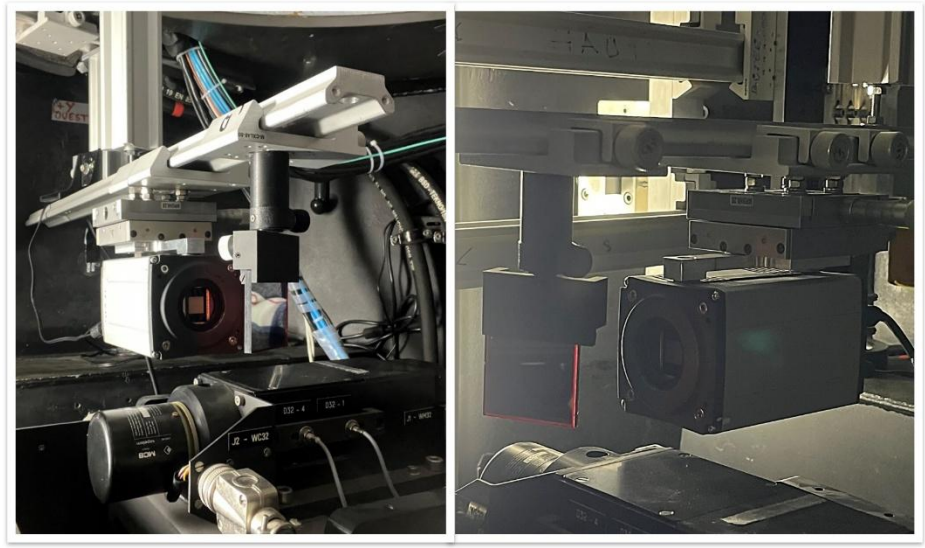
TAO going live on NOAA 12975

- Successive recordings in equivalent seeing conditions
- 55” square field, 20 image/s (0.3 ms), 2k x 2k (0.03” /px) on Broadband Imaging Camera



THEMIS at diffraction limit: NOAA 12975

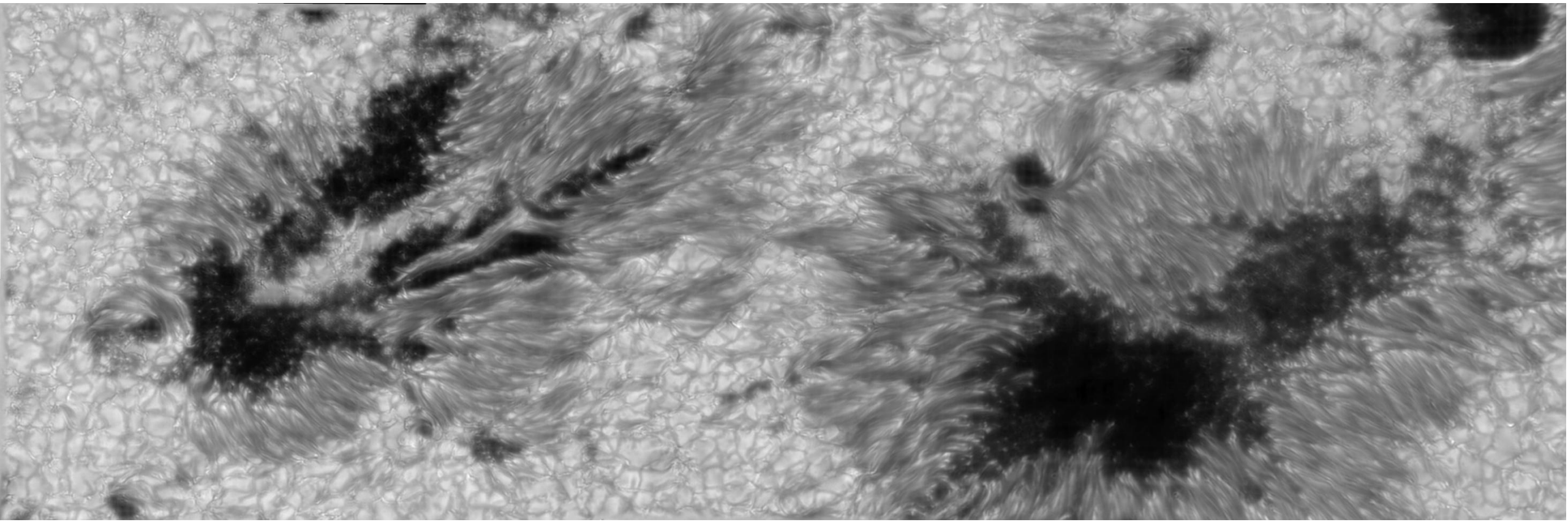




THEMIS Broadband Imaging (BBI)

- NOAA 12975 on 2022/03/31
- Observed @ 630nm ; 1nm broadband red filter
- 55”x55” FOV
- 100 BBI acquisition @ 40 images/s
- Knox-Thompson image post processing
- **➔ 0.17’’ resolution (0.035”/pixel) near THEMIS theoretical diffraction limit of 0.15”**

THEMIS at diffraction limit: NOAA 13354

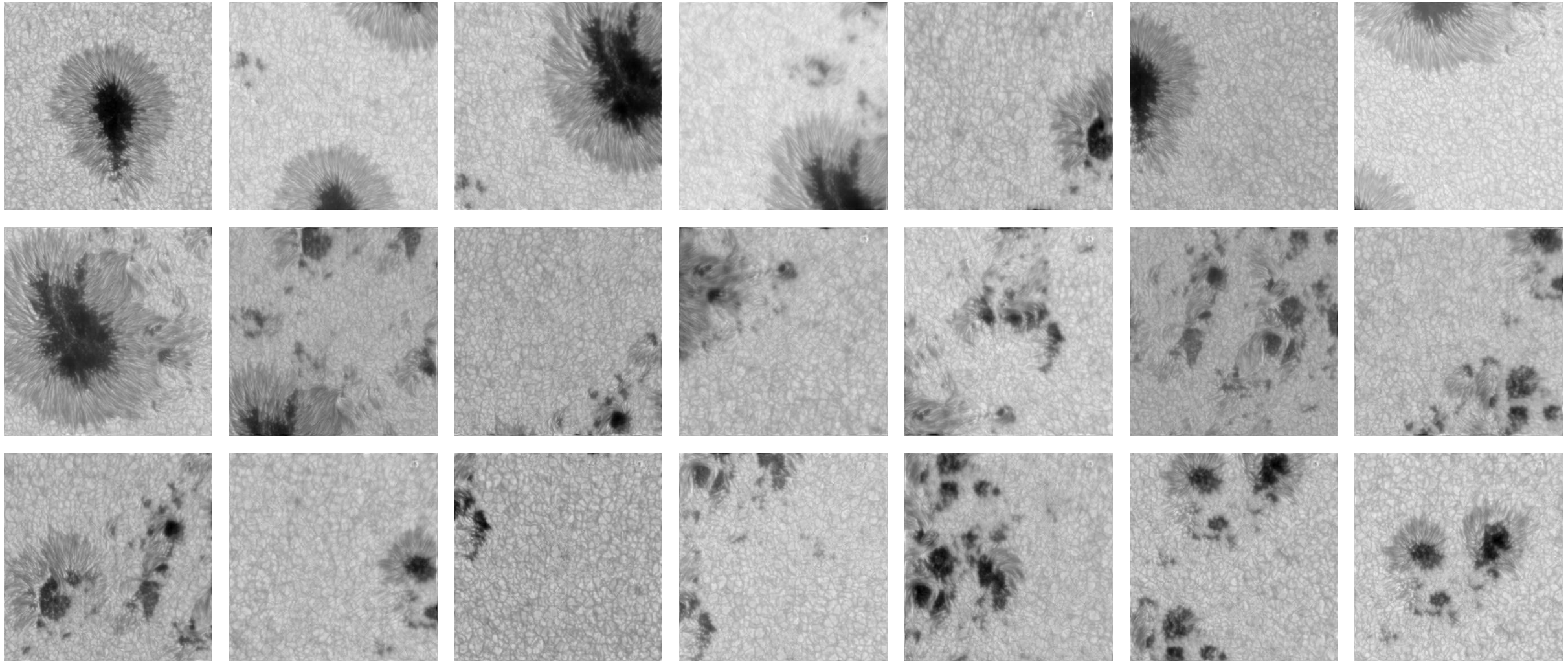


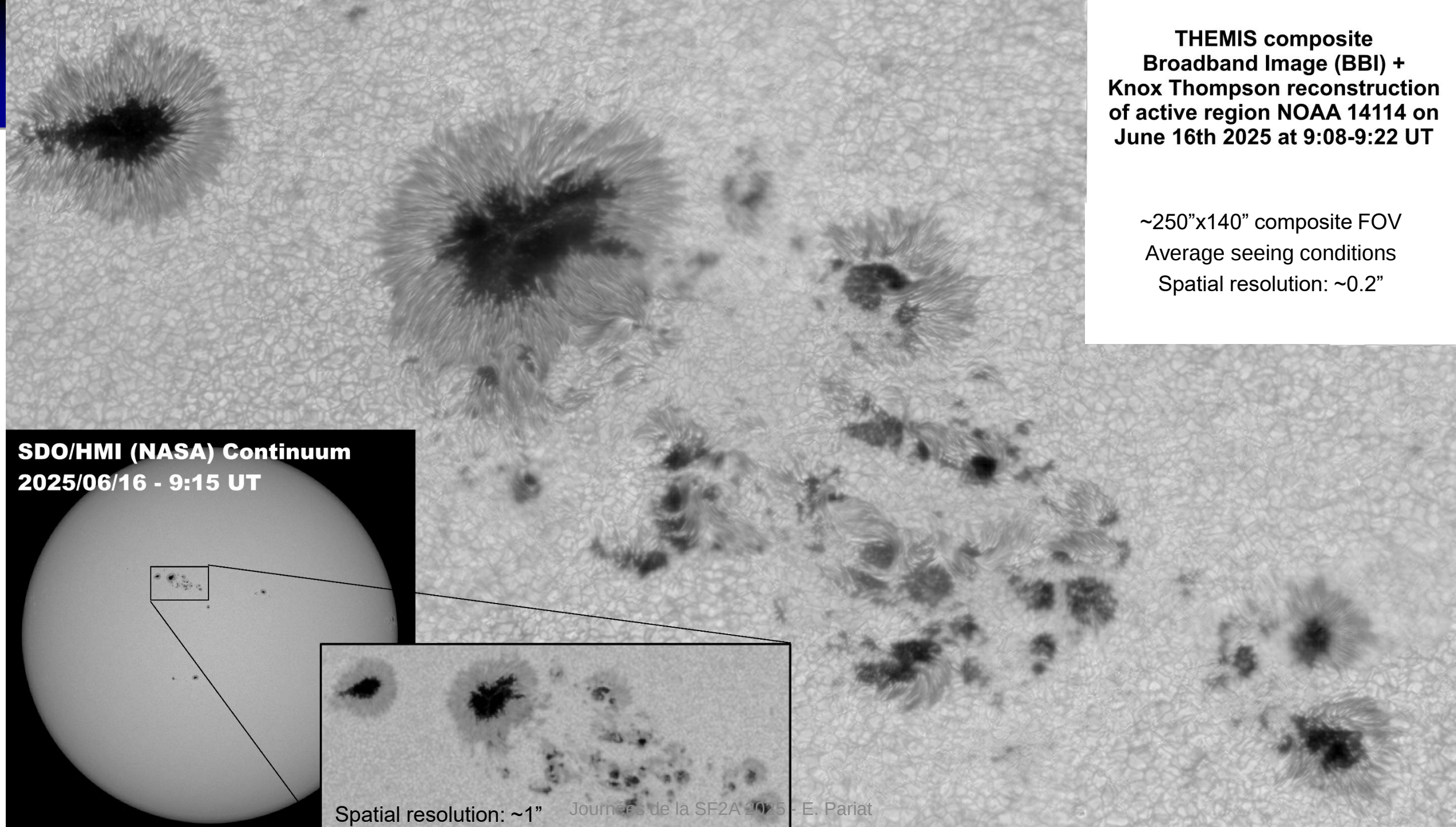
- NOAA 13354 on 2023/06/28 ; good seeing
- 150”x50” composite FOV
- **0.17’’ resolution (0.035”/pixel) near diffraction limit**
- Observed @ 630nm with 1nm broadband red filter

- **Several 55”x55” FOV acquisition by BBI camera in burst mode (40 images/s) + image restoration from residual seeing ➔ Routine operation with pipeline !**
- Images stitched together with Hugin software

THEMIS large FOV reconstruction: NOAA 14114

- Acquisition of sequential 21 BBI bursts (55x55” FOV) of NOAA 14114





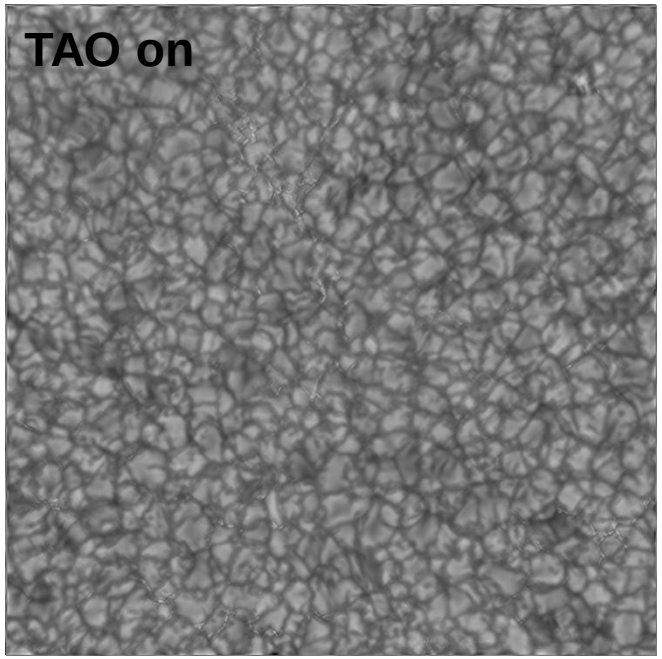
THEMIS composite Broadband Image (BBI) + Knox Thompson reconstruction of active region NOAA 14114 on June 16th 2025 at 9:08-9:22 UT

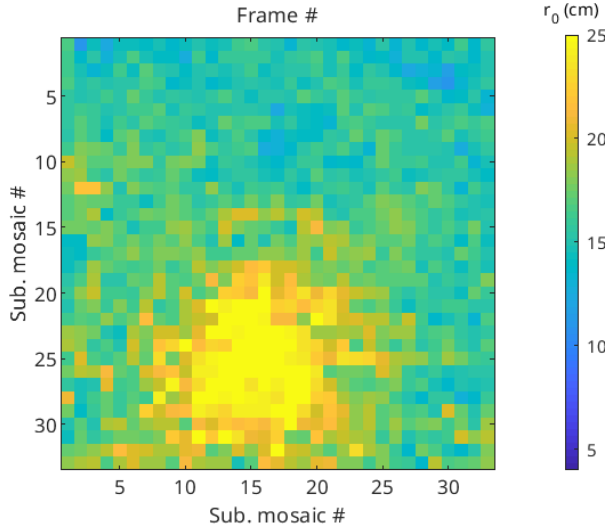
~250”x140” composite FOV

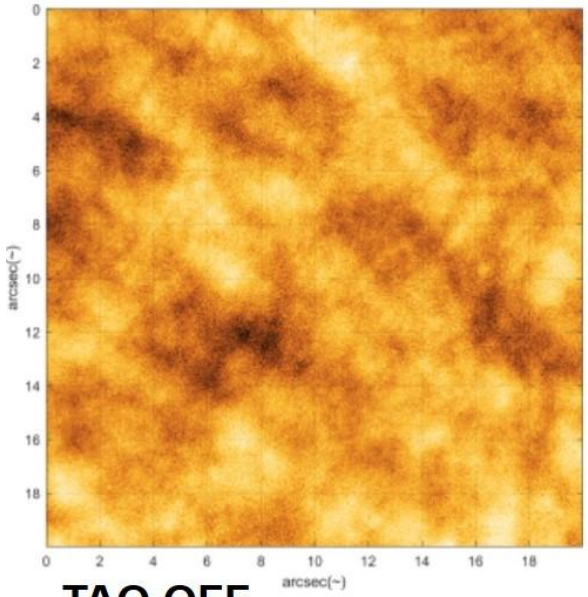
Average seeing conditions

Spatial resolution: ~0.2”

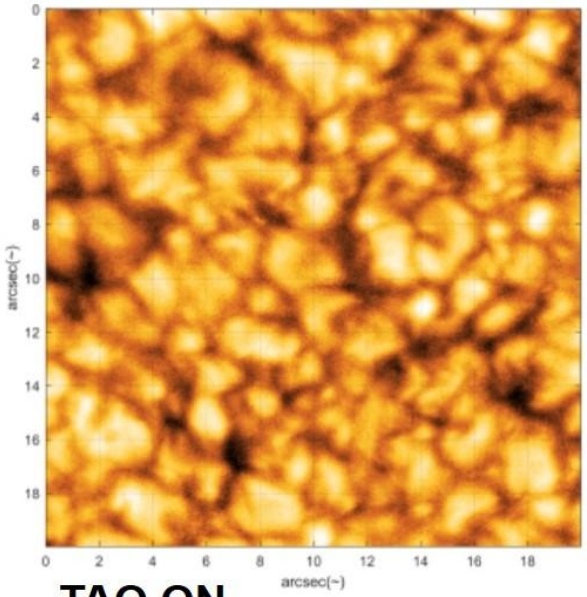
THEMIS Adaptive Optics (TAO): results on granulation



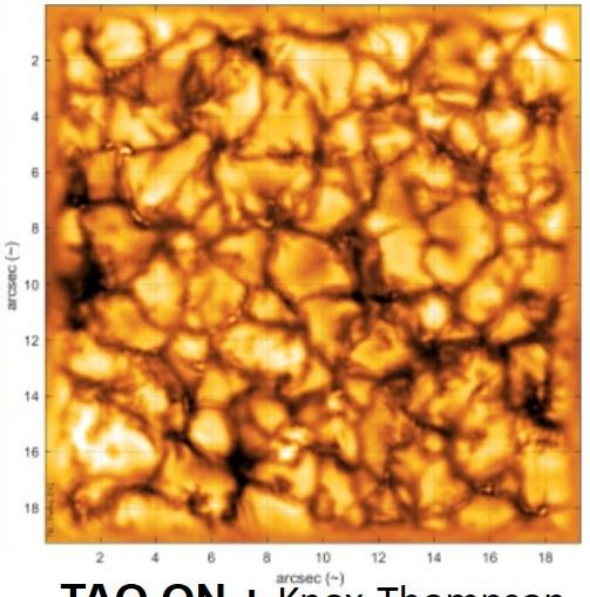




TAO OFF
- seeing "daytime bad" : $r_0 \approx$ 3-4 cm
- granulation contrast: 1.6 %



TAO ON
- seeing "daytime bad" : $r_0 \approx$ 3-4 cm
- granulation contrast: 4.2 %

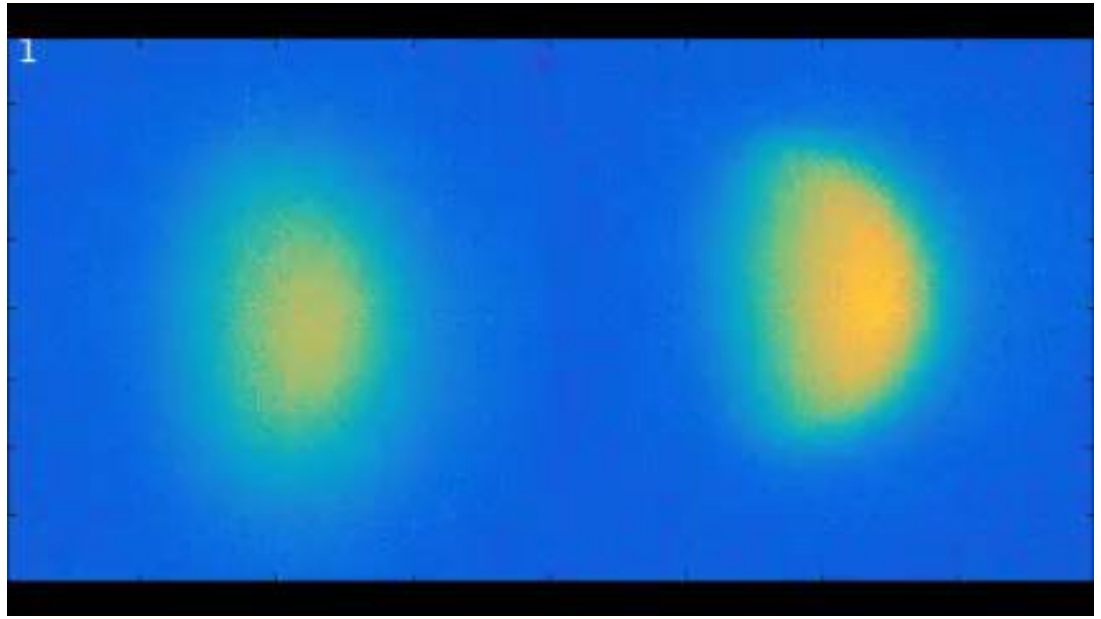


TAO ON + Knox-Thompson reconstruction (100 frames)
- granulation contrast: 9.6 %

- TAO permits significant gain:
  - in effective seeing: e.g. Fried's coherence length from ~7cm (medium seeing) to ~25cm at TAO focus & ~17cm on rest of FOV
  - in granulation contrast

THEMIS Adaptive Optics (TAO): results on Mercury

- **Themis is one of the best-suited telescope for ground based observation of Mercury.**
  - Work in daytime → extended period of observation of Mercury
  - Handle the low contrast of hermian emission relatively to the diffuse sky emission.
- TAO successfully running for Mercury observations since 2021
  - Hardware and software identical to solar obs.
  - Requires slowing down AO from 1kHz to 150Hz
- Sub-arcsecond mapping of Mercury sodium exospheric emission
  - Study hourly dynamics of Na emission distribution in regards of space weather acting on Mercury



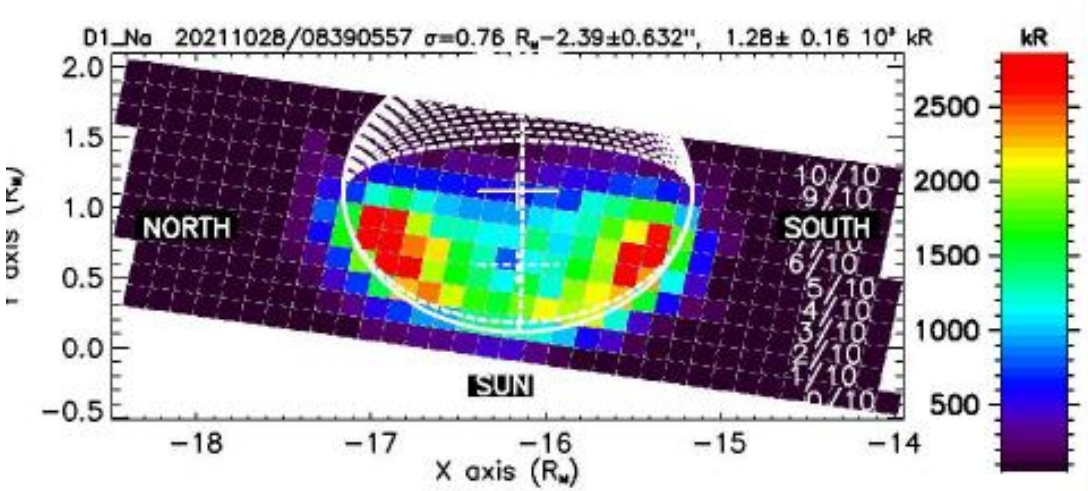


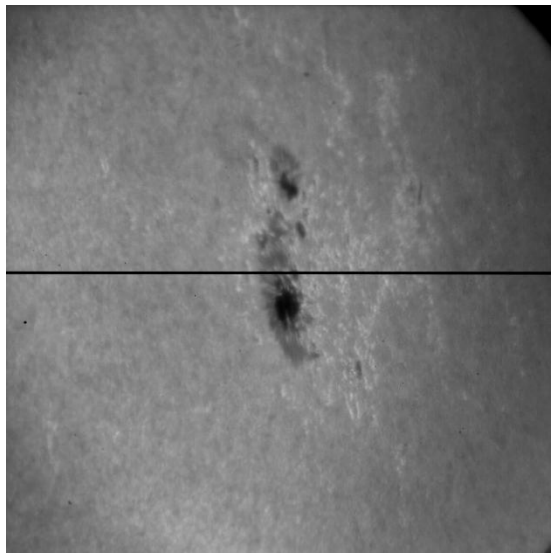
Image Courtesy: Mangano, Leblanc

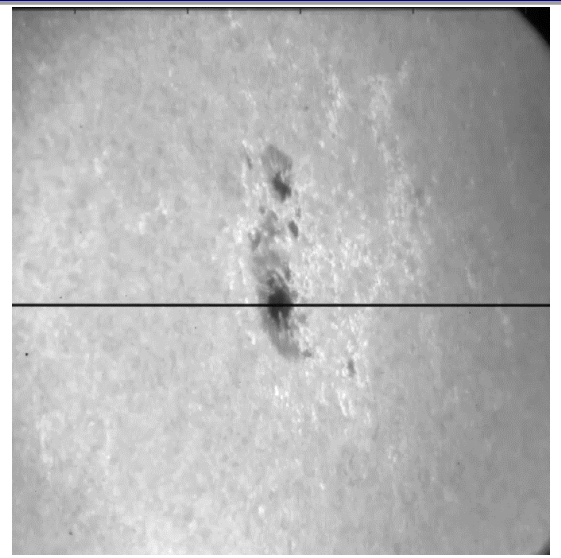
TAO for spectroscopy

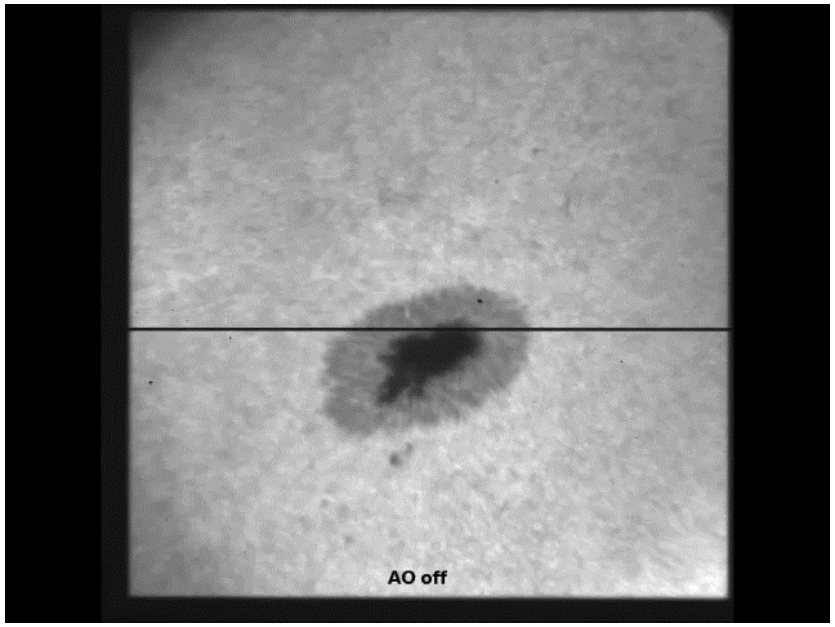
- Main strength and raison-d'être of THEMIS is spectropolarimetry!

- Requires scans of the region of interest by the spectrograph slit:
  - Scan duration of a 90" domain
    - with 0.3" steps &
    - 0.1 s spectral camera acquisition time
    - 3 min without polarimetry
    - 25 min with polarimetry

- **Spectroscopic measurement requires that TAO must hold and stabilize wavefront over FOV during extended periods of time.**

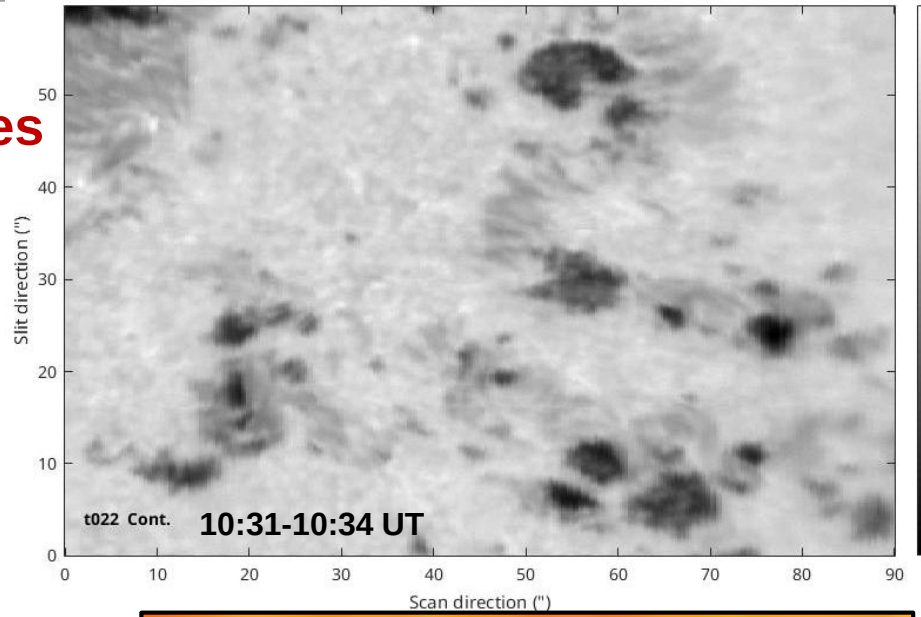


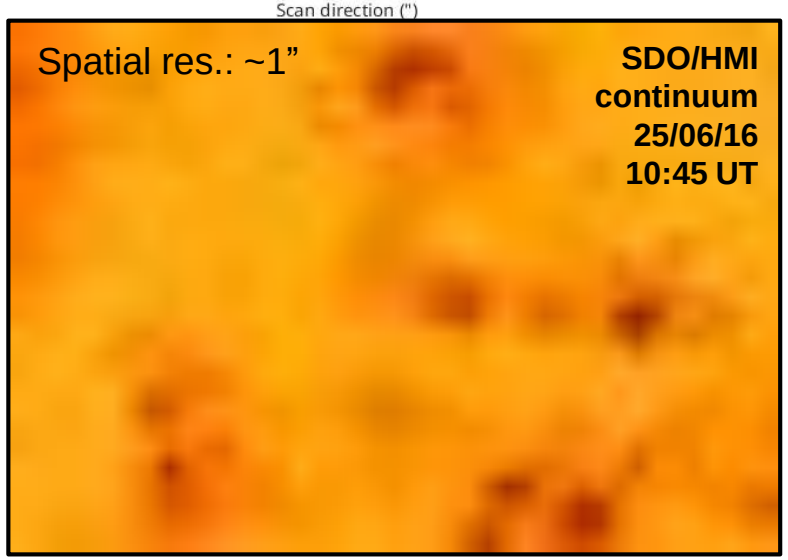


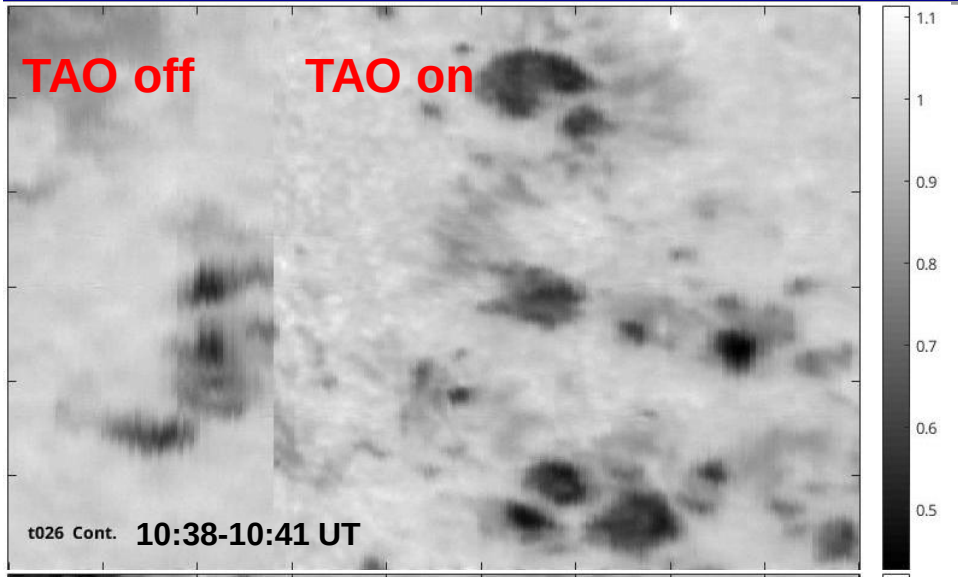


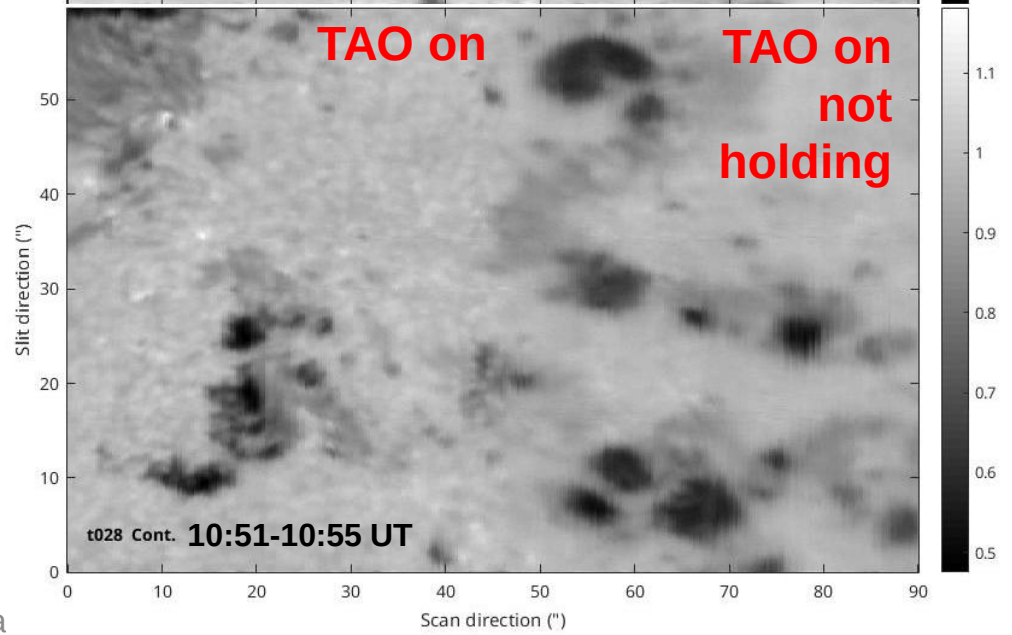
TAO for spectroscopy

- **Spectroscopic measurement requires that TAO must hold and stabilize wavefront over FOV during extended periods of time.**
- Challenging
- Isoplanatic patch away from spectrograph slit in long scan
- Stable seeing over extended period of time remains needed

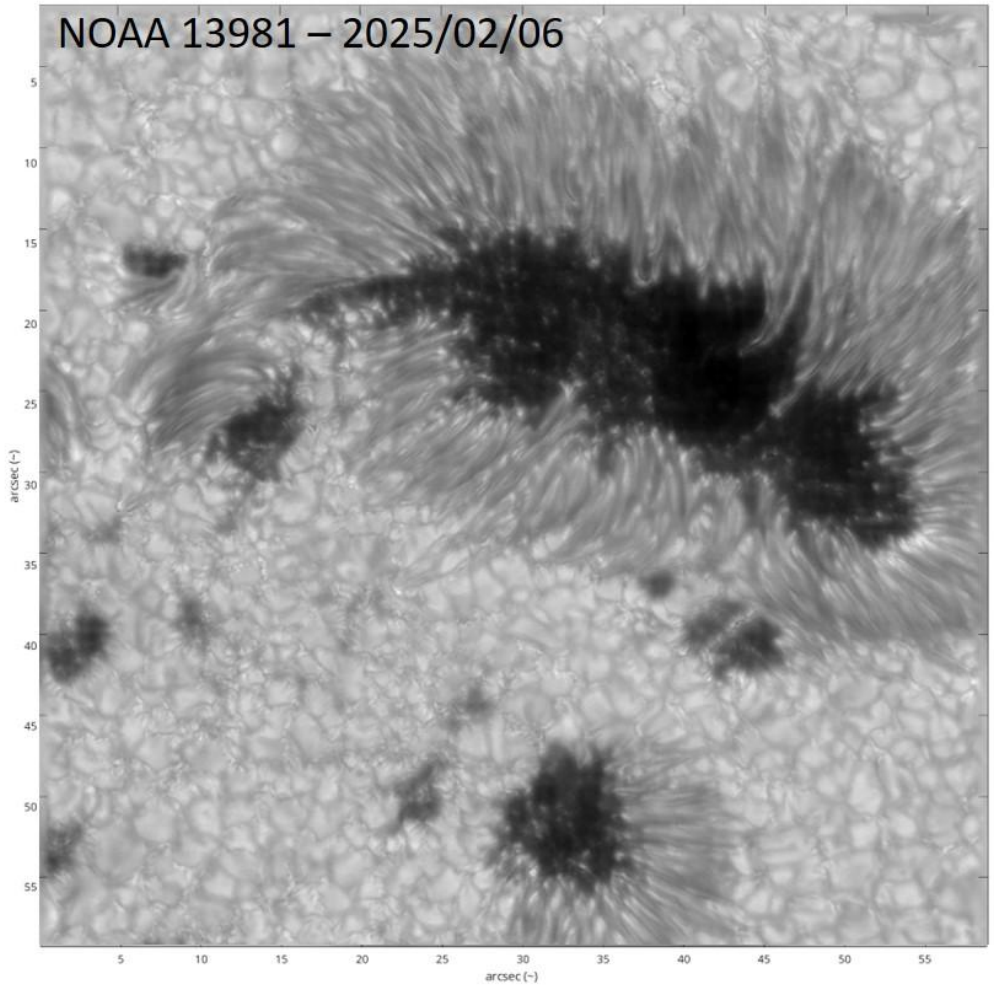




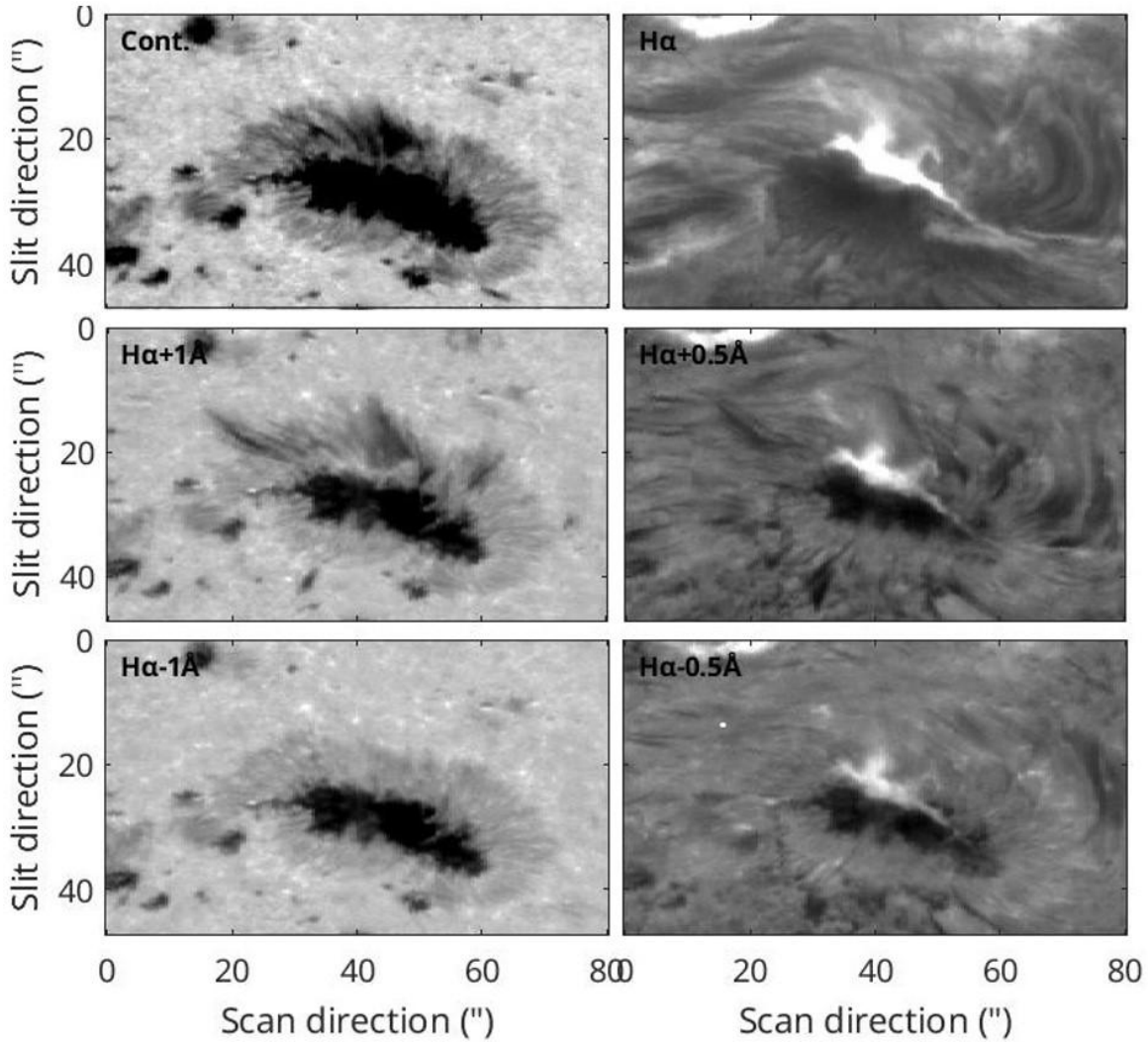




TAO for spectroscopy: good seeing conditions



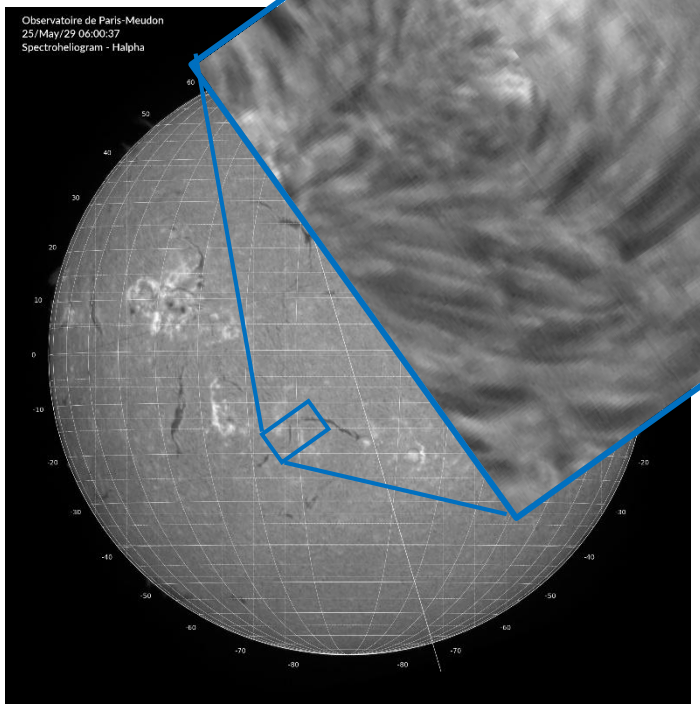
Broadband Image (red continuum)
+ image reconstruction

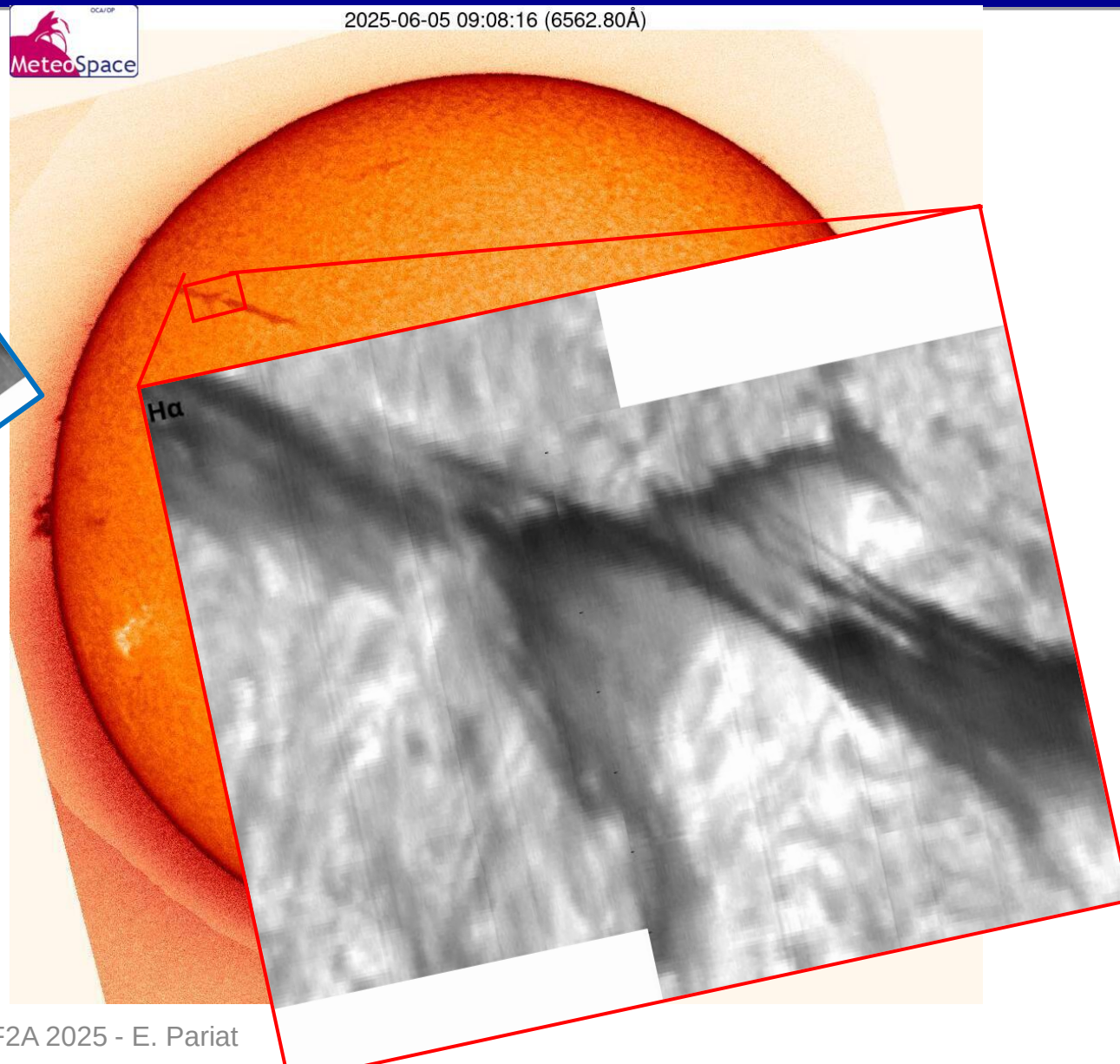


MTR2 spectrograph
reconstructed intensity maps

TAO for spectroscopy: good seeing conditions

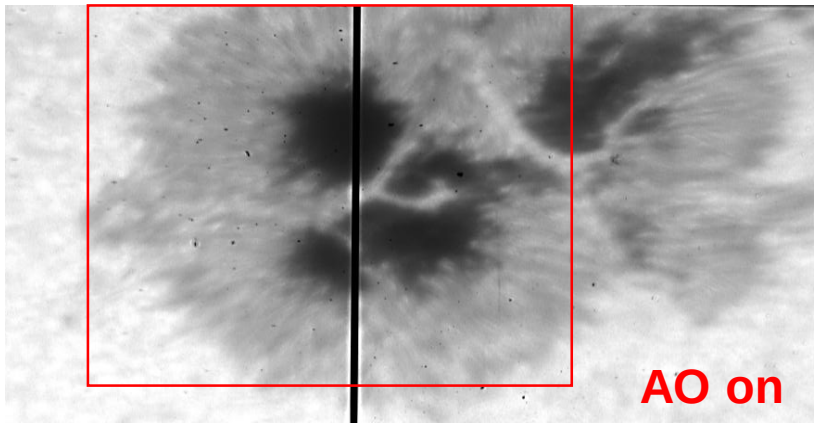
- TAO stabilization can hold over several scans
- 2-3 Hα reconstructed images of solar filaments + image stitching
  - 2025 Observations campaign of B. Schmieder

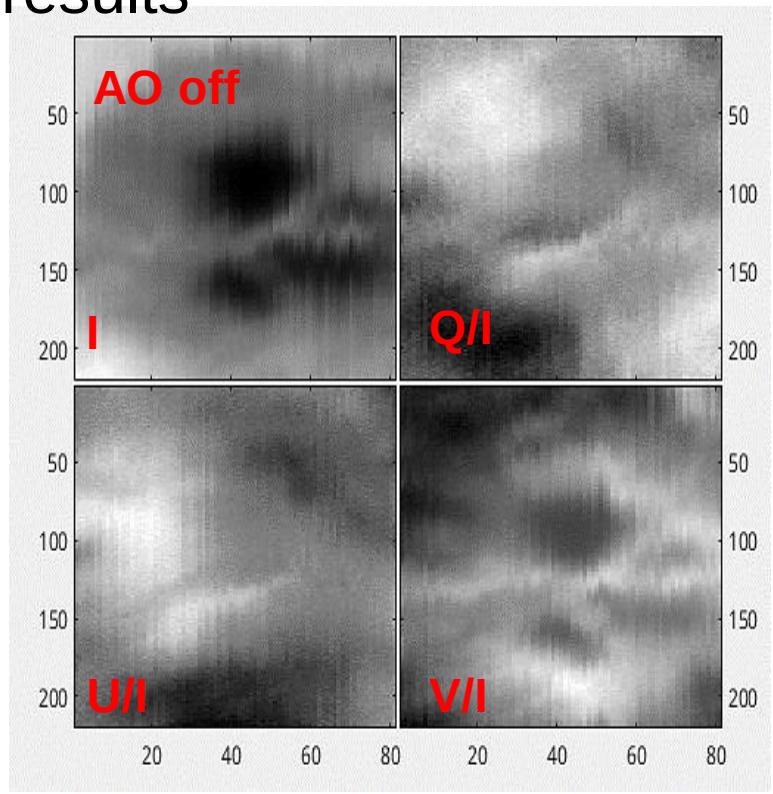


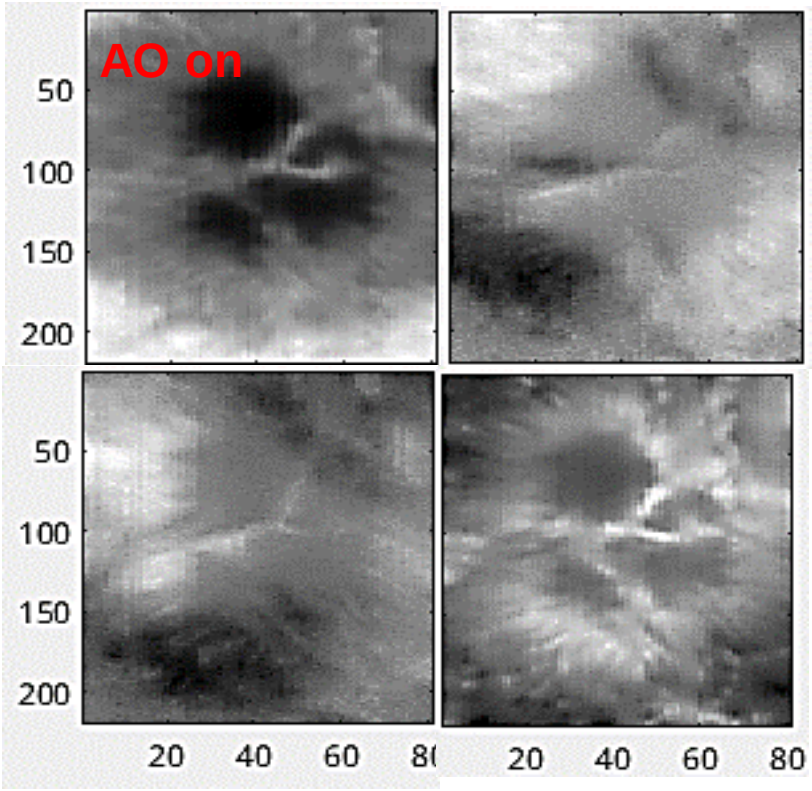


TAO for spectro-polarimetry

- TAO can also give good results on long spectropolarimetric scans
- **THEMIS goals : B maps with spatial resolution better than 0.5” arcsec**
  - 3 times better than before
  - equivalent to HINODE results

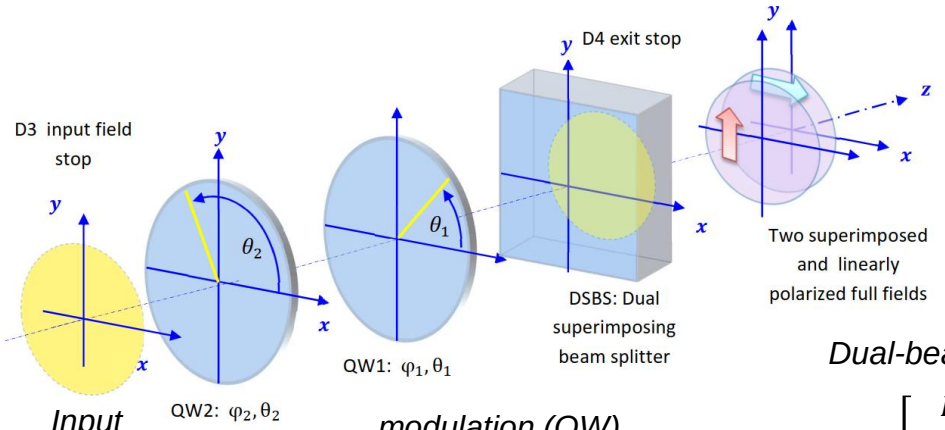






THEMIS new polarimetric analysis scheme - 1

Full-Stokes analyzer (An4) located at the F1 prime focus, delivering dual-beam polarimetry with beam exchange.



Input *modulation (QW)*

$$S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad S_Q = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad S_V = \begin{bmatrix} I \\ V \\ Q \\ U \end{bmatrix} \quad S_U = \begin{bmatrix} I \\ U \\ V \\ Q \end{bmatrix}$$

Double Savart plates:
- generate the dual beam feature
- then superimpose both beams: behave as one, differing only by their linear polarization state.

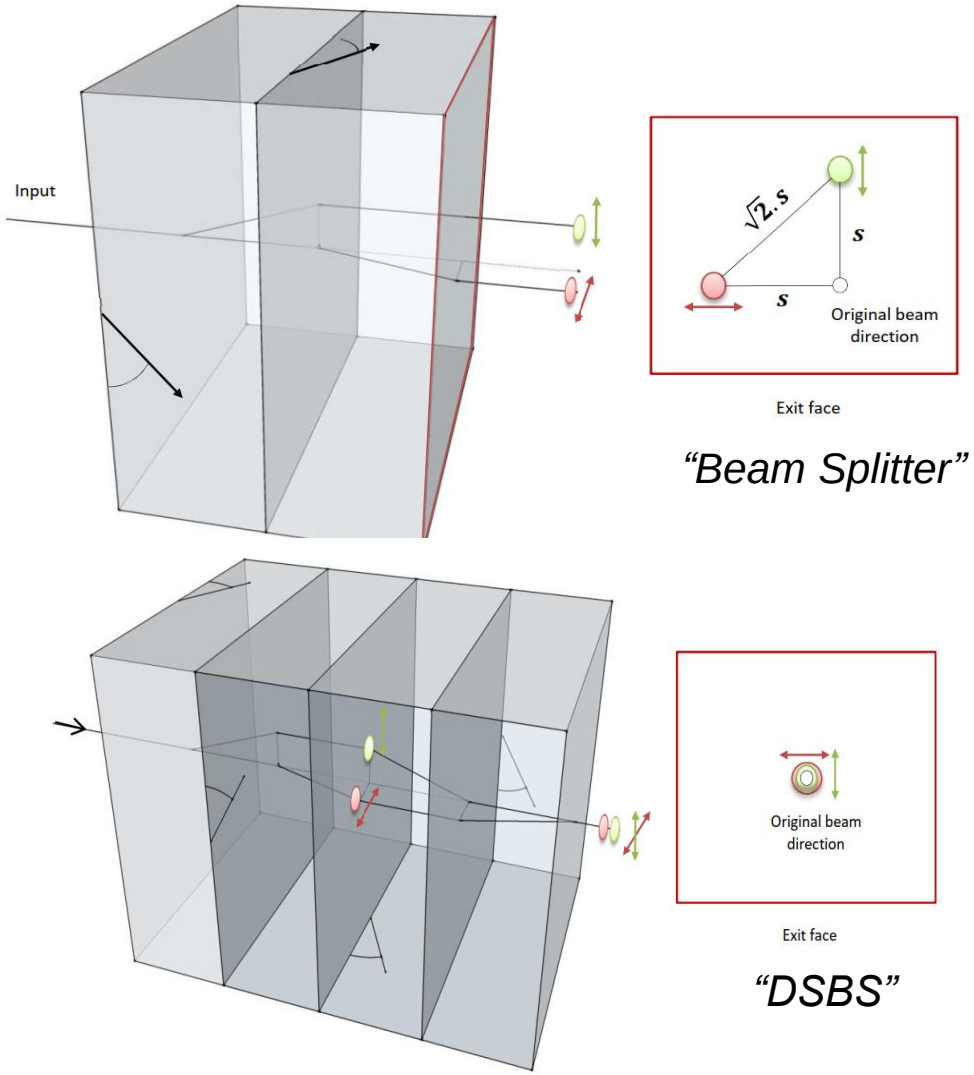
Dual-beam (single Savart plate)

$$S_{+Q} = \begin{bmatrix} I \\ +Q \\ 0 \\ 0 \end{bmatrix} \quad S_{-Q} = \begin{bmatrix} I \\ -Q \\ 0 \\ 0 \end{bmatrix}$$

$$S_{+V} = \begin{bmatrix} I \\ +V \\ 0 \\ 0 \end{bmatrix} \quad S_{-V} = \begin{bmatrix} I \\ -V \\ 0 \\ 0 \end{bmatrix}$$

$$S_{+U} = \begin{bmatrix} I \\ +U \\ 0 \\ 0 \end{bmatrix} \quad S_{-U} = \begin{bmatrix} I \\ -U \\ 0 \\ 0 \end{bmatrix}$$

Beam exchange

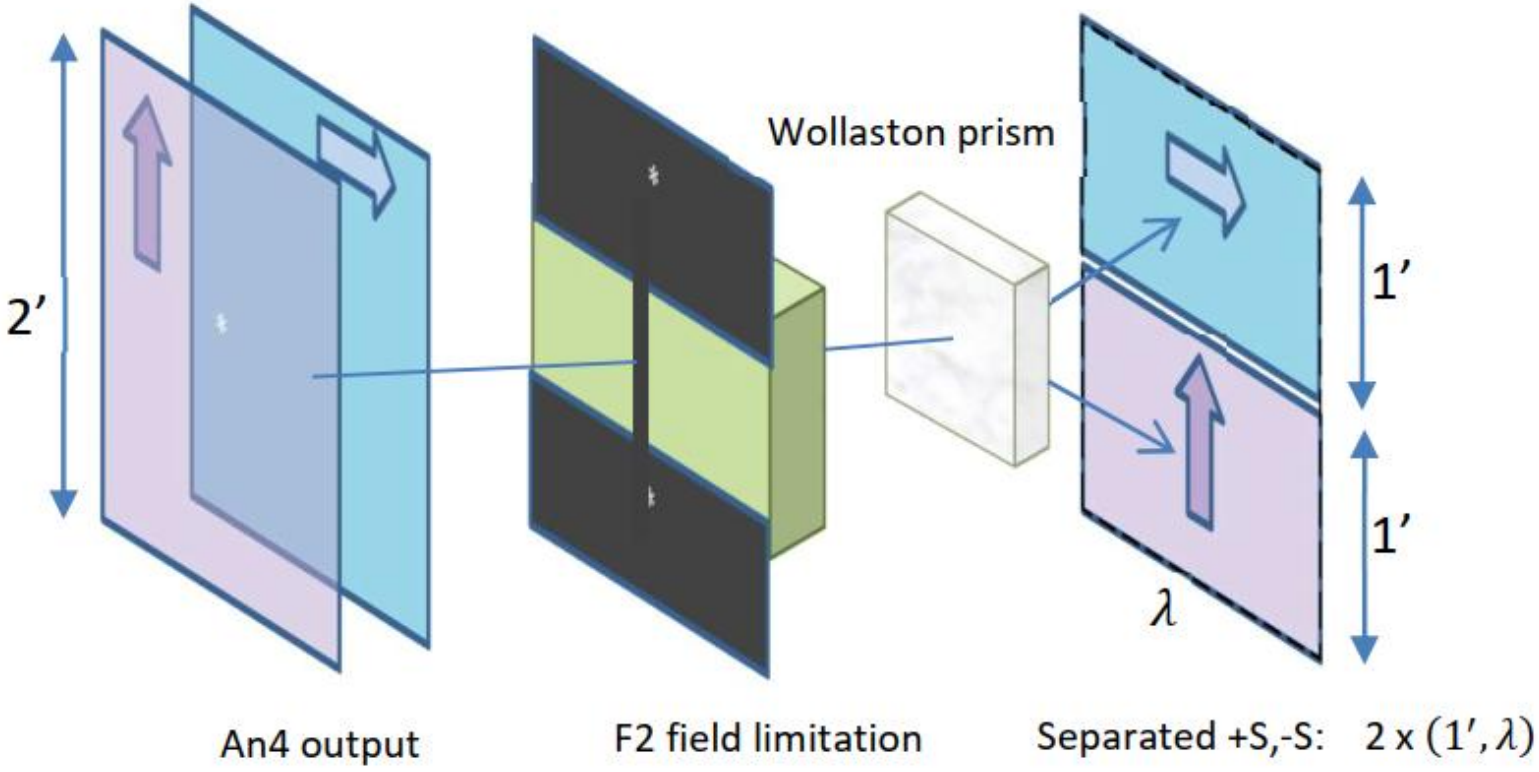


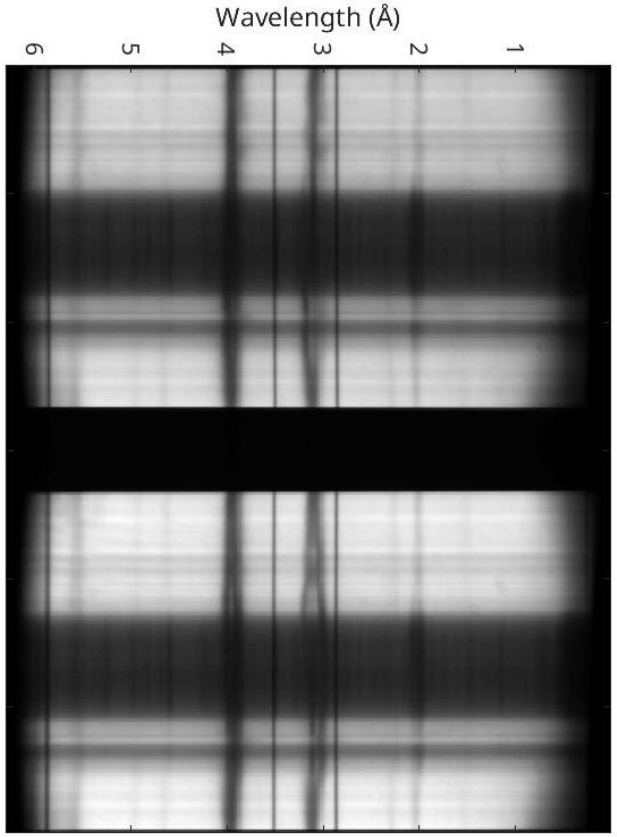
"Beam Splitter"

"DSBS"

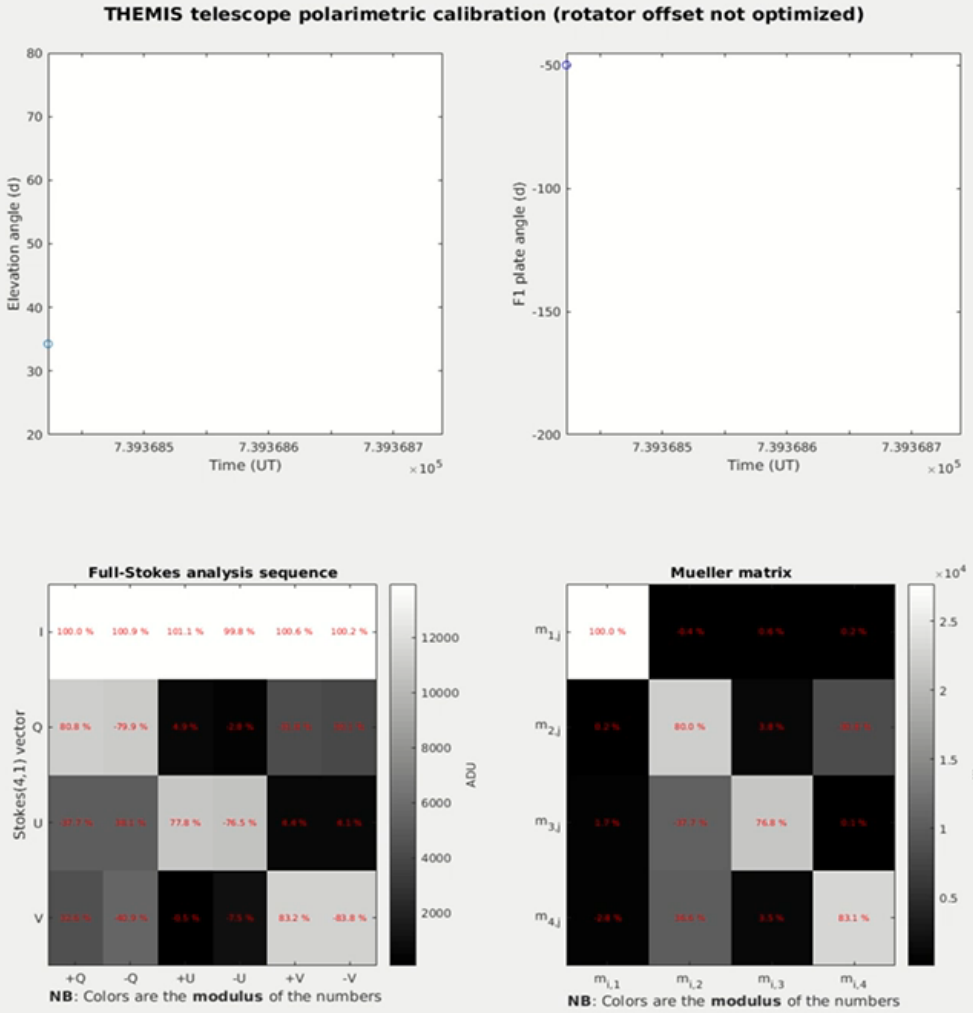
THEMIS new polarimetric analysis scheme - 2

- Thanks to THEMIS “**polarization friendly**” new optical path (**geometry of the elevation axis, field rotator, coatings)**, polarizer output can travel through the telescope and reach the spectrograph cameras “minimally perturbed”
- **Just in front of each of the spectral cameras, a Wollaston prism splitter separates the superimposed beam into complementary Stokes components** to form the spectral focal plane.





THEMIS Mueller matrix@~600nm



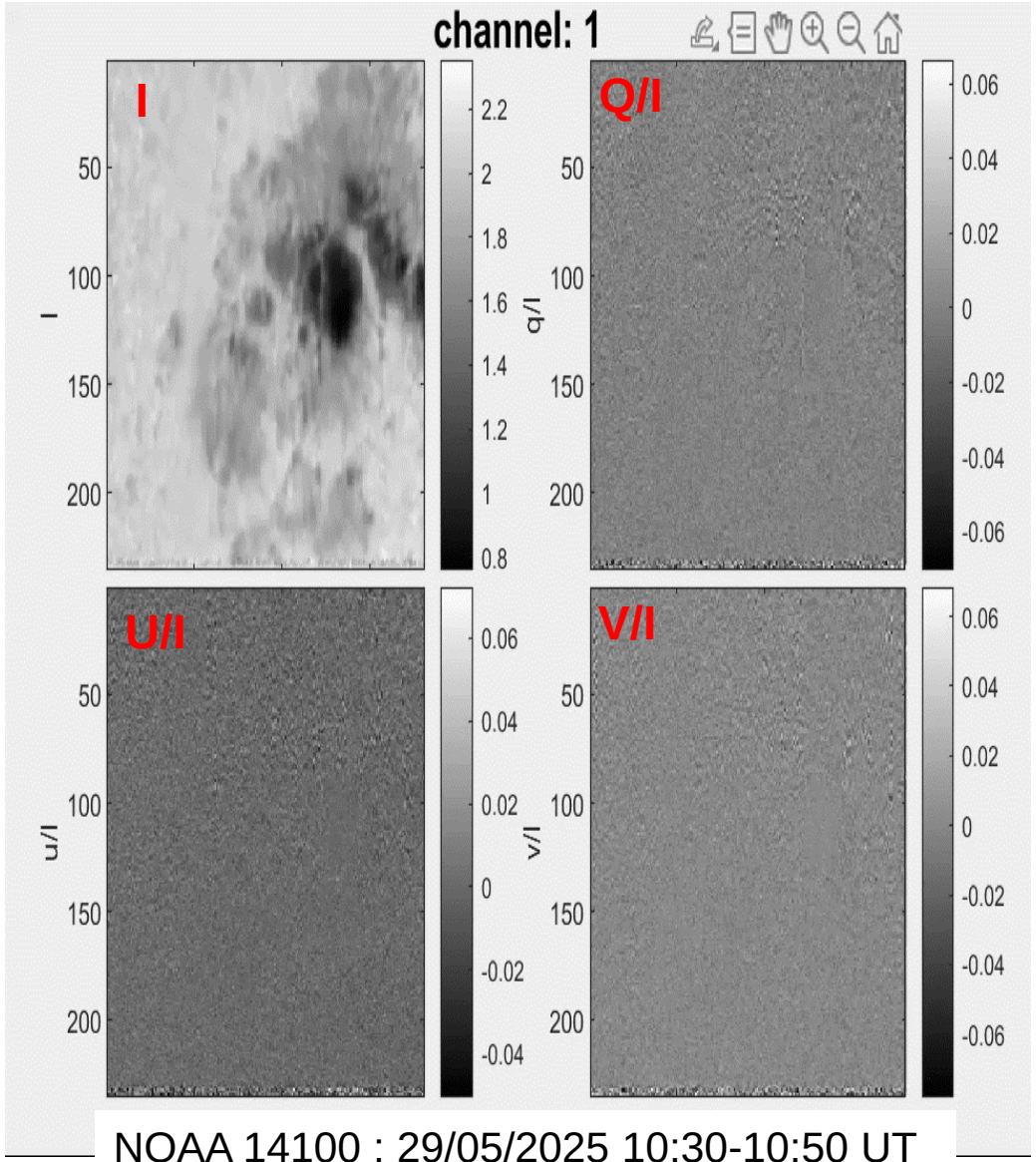
- THEMIS Mueller matrix:

$$M_{THEMIS} = \begin{pmatrix} 1.000 & -0.009 & -0.003 & 0.001 \\ -0.008 & 0.885 & 0.016 & -0.033 \\ 0.014 & -0.436 & 0.872 & 0.033 \\ -0.019 & 0.415 & 0.008 & 0.873 \end{pmatrix}$$

  - Averaged over one full day
  - Includes changing elevation axis and field derotation
  - Quite constant along one day

- **THEMIS remains a strongly polarization-calibration-free telescope, ideal for excellent spectropolarimetric measurements.**

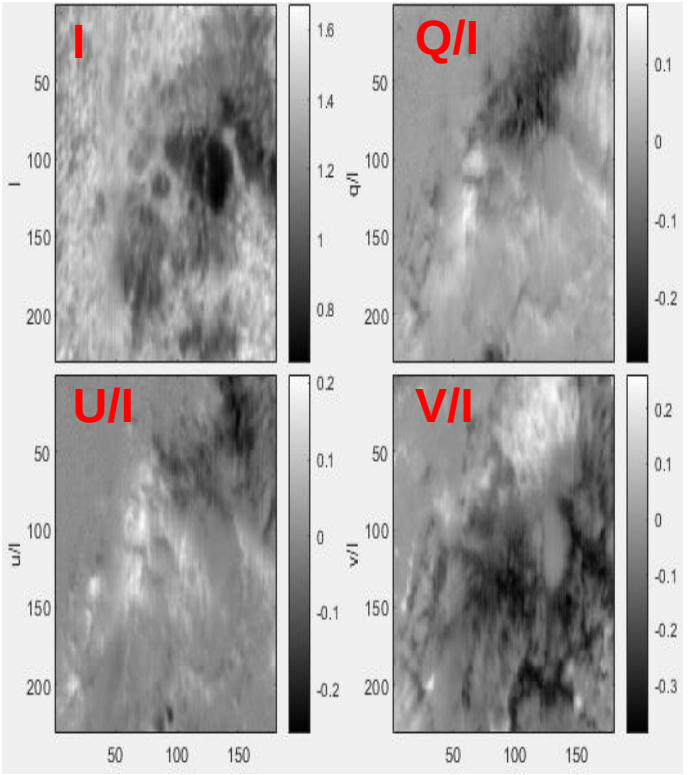
Stokes parameters



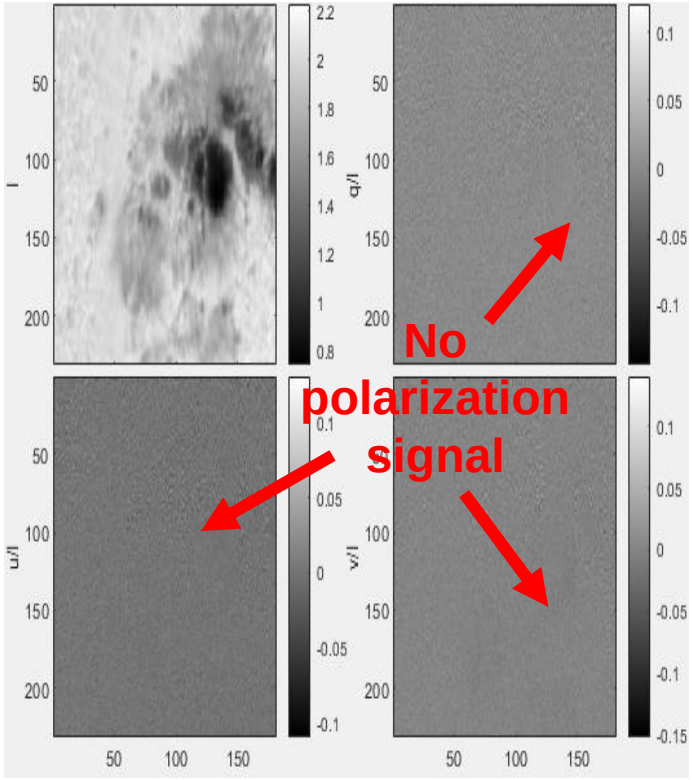
NOAA 14100 ; 29/05/2025 10:30-10:50 UT

- **Complete polarization signal is now routinely outputted**
  - 4D data array of 4 Stokes parameter (x, y, λ, S).
  - User-friendly software in development.
- THEMIS is on the verge of producing vector B maps

In Fe I Line

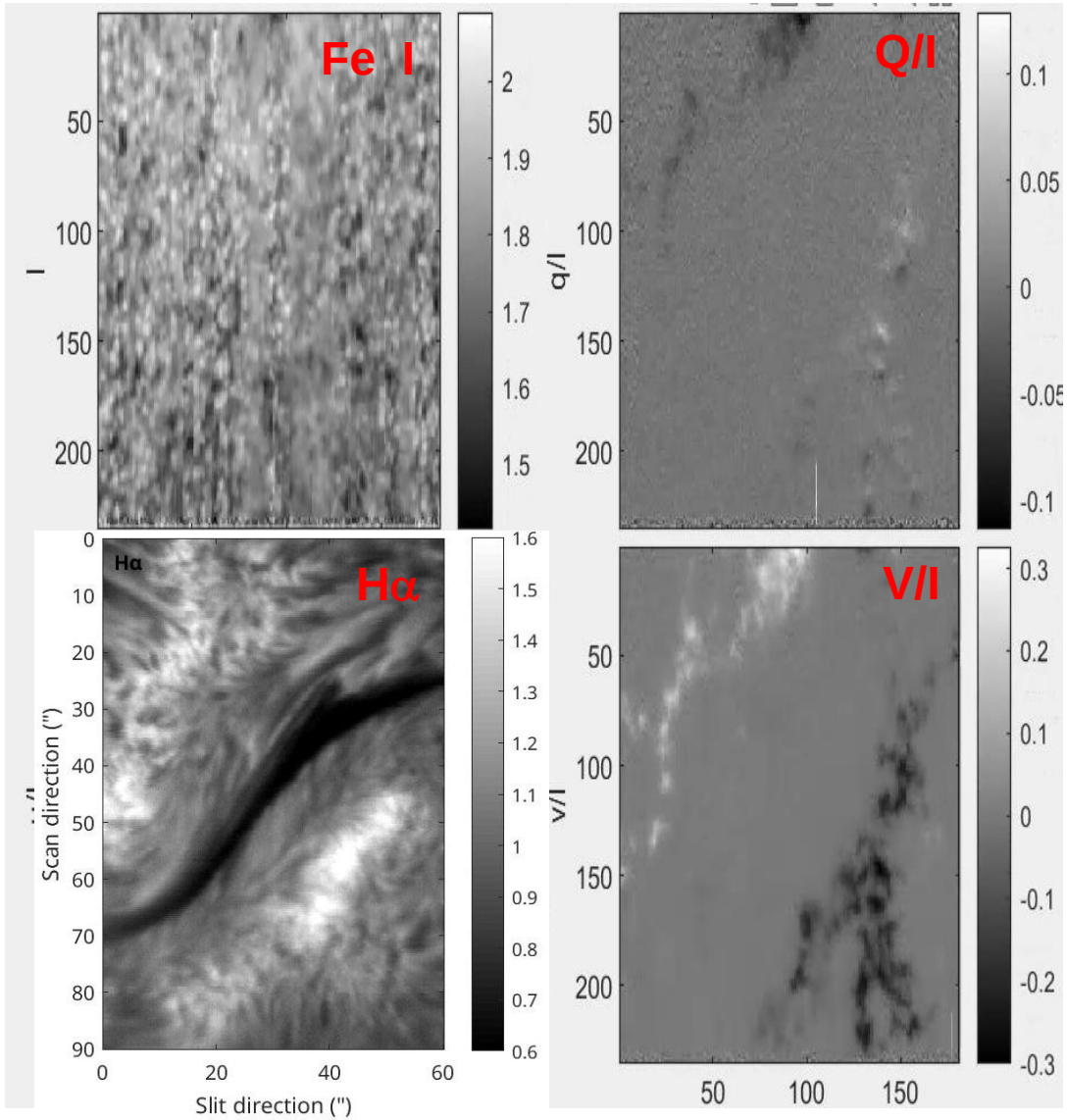


In continuum



In consideration: THEMIS for space weather

- Research for space weather is a strength of the French heliophysics community
- THEMIS shall eventually be out passed by 4m-class telescope (DKIST, EST)
- THEMIS is the main French-owned asset that can provide **B** field maps
  - Presently, high-dependence on NASA SDO/HMI for vector magnetic field measurements of EU community
- THEMIS is presently an INSU observation station (ANO-3)
  - Mutualization of several solar-related SNOs in consideration at ATST & INSU toward space weathers
- **Reflection toward part usage of THEMIS in service mode with the production of datasets of interest for SW: magnetic map of eruptive regions (active regions, filaments, …)**



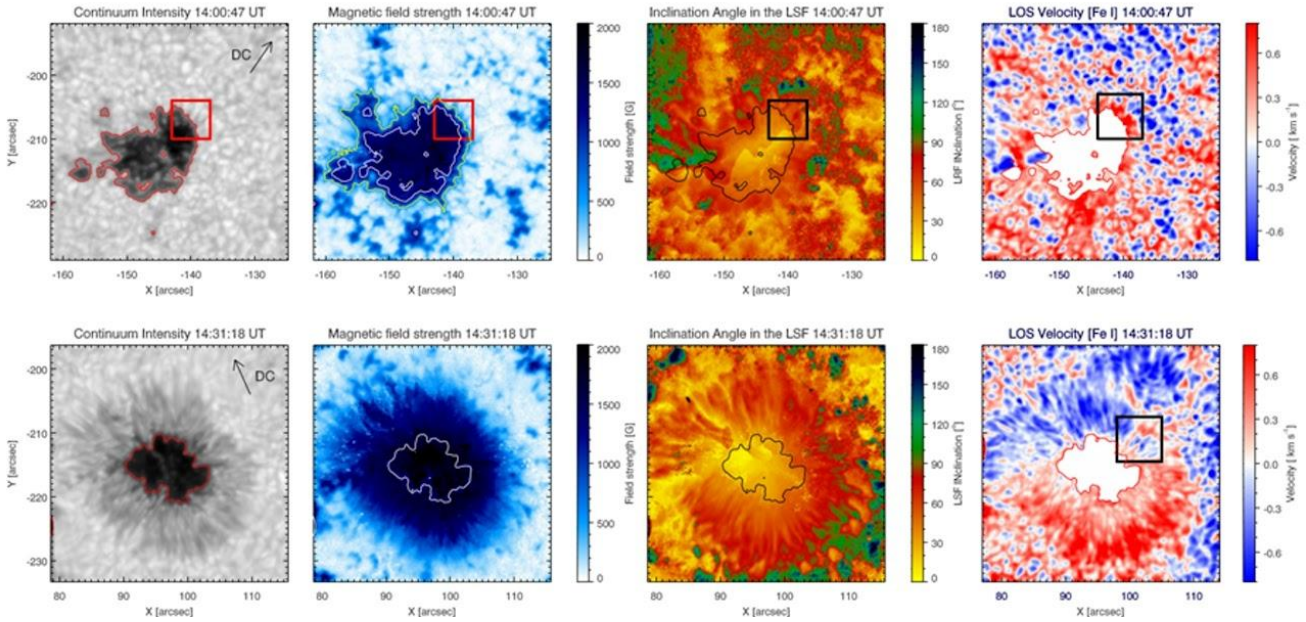
Upcoming : IBIS 2.0 to THEMIS

IBIS : Interferometric BIdimensional Spectrometer

- INAF solar spectro-imager (x, y, λ), dual Fabry-Perot / 200 000 spectral res. / short exposure times / polarimetric mode
- Running at the Dunn solar tower (DST) from 2003 to 2019: ~100 papers based on IBIS over 15 years

IBIS2.0 @THEMIS

- Upgraded IBIS waiting for suitable telescope since 2019
- TAO performance attractive for IBIS
- THEMIS has no equivalent instrumental mode. **Memorandum of understanding (MOU) signed !**
- **Winter 2025-2026 : IBIS 2.0 installation and commissioning.**



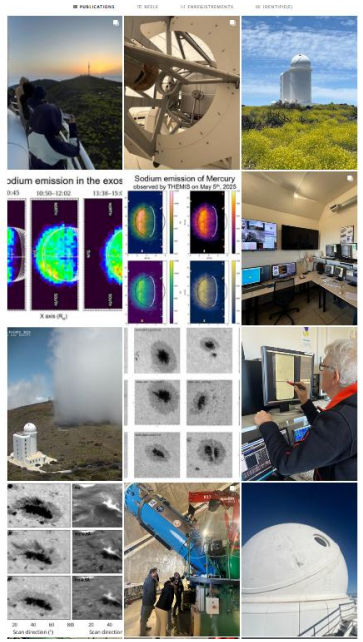
Intensity, magnetic field strength, field inclination angle, and LOS velocities on 2012 May 28 (14:00-14:30 UT): before (top) and after (bottom) penumbra formation. SIR inversion of the Stokes profiles of the Fe I 630.25 nm line acquired by IBIS. **(from Murabito et al. 2016)**

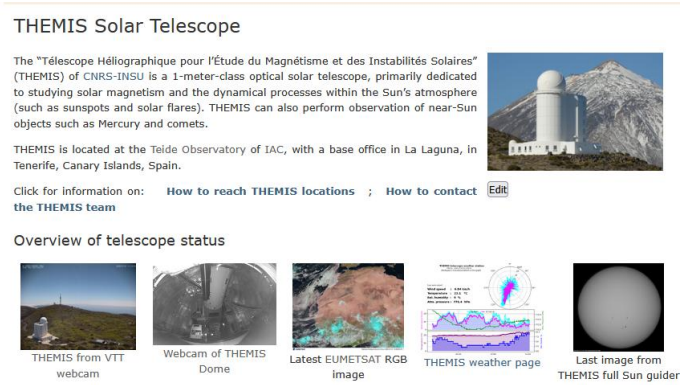
- **Outstanding synergic complement of THEMIS long slit spectrograph**
- **High scientific return for a limited technical investment**
- **Foster and renew French-Italian scientific collaboration** in high-res. solar phys.
- THEMIS offers IBIS2.0 a chance at planetary observations with AO.

Outreach

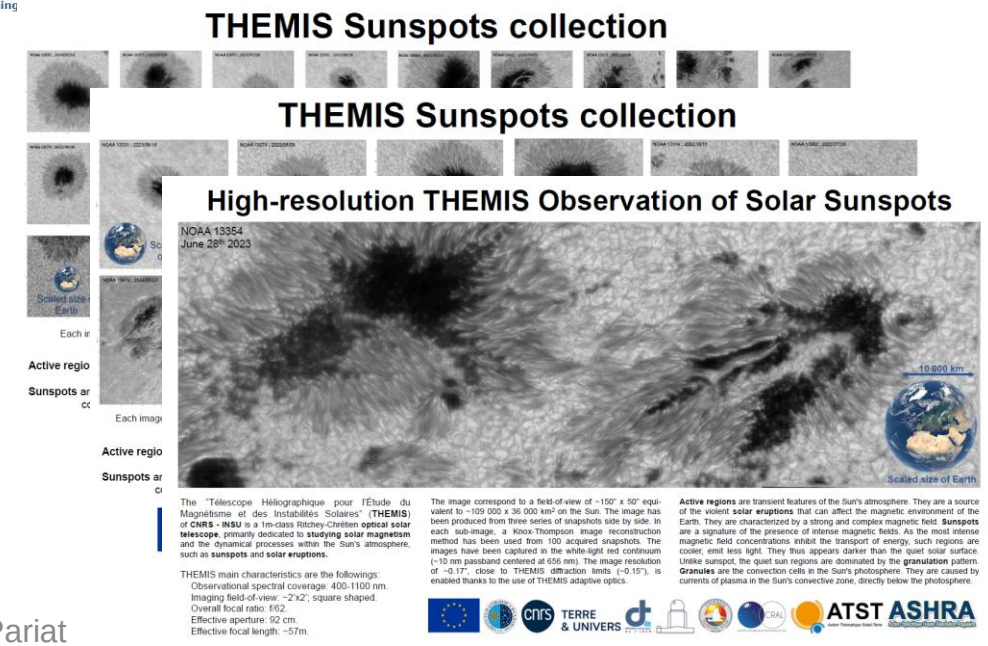
- New THEMIS website:
  - Please provide feedbacks
- New Instagram account
  - Follow us @themis_solar
- Downloadable posters on THEMIS highlights (soon)

THEMIS_SOLAR



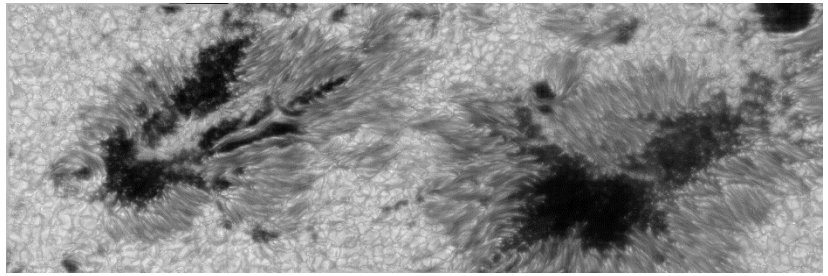


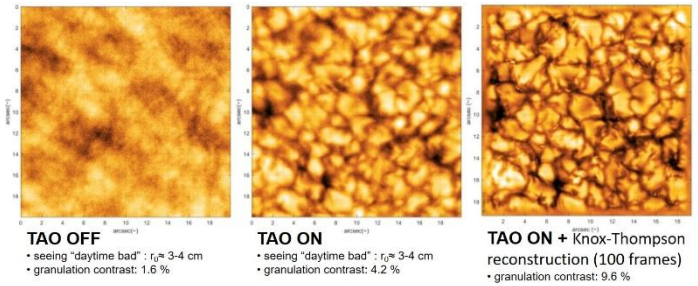
https://www.themis.iac.es/

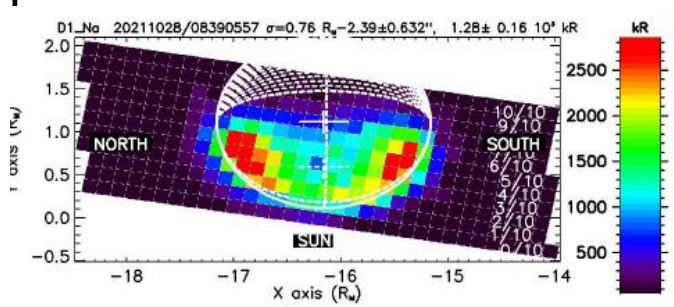


Takeaways ...

- THEMIS is a competitive 21st century telescope with unprecedented capacities
  - THEMIS is a real challenger in the 1m-1.5m class of solar telescopes.



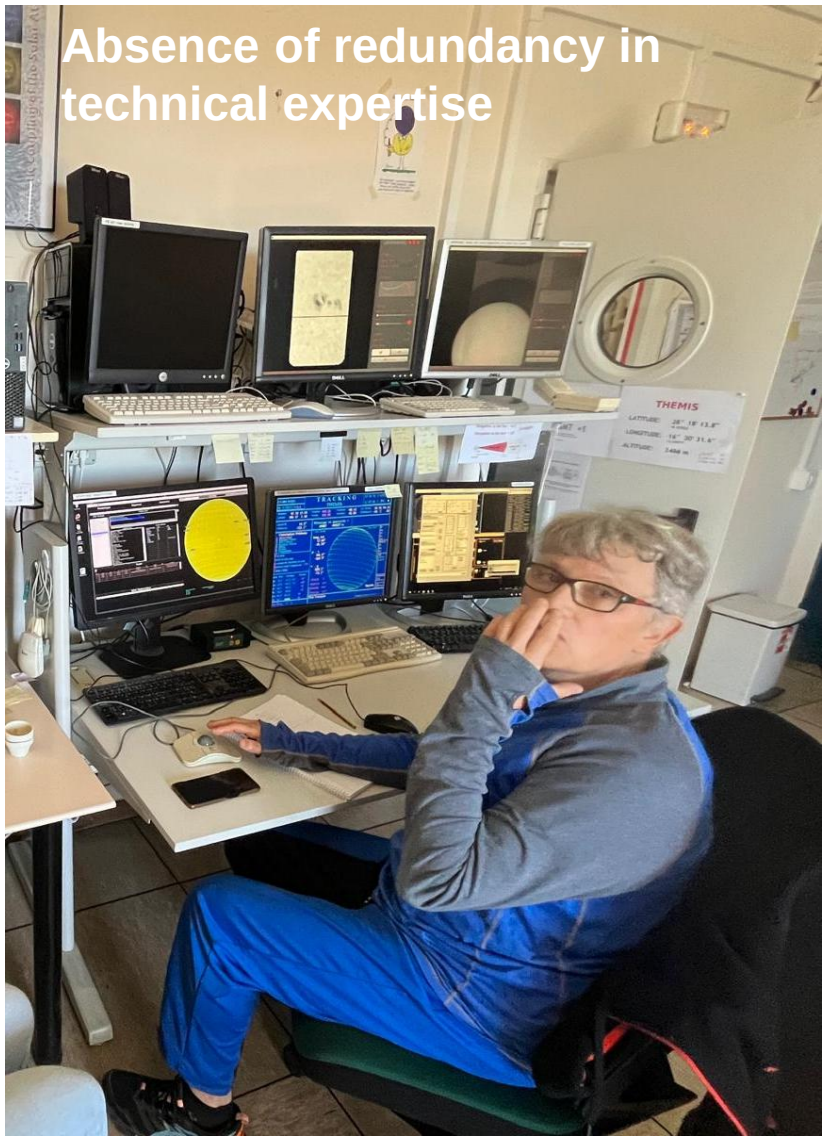




- Installation of the IBIS 2.0 spectro-imager (winter 2025-26) will trigger an even larger European wide interest.

- **Reminder: 50-75% of THEMIS obs. time dedicated to French-lab.-based PIs**
  - THEMIS is highly open to all scientists based in a French laboratory
  - Observation at THEMIS is not reserved to an elite of high-resolution spectro-polarimetry expert !
  - The THEMIS team is dedicated to assist anyone in performing observations with THEMIS
  - **Young-researchers at French laboratories are highly welcomed to discover/run/follow ground-based solar observations campaigns**

… critical threats exits …

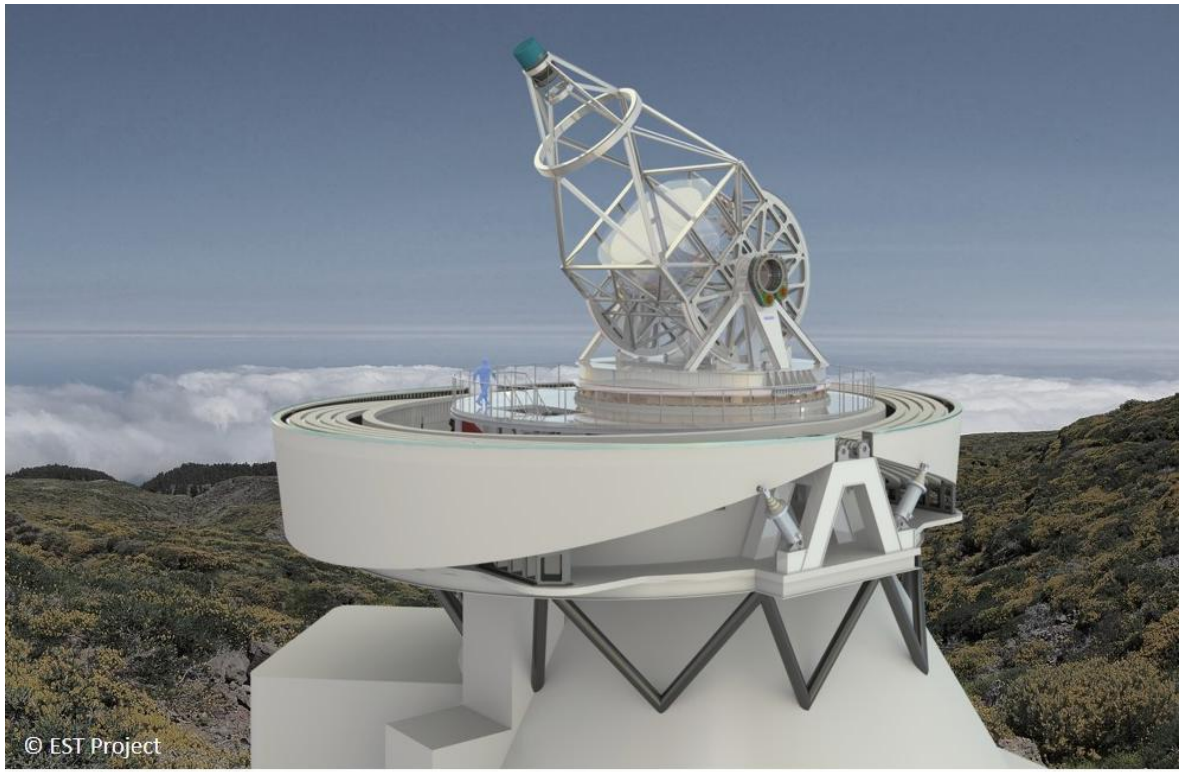


… and nevertheless !

THEMIS **IS NOT** the future of ground-based solar physics because

the European Solar Telescope

IS THIS FUTURE !



White paper on interest, contribution & participation of the French community to the EST project is being written:

JOIN NOW !

TAO linearized model of wavefront sensor data and DM commands in the THEMIS system

WFS data — Actual wavefront — Actuator commands — … some noise

$$\boldsymbol{d_t = S.(w_t + M.a_t) + z_t}$$

Sensor linear response — Mirror influence matrix

$\boldsymbol{G = S.M}$ is the **interaction matrix**

$\boldsymbol{y_t = d_t - G.a_t}$ are ≈ open loop data

$\mu_t > 0$ and $\boldsymbol{W} \approx Cov(w_t)$ are loop parameters to enforce **spatial regularization**

$\rho_t > 0$ is a loop parameter to impose **temporal continuity**

- Wavefront is represented in the basis of influence functions of the DM
- No predictions in TAO v.2 (but will appear in TAO v.3)

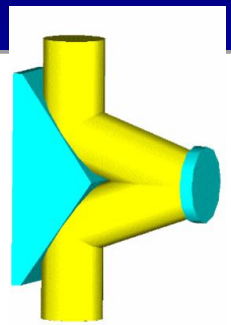
$$\boldsymbol{a_{t+\delta t}} = argmin\{ \|\boldsymbol{y_t + G.a}\|^2_{Cov(\boldsymbol{z_t})^{-1}} + \mu_t \|\boldsymbol{a}\|^2_{\boldsymbol{W}} + \rho_t \|\boldsymbol{a - a_t}\|^2 \}$$

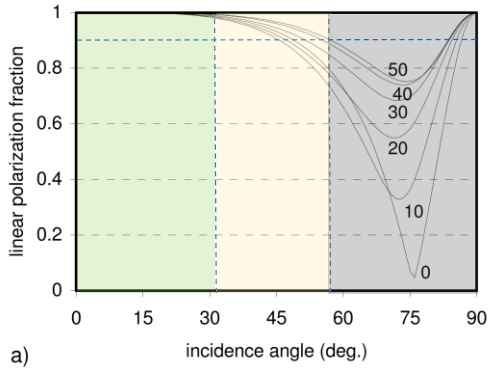
→ Requires to solve an inverse problem (*argmin*…) at each step (all terms may change with time)

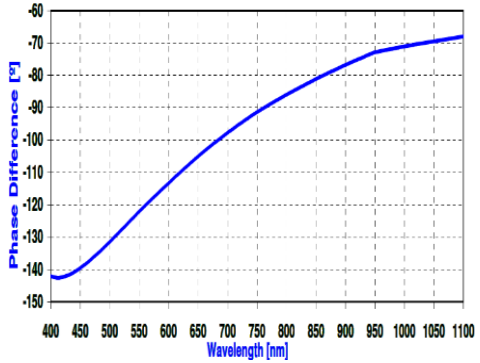
Thiebaut, E., Tallon, M. et al, SPIE proceedings 2

Example of a "polarization friendly" field rotator

- **BAD (really bad …)**
- Made of 3 mirrors with incidence = **55º** / 20° / **55°**
- chromatic retardance is enormous (60°)

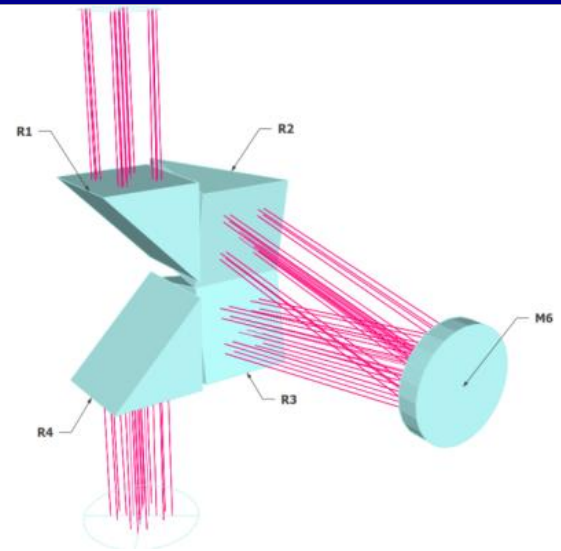


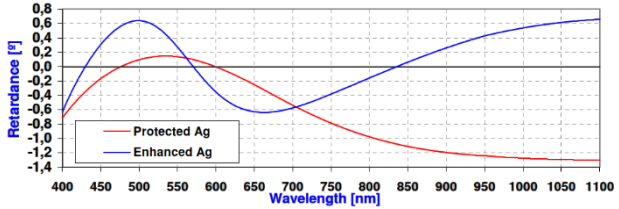




$$\mathrm{M}_{Rot}(Ag) = \begin{bmatrix} 0.943 & 0.057 & 0 & 0 \\ 0.057 & 0.943 & 0 & 0 \\ 0 & 0 & 0.007 & -0.941 \\ 0 & 0 & 0.941 & 0.007 \end{bmatrix}$$

- **MUCH BETTER !!**
- Rotator, composed of 2 prisms and one mirror incidence=45º /45°/ 10° / 45° /45°
- **Retardance cancellation** of the crossed prisms@100° (zero retardance for 90° only)
- **Coating required** on prisms hypothenuse





$$\mathrm{M}_{ROT} = \begin{bmatrix} 0.9991 & 0.0009 & 0 & 0 \\ 0.0009 & 0.9859 & -0.0205 & 0.1605 \\ 0 & 0.0179 & 0.9989 & 0.0189 \\ 0 & -0.1607 & -0.0157 & 0.9859 \end{bmatrix}$$