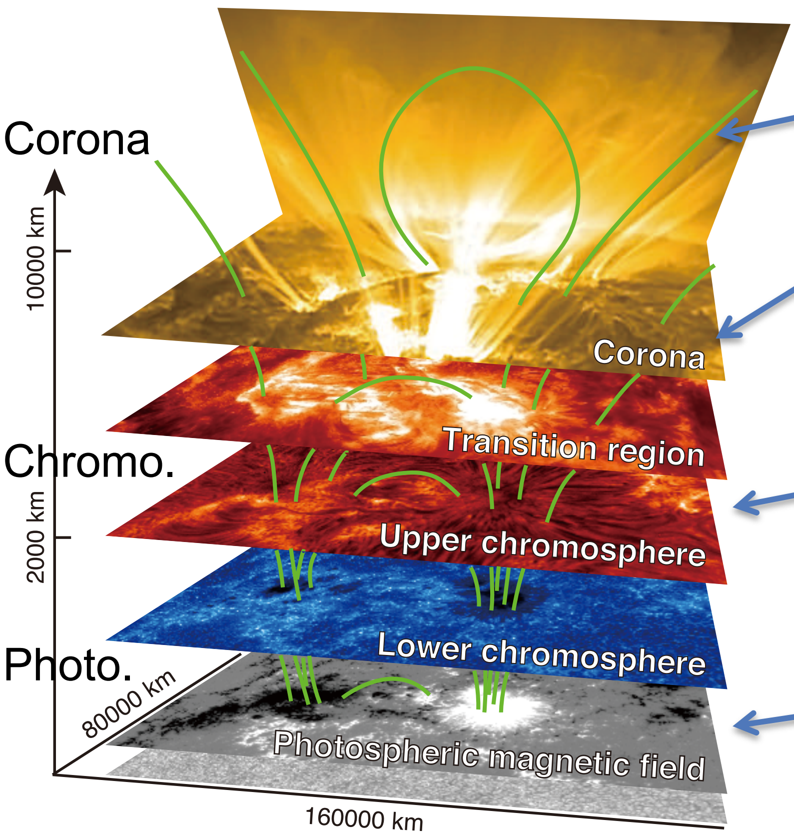
Achievement in Solar Astronomy

KATSUKAWA Yukio
(NAOJ)

Thanks to H. Hara, R. Ishikawa, RT. Ishikawa, T. J. Okamoto, M. Shoda, and M. Yoshida

Targets of solar-stellar research



Solar-stellar wind

Corona-chromosphere heating

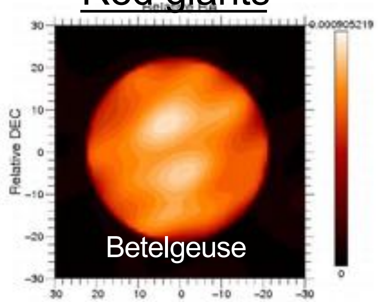
Energy transfer

Generation of NT energy by turbulent convection

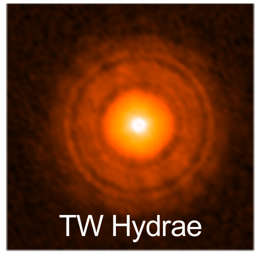
Common mechanism are working in many objects

Red dwarfs

Red giants

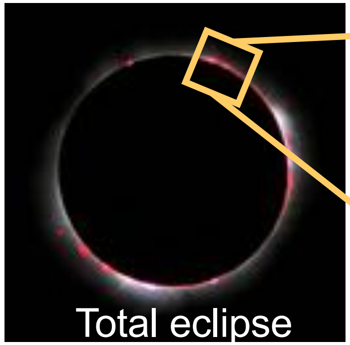


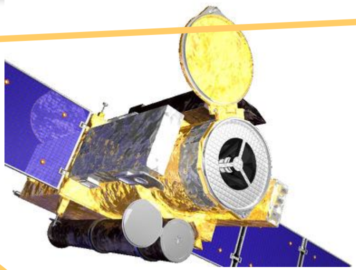
Protoplanetary disk



The Sun is only a star that can be studied with detailed temporal-spatial resolution.

Measurement of magnetic fields to understand active atmosphere

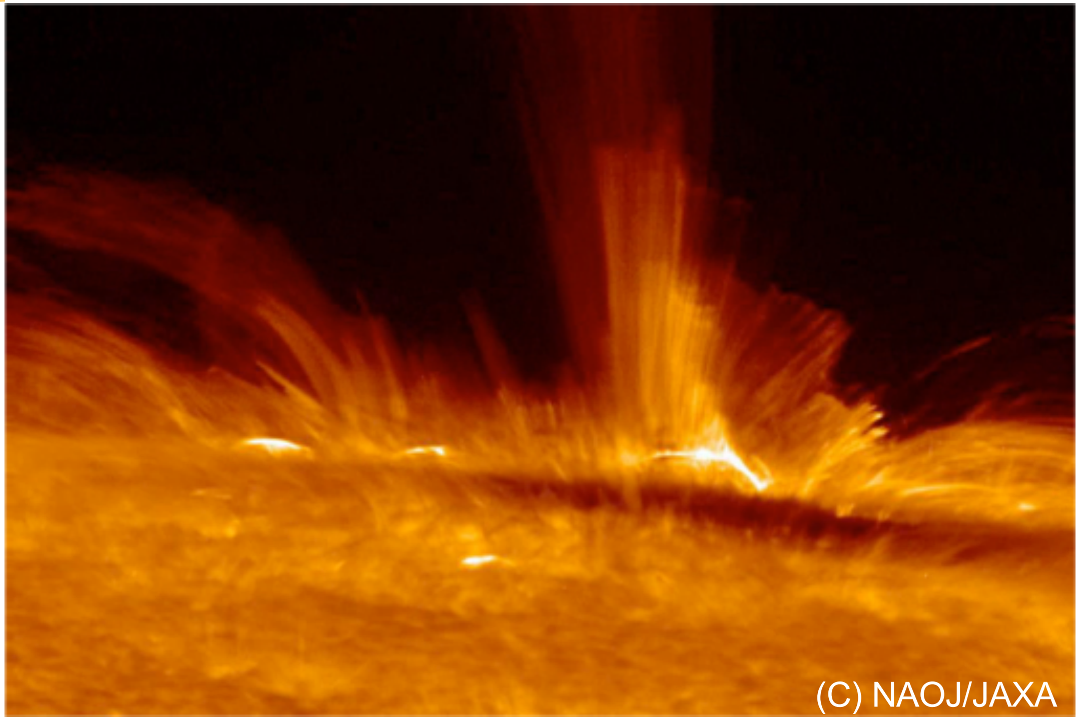




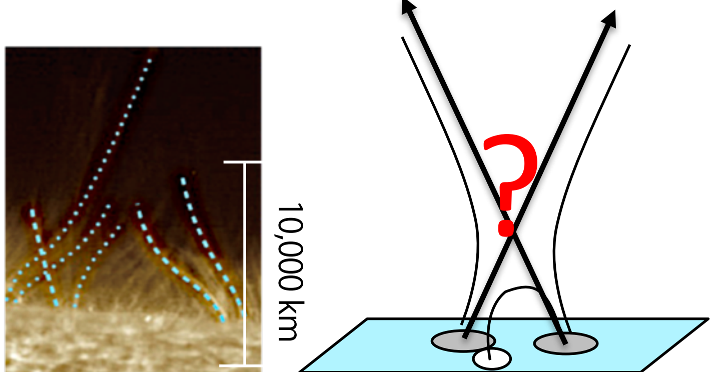
HINODE
(2006–)

Dynamical phenomena responsible for energy transfer and dissipation.

- Jets, shocks, MHD wave and its mode conversion.



Imaging obs of the chromosphere by HINODE



$$E \approx 10^{25}\,\mathrm{erg} = \frac{1}{8\pi}\Delta B^2 V = \frac{1}{8\pi}(\sim 100\ \mathrm{G})^2(\sim 300\,\mathrm{km})^3$$

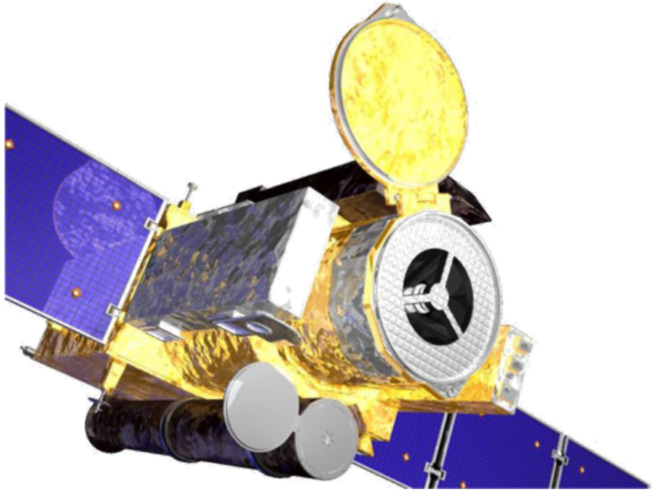
Change of B

Spatial scale

Frontier in solar–stellear obs

Spectro and polari obs to get quantitative information (B, T, v,,) at the site

Projects in the solar physics group



HINODE (2006-, 13 years old)

Nobeyama Radio Heliograph (1992-) and Polarimeter

(C) US Army Photo, White Sands Missile Range

CLASP/CLASP2 (2015, 2019)

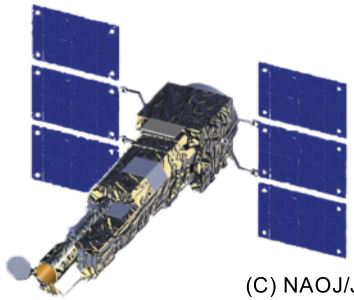
FOXSI-3 (2018)

(C) MPS

SUNRISE-3 (2022)

Solar Flare Telescope (1990-)
IR magnetrograph (2010-)

ALMA solar (2016-)



(C) NAOJ/JAXA

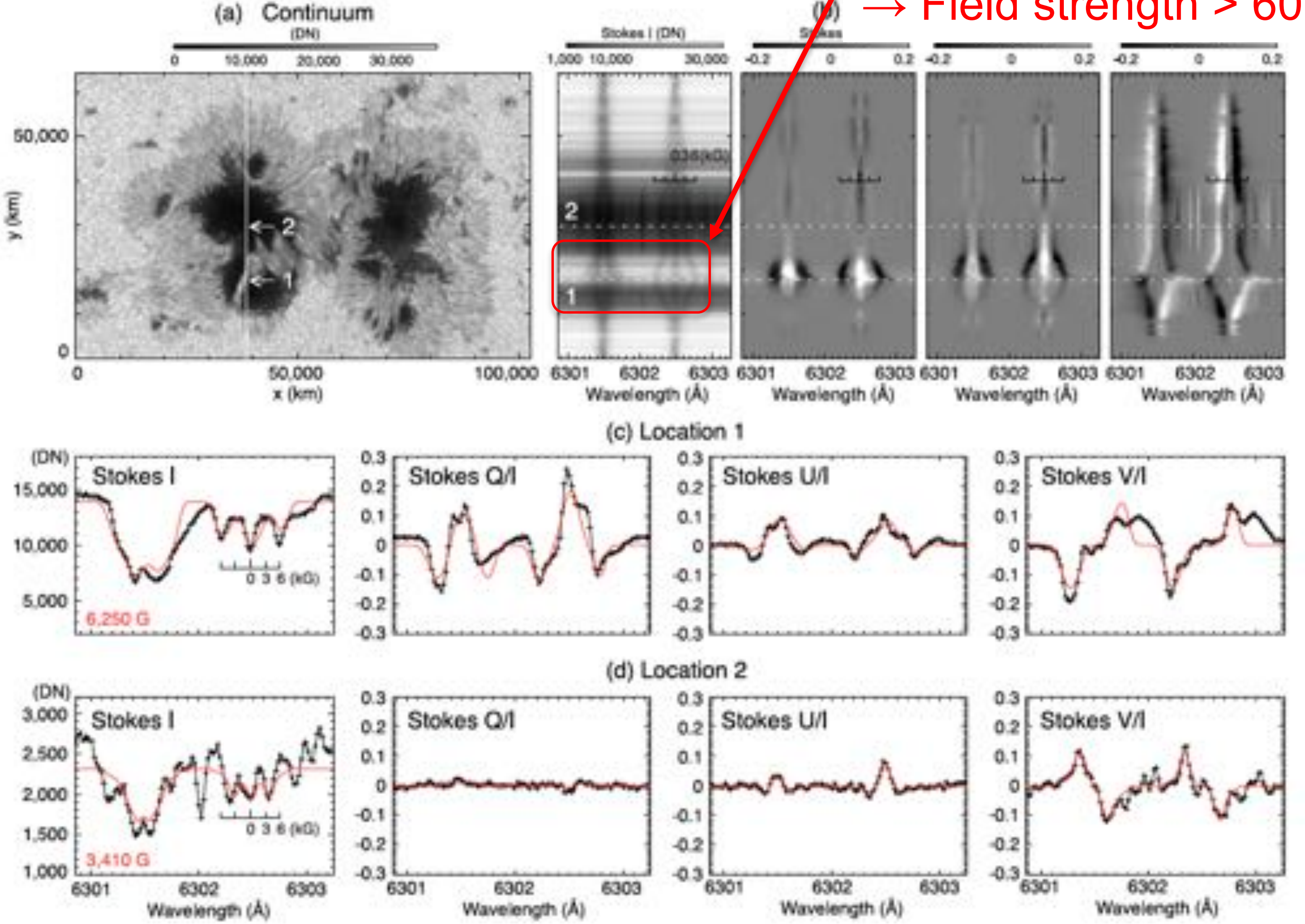
Solar-C_EUVST

NOTE: I picked up scientific results according to my interest.

Super-strong magnetic fields in a sunspot

Okamoto and Sakurai (2018, ApJL)

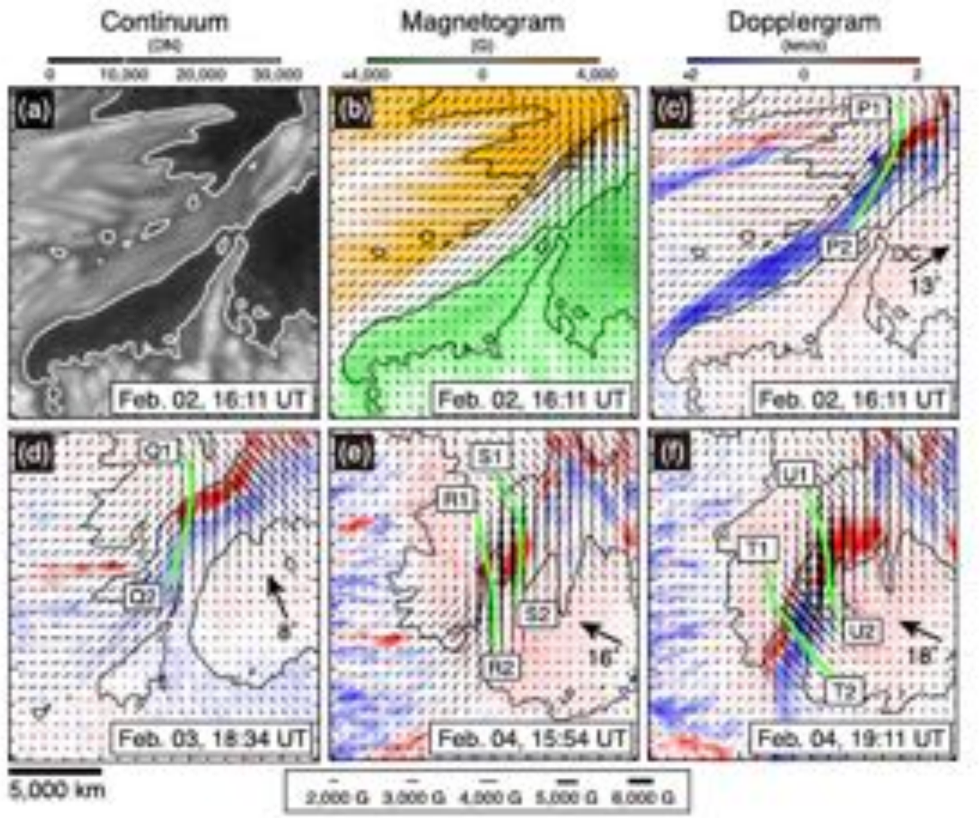
Anomalously large Zeeman splitting
→ Field strength > 6000 Gauss.

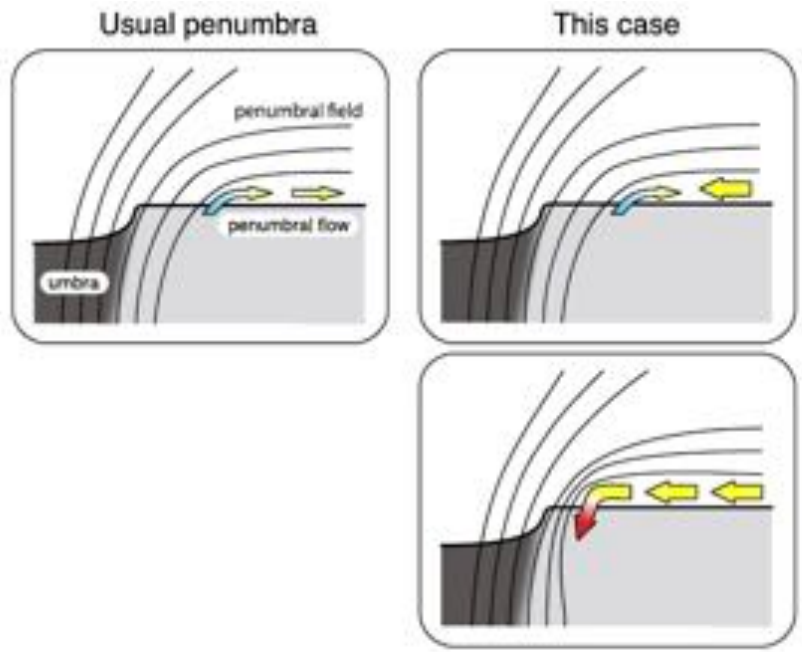


This kind of observation is possible only with a high-resolution spectro-polarimeter.

Super-strong magnetic fields in a sunspot

Okamoto and Sakurai (2018, ApJL)

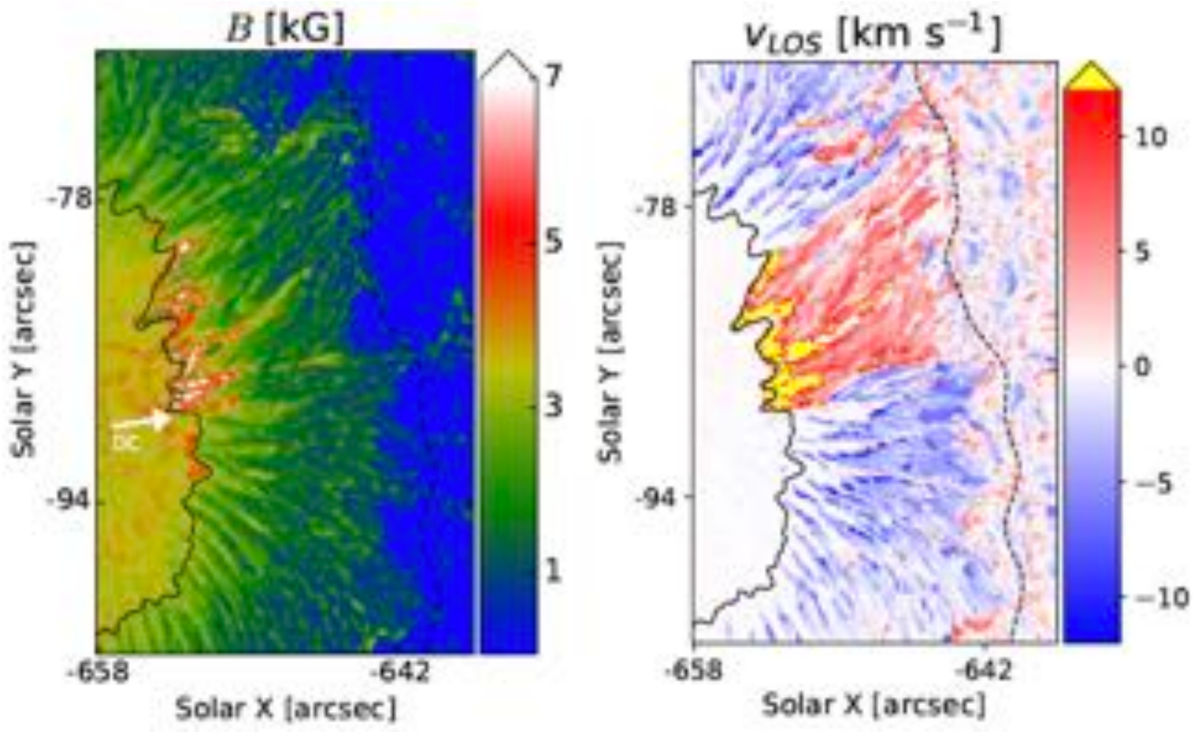




- Super-strong fields found in a bright region sandwiched by two opposite-polarity umbrae, not in a darkest region.
- Horizontal flows push the umbra boundary to strengthen the field (?)

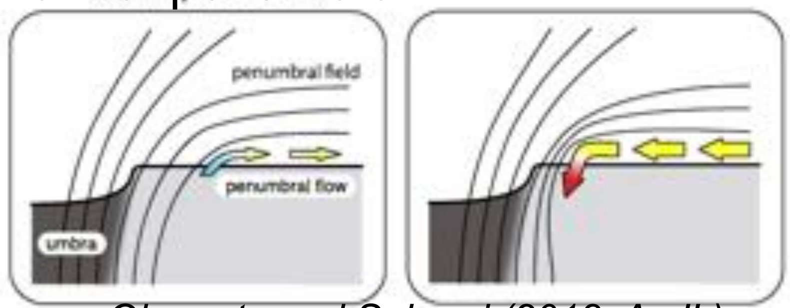
Another super-strong field

Siu-Tapia et al. (2019, A&A)



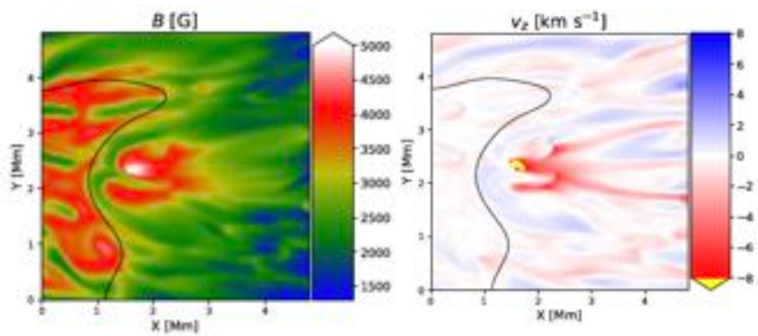
- Reported >7kG field near the boundary of "counter-Evershed" flow.
  - Used more sophisticated technique for deconvolution and to get height dependence.

Normal penumbra Counter-flow



Okamoto and Sakurai (2018, ApJL)

- Suggested possibility to create strong magnetic fields by dynamical compression using a numerical simulation.
  - But it was not successful yet.

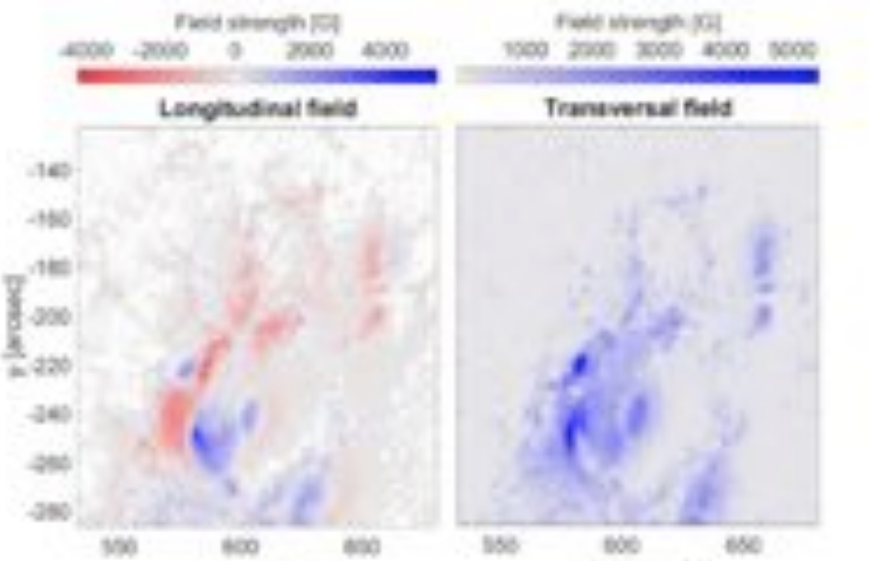


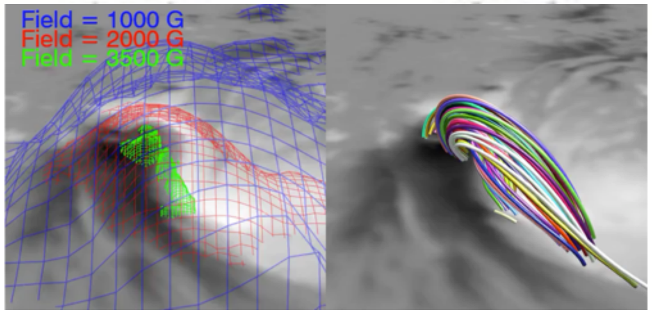
Result by a numerical simulation

Super-strong fields in the corona

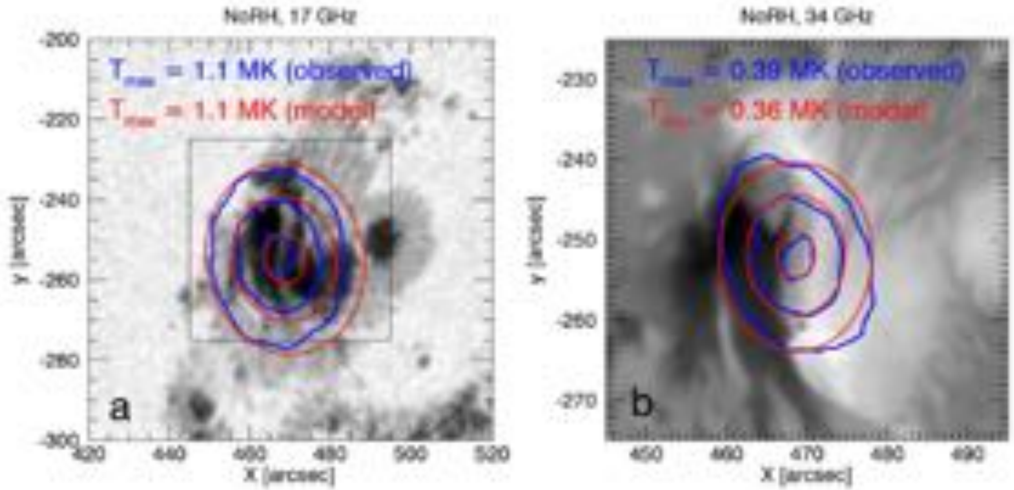
Anfinogentov et al. (2019)

- Bright gyro-resonance radio source, suggesting 4 kG at the base of corona above a flare productive active region.
- Extrapolation of coronal B from the surface B, and confirmed the super-strong field.





<u>Nobeyama Radio Heliograph</u>

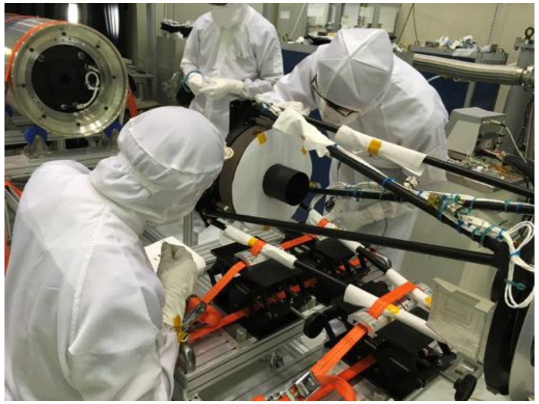


Important to quantify free energy to drive a solar flare

NASA Sounding Rocket Experiment
CLASP and CLASP2

(**C**hromospheric **LA**yer **S**pectro-**P**olarimeter)

- Pathfinder mission in solar physics
  - Aim to establish means to diagnose the magnetic field in upper solar atmosphere with UV spectropolarimetry
    - CLASP: Ly α @ 121 nm
    - CLASP2: Mg II h/k 280 nm
- International project by Japan, USA, Spain, France and Norway
  - NAOJ led the development of the instrument



I&T at the clean room of NAOJ/ATC

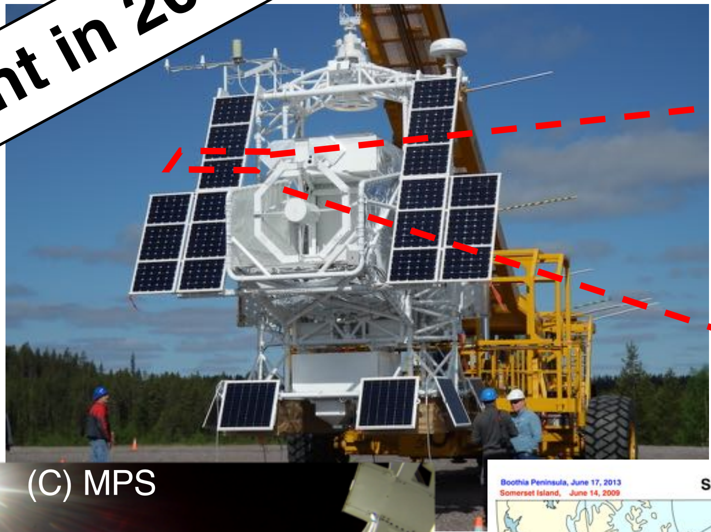
Successful flight in April 2019 at WSMR, US

Credit: US Army Photo, White Sands Missile Range

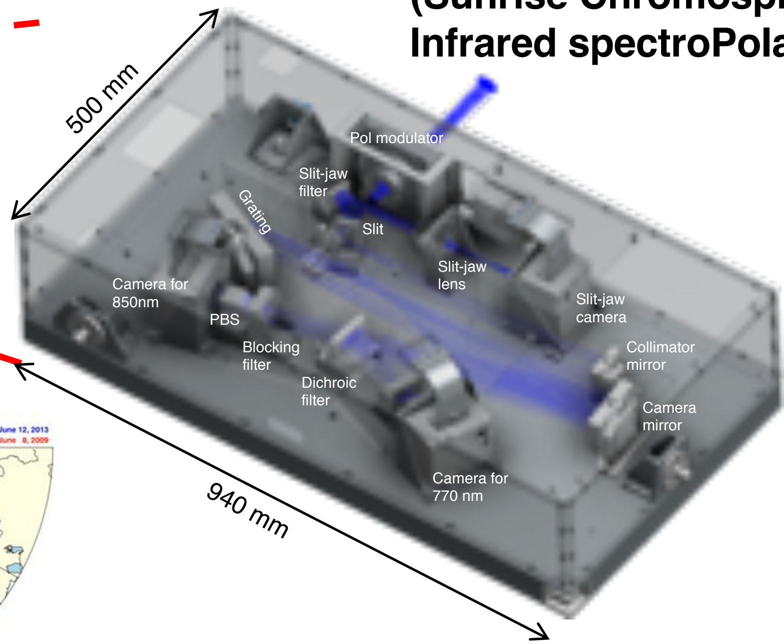
See the poster by R. Ishikawa for initial results

NASA/APL, Germany, Spain SUNRISE-3 balloon experiment

Flight in 2022



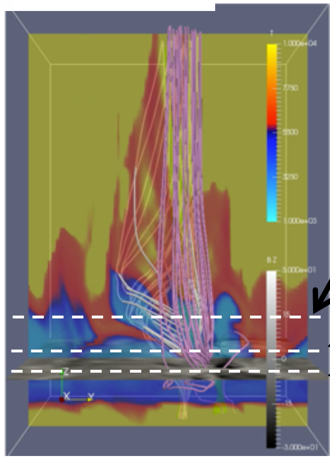
SCIP
(Sunrise Chromospheric Infrared spectroPolarimeter)



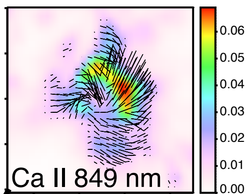
- Φ1m optical telescope (x2 of Hinode-SOT)
- Flight at >35 km from Sweden to Canada over the Atlantic for a week.
  - Wide λ coverage: 300 nm to 860 nm
  - High polarimetric sensitivity without affected by atmospheric seeing.

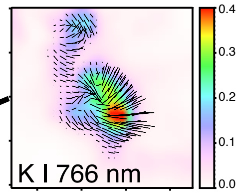
Linear pol. measured by SCIP

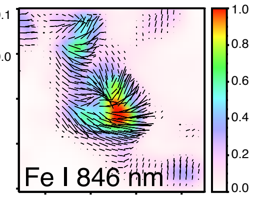
Quintero Noda et al. (2019, MNRAS)



Iijima and Yokoyama (2017)

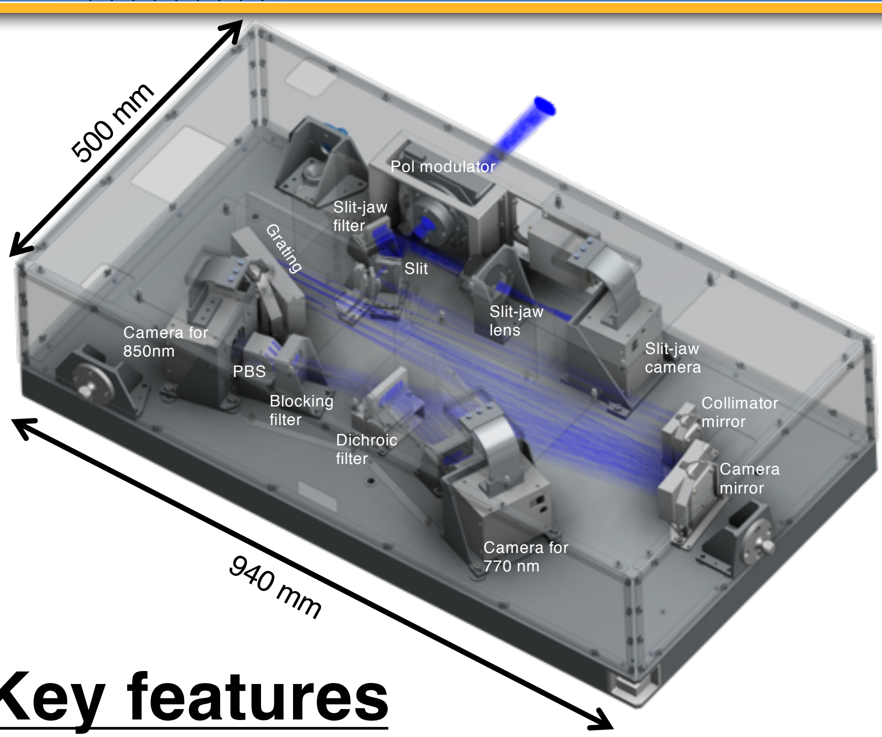






SCIP for SUNRISE-3
Sunrise Chromospheric Infrared spectroPolarimeter

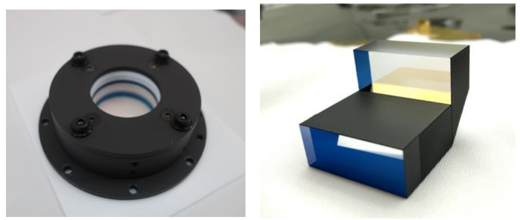
National Astronomical Observatory of Japan



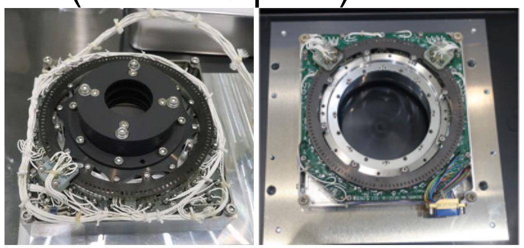
Development is progressing at NAOJ/ATC

High precision optics and their mount mechanism

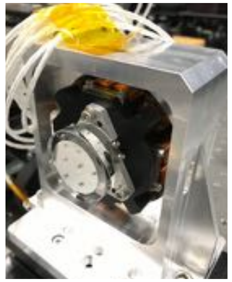
High precision pol. optics



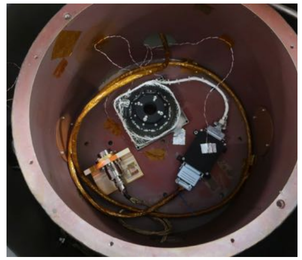
Polarization modulator (rot. wave plate)



Scan mirror

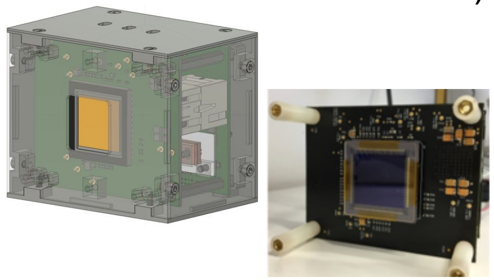


Verification in vac.



Low CTE optical bench

Camera (collaboration with IAA/CSIC)

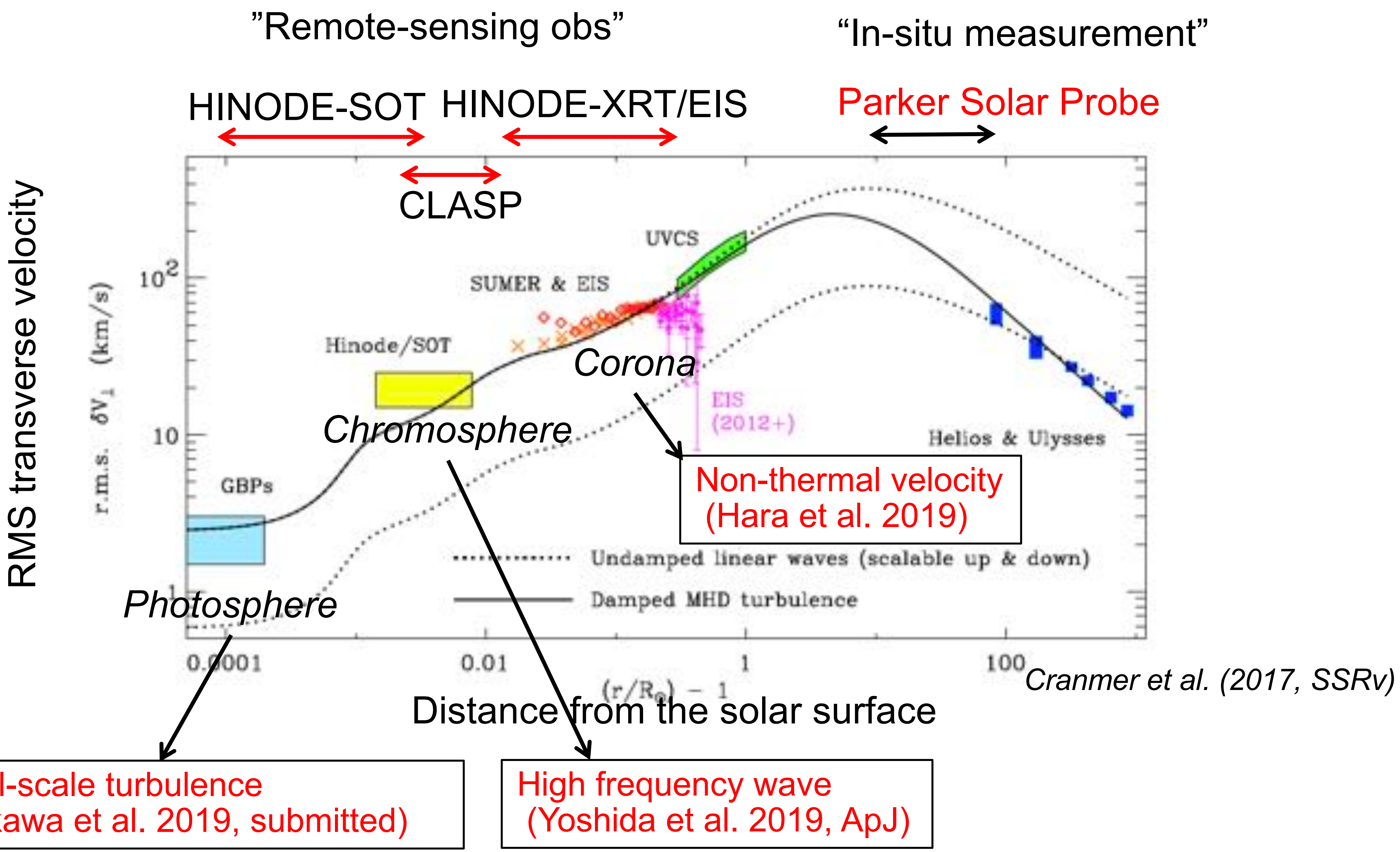


Key features

- High spatial resolution
  - 0.21” (Diff. limit at 850 nm)
- High polarization sensitivity
  - 0.03% (1σ) sensitivity in 10 sec at Ca II line to measure ~ 5 G magnetic fields
- Multi-line spectro-polarimetry for 3D diagnostics

Poster by Y. Katsukawa

Energy generation, propagation, and dissipation

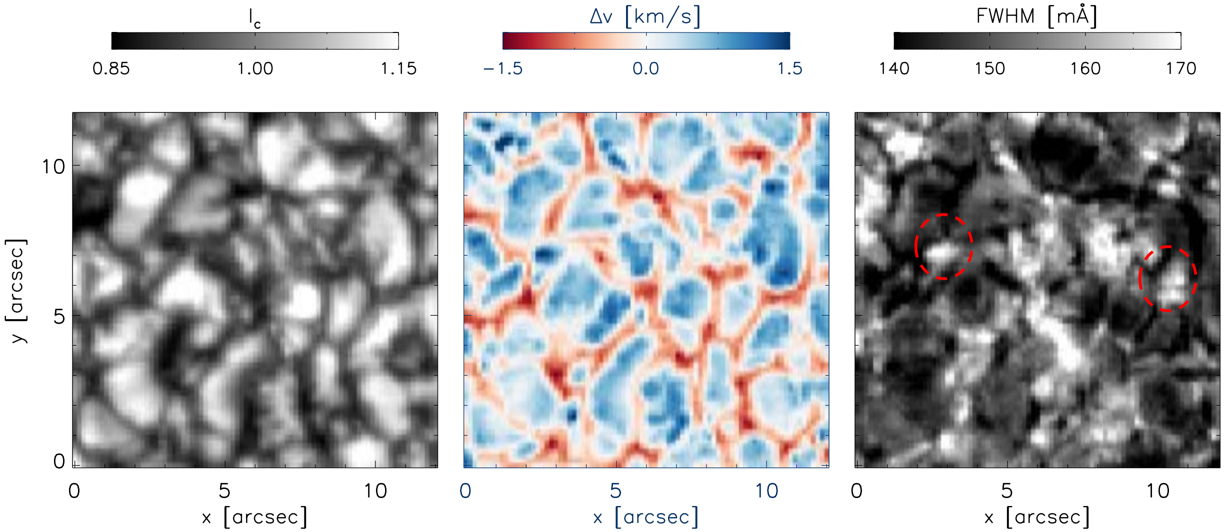


Cranmer et al. (2017, SSRv)

Significant line broadening in the photosphere not known so far

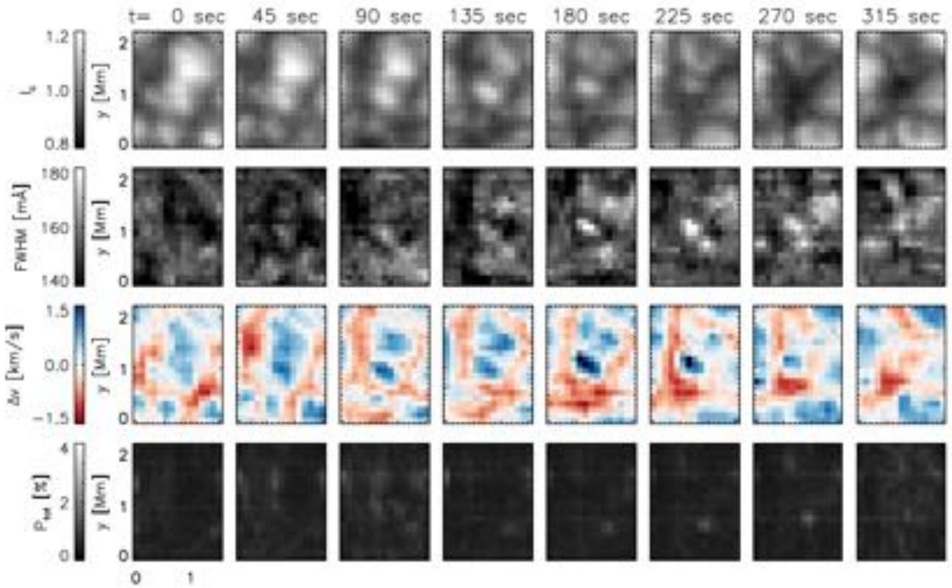
Intensity (T fluctuation) Velocity gradient Line width

Ishikawa et al. (2019, submitted)



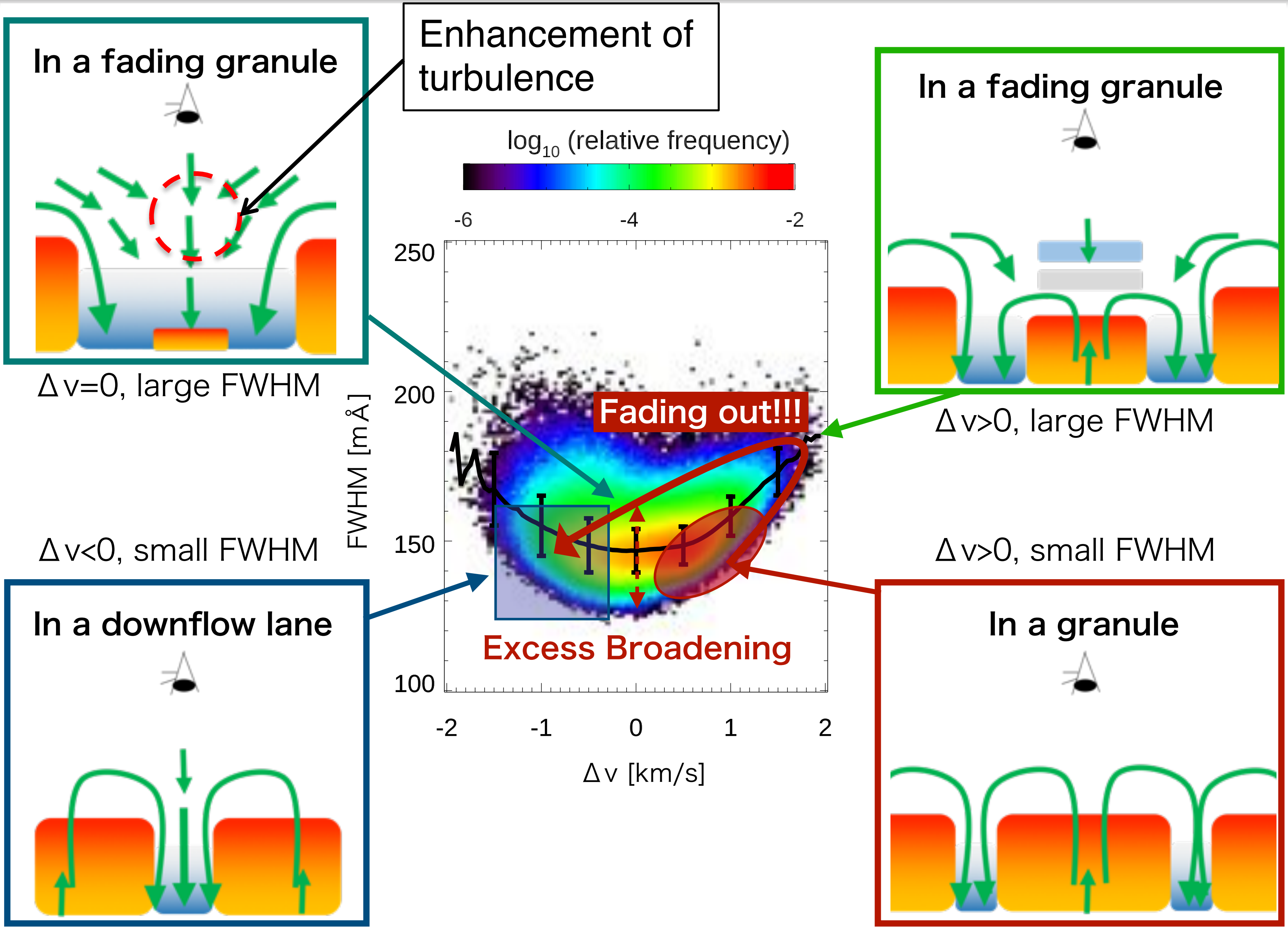
Sporadic enhancement of the spectrum line broadening.

Time evolution



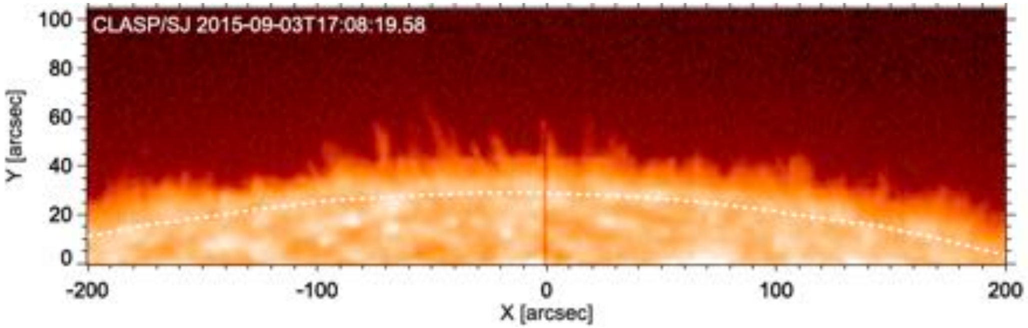
Excessive line broadening in fading granules, that cannot be explained only by the LOS velocity gradient.

Significant line broadening in the photosphere not known so far

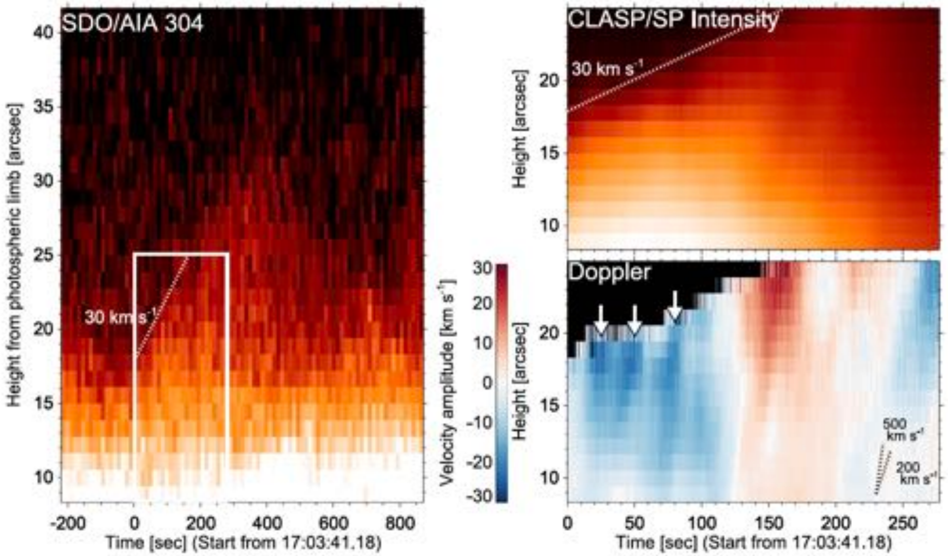


Propagation of high-f waves

Yoshida et al. (2019, ApJ)

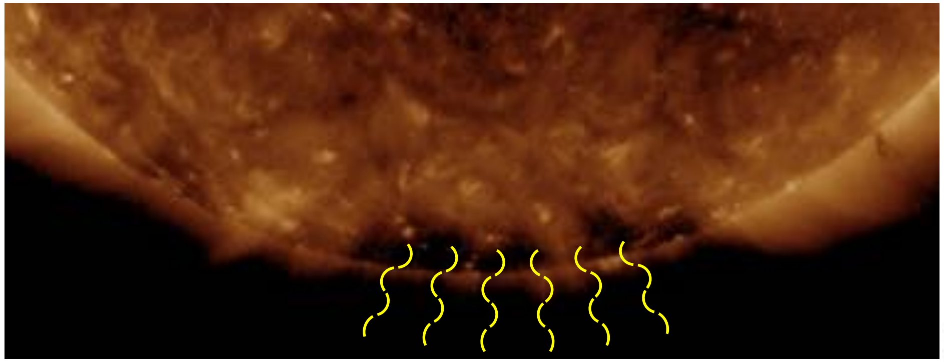


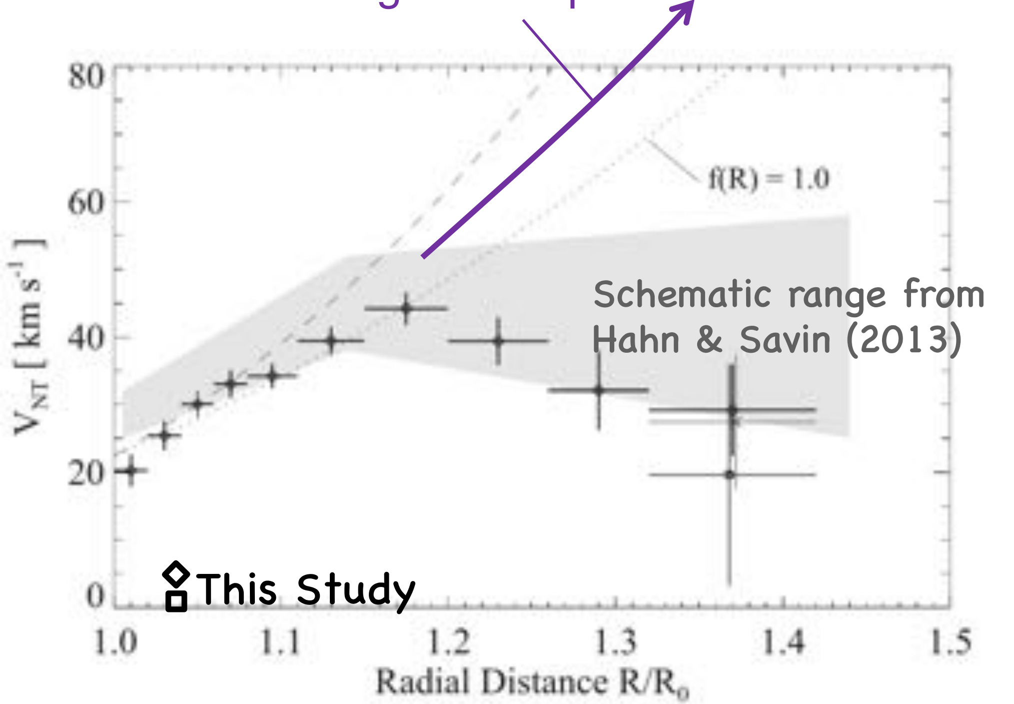
CLASP1 observation (~5 mins) of a spicule (jet in the chromosphere) near the limb.



- Clear detection of propagating high frequency waves by Ly-alpha spectrtoscopic obs.
- Energy flux carried by the high frequency waves was estimated and was probably a minor contribution to the coronal heating.
- Trigger of high-f waves associated with a driver of a jet(?) We need more statistics.

Nonthermal motions in a corona as the source of solar winds



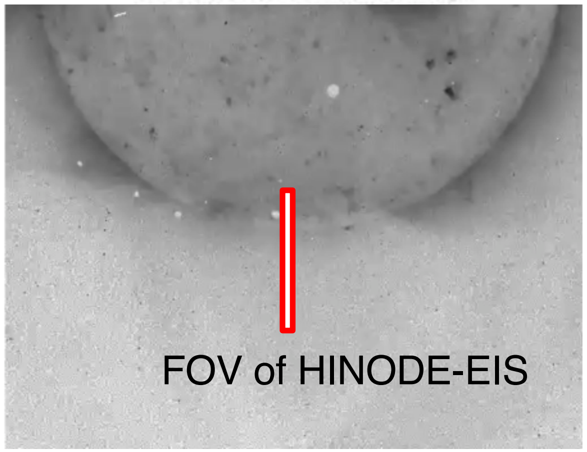


- Nonthermal component V_{NT} in an emission line width is a measure of velocity fluctuations associated with coronal Alfven waves.

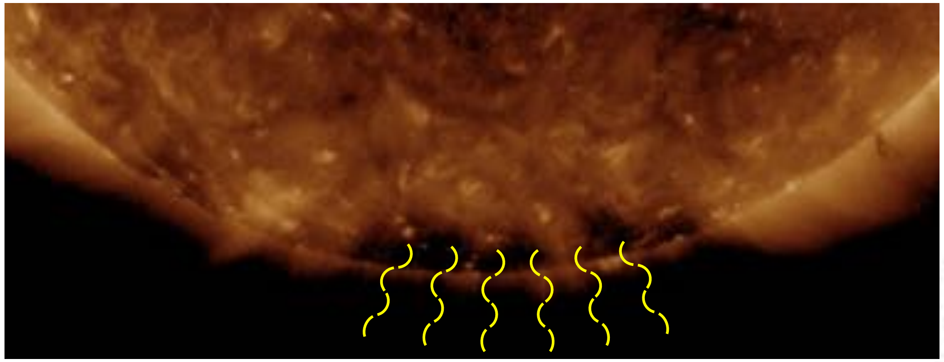
Emission Line width (FWHM) of Fe XII from HINODE-EIS Observation

$$W = \sqrt{W_{instr}^2 + 4ln2(2k_BT_i/M_i + V_{\rm NT}^2)}$$

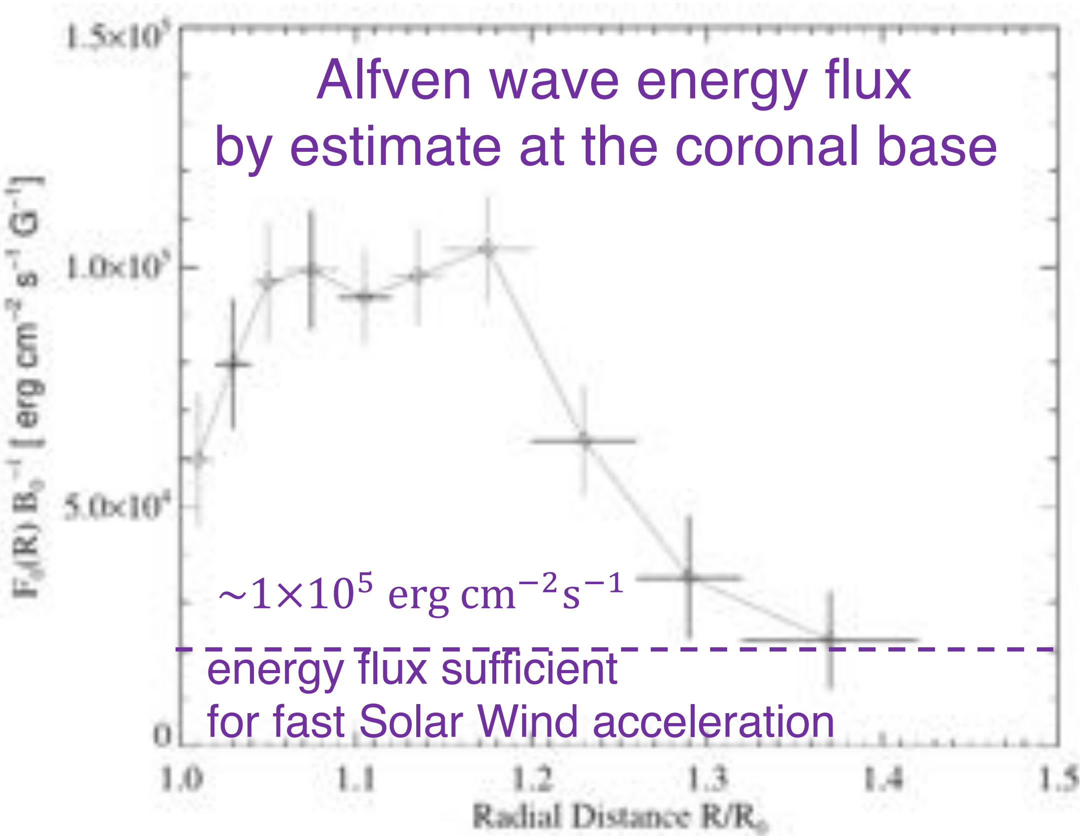
- Weak signals on the background by scattering from other regions are measured and subtracted during the on-orbit eclipse.



Nonthermal motions in a corona as the source of solar winds



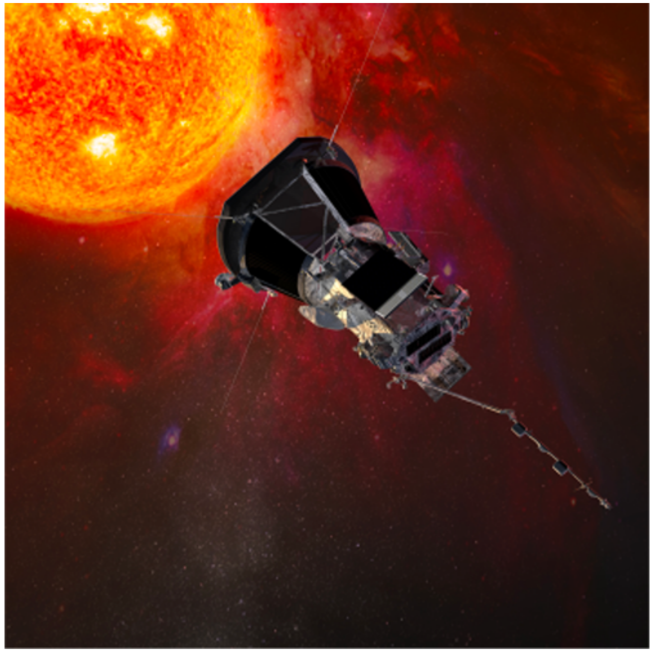
Hara (2019, ApJ)

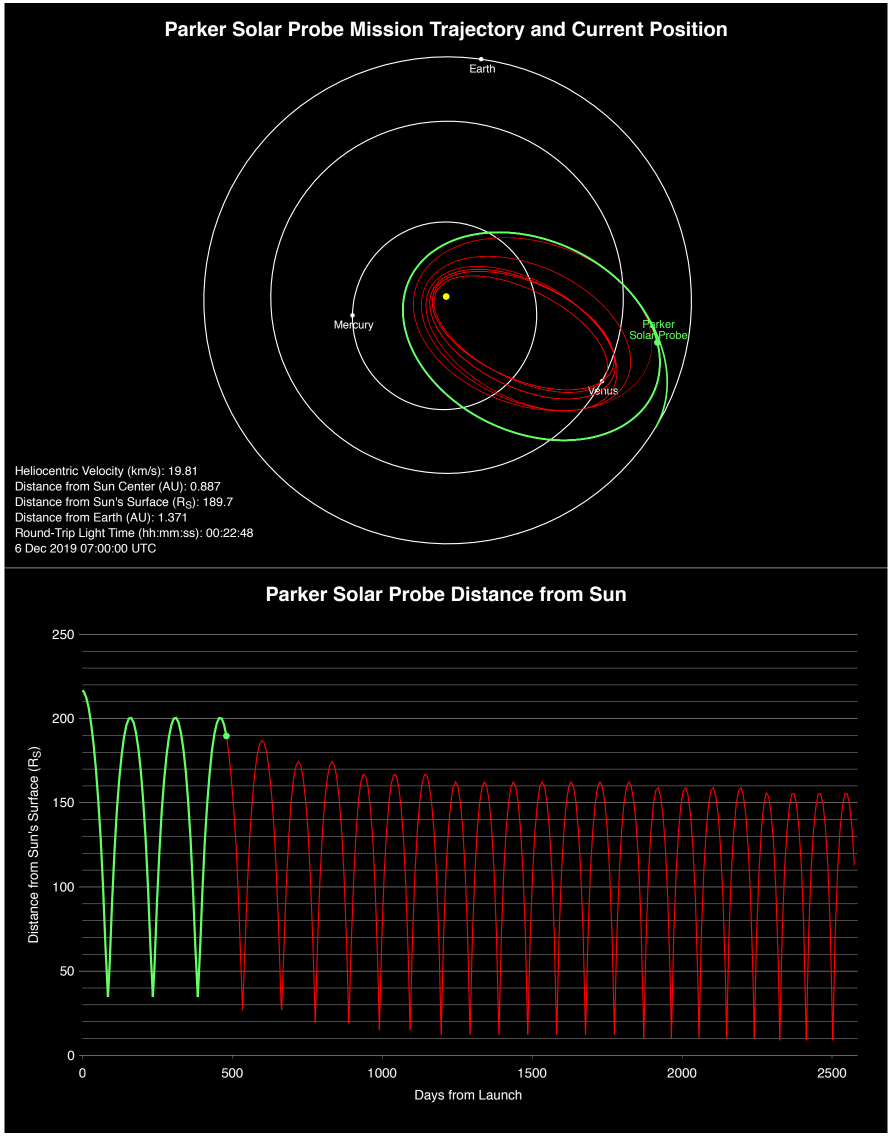


- Estimate energy flux carried by the Alfven wave.
- The damp of the V_{NT} is a signature of Alfven wave dissipation in the inner corona.

Need confirmation by theoretical/numerical studies as well as in-situ measurements by Parker Solar Probe.

Parker Solar Probe (PSP)



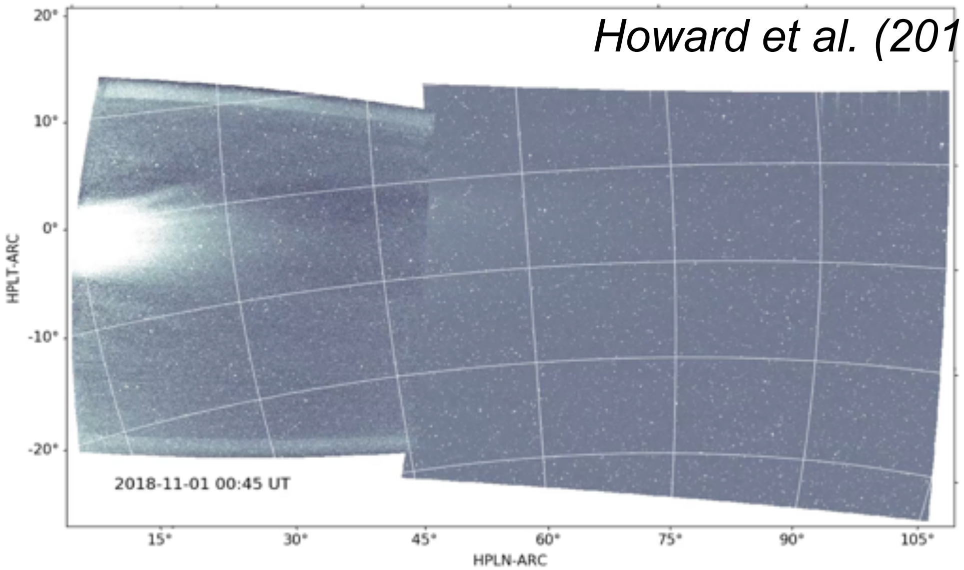


- Launched in Aug 2018
- Already experienced three perihelions at ~25Rs.
  - HINODE ran coordinated observations to observe the roots of magnetic fields.
- Finally it approaches the Sun as close as ~10Rs.

Initial results just published

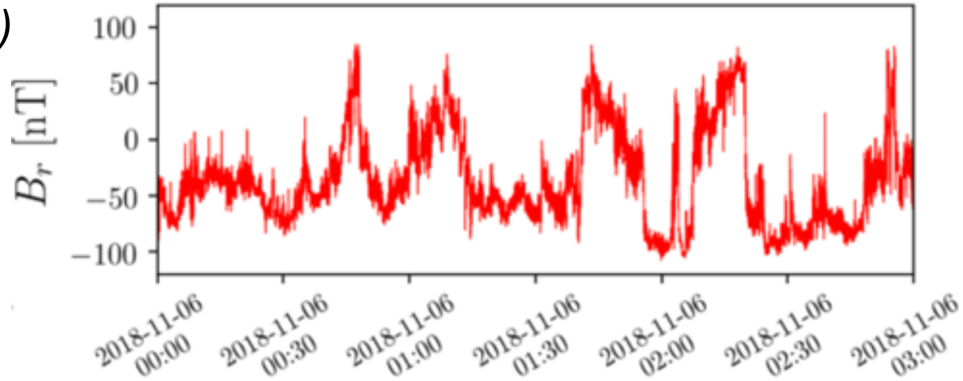
WISPR (coronagraph observation)

Howard et al. (2019)

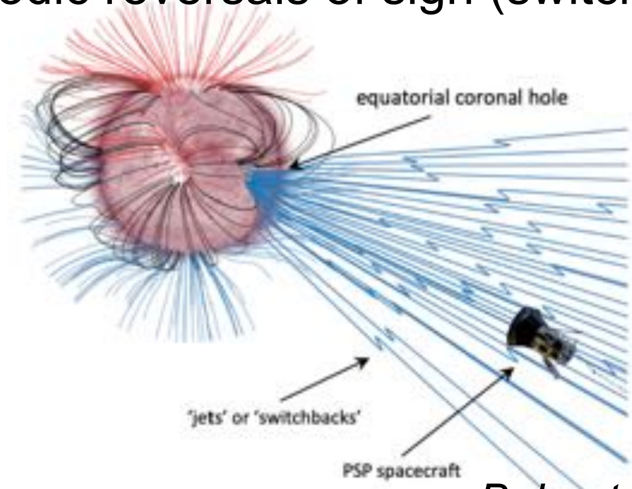


- Imaging of flux rope and plasmoid (magnetic islands) ejection.
  - Plasmoids generated by the tearing-mode instability in the current sheet?
- Dust-free (low scattered light) zone near the Sun.

FIELDS (direct measurement of E and B)



Radial magnetic field Br shows quasi-periodic reversals of sign (switch-back)



Bale et al. (2019)

"Multi-messenger" observation

- Solar Physics is a pioneer of "multi-messenger" astronomy!!
  - We have observed energetic particles and disturbances of magnetic fields at 1 AU for major solar flares.
  - But it has been difficult to use such obs for understanding of coronal heating and acceleration.

- Synergy with HINODE in coming years
  - Combination of remote-sensing obs near the Sun by HINODE and in-situ measurements of particles and B by PSP.
  - Many science cases:
    - Relationship of transverse velocity amplitude between near and outer coronae.
    - Identification of a source of "switch-back" near the Sun.

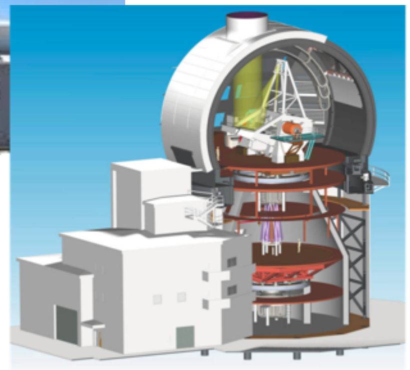
PSP data are already released for the past two contacts

- The multi-messenger approach is expected also for the Solar Orbiter
  - To be launched in Feb. 2020. Good for high-latitude targets although SO's perihelion is at 60 Rs.

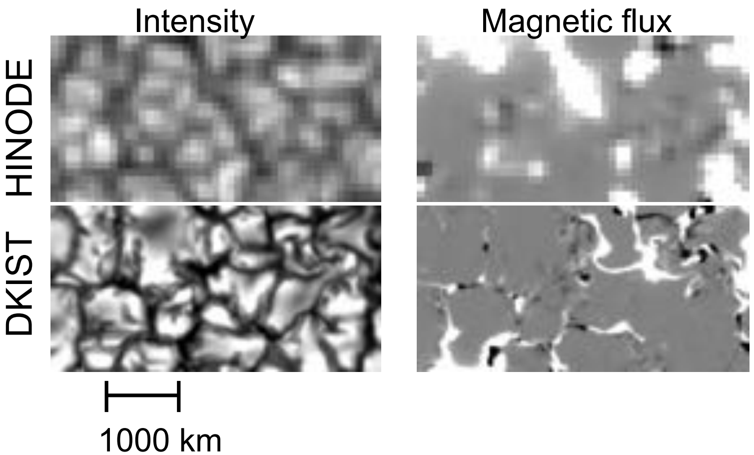
DKIST is coming soon

- Φ4m solar telescope in Hawaii
  - The largest aperture was 1.6 m so far.
- Coordination with HINODE is highly demanded.
  - Cross-calibration of polarimetric obs because HINODE-SP is a "world-standard" with larger FOV.
  - HINODE-EIS coronal spectroscopy is the unique capability to diagnose corona (until Solar-C EUVST).

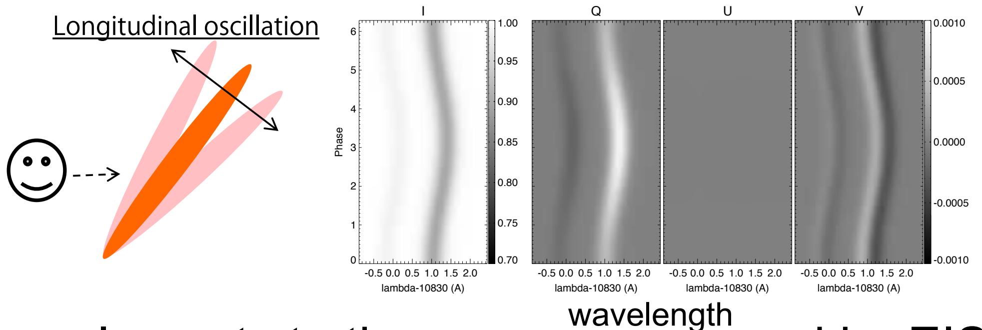
First light in 2019



Generation of small-scale turbulent velocity and magnetic fields

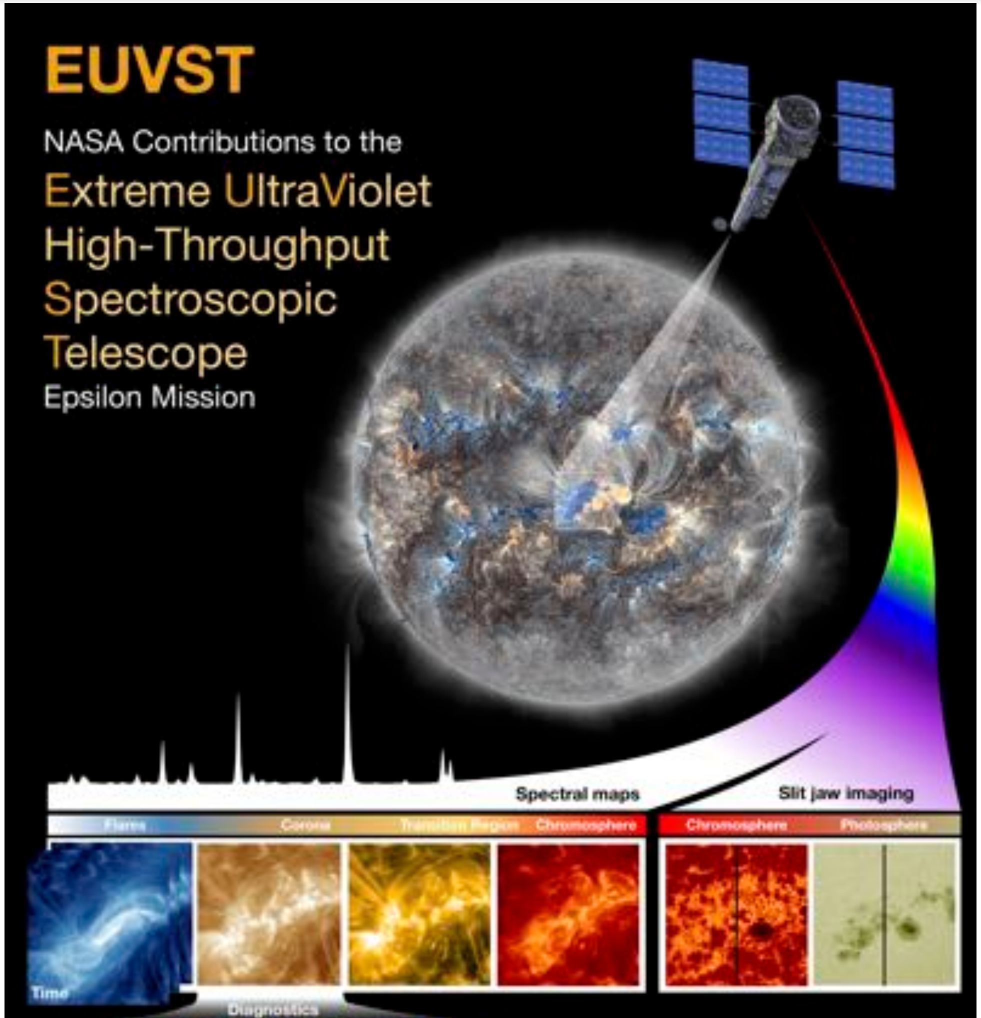


Direct evaluation of "Poynting flux" by a polarimetic observation



Impacts to the corona measured by EIS

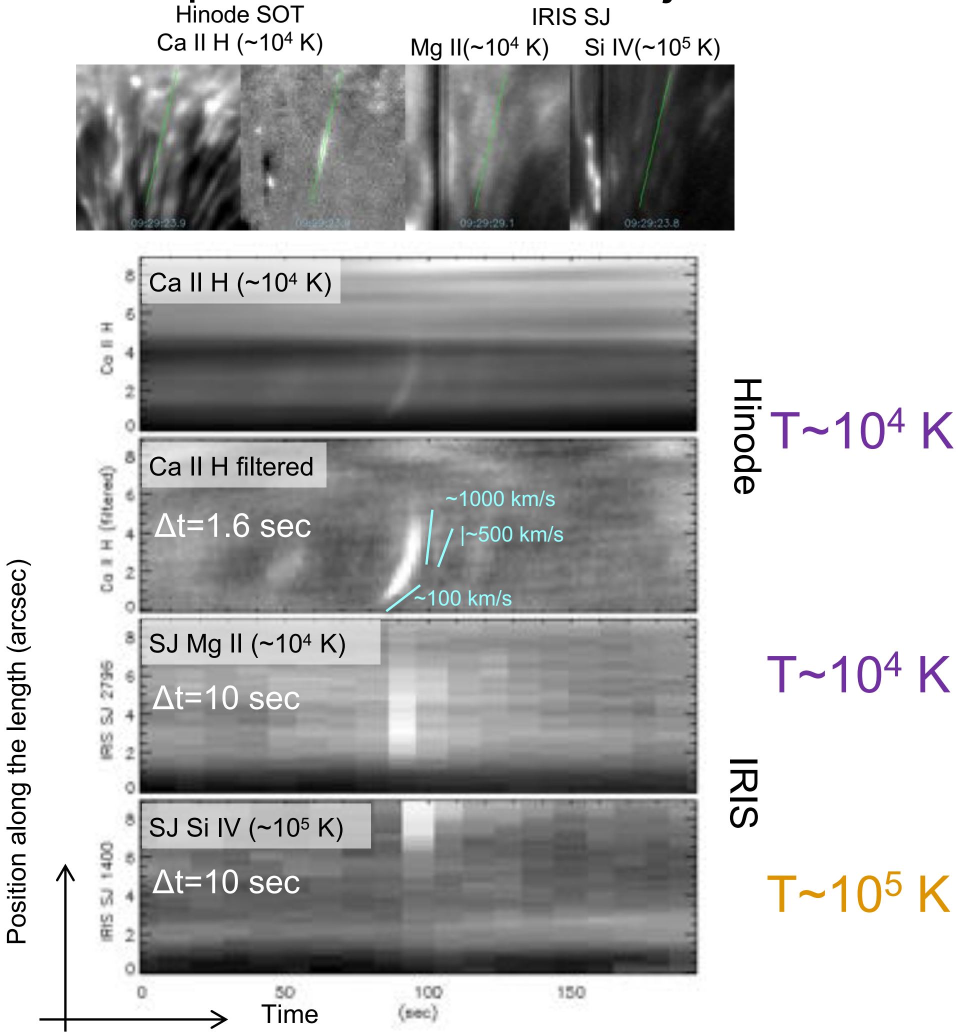
EUVST: high resolution EUV spectroscopy



High resolution (0.4”)

Wide temperature coverage

Example of an “elemental” jet



Lack of high resolution observation in a corona (>10^6 K)

Summary

- HINODE is already 13 years old, but is continuously providing unique data.
  - We can still do new science using existing data.
- The strategic coordination with ALMA, PSP, SO, and DKIST is critical to enhance scientific outcomes.
  - The coordination is also important to strengthen the international collaboration for future projects such as EUVST.
- The small-scale experimental projects (rockets, balloon etc.) are important to keep and develop uniqueness of our group.