Hinode Seminar
22-April 2019

# Recent progress and future prospects in solar observations

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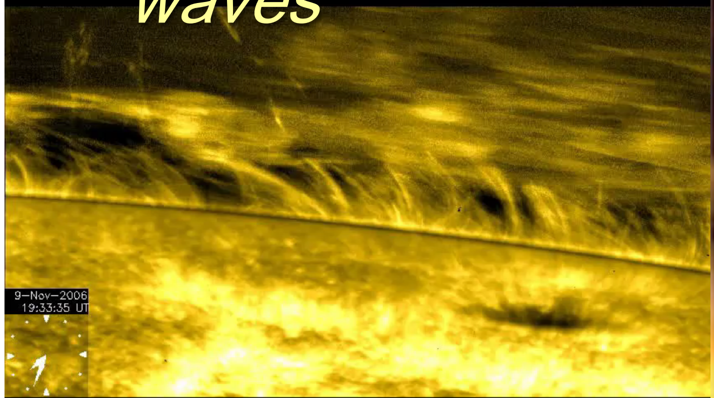
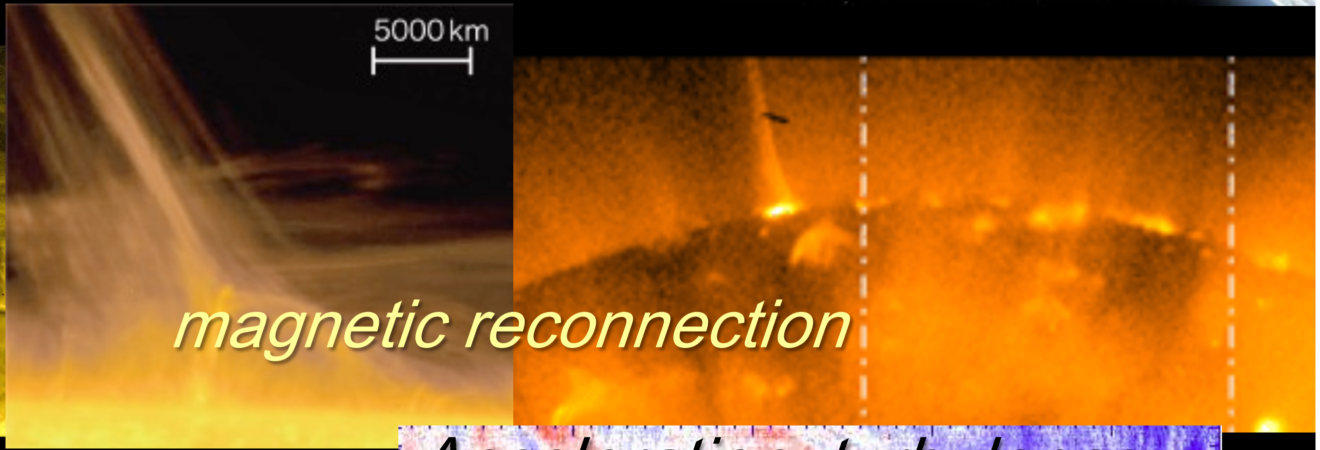
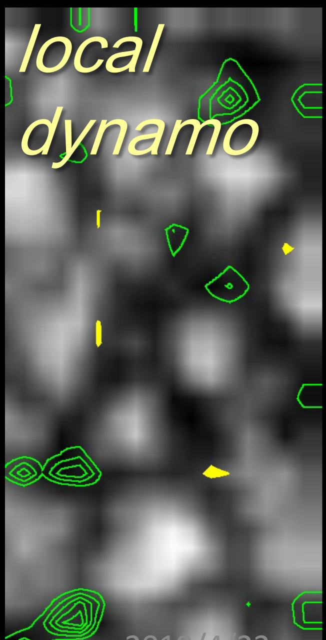
# My missions, Our missions

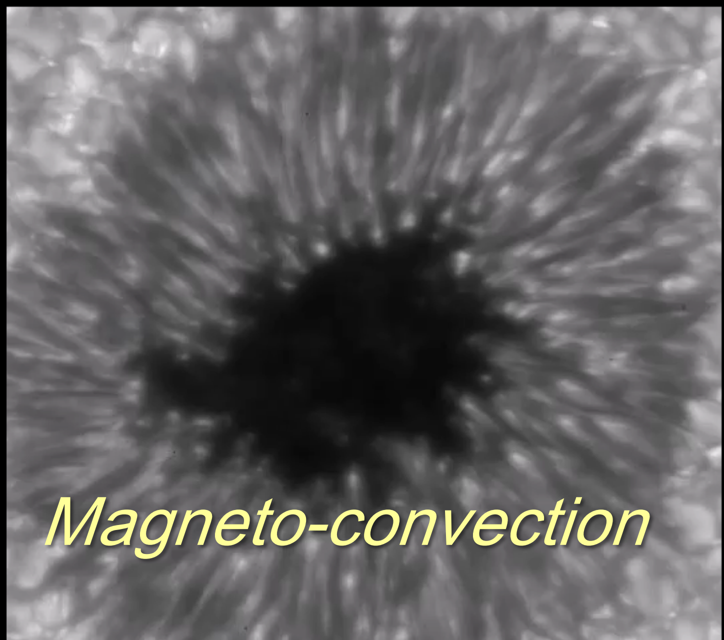
- Spectro-polarimetry for solar magnetism
  - Rotating wave plate mechanism
    Solar-C/SUVIT → CLASP1/2 → Sunrise 3/SCIP
  - Sunrise 3/SCIP in 2021
  - DKIST
- Spectroscopy in EUV
  - Mass and energy transfer in upper atmosphere
  - For bridging to the heliosphere
  - Solar-C_EUVST in 2025
- Longer-term future prospects

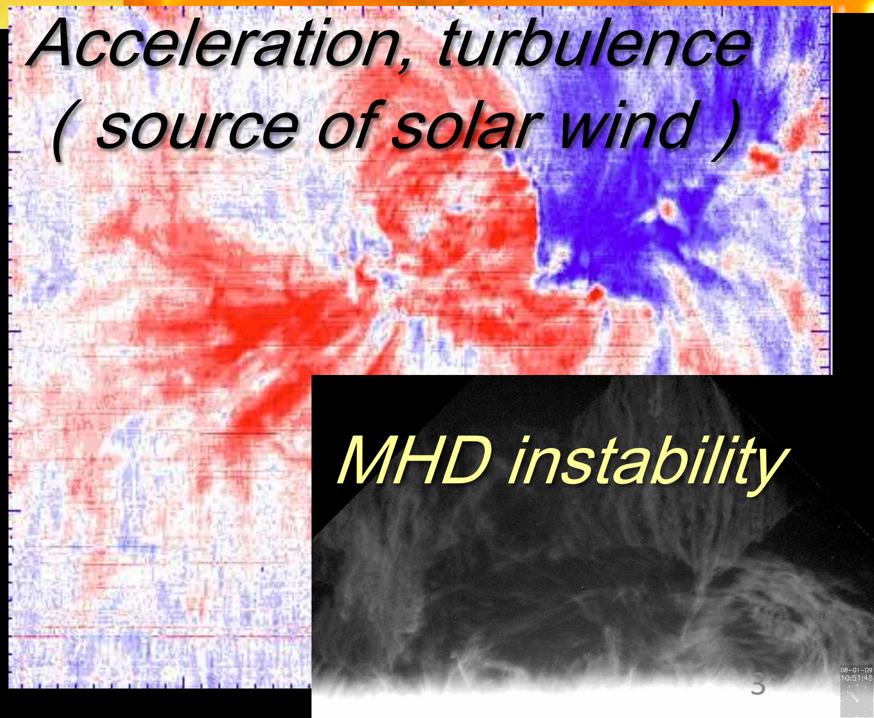
# Better understanding of MHD processes, advanced with Hinode observations



# Key objectives in solar physics

**Physical processes governed in plasma universe**
**Influence to the heliosphere**

- How hot and dynamic outer atmosphere is created?
  - chromospheric fine structures, nanoflares, MHD waves, magnetic emergence, solar wind, prominence formation
- What causes flares and plasma eruption?
  - Energy storage, trigger, CME propagation, fast reconnection, $\delta$-sunspot formation, particle acceleration
- How the solar magnetic field is created and maintained?
  - Velocity and B field structure in interior, turbulence and dynamo, irradiance variation

image: Hinode/XRT

From NGSPM-SOT report (2017)

# High priority instruments for solar science in 2020s

- Sharpening science objectives and mission
  - Domestic discussions after large strategic (original) SOLAR-C cannot move forward in 2015.
  - International: Recommendations from JAXA-NASA-ESA "NGSPM-SOT" (2017)

Large original Solar-C (2015)

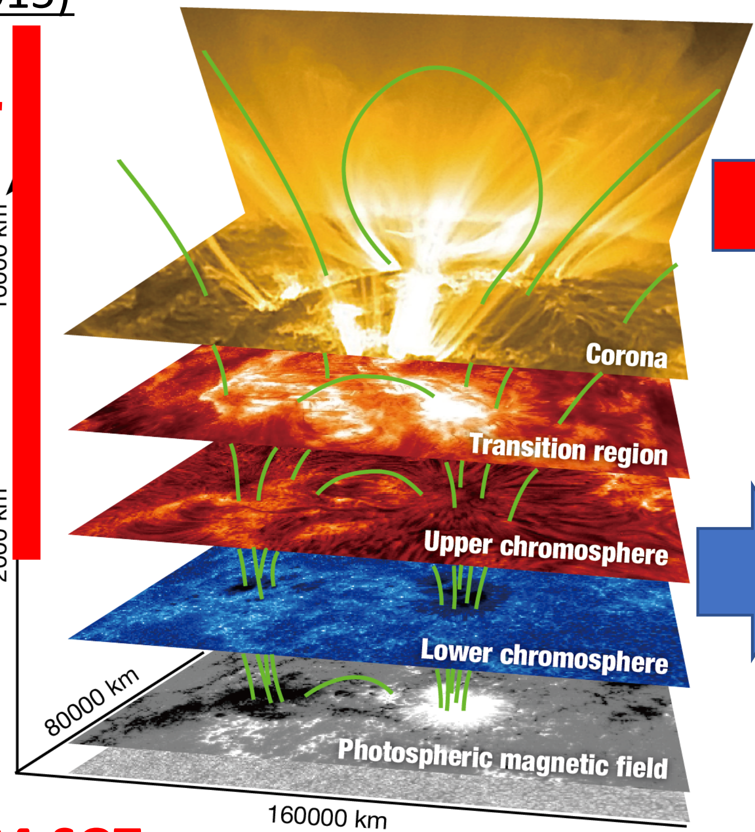
1. **Coronal/TR spectrograph** (0.3~0.4")

seamless plasma diagnostics through the atmosphere

2. **High-resolution Coronal imager** (0.3")

3. **1m magnetic-field telescope** (0.1~0.2")

Magnetic and velocity fields at chromo/photosphere




**Priority given by NGSPM-SOT**

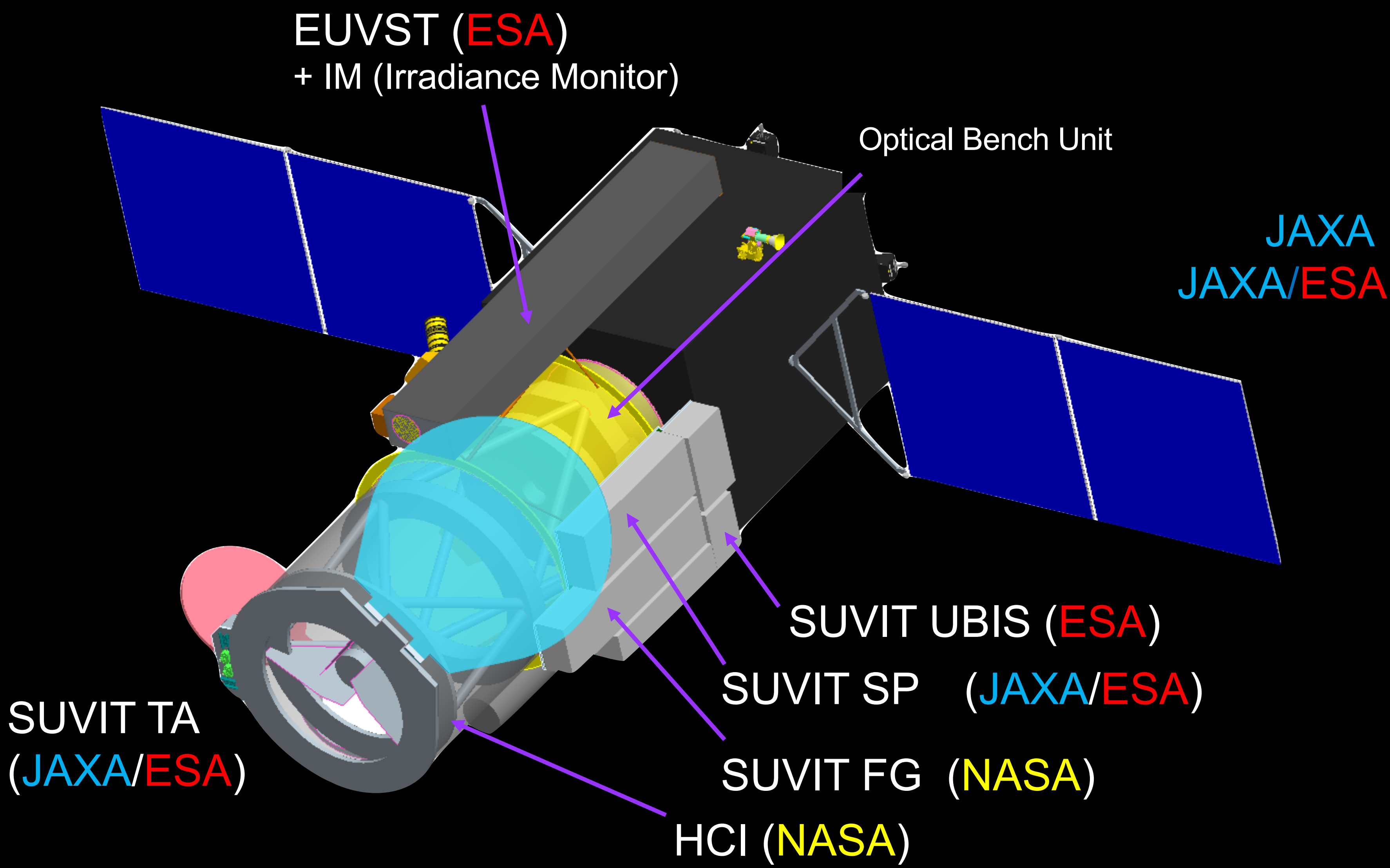
Strategy In 2020s

**Solar-C_EUVST**
during the next solar maximum (around 2025)

Spectro-polarimetry
1) CLASP1/2 sounding rocket, Sunrise-3 balloon
2) 4m ground-based DKIST, collaborated with Solar-C_EUVST

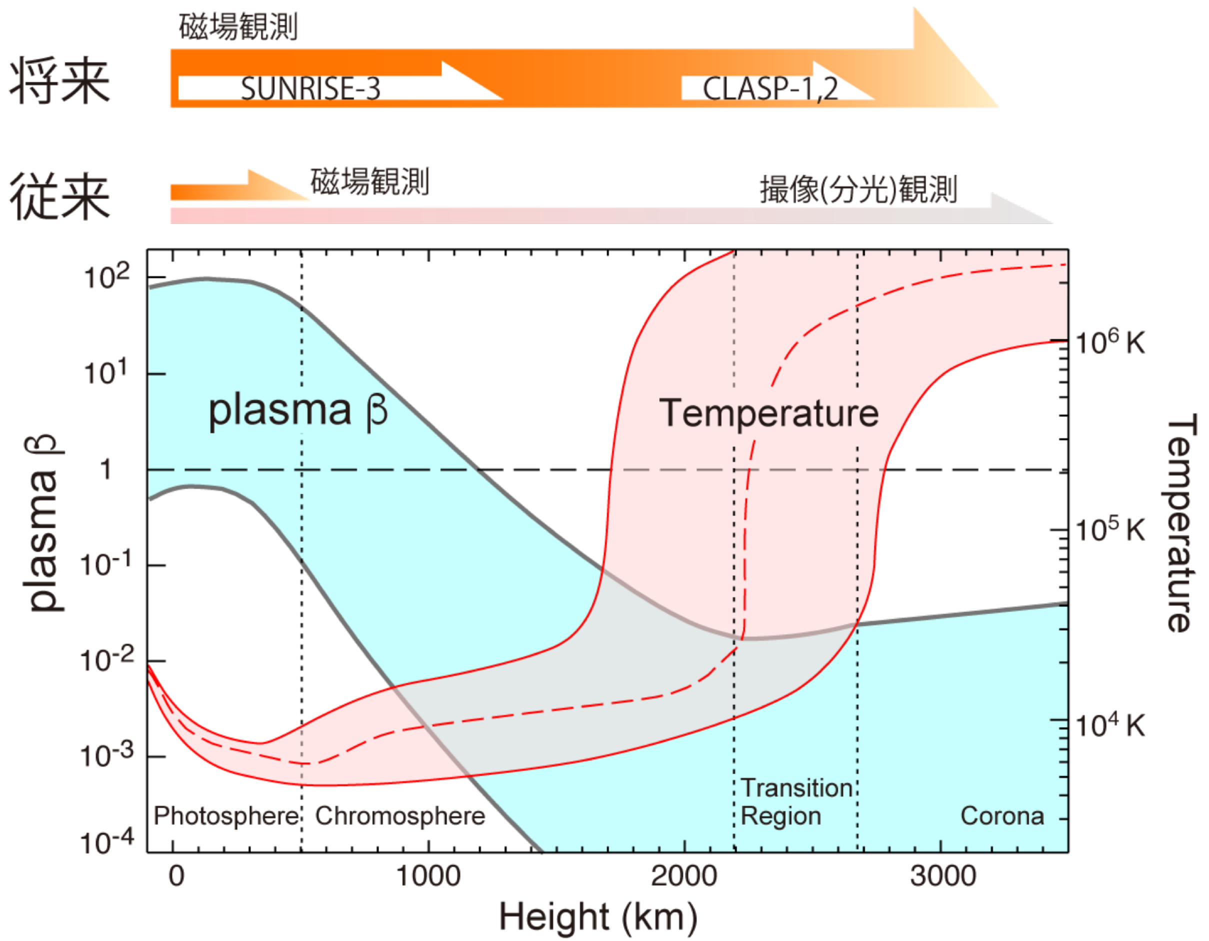
Bridge to space telescopes in early 2030s

# Original Solar-C proposal (2015)



# 1. Spectro-polarimetry for solar magnetism

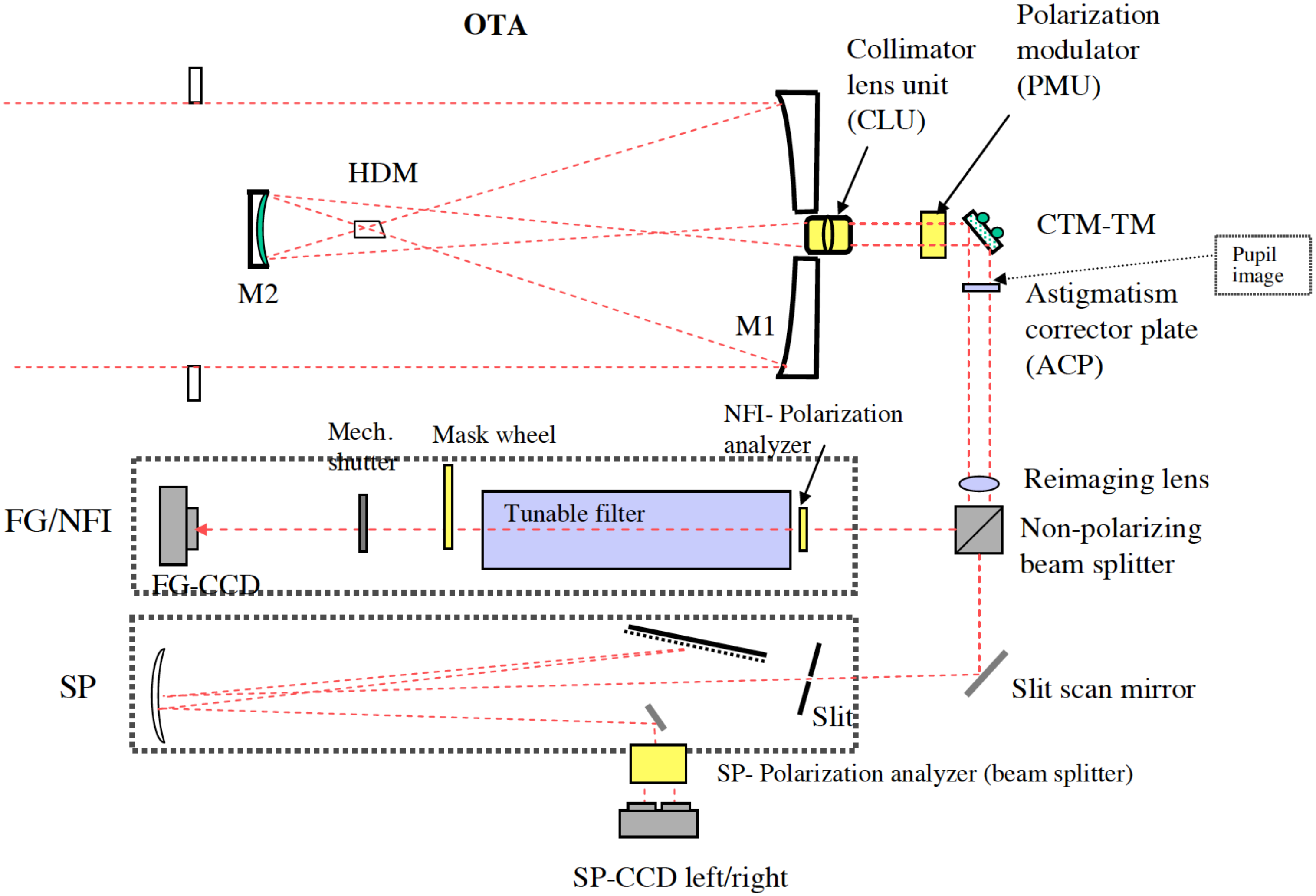
# Measurements of magnetic fields in and above the chromospheric layer




Current: Magnetic field measurements at high beta condition

→ Non-linear force-free extrapolation to the corona (used in space weather research)

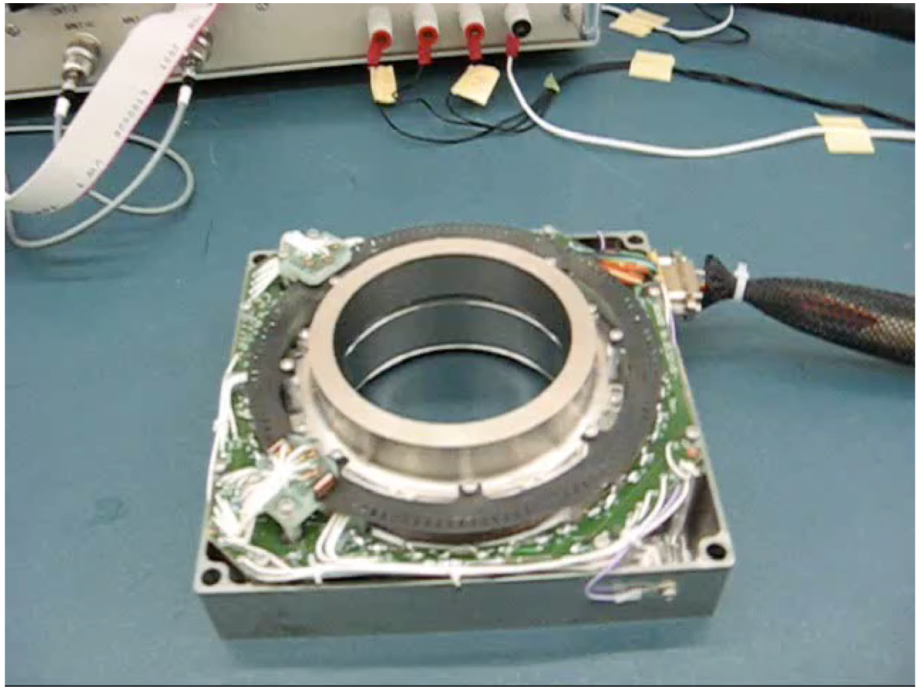
# *Hinode/SOT* Polarization modulator (PMU) – Polarization analyzer




(Ichimoto et al. 2008 Solar Physics)

# A key technology for precise spectro-polarimetry

- Mechanism for continuously rotating wave-plate



→ A key technology for Solar-C SUVIT (R&D in 2009 – 2016)
→ Applied to CLASP1/CLASP2 and Sunrise/SCIP
→ 3 years continuous rotation has been confirmed.
Good steps for satellite observations

(Shimizu et al. 2018 JAXA RR)

# Experiments for chromospheric magnetic fields

A new diagnostic window！

CLASP1&2 (Sounding rocket)

Method

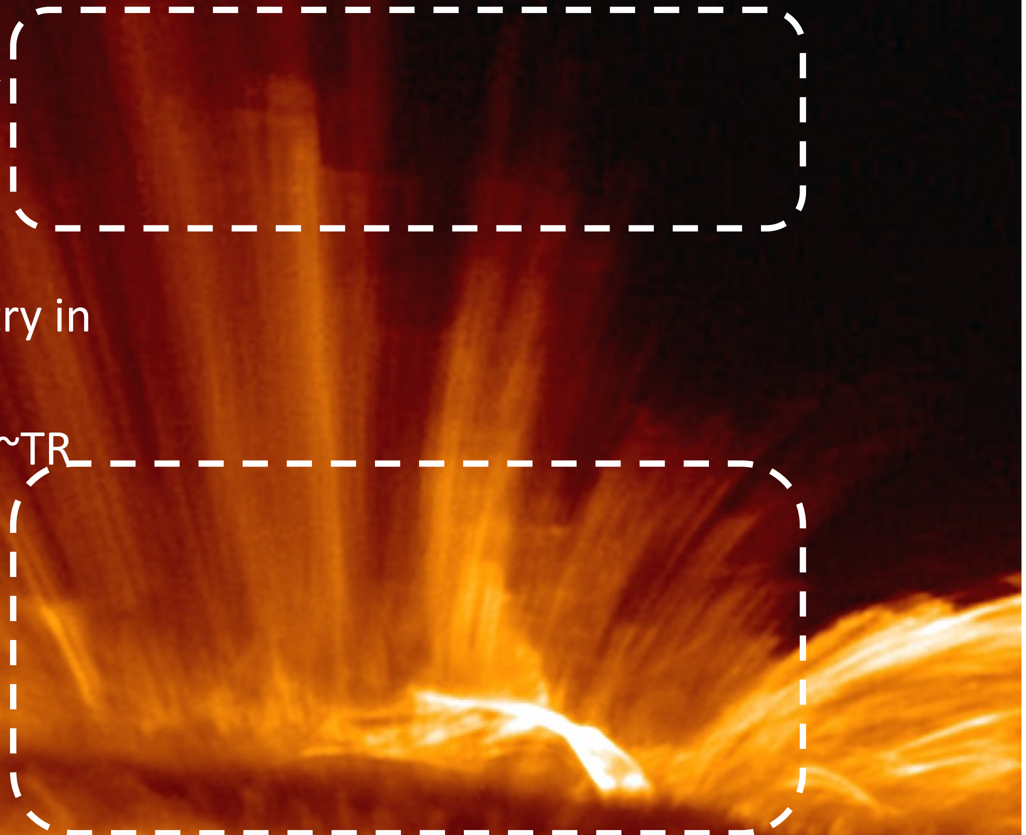
- The first experiments of spectro-polarimetry in UV
- Hanle effect by B in upper chromospheric ~TR in scattering polarization

Chromospheric diagnostics！

SUNRISE-3 (Balloon)

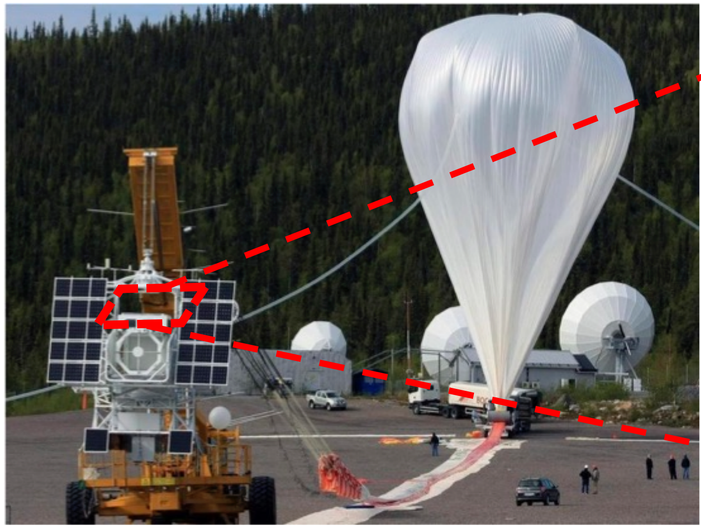
Method

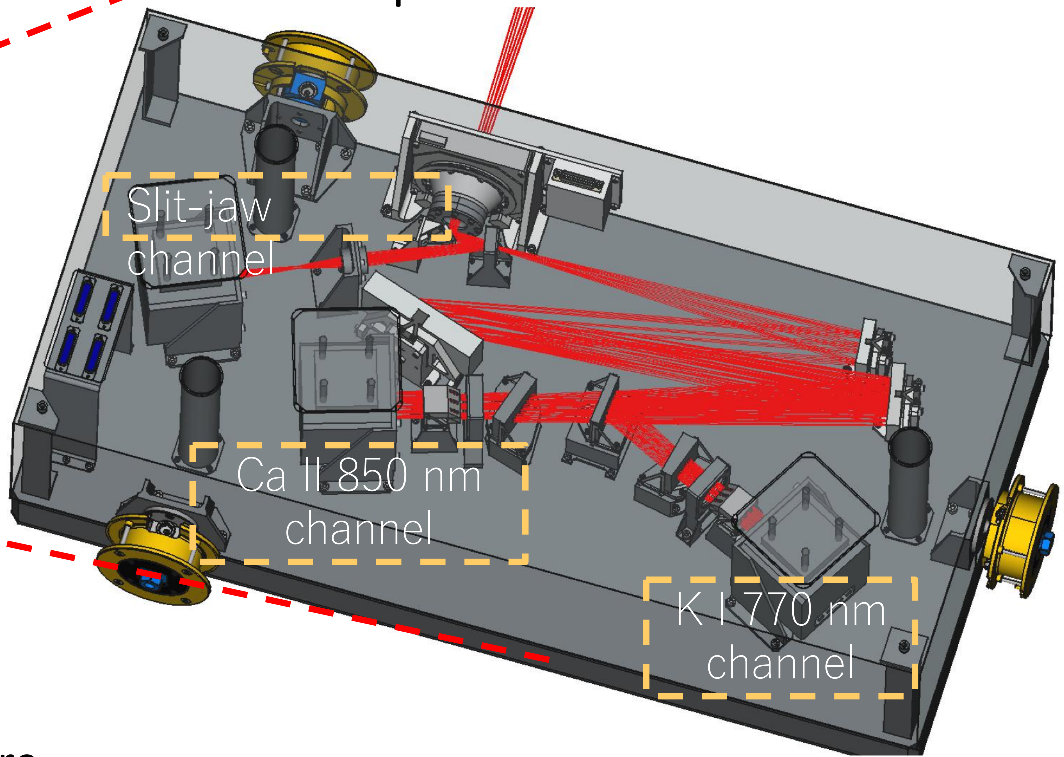
- Near IR spectro-polarimetry from space
- Zeeman effect for upper photosphere ~ lower chromosphere



# SUNRISE-3/SCIP (2021)

## Sunrise Chromospheric Infrared spectroPolarimeter



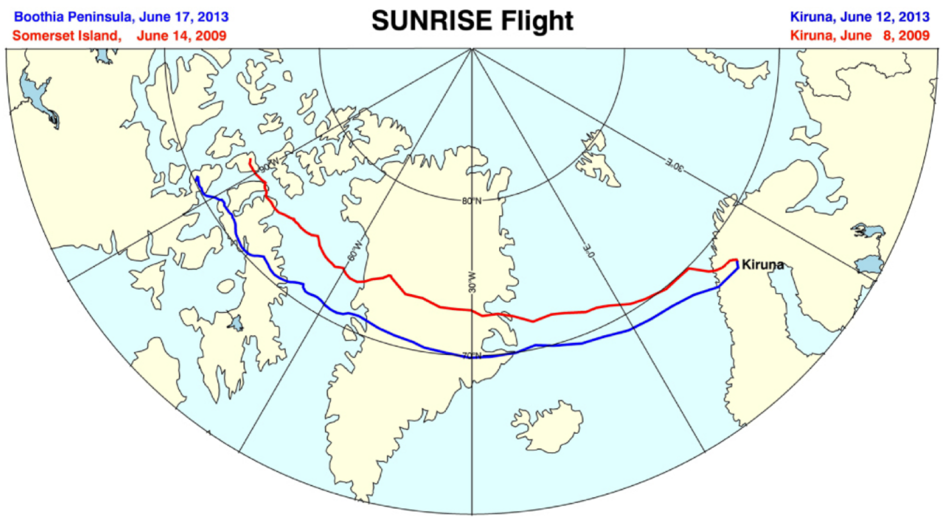


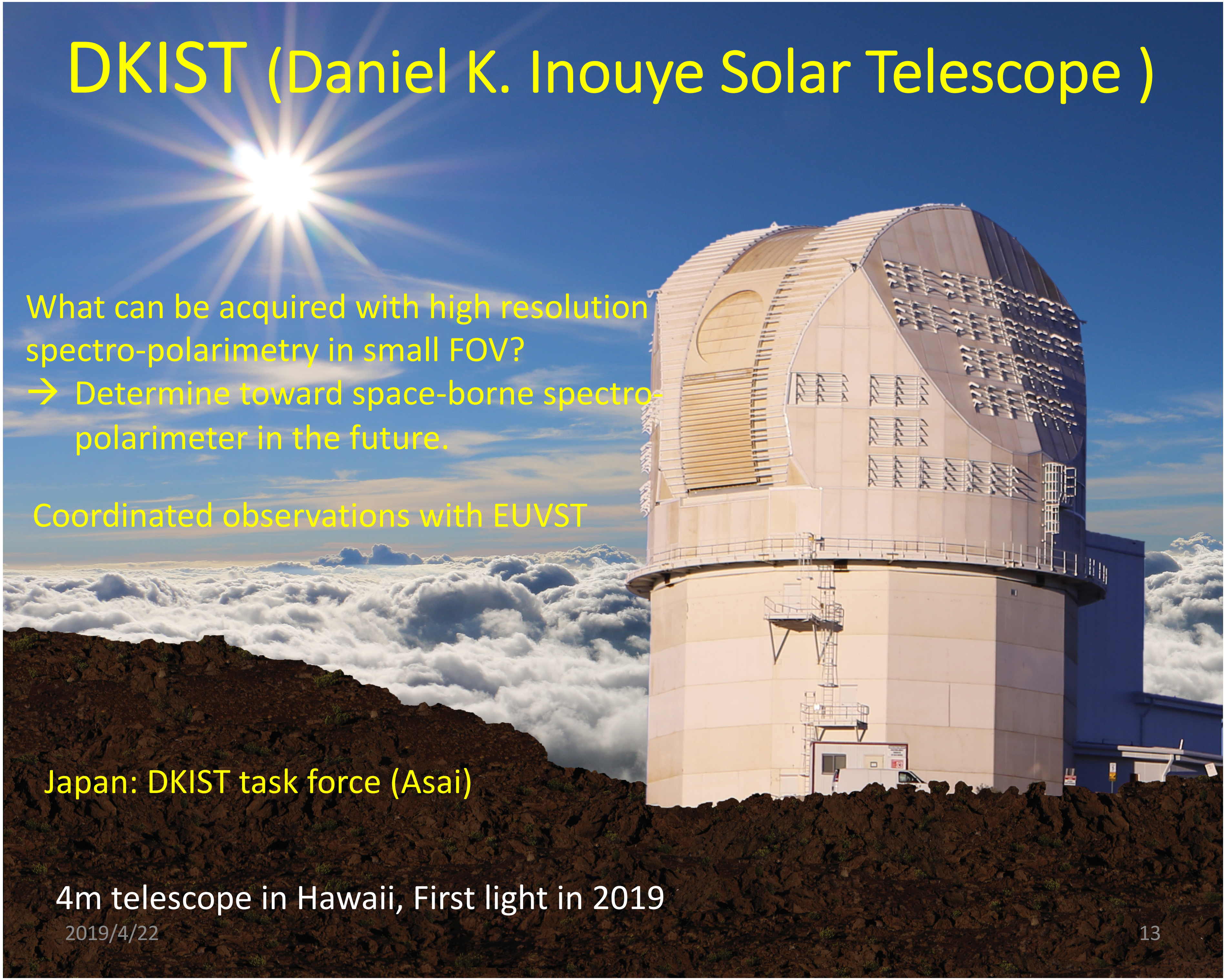

### Science goal

- Measurements of 3D magnetic structures from the photosphere to the chromosphere along with T and V.
  - To reveal mechanisms of chromospheric jets and propagation of MHD waves.

### Instruments

- High-resolution (0.2”) and precise polarimetry (0.03%) in multiple spectral lines (Ca II, K I, and Fe I lines).



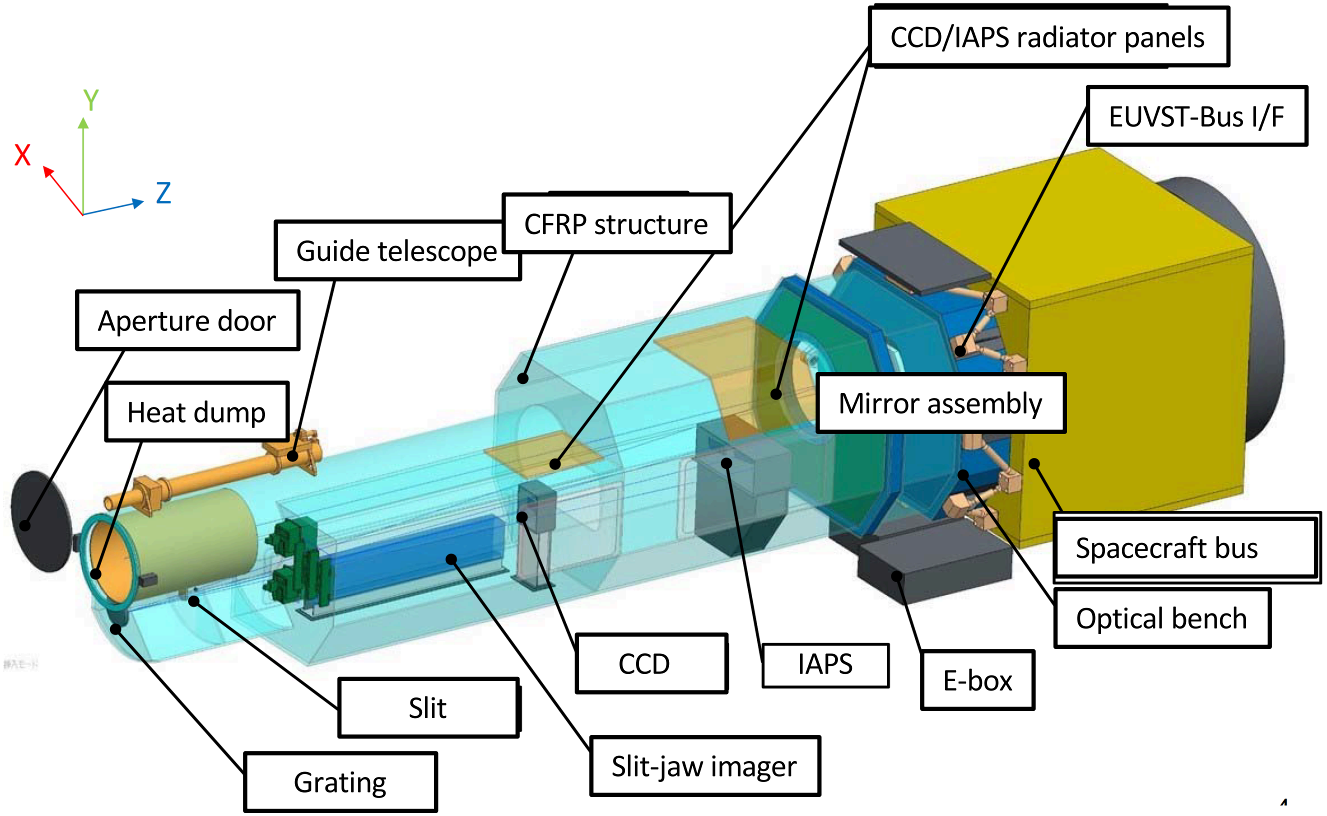

DKIST (Daniel K. Inouye Solar Telescope )
What can be acquired with high resolution spectro-polarimetry in small FOV?
→ Determine toward space-borne spectro-polarimeter in the future.
Coordinated observations with EUVST
Japan: DKIST task force (Asai)
4m telescope in Hawaii, First light in 2019

# 2. Spectroscopy in EUV

- Mass and energy transfer in upper atmosphere
- For bridging to the heliosphere
- **Solar-C_EUVST in 2025**

# Solar-C_EUVST mission

= Solar-C EUV High-throughghput Spectroscopic Telescope

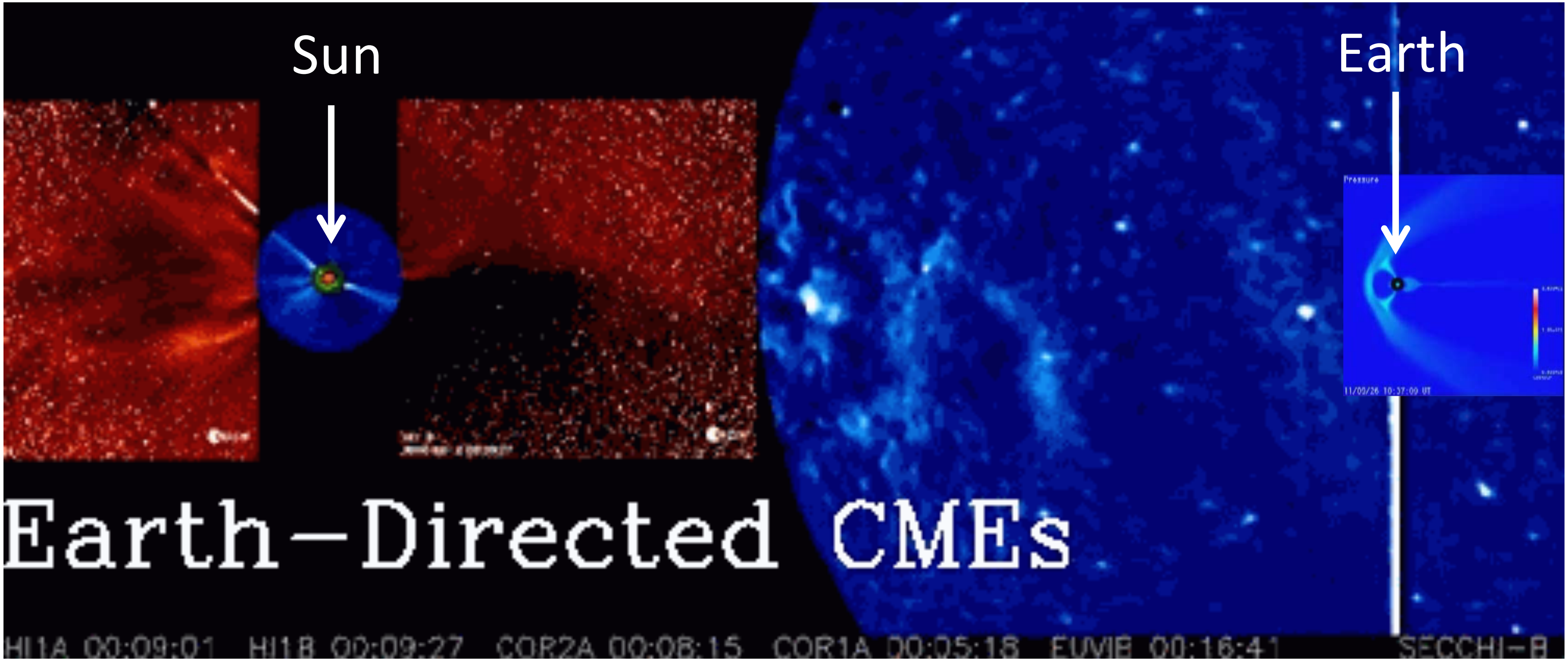



- Down-selected as one of candidates for competitively chosen M-class mission with Epsilon rocket, to be launched around early 2025
- Synergy with PSP, SO, and Mio for the Sun-Inner heliosphere investigations

# Science goals of the mission

The importance of observing the solar atmosphere

- **How the plasma universe is created and evolves?**
- **How the Sun influences the Earth and other planets in our solar system?**




The interplay of magnetic fields and plasma creates behaviors

Quasi-steady: corona, solar winds

Transient: Flares, CMEs



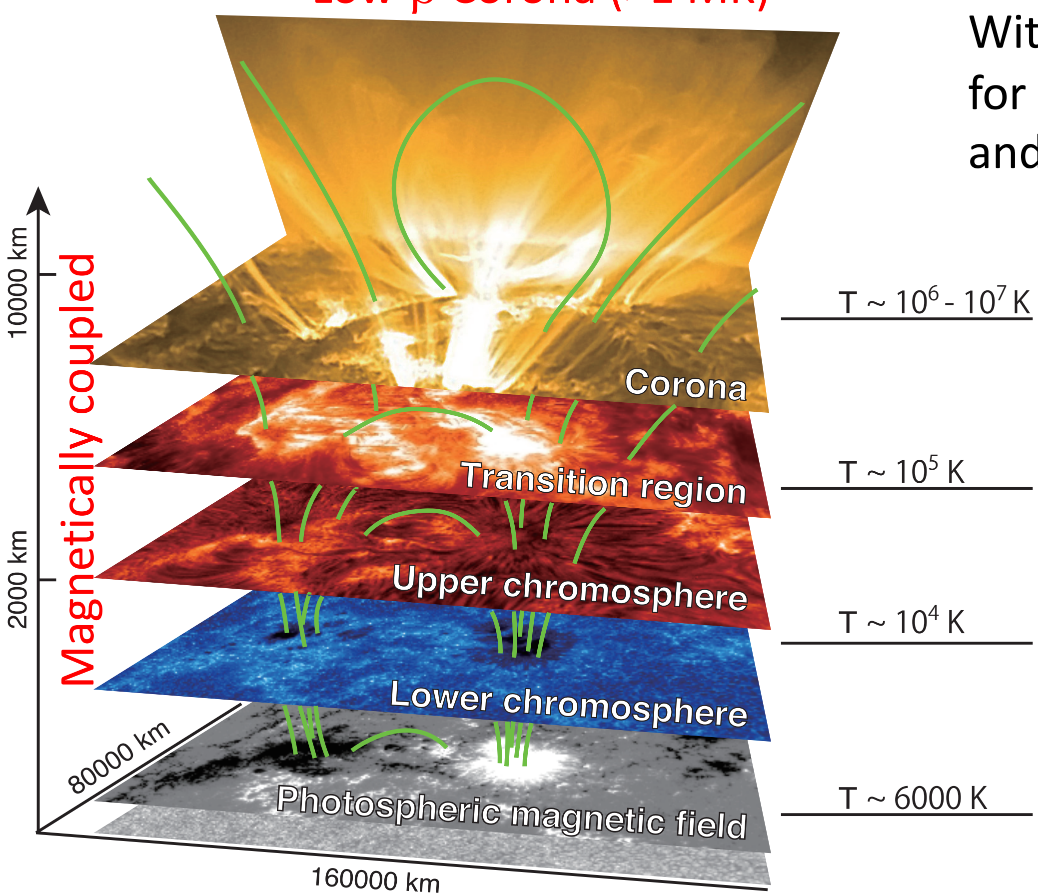
**Energy and mass transfer and energy dissipation**

# Solar-C_EUVST: Scientific objectives

I. **Understand how fundamental processes lead to the formation of the solar atmosphere and the solar wind**

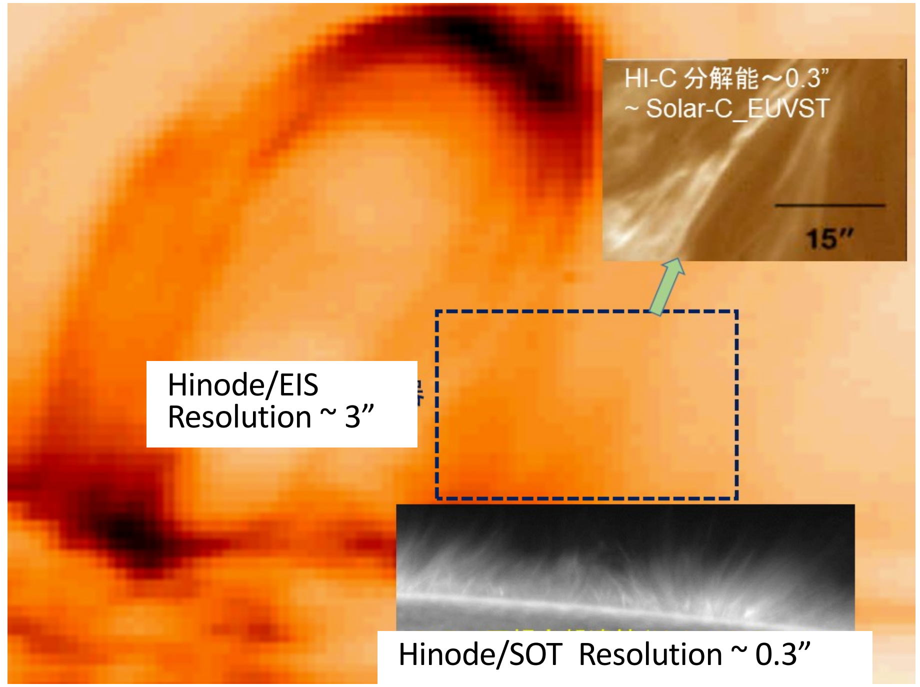
II. **Understand how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions**

Low-β Corona (>1 MK)

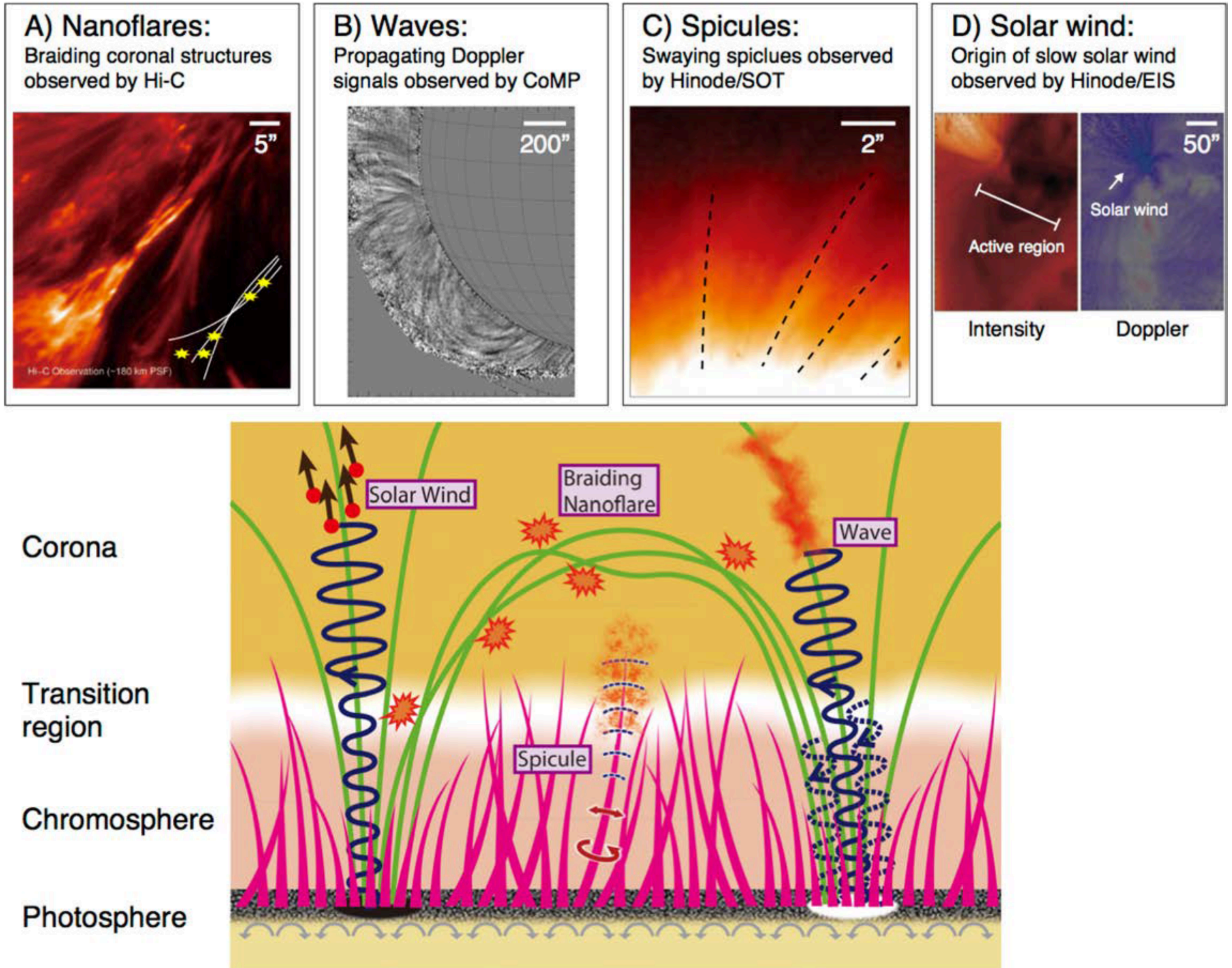



High-β Photosphere (6000 K)

With too different spatial resolution, impossible for the existing instruments to trace the energy and mass transport toward the corona.

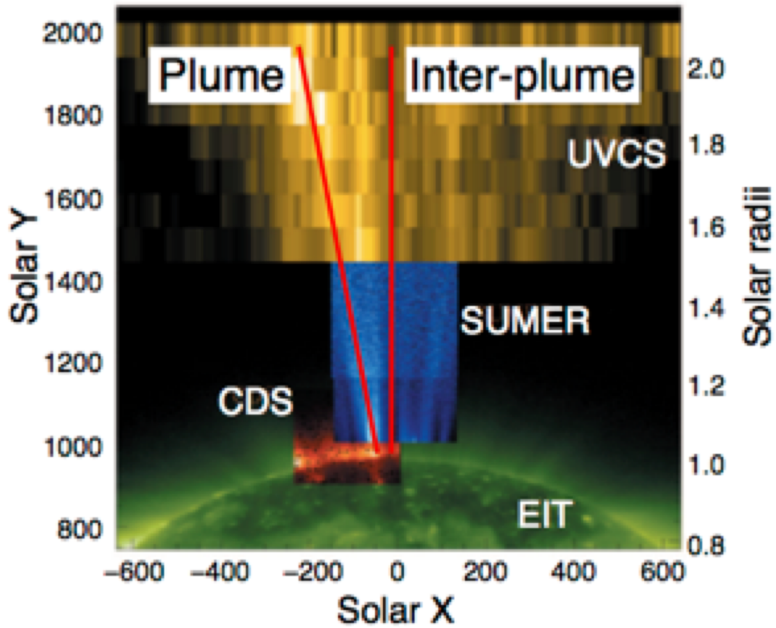


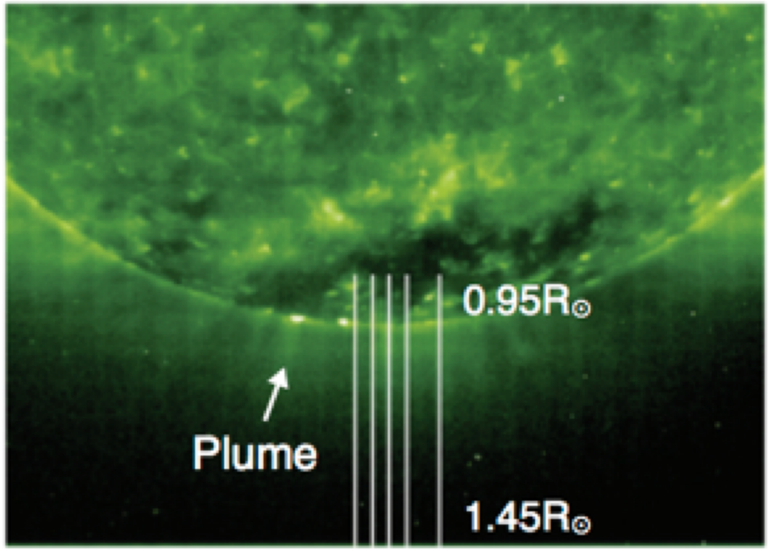
High Spatial resolution | High Temporal resolution | Simultaneous observation | Dark region observation



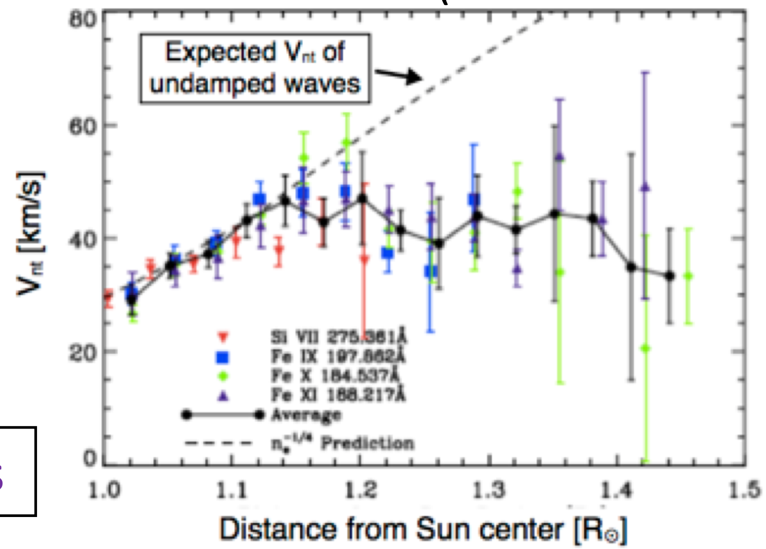
# Source regions of solar winds

(Teriaca et al. 2003)




(Hahn and Savin 2013)




Still under debate:

polar plumes vs. inter-plume region (for fast wind)

persistent flows at edges of ARs vs. steamers in higher corona (for slow wind)

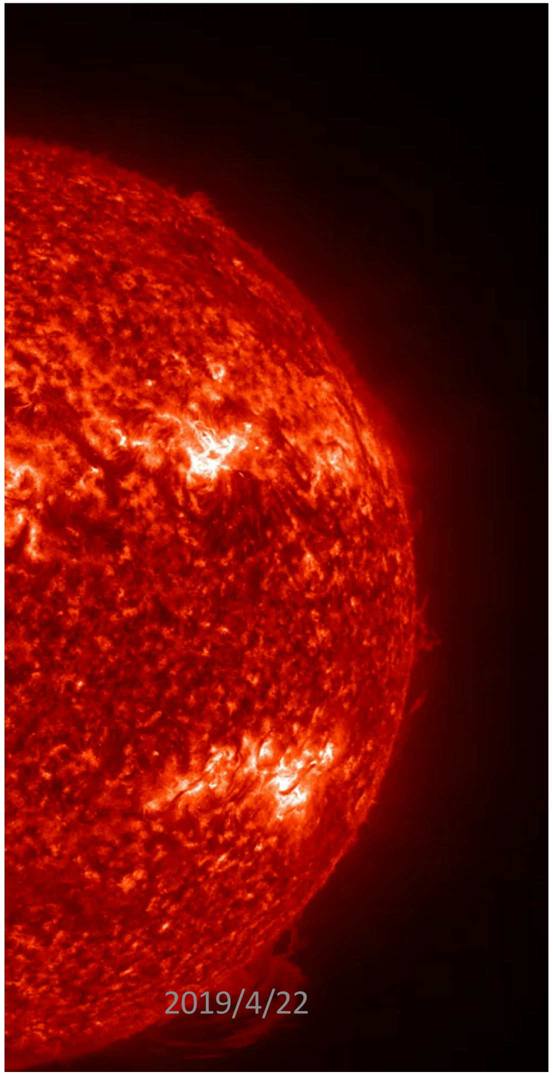
High throughput for faint source regions

signatures of coronal Alfvén waves in plume and inter-plume regions

# Solar-C_EUVST: Scientific objectives

I. Understand how fundamental processes lead to the formation of the solar atmosphere and the solar wind

II. **Understand how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions**

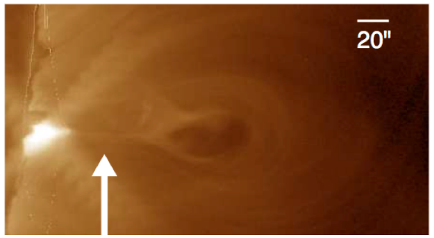


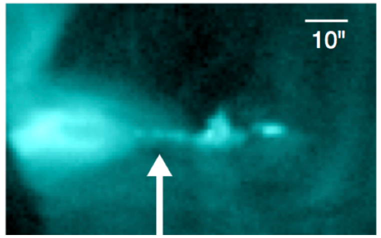

Ideal MHD instability

Reconnection

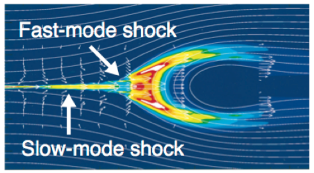
Flare trigger

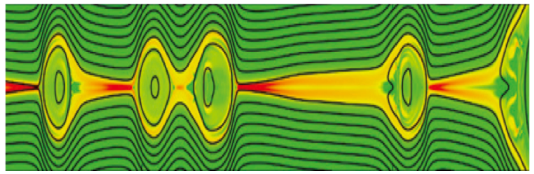
Higher cadence (~100sec) to track dynamics in large-scale structures (low spatial mode)




Petschek v.s. Plasmoid-unstable reconnection



High resolutions (0.4”, ~10sec) to diagnose reconnection region structures (narrow FOV)
➔acceleration, turbulence, shock, heating

High resolutions to identify the first trigger either in chromosphere, transition region, or corona.

# Approach to tackle the scientific objectives

## EUV spectroscopic telescope with three significant advances

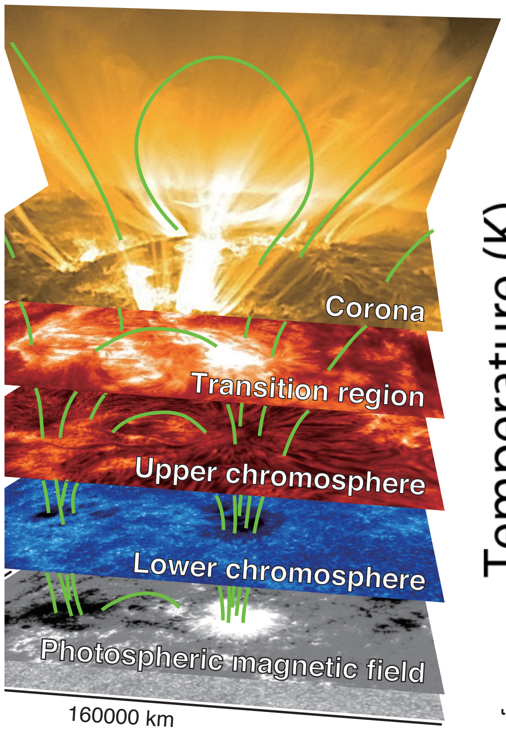
A: Seamlessly observe all the temperature regimes of the atmosphere from the chromosphere to the corona simultaneously at the same spatial resolution
(10^4-10^7 K)

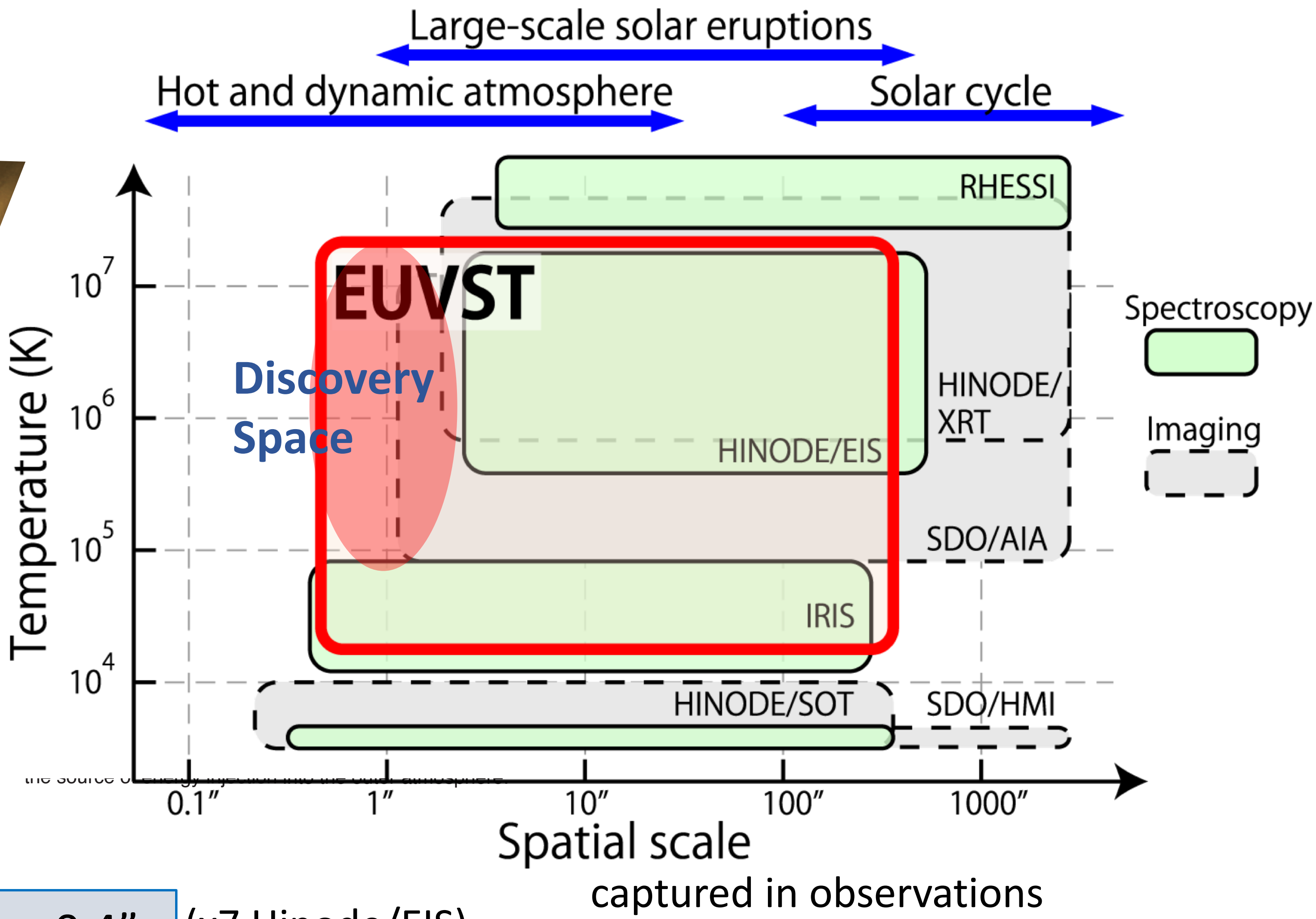
B: Resolve elemental structures of the solar atmosphere and track their changes with sufficient cadence
(0.4”, 1 sec exposure)

C: Obtain spectroscopic information on dynamics of elementary processes taking place in the solar atmosphere
(V, $\rho$, T, composition, ionization etc)

# EUVST: Three significant advances

(**spatial** & temporal resolutions, **temperature seamless coverage**)




Spatial resolution: 0.4” (x7 Hinode/EIS)
FOV: 300”x280”

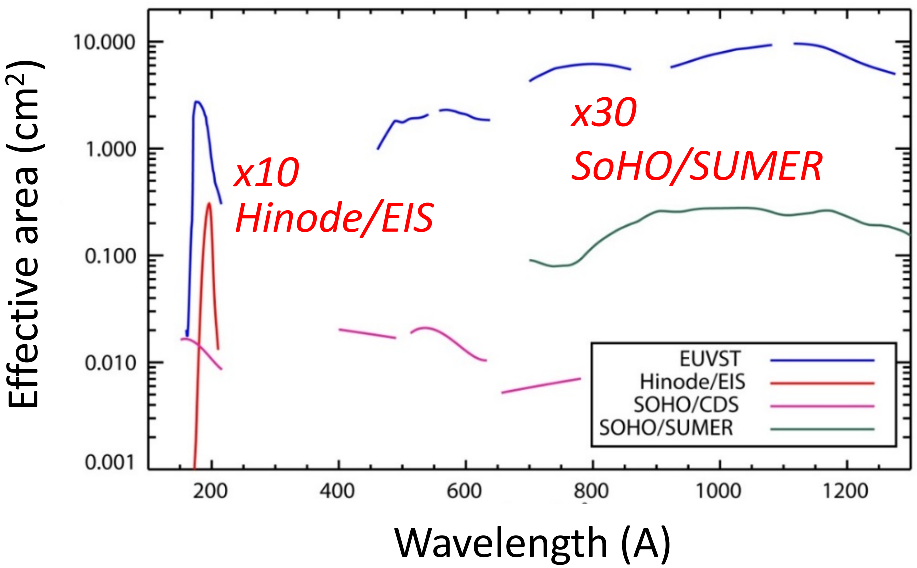
# EUVST: Three significant advances

（spatial & **temporal resolutions, temperature seamless coverage**)

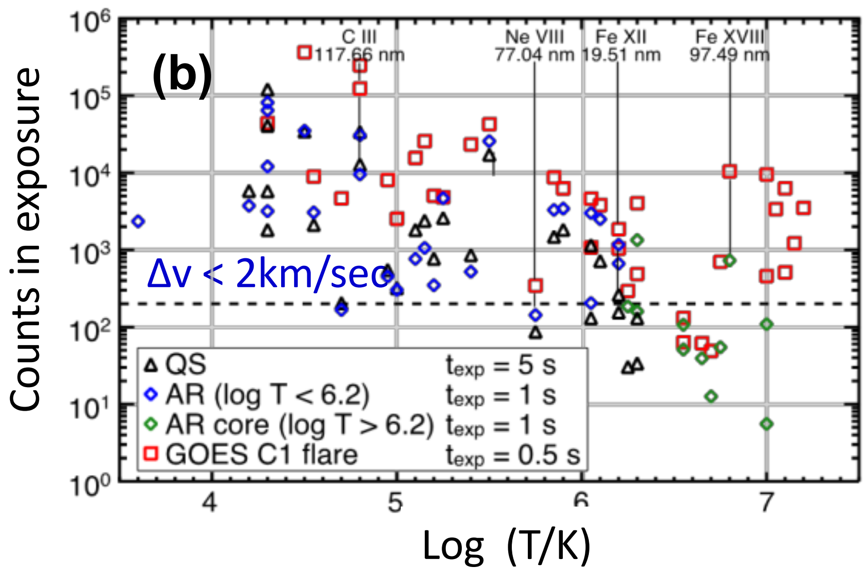
- High throughput and low scattered light
  → High temporal resolution, faint objects

- A variety of spectral lines, seamlessly covering temperatures from chromosphere to the corona/flare

Effective area vs. wavelength




Count rate vs. temperature



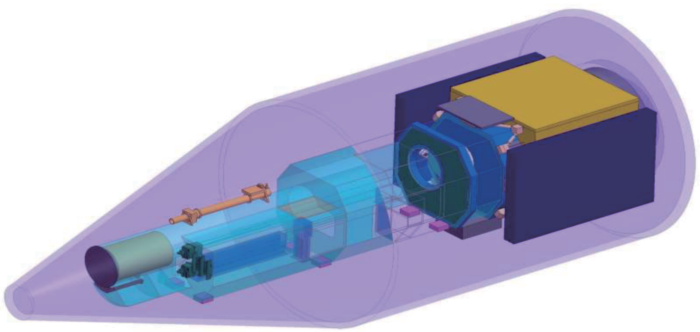
# Solar-C_EUVST concept

- Single-active-mirror telescope (an 28cm-diameter off-axis parabola with pointing capabilities)

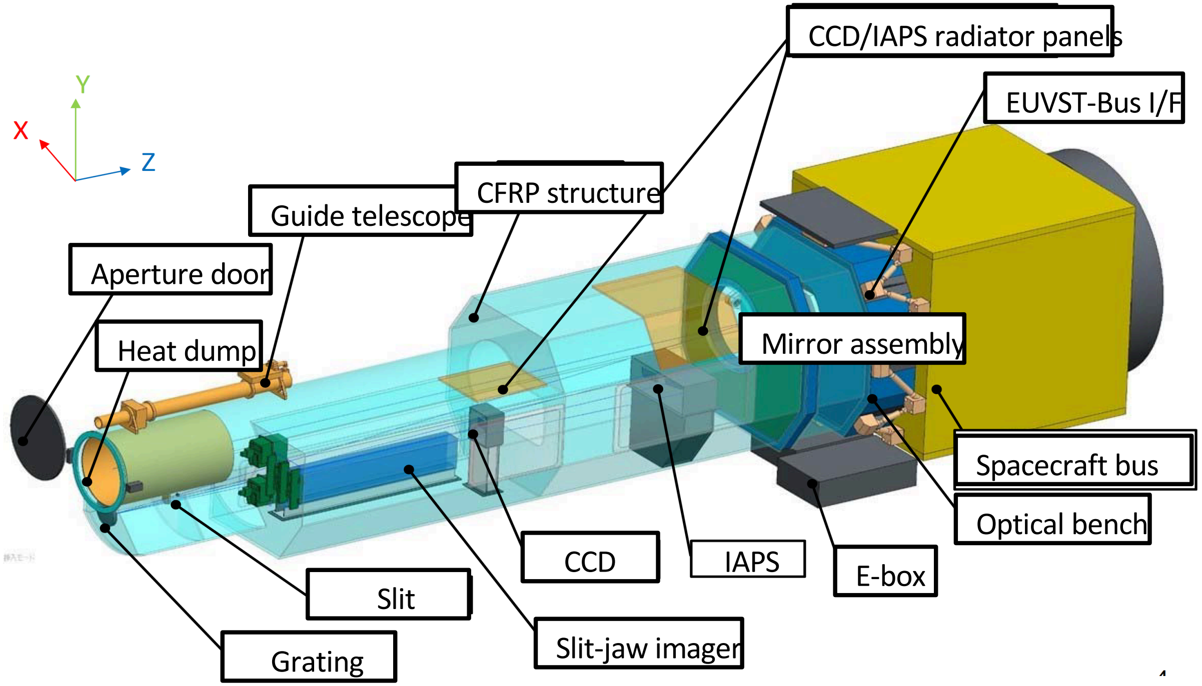
＋Slit/TVLS gratings/large-format detectors (CCD, IAPS)

Wavelengths: 17-21.5nm,
46-128nm
Spatial resolution: 0.4”
FOV: 300”x280”

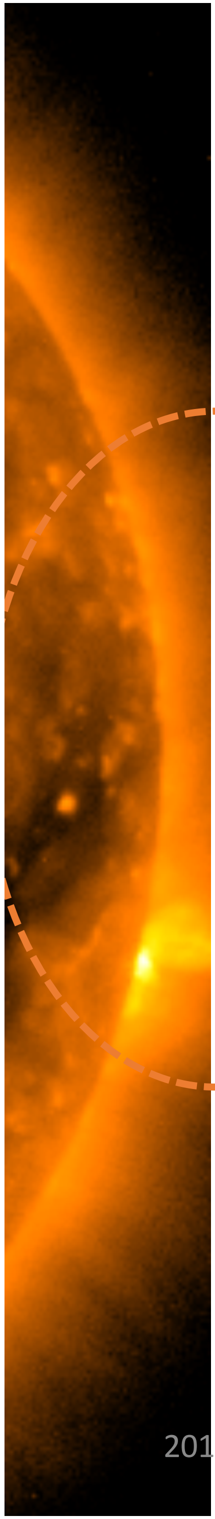
- EUVST mounted on the spacecraft bus
- Total mass about 517 kg
- Epsilon vehicle is used to install the mission into Sun Synchronous polar orbit.



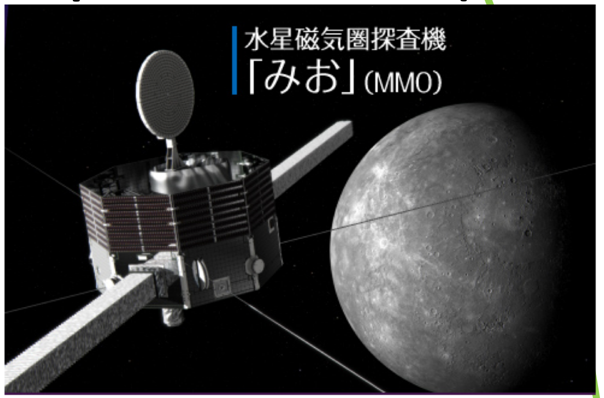
Launch in 2025



# 3D structure of the Inner heliosphere

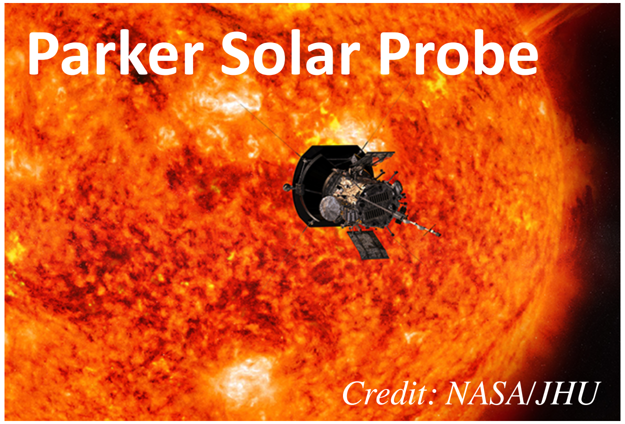


**BepiColombo/Mio (MMO)**



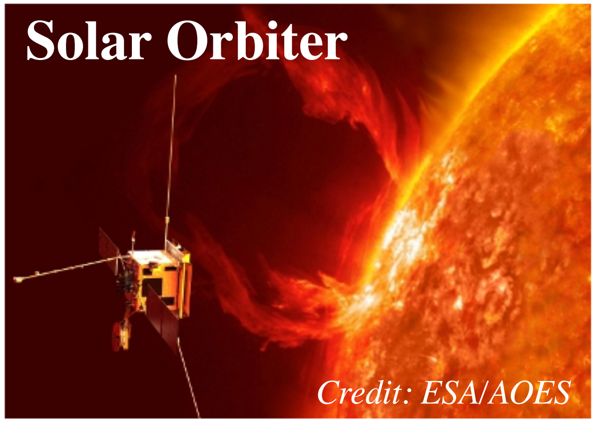

65Rs – 100 Rs @Mercury
(2025~)

“in situ” measurements




8.9Rs (closest) (2025~)

“in situ” measurements

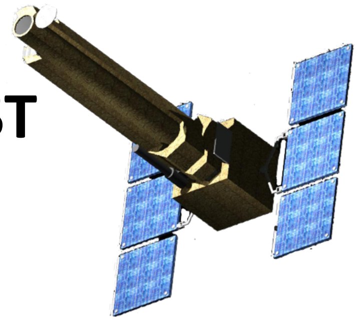



60Rs (closest),
25 deg. solar latitude
(2026~)

“in situ” measurements

***IPS***

**Solar-C_EUVST**
**(2025~)**



Coronal image/spectra,
photospheric magnetogram

# NASA and ESA missions in 2020s

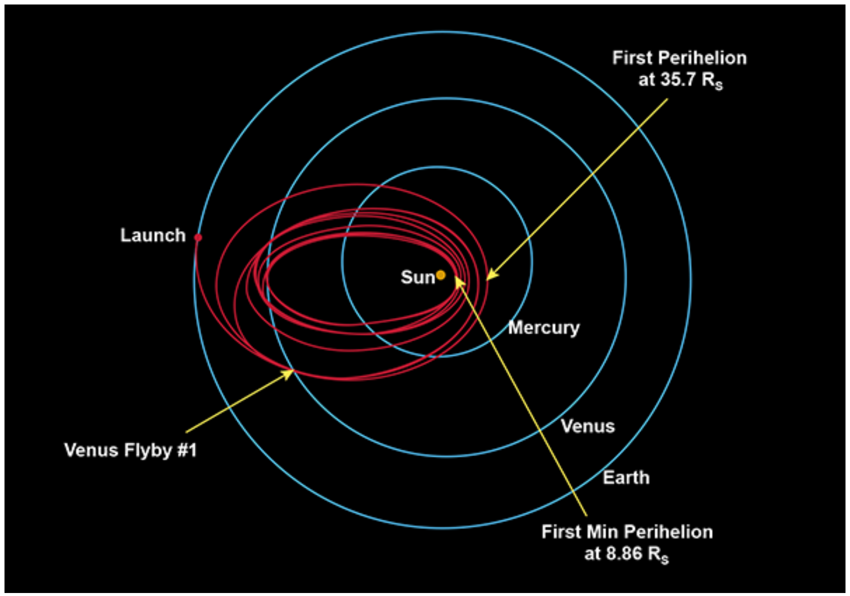
## Parker Solar Probe (NASA)

Characteristics：

- 9 solar radii form solar surface
- Launch in 2018 summer and first close approach in 2024
- In-situ measuring instruments

Scientific objectives：

- Origin of solar wind




Orbit of Parker Solar Probe

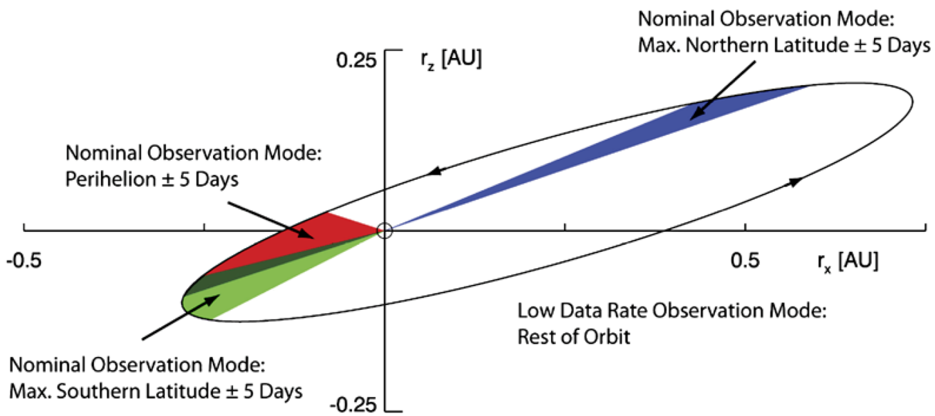
## Solar Orbiter (ESA)

Characteristics：

- Out-of-ecliptic viewpoints （up to 25° of solar latitude until 2027, 0.3AU at the closest approach）
- Launch in 2020
- In-situ instruments + many remote-sensing instruments
- Moderate instrument performance

Scientific objectives：

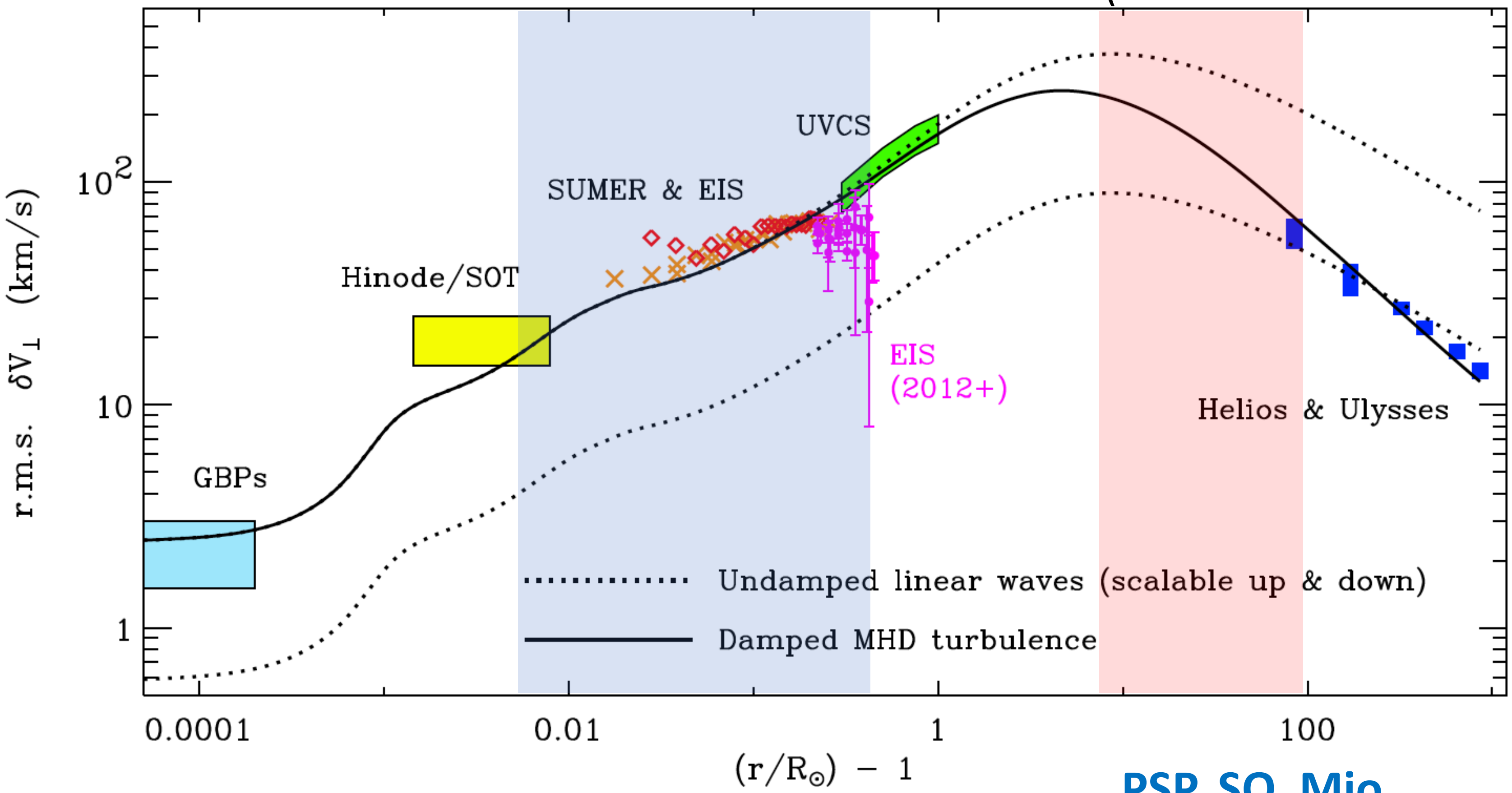
- Coronal heating, solar wind, solar dynamo




Orbit of Solar Orbiter

# Height dependence of transverse velocity amplitude in fast wind

(Cranmer et al. 2017 SSRev)



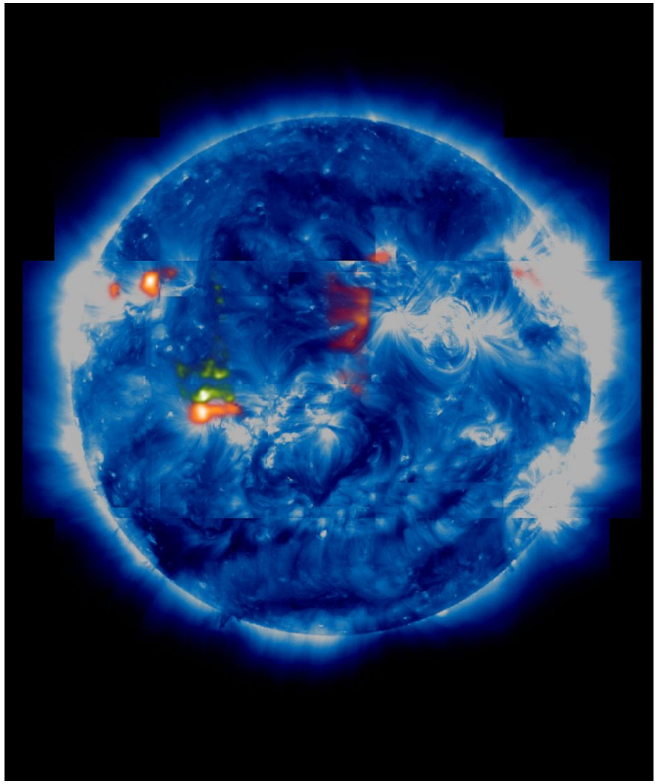

**Solar-C_EUVST: high throughput**

**PSP, SO, Mio**

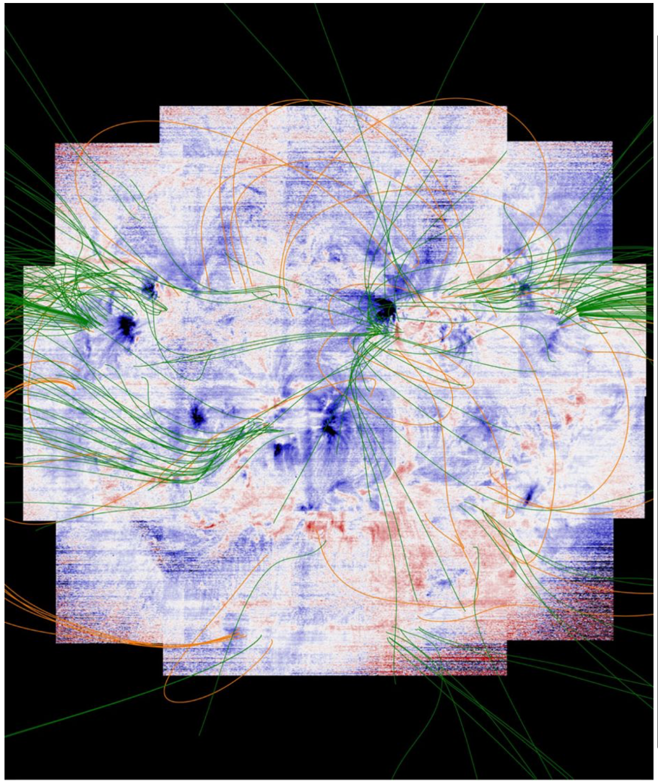
Time variable, dependence on the location of source regions etc.

# EUV spectroscopy to provide plasma conditions at wind source

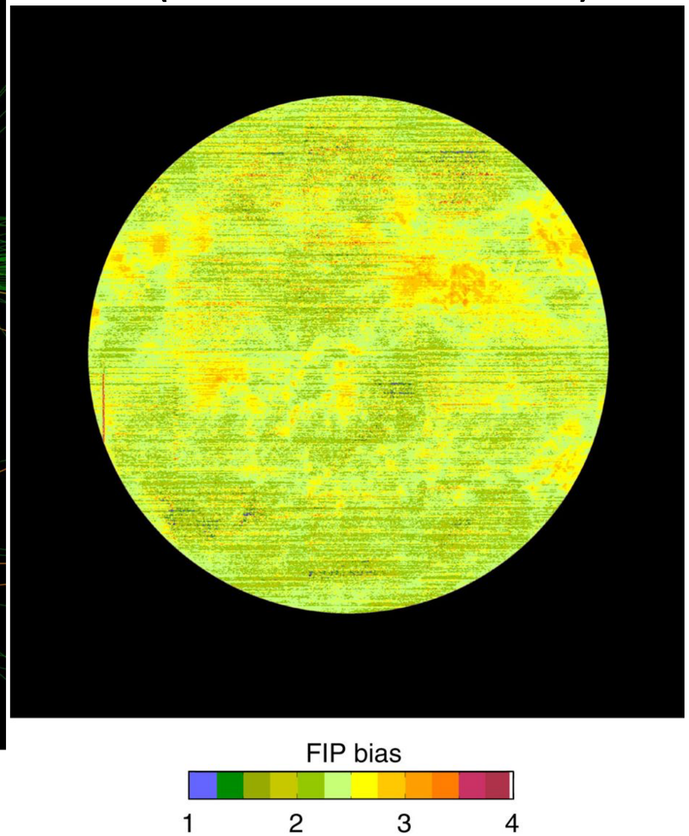
From Hinode/EIS Full-Sun Mosaic mapping
(Brooks et al. 2015)



Slow SW sources overlaid on AIA 193 intensity



Doppler velocity at 2MK with magnetic field overlaid

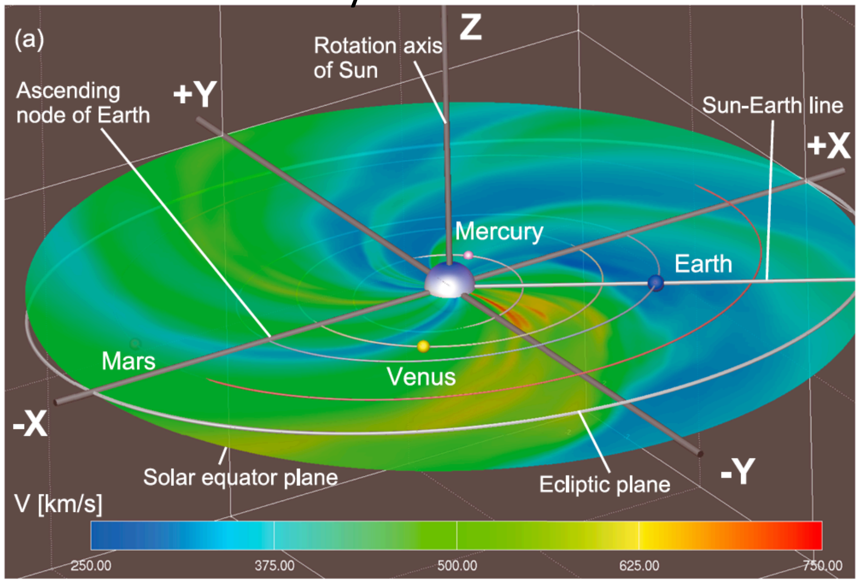


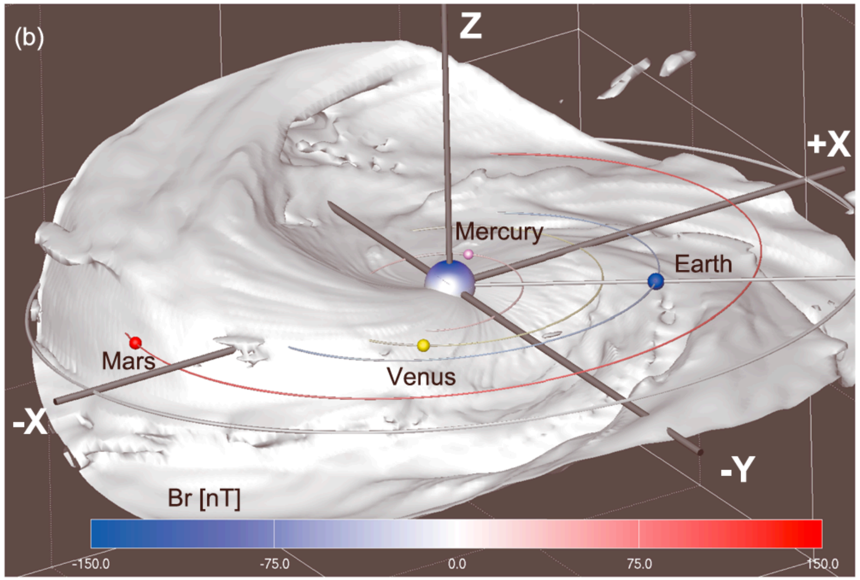

Plasma composition
Connect to
in-situ measurements

(Shiota, Kataoka et al. 2014 Space Weather)

# Inner heliosphere MHD modeling

Solar wind velocity




Sector boundary of interplanetary field

- Inner boundary condition: *B*
  - R=25 Rs
  - Given by a synoptic map of the photospheric magnetic field (observation, 1Rs)
  - PFSS model (current-free in corona)
  - All field lines open out at source surface (2.5Rs)
  - Extending the radial field to 25 Rs
  - Expansion factor fs from 2.5Rs/1Rs
- Inner boundary condition: V_s
  - Solar wind velocity map, by an empirical WSA formula

(Wang & Sheeley 1990, Arge & Pizzo 2000)

$$V_{sw}(f_s) = 267.5 + 410/f_s^{0.4}$$

次期太陽観測衛星

# Solar-C_EUVST

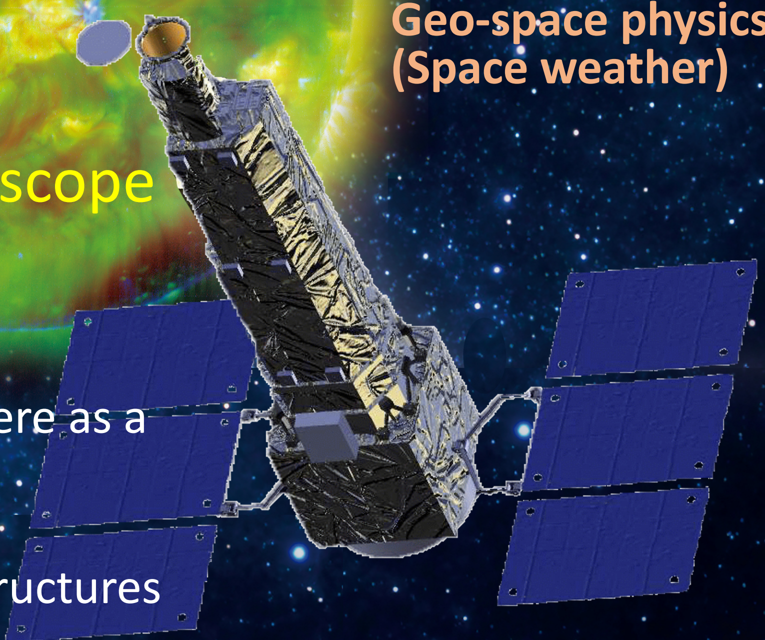
JAXA Epsilon M-class mission

A fundamental step towards answering how the plasma universe is created and evolves, and how the Sun influences the Earth and other planets in our solar system

## Science objectives

I. **Understand how fundamental processes lead to the formation of the solar atmosphere and the solar wind**

II. **Understand how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions**



**Close connection to**

**Astrophysics**

**Plasma physics**

**Geo-space physics (Space weather)**

## EUV high-throughput Spectroscopic Telescope

to quantify how mass and energy are transferred with 1st-ever capabilities to

**A)** ***Wide T-coverage*** (10^4-10^7 K)
Observe the whole regimes of the solar atmosphere as a single, coupled system

**B)** ***High resolution*** (spatial ~ 0.4”, temporal ~ 1 sec)
Capture the dynamic evolutions of elementary structures

**C)** ***Spectroscopy***
Determine the physical states of the targets
(V, ρ, T, composition, ionization)

# 3. Longer-term future prospects

Future plans following the Solar-C_EUVST around 2030s and beyond

They are defined by not me, by younger generation.
My role is to help to define the future directions with higher reality.

# Roadmap in solar observations

Toward upper atmospheres

magnetic field (spectro-polarimetry) and seamless (spectroscopy)

at Photosphere

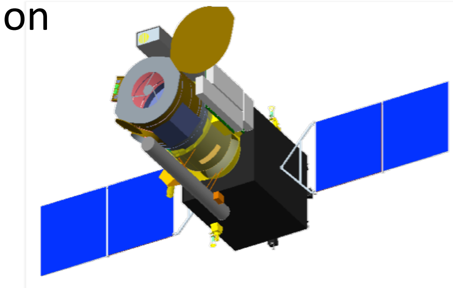
Hinode 2006 –(2021)

SUNRISE-3 balloon (2021)

Photo-chromosphere

Scientific contribution to large telescopes (DKIST) (2020~)

Super high resolution



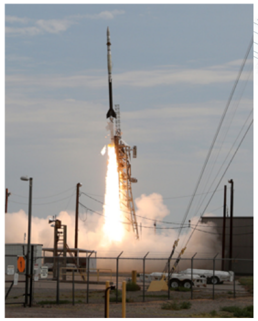
Now

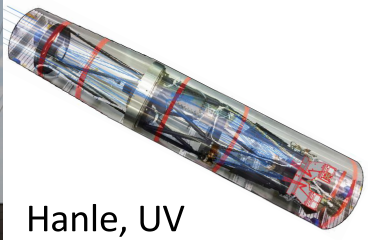
Diagnose solar magnetism

Explore technique for upper layers

CLASP1 sounding rocket (2015)

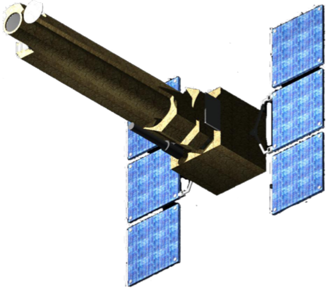
CLASP2 sounding rocket (2019)





Hanle, UV

Coordinated



EUV spectroscopy for uppler layers

**Solar-C_EUVST (2025)**

Seamless coverage from coromosphere to corona/flare, high spatial/throughput

Options after Solar-C_EUVST

Priority has not yet been determined

- >1m space telescope (2030s~)
  
  High precision, constant, large FOV
- Polar regions from out-of-ecliptic vantage point (2030s~)
  
  Solar cycle, connection to heliosphere
- PhoENiX (2026~)
  
  Particle acceleration in MR
  
  Not restricted to solar physics