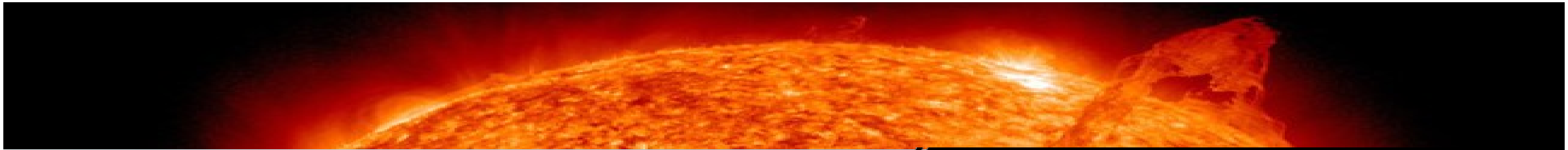
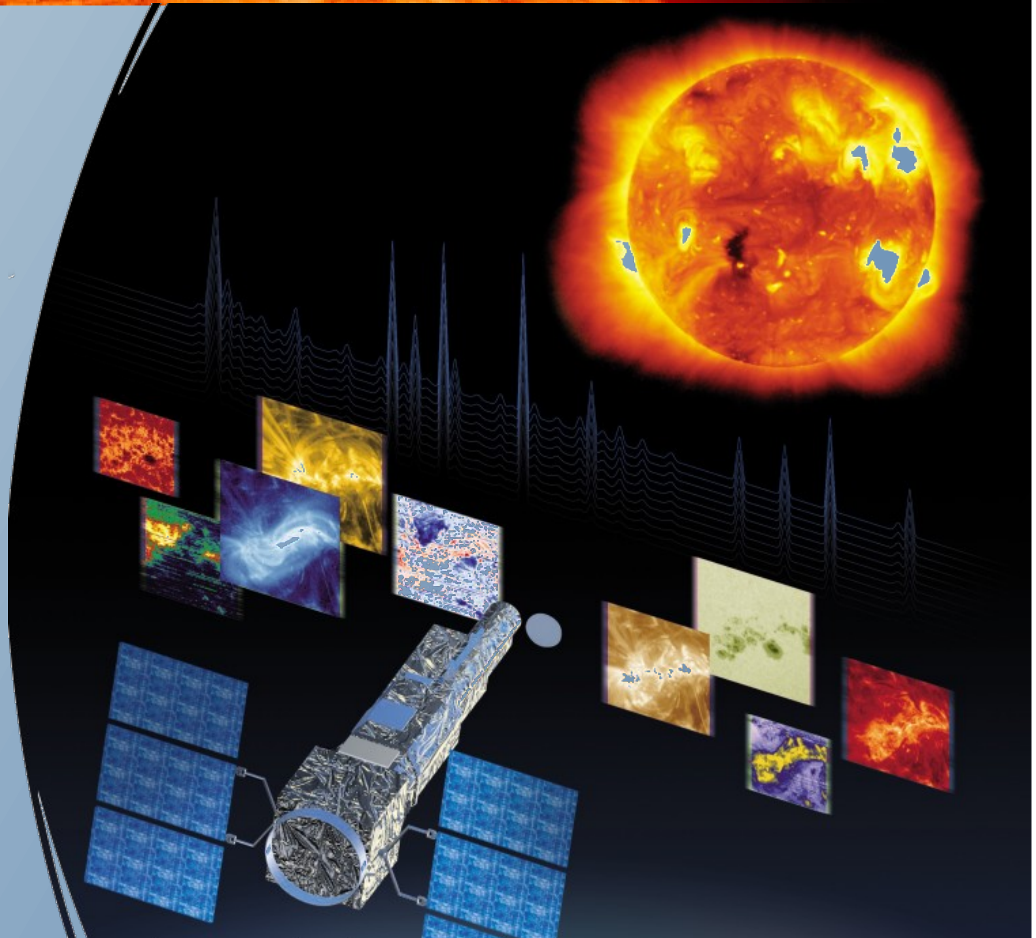


The ultimate EUV solar spectrometer: SOLAR-C/EUVST

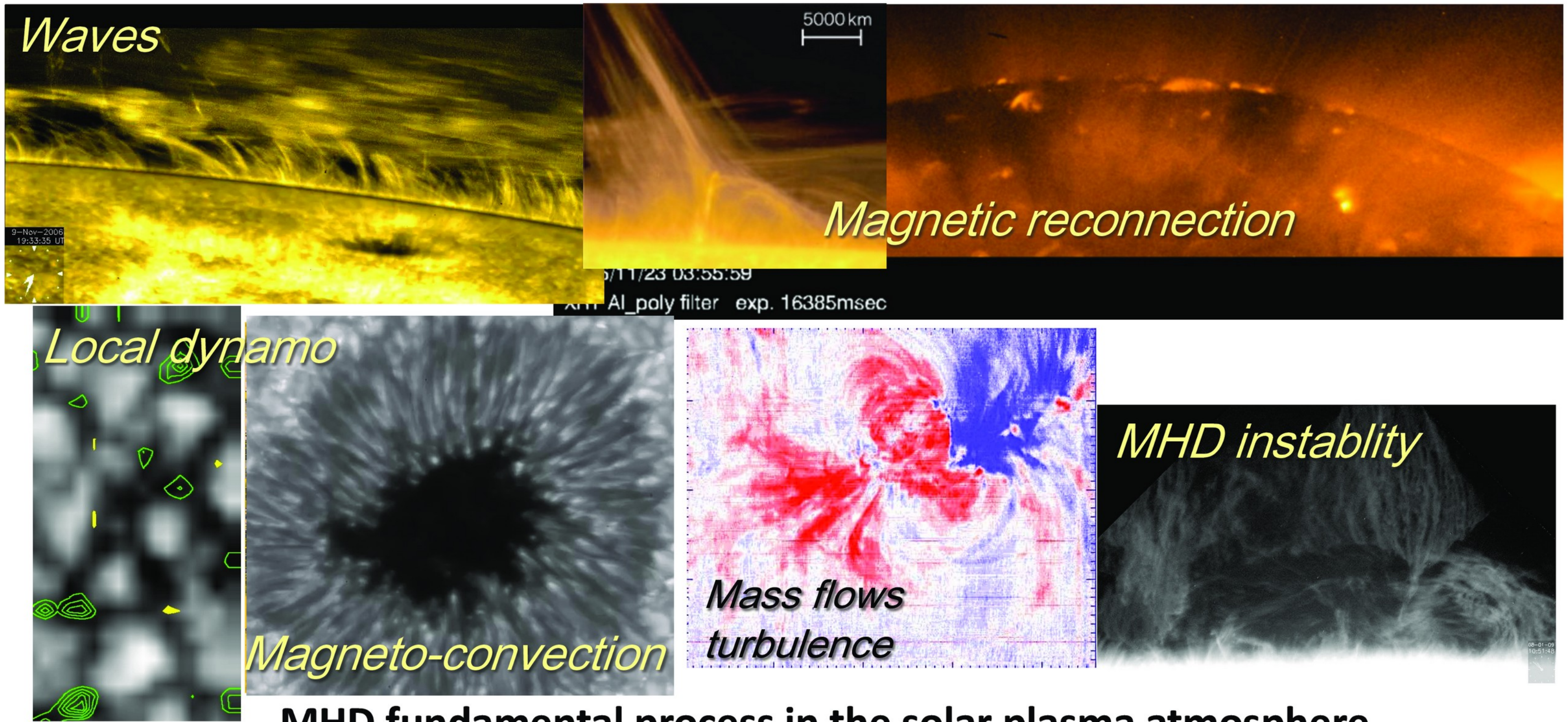
V. Andretta

INAF, Capodimonte Astronomical Observatory
Naples, Italy



Heritage

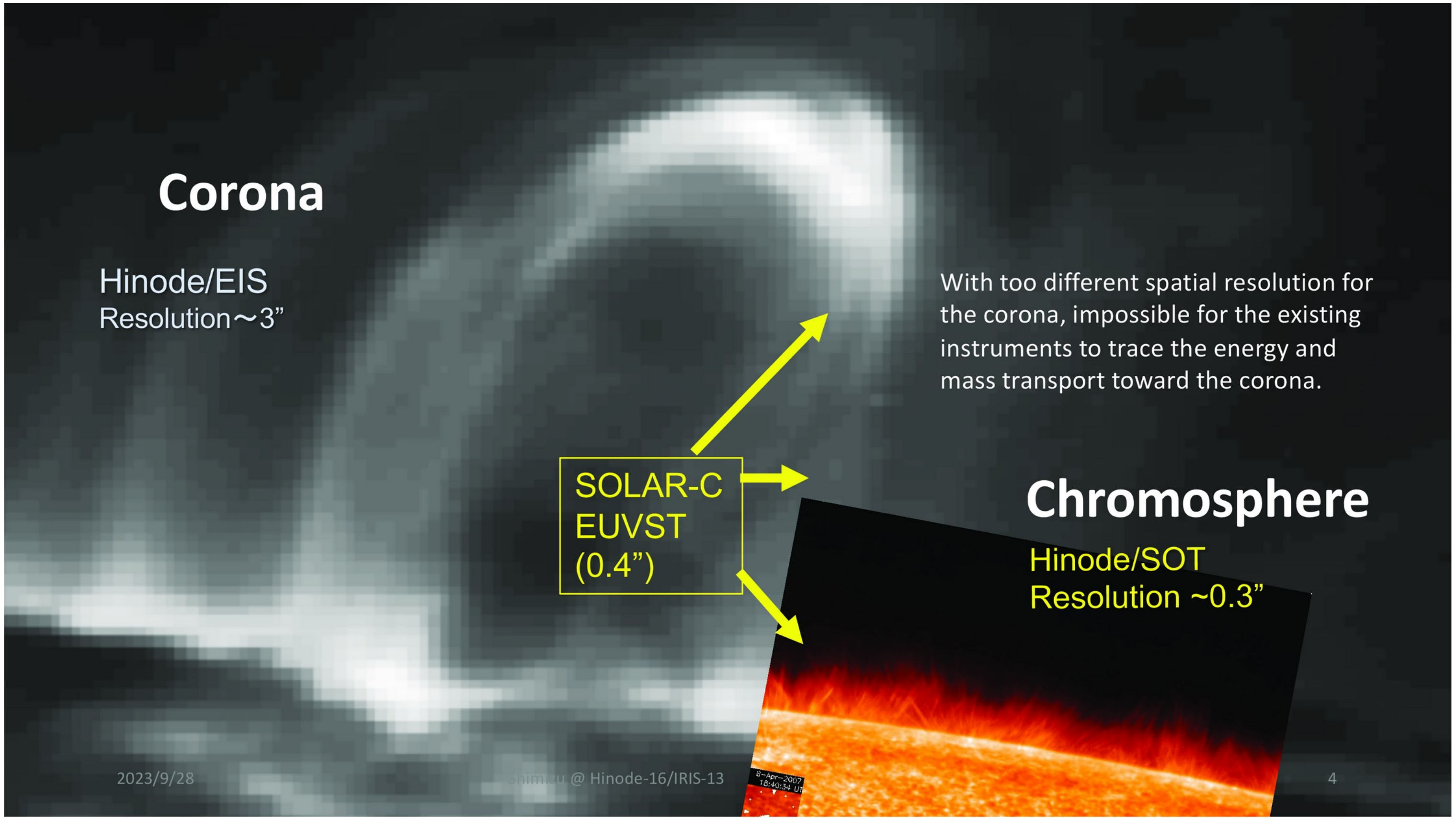
Hinode and IRIS: High resolution solar physics promoted from space



MHD fundamental process in the solar plasma atmosphere

Source: T. Shimizu (2023)

A fragmented view of the solar atmosphere



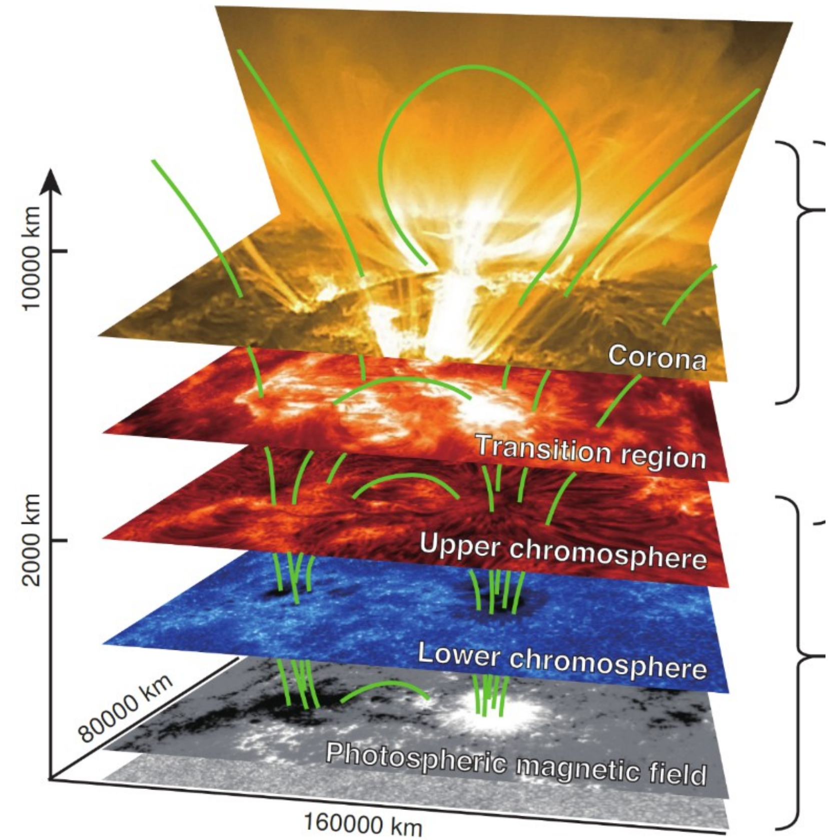
Source: T. Shimizu (2023)

What do we need?

A) Seamlessly observe all the temperature regimes of the atmosphere from the chromosphere to the corona, simultaneously and at the same spatial resolution.

B) Resolve elemental structures of the solar atmosphere and track their changes with sufficient cadence.

C) Obtain spectroscopic information on dynamics of elementary processes taking place in the solar atmosphere.



What will SOLAR-C/EUVST provide

A) Seamlessly observe all the temperature regimes of the atmosphere from the chromosphere to the corona, simultaneously and at the same spatial resolution.

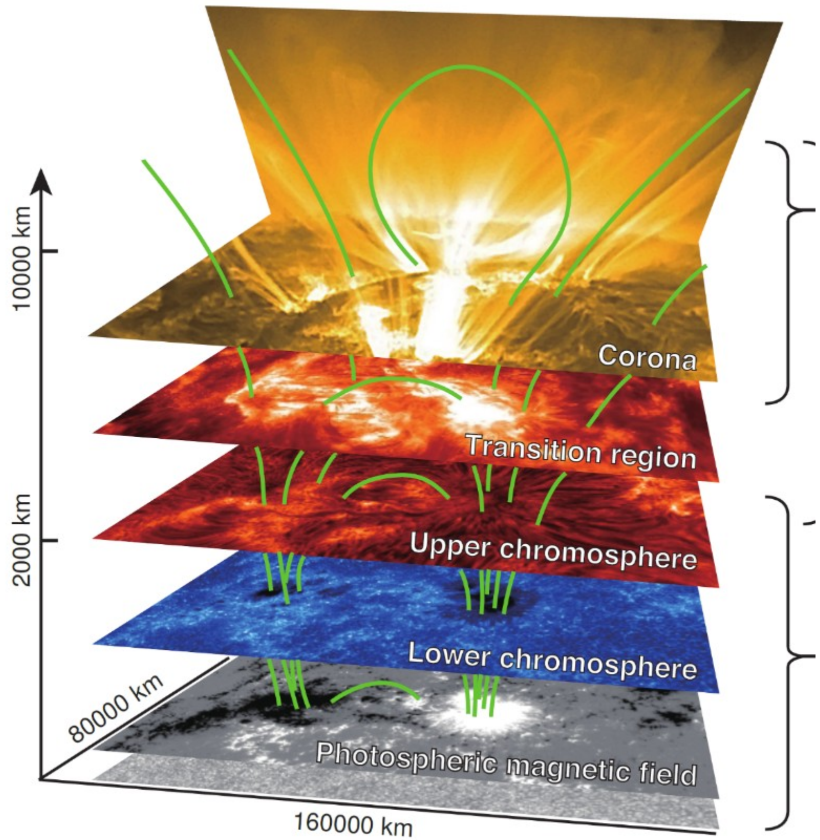
(Temperature range: 10^4 - 10^7 K)

B) Resolve elemental structures of the solar atmosphere and track their changes with sufficient cadence.

(Spatial resolution: 0.4” (300 Mm) at < 1 s exposure)

C) Obtain spectroscopic information on dynamics of elementary processes taking place in the solar atmosphere.

(Velocity, density, temperature, composition, ionization, etc)



A bit of history

ESA calls:

- M3: LEMUR (2010)
- M4: EPIC (2014)

NASA (2020)

US Contribution Funded

INAF (2020)

Phase A for Italian Contribution

JAXA (2021):

Mission Approved

ESA MoO (2022)

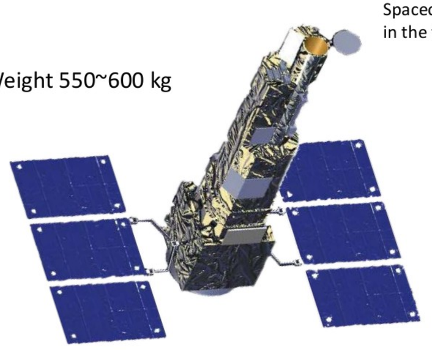
Short Wavelength Channel

The SOLAR-C mission at glance

Spacecraft system

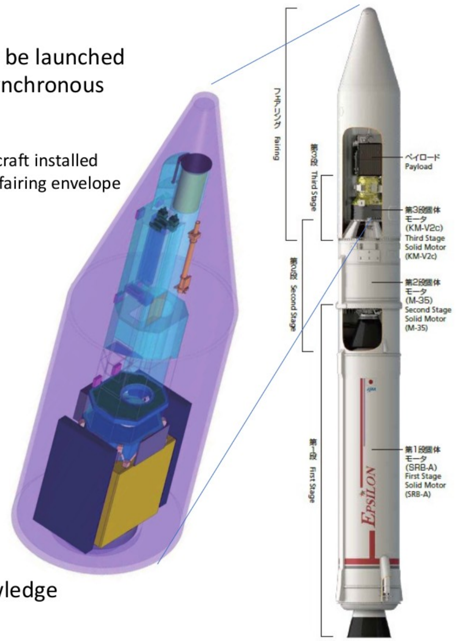
- EUVST mounted on a spacecraft bus, to be launched aboard an Epsilon-S rocket into a sun synchronous polar orbit (>600 km).

Weight 550~600 kg



Spacecraft installed in the fairing envelope

JAXA Epsilon-S rocket
(→ IHI Aerospace after 2025)



Sun synchronous polar orbit (>600 km)

High pointing stability, based on Hinode knowledge

- **Mission instruments**
- ✓ EUV high-throughput Spectroscopic Telescope (EUVST)
- ✓ With Solar EUV Spectral Irradiance Monitor (SoSpIM)

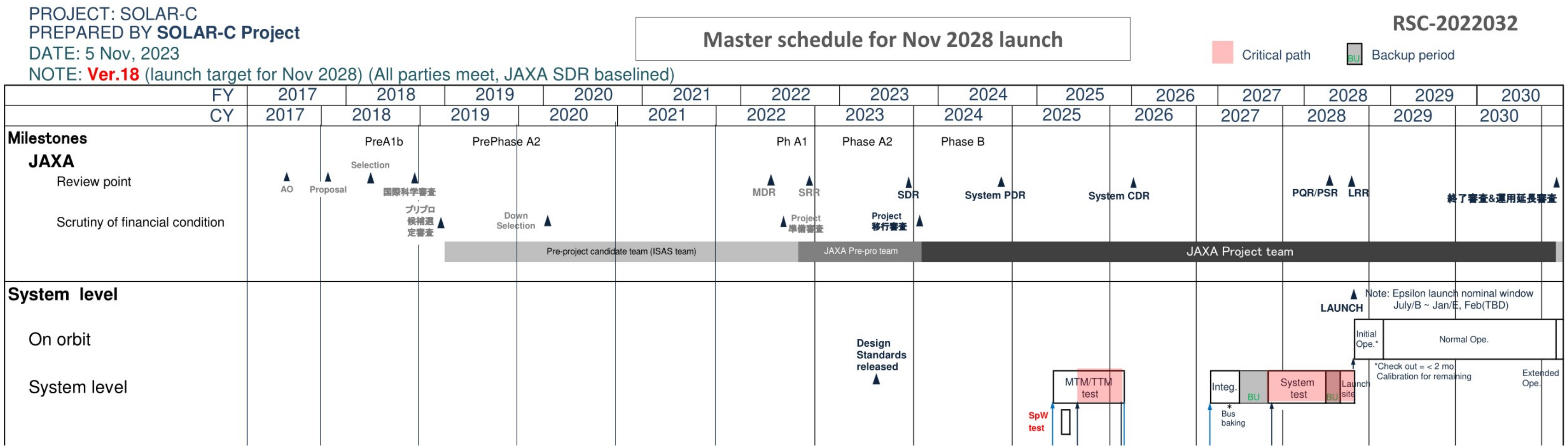
- **Much advanced EUV spectroscopy**
- ✓ Temp coverage: 10^4-10^7 K
- ✓ Spatial resolution: 0.4”
- ✓ High throughput: x10 ~ x40 higher (Temporal resolution: 0.5-sec cad.)
- ✓ Strategic coordination with MUSE and ground-based observatories

Currently in Design and Development Phase
Launch: November 2028

Source: T. Shimizu (2023)

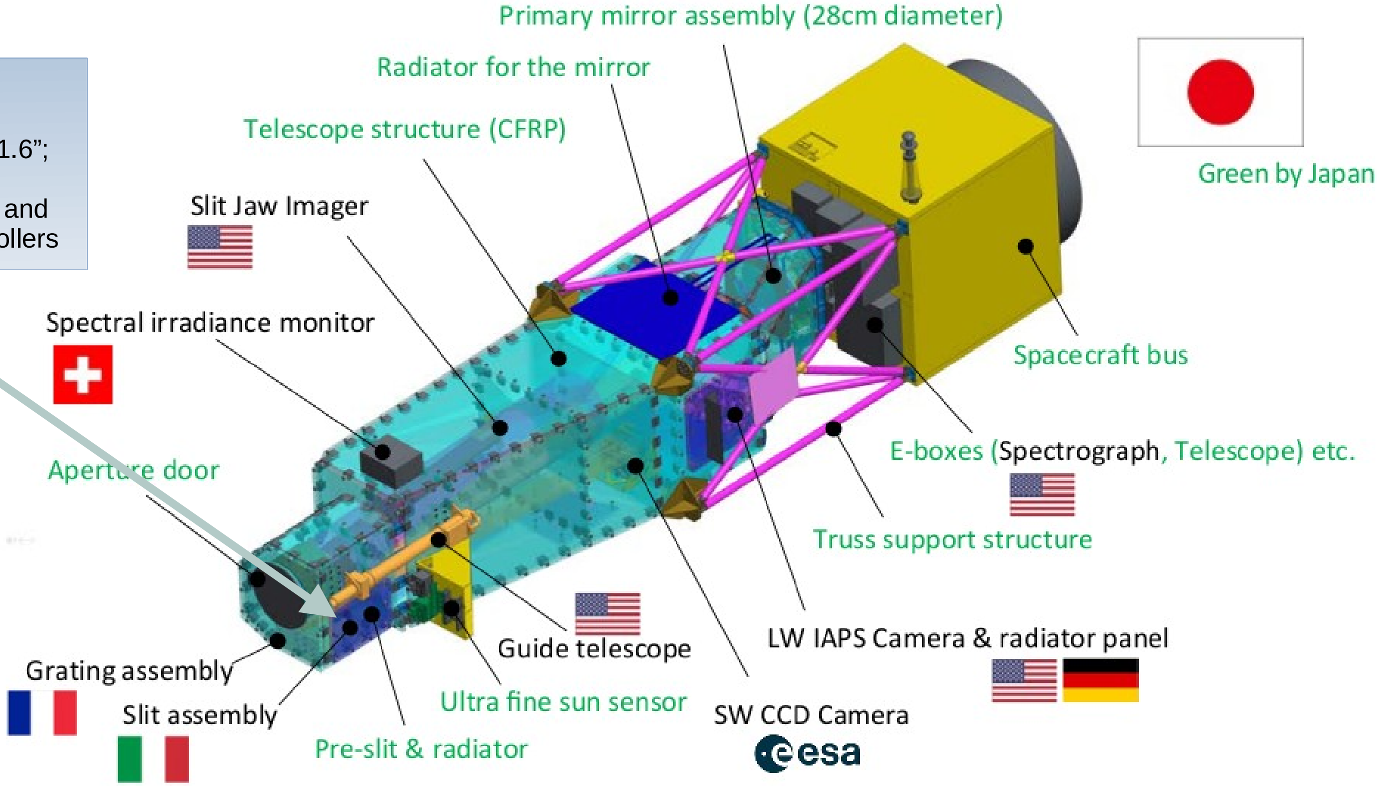
Latest project schedule

- **JAXA System Definition Review (SDR) completed in November 2023**
- **Working towards system PDR in February 2025 (now…)**
- **Launch currently scheduled for November 2028**
- **Mission duration: 2 years (nominal mission) + 4 months (commissioning)**

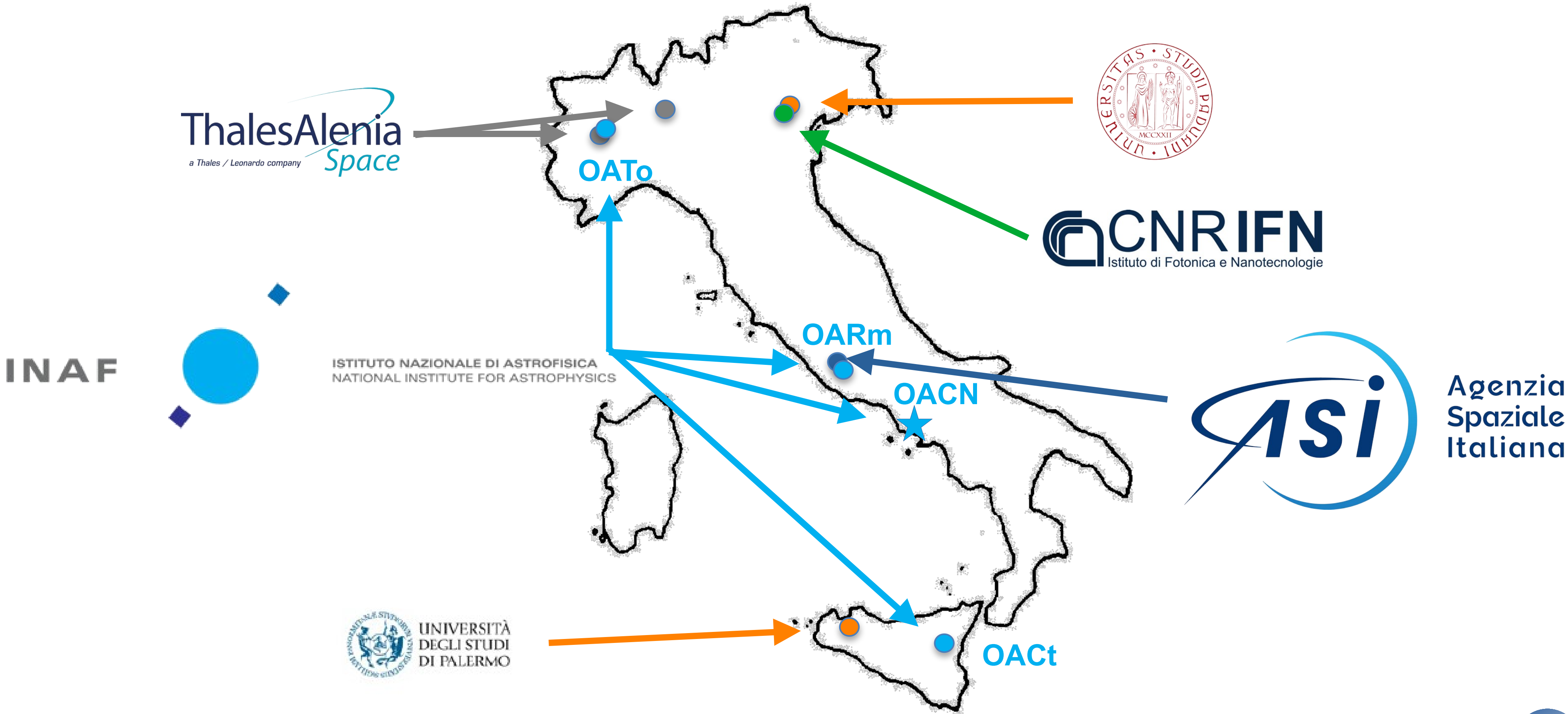


Contributions to the SOLAR-C Mission

Slit assembly:
1) Set of 5, 280" long slits:
   - Science slits: 0.2", 0.4", 0.8", 1.6";
   - Calibration (wide) slit.
2) Slit exchange mechanisms (main and redundant), and associated controllers



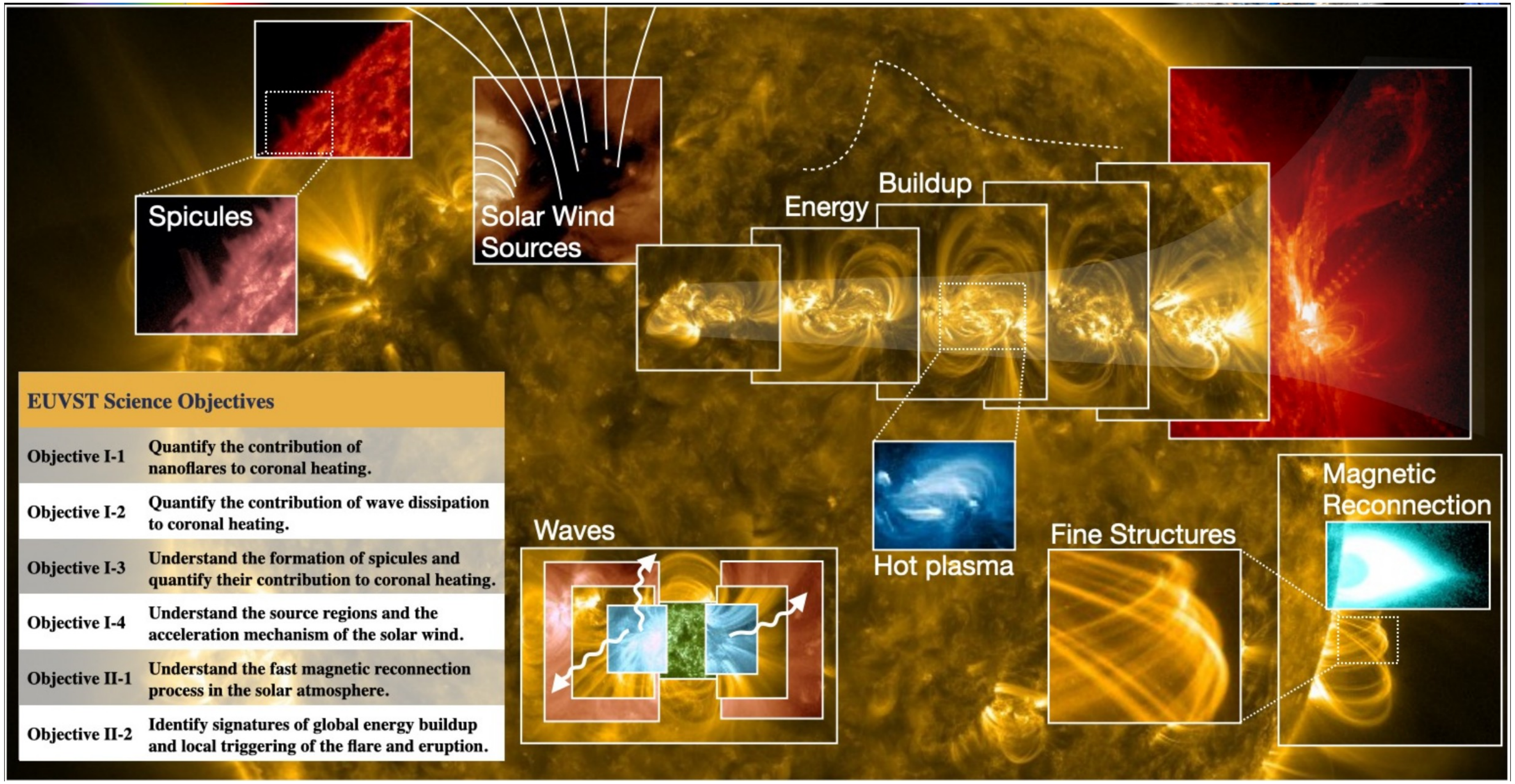
The Italian contribution to SOLAR-C



Science with EUVST

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

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



EUVST Science Objectives	
Objective I-1	Quantify the contribution of nanoflares to coronal heating.
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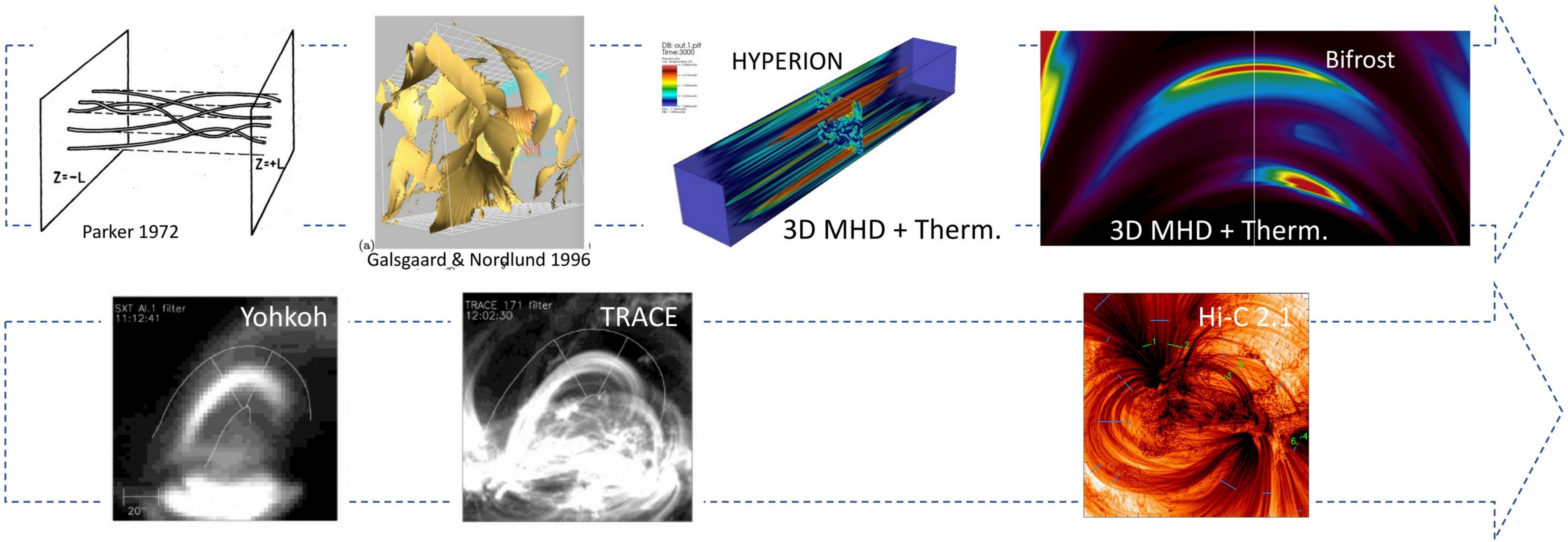
Objective II-1	Understand the fast magnetic reconnection process in the solar atmosphere.
Objective II-2	Identify signatures of global energy buildup and local triggering of the flare and eruption.

Goals and Objectives: Evolution from heritage

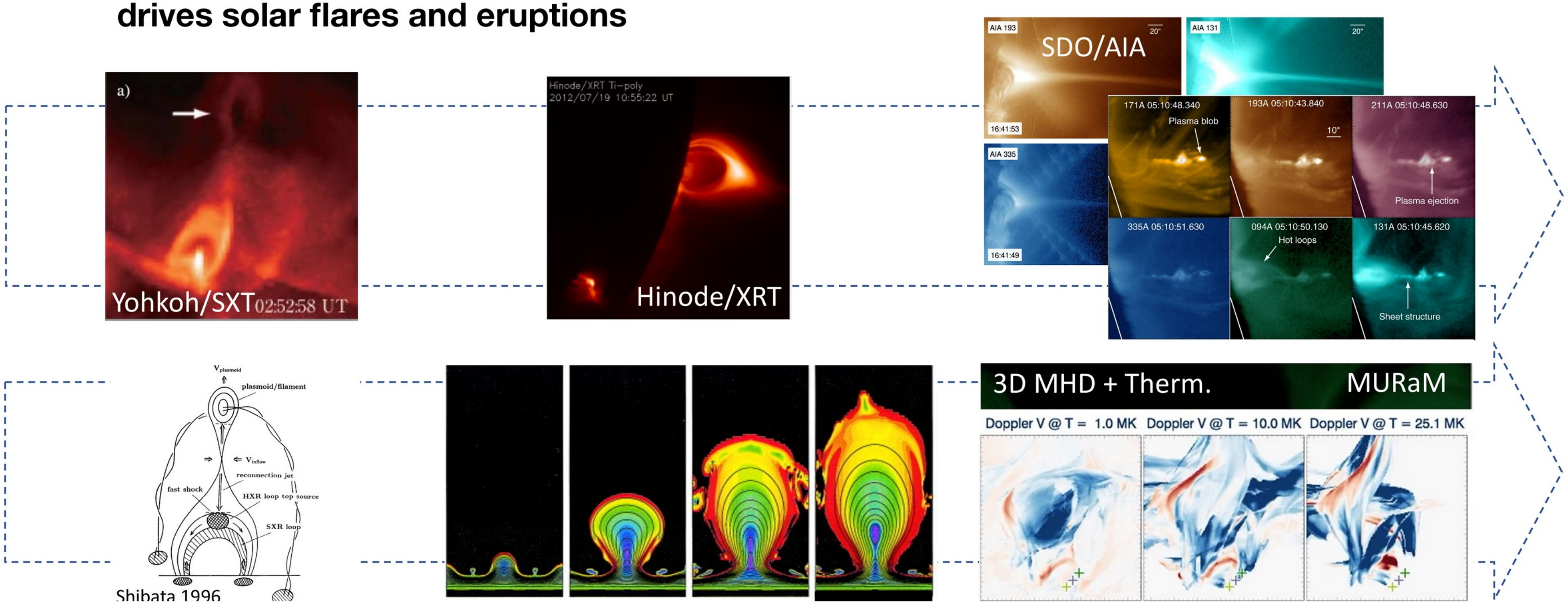
Goal I
Understand how fundamental processes lead to the formation of the solar atmosphere and the solar wind



Source: I. Ugarte (2023)

Goals and Objectives: Evolution from heritage

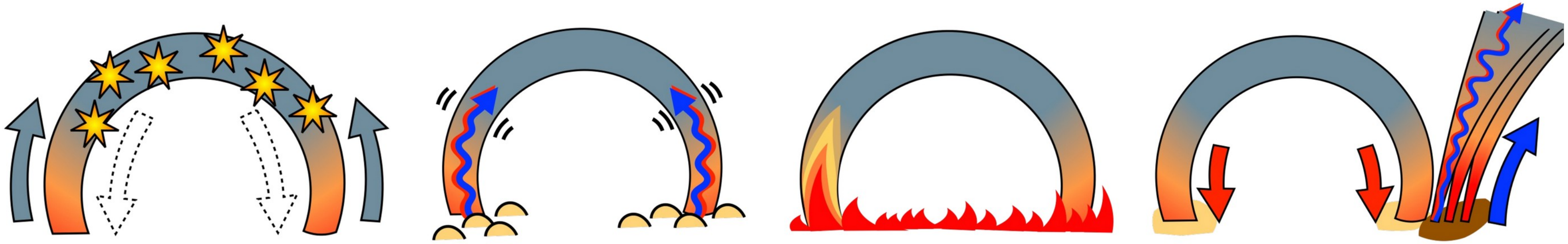
Goal II
Understand how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions



Source: I. Ugarte (2023)

Goals and Objectives

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



I-1: Quantify the contribution of **nanoflares** to coronal heating by observing **small heating events**, measuring evaporative **upflows**, and searching for evidence of **braiding**.

I-2: Quantify the contribution of **wave** dissipation to coronal heating by detecting **Alfven wave propagation**, the **response of plasma** to waves, and identifying the **sources** of waves in the low atmosphere.

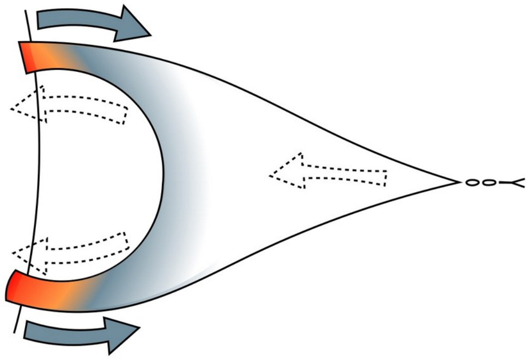
I-3: Understand the formation of **spicules** and quantify their contribution to coronal heating by observing their **evolution** at all temperatures and observing their **source regions** low in the atmosphere.

I-4: Understand the source regions and the **acceleration** mechanism of the **solar wind** by measuring **velocities**, **temperatures**, and **composition** and the **wave propagation** with height in plume and inter-plume regions.

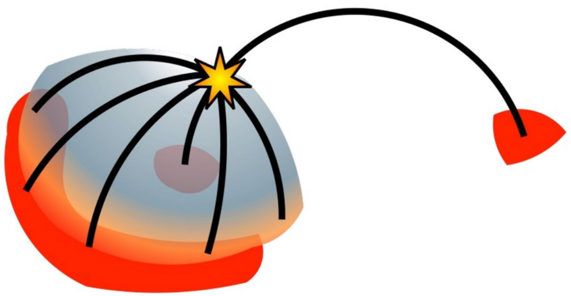
Source: I. Ugarte (2023)

Goals and Objectives

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



II-1: Understand the **fast magnetic reconnection** process in the solar atmosphere by probing **plasma conditions** inside the **current sheet** and measuring the **response of the chromosphere and transition region** at very high cadence.



II-2: Identify signatures of **global energy buildup** and local triggering of **flares and eruptions** by monitoring the long-term, large-scale evolution of active regions and their relationship to **magnetic topology**.

Source: I. Ugarte (2023)

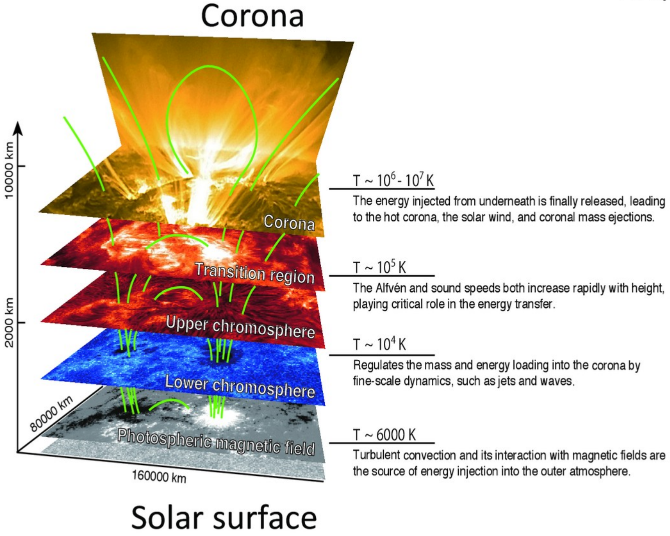
Coordination and synergies

High resolution solar investigations in 2020s

SOLAR-C

The NGSPM-SOT* report (2017/7) recommended a minimum set of instruments with which next generation solar-physics mission can address the greatest number of sub-objectives and maximize the science return of the mission.

* Next Generational Solar Physics Mission Science Objectives Team, chartered by NASA, JAXA and ESA.



Temperature

Recommended instruments
Higher priority in order from the top

Constellation of small/med-class missions in mid-2020s.

0.3″ coronal/TR spectrograph (T-9) → **JAXA SOLAR-C** as competitive M-class mission

seamless plasma diagnostics through the atmosphere

0.2″-0.6″ coronal imager (T-7) → **NASA MUSE** as MiDEX mission

High resolution of coronal imaging

0.1″ – 0.3″ chromospheric imager and magnetograph (T-4)
0.1″ photospheric magnetograph (T-1)
0.1″ chromospheric spectrograph (T-5)
→ **Ground-based large telescopes, such as DKIST**

Magnetic and velocity fields at chromosphere

Strategic coordination

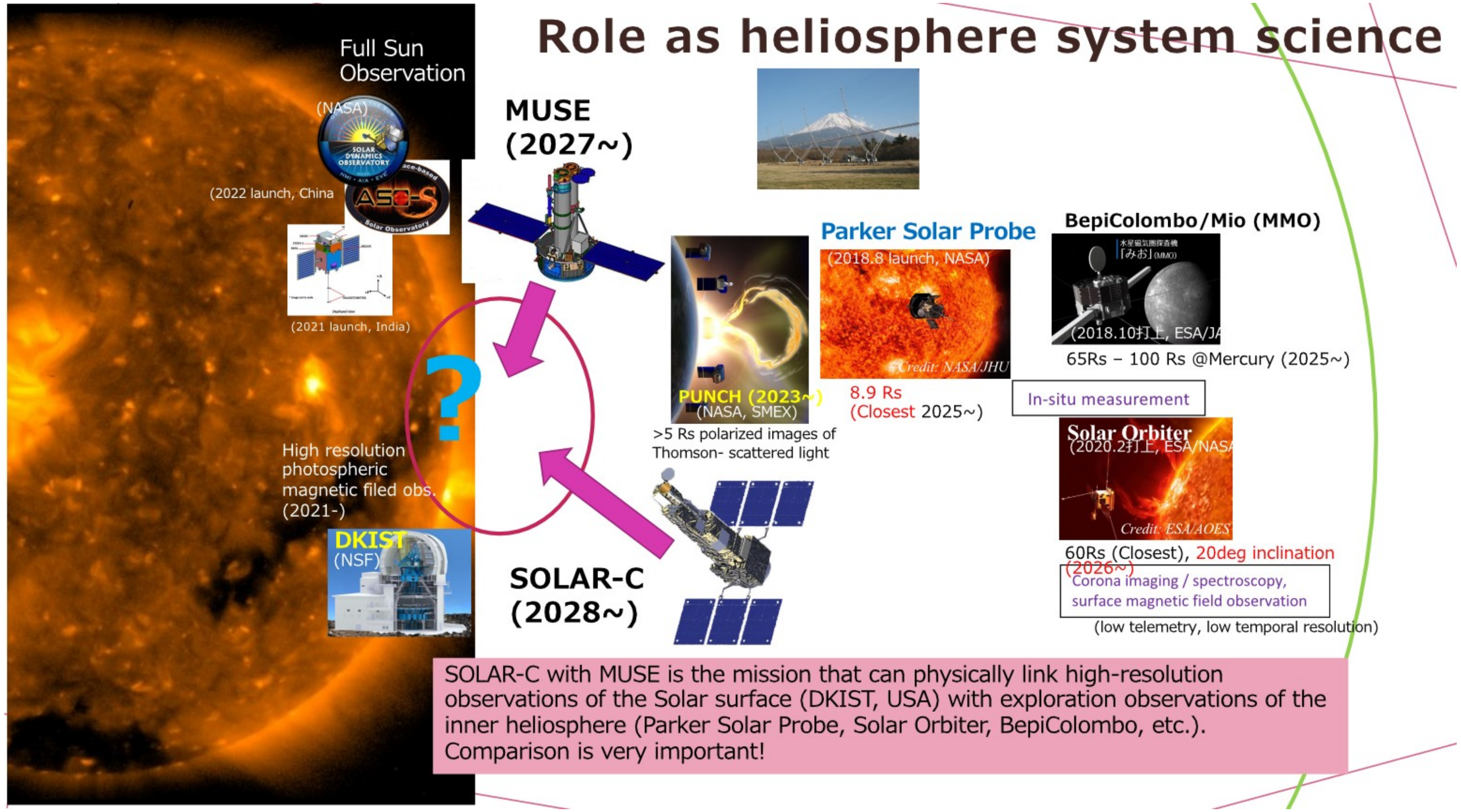
Coordination and synergies (examples)

Solar Orbiter:
Magnetic field measurements (PHI)
Spectroscopy (SPICE)
Stereoscopy (EUI, STIX)

Ground Based Observatories (e.g.: DKIST, EST):
High resolution in V, IR; spectropolarimetry

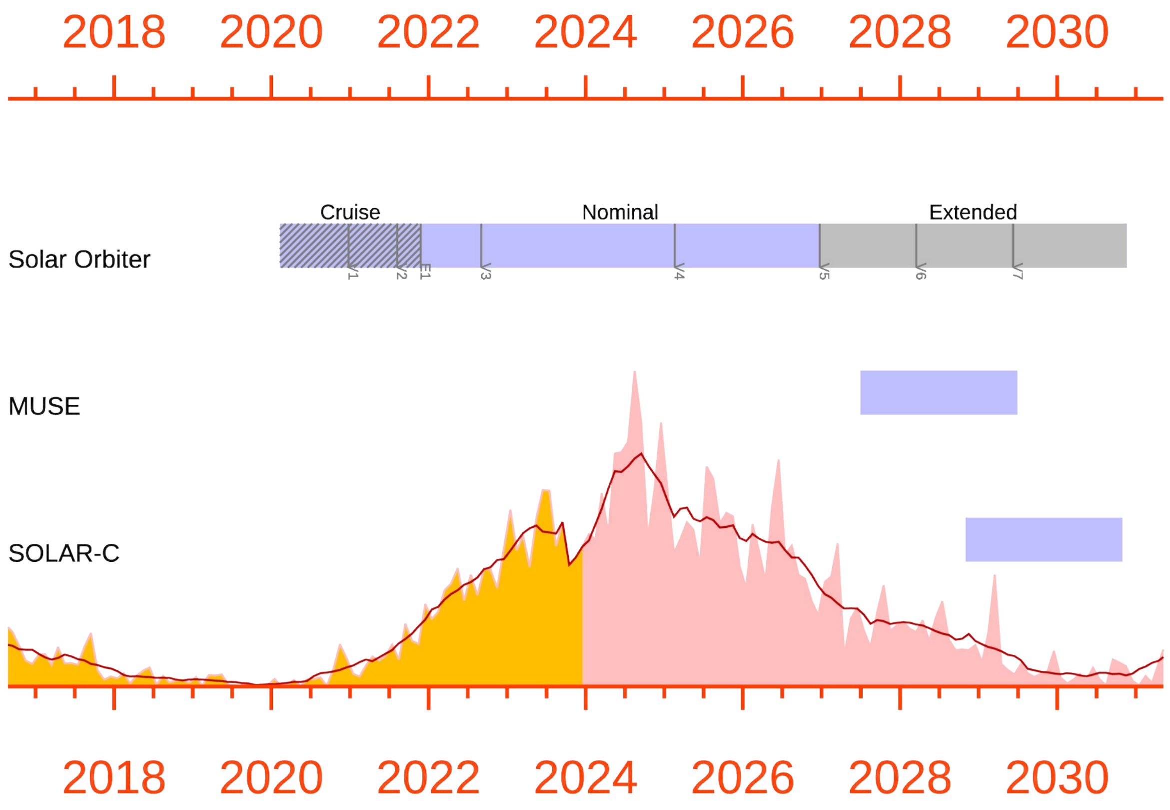
MUSE:
time resolution/FoV vs. Temperature coverage
Intercalibration (Fe XIX 111.8 nm vs. Fe XIX 10.8 nm)

Solar Physics in the 2020’s and beyond



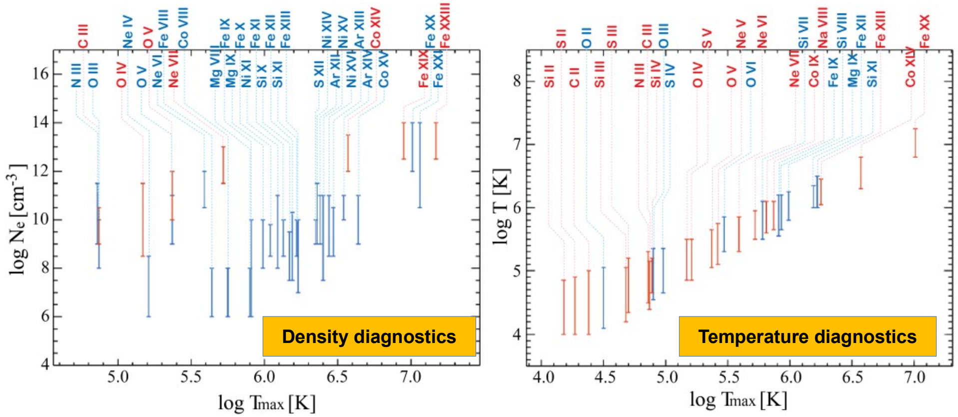
Source: S. Imada (2023)

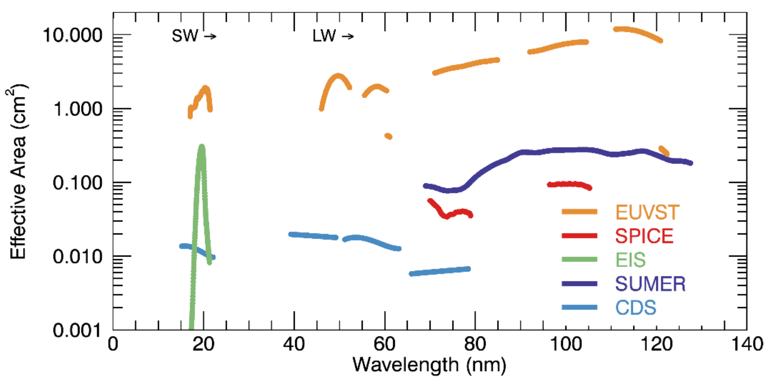
Synergies with other space missions

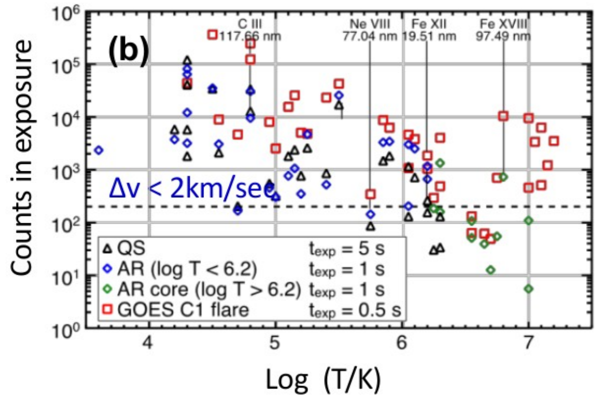


The EUVST spectrograph: Performance requirements

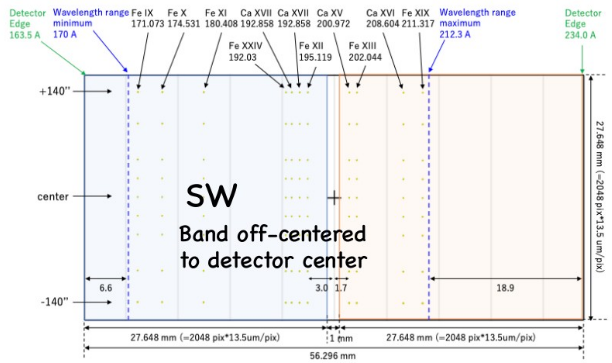
- ✔ Four wavelength bands in the FUV/EUV, covering the ranges 170 - 215 Å and 460 - 1280 Å, with sufficient signal to allow full plasma diagnostics throughout that range
- ✔ Spatial resolution: 0.4”
- ✔ Field of view (through scanning): 300” x 280”
- ✔ Esposure times: as low as 0.5 s
- ✔ Slit-jaw imaging of the photosphere and chromosphere (as done in the IRIS mission)

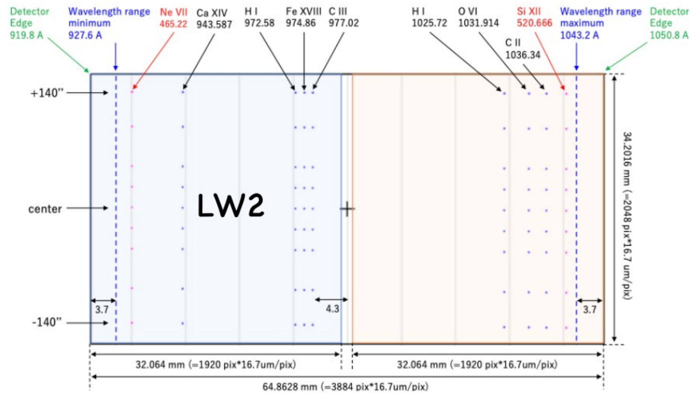


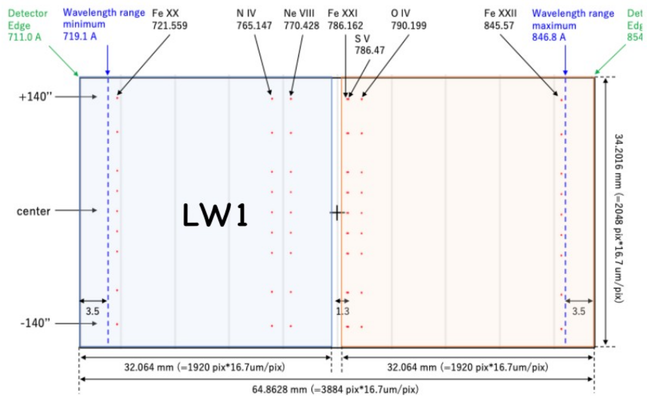


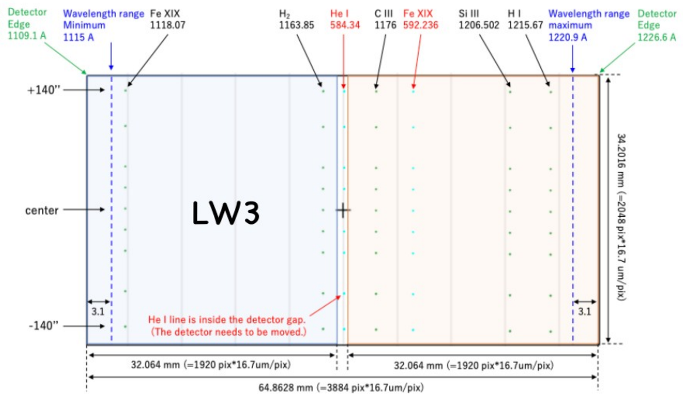


The EUVST spectrograph: Wavebands

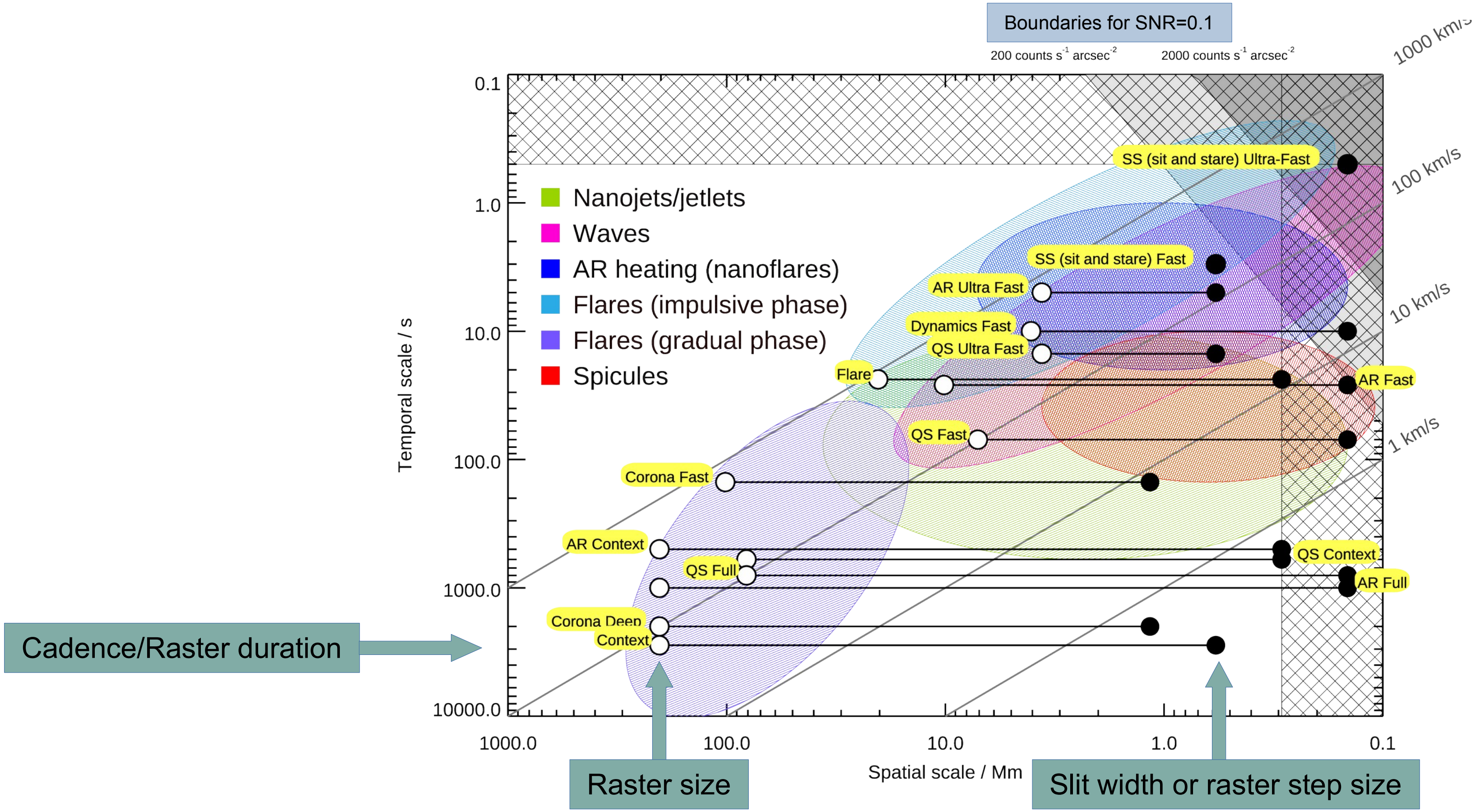






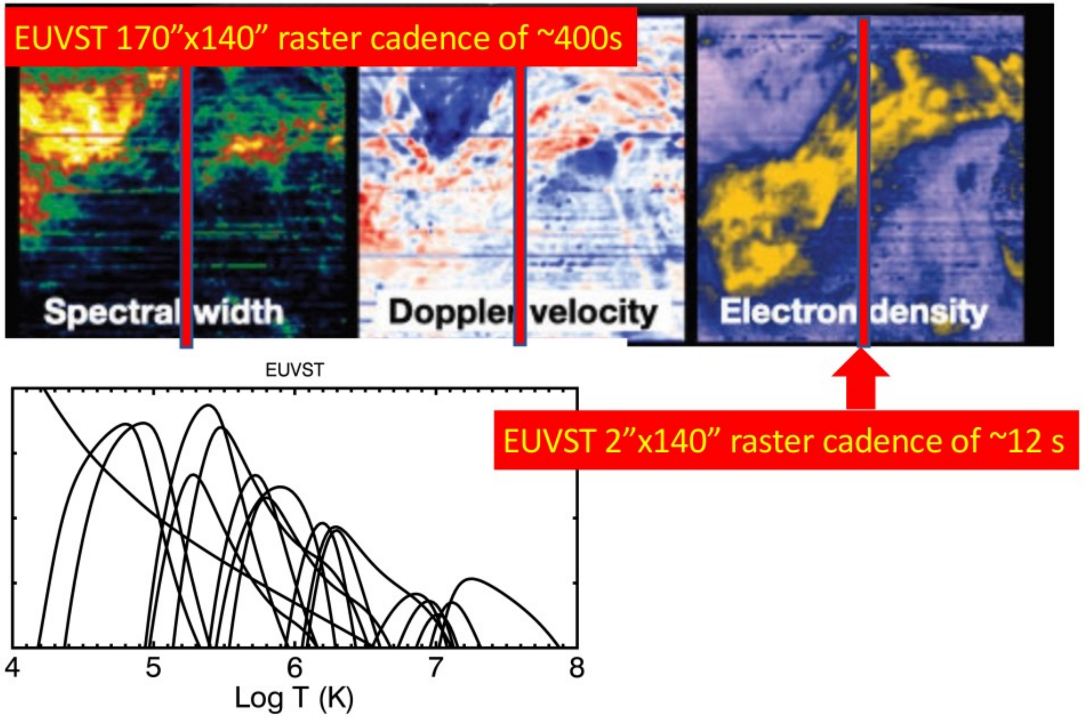


Designing observing modes with EUVST

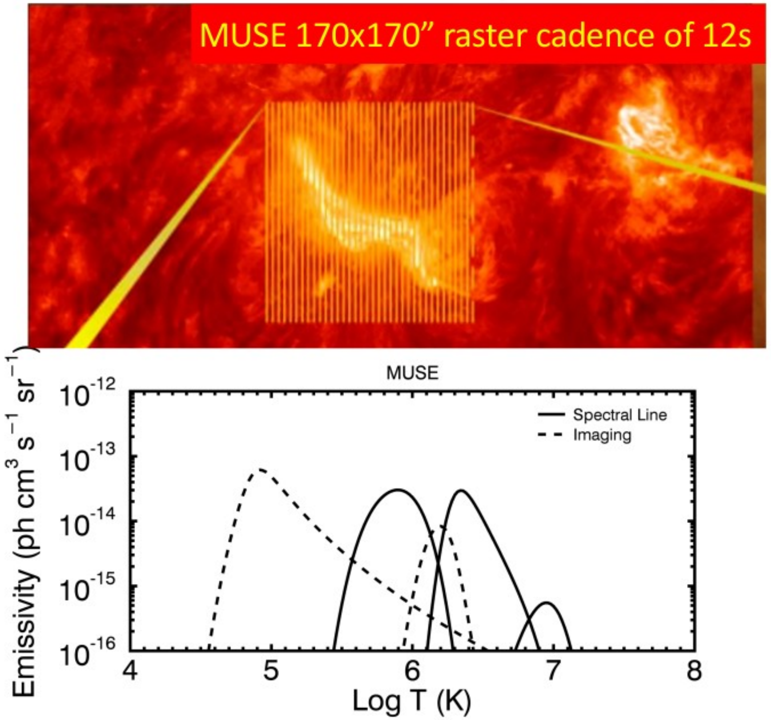


Synergies with MUSE

SOLAR-C EUVST Single slit spectrograph



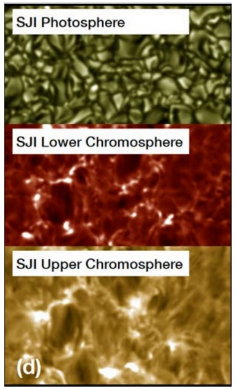
MUSE Multi slits spectrograph



(Source: T. Shimizu)

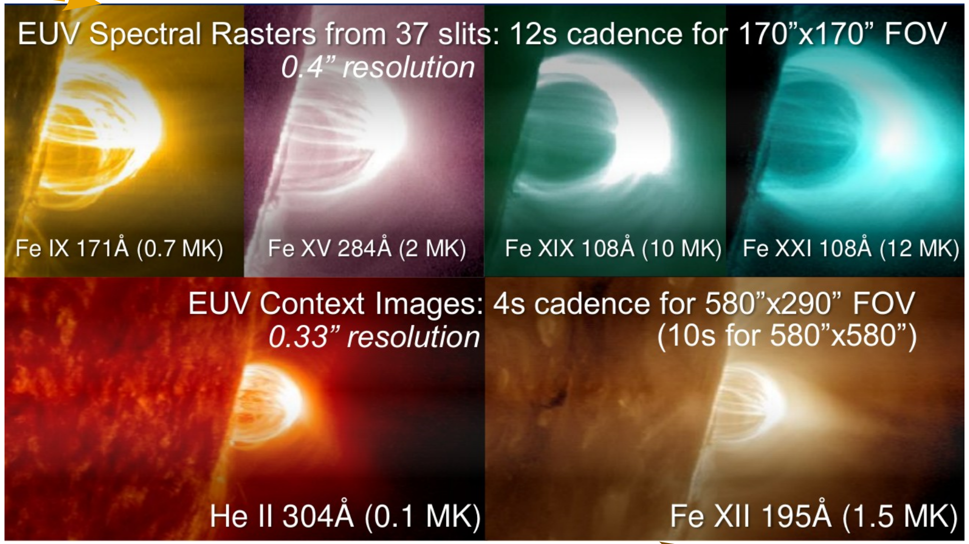
Synergies with MUSE

Slit-jaw imager



Spectrograph

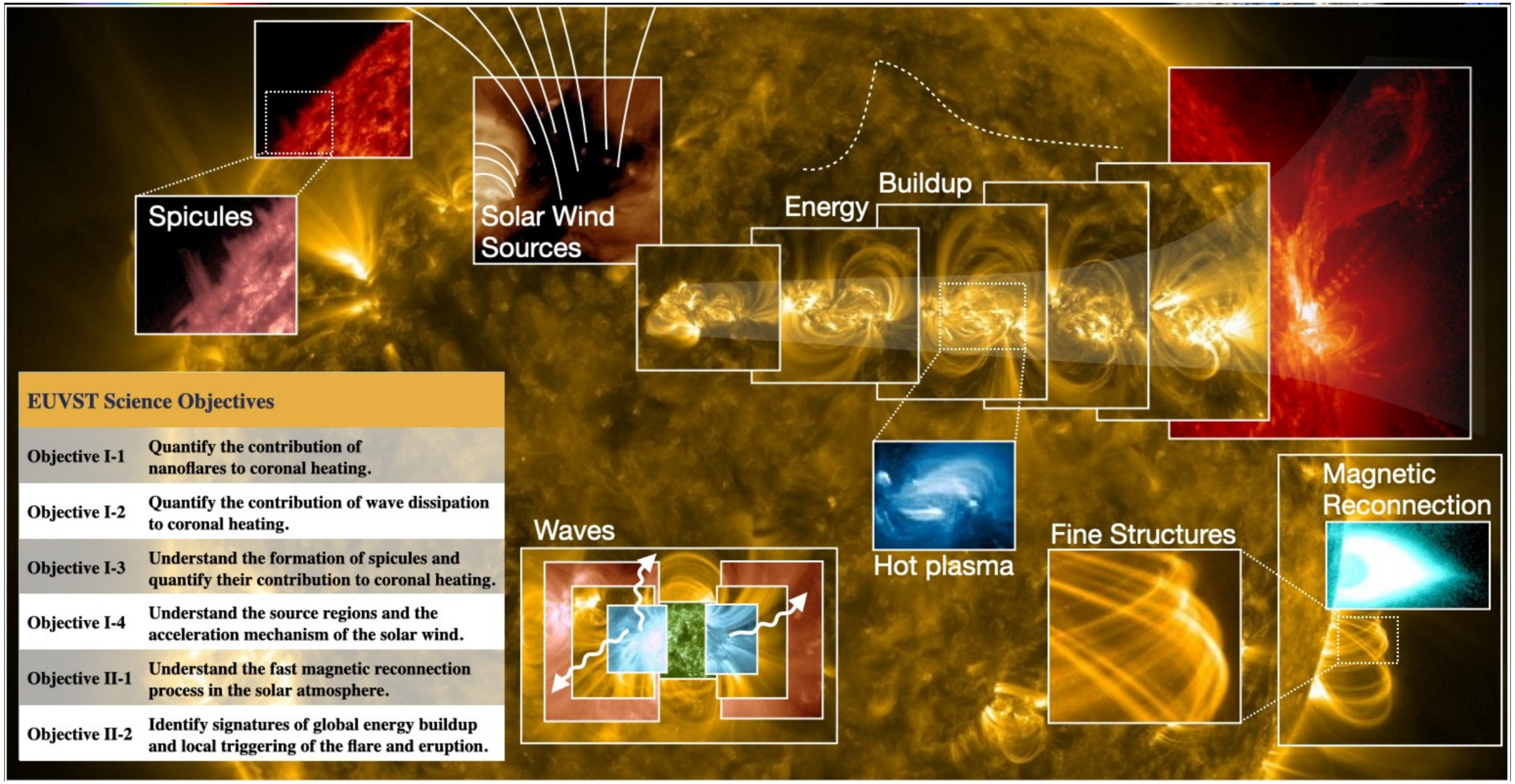
Ion	Wavelength [Å]	Log T [K]	Radiance [erg/s·cm²·sr] QS	AR	Flare (GOES C1.1)	Channel (order)
H_2	1163.85	3.60	—	193[a]	—	LW-3
H I	1215.67	4.30	65000[b]	220000[b]	>AR	LW-3
H I	1025.72	4.30	793[a]	6253[b]	>AR	LW-2
H I	972.58	4.30	139[a]	1452[b]	>AR	LW-2
He I	584.34	4.30	580[b]	5080[b]	140000[g]	LW-3 (2)
Si III	1206.502	4.50	695[b]	[illegible][b]	74000[h]	LW-3
C II	1036.340	4.55	40[a]	290[b]	1690[h]	LW-2
C III	977.020	4.80	[illegible][a]	3666[b]	58700[h]	LW-2
C III	1176.0 (6 lines)	4.80	221[c]	823[d]	21310[h]	LW-3
N IV	765.147	5.10	67[a]	142[a]	5750[h]	LW-1
O IV	790.199 (2 lines)	[illegible]	83[b]	184[b]	8900[h]	LW-1
S V	786.470	5.20	27[c]	61[d]	1760[h]	LW-1
O VI	1031.914	5.50	328[a]	2460[b]	8110[h]	LW-2
Ne VII	465.22	5.75	120[b]	989[b]	4760[h]	LW-2 (2)
Ne VIII	770.428	5.85	54[b]	600[b]	3170[h]	LW-1
Fe IX	171.073	5.90	892[c]	8400[d]	30600[h]	SW
Fe X	174.531	6.05	406[c]	5320[d]	16300[h]	SW
Fe XI	180.408	6.15	251[c]	4380[d]	13300[h]	SW
Fe XII	195.119	6.20	174[c]	3890[d]	12300[h]	SW
Fe XIII	202.044	6.25	41[c]	1248[e]	3960[h]	SW
Si XII	520.666	6.25	22[c]	1130[f]	6790[h]	LW-2 (2)
Fe XIV	211.317	6.30	73[c]	1720[f]	10500[h]	SW
Ca XIV	193.974	6.55	—	312[e]	766[h]	SW
Ca XIV	943.587	6.55	—	7.3[f]	18[h]	LW-2
Ca XV	200.972	6.65	—	239[e]	751[h]	SW
Ca XVI	208.604	6.70	—	122[e]	946[h]	SW
Ca XVII	192.858	6.75	—	147[e]	3780[h]	SW
Fe XVIII	974.860	6.80	—	88[f]	[illegible][h]	LW-2
Fe XIX	592.236	7.00	—	9.3[f]	1530[h]	LW-3 (2)
Fe XIX	1118.07	7.00	—	8.6[f]	1500[h]	LW-3
Fe XX	721.559	7.05	—	—	1580[h]	LW-1
Fe XXI	786.162	7.10	—	—	178[h]	LW-1
Fe XXII	845.57	7.10	—	—	2180[h]	LW-1
Fe XXIV	192.03	7.20	—	—	18100[h]	SW



Synergies with Solar Orbiter and Metis

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

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



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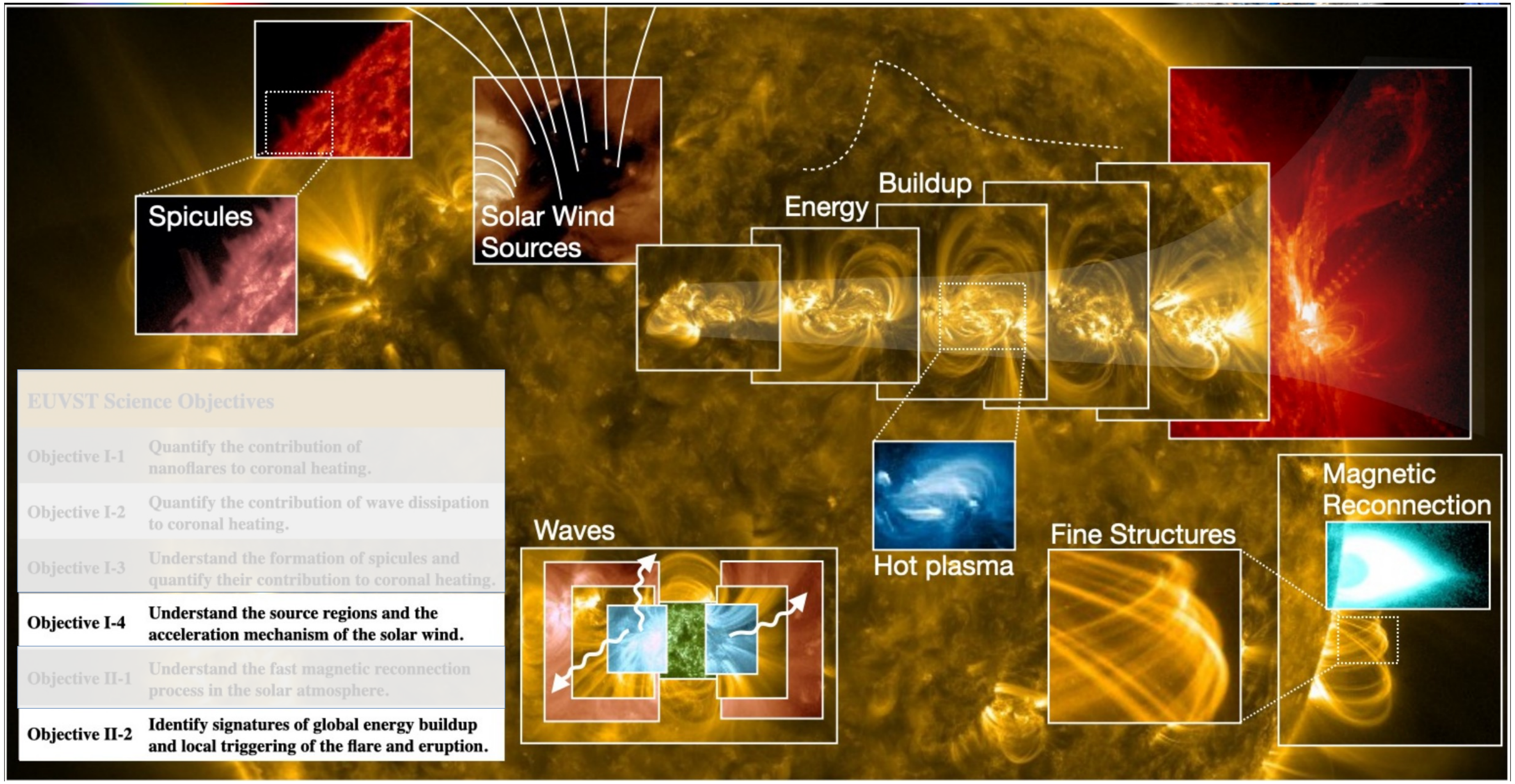

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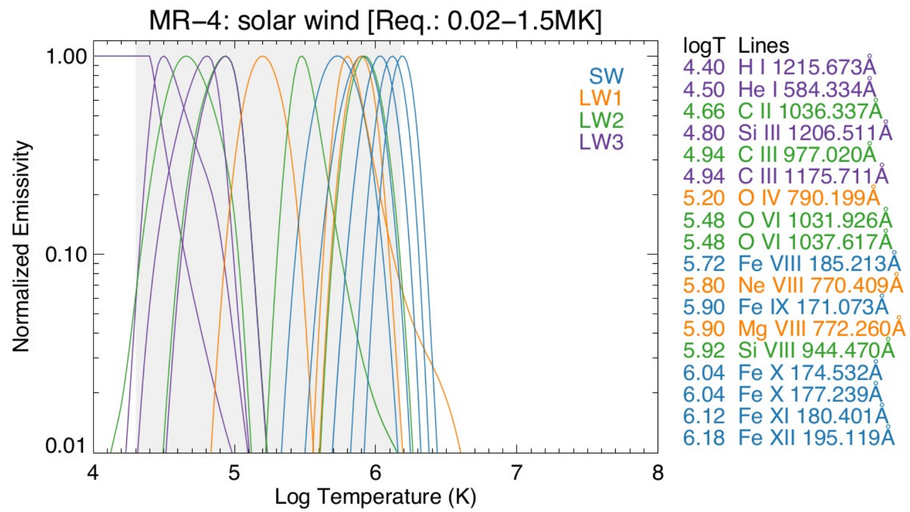
Objective II-1	Understand the fast magnetic reconnection process in the solar atmosphere.
Objective II-2	**Identify signatures of global energy buildup and local triggering of the flare and eruption.**

Synergies: Objective I-4 (Solar Wind)

- The source regions of the fast and slow solar wind are still under debate.
- Scenarios: plumes, inter-plumes, jets (fast wind), interchange reconn., ARs, streamers (slow wind).
- Challenge: very long exposures needed to observe faint, open-field structures.
- Task 1: Observe v, T, N_e, and composition of source regions ⇔ magnetic field structures
- Task 2a: Detect signatures of propagating coronal Alfvén waves in plume and inter-plume region
- Task 2b: Measure energy fluxes with height

KEY FACTORS

- Comprehensive temperature evolution
- Throughput (x10) ⇒ weak sources
- Synergy with Solar Orbiter and Parker



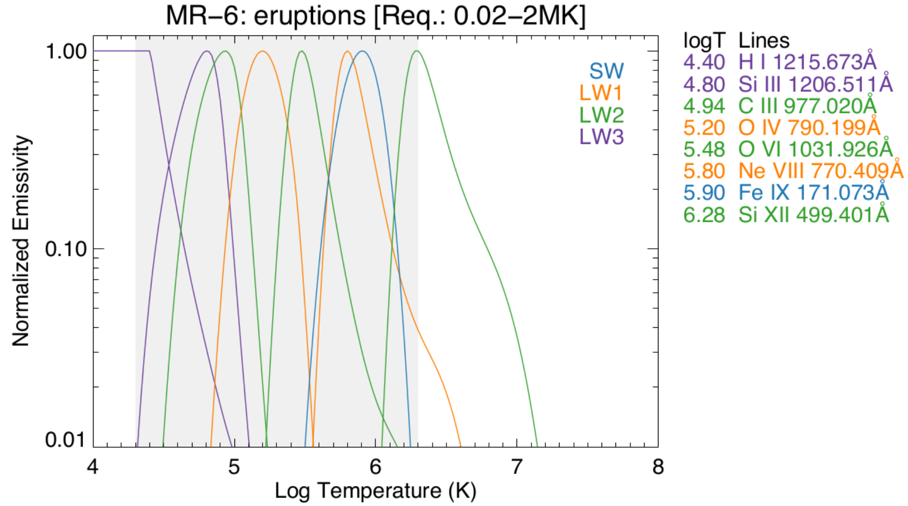
(Source: I. Ugarte)

Synergies: Objective I-6 (Energy Buildup)

- Lack of spectroscopic monitoring of active regions in timescales of minutes over full T range.
- Flare predictions based on magnetic field!, but spectroscopy mostly untried due to the absence of suitable data-sets.
- Task 1: Monitor long-term, large-scale evolution of ARS ⇒ spectroscopic signatures of E buildup.
- Task 2: Characterize the dynamics of small-scale magnetic structures that trigger eruptions

KEY FACTORS

- Comprehensive temperature evolution
- Throughput (x10) ⇒ fast cadence (0.5s)
- 0.4” resolution ⇒ fine structure
- Slit-jaw imaging ⇒ morphology + alignment

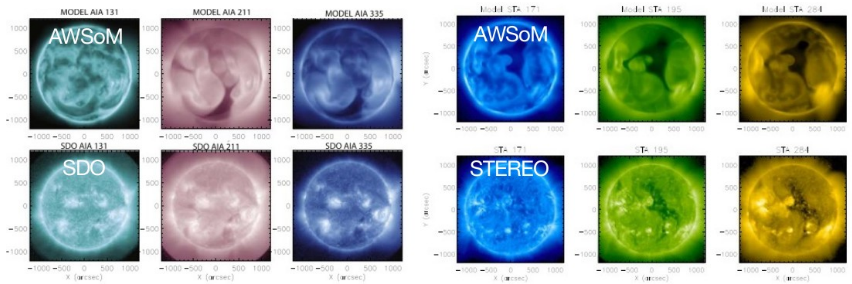


(Source: I. Ugarte)

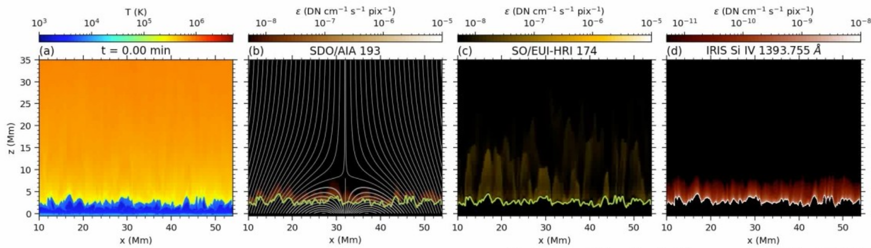
Synergies: Objective I-4 (Solar Wind)

Numerical models

EUVST measured line widths will be compared to predictions from Alfvén-wave driven models, e.g. global 3D MHD AWSoM model.

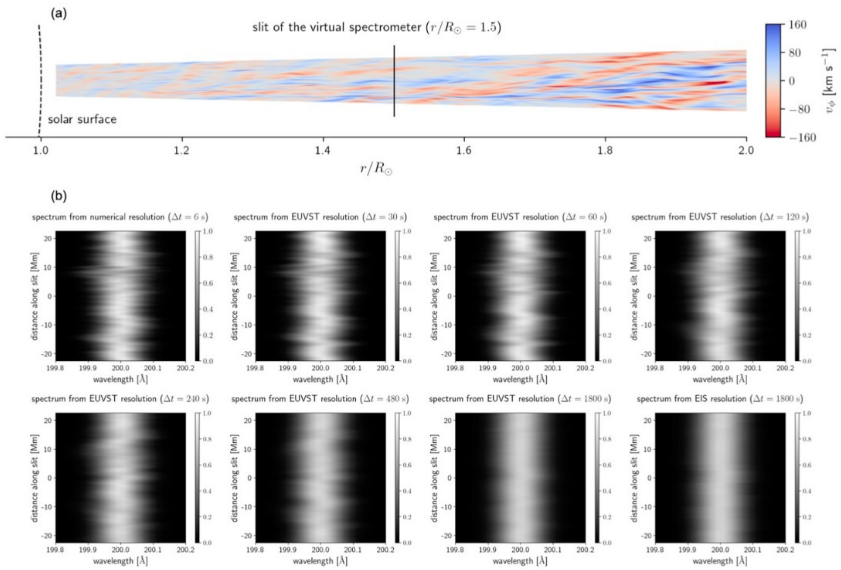


Sachdeva et al., 2021



Nobrega-Siverio & Moreno-Insertis, 2022

EUVST will measure energy fluxes of solar wind candidate sources, such as e.g. jets and can be compared to model predictions. Battery of diagnostics: radiance, velocity, density, composition…

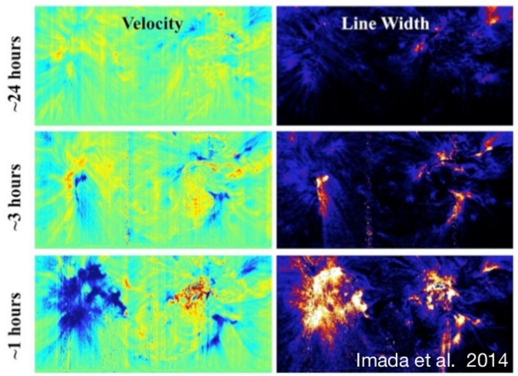


Shoda et al. (2021) + Solar-C synthetic observables

Simulated observations of turbulence-driven solar wind. EUVST performance (spatial and temporal resolution) allows to resolve turbulent wave dynamics.

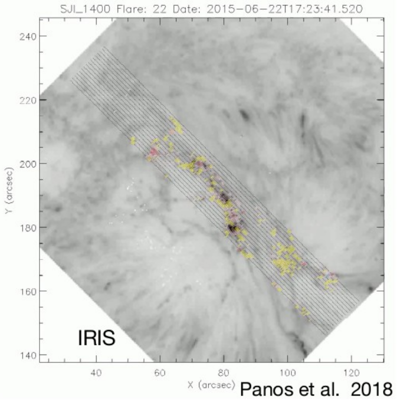
(Source: I. Ugarte)

Synergies: Objective I-6 (Energy Buildup)

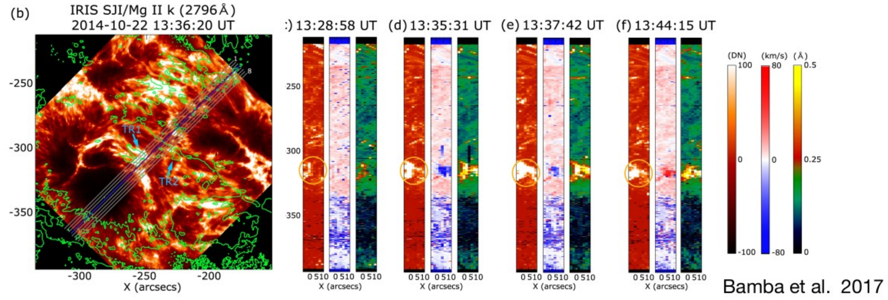


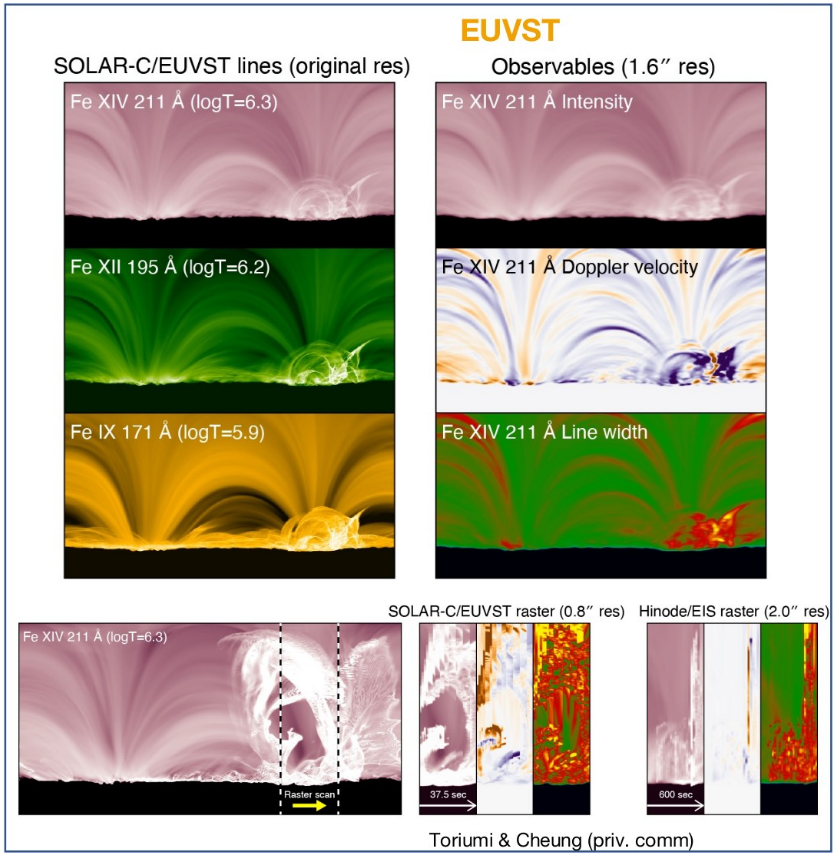
Hinode/EIS pre-eruption signatures.
Raster scans took hours

Machine Learning techniques to classify spectral signatures

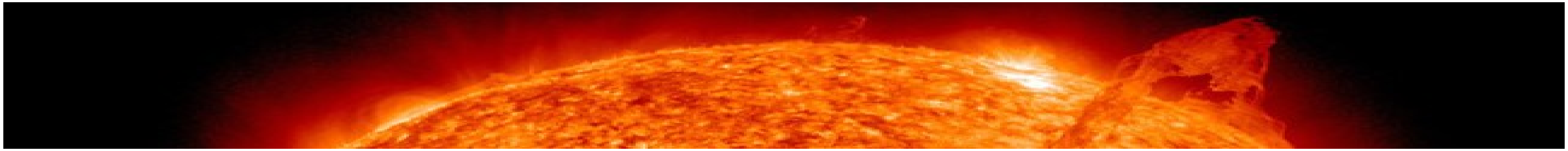


IRIS observed pre-eruption signatures at shorter timescales. No coronal info.





(Source: I. Ugarte)



Thank you for your attention