# The MUSE mission and the modeling of reconnection events

MULTISLIT SOLAR EXPLORER

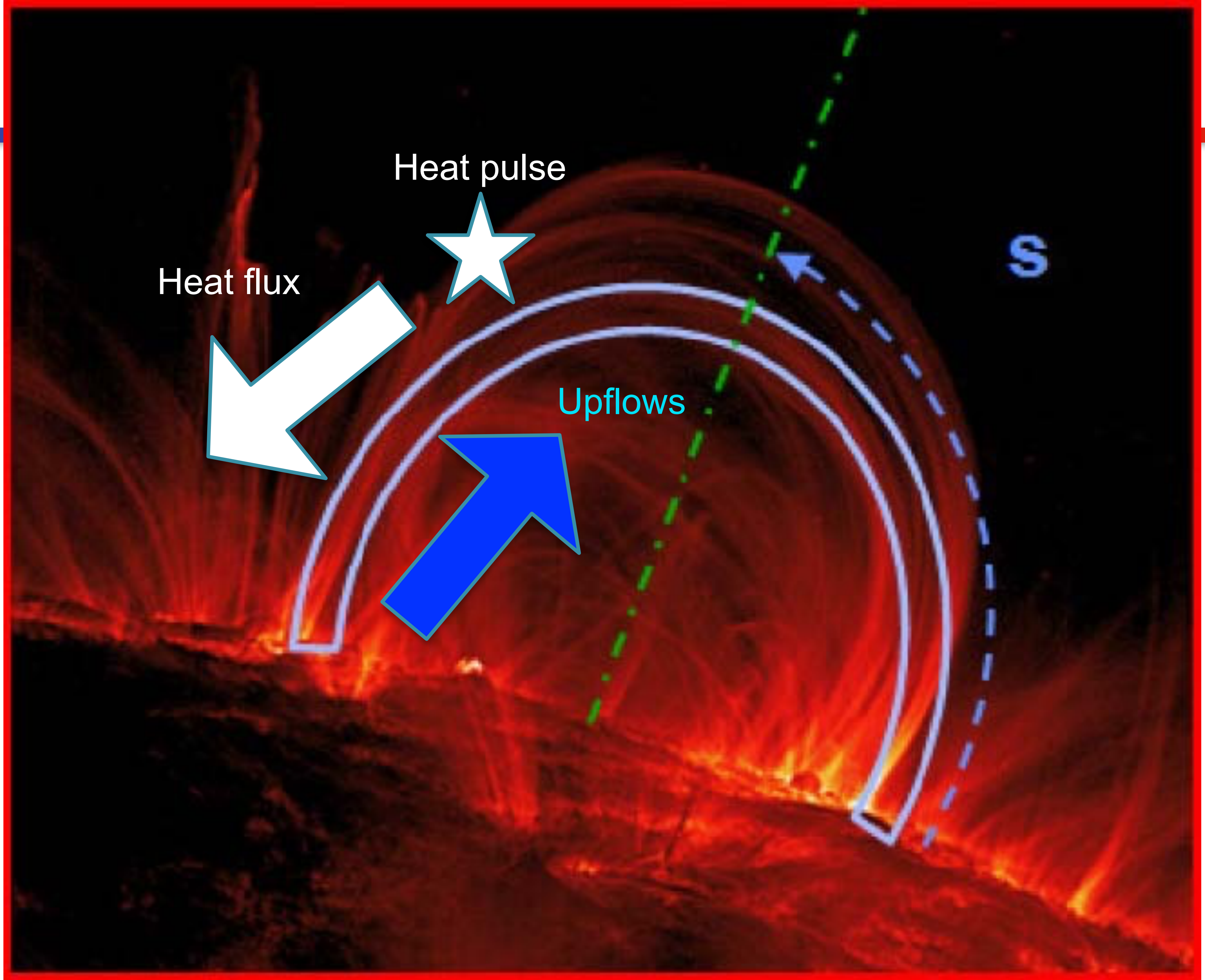
**Fabio Reale, University of Palermo&INAF,**

**G. Cozzo, P. Pagano, A. Petralia, C. Argiroffi, Denise Perrone, Marco Stangalini, and the MUSE Team**

Lockheed Martin Solar & Astrophysics Laboratory (LMSAL), Harvard Smithsonian Astrophysical Observatory (SAO), Goddard Space Flight Center (GSFC), Montana State University (MSU), UC Berkeley Space Sciences Laboratory (UCB), Rosseland Center for Solar Physics, University of Oslo (RoCS)

**Science Co-Is**: High Altitude Observatory, Naval Research Laboratory, Lawrence Livermore National Laboratory, NASA-MSFC, National Solar Observatory, University of Northumbria, Stockholm University, University of Glasgow, St. Andrews University, Max Planck Institute for Solar System Physics, University of Palermo, INAF, CSIRO

**International Partners**: Norwegian Space Agency (NOSA), Italian Space Agency (ASI), German Aerospace Center (DLR)


Heat pulse
Heat flux
Upflows
S

Solar Physics (2006) 234: 41–77
DOI: 10.1007/s11207-006-0055-z


# ON SOLVING THE CORONAL HEATING PROBLEM

*Invited Review*

JAMES A. KLIMCHUK

- The importance: signature of impulsive heating

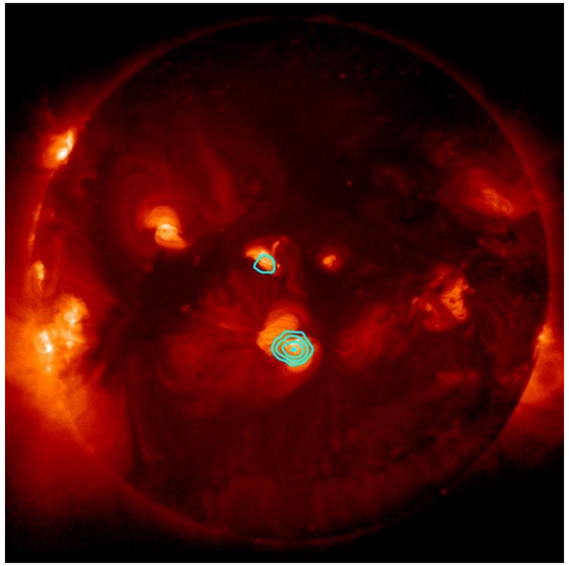
the temperature range from about 0.5 to 10 MK. The high end of the temperature range is especially important for diagnosing impulsive heating, since relatively little can be learned about the energy release (duration, spatial distribution along the field, etc.) once the plasma enters the slow radiative cooling phase (Winebarger and Warren, 2004, 2005; Patsourakos and Klimchuk, 2005a,b). Since the evolution

❑Hot loops may require temporarily T ~ 10 MK

# Detection of nanoflare-heated plasma in the solar corona by the FOXSI-2 sounding rocket

Shin-nosuke Ishikawa, Lindsay Glesener, Säm Krucker, Steven Christe, Juan Camilo Buitrago-Casas, Noriyuki Narukage & Juliana Vievering

*Nature Astronomy* **1**, 771–774 (2017) | Cite this article



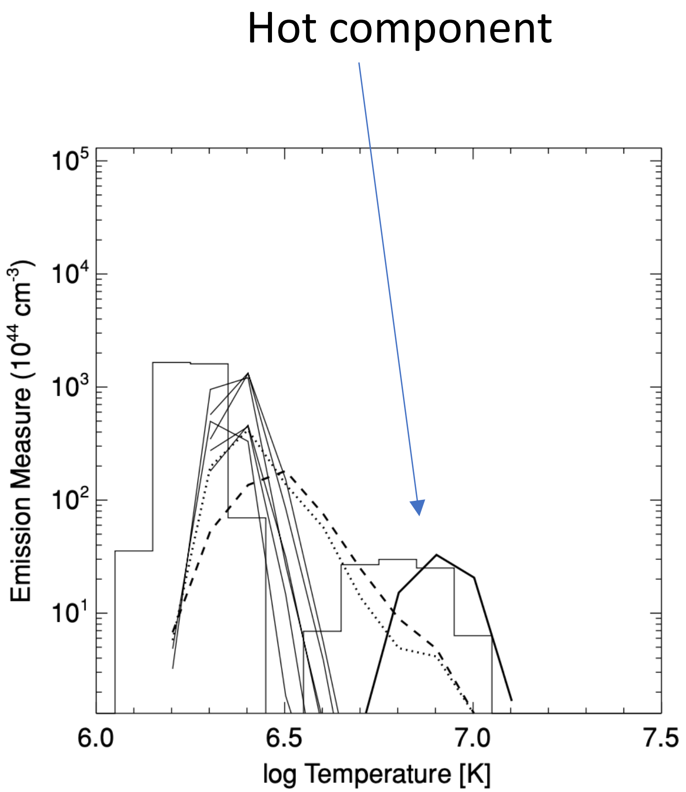
Focusing Optics X-ray Solar Imager (FOXSI-2), which detected emission above 7 keV from an active region of the Sun with no obvious individual X-ray flare emission. Through differential emission measure computations, we ascribe this emission to plasma heated above 10 MK, providing evidence for the existence of solar nanoflares. The quantitative evaluation of the

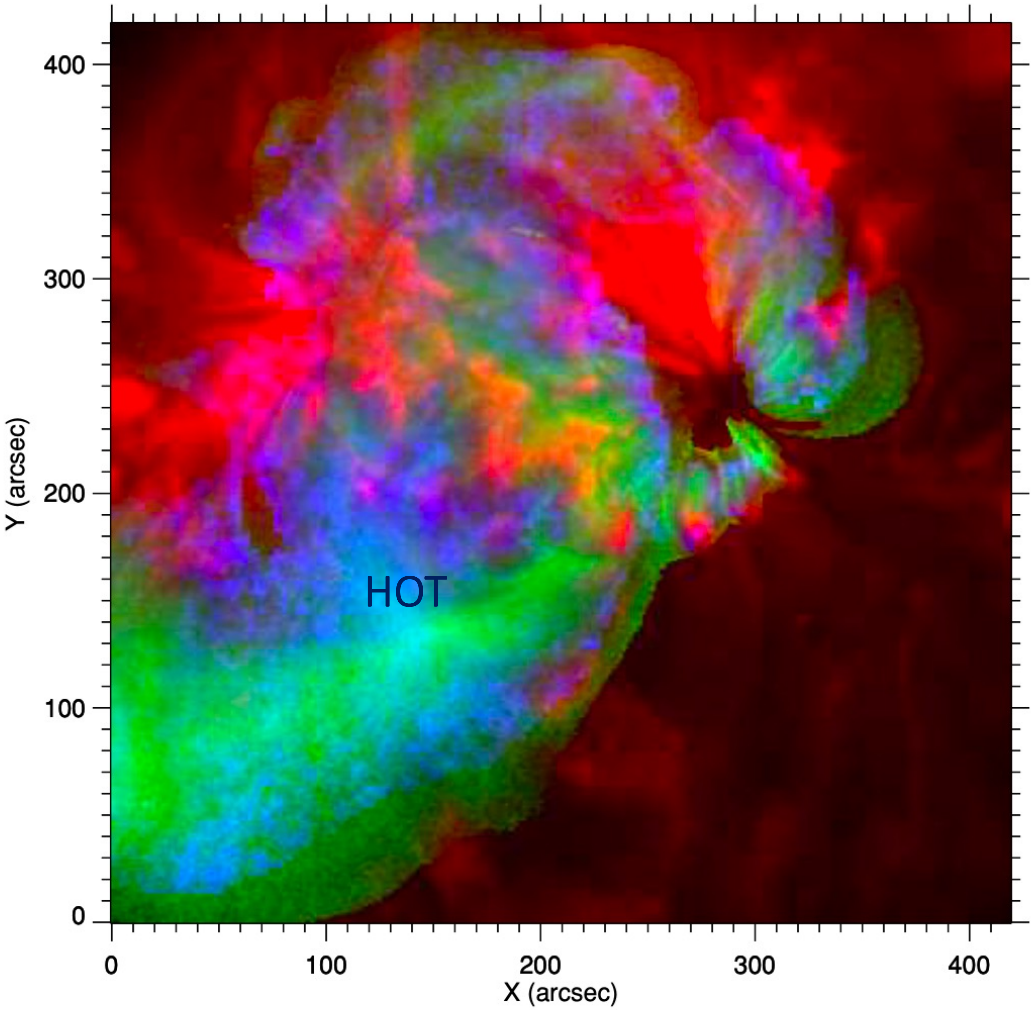
The Astrophysical Journal, 698:756–765, 2009 June 10 doi:10.1088/0004-637X/698/1/7


*Are loops impulsively heated?*

# EVIDENCE OF WIDESPREAD HOT PLASMA IN A NONFLARING CORONAL ACTIVE REGION FROM *HINODE/X-RAY TELESCOPE*

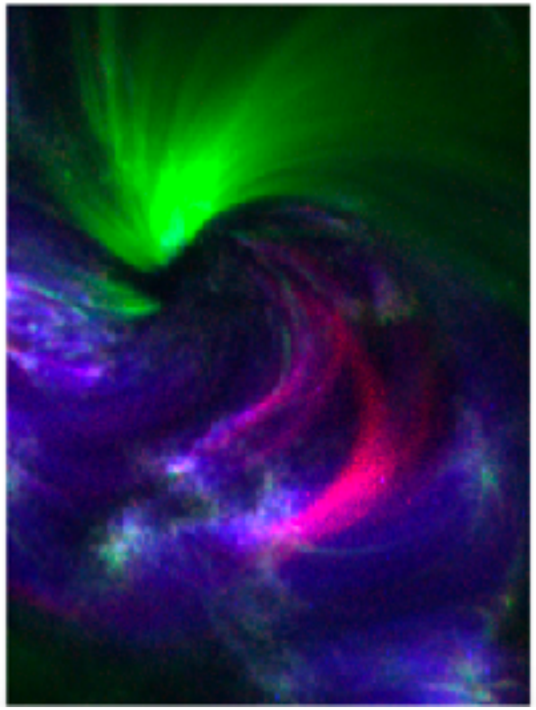
Fabio Reale[1,5], Paola Testa[2], James A. Klimchuk[3], and Susanna Parenti[4]

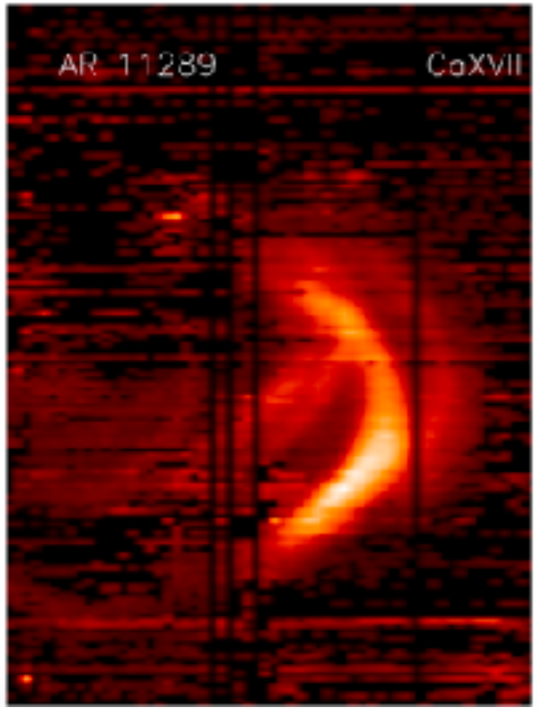


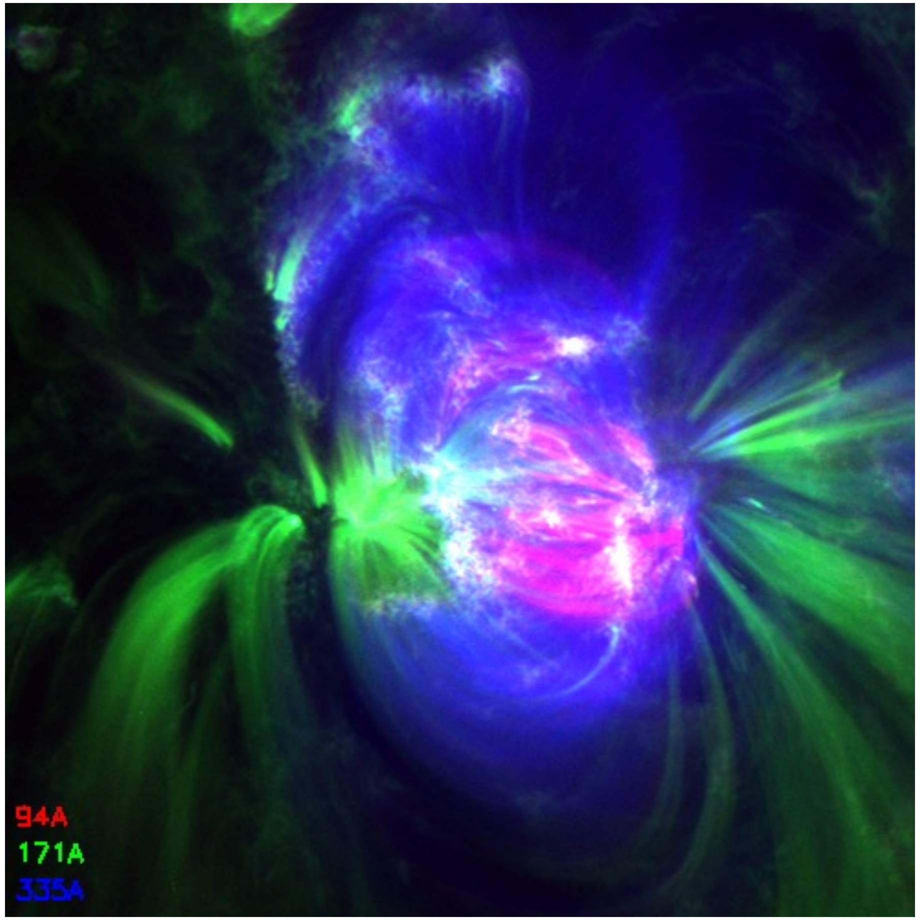



# Pink is hot (6-8 MK) (Reale+ 2011)

Testa & Reale 2012



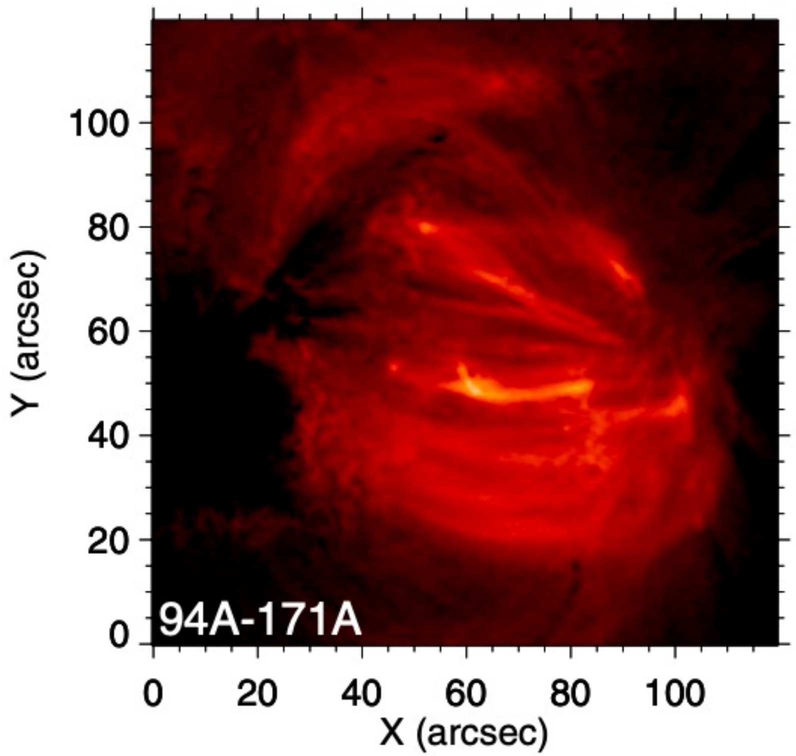


The Astrophysical Journal Letters, 736:L16 (5pp), 2011 July 20 doi:10.1088/2041-8205/736/1/L

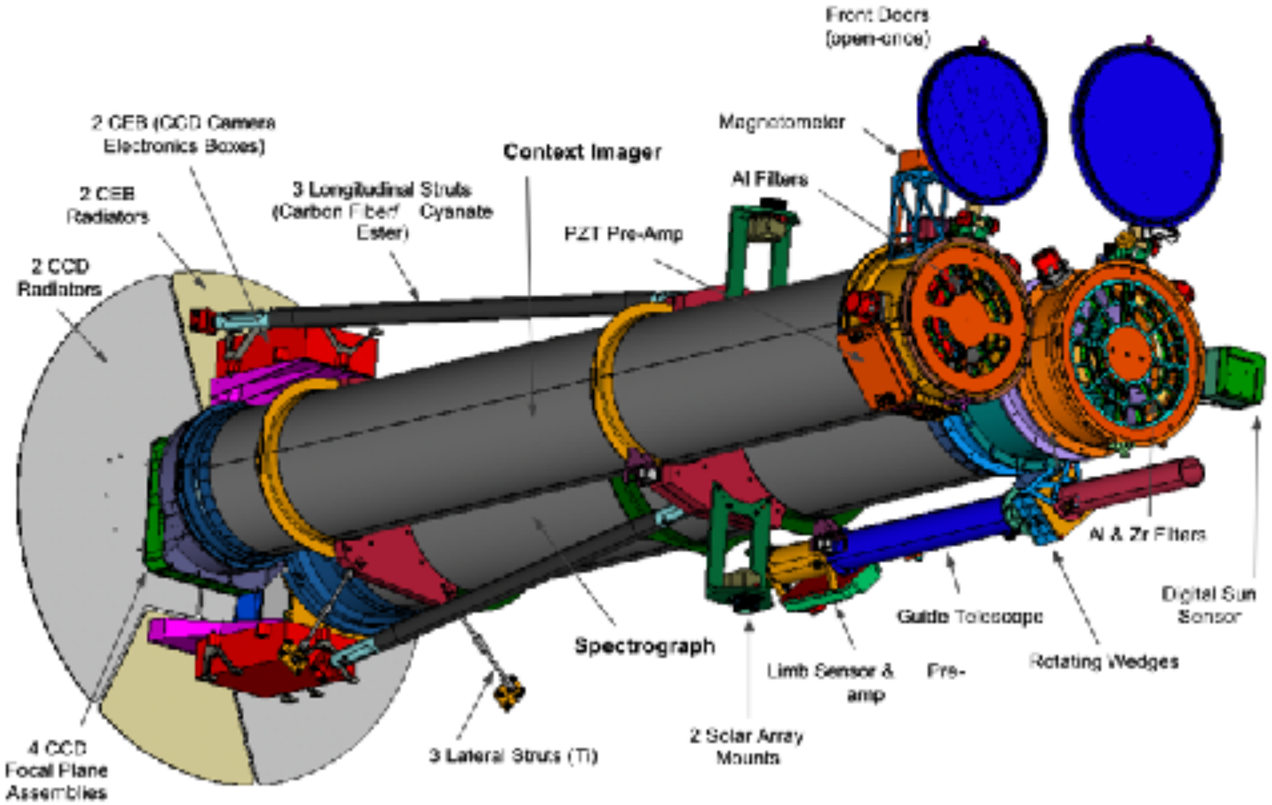

# *SOLAR DYNAMICS OBSERVATORY* DISCOVERS THIN HIGH TEMPERATURE STRANDS IN CORONAL ACTIVE REGIONS

Fabio Reale[1,2], Massimiliano Guarrasi[1], Paola Testa[3], Edward E. DeLuca[3], Giovanni Peres[1,2], and Leon Golub[3]




Prediction confirmed by SDO/AIA images in “hot” channels

# Overall View of the MUSE Instruments




- **Spectrograph (SG)**
  - 25 cm aperture, 3 channel design, common grating substrate
  - multiple (**35**) slit design, **0.4 arcsec resolution**
  - **Centroiding resolution <5 km/s**
- **Context Imager (CI)**
  - 20 cm aperture, dual bandpass, **0.33 arcsec resolution**
  - Modified SDO-AIA design incorporating lessons learned from IRIS & Hi-C


***MUSE instruments leverage IRIS, SDO/AIA, HiC heritage***

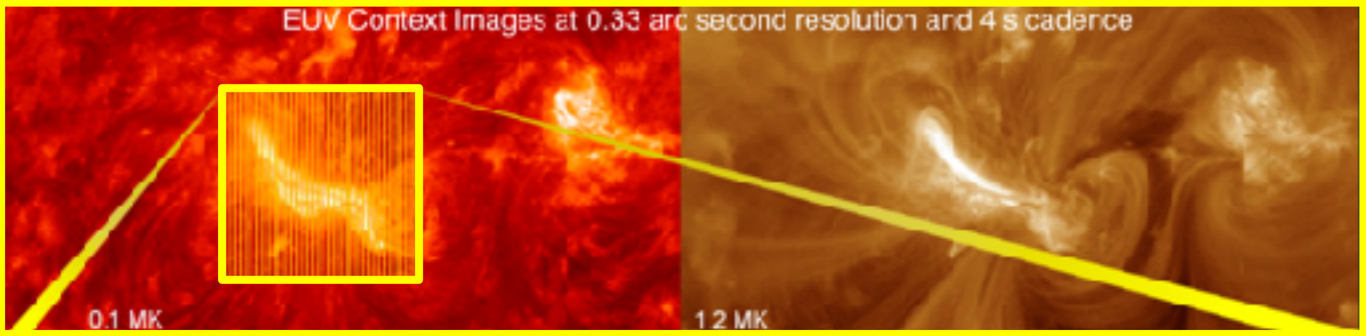
***Sun-synchronous orbit (600-700 km)***

***Sustained datarate of 20 Mbit/s (~40x-1000x more than previous spectrographs)***

# MUSE captures dynamic coronal properties at key scales

**Breakthrough in Resolution & Cadence (x40-100)**

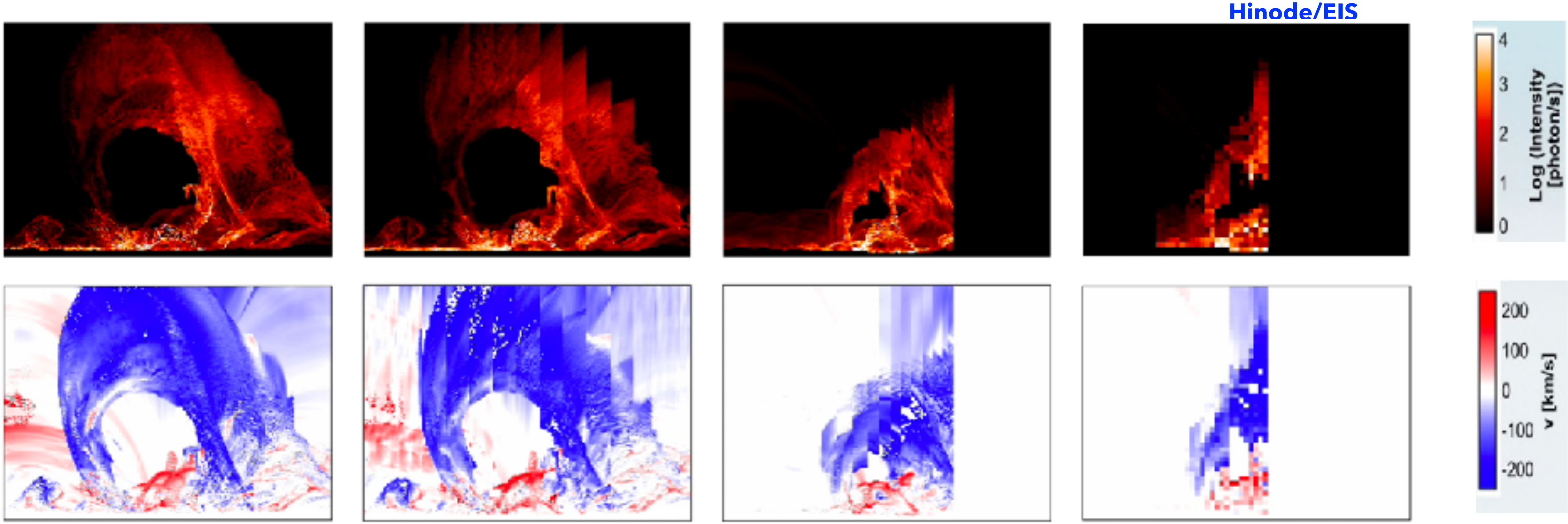
- **Reveal processes invisible to imagers**
- **For the first time capture multi-scale physical processes from driving scales at 0.5″ to active region size impact, on short time scales (20s)**
- **Distinguish between competing state-of-the-art models**




High-cadence context & broad temperature coverage (580″x580″)

**Multi-slit spectroscopy**
Intensity -> Temperature
Velocity
Non-thermal motions
To diagnose reconnection, flows, waves, heating

# What is unique about MUSE?

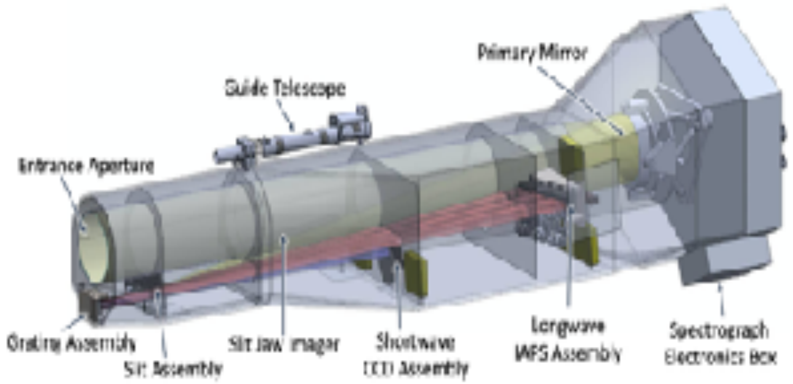



**Breakthroughs** in:

-cadence: 40-100x faster & larger FOV than current/planned spectrographs – **for the first time freezes "coronal evolution" under spectrograph slits**

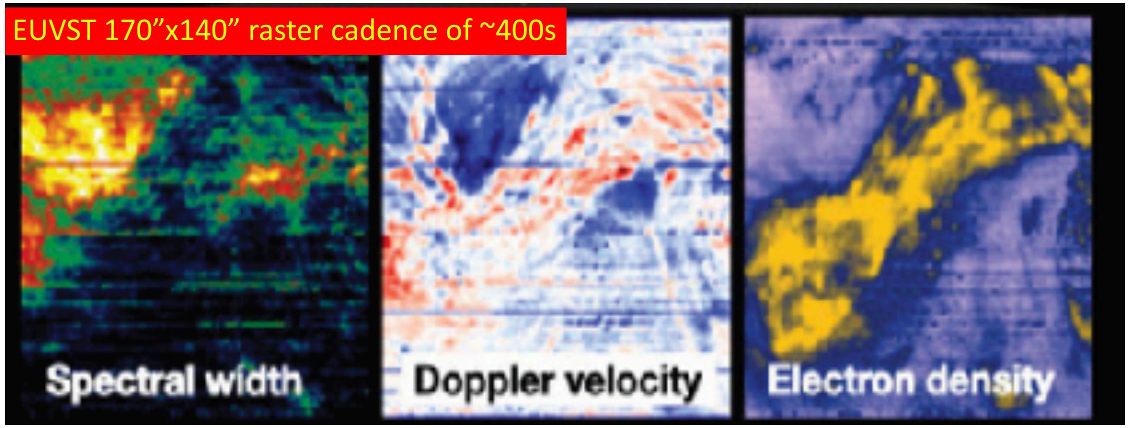
-spatial resolution: 10x higher than AIA, 25x better than EIS or SOLO/SPICE

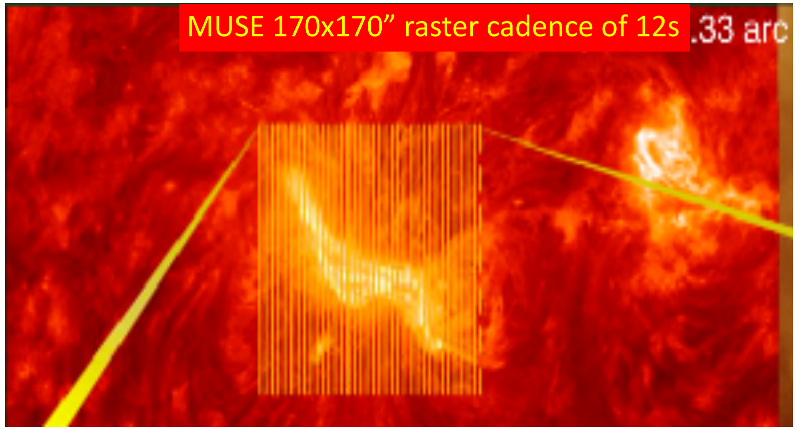
# Synergy between MUSE and Solar-C/EUVST: Both are key parts of NGSPM




- **Joint JAXA/NASA/ESA report on Next Generation Solar Physics Mission (NGSPM) calls out need for coordinated observations between:**
  - **JAXA-led Solar-C/EUVST single-slit spectrograph with broad temperature coverage from photosphere to hot flaring corona**
  - **MUSE-like instrument with high-speed spectral rasters over large FOV and context imaging**

EUVST




MUSE

| Instrument | Resolution | Spectroscopy | | | Imaging | Datarate [Mbit/s] |
|---|---|---|---|---|---|---|
| | | Temperature | Cadence | FOV | | |
| EUVST | 0.4" | 0.01-15 MK w/ 10-20 lines | 12s (AR) | 2" x 140" | Photosphere & chromosphere over 300"x300" | 0.7 |
| MUSE | 0.33-0.4" | 0.7 – 11 MK w/ 4 lines | 12s (AR) | 170"x170" | TR & corona (1.2 MK) over 580"x580" | 21.4 |

**MUSE provides coronal imaging/context and captures multi-scale processes involved in coronal heating and flares/eruptions**

# How can MUSE distinguish between competing physical mechanisms?

The Astrophysical Journal, 00:000000 (36pp), 2021 Month Day


## Probing the Physics of the Solar Atmosphere with the Multi-slit Solar Explorer (MUSE). I. Coronal Heating

Bart De Pontieu[1,2,3], Paola Testa[4], Juan Martínez-Sykora[1,2,3,5], Patrick Antolin[6], Konstantinos Karampelas[6,7], Viggo Hansteen[1,2,3,5], Matthias Rempel[8], Mark C. M. Cheung[1], Fabio Reale[9,10], Sanja Danilovic[11], Paolo Pagano[9,10], Vanessa Polito[1,5], Ineke De Moortel[2,12], Daniel Nóbrega-Siverio[2,3,13,14], Tom Van Doorsselaere[7], Antonino Petralia[10], Mahboubeh Asgari-Targhi[4], Paul Boerner[1], Mats Carlsson[2,3], Georgios Chintzoglou[1,15], Adrian Daw[16], Ed DeLuca[4], Leon Golub[4], Takuma Matsumoto[17], Ignacio Ugarte-Urra[18], and Scott McIntosh[8]
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[16] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
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**Abstract**

The Multi-slit Solar Explorer (MUSE) is a proposed mission composed of a multislit EUV spectrograph (in three spectral bands around 171 Å, 284 Å, and 108 Å) and an extreme ultraviolet (EUV) context imager (in two passbands around 195 Å and 304 Å). MUSE will provide unprecedented spectral and imaging diagnostics of the solar corona at high spatial (≲0.″5) and temporal resolution (down to ~0.5 s for sit-and-stare observations), thanks to its innovative multislit design. By obtaining spectra in four bright EUV lines (Fe IX 171 Å, Fe XV 284 Å, Fe XIX–Fe XXI 108 Å) covering a wide range of TR and coronal temperatures along 37 slits simultaneously, MUSE will, for the first time, "freeze" (at a cadence as short as 10 s) with a spectroscopic raster the evolution of the dynamic coronal plasma over a wide range of scales: from the spatial scales on which energy is released (≲0.″5) to the large scale (~170″ × 170″) atmospheric response. We use numerical modeling to showcase how MUSE will constrain the properties of the solar atmosphere on spatiotemporal scales (≲0.″5, ≲20 s) and the large field of view on which state-of-the-art models of the physical processes that drive coronal heating, flares, and coronal mass ejections (CMEs) make distinguishing and testable predictions. We describe the synergy between MUSE, the single-slit, high-resolution Solar-C EUVST spectrograph, and ground-based observatories (DKIST and others), and the critical role MUSE plays because of the multiscale nature of the physical processes involved. In this first paper, we focus on coronal heating mechanisms. An accompanying paper focuses on flares and CMEs.

*Unified Astronomy Thesaurus concepts:* Solar coronal heating (1989); Theoretical models (2107); Solar instruments (1499);

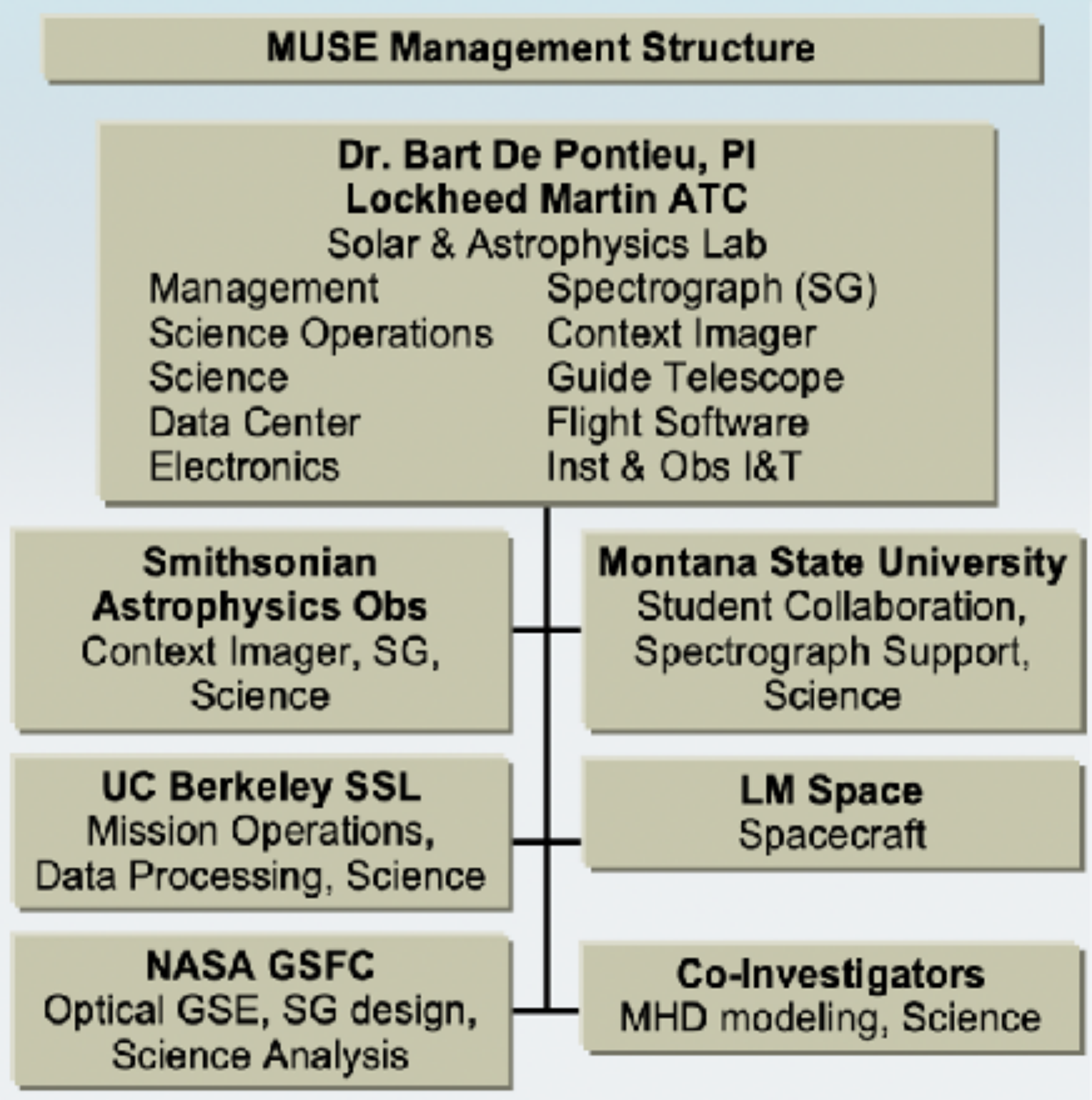
*Supporting material:* animations

Table 3. Predicted *MUSE* diagnostics for various models of heating mechanisms

| Mechanism | Predicted Diagnostic | λ[a] [Å] | Figures |
|---|---|---|---|
| Spicules | - type I and type II spicules | 304 | 2, 3 |
| | - short-lived blue-shifted brightenings at loop footpoints associated w/ spicules | 171 | 2, 3 |
| | - propagation of Alfvénic waves (Doppler and POS motions), triggered by spicules, along loops | 304, 171, 195, 284 | 13a, 16-18 |
| | - dissipation of Alfvénic waves through impulsively-driven KHI | 171, 284 | 13, 16-18 |
| | - formation of coronal loop, associated with spicules | 171, 195, 284 | 2, 3 |
| | - evaporative flows at loop footpoints, associated with spicules | 284 | 2, 3 |
| Braiding | - visibly braided loops | All | 7 |
| | - spatio-temporal coherence of intensity and line width along loops (20-60s, ~ 5-30″) | 171, 284, 108 | 4, 5, 10 |
| | - short-lived (≈ 20s single, ≈ 60s cluster) nanojets: high velocities (<~ 100 km s$^{-1}$) and line widths, transverse to guide field | 171, 284, 108 | 4, 8, 9 |
| | - loop formation associated with nanojets | 171, 195, 284, 108 | 8 |
| | - twisting and unwinding motions | 171, 195, 284 | 7 |
| | - evaporative flows in loops | 171, 284, 108 | 6, 10, 11 |
| | - nanoflare driven short-lived brightenings at loop footpoints, and associated short-lived hot loop emission | 171, 284, 108 | 10, 11 |
| Waves | - propagating or standing oscillatory displacements of loops and jets | 304, 171, 195, 284 | 18-19 |
| | - oscillations in velocity, line width along loops | 171, 284 | 12-14,16-19 |
| | - spatial dependence of FFT power spectrum along loop | 171, 284 | 13 |
| | - propagation of Doppler shift oscillations along loops | 171, 284 | 14, 16-19 |
| | - spatio-temporal coherence of velocities and line width along loops from wave propagation | 171, 284 | 12, 14, 16-18 |
| | - specific phase relationships between intensity, velocity, line width | 171, 284 | 19-19 |
| | - concentration of wave power at edge of flux tubes (KHI, RA) | 171, 195, 284 | 16-18 |
| | - steady downflows/upflows around edge of flux tubes (KHI, RA) | 171, 195, 284 | 16-18 |
| Flux Emerg. | - short-lived, low-lying loops, possible EUV absorption from overlying cool plasma | 304, 171, 195, 284 | 20 |
| | - flow patterns associated with draining of rising loops and topological evolution including footpoint separation | 171, 284, 195 | 20, 21 |
| | - strong short-lived brightenings and bi-directional flows (> 100 km s$^{-1}$), large line widths (from large-angle reconnection) | 171, 284, 108 | 20, 21 |
| | - spatio-temporal coherence of highly dynamic "storms" of sudden brightenings and line width increase (10-30″, 20s) | 304, 171, 195, 284, 108 | 20, 21 |
| | - various types of jets, including erupting (mini-)filaments | 304, 171, 195, 284 | 20, 21 |

[a] For 304 and 195 imaging is desired. For 171, 284, and 108, intensity, Doppler shift, and line broadening are typically desired.

# Institution Teams and Roles similar to IRIS SMEX




- MUSE team structure similar to IRIS SMEX team
  - ATC leads development and science operations and analysis
  - Including long-term collaborators:
    - Harvard Smithsonian Astrophysics Observatory (SAO),
    - NASA GSFC,
    - Montana State University,
    - UC Berkeley (Mission Ops),
    - and many science institutes
- **Contributions by:**
  - **Norwegian Space Agency (NOSA) for downlinks, data center and science**
  - **Italian Space Agency (ASI) for mirrors, thin film filters, coating tests, and science**
  - **German Aerospace Center (DLR) for grating, calibration, and science**

# Science Co-I Team

| Co-I | Inst. | Responsibilities (expertise) |
|---|---|---|
| De Pontieu, B. | LMSAL | PI; IRIS Coordination (PI IRIS) |
| Boerner, P. | LMSAL | Deputy PI; Project Scientist |
| Hansteen, V. | LMSAL | Models flux emergence, braiding; obs. programs braiding; obs. analysis tools; public release of models, Hinode coordination |
| Jin, M. | LMSAL | Models of flux rope driven CMEs, global corona; obs. programs for CMEs; comparison of CME models and observations; AIA coordination (PI AIA) |
| Martinez Sykora | LMSAL | Deputy Science Lead; Models of spicules and impact on corona; observational programs for spicules, numerical modeling tools |
| Polito, V. | LMSAL | Models of nanoflares incl. non-thermal particles and Alfven waves; comparison with observations; analysis of flare obs. |
| Chintzoglou, G. | LMSAL | Work on numerical simulations on flaring-productive active regions and closely with the Project Scientist/Deputy PI Dr. Paul Boerner |
| Cheung, M. | CSIRO | Science Lead; Space weather applications (incl. MURAM and data-driven models); AI techniques |
| Golub, L. | SAO | Institutional PI at SAO; SAO Project Scientist; CI design, I&T |
| Samra, J. | SAO | Dep. Instrument Scientist; SAO CI Inst. Scientist, lead CI calib. |
| Testa, P. | SAO | Obs. programs for nanoflares; validation of multi-slit disambiguation; analysis of TR & coronal observations |
| Reeves, K | SAO | Studies that connect MUSE observations with heliospheric data from various missions including PSP, Solar Orbiter, and PUNCH. |
| Daw, A. | GSFC | Institutional PI at GSFC; optical GS E lead for SG & CI; atomic physics sensitivity analysis; analysis of EUV spectra |
| Kankelborg, C. | MSU | Lead of student collaboration; assist instrument design, contribute to science ops; obs. programs for coronal holes |
| Winebarger, A. | MSFC | Validation of multi-slit disambiguation methods; obs. programs for quiet Sun; analysis of coronal spectroscopy and imaging |
| Rempel, M. | HAO | Models of flares and CMEs driven by flux emergence |

| Co-I | Inst. | Responsibilities (expertise) |
|---|---|---|
| Jaeggli, S. | NSO | DKIST coordination, SG calib., analysis DKIST/MUSE obs. |
| Bale, S. | UCB | Institutional PI at UCB; PSP coordination, analysis PSP/MUSE |
| Carlsson, M. | UiO | Models of flares, coupling to low atmosphere (He II synthesis); UiO data center, liaison with NSA; SoLO coord. (SPICE co-PI) |
| Leenaarts, J. | ISP | SST coordination (SST dir.); models of low atmosphere incl. non-equilibrium ionization and non-LTE radiative transfer |
| De la Cruz Rodriguez, J. | ISP | Perform inversions of the photospheric and magnetic field using DKIST coordinated datasets |
| De Moortel., I. | St.And. | Models of wave propagation/heating; obs. progs. waves |
| Antolin, P. | NUni | Models resonant absorption, plasma instabilities; wave analysis |
| Fletcher, L. | UGI | Obs. Programs for flares; comparison flare models & MUSE obs |
| Peter, H. | MPS | Data-driven models of corona; comparison w/ MUSE obs |
| Solanki, S. | MPS | Coordination with GREGOR and SoLO/PHI (PHI PI) |
| Ugarte-Urra, I. | NRL | Coordination with EUVST, development of NGSPM observing programs, analysis of coordinated EUVST/MUSE datasets |
| Soufli, R. | LLNL | Response for EUV coatings of the grating and the SG and CI mirrors |
| Reale, F. | UoP | Perform MHD modeling of coronal heating via braiding. |
| Spadaro, D. | UoC | Analysis of spectral data, and coordination with Solar Orbiter. |

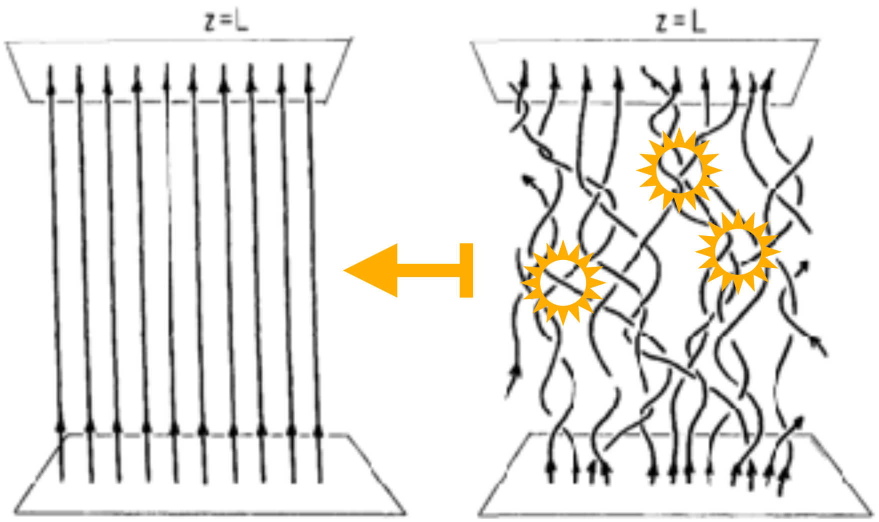
# Italian contribution: ASI/INAF Agreement

D. Perrone, ASI

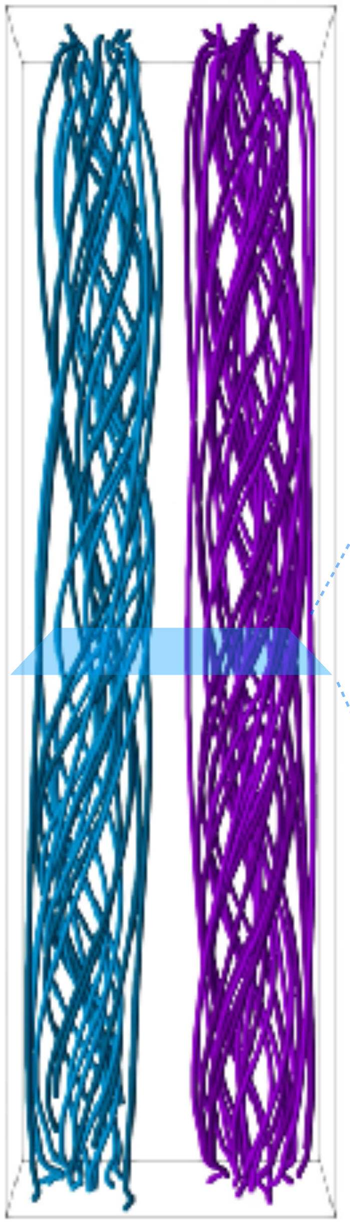
- Hardware:
  - EUV Filters (M. Barbera, UniPa, INAF/OAPa)
  - Mirrors (D. Spiga, INAF/OA Brera)
  - Test coating (M. Pelizzo, CNR/IFN)
- Scientific support:
  - UniPa (F. Reale)
  - INAF/OACt (D. Spadaro)
  - INAF/OACN (V. Andretta)
  - UniCal (F. Malara)

## Loop kink instability and MHD avalanches (Cozzo, Hood, et al. 2023)

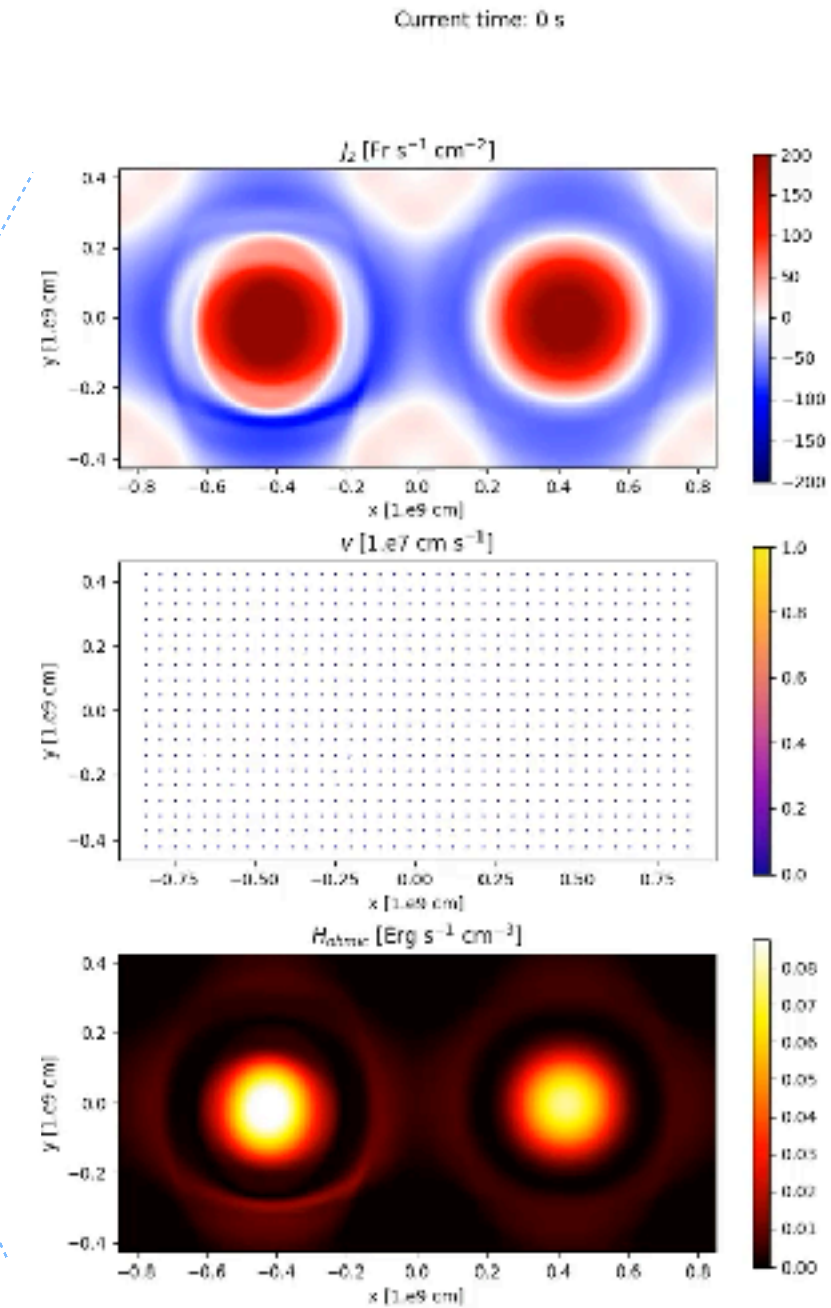
- Localised instability leading to a large heating event (Tam et al 2015, Hood et al 2016, Reid et al 2018, 2020);
- Stratified atmosphere (chromosphere + TR + corona), magnetic field tapering, thermal conduction, radiative cooling, anomalous diffusivity, gravity in curved loop;
- **Kink Instability** can trigger an MHD avalanche.



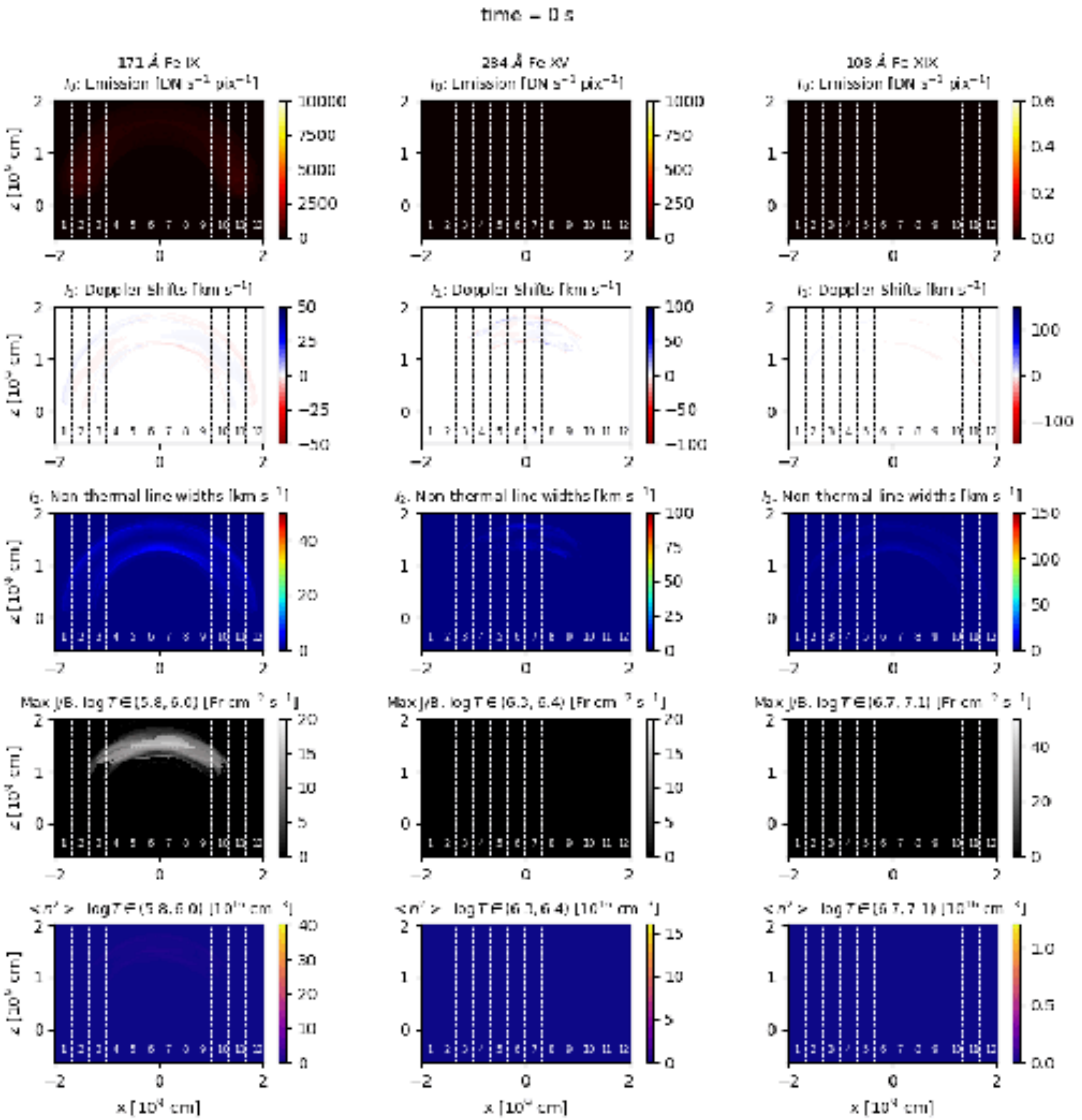

Unstable loop v.s. nearby stable loop



Full 3D multi threaded coronal loops



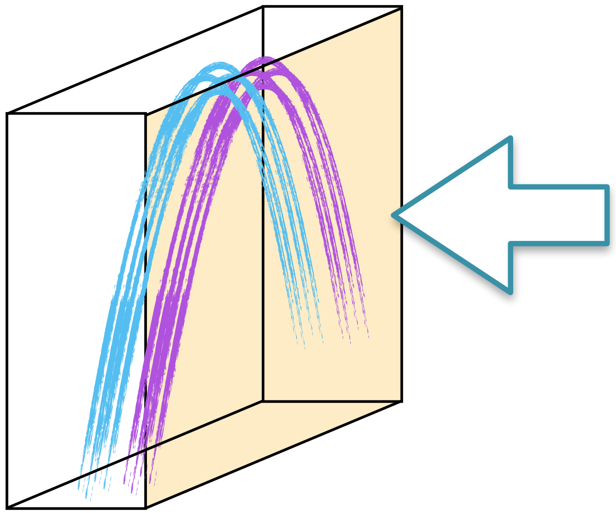

Horizontal cut: current density / velocity / heating



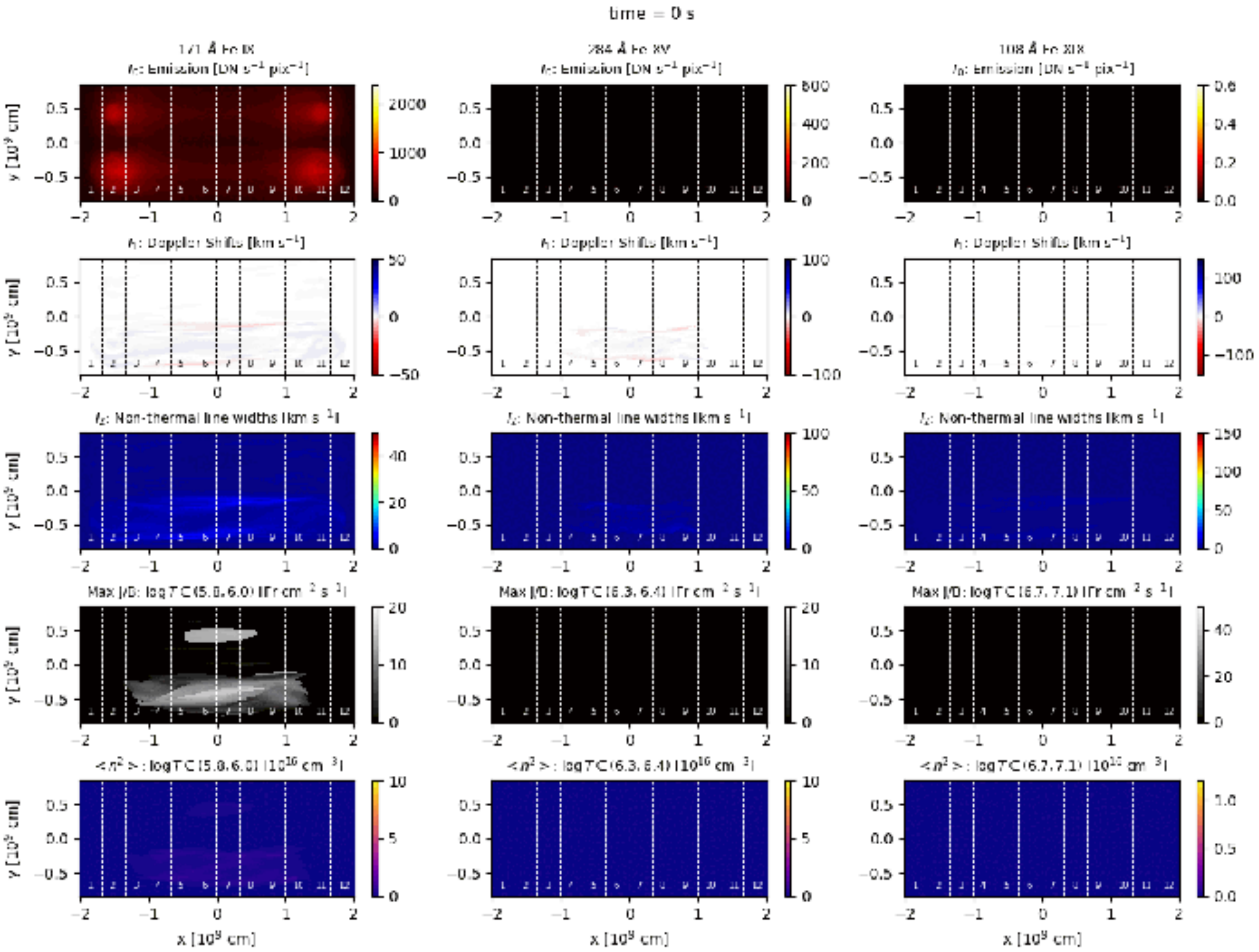

Coronal energy release by MHD avalanches
- II. EUV diagnostics of a multi-threaded coronal loop

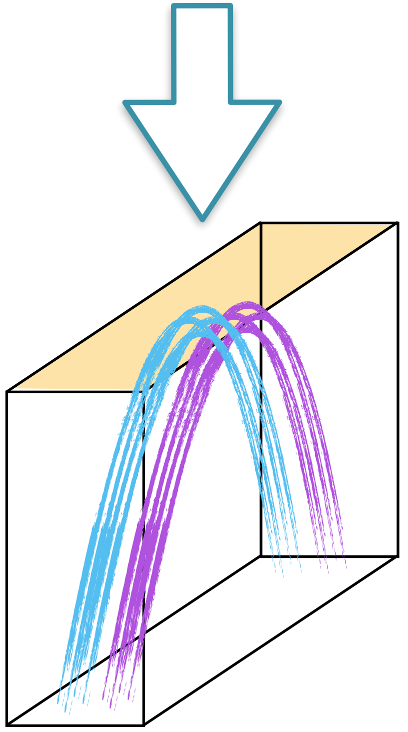
Cozzo et al. 2024, in preparation

# MUSE lines



**- Front view**


time = 0 s
171 Å Fe IX
284 Å Fe XV
108 Å Fe XIX
Emission [DN s⁻¹ pix⁻¹]
Doppler Shifts [km s⁻¹]
Non-thermal line widths [km s⁻¹]
y [10⁹ cm]
x [10⁹ cm]



- Top view

# Conclusions

- MUSE will provide unprecedented spectra at 0.4 arcsec resolution, 12s cadence, over a FOV of 170"x170", and context images at 5s cadence (up to 580"x580")
- Launch in 2027, strong synergy with Solar-C EUVST, but also with Solar Orbiter
- MUSE spectroscopy 40x-100x faster and 10x higher res than current spectrographs
- MUSE will provide important constraints and diagnostics for magnetic reconnection and heating in coronal loops
- MUSE will spectroscopically capture the multi-scale nature of coronal heating and solar flares and eruptions
- MUSE will allow comparisons between unprecedented observational constraints and state-of-the-art models:
  - Physics of flares and eruptions: triggers, reconnection/current sheet, non-thermal particle properties, flare energy thermalization, etc
  - Fundamental physical processes: instabilities, non-thermal particle acceleration
  - Connection with space weather and Solar Orbiter/Metis