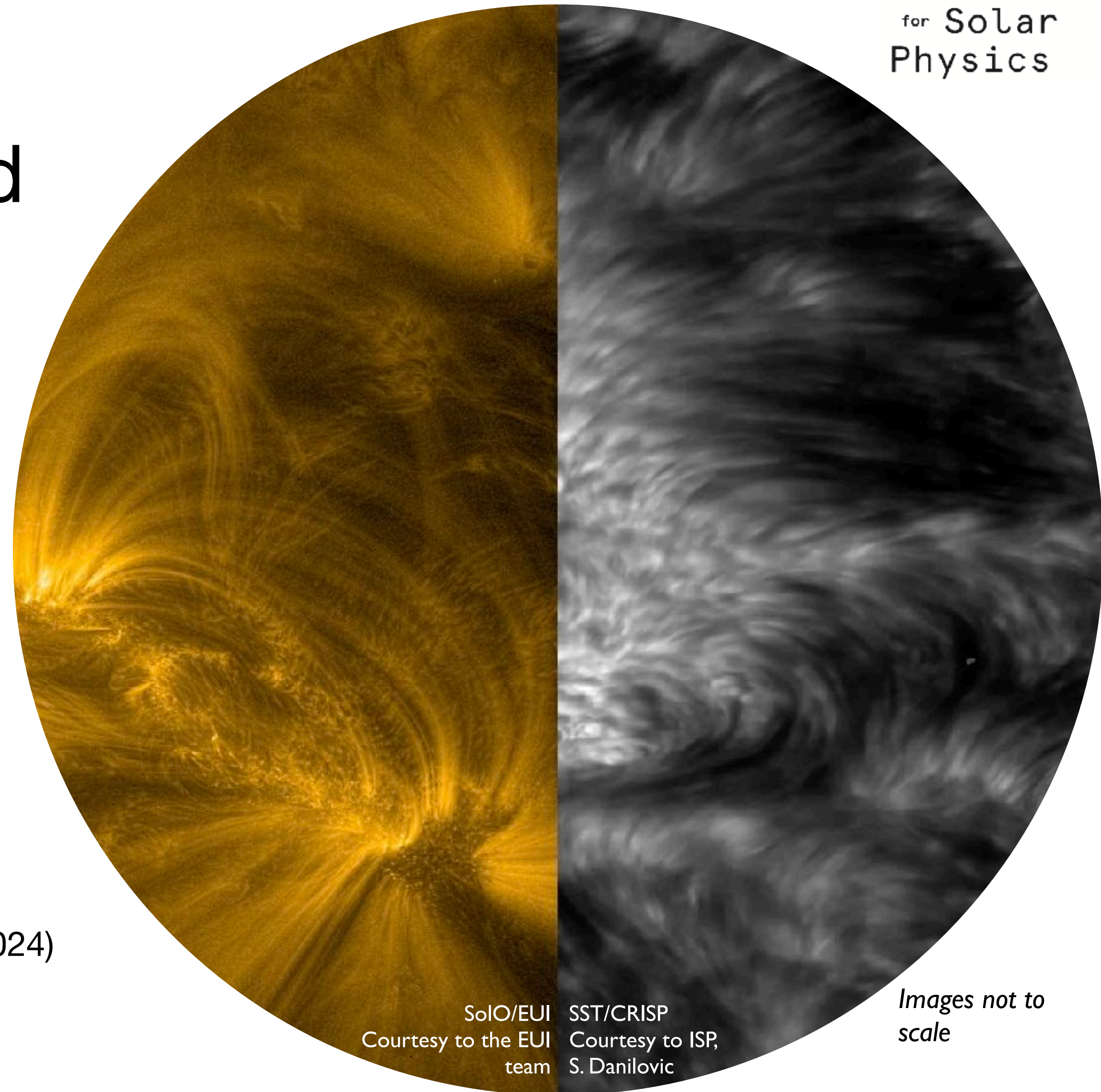




About the nature of sustained kink oscillations in coronal loops:

*combining coronal
&
chromospheric diagnostics*

Nicolas Poirier,
Petra Kohutova, Reetika Joshi, Luc Rouppe Van Der Voort et al. (2024)
(in prep)



SoI/O/EUI
Courtesy to the EUI
team

SST/CRISP
Courtesy to ISP,
S. Danilovic

*Images not to
scale*

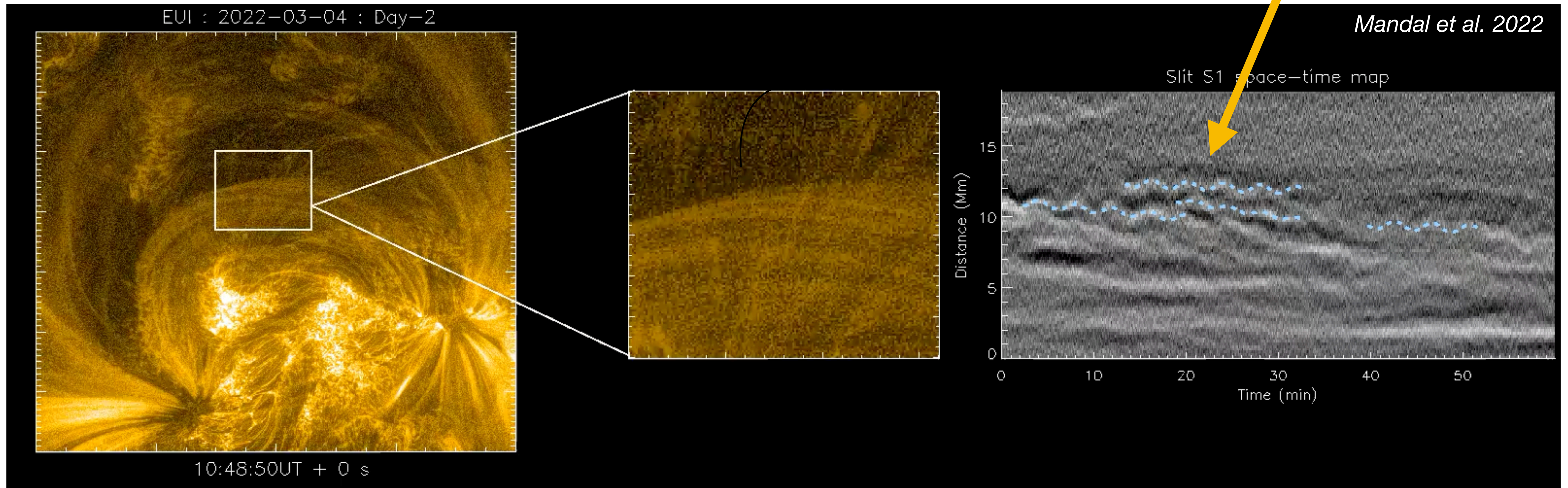
Introduction

Transverse coronal oscillations have long been observed in active region loops, first discovered by TRACE
(*Nakariakov 1999, Aschwanden 1999*)

Routine observations by AIA then showed a great diversity of them:

Large/**small** amplitudes
With/**without** (apparent) decay
Propagating/**standing**

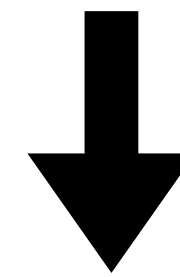
➔ **Decay-less kink oscillations**



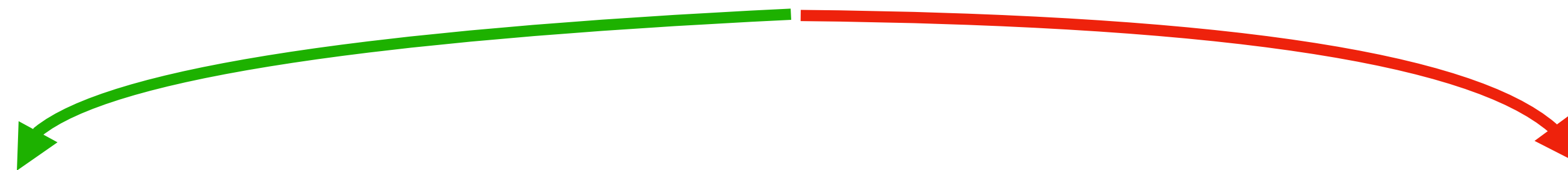
Can coronal kink oscillations contribute to coronal heating? **Yes** and **No**

For large-amplitude oscillations -> most of the energy is already provided by the impulsive driver (e.g. flare, jet, EUV wave...)

For small-amplitude oscillations -> the energy was said **insufficient** to heat the solar corona
(Klimchuk 2015; Li et al. 2022; Gao et al. 2022)



Using SoI/O/EUI data, Li & Long (2022) estimated an average energy flux of 820 W.m^{-2}



However, the recent detection of high-frequency oscillations in SoI/O/EUI shows **sufficient power to heat up at least the quiet-corona** (Petrova et al. 2022)

This is likely **not enough to heat up plasmas at $>1 \text{ MK}$ in active regions**
(which requires $\sim 10^4 \text{ W.m}^{-2}$ according to *Withbroe & Noyes 1977*)

What drives decayless coronal loop oscillations?

- Up/down flows along the loop (*Kohutova & Verwichte 2017; Verwichte & Kohutova 2017*)
- Siphon flows (*Kohutova & Verwichte 2018*)
- Kelvin Helmholtz (KH) vortices (*Antolin et al. 2016*)
- **Self-oscillatory mechanism** through excitation at loop footpoints:
 - ~~Random: granular motion, vortex flows~~ (*Carlsson et al. 2010; Shelyag et al. 2011; Liu et al. 2019*)
 - ~~Harmonic: P-modes (+mode conversion)~~ (*Tomczyk & McIntosh 2009; Nisticò et al. 2013; Morton et al. 2016, 2019; Riedl et al. 2019, Gao et al. 2023*)

Disagrees with the polarisation of kink modes (*Zhong et al. 2023*)

+

The simulated perturbation velocities tend to be smaller than in observations (*Gao et al. 2023*)

What drives decayless coronal loop oscillations?

- Up/down flows along the loop (*Kohutova & Verwichte 2017; Verwichte & Kohutova 2017*)
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- **Quasi-steady: super-granular flows or footpoint migration** (*Nakariakov et al. 2016; Karamelas & Van Doorselaere 2020*)

Coupled with the kink mode + produce heating (*Guo et al. 2019*)

Agrees with the polarisation of kink modes (*Zhong et al. 2023*)
+ reproduce the other observed properties (*Karamelas & Van Doorselaere 2020*)



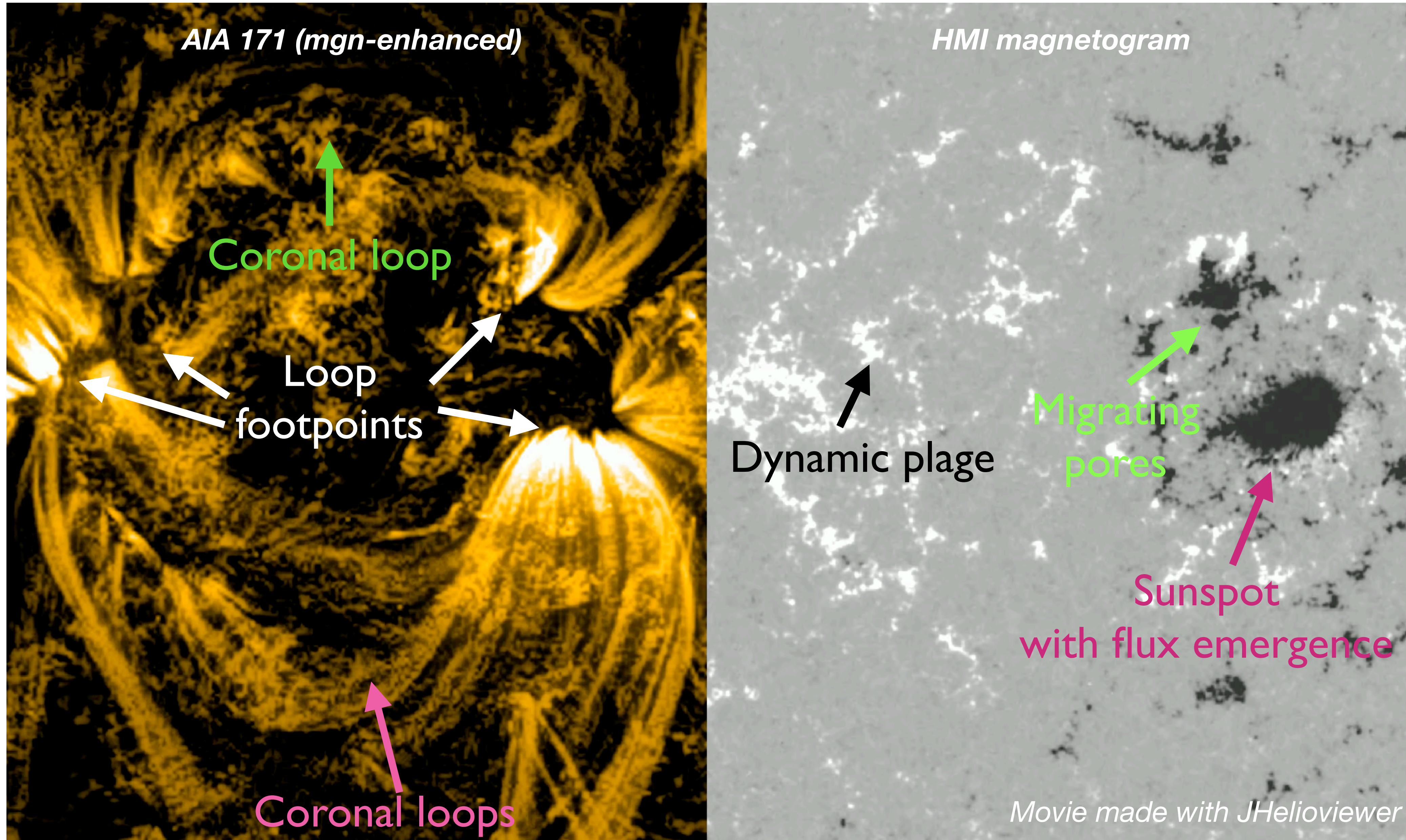
The bow-on-a-violin model:
Bow = super-granular flows
Violin = coronal loop

Motivation

Can we observe the bow-on-a-violin model?

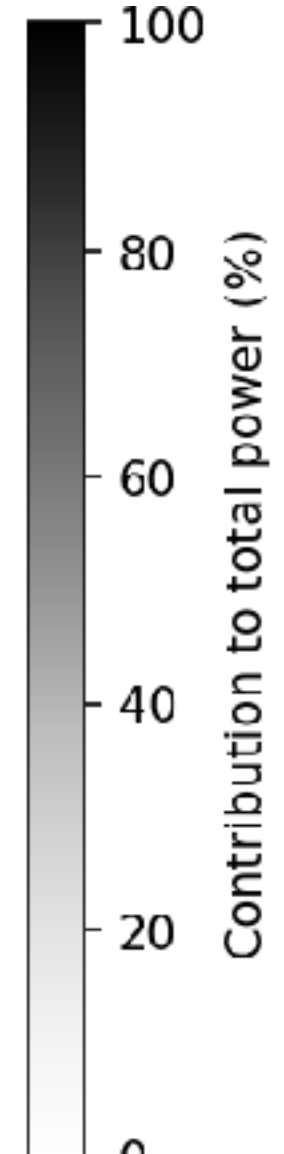
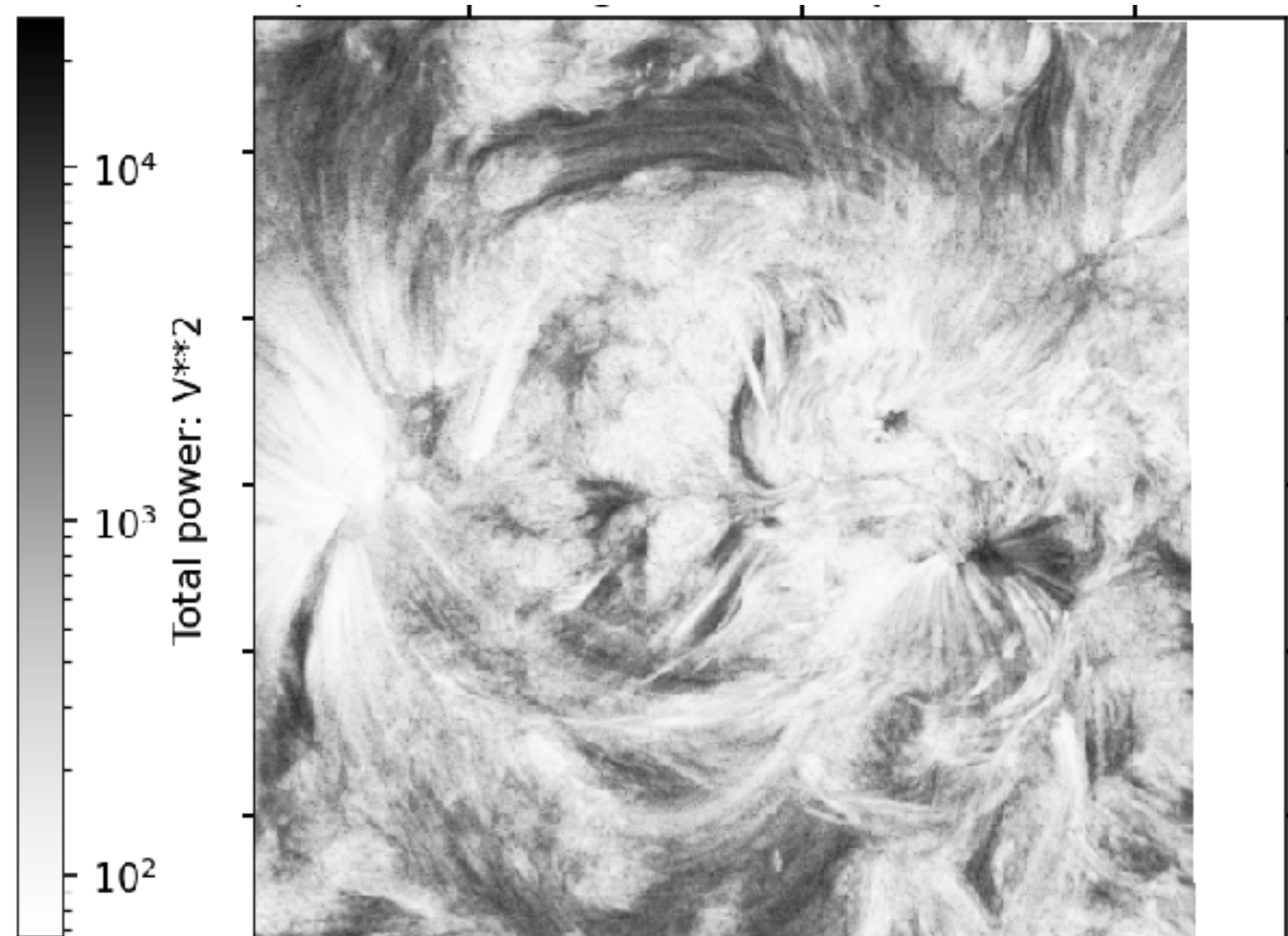
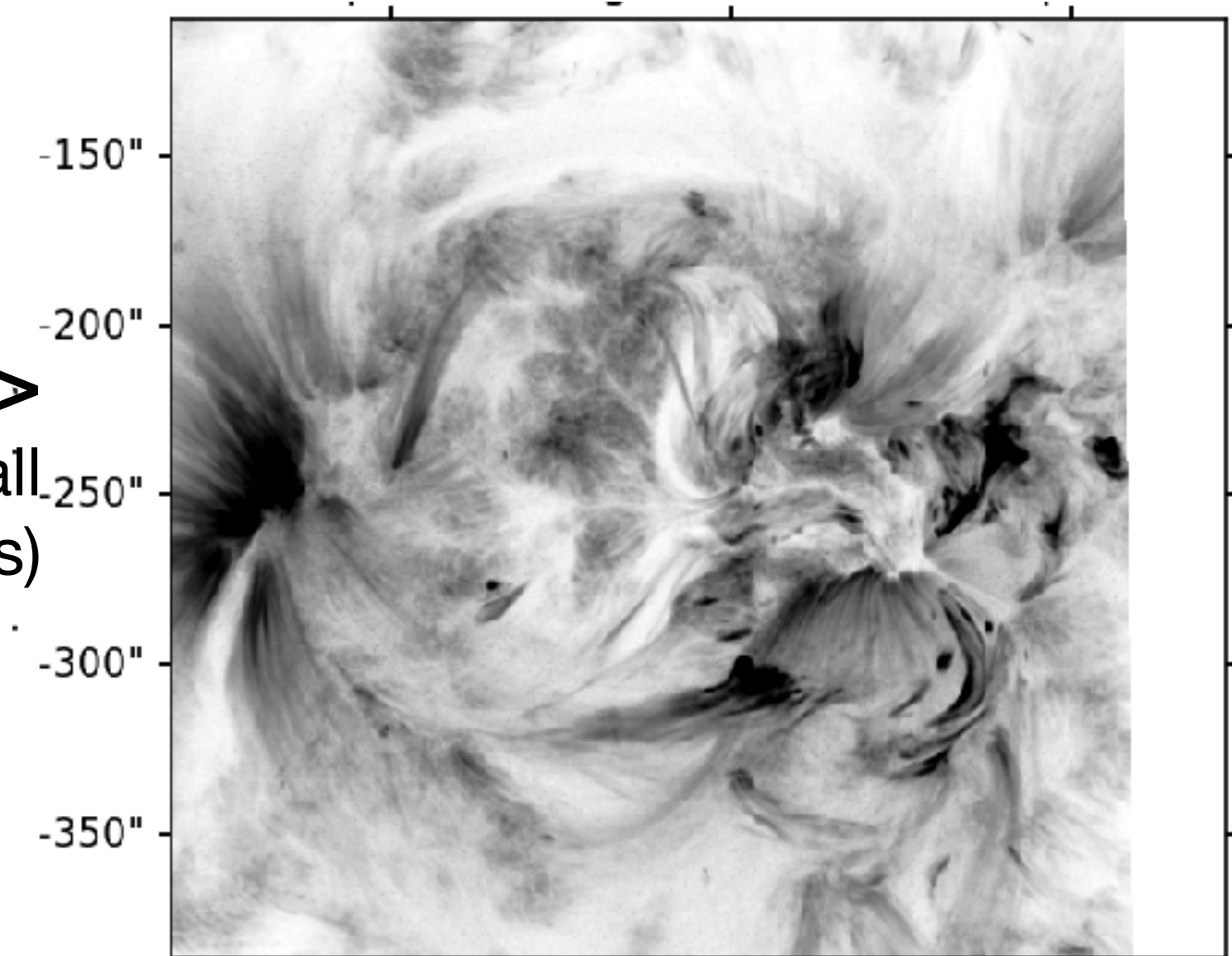
What kind of “quasi-steady flow” should we search for?

Can we observe the bow-on-a-violin model? **Context**



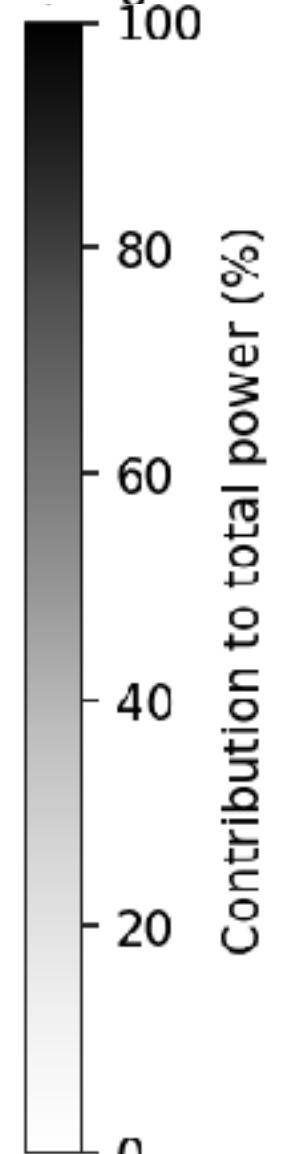
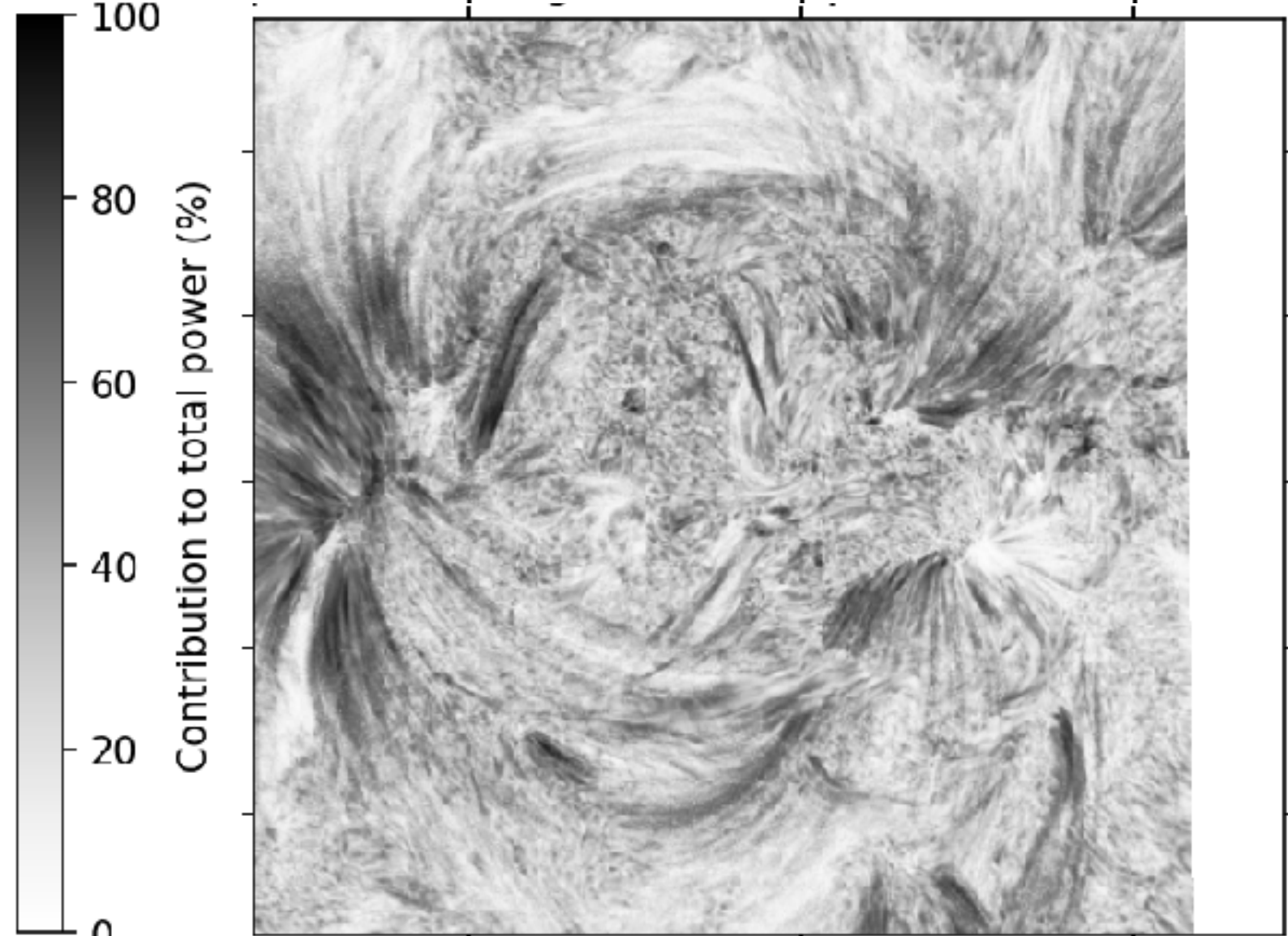
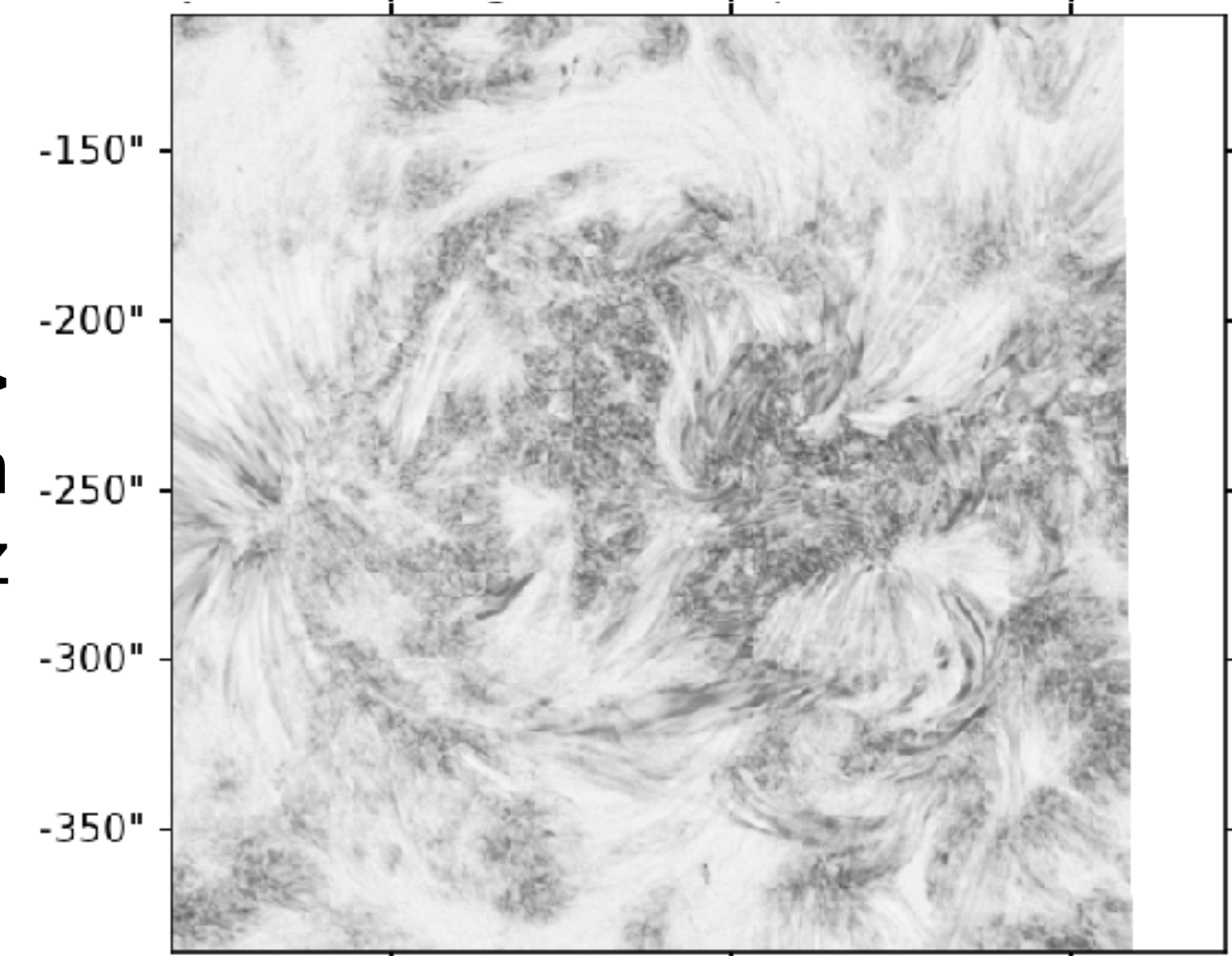
Can we observe the bow-on-a-violin model? *Oscillation analysis I*

Total power->
(integrated over all frequencies)



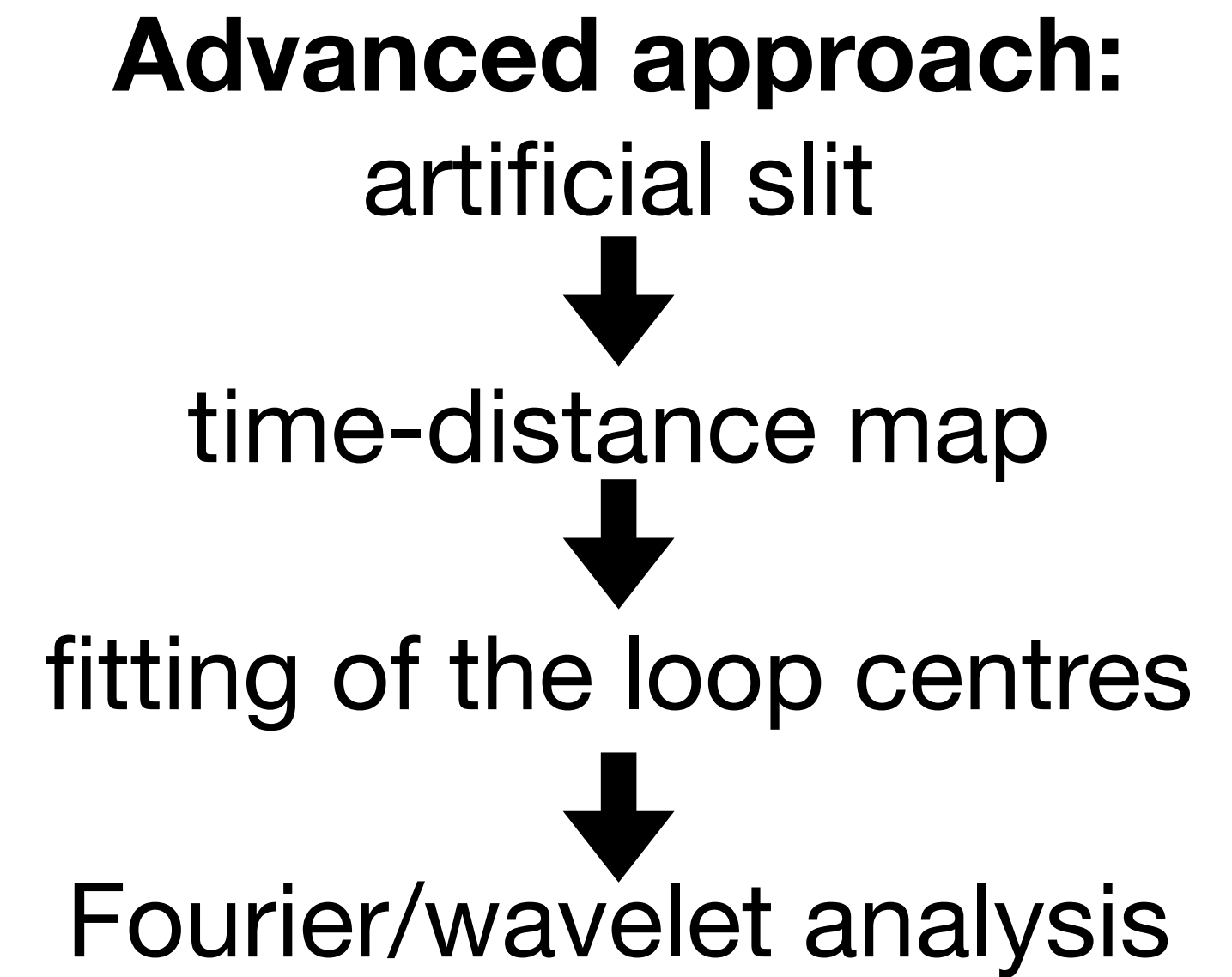
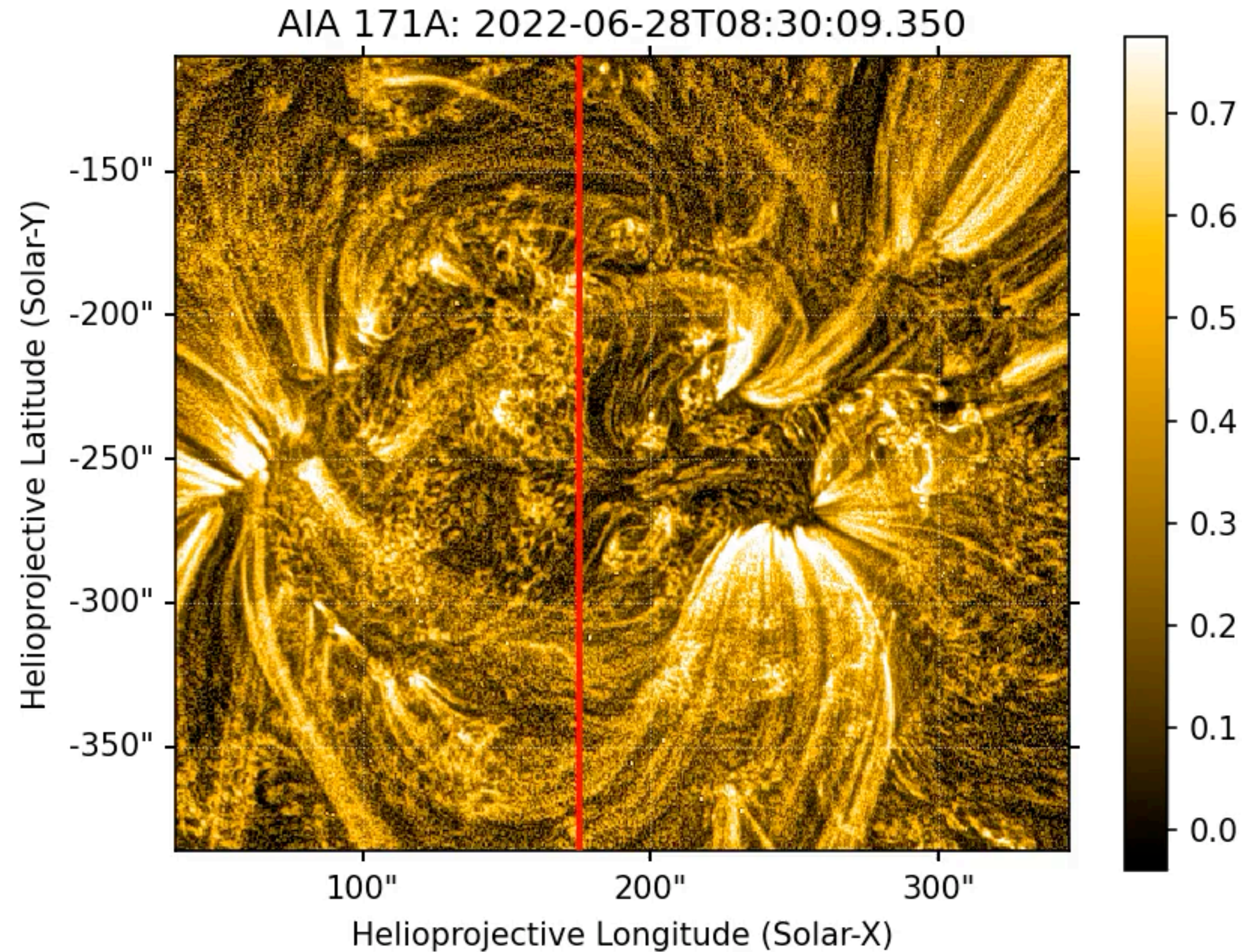
<-Contrib from
24sec<->3min
5.5<->42mHz

Contrib from->
3<->17min
1<->5.5mHz

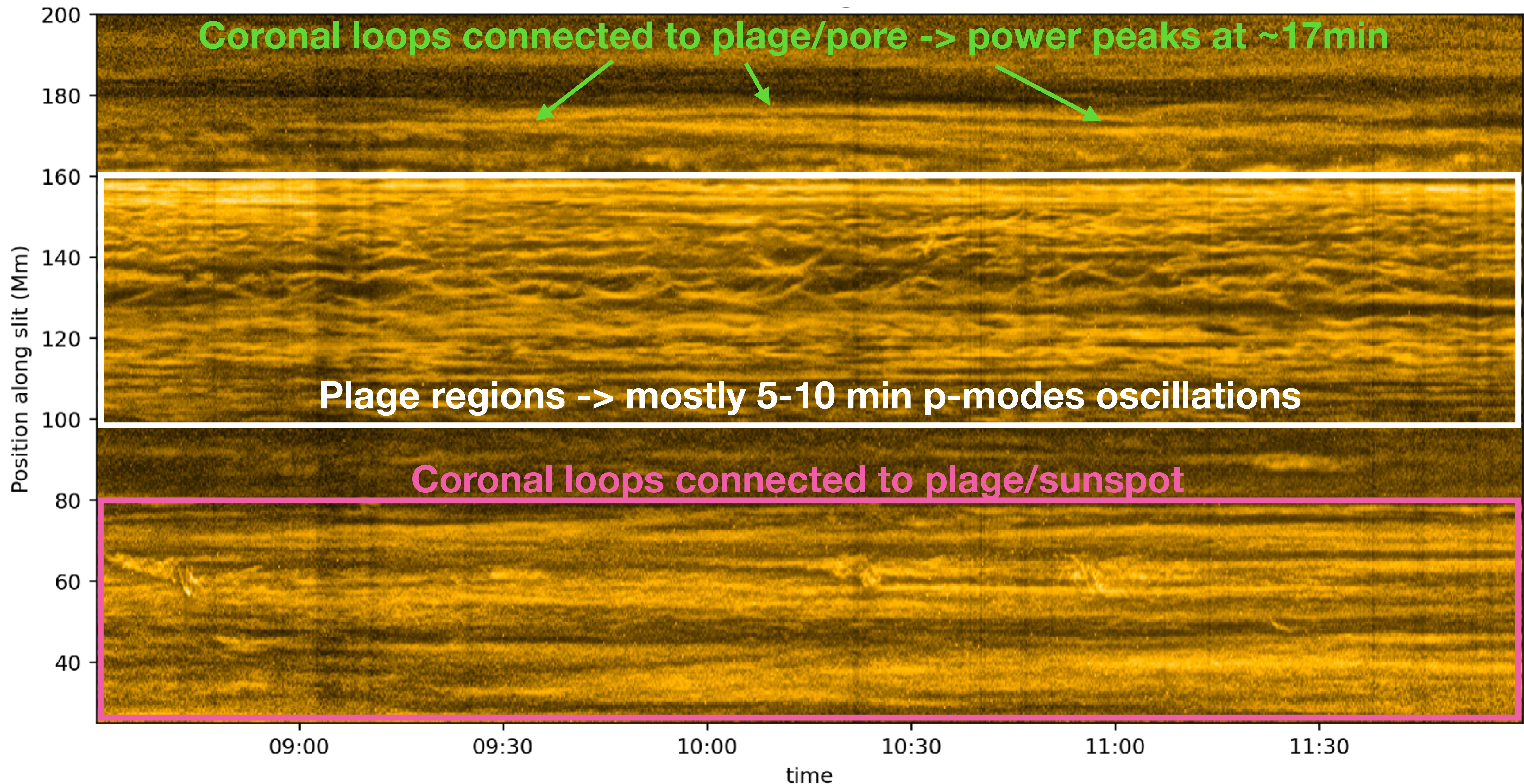


<-Contrib from
17<->50 min
0.3<->1mHz

R ● C S
Can we observe the bow-on-a-violin model? *Oscillation analysis II*



Can we observe the bow-on-a-violin model? *Oscillation analysis II*



Can we observe the bow-on-a-violin model? **Coronal seismology**

1) If standing mode (fundamental): $V_{ph} = 2L/P$ \rightarrow for $P \sim 17\text{min}$ and $L \sim 150\text{Mm}$ $\rightarrow V_{ph} \sim 300\text{km/s}$

Agrees with Li & Long (2022)

2) Thin-tube approximation: $V_{ph} \approx C_k [1 - Q K_0(\mathcal{T}|k_z|a)(k_z a)^2]$,

$$Q = \frac{\rho_{0i}\rho_{0e}\mathcal{T}^2(C_{Ae}^2 - C_{Ai}^2)}{2C_k^2(\rho_{0i} + \rho_{0e})^2}, \quad \mathcal{T} = \left(1 - \frac{C_k^2}{C_{Ae}^2}\right)^{1/2}, \quad \text{Nakariakov et al. (2021)}$$

$$C_k = \left(\frac{\rho_{0i}C_{Ai}^2 + \rho_{0e}C_{Ae}^2}{\rho_{0i} + \rho_{0e}}\right)^{1/2},$$

Work in progress

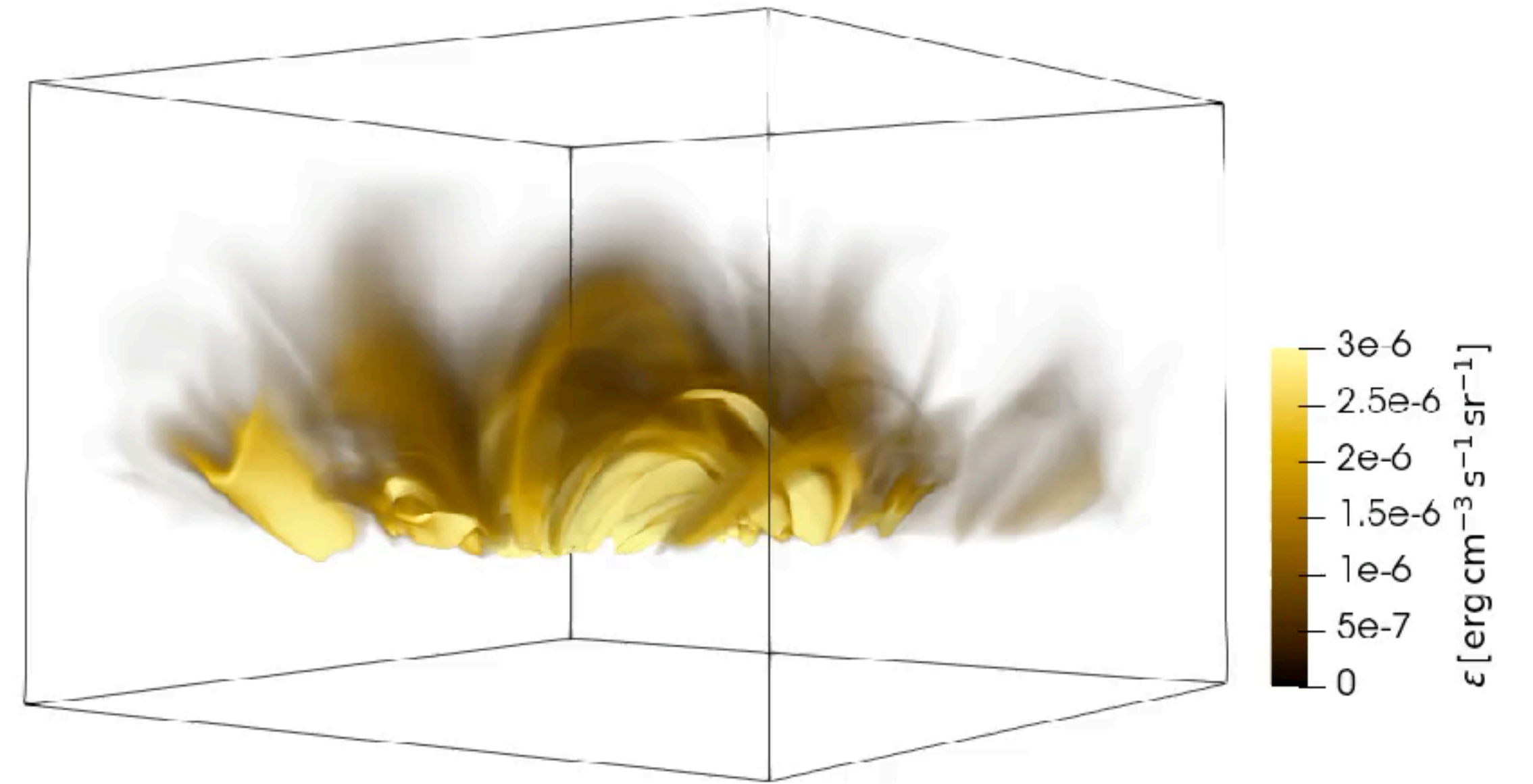
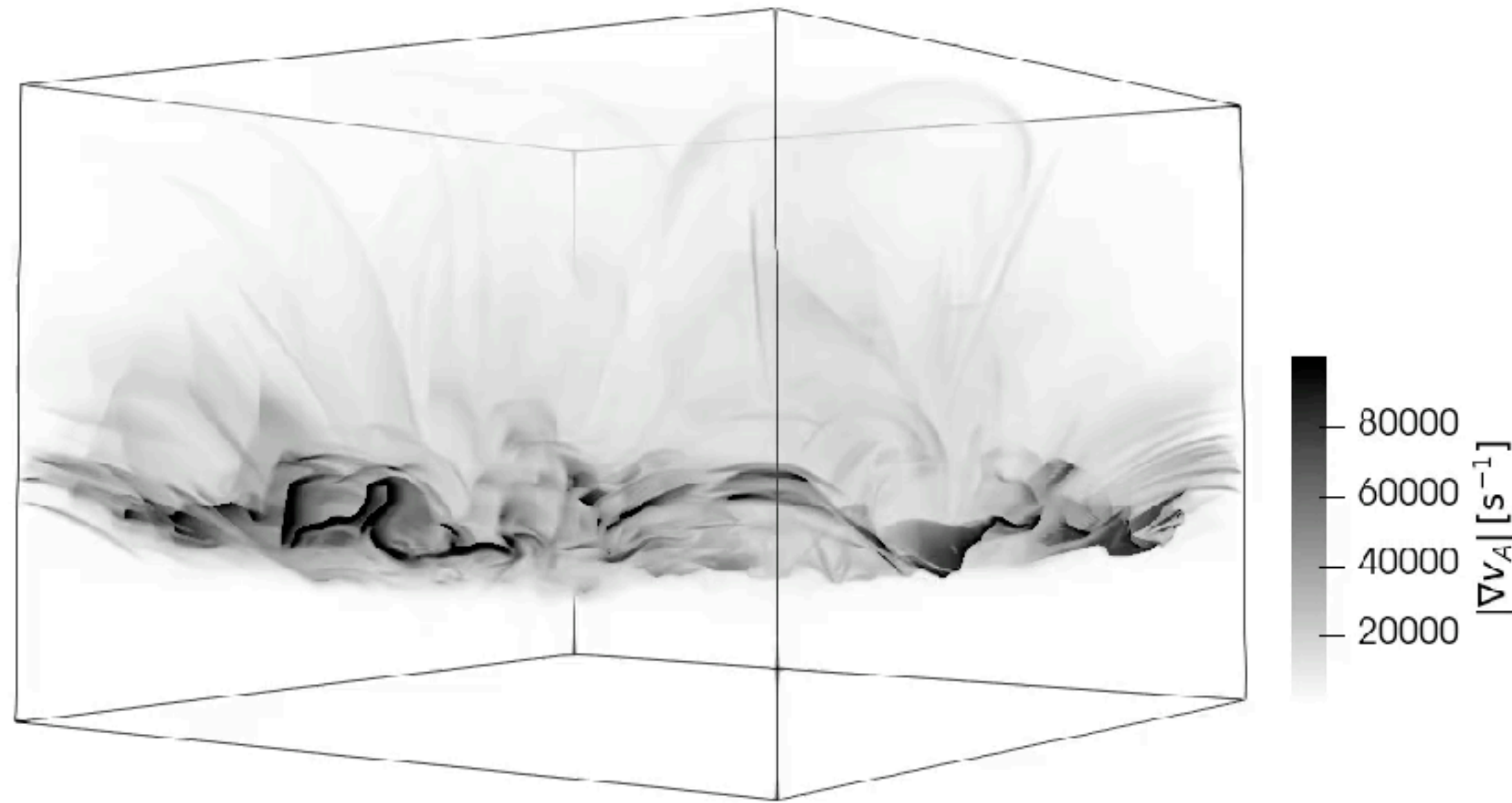
3) Zero-beta limit (Bi=Be): $C_k = C_{Ai}\sqrt{\frac{2\zeta}{\zeta+1}}$, $\zeta = \rho_{0i}/\rho_{0e}$ for $\zeta = 2 - 3 \rightarrow C_{Ai} \approx 245 - 260\text{km/s}$

Warmuth & Mann (2005) got an Alfvén speed of $\sim 300\text{km/s}$ at the coronal base of the quiet-Sun

All of the classical theory behind coronal seismology assumes loops as perfect cylinders

Are coronal loops made of individual strands? **The Coronal Veil** (Malanushenko 2022)

How coronal waveguides may actually look like? The coronal veil



How wrong the classical coronal seismology is in this case?



This is **work in progress** using a Bifrost simulation!

Courtesy to Petra Kohutova

R ● C S
Can we observe the bow-on-a-violin model? ***Oscillation analysis III***

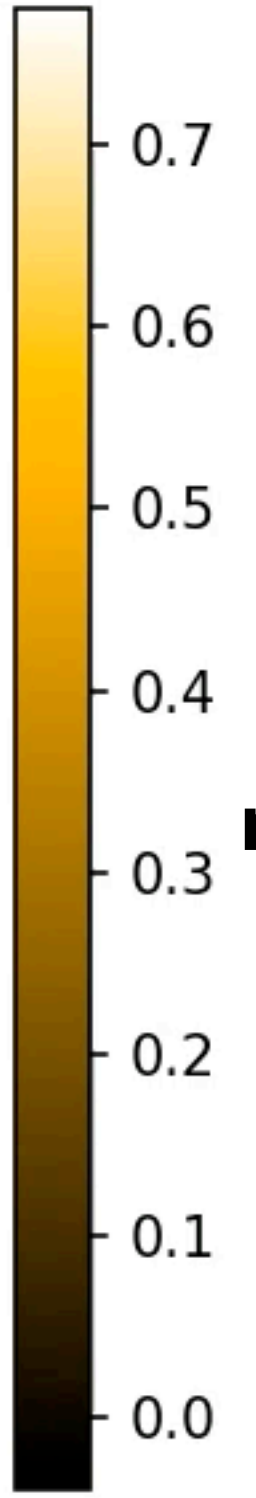
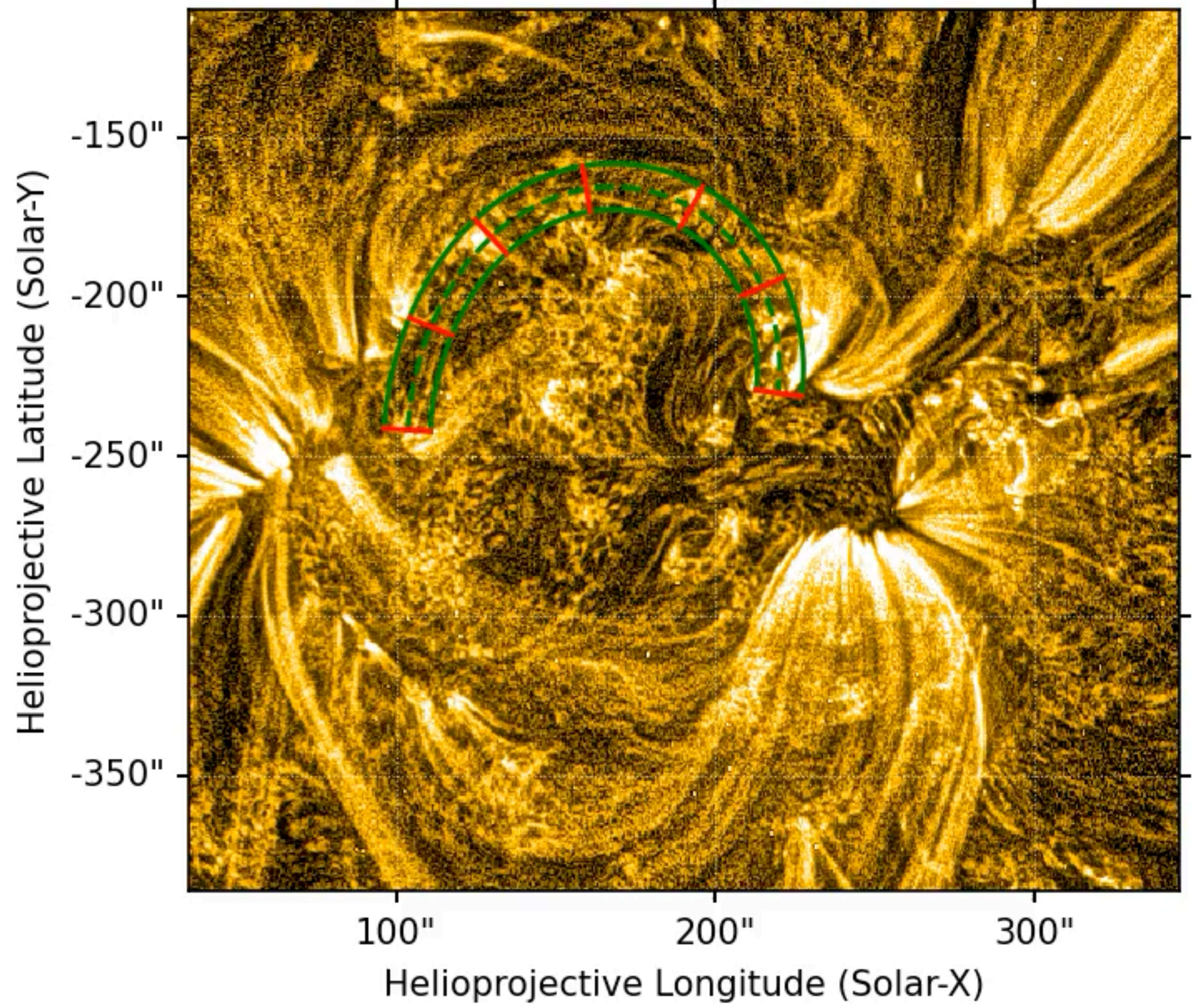
Can we further characterise the oscillations?

R ● C S

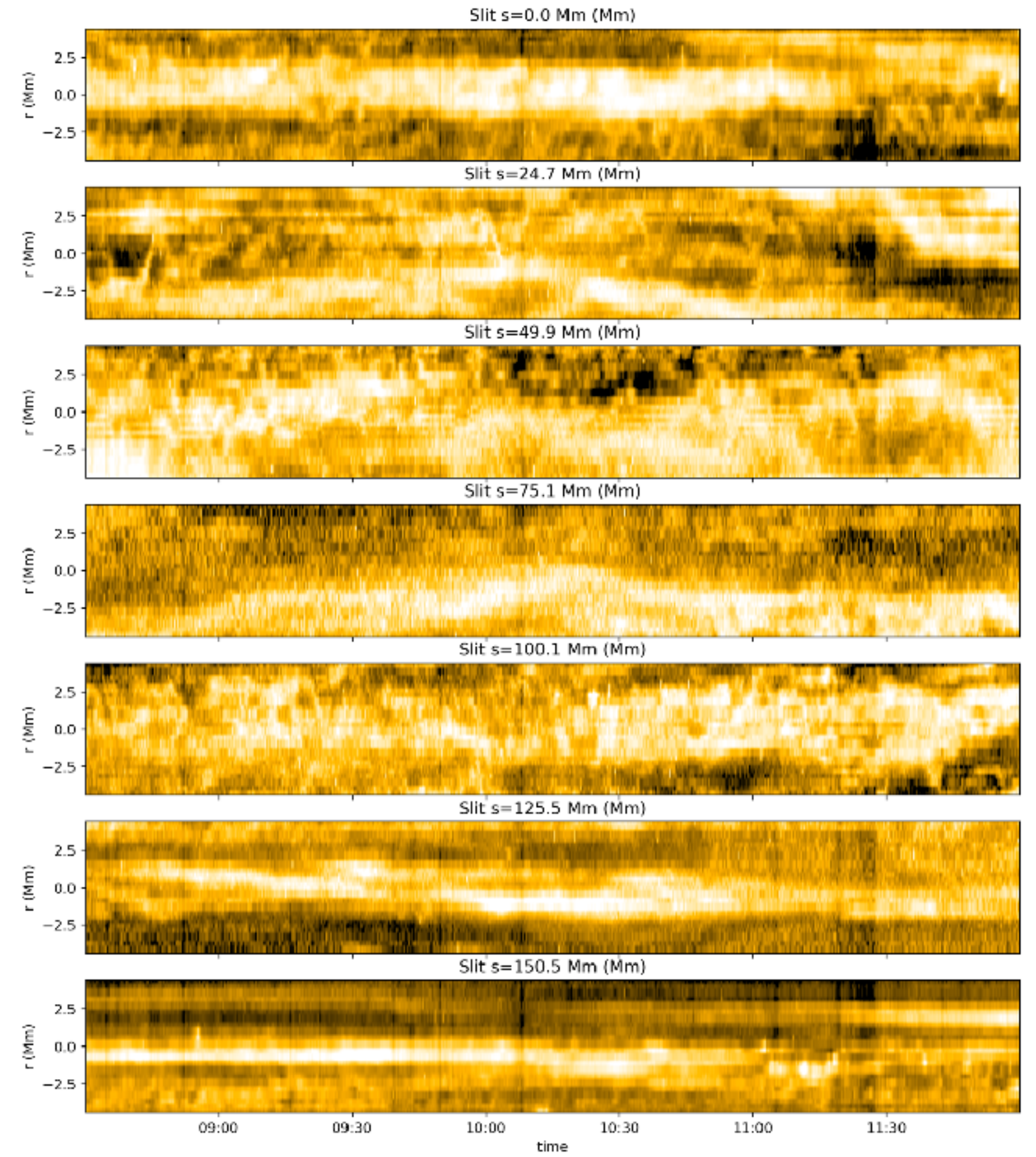
Can we observe the bow-on-a-violin model? *Oscillation analysis III*

Is it propagating or standing?

AIA 171A: 2022-06-28T08:30:09.350

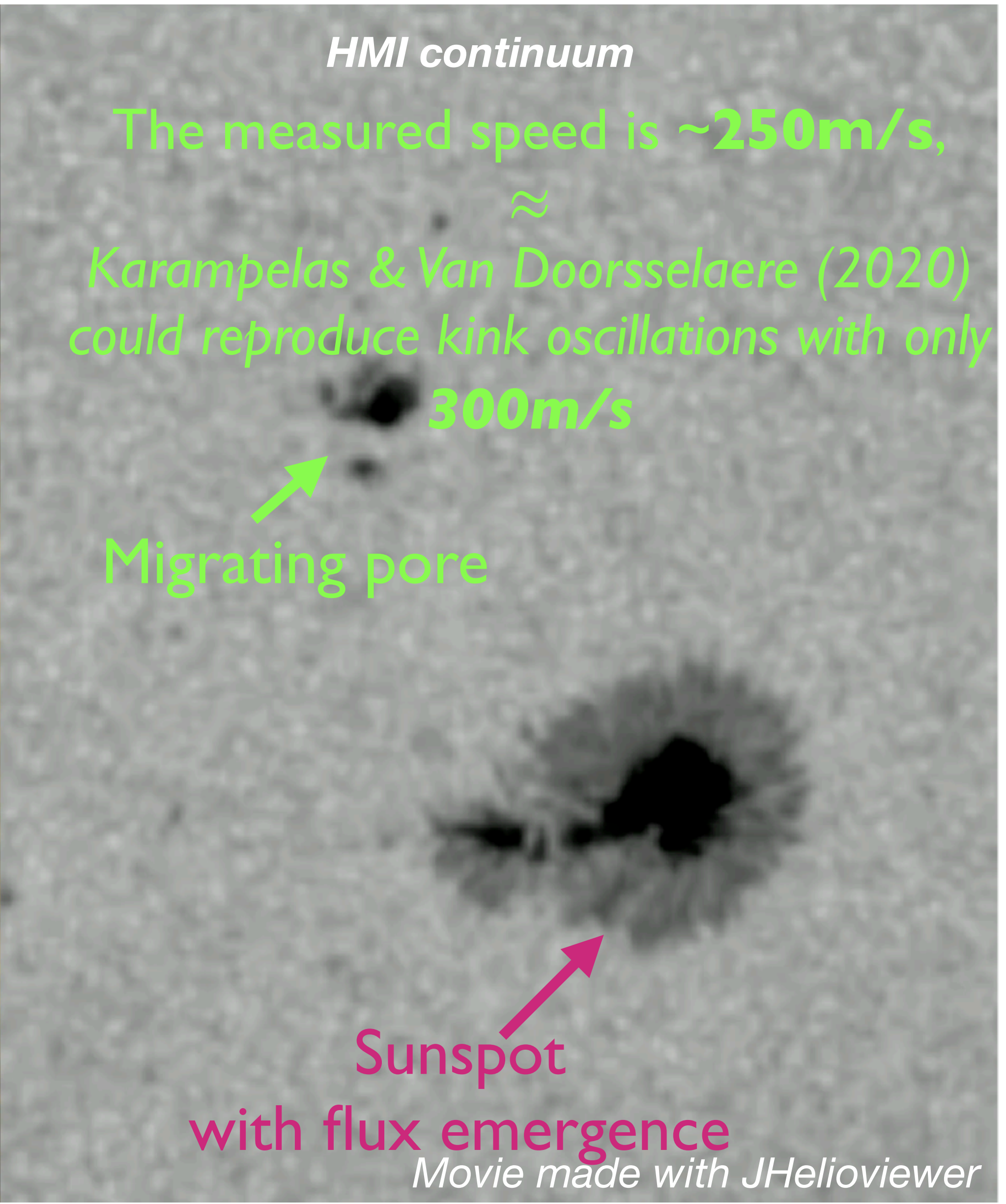
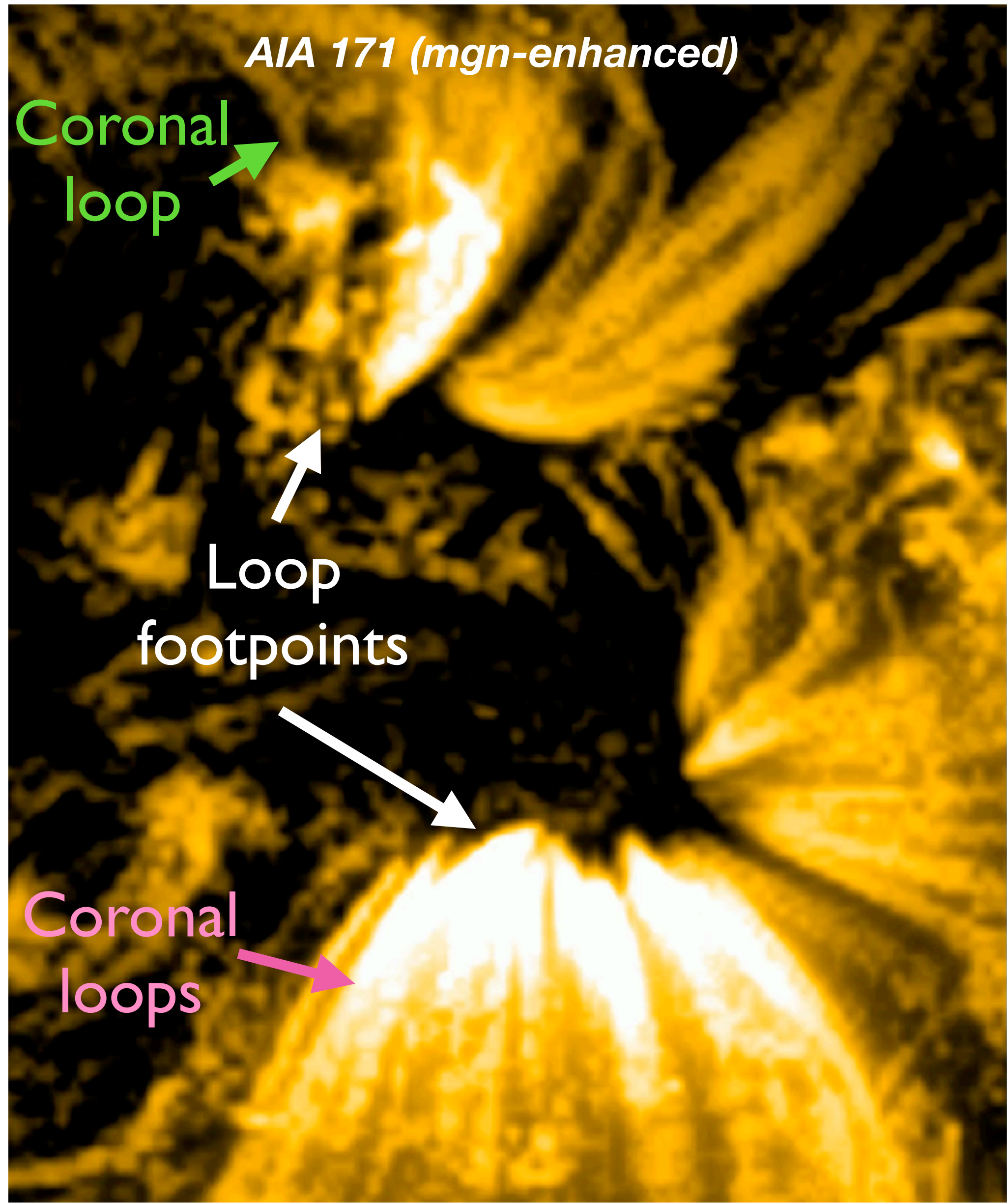


->
need multi-slit analysis

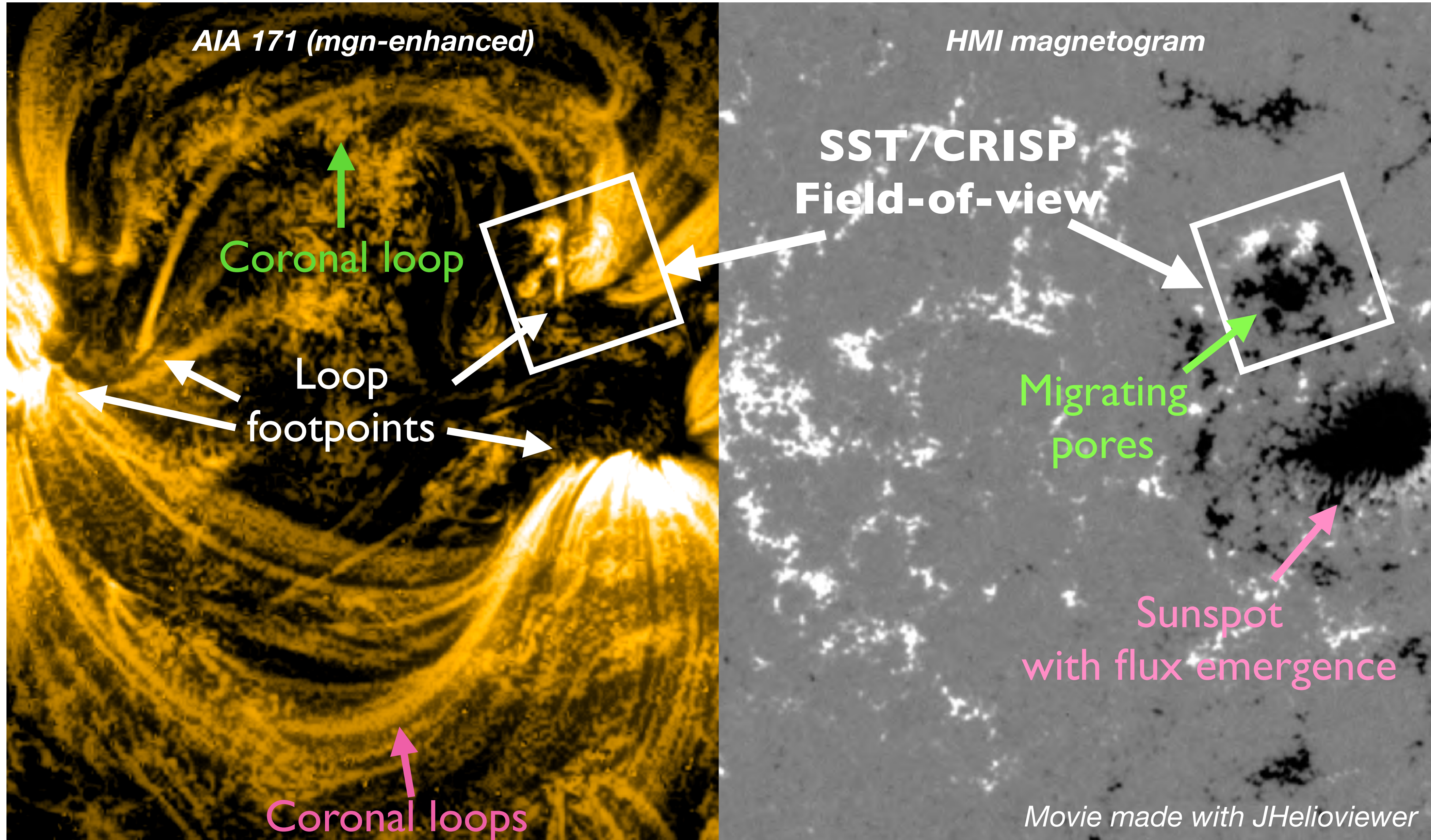


The perturbation amplitude and velocities allow to determine the energy of the kink modes
 -> fitting of the loop centers
 (e.g. using multi-gaussian fitting with MCMC ensemble sampler *emcee.py*)

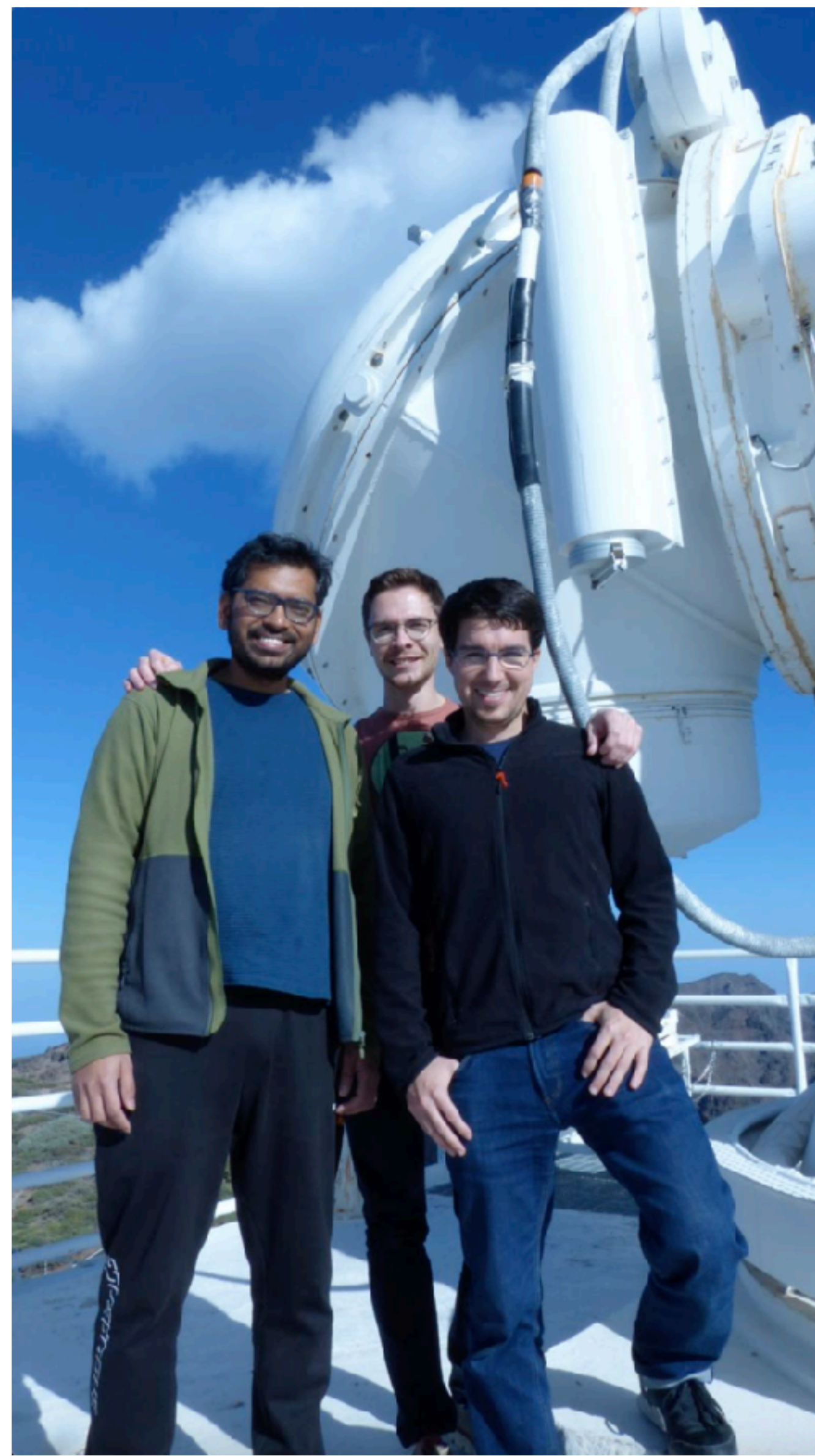
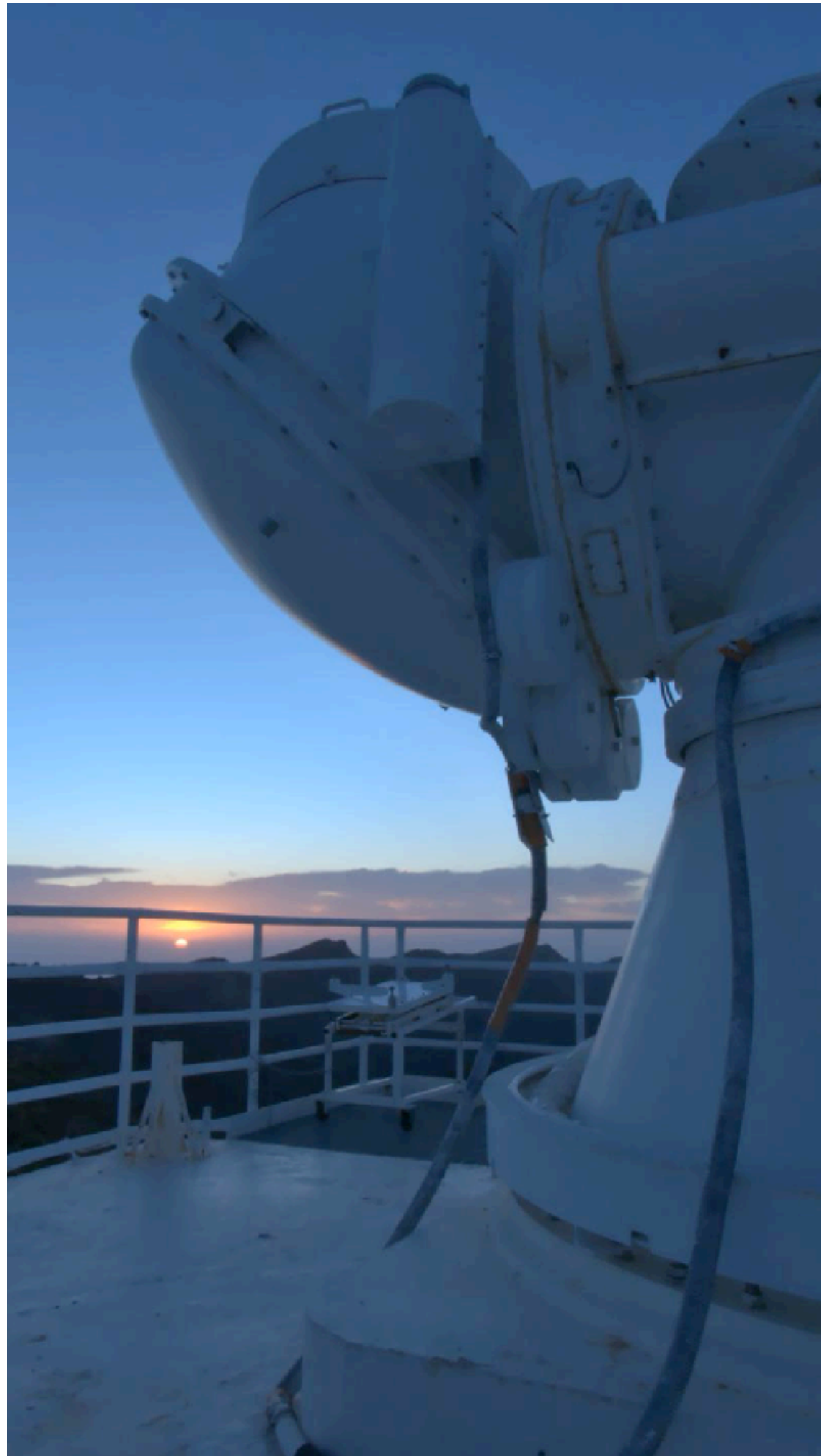
Can we observe the bow-on-a-violin model? *Interpretation*



Can we observe the bow-on-a-violin model? *Looking closer with the SST*



Can we observe the bow-on-a-violin model? *Observing at the SST*



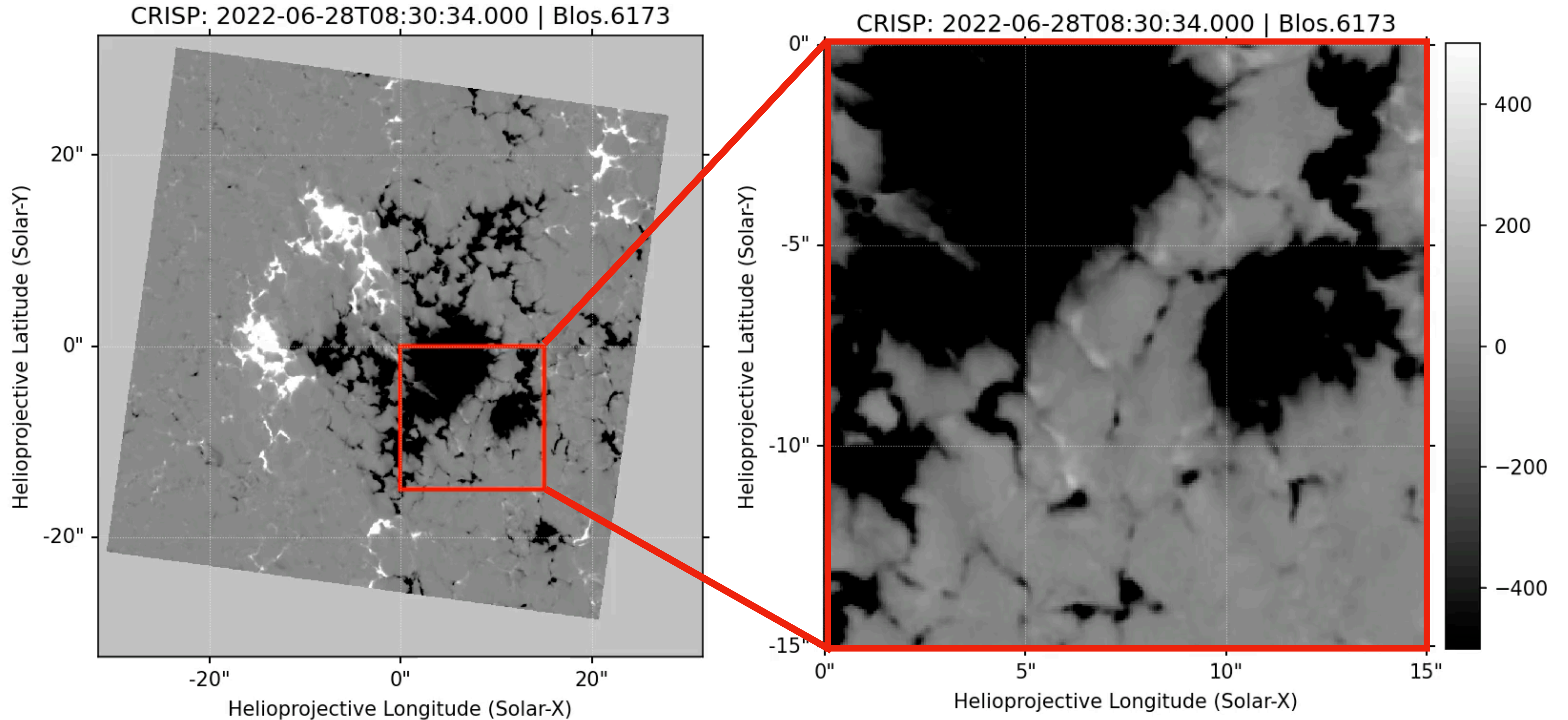
SST=Swedish 1-meter Solar Telescope
Location: La Palma, Canaries ~2400m

Aperture: 1m

**Spectro-polarimetric observations from photosphere to upper chromosphere:
H α , H β , Ca II h and k, Mg II, Fe I**

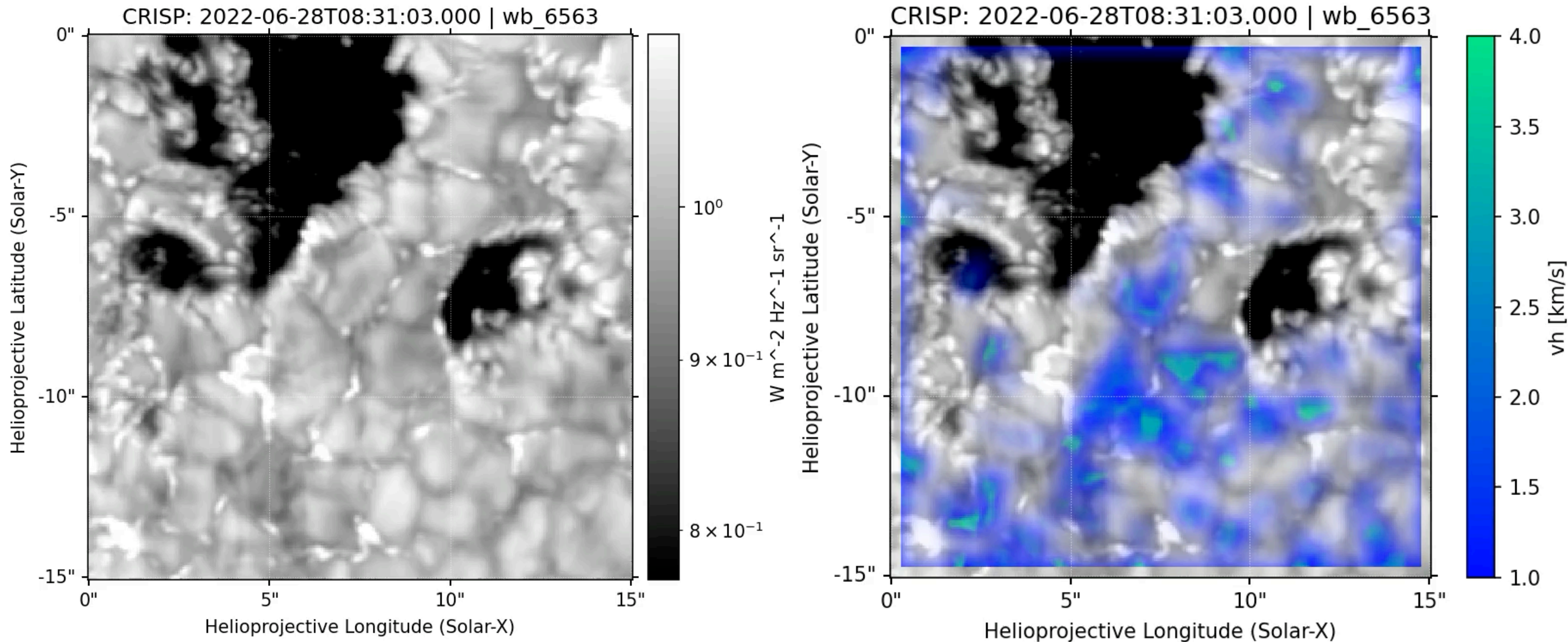


R ● C S
Can we test the bow-on-a-violin model? *Looking closer with the SST*



SST observations taken by: Luc Rouppe van der Voort, Reetika Joshi, Daniel Nobrega Siverio, Kilian Krikova & Ana Belen Grinon Marin

Can we observe the bow-on-a-violin model? *Looking closer with the SST*

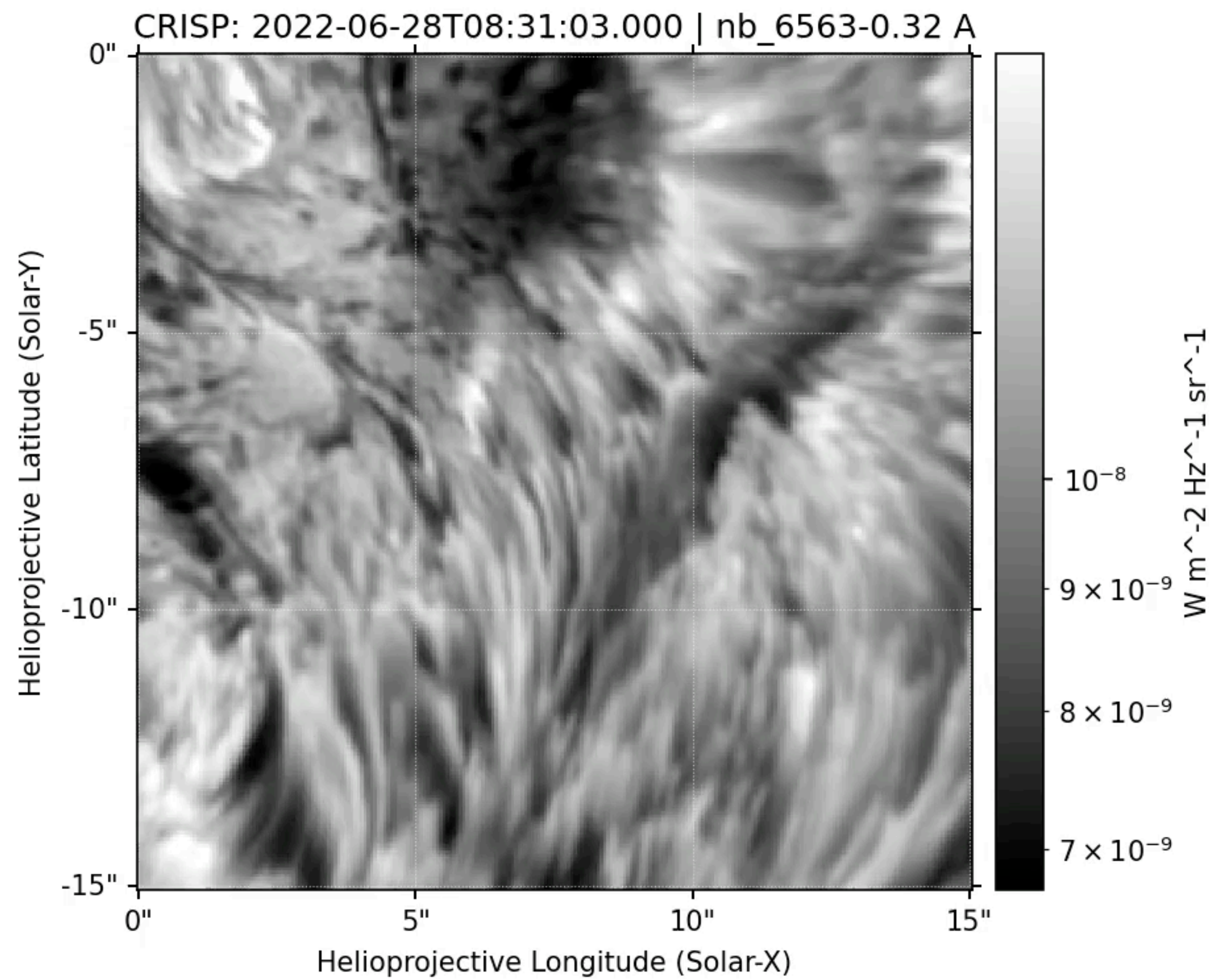
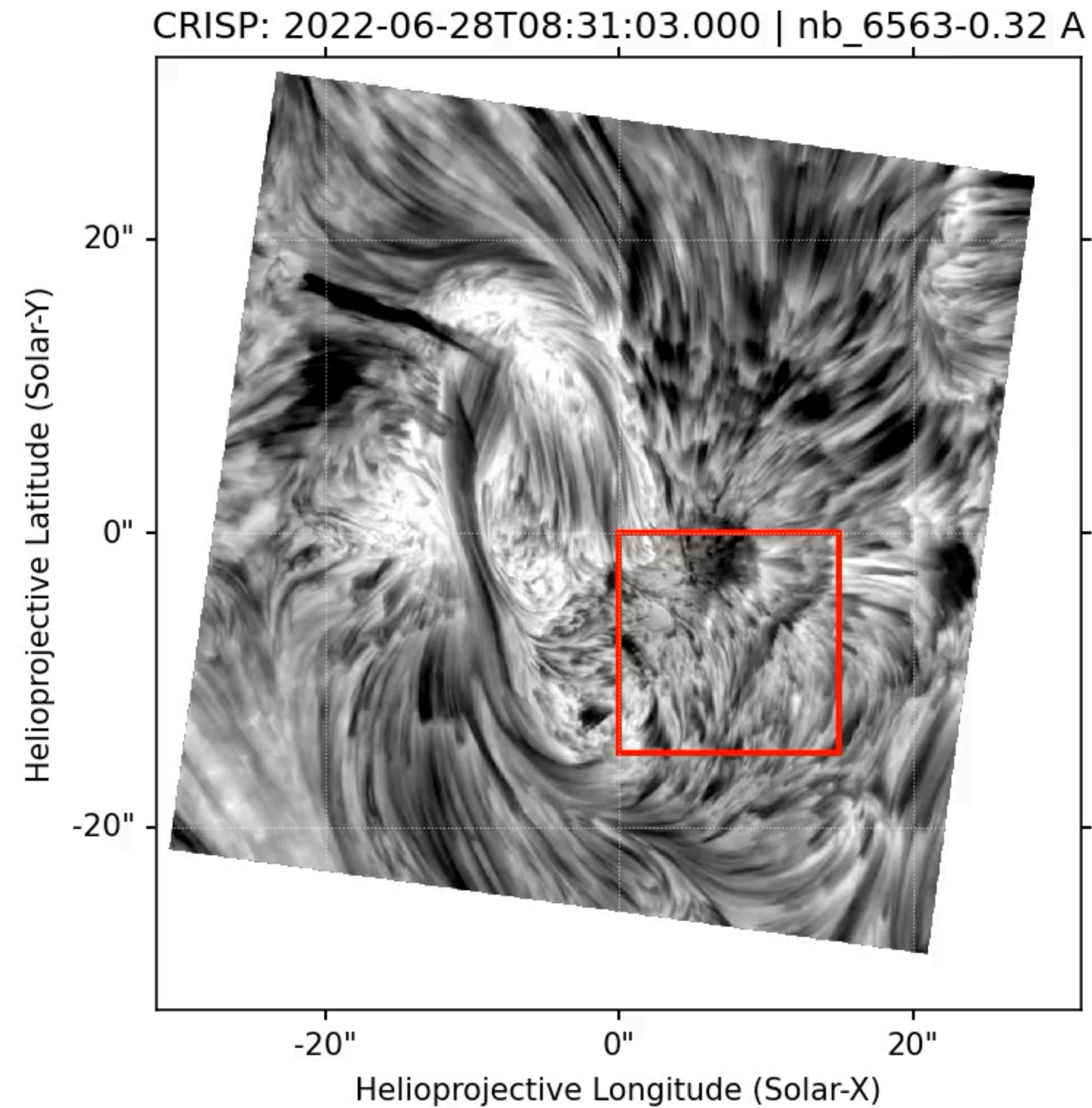


Continuum of the H α line
from SST/CRISP

+

Blue-green = horizontal velocities
Calculated with Local Correlation Tracking (fwhm=0.5", dt=10min)

Can we observe the bow-on-a-violin model? *Looking closer with the SST*



SST/CRISP H α line core

Conclusions

- **Decay-less transverse oscillations** in coronal loops are **ubiquitous**
- They can potentially contribute to the **heating of the quiet-corona**
- The **bow-on-a-violin** model is one of the most promising to drive them
- There is still no observational evidence to support this model

Next steps

- Make detailed magnetic field reconstruction using SST/CRISP and SDO/HMI
- **Look at chromospheric SST channels** (H α /beta & Ca II) + **spectral info**
- **Plan & exploit coordinated observations between SoI/O/EUI and SST**

Follow-up study: the Oct 12-20 SolO/SST coordination

