Large-scale EUV Waves in the Solar Corona and Their Diagnostic Implications

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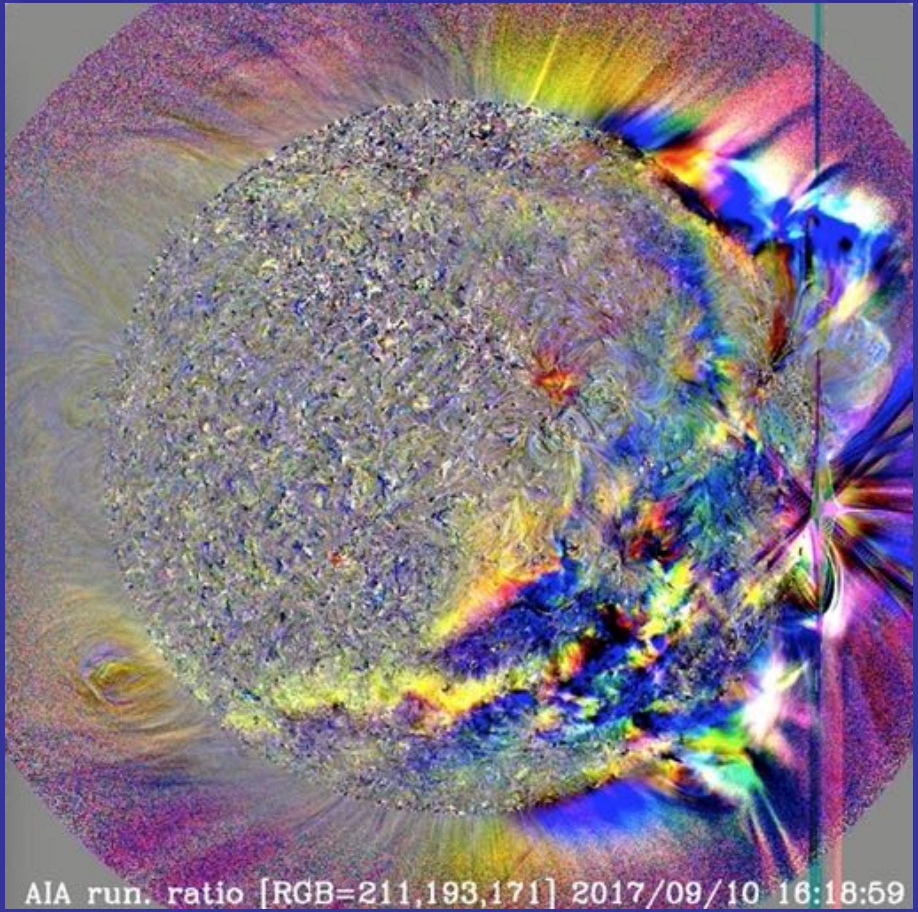
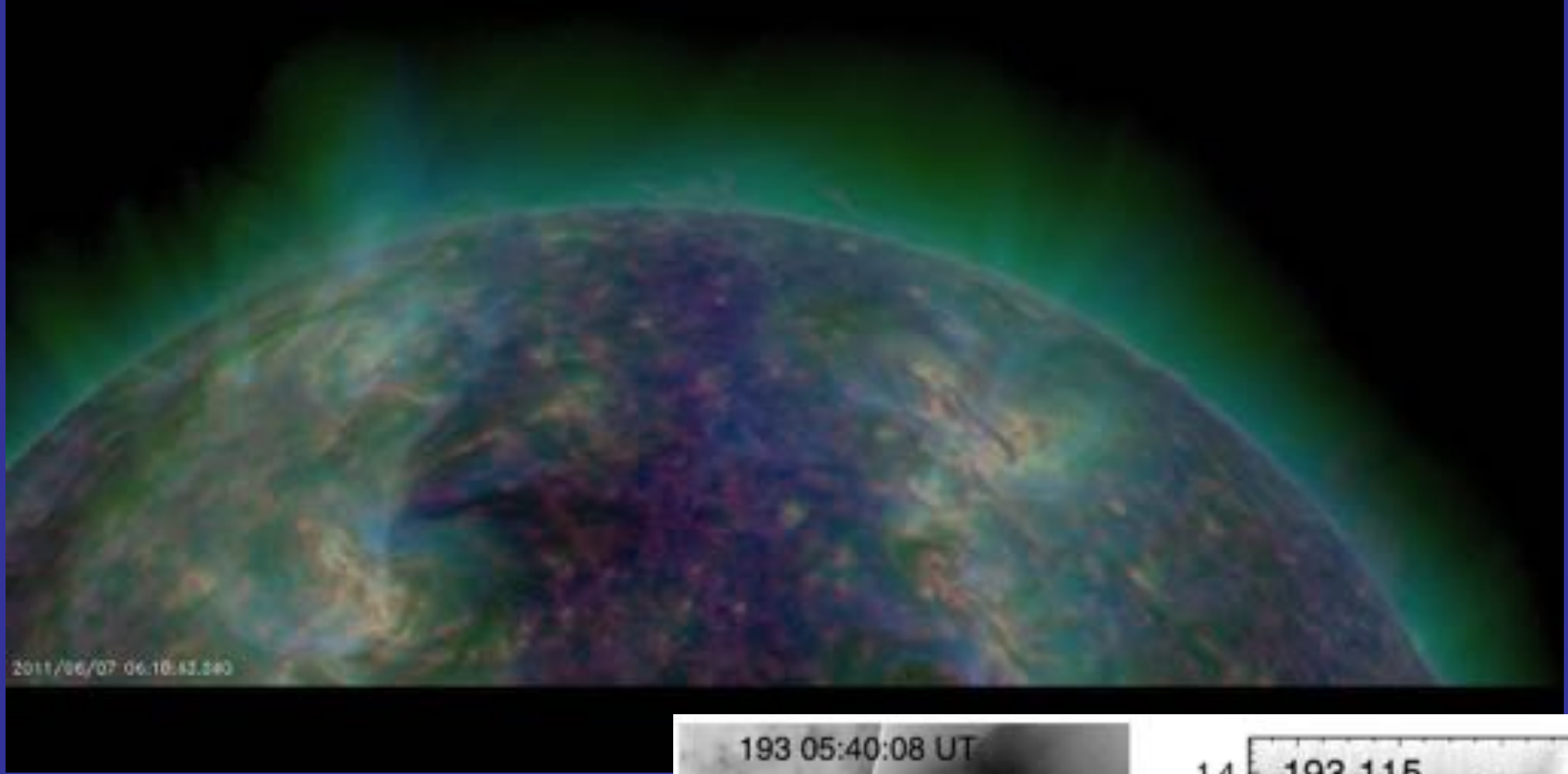
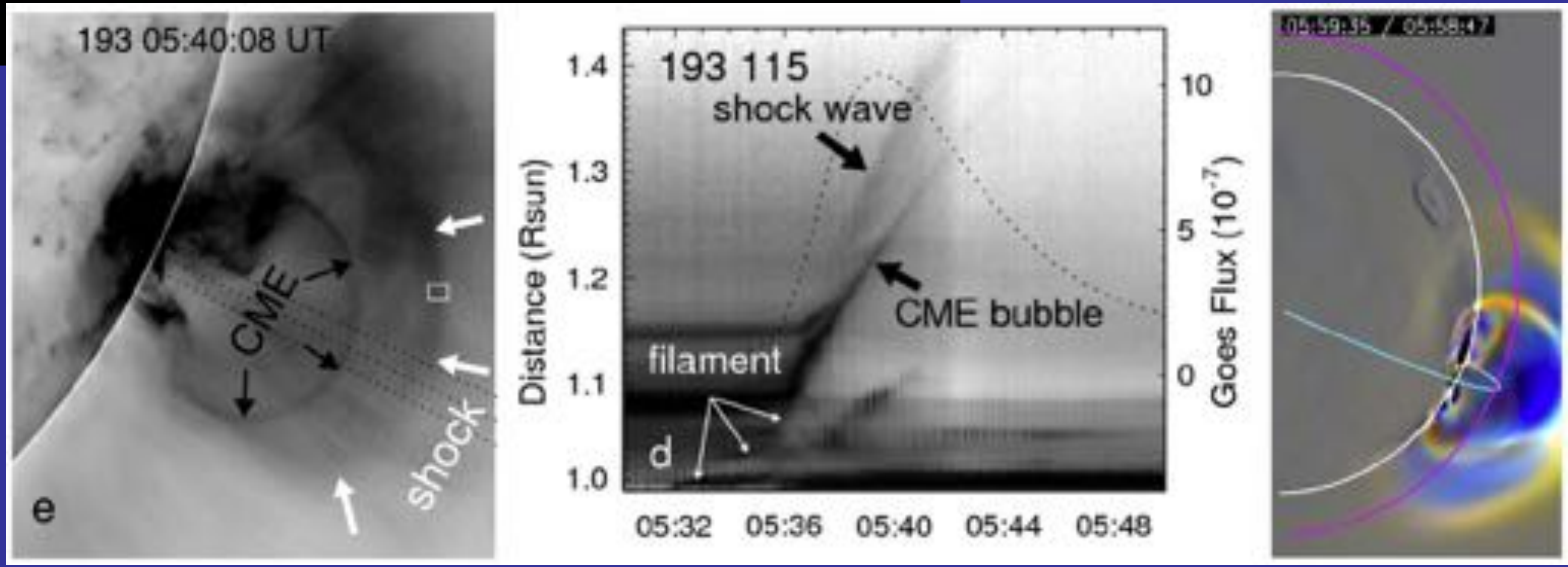




1. Global EUV (EIT) waves

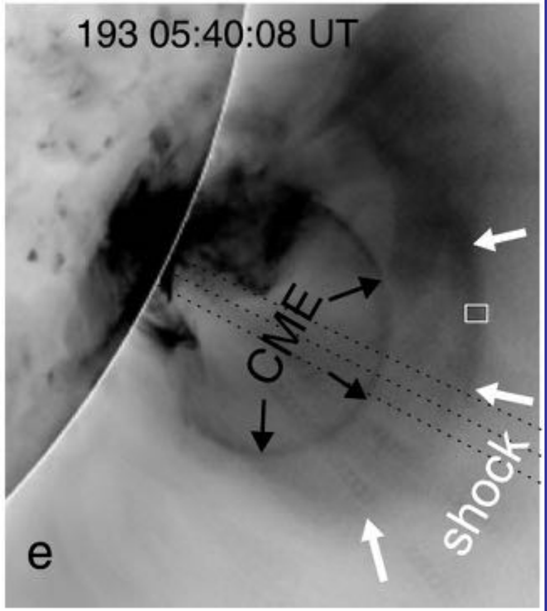
After a 15-year debate, an established picture of two-component composition (e.g., Liu & Ofman 2014; Long+2016):

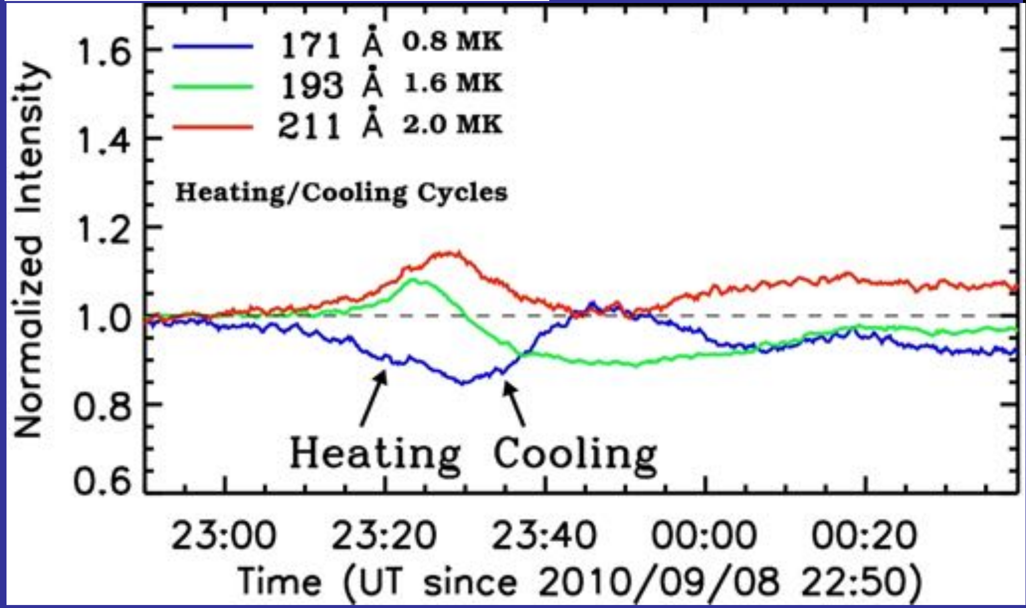
- Leading component: A true fast-mode magnetosonic (sometimes shock) wave – coronal seismology
- Trailing component: CME expansion front

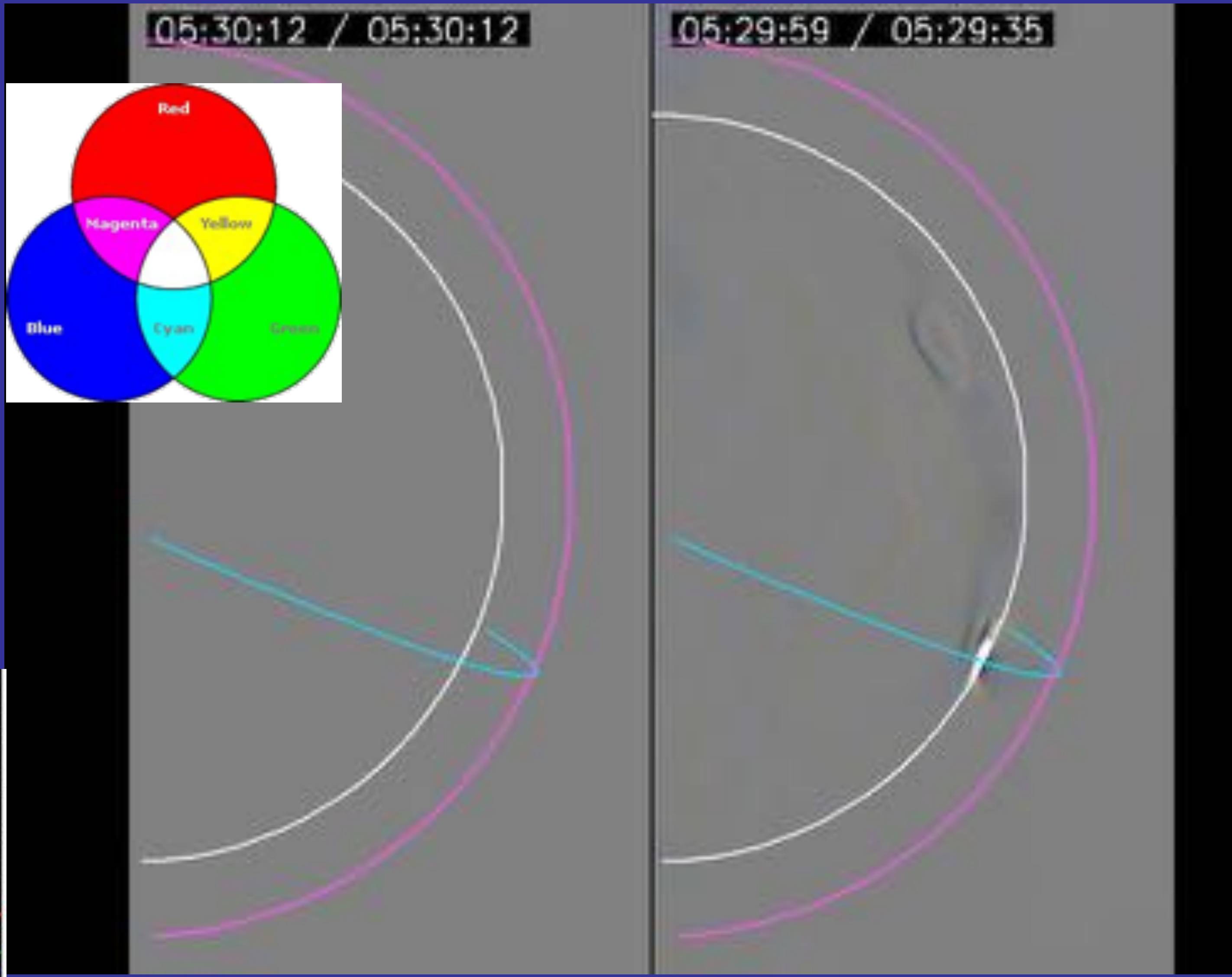


Ma et al. (2011) (also Kozarev et al. 2011; Gopalswamy et al. 2012); Downs et al. (2012)

Thermal seismology –
EUV channels' *temperature* sensitivity



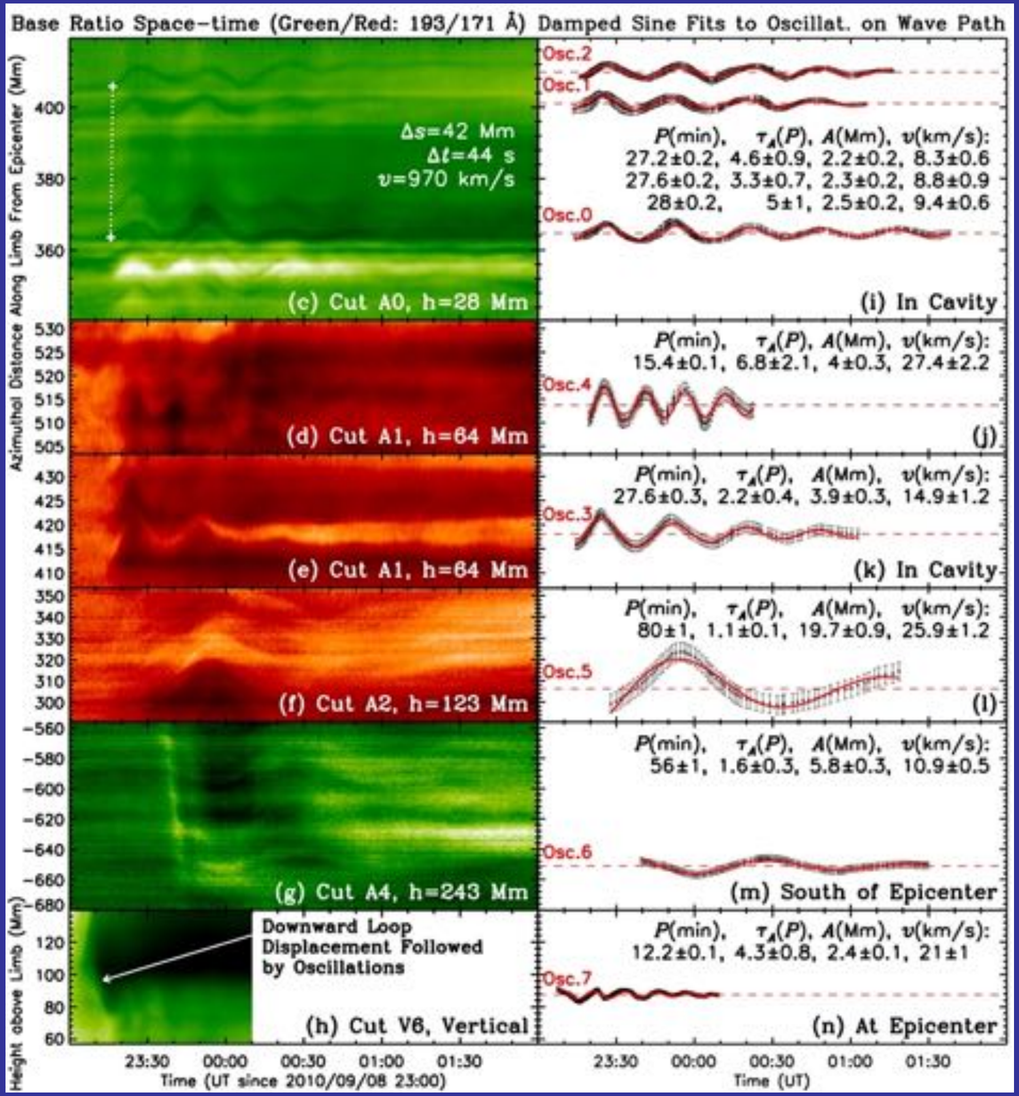


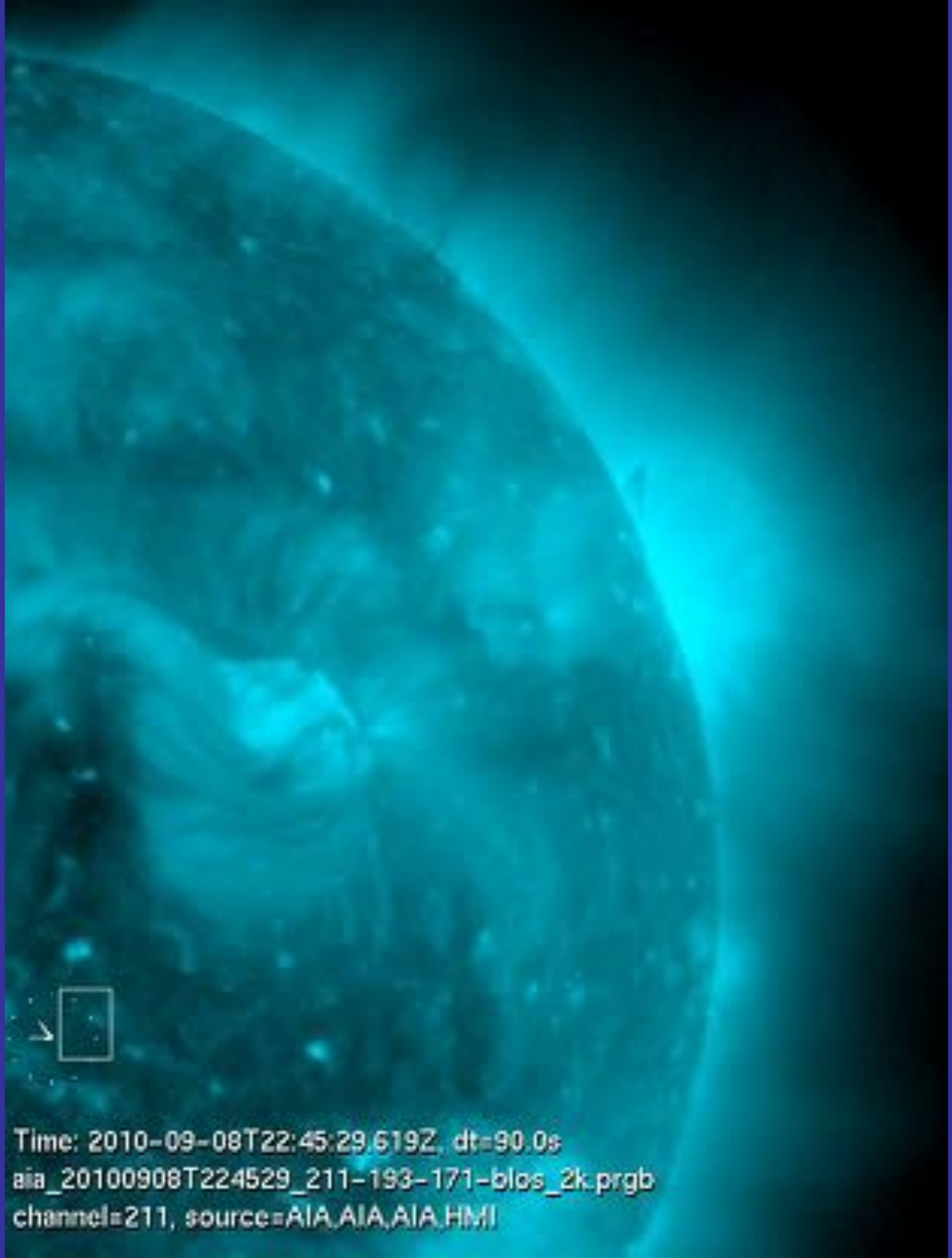


(Ma+ 2011; Downs+ 2012; Liu+ 2010, 2012;)

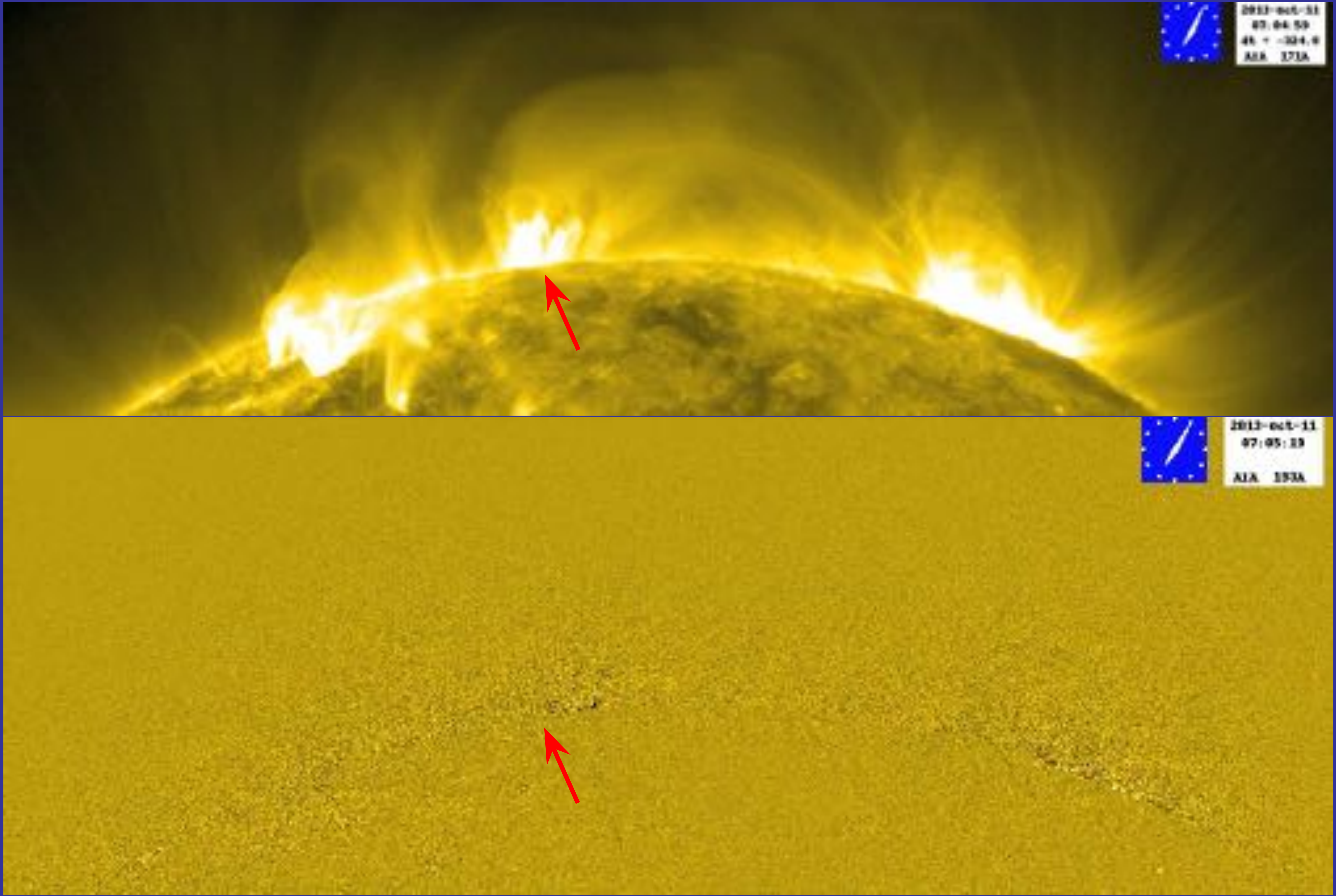
Oscillations triggered by EUV waves

- A global wave (solar Tsunami) instigated oscillations of local coronal structures on its path,
- Broad range of period (e.g., 12 – 80 min.), amplitudes, damping times – seismological tools (Liu et al. 2012, 2014)

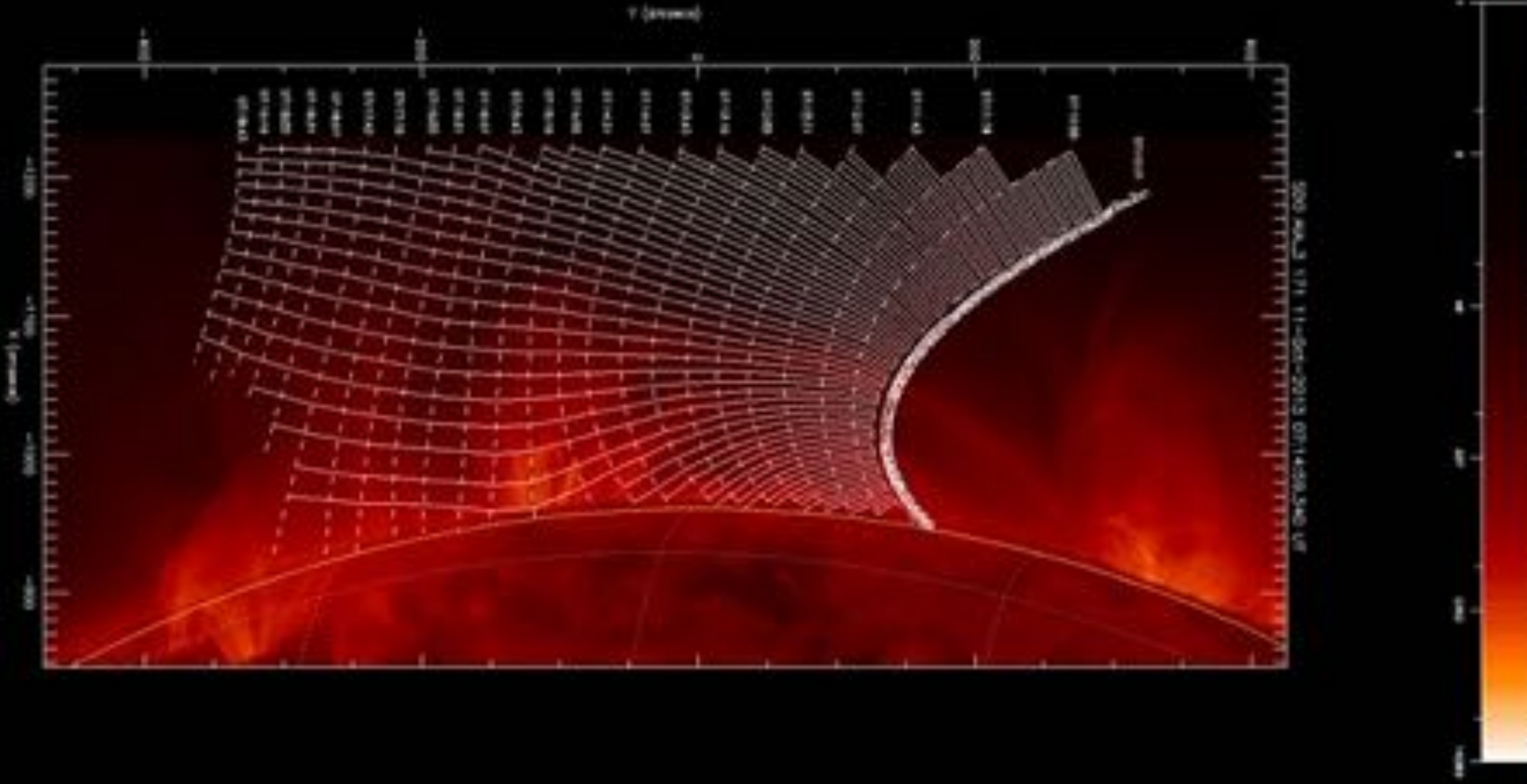




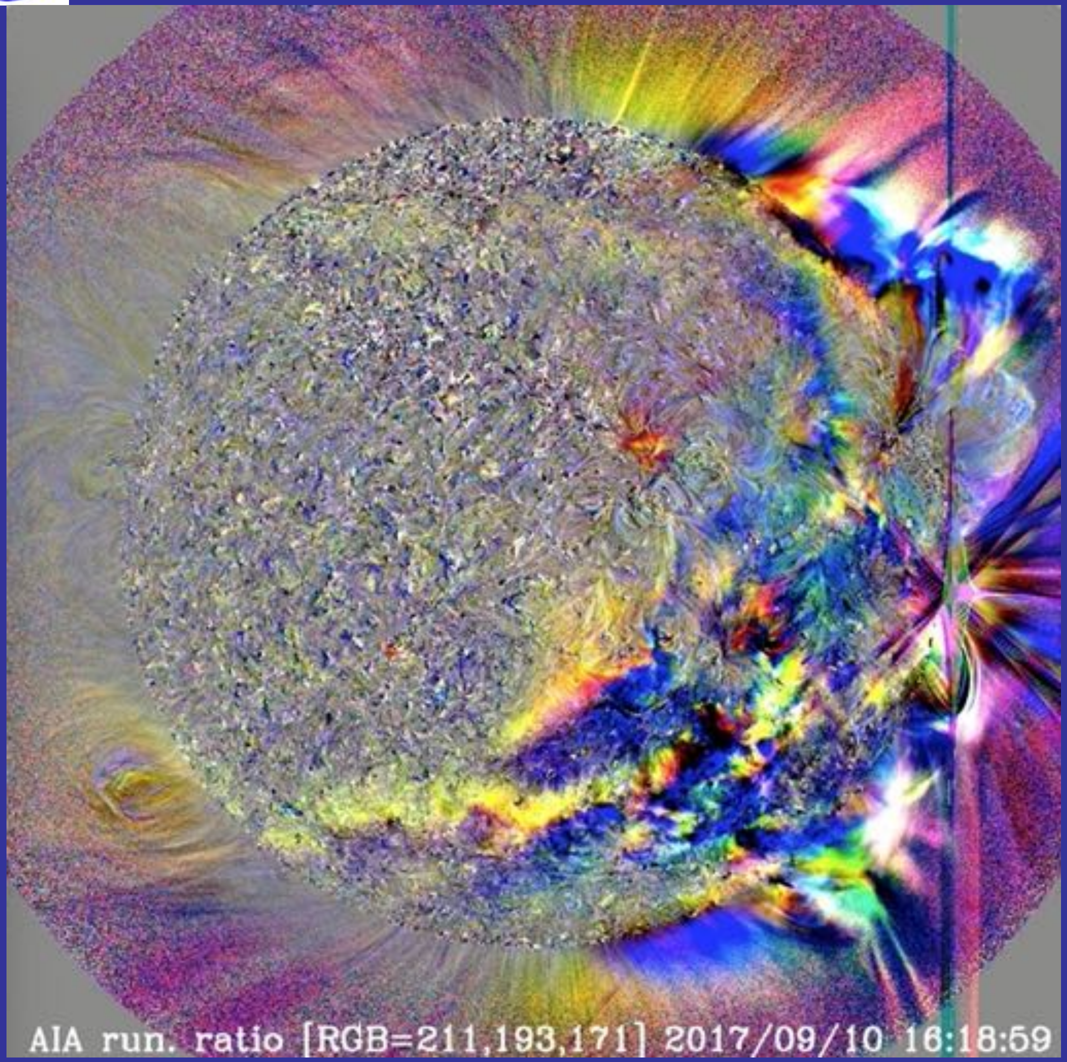
EUV wave refraction from a remote active region

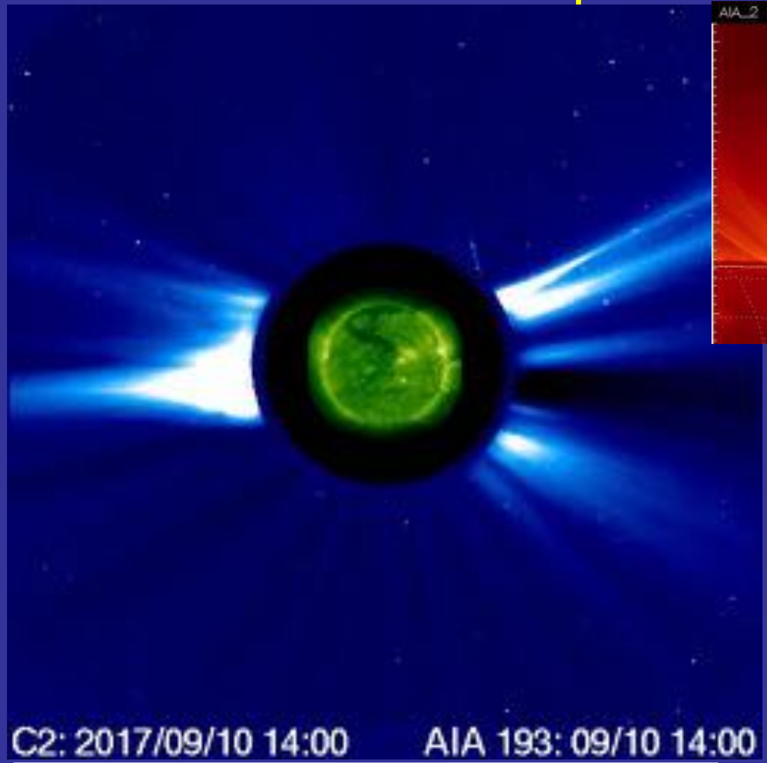


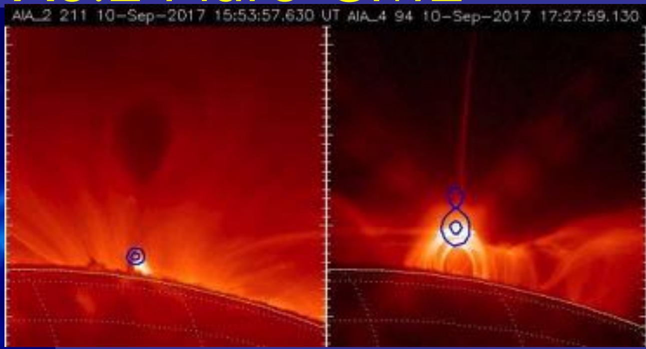
History of wave fronts => wave paths (*Huygens Principle*) => map of fast-mode speeds => map of magnetic field strengths

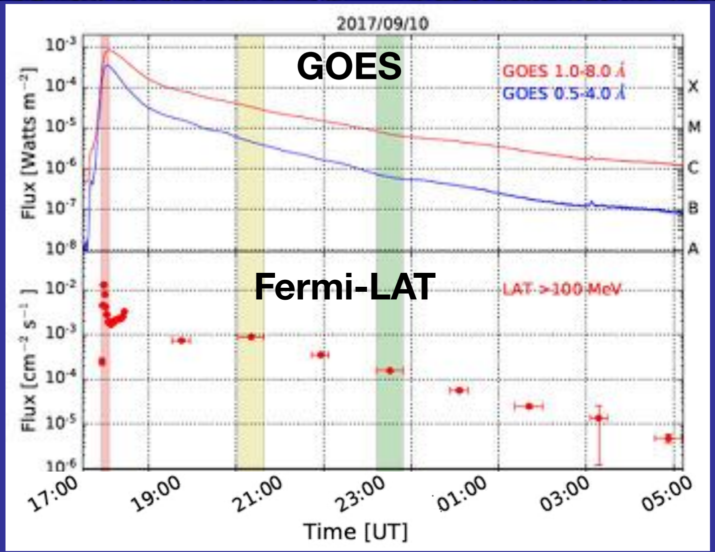


2. Case Study: A Truly Global EUV Wave from the 2017-Sep-10 X8.2 Flare-CME







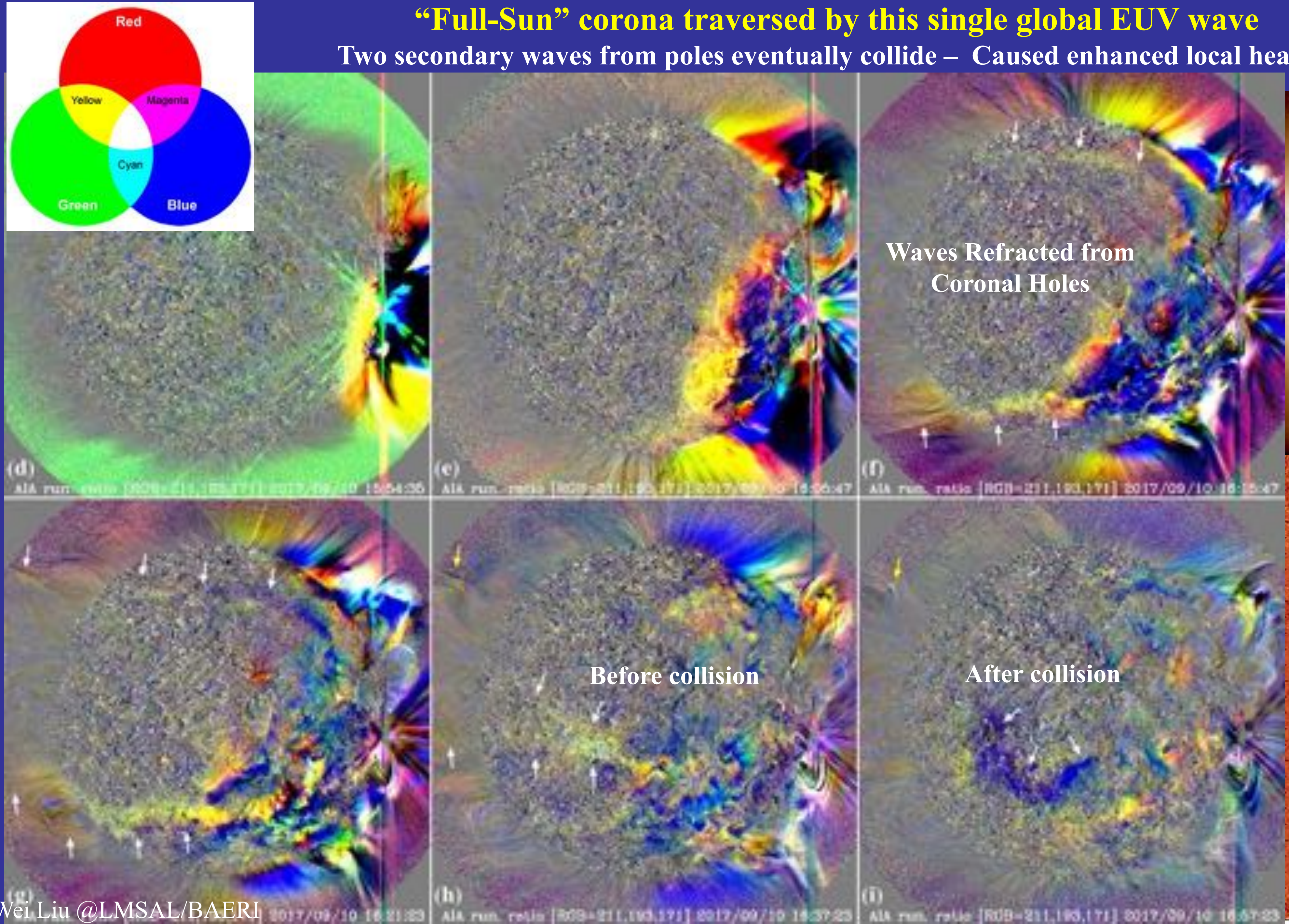


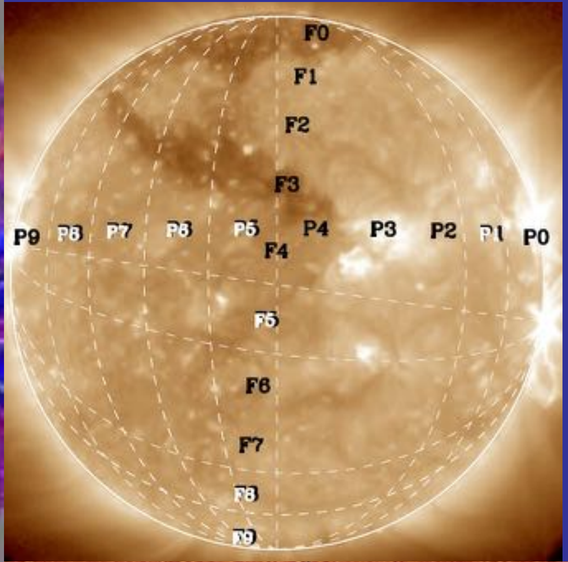
(Liu et al. 2018; Omodei et al. 2018)

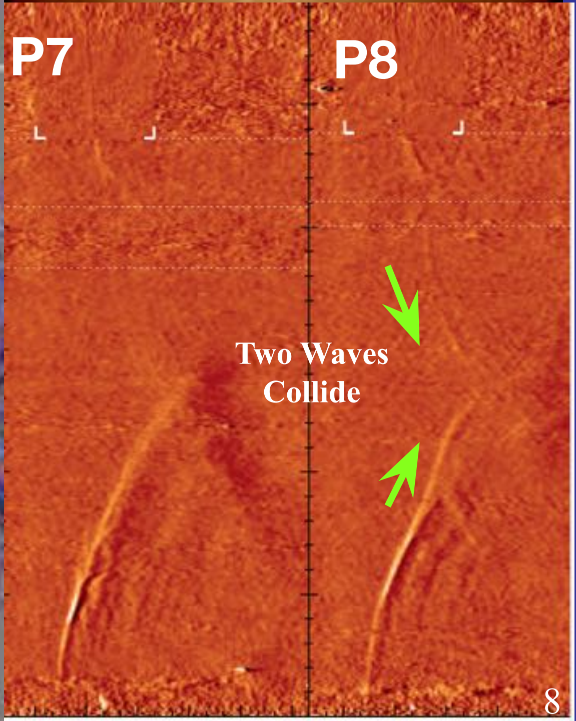
- **Produced a spectacular global EUV wave that transversed the *entire visible solar disk and off-limb circumference* (cf., Seaton+2018; Podladchikova+2018)**
- **A CME with speed > 3000 km/s, one of the fastest ever recorded.**
- **Solar Energetic Particles (SEPs) and Ground Level Enhancement (GLE) events at Earth (& Mars; Mishev+2018; Guo+2018).**
- ***Fermi-LAT* observed long-duration gamma-rays over 12 hours (Omodei+2018); EOVSA microwaves (Gary+2018); LOFAR (Morosan+2018)**

"Full-Sun" corona traversed by this single global EUV wave

Two secondary waves from poles eventually collide – Caused enhanced local heating



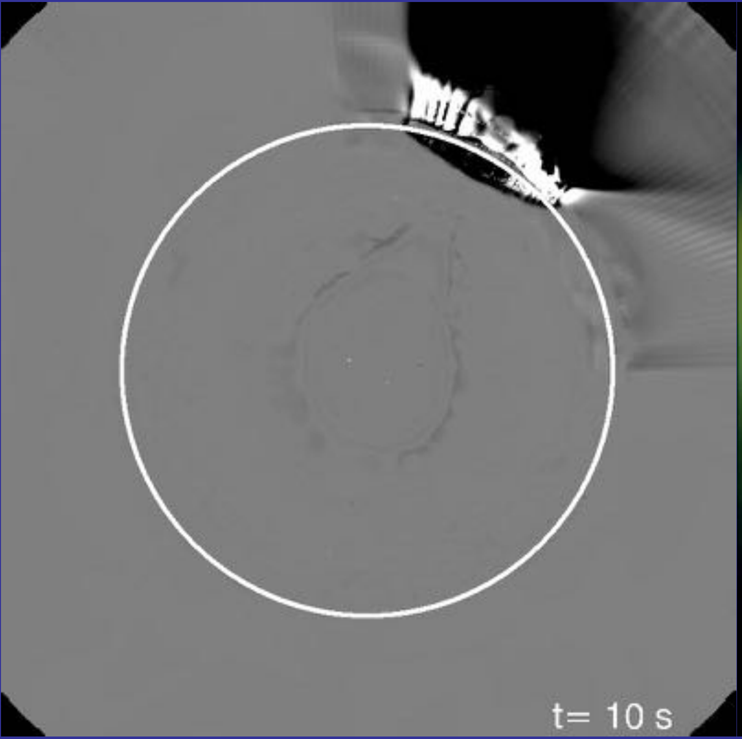


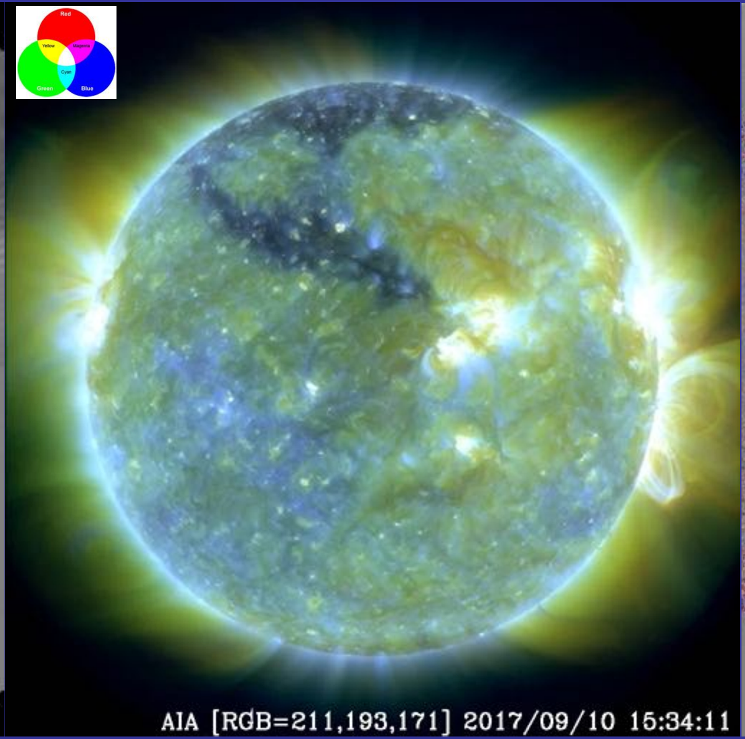


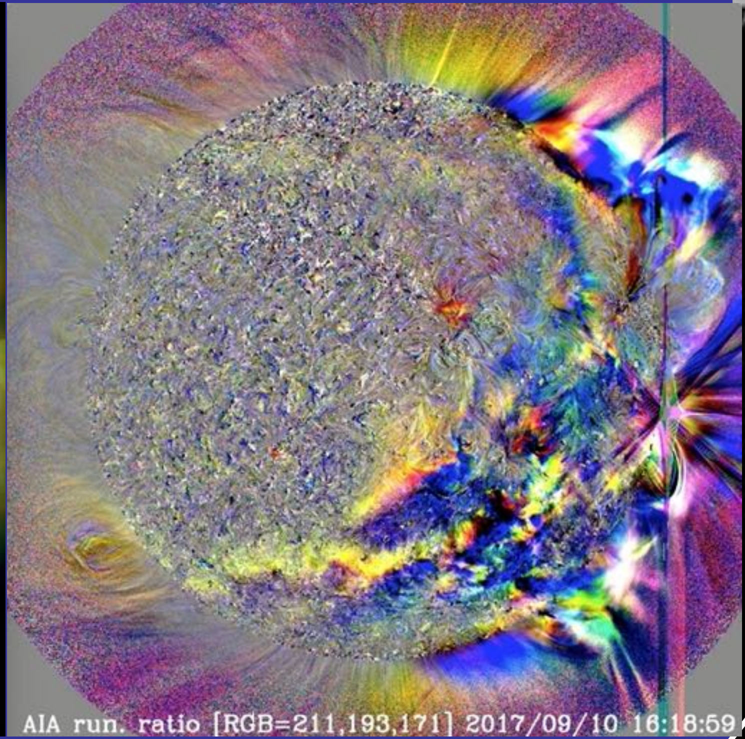
EUV Waves in the Polar Coronal Hole

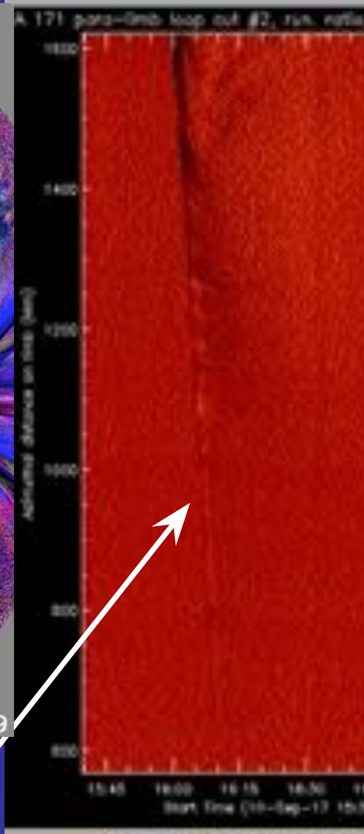
Synthetic 211 A from MHD simulation, top-down view from the South Pole of the Sun

Earth-view Observation of the EUV wave: 1) original, 2) running ratio, 3) response of Polar Plumes in space-time plot







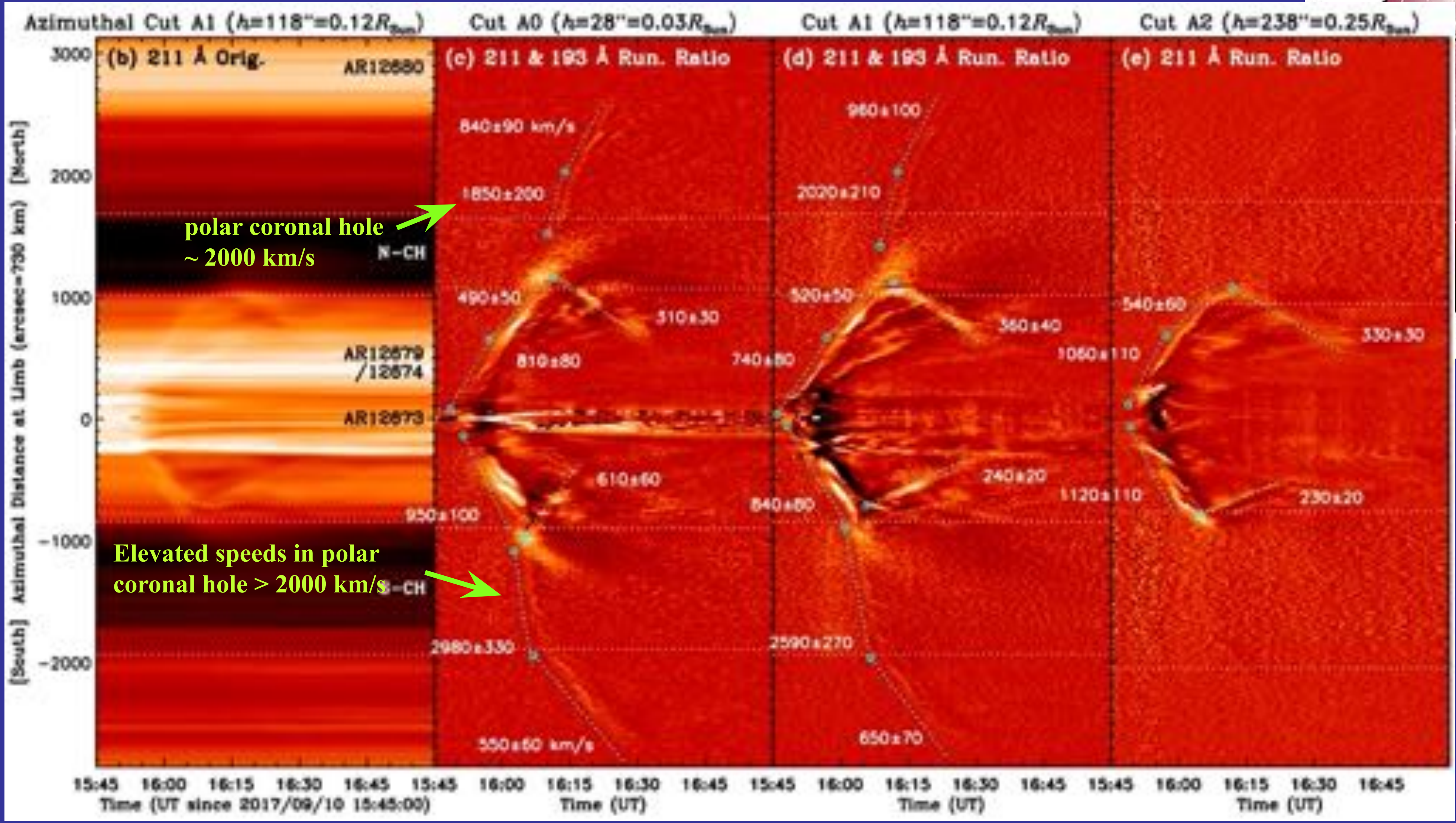


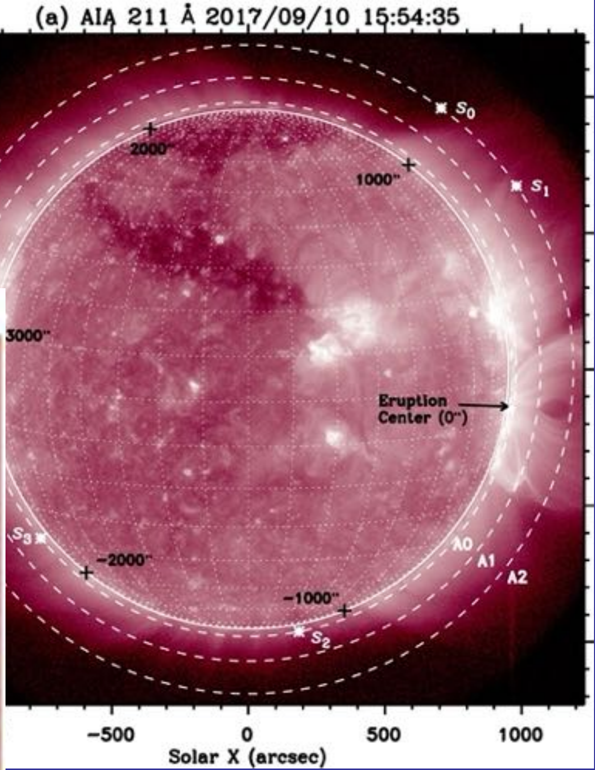
Polar plumes displaced by wave arrival

- **Simulation: EUV waves propagating into both the northern and southern polar coronal holes, then refracted out of them, each CH serving as a new "Radiation Center" for the refracted waves (cf., Schmidt & Ofman 2010; Afanasyev & Zhukov 2018)**
- **Observation: sequential displacement of polar plumes as short feather like patterns, upon the arrival of the wave front.**

Azimuthal cuts: Wave front kinematics – warm channels (211/193 A)

- Both Reflection at and Transmission into polar coronal holes (CHs)
- Significantly elevated speeds inside CHs, as expected b/c of higher Alfven and fast-mode magnetosonic speeds there.



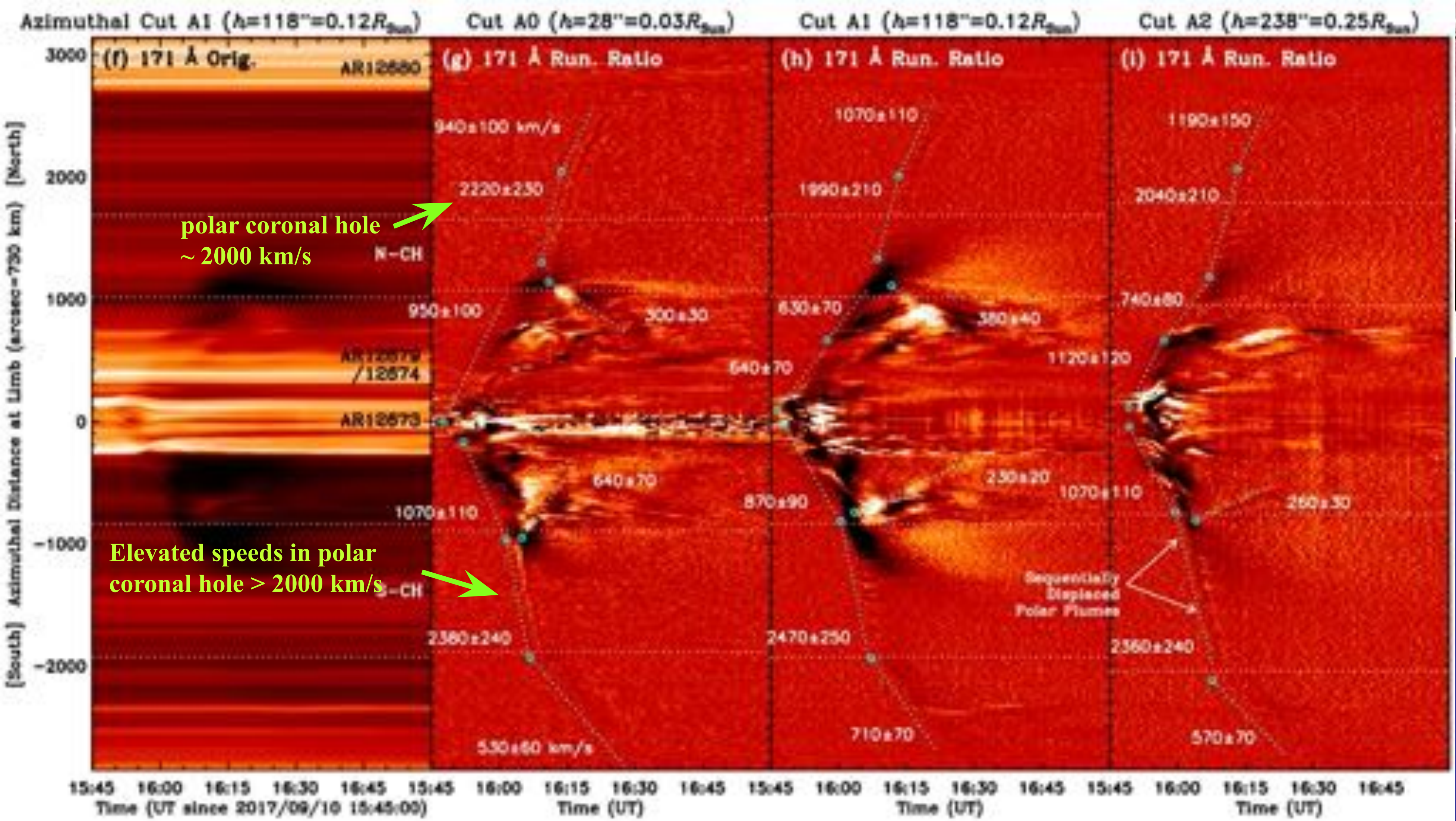


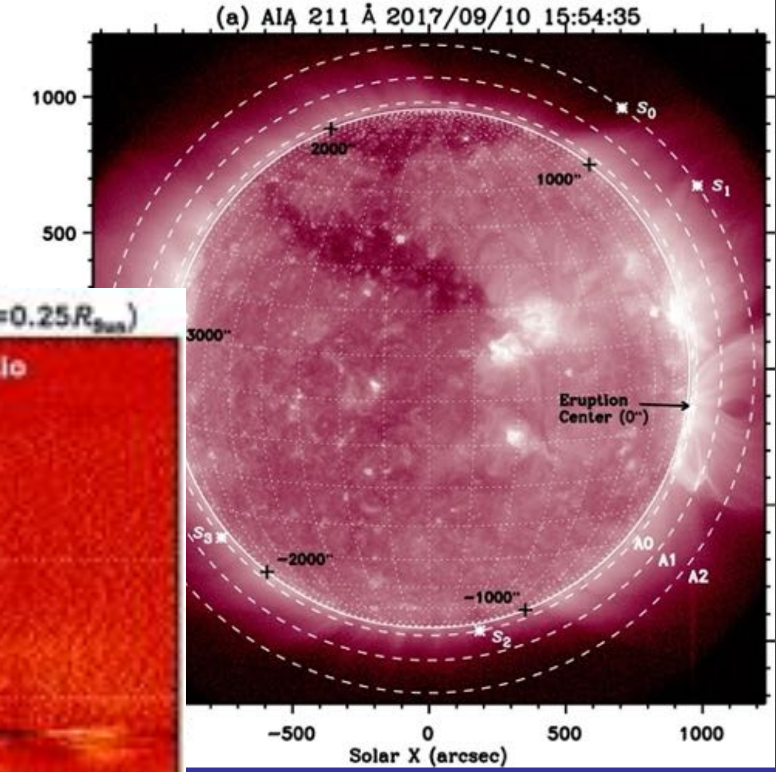
Time-slice from the off-limb Azimuthal Cuts.

Distance measured from flare in CCW direction, then mapped onto the limb.

Azimuthal cuts: Wave front kinematics – cool channels (171 A)

- Both Reflection at and Transmission into polar coronal holes (CHs)
- Significantly elevated speeds inside CHs, as expected b/c of higher Alfven and fast-mode magnetosonic speeds there.



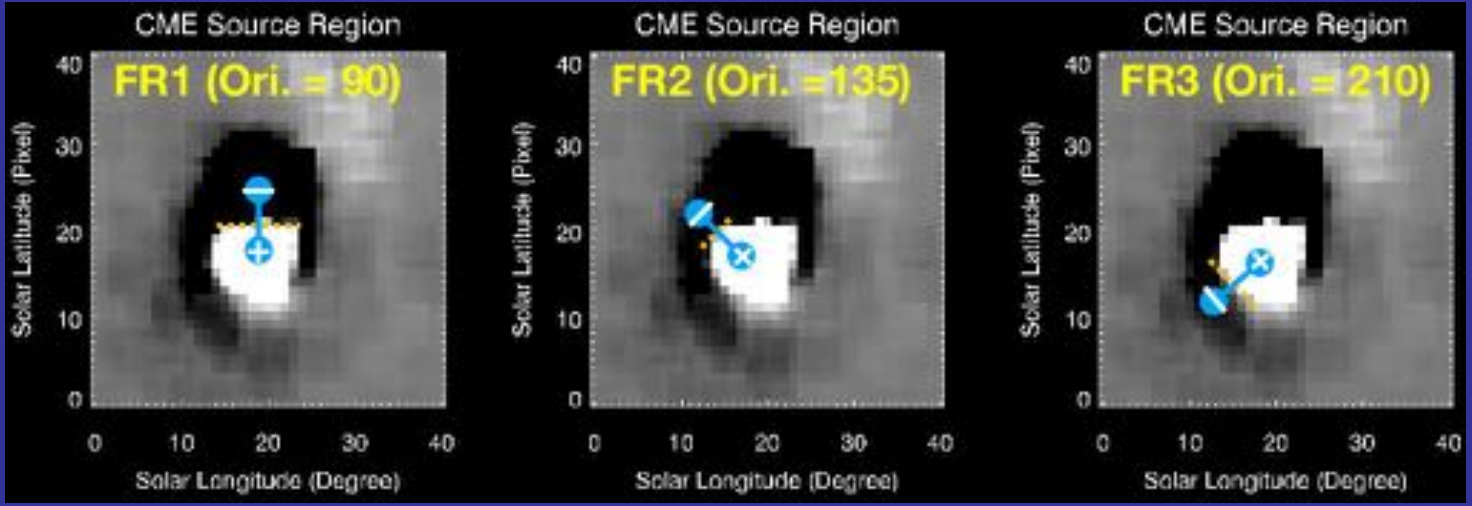


Time-slice from the off-limb Azimuthal Cuts.

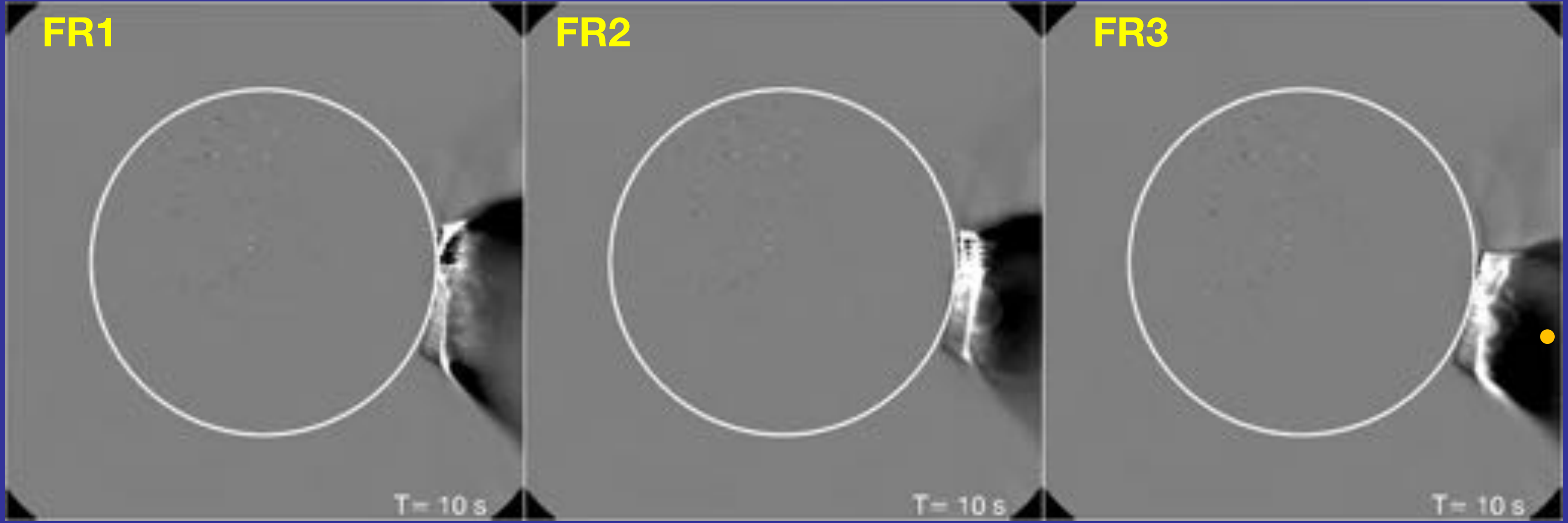
Distance measured from flare in CCW direction, then mapped onto the limb.

Gibson-Low Flux Rope Simulation

(Jin, M. et al. in prep. Using Univ. of Michigan AWSoM model)

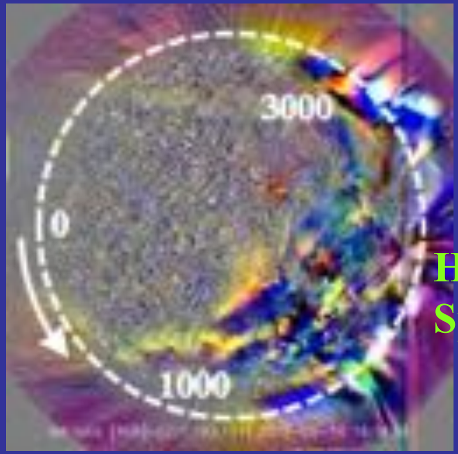


Synthetic AIA 211 Running Difference Movie



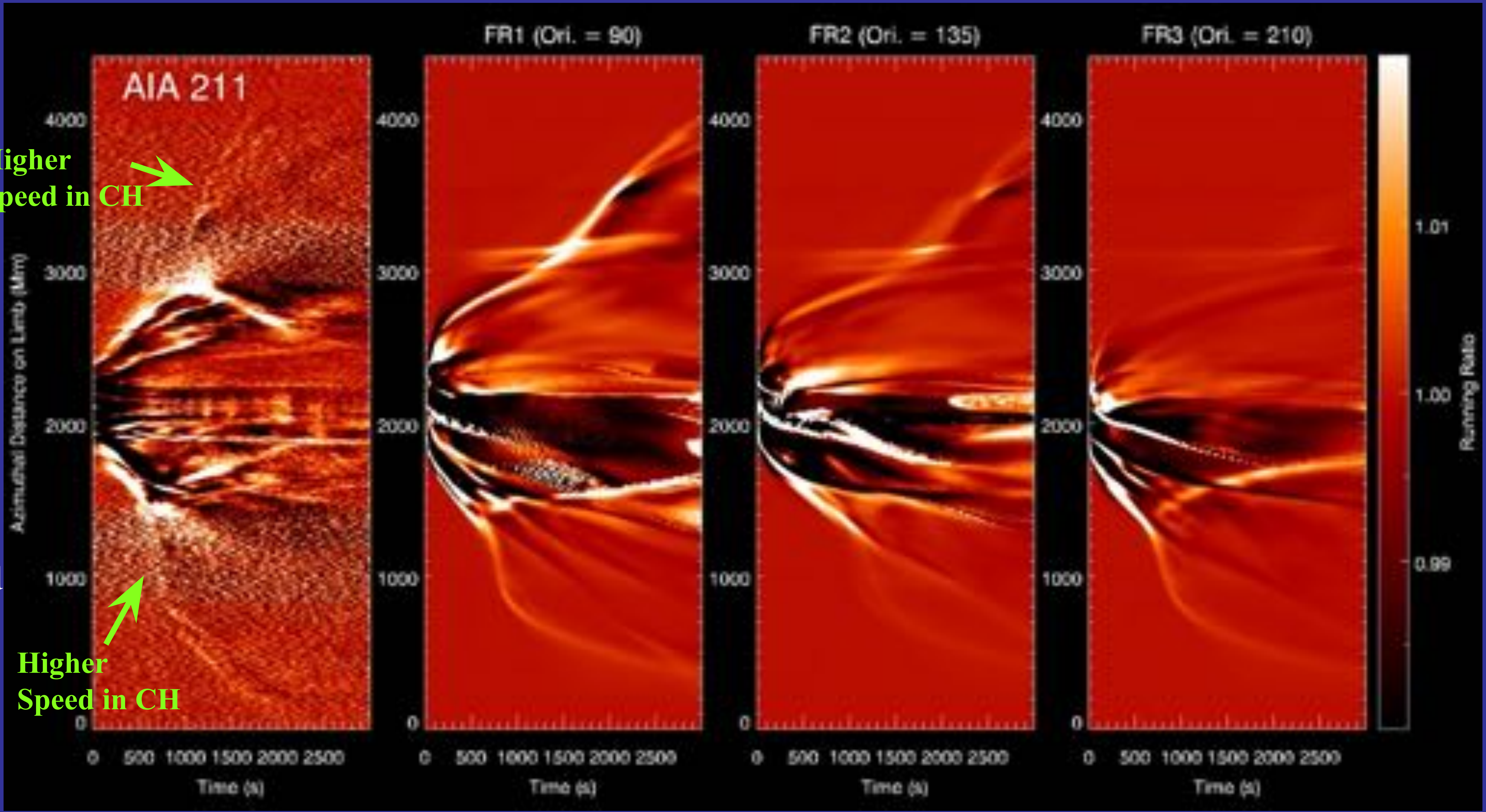
- 2017 September 10 event occurred at the **west limb**. Without direct observation of the source region; it is uncertain which **PIL** the eruption was initiated from.
- Based on the magnetic field configuration of the source region, we initiate CMEs from three **PILs** with different flux rope orientations.
- **The resulting EUV waves show different characteristics.**

Observation: **Three MHD Simulation Cases:**



Time-slice from the Off-limb Azimuthal Cut A1

Distance measured from origin in CCW direction, then mapped onto the limb.

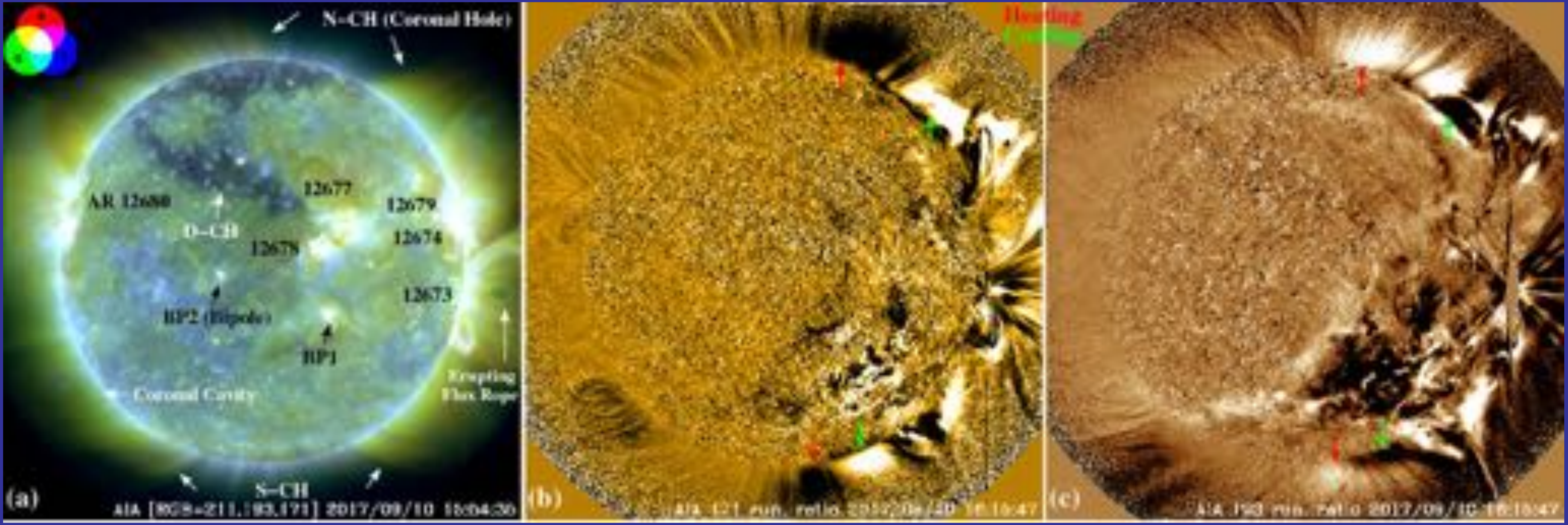


- **With different flux rope orientations, the EUV waves show different features among three cases.**
- **In general, the flux rope with 90° orientation best reproduces observations.**

Thermal Effects

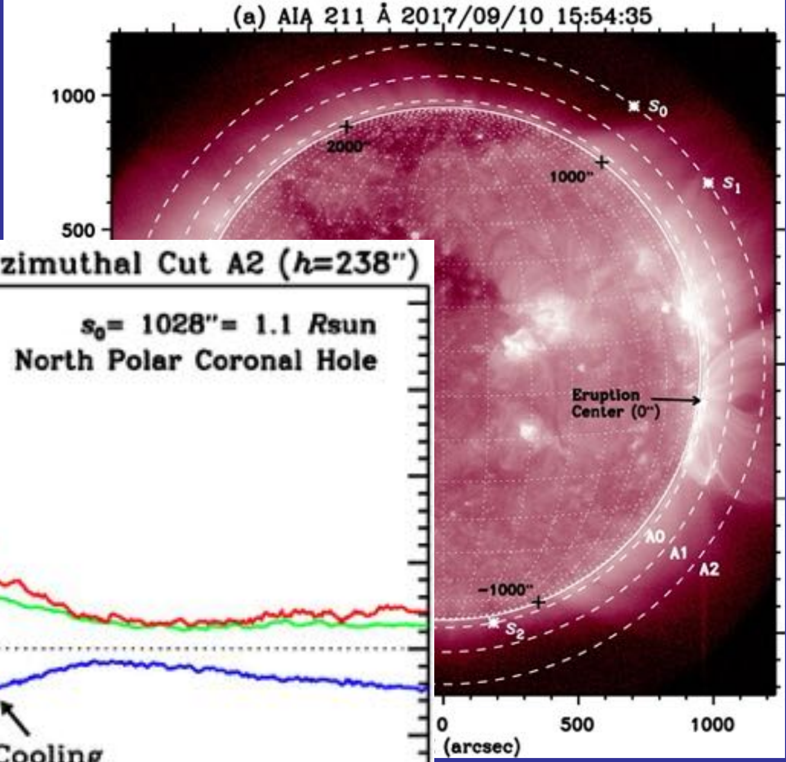
- Significant plasma heating (followed by cooling) due to wave compression (followed by rarefaction);
- anti-correlated EUV intensity changes between cool (171 A) and warm (193 & 211 A) channels

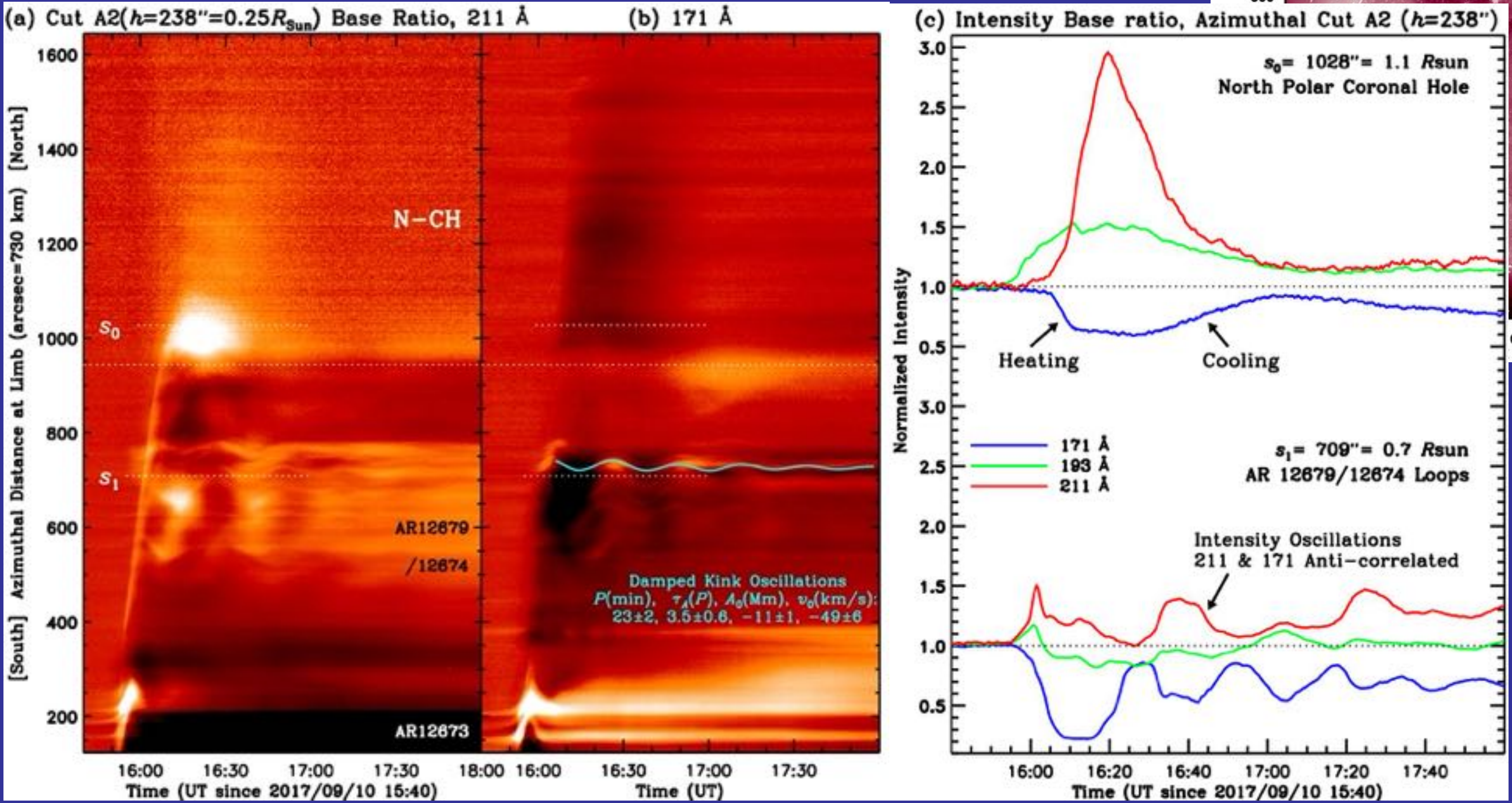
Tri-color: 211R / 193G / 171B **171 running ratio** **193 running ratio**



Thermal Effects & Perturbations to Local Plasma

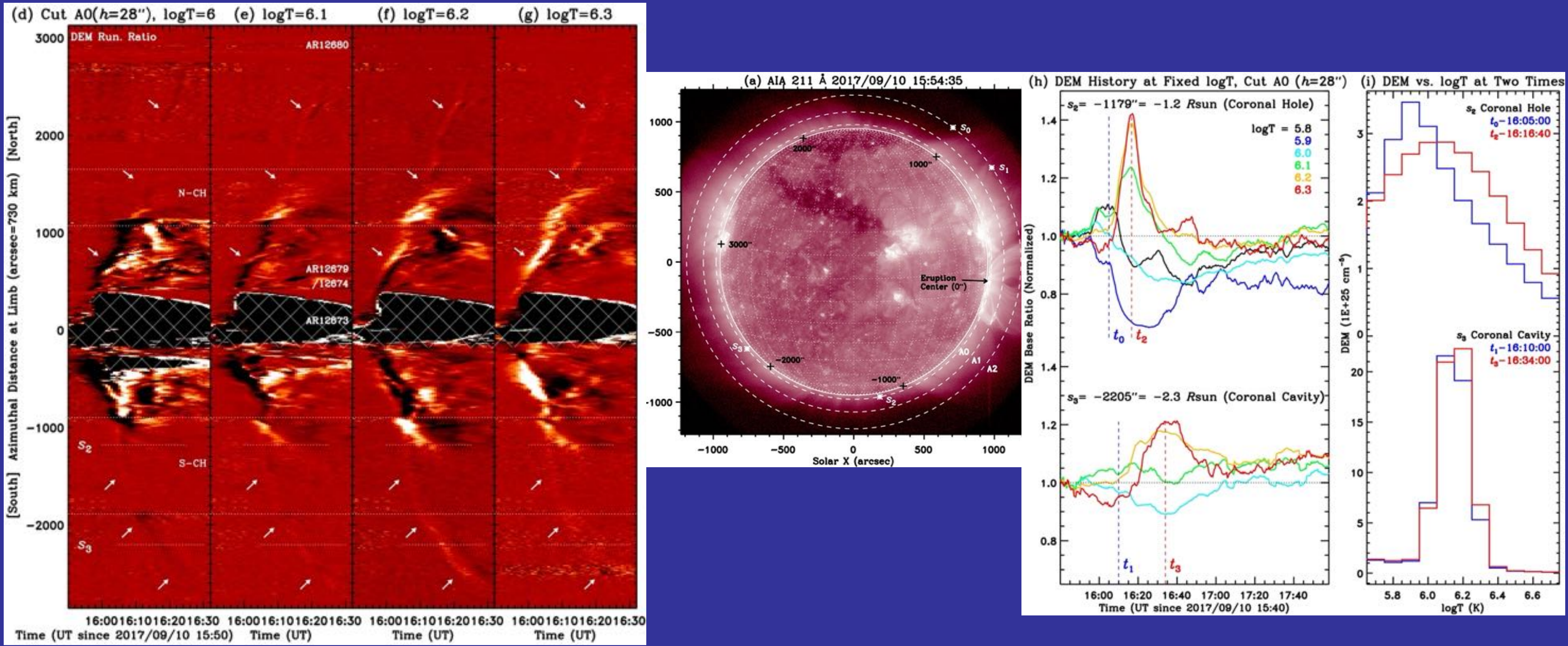
- **Anti-correlated intensity changes between warm (211 A) and cool (171 A) channels**
- **kink oscillations triggered by the wave impact**





Thermal effects (wave compressional heating): DEM inversion

Azimuthal Cut #0: running-ratio space-time of DEM maps. Note the general decrease at logT= 5.9 & 6.0, and increase at logT= 6.2 & 6.3, indicative of heating of plasma traversed by the EUV wave.



3. Summary

1. **Global coronal seismology, using such extreme EUV waves to probe the entire solar corona's thermal and magnetic properties. Some EUV waves can traverse the entire visible solar disk – provide novel diagnostic potential.**

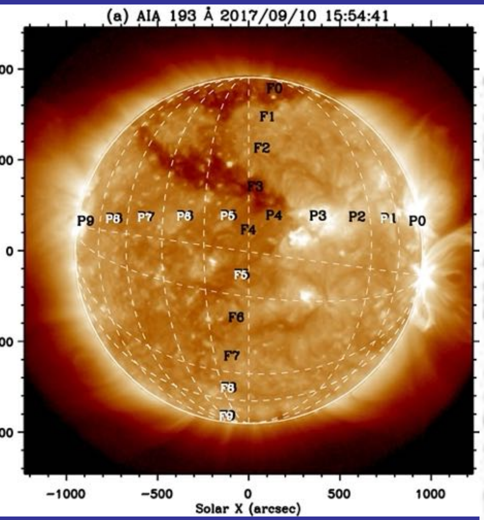
2. **Data-driven MHD simulations, in comparison with observations, can provide further insights and useful constraints.**

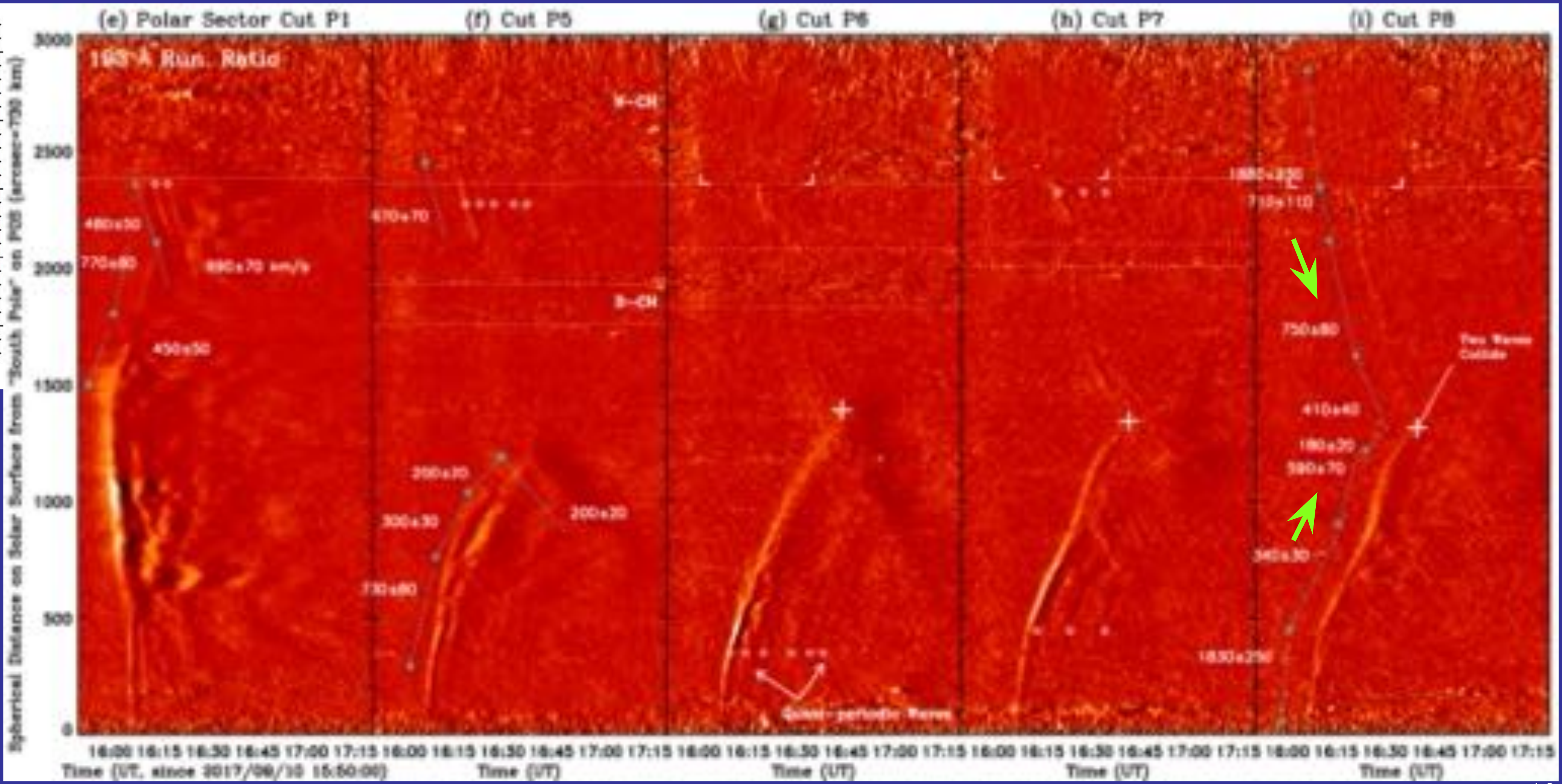
Backup Slides

Slides potentially useful for discussions

Polar sector cuts: wave kinematics, 193 space-time along spherical sectors originating from the south pole.

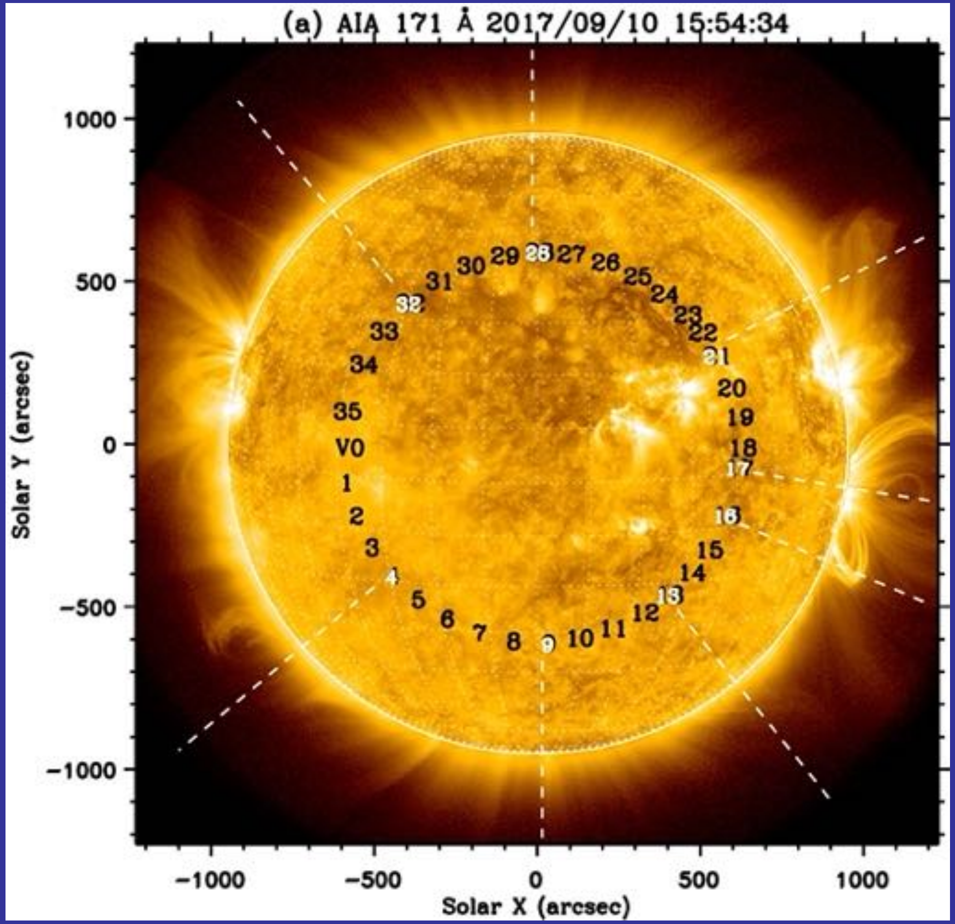
- **Multiple pulses (up to 6!) in waves refracted from both polar coronal holes (cf., Schmidt & Ofman 2010; Piantschitsch+ 2017, 2018)**
- **Two wave fronts traveling (refracted) from the north and south poles toward the equator eventually collide head-on; generating additional EUV enhancements (i.e., counter-propagating waves – turbulence generation – then dissipation – heating; cf. Ofman & Liu 2018).**

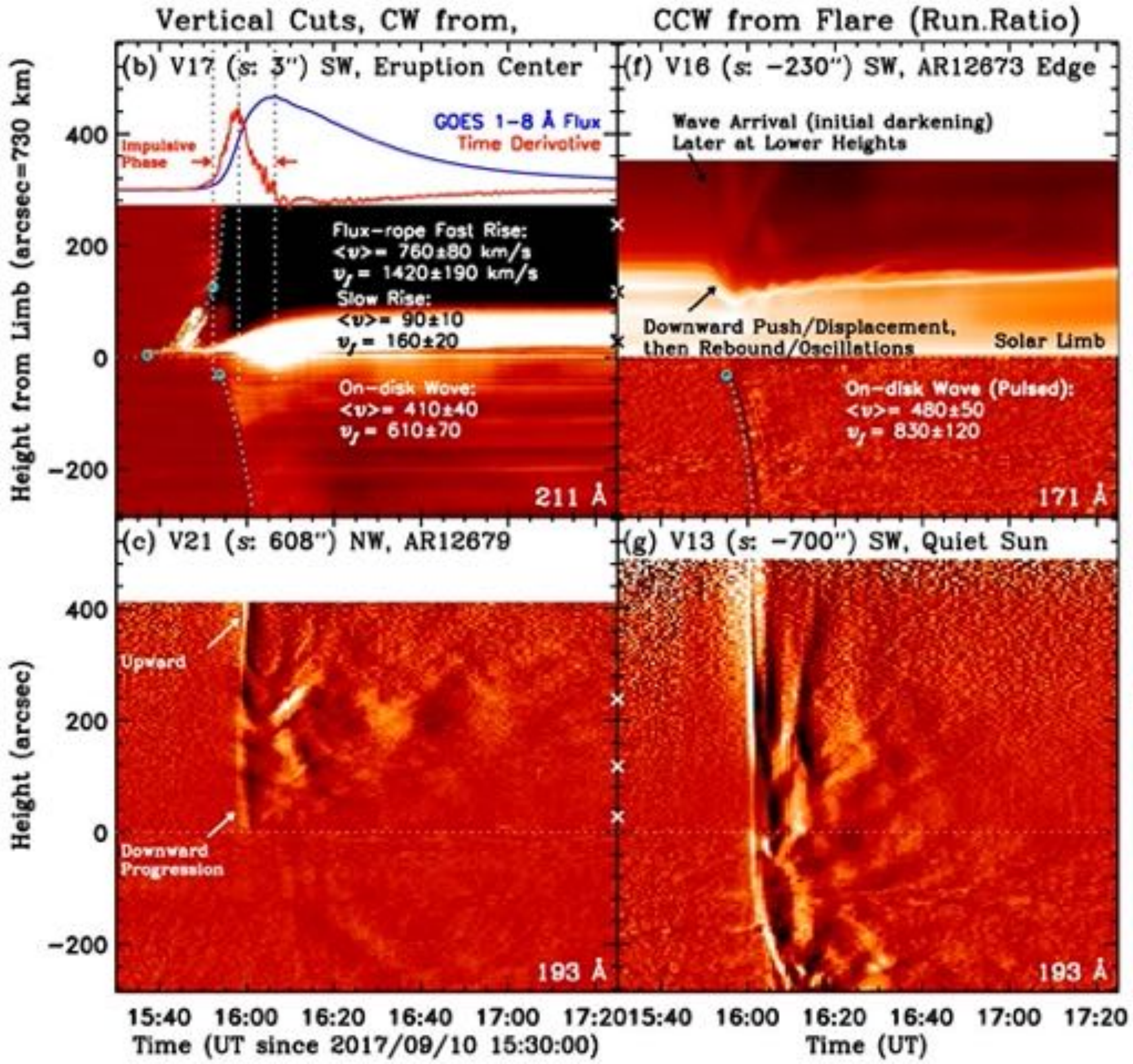




Vertical cuts: EUV Wave Generation and Early Development

- Wave generation coincides with flare impulsive phase and rapid CME acceleration (~10 km/s^2) and lateral expansion.
- Forward-inclined wave front in the low corona, partly due to downward compression from CME expansion (Harra+2011).





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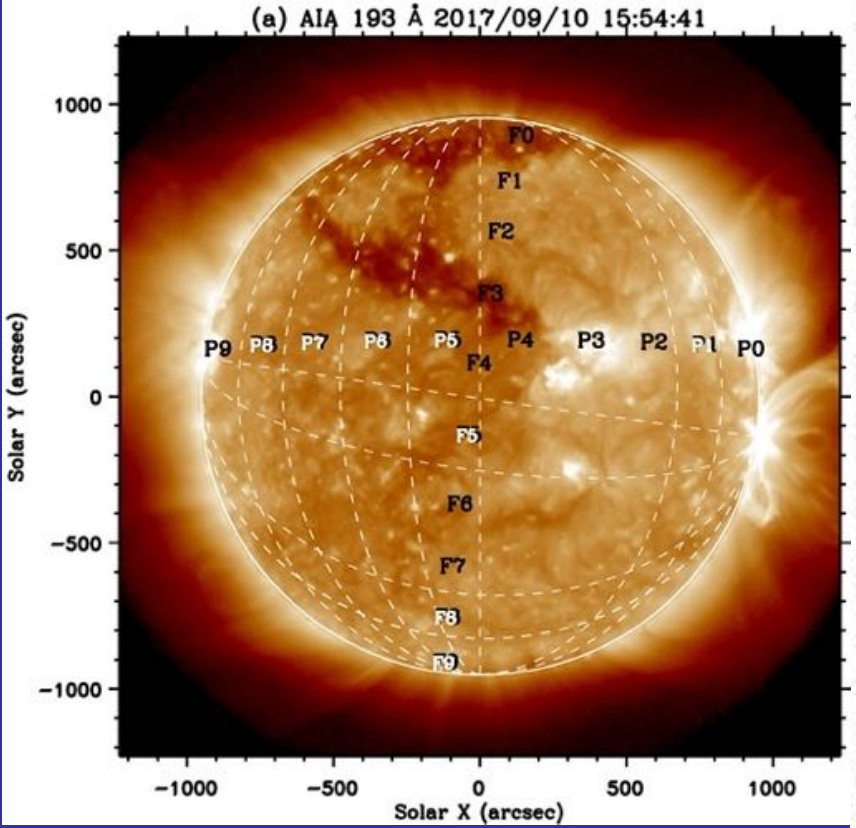
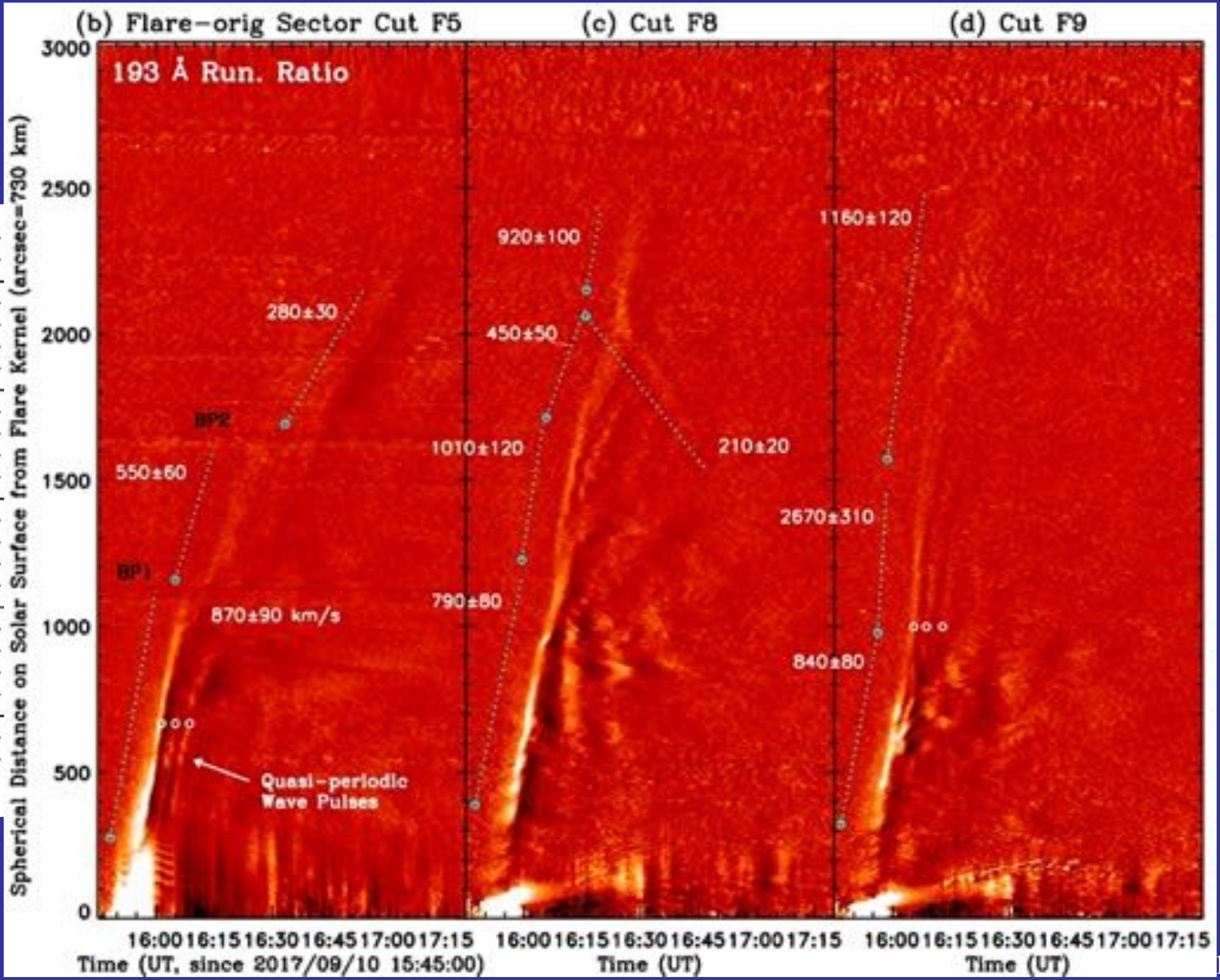
Flare-origin sector cuts: Quasi-periodic Fast-mode Propagating (QFP) wave trains (Liu+ 2011; Ofman & Liu 2018)

QFPs rarely observed in all 3 channels, but Yes in this event:
171 (common), 193 and 211 (rare).





Shock Evolution from MHD simulation