Heating of the Solar Corona

SOLARNET IV
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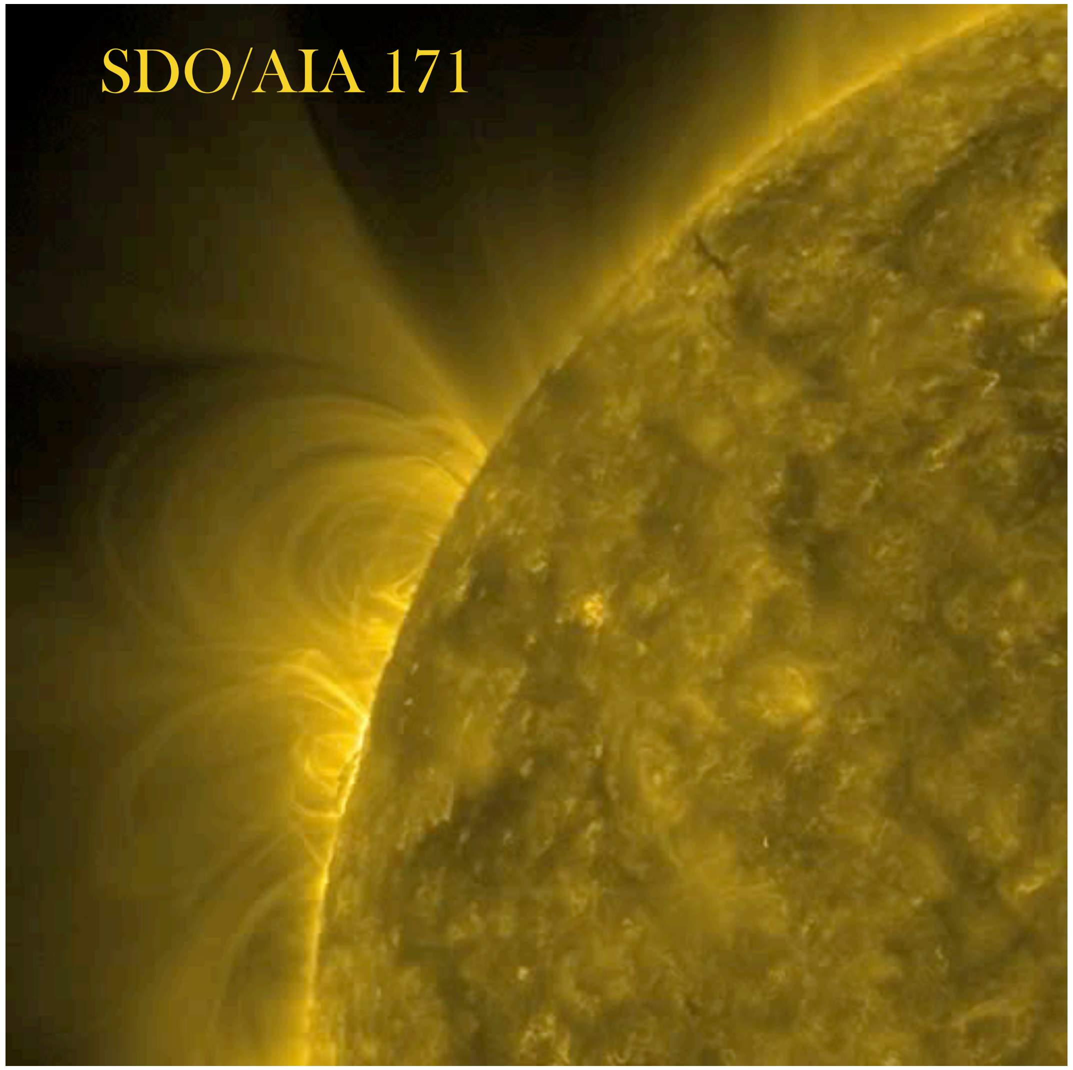
The Coronal Heating Problem

1943: Fe IX and Ca XIV lines identified in the corona by Edlén & Grotrian



Corona consists of fully ionised plasma

What physical mechanism(s) balance thermal conduction, radiative and solar wind losses?

Withbroe & Noyes (77)

Coronal hole:	8×10^5	erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Quiet Sun	3×10^5	
Active region	10^7	

Coronal Heating Mechanisms

Kuperus (61) - Withbroe & Noyes (77) - Narain & Ulmschneider (90;96) - Kuperus, Ionson, Spicer (81) - Aschwanden (04) - Klimchuk (06) - Parnell & De Moortel (12) - De Moortel & Browning (15)

Source: photospheric driver

perturbation time > < reorganisation time

DC mechanisms (>)

Direct dissipation of magnetic stresses

- Reconnection	Sturrock & Uchida (81)
- Current cascade	Parker (83)
- Viscous turbulence	Van Ballegooijen (86)
	Heyvaerts & Priest (92)
	etc.

AC mechanisms (<)

Waves	
- Alfvénic resonance	Ionson (78)
	Hollweg (87)
- Resonance absorption	Goossens et al. (92,95)
- Phase-mixing	Heyvaerts & Priest (83)
	etc.

Discussion in terms of mutually exclusive
AC or DC mechanisms
beside the point

A Note on Theoretical/Numerical Modelling

Complexity

Applicability

Simple models with simple analytical solutions/scalings

- Basic, detailed understanding of physical processes
- Not very useful signatures for comparison to observations

Intermediate models - nonlinear physical processes

- Reasonable modelling of relevant physical processes
- 1D to 3D information - useful observational signatures

Global Numerical Models

- Prescribed/observed boundaries/drivers + numerical solution
- Global information - useful obs. signatures - prediction
- Make possible to include almost any physical ingredient

Detailed Understanding

Simplicity

New Approaches in Coronal Heating

De Moortel & Browning (15)

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PHILOSOPHICAL
TRANSACTIONS A

350 YEARS
OF SCIENTIFIC
PUBLISHING

New approaches in coronal heating

Theo Murphy meeting issue compiled and edited by Ineke De Moortel and Philippa Browning

THE
ROYAL
SOCIETY
PUBLISHING

12 Review Articles

Key Aspects	Klimchuk
Observations	Schmelz & Winebarger
Stellar Activity	Testa +
Nanoflares	Cargill +
3D Numerical Models	Peter
Magnetic Topology	Parnell +
Magnetic Reconnection	Longcope +
Flux Braiding	Wilmot-Smith
Shock Heating	Bareford & Hood
Waves	Arregui
Partial Ionisation	Martínez-Sykora +
Turbulence	Velli +

This Talk

Waves - Nanoflares - AW Turbulence

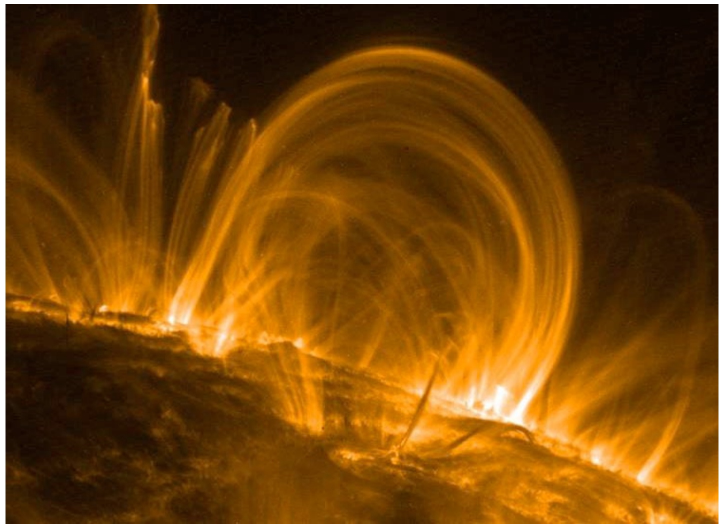
Observations, modelling and their comparison

Wave Activity

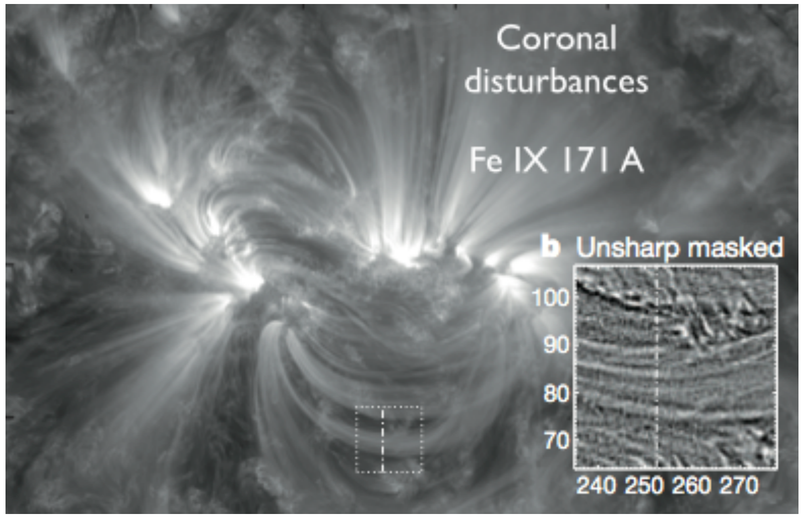
Rosenberg (70); Trottet+(79) … Aschwanden+(99); Nakariakov+(99); De Pontieu+(07); Okamoto+(07); Cirtain+(07); McIntosh+(11); Morton+(12,13,14); Arregui+(12); Threlfall+(13); Mathioudakis+(13)…

Existence of wave-like dynamics beyond question

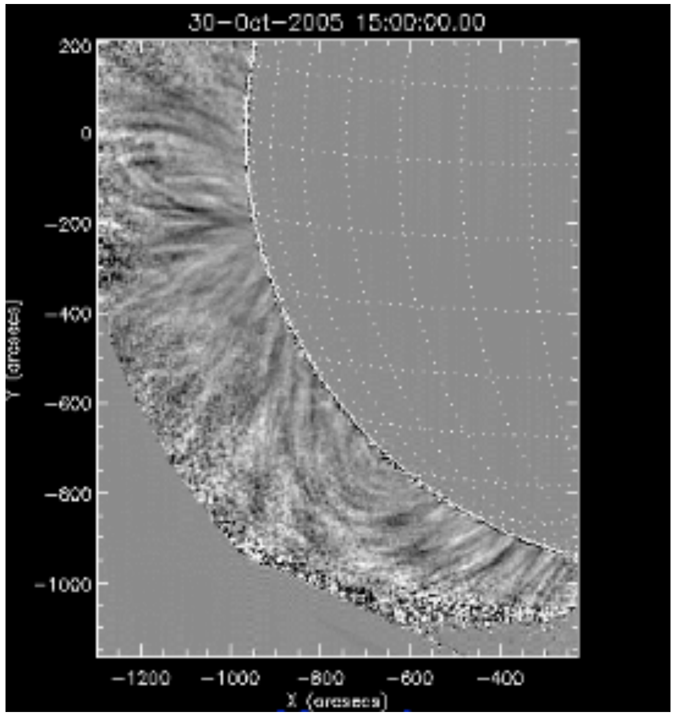
Coronal Loops



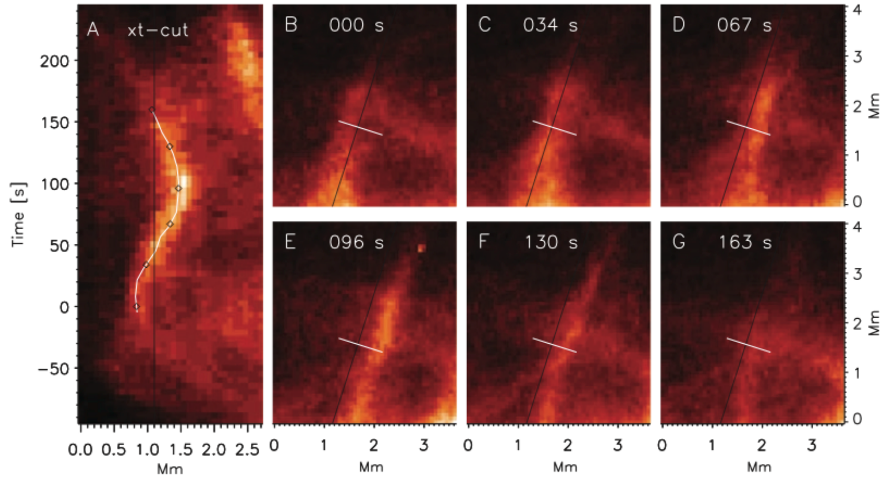
AR Corona



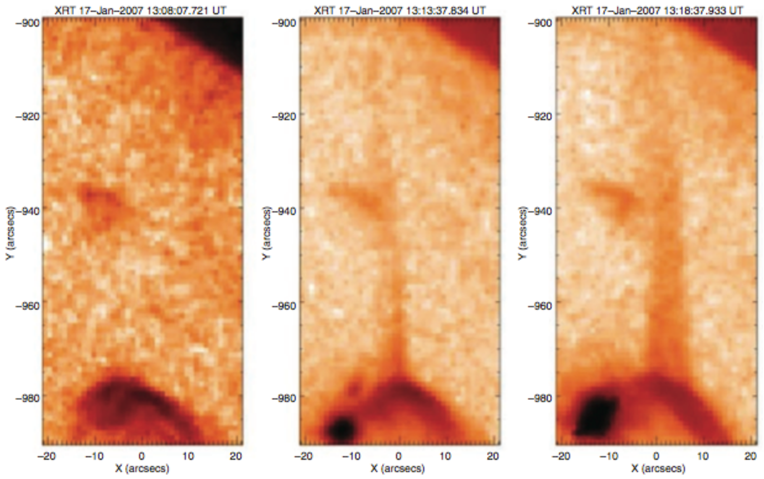
Extended Corona



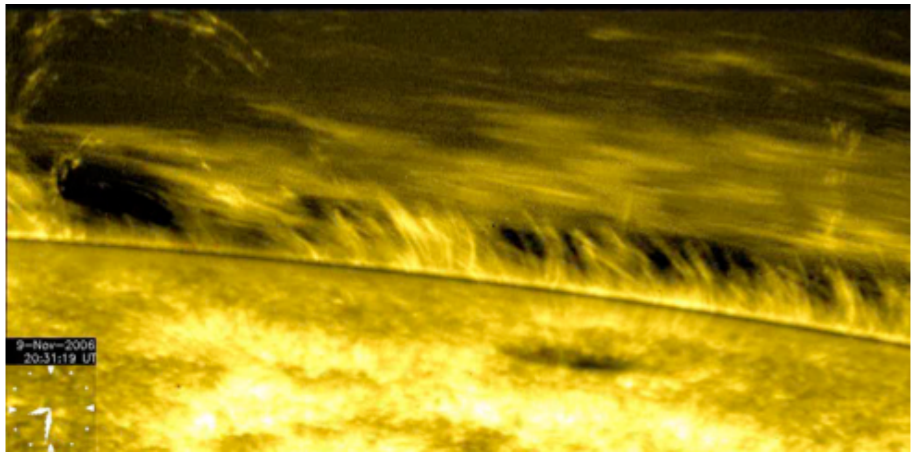
Chromospheric Spicules



X-ray Jets



Prominence plasmas



+ chromospheric bright points/mottles + coronal hole structures + filament threads…

Time/spatial variation of spectral line properties / imaged emission

SST, DST, CoMP, SoHO, TRACE, Hinode, STEREO, SDO, Hi-C, IRIS: increased detail/coverage

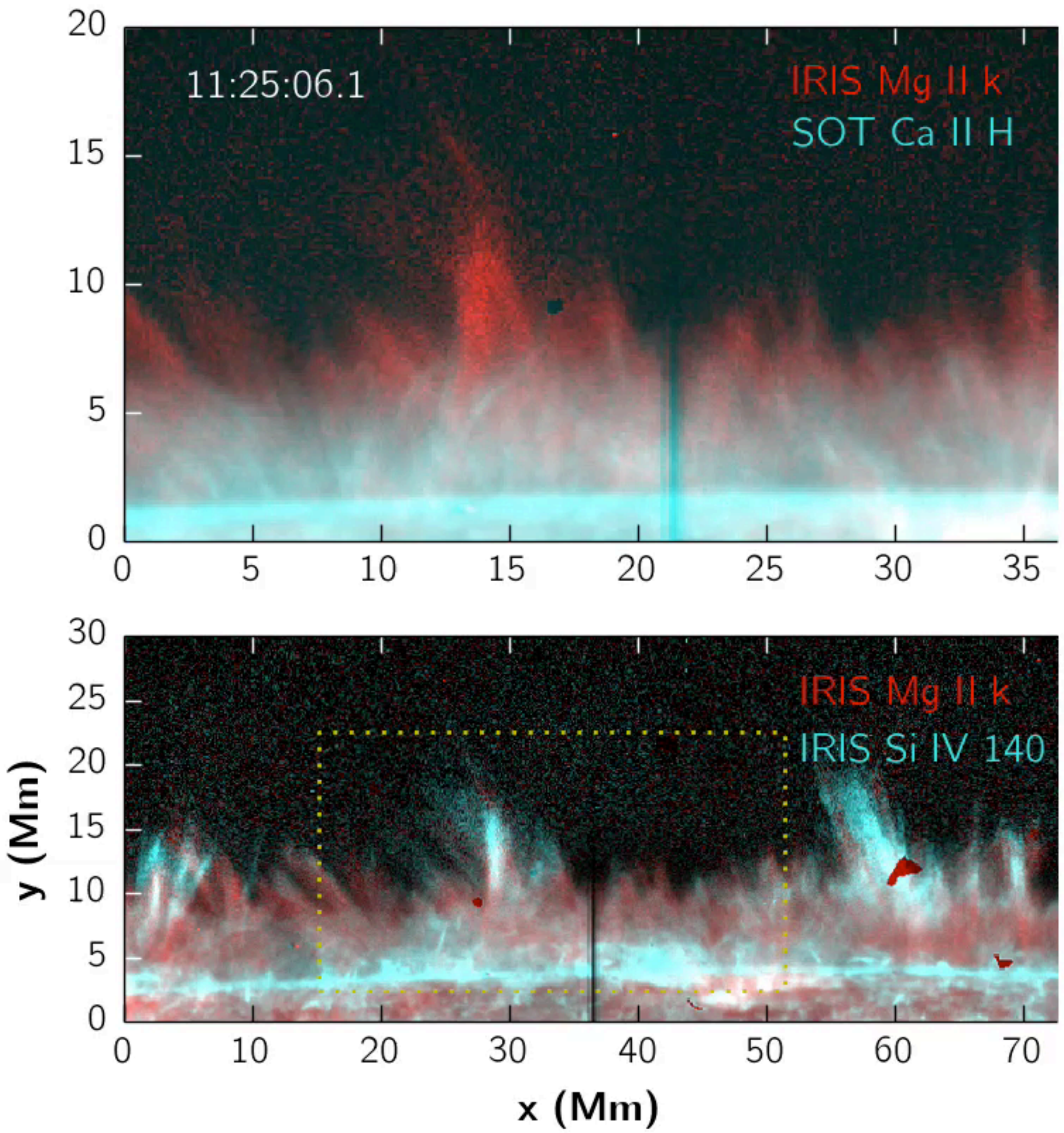
Talks
T. Arber
I. De Moortel

Alfvén Waves in Spicules

e.g. De Pontieu+(07,12): Okamoto & De Pontieu (11); Morton (14)

Present everywhere / all the time

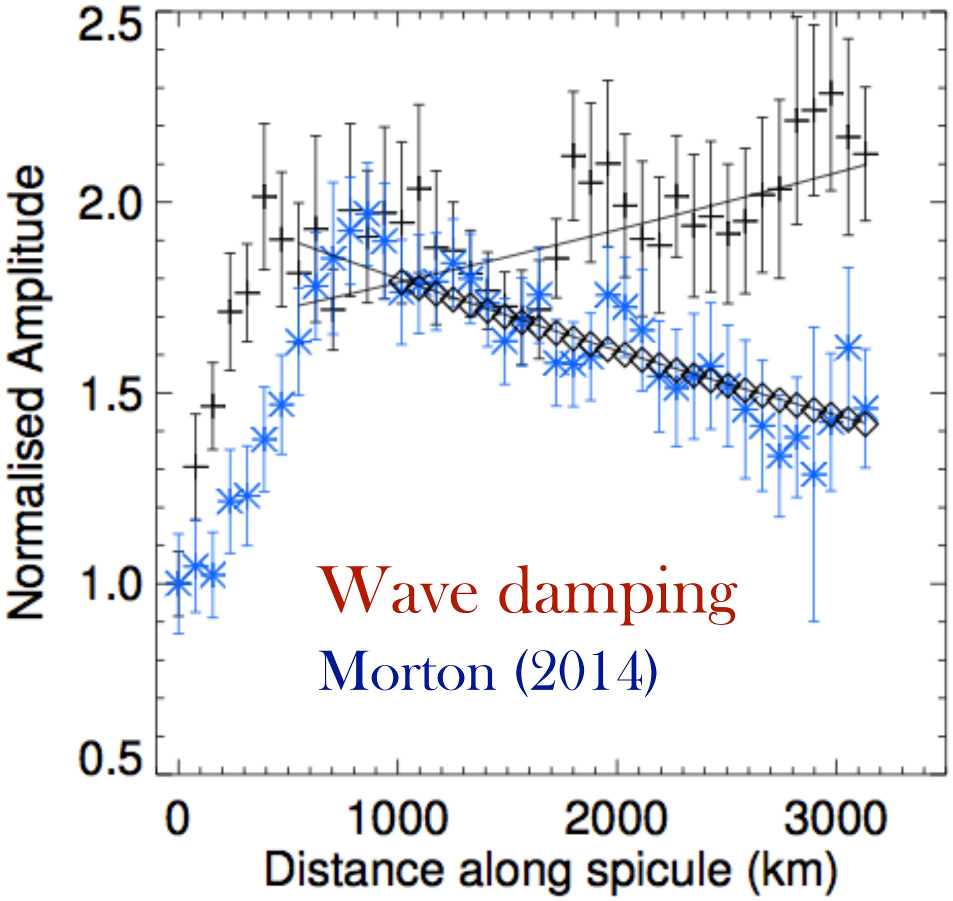
Pereira et al. (2014) - IRIS & Hinode SOT



Physical connection at interface

De Pontieu +(12) - Hinode SOT

Complex Dynamics	
Lateral Swaying	15-20 km/s
Upward Mass Motions	50-100 km/s
Torsional Motions	25-30 km/s

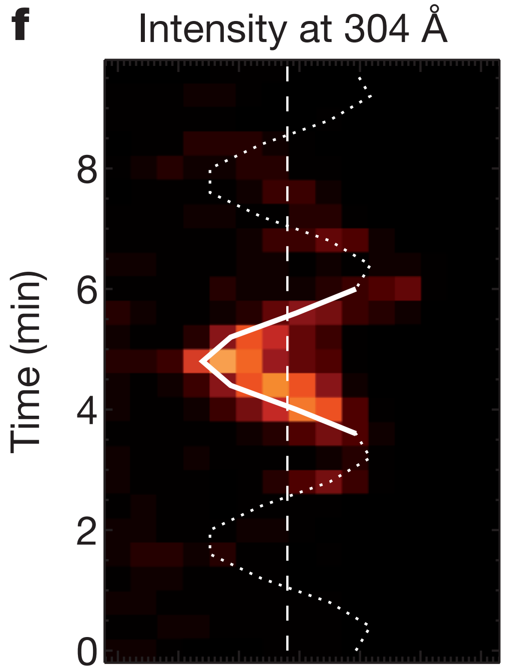


Wave damping

Morton (2014)

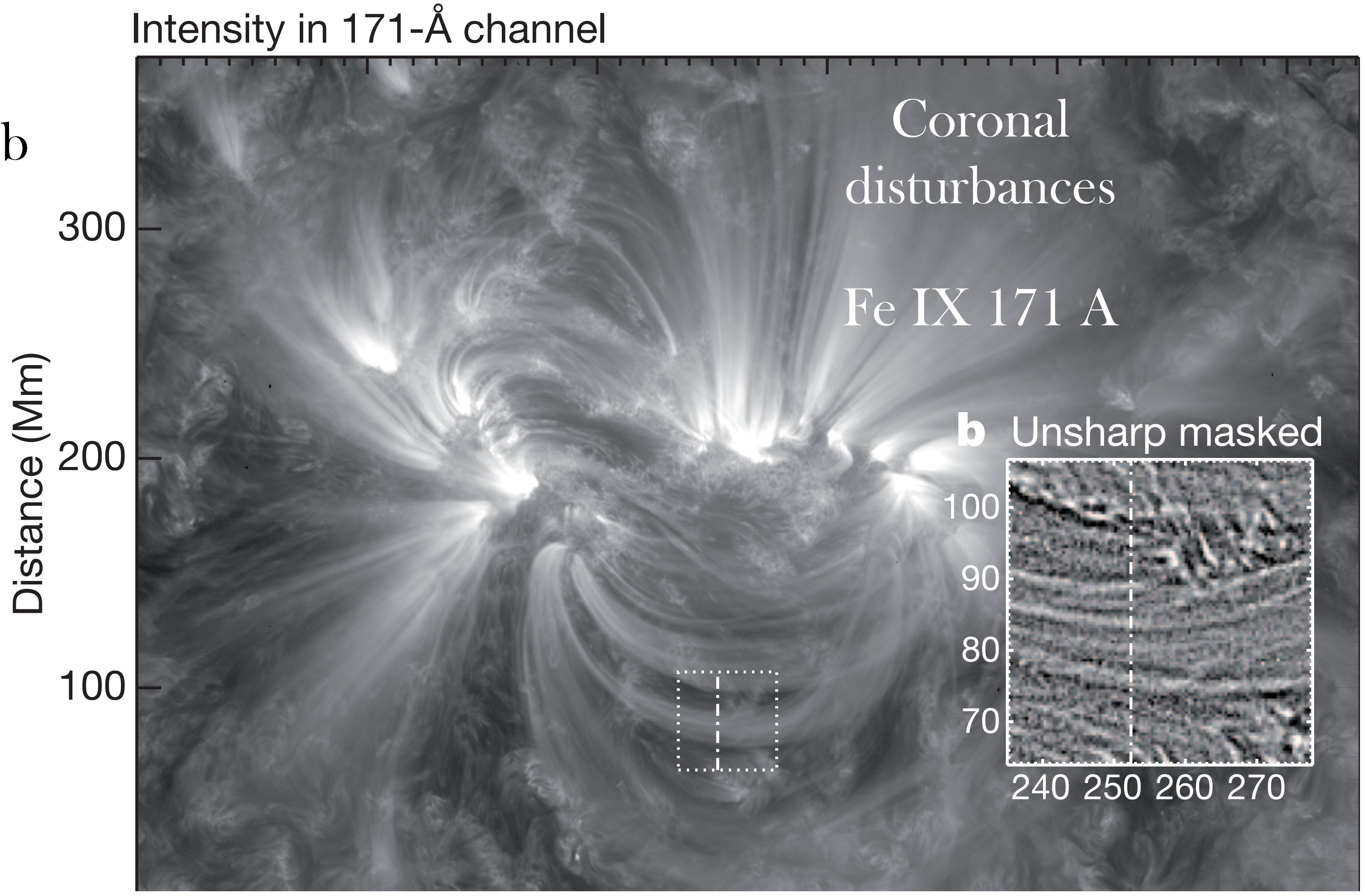
Excellent candidates for wave energy and mass transport to the corona

Alfvén waves in TR and corona McIntosh et al. (2011) SDO/AIA



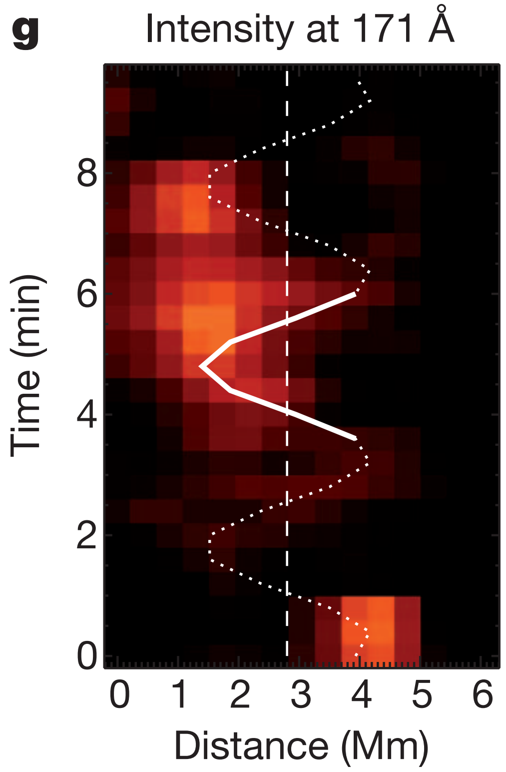
Spicules on the limb

He II 304 A



Coronal disturbances

Fe IX 171 A



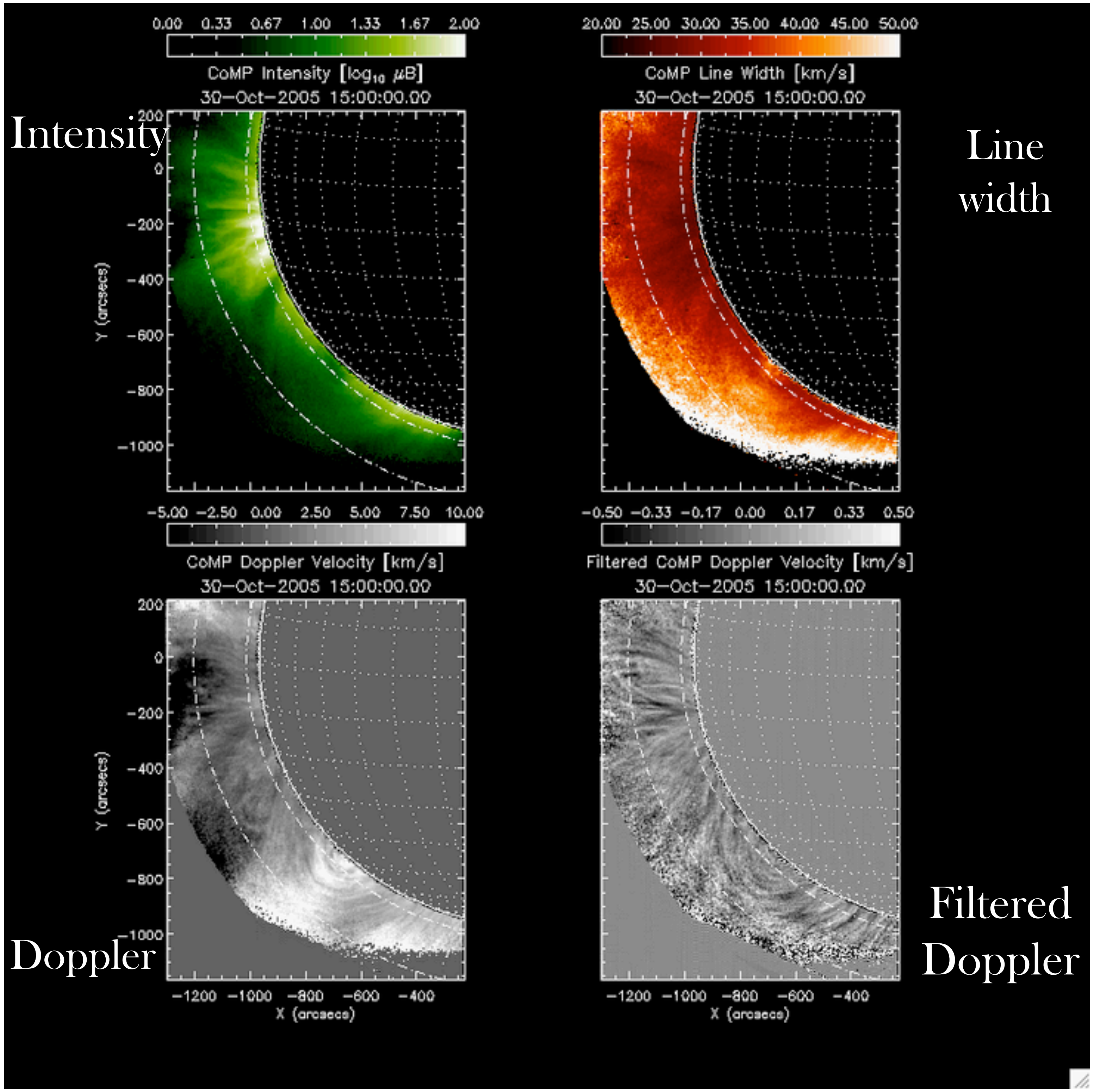
Region	Amplitude (km/s)	Period (s)	Phase Speed (km/s)	Power (Wm^{-2})	Required (Wm^{-2})
Coronal Hole	25 ± 5	150 - 600	~300 (@15Mm)	~100 - 200	**100 - 200**
Quiet Sun	20 ± 5	150 - 600	~250 (@15Mm)	~100 - 200	**100 - 200**
Active Region	5 ± 5	100 - 400	~600	~100	**~2,000**

Motions visible in TR/corona share a common origin (De Pontieu+07,09,11)

Energetic enough to power solar wind and heat quiet corona

Coronal Alfvén Waves

Tomczyk+(07), Tomczyk & McIntosh (09)



CoMP

(intensity - LOS velocity - linear polarization)

1.05-1.35 R_{SUN}

Coronal disturbances present everywhere / at all times

Doppler velocity fluctuations

<v> ~ 0.3 km/s

No intensity fluctuations

~ incompressible wave

Propagating Alfvén waves with phase speeds ~ 1 - 4 Mm/s

Signatures of in situ damping (discrepancy inward/outward power)

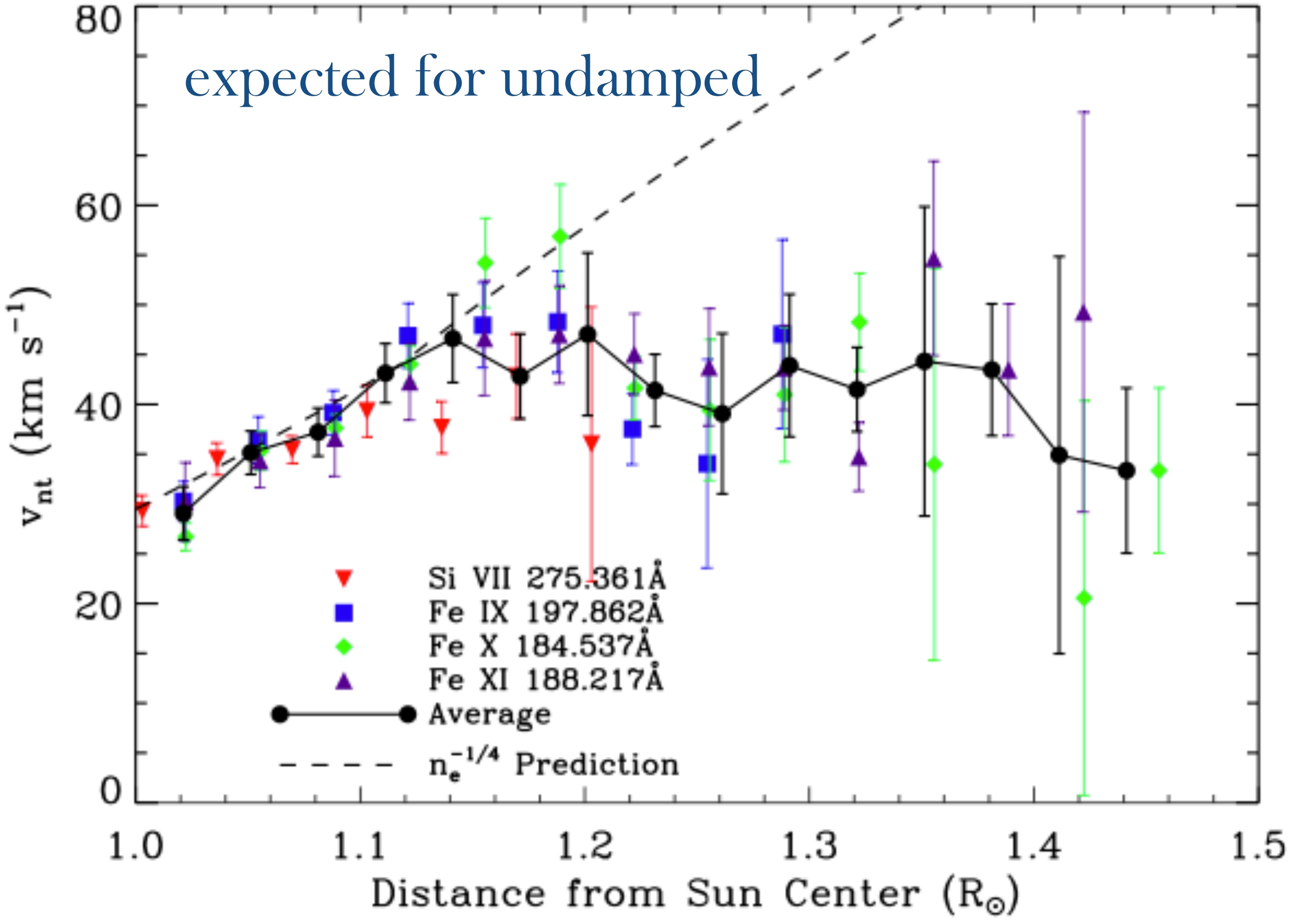
Do not seem to carry enough energy to heat ambient plasma ~0.01 W/m^2

Alfvén Wave Damping in Polar Coronal Hole Regions

Hahn & Savin (13) using Hinode/EIS data - analysis of non-thermal line widths with height

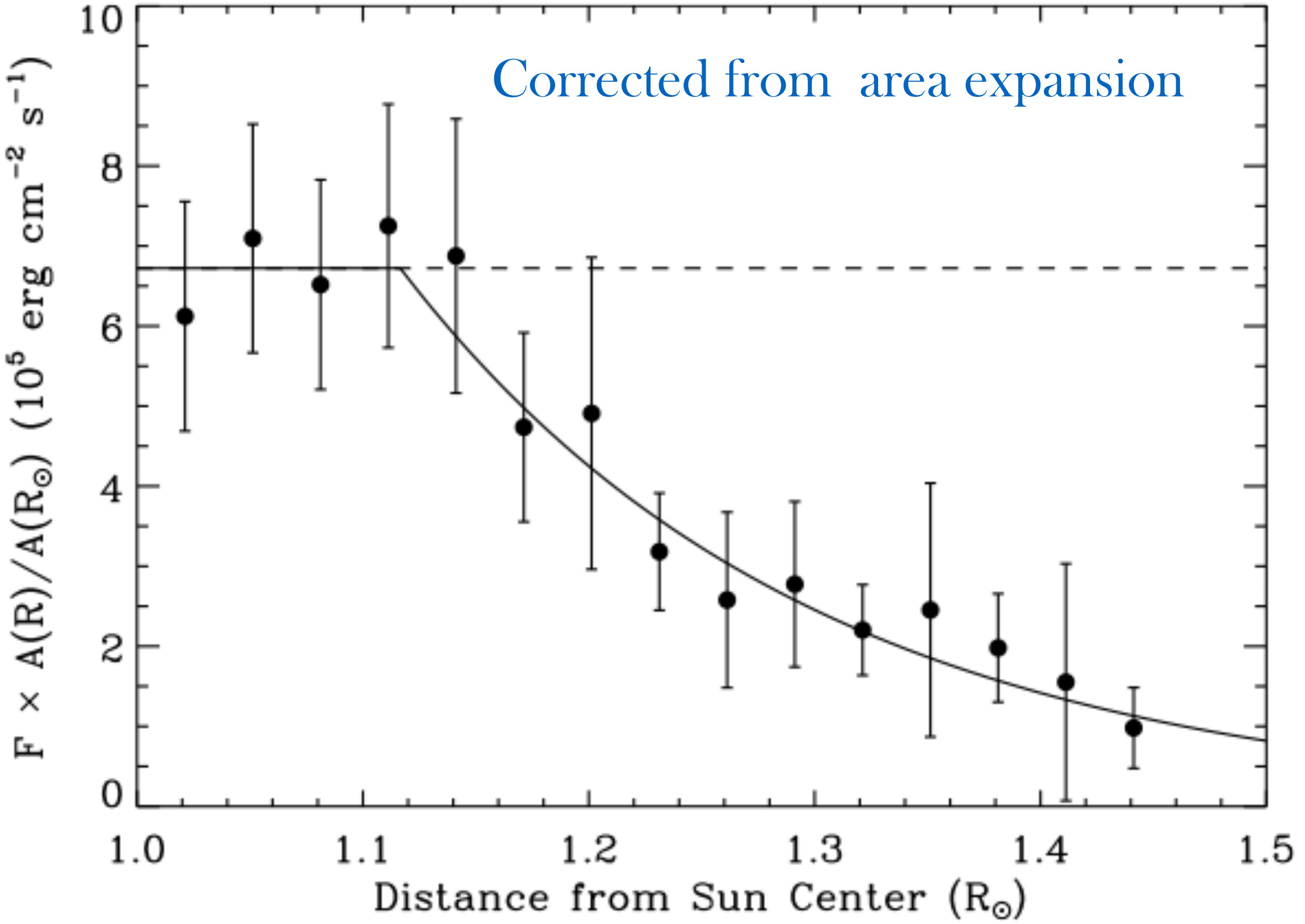
Spectroscopic diagnostics - non-thermal line width variation with heigh

Non-thermal velocity



expected for undamped

Energy Flux



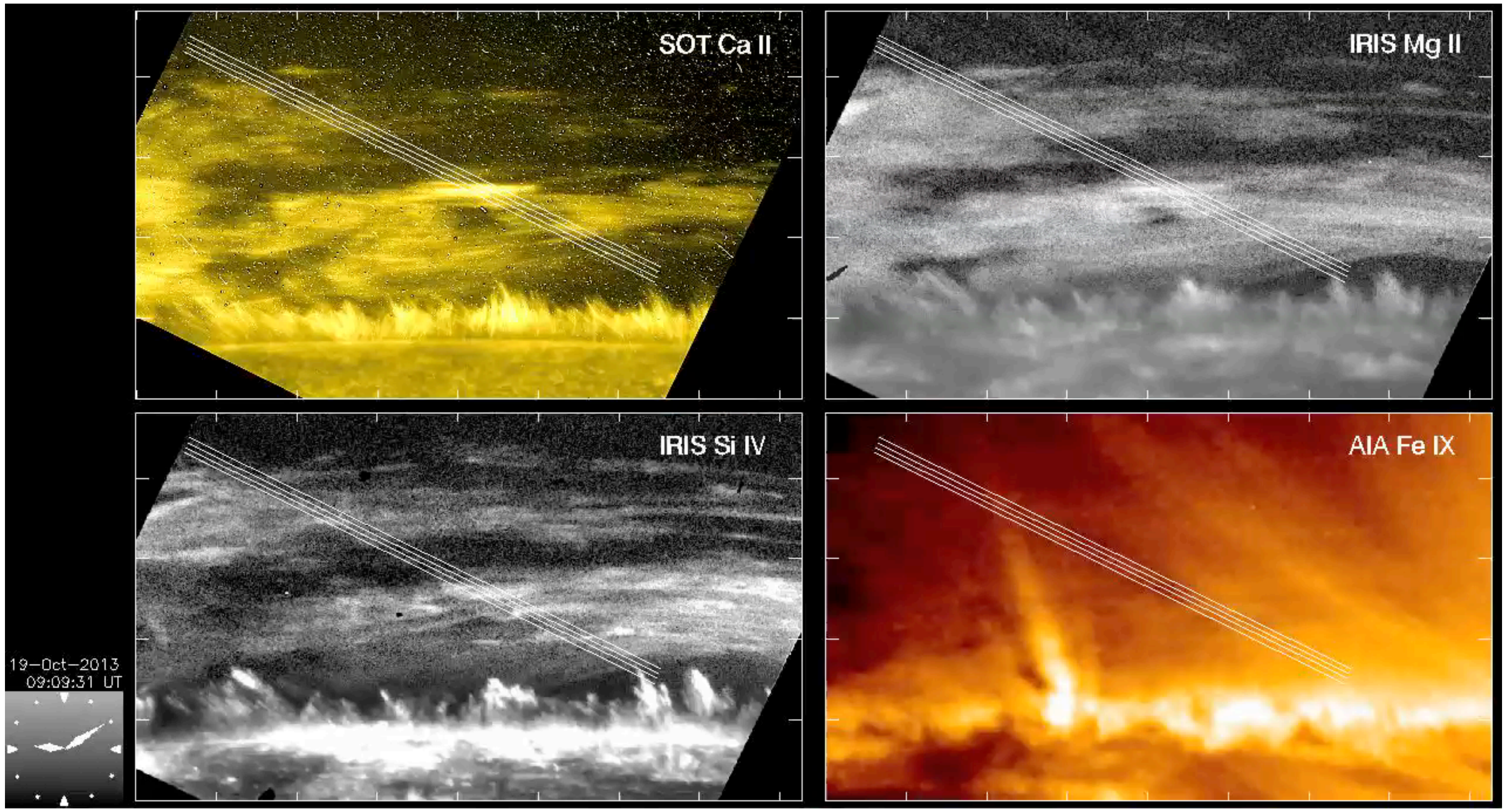
Corrected from area expansion

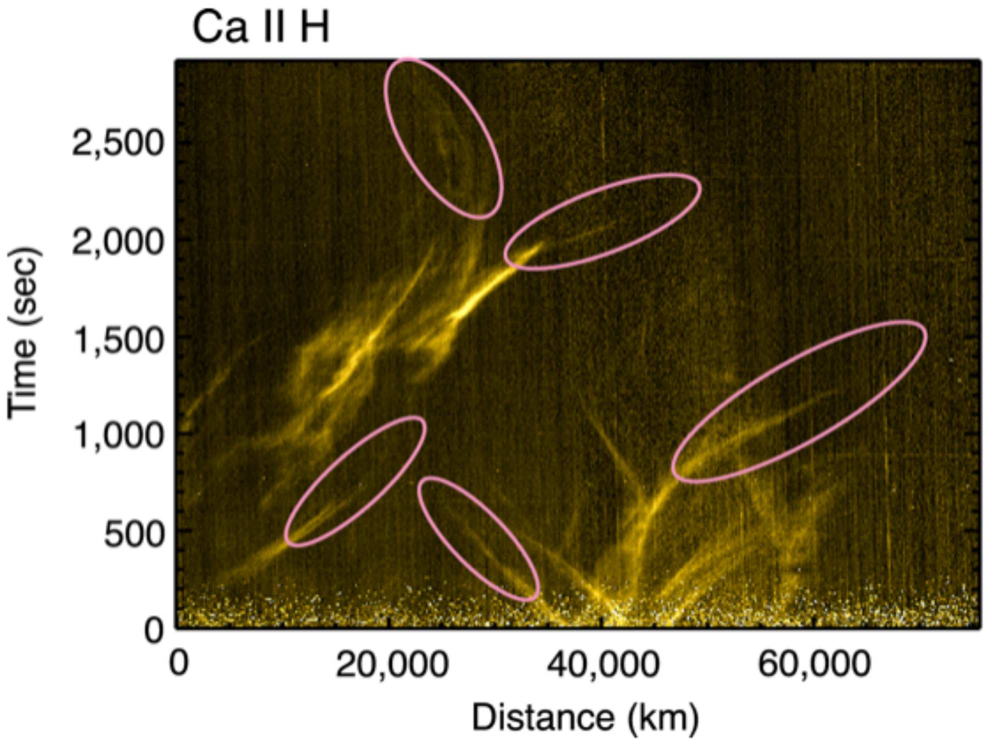
First measurement of energy carried /dissipated by Alfvén waves in a coronal hole

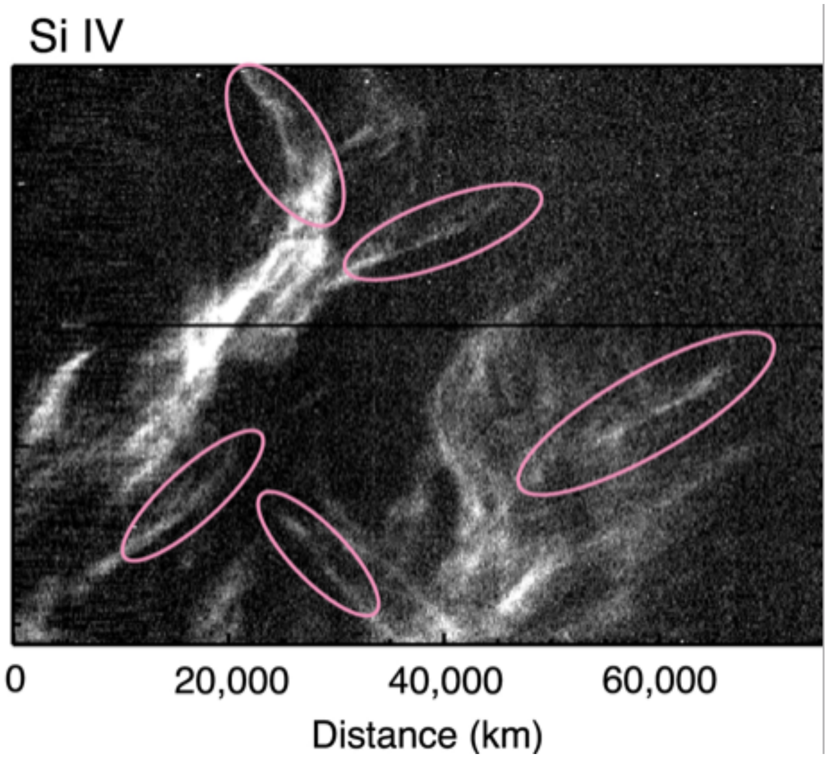
Wave Heating in Prominence Plasmas

Okamoto+(15) & Antolin+(15)

IRIS + Hinode







Coherence in transverse direction

180 degrees phase difference between transverse motions in POS and LOS velocities

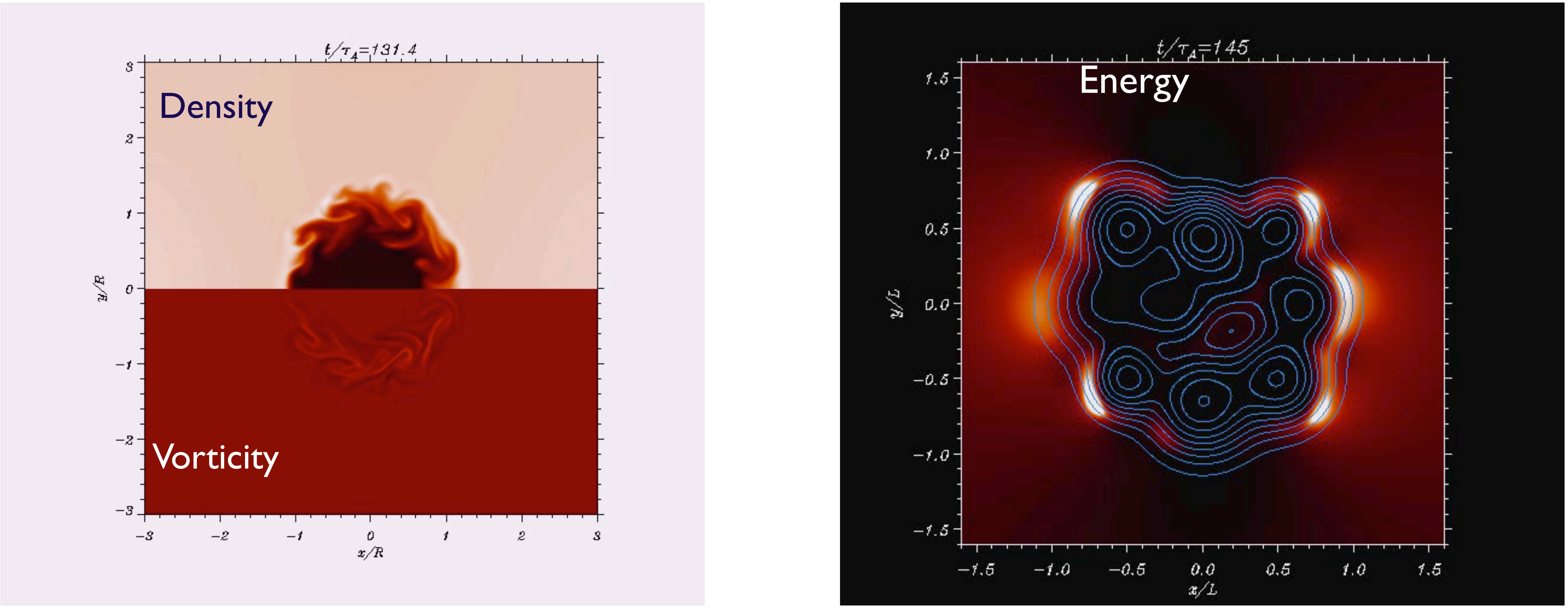
Moving threads fade away in Ca II H and co-spatial threads appear in the hotter Si IV emission

Claim first direct evidence for resonant wave heating in a solar prominence

Poster
M. Montes-Solis

Resonant Damping of Transverse Waves

Ionson (78); Hollweg & Yang (88); Goossens+(02); Ruderman & Roberts (02); Goossens+(09;12,14); Pascoe+(10,11)



3D non-linear - Terradas+(08a)

3D multistranded - Terradas+(08b)

Cross-sectional view of waveguide

- Mechanisms relies on non-uniform medium across magnetic field
- Eventual heating at the tube boundary in tubes (non-uniformly distributed otherwise)
- Works for both standing/propagating waves - produces time/spatial damping

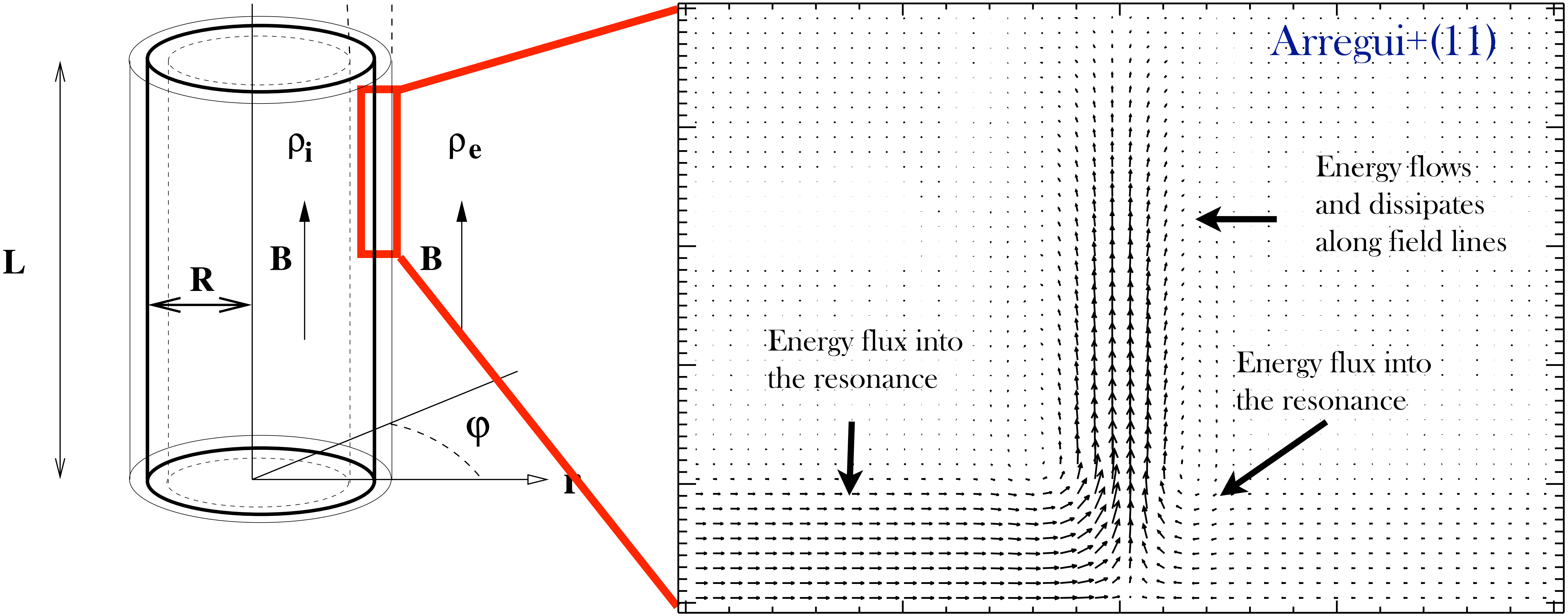
Transfer of wave energy from large to small scales

Talk
P. Pagano

Energy Flow and Damping

Wright & Thompson (94); Arregui+(11)

Time averaged energy flux into the resonance



Arregui+(11)

Energy flows and dissipates along field lines

Energy flux into the resonance

Energy flux into the resonance

Energy flows into the resonant in the cross-field direction and gets damped along the field

Damping does not mean Dissipation

wave energy transfer - phase mixing - resistive diffusion

see also Lee & Roberts (86); Davila (87)

Resonant damping

$$\tau_{\rm damping} \sim \frac{R}{l}\left(\frac{\zeta+1}{\zeta-1}\right) P$$

Phase-mixing > creation of small scales

$$L_{pm} = 2\pi/(t|\omega'_{\rm A}|)$$

Resistive dissipation important when

$$l_{ra} =\sim (R_{\rm m}|\omega'_{\rm A}|)^{-1/3}$$

This scale is reached in a time

$$t_{ra} = 1/(l_{\rm la}|\omega'_{\rm A}|) = R_{\rm m}^{1/3}|\omega'_{\rm A}|^{-2/3}$$

$R_{\rm m} = 10^{12}$	$R_{\rm m} = 10^4$
$l/R = 0.1$	$l/R = 0.1$
$\tau_{damping}/P = 13$	$\tau_{damping}/P = 13$
$t_{\rm diff}/P = 170$	$t_{\rm diff}/P = 0.36$
$l/R = 0.5$	$l/R = 0.5$
$\tau_{damping}/P = 3$	$\tau_{damping}/P = 3$
$t_{\rm diff}/P = 500$	$t_{\rm diff}/P = 1$
NO heating during oscillation	Heating during oscillation

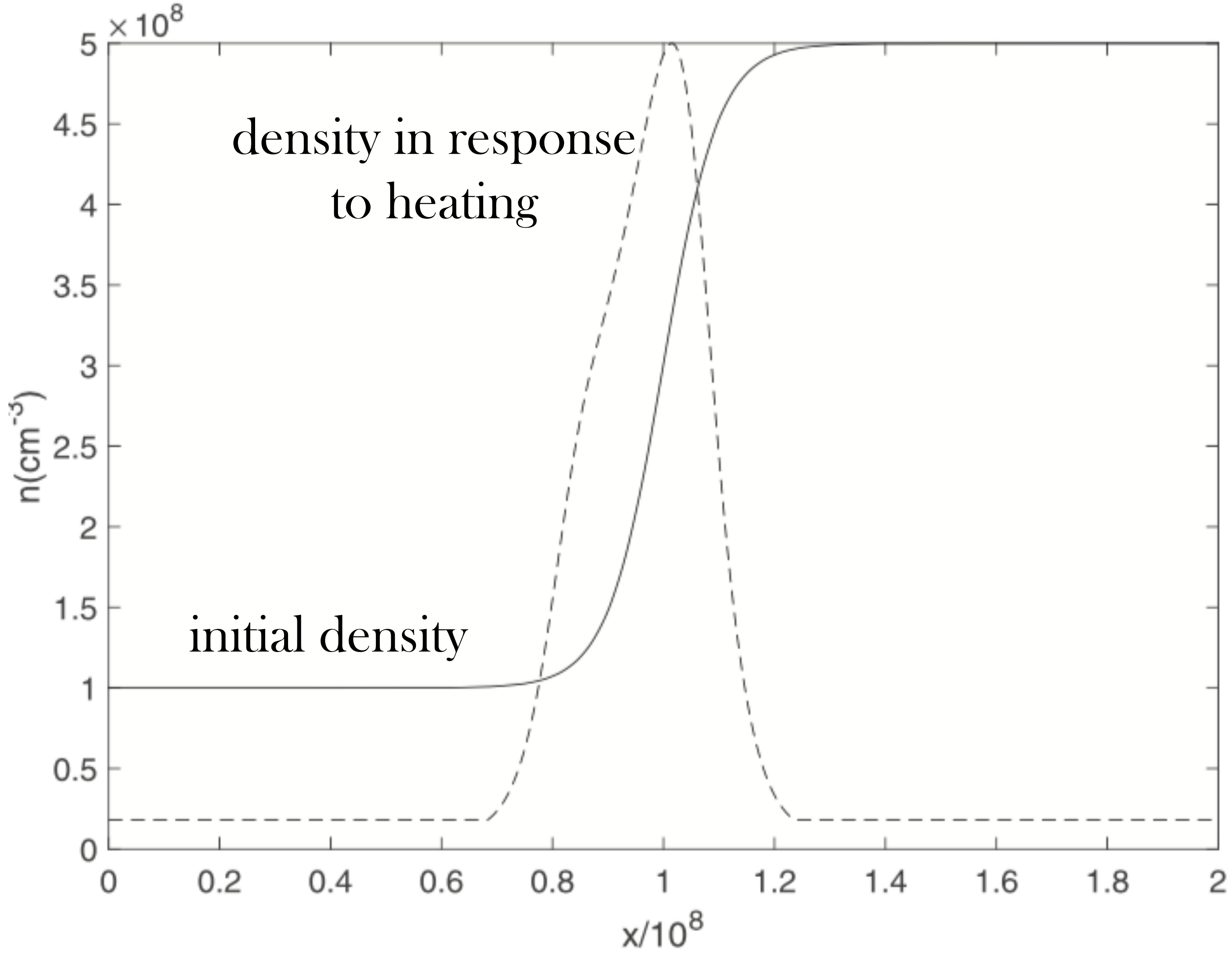
To obtain observational evidence about dissipative processes might be difficult

Poster
I. De Moortel

Evolution of the Density Gradient

Cargill+(16)

Analysis of the feedback between heating and density



Initial density profile evolves to a localised peak

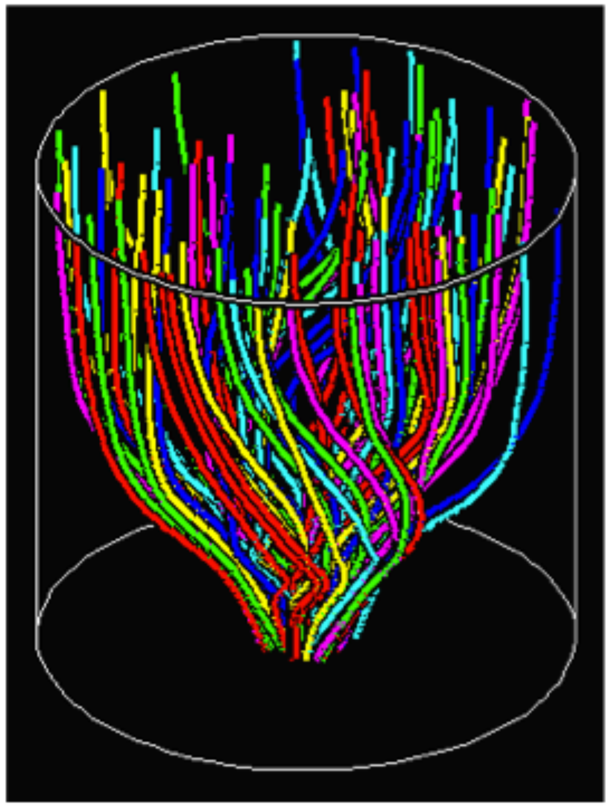
Wave heating cannot sustain the assumed density structure

Fundamental difficulties for wave-based heating mechanisms

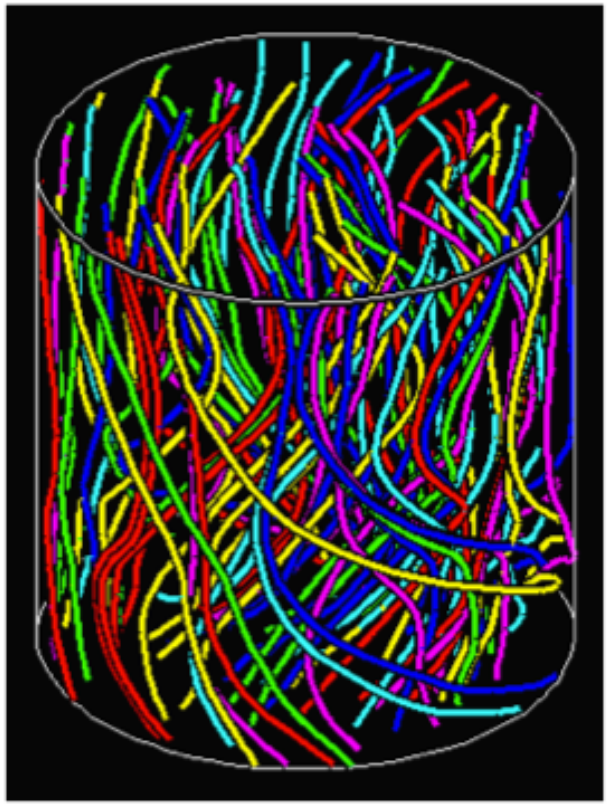
Alfvén Wave Turbulence

Van Ballegooijen + (11,14); Asgari-Targui + (13)

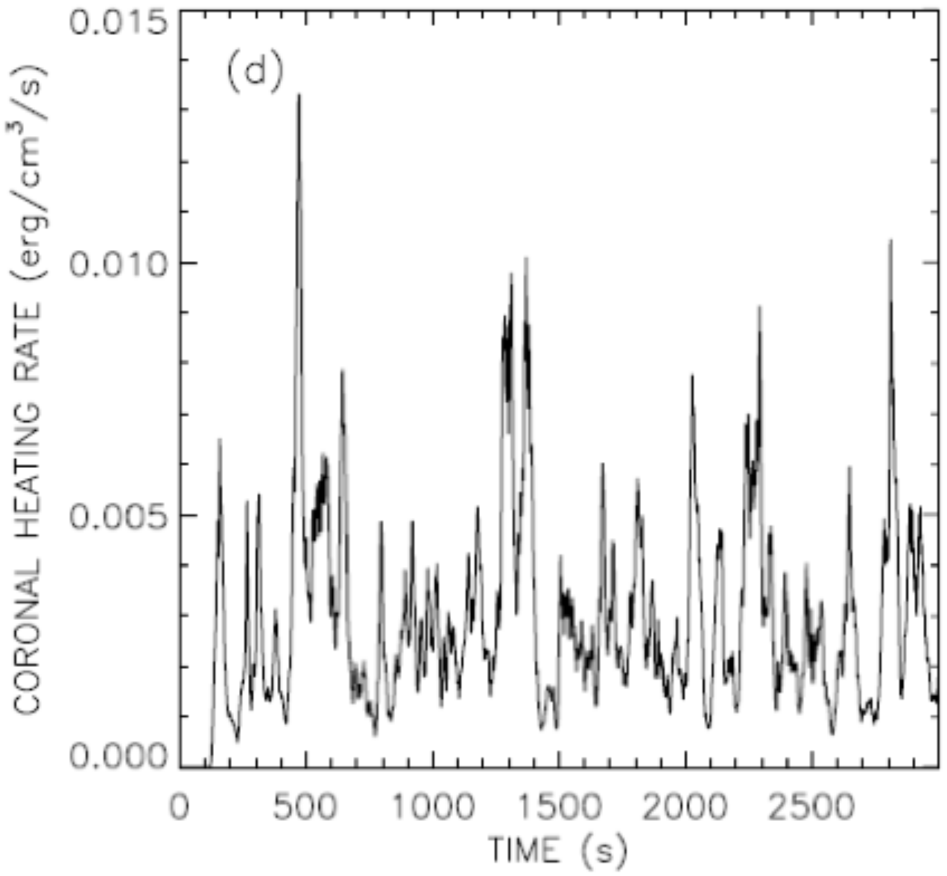
Photospheric foot-point motions transported along loops - reflected at chromosphere and TR- counter propagation of waves - energy into small scales by Alfvén wave turbulence



Z = 0 - 2 Mm



Z = 2 - 50 Mm



Dissipation rate able to reproduce chromospheric and coronal heating requirements

Heating rate increases with field strength - larger for shorter loops

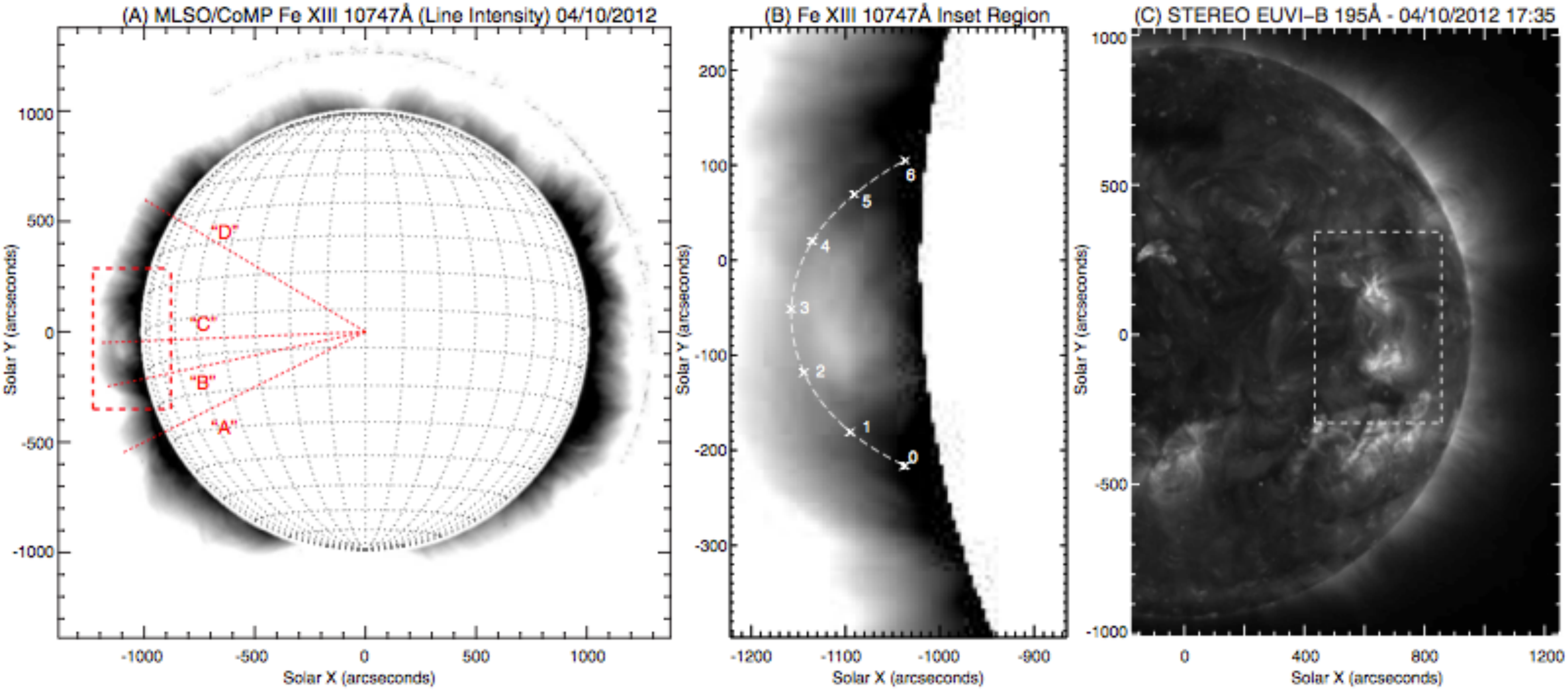
Realistic lower atmosphere modelling favours AC heating with sufficient energy flux

Dynamic plasma response remains to be included - temperature and density profiles

Observational signatures of AWT

De Moortel + (14)

CoMP Doppler shift oscillations - broad range of frequencies - similar power spectra at both sides of a large trans-equatorial loop system (prop. speed 500 km/s)



Excess of high frequency power at the apex suggests possible evidence of low/mid frequency waves cascading into Alfvén wave turbulence

Observational signatures of AWT

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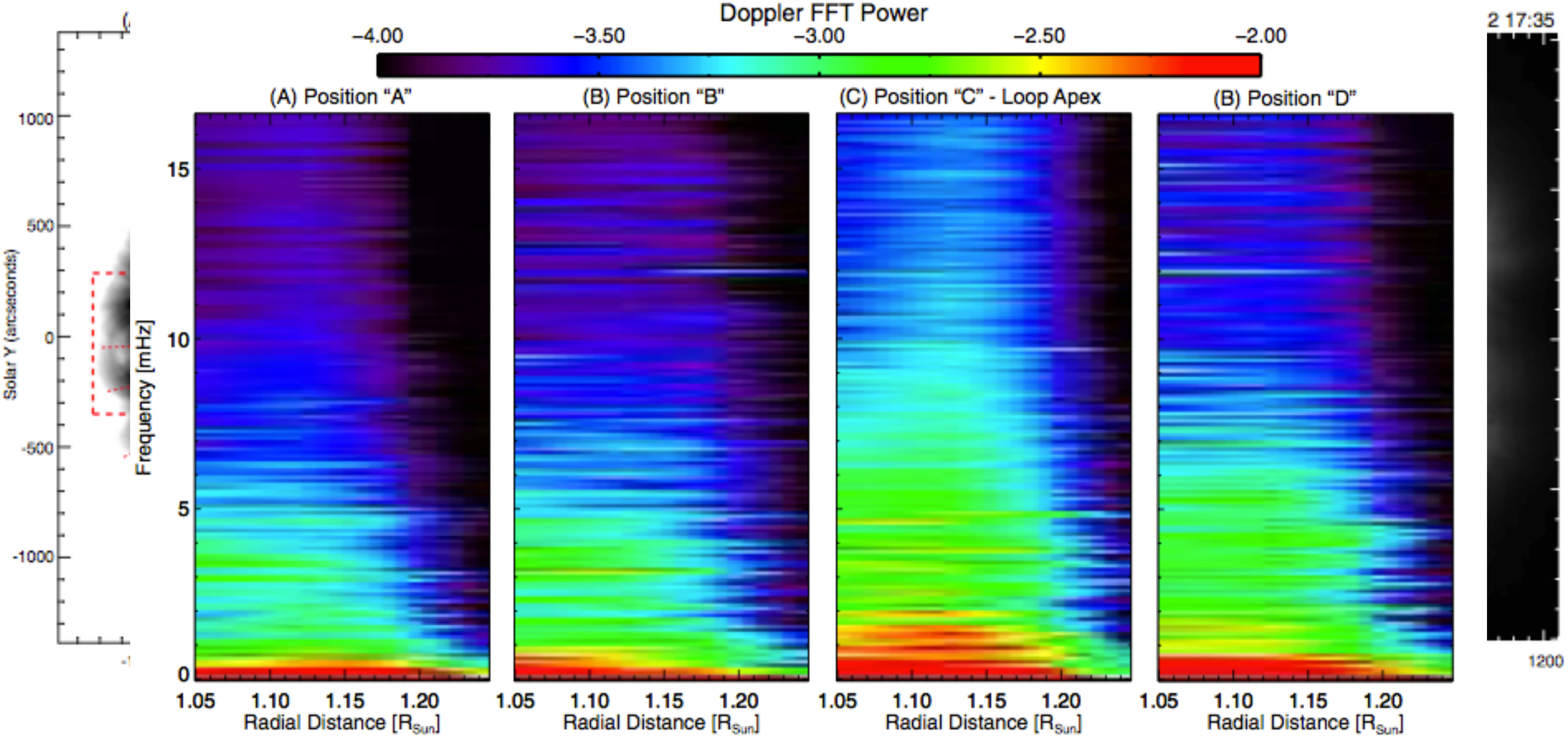
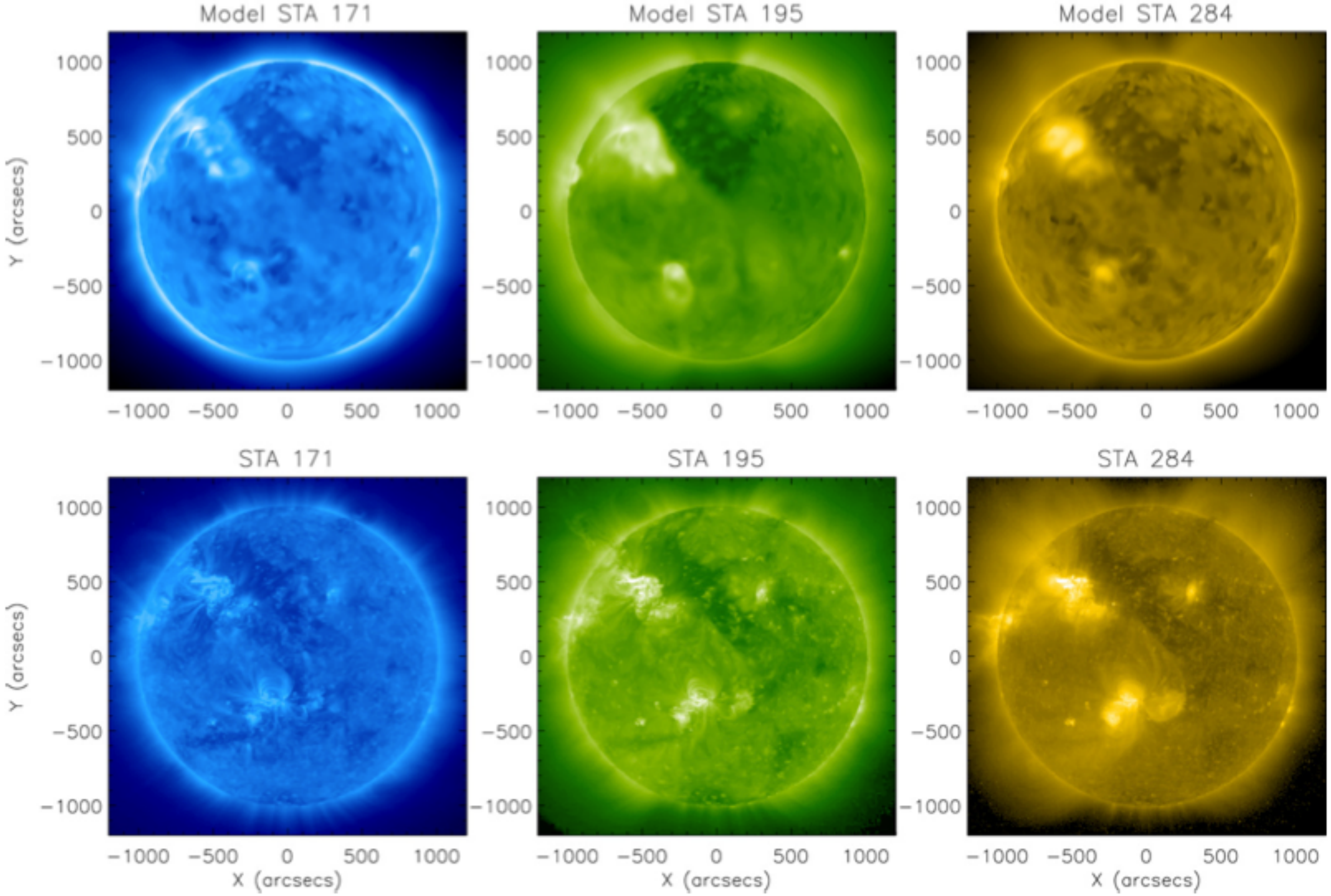


Excess of high frequency power at the apex suggests possible evidence of low/mid frequency waves cascading into Alfvén wave turbulence

3D Global Numerical Models

e.g. Sokolov + (13) - Van der Holst + (14)

Address coronal heating and solar wind acceleration



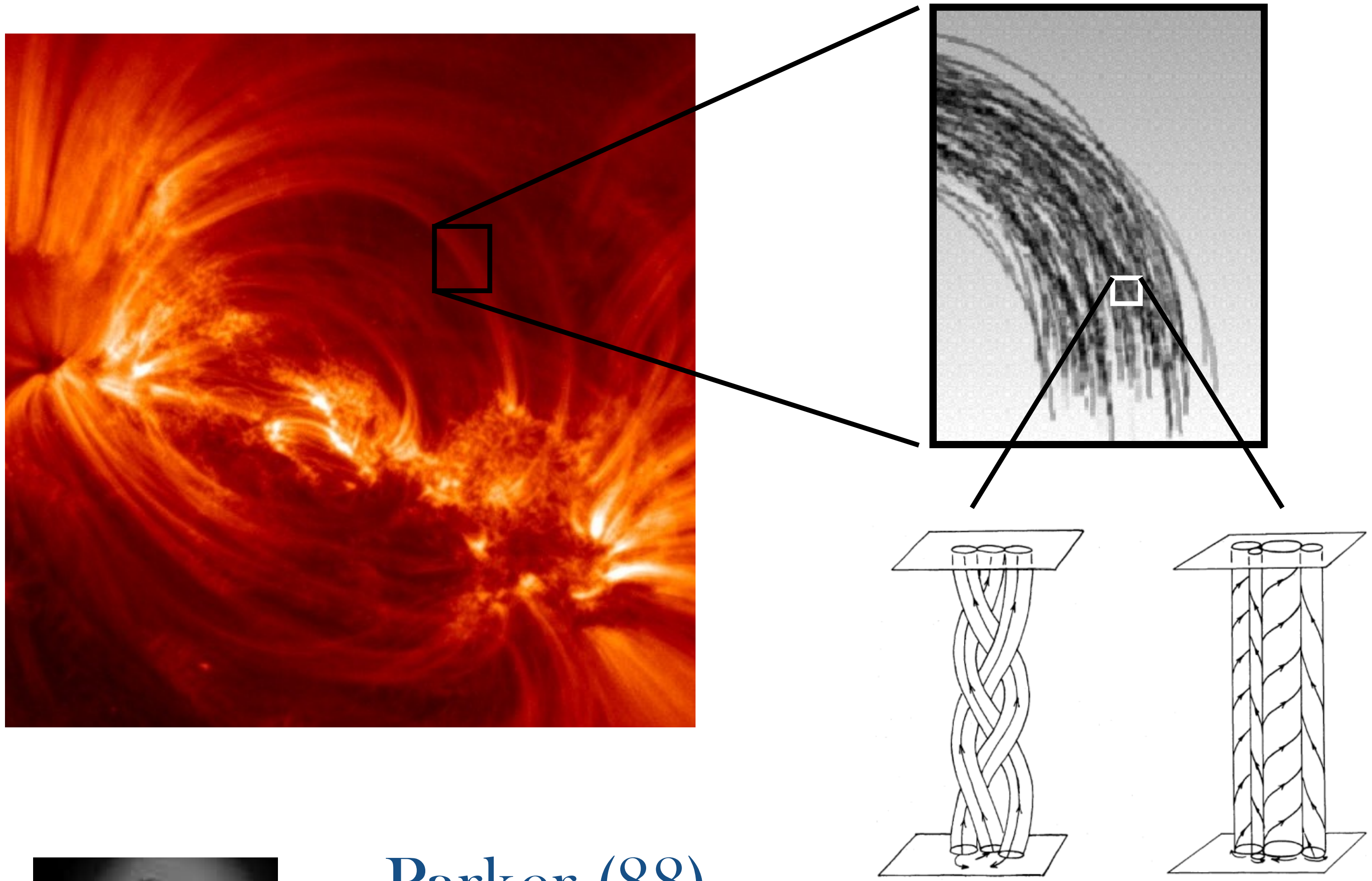
AWSoM

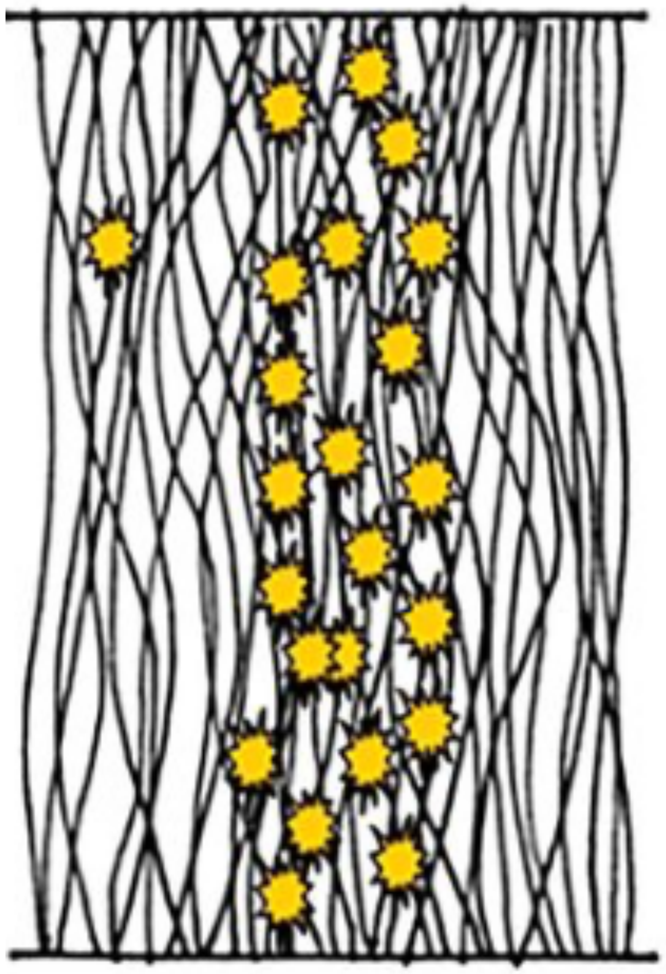
STEREO

Able to reproduce observed EUV emission and produce solar wind predictions

Talk
N. Viall

Nanoflare heating





Parker (88)

Small scale (unobservable) magnetic reconnection event

Converts magnetic energy into plasma motion

Energy gets dissipated by turbulence

Klimchuk (06,15)

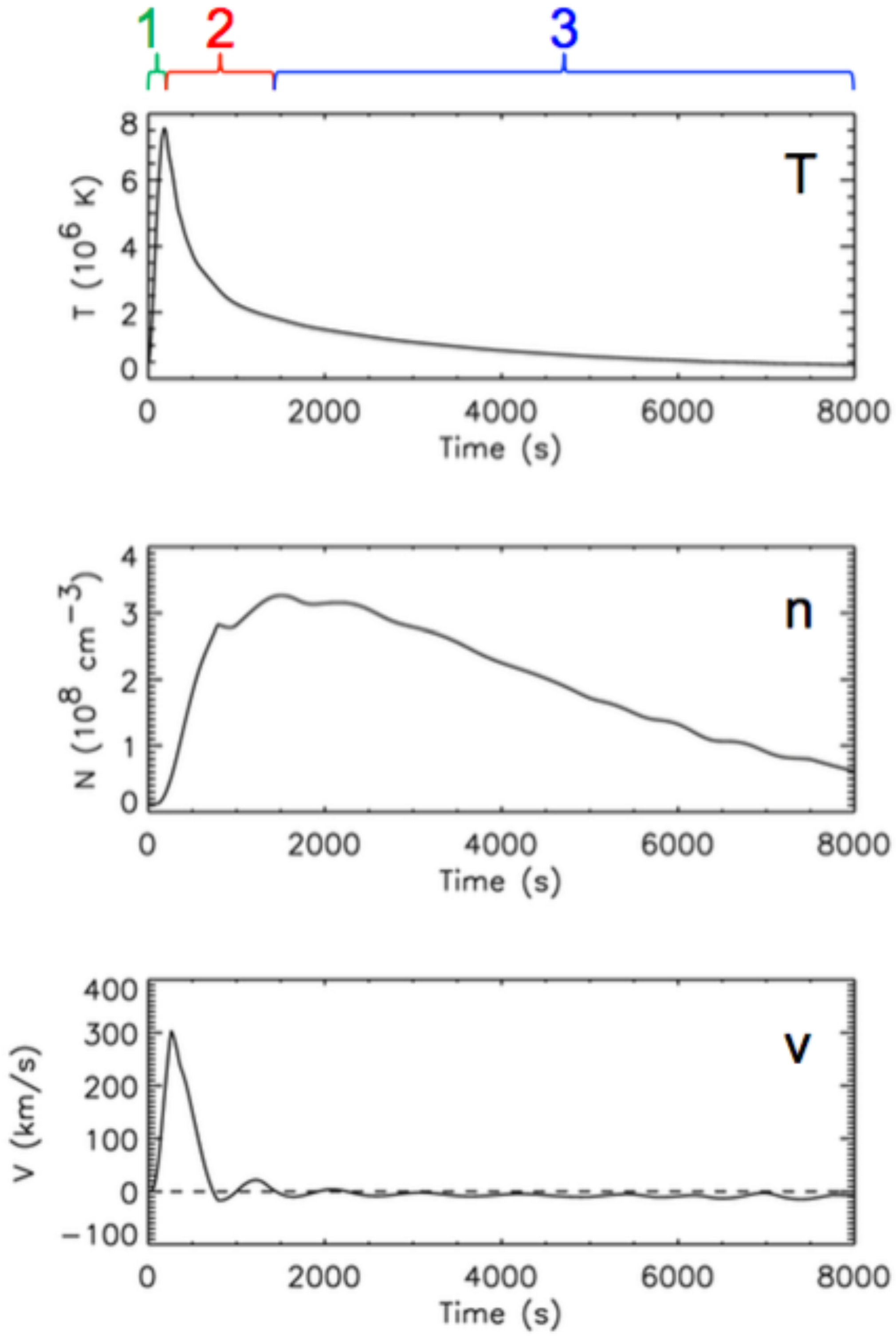
A nanoflare is “an impulsive energy release on a small cross-field spatial scale without regard to physical mechanism”

This definition includes wave heating

Nanoflare Observations

No direct evidence - only indirect but robust signatures

Nanoflare Heating - Modelling



Klimchuk (06)

3 phases

1 Rapid heating

2 Cooling by thermal conduction

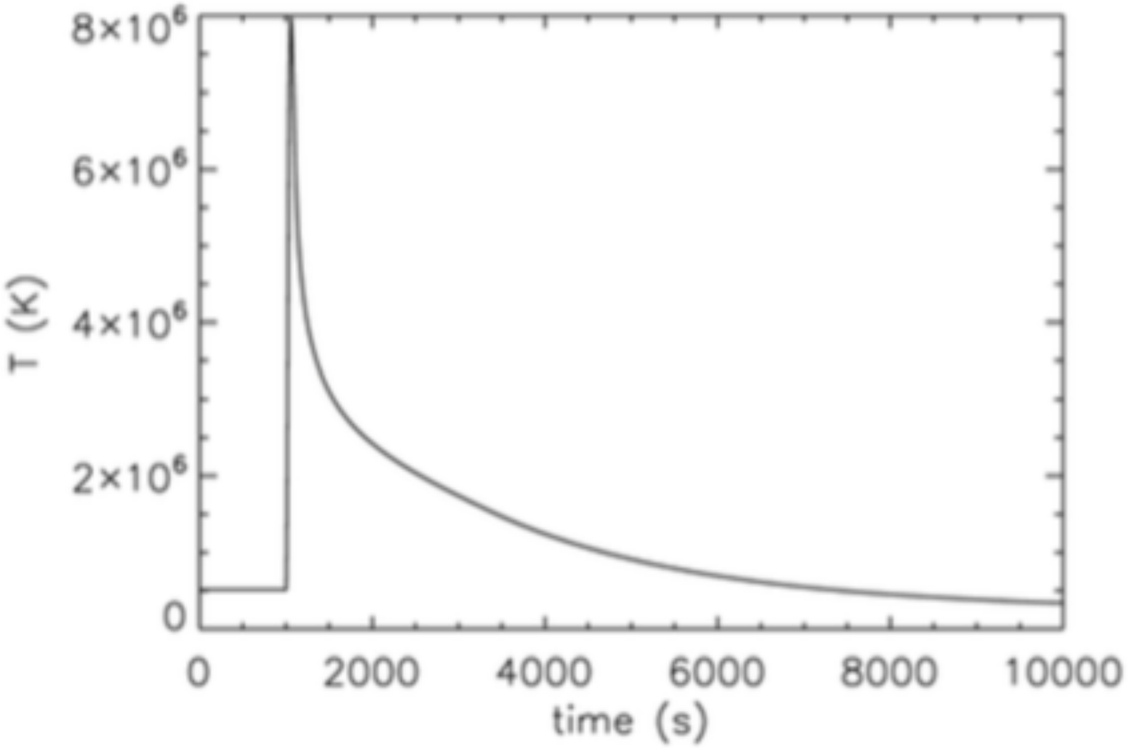
3 Equilibrium between conduction and radiation

A single nanoflare is not enough

Nanoflare Frequency

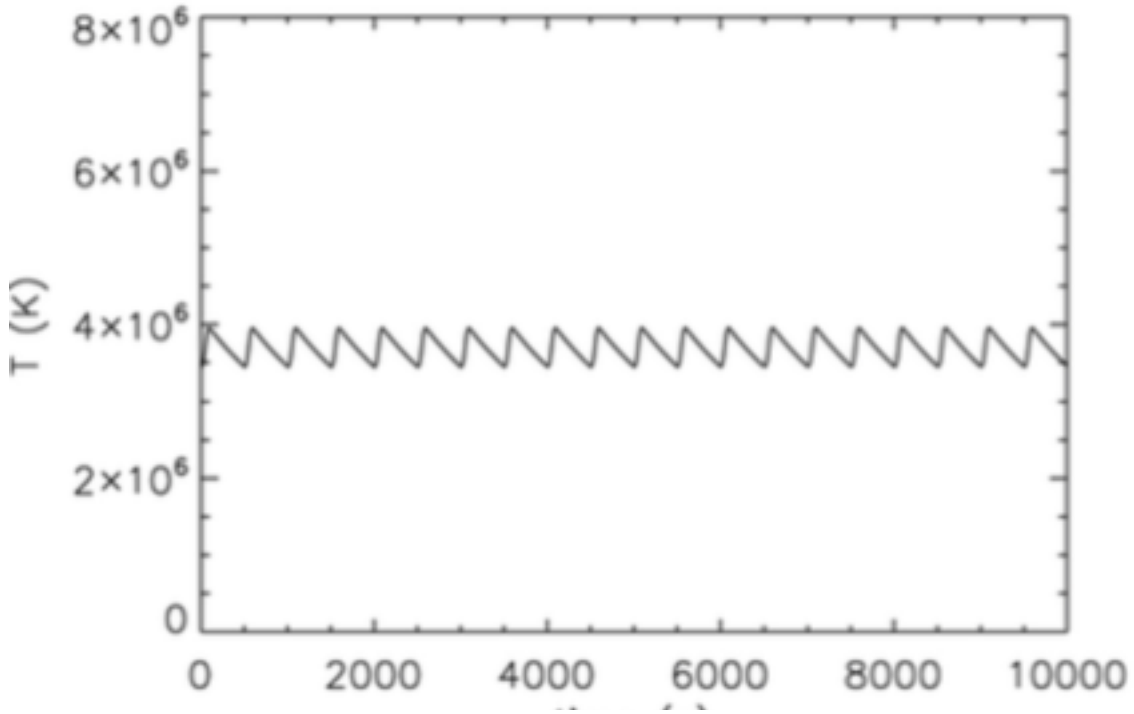
low frequency

repetition time > cooling time



high frequency

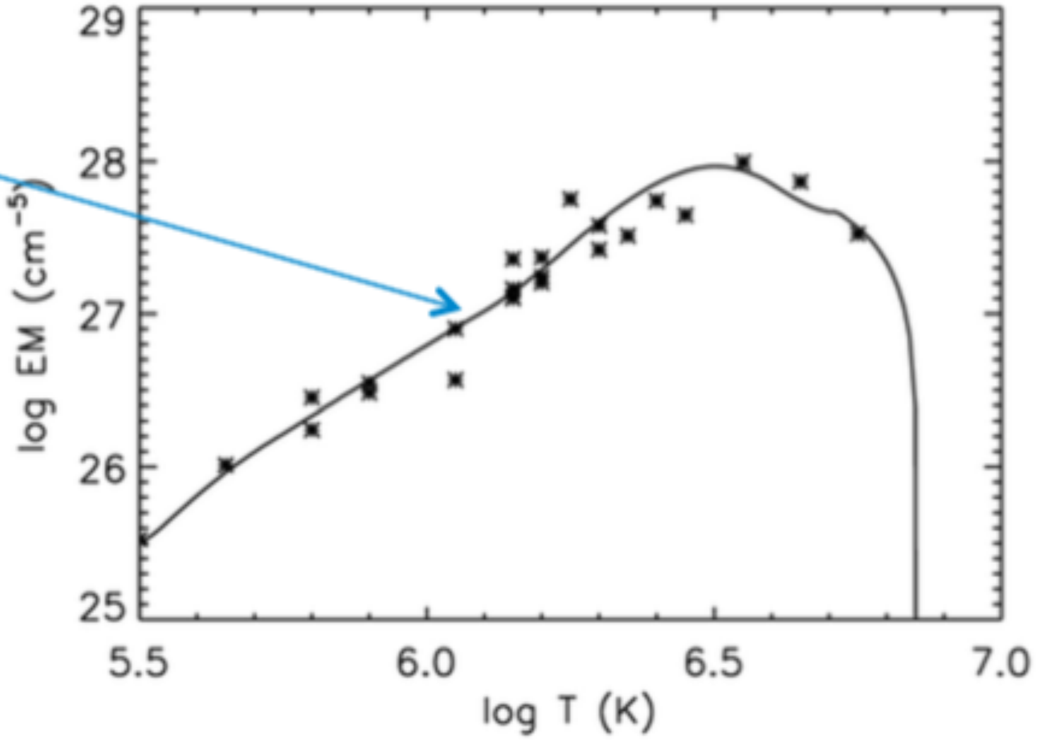
repetition time < cooling time



Analysis of the temperature distribution of the plasma, as a diagnostic tool for the heating frequency

see e.g Guennou et al. (13)

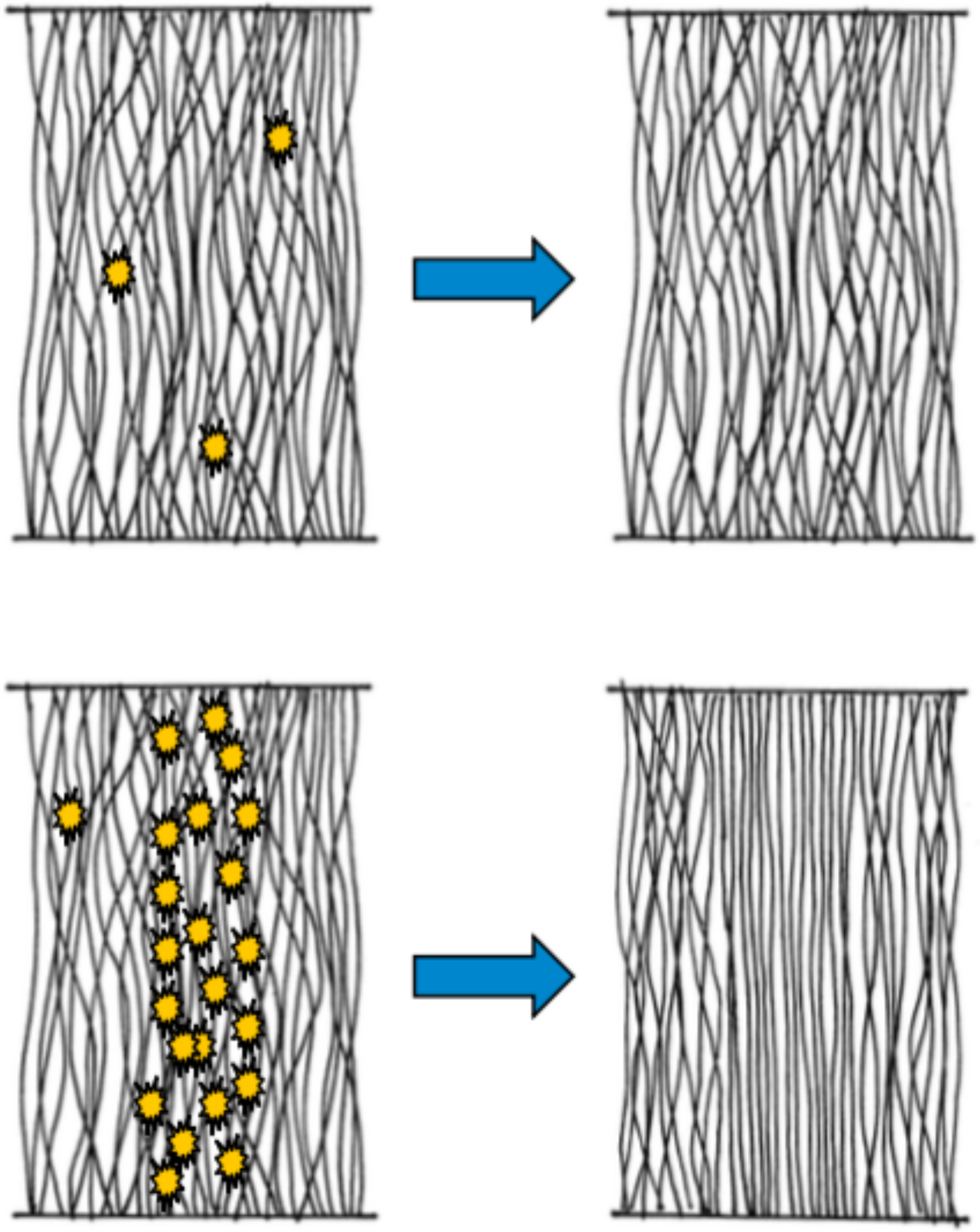
Slope indicates nanoflare frequency



Nanoflare Frequency and Coronal Emission

Klimchuk (15)

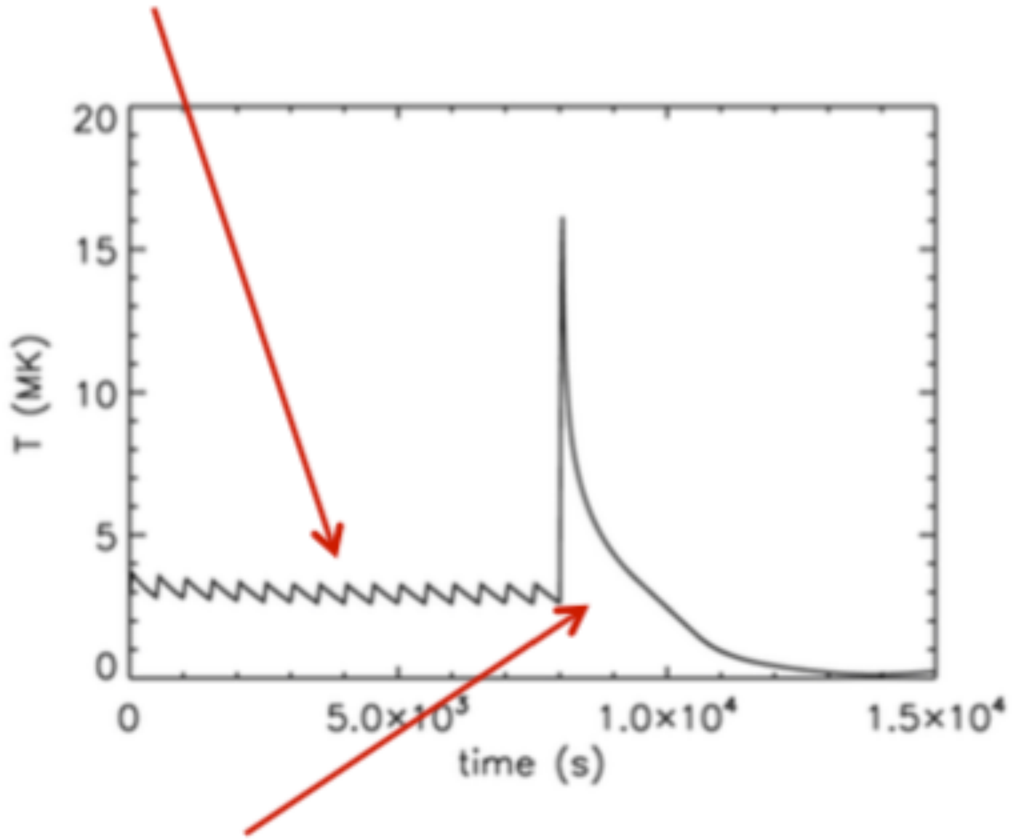
A unifying picture



Nanoflare Storm

Needs time to "recharge"

Diffuse component
(weak, high freq. nanoflares)

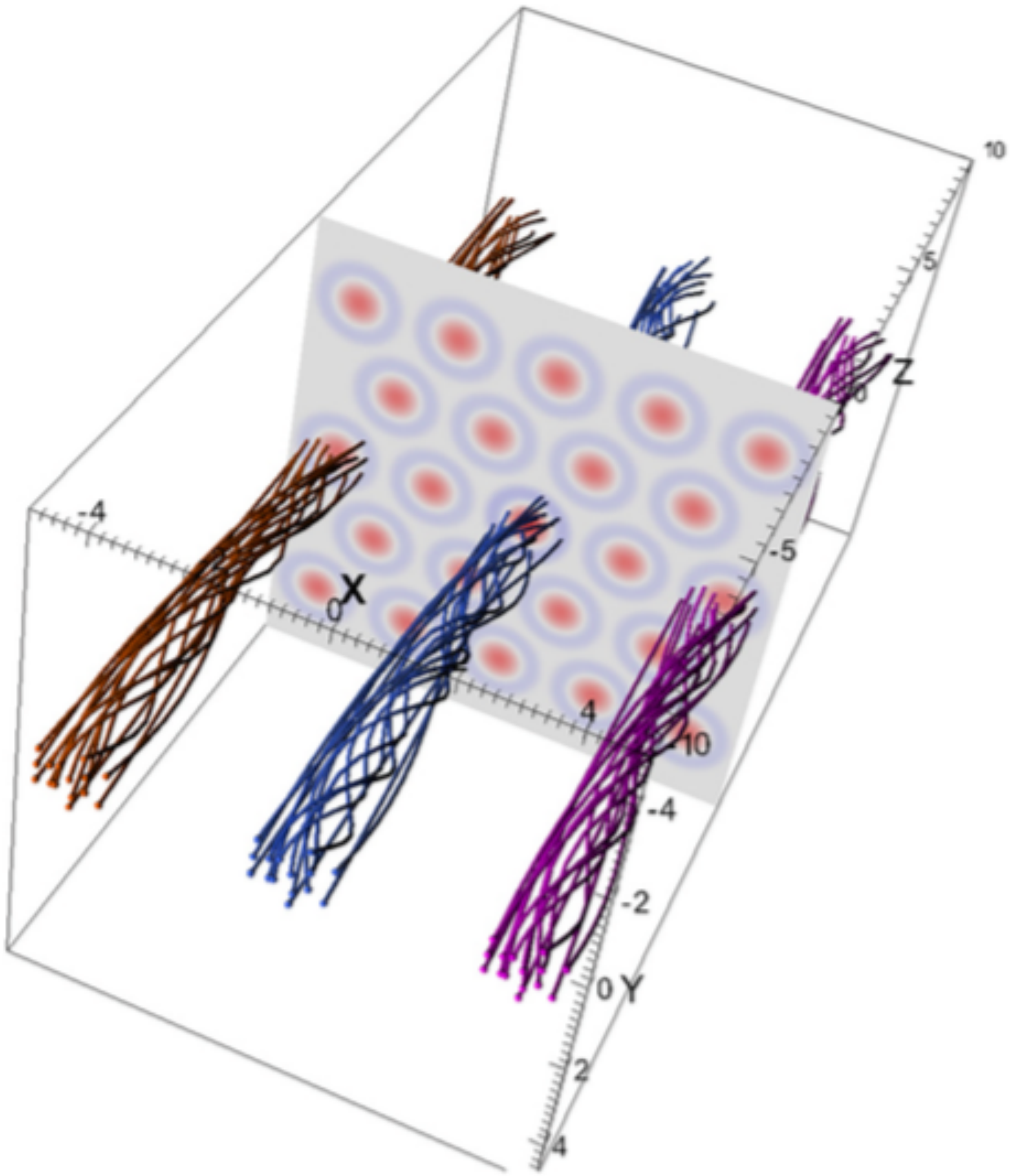


Loop
(strong, low freq. nanoflares)

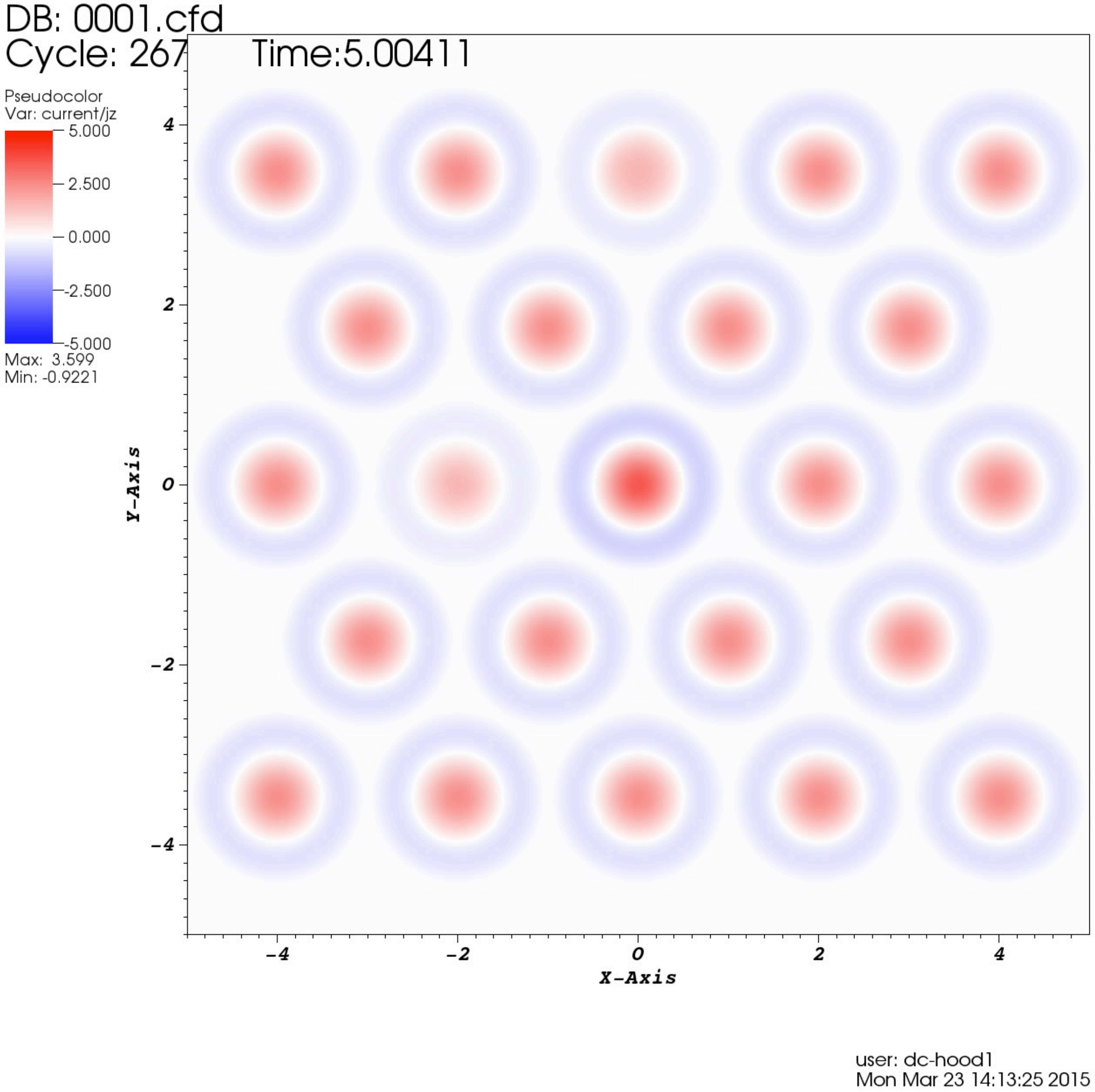
Avalanche of nanoflares

Hood + (2016)

Nanoflares could be a consequence of an instability in cascade among fibrils in multithreaded loops



Time evolution of electric current



Loss of equilibrium in one of them spreads the instability to the remaining fibrils

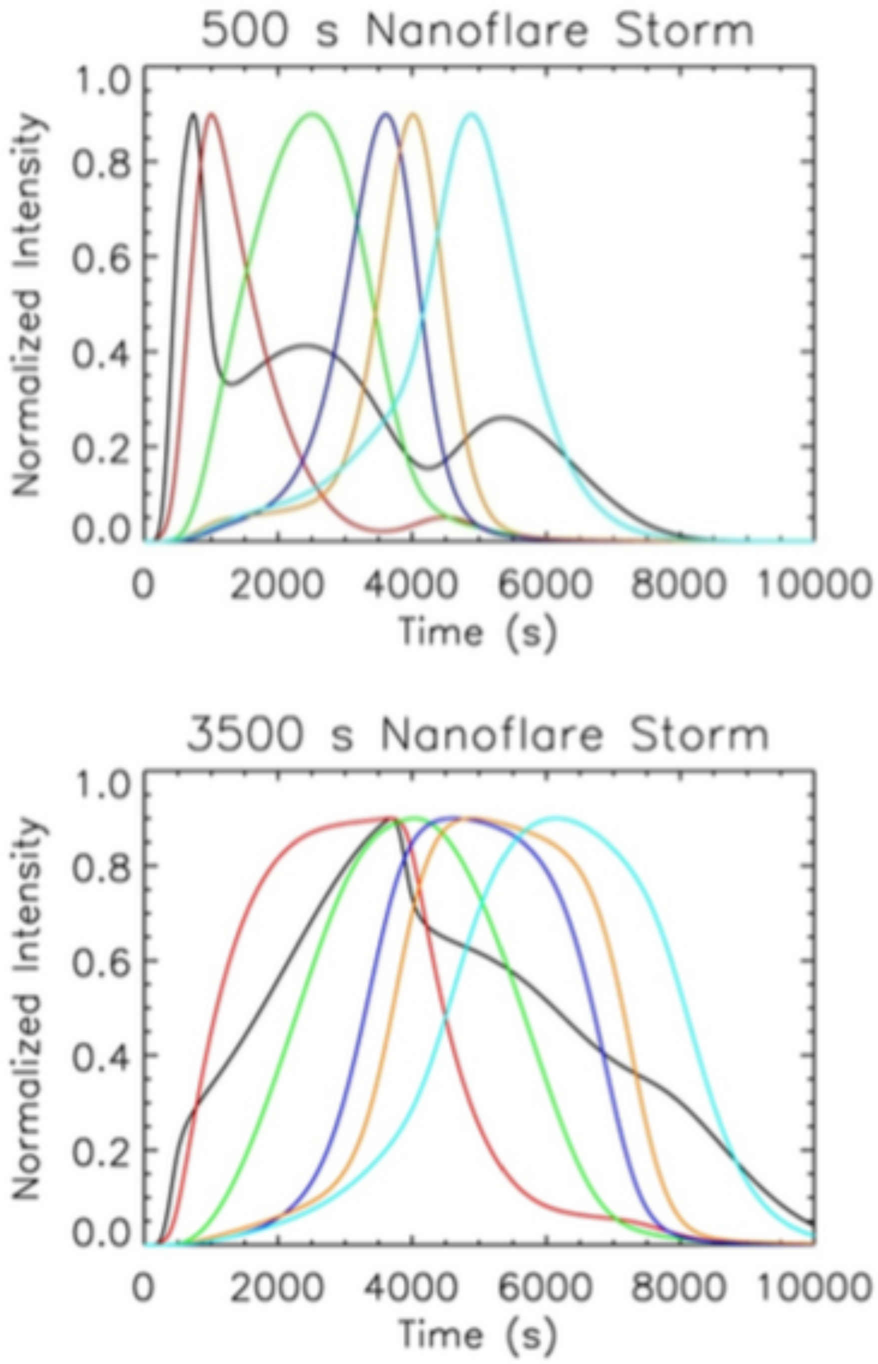
Talk
N. Viall

Nanoflare Heating Signatures

Viall & Klimchuk (11)

Analysis of time-lags between SDO/AIA light curves at different wavelengths

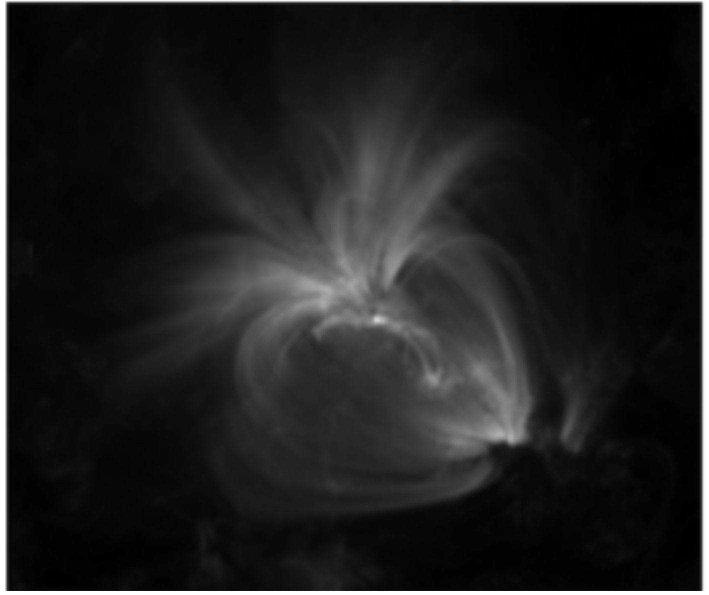
Simulated SDO / AIA light curves



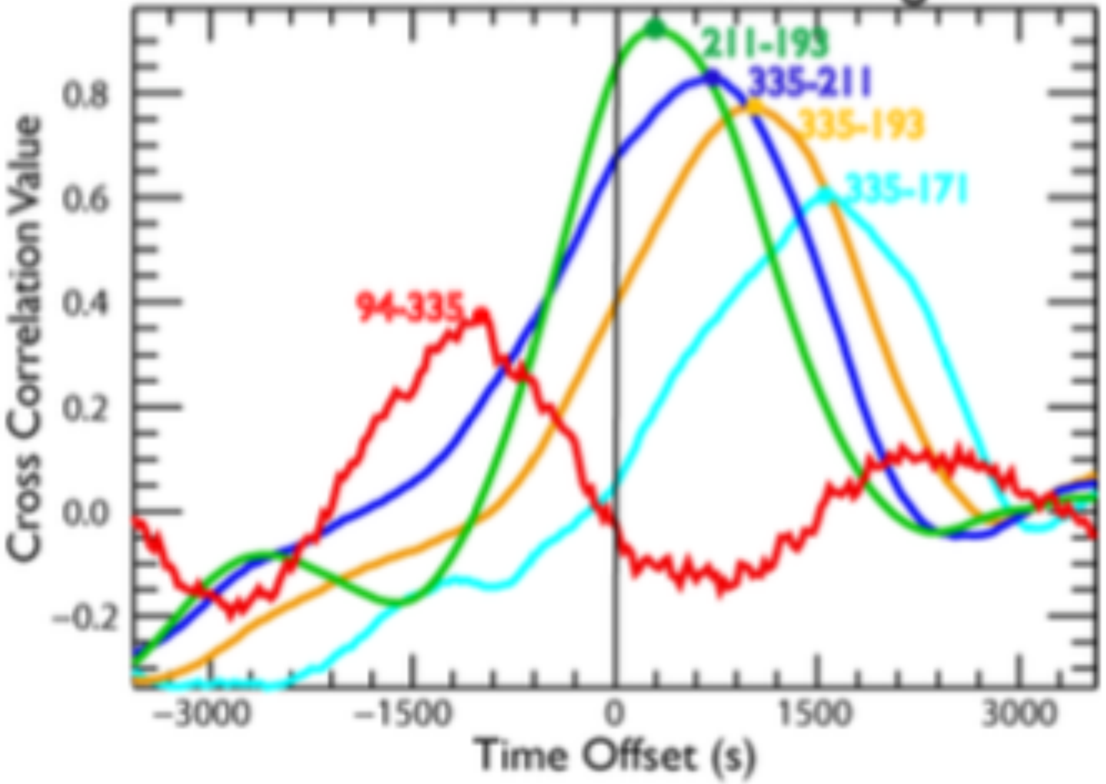
AIA Channels

131 Hot
94
335
211
193
171 Cool

Intensity



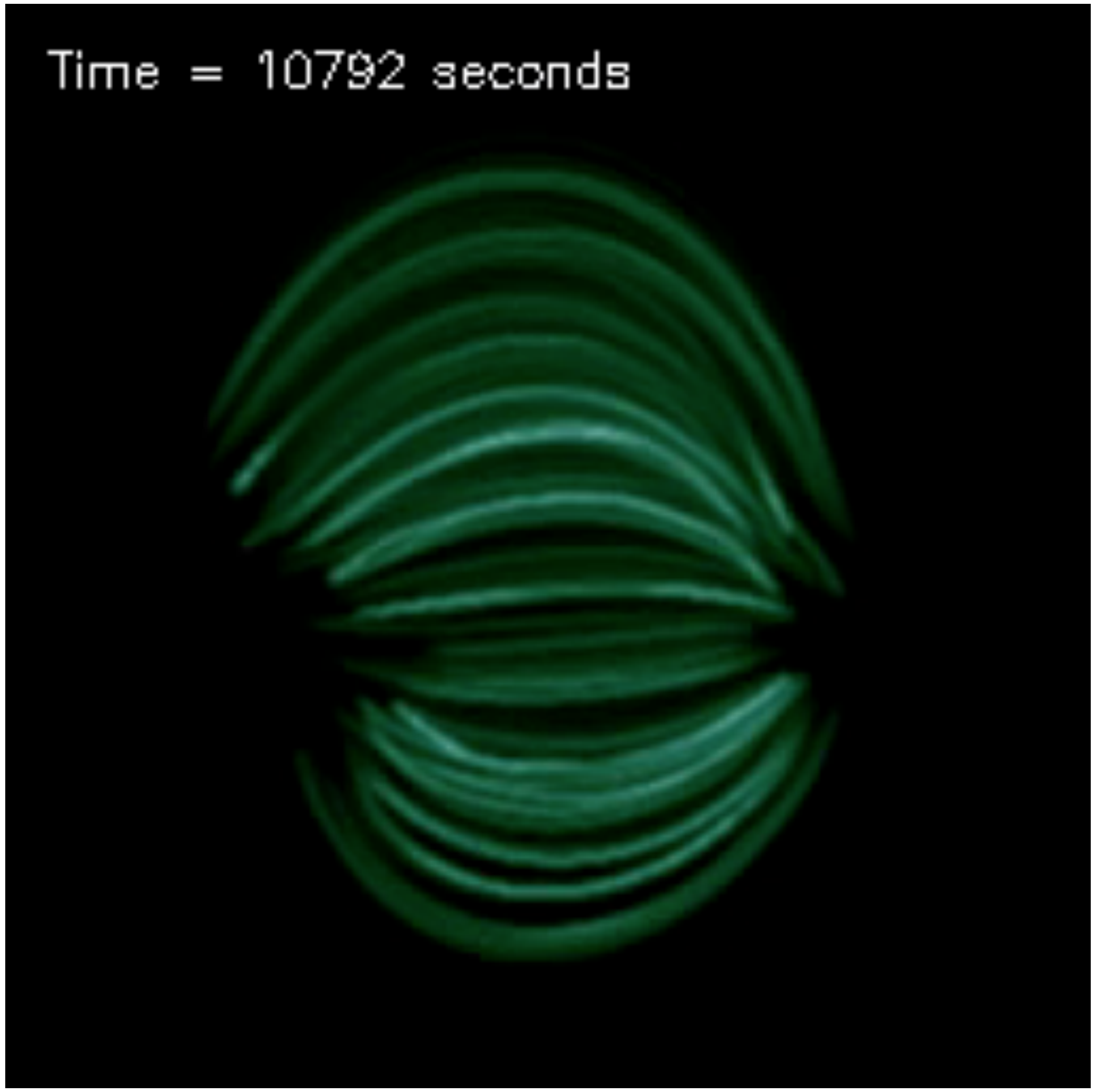
Diffuse Emission Time Lags

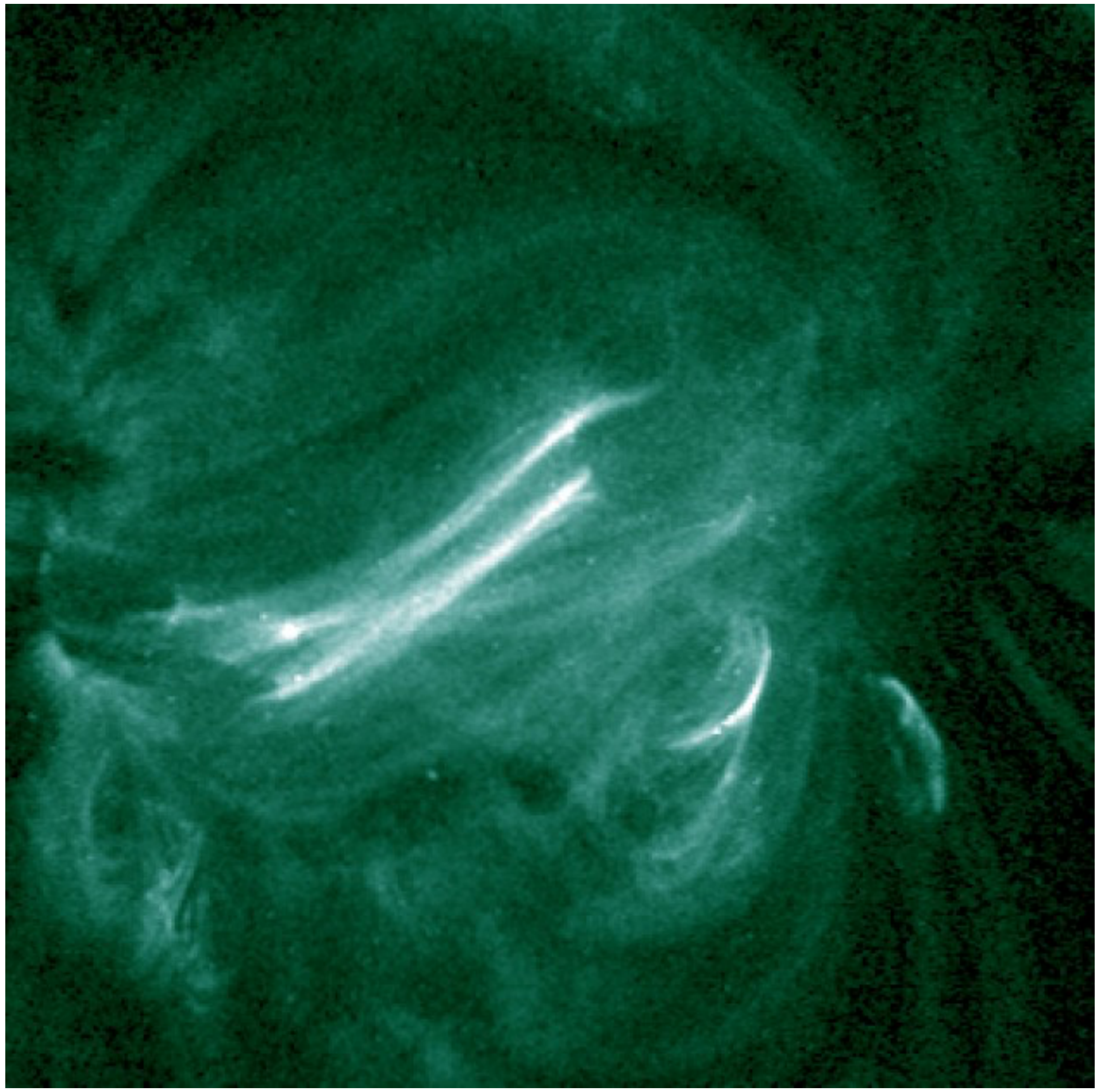


Nanoflare Heating Signatures

Bradshaw & Viall (16)

Forward modelled emission from an active region heated by nanoflares





Synthetic predictions agree (qualitatively) with observed corona

Nanoflare Heating Signatures

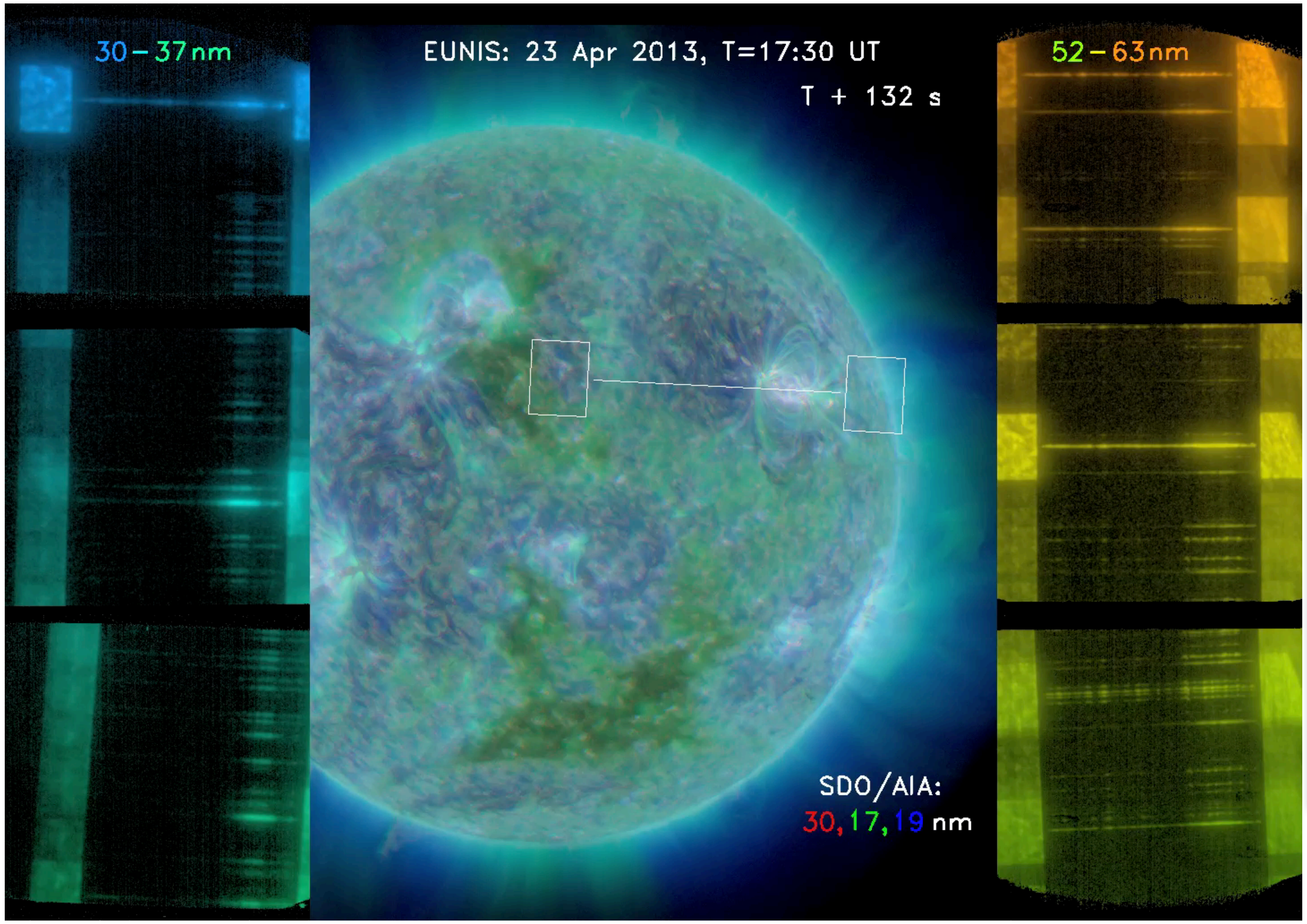
Brosius, Daw, Rabin (13)

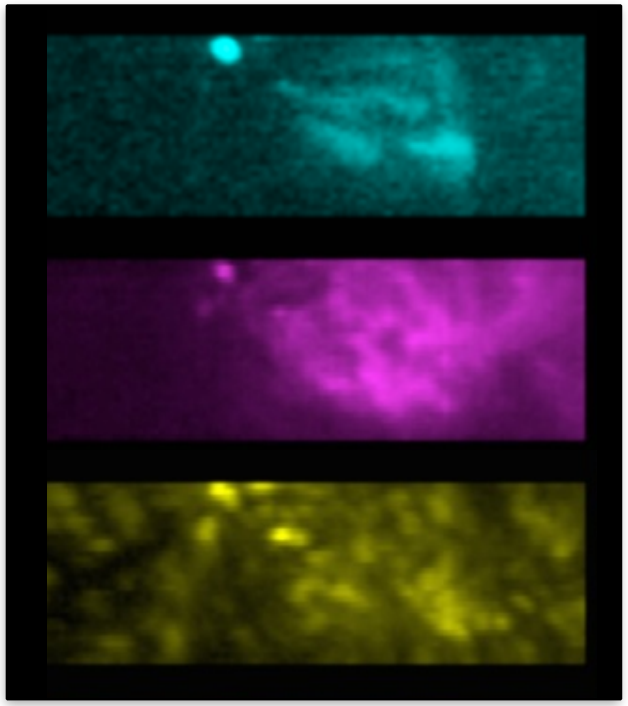
2013 Eunis sounding-rocket observations

EUV Normal Incidence Spectrograph

Detection of FeXIX emission @ 592.12 A

T= 8.9 MK





Superhot corona:
10 MK

1 MK
Corona

Lower Atmosphere:
0.1 MK

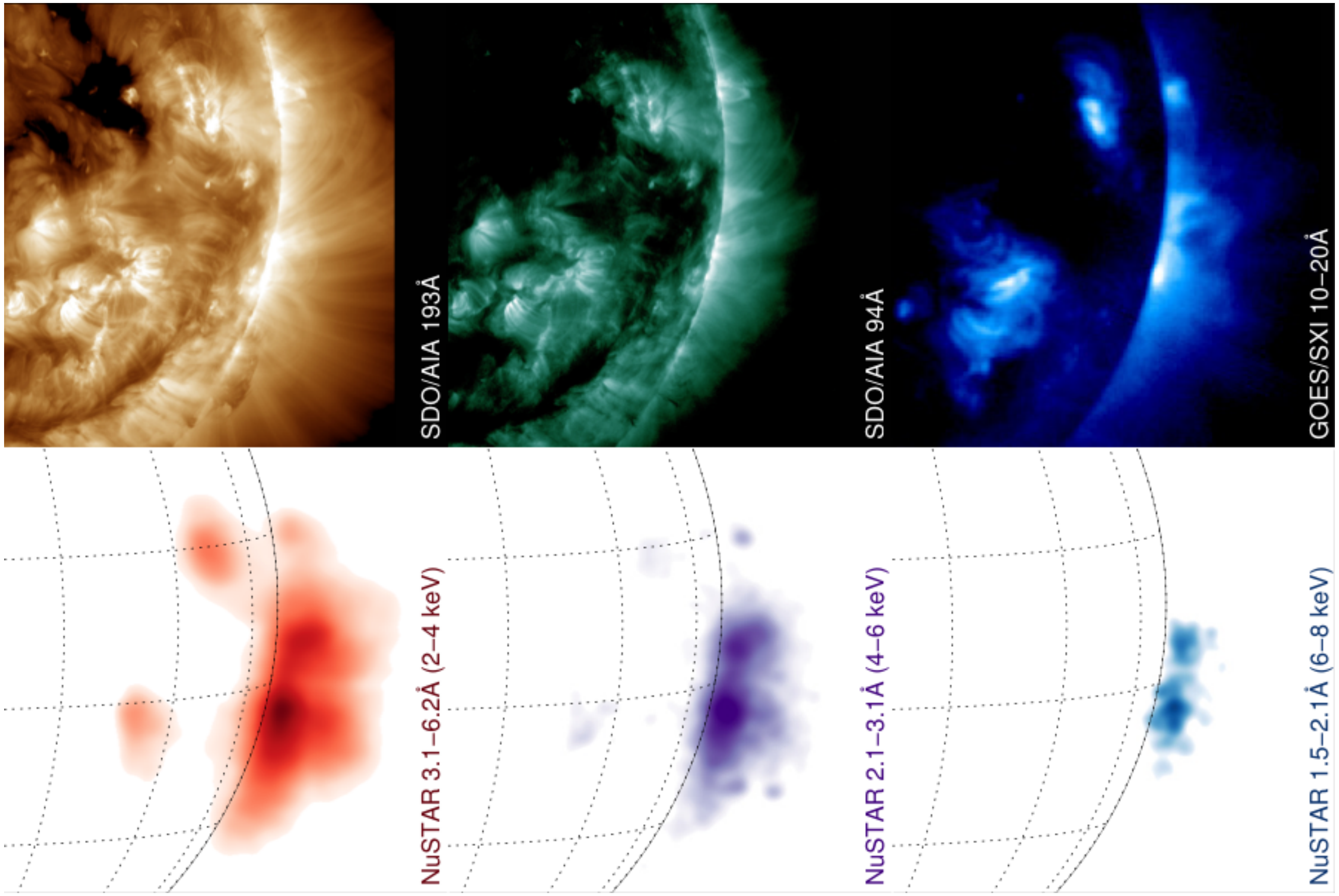
Interpreted as evidence of presence of nanoflare heating

Nanoflare Heating Signatures

Hannah + (16) NuSTAR Nuclear Spectroscopic Telescope Array

Initially designed to explore emission from X-ray sources, such as BHs
NuSTAR ha produced evidence about the presence of nanoflares

EUV SDO/AIA X-rays 2-3 keV 3-5 keV



Summary

Coronal heating problem

- An evolving problem
- We have substituted a single problem by a bunch of problems (including controversies)

Most considered heating theories remain plausible

- Waves present beyond doubt
- Damping quantified / dissipated energy not
- Most models are simple, but robust
- Observational consequences not fully developed

- No direct evidence for nanoflares
- Models are simple
- But observational signatures developed and robust

Comparison between theory and observations is essential

- All mechanisms remain plausible
- Many advances theory and observations
- Need to develop model comparison techniques

all models are wrong, but some are useful - George E. P. Box