United Nations/Azerbaijan Workshop on
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The Sun, Space Weather and Geosphere,
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16:40-17:00

Diagnostics of the pre-flare and pre-eruption magnetic field in the solar corona

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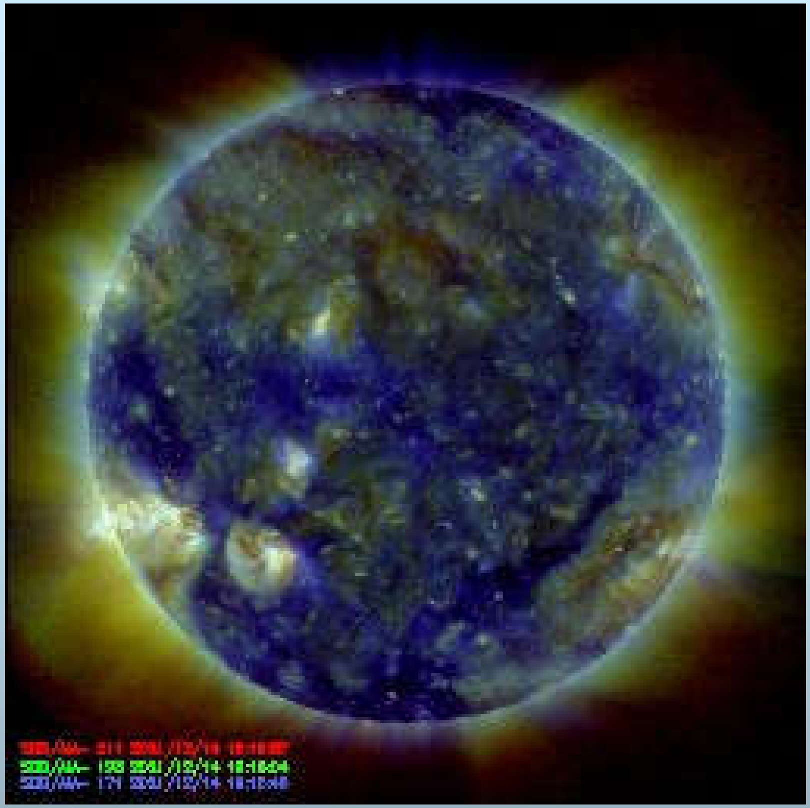
Main unresolved problems of the solar corona:



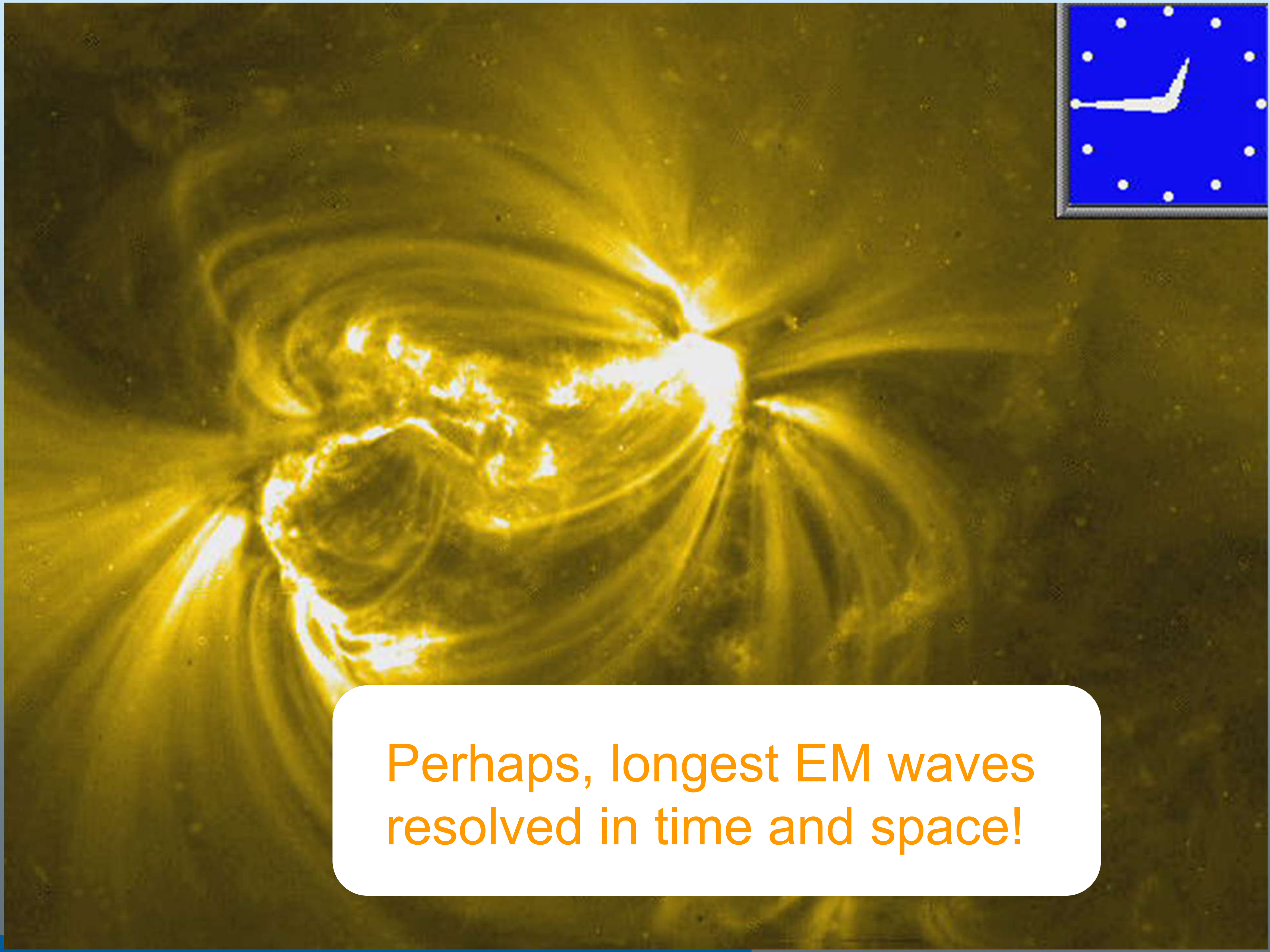
- Why is the corona so hot?
- Why is the magnetic energy released in solar flares so rapidly?
- What does accelerate the solar wind to 1000 km/s?
- Why is the coronal plasma so filamented?

Solving those problems requires detailed diagnostics of physical parameters of the plasma

– could be made by MHD waves (MHD Seismology).

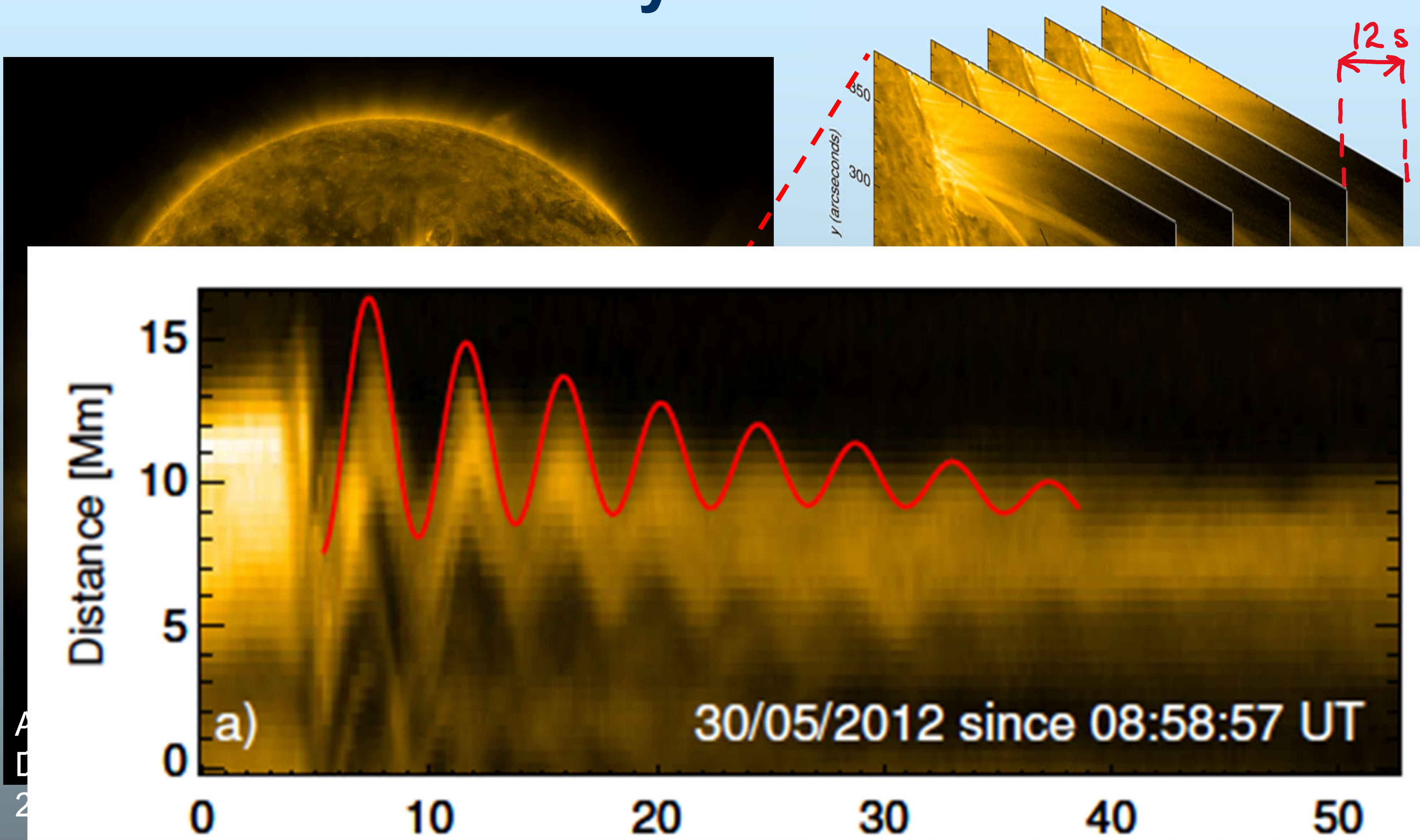
Kink oscillations of coronal loops

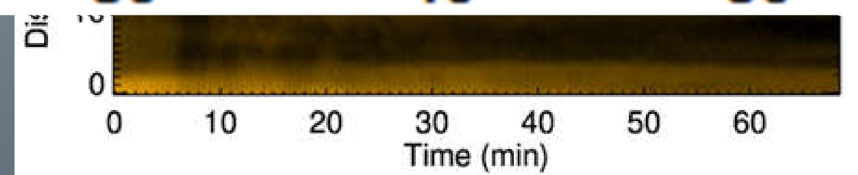
First observation: 14/08/1998
(EUV, TRACE)



Perhaps, longest EM waves resolved in time and space!

Time-distance analysis of kink oscillations





$$y(t) = \xi \cos\left(\frac{2\pi(t-t_0)}{P} - \phi\right)\exp\left(-\frac{t-t_0}{\tau}\right) + f(t),$$

Seismological estimation of the magnetic field by kink oscillations of coronal loops:

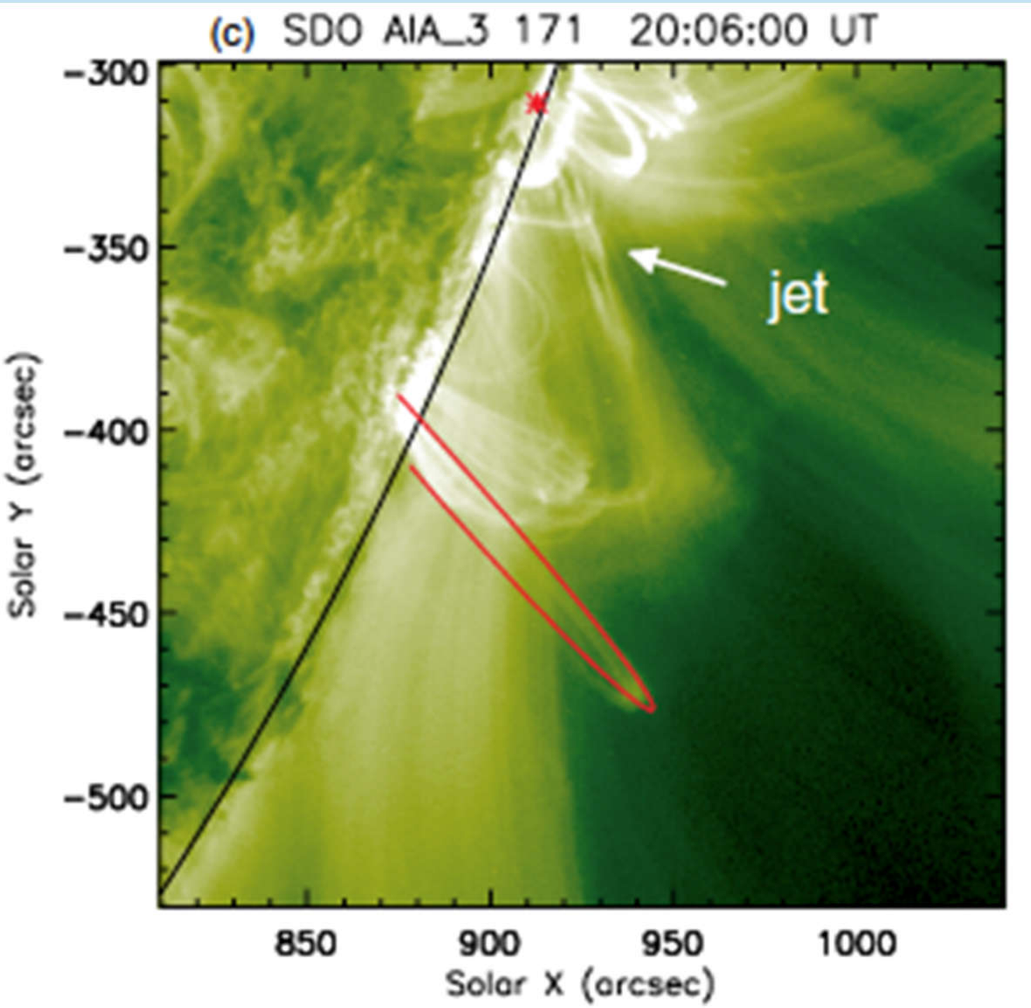
$$B = \sqrt{\mu_0}\,\frac{\sqrt{2}\,L_{\mathrm{loop}}}{P}\sqrt{\rho_i\left(1+\frac{\rho_e}{\rho_i}\right)}$$

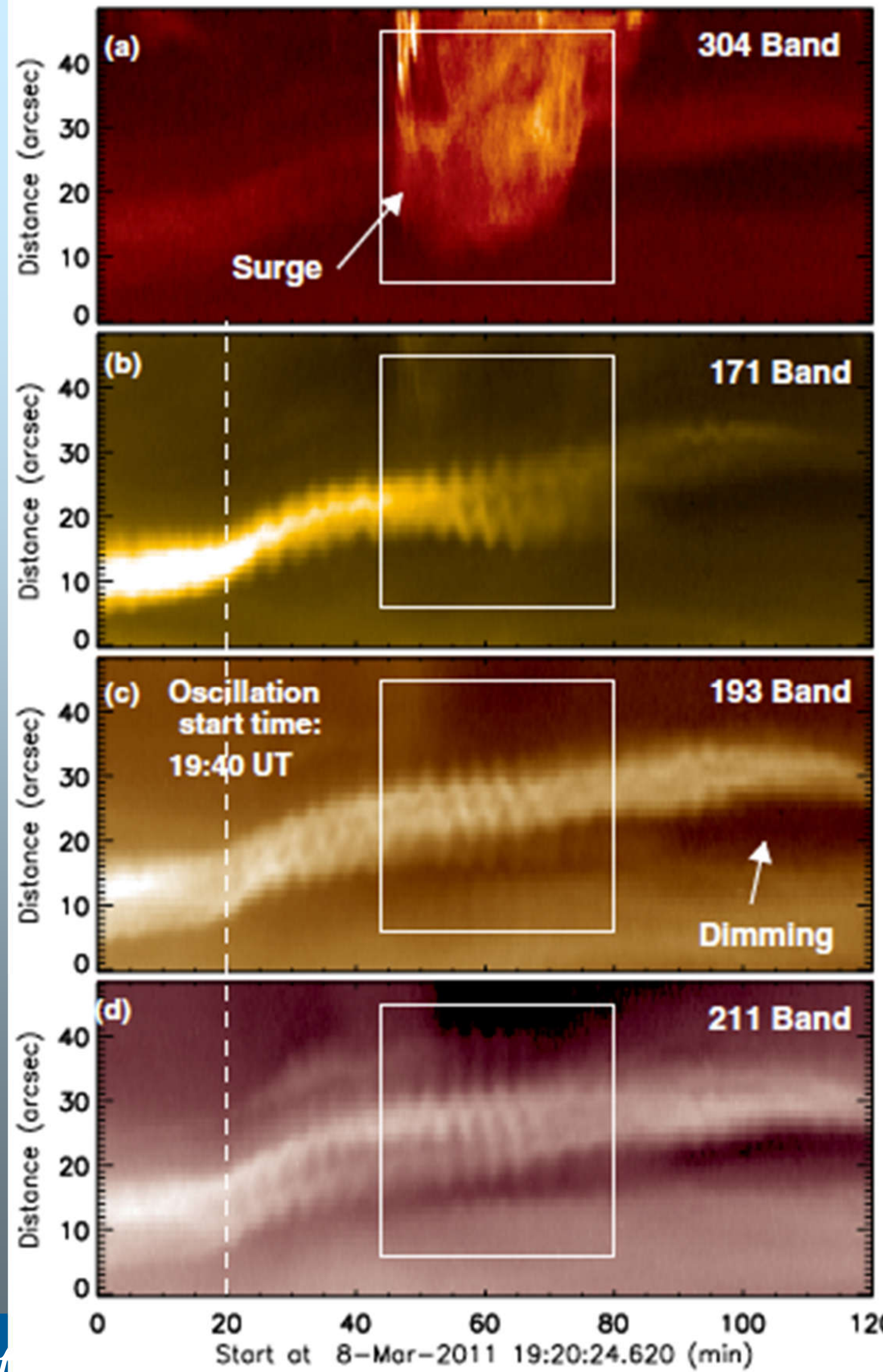
Assuming that

- The loop cross-section is constant;
- There is no stratification;
- There is no twist / sigmoidity.

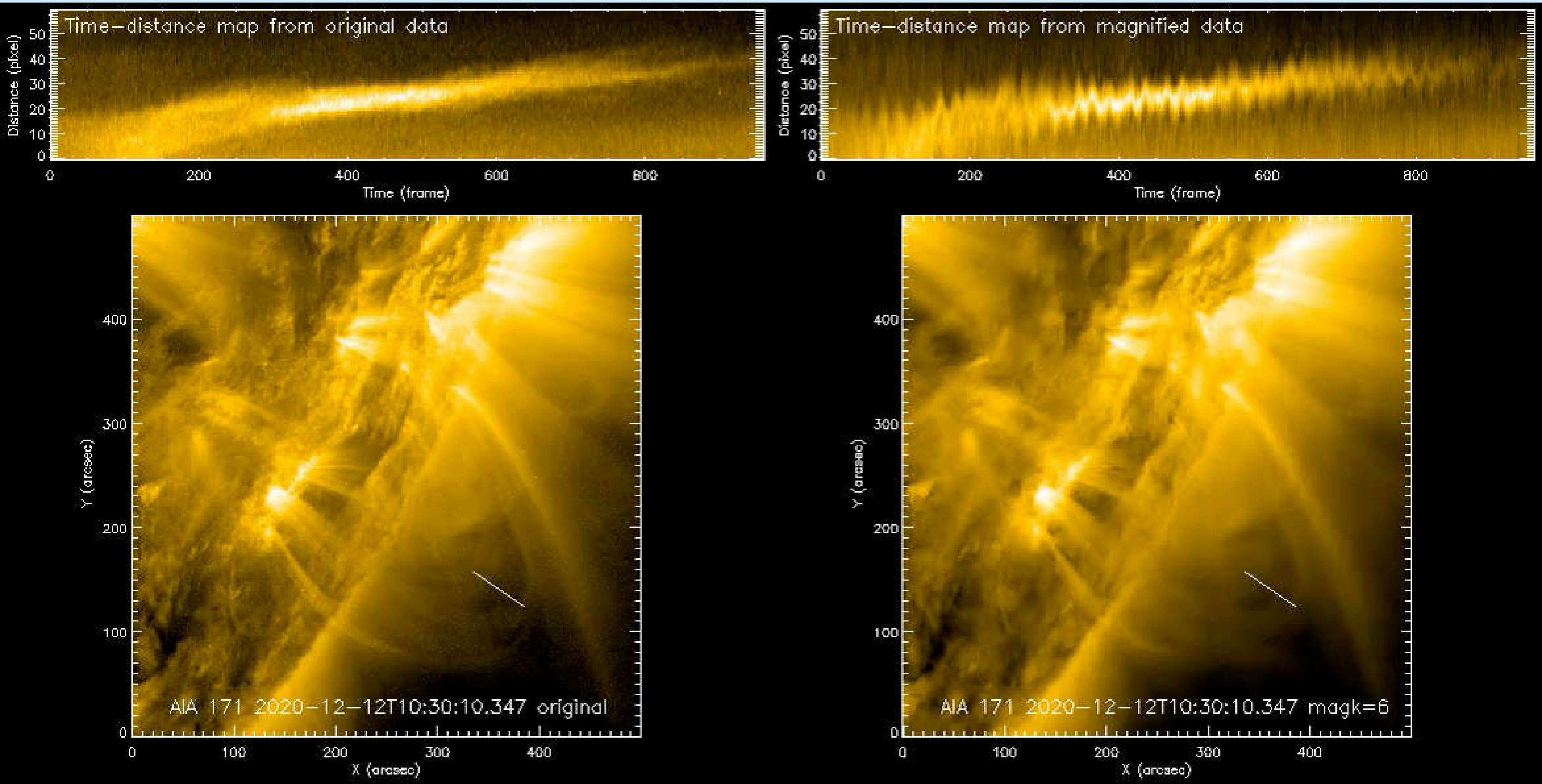
If those conditions are not fulfilled: the field at antinodes.

Decayless regime:



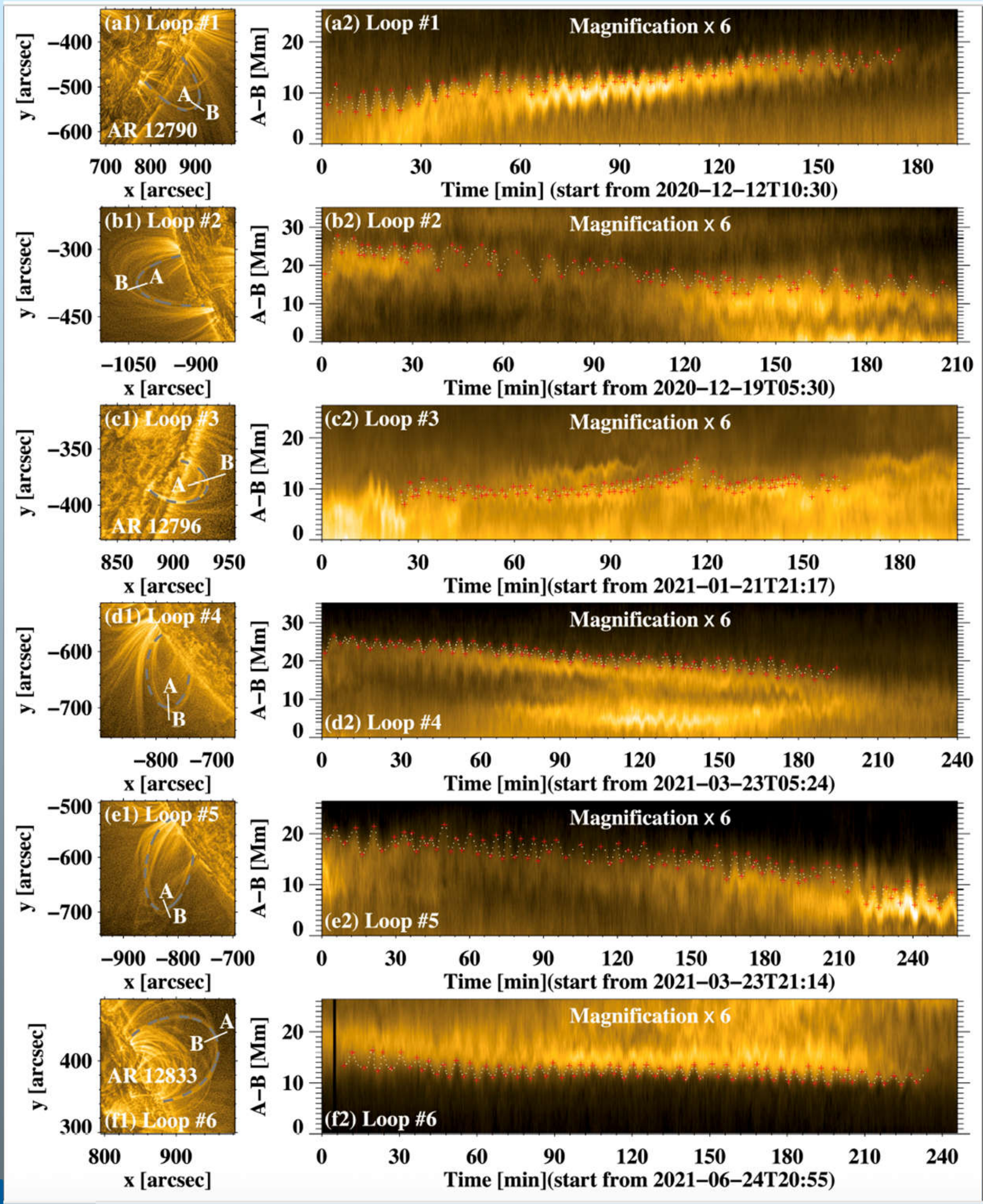


Wang et al. ApJ 751, L27, 2012



The Motion Magnification (MM) technique
(2016SoPh..291.3251A; 2021SoPh..296..135Z)

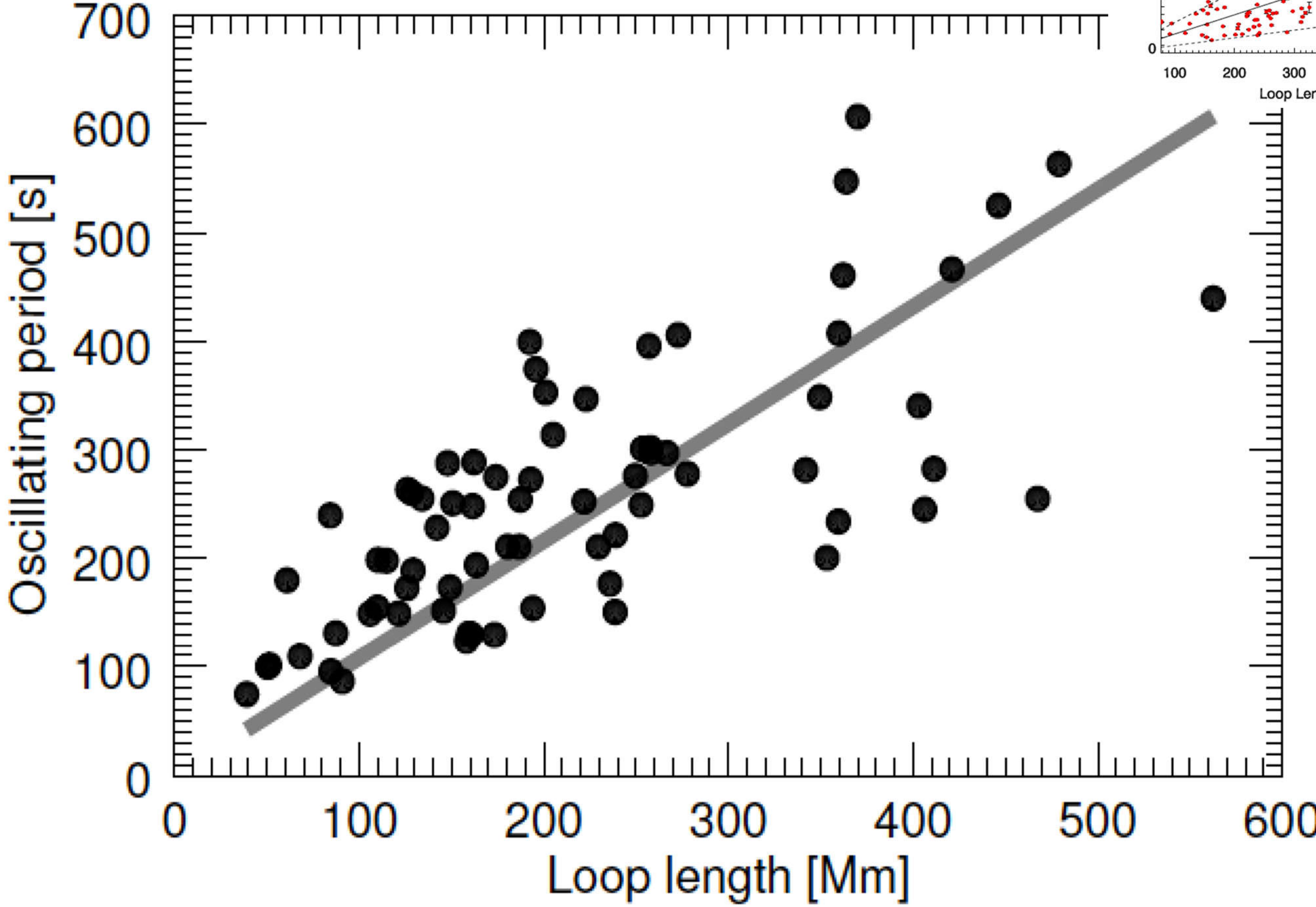
Long-durational evolution of decayless kink oscillations with AIA:

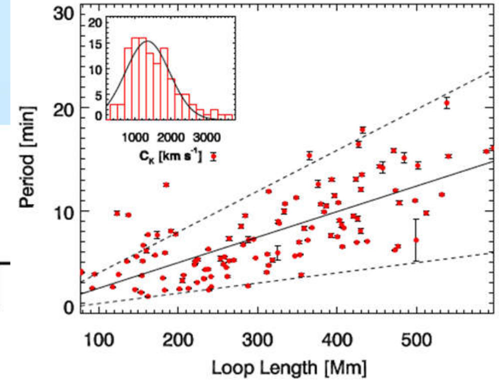


Oscillations last for 38, 38, 48, 40, 47, and 26 cycles without any **systematic** modification of the oscillation pattern or the host loop.

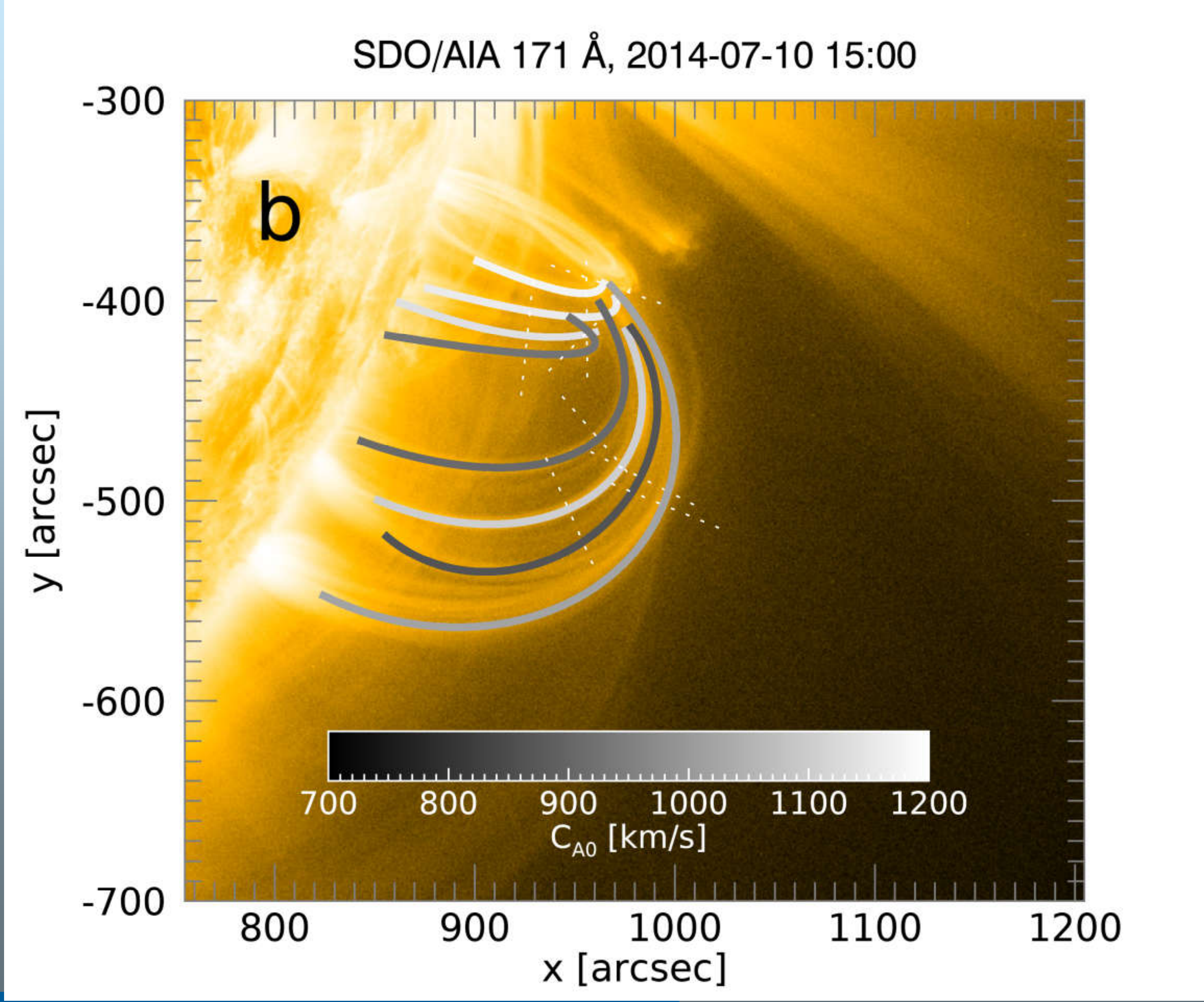
Zhong, S. et al. Long-term evolution of decayless kink oscillations of solar coronal loops, *MNRAS* **513**, 1834, 2022

The parameters of oscillating loops





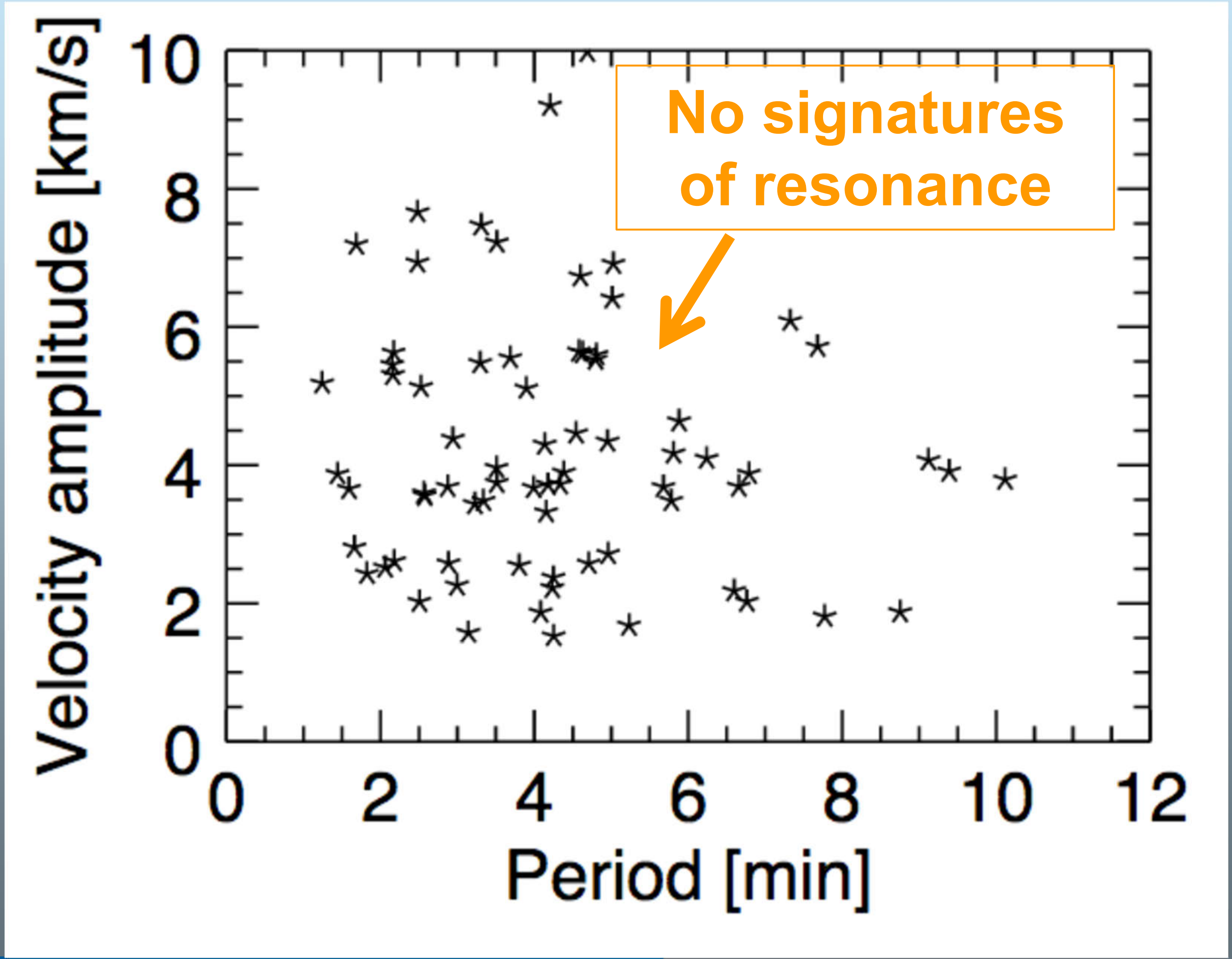
Seismology of a "quiet" active region by decayless oscillations: **Alfvén speed map of AR**



Anfinogentov & Nakariakov *ApJL* **884**, L40, 2019

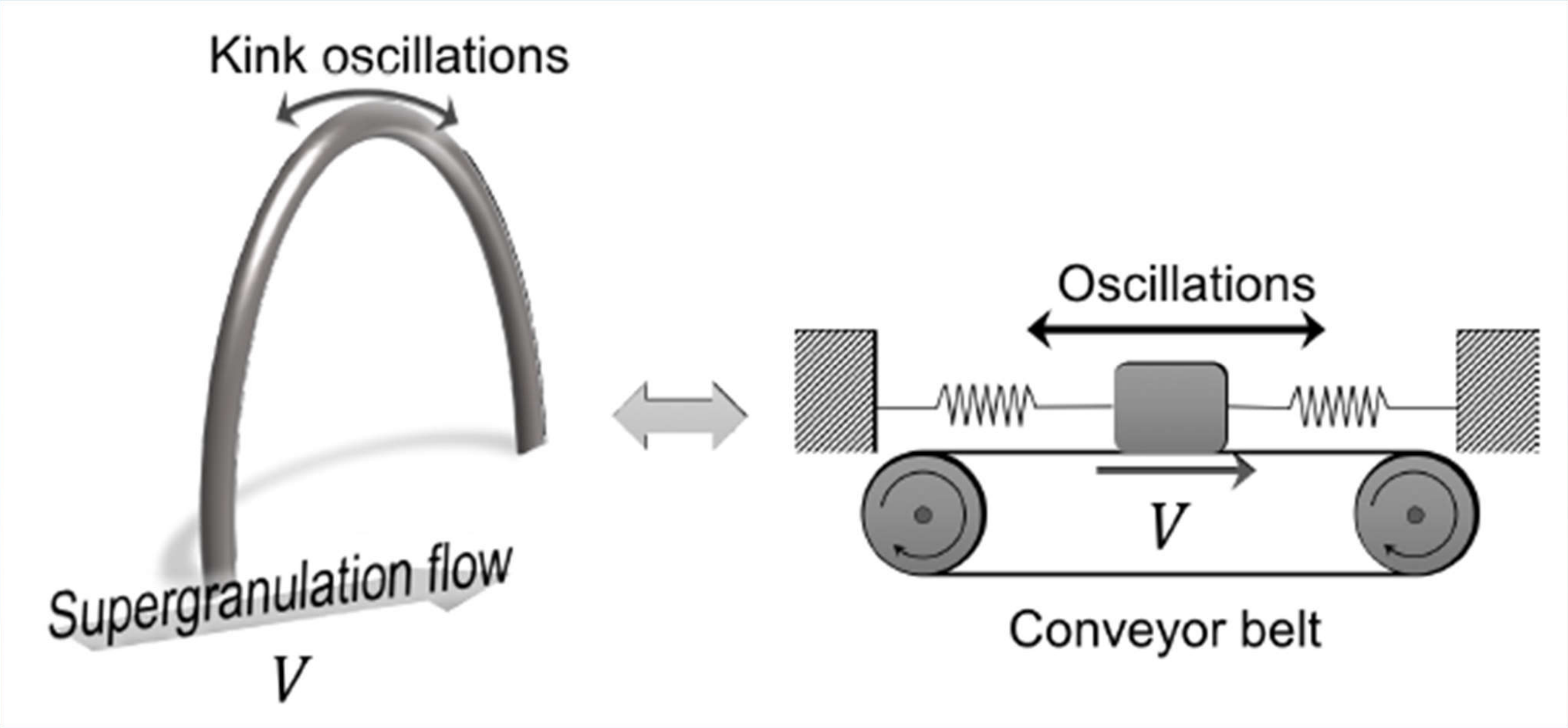
Demonstration that the decayless kink oscillations are not excited by the leakage of p-modes or 3-min oscillations:

Nakariakov et a., A&A 591, L5, 2016

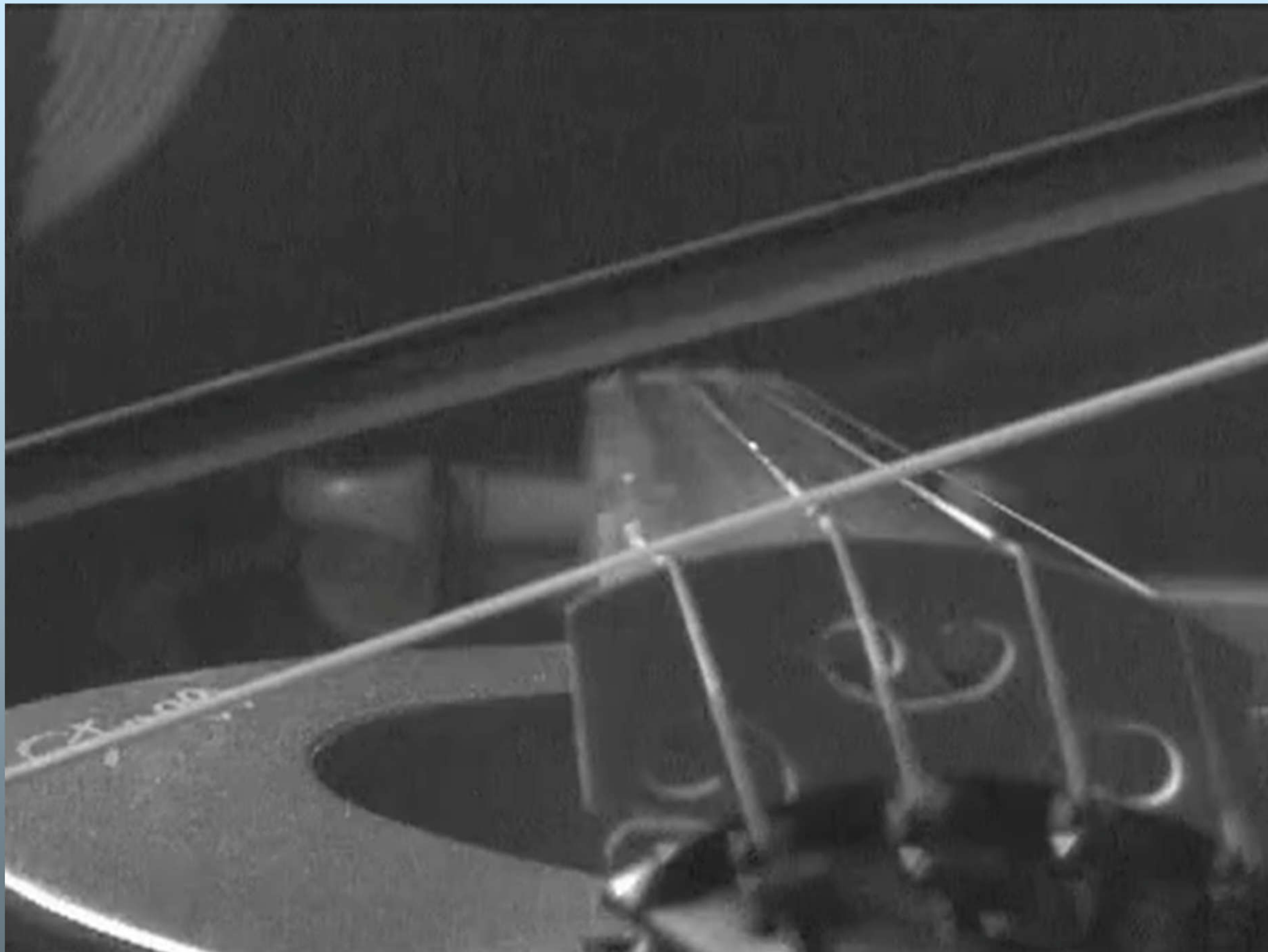


Decayless kink oscillations can be **self-oscillations**:

In contrast with driven oscillations, a self-oscillator itself sets the **frequency** and **phase** with which it is driven, **keeping the frequency and phase** for a number of periods.



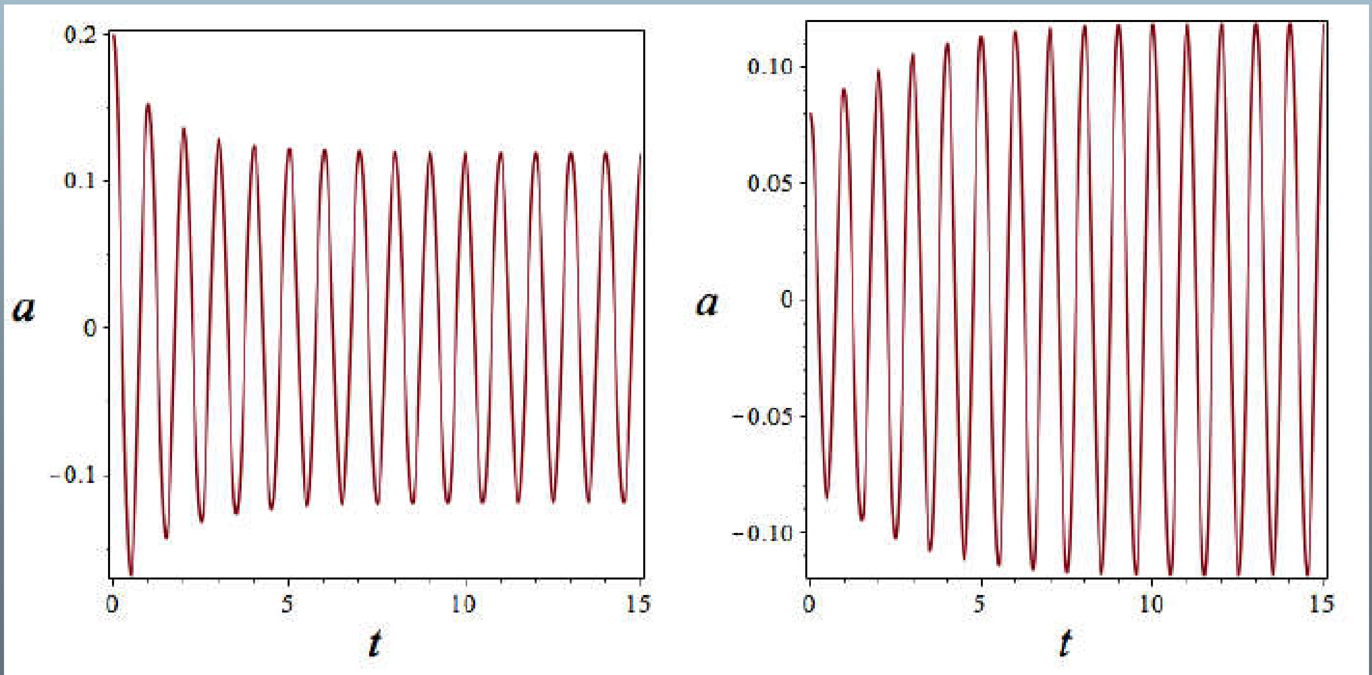
An example of a self-oscillatory system: violine



$$\frac{d^2a(t)}{dt^2} + \delta\frac{da(t)}{dt} + \Omega_{\mathrm{K}}^2 a(t) = F\left(v_0 - \frac{da(t)}{dt}\right)$$

Rayleigh Eq.:

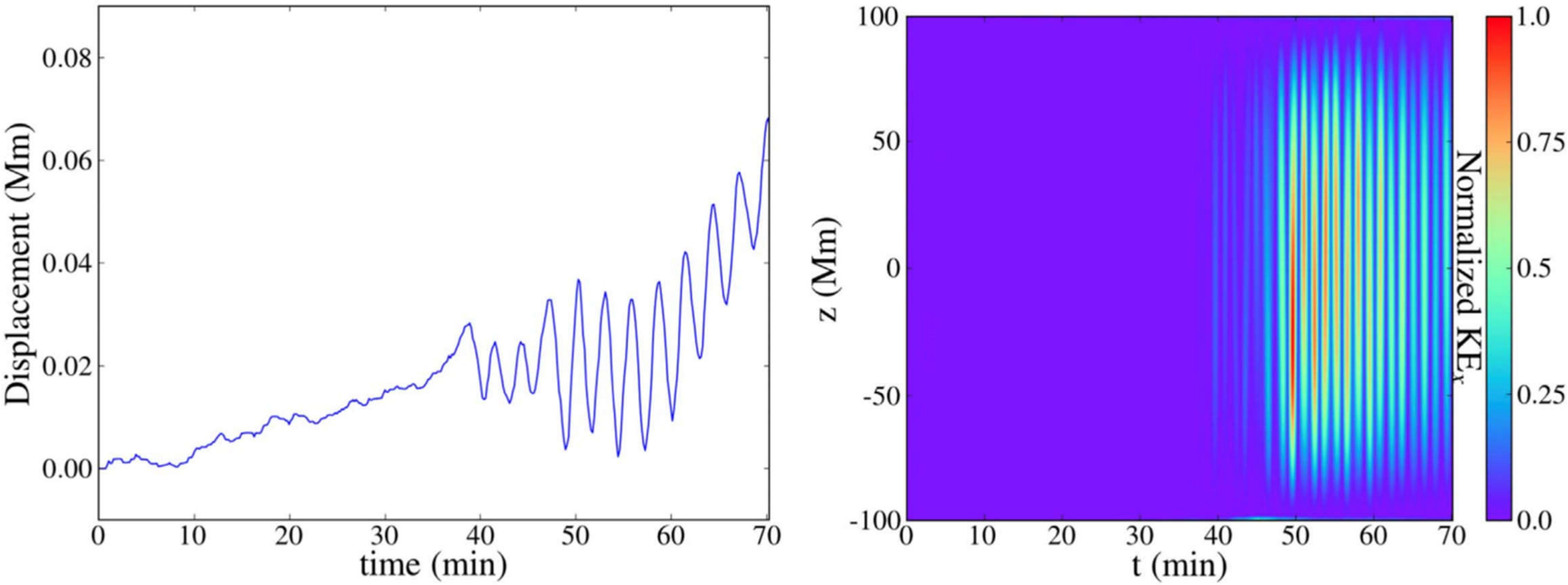
$$\frac{d^2a(t)}{dt^2} - \left[\Delta - \alpha\left(\frac{da(t)}{dt}\right)^2\right]\frac{da(t)}{dt} + \Omega_{\mathrm{K}}^2 a(t) = 0$$



$$a_\infty = \sqrt{\frac{4\Delta}{3\alpha\Omega_K^2}}$$

Karampelas & Van Doorsselaere 2020ApJ...897L..35K

3D simulations of kink self-oscillations:



Thus, it works!

Does this formula work in the presence of noise?

$$B = \sqrt{\mu_0}\,\frac{\sqrt{2}\,L_{\mathrm{loop}}}{P}\sqrt{\rho_i\left(1+\frac{\rho_e}{\rho_i}\right)}$$

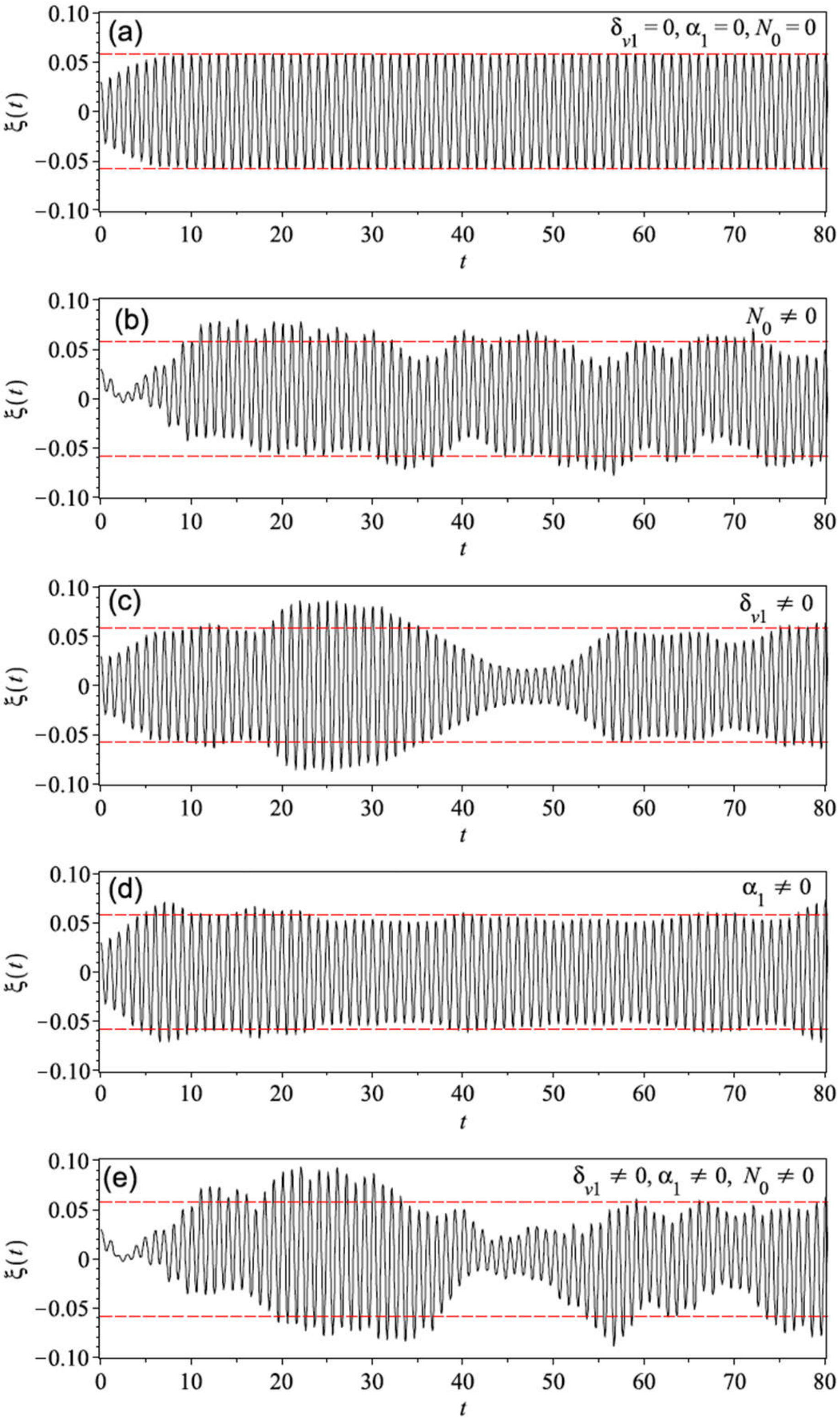
Generalised model (self-oscillations + noise):

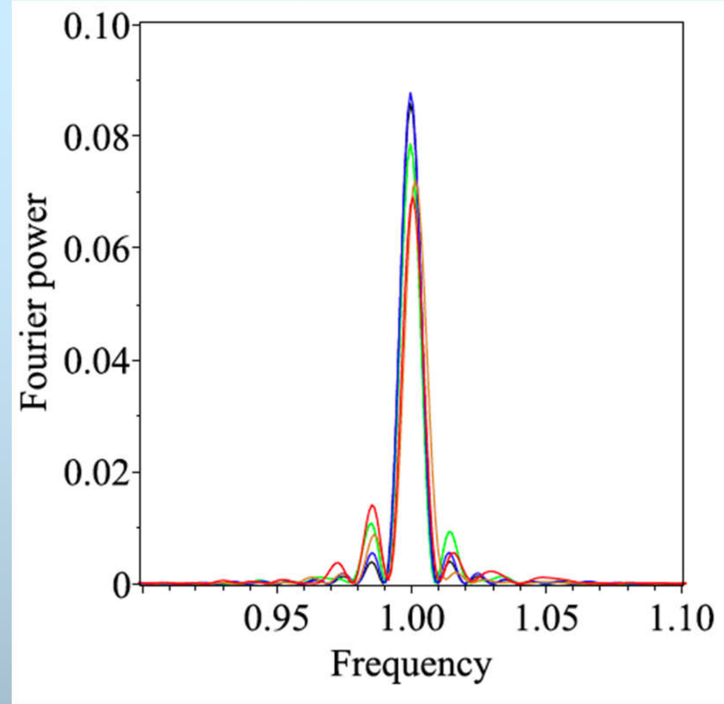
$$\ddot{\xi} + \left[(\delta - \delta_v) + \alpha\left(\dot{\xi}\right)^2\right]\dot{\xi} + \Omega_{\mathrm{k}}^2\xi = N(t)$$

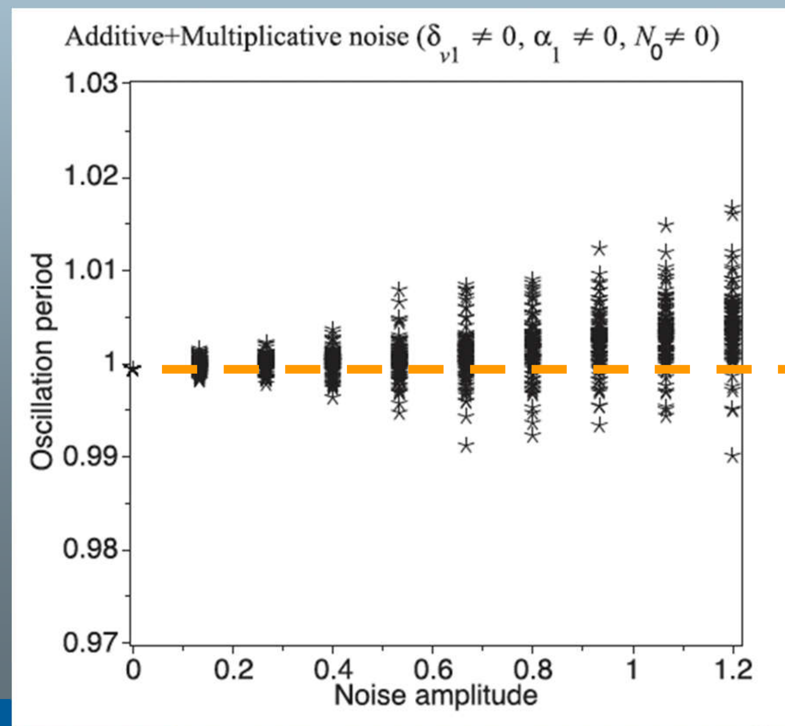
$$\delta_v = \delta_{v0} + \delta_{v1}\eta_v(t)$$

$$N = N_0\eta_{\mathrm{N}}(t)$$

$$\alpha = \alpha_0 + \alpha_1\eta_\alpha(t)$$

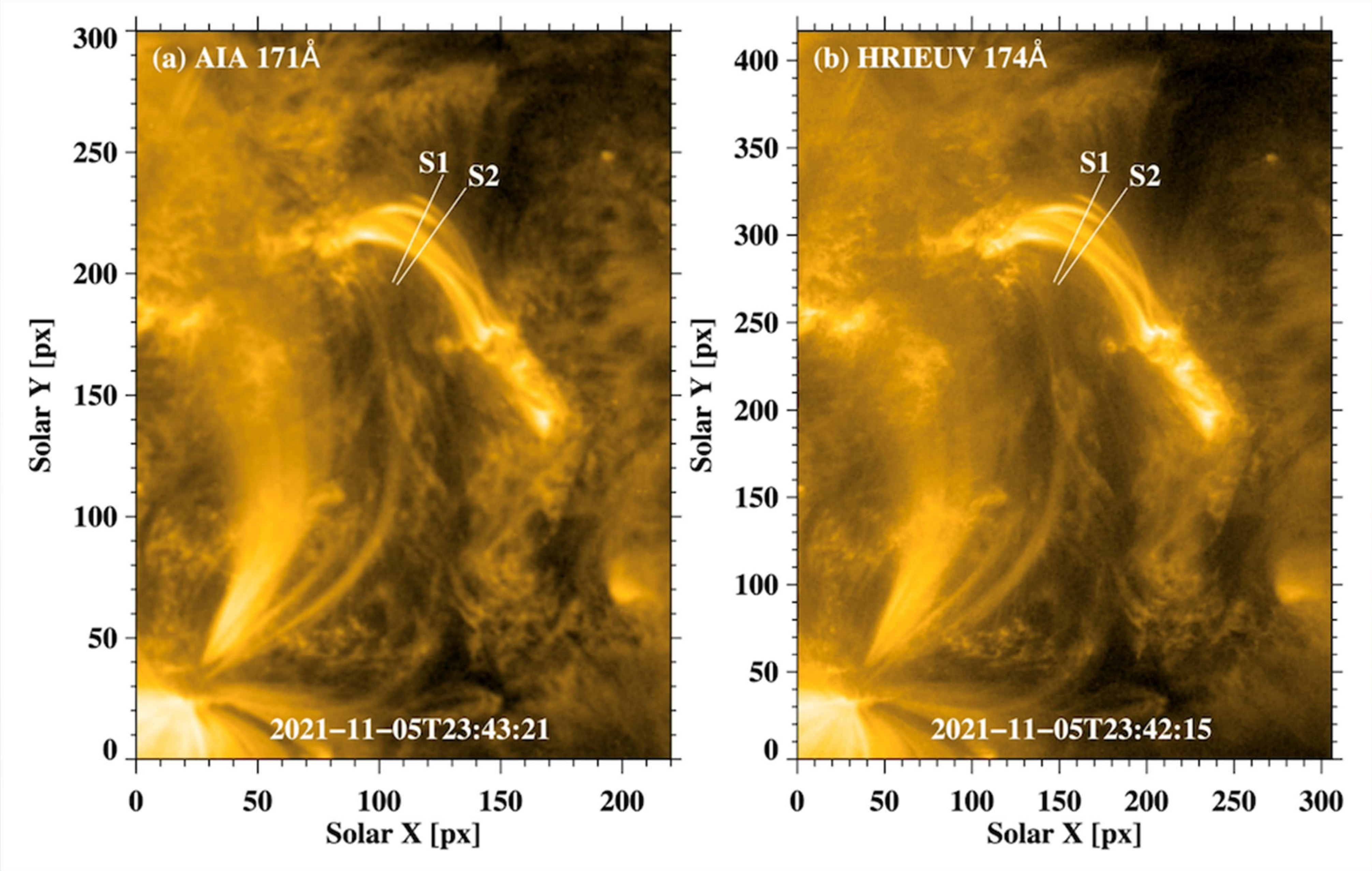






Nakariakov et al., MNRAS *516*, 5227, 2022

Kink oscillations seen with SDO/AIA and SolO/EUI:



Thread	Data	P [s]	A [km]	C
T1	AIA 171	82 ± 6	47 ± 9	-
T2	EUI HRI AIA 171	66 ± 3 76 ± 3	21 ± 2 30 ± 5	0.97
T3	EUI HRI AIA 171	117 ± 3 111 ± 5	55 ± 5 45 ± 10	0.93
T4	EUI HRI AIA 171	86 ± 5 90 ± 6	31 ± 5 68 ± 14	0.96
T5	EUI HRI AIA 171	83 ± 2 90 ± 2	42 ± 3 42 ± 6	0.82
T6	EUI HRI AIA 171	100 ± 4 112 ± 6	23 ± 6 43 ± 11	0.95
T7	EUI HRI AIA 171	125 ± 13 118 ± 8	77 ± 11 88 ± 9	0.97

Zhong et al. *MNRAS* **516**, 5989, 2022

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Conclusions

- Kink oscillations of loops are eigenmodes (standing fast magnetoacoustic waves).
- Decayless kink oscillations: seismology **before** flares.
- What is the nature of decayless oscillations? Self-oscillations and/or random driver? Implications for the energy balance in the corona?

ANNUAL
REVIEWS

Annual Review of Astronomy and Astrophysics

Magnetohydrodynamic Waves in the Solar Corona

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Keywords

Sun: corona, Sun: oscillations, waves

Abstract

The corona of the Sun is a unique environment in which magnetohydrodynamic (MHD) waves, one of the fundamental processes of plasma astrophysics, are open to a direct study. There is striking progress in both observational and theoretical research of MHD wave processes in the

Space Science Reviews (2021) 217:73
https://doi.org/10.1007/s11214-021-00847-2

Kink Oscillations of Coronal Loops

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Abstract
Kink oscillations of coronal loops, i.e., standing kink waves, is one of the most studied dynamic phenomena in the solar corona. The oscillations are excited by impulsive energy releases, such as low coronal eruptions. Typical periods of the oscillations are from a few to several minutes, and are found to increase linearly with the increase in the major radius of