NJIT Webinar, 04/03/2020

MHD Seismology of the Coronal Plasma with Kink Oscillations

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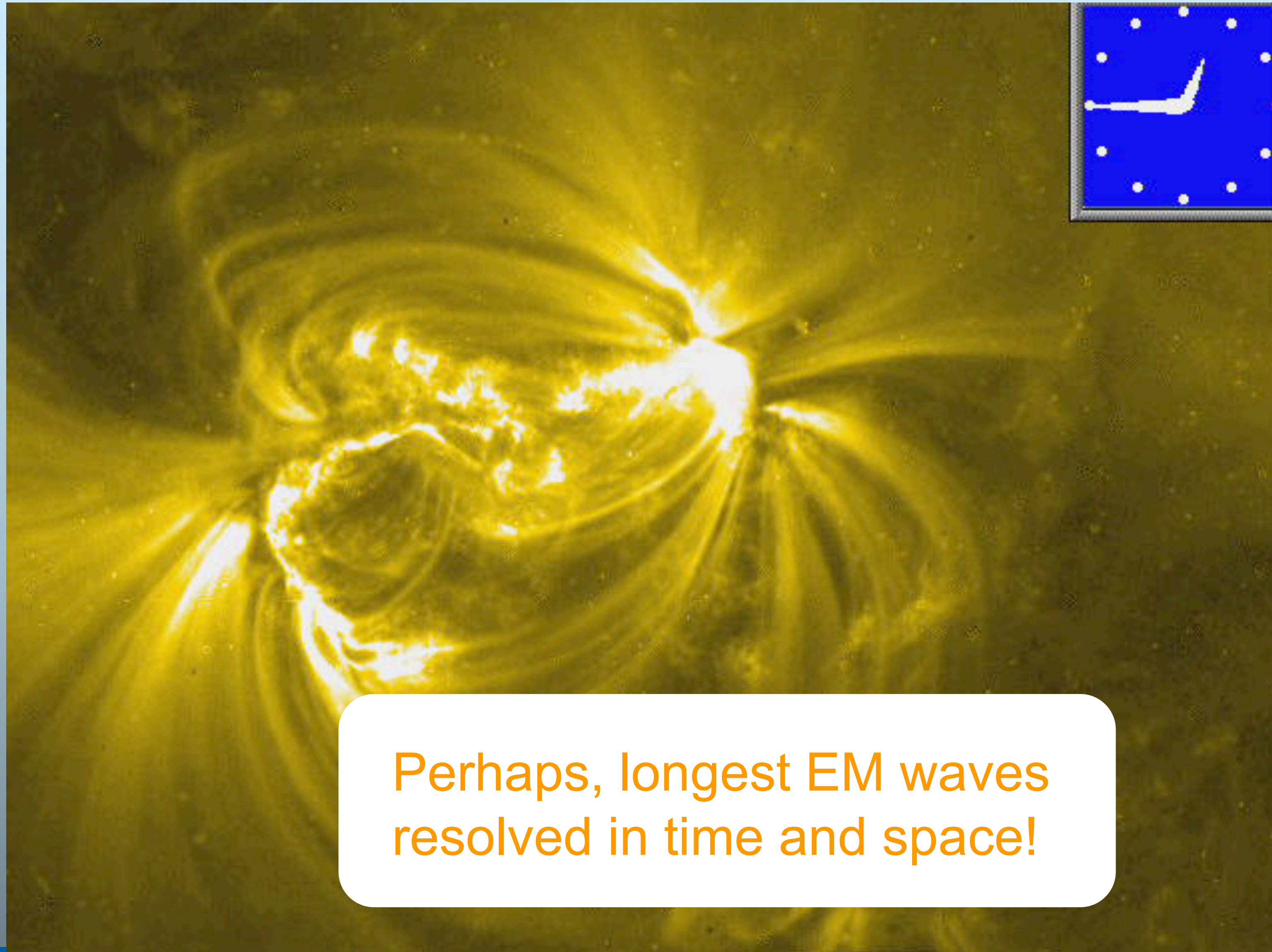
Kink oscillations of coronal loops:

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

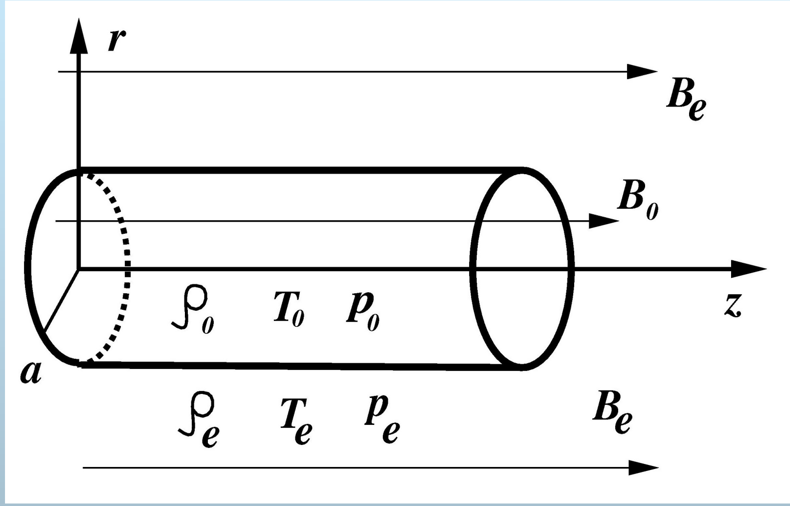


Perhaps, longest EM waves resolved in time and space!

MHD seismology – MHD-wave-based diagnostics of a natural plasma environment

- One of the dedicated aims of SDO/AIA.
- One of the science objectives of future ESA Proba 3/ASPIICS, NASA/KASI ISS/COR, and NASA HI-C.
- One of the key methods proposed to be developed in the report “Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS” (Schrijver et al. 2015).
- c.f.: magneto(spheric)-seismology; MHD spectroscopy.
- This talk: mainly observational aspect.

"Standard theory": interaction of MHD waves with plasma structures (Zaitsev & Stepanov, 1975; B. Roberts and colleagues, 1981-1986)



Magnetohydrodynamic (MHD) equations →

Equilibrium →

Linearisation →

Boundary conditions

Dispersion relations of MHD modes of **a magnetic flux tube**:

$$\rho_e(\omega^2 - k_z^2 C_{Ae}^2) m_0 \frac{I_m'(m_0 a)}{I_m(m_0 a)} - \rho_0(\omega^2 - k_z^2 C_{A0}^2) m_e \frac{K_m'(m_0 a)}{K_m(m_0 a)} = 0$$

Characteristic speeds:

Sound speed: $C_S \propto \sqrt{T}$, - gradient of gas pressure

Alfve′n speed: $C_A \propto B / \sqrt{\rho}$, - magnetic tension,

Fast speed:

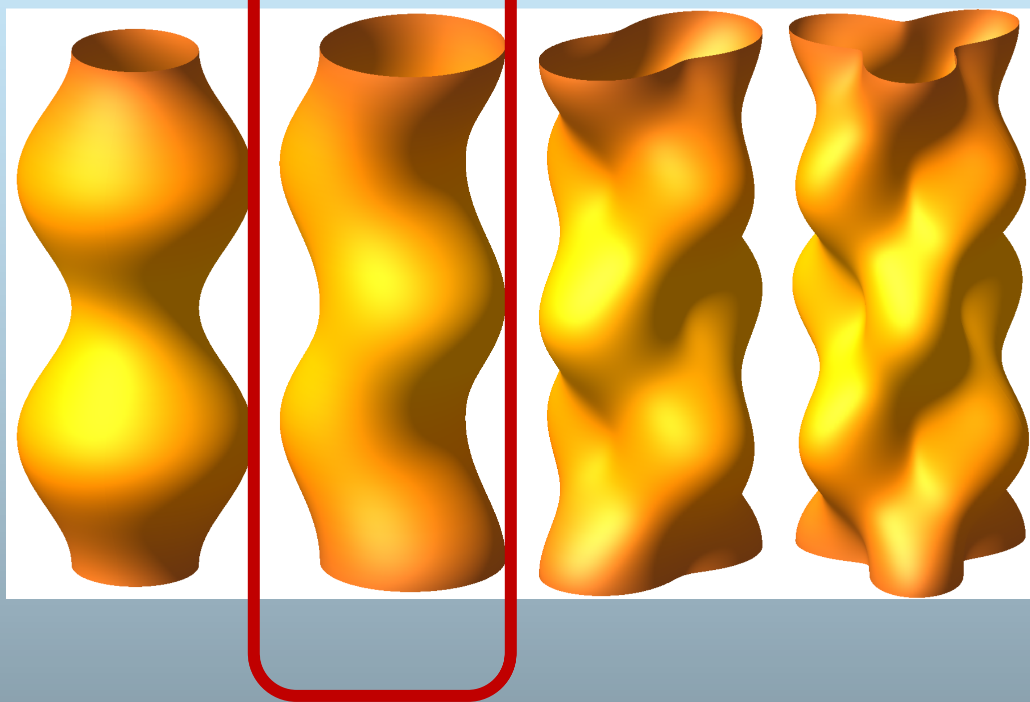
$C_F = \sqrt{C_A^2 + C_S^2}$ - gradient of (magnetic pressure + gas pressure)

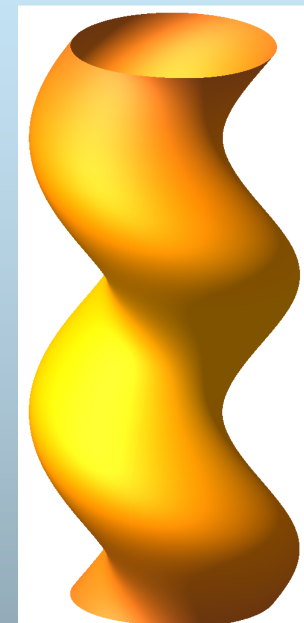
Tube speed:

$$C_T = \frac{C_S C_A}{\sqrt{C_A^2 + C_S^2}}$$

Kink speed: $C_K = \left(\frac{\rho_0 C_{A0}^2 + \rho_e C_{Ae}^2}{\rho_0 + \rho_e} \right)^{1/2}$; in low-β : $C_K = C_{A0} \sqrt{\frac{2}{1 + \rho_e / \rho_0}}$

Depending on the azimuthal wave number *m*:

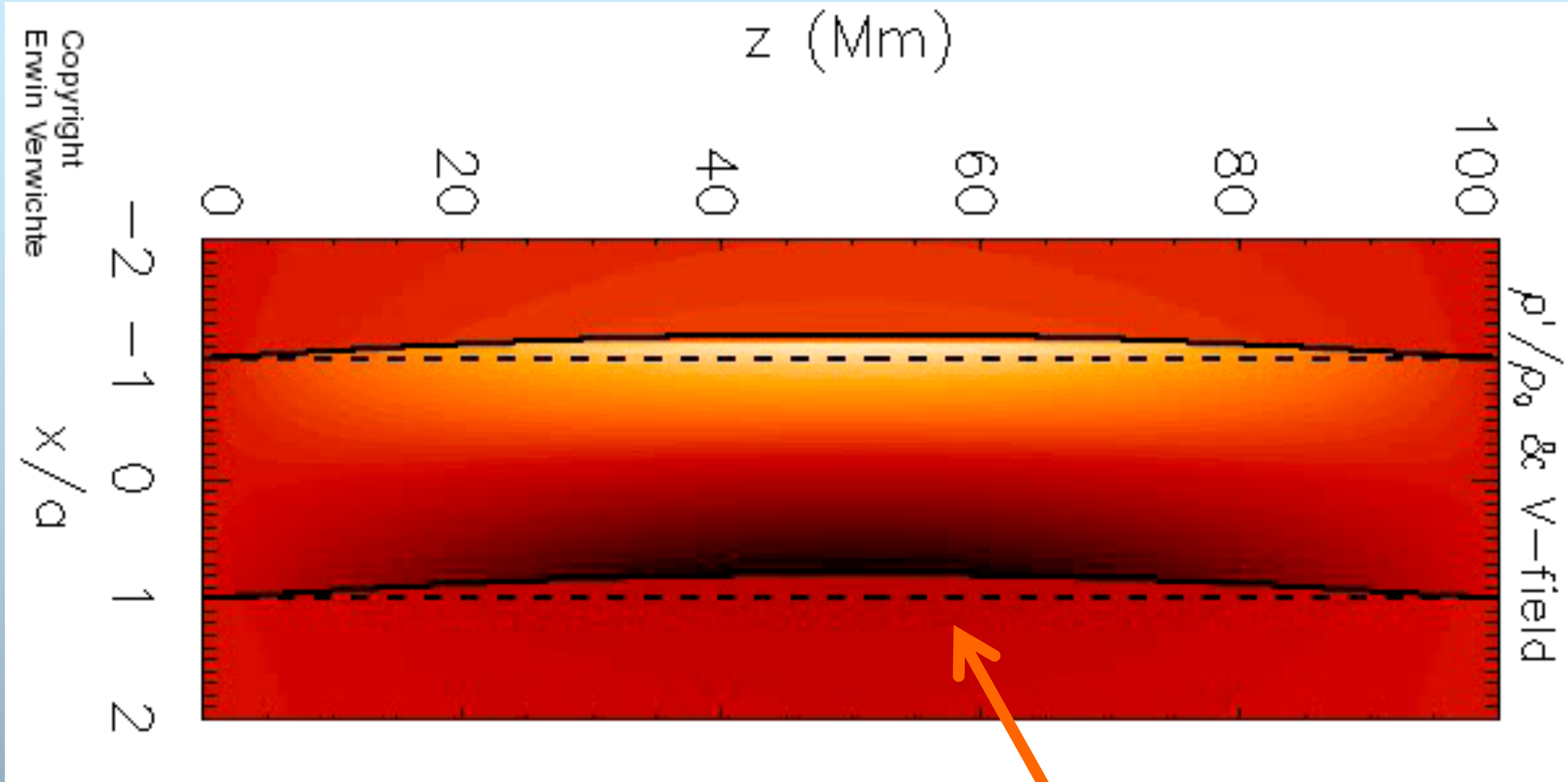




Kink (m=1) mode
(linear polarization)

RHS or LHS
circular
polarisation

Kink modes are guided fast waves:



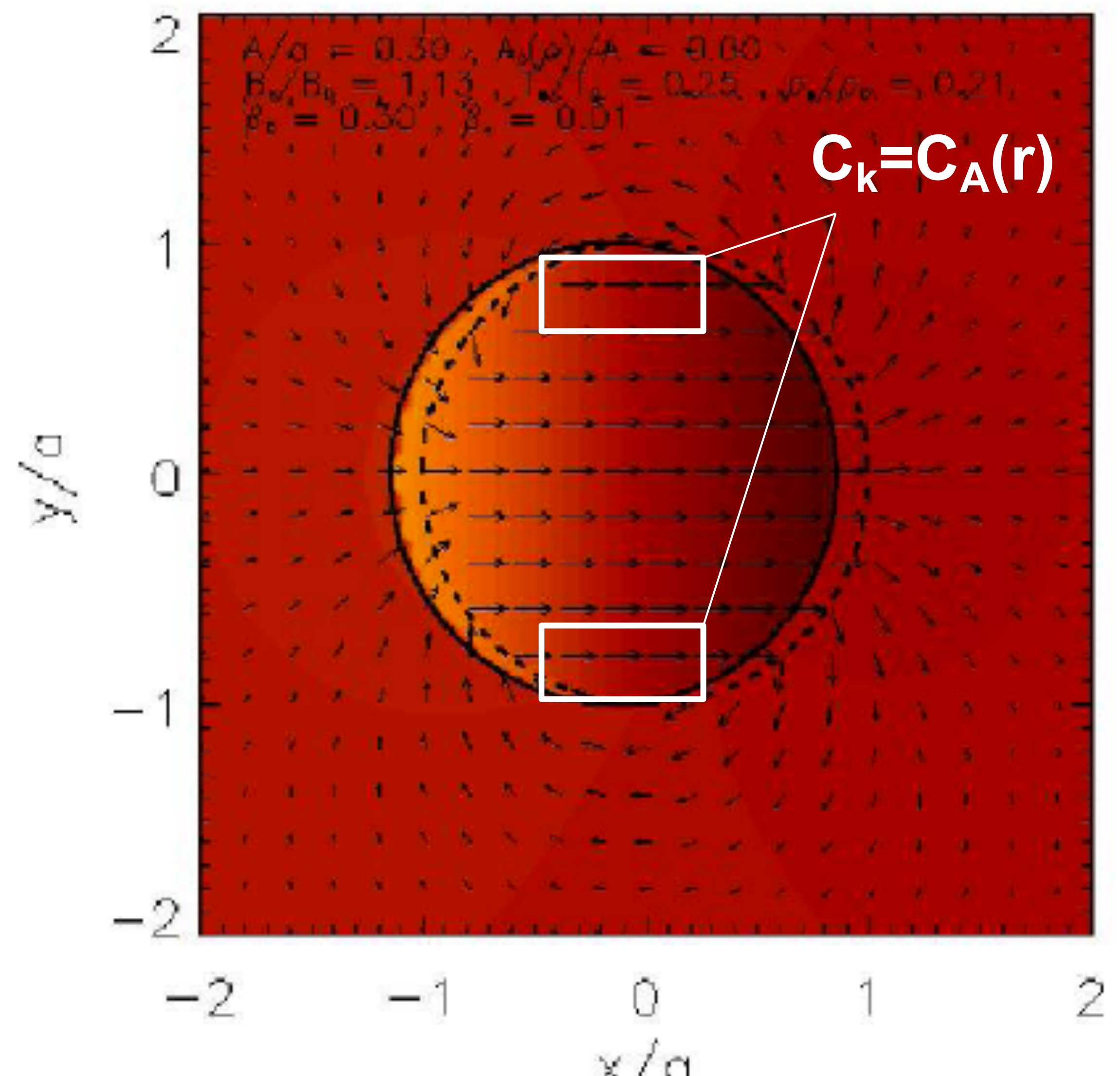
This mode is essentially compressive, and must not be confused with the Alfvén (torsional) wave

(while, sometimes it is called "Alfvénic")

Damping: linear coupling with Alfvén waves -- effect of **resonant absorption** of kink waves

If the Alfven speed is nonuniform in the radial direction, $C_A(r)$,

In the loop there are regions where the kink motions are in resonance with the local torsional (Alfven) perturbations.



Mathematically, it corresponds to the appearance of the singularity in the governing equations:

$$D\,\frac{d}{dr}\left(r\xi_r\right) = \left(C_A^2 + C_s^2\right)\left(\omega^2 - C_T^2 k_z^2\right)\left(\kappa^2 + \frac{m^2}{r^2}\right) r\delta P_{\mathrm{tot}}\ ,$$

$$\frac{d\delta P_{\mathrm{tot}}}{dr} = \rho_0\left(\omega^2 - C_A^2 k_z^2\right)\xi_r\ ,$$

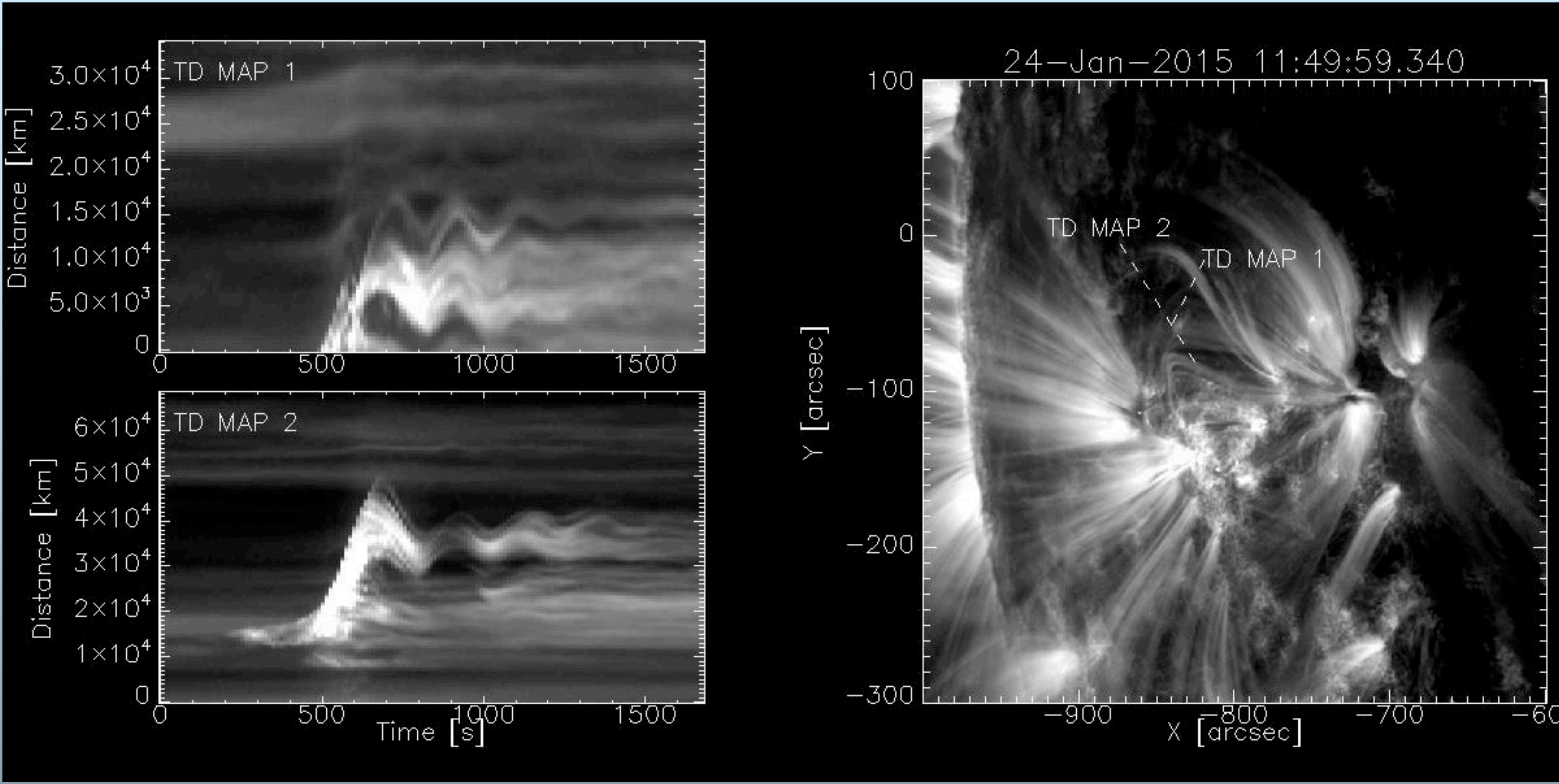
$$\rho_0\left(\omega^2 - C_A^2 k_z^2\right)\xi_\varphi = -\frac{im}{r}\delta P_{\mathrm{tot}}\ ,$$

$$D = \rho_0\left(C_A^2 + C_s^2\right)\left(\omega^2 - C_A^2 k_z^2\right)\left(\omega^2 - C_T^2 k_z^2\right)$$

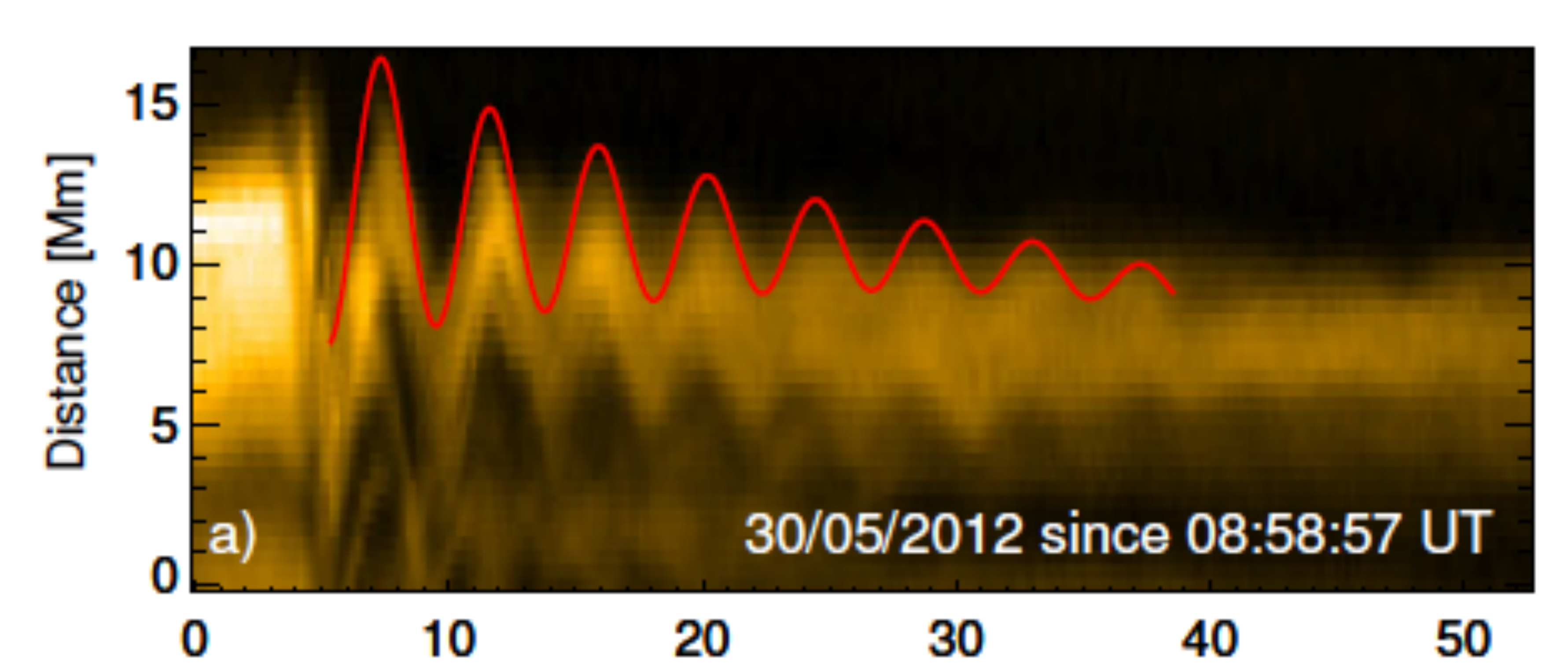
$$\frac{\tau}{P} = \frac{2}{\pi}\left(\frac{\ell}{a}\right)^{-1}\left(\frac{\rho_0+\rho_e}{\rho_0-\rho_e}\right)$$

Why is it ***always*** about 3-5??

Kink oscillations with SDO/AIA:



How we analyse it:

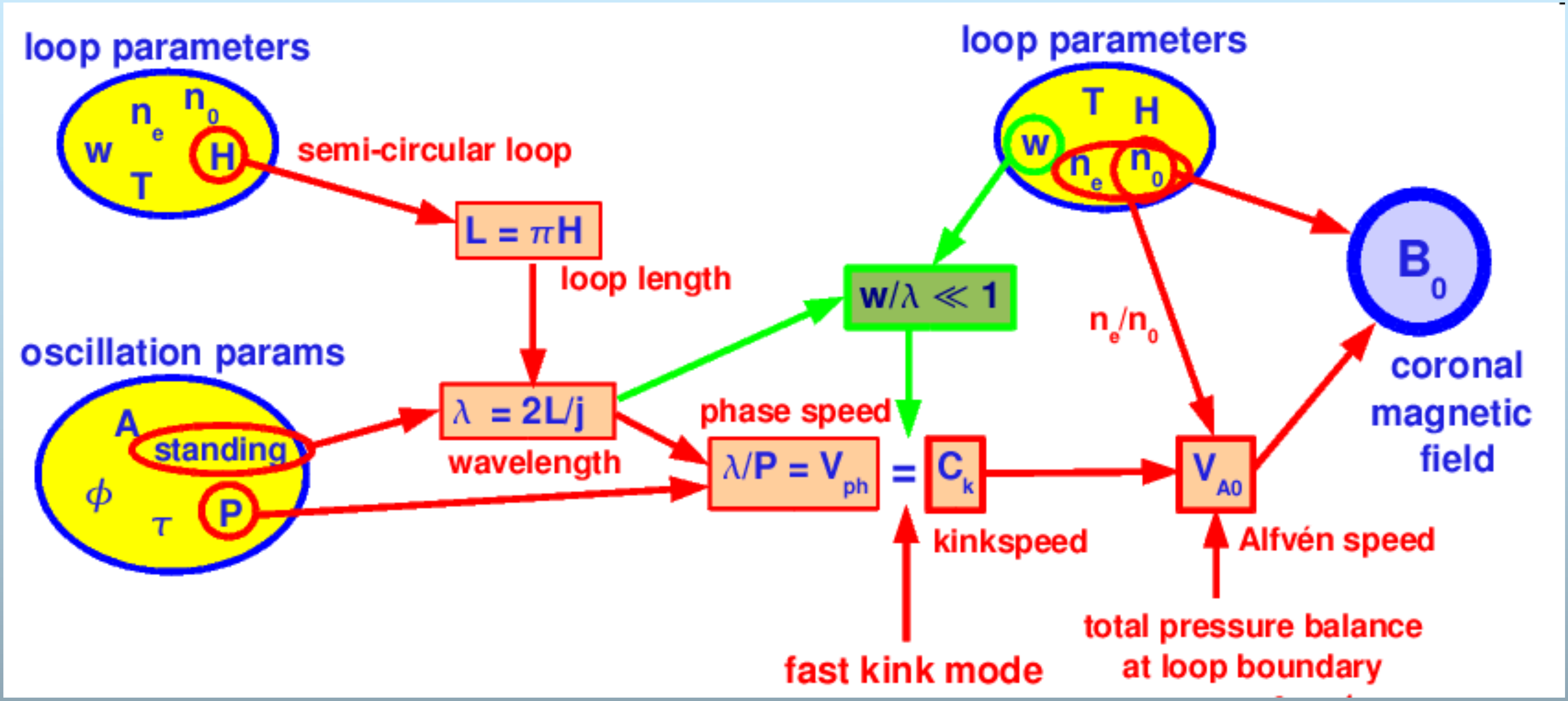


$$\xi_n(t) = A e^{-\gamma_n t^n} cos(\omega t + \phi),$$

→

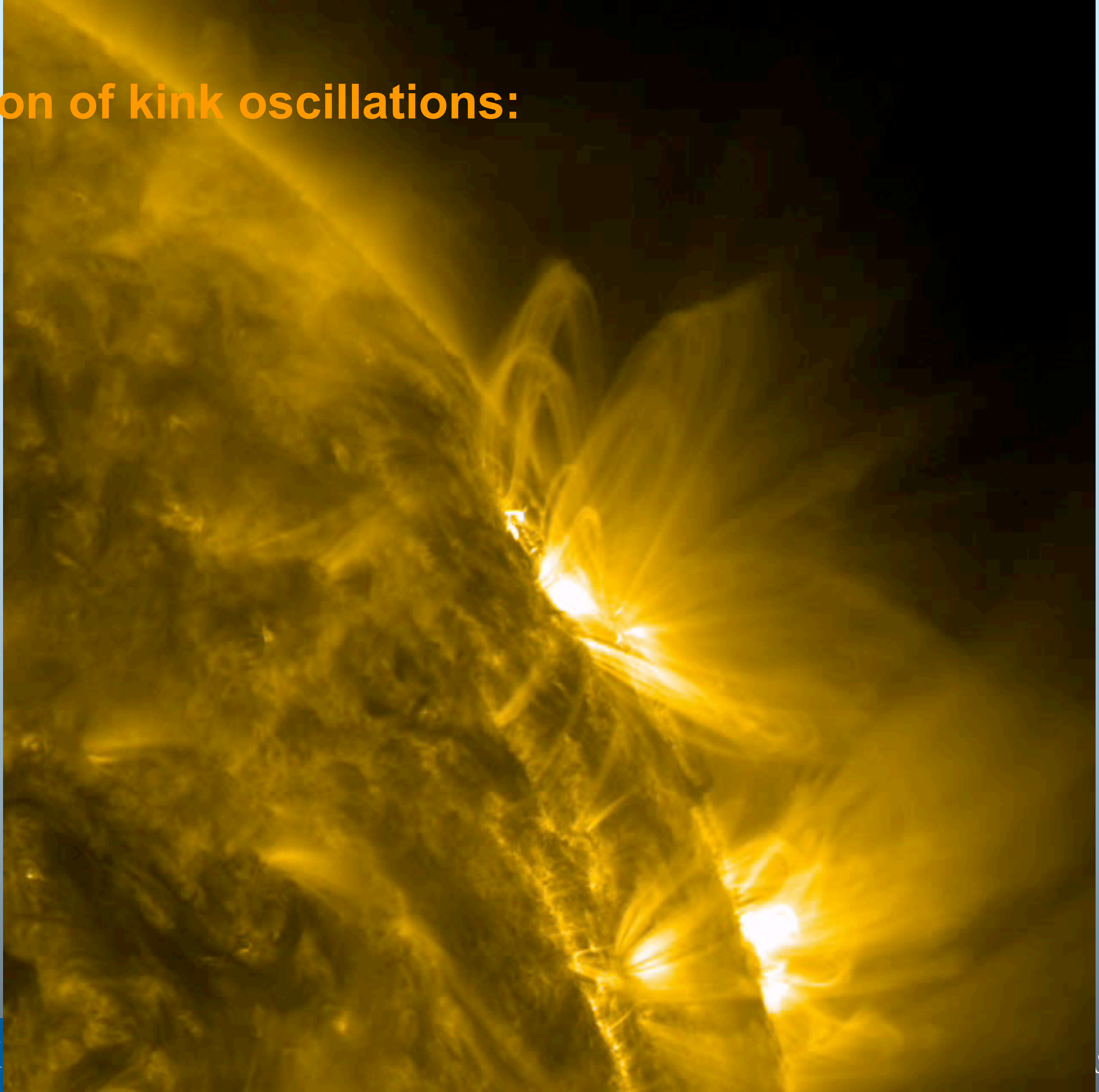
- Oscillation period,
- Decay time

Seismological estimation of the magnetic field:



- One of the specific aims of SDO/AIA

Excitation of kink oscillations:



SDO/AIA 171

Zimovets &Nakariakov, *Astron. Astrophys.* **577**, A4, 2015

A possible mechanism: mechanical displacement of the loop by **LCE** from the equilibrium

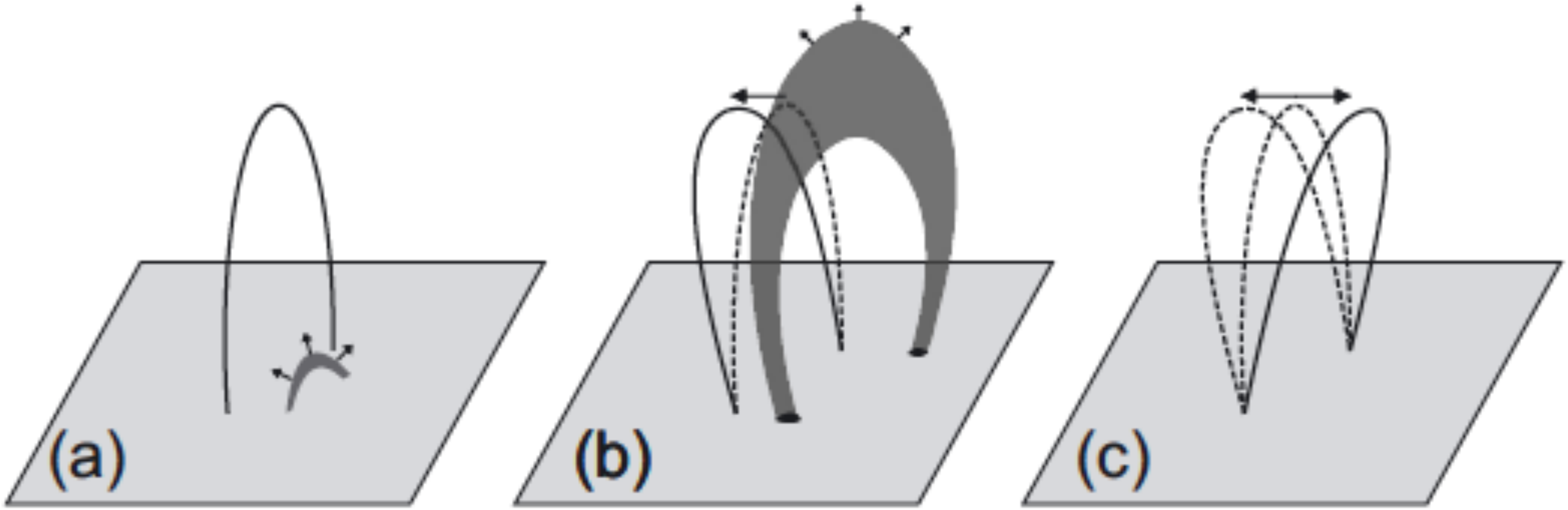
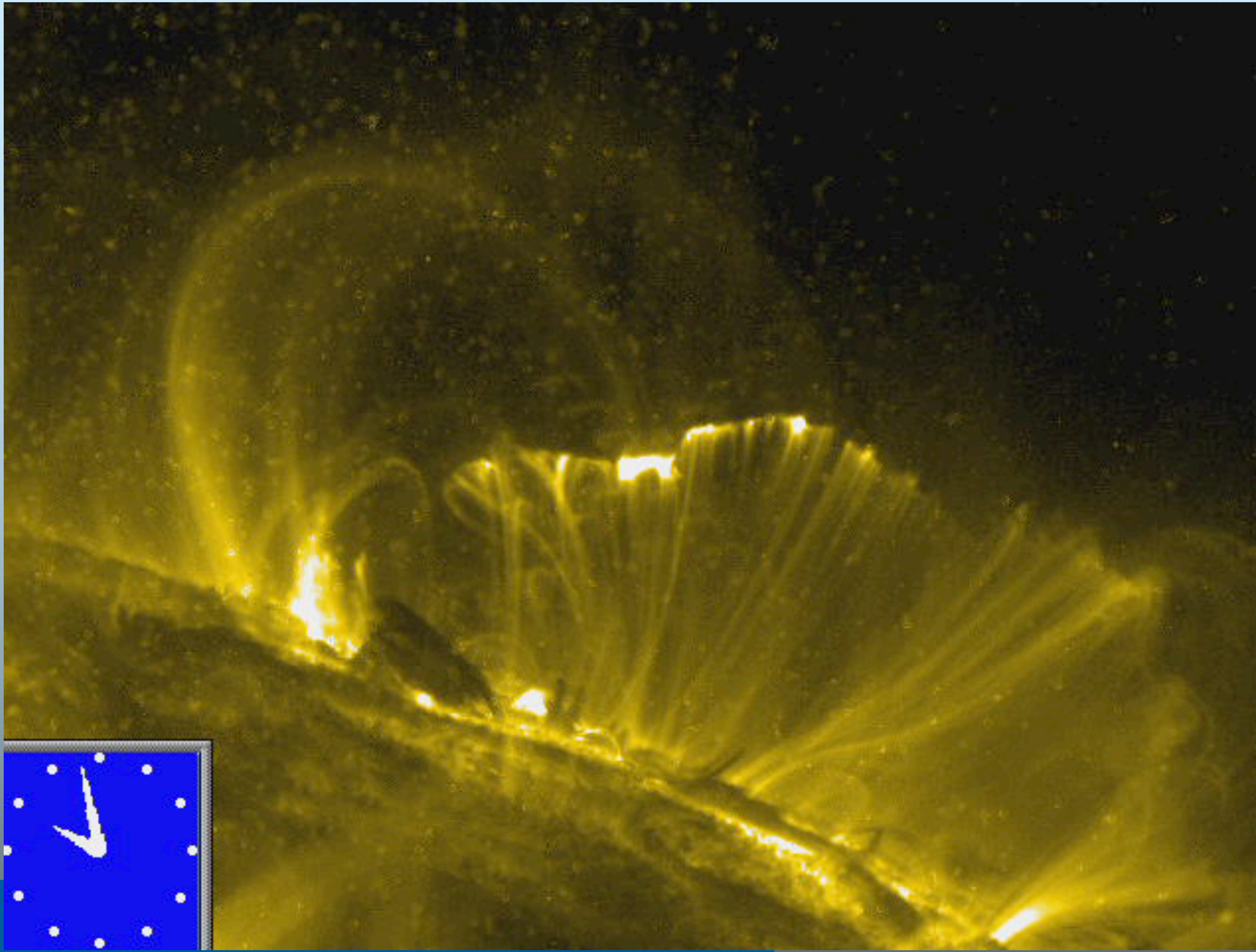
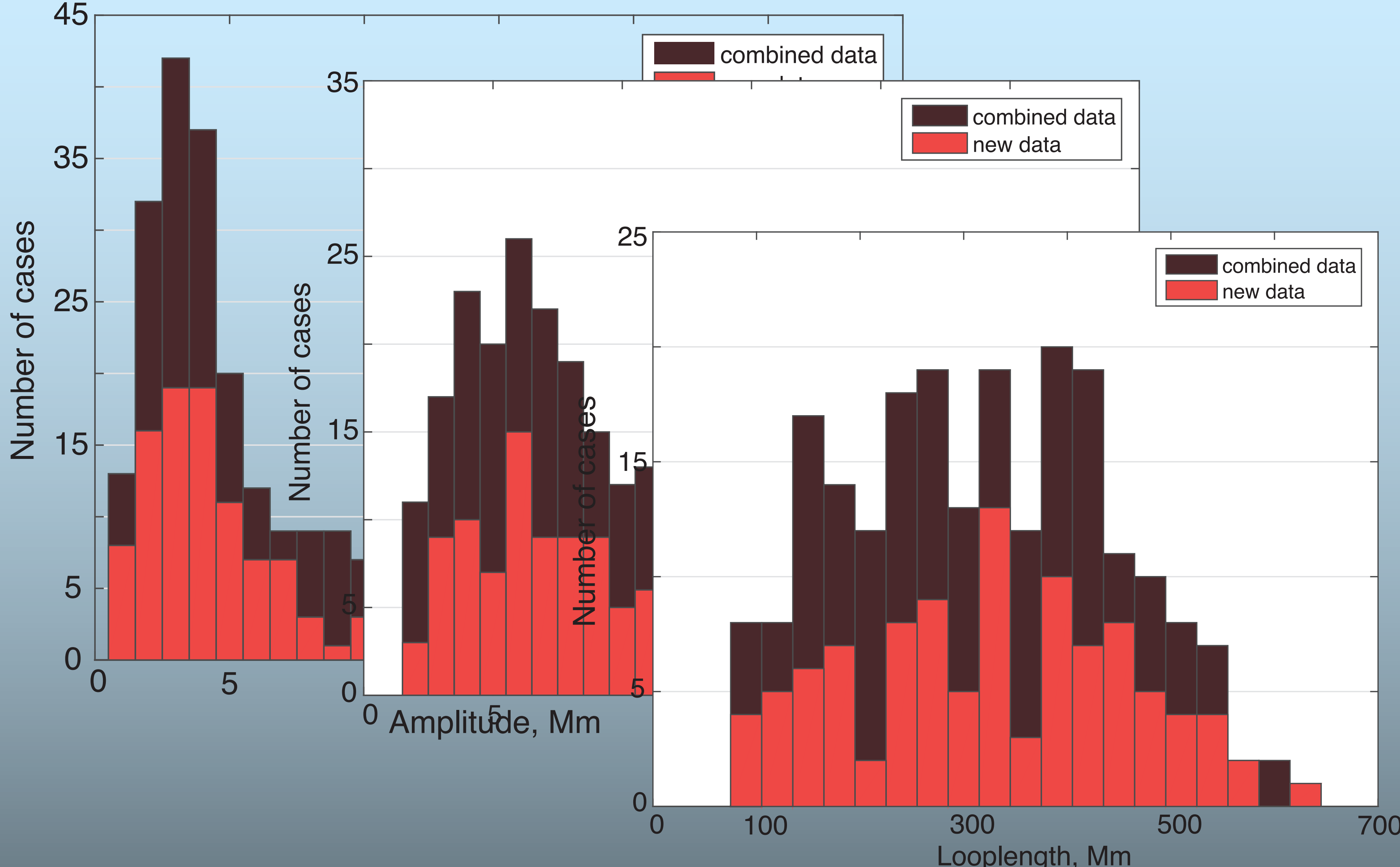


Fig. 2. Schematic illustration of the mechanism for the excitation of kink oscillations of coronal loops, observed in the majority of the studied events. **a**) Pre-eruption state of the active region. **b**) Displacement of a coronal loop (solid black curve) from its equilibrium state (dashed black line) by an erupting and expanding plasma structure, e.g. a flux rope (grey loop-shaped structure). **c**) Oscillatory relaxation of the loop to its equilibrium state after the eruption.

Exception: "Harmonica" event



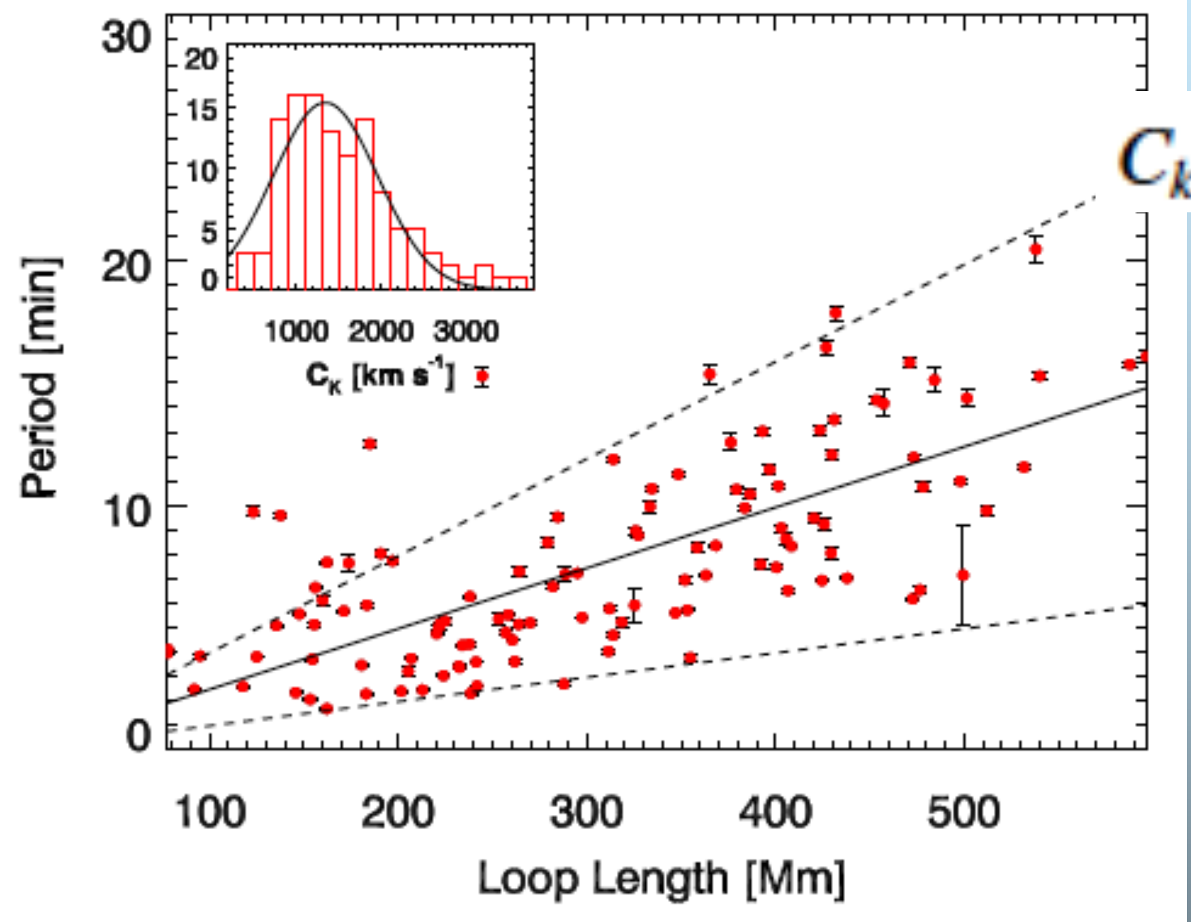
Statistics of decaying kink oscillations



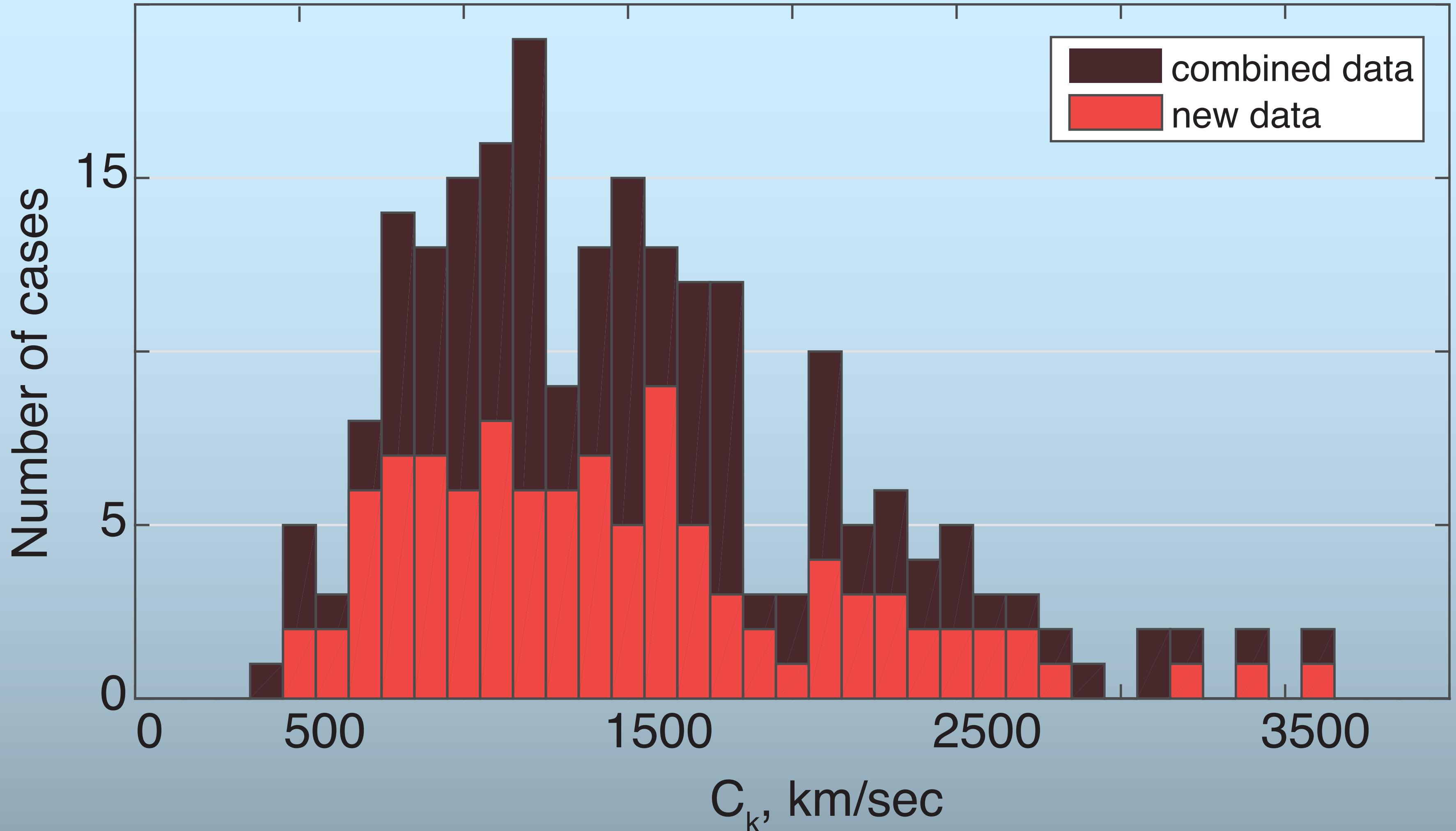
Final demonstration that kink oscillations are natural standing modes of loops

Kink mode: $P_{\text{kink}} \approx 2L / C_K$

$C_k = (1300 \pm 50)\,\text{km s}^{-1}$

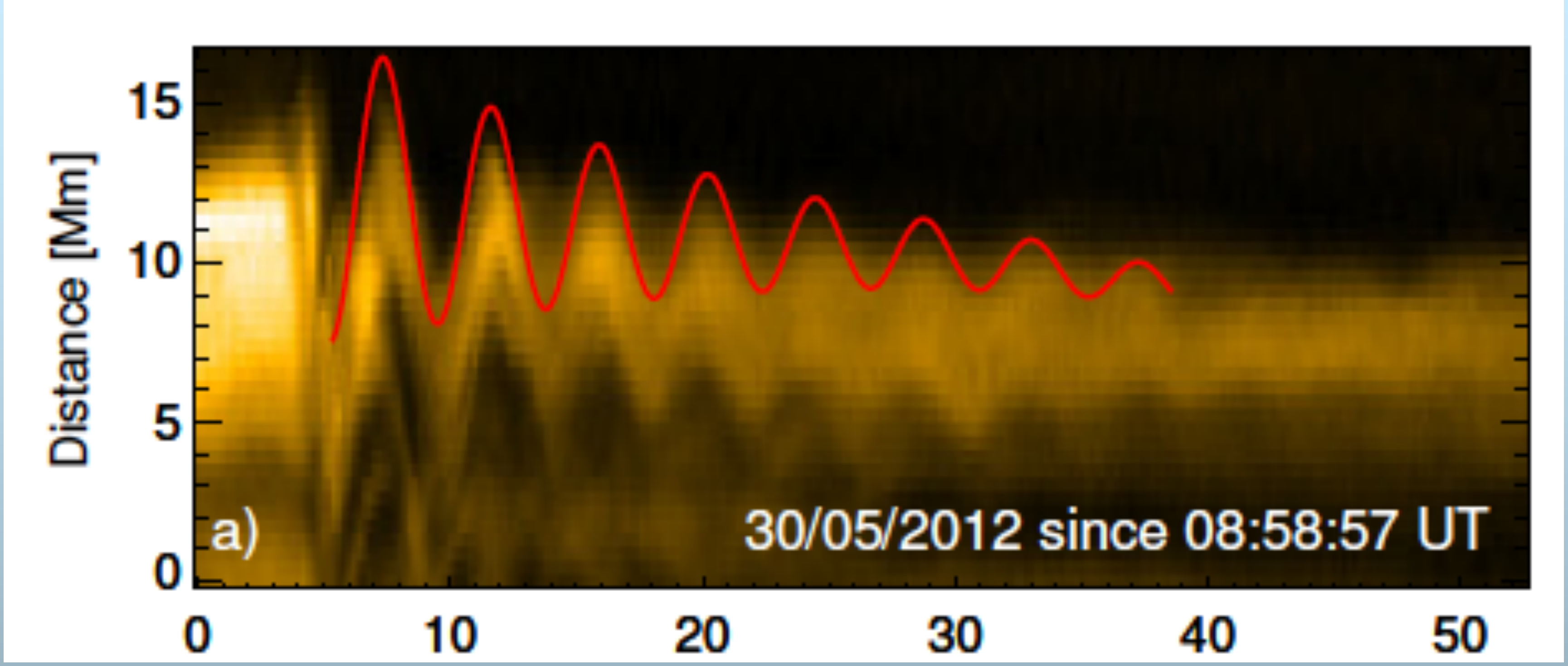


Goddard et al., A&A 585, A137, 2016



combined data
new data
Number of cases
15
5
0
0
500
1500
2500
3500
C_k, km/sec

Mechanism for damping

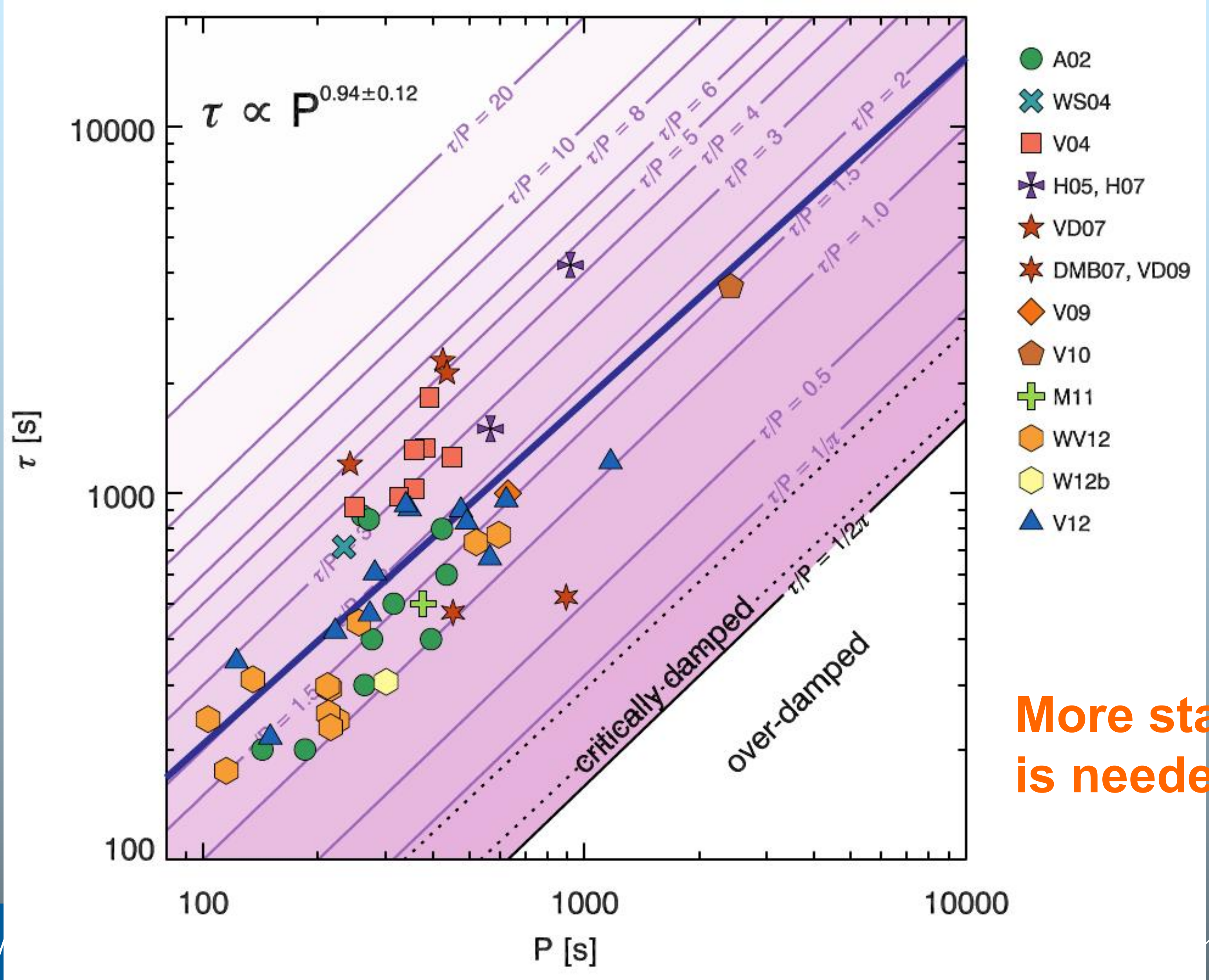


$$\xi(t) = A_0 \exp\left(-\frac{t}{t_D}\right)\cos\left(\frac{2\pi}{P}t + \phi_0\right)$$

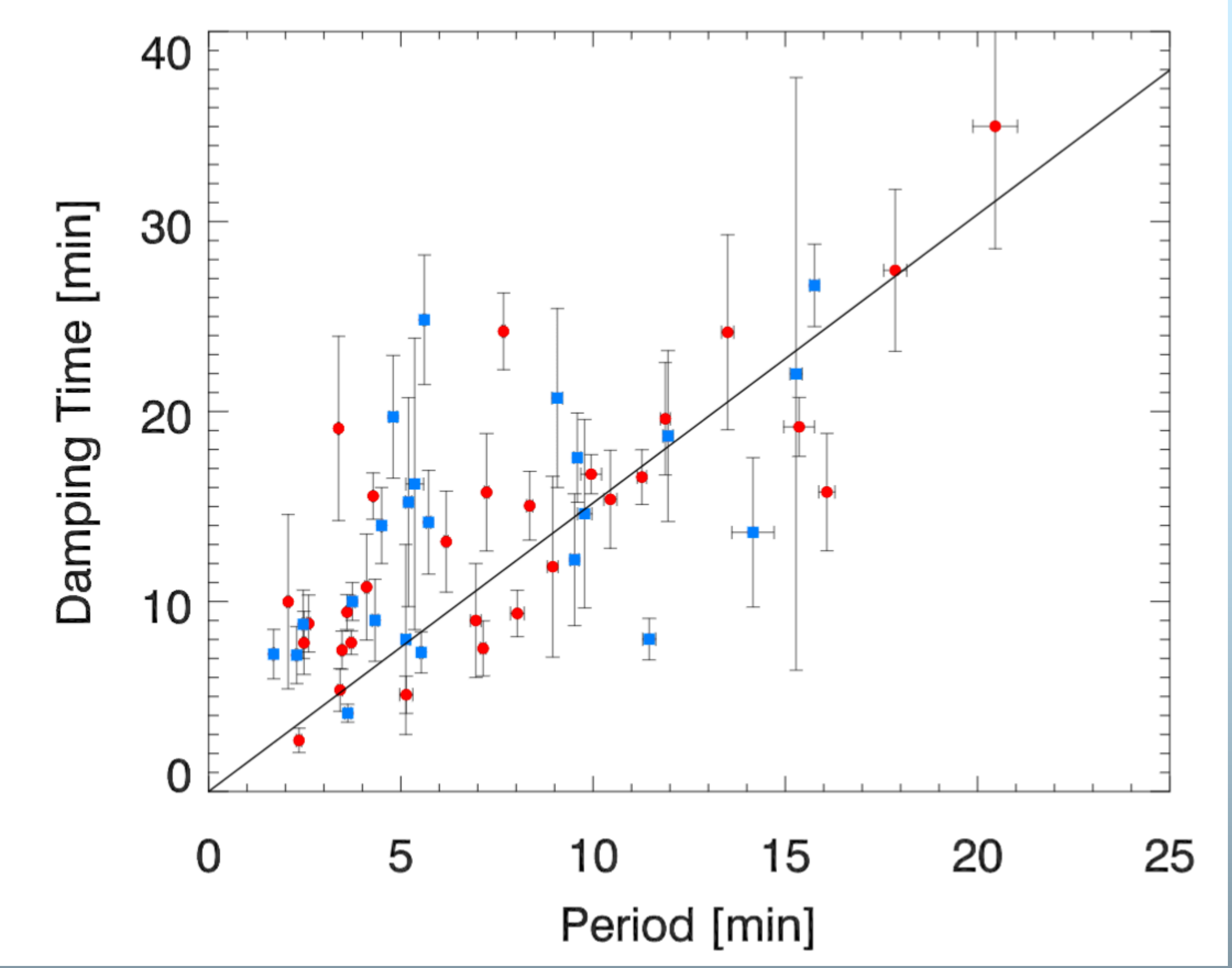
- **Oscillation period,**
- **Decay time**

Decay time vs **Period**:

$$\tau \propto P$$

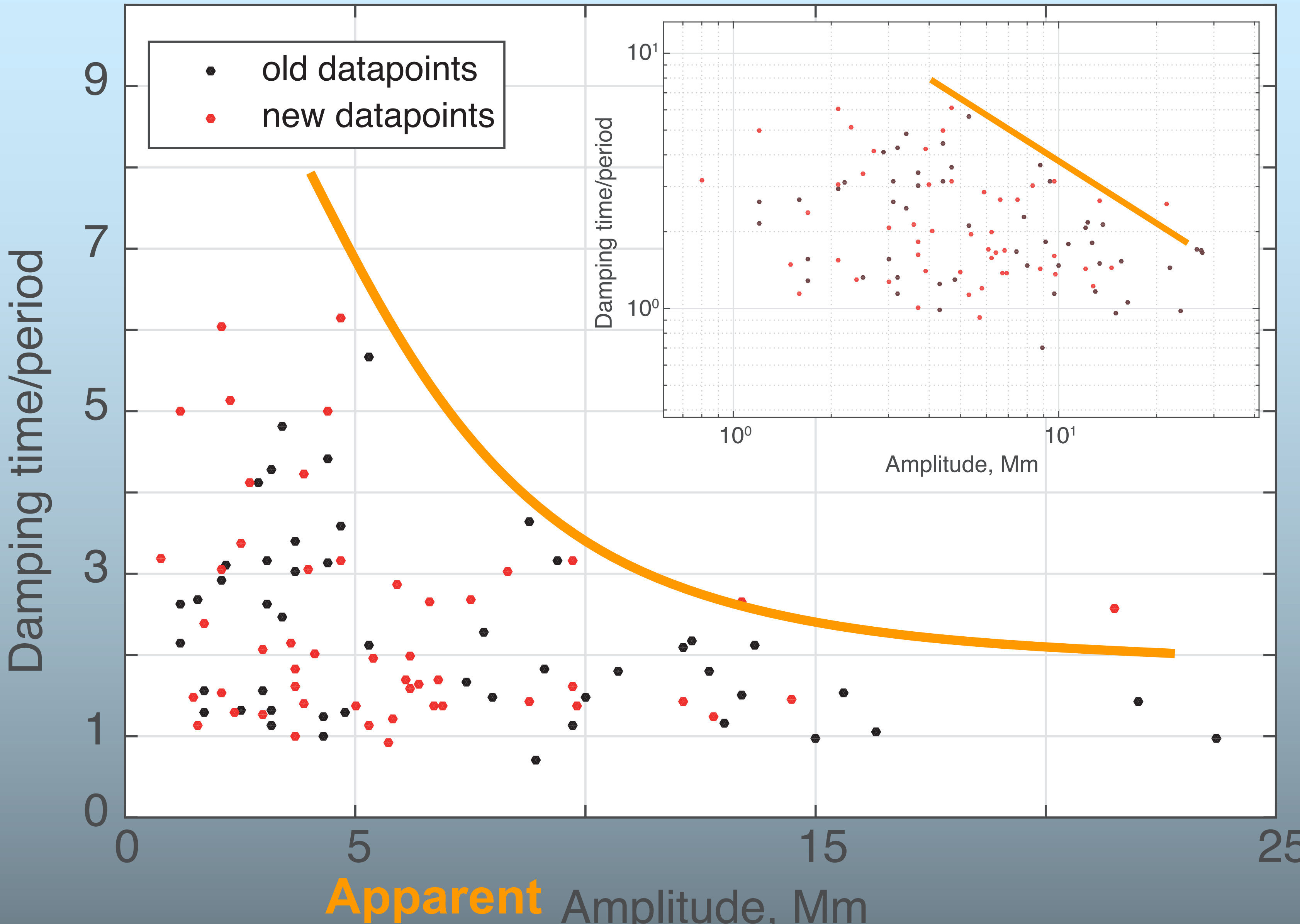


More statistics is needed

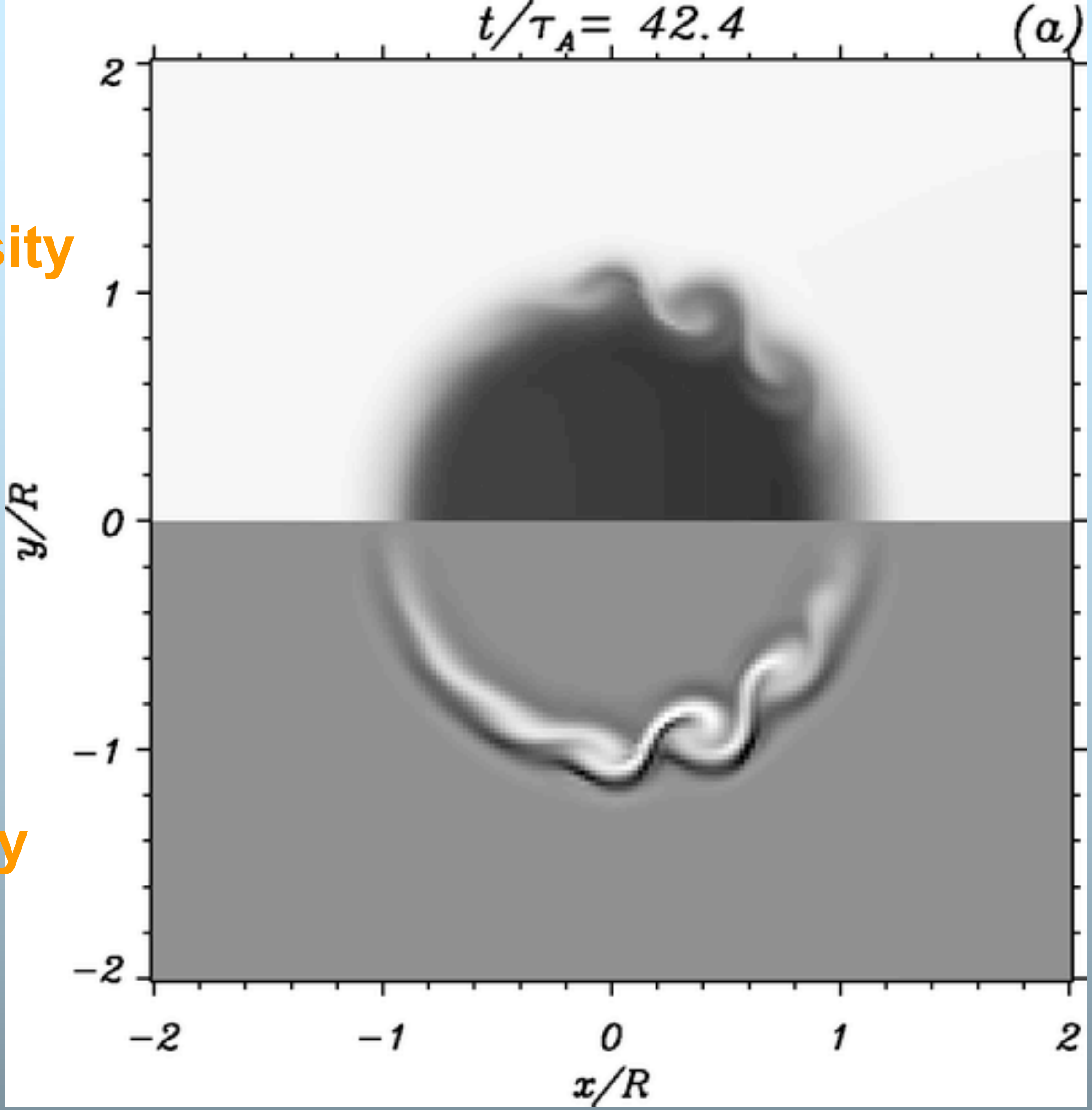


$\tau \propto P$ - Consistent with resonant absorption

Is the damping a **nonlinear** process?



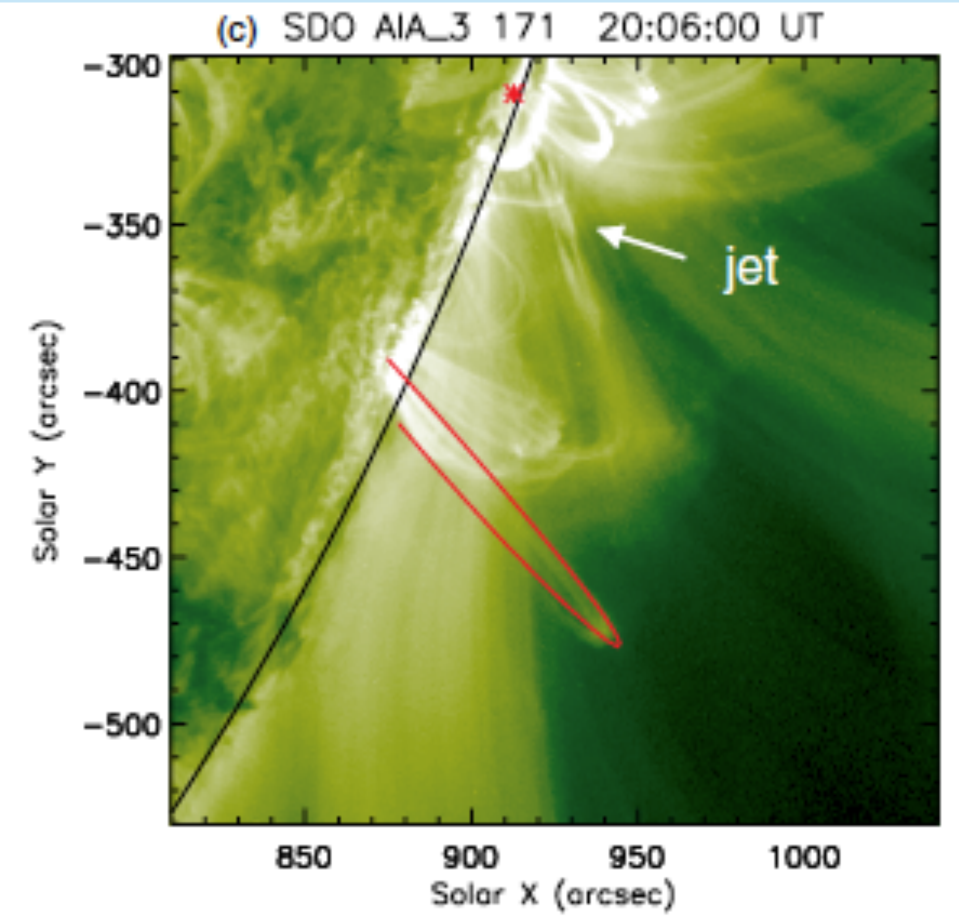
Kelvin – Helmholtz Instability?

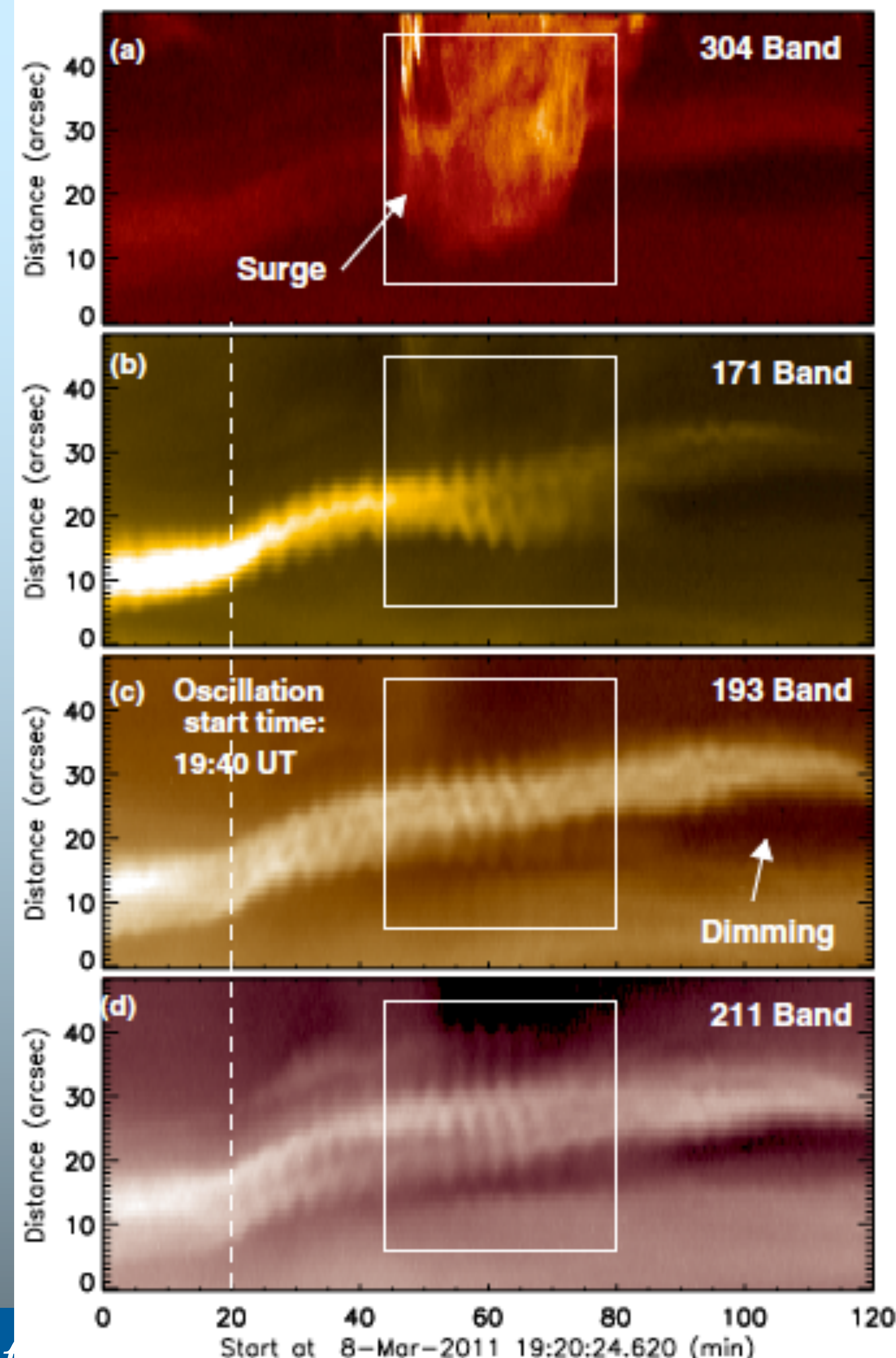


Terradas et al. ApJ 687, L115, 2008

More work needs to be done.

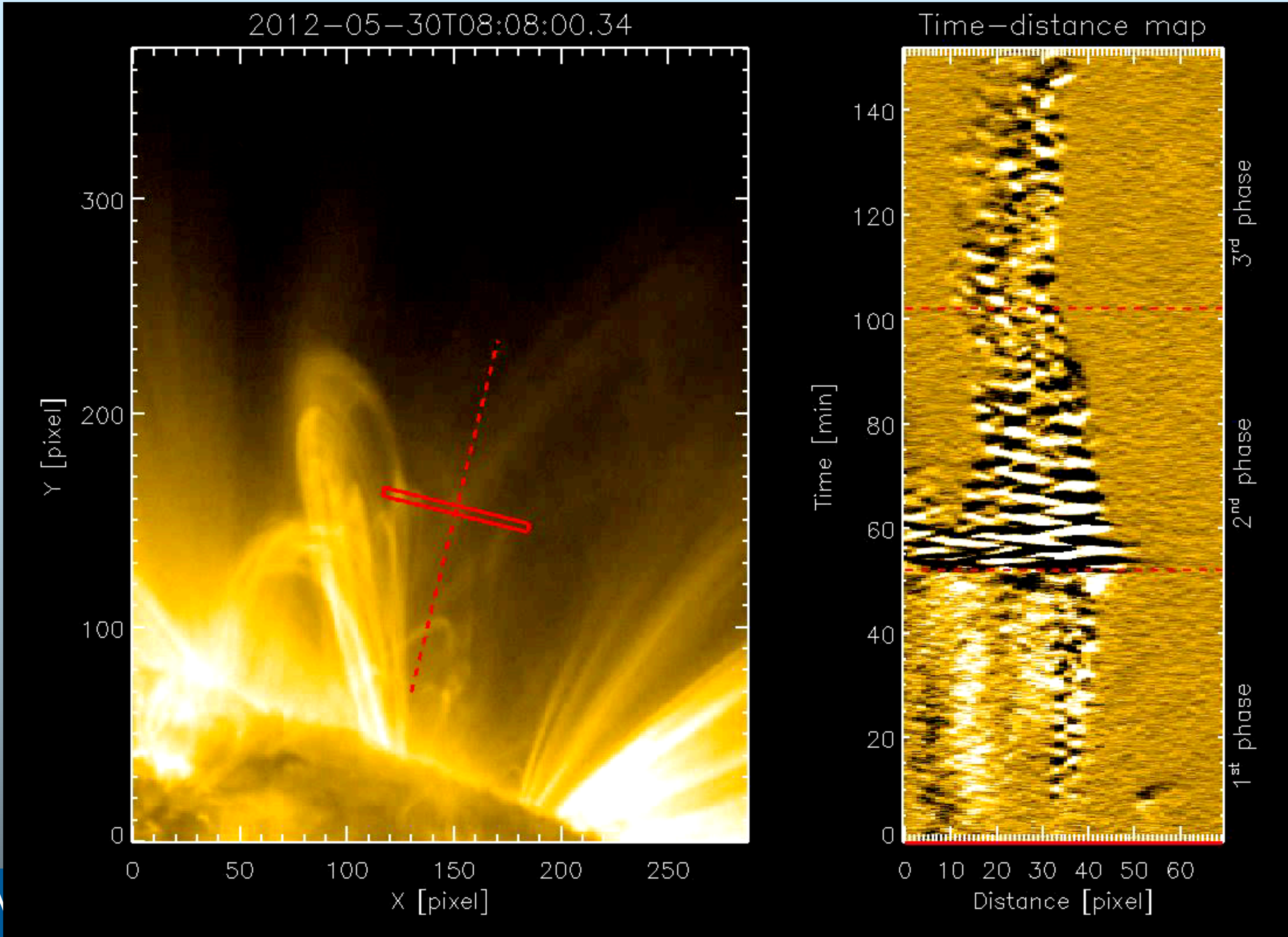
New regime: decayless



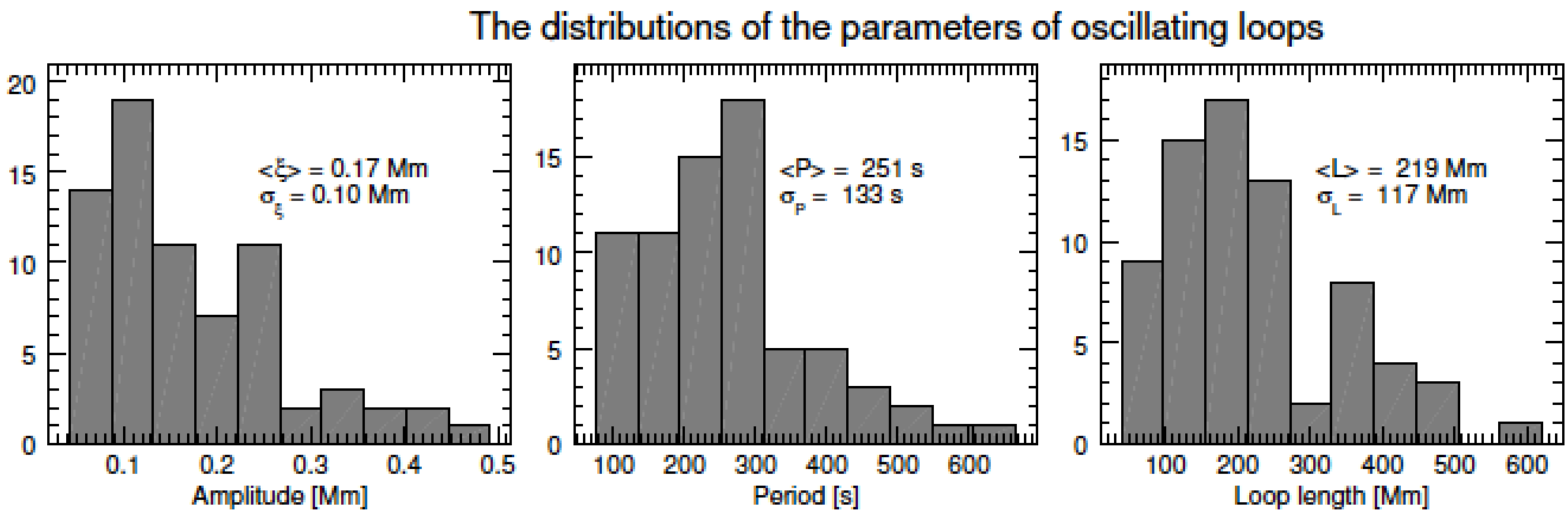


Wang et al. ApJ 751, L27, 2012

An oscillatory pattern occurs before the onset of the main oscillation:

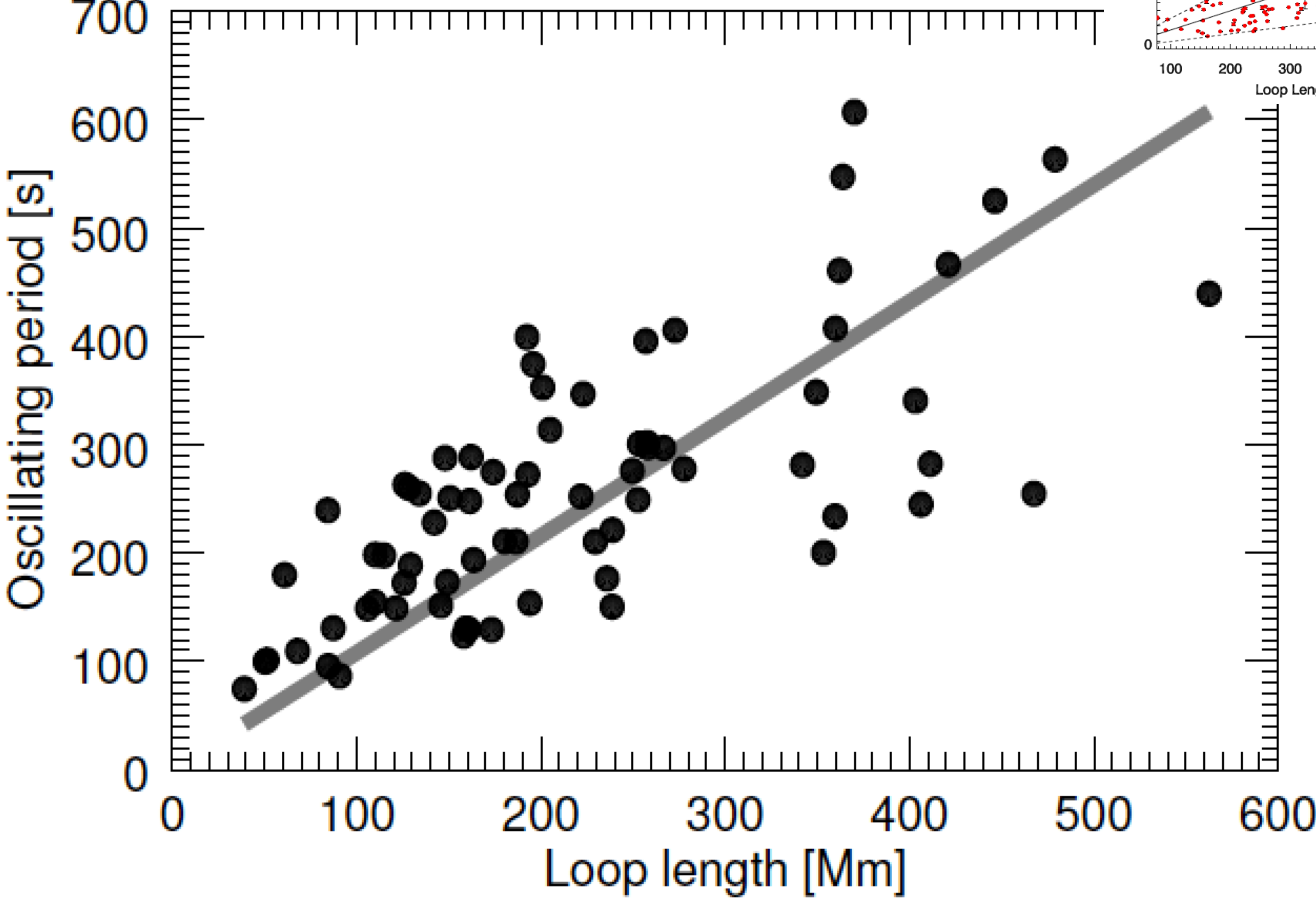


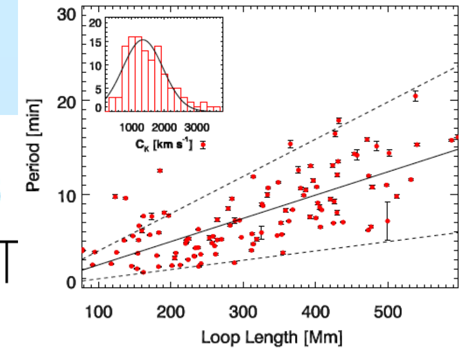
Decayless regime of kink oscillations:



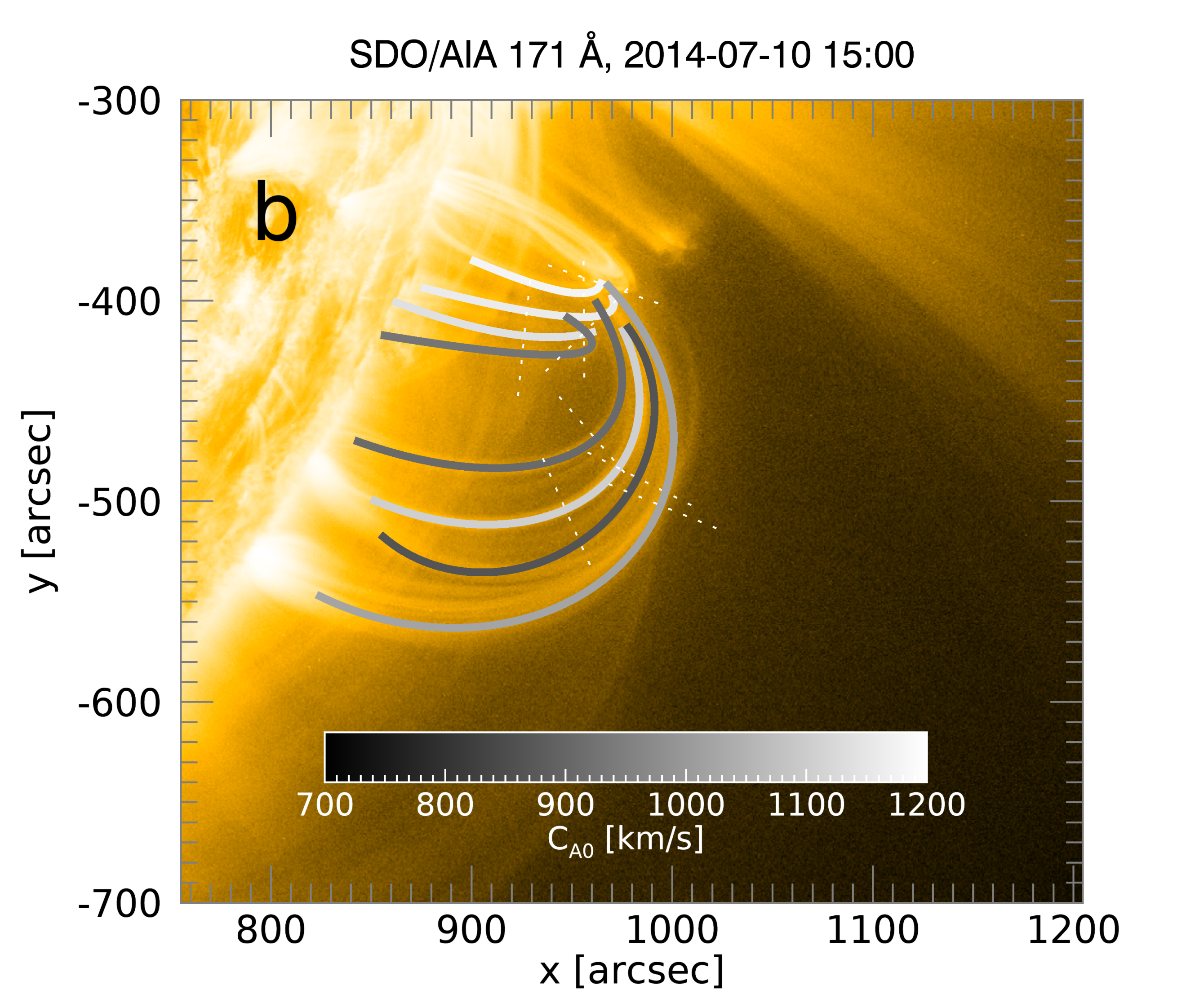
Anfinogentov et al., *Astron. Astrophys.* **583**, A136, 2015

The parameters of oscillating loops





Seismology of a "quiet" active region by decayless oscillations



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

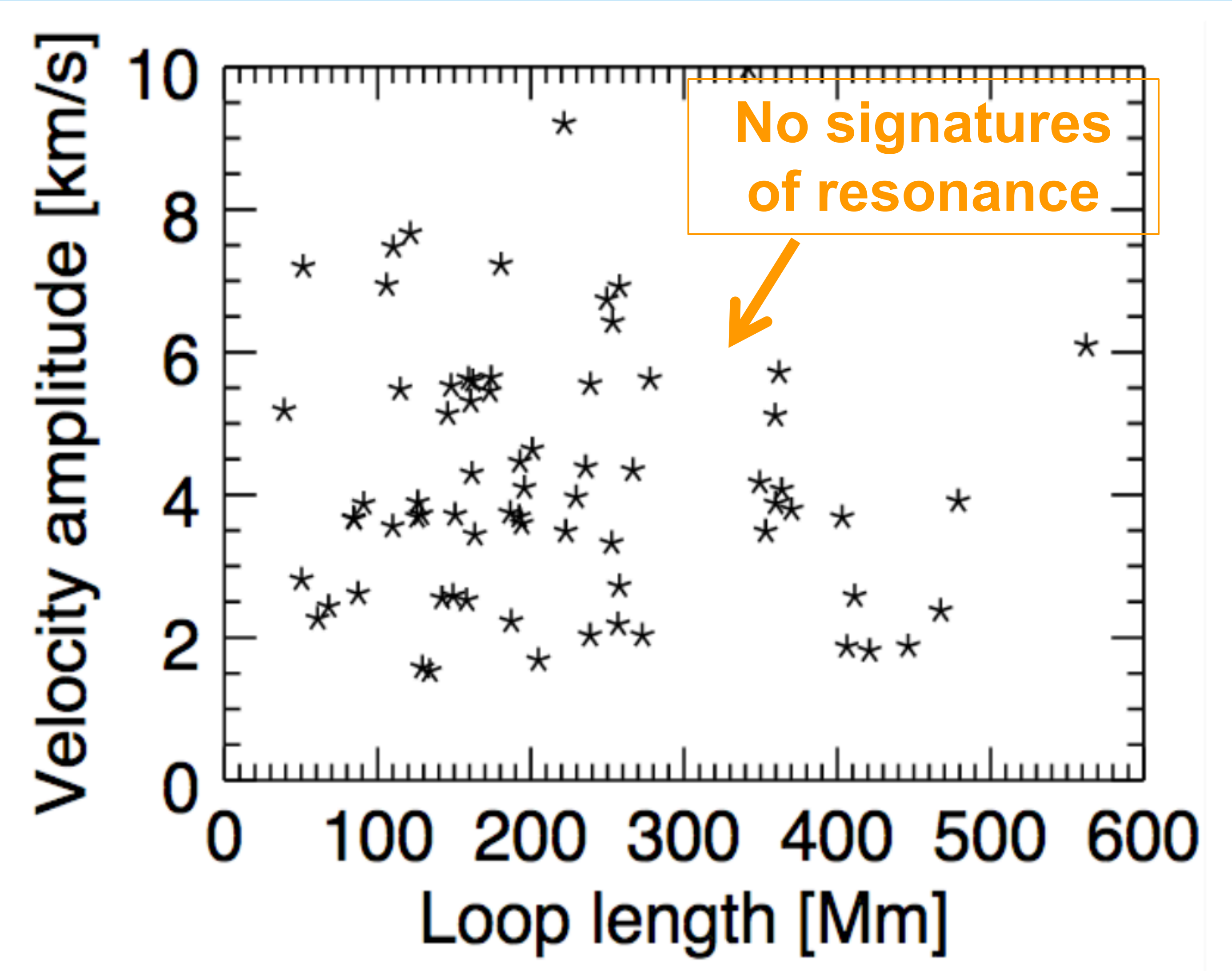
How can we have a decayless monochromatic oscillation of a damped oscillator?

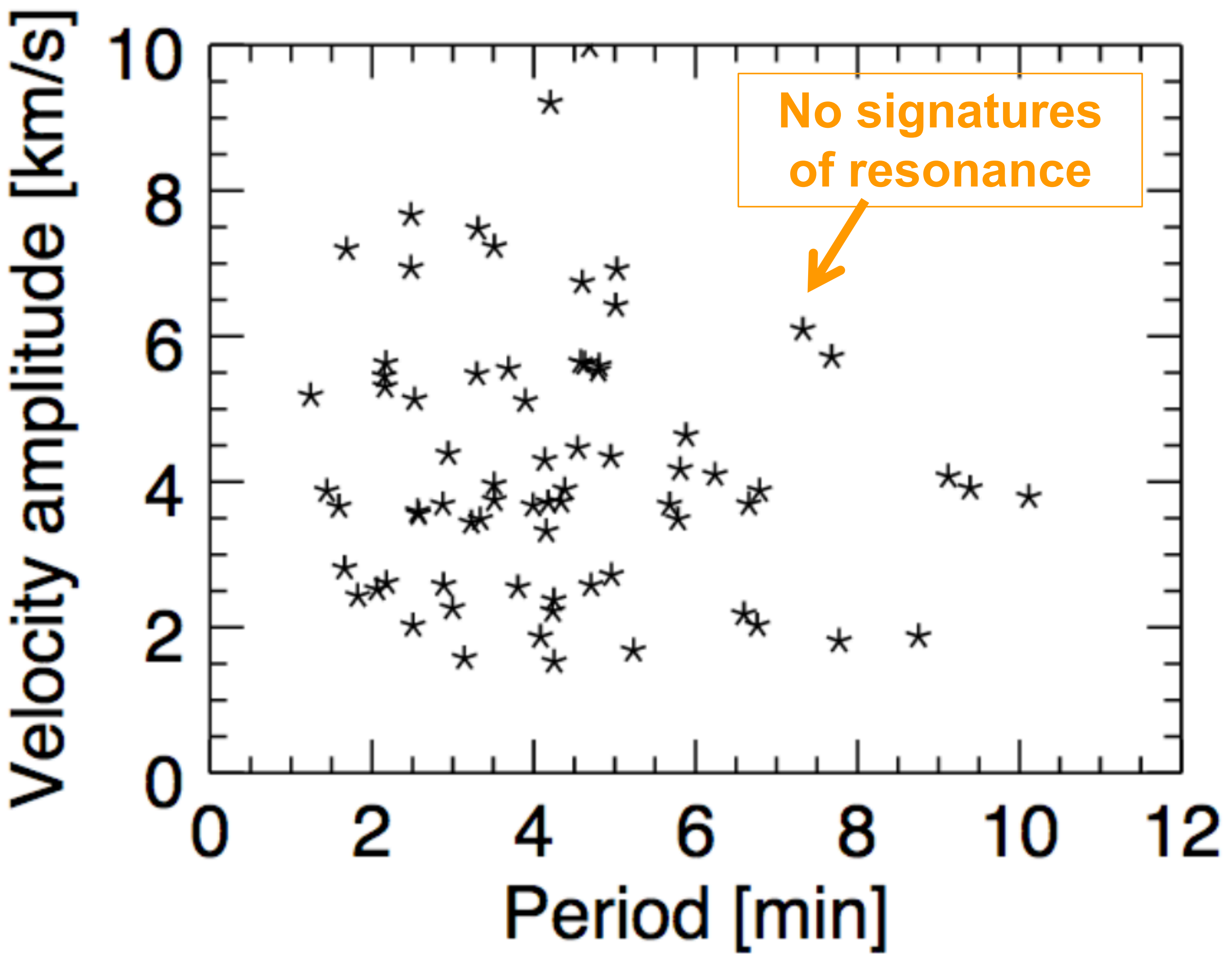
$$\frac{d^2a(t)}{dt^2} + \delta\frac{da(t)}{dt} + \Omega_{\mathrm{K}}^2 a(t) = f(t),$$

Can *f(t)* be periodic? (E.g., leakage of p-modes, chromospheric 3-min oscillations)

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

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




No signatures of resonance
Velocity amplitude [km/s]
Period [min]
0
2
4
6
8
10
12

Thus, *f(t)* cannot be periodic:

no signature of resonance.

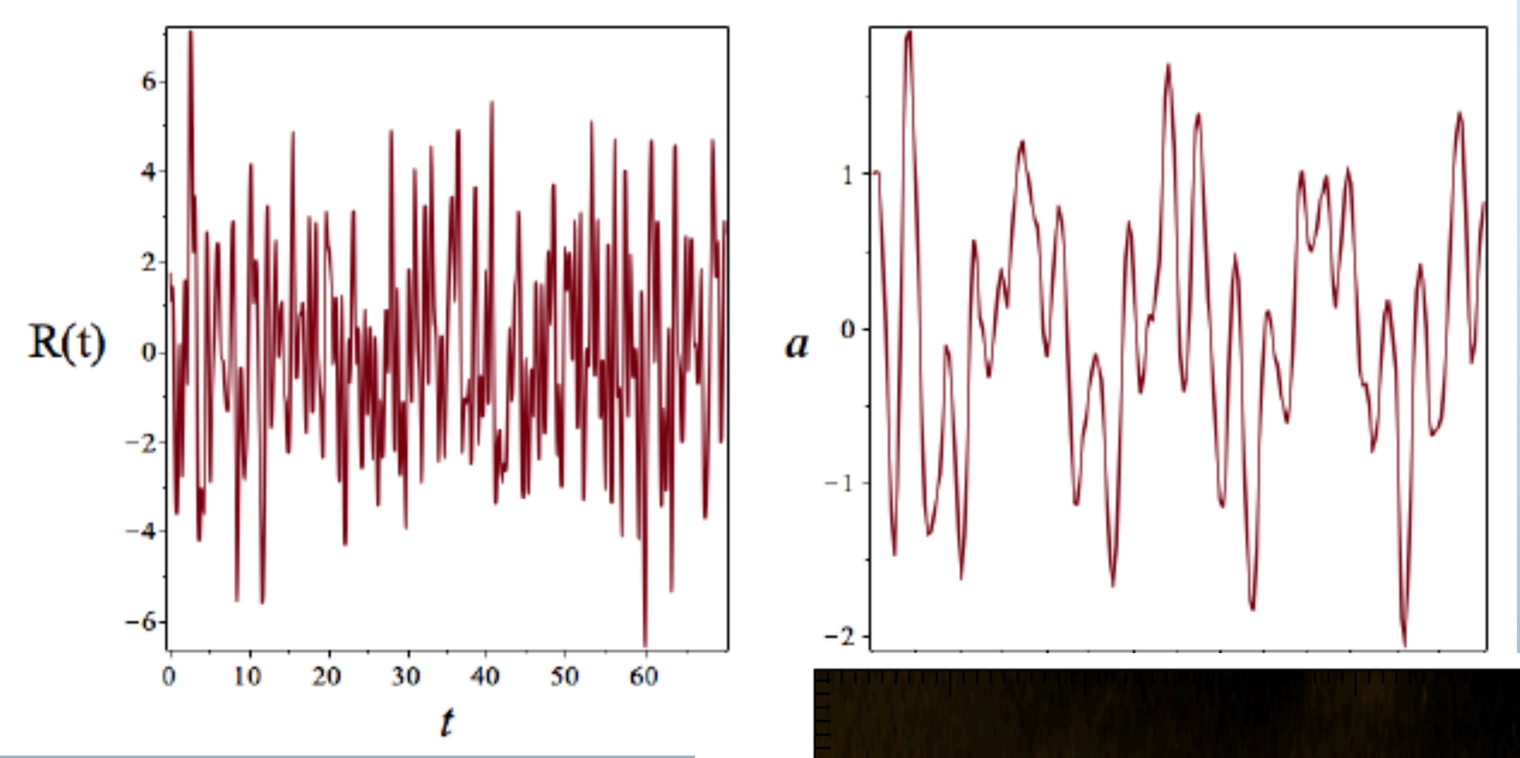
→ We exclude the illusive leakage of p-modes or 3-min oscillations as a driver of decayless kink oscillations

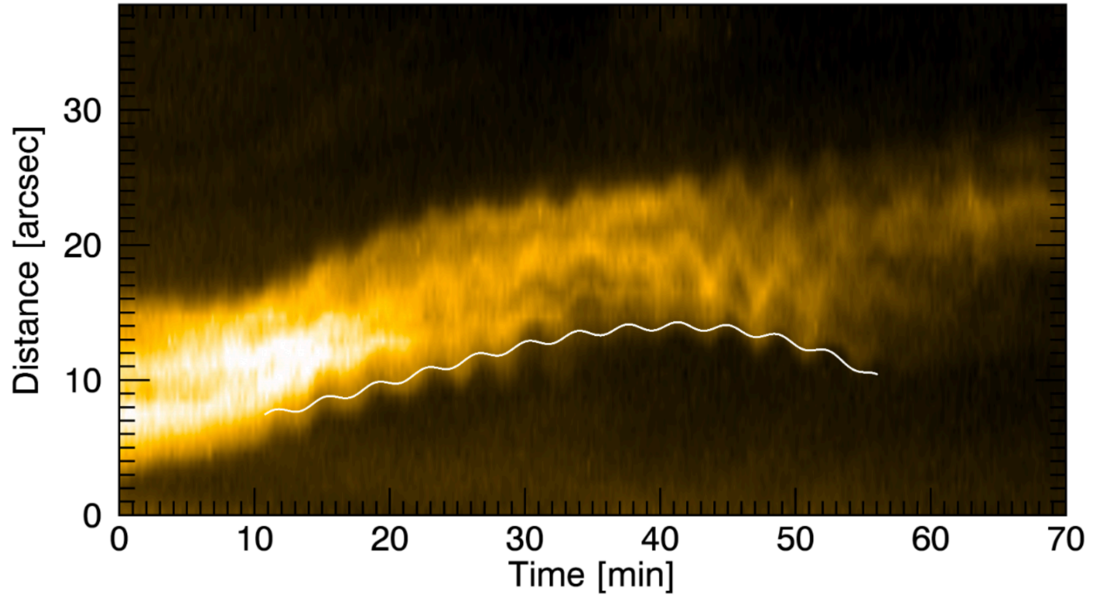
How can we have a decayless monochromatic oscillation of a damped oscillator?

$$\frac{d^2a(t)}{dt^2} + \delta\frac{da(t)}{dt} + \Omega_{\mathrm{K}}^2 a(t) = f(t).$$

Could the driver *f(t)* be random, *f(t)=R(t)*?
(E.g. granulation motions)

Response of an oscillator to random driving

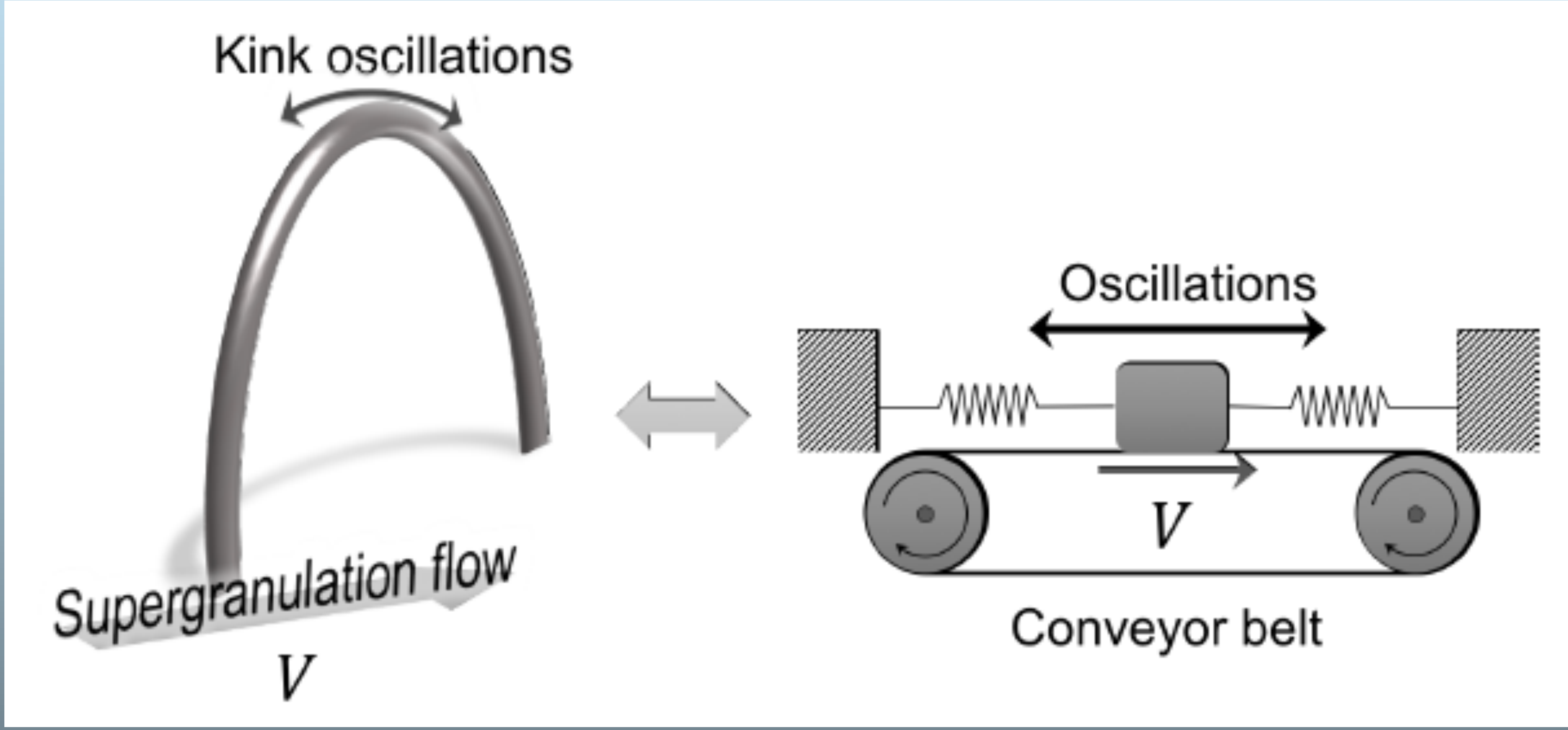




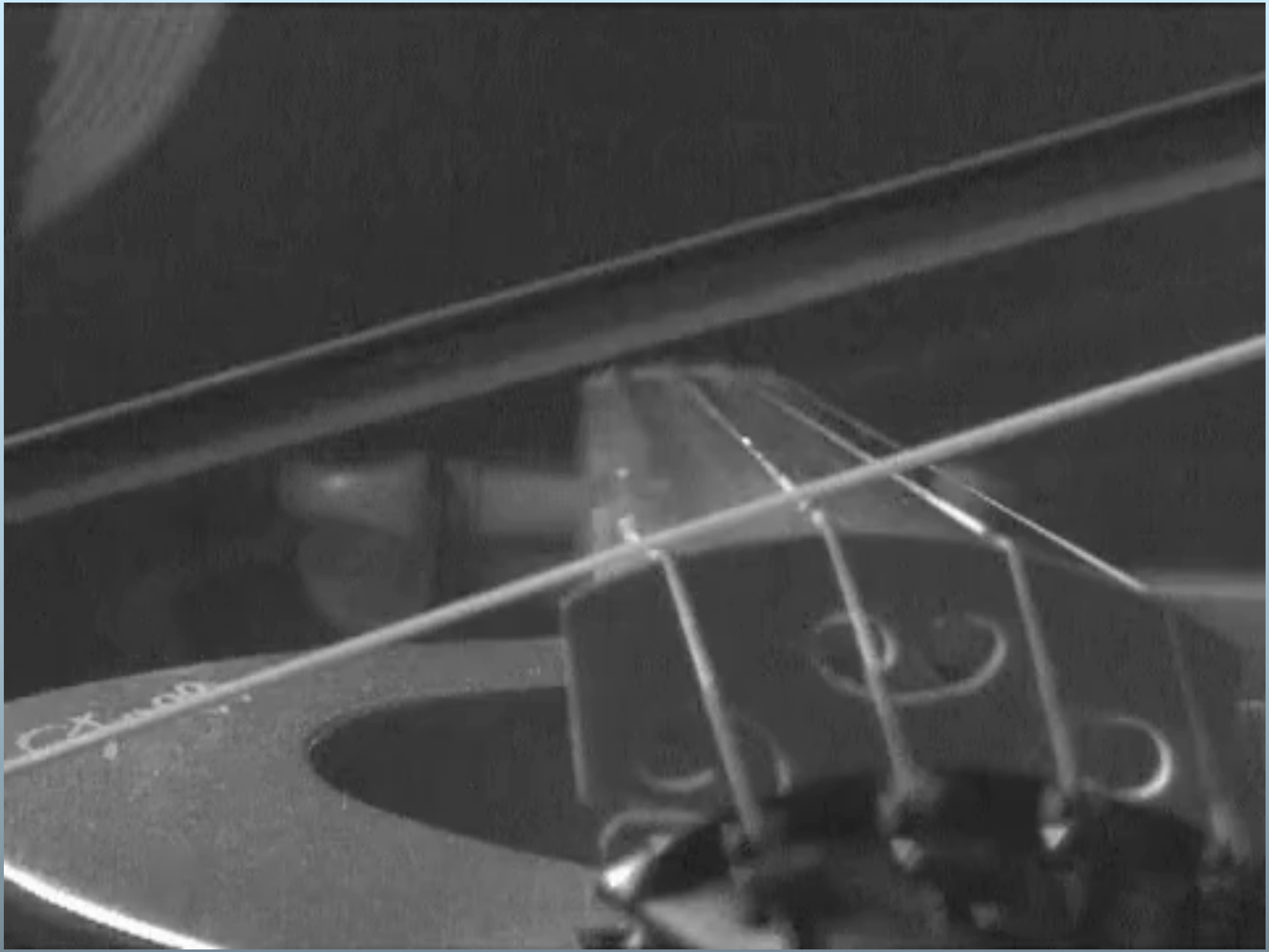
The phase is not stable, does not match observations

Undamped 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



In a self-sustained oscillator (self-oscillator), the driving force is controlled by the oscillation itself
so that it acts in phase with the velocity, causing a negative damping that feeds energy into the vibration:

no external rate needs to be adjusted to the resonant frequency.

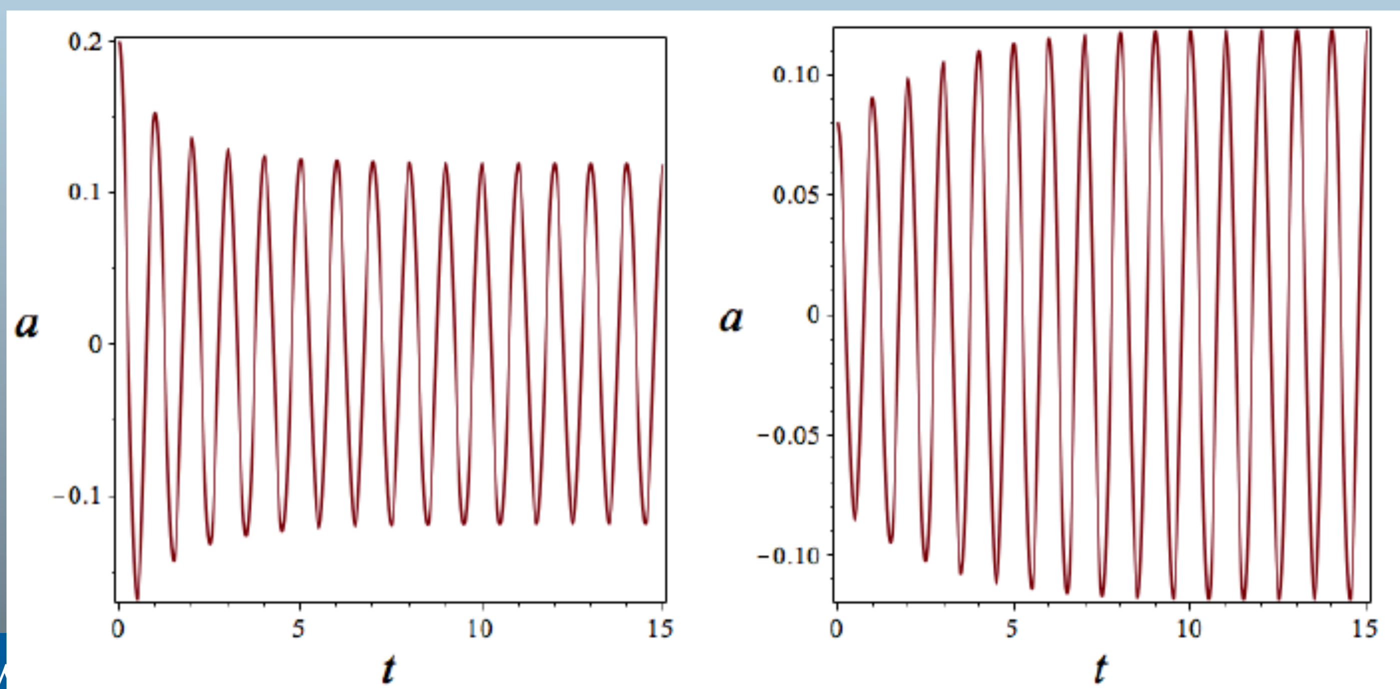
Examples:

- Heart,
- Clocks,
- Bowed and wind musical instruments,
- Devices that convert DC in AC.

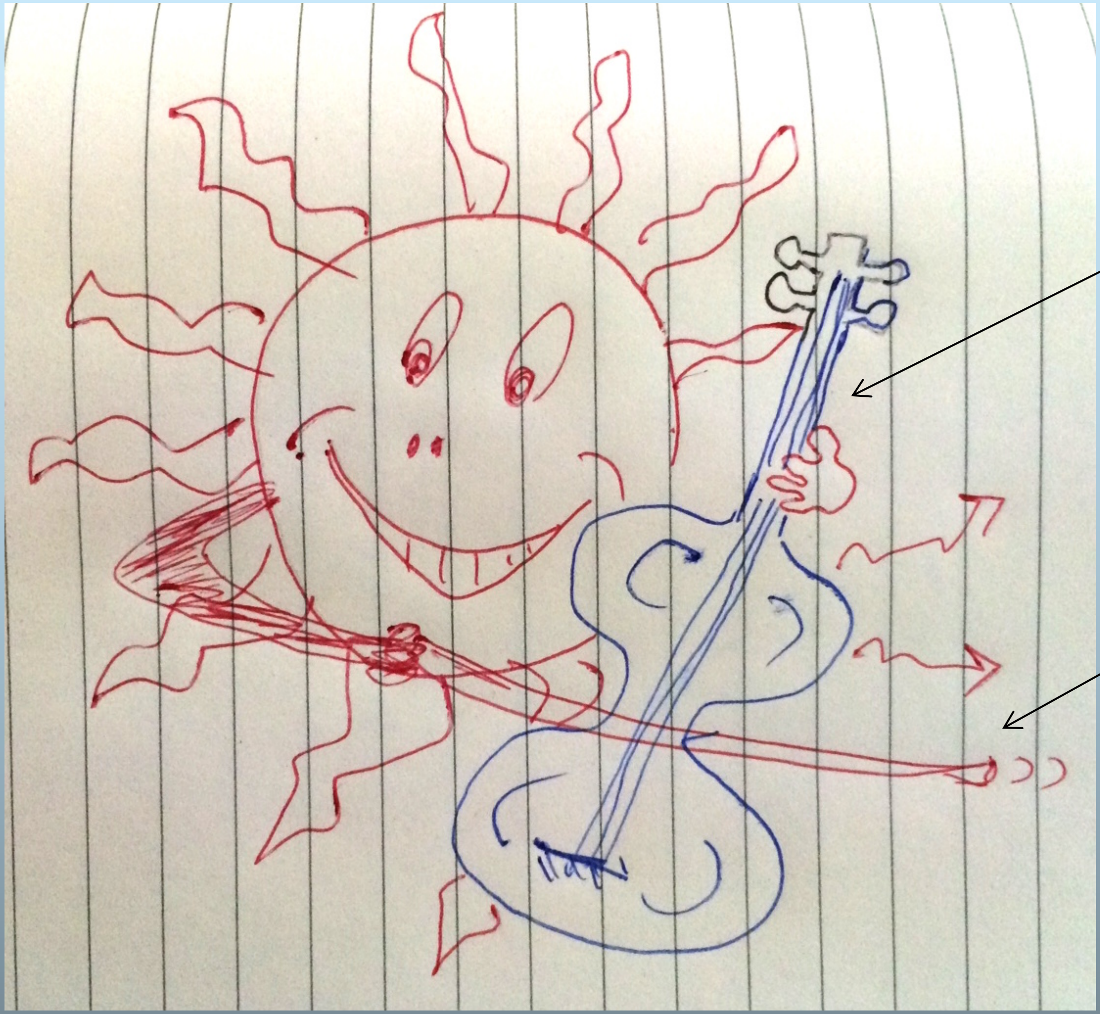
$$\frac{d^2a(t)}{dt^2} + \delta\frac{da(t)}{dt} + \Omega_K^2 a(t) = F\left(v_0 - \frac{da(t)}{dt}\right)$$

Rayleigh Eq.:

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



Sketch of our model of undamped kink oscillations of loops:



Loops

Quasi-steady flows (supergranulation?)

A&A 633, L8 (2020)
https://doi.org/10.1051/0004-6361/201937187

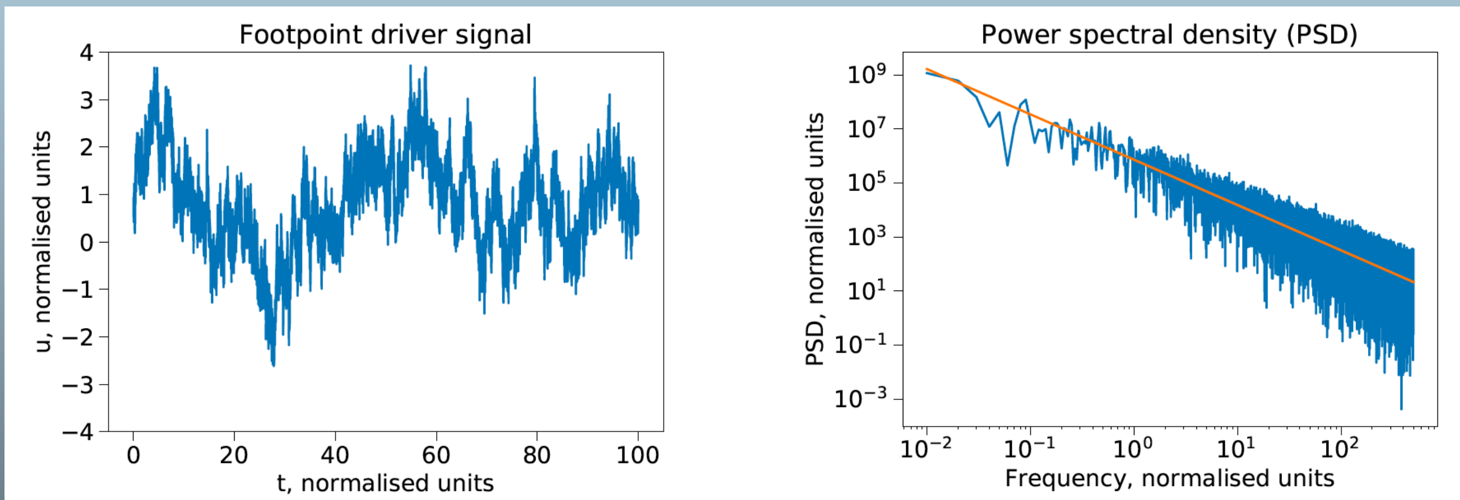
Astronomy & Astrophysics

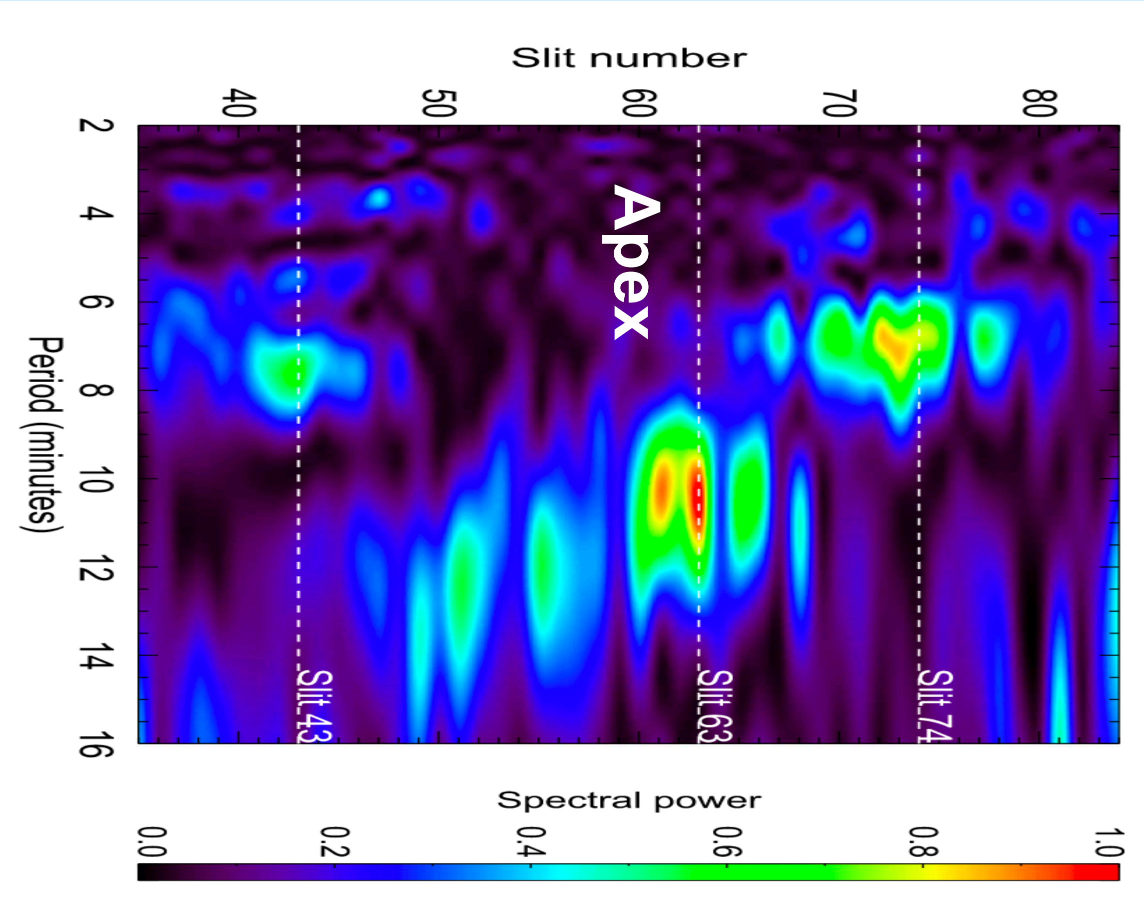
Letter to the Editor

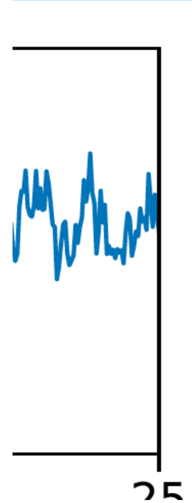
Excitation of decay-less transverse oscillations of coronal loops by random motions

A. N. Afanasyev (А.Н. Афанасьев)[1,2], T. Van Doorsselaere[1], and V. M. Nakariakov (В.М. Накаряков)[3,4]

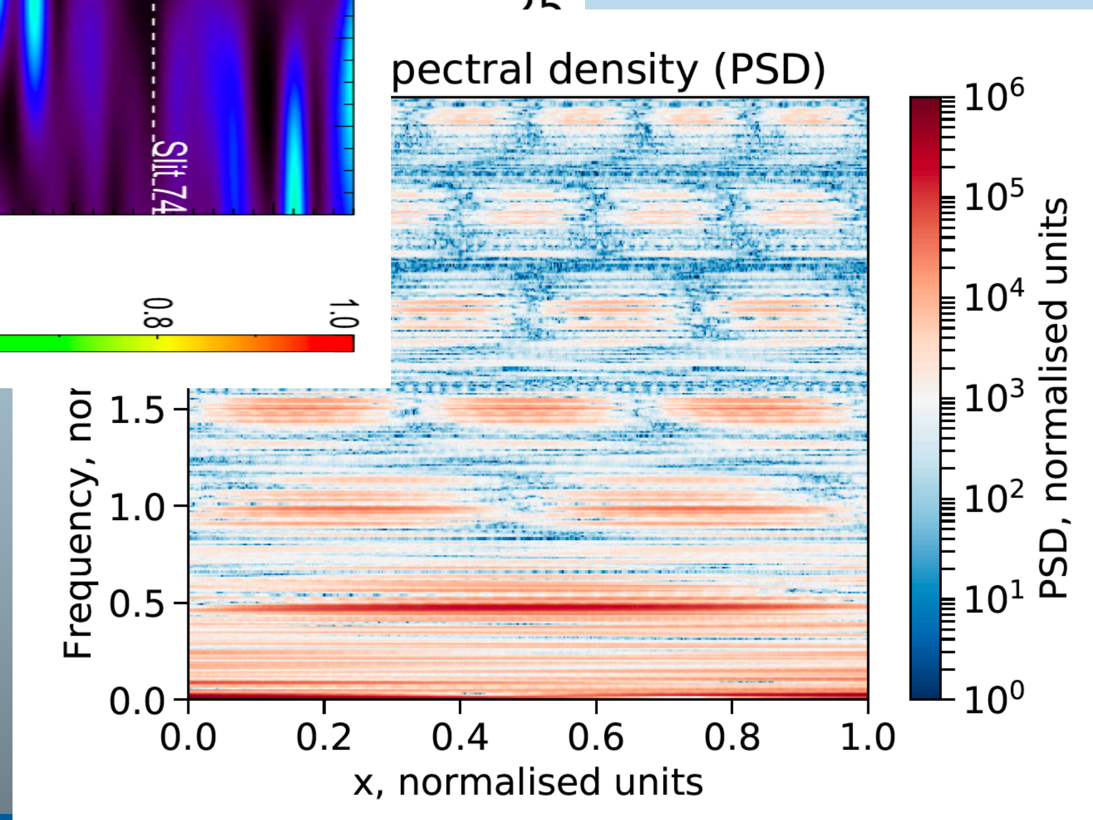
$$\frac{\partial^2 u}{\partial t^2} + \alpha \frac{\partial u}{\partial t} = C_{\mathrm{k}}^2(x) \frac{\partial^2 u}{\partial x^2},$$







Random driver is able to sustain decayless oscillatory patterns too…



So, randomly-driven oscillations or self-oscillations?

Conclusions

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- Appearance of large-amplitude rapidly-damped kink oscillations is associated with low coronal eruptions (LCE).
- Possible excitation mechanism is the mechanical displacement of the loop from the equilibrium by the LCE (observed in **86%** cases).
- Some cases are clearly inconsistent with this mechanism.
- Evidence of nonlinear damping: the quality-factor depends on the oscillation amplitude.

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Conclusions - 2

- There is another, decayless and low-amplitude regime of the oscillations.
- The period also depends on the loop length.
- Seismology during quiet periods.
- The amplitude does not depend on period.
- What is the nature of decayless oscillations? Self-oscillations or random driver? (In both scenarios the energy comes from long-period surface motions).