Decay-less kink oscillations: detection of higher harmonics

T. J. Duckenfield

S. Anfinogentov, D. J. Pascoe, V. M Nakariakov

Centre for Fusion, Space and Astrophysics,
University of Warwick

BUKS2018, 07/09/2018

Outline

i) Kink oscillations in coronal loops

ii) Parallel harmonics as a tool for seismology

iii) “Decay-less kink” oscillation regime

iv) Detection of the second harmonic of decay-less kink oscillations

Kink modes: in coronal loops

- Observed as **transverse** displacements of plasma non-uniformities, such as coronal loops.

- In long wavelength limit $k_z \to 0$ (relative to tube radius), phase speed tends to the *kink speed* C_K;

$$C_K \approx \left(\frac{2}{1+\rho_e/\rho_0}\right)^{1/2} C_{A0}$$

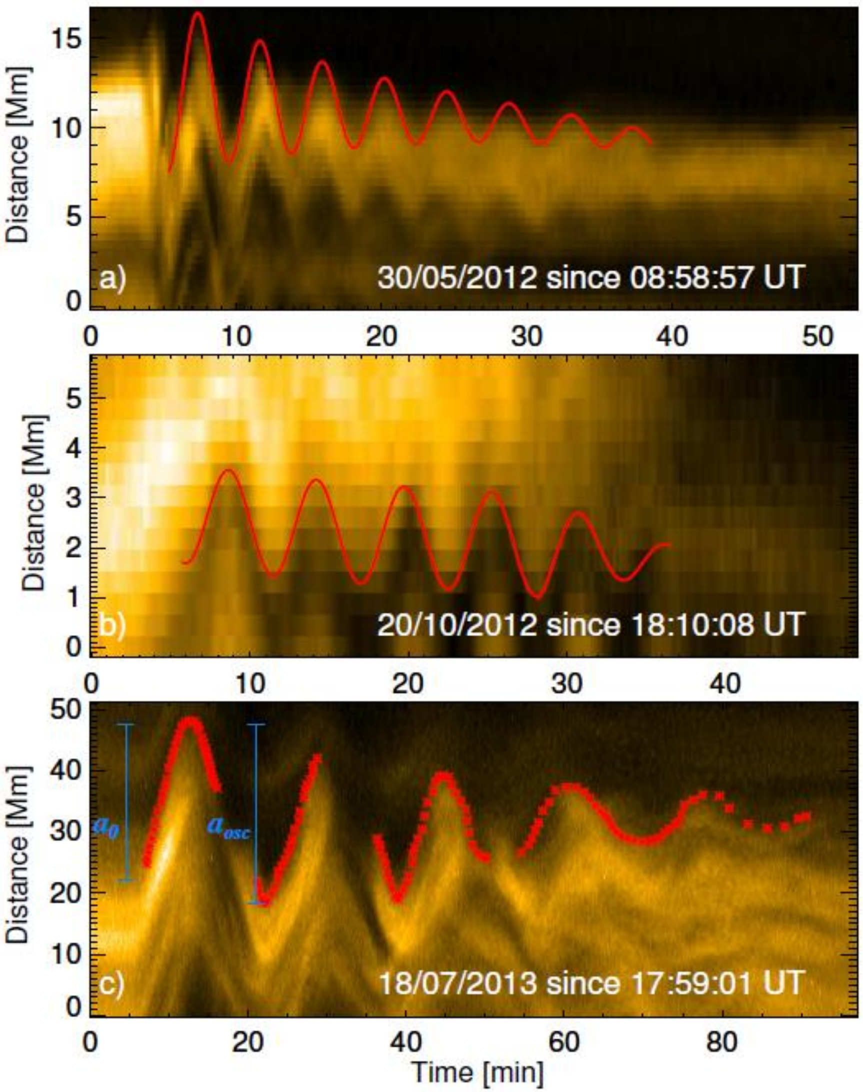
- Exists as both *propagating* and *standing* modes.

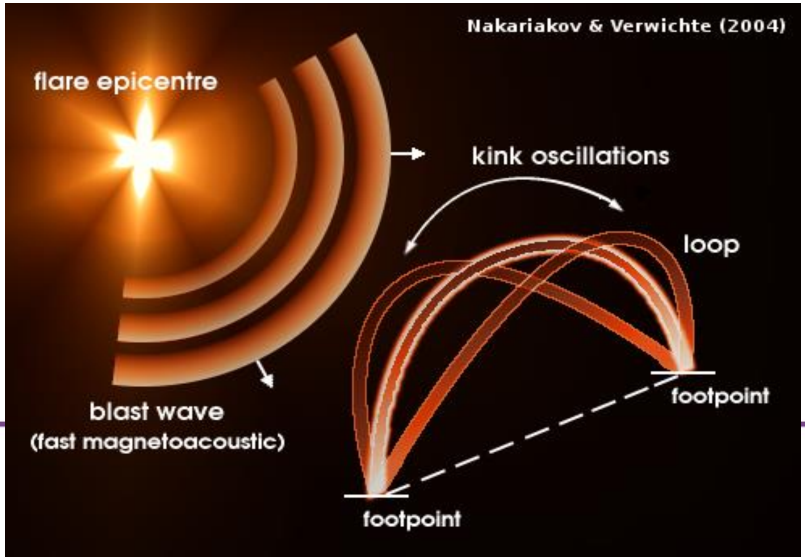
- For standing modes, boundary conditions quantise k_z, introducing longitudinal wavenumber (harmonics) $n = 0,1,2$ ...

- Period scales with loop length, $\boldsymbol{P_{\mathrm{kink}} = 2L/C_K}$. (Goddard et al 2016)

Kink modes: observations

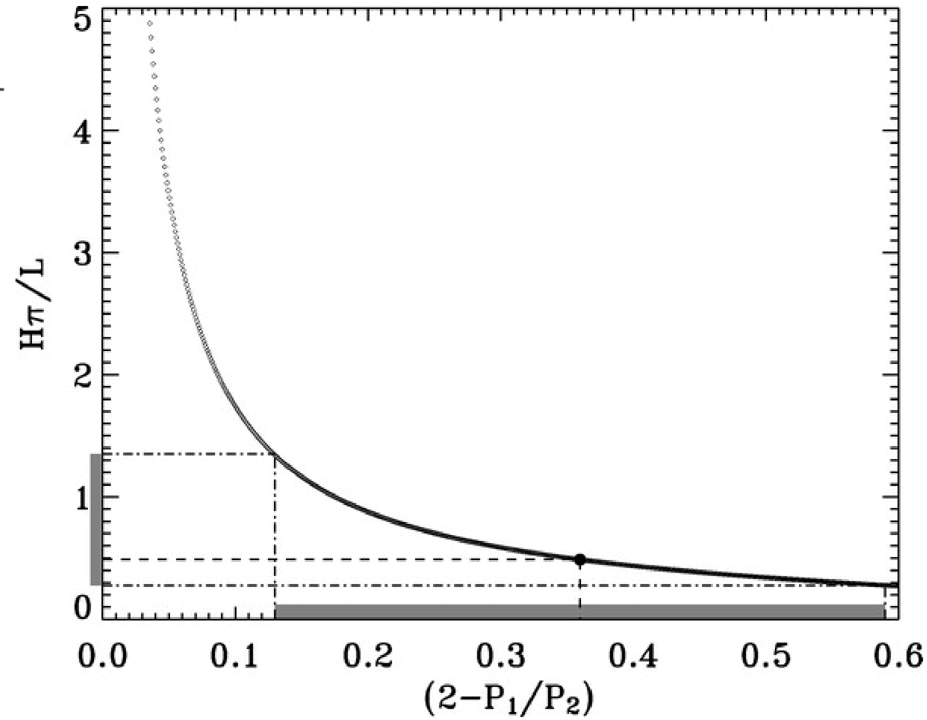
- Typical period values of several minutes (c.f. Goddard et al 2016), **different periods for different loops**.
- Large amplitudes, generally excited by mechanical displacement (Zimovets & Nakariakov 2015).
- Until 2012, all cases seen decaying within a few periods (c.f. Schrijver et al 1999, Aschwanden et al 1999, Verwichte & Nakariakov 2004)





Kink modes: longitudinal harmonics

- Expect for the n^{th} harmonic, $f_n = n \times f_1$ i.e. $P_1/nP_n = 1$.
- Any departure from unity indicates non uniform C_K throughout loop (e.g. Jain & Hindman 2012).
- Detections of such departures include Verwichte et al 2004, Andries et al 2005.
- Attribute to **density stratification** (Andries et al 2005, McEwan et al 2008, Safari et al 2007, Ruderman & Petrukhin 2016).



$$\begin{cases} P_1 = P_{\text{kink}}\left(1 + L/(3\pi^2 H)\right)^{-1} \\ 2P_2 = P_{\text{kink}}\left(1 + L/(15\pi^2 H)\right)^{-1} \end{cases}$$

Kink modes: $P_1/2P_2$ ratio for seismology

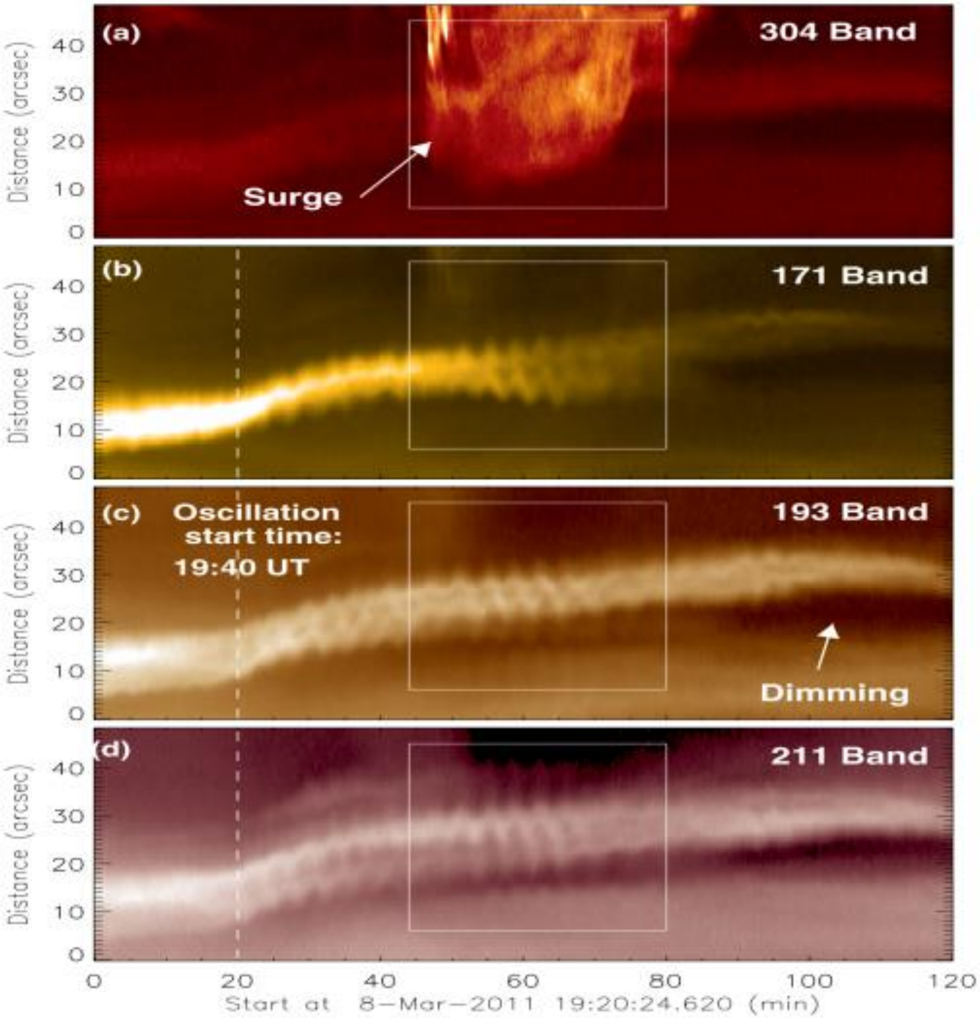
Other effects predicted to modify period ratio;

- Cross-section (magnetic) variation (e.g. Verth & Erdelyi 2008; Pascoe & Nakariakov 2016)
- Siphon flows (Yu et al. 2016)
- Temperature difference effects (e.g. Guo et al. 2015; Lopin & Nagorny 2017)
- Ellipticity (Dymova & Ruderman 2006)

Many mechanisms may cause similar departures from unity. Use Bayes factors to compare models? (Arregui et al 2013)

Decay-less oscillations: observations

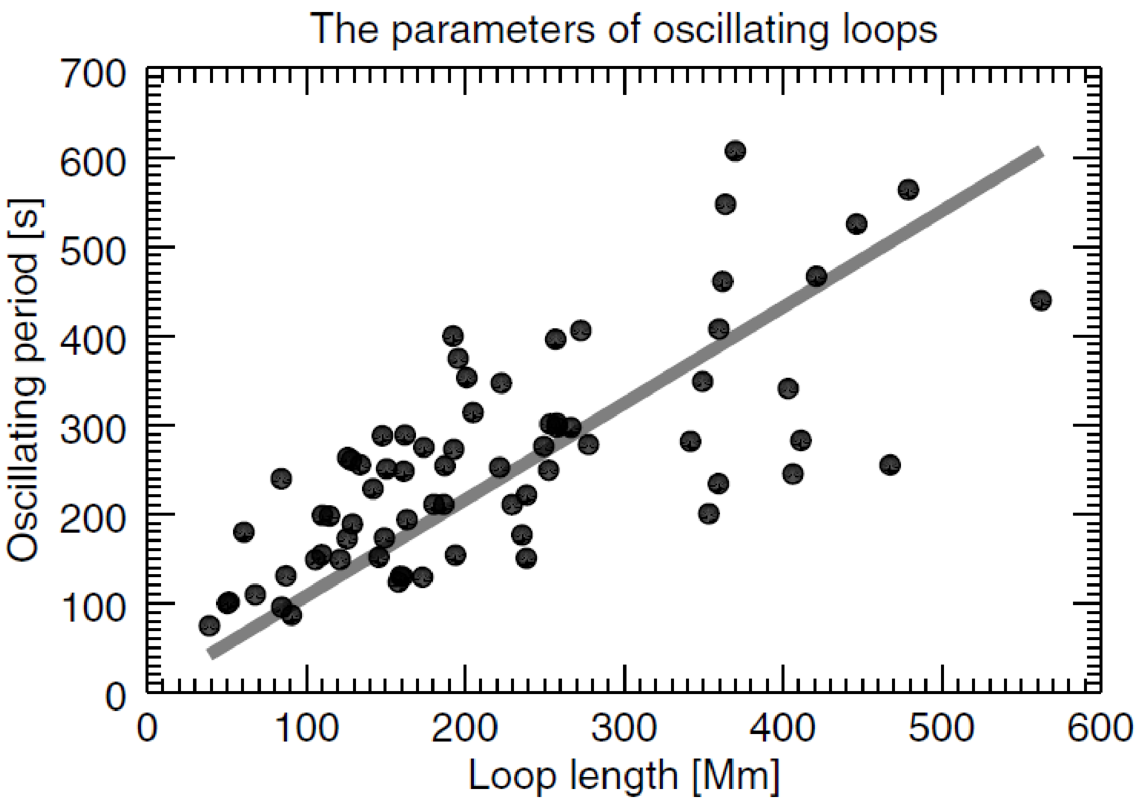
- Amplitude ~ 0.2 Mm, (apparent) velocity ~ 2 km/s
- Independent of eruptive events
- Last many periods with no significant decay, may even grow
- Omnipresent (19/21 AR) (Anfinogentov et al 2015, c.f. Magyars talk on Monday)
- Can co-exist with decaying oscillation, same period (Nisticò et al 2013)



First detection: Wang et al (2012) [above].

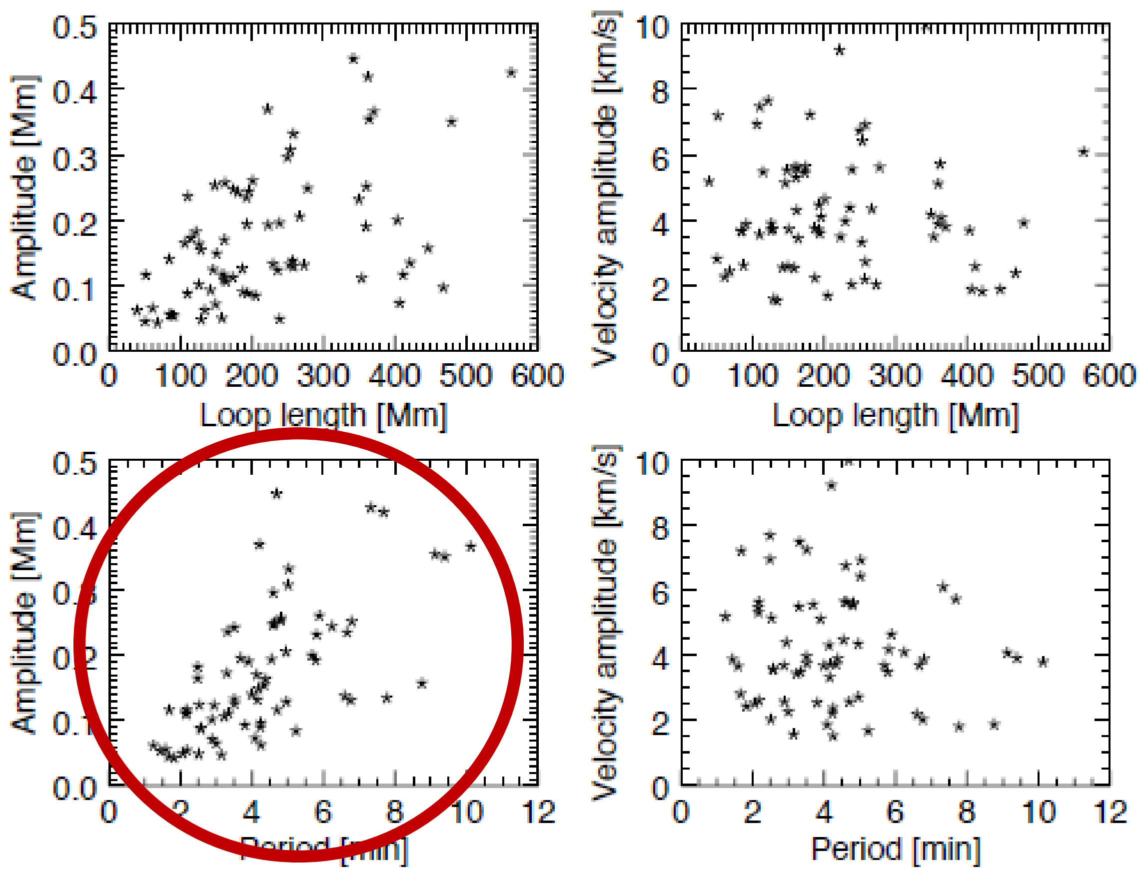
Decay-less oscillations: as kink modes

- Not thermal effect (intensity stable in multiple channels), kink mode quasi-incompressible
- Travel at kink speeds, period scales with loop length as in the decaying regime (Anfinogentov et al 2015), interpret as **kink mode**.
- Subject to same damping mechanisms (phase mixing, resonant absorption) but apparently undamped –> continuously driven?



Decay-less or continuously driven?

- For a monochromatic photospheric driver (for example 5 min oscillations), expect loops with ω_K near driving frequency to be in resonance -> Lorentzian spike in amplitude, velocity amplitude. Not seen.
- 'Bursty' driver would excite series of decaying oscillation trains, inconsistent with observations.



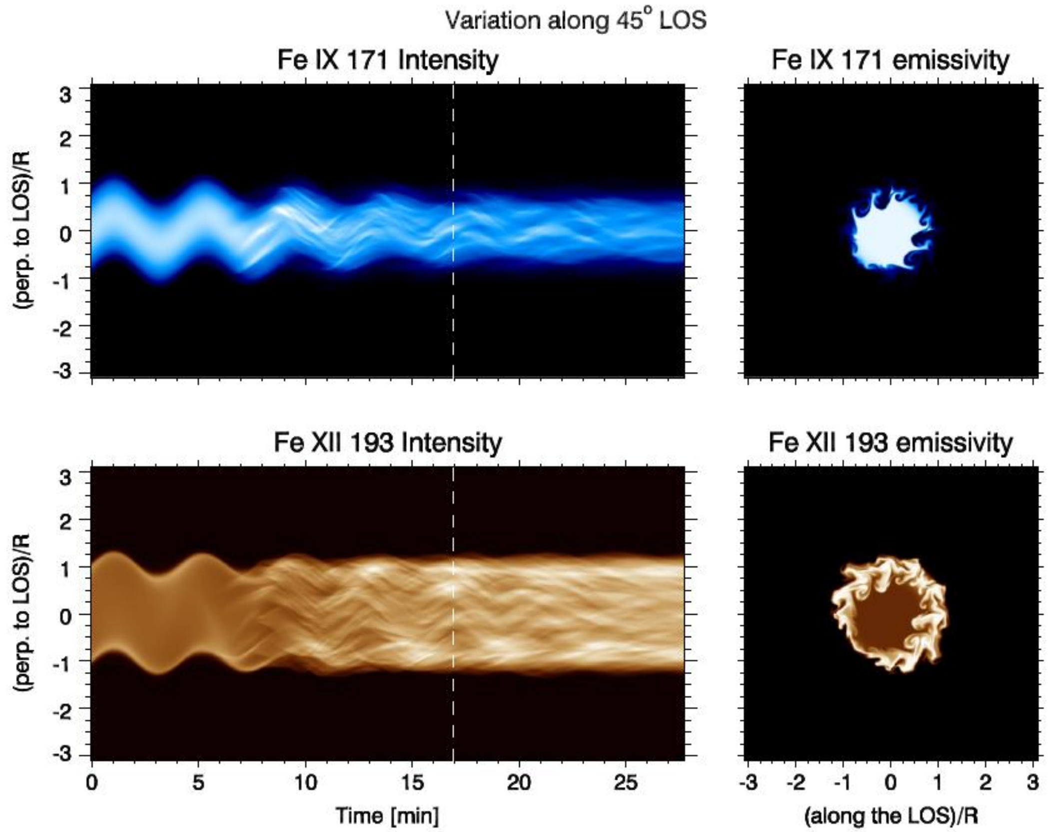
Excerpt above: Nakariakov et al. 2016a

Decay-less oscillations: driving mechanisms

Suggestions:

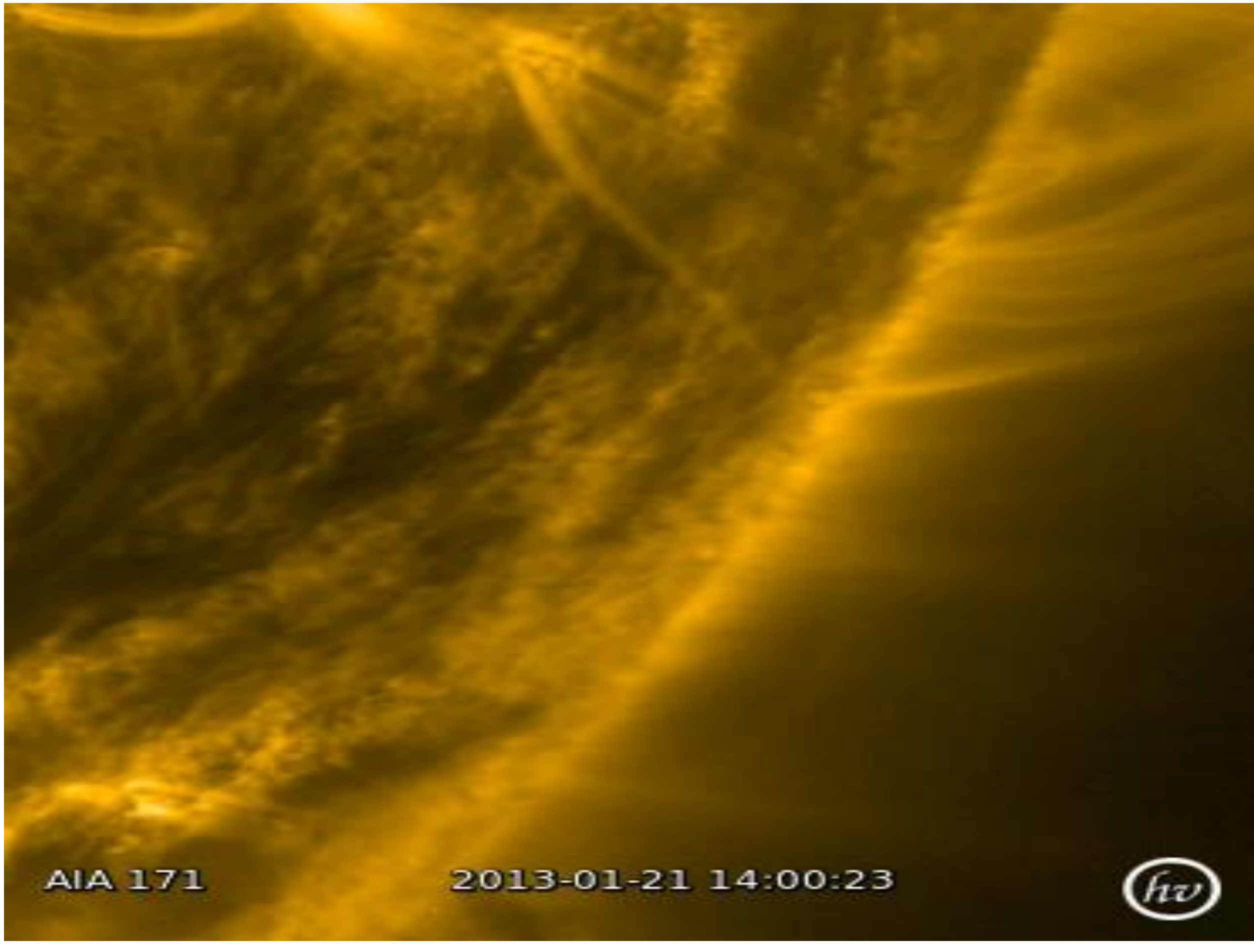
- Driven by stochastic super-granulation flows at footpoints? -> Self-oscillation (Nakariakov et al. 2016a)? Coronal rain at apex (Kohutova & Verwichte 2017, c.f. TNE, Froment this morning)? Centrifugal force (Allan & Manuel 1996)? Colliding flows (c.f. Van Damme, Monday)?

- Line of sight effect: KHi induced by initial kink mode? (excerpt right, c.f Antolin et al 2016, 2017)



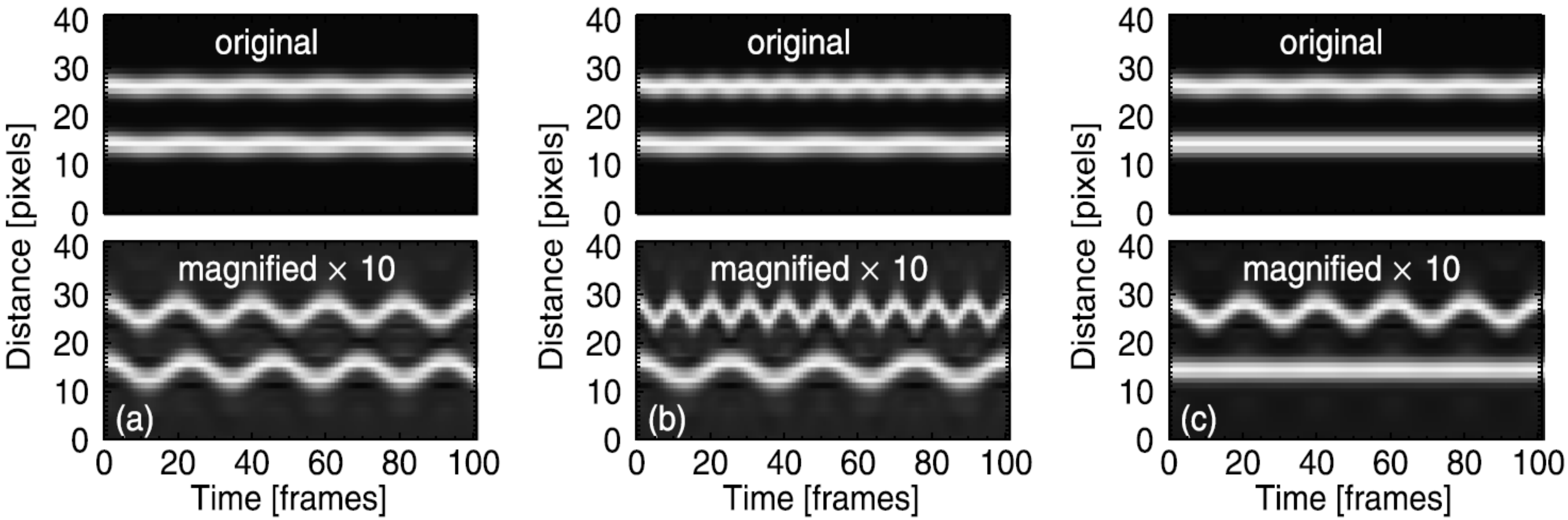
Detection of the second harmonic of decay-less kink oscillations in the solar corona

- SDO/AIA data, loop visible for approx. ten hours (171Å). Also seen in 193Å and 211Å channels.
- Not in active region, no flares/eruptive events.
- Distinct strands, each lasting ~30-60 minutes.
- Some small loop motions discernable.
- Details found in Duckenfield et al 2018.

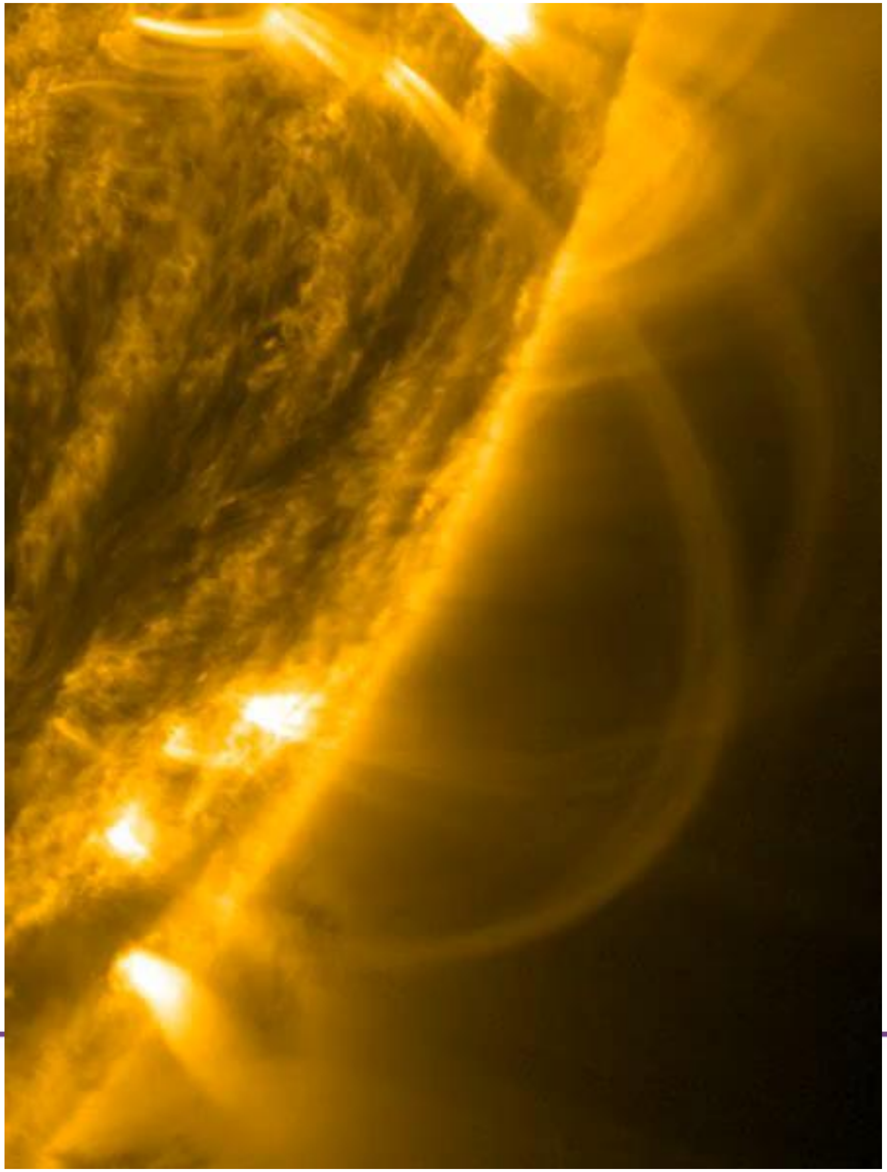


Detection of the second harmonic: motion magnification

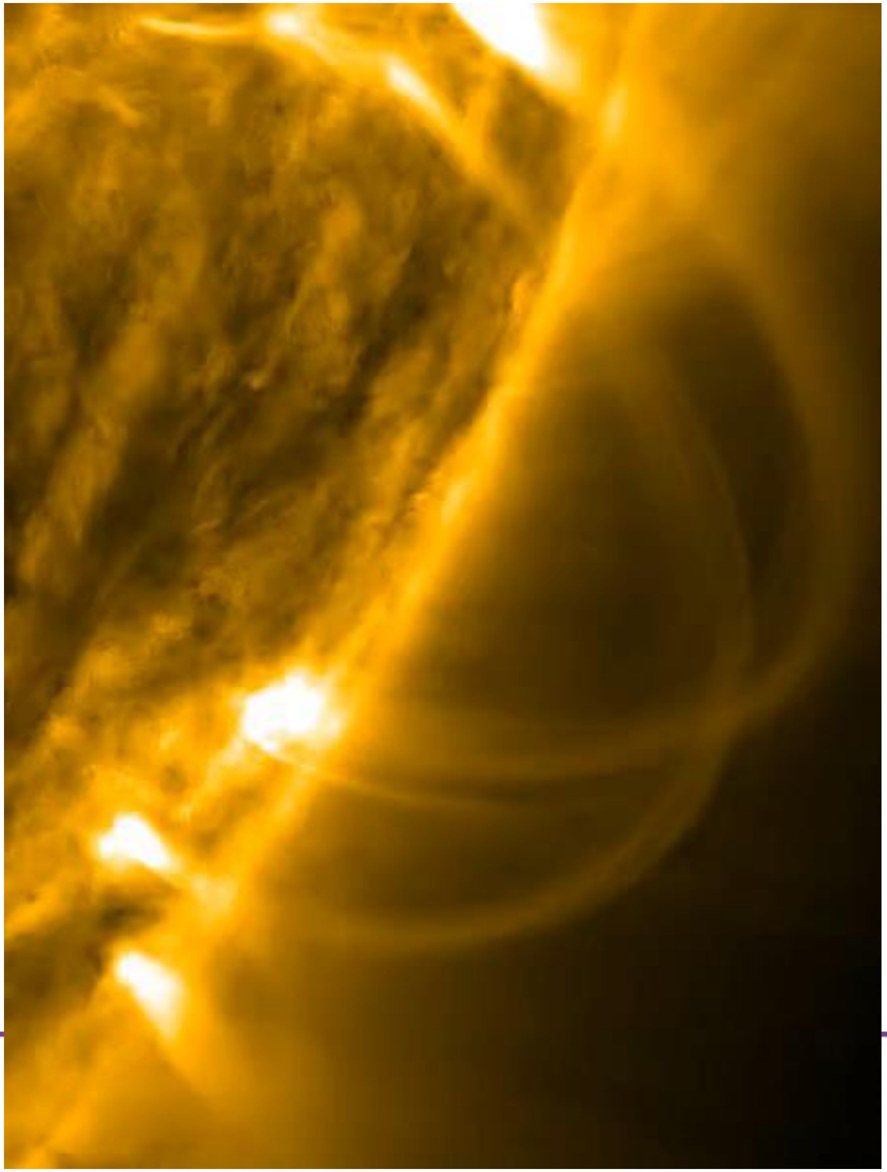
- To enhance transverse motions in plane of sky, run datacube through a ***motion magnification*** routine. For detailed analysis, used 30 mins data.
- Uses a 2D dual-tree complex wavelet transform (DTℂWT), both spatial and temporal information used to reconstruct image (enhanced transverse motion, stable background)
- See Anfinogentov & Nakariakov (2016) for details (excerpted below).



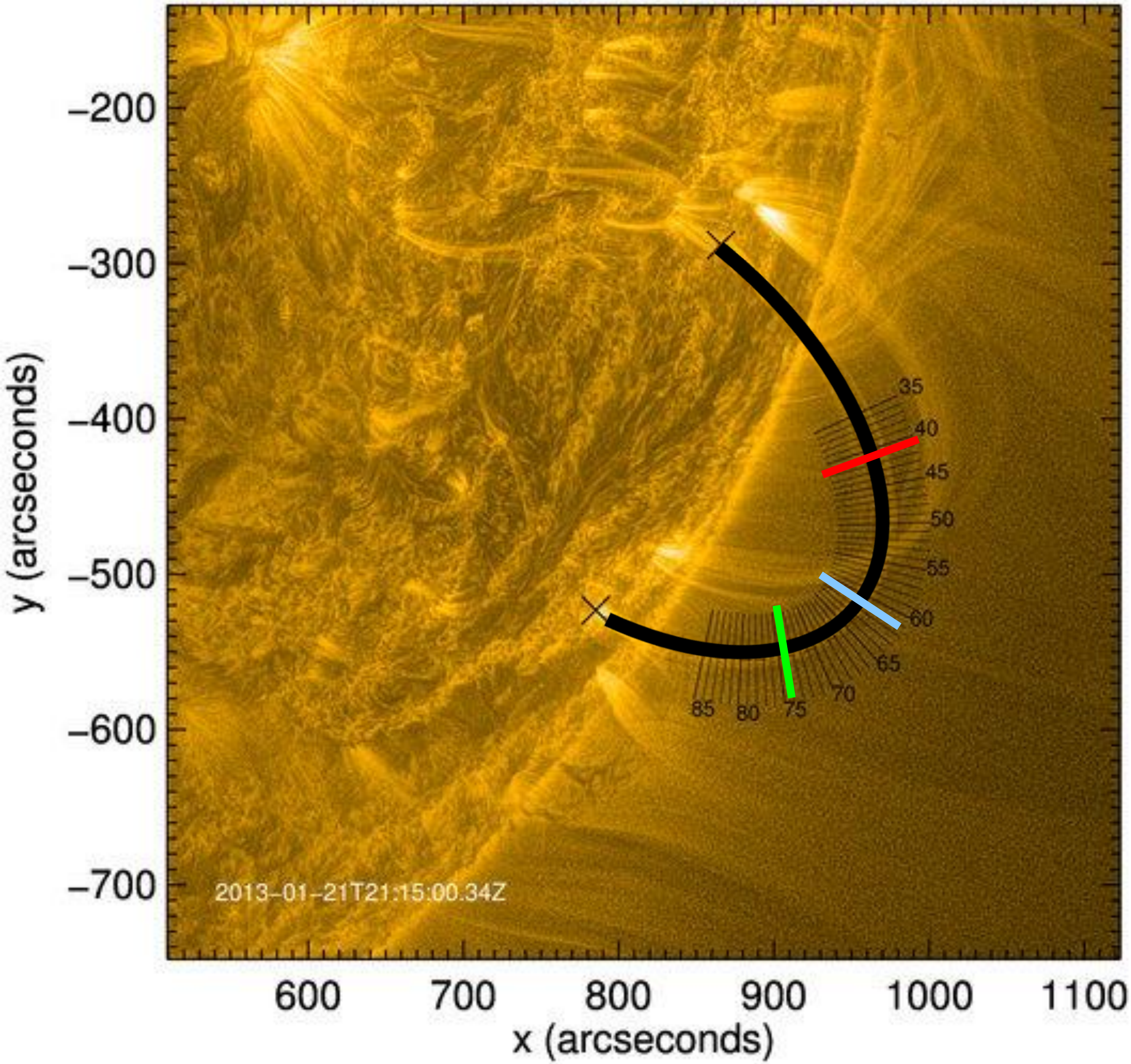
Unmagnified data



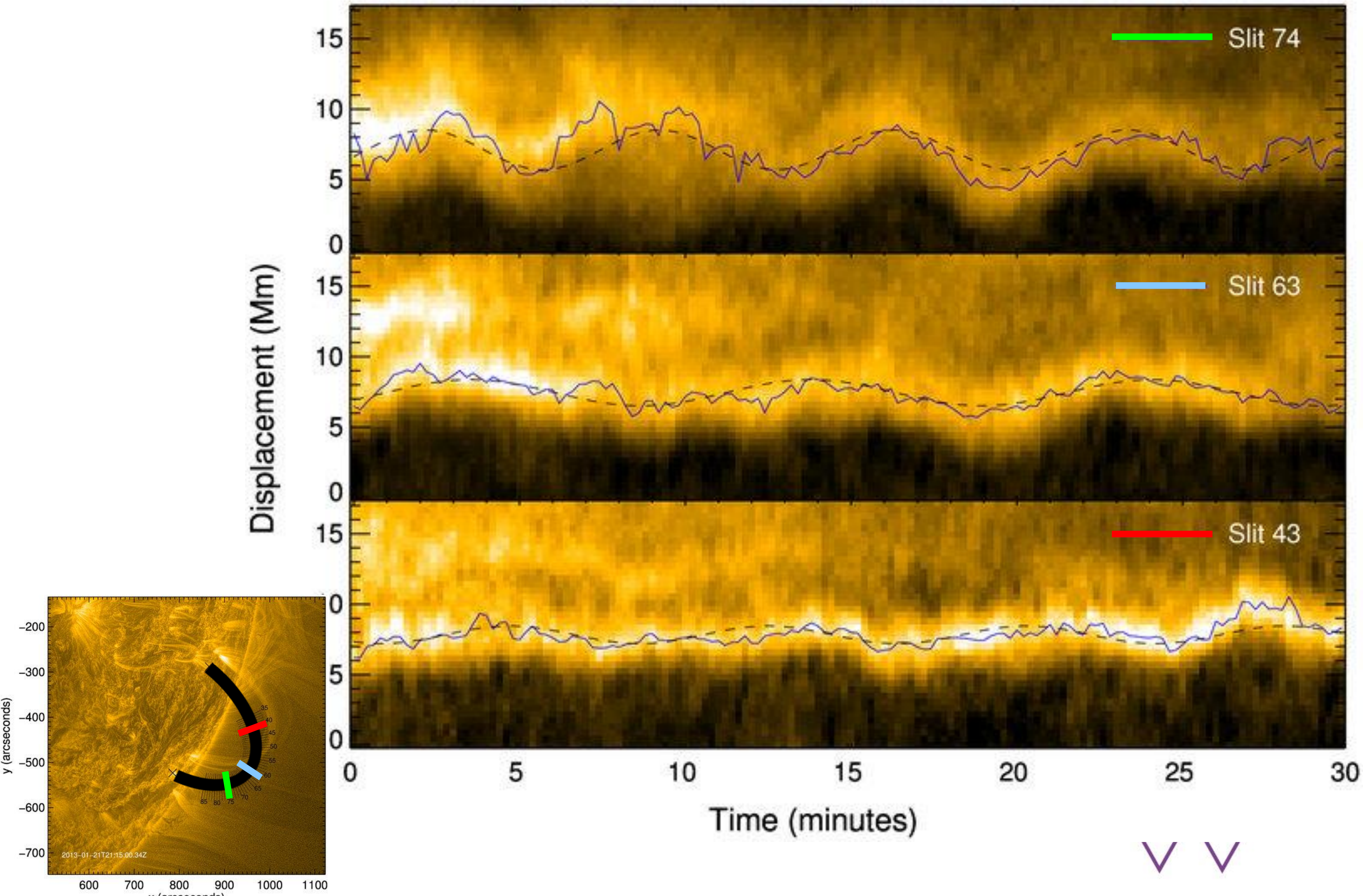
Magnified data (x6)



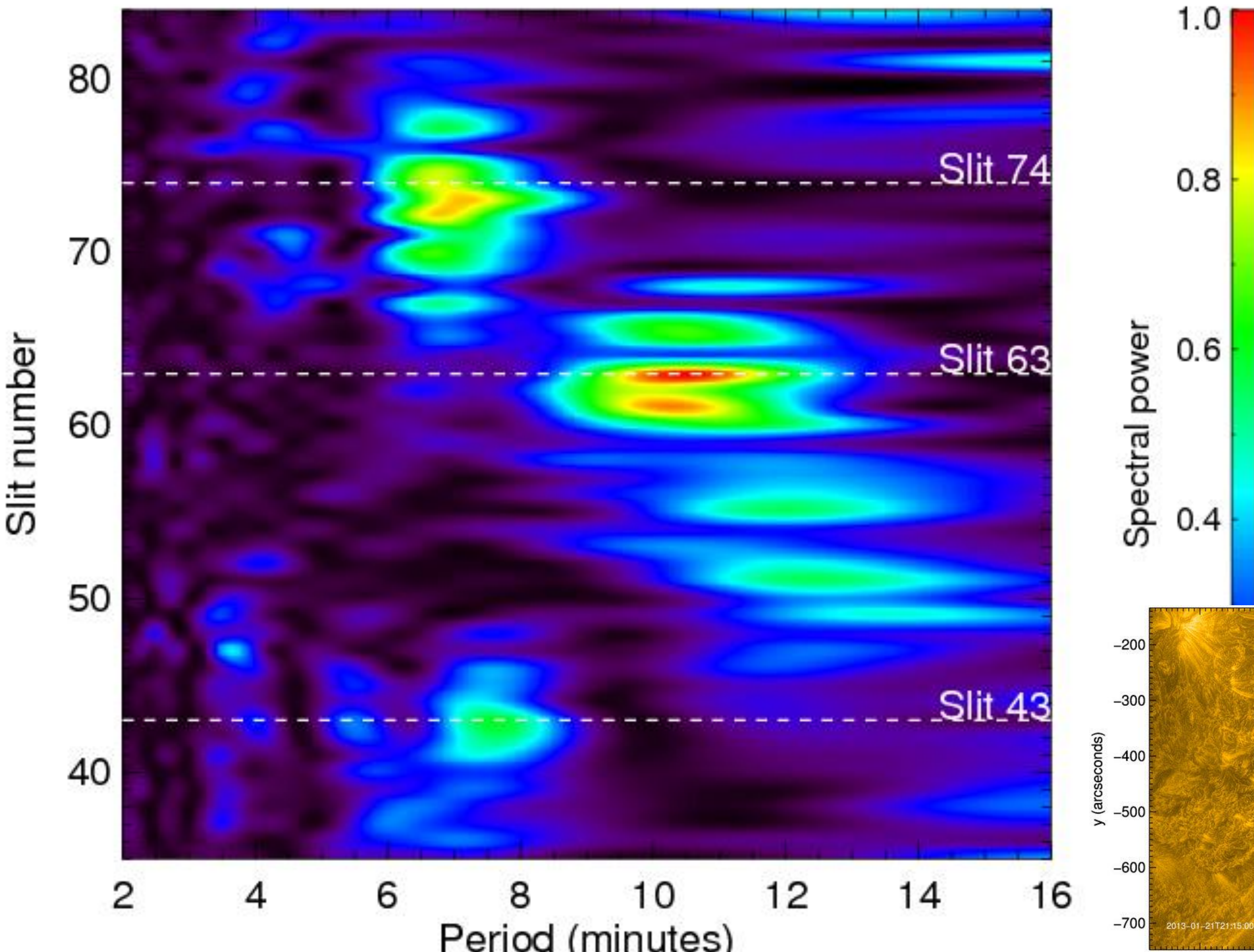
Detection of the second harmonic: 50 slits

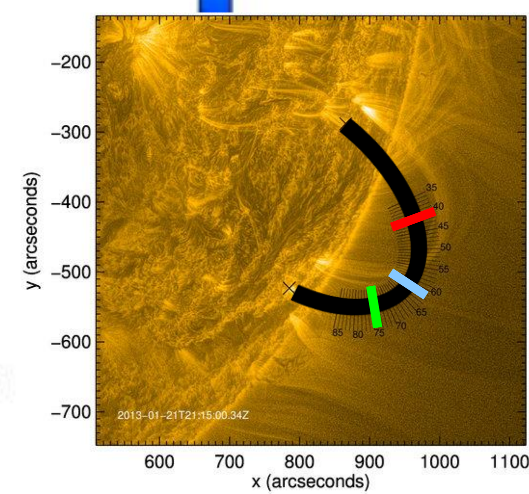


Detection of the second harmonic: time-distance maps



Detection of the second harmonic: spectral distribution





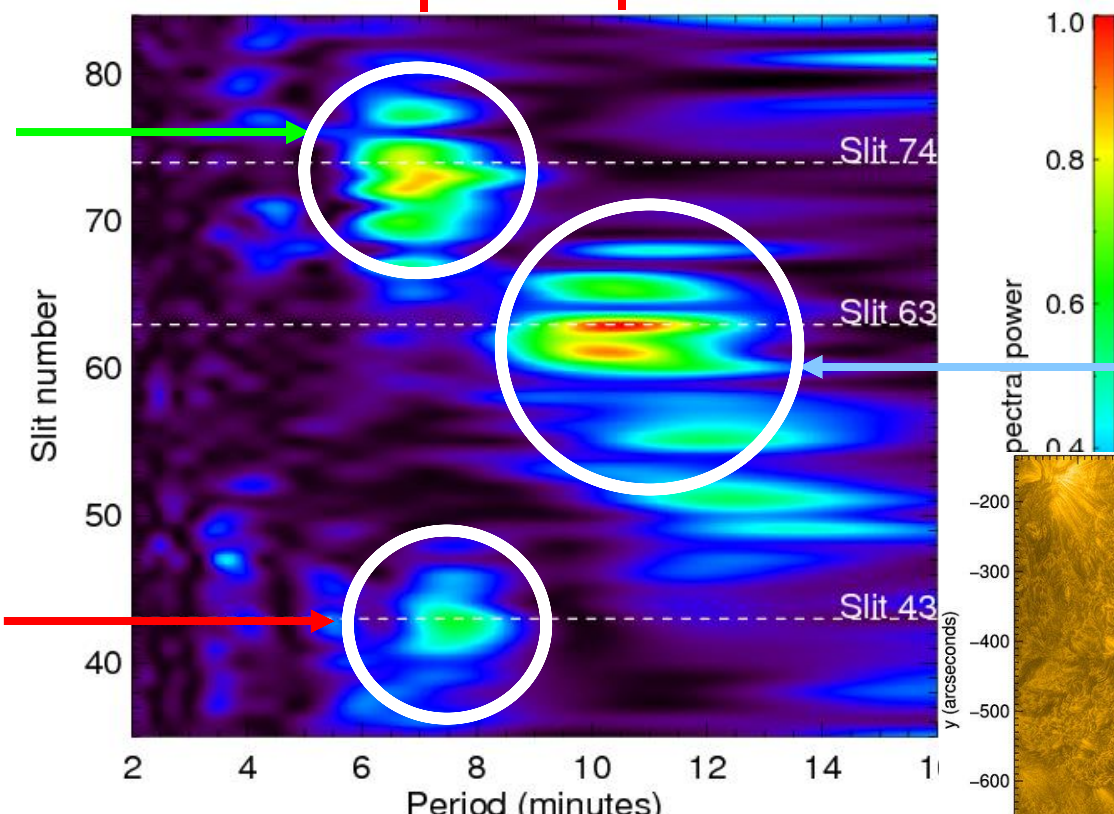
Detection of the second harmonic: two periods

$$P_2 = 7.4^{+1.1}_{-1.3}$$

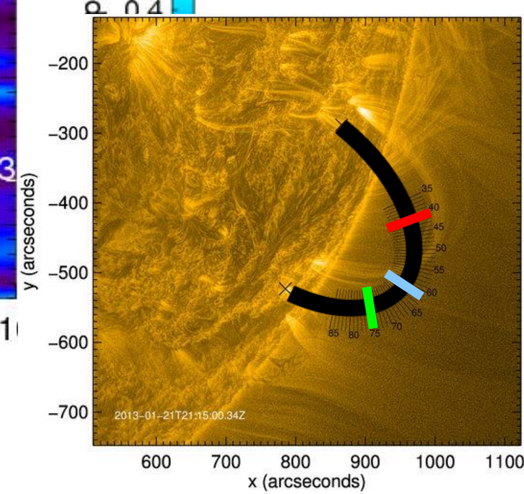
$$P_1 = 10.3^{+1.5}_{-1.7}$$

Period $= 7.1^{+0.8}_{-1.0}$

Period $= 7.7^{+0.8}_{-0.9}$

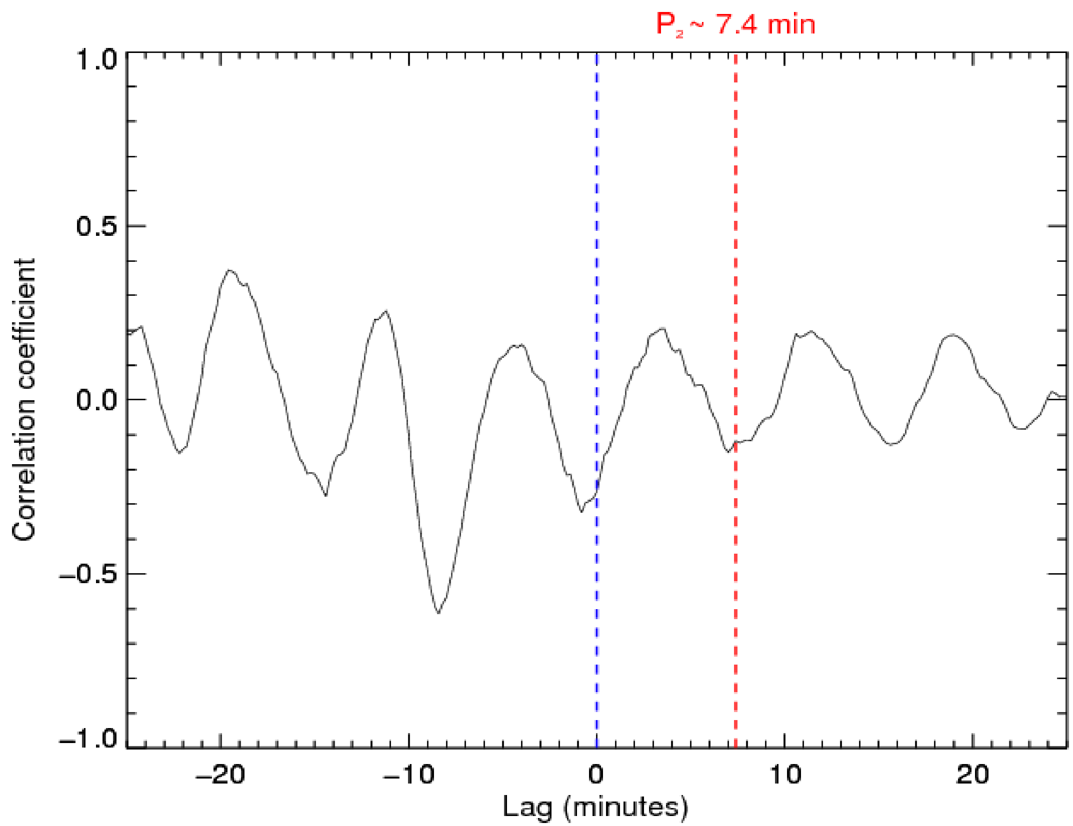


Period $= 10.3^{+1.5}_{-1.7}$



Detection of the second harmonic: phase

- Two distinct periods, spatially separated.
  - $\boldsymbol{P_1 = 10.3^{+1.5}_{-1.7}}$ seen most strongly near loop apex.
  - $\boldsymbol{P_2 = 7.4^{+1.1}_{-1.3}}$ seen most strongly down both legs.
- Figure shows the cross-correlation between slits 43 and 74 (legs).
- Clearly same frequency, **in anti-phase.**
- Evidence for even harmonic.



Detection of the second harmonic: seismology

- Seen evidence of presence of both fundamental and second longitudinal harmonics.

- Estimate kink speed $C_K \approx 0.9$ Mm/s, consistent with other standing kink modes. If assume density contrast, could estimate magnetic field…

$$B_0 = \sqrt{\mu_0 \rho_0}\, C_{A0} \approx \frac{\sqrt{2\mu_0} L}{P} \sqrt{\rho_0 (1 + \rho_e / \rho_0)},$$

- Using the $P_1/2P_2$ ratio ≈ 0.69 can estimate *density scale height* in range $\mathbf{7-45}$ **Mm.**

- Consistent with literature c.f $18 - 42$Mm (Pascoe et al 2017a), 30^{+5}_{-4} Mm (Van Doorsselaere et al 2007)

Summary

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We report the detection of second harmonic of decay-less kink oscillations for the first time.

- Two periods were found: $10.3^{+1.5}_{-1.7}$ and $7.4^{+1.1}_{-1.3}$ minutes. Yield $C_{\mathrm{K}} \sim 0.9$ Mm/s.
- Standing wave signatures
  - Spatial structure (nodes and antinodes).
- The $P_1/2P_2$ ratio gives information about non-uniformity of C_{K}
  - Density stratification? Scale height ~ 7-45 Mm.
  - Expansion of loop cross section with height? Other effects?
- Useful for seismology away from eruptive events.

Open Questions

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i) Are decay-less oscillations continuously driven? By what mechanism(s)?

ii) Can we use additional seismological information to distinguish the mechanism behind departure from unity of the $P_1/2P_2$ ratio?

iii) Do higher order harmonics of decay-less oscillations experience different driving mechanisms to the fundamental harmonic?

iv) Does loop structuring play a role in decay-less oscillations? $P_1/2P_2$ ratio?

v) Do propagating decay-less oscillations exist? Horizontally polarised?