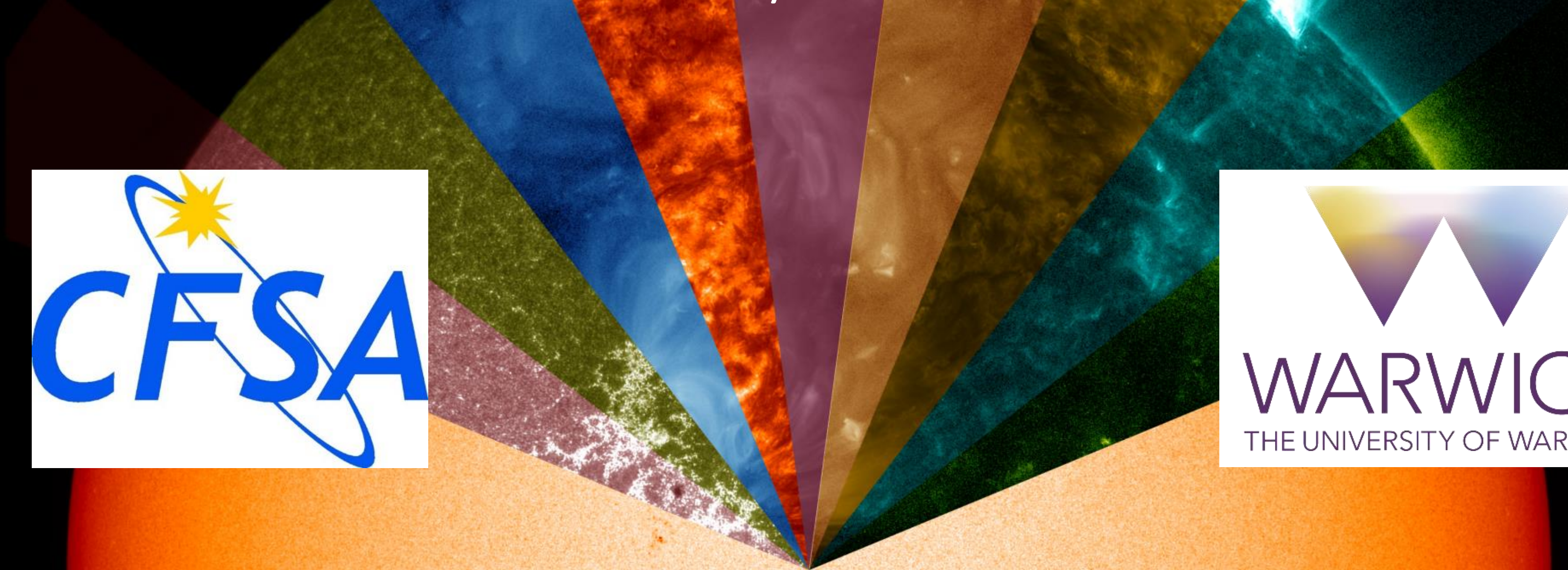
Kink oscillations - a statistical study and follow up

C. R. Goddard

V. M Nakariakov, D. J. Pascoe, S. Anfinogentov,
G. Nistico, I. V. Zimovets

Centre for Fusion, Space and Astrophysics
University of Warwick



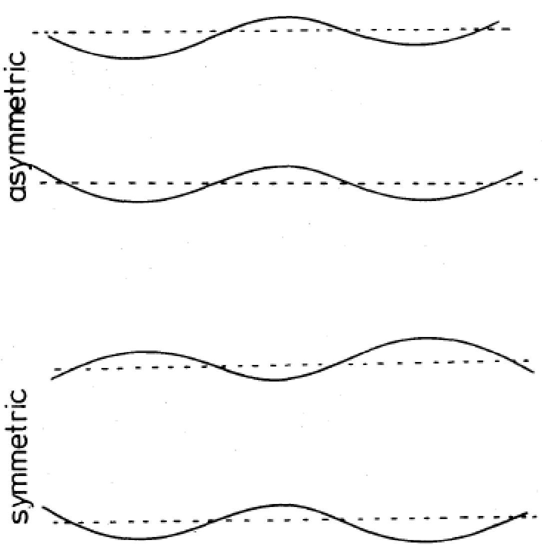
MHD Modes of a Plasma Cylinder

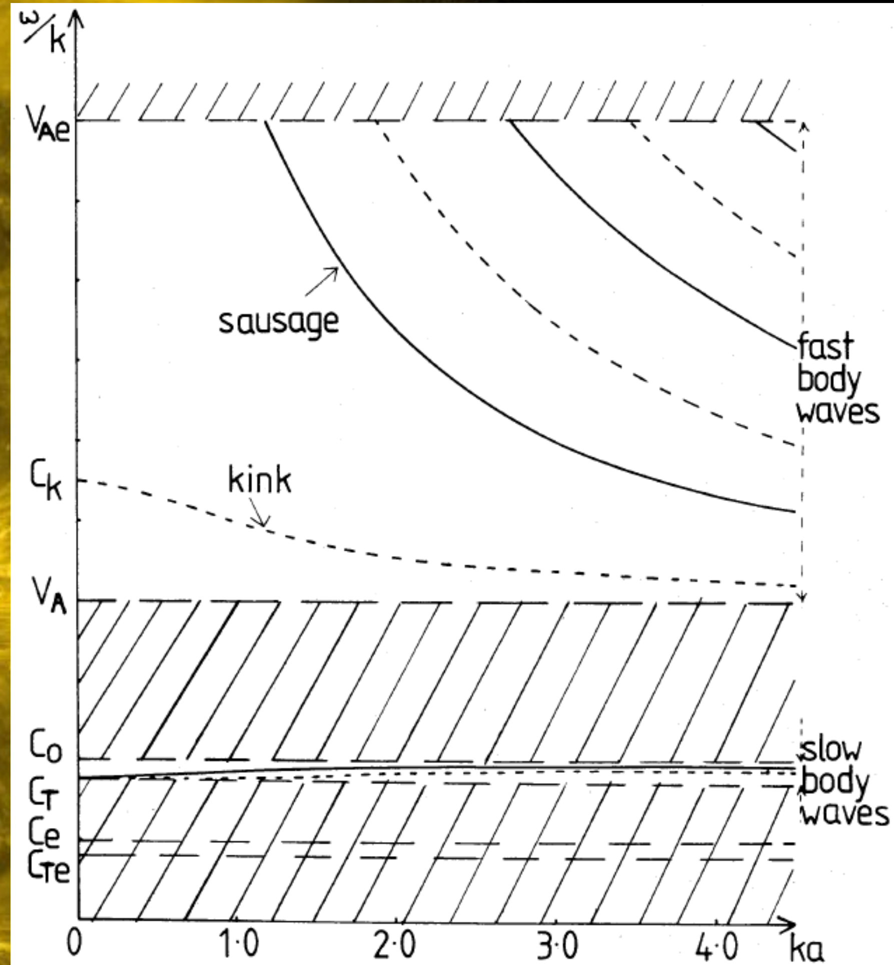
$$\rho_0(k^2 v_A^2 - \omega^2) m_e \frac{K_n'(m_e a)}{K_n(m_e a)} = \rho_e(k^2 v_{Ae}^2 - \omega^2) n_0 \frac{J_n'(n_0 a)}{J_n(n_0 a)}, \quad (1)$$

where

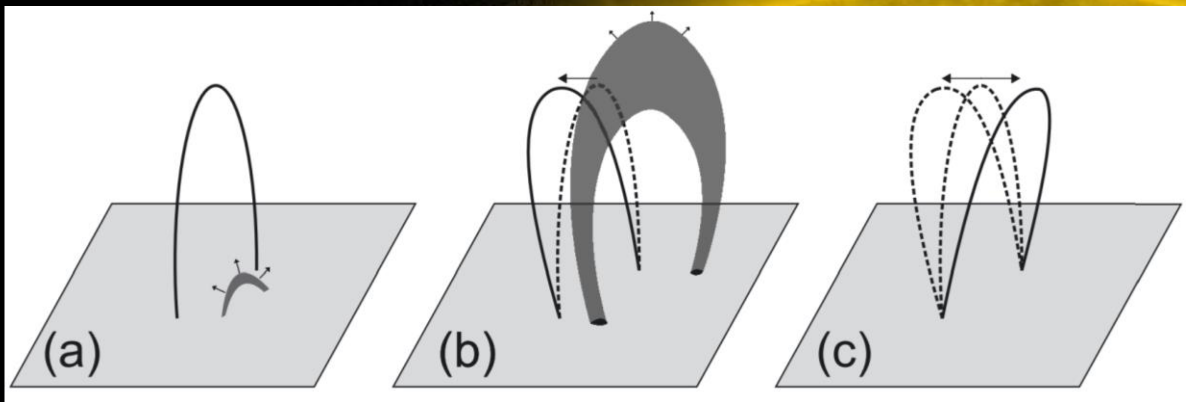
$$m_e^2 = \frac{(k^2 c_e^2 - \omega^2)(k^2 v_{Ae}^2 - \omega^2)}{(c_e^2 + v_{Ae}^2)(k^2 c_{Te}^2 - \omega^2)},$$

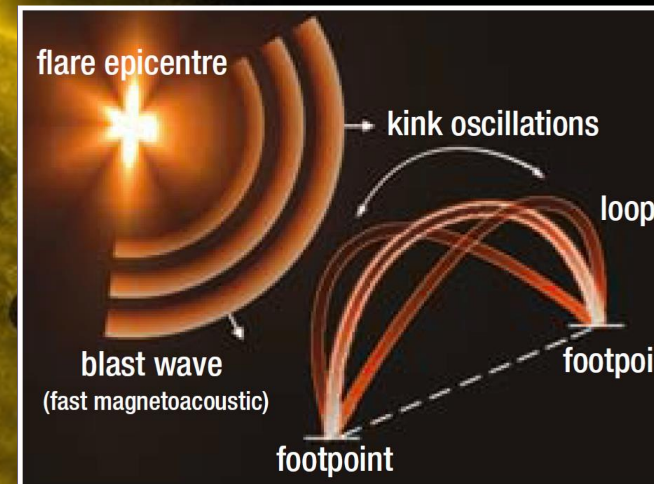
$$n_0^2 = \frac{(k^2 c_0^2 - \omega^2)(k^2 v_A^2 - \omega^2)}{(c_0^2 + v_A^2)(\omega^2 - k^2 c_T^2)},$$

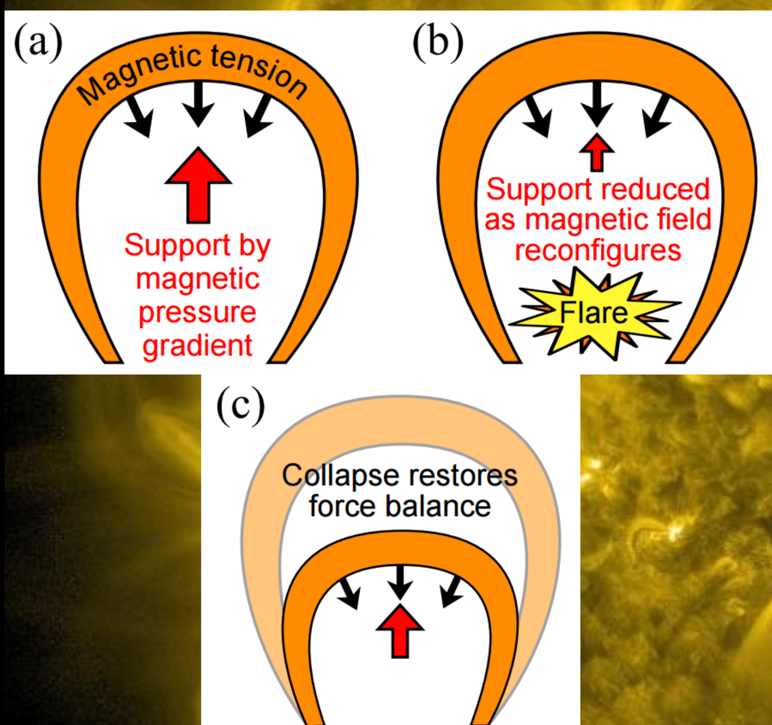


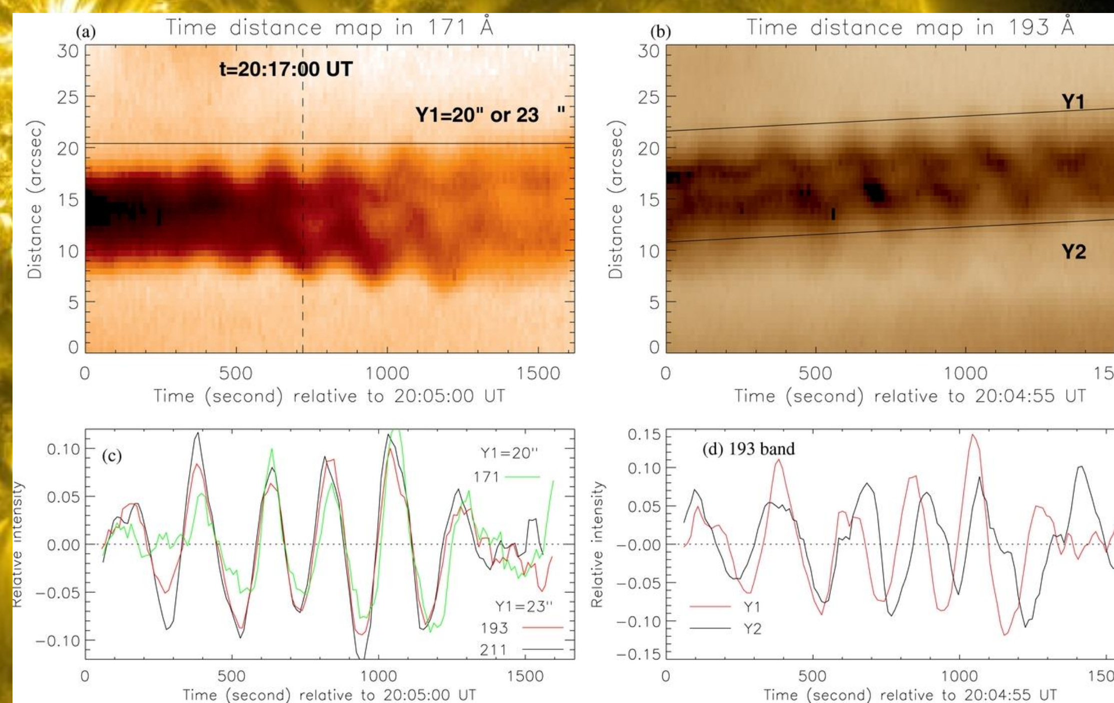


Excitation Mechanism



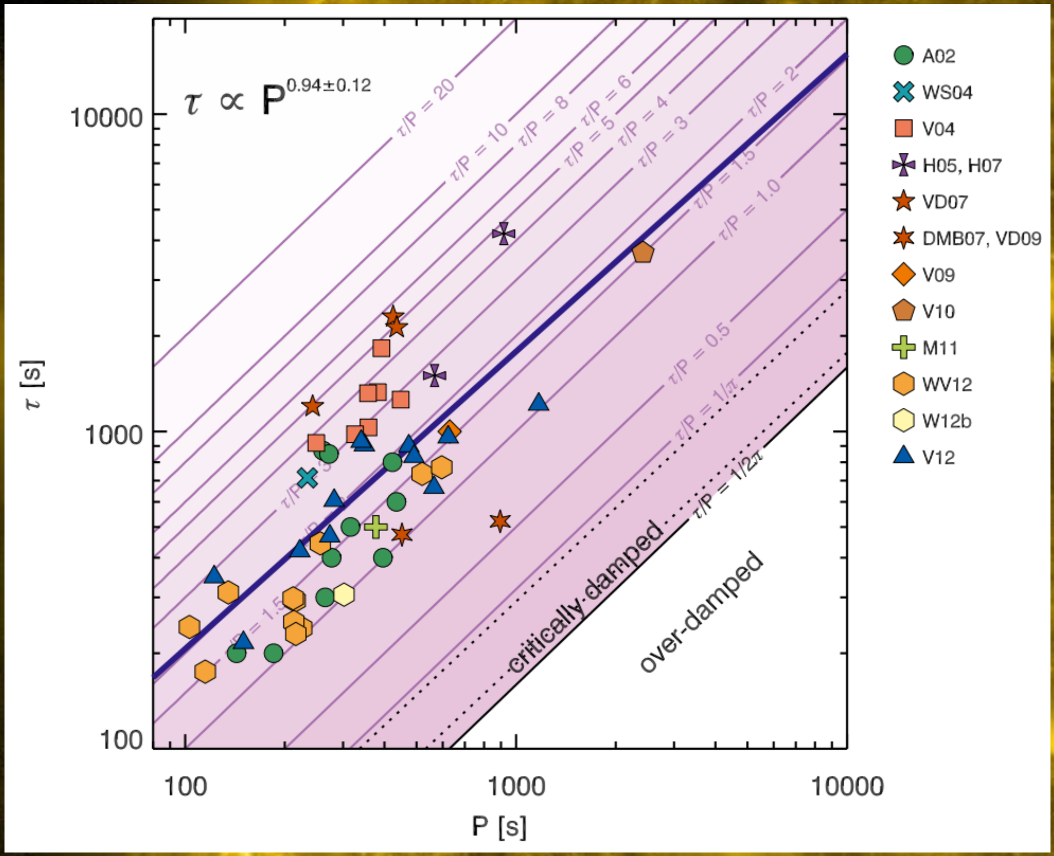


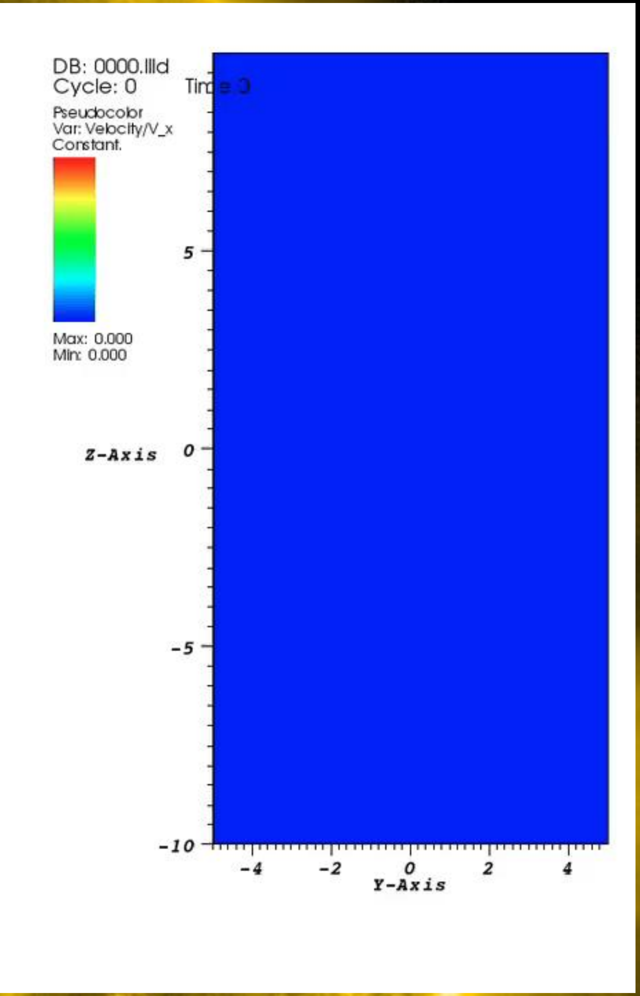




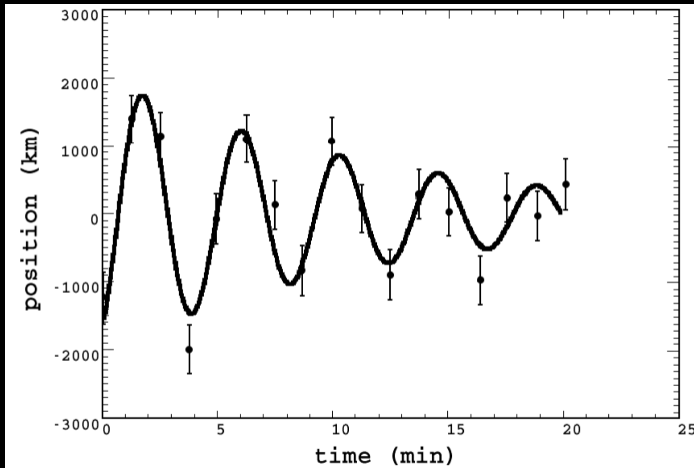
Damping

- Dissipative and resistive damping
- Phase mixing
- Mode Coupling (resonant absorption)





Seismology



$$C_{\mathrm{K}} \approx \left(\frac{2}{1 + \rho_{\mathrm{e}}/\rho_0} \right)^{1/2} C_{\mathrm{A0}}$$

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

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

$$\frac{\tau}{P} = \left(\frac{3}{4\pi^2} \right)^{1/3} \left(\frac{\ell}{L} \right)^{2/3} \mathrm{Re}^{1/3}$$

$$\frac{\tau}{P} = 16.3\, \mathrm{Re}^{0.22}$$

Aims

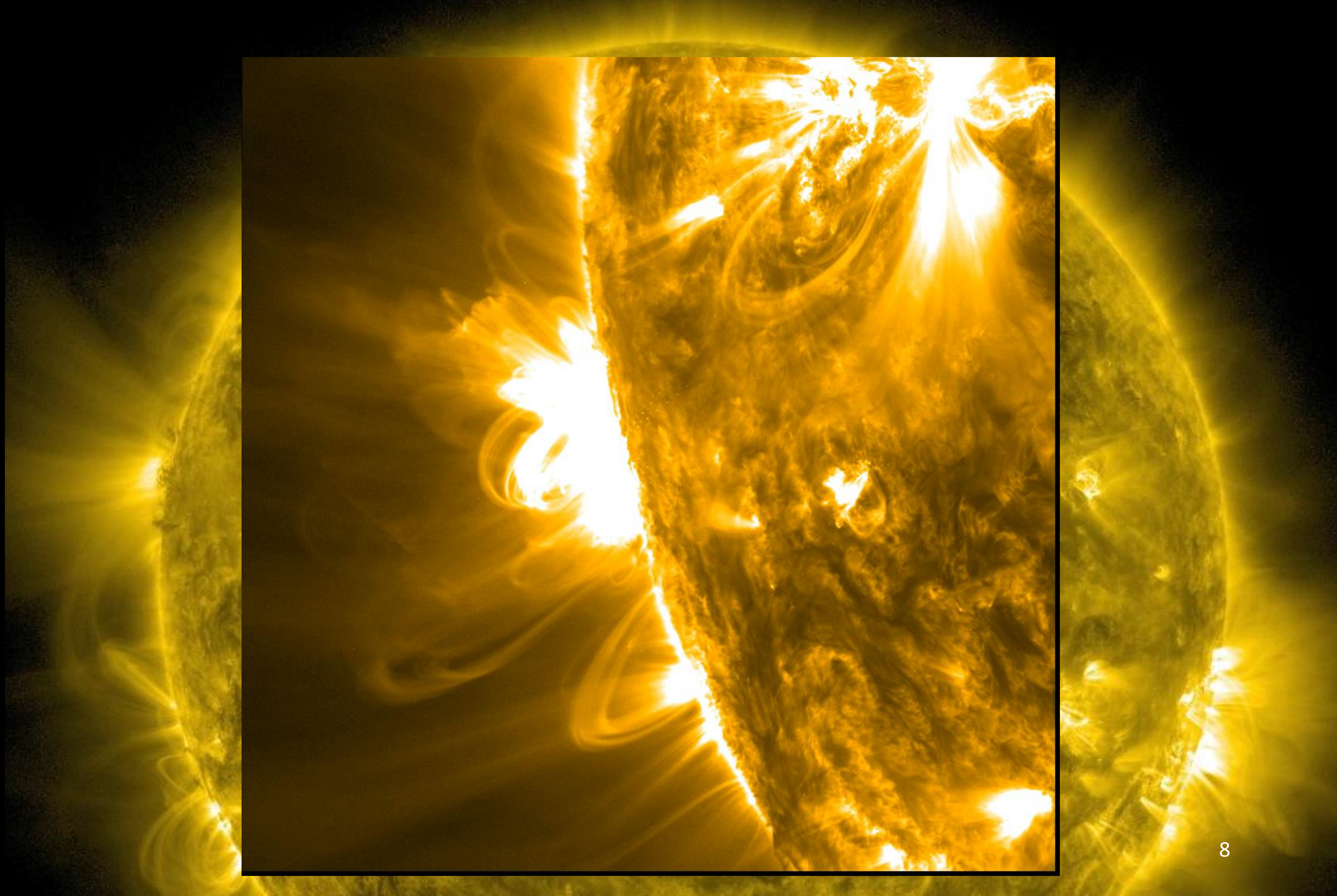
- Use the existing catalogue of oscillation events to perform a statistical study of decaying kink oscillation parameters.
- Analyse the distributions and dependencies of the parameters.
- Analyse detected damping profiles.
- Perform seismology based on the damping profiles.

Initial Catalogue

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
N	Date dd/mm/yy	t_0^{osc} UT	x^{osc}, y^{osc} arcsec	t_0^{flare} UT	t_{max}^{flare} UT	x^{flare}, y^{flare} arcsec	GOES class	Δt^{flare} s	v^{flare} km s^{-1}	t_0^{LCE} UT	x^{LCE}, y^{LCE} arcsec	Δt^{LCE} s	v^{LCE} km s^{-1}	t_0^{CME} UT	t_0^{t2rdb} UT	f_0^{t2rdb} MHz	Event type
1	02/08/10	04:23:12 04:24:24	–992, –326 –928, –377	04:19	04:26	–931, –269 (BEL)	B8.9	252 314	240 249	04:19:19	–933, –269	233 295	255 266	05:24 (C/SA)	–	–	1
2	16/10/10	19:15:24 19:16:36	689, –242 762, –193	19:07	19:12	403, –411	M2.9	504 576	478 529	19:10:33	493, –411	291 363	645 692	20:12	19:14	*180	?
3	03/11/10	12:14:36	–979, –379	12:07	12:21	–915, –323 (BEL)	C4.9	456	135	12:12:45	–919, –345	111	450	12:36	12:15	560	1
4	09/02/11	01:29:26 01:29:26 01:29:26	1048, 353 939, 444 983, 258	01:23	01:31	869, 316	M1.9	386 386 386	343 274 240	01:25:45	873, 310	221 221 221	591 490 399	–	–	–	1
5	10/02/11	04:43:48 04:43:48	1064, 418 1081, 366	04:39	04:43	884, 353	B6.0	288 288	482 497	04:37:45	890, 356	363 363	369 382	–	–	–	1
6	10/02/11	06:42:36	1059, 400	06:20	06:40	953, 233	C1.9	1356	106	06:37:48	1049, 435	288	92	07:36 (C/L)	–	–	1
7	10/02/11	06:58:12 06:58:12 06:58:12	1062, 394 1103, 369 1102, 262	06:56 (ZN)	06:58	923, 276	C2.1	132 132 132	1001 1113 986	06:57:00	1006, 364	72 72 72	640 978 1410	07:36 (C/L)	–	–	1
8	10/02/11	12:32:24	1045, 297	12:28	12:34	924, 278	C4.7	264	336	12:29:26	1010, 308	178	149	–	–	–	1
9	10/02/11	13:44:24 13:45:00	1061, 317 990, 408	13:33	13:52	927, 282	C2.6	684 720	148 145	13:33:33	931, 288	651 687	148 141	14:12	13:50	170 –	1
10	11/02/11	08:11:48	1100, 207	07:58	08:13	917, 317 (BEL)	B9.0	828	187	07:52:48	951, 307	1140	114	08:49	–	–	1
11	13/02/11	17:33:36 17:35:26 17:36:00 17:36:14	–77, –272 –75, –347 –274, –74 –49, –55	17:28	17:38	–85, –224	M6.6	336 446 480 494	105 201 364 254	17:33:02	–87, –231	34 144 178 192	900 587 995 680	08:49	17:35	180	1
12	13/02/11	20:22:36	–275, –54	20:22 (ZN)	20:24	–122, –225	B7.6	96	1733	20:13:36	–132, –229	540	303	–	–	–	2

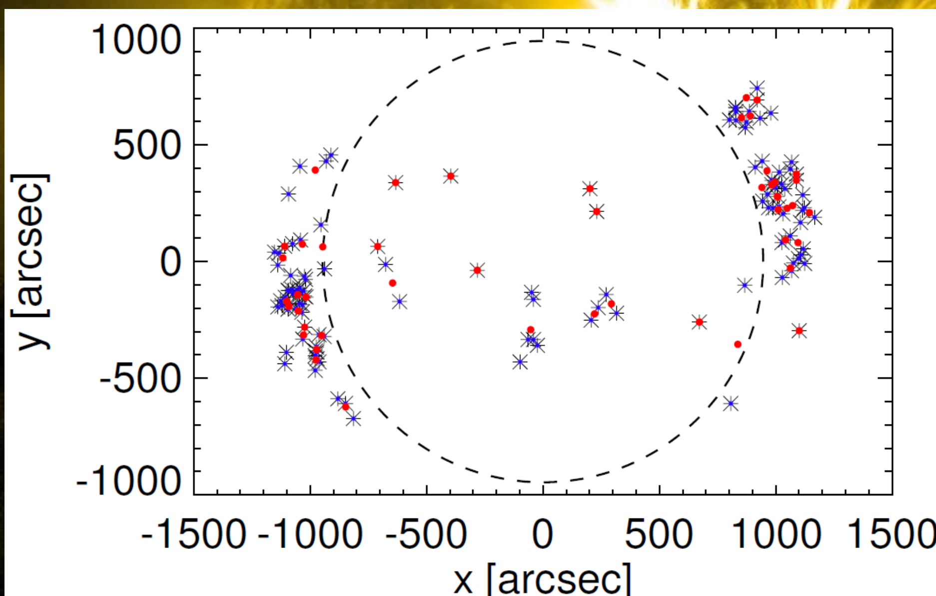
Table 1. : Zimovets, I. V. & Nakariakov, V. M., 2015, A&A, 577, A4

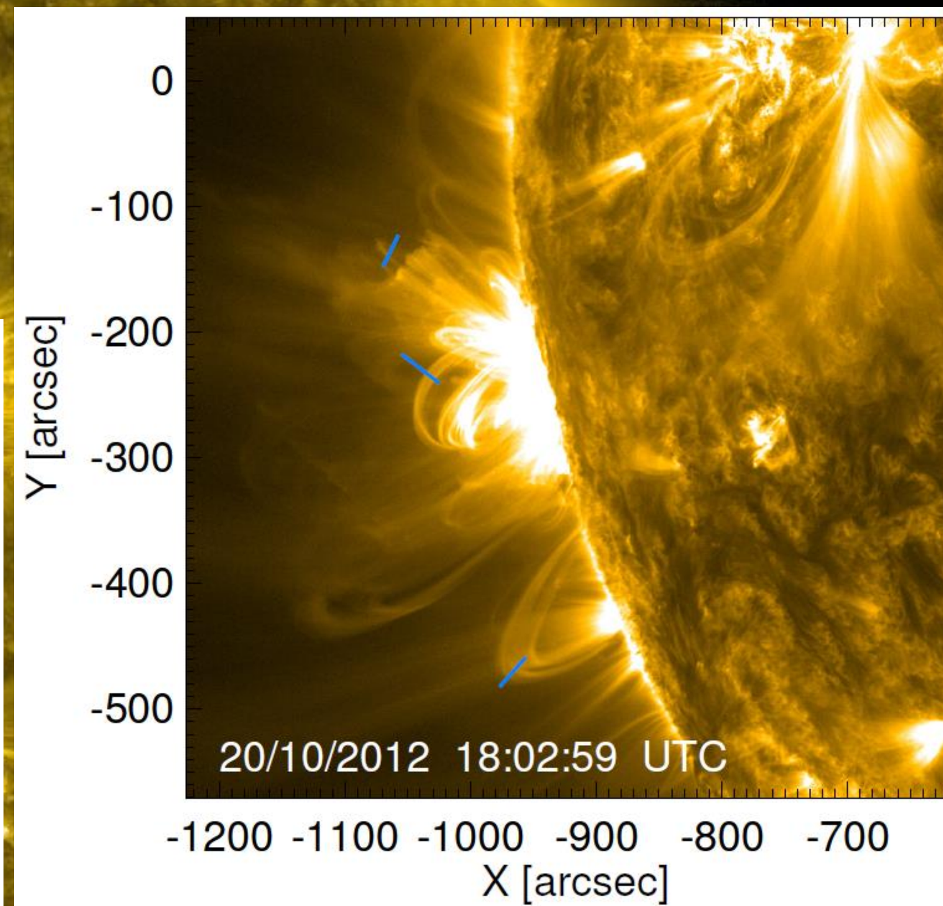
Locating suitable oscillations



Final sample

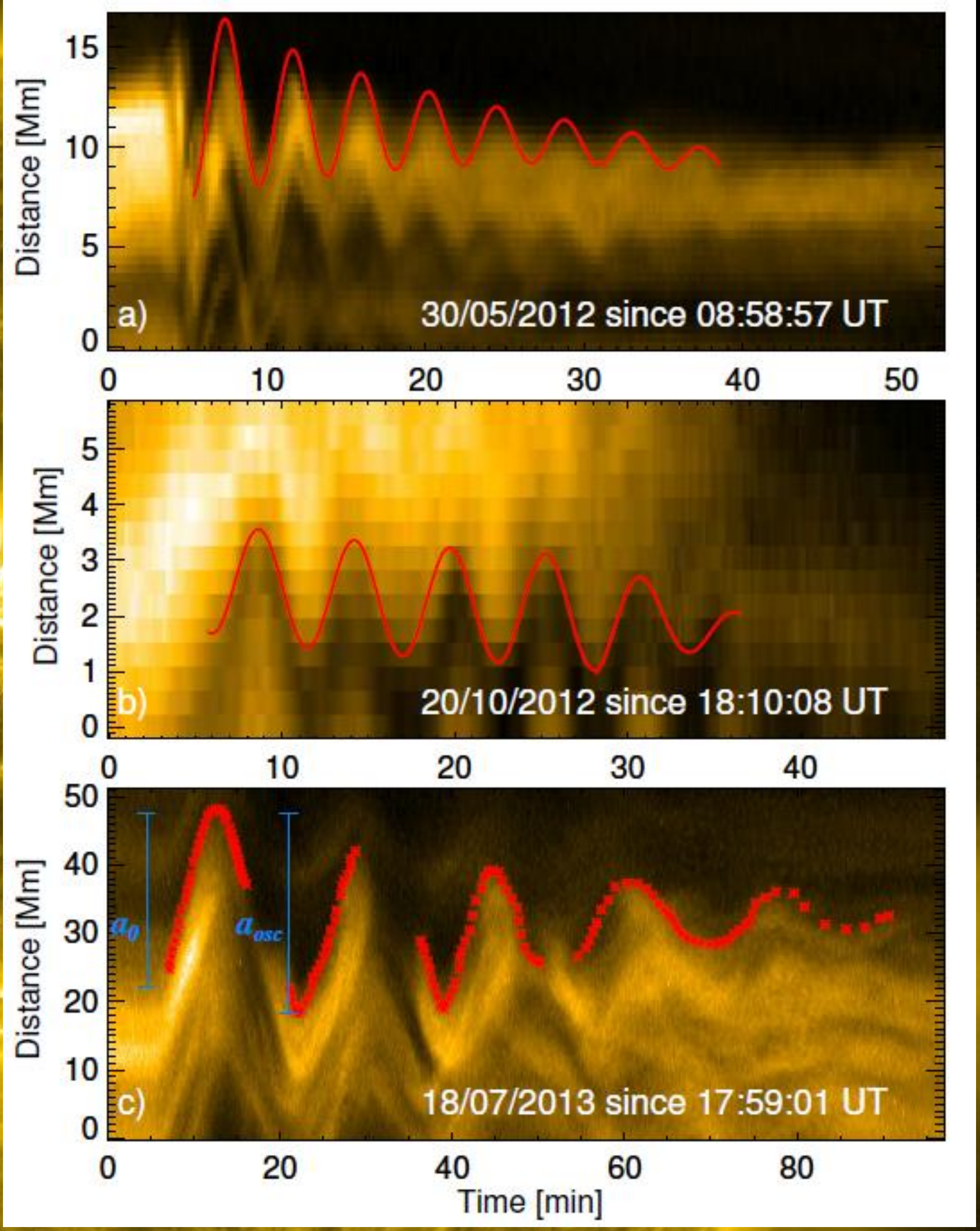
- 56 events analysed
- 120 individual kink oscillations recorded
- TD maps analysed for each loop



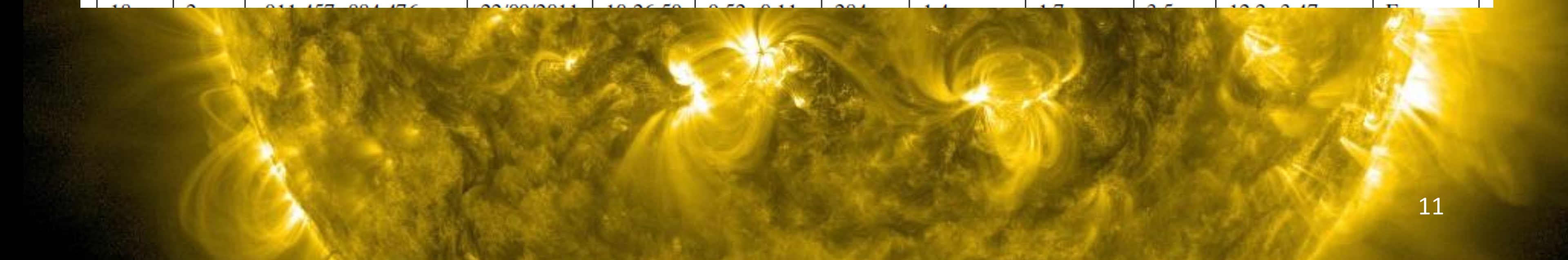


Time-Distance maps

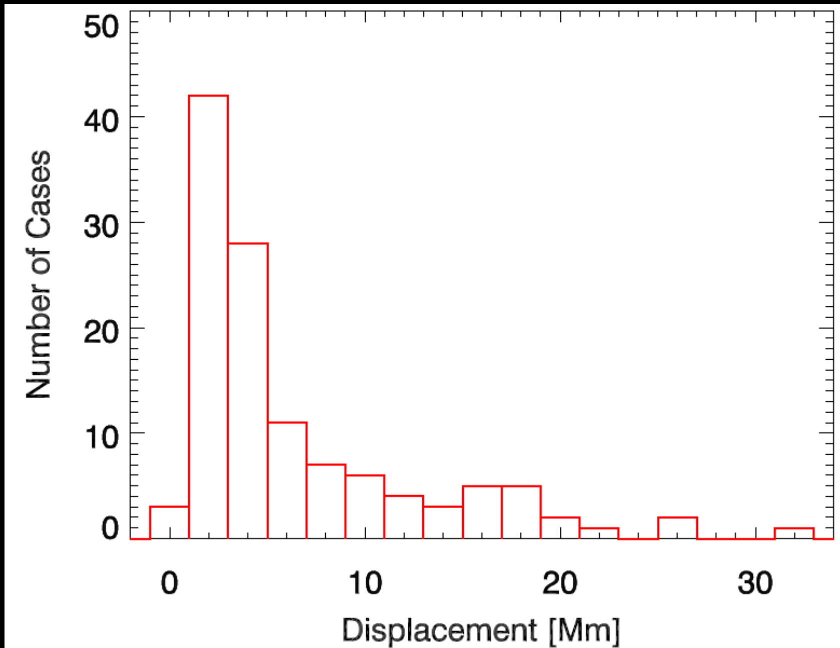
- TD maps zoomed to region of interest
- Initial displacement and amplitude of oscillation measured
- Points taken to map out the oscillations by hand
- Points fit to obtain a period and damping time

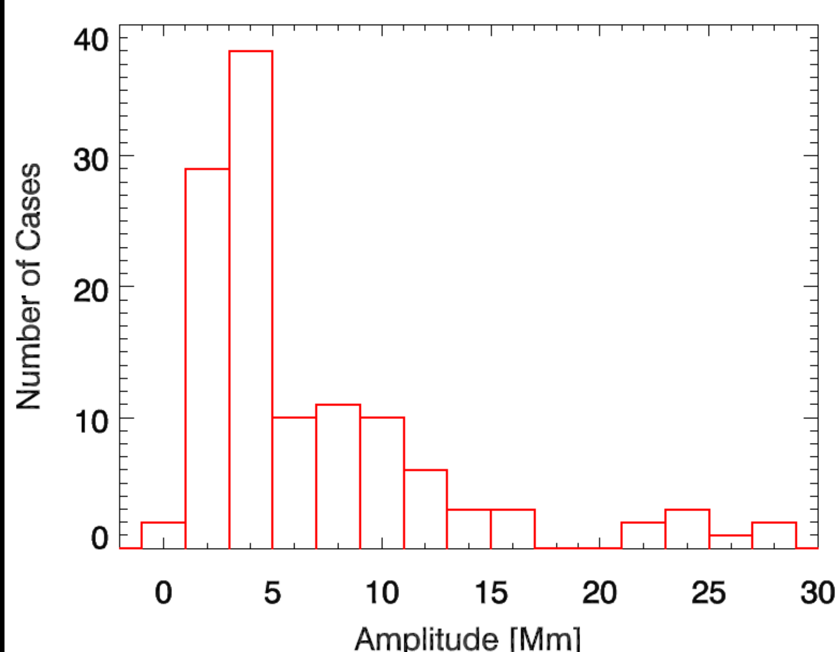


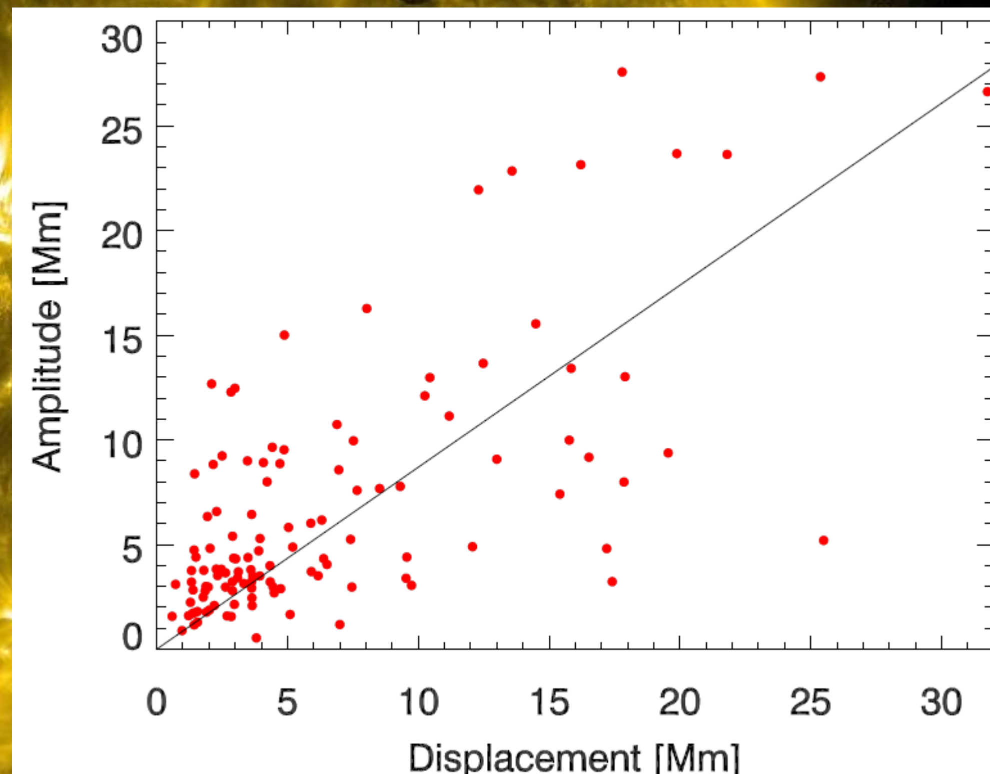
Event ID	Loop ID	Slit Position [x1,y1,x2,y2] (arcsec)	Date	Time UT	Period (min)	Length (Mm)	Disp Amp (Mm)	Osc Amp (Mm)	N Cyc	Damping Time (min)	Damping Profile
1	1	-940,-321,-964,-308	02/08/2010	04:22:49	3.42±0.06	232	5.1	1.7	3	5.34±1.12	E
1	2	-962,-313,-997,-322	02/08/2010	04:22:13	4.11±0.05	78	7.0	1.2	3	10.76±2.79	E
2	1	672,-259,711,-223	16/10/2010	19:13:07	6.64±0.06	156	2.0	4.8	3.5		
3	1	-977,-383,-988,-368	03/11/2010	12:13:48	2.46±0.03	213	1.4	4.7	8	8.8±1.8	E,NE
3	2	-970,-416,-1001,-393	03/11/2010	12:14:35	3.62±0.08	262	4.4	9.7	3	4.12±0.47	E,NE
3	3	-978,-466,-1027,-411	03/11/2010	12:14:23	4.04±0.1	311	4.1	8.9	2		
4	1	912,405,889,433	09/02/2011	01:30:02	2.29±0.03	183	2.9	4.4	4.5	7.18±1.5	E,NE
4	2	969,231,974,278	09/02/2011	01:31:54	3.47±0.03	181	1.4	1.2	3	7.44±1	E
5	1	1089,375,1050,423	10/02/2011	04:43:38	7.03±0.06	438	4.5	3.0	3		NE
6	1	1089,349,1057,398	10/02/2011	06:44:22	8.05±0.26	430	3.8	0.5	2		
7	1	983,330,970,342	10/02/2011	06:57:46	1.69±0.02	162	2.9	3.2	6	7.23±1.3	E,NE
8	1	1007,280,1021,305	10/02/2011	12:35:01	3.74±0.07	207	1.2	1.6	3	10±1	E,NE
9	1	983,348,947,414	10/02/2011	13:43:37	5.14±0.17	264	3.0	4.3	3	5.09±0.98	E
9	2	942,431,934,461	10/02/2011	13:46:31	8.95±0.14	326	3.6	3.2	2.5	11.83±4.76	E
10	1	1106,168,1133,214	11/02/2011	08:07:07	11.46±0.17	397	4.7	8.9	2.5	8.02±1.09	E,NE
10	2	1039,313,1041,334	11/02/2011	08:08:17	8.48±0.16	279	5.9	6.0	2		
11	1	-41,-162,-43,-146	13/02/2011	17:34:28	3.96±0.07	78	3.5	4.4	3		
11	2	-49,-132,-51,-108	13/02/2011	17:34:50	3.85±0.11	95	3.7	2.1	3		
11	3	-64,-334,-69,-316	13/02/2011	17:37:13	2.6±0.05	118	3.1	3.7	6	8.84±1.5	E
11	4	-41,-334,-54,-322	13/02/2011	17:33:52	3.81±0.04	125	2.9	5.4	5		
11	5	-24,-359,-44,-336	13/02/2011	17:33:42	5.09±0.06	135	1.9	6.3	2		
11	6	-98,-430,-89,-394	13/02/2011	17:38:33	6.13±0.21	160	11.2	11.1	2		
12	1	-282,-37,-309,-47	13/02/2011	20:19:17	5.56±0.07	148	1.9	1.8	2		
15	1	202,313,175,371	27/05/2011	10:47:58	7.64±0.37	174	6.3	6.2	1.5		
16	1	1014,235,991,257	11/08/2011	10:17:19	2.62±0.04	242	3.3	3.1	3		
16	2	988,229,1026,229	11/08/2011	10:10:22	2.35±0.07	146	17.4	3.2	2	2.69±0.64	E
16	3	1031,205,1067,241	11/08/2011	10:10:54	5.23±0.19	318	25.5	5.2	2.5		
17	1	231,215,216,263	06/09/2001	22:20:15	2.07±0.04	153	9.5	3.4	3.5	9.99±4.59	E
18	1	-931,431,-960,472	22/09/2011	10:35:08	7.18±0.32	289	15.8	10.0	2.5		



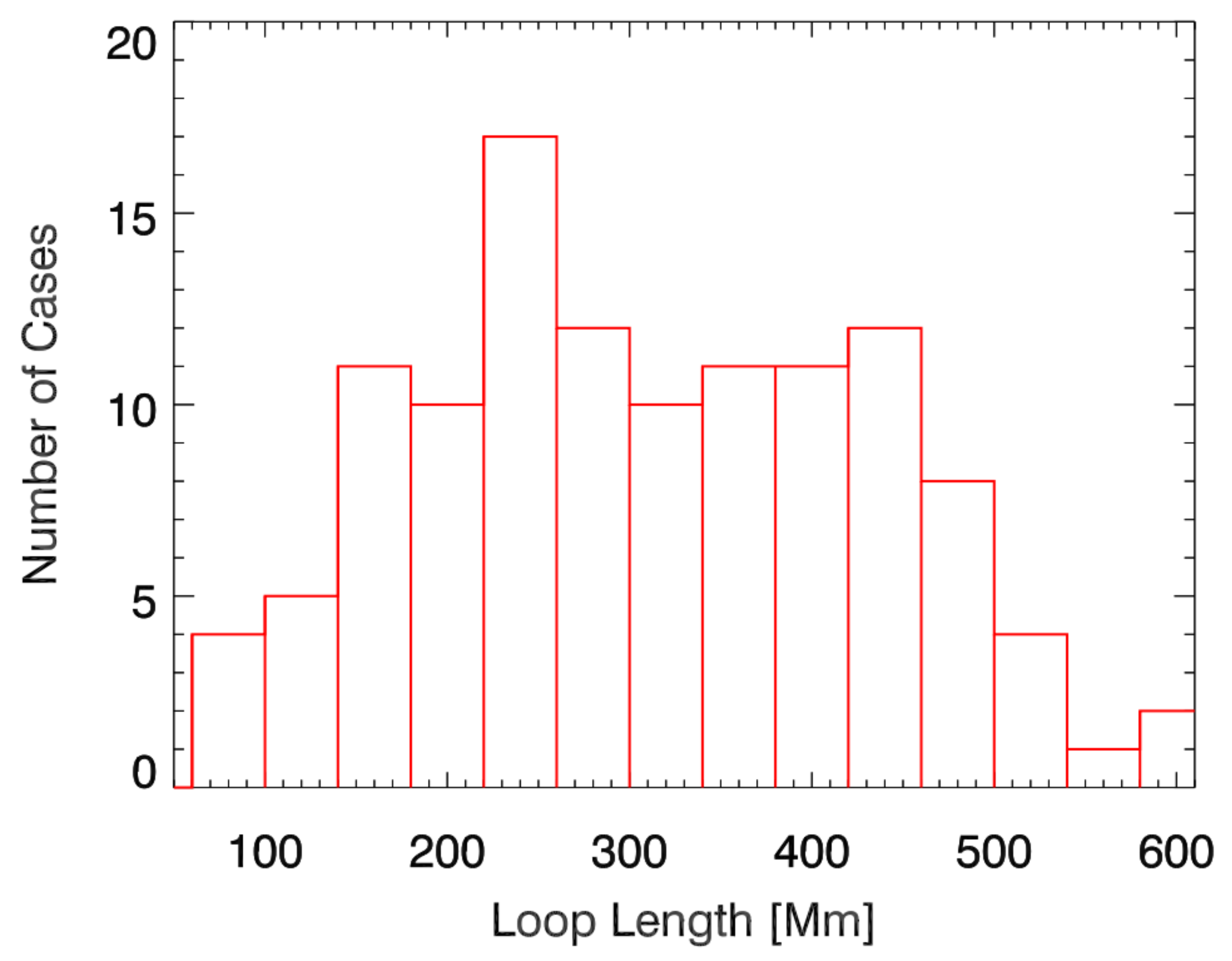
Initial displacement and oscillation amplitude



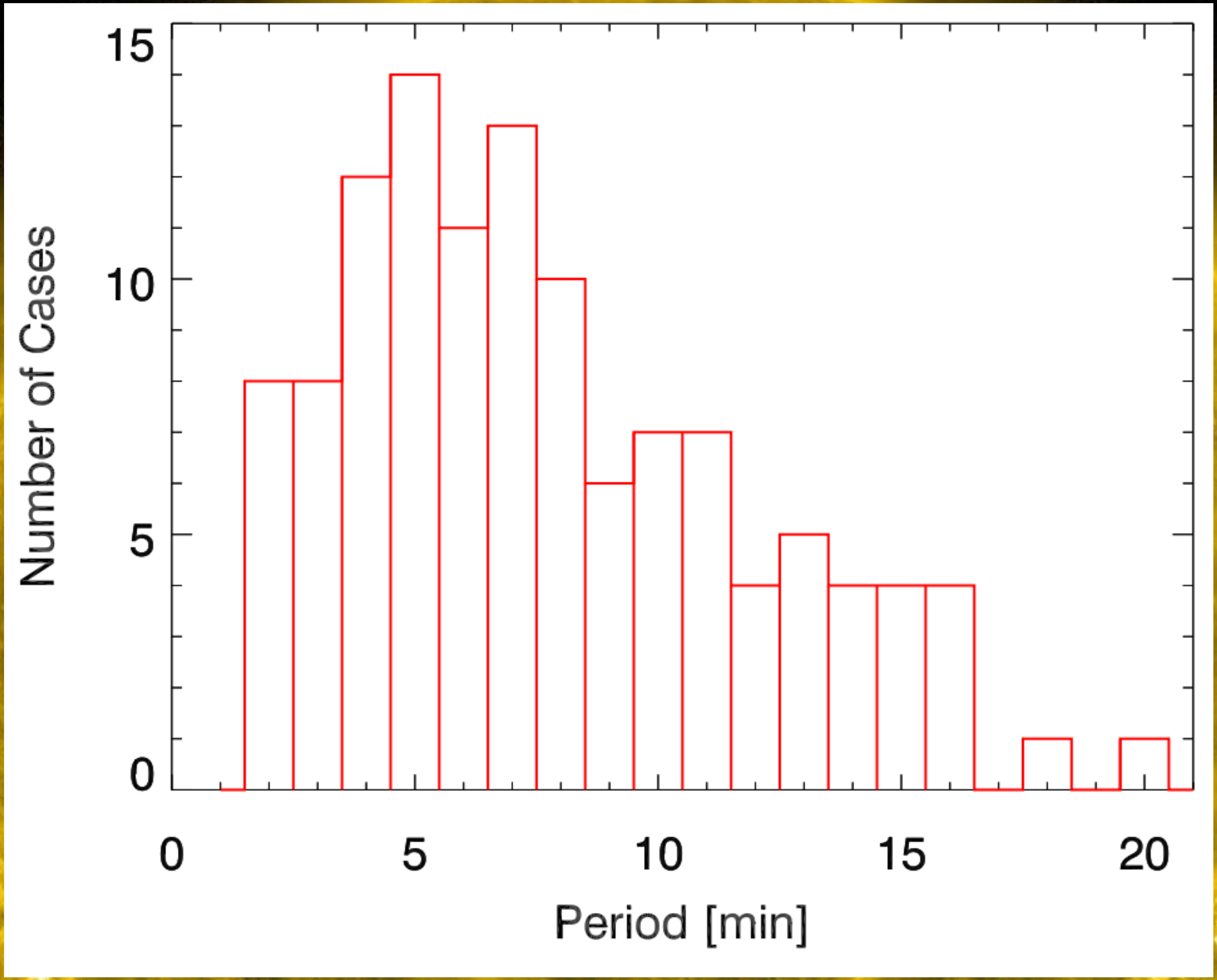




Loop length and period distributions



Loop length and period distributions



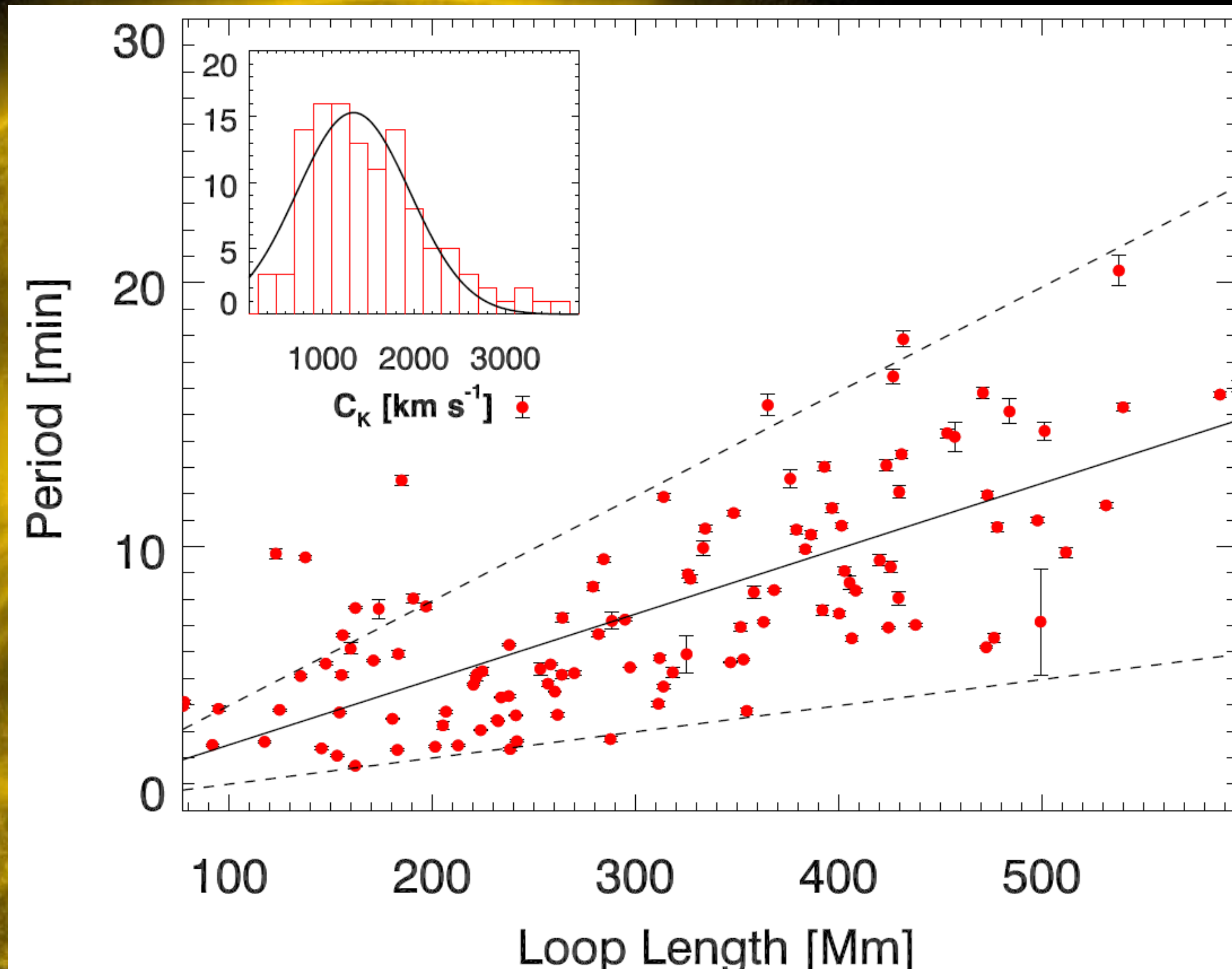
Period against loop length

P = 2L/C_k

C_k=(1330±50) km s^{-1}

Range = 800-3300

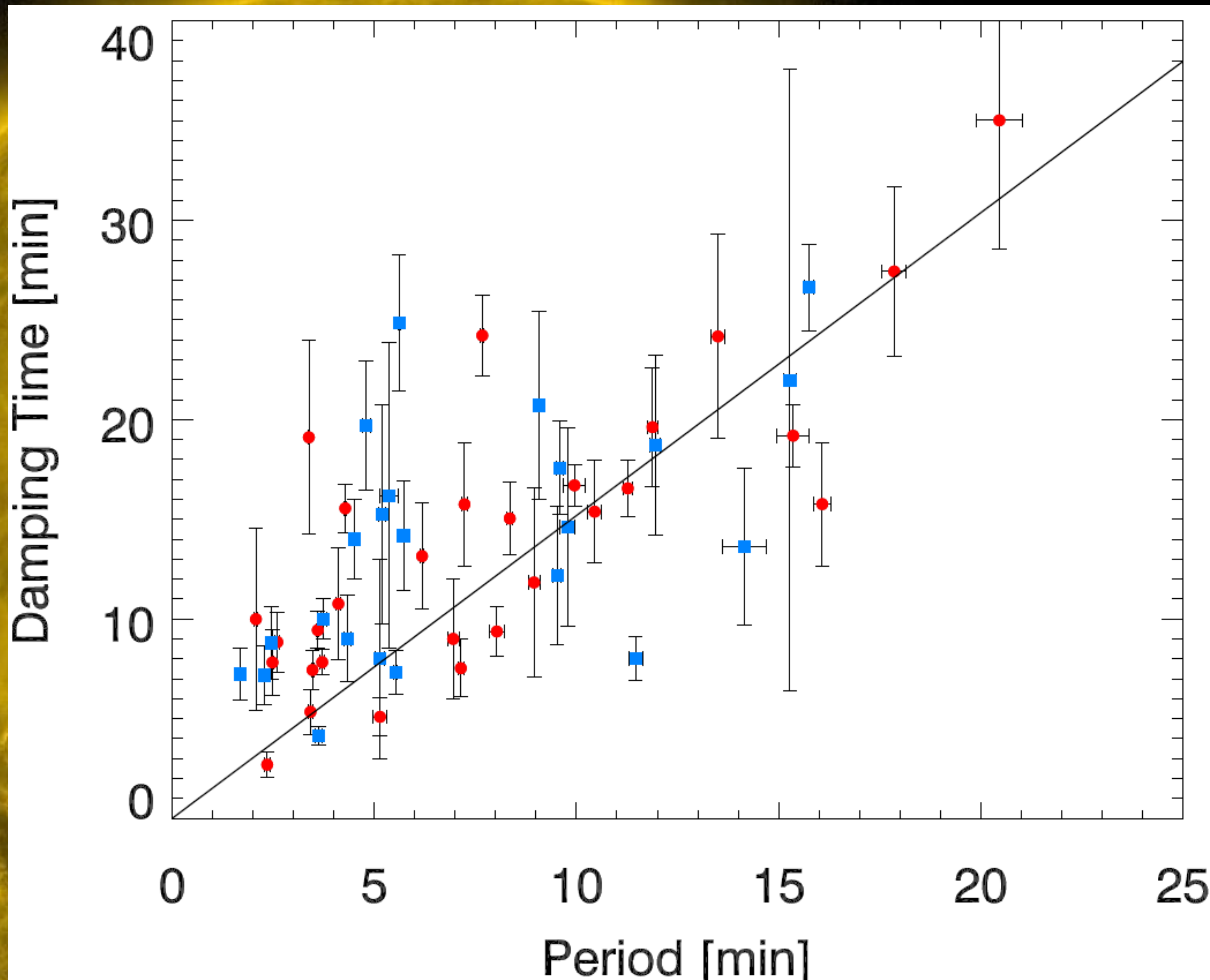
$$C_{\rm K} \approx \left(\frac{2}{1+\rho_{\rm e}/\rho_0}\right)^{1/2} C_{\rm A0}$$



Damping time against period

22 of the 52 profiles measured may include 'non-exponential' sections in the damping profile.

$\tau=(1.53\pm0.3)P$

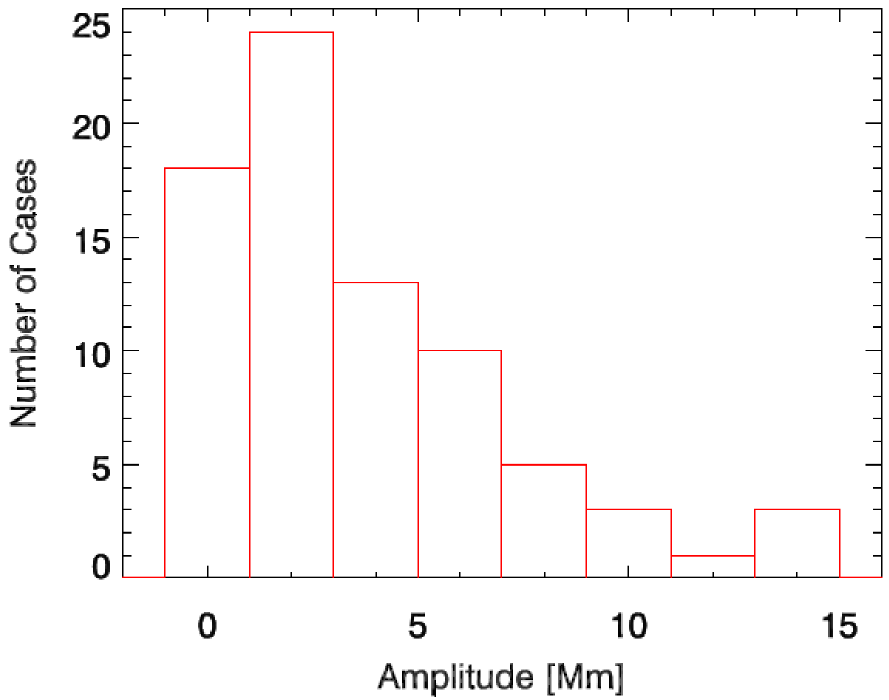


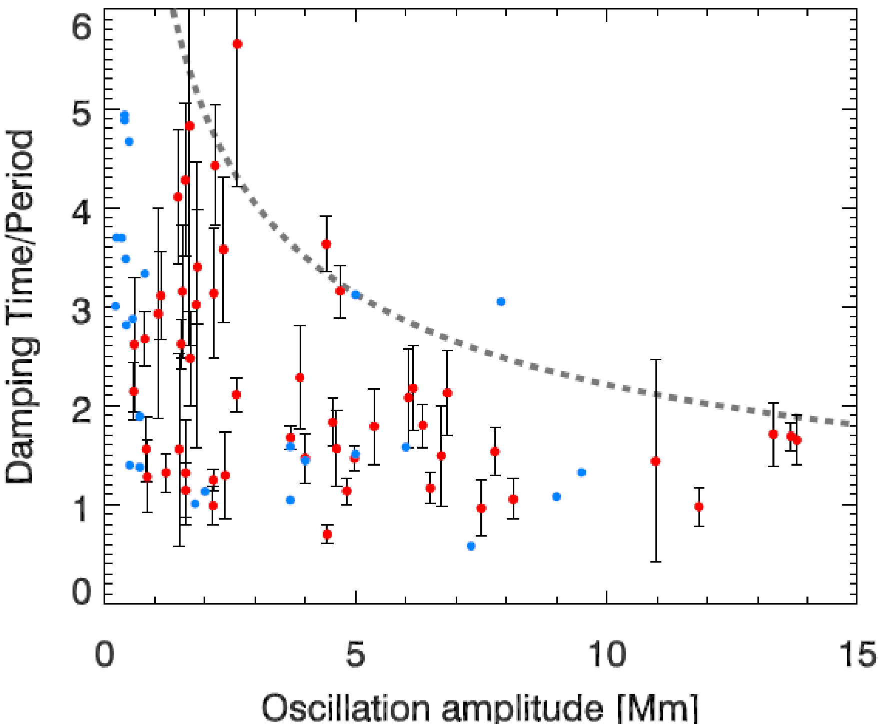
Conclusions

- The initial loop displacement prescribes the initial oscillation amplitude in the majority of cases.
- The period scales linearly with the loop length and a kink speed of C_k=(1330±50) km s^{-1} is obtained; the majority of the data points are in the range (800–3300) km s^{-1}, following a Gaussian distribution.
- A linear scaling of the damping time with period is observed and non-exponential damping profiles have been detected.

Goddard, C. R., Nisticò, G., Nakariakov, V. M., & Zimovets, I. V. 2016, A&A, 585, A137

Amplitude dependence of damping

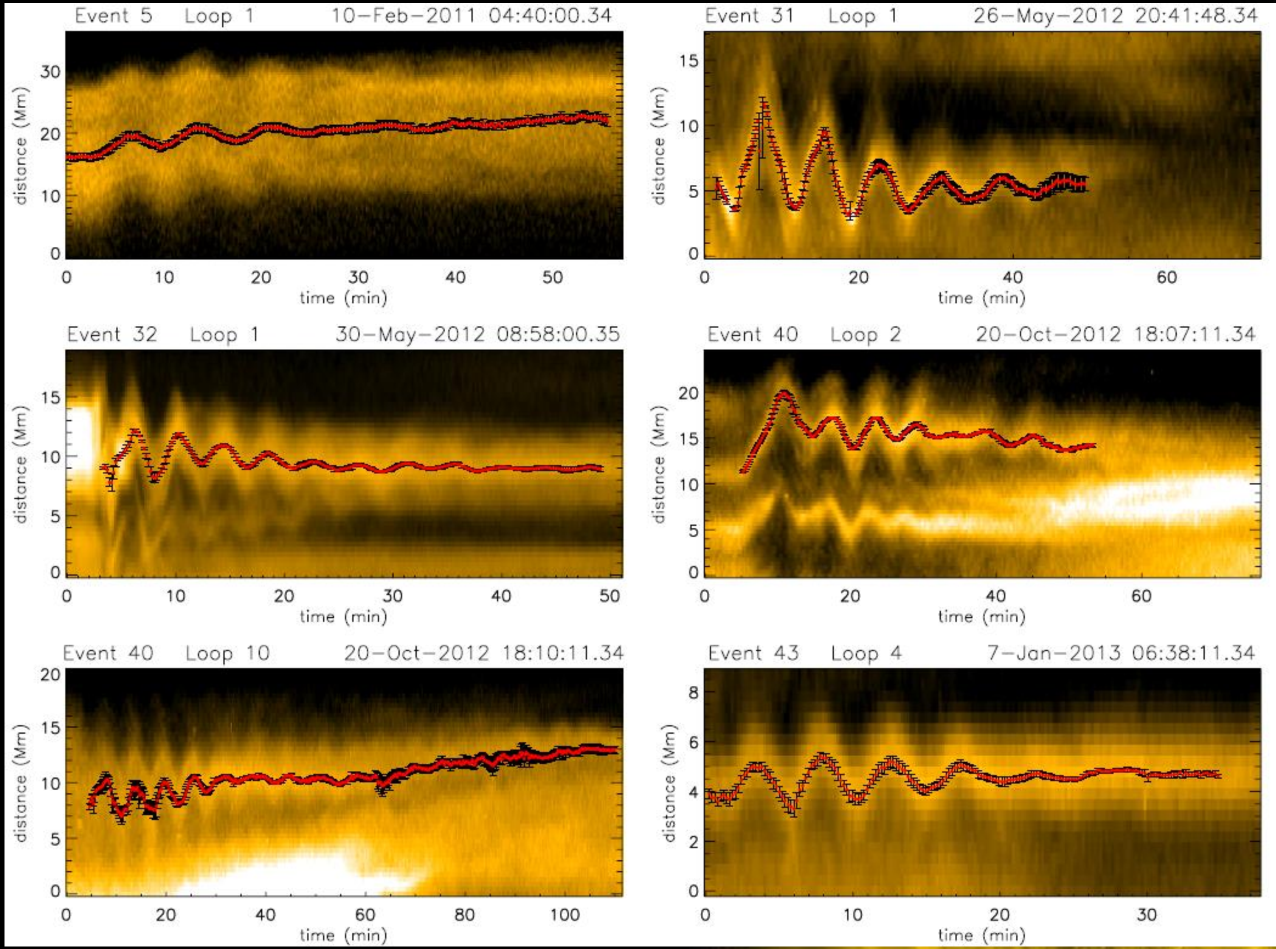




The damping of kink oscillations depends on the oscillation amplitude, indicating the possible role of non-linear mechanisms

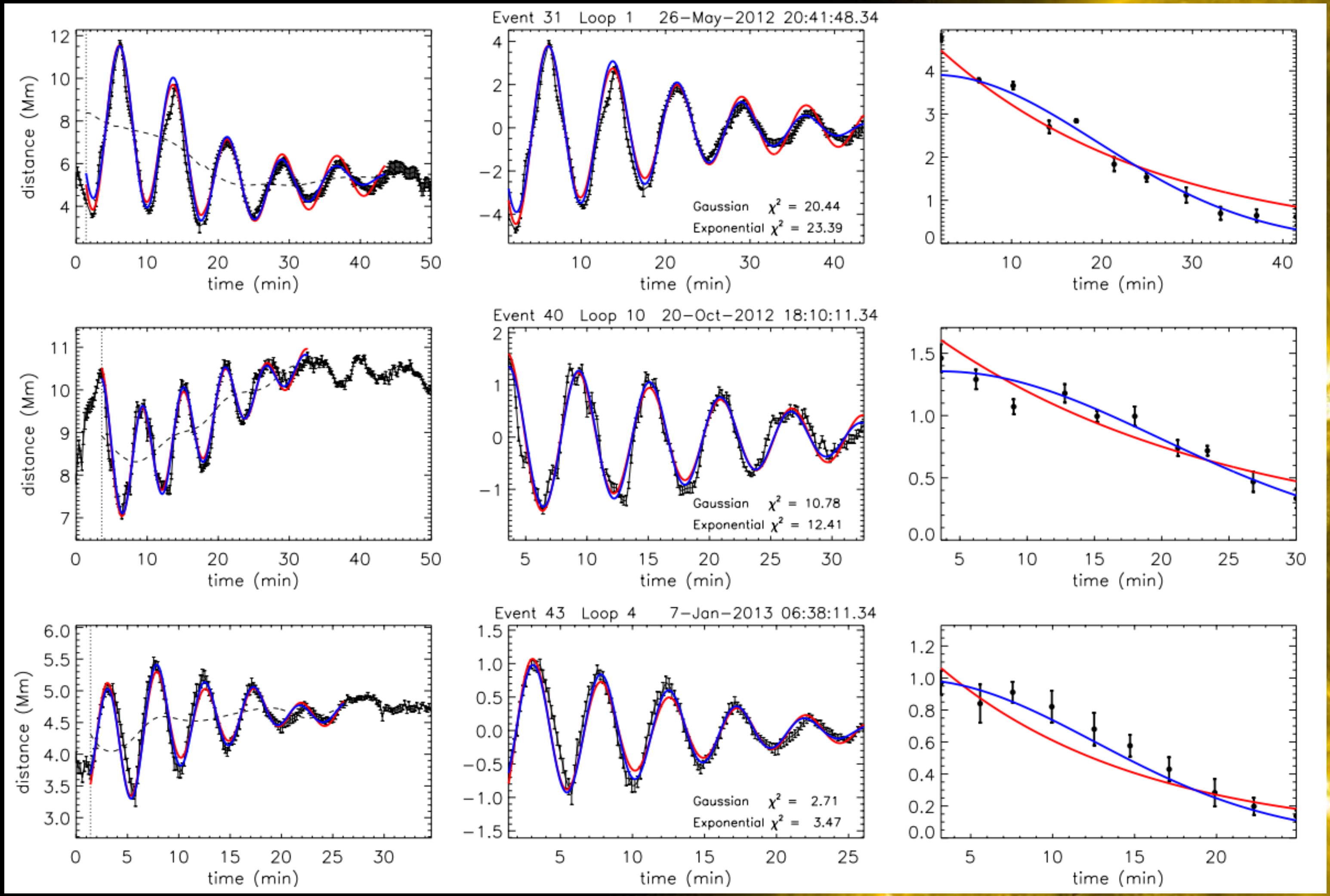
Goddard, C. R., & Nakariakov, V. M. 2016, A&A, 590, L5

Damping envelopes



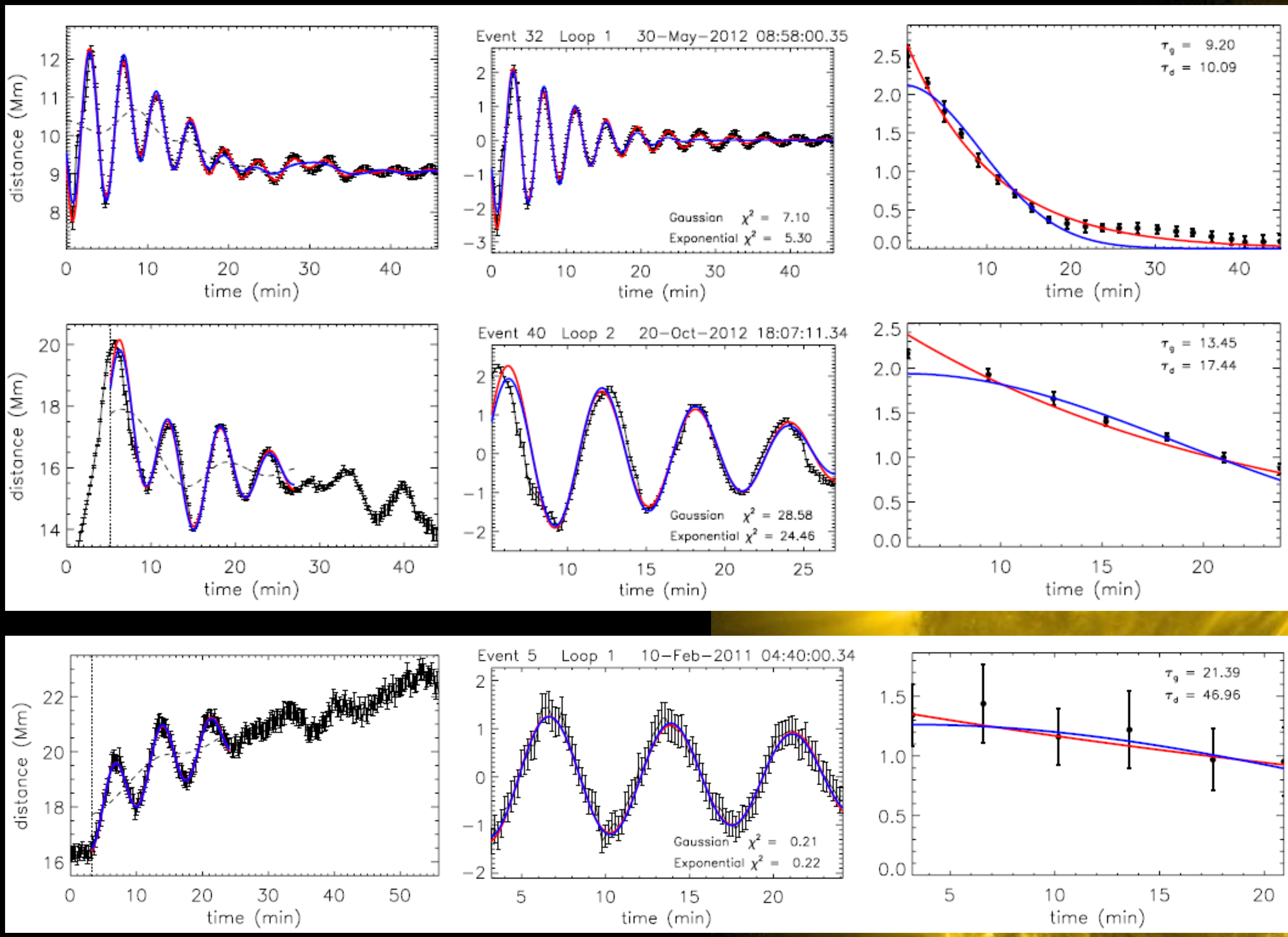
Pascoe, D. J., Goddard, C. R., Nistic`o, G., Anfinogentov, S., & Nakariakov, V. M. 2016, A&A, 585, L6

Damping envelopes - Gaussian



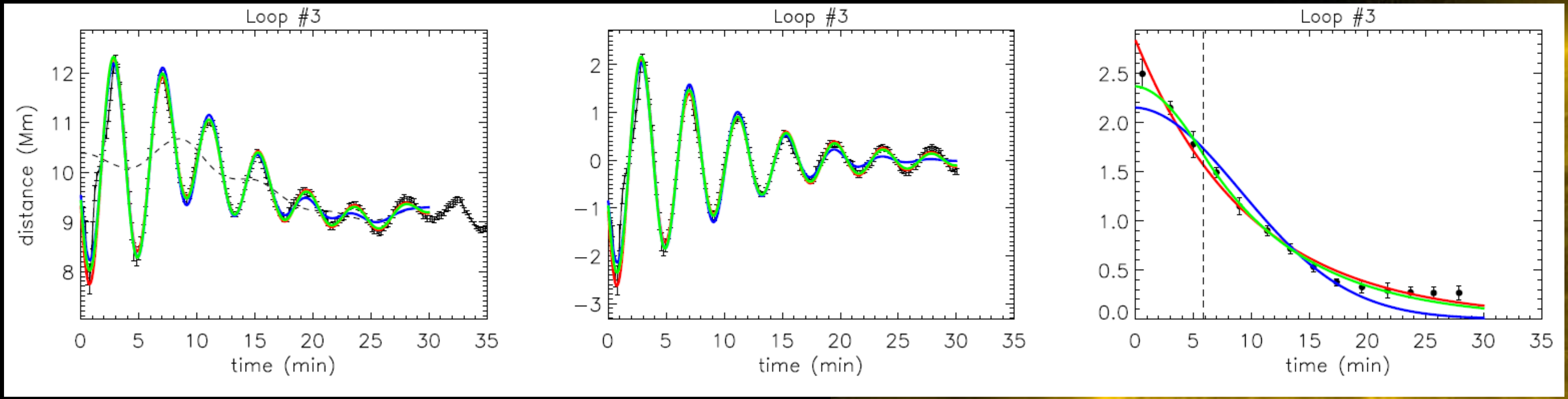
Pascoe, D. J., Goddard, C. R., Nistic`o, G., Anfinogentov, S., & Nakariakov, V. M. 2016, A&A, 585, L6

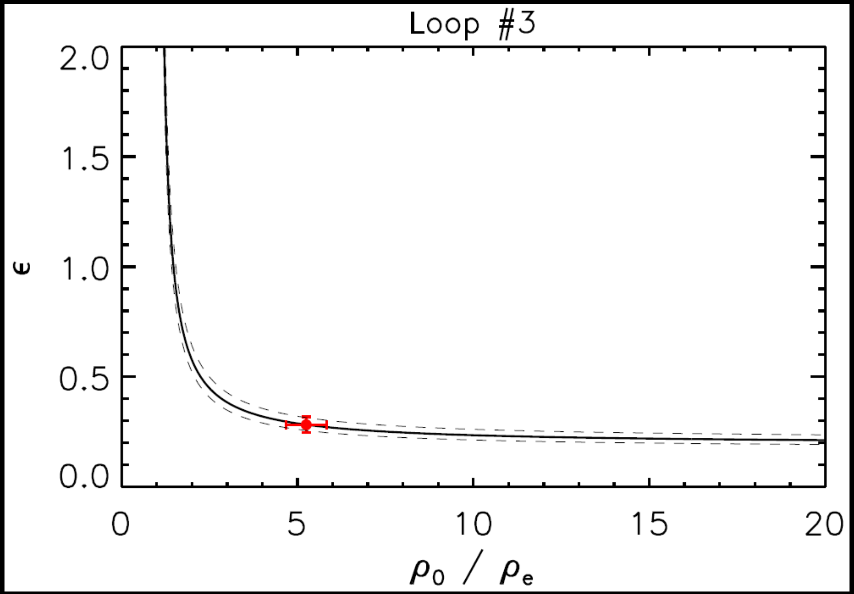
Damping envelopes - Exponential

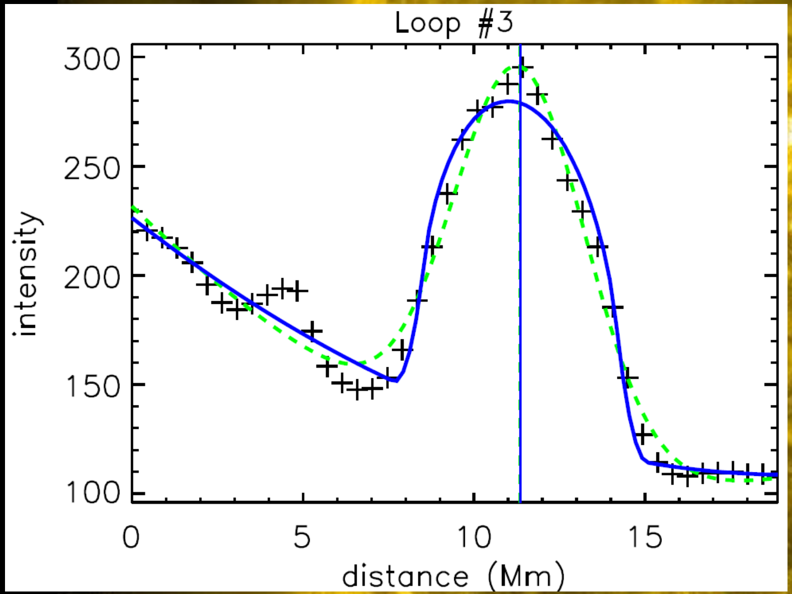


Pascoe, D. J., Goddard, C. R., Nistic`o, G., Anfinogentov, S., & Nakariakov, V. M. 2016, A&A, 585, L6

Damping envelopes - Seismology

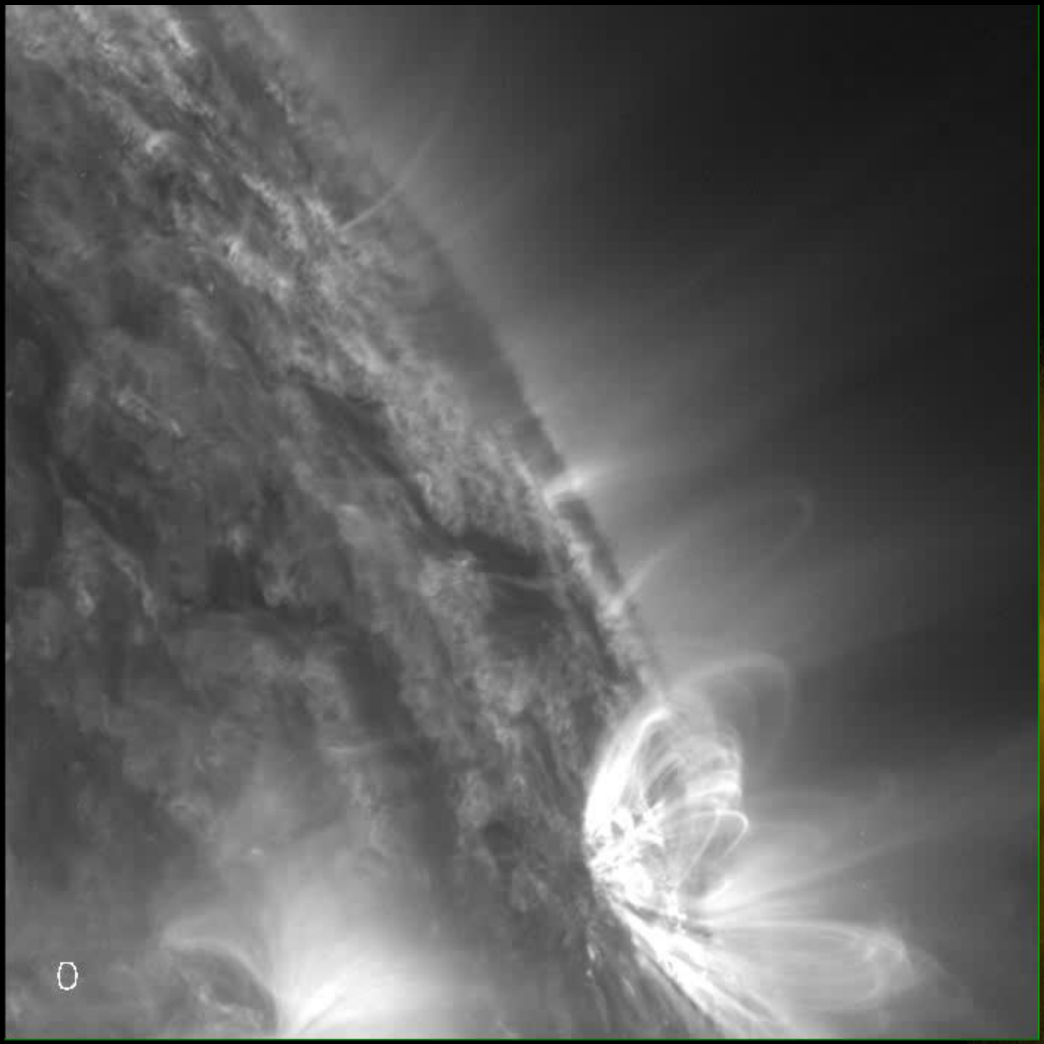


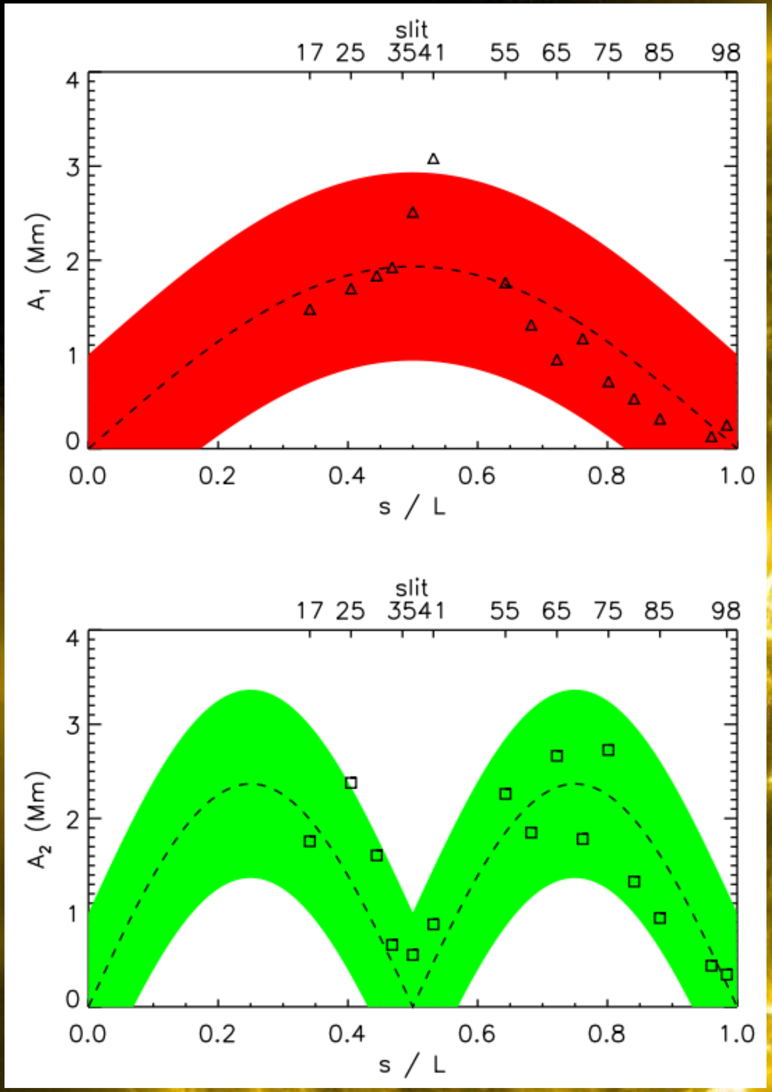




Pascoe, D. J., Goddard, C. R., Nistic`o, G., Anfinogentov, S., & Nakariakov, V. M. 2016, A&A, 585, L6

Multiple harmonics example





Pascoe, D. J., Goddard, C. R., & Nakariakov, V. M. 2016, A&A, 593, A53

Further follow up work

- Normalise distributions where required, and use parameters for ‘large scale’ seismology and inferences.
- Detailed study of the cross-sectional intensity profile of loops and what (inferred) density profiles are the most probable/common.
- Explore how the cross-sectional profile of loops changes during oscillations.
- Look for signatures of non-linear effects such as KHI vortices.

Questions?