Spatiotemporal Analysis of Coronal Loops Using Seismology and Forward Modelling

David J. Pascoe
KU Leuven

in collaboration with
C.R. Goddard, S.A. Anfinogentov, G. Nisticò, V.M. Nakariakov
A.J.B. Russell, P.J.A. Simões, L. Fletcher
P. Antolin, P. Pagano, I. De Moortel

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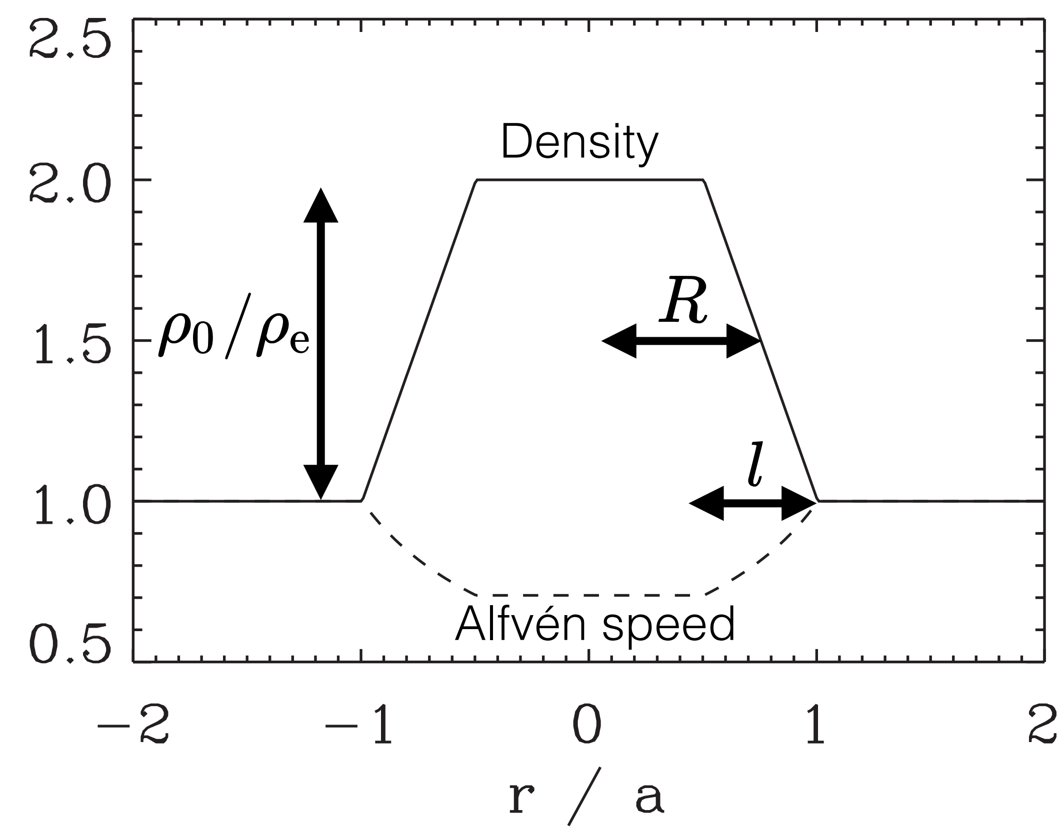
Overview

- **Temporal** analysis — seismology using damped kink oscillations of coronal loops
    - Resonant absorption as damping mechanism
    - Shape of damping profile contains information about transverse density profile
- **Spatial** analysis — forward modelling of transverse EUV intensity profile
    - Optically thin corona so emission is integrated along the line of sight
    - Test different transverse density profiles
- Both methods are concerned with determining the **transverse structuring** which is crucial to coronal physics, e.g. rates of
    - resonant absorption
    - phase-mixing
    - Kelvin-Helmholtz instability

Transverse structure of coronal loop

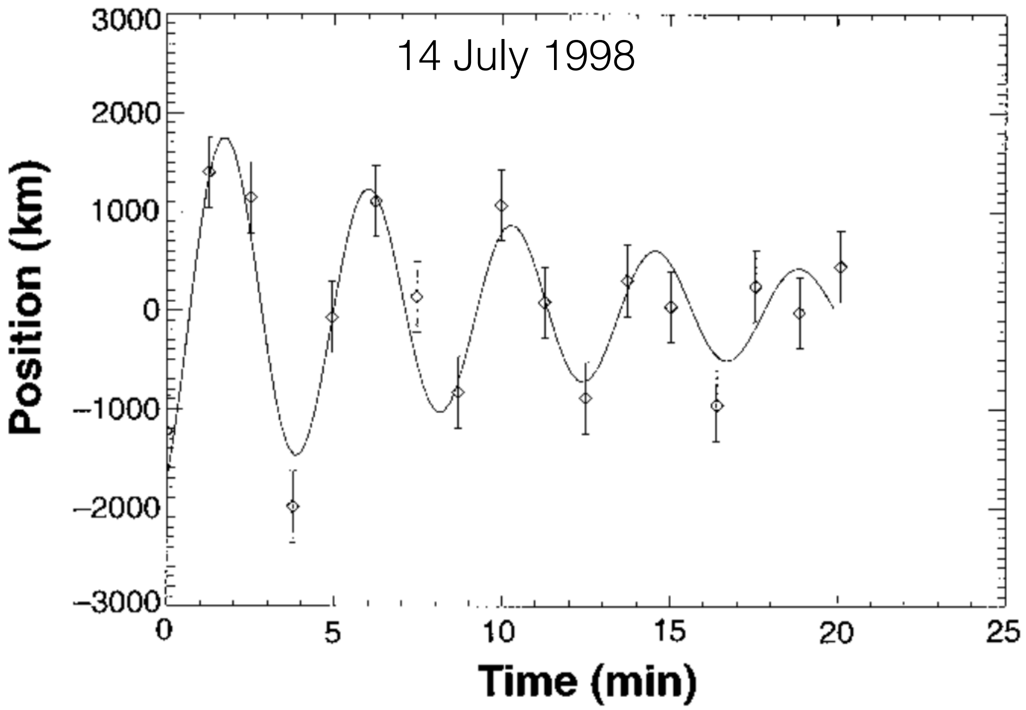


Key parameters:

density contrast ratio ρ_0/ρ_e

inhomogeneous layer width $\epsilon = l/R$

Standing kink oscillation observed with TRACE



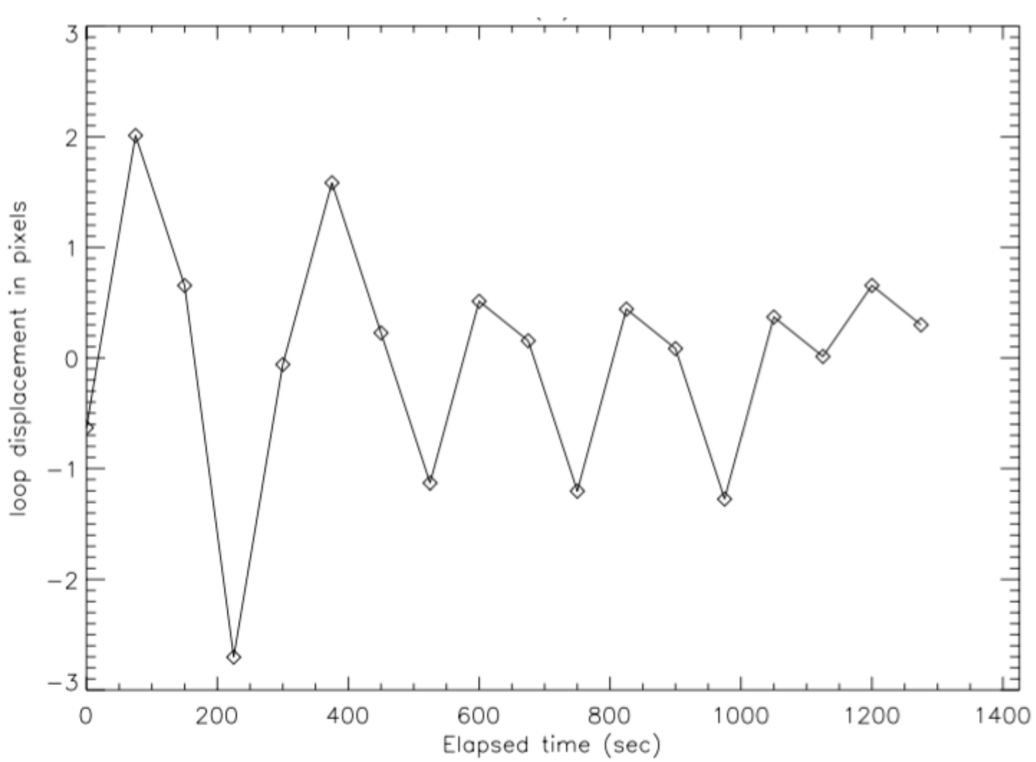
0.5 arcsec/pixel, ~75 second cadence

$$A(t) = A_0 \sin(\omega t + \phi) e^{-\lambda t}$$

Estimate kink speed as $C_k = \frac{2L}{P}$

$$B = 13 \pm 9\mathrm{G}$$

Nakariakov et al. (1999)
Nakariakov & Ofman (2001)



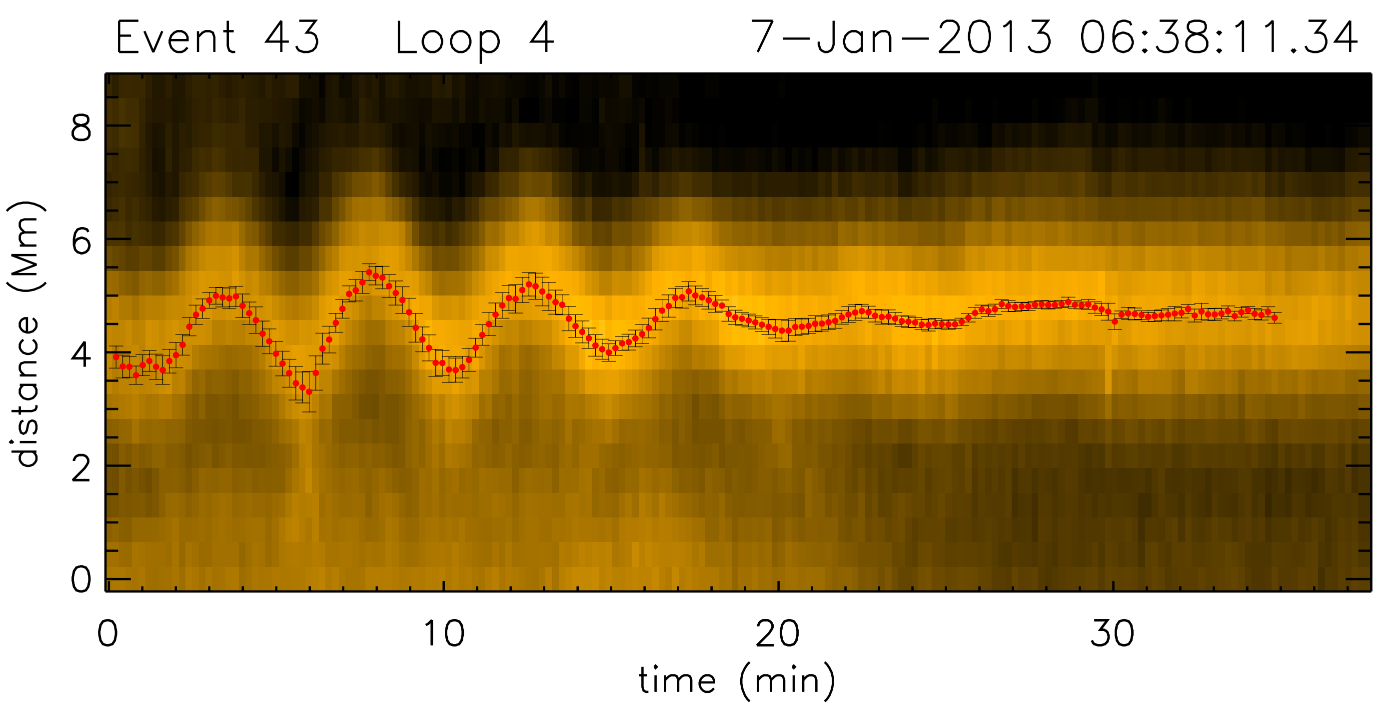
Evidence for non-exponential damping profile, but large uncertainties due to low cadence

$$\propto \exp\left(-kt^N\right)$$

$$N \approx 2.0 \pm 1.2$$

De Moortel et al. (2002)
Ireland & De Moortel (2002)

SDO allows high-resolution seismology



0.6 arcsec/pixel (full disk)

12 second cadence

We can now take advantage of improvements in theoretical models and consider, e.g,

- shape of **damping profile** allows us to estimate the transverse density profile

e.g. Pascoe et al. (2013, 2016), Arregui et al. (2013)

- **longitudinal harmonics** in addition to the fundamental mode may reveal longitudinal structuring e.g. density stratification or loop expansion

e.g. Andries et al. (2005), Safari et al. (2007), McEwan et al. (2008), Verth & Erdélyi (2008)

- **time-dependent** period of oscillation and its relationship to the background trend i.e. loop expansion/contraction/displacement

e.g. De Moortel et al. (2002), White et al. (2013), Morton & Mooroogen (2016), Su et al. (2018)

- discovery of **decayless regime** of kink harmonics

e.g. Nisticò et al. (2013), Anfinogentov et al. (2013), Pascoe et al. (2017), Duckenfield et al. (2018)

Seismological method

Loop Position = Oscillation x Damping Envelope + Background trend

Oscillation:
- Additional harmonics
- Time-dependent period
- Decayless component

Damping Envelope:
- Frequency-dependent rate
- Gaussian regime
- Exponential regime

Background trend:
- Spline interpolation
- Large initial shift in equilibrium

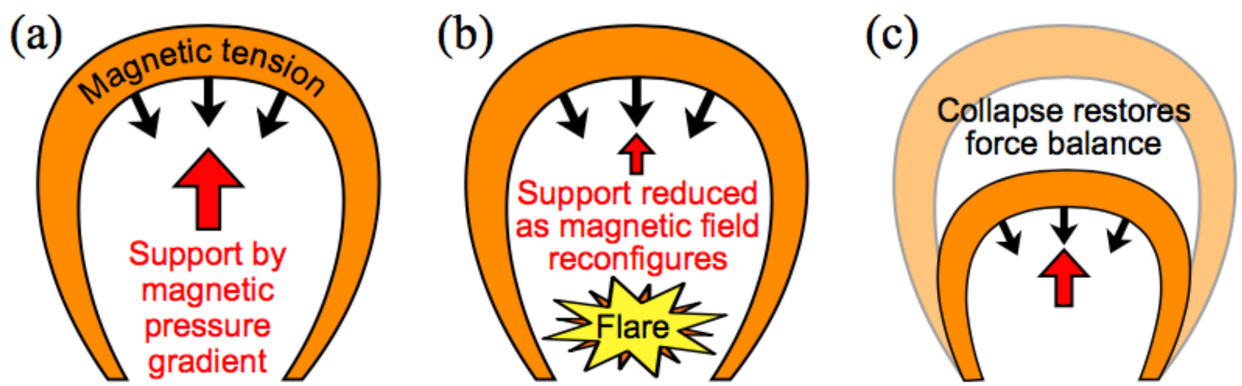
- Large number of model parameters so must take care to avoid over-interpretation
- We test our models against observational data using Bayesian analysis and Markov chain Monte Carlo (MCMC) sampling
  - accurate estimates of parameter uncertainties
  - quantitative model comparison using Bayes factors

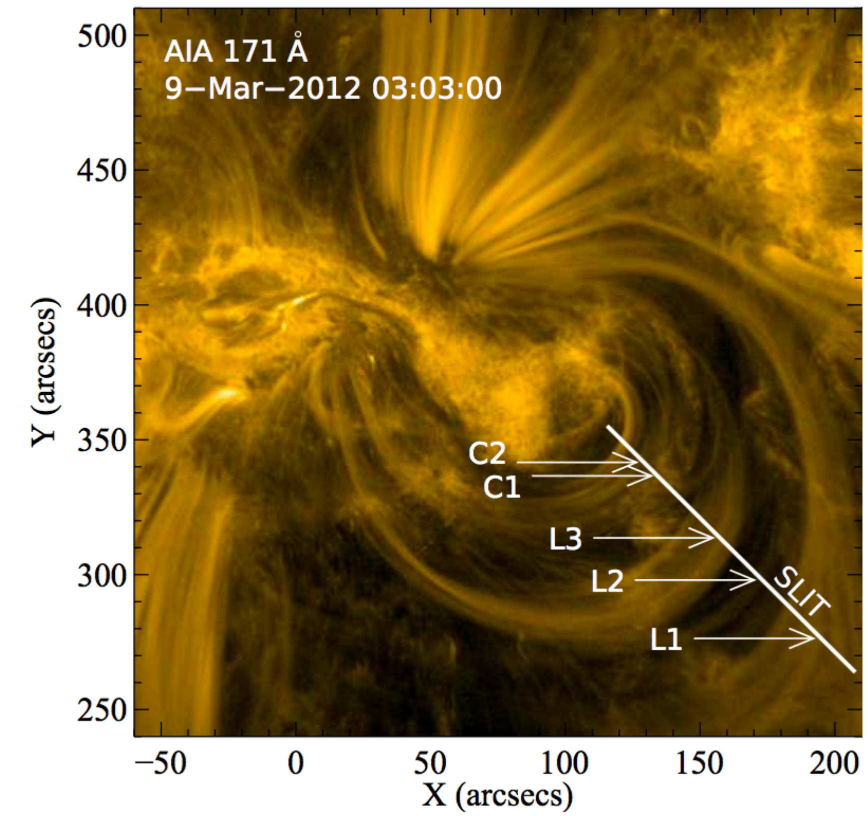
review by Arregui (2018, AdSpR, 61, 655)

Seismology of a contracting loop

Simões et al. (2013)

Russell et al. (2015)





$$B = 13 \pm 2 \;\; \mathrm{G}$$

Shape of damping profile allows density profile to be estimated…

$$\rho_0 / \rho_e = 3.0 \pm 0.9$$

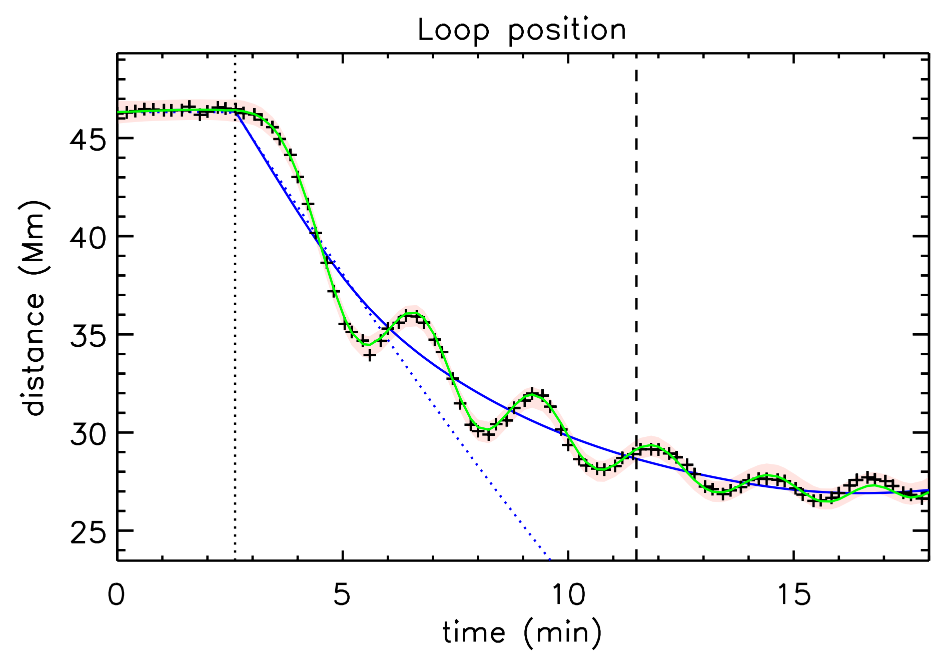
$$\epsilon = 0.3 \pm 0.1$$

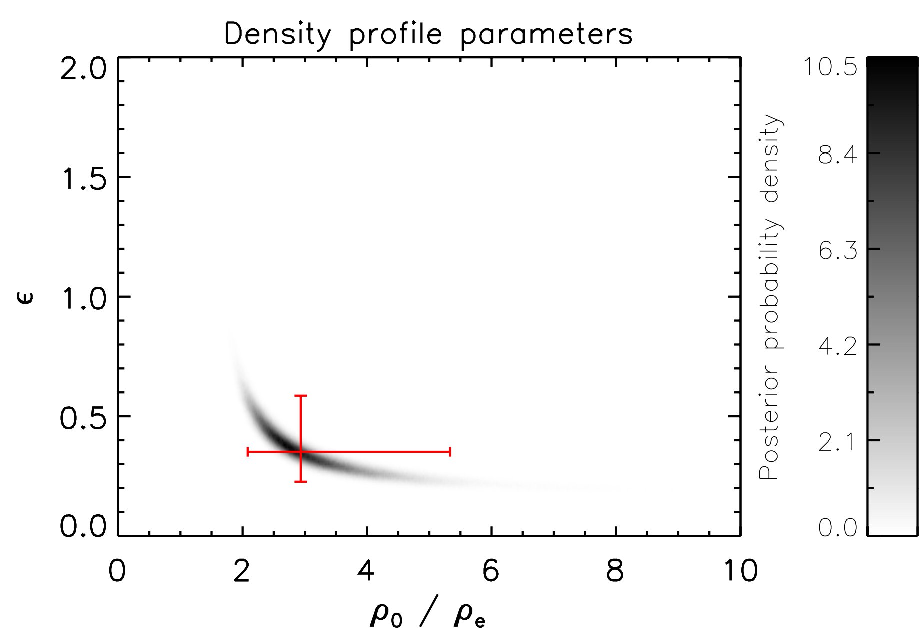
…and hence internal and external Alfvén speeds

$$C_{A0} = 1.4 \pm 0.1 \;\; \mathrm{Mm/s}$$

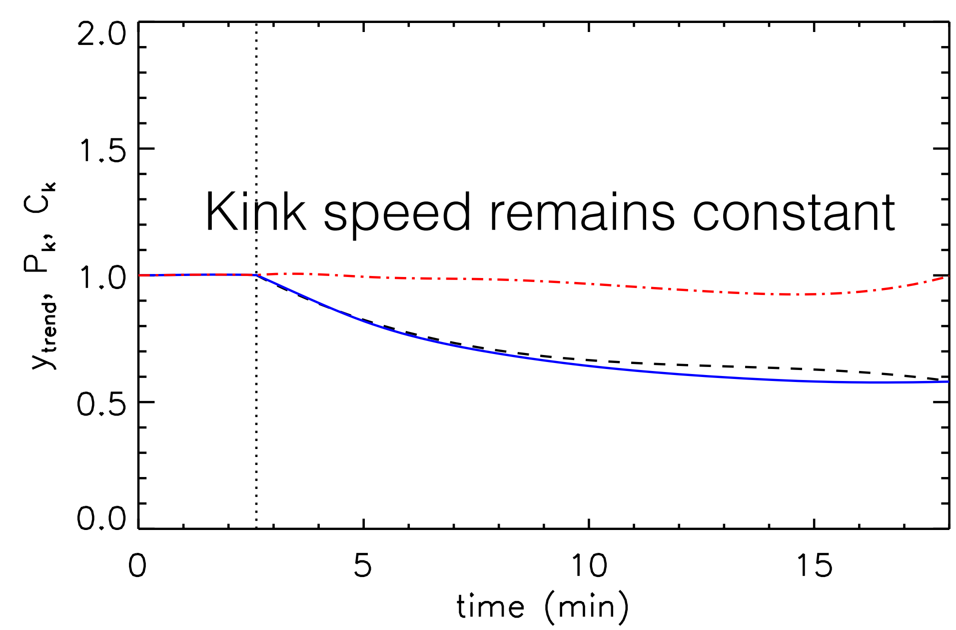
$$C_{Ae} = 2.5 \pm 0.4 \;\; \mathrm{Mm/s}$$

Pascoe et al. (2017, A&A, 607, A8)



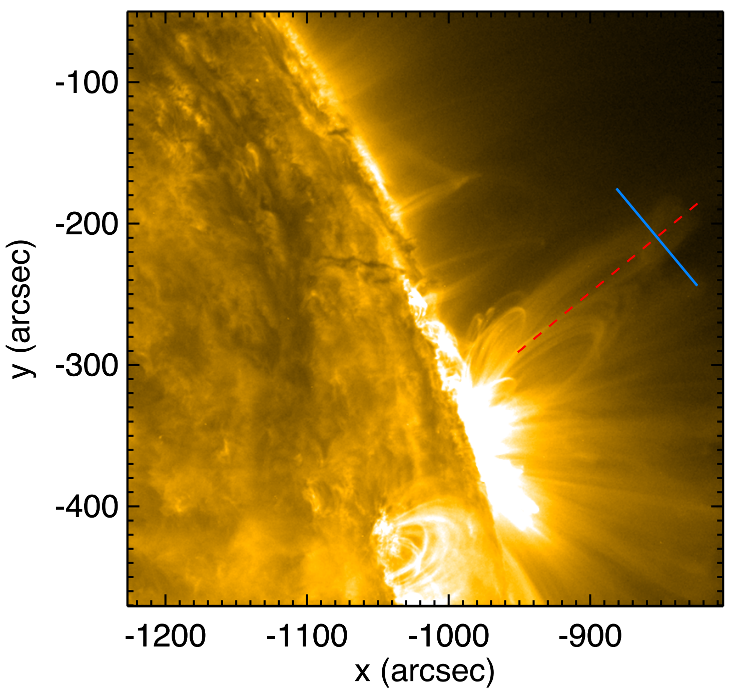


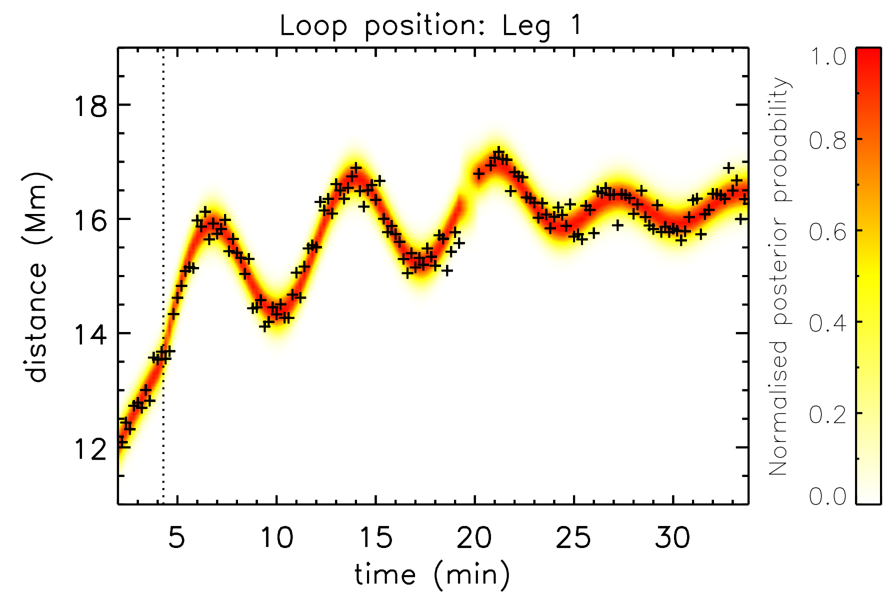
Period of oscillation decreases as loop contracts

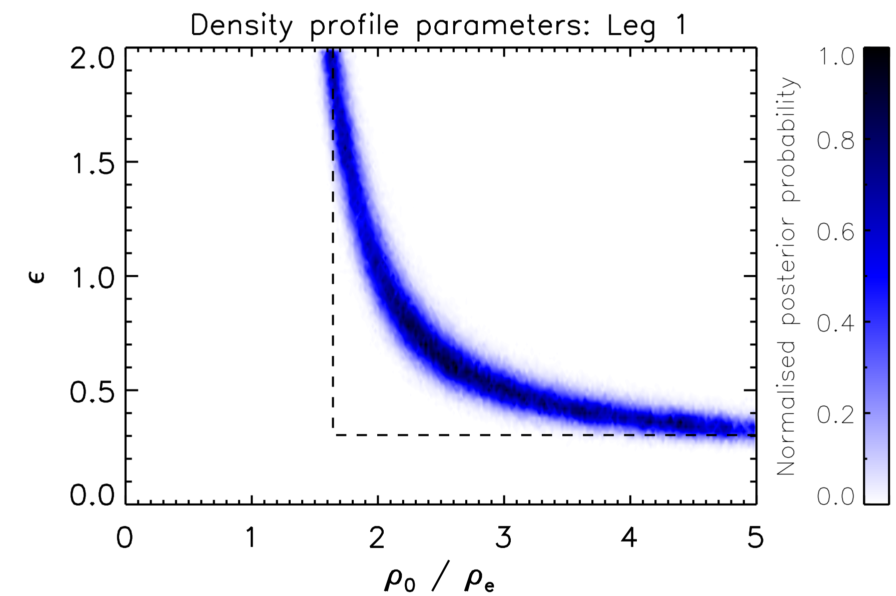


Seismological estimate for noisy oscillations

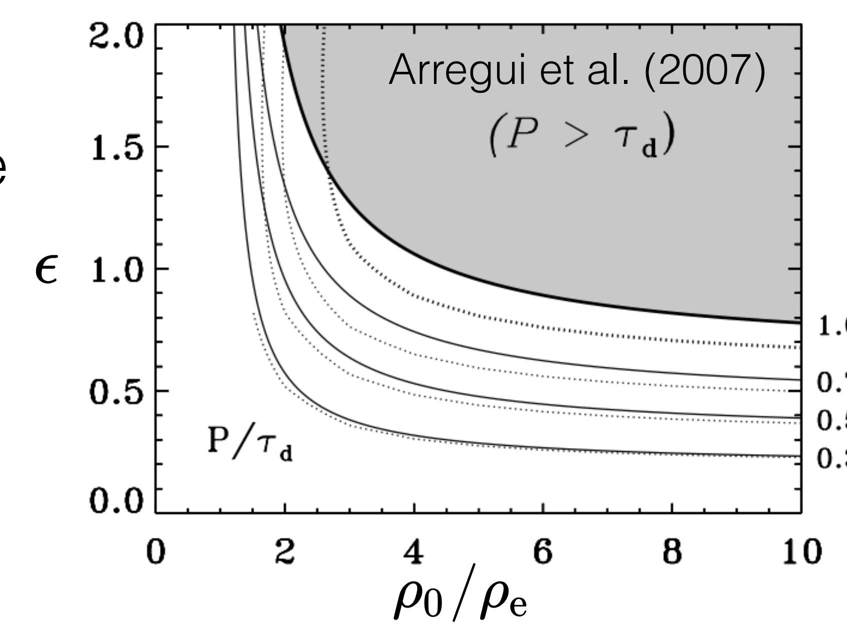
- Seismological estimate of transverse density profile is based on detecting **both** the **Gaussian** and **exponential** damping regimes of resonant absorption
- The shape of the damping profile (transition from Gaussian regime to exponential) is more sensitive to the level of noise than the overall damping rate is





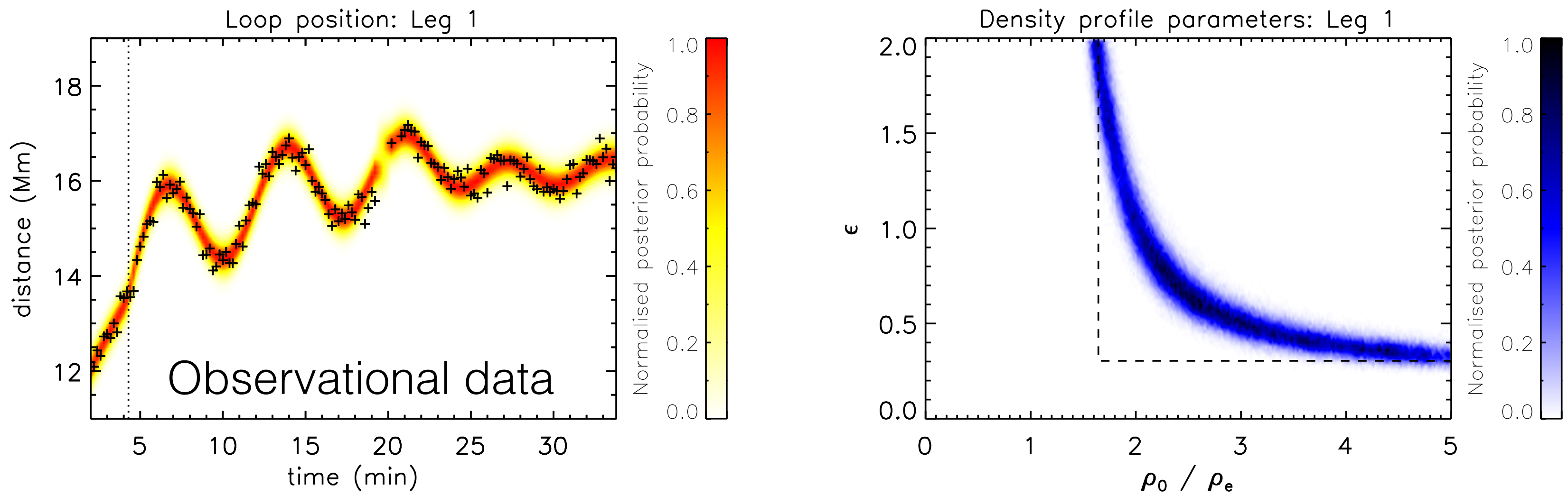


- Without shape information, the constraint on the density profile is a curve in parameter space as previously studied for inversions based only on the damping rate
- Note we can still test whether a purely exponential or purely Gaussian damping profile best describes the data (in this case the latter is supported with a Bayes factor K_{GE}=7.5)

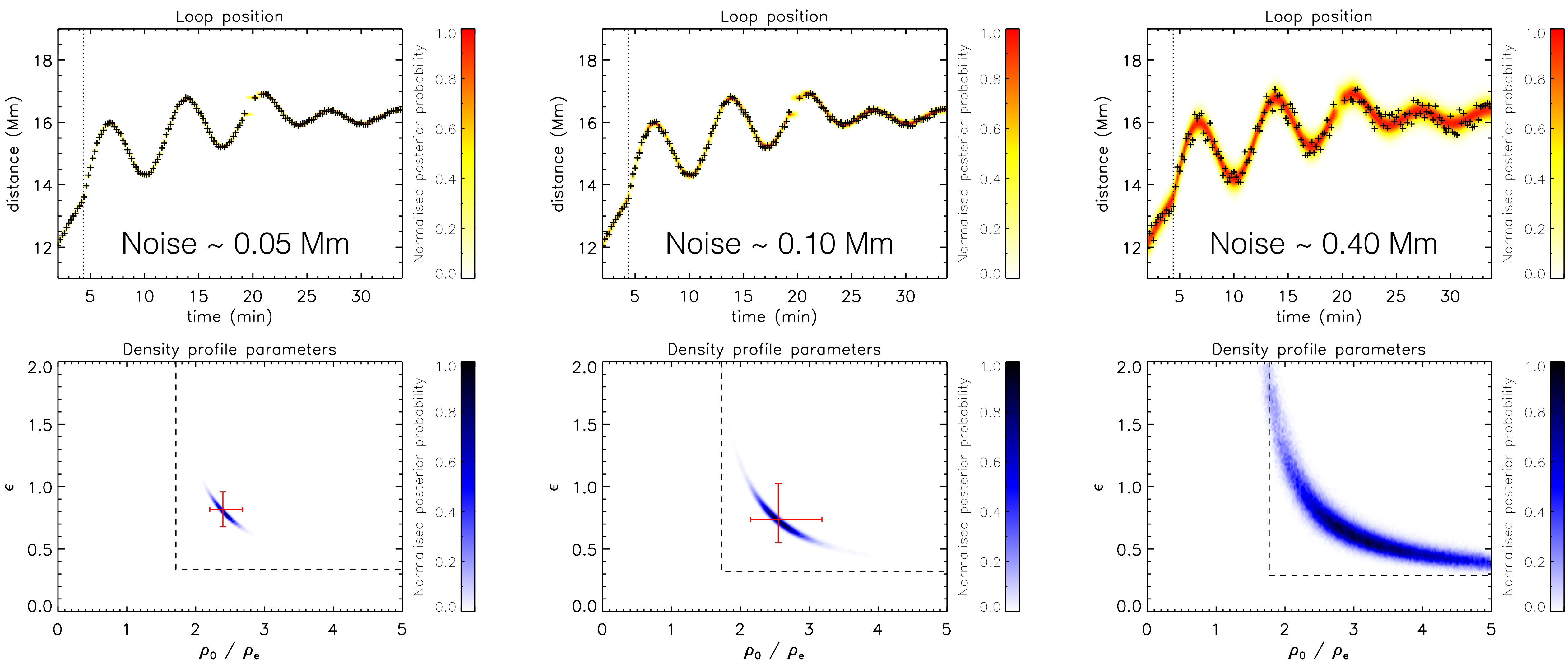


see also Goossens et al. (2008), Arregui & Asensio Ramos (2014)

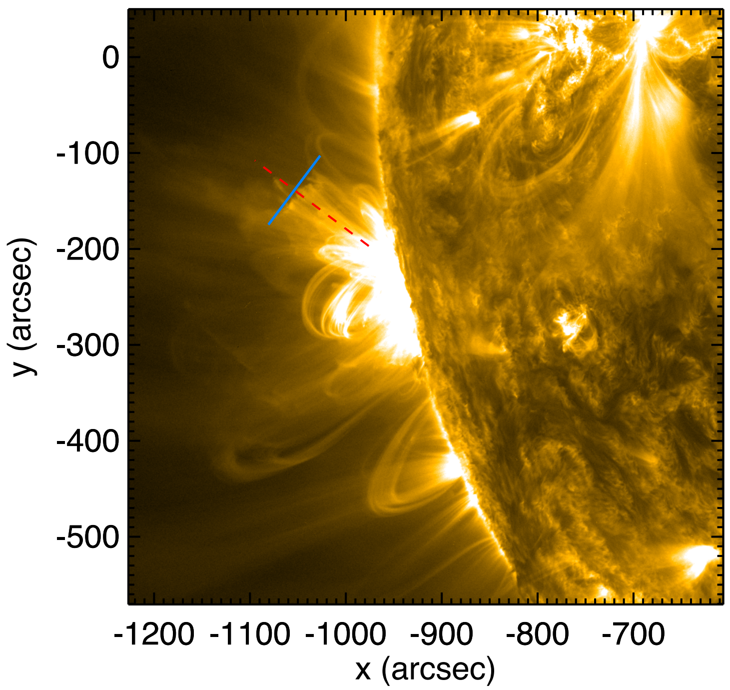
Seismological estimate for noisy data

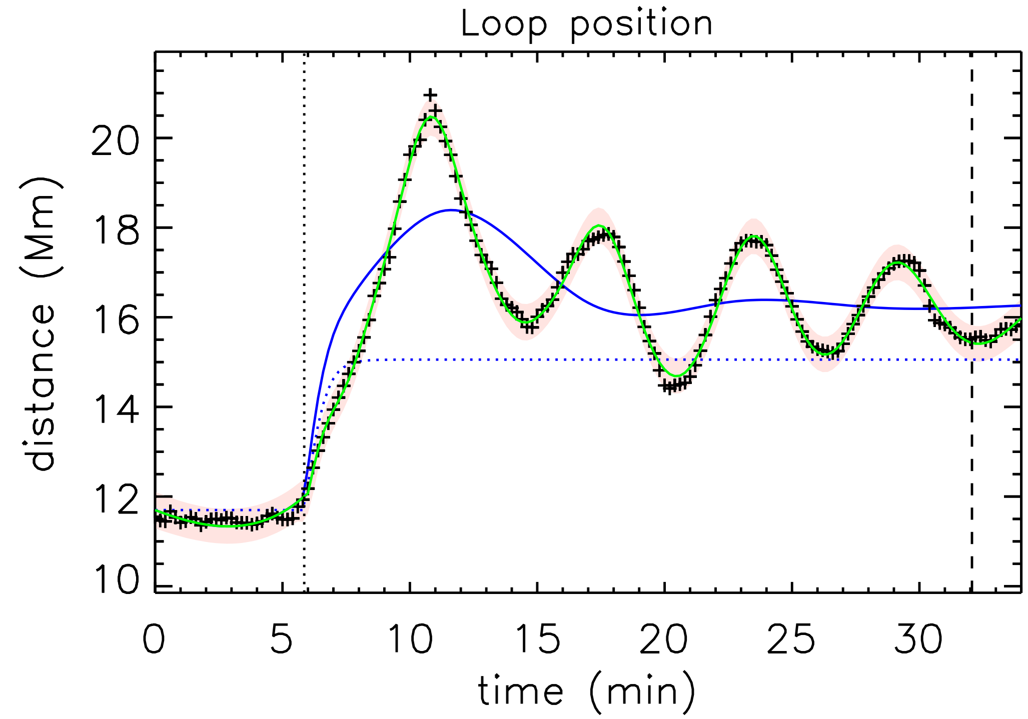


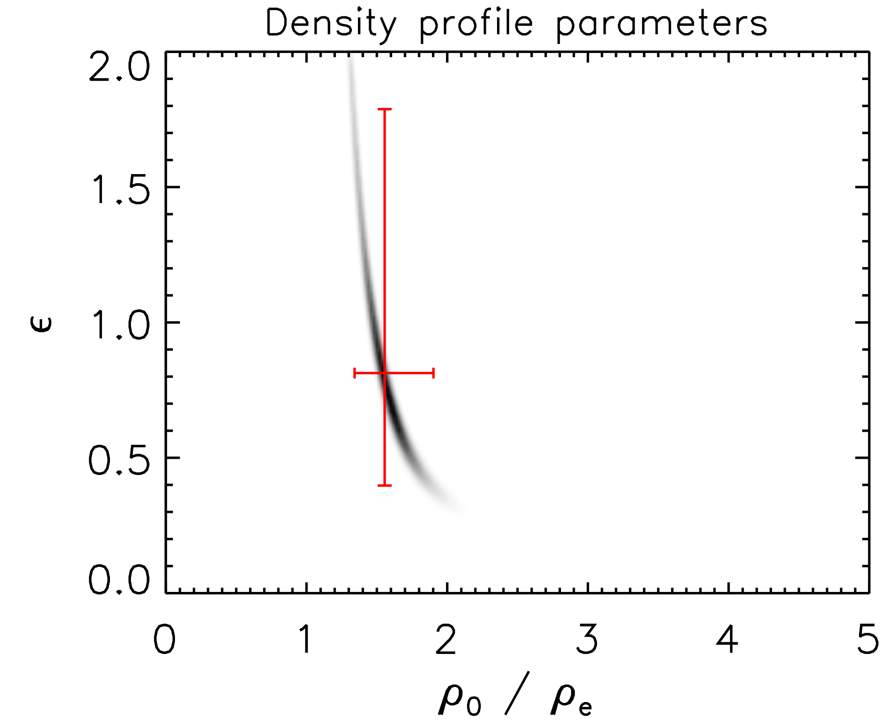
Synthetic signals with same properties but varying the level of noise — increasing noise leads to weaker constraints on parameters:



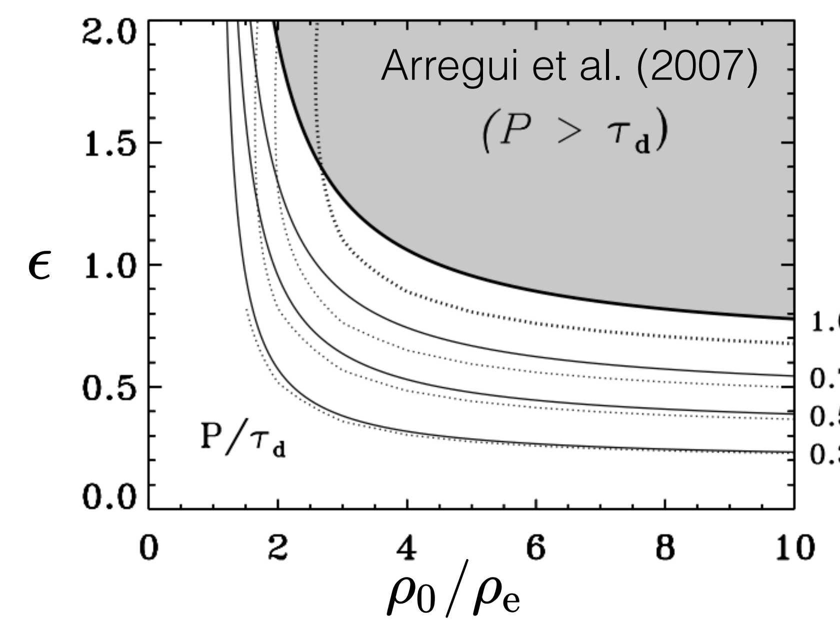
Low density contrast loop







- Noise isn't the only factor in how well density profile parameters can be constrained
- Example of loop with density contrast < 2
- Oscillation data has low noise
- ε is poorly constrained due to asymptotic nature of inversion curve
- Additional method to constrain ε is desirable…



see also Goossens et al. (2008), Arregui & Asensio Ramos (2014)

Forward modelling of EUV intensity profile

- Extreme ultraviolet (EUV) emission depends on density and temperature

e.g. De Moortel & Bradshaw (2008)
FoMo by Van Doorsselaere et al. (2016)

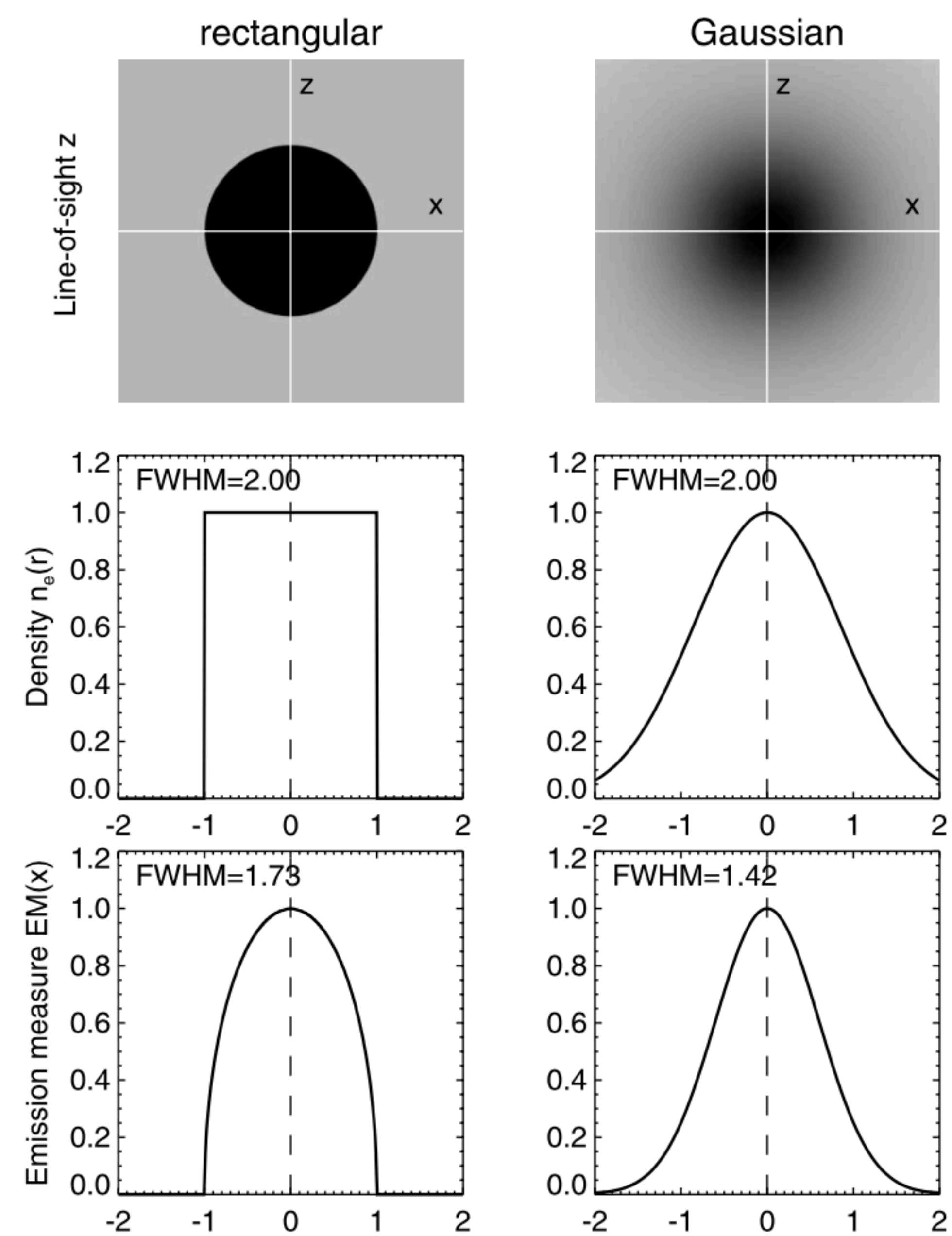
$$I(z) = \frac{0.83 \times A \times d \times B(T_e) \times R(\lambda) \times E(\lambda, n_e, T_e) \times \lambda}{n_e h c 4\pi}$$

- Isothermal and optically thin approximations greatly simplify:

e.g. Warren et al. (2008)
Aschwanden & Boerner (2011)
Brooks et al. (2013)

c.f. multi-thermal loops e.g.
Schmelz et al. (2010, 2014)
Nisticò et al. (2014, 2017)

$$I \propto \int \rho^2$$



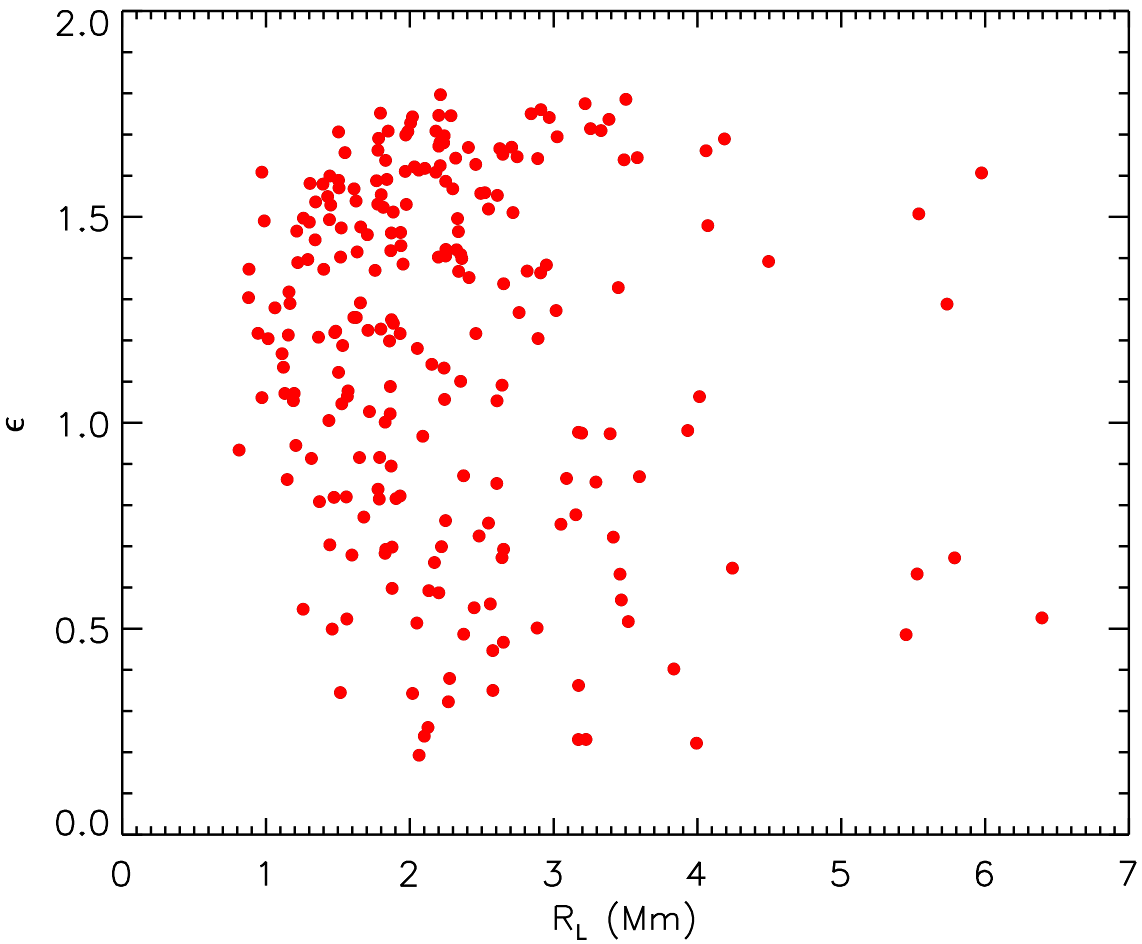
Aschwanden et al. (2007, ApJ, 656, 577)

- Assume cylindrically symmetric cross-section

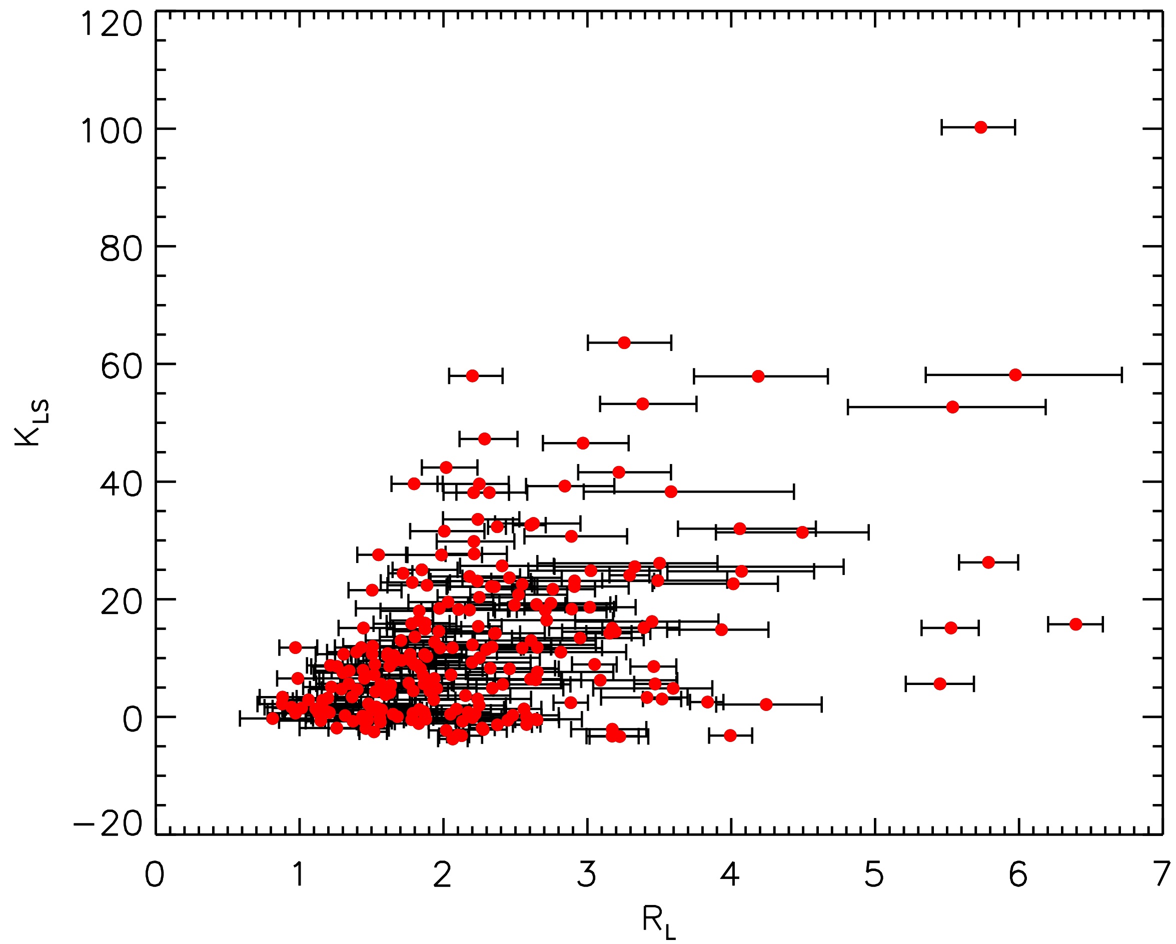
- Use point spread function (PSF) for particular instrument (SDO/AIA 171 in our case)

Statistical study for ε

- 233 (non-oscillating) loops analysed using EUV forward modelling method



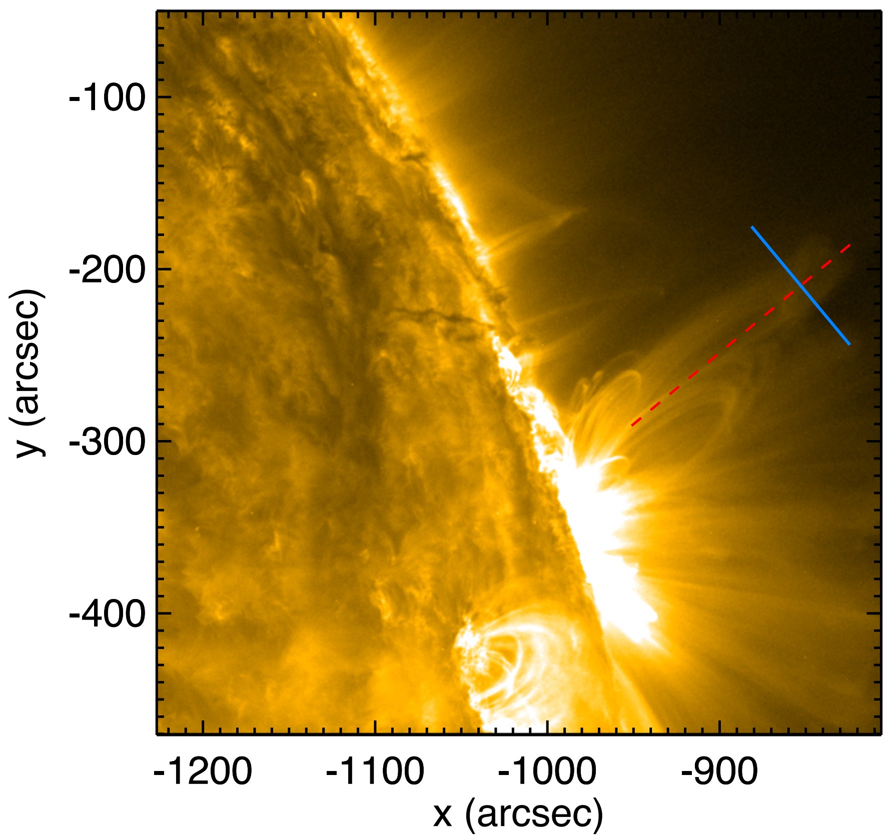
No correlation between ε and loop radius



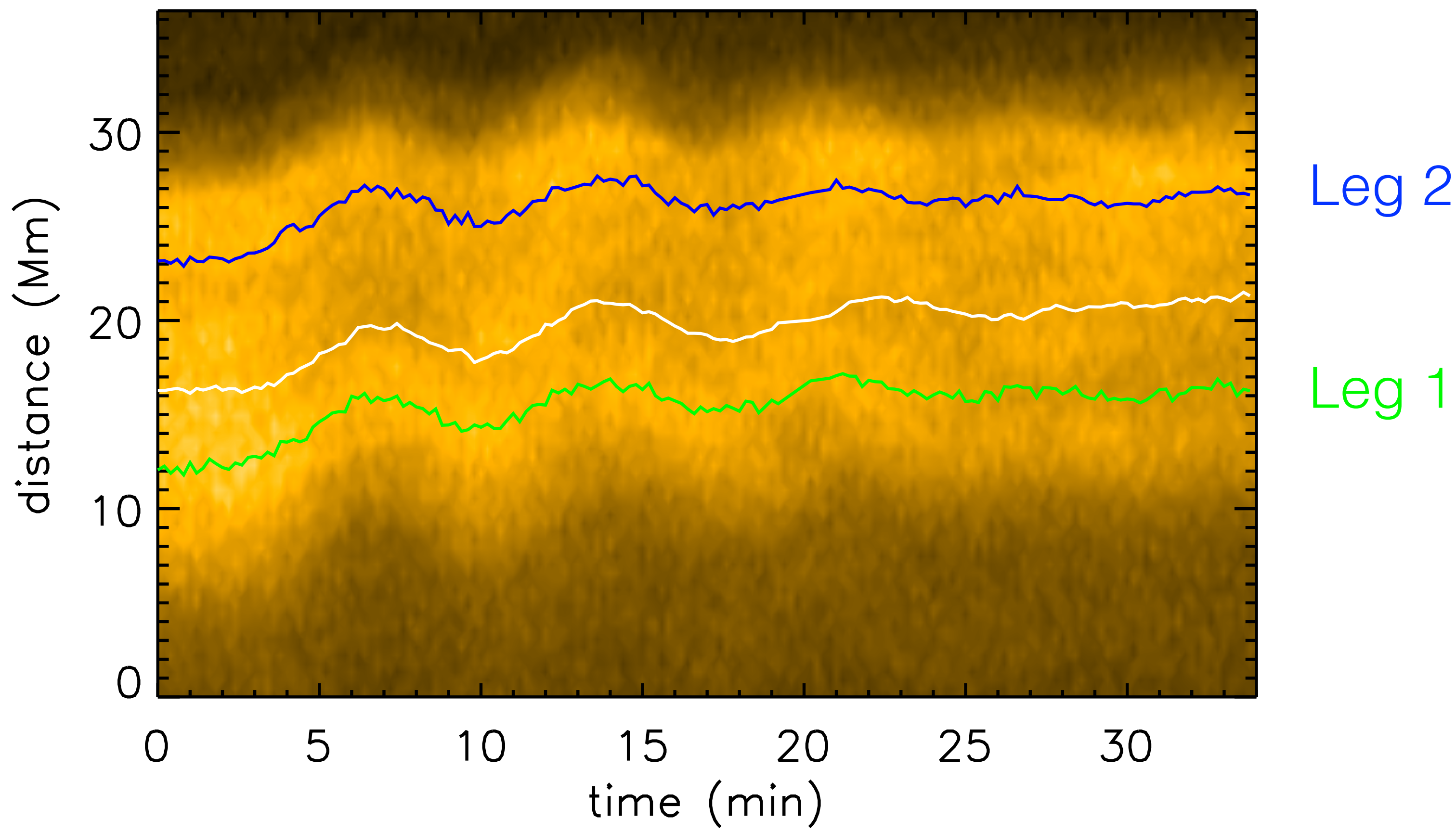
Bayesian evidence for presence of finite transition layer depends on loop radius (i.e. effective resolution)

Goddard et al. (2017, A&A, 605, A65)

Applying the spatial method to the oscillating loop



Oscillating loop viewed from side



Two loop legs appear as slightly overlapping in TD map

- We assume the same values of R and ε for both loop legs

Pascoe et al. (2018, ApJ, 860, 31)

Estimate ε by forward modelling intensity profile

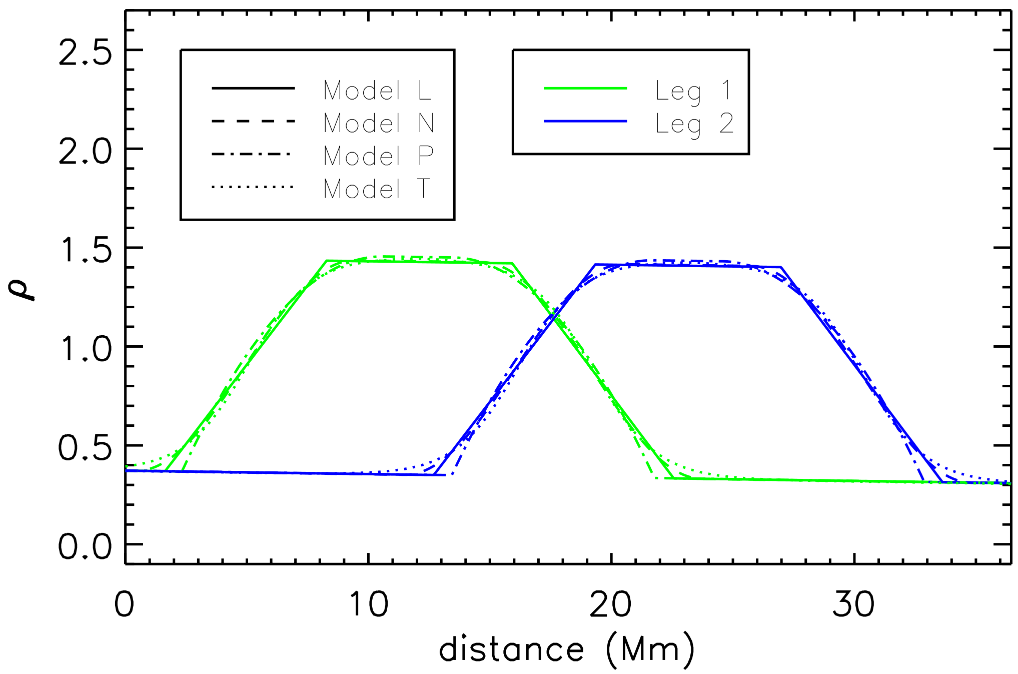
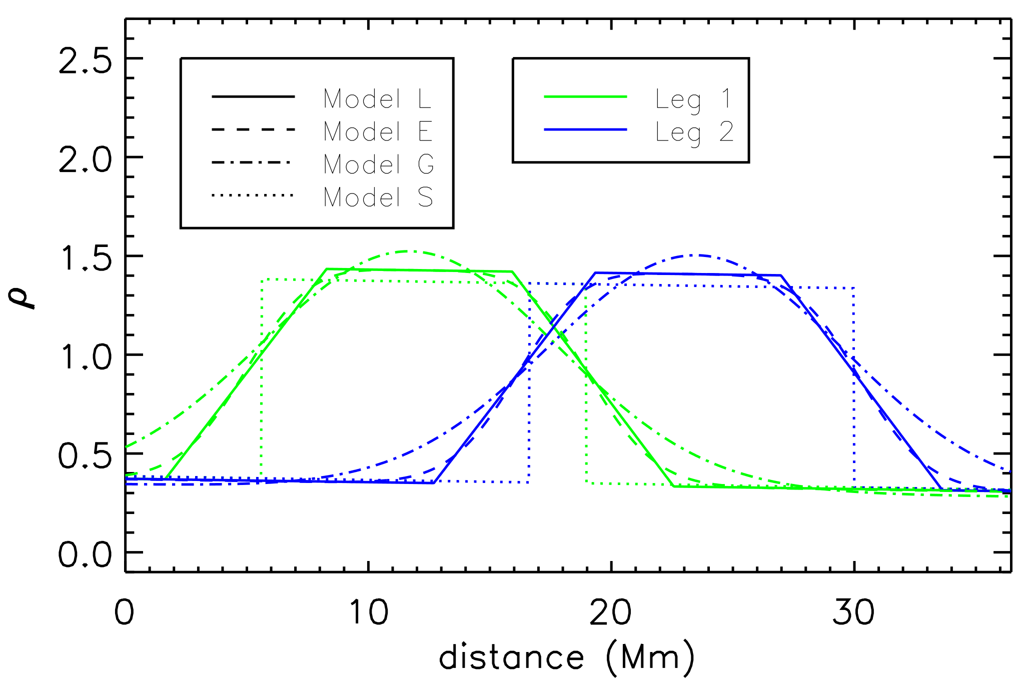


Table 1. Parameters for different transverse density profile models (M_i); linear transition layer profile (Model L), sinusoidal transition layer profile (Model N), parabolic transition layer profile (Model P), hyperbolic tangent profile (Model T), generalised symmetric Epstein profile (Model E), Gaussian density profile (Model G), and step function density profile (Model S).

M_i	A	x_1 (Mm)	x_2 (Mm)	R (Mm)	ϵ	p	K_{iS}	K_{iG}	K_{Li}
L	$1.08^{+0.05}_{-0.05}$	$12.1^{+0.3}_{-0.4}$	$23.2^{+0.3}_{-0.3}$	$7.1^{+0.3}_{-0.2}$	$0.9^{+0.2}_{-0.2}$	–	56.1	19.2	–
N	$1.08^{+0.06}_{-0.05}$	$12.1^{+0.3}_{-0.4}$	$23.2^{+0.3}_{-0.3}$	$7.1^{+0.3}_{-0.3}$	$1.3^{+0.3}_{-0.2}$	–	55.1	18.1	1.1
P	$1.10^{+0.07}_{-0.05}$	$12.0^{+0.4}_{-0.3}$	$23.2^{+0.3}_{-0.3}$	$5.6^{+0.4}_{-0.6}$	$1.5^{+0.5}_{-0.4}$	–	52.0	15.1	4.1
T	$1.10^{+0.10}_{-0.05}$	$12.1^{+0.3}_{-0.5}$	$23.2^{+0.3}_{-0.3}$	$7.1^{+0.3}_{-0.3}$	$1.0^{+0.5}_{-0.2}$	–	51.7	14.7	4.4
E	$1.08^{+0.05}_{-0.04}$	$12.0^{+0.4}_{-0.4}$	$23.2^{+0.3}_{-0.3}$	$7.6^{+0.3}_{-0.3}$	–	$2.1^{+0.6}_{-0.5}$	49.6	12.7	6.5
G	$1.20^{+0.05}_{-0.07}$	$11.7^{+0.6}_{-0.6}$	$23.5^{+0.4}_{-0.4}$	$6.1^{+0.6}_{-0.4}$	–	–	37.0	–	19.2
S	$1.01^{+0.04}_{-0.06}$	$12.3^{+0.4}_{-0.4}$	$23.3^{+0.4}_{-0.4}$	$6.7^{+0.3}_{-0.3}$	–	–	–	−37.0	56.1

NOTE—Posterior summaries are given at the maximum a posteriori probability (MAP) and uncertainties by the 95% credible interval.

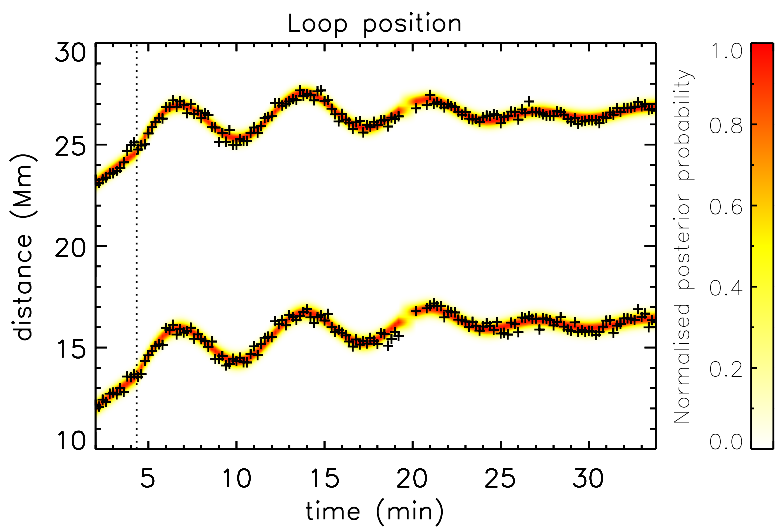


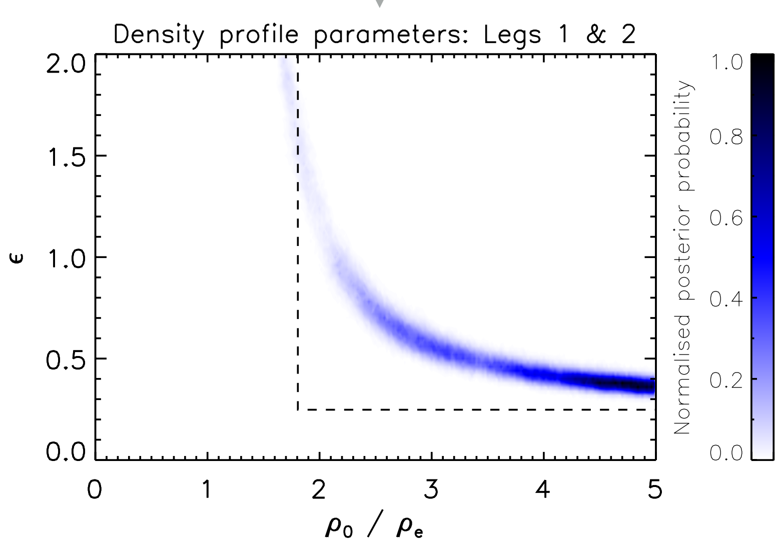
- We test 7 different density profile models — step function, Gaussian, and 5 different ways to describe a finite inhomogeneous layer
- Profiles containing an inhomogeneous layer all describe the same overall density profile shape
- Particular value of ε depends on choice of density profile — comparing different density profiles should be done on the basis of shape not value of ε

Pascoe et al. (2018, ApJ, 860, 31)

Simultaneous spatial and temporal analysis

Temporal analysis
(kink oscillation seismology)





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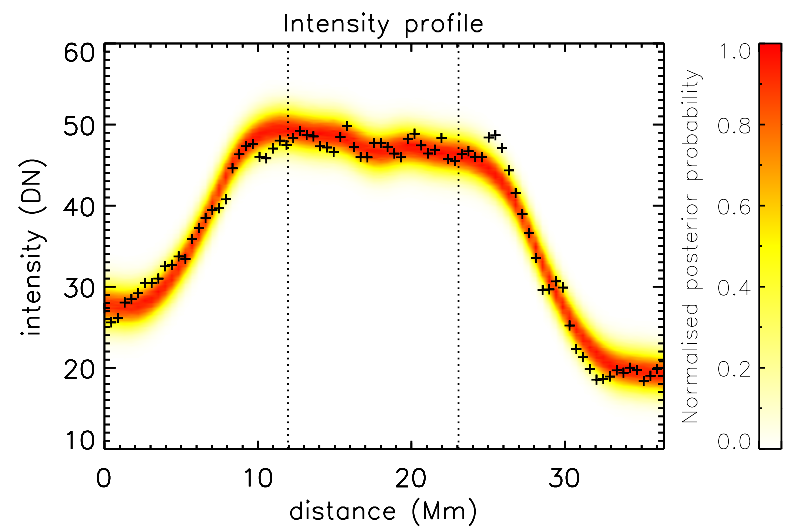
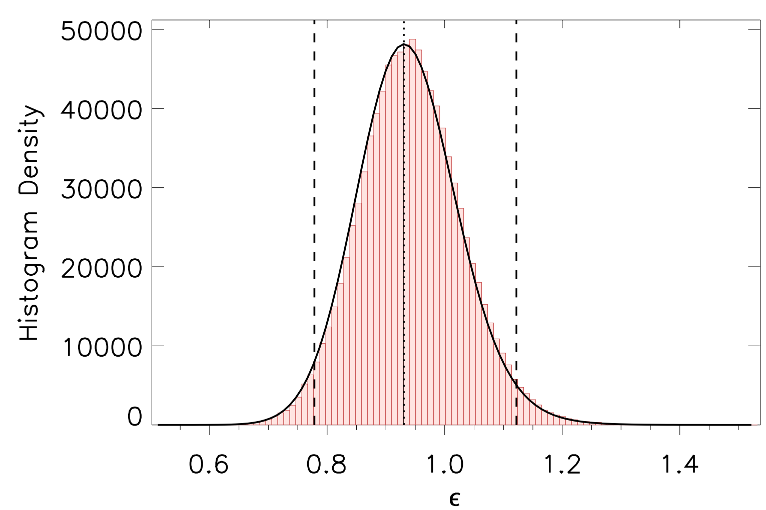
Spatial analysis
(EUV intensity profile)





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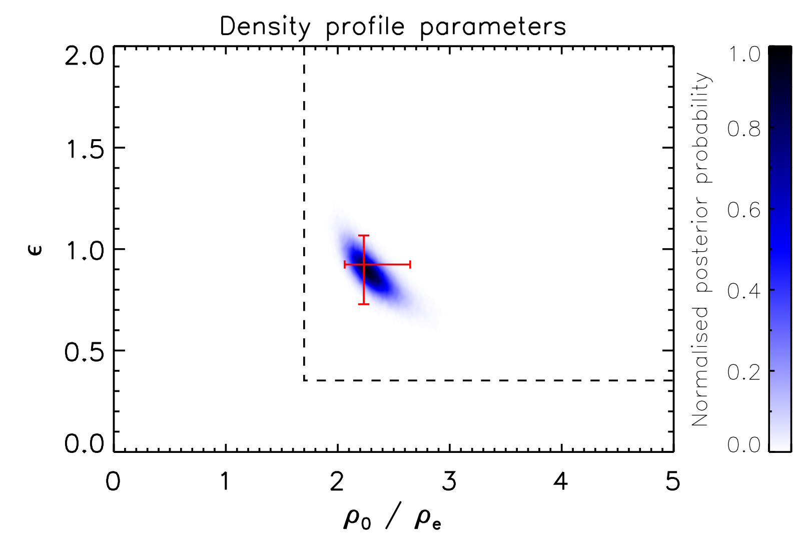
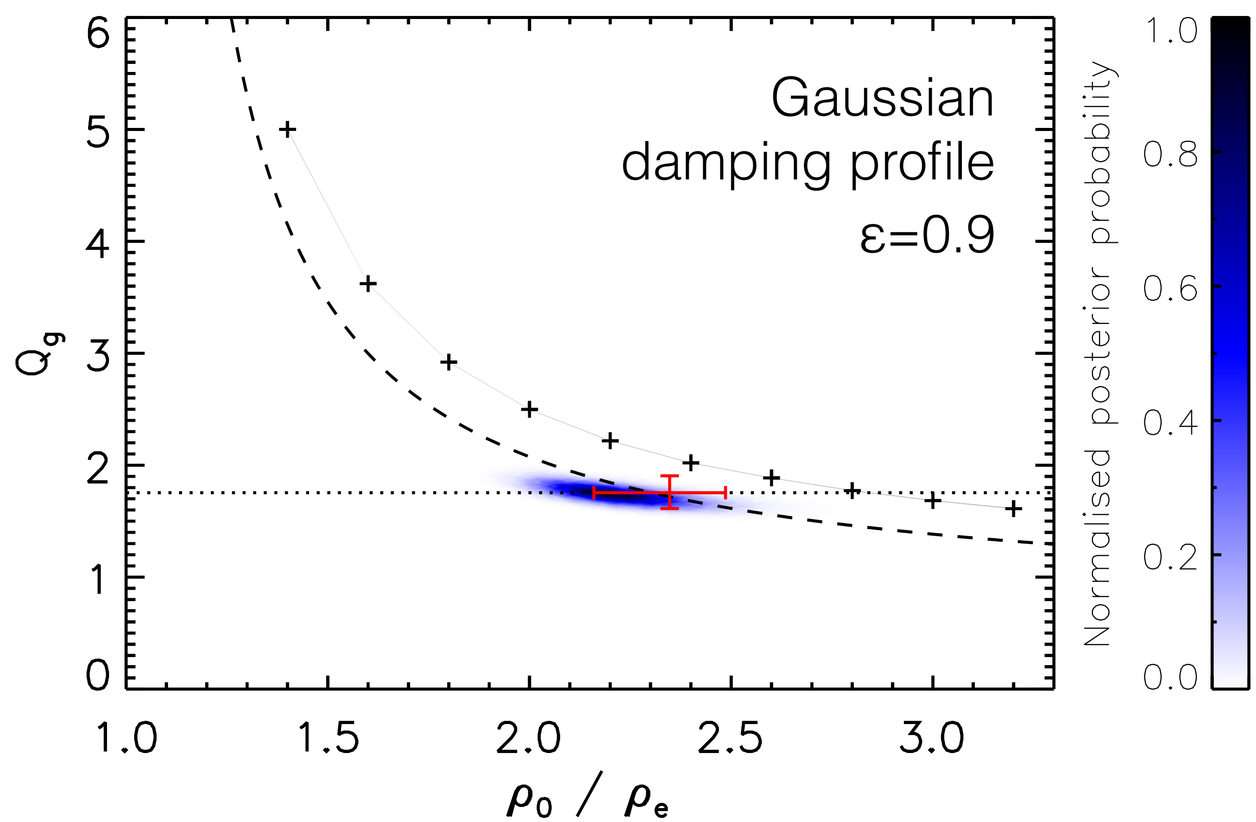


Applying these two methods simultaneously allows density profile parameters to be well-constrained

Error estimates

- Seismological method is based on thin boundary (TB) approximation whereas forward modelling implies a thick boundary (ε ~ 0.9)

- Parametric study allows seismological estimate to be refined, suggesting a density contrast ~2.8



- Error using TB approximation (and Gaussian profile) ~18%

c.f. Van Doorsselaere et al. (2004),
Soler et al. (2014)

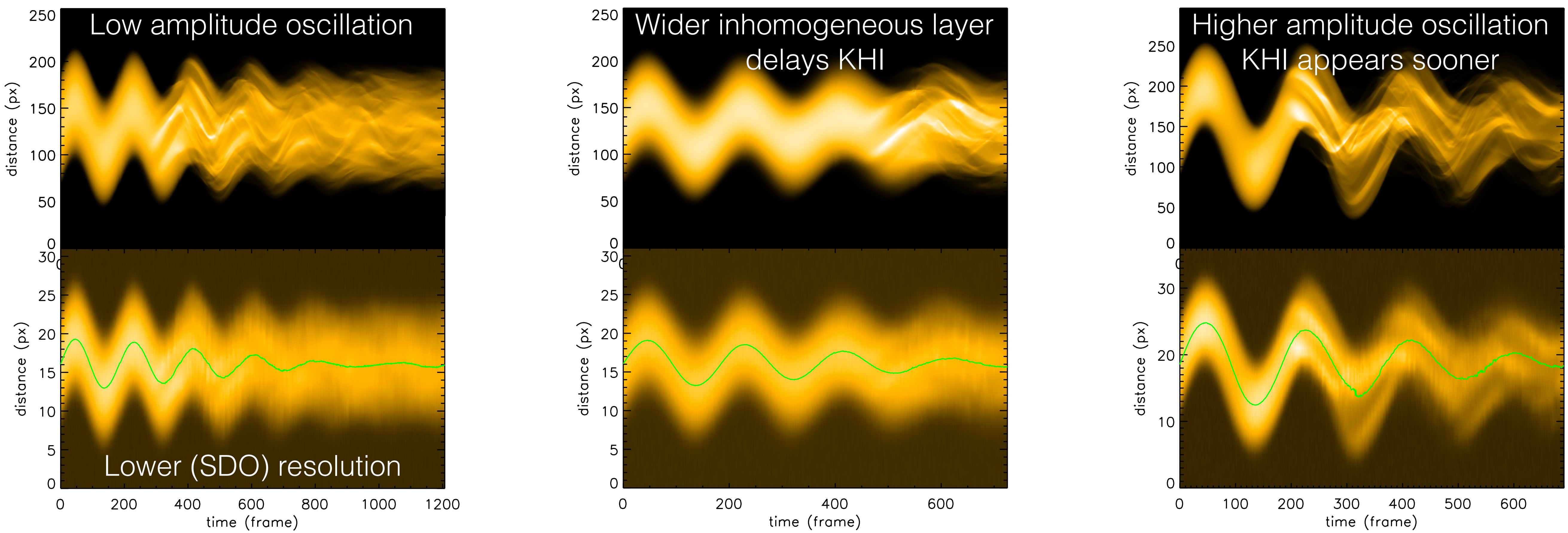
- Error using exponential damping profile rather than Gaussian would be ~46%

- Difference between linear and sinusoidal density profiles ~8%

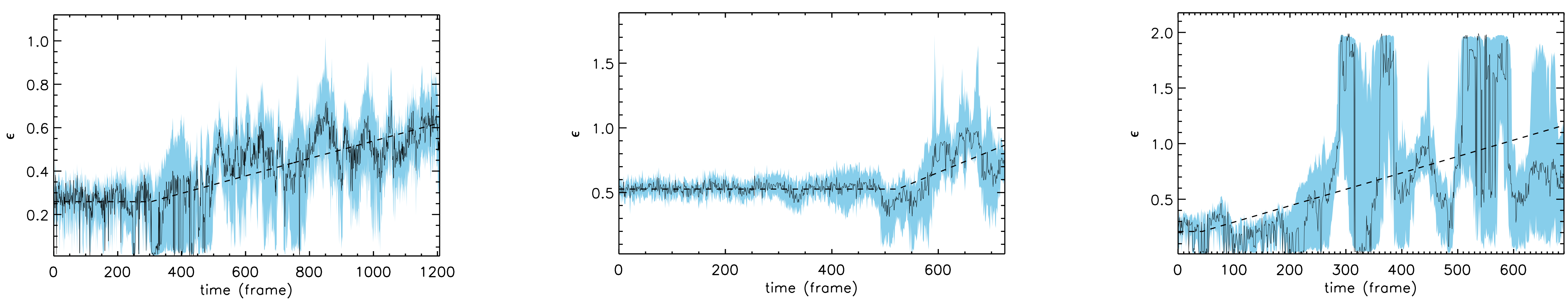
Observational signature of KHI

Goddard et al. (2018),
see also Pagano et al. (2018)

- Numerical simulations by Patrick Antolin:



KHI generates fine structure and mixes plasma inside and outside the loop, appearing as an **increase in ε** with time when viewed at lower spatial resolutions



Summary

- We cannot infer the transverse density profile of coronal loops using the damping rate of kink oscillations alone, some extra information is needed:
  - shape of damping profile if time series data is high quality, and/or
  - transverse EUV intensity profile if spatial resolution is good (wide loops)
- Seismological method is still reliant on thin boundary approximation, but largest source of error is incorrect damping profile
  - use Gaussian damping profile for low density contrast loops
  - can always test if exponential or Gaussian damping profile best describes data
- Evolution of transverse density profile can be used to test for Kelvin-Helmholtz instability
  - appears as an increase in ε with time
  - clear in numerical simulations but not yet observationally confirmed