Cut-off of transverse waves through the solar transition region

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Transverse waves are observed in coronal loops.

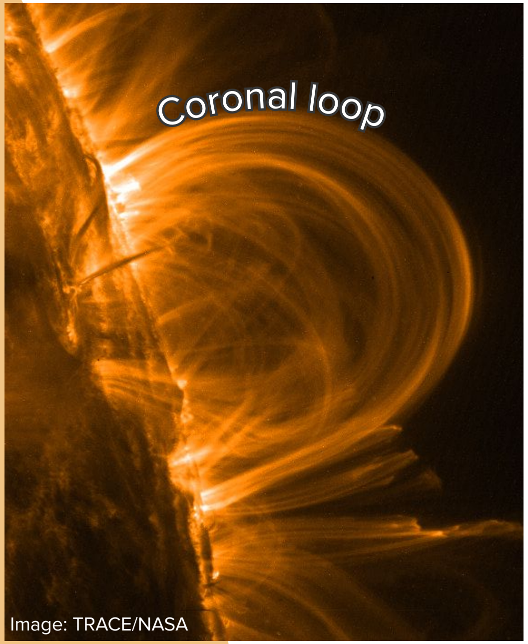
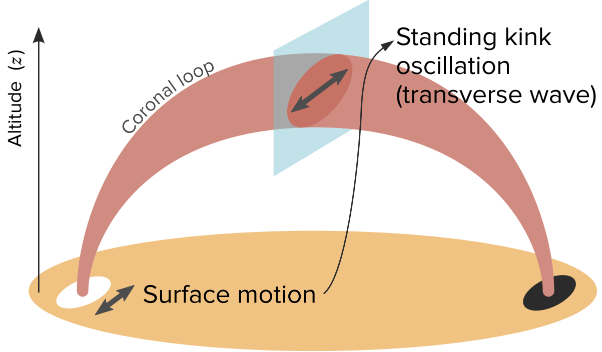
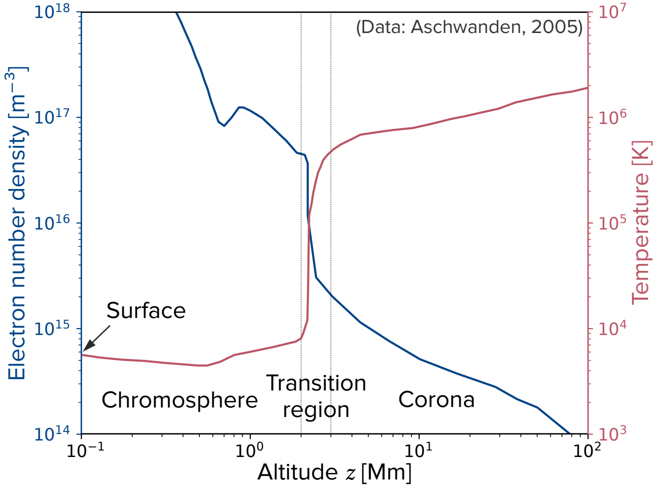


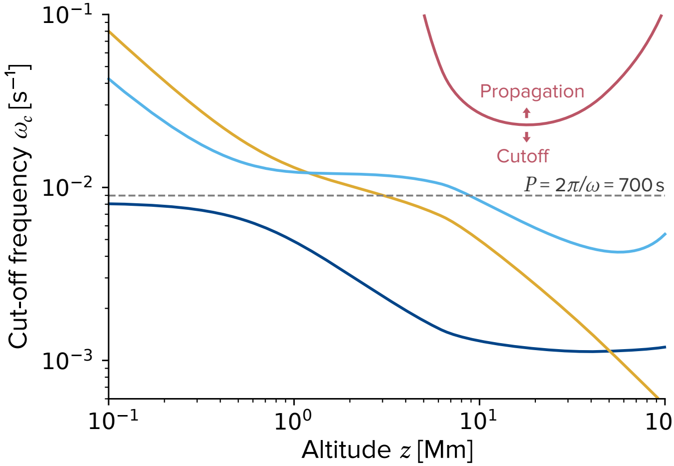
Image: TRACE/NASA





Analytical works predict: **transverse waves are cut-off in the transition region.**

But… – The cut-off hasn't been modelled or observed so far.
– There are inconsistent expressions for the cut-off frequency $\omega_c(z)$.



	E.g. for $P = 700\,\mathrm{s}$:
Petrukhin et al. (2015)	**No propagation**
Snow (NAM 2017)	**Propagation $z > 9$ Mm**
Spruit (1981)	**Propagation $\forall z$**
Lopin & Nagorny (2017)	**Propagation $z > 3$ Mm**

- → **Are transverse waves cut-off through the transition region?**
- → **Which model best predicts the cut-off frequency?**

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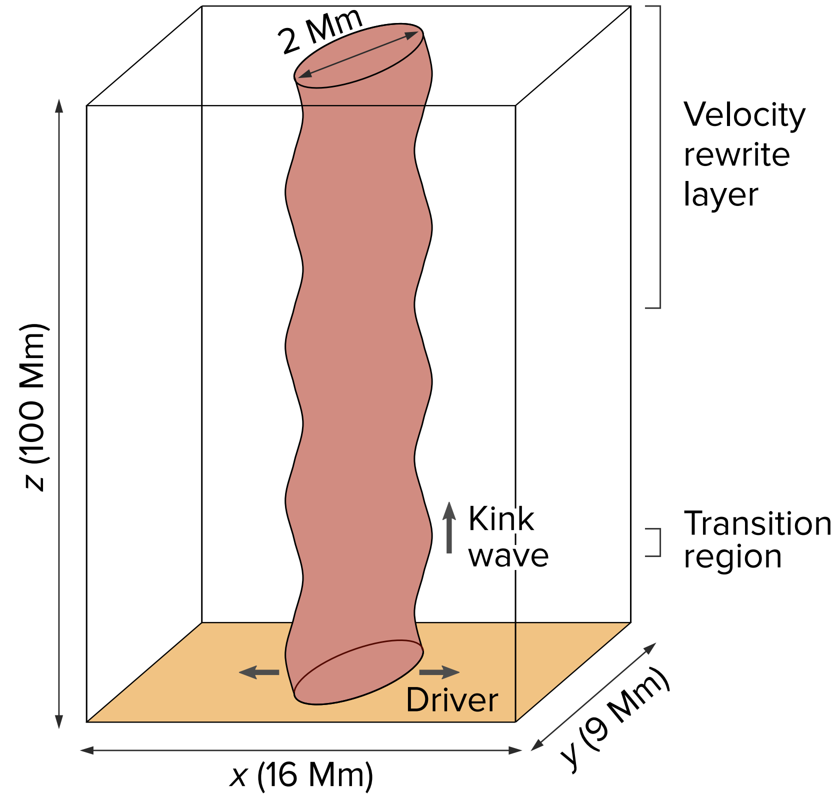
Method: numerical simulations of a magnetic flux tube, containing chromosphere, transition region and corona

➜ **PLUTO** code (Mignone et al. 2012)

➜ **Initial conditions**

- Uniform magnetic field along z ($B_0 = 42$ G)
- Tube radius of 1 Mm, with cross-loop stratification $N_{\mathrm{int}} / N_{\mathrm{ext}} = 3$ and $T_{\mathrm{int}} / T_{\mathrm{ext}} = 1/3$
- Imposed temperature profile ($T_{\mathrm{int}}(0) = 20\,000$ K, $T_{\mathrm{int}}(100\ \mathrm{Mm}) = 3.6$ MK)
- Field-aligned hydrostatic equilibrium ($N_{\mathrm{int}}(0) = 7{\cdot}10^{18}\ \mathrm{m}^{-3}$, $N_{\mathrm{int}}(100\ \mathrm{Mm}) = 10^{15}\ \mathrm{m}^{-3}$).



➜ **Relaxation in 2D**

Residual velocities < 0.5 km s^{-1} after 47 ks

➜ **Drive transverse waves in 3D**

- Initialized from 2D run (cylindrical symmetry)
- Side boundaries (x and y): outflow
- Lower boundary ($z = 0$; see Karampelas et al. 2019a):
  - extrapolate density, pressure, and magnetic field
  - monoperiodic driver along x, amplitude 2 km s^{-1}
- Upper boundary ($z \in [50, 100]$ Mm): *velocity rewrite layer* to absob waves. At each time step, rewrite all velocity components $v(x, y, z) = \alpha_v(z)\, v(x, y, z)$, where $\alpha_v(z)$ varies linearly from 1 to 0.9995 between 50 Mm and 100 Mm.
- Run for 1 to 4 ks, depending on the driver period.

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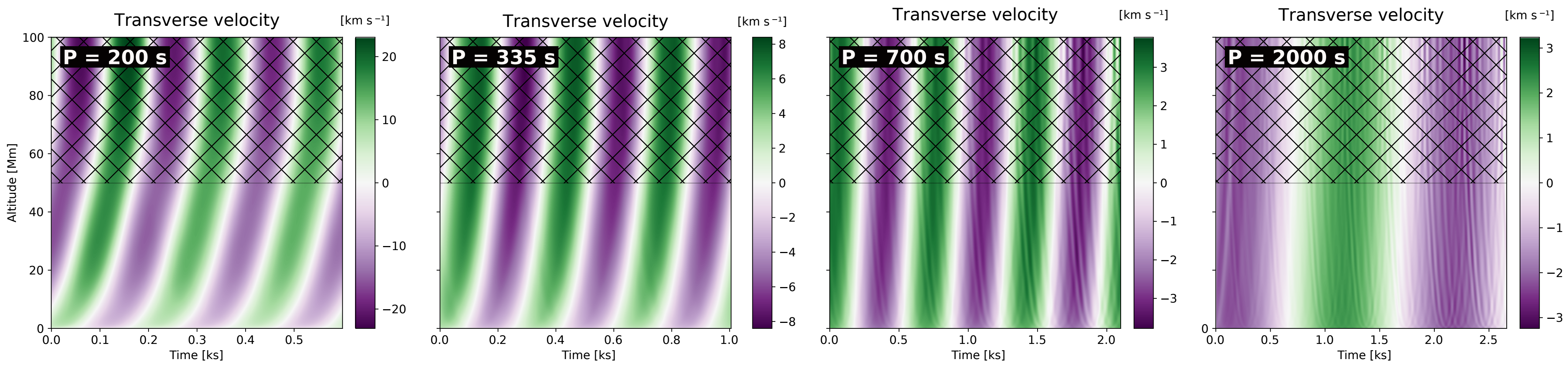
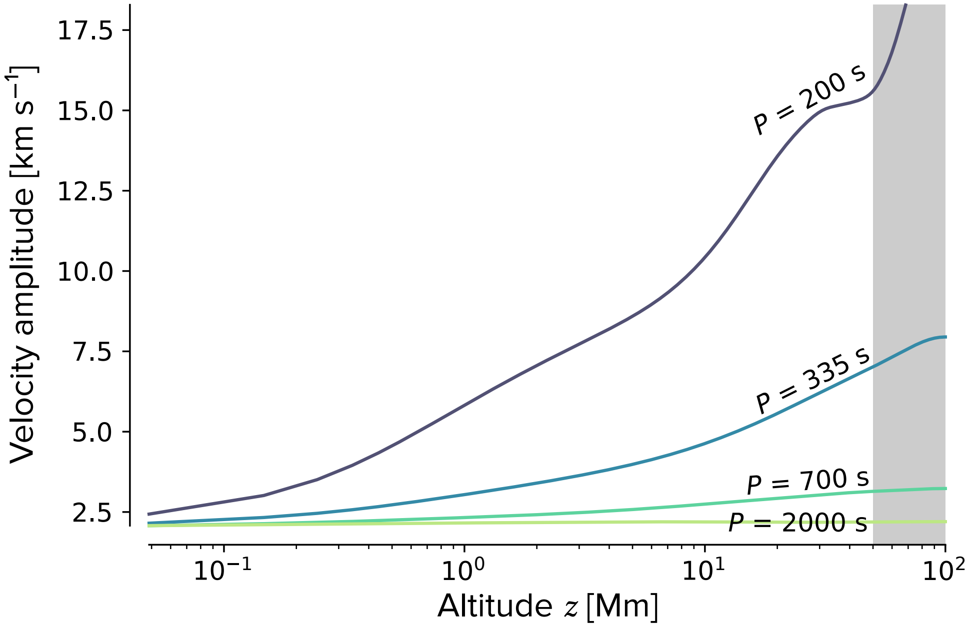
Results: amplitude decreases with frequency





- We drive a magnetic flux tube below the transition region, at different periods: 200 s, 335 s, 700 s, and 2000 s.
- We measure the amplitude of the transverse velocity as a function of altitude.

- ➜ Velocity amplitude decreases with wave frequency.
- ➜ **Higher frequencies propagate better through the transition region.**
- ➜ This is consistent with the low frequency cut-off predicted by theoretical studies.

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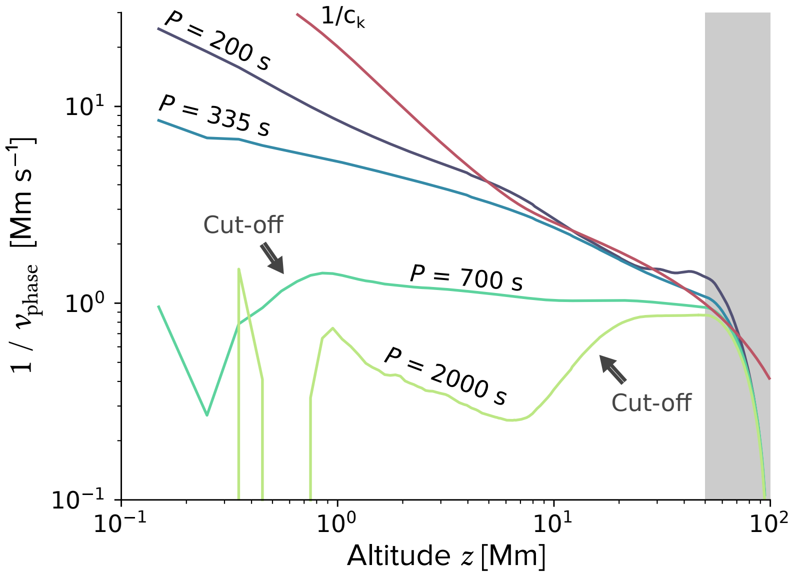
Discussion & conclusions



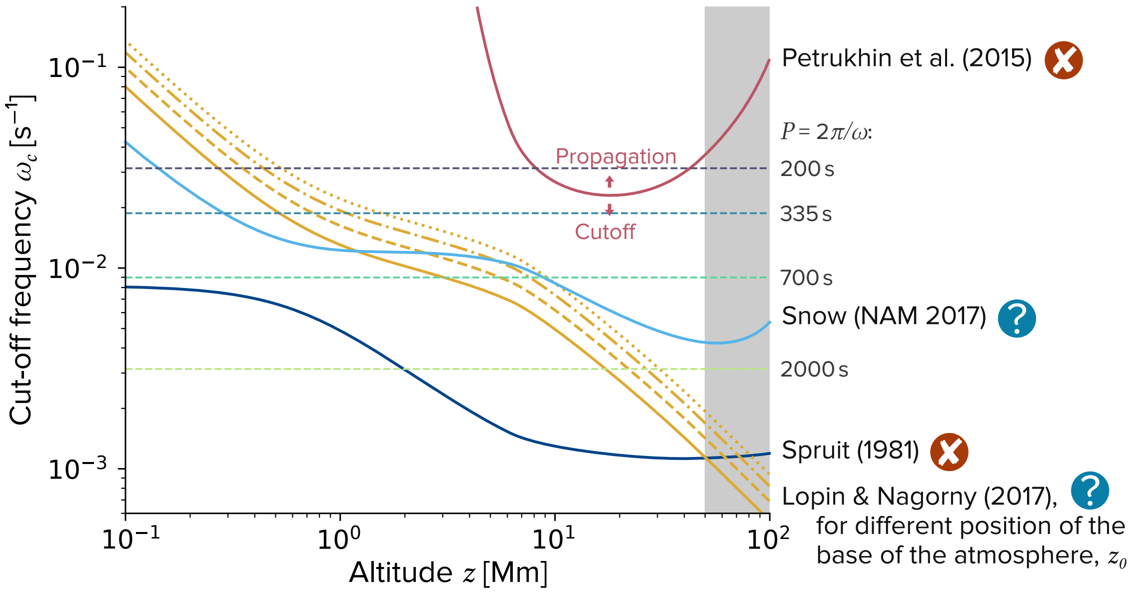
- We measure the **phase speed** as a function of altitude.
  To that end, we compute the maximum cross-correlation between the velocity at $z - \Delta z/2$ and at $z + \Delta z/2$ to obtain the time delay, and in turn the phase difference between these two altitudes.
- The inverse of the phase speed (like the phase difference) tells us whether a wave is propagating or not:

$$\frac{1}{v_p(z)} = \frac{\Delta\phi(z)}{\omega\,\Delta z}$$

→ ~ $1/c_k$ propagating wave ➔ **no damping**

→ << $1/c_k$ standing / evanescent wave ➔ **damping**

- High frequencies ($P = 200$ s and 335 s) are always propagating
- Low frequencies ($P = 700$ s and 2000 s) are evanescent below a given altitude z_t.
  ➔ tunnelling between $z = 0$ and $z = z_t$.



➔ **Transverse waves are cut-off** through the transition region.

➔ The cut-off frequency is best predicted by either Lopin & Nagorny (2017) or Snow (NAM 2017)