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Large-amplitude longitudinal oscillations in solar prominences derived from high-resolution simulations

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We aim to study the damping mechanism of the large-amplitude longitudinal oscillations (LALOs) in solar prominences hidden by numerical dissipation using the 2D magnetic configuration that contains the dipped region. After the prominence mass loading in the magnetic dips, we triggered LALOs perturbing the prominence mass along the magnetic field. Using the same numerical setup, we gradually increase spatial resolution. The convergence experiment revealed that the damping time saturates at the bottom prominence region with increasing resolution, indicating the existence of a physical reason for the damping of oscillations. At the prominence top, the oscillations are amplified during the first minutes and are then slowly attenuated. The characteristic time suggests more significant amplification in the experiments with the highest spatial resolution. The analysis revealed that the energy exchange between the bottom and top prominence regions is responsible for the attenuation and amplification of LALOs. High-resolution experiments are crucial when studying the periods and the damping mechanism of LALOs. The period agrees with the pendulum model only when using a sufficiently high spatial resolution. The results suggest that numerical diffusion in simulations with insufficient spatial resolution can hide important physical mechanisms, such as amplification of oscillations.

Context of the research

Damping of LAOs is equal to several oscillatory periods. In some observations, the amplitude is constant or growing.

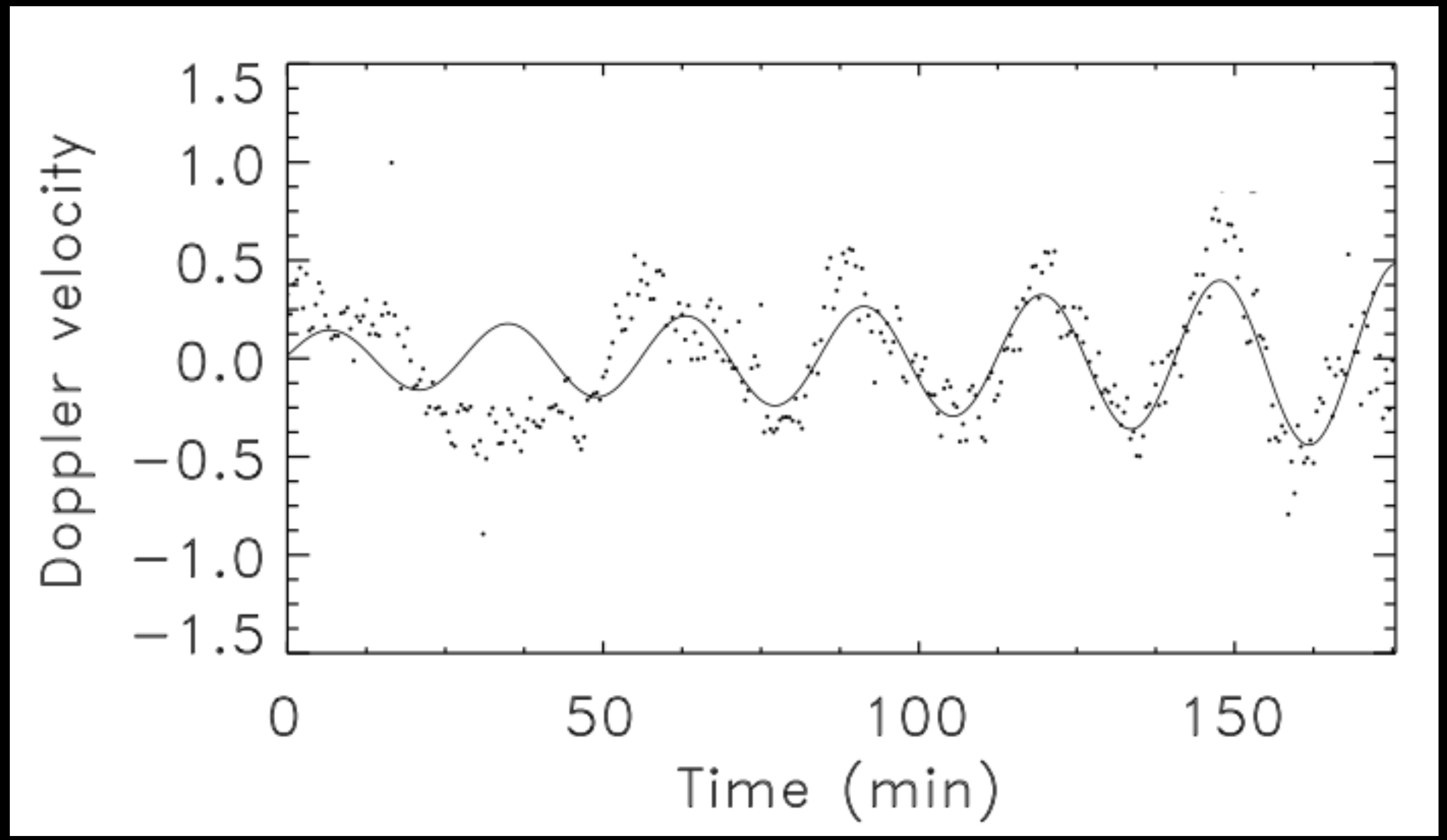
Damping mechanism:

- Non-adiabatic effects (Zhang et al. 2020a).
- Accretion or drainage of the mass (Zhang et al. 2013;Ruderman & Luna 2016).
- Resonant absorption (Adrover-González & Terradas 2020).
- Wave leakage (Zhang et al. 2019).

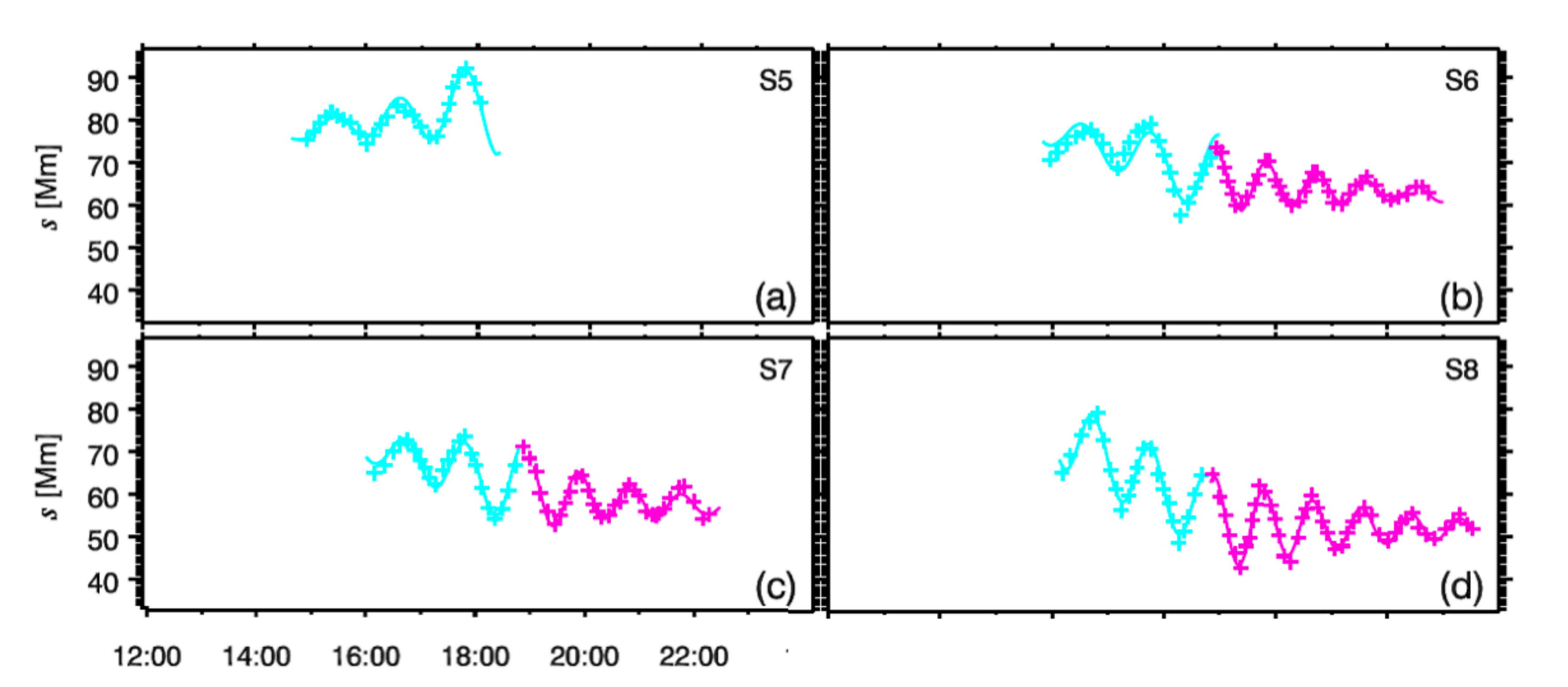
Amplification mechanism:

- Decrease of background temperature (Ballester et al. 2016).
- Energy exchange between threads (Zhang et al. 2017; Zhou et al. 2017).
- External perturbation (Zhang et al. 2020a).

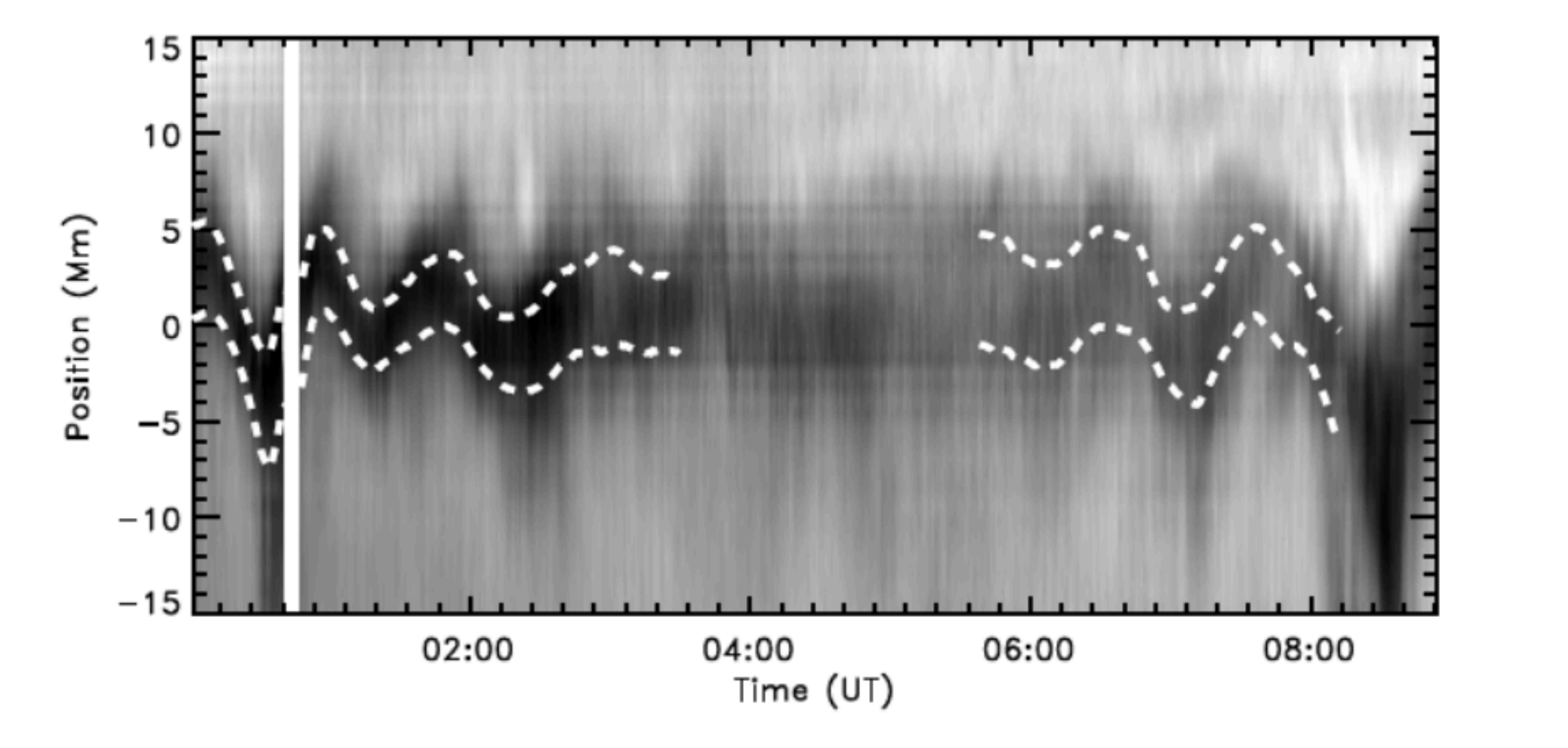
Molowny-Horas et al. 1999



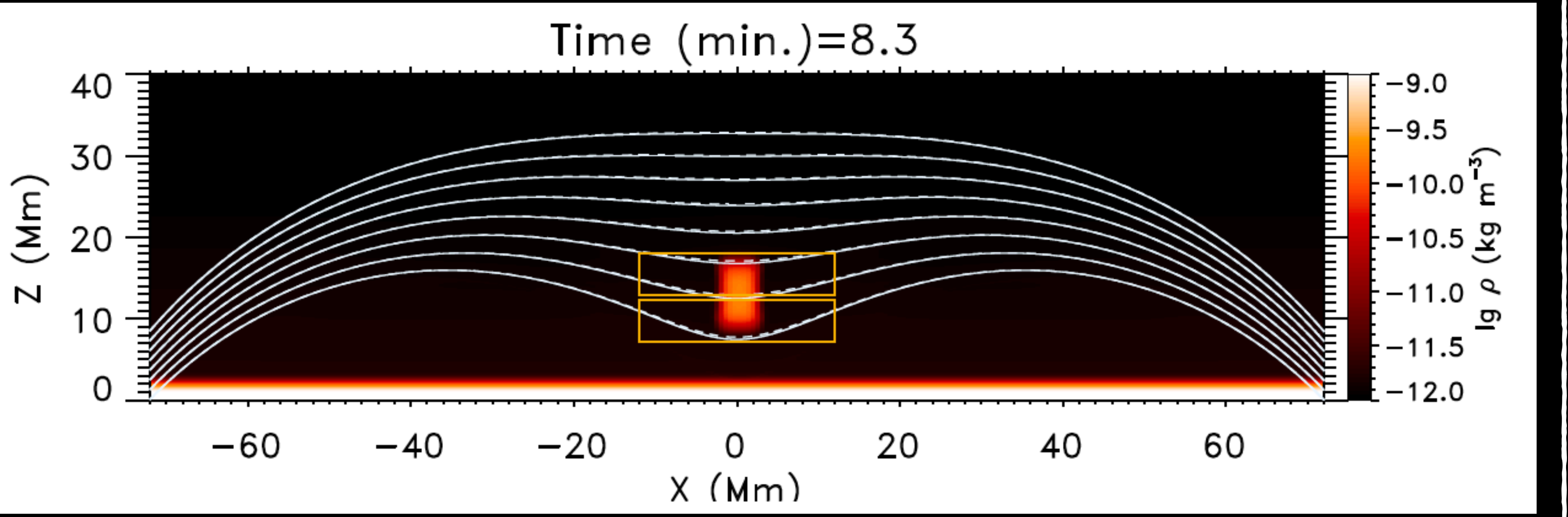
Zhang et al. 2017



Luna et al. 2018

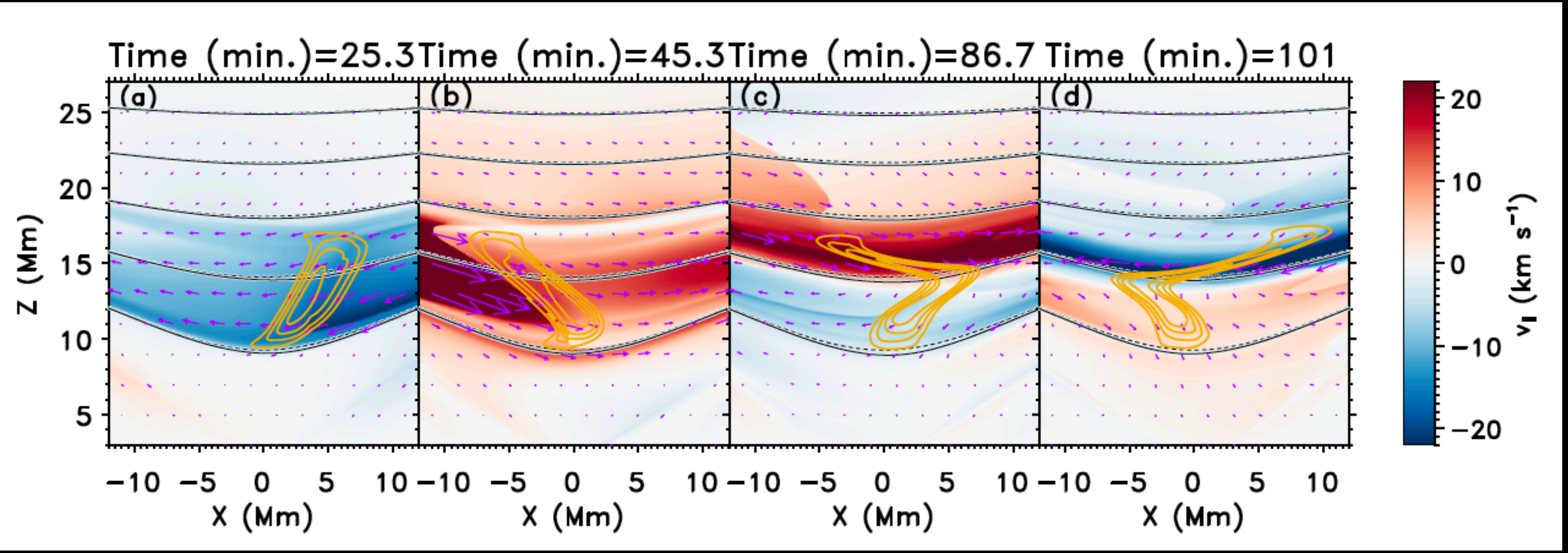


Numerical model



2D prominence model:

- Initial atmosphere: chromosphere, transition region, and corona.
- Periodic force-free magnetic field.
- Line-tying boundary condition at the base.
- Magnetic field strength: B=9-12 G.
- Cold prominence mass is loaded in the dips.
- Density contrast: χ=110.
- Prominence mass is perturbed along magnetic field.
- Velocity of perturbation: V=22 km s^{-1}.

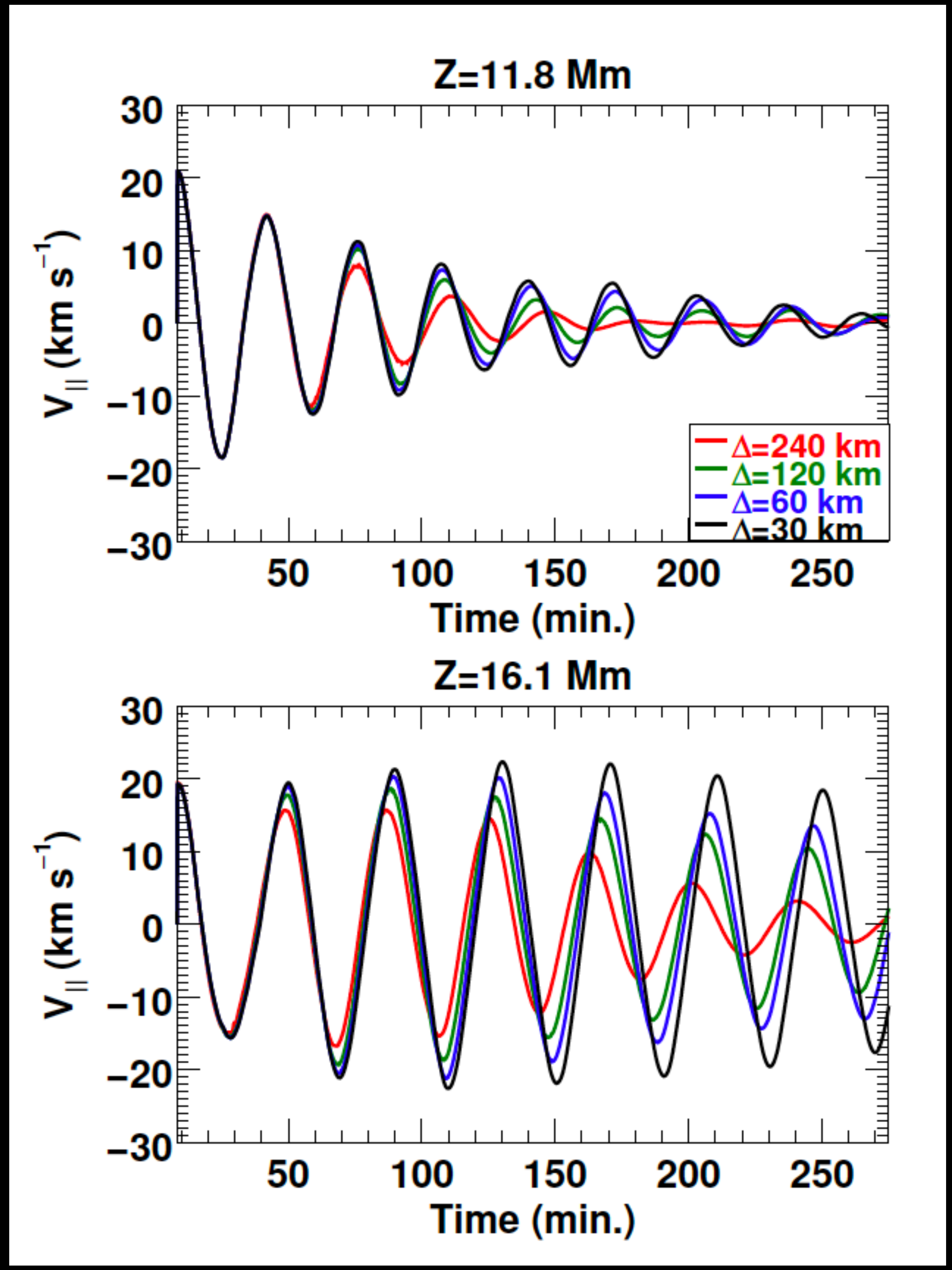


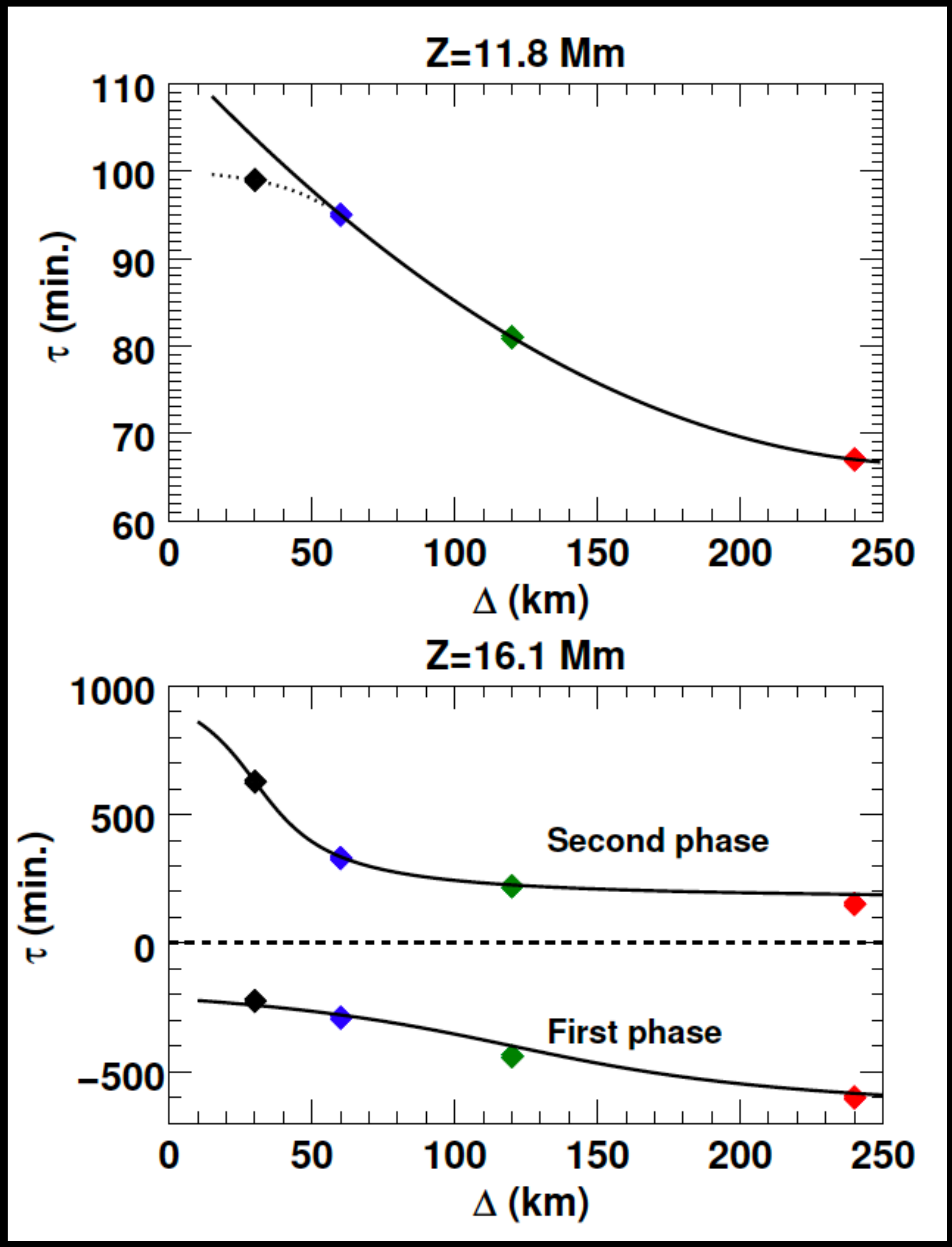
- Initial horizontal displacement: 9 Mm.
- The zigzag shape of motions.
- Oscillations at the bottom were strongly damped for 100 minutes.
- The displacement of the bottom part increases up to 11 Mm.

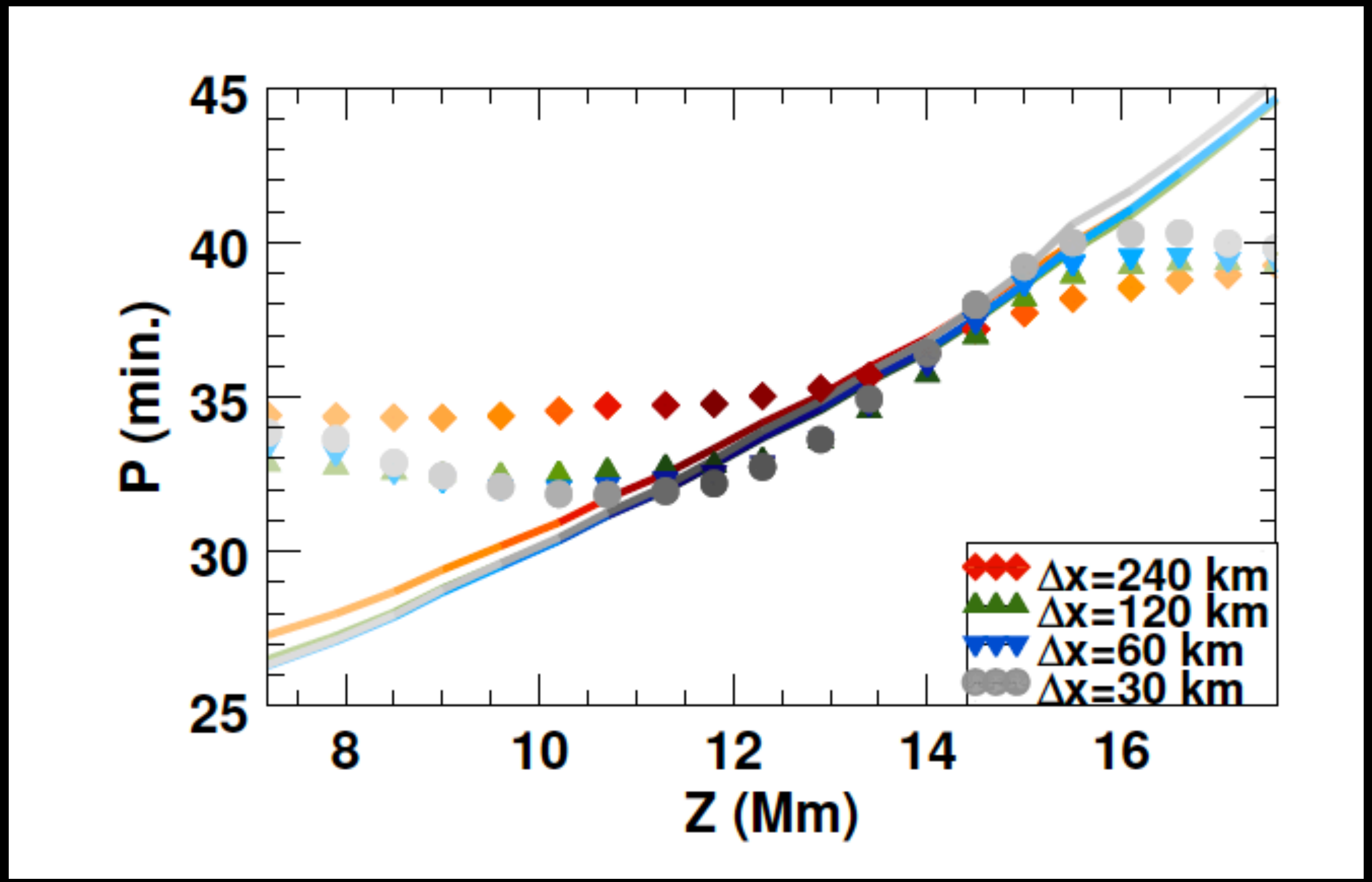
Properties of oscillations

- Velocity is fitted with the decayed sinusoid function.
- Damping time from the best fit: τ=[67,99] minutes.

- Two stages are distinguished: amplification and attenuation.
- Characteristic times: τ=[-600,-225] minutes (first phase), τ=[152,628] minutes (second phase).
- The amplification phase is more significant and extended in time in the high-resolution experiment.

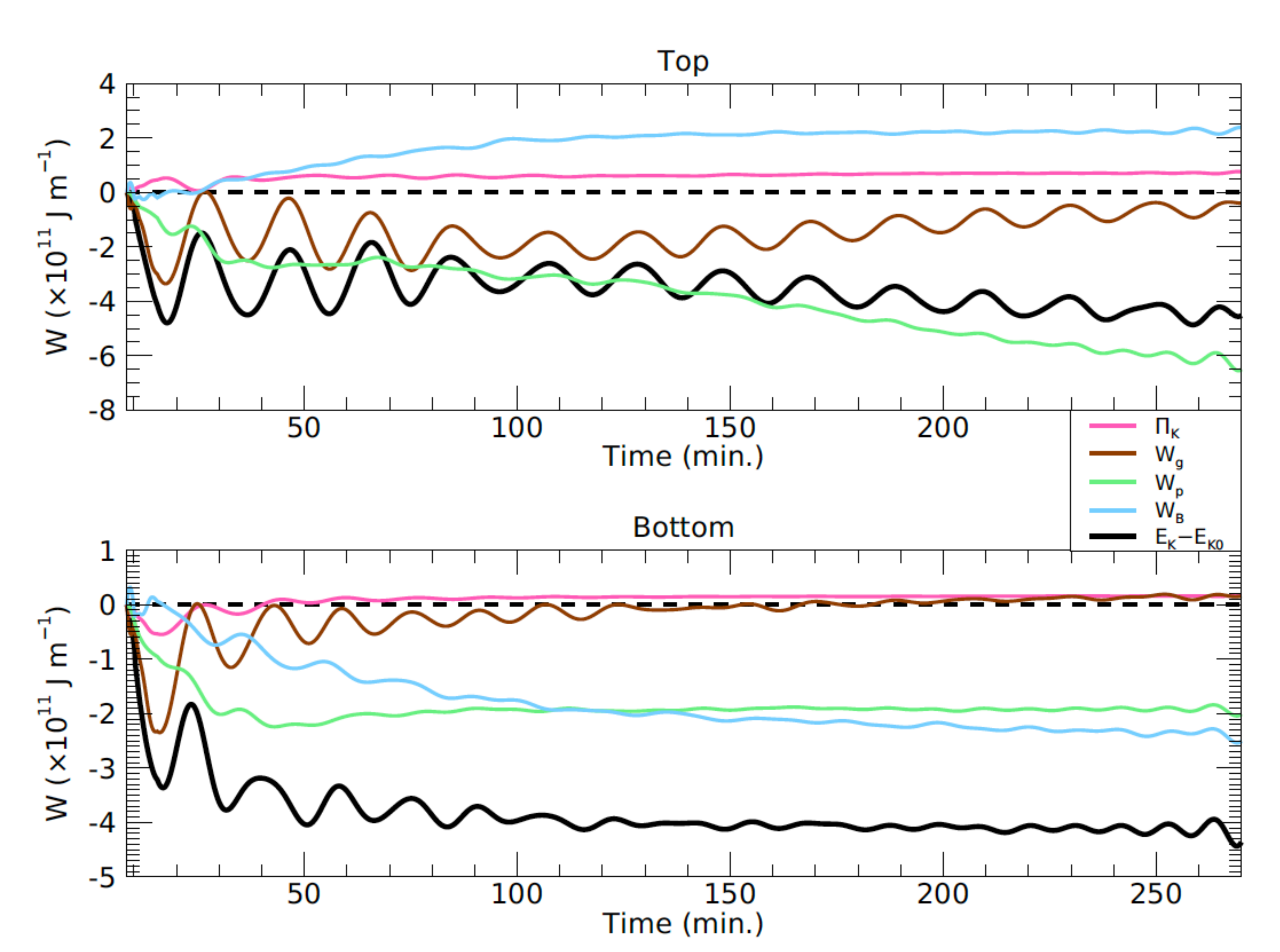


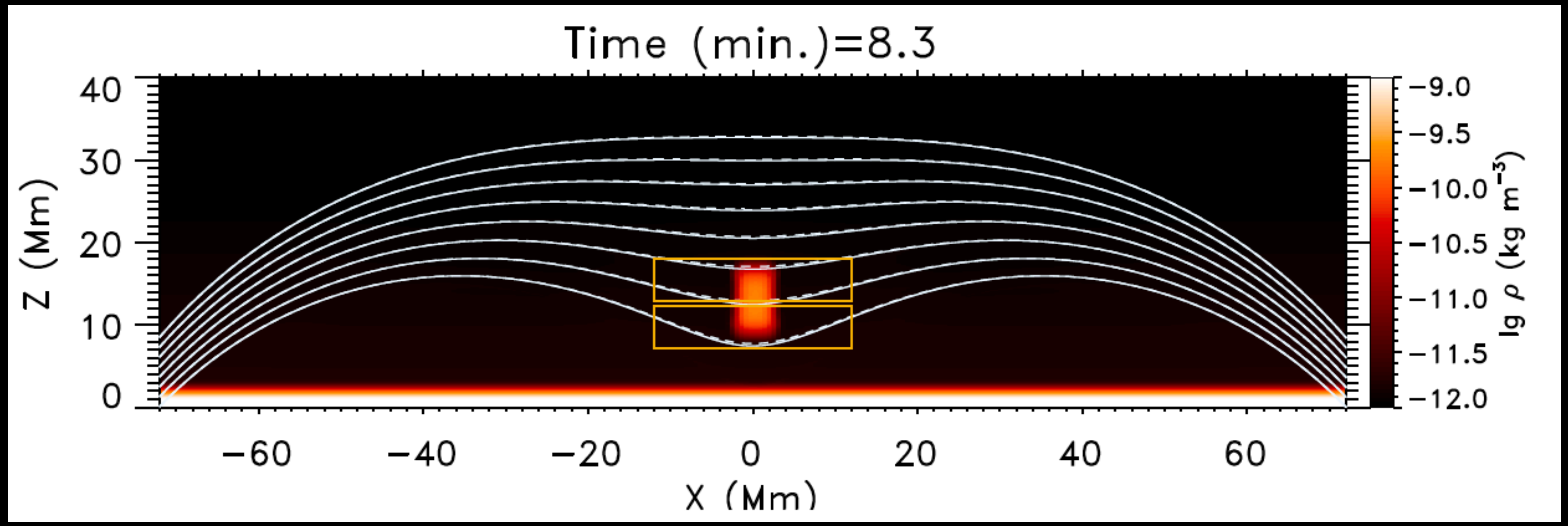


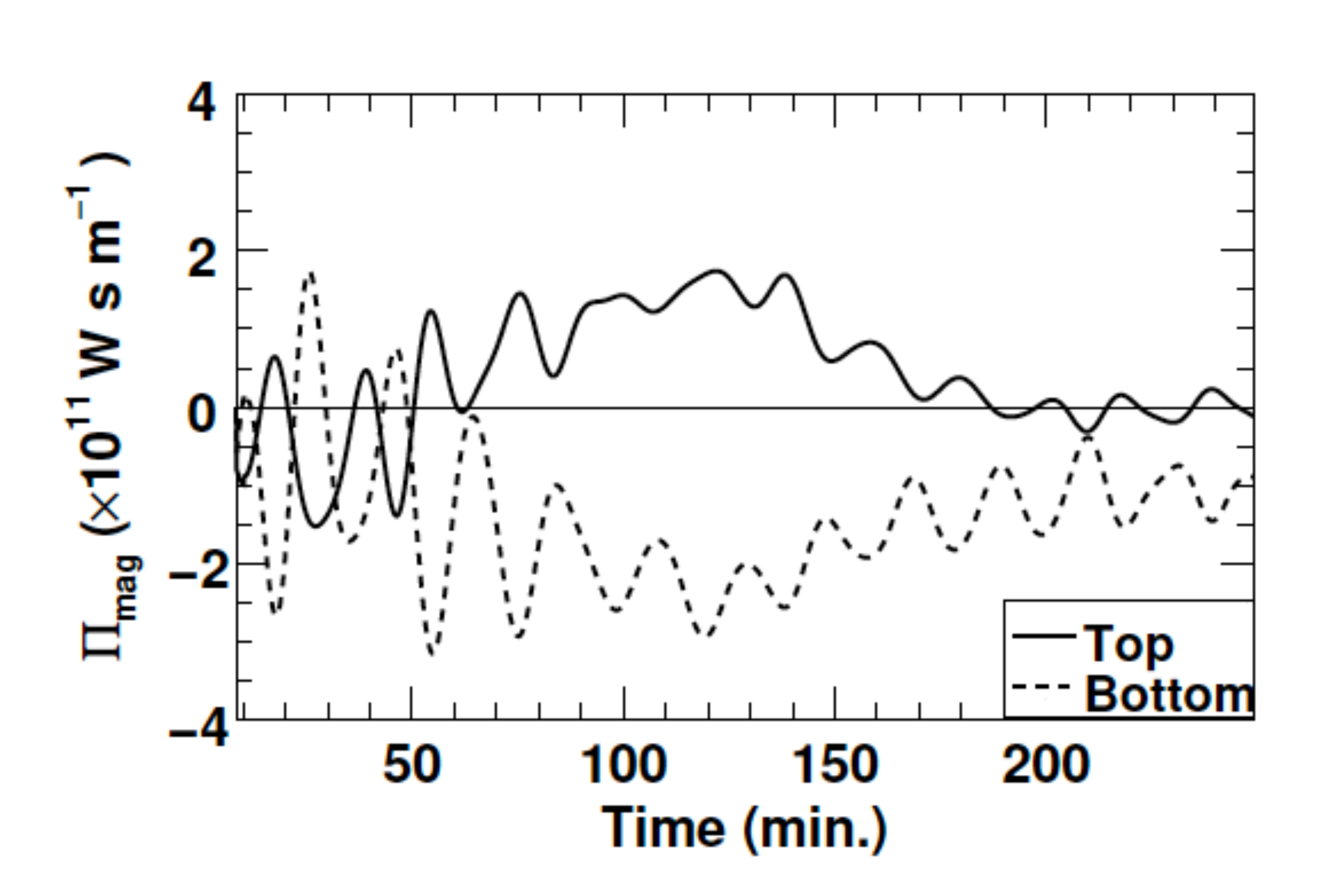


- Period shows good agreement with the pendulum model in the main region of the prominence when using high spatial resolution.

Physical reasons for damping and amplification



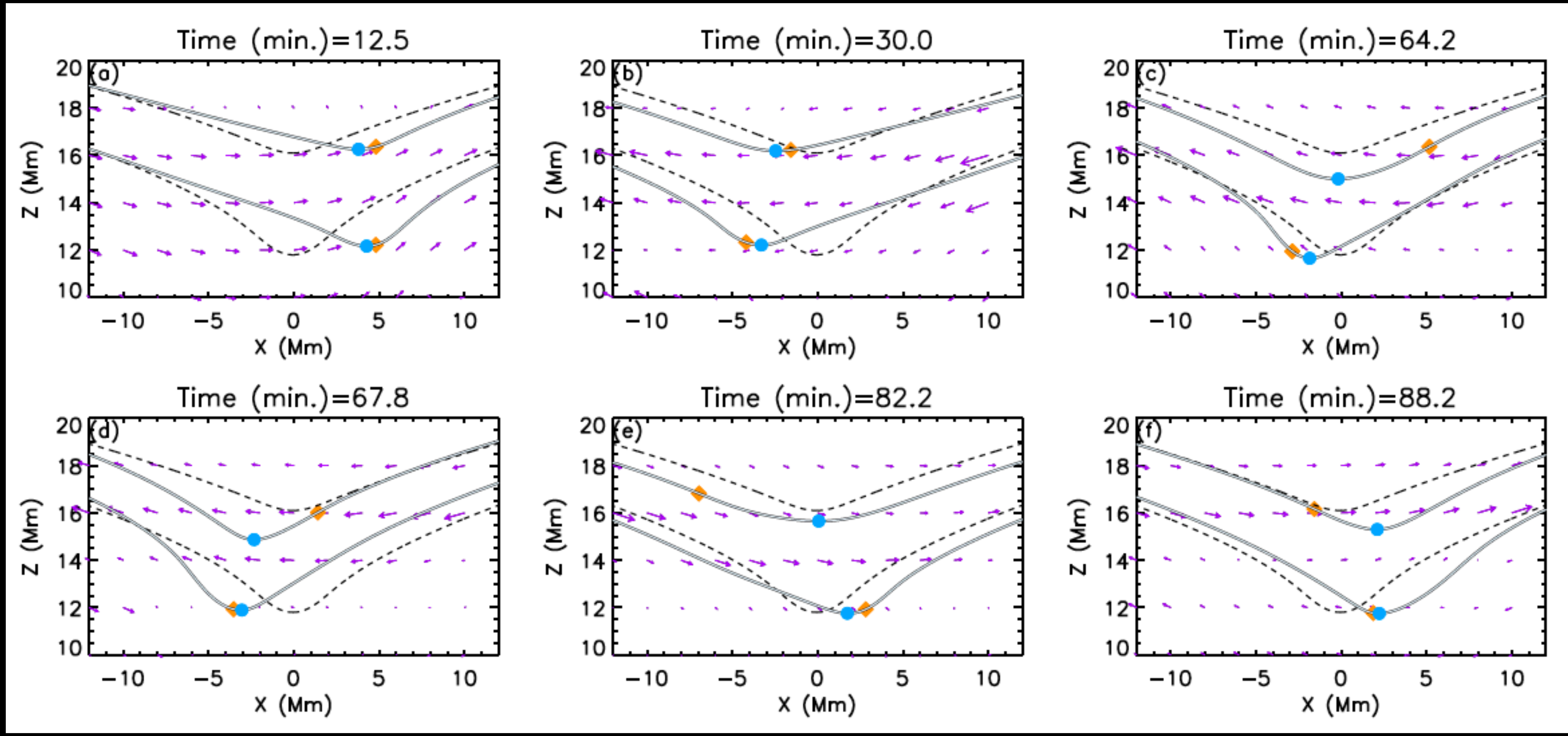


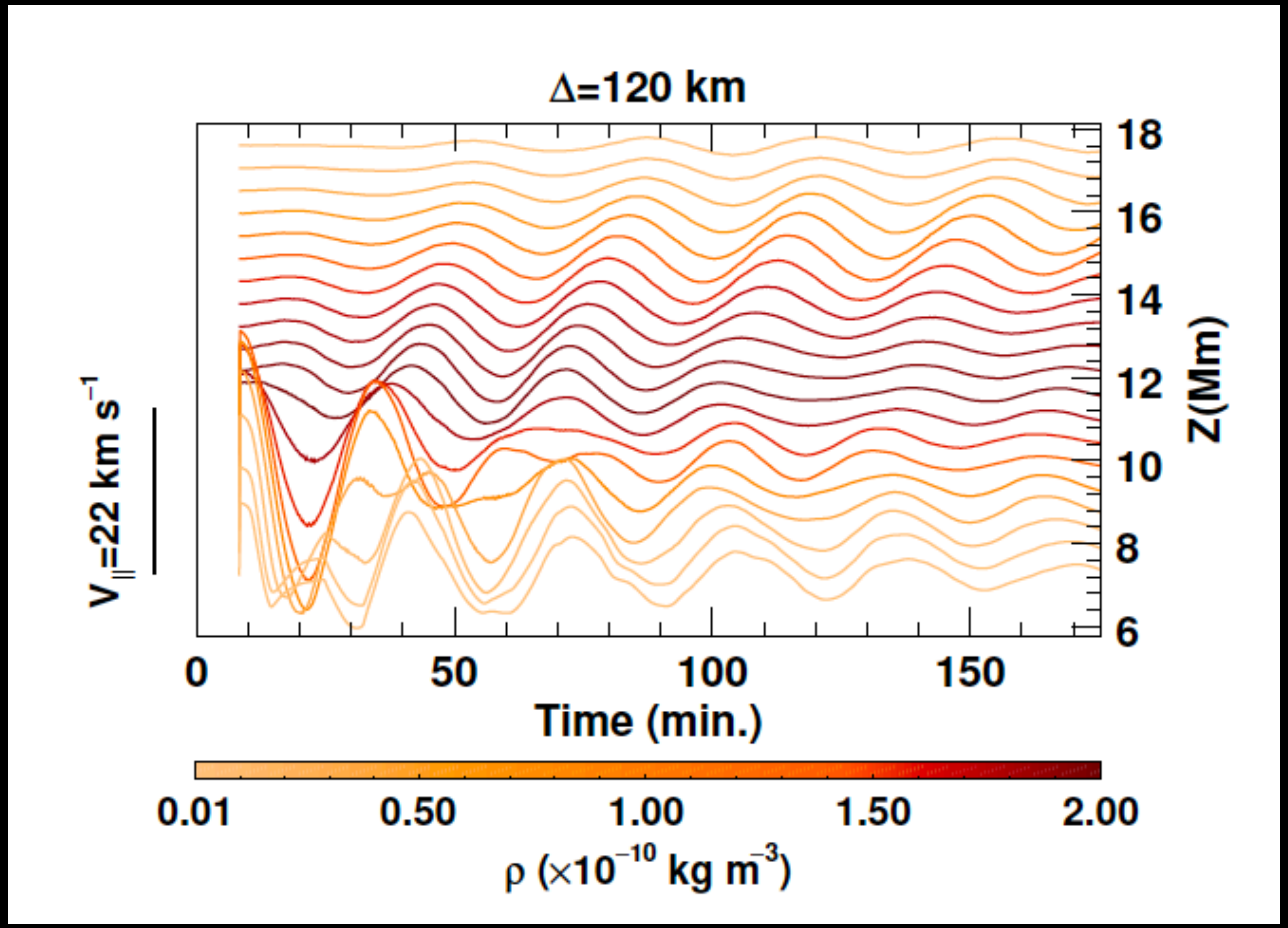


- Works and inflow of kinetic energy are integrated into two regions (orange rectangles).
- Works done by gas pressure force make the most significant contribution to kinetic energy losses in both regions.
- In the bottom region work of a magnetic force is negative, while at the top, its contribution is positive.

- Time integral of incoming Poynting flux through the boundaries of two areas.
- The inflow of magnetic energy during the first 100 minutes at the top and outflow during the same time interval at the bottom.

Physical reasons for damping and amplification





- Fluid elements (orange diamonds) and magnetic dips (blue circles).
- After initial displacement, at the upper line, the dip is located ahead of the particle. Particle reaches the dip in a position displaced from the original dip position and gains an increment in velocity during each half-period.
- The changes in the magnetic configuration at the bottom part of the structure affect the top part.
- At the bottom, the situation is opposite: the dip approaches the particle, and the oscillatory amplitude is reduced in each oscillation period.

Additional experiment with perturbation only at the bottom region showed:

- Significant attenuation in the bottom region.
- Excitation of oscillations at the top region where oscillations are not excited initially.

Summary and Conclusions

- The period shows good agreement with the pendulum model in our simulations with the highest resolution, namely of 30 km.

- The bottom part of the prominence is characterized by strong attenuation of oscillations, even in the highest resolution experiments. The experiments with the finest resolution, 60 and 30 km, demonstrated that further improvement of the spatial resolution does not significantly affect the damping time.

- The oscillations at the prominence top are amplified during the first 130 minutes and then slowly attenuated. The amplification appears to be more efficient and extended in time in the high-resolution experiments.

- At the bottom, the Lorentz force contributes to the kinetic energy losses and acts to decelerate plasma; in contrast, it amplifies oscillations at the top of the prominence.

- The analysis of the Poynting flux revealed that a significant portion of the energy leaving the bottom part is transferred to the top.

- The results suggest that the energy losses in the bottom region are caused by both wave leakage and energy and momentum transfer to the upper prominence region.