



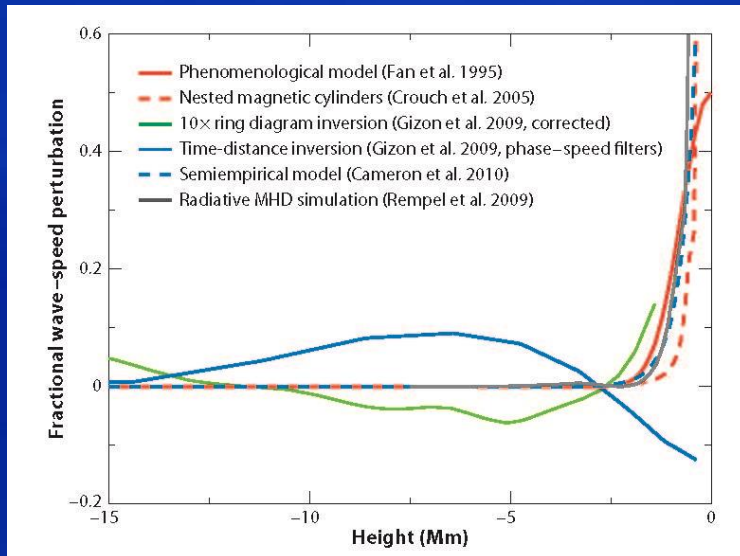
# Advancing the Understanding of Subsurface Structure and Dynamics of Solar Active Regions: An opportunity with ngGONG

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# What is wrong with sunspot/active region Seismology

- Active regions/sunspots have a key role in the coupling between the solar interior and the atmosphere
- The understanding the sunspot formation, structure, stability, decay are one of the outstanding problems
- The wave-speed beneath the sunspots inferred from different helioseismic techniques and models were inconsistent (Gizon et al., 2009,2010)



- ❖ In the top 2 Mm, models and RD agree with an increased wave speed
- ❖ A big discrepancy between TD and RD
- ❖ The models favor a positive wave speed perturbation while TD and RD favor a two-layer model

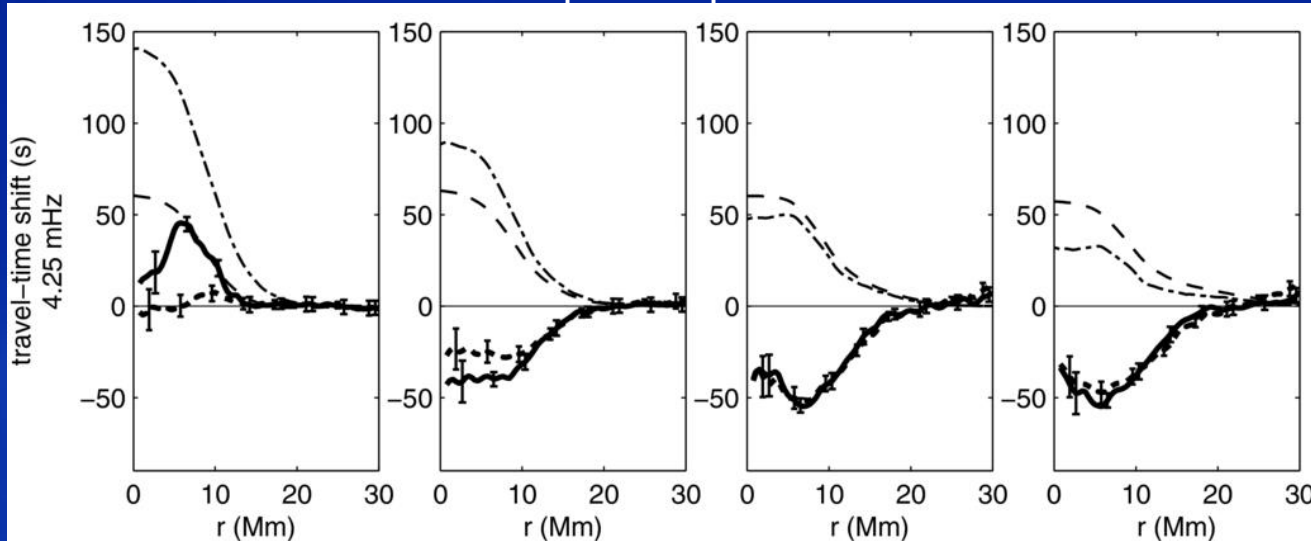
# What is wrong with sunspot/active region Seismology

Several simulations/forward models further demonstrate that

1. Inversions do not reproduce travel-time shifts from simulations (Braun et al. 2012)
2. The thermal sunspot provide a better characterization of the sunspot travel time measurements while those from magnetic-only sunspot simulation are completely different (Felipe et al. 2016/2018).

# Travel time shifts measured from simulations and forward model

Different phase speed filters



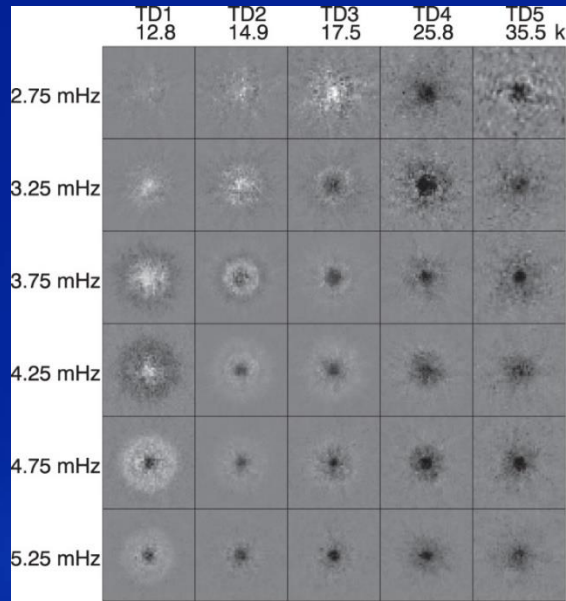
Solid line: Travel time shifts measured from magneto-convective sunspot simulations (Rempel et al. 2009)

Dashed and dash-dot: shifts measured using Born and ray approximation

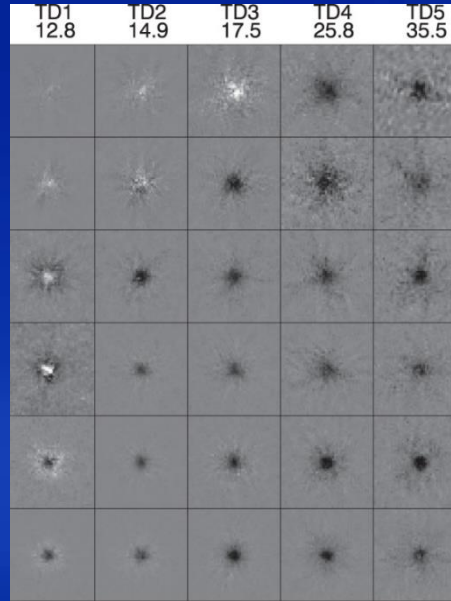
Major disagreement between the simulated and forward model  
=> A challenge to understand the influence of the magnetic field on travel-time measurements (Braun et al. 2012)

# Mean Travel time shifts as a function of frequency and phase speed filters using Helioseismic Holography from simulated sunspot model

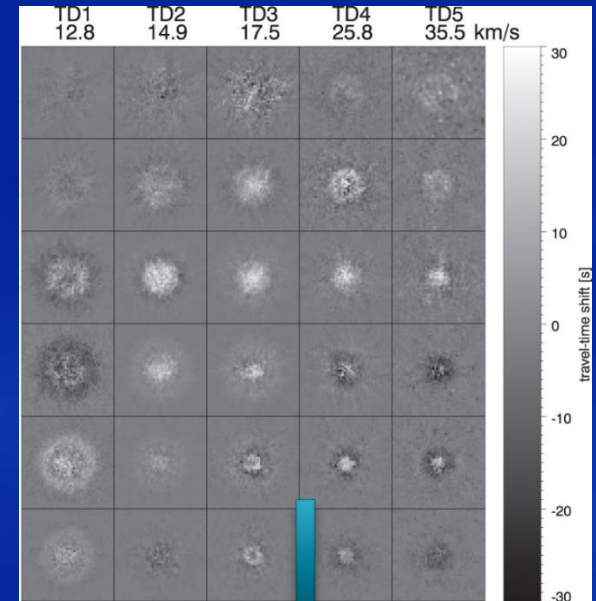
## Full simulation



## Thermal simulation



## Magnetic simulation



Thermal sunspot: mostly negative shifts  
Expected positive shifts since the wave travel slowly in the thermal sunspot  
=> Height of the upper turning point shifts to lower height and the wave path is shorter and time needed is shorter.

Observed mostly positive shifts while it was expected to have negative shifts since the fast mode propagates faster in magnetic region

**The thermal sunspot (and not the magnetic sunspot) provide accurate characterization of the full sunspot travel-time measurements (Felipe et al. 2016/2018).**

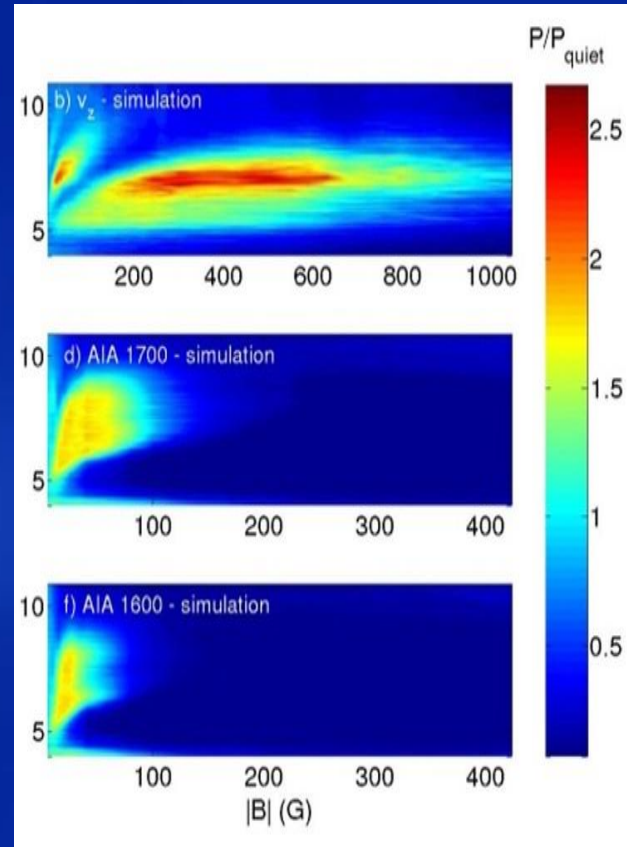
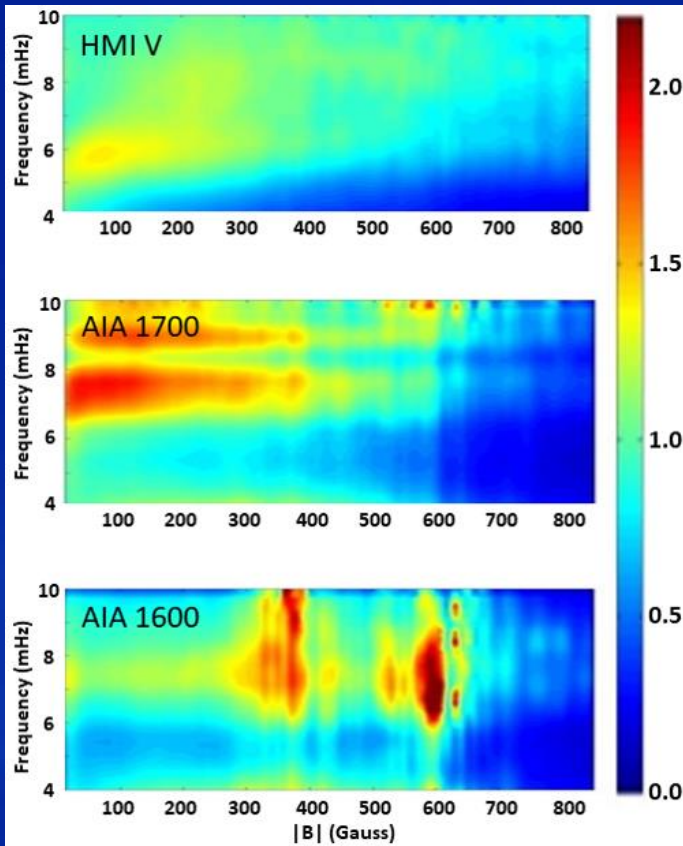
**Mode conversion may change the phase of the wave and travel time measurements is sensitive to changes in the phase of the wave.**

# Sunspot/active region Seismology

- Theory suggests that waves leak into higher atmosphere through active regions and mode conversion occurs near  $\beta=1$  layer where acoustic modes convert to fast and slow modes. Some of these modes reflect back to the interior and contaminate the phase of the acoustic waves.
- Simulations demonstrate that the magnitude of the travel-time shift strongly depends on frequency and strength, inclination and azimuth angles of magnetic field; Wilson effect can not account for the travel time shifts (Moradi et al. 2015)
- Acoustic halos seen in numerical simulation shows the signature of mode conversion.



# Acoustic Halos: Observation (AR 11092) vs Simulations

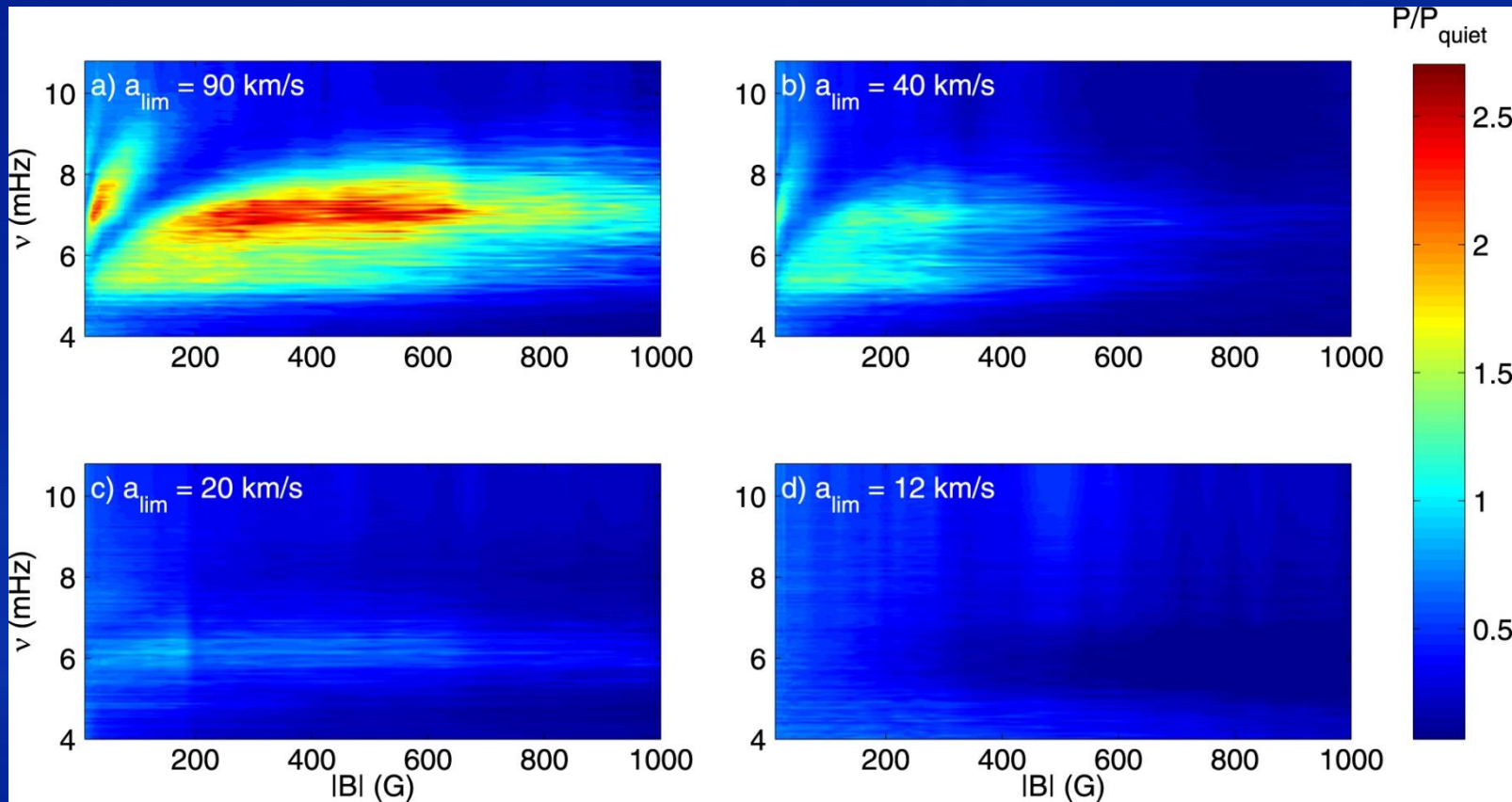


Rijs et al. ApJ, 2016

Tripathy et al. Adv. Space. Res. 2018

- Attack angle is maximum for velocity and hence stronger halo in V
- Mode conversion at  $a = c$  height, fast waves reflect back and inject energies at the observable heights.
- At higher observing heights, the spreading of the magnetic canopy results in halos at much weaker field. ( $B$  is assumed to be photospheric)

# Signature of mode conversion (Effect of reducing the Alfvén limiter)



Rijs et al. ApJ, 2016

As the Alfvén limiter is decreased, the height of the 'cap' is reduced => refraction and reflection of the fast wave is restricted in height-space and the halo gradually disappears.



# The Path Forward

- The key to understand the structure of sunspots/ARs below the surface depends on understanding the interaction of the magnetic field with the waves at different heights of the atmosphere (not an established science but a component of basic research)
- Simultaneous measurements of acoustic waves and vector magnetic fields from the photosphere to the chromosphere up to  $\beta = 1$  layer.
- This could be an additional research topic for the proposed ngGONG.

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