Evershed Meeting at IIA

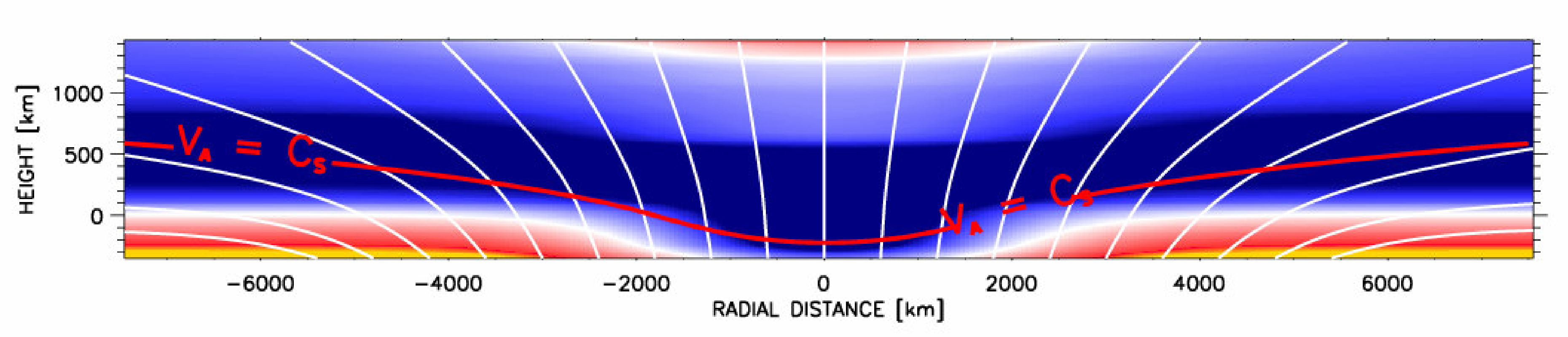
Bangalore, December 2-5, 2008

Observations and interpretation of waves in sunspots

Elena Khomenko [1,2]

[1] *Instituto de Astrofisica de Canarias, Tenerife, Spain;*

[2] *Main Astronomical Observatory, Kiev, Ukraine.*



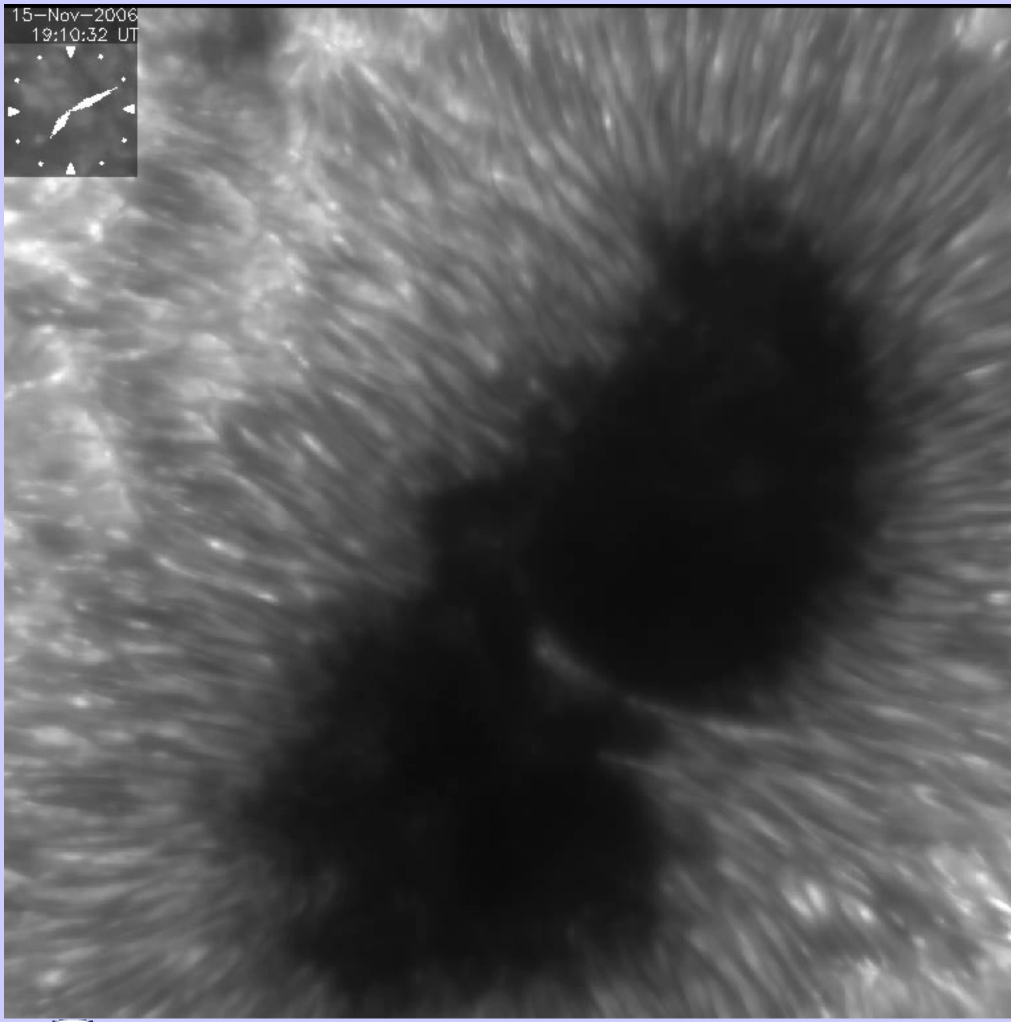
Outline

Interpretation of oscillations in terms of MHD waves

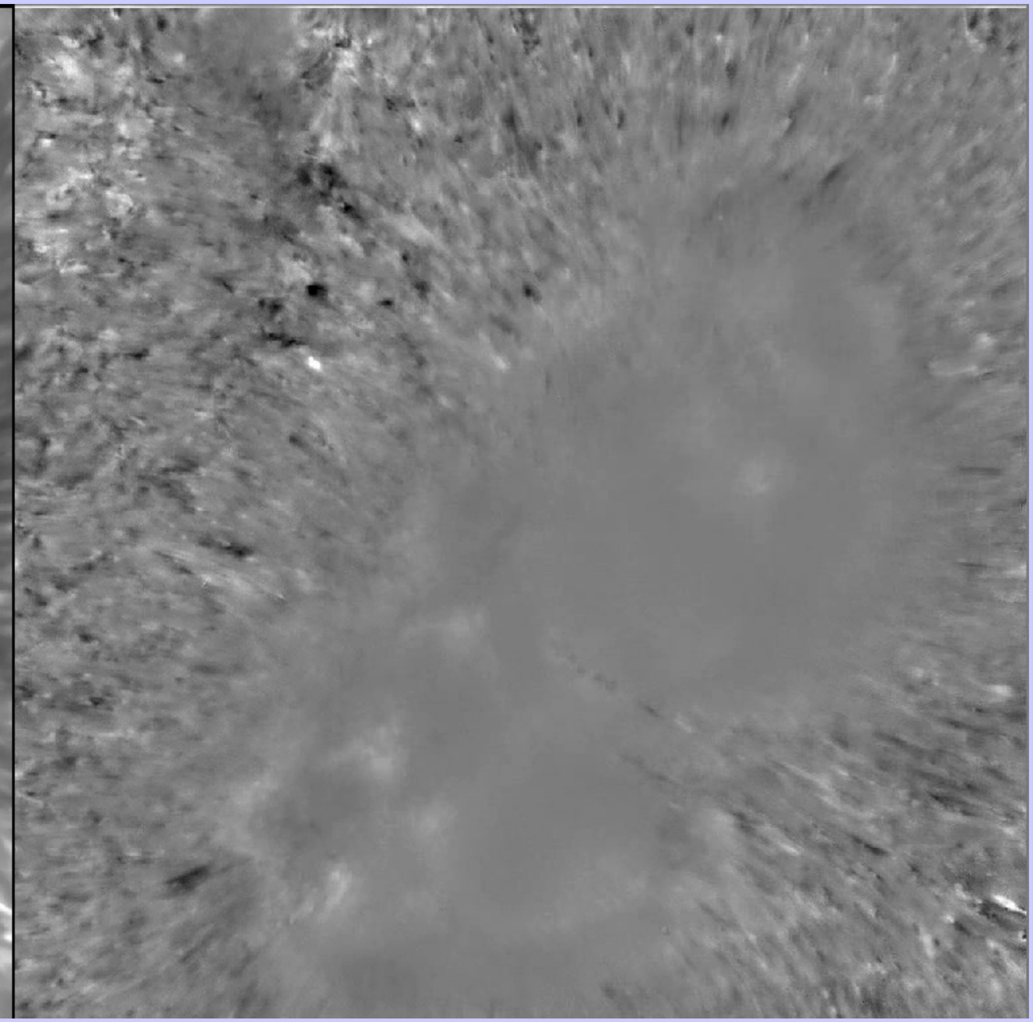
- *Frequency distribution*
- *Mode transformation*
- *Local helioseismology in active regions*

HINODE observation of chromospheric sunspot dynamics

Ca II H intensity



Doppler velocity



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Sunspot dynamics from hi-res observations

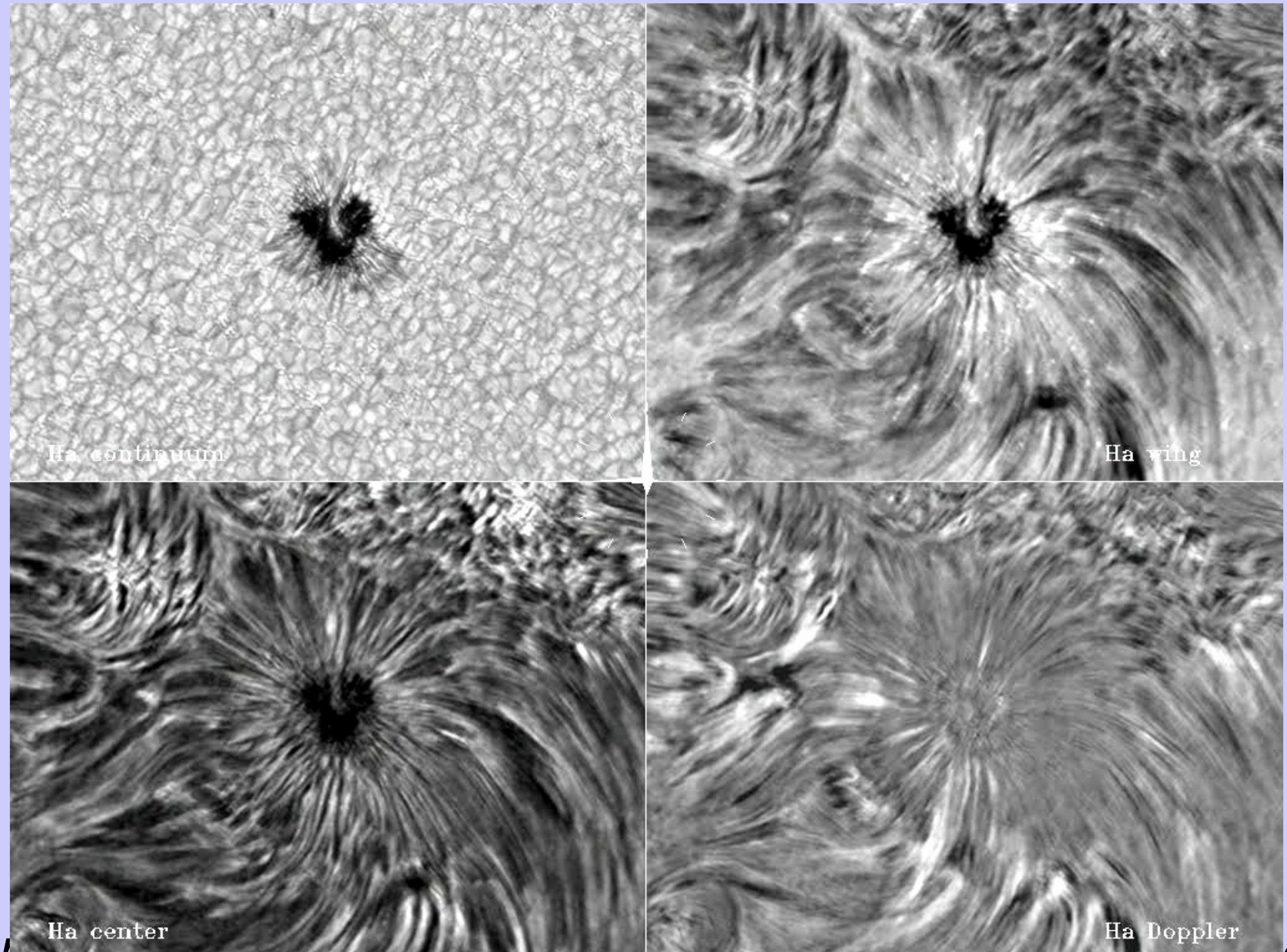
Spatial pattern of waves in sunspots, in contrast to the quiet sun, were it is random.

Continuum,

deep photosphere

Hα wing,

middle photosphere



Hα core,

chromosphere

Hα Doppler,

chromosphere

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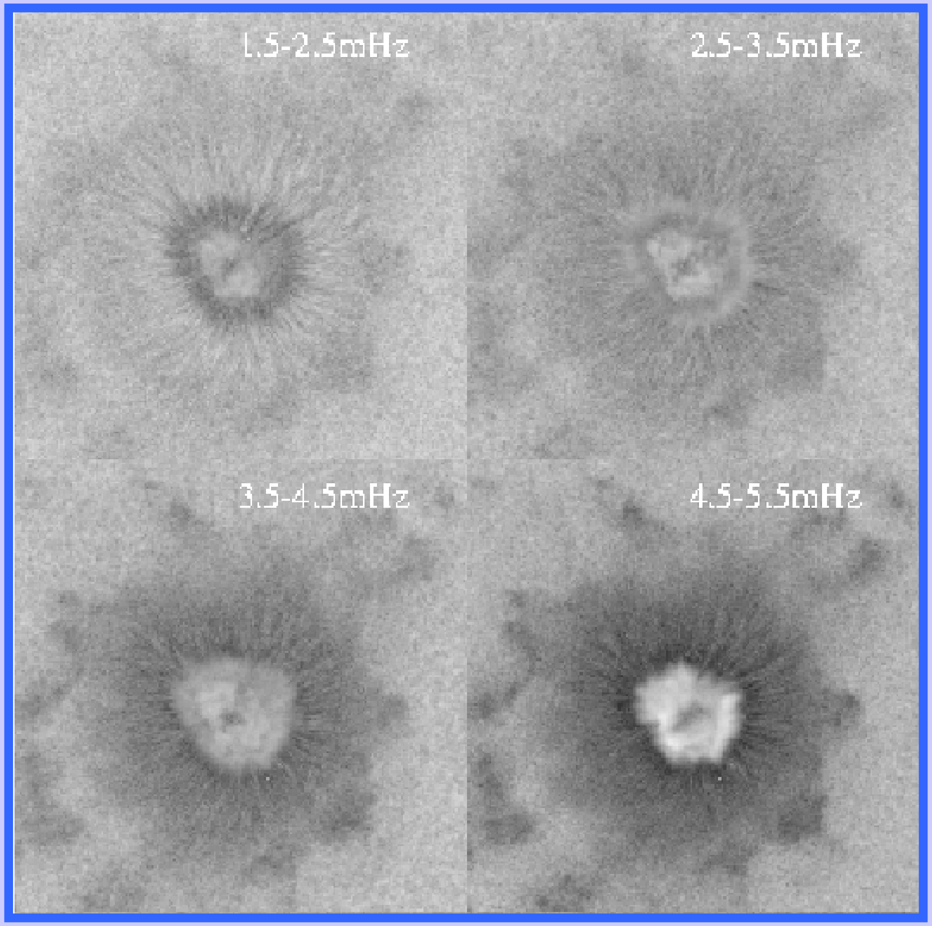
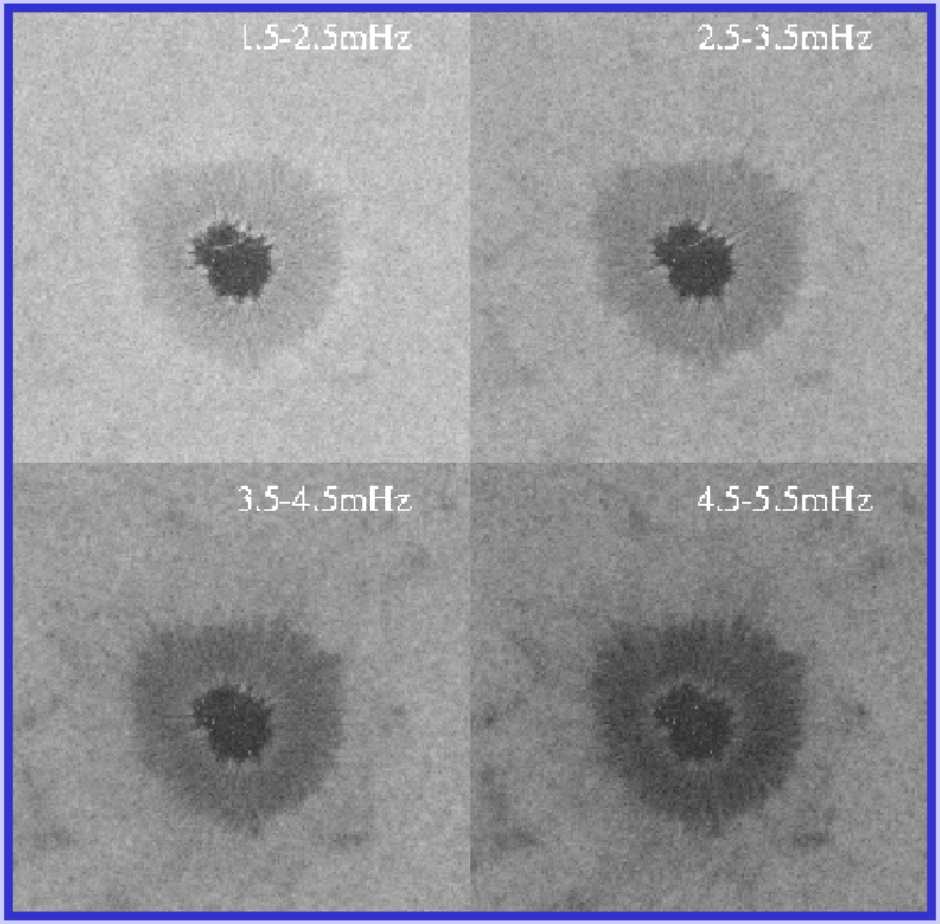
Power maps at different frequencies

Chromosphere (Ca II H)



Photosphere (G band)



Nagashima et al. (2007)

Sunspots and pores

Photosphere:

- **5 min** oscillations in the umbra
- **5 min** oscillations in the penumbra. However, the relative power of the **3 min** oscillations increases in the penumbra
- Linear oscillations

•Magnetic field oscillations of a few G

Chromosphere:

- **3 min** oscillations in the umbra
- **5 min** oscillations in the penumbra (RP waves). Possibly, PR waves and umbral flashes are the same phenomenon.
- Shocks of 5-15 km/s amplitude depending on structure size

References:
Beckers and Schultz 1972
Lites et al. 1984, 1986, 1988
Maltby et al. 1999, 2001
Christopoulou et al. 1999, 2000, 2001
Bellot Rubio et al. 2000
Socas-Navarro et al. 2000
Brynildsen et al. 2000, 2002
Jain and Haber 2002
De Moortel et al. 2002
Khomenko et al. 2003
Rouppe van der Voort et al. 2003
Centeno el at. 2006
Bloomfield et al. 2007
Tziotziou et al. 2006, 2007

Questions:

- *Are these waves externally driven or excited in-situ?*
- *Relationships between photospheric and chromospheric oscillations? Types of waves?*
- *Frequency shift with height and spatial frequency distribution?*
- *Power distribution over AR? Acoustic halo?*
- *Role of the mode transformation?*
- *Source of helioseismological velocity signals in active regions?*

Questions:

- *Relationships between photospheric and chromospheric oscillations? Types of waves?*
- *Frequency shift with height and spatial frequency distribution?*

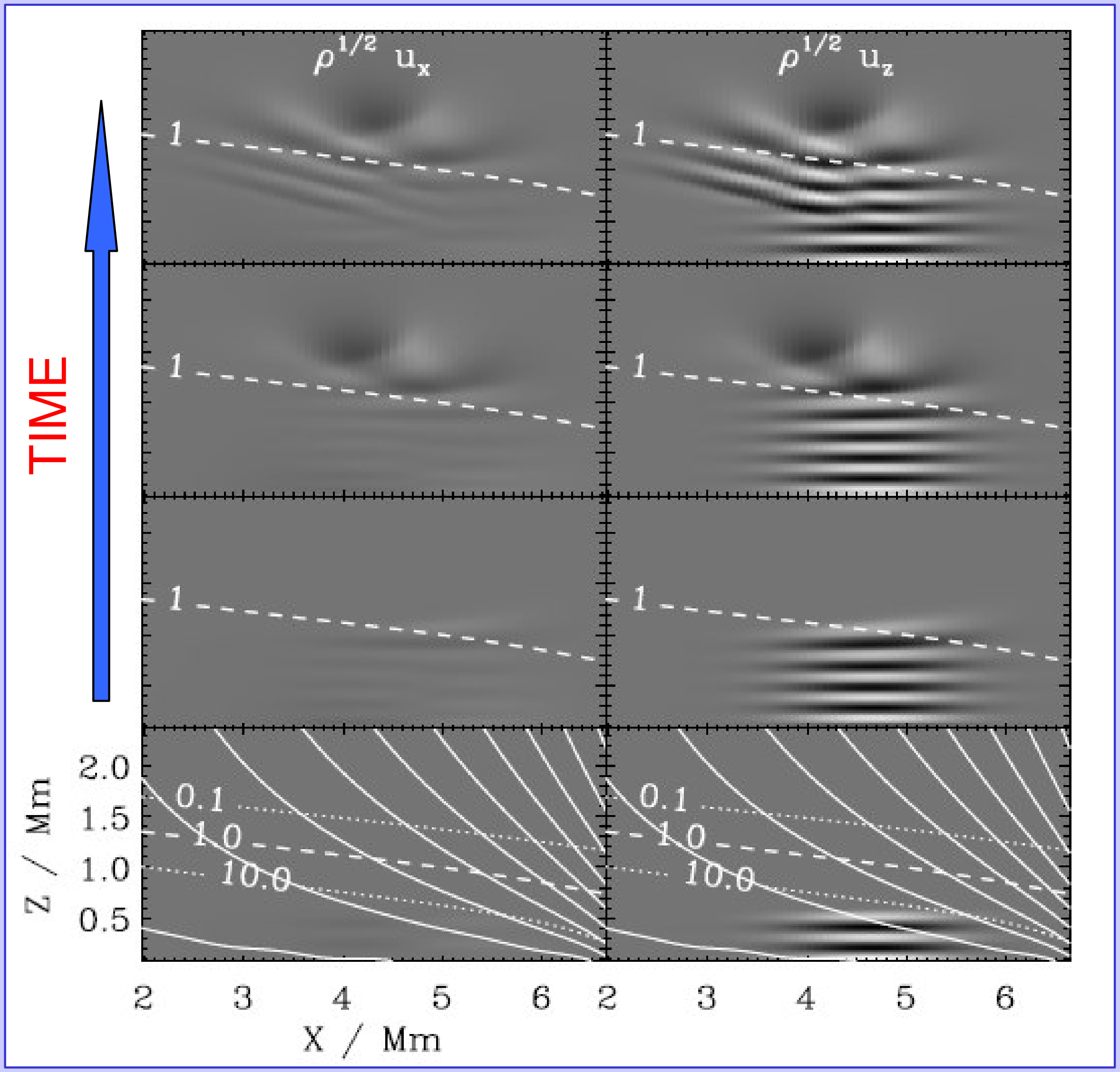
Numerical wave propagation in non-trivial magnetic field configurations

Bogdan et al. (2003),

Rosenthal et al. (2002)

- 2D
- Isothermal stratified atmosphere
- Potential field
- Internetwork magnetic flux tubes
- Short-period waves

  - *Mode conversion*
  - *Wave refraction at β =1*
  - *Importance of mode mixing*



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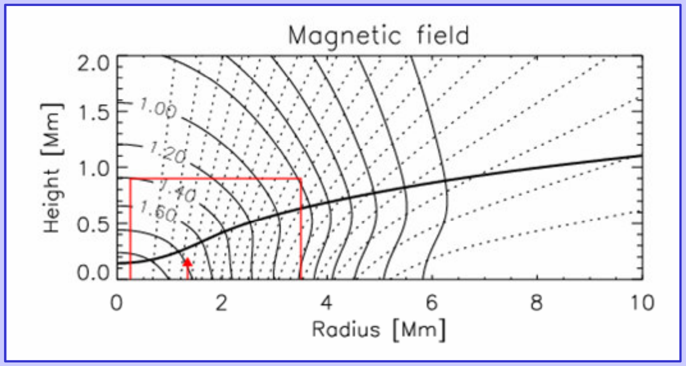
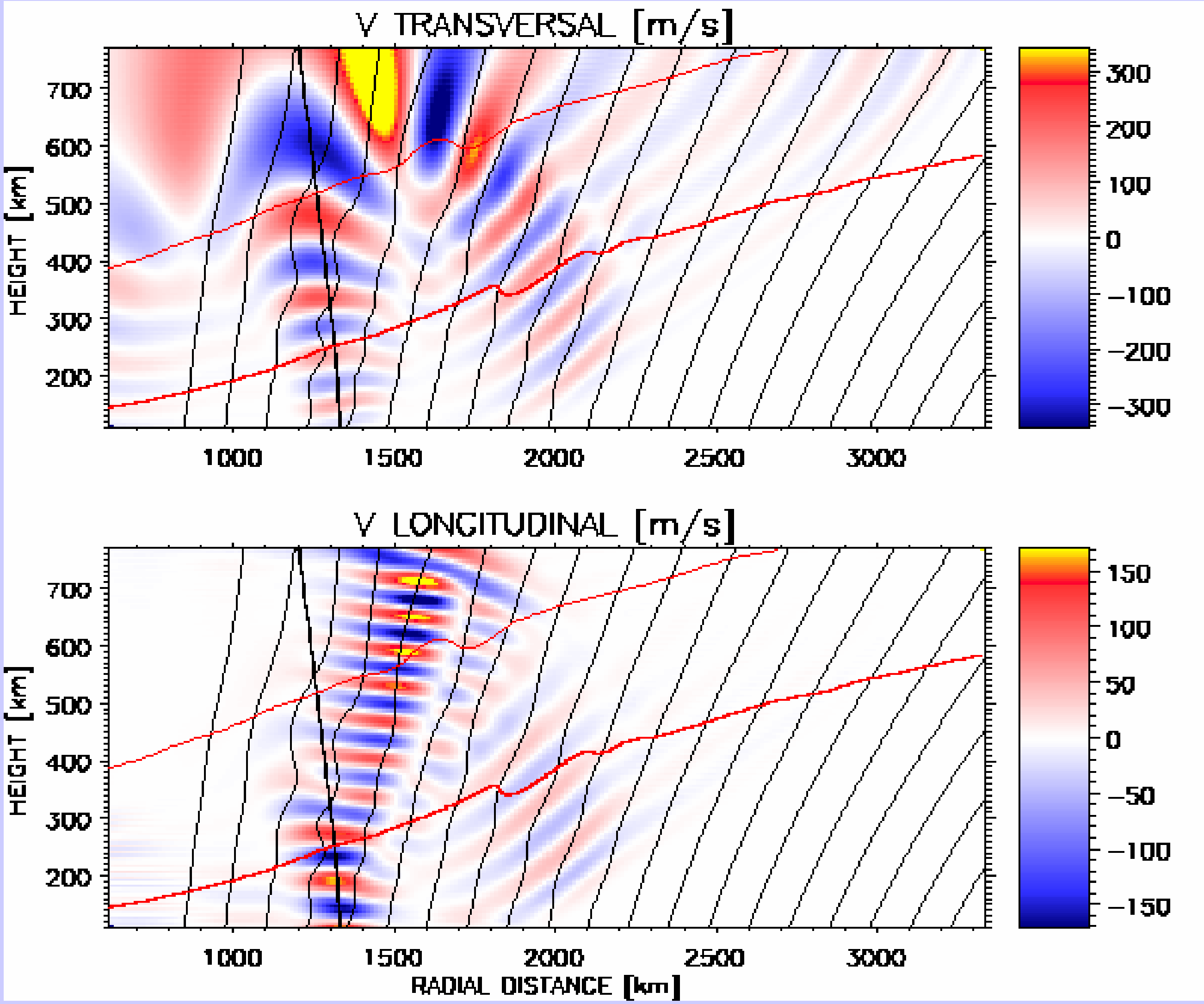
Numerical wave propagation in non-trivial magnetic field configurations

Khomenko & Collados (2006)



- 2D
- Temperature stratification
- Current-distributed MHS
- Small sunspot
- Short-period waves
  - *Mode conversion*
  - *Wave refraction above β =1*
  - *Slow mode longitudinal propagation*



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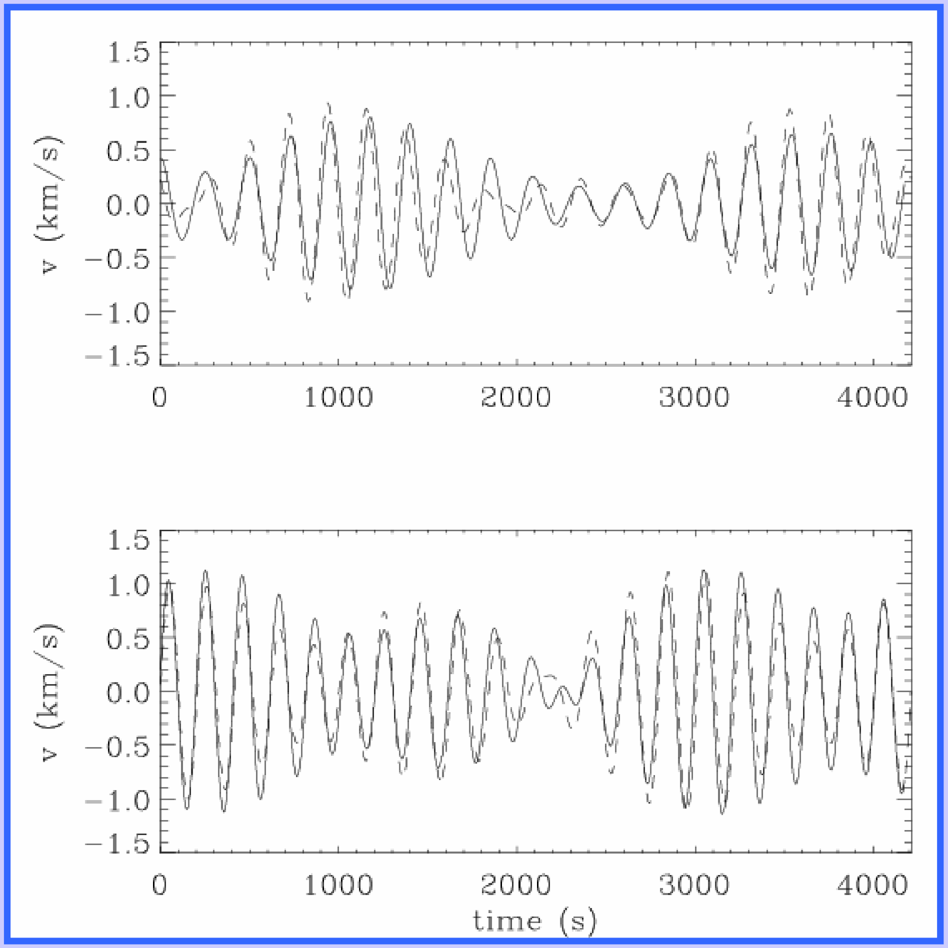
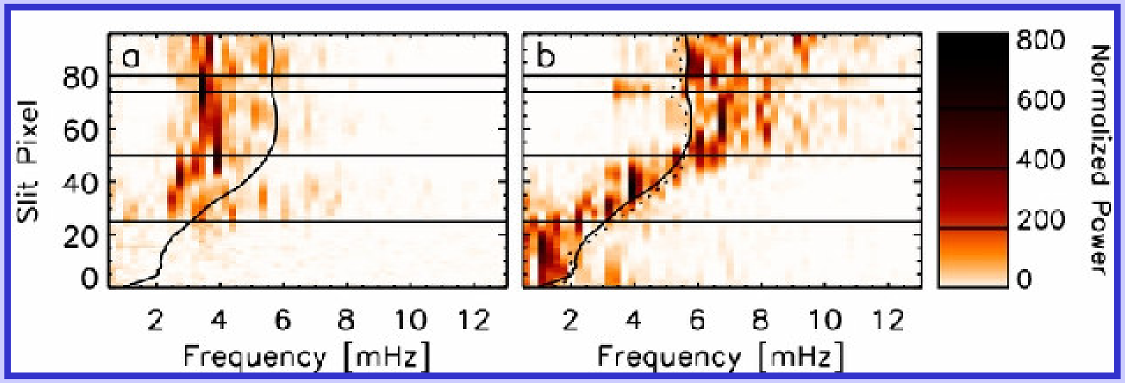
Wave propagation from photosphere to chromosphere

Bloomfield et a. (2007)

Centeno et al (2006)





Observations are compatible with longitudinal low-β slow mode propagation along inclined penumbral magnetic field lines.

Penumbral waves are apparent effect of this propagation.

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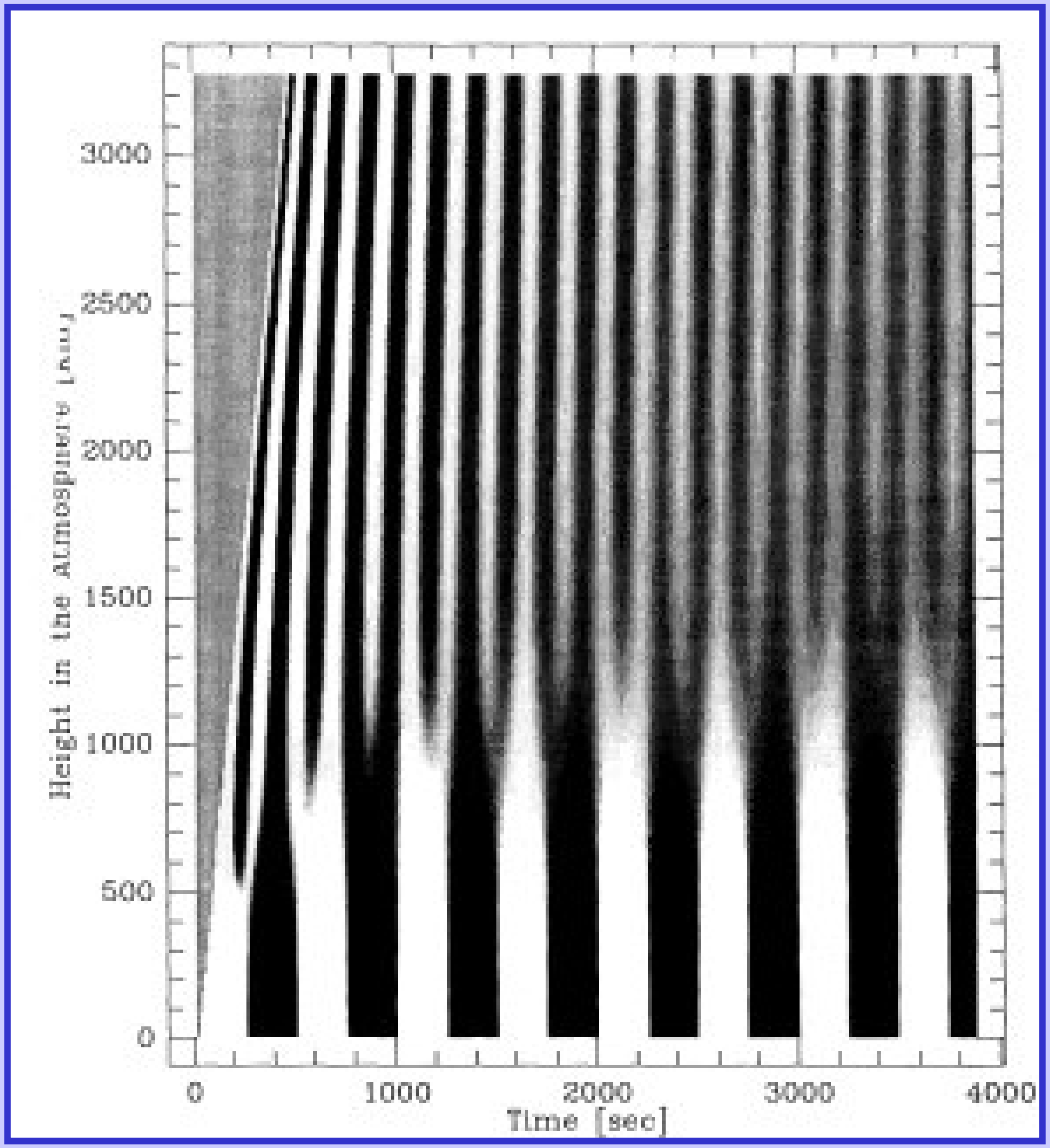
Frequency shift with height from 3 to 5 mHz

Fleck & Schmitz (1991)

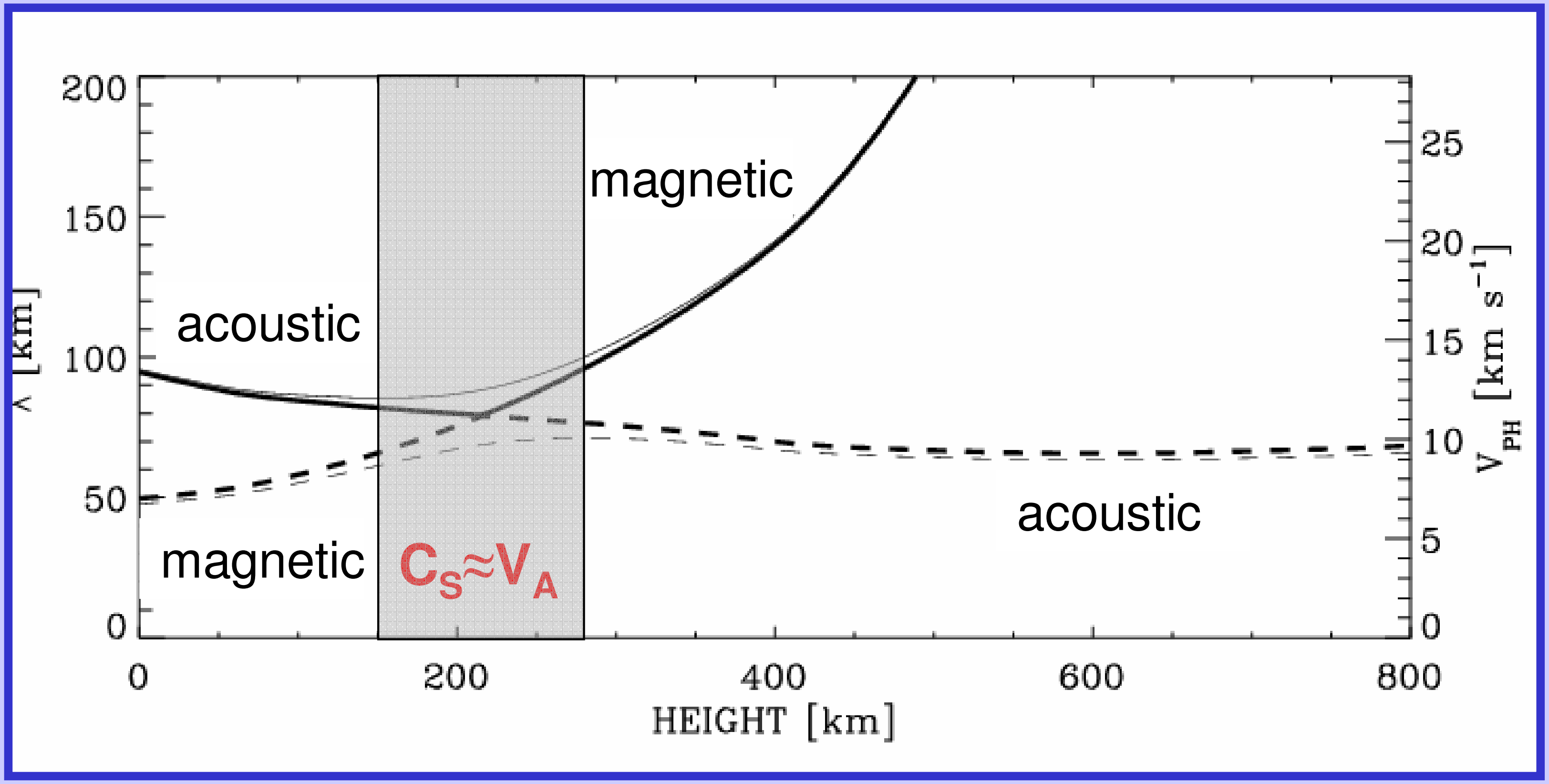
Basic physical effect due to a resonant excitation at the atmospheric cut-off frequency.



Questions:

- *Power distribution over AR? Acoustic halo?*
- *Role of the mode transformation?*

Mode conversion



In the $C_S \approx V_A$ region the phase speeds of the modes become close and the energy can be partially transferred between the different branches of the dispersion relation

FAST-to-SLOW mode transformation coefficient

Cally 2005, 2006

$$C = \exp\left[-\frac{k\pi \sin^2 \psi}{\left|\frac{d}{ds}\frac{c_S^2}{v_A^2}\right|}\right]$$

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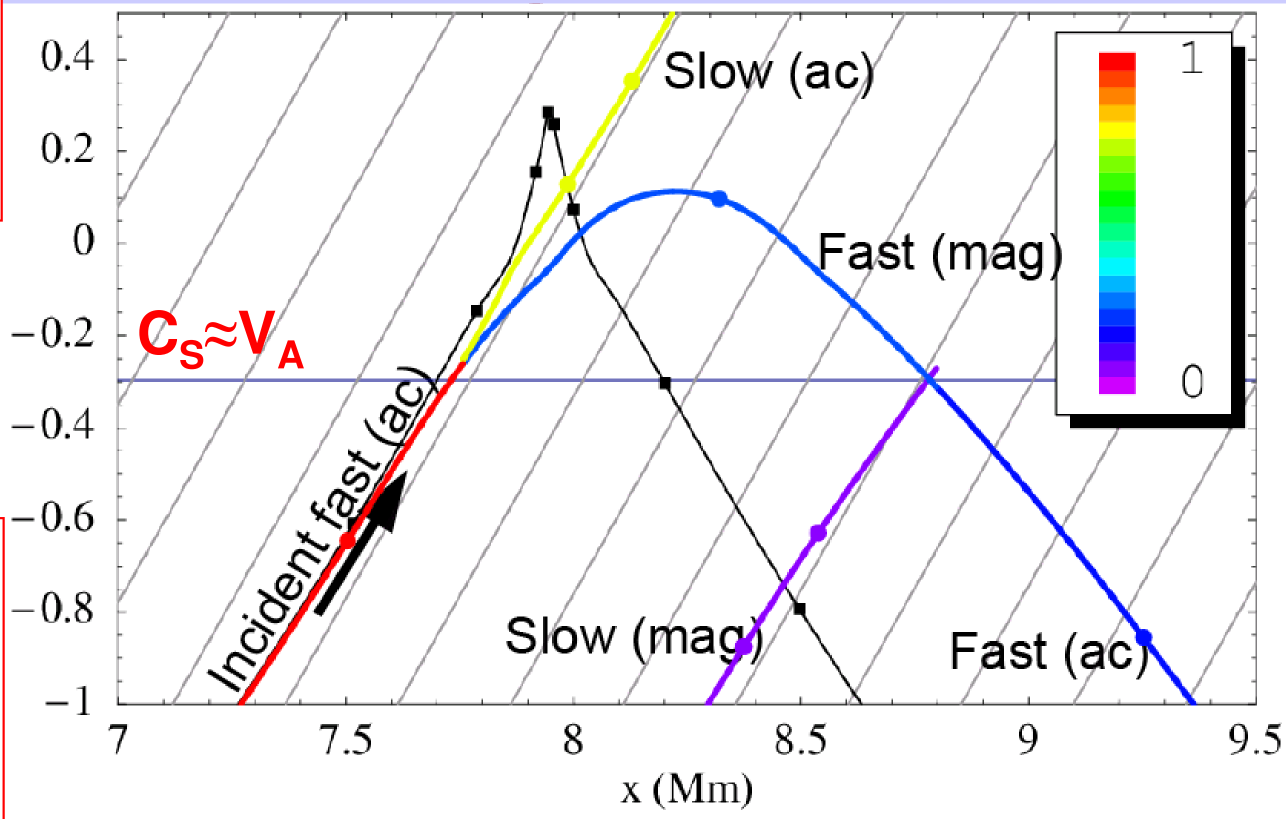
Wave path through the magnetic field

In the $C_S \approx V_A$ region the phase speeds of the modes become close and the energy can be partially transferred between the different branches of the dispersion relation

photosphere



Convection zone

Ray path of a fast acoustic wave incident on the inclined magnetic field.

Cally (2007)

Increased acoustic emission for 20-30 inclined field

$$C = \exp\left[-\frac{k\pi \sin^2 \psi}{\left|\frac{d}{ds}\frac{c_S^2}{v_A^2}\right|}\right]$$

FAST-to-SLOW mode transformation coefficient

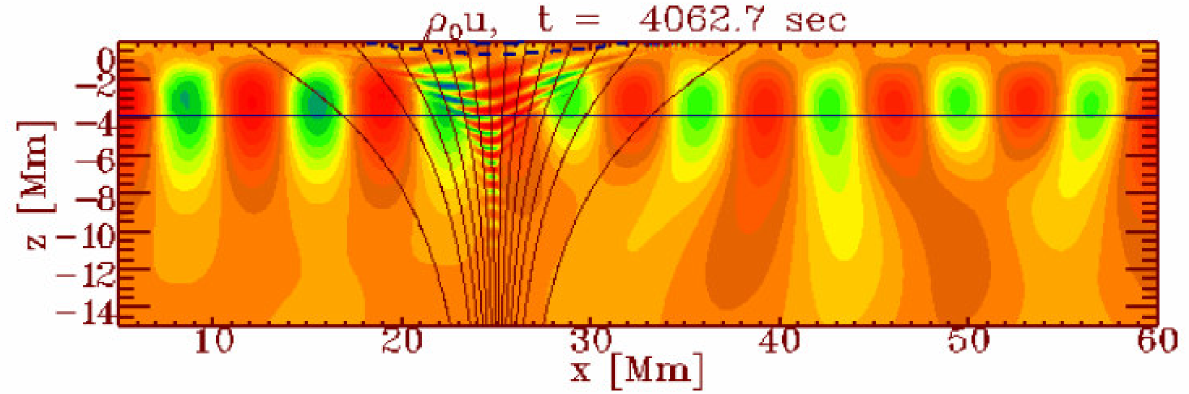
Cally 2005, 2006

Mode transformation in sunspot model

Cally and Bogdan (1997), Cally (2007)

Cameron, Gizon, Duvall (2008)

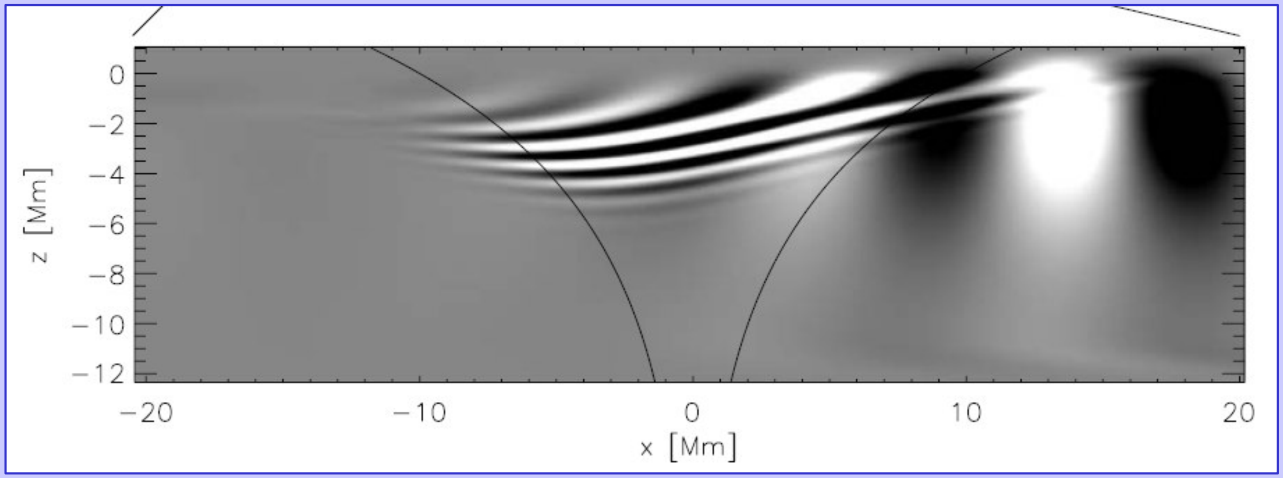
- 2D/3D
- Polytrope atmosphere
- Large sunspot
- Single *p* / *f* mode



A p_1 mode meets a spreading sunspot field with clear slow mode conversion.

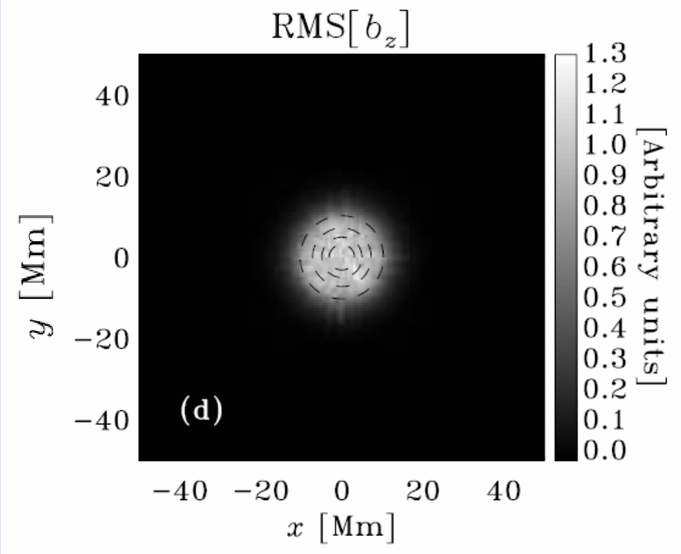
- Surface wave amplitudes reduced due to mode conversion

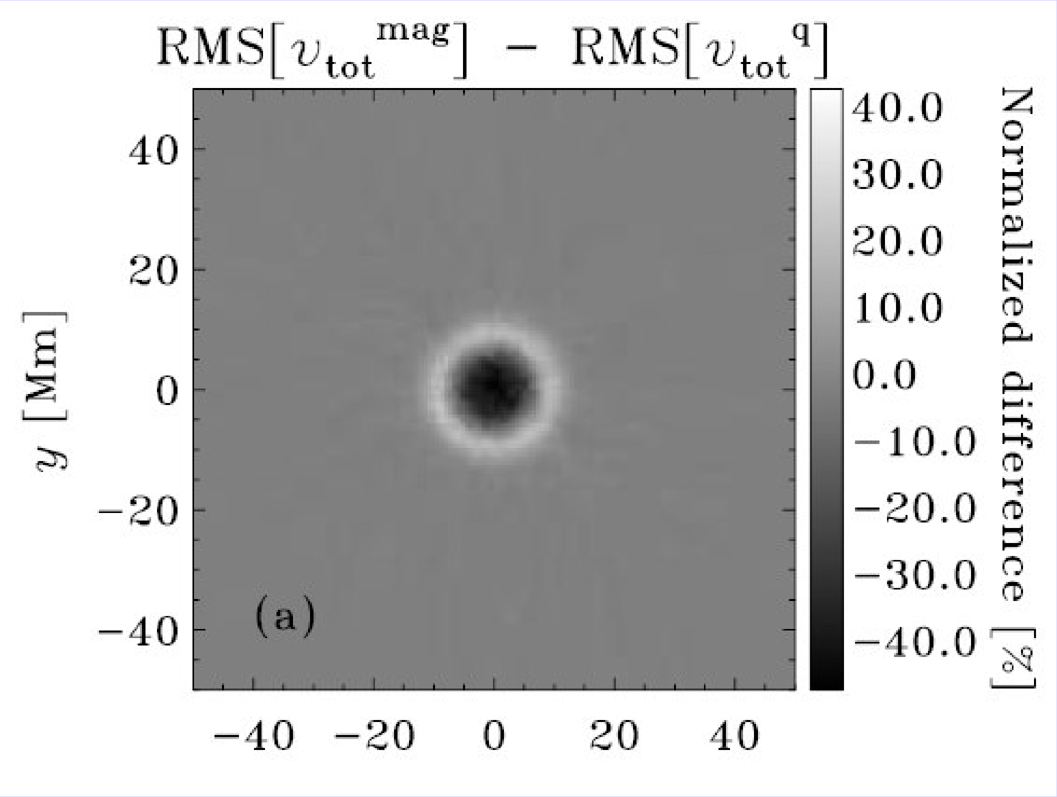
- Phase shift compared to the quiet Sun



Mode transformation in sunspot model

Hanasoge (2008)





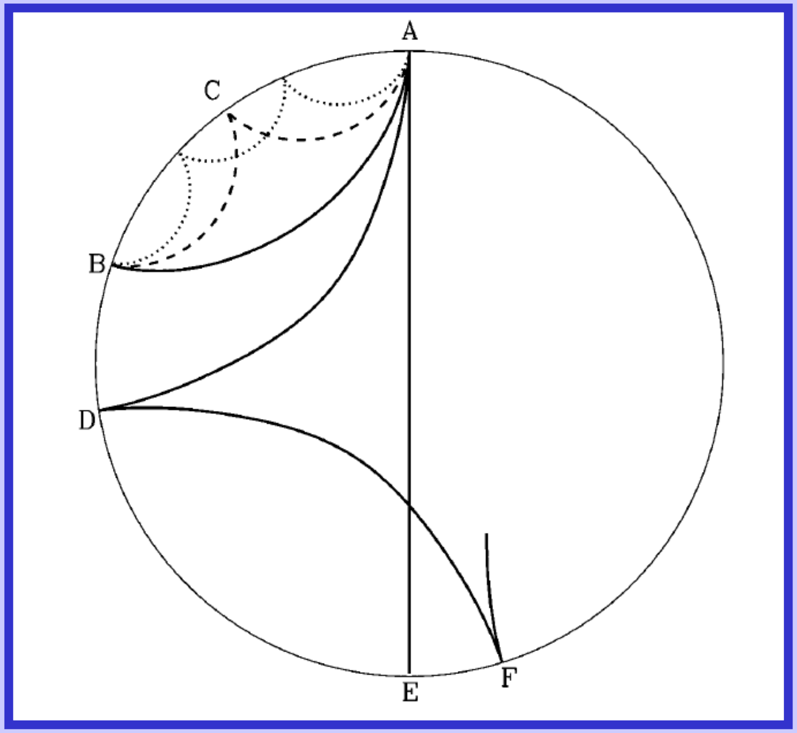
- 3D
- Polytrope atmosphere
- Self-similar MHS
- Random sources
  - *Strong power reduction in the umbral regions*
  - *Halo of increased wave power in the penumbral regions*
  - *Frequency dependence*

Questions:

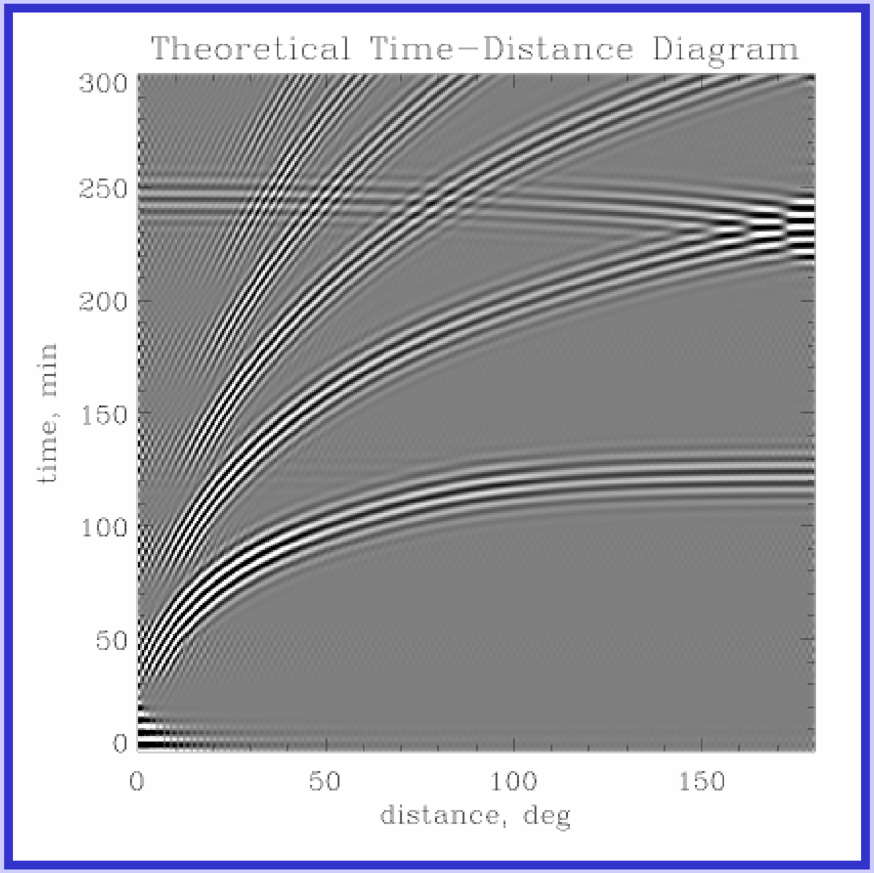
• *Source of helioseismological velocity signals in active regions?*

Local Helioseismology

The purpose of time-distance helioseismology is to measure and interpret the travel times of solar waves between any two locations on the solar surface.



$$C(\boldsymbol{x}_1, \boldsymbol{x}_2, t) = \frac{h_t}{T - |t|} \sum_{t'} \Psi(\boldsymbol{x}_1, t')\, \Psi(\boldsymbol{x}_2, t' + t),$$



Kosovichev, Duvall and Scherrer (2000)
Gizon and Birch (2005)

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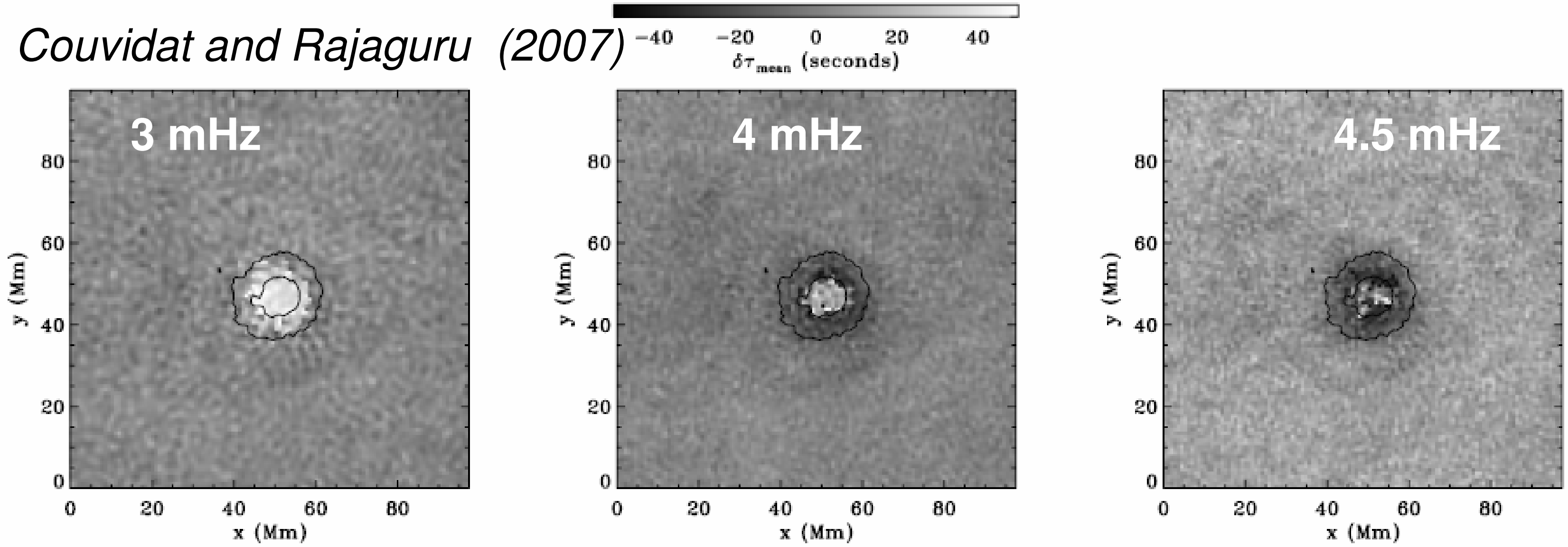
Results from time-distance helioseismology in AR

Waves travel 20-50 seconds faster deep below sunspots.

Positive travel times (waves slow down) for small skip distances, negative travel times (waves speed up) for large skip distances.

Strong frequency dependence of the travel times (high-frequency waves travel faster).

Couvidat and Rajaguru (2007)



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WKB solution of the MHD equations

Wentzel-Kramers-Brillouin (WKB) approximation allows to obtain analytical solution assuming that the wavelength of the perturbation is much smaller than the characteristic scale of the variations of the background atmospheric parameters.

Cally (2006), Moradi & Cally (2008) incirporate cut-off frequency in the WKB solution for MHD waves.

$$F(x,z,\phi,p,q)=\omega^4-\omega^2(c_S^2+v_A^2)(p^2+q^2)+c_S^2(p^2+q^2)(v_{Ax}p+v_{Az}q)^2-\omega_c^2(\omega^2-c_S^2q^2)+c_S^2N^2p^2=0\,,$$

Partial differential equation is solved by Charpit's method of characteristics:

$$\begin{aligned}\frac{dp}{ds}&=-\frac{\partial F}{\partial x}\\ \frac{dq}{ds}&=-\frac{\partial F}{\partial z}\\ \frac{dx}{ds}&=\frac{\partial F}{\partial p}\\ \frac{dz}{ds}&=\frac{\partial F}{\partial q}\end{aligned}$$

→

- Trajectory of the wave;
- Phase and group velocities

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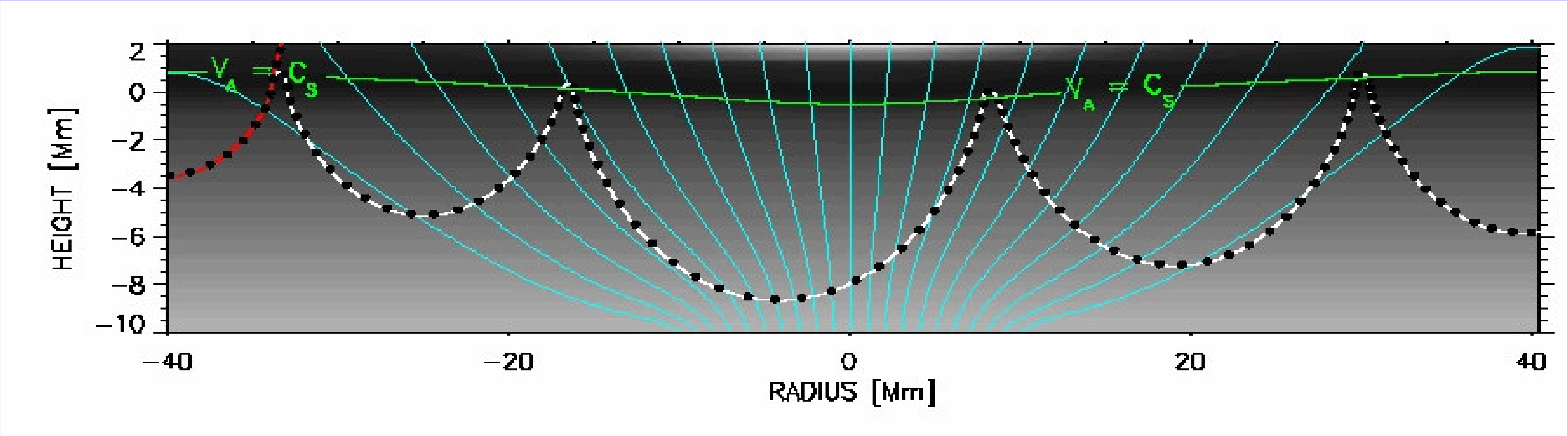
WKB explaining frequency dependence

Fast mode frequency 6 mHz

No cut-off !



Sunspot model Khomenko & Collados (2008)

Magnetic field + sound speed perturbations

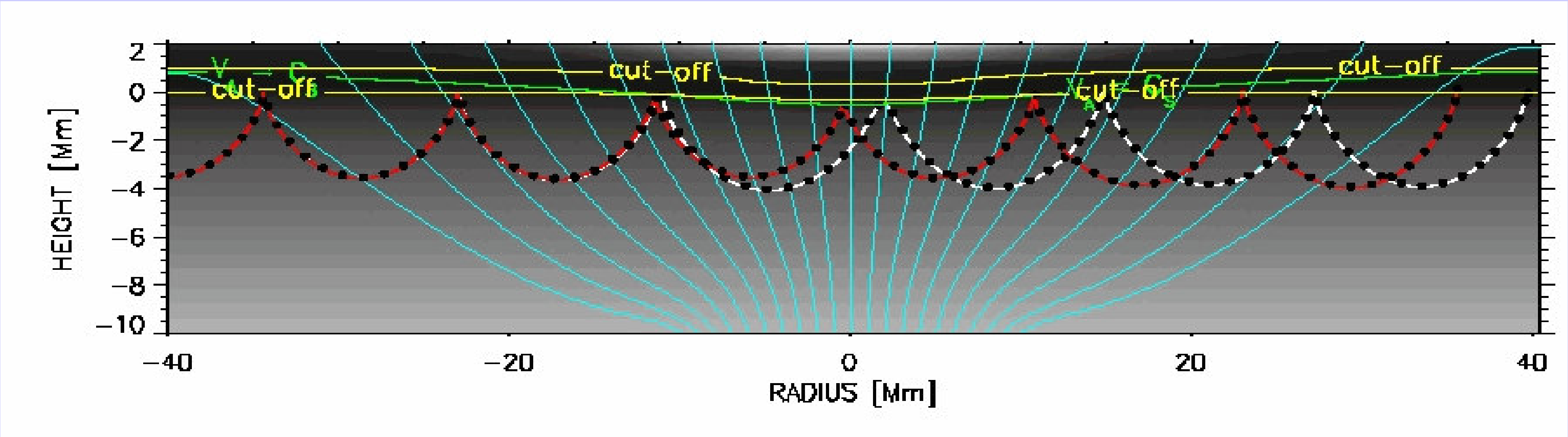
Only sound speed perturbations

Each black point separated 1 minute in time

WKB explaining frequency dependence

Fast mode frequency 4.5 mHz

Cut-off and C_S=V_A heights at the same place



Sunspot model Khomenko & Collados (2008)

Magnetic field + sound speed perturbations

Only sound speed perturbations

Each black point separated 1 minute in time

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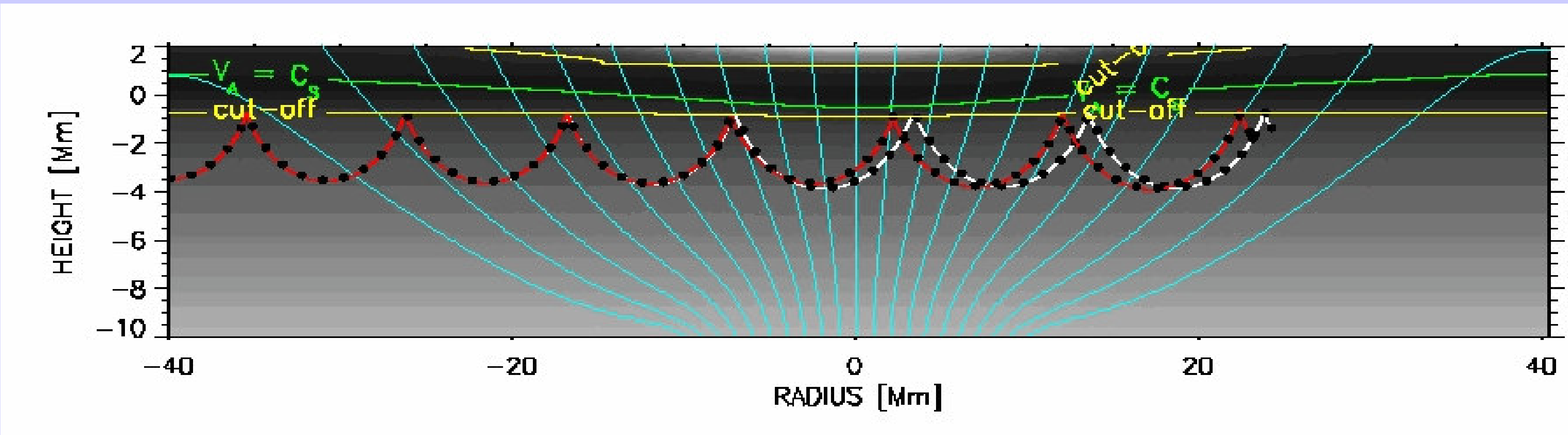
WKB explaining frequency dependence

Fast mode frequency 3 mHz

Cut-off height below $C_S=V_A$ height



Sunspot model Khomenko & Collados (2008)

Magnetic field + sound speed perturbations

Only sound speed perturbations

Each black point separated 1 minute in time

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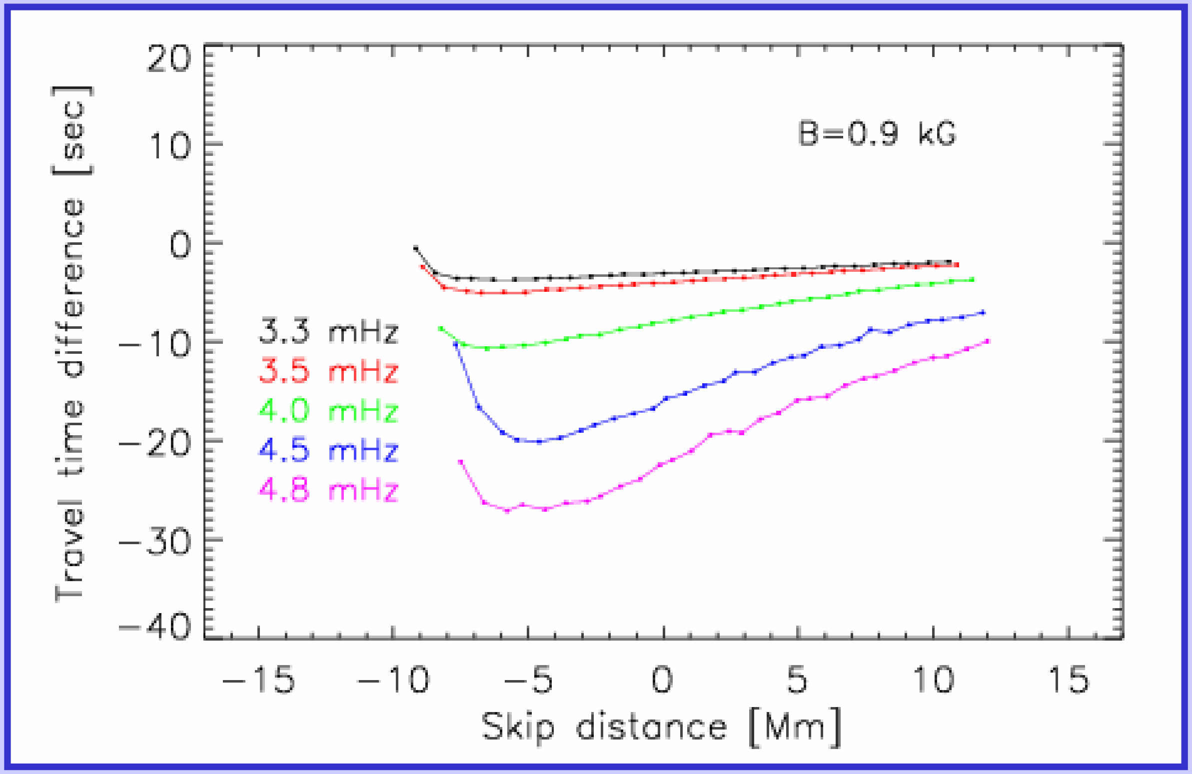
Travel time differences from WKB



High frequencies affected more by magnetic field effects!

WKB gives similar values of $\delta\tau$ as observations!

Sunspot model and simulations setup

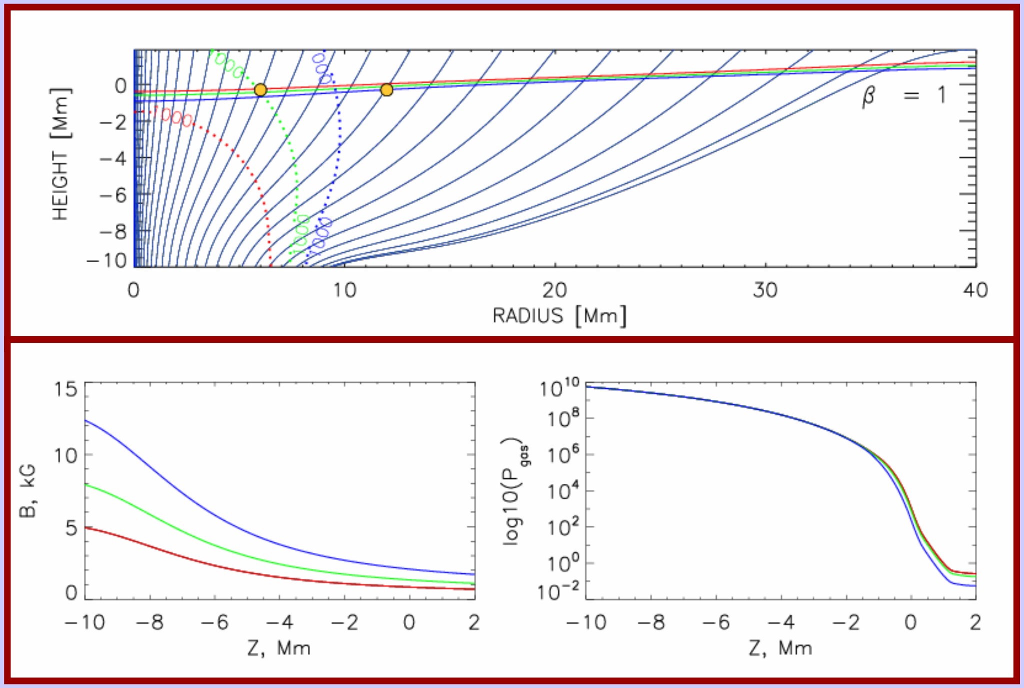
$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{V}) = 0\,,$$

$$\frac{\partial(\rho\vec{V})}{\partial t} + \vec{\nabla}\cdot[\rho\vec{V}\vec{V} + (P + \frac{\vec{B}^2}{8\pi})\mathbf{I} - \frac{\vec{B}\vec{B}}{4\pi}] = \rho\vec{g}\,,$$

$$\frac{\partial E}{\partial t} + \vec{\nabla}\cdot[(E + P + \frac{\vec{B}^2}{8\pi})\vec{V} - \vec{B}(\frac{\vec{B}\cdot\vec{V}}{4\pi})] = \rho\vec{V}\cdot\vec{g} + \rho Q\,,$$

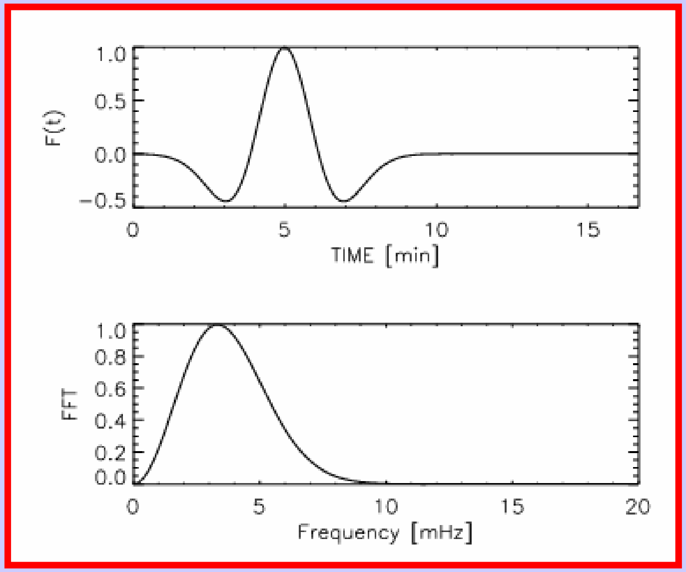
$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{V}\times\vec{B})\,,$$

Sunspot-like MHS models with B_{phot}=0.9, 1.5 and 2.3 kG



Khomenko & Collados (2008)

Acoustic source spectral properties



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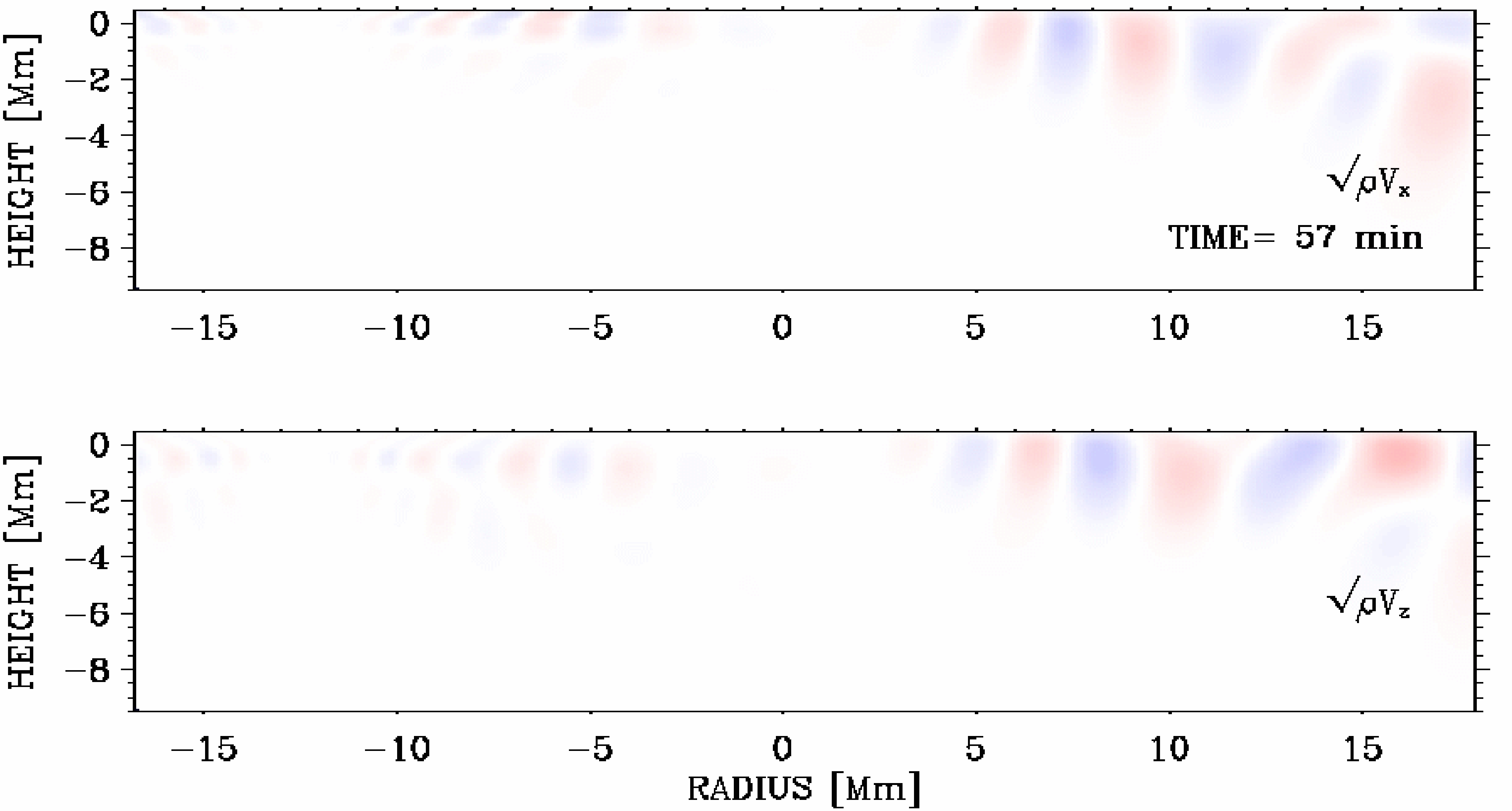
Numerical simulations of acoustic waves produced by a localized source: no field



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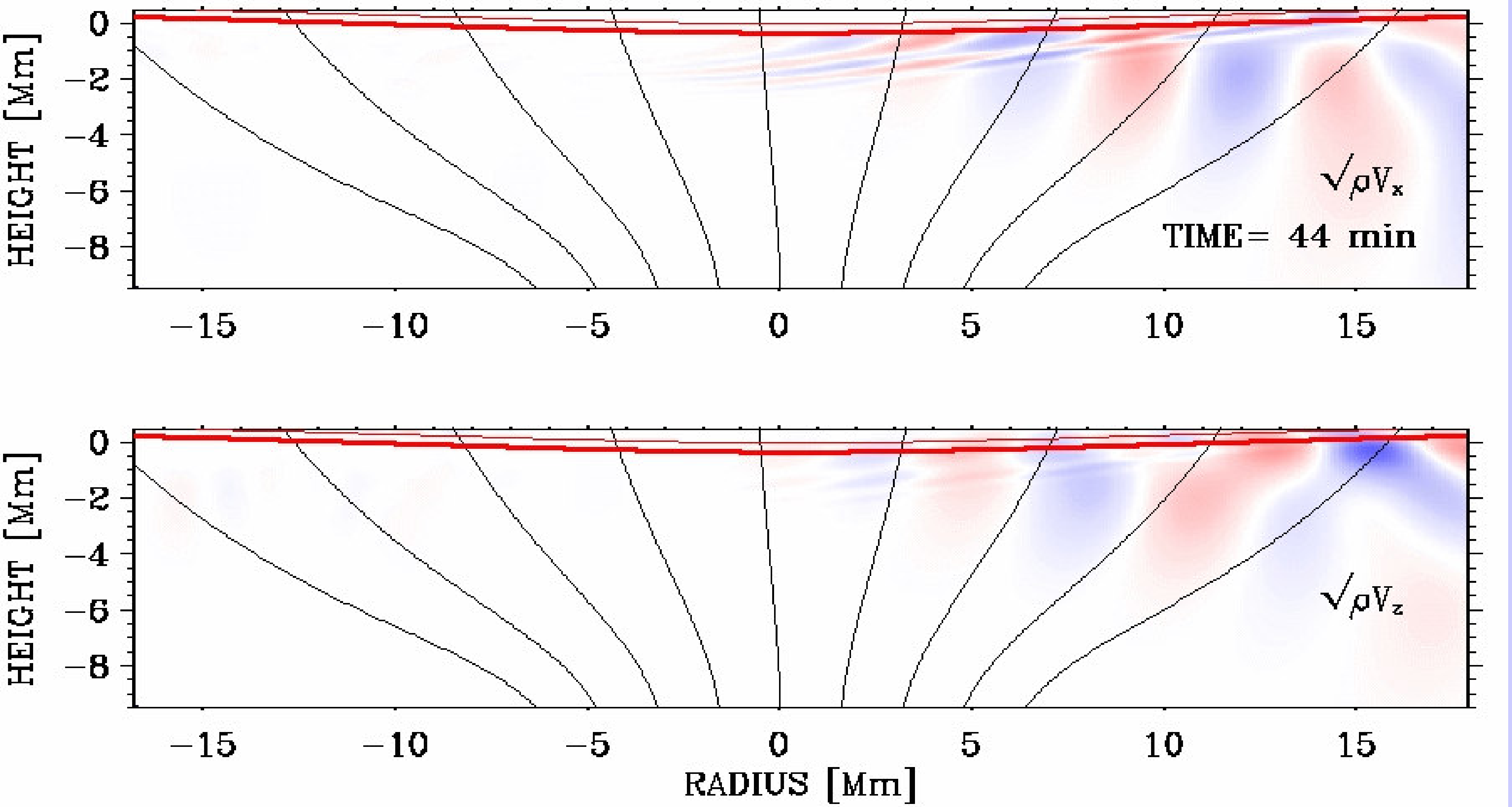
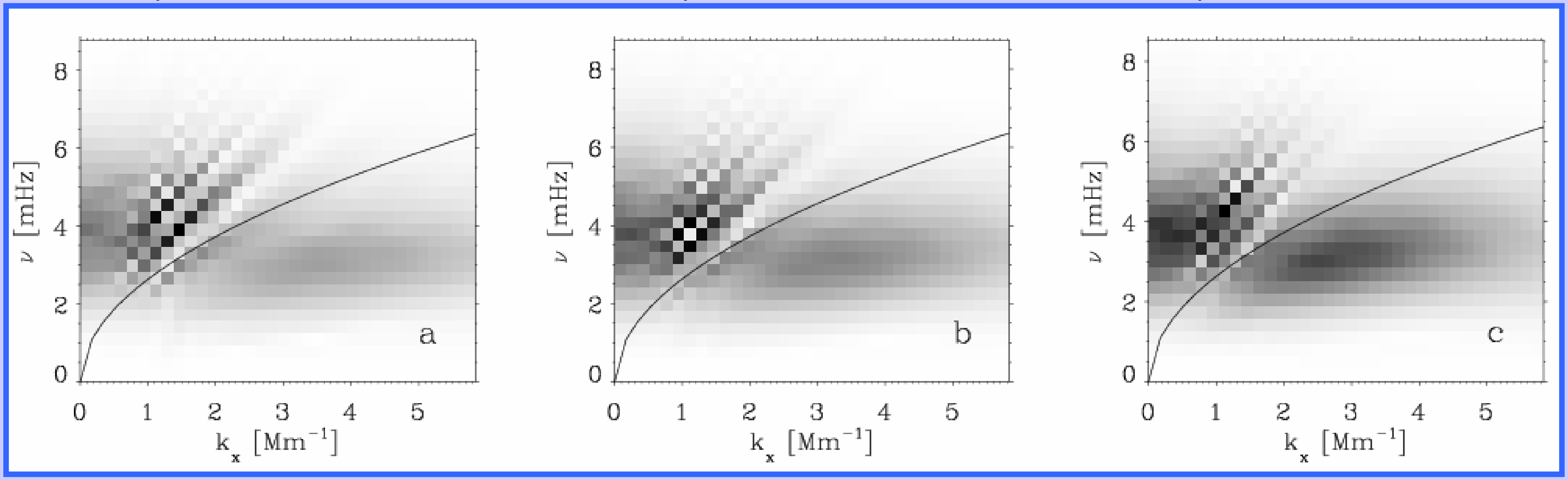
Numerical simulations of MHD waves produced by a localized source inside the sunspot



Power spectra from simulations: non-magnetic vs. magnetic

B_{phot}=0.9 kG B_{phot}=1.5 kG B_{phot}=2.4 kG

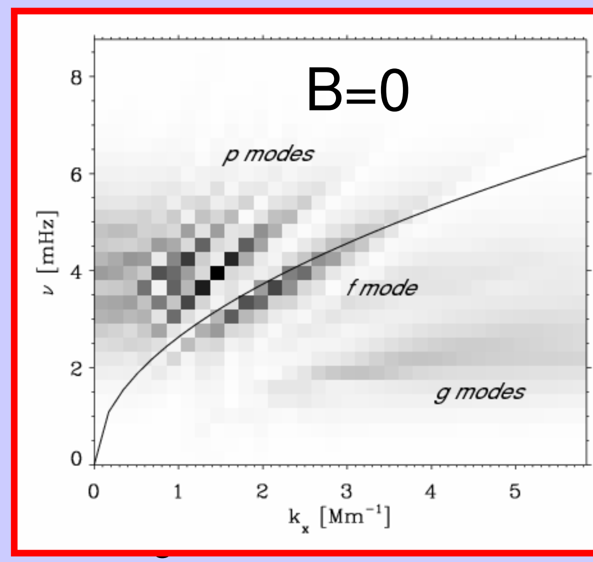


modified *p*-modes

no *f*-mode

Increase with B of ridges inclination

Increase with B of magneto-gravity wave power



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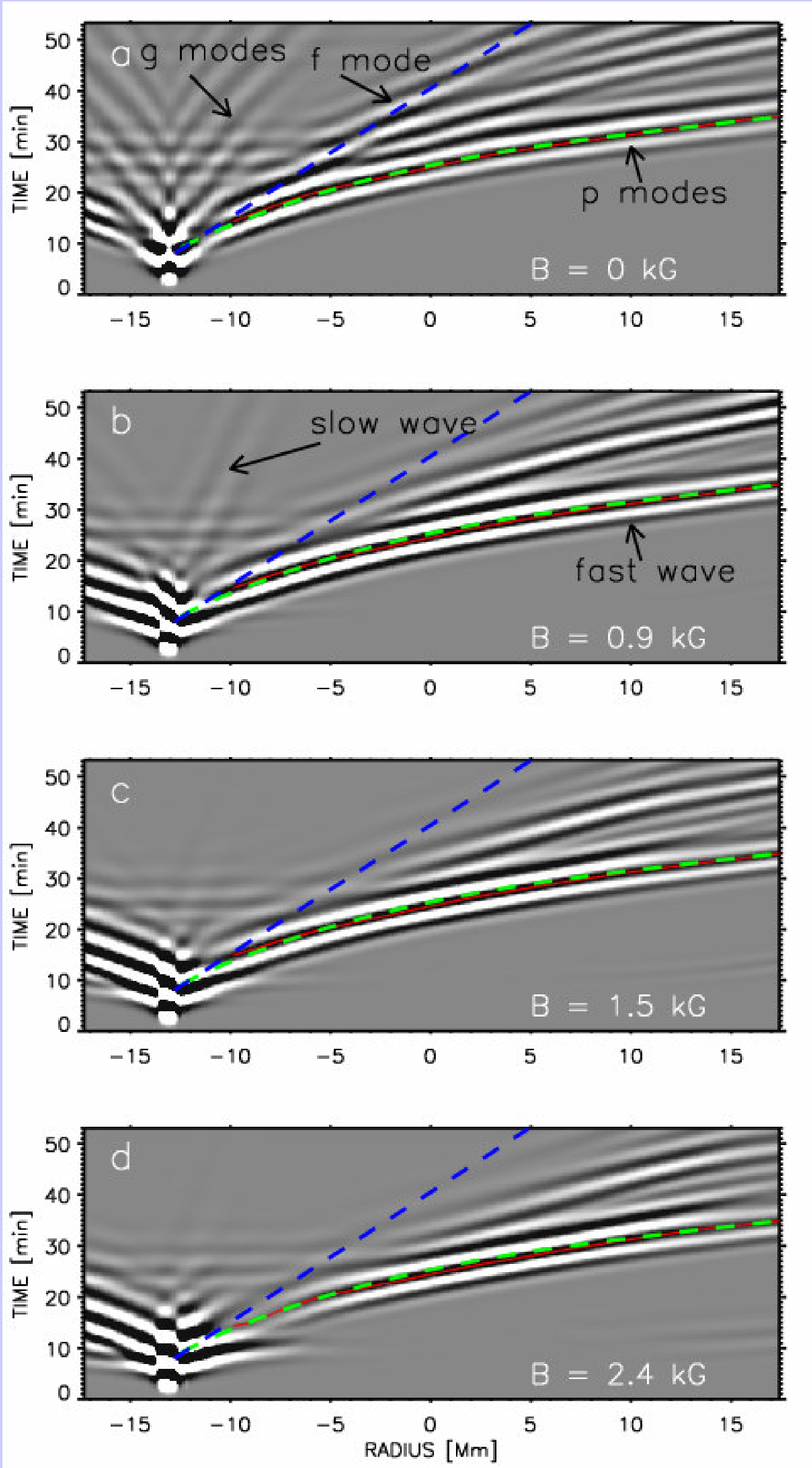
Time-distance diagrams from simulated vertical velocity and magnetic field

Measurements of V_Z at $\log\tau_5$=-1.6



modified *p*-modes

no *f*-mode in simulations with magnetic field

slow mode ridges well isolated

Increase with of propagation speed with magnetic field

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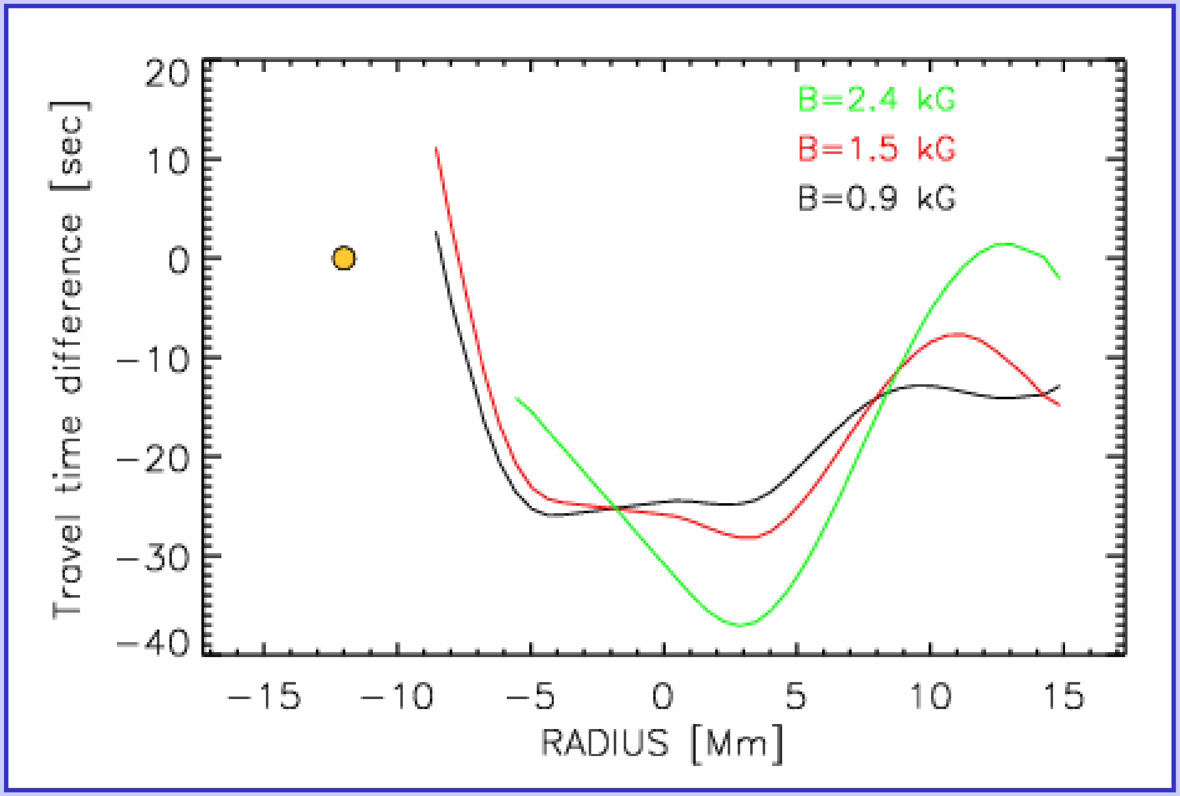
Travel time difference from simulations

Travel times decrease with magnetic field.

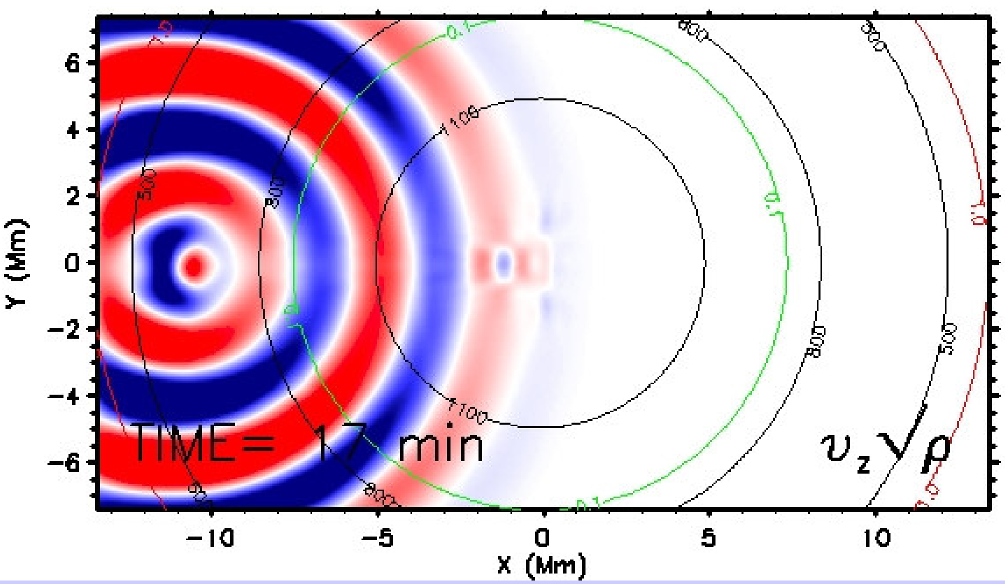
High-β fast mode wave travel times from simulations are similar to observations.



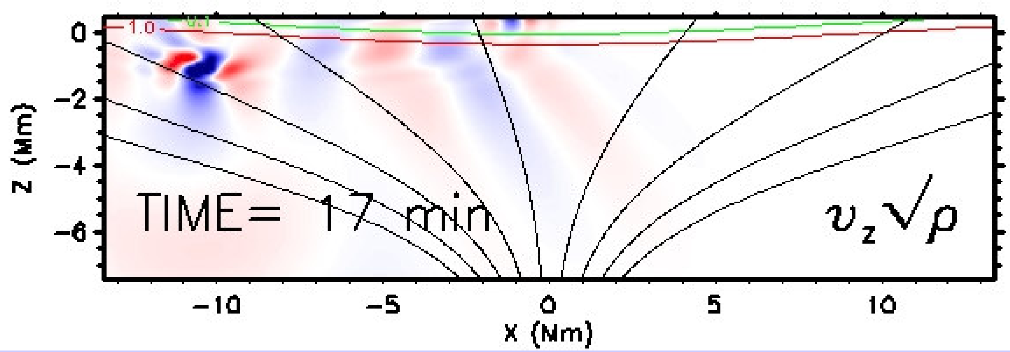
Khomenko, Kosovichev, Collados Parchevsky & Olshevsky, (2008)

3D simulations of waves from localized source

V_Z at Z=0 (photospheric base)



V_Z at Y=0 (sunspot axis)



Olshevsky, Khomenko & Collados (in preparation)

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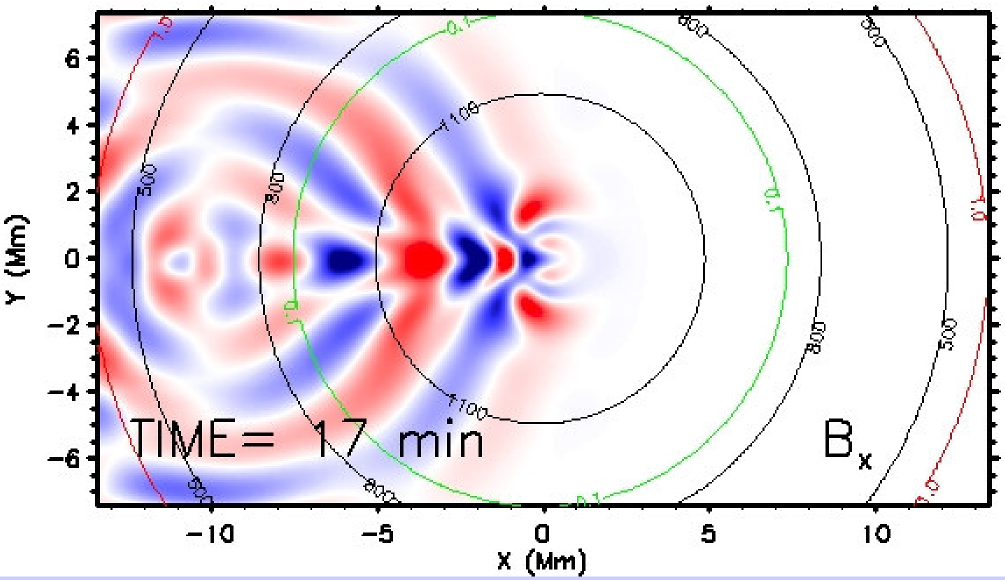
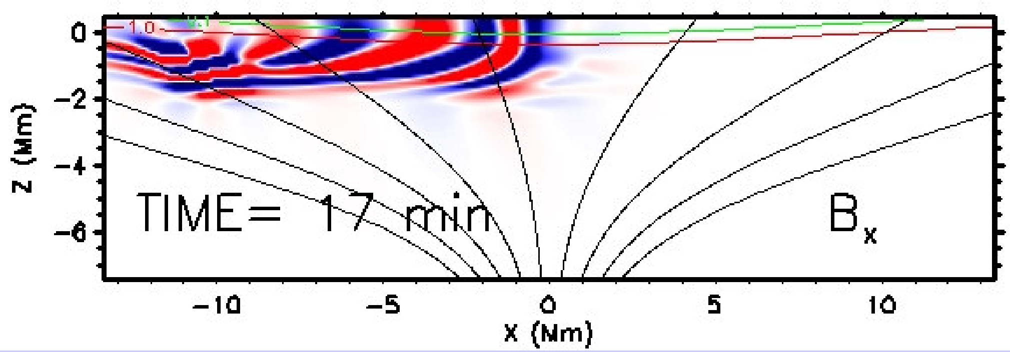
3D simulations of waves from localized source

B_X at Z=0 (photospheric base)



B_X at Y=0 (sunspot axis)



Olshevsky, Khomenko & Collados (in preparation)

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Summary

- (1) Theoretical interpretation of waves in sunspot has made big advances during the last decades.

•(2) The influence of β=1 level and field inclination is being clarified.

•(3) The observed wave pattern in the upper photosphere and chromosphere is compatible with longitudinal propagation of low-β slow mode waves.

•(4) Mode transformation redistributes the wave power over active regions.

•(5) The first simulations of helioseismic waves in sunspots indicate that they are due to fast mode high-β waves (modified *p*-modes).

•(6) Waves below sunspot are speed up by magnetic field. The travel times are shorter by 20-50 sec compared to non-magnetic case.

•(7) Magnetic field produces strong frequency dependence. High-frequency waves travel faster than in non-magnetic case.

•(8) 3D simulations including chromospheric layers are important to analyze in the future.