Hinode-15 / IRIS-12 / Prague

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Generation of umbral oscillations and subsurface structure of sunspots

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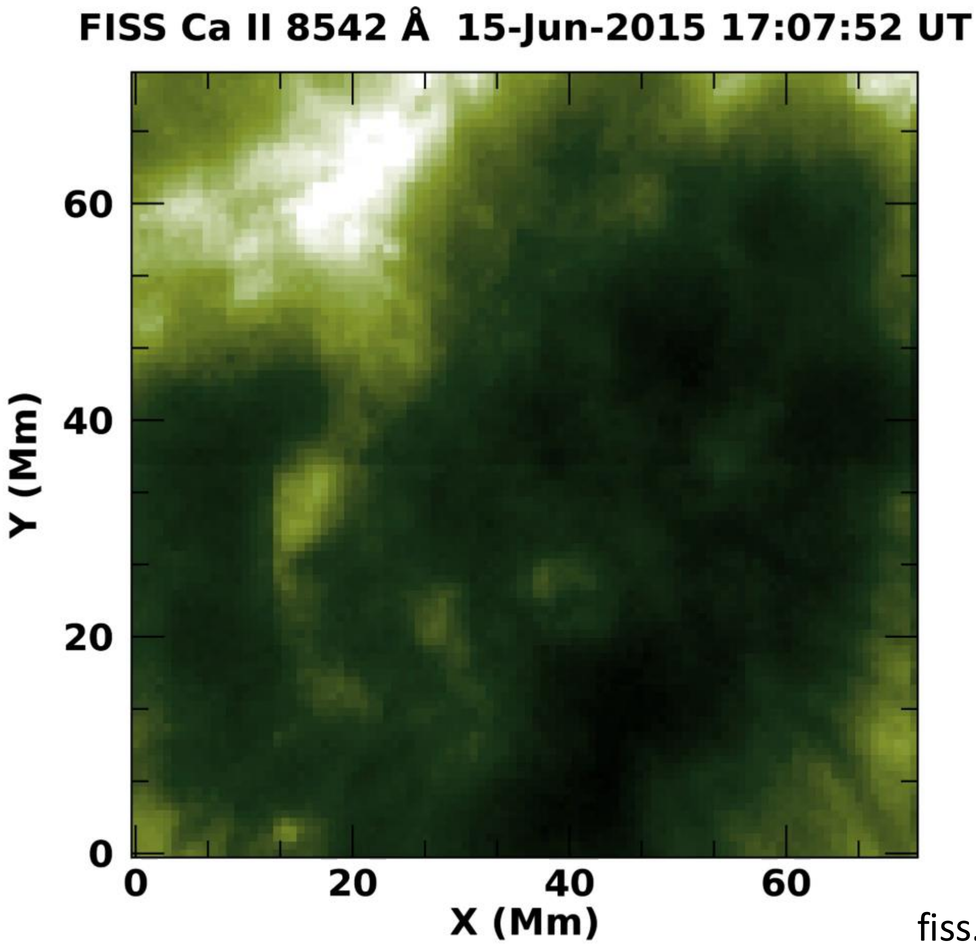
Umbral Oscillations



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Umbral Oscillations

- Sunspot umbral oscillations
  - Common phenomena
    - Intensity oscillations (e.g. Umbral flashes)
    - Velocity oscillations
  - Upward propagating slow waves in gravitationally stratified medium

    (Centeno et al. 2006, Felipe et al. 2010, Jess et al. 2013 …)

Wave source & propagation

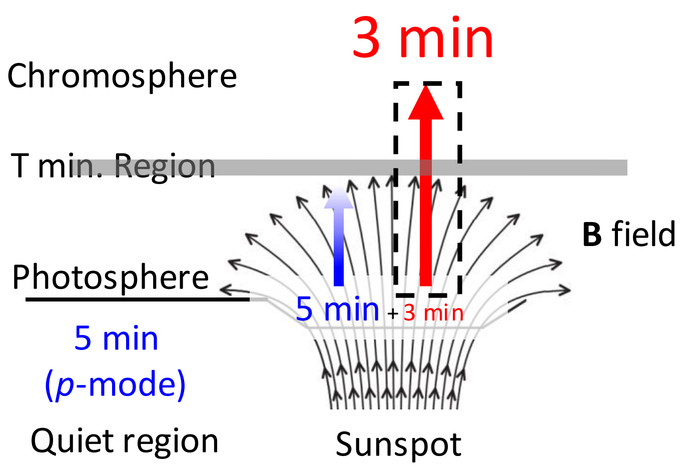
- Upward propagation

  : source is below the photosphere
- Slow waves (magnetic field)
  - Field guided sound waves in $\beta < 1$ region
  - Upward propagating (along the **B** field) with c_s

Frequency dependence

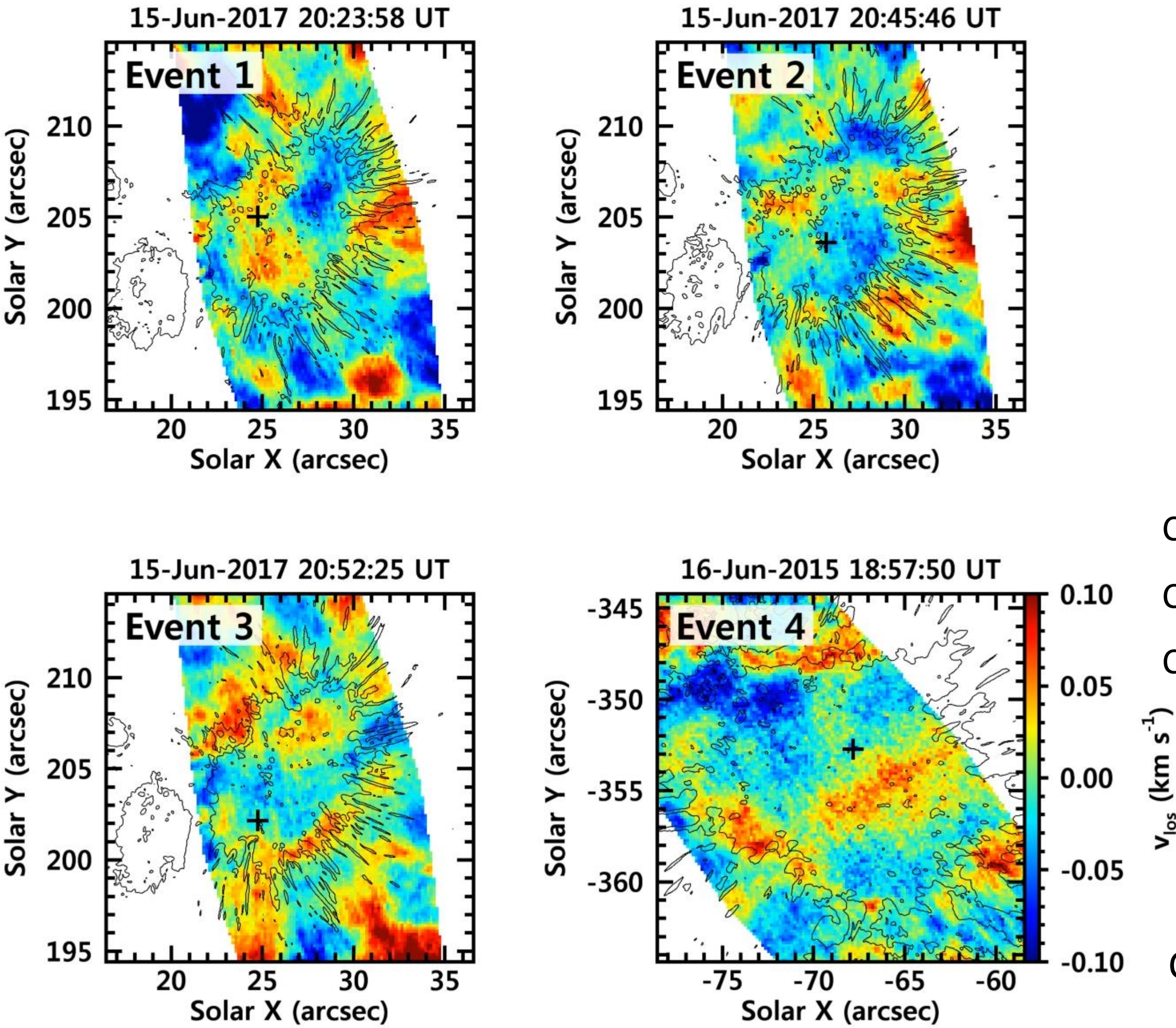
- Gravitationally stratified medium

  ⇨ Acoustic cutoff
  - Change of the main period (5 → 3 min)



Velocity Oscillation (T min region)

- Internally excited oscillation patterns



Color : Fe I 5435Å Doppler velocity (1-4 min)

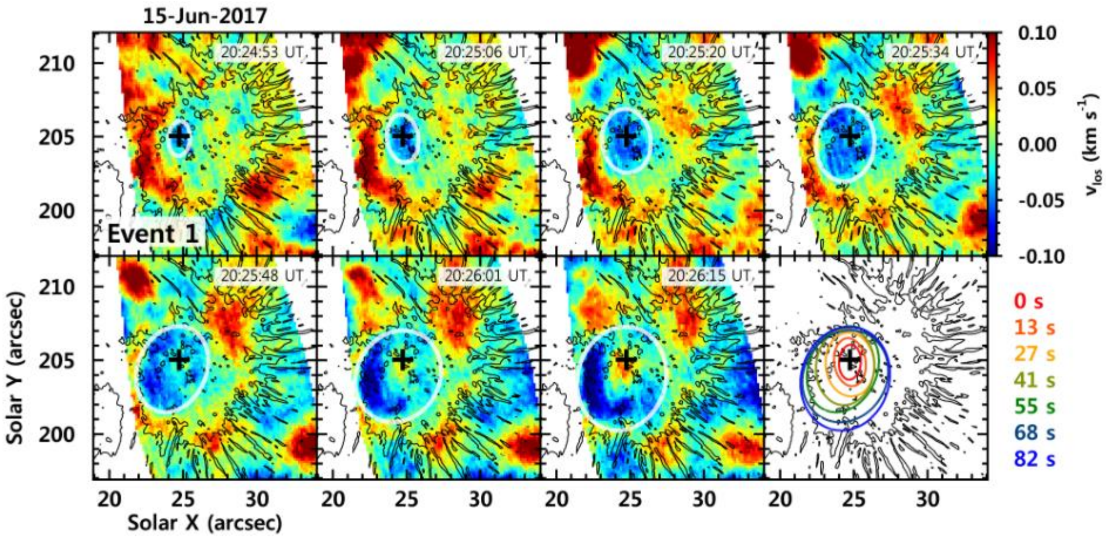
Contour : TiO BFI (U-P boundary, umbral dots)

Cross : Oscillation center

Cho et al. (2019)

Velocity Oscillation (T min region)

- Internally excited oscillation patterns
  - Oscillation center



Cho et al. (2019)

  - Parameters

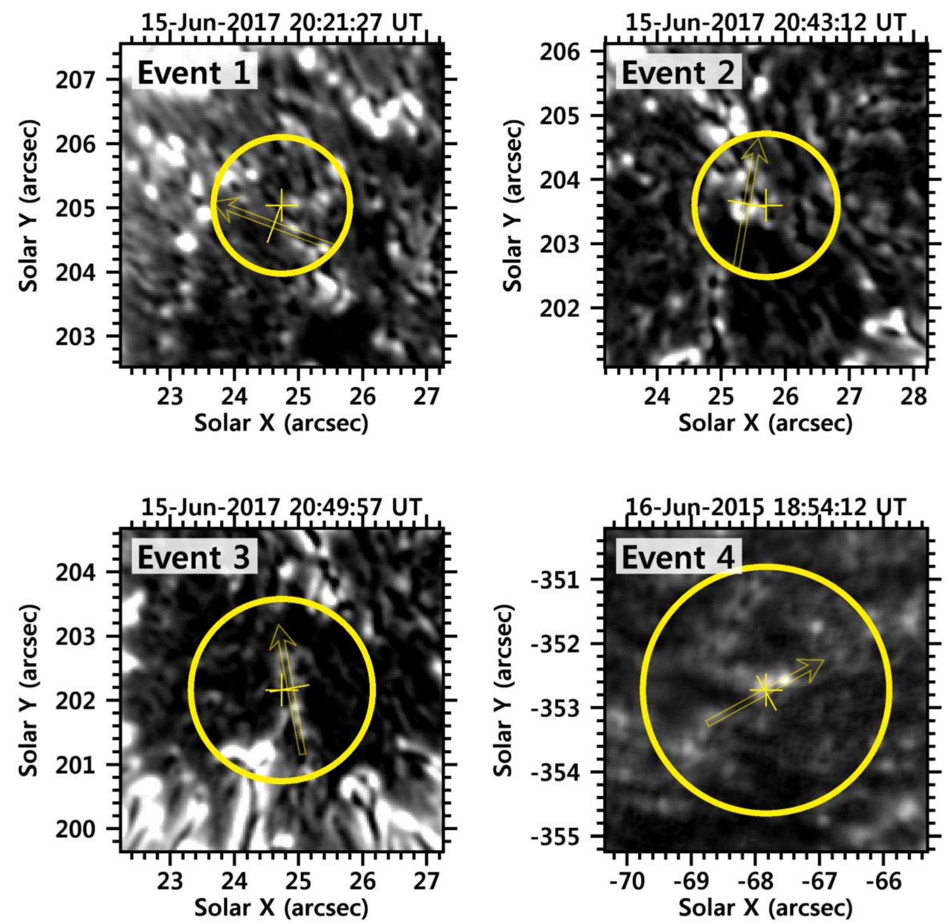
Table 1. Observable parameters of the oscillation patterns

Event number	Amplitude ($km\,s^{-1}$)	Coherent size ($''$)	Duration (s)	Apparent speed ($km\,s^{-1}$)
1	0.07	2.46	434	14.5
2	0.08	2.46	392	12.7
3	0.08	2.27	490	16.6
4	0.12	3.80	576	15.2
Mean	0.09	2.74	473	14.8

Photospheric Features - UD

- Oscillation center
  - Association with umbral dots (UDs)
    - Intensity variation
      : brighten, darken, collide, break, move, disappear

Cho et al. (2019)

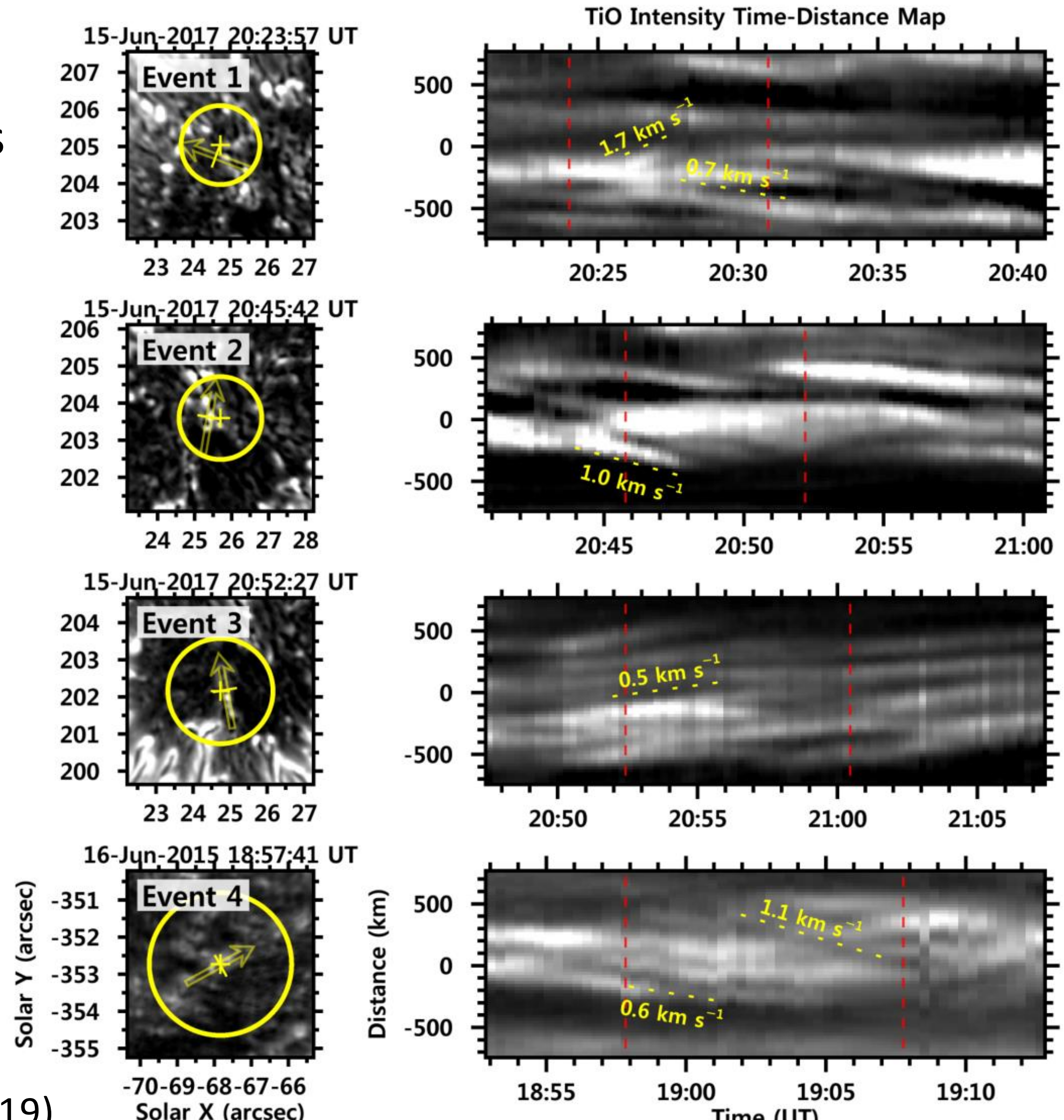


Photospheric Features - UD

- Oscillation center
  - Association with umbral dots
    - Fast moving ∽ 1 km s^{-1}

      *cf. typical speed : 0.4 km s^{-1}
      (Riethmüller et al. 2008)
    - Intensity variation

      : brighten, darken, collide, break, disappear
    - Dark lanes



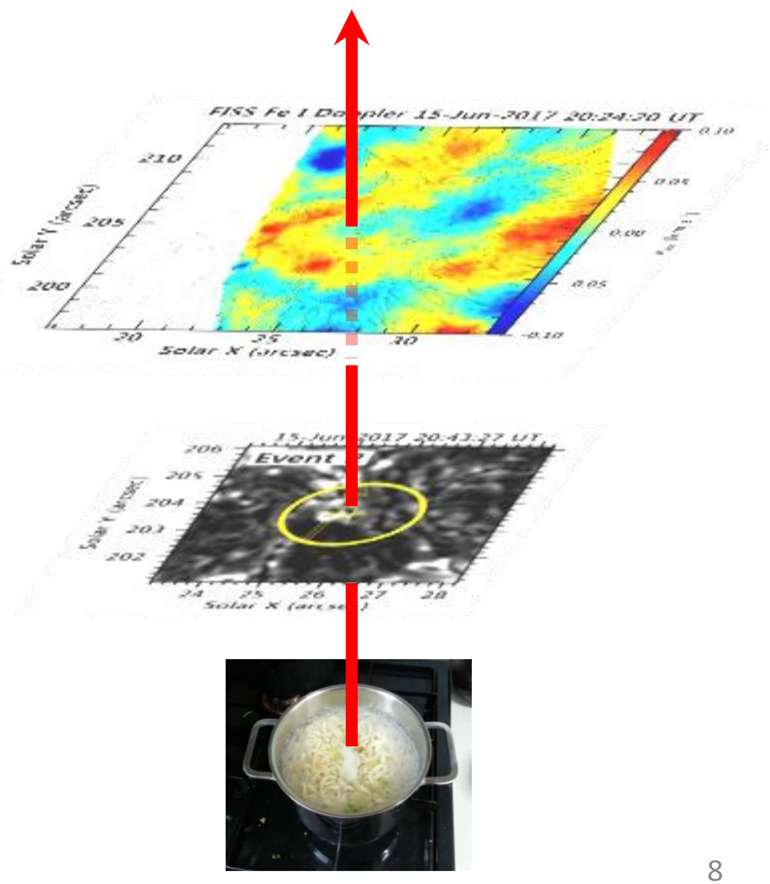
Cho et al. (2019)

Discussion 1

- Active umbral dots
  - Fast horizontal motion
  - Upward and downward motion
    (Ortiz et al. 2010; Watanabe et al. 2012)
  - Morphological change
  ⇨ Vigorous convective motion inside umbra

  - Spatially & temporally associated with the concentric oscillation patterns at the temperature minimum region

⇨ Wave generation mechanism is related to the convective motions inside umbra. (Internal source)

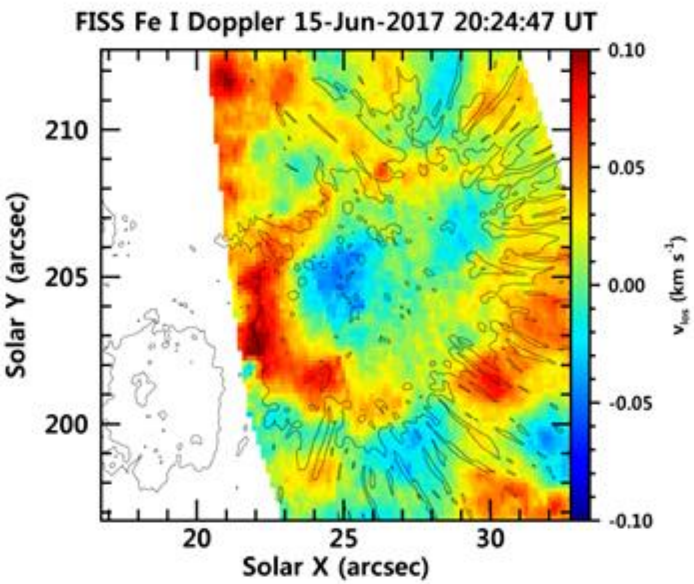


Summary

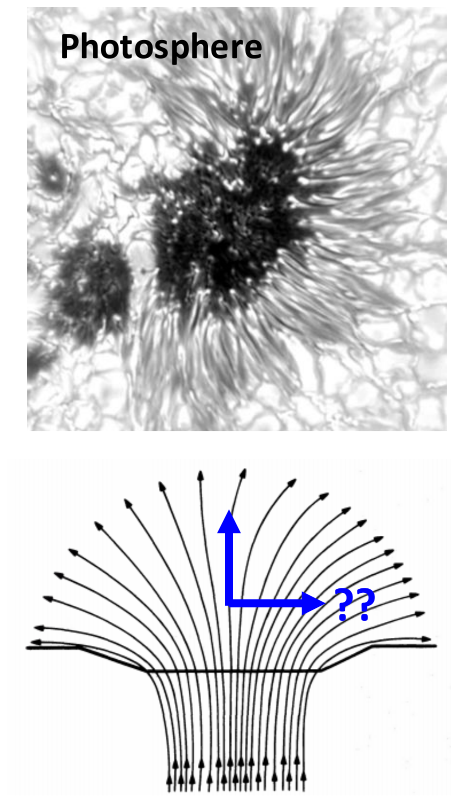
- Origin of 3-min umbral oscillations
  - Convective motion inside sunspot umbra

Across / Along the Field Line

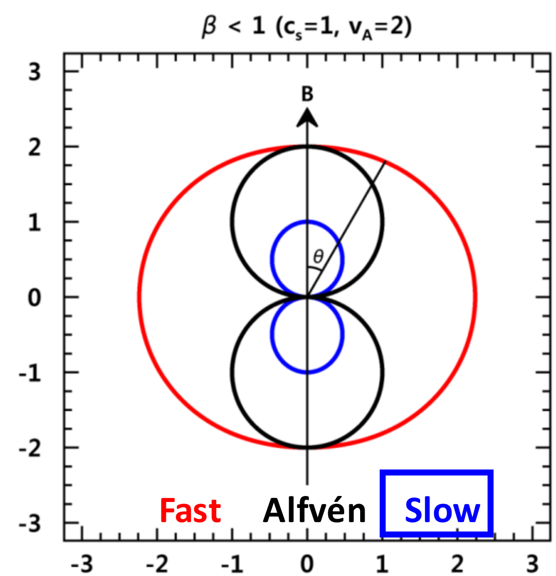
- 3-minute umbral oscillations
  - Upward propagating slow MHD waves in gravitationally stratified medium
  - Horizontal propagation in umbra ↔ Upward propagating slow waves



Temperature Minimum Region
(~ 300 km)

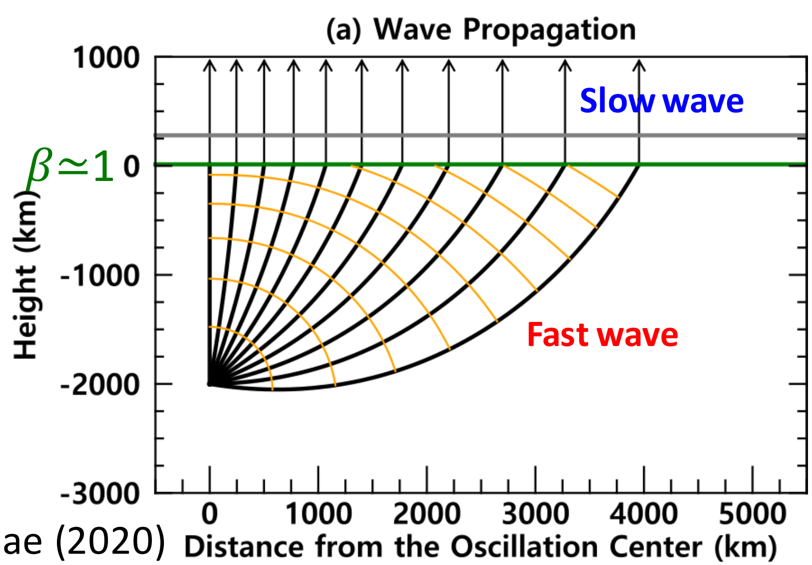


Parker (1979)

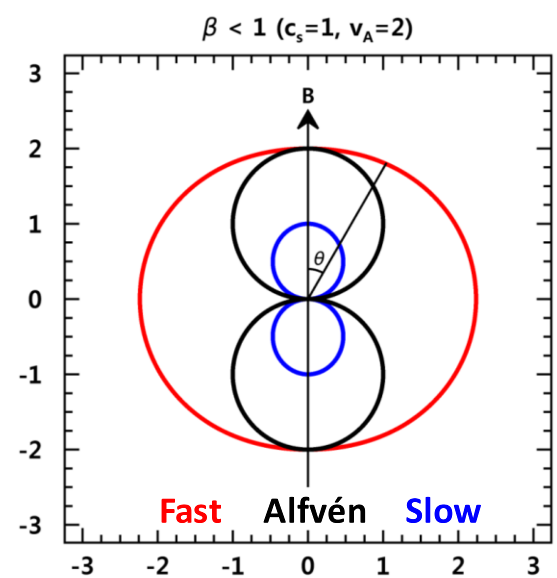


Horizontal Apparent Waves

- Horizontal propagation in umbra ⇨ Apparent wave patterns
  - From a point source
  - Fast waves propagation
  - Difference in arrival time at the $\beta \simeq 1$ layer
  - Mode conversion: Fast ⇨ Slow waves (Cally 2001; Schunker & Cally 2006)
  - Slow waves propagation along the **B** fields
  - Observed at the Fe I 5435 Å line formation height



Cho & Chae (2020)

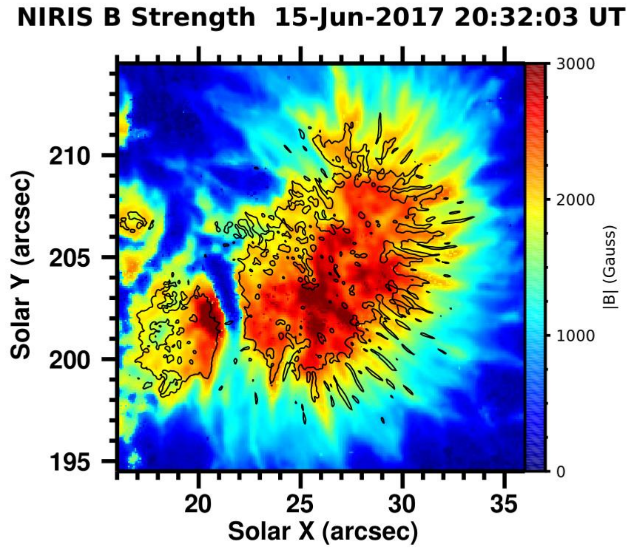


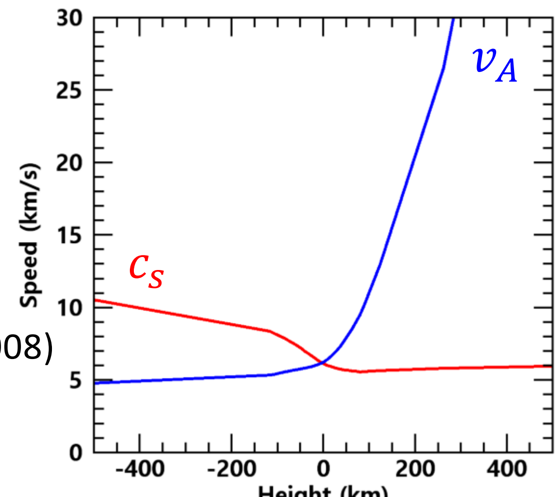
Sunspot Interior Model

Cho & Chae (2020)

- Fast wave speed
  - $v_f = \left(\frac{1}{2}(c_s^2 + v_A^2) + \sqrt{(c_s^2 + v_A^2)^2 - 4c_s^2 v_A^2 \cos^2\theta}\right)^{1/2}$
  - $c_s = \sqrt{\frac{\gamma P_{gas}}{\rho}}, \quad v_A = \frac{B}{\sqrt{4\pi\rho}}$
    - Wilson depression : 600 km
    - $\rho(z),\ P_{gas}(z)$: Maltby E model (Maltby et al. 1986)
      + Solar interior model (Cox 1999)
    - $B(z)$
      - GST/NIRIS data (I, Q, U, V)
        + Mline-Eddington inversion (vector magnetogram)
        ⇨ 2480 G at 90 km
      - $\Delta B/\Delta z = -1$ G km^{-1} (Borrero, & Ichimoto 2011)
  - $\beta(z) = \frac{8\pi p_{gas}(z)}{B^2(z)} = \frac{2}{\gamma}\frac{c_s^2(z)}{v_A^2(z)}$
  - $\beta(z = 13\ km) = 1$
- Fast waves propagation: Eikonal method

(Weinberg 1962; Moradi & Cally 2008)

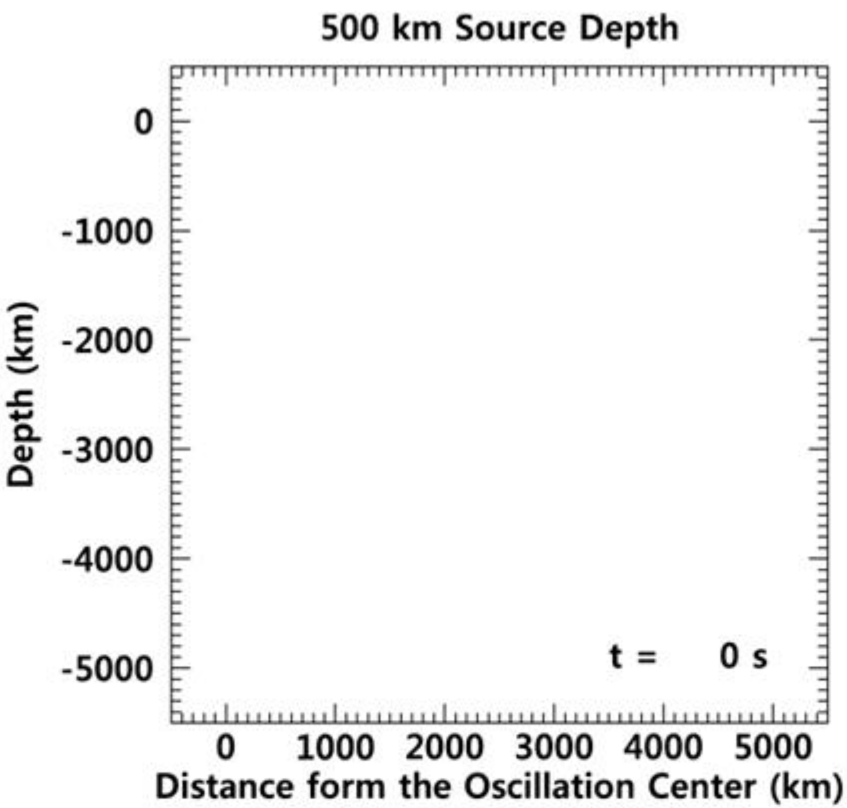


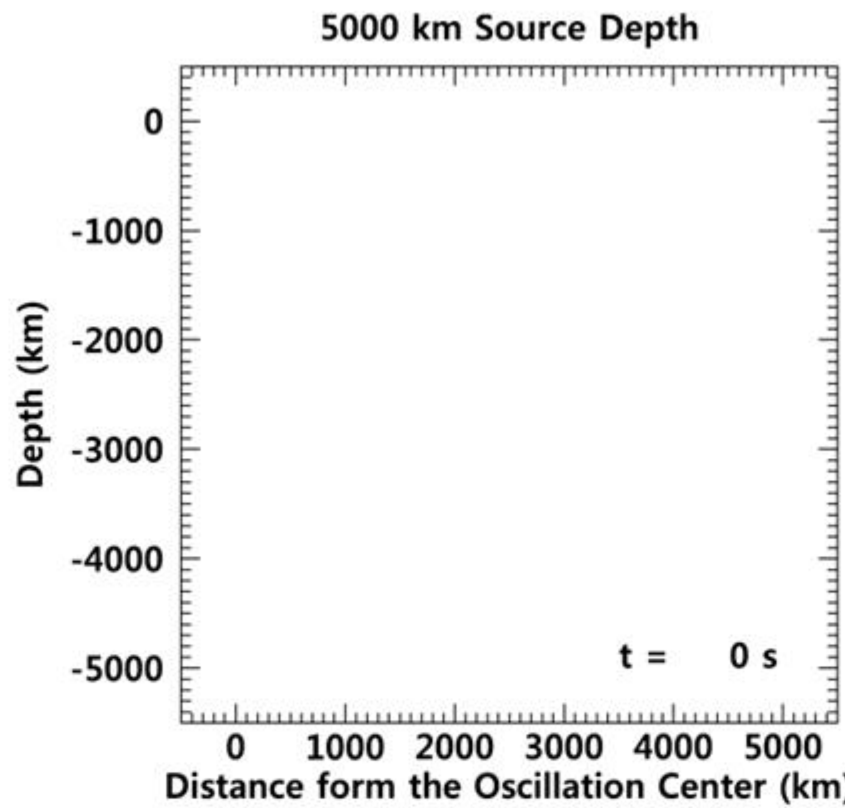


Effect of Source Depth

- Internally excited oscillation patterns
  - Horizontal apparent wave speed

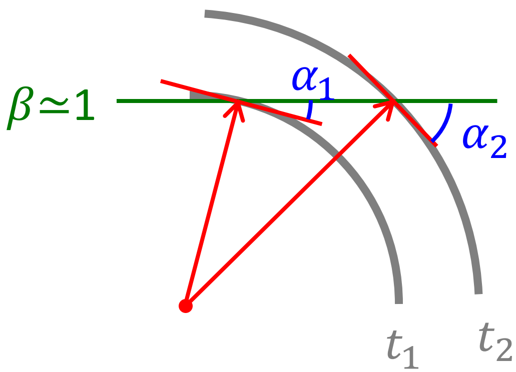
    ⇨ Information about the source depth !

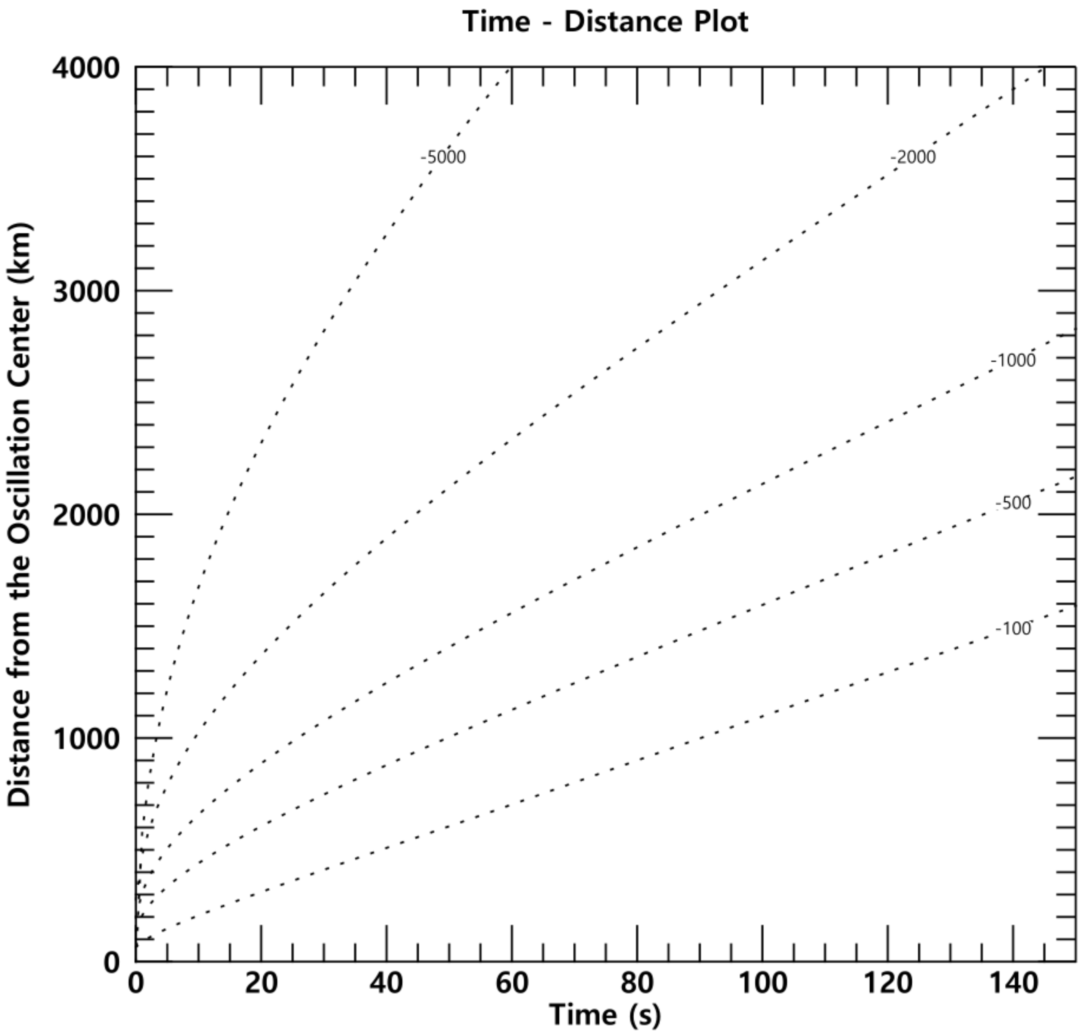




Effect of Source Depth

- Horizontal apparent wave
  - Deeper source depth
    ⇨ Faster
  - Distant from the oscillation center
    ⇨ Deceleration



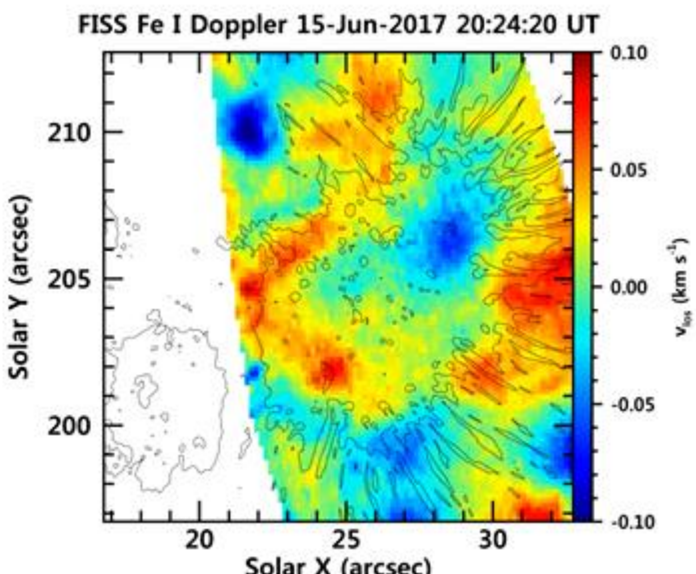


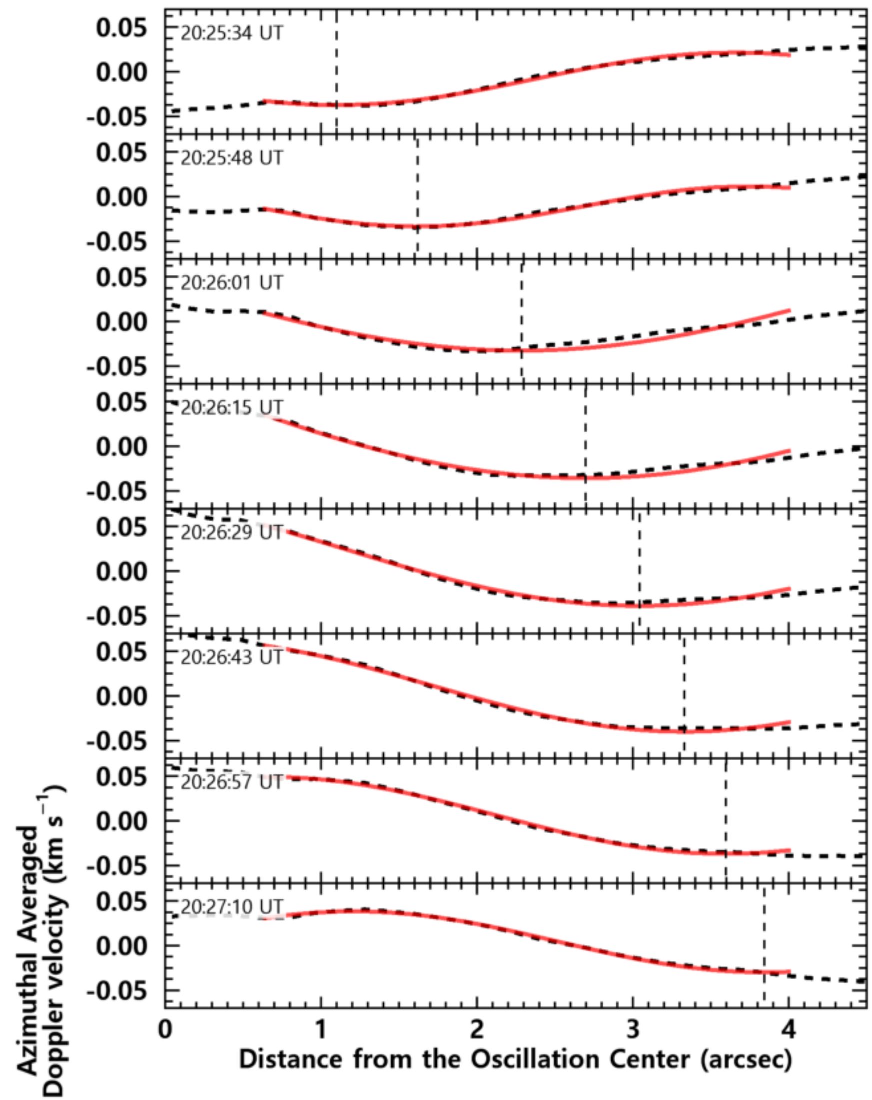
Measurement of Horizontal Propagation

- Trace a blueshift position
  - Azimuthally averaging
  - Fit sinusoidal function

    $v_{Dop} = a_0 \sin(a_1 x + a_2) + a_3$
  - Minimum position

    $a_1 x + a_2 = 3\pi/2$
  - Receding from the oscillation center

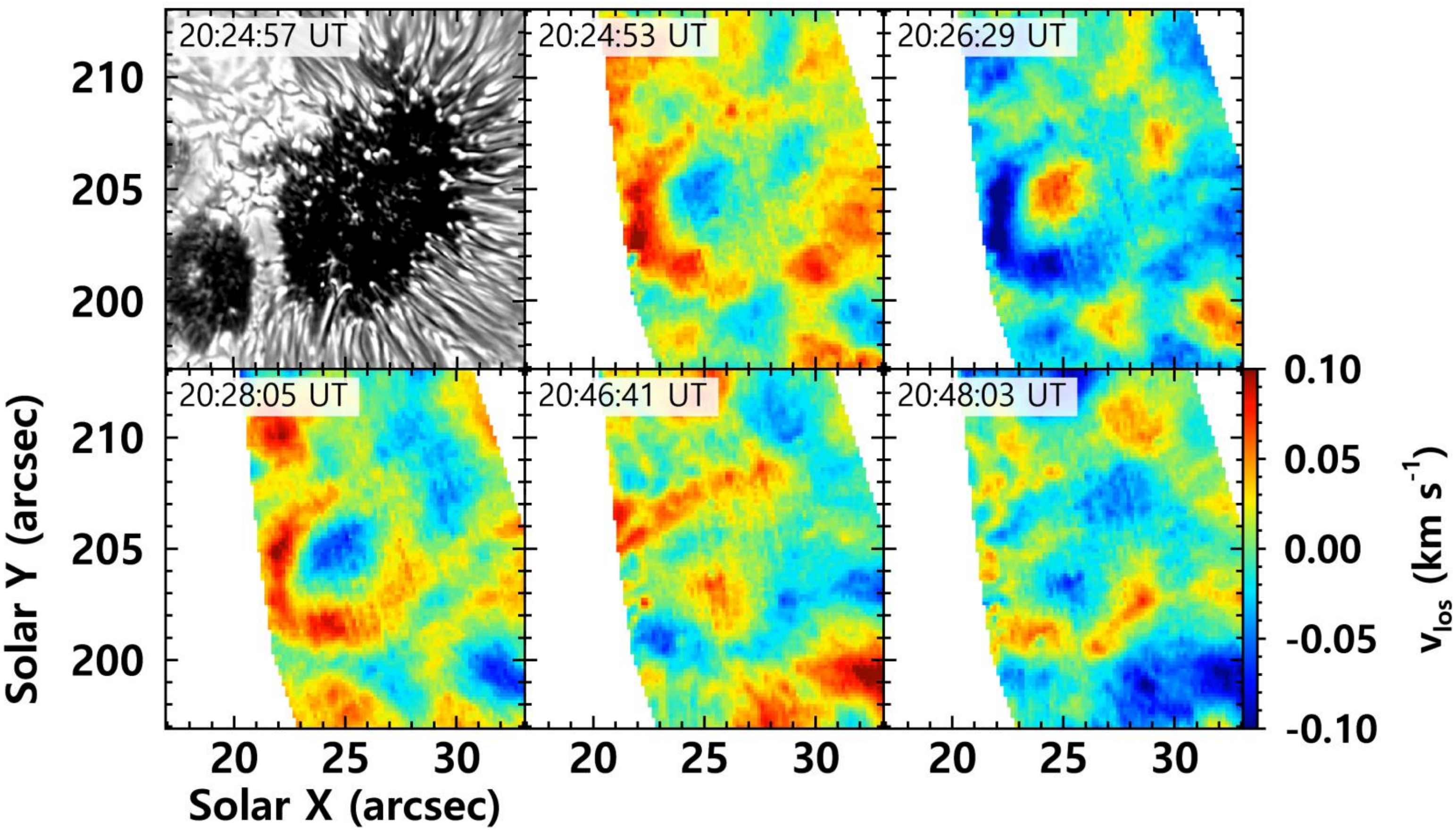




Cho & Chae (2020)

Horizontal Propagation

- Trace blue / redshift positions of 5 ripples

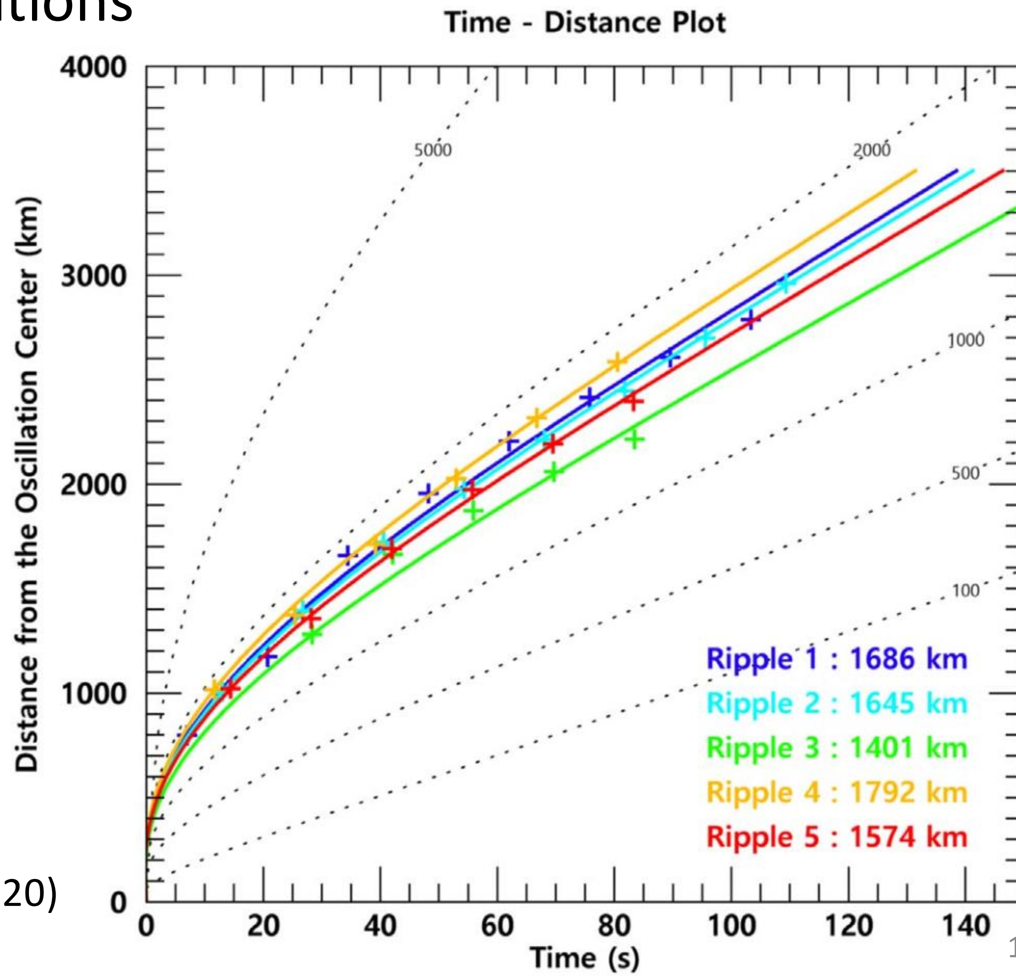


Cho & Chae (2020)

Source Depth

- Depth estimation : 1000 ~ 2000 km
- Similar to the model calculations

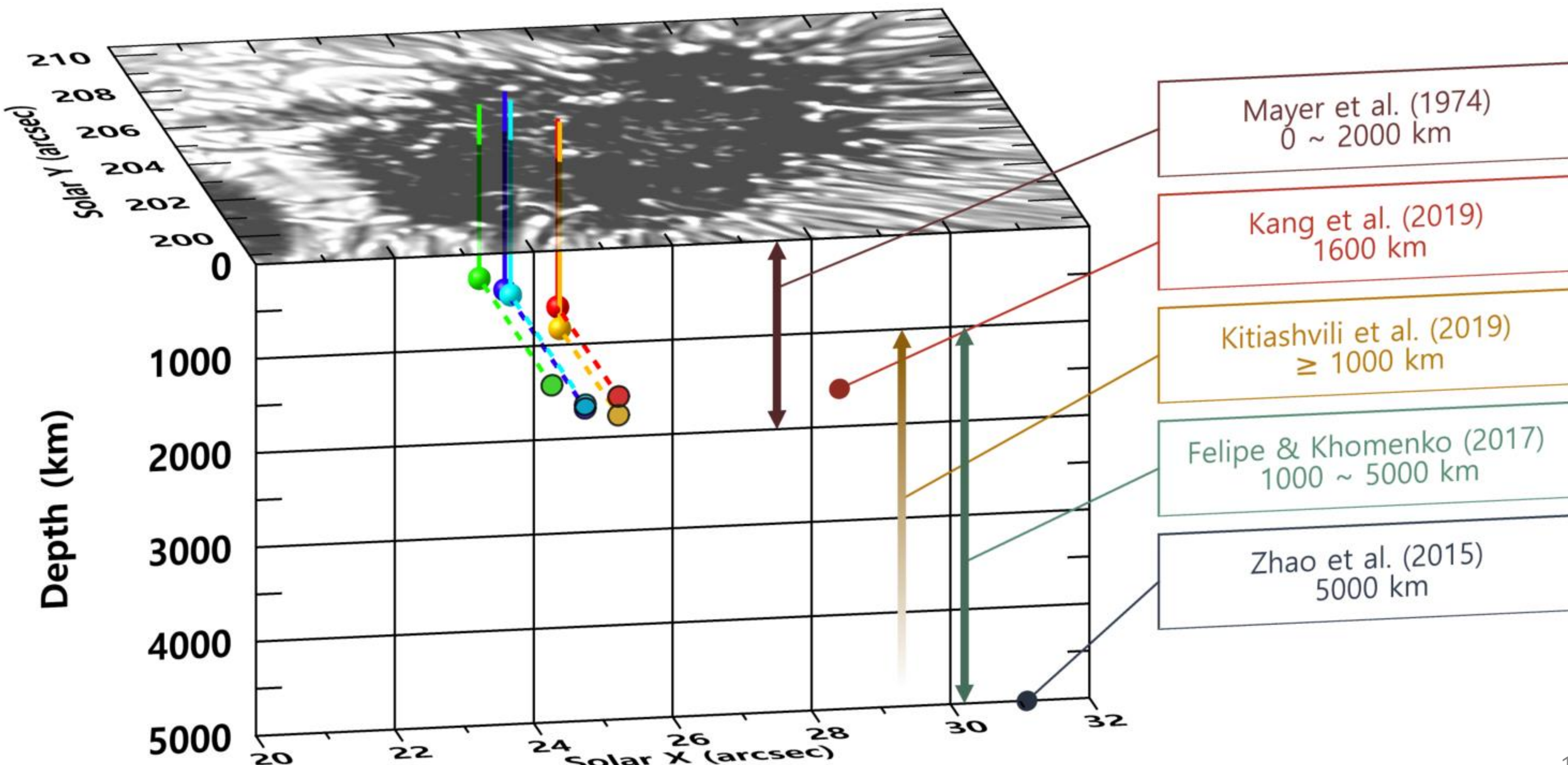
  ⇨ Deceleration



Cho & Chae (2020)

Previous Studies

- Depth estimation : 1000 ~ 2000 km
- Consistent with previous studies



Cho & Chae (2020)

Summary

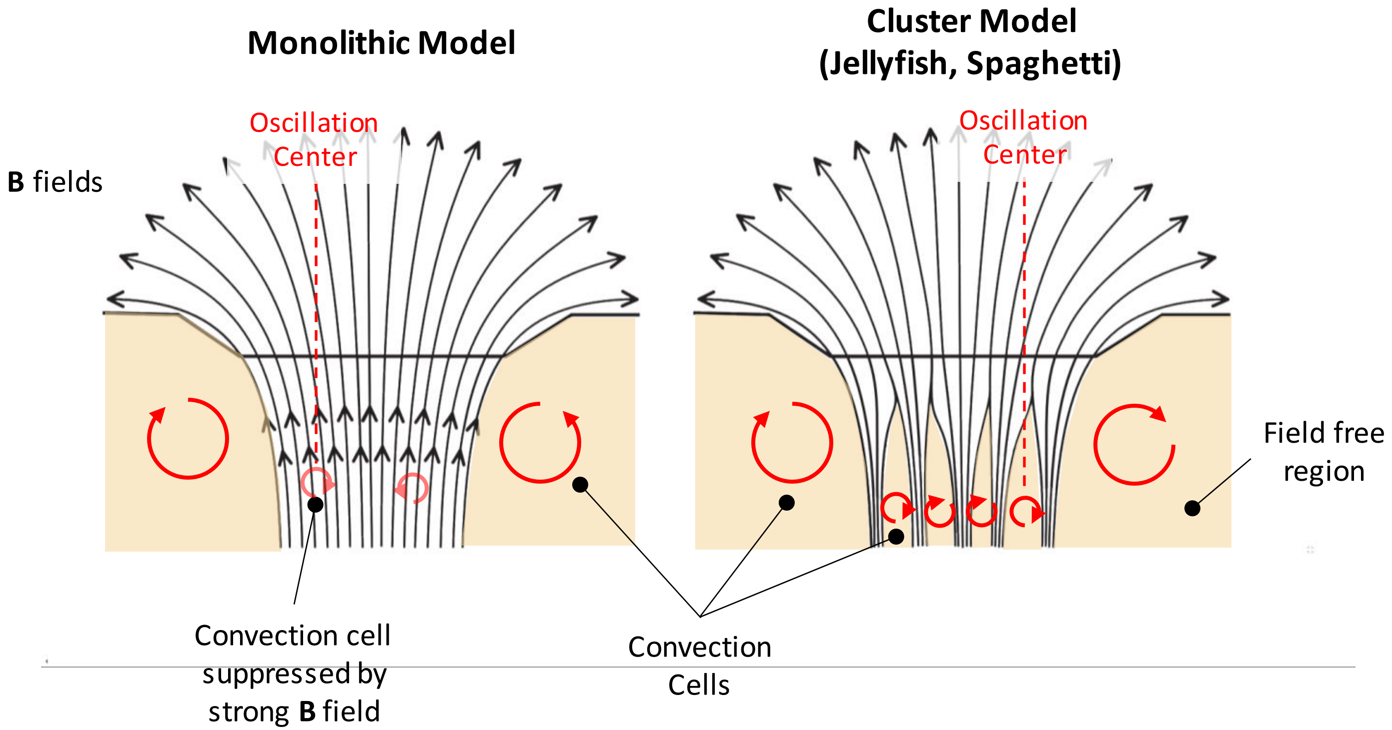
- Origin of 3-min umbral oscillations
  - Convective motion inside sunspot umbra

- Apparent propagating speed of 3-min umbral oscillations
  - Estimation of source depth

- Distribution of convection cells below the sunspot?

  ⇨ Sunspot subsurface structure !

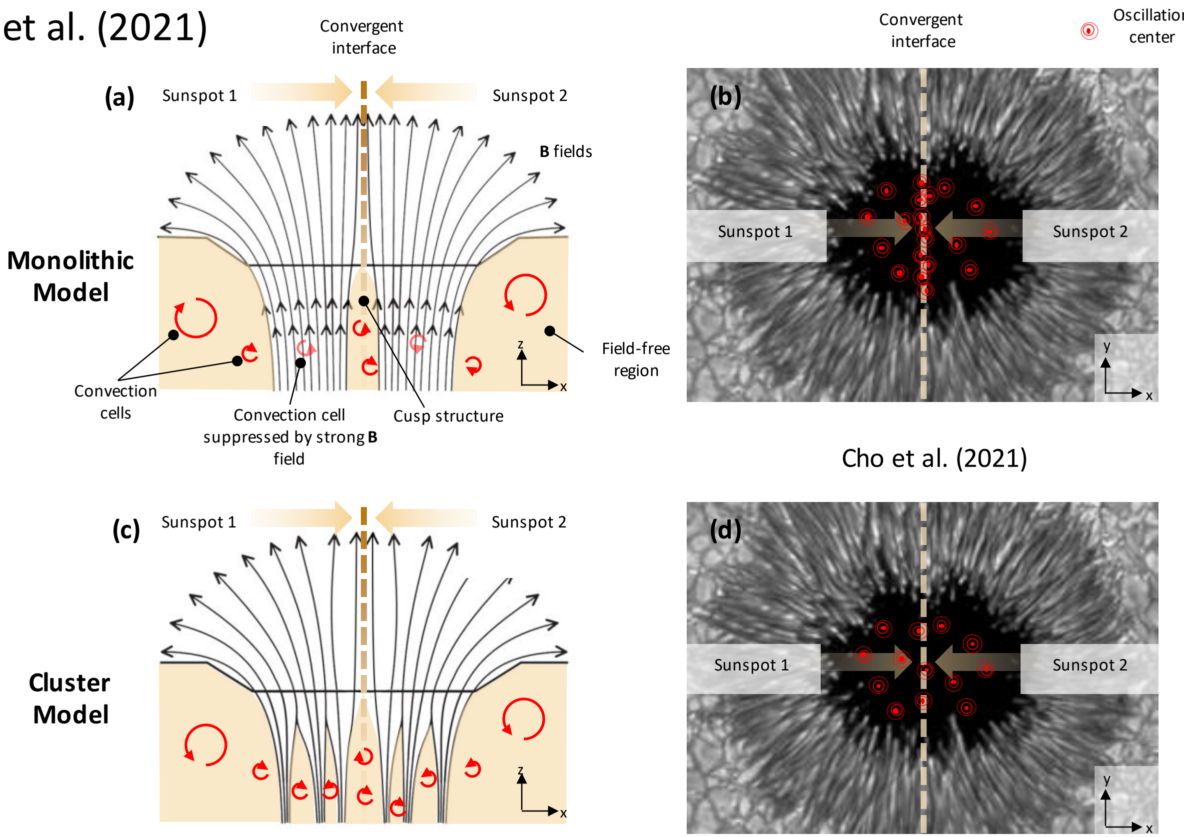
Convection Cells



- Convection: **B** Field region << Field free region
- Magneto-convection Vs Convection in the field free hot gas
- No information about the absolute value of the convection occurrence rate

Merging Sunspot Case

Cho et al. (2021)



# of oscillation centers

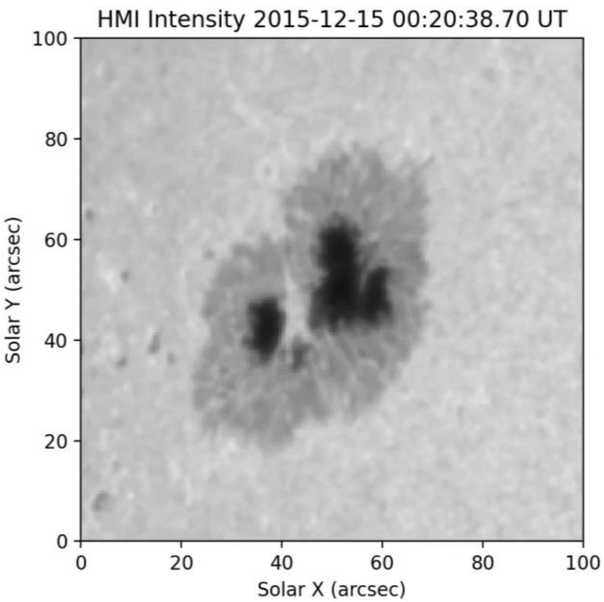
Convergent interface $\gg$ umbra

Convergent interface $\simeq$ umbra

- Distribution of the oscillation centers (convection cells)
  ⇨ Clue for sunspot’s subsurface structure

Observational Data

- Merging sunspot observed by IRIS SJI Mg II 2796 Å



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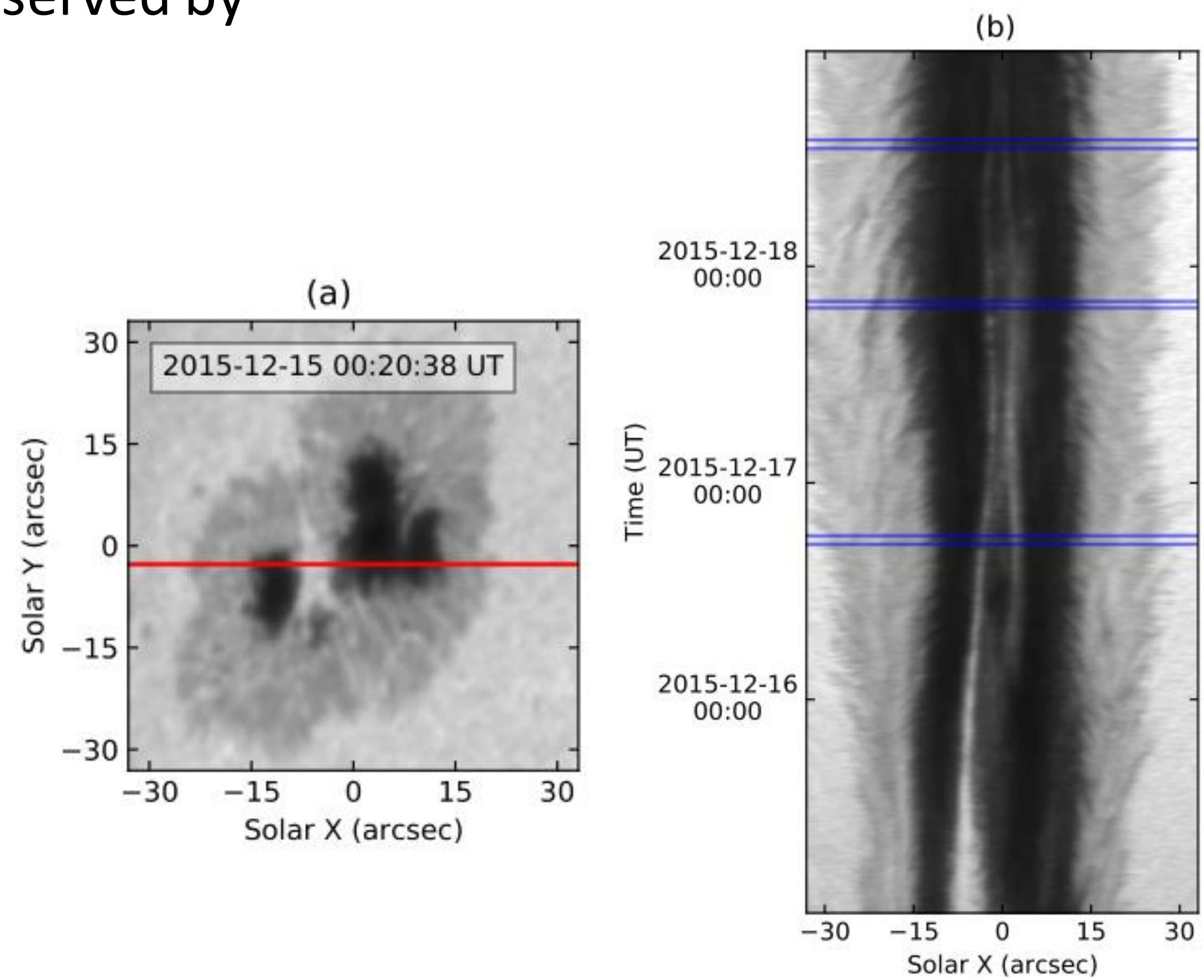
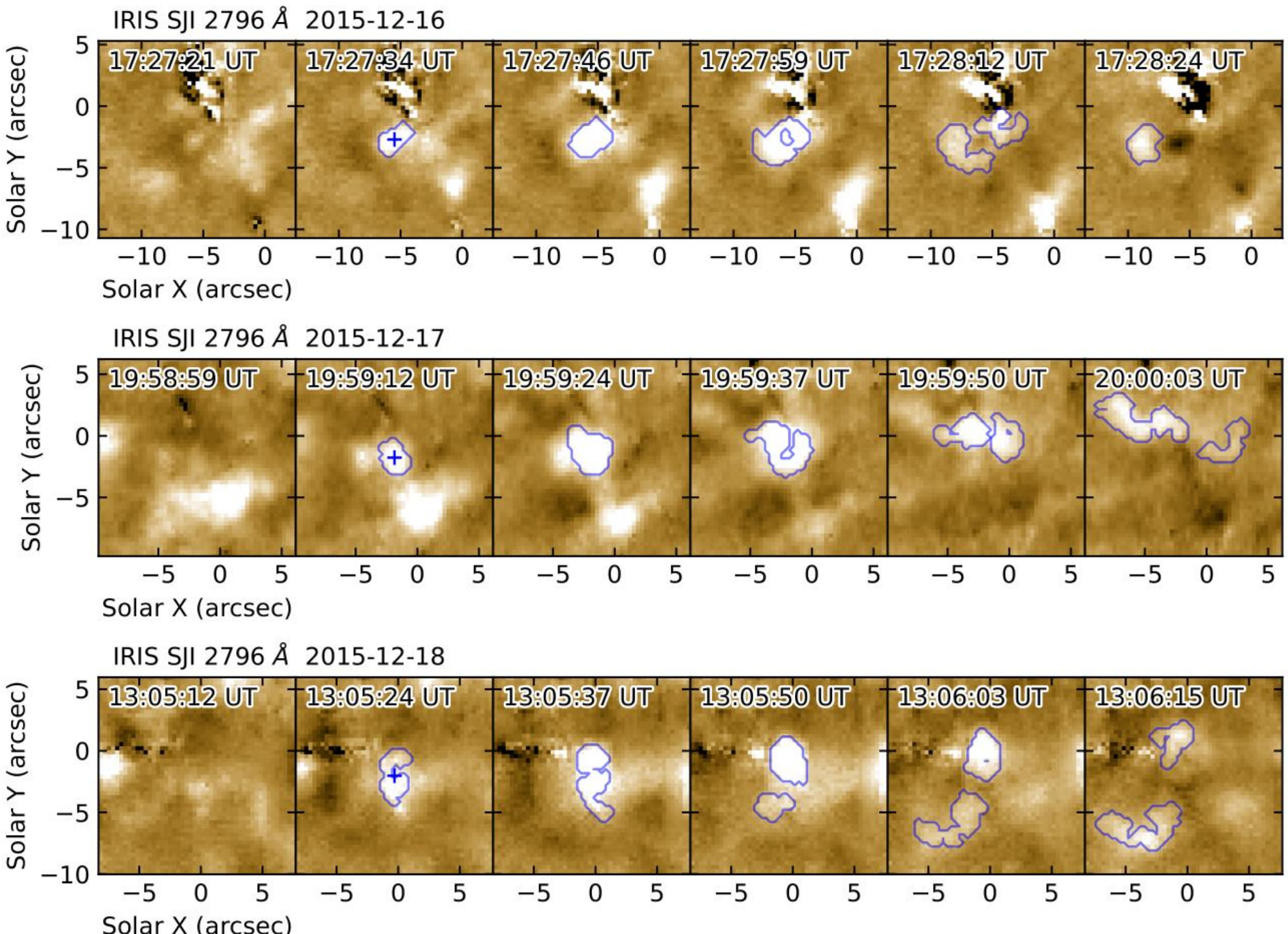


Examples of Oscillation Centers



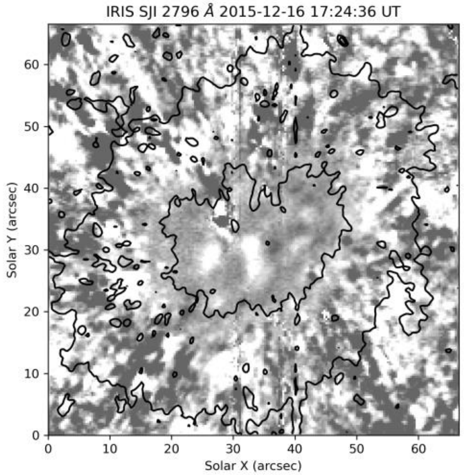
Cho et al. (2021)

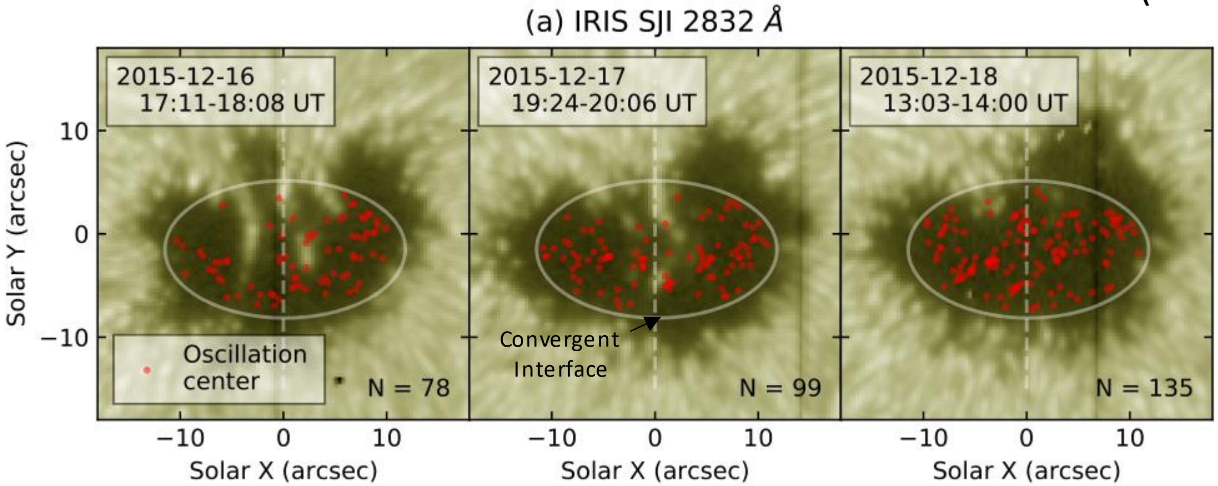
Positions of Convection Cells

- Merging sunspot observed by IRIS SJI Mg II 2796 Å
- Analyzing the motion of umbral flashes
- Determine the position of oscillation centers
- Role of the convergent interface? probably not!
- Below the umbra – similar to the convergent interface

  ⇨ supports to the cluster model

Cho et al. (2021)





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