Where do running penumbral waves emerge in Chromosphere?

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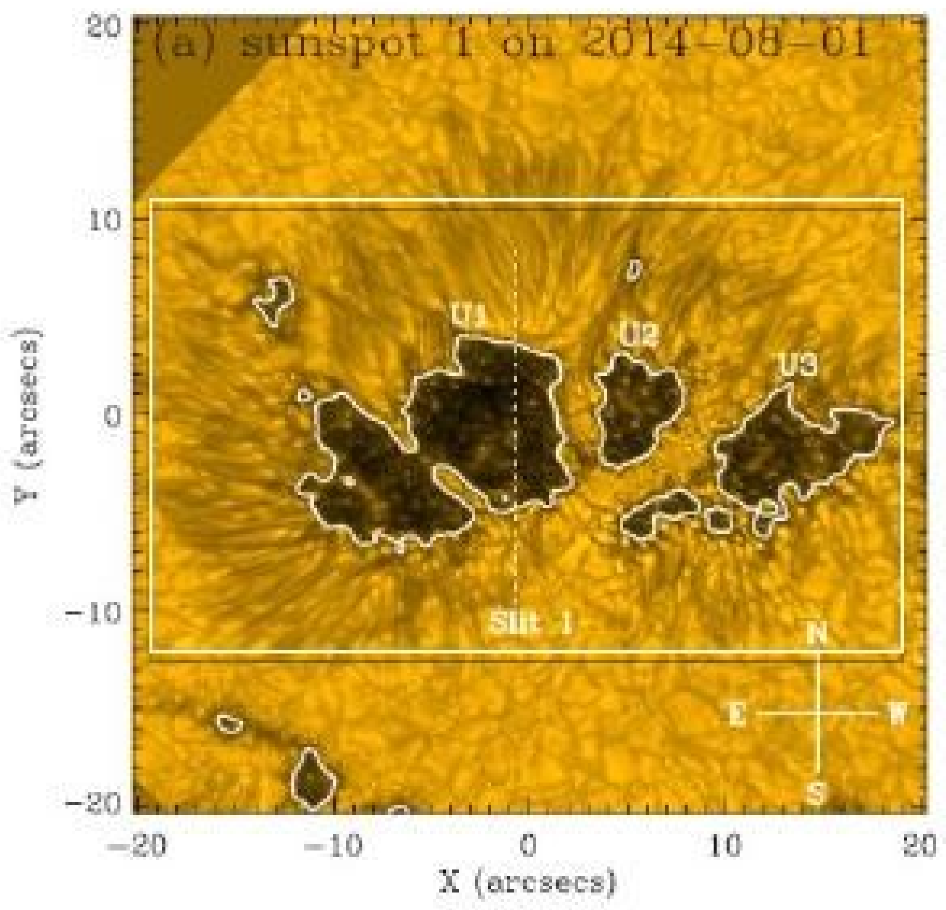
Umbral and Penumbral Oscillations

TiO **AR 12127**



- Running penumbral waves (RPWs)
- - Zirin & Stein 1972; Giovanelli, 1972

- Umbral oscillations: Photosphere and Chromosphere - Beckers & Schultz; Giovanelli, 1972

- RPWs : Period of 3-5 min
- Outward propagation - Phase velocity of
  10 - 40 Km/s : Inner penumbra
  2 - 3 Km/s : Outer Penumbra:
- - Brisken & Zirin 1997; Sigwarth & Mattig 1997; Tsiropoula et al. 1996, 2000

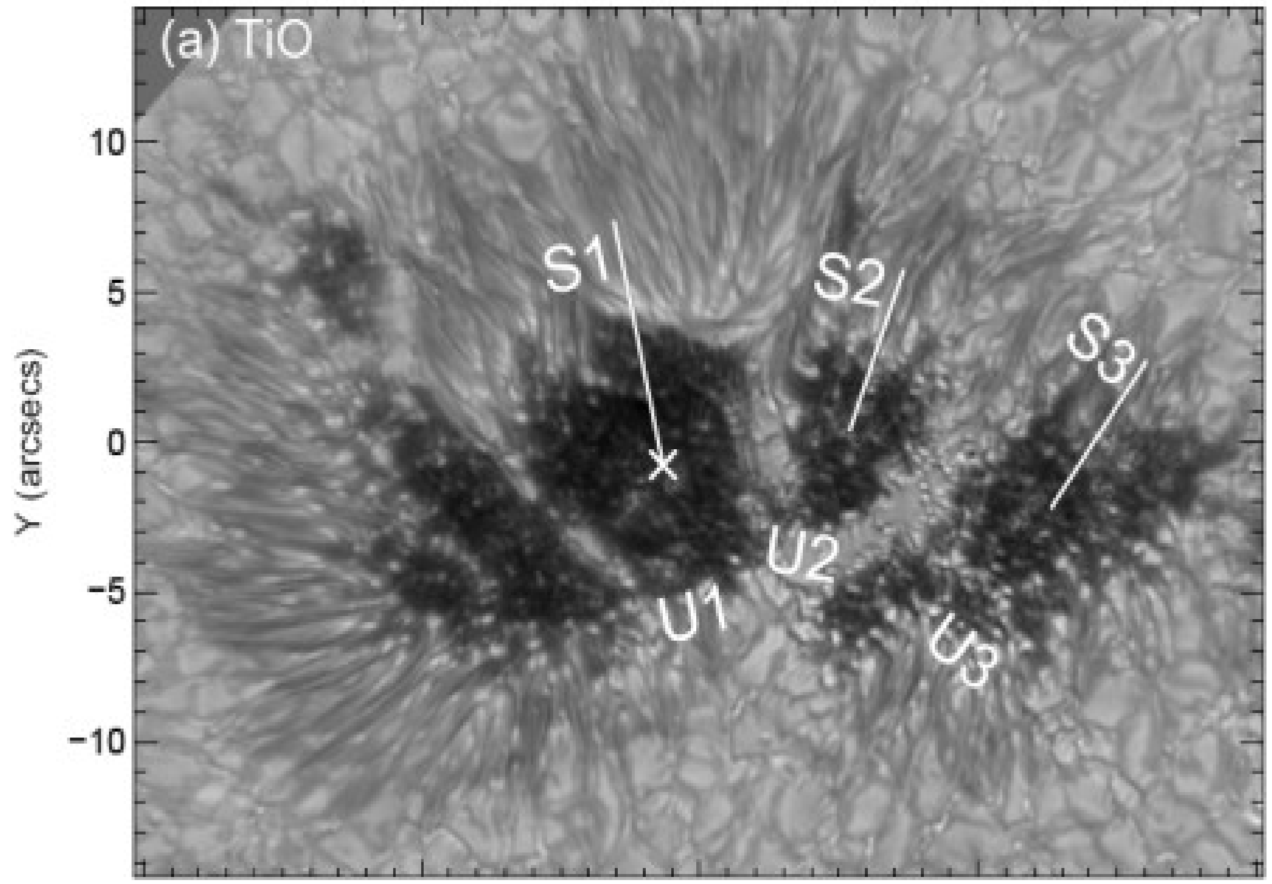
Umbral and Penumbral waves - Low-slow-mode waves - Bogdan & Judge (2006)

Relationship between RPWs (5-min) and umbral oscillations (3-min) is not well understood

Active region NOAA 12127

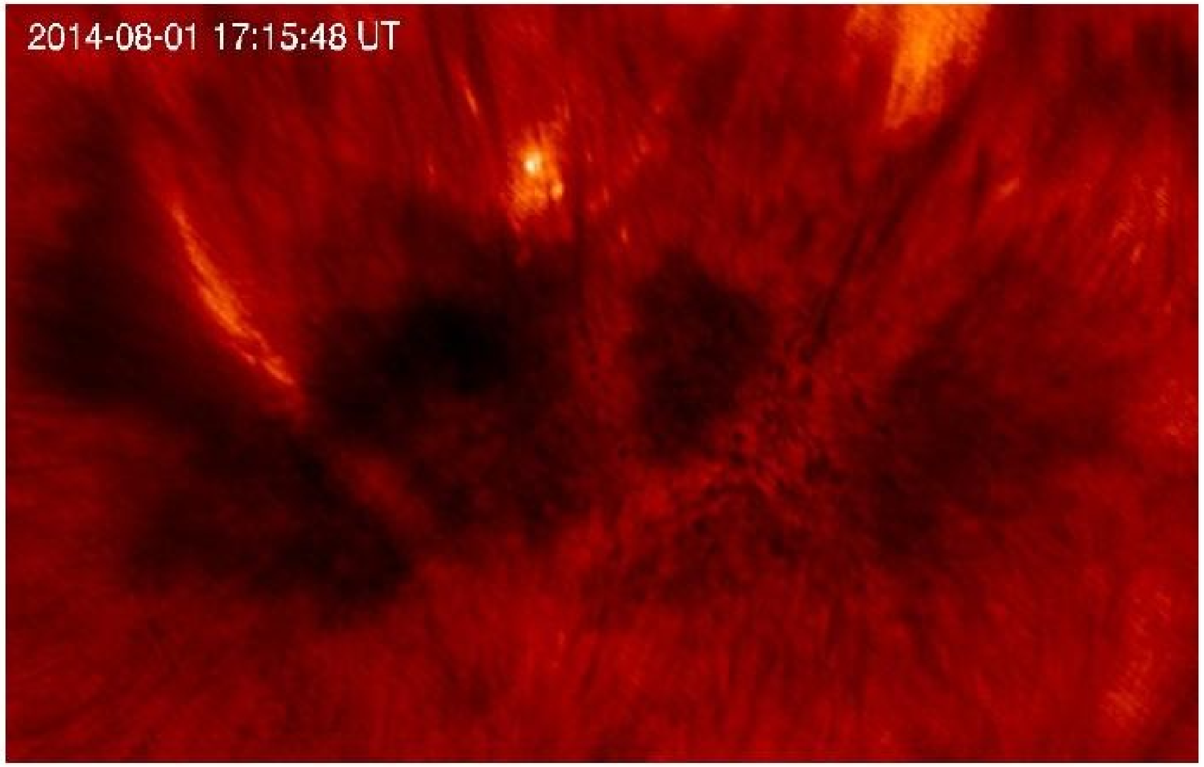
Observations: 1.6 m NST/BBSO

- 2014/08/01 17:15-17:55 UT
- TiO : FOV 70"x70"; Cad - 15 s

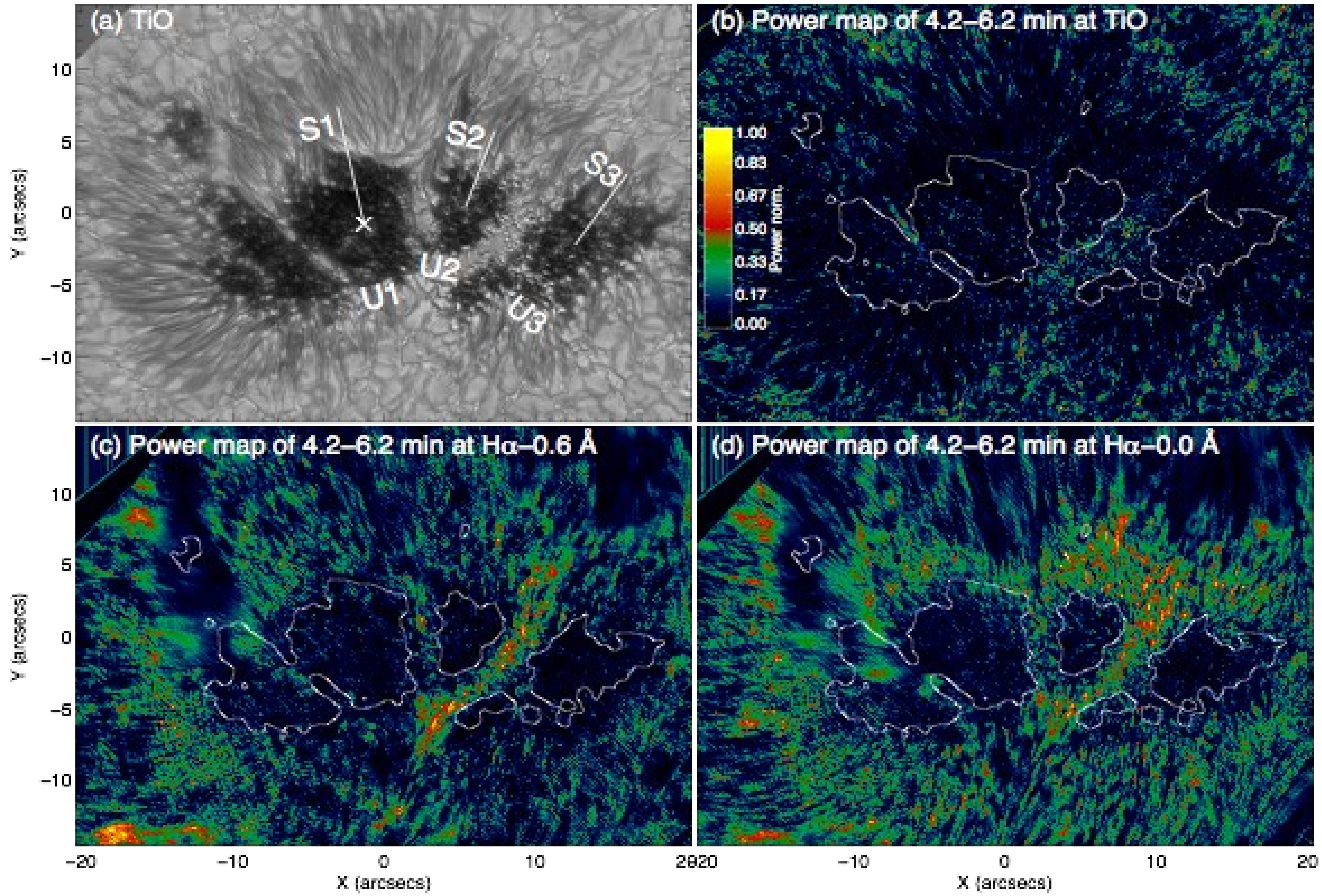


- *2014/08/01 17:15-17:55 UT*
- *Hα: FOV 70"x70"; Cad - 23 s*
- *6563±1.0, ±0.8, ±0.6, ±0.4, ±0.2 & 0 Å*

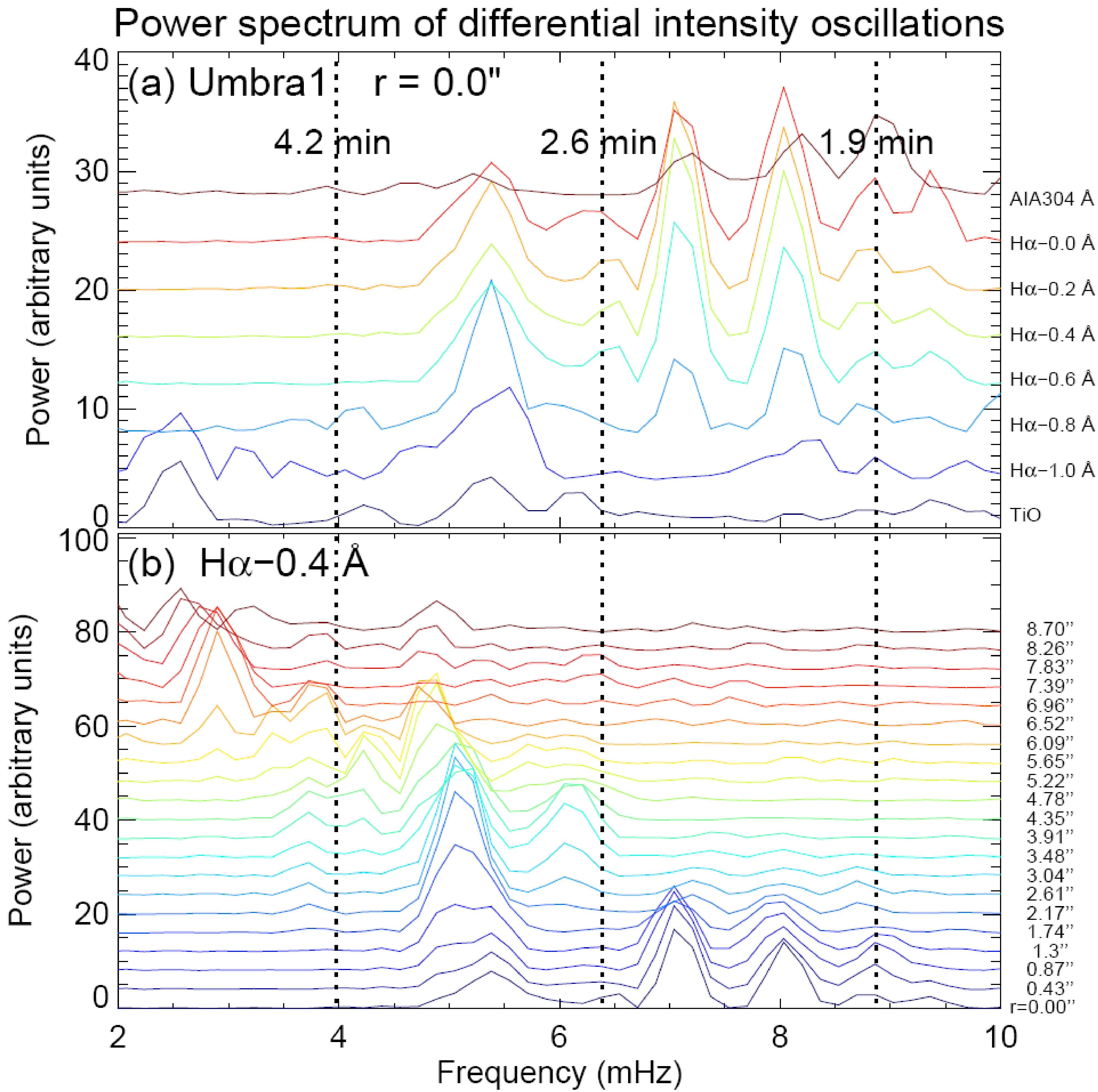
Hα-0.4 Å



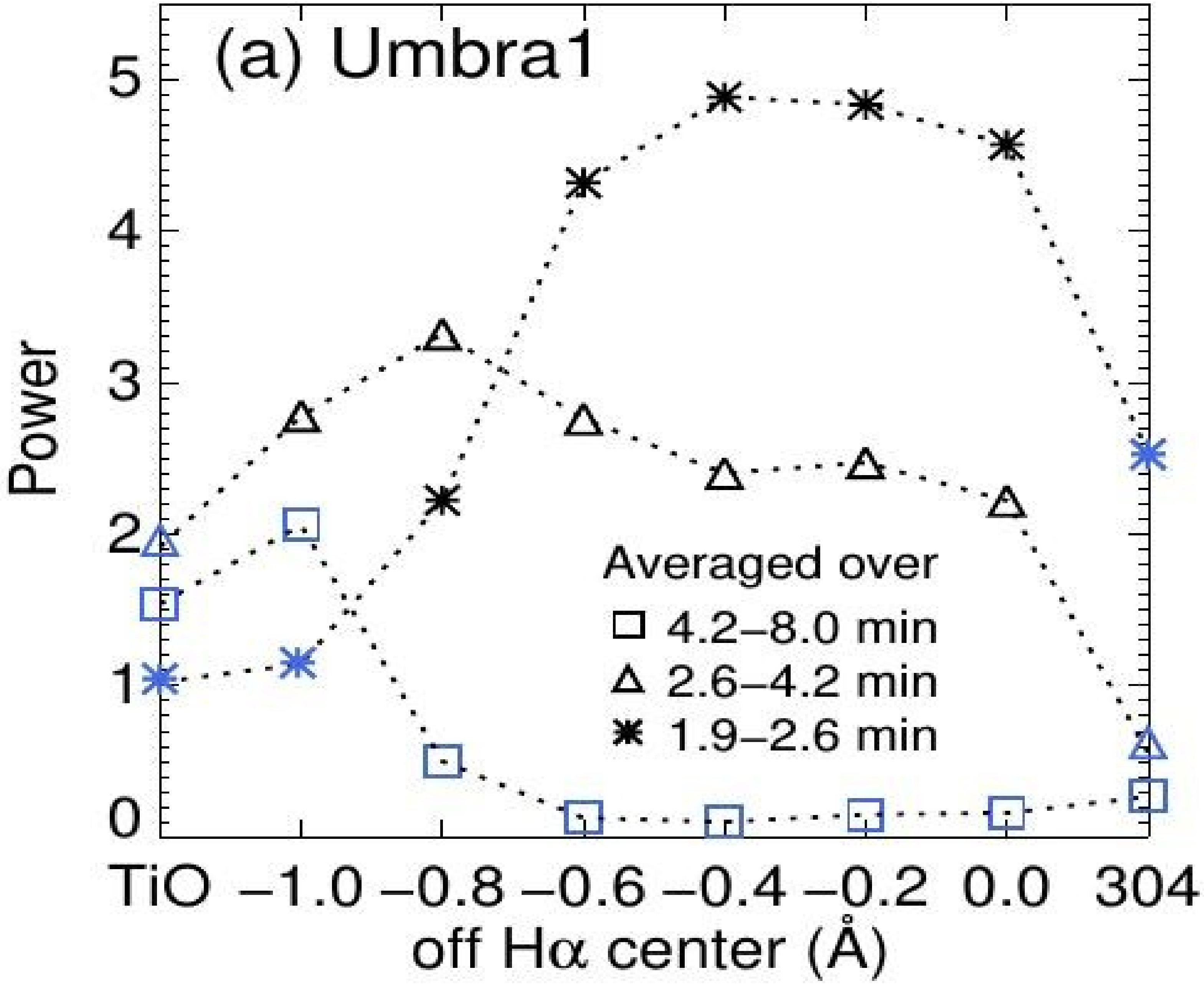
Power maps



(a) TiO
S1
S2
S3
U1
U2
U3
(b) Power map of 4.2–6.2 min at TiO
1.00
0.83
0.67
0.50
0.33
0.17
0.00
Power norm.
(c) Power map of 4.2–6.2 min at Hα–0.6 Å
(d) Power map of 4.2–6.2 min at Hα–0.0 Å
Y (arcsecs)
X (arcsecs)
10
5
0
−5
−10
−20
20



Power spectrum of differential intensity oscillations
(a) Umbra1 r = 0.0"
4.2 min
2.6 min
1.9 min
AIA304 Å
Hα−0.0 Å
Hα−0.2 Å
Hα−0.4 Å
Hα−0.6 Å
Hα−0.8 Å
Hα−1.0 Å
TiO
Power (arbitrary units)
(b) Hα−0.4 Å
8.70''
8.26''
7.83''
7.39''
6.96''
6.52''
6.09''
5.65''
5.22''
4.78''
4.35''
3.91''
3.48''
3.04''
2.61''
2.17''
1.74''
1.3''
0.87''
0.43''
r=0.00''
Frequency (mHz)



$$f_c = \frac{g\gamma}{4\pi c_s} = 1.28 g_0 cos\theta T_{min}^{-0.5} [mHz].$$

f_c = 5.8 mHz (2.9 min)

Reznikova et al. (2012)

Propagation height of short period oscillations:

$$d = 2\Lambda log_e(1 + \frac{Pc_s^2}{2(\gamma + 1)\Lambda v_1}),$$ → Distance required for a shock to form in the stratified medium

(Stein & Leibacher 1974)

where $\gamma = 5/3$, $c_s = 9.6$ km s^{-1}, $P = 1.9$ min, $\Lambda = 200$ km (scale height) and v_1=1 km s^{-1}

d $\sim$1000 km → Formation height of Hα -0.4Å

Propagation height of long period oscillations in chromospheric umbra:

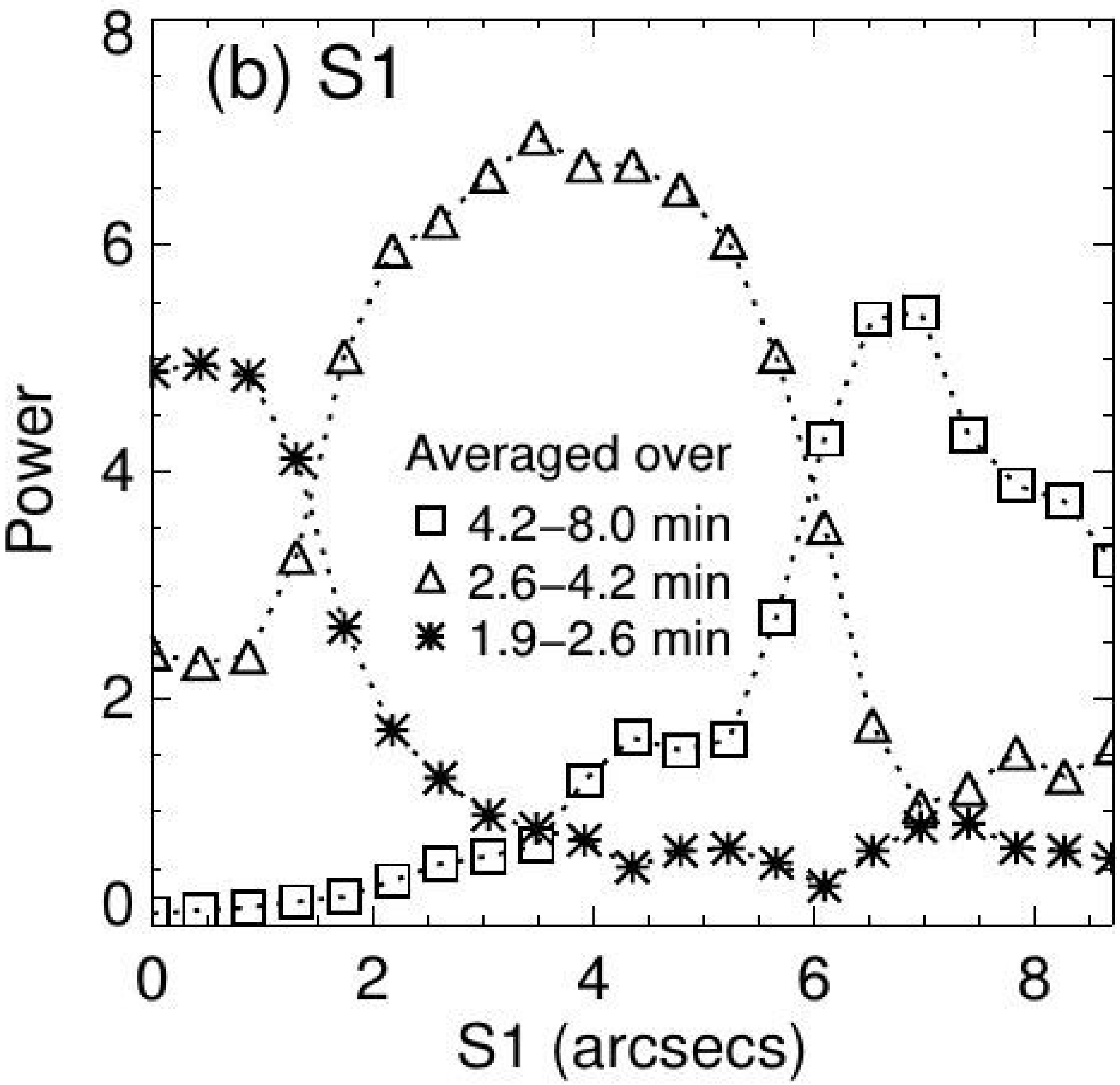
$$\frac{P_{chromo}}{P_{photo}} = \frac{\rho(photo)}{\rho(chromo)} \sim \exp^{(z/\Lambda)}$$

(*Bogdan & Judge 2006; Wang et al. 2009; Priest 2014*)

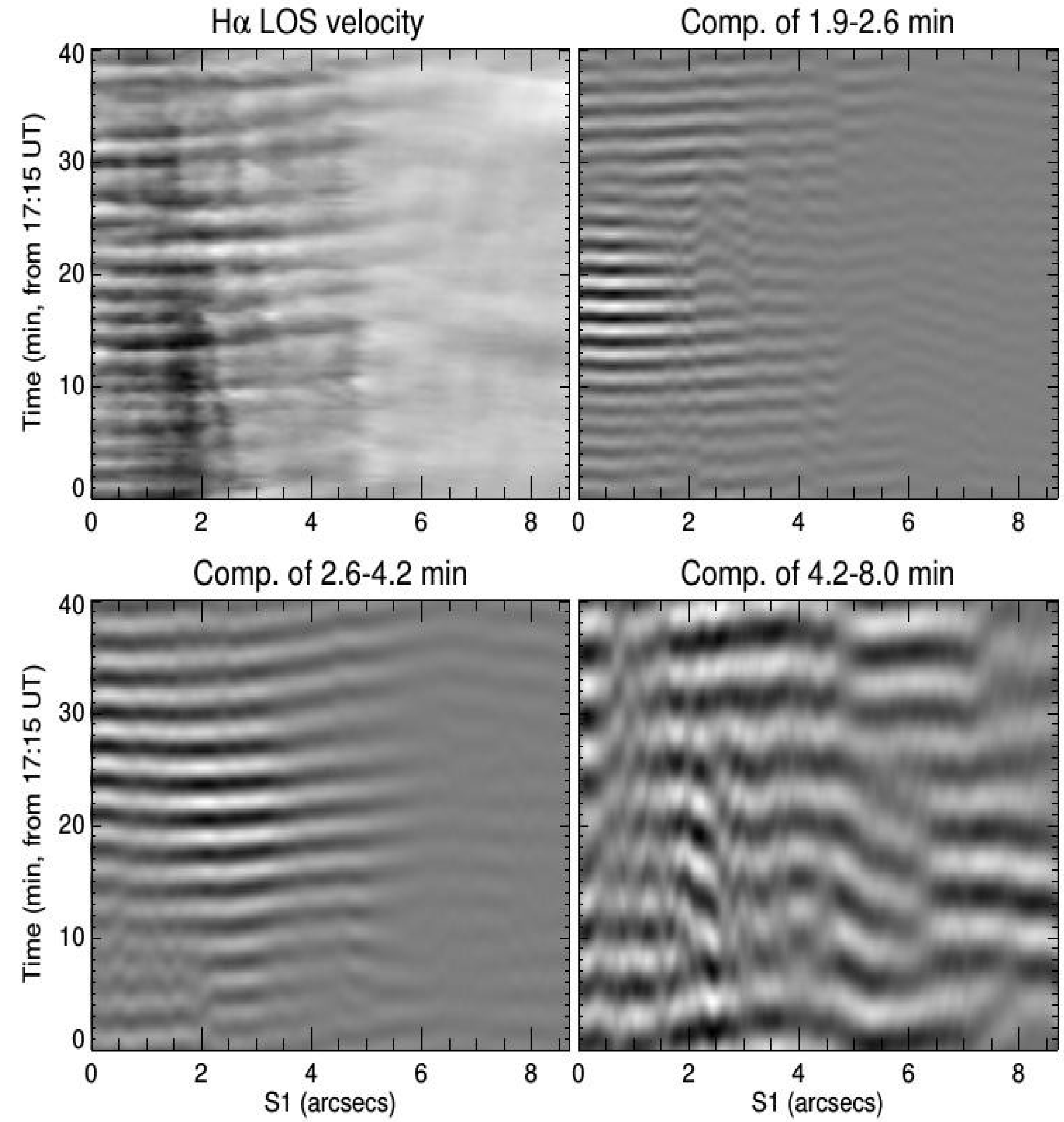
Λ falls in the range of $200 - 500$ km for a given temperature range 4000-10000 K

$\bar{h} \sim 300$ km → Formation height of Hα -0.8Å

Power variation with distance from umbral center



Space-Time plot for LOS velocity of Hα



$$P_{4.2-8.0\,\mathrm{min}}/P_{2.6-4.2\,\mathrm{min}} \approx 5\%$$

$$P_{4.2-8.0\,\mathrm{min}}/P_{1.9-2.6\,\mathrm{min}} \approx 3\%$$

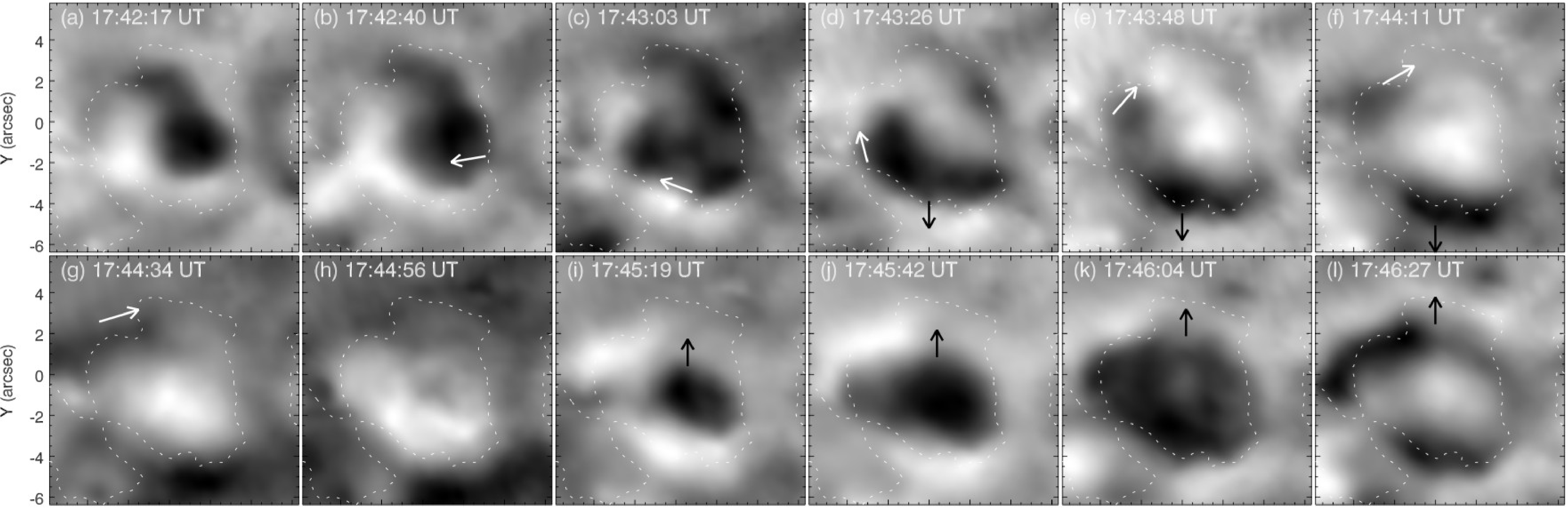
Intensity oscillations are no longer detected when their amplitudes are decreased by a factor of about four (De Moortel & Hood 2003).

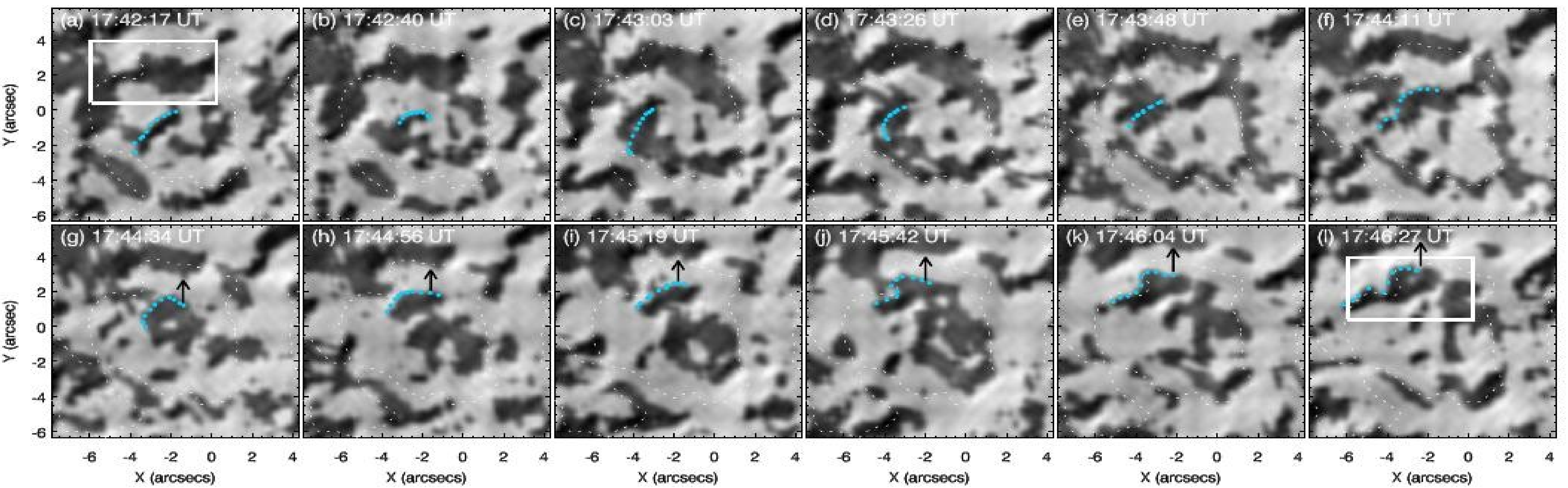
Weaker long period oscillations are difficult to detect over the dominant part of short and/or middle-period oscillations in sunspot

Phase-speed filter (at the passband of Hα-0.4 Å)

$H^{low}(v, v_c) = \frac{1}{1+[\frac{v}{v_c}]^{2n}},$	$v > 14 \ km/s$	Umbral waves
$H^{low}(v, v_{c1}) * H^{high}(v, v_{c2})$	$4 < v < 14 \ km/s$	Penumbral waves
$H^{high}(v, v_c) = \frac{1}{1+[\frac{v_c}{v}]^{2n}},$	$v < 4 \ km/s$	Fine structures

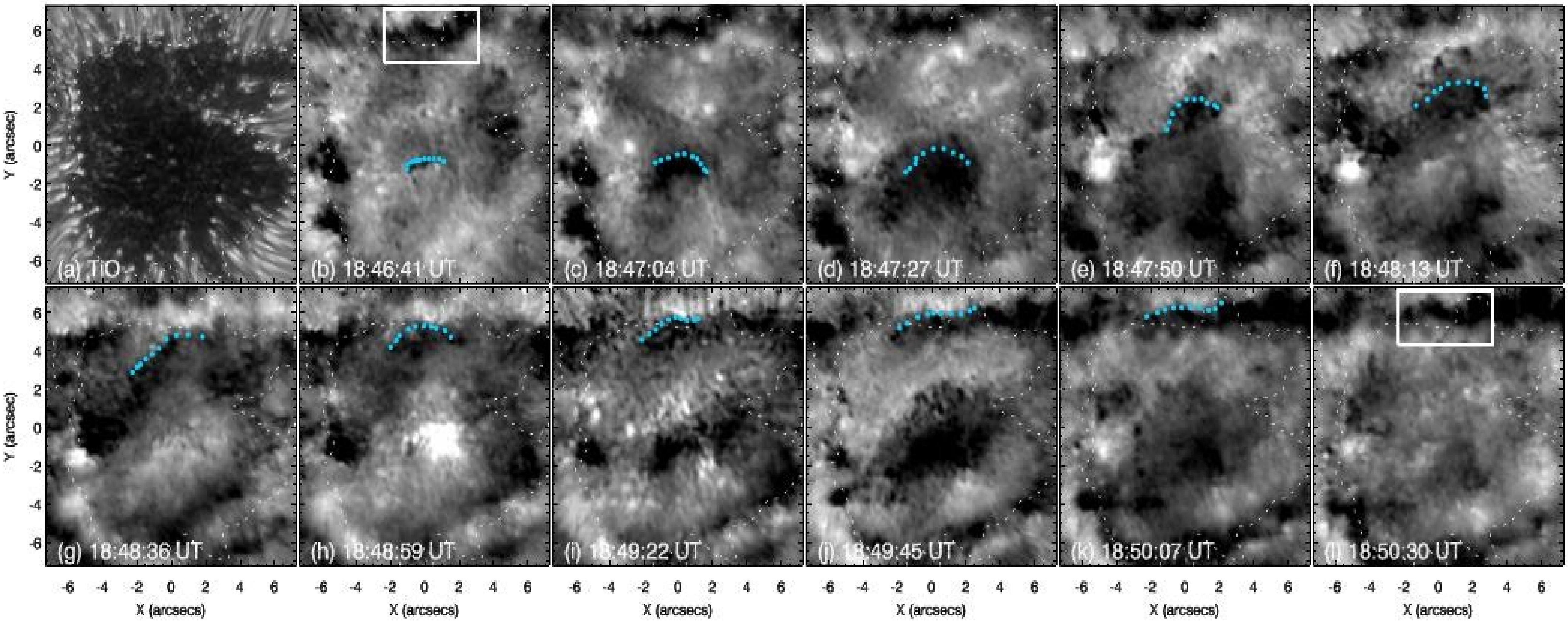
Frequency filter





The mean intensity of the top panels is 2% of the bottom ones

Single sunspot of NOAA AR 12132



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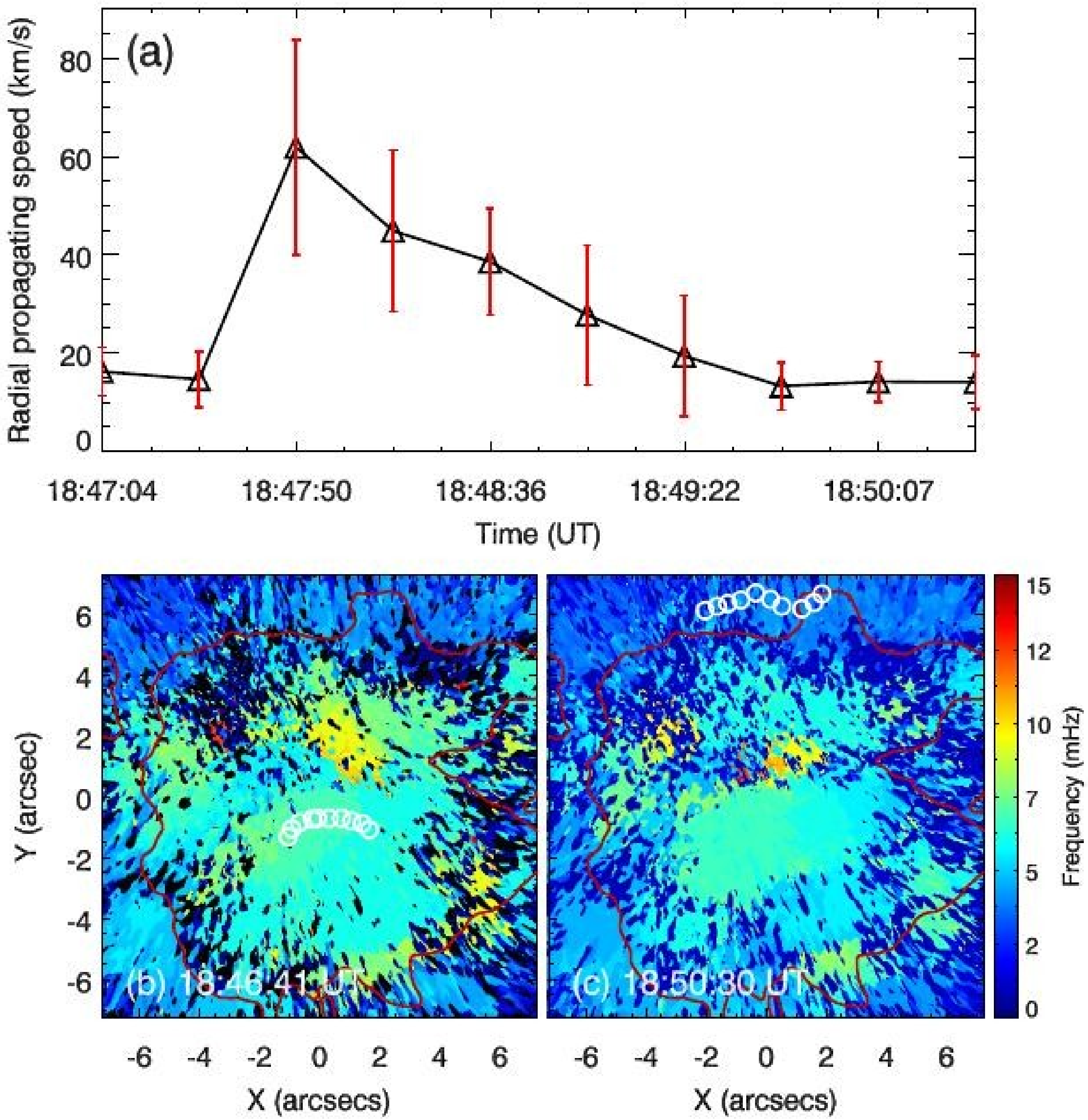
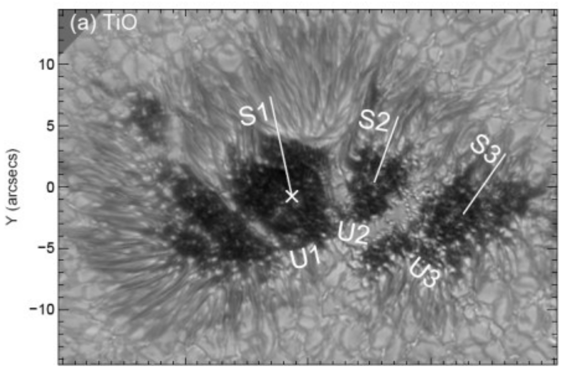
Hα − 0.4 Å images with phase speeds v > 4 km/s



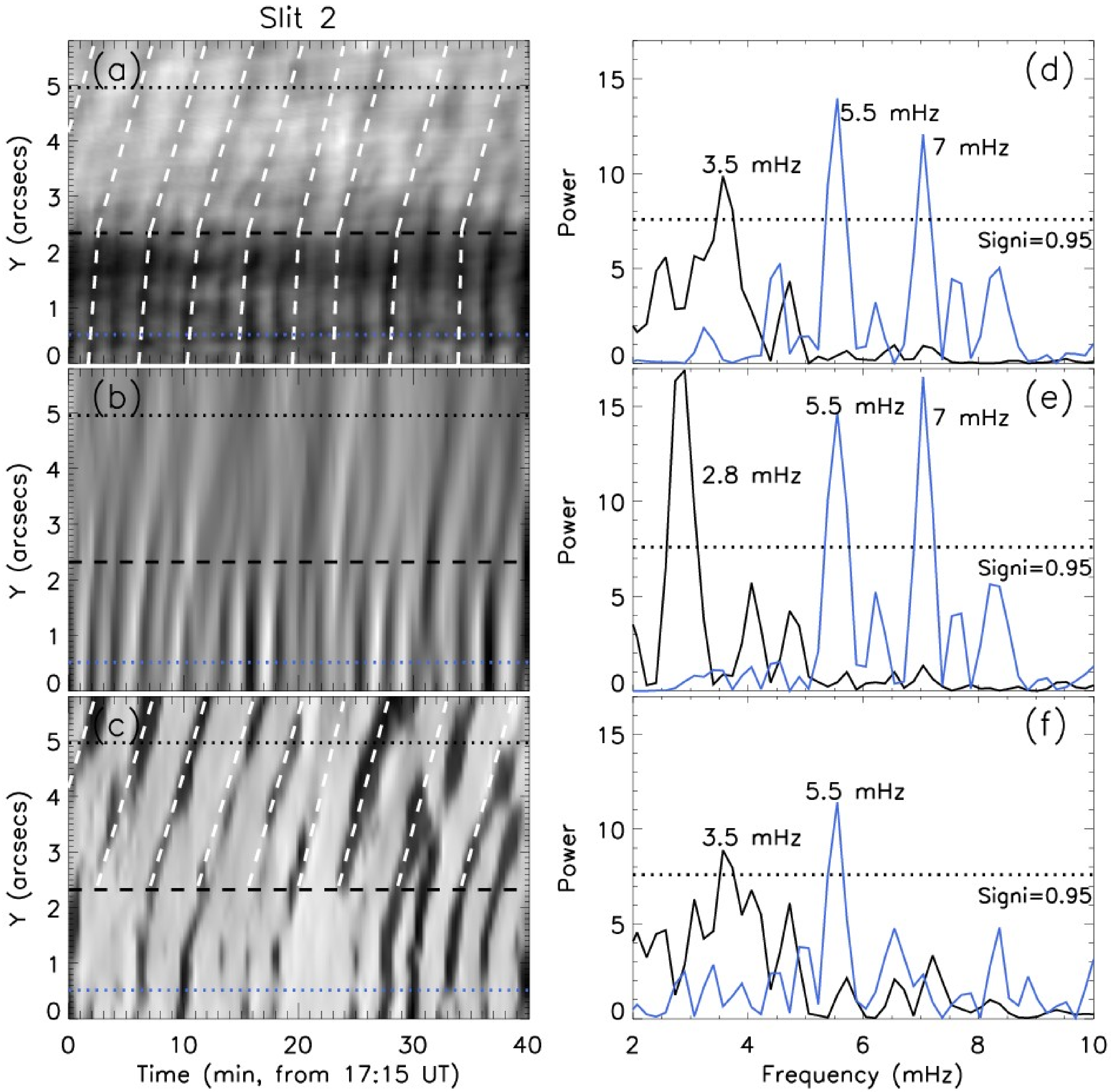
Radial propagation velocity of a wavefront

Distributions of dominant oscillating frequency of the umbra



$v > 14$ km/s

$4 < v < 14$ km/s



Results

- Umbral waves with periods of ≤ 3 min and ~ 4.2 min simultaneously emerge in the umbral centers
- ≤ 3 min waves would be evanescent after crossing the umbral boundaries
- ≥ 4.2 min waves become enhanced before crossing the umbral boundaries and finally develop into RPWs

THANK YOU