Helioseismic Evidence for Large-Scale Flow Cells in the Solar Convection Zone

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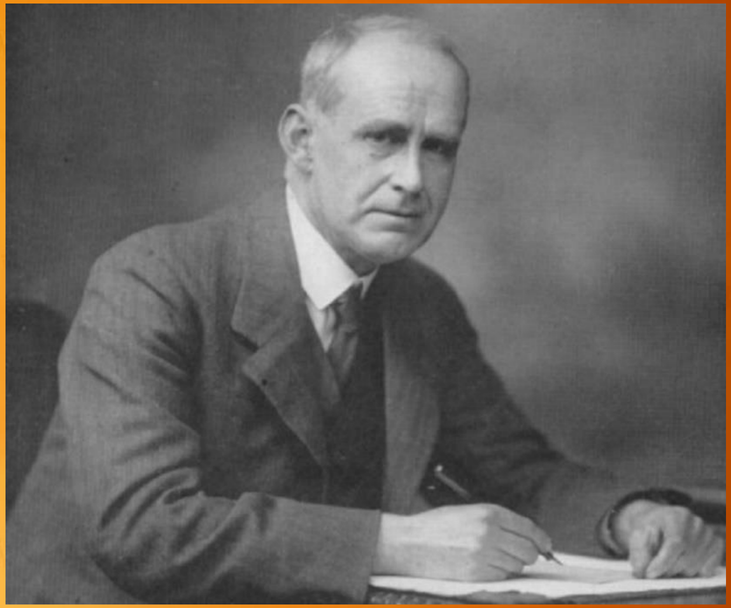


At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?

Sir A. S. Eddington, *The Internal Constitution of the Stars*, 1930

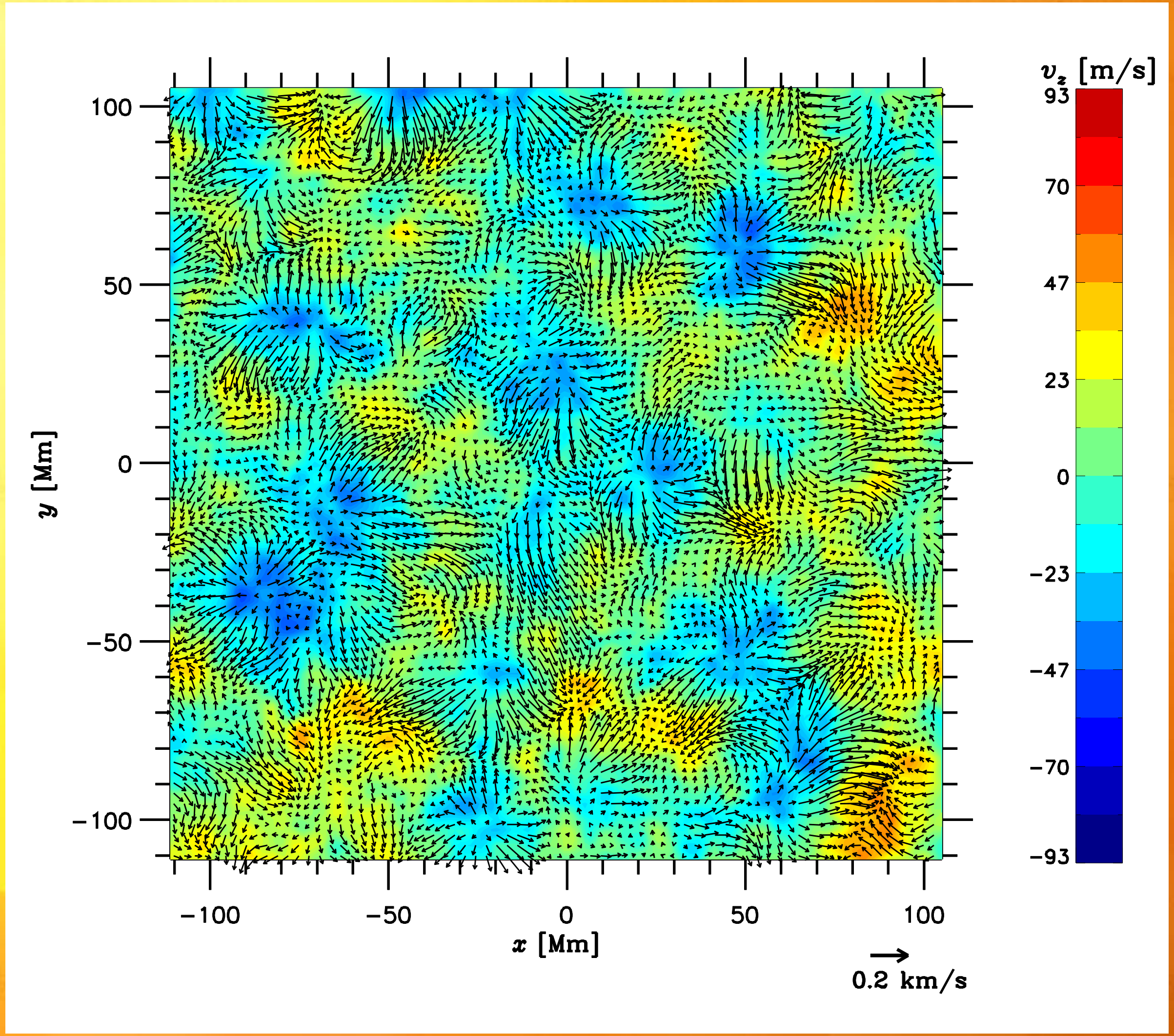
Our aim: investigation of the structure (and also dynamics) of convective flows in the subsurface layers of the Sun based on helioseismological data

Source data: velocity components v_x and v_y obtained using space–time helioseismology techniques from data of the Helioseismic and Magnetic Imager (HMI) of the Solar Dynamics Observatory (SDO) for May 2010 — September 2020.

These data are represented by 1026 × 1026 maps with a step of 0.12° in both heliographic latitude and longitude (123° × 123°) and a time cadence of 8 h for 8 levels under the photosphere:

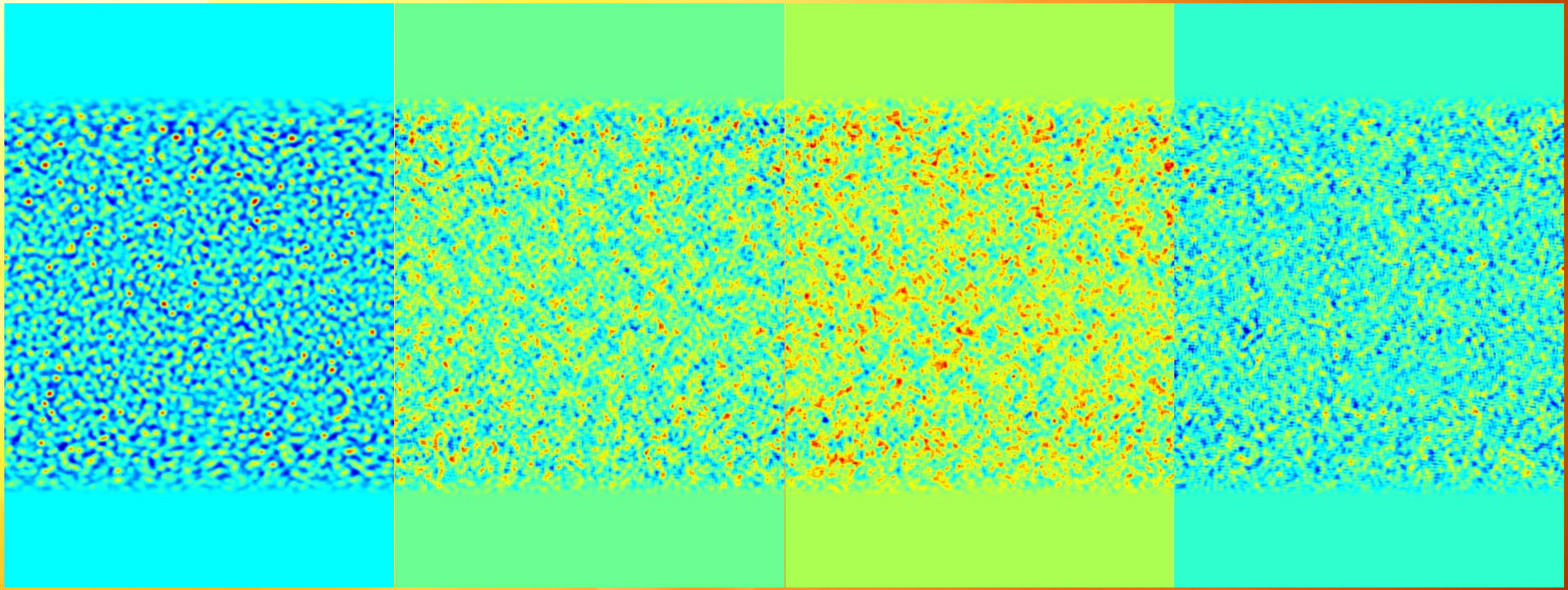
0. **d = 0.50 (0–1) Mm**
1. **d = 2.00 (1–3) Mm**
2. **d = 4.00 (3–5) Mm**
3. **d = 6.00 (5–7) Mm**
4. **d = 8.50 (7–10) Mm**
5. **d = 11.50 (10–13) Mm**
6. **d = 15.0 (13–17) Mm**
7. **d = 19.0 (17–21) Mm**

Velocity field inferred from helioseismological data



Divergence field for horizontal velocities

$$\operatorname{div} \mathbf{V}(\theta, \varphi) = \frac{1}{r \sin\theta} \frac{\partial}{\partial\theta} (V_\theta \sin\theta) + \frac{1}{r \sin\theta} \frac{\partial}{\partial\varphi} V_\varphi$$



d = 2 Mm *d* = 6 Mm *d* = 8.5 Mm *d* = 15 Mm

$$Y_{l1}^{m}(\theta,\varphi)=\sqrt{(2l+1)(2-\delta_{m0})\frac{(l-m)!}{(l+m)!}}P_l^m(\cos\theta)\cos m\varphi,$$

$$Y_{l2}^{m}(\theta,\varphi)=\sqrt{(2l+1)(2-\delta_{m0})\frac{(l-m)!}{(l+m)!}}P_l^m(\cos\theta)\sin m\varphi,$$

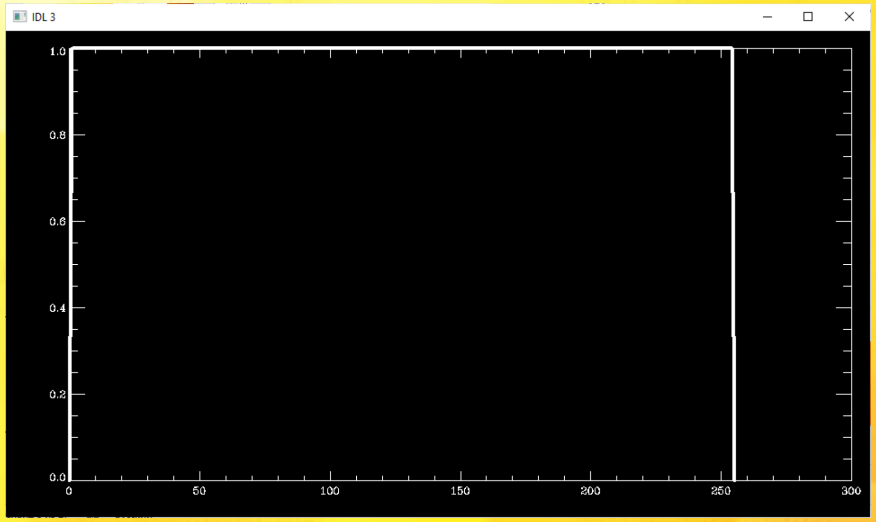
$$l=0,\dots,l_{\max},\quad m=0,\dots,l$$

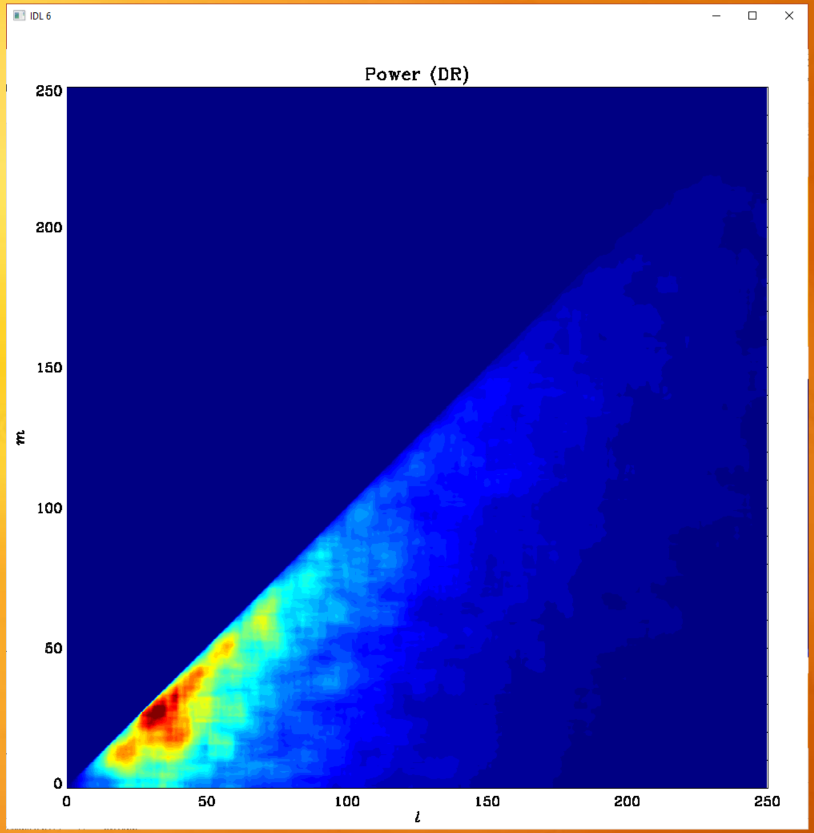
$$f(\theta,\varphi)=\sum_{l=0}^{l_{\max}}\sum_{m}^{l}\left[A_{lm}Y_{l1}^{m}(\theta,\varphi)+B_{lm}Y_{l2}^{m}(\theta,\varphi)\right]$$

$$A_{lm}=\frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}f(\theta,\varphi)Y_{l1}^{m}(\theta,\varphi)\cos\theta\,d\varphi\,d\theta$$

$$B_{lm}=\frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}f(\theta,\varphi)Y_{l2}^{m}(\theta,\varphi)\sin\theta\,d\varphi\,d\theta$$

The effect of the window function (as applied to convection simulations)





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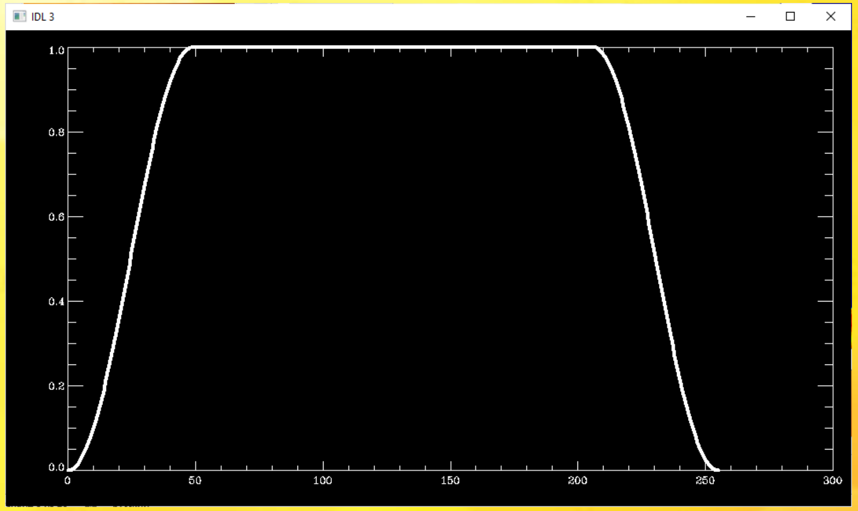

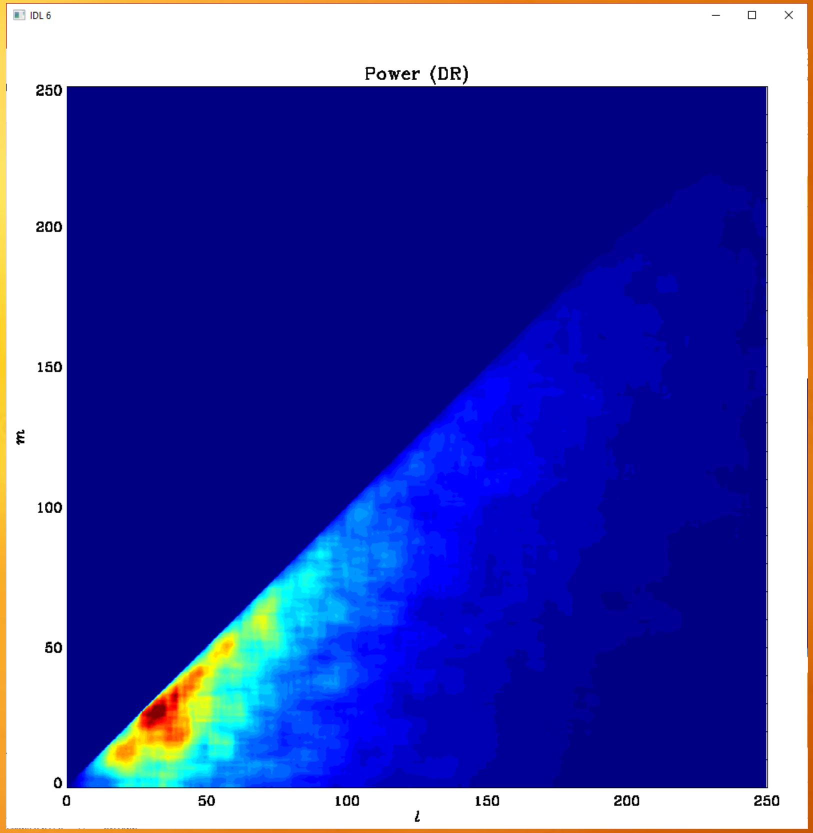

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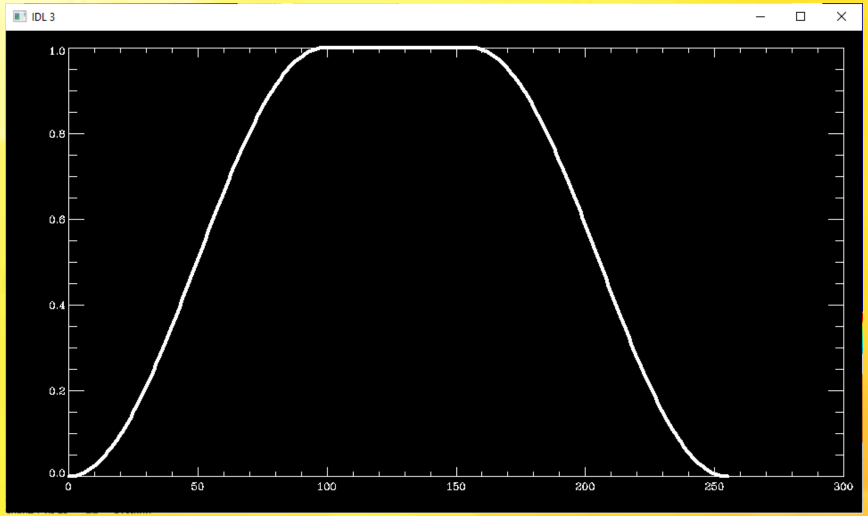
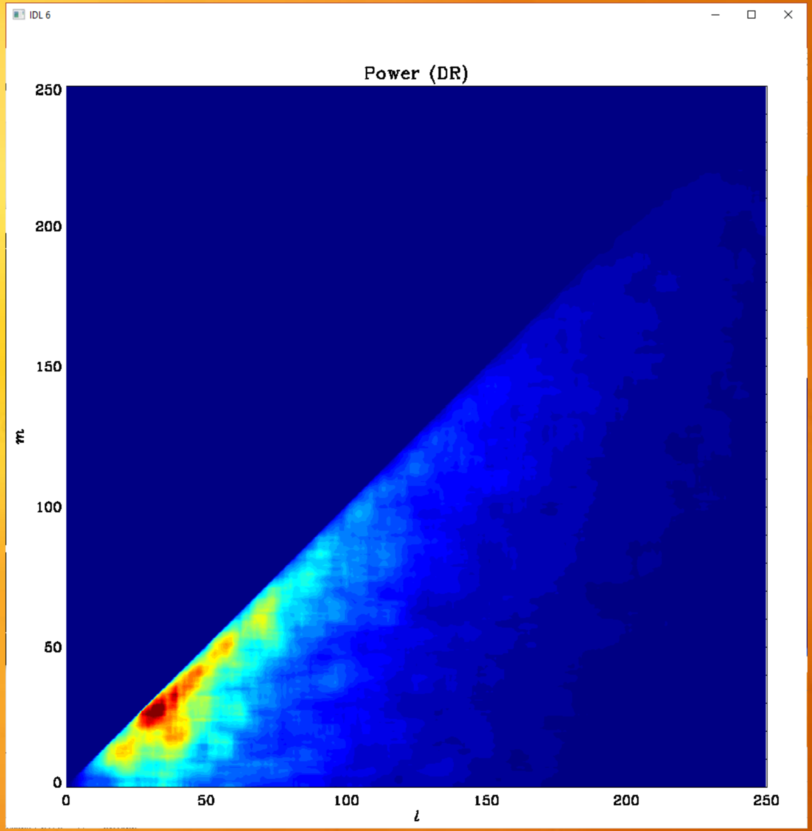
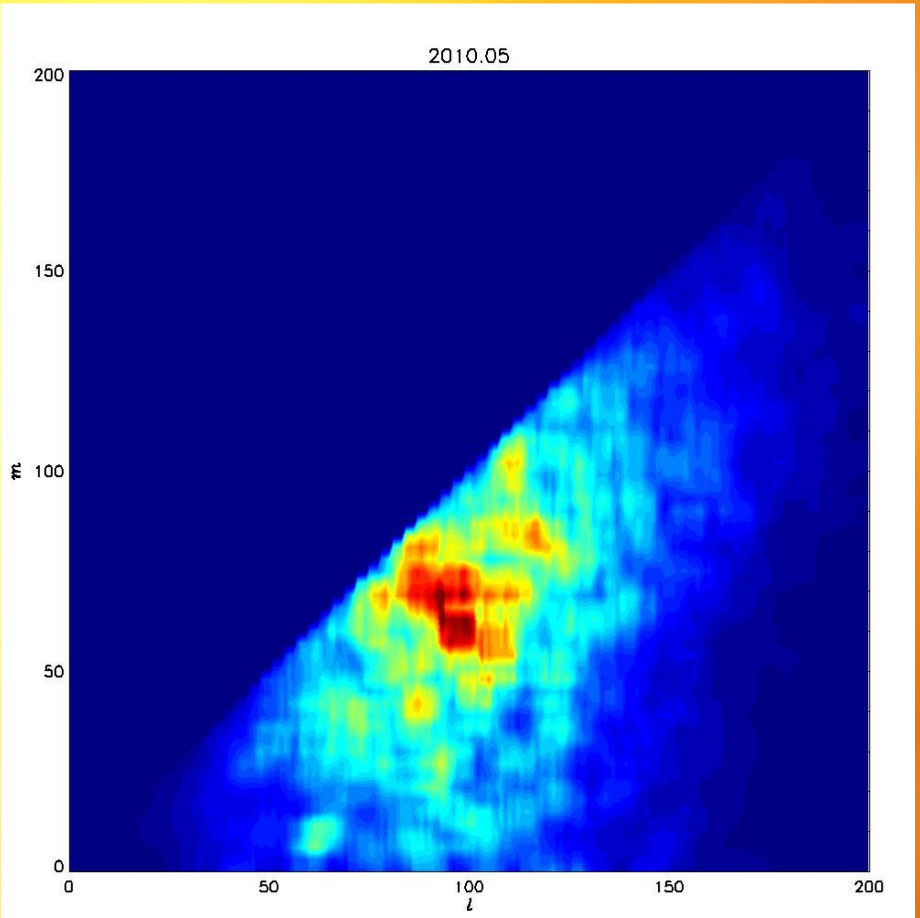
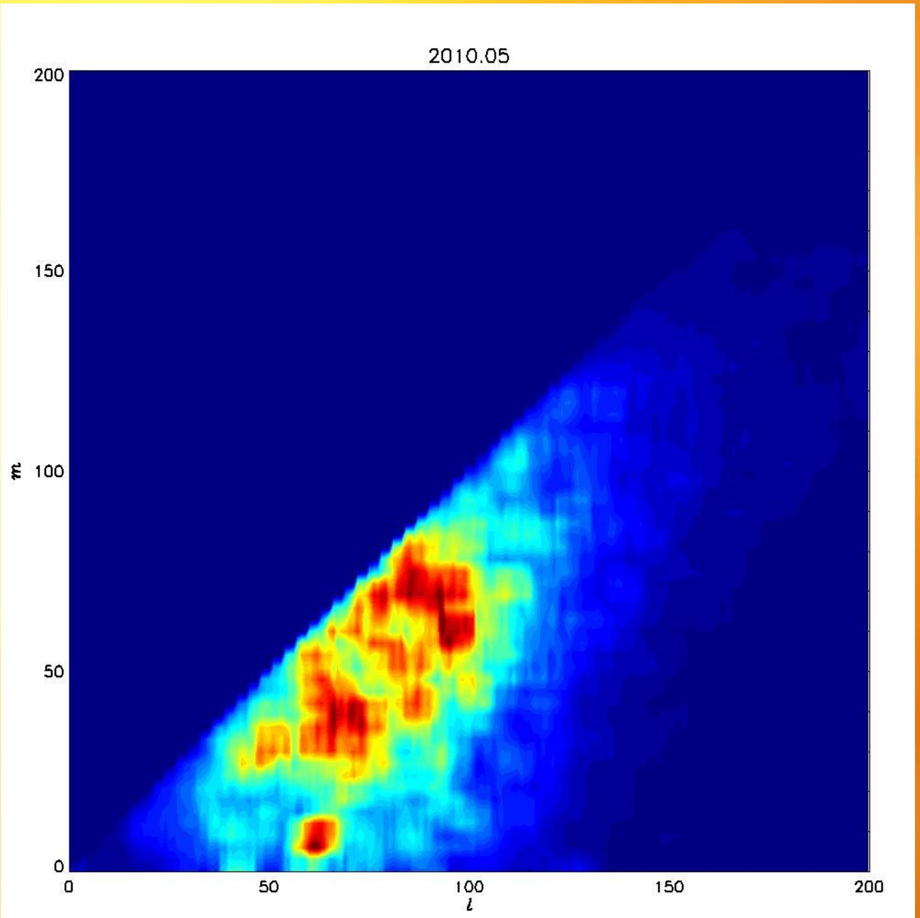




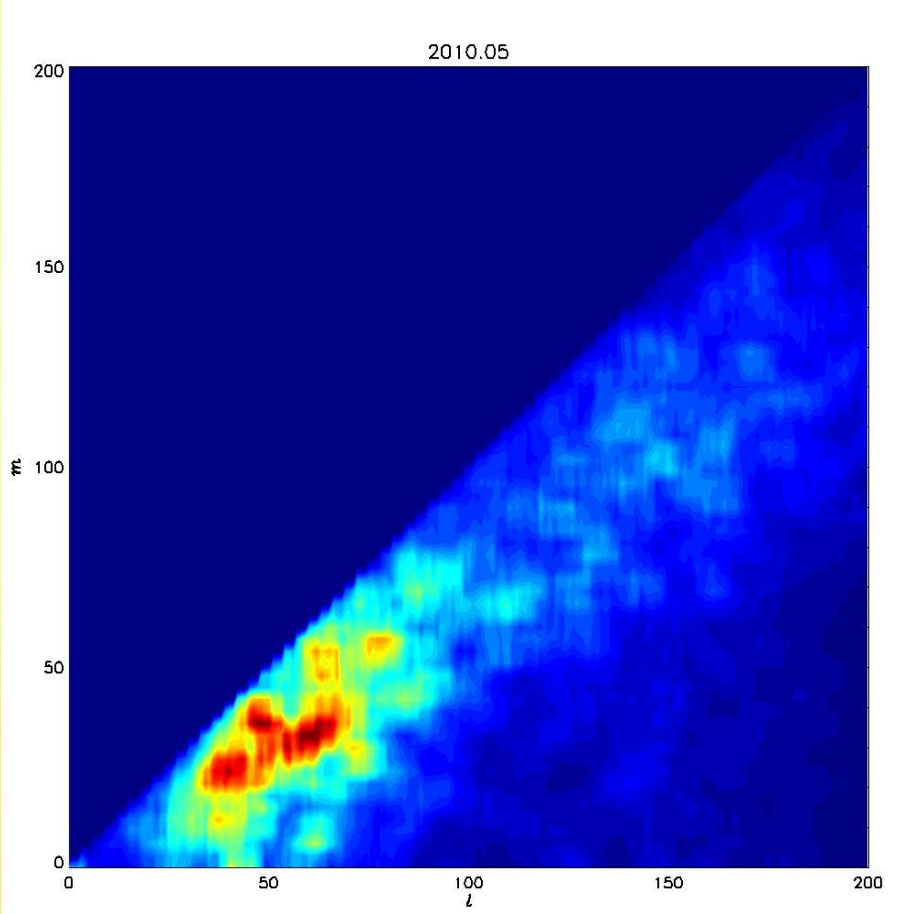
Depth variations in the spectrum, May 2010
d = 2 Mm



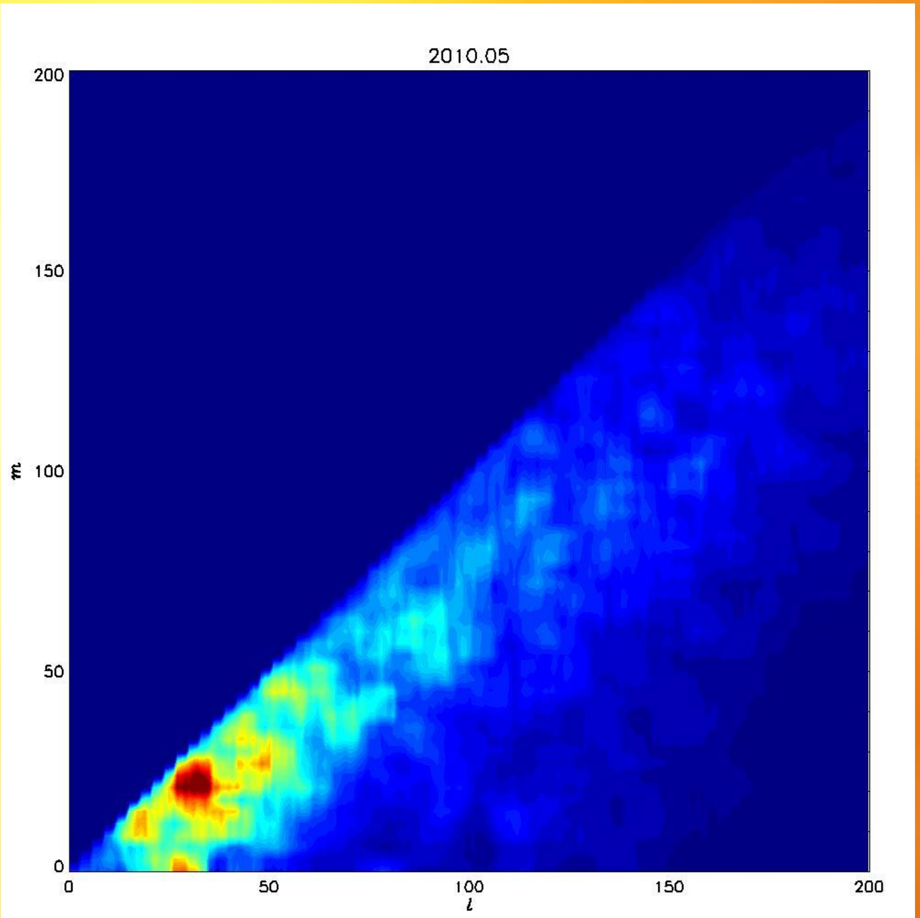
Depth variations in the spectrum, May 2010
d = 4 Mm



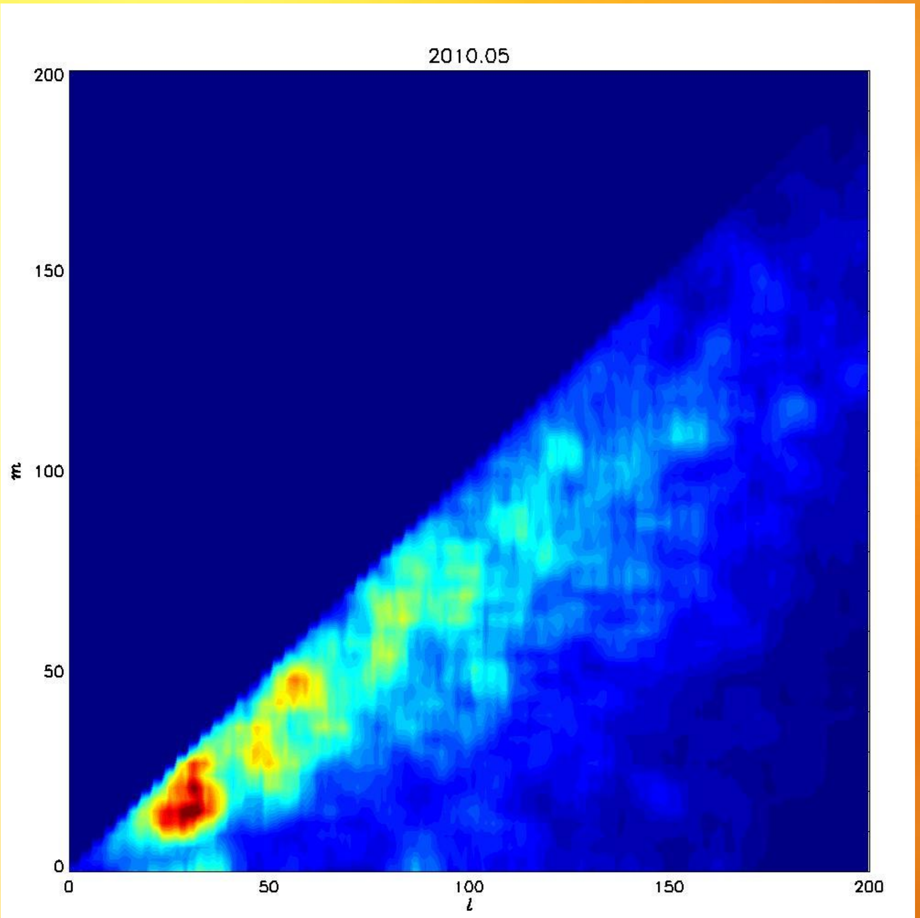
Depth variations in the spectrum, May 2010
d = 6 Mm



Depth variations in the spectrum, May 2010
d = 9.5 Mm

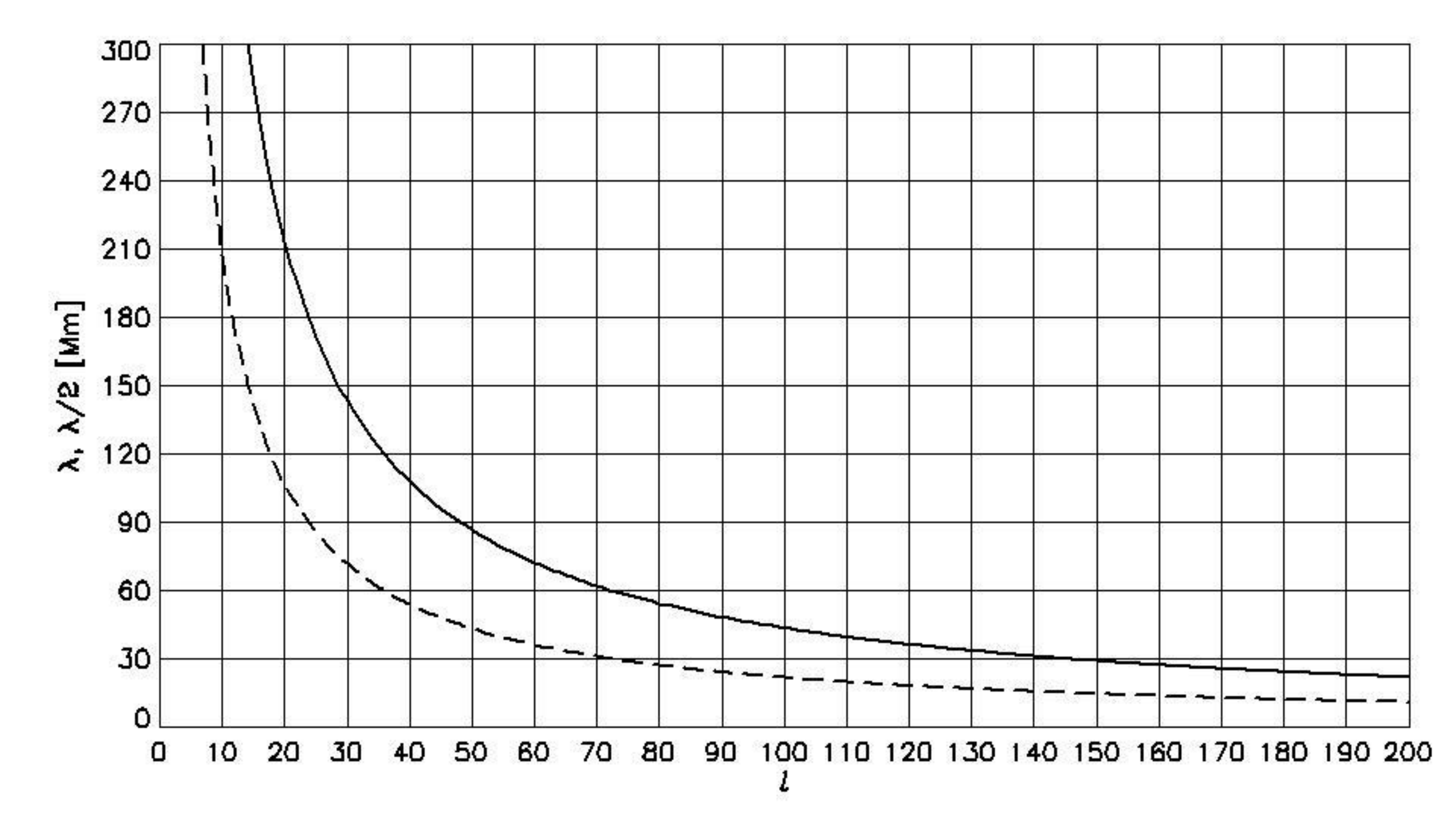


Depth variations in the spectrum, May 2010
d = 11.5 Mm

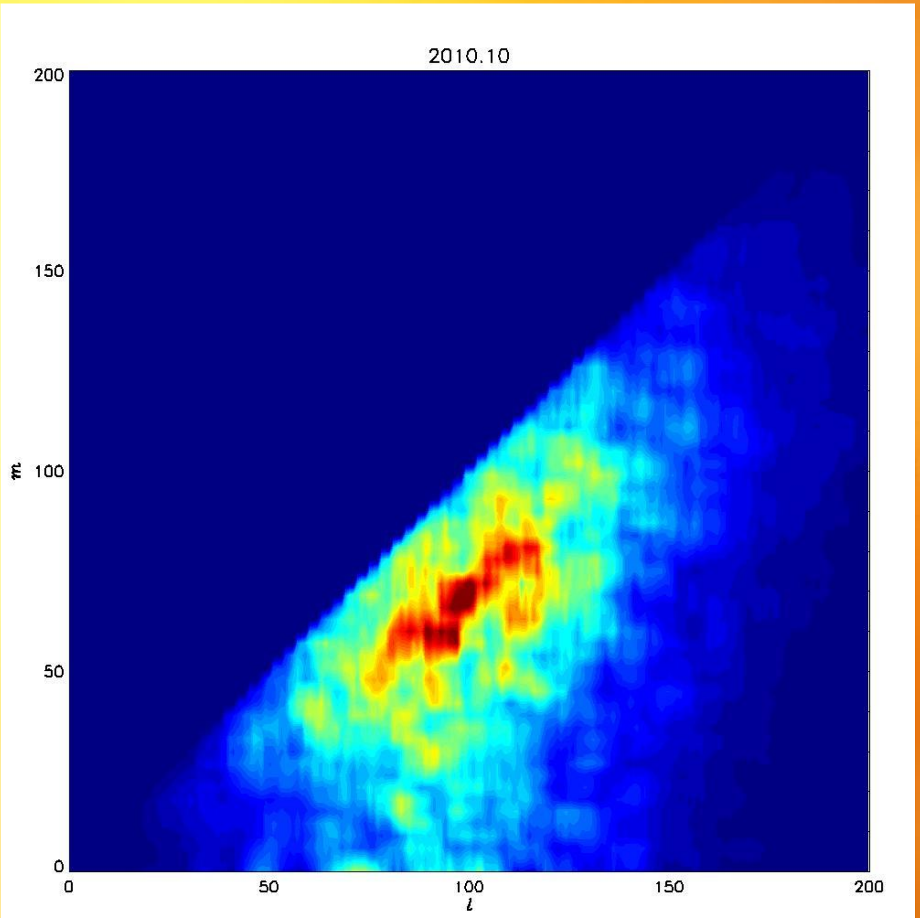


Scale estimate according to Jeans' formula

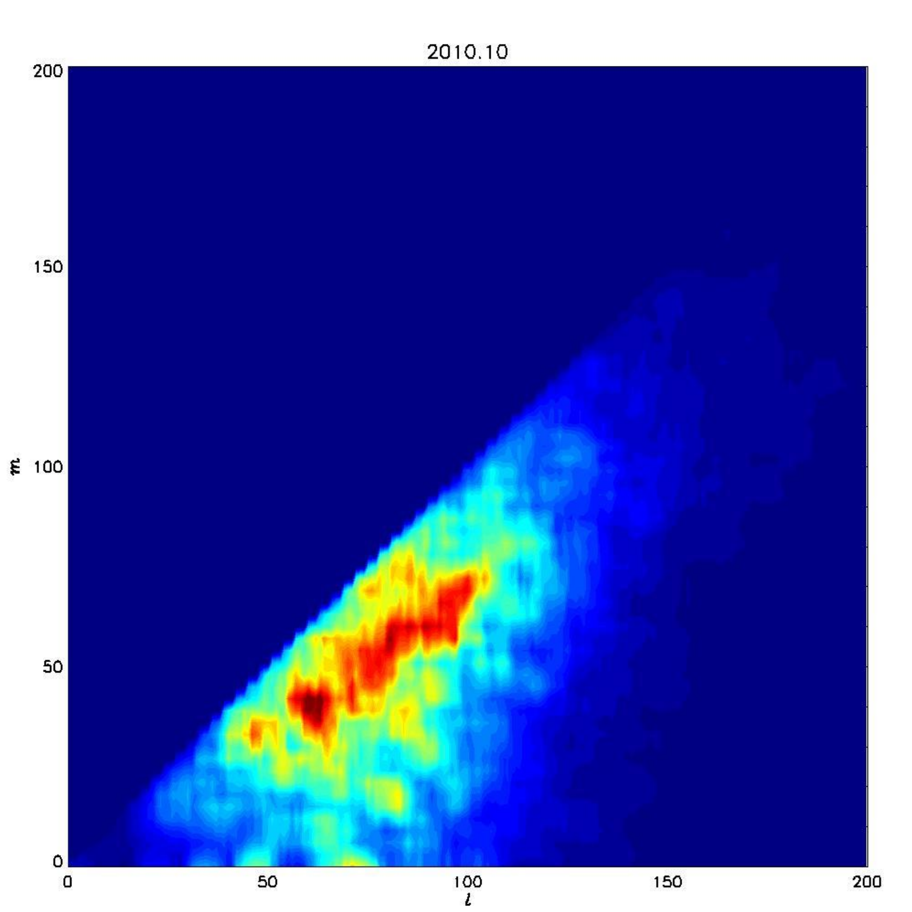
$$\lambda = \frac{2\pi r}{\sqrt{l(l+1)}}$$



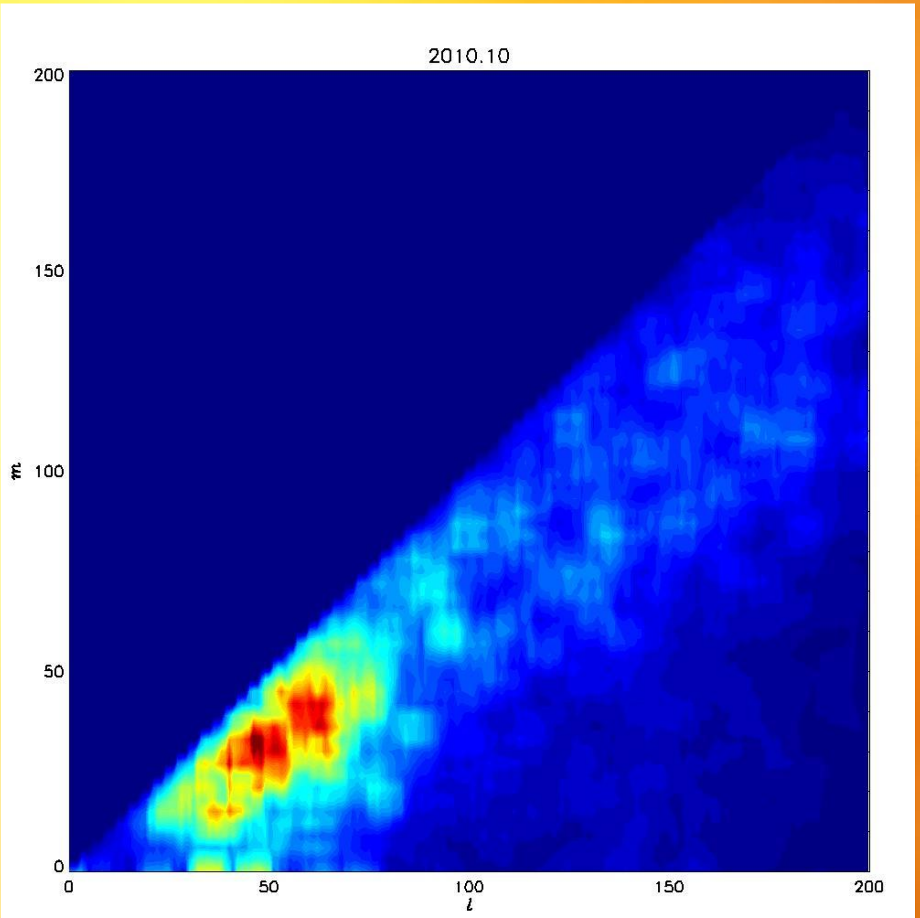
Depth variations in the spectrum, October 2010
d = 2 Mm



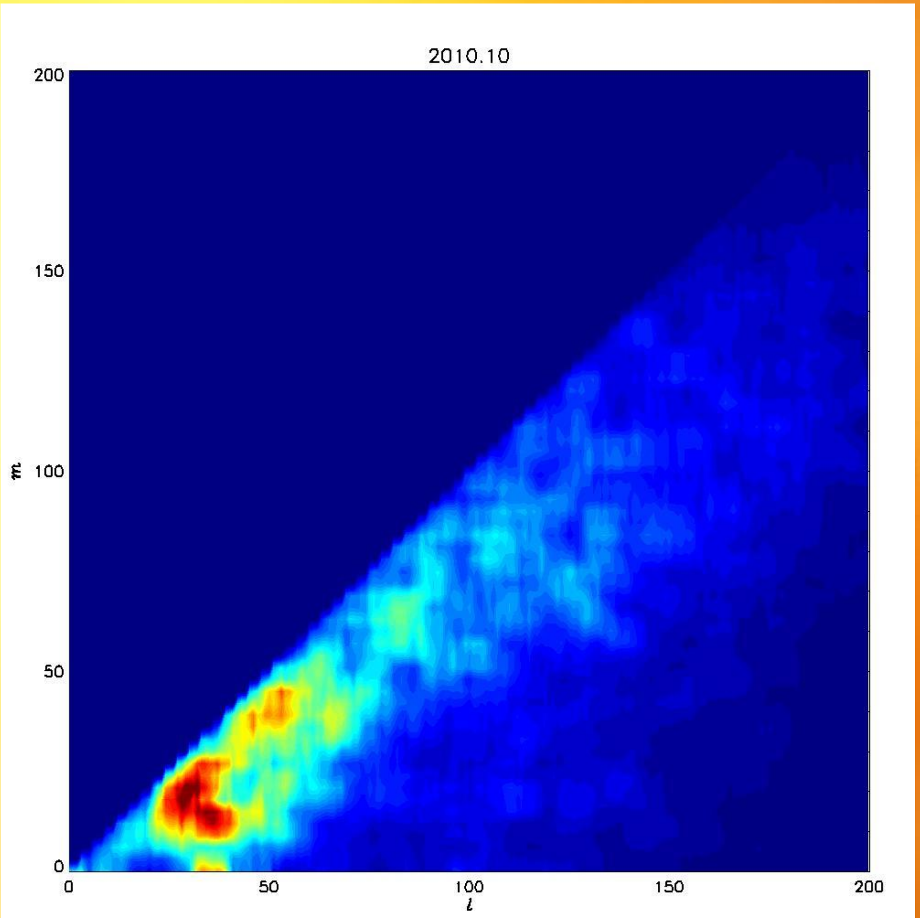
Depth variations in the spectrum, October 2010
d = 4 Mm



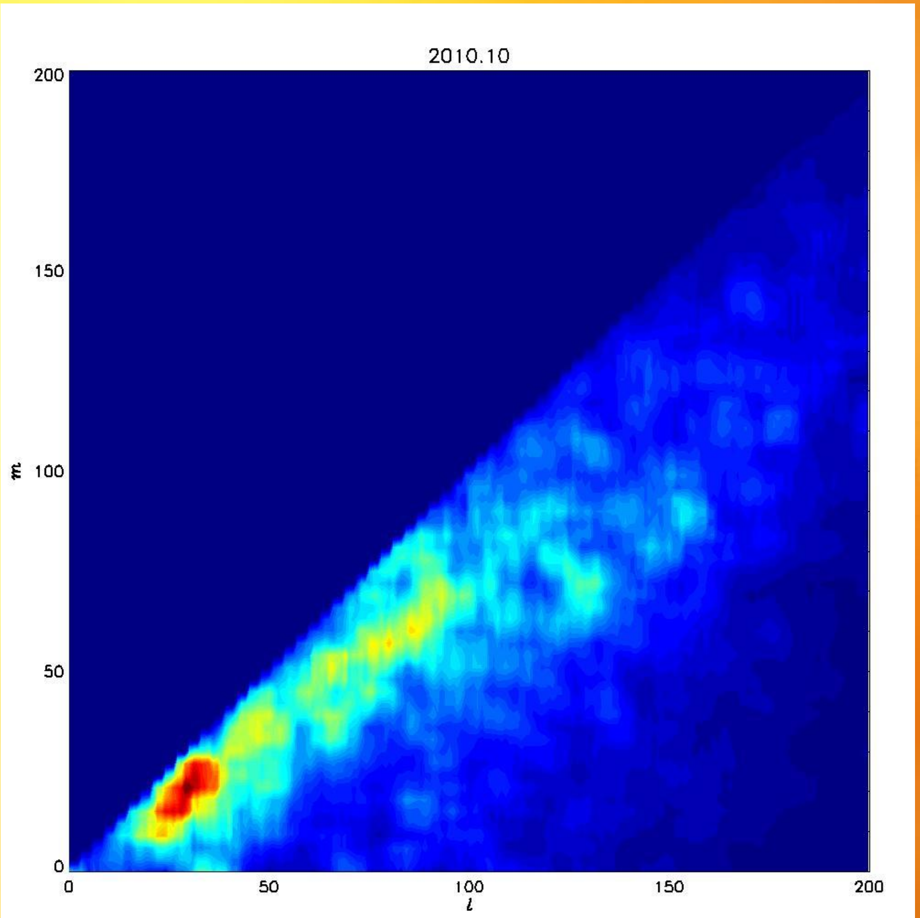
Depth variations in the spectrum, October 2010
d = 6 Mm



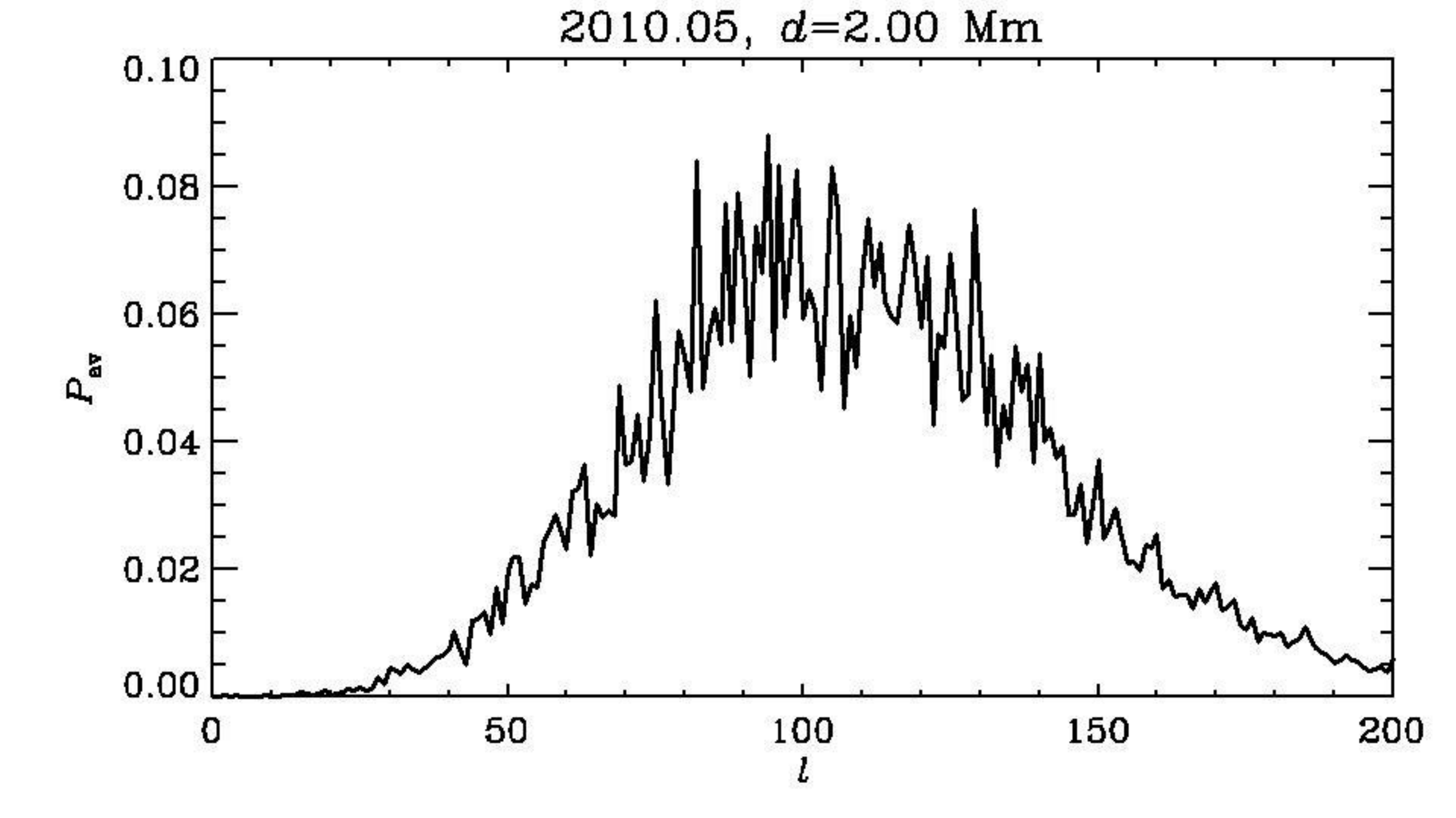
Depth variations in the spectrum, October 2010
d = 8.5 Mm



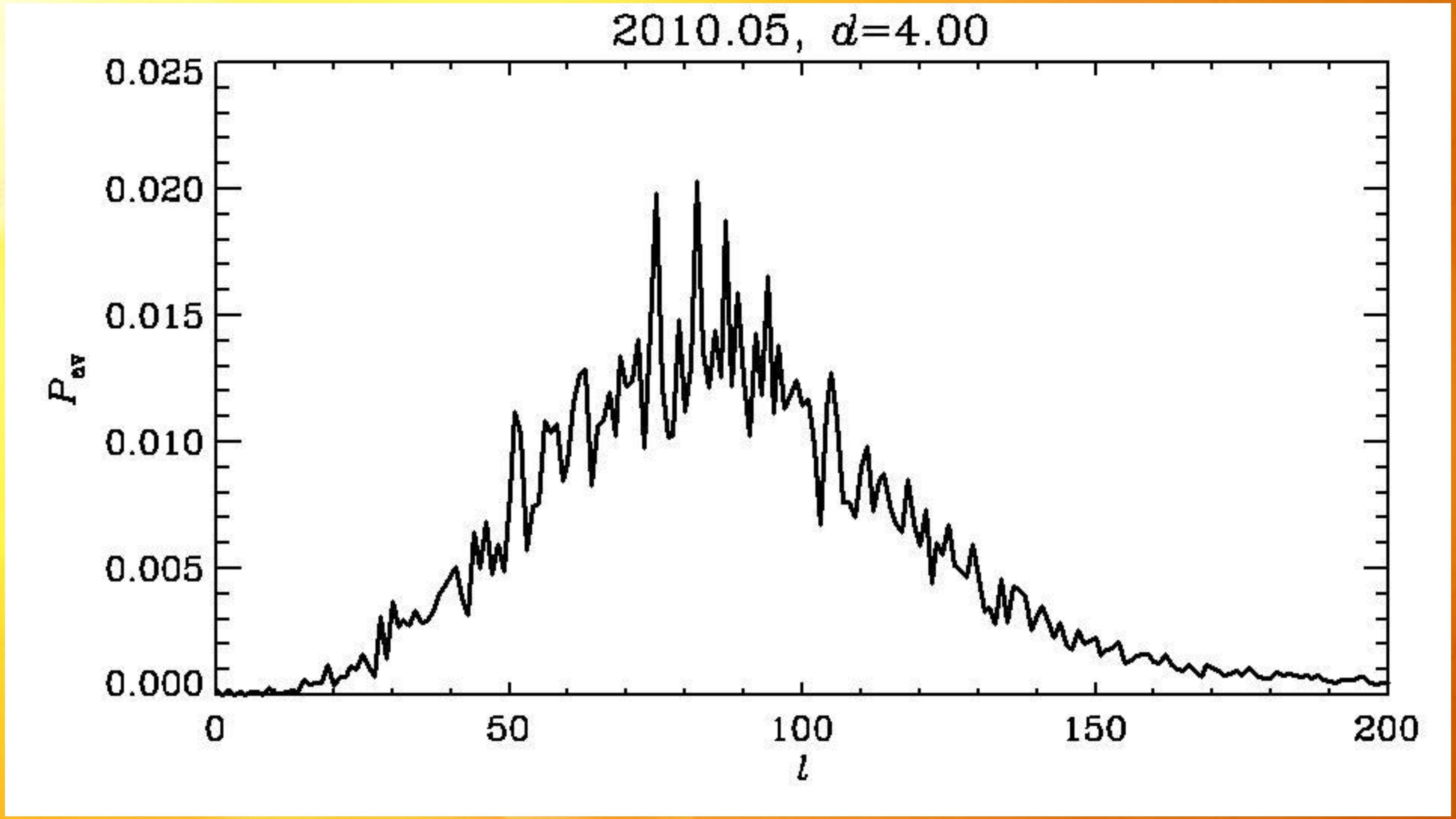
Depth variations in the spectrum, October 2010
d = 11.5 Mm



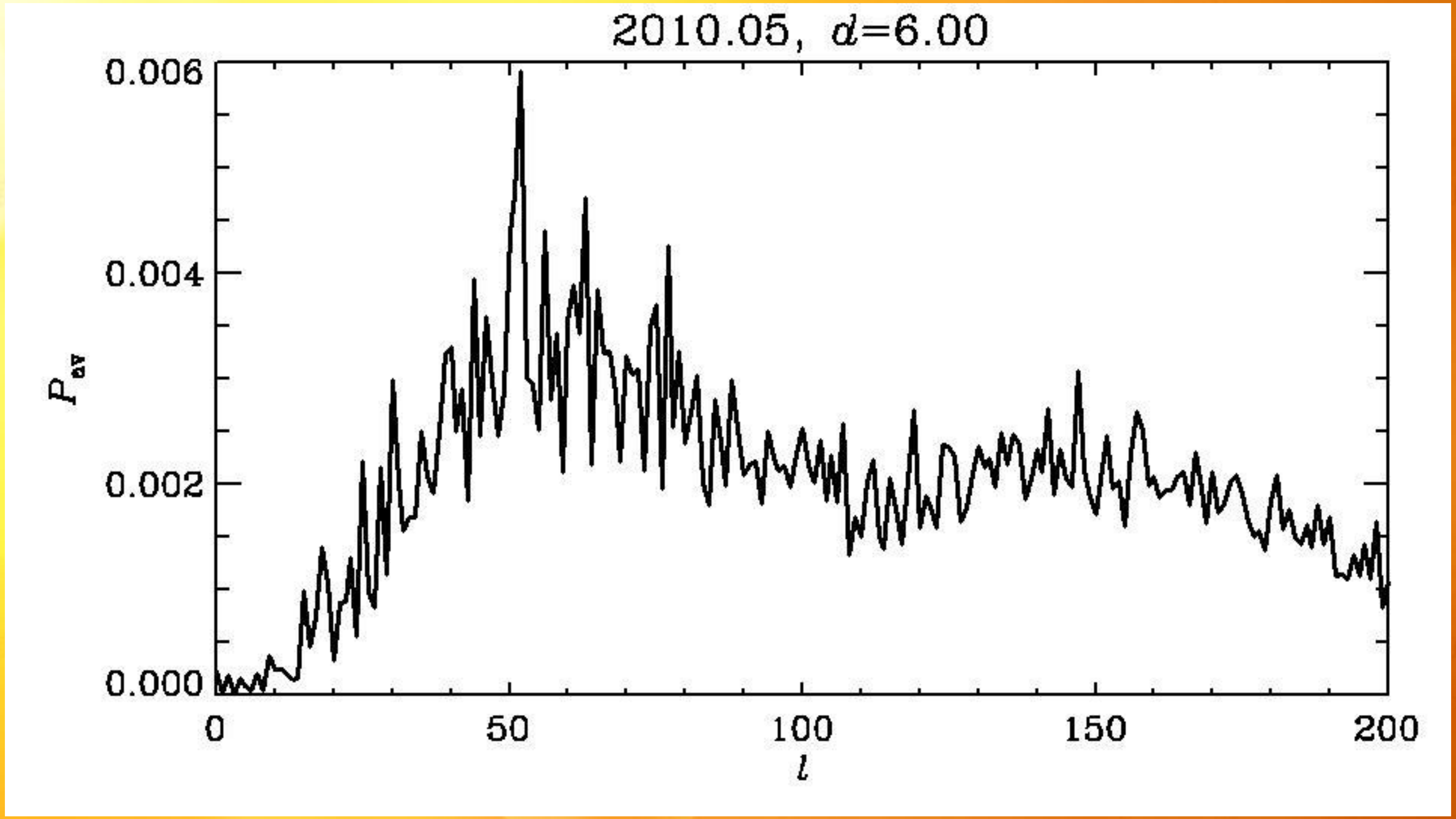
The *l*-dependence of the *m*-averaged spectrum; May 2010, *d* = 2 Mm



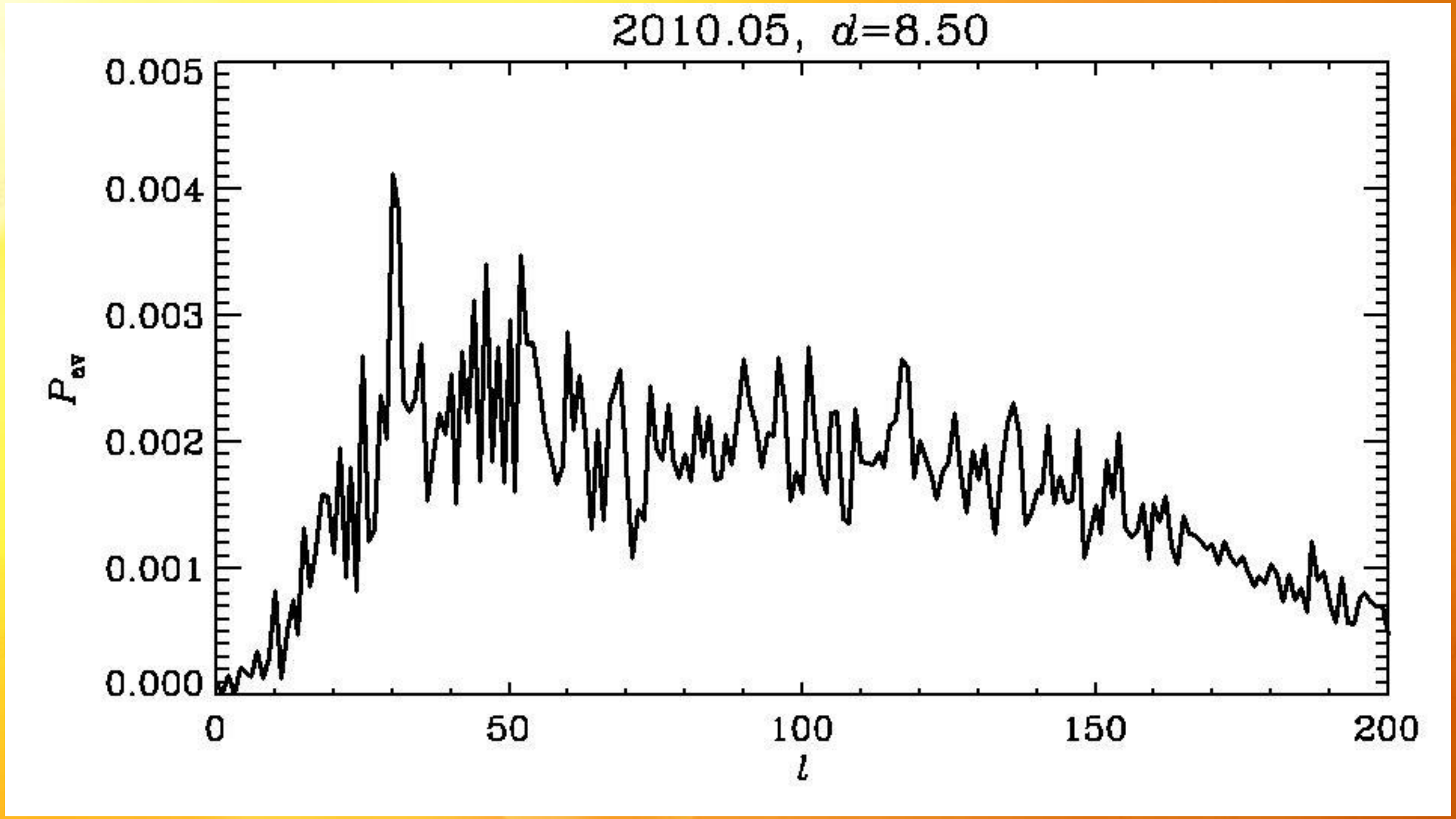
The *l*-dependence of the *m*-averaged spectrum; May 2010, *d* = 4 Mm



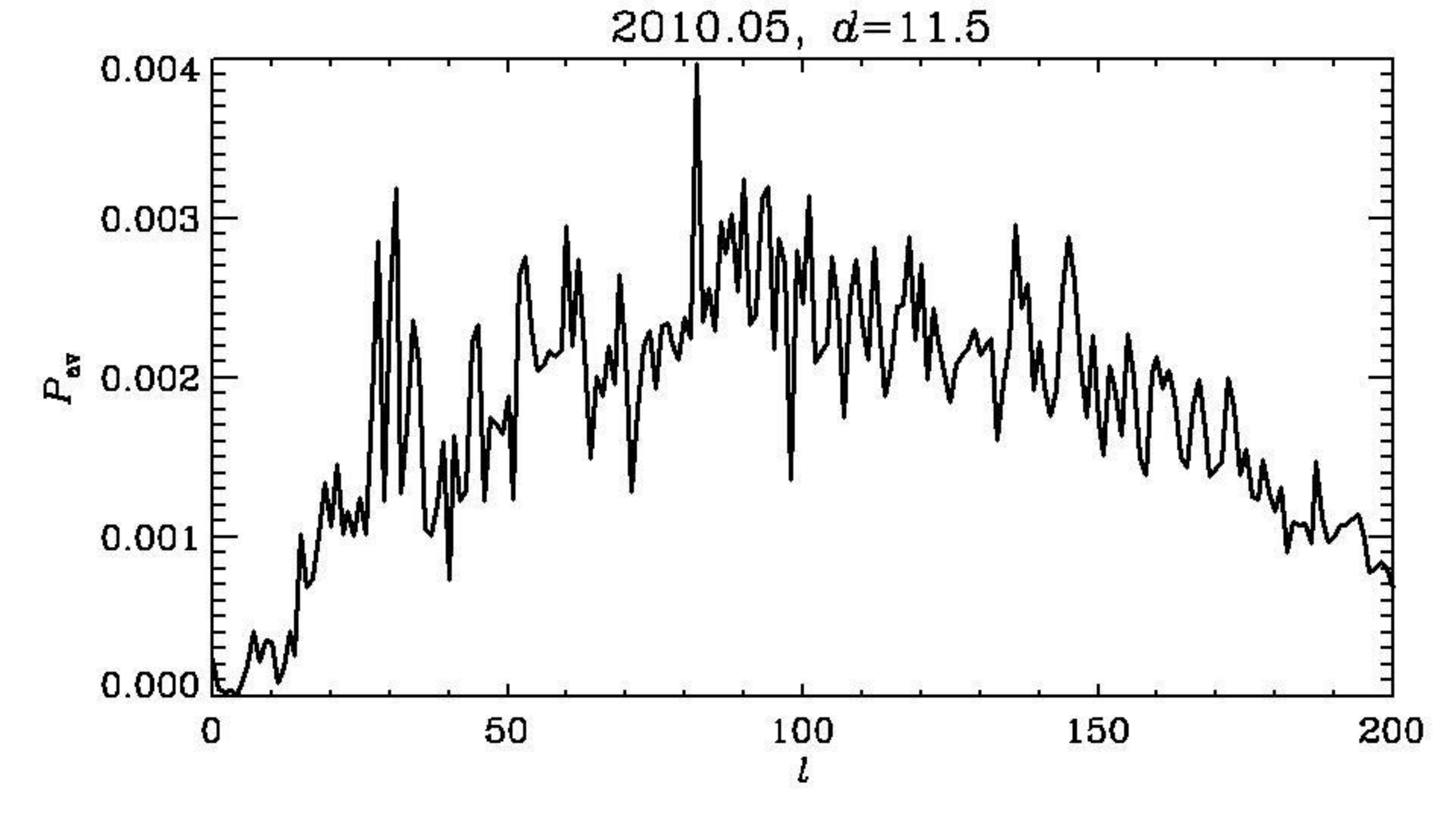
The *l*-dependence of the *m*-averaged spectrum; May 2010, *d* = 6 Mm



The *l*-dependence of the *m*-averaged spectrum; May 2010, *d* = 8.5 Mm



The *l*-dependence of the *m*-averaged spectrum; May 2010, *d* = 11.5 Mm



Conclusion

- **The characteristic scale of convection increases with depth**
- **The wideband convection spectrum at shallow layers may be an indication for a superposition of differently scaled flows**
- **Moreover, in a certain depth range (around 6 Mm), signs of spectral bimodality are present (scales of 15–30 and 40–80 Mm)**
- **The approach of the spectral peak to the line $l = m$ corresponding to sectorial harmonics, observed with a transition to large depths, may reflect the tendency to a meridional elongation of convection cells**
- **In a methodical aspect: The lack of data for the polar caps seemingly does not substantially distort the convection spectrum**

Thank you for your attention