Observations of the Sun's Meridional Flow

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University of Sheffield

Sasha Kosovichev & SOHO/MDI team
Stanford University

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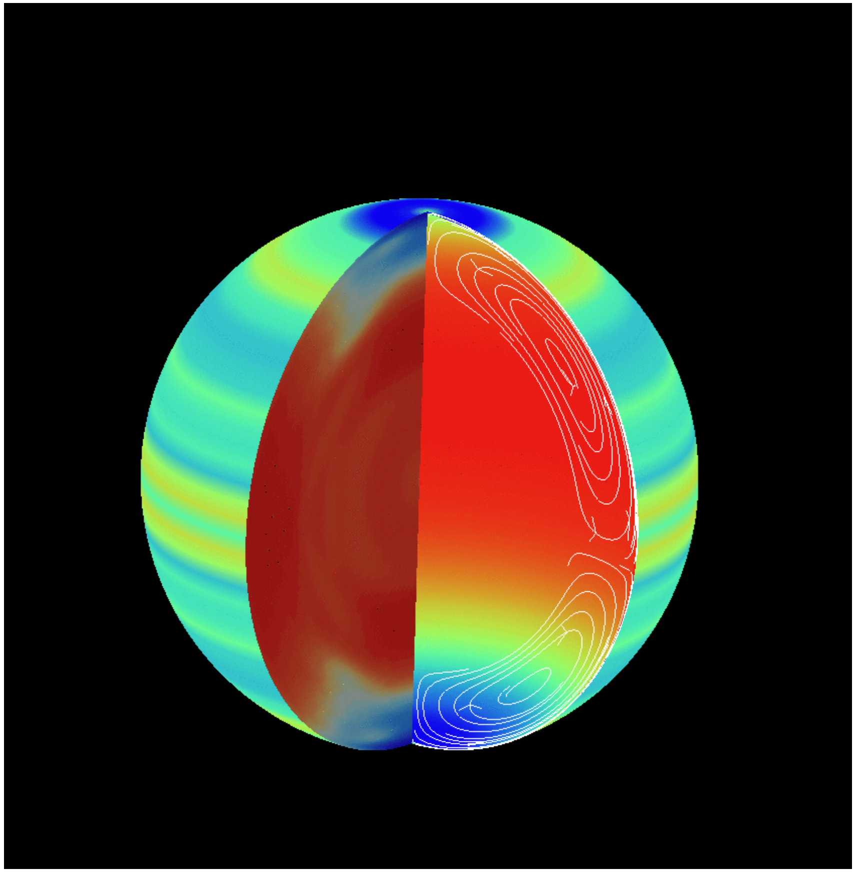
Overview

- Introduction, Motivation
- Data set-up and analysis
- Radial meridional flow profile of the quiet Sun
- Variations with the solar cycle
- Conclusions

The meridional flow

- First meridional flow measurements at the solar surface were made in the late 1970’s
  - Duvall (1979), Howard (1979), Beckers & Taylor (1980)
- Poleward flow of around 15 – 20 m/s
- Conservation of mass: flow needs to return equatorward at some depth



Comparison of flow velocities

- Differential Rotation at surface
  - 0° : P=25 days; v=2000 m/s
  - 45°: P=27 days; v=1300 m/s
  - 60°: P=28 days; v=900 m/s
- Meridional Flow
  - At surface v ≈ 20 m/s poleward
  - Predicted at base of convection zone
  - v ≈ 1 – 3 m/s

Why are we interested?

- The radial meridional flow profile would give strong constraints to many theories of the solar interior and dynamo models
- Mean-field models of angular momentum transport (e.g. Gilman 1972, Rüdiger 1989; reviews by Thompson et al. 2003, Miesch 2005, Shibahashi 2007)
  - Establish and maintain differential rotation
  - Balance of differential rotation, Reynolds' stresses and meridional circulation (and magnetic field, and viscosity, etc.)
- Flux-transport models of solar dynamo (Babcock-Leighton models) (e.g. Wang et al. 1991, Dikpati & Charbonneau 1999)
  - Transport surface poloidal magnetic field to bottom of convection zone, where it can then be converted into toroidal magnetic field by rotational shear

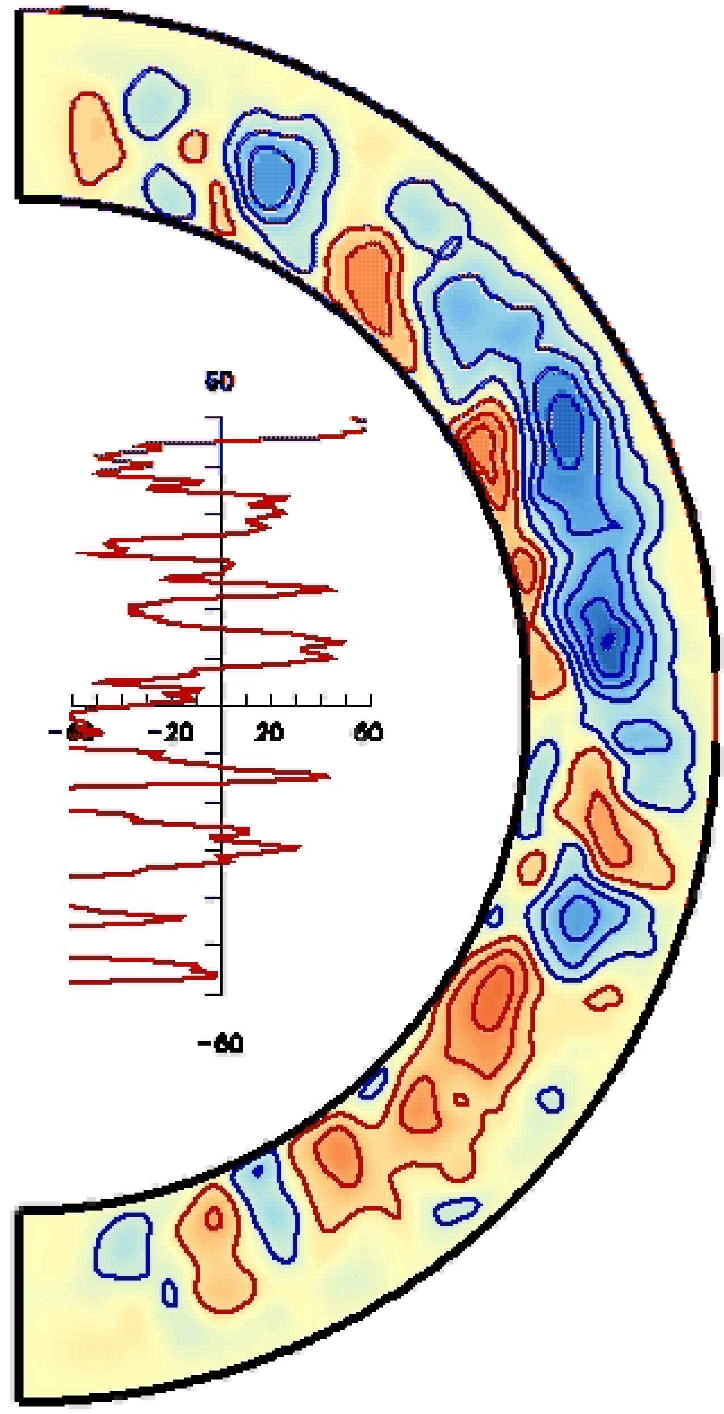
Open Questions

- Is the meridional circulation contained within the convection zone?
- Is the equatorward return flow above or below the tachocline?
- Is there a single, or are there multiple meridional cells?
- How does the meridional flow vary with the solar cycle?

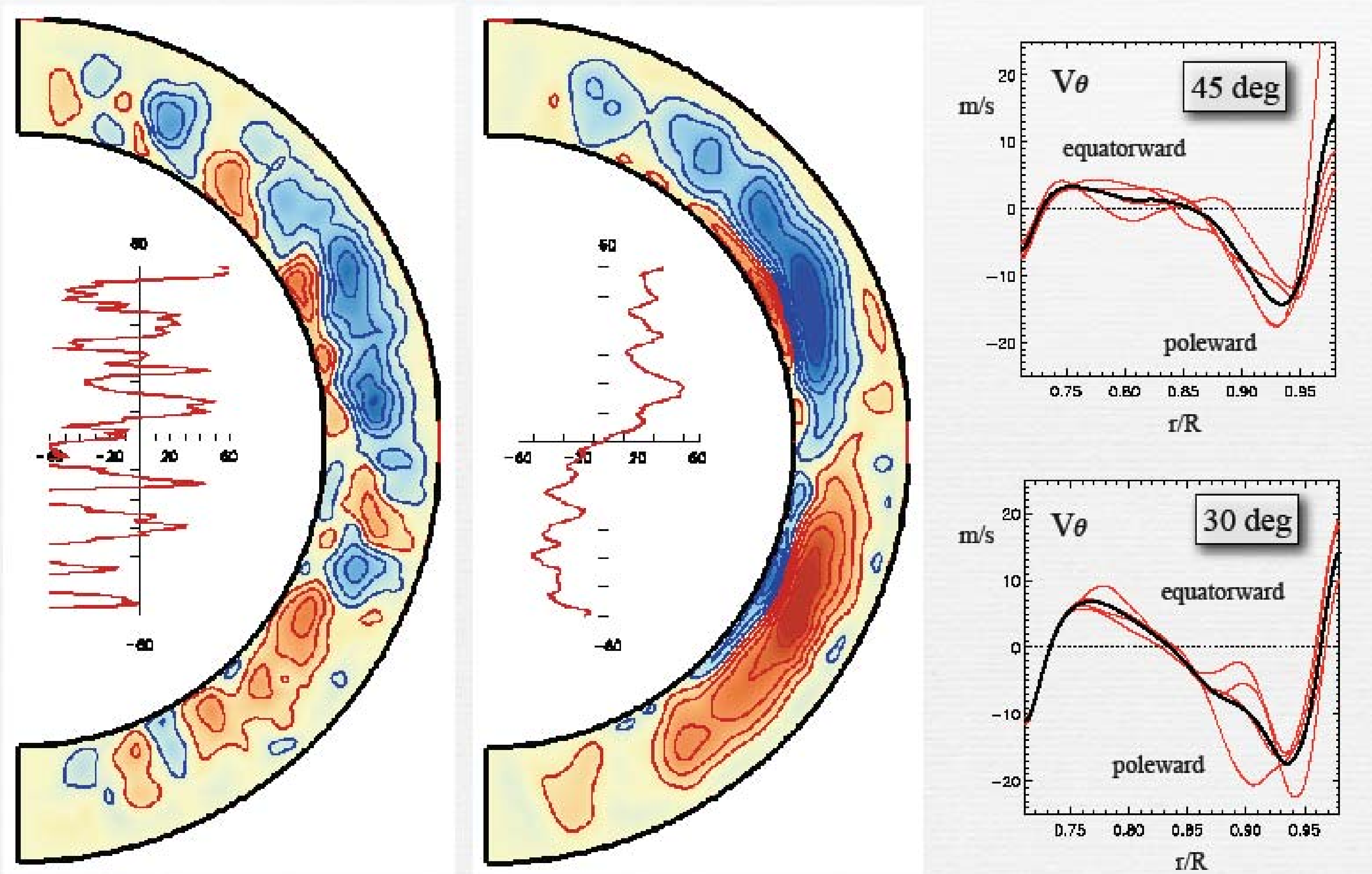
Numerical simulation of meridional circulation

using turbulent convection model

Courtesy of Mark Miesch



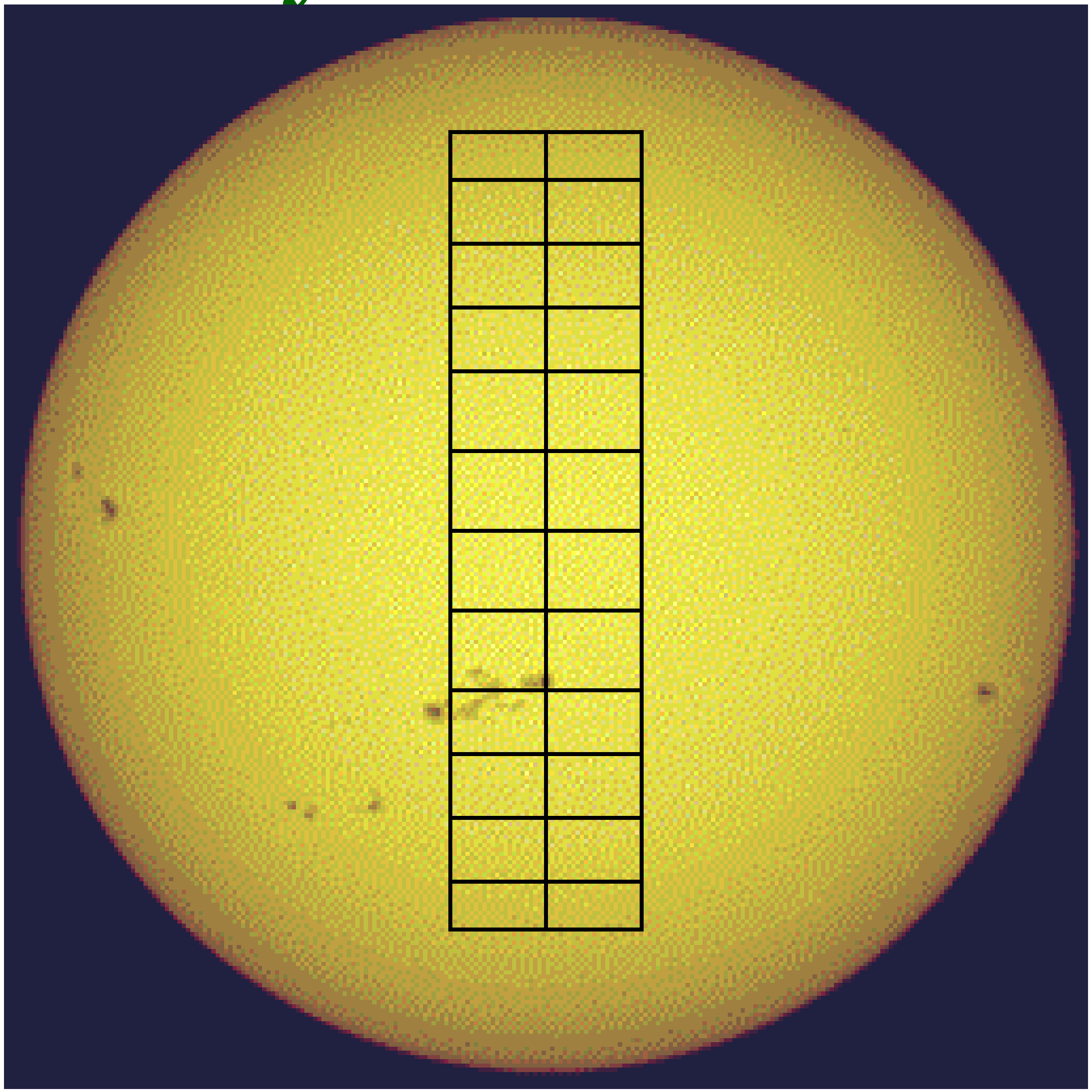
Variability of Meridional Circulation



Data Layout

Large FOV to probe deep → SOHO/MDI data

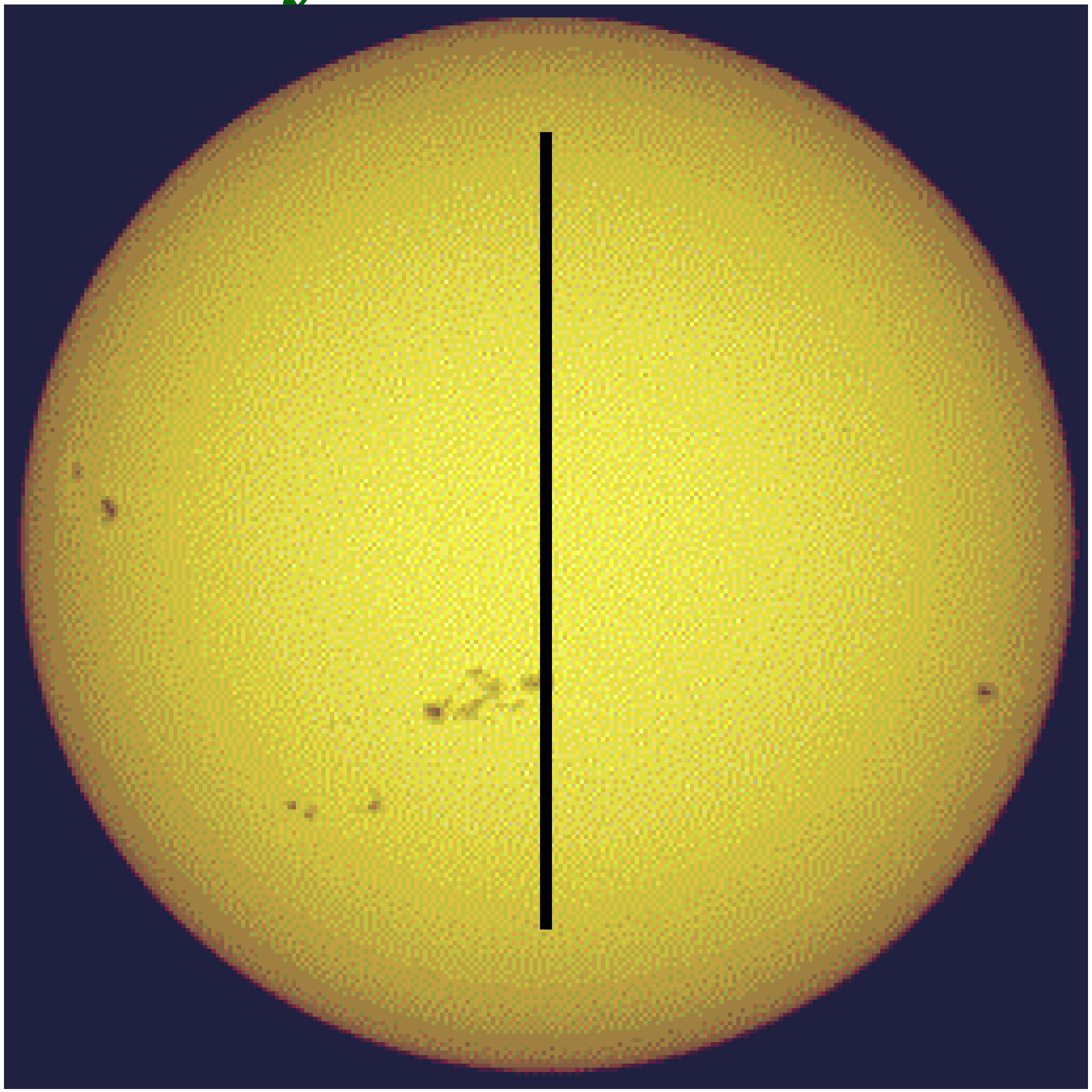
SOHO/MDI tracked velocity data along the Center Meridian



Data Layout

Set-up: 1+1D along center meridian

Merge data to form a spatially 1dimentional grid in North-South direction, evenly spaced in latitude



Data Layout

Signal: $f(t,\theta)$

Power spectrum:

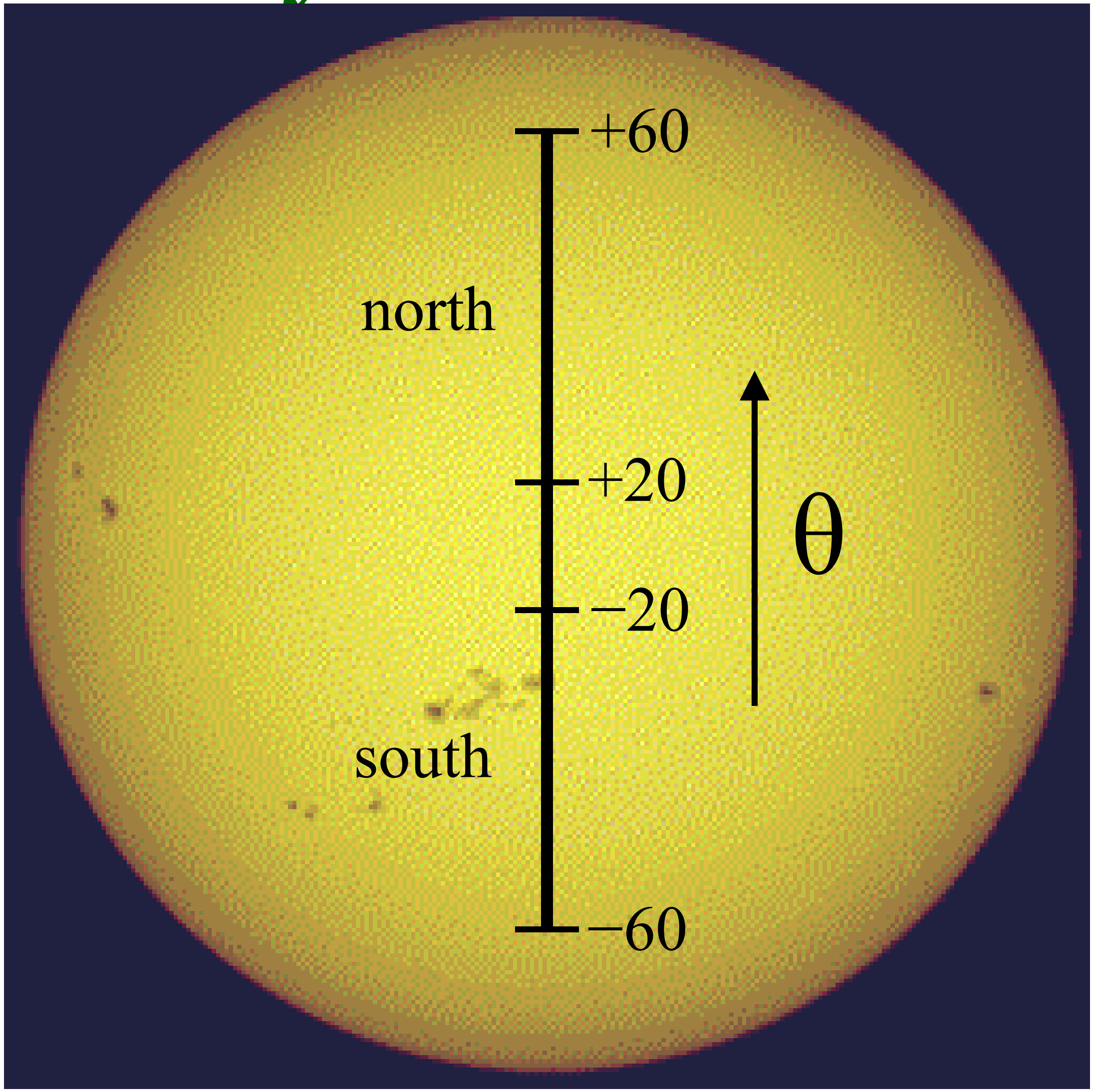
$$P(\omega,k_\theta) = |\hat{f}(\omega,k_\theta)|^2$$

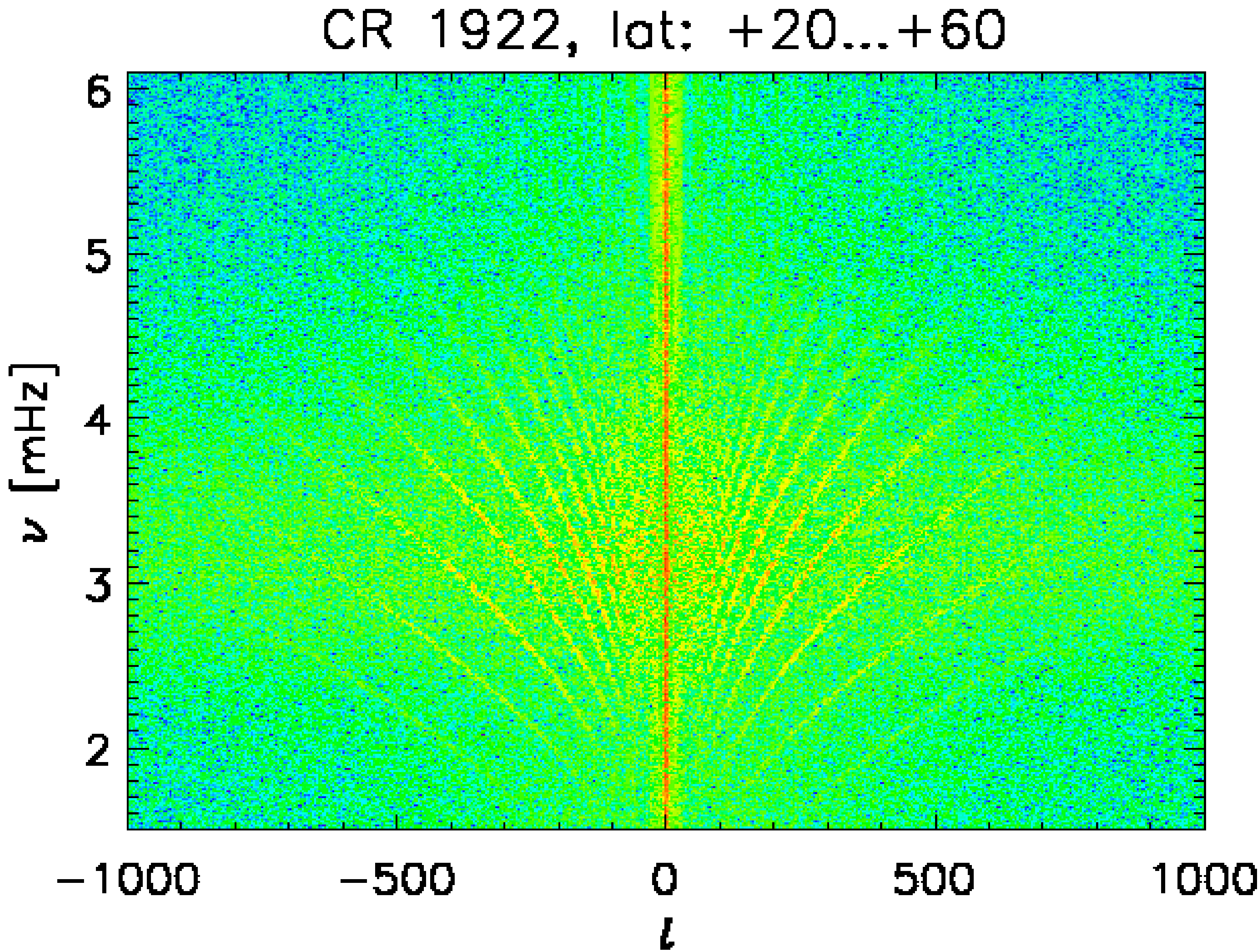
with $\omega = 2\pi\nu$

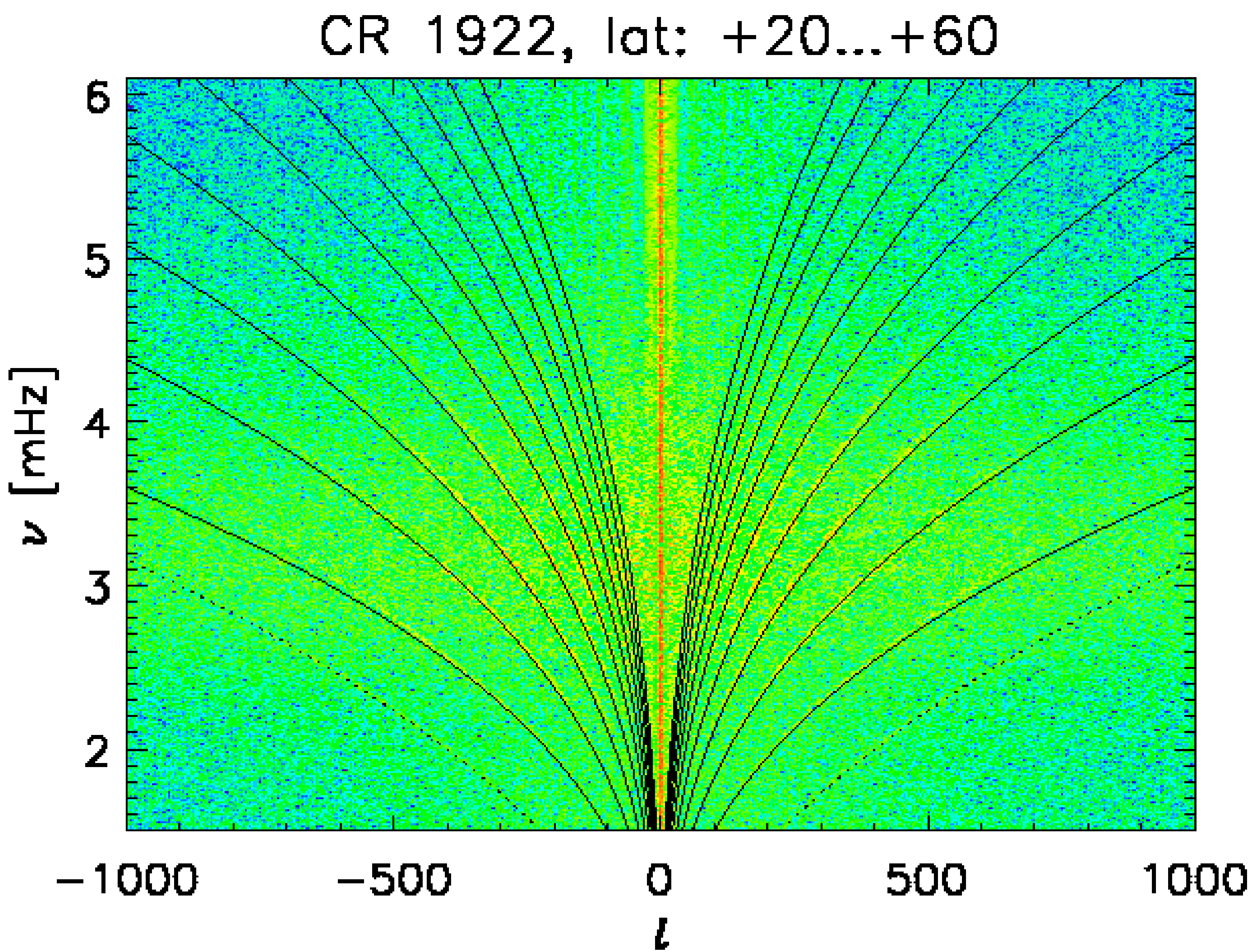
and $k_\theta \hat{=} l$

we get the power spectrum as a function of ν and l:

$$P(\nu,l)$$




CR 1922, lat: +20...+60
ν [mHz]
6
5
4
3
2
−1000
−500
0
500
1000
l


CR 1922, lat: +20...+60
ν [mHz]
6
5
4
3
2
−1000
−500
0
500
1000
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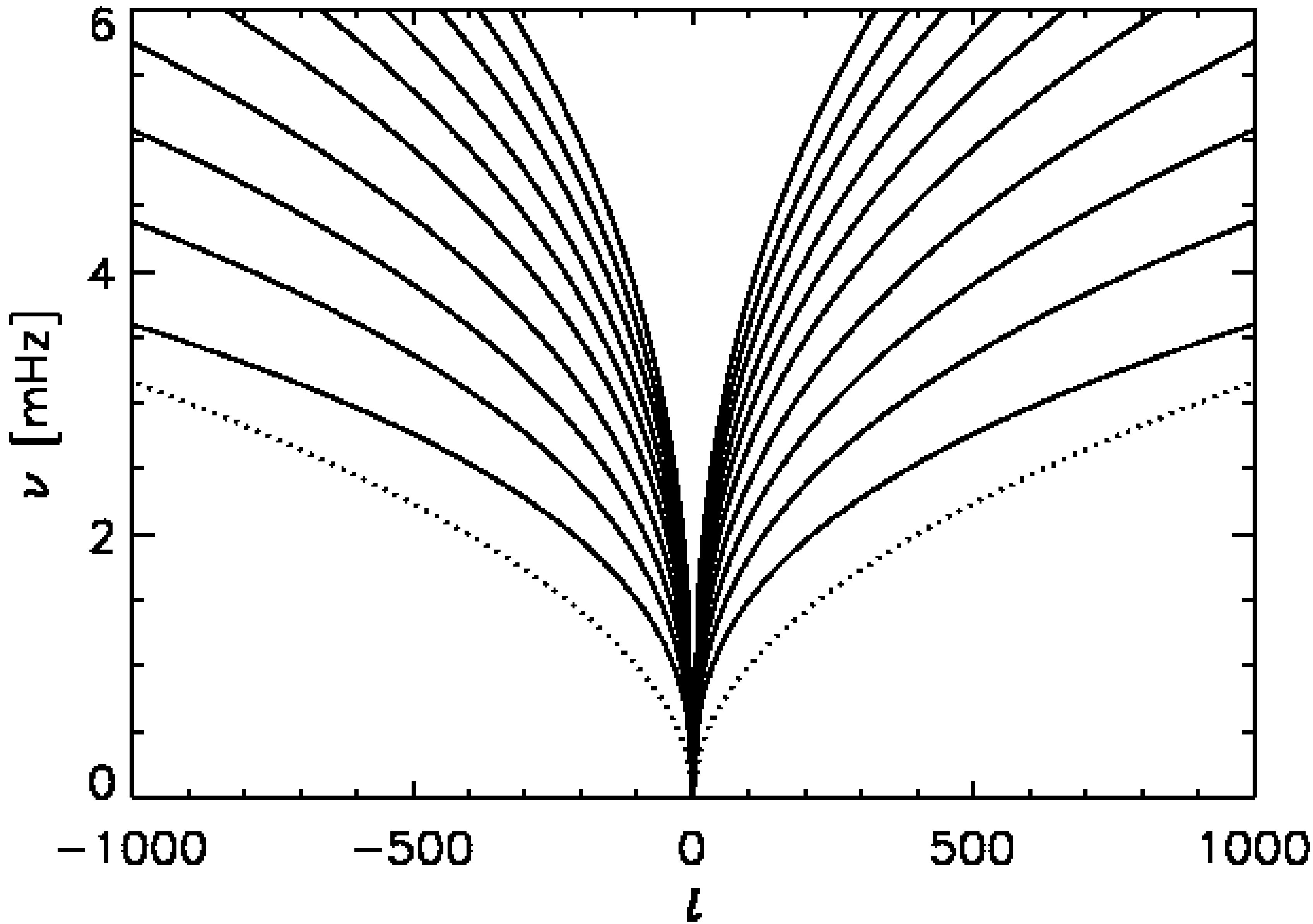
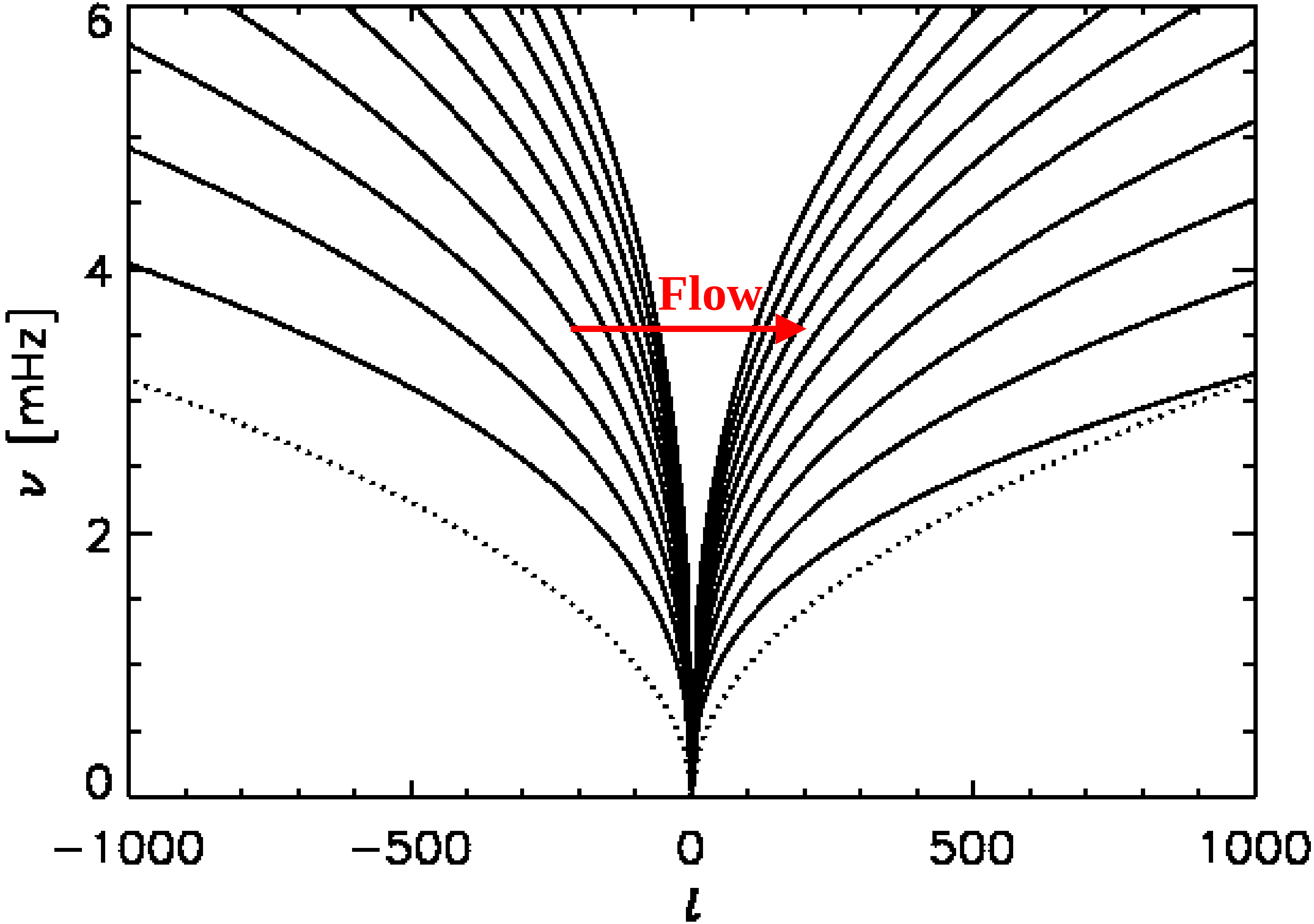
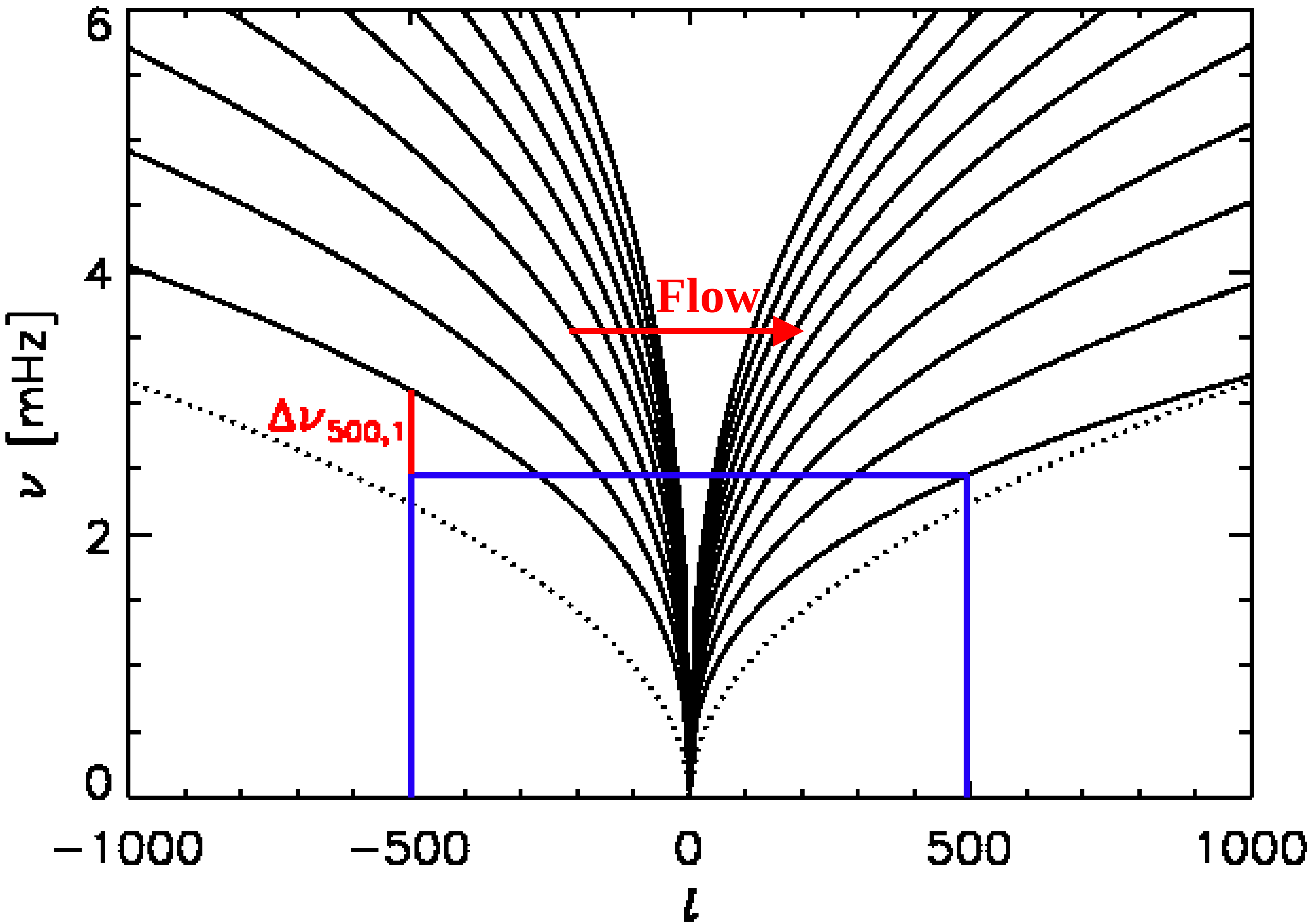


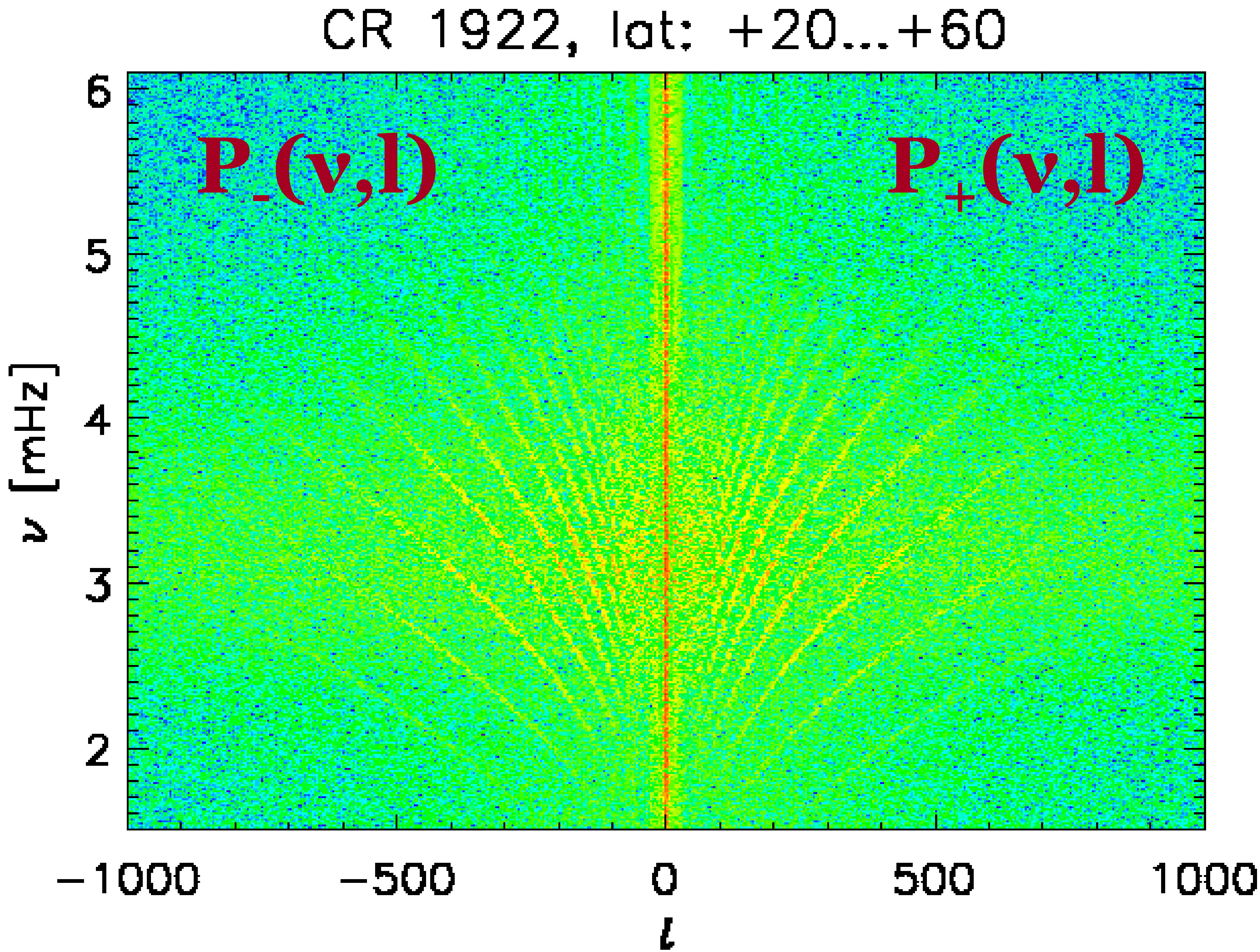
6
4
2
0
ν [mHz]
−1000
−500
0
500
1000
l



6
4
2
0
ν [mHz]
−1000
−500
0
500
1000
l
Flow

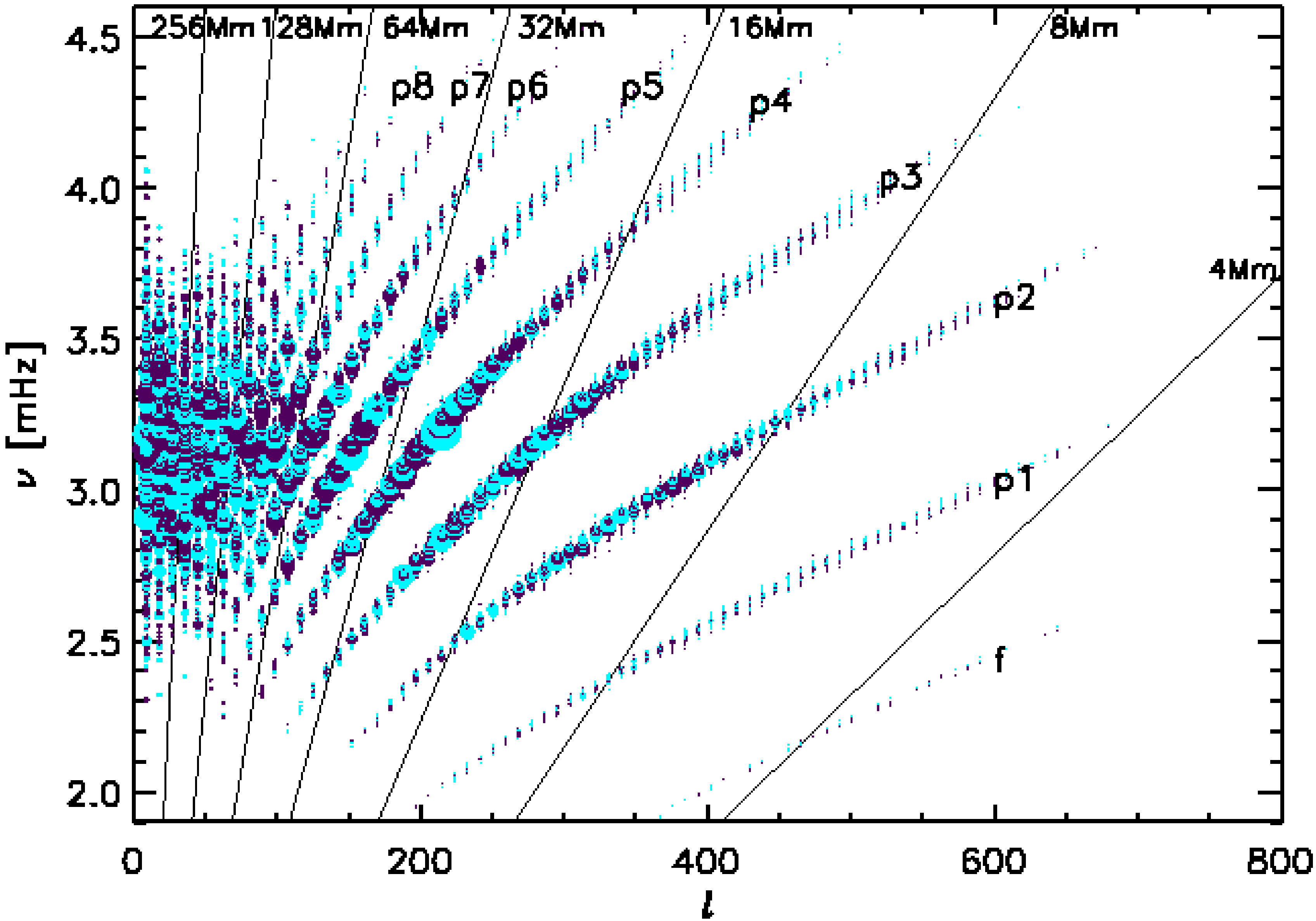
Flow $U'(\nu/l) = \Delta\nu_{lp}\, \pi\, R_{sun} / l$





CR 1922, lat: +20...+60
P-(v,l)
P+(v,l)
ν [mHz]
6
5
4
3
2
−1000
−500
0
500
1000
l

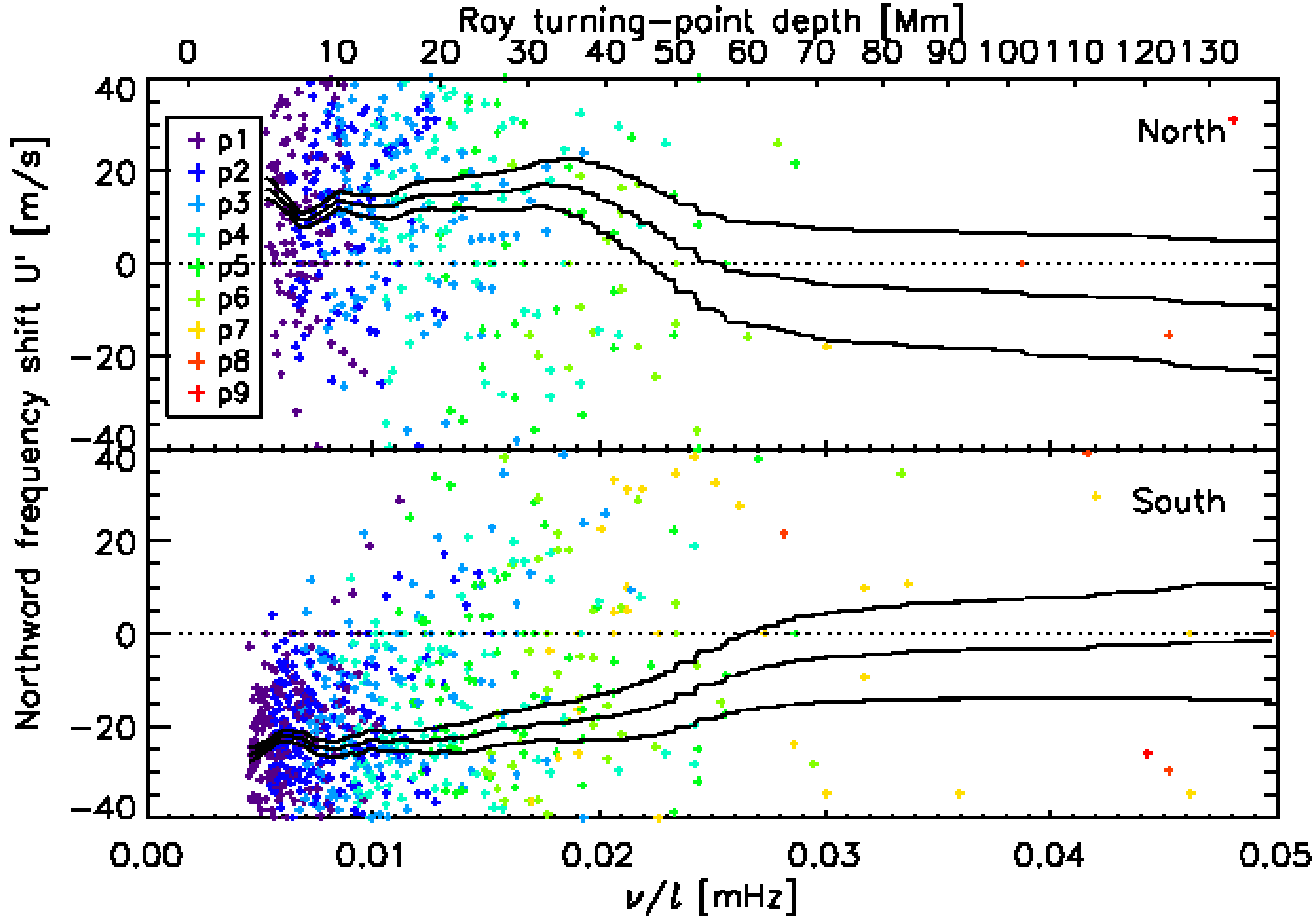
$P_+(\nu,l) - P_-(\nu,l)$



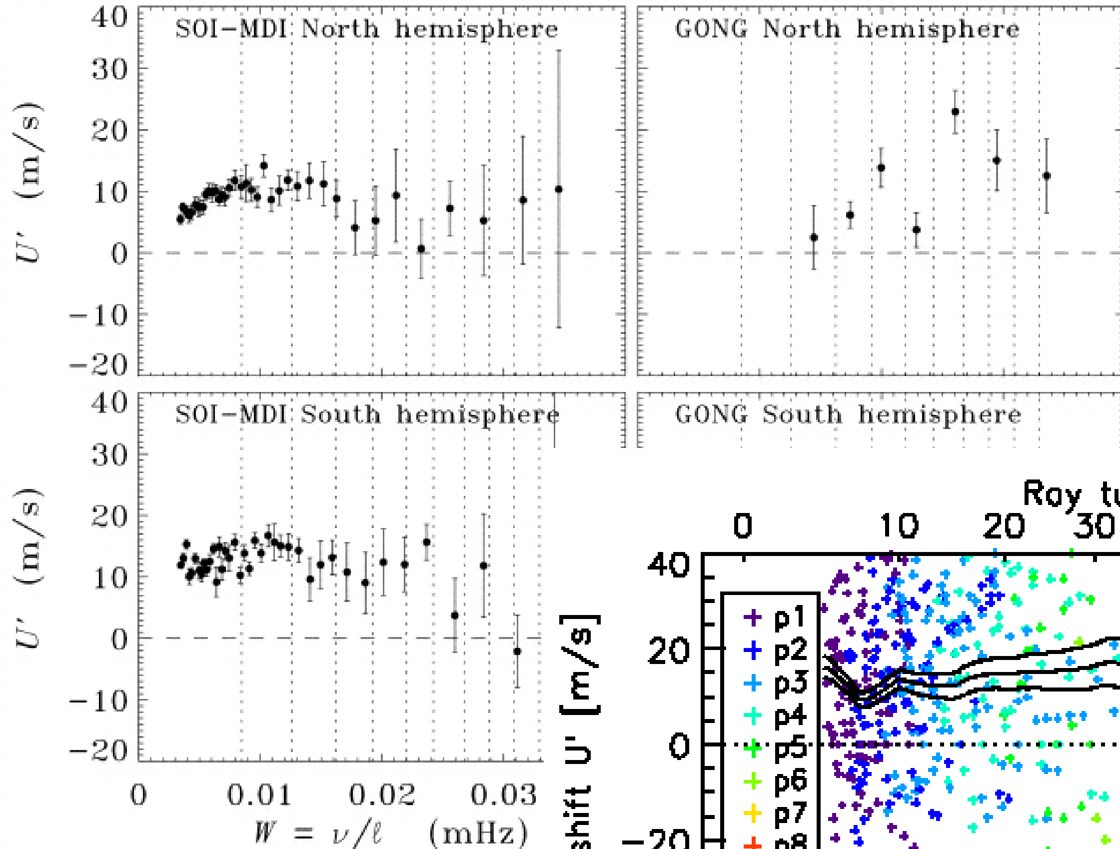
256Mm
128Mm
64Mm
32Mm
16Mm
8Mm
4Mm
p8
p7
p6
p5
p4
p3
p2
p1
f
4.5
4.0
3.5
3.0
2.5
2.0
ν [mHz]
0
200
400
600
800
l

Average 80 days frequency shift during solar min

Mitra-Kraev & Thompson (2007) AN **328** 1009

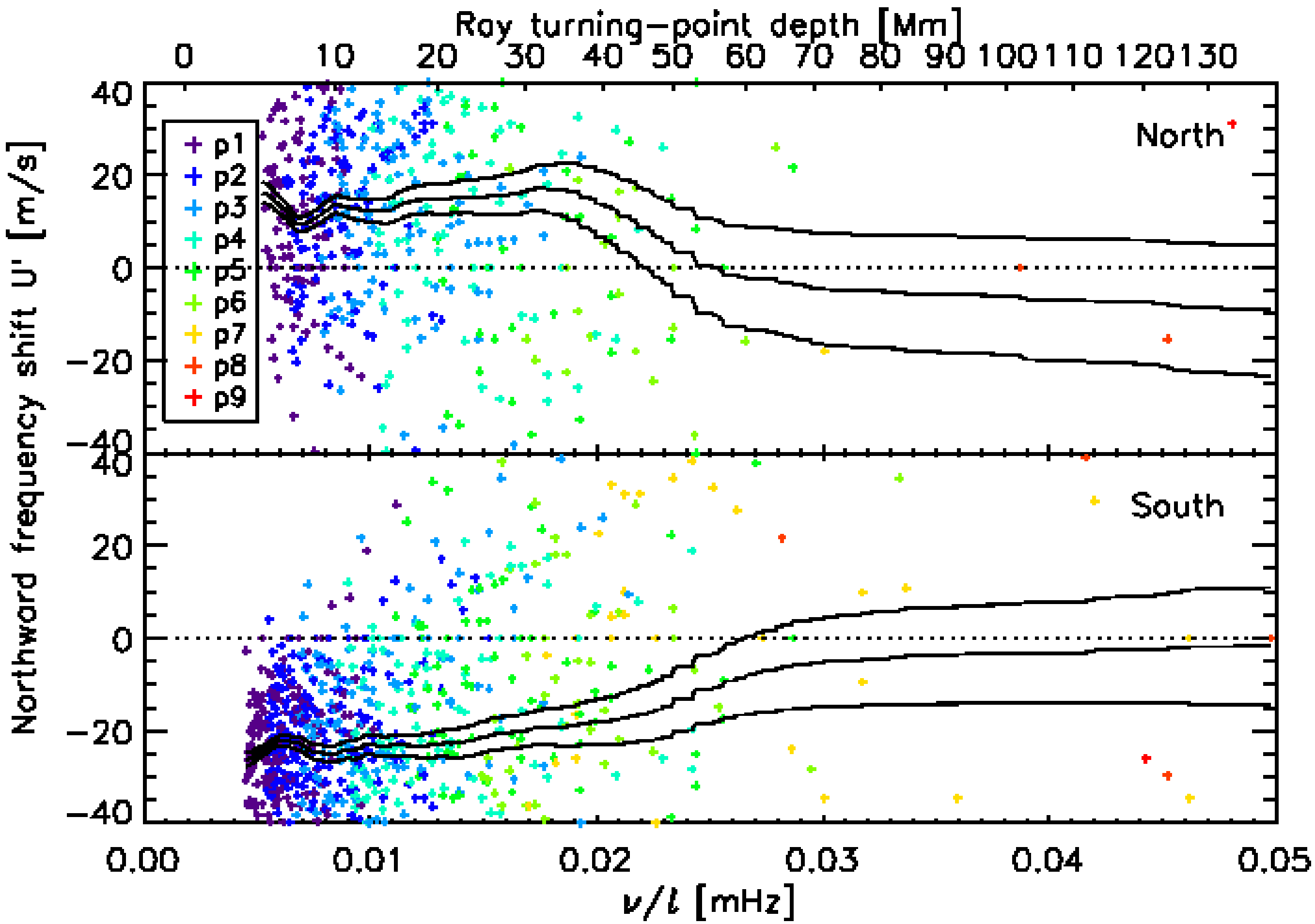


. shift during
n



Braun & Fan (1998) ApJ **508** L105

a-Kraev & Thompson (2007) AN **328** 1009



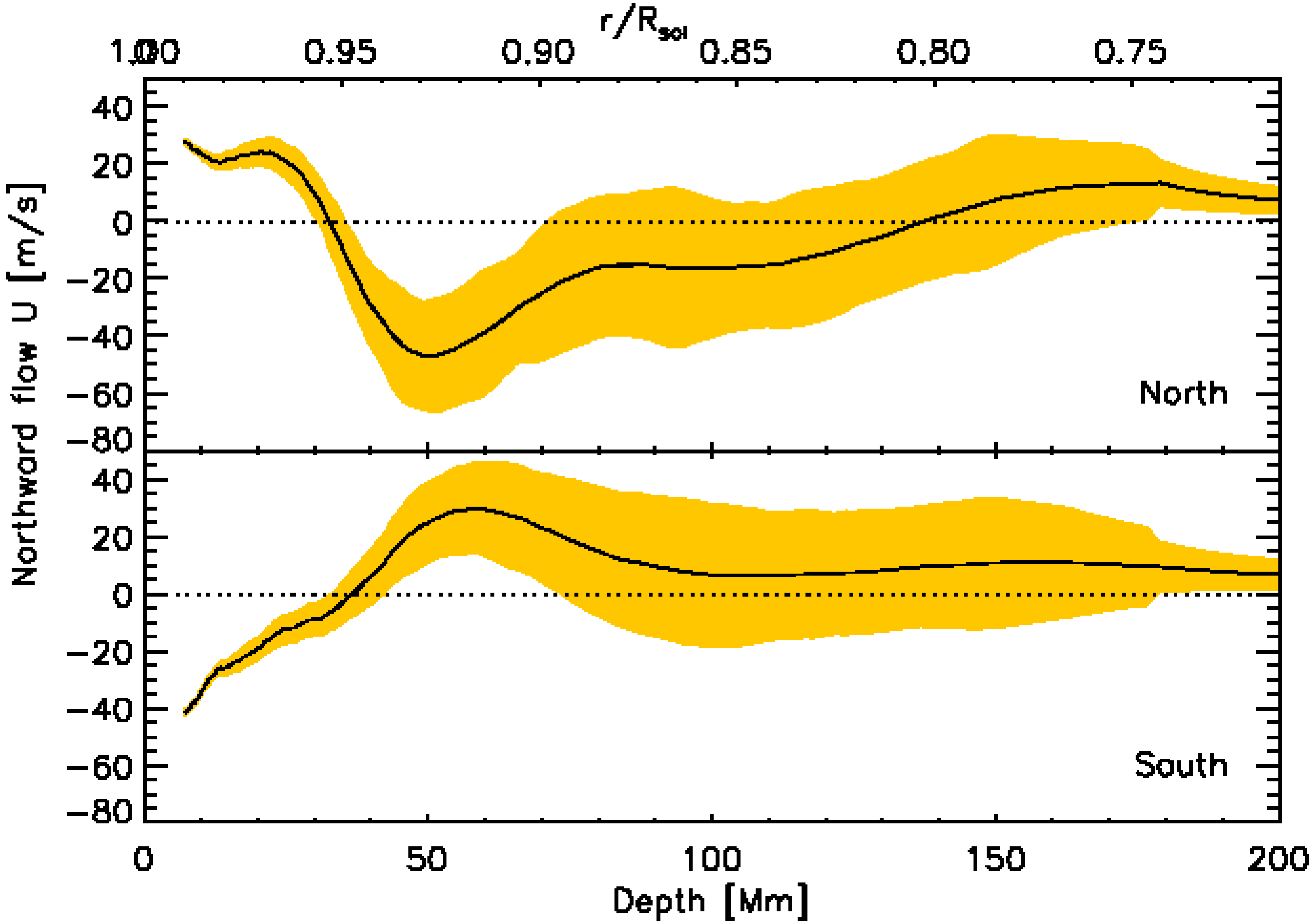
Asymptotic inversion

(Christensen-Dalsgaard et al. 1990)

$$U(r) = \frac{-2a(r)}{\pi} \frac{\mathrm{d}}{\mathrm{d}\ln r} \int_{a(R_\odot)}^{a(r)} \sqrt{\frac{1}{a^2(r) - w^2}}\; D(w)\, dw$$

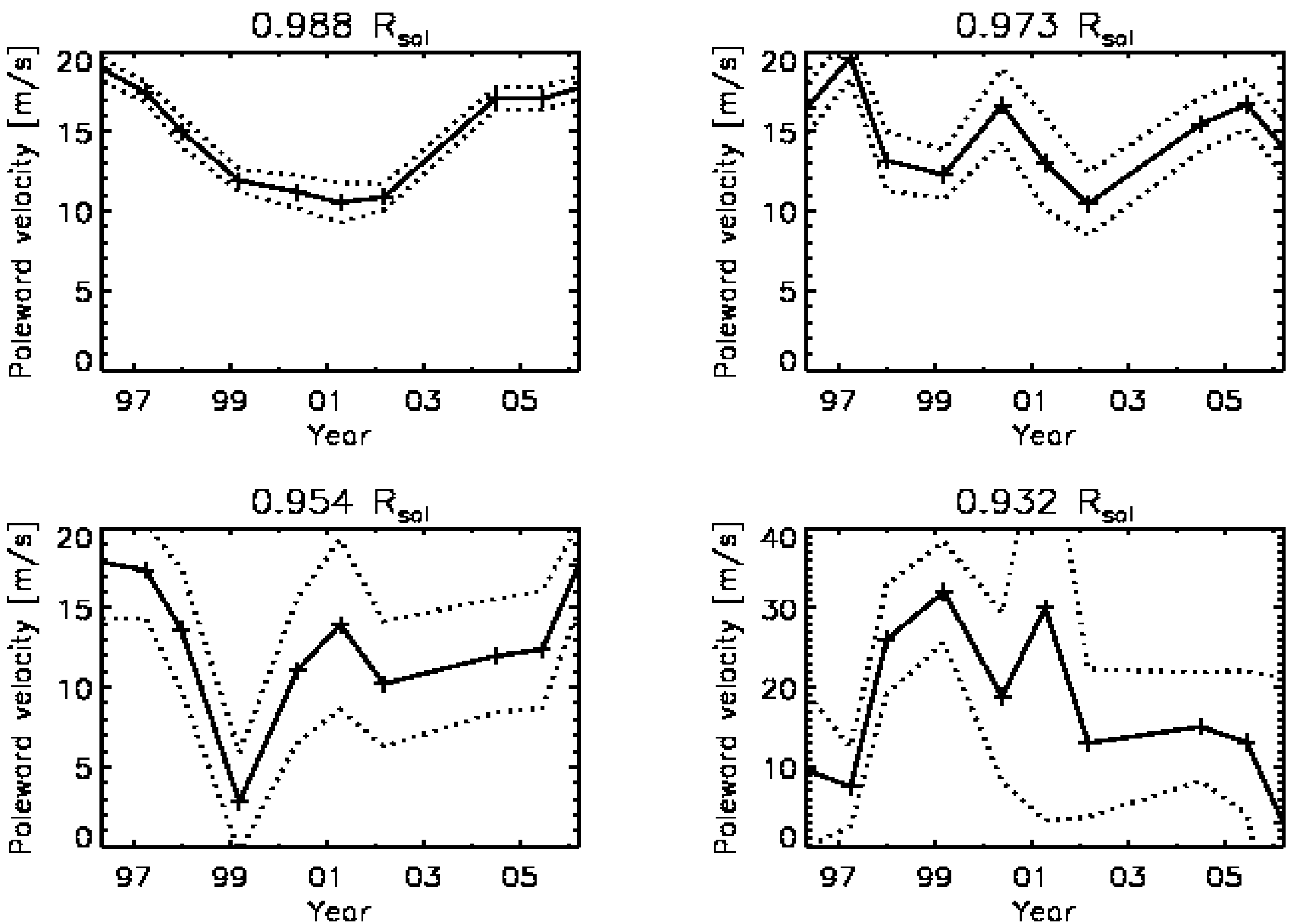
- With radial coordinate r
- flow profile U(r)
- $a(r) := c(r)/r \qquad w = 2\pi\nu/l.$
- c(r) sound speed profile given by ModelS (Christensen-Dalsgaard et al. 1989, see also Sekii & Shibahashi 1989)
- D(w) = U’(w) (“measured” velocity)

Average 80 days inversion result during solar minimum

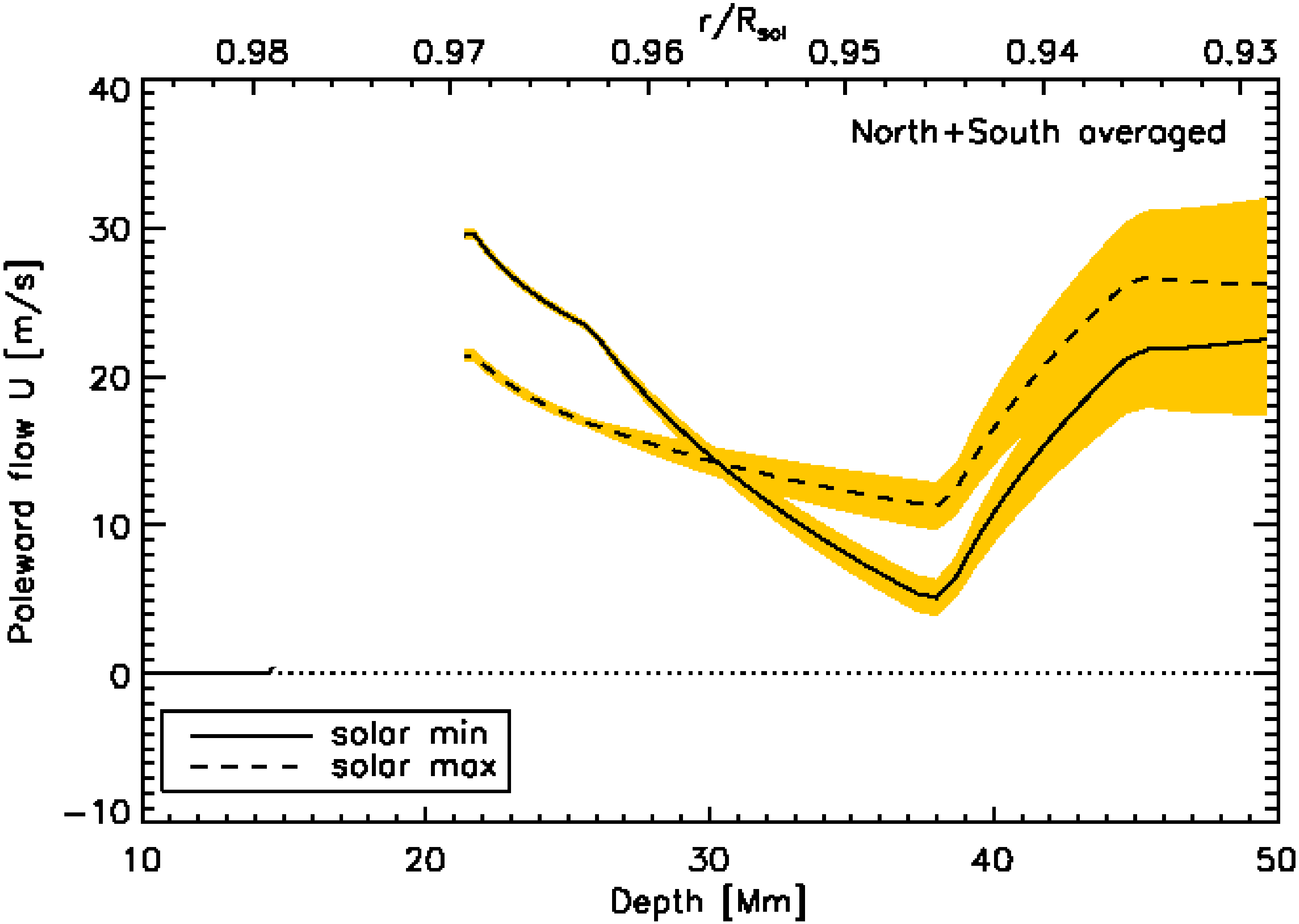


Mitra-Kraev & Thompson (2007) AN in **328** 1009

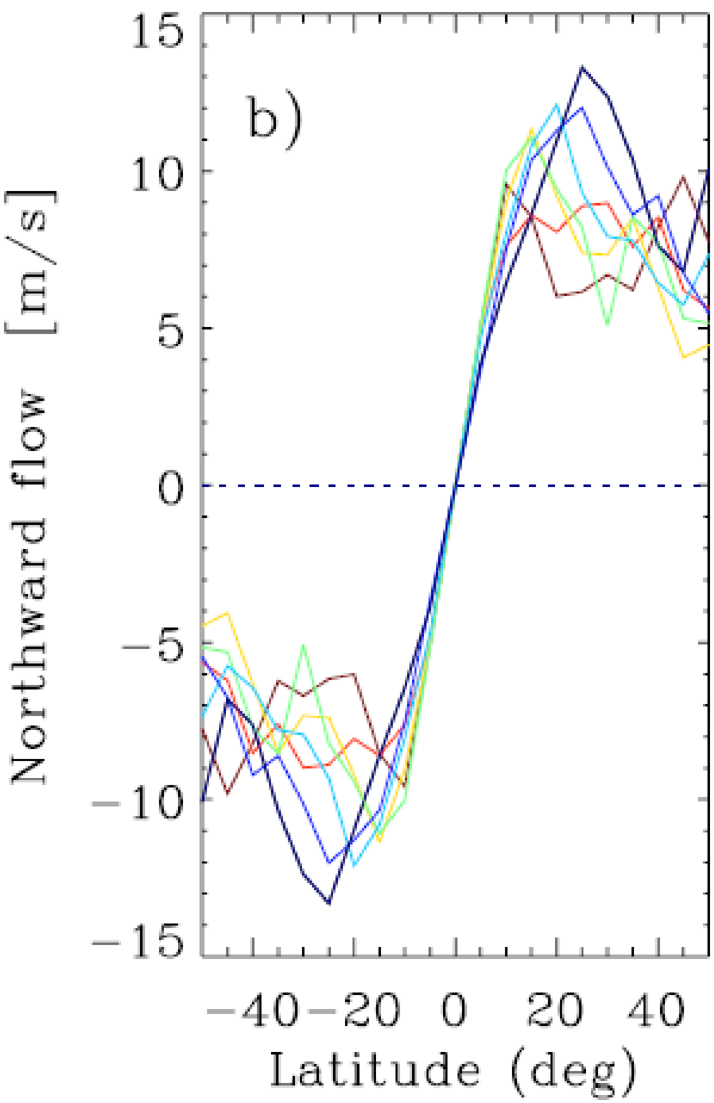
Variations with the solar cycle



Inversion result of solar min vs max



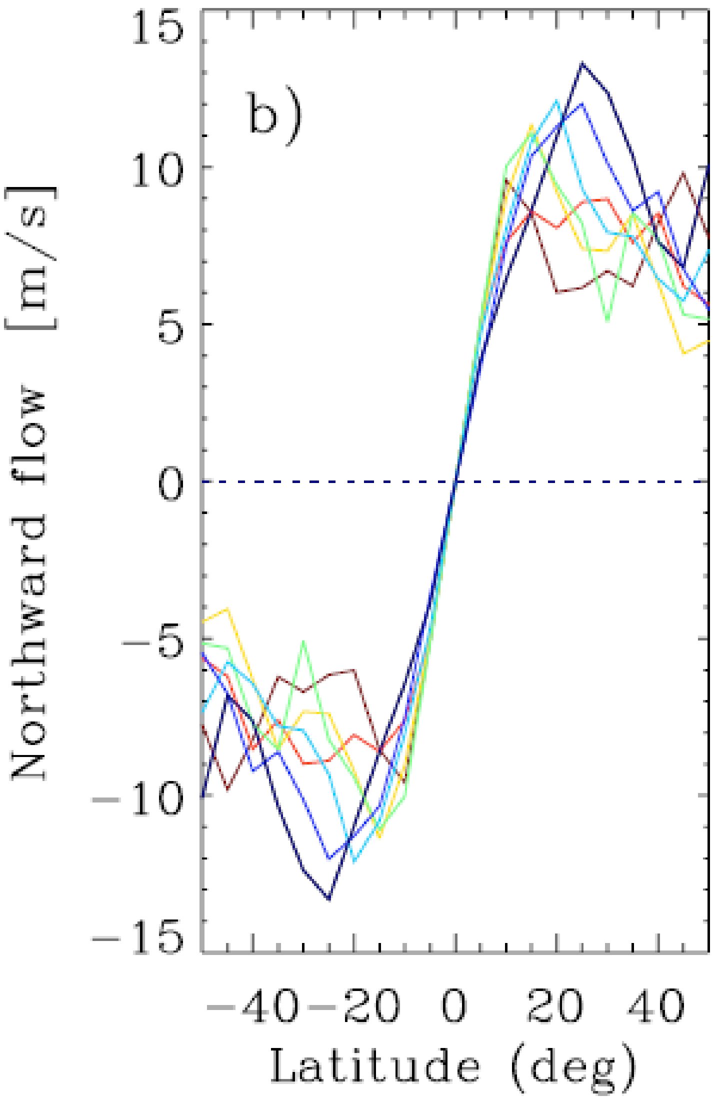
Comparisons with other recent results

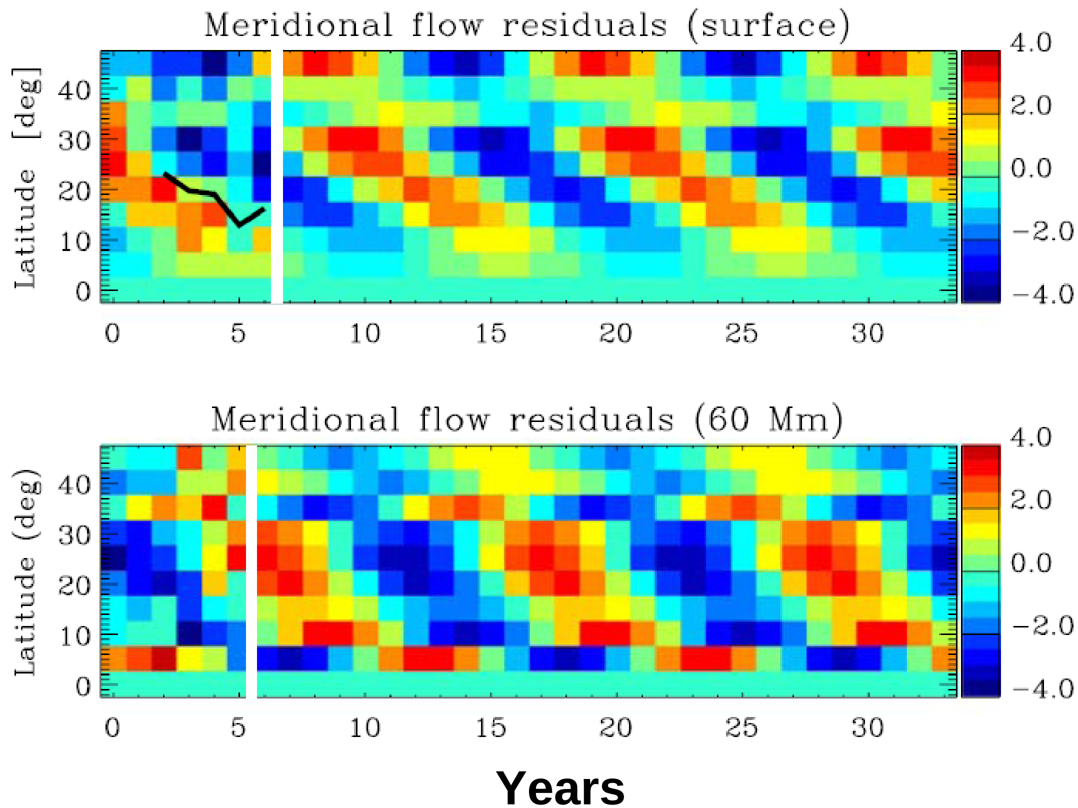


- Meridional flow near solar surface:
- From solar min in 1996 (blue) to solar max in 2002 (red)

Gizon & Rempel (2008) Solar Phys. **251** 241

Comparisons with other recent results





Gizon & Rempel (2008) Solar Phys. **251** 241

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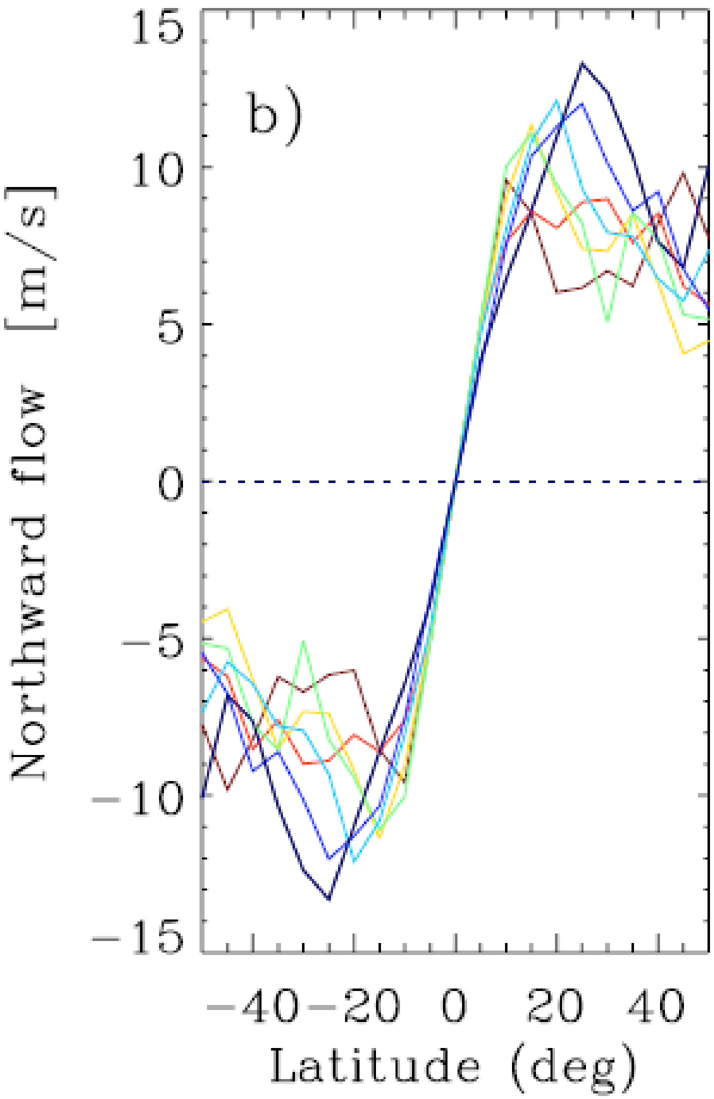

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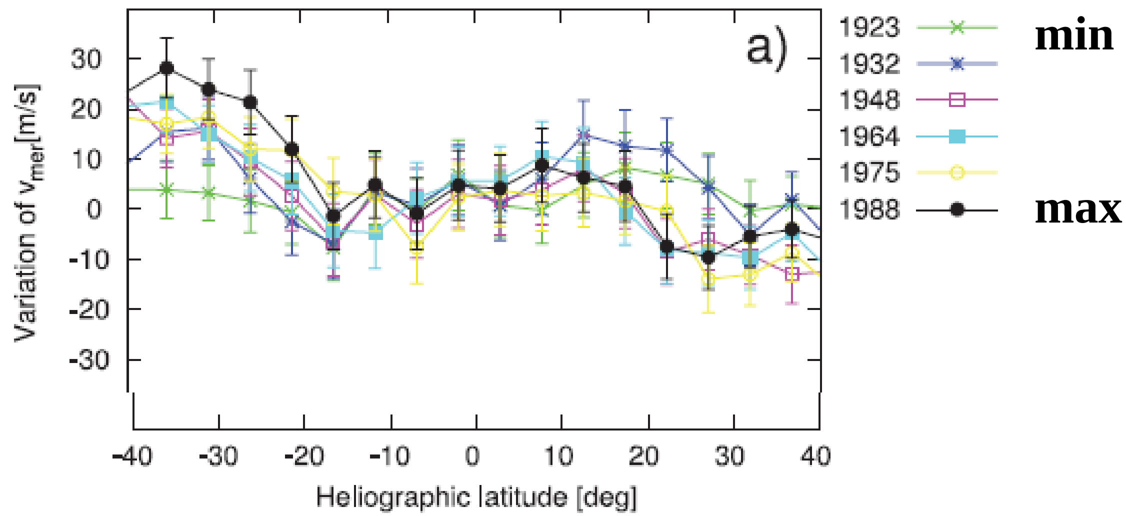

Svanda, Kosovichev, Zhao (2008) ApJ **680** L161

Conclusions

- For quiet Sun, find return flow at a depth of around 40 Mm -> Possibly two flow cells lying on top of each other
- Found variations with the solar cycle
  - Near-surface flow decreases from 20m/s to 10m/s, while the flow at deeper layers increases from solar min to solar max