Contributions instrumentales et théoriques à l'héliosismologie

Habilitation à diriger des recherches

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European Space Agency

Nice le 8 Juin 2000

Outline of the talk

- What is the purpose of this?
- What is helioseismology?
  - Overview of the field...and my contributions
- Interaction with other scientists
- The future

What is the purpose of this?

- Recapitulation for a new start
- Outline genuine contributions to the field
- Ability:
  - To conduct research
  - To collaborate with other scientists
  - To pass knowledge on

What is helioseismology?

- Historical perspective
- Theory
- Helioseismic observations
- Data analysis
- Some scientific results

Historical perspective of helioseismology

- The formative years (1962-1975)
  - Leighton (1962), Ulrich (1970), Deubner (1975)
- The understanding years (1975-1985)
  - Claverie et al. (1979), Grec et al. (1980), Duvall and Harvey (1985)
- The pre-space age (1985-1996)
  - BiSON, GONG, IRIS, LOWL
- The golden age (1996-present)
  - SOHO and the networks

Solar radial velocities in 2-D

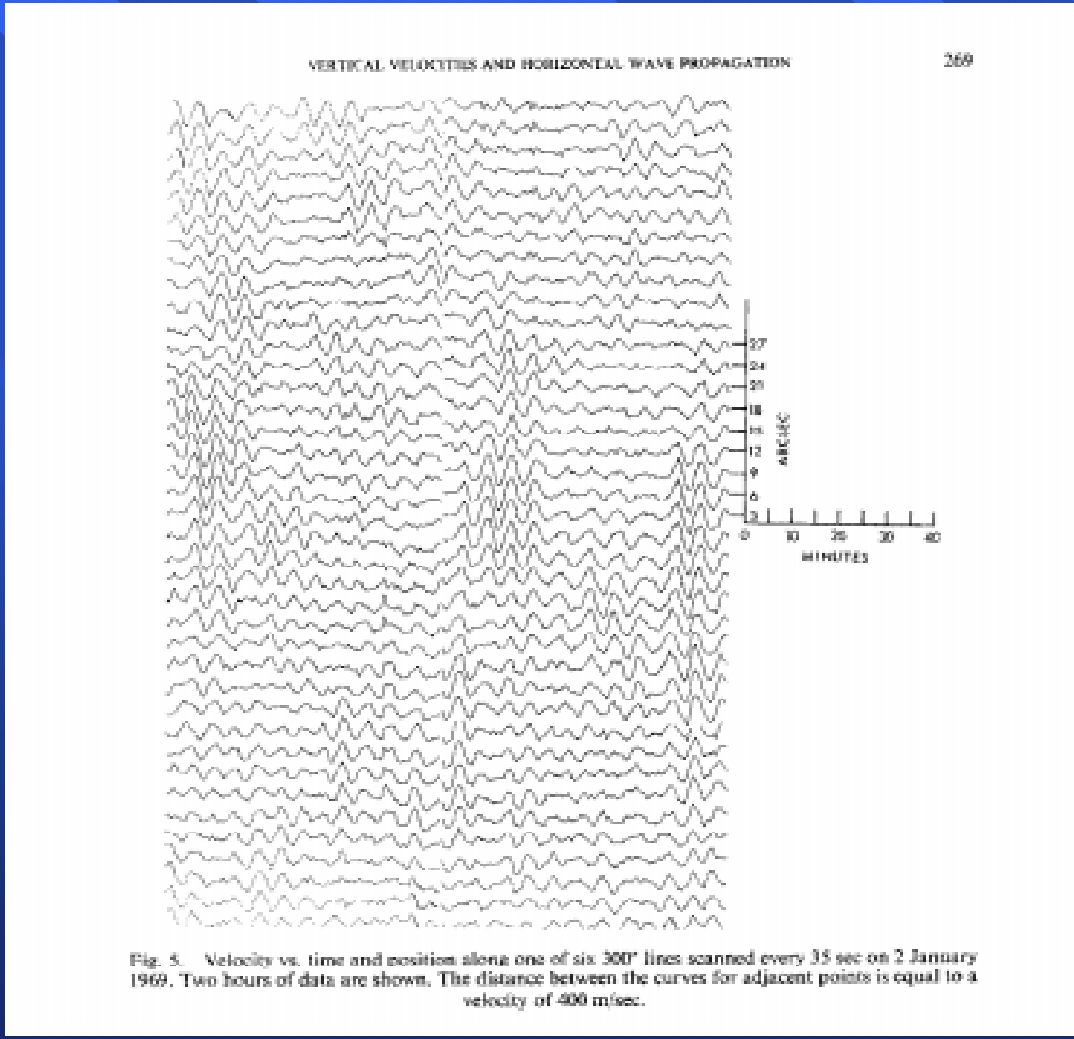
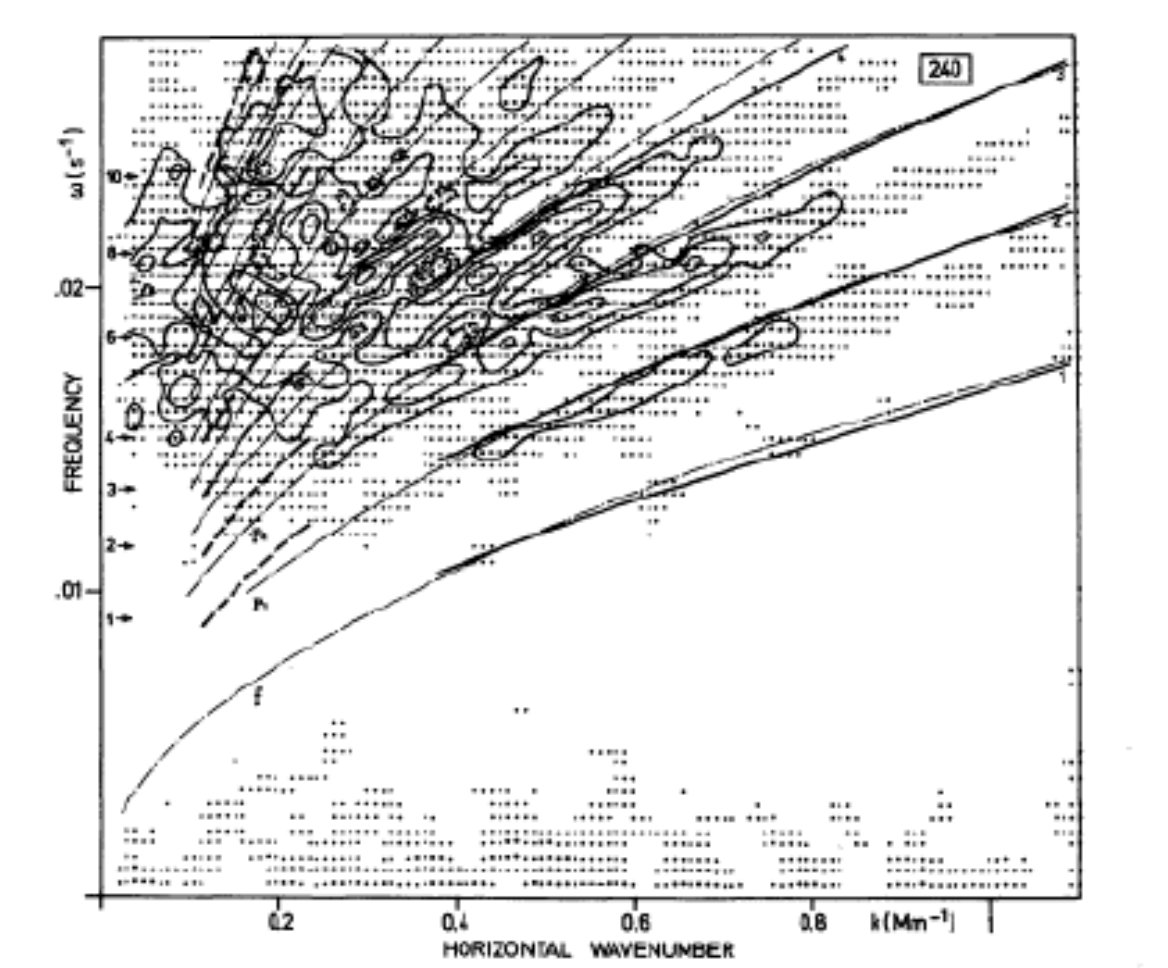


Fig. 5. Velocity vs. time and position along one of six 300° lines scanned every 35 sec on 2 January 1969. Two hours of data are shown. The distance between the curves for adjacent points is equal to a velocity of 400 m/sec.

Musman and Rust (1970)

The Deubner's (k,ω) diagramme



Deubner (1975)

The sun seen as a star

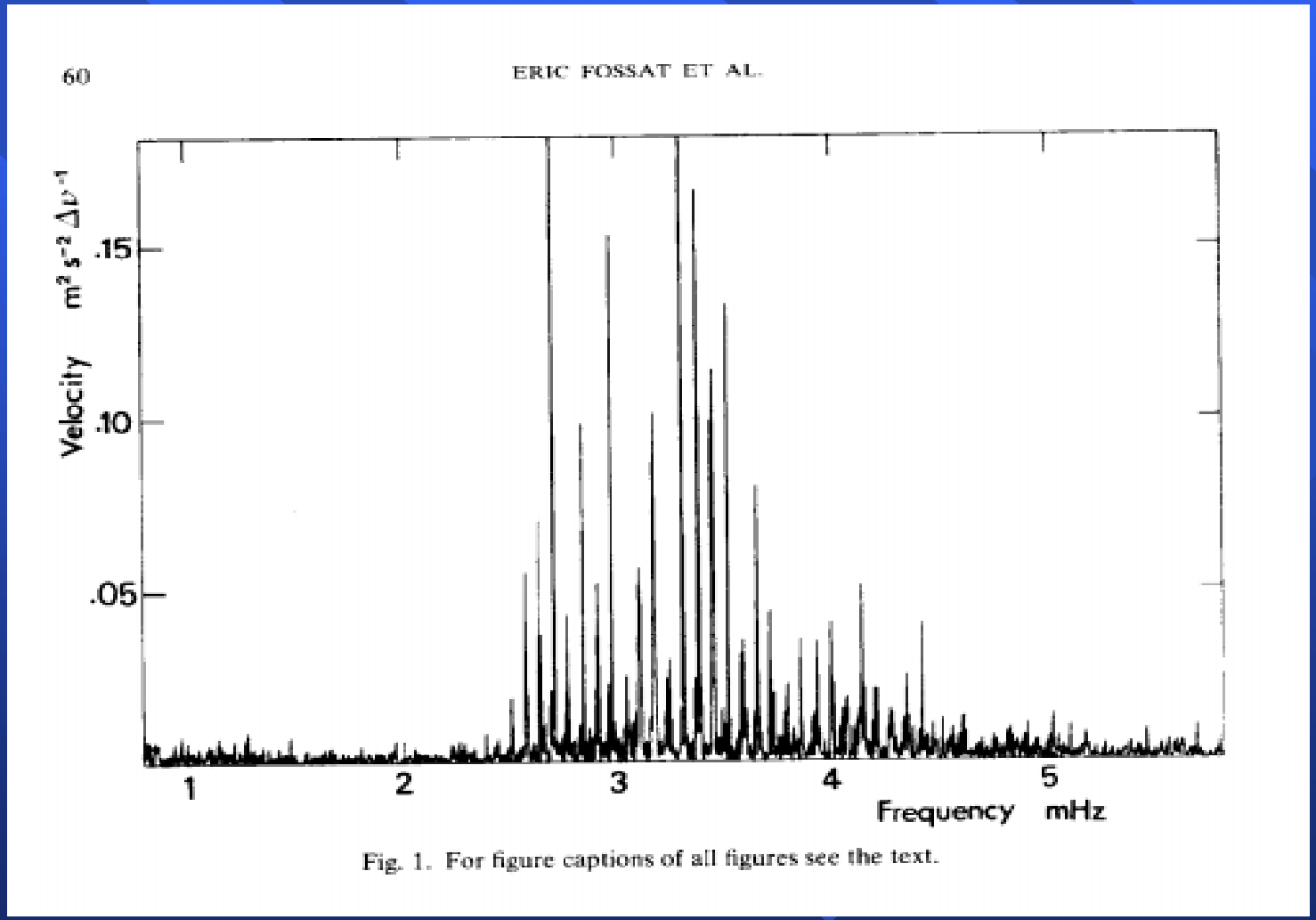
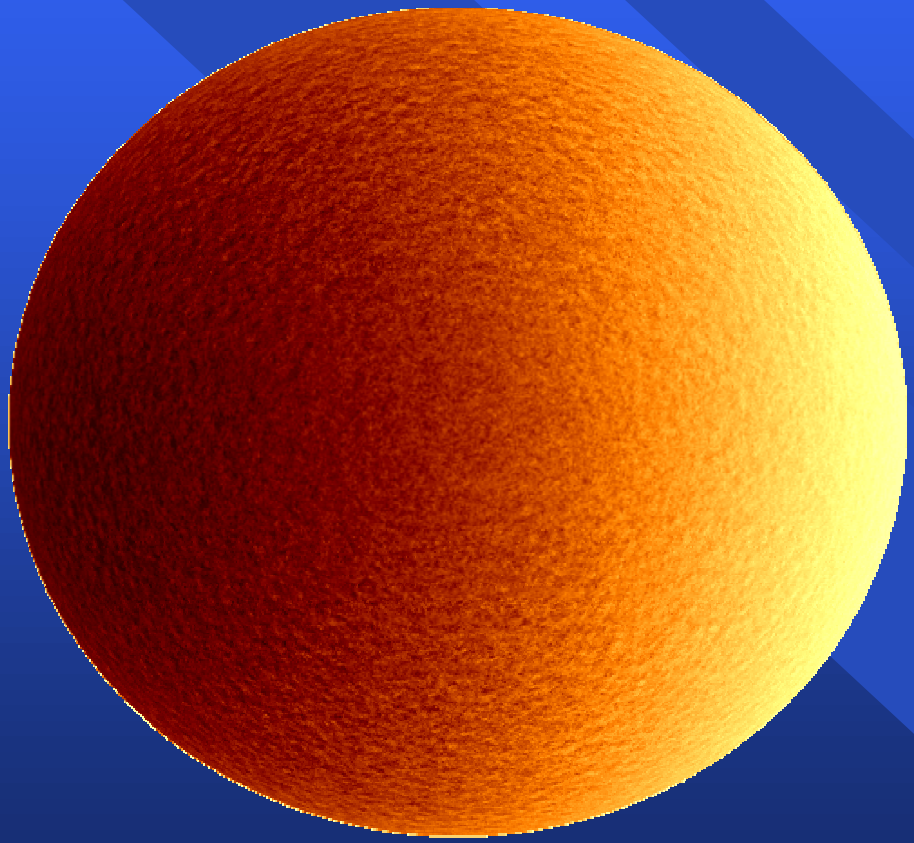


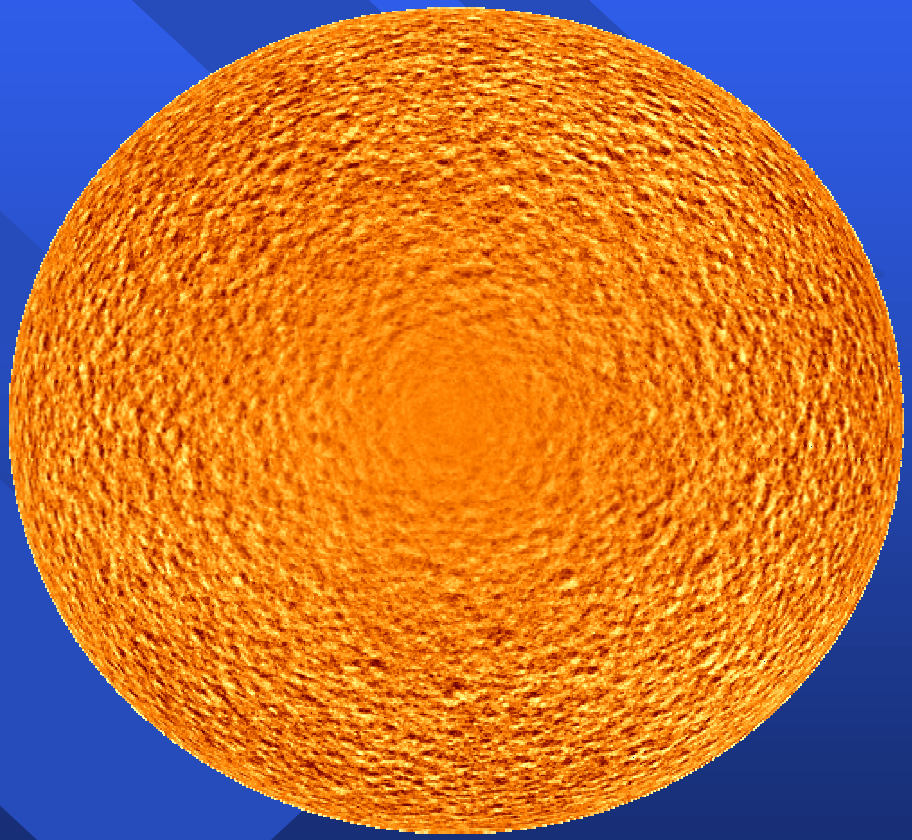
Fig. 1. For figure captions of all figures see the text.

Fossat et al. (1981)

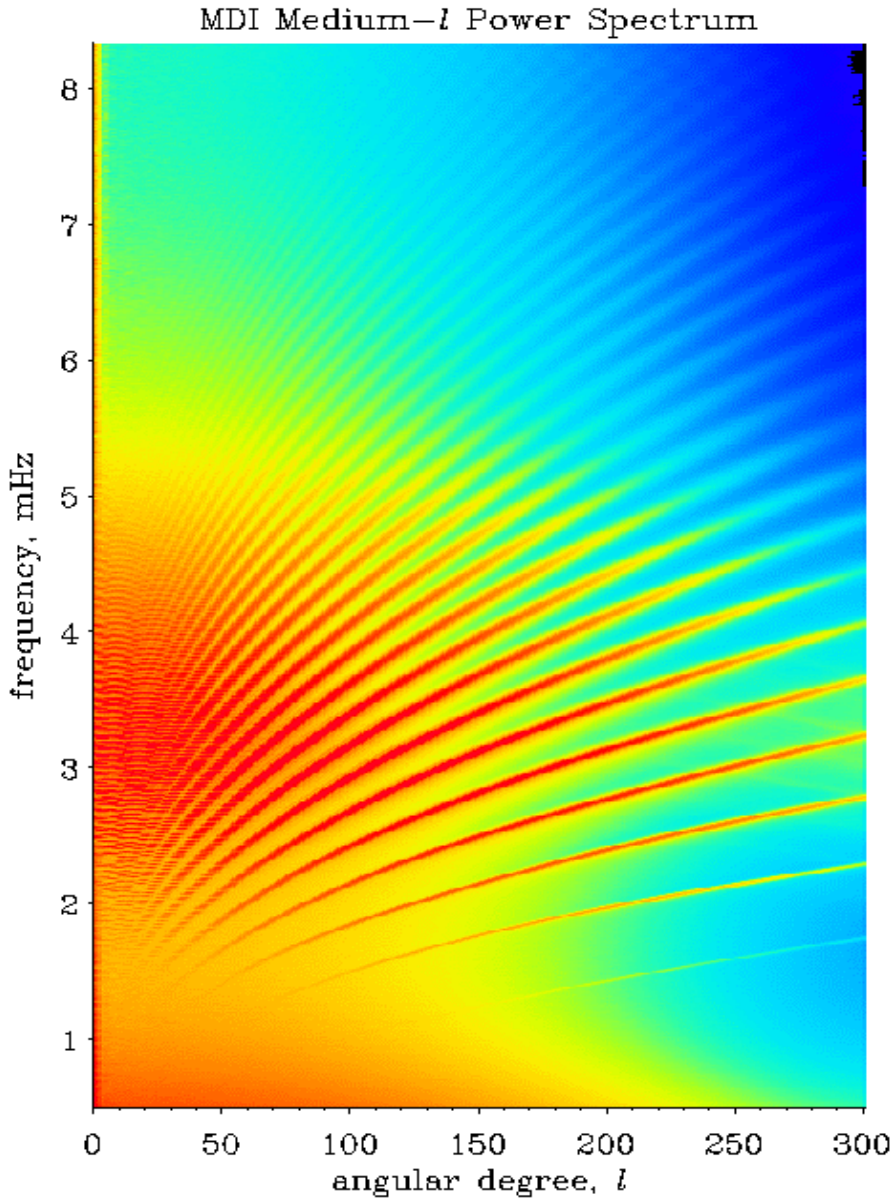
The sun is an orange



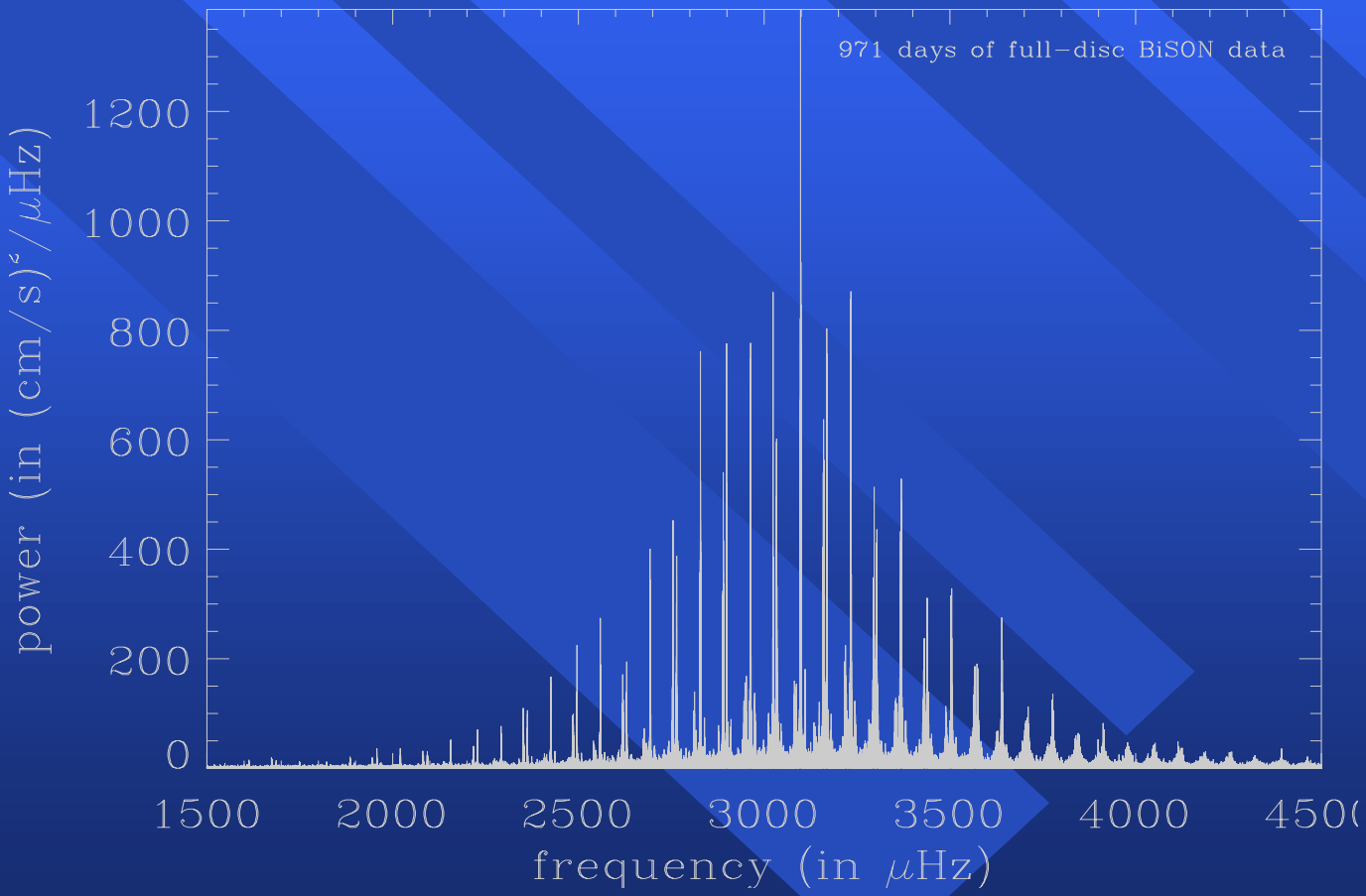
The rotation of the Sun



Solar supergranulation

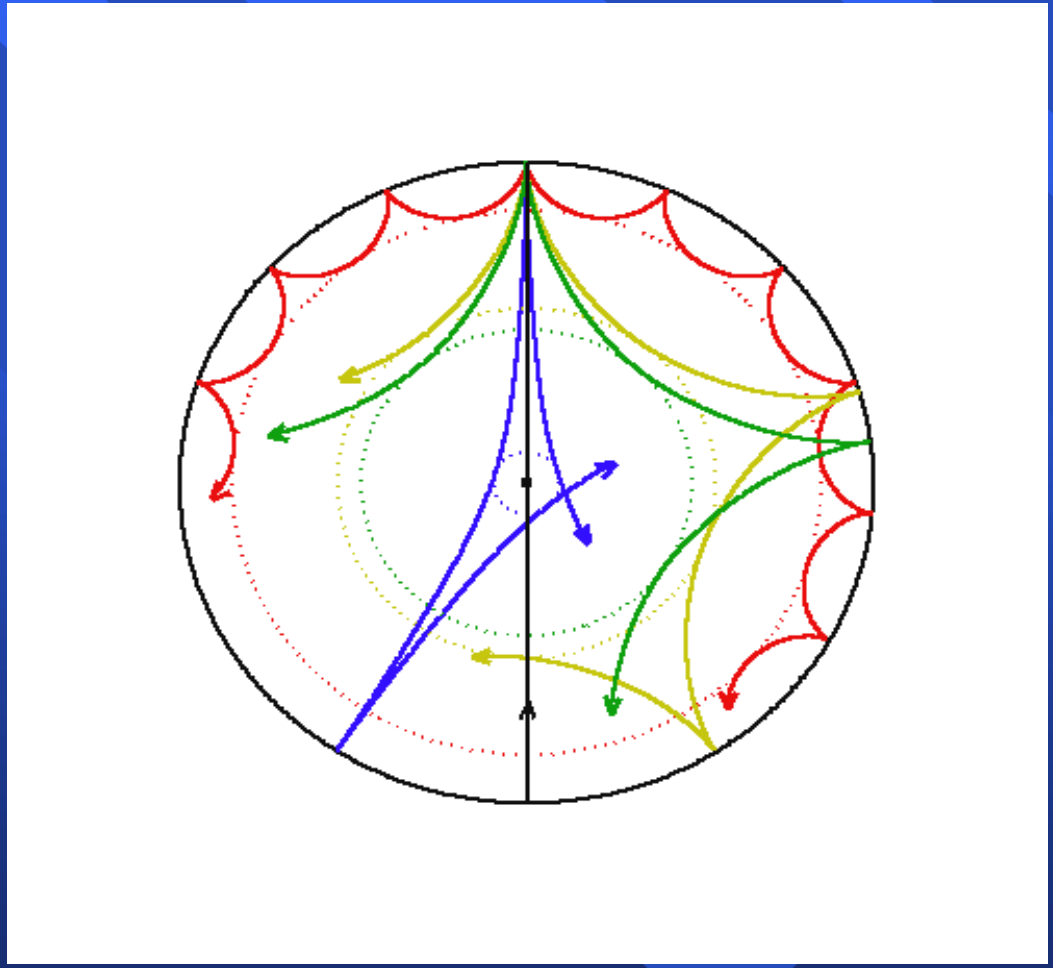

MDI Medium−l Power Spectrum
frequency, mHz
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
angular degree, l

BiSON Spectrum



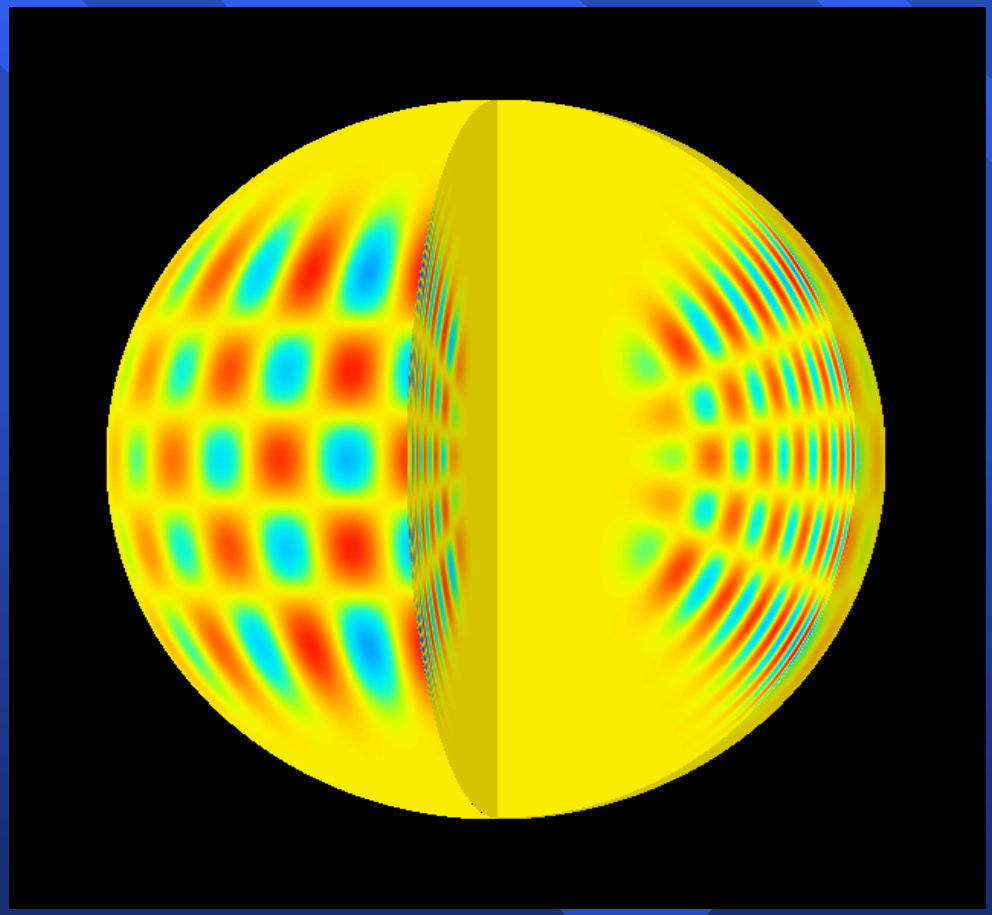
Courtesy of BiSON

Waves propagation



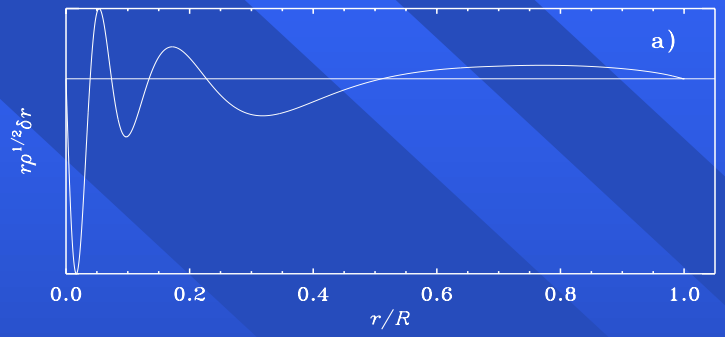
Courtesy of TAC, Aarhus

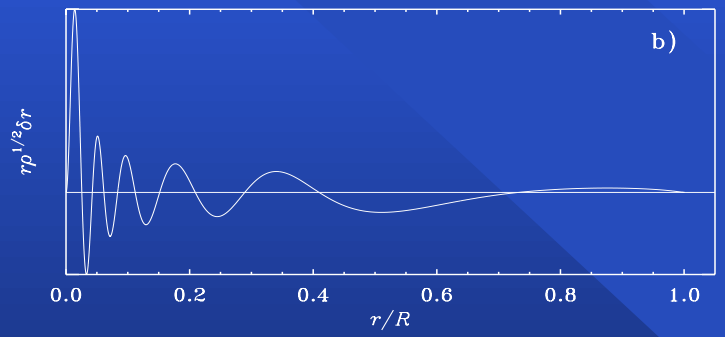
3-D eigenfunction

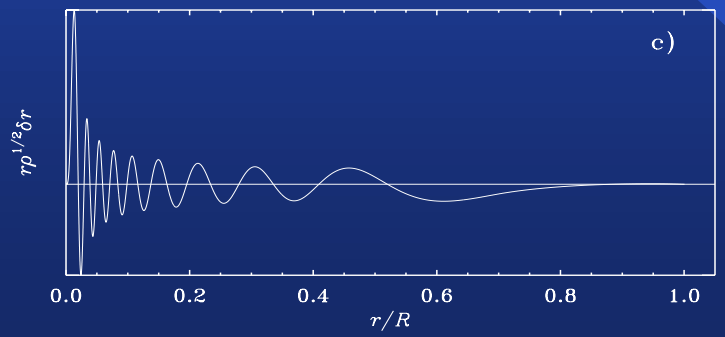


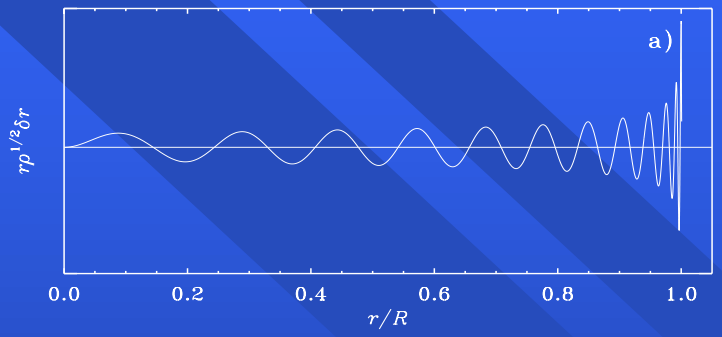
Kosovichev (1996)

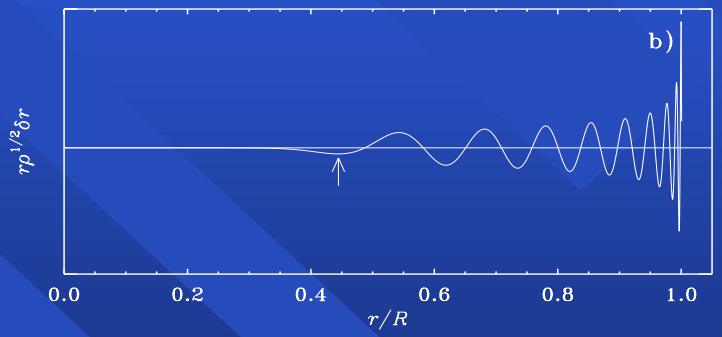
Radial eigenfunctions

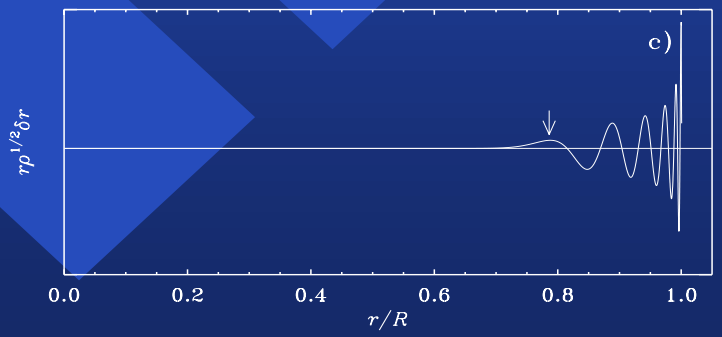






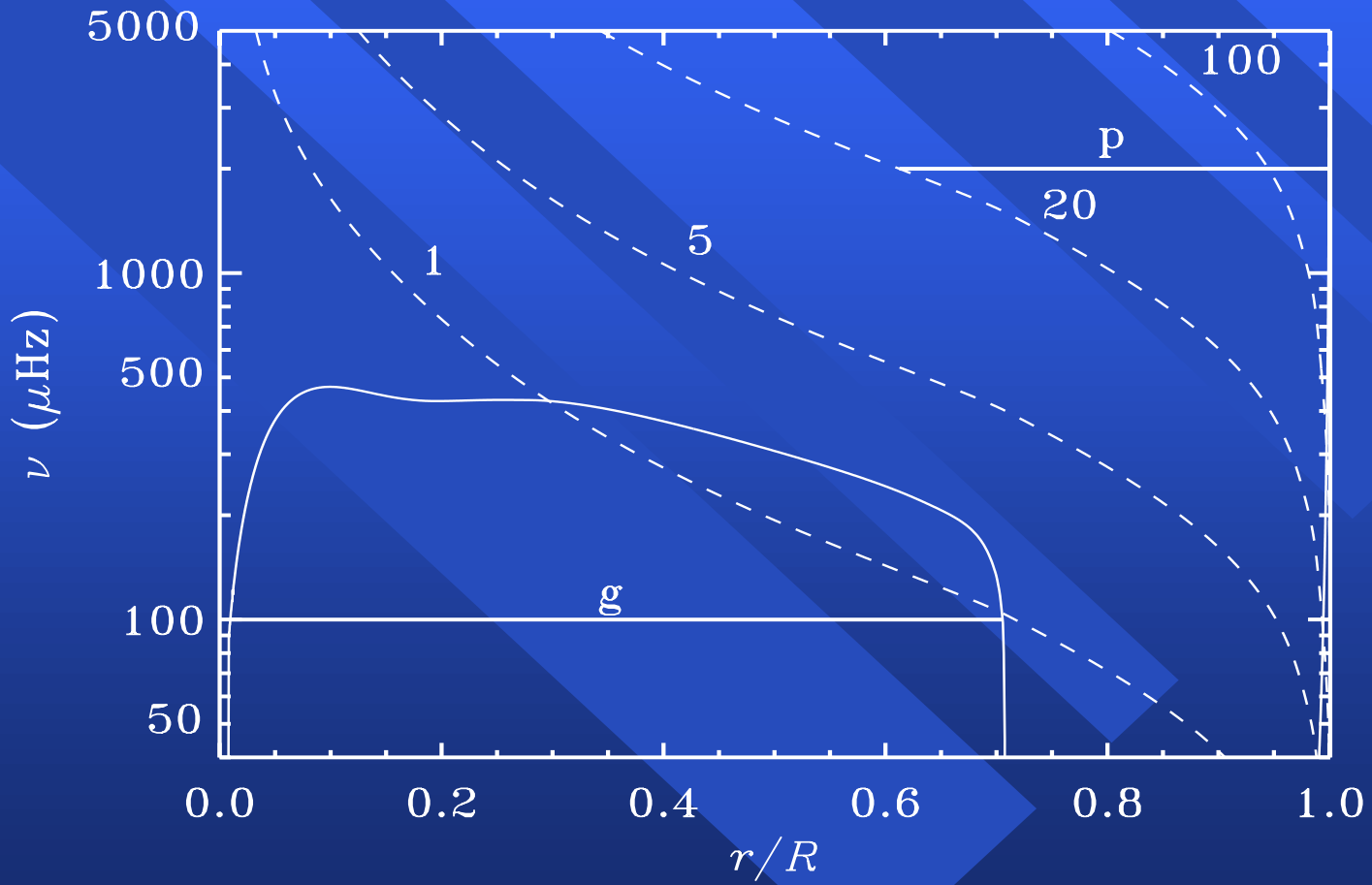






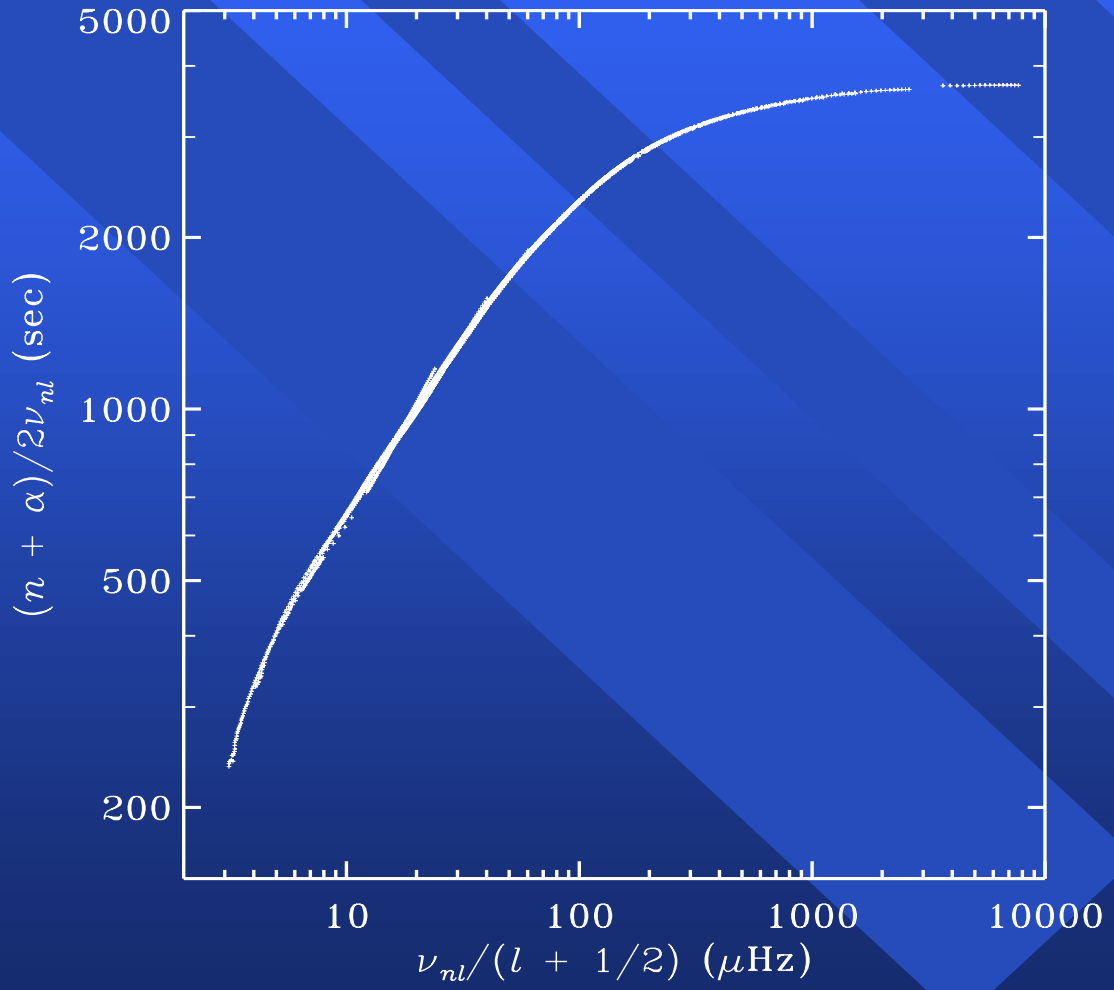
Christensen-Dalsgaard (1998)

Propagation diagramme



Christensen-Dalsgaard (1998)

Duvall's law

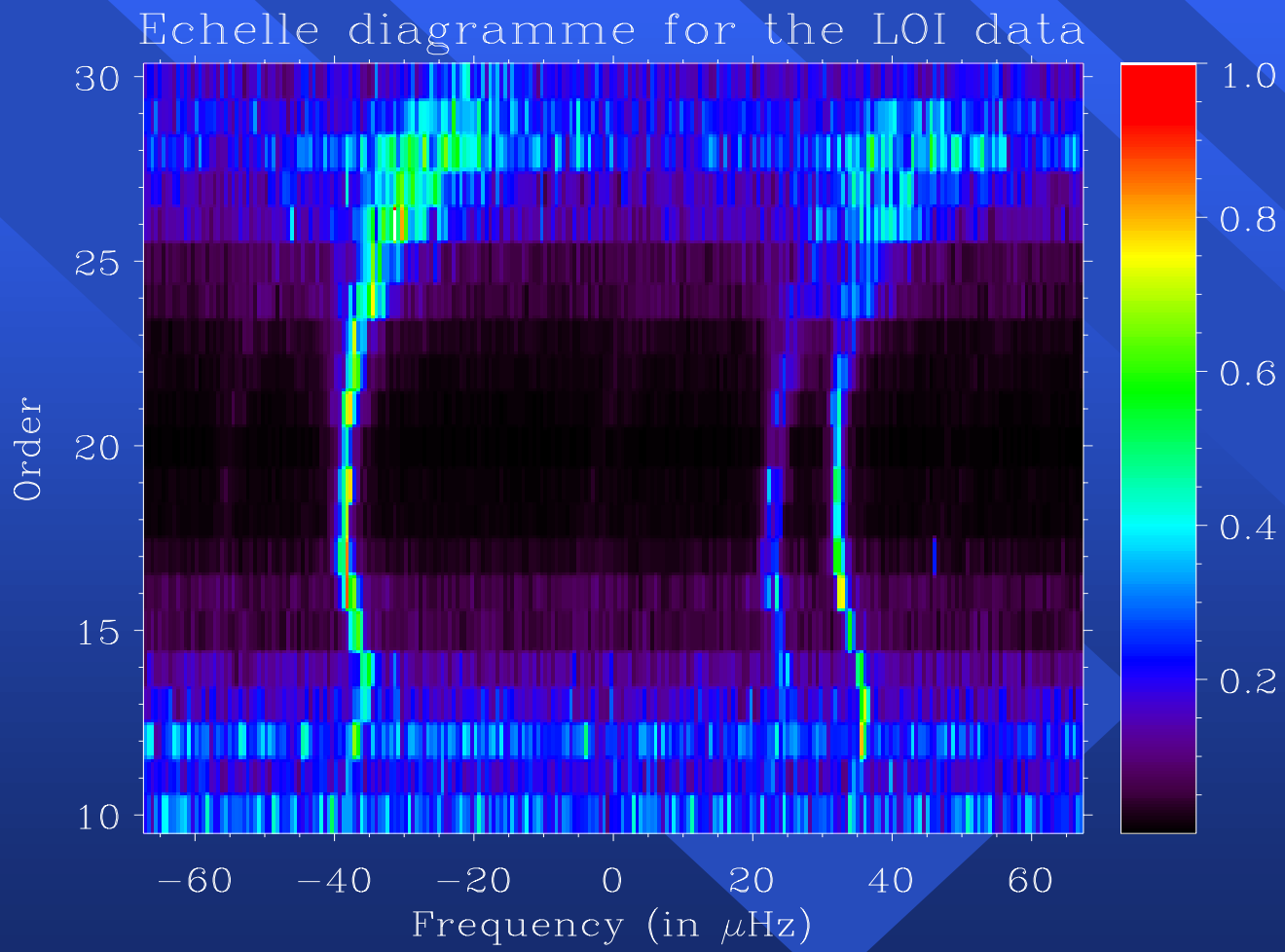


$$k \approx \frac{\omega}{c}$$

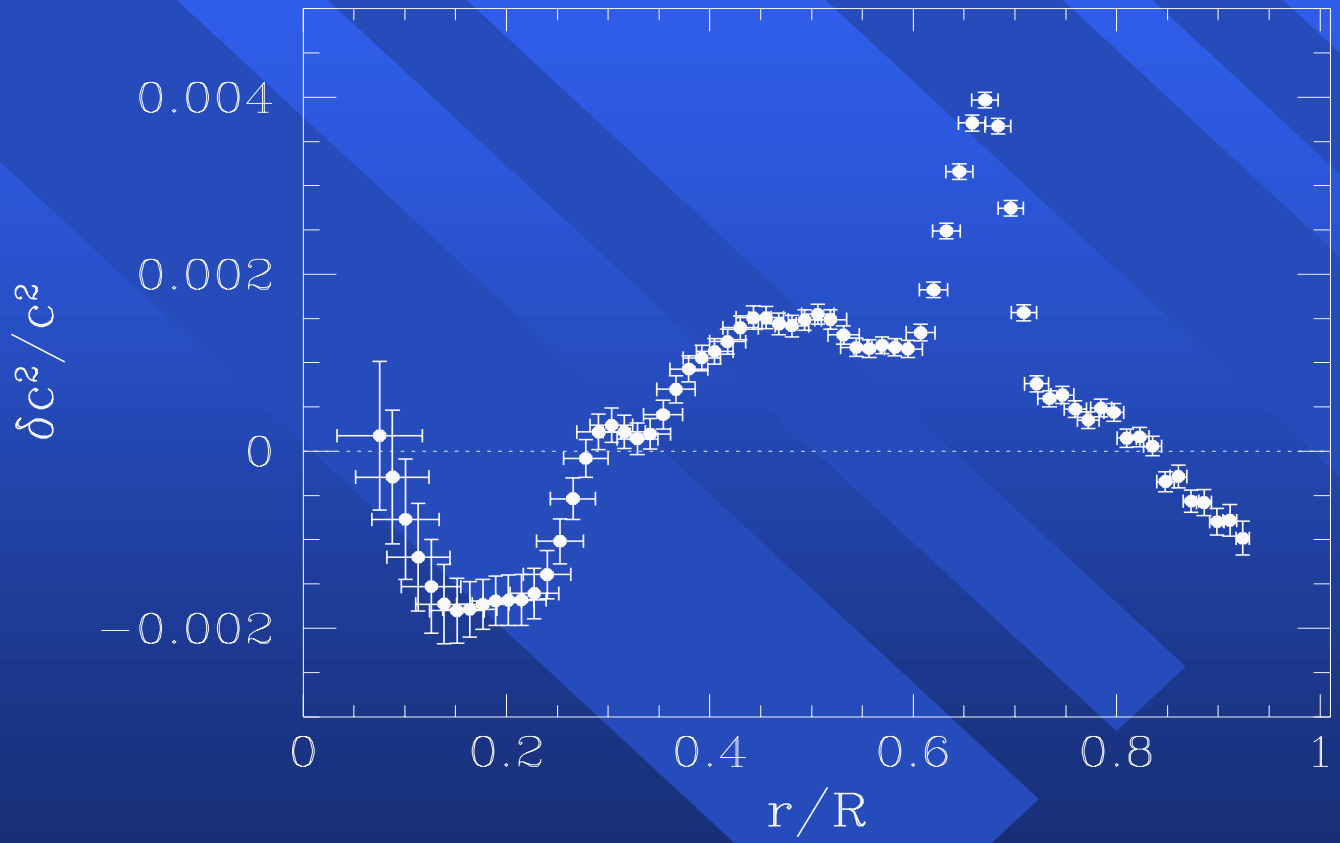
$$\int_{r_t}^{R_0} k \mathrm{d}r = \left(n - \frac{1}{2}\right)\pi$$

Christensen-Dalsgaard (1998)

Echelle diagramme



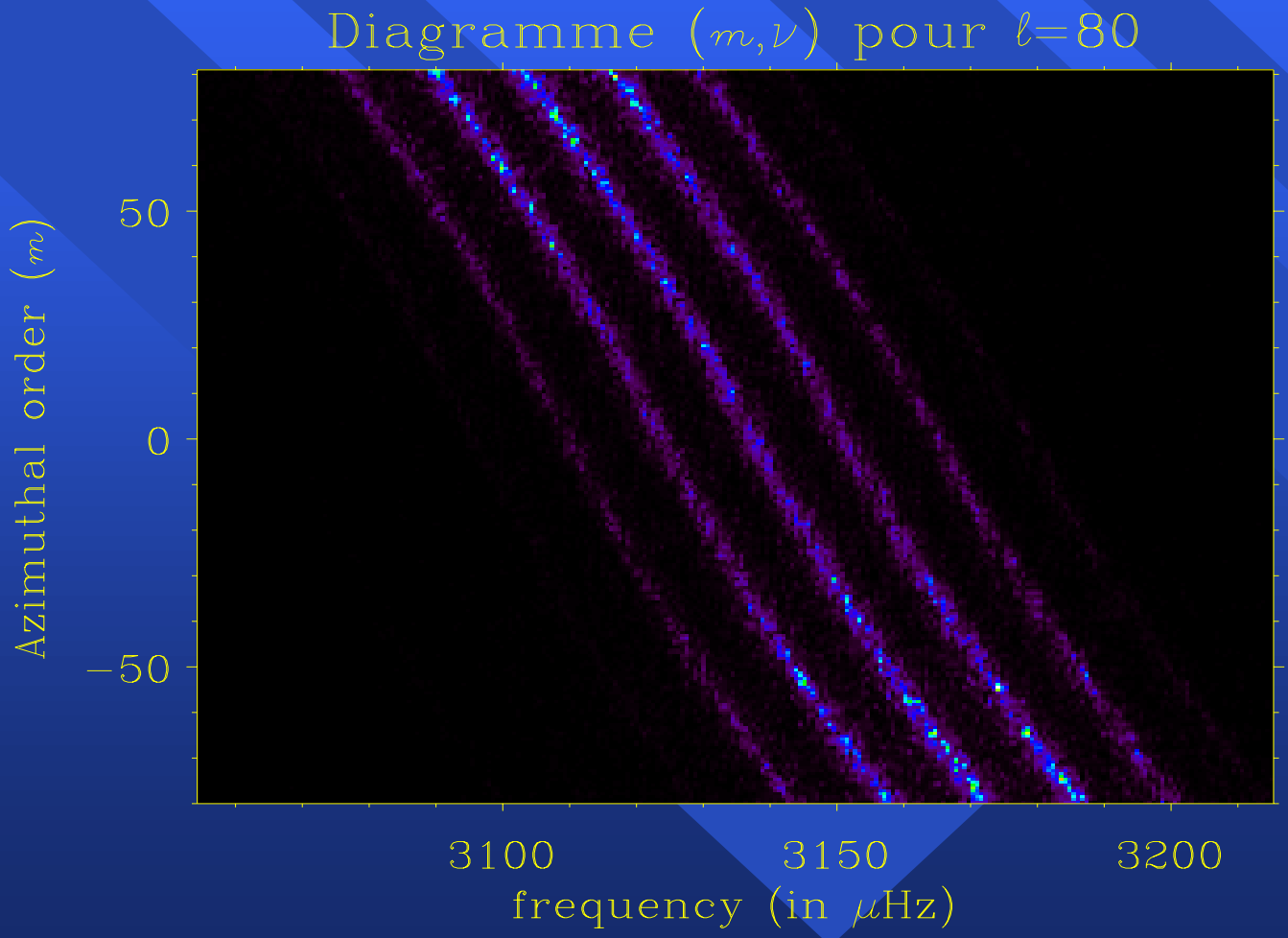
Structure inversion



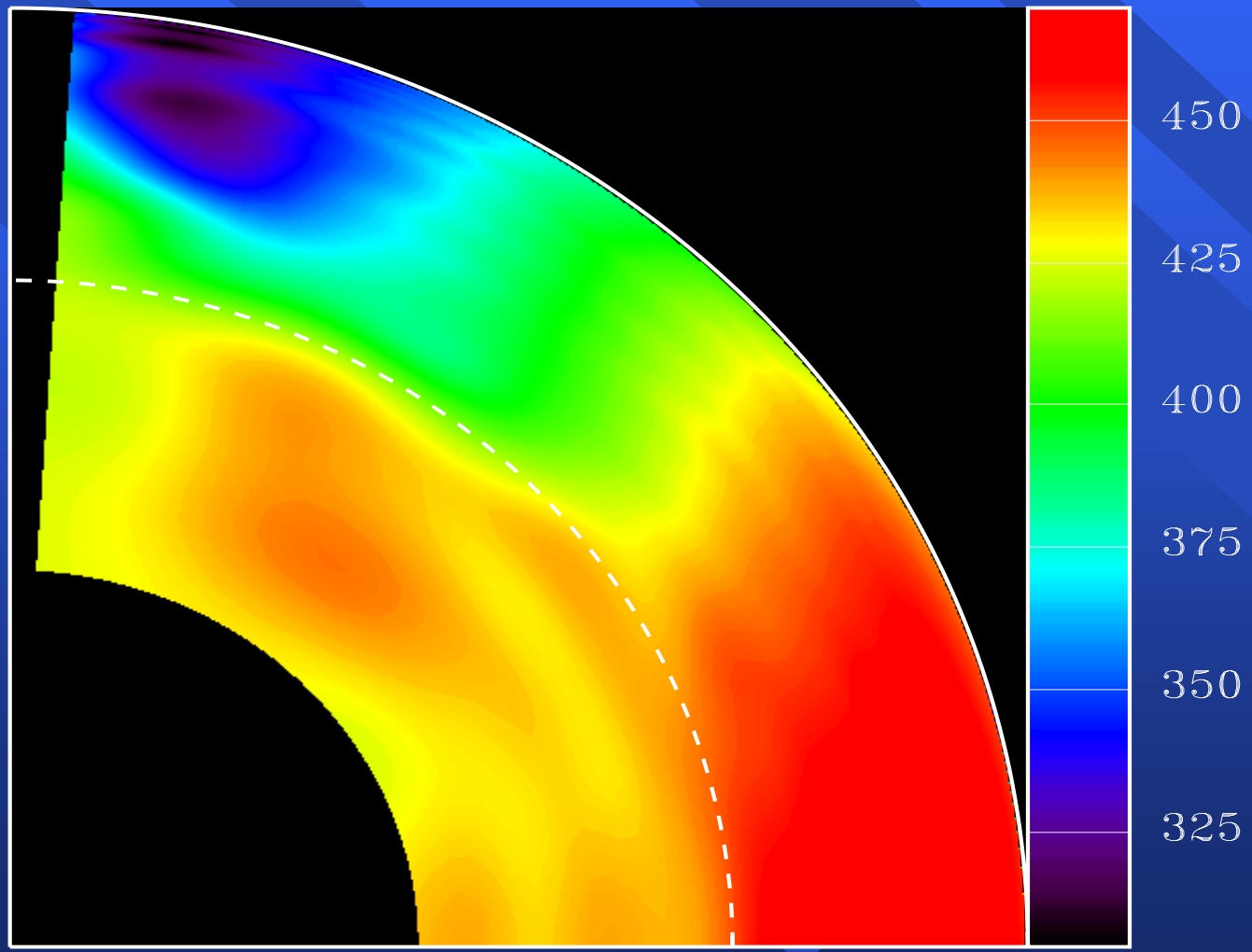
Kosovichev et al (1996)

Splitting and rotation

$\nu_{nlm} = \nu_0 + m\Omega$



Rotation inversion



Schou et al (1996)

Theory: a summary

- Eigenmodes are characterized by 3 quantum numbers: n, l, m
- Each mode has a given frequency associated with a given volume in the Sun
- Each mode is stochastically excited
- Mode lifetime ranges from a few days to few years
- The mode frequencies can be inverted to provide the structure and internal dynamics of the Sun

Helioseismic observations

- Observables:
  - Solar radial velocities (1 cm/s)
  - Intensity fluctuations (ppm)
  - Limb figure (eq. marcsec)
- Instrumentation :
  - Spectrophotometer
  - Tachometer
  - Photometer
- Observations:
  - 0-D to 2-D

Solar radial velocities

- Resonance cell (0-D)
  - Na, K cells (Claverie et al, 1979; Grec et al, 1980)
- Spectrometer (1-D)
  - Deubner (1975)
- Michelson interferometer(s) (2-D)
  - Brown (1985)
- Etalon: pressure scanned, lithium niobate (2-D)
  - Rhodes et al (1984), Rust et al (1988)
- Magneto-optical filter (2-D)
  - Cacciani type

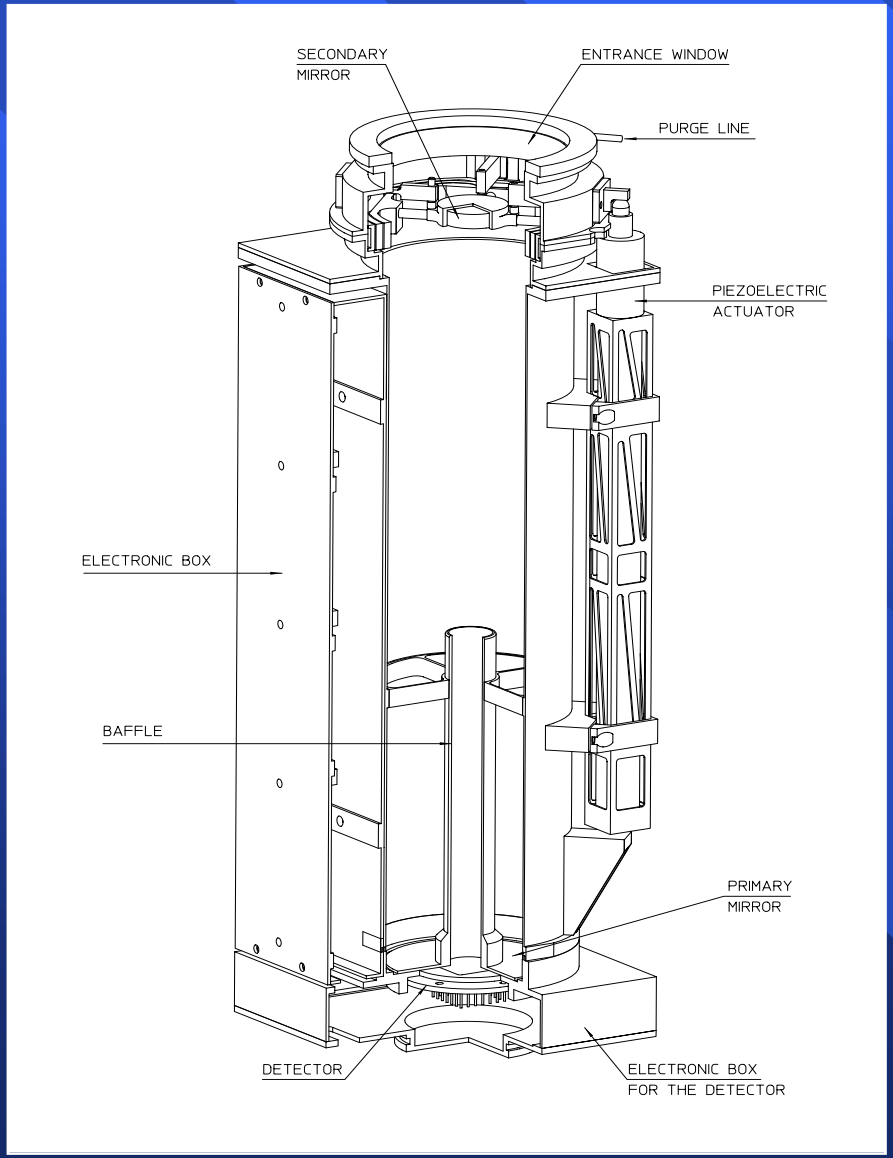
Intensity fluctuations

- Photometer (0-D)
  - IPHIR (Toutain and Fröhlich, 1992)
- Irradiance measurements (0-D)
  - ACRIM (Woodard and Hudson, 1983)
- Photometer (1-D)
  - Ca line (Duvall et al, 1986)
- Luminosity Oscillations Imager (2-D)

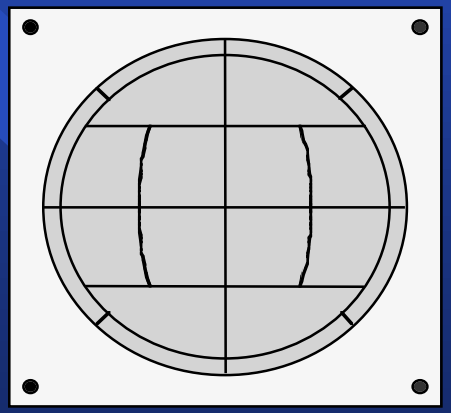
Limb figure

- Princeton Solar Distortion Telescope (1-D)
  - Libbrecht and Kuhn (1984)
- SCLERA (1-D)
  - p modes (Hill, 1985), g modes (Hill, 1992)
- SOI/MDI (2-D)
  - Kuhn (1996), Toner et al (1999)
- Luminosity Oscillation Imager (0-D)

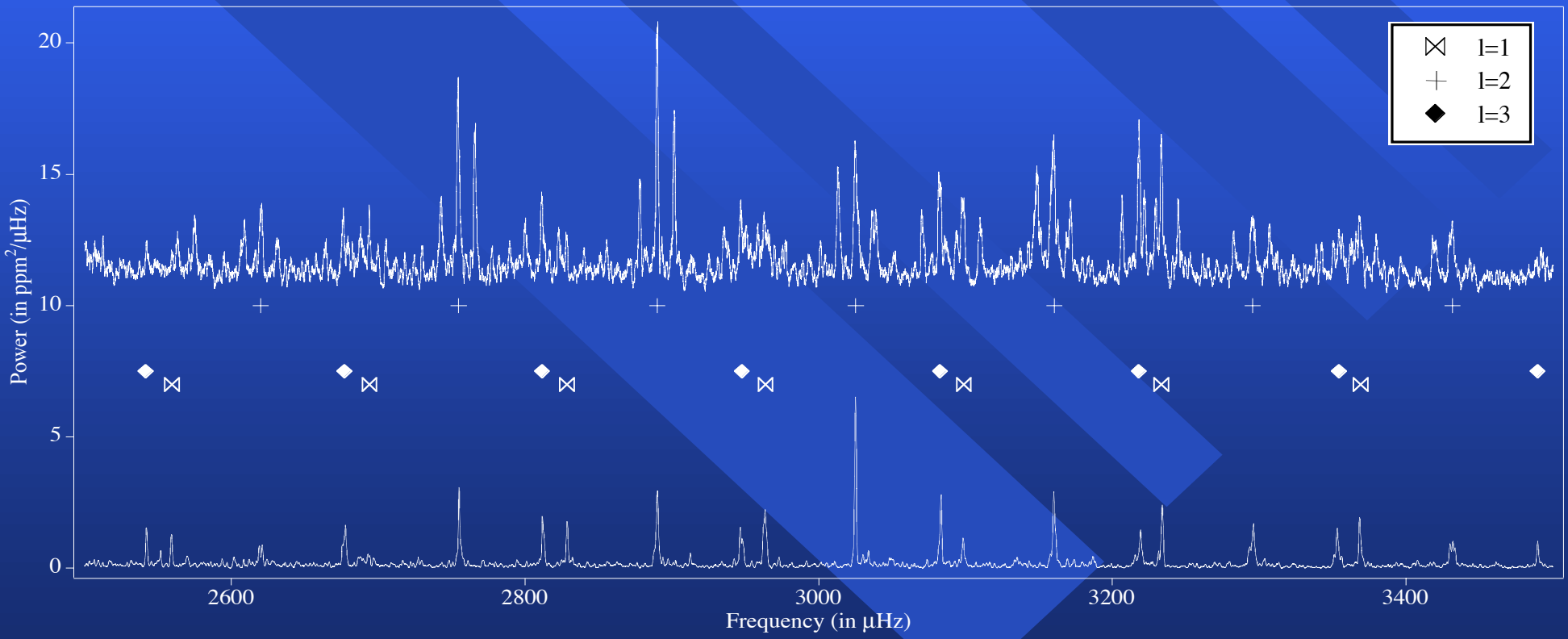
Luminosity Oscillations Imager



- Concept by Andersen et al (1988)
- First results in 1994
- Operational on board SOHO since 27 March 1996



Space- vs ground-based observations

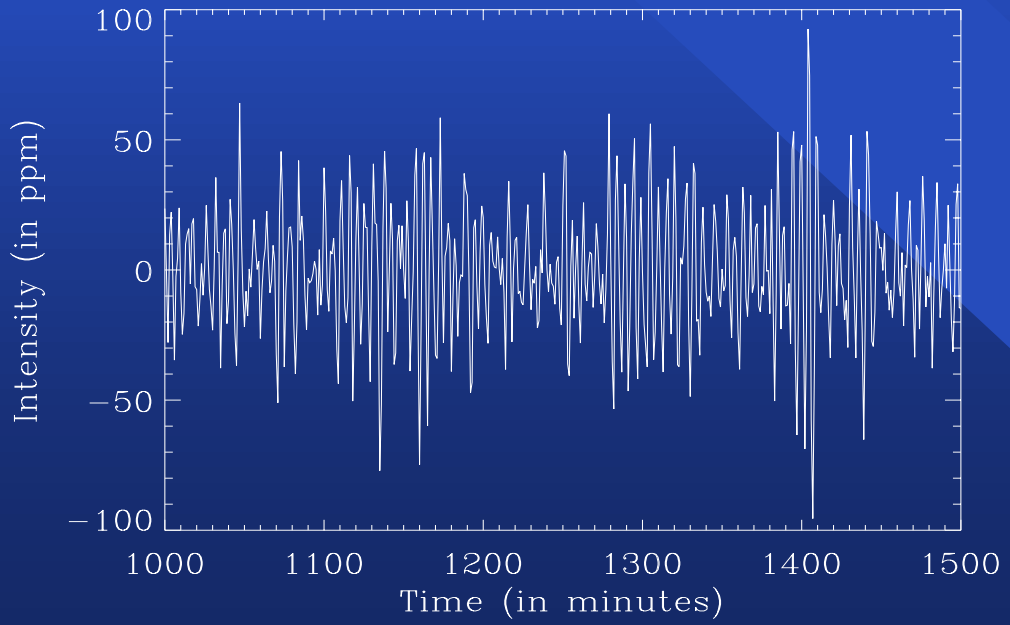


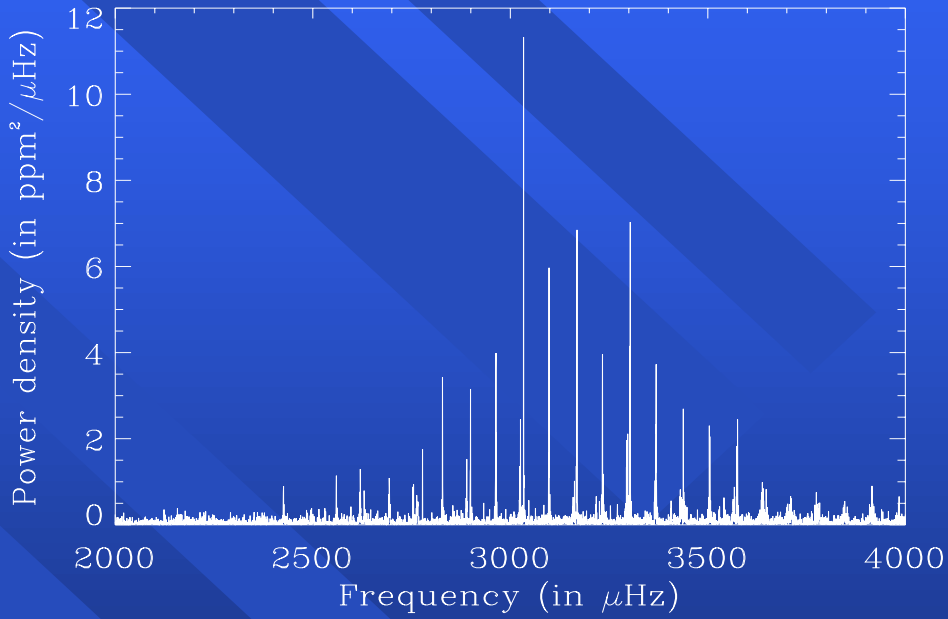
Data analysis

- Spatial filters:
  - Full-disk integrated data
  - Images (Spherical harmonics or special filters)
- Spectral analysis:
  - Fourier transform
  - Wavelet
  - Other
- Data fitting:
  - Maximum Likelihood estimation (errors, bias)
  - Least square estimation
  - Others

The use of Fourier transform

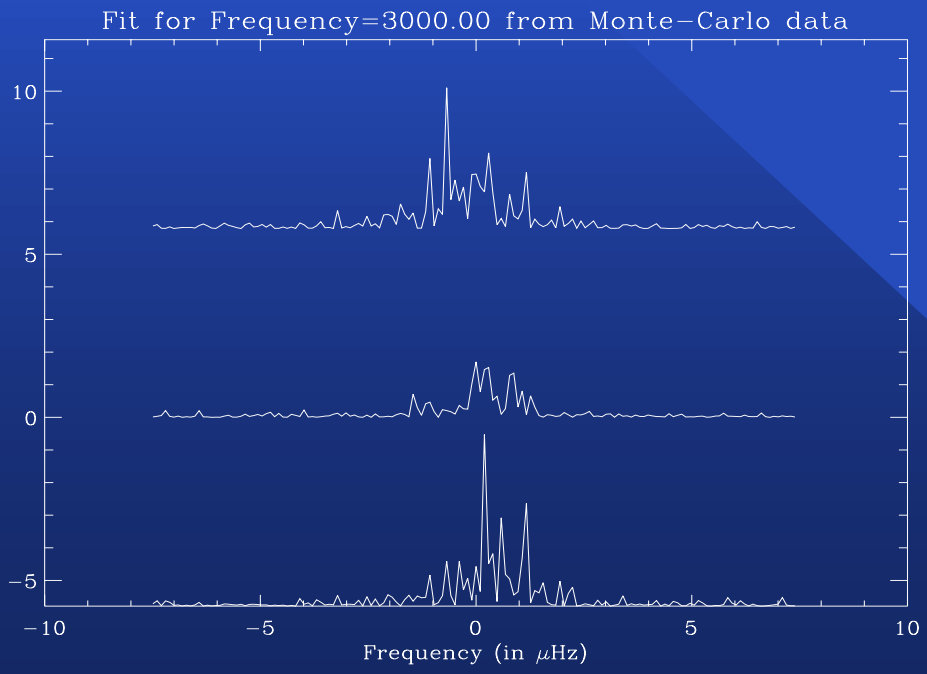
Full-disk integrated LOI data

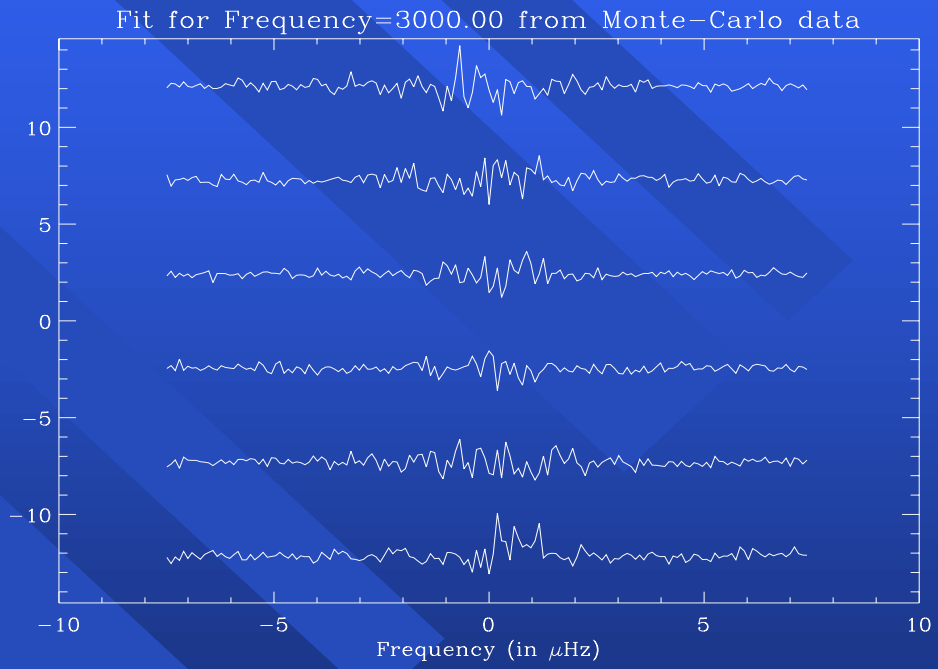




Fitting power spectra or Fourier spectra?

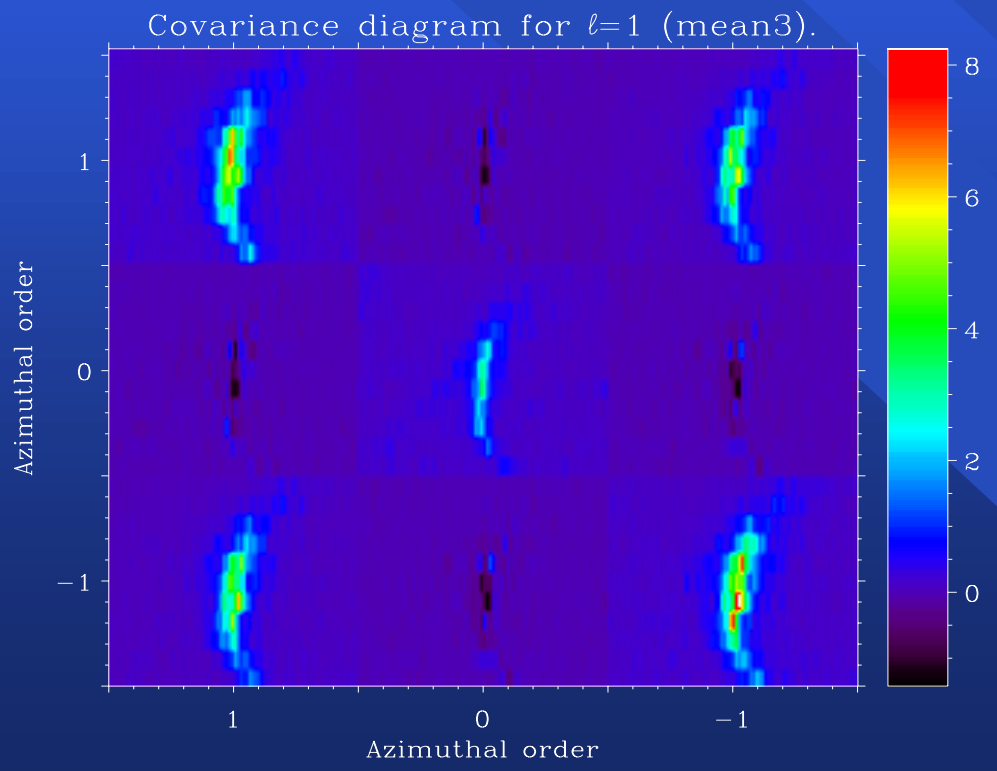
Spatially Resolved LOI data

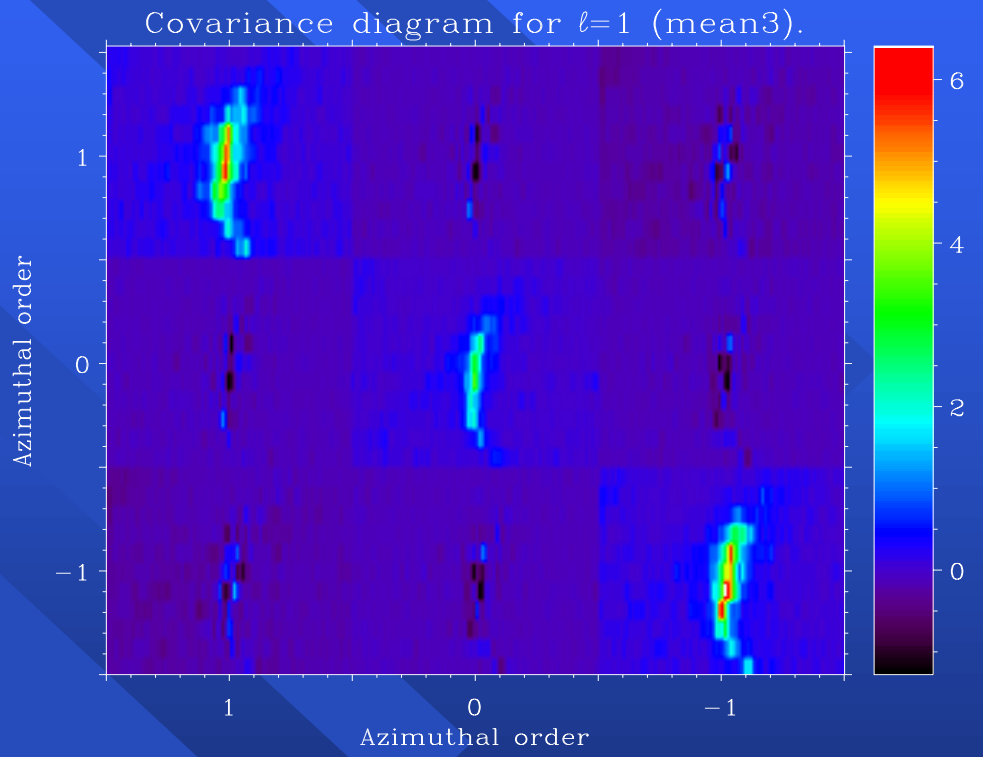




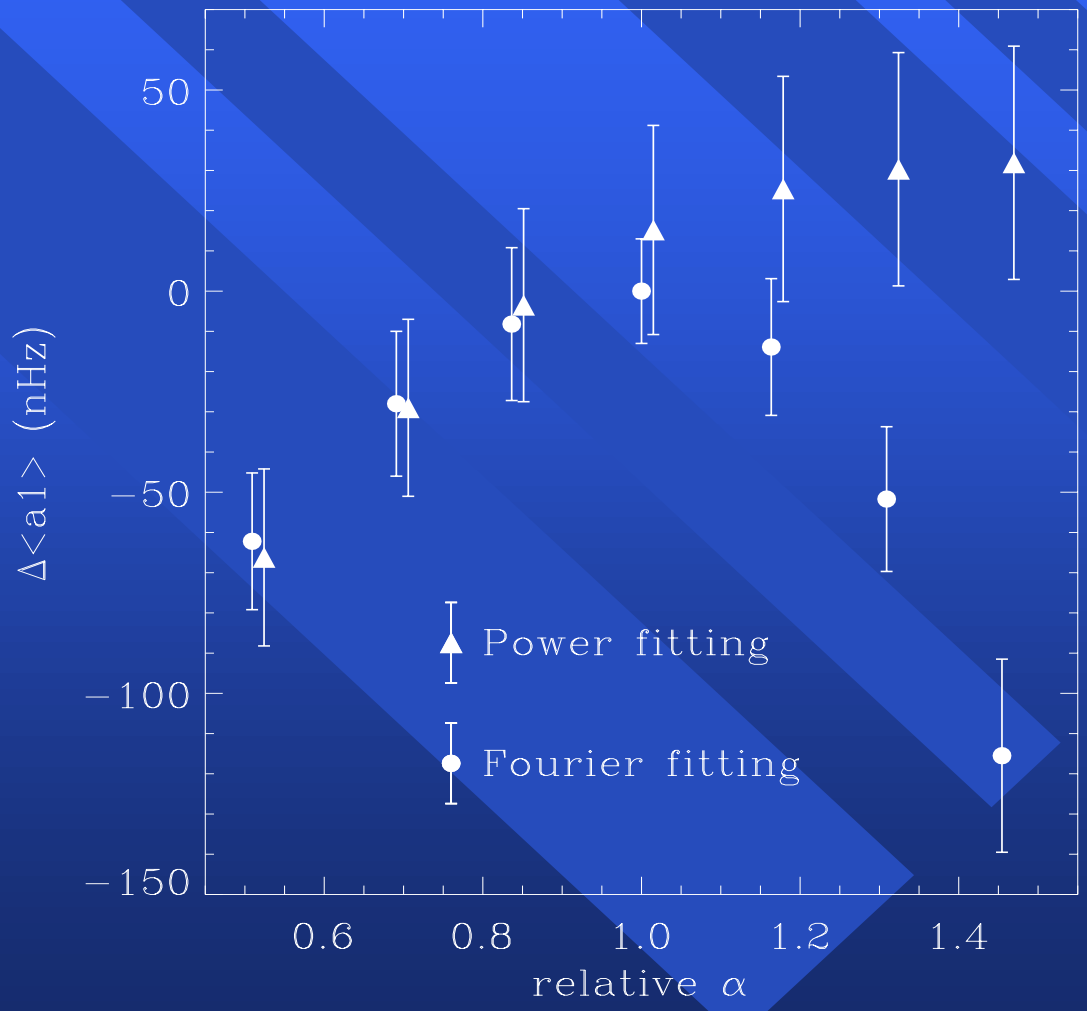
On cleaning data…sort of

Spatially Resolved LOI data





Power spectra vs Fourier spectra

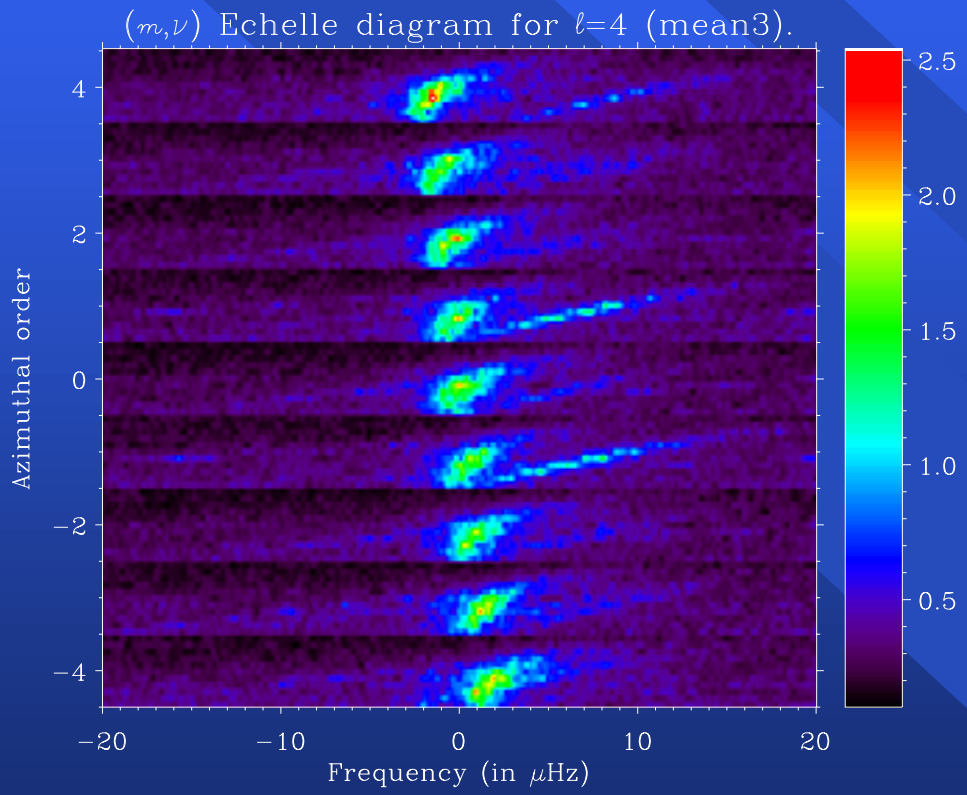


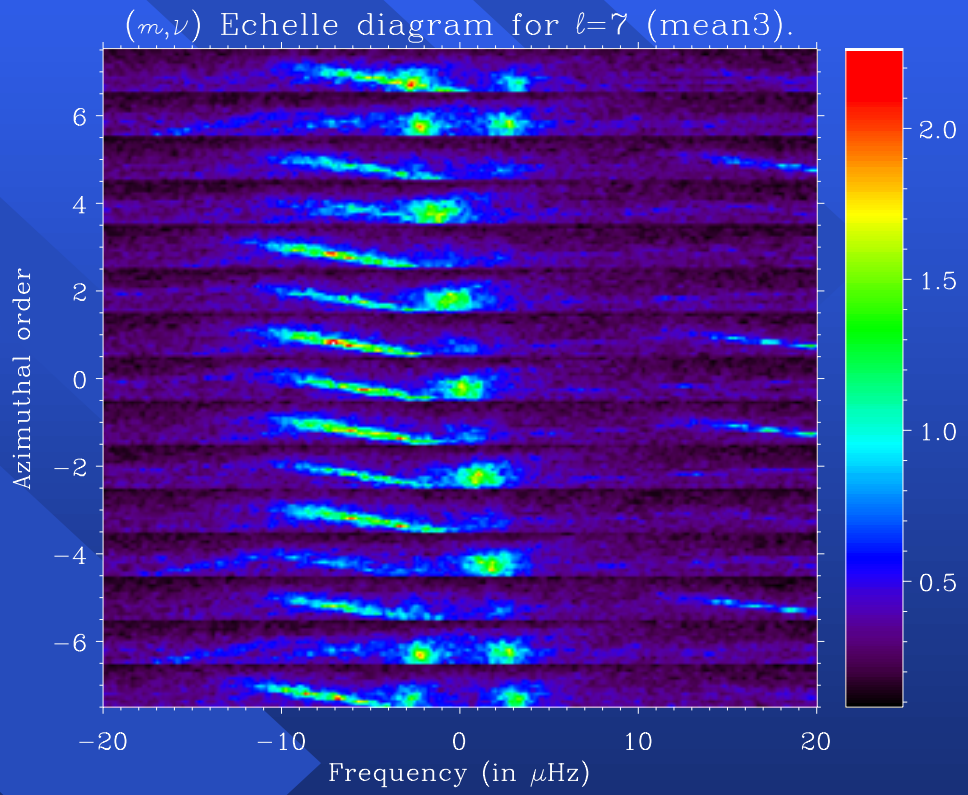
Rabello-Soares and Appourchaux (1998)

Some source of systematic errors

- Fitting techniques:
  - Power spectra: over- and under- estimation
  - Fourier spectra: smallest biased estimates
- Leakage matrix:
  - Power spectra: over- and under- estimation
  - Fourier spectra: quadratic underestimation
- Aliasing modes or *l* leaks:
  - Strong effects on any a_i for any fitting technique

What are those *l* leaks?





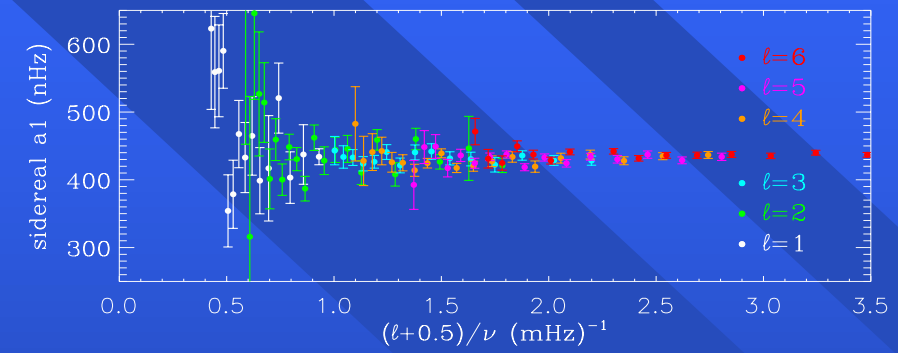
l=7 modes leaking into the *l*=4 modes

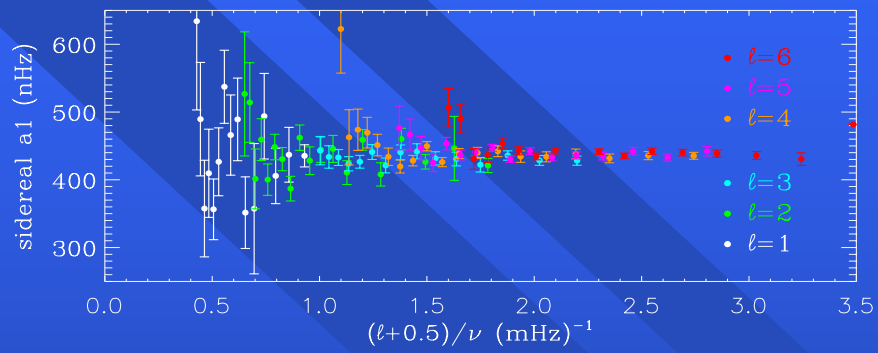
…and vice versa...

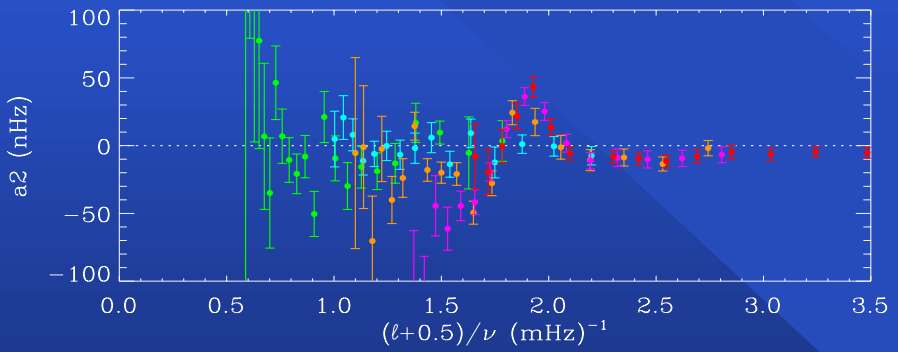
Some *real* scientific results

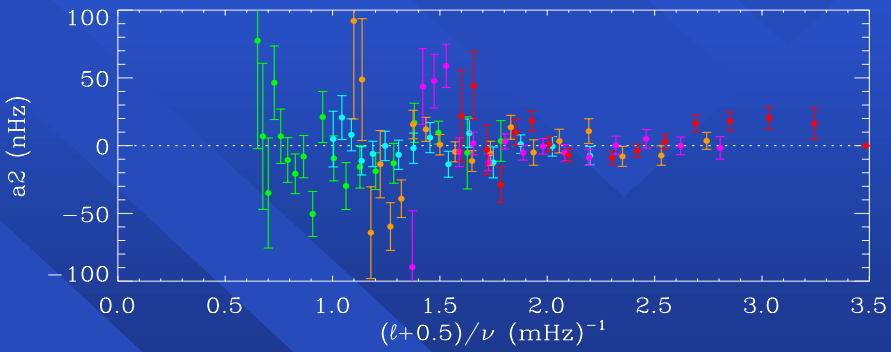
- Low-degree rotational splittings
- g-mode detection techniques
- Asymmetry of the low-*l* p-mode line profile
  - Full-disk and resolved data
  - Source location
- Solar activity effects for low-*l* modes
  - Frequencies
  - Linewidth

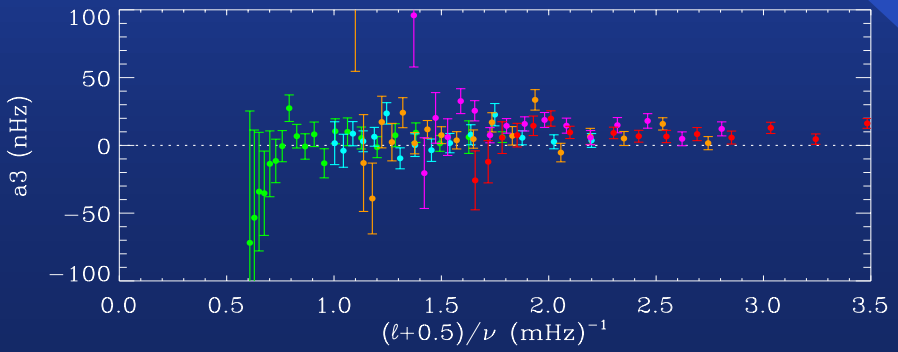
GONG splitting results (cleaned)

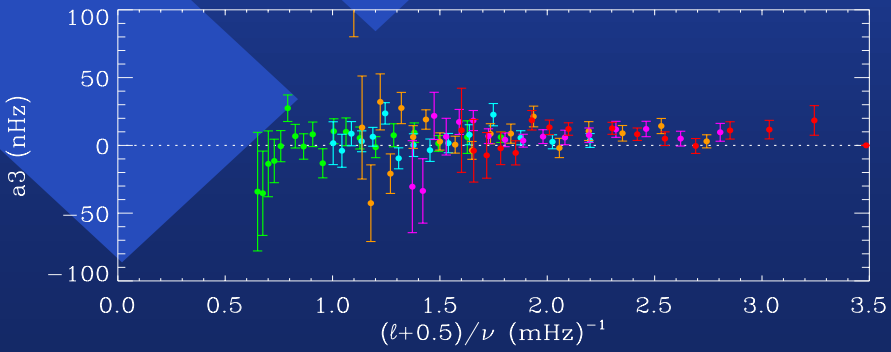




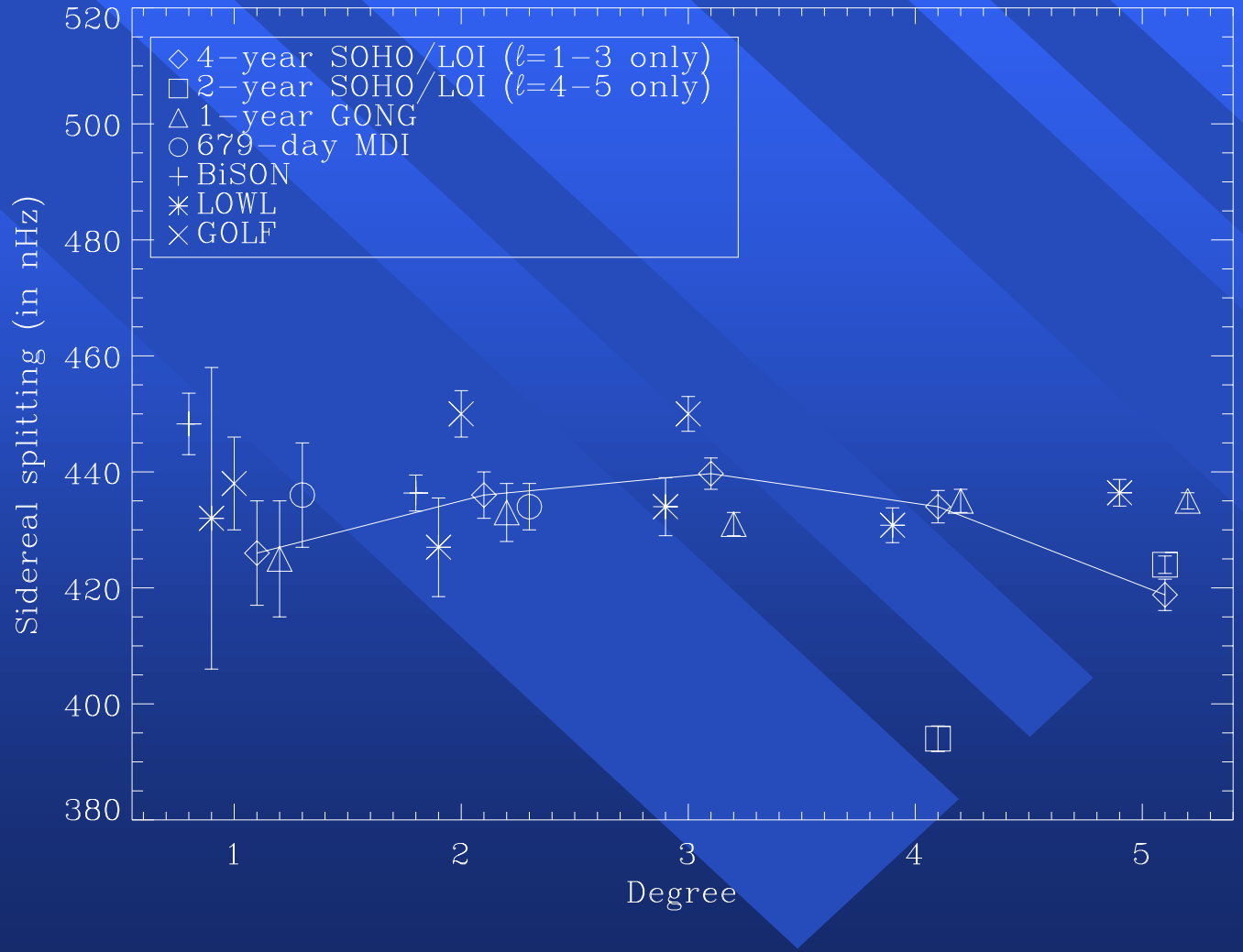








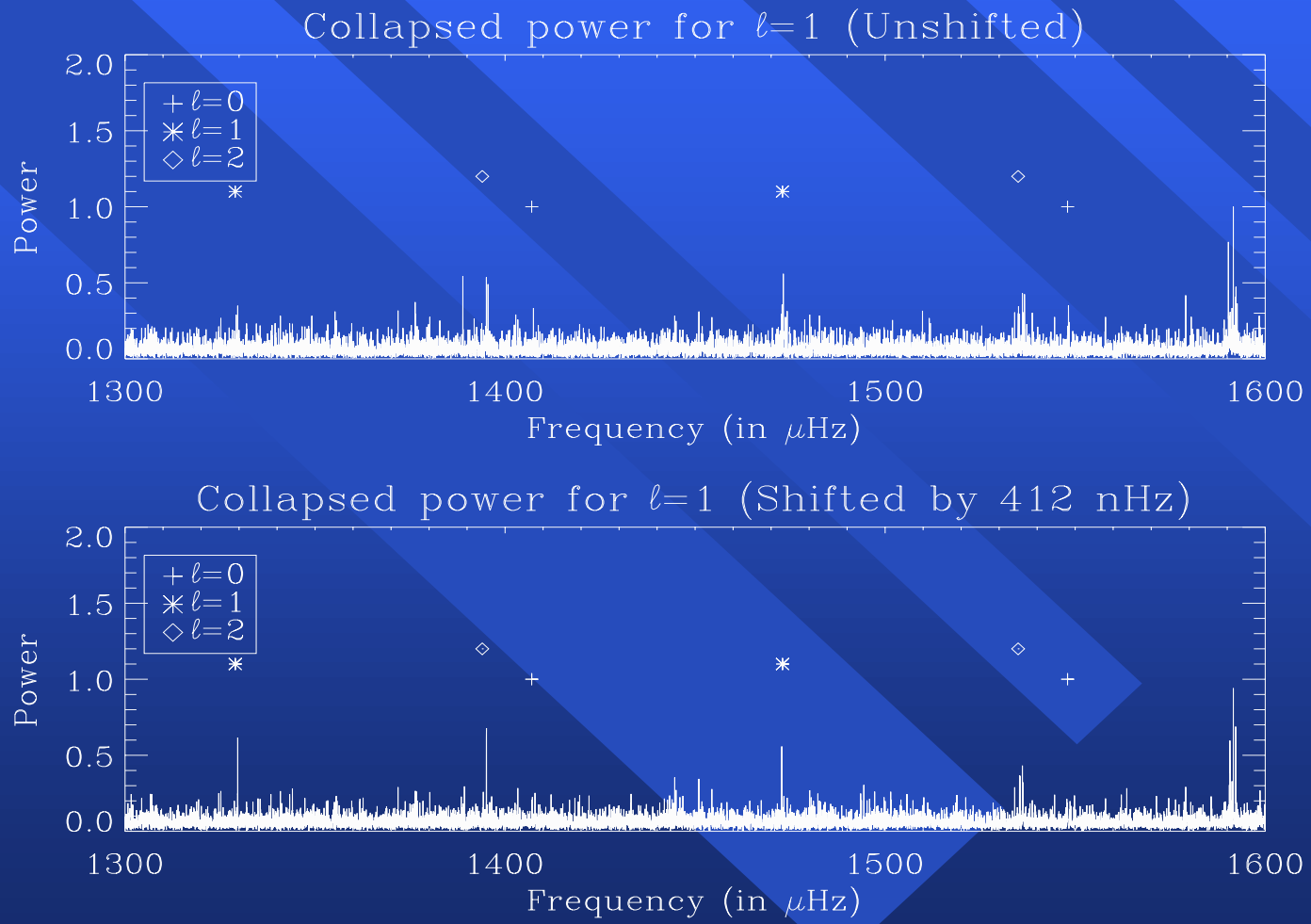
Splitting comparison



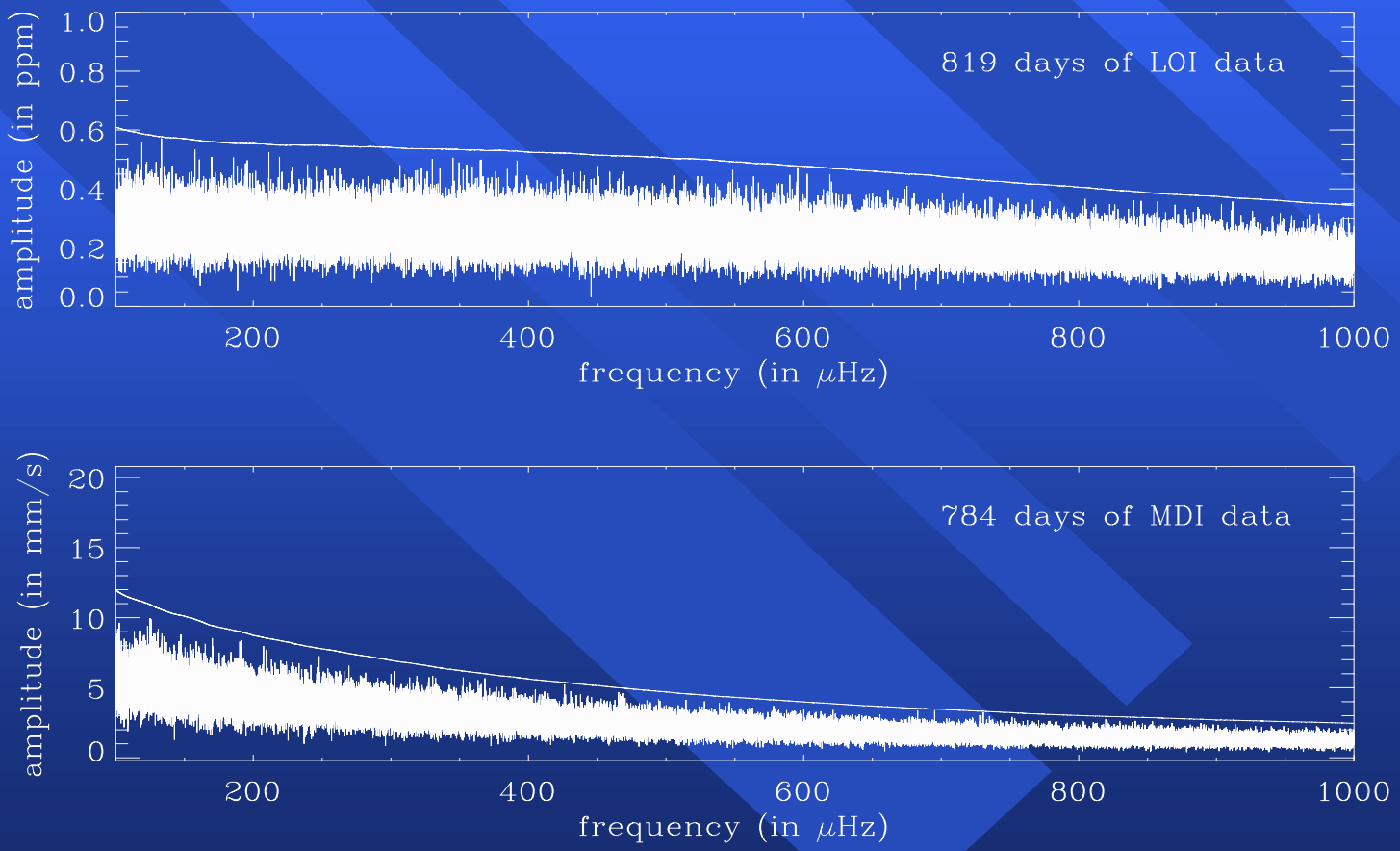
g-mode detection techniques

- Statistical methods
- Patterns:
  - Splitting (Collapsogramme)
  - Splitting + P_0
- Autocorrelation of spectra
- Data combination:
  - multivariate analysis
  - cross spectra

Collapsogramme



Statistical methods: the 10% limit



Contribution Summary

- Instrumentation:
  - Etalon, MOF filter
  - Low resolution Imager
- Measurement theory:
  - 2-point solar radial velocity
  - MLE theory (full disk, resolved)
  - Bias and statistical errors
- Solar interior:
  - Asymmetry
  - Splitting
  - g-mode search

Science management

- Scientific teams:
  - LOI (5 Engineers, 4 contractors)
  - PRISMA (10 Scientists)
  - Phoebus (14 Scientists)
- Post-docs or students:
  - T.Toutain (tenure track at Obs. de Nice)
  - L.Gizon (PhD student at Stanford University)
  - M.C.Rabello-Soares (Post-doc at TAC and Stanford)
  - W.Chaplin (tenure track at University of Birmingham)

Collaborations

- GONG project (DUC member)
- Norwegian Space Center, N
- Observatoire de Nice, F
- University of Birmingham, UK
- University of Cambridge, UK
- Stanford University, CA
- Service d'Aéronomie, F
- World Radiation Center, CH

What is next?

- The Sun:
  - The rotation of the solar core: need time
  - The structure of the solar core: g modes via limb data?
- The stars:
  - COROT
  - Ground-based efforts
- And beyond: exoplanets

Thank you, LOI and SOHO for behaving!