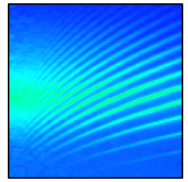
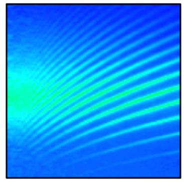


Helioseismic constraints: past, current and future observations

T. Appourchaux

Institut d’Astrophysique Spatiale



Contents

- What are the observables?
- Instruments for a given observable
- Data sets
- The future (if there is any...)
- Conclusions

The observables: back to the basics

Then equation (4.59) can be written as

Adiabatic approximation

$$\frac{\mathrm{d}\xi_r}{\mathrm{d}r} = -\left(\frac{2}{r} + \frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r}\right)\xi_r + \frac{1}{\rho c^2}\left(\frac{S_l^2}{\omega^2} - 1\right)p' + \frac{l(l+1)}{\omega^2 r^2}\Phi' \,. \qquad (4.61)$$

Equation (4.35) gives

$$\frac{\mathrm{d}p'}{\mathrm{d}r} = \rho(\omega^2 - N^2)\xi_r + \frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r}p' - \rho\frac{\mathrm{d}\Phi'}{\mathrm{d}r} \,, \qquad (4.62)$$

where, as in equation (3.73), N is the buoyancy frequency, given by

$$N^2 = g\left(\frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right) \,. \qquad (4.63)$$

Finally, equation (4.36) becomes

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}\Phi'}{\mathrm{d}r}\right) = 4\pi G\left(\frac{p'}{c^2} + \frac{\rho\xi_r}{g}N^2\right) + \frac{l(l+1)}{r^2}\Phi' \,. \qquad (4.64)$$

Equations (4.61), (4.62) and (4.64) constitute a fourth-order system of ordinary differential equations for the four dependent variables ξ_r, p', Φ' and $\mathrm{d}\Phi'/\mathrm{d}r$. Thus it is a complete set of differential equations.

Christensen-Dalsgaard (2014)

Three observables

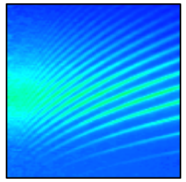
- ξ_r displacement pert.
- p' pressure pert. (T', J')
- Φ' potential pert.

3.1. Adiabatic intensity fluctuation and wave velocity

In the adiabatic case, the linearisation of Eqs. (8.4) and (8.6) gives $\delta T/T = \nabla_{\mathrm{ad}}\delta p/p$ and $\delta J/J = 4\delta T/T$.

Berthomieu and Provost (1990)

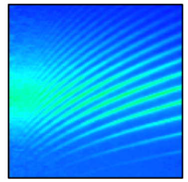
The observables: how to *observe*?



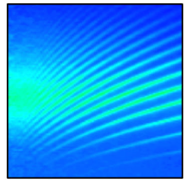
ξ_r displacement pert.
- Limb measurement: SCLERA, *MDI, LOI, HMI,* Picard
- Velocity (thru derivative): IRIS, BiSON, GOLF, MDI, HMI, GONG

p' pressure pert. (T', J')
- Intensity fluctuations: ACRIM, VIRGO, LOI, *MDI*, *HMI*, *Picard*

Φ' potential pert.
- Gravitational waves: LISA, ASTROD

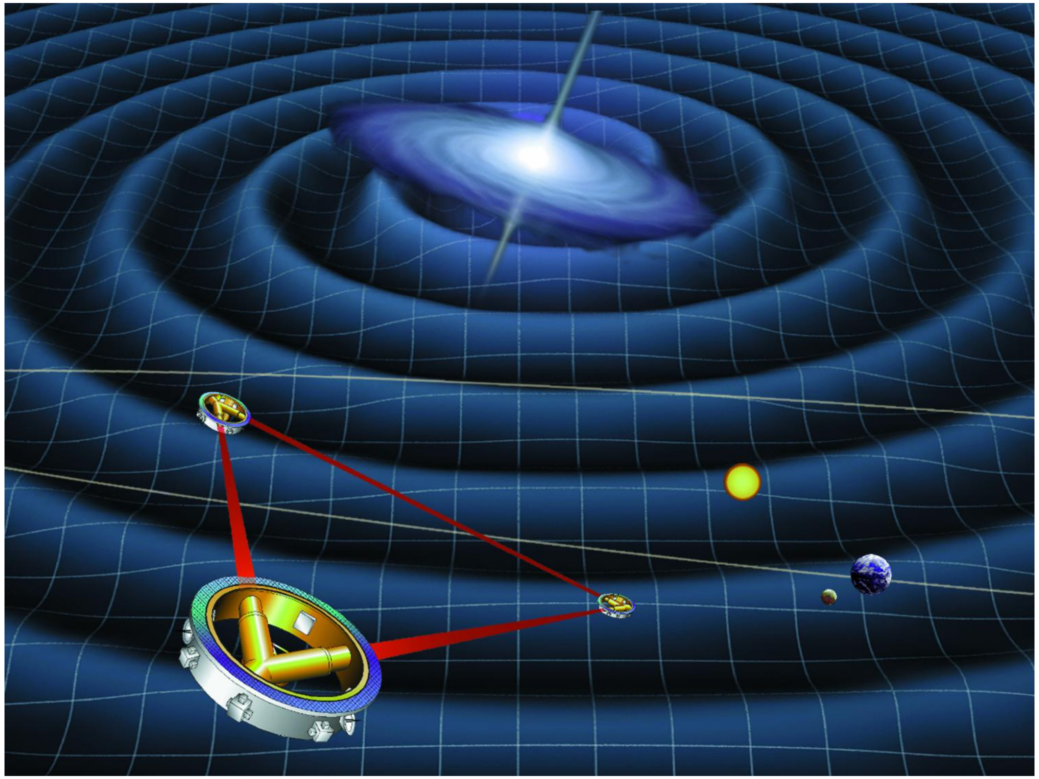


The instruments



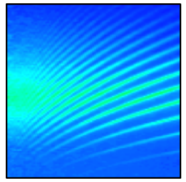
Φ' potential pert.

- LISA: Laser Interferometry Space Antenna

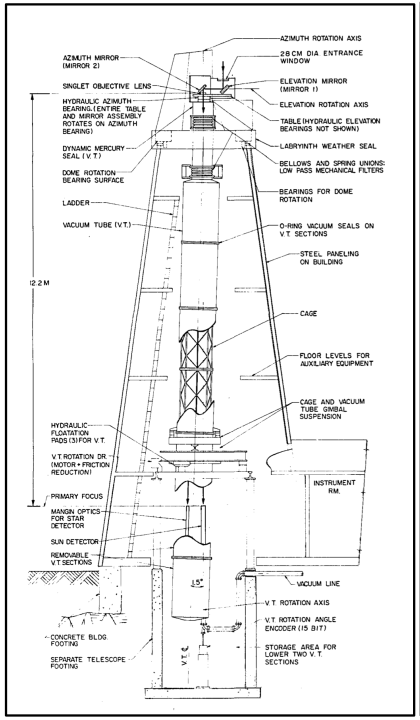


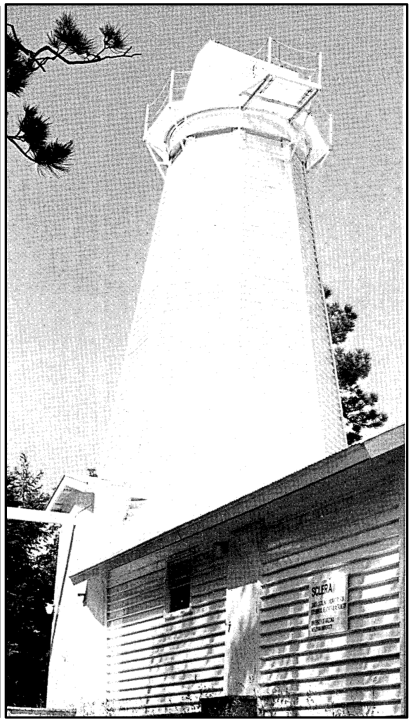
- Gravitational potential (Φ')
- Gravitational waves from quadrupole
- Interferometry
- Joint ESA-NASA mission
- First proposed to ESA in 1993…
- To be launched in 2037

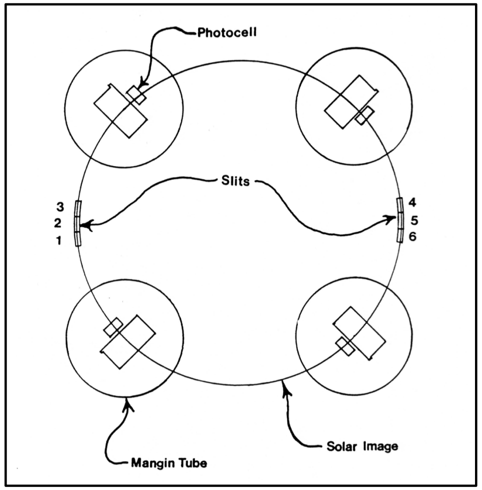
ξ_r displacement pert. (I)



- SCLERA: Santa Catalina Laboratory for Experimental Relativity by Astrometry

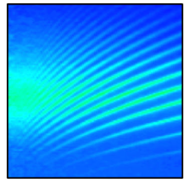




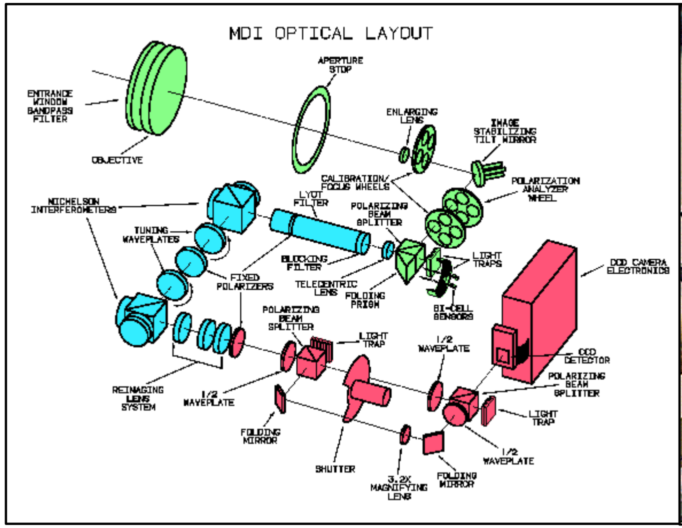


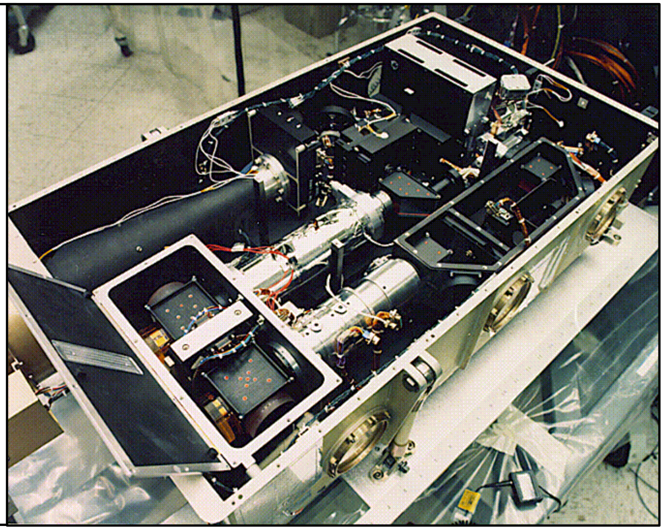
- Limb image (ξ_r)
- Radial velocity (derivative of ξ_r)
- Narrow passband at 550 nm
- Limb detectors
- Operated on Earth from 1975 to 1992?

ξ_r displacement pert. (II)



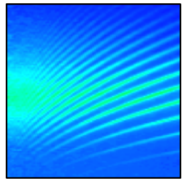
- MDI / SoHO: Michelson Doppler Imager
- HMI / SDO: Helioseismic and Magnetic Imager



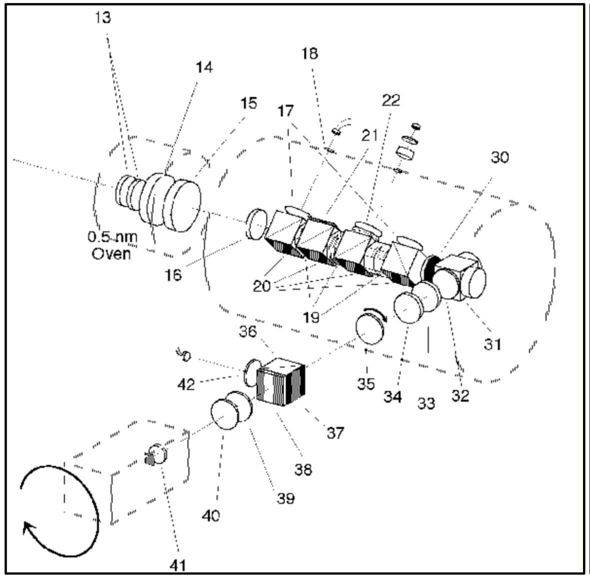


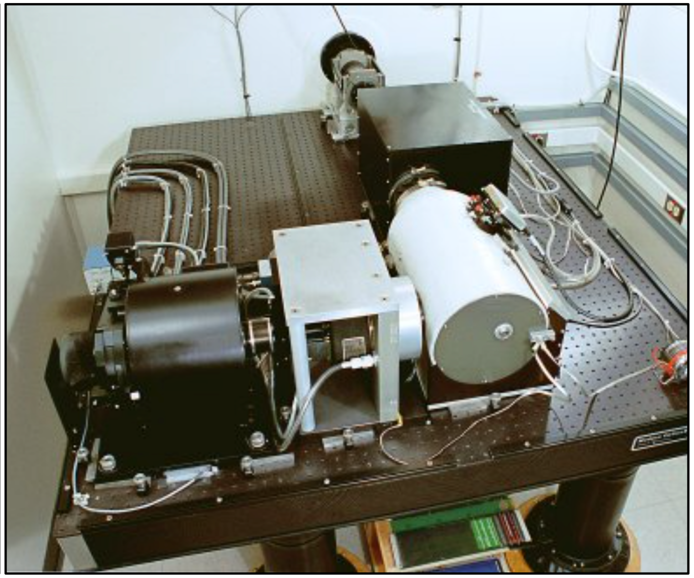
- Limb image (ξ_r)
- Radial velocity (derivative of ξ_r)
- Intensity fluctuations (p' producing T', J')
- Fraunhöfer line (Ni I)
- Line profile analyzed with a double Michelson and a Lyot filter
- 6-point measurement (linear)
- CCD:
  - MDI 1k x 1k
  - HMI 4k x 4k
- MDI: Operated aboard SoHO from 1996 to April 2011 at a cadence of 60 s
- HMI: Operated aboard SDO since 2010 at a cadence of 45 s

ξ_r displacement pert. (III)

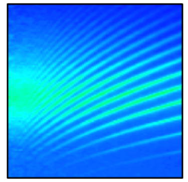


- GONG: Global Oscillation Network Group



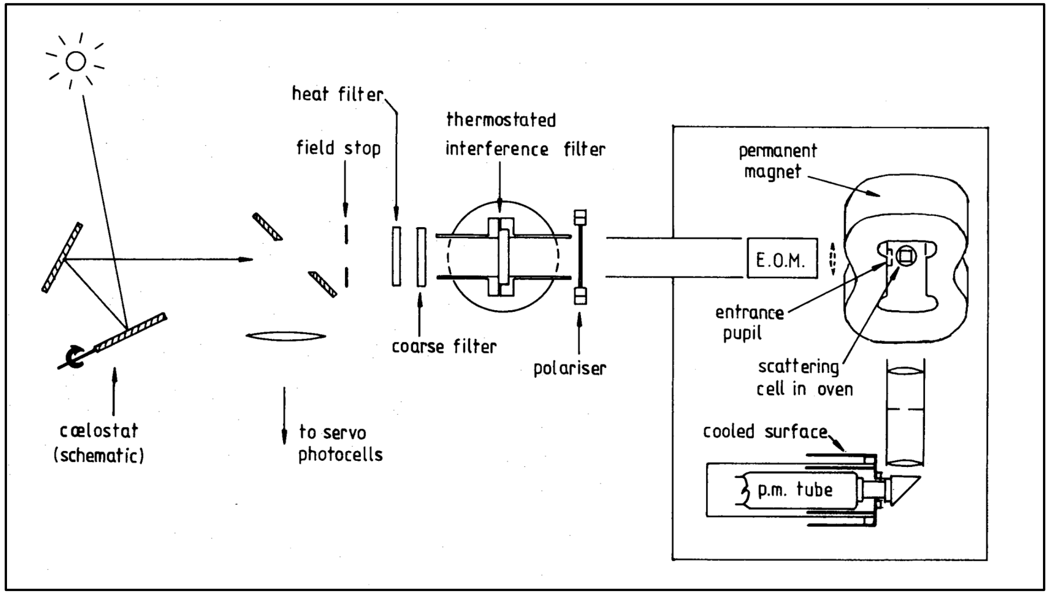


- Radial velocity (derivative of ξ_r)
- Fraunhöfer line (Ni I)
- Line profile analyzed with a Michelson and a prefilter
- 4-point measurement (linear)
- CCD: 256 x 256 then 1k x 1k in 2005
- Operated on Earth since 1995 at a cadence of 60 s



ξ_r displacement pert. (IV)

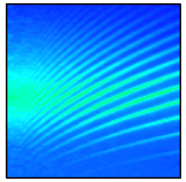
- IRIS: International Research on the Interior of the Sun
- BiSON: Birmingham Oscillation Network



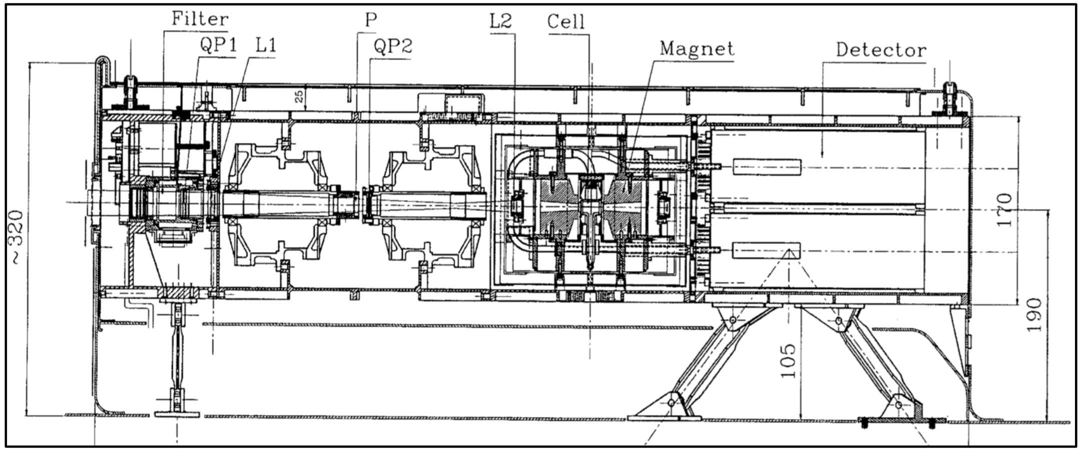
Brookes et al (1978)

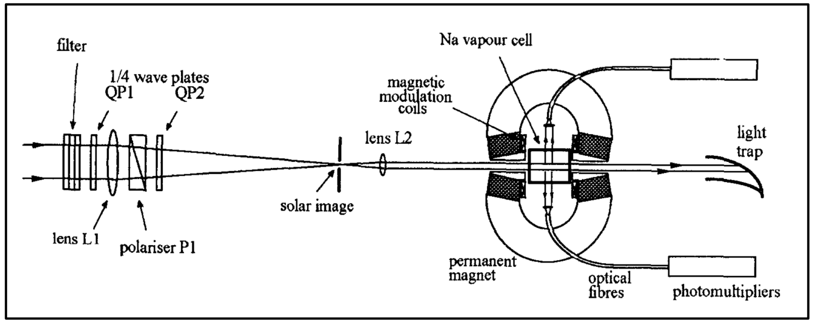
- Radial velocity (derivative of ξ_r)
- Resonance line: Na (IRIS), K (BiSON)
- Line profile analyzed with a resonance cell using the Zeeman effect
- 2-point measurement
- Sun as a star
- Cadence of 60 s (IRIS) and of 40 s (BiSON)
- Operated on Earth from 1990 to 2001 (IRIS), since 1985 (BiSON)

ξ_r displacement pert. (V)



- GOLF / SoHO: Global Oscillations at Low frequencies

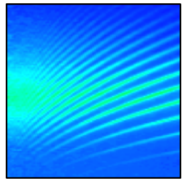




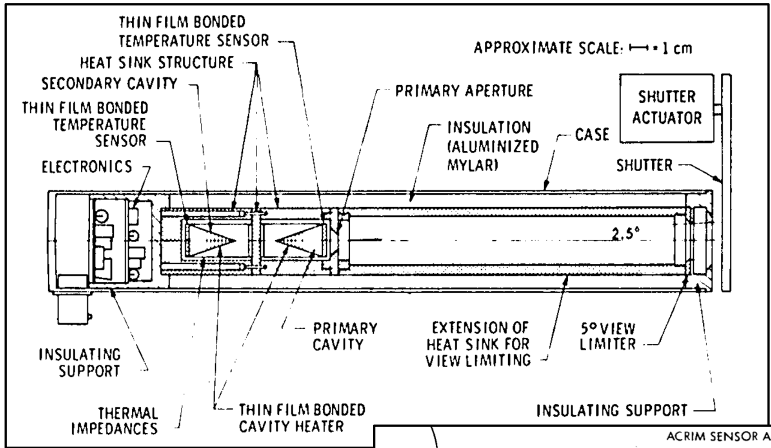
Gabriel et al (1995)

- Radial velocity (derivative of ξ_r)
- Resonance line: Na
- Line profile analyzed with a resonance cell using the Zeeman effect
- 2-point measurement (+2 points for calibration)
- Sun as a star
- Cadence of 20 s
- Operated on SoHO since 1995

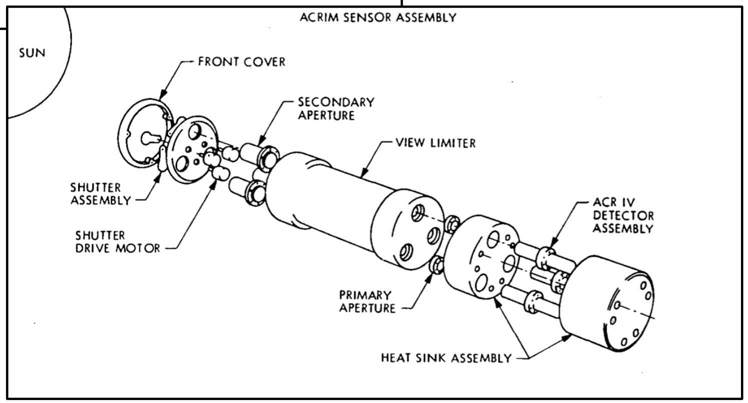
p' pressure pert. (I)



- ACRIM: Active Cavity Radiometer Irradiance Monitoring

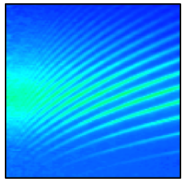


Willson (1979)

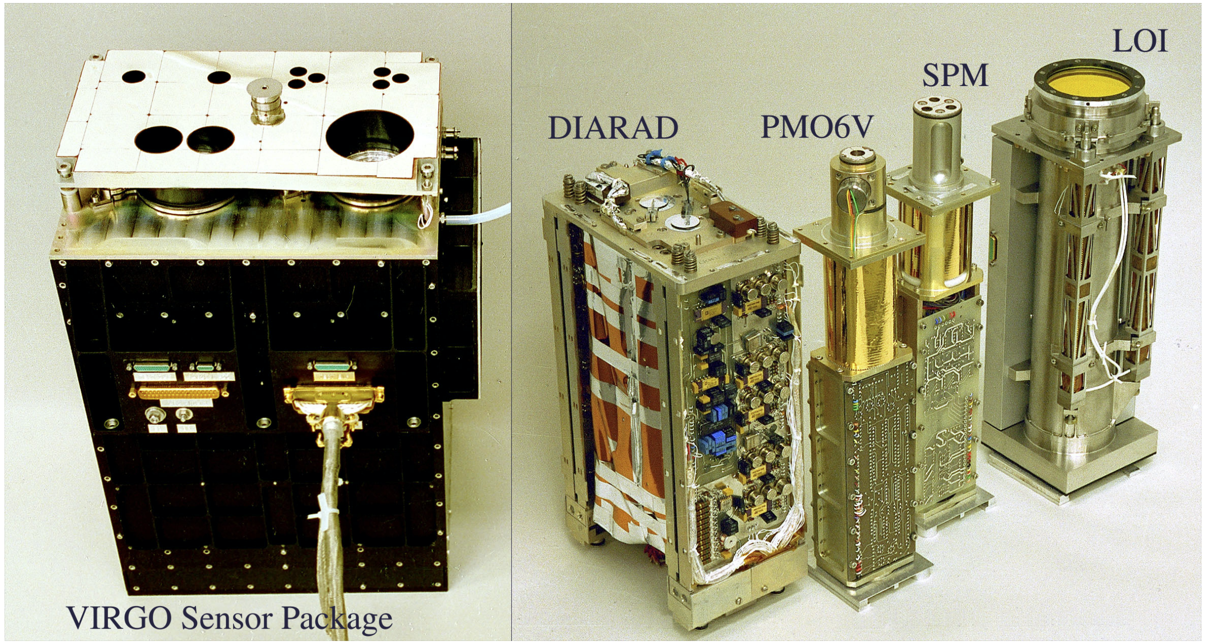


- Intensity fluctuations (p' producing T', J')
- Radiometer (double cavity)
- Sun as a star
- Cadence of 1.024 s
- Operated on Solar Max Mission from 1980 to 1989

p' pressure pert. (II)



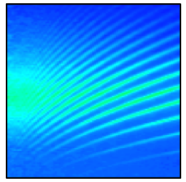
- VIRGO: Variability of Irradiance and Gravity Oscillations



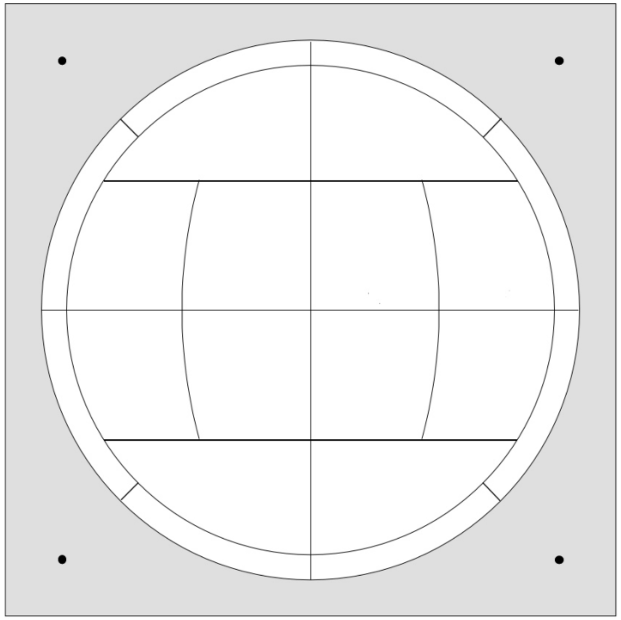
Fröhlich et al (1995)

- Intensity fluctuations (p' producing T', J')
- Radiometer: DIARAD, PMO6V (double cavity)
- Narrowband filter: SPM (3 colors)
- Low resolution image: LOI
- Sun as a star and low resolution
- Cadence of 60 s (SPM, LOI)
- Cadence of 3 min (DIARAD, PMO6V)
- Operated on SoHO since 1995

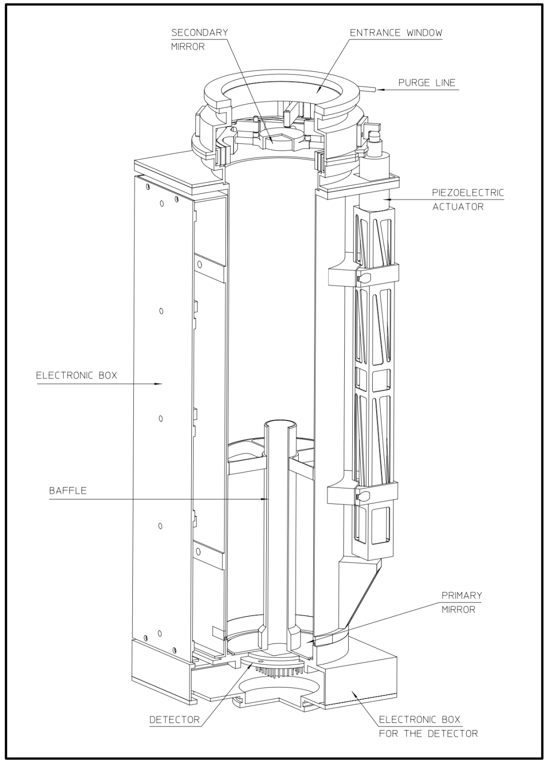
p' pressure pert. (III)



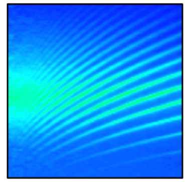
- LOI: Luminosity Oscillations Imager



Appourchaux (1995)

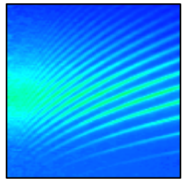


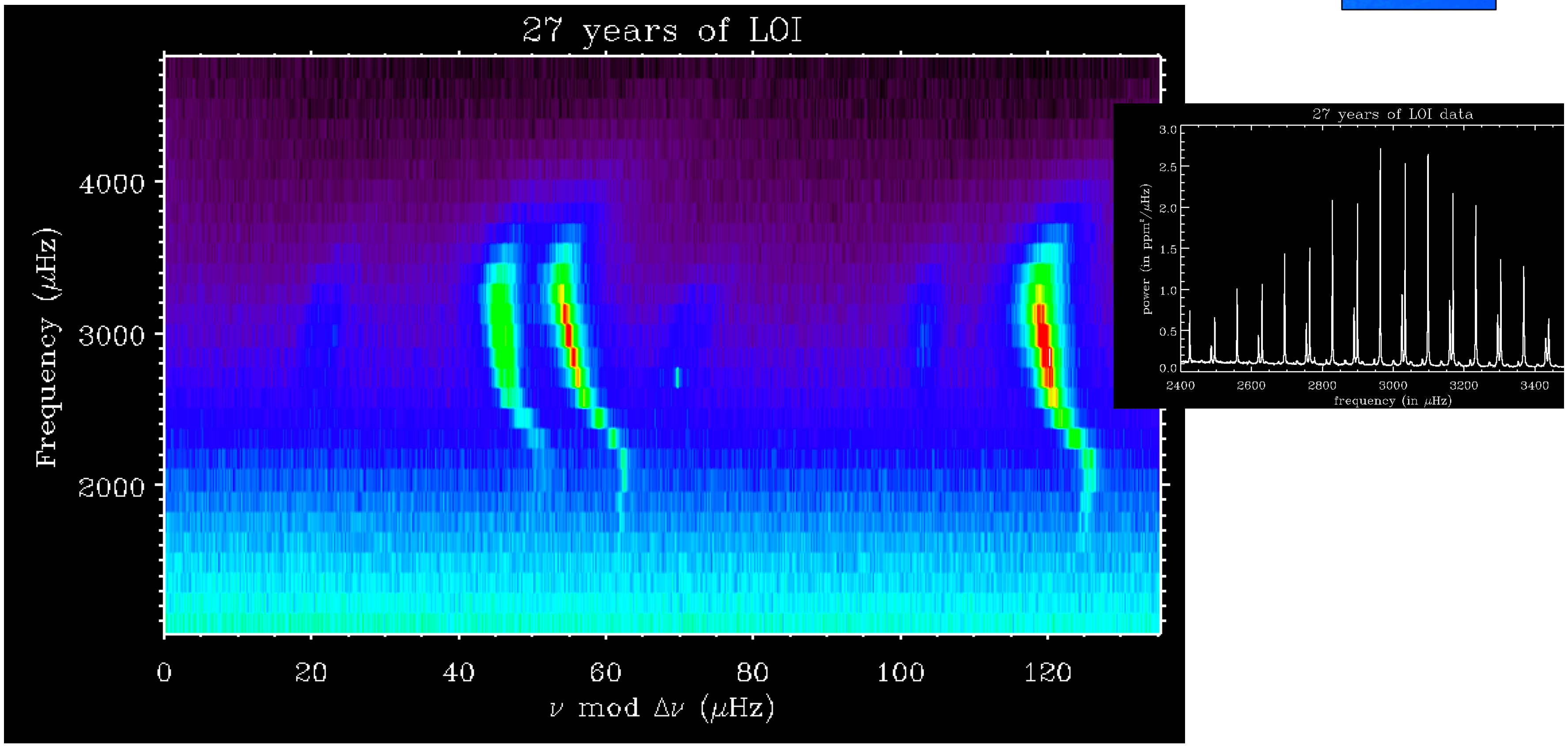
- Intensity fluctuations (*p'* producing *T'*, J')
- Narrowband filter
- Low resolution image including limb
- Sun as a star and low resolution
- Cadence of 60 s (LOI)
- Operated on SoHO since 1995



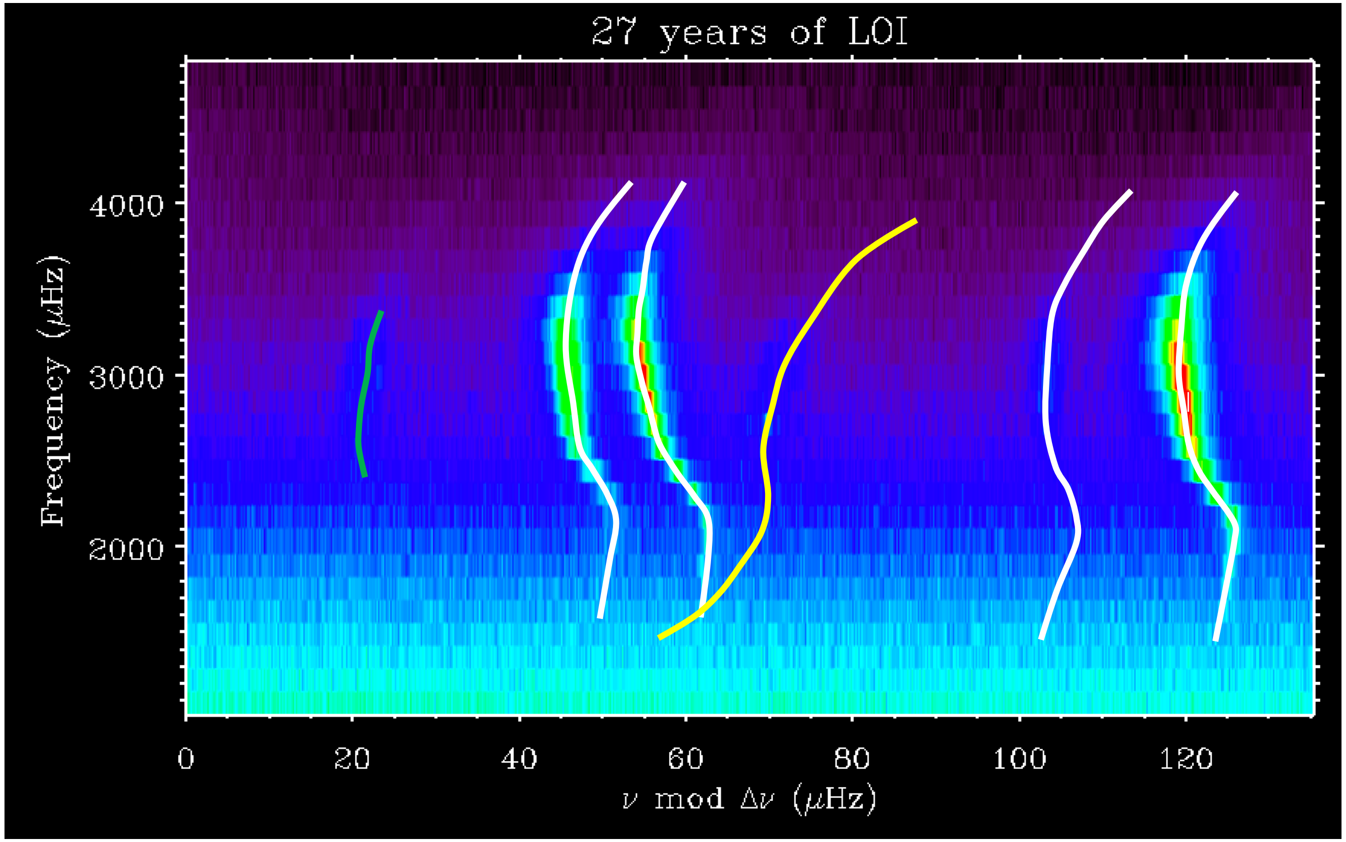
The observations

LOI, Sun as a star



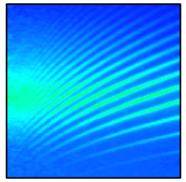


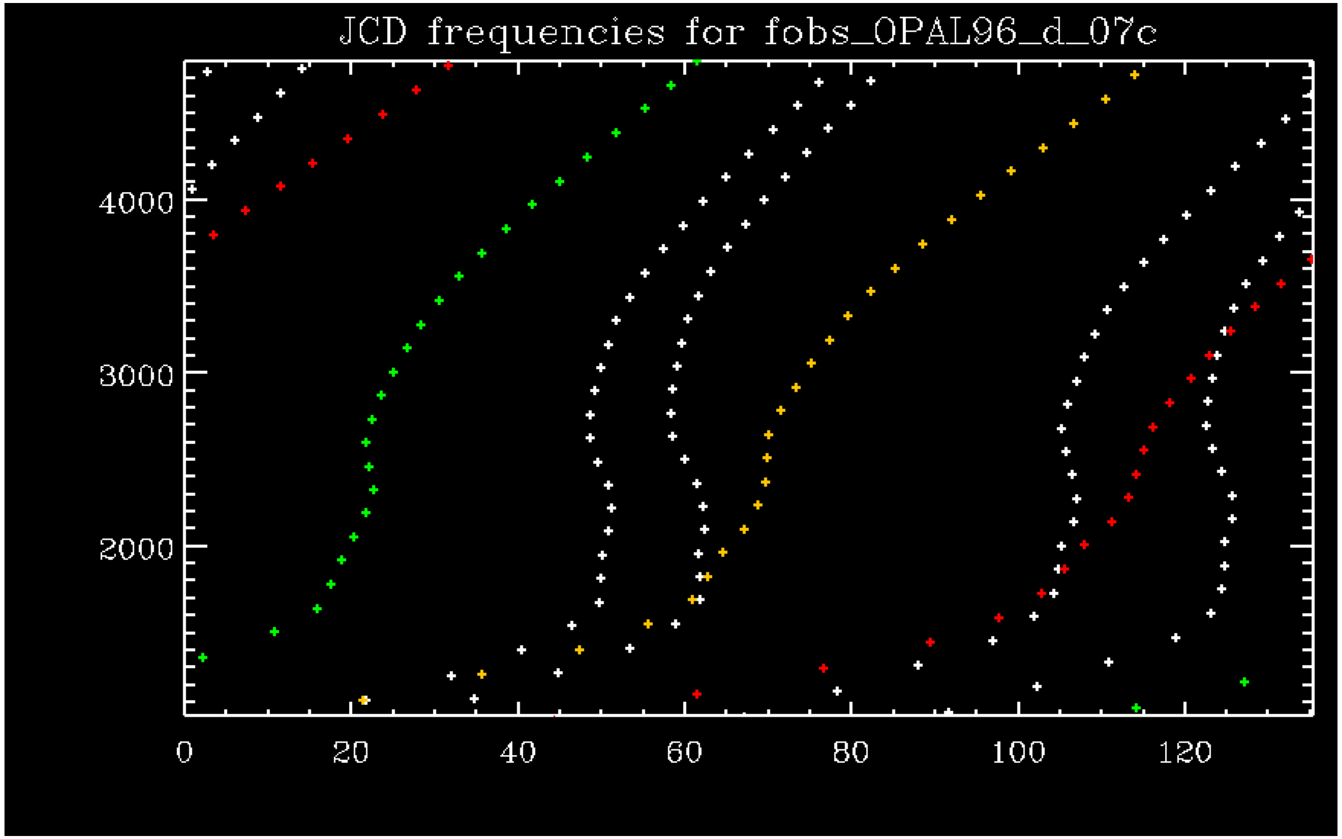
LOI, Sun as a star



l=0,2 pair and *l*=1,3 pair are visible, as well as *l*=4,5

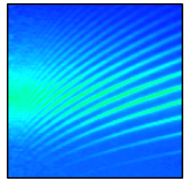
Theoretical échelle diagram

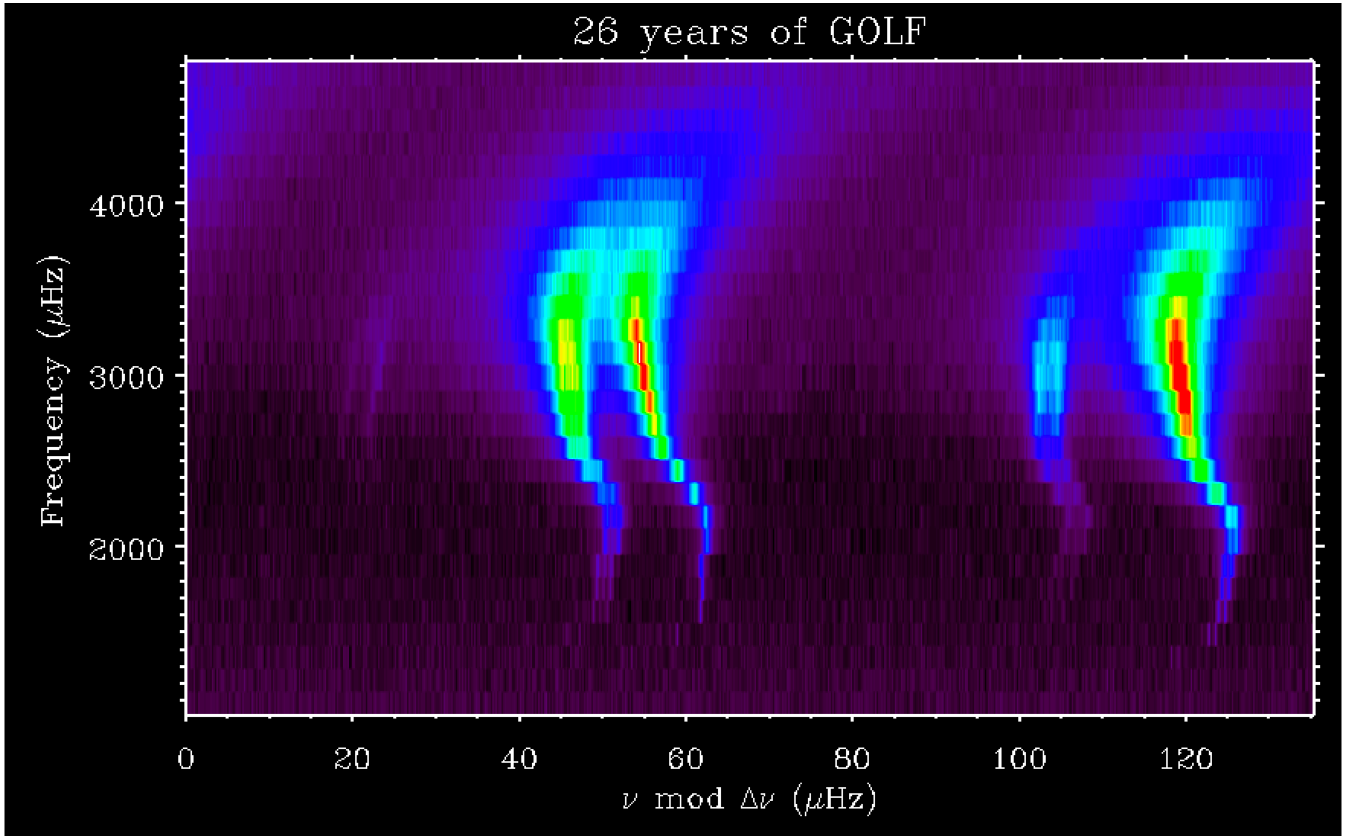




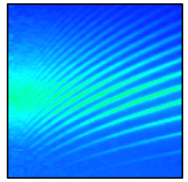
In white, the *regular* *l*=0-2 and *l*=1-3 mode pairs as seen Full Disk, in color…

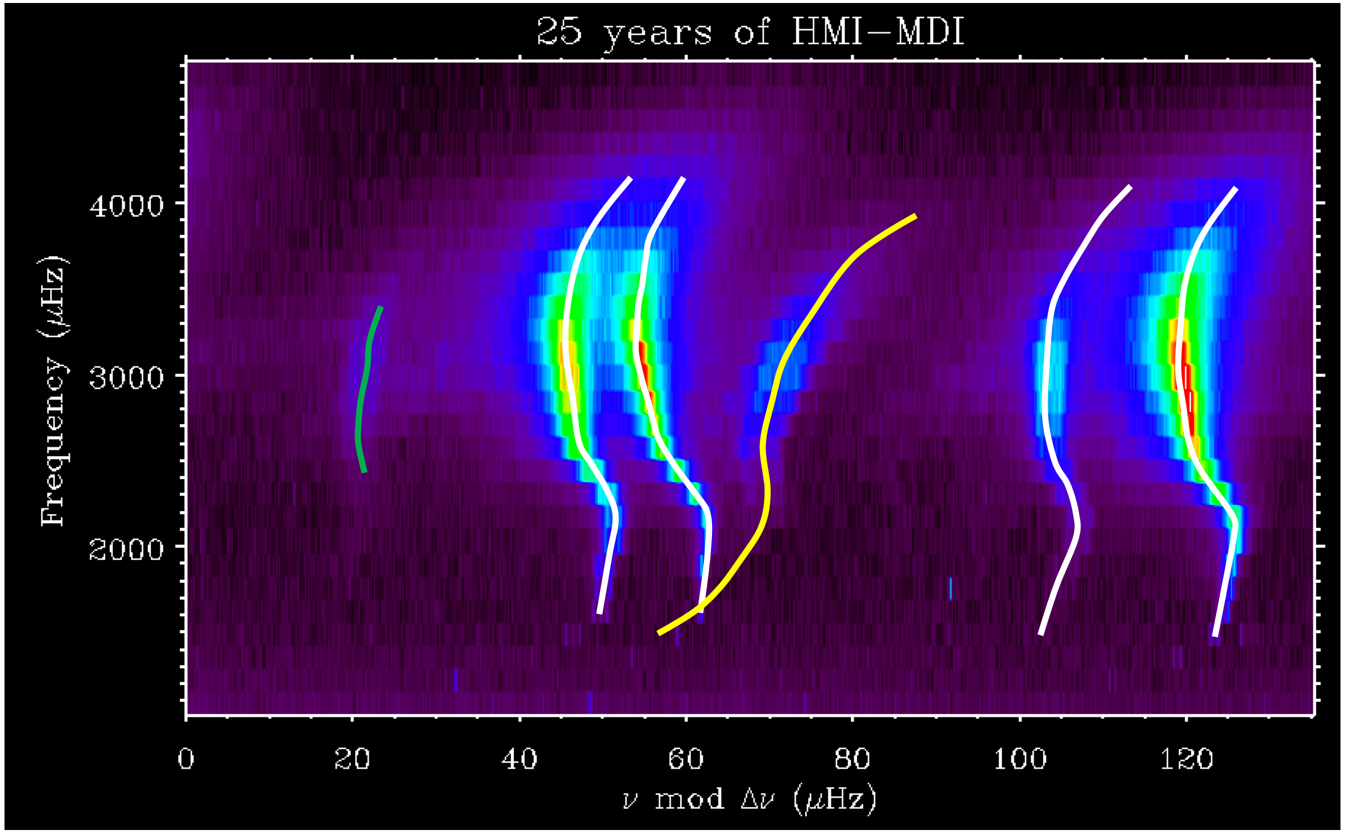
GOLF, Sun as a star



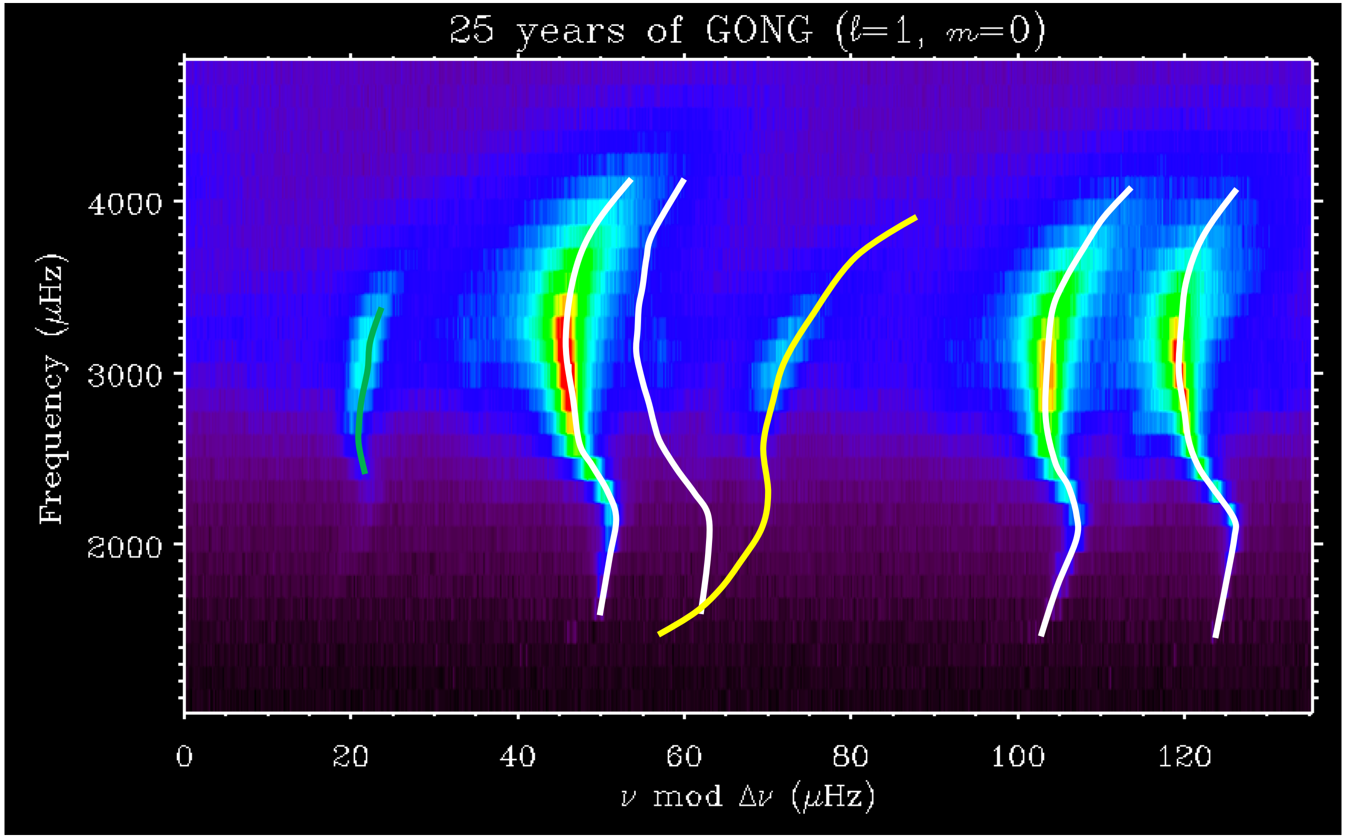


HMI-MDI, Sun as a star

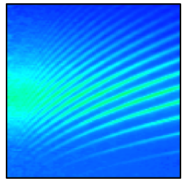




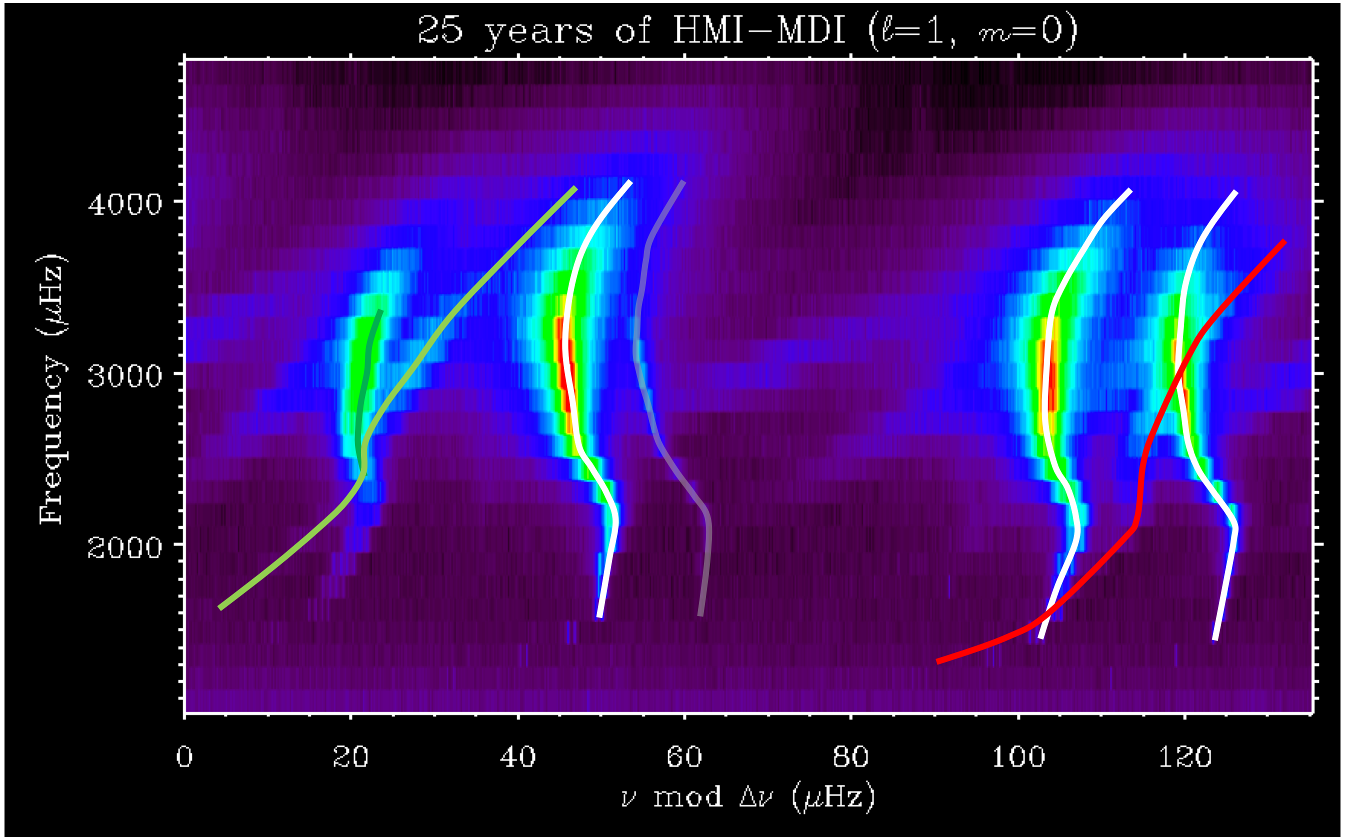
GONG (l=1, m=0)

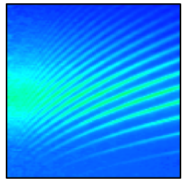


25 years of GONG (ℓ=1, m=0)
Frequency (μHz)
4000
3000
2000
0
20
40
60
80
100
120
ν mod Δν (μHz)



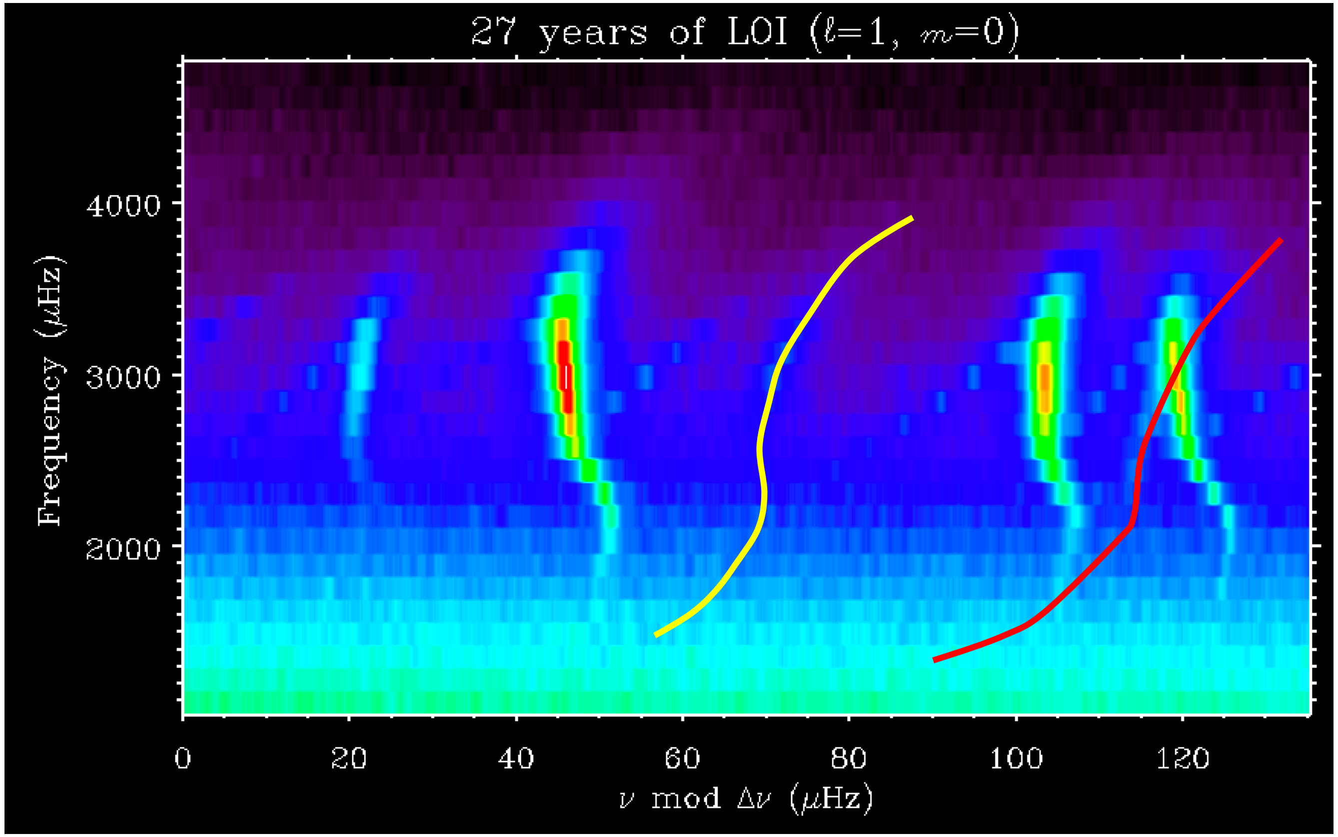
HMI-MDI (l=1, m=0)



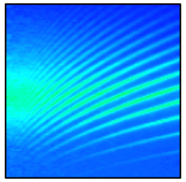


l=7 in l=4, and l=6 in l=1, higher l as well…

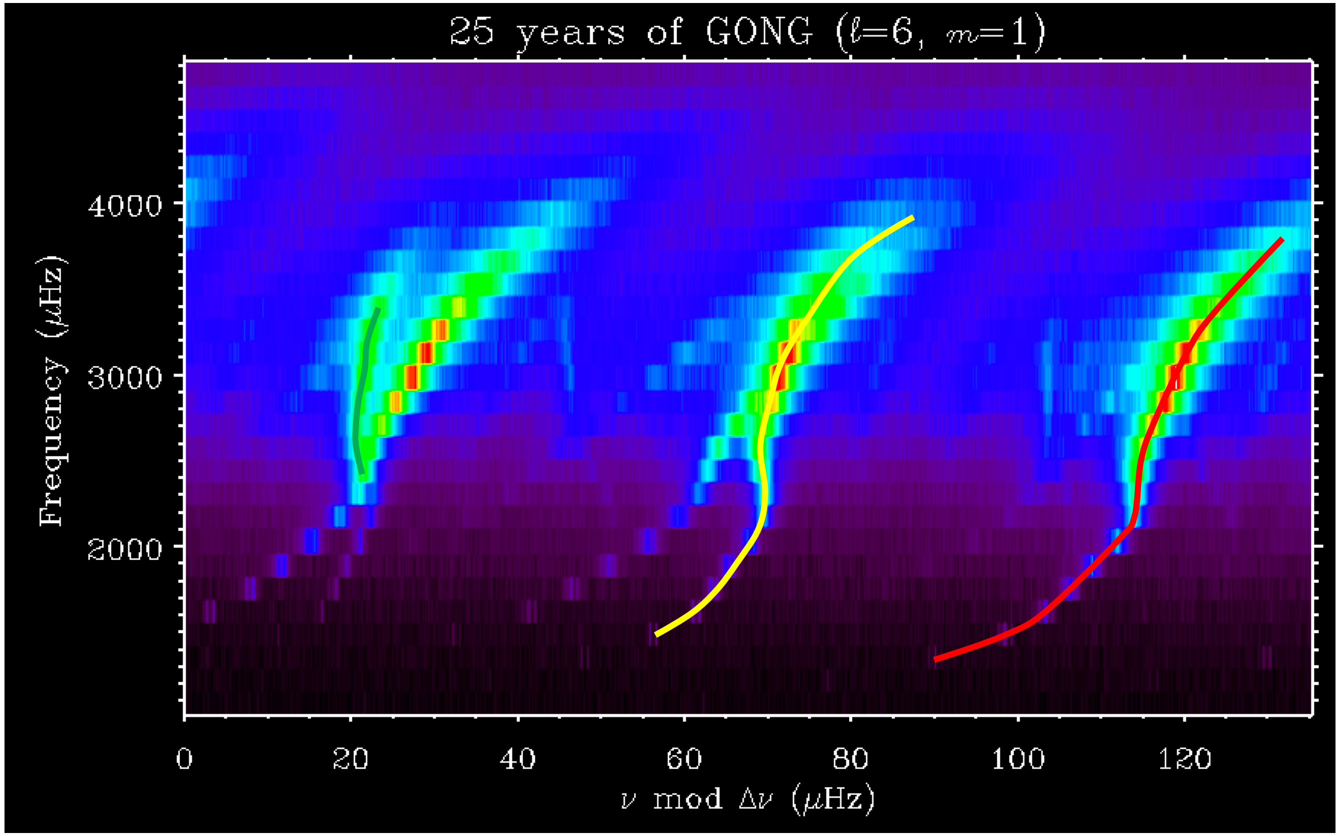
LOI (l=1, m=0)



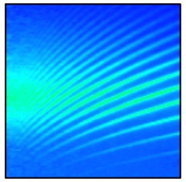
27 years of LOI (ℓ=1, m=0)
4000
3000
2000
Frequency (μHz)
0
20
40
60
80
100
120
ν mod Δν (μHz)



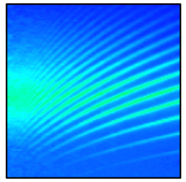
GONG (l=6, m=1)

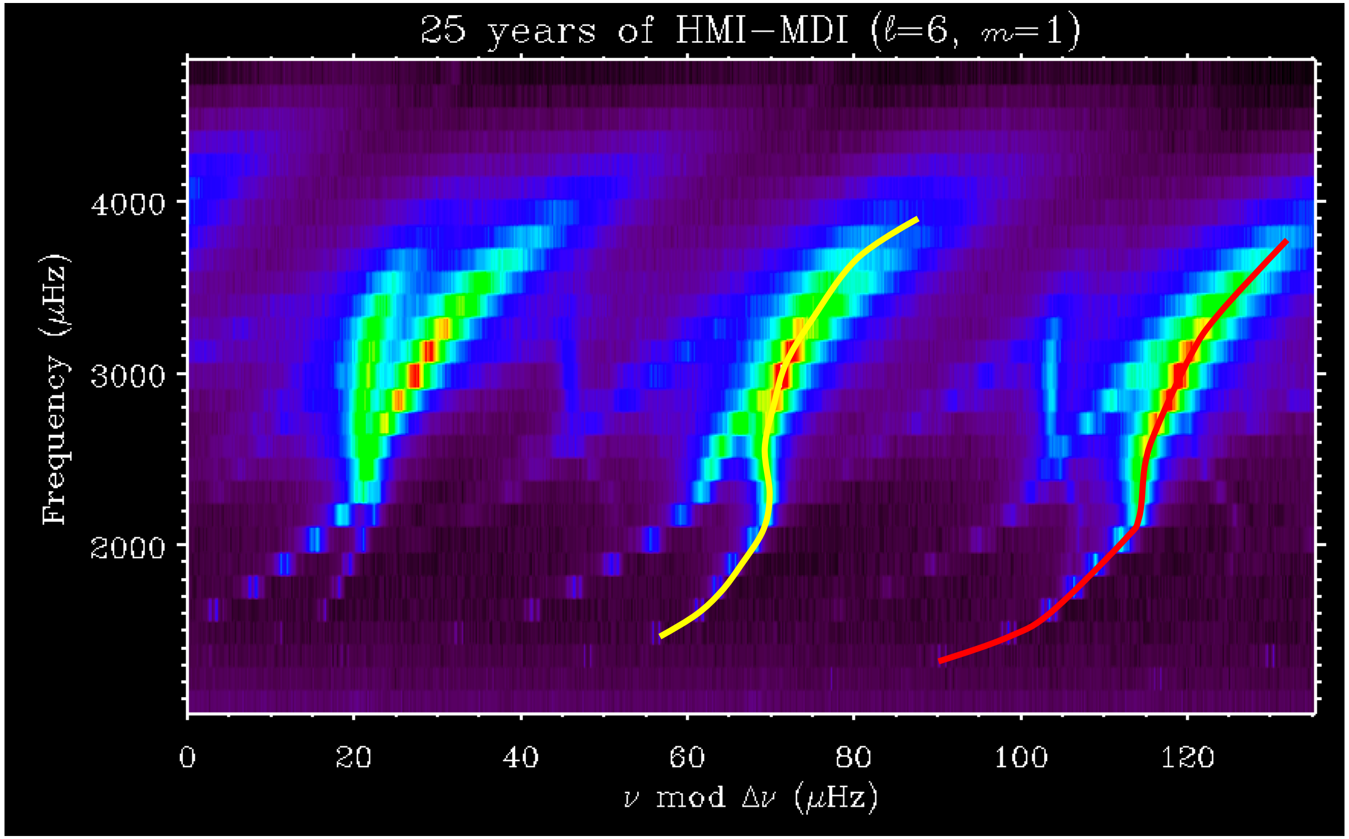


25 years of GONG (ℓ=6, m=1)
Frequency (μHz)
4000
3000
2000
0
20
40
60
80
100
120
ν mod Δν (μHz)

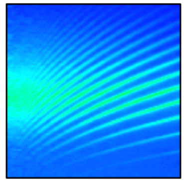


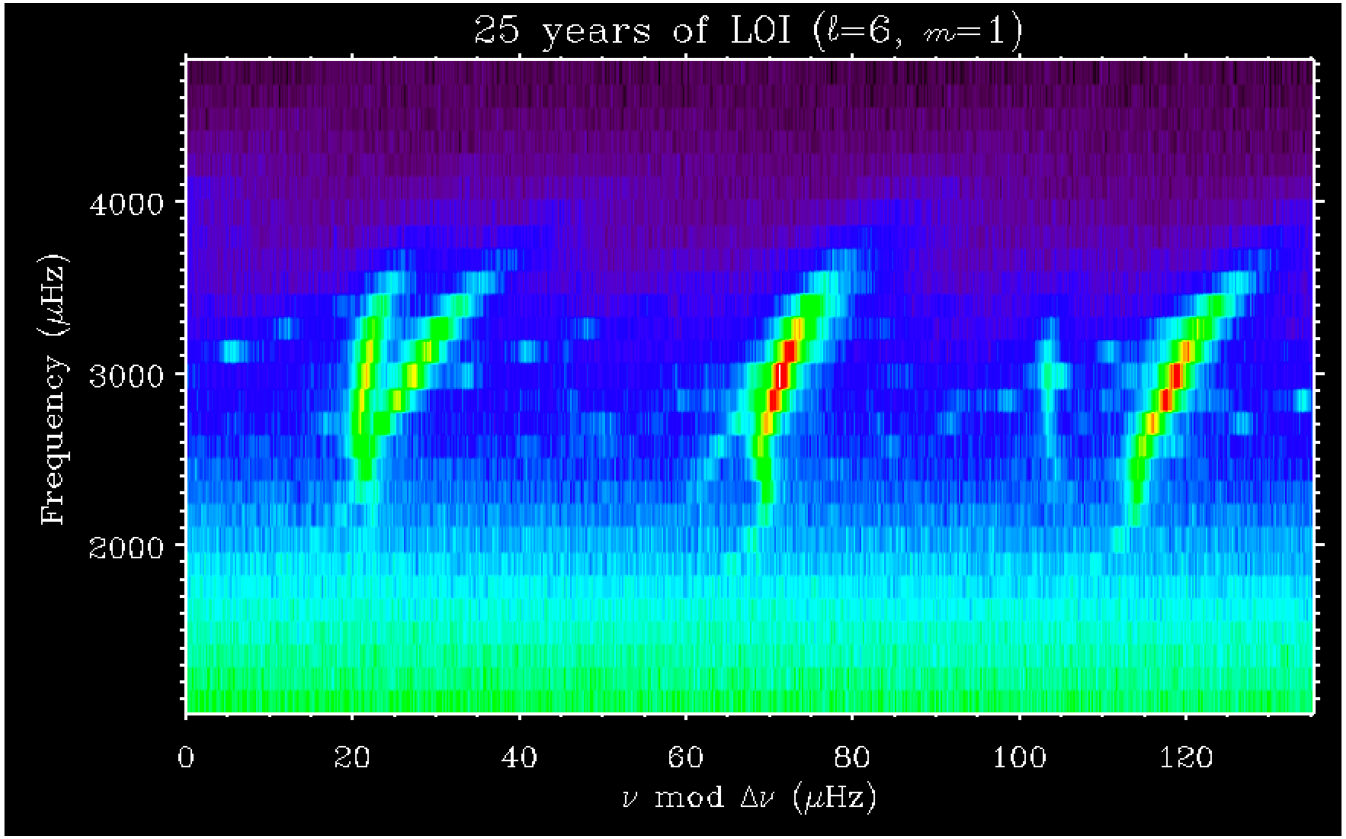
HMI-MDI (l=6, m=1)




25 years of HMI–MDI (ℓ=6, m=1)
Frequency (μHz)
4000
3000
2000
0
20
40
60
80
100
120
ν mod $\Delta\nu$ (μHz)

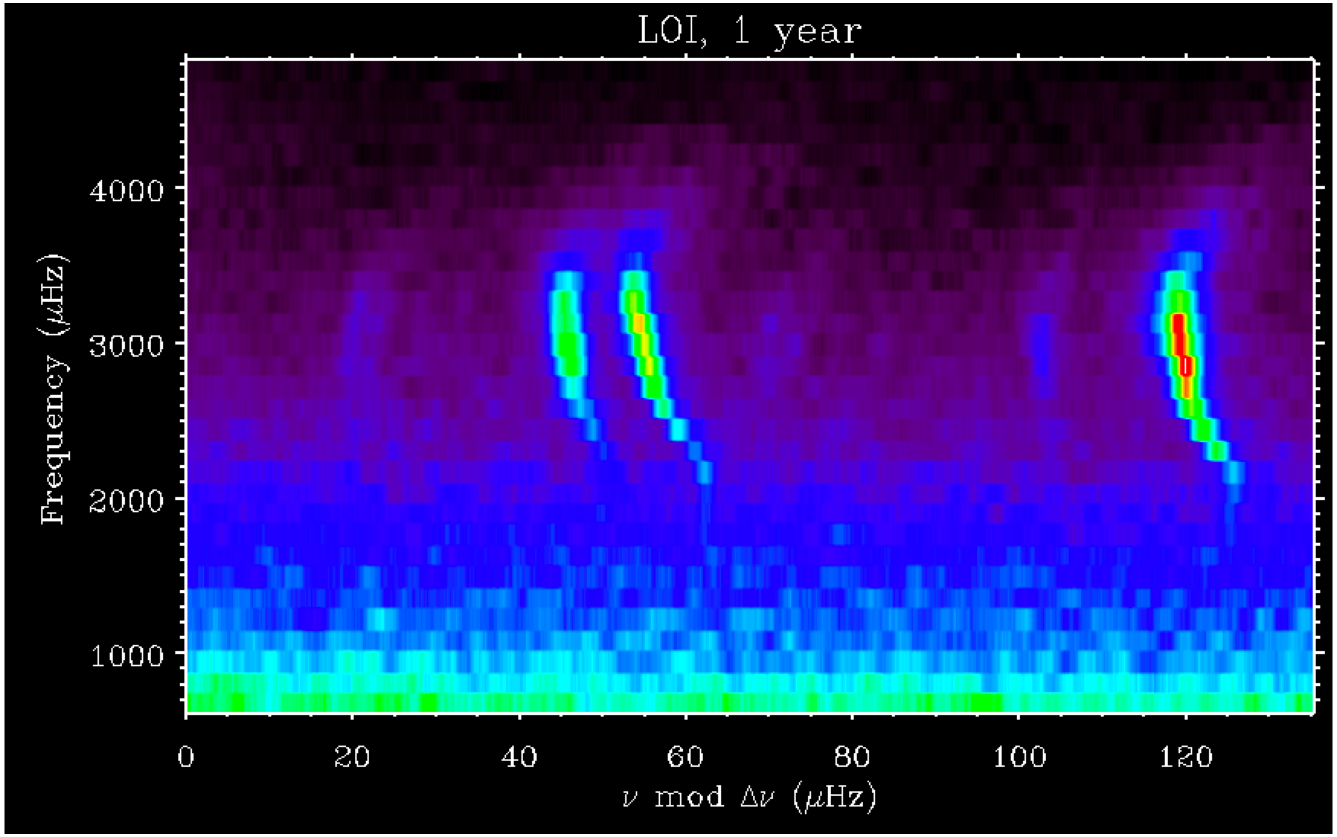
LOI (*l*=6, *m*=1)



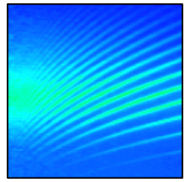


l as high as 12, 13, 14 are visible

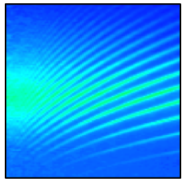
On fitting…

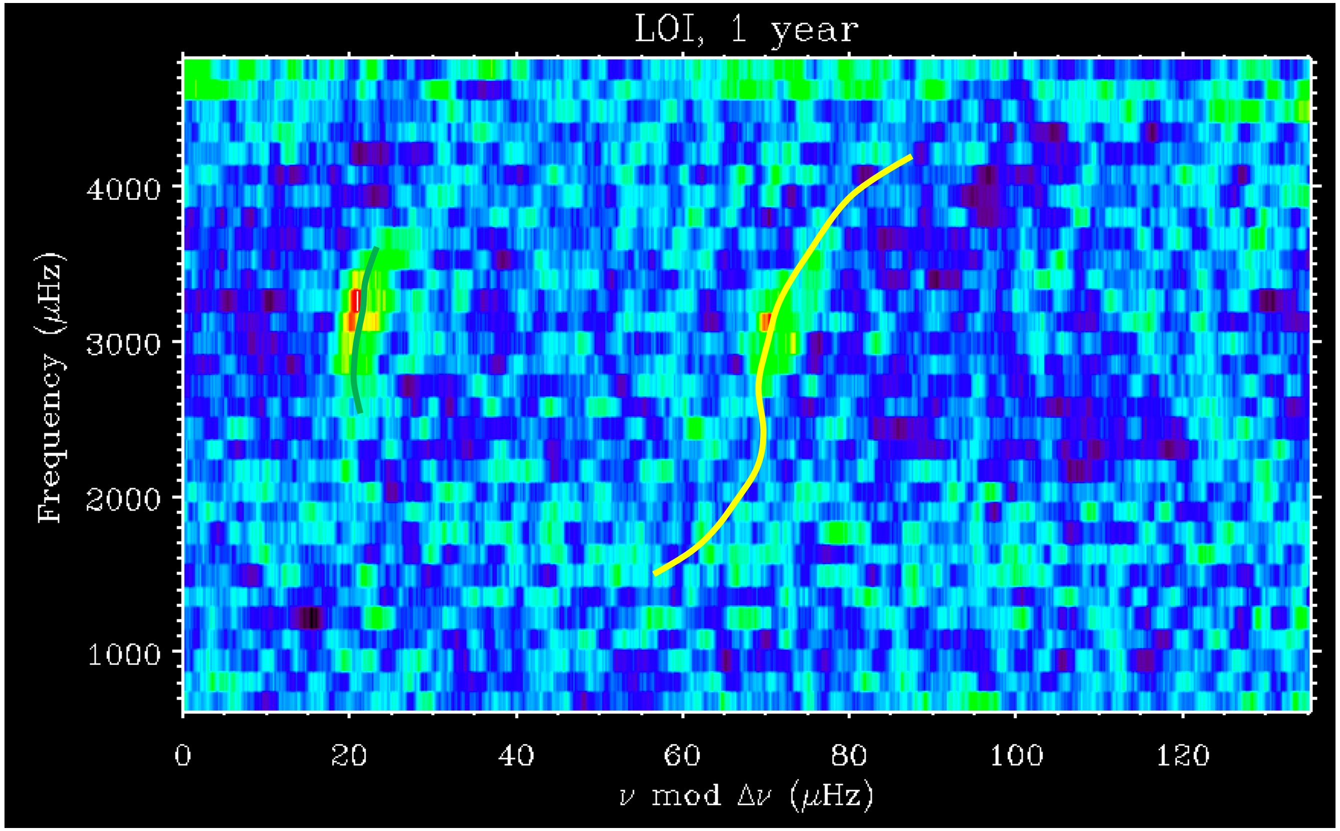


LOI, 1 year
Frequency (μHz)
4000
3000
2000
1000
0
20
40
60
80
100
120
ν mod Δν (μHz)



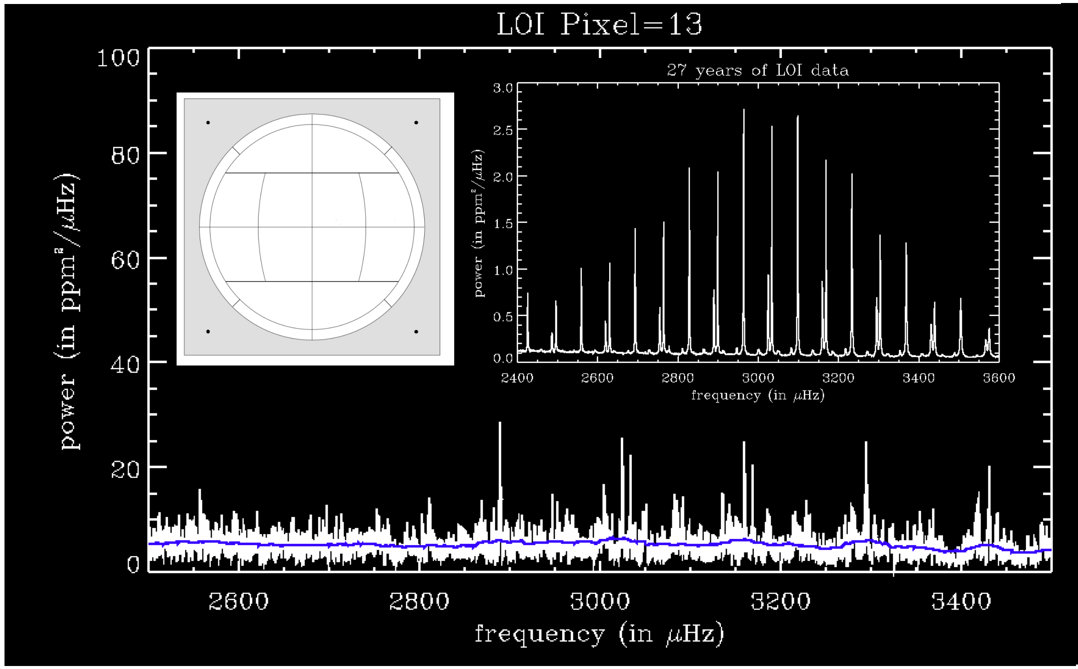
…all modes

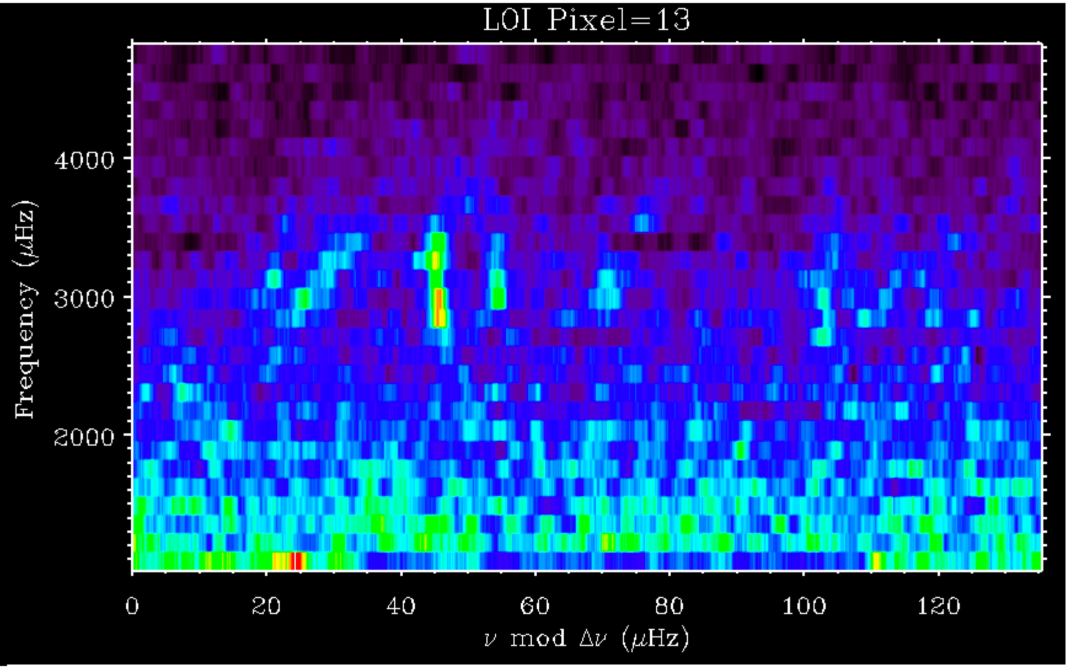




Ratio of data to fit…what remains…

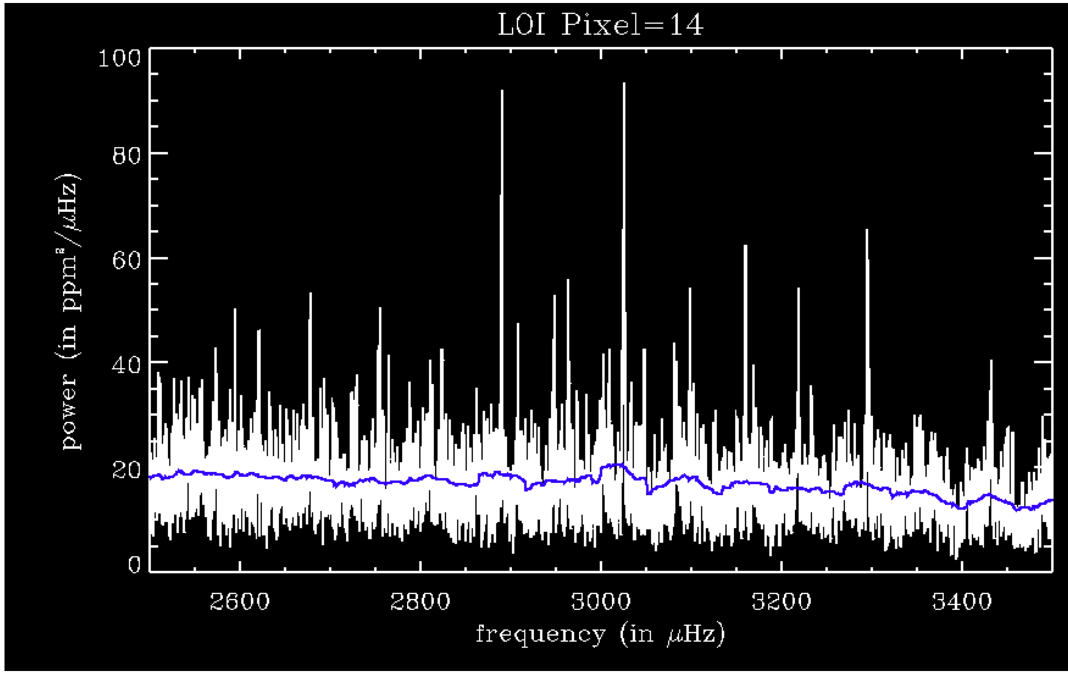
A bonus result…North-South pixels

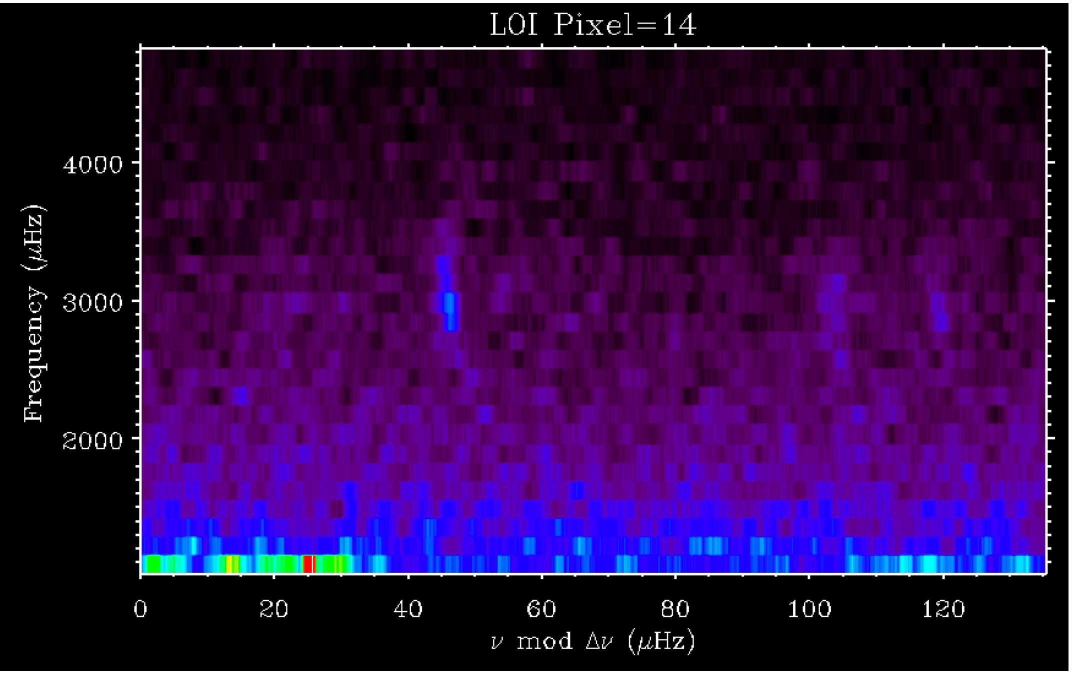




A mode peak of 30 ppm^2 corresponds to 0.08 marcsec^2

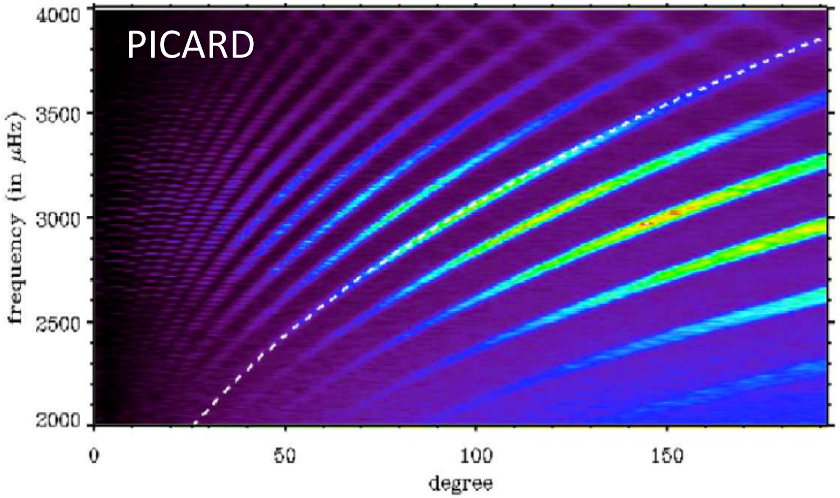
A bonus result…East-West pixels

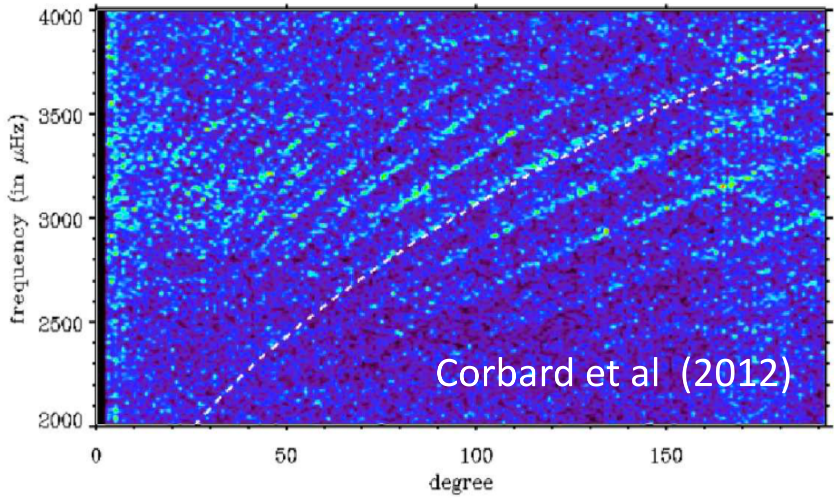


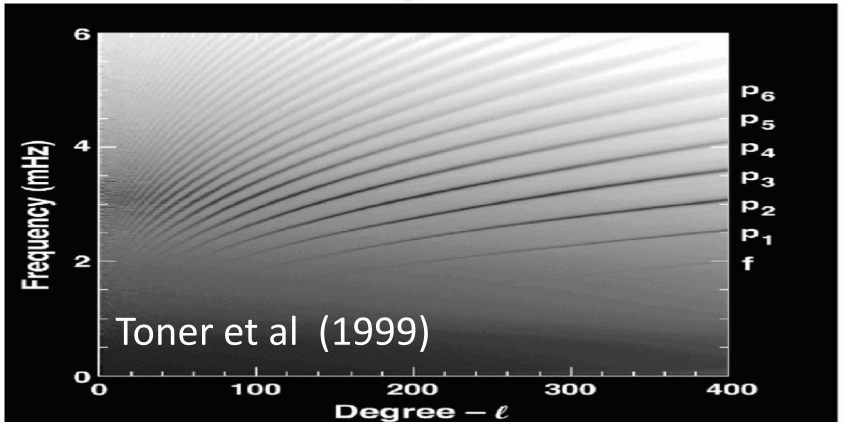


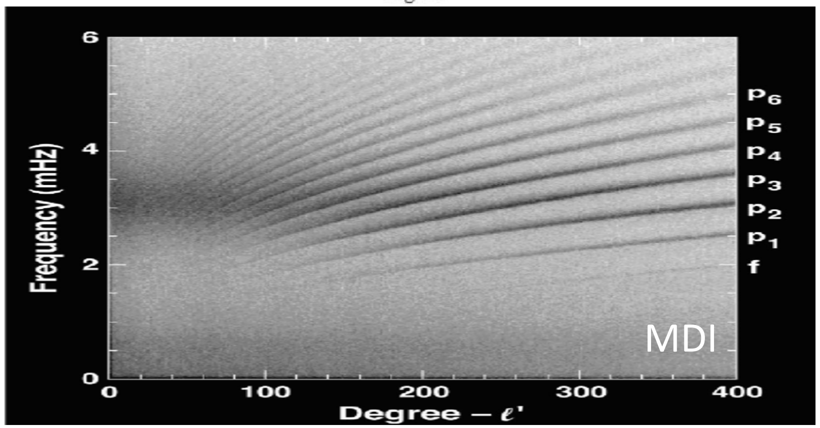
A mode peak of 100 ppm^2 corresponds to 0.25 marcsec^2

Limb seismology

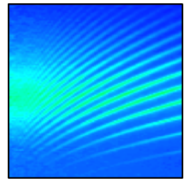


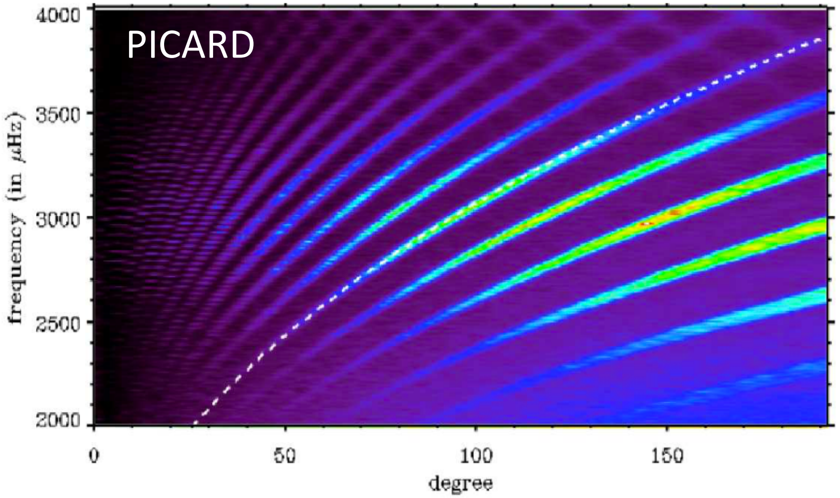


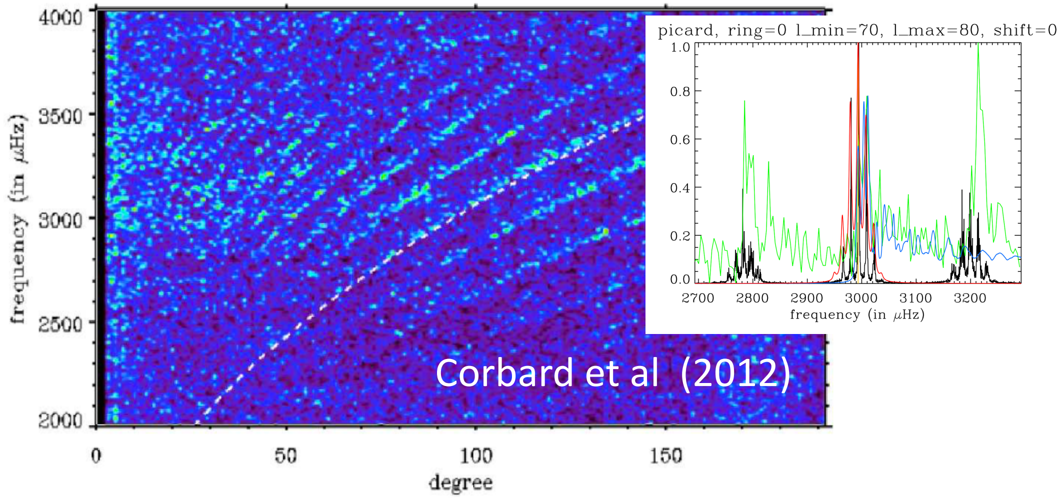


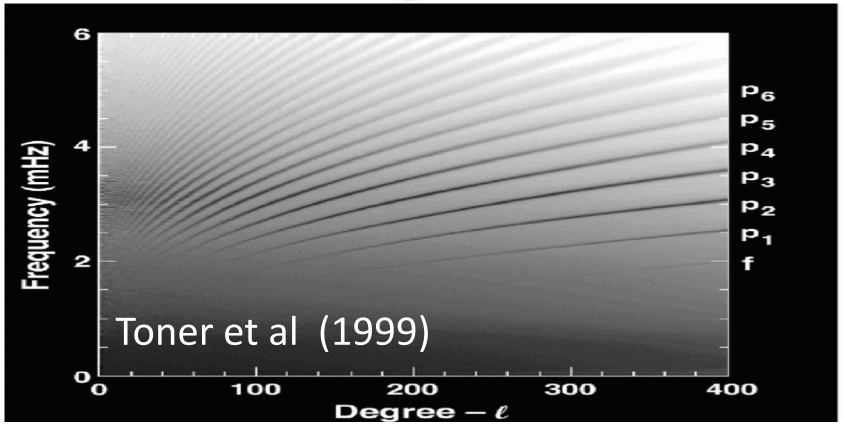


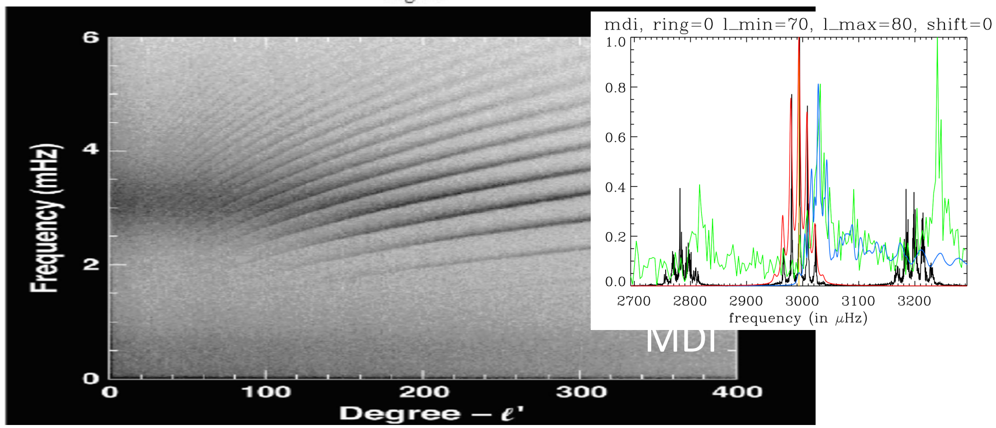
Limb seismology



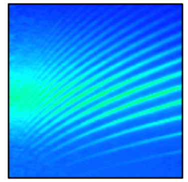








Limb seismology: a parenthesis



A time capsule: SCLERA…what was observed?

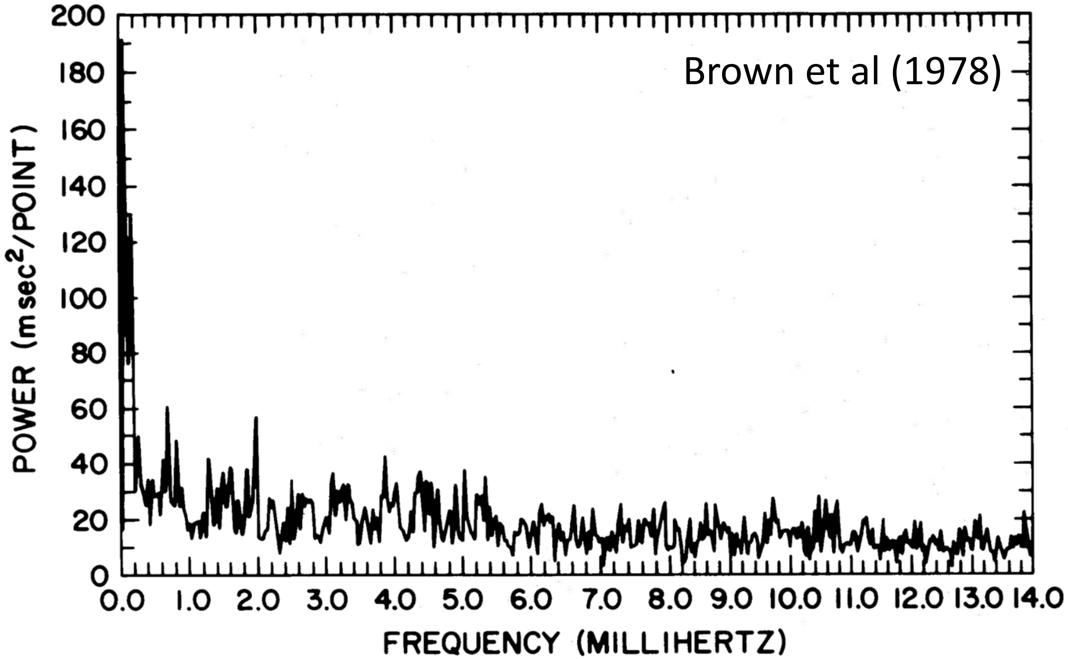
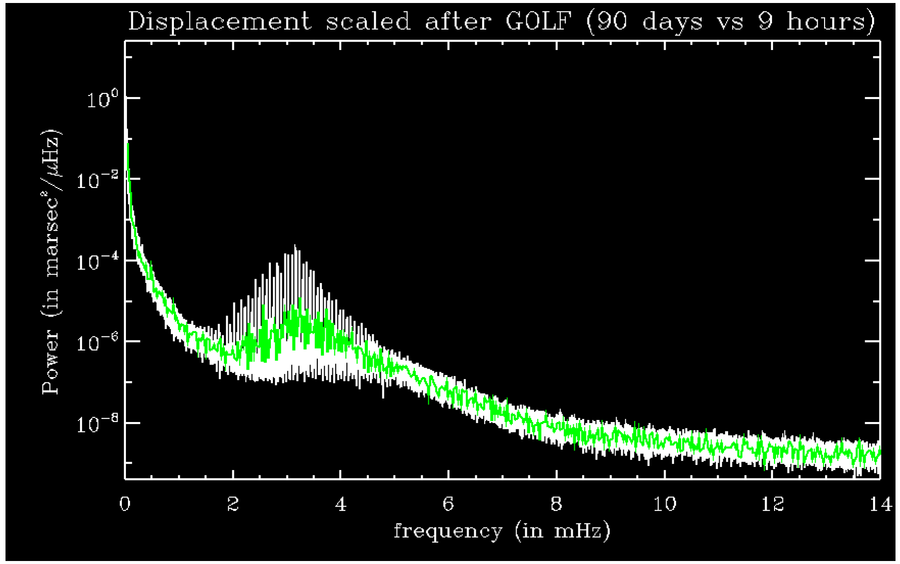
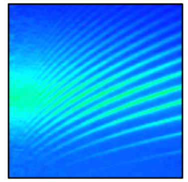


FIG. 2.—Average of 11 daily power spectra



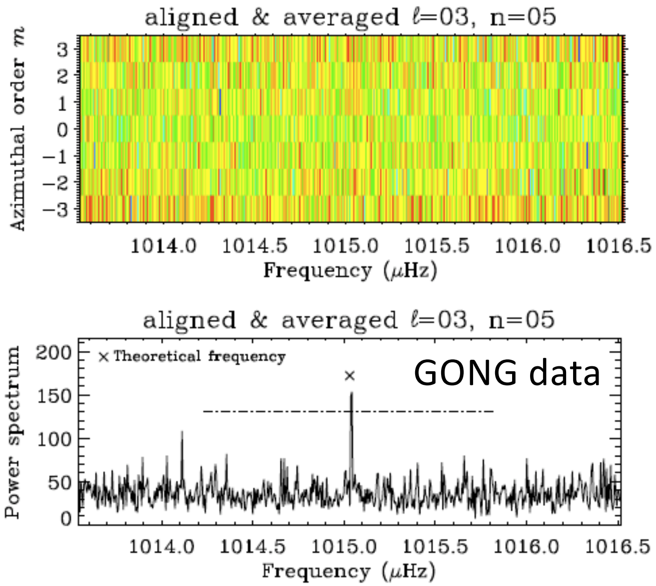
GOLF: max mode would be 10^{-2} marcsec

LOI: max observed mode is 0.5 marsec

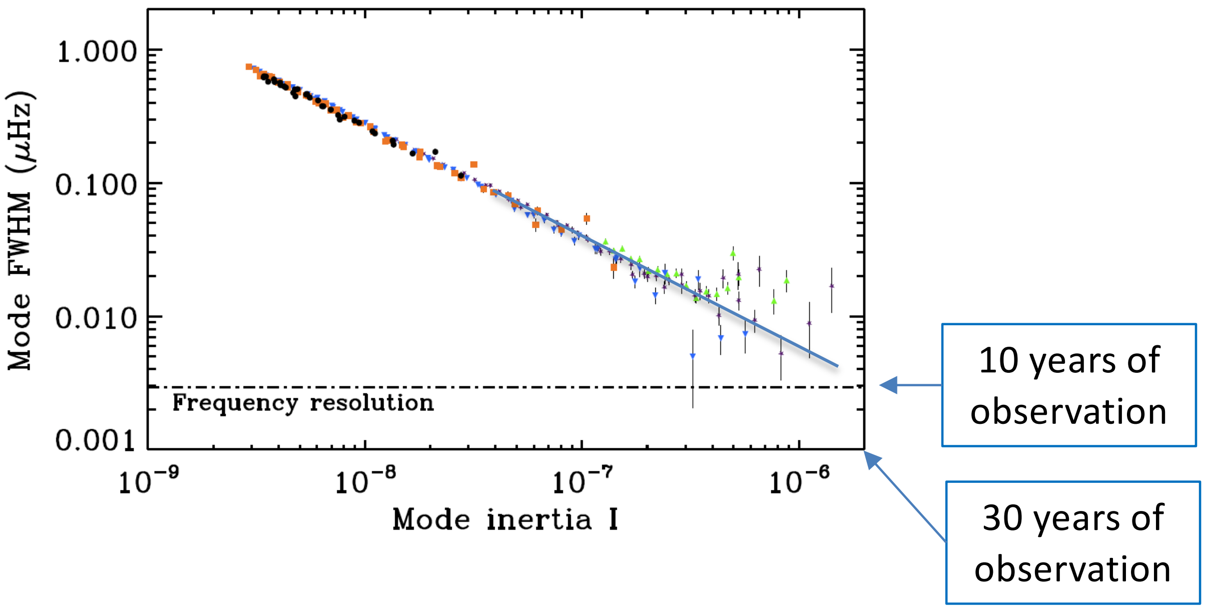


The future

Why do we need to observe for so long?

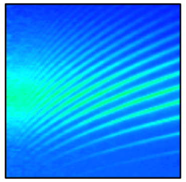


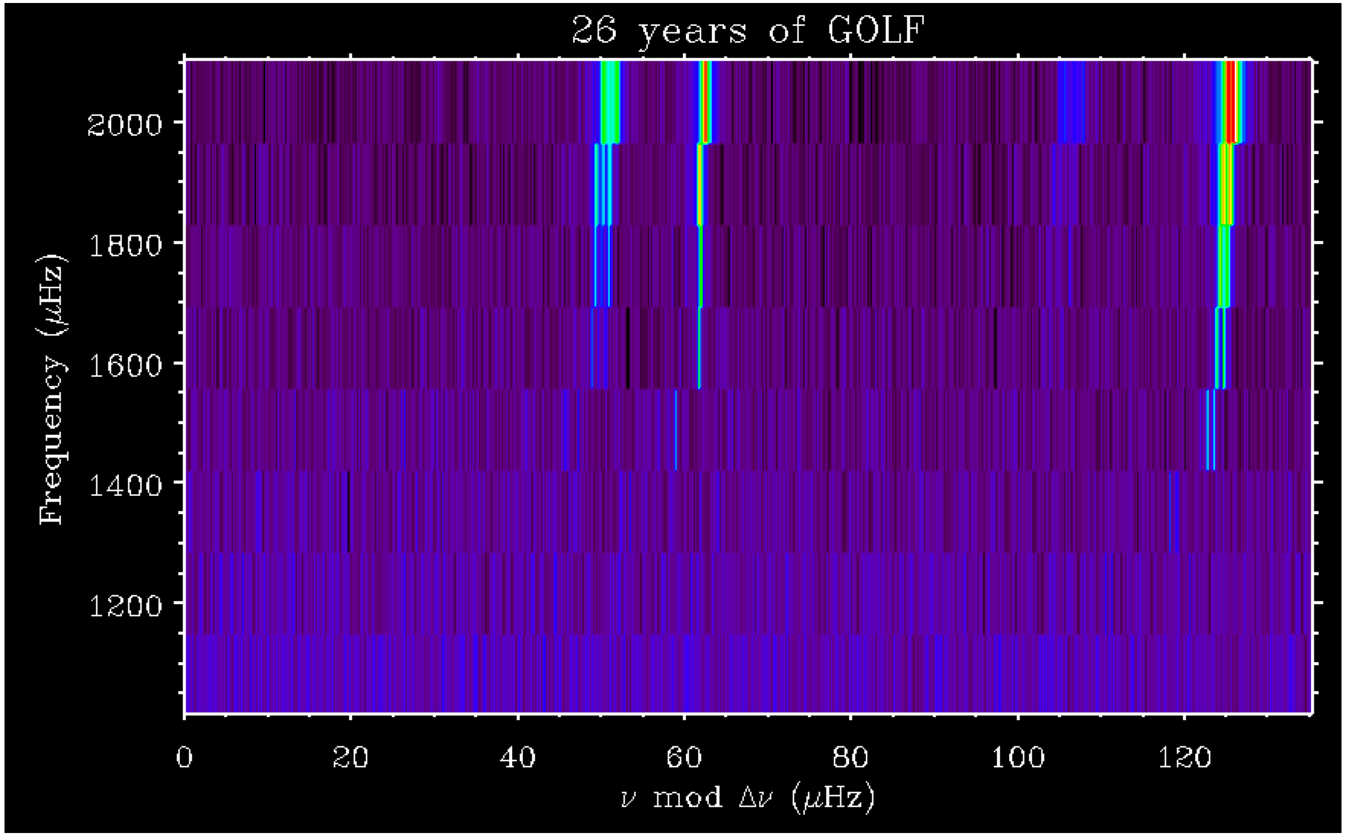
Lifetime from a few days to a few years !



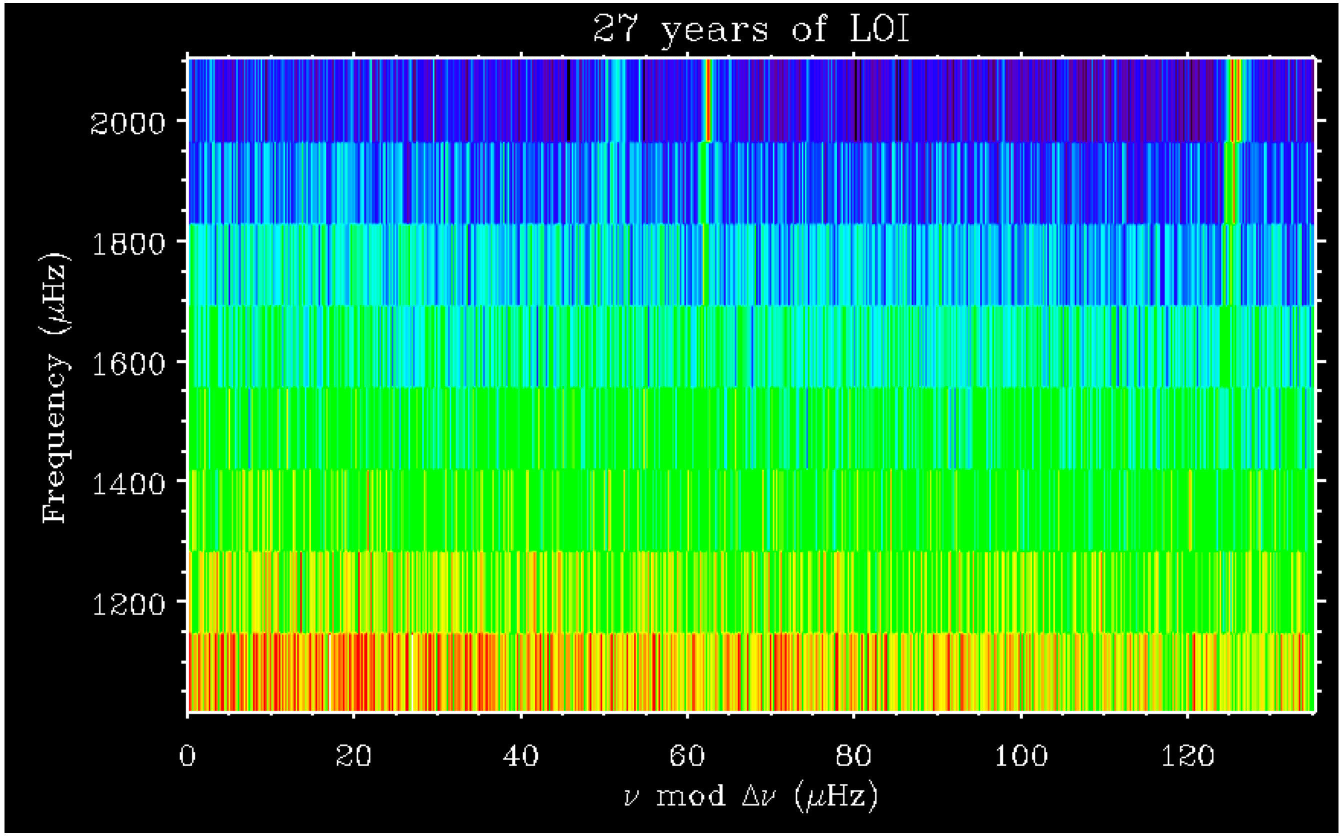
Salabert et al (2009)

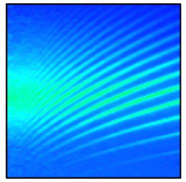
GOLF at low frequency



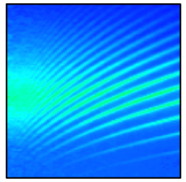


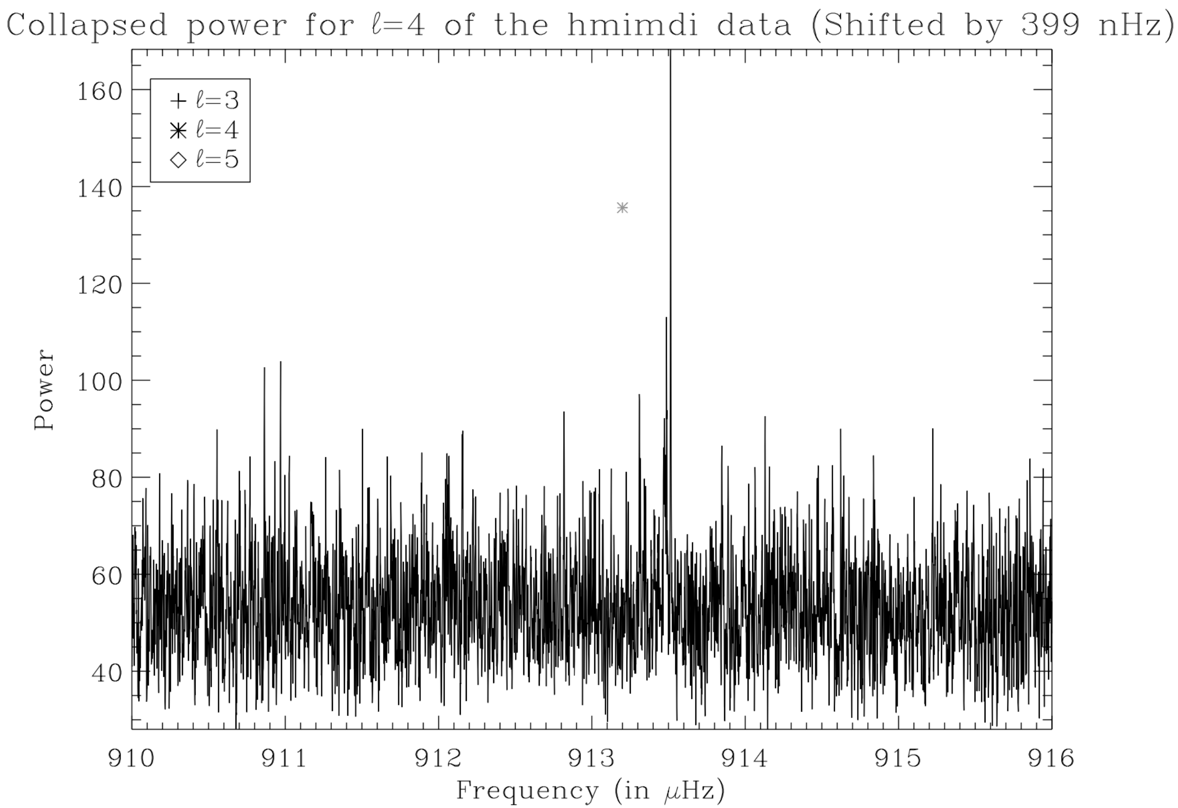
LOI at low frequencies





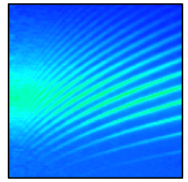
HMI-MDI collapsed power (*l*=4)

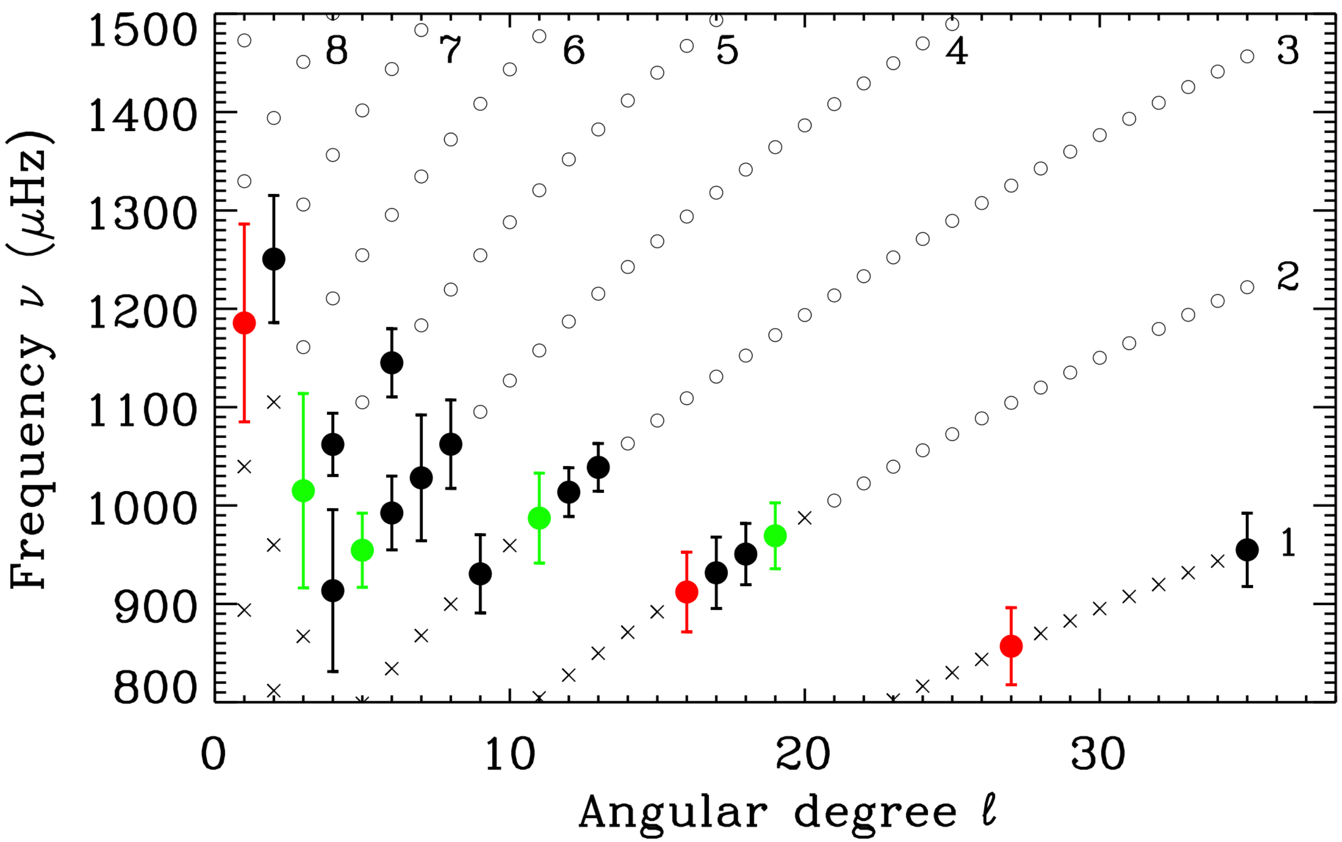




Appourchaux (2020)

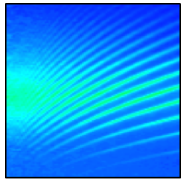
Low-frequency modes (I)

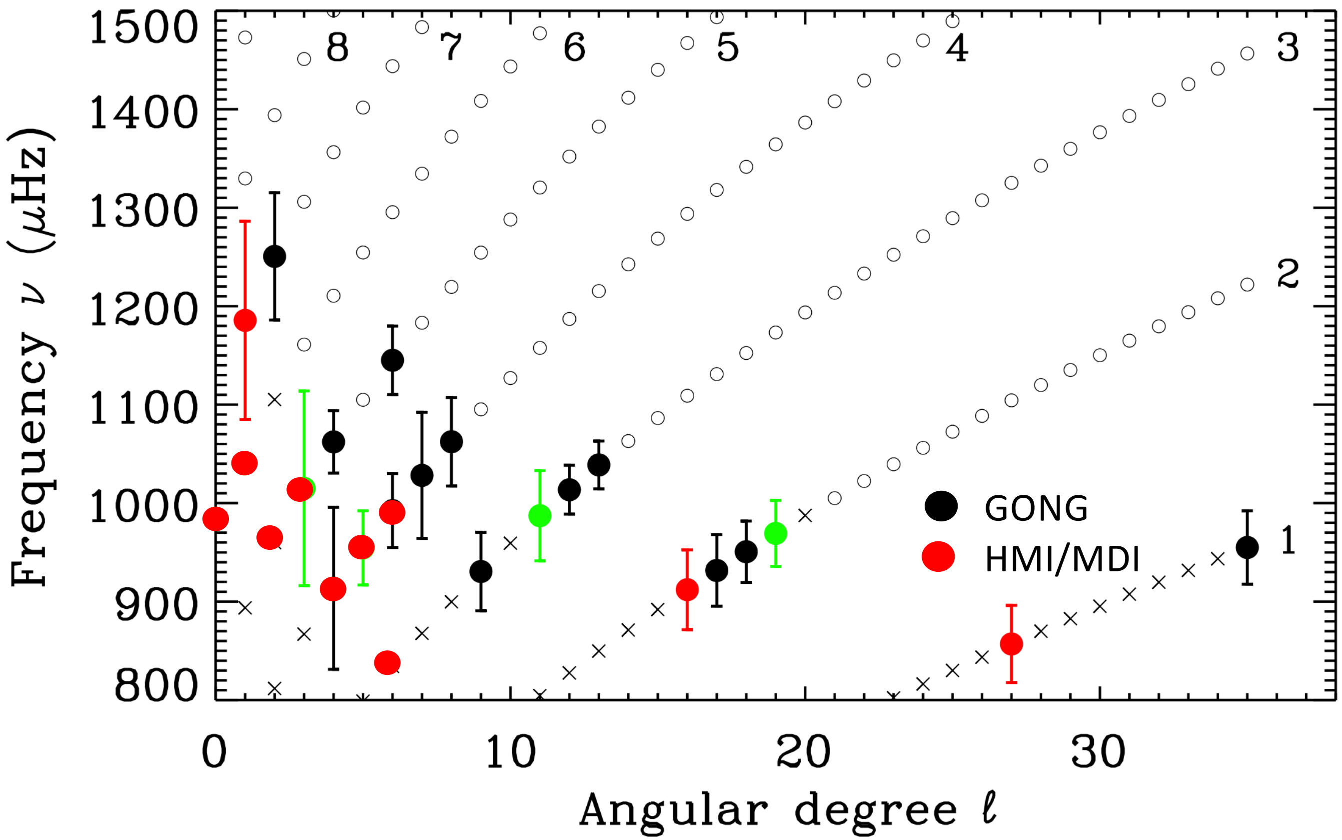




Salabert et al (2009)

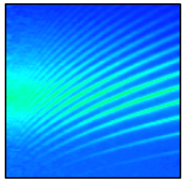
Low-frequency modes (II)

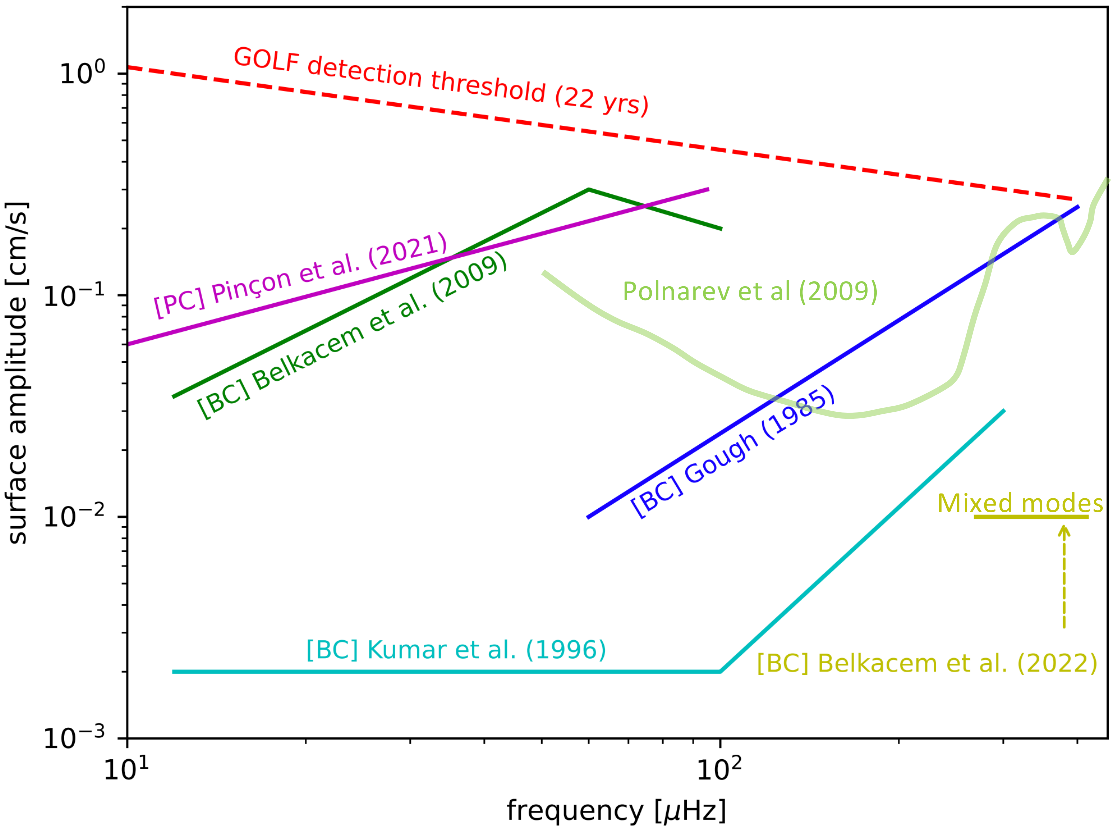




Appourchaux (2020)

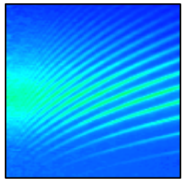
...but elusive g modes...

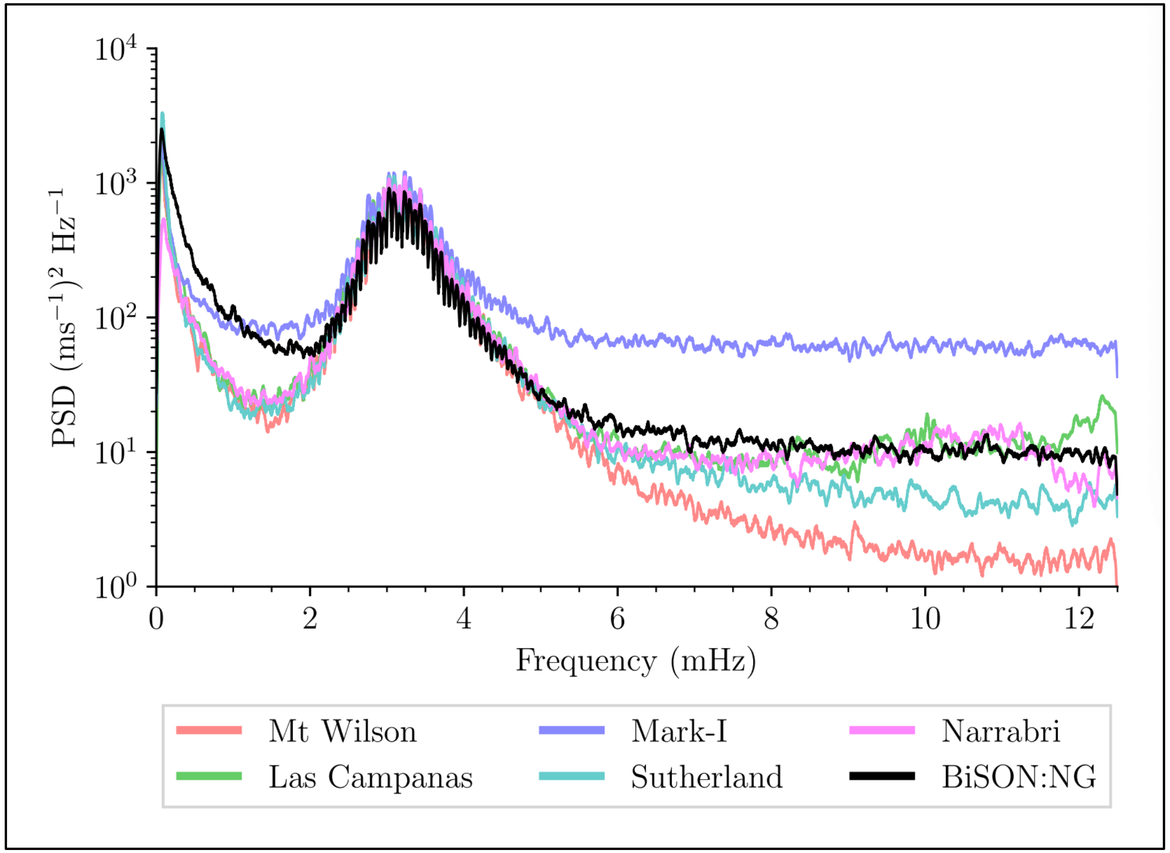




Belkacem et al (2022)

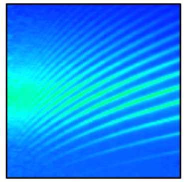
Next Generation BiSON

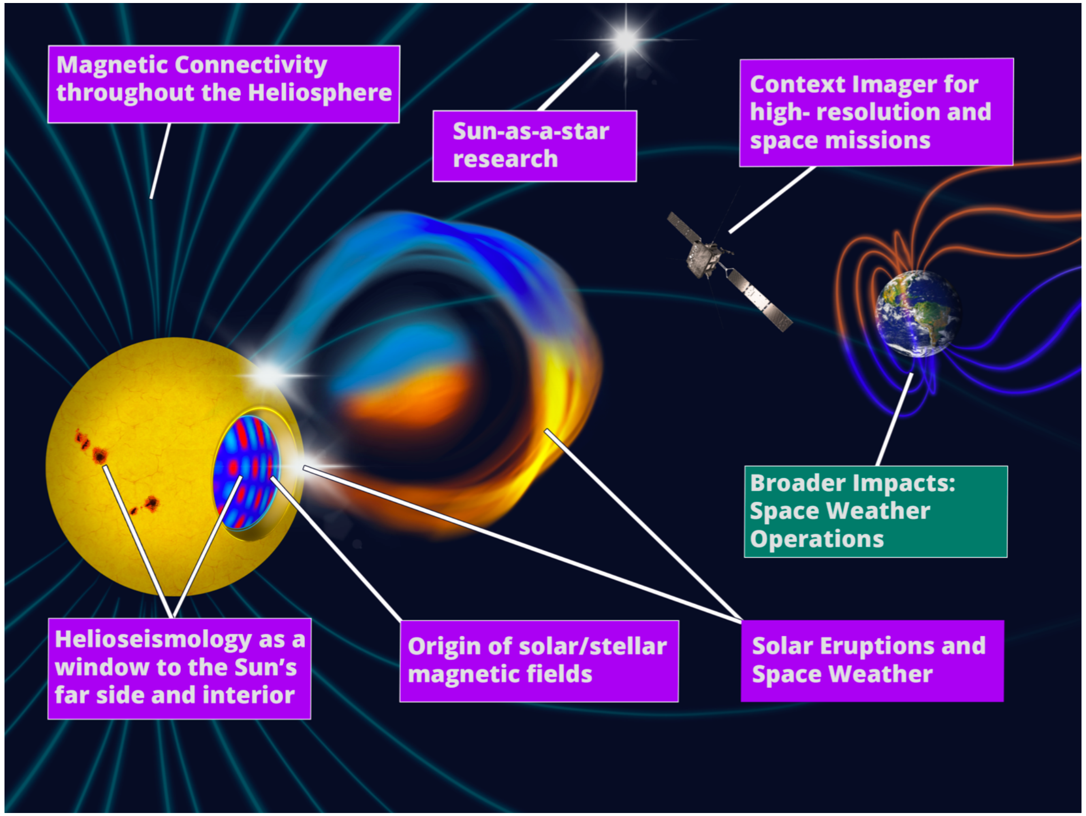




Hall et al (2022)

Next Generation GONG

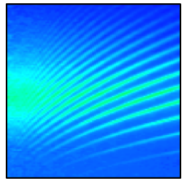




Hill et al (2020), Pevstov et al (2024)

- Radial velocity (derivative of ξ_r)
- Three Fraunhöfer lines (Ni I)
- Line profile analyzed with a Michelson and a prefilter
- 10-point measurement (linear)
- CCD: 2k x 2k
- Operated on Earth from mid-2031 to 2052 at a cadence of 60 s

Launch of Solar Orbiter (2020)



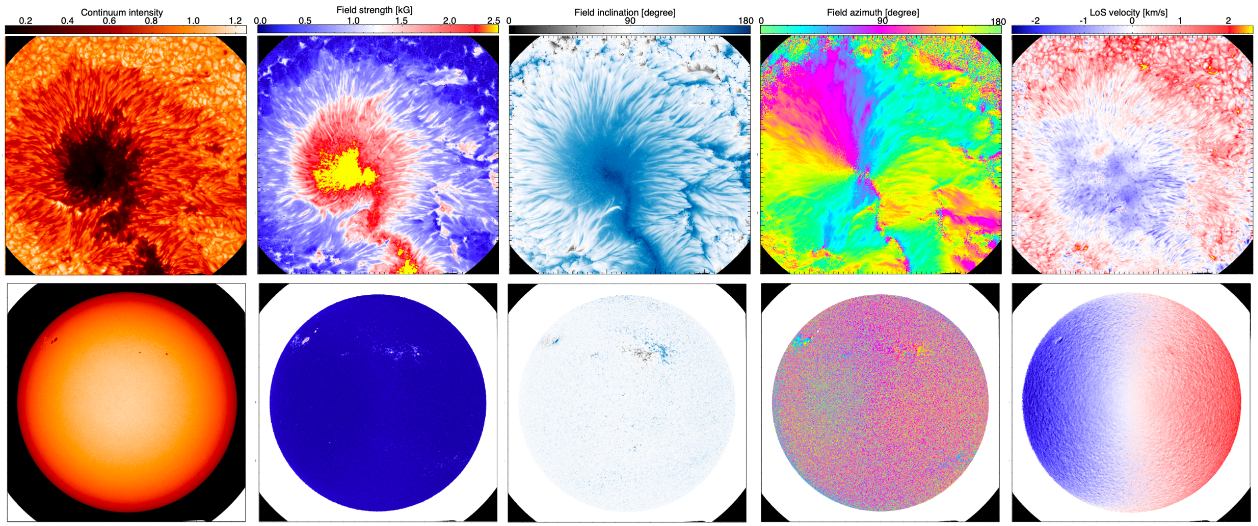
Polarimetric and Helioseimic Imager

Data products:

- continuum intensity, I_c
- LOS velocity, v_{LOS}
- LOS magnetic field strength, B_{LOS}
- magnetic field inclination, γ
- magnetic field azimuth, ϕ

Requirements:

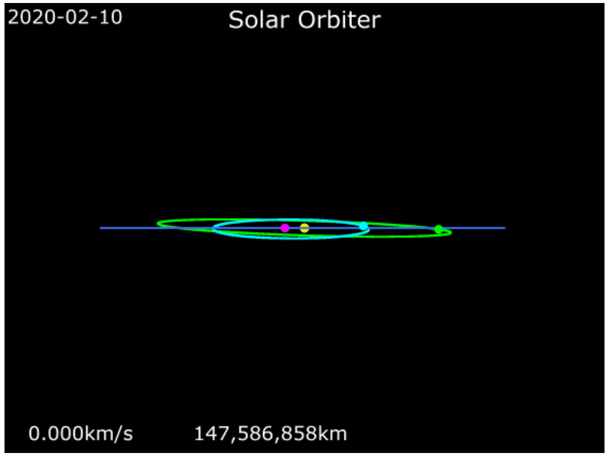
- high-resolution data (~150 km)
- full-disk data
- 2k x 2k FOV
- 1 data set per minute
- 4...5 bits (compressed) digital depth

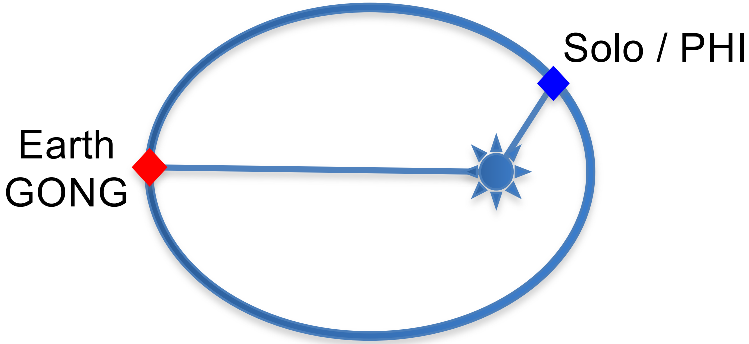


I_c B γ ϕ v_{LOS}

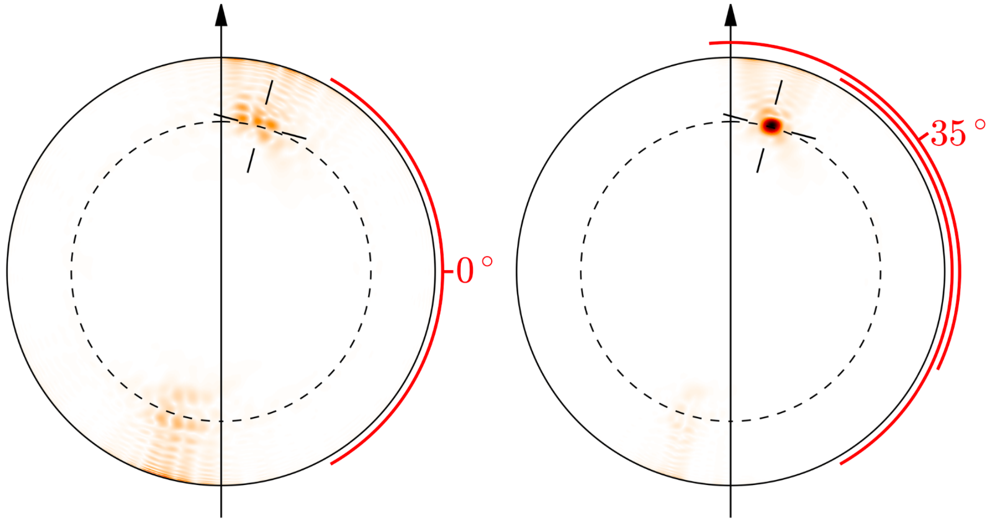
Solanki et al (2020)

The power of stereoscopy





Spatial sensitivity of helioseismic stereroscopy to the meridional flow at latitude 75° and radius $0.7R_{\odot}$.

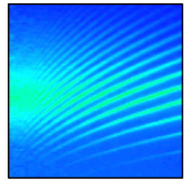


The resolution is poor when using only observations of solar oscillations in the equatorial plane (left panel, data coverage indicated in red).

The resolution is greatly enhanced when combining the previous data with observations from a line of sight inclined by 35°

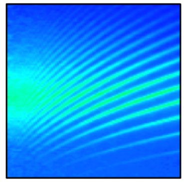
Solanki et al (2020)

A forest of data



- HMI-MDI: from *l*=0 to high *l,* 27 years…(till 2030)
- GONG: from *l*=0 to high *l,* 28 years…(till 2052?)
- BiSON: from *l*=0 to *l*=4, 37 years…(till 2027?)
- VIRGO: from *l*=0 to *l*=14, 27 years+ (till 2025)
- GOLF: from *l*=0 to *l*=4, 27 years+ (till 2025)
- PHI: from *l*=2 to high *l*, high latitudes from 2027
- LISA: *l*=2 modes from 2037

Conclusions



- Perturbations observed are displacement (velocity), pressure (intensity)
- Different instruments provide different mode response (degree) providing different systematics to be taken into account in stellar models
- Time series longer than 25 years are available…the longer the better
- Lower frequency p modes are detected with longer time series
- No confirmation of g modes, yet…
- Hope to continue for the next 25 years…50 years (longer than a scientist career) !
- There is a definite need for younger bloods…the Science vampire must live on !