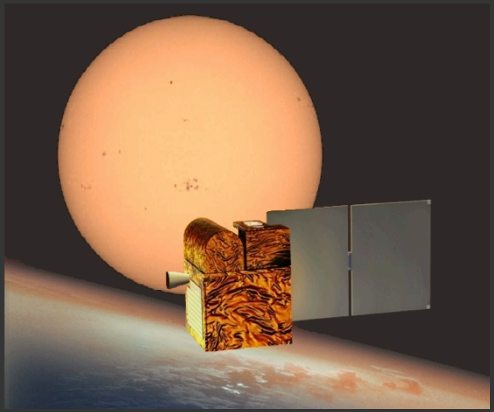
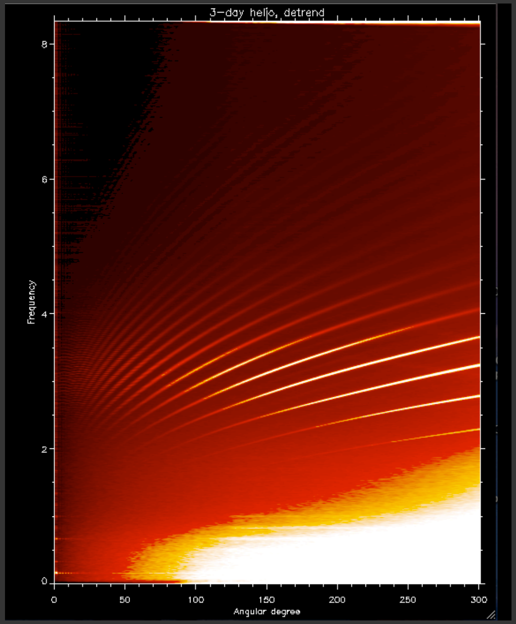
Global Helioseismology with PICARD

Salabert, Corbard, Boumier

CEA/SAp, OCA, IAS





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Outline

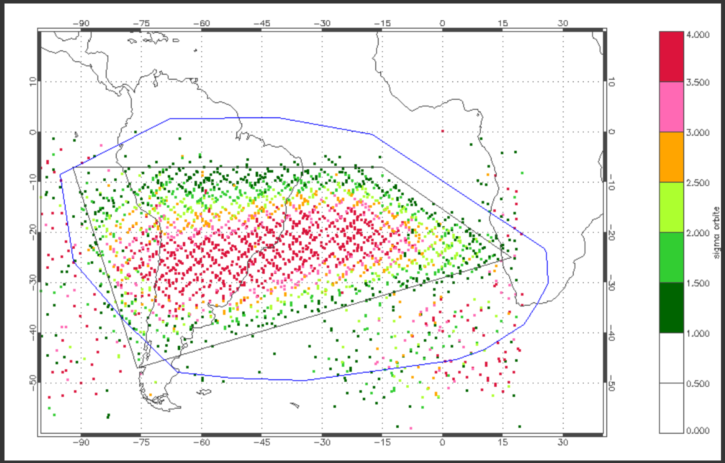
1. Description of the SODISM helioseismic signal
2. Data calibration pipeline for helioseismic analysis
3. Analyzed dataset and peak-fitting pipeline
4. Internal rotation with SODISM
5. Comparison with HMI Intensity data

Characteristics of the SODISM Helioseismic Signal (1/5)

- **Main characteristics can be outlined:**
  1. Regular passages through the South Atlantic Anomaly (SAA) due to the PICARD orbit
  2. Orbital period around the Earth of about 100 min
  3. Presence of CCD persistence with a 2-min aliasing due to routine interruptions for the radius program

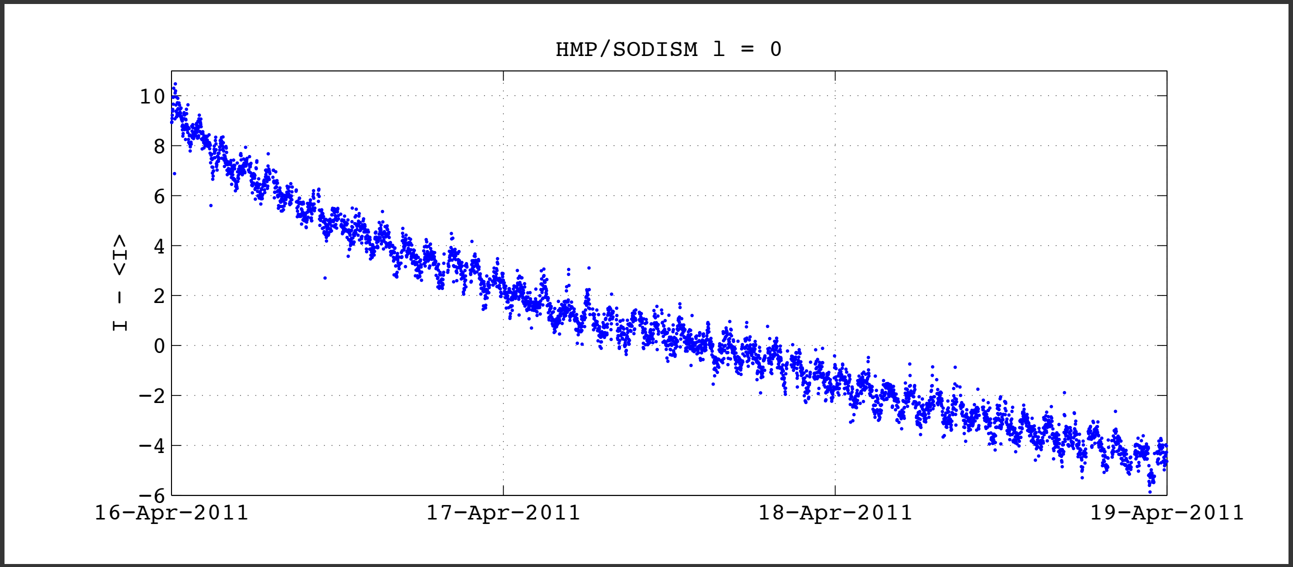
Characteristics of the SODISM Helioseismic Signal (2/5)

- **South Atlantic Anomaly (SAA)**
  - PICARD: low-altitude, Sun-synchronous orbit
  - Onboard instruments exposed to several minutes of strong radiations
  - Represents about 7% of measurements which are unexploitable



Characteristics of the SODISM Helioseismic Signal (3/5)

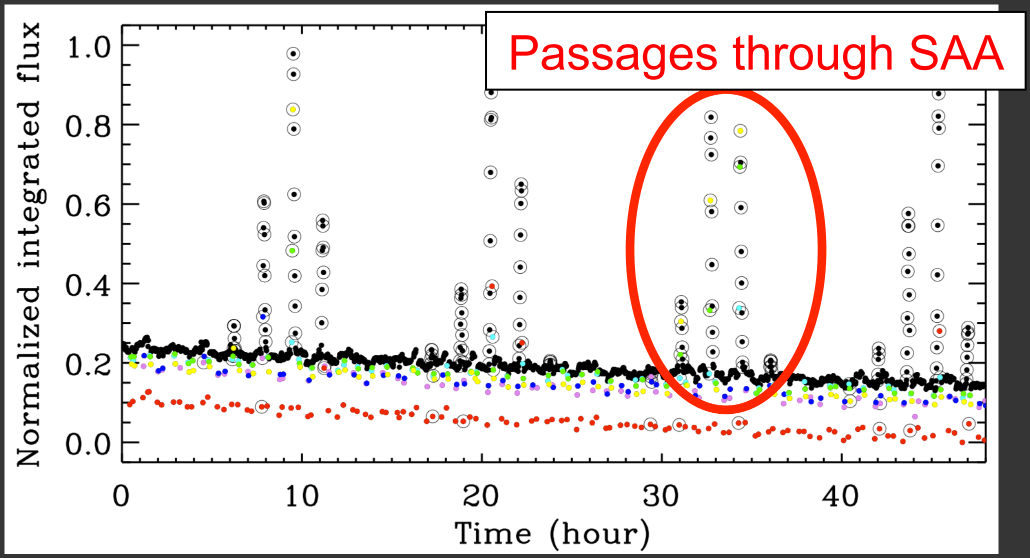
- **<u>Orbital period around the Earth of about 100 min</u>**
  - Visible on the low-degree oscillations



Characteristics of the SODISM Helioseismic Signal (4/5)

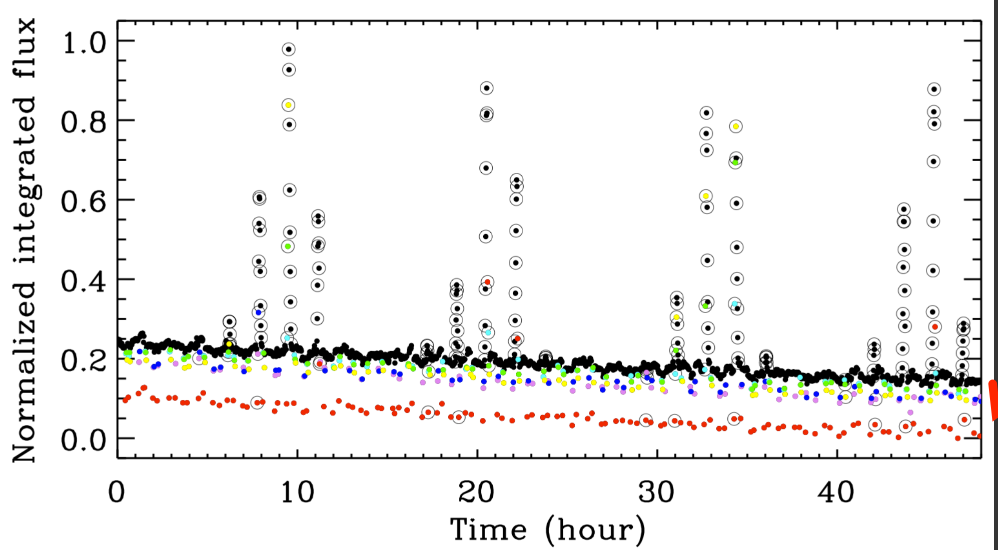
- <u>**Presence of CDD persistence**</u>
  - Most problematic source of noise for helioseismic analysis
  - Photometric level at a given minute depends on what measurement was done 1 minute before: radius, dark currents
  - Origin not properly understood yet: filter wheel likely the cause
  - Affects 10% of the measurements

Color code shows what type of measurement was made the minute before



Characteristics of the SODISM Helioseismic Signal (5/5)

- **Presence of CDD persistence**
  - Different photometric levels are thus introduced after dark currents and radius measurement at different wavelengths



For ex.

Categories	%
Dark current	0.199
λ = 215 nm	0.121
λ = 393 nm	0.075
λ = 535D nm	0.032
λ = 607 nm	0.031
λ = 782 nm	0.063

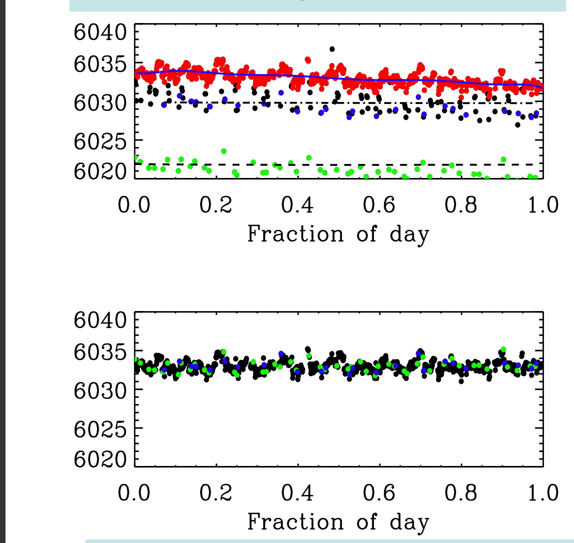
Data Calibration for Helioseismic Analysis (1/2)

- Determination of the measurements taken in the SAA through the geolocalization of the spacecraft
- *Ad-hoc* correction of the CDD persistence
- High-pass filtering of the light curves by fitting Legendre polynomials
- Gap-filling (< 5 min) using a linear prediction

Data Calibration for Helioseismic Analysis (2/2)

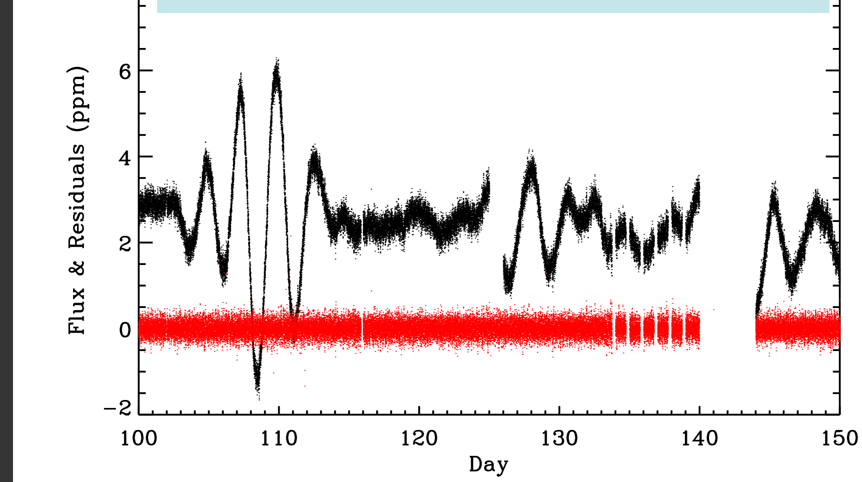
- **<u>Simultaneous high-pass filtering and persistence correction</u>**
  1. Non-remanent points high-pass filtered using Legendre polynomials
  2. Same filter used to correct each category of persistence, with corresponding mean value, y(x = 0)

Raw light curve: non-remanent points in red



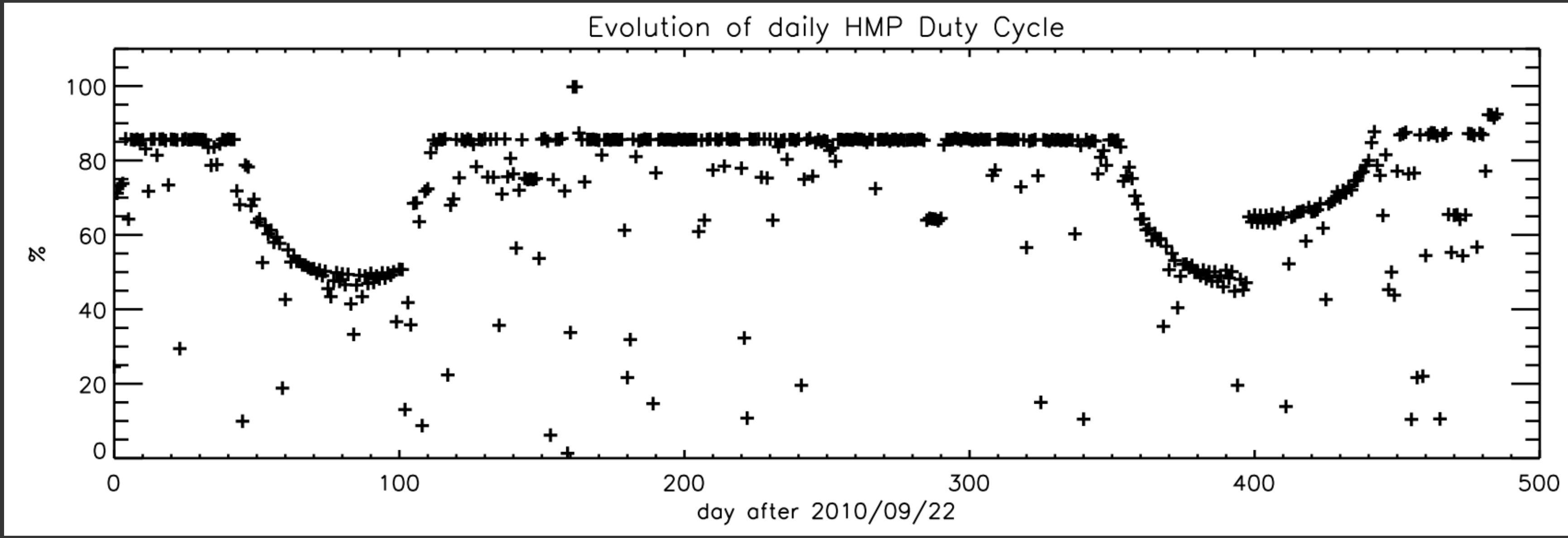
Corrected and detrended light curve

Example of 50- day light curve of l=15, m=11: Raw and Corrected curves



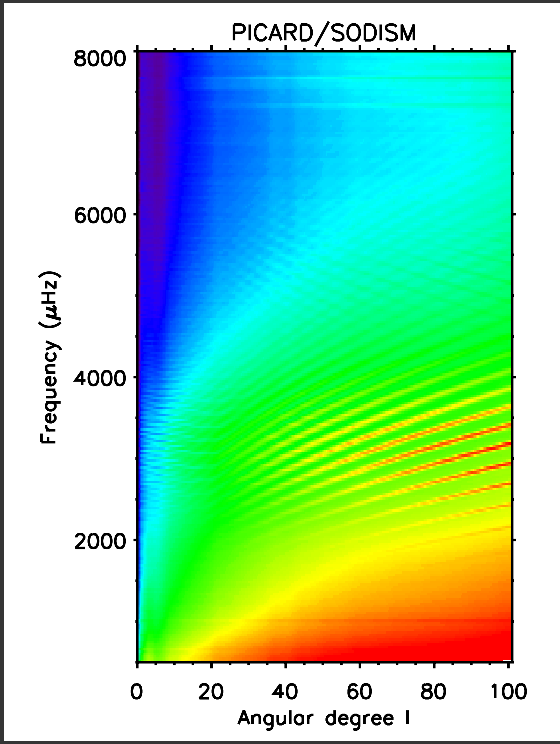
Mission Duty Cycle

- Duty cycle during the first 500 days of the mission



HMP Dataset

- Full continuum images at 535.7 nm, 256^2 pixels
- 209 days (2011 Apr 16 – 2011 Nov 10): Duty cycle 74.4%
- l-v diagram up to l=100 from the 209-day dataset



- Temporal aliasing above 4500 μHz: signature of a cycle with a 2-min sampling corresponding to the astrometric program sequences

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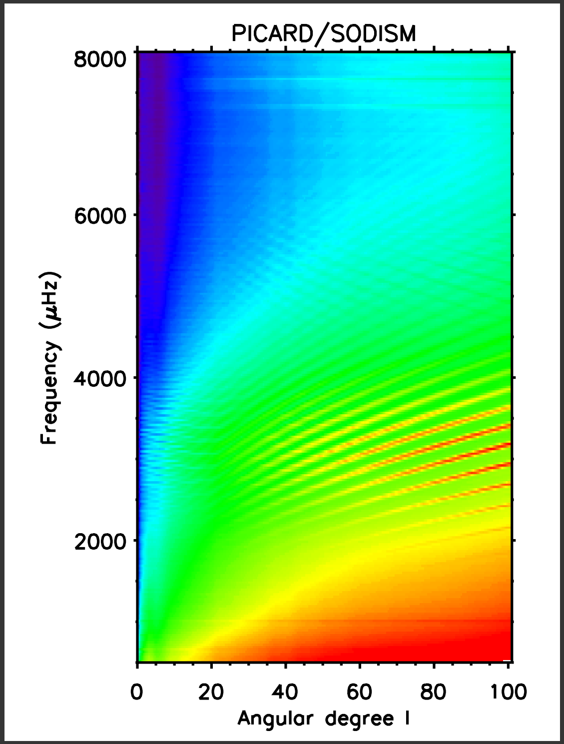
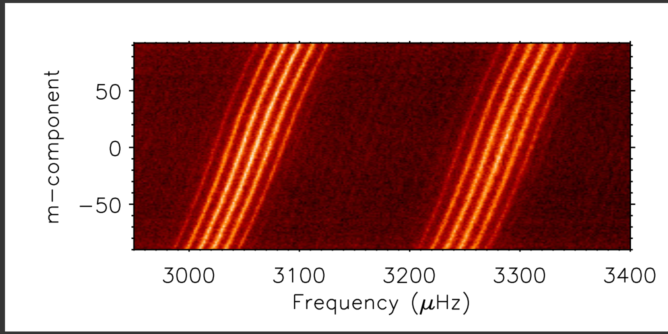


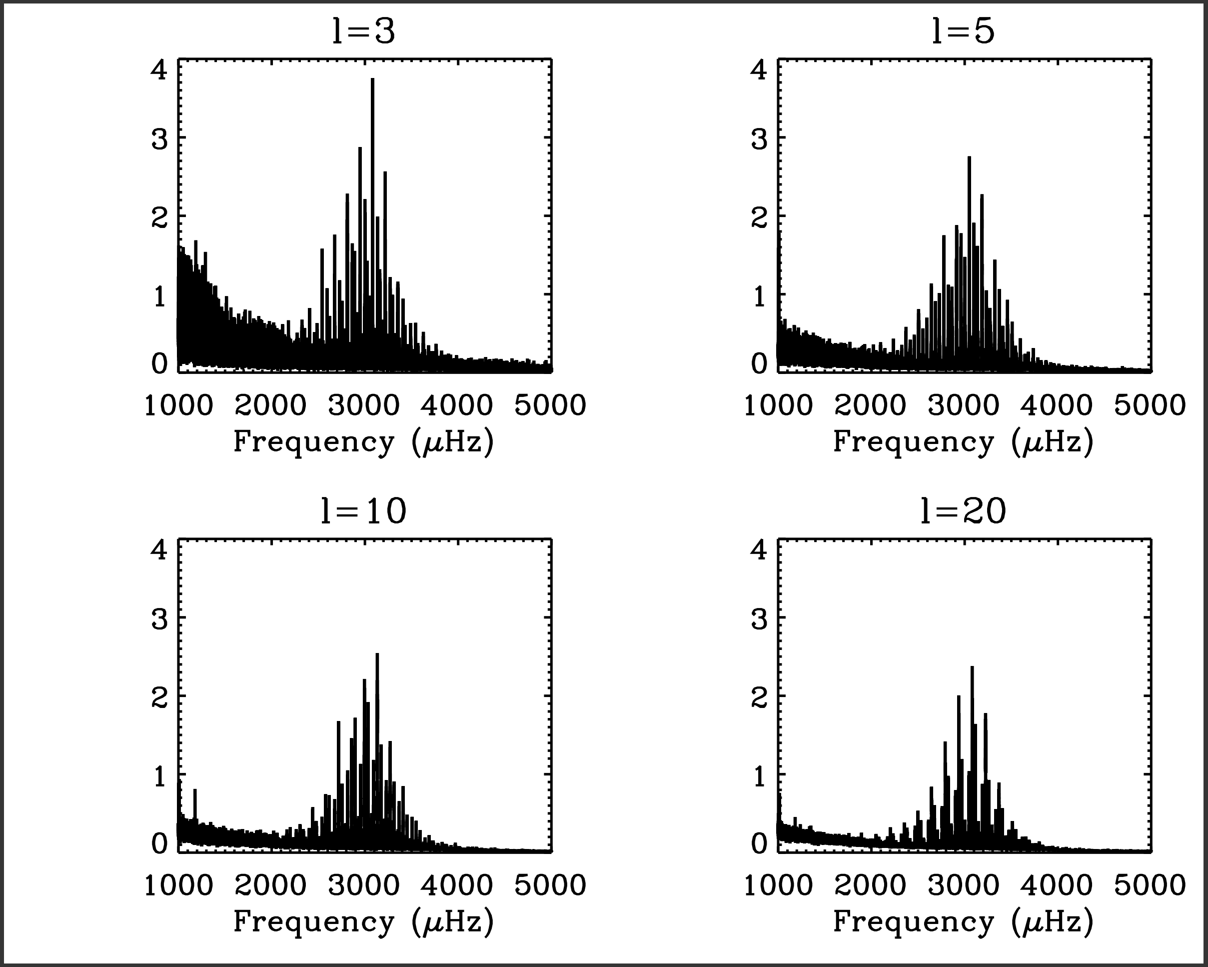
- Temporal aliasing above 4500 μHz: signature of a cycle with a 2-min sampling corresponding to the astrometric program sequences

- m-ν diagram for l=90 for 2 consecutive orders (with leakage from other degrees)



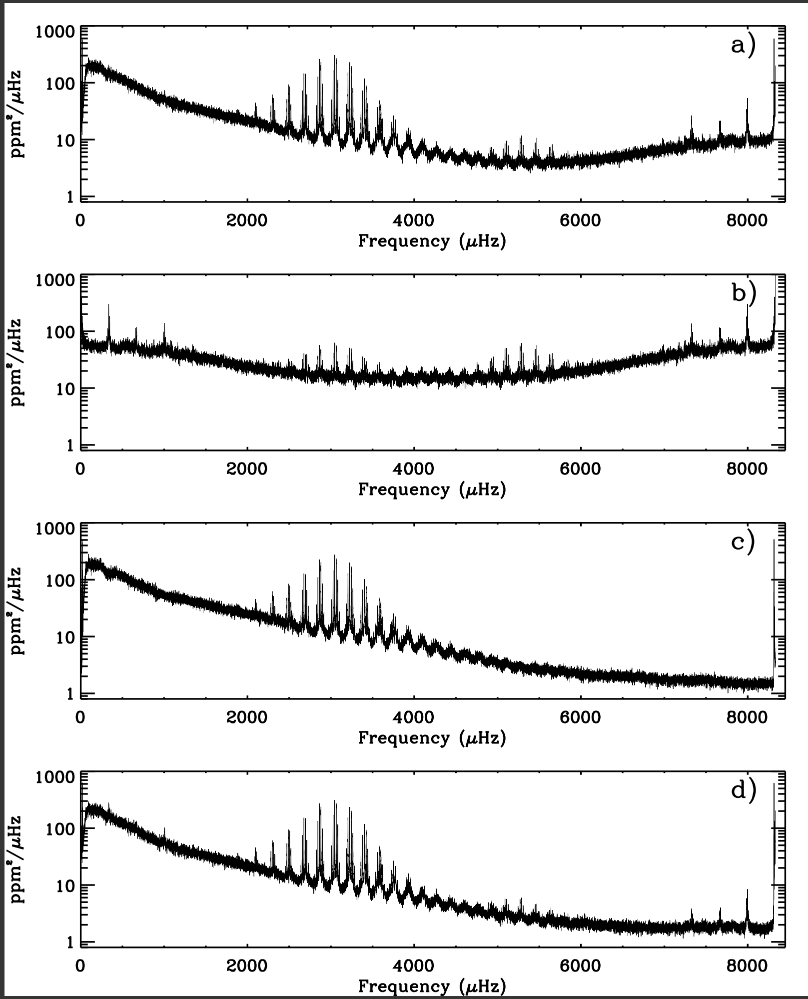
S-like lines
=
Differential rotation

Examples of SODISM Power Spectra



Impact of CCD persistence in SODISM data

Rotation-correction, m-averaged spectrum of l=50 in 4 cases:



All points (remanent and non-remanent)
After correction of CCD persistence

Remanent points only
After correction of CCD persistence

Non-remanent points only

All points
After correction of CCD persistence
After gap-filling (5 minutes)

Peak-fitting Pipeline: Spherical Harmonics and Leakage Matrix

- Isolate individual mode (l, m) with spatial filters: spherical harmonics
- Observing only ½ the Sun: correlations between different (l, m) modes
- Imperfect isolation of the individual modes: *leakage matrix* $C^{\ell,\ell'}_{m,m'}$
- For a given (l,m) mode, its power spectrum ($y_{l,m}$) corresponds to the sum over sevral modes ($x_{l,m}$):

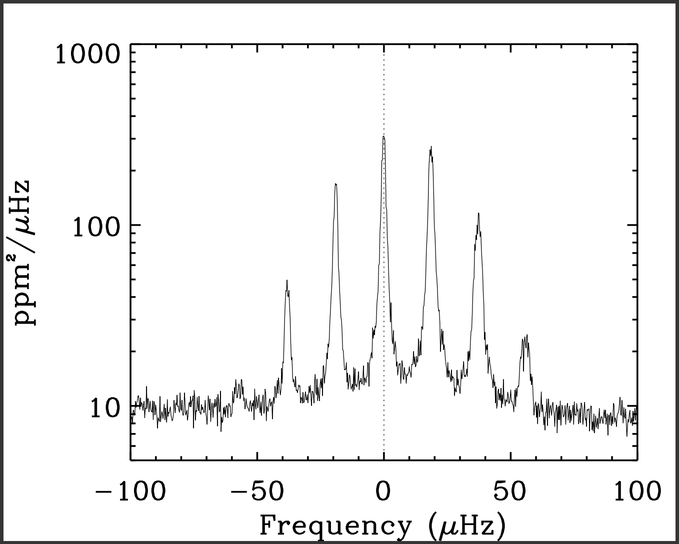
$$y_{\ell,m}(\nu) = \sum_{\ell',m'} C^{(\ell,\ell')}_{m,m'} x_{\ell',m'}(\nu) \quad \text{with} \quad C^{\ell,\ell}_{m,m} = 1$$

$C^{\ell,\ell'}_{m,m'}$ contribution from each one of the modes (l',m') to a given mode (l,m)

- 2 types of leakage:
  - m-leakage: correlation between different m-components with equal l
  - l-leakage: correlation between different degrees l

Spatial Contamination and Leakage Asymmetry

- Rotation-corrected, m-averaged spectrum of l=50, n=10 (dotted line) centered on zero
- First spatial leaks Δl= ±3 visible



- Clear leakage asymmetry:
  - Such asymmetry mentioned by Korzennik (1998) in MDI intensity data but remained unexplained.
  - Hill & Howe (1998) discussed that an error in the image radius can lead to a leakage asymmetry around the target mode.
  - A proper understanding of all the instrumental effects on the geometry of SODISM images is required to build a proper leakage matrix.

Peak-fitting Pipeline: Fitting Procedure

- Fit all the multiplets m (2l+1) of a given degree l simultaneously

- Mode component described by an asymmetric Lorentzian profile:

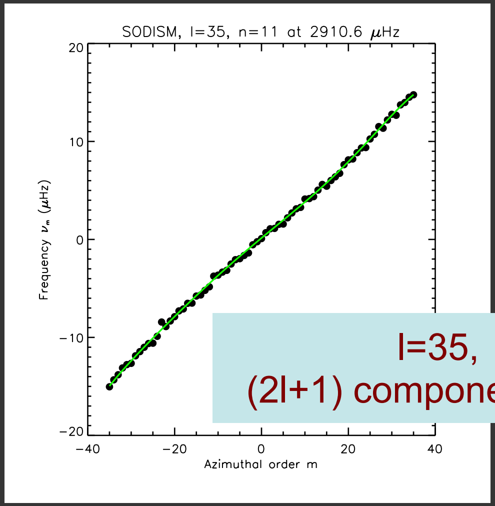
$$\boxed{\mathrm{M}_{n,\ell,m}(\nu) = \frac{A_{n,\ell,m}(\Gamma_{n,\ell}/2)^2}{(\Gamma_{n,\ell}/2)^2 + (\nu - \nu_{n,\ell,m})^2}}$$

- Central frequency $\nu_{n,l,m}$ for each m-component (2l+1) represented by:

$$\boxed{\nu_{n,\ell,m} = \nu_{n,\ell} + \sum_{i=1}^{N} a_i(n,\ell) P_i^{\ell}(m)}$$

where $\nu_{n,l}$, the unperturbed central frequency of the multiplet

$P^l(m)$, Clebsch-Gordon polynomials ($P^l(l)=l$)
$a_i(n,l)$'s, shift in frequency induced mainly by the internal rotation.
9 $a_i(n,l)$'s are fitted



l=35,
(2l+1) components = 71

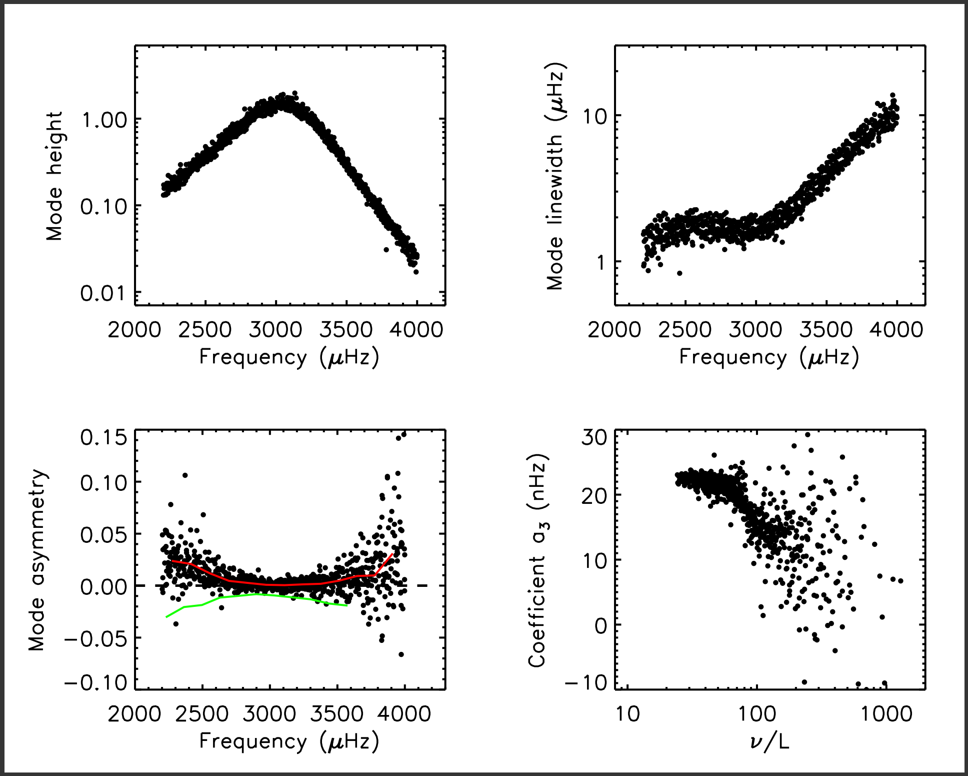
Fitted p-Mode Parameters from PICARD/SODISM Data

- Modes up to l=100 fitted between 2200 and 4000 μHz
- ~ 800 modes successfully fitted

Mode height

Mode asymmetry

In green, negative asymmetry from velocity GOLF



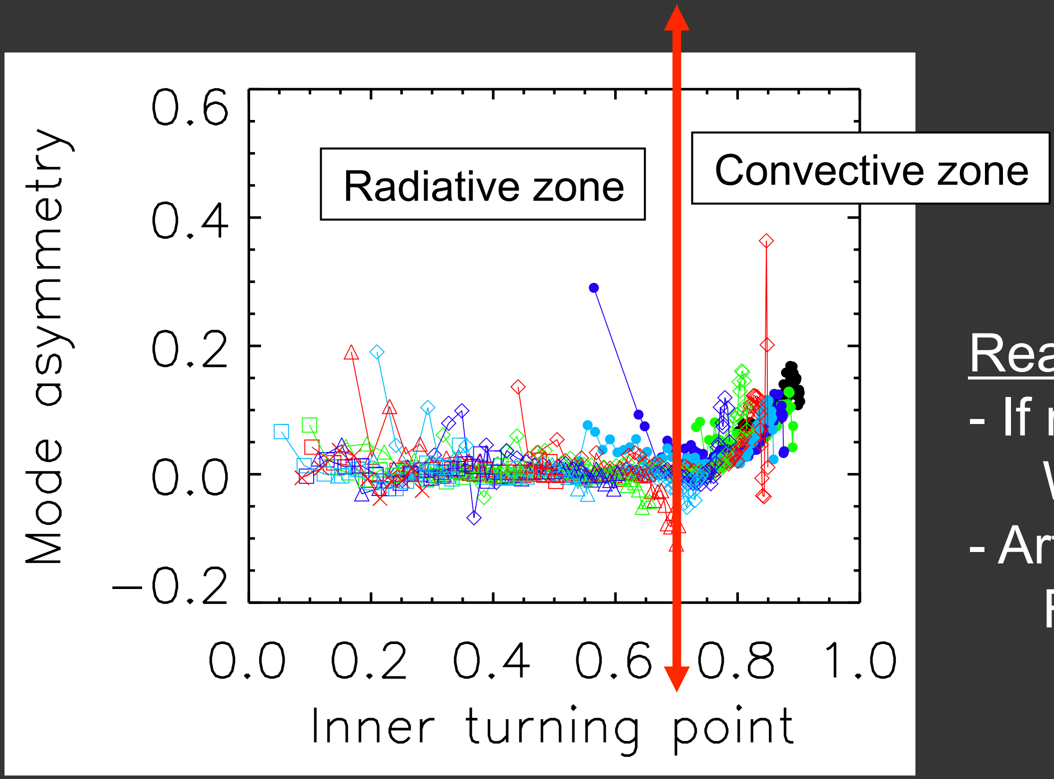
Mode linewidth

≈ to mode damping

Mode a3 splitting coefficients

Gradient, typical signature of the tachocline

Interesting behavior of the mode asymmetry

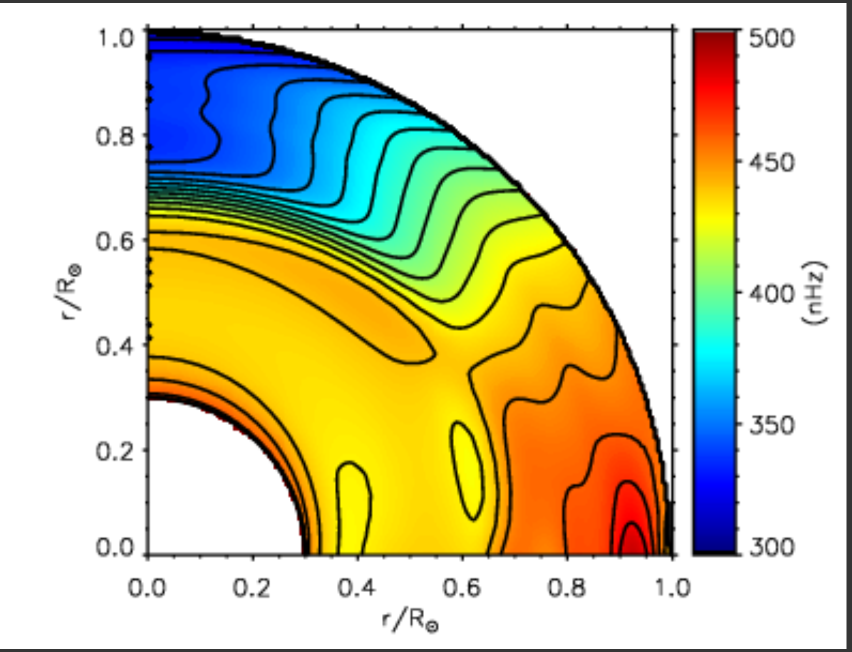


<u>Real or artefact?</u>

- If real,
  What is the physical reason?
- Artefact:
  From mode leakage?

Internal Solar Rotation Rate from PICARD

- Regularized Least-Square inversion: splittings l=1-99 (9 a-coefficients)
- Tachocline: Steep gradient at base of the convection zone $0.7R_{\odot}$
- Inferred rotation rate similar to one previously obtained from velocity data
  - radial gradient close to the surface
  - latitudinal differential rotation through convection zone
  - radiative interior roughly rigid (435±5 nHz)



- Preliminary results very encouraging
- Currently working to:
  - extend peak-fitting analysis towards higher l
  - increase the number of fitted a-coefficients

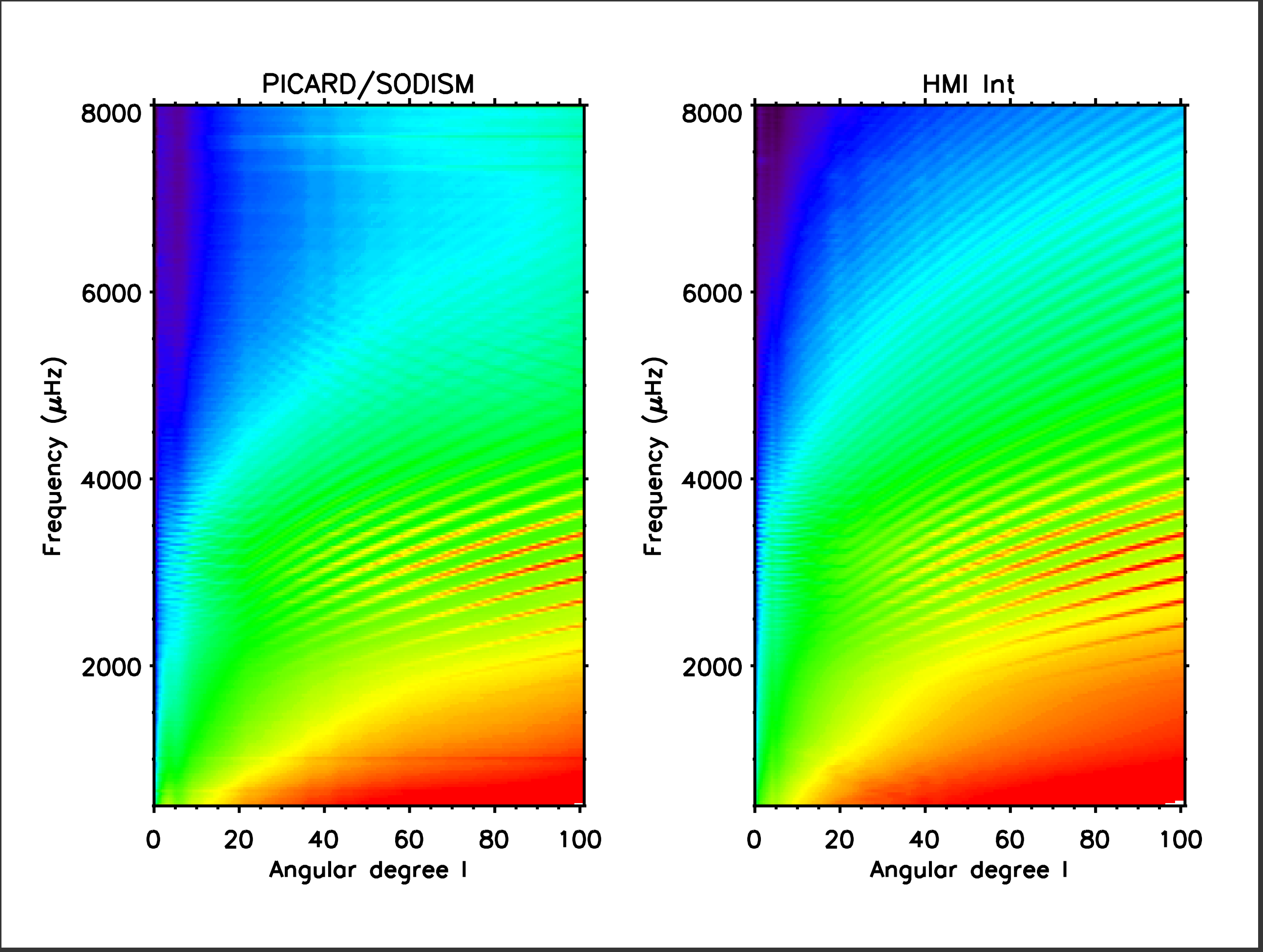
=> Improved resolution

Comparison with HMI Intensity

- HMI onboard SDO, launched in Feb. 2010 (NASA mission)
- Record both velocity and intensity images (4096^2 pixels)
- HMI continuum images at 607 nm reduced to 256^2 pixels (as HMP)
- Same 209-day period (2001/04/16-2011/11/10)
- Duty cycle 98.0% (Δt=45s) (PICARD for same period, 74.4%, Δt=60s)
- HMI data processed through the same pipeline as SODISM images

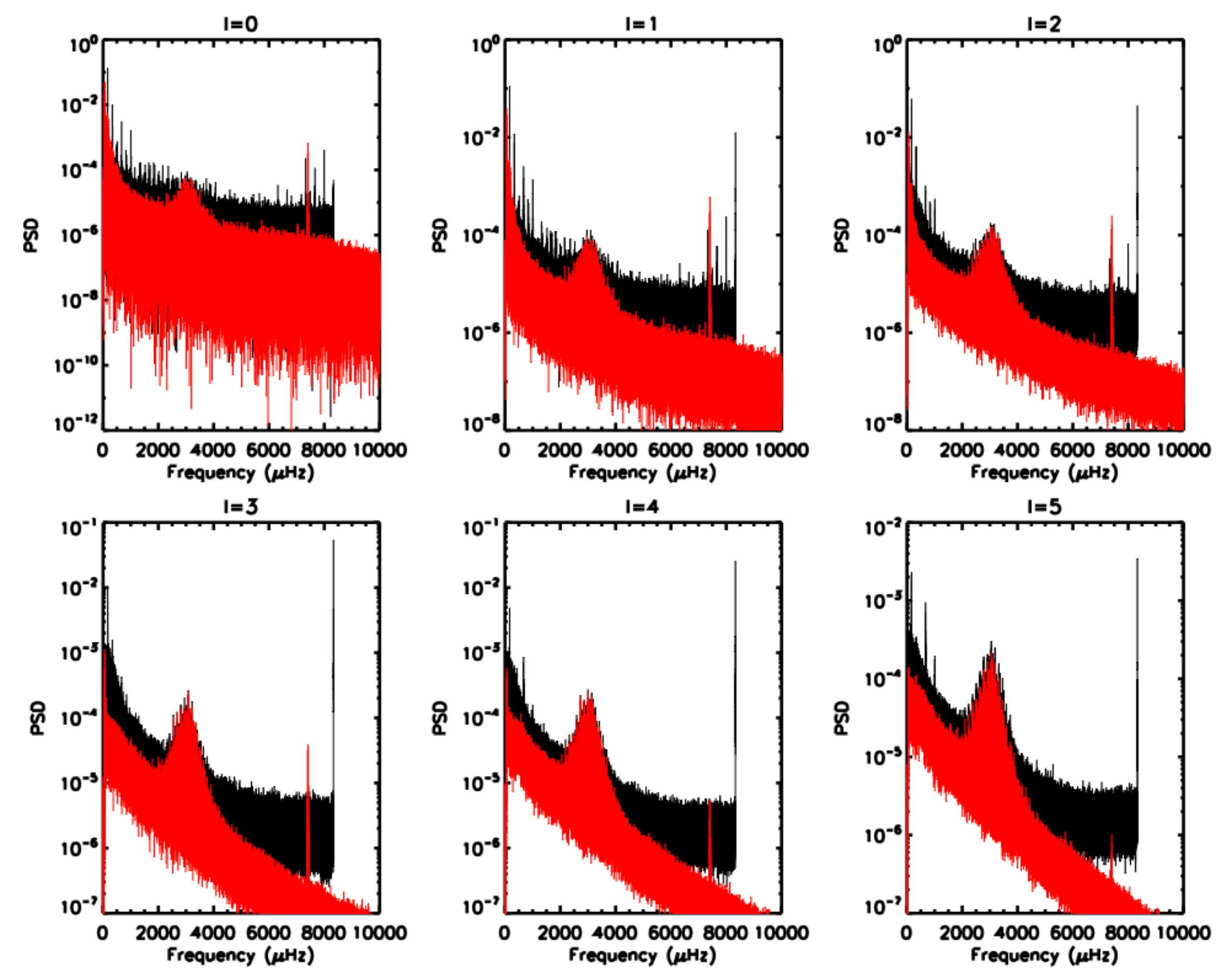
SODISM and HMI Intensity l-nu Diagram

2011-04-16 / 2011-11-10



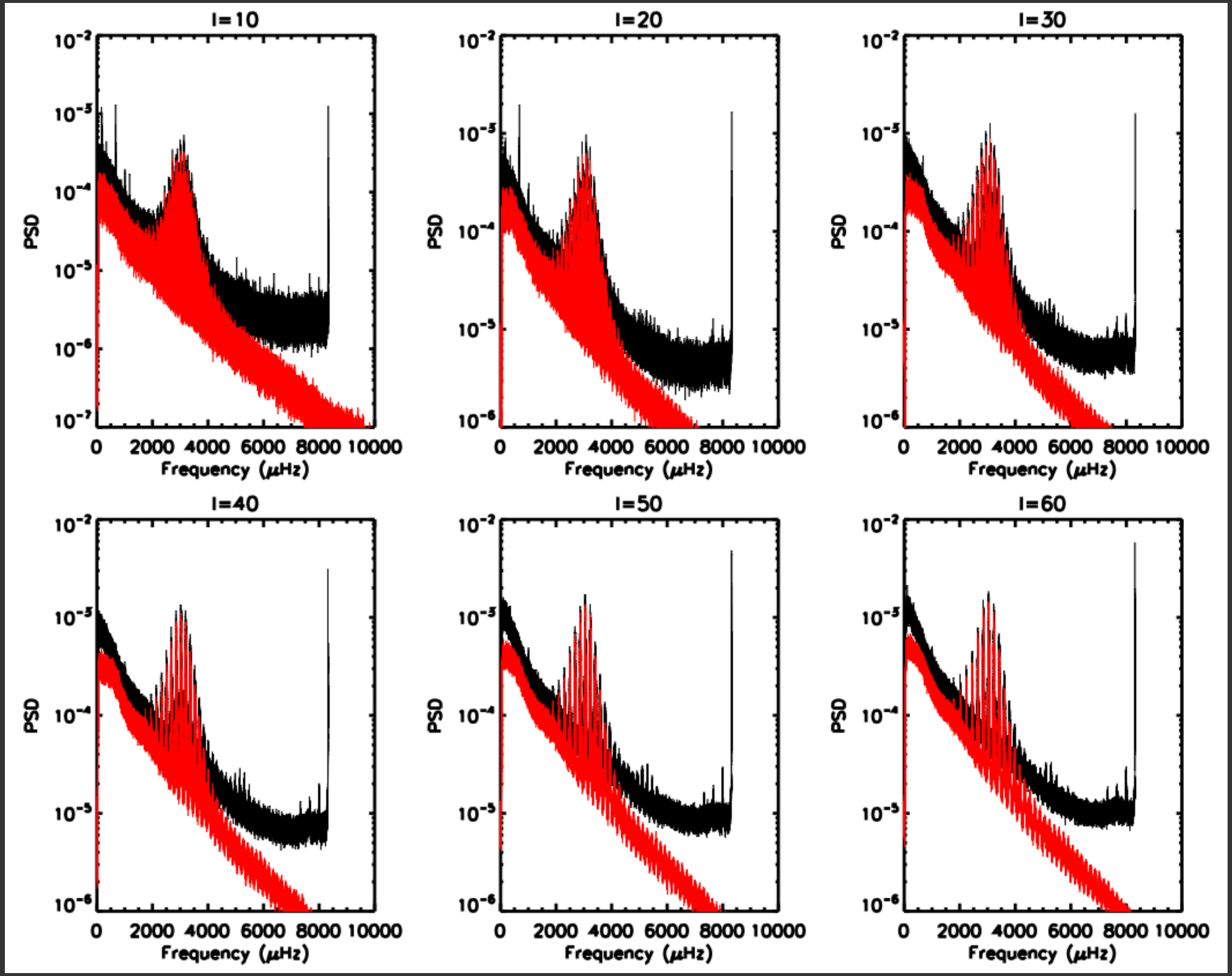
Examples of power spectra
low-angular degrees

SODISM
HMI Int.



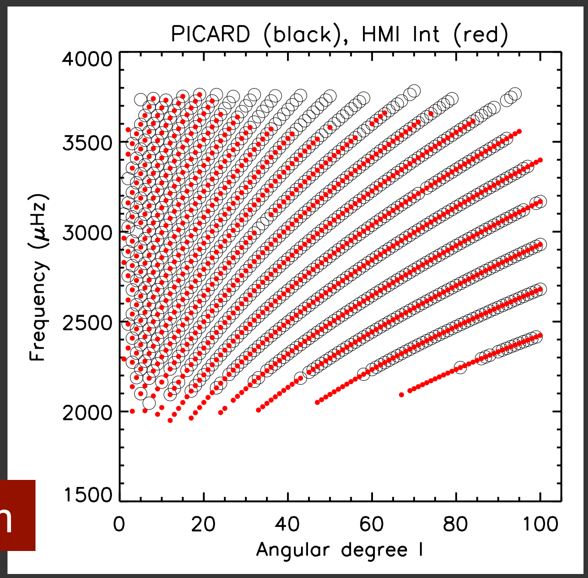
Examples of power spectra
medium-angular degrees

SODISM
HMI Int.



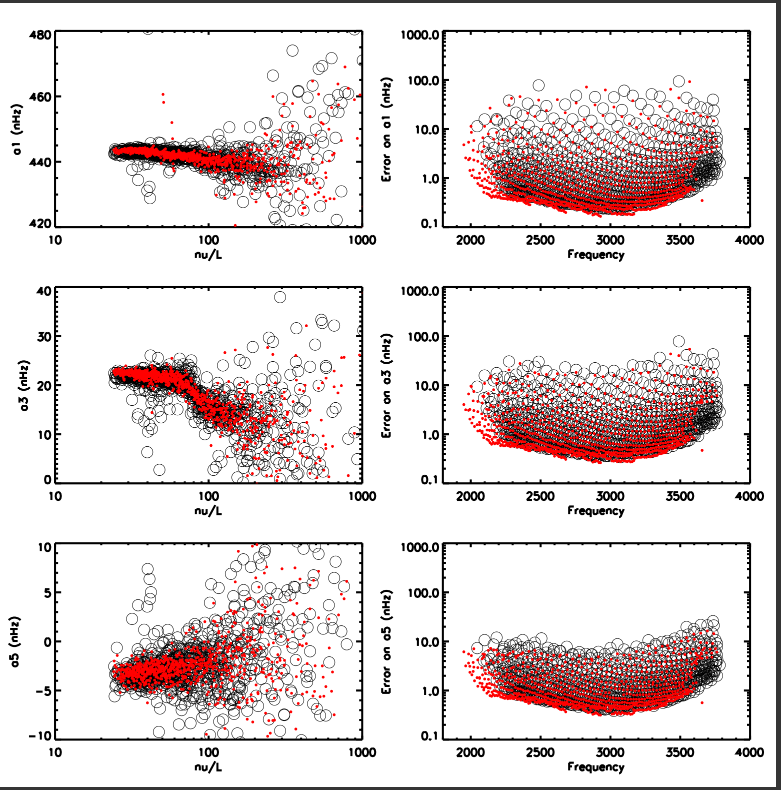
Fitted p-mode parameters SODISM and HMI int.

SODISM
HMI Int.

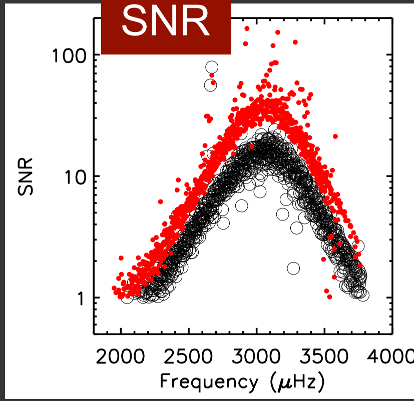


l-v diagram

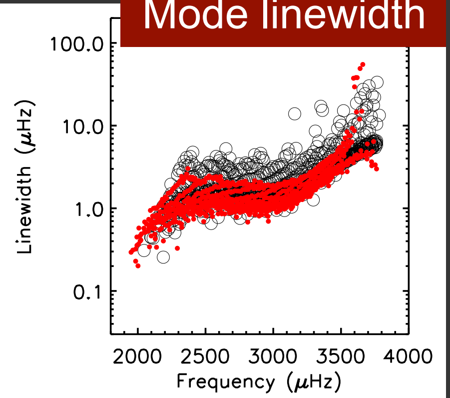
Splitting coefficients and errors



SNR

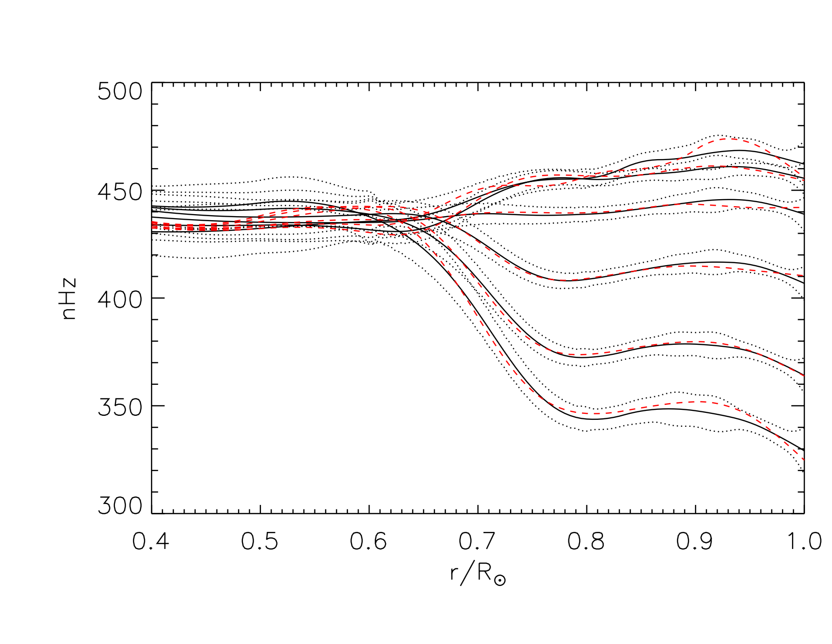


Mode linewidth



Rotation Rate from SODISM and HMI Int.

- Internal rotation rate as a function of the fractional solar radius
  - From radiative interior up to photosphere
  - Latitudes of 0°, 15°, 30°, 45°, 60°, and 75°



HMI Int.: Black solid lines (with 1σ errors)
SODISM: Red dashed lines

- SODISM and HMI Int. compatible within 1σ for all latitudes and depths

- Main differences found very close to surface
  - ➢ higher l modes needed to increase resolution
  - ➢ local maximum found at 0.93R⊙ at equator (0°) in SODISM data (Corbard et al. 2013) less pronounced in HMI Int. data

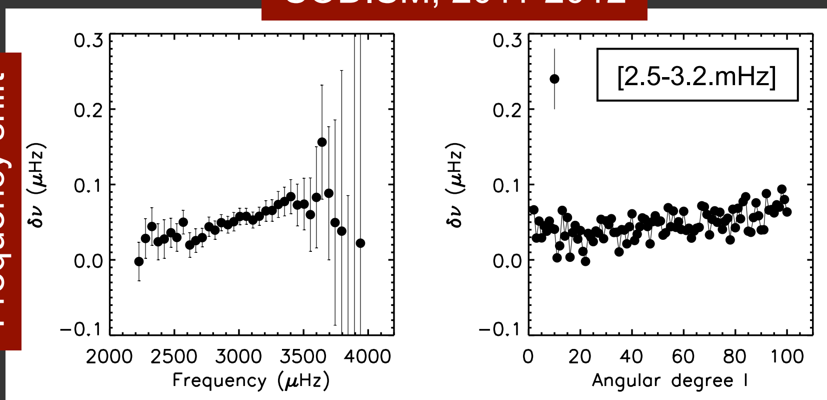
Solar Variability Observed by SODISM

- Solar frequencies vary with solar activity:

Higher activity == Larger frequencies

SODISM, 2011-2012

Frequency shift

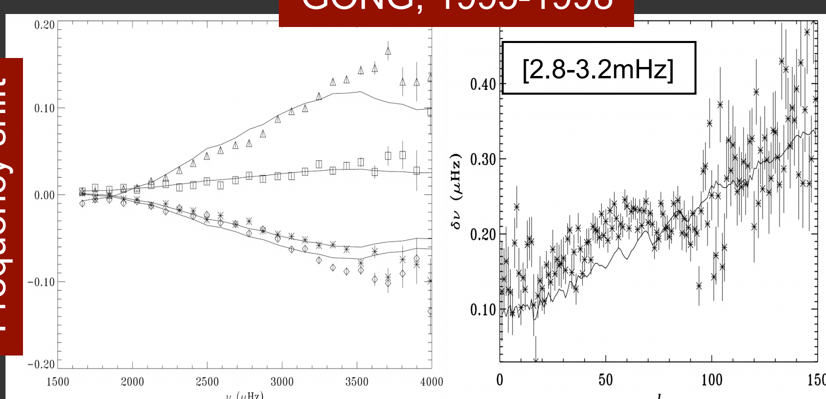


- Related to changes in the outer layers of the Sun

- Close temporal and spatial correlation with the surface magnetic field distribution

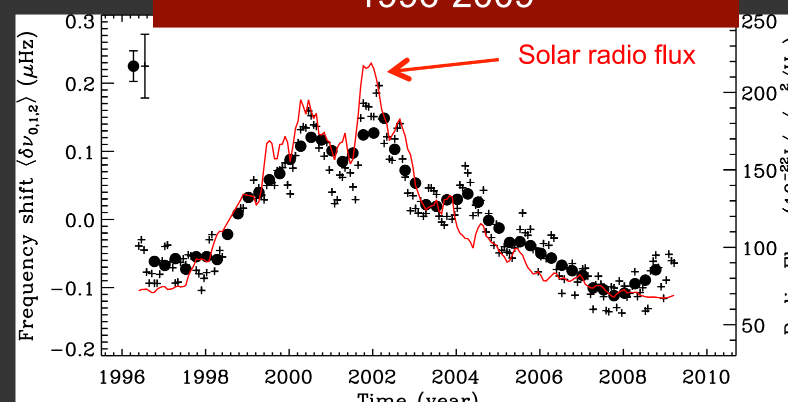
GONG, 1995-1998

Frequency shift



(Howe et al., 1999)

GOLF, solar frequencies *vs.* time 1996-2009



(Salabert et al., 2009)

Conclusions

1. Calibration of SODISM helioseismology data is a difficult task
   - Low orbit, interruptions, instrumental problems: CCD persistence, …

2. First helioseismic analysis of the medium-l HMP continuum SODISM data
   - Oscillation mode parameters for a wide range of eigenmodes
   - Results consistent with what know from previous studies in velocity

3. First comparison with HMI continuum intensity data
   - Shows we reached a first satisfactory level of calibration
   - Results compatible within 1σ

Future and Scientific Perpectives

- Need to properly model the leakage matrix in order to fit higher l
- Still working on improving our calibration pipeline
  - Comparisons between SODISM and HMI needed for cross-calibration

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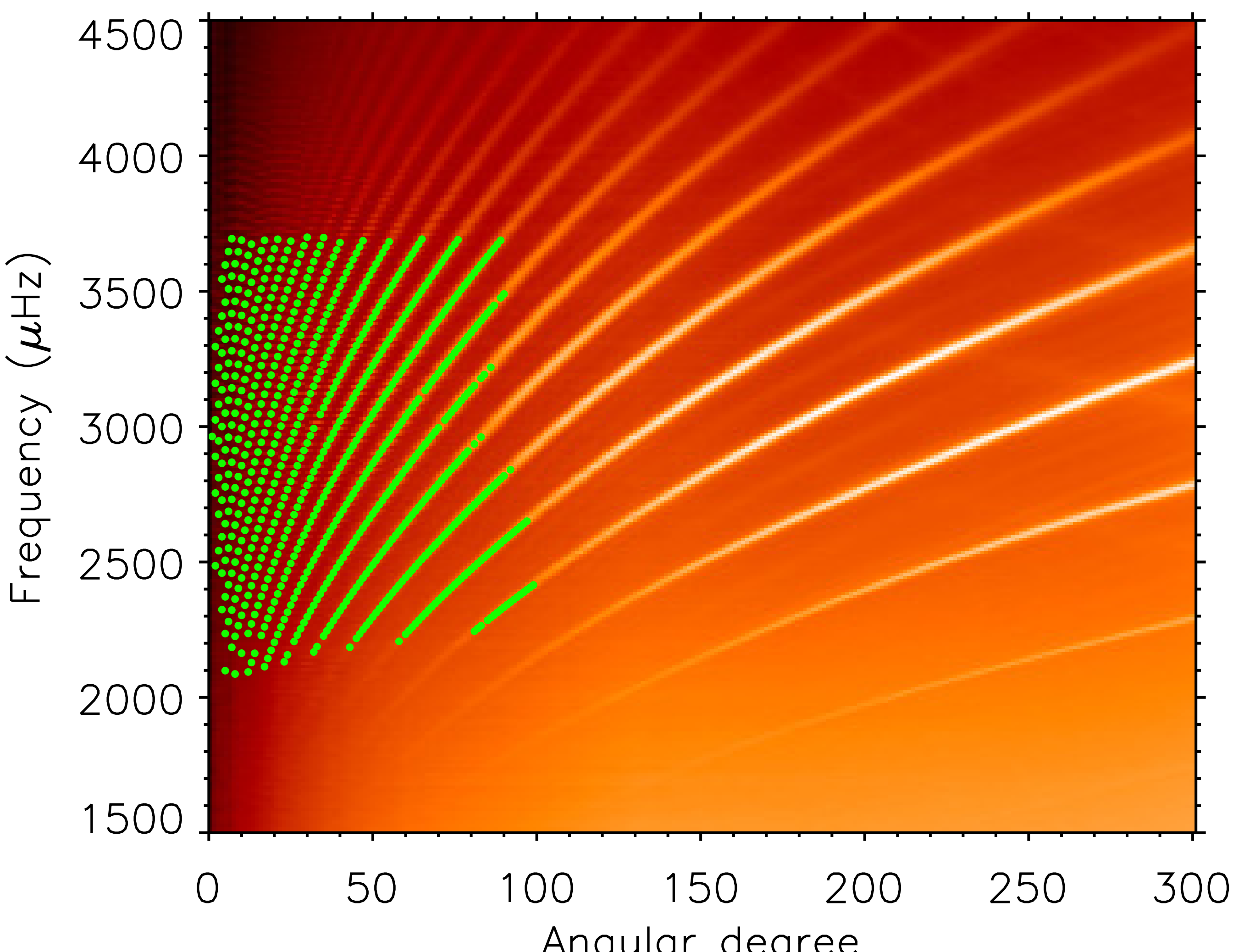
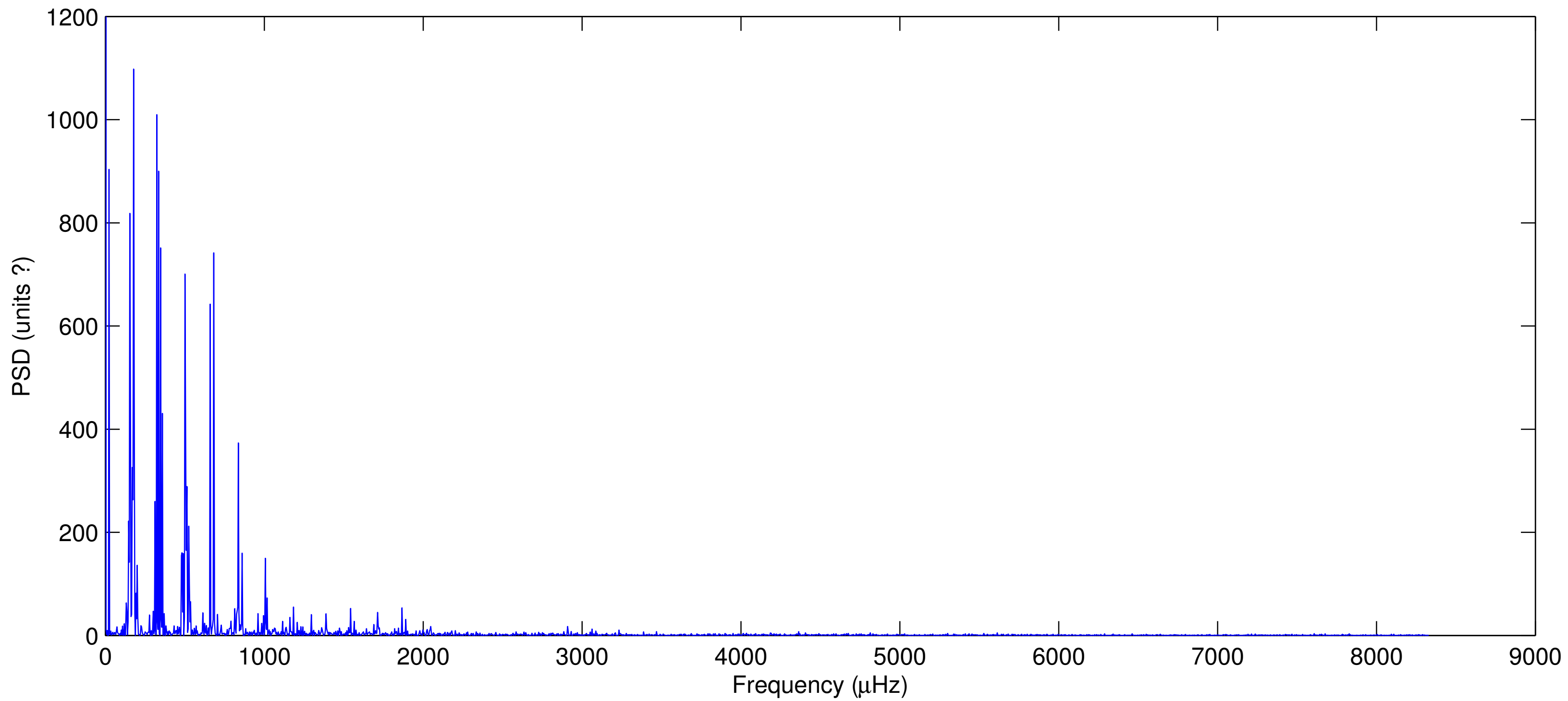
- In-depth comparison between SODISM, HMI intensity and velocity
- Cross-calibration and systematics between the different observations
- Development of tools and collaborations (NSO, Stanford…) for local helioseismology:
  - Time-distance analysis, Ring-diagram analysis
  - Multi-instrument comparisons
  - …
- SODISM helioseismic data as an solar activity proxy

Thank you!



Frequency (μHz)
4500
4000
3500
3000
2500
2000
1500
0
50
100
150
200
250
300
Angular degree


1200
1000
800
600
400
200
0
PSD (units ?)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Frequency (μHz)