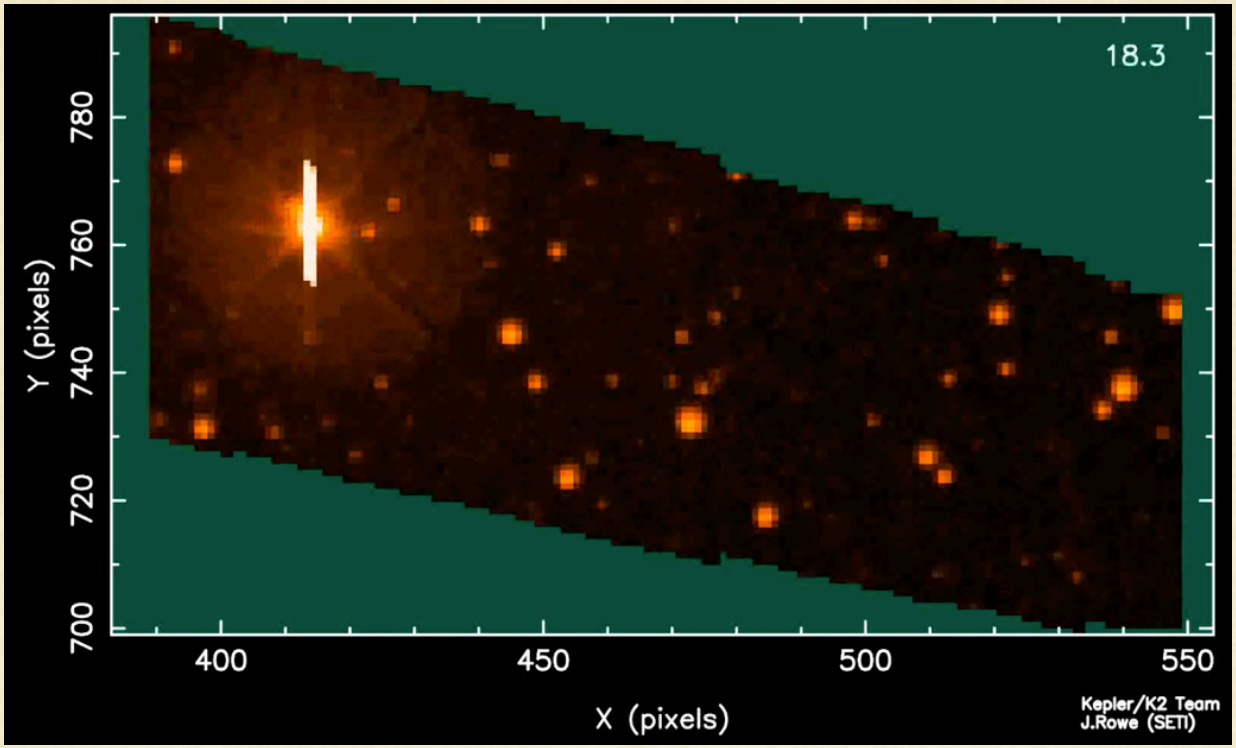
K2 Observations of Neptune



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An Interdisciplinary Project

- Scientific objectives
  - Oscillations of Neptune (seismology)
  - Atmospheric Dynamics
  - Oscillations of the Sun seen as a *Kepler* star
- Large group of support
  - **PIs:** J. Rowe (data), A. Simon (atmosphere), P. Gaulme (seismo).
  - T. Bedding, O. Benomar, E. Corsaro, G. R. Davies, S. Hale, R. Howe, R. A. Garcia, D. Huber, S. Mathur, T. Appourchaux, P. Boumier, J. Jackiewicz, J. Leibacher, B. Mosser, F.-X. Schmider, H. B. Hammel, J. J. Lissauer, M. S. Marley, A. A. Simon, W. J. Chaplin, Y. Elseworth, J. A. Guzik, N. Murphy, V. Silva Aguirre, T. Barclay, S. L. Casewell, J. J. Fortney, J. E. Gizis, R. Morales-Juberias, G. S. Orton, M. H. Wong
- Imaging follow-up
  - Keck, HST

Outline

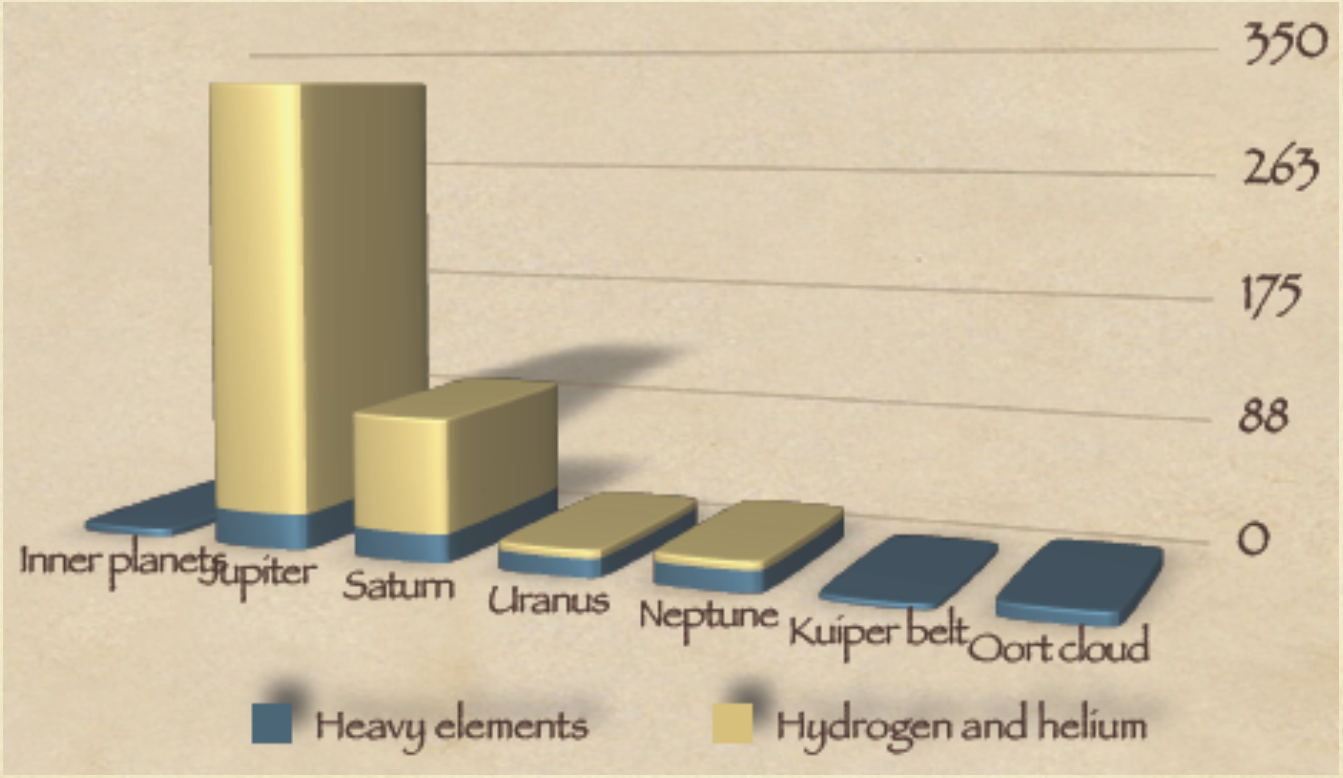
- Seismology of Giant Planets
  - State of the art: Jupiter and Saturn
  - The ice giants
  - K2 data
- The Sun as a star
  - First non-direct detection of solar oscillations with photometry
  - Global asteroseismic measurements
  - Peak-bagging

Part 1:

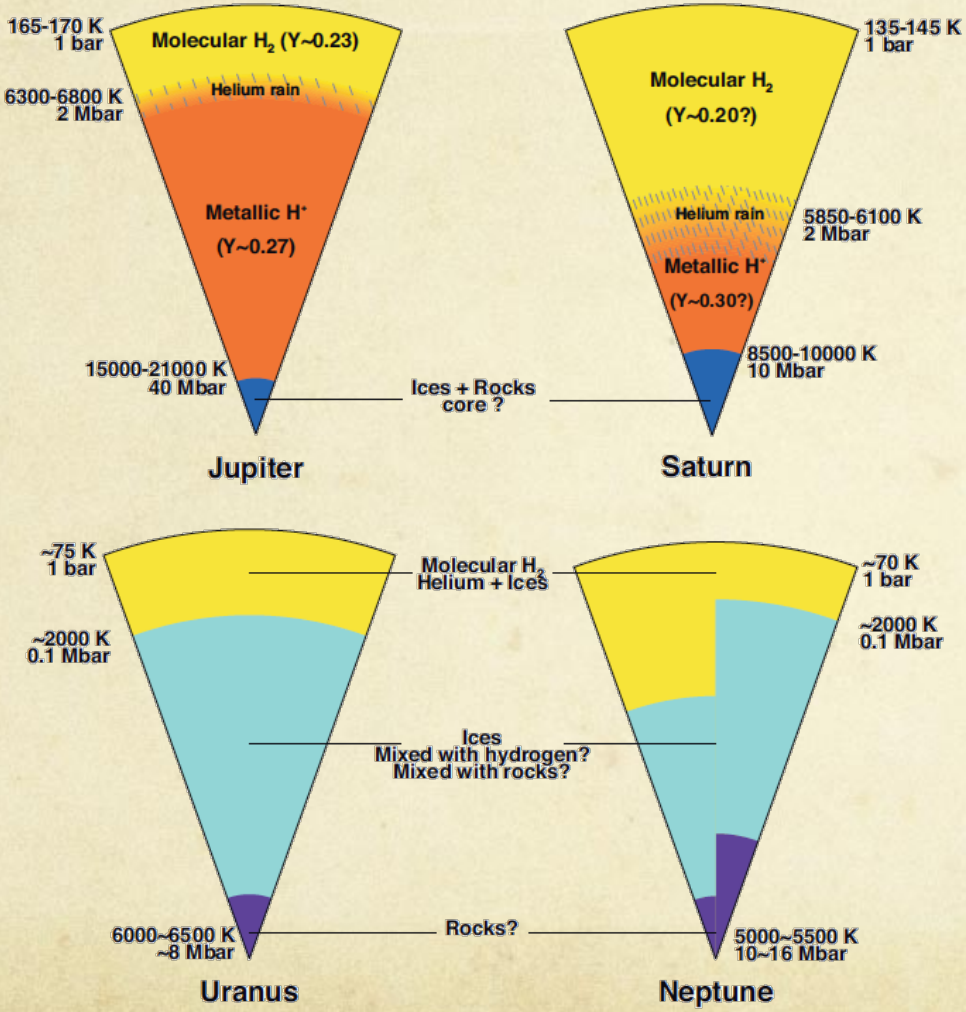
Seismology of the giant planets

Why are we interested

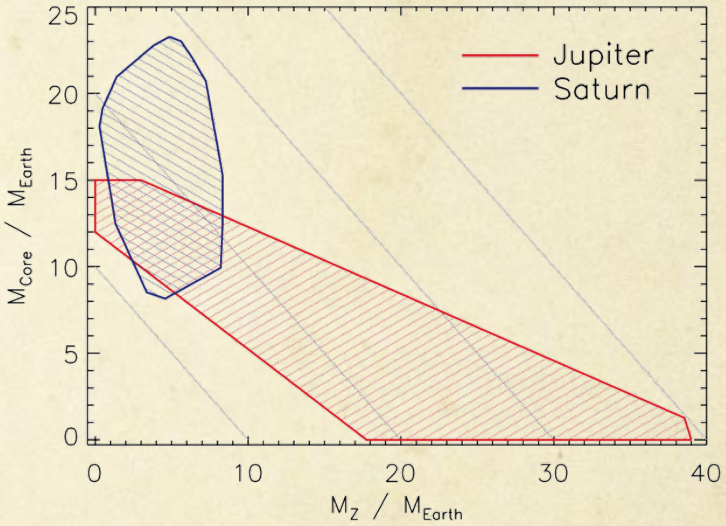
- Solar System planets: Jupiter represents 71% of total mass, Saturn 21%



Why are we interested



- Heavy elements
  - Jupiter & Saturn



Observational techniques

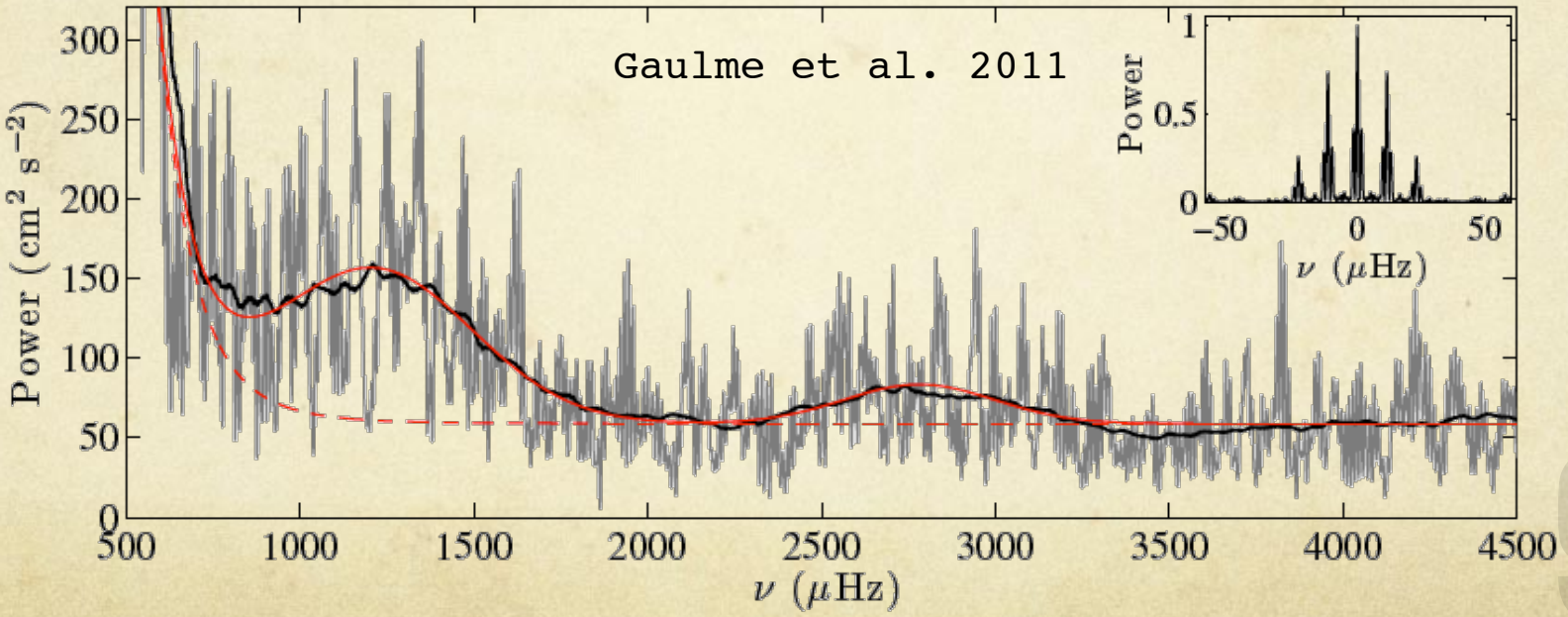
Frequencies: $\nu_{max} \approx [1000, 2500]$ μHz, $\Delta\nu \approx [110, 220]$ μHz

Observational techniques

- Photometry of thermal emission (mid-IR)
  - Equivalent to visible helio/asteroseismology
- Doppler spectrometry
  - Tracking motions in atmosphere, as GONG, SOHO MDI, SONG, etc.
- Photometry of reflected solar light
  - Distorted mirror

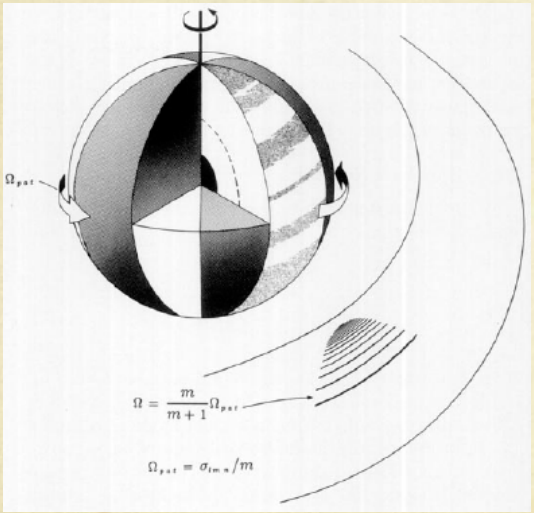
Giant planets do oscillate

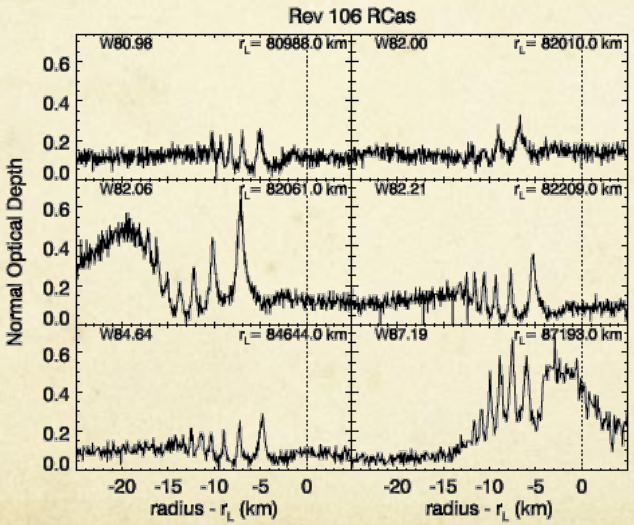
- Jupiter
  - Dedicated imaging spectrometer SYMPA (Schmider et al. 2007)
  - First clear detection of Jupiter's p-modes (amplitudes < 50 cm/s)
  - No mode identification though (noise, window)

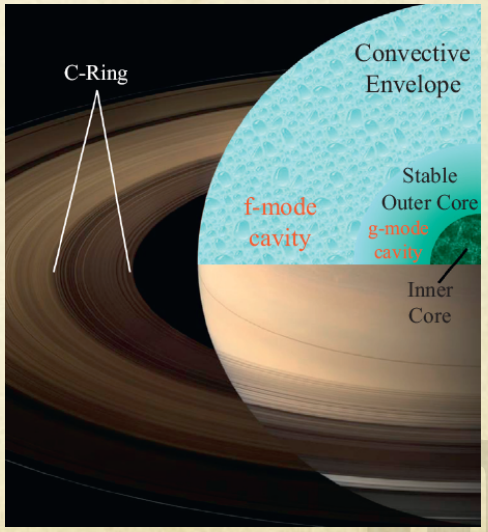


Giant planets do oscillate

- Saturn
  - Rings act as a seismograph for f modes (Marley & Porco 1993)
  - Stellar occultation by Cassini (Hedman & Nicholson 2013)
  - Stable region in deep interior? (Fuller 2014)

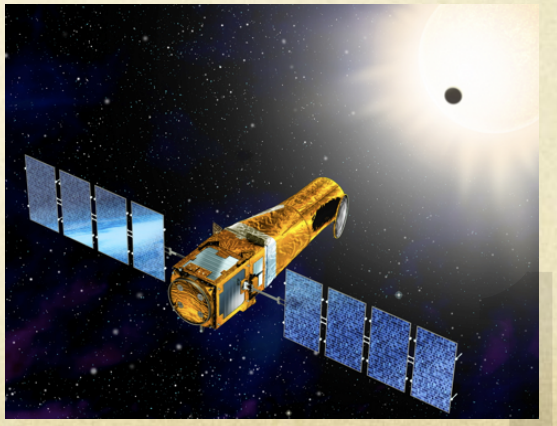






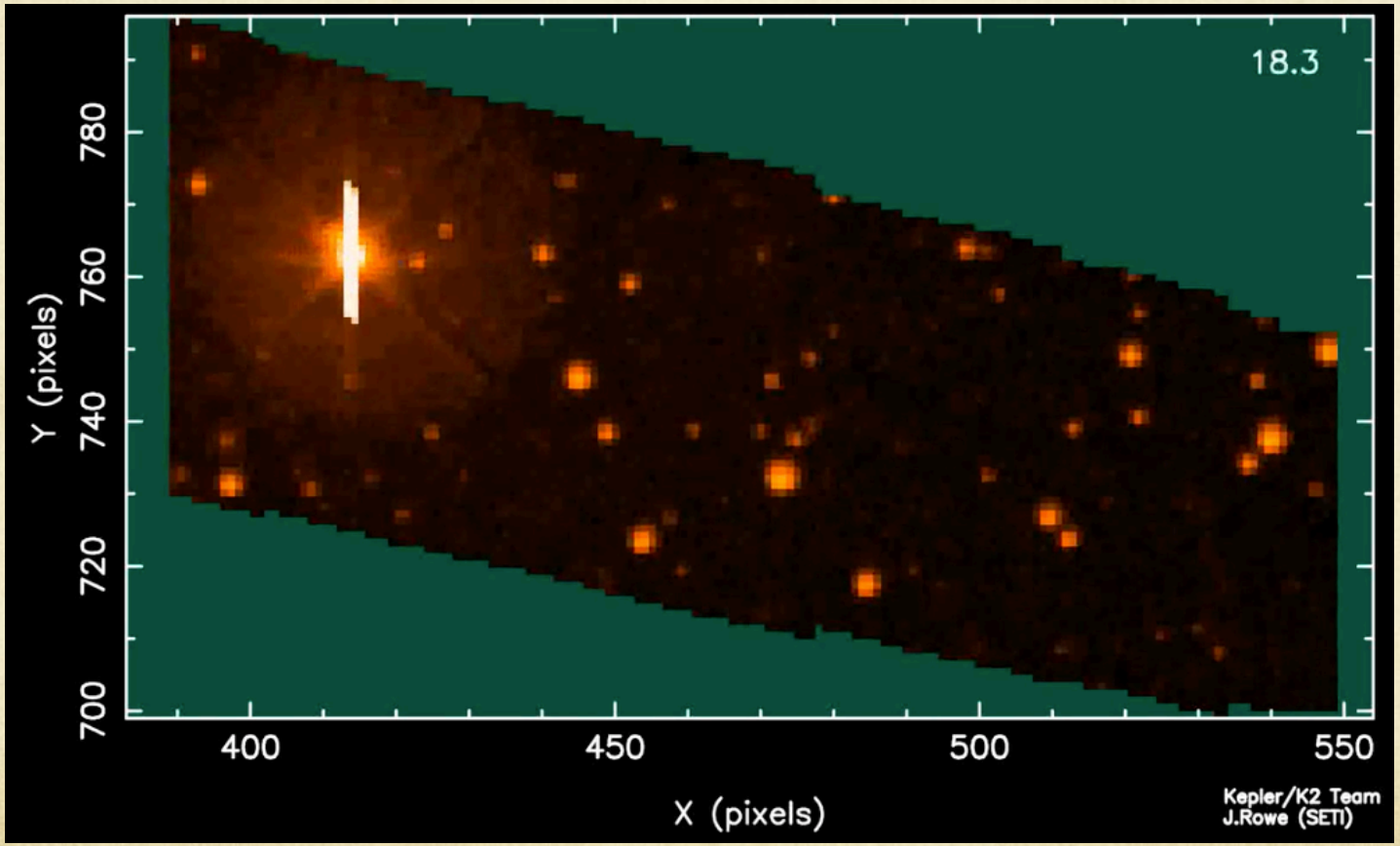
Visible photometry for giant planet seismology

- Micro-photometry era
  - CoRoT, Kepler for asteroseimology
- Geometric distortions for radial mode (l=0)
  - $\delta\Phi/\Phi = 2\delta R/R$ and $\delta R = c_s\, u/g$,
  - 1 m s^{-1} velocity ⇔ 200 m amplitude
    ⇔1 ppm fluctuations on reflected flux
- Drawbacks/unknowns
  - Cloud reaction (Gaulme & Mosser 2005)
  - Mode identification noise sensitive
  - Noisier spectra in photometry vs Doppler (cf helioseismology)
  - Ice giants vs. gas giants



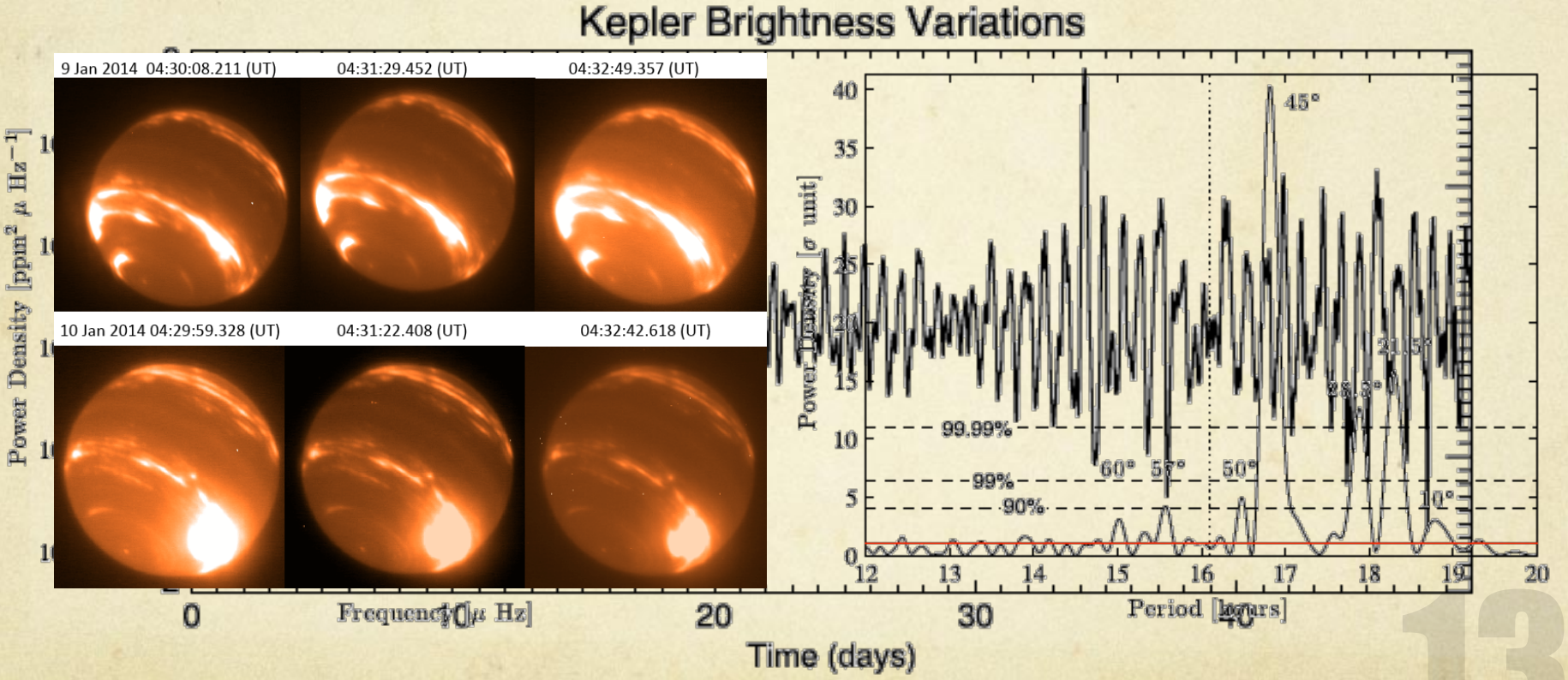
K2 data

- 49 days at short cadence (1 measurement per minute)

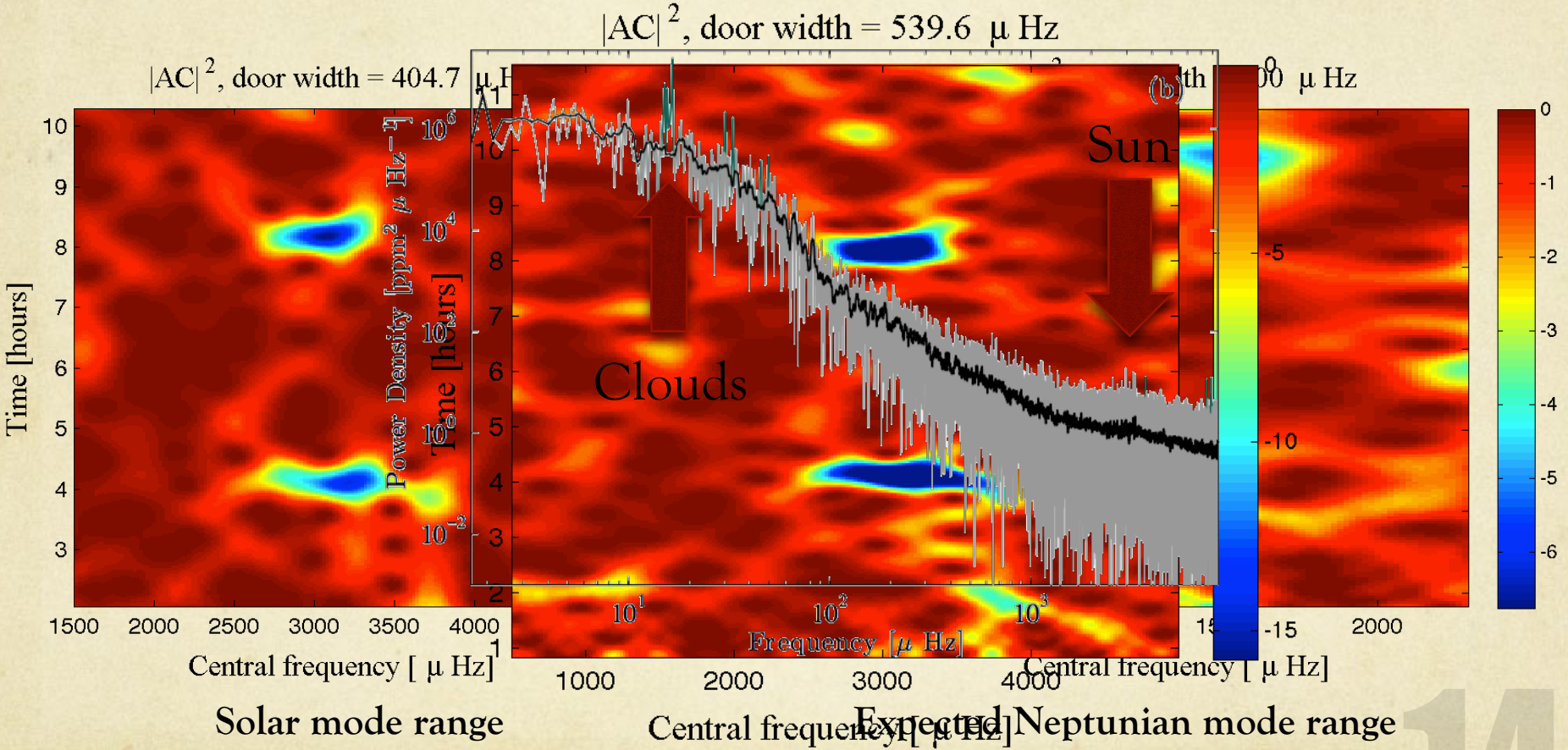


K2 data

- Cloud features: peak-to-peak fluctuation of about 2%



Vain search for Neptune oscillations

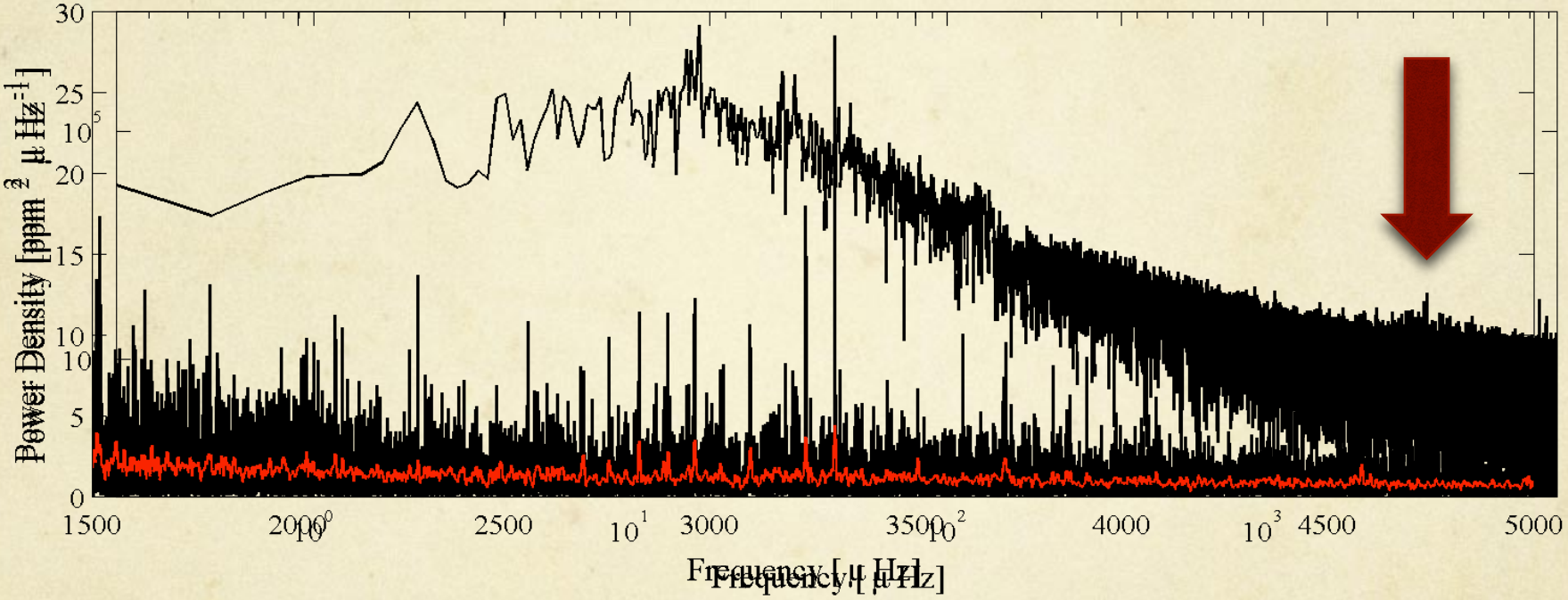


Part 2:

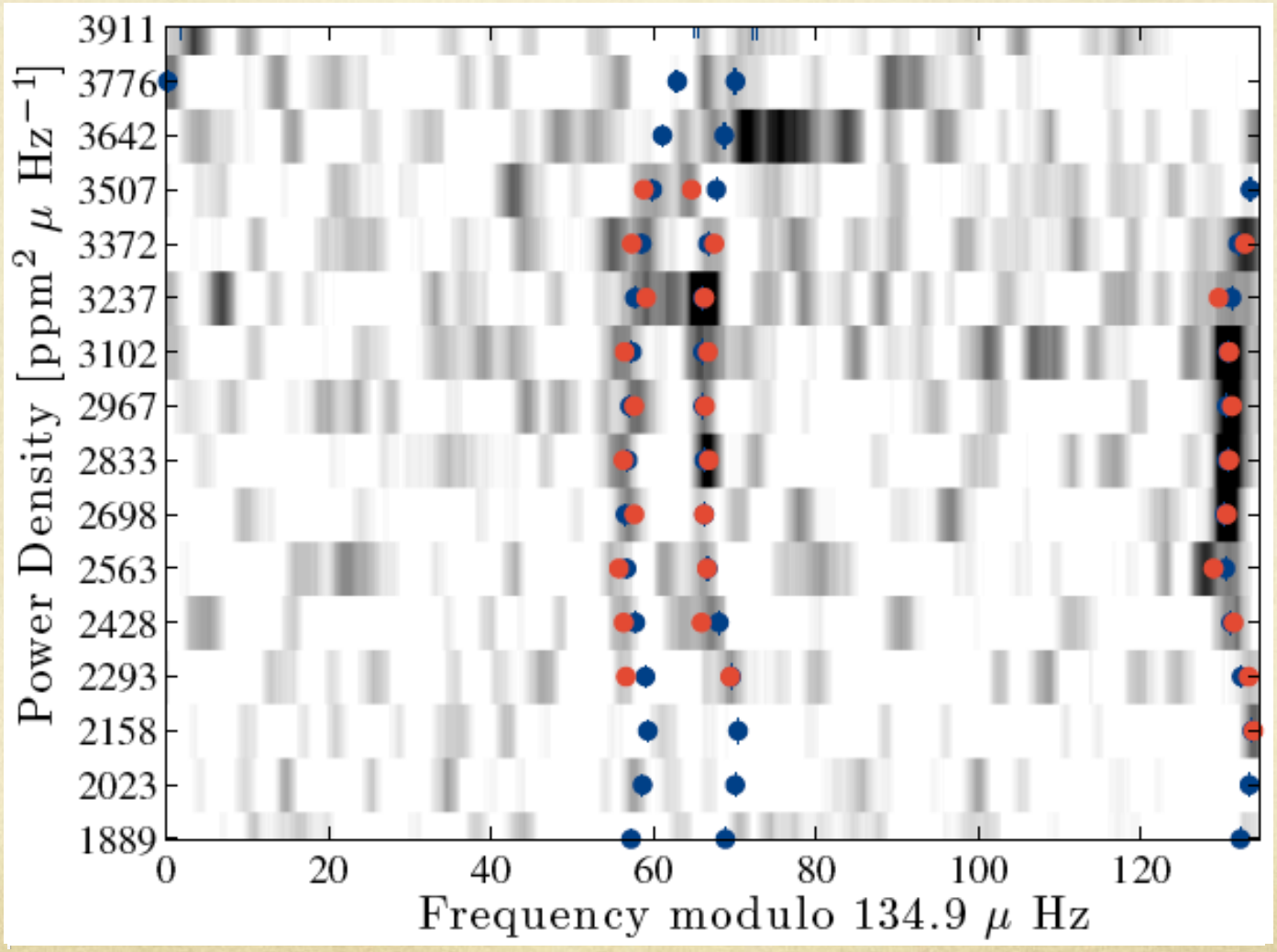
Here comes the Sun

Here comes the Sun

- First non-direct detection of solar oscillations with photometry



Here comes the Sun



The Sun as a Kepler star

- Global asteroseismic approach

$$\frac{R}{R_\odot} = \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

$$\frac{M}{M_\odot} = \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

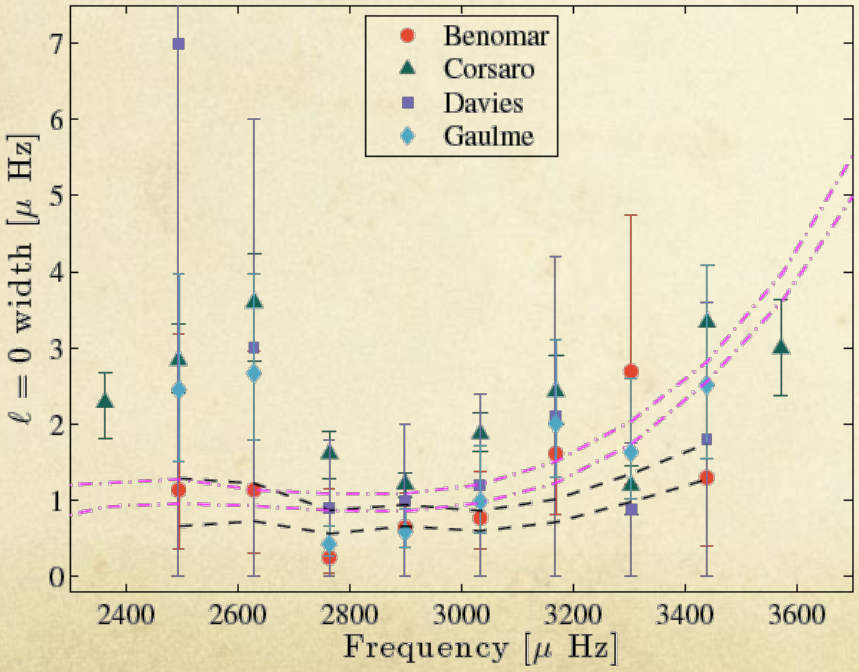
Global Asteroseismic Parameters

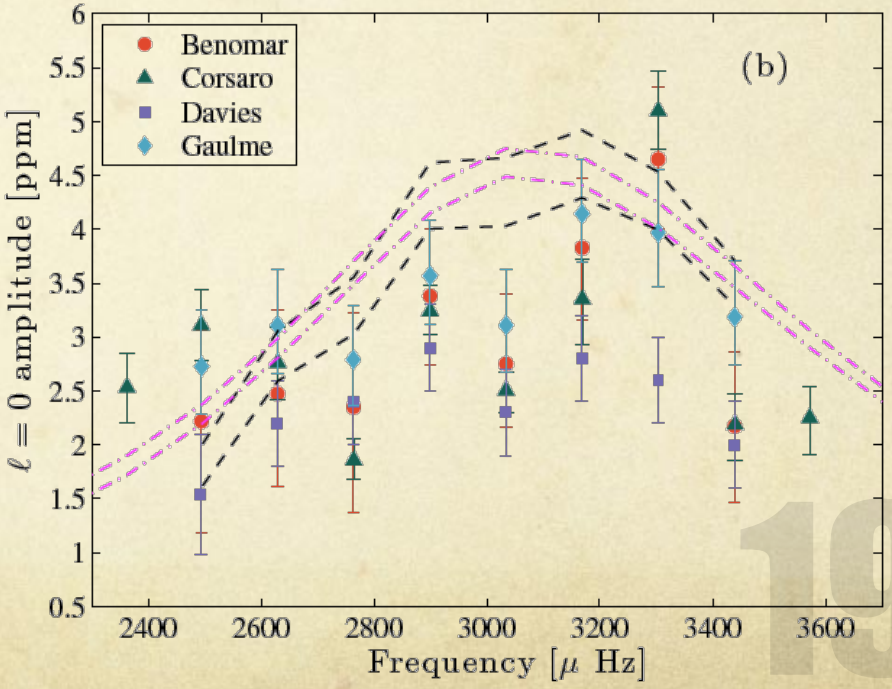
	$\nu_{\rm max\odot,ref}$	Benomar	Corsaro	Davies	Gaulme	Huber	Garcia-Mathur
$\nu_{\rm max}$		3211(46)	3260(23)	3207(49)	3301(51)	3268(56)	3235(78)
$\Delta\nu$		134.9(1)†	135.0(2)†	134.6(3)	134.9(3)	135(2)	134.9(8)
$M_{\rm ast}$	3050	1.17(5)	1.22(3)	1.17(5)	1.27(6)	1.22(9)	1.19(9)
	3150	1.06(5)	1.11(2)	1.06(5)	1.15(5)	1.11(8)	1.08(8)
$R_{\rm ast}$	3050	1.05(2)	1.067(8)	1.06(2)	1.08(2)	1.07(3)	1.06(3)
	3150	1.02(2)	1.033(8)	1.02(2)	1.05(2)	1.03(3)	1.03(3)

M = 1.11 ± 0.05 to 1.21 ± 0.06 Msun R = 1.04 ± 0.02 to 1.07 ± 0.02 Rsun

The Sun as a Kepler star

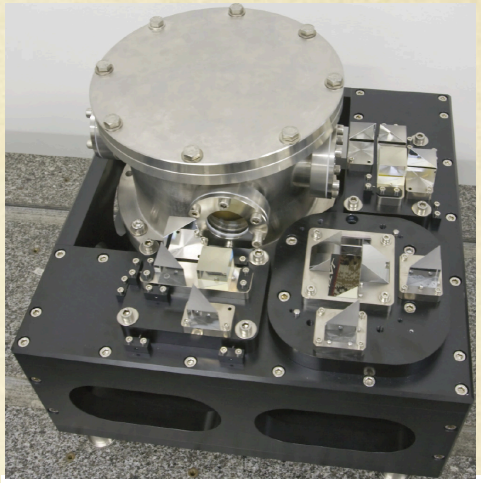
- Peak bagging: K2 vs. SOHO-VIRGO
  - 4 fitters: Benomar, Corsaro (DIAMONDS™ BAYESIAN SOFTWARE), Davies, Gaulme
  - Mean widths and amplitudes fit within error bars
  - K2 amplitudes are consistently lower (30% at ν_{max}) than VIRGO's

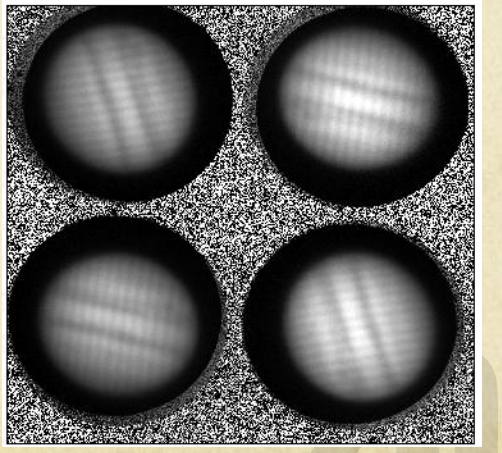




Summary and Conclusion
Giant Planets

- State of the Art
  - Jupiter p-modes Doppler spectrometry (Gaulme et al. 2011)
  - Saturn f-modes (Hedmann & Nicholson 2013)
- K2 observations
  - Cheap test of an uncertain method
  - No detection in K2 data
  - Uranus with K2: saturation, shorter time series
- Prospects: JIVE/JOVIAL
  - Doppler tachometer inherited from SYMPA (Schmider et al 2013)
  - Network of 3 instruments (France, USA, Japan) in 2018
  - NASA (USA) and ANR (Fr) 1.5M$ funding





Summary and Conclusion
Helioseismology

- Sun as a star
  - First indirect detection of solar with photometry.
  - Asteroseismic global parameters lead to overestimation of M, R
  - Peak bagging: amplitudes appear slightly lower than SOHO
  - Spotty stars
- 3 papers: Simon et al. 2016 (ApJ 817), Rowe et al. (submitted), Gaulme et al. (to be submitted)
- Stereo helioseismology
  - Correlate K2 with SOHO/BiSON data