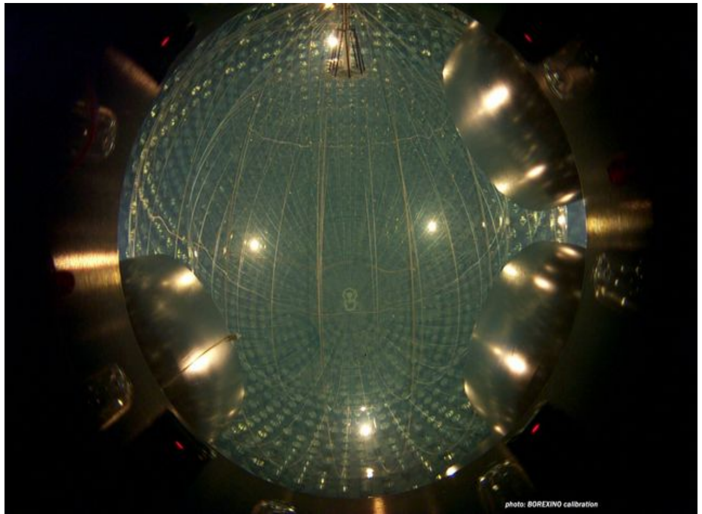
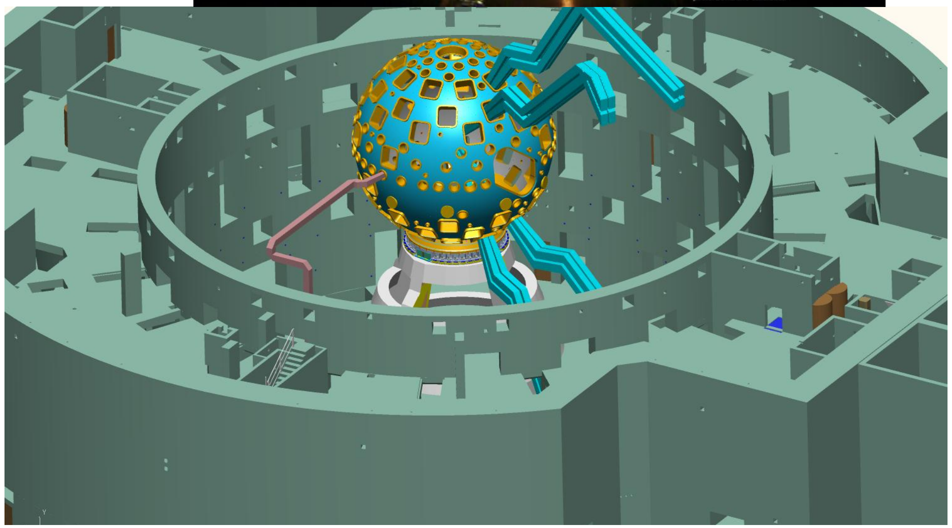
Gravity modes: Results, limitations and perspectives

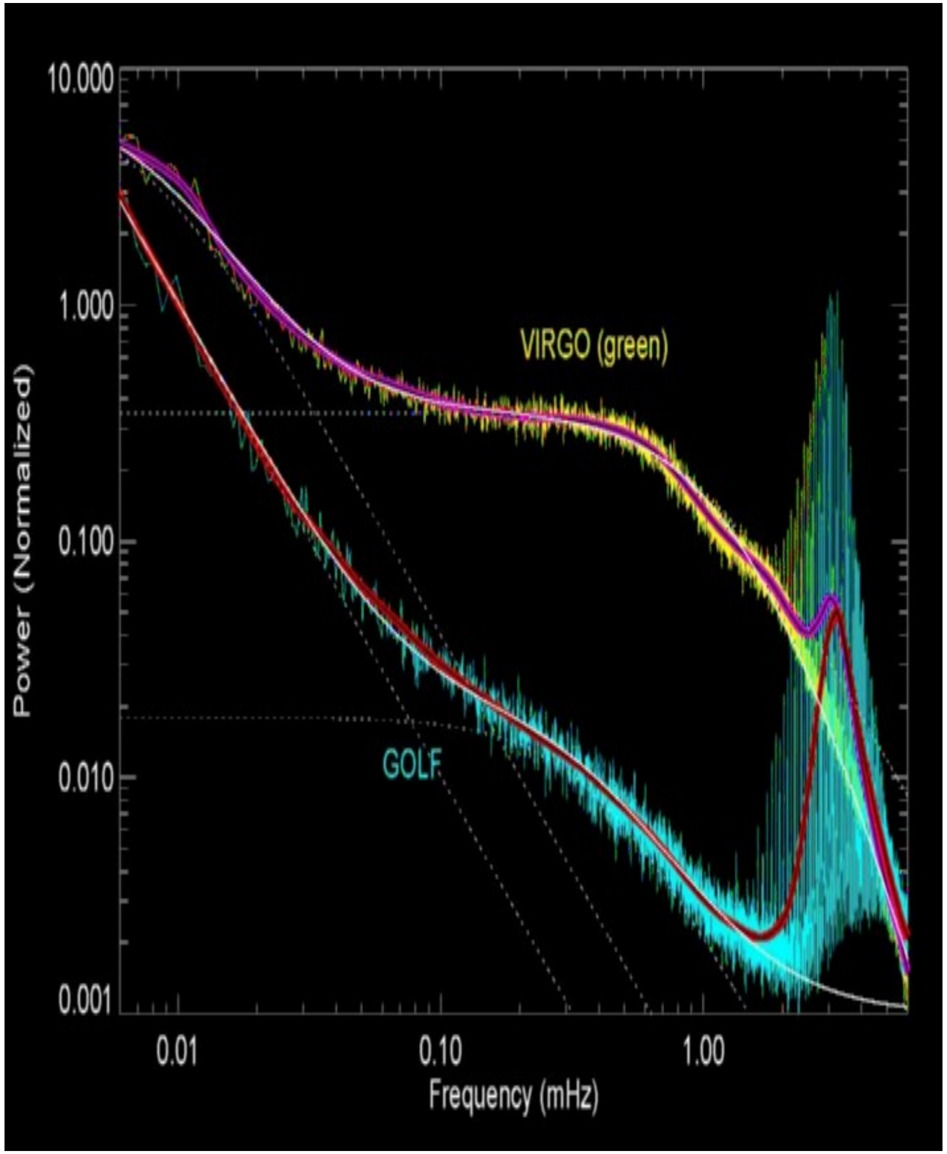
Sylvaine Turck-Chièze

Context *SOHO 1988-2011*
New neutrino detections 1990-2008
LASERS 2007-2025…





Since the beginning, VERY Important issues



- Verify the hypotheses of the pure theoretical SSM

  Acoustic modes:
GOLF+MDI, GOLF+SDO ?

- Go beyond a transition toward dynamics

  Gravity modes

  GOLF versus VIRGO

Acoustic modes: Fundamental physics

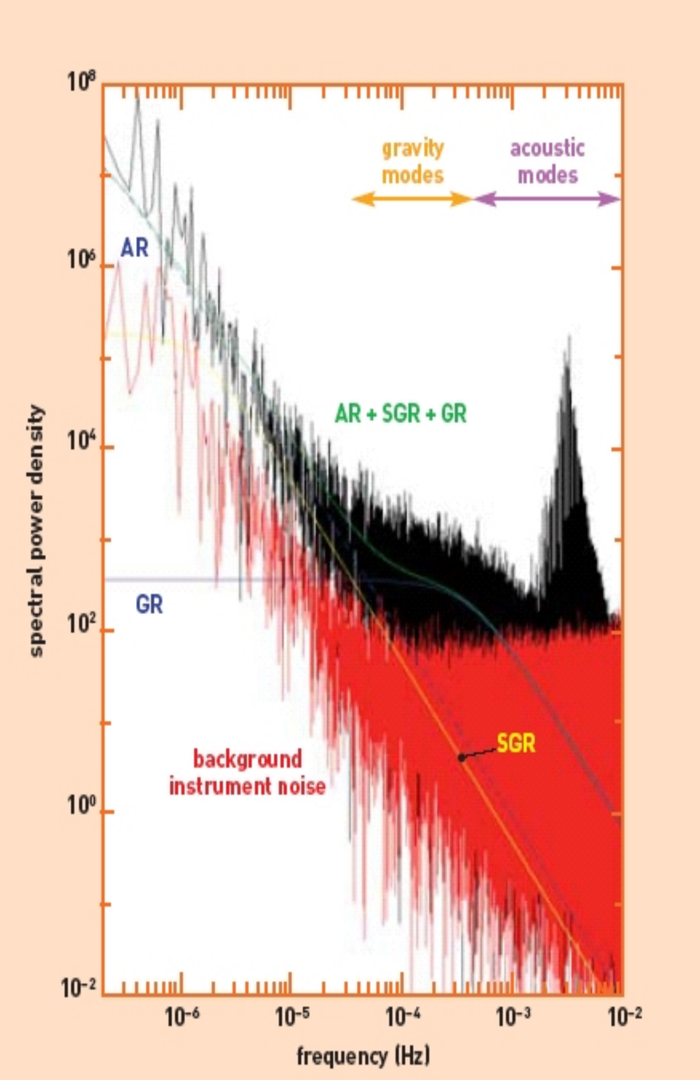
- **Seismic model** for the prediction of different neutrino sources face to new detections in 4 important detectors **in addition to SSM** predictions: perfect and better agreement between them than SSM

2 Nobel prizes (2002, 2008)

- **Better CNO photospheric** abundances
- **Better opacity tables** (2 sets) CEA and Los Alamos

- New opacity measurements at la Sandia and first criticism on calculations, other experiment in development, we wait the results 2020 ? **other proposals status: Vol 515 ASP Conf Series**

Before and just after the launch



- Designed and verified performances of GOLF: 1mm/s integrated on 3 weeks for 6 10^6 cnts/s per PM

- Study in laboratory to get detector + electronics that allow these performances
- **Choice of the detector**: Hamamatsu PM
- **Choice of the electronic**: a lot of studies to improve it
- Then 2 years of laboratory checks 1992-1994 + … very useful

Just after the launch: verification of the noise: the quality of GOLF detection justifies to look for gravity modes

Involved persons in Saclay

- **Hervé Dzitko** : thesis 1995, preparation of the GOLF detector, performances
- **Sébastien Couvidat**: thesis 2003, search for gravity modes detection, characteristics of the modes and the splitting
- **Jérome Ballot**: thesis 2004 extension to asteroseismology

  then data analysis of GOLF
- **Savita Mathur**: thesis 2007, mode predictions and participation to GOLF-NG beyond GOLF
- **Rafael Garcia** since 1998 analysis of the data, methods
- **Myself** from 1988 to 2013: predictions, methods, analysis, models and preparation of the future

Altogether more than 50 refered papers including 3 reviews PhysRep with **Eric** 1993 before launch, RPPh2011 with S. Couvidat , RAA 2012 **with I. Lopes** with all the frequency values that we have explored

Gravity modes with GOLF

internal dynamics of the Solar core ?

Different approaches (methods) have been investigated:

The asymptotic region has been explored before SoHO (Stanford, Nice) : no detection

- High frequency range: mixed modes research for individual pattern to see the dynamics and characteristics of the modes (Saclay)
- Global approach (Saclay) of intermediate g modes
- Asymptotic behaviour (Nice)

TABLE 1

List of g-Mode Frequencies for the Solar Model seismic2

$\ell = 1$				$\ell = 2$			
n	ν (μHz)	n	ν (μHz)	n	ν (μHz)	n	ν (μHz)
−46	14.6	−22	30.0	−46	24.9	−22	50.6
−45	14.9	−21	31.4	−45	25.5	−21	52.8
−44	15.3	−20	32.9	−44	26.0	−20	55.3
−43	15.6	−19	34.5	−43	26.6	−19	58.0
−42	16.0	−18	36.3	−42	27.2	−18	60.9
−41	16.4	−17	38.4	−41	27.9	−17	64.3
−40	16.8	−16	40.6	−40	28.5	−16	67.9
−39	17.2	−15	43.2	−39	29.2	−15	72.0
−38	17.7	−14	46.1	−38	29.9	−14	76.6
−37	18.1	−13	49.3	−37	30.8	−13	49.3
−36	18.6	−12	53.1	−36	31.6	−12	87.8
−35	19.1	−11	57.4	−35	32.5	−11	94.6
−34	19.7	−10	62.5	−34	33.4	−10	102.5
−33	20.2	−9	68.5	−33	34.3	−9	111.7
−32	20.9	−8	75.7	−32	35.4	−8	122.6
−31	21.5	−7	84.4	−31	36.5	−7	135.6
−30	22.2	−6	95.2	−30	37.6	−6	151.3
−29	22.9	−5	109.1	−29	38.9	−5	170.5
−28	23.8	−4	127.7	−28	40.2	−4	194.2
−27	24.6	−3	153.3	−27	41.6	−3	222.1
−26	25.5	−2	191.6	−26	43.2	−2	256.2
−25	26.5	−1	262.9	−25	44.8	−1	296.4
−24	27.6			−24	46.6		
−23	28.7			−23	48.5		

Note.— Values calculated for modes $\ell = 1$ and $\ell = 2$ and for $n = -46$ to -1.

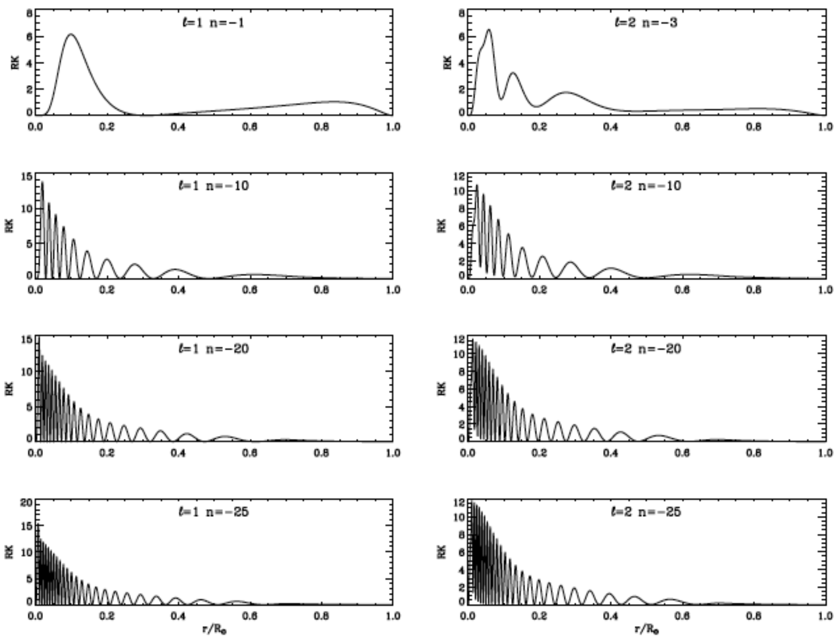
Theoretical gravity mode frequencies

for the range of observations covered by the different analyses obtained with the solar seismic model

Mathur et al. 2007

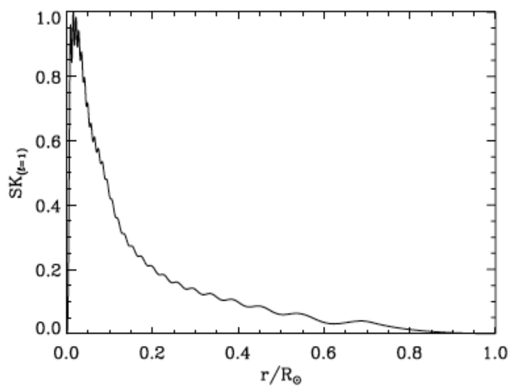
Sensitivity of the different gravity modes

Mathur et al. 2007



Mixed modes

Asymptotic ones



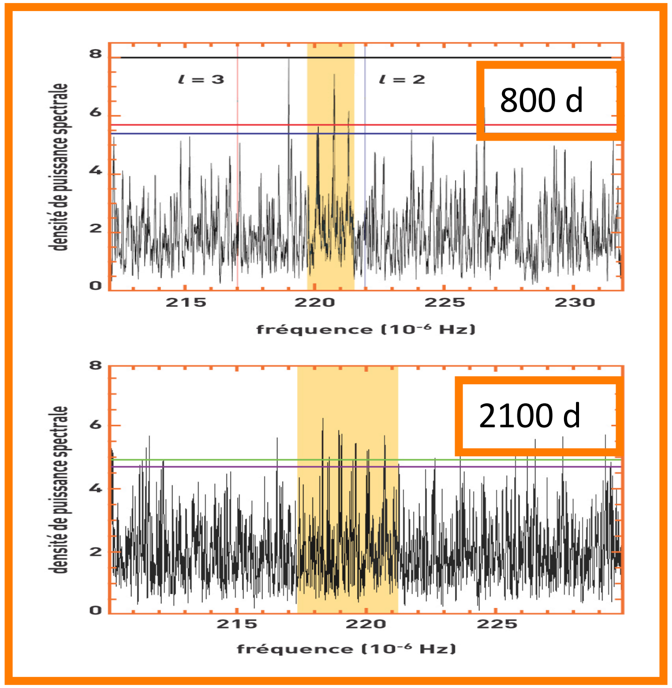
Sum of the

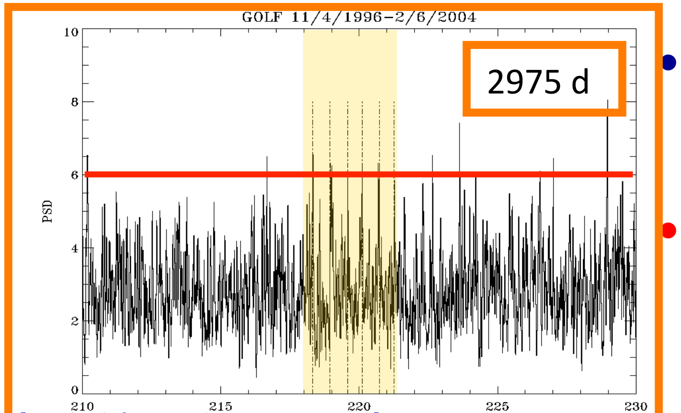
different ℓ =1

n= - 4 to n=-24

Method 2

High frequency range: research of multiplets along time : Turck-Chièze et al AA 2004, 2005, Mathur et al. 2007





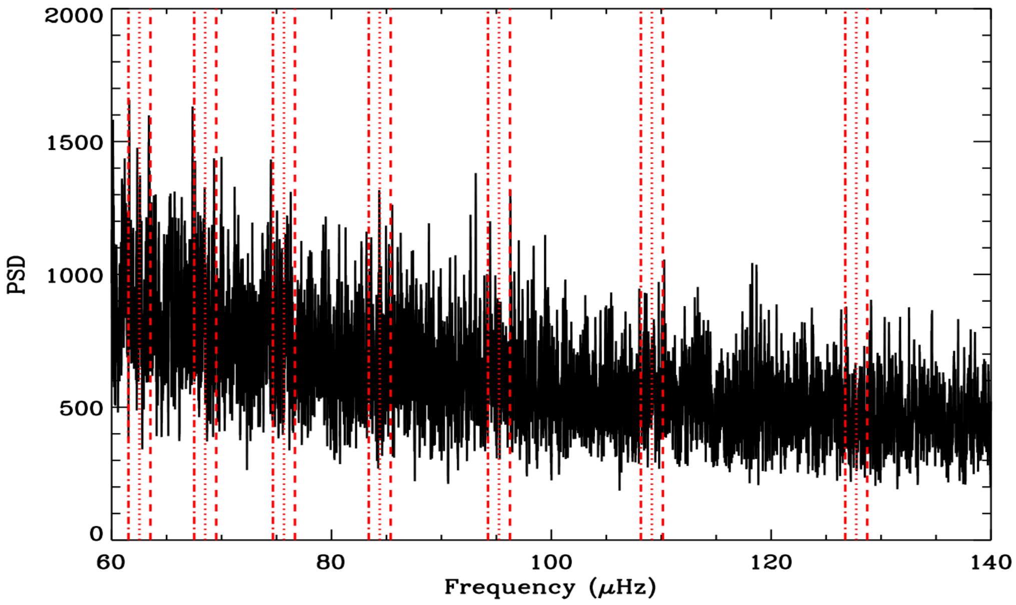
[Turck-Chièze, et al., SoHO 14, 2005]

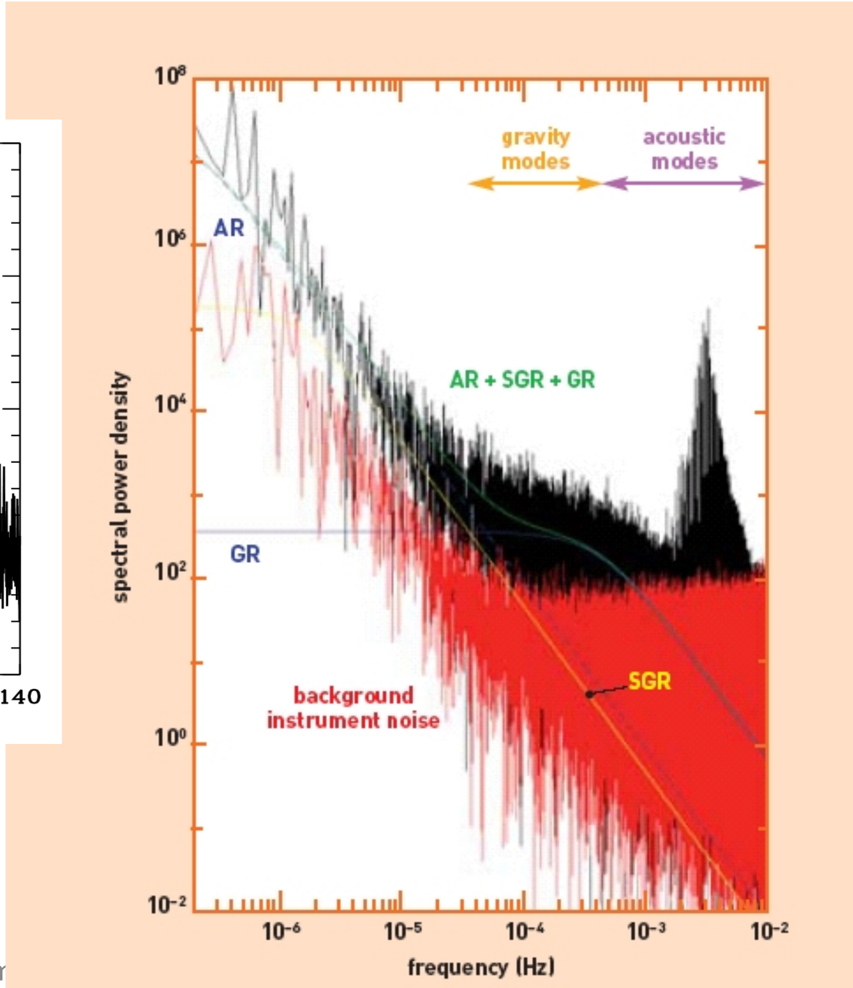
- See explicitly the **splitting**
- See if they show the **same core rotation axis than** the rest of the Sun
- See **characteristics of excitation**: no stability (10nHz variability), no long duration excitation
- See the **amplitude**, the 220 μHz mode is the highest excited one (Guzik et al.), some components at more than 98% CL
- Improve the **density profile** in complement to sound speed profile
- Limitations due to the malfunctioning of the mechanisms and the increase of the photon noise or solar noise: no clear peaks for 4182 days

Limitations on the duration and noise

10 years: followed patterns

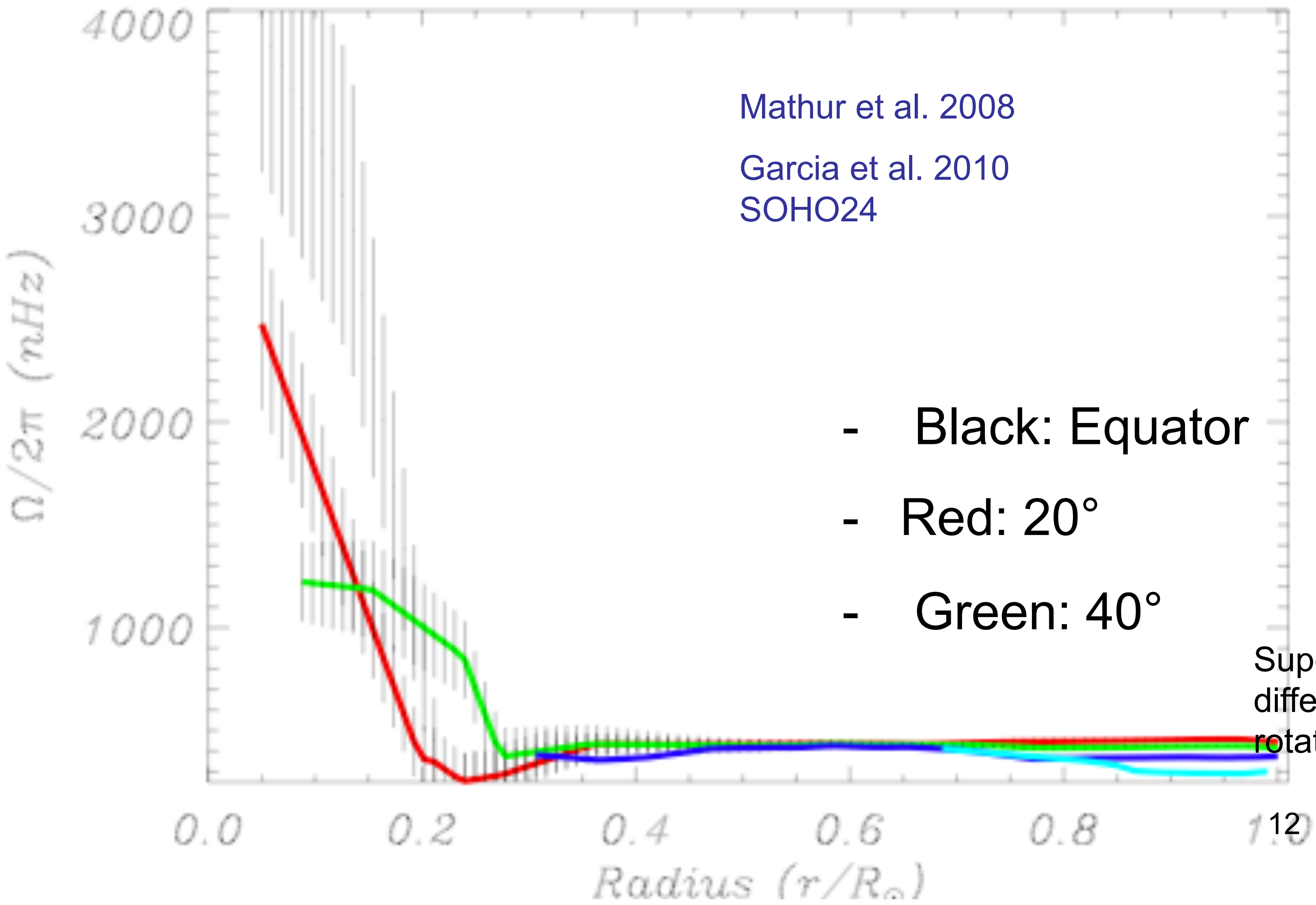
Need to be confirmed by future instruments





Constraints on solar core rotation from individual g modes

2D inversion from A. Eff Darwich code !!



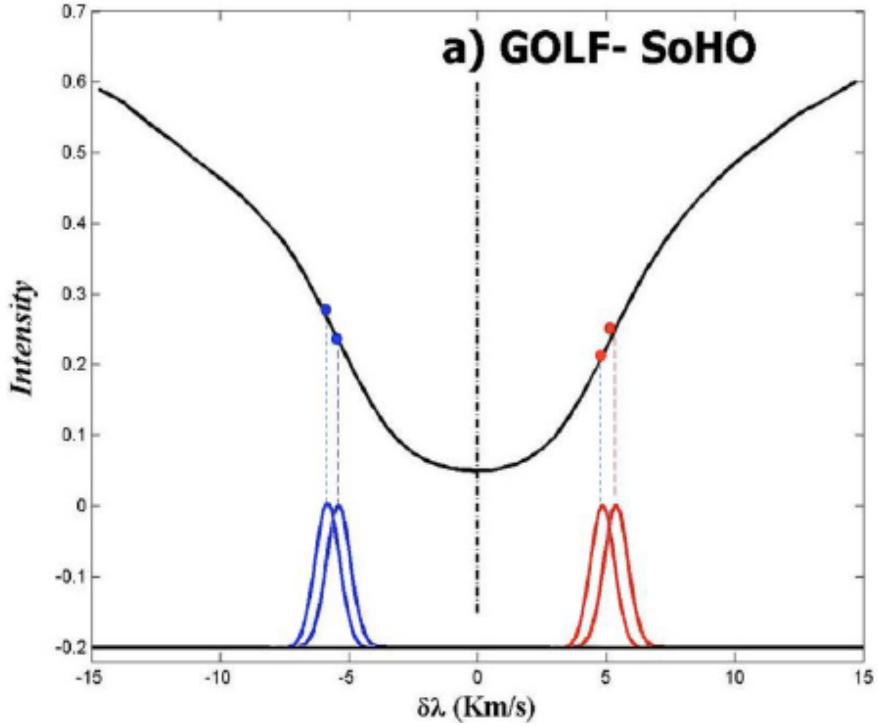
Mathur et al. 2008

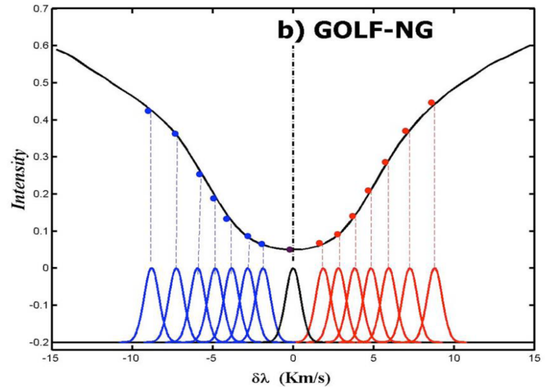
Garcia et al. 2010
SOHO24

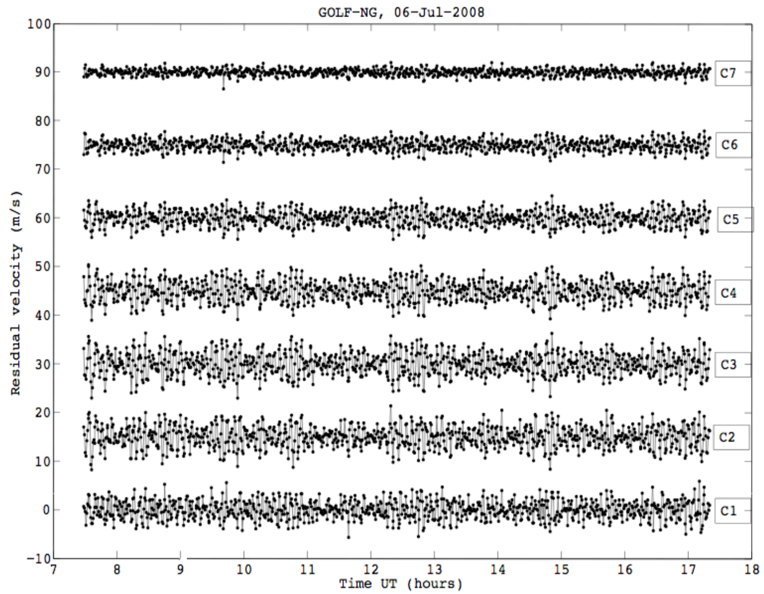
- Black: Equator
- Red: 20°
- Green: 40°

Superficial differential rotation

Limitations of the velocity measurements on sodium line from IRIS, GOLF to GOLF-NG

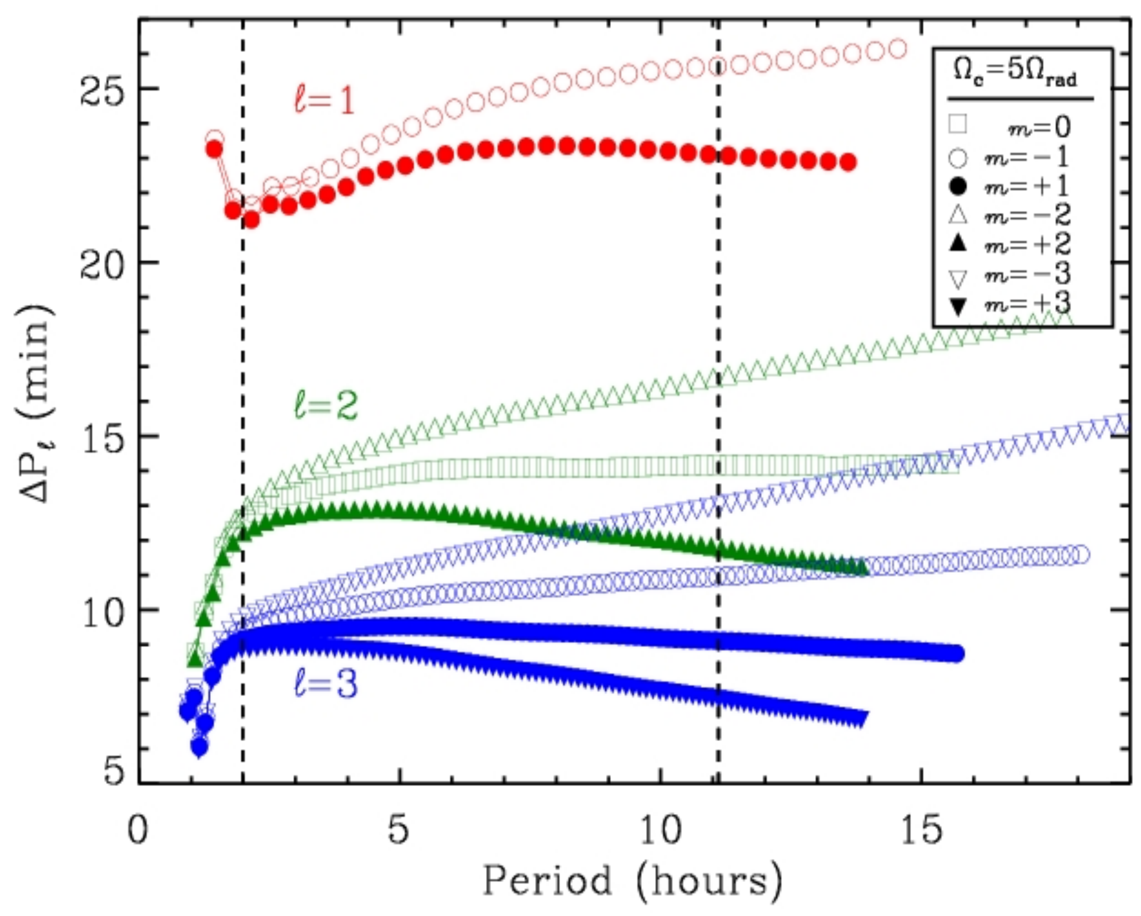






Principle is one thing and very promising, detector and electronic another !!

Second approach: one sums 20 modes below 150 μHz: Garcia, T-C et al. Science 2007



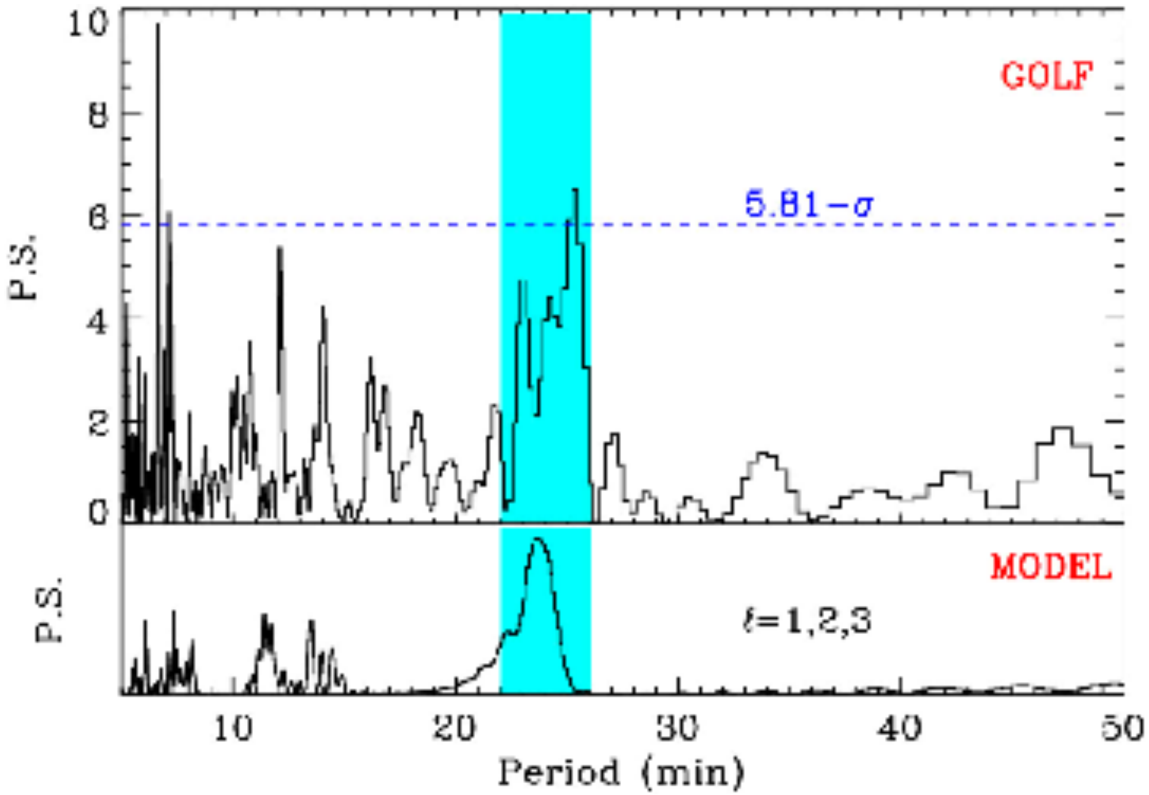
In the intermediate regime

If p modes are equidistant in frequency but g modes are equidistant in period in the asymptotic regime

$\Delta P_\ell = P_{\ell,n+1} - P_{\ell,n}$

$\Delta P_1 = P_o/2^{1/2}$

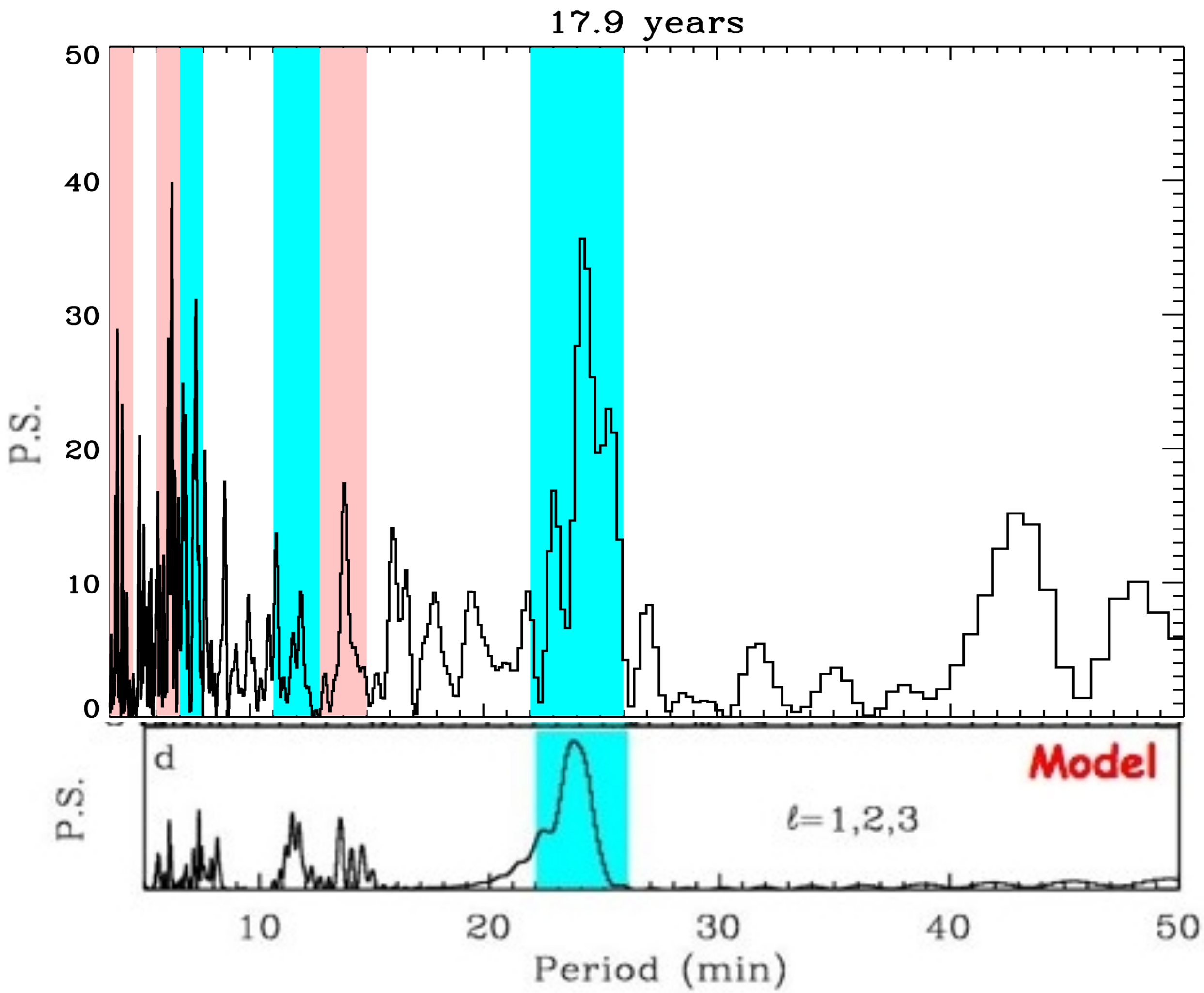
Comparison between GOLF data and simulations



In the simulations, a splitting corresponding to a central rotation of 5 times the surface rotation is considered

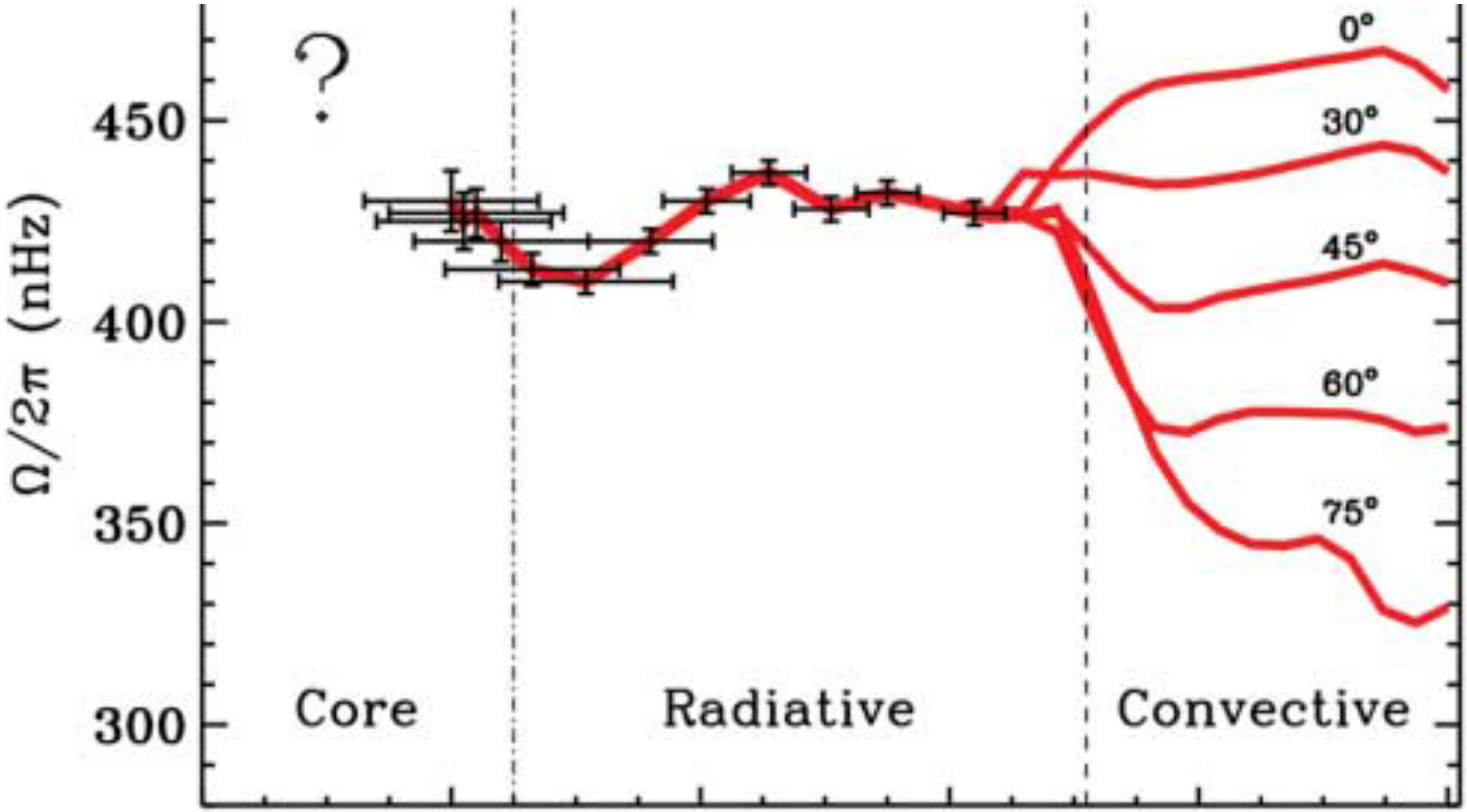
A probability of noise is estimated more than 99.9% is observed with time First after 10 yrs and the pattern is still present after 18 yrs

More noise (counting rate reduced by about 30: photocathode, filters, cell…) but the pattern is still there and may be more structured



Be careful: this figure is not a result of our Science paper

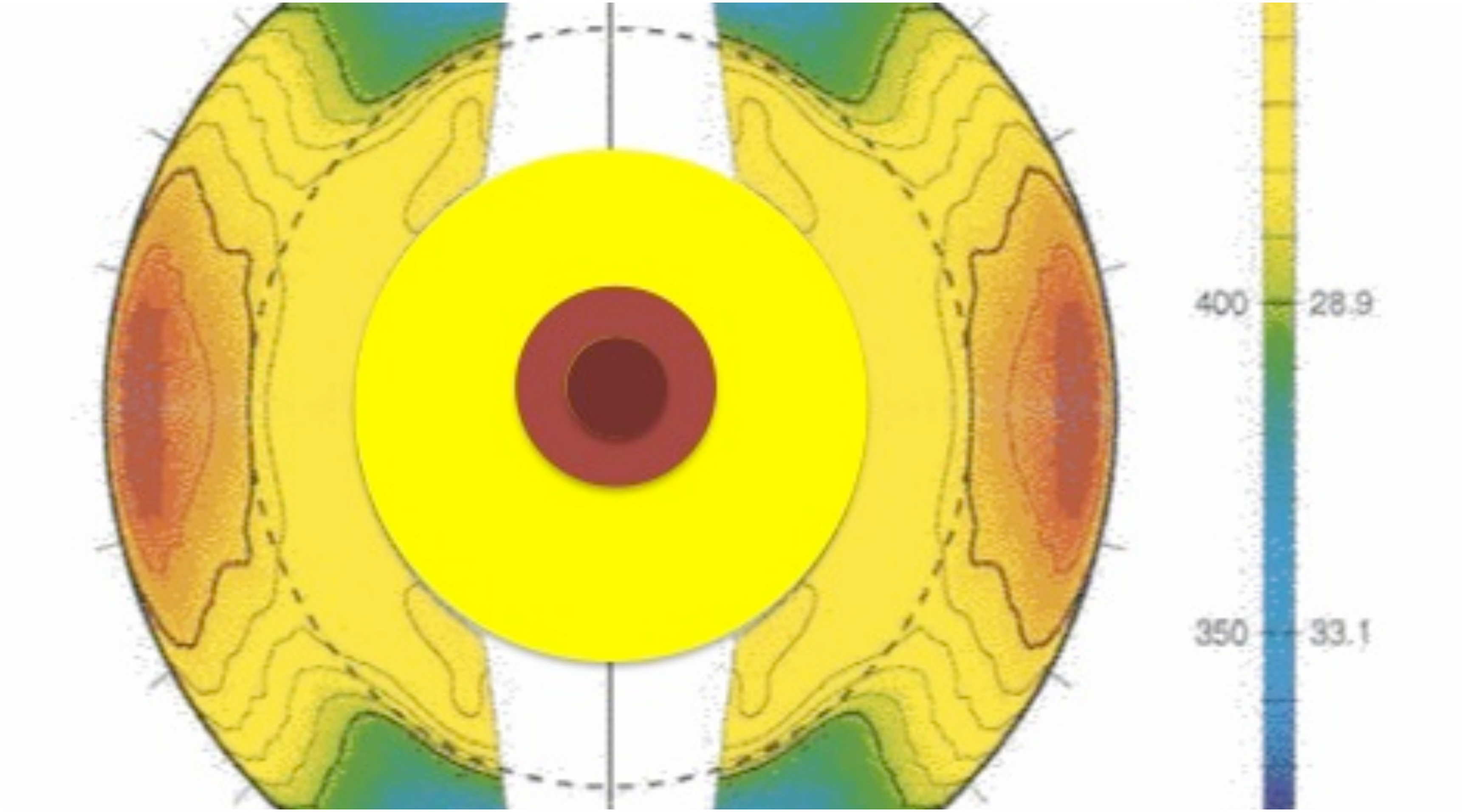
it is figure I of the paper that shows the limitations of acoustic modes: echo of previous fights between IRIS and BISON



Result of the Science paper 2007

the detection of intermediate gravity modes are compatible with a core rotating 5 times quicker than the surface

T-C & Couvidat 2011



Third Search: asymptotic region

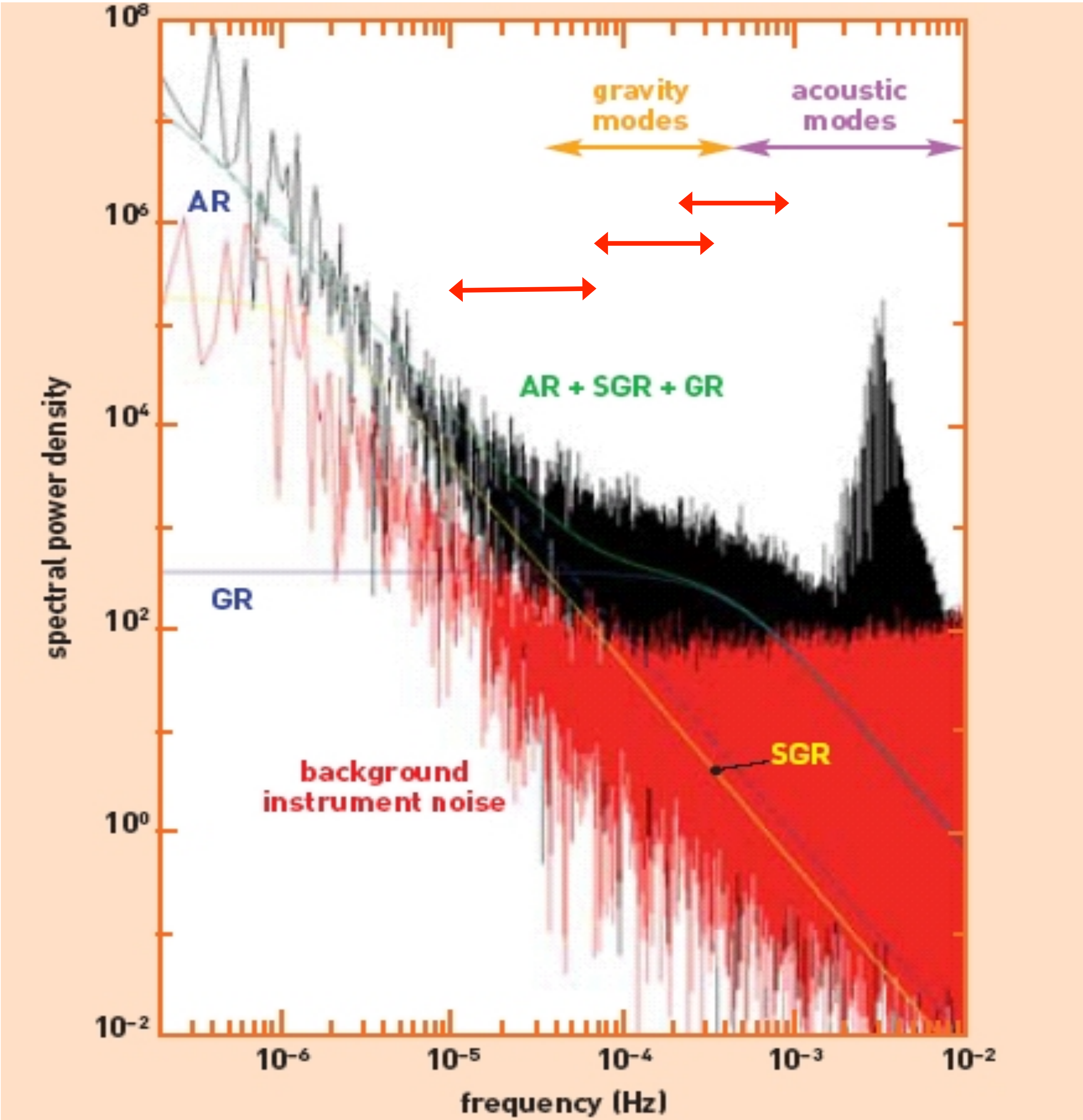
- See talk of Eric

Summary

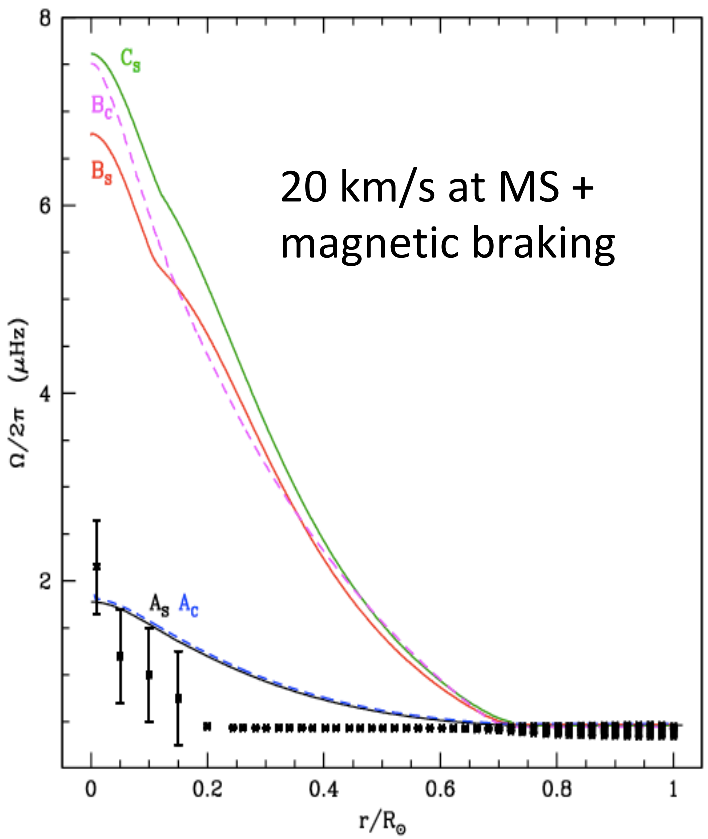
I: individual search ℓ =1, ℓ=2 above 150 μHz then 60-230 μHz
1998-2004-2005

II: global research
ℓ = 1,2,3
25-140 μHz
20 modes

III: global research
7-30 μHz
79 ℓ=1, 117 ℓ=2



Implication of the different results of g-mode detections characteristics and rotation on solar physics



Weak initial rotation without magnetic braking

- SSM is unsufficient to describe the Sun
- Gravity modes do not produce infinite narrow peaks, they are often reexcited in the turbulent BCZ
- The solar rotation of the core is 4-5 times greater than the surface rotation,
- It seems not to be explained as a rapidly rotating young star that has been braked by magnetic wind at MS T-C et al. 2010, A&A 715, 1539
- **The core rotation is probably the relics of an initial rotation of a slow rotating star**

Atmosphere in the seismic community !!

- Different communities - different atmospheres: neutrino community, seismic one, plasma physics one
- **Doubt and research of truth is normal in science** but not pretentious posterings, « mockeries » or absence of quotation of the previous papers …
- Space mission is **sufficiently expensive and rare** to explore the data with completeness and **to document the results for future works**

For me, **GOLF has detected gravity modes**, we have several results that do not contradict each other, it is a difficult research and the community must not neglect this fact for future projects, even there is space for complementary useful information and theoretical work.

We have a second detector aboard GOLF/SoHO: do we use it ?

Do we verify temperature of filters and cell, HT PM ? We must as we observe too much noise to use seriously GOLF data today

Merci à Lionel Bigot, ESA, CNES to initiate **this 29th** meeting ….

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