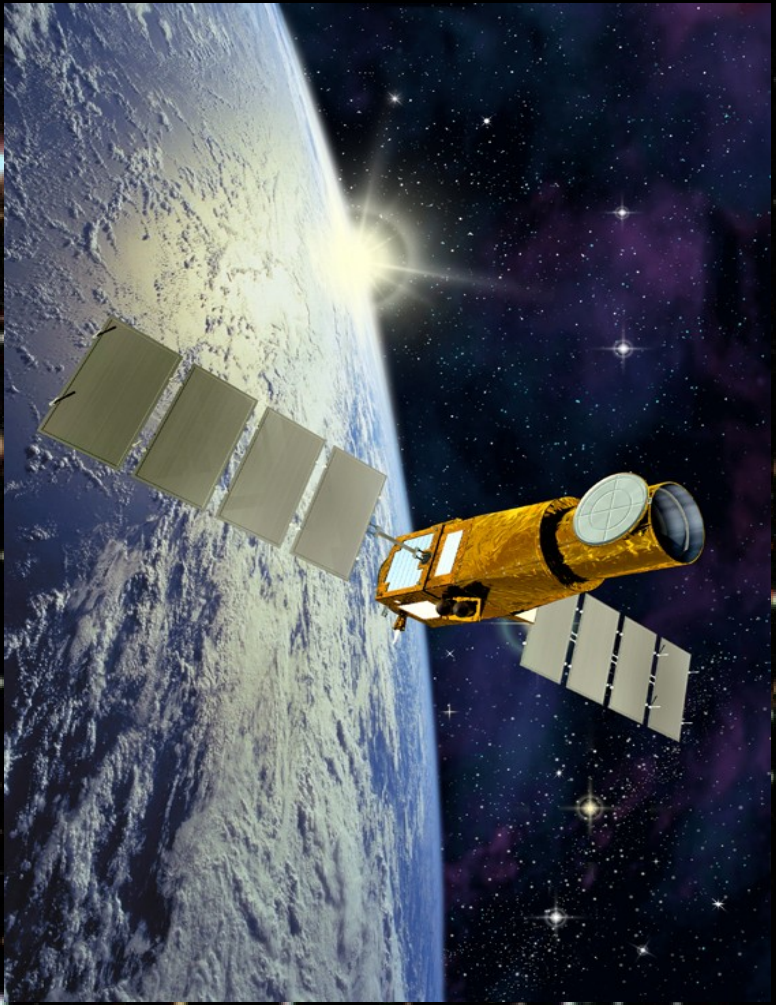
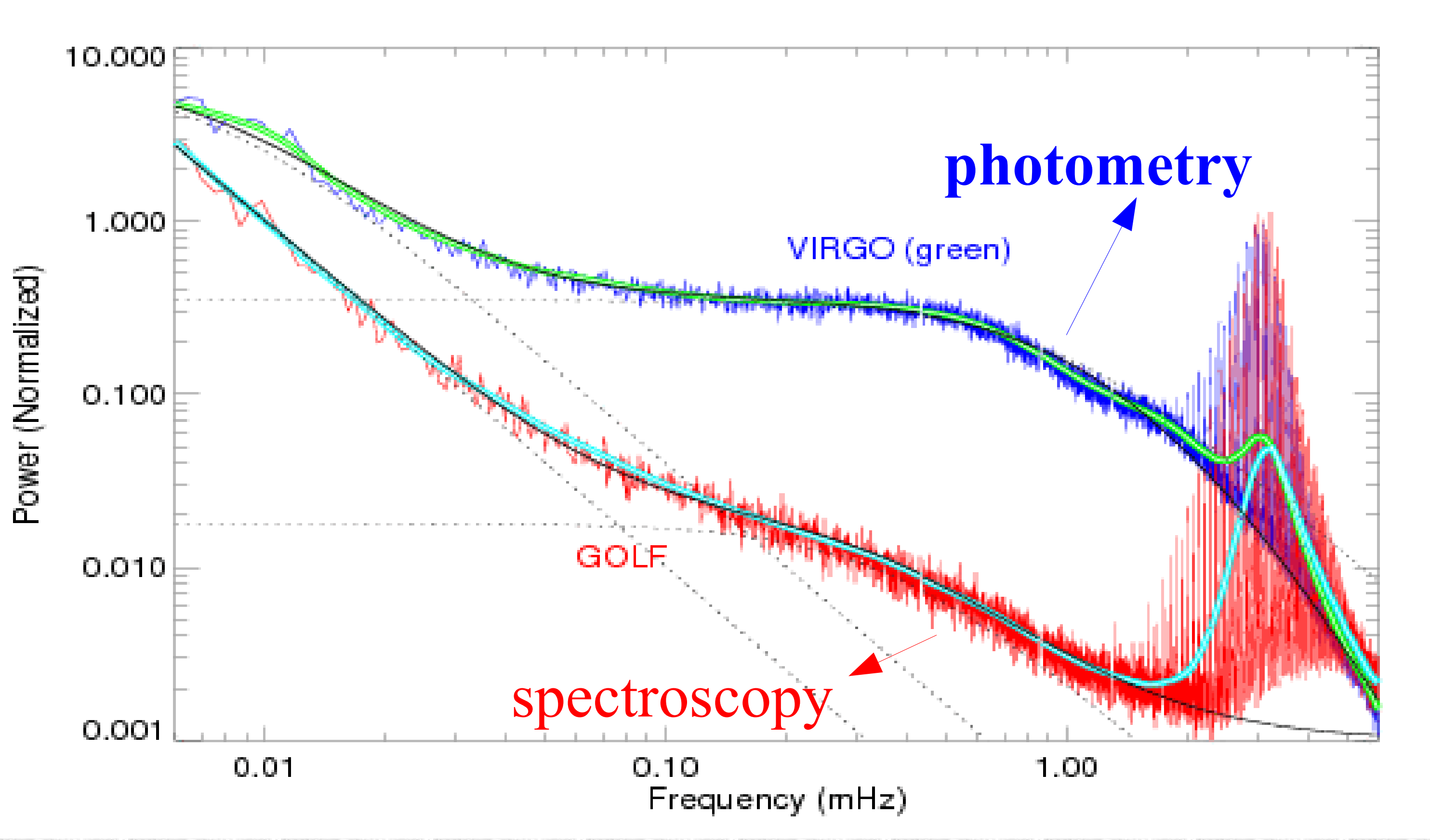
Asteroseismology with the CoRoT and Kepler space missions



Comparison space versus ground

high-precision spectroscopy versus space photometry

SoHO data of the Sun

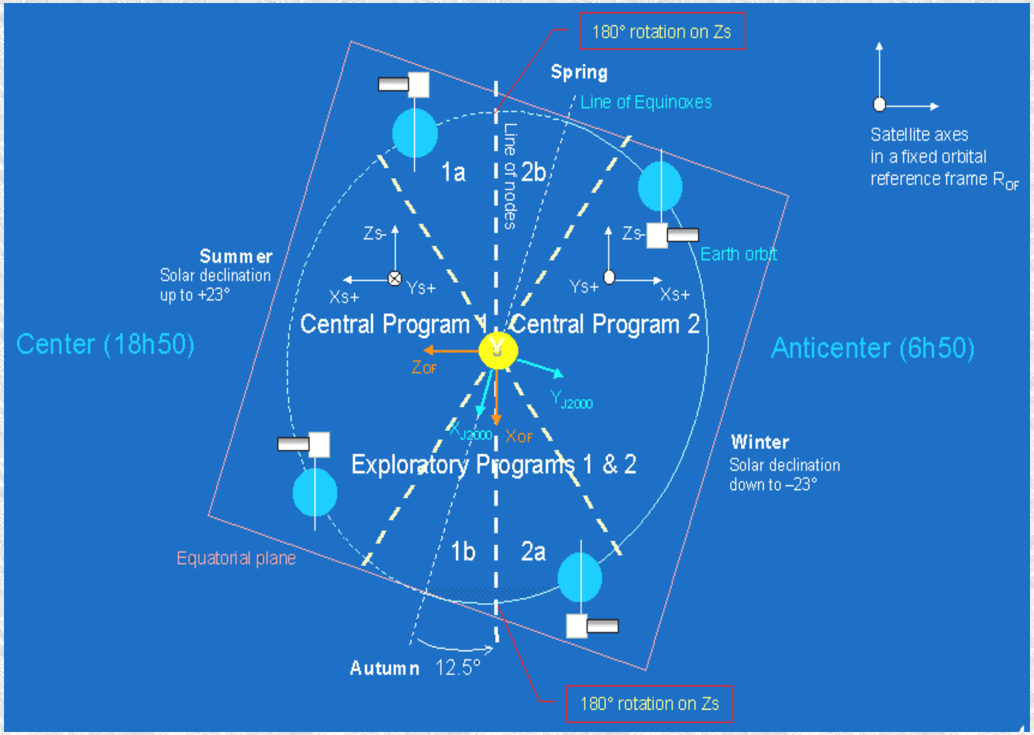


CNES-led CoRoT space mission

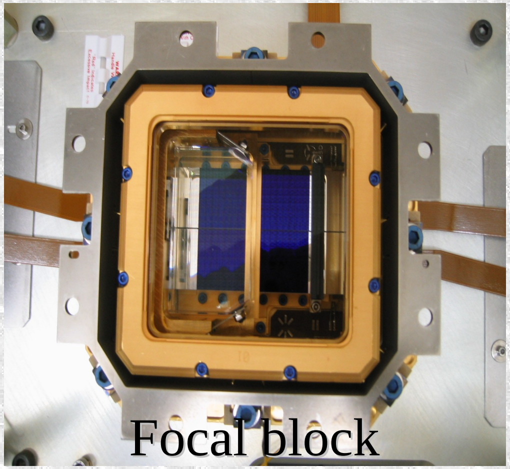
Space photometer, mounted on 0.27m mirror, Vmag 5 to 16

Launched 26 December 2006

Goal: asteroseismology and detection of exoplanets

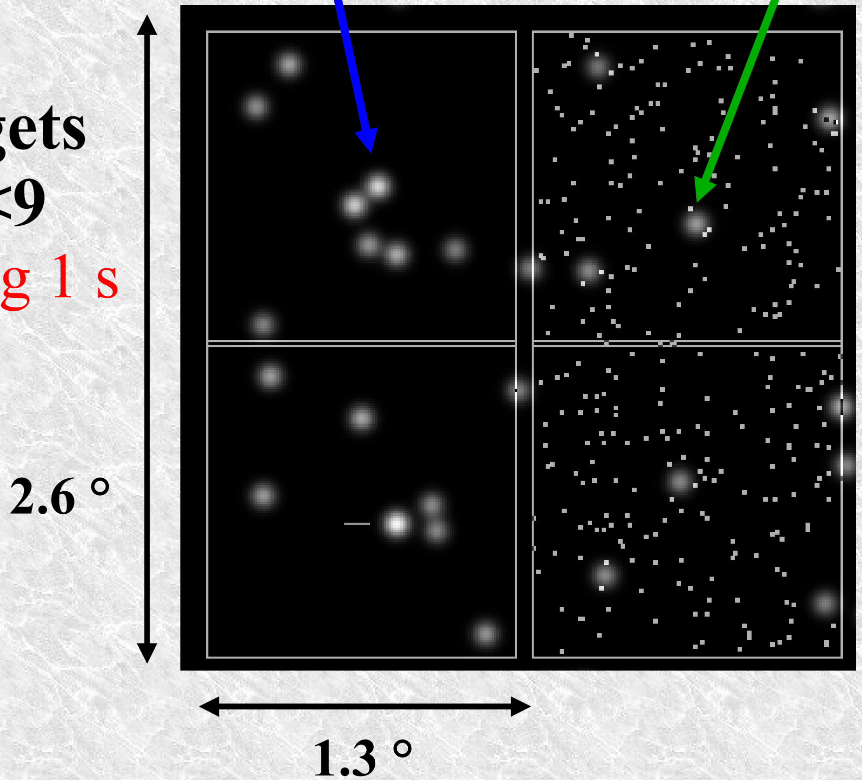


CoRoT focal plane



Seismology field
highly defocused

Exoplanet field
focused + prism



10 targets
5.4<V<9
sampling 1 s

12000 targets
11<V<16
sampling 512 s

4 CCDs 2000x4000 px
Frame transfer

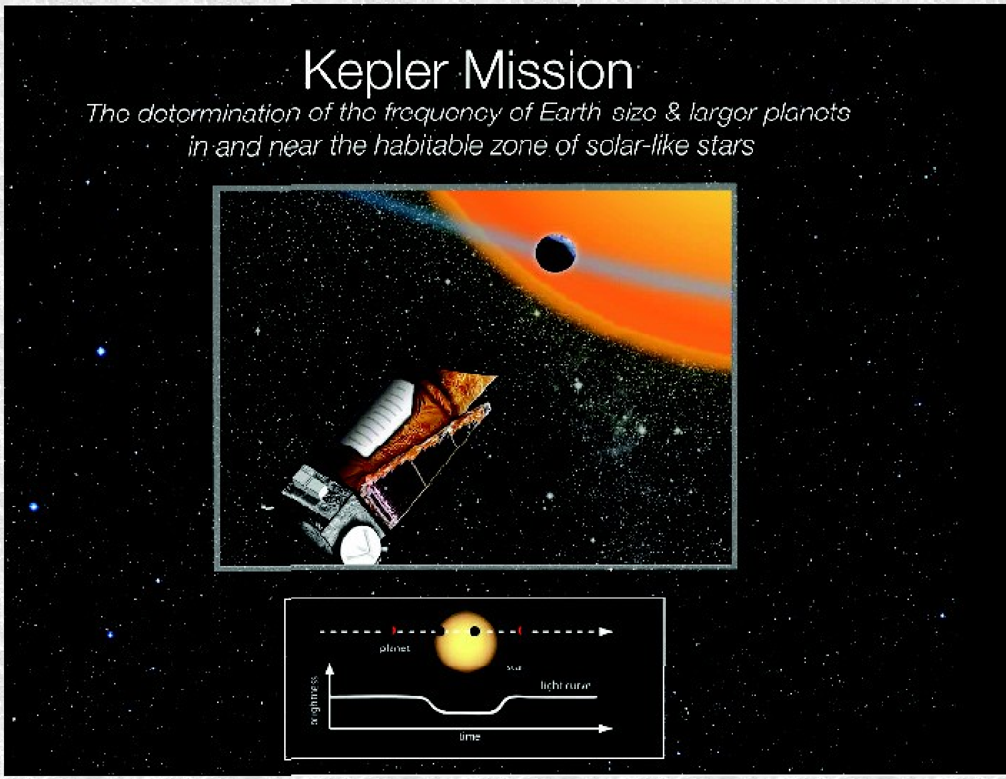
> 100 stars in the Seismo-field
> 100000 stars in the Exo-field

NASA Kepler space mission

Space photometer, mounted on 0.95m mirror, Vmag 9 to 16

Launched 7 March 2009

Goal: detection of Earth-like planets in habitable zone of stars

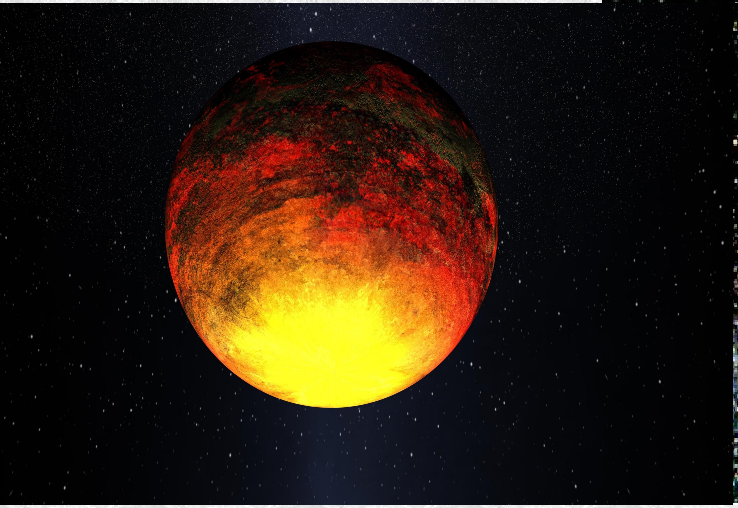


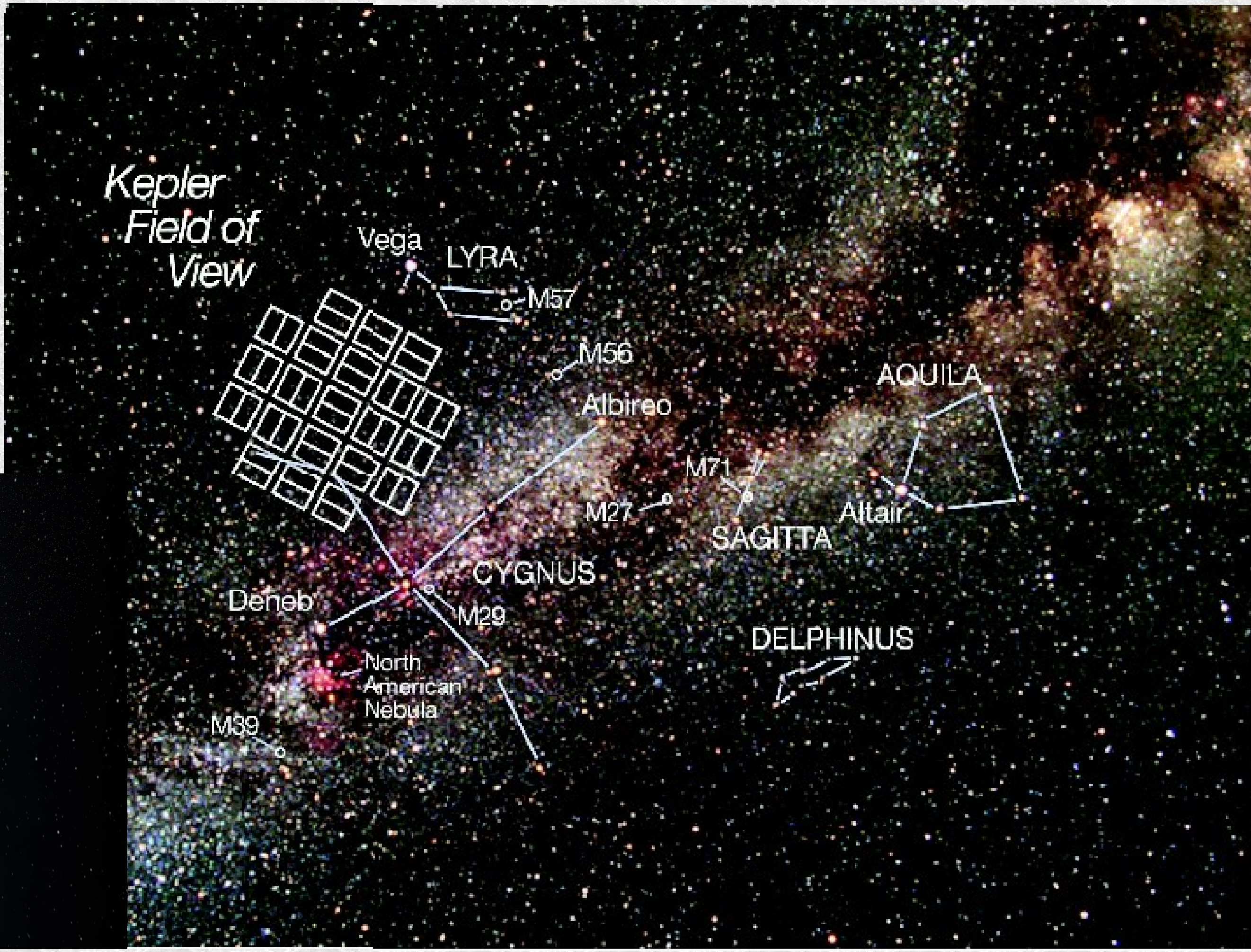
Kepler space mission

Monitors > 100000 solar-like stars at ultra-high precision
Planet discoveries through transit method

10 confirmed so far,
700 candidates

Kepler10b has
R=1.4 Earth R
(NASA PR, Jan.2010)



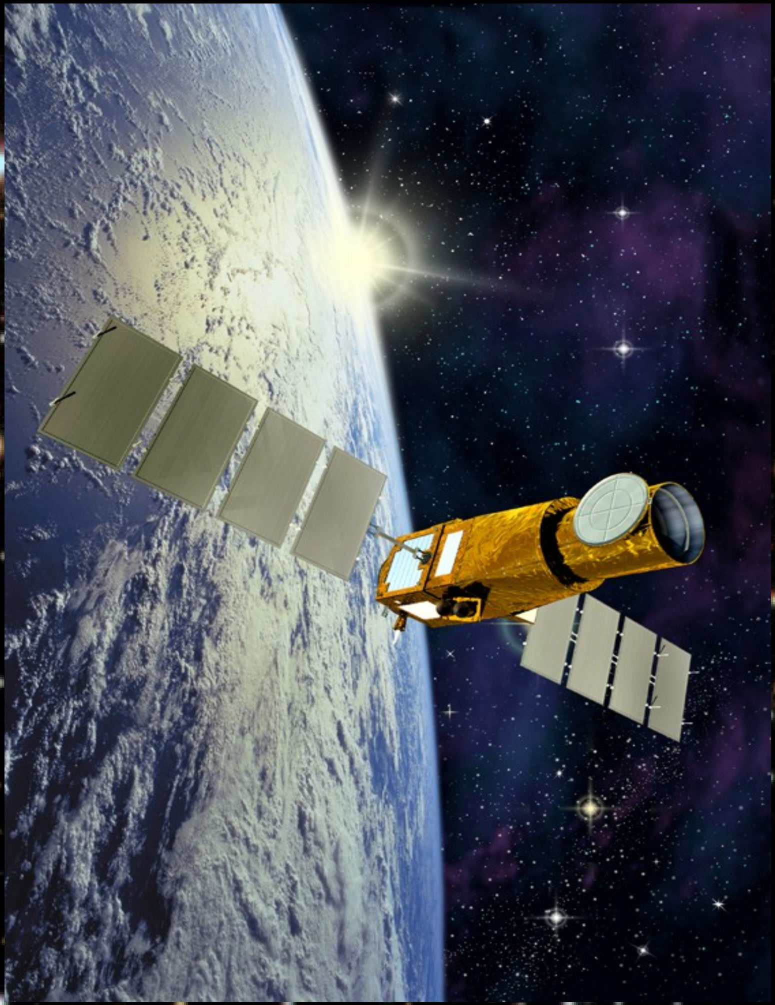


Kepler's asteroseismology: why?

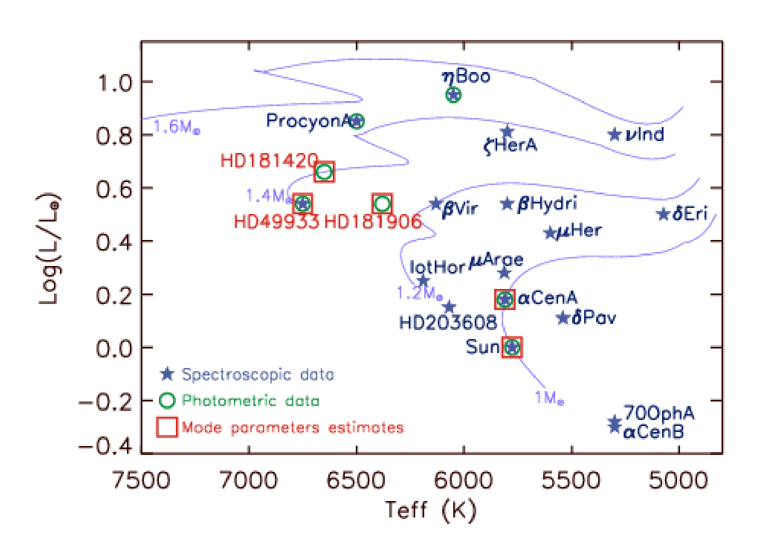
- Understanding formation and evolution of planetary systems:
  - Planet size and composition: we want host star masses and radii
  - Planet age = host star age

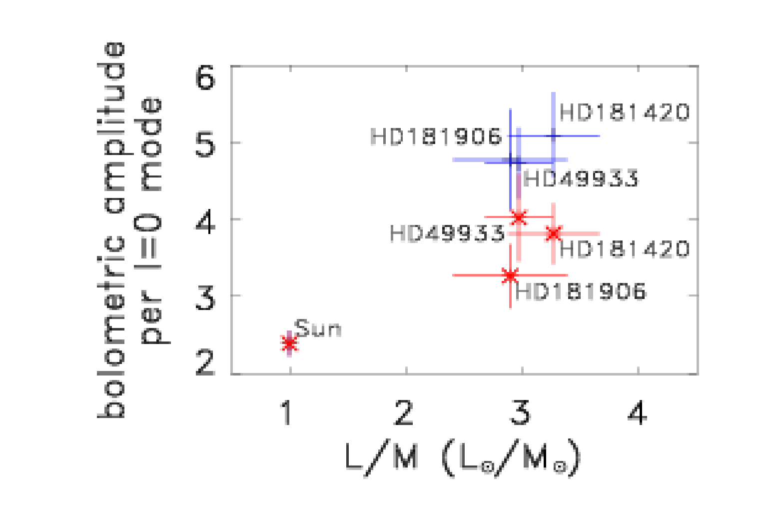
- To improve drastically stellar evolution models across HRD and all fields in astrophysics that rely on it

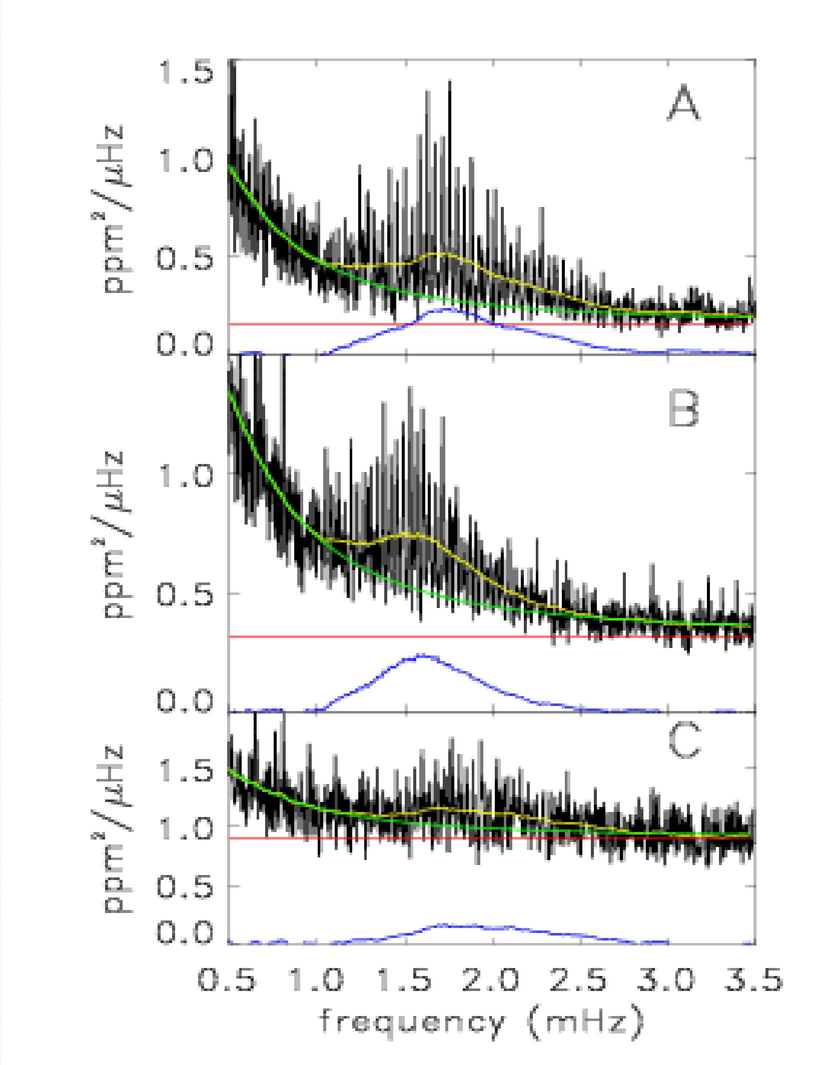
Solar-like Oscillations in unevolved stars



First CoRoT results : AF stars







6th

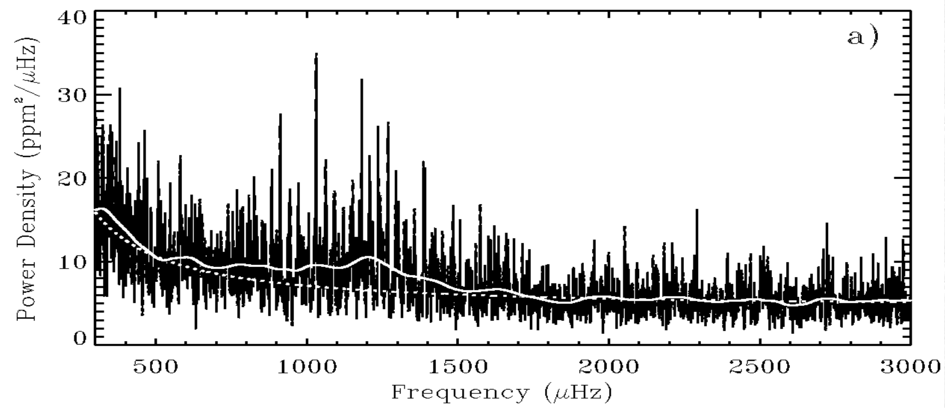
7th

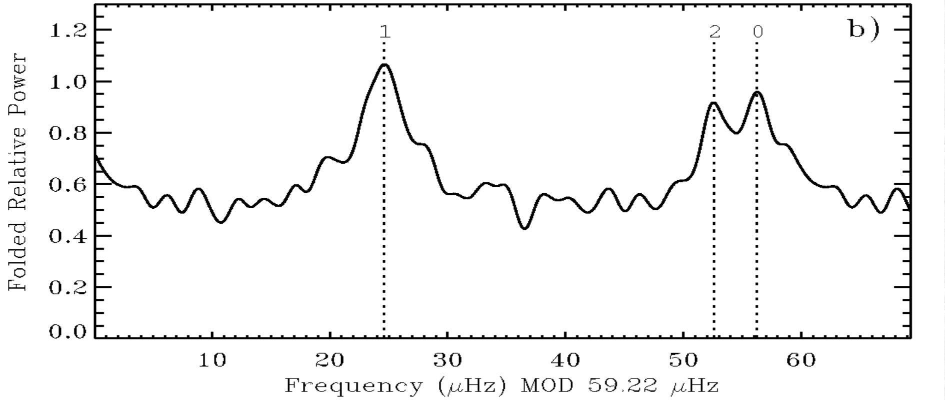
8th

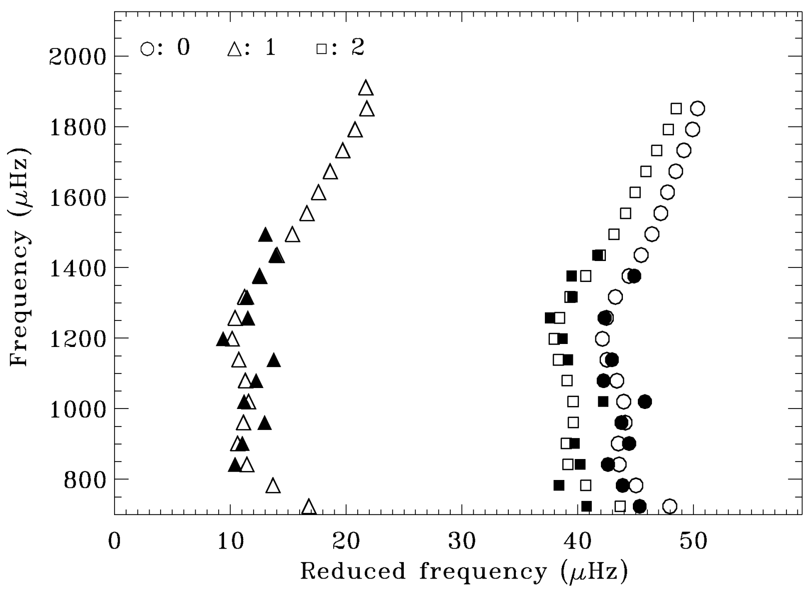
Michel et al. (2008): lower amplitudes, granulation 3x solar

Exoplanet host star seismology: HAT-P-7

Kepler data (JCD et al. 2010):
average density =
0.2712 ± 0.0032 g/cm^3
M=1.520 ± 0.036 Msun ,
R=1.991 ± 0.018 Rsun
age = 2.14 ± 0.26 Gyr



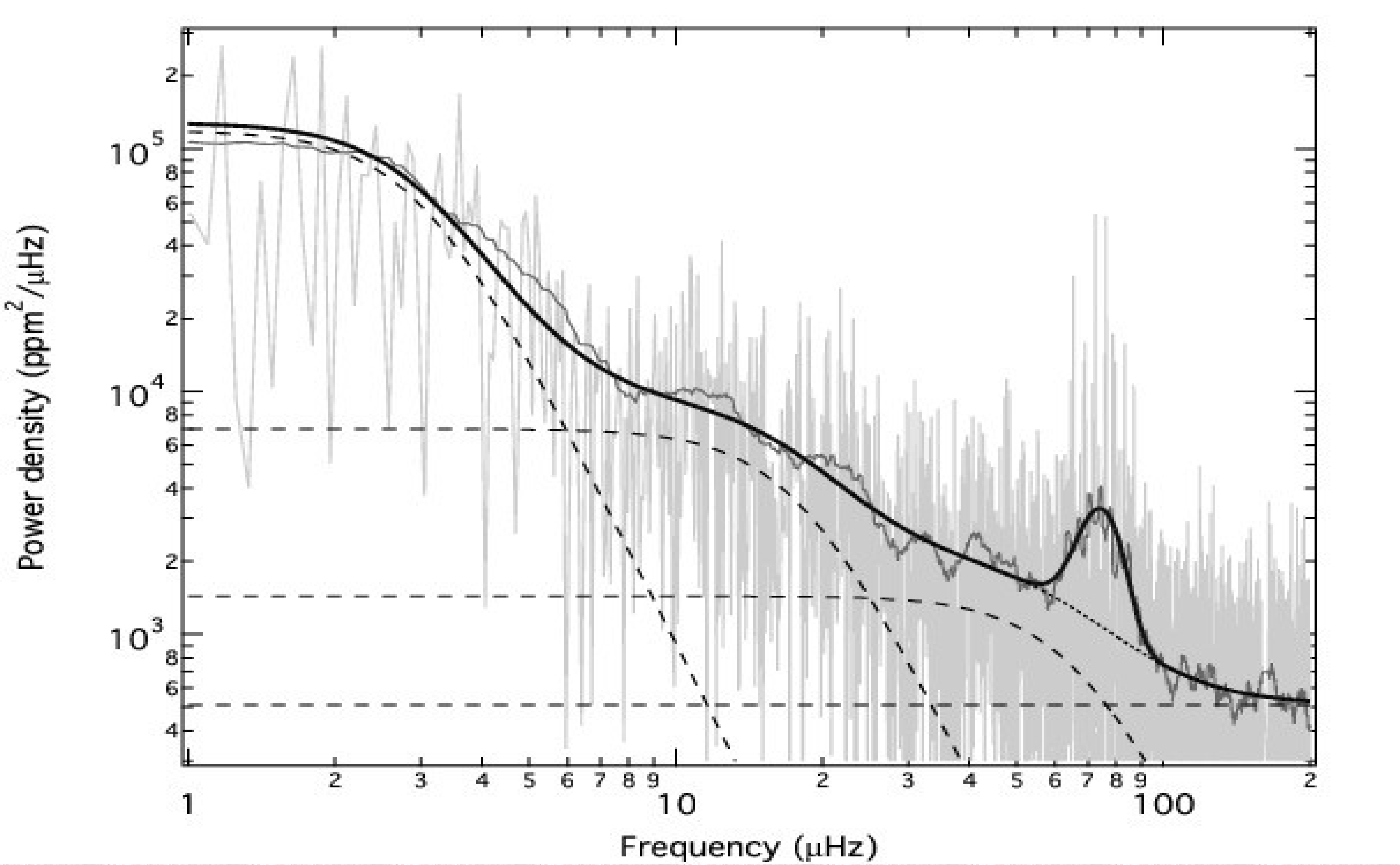




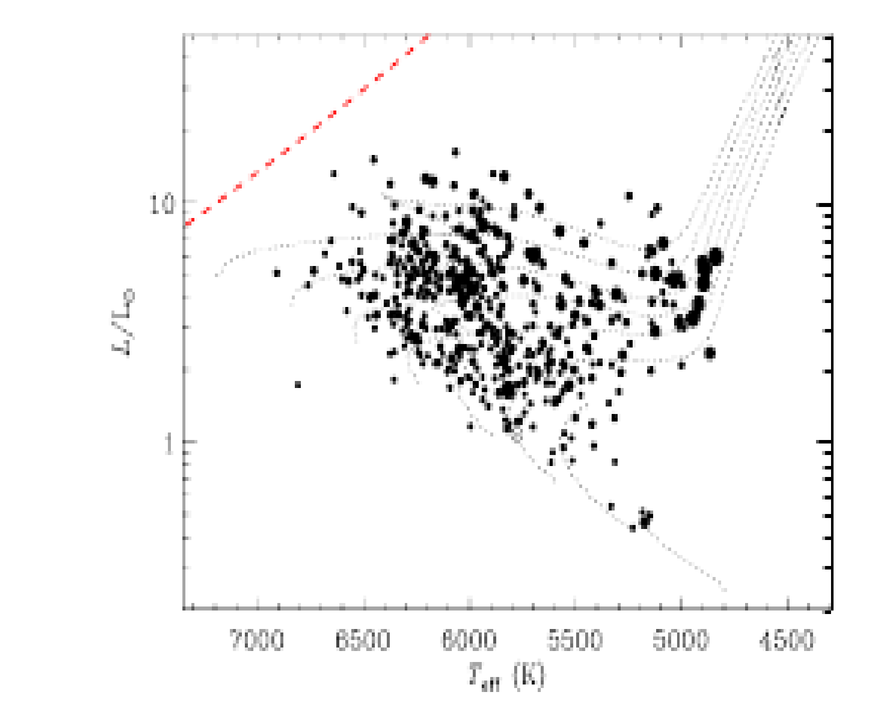
Largest limiting factor: unknown convective overshooting in models...

Kepler asteroseismology

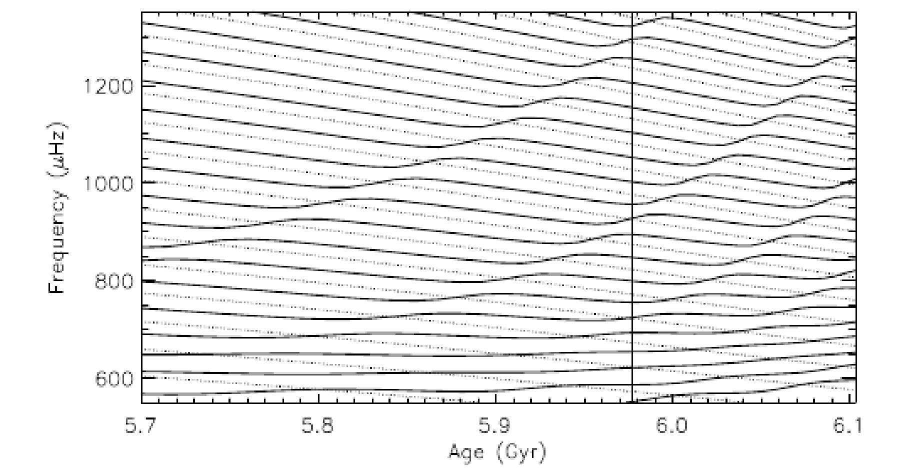
Kallinger et al (2010): disentangling of granulation, stellar activity and oscillations IMPORTANT in context of exoplanetary formation and evolution of angular momentum



Kepler ensemble asteroseismology



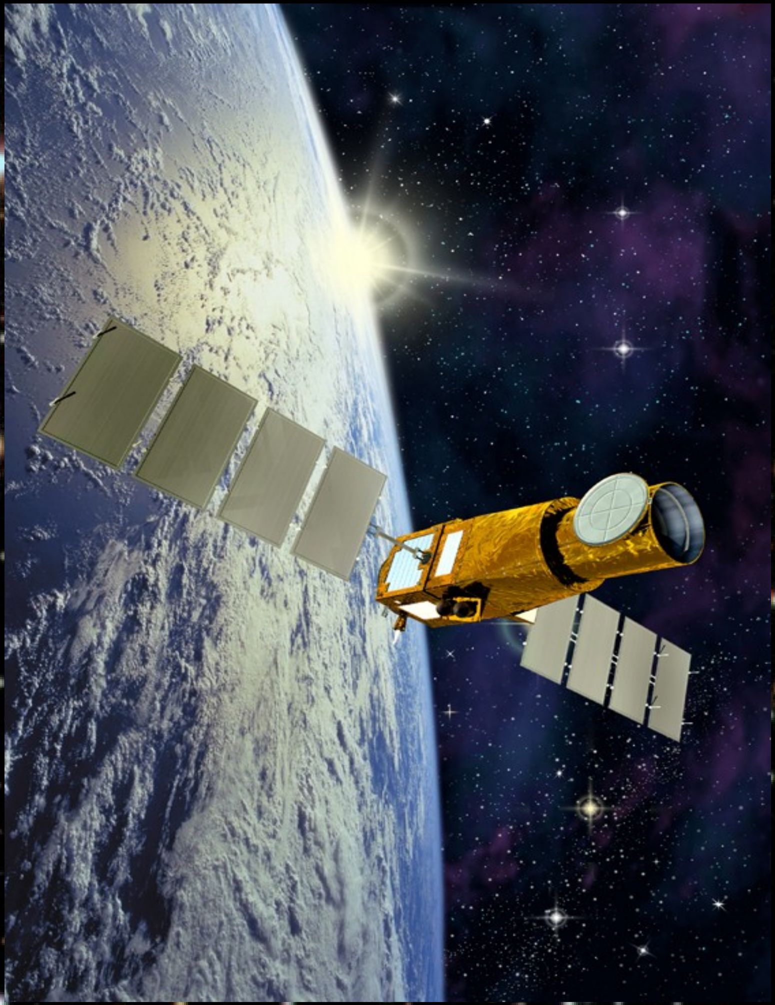
The power of mixed modes when deducing stellar ages



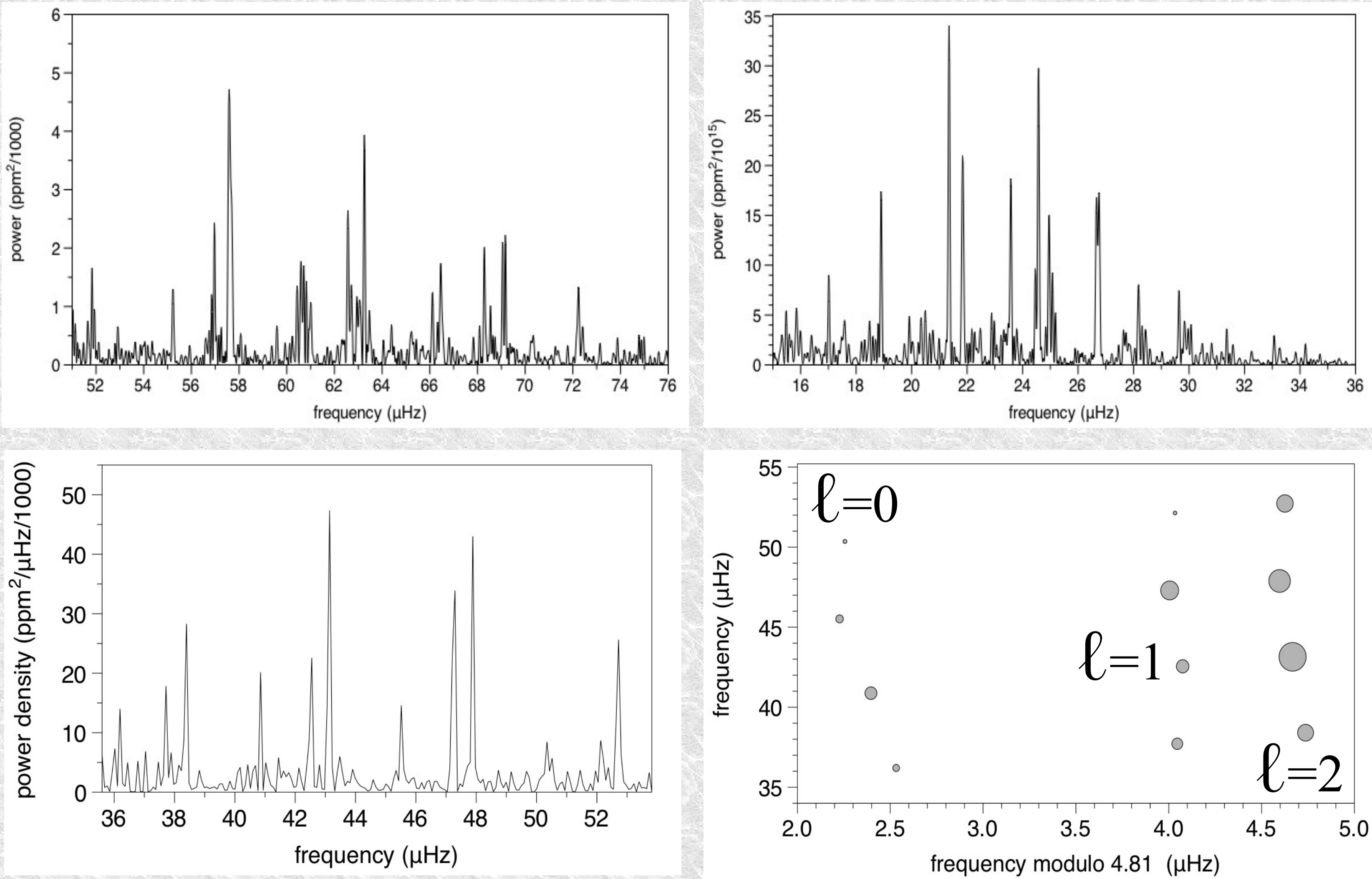
Stellar ages factor 10 better than classical methods (see Soderblom, ARA&A, 2010):

Chonology of stellar and planetary systems!

Red-Giant Asteroseismology : from stars to populations

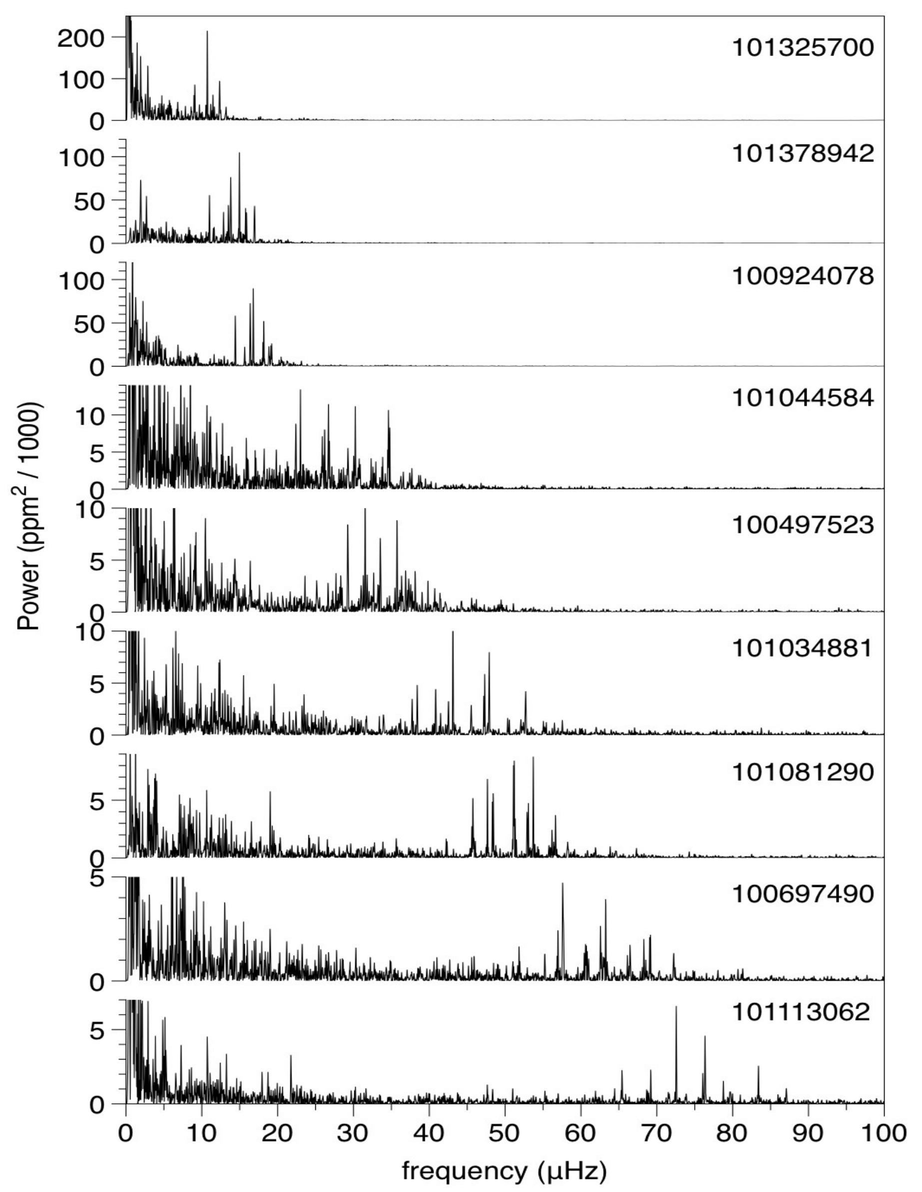


First CoRoT results : red giants



De Ridder et al. (2009): > 100s new exo RG pulsators

First CoRoT results : red giants



De Ridder et al. (2009):

observations in sismo and exo CCDs

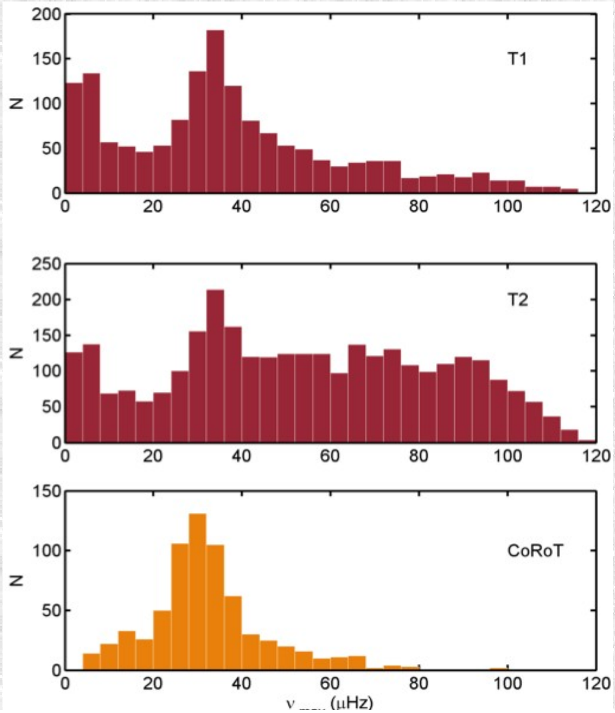
numerous RG pulsators found in exo data

non-radial pulsations!!

both short and long mode lifetimes: few to tens of days

opens up red part of HRD for asteroseismology

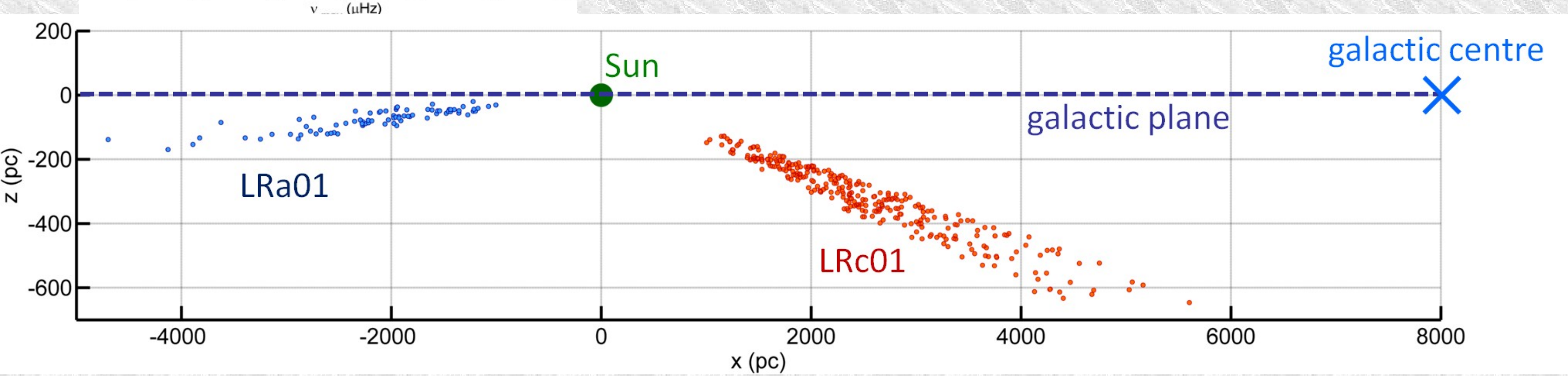
CoRoT: population seismology



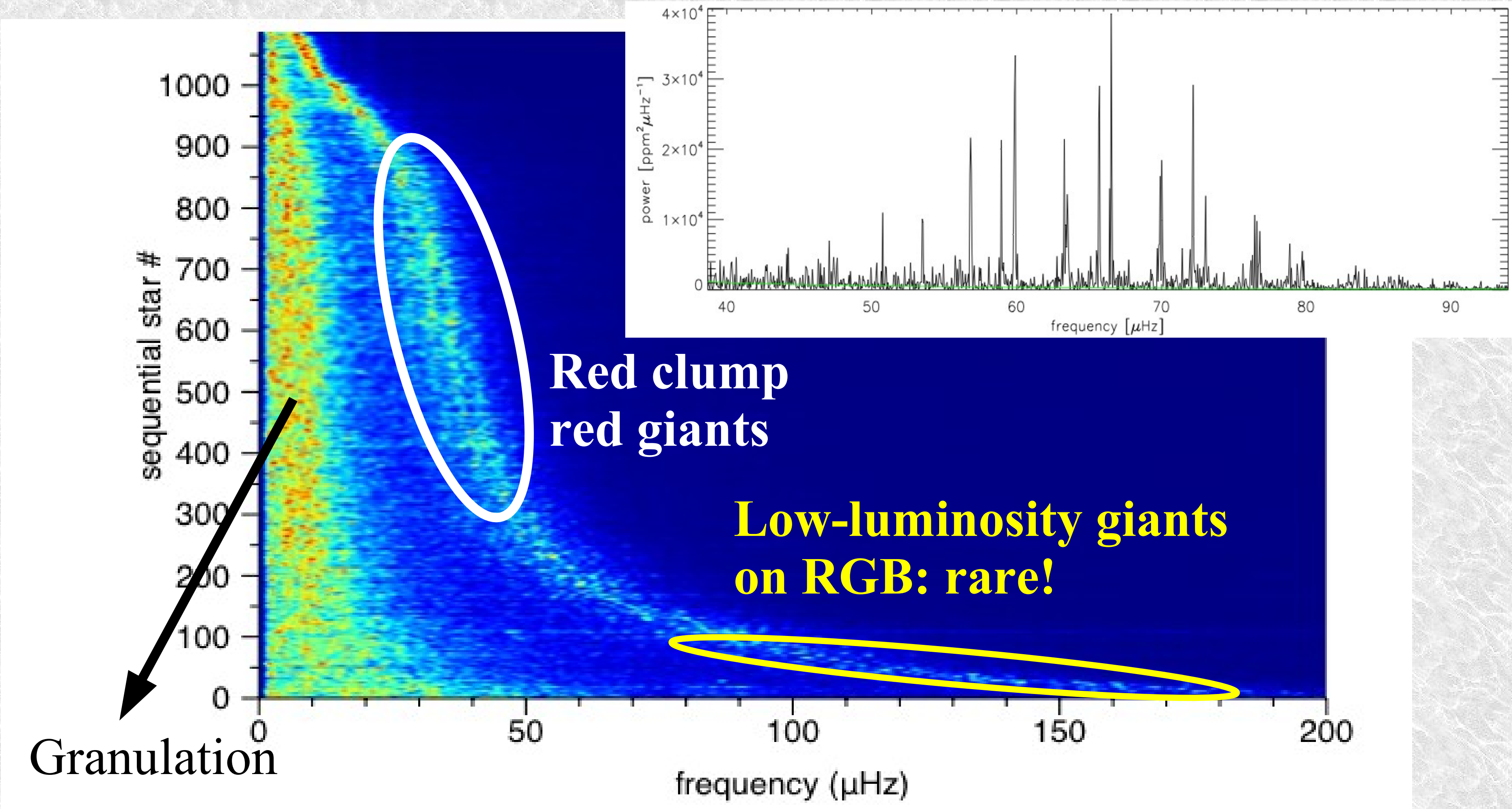
Miglio et al. (2009):
population synthesis combined with asteroseismology in large sample of RG

recent starburst or not?

No longer restricted to individual stars, but entire populations and probing of the structure and evolution of the Milky Way!

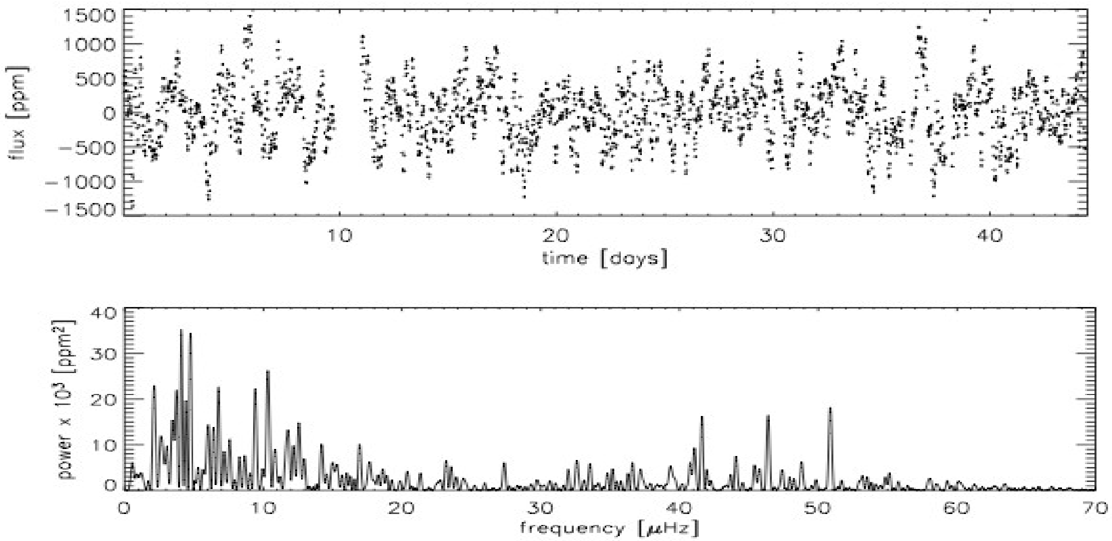


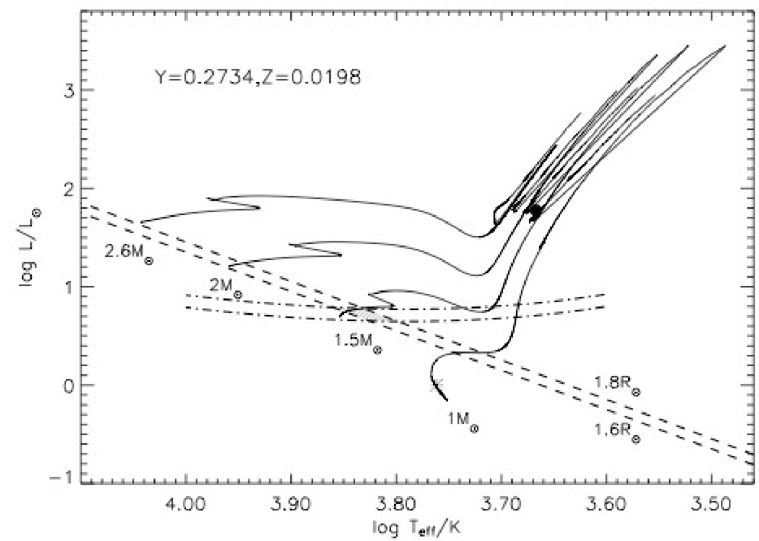
Kepler red giants: beautiful!! (Q1)



Bedding et al. (2010), Hekker et al. (2010), Huber et al. (2010), Kallinger et al. (2010) : much more to come!! (embargoed...)

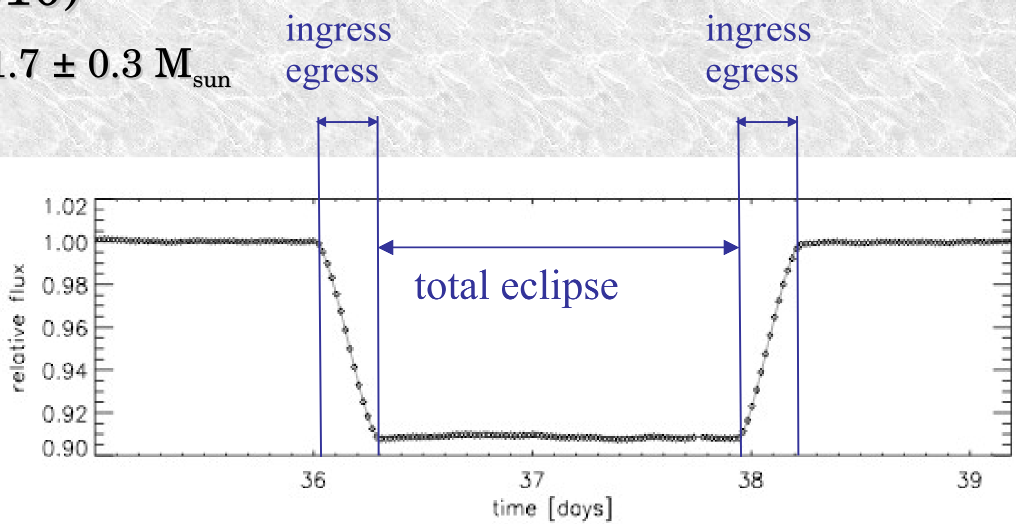
Seismology of pulsators in EBs: timing!...



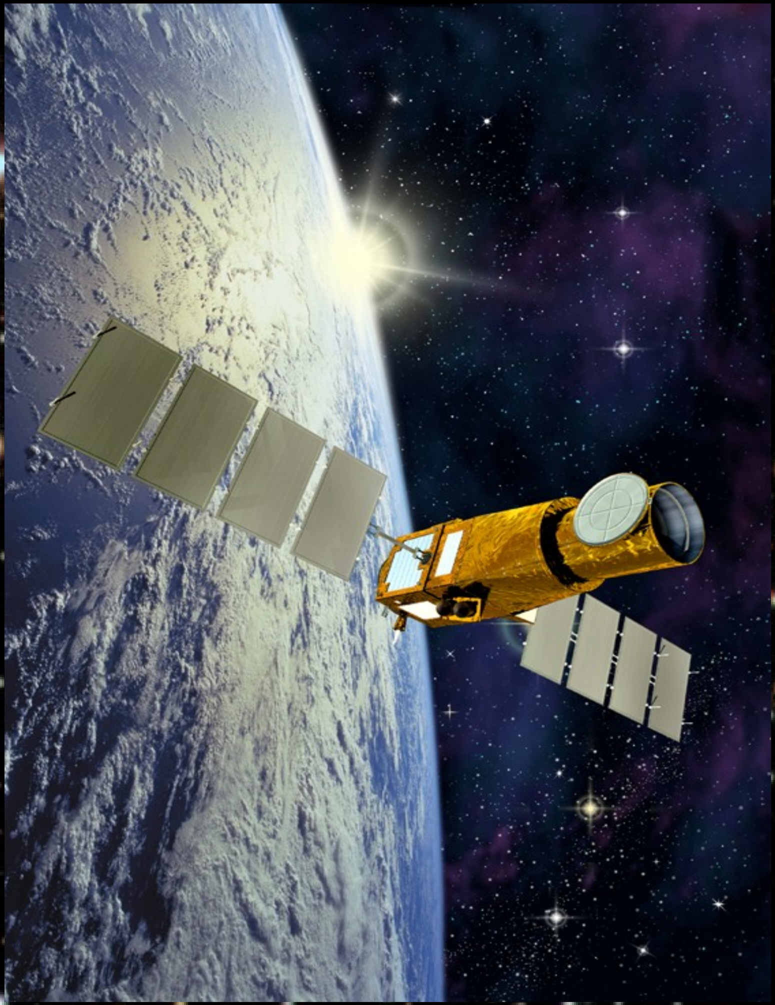


Hekker et al. (2010)

- $R_R = 11.8 \pm 0.6\ R_{sun}$ $L_R = 58 \pm 6\ L_{sun}$ $M_R = 1.7 \pm 0.3\ M_{sun}$
- Eclipse depth = 9% $\Rightarrow L_2 = 5.2 \pm 0.7\ L_{sun}$ thus $M_2 = 1.44 \pm 0.05\ M_{sun}$
- Eclipse time = 1.64 ± 0.01 d, Ingress/egress time = 0.276 ± 0.007 d
- $R_2 \leq 1.7 \pm 0.1\ R_{sun}$ $T_{eff,2} = 6700 \pm 200$ K



Massive Star Asteroseismology : some unexplainable suprises...



Pre-Space results for B stars

Compatible with EB & isochrone fitting

Ref.	Star	Mass ($M_\odot$)	SpT	α_{ov} (Hp)	ΩR(km/s)	$\Omega_{core}/\Omega_{env}$
(1)	HD 16582	10.2 ± 0.2	B2IV	0.20±0.10	28(14?)	
(2)	HD 29248	9.2 ± 0.6	B2III	0.10±0.05	6±2	~5
(3)	HD 44743	13.5 ± 0.5	B1III	0.20±0.05	31±5	
(4)	HD 129929	9.4 ± 0.1	B3V	0.10±0.05	2±1	3.6
(5)	HD 157056	8.2 ± 0.3	B2IV	0.44±0.07	29±7	~1

(1) Aerts et al. (2006): 20 d MOST photometry + 1 week spectra

(2) Pamyatnykh et al. (2004); Ausseloos et al. (2004): 5 months multisite photometry + spectroscopy

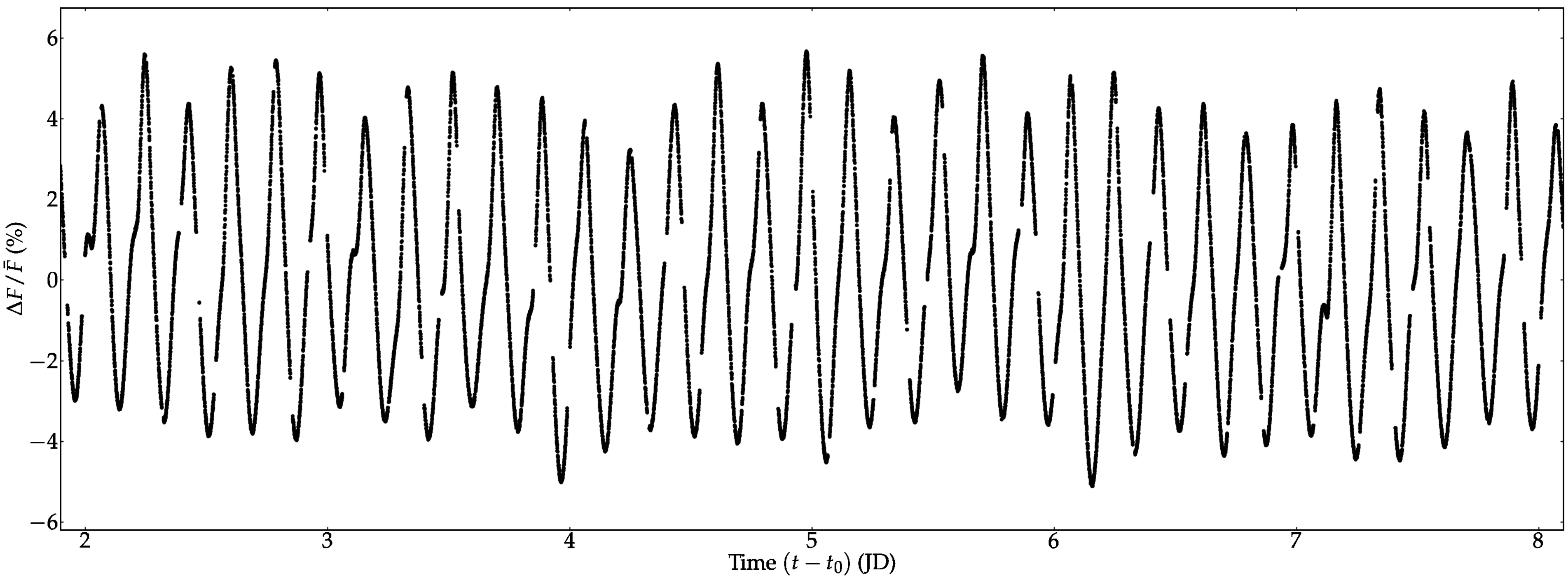
(3) Mazumdar et al. (2006): 4 years high-resolution spectroscopy

(4) Aerts et al. (2003, 2004); Dupret et al. (2004): 20 years photometry

(5) Briquet et al. (2007): 2 years spectroscopy + few months photometry

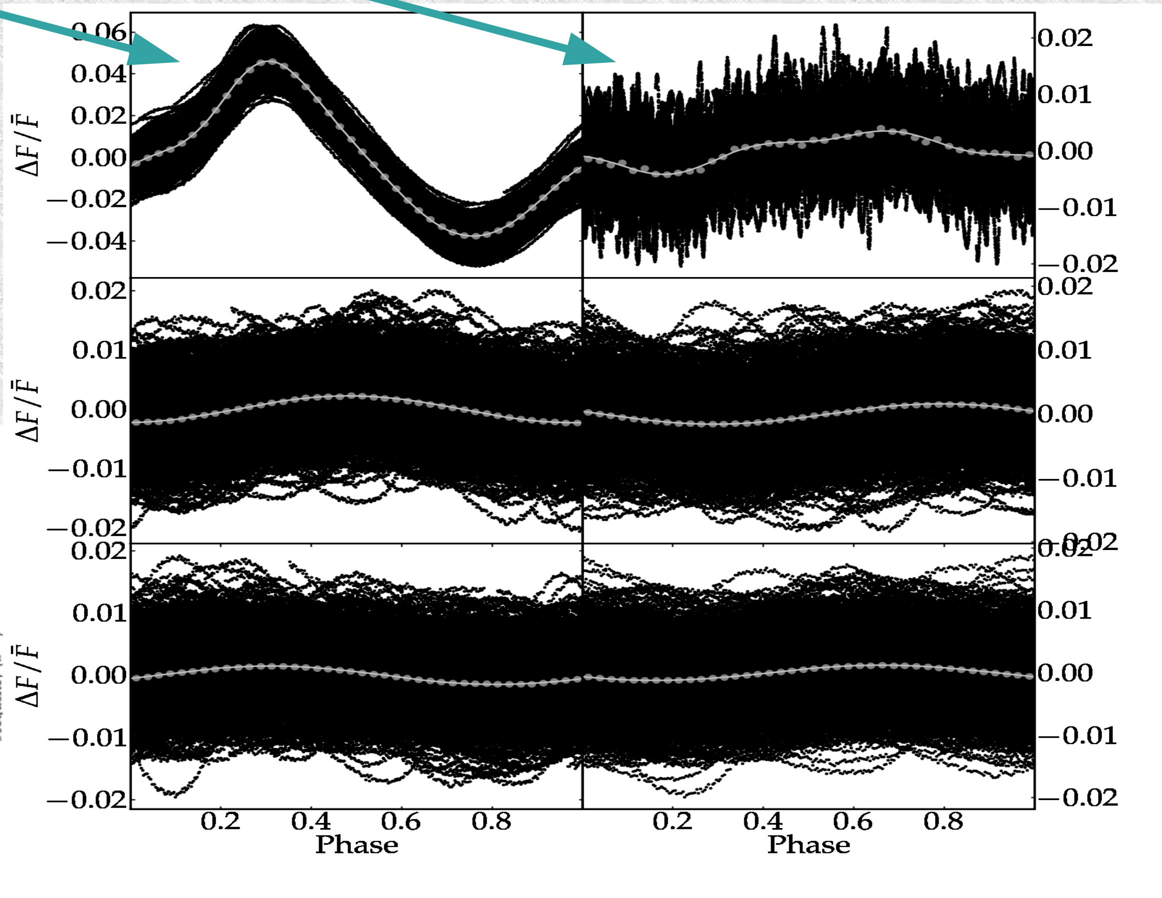
CoRoT data of a Beta Cep star

- HD 180642 discovered from HIPPARCOS (Aerts 2000)
- SpT B1.5II/III, dominant nonlinear radial mode
- CoRoT 379785 datapoints, 32sec integration, 156.6 days
- Worked in flux, not magnitude; linear trend removed

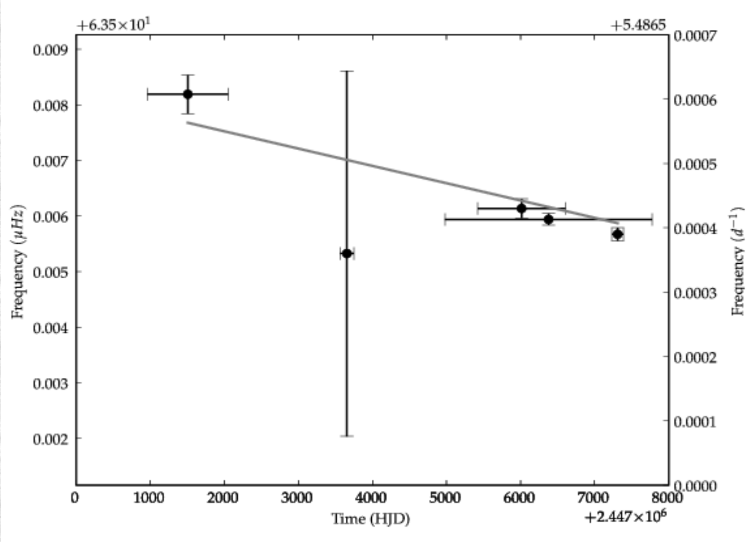


HD 180642: LC modelling

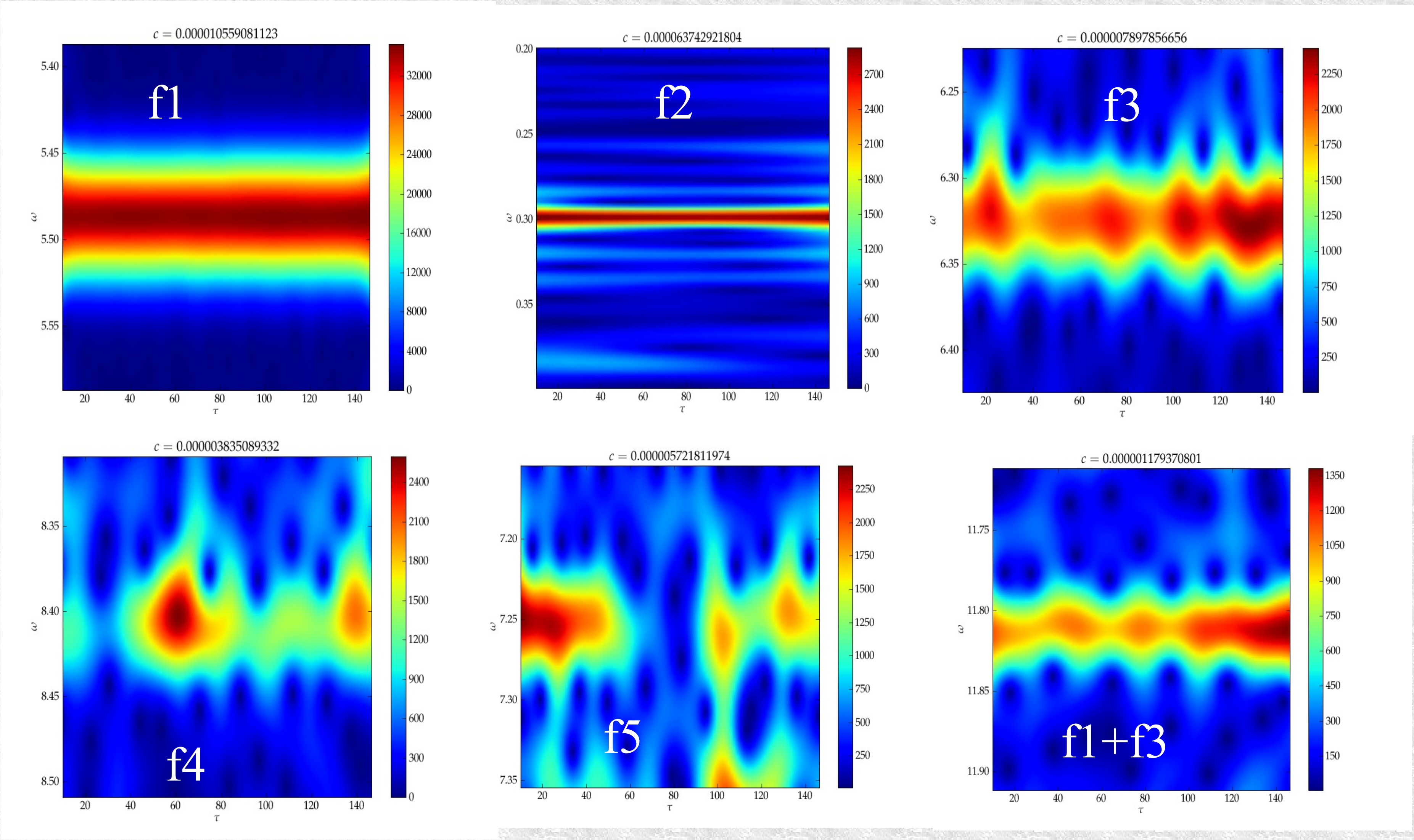
- **Dominant modes (in μHz): 63.50566 (5 harmonics), 3.46262 (3 harmonics), 73.20389, 97.32853, 83.96709, 136.70880**



- **Evolutionary frequency decrease of 0.027 sec/year**

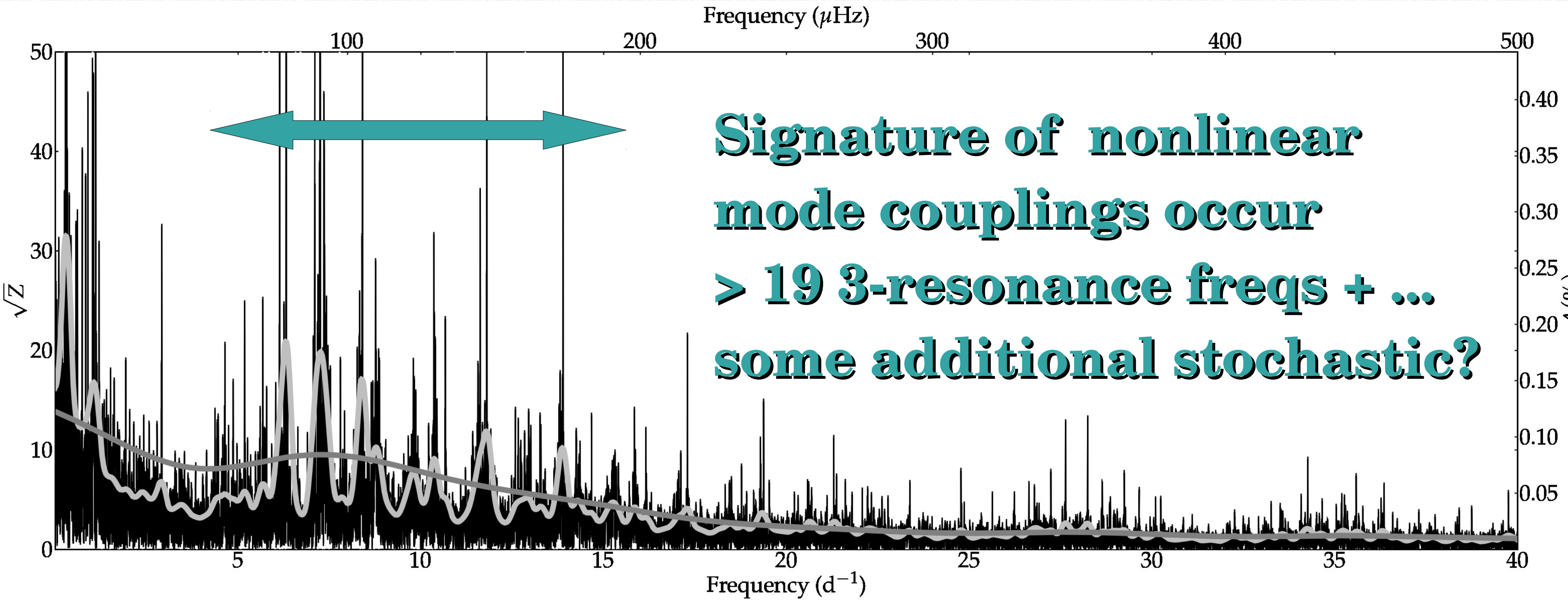


CoRoT data of a Beta Cep star



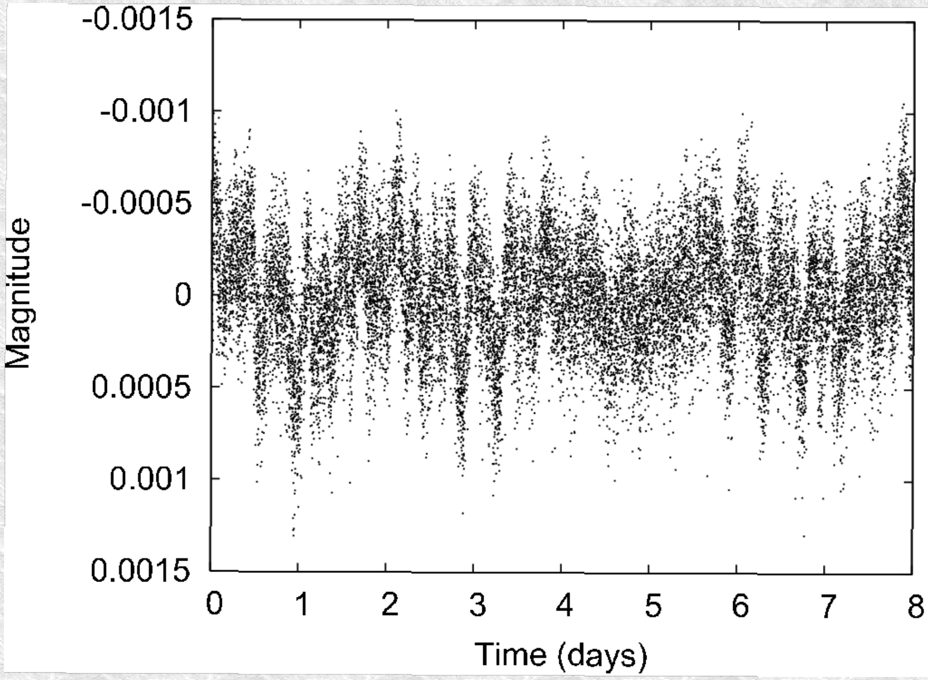
HD 180642: LC modelling

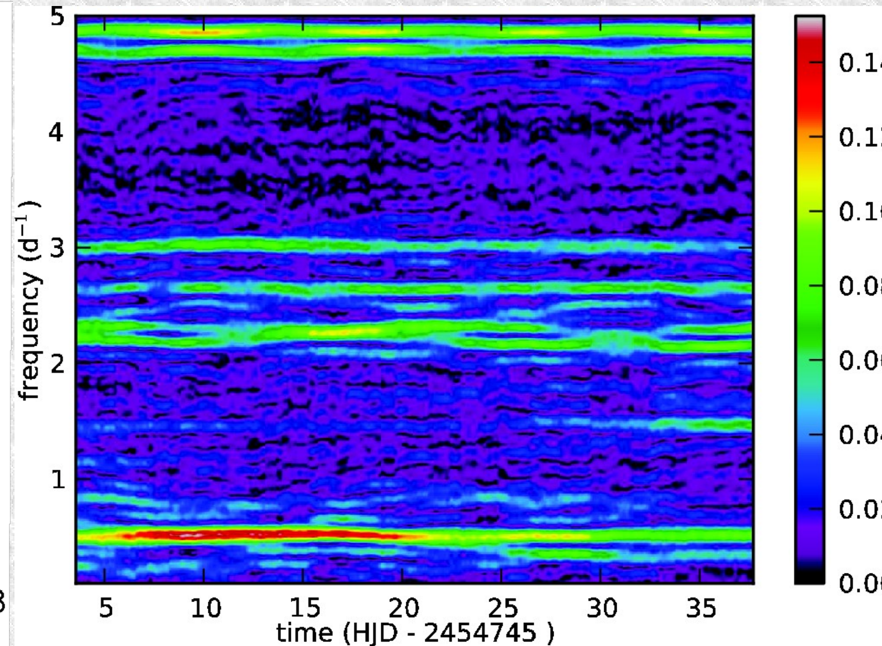
- Periodogram after prewhitening of dominant mode
- Light gray: smoothed over 0.1/d, dark: over 2/d



- Star is most evolved of all known Beta Cephei stars, near TAMS
- Rotational splitting ?; theoretical modelling is ongoing (standard MI methods do not work due to nonlinearity...)

CoRoT data of an O9V star



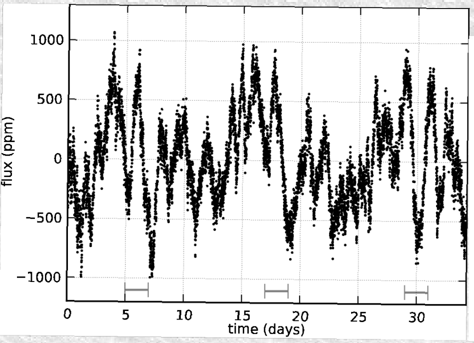


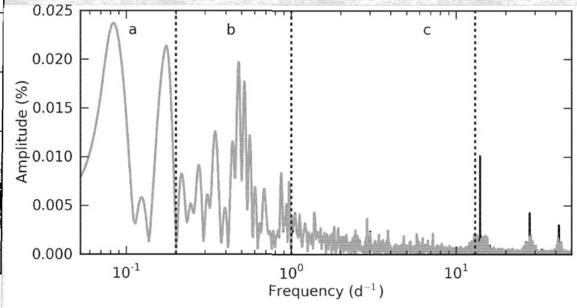
ID	$f(\mathrm{d}^{-1})$	$f(\mu\mathrm{Hz})$	Amplitude (mmag)	S/N ratio
f_1	0.510	5.901	0.1079	9.3
f_2	4.856	56.204	0.0934	11.7
f_3	4.691	54.295	0.0798	10.7
f_4	2.290	26.500	0.0708	8.5
f_5	2.643	30.586	0.0645	7.7
f_6	3.004	34.769	0.0587	7.2
f_7	2.195	25.404	0.0460	5.7
f_8	1.462	16.919	0.0426	5.6
f_9	2.222	25.722	0.0339	4.8
f_{10}	0.804	9.305	0.0314	4.5
f_{11}	2.127	24.613	0.0307	4.3
f_{12}^*	13.973	161.728	0.0298	10.6

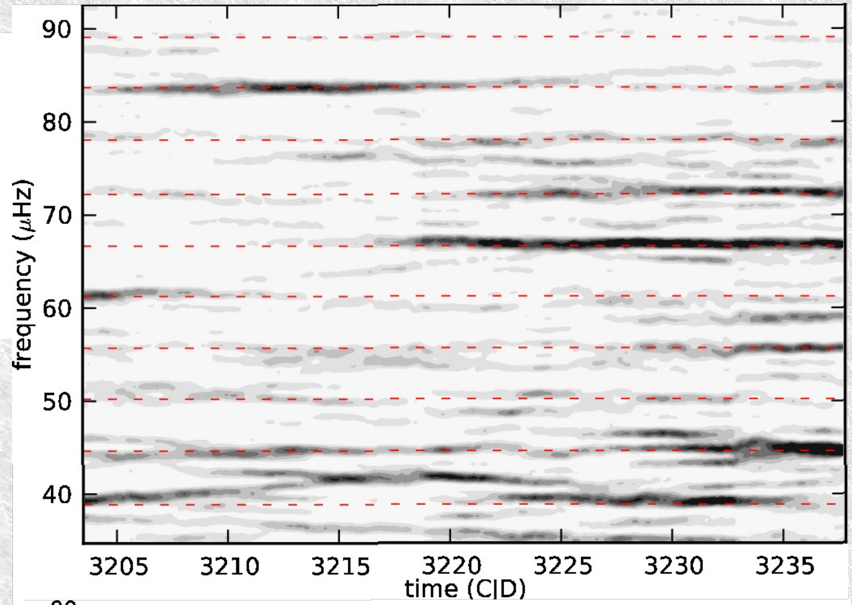
* the satellite's orbital frequency

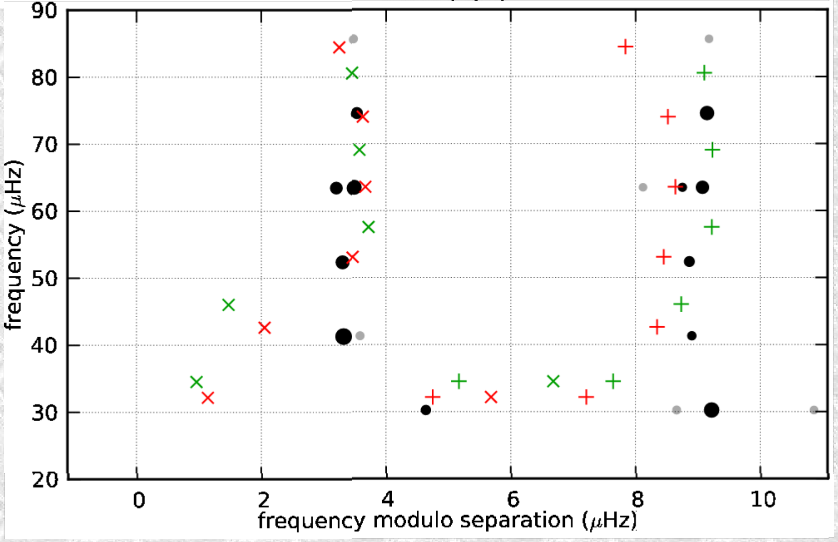
HD 46202, O9V
none of detected freqs predicted to be excited...

CoRoT data of a O8 binary









HD 46149, an O8V+B

Porb=829d, e=0.59

M_1=35M☉, M_2=19M☉

Stochastic oscillations following scaling law of solar-like stars:

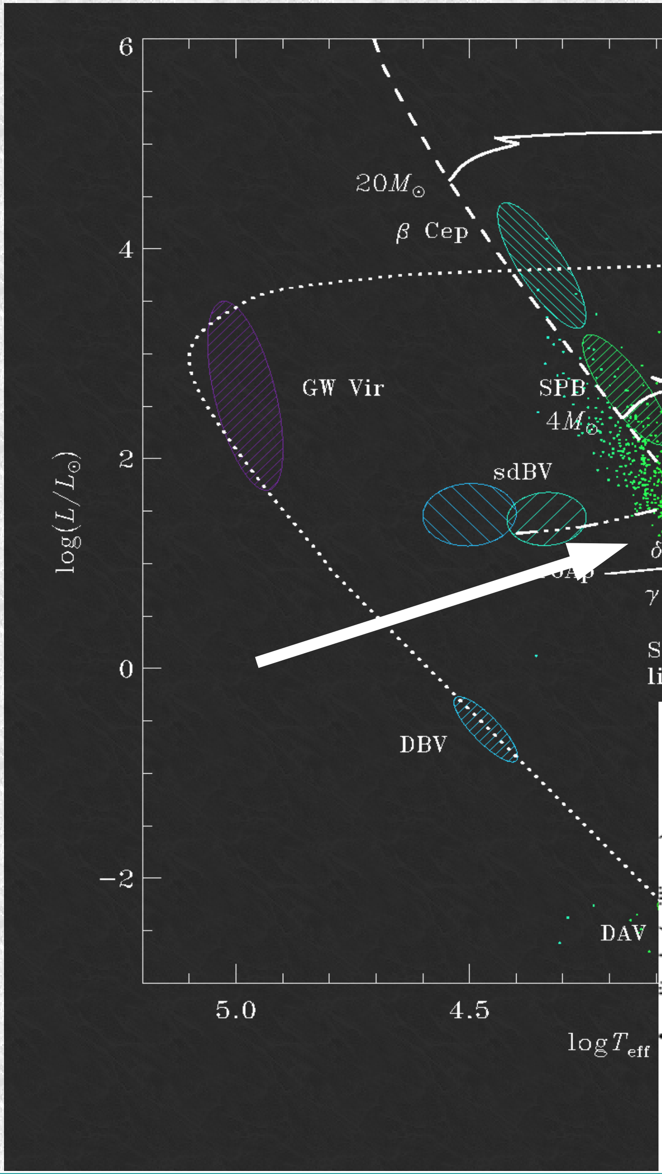
unknown convection...

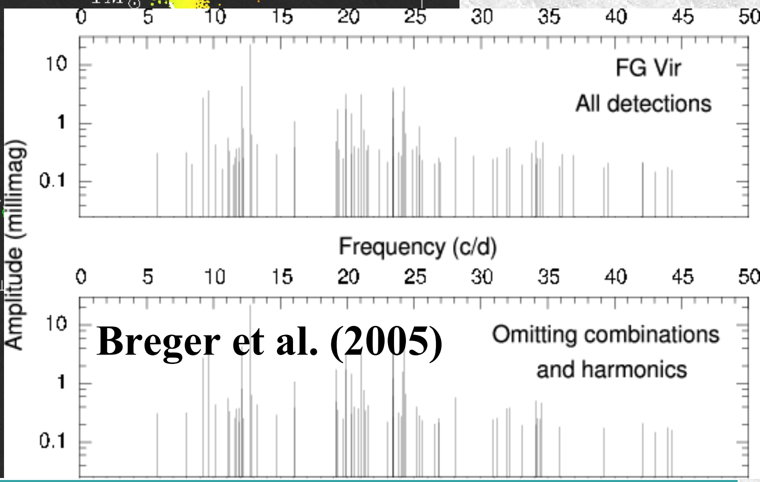
Pre-CoRoT results for AF stars

α_{ov} (Hp) ??
$\Omega(r)$??

seismic modelling not successful due to lack of mode id.

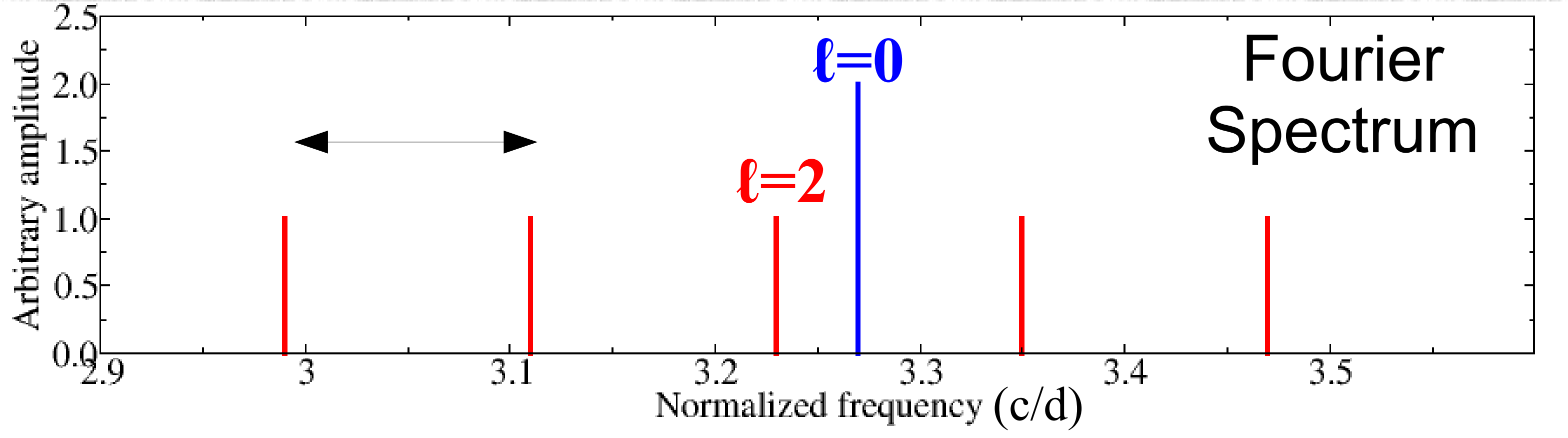
numerous frequency detections from ground networks and MOST team





Breger et al. (2005)

Problem: merged multiplets



Rotation splits each mode in

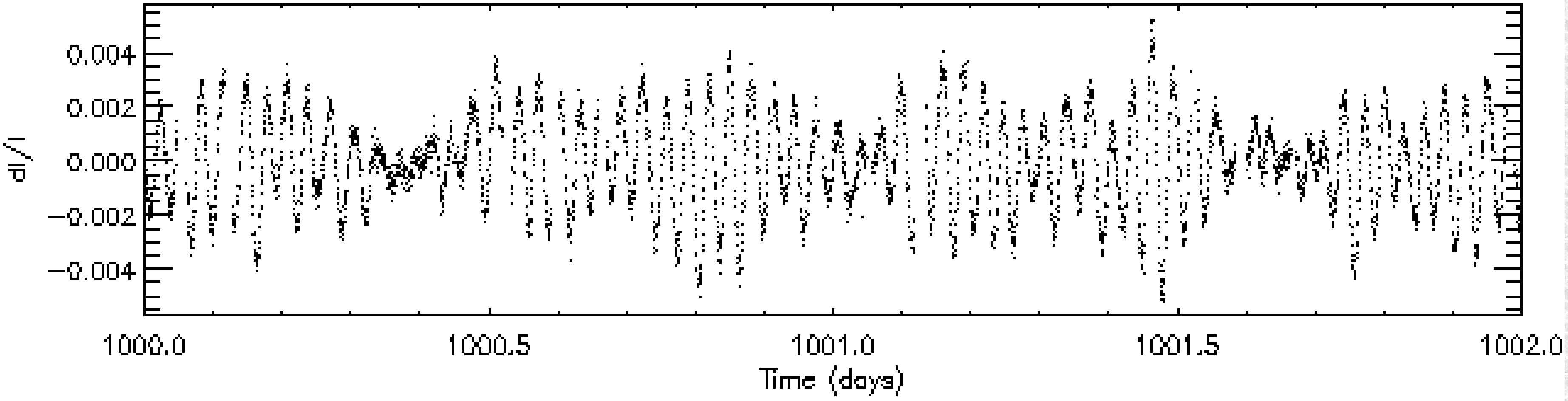
2ℓ +1 unequidistant components

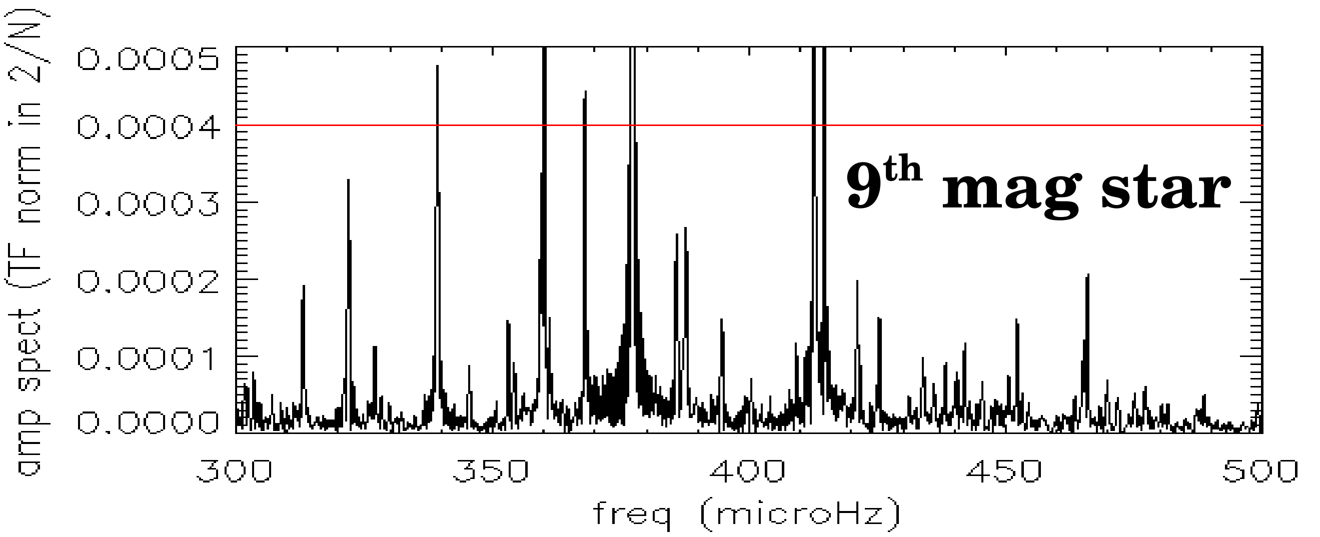
Example shown: simulated

1.8 Msun Delta Scuti star (Goupil et al., 2000)

$$\nu_m = \nu_0 \left(1 + a\, m \left(\frac{\Omega}{\nu_0}\right) + (b\, m^2 + c) \left(\frac{\Omega}{\nu_0}\right)^2 + \cdots \right)$$

CoRoT data of a new Delta Sct star

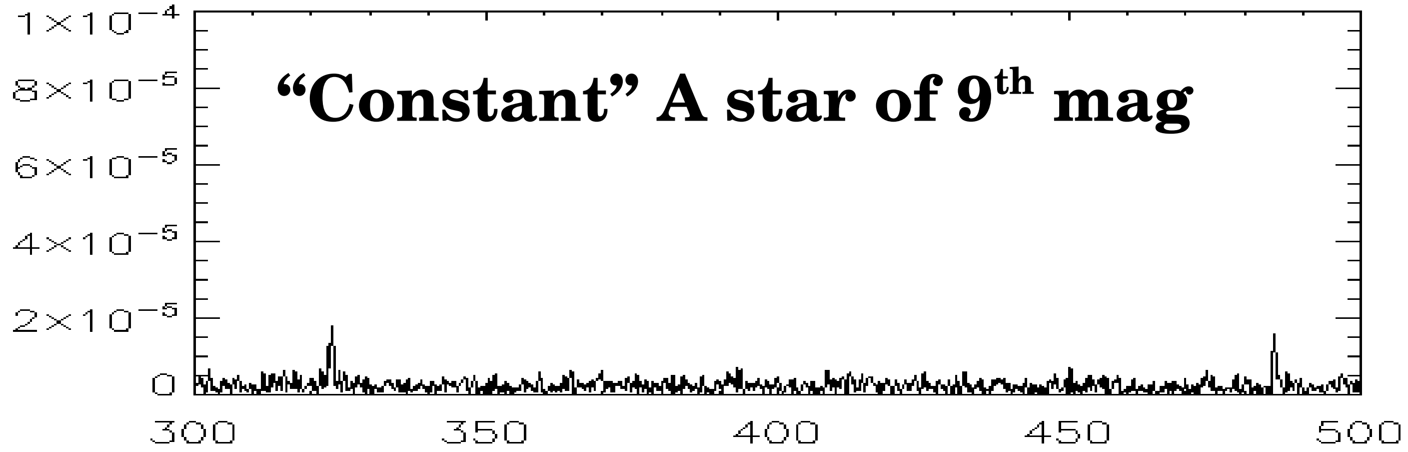




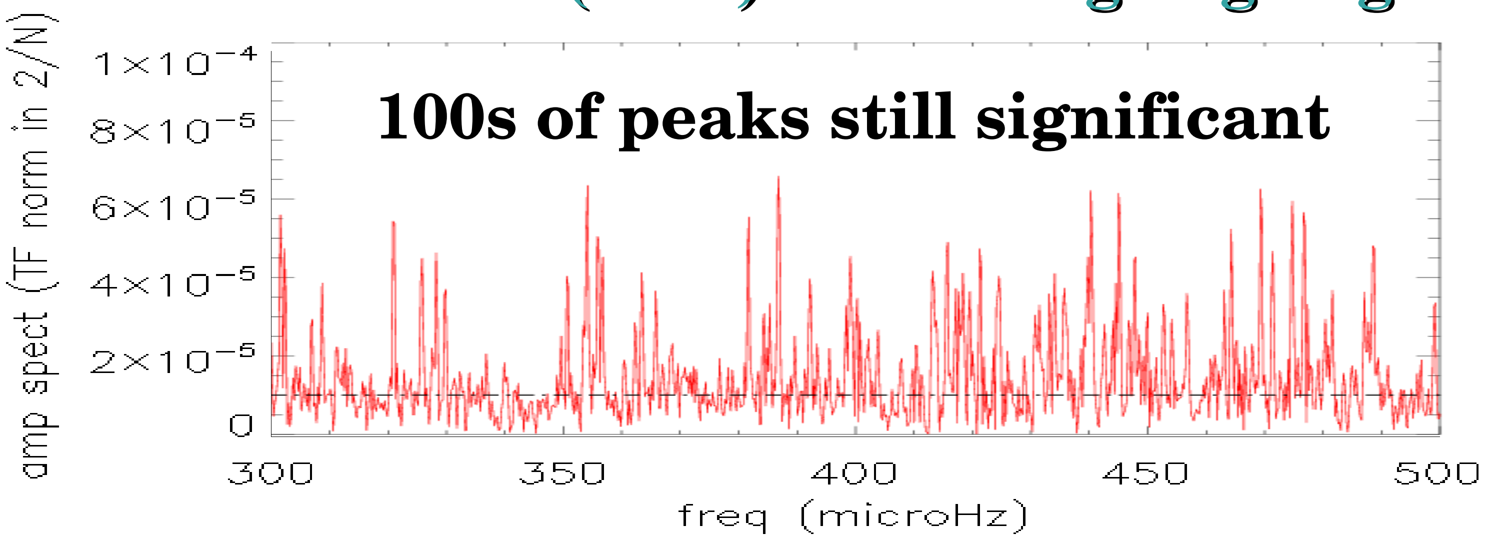
Ground based limit after several weeks

Michel et al. (2009)

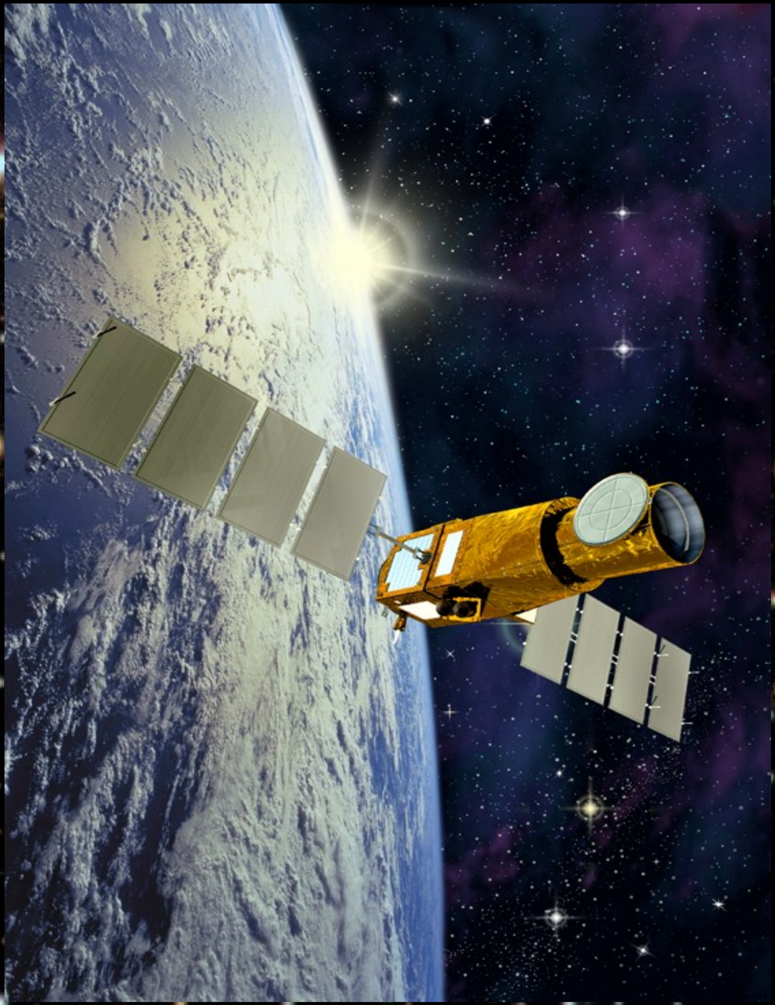
CoRoT data of Delta Sct star



Michel et al. (2009): modelling ongoing



Compact Star Asteroseismology with Kepler



Kepler Compact Pulsator Survey

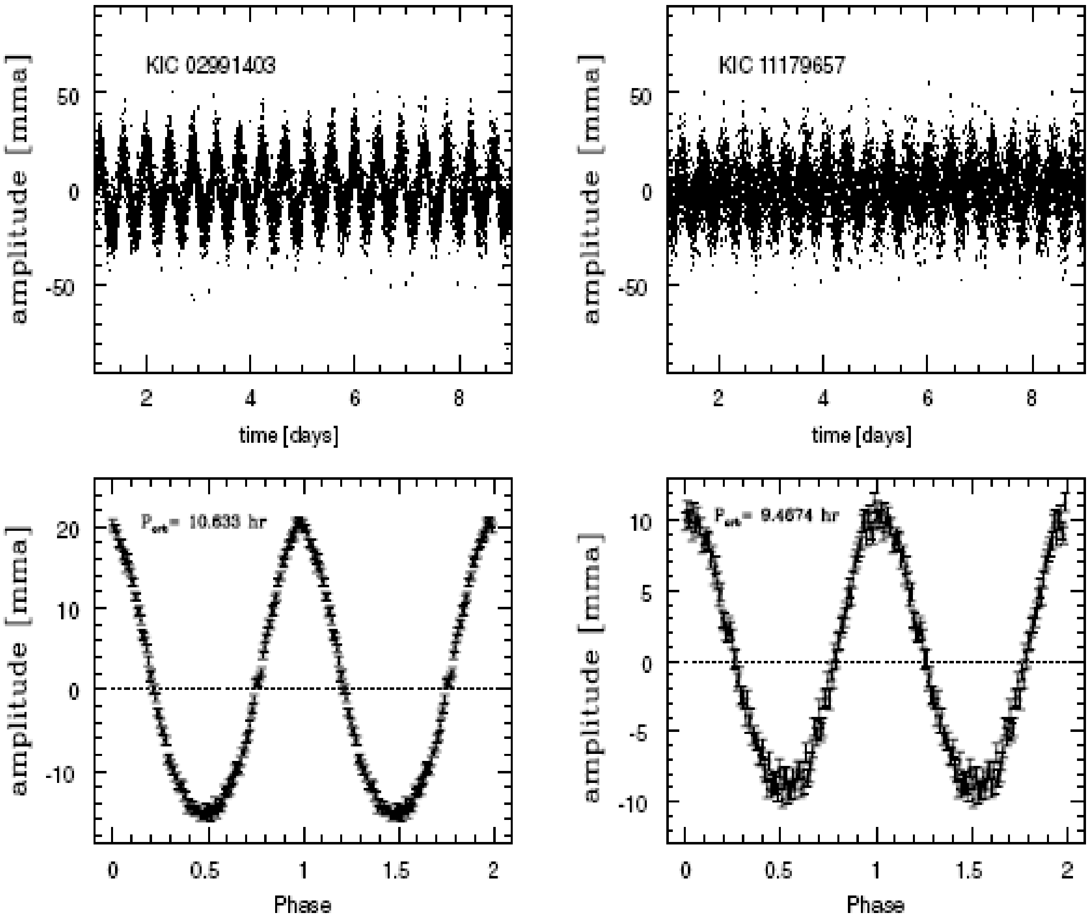
New discoveries among 110 surveyed stars

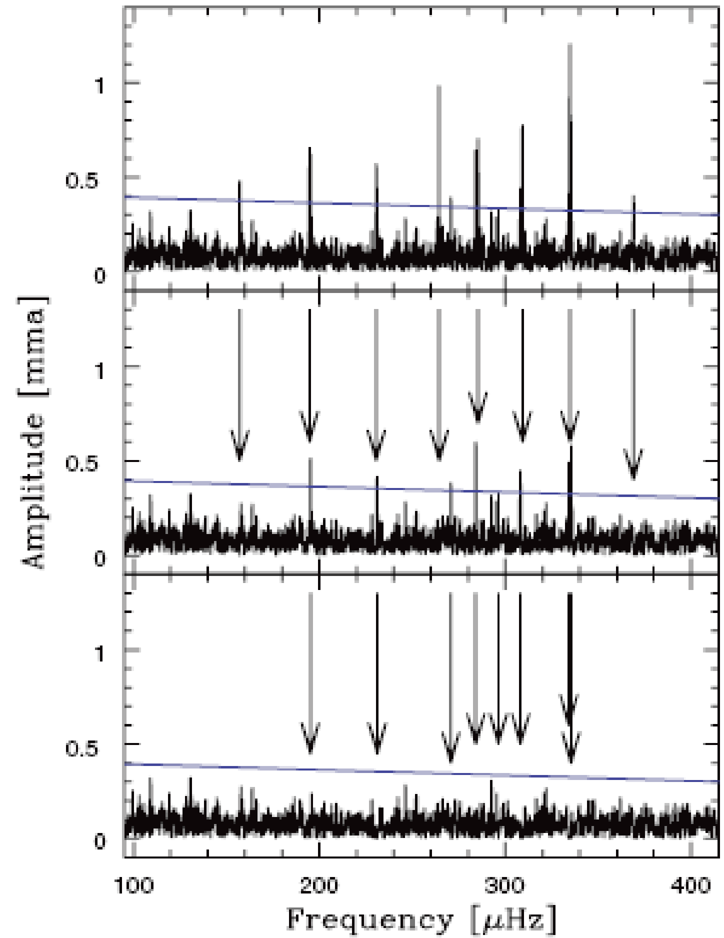
1. **Cataclysmic variables:**
   - **Nova like: 2**
   - **AM CVn: 1**
2. **Compact binaries:**
   - **eclipsing sdB+DM: 1**
   - **non-eclipsing beaming sdB+DM: 2**
   - **eclipsing pulsating sdB+DM: 1**
   - **non-eclipsing sdO+dM: 1**
   - **pulsating sdO/B+ F/G/K secondaries: 10**

Some nice results: sdB + DM

Gravity-mode pulsations in compact binaries

Kawaler et al. (2010)

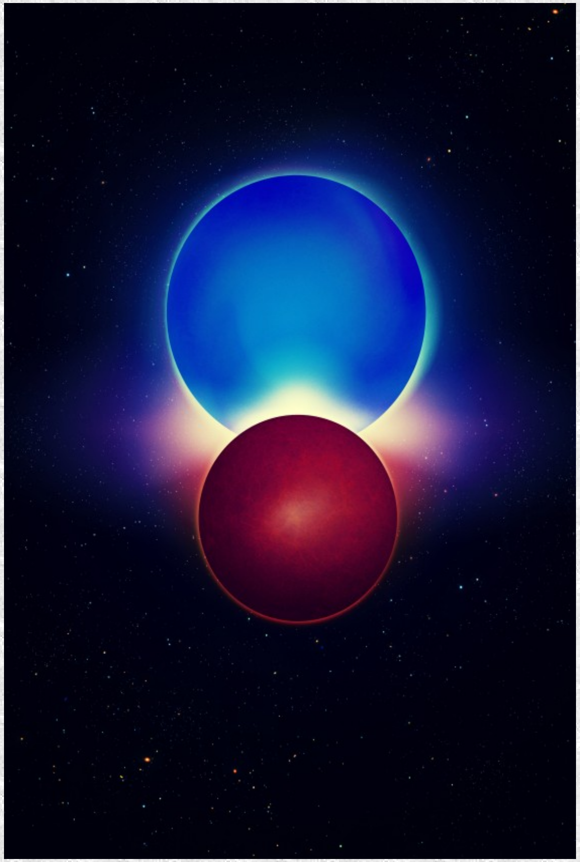


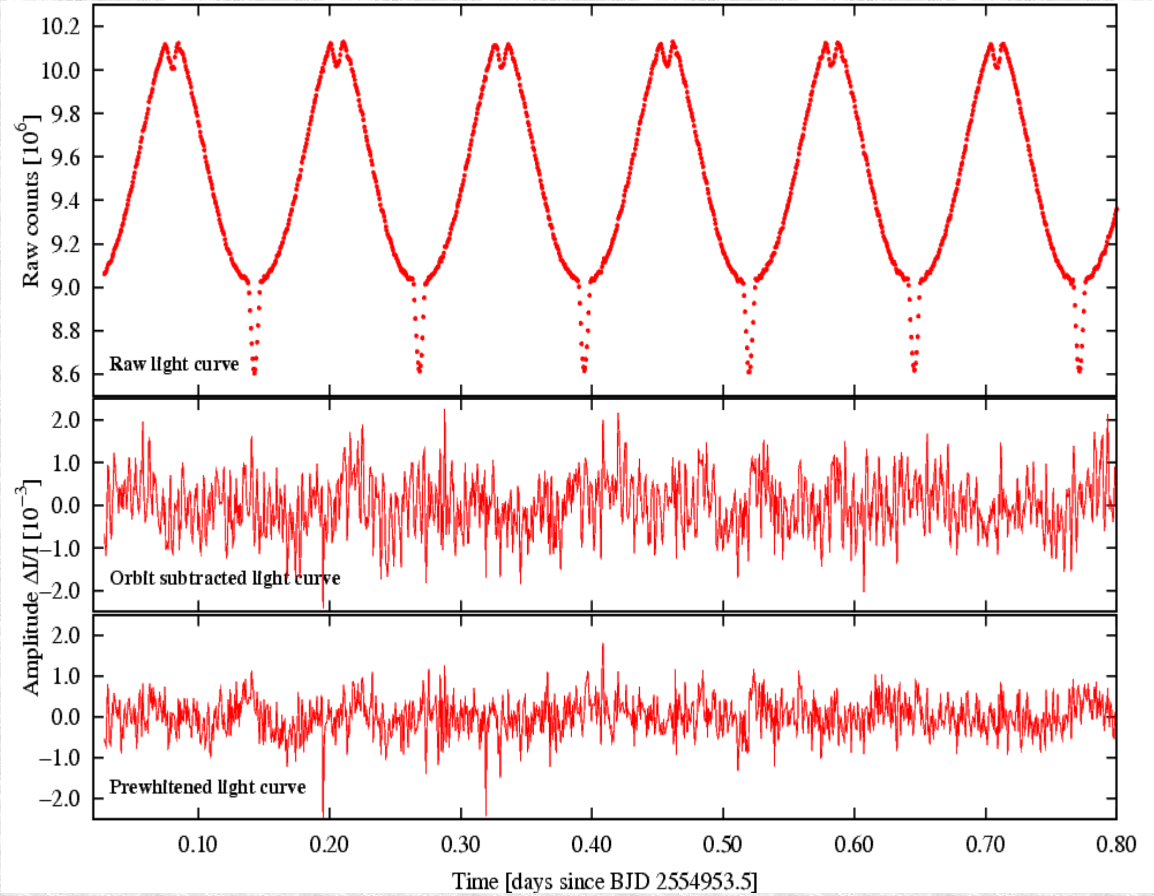


Nice result: hybrid pulsator EB

Physics of NRP at extreme irradiation?

Porb = 0.125765300(21)d, (Østensen et al. 2010)

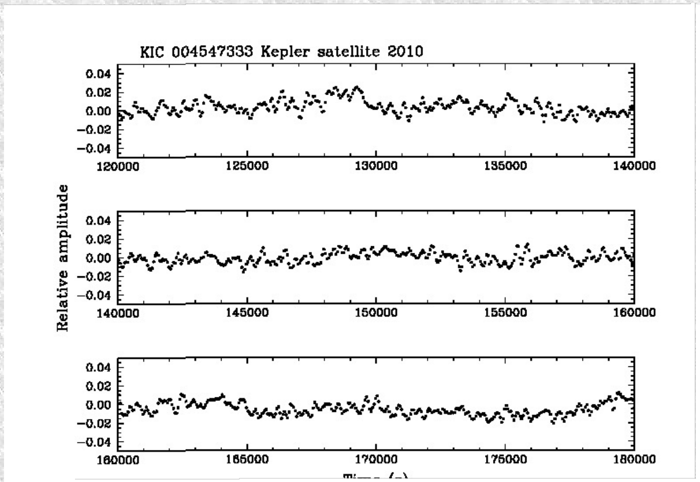


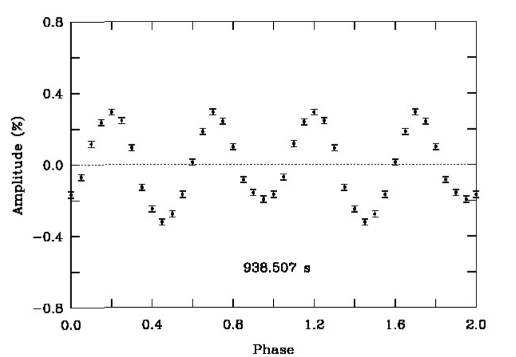


Discovery of AM CVn star in FoV

AM CVn nature deduced from spectroscopy

Porb = 938 s, Prot = 16.8 h (Fontaine et al. 2010)





Will surely bring new insights in tidal and accretion theory

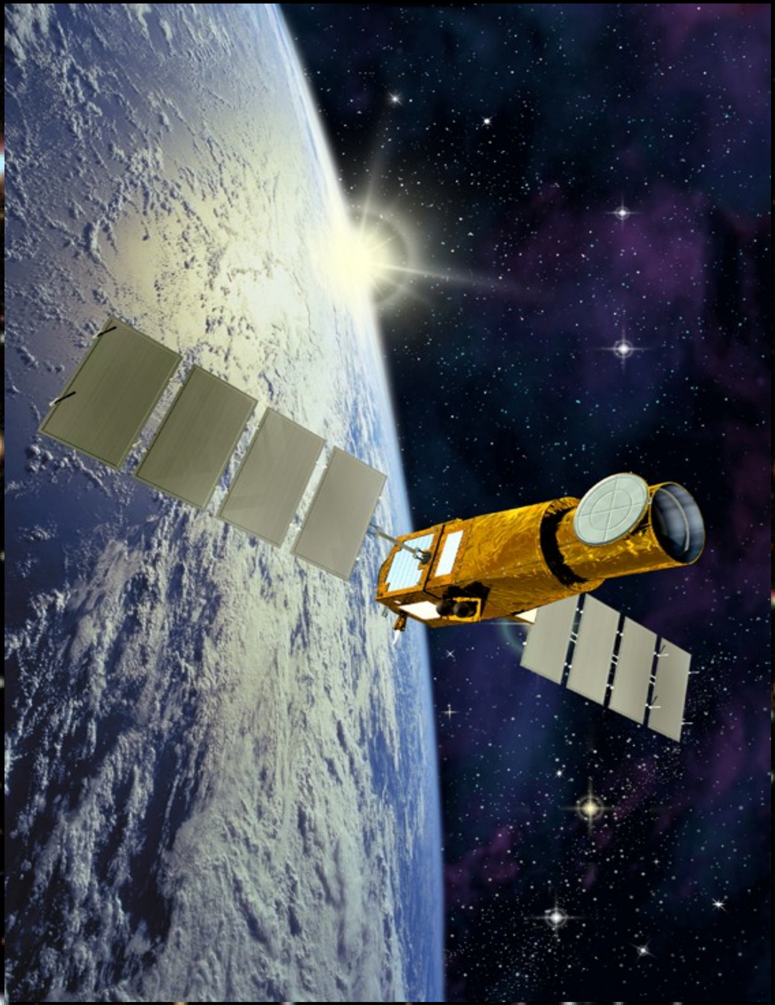
Table 1. A Possible Three-Clock Model

Combination	Combination Frequency (μHz)	Observed Frequency (μHz)	ID
$\omega - \Omega$	1048.993±0.047	1049.030±0.017	f_{01}
ω	1065.523±0.028	1065.523±0.028	f_{02}
$\omega + N$	1295.990±0.039	1296.031±0.023	f_{03}
$2\omega - 2\Omega - N$	1867.518±0.097	1867.683±0.046	f_{04}
$2\omega - \Omega$	2114.515±0.067	2114.664±0.041	f_{05}
2ω	2131.045±0.056	2131.133±0.005	f_{06}
$2\omega - \Omega + N$	2344.982±0.073	2345.101±0.027	f_{07}
$3\omega + N$	3427.035±0.075	3427.186±0.030	f_{08}
$3\omega - \Omega + 2N$	3640.972±0.107	3641.115±0.035	f_{09}
$4\omega + N$	4492.557±0.116	4492.857±0.050	f_{10}
$4\omega + 2N$	4723.024±0.119	4723.244±0.043	f_{11}

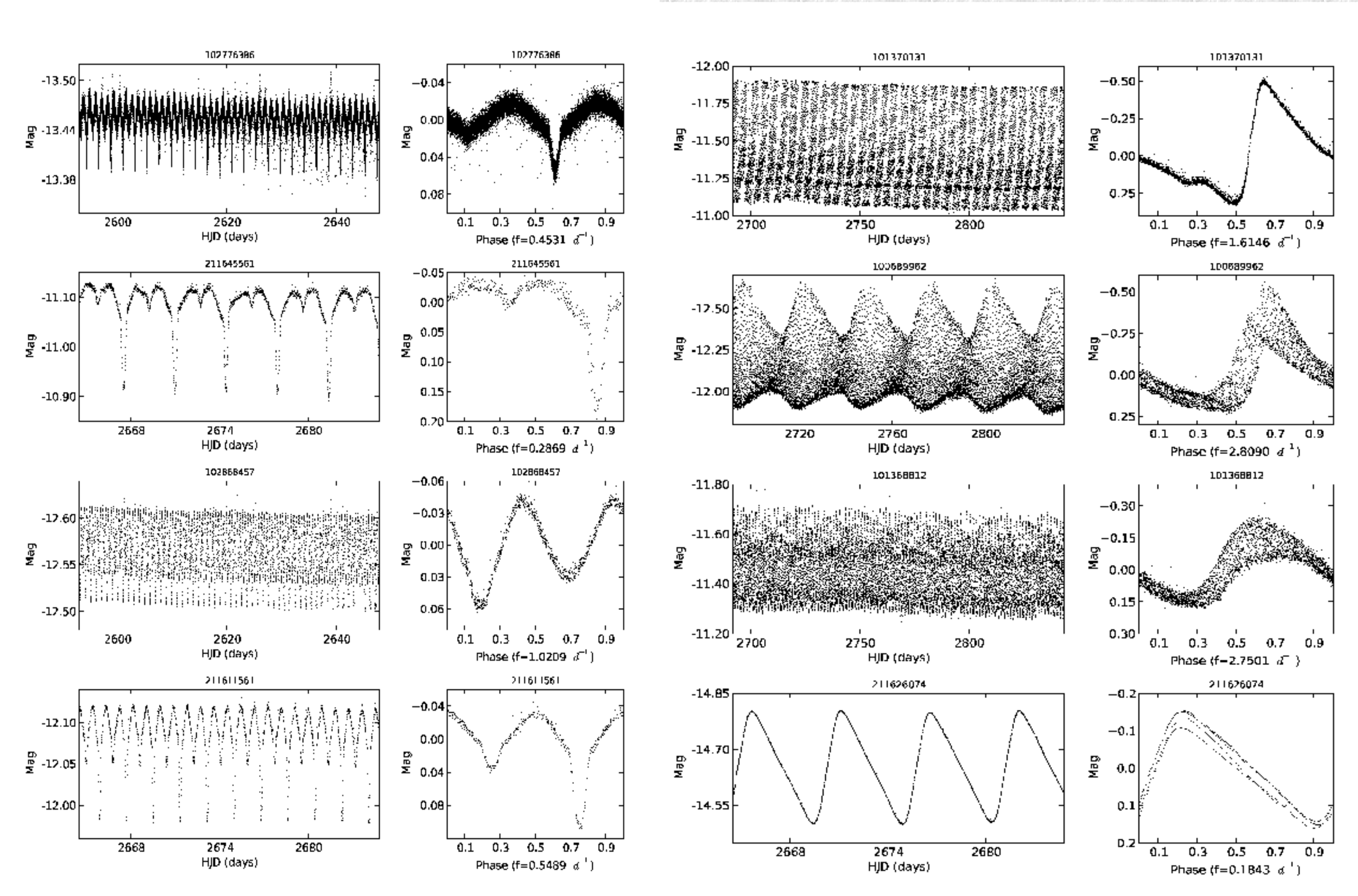
Note. — The three basic periodicities are $\omega = 1065.523$ μHz (period = 938.51 s), $\Omega = 16.530$ μHz (period = 16.80 h), and $N = 230.467$ μHz (period = 1.21 h).

All pulsation frequencies connected with the orbit and rotation...

Free By-Product of Exoplanet Search: discovery of 1000s pulsators

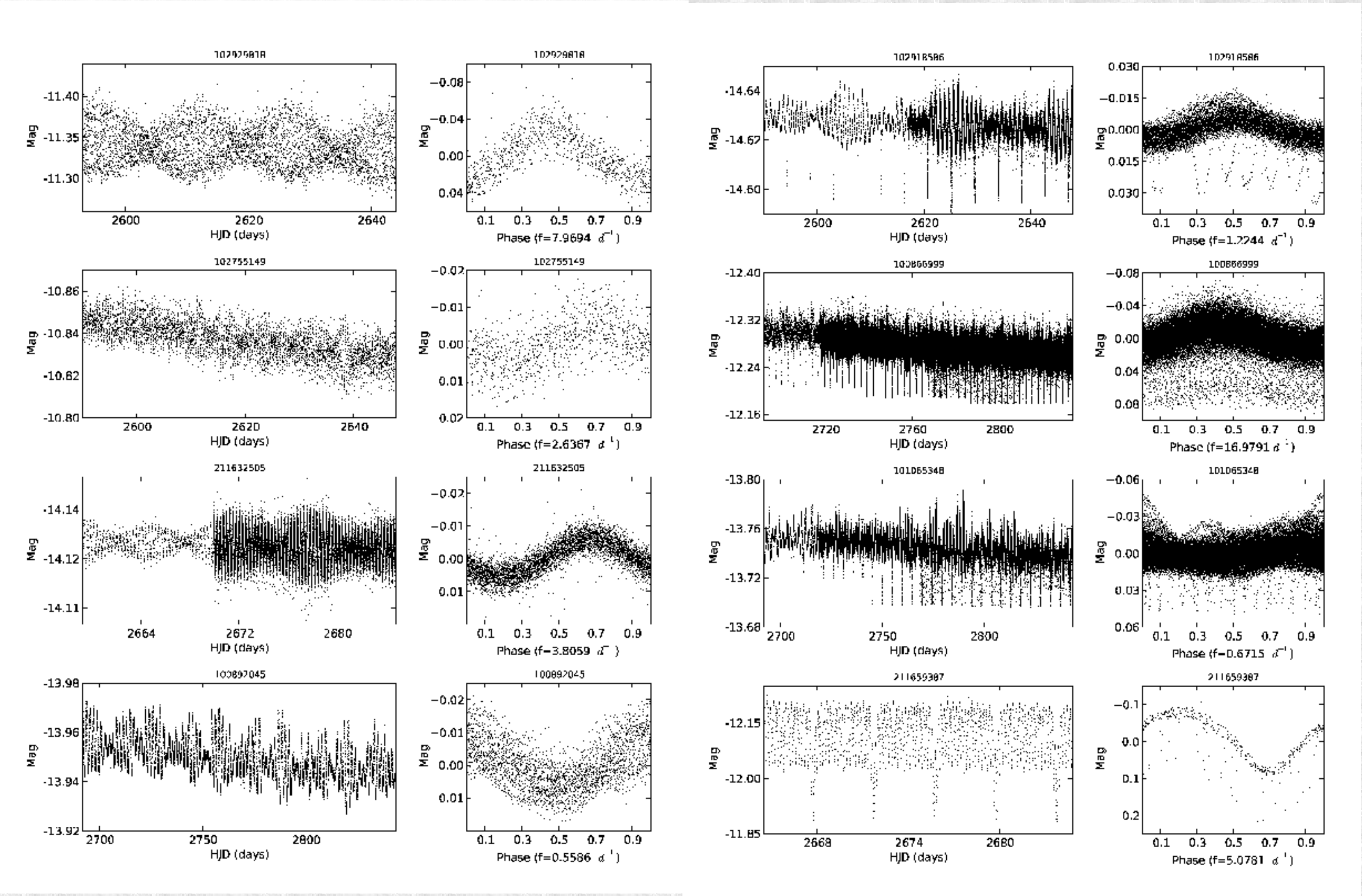


1000s of new pulsators + EBs



CVC: Debosscher et al. (2009, 2011)

1000s of new pulsators



CVC: Debosscher et al. (2009, 2011)

Asteroseismology in its golden age

- Ground-based network data have opened up the field, after helioseismology, particularly for WDs
- MOST as pioneer & CoRoT functioning excellently, they revolutionize observational asteroseismology
- Basic theory is mature; needs refinement for dense cores, rapid rotation, nonlinear mode coupling, outbursts,...
- Kepler has unique capabilities: long-term, solar-like stars, compact pulsators,... + easier for follow-up than CoRoT thanks to slightly brighter targets
- Ground-based data needed for target characterisation, mode identification, abundances, vsini,... and for final tuning of the models + RV monitoring for EB pulsators