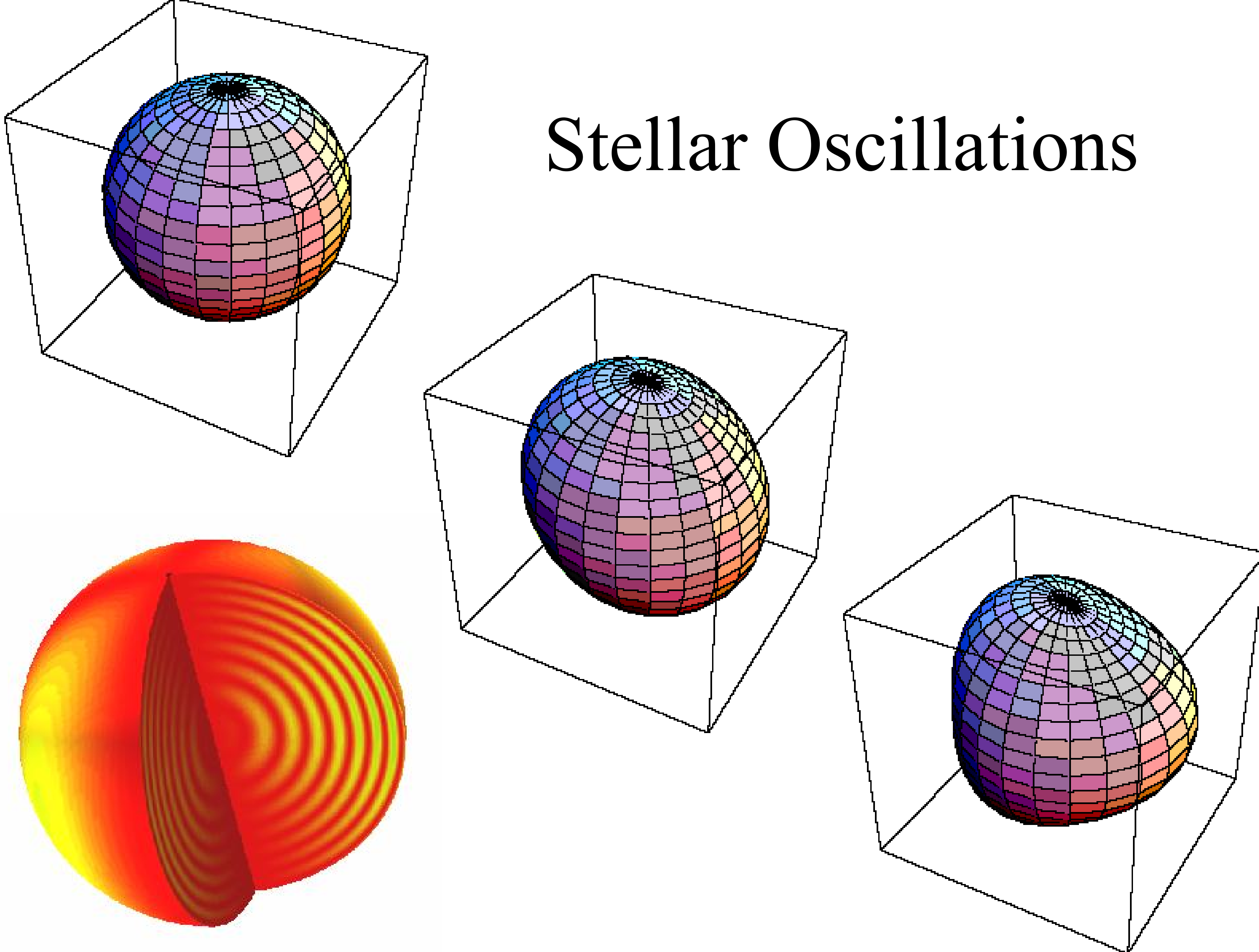
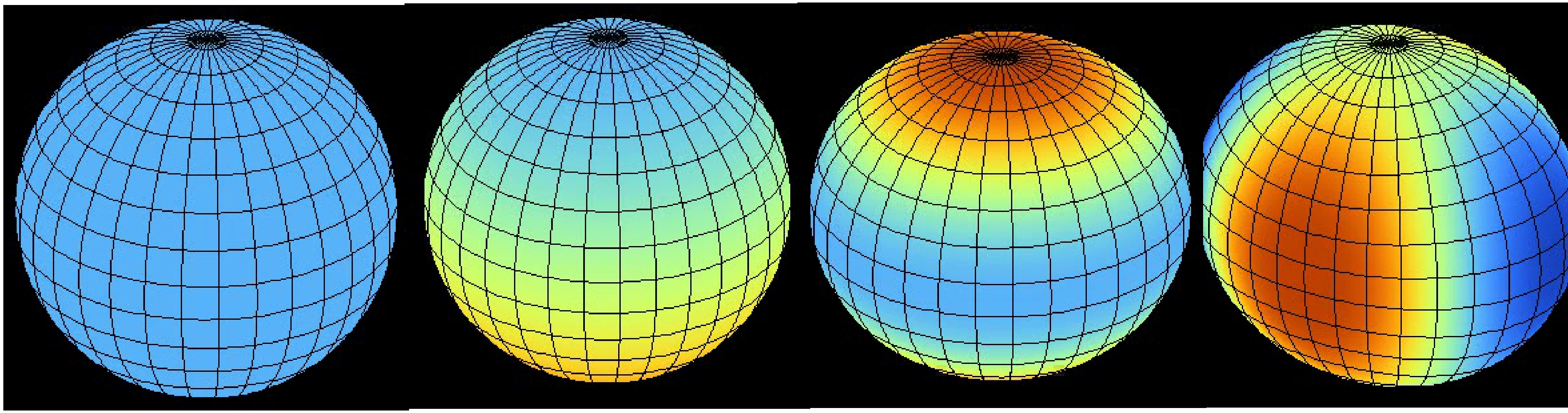
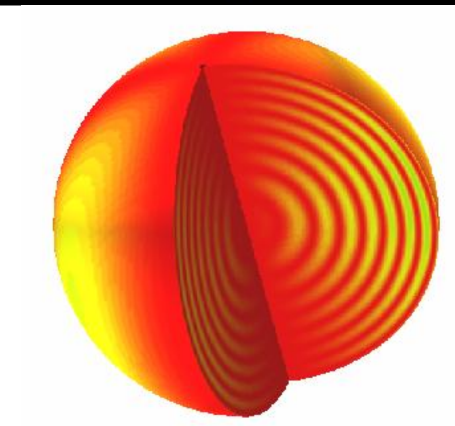

Helio- and Asteroseismology
Torben Arentoft – Aarhus Universitet – Denmark

Stellar Oscillations

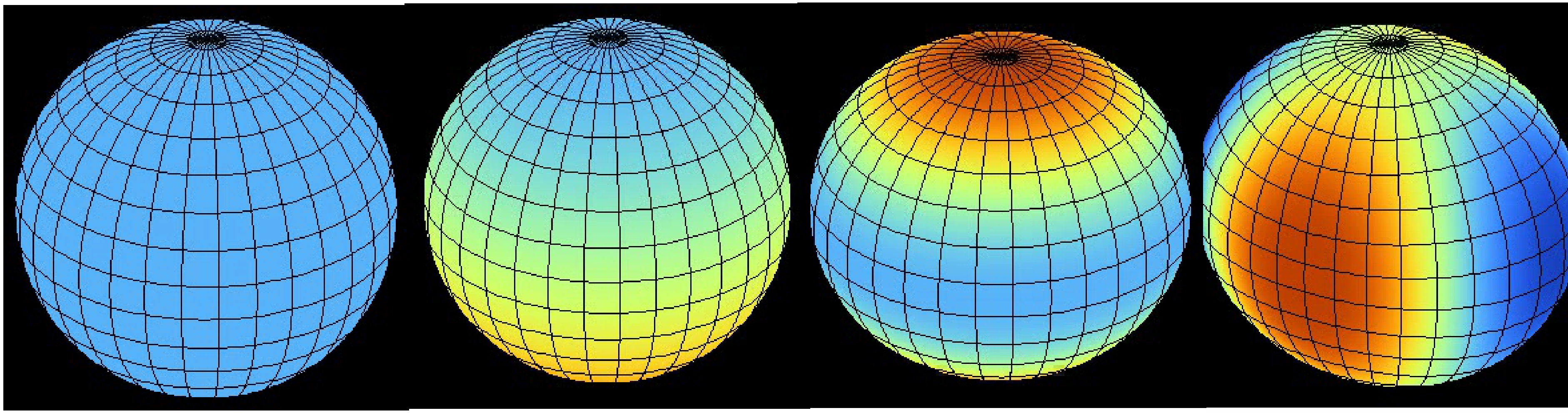


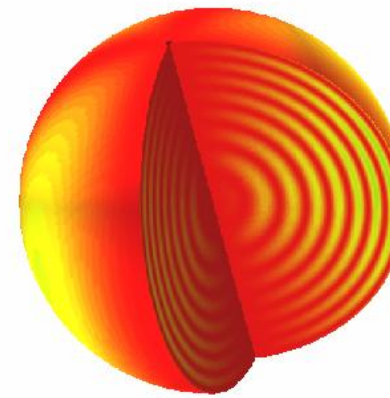


A star is a gaseous sphere that can oscillate in many different modes, or tones, when suitably excited.



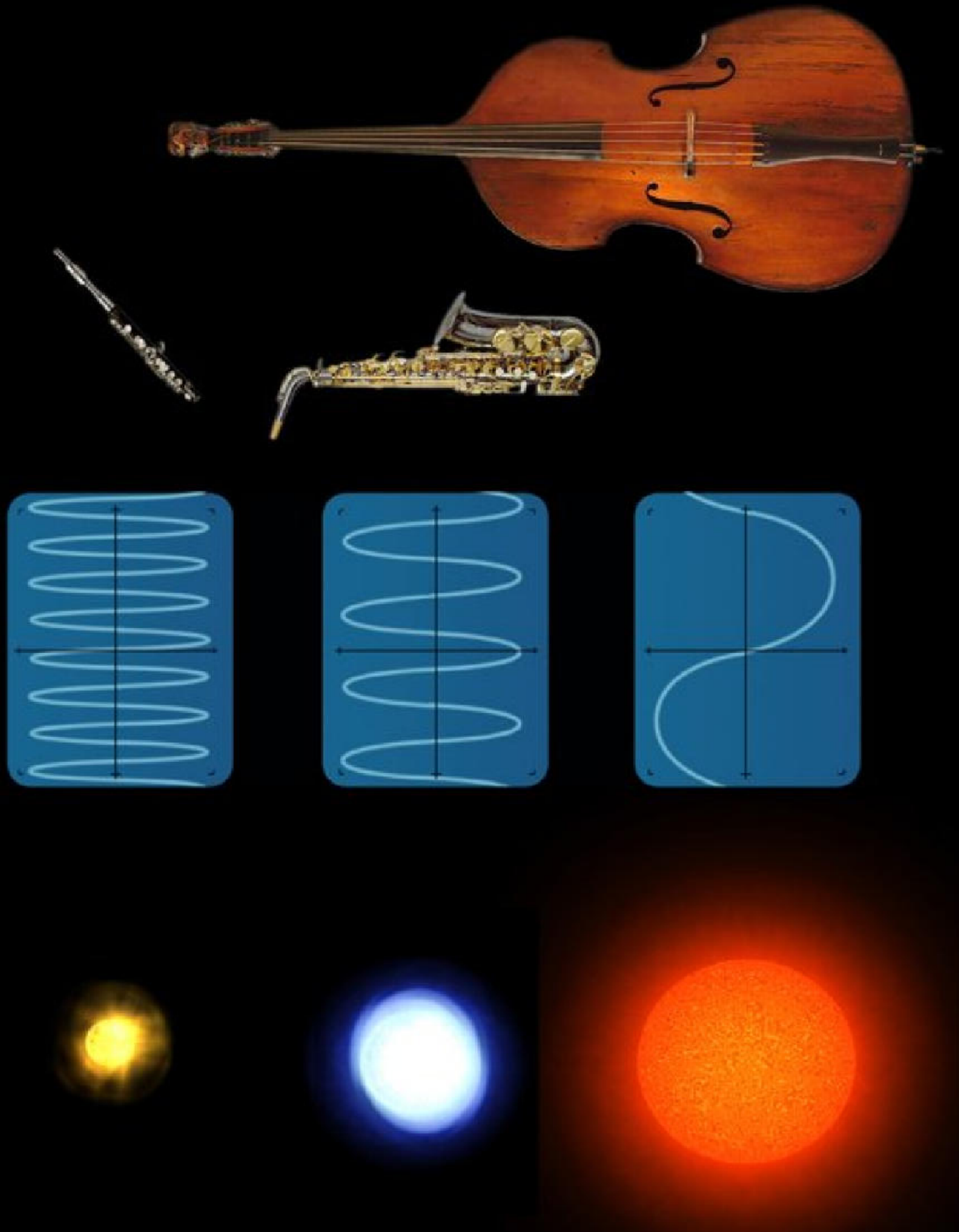
The oscillation frequencies depend on the Sound Speed inside the star, which in turn depends on the stellar properties (P,T,ρ,X)



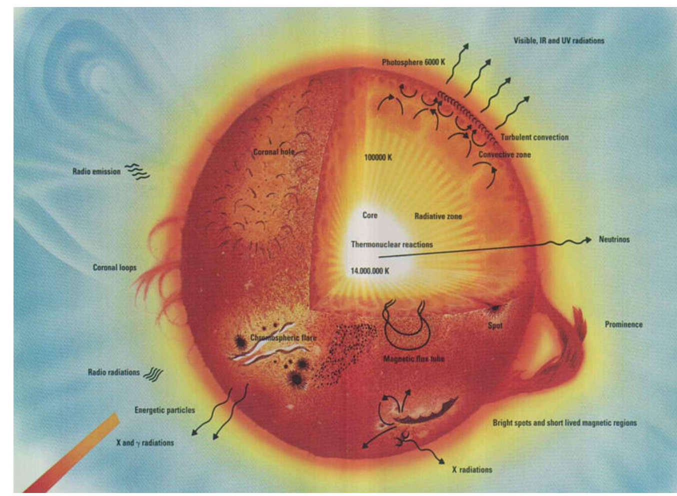


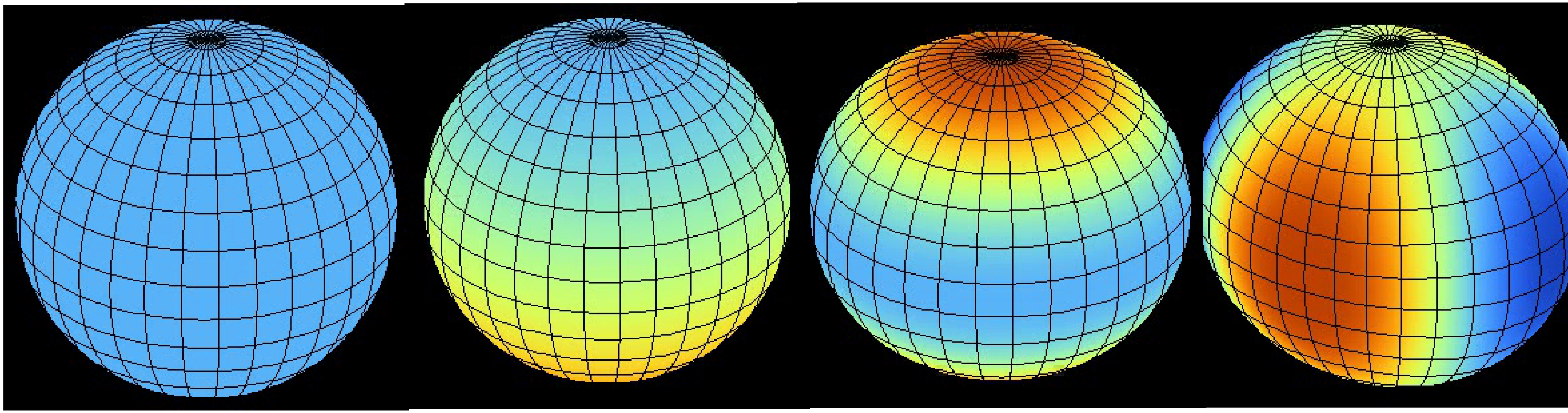
The oscillations are sound-waves,
each oscillation has a different period
and amplitude;

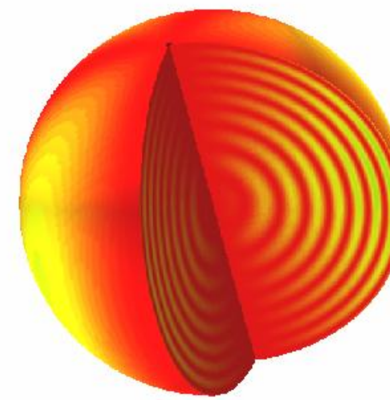
The stellar surface and brightness changes
in a very complex way because of the oscillations



The oscillations give us information about distant stars that cannot be otherwise obtained – and enable us to ”see” inside the stars…

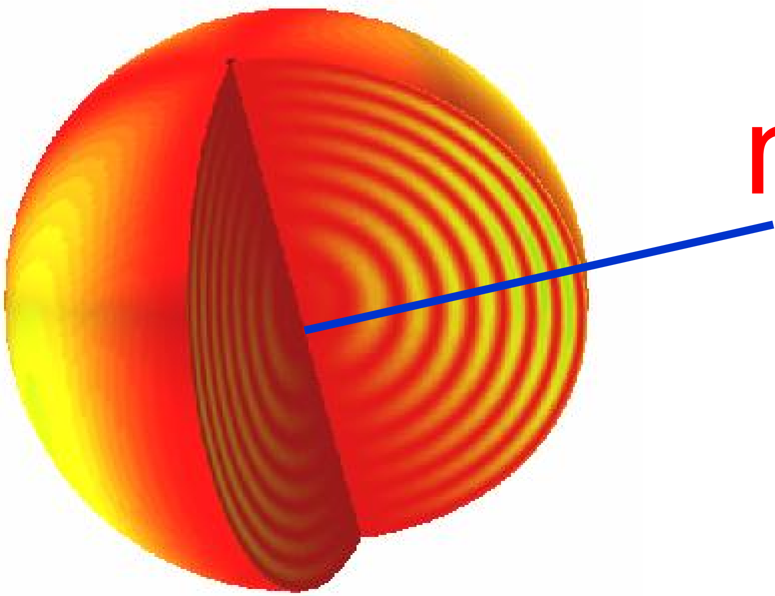




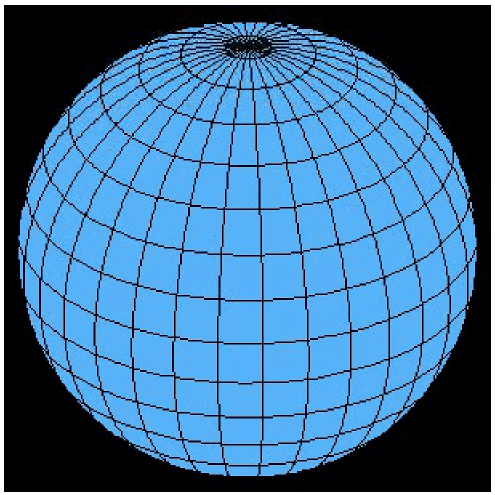


Each oscillation mode is described by spherical harmonics characterized by three numbers: n, l and m

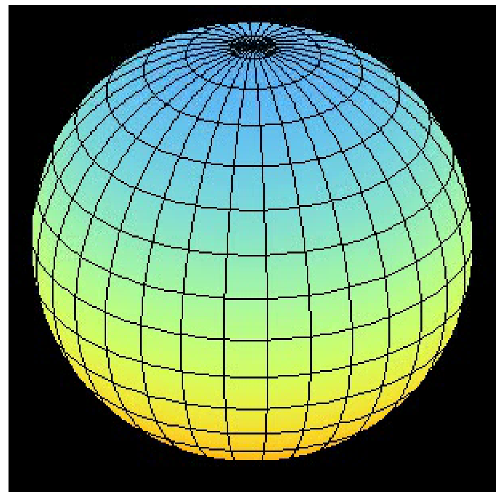
Radial order: n



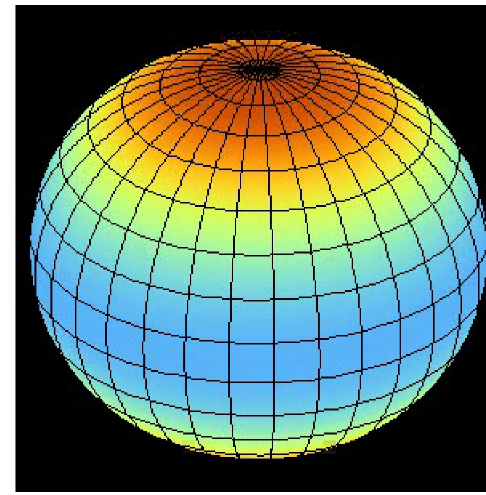
l = 0



l = 1

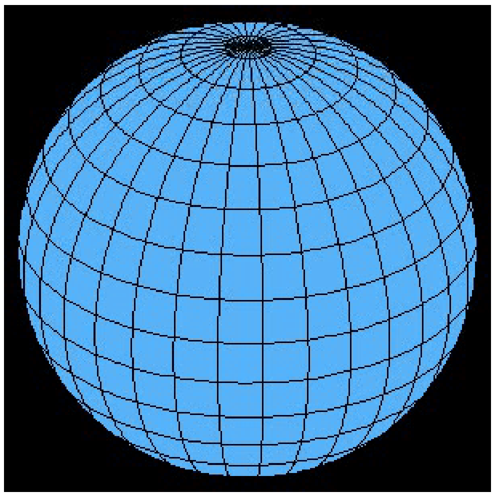


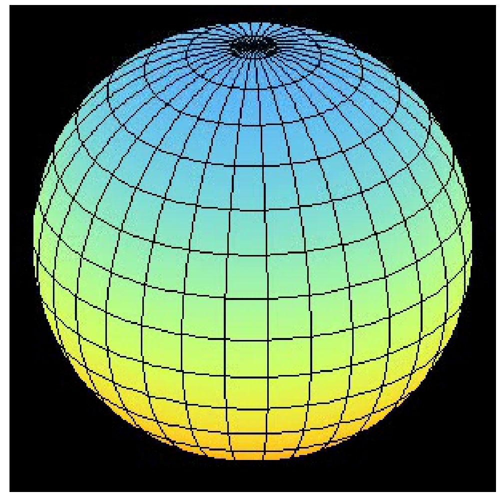
l = 2

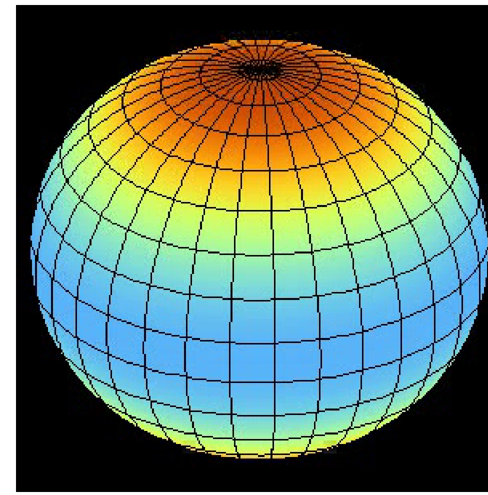


Degree ℓ: Total number of node lines

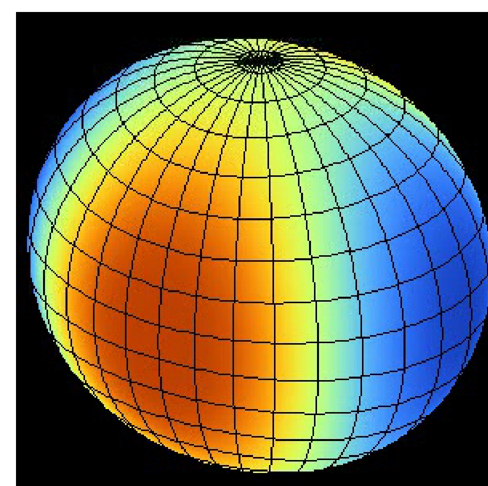
$l = 0$ $l = 1$ $l = 2$



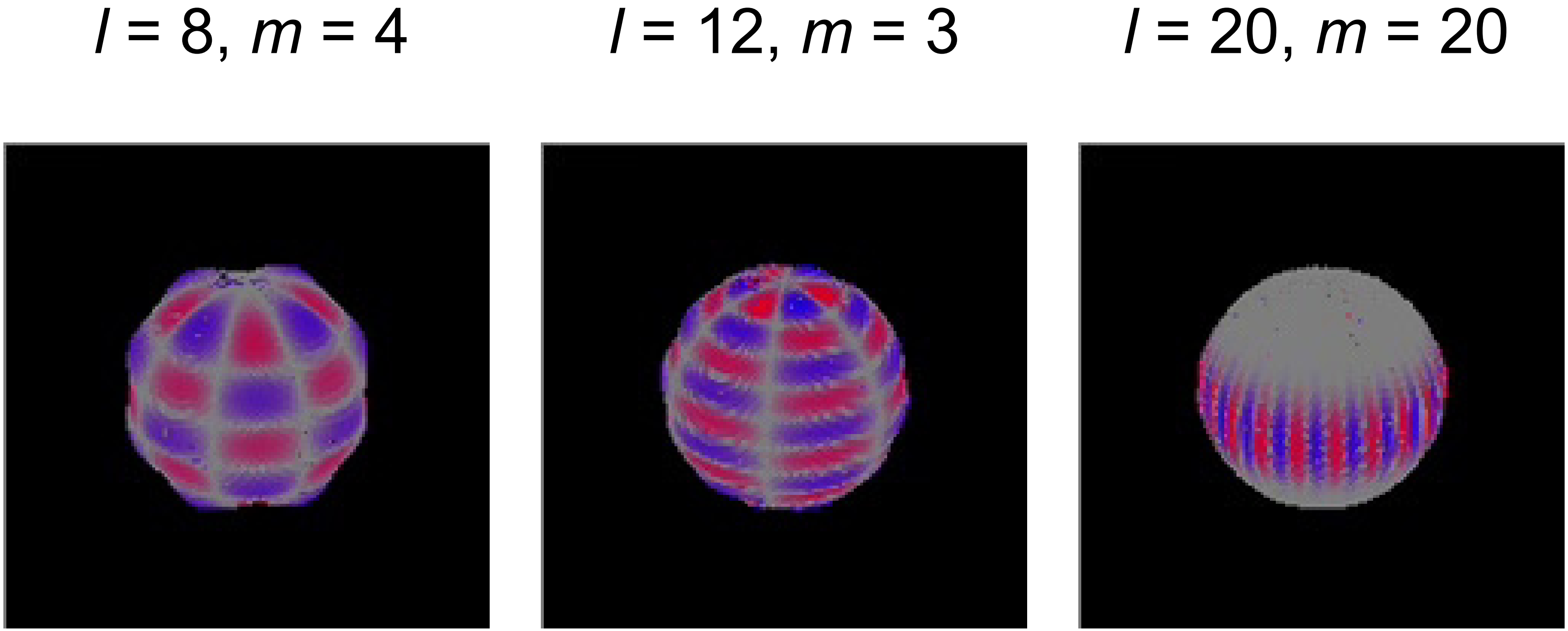




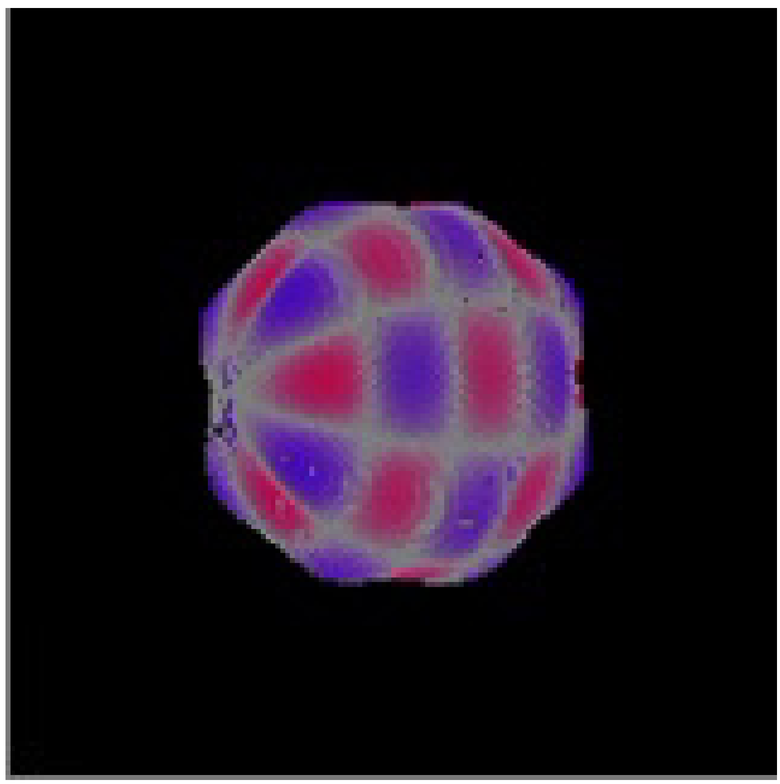
($l = 2$, $m = 2$)

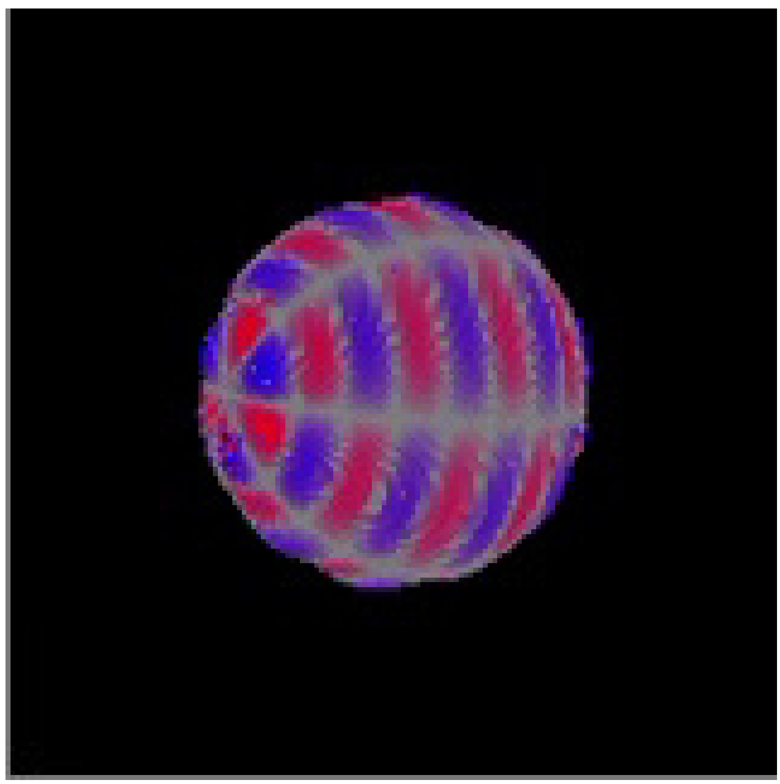


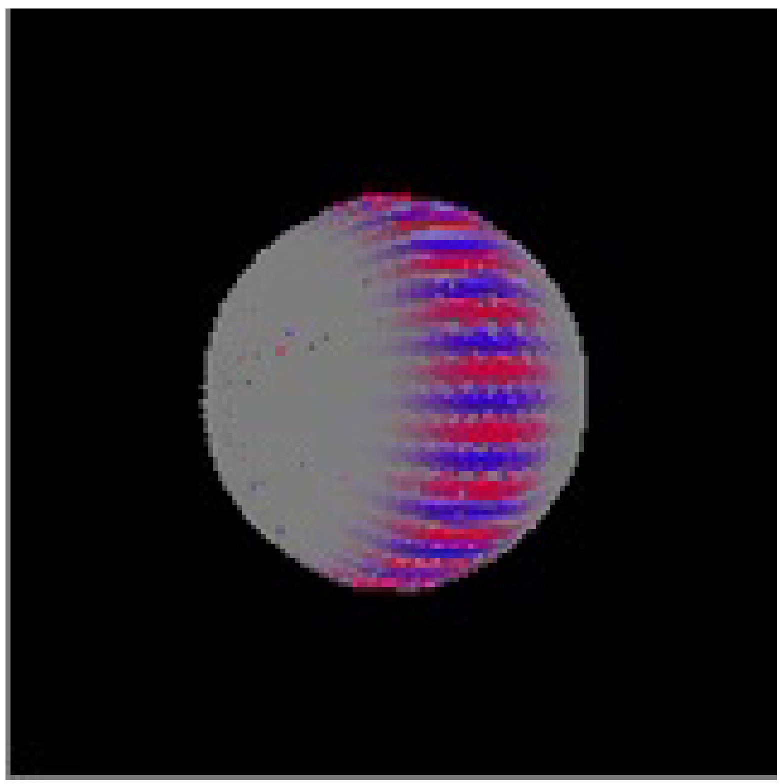
m: #nodes at const. longitude

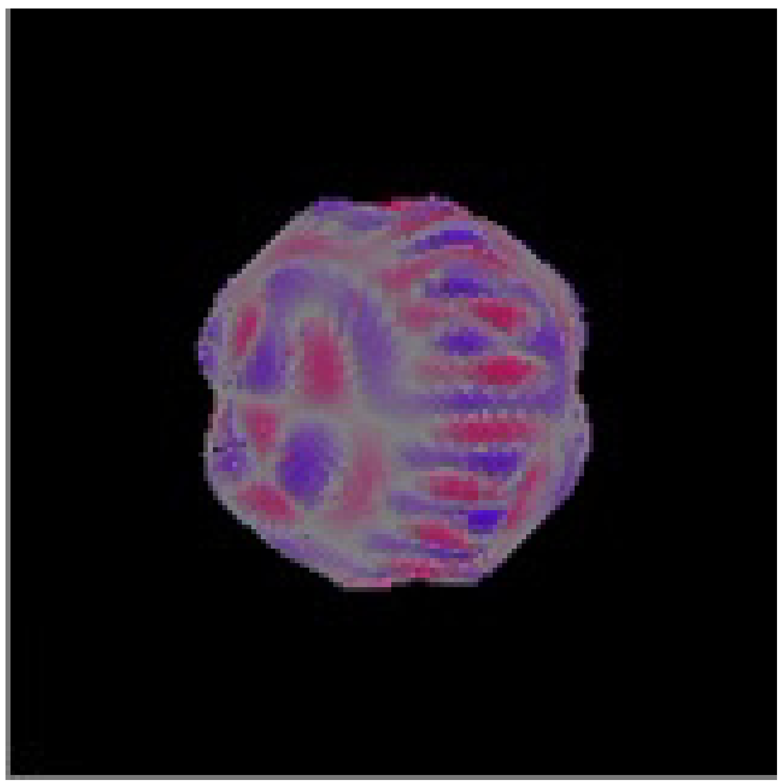


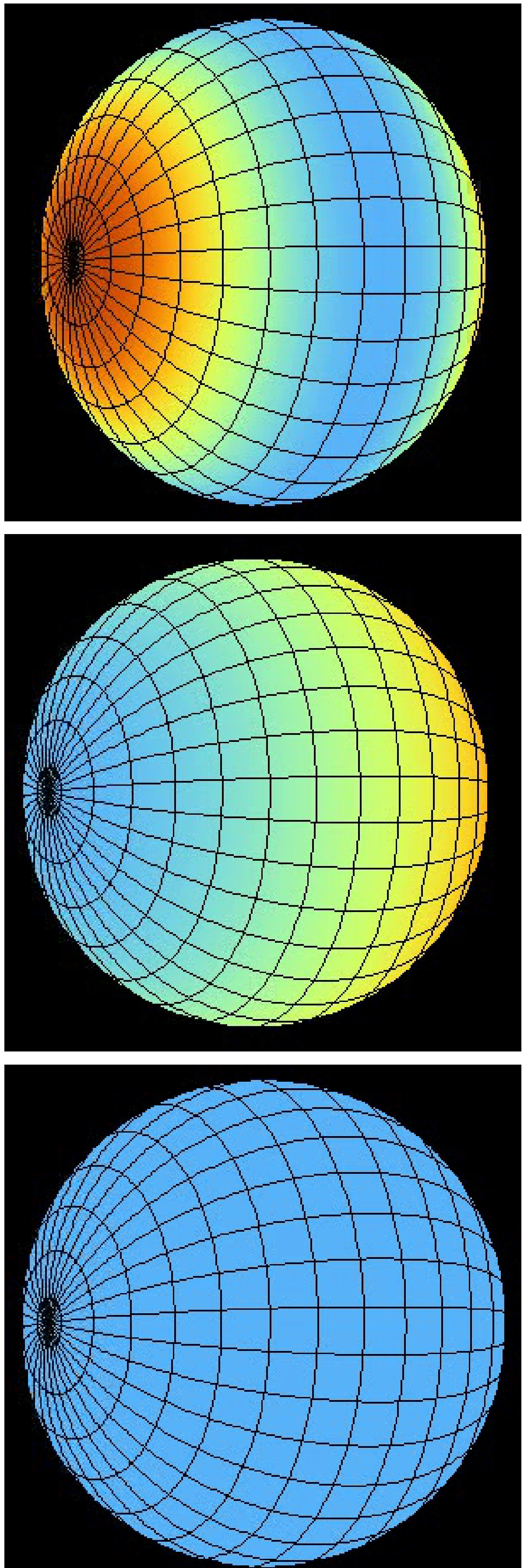
$l = 8, m = 4$
$l = 12, m = 3$
$l = 20, m = 20$

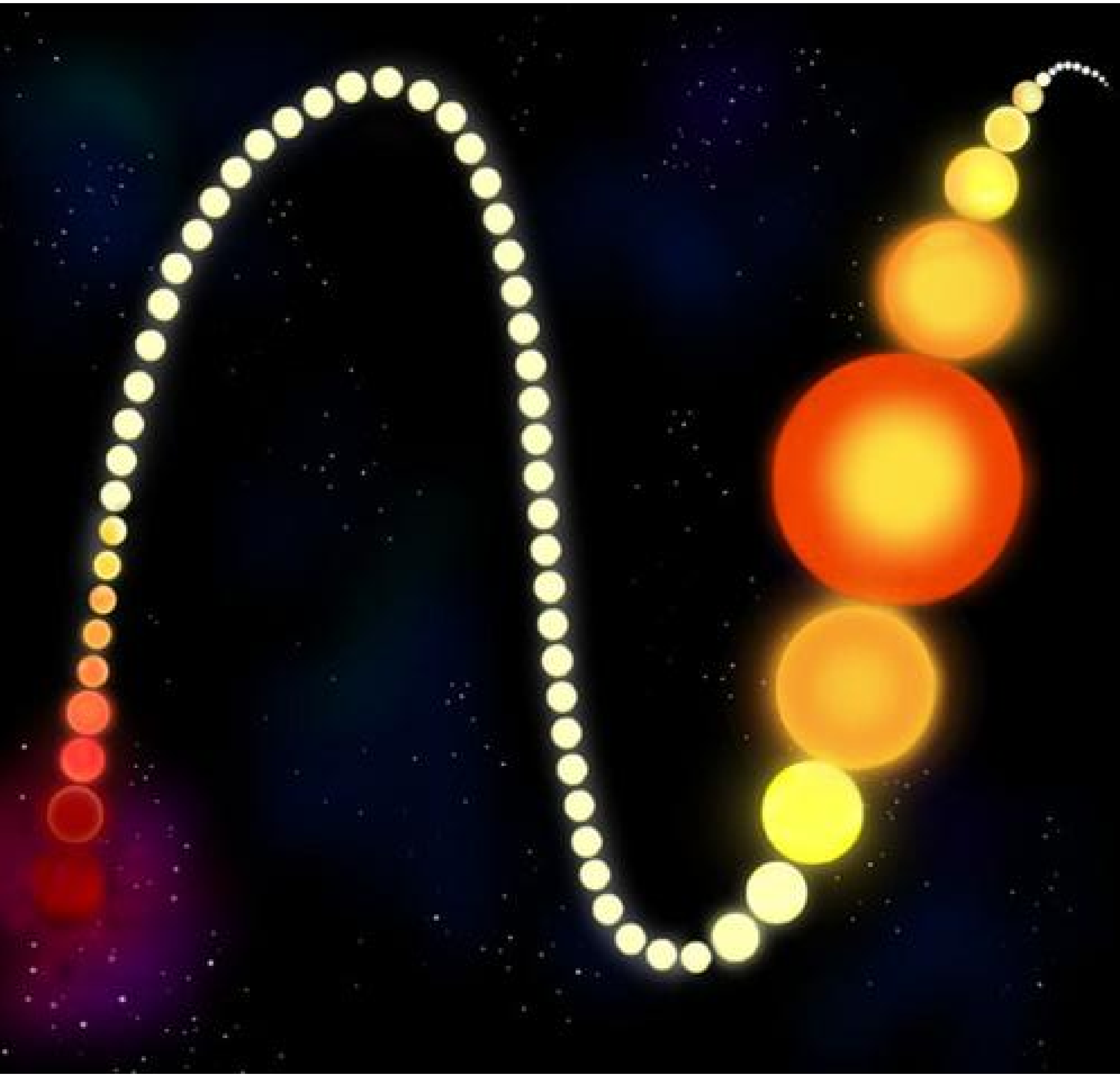




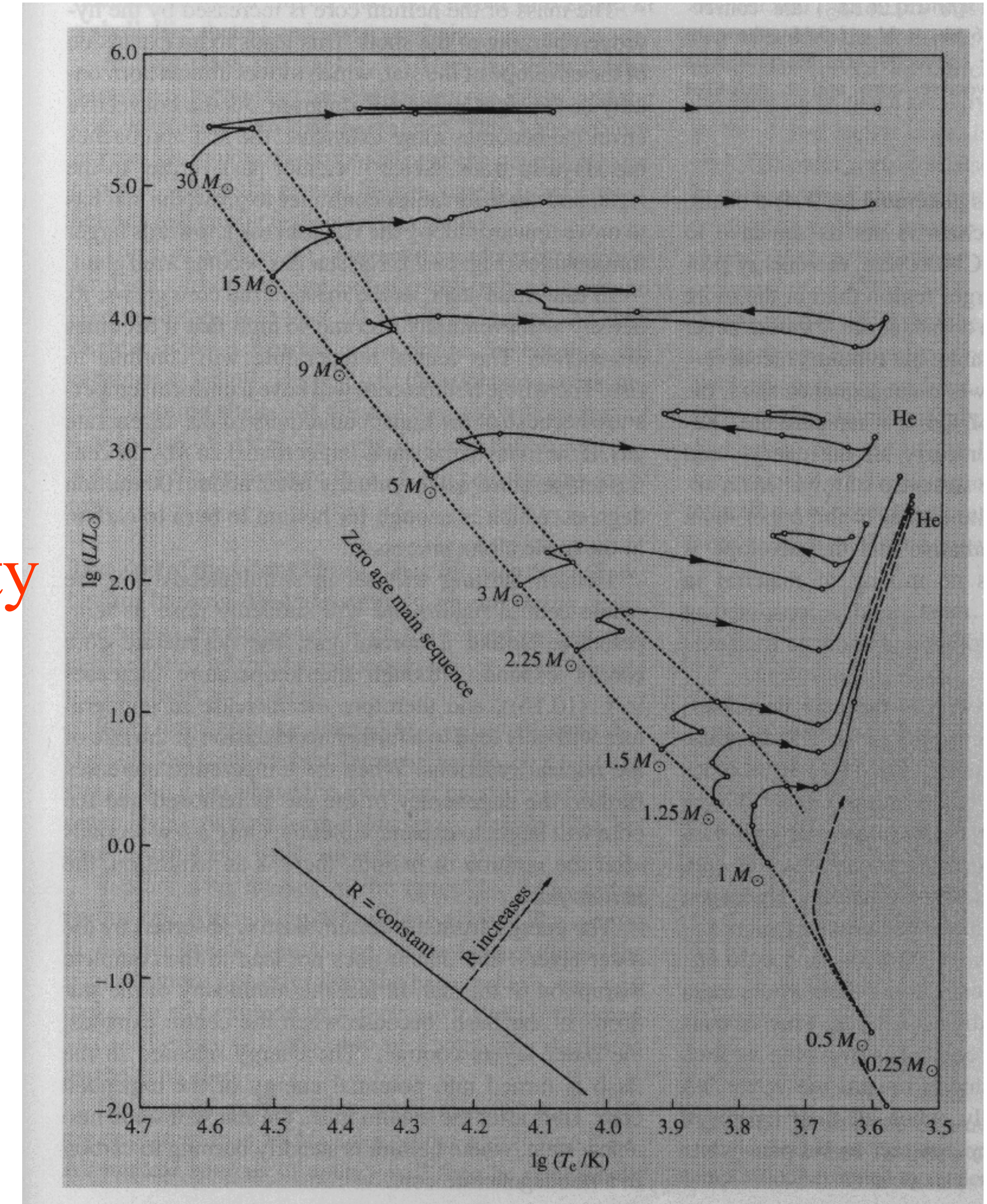




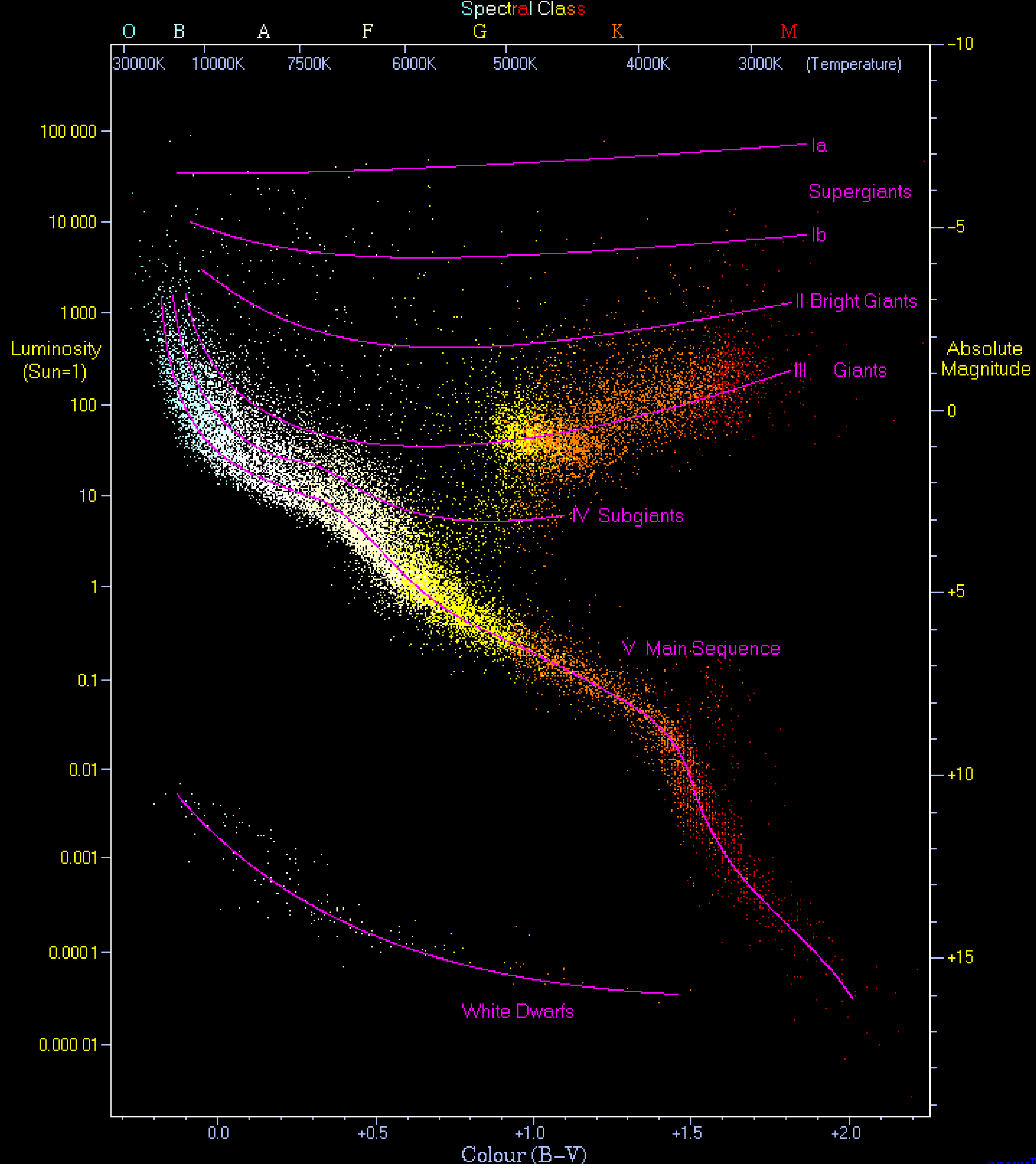




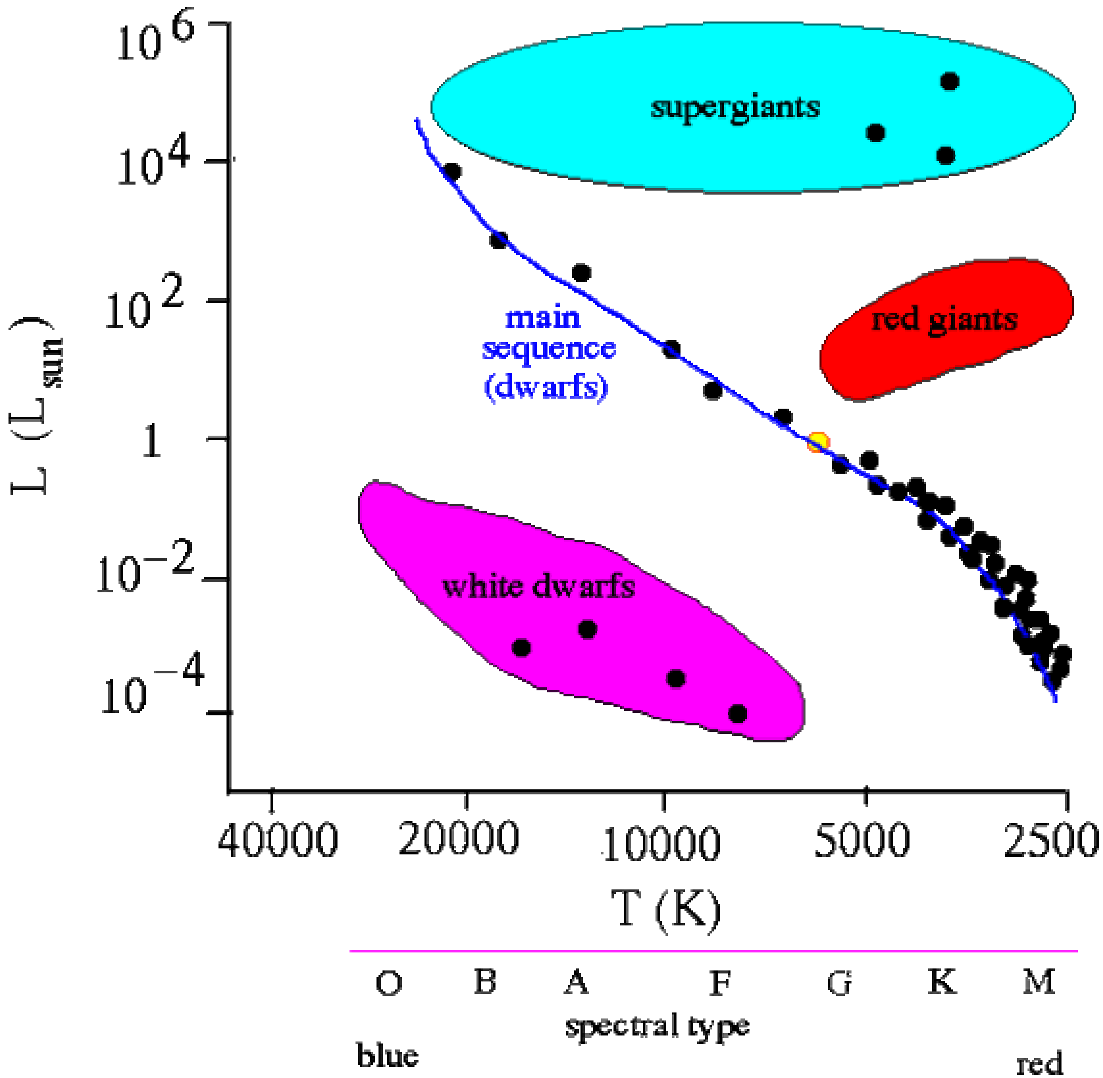
Luminosity

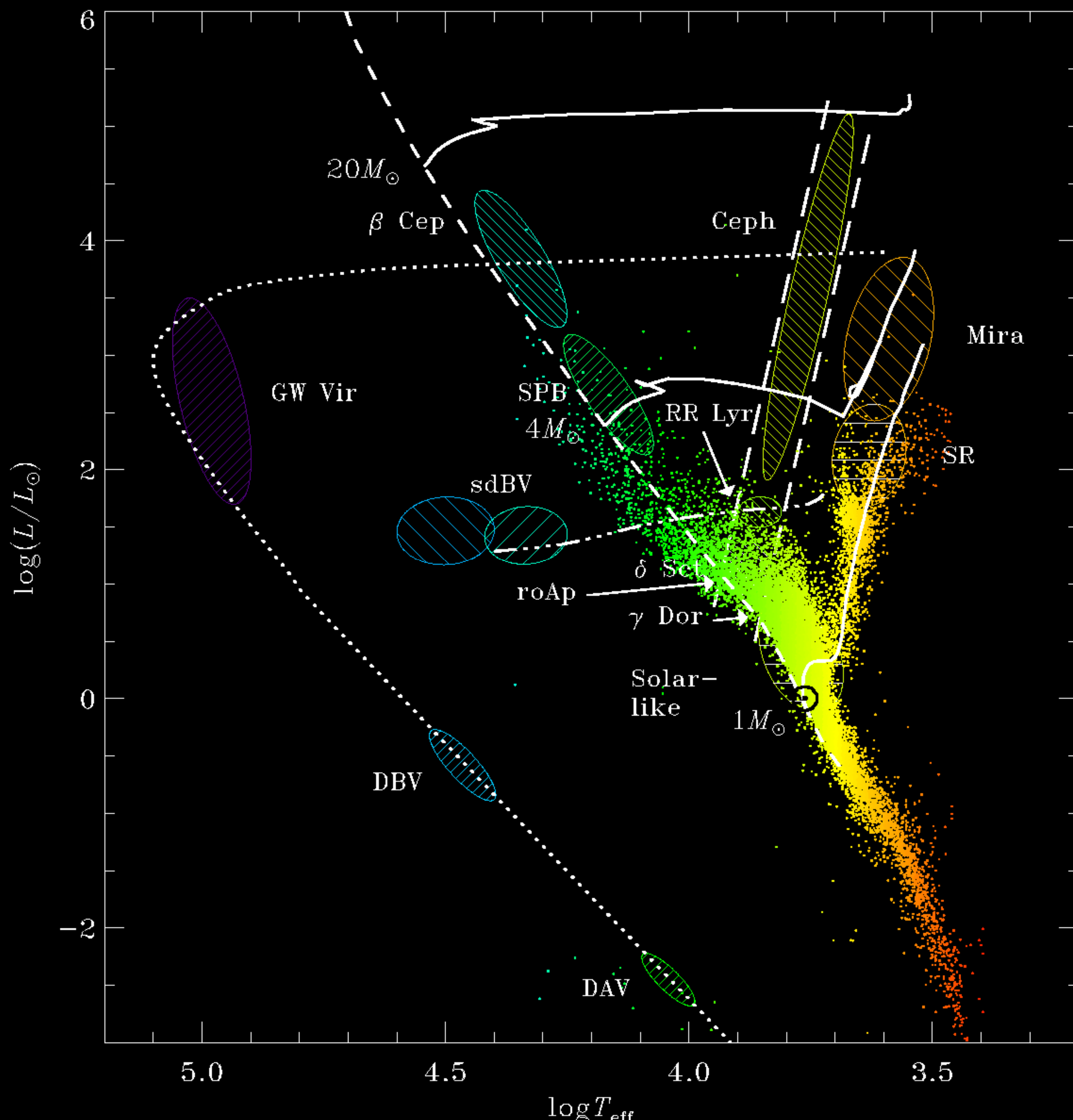


Temp.


Spectral Class
O
B
A
F
G
K
M
30000K
10000K
7500K
6000K
5000K
4000K
3000K
(Temperature)
100 000
10 000
1000
Luminosity
(Sun=1)
100
10
1
0.1
0.01
0.001
0.0001
0.000 01
-10
-5
0
+5
+10
+15
Absolute
Magnitude
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
V Main Sequence
White Dwarfs
0.0
+0.5
+1.0
+1.5
+2.0
Colour (B–V)
r.powell

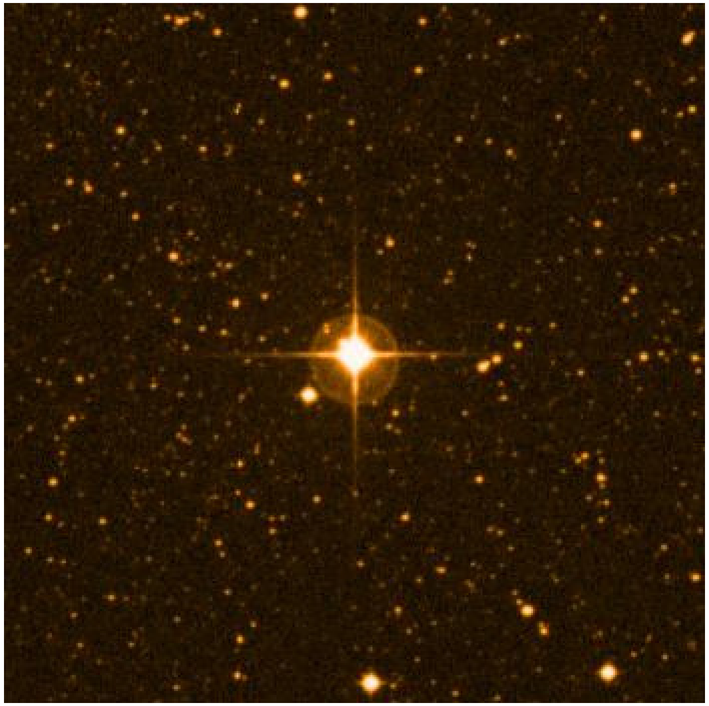
The Hertzsprung-Russell Diagram

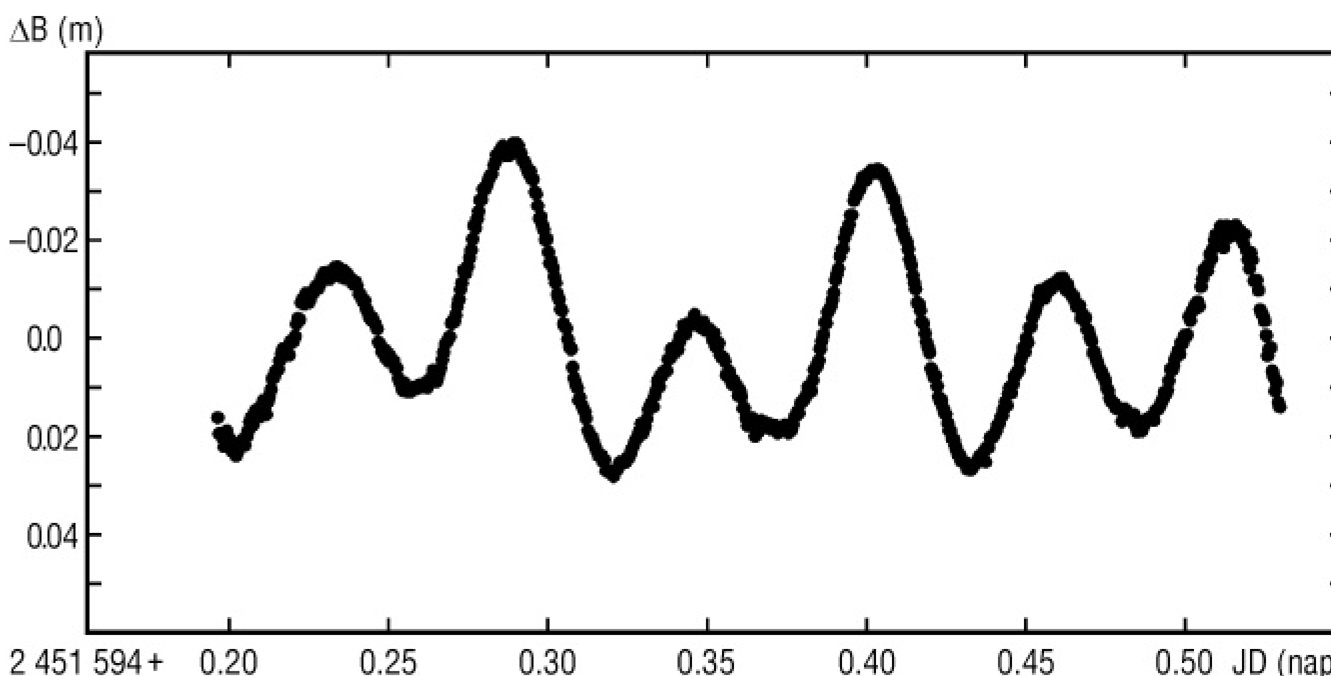




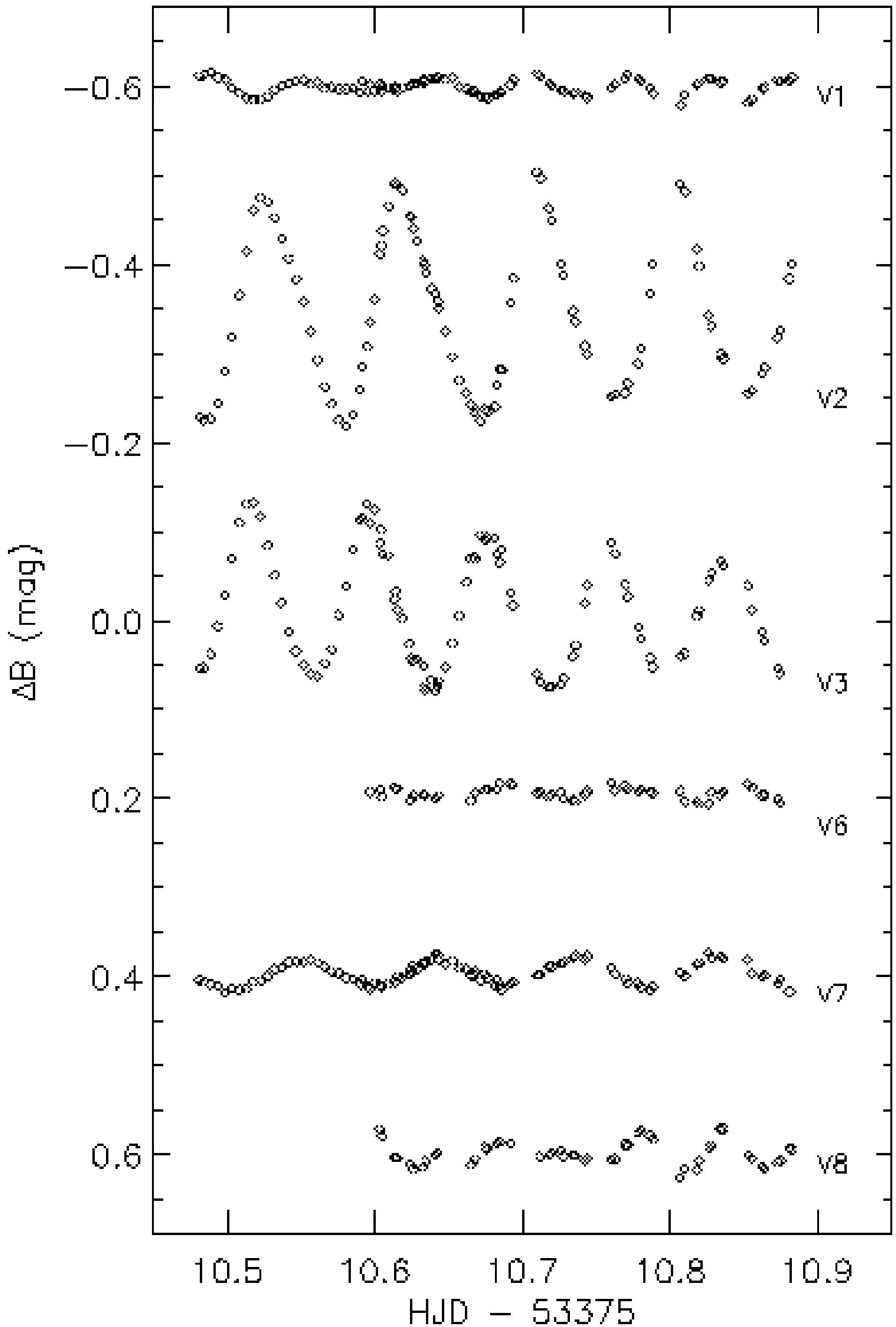
6
4
2
0
−2
log(L/L⊙)
5.0
4.5
4.0
3.5
log Teff
20M⊙
β Cep
Ceph
Mira
GW Vir
SPB
4M⊙
RR Lyr
SR
sdBV
δ Sct
roAp
γ Dor
Solar-
like
1M⊙
DBV
DAV

Example: delta Scuti





Delta Scuti stars



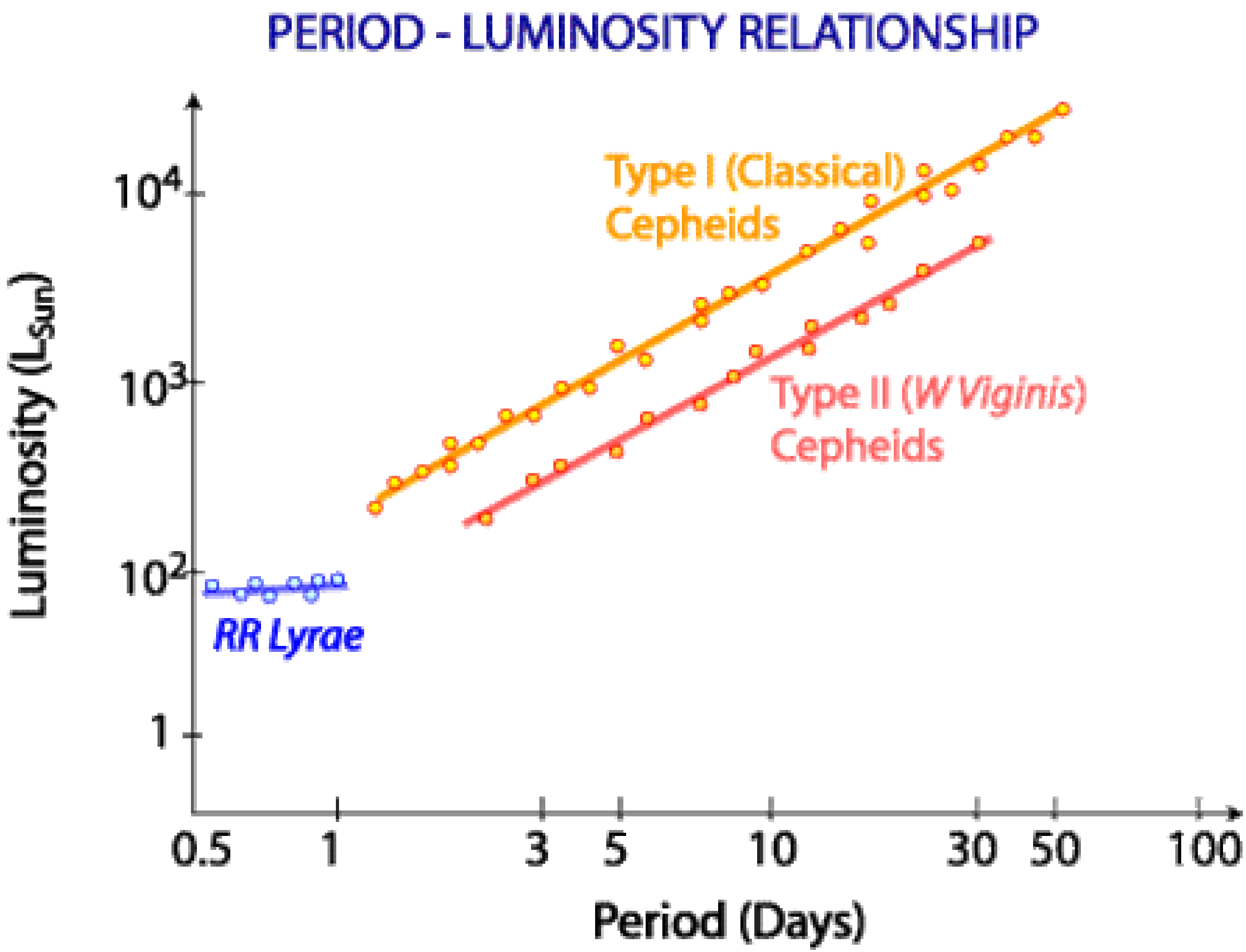
Example: Delta Scuti stars

- Somewhat heavier than the Sun (1.5-2.5 M_{sun})
- Structural differences to the Sun
- Many frequencies per star (P ~ 30 min – 2 timer);

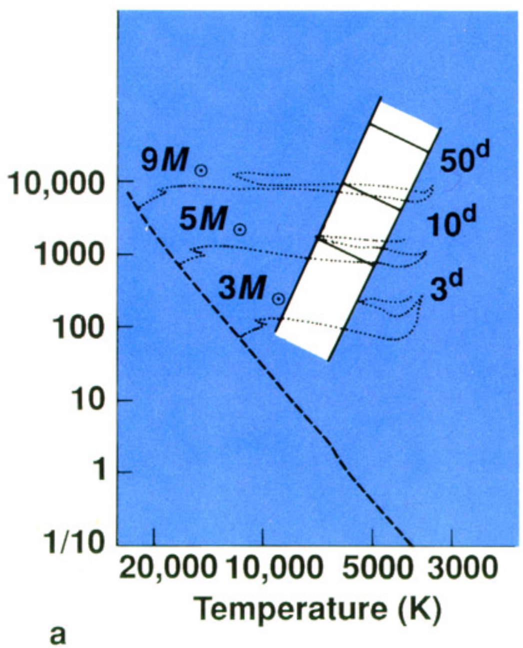
  → good targets for *asteroseismologi*…

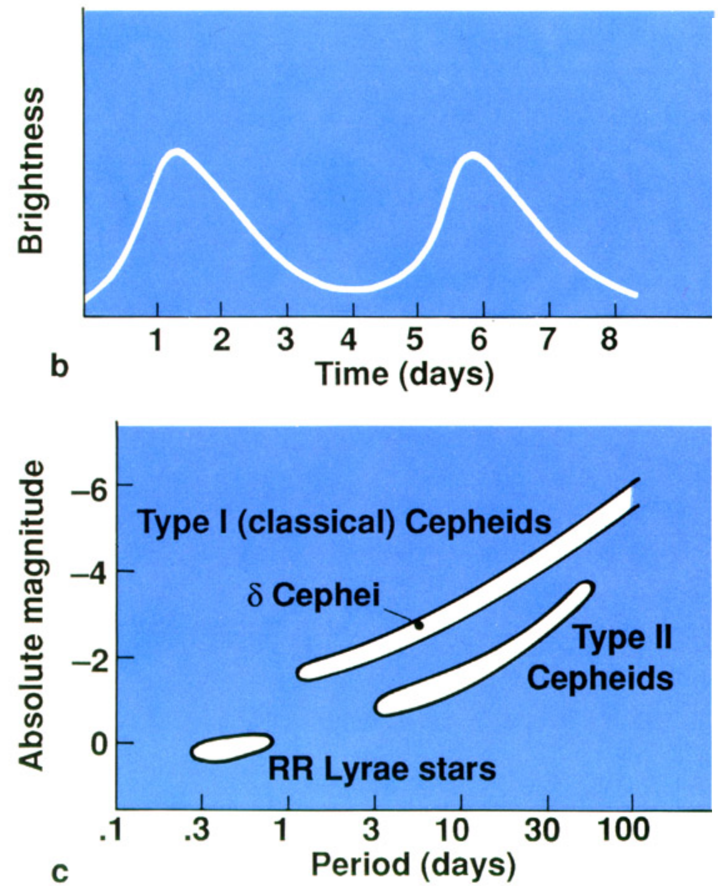
- Problem: Which types of oscillations (which *modes*)

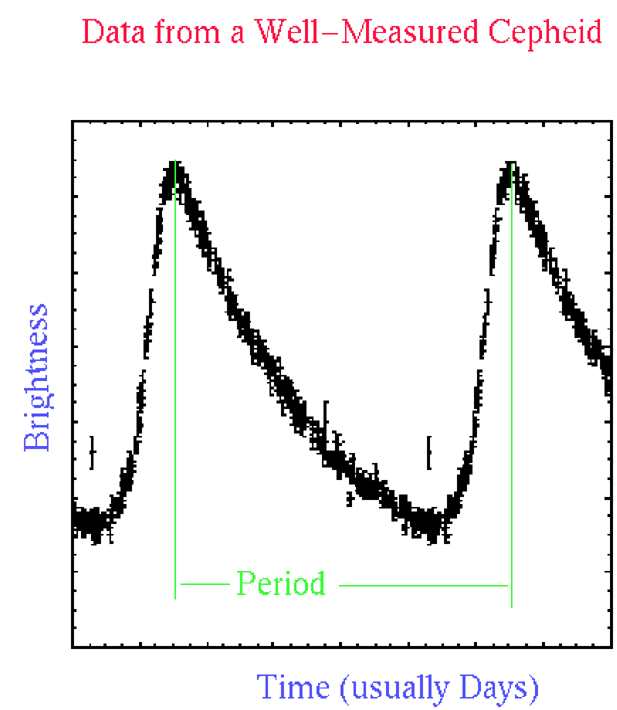
  → difficult to compare theori and observations


PERIOD - LUMINOSITY RELATIONSHIP
Type I (Classical)
Cepheids
Type II (W Viginis)
Cepheids
RR Lyrae
10^4
10^3
10^2
1
Luminosity (L_{sun})
0.5
1
3
5
10
30
50
100
Period (Days)

Cepheids

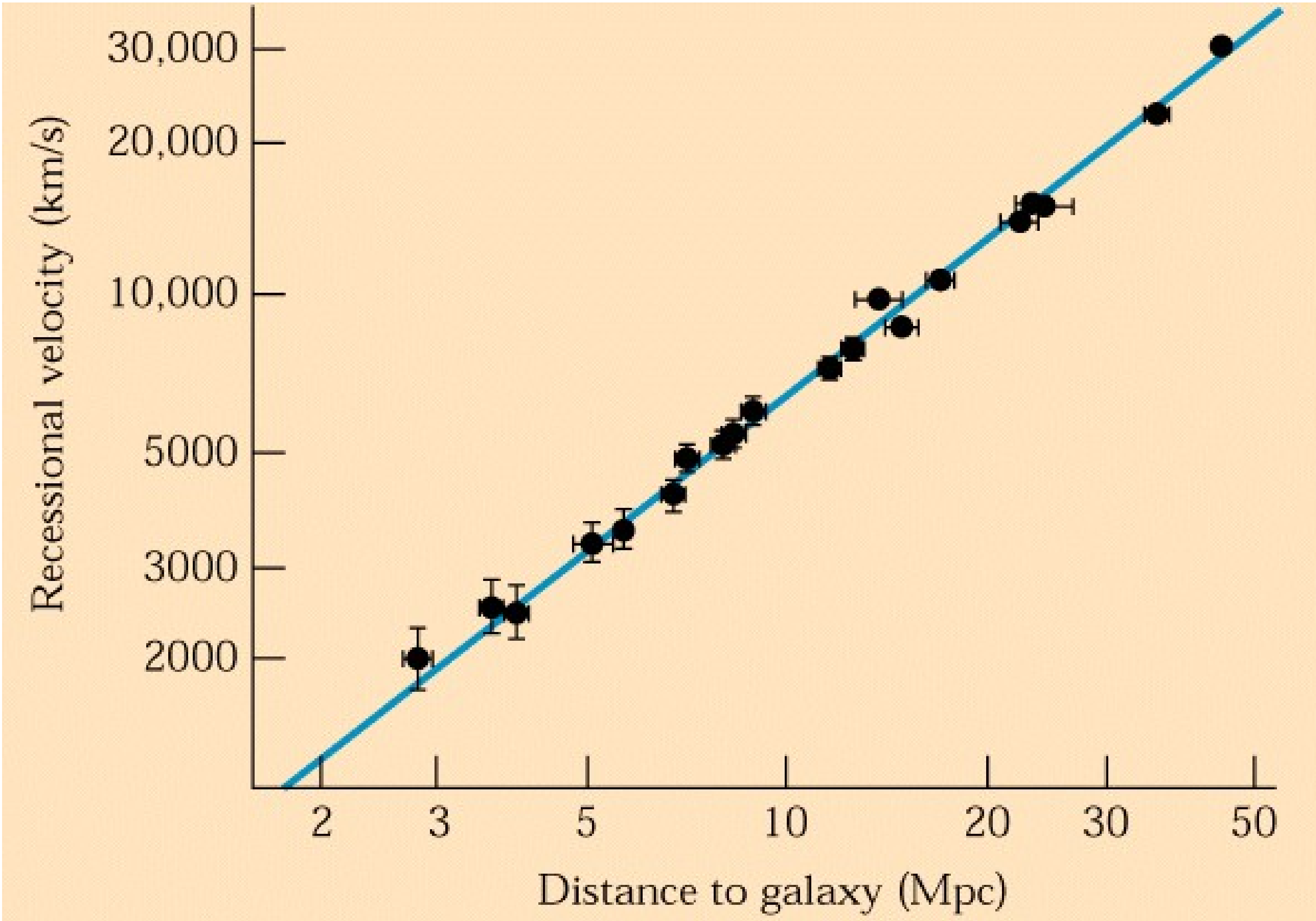




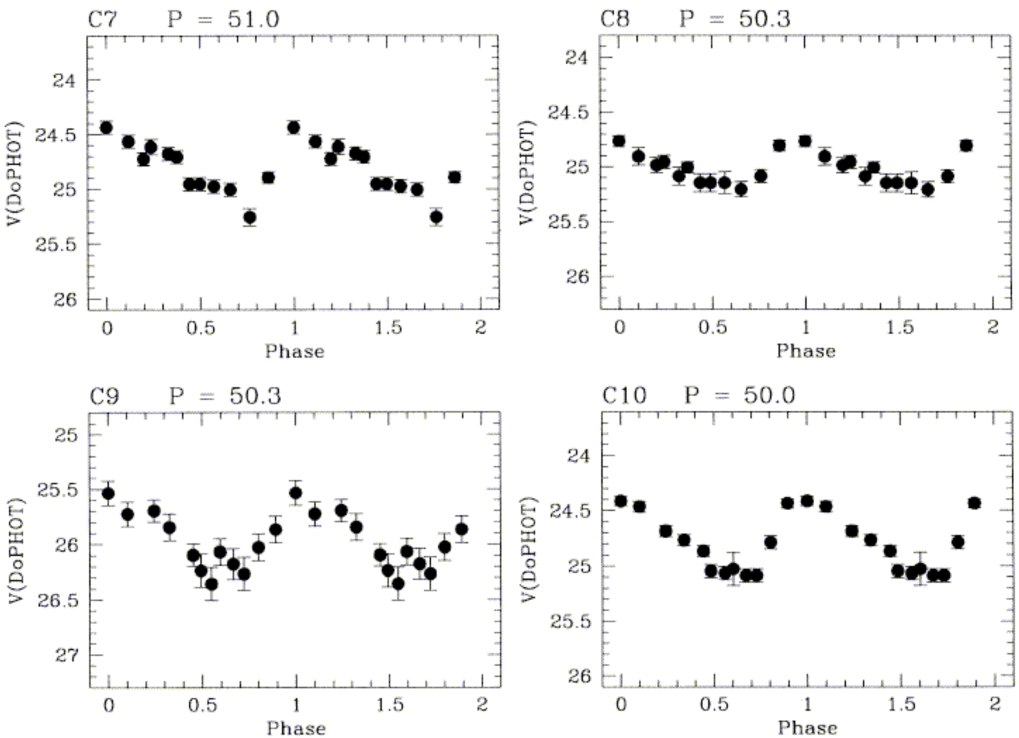


$$\langle M_V \rangle = -2.76\log(P) - 1.40$$

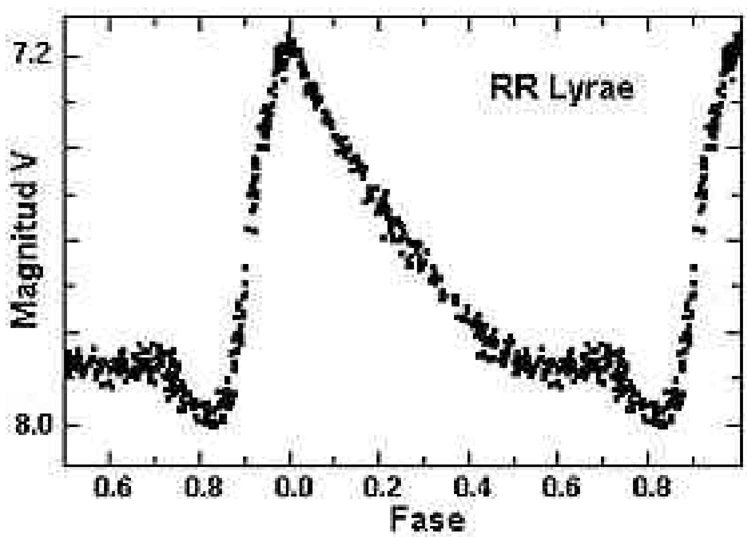
Hubble's law: *velocities* from redshifts – distance from Cepheids

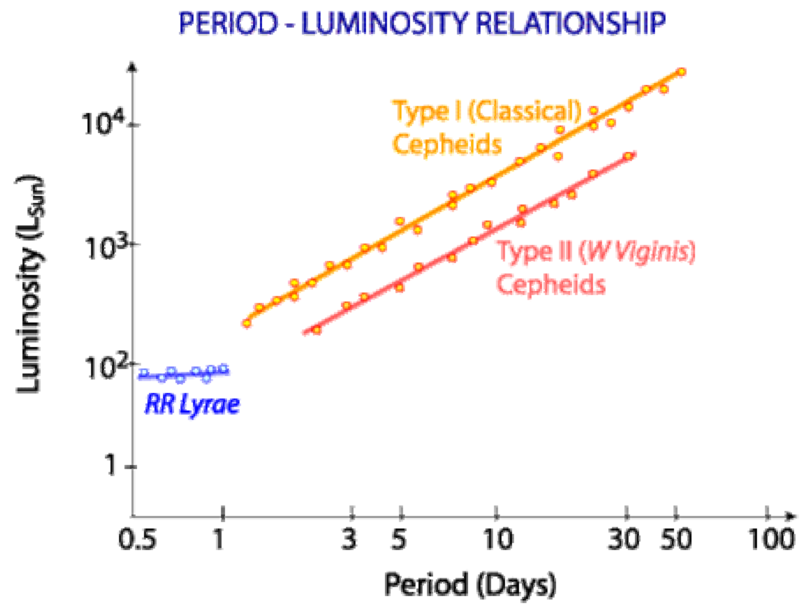


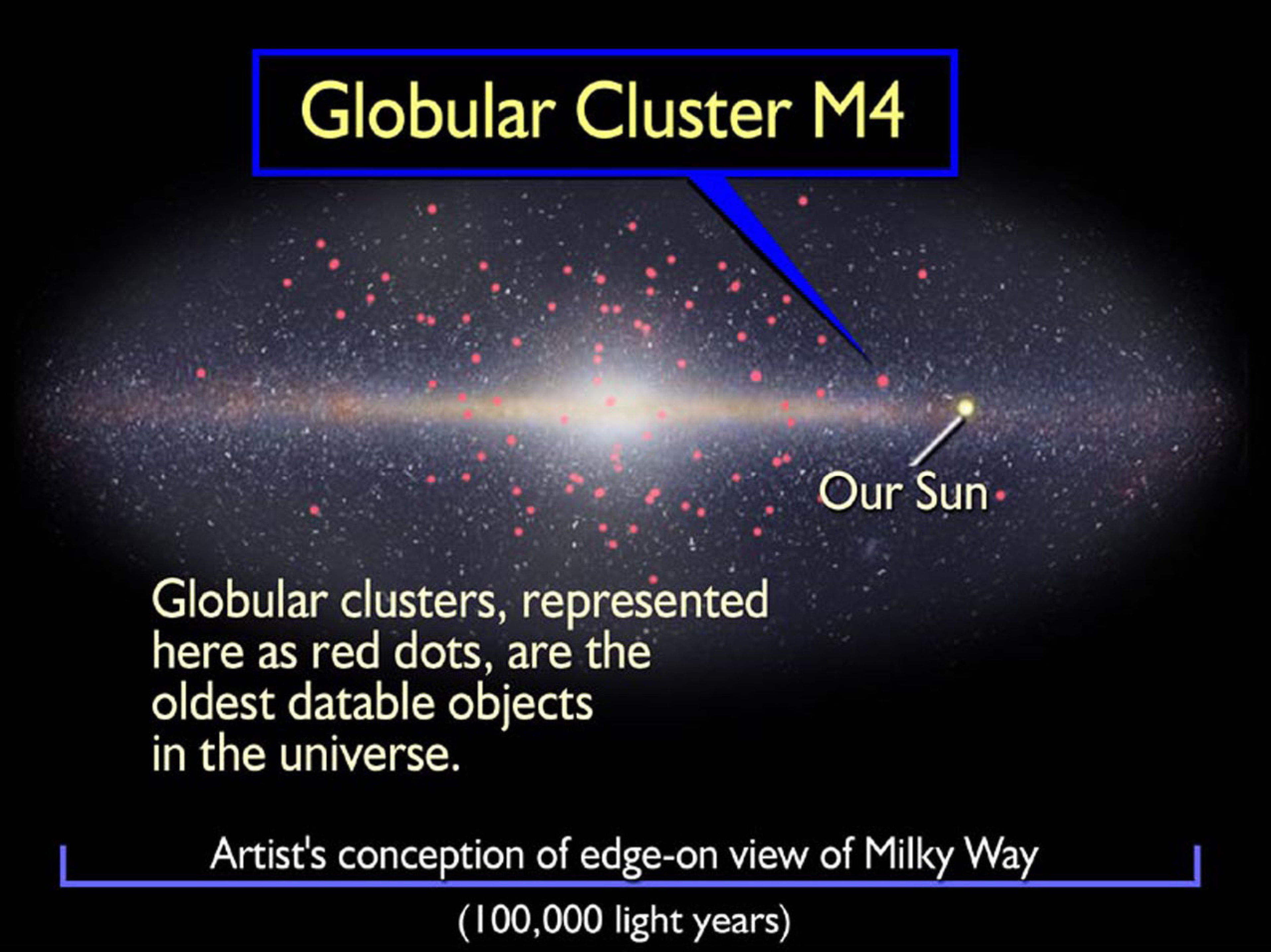
Cepheids: HST Key Project



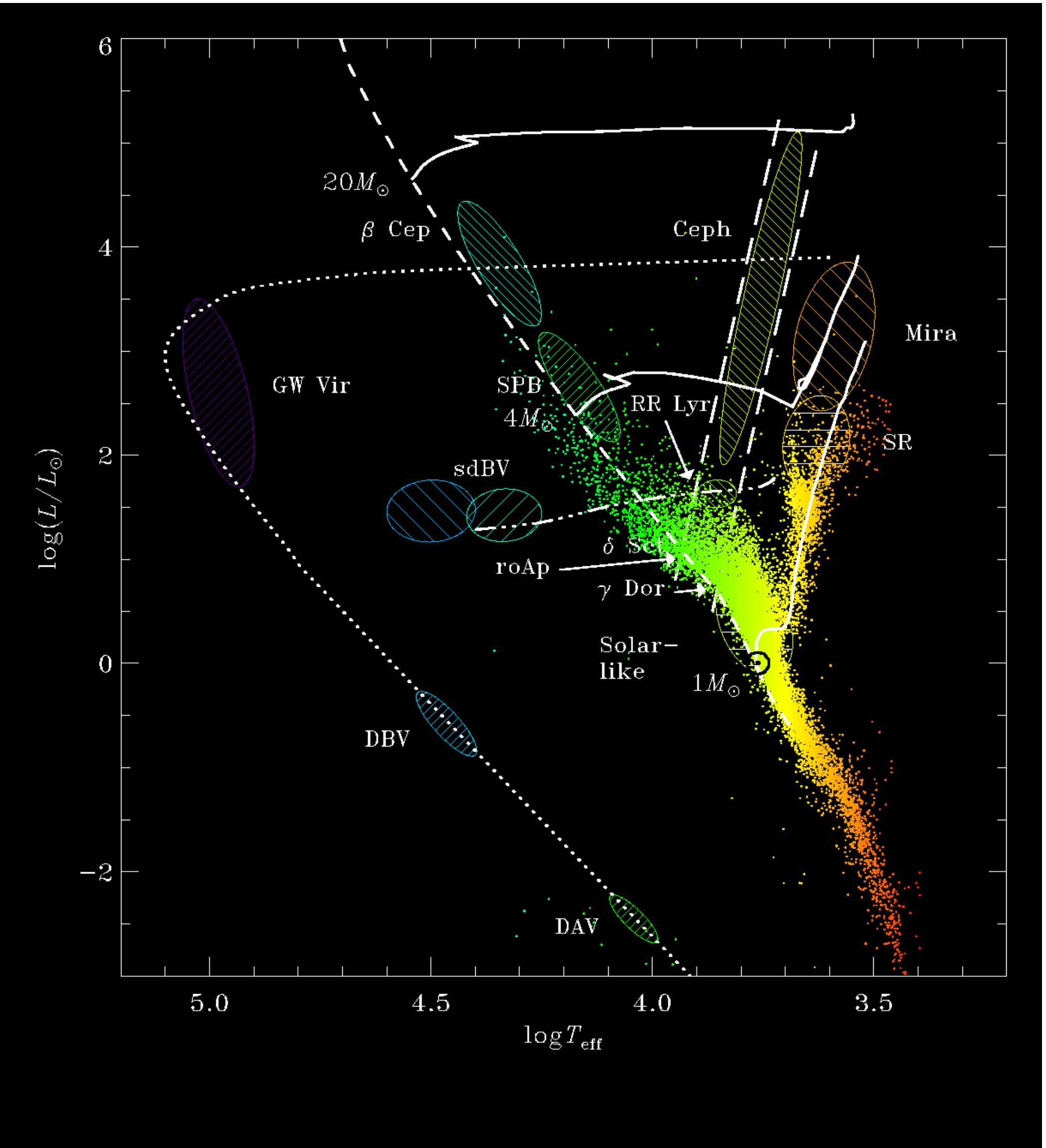
RR Lyrae Stars:






Globular Cluster M4
Our Sun
Globular clusters, represented here as red dots, are the oldest datable objects in the universe.
Artist's conception of edge-on view of Milky Way
(100,000 light years)

The HR-diagram: Many types of pulsating stars



The Kappa-mechanism:

- Delta Scuti
- Beta Cepheid
- Cepheids
- RR Lyrae

The HR-diagram: Many types of pulsating stars

The Kappa-mechanism:

- Partial Ionization zones

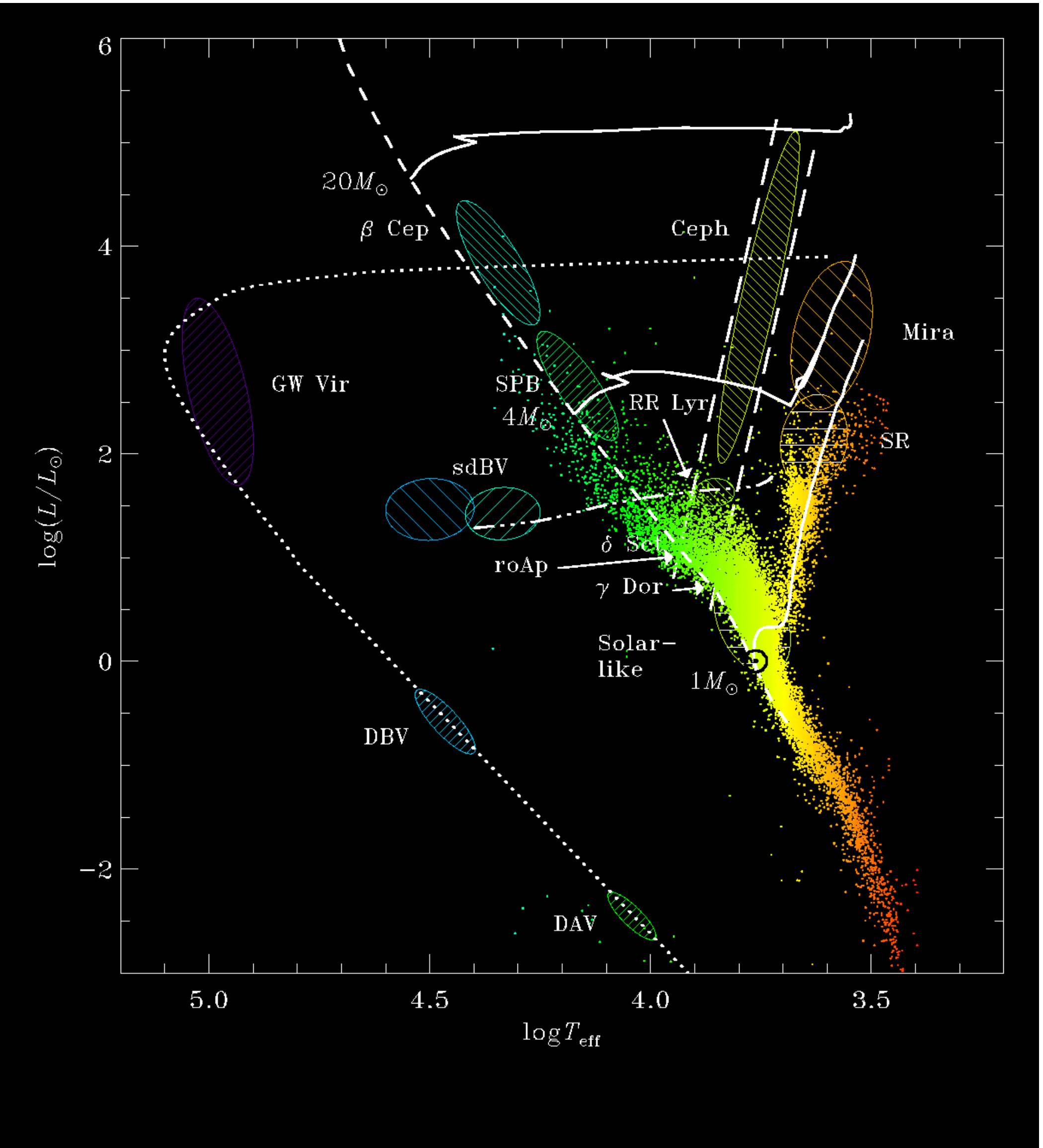
- The gas is compressed → T would normally grow
  → instead ionization at constant T

- The density and *opacity* increase ($\kappa \sim \rho/T^{3.5}$)

- The Energy from below is blocked
  → the pressure increases – the gas is pushed upwards

- The opacity and pressure drops again
  → the star contracts…

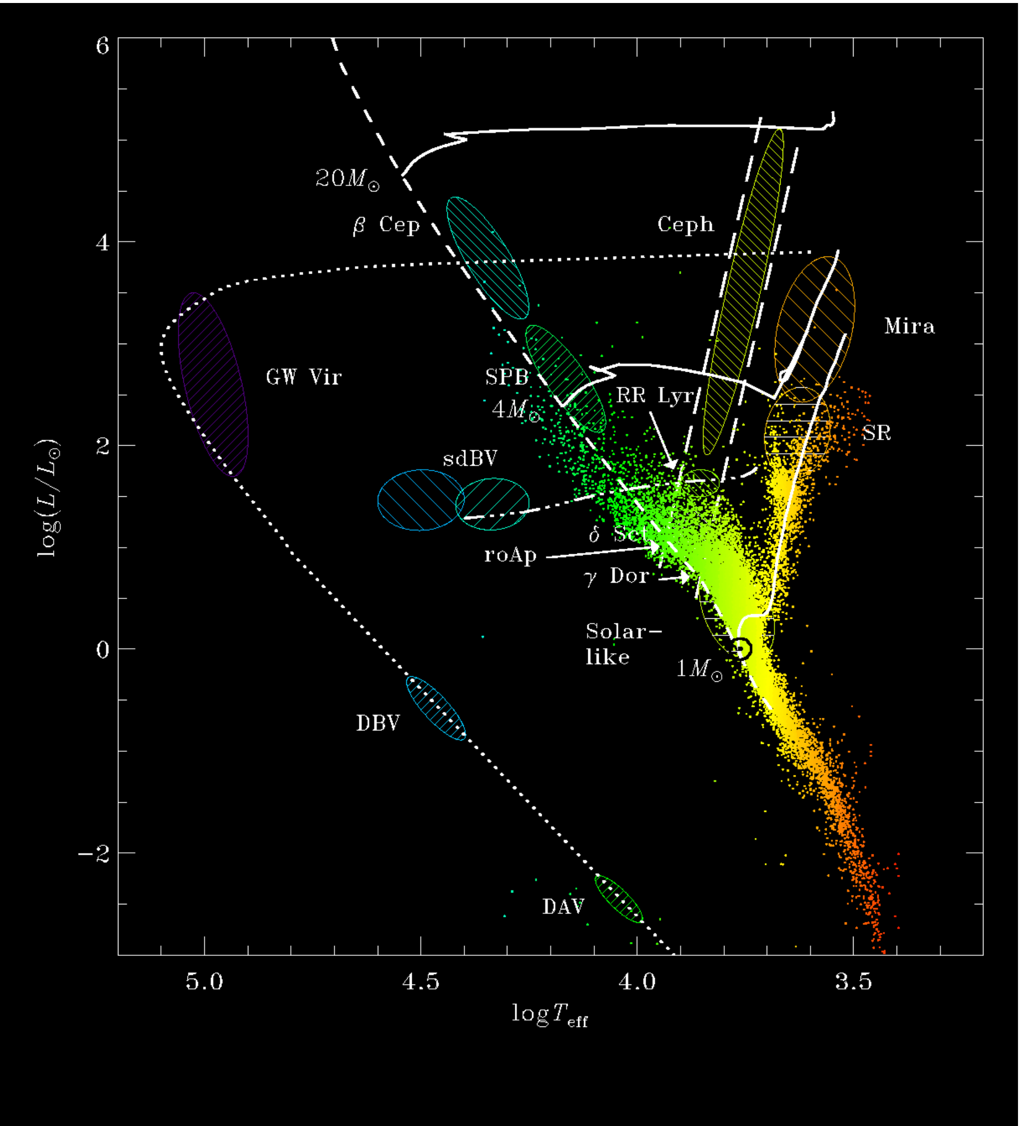
The HR-diagram: Many types of pulsating stars



Kappa-mekanismen:

- Delta Scuti (He)
- Beta Cepheid (Fe)
- Cepheider (He)
- RR Lyrae (H+He)

The HR-diagram: Many types of pulsating stars



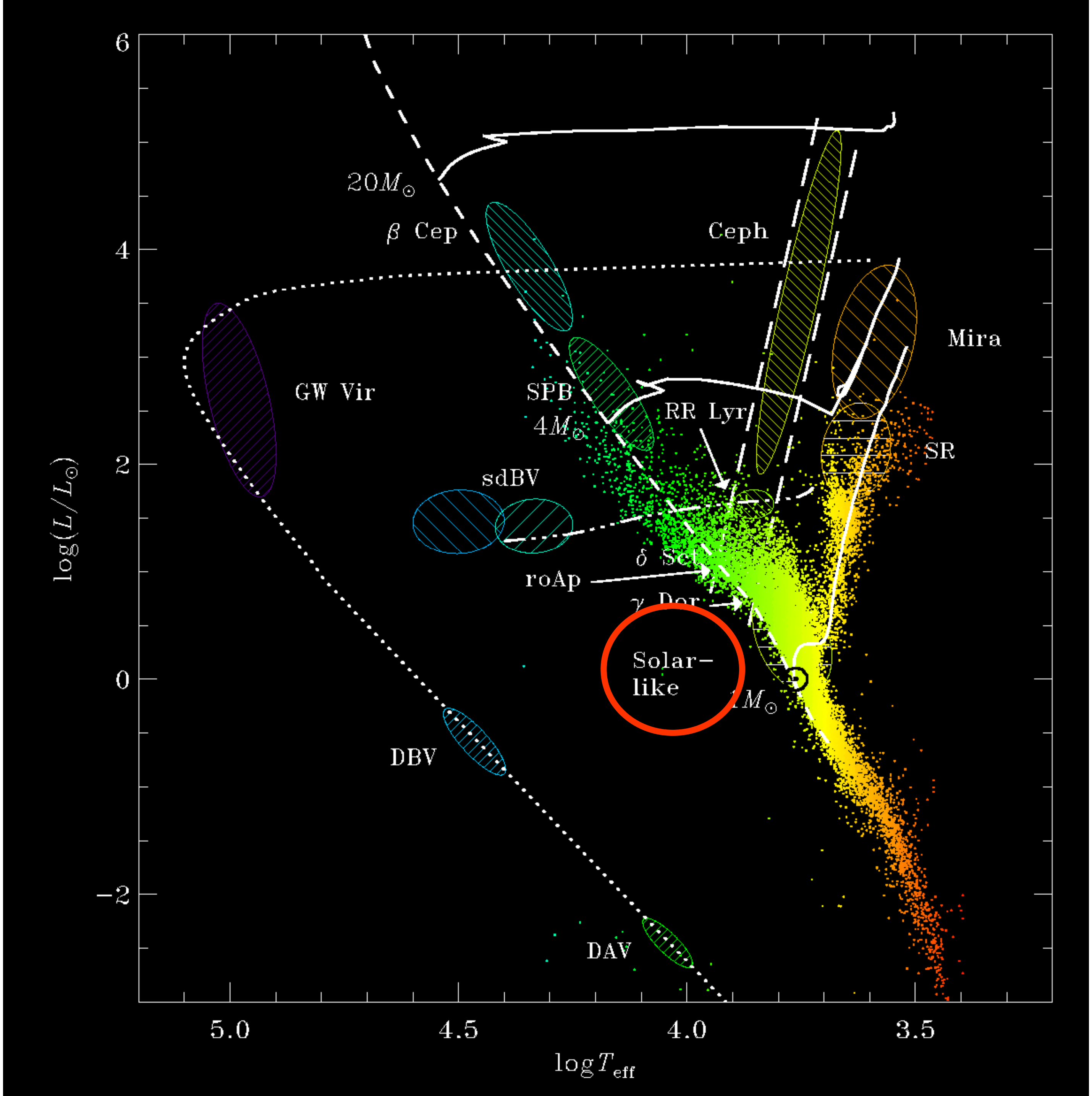
The Kappa-mechanism:

- Blue border:

  Ionization zones lie too high in the star (low density)

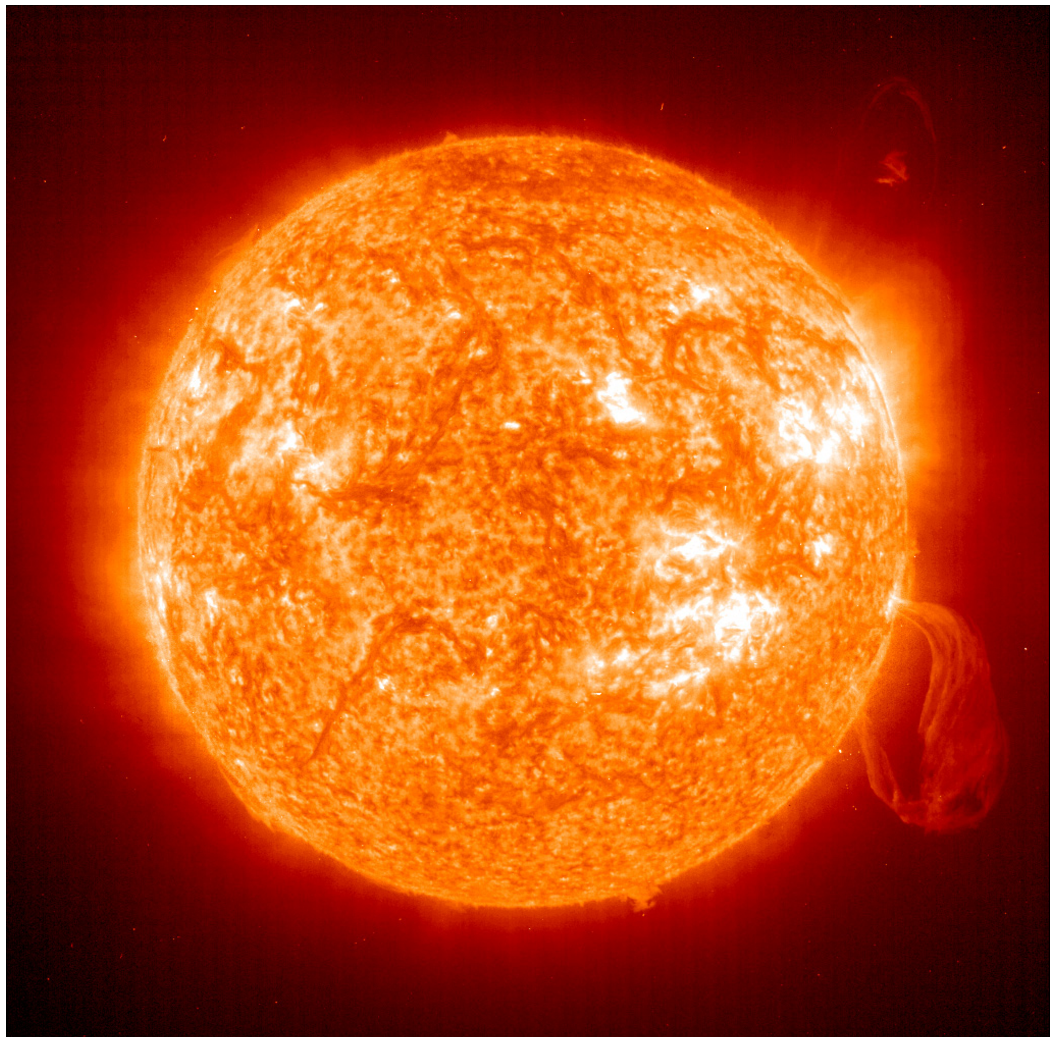
- Red border:

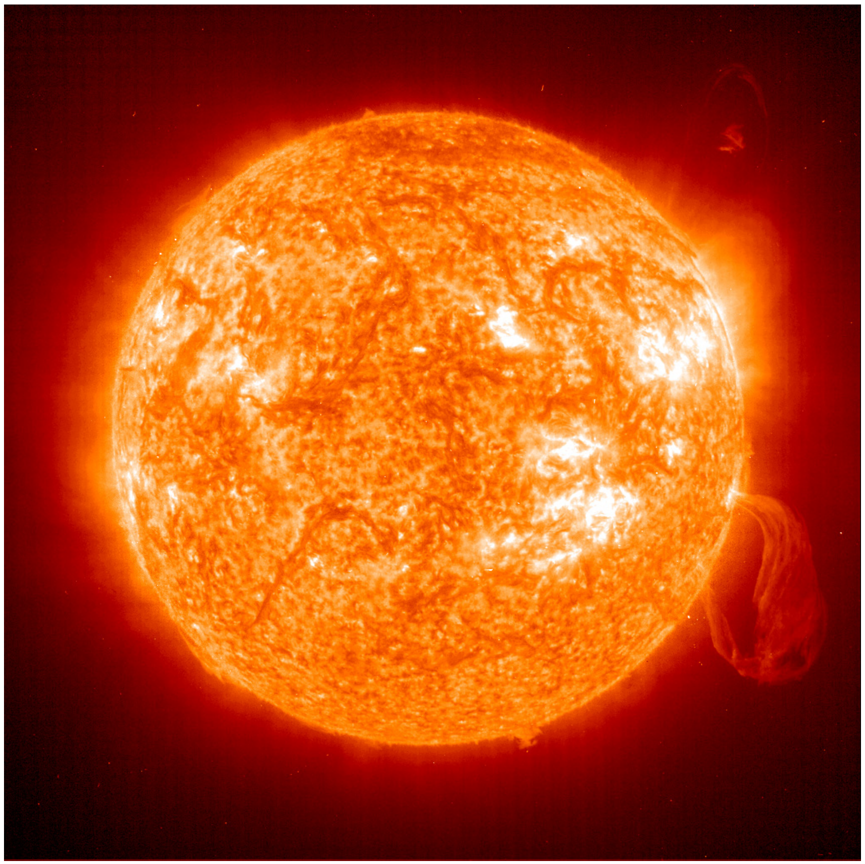
  (probably) convection



6
4
2
0
−2
log(L/L⊙)
5.0
4.5
4.0
3.5
log T_eff
20M⊙
β Cep
Ceph
Mira
GW Vir
SPB
4M⊙
RR Lyr
SR
sdBV
δ Sct
roAp
γ Dor
Solar-
like
1M⊙
DBV
DAV

The Sun is oscillating in about 10 million different modes with Periods of 3 – 15 minutes

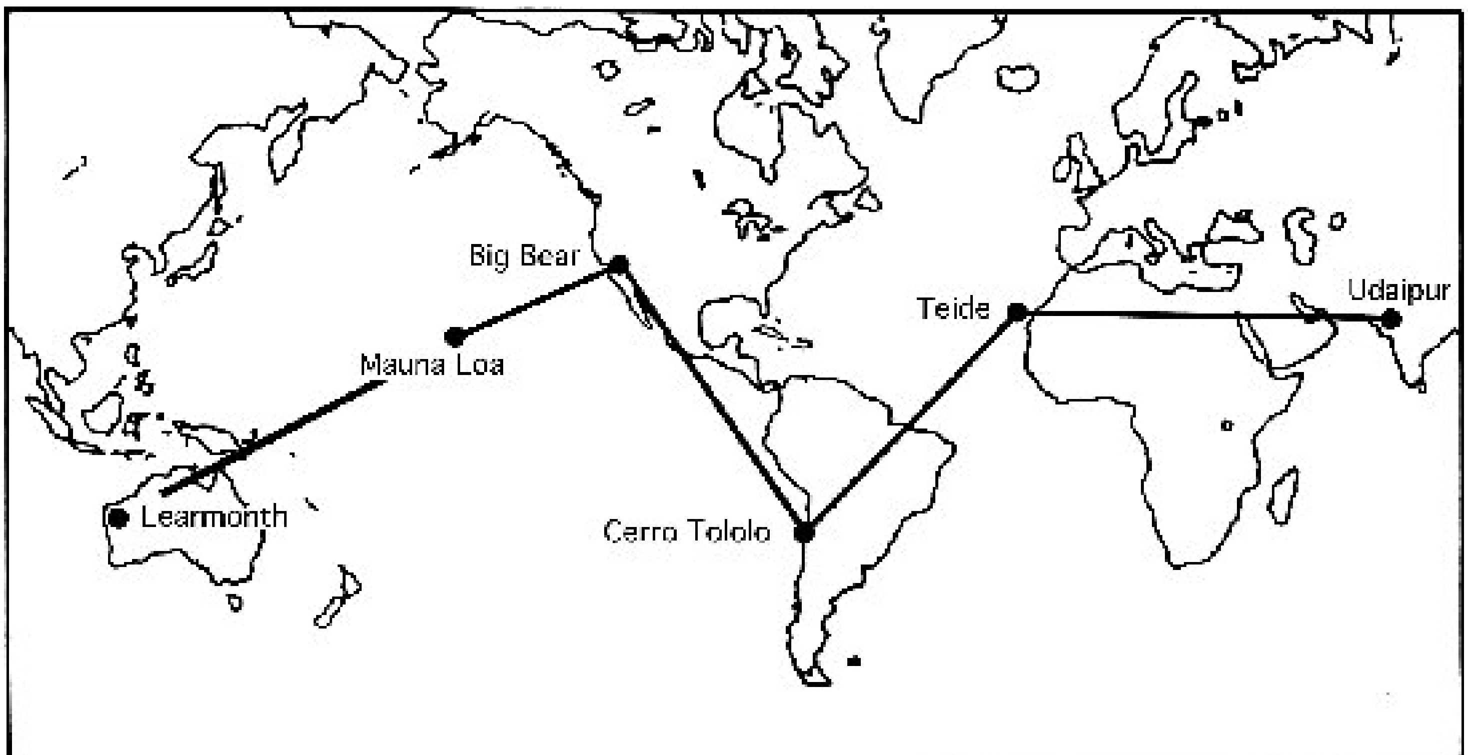




The oscillation periods of the Sun are determined from very extensive time-series observations from ground and from space…

National Solar Observatory

Global Oscillation Network Group



National Solar Observatory

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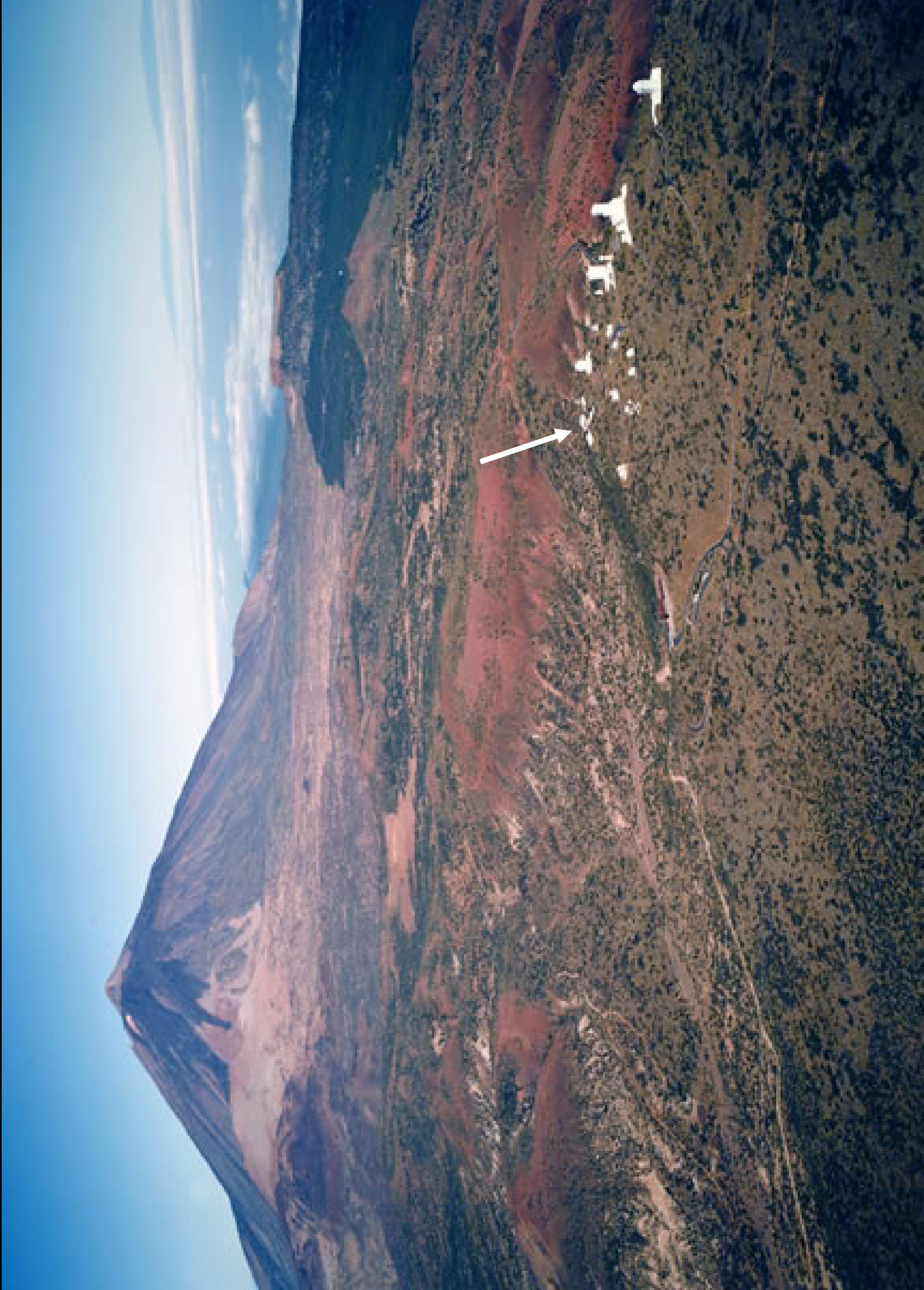
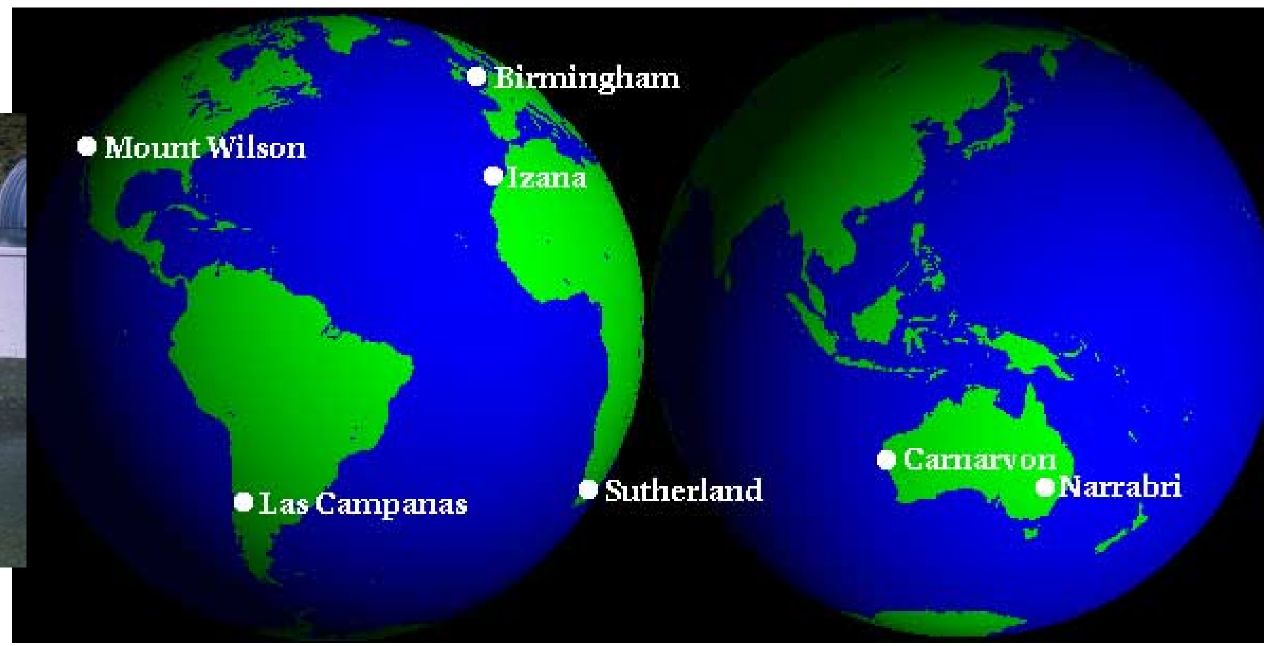
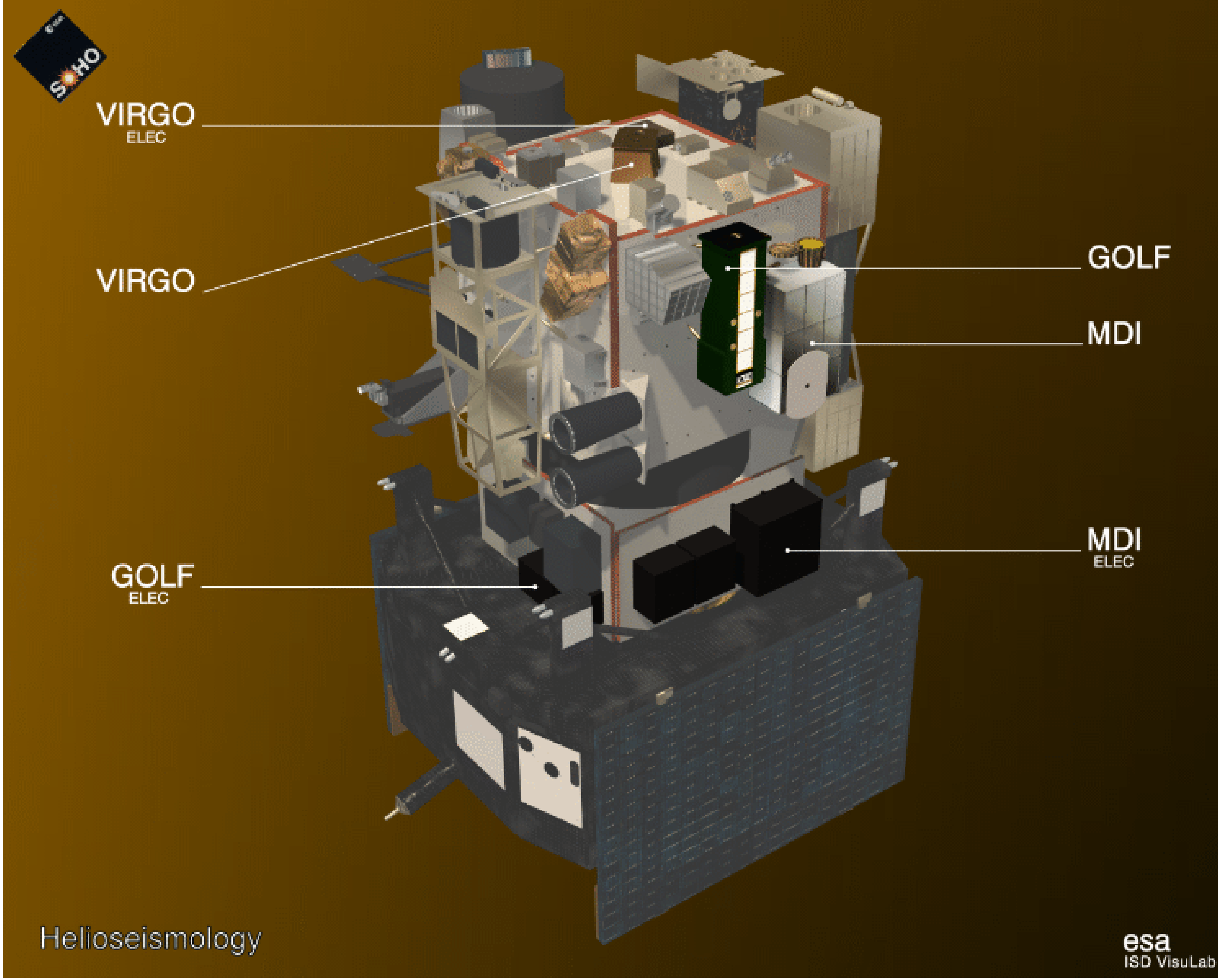


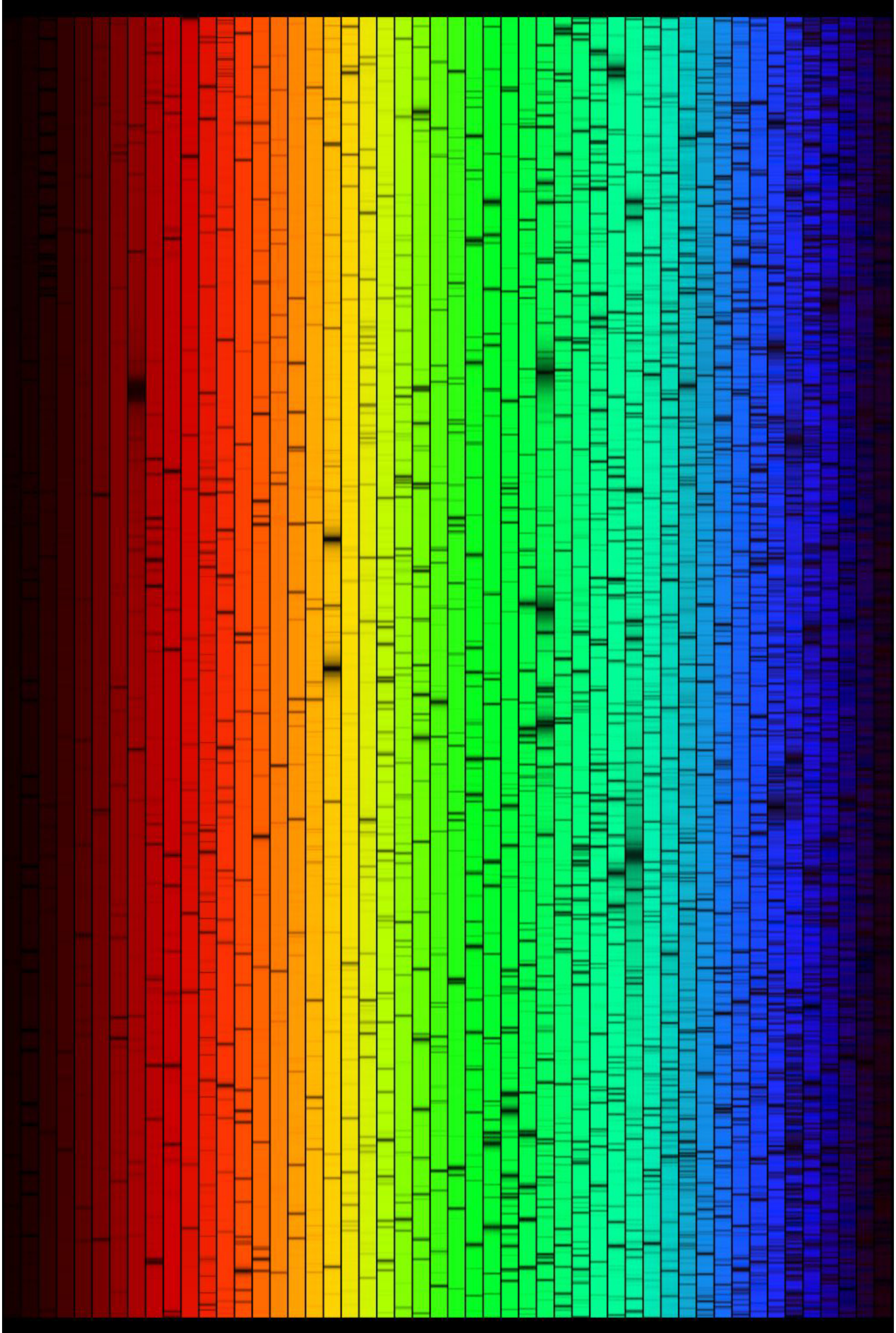
Birmingham Solar Oscillation Network (BiSON):

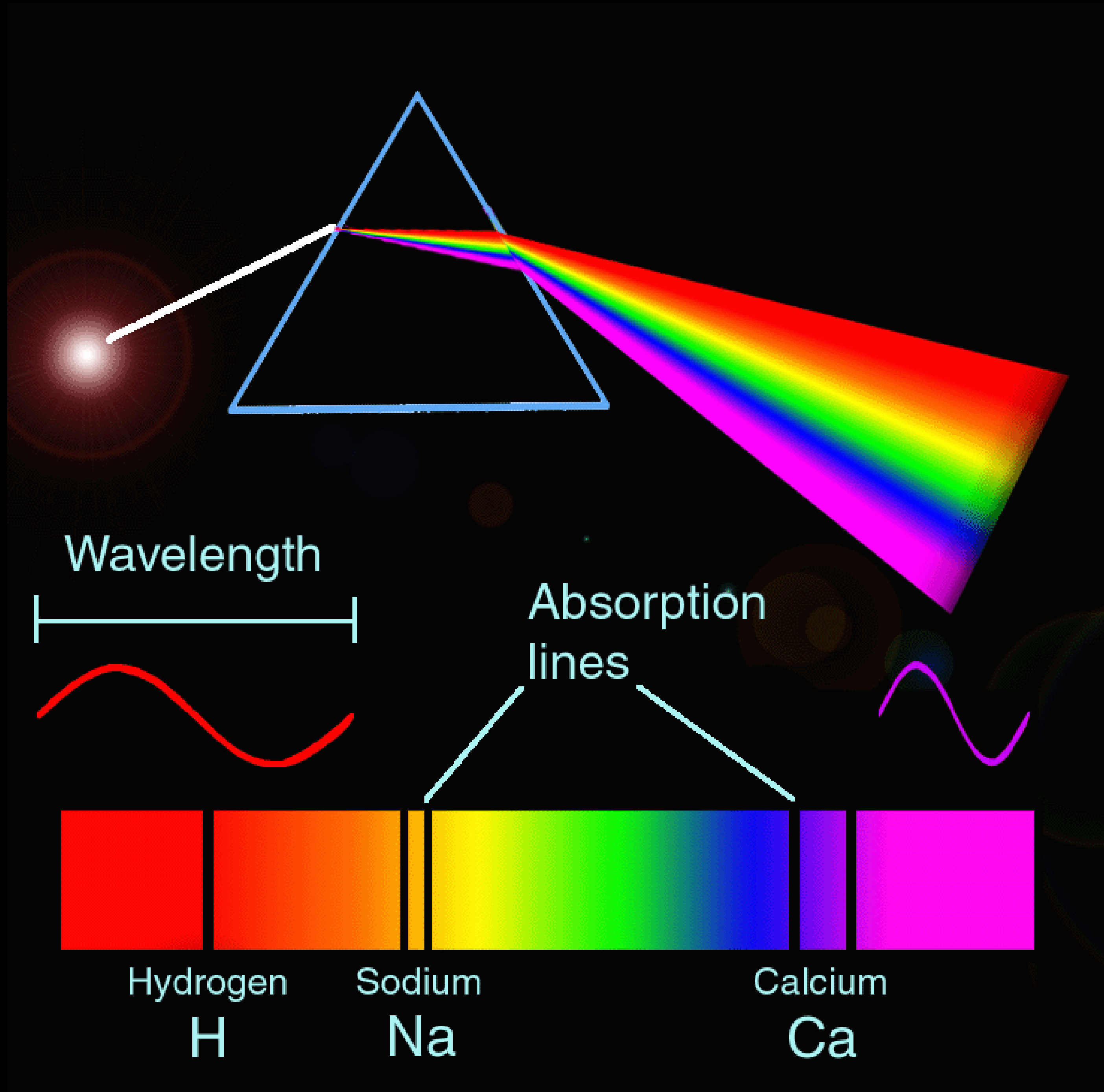


GOLF

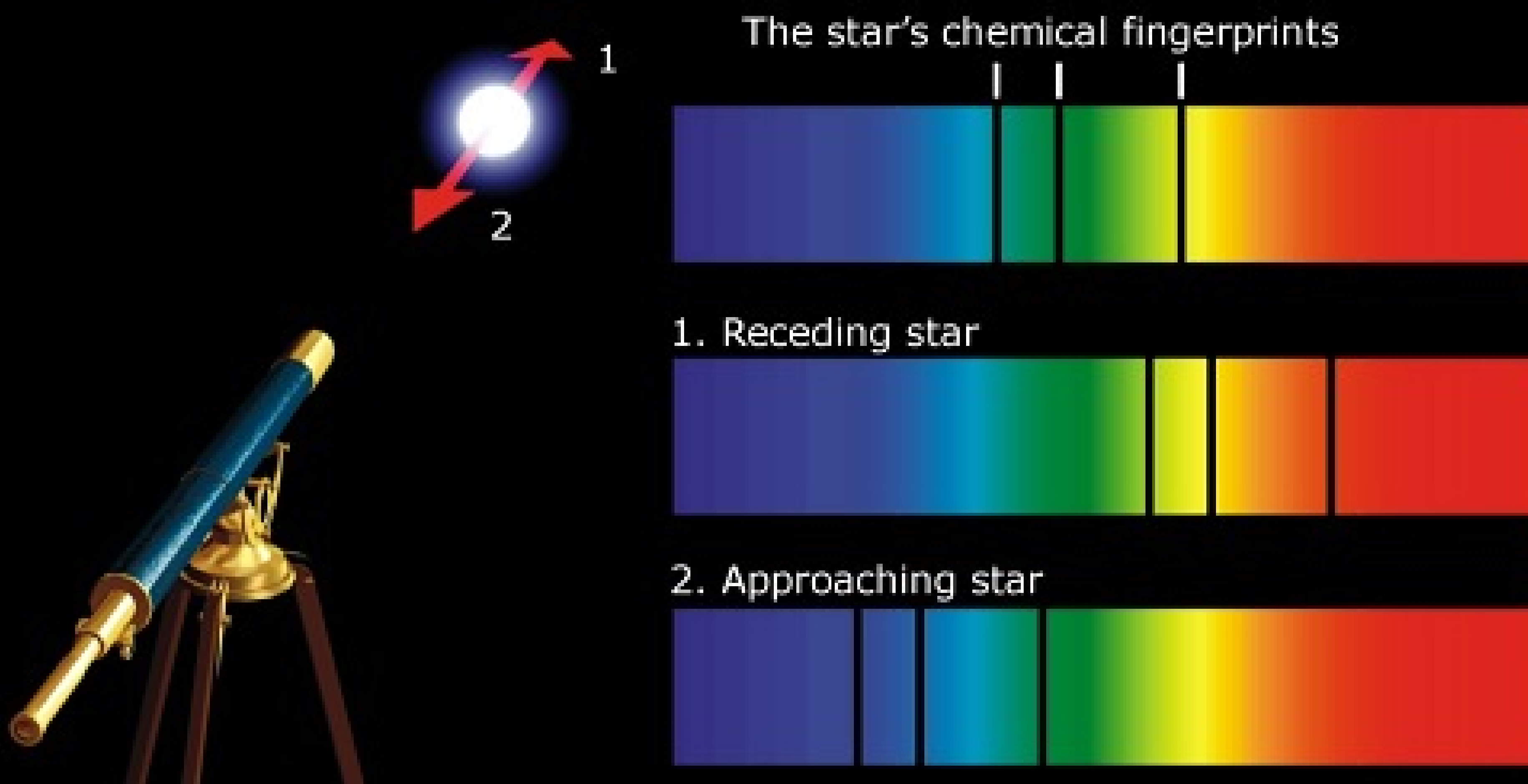
Global Oscillations
at Low Frequencies

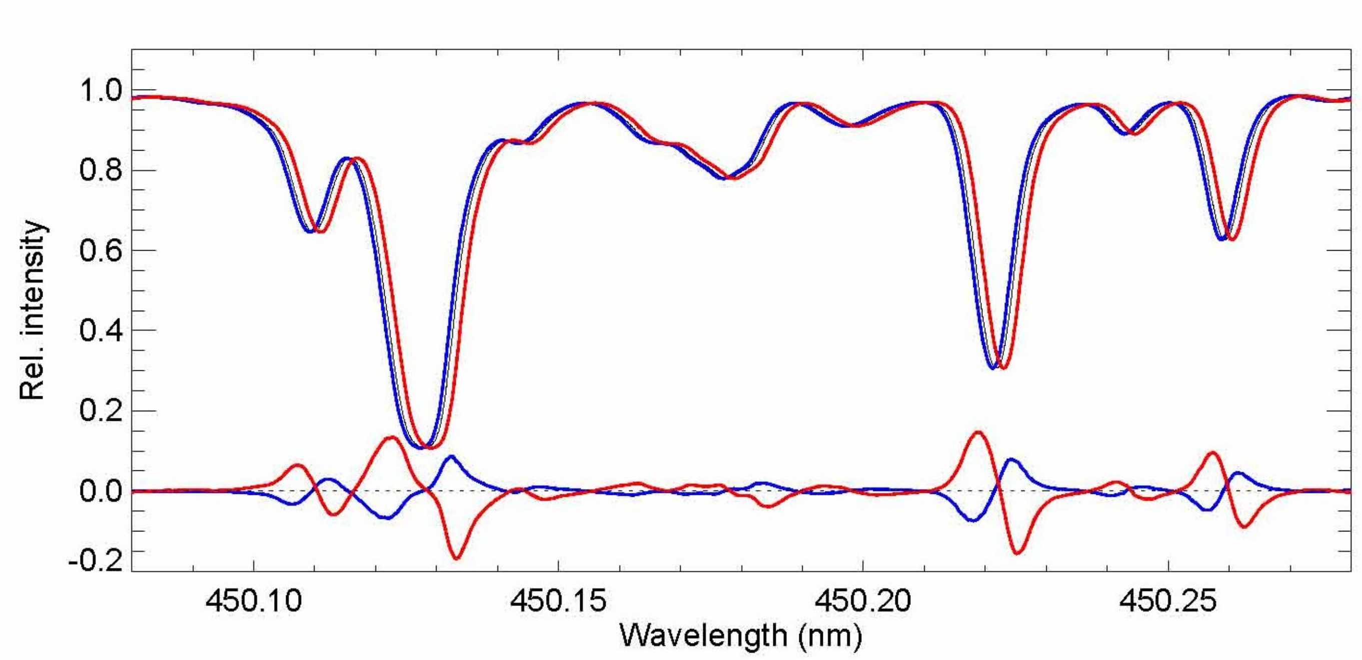

SOHO
VIRGO ELEC
VIRGO
GOLF ELEC
GOLF
MDI
MDI ELEC
Helioseismology
esa
ISD VisuLab





Wavelength
Absorption
lines
Hydrogen
H
Sodium
Na
Calcium
Ca

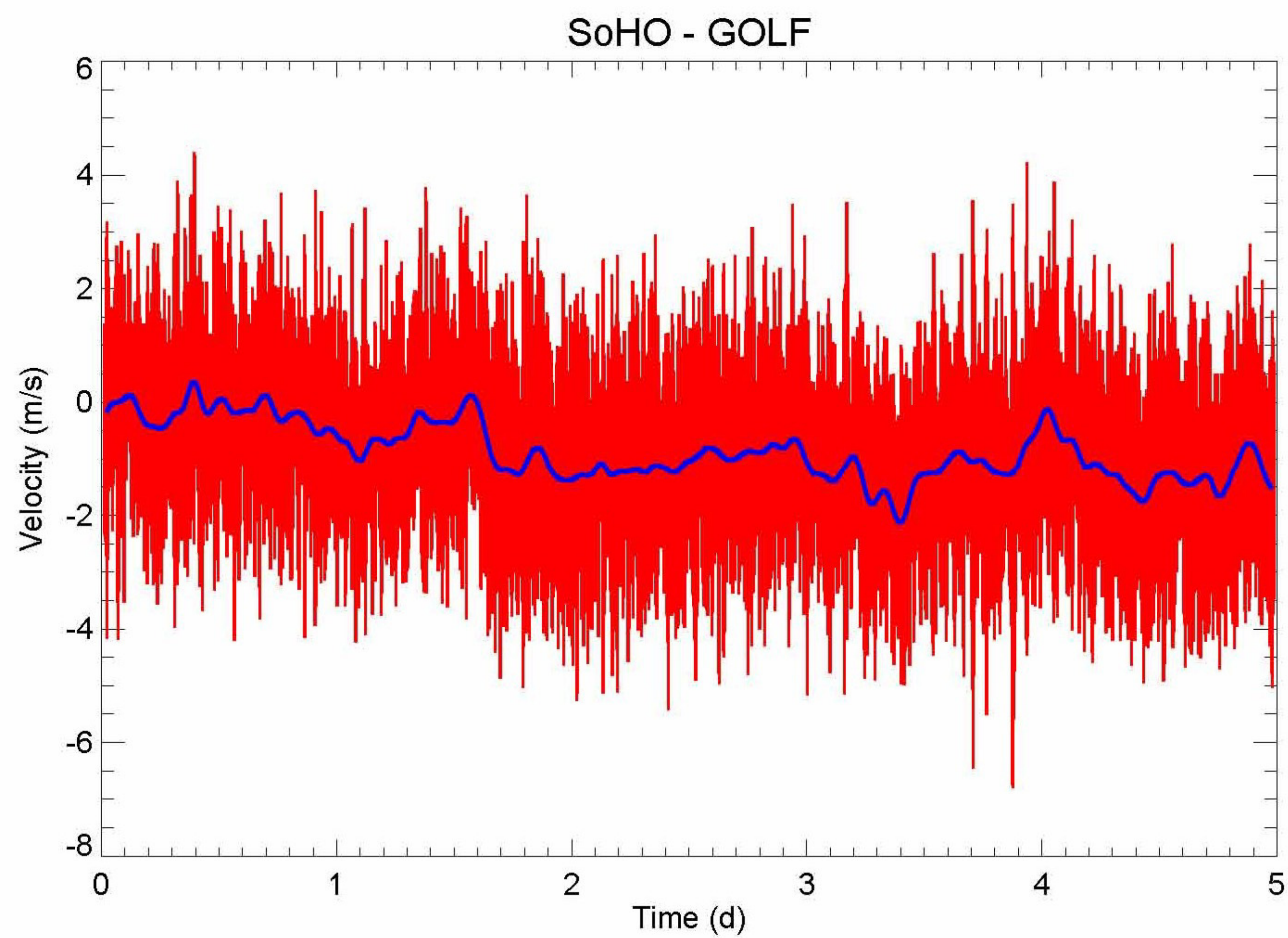

1
2
The star's chemical fingerprints
1. Receding star
2. Approaching star

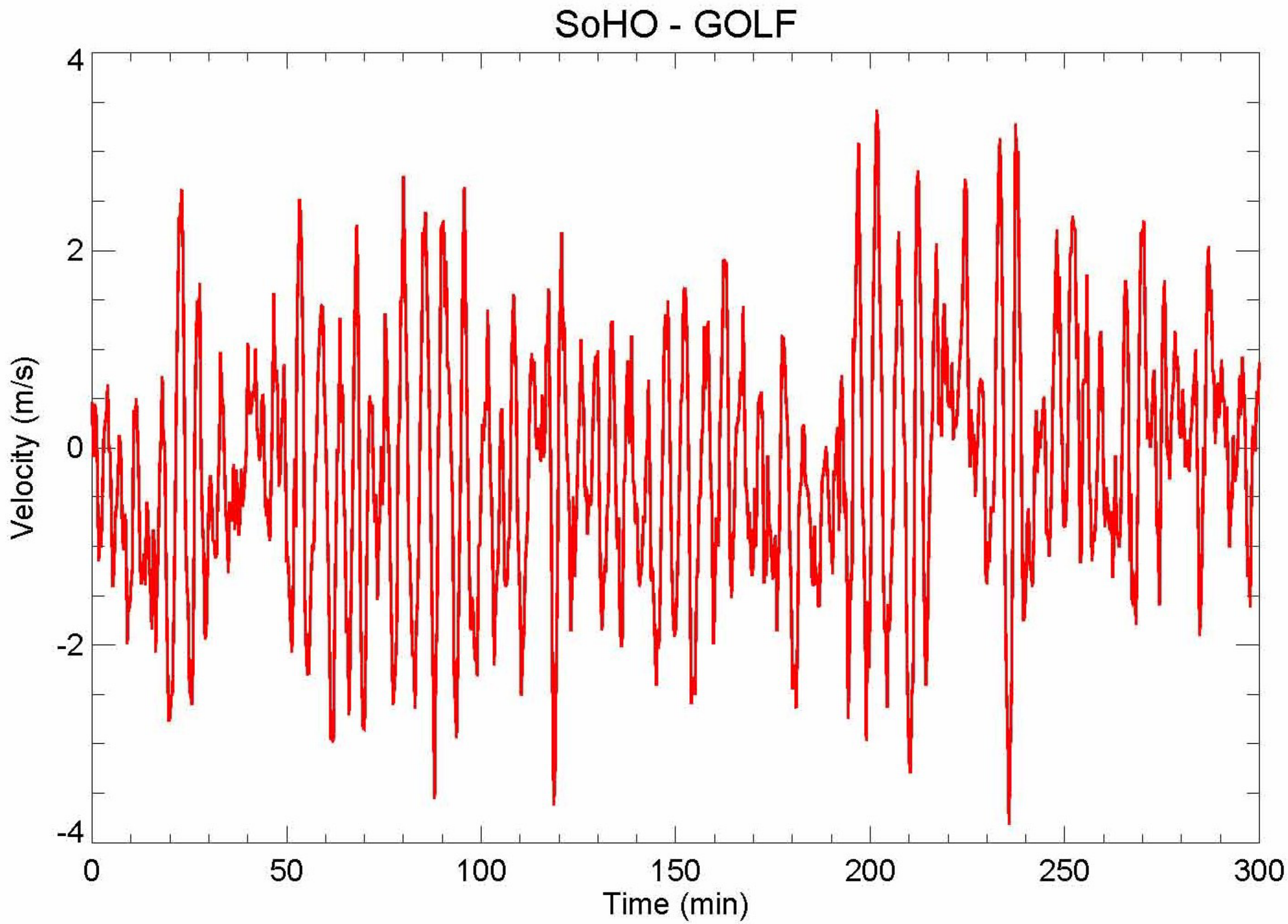


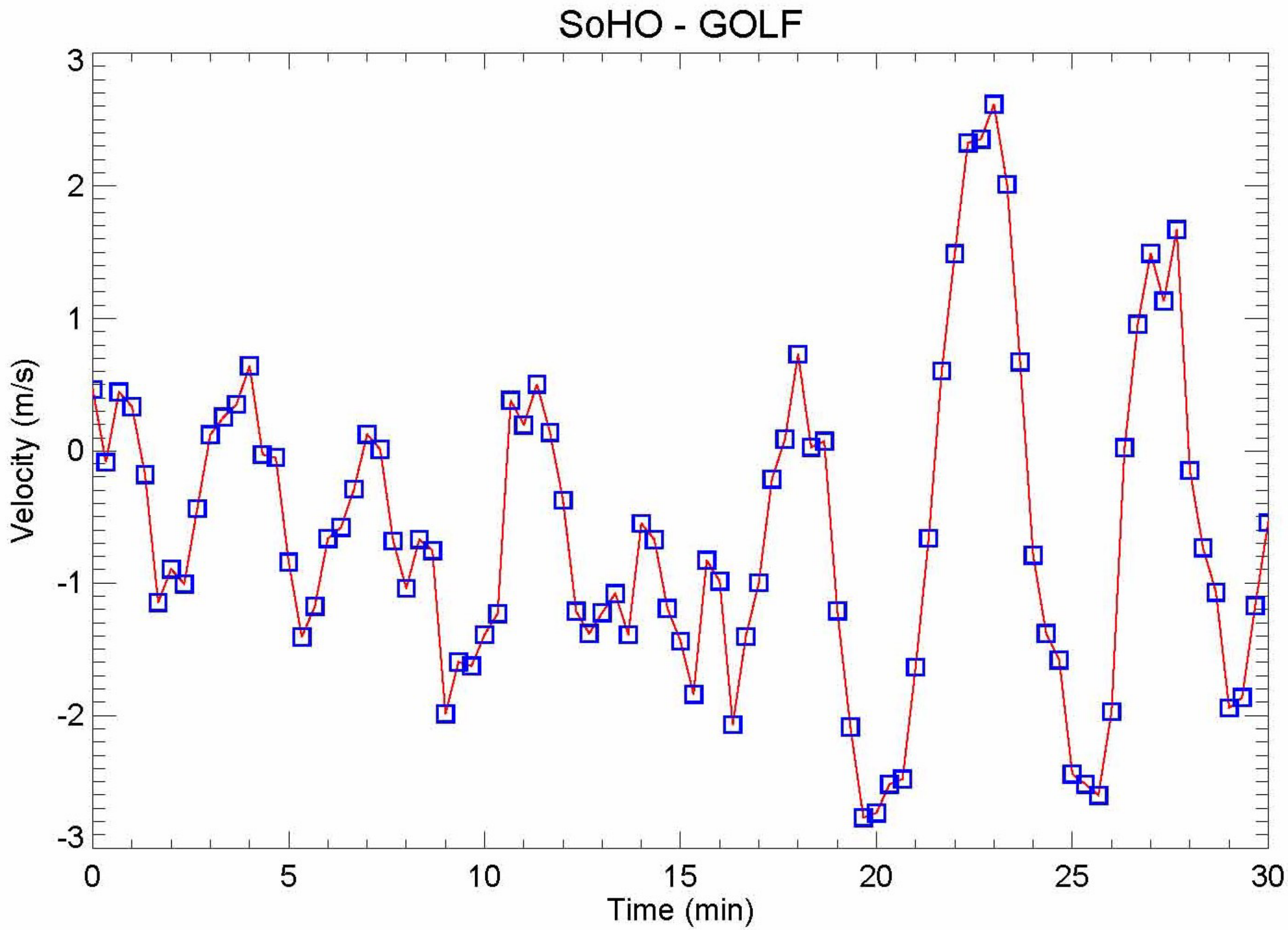
+ 800 m/s: redshifted: 12 mÅ

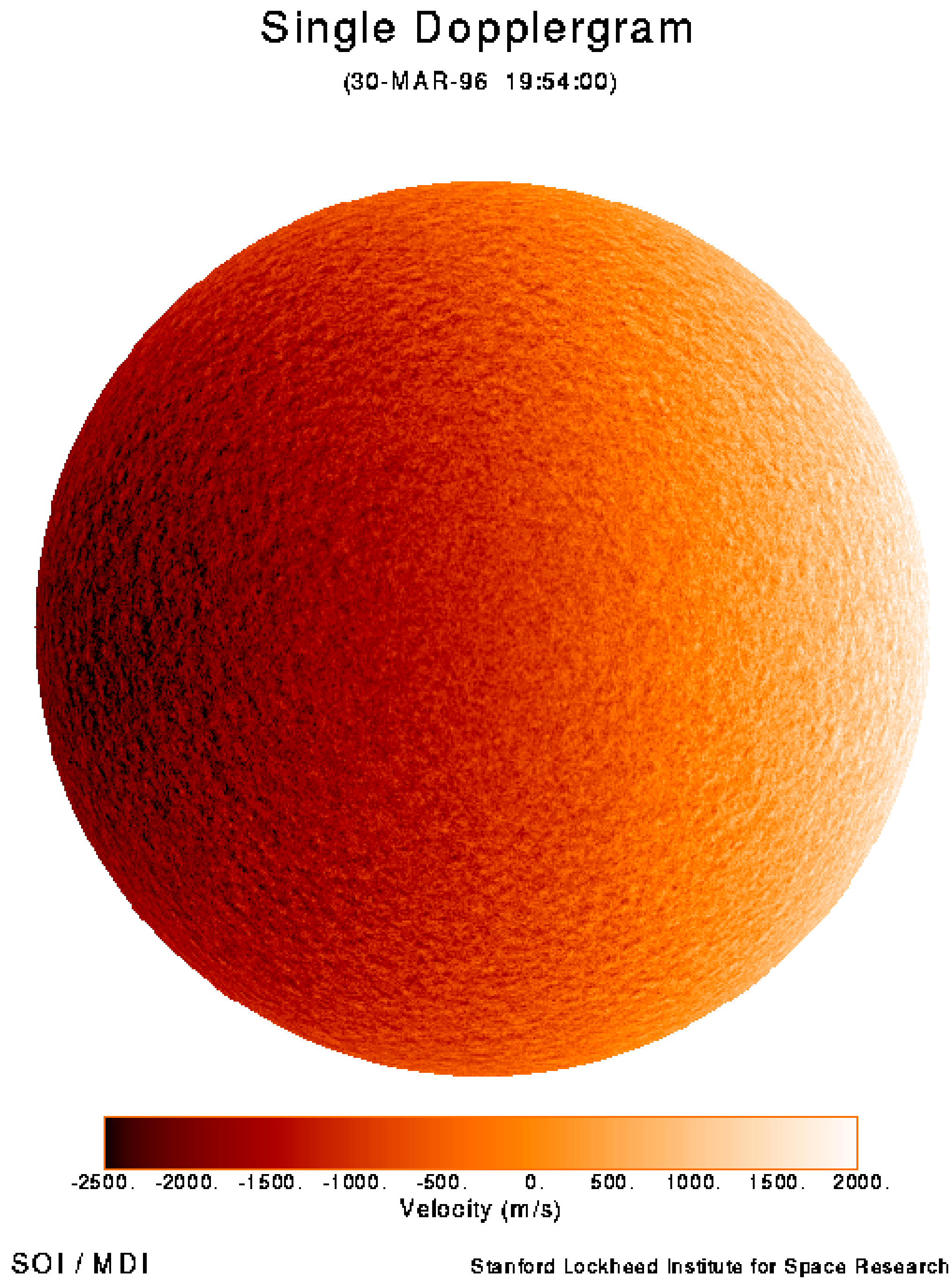
- 400 m/s: blueshifted: 6 mÅ

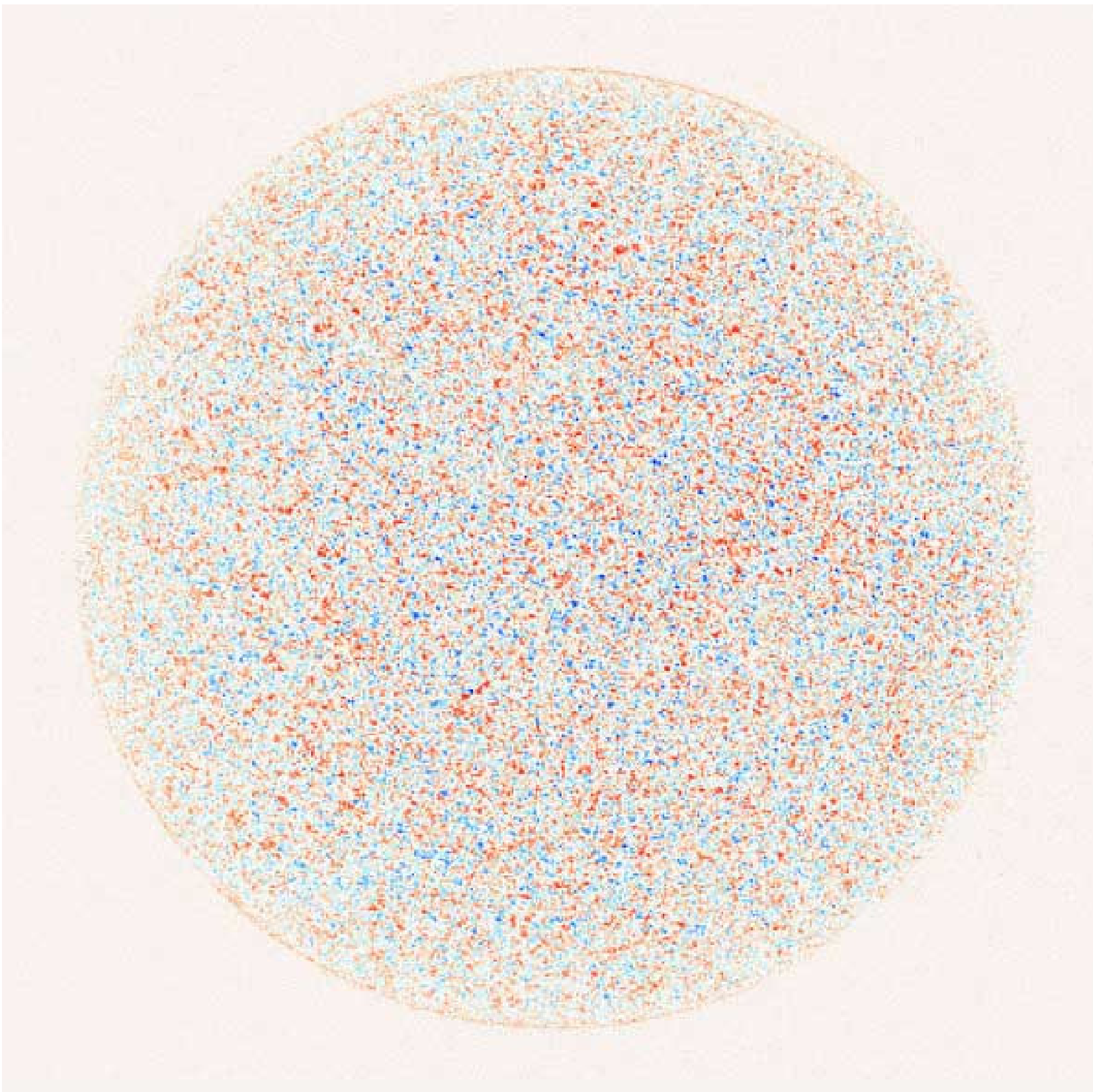
Time-series Spectroscopy → Doppler-shifts of Radial Velocities due to the oscillations…


SoHO - GOLF
Velocity (m/s)
Time (d)
6
4
2
0
-2
-4
-6
-8
0
1
2
3
4
5

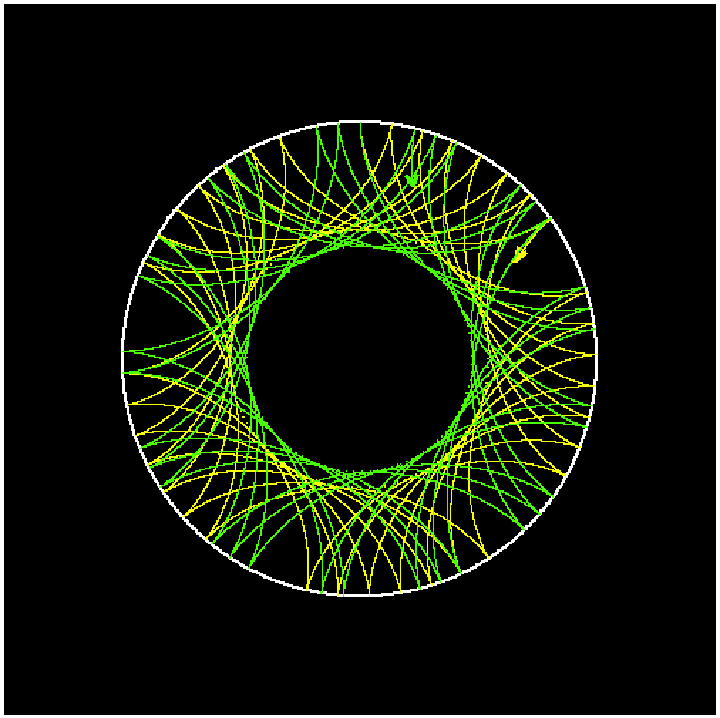

SoHO - GOLF
Velocity (m/s)
4
2
0
-2
-4
0
50
100
150
200
250
300
Time (min)


SoHO - GOLF
Velocity (m/s)
3
2
1
0
-1
-2
-3
0
5
10
15
20
25
30
Time (min)

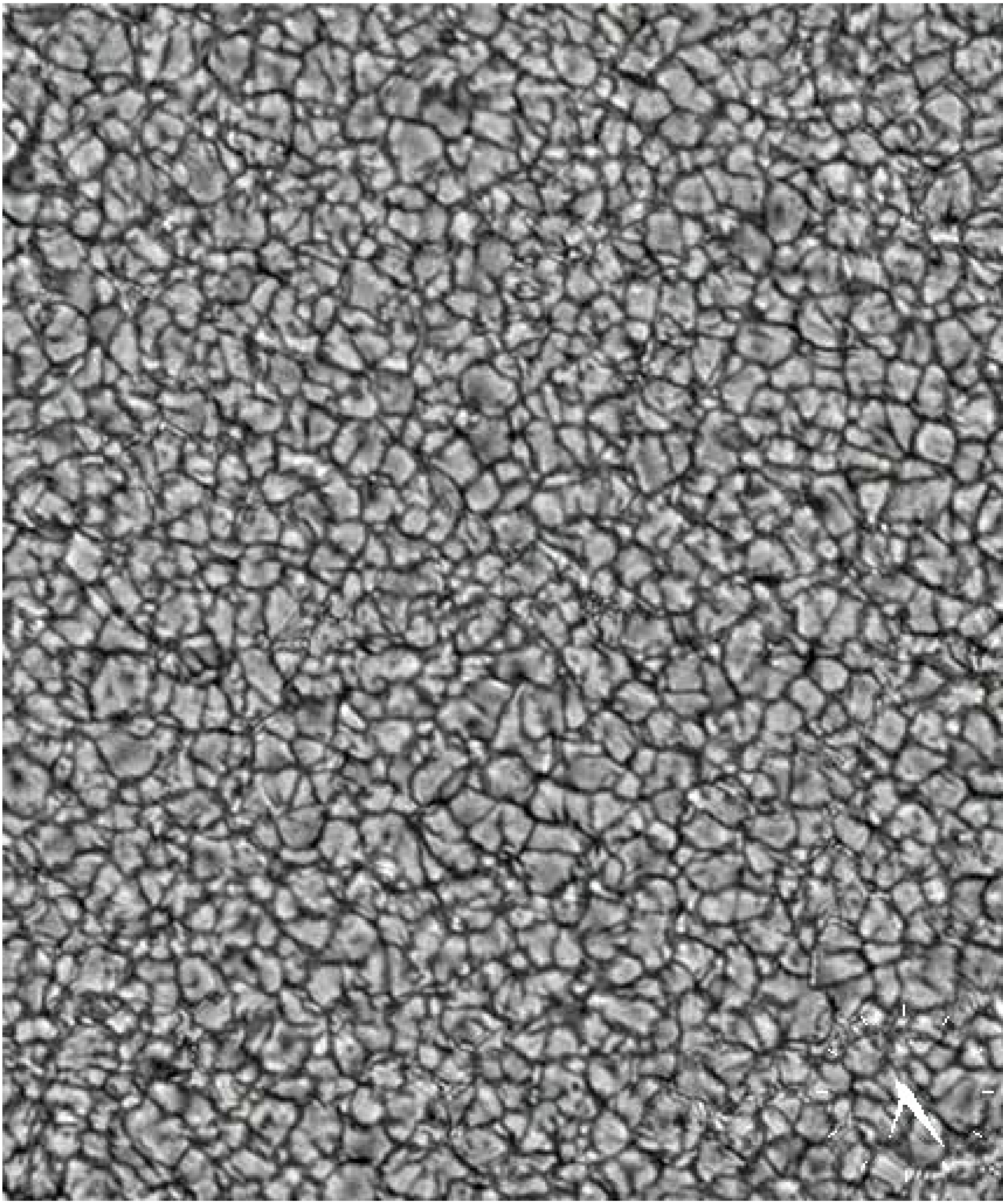

Single Dopplergram
(30-MAR-96 19:54:00)
-2500. -2000. -1500. -1000. -500. 0. 500. 1000. 1500. 2000.
Velocity (m/s)
SOI / MDI
Stanford Lockheed Institute for Space Research



Helioseismology:



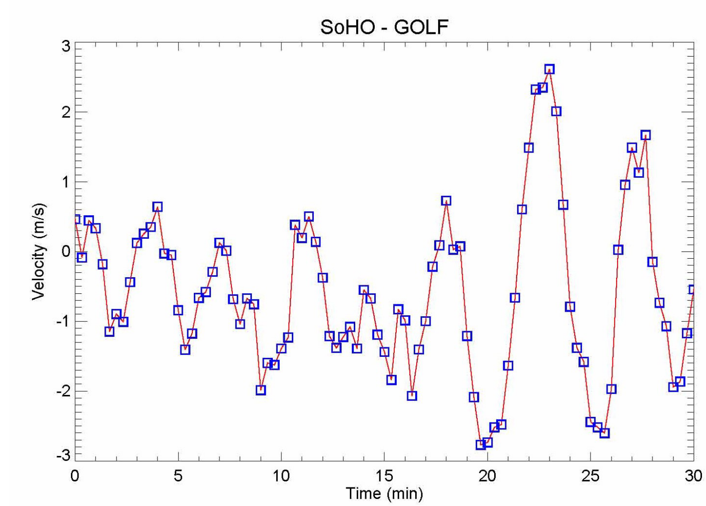
- Modes with different (*n*,*l*,*m*) follow different paths in the star, with slightly different Sound Speed
- The Sun: Measuring millions of oscillation modes has resulted in a precise measure of the Sound Speed and hence of the physical conditions, in every part of the Sun
- This is obtained through Inversion Techniques

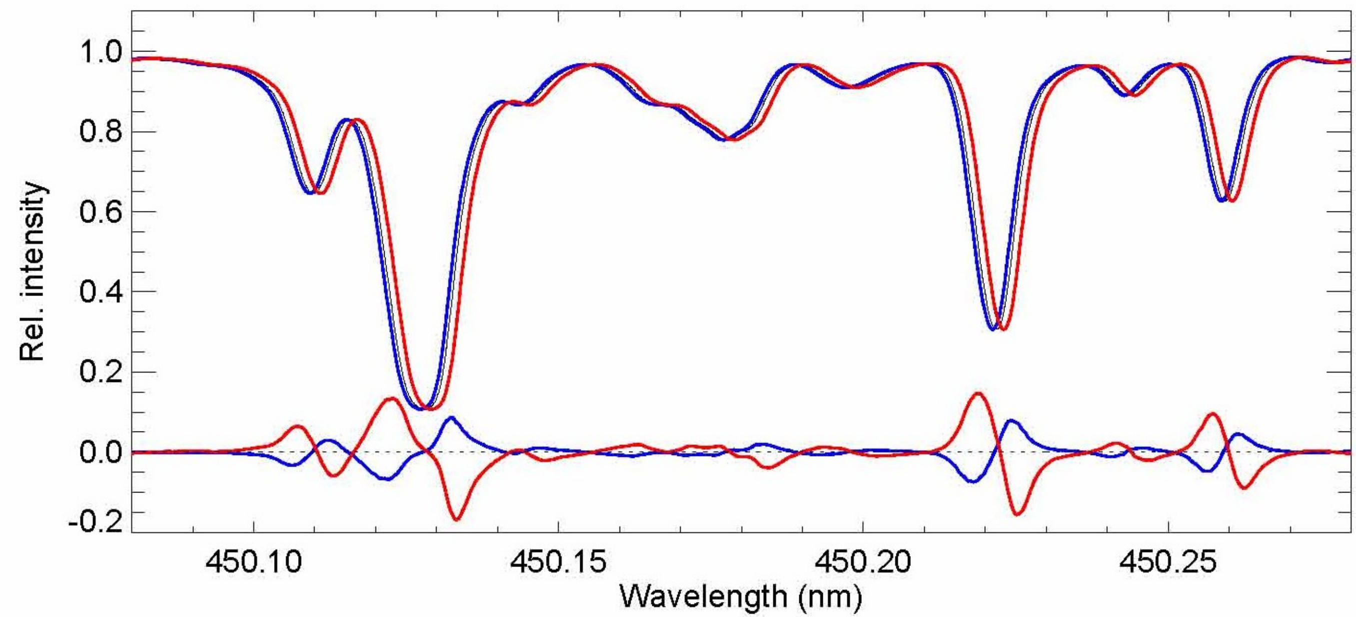


The Solar 5-min oscillations

- Amplitudes are very low;

  20 cm/s in velocity, or
  20-30 m in displacement,
  a fraction of a degree in temperature,
  a few ppm in brightness

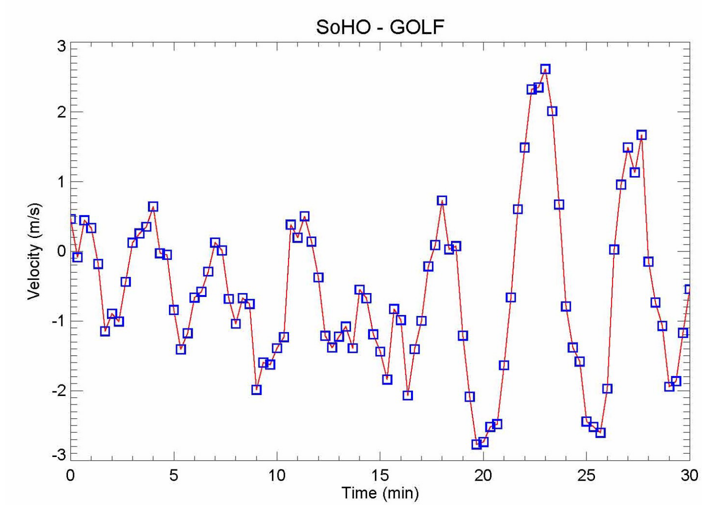




+ 800 m/s:	redshifted:	12 mÅ
- 400 m/s:	blueshifted:	6 mÅ

20 cm/s: 3-6 μÅ (~ 80 Si-atoms on the CCD-detector)

The Solar 5-min oscillations



- Amplitudes are very low;

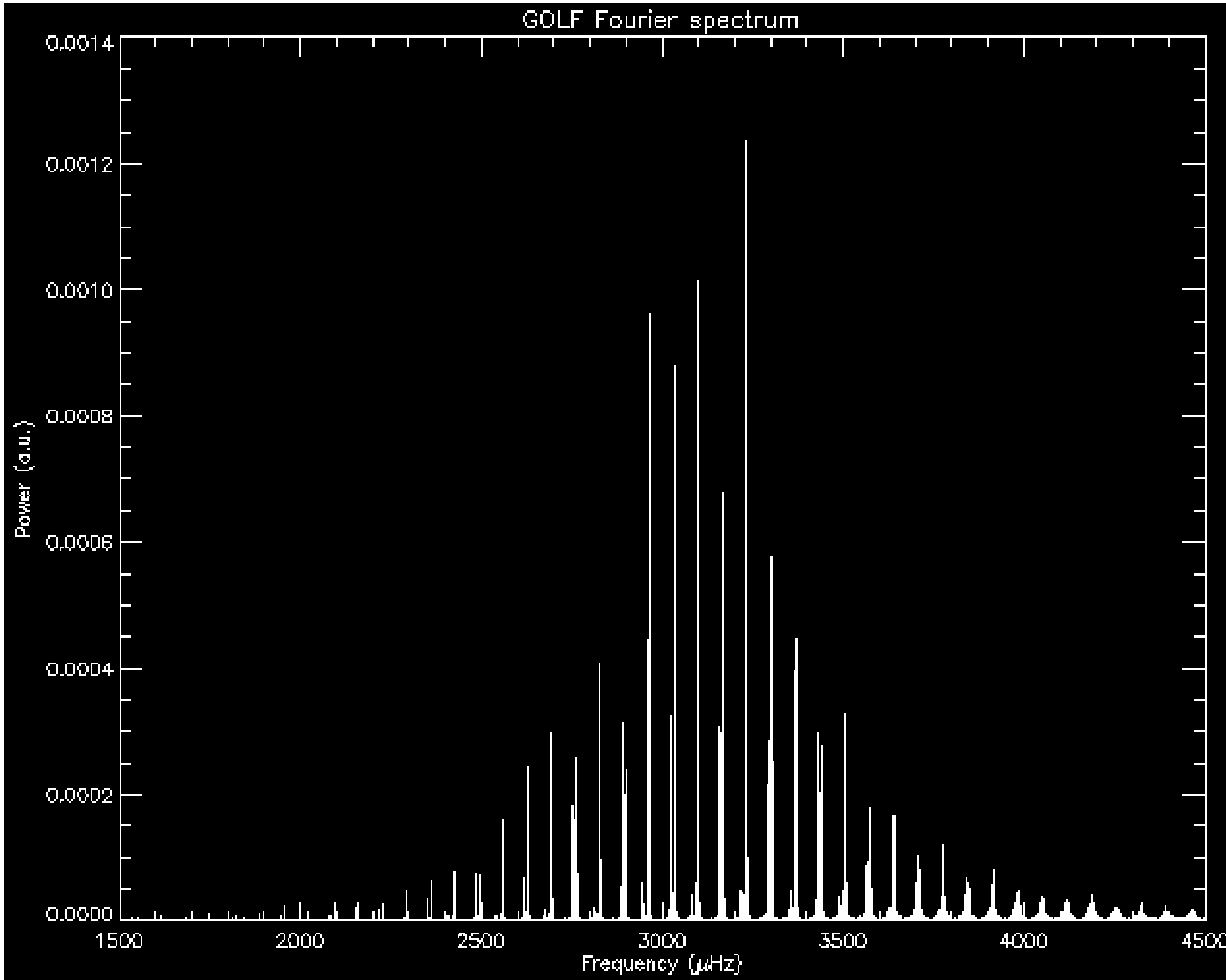
  20 cm/s in velocity, or
  20-30 m in displacement,
  a fraction of a degree in temperature,
  a few ppm in brightness

- Millions of oscillation modes (or notes) excited,

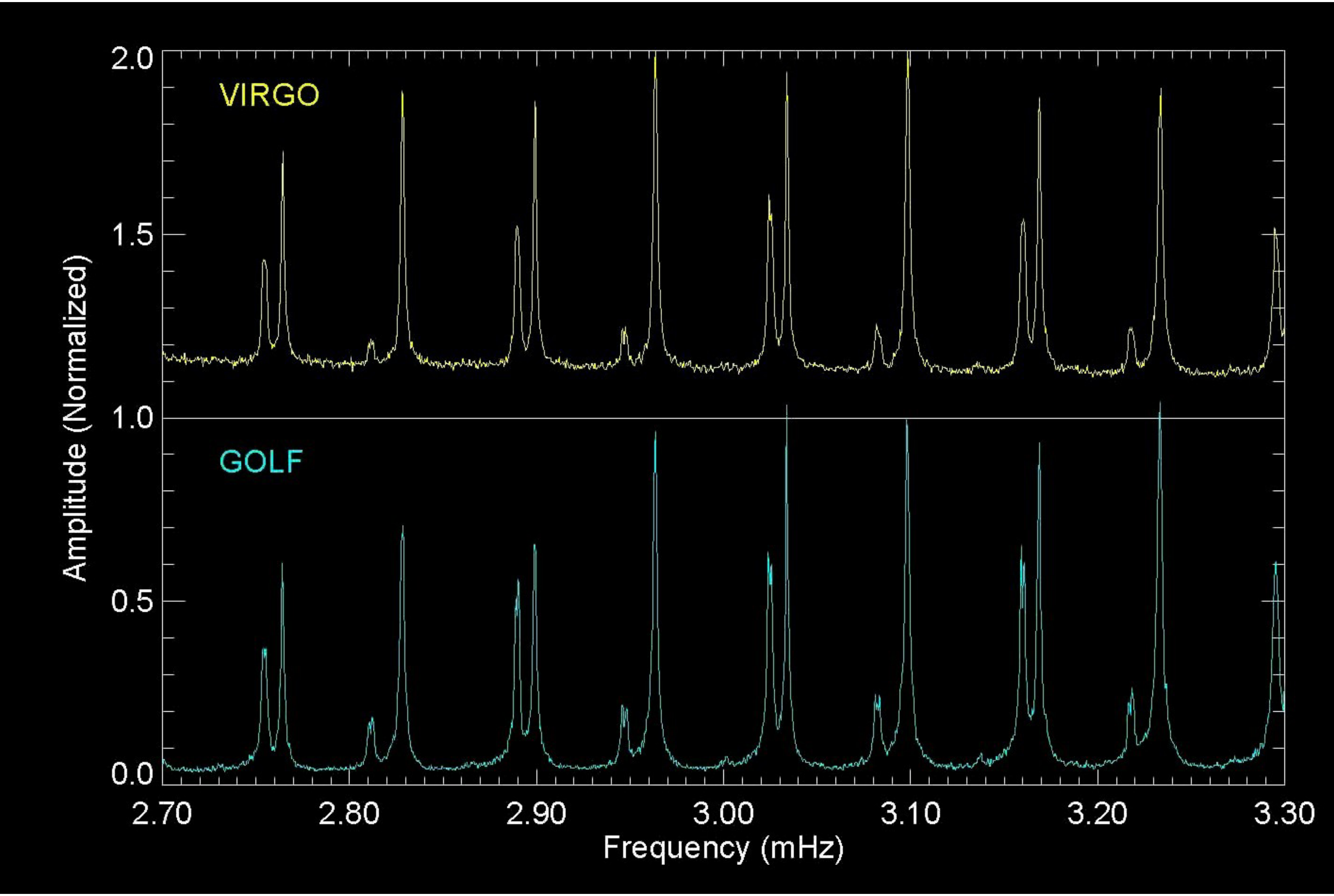
- Very extensive observations are required to determine the individual frequencies through FOURIER ANALYSIS

$$f = A_i \sin(2\pi\nu_i t + \varphi_i) \rightarrow$$ LSQ fit to the time series

Ampl.

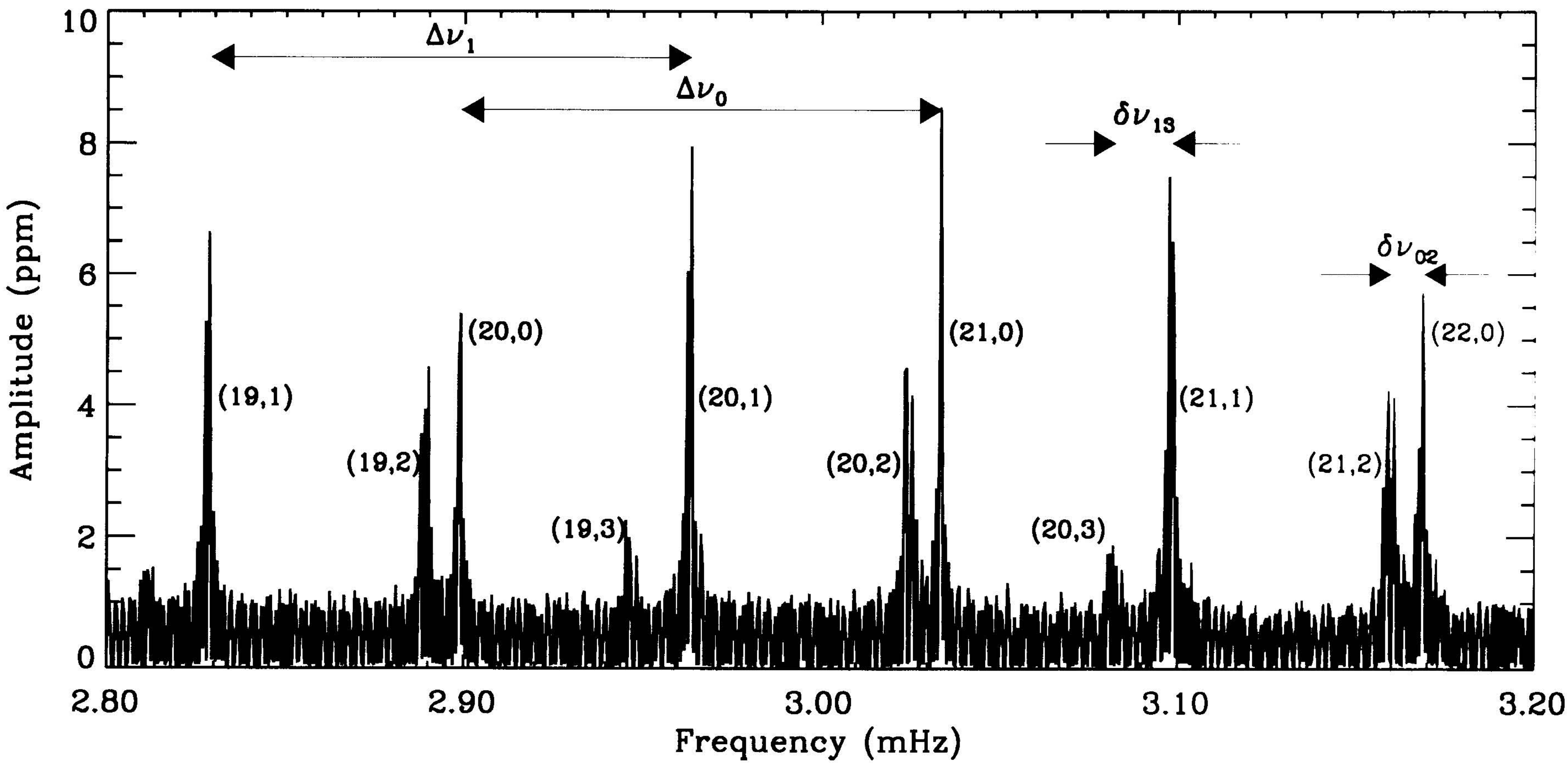


Frequency

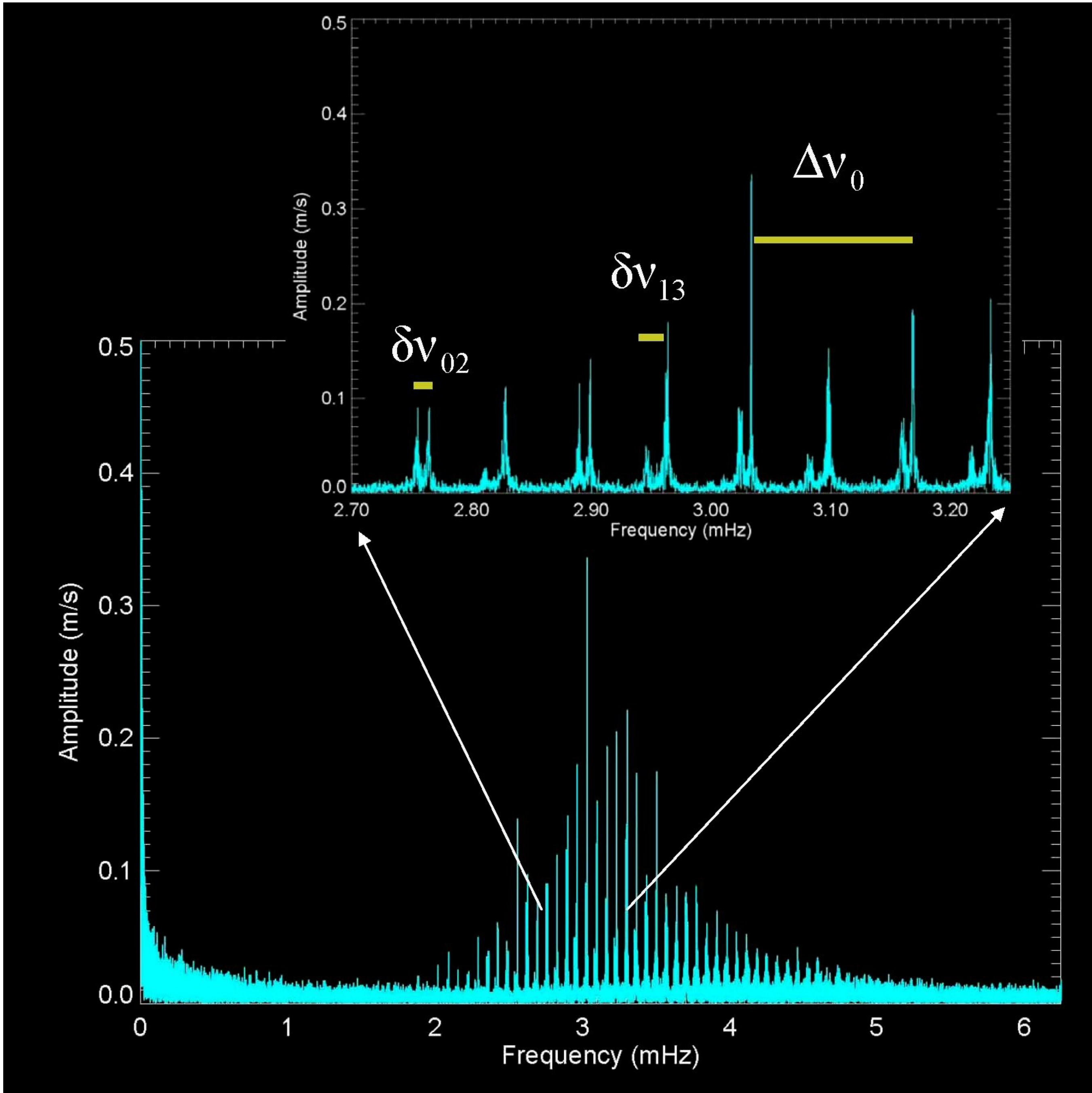


VIRGO
GOLF
Amplitude (Normalized)
2.0
1.5
1.0
0.5
0.0
2.70
2.80
2.90
3.00
3.10
3.20
3.30
Frequency (mHz)

$$\nu_{n,l} = \Delta\nu(n + \frac{1}{2}l + \varepsilon) - l(l+1)D_0$$

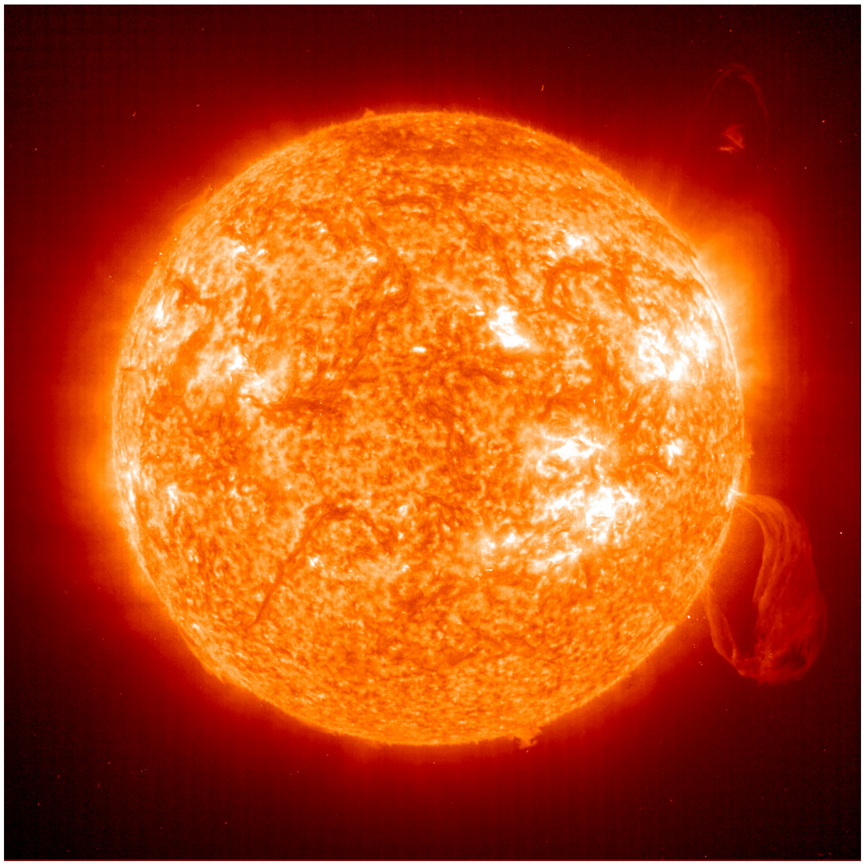


$$D_0 = \frac{1}{6}\delta\nu_{02} = \frac{1}{2}\delta\nu_{01} = \frac{1}{10}\delta\nu_{13}$$



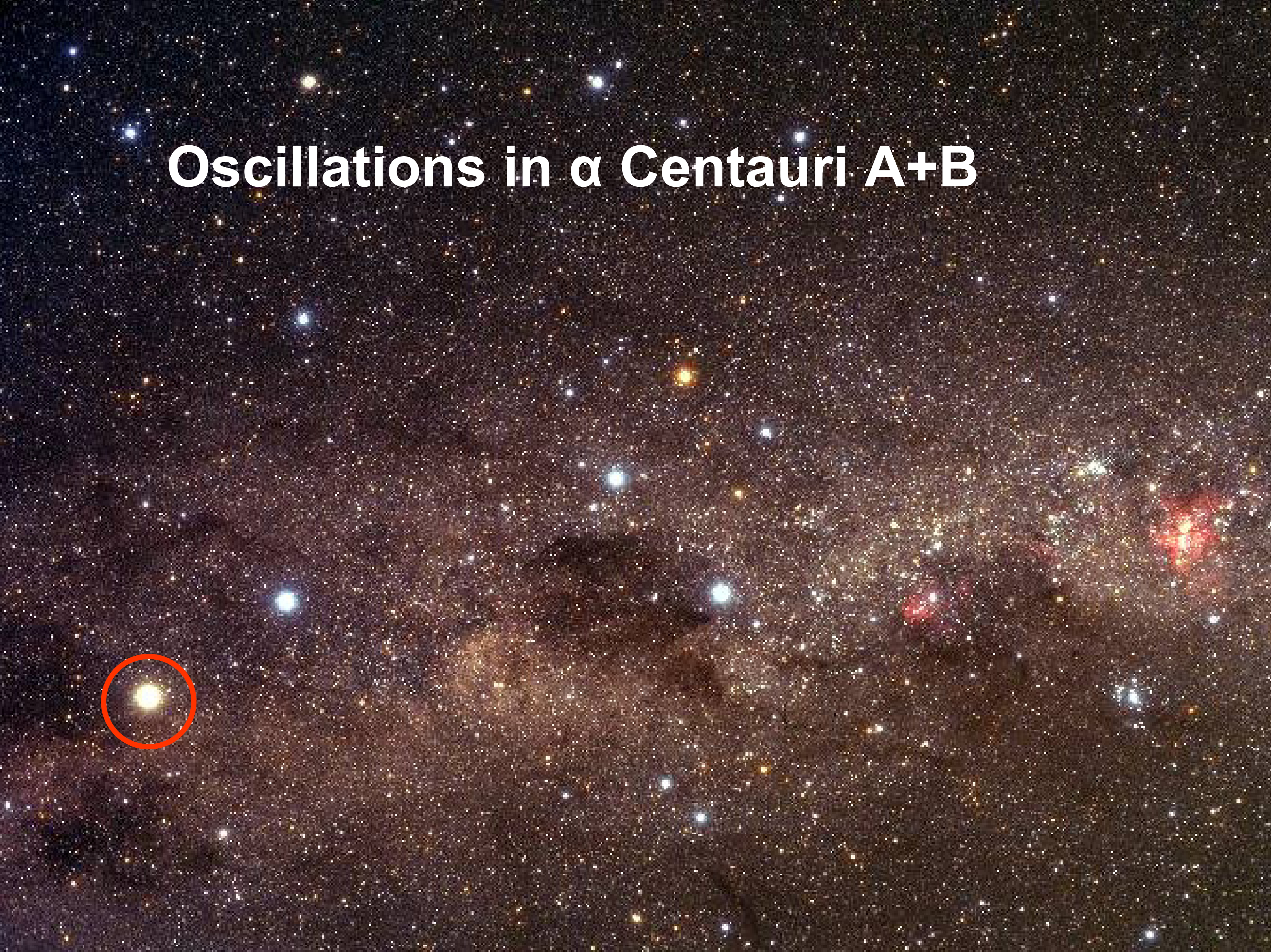
Amplitude (m/s)
Frequency (mHz)
Amplitude (m/s)
Frequency (mHz)
$\delta\nu_{02}$
$\delta\nu_{13}$
$\Delta\nu_0$

The Sun is oscillating in about 10 million different modes with Periods of 3 – 15 minutter and extremely low amplitude

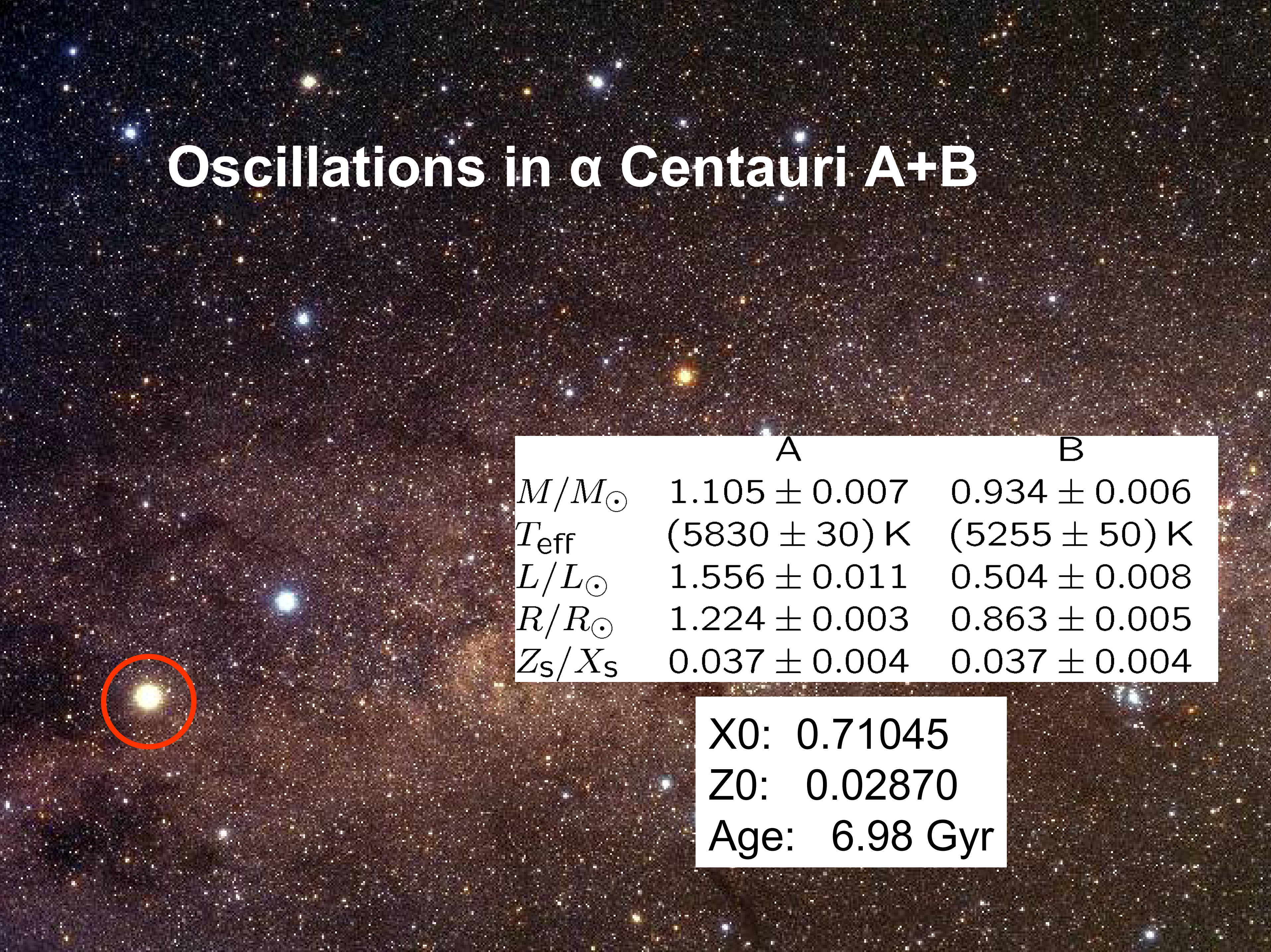


So does other solar-like stars – but this can only be measured in the bright, nearby stars

Oscillations in α Centauri A+B



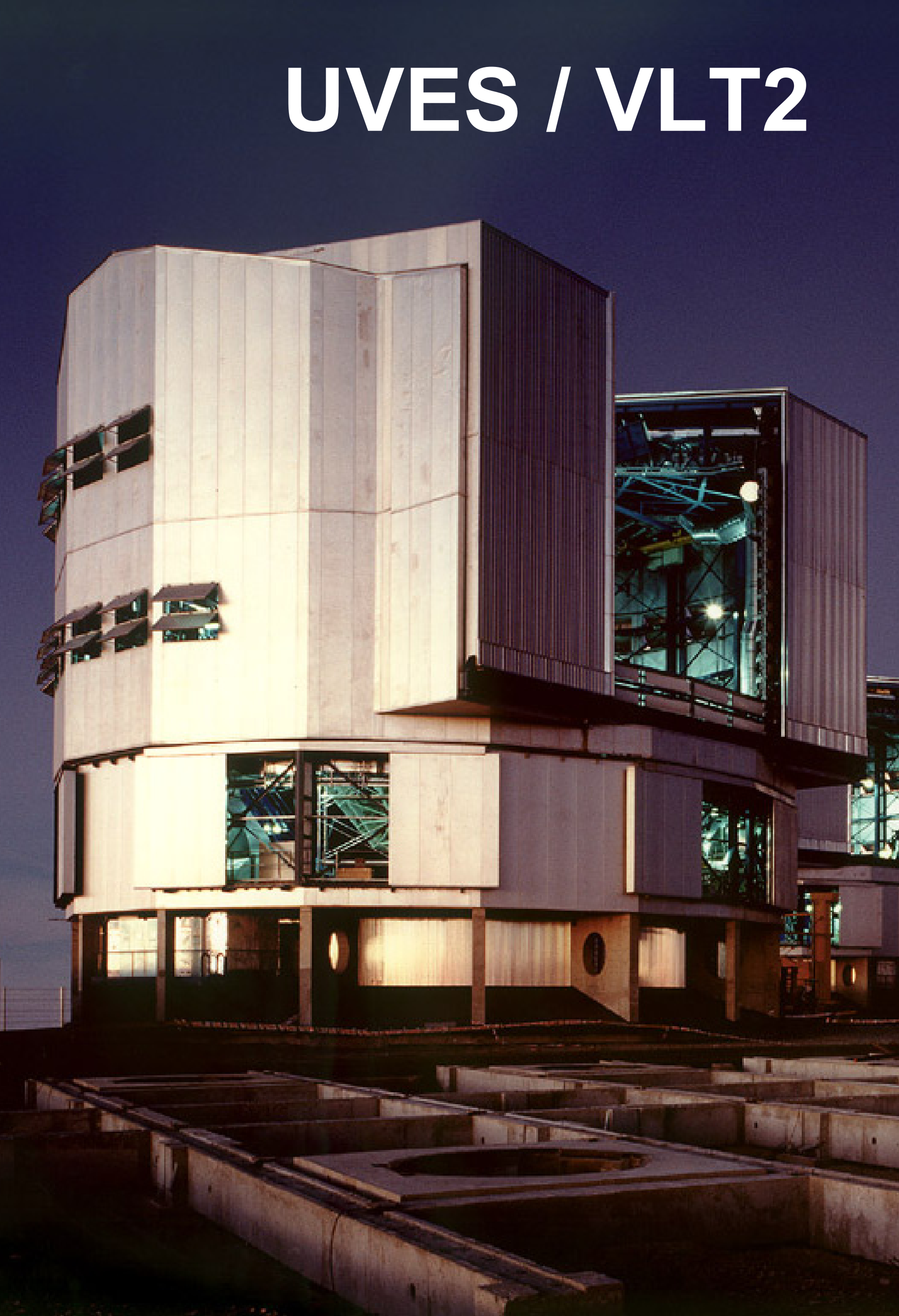
Oscillations in α Centauri A+B

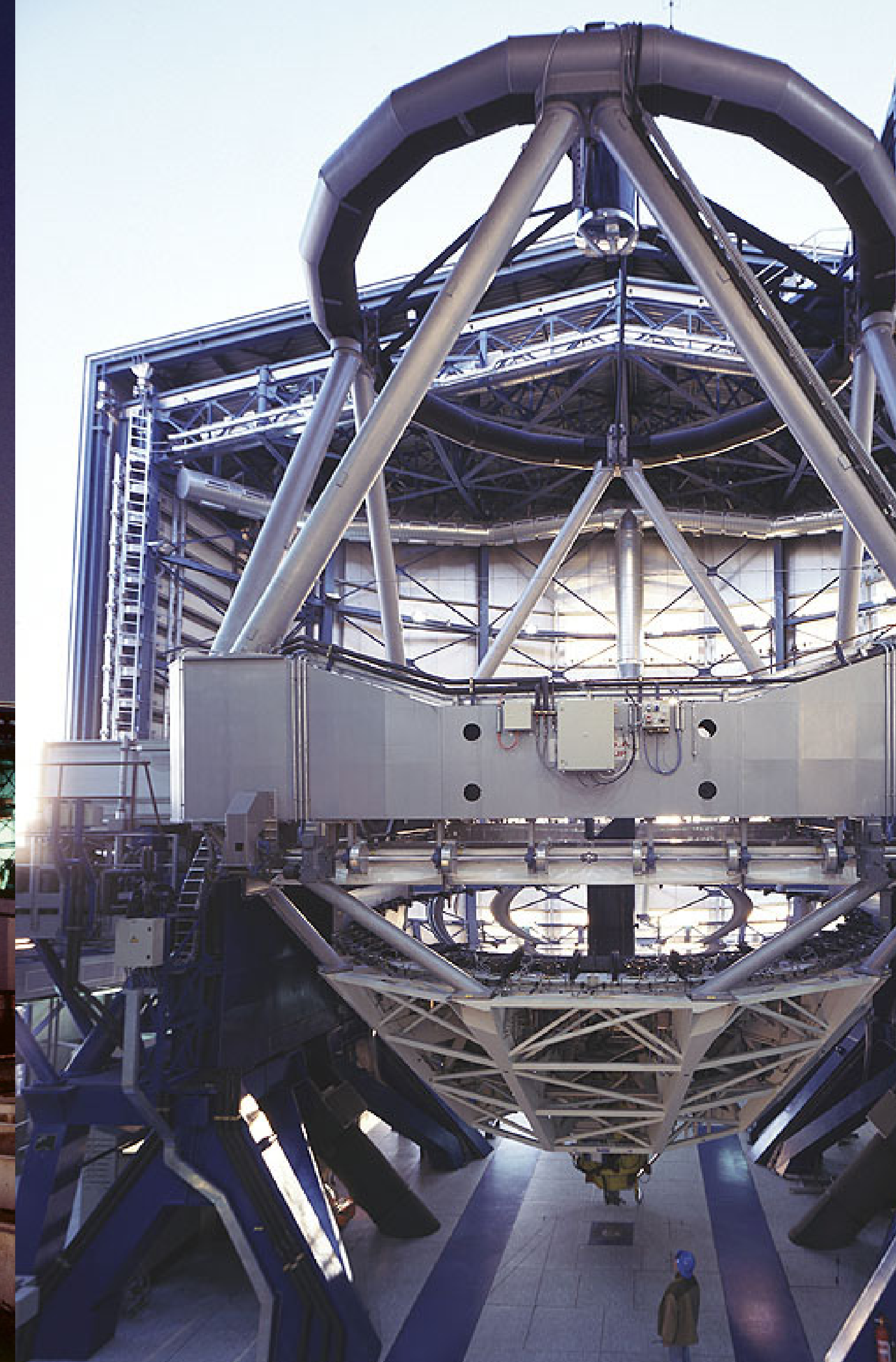


	A	B
$M/M_\odot$	1.105 ± 0.007	0.934 ± 0.006
$T_{\rm eff}$	(5830 ± 30) K	(5255 ± 50) K
$L/L_\odot$	1.556 ± 0.011	0.504 ± 0.008
$R/R_\odot$	1.224 ± 0.003	0.863 ± 0.005
$Z_{\rm s}/X_{\rm s}$	0.037 ± 0.004	0.037 ± 0.004

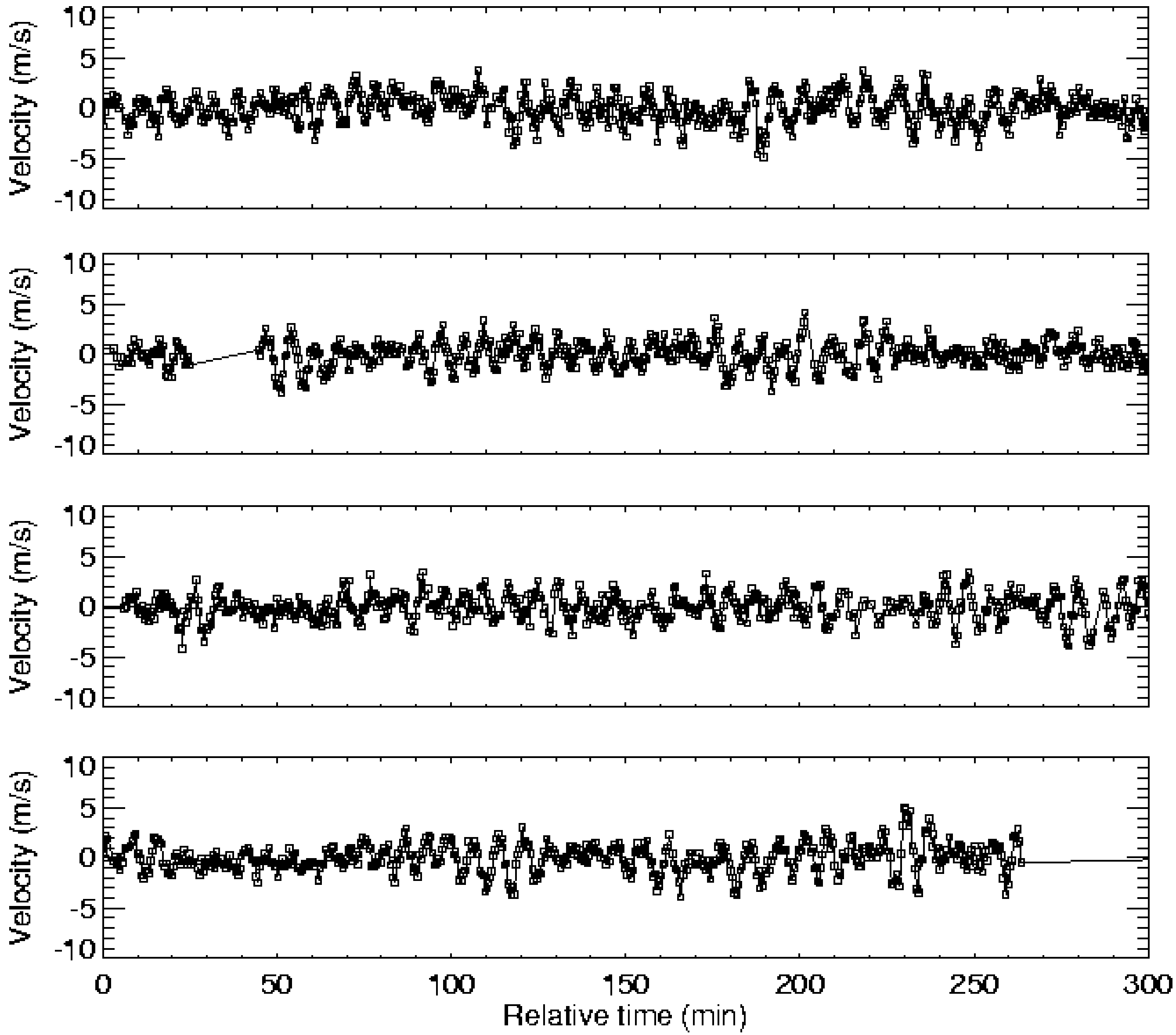
X0: 0.71045
Z0: 0.02870
Age: 6.98 Gyr


ESO VLT – Cerro Paranal, Chile

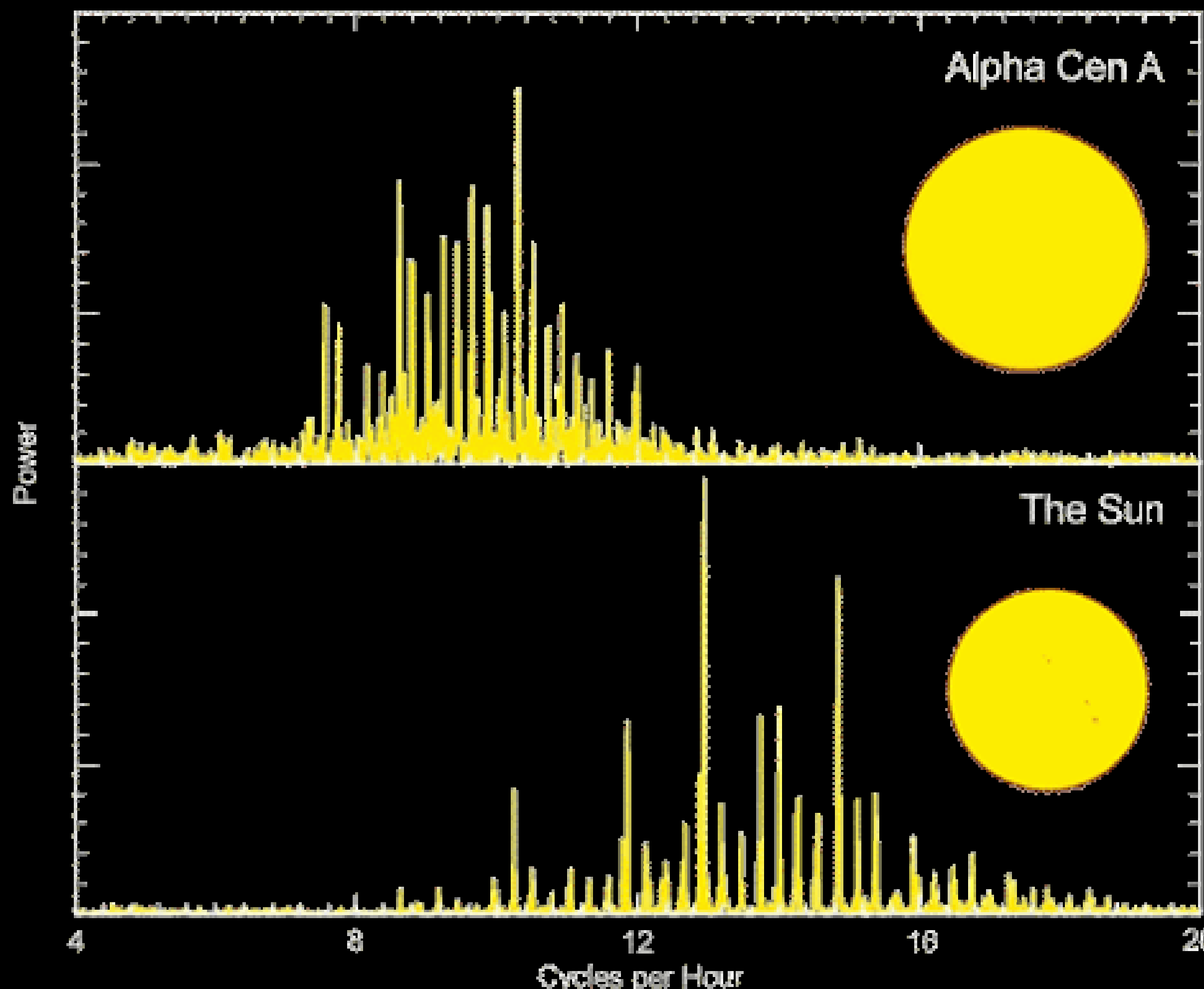

UVES / VLT2

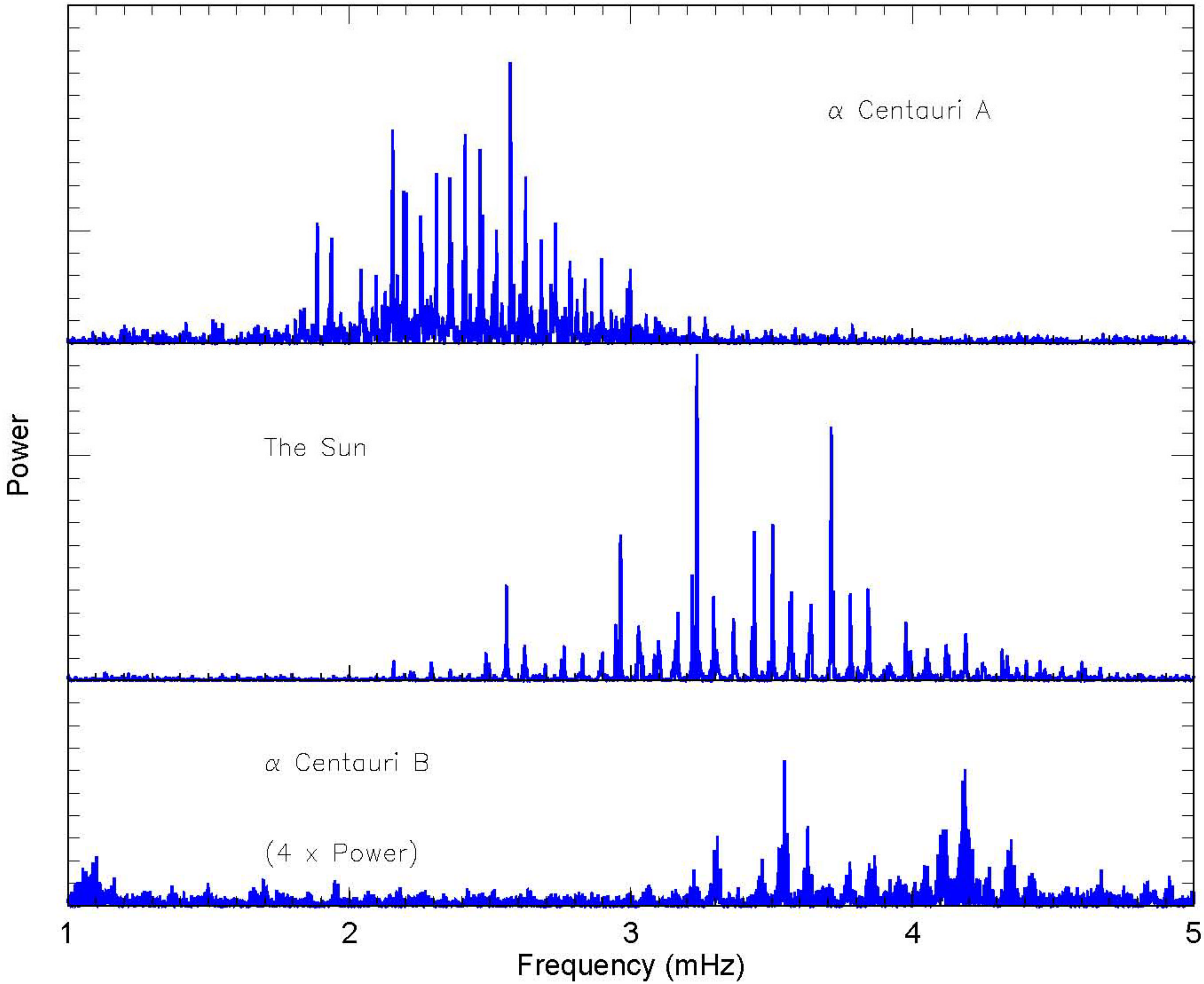


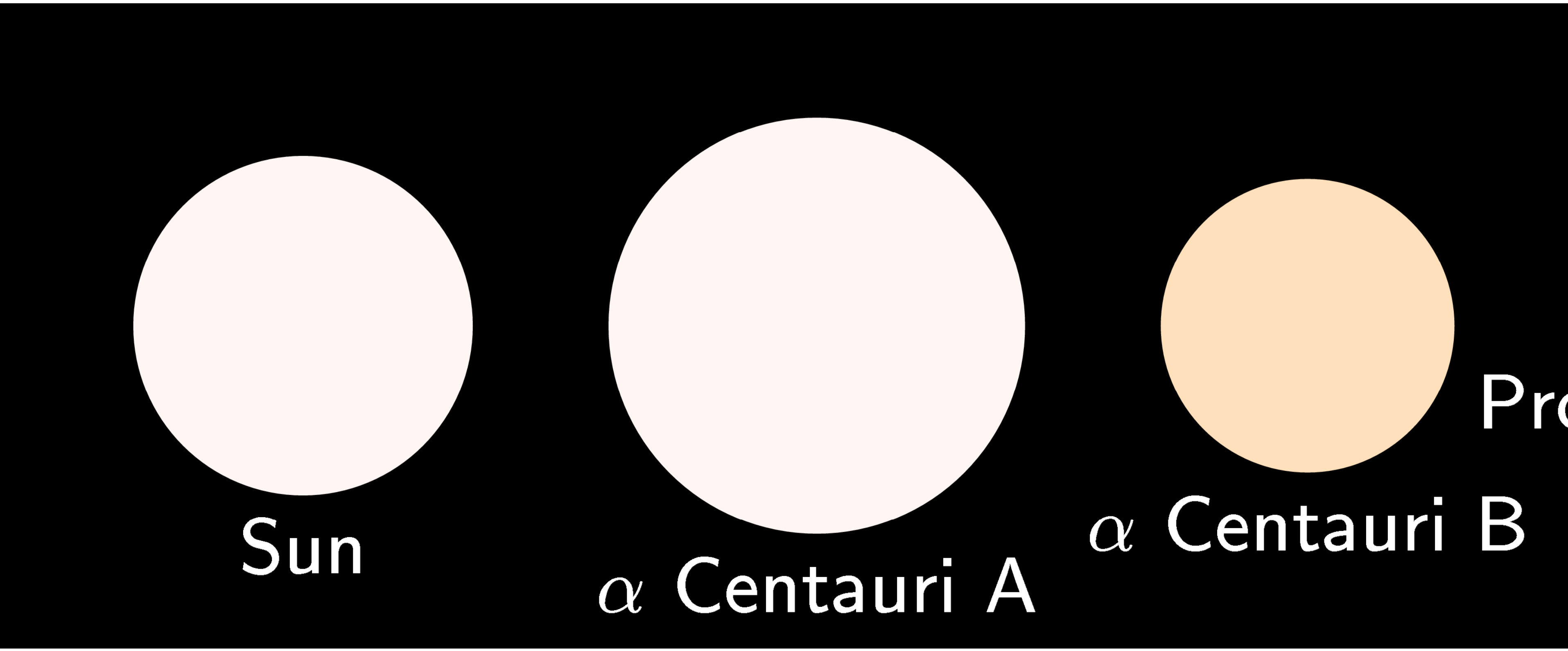
Velocities of α Cen A with UVES/VLT



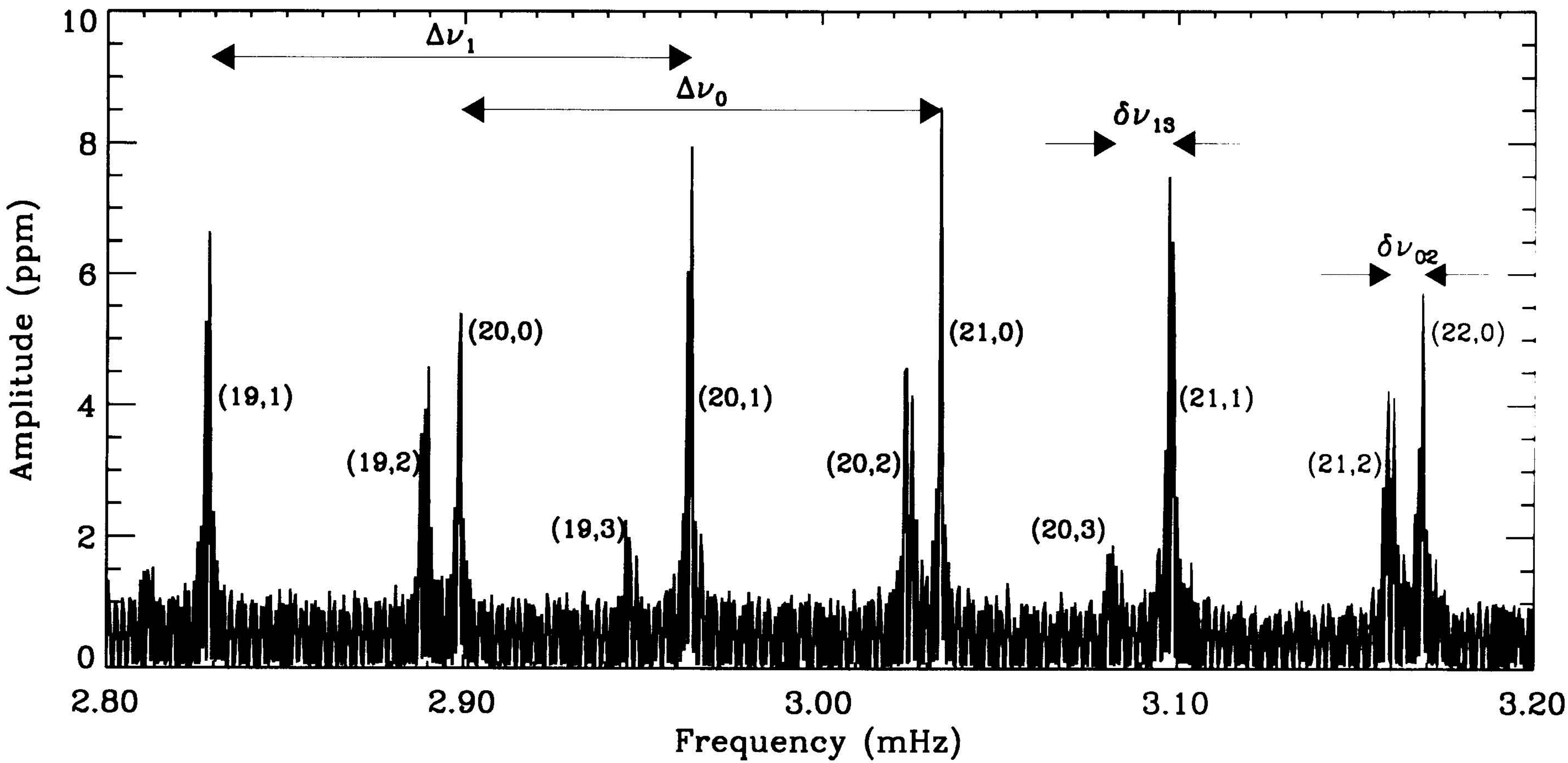
Precision: 50-70 cm/s. Cadence 26 seconds!


Alpha Cen A
The Sun
Power
4
8
12
16
20
Cycles per Hour


α Centauri A
The Sun
α Centauri B
(4 x Power)
Power
1
2
3
4
5
Frequency (mHz)


Sun
α Centauri A
α Centauri B
Pro

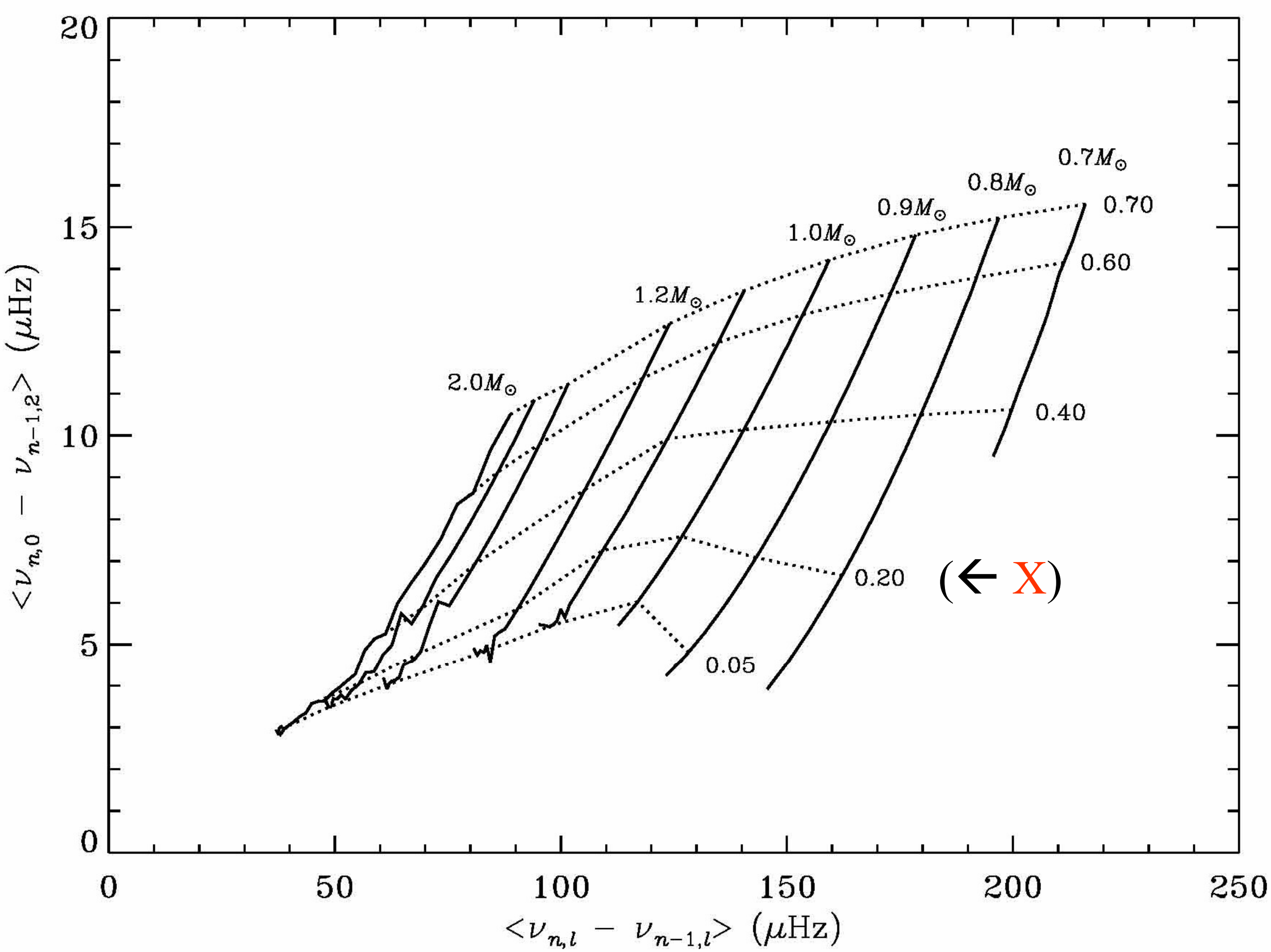
$$\nu_{n,l} = \Delta\nu(n + \frac{1}{2}l + \varepsilon) - l(l+1)D_0$$



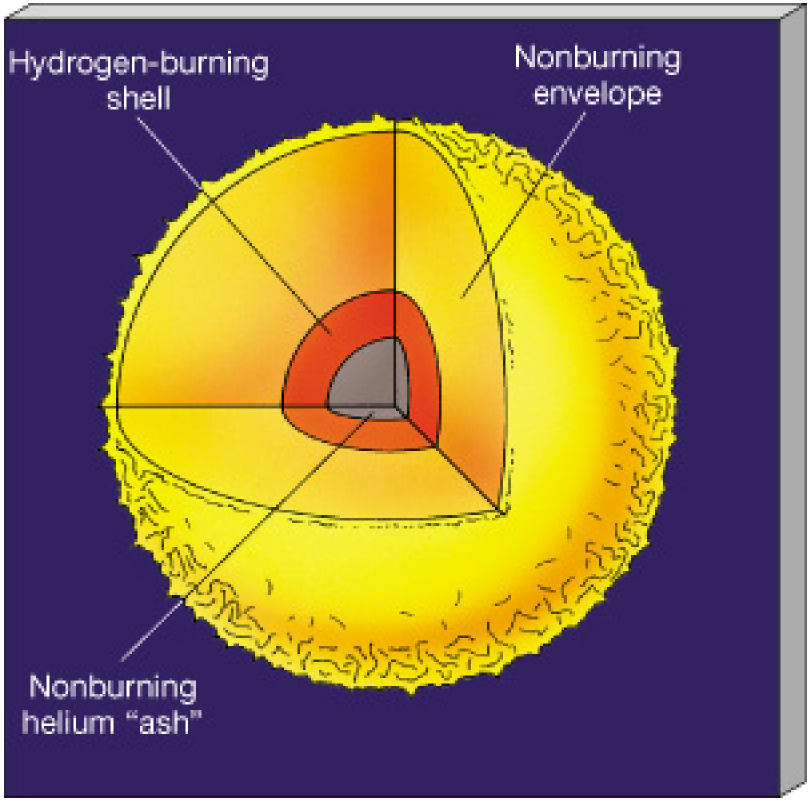
$$D_0 = \frac{1}{6}\delta\nu_{02} = \frac{1}{2}\delta\nu_{01} = \frac{1}{10}\delta\nu_{13}$$

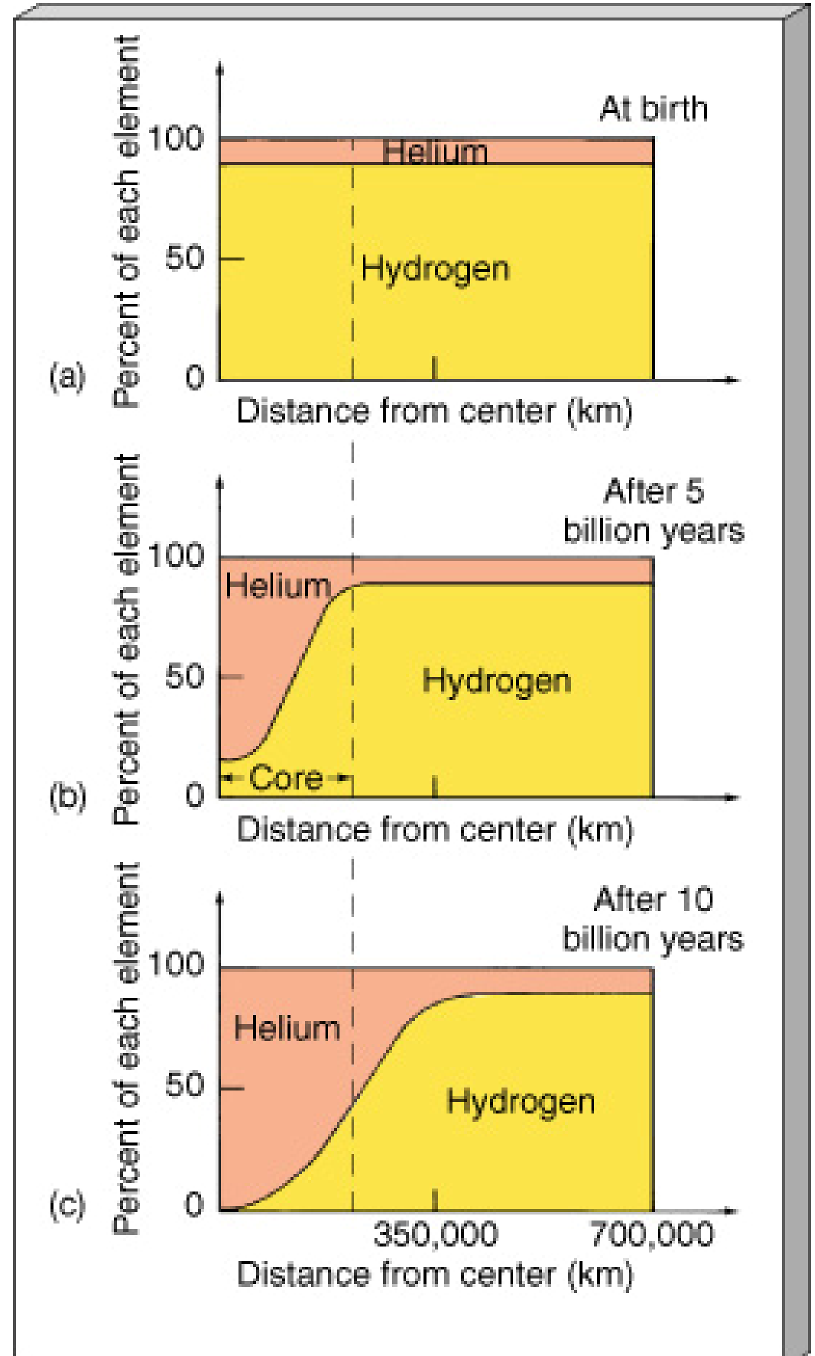
Theoretical Separations from stellar models:

Small Separation



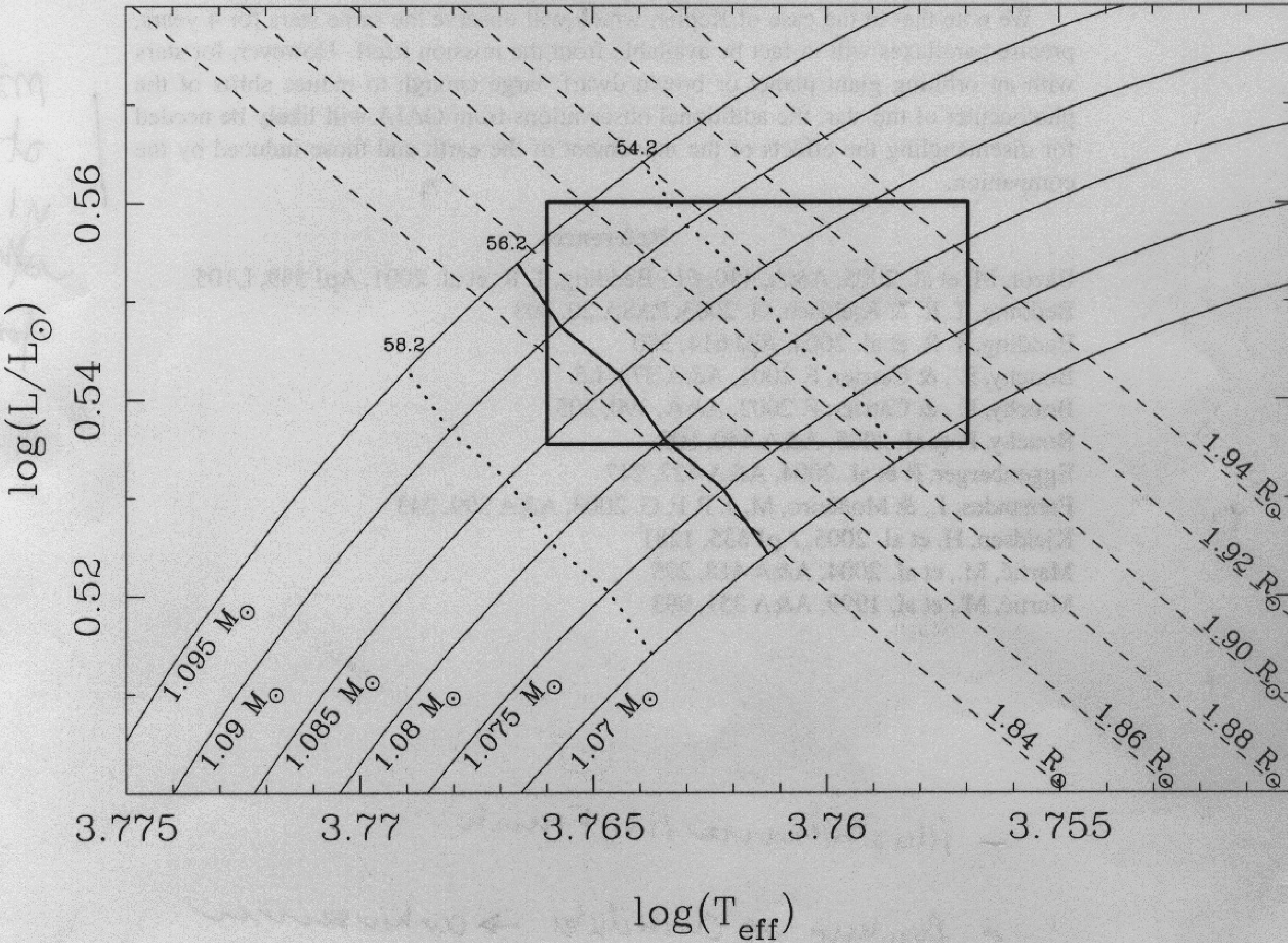
Large Frequency Separation



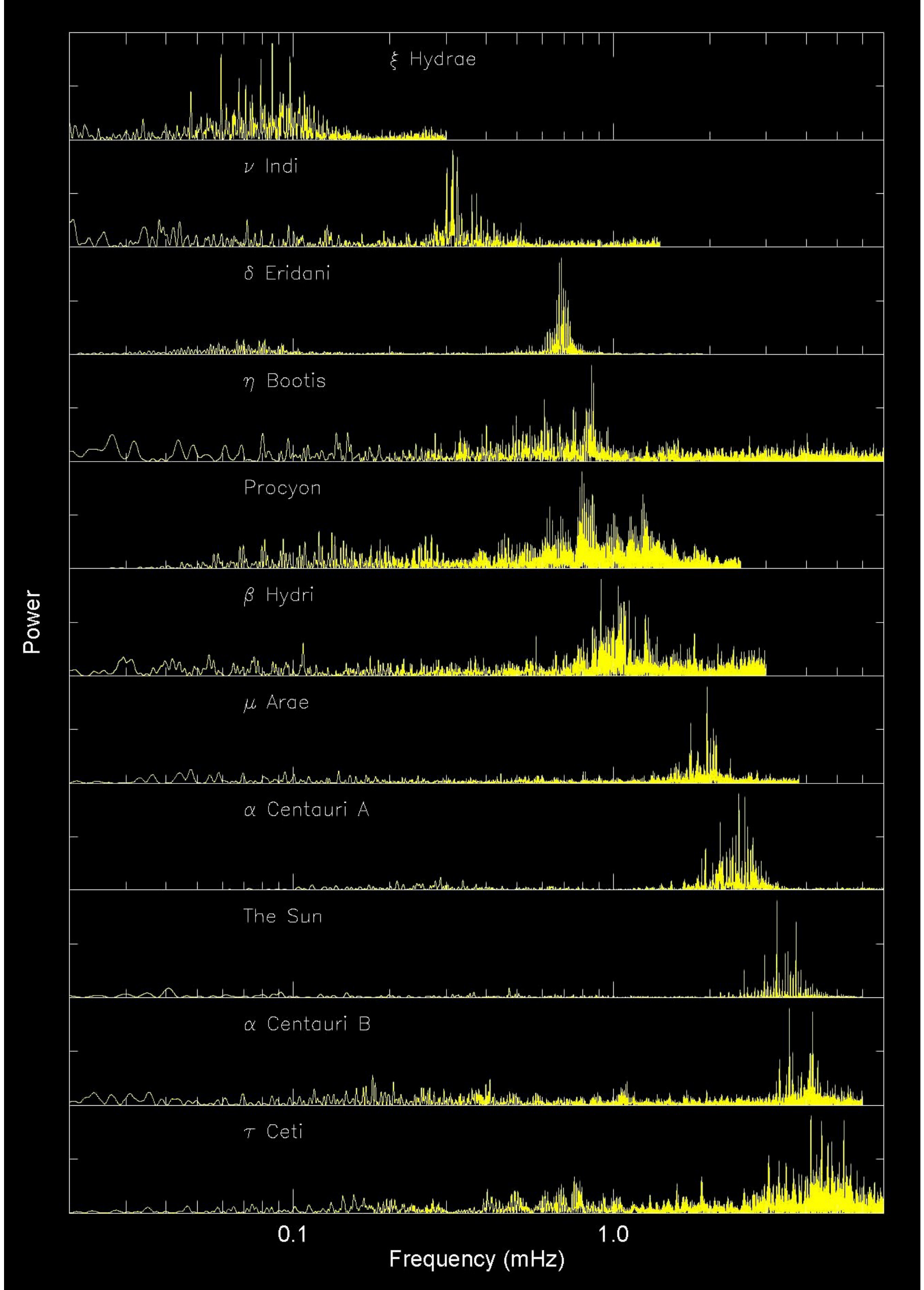


$$T = \frac{10 - 14.3X}{M^3}$$

$$\Delta \nu_0 \approx 135 \mu Hz \sqrt{M / R^3}$$



log(L/L$_\odot$)
0.56
0.54
0.52
log(T$_{eff}$)
3.775
3.77
3.765
3.76
3.755
1.095 M$_\odot$
1.09 M$_\odot$
1.085 M$_\odot$
1.08 M$_\odot$
1.075 M$_\odot$
1.07 M$_\odot$
1.84 R$_\odot$
1.86 R$_\odot$
1.88 R$_\odot$
1.90 R$_\odot$
1.92 R$_\odot$
1.94 R$_\odot$
54.2
56.2
58.2



Power
ξ Hydrae
ν Indi
δ Eridani
η Bootis
Procyon
β Hydri
μ Arae
α Centauri A
The Sun
α Centauri B
τ Ceti
0.1
1.0
Frequency (mHz)