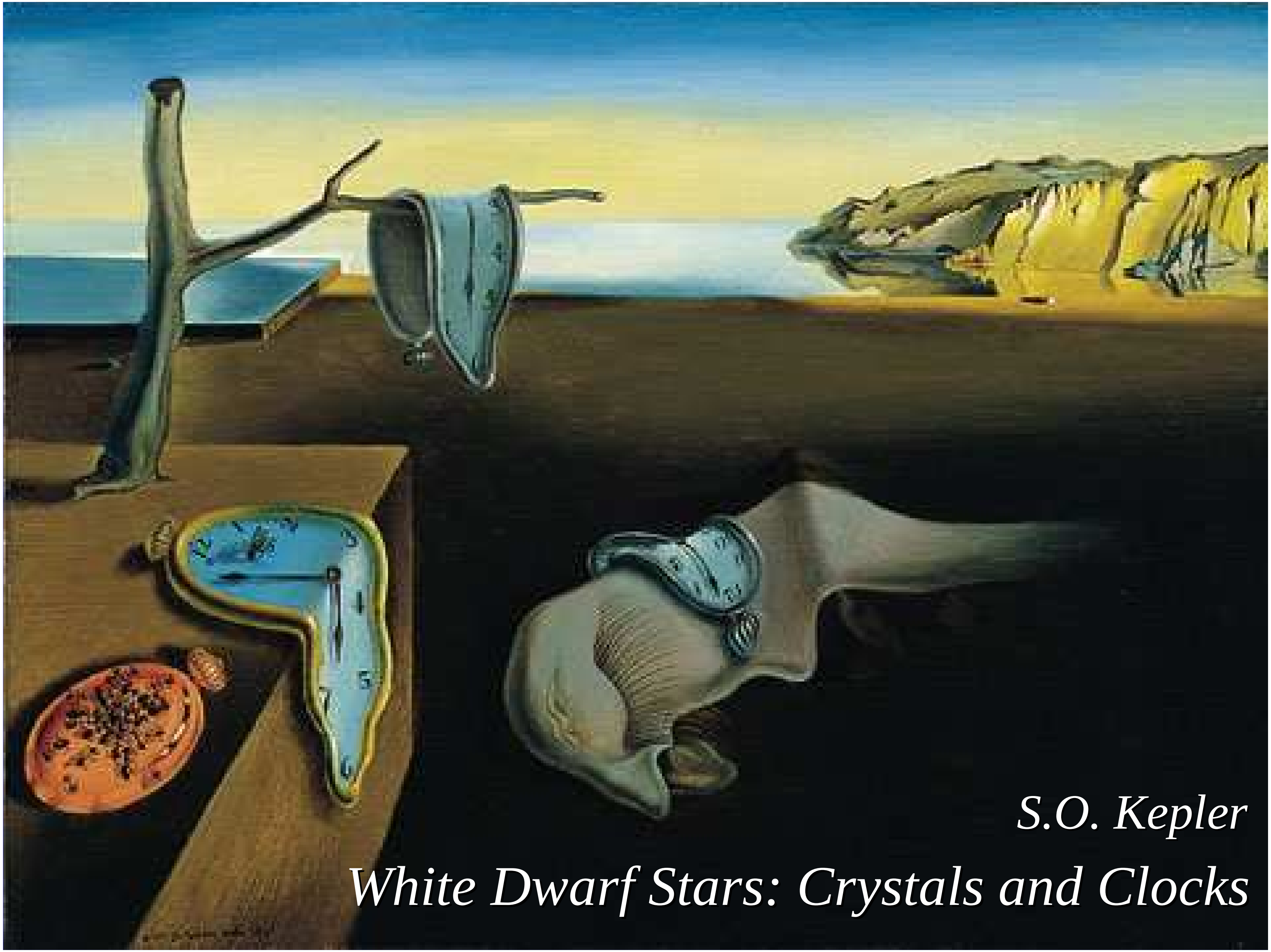
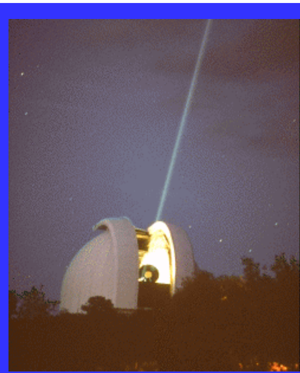


S.O. Kepler

White Dwarf Stars: Crystals and Clocks



White Dwarf Stars as Laboratories

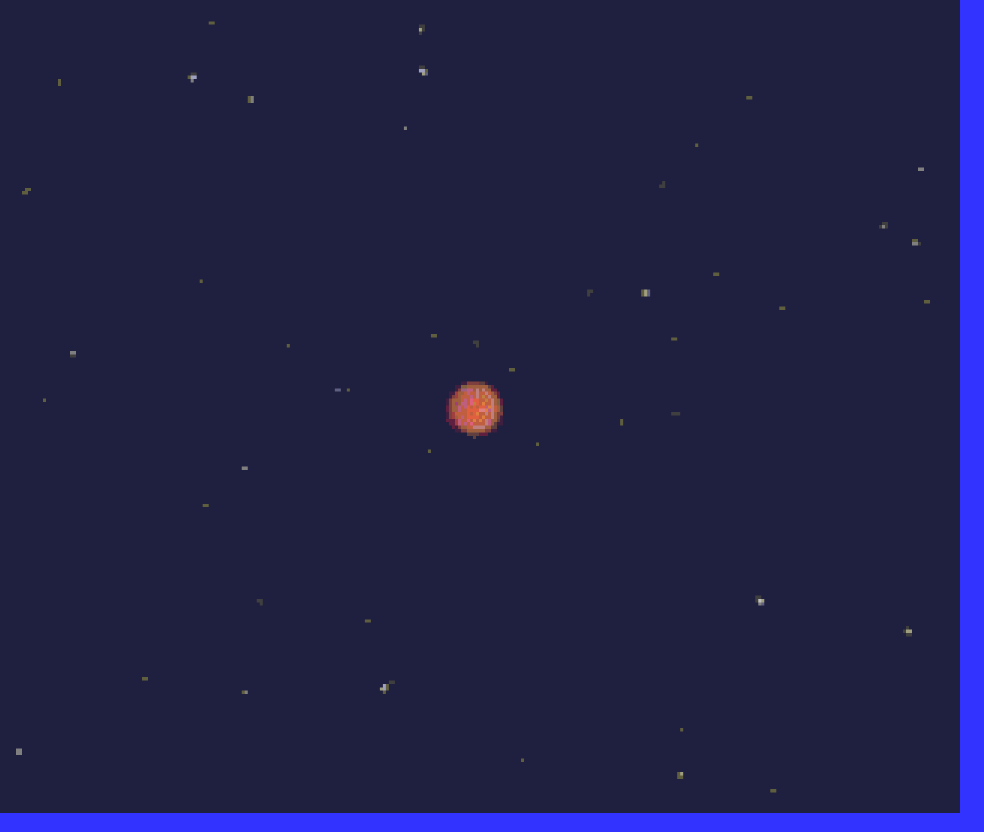
S.O. Kepler

Department of Astronomy

UFRGS - Brazil

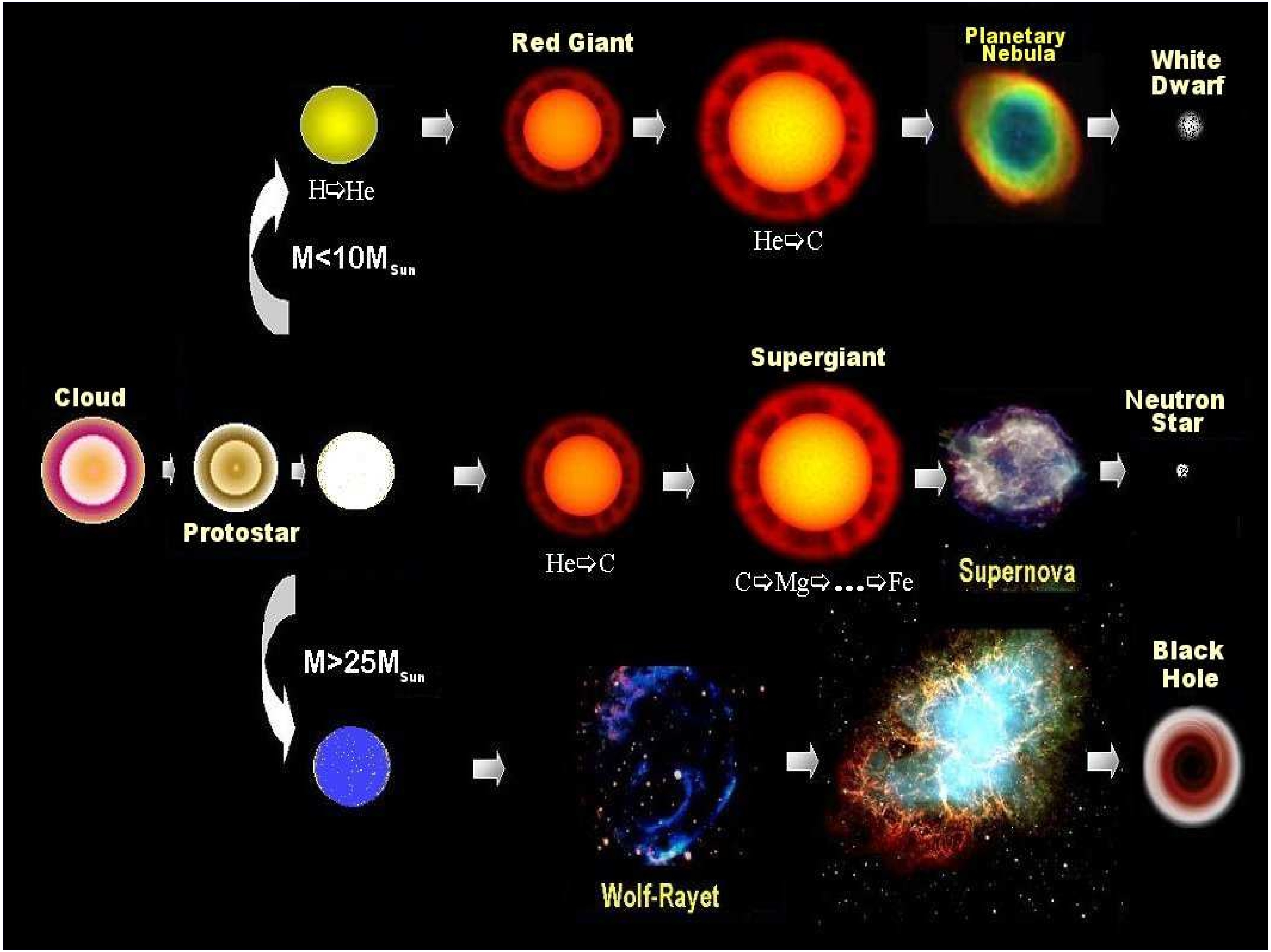
Stellar Evolution

Mass < 10 M_{sun} : White Dwarf



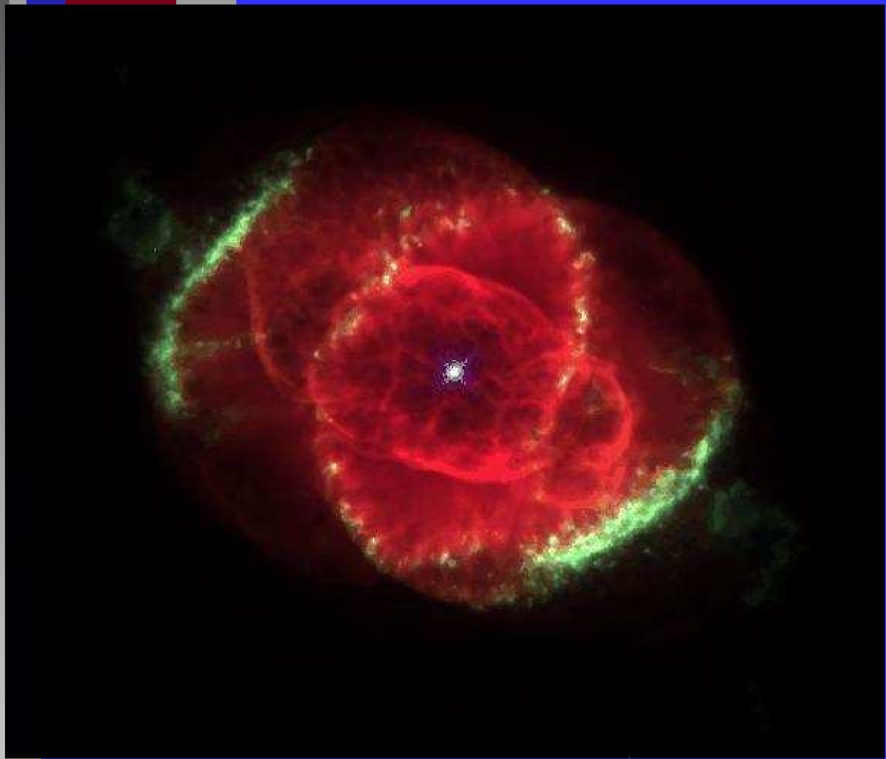
10 M_{sun} < Mass < 25 M_{sun} : Neutron Star

Mass > 25 M_{sun} : Black Hole



Red Giant
Planetary Nebula
White Dwarf
H⇨He
He⇨C
M<10M$_{Sun}$
Supergiant
Cloud
Neutron Star
Protostar
He⇨C
C⇨Mg⇨...⇨Fe
Supernova
M>25M$_{Sun}$
Black Hole
Wolf-Rayet

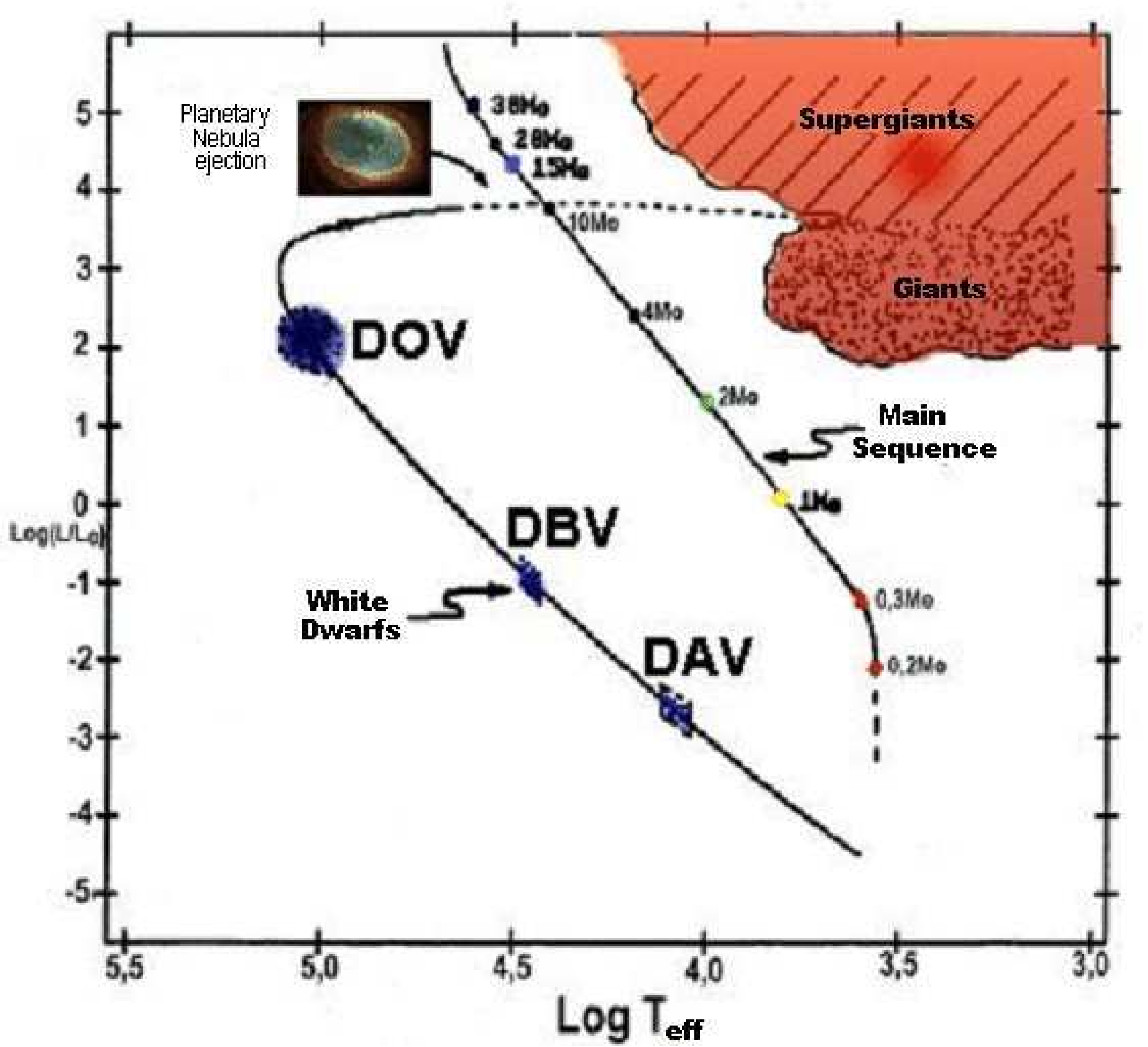
Planetary Nebula



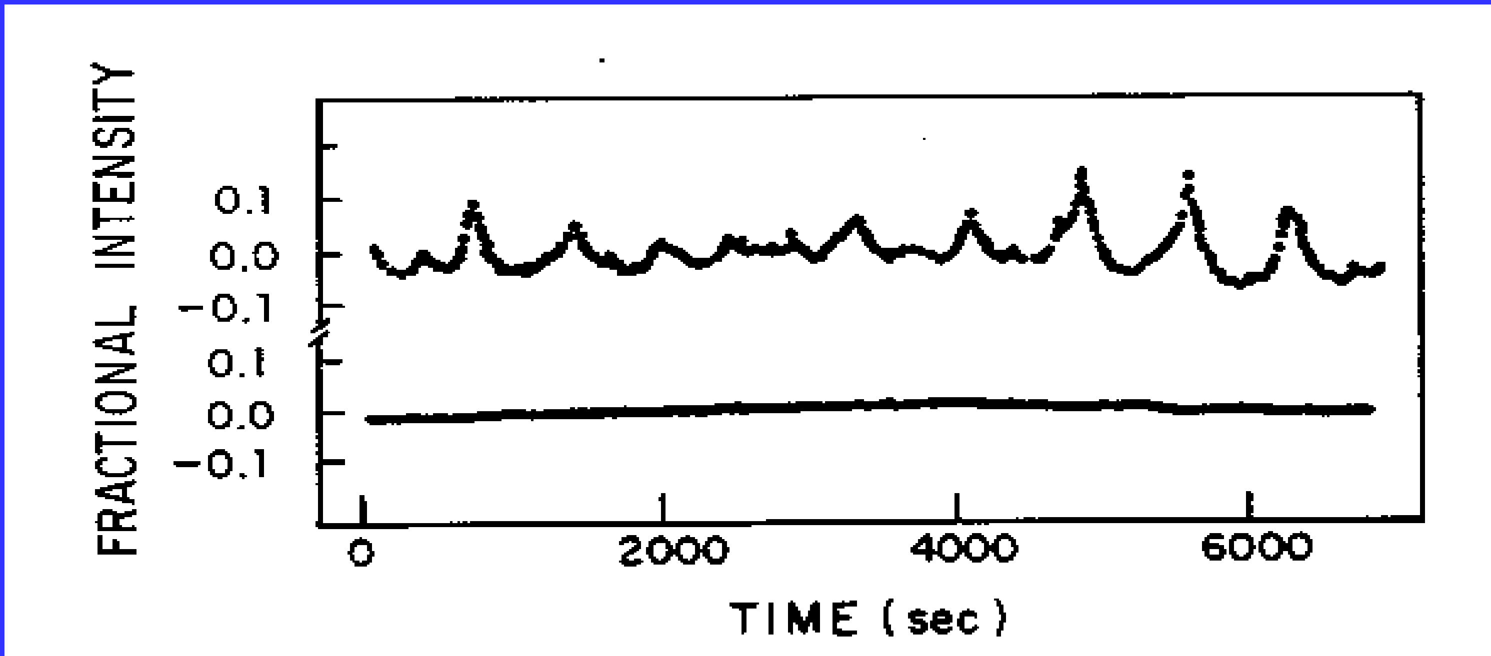
Observed by the Hubble Space Telescope

Sirius and the White Dwarf

White dwarfs pulsate as they cool



Intensity Changes With Time



Multiperiodic, P=71s to 1500s, amp=4 mma to 300 mma

Pulsating White Dwarfs

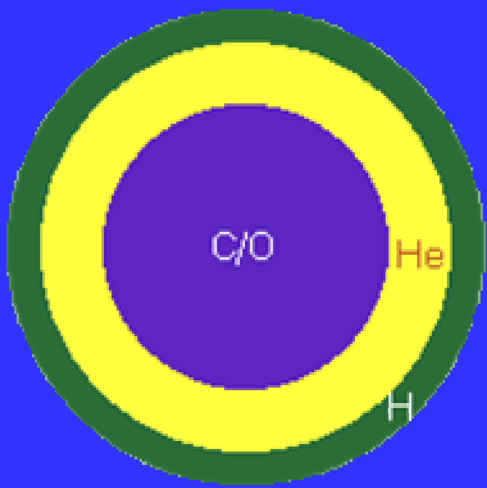
- Internal structure of the white dwarf (SNIa progenitors)
- Cooling timescale
- Age of the oldest stars in our galaxy

→ High energy and high density physics

Pulsating White Dwarfs

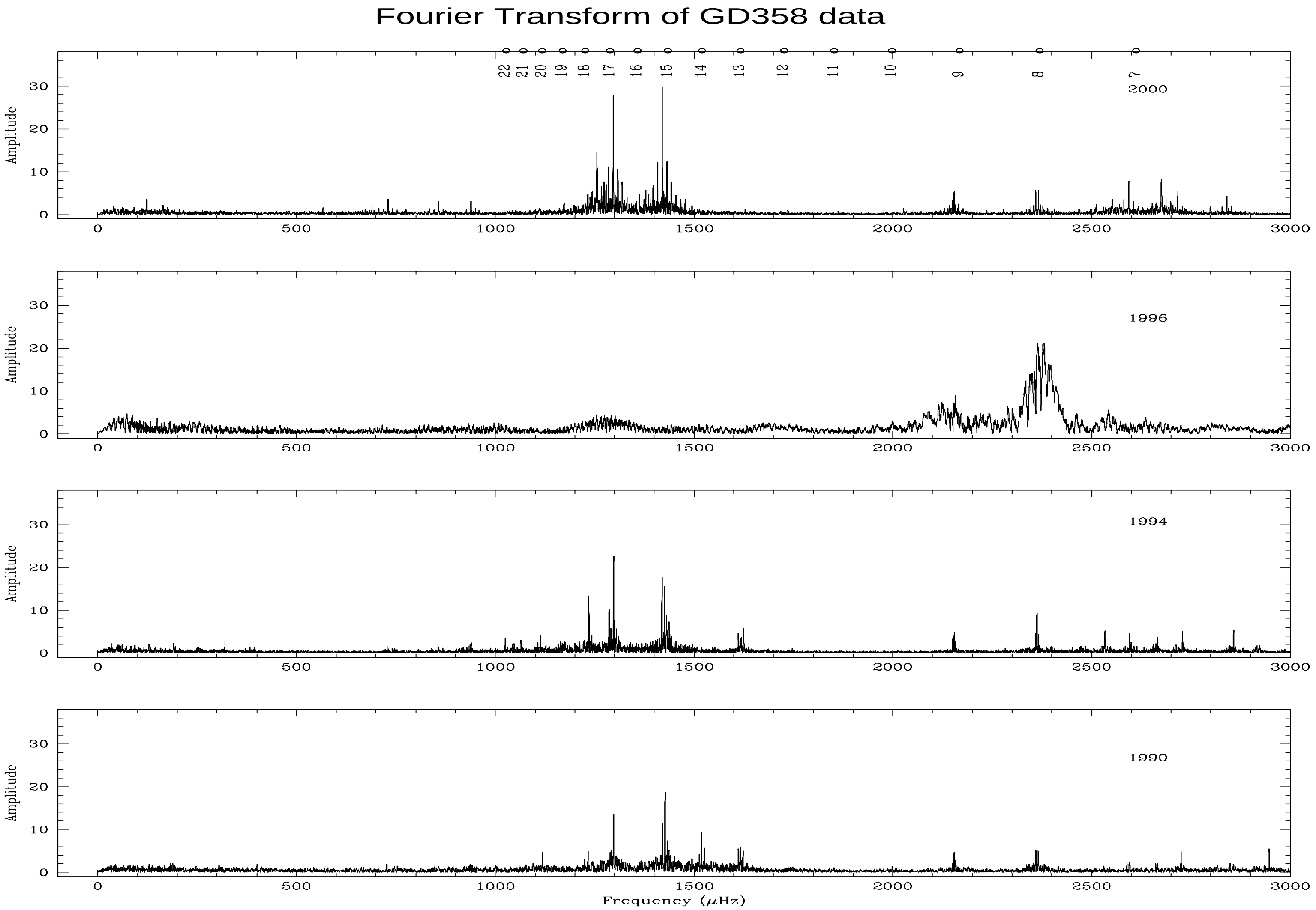
- White Dwarfs ~ 6000 (doubled in 2004)
- Variable~ 115 (tripled in 2004)

- DOV T_{eff} =160 000-75 000K
  10 known, M= -1
- DBV T_{eff} = 25 000-22 000K
  13 know, M= 8
- DAV T_{eff} = 12 000K
  92 known, M=12



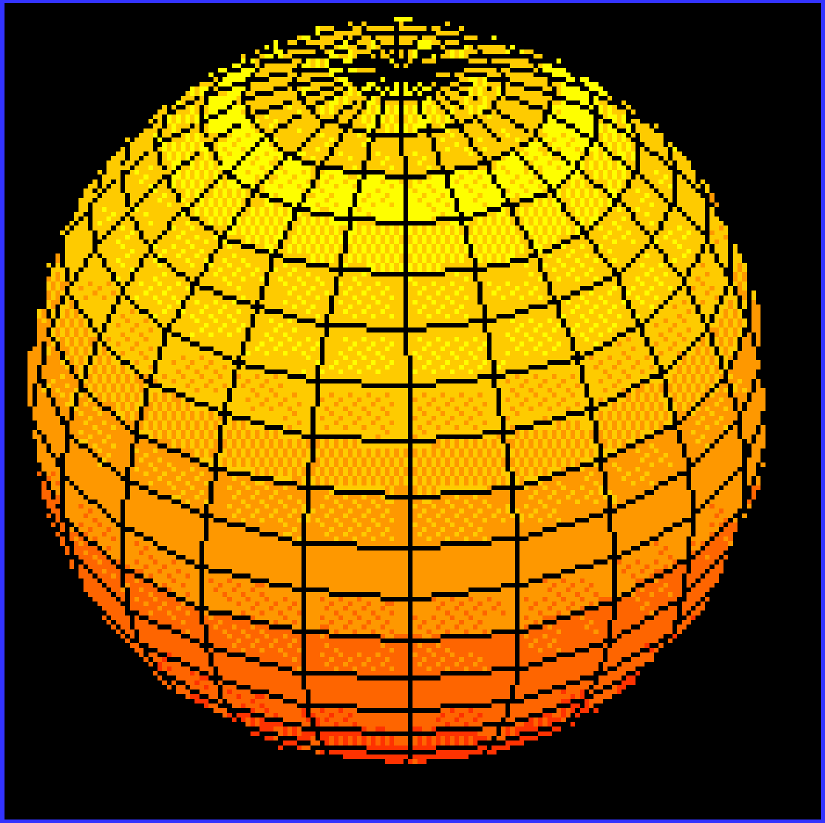
Structure – SNIa progenitors

DBV GD 358

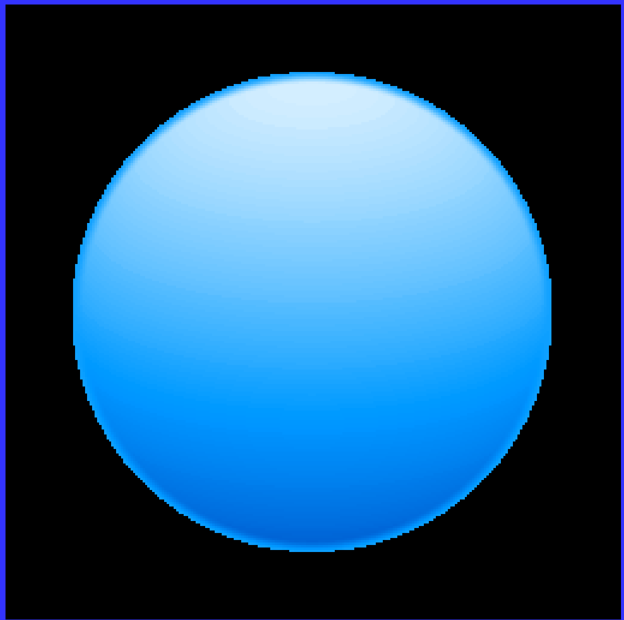


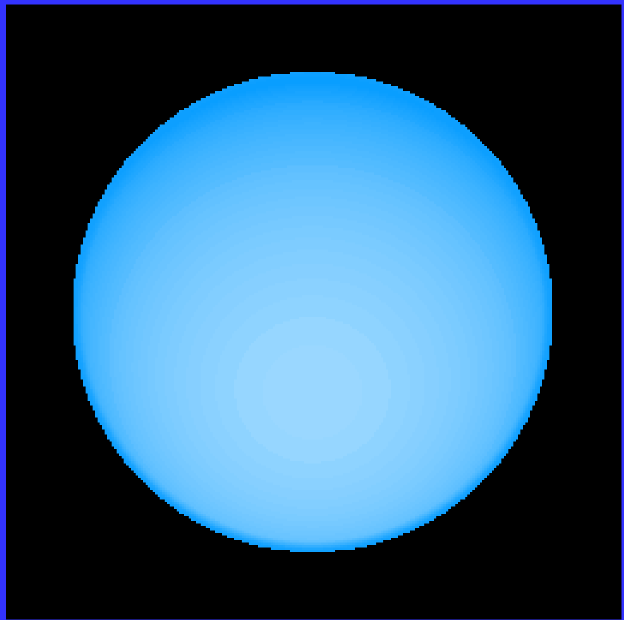
Fourier Transform of GD358 data
22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7
2000
1996
1994
1990
Amplitude
0 10 20 30
0 500 1000 1500 2000 2500 3000
Frequency (μHz)

Pulsations … Seismology

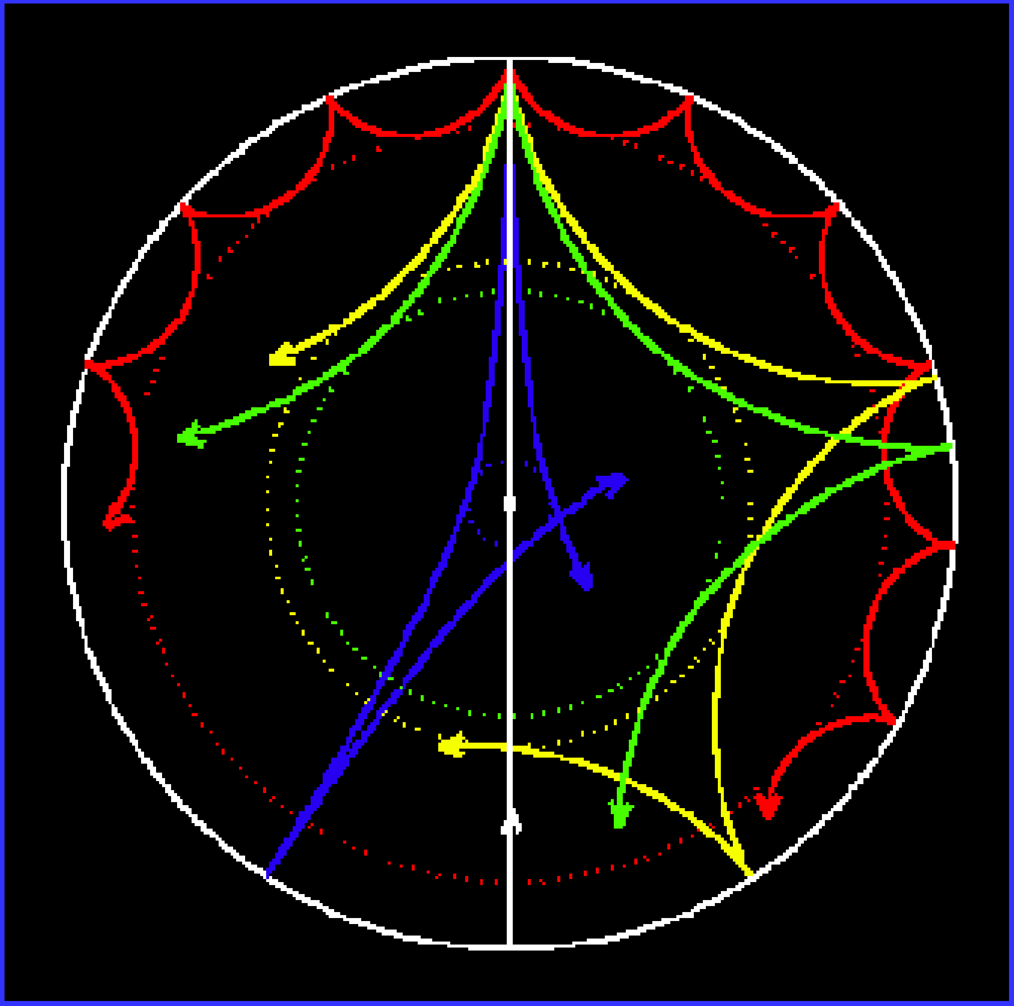


Pulsations/Seismology: Y_{10} e Y_{11}





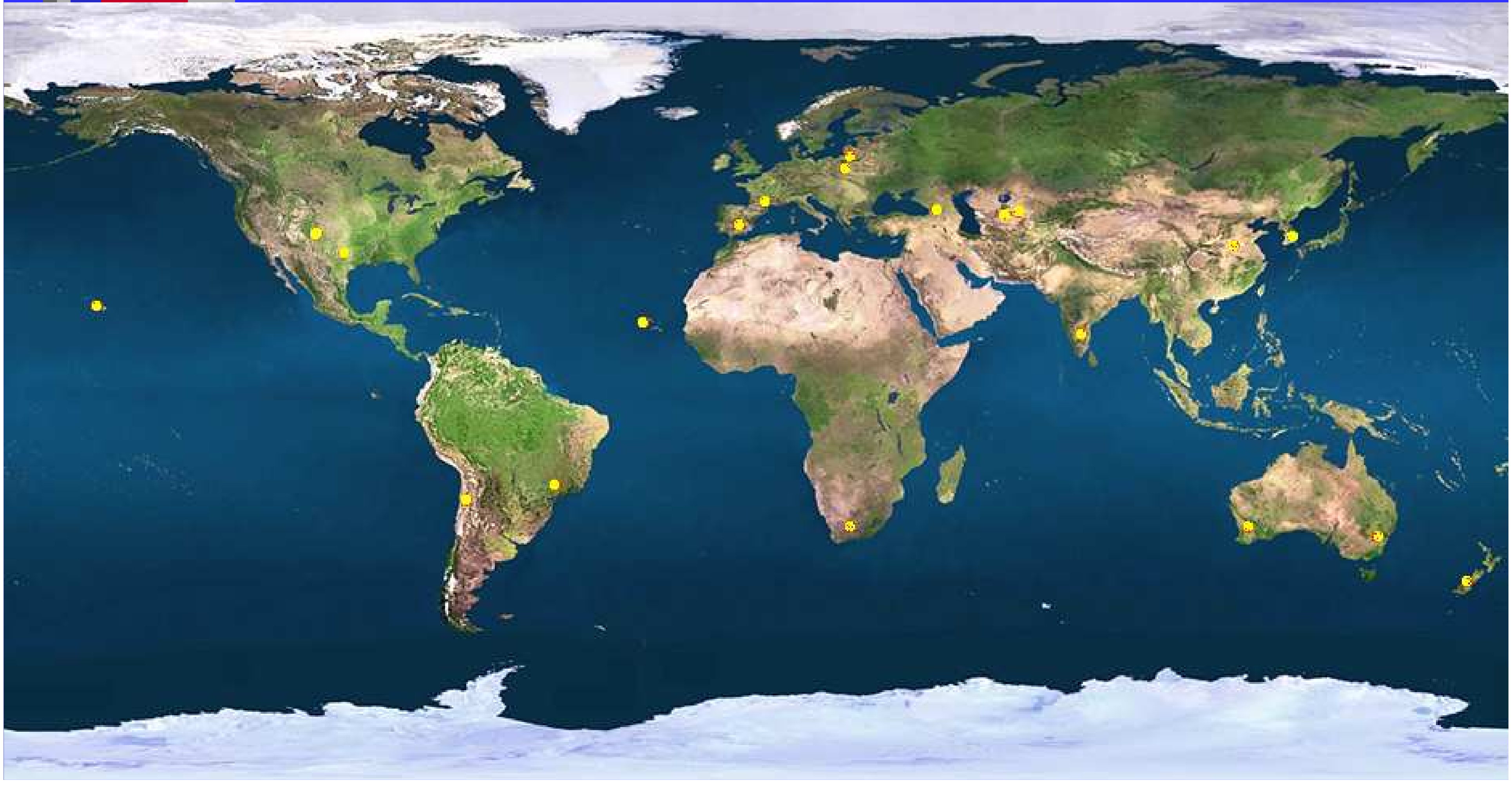
Pulsations are global



Observations: 1.6 m telescope
Laboratório Nacional de Astrofísica

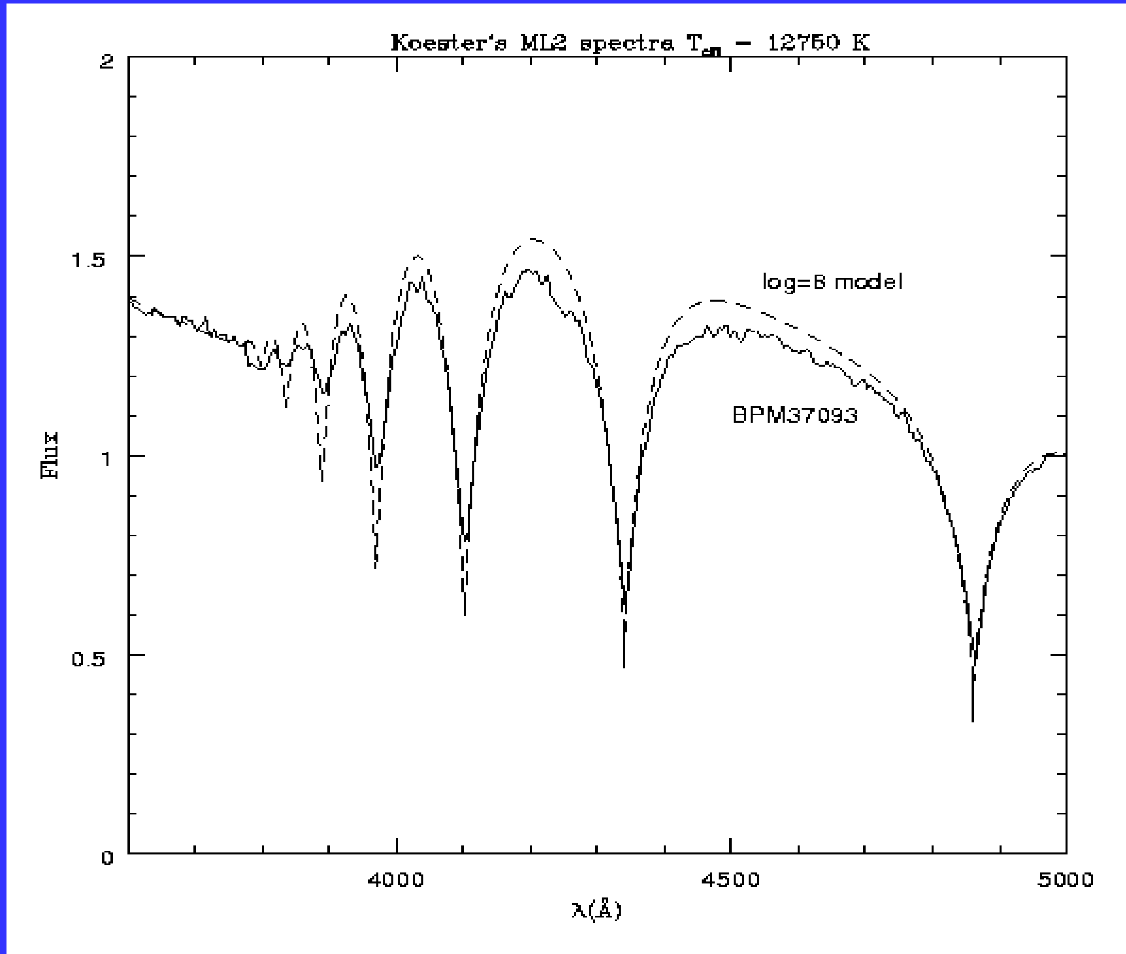
Brasópolis, MG

Whole Earth Telescope

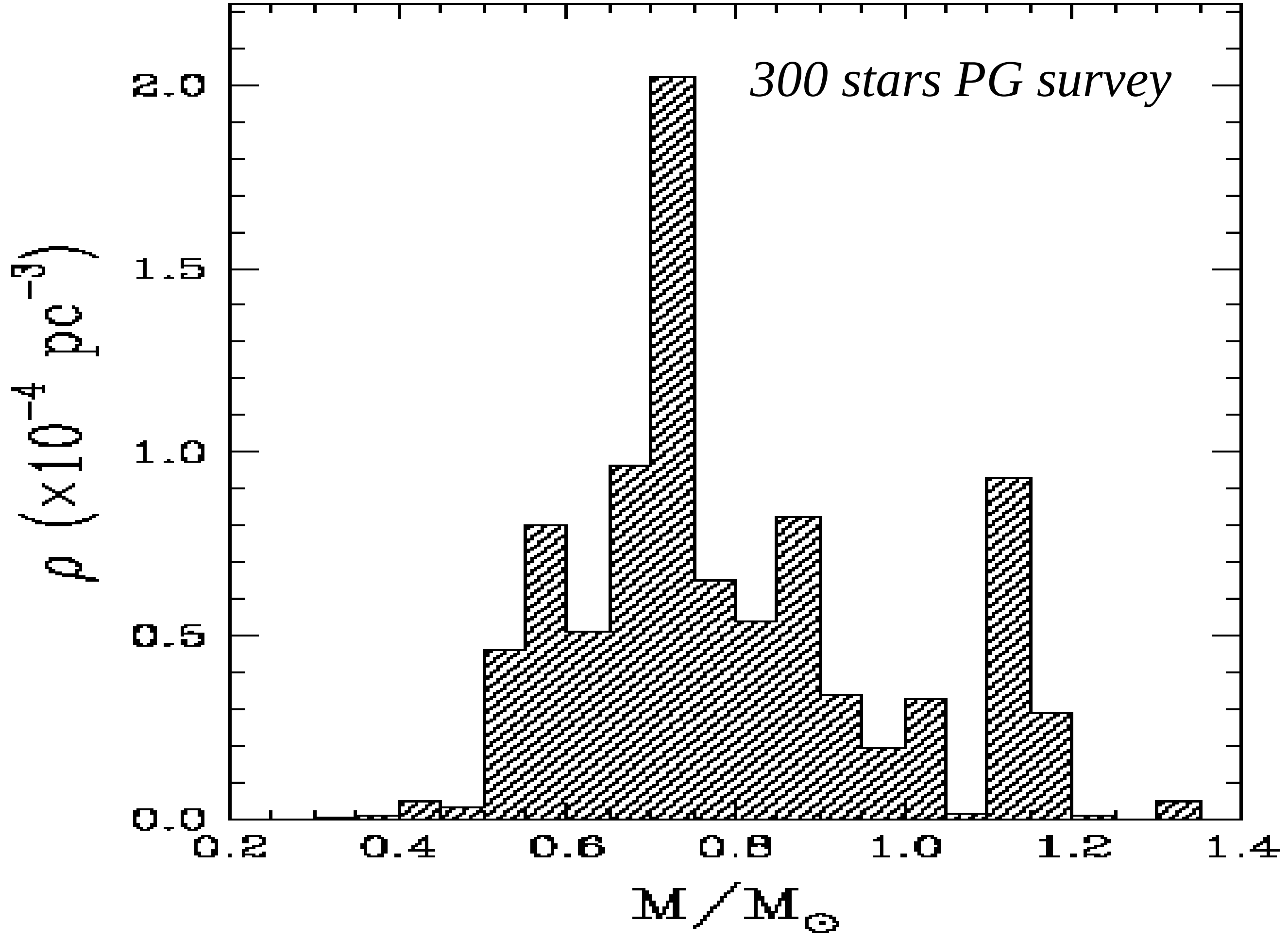


Mass determination

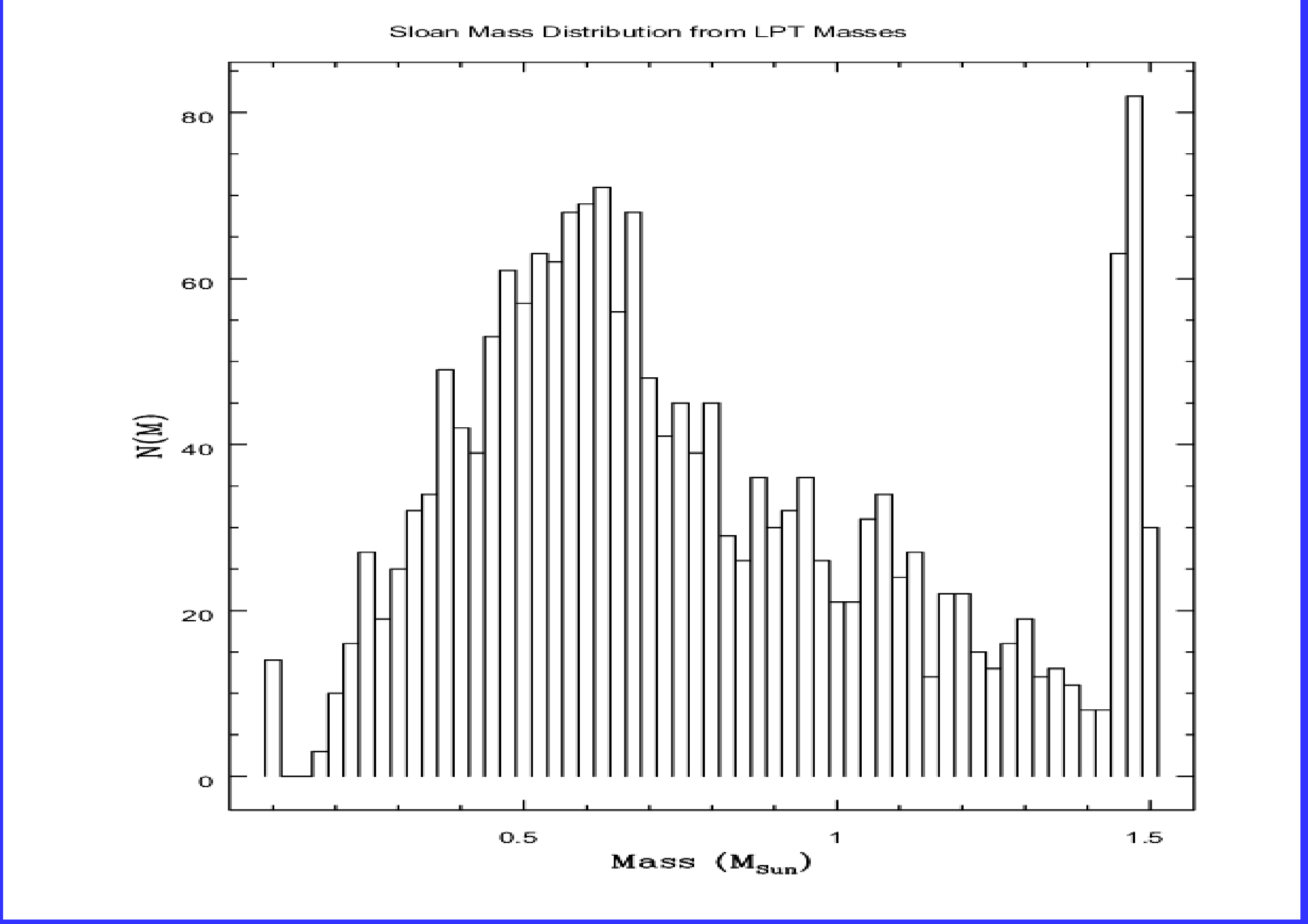
- *UV spectra*
- *Optical spectra*
- *T_{ef} = 12 500K*
- *Massa = 1,1 M_{sol}*



Mass distribution

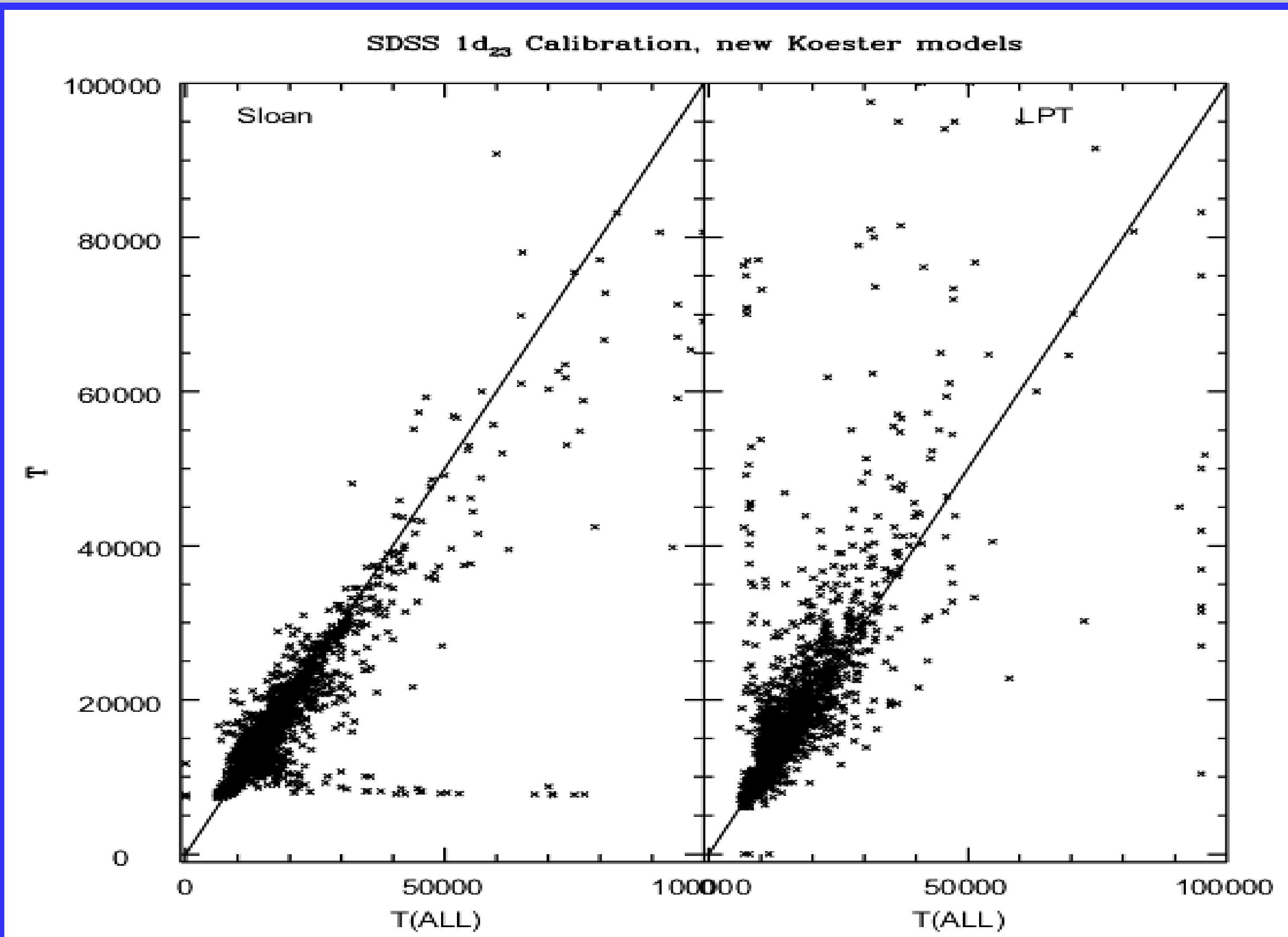


SDSS

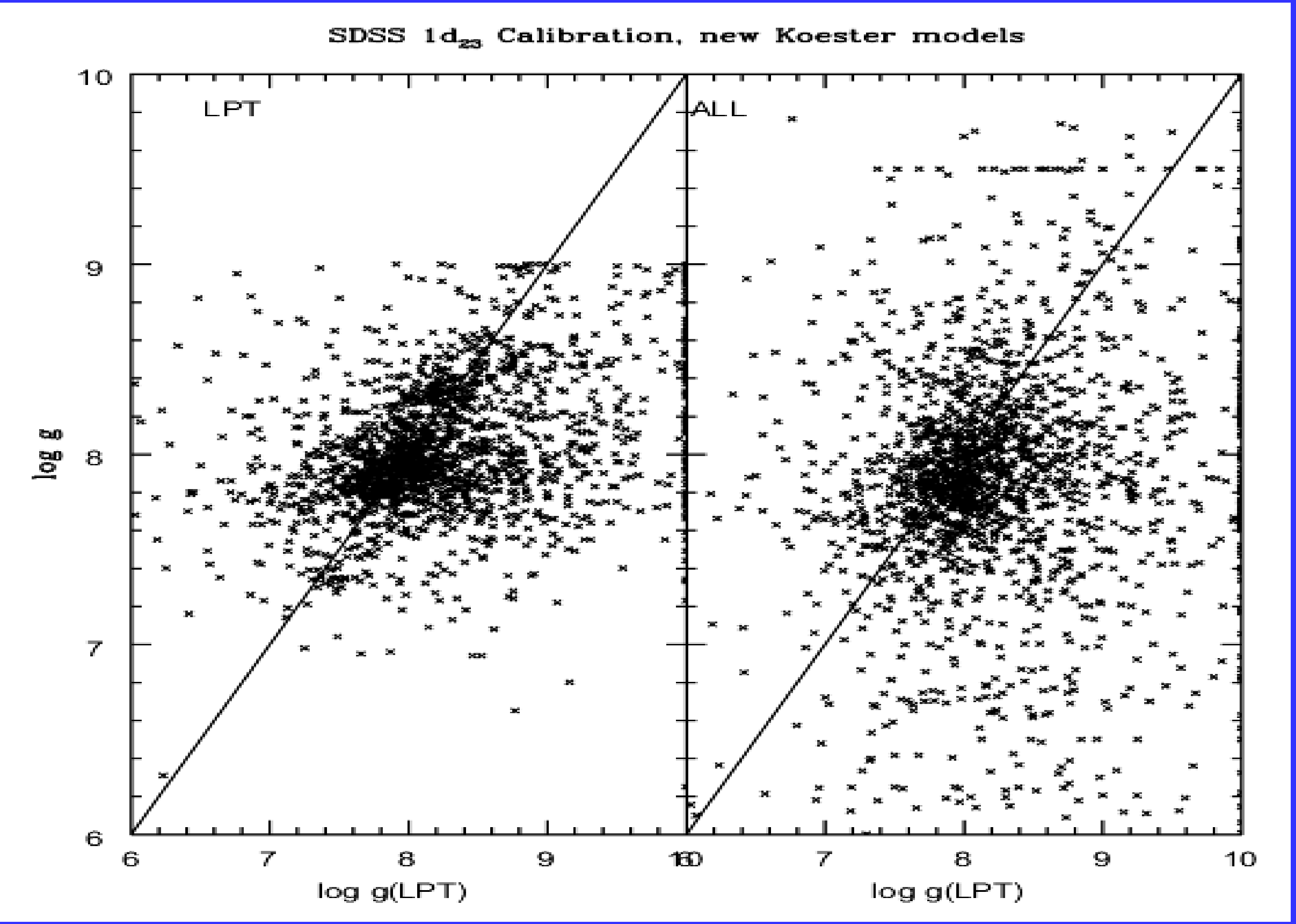


We fit all 1872 DA white dwarfs in SDSS

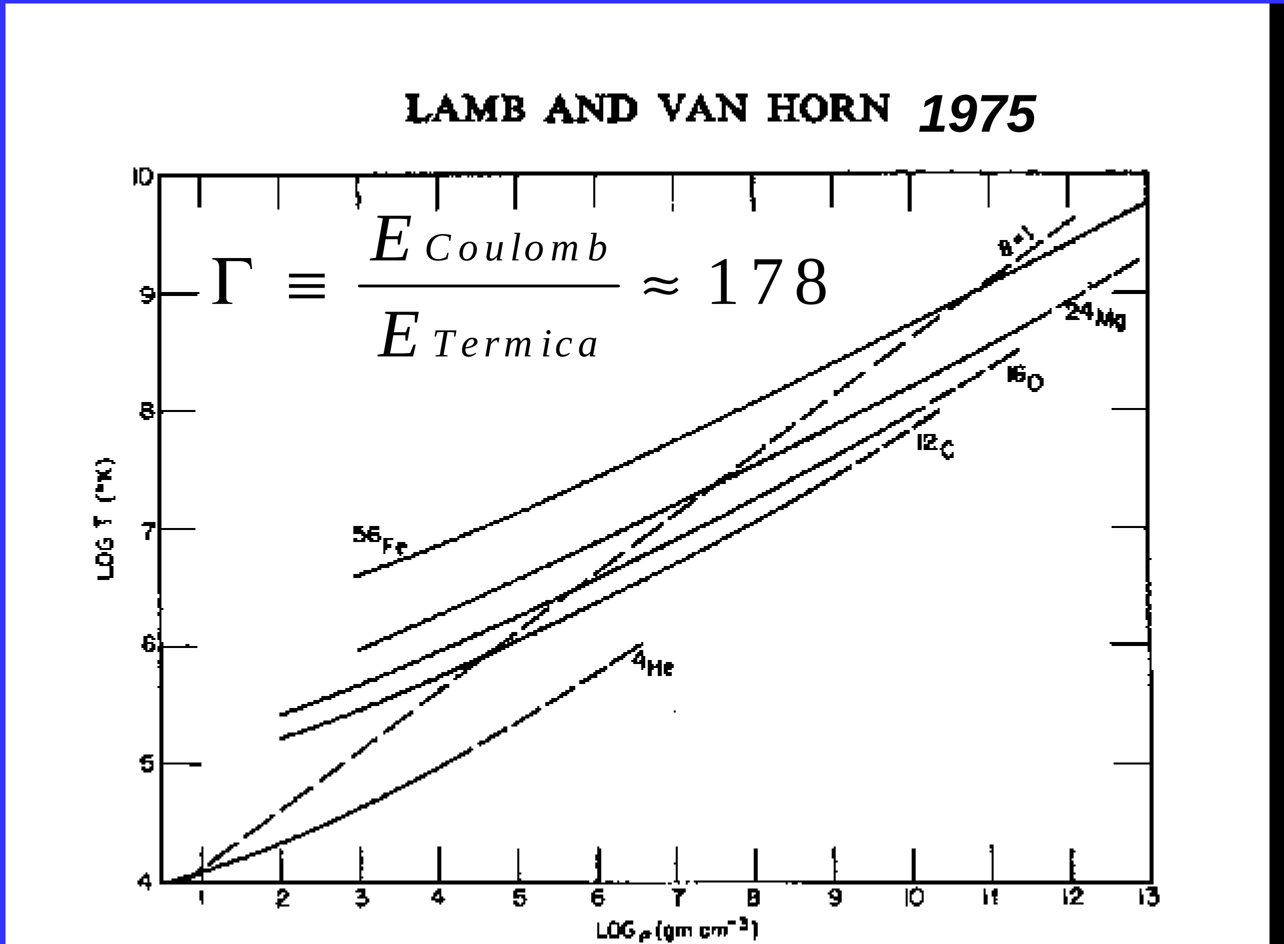
SDSS T_{eff} determination



SDSS log g determination



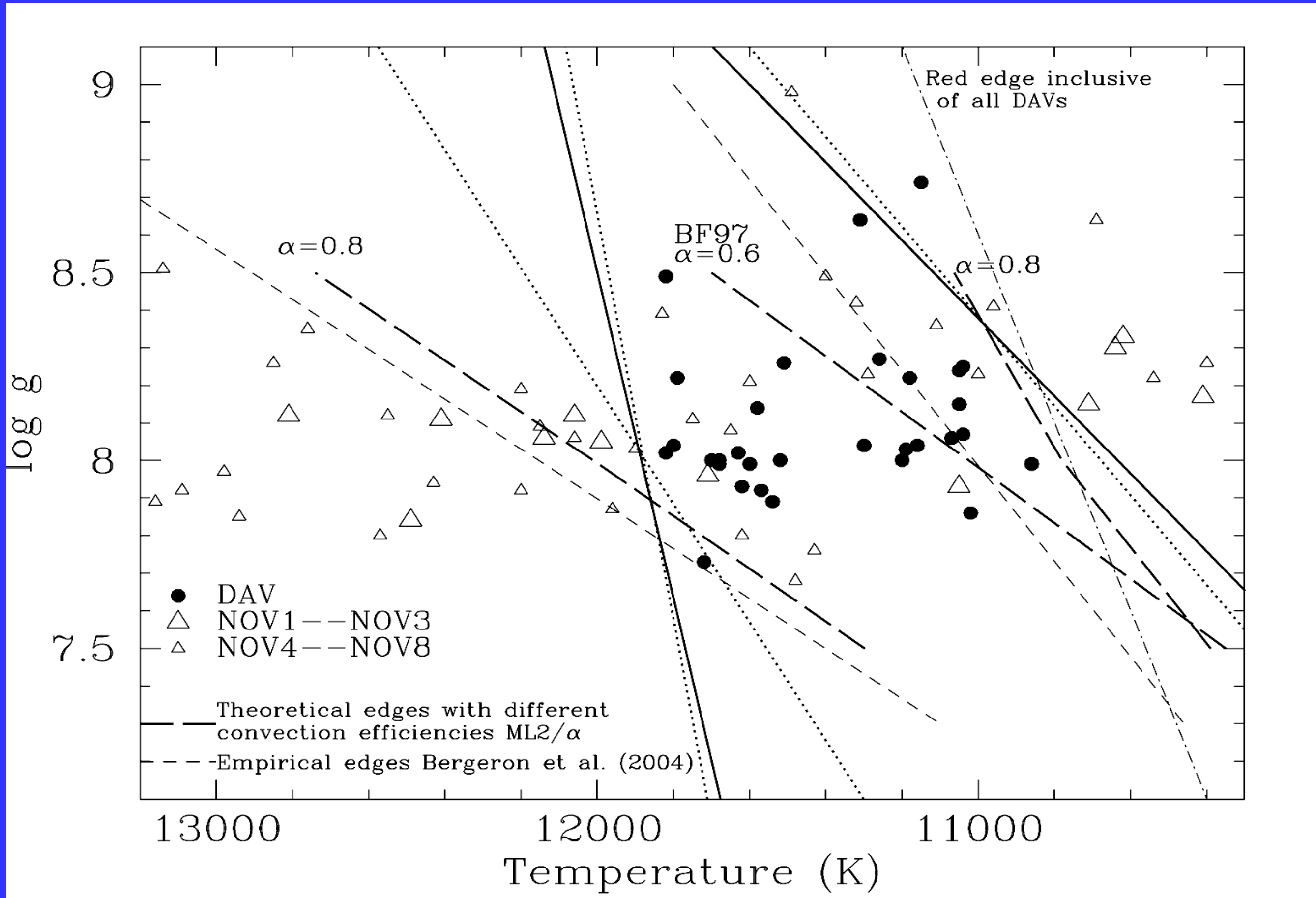
Transição de fase para cristal



$$\Gamma \equiv \frac{E_{Coulomb}}{E_{Termica}} \approx 178$$

A parte pontilhada corresponde a P(líquido quântico)/P(gás ideal) > 1. Efeitos quânticos iônicos são importantes à direita desta linha (θ=1).

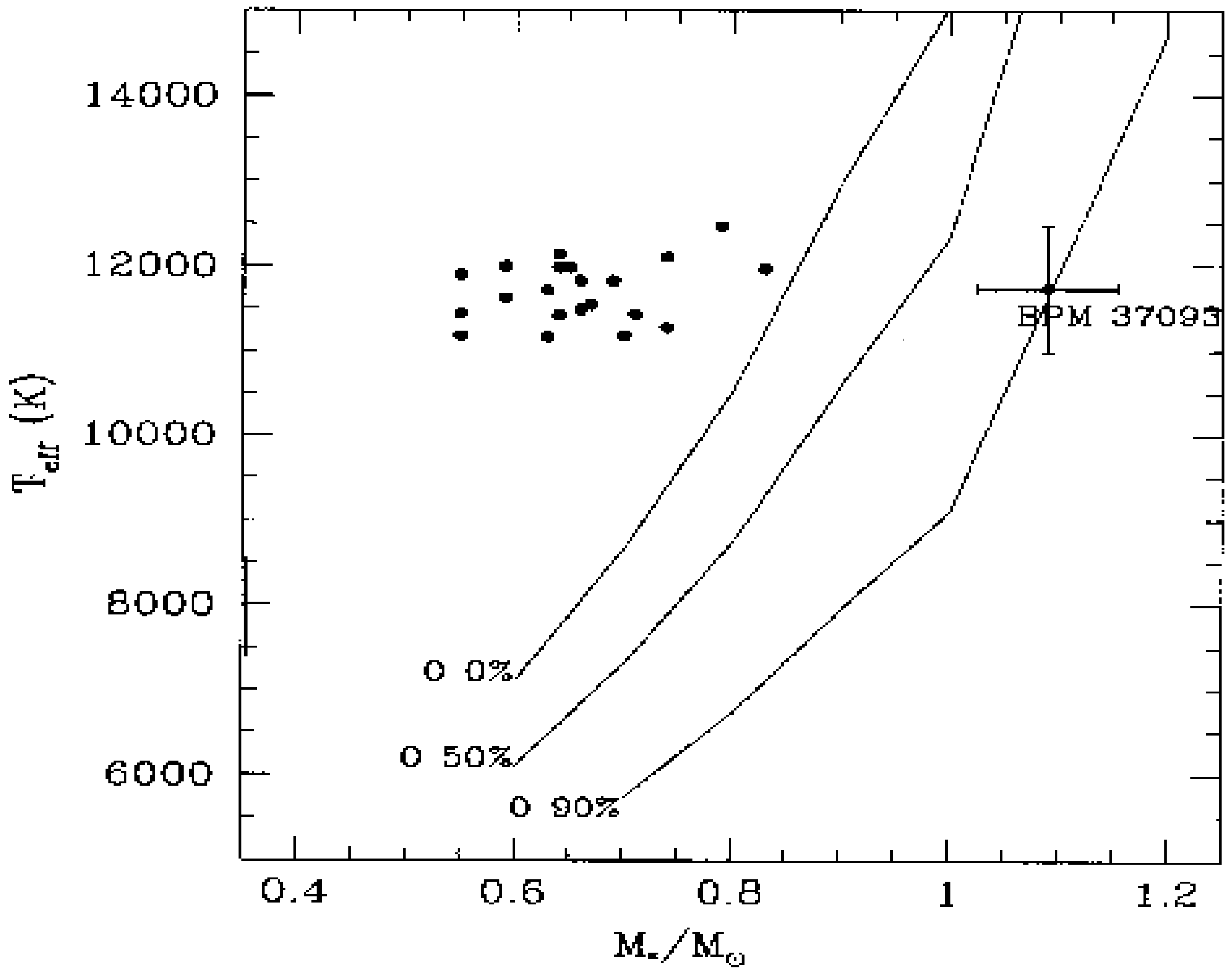
DAV instability strip



Need high S/N spectra of variables and non-variables to refine Teff and log g

Need to find more variables and non-variables to determine log g dependence

Most Massive Pulsating WD

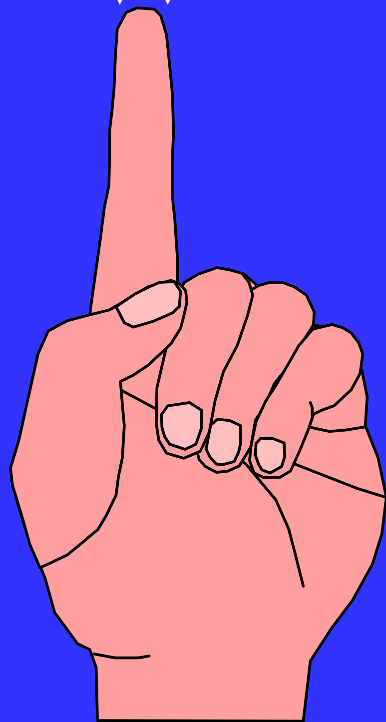


17 light yr distant
(40 quadrillion km)

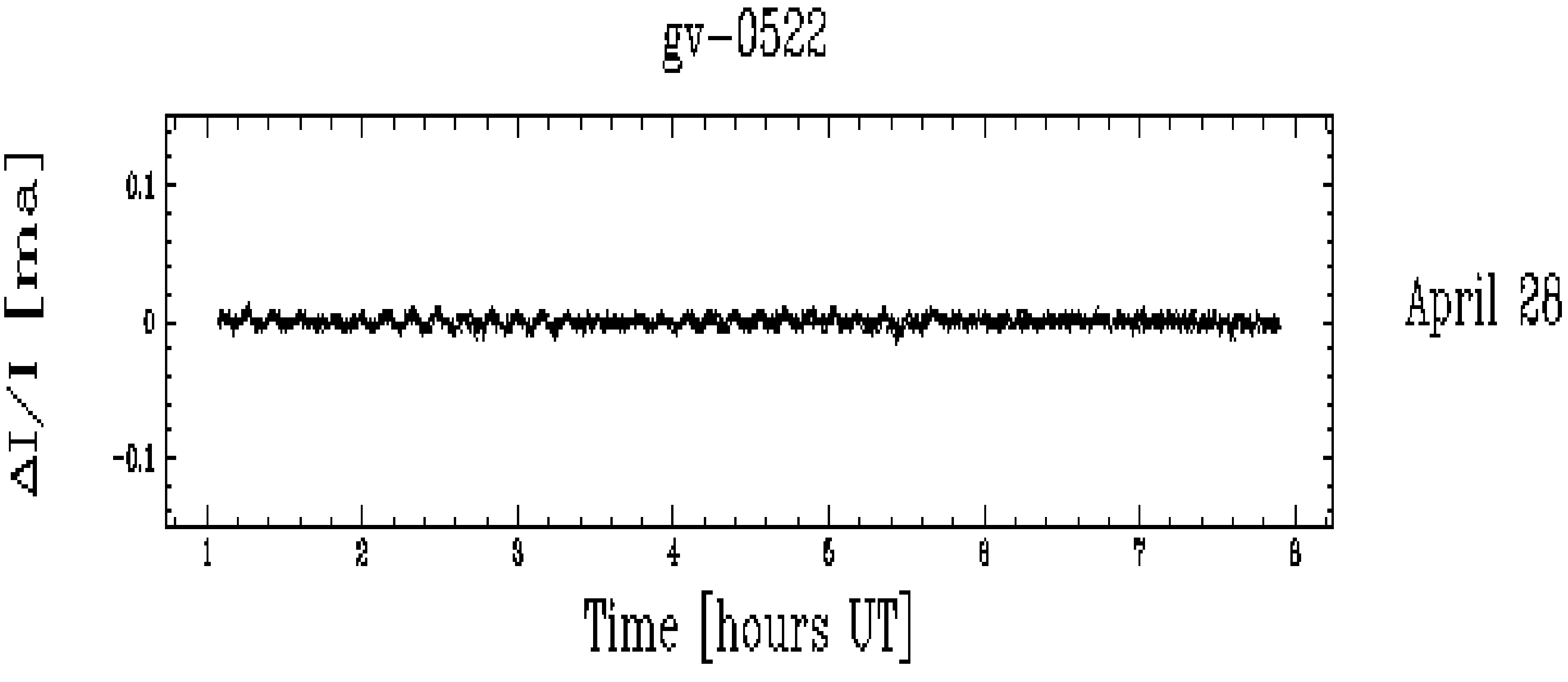
BPM37093 – Diamond in the Sky!

10'

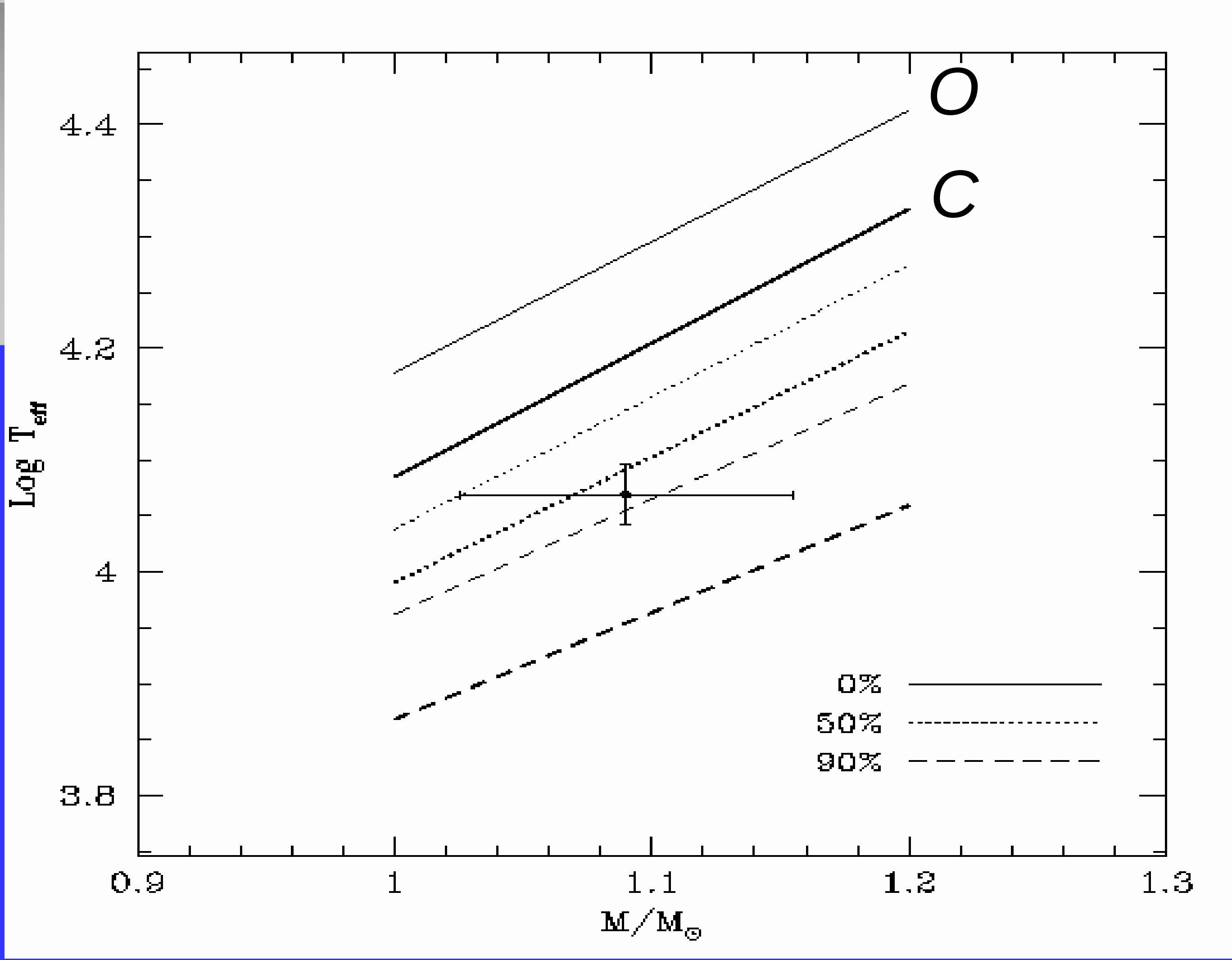
$2^{o} = 12 \times 10'$



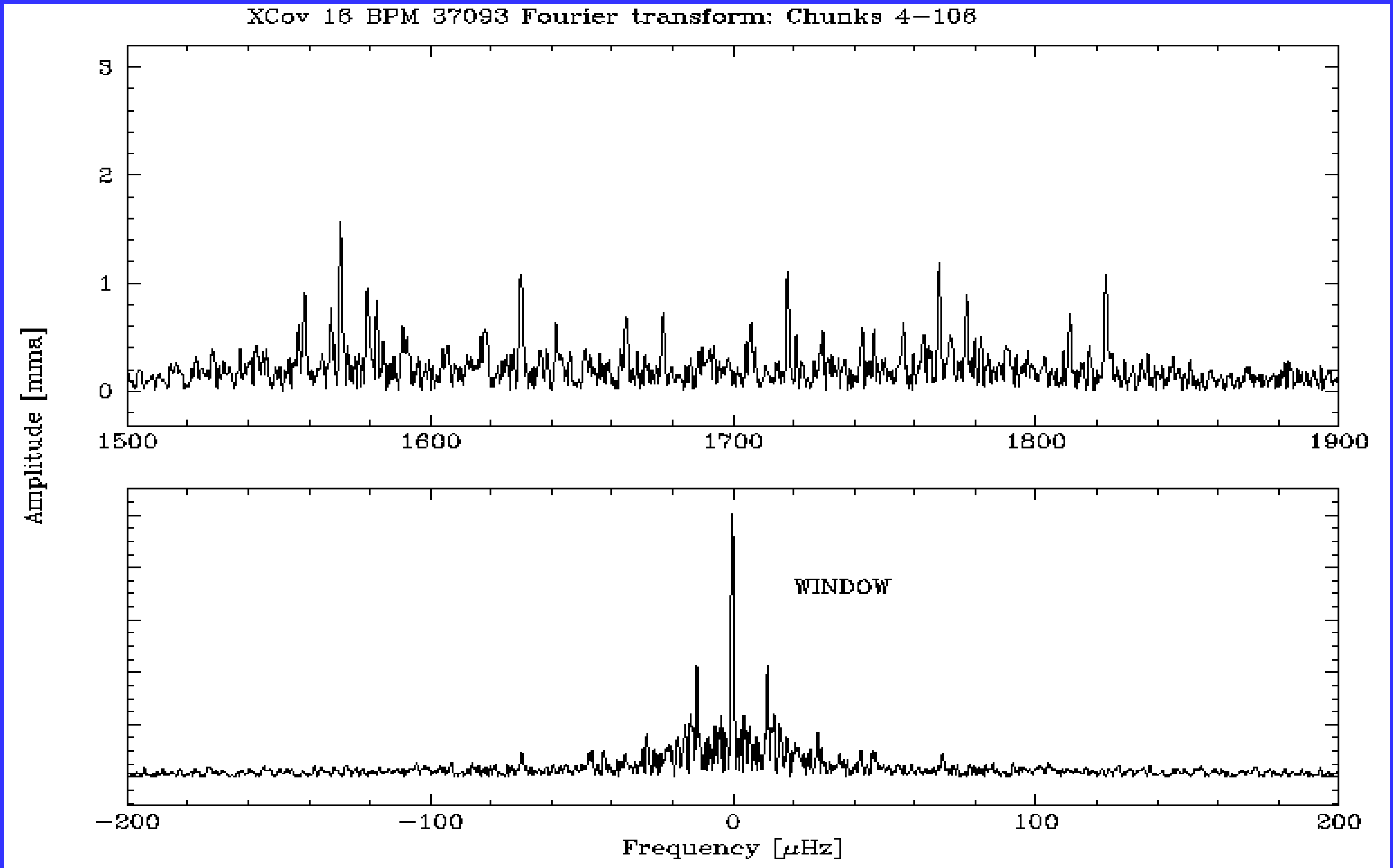
Light Curve



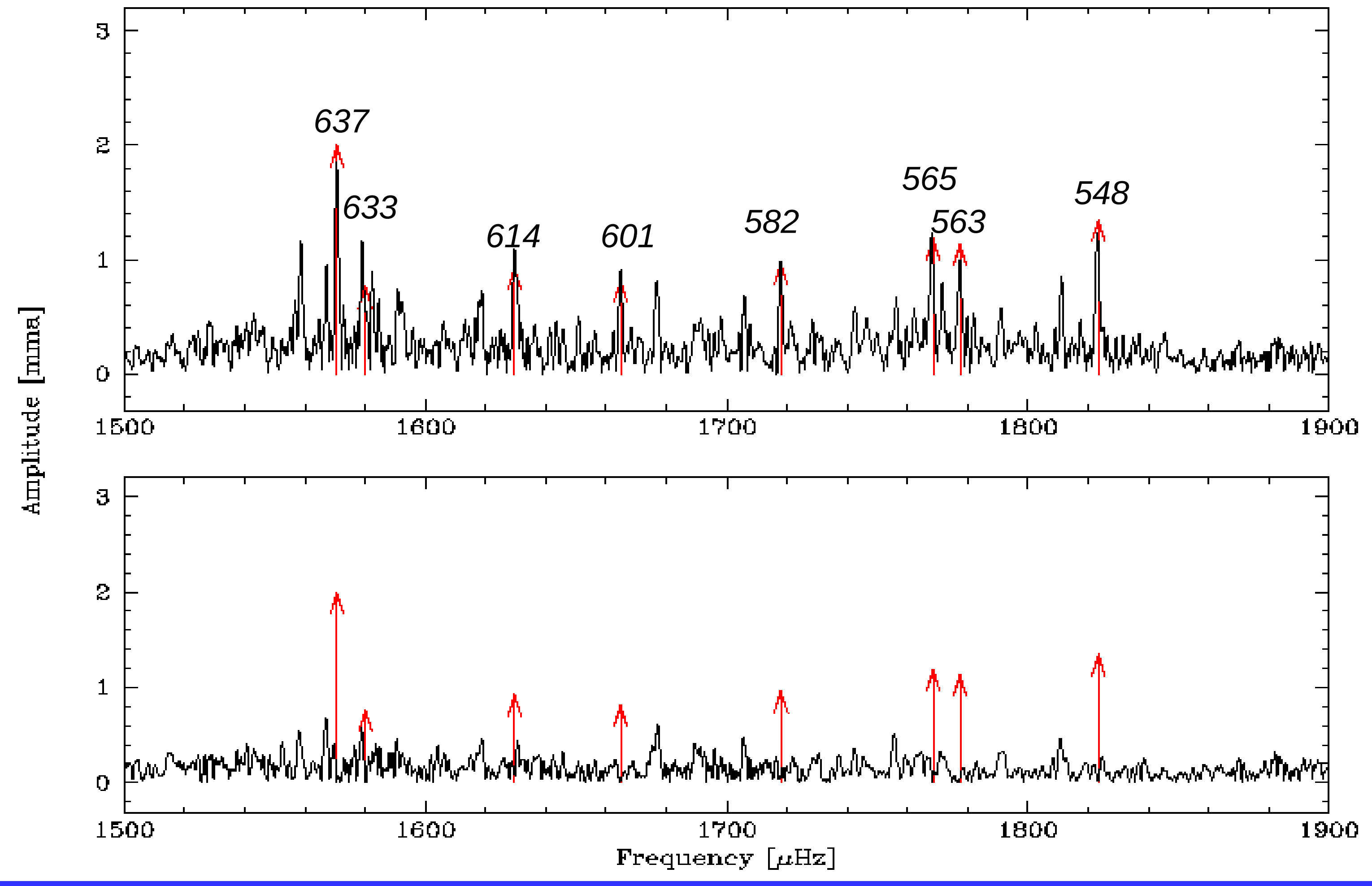
Crystallization

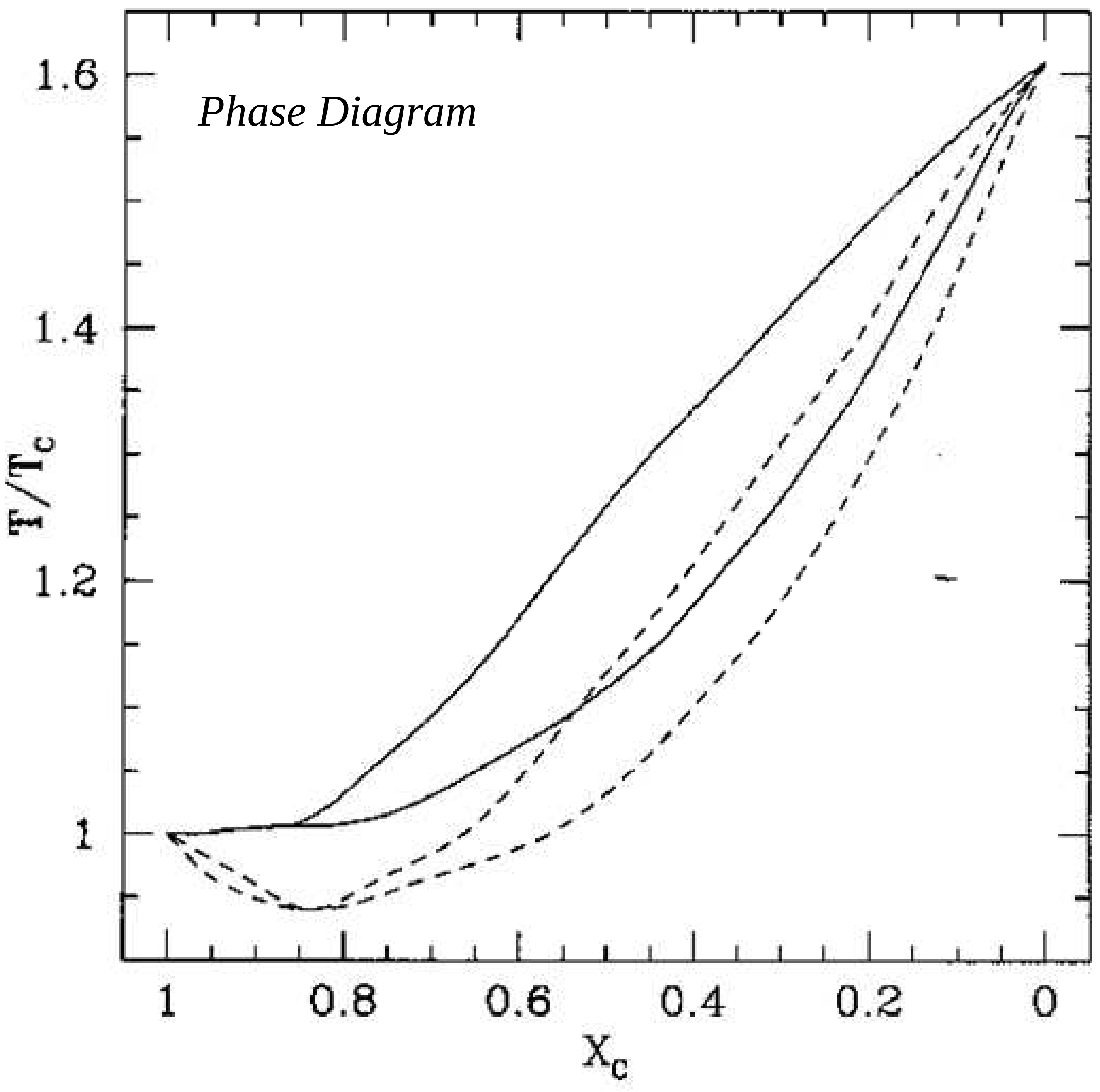


Pulsations Present

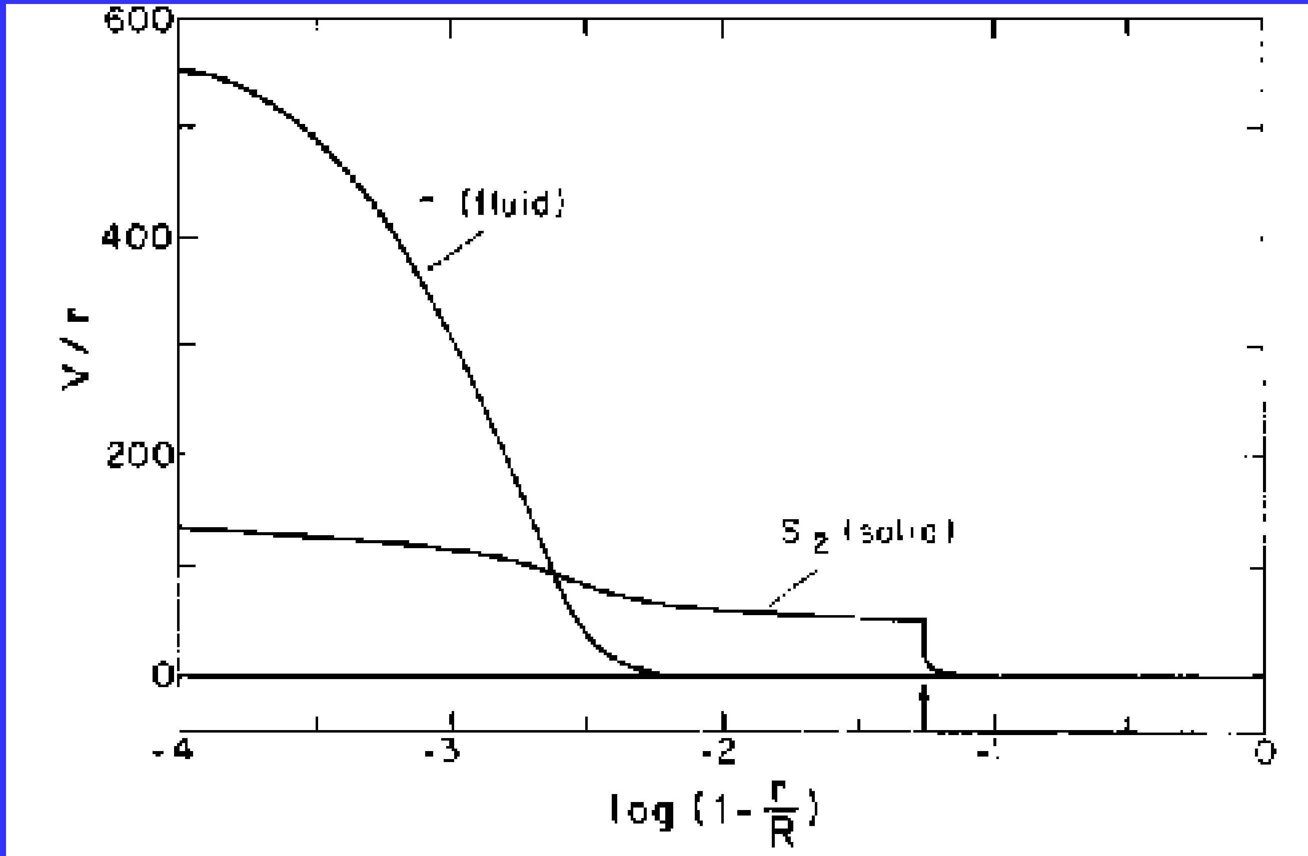


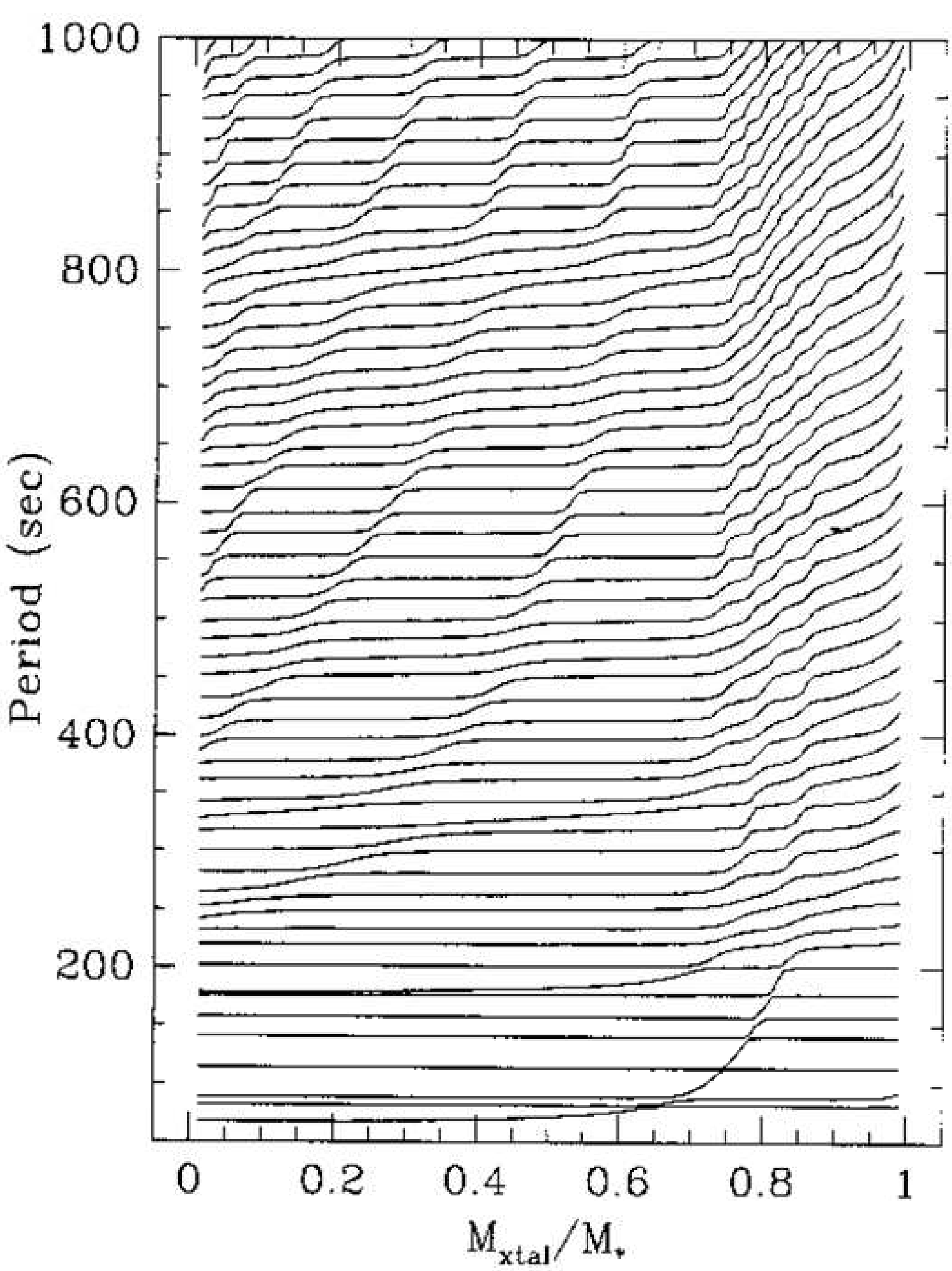
Period in seconds



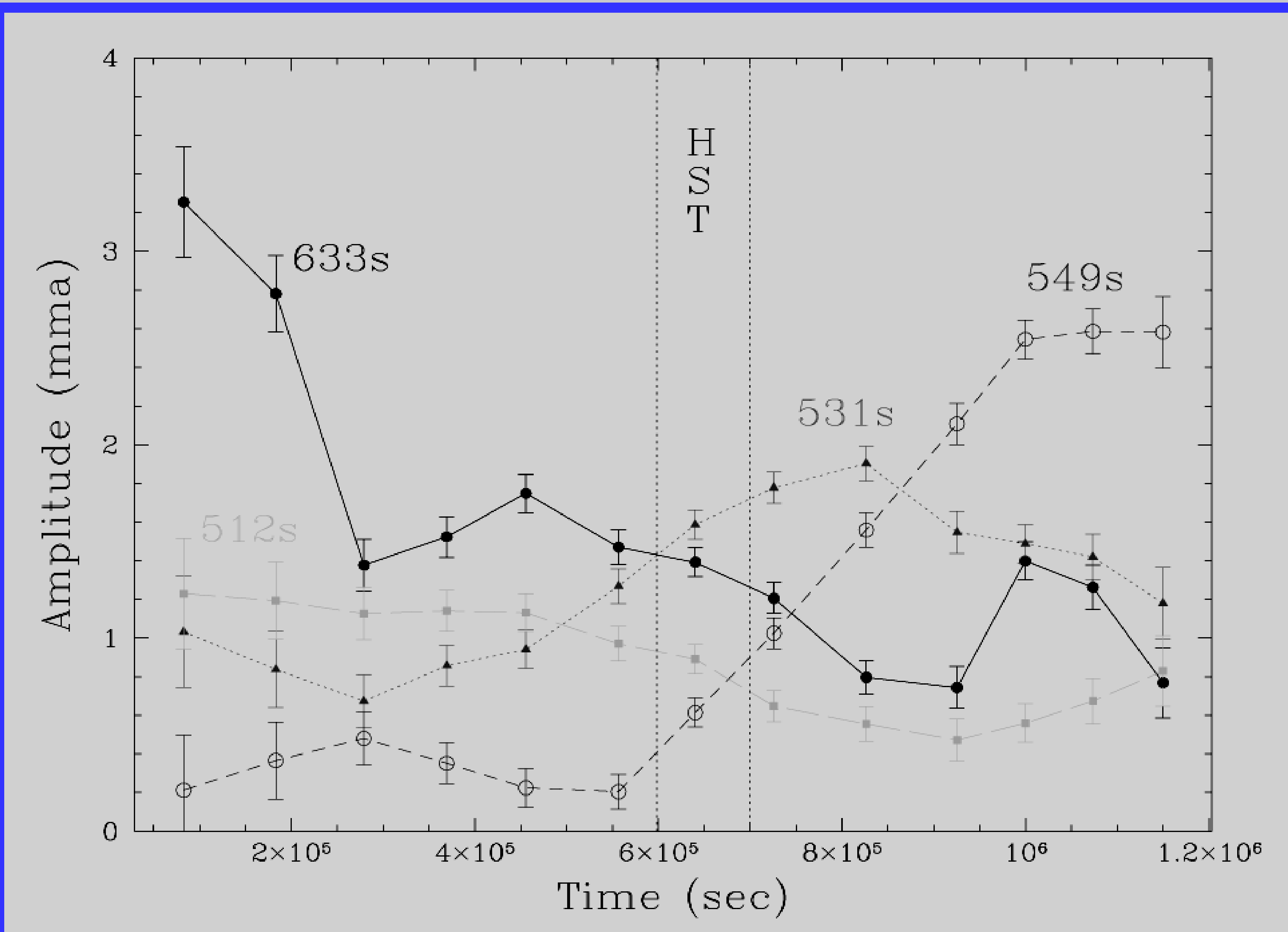

Phase Diagram
1.6
1.4
1.2
1
T/T_c
1
0.8
0.6
0.4
0.2
0
X_c

Crystallized or not?




1000
800
600
400
200
Period (sec)
0
0.2
0.4
0.6
0.8
1
M_{xtal}/M_*

BPM37093 in 1999

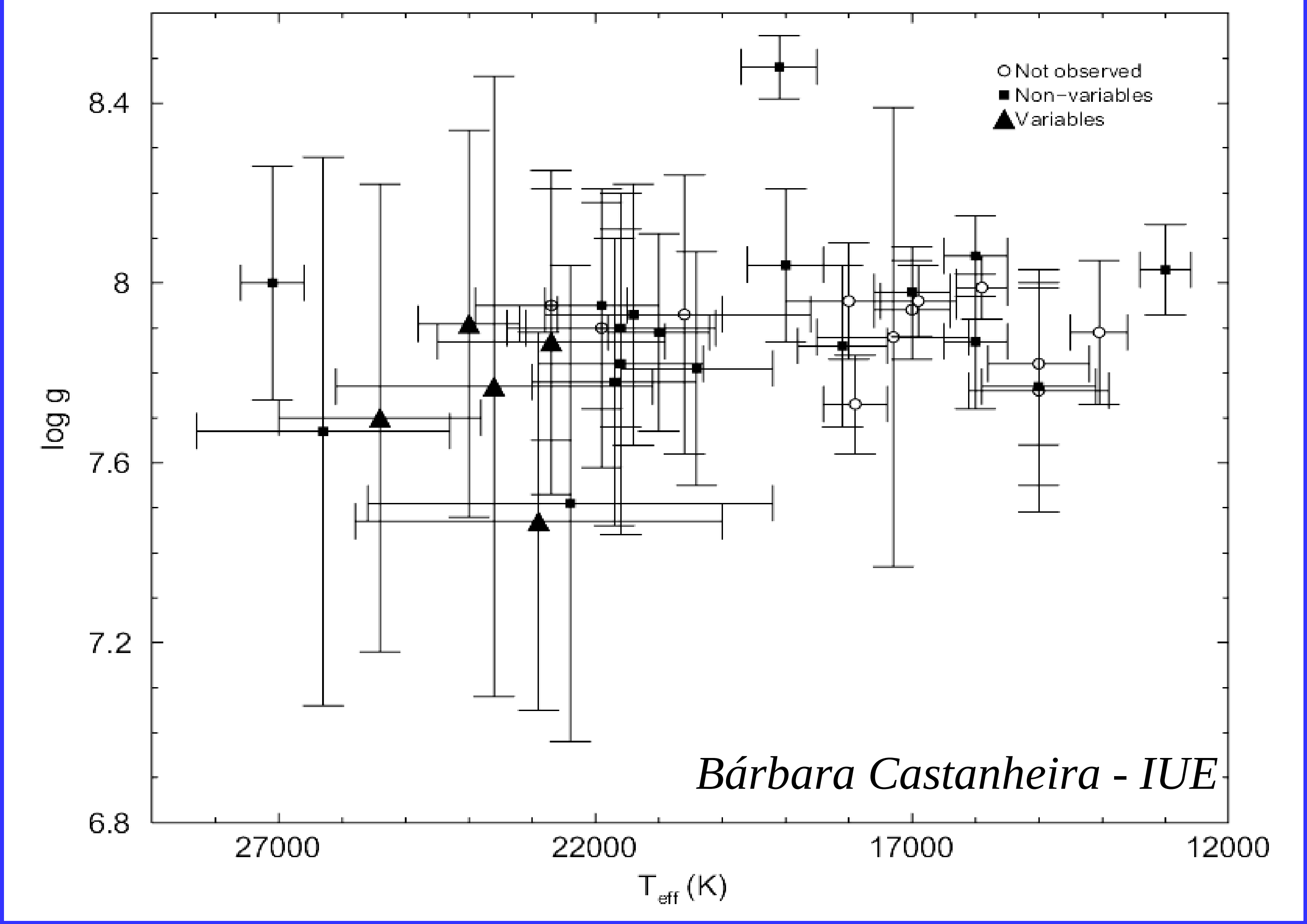


Super-Diamond?

- **Diamond**
- C crystal
- FCC
- 3,08Å between atoms
- 2 shared electrons
- T < 8000 K
- 10 K atm < P < 1,2x10^8 atm

- **BPM37093**
- C crystal
- BCC
- 0,01Å between nucleons
- all electrons are free (degenerate)
- T = 7 million K
- P = 5x10^{18} atm
- ρ = 36 Ton/cm^3
- E_{ions}> 2kT (quantized)
- **metallic quantum crystal**

DBV instability strip



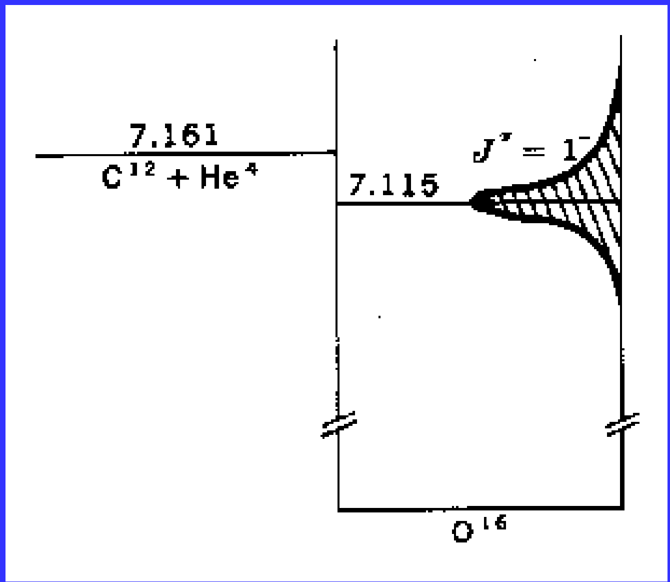
181 periodicities detected

- *Mass of each layer*
- *M(R): Luminosity -> distance*
  (1/10 uncertainty of parallax)
- *Rotation law(r) [splitting (k)]*
- *Magnetic field limit (6000 G)*
- *6^{th} order harmonics and combinations*

Nuclear reaction rate

- *Quantity of ^{22}Ne dependes mainly on*

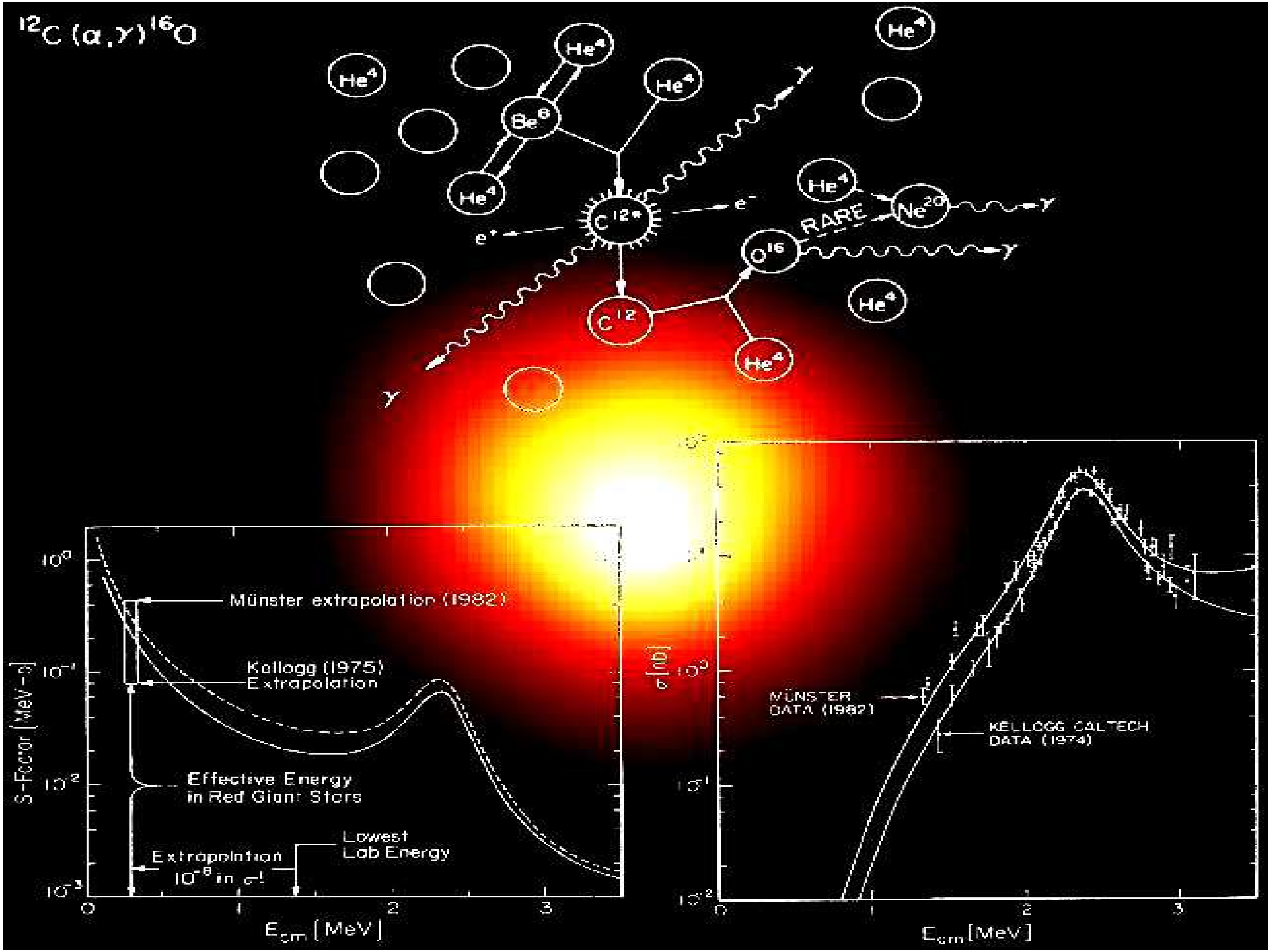
$$\sigma\,[C^{12}(\alpha,\gamma)O^{16}(\alpha,\gamma)Ne^{20}(\alpha,\gamma)Mg^{24}(\alpha,\gamma)]$$



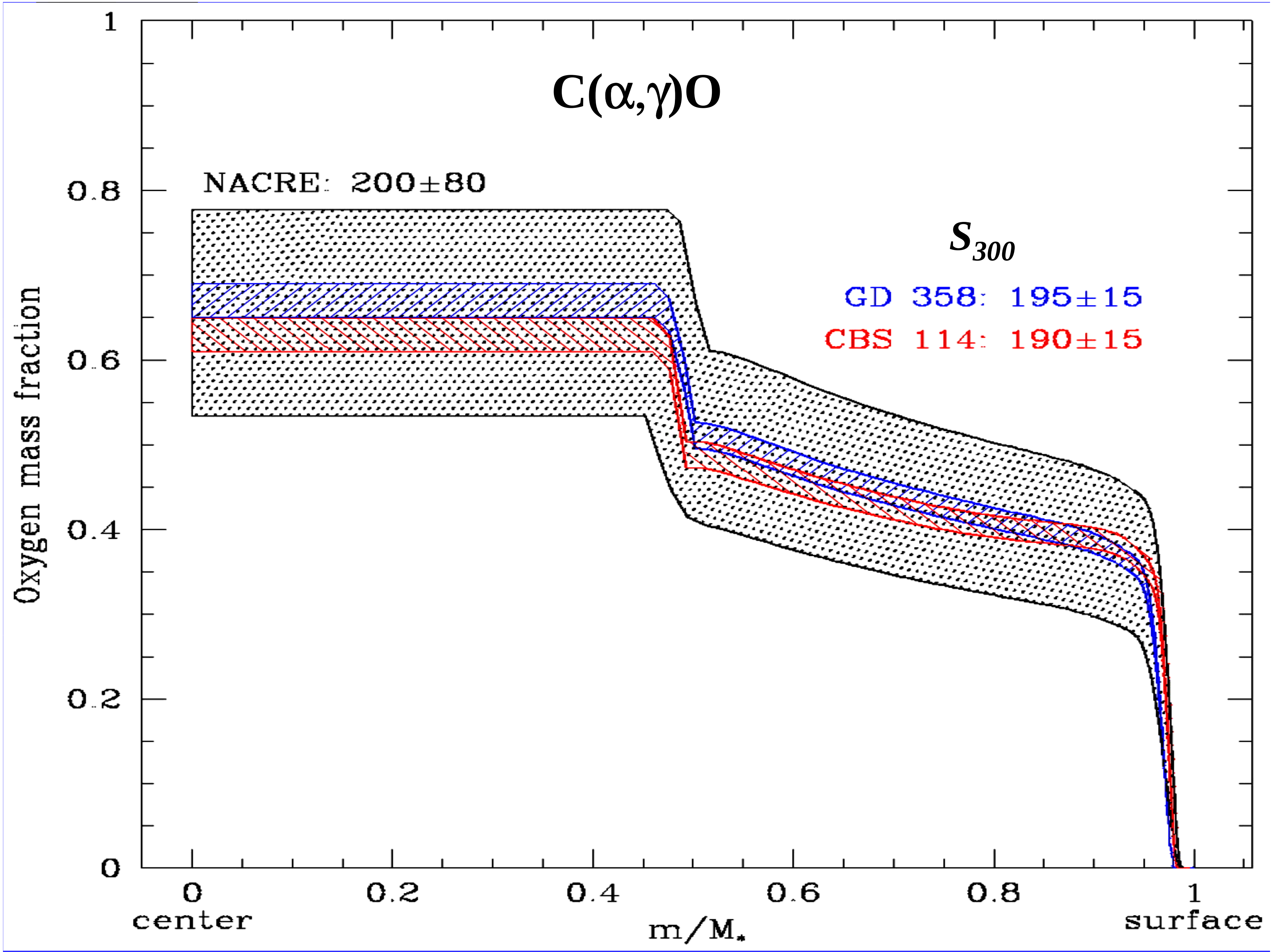
Non Resonant Reaction

$T > 10^8$ K and $\rho > 10^5$ g/cm^3

Uncertainty is around 50%!



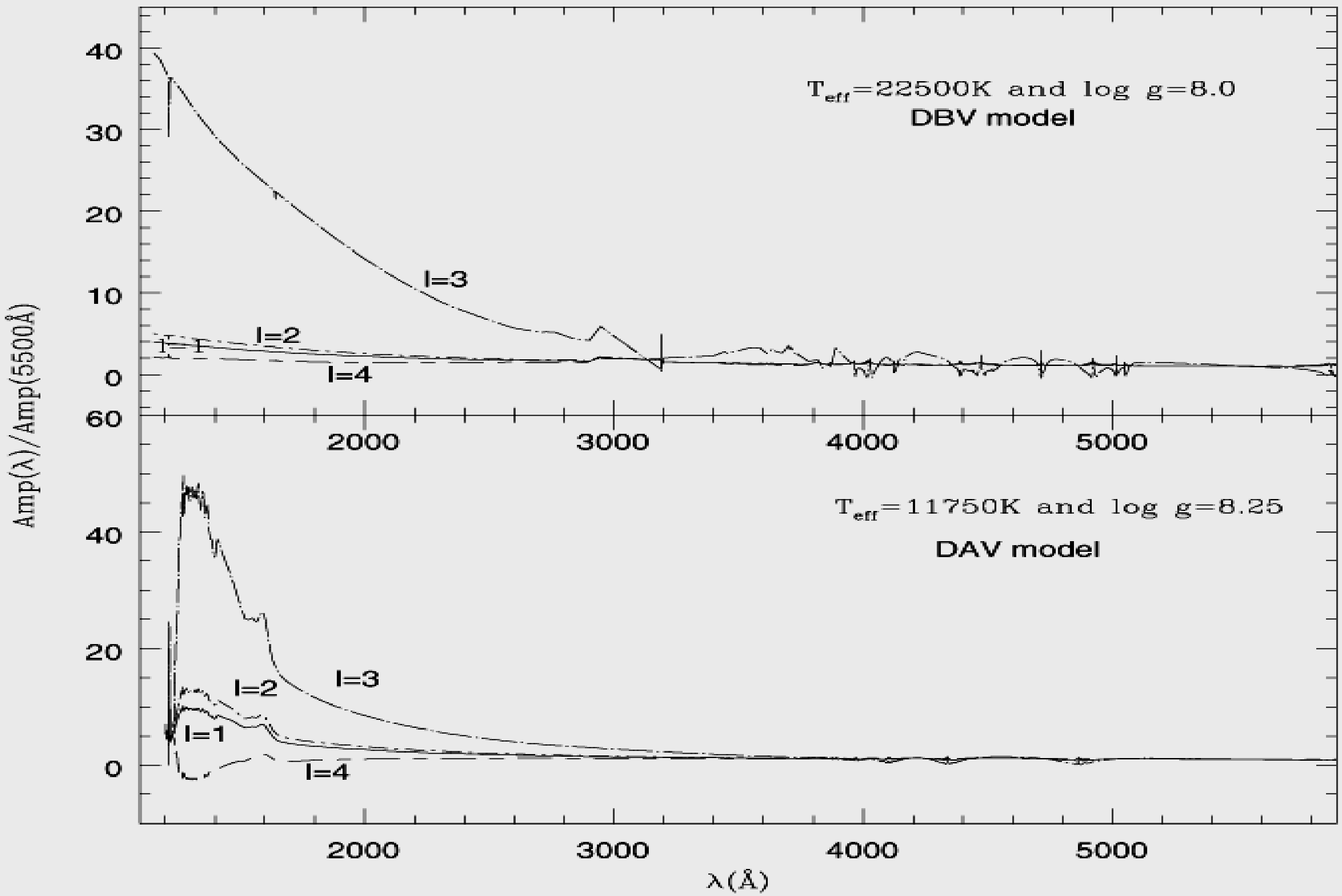
$^{12}C(\alpha,\gamma)^{16}O$
He4
Be8
C12*
e+
e-
RARE
Ne20
O16
C12
γ
Münster extrapolation (1982)
Kellogg (1975) Extrapolation
Effective Energy in Red Giant Stars
Extrapolation 10-8 in σ!
Lowest Lab Energy
S-Factor [MeV-b]
Ecm [MeV]
σ [nb]
MÜNSTER DATA (1982)
KELLOGG CALTECH DATA (1974)



C(α,γ)O
NACRE: 200±80
S300
GD 358: 195±15
CBS 114: 190±15
Oxygen mass fraction
m/M*
center
surface
0
0.2
0.4
0.6
0.8
1

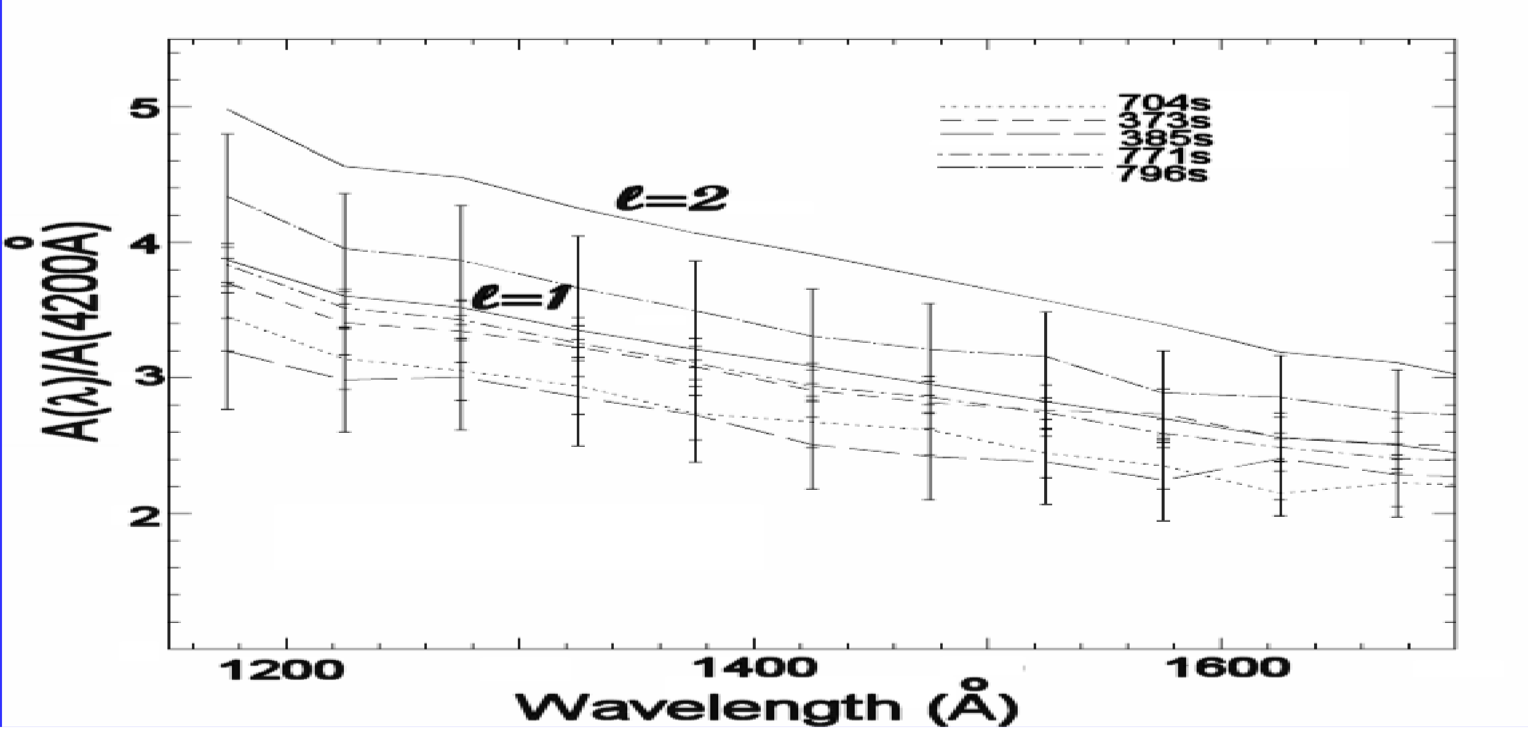
Mode identification with HST

Chromatic amplitude changes



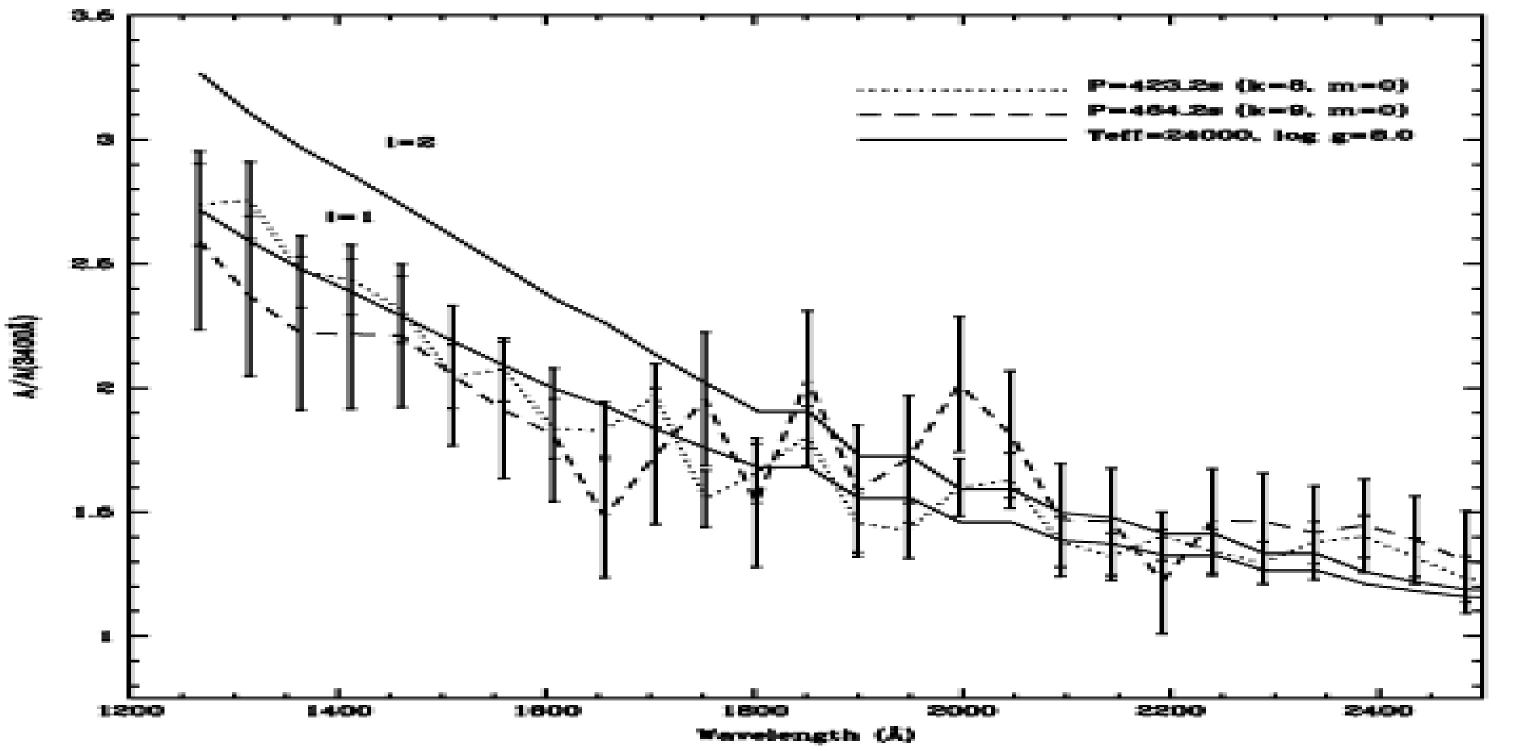
GD358 mode identification HST

- Bárbara Castanheira
- $\ell = 1$ for k=8 and 9 in 1996
- probably $\ell = 1$ for other modes in 2000

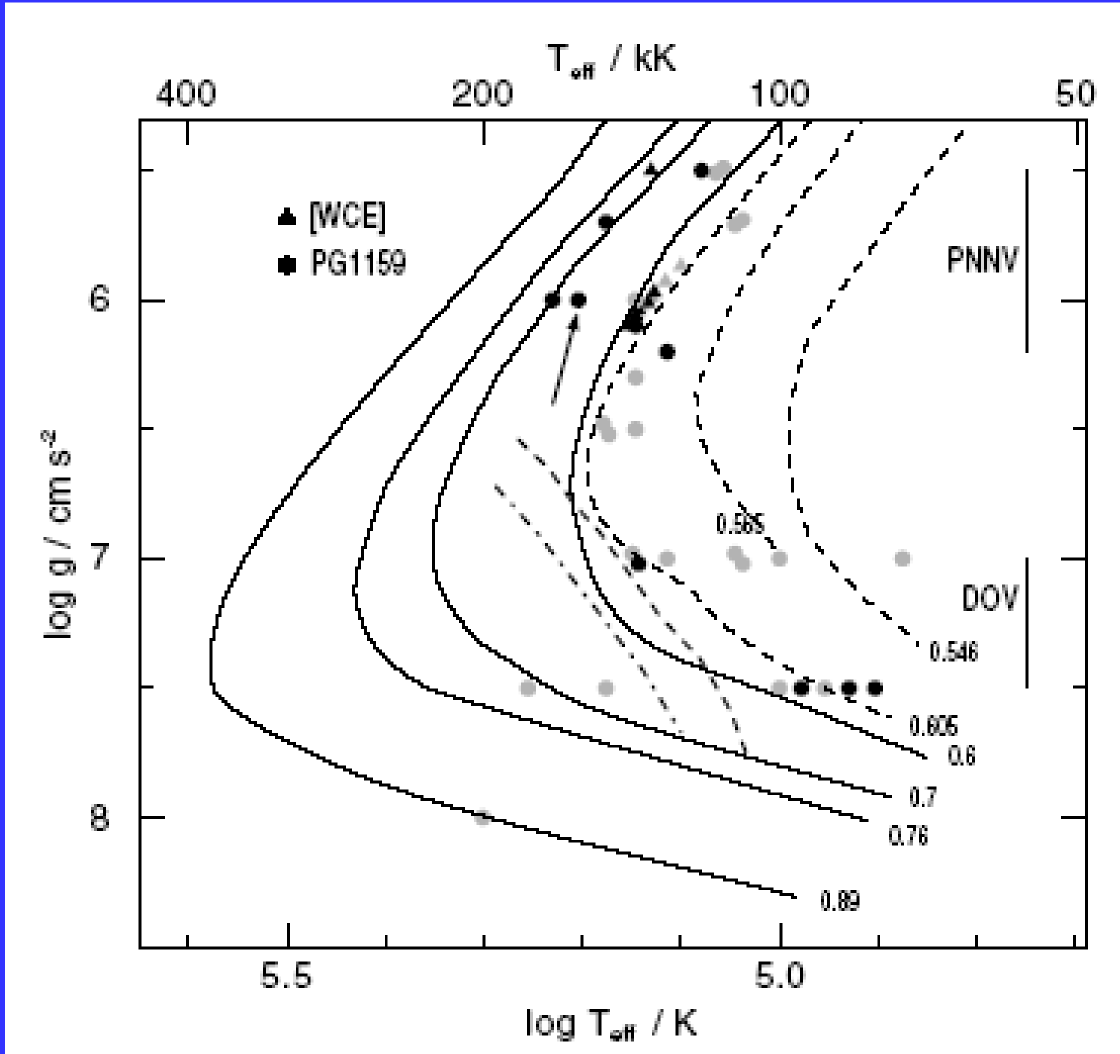


GD358 mode identification HST

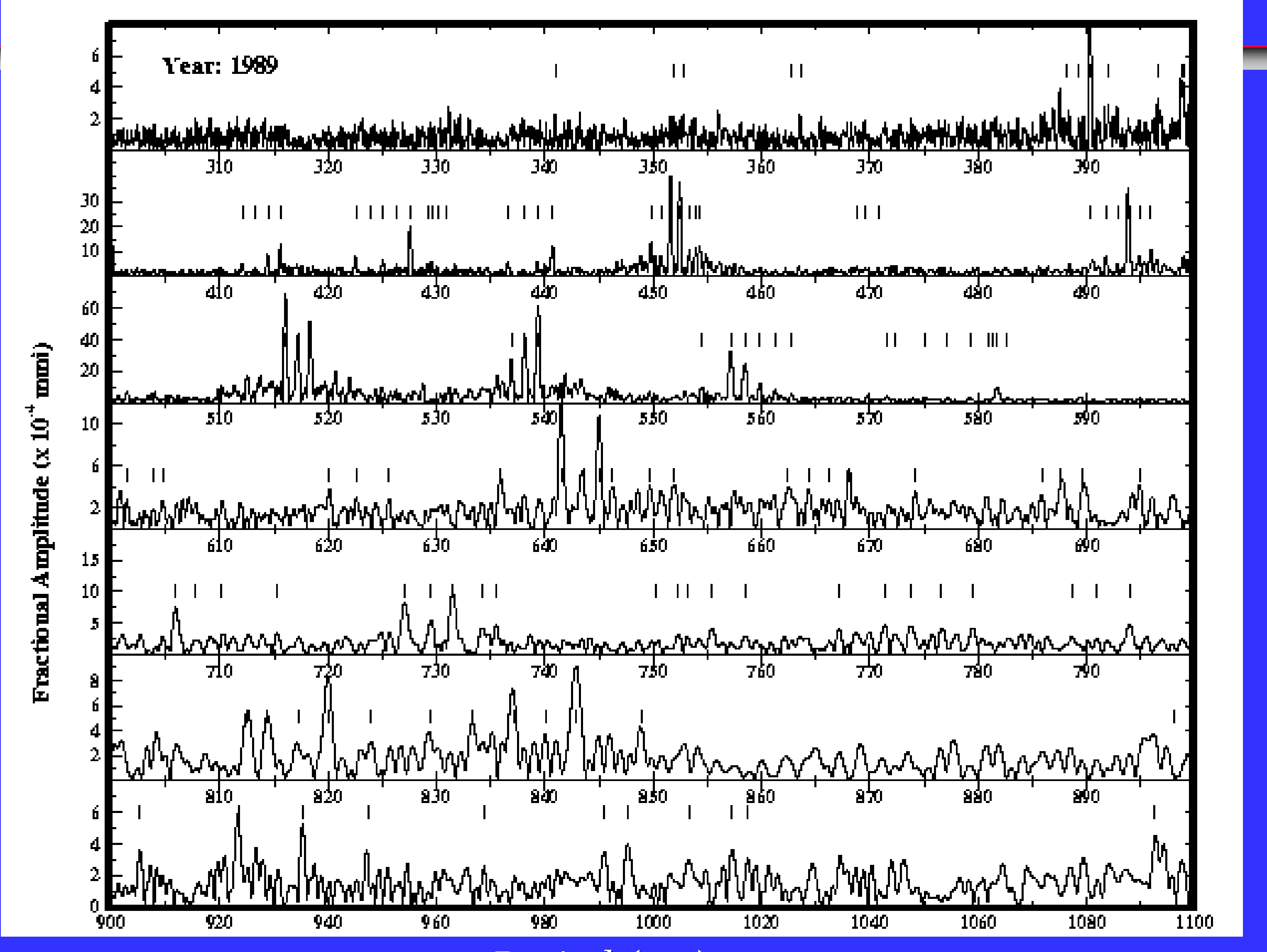
- *Bárbara Castanheira*
- *$\ell = 1$ for k=8 and 9 in 1996*
- *probably $\ell = 1$ for other modes in 2000*



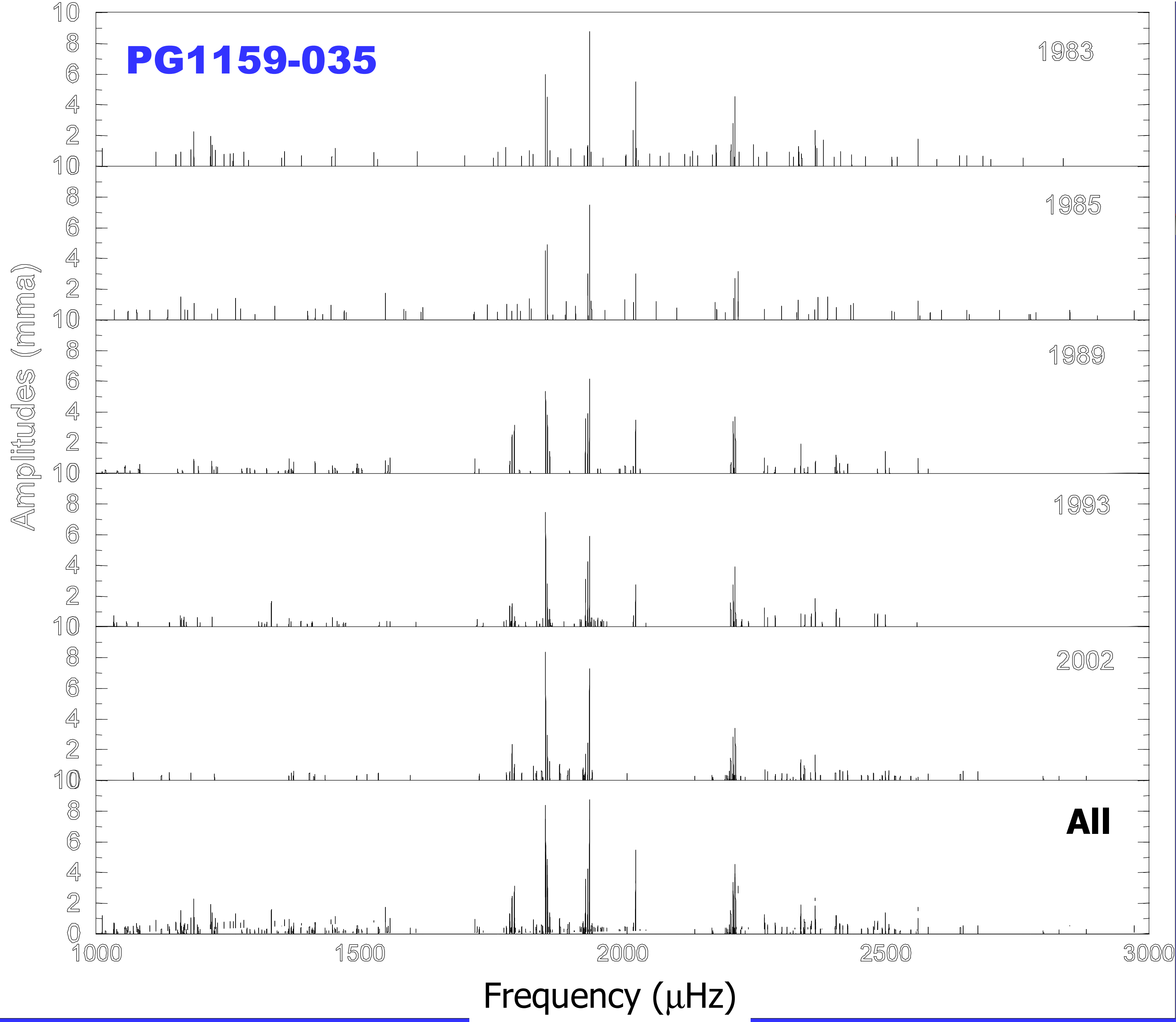
PNNV – DOV instalibility strip



PG1159-035



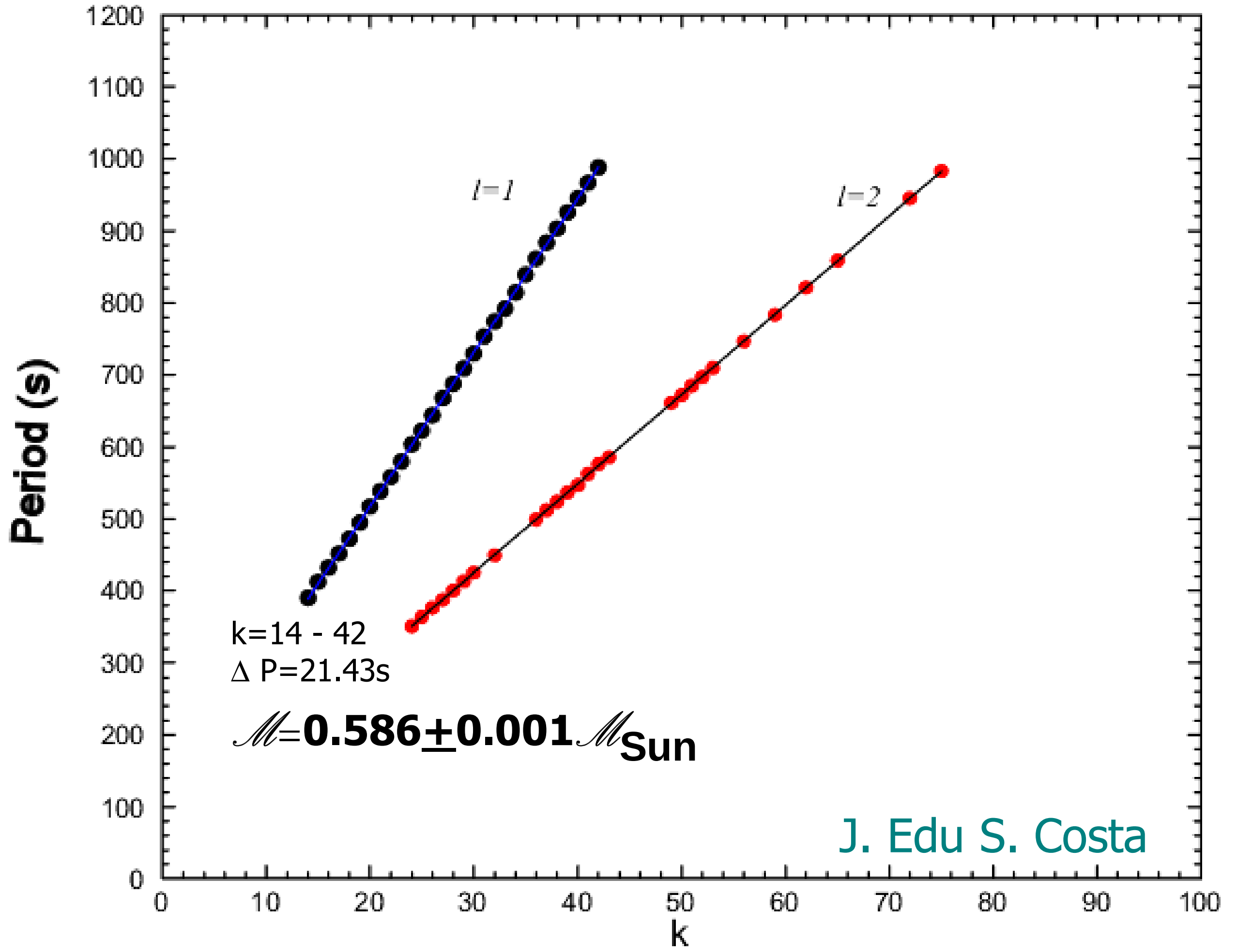
Period (sec)


PG1159-035
1983
1985
1989
1993
2002
All
Amplitudes (mma)
Frequency (μHz)
1000
1500
2000
2500
3000

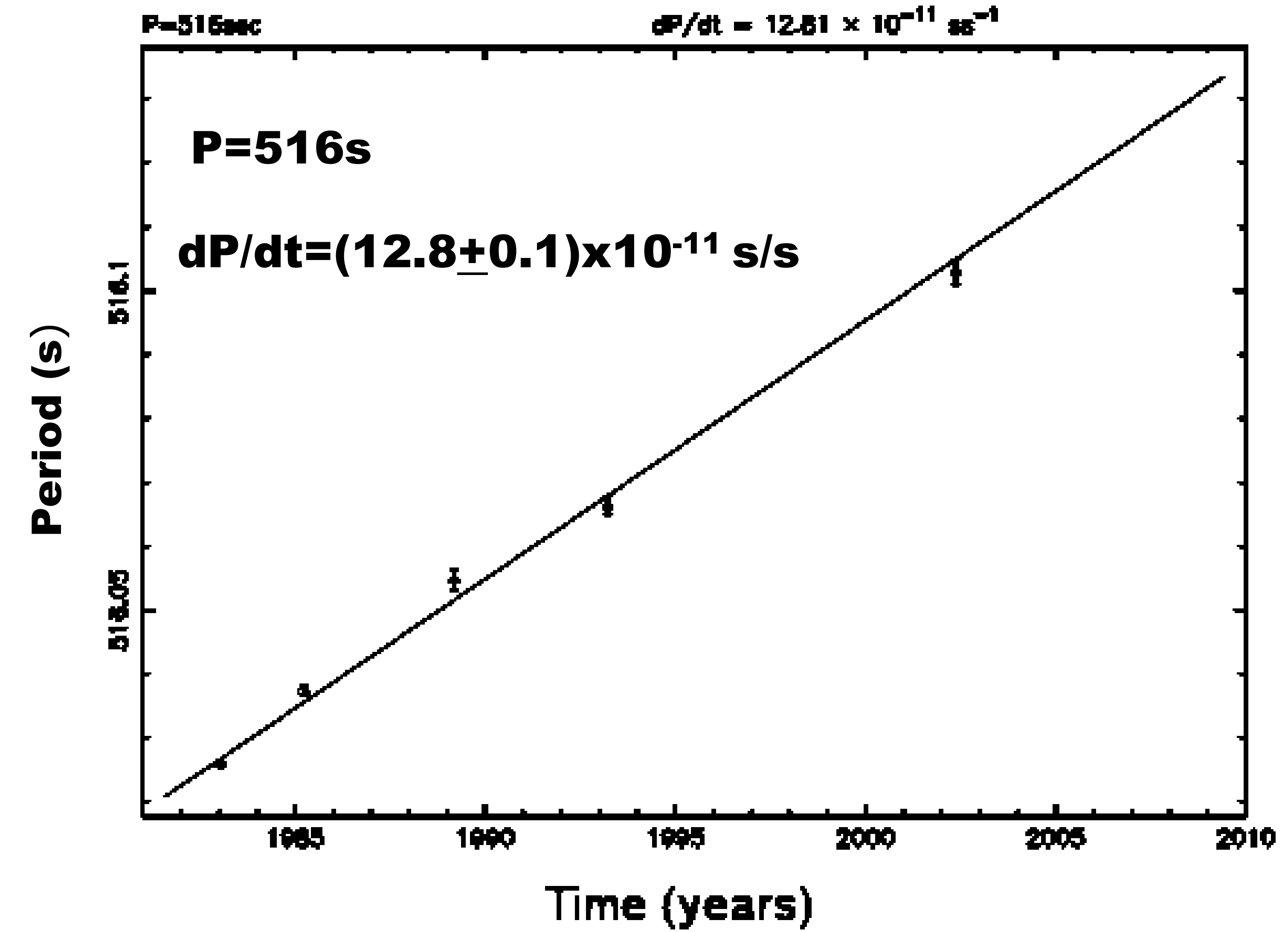
PG1159-035: 101 pulsations detected

- T_{eff} = 140 000K
- Total mass : (0.586 +/- 0.001) M_{Sun}
- M(R): Luminosity -> distance
- Mass of external layers
- no harmonics or linear combination (no convection zone)

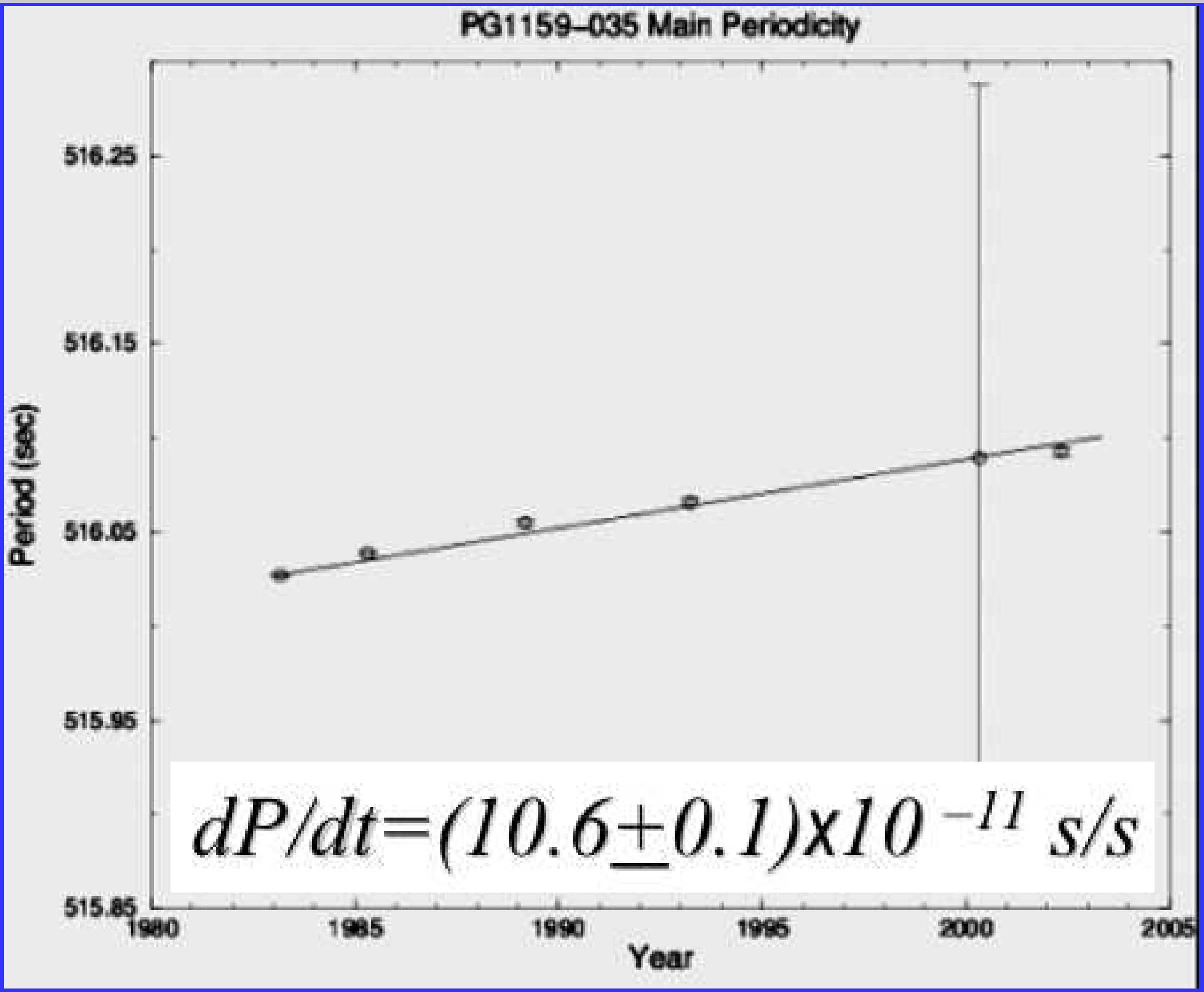
PG1159-035 modes detected



Direct Method dP/dt



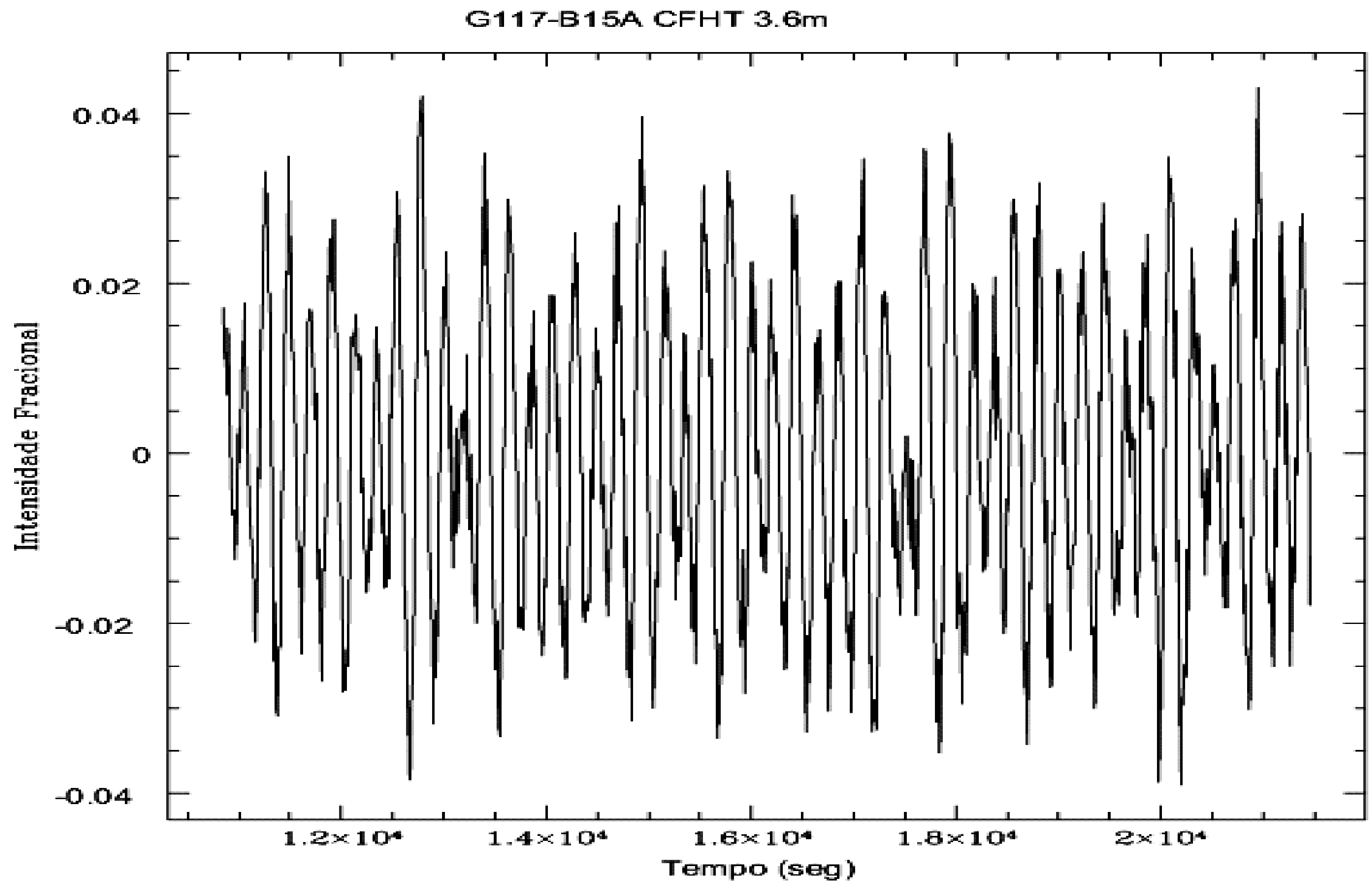
But period increases with time!



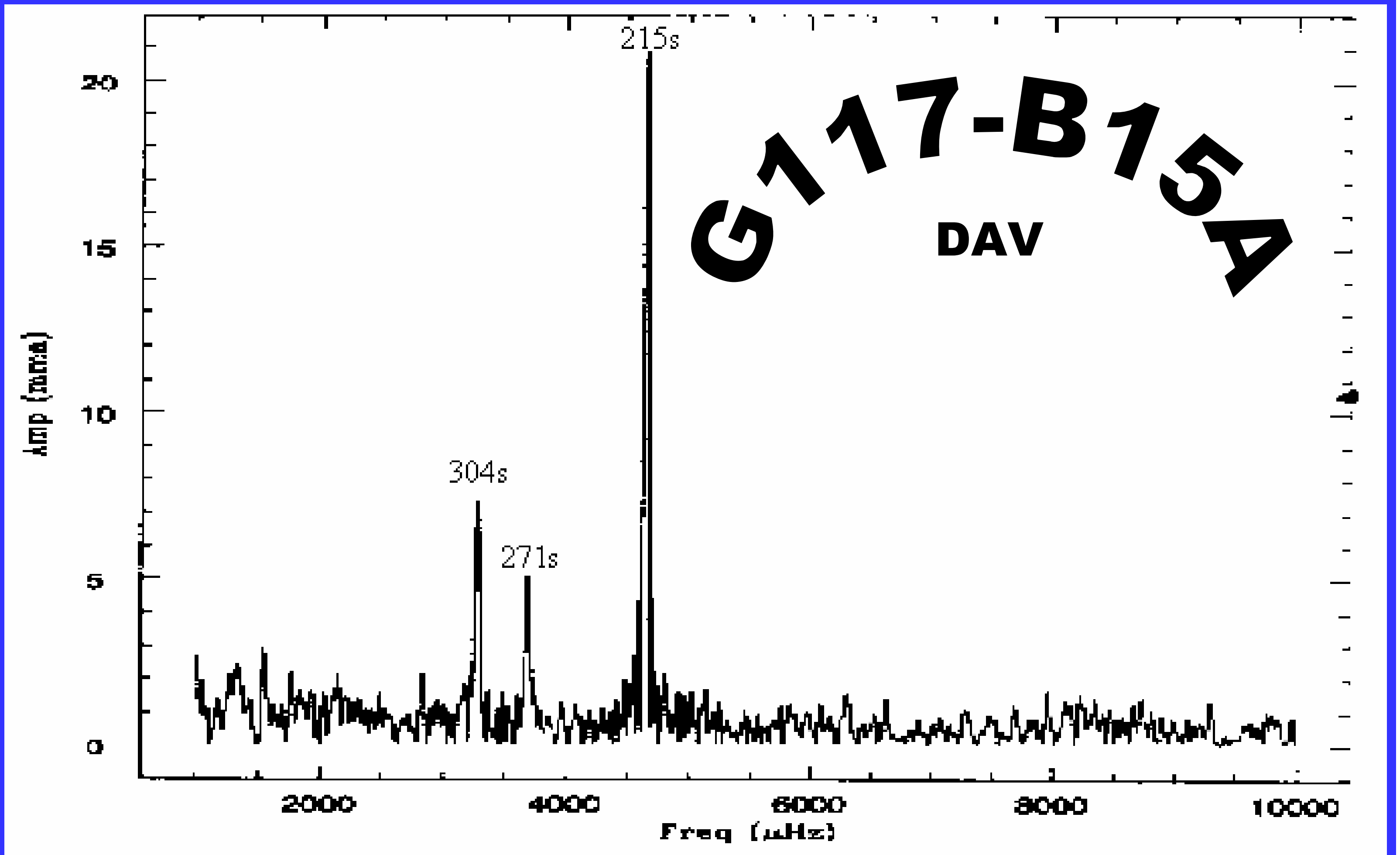
$dP/dt = (10.6 \pm 0.1) \times 10^{-11}$ s/s

1s/300 years

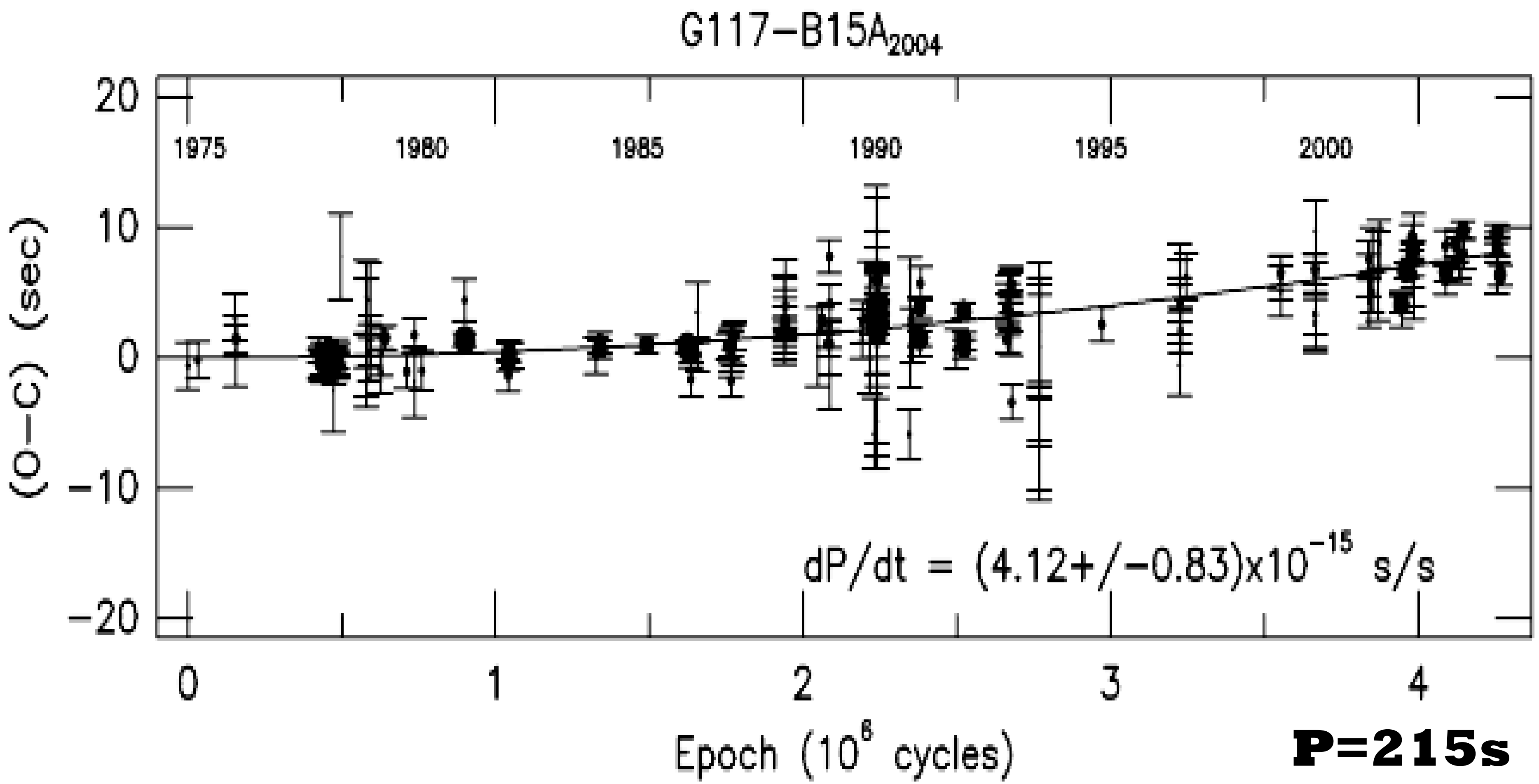
Most stable optical clock known



Most stable optical clock known



G117-B15A 2004



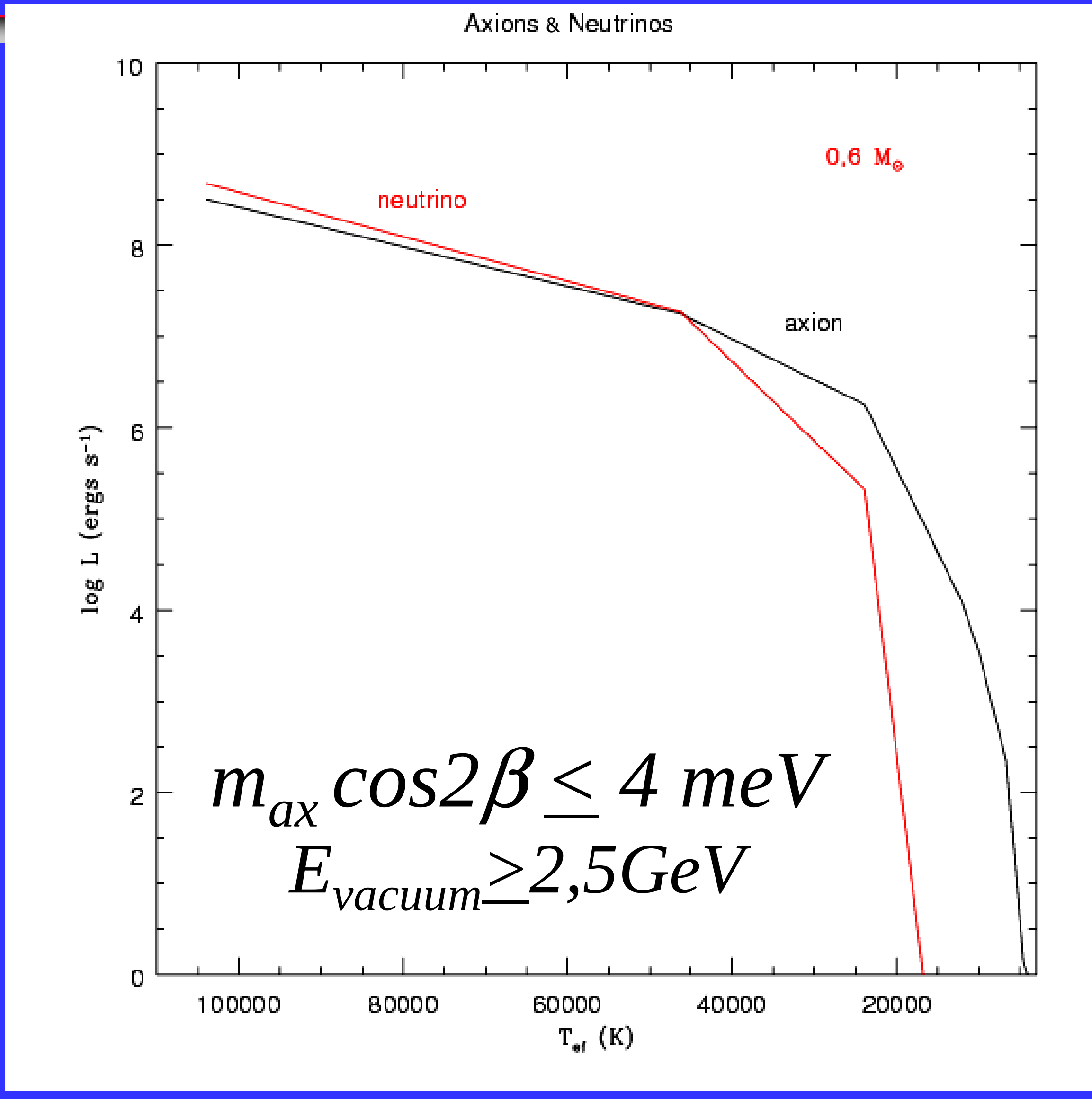
P=215s

Stable?

$$\text{Time scale} = \frac{P}{\dot{P}} \cong 2.2 \text{ Gyr}$$

Pulsars with dP/dt = 10^{-18} s/s have timescale 0.1 Gyr, but PSR B1885+09, with P=5.3 ms and dP/dt=1.8×10^{-20} s/s has timescale of 9.5 Gyr.

Axions



$$m_{ax}\cos 2\beta \leq 4\ meV$$

$$E_{vacuum} \geq 2{,}5 GeV$$

Axions

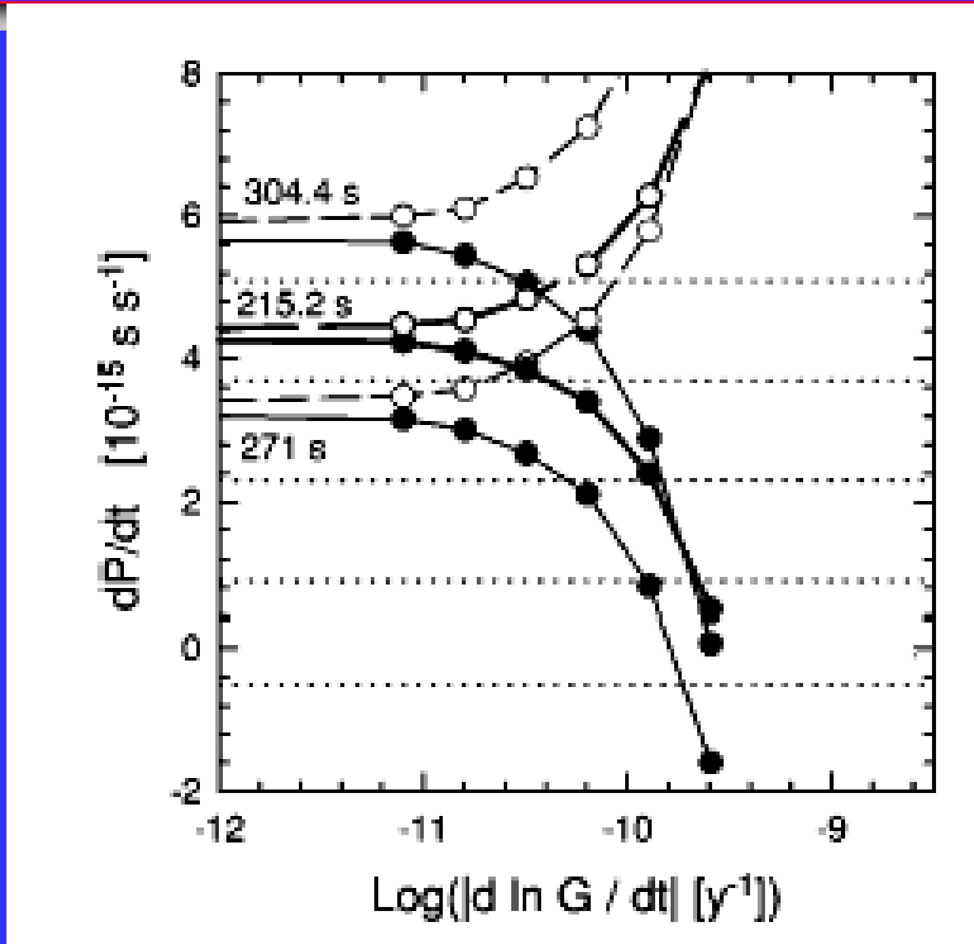
$m_{ax} > 1\ \mu eV$ or $\Omega_{ax} > 1$

tan β: ratio of the vacuum energy of the two Higgs fields

Gravitons?

Biesada & Malec (2002) Phys Rev D, 65
dP/dt: the string mass scale
$M_s \geq 14{,}3$ TeV/c^2 for 6 dimensions
for Kaluza-Klein gravitons.
The limit is negligible for higher dimensions

Variable G?



Asteroseismological bound on $\dot{G}/G$ from pulsating white dwarfs

Omar G. Benvenuto, Enrique García-Berro, and Jordi Isern

PHYSICAL REVIEW D **69**, 082002 (2004)

Why do pulsation periods change?

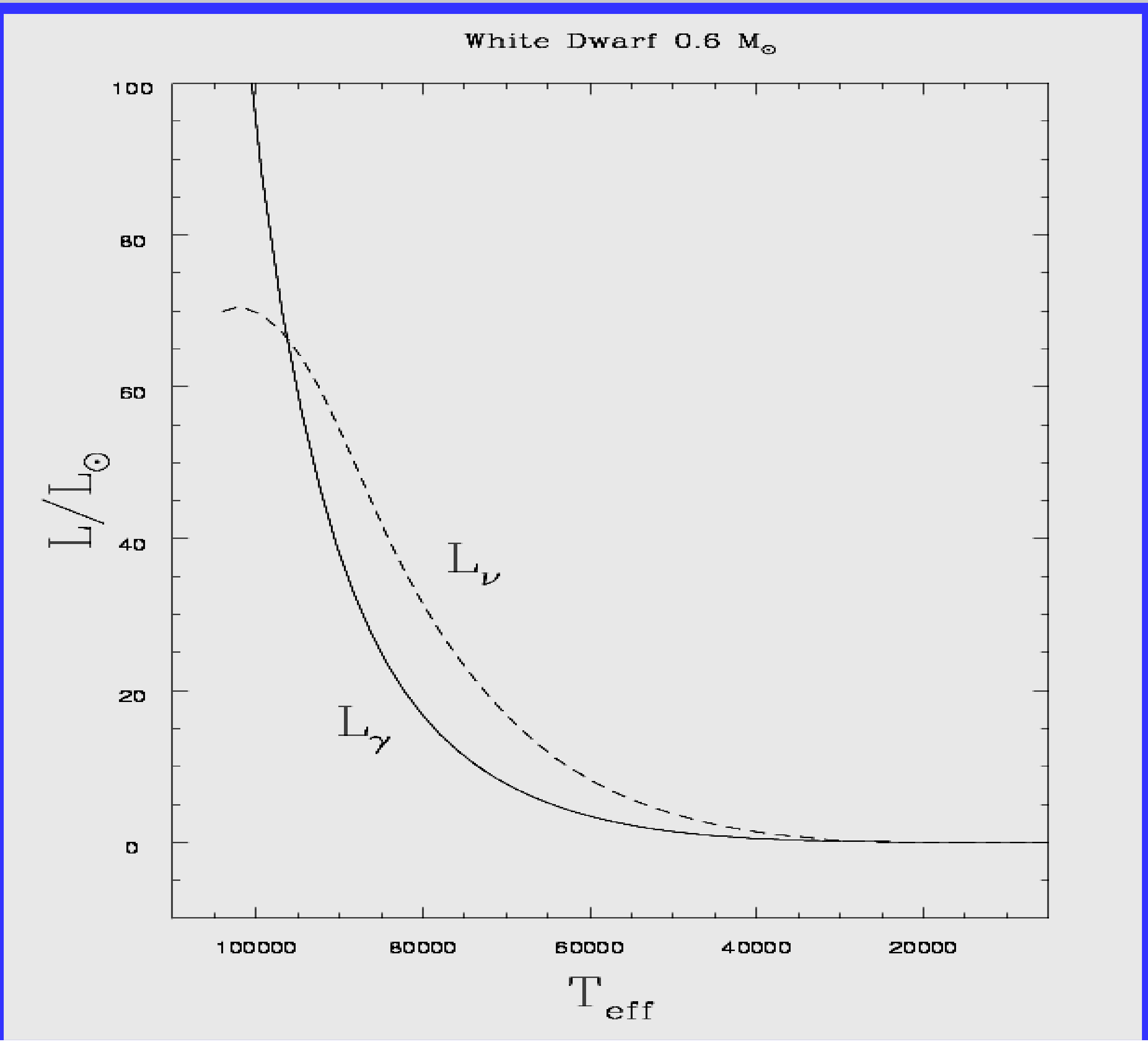
$$\frac{P}{\dot{P}} = -a\frac{T}{\dot{T}} + b\frac{R}{\dot{R}}$$

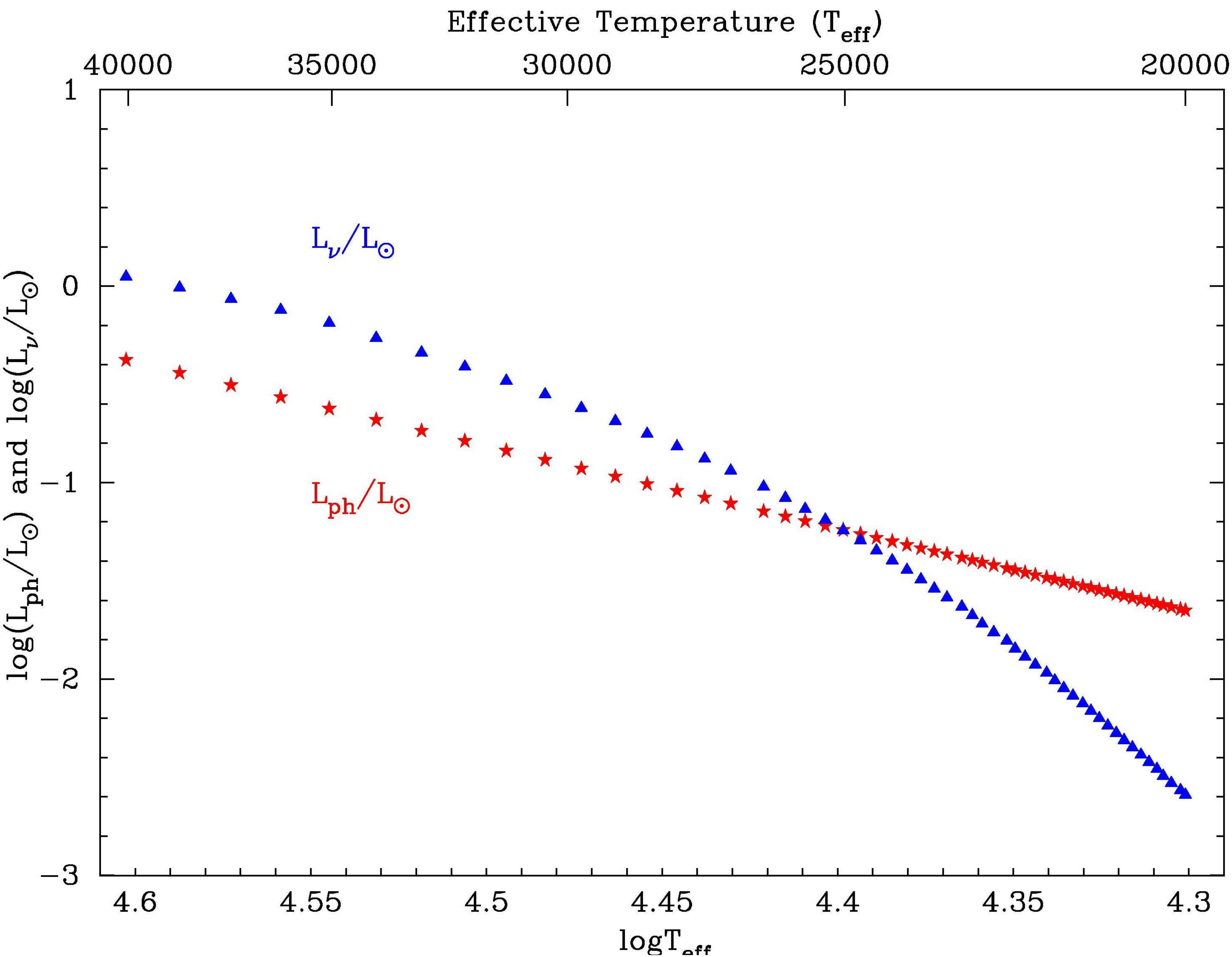
DAV

- $R = 9{,}6 \times 10^8$ cm, dR/dt = 1 cm/yr
- $T_{nucleus}$=12 million K, dT/dt = 0.05 K/year

$$\frac{R}{\dot{R}} = 0{,}025\,\frac{T}{\dot{T}}$$ ➡ **Cooling dominates!**

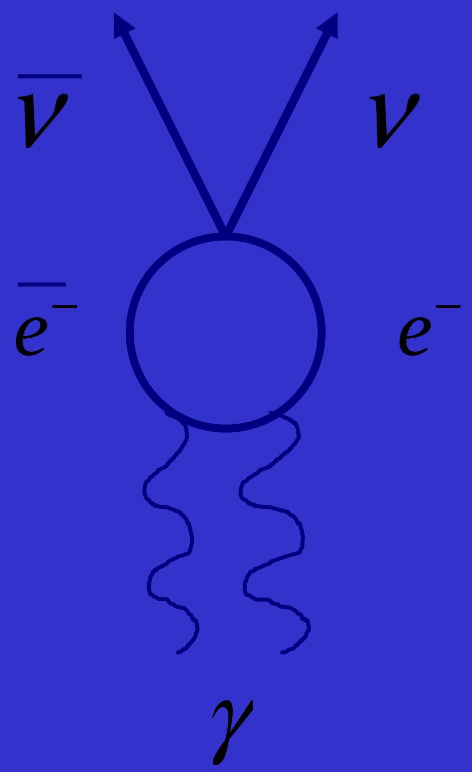
Photon vs neutrino emission





Effective Temperature (T_{eff})
40000
35000
30000
25000
20000
1
0
−1
−2
−3
$L_\nu/L_\odot$
$L_{ph}/L_\odot$
$\log(L_{ph}/L_\odot)$ and $\log(L_\nu/L_\odot)$
4.6
4.55
4.5
4.45
4.4
4.35
4.3
$\log T_{eff}$

The Feynman diagram



Plasma neutrino (Weak interaction)

$$\hbar^2 w^2 = \hbar^2 w_p^2 + k^2 c^2$$

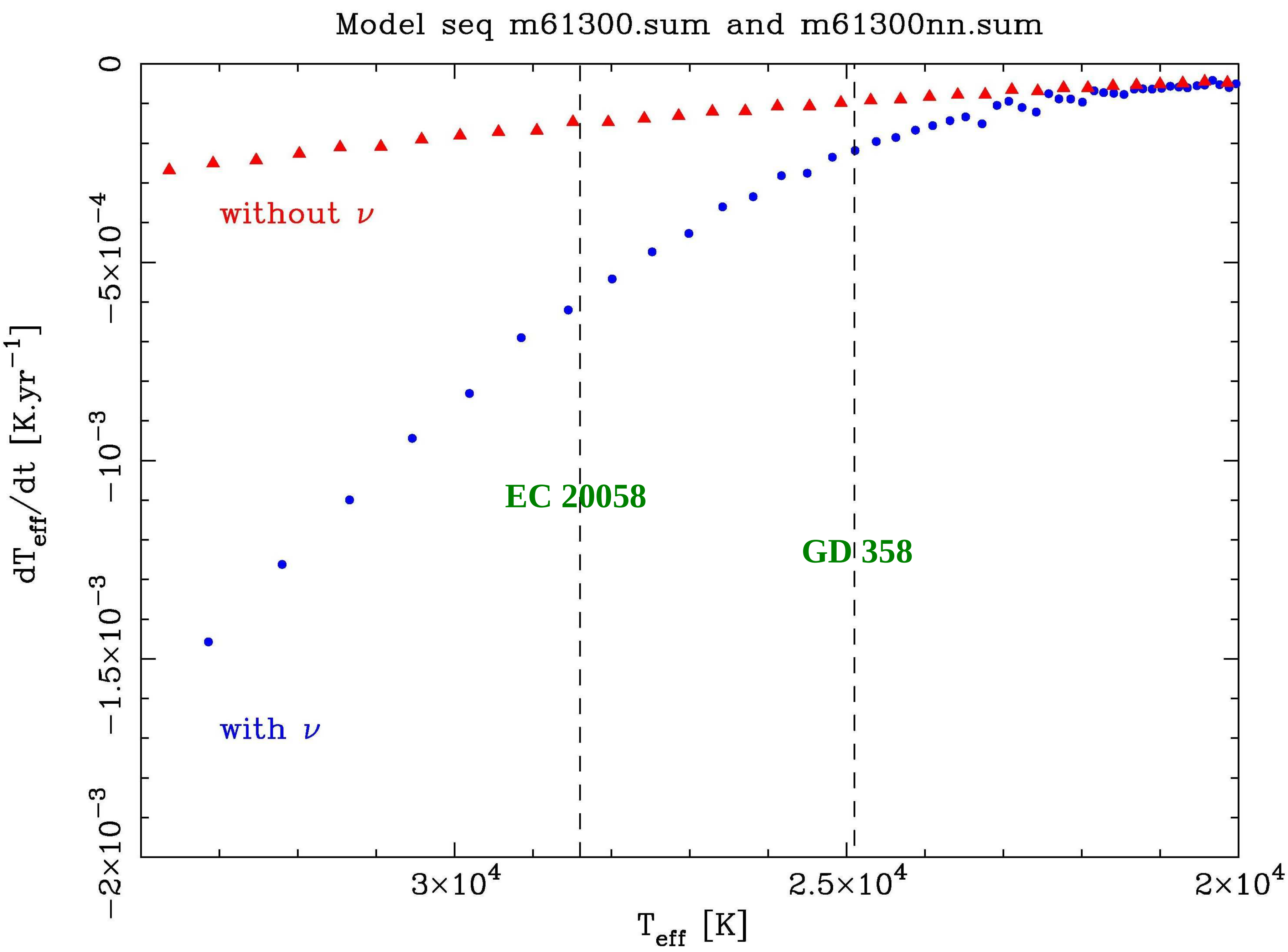
$$w_p^2 = \frac{4\pi n_e e^2}{m_e}\left[1 + \left(\frac{\hbar}{m_e c}\right)^2 \left(3\pi^2 n_e\right)^{2/3}\right]^{-\frac{1}{2}}$$

Two keys…

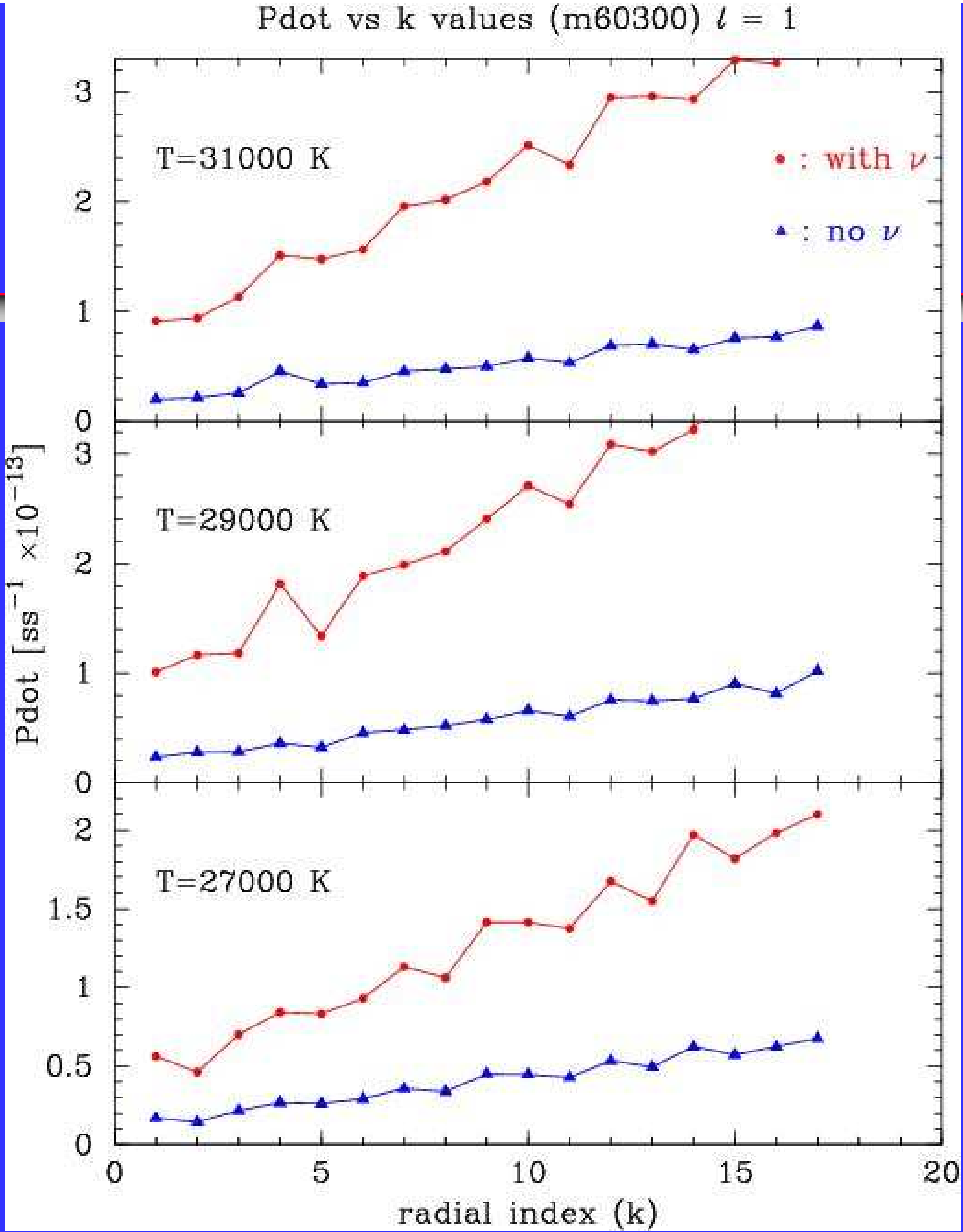
- *To excite the plasmon we must have*

$$\hbar\omega_o \leq kT$$

- *The plasma frequency is much higher for a degenerate gas, and increases with increasing density…*

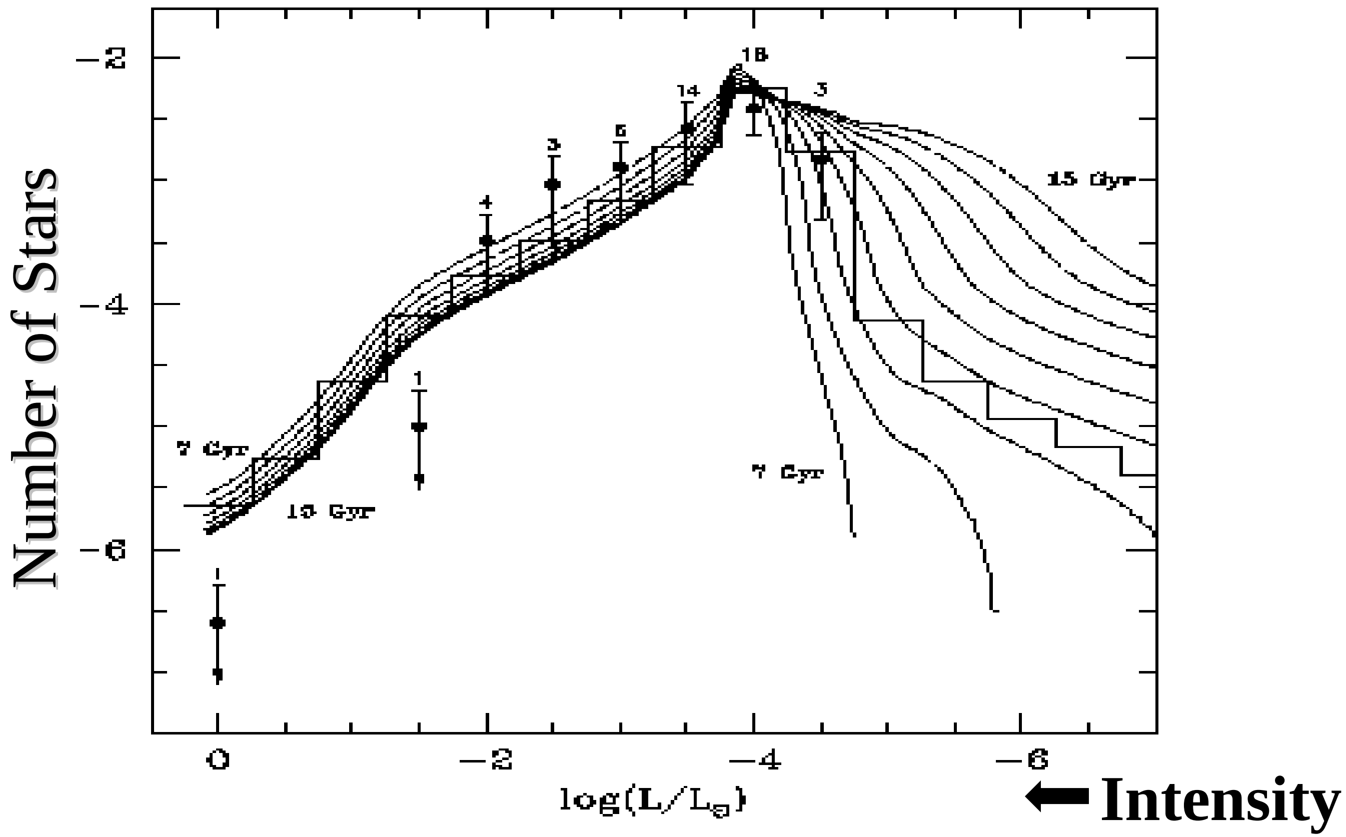


Model seq m61300.sum and m61300nn.sum
without ν
with ν
EC 20058
GD 358
0
−5×10⁻⁴
−10⁻³
−1.5×10⁻³
−2×10⁻³
3×10⁴
2.5×10⁴
2×10⁴
dT_eff/dt [K.yr⁻¹]
T_eff [K]



DBVs: dP/dt and Plasmon Neutrinos: 3-4!

Luminosity Function and Age of the Galaxy



Age of the disk: 9 ± 2 yr

Age of the Universe

Age of Universe =

Age of disk + Halo + Formation of galaxy

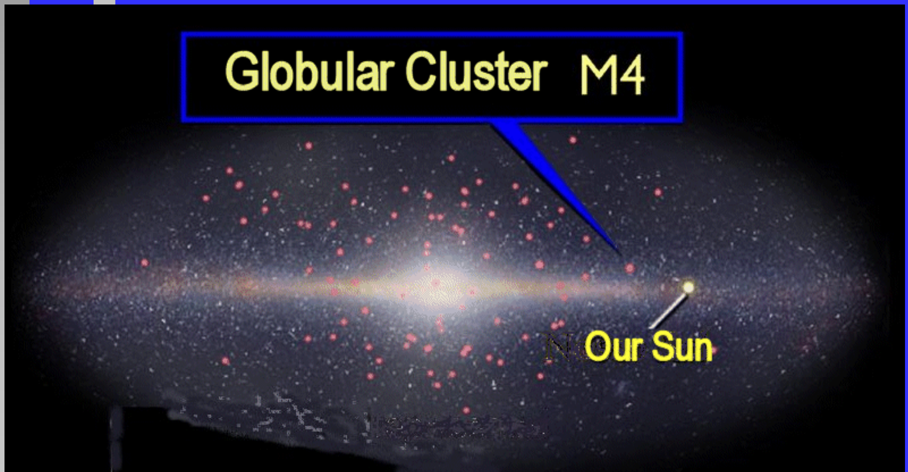
9 ± 2 1,5 ± 1,5 1 ± 1 billion yr

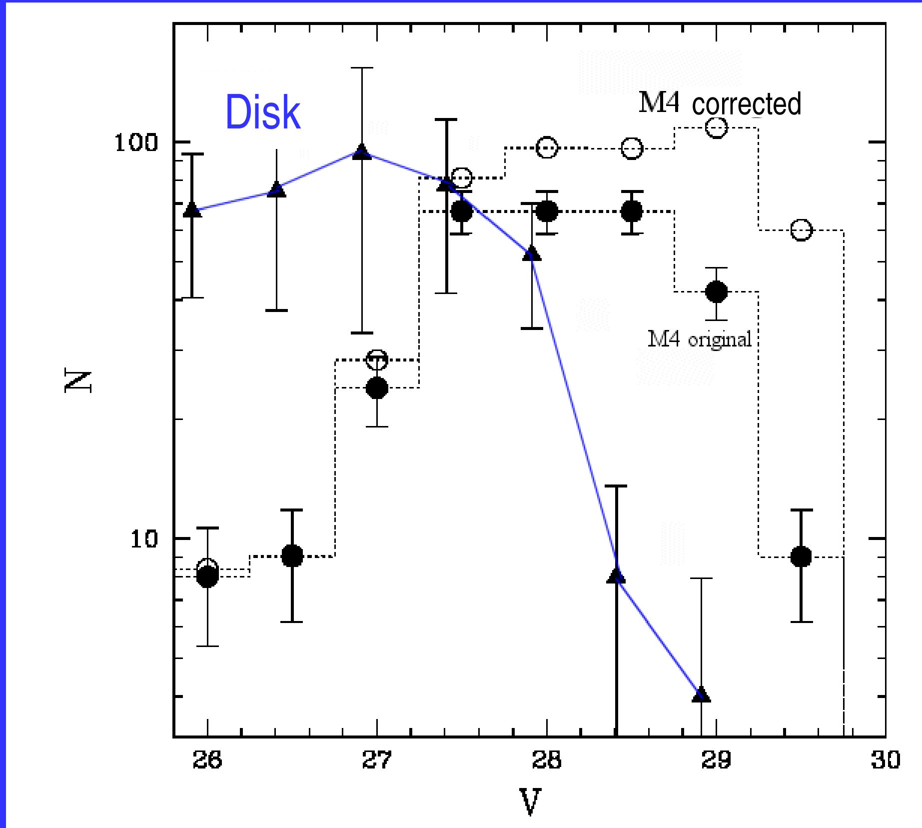
Age = (11,5 ± 2,7) billion years

HST: Galaxies formed 1 Gyr after Big-Bang

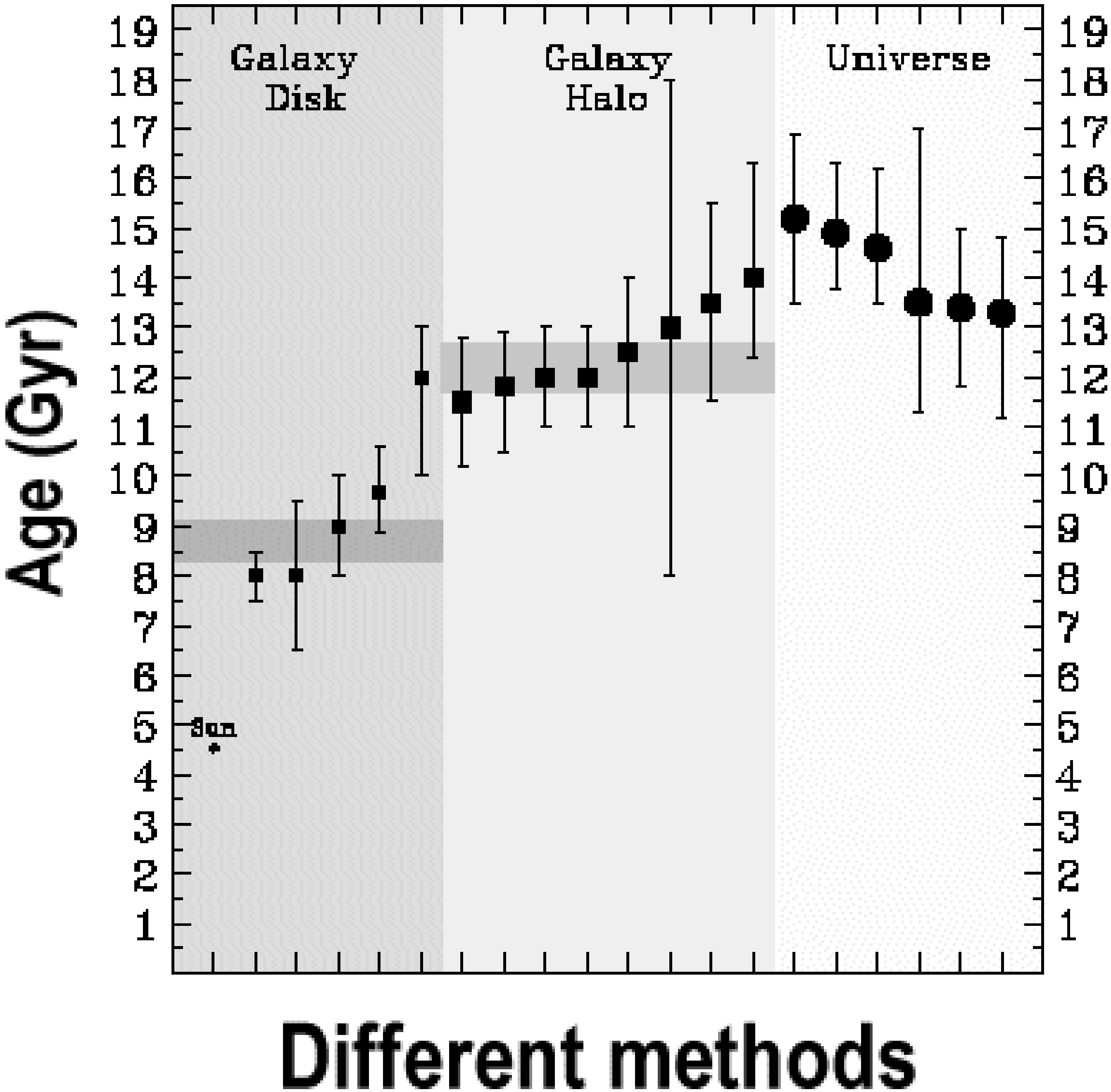
White dwarfs in globular cluster M4

2002 – 8 days of exposure with HST
Age= 12.7± 0.7 Gyr





we will do other globulars with SOAR

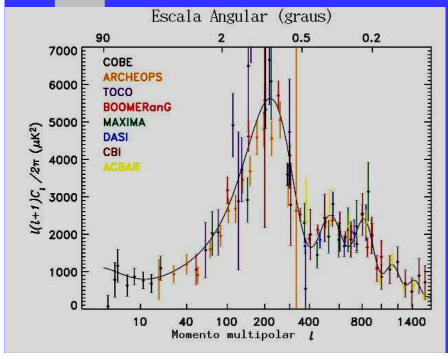


Galaxy Disk
Galaxy Halo
Universe
Age (Gyr)
Sun
Different methods

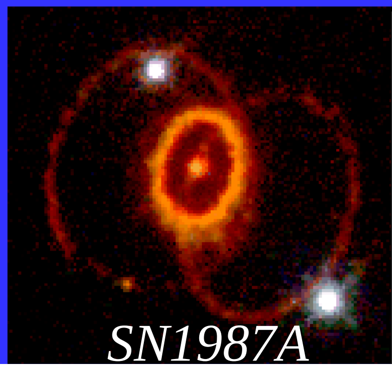
Age of the Universe in 2004

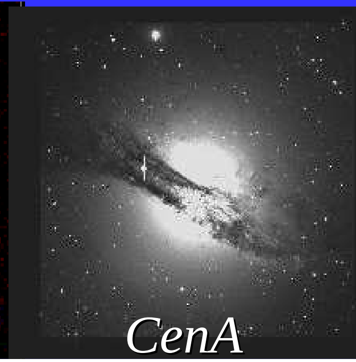
10 years ago only white dwarfs gave age smaller than 15 billion years:

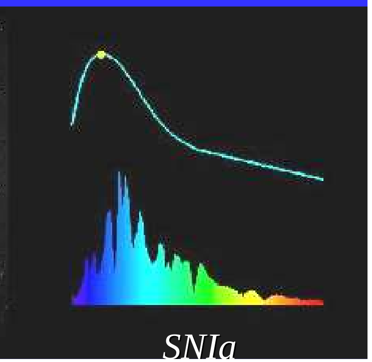
- *CMB - WMAP =* *(13.7±0.2) Gyr*
- *Hubble constant: 1/H =* *(12 ± 1) Gyr*
- *Globular clusters:* *(13.2 ± 1.5) Gyr*
- *Radiactive decay:* *(12.5 ± 3) Gyr*
- *Cooling of white dwarf stars:* *(12.7 ± 0.7) Gyr*
- *Distances to SNIa:* *14.9± 1.4 (0.63/h)Gyr,* Λ



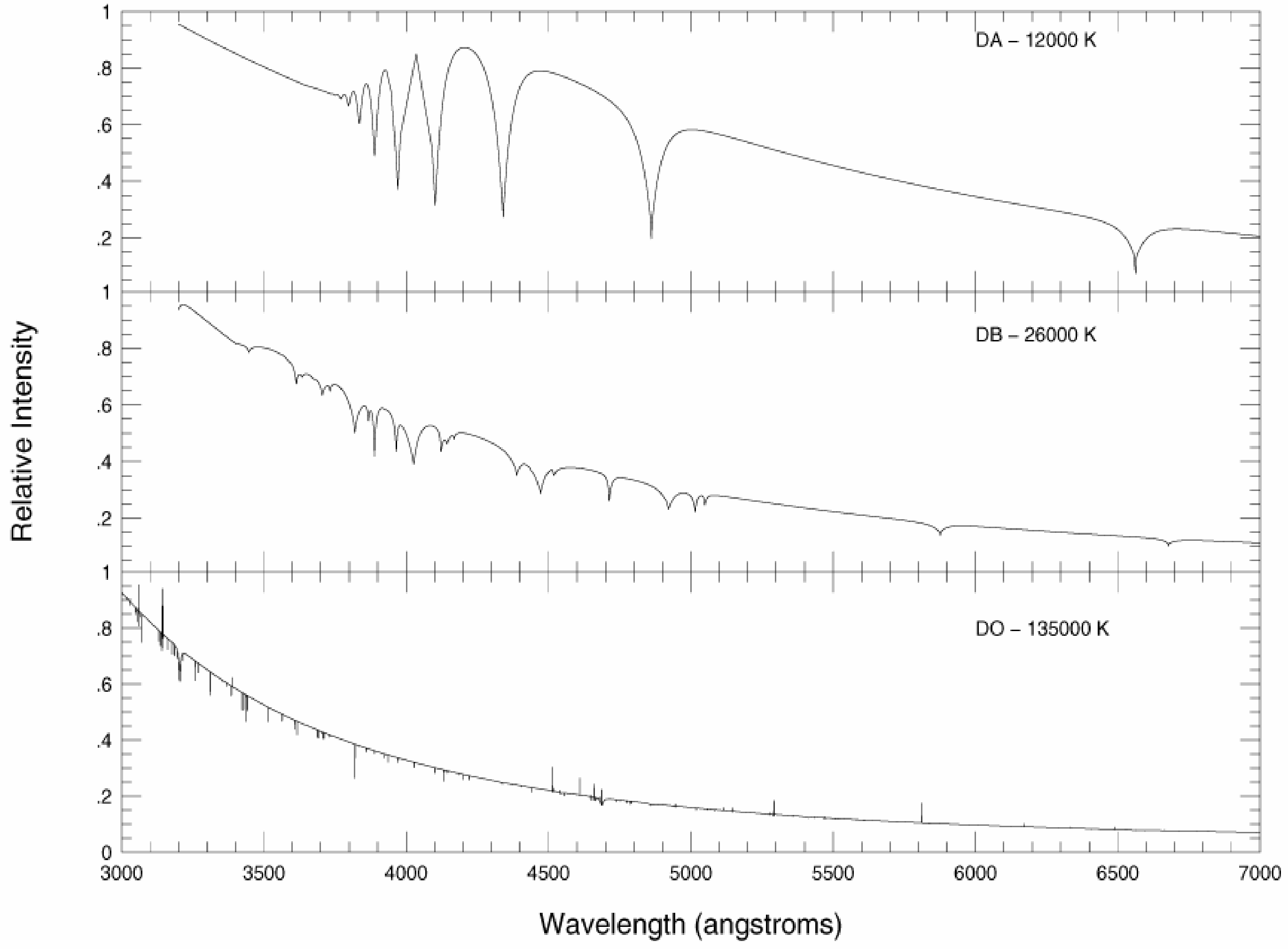

NGC6903


SN1987A

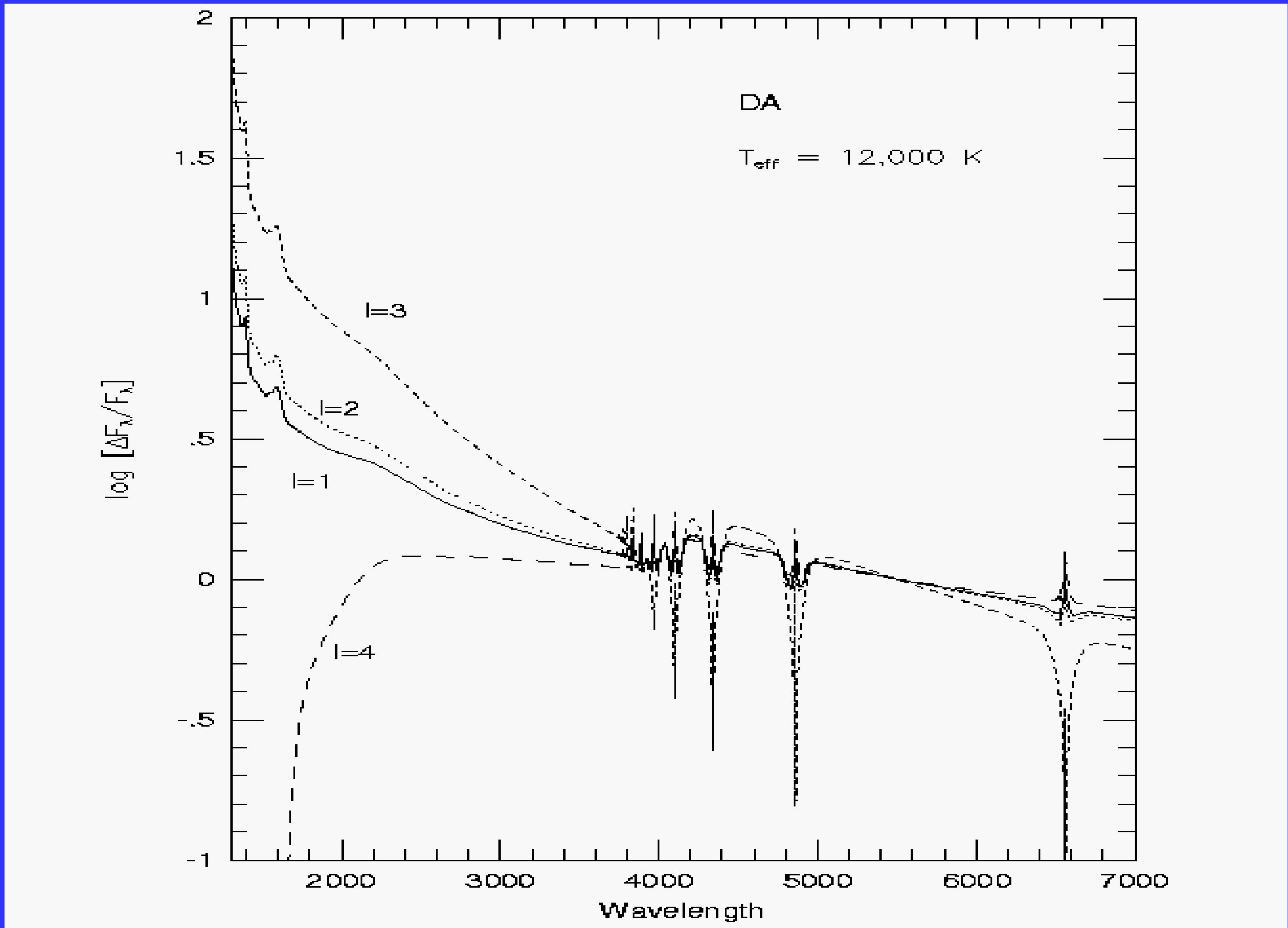

CenA


SNIa

Spectra of DA, DB and DO

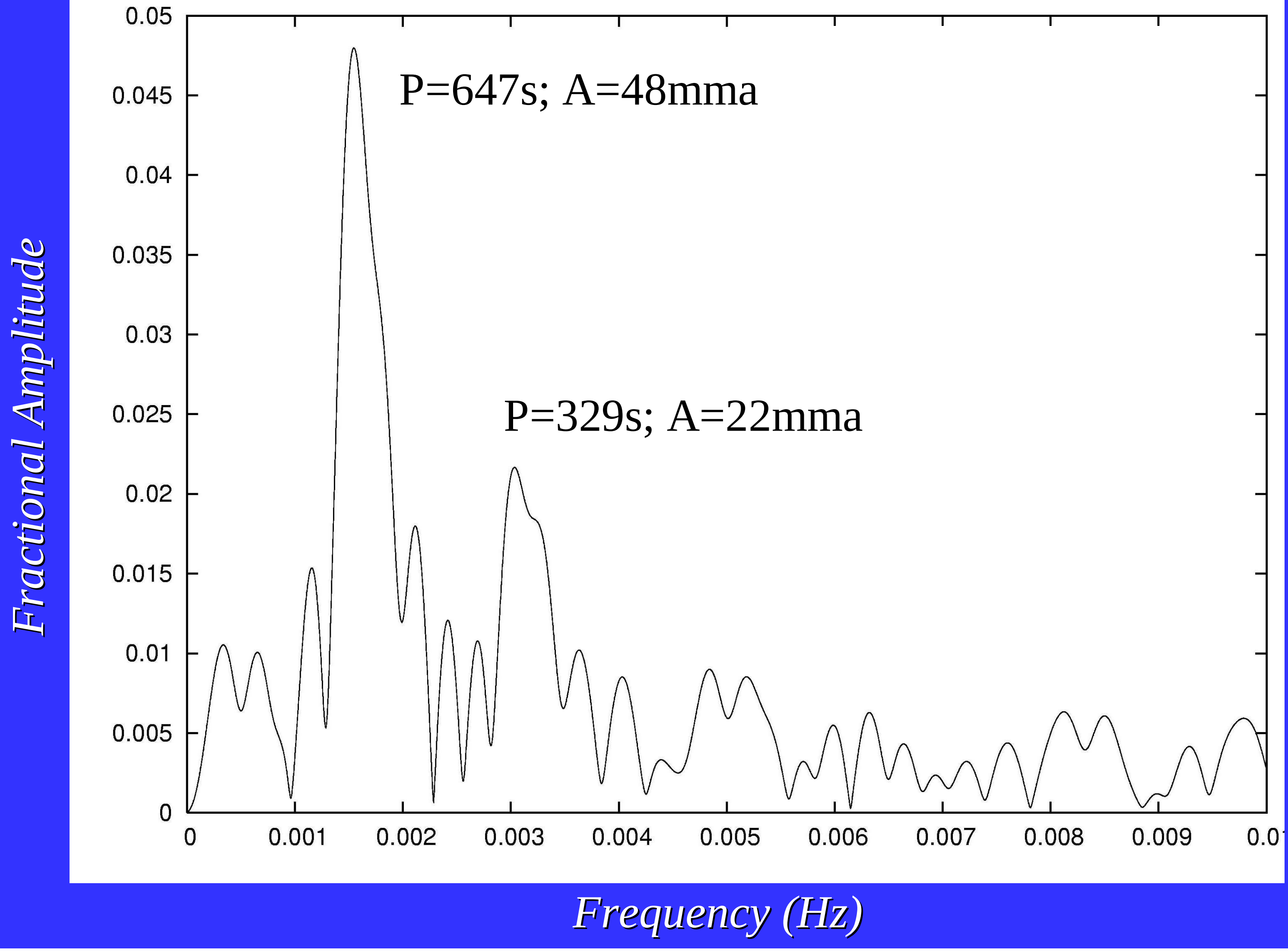


Mode identification with SOAR

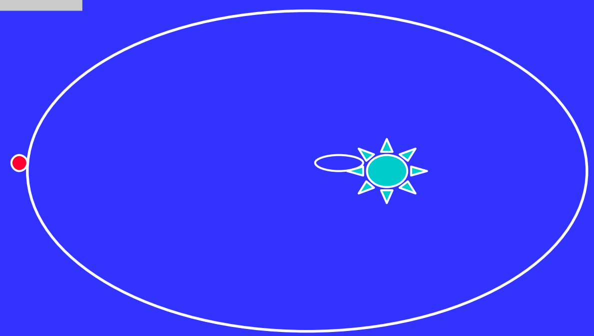


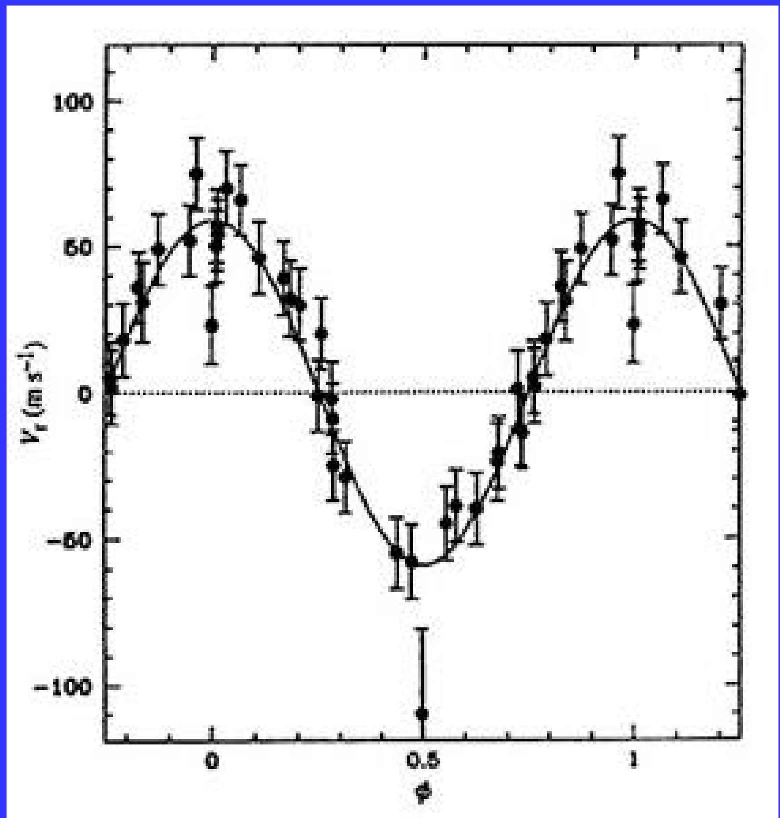
Find more variables

(V=18.6)



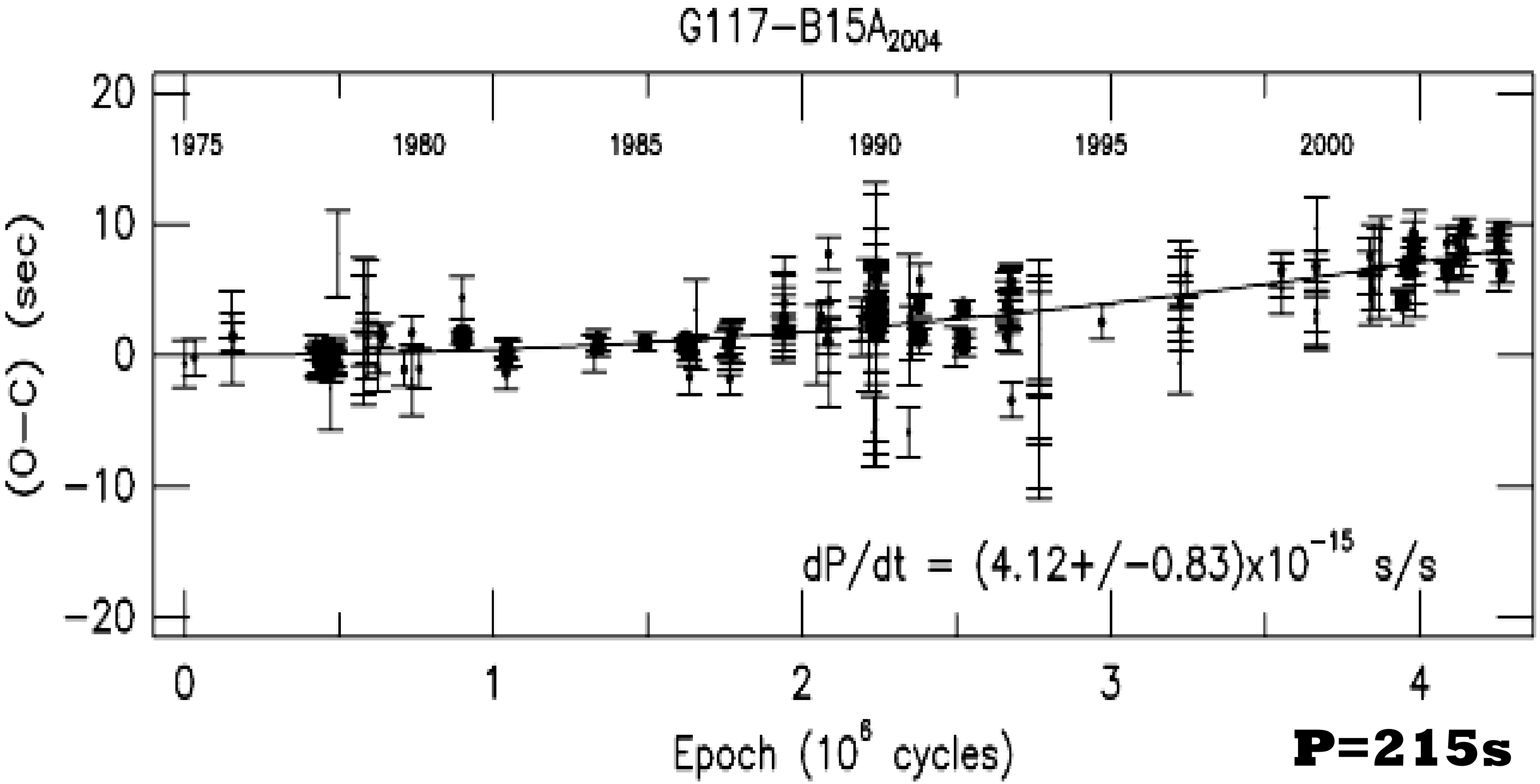
Detection of extra-solar planets





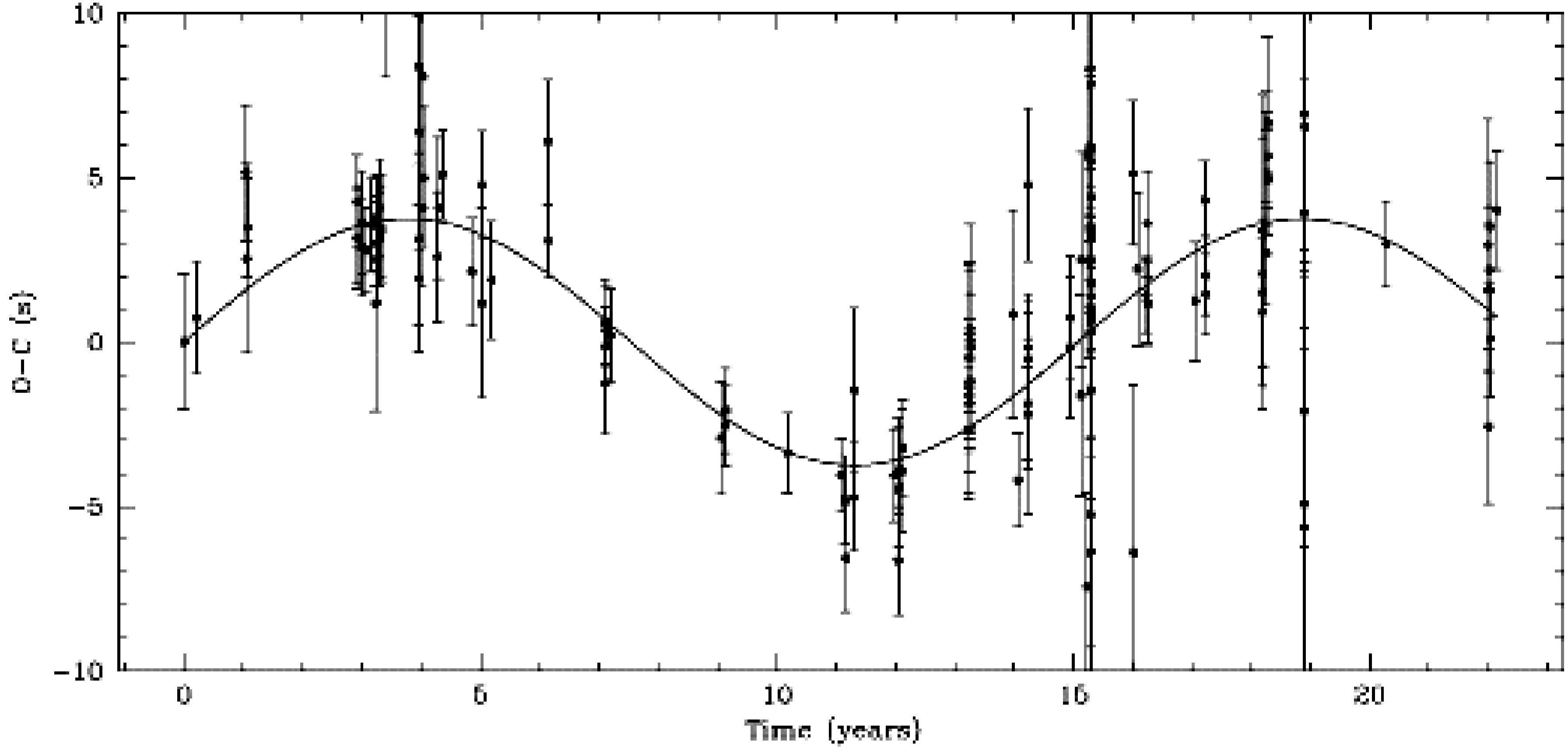
Spectroscopy: detection of radial velocity variation around the center of mass

G117-B15A 2004



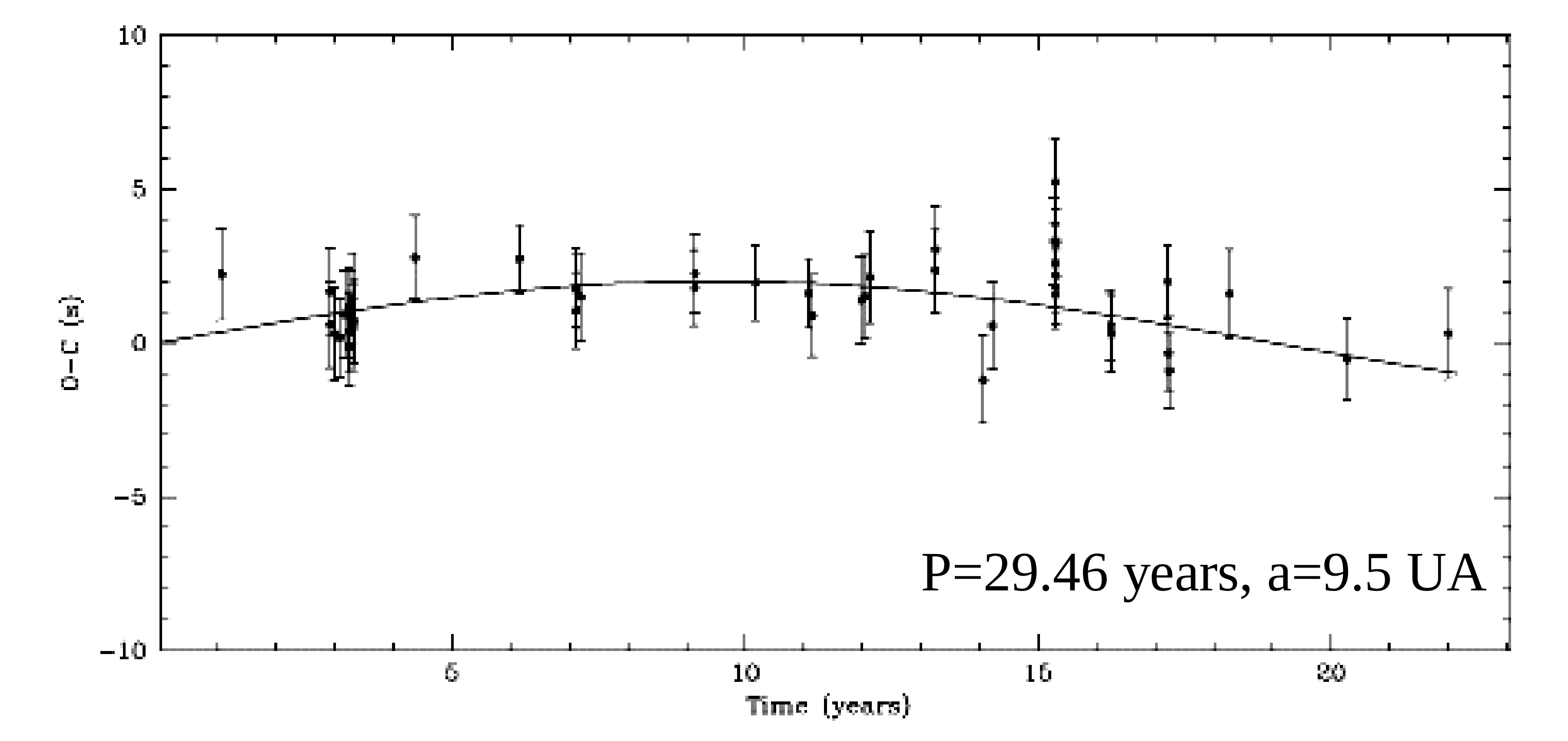
P=215s

Jupiter around G117-B15A?



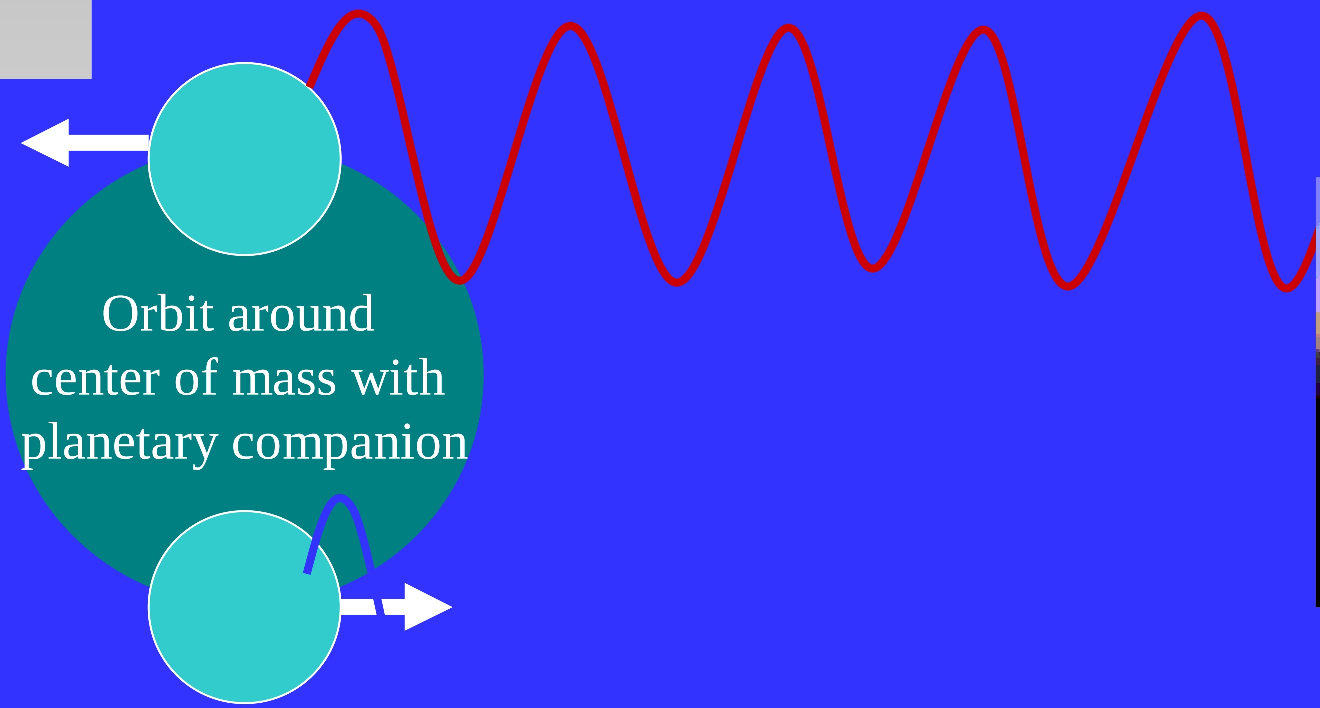
P=11.86 years, a=5.2 UA

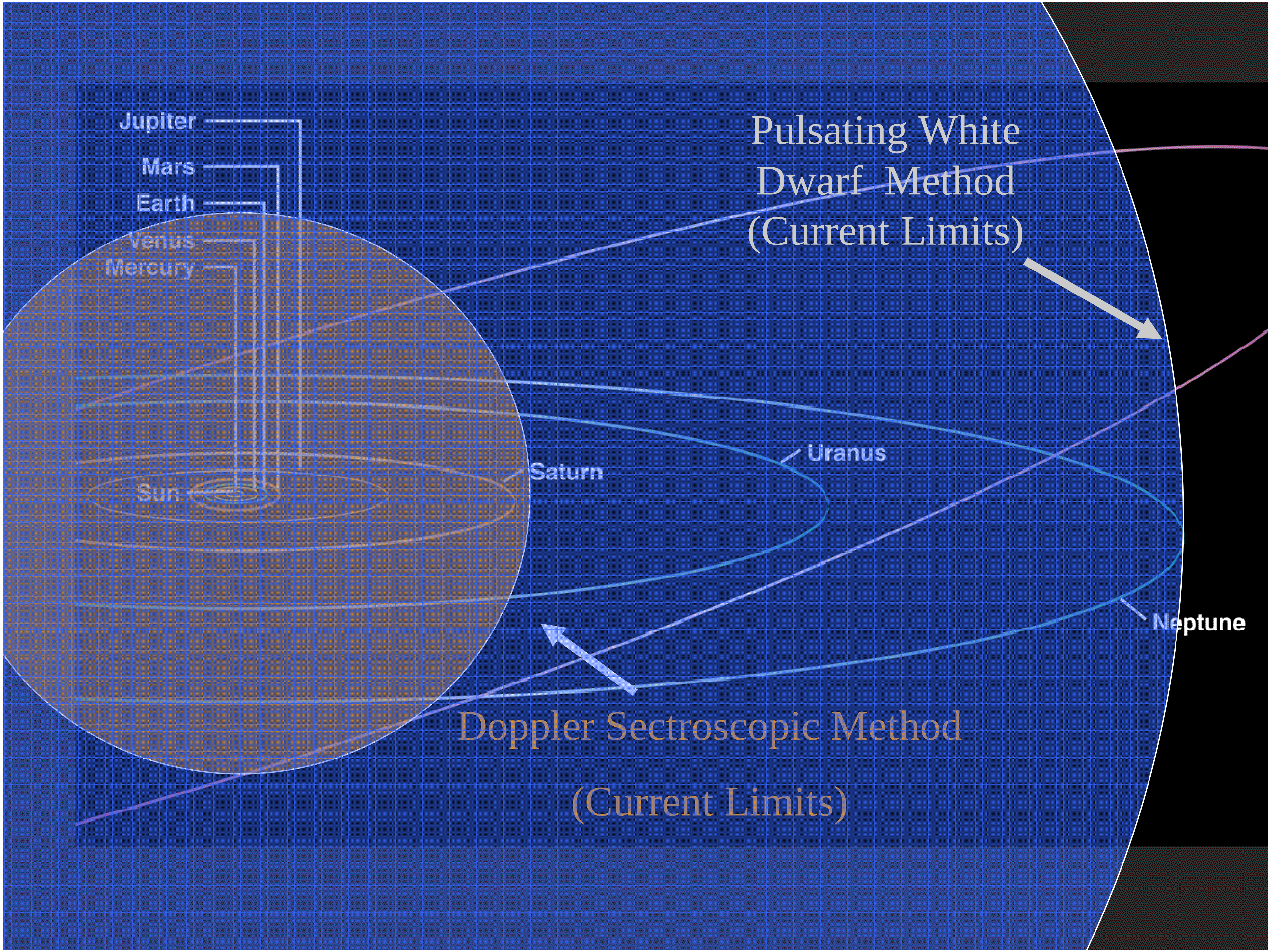
Saturn around?



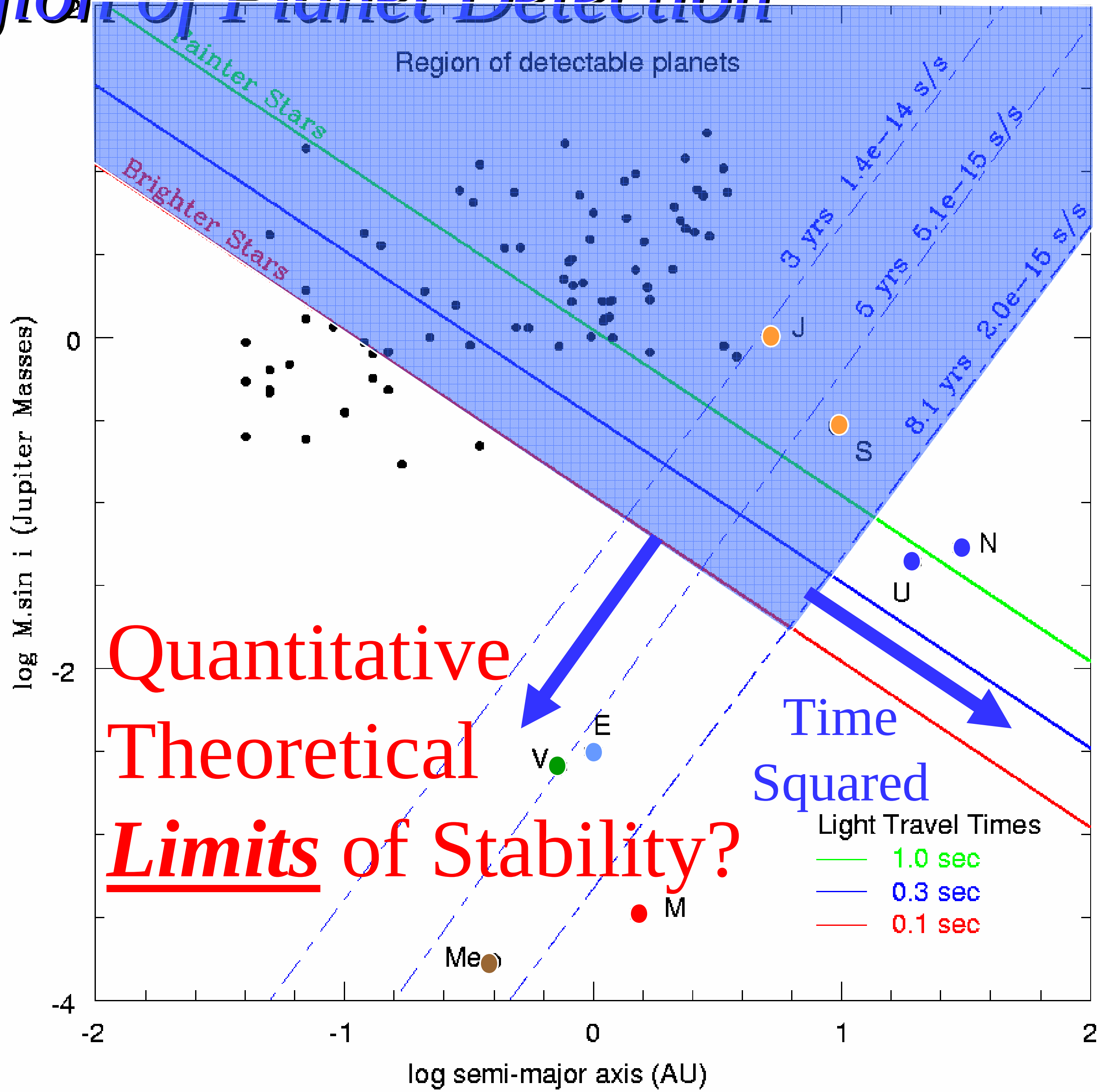
Search for planetary companions

monitoring changes in pulse arrival time due to motion of star around barycenter.

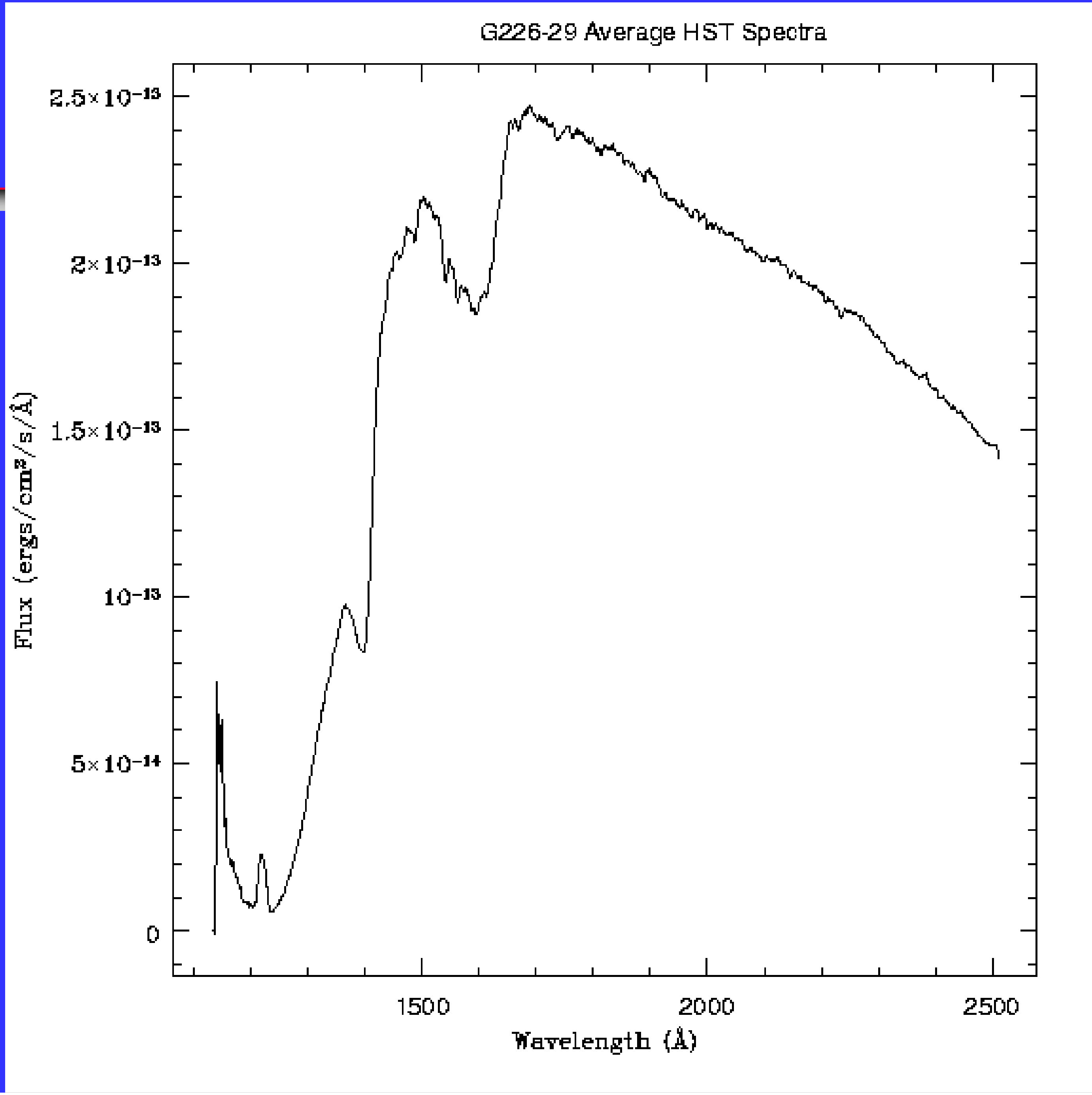



Jupiter
Mars
Earth
Venus
Mercury
Sun
Saturn
Uranus
Neptune
Pulsating White Dwarf Method (Current Limits)
Doppler Sectroscopic Method
(Current Limits)

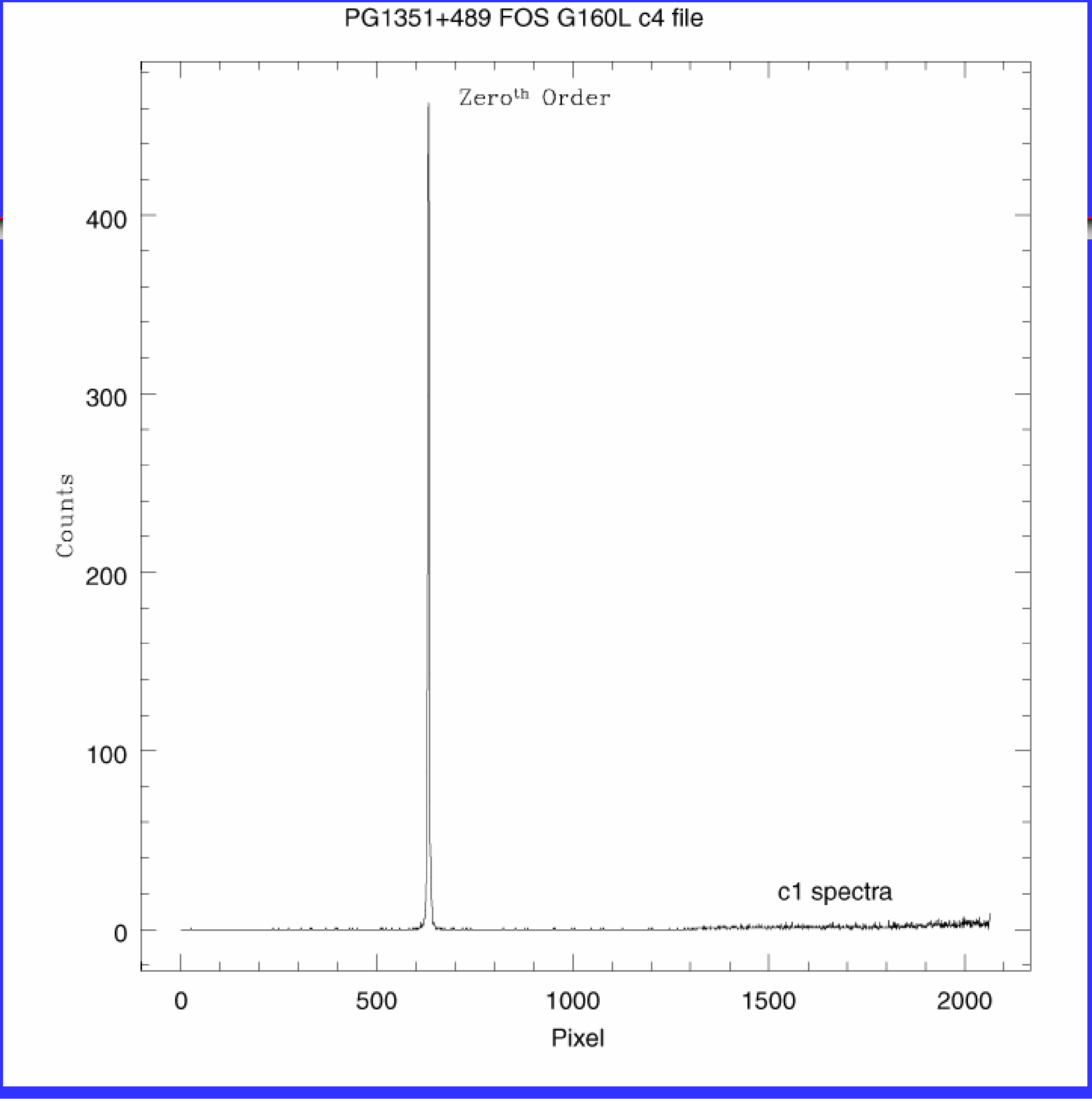
Region of Planet Detection



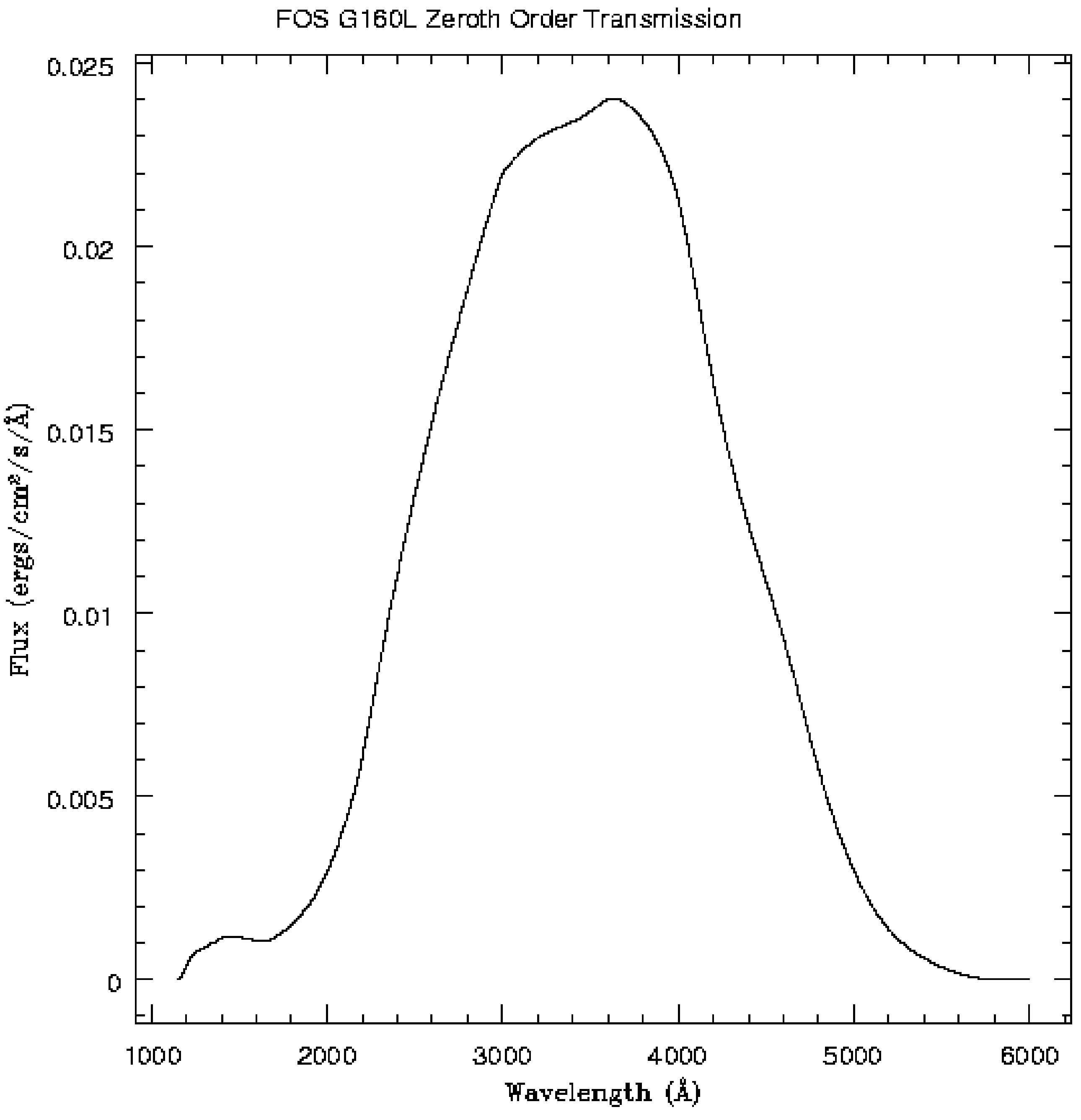
Quantitative Theoretical ***Limits*** of Stability?



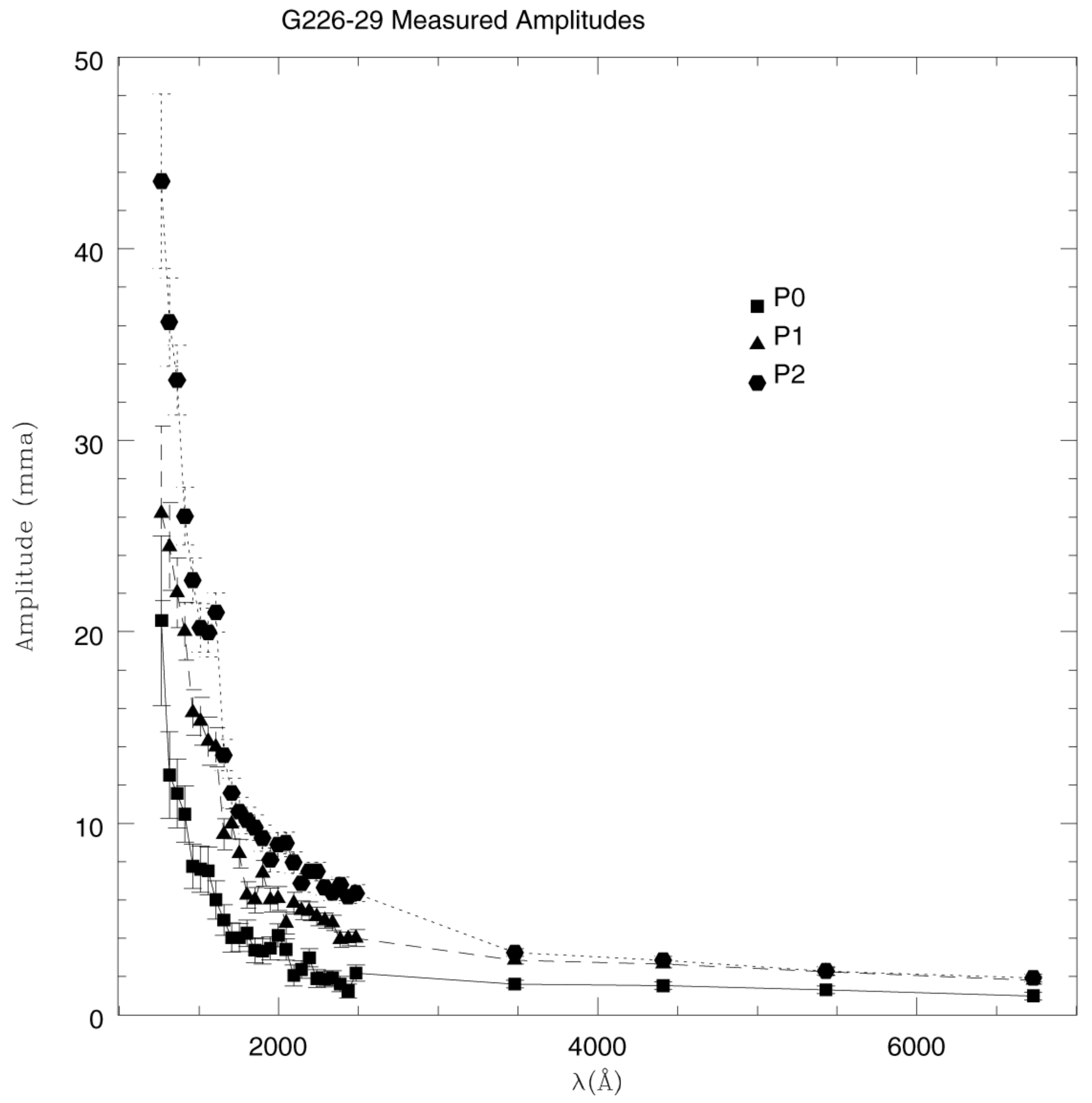
G226-29 Average HST Spectra
2.5×10⁻¹³
2×10⁻¹³
1.5×10⁻¹³
10⁻¹³
5×10⁻¹⁴
0
Flux (ergs/cm²/s/Å)
1500
2000
2500
Wavelength (Å)

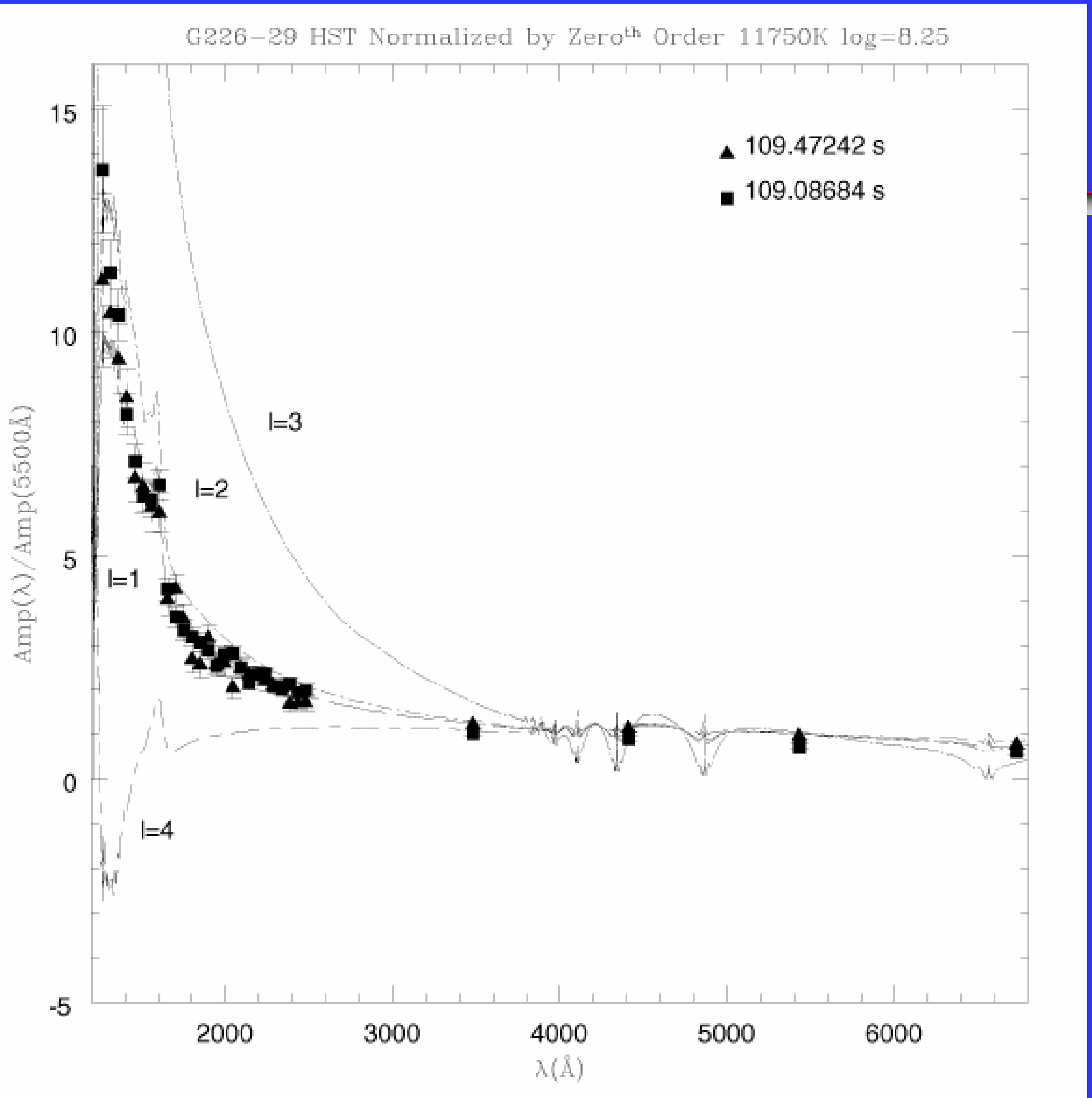


PG1351+489 FOS G160L c4 file
Zeroth Order
c1 spectra
Counts
Pixel
0
100
200
300
400
0
500
1000
1500
2000

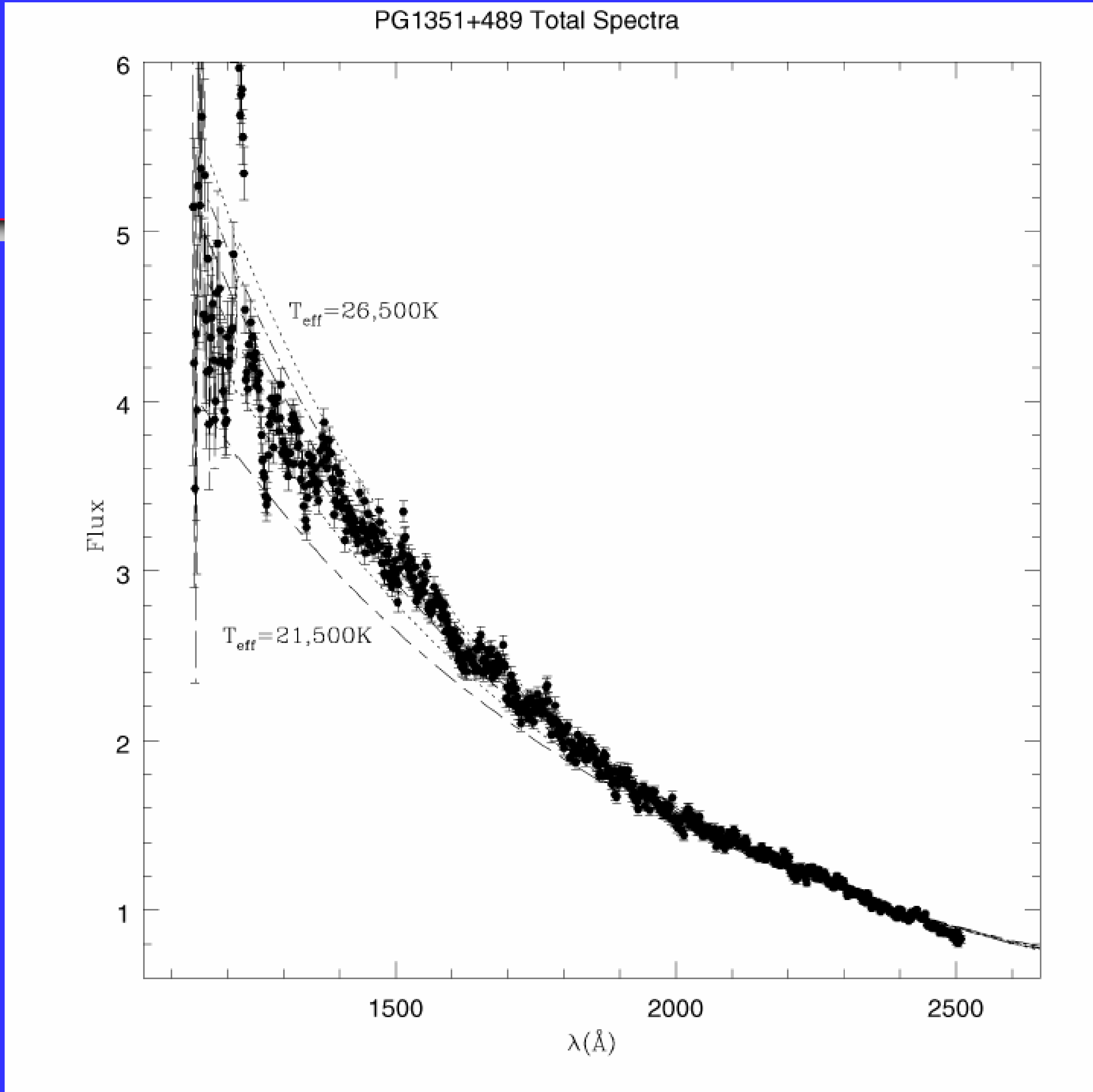


FOS G160L Zeroth Order Transmission
Flux (ergs/cm²/s/Å)
0.025
0.02
0.015
0.01
0.005
0
1000
2000
3000
4000
5000
6000
Wavelength (Å)

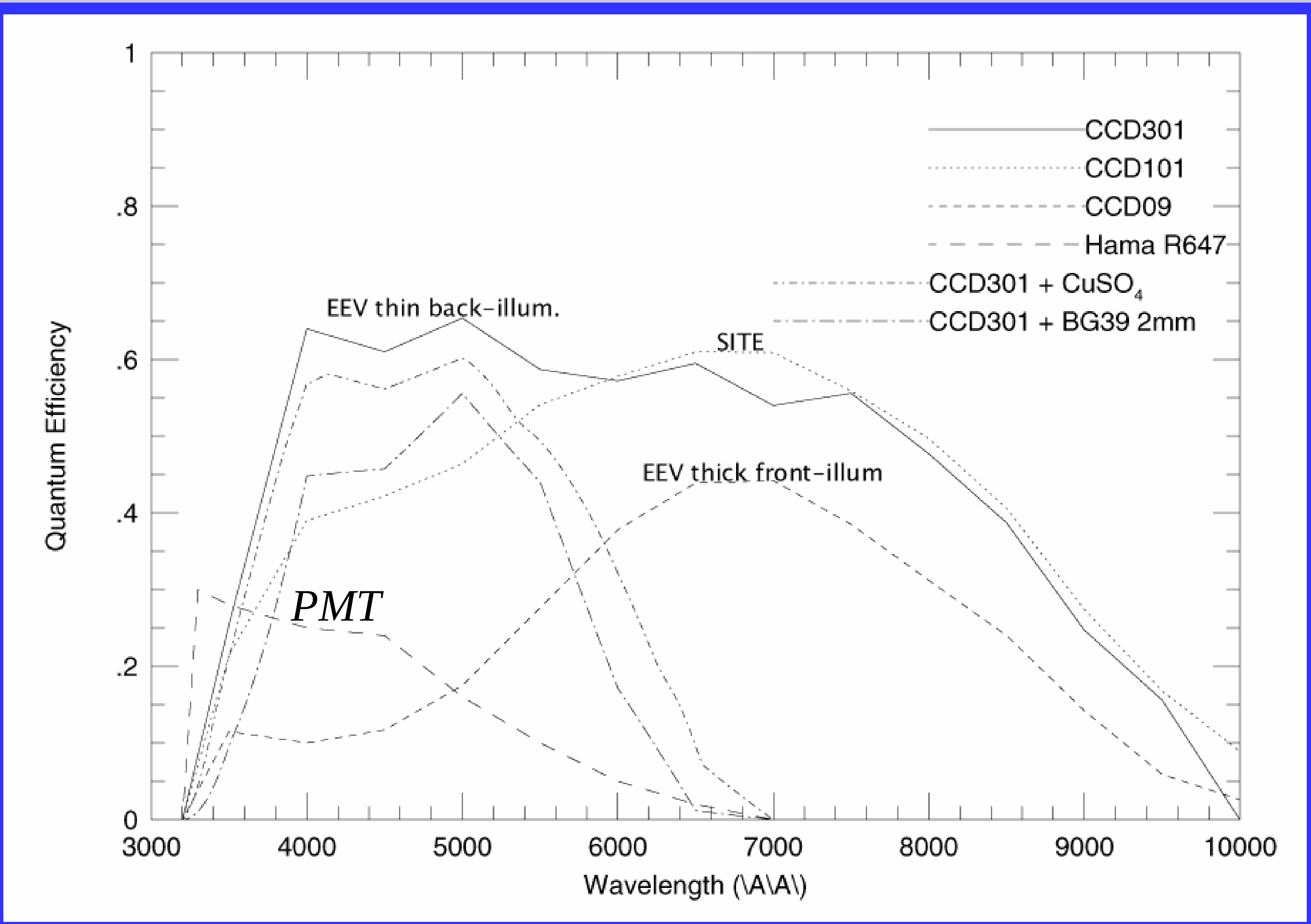

G226-29 Measured Amplitudes
Amplitude (mma)
λ(Å)
P0
P1
P2
0
10
20
30
40
50
2000
4000
6000



G226-29 HST Normalized by Zeroth Order 11750K log=8.25
109.47242 s
109.08684 s
l=3
l=2
l=1
l=4
Amp(λ)/Amp(5500Å)
λ(Å)
15
10
5
0
-5
2000
3000
4000
5000
6000

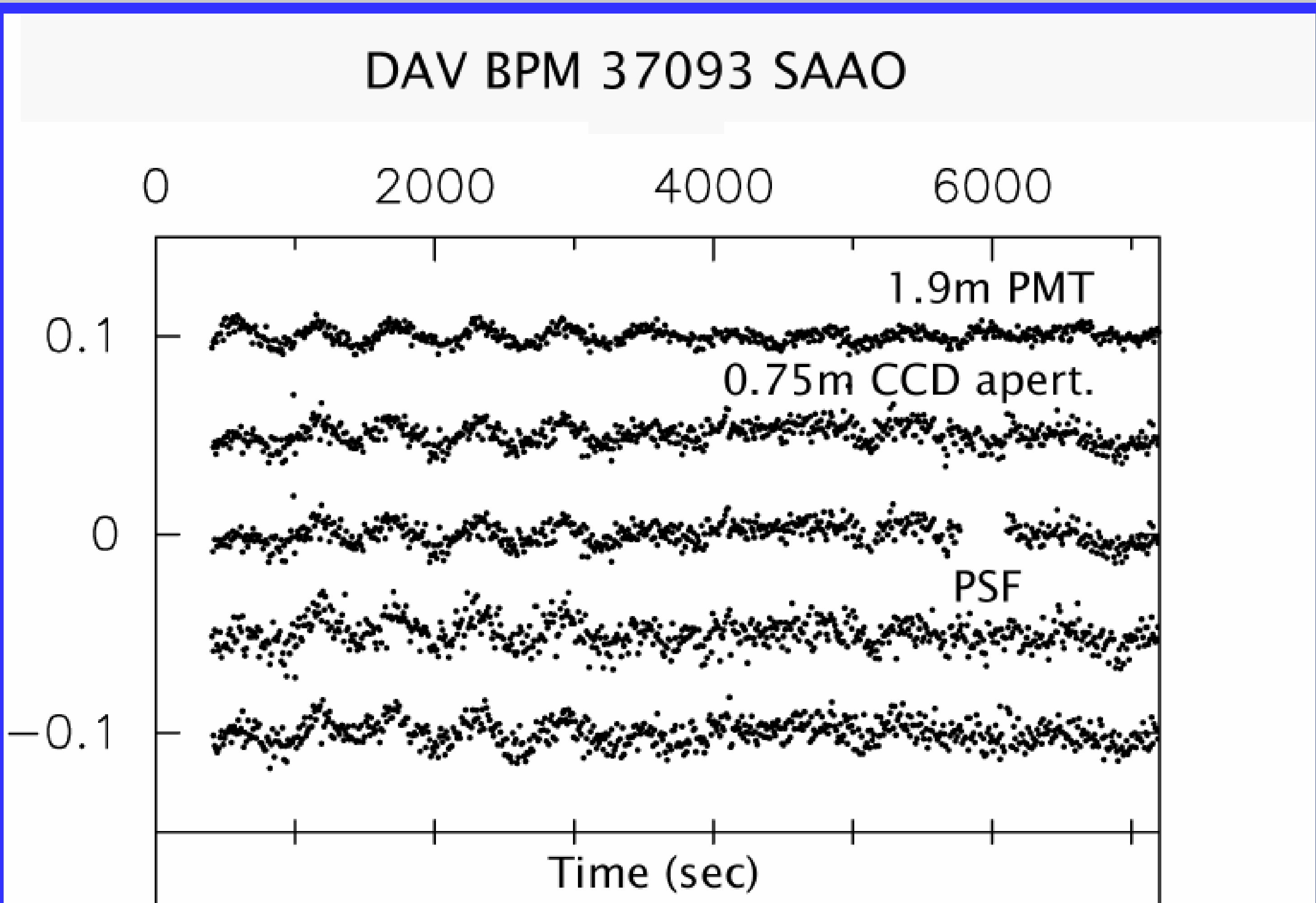

PG1351+489 Total Spectra
Flux
λ(Å)
T_eff=26,500K
T_eff=21,500K
1
2
3
4
5
6
1500
2000
2500

CCD vs PMT



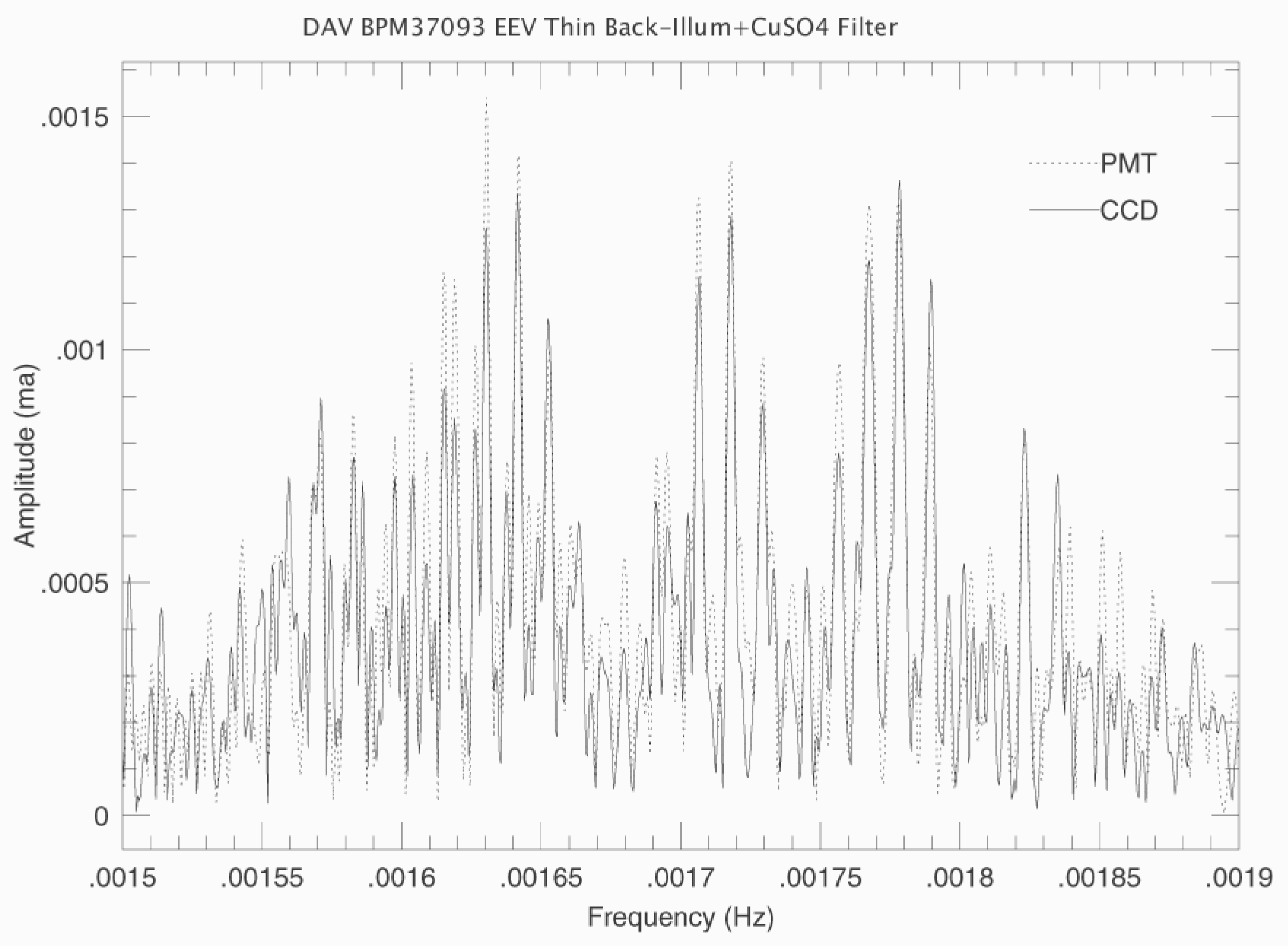
CCD301
CCD101
CCD09
Hama R647
CCD301 + CuSO4
CCD301 + BG39 2mm
EEV thin back-illum.
SITE
EEV thick front-illum
PMT
Quantum Efficiency
Wavelength (\A\A\)
0
.2
.4
.6
.8
1
3000
4000
5000
6000
7000
8000
9000
10000

CCD vs PMT



DAV BPM 37093 SAAO
0
2000
4000
6000
1.9m PMT
0.75m CCD apert.
PSF
0.1
0
−0.1
Time (sec)

Measured Amplitude Difference



Change in Amplitudes

Temperature Flux | Difference in Amp

DAV

CCD	11500	12000	Rel/PMT	12500	Amplitude	% Rel/PMT
FI	1.417e+18	1.528e+18	1.29	1.623e+18	0.134	-20.85
TBI2	2.964e+18	3.215e+18	2.71	3.427e+18	0.143	-15.27
TBI	3.544e+18	3.856e+18	3.26	4.117e+18	0.148	-12.43
TBI + BG39	1.838e+18	2.015e+18	1.70	2.163e+18	0.161	-4.86
TBI + $CuSO_4$	2.406e+18	2.638e+18	2.23	2.832e+18	0.161	-4.90
PMT	1.074e+18	1.182e+18	1.00	1.275e+18	0.169	0.00

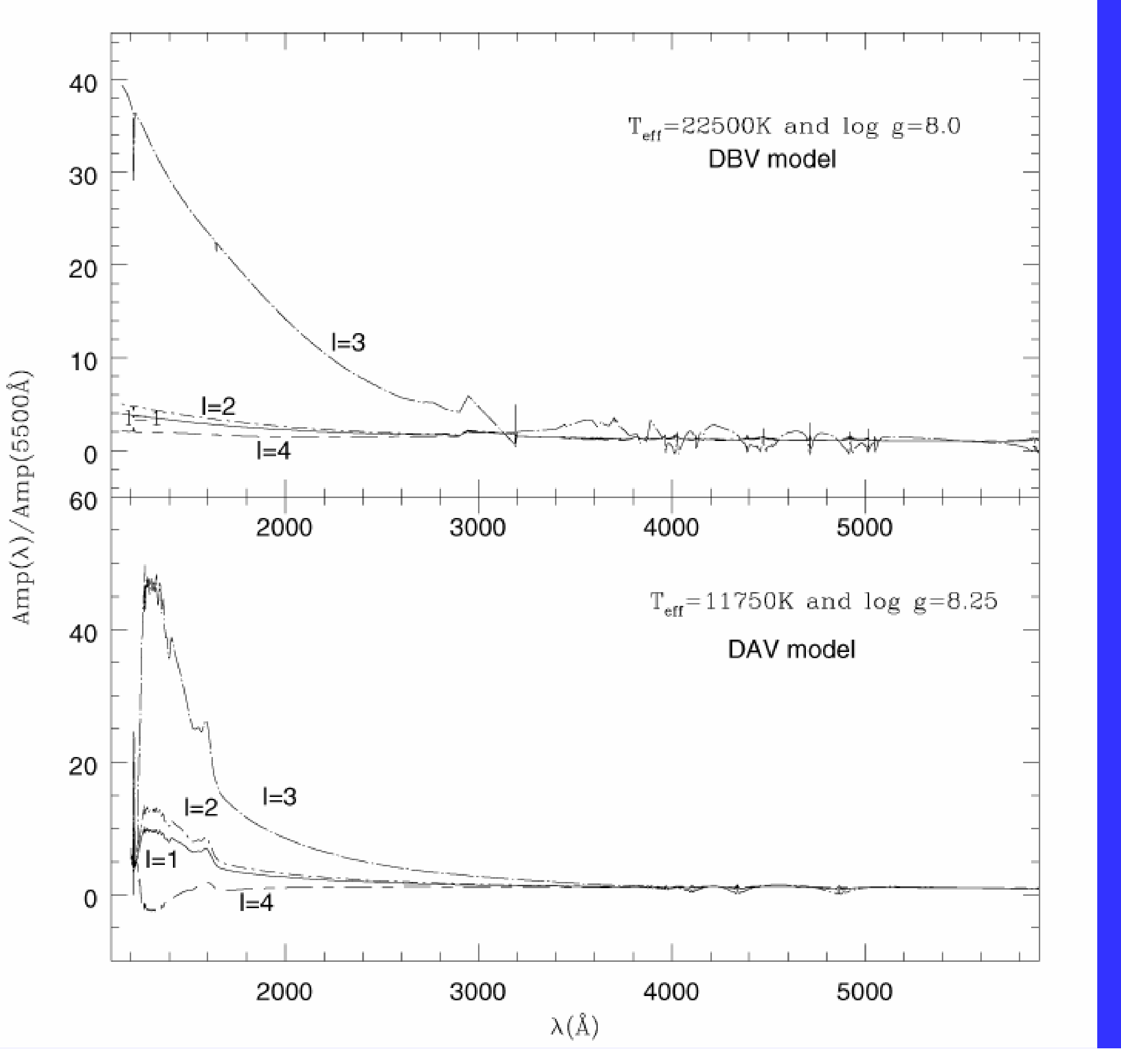
DBV

CCD	25500	26000	Rel/PMT	26500	Amplitude	% Rel/PMT
FI	1.128e+19	1.155e+19	0.901	1.183e+19	0.0477	-14.57
TBI2	2.541e+19	2.606e+19	2.032	2.671e+19	0.0497	-10.99
TBI	3.130e+19	3.210e+19	2.503	3.291e+19	0.0503	-9.95
TBI + BG39	1.706e+19	1.752e+19	1.366	1.797e+19	0.0516	-7.60
TBI + $CuSO_4$	2.312e+19	2.374e+19	1.851	2.436e+19	0.0522	-6.56
PMT	1.246e+19	1.282e+19	1.000	1.318e+19	0.0559	0.00

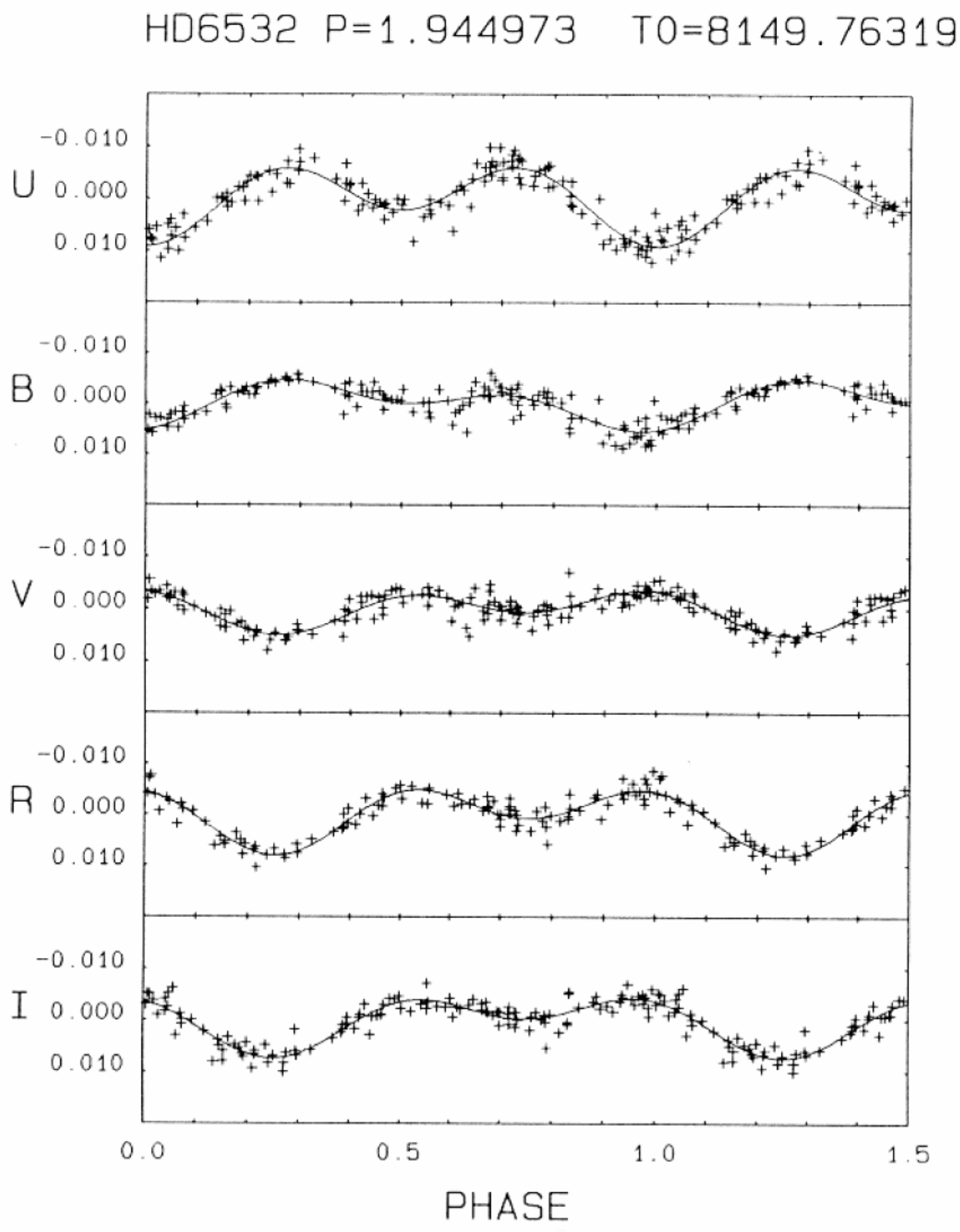
DOV

CCD	130000	135000	Rel/PMT	140000	Amplitude	% Rel/PMT
FI	1.068e+21	1.132e+21	0.743	1.181e+21	0.100161	-0.719
TBI2	2.720e+21	2.883e+21	1.893	3.010e+21	0.100483	-0.400
TBI	3.153e+21	3.342e+21	2.195	3.488e+21	0.100374	-0.508
TBI + BG39	1.761e+21	1.867e+21	1.226	1.949e+21	0.100471	-0.412
TBI + $CuSO_4$	2.422e+21	2.568e+21	1.686	2.681e+21	0.100523	-0.360
PMT	1.436e+21	1.522e+21	1.000	1.589e+21	0.100887	0.000

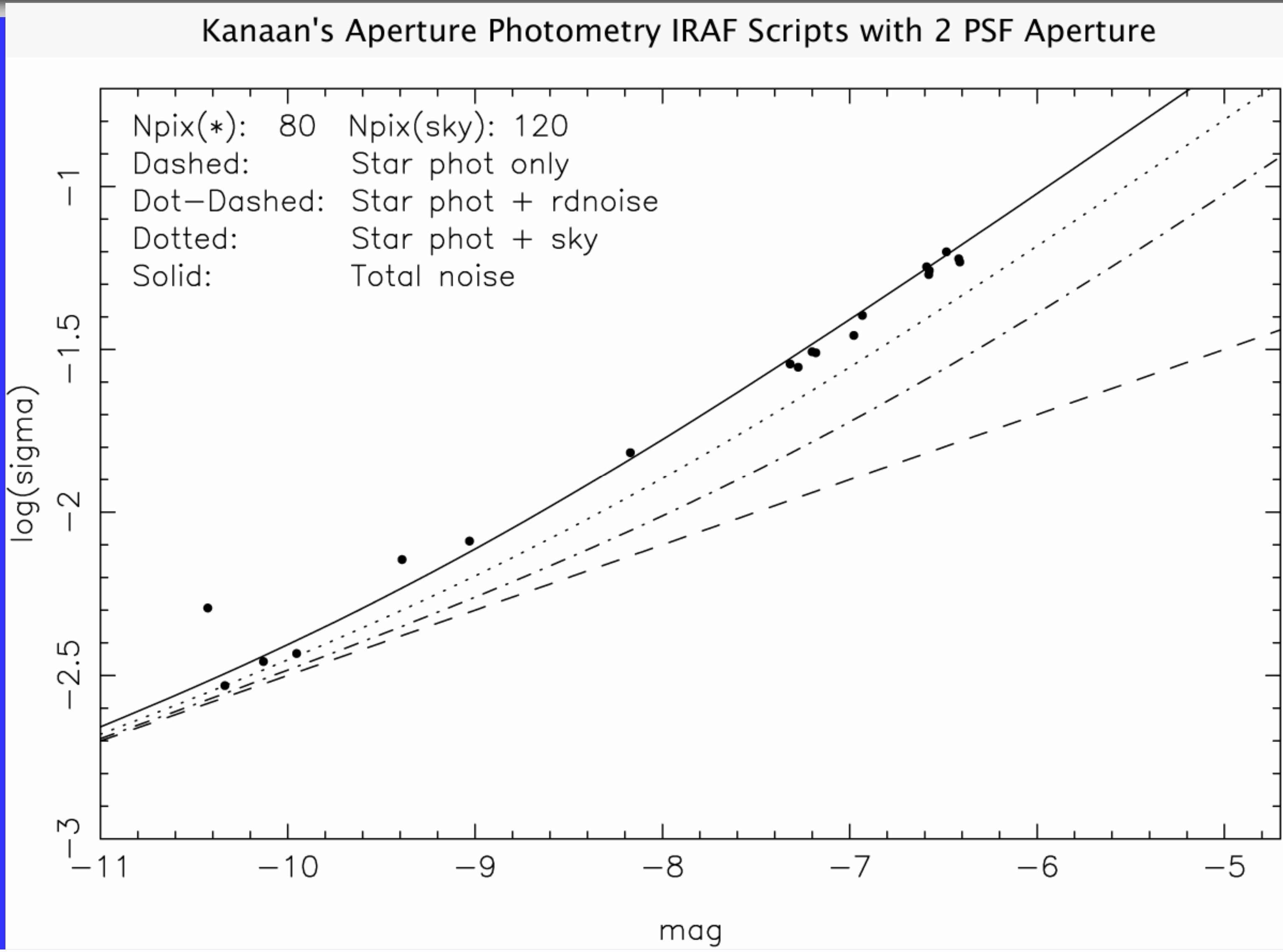
Amplitude vs Wavelength



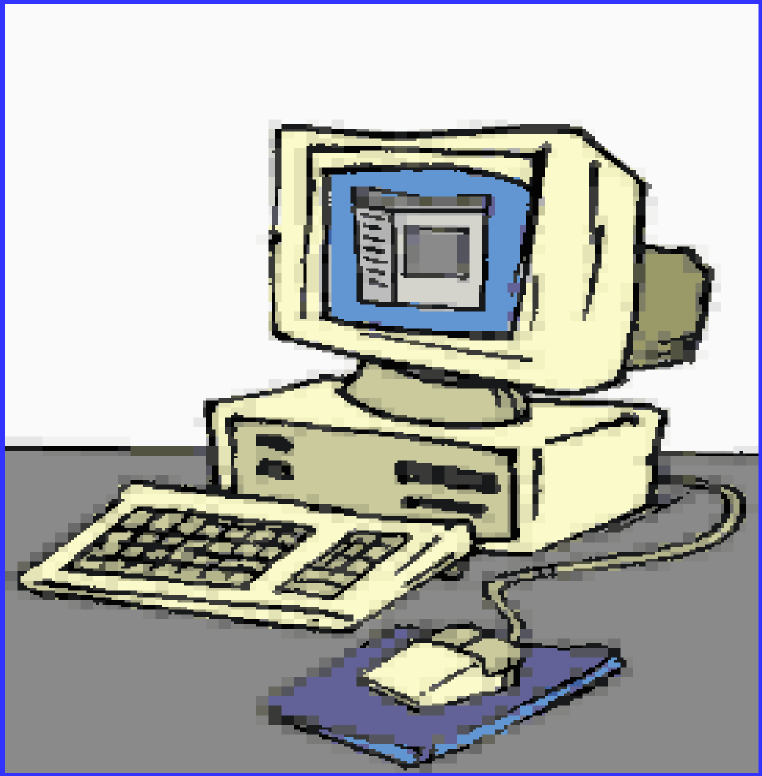
Variable Ap Star



CCD Data Analysis



That's all folks!



Music?