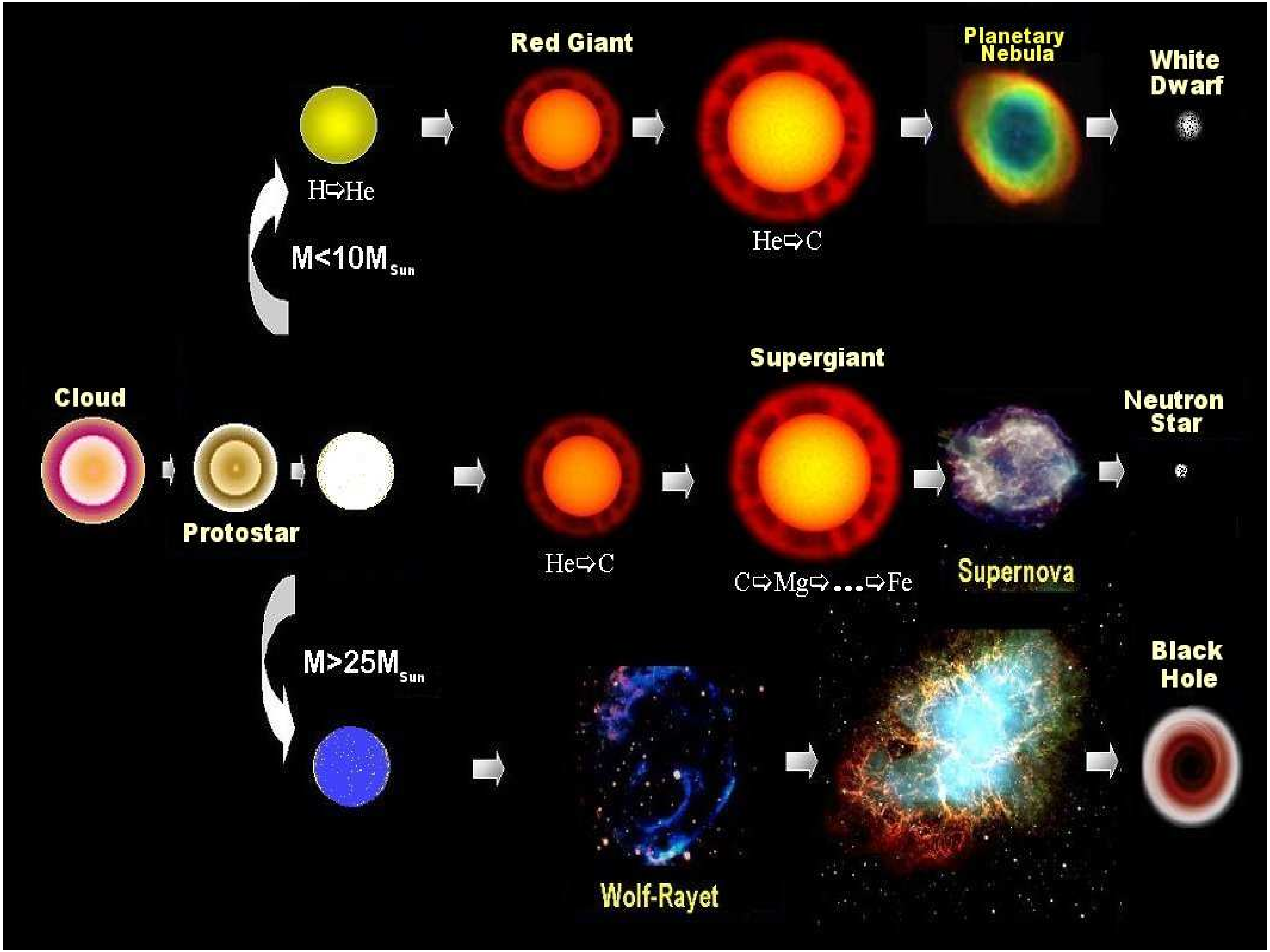
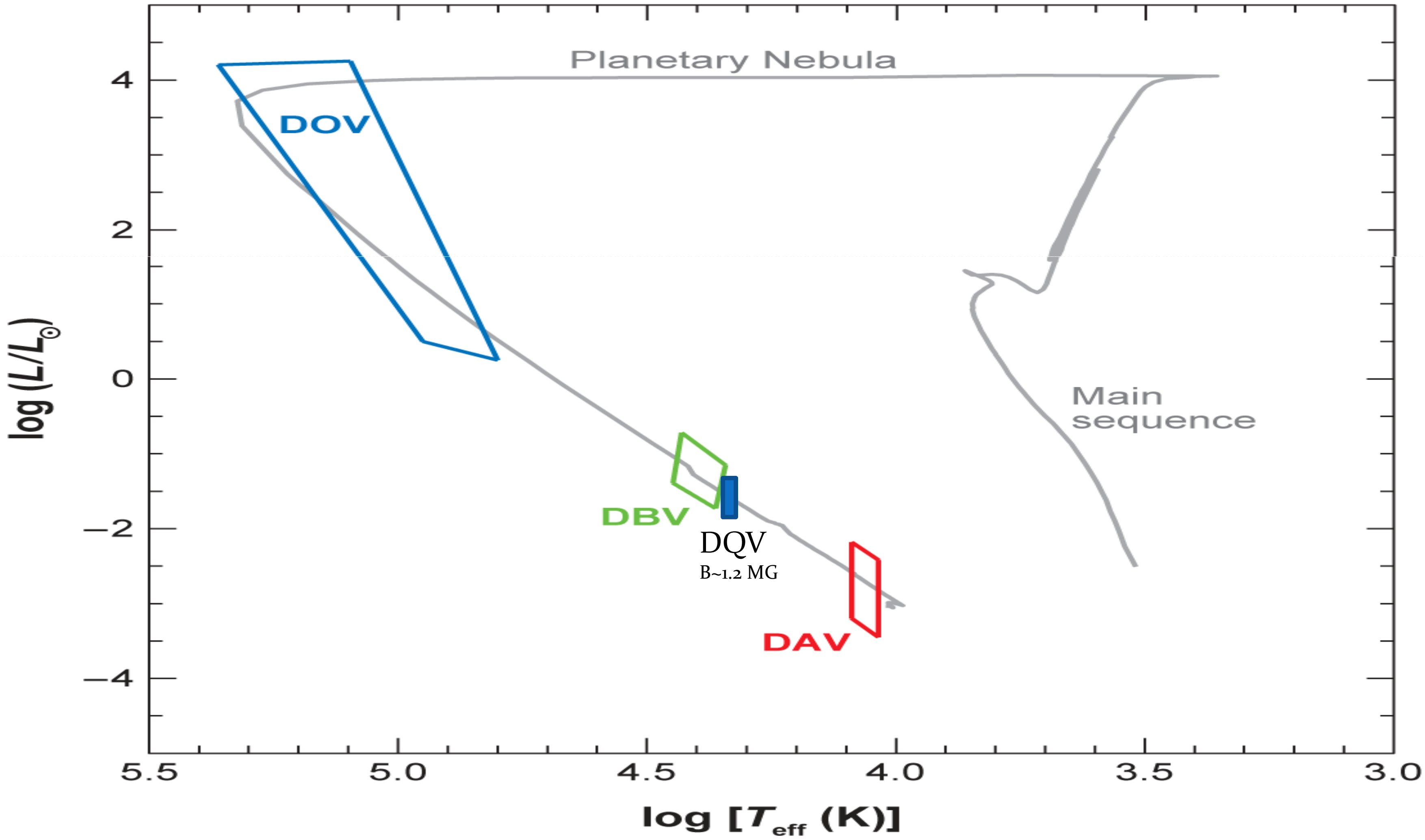
White dwarf stars

Kepler
Luciano Fraga
Bárbara Castanheira
Group of Brazilian Resident Astronomers

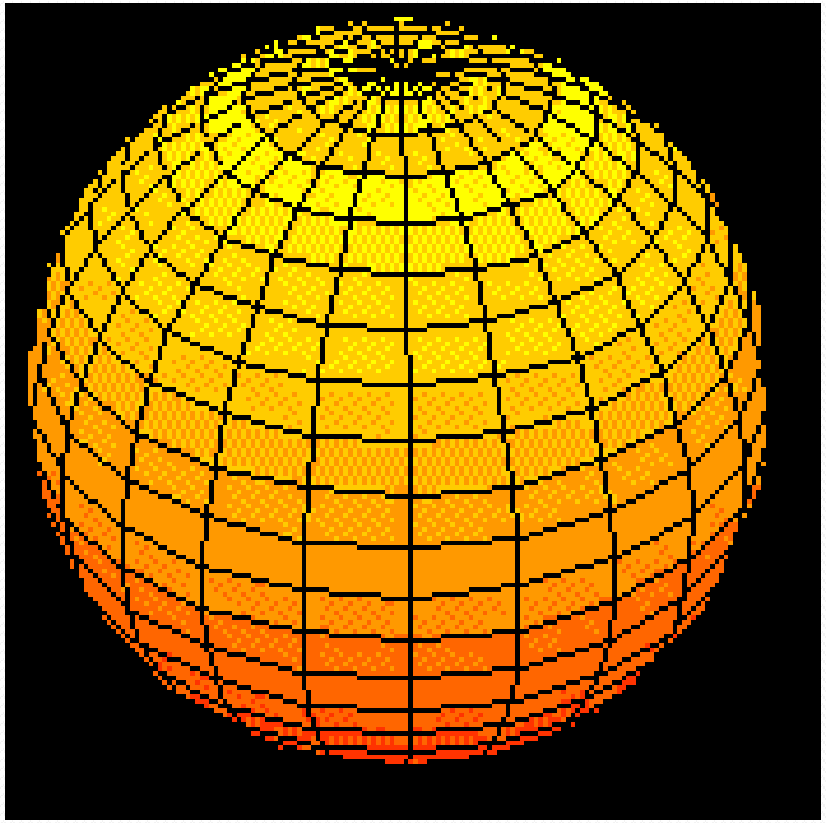


Red Giant
Planetary Nebula
White Dwarf
H⇨He
He⇨C
M<10M$_{Sun}$
Supergiant
Cloud
Neutron Star
Protostar
He⇨C
C⇨Mg⇨...⇨Fe
Supernova
M>25M$_{Sun}$
Black Hole
Wolf-Rayet

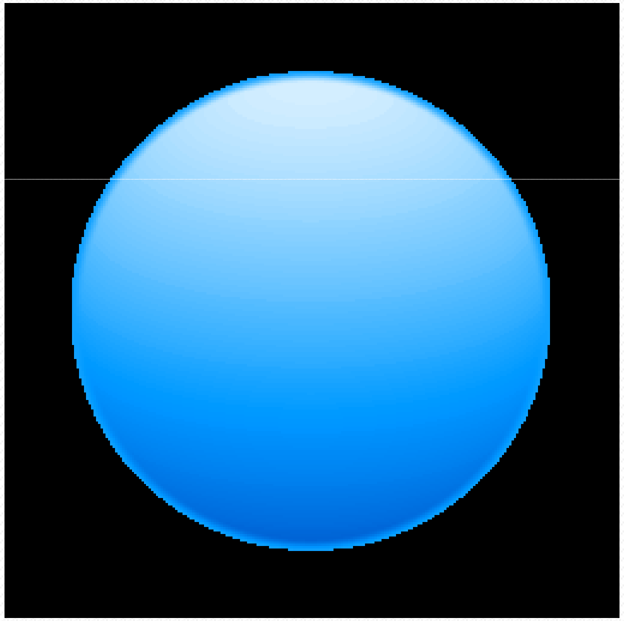
White dwarf pulsations

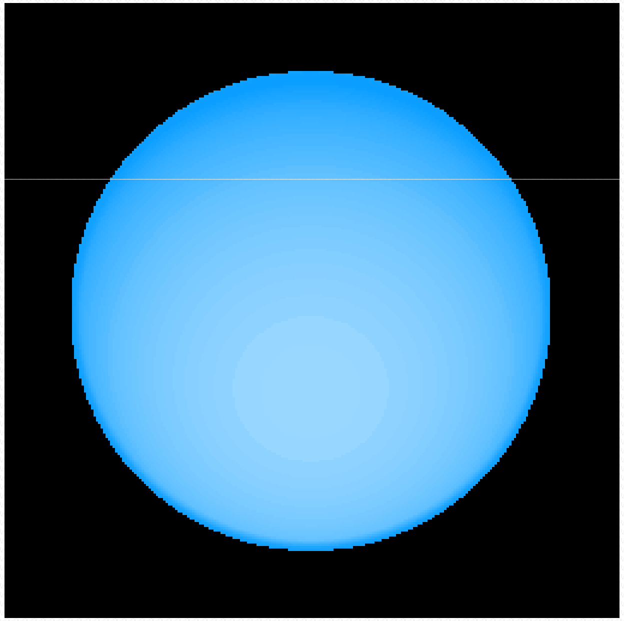


Pulsations … Seismology



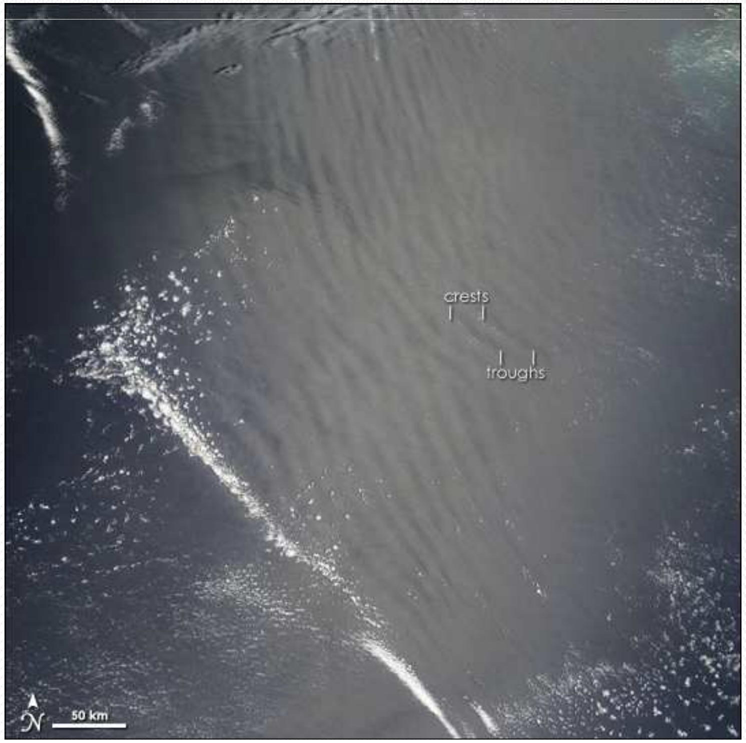
Pulsations/Seismology: Y_{10} e Y_{11}



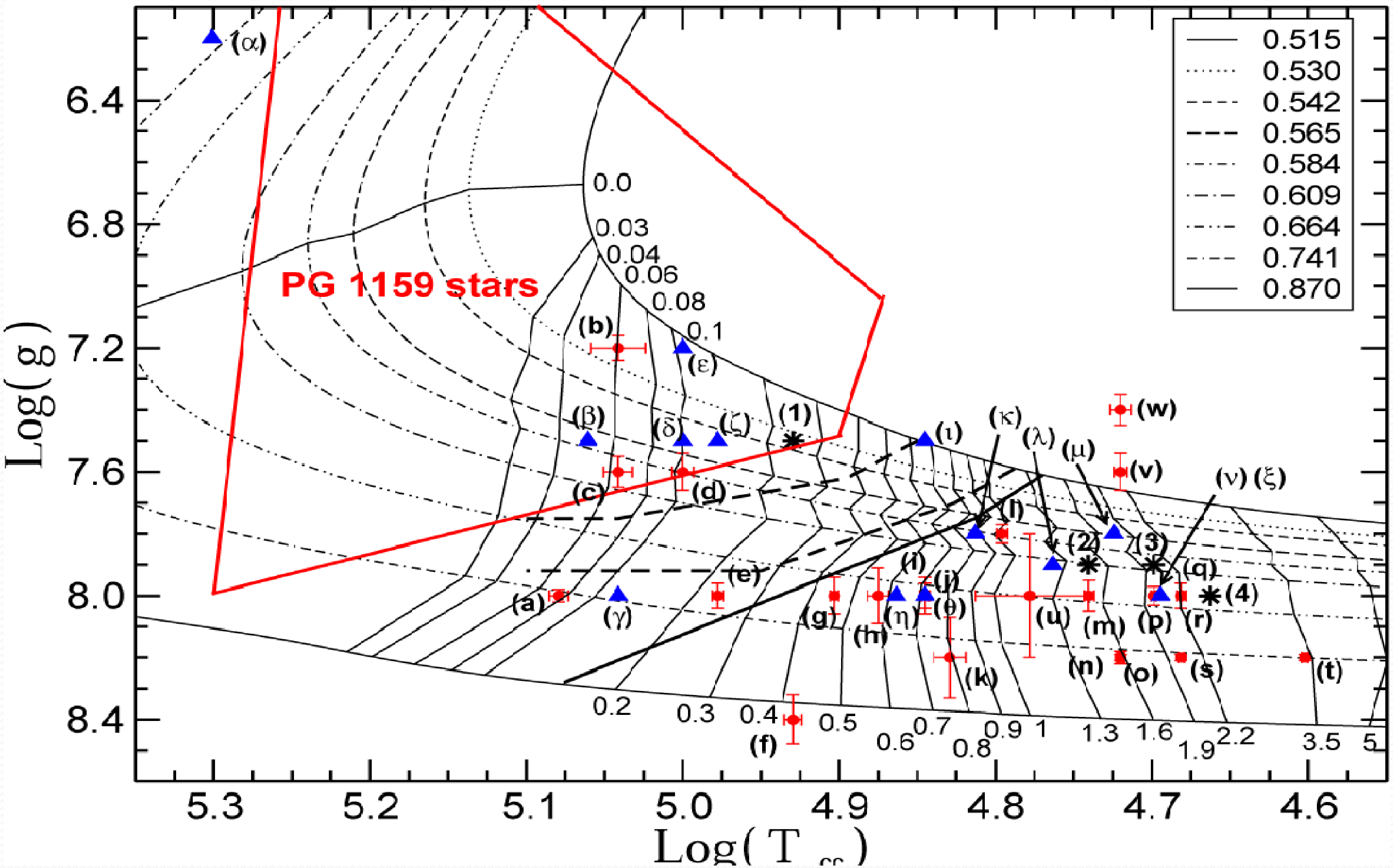


Photometry

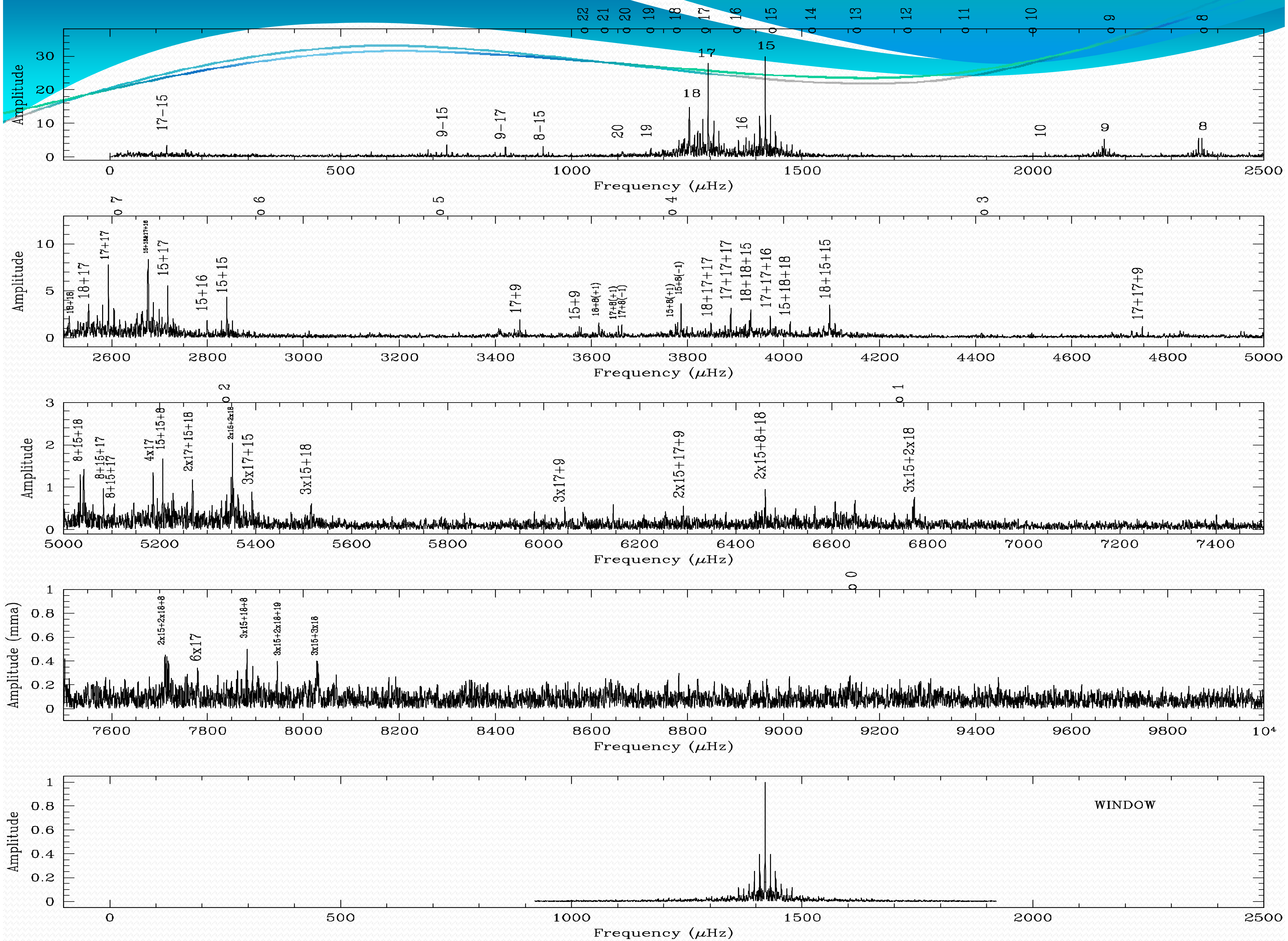
- CCD: star + comparisons + skies
- g-modes in Earth's atmosphere

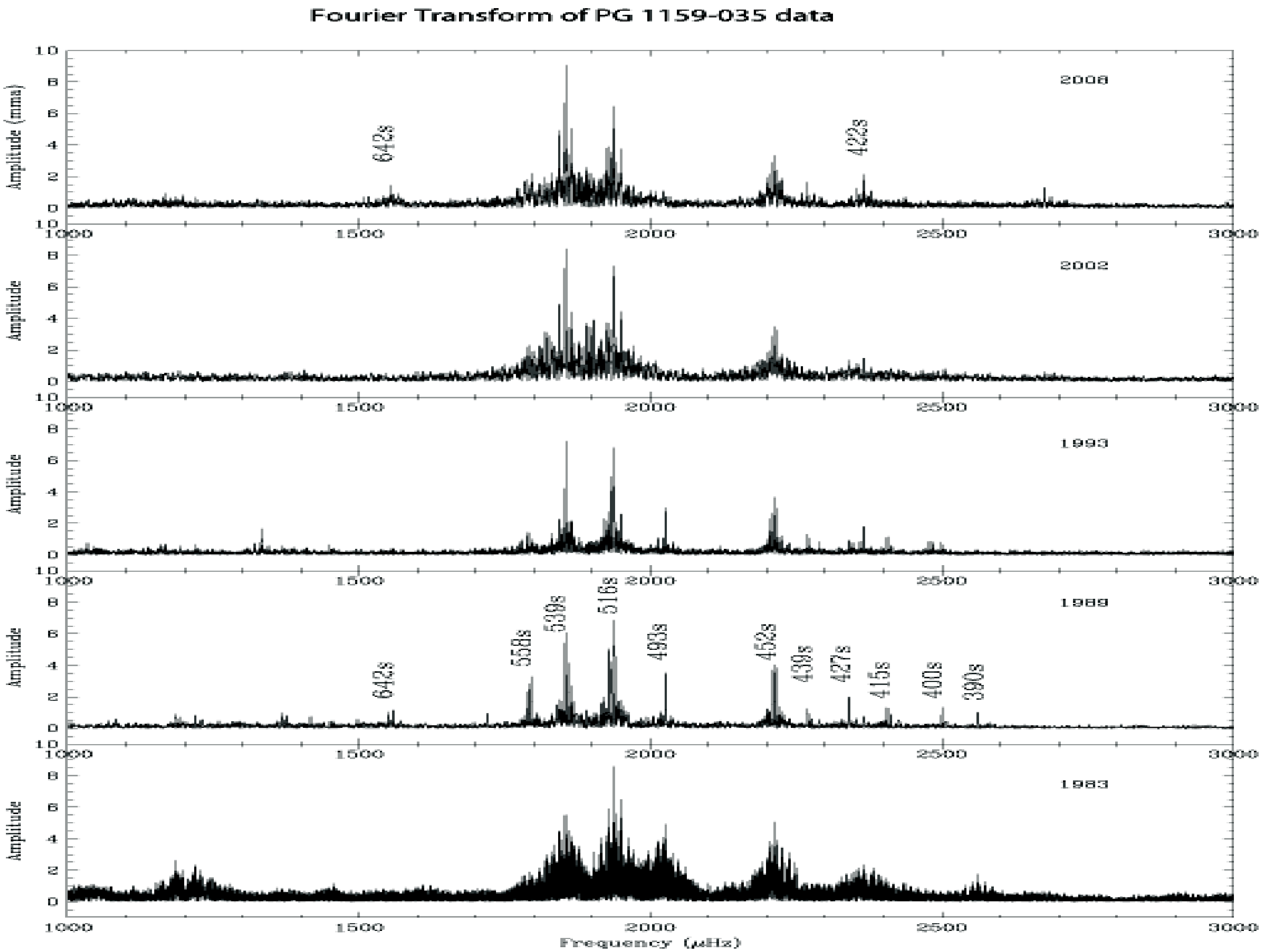


Althaus et al. 2010 ARA&A

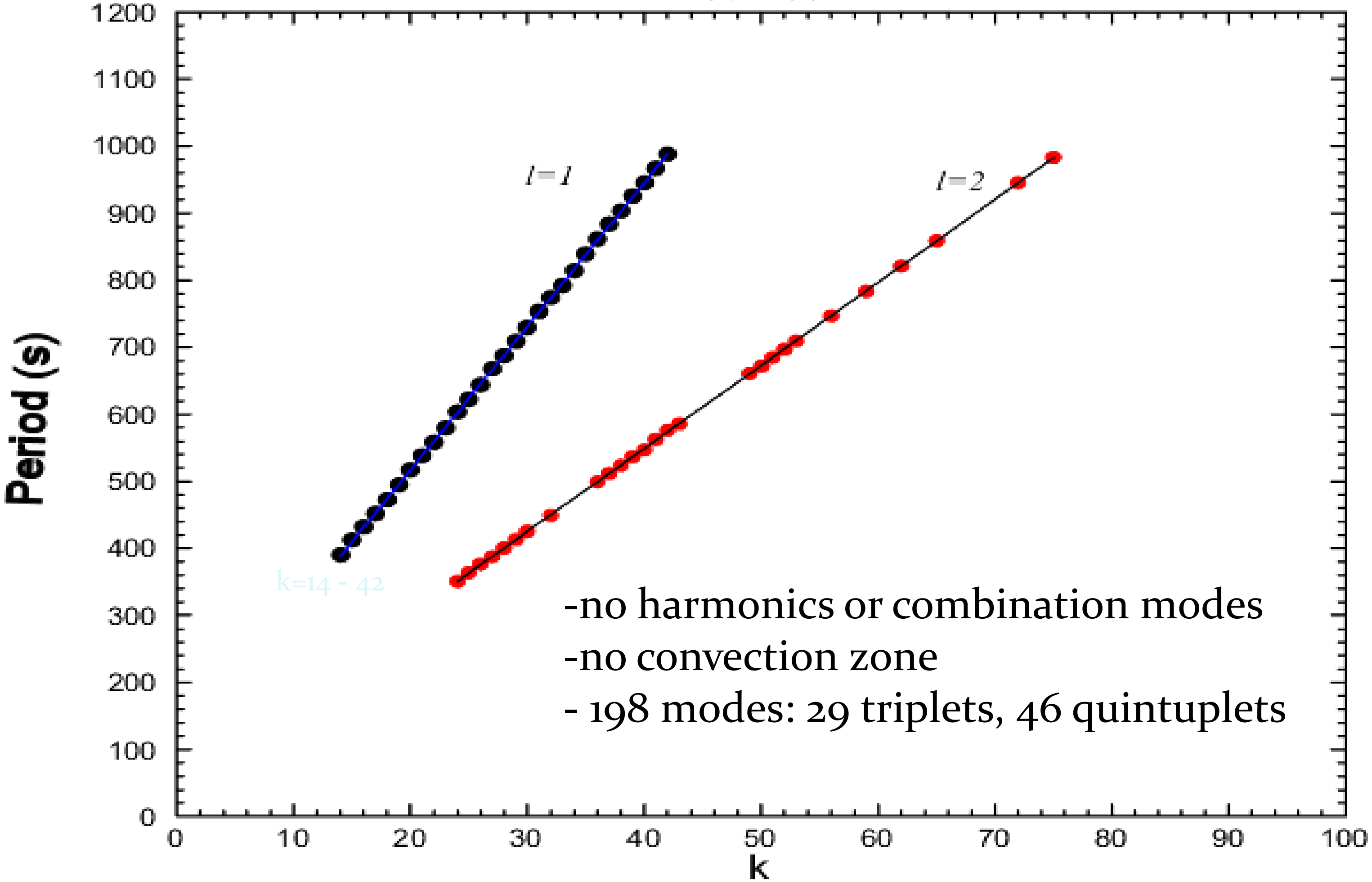


FT of GD358 data Xcov19 2000



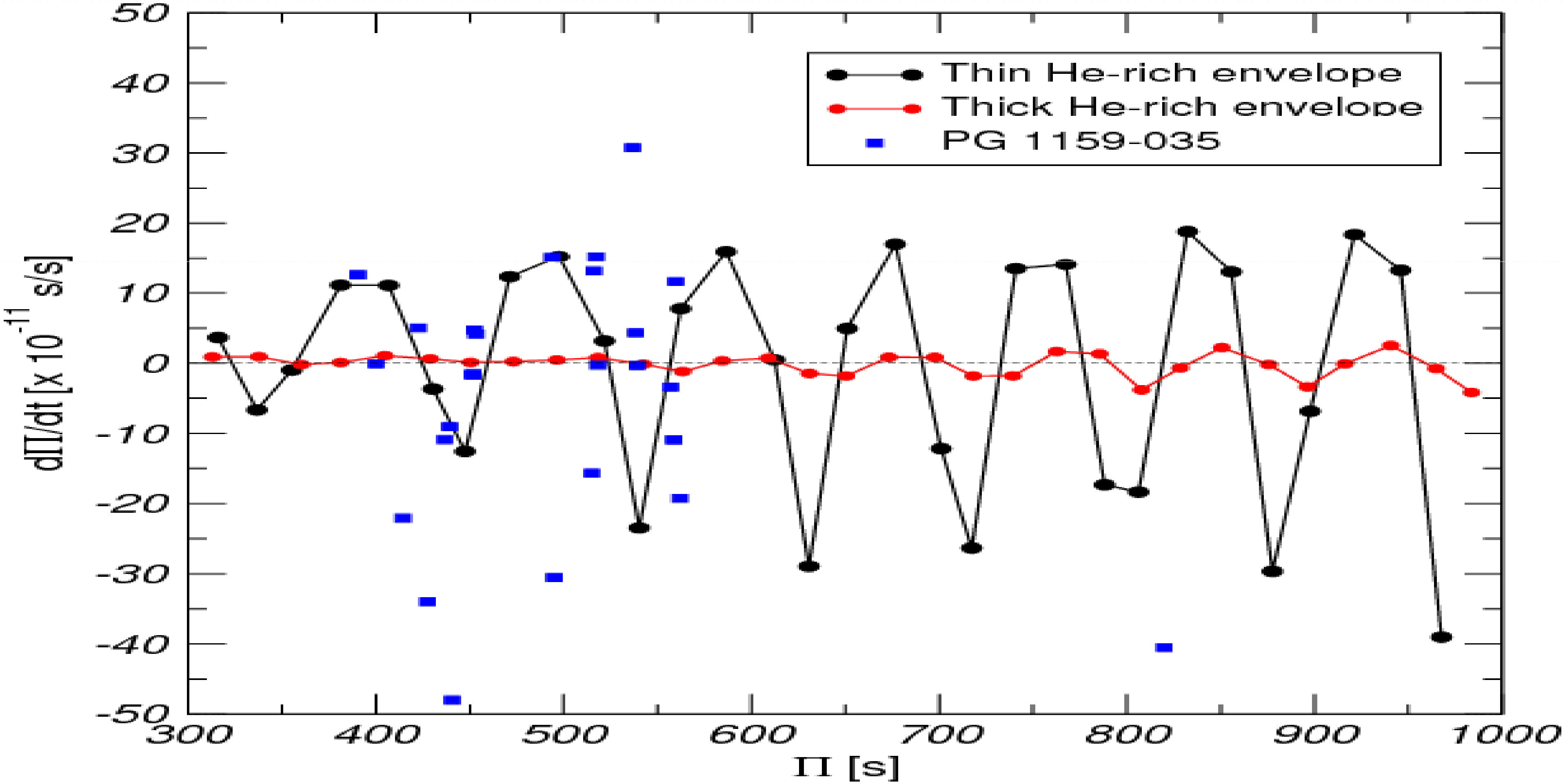

Fourier Transform of PG 1159-035 data
2008
2002
1993
1989
1983
642s
422s
558s
539s
516s
493s
452s
439s
427s
415s
400s
390s
Amplitude (mma)
Amplitude
Frequency (μHz)
1000
1500
2000
2500
3000

PG1159-035



J. Edu S. Costa

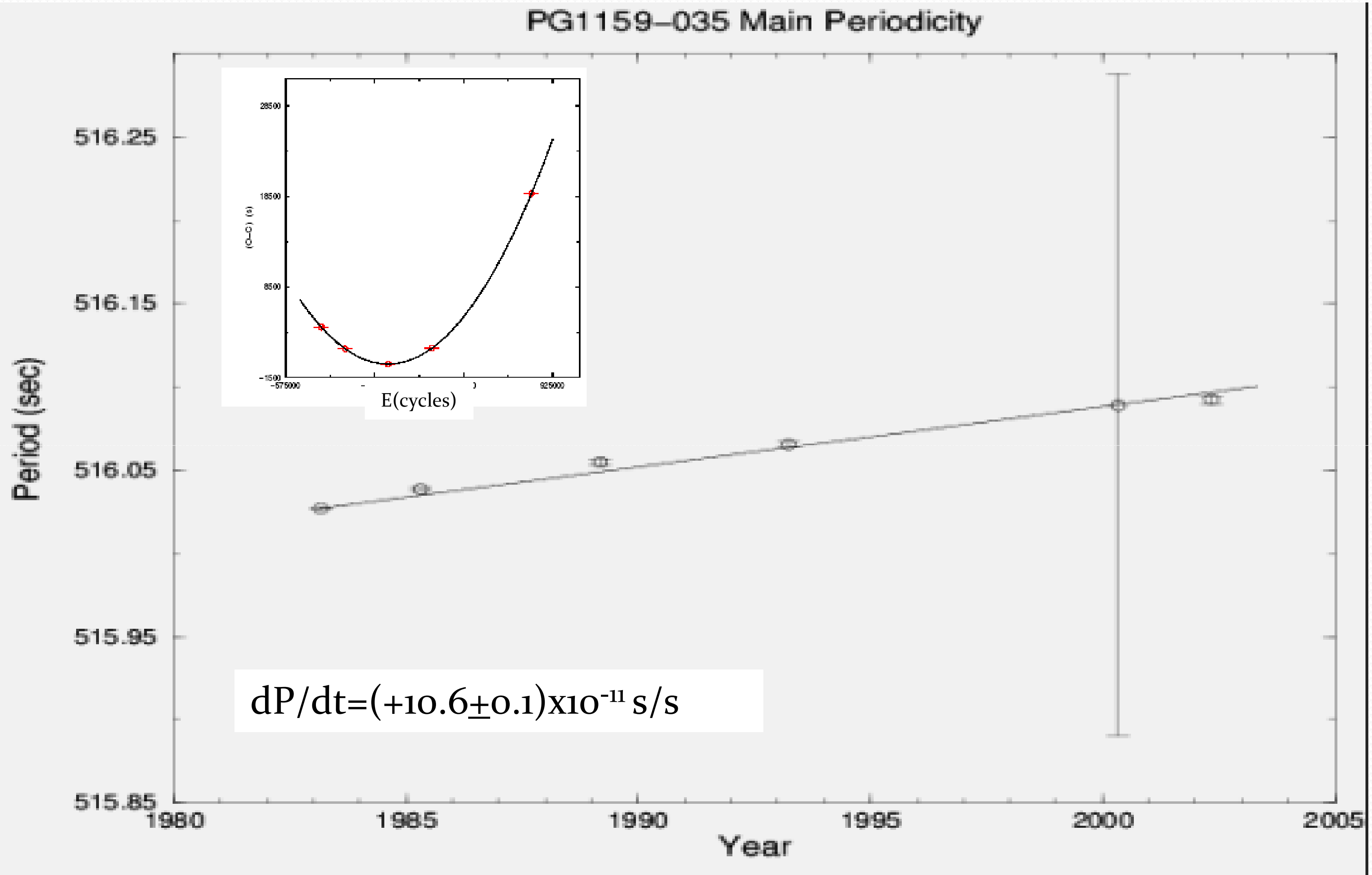
Measure thickness of envelope

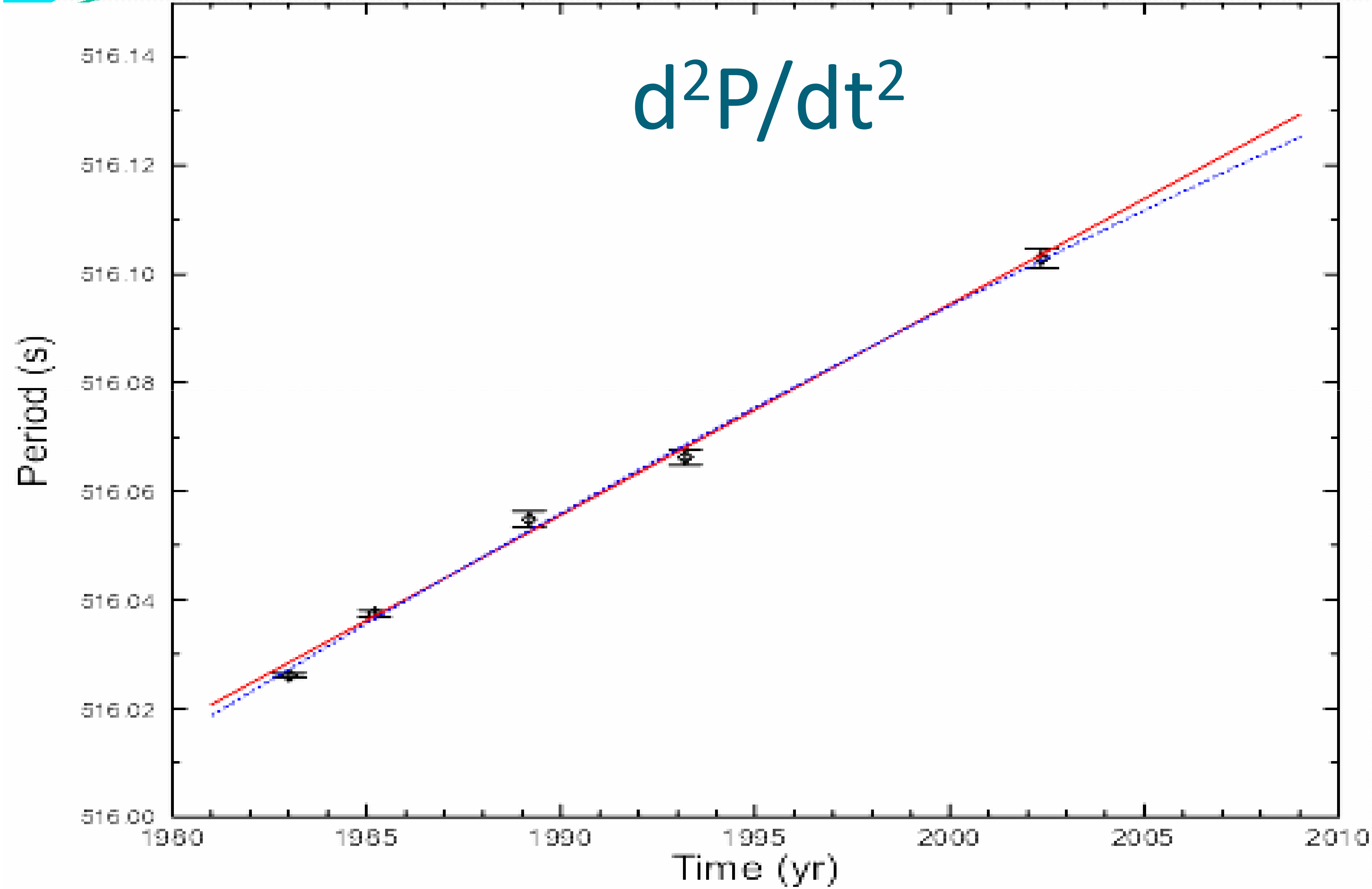


Córsico et al. 2008

S.O. Kepler

White Dwarf Stars: Crystals and Clock

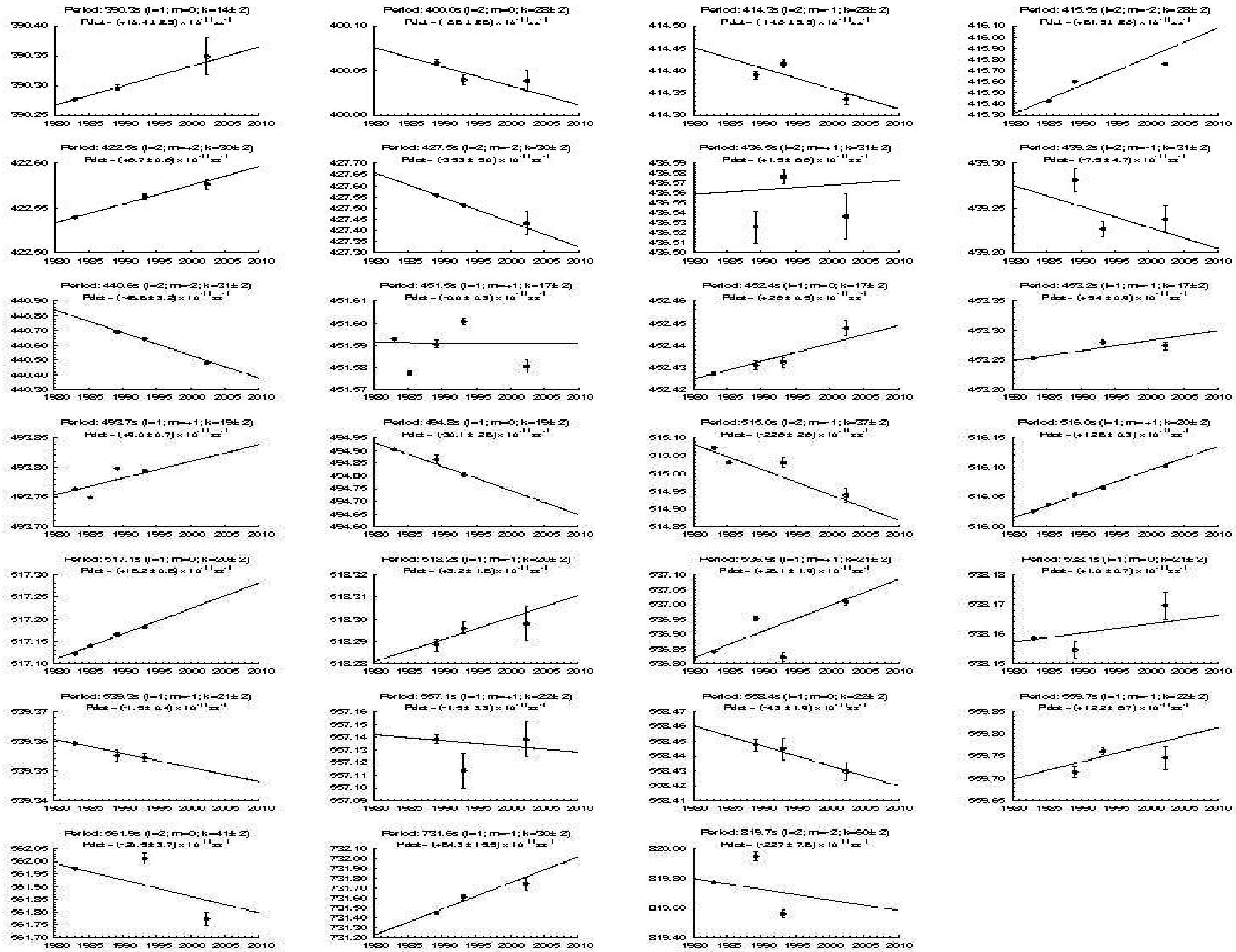

PG1159–035 Main Periodicity
Period (sec)
516.25
516.15
516.05
515.95
515.85
1980
1985
1990
1995
2000
2005
Year
E(cycles)
dP/dt=(+10.6±0.1)x10⁻¹¹ s/s



d²P/dt²
Period (s)
516.14
516.12
516.10
516.08
516.06
516.04
516.02
516.00
1980
1985
1990
1995
2000
2005
2010
Time (yr)

Costa & Kepler 2008: rotation, contraction rates, cooling rates

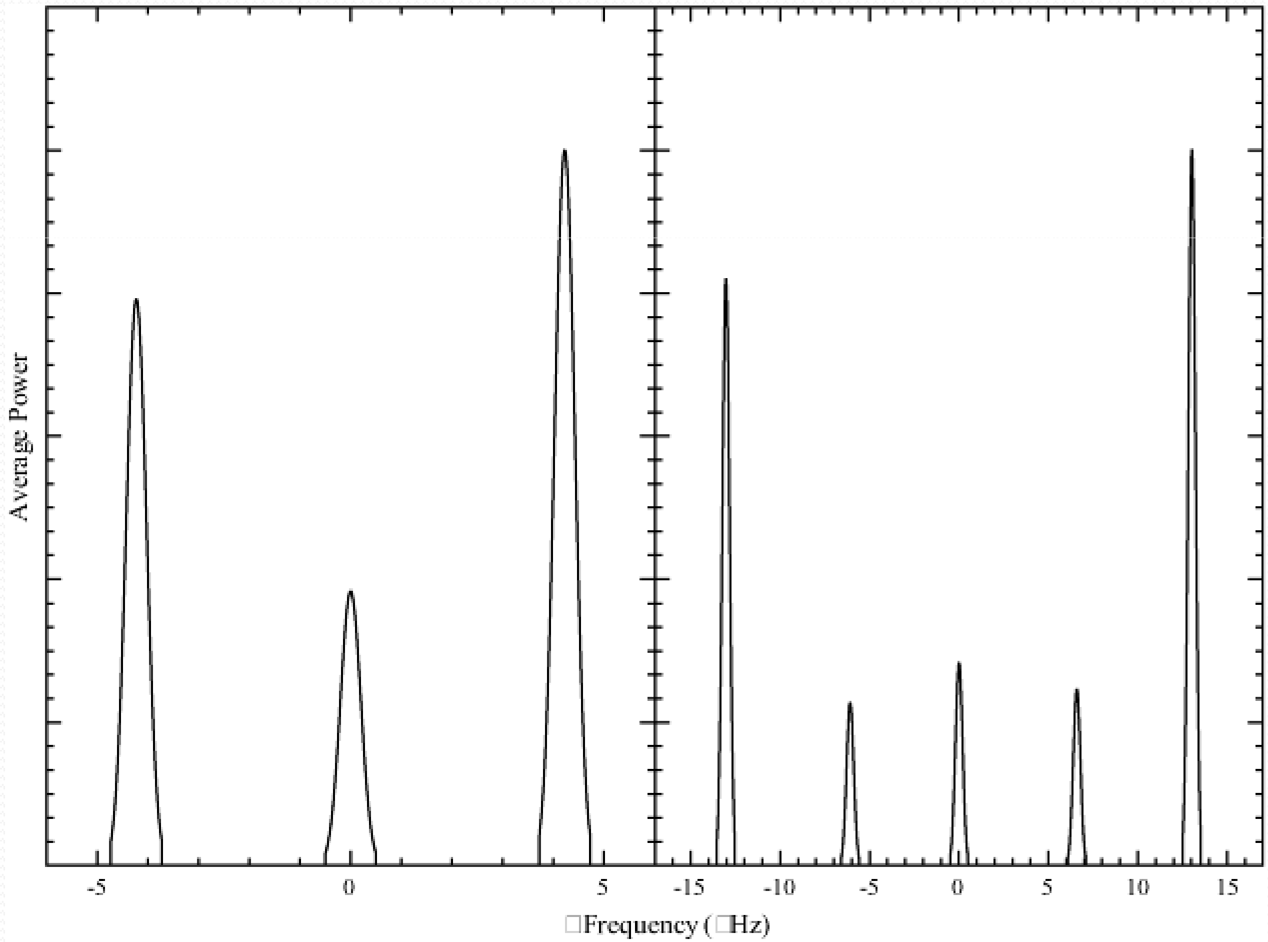
- dP/dt
- $dP_{Rotation}/dt$
- dR/dt
- dT/dt



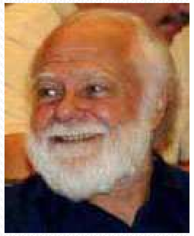
Results

- dP/dt (516s)= 1ms/yr = $(13.146 \pm 0.003) x10^{-11}$ s/s,
- (517s)=$(15.172 \pm 0.045) x10^{-11}$s/s , (539s)=$(-0.339 \pm 0.015) x10^{-11}$s/s
- $d^2P/dt^2 = (1.93 \pm 0.08) x10^{-20}$ s/s, (517s)=$(-81.7 \pm 2.7)+10^{-20}$ s/s
- $P_{rotation} = 1.3935 \pm 0.0008$ d
- $dP_{rot}/dt = (-2.13 \pm 0.05) x10^{-6}$ s/s
- $dR/dt = (-2.8 \pm 0.2) x10^{-12}$ s/s
- $dT/dt = (-7.6 \pm 0.2) x10^{-11}$ s/s →
- Trapping at $0.83R_* \pm 0.05$
- $\Delta P(l=1) = 21.43 \pm 0.03$s $M = 0.59 \pm 0.02\ M_{Sun}$
- $\Delta P(l=2) = 12.38 \pm 0.01$s
- B<2000G

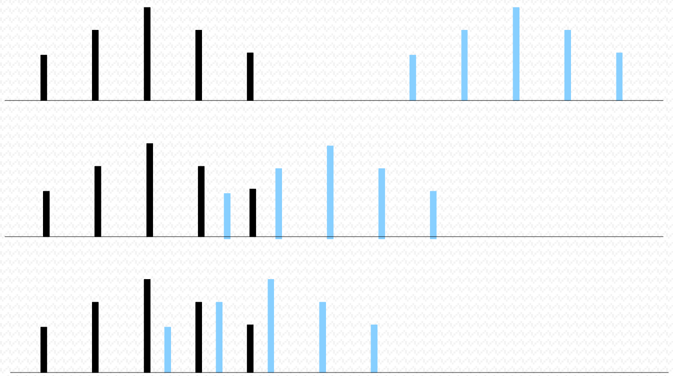
Average multiplets i=70º



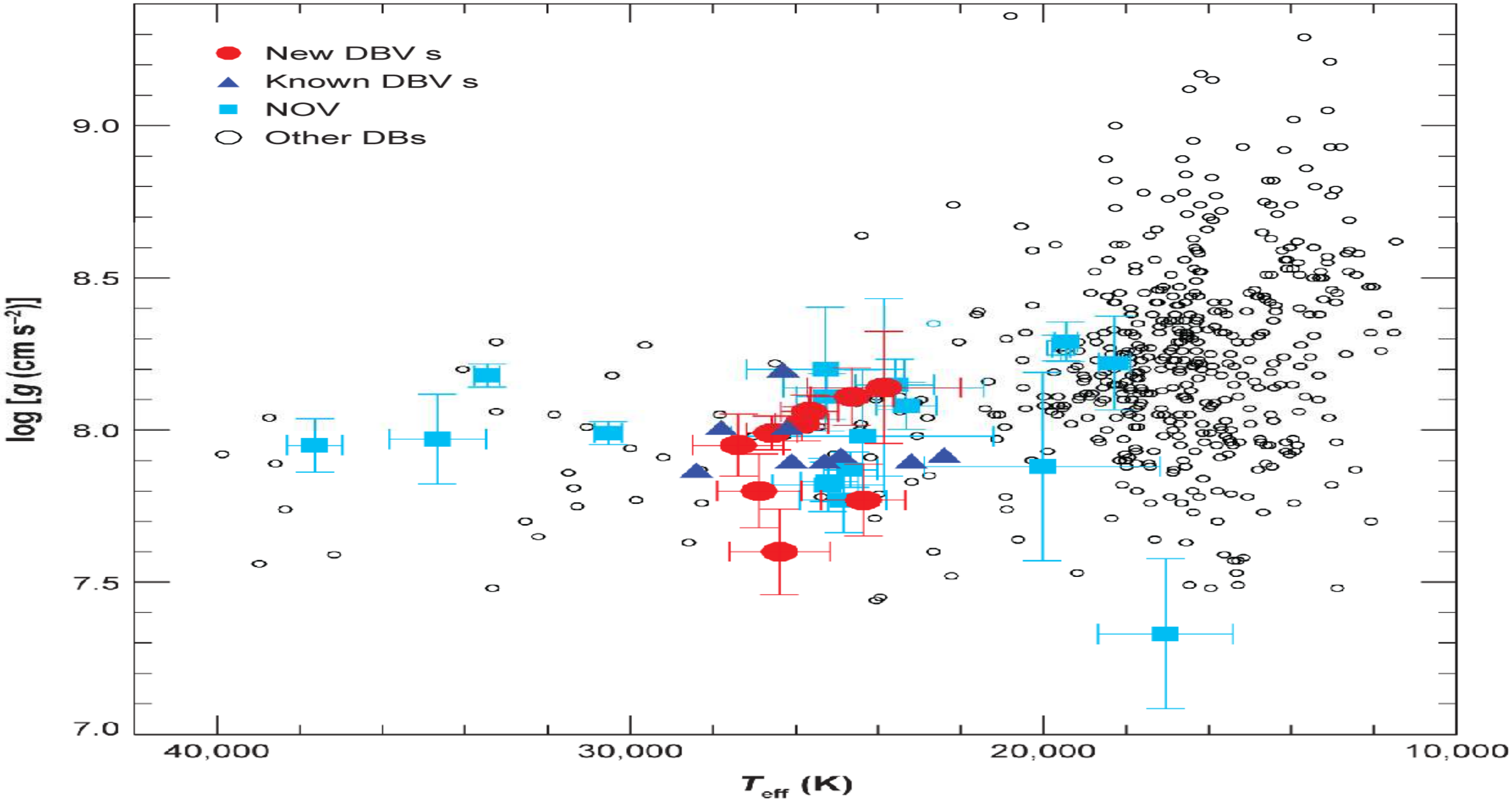
Rotation effects



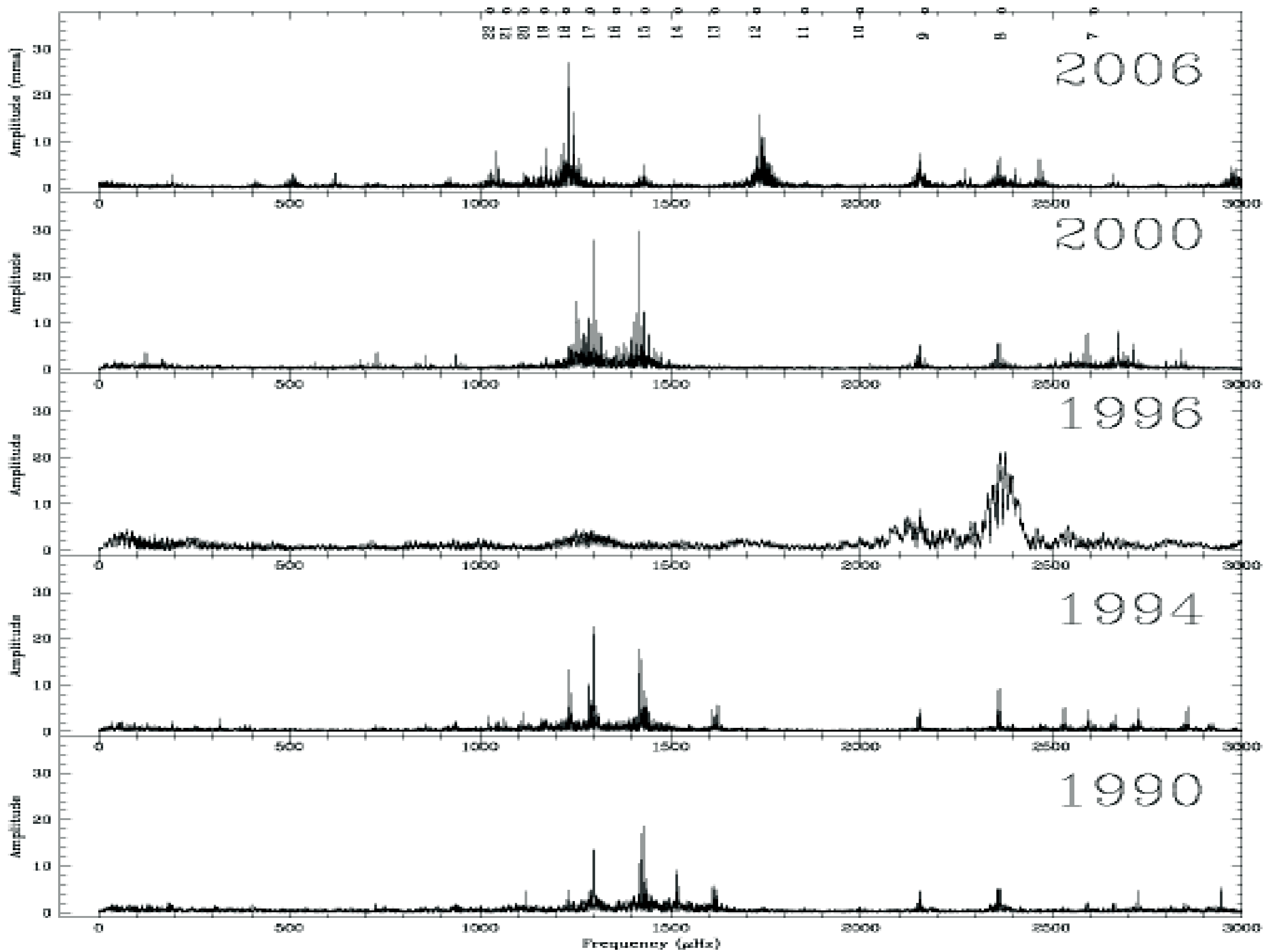
- Multiplets have different amplitudes
- Amplitudes change (energy exchange with rotation?)
- *Gough:* "…if there is an $m = +1$, $m = -1$ *asymmetry … it has to be a* consequence of rotation."



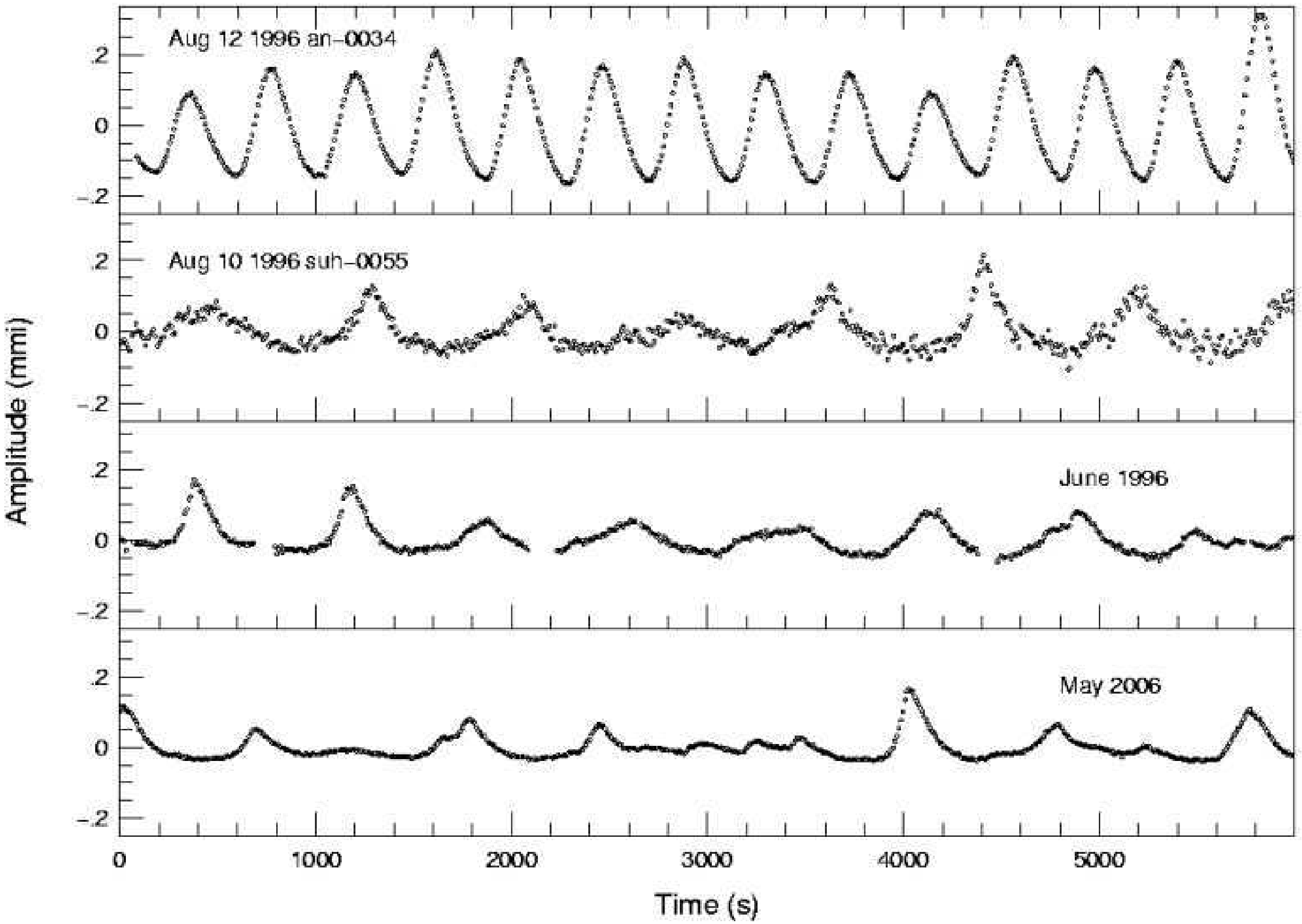
DBVs – Atsuko Nitta et al. 2009

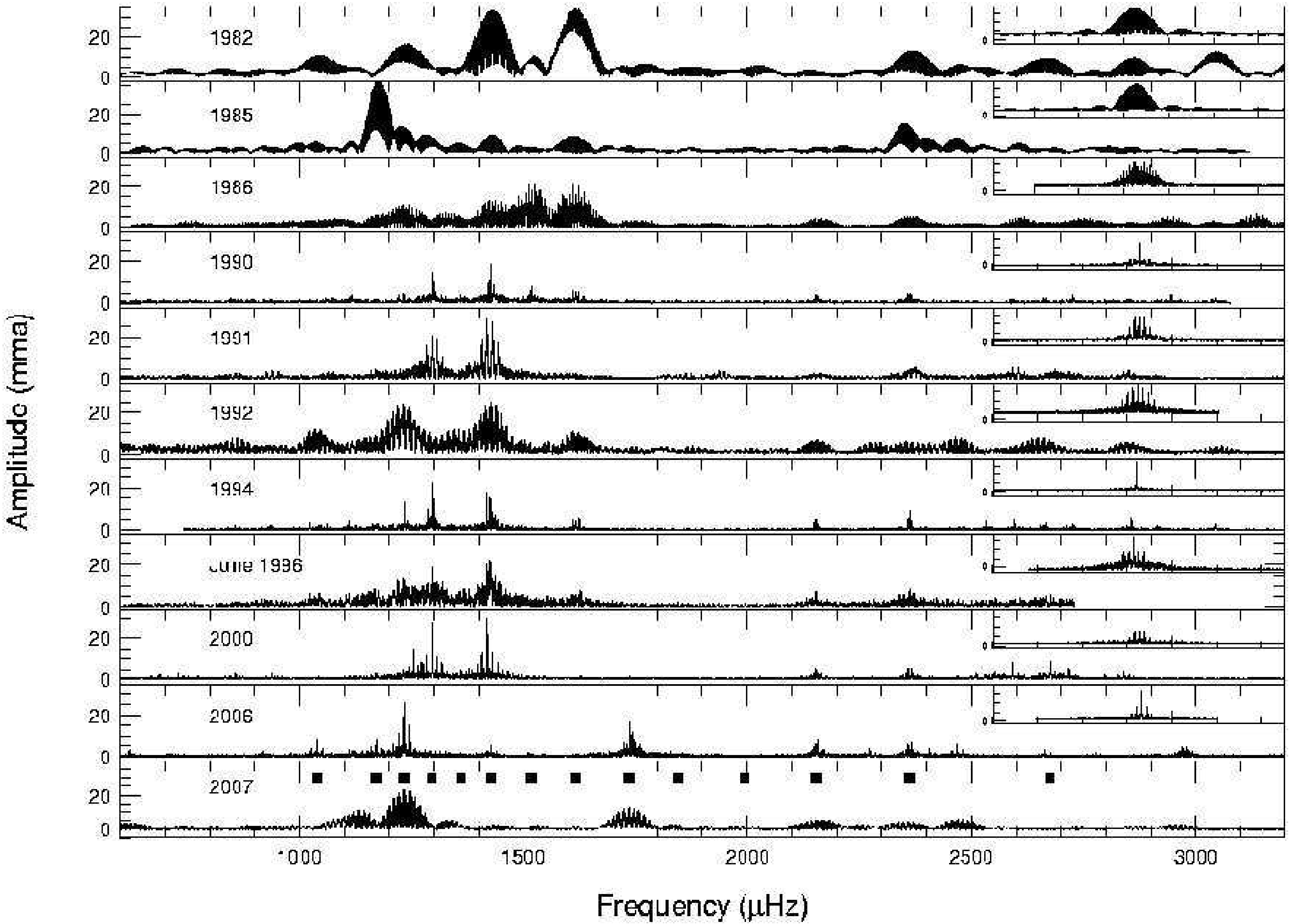


Fourier Transform of GD358 data



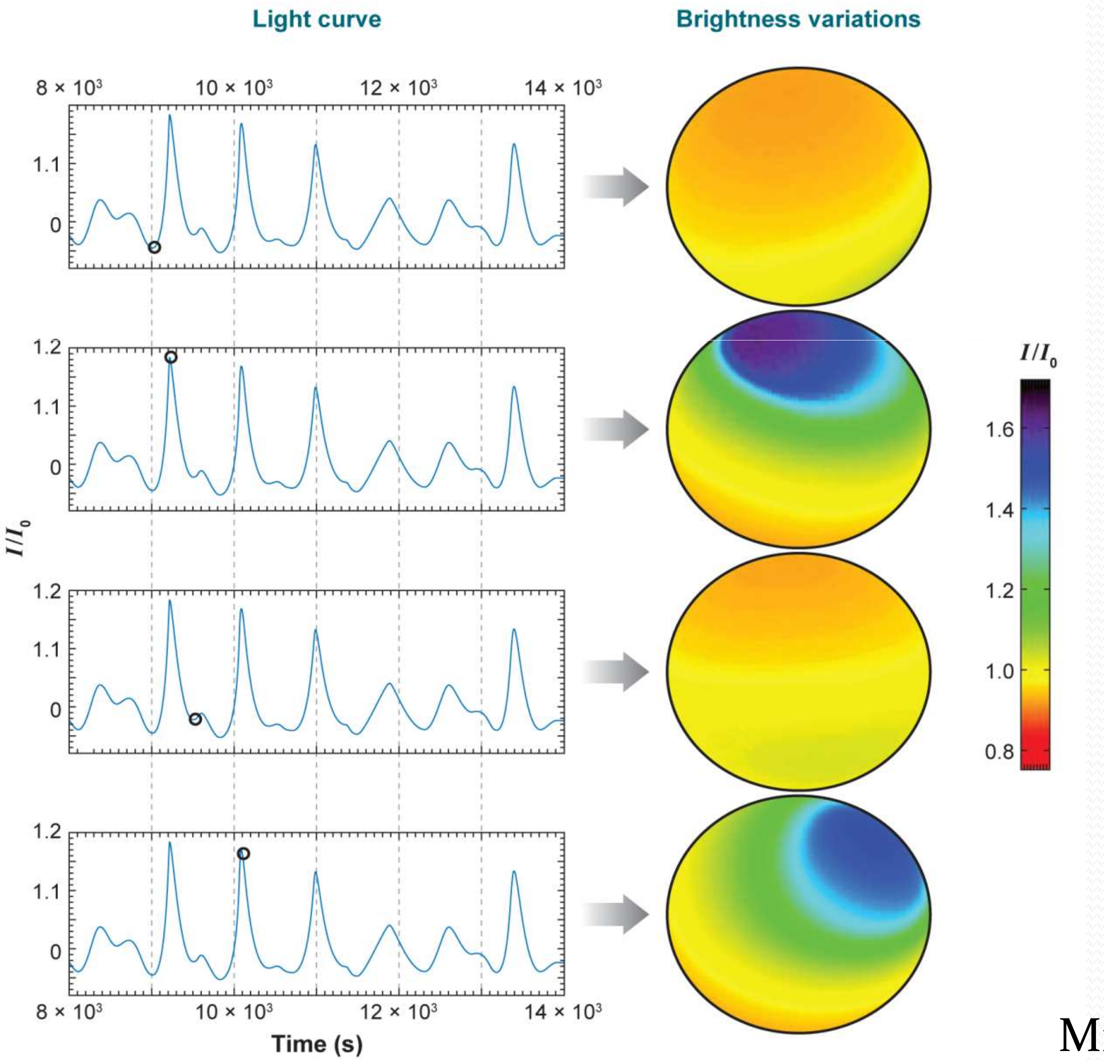
GD 358 light curve in 1996



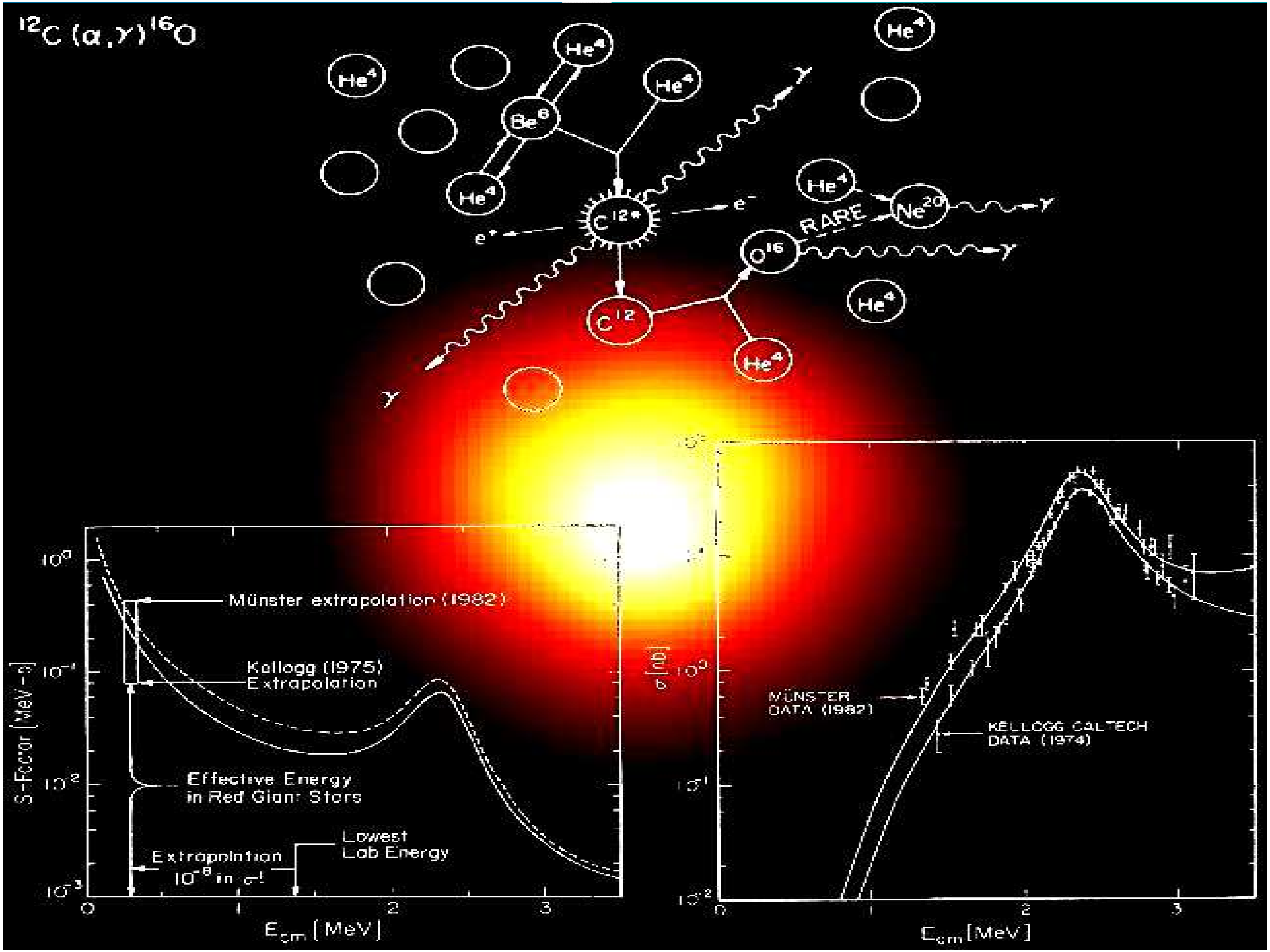


1982
1985
1986
1990
1991
1992
1994
June 1996
2000
2006
2007
Amplitude (mma)
Frequency (μHz)
0
20
1000
1500
2000
2500
3000

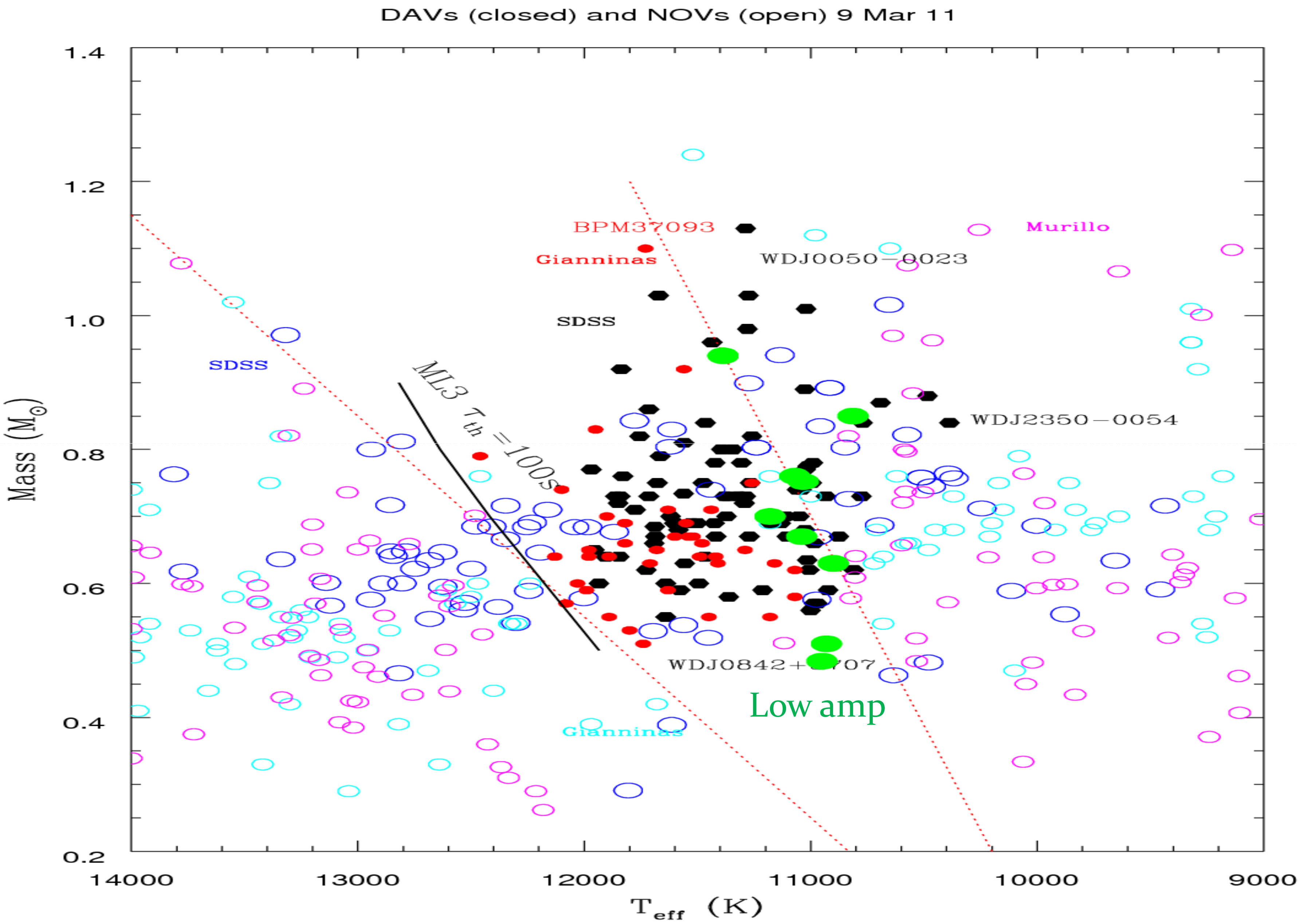
Combination frequencies



Mike Montgomery

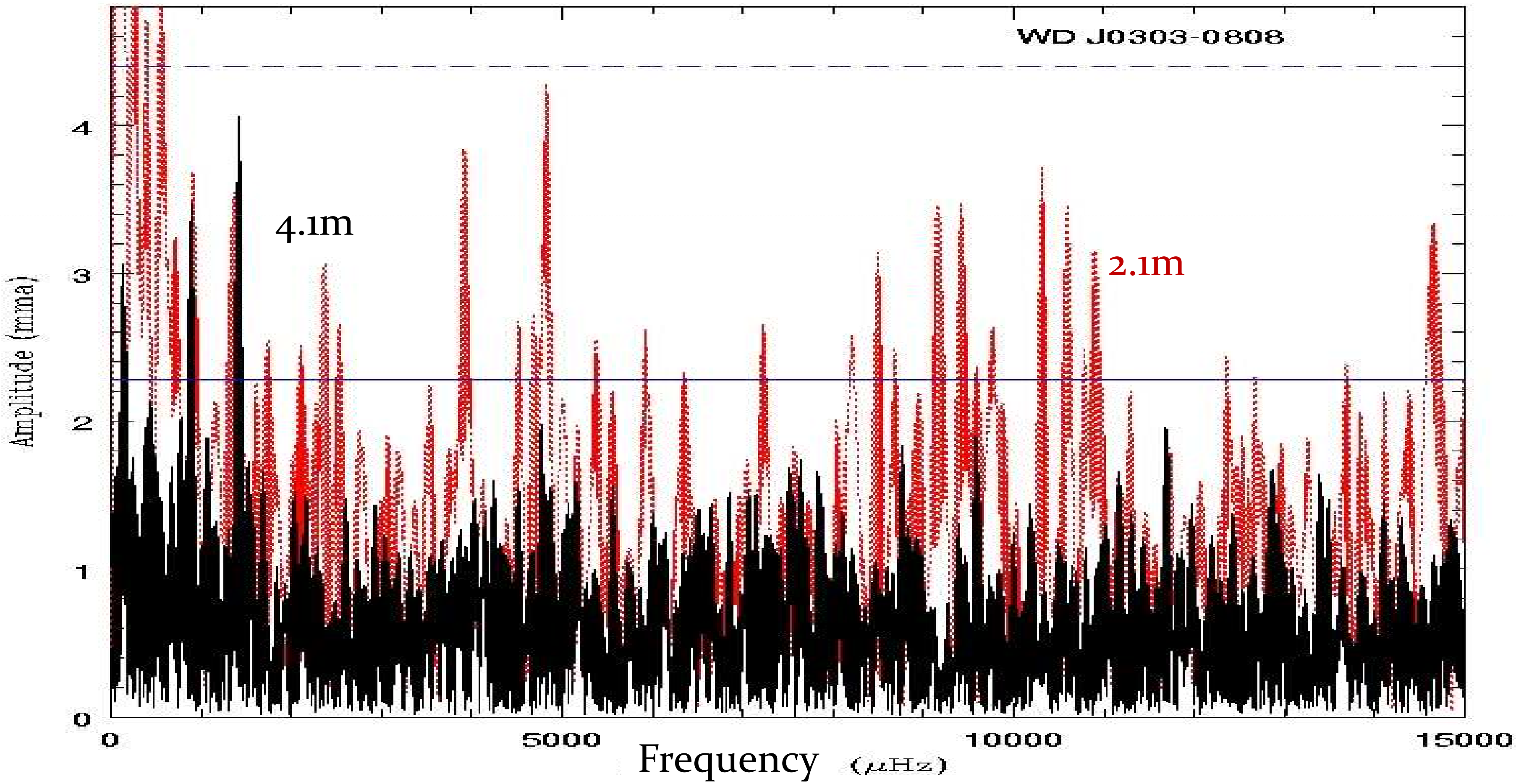


$^{12}C(\alpha,\gamma)^{16}O$
He4
Be8
C12*
e+
e-
γ
O16
Ne20
RARE
C12
Münster extrapolation (1982)
Kellogg (1975) Extrapolation
Effective Energy in Red Giant Stars
Lowest Lab Energy
Extrapolation 10^{-8} in σ!
S-Factor [MeV-b]
E_{cm} [MeV]
σ [nb]
MÜNSTER DATA (1982)
KELLOGG CALTECH DATA (1974)

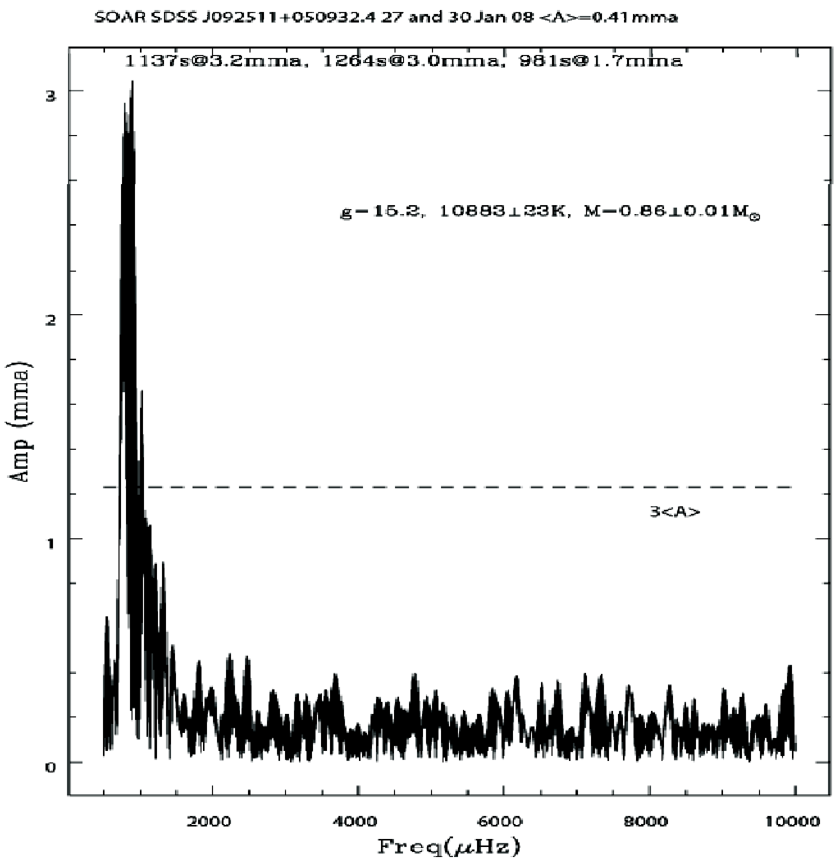


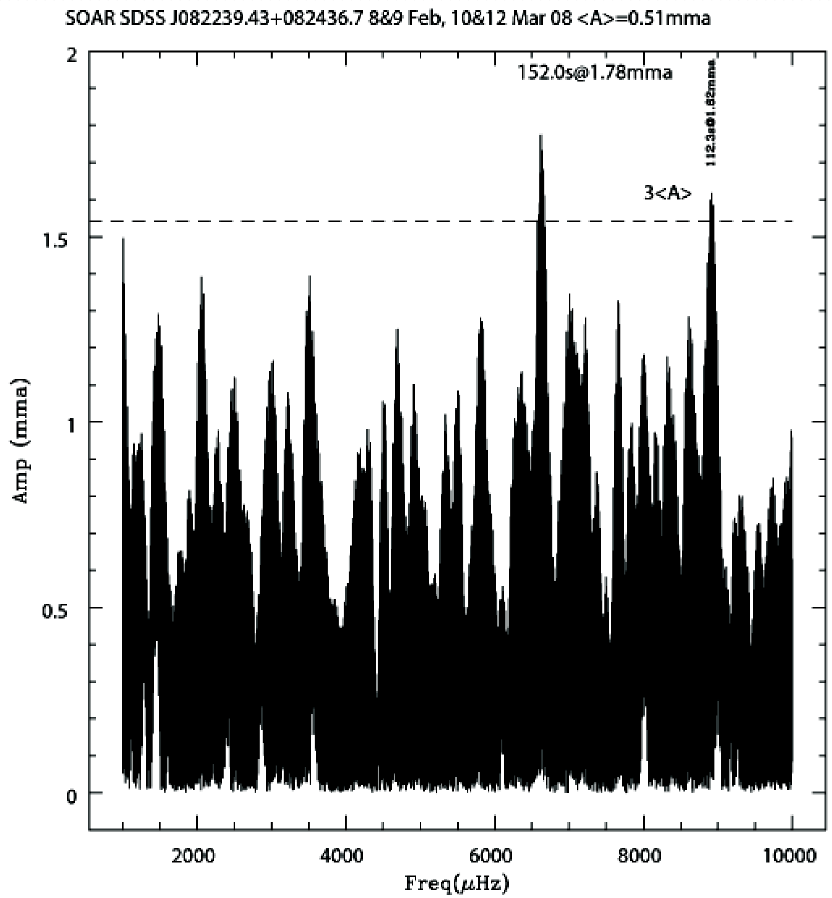
DAVs (closed) and NOVs (open) 9 Mar 11
Mass ($M_\odot$)
T_{eff} (K)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
14000
13000
12000
11000
10000
9000
BPM37093
Gianninas
WDJ0050−0023
Murillo
SDSS
SDSS
ML3 τ_{th} =100s
WDJ2350−0054
WDJ0842+
Low amp
Gianninas

Large telescope, small amplitudes

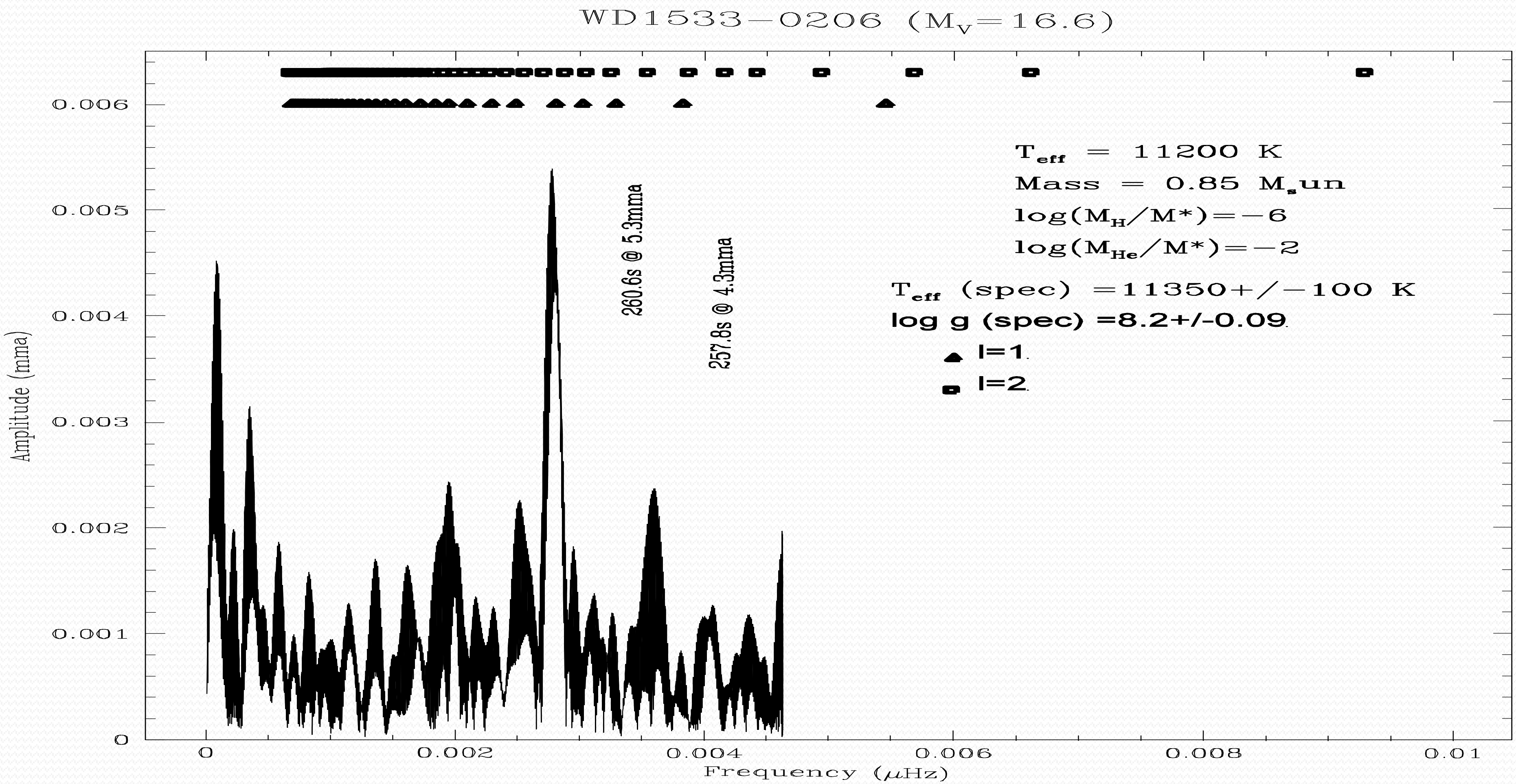


Low amplitude pulsators

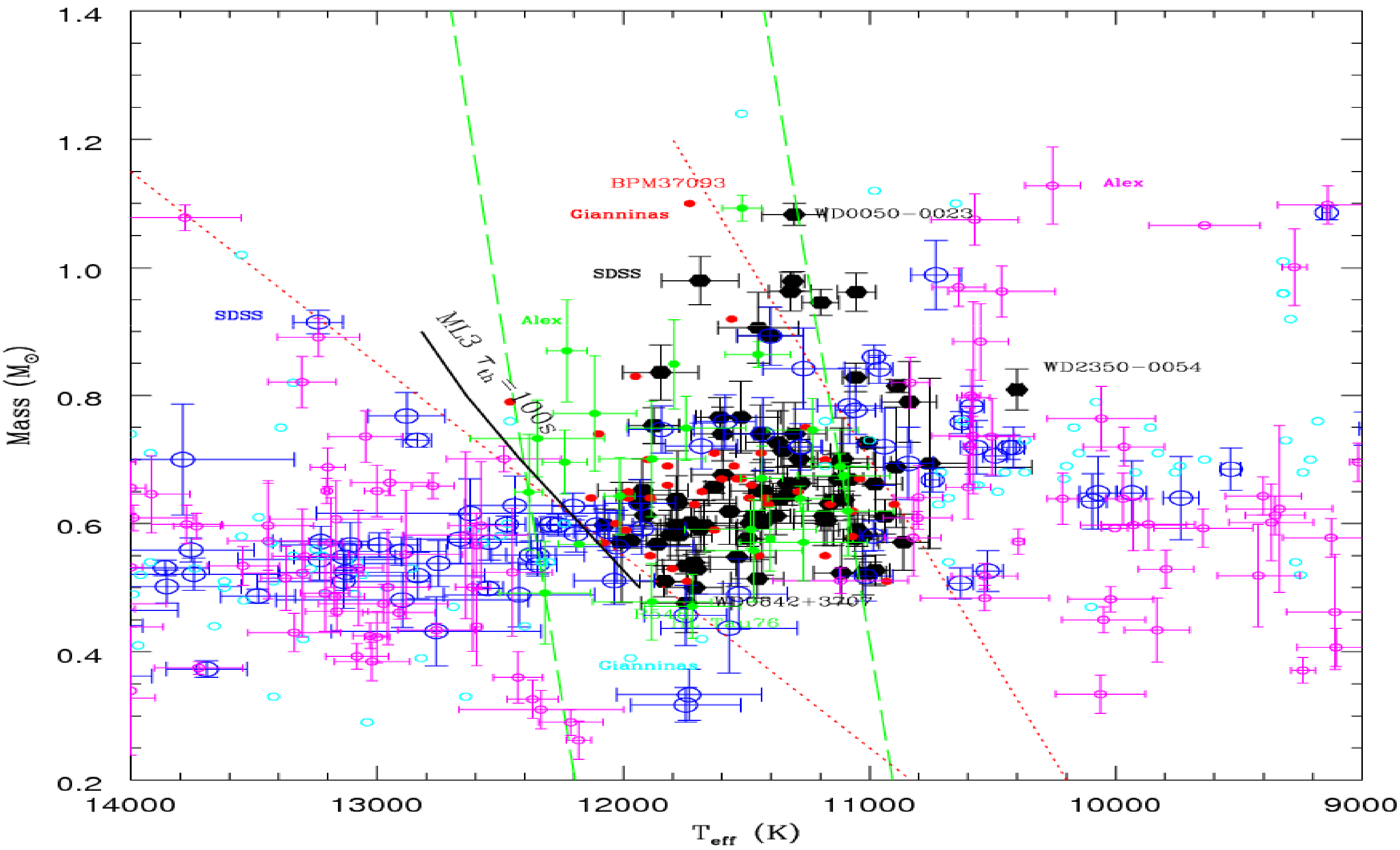


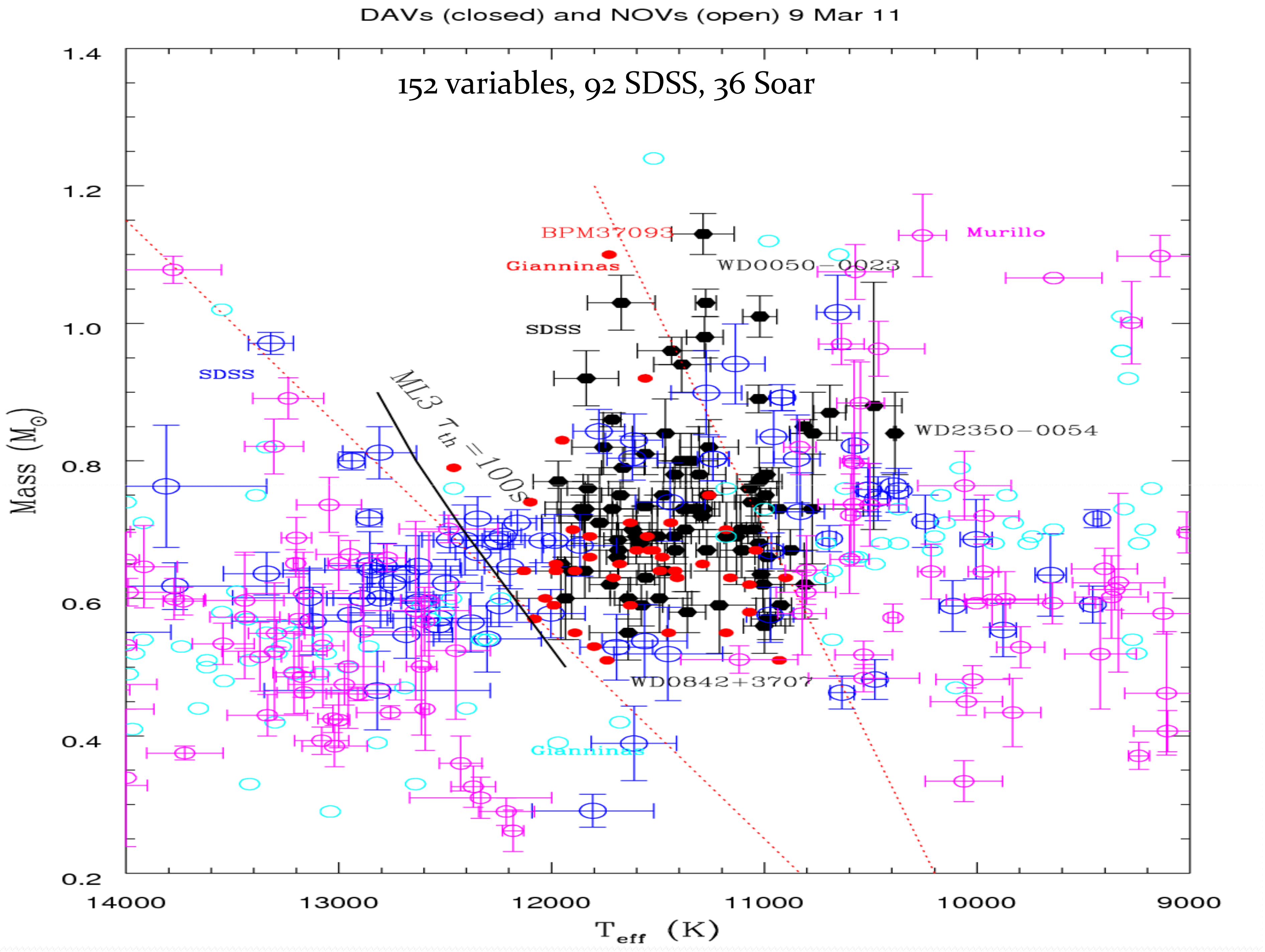


Mode identification

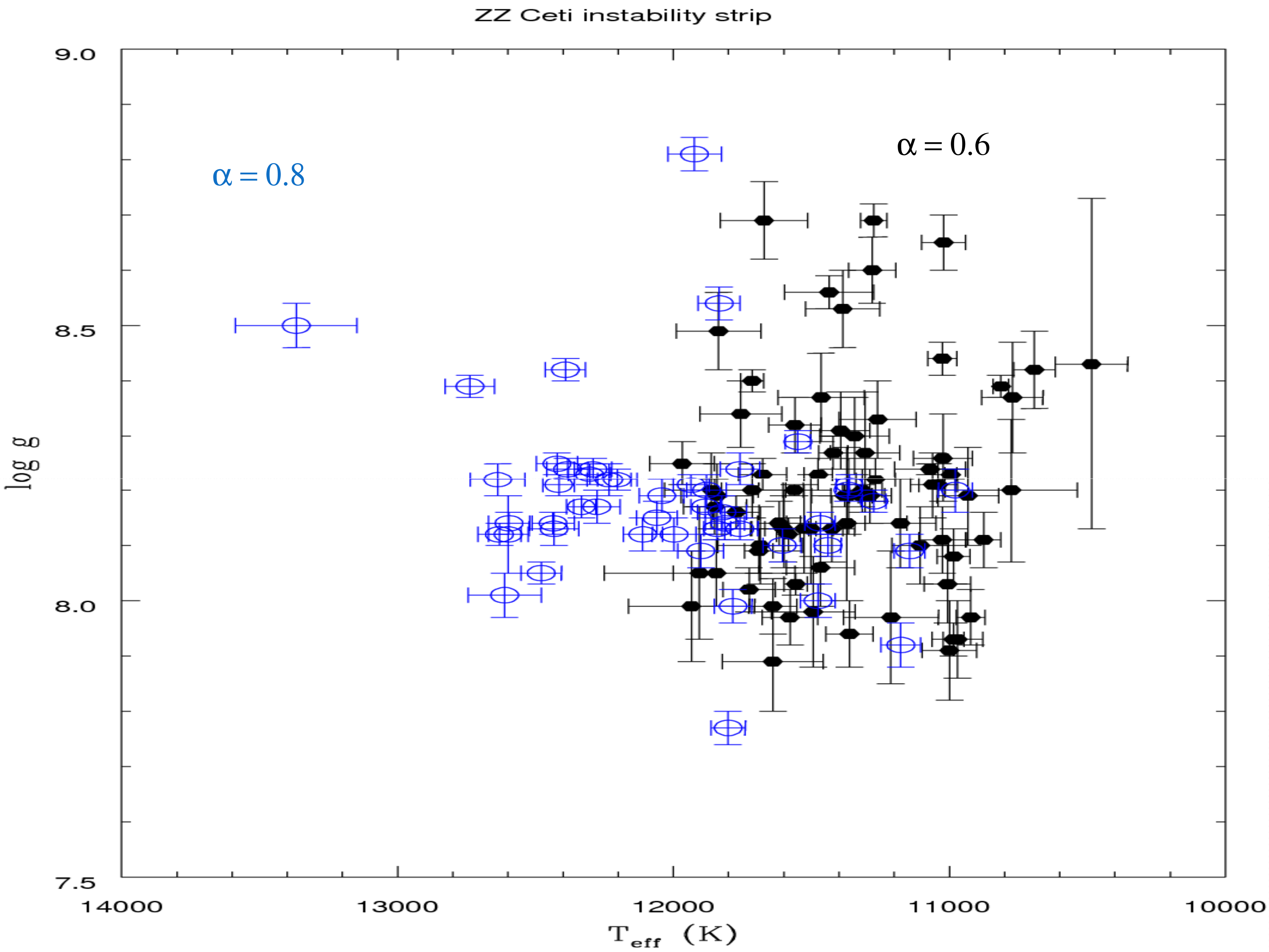


DAVs (closed) and NOVs (open)

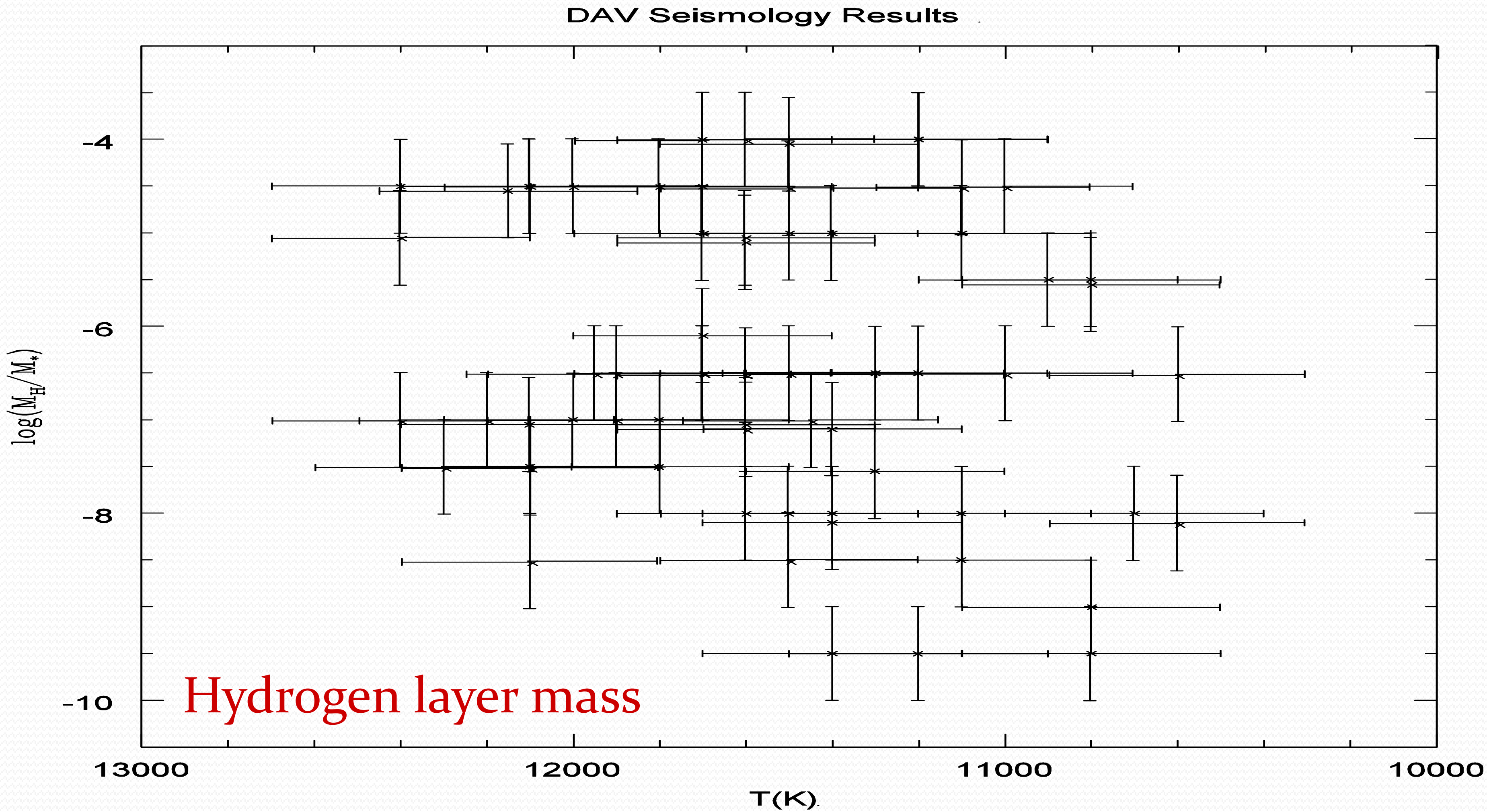




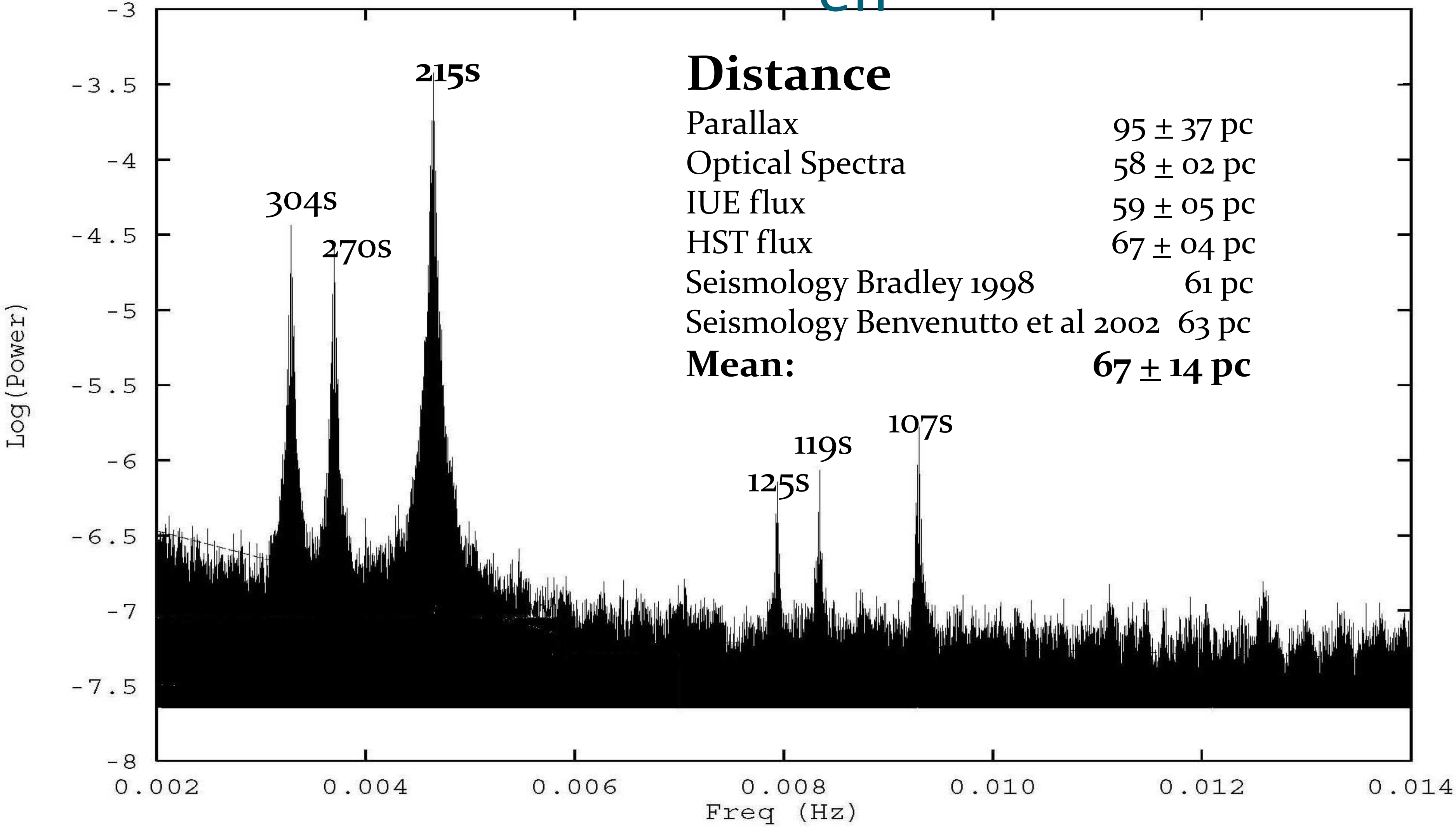
DAVs (closed) and NOVs (open) 9 Mar 11
152 variables, 92 SDSS, 36 Soar
BPM37093
Gianninas
WD0050−0023
Murillo
SDSS
SDSS
ML3 τ_{th} = 100s
WD2350−0054
WD0842+3707
Gianninas
Mass ($M_{\odot}$)
T_{eff} (K)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
14000
13000
12000
11000
10000
9000


ZZ Ceti instability strip
α = 0.8
α = 0.6
log g
9.0
8.5
8.0
7.5
14000
13000
12000
11000
10000
T eff (K)

Castanheira & Kepler 2008



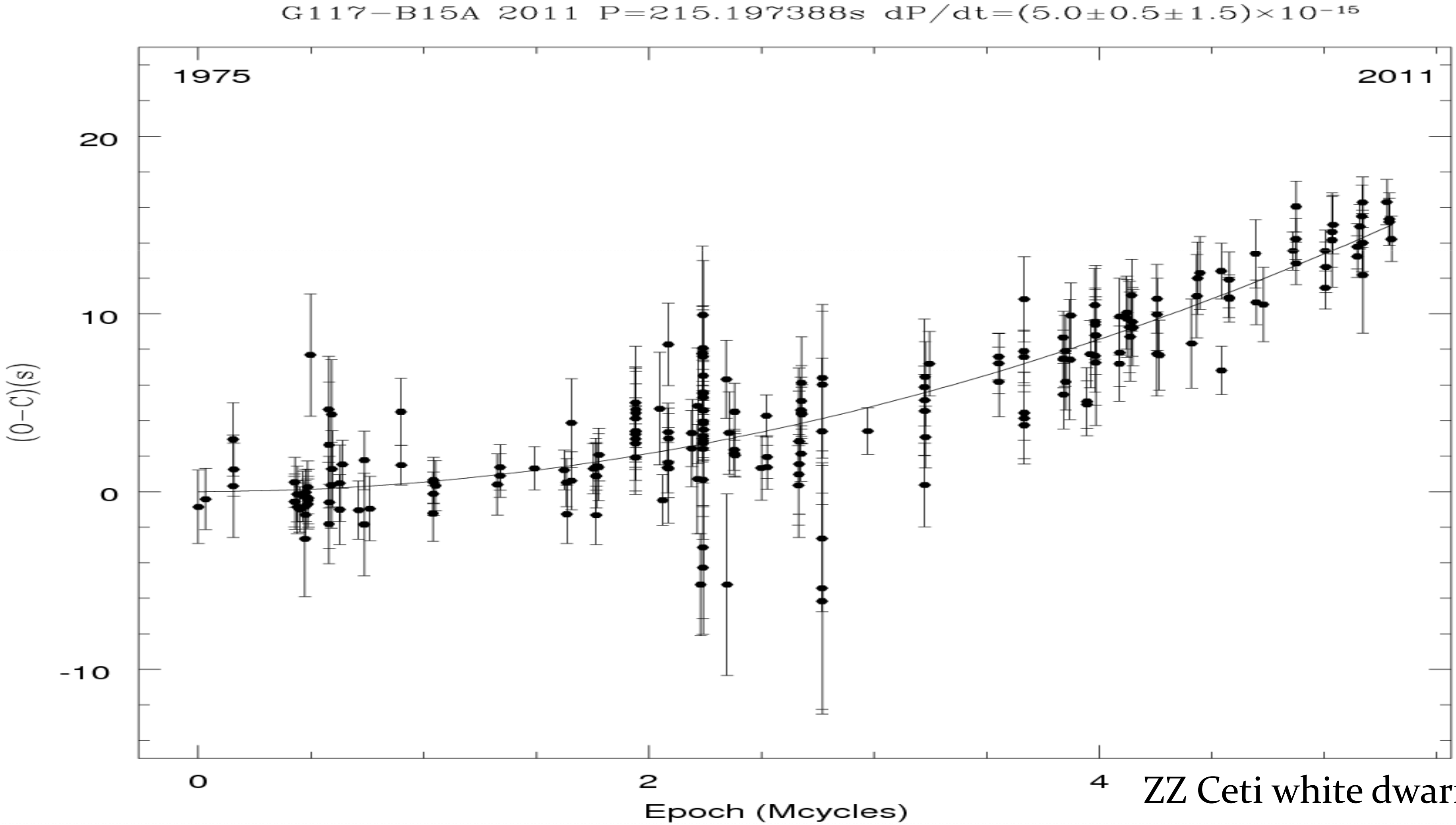
G117-B15A: DAV T_{eff} = 12000K



Distance

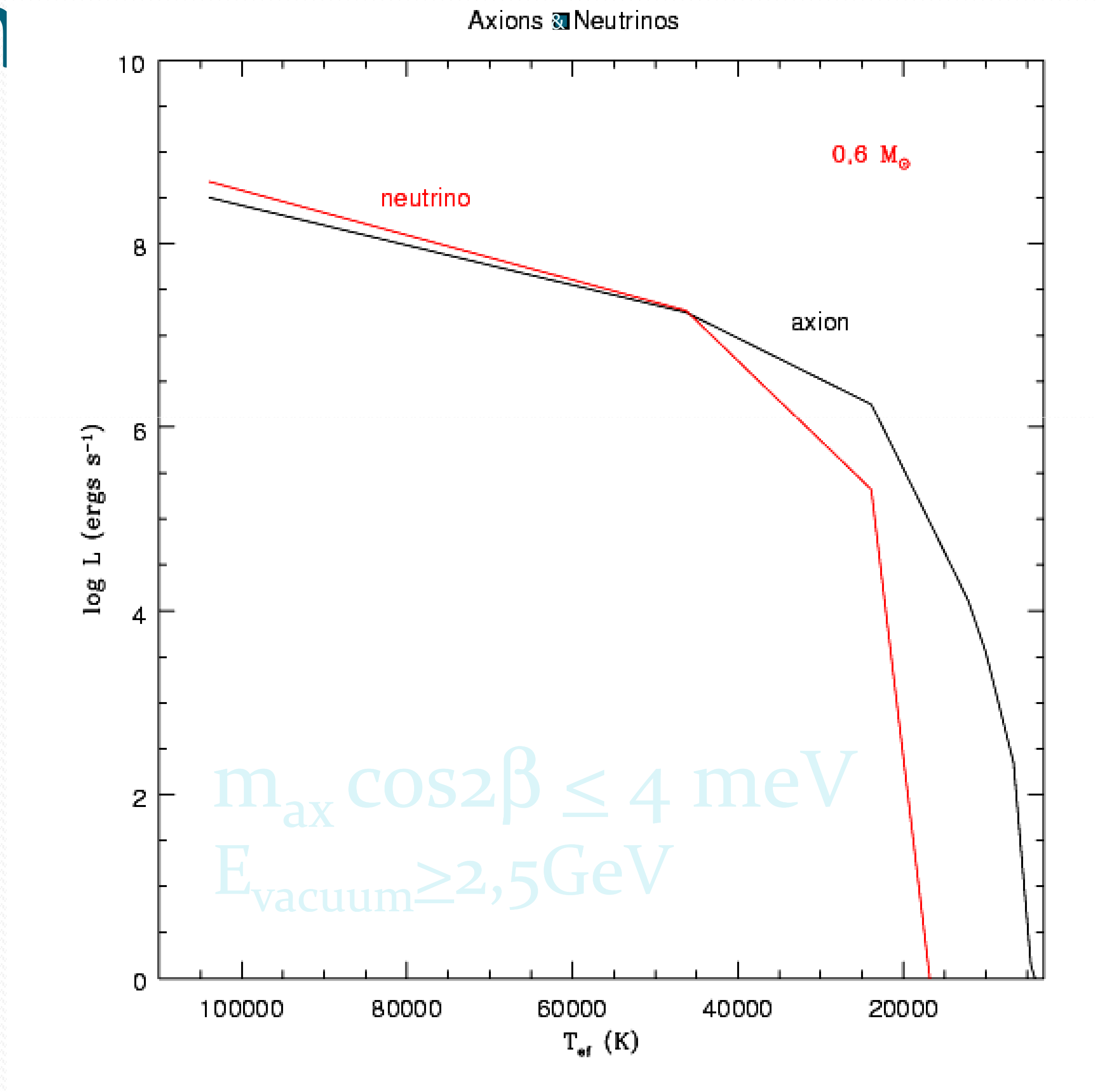
Parallax	95 ± 37 pc
Optical Spectra	58 ± 02 pc
IUE flux	59 ± 05 pc
HST flux	67 ± 04 pc
Seismology Bradley 1998	61 pc
Seismology Benvenutto et al 2002	63 pc
Mean:	**67 ± 14 pc**

Measure evolution
core composition, axions, dG/dt



ZZ Ceti white dwarf

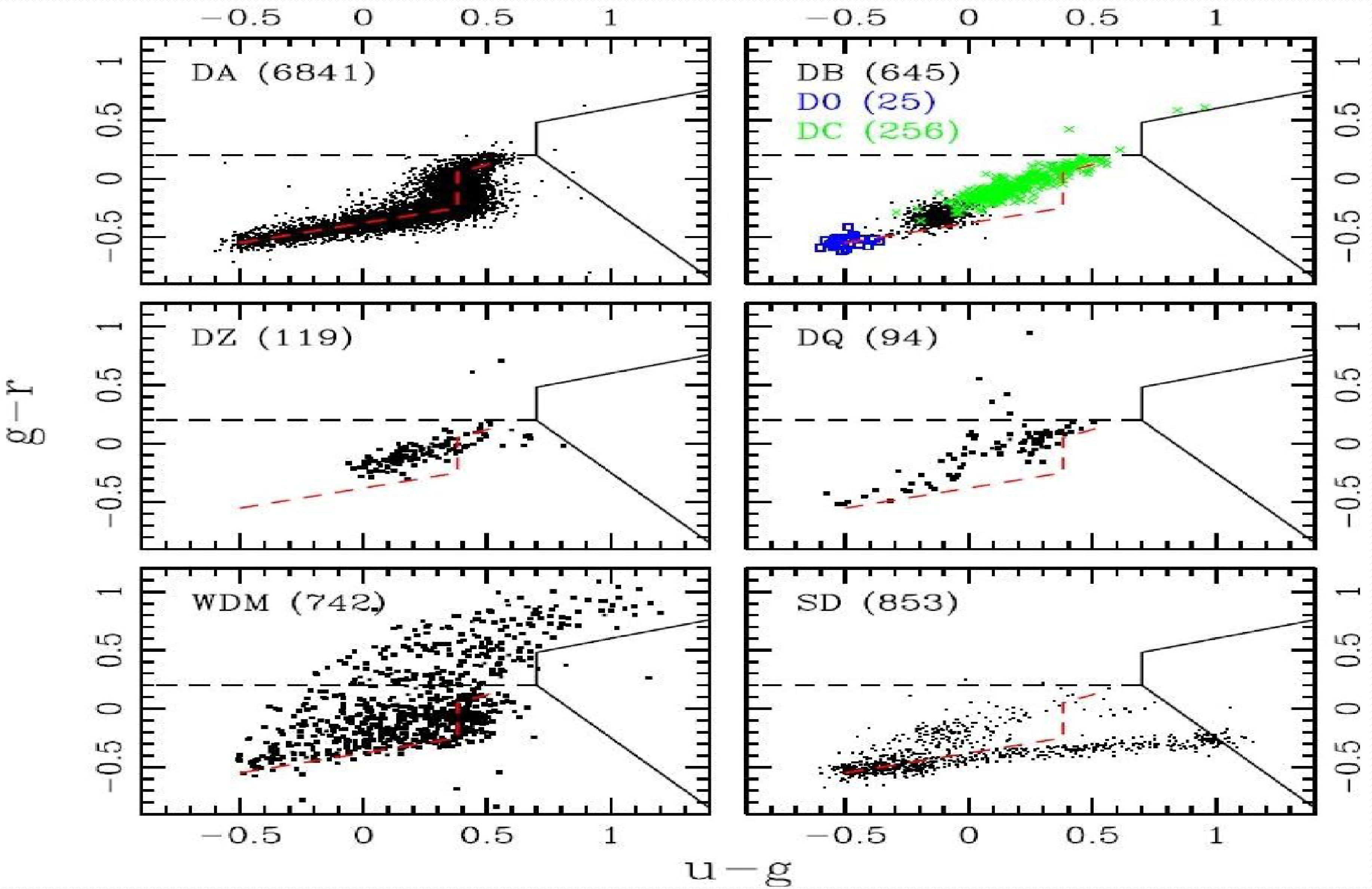
Axion



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

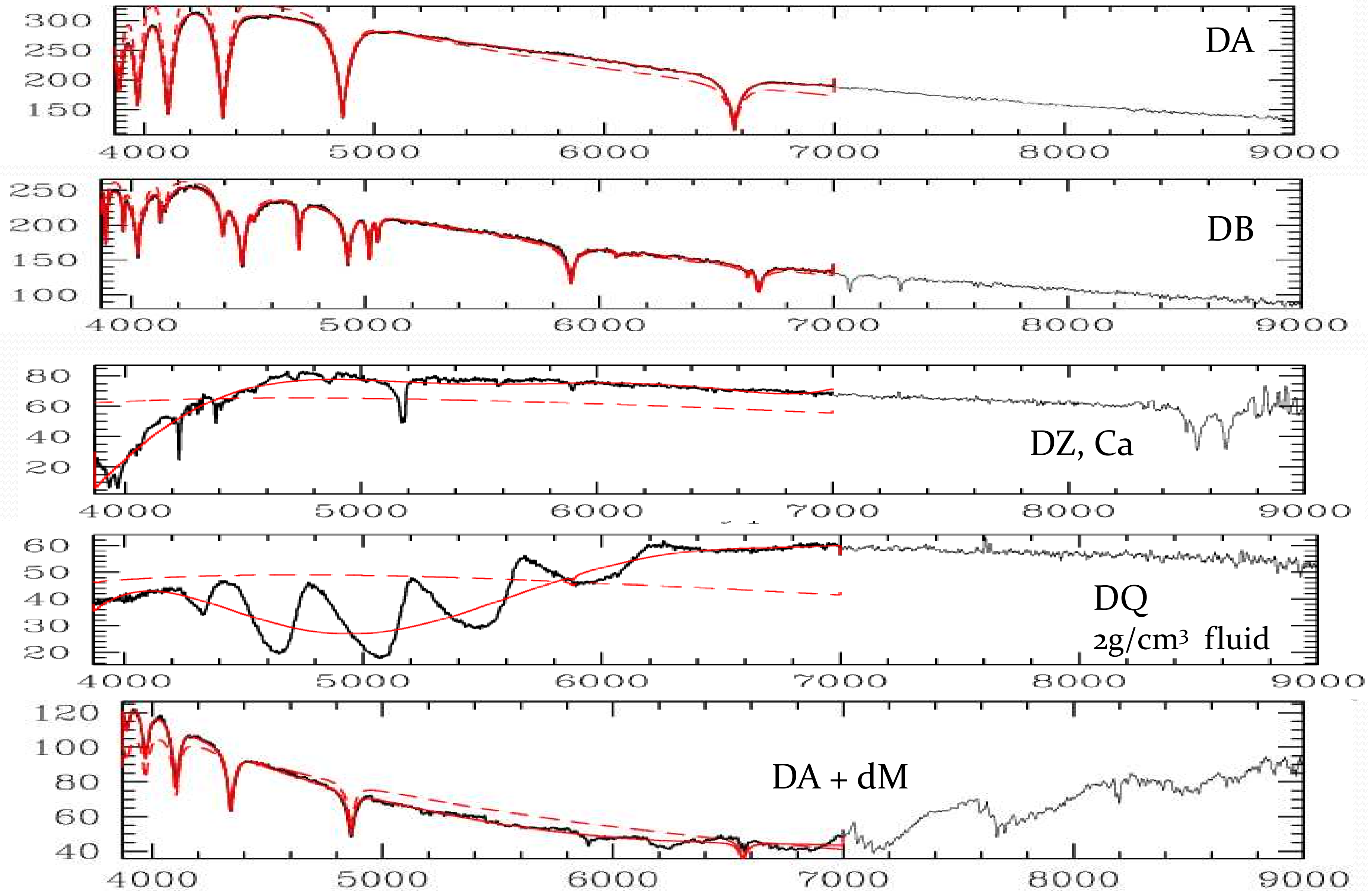
$E_{vacuum} \geq 2{,}5$GeV

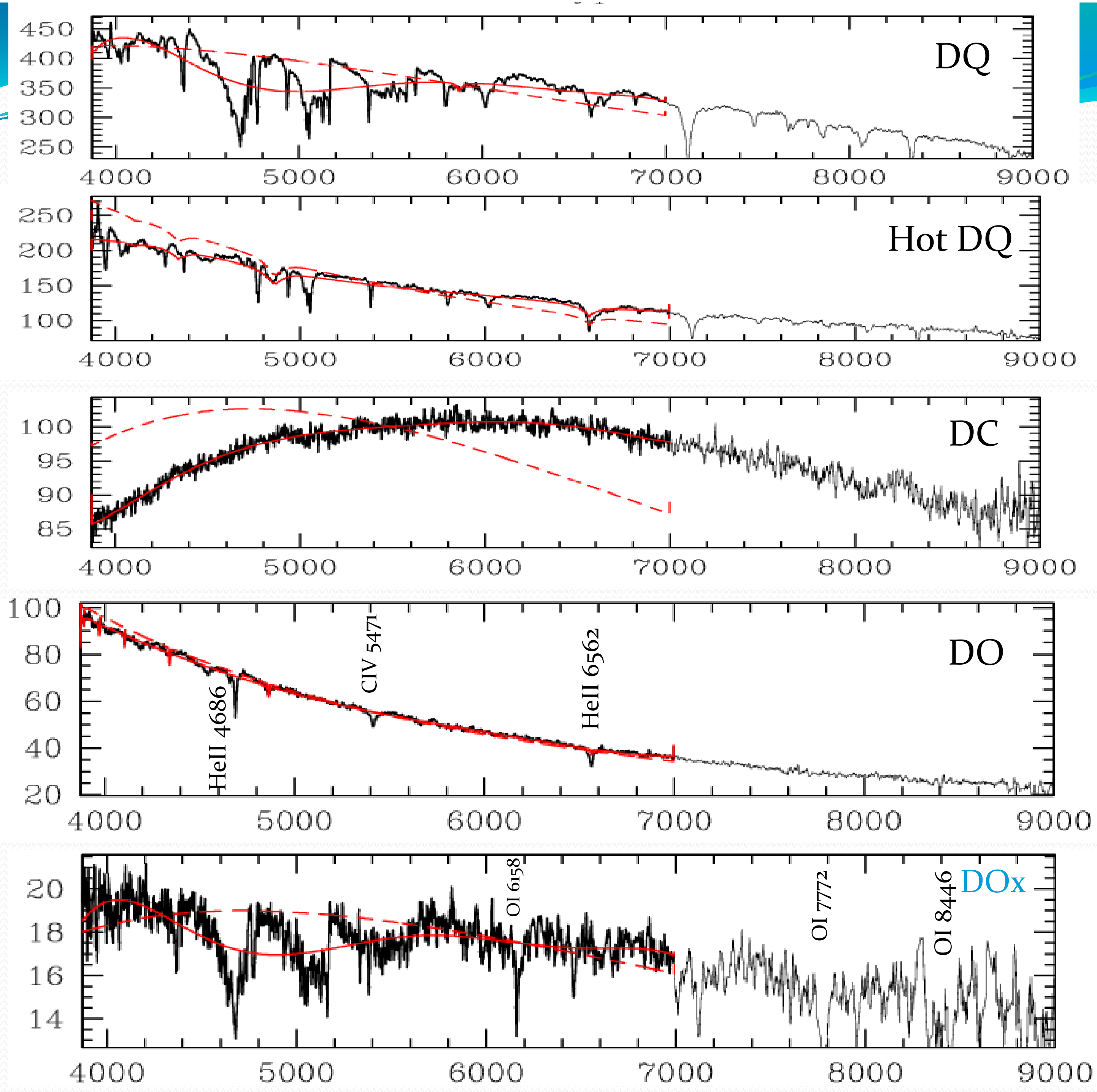
SDSS DR4



DA (6841)
DB (645)
DO (25)
DC (256)
DZ (119)
DQ (94)
WDM (742)
SD (853)
g−r
u−g
−0.5
0
0.5
1

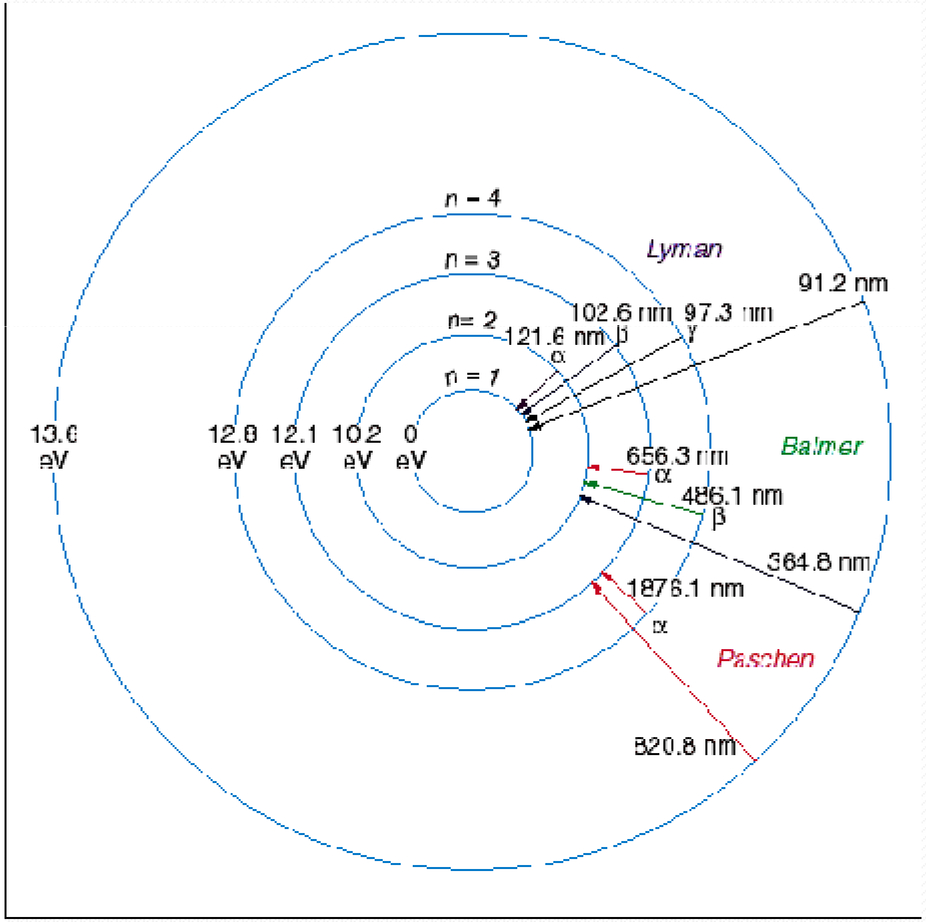
SDSS 43800 spectra

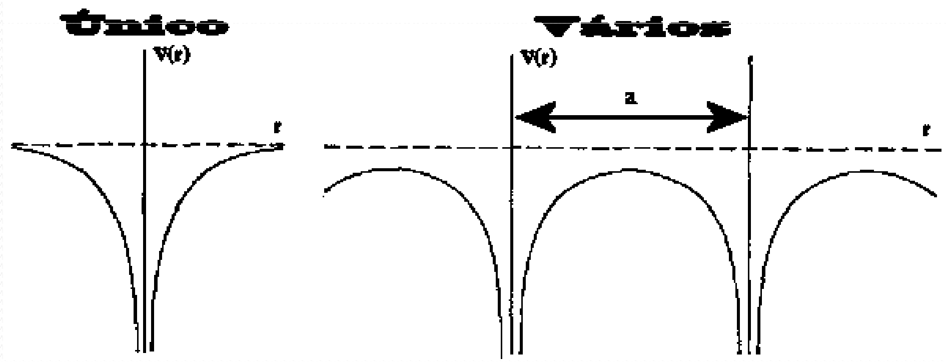




DQ
Hot DQ
DC
DO
HeII 4686
CIV 5471
HeII 6562
DOx
OI 6158
OI 7772
OI 8446
4000
5000
6000
7000
8000
9000

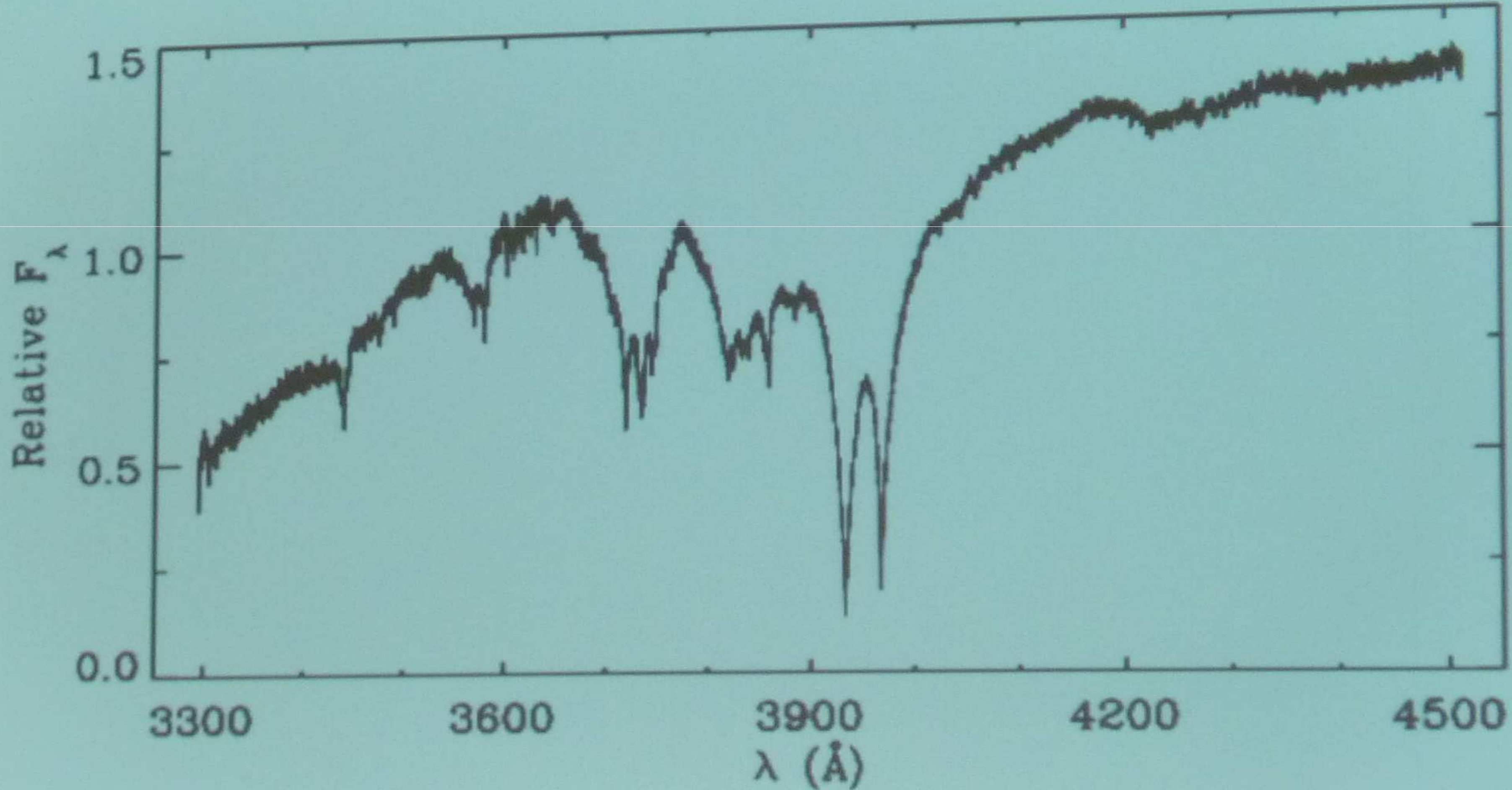
Átomo de hidrogênio





van Maanen's Star

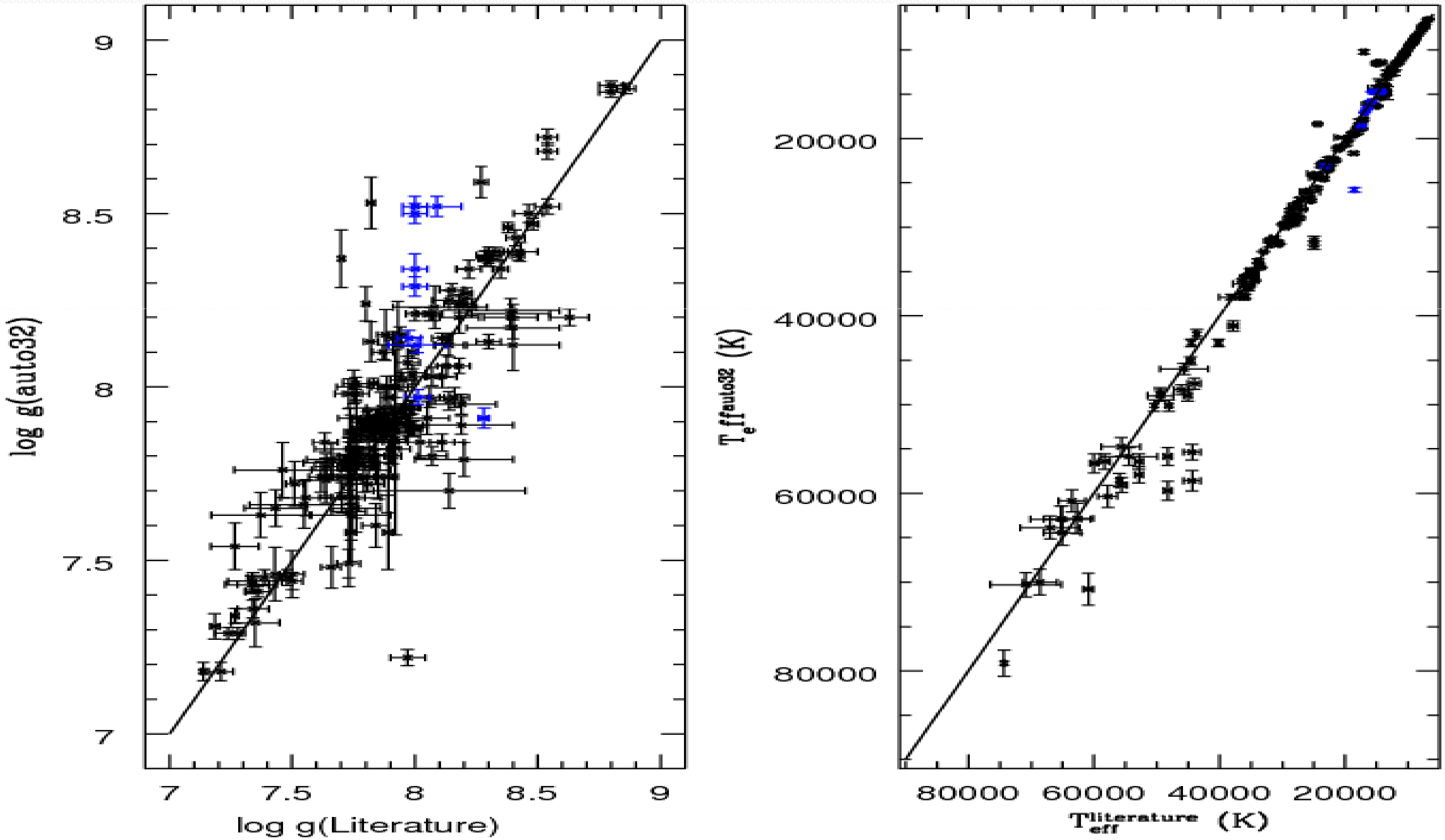
(van Maanen 1917; SPY project: R. Napiwotzki)

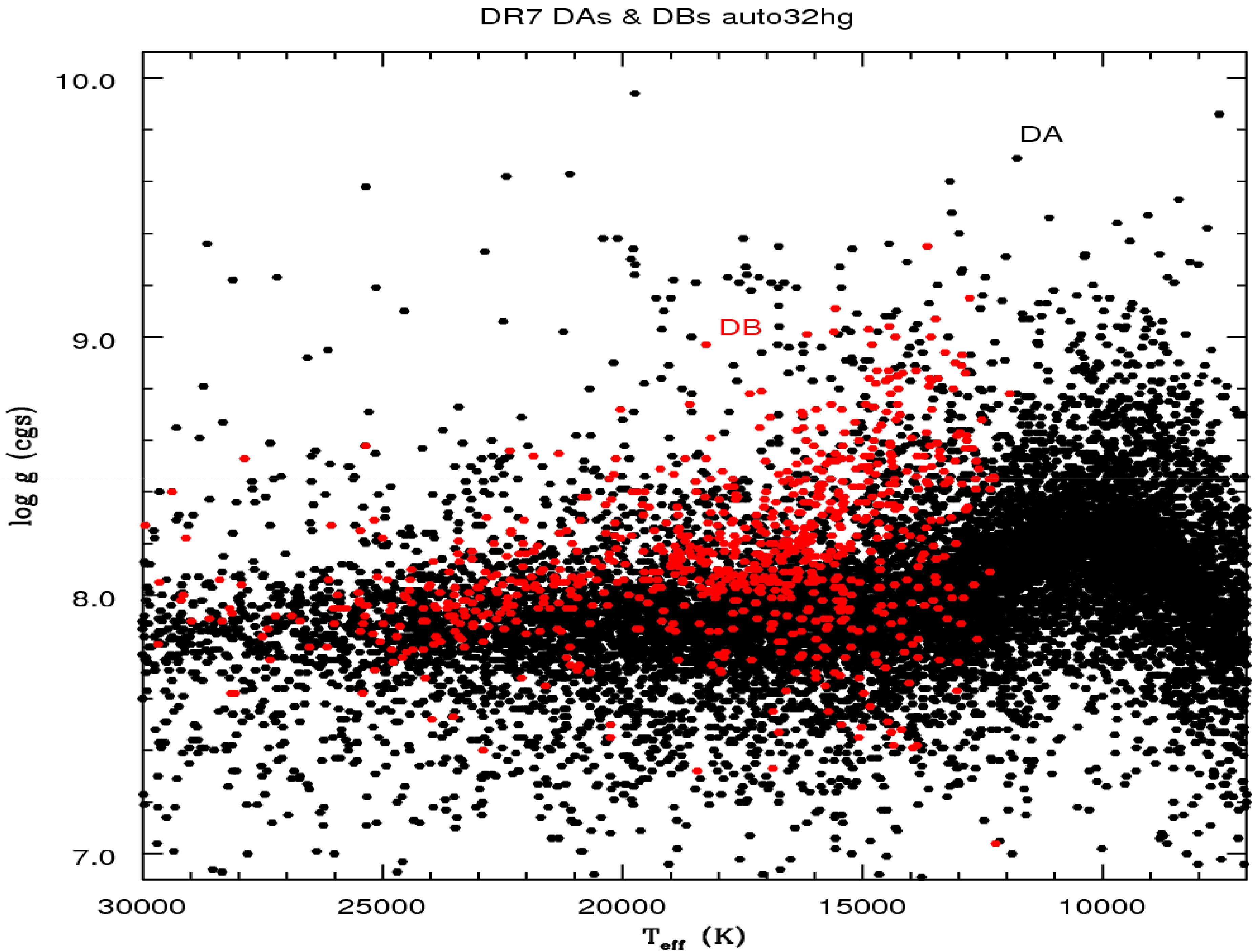


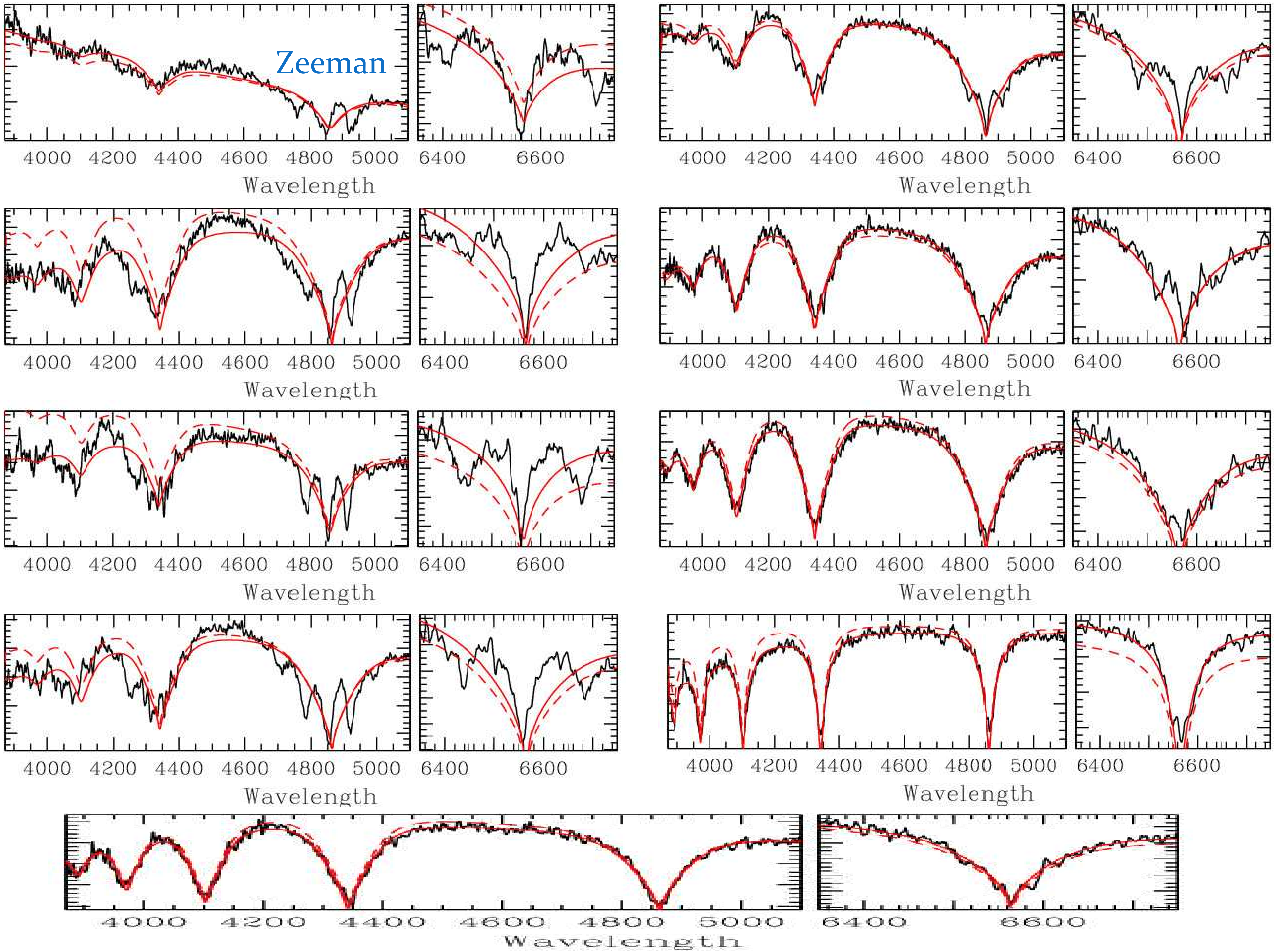
DR7 – Kleinman, Kepler, Nitta et al. 2011

- 13724 DAs
  7.3,1.7 x DR1,DR4
- 961 DBs
  5.6,1.35 x DR1,DR4
- 968 DHs
  32.3,108 x DR1,DR4
  - 785 DAH
  - 62 DBH
- 609 DCs
  4.5, 2.1 x DR1,DR4
- 437 DZs
  7.7, 3.3 x DR1, DR4
- 218 DQs
  4.8, 2.1 x DR1, DR4
- 48 DOs
  3.7, 1.2 x DR1, DR4
- 1640 WDMs
  8.2 x DR1
- 98 Mixed WDs
- 1135 Uncertain WDs
- 1409 Subdwarfs

Literature


log g(auto32)
9
8.5
8
7.5
7
7
7.5
8
8.5
9
log g(Literature)
Teffauto32 (K)
20000
40000
60000
80000
80000
60000
40000
20000
Tliterature eff (K)


DR7 DAs & DBs auto32hg
10.0
9.0
8.0
7.0
log g (cgs)
30000
25000
20000
15000
10000
T_eff (K)
DA
DB



Zeeman
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength
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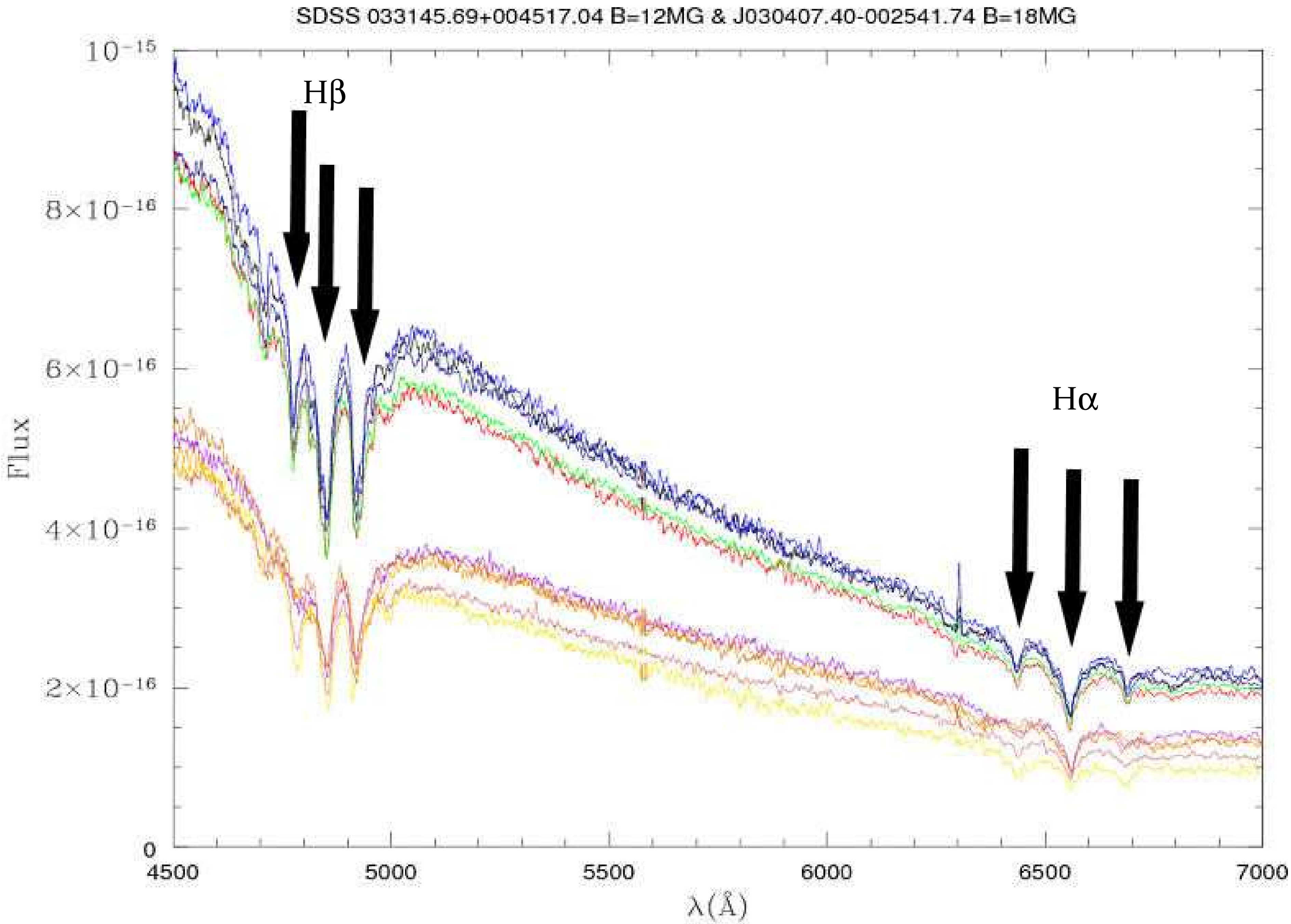
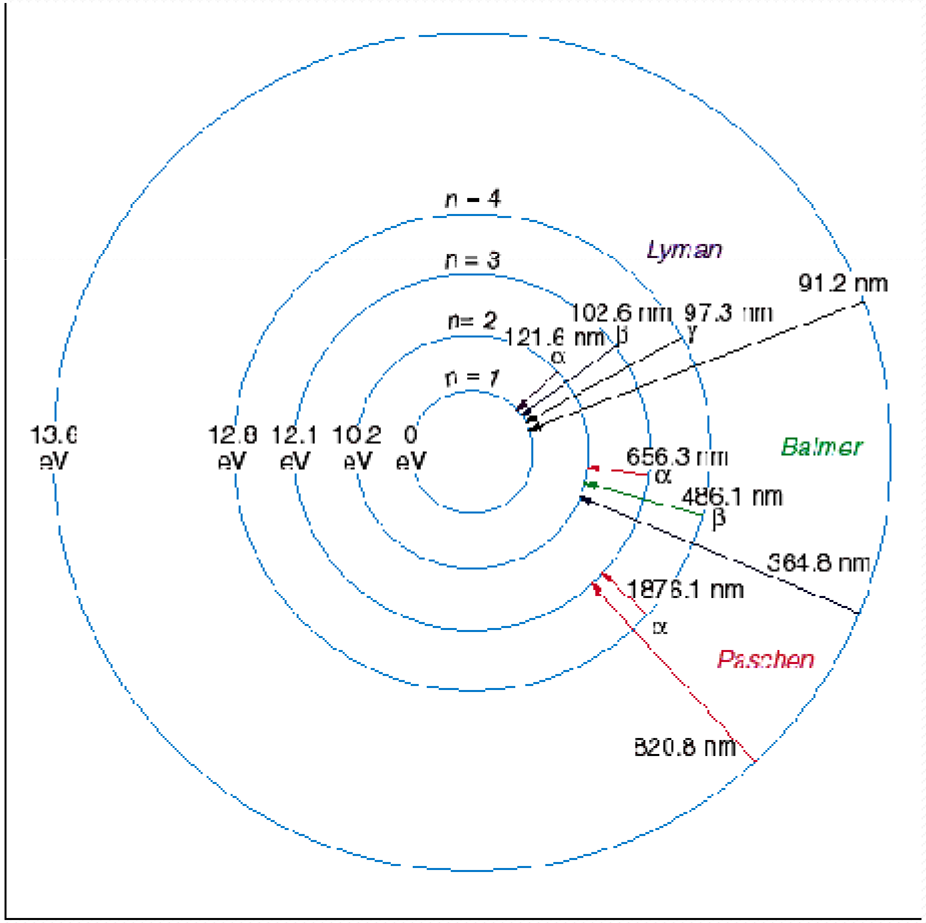
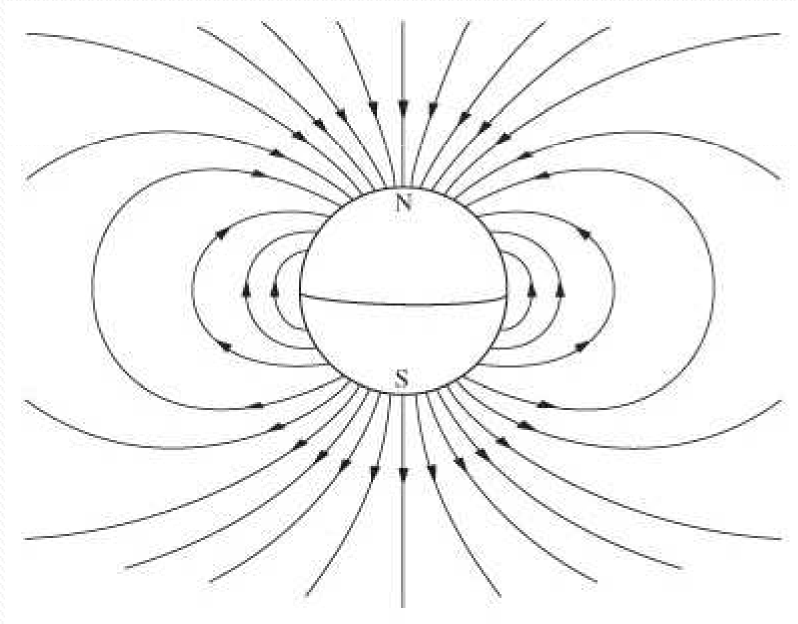
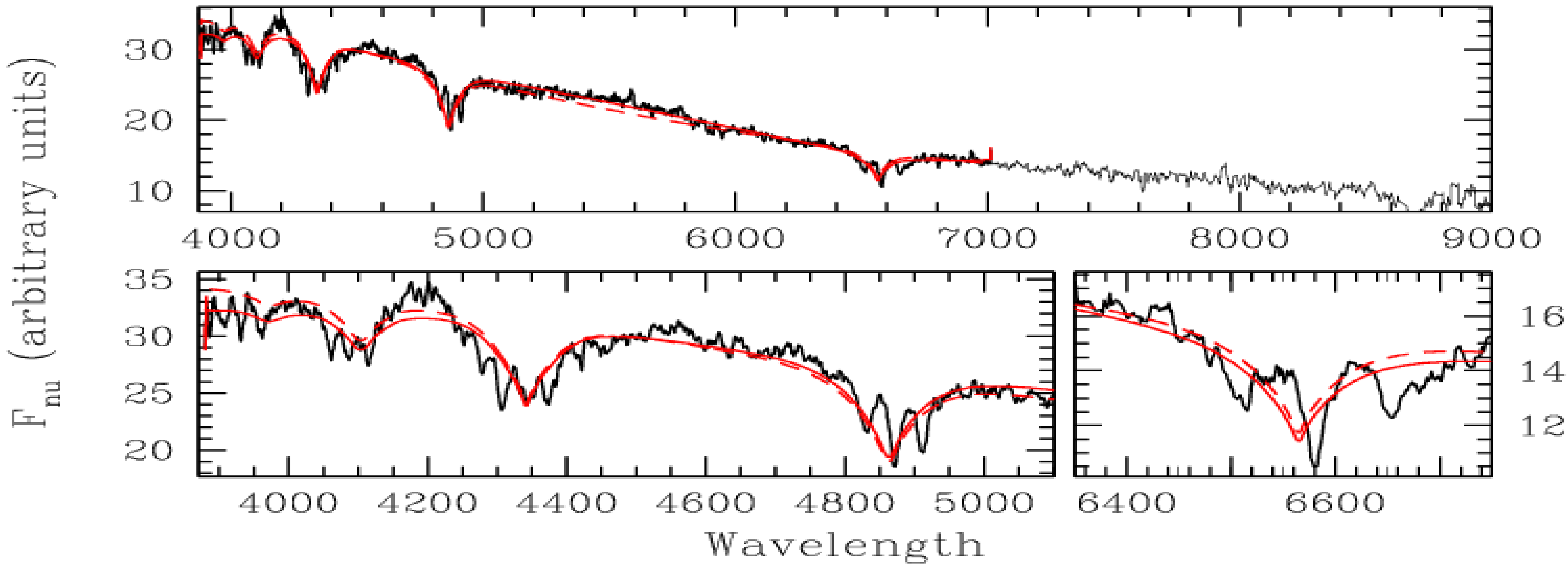
6400 6600
Wavelength
4000 4200 4400 4600 4800 5000
6400 6600
Wavelength

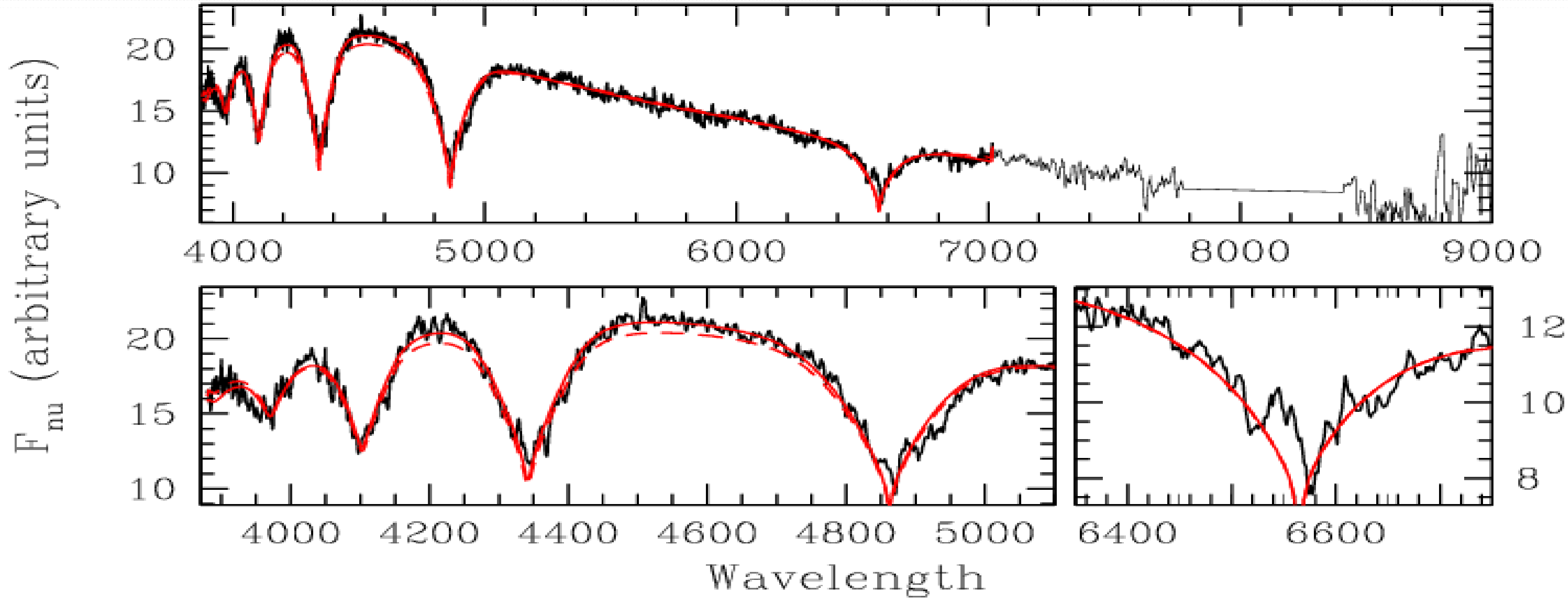

SDSS 033145.69+004517.04 B=12MG & J030407.40-002541.74 B=18MG
Hβ
Hα
Flux
λ(Å)
10⁻¹⁵
8×10⁻¹⁶
6×10⁻¹⁶
4×10⁻¹⁶
2×10⁻¹⁶
0
4500
5000
5500
6000
6500
7000

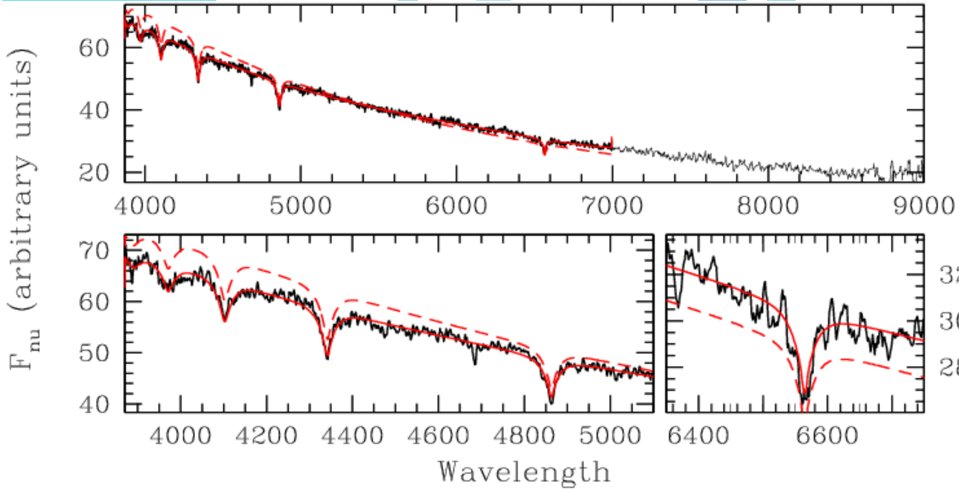
Potential central & directional



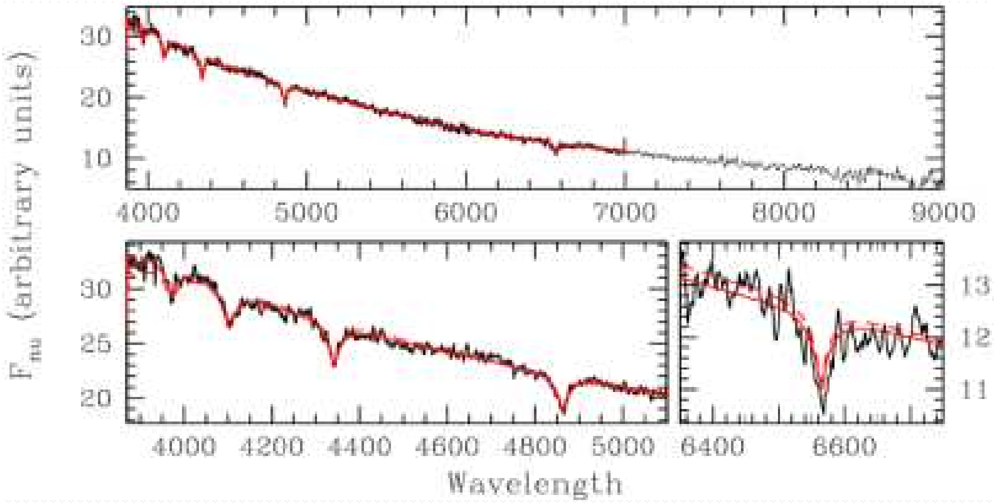



F_nu (arbitrary units)
Wavelength
10
20
30
4000
5000
6000
7000
8000
9000
20
25
30
35
4000
4200
4400
4600
4800
5000
6400
6600
12
14
16

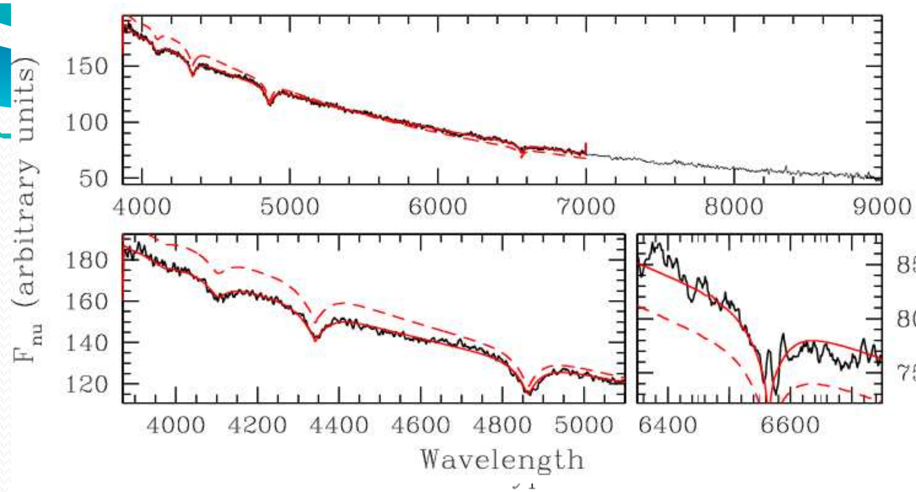

F_nu (arbitrary units)
Wavelength
10
15
20
4000
5000
6000
7000
8000
9000
10
15
20
4000
4200
4400
4600
4800
5000
6400
6600
8
10
12



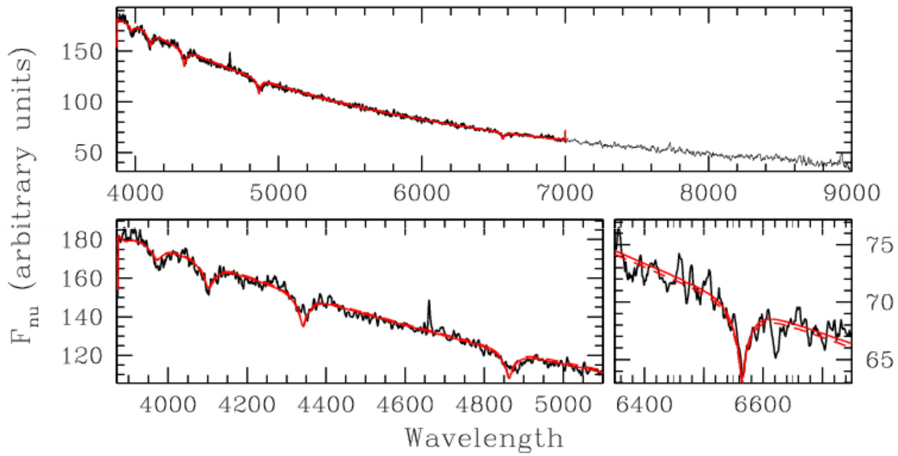
Fnu (arbitrary units)
Wavelength
4000 5000 6000 7000 8000 9000
4000 4200 4400 4600 4800 5000 6400 6600



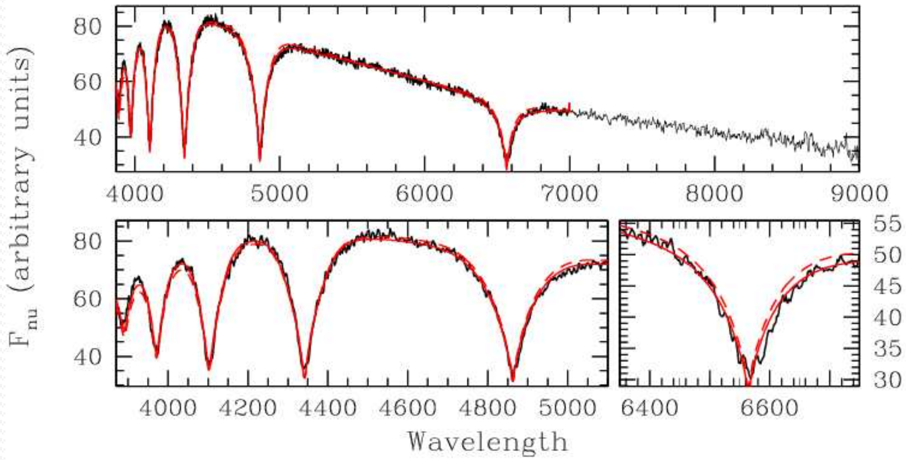
Fnu (arbitrary units)
Wavelength
4000 5000 6000 7000 8000 9000
4000 4200 4400 4600 4800 5000 6400 6600



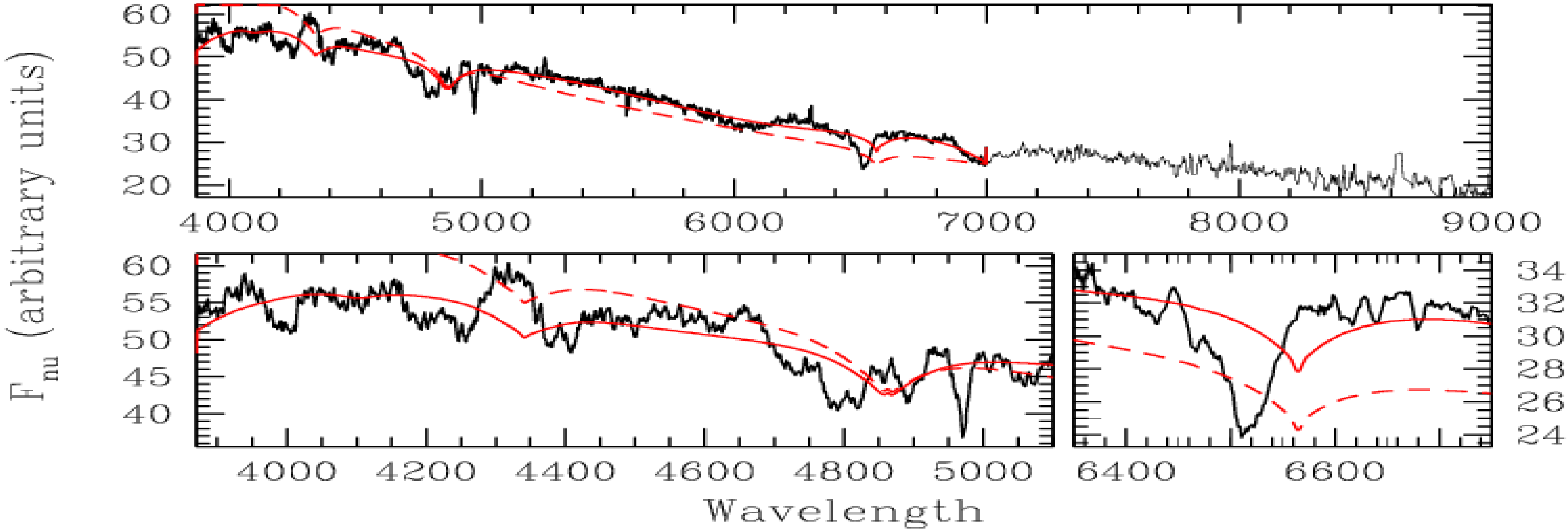
Fnu (arbitrary units)
Wavelength
4000 5000 6000 7000 8000 9000
4000 4200 4400 4600 4800 5000 6400 6600



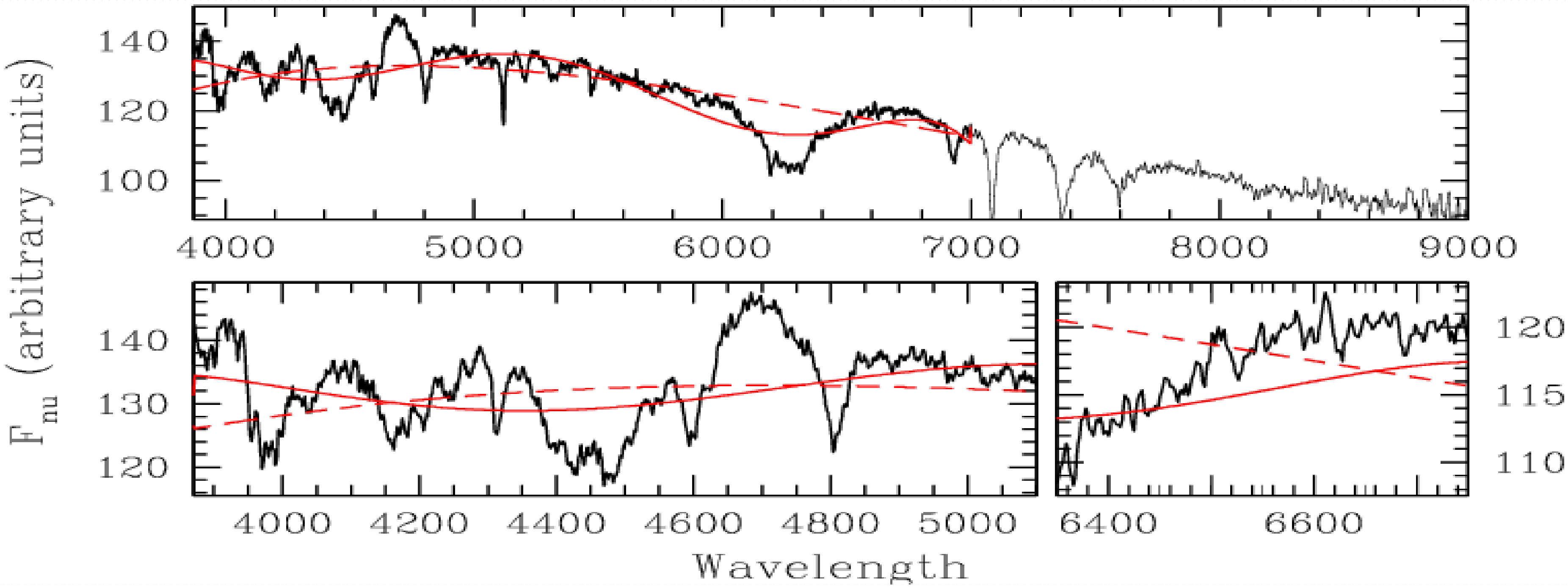
Fnu (arbitrary units)
Wavelength
4000 5000 6000 7000 8000 9000
4000 4200 4400 4600 4800 5000 6400 6600



Fnu (arbitrary units)
Wavelength
4000 5000 6000 7000 8000 9000
4000 4200 4400 4600 4800 5000 6400 6600



F_nu (arbitrary units)
Wavelength



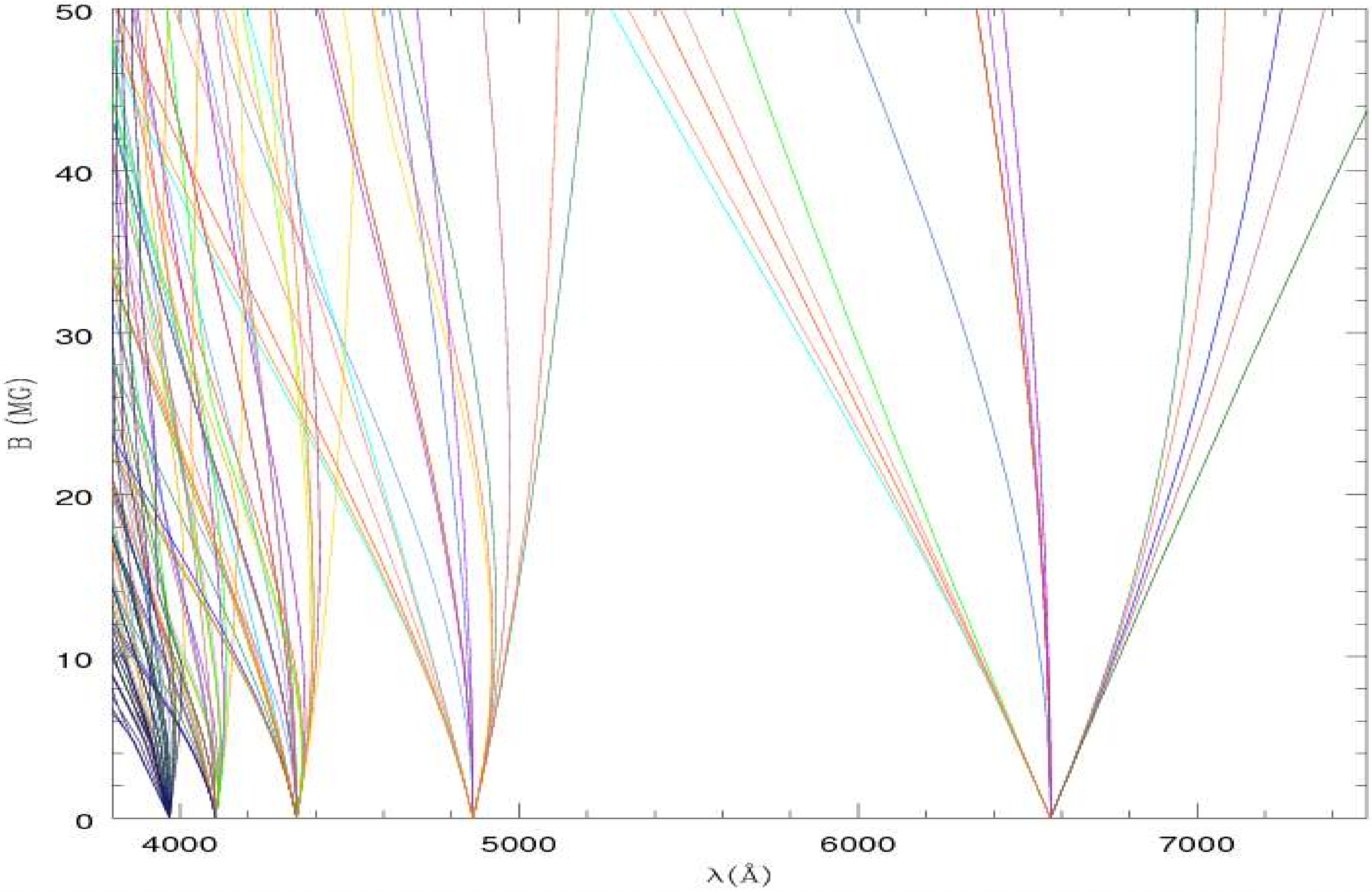
F_nu (arbitrary units)
Wavelength

Analysis of hydrogen-rich magnetic white dwarfs detected in the Sloan Digital Sky Survey

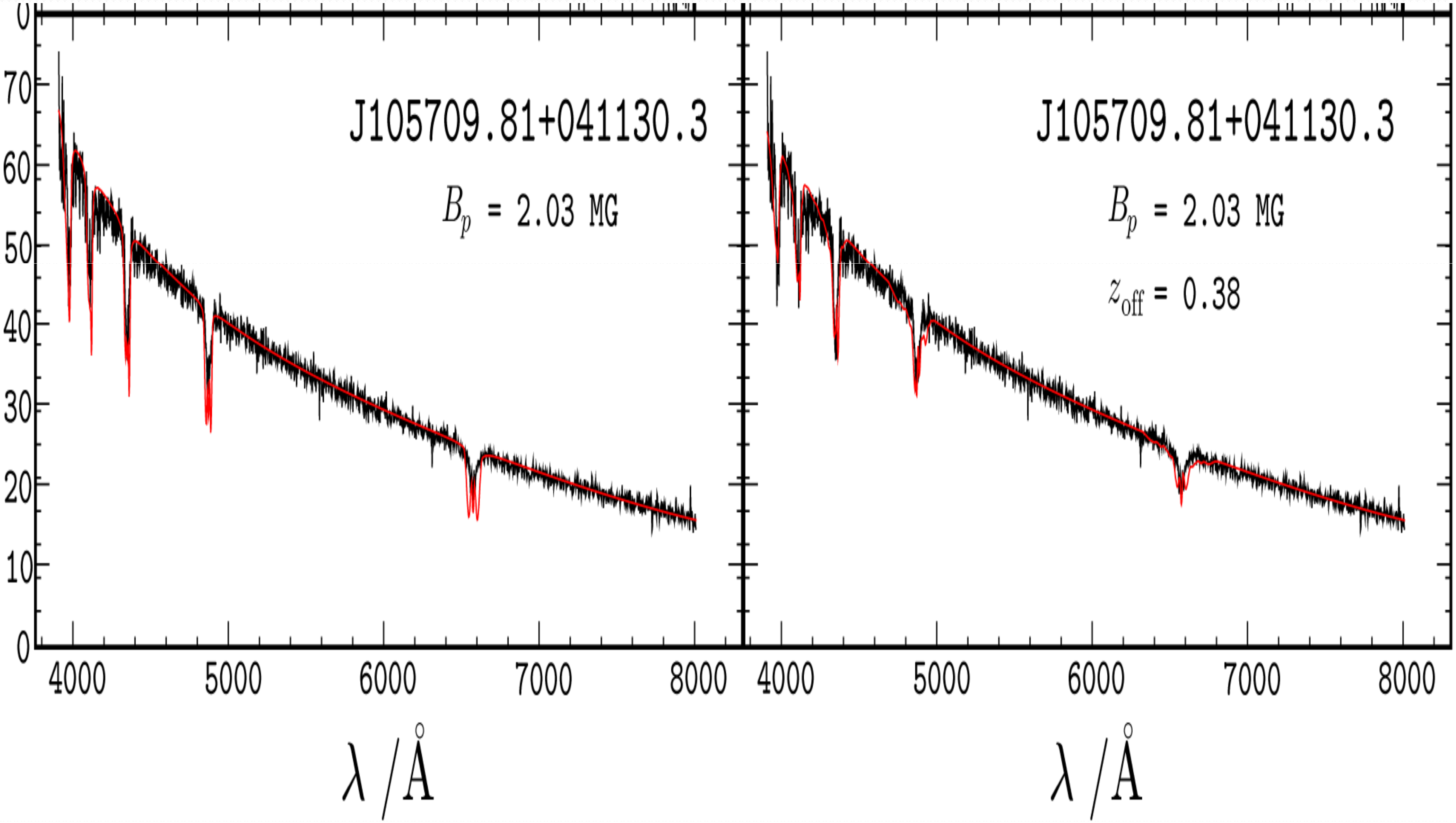
Baybars Külebi, Stefan Jordan, Fabian Euchner, Boris Gänsicke & Heiko Hirsch 2009

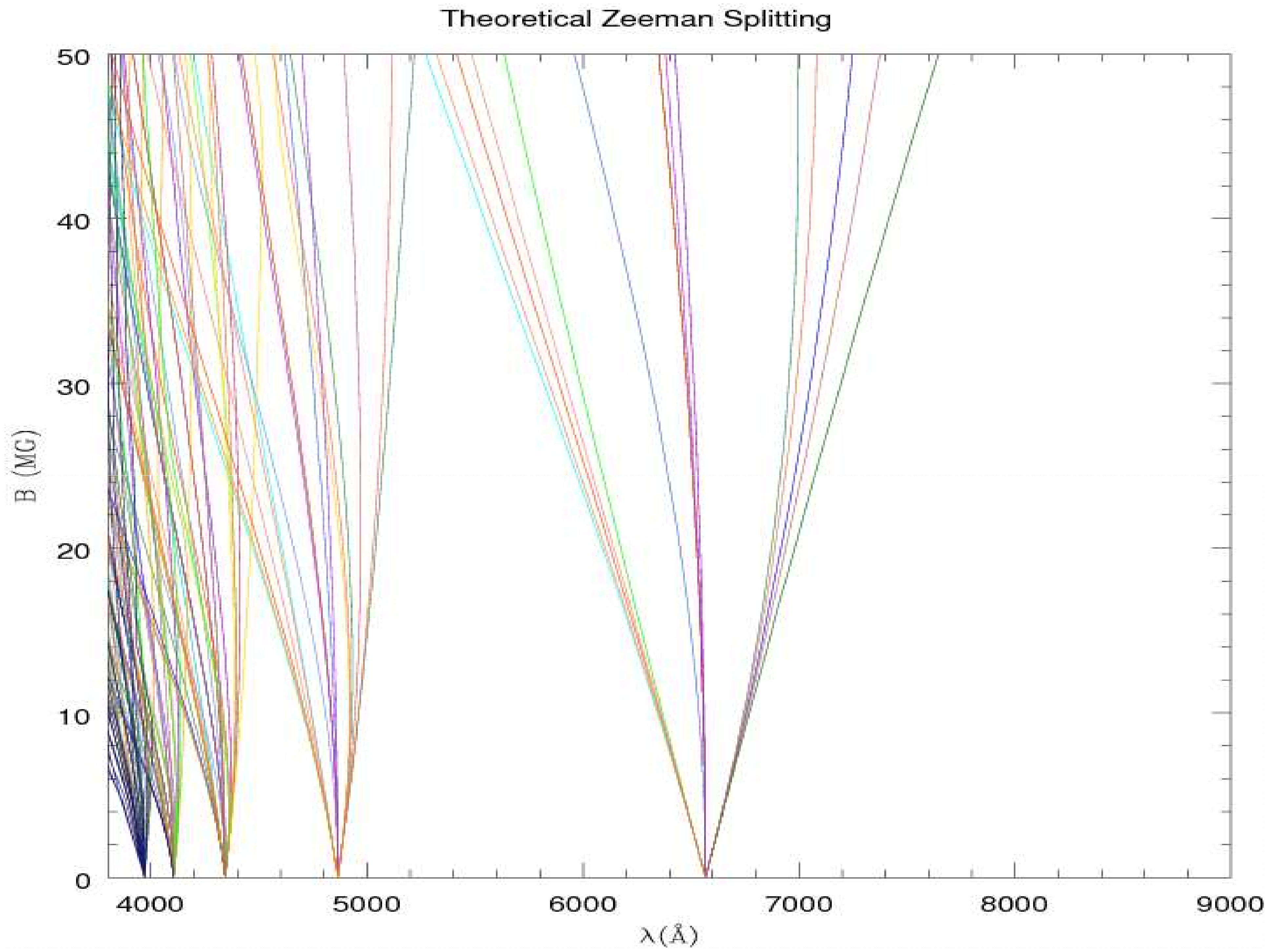
-modeled the structure of the surface magnetic fields of the hydrogen-rich white dwarfs and

-analysed the spectra of all known magnetic DAs from the SDSS : 97 previously published plus 44 newly discovered.

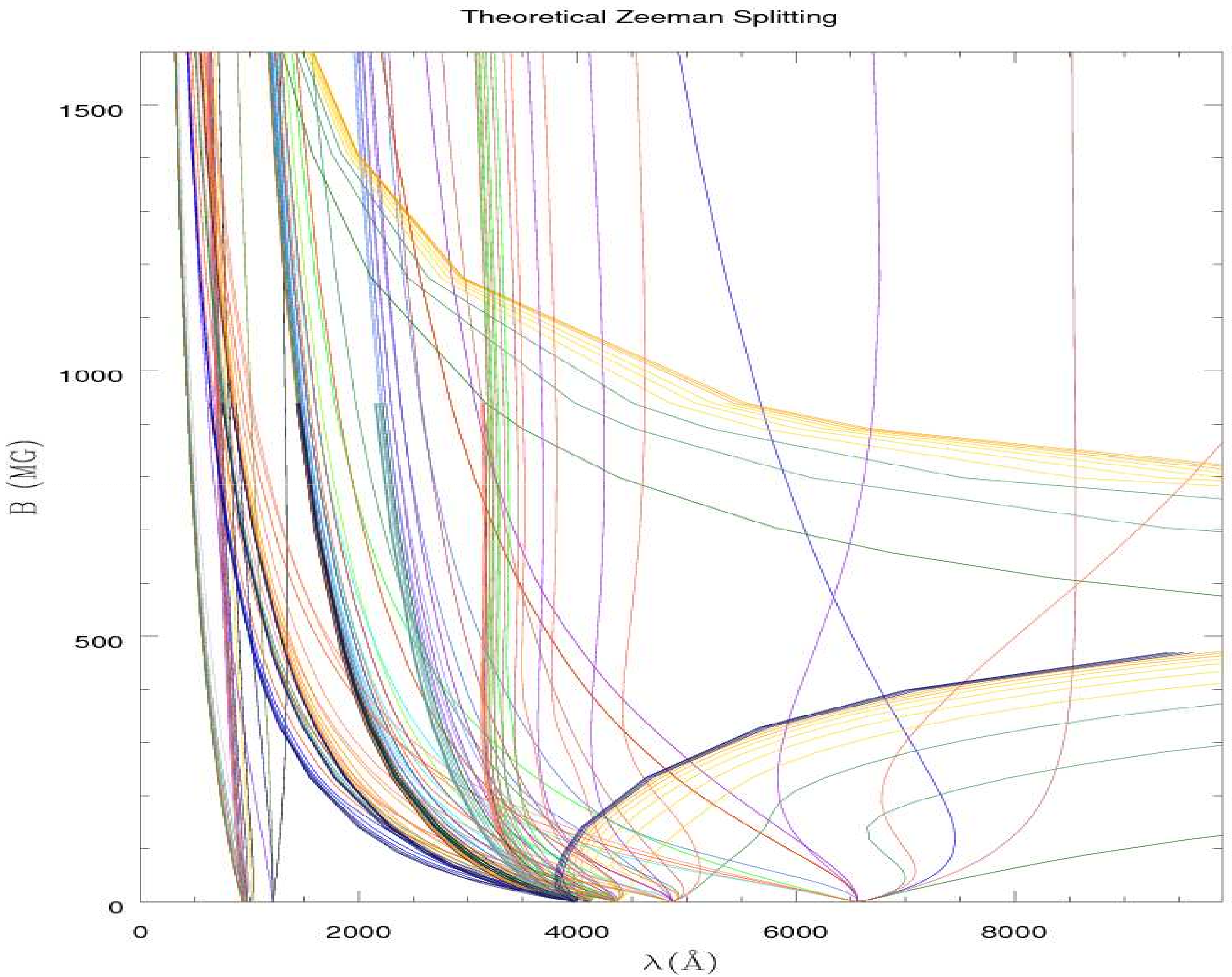


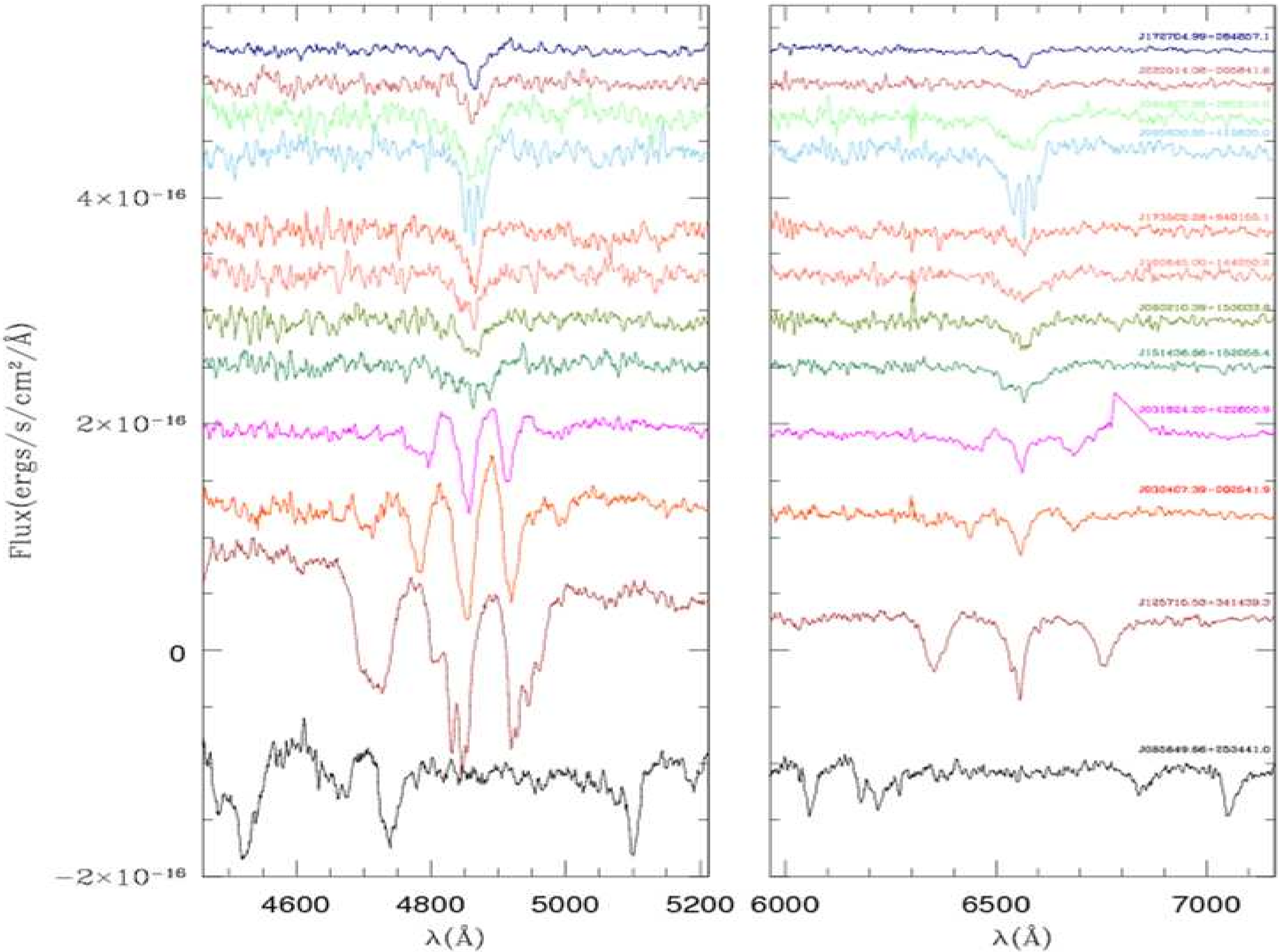
Off-center dipole – Külebi 2010

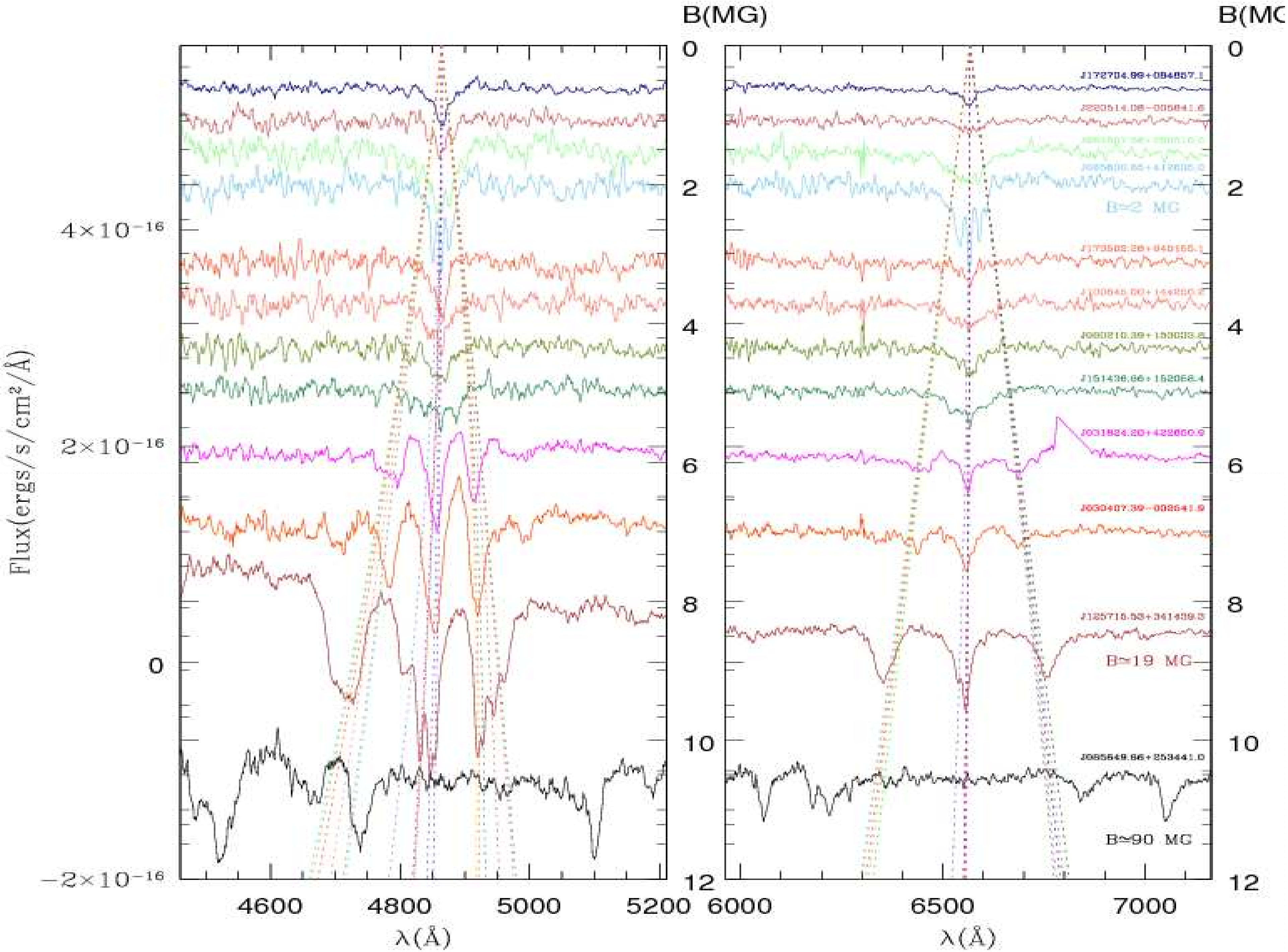




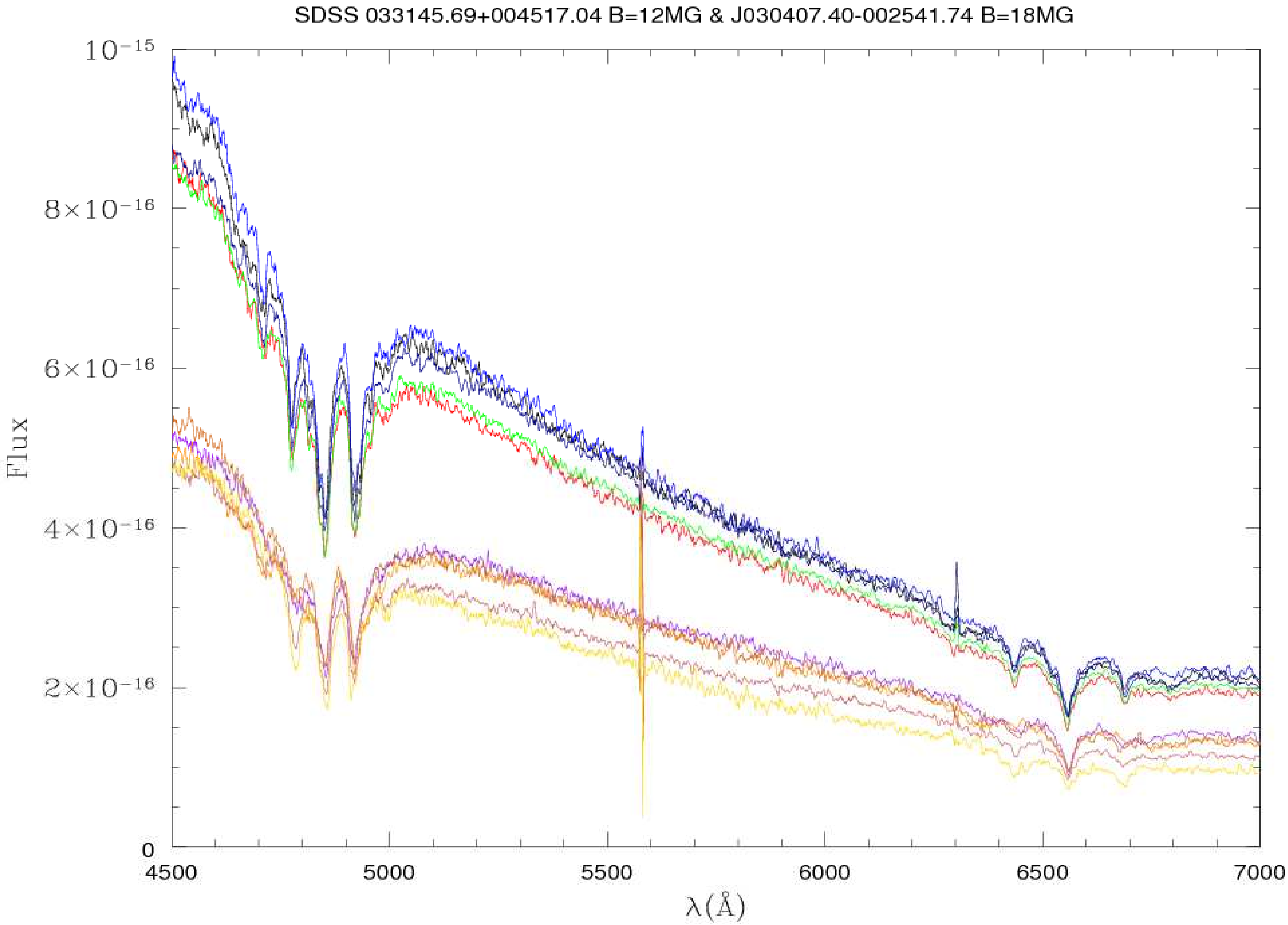
Theoretical Zeeman Splitting
B (MG)
λ(Å)
0
10
20
30
40
50
4000
5000
6000
7000
8000
9000


Theoretical Zeeman Splitting
B (MG)
1500
1000
500
0
2000
4000
6000
8000
λ(Å)

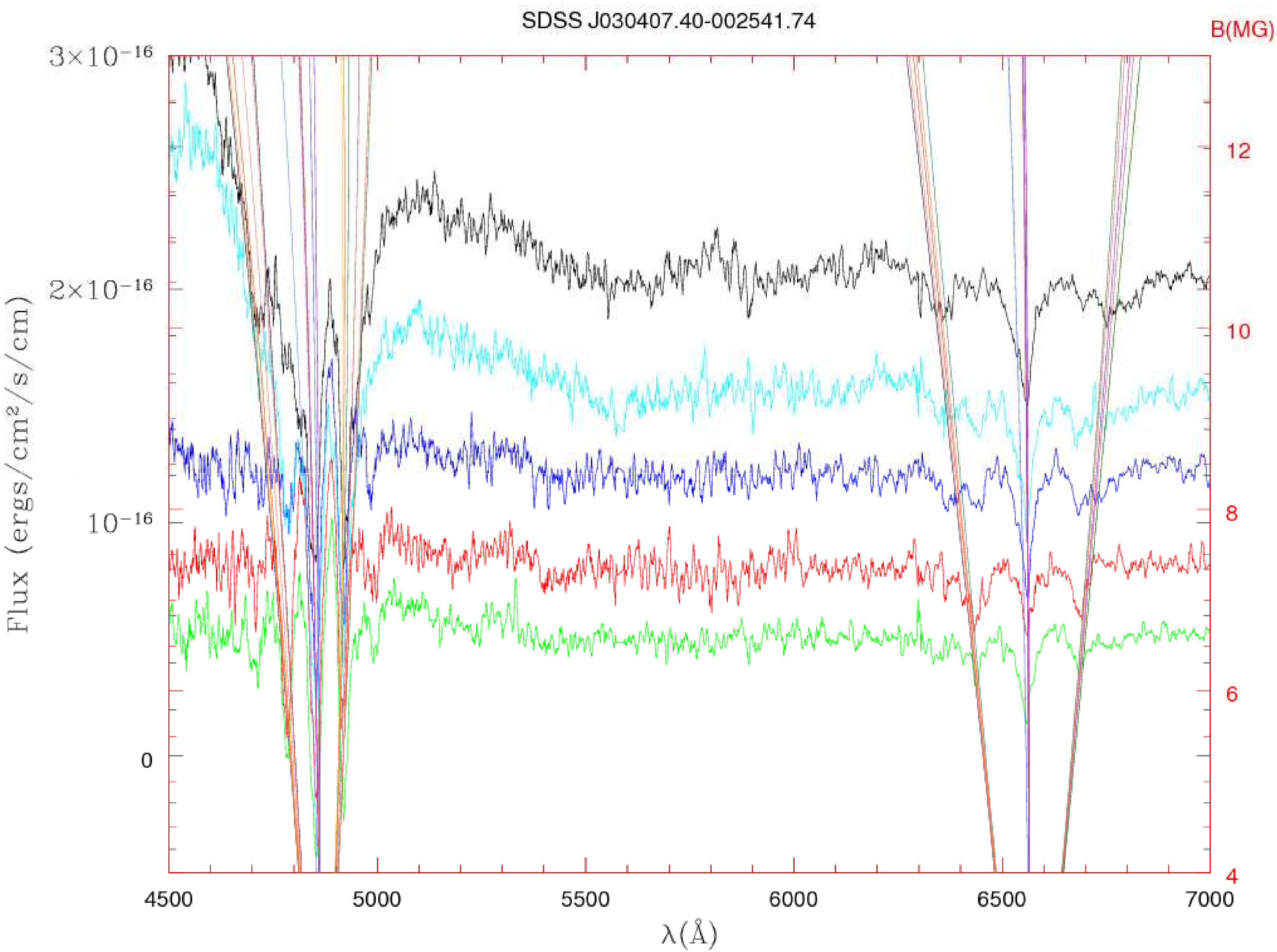

Flux(ergs/s/cm²/Å)
4×10⁻¹⁶
2×10⁻¹⁶
0
−2×10⁻¹⁶
4600
4800
5000
5200
λ(Å)
6000
6500
7000
λ(Å)

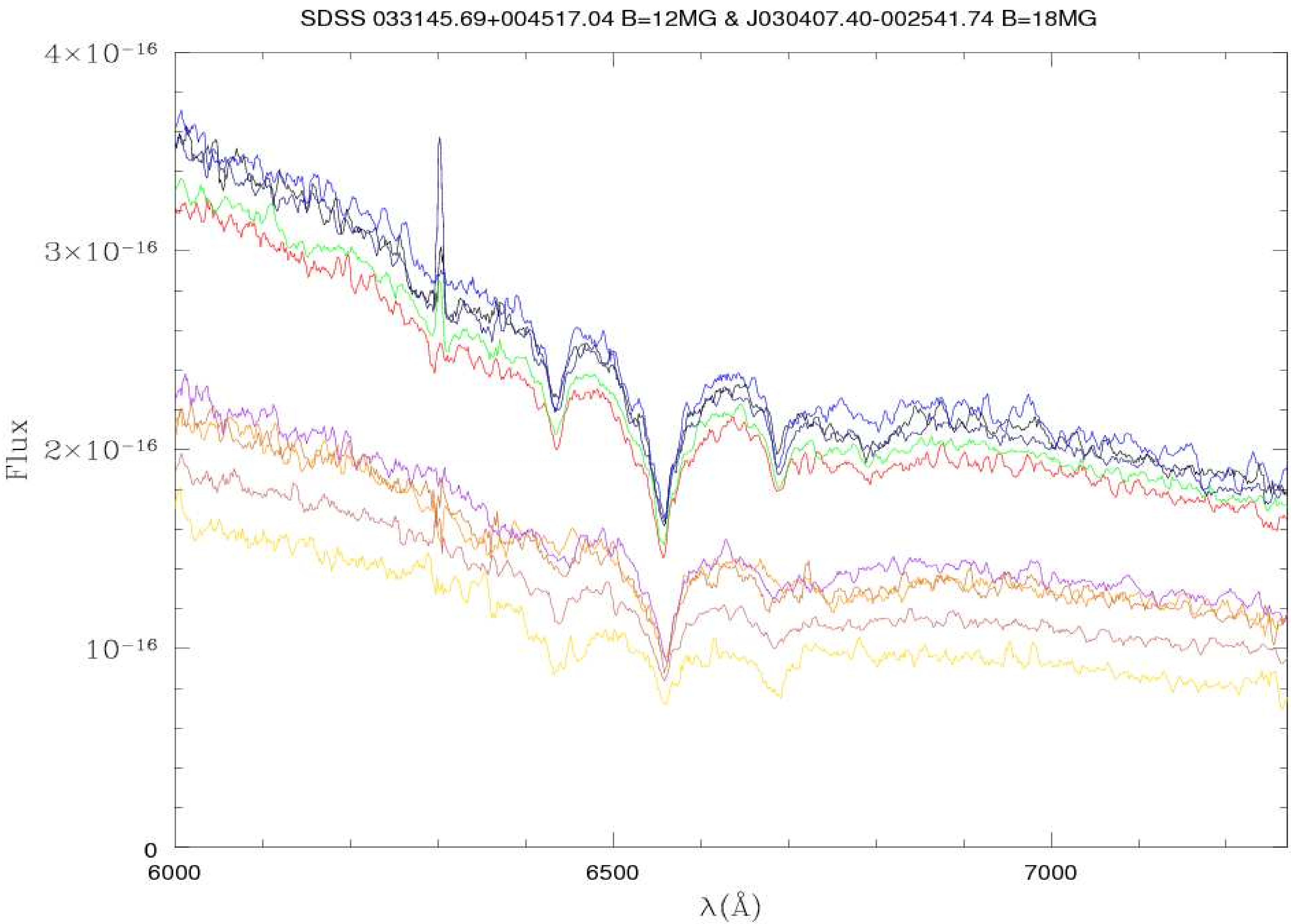


B(MG)
Flux(ergs/s/cm²/Å)
4×10⁻¹⁶
2×10⁻¹⁶
0
−2×10⁻¹⁶
4600
4800
5000
5200
6000
6500
7000
λ(Å)
0
2
4
6
8
10
12
B≃2 MG
B≃19 MG
B≃90 MG

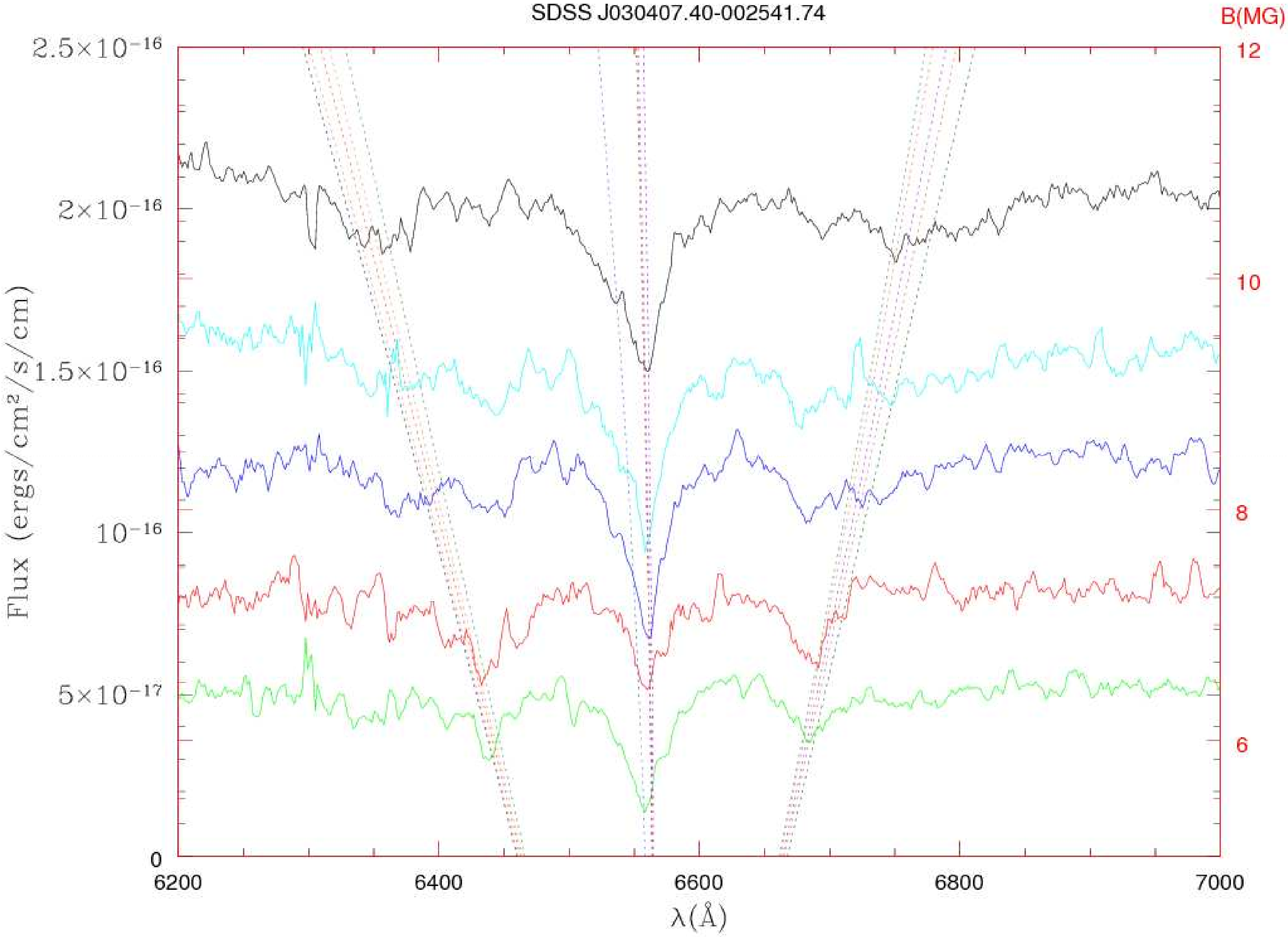


SDSS 033145.69+004517.04 B=12MG & J030407.40-002541.74 B=18MG
10^{-15}
8×10^{-16}
6×10^{-16}
4×10^{-16}
2×10^{-16}
0
Flux
4500
5000
5500
6000
6500
7000
λ(Å)

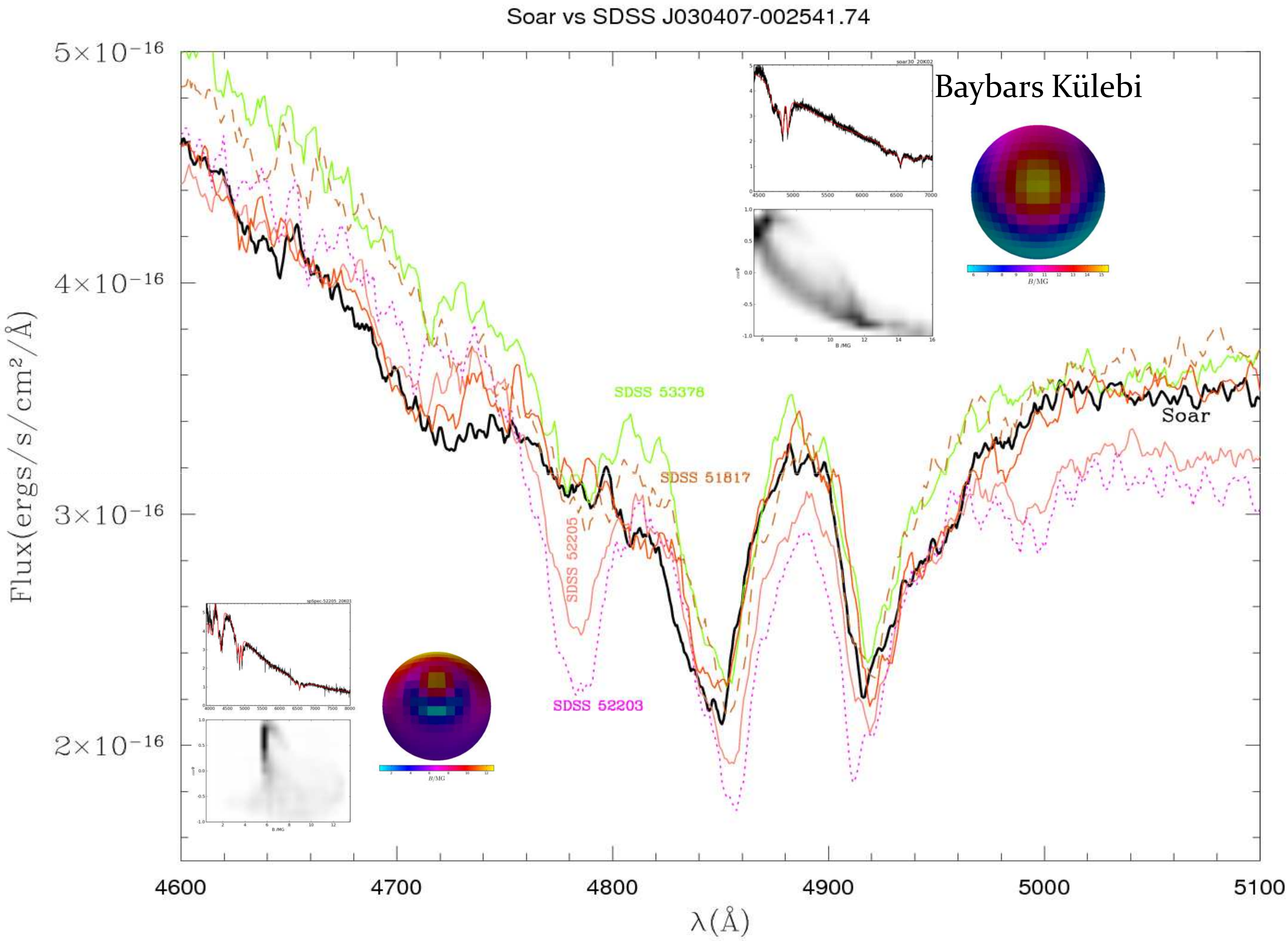

SDSS J030407.40-002541.74
B(MG)
Flux (ergs/cm²/s/cm)
3×10⁻¹⁶
2×10⁻¹⁶
10⁻¹⁶
0
12
10
8
6
4
4500
5000
5500
6000
6500
7000
λ(Å)



SDSS 033145.69+004517.04 B=12MG & J030407.40-002541.74 B=18MG
4×10^{-16}
3×10^{-16}
2×10^{-16}
10^{-16}
0
Flux
6000
6500
7000
λ(Å)

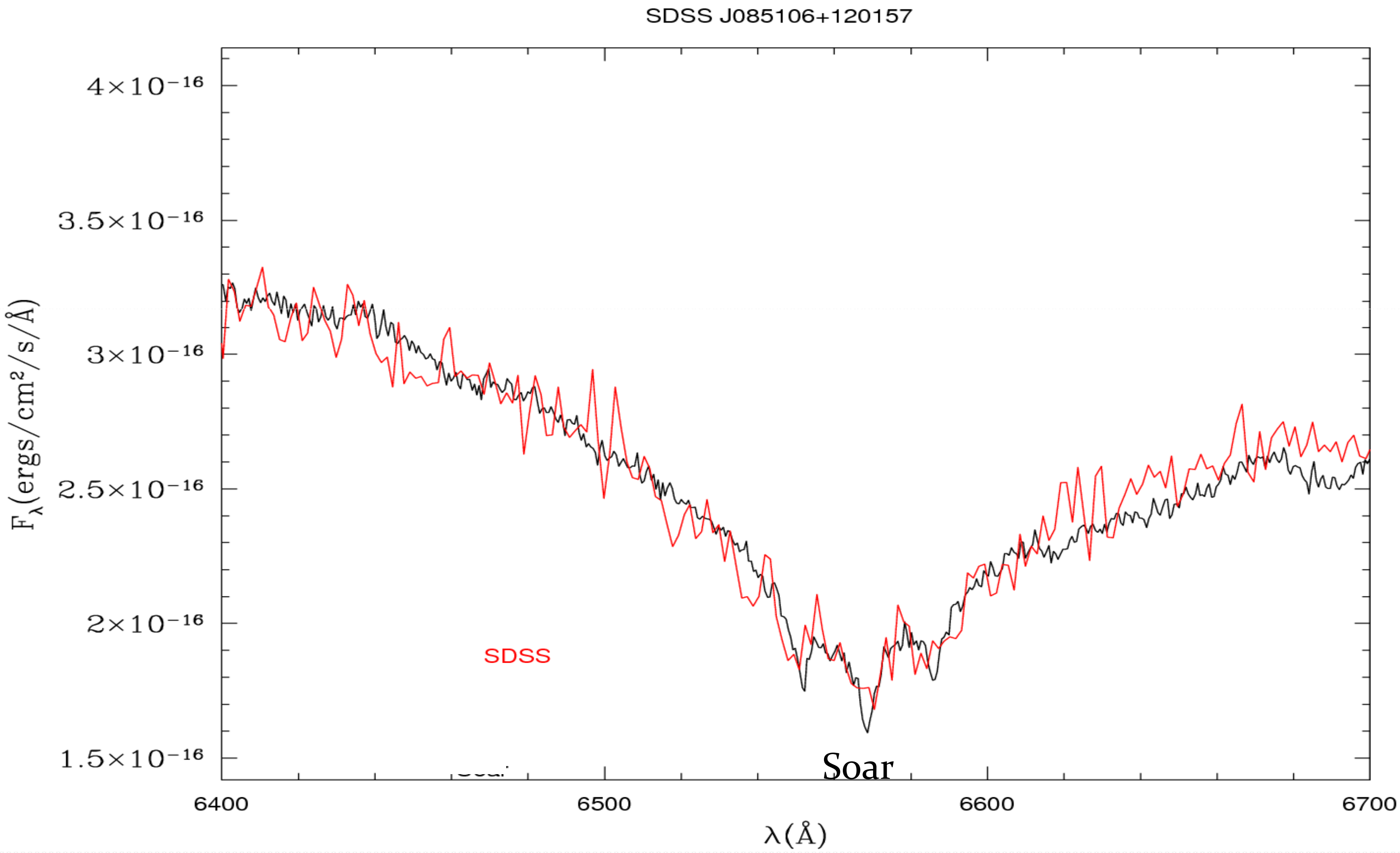


SDSS J030407.40-002541.74
B(MG)
Flux (ergs/cm²/s/cm)
2.5×10⁻¹⁶
2×10⁻¹⁶
1.5×10⁻¹⁶
10⁻¹⁶
5×10⁻¹⁷
0
12
10
8
6
6200
6400
6600
6800
7000
λ(Å)



Soar vs SDSS J030407-002541.74
Baybars Külebi
SDSS 53378
SDSS 51817
SDSS 52205
SDSS 52203
Soar
Flux(ergs/s/cm²/Å)
λ(Å)
5×10⁻¹⁶
4×10⁻¹⁶
3×10⁻¹⁶
2×10⁻¹⁶
4600
4700
4800
4900
5000
5100
B/MG
B /MG

Goodman 1200 l/mm



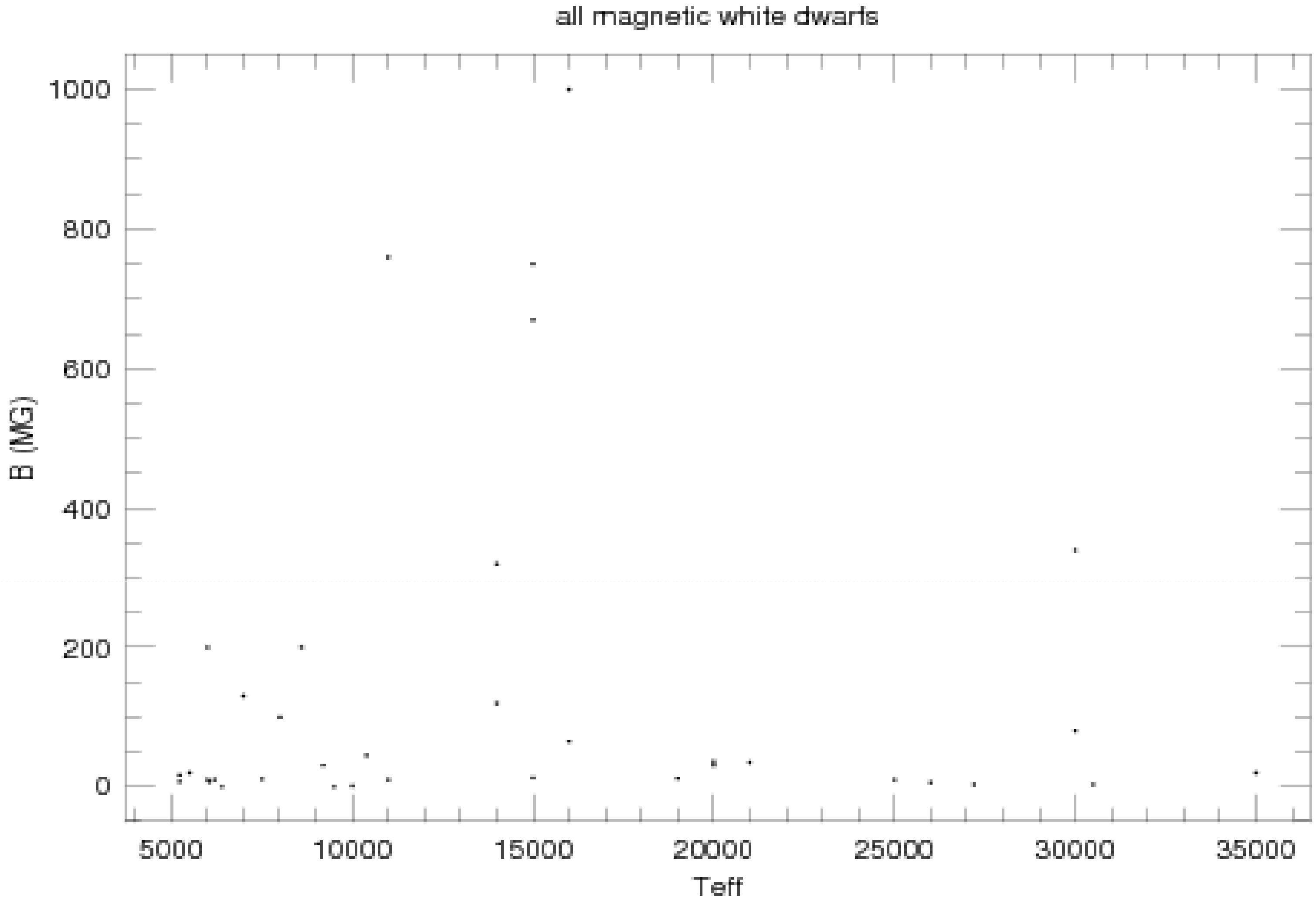
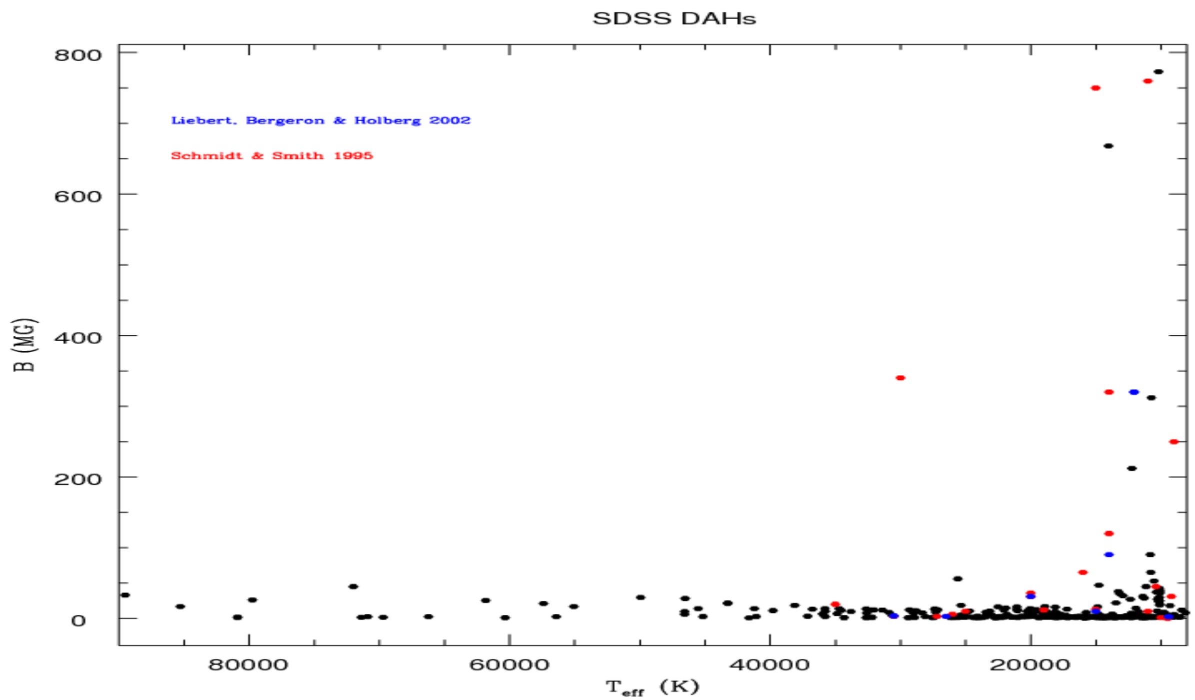
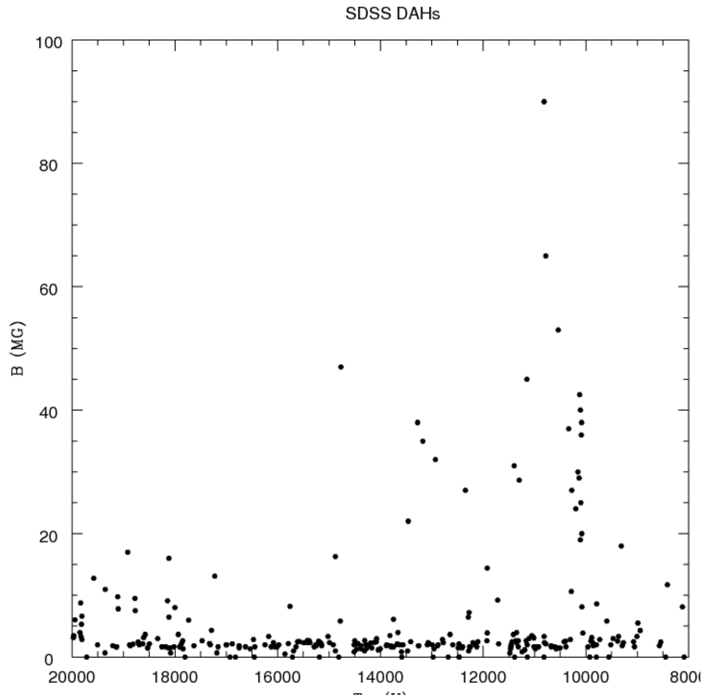
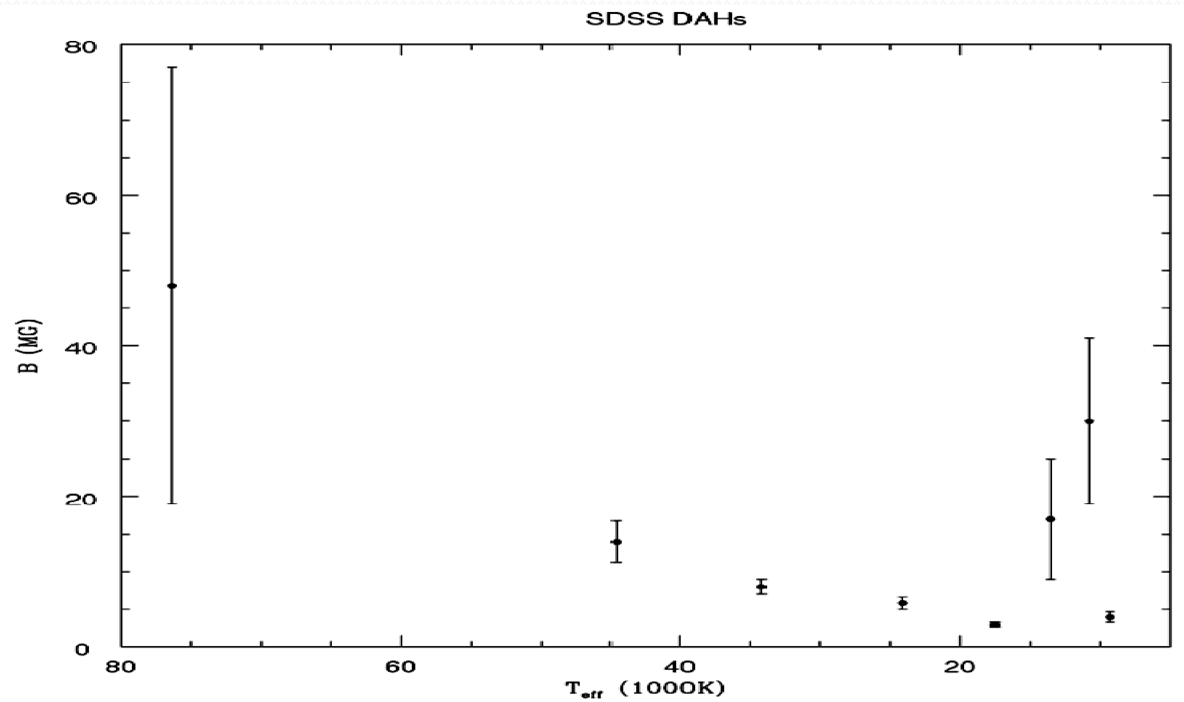


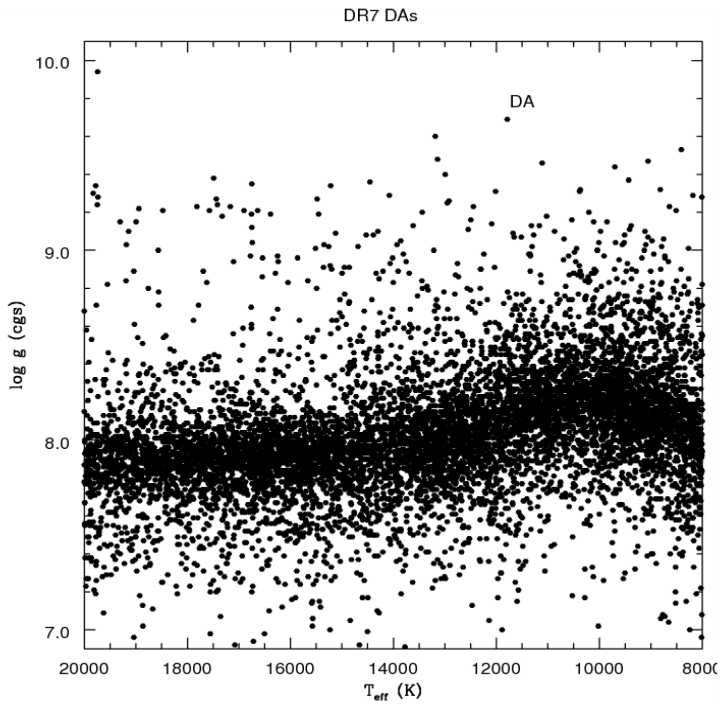
Fig. 6.1.— The distribution of magnetic field strengths as a function of effective temperature.

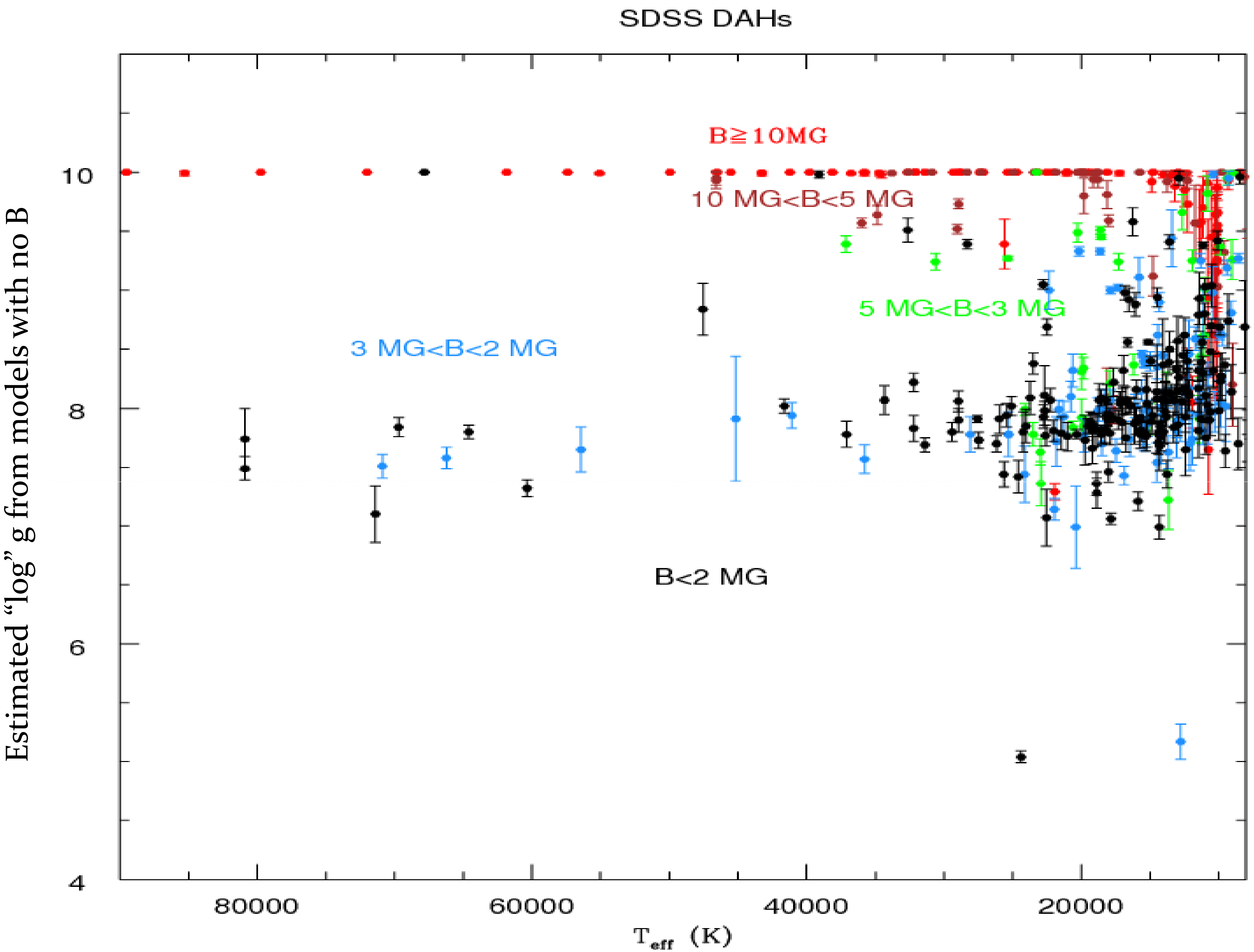
Kanaan 1996


SDSS DAHs
Liebert, Bergeron & Holberg 2002
Schmidt & Smith 1995
B (MG)
T_{eff} (K)
800
600
400
200
0
80000
60000
40000
20000


SDSS DAHs
B (MG)
100
80
60
40
20
0
20000
18000
16000
14000
12000
10000

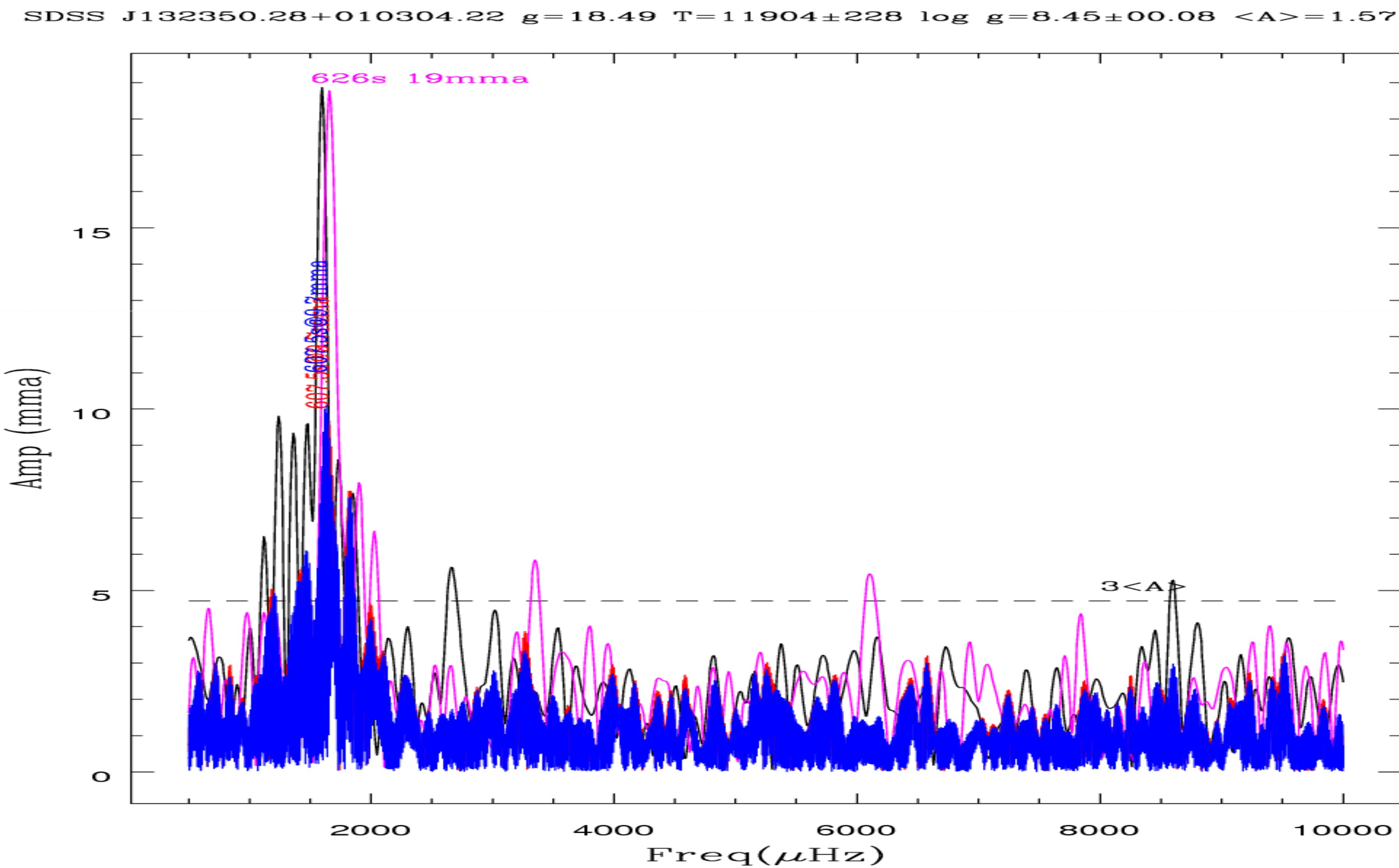

SDSS DAHs
B (MG)
T_{eff} (1000K)
80
60
40
20
0

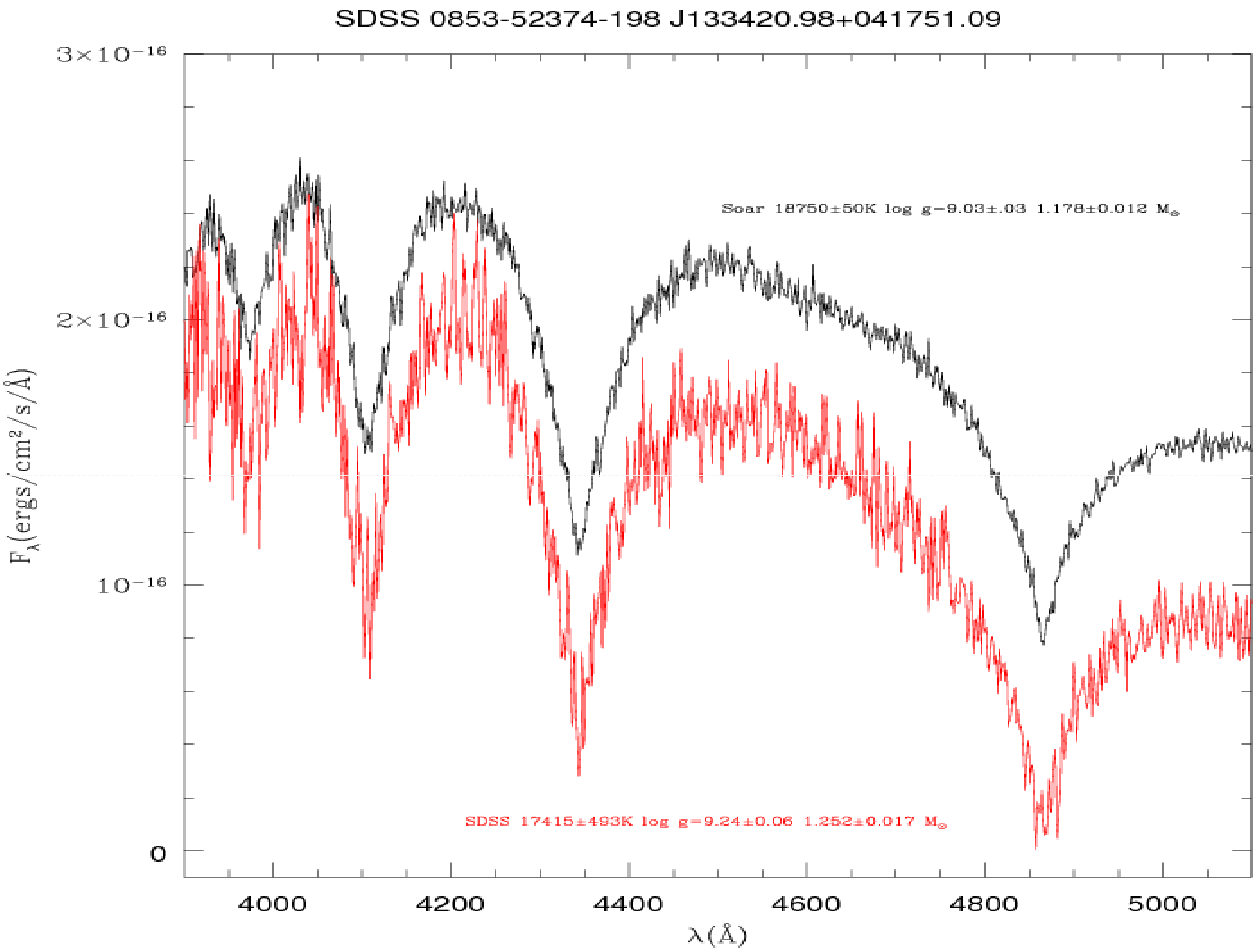

DR7 DAs
DA
log g (cgs)
T_{eff} (K)
10.0
9.0
8.0
7.0
20000
18000
16000
14000
12000
10000



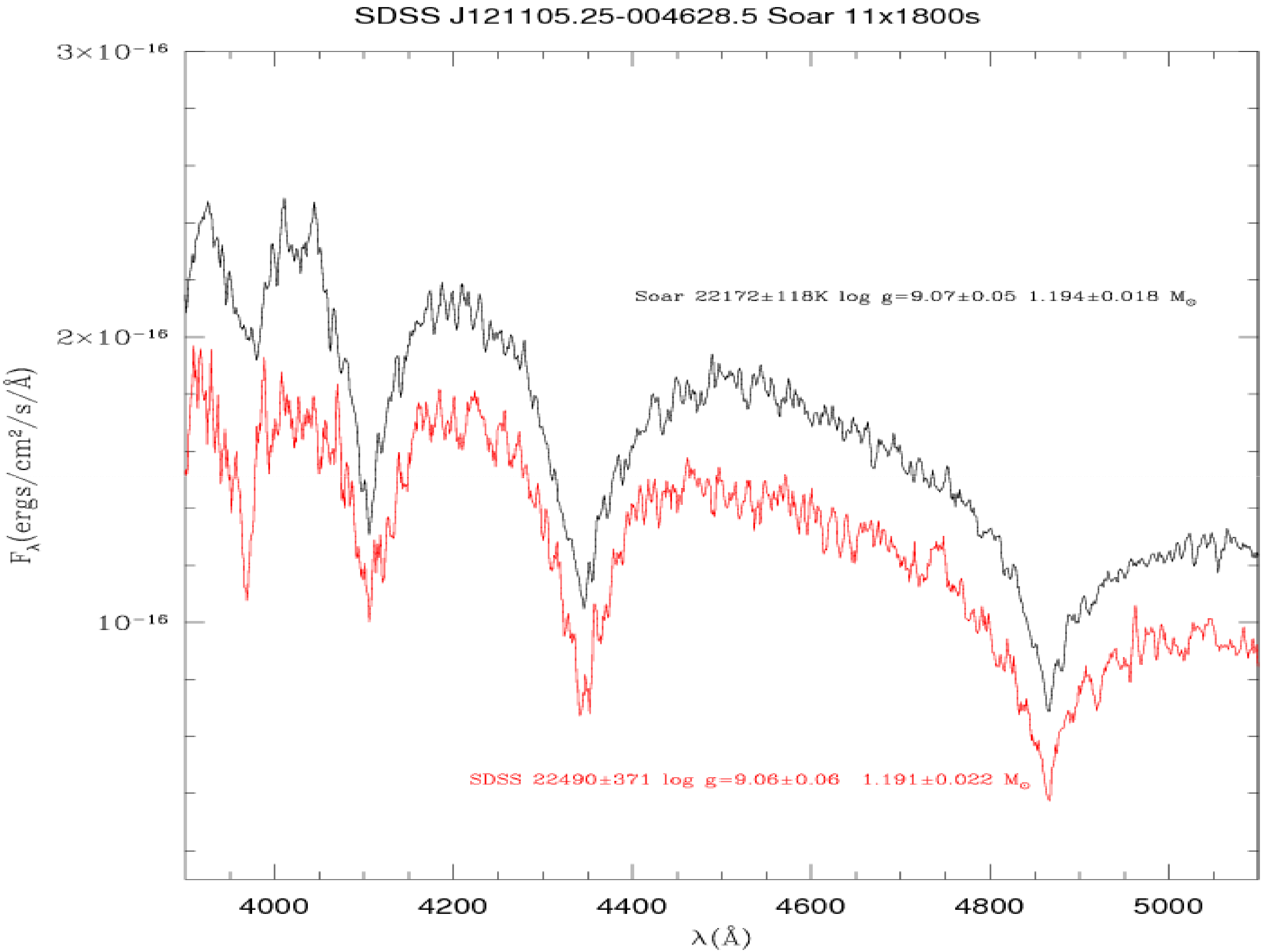
SDSS DAHs
B≧10MG
10 MG<B<5 MG
5 MG<B<3 MG
3 MG<B<2 MG
B<2 MG
Estimated "log" g from models with no B
T_{eff} (K)
10
8
6
4
80000
60000
40000
20000

Magnetic Pulsating DA



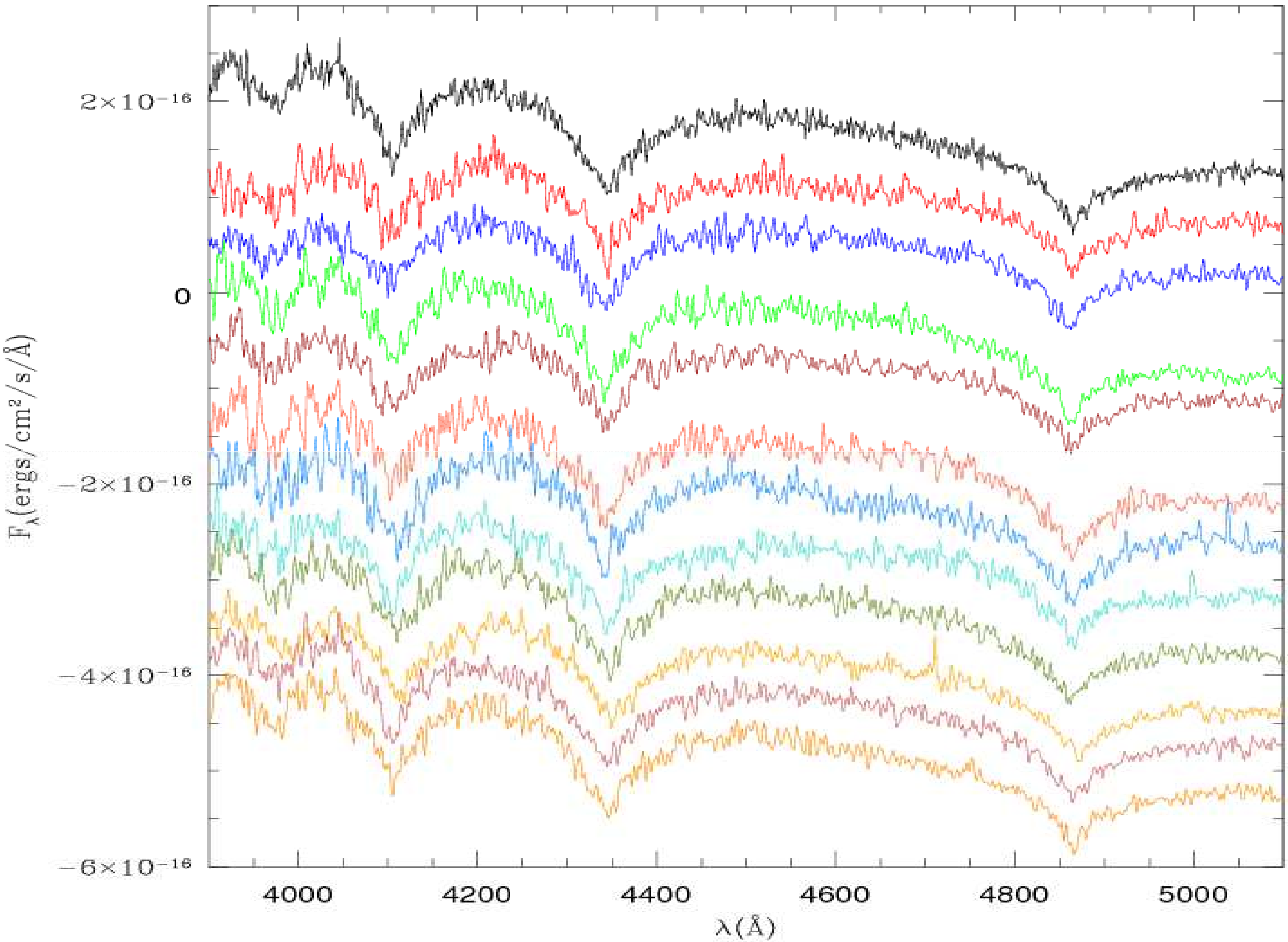


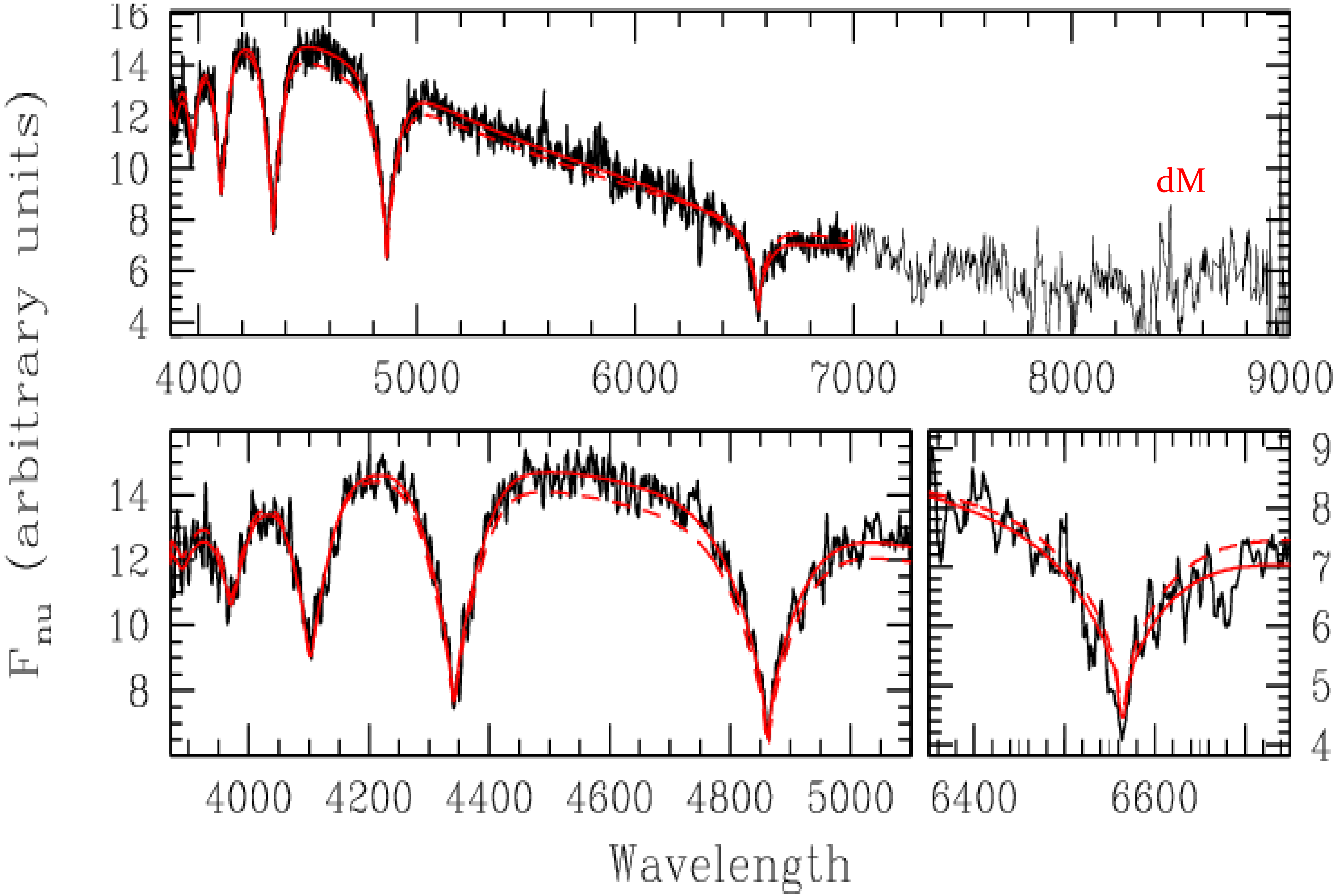
SDSS 0853-52374-198 J133420.98+041751.09
Soar 18750±50K log g=9.03±.03 1.178±0.012 M⊙
SDSS 17415±493K log g=9.24±0.06 1.252±0.017 M⊙
3×10⁻¹⁶
2×10⁻¹⁶
10⁻¹⁶
0
Fλ(ergs/cm²/s/Å)
4000
4200
4400
4600
4800
5000
λ(Å)



SDSS J121105.25-004628.5 Soar 11x1800s
Soar 22172±118K log g=9.07±0.05 1.194±0.018 M⊙
SDSS 22490±371 log g=9.06±0.06 1.191±0.022 M⊙
3×10⁻¹⁶
2×10⁻¹⁶
10⁻¹⁶
Fλ(ergs/cm²/s/Å)
4000
4200
4400
4600
4800
5000
λ(Å)

SDSS J121105.25-004628.5 Soar 11x1800s





SDSS J121105.25-004628.5 0287-253-52023 DAH S/N=14 T_{eff}=22490±371K, log g=9.06±0.06

B>1 MG

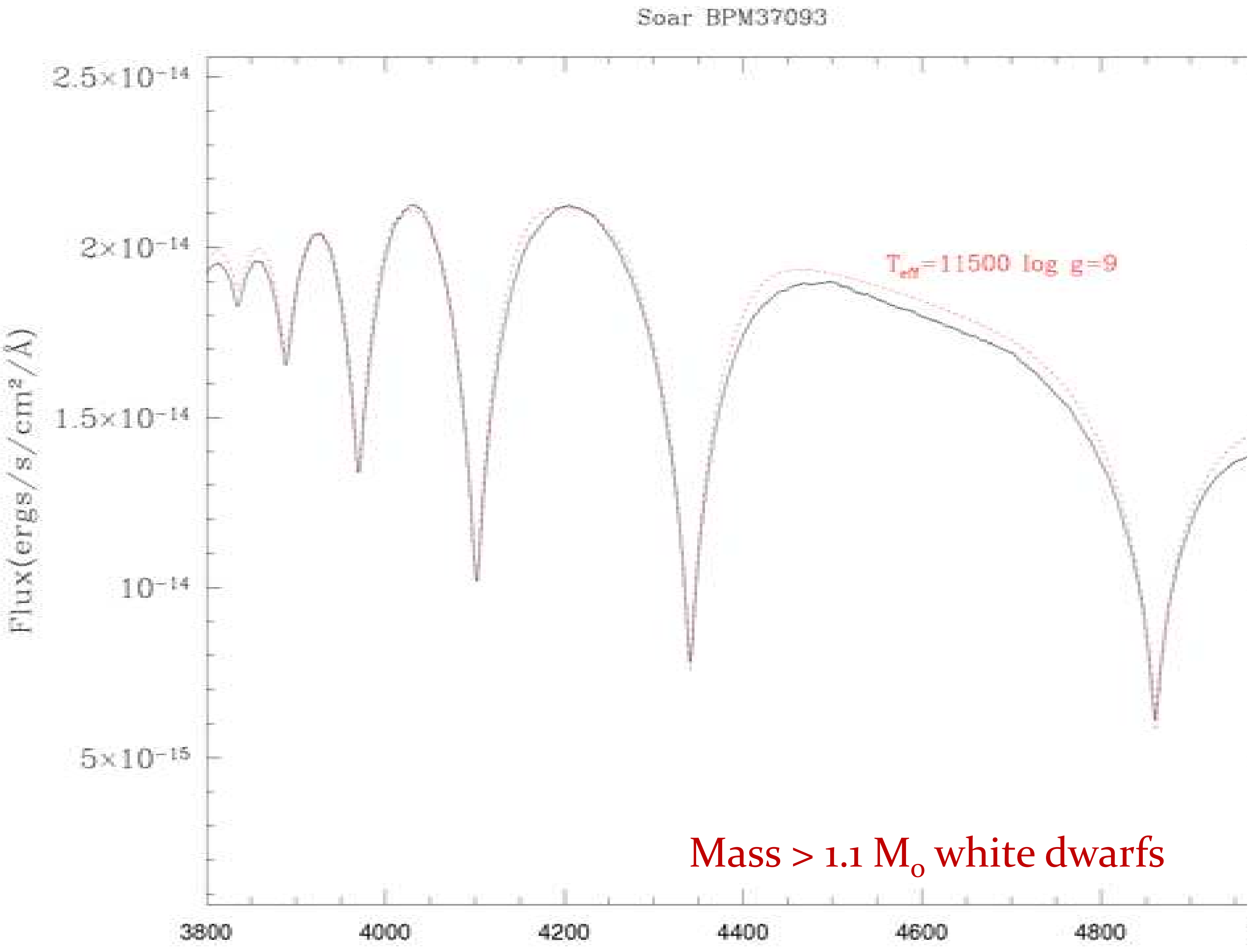
755 DAH and 12549 DA, 5.7%
62 DBH and 889 DB, 6.5%
$937 \pm^{767}$ DH in 19503 WD, $4.8\%^{\pm 3.9}$

B<1 MG

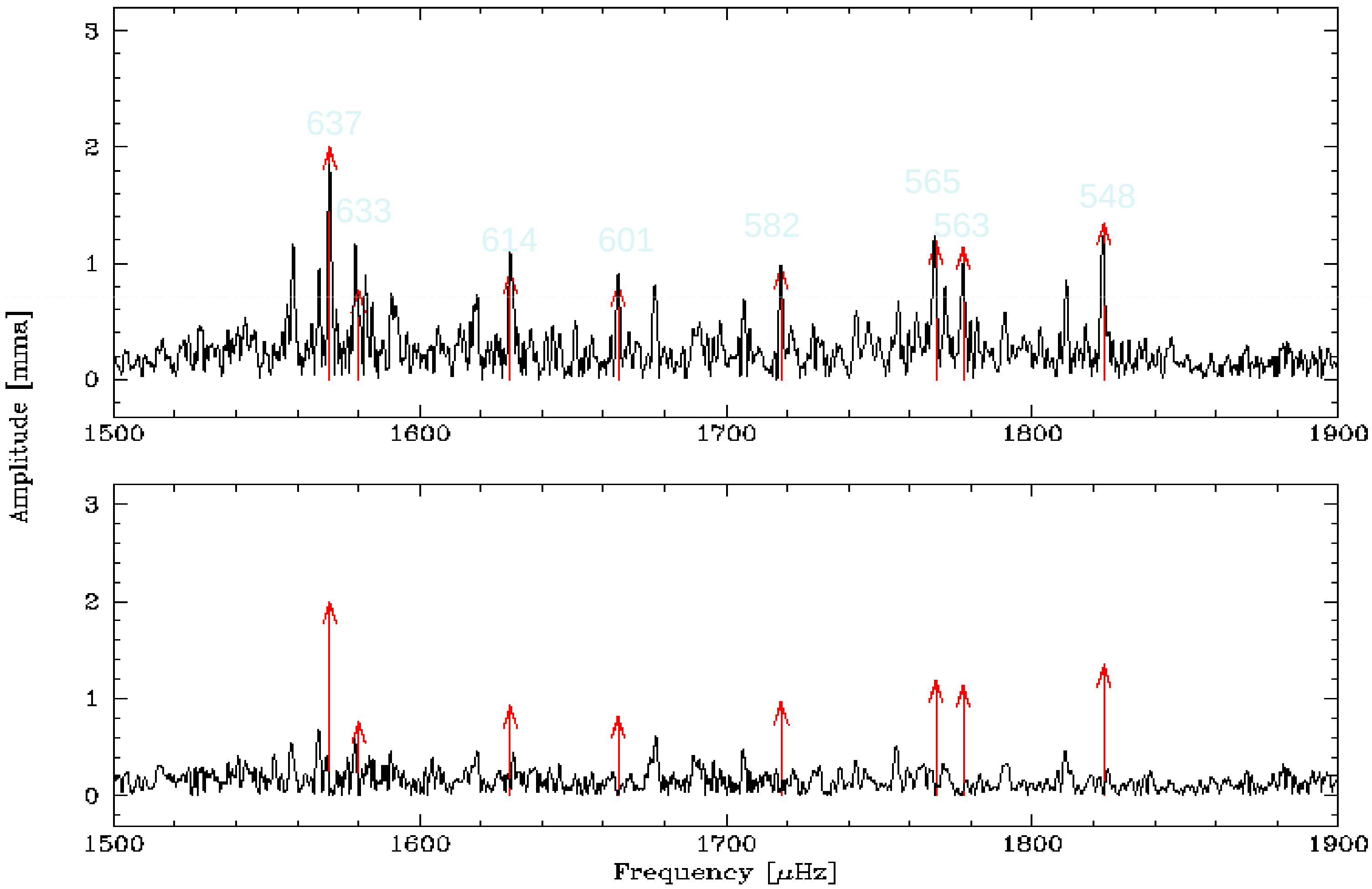
<M>=0.604±0.003 M_{sun}, DAs, S/N>20, T_{eff}>12000K, <S/N>=30, N=1505
<M>=0.651±0.005 M_{sun}, DBs, S/N>20, T_{eff}>16000K, <S/N>=27, N=82

DBs, S/N>25, 1:3:18 for T_{eff}>45000K:30000K:20000K
exactly what expected by age -> NO DB GAP!

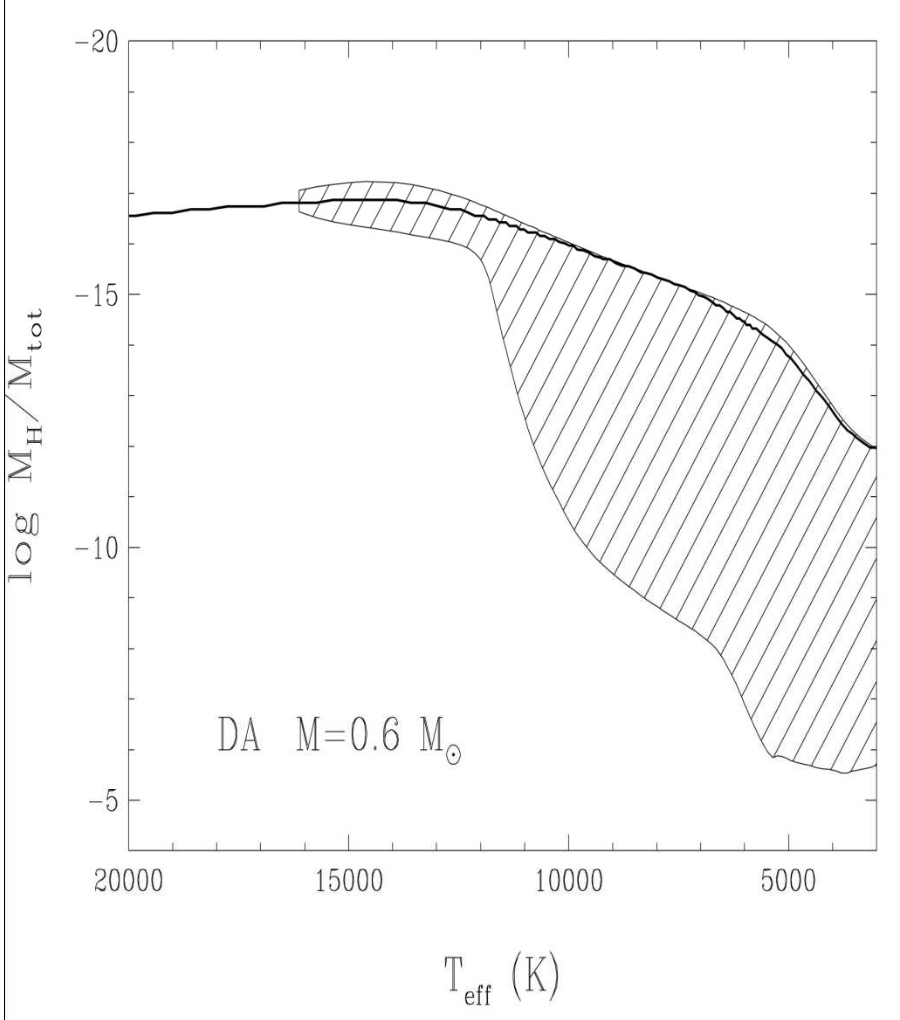
-A Spectroscopic Analysis of White Dwarfs in the Kiso Survey
M.-M. Limoges and P. Bergeron 2010
0.606 M_{sun} and a dispersion of 0.135 for 149 DAs (but Gianninas et al. 2010 0.64M_{Sun} N=1304)
0.758 M_{sun} and a dispersion of 0.192 for 19 DBs (but 0.696 M_{sun} for 103 DBs from SPY)
-Spectroscopic Analysis of DA WD: Stark Broadening of H including non-ideal effects
P.-E. Tremblay and P. Bergeron 2009
0.649 M_{sun} for 250 DAs – same value Ross Falcon got for mean gravitational redshift for SPY
-no He in Keck spectra of cool white dwarfs – no convection mixing

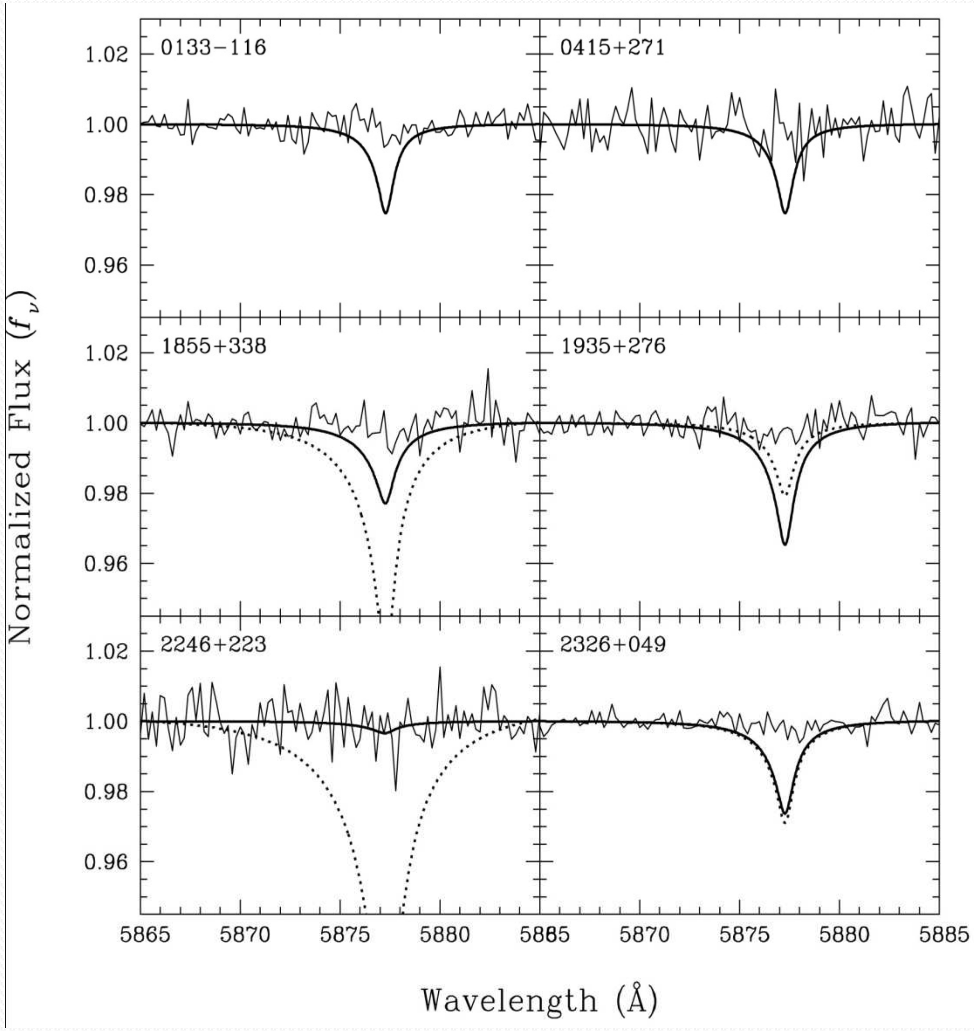

Soar BPM37093
2.5×10⁻¹⁴
2×10⁻¹⁴
1.5×10⁻¹⁴
10⁻¹⁴
5×10⁻¹⁵
Flux(ergs/s/cm²/Å)
3800
4000
4200
4400
4600
4800
Teff=11500 log g=9
Mass > 1.1 M0 white dwarfs

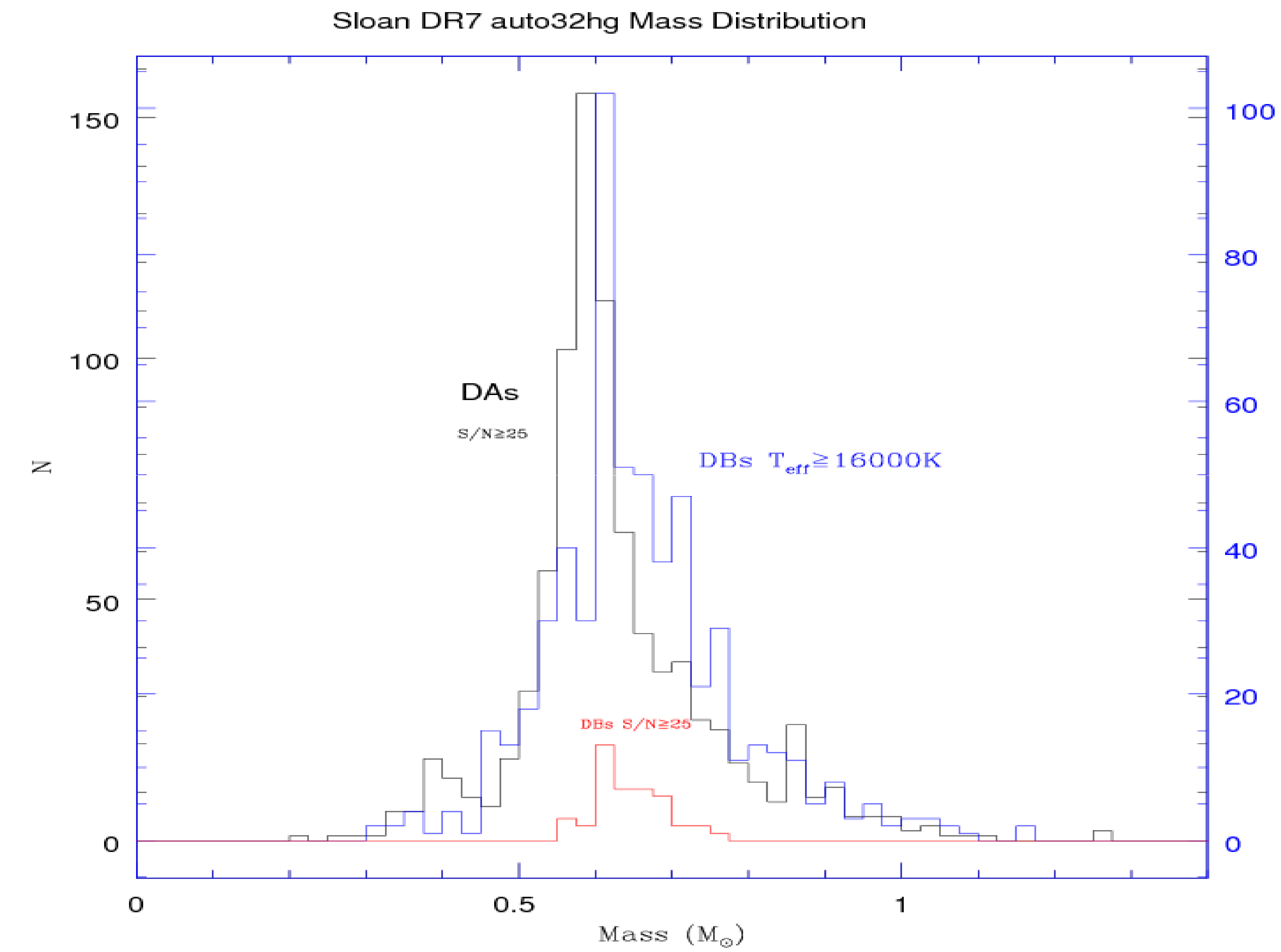
Crystal Pulsator



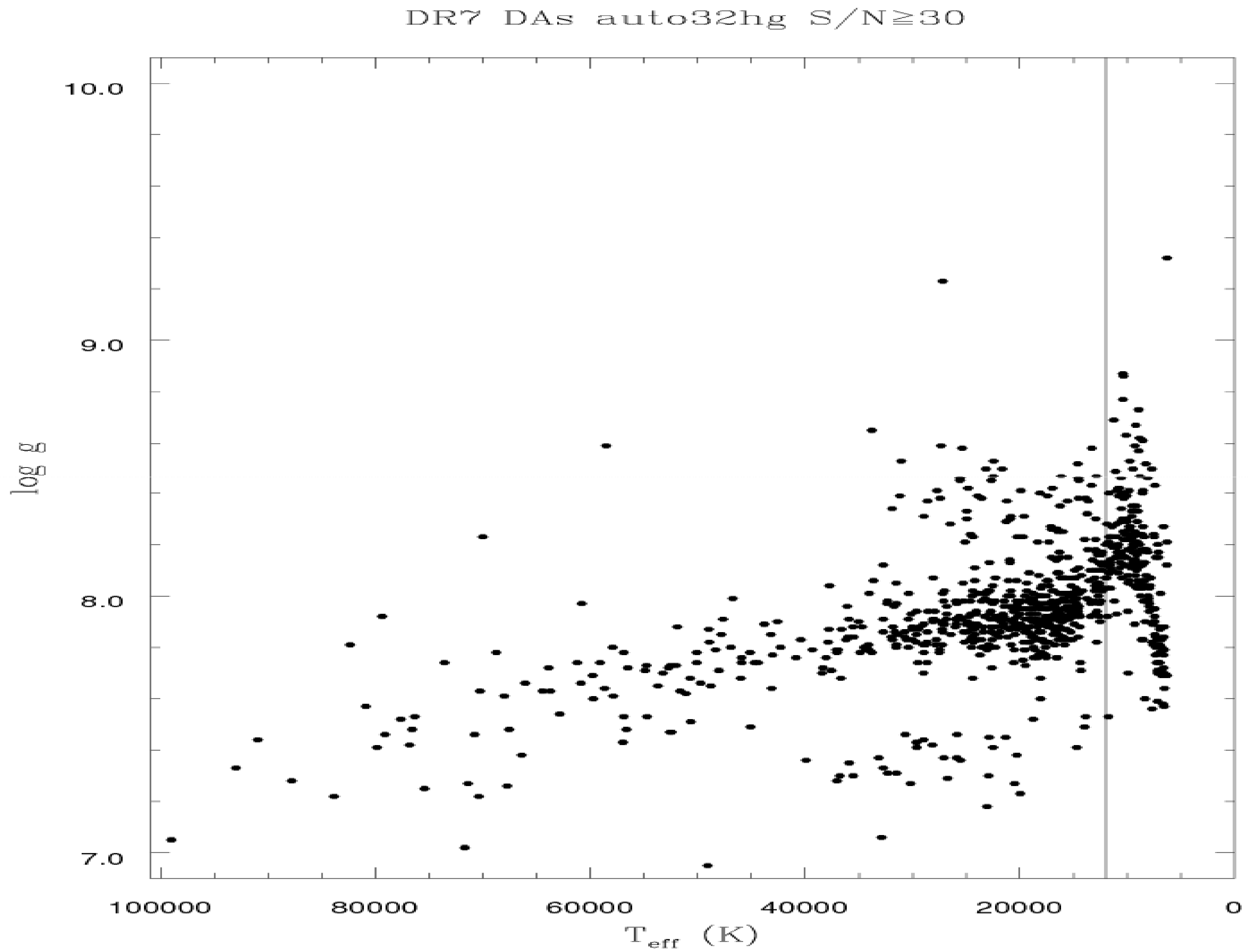
Keck spectra – no He



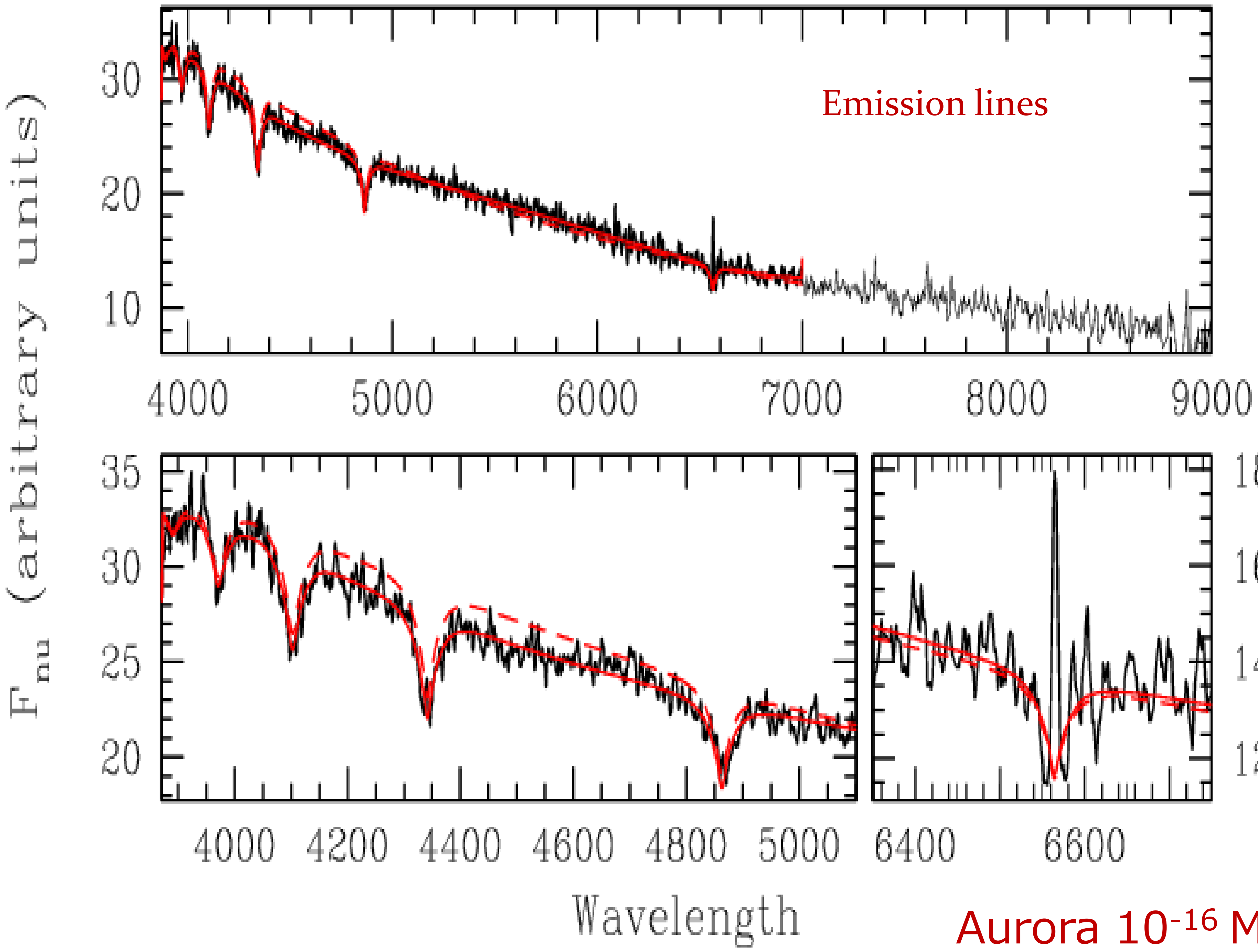




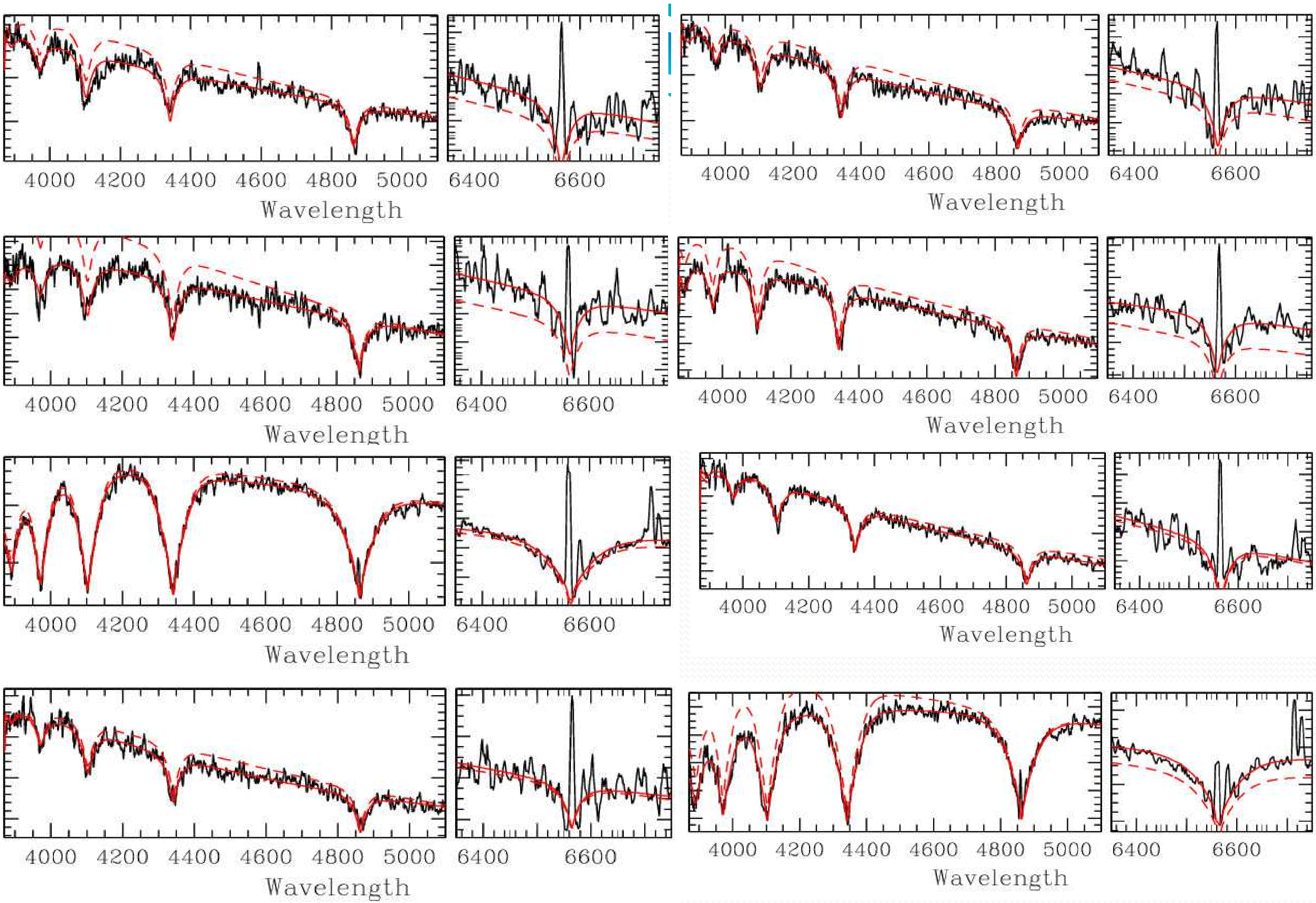
Sloan DR7 auto32hg Mass Distribution
150
100
50
0
100
80
60
40
20
0
N
DAs
S/N≥25
DBs T_eff≥16000K
DBs S/N≥25
0
0.5
1
Mass (M_⊙)



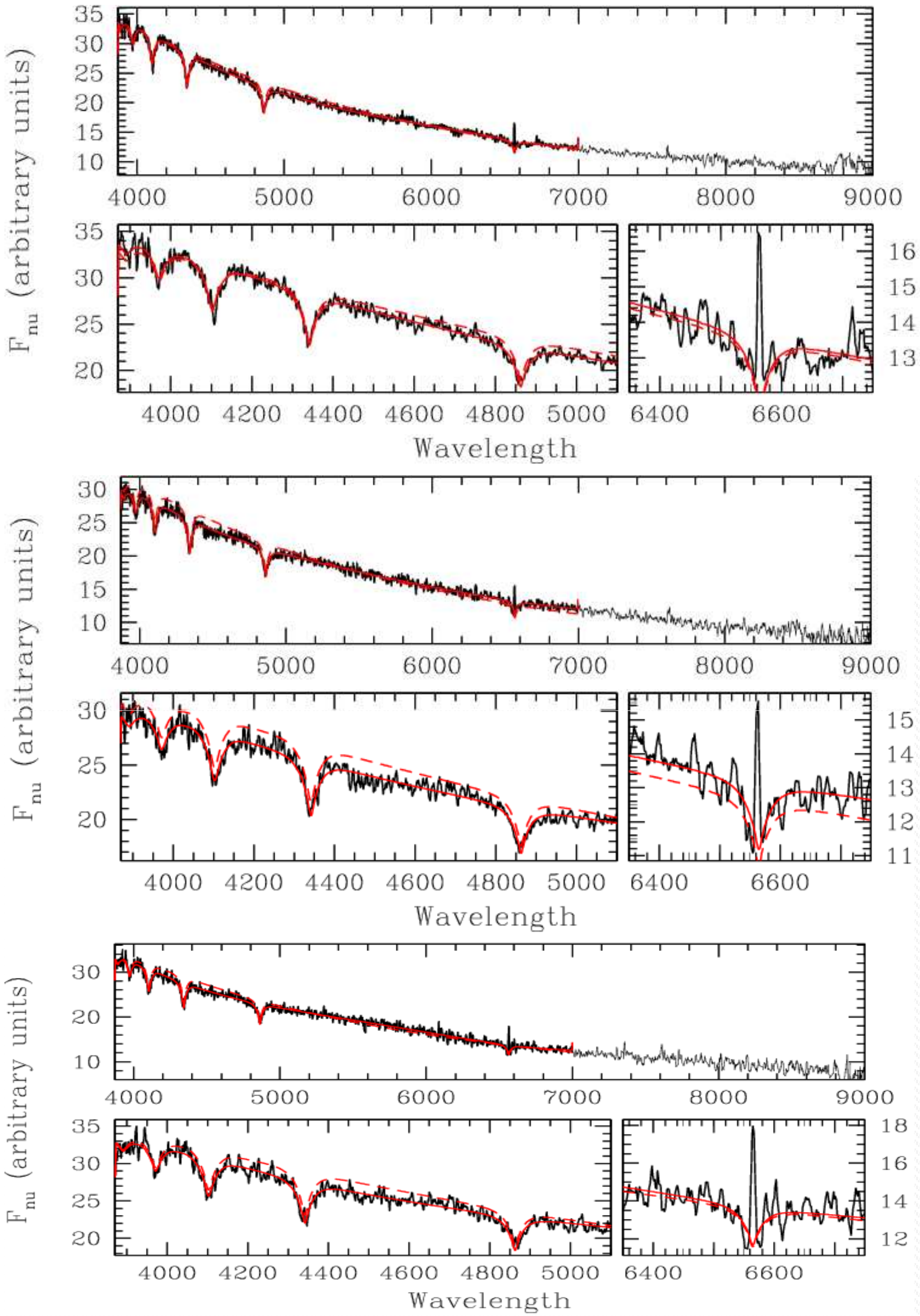
DR7 DAs auto32hg S/N≧30
10.0
9.0
8.0
7.0
log g
100000
80000
60000
40000
20000
0
T_eff (K)



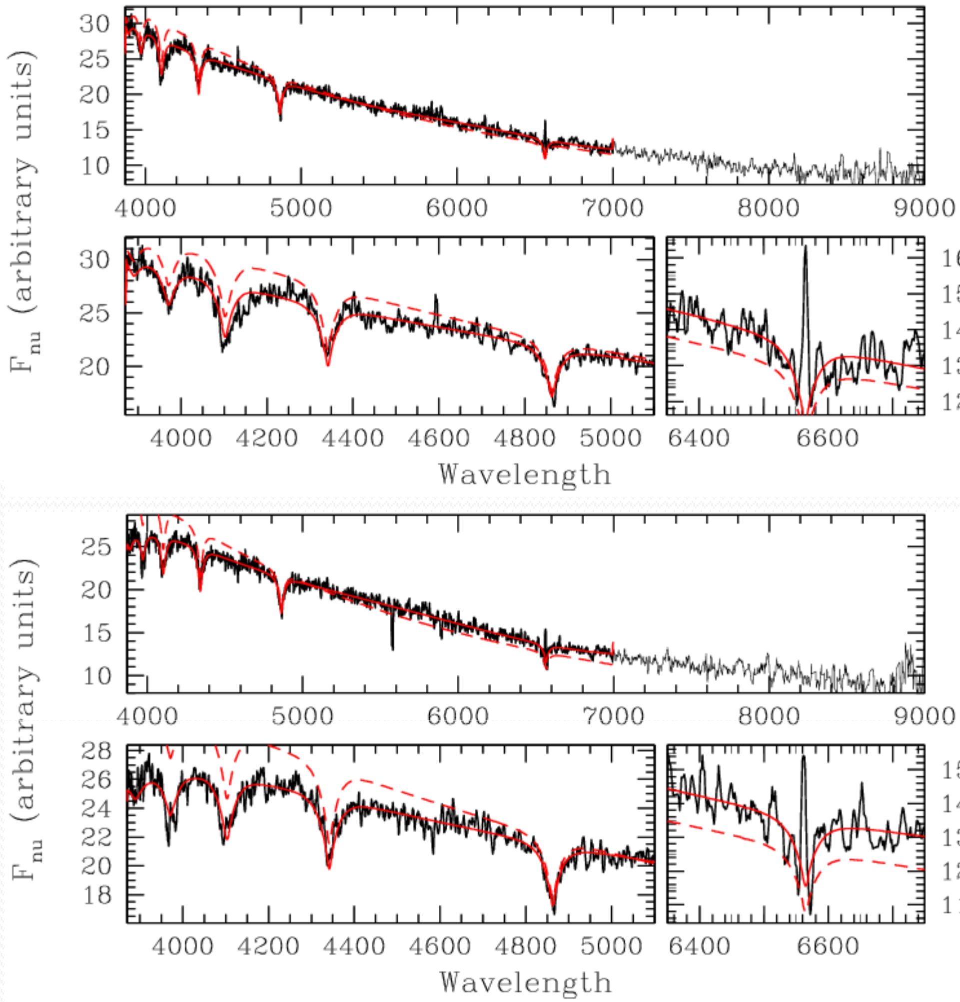
Aurora 10^{-16} M_o



Aurora? 10^{-16} M_o = comet - but 16% of dMs show Hα chromosferic emissio

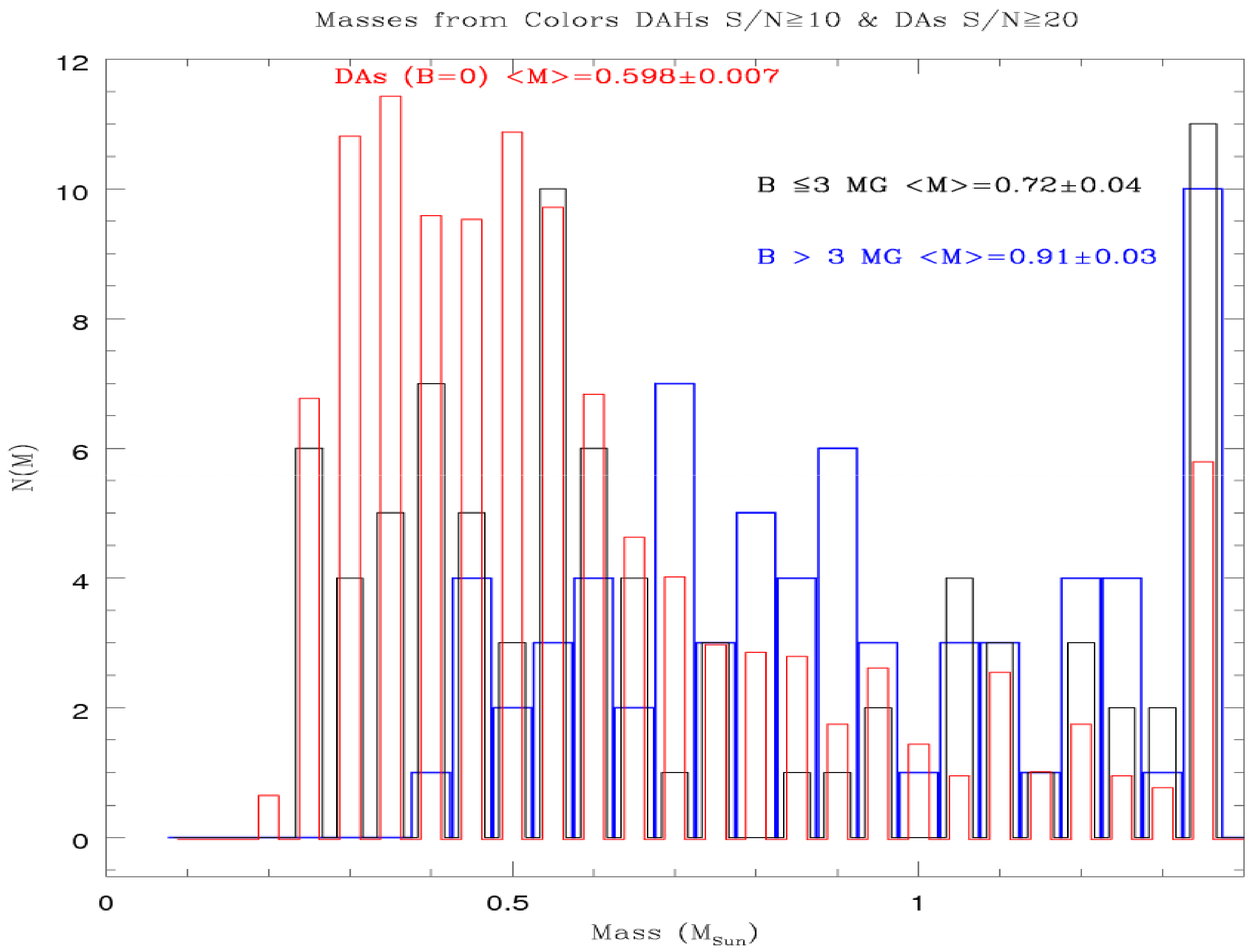


F nu (arbitrary units)
Wavelength
F nu (arbitrary units)
Wavelength
F nu (arbitrary units)
Wavelength

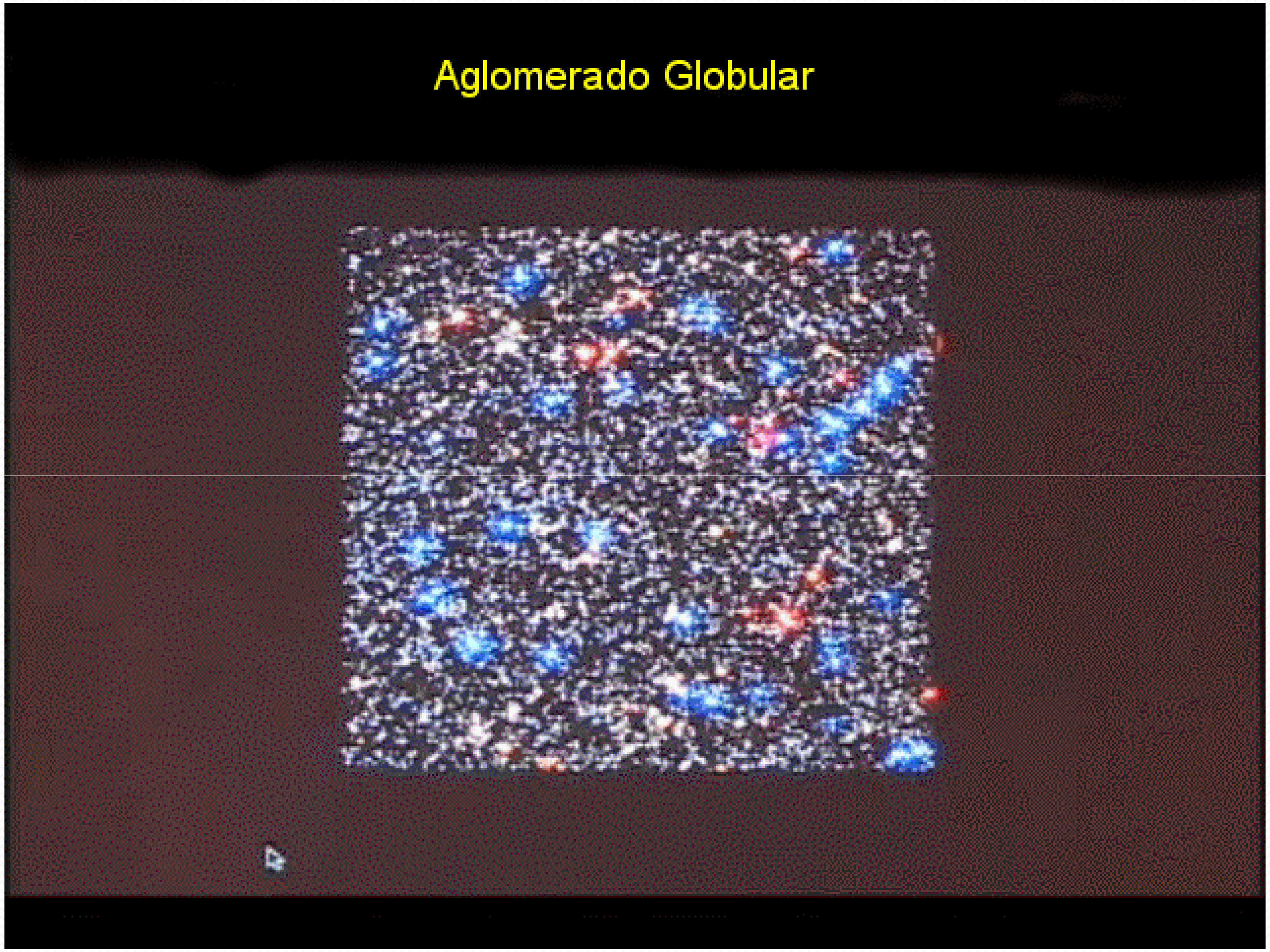


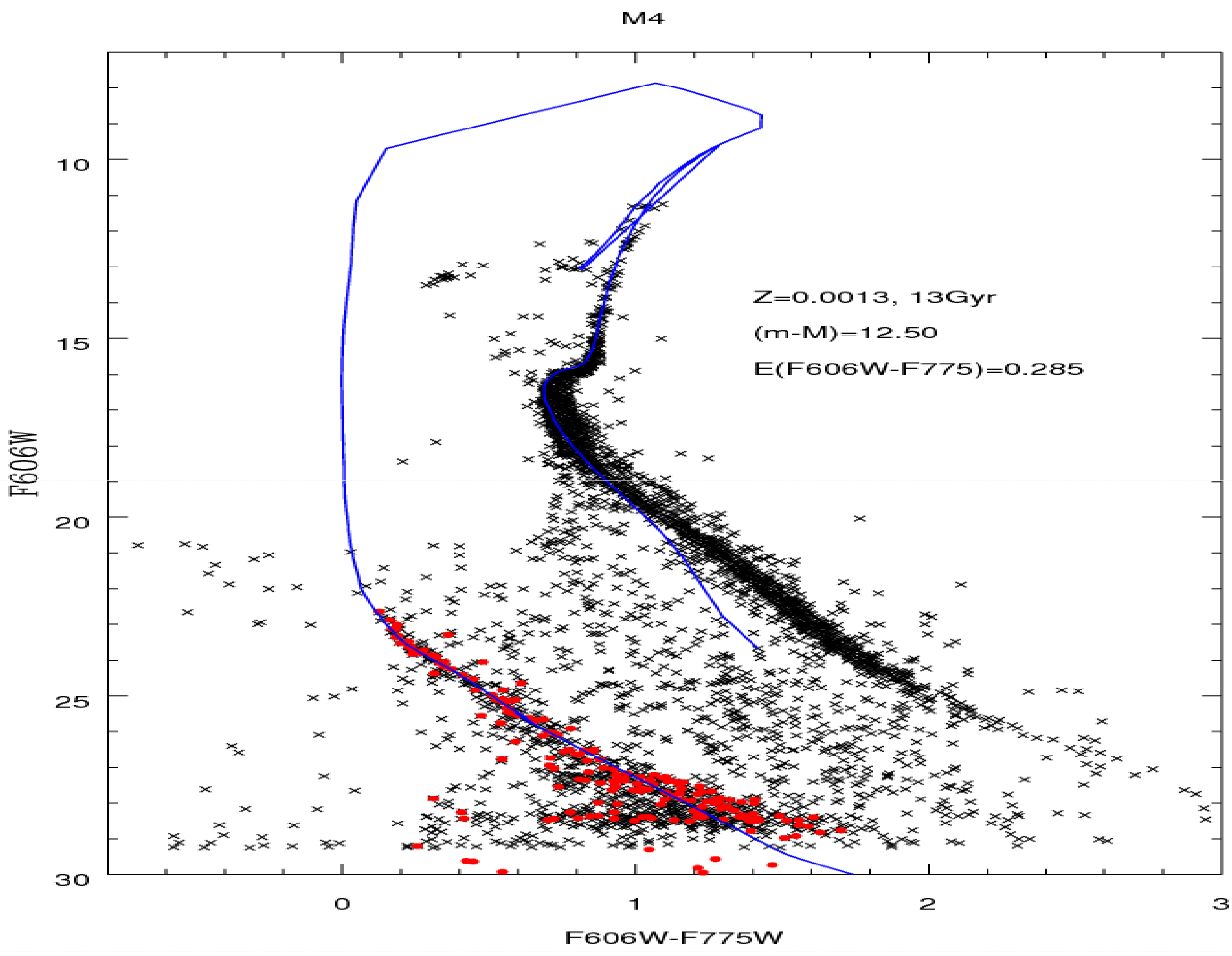
F nu (arbitrary units)
Wavelength
F nu (arbitrary units)
Wavelength

Same star!

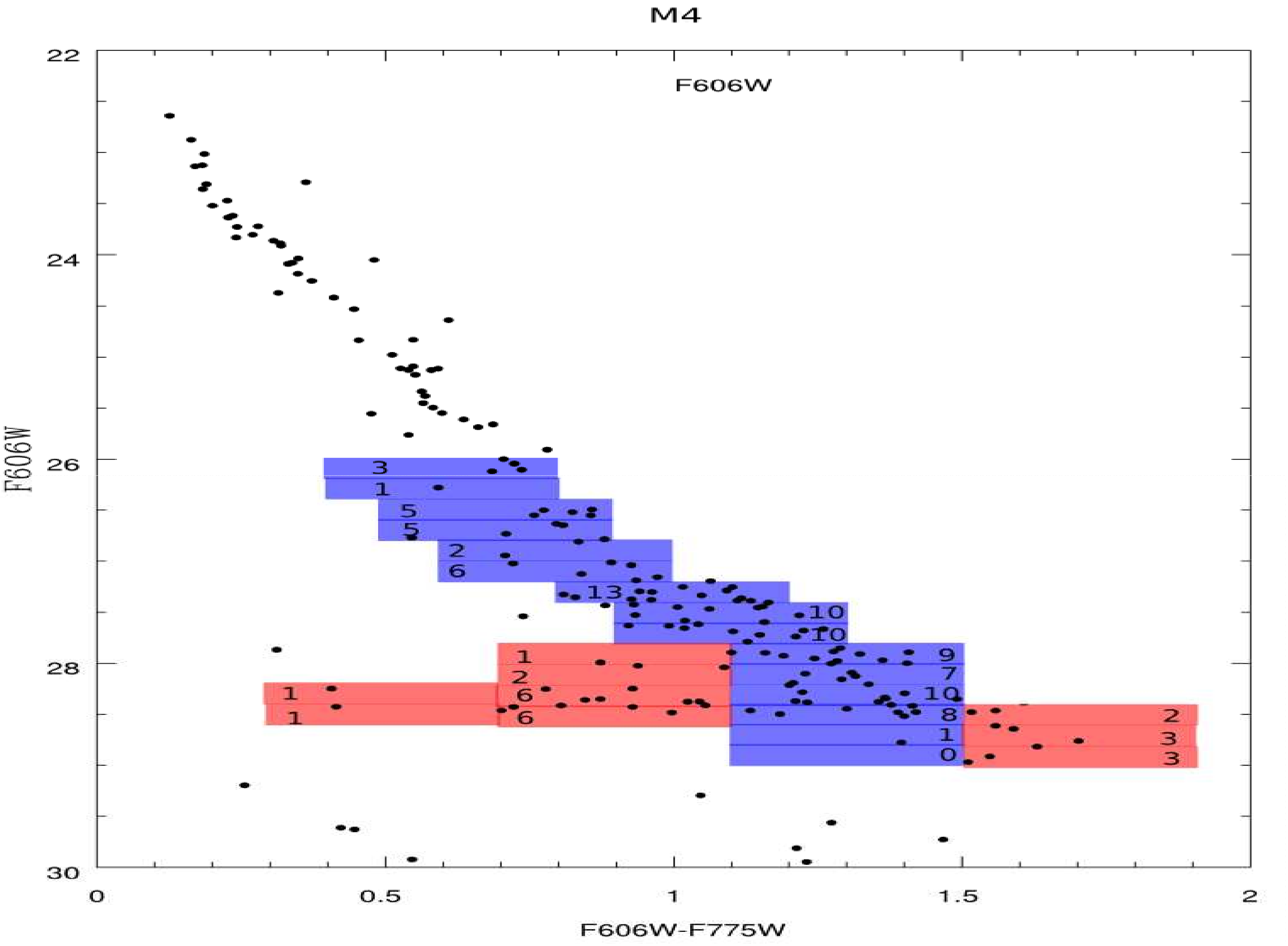


Masses from Colors DAHs S/N≧10 & DAs S/N≧20
DAs (B=0) <M>=0.598±0.007
B ≦3 MG <M>=0.72±0.04
B > 3 MG <M>=0.91±0.03
N(M)
Mass (M_Sun)
0
2
4
6
8
10
12
0
0.5
1

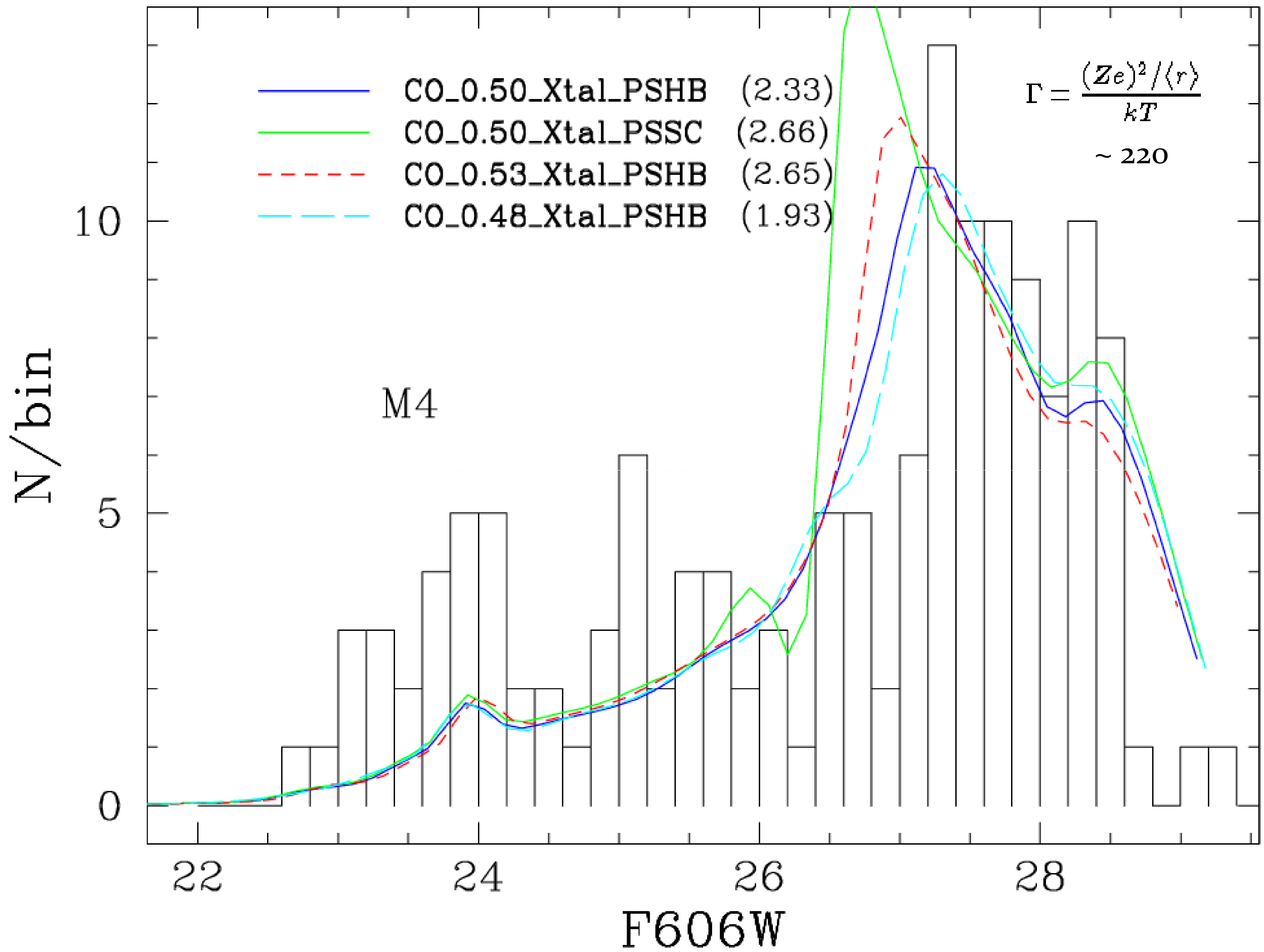

Aglomerado Globular



M4
Z=0.0013, 13Gyr
(m-M)=12.50
E(F606W-F775)=0.285
F606W
F606W-F775W
10
15
20
25
30
0
1
2
3

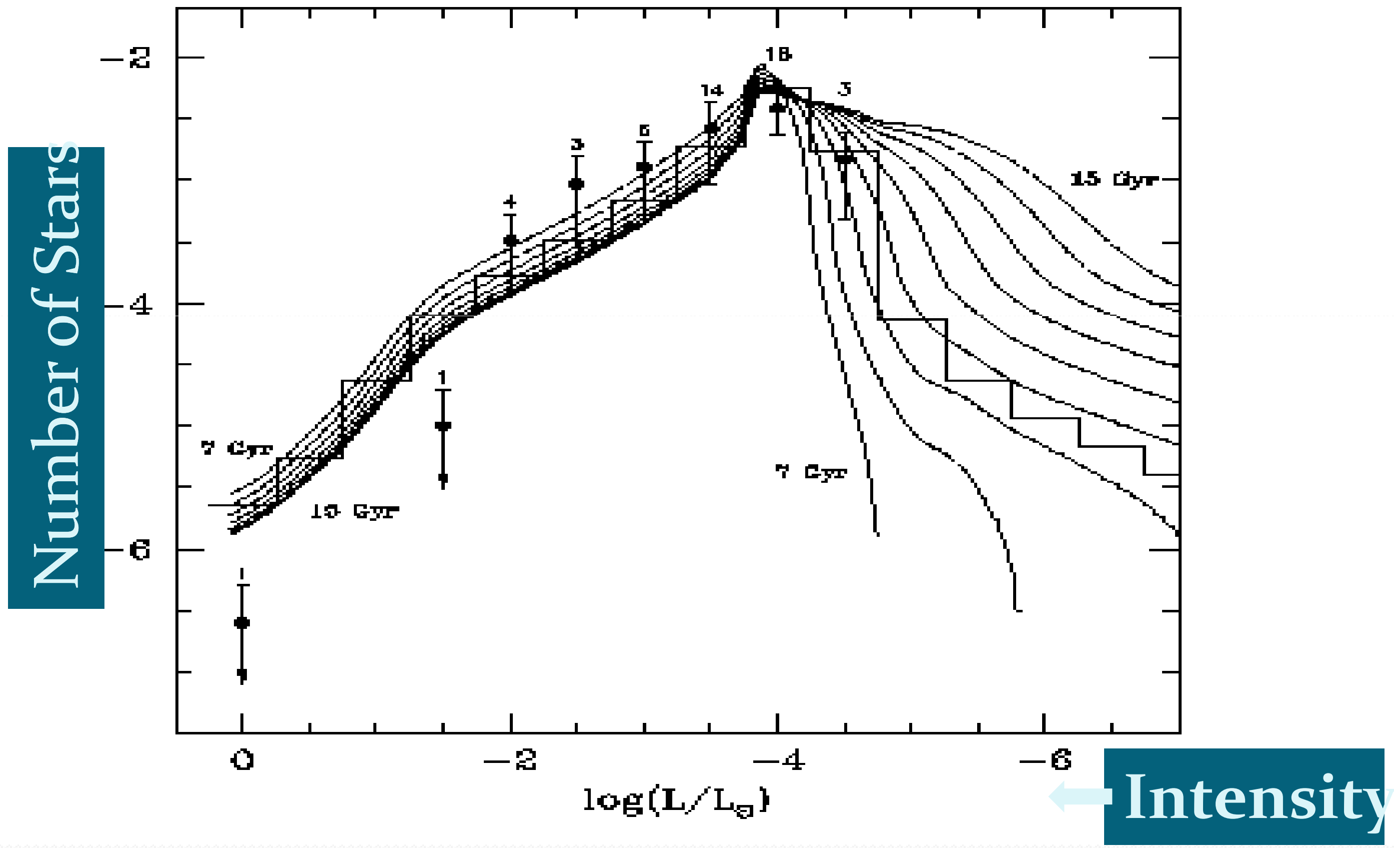


M4
F606W
F606W
F606W-F775W
22
24
26
28
30
0
0.5
1
1.5
2
3
1
5
5
2
6
13
10
10
9
7
10
8
1
0
1
2
6
6
1
1
2
3
3



CO_0.50_Xtal_PSHB (2.33)
CO_0.50_Xtal_PSSC (2.66)
CO_0.53_Xtal_PSHB (2.65)
CO_0.48_Xtal_PSHB (1.93)
$\Gamma = \frac{(Ze)^2/\langle r \rangle}{kT}$
~ 220
M4
N/bin
0
5
10
22
24
26
28
F606W

Luminc

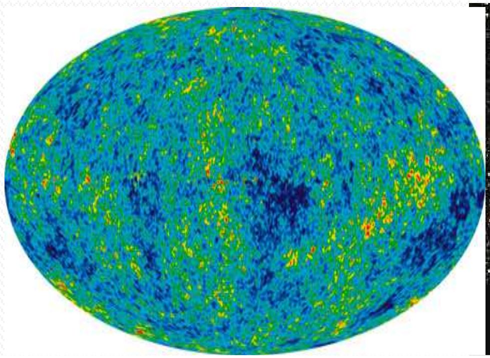


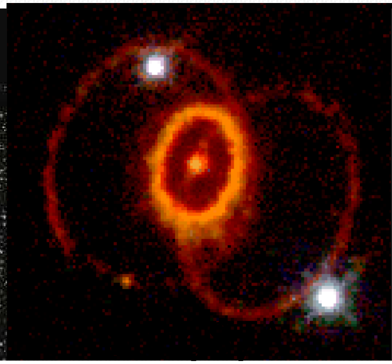
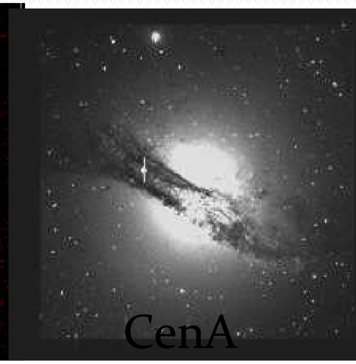
Age of the disk: 9 ± 2 yr

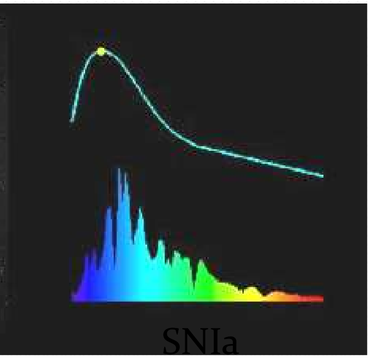
Age of the Universe 2011

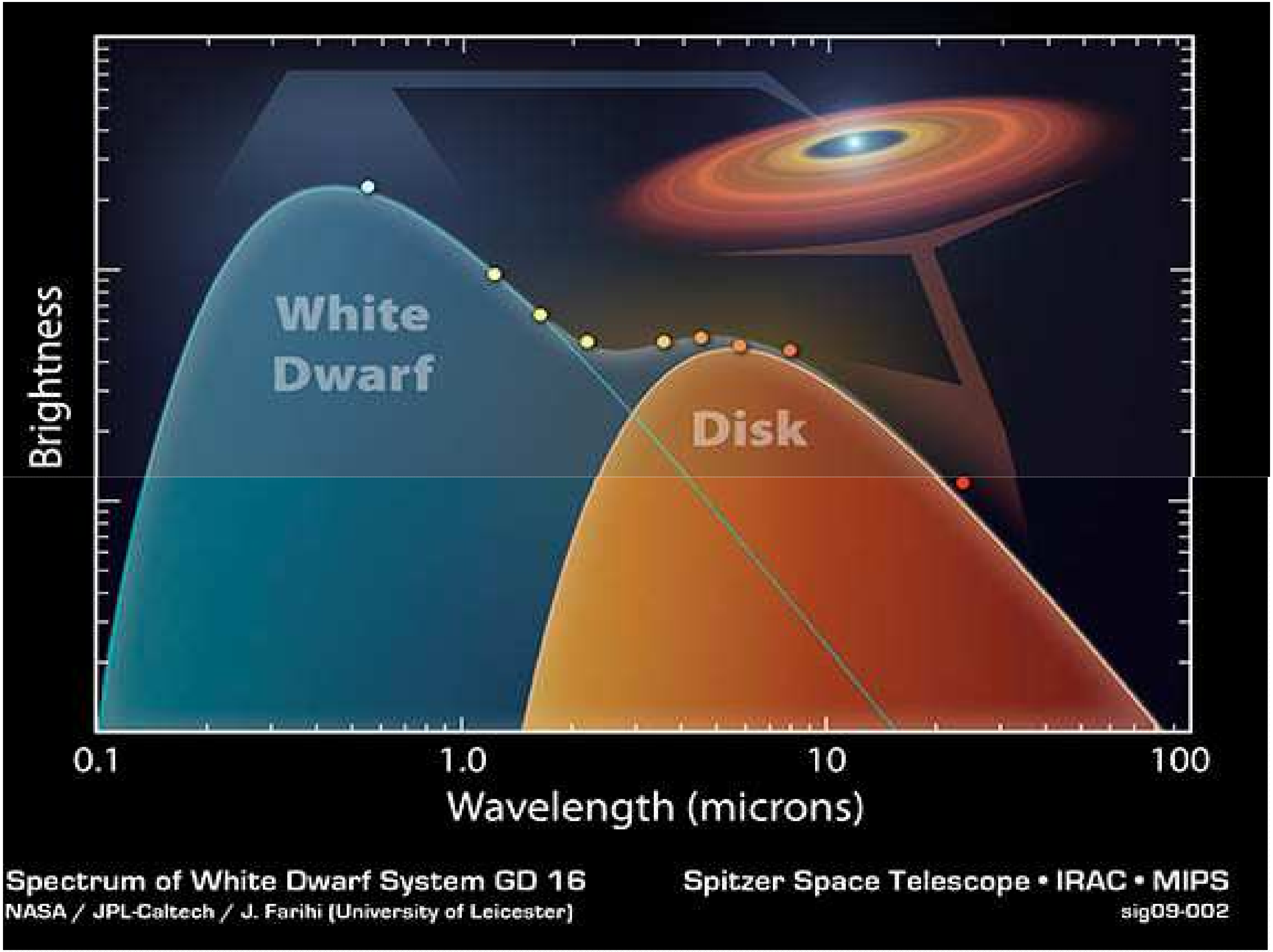
20 years ago only white dwarfs gave smaller than15 billion years

•WMAP	(13.75+0.11) Gyr
•1/H	(13 + 1) Gyr
•Globular Clusters	(13.2 + 1.5) Gyr
•Radioactive Decay	(12.5 + 3) Gyr
•While Dwarf Cooling	(12.7 + 0.7) Gyr
•Distance to SNIa	13.0 +1.2 (0.72/h)Gyr,Λ

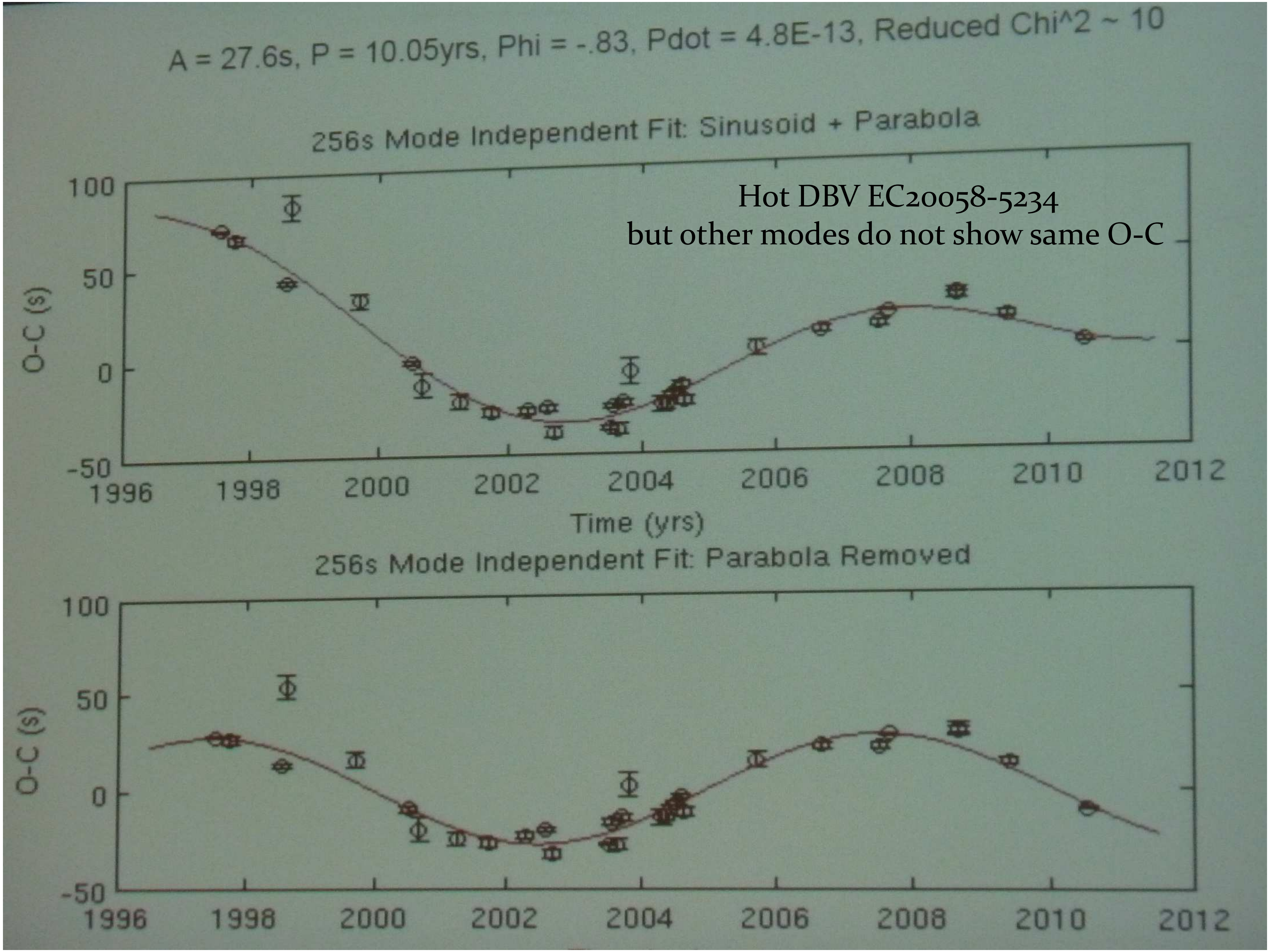






Brightness
White Dwarf
Disk
0.1
1.0
10
100
Wavelength (microns)
Spectrum of White Dwarf System GD 16
NASA / JPL-Caltech / J. Farihi (University of Leicester)
Spitzer Space Telescope • IRAC • MIPS
sig09-002



A = 27.6s, P = 10.05yrs, Phi = -.83, Pdot = 4.8E-13, Reduced Chi^2 ~ 10
256s Mode Independent Fit: Sinusoid + Parabola
Hot DBV EC20058-5234
but other modes do not show same O-C
O-C (s)
Time (yrs)
256s Mode Independent Fit: Parabola Removed
O-C (s)