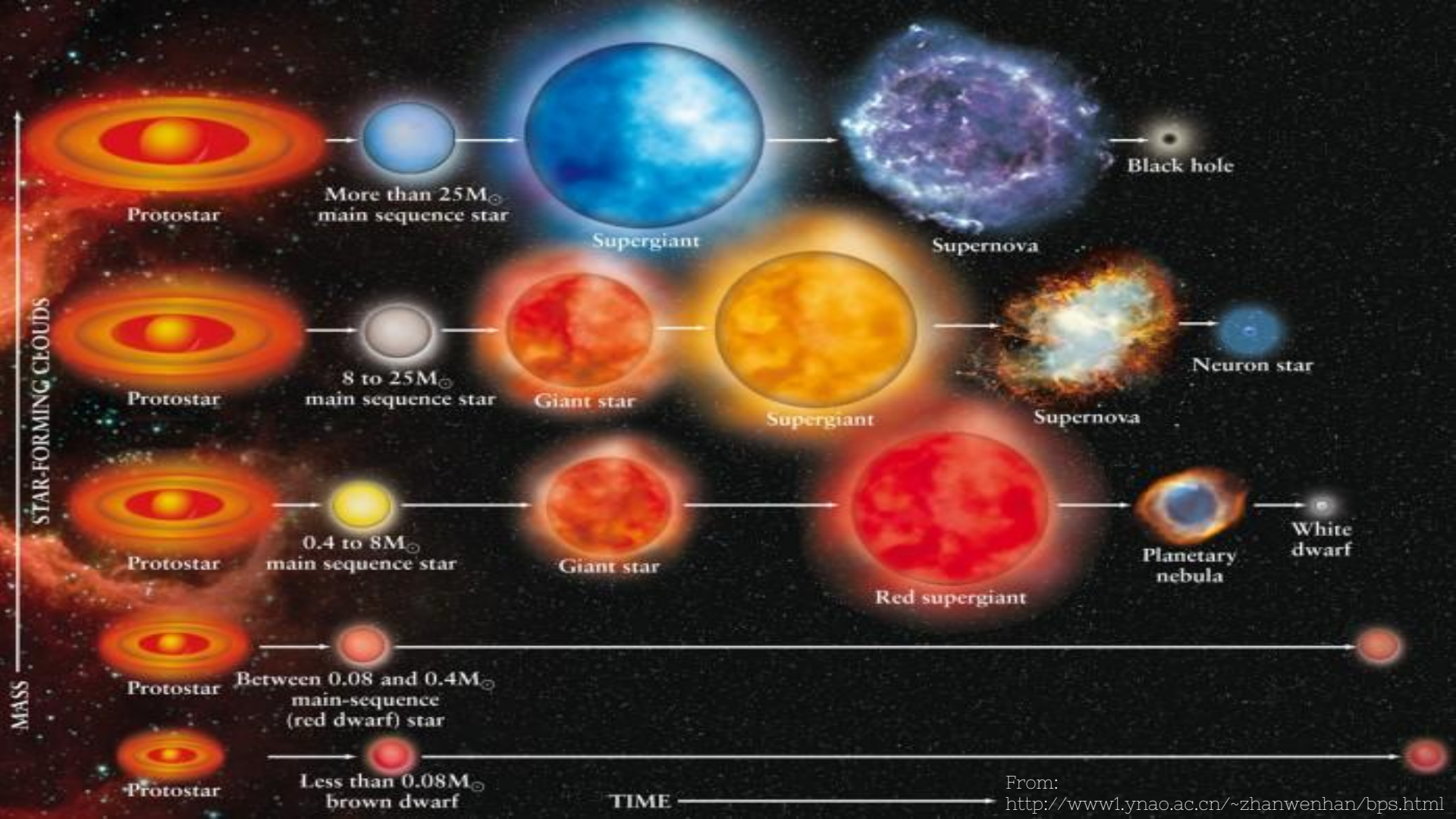
Where are the missing ELMs?

Ingrid Pelisoli
S. O. Kepler, D. Koester, L. Fraga, B. Castanheira, T. G. Wilson

ING Seminars
December 14, 2017

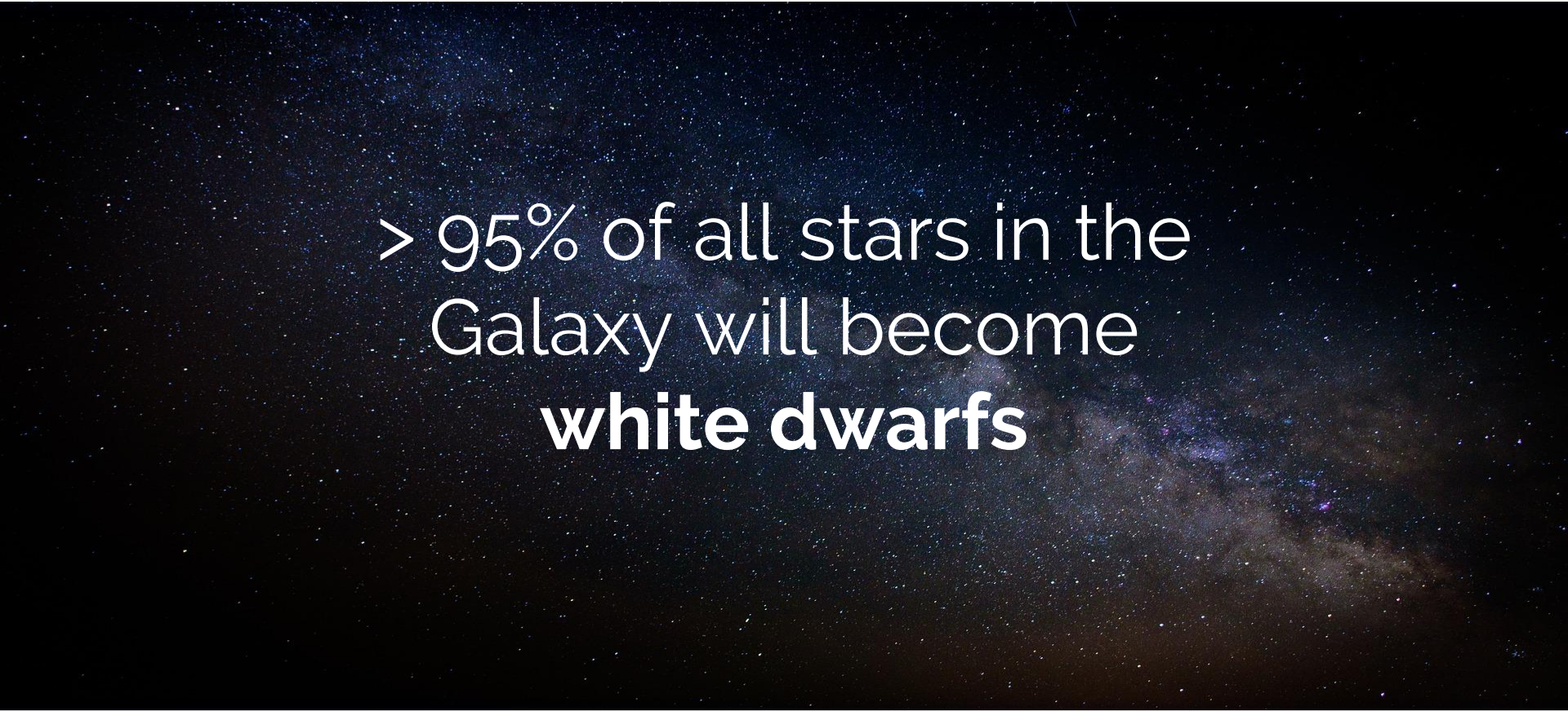
Overview

- **White dwarf stars**
  - *Why* study them?
  - Results from the SDSS catalogues
- **Beyond single evolution**
  - Extremely-low mass WDs
  - The missing population
- **Where are the missing ELMs?**
  - Results from targeted follow-up
- **Conclusions & Perspectives**

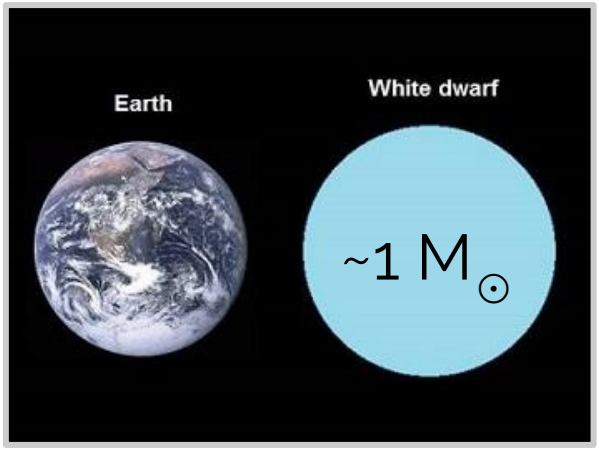


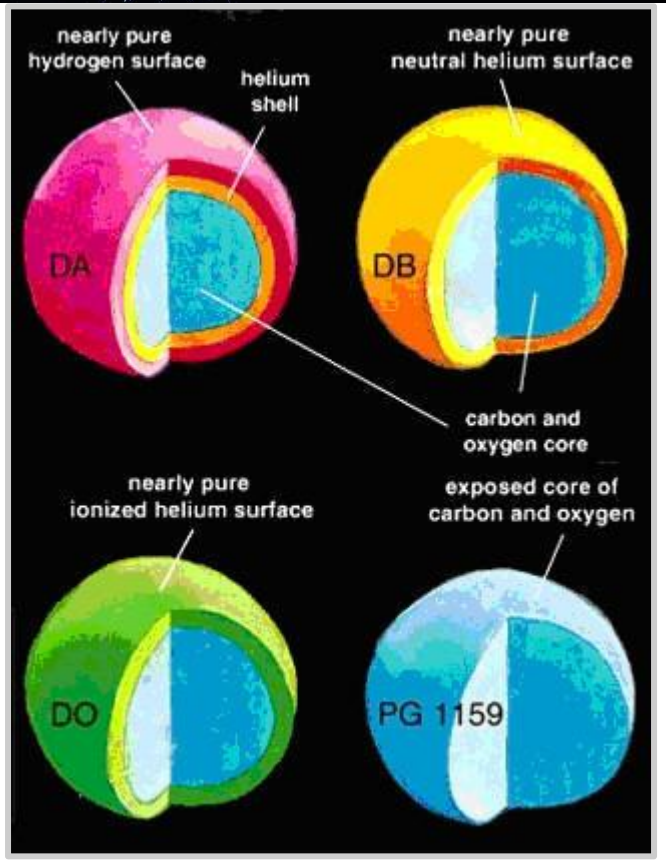
From:
http://www1.ynao.ac.cn/~zhanwenhan/bps.html

White dwarfs are *abundant*

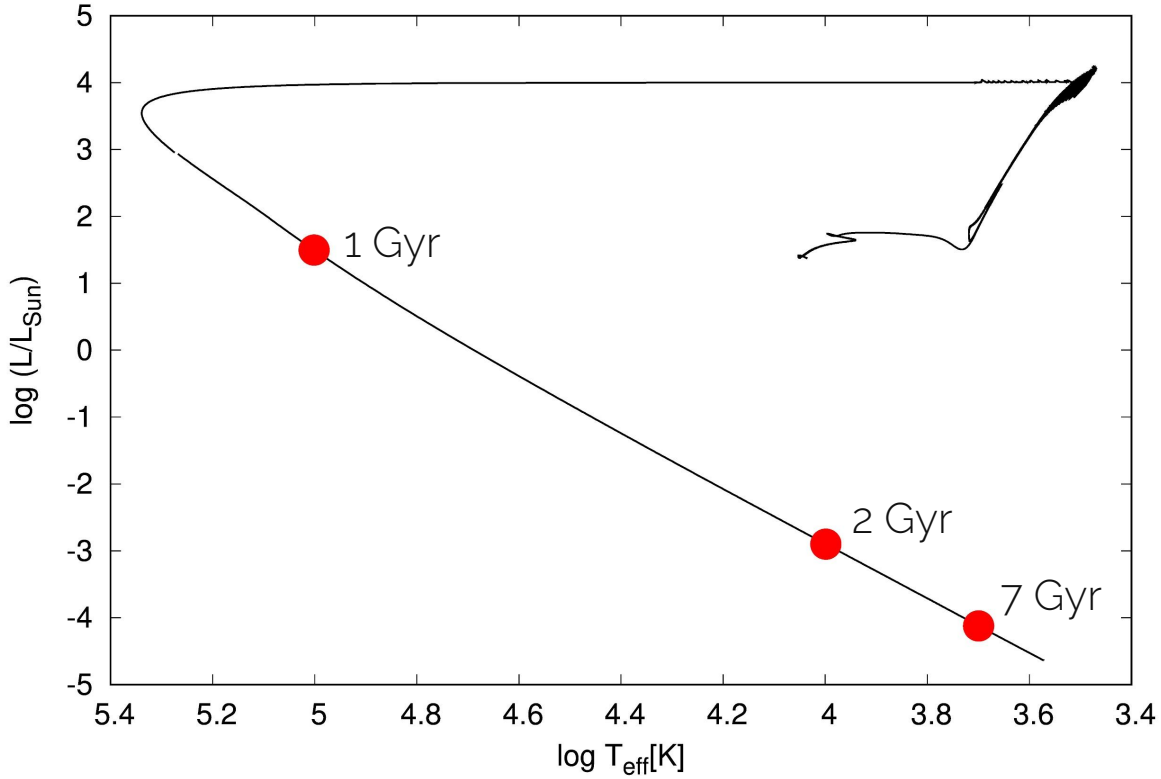


White dwarfs are *simple*





White dwarfs are *old*



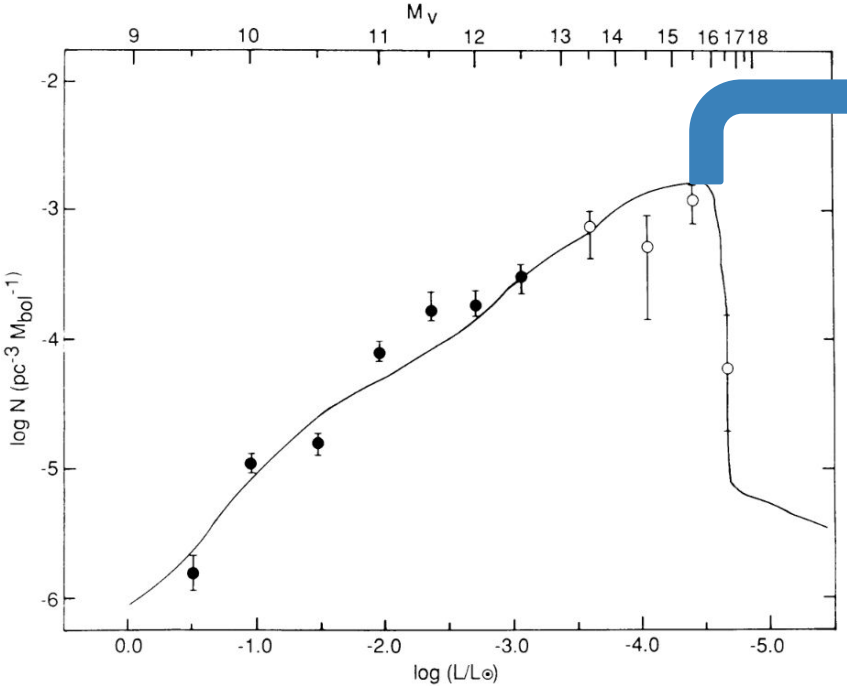
Evolution of a 2M$_\odot$ star (A-type)

THE ASTROPHYSICAL JOURNAL, 315:L77–L81, 1987

AN INDEPENDENT METHOD FOR DETERMINING THE AGE OF THE UNIVERSE

D. E. WINGET,[1,2] C. J. HANSEN,[3] JAMES LIEBERT,[4] H. M. VAN HORN,[5] G. FONTAINE,[6,7]
R. E. NATHER,[1] S. O. KEPLER,[8] AND D. Q. LAMB[9]

Received 1986 December 1; accepted 1987 February 1



Drop in WD count

↓

Haven't had the time to cool down yet

↓

Limit in age!

Estimate the age of the Universe to be 10.3 ± 2.2 Gyr

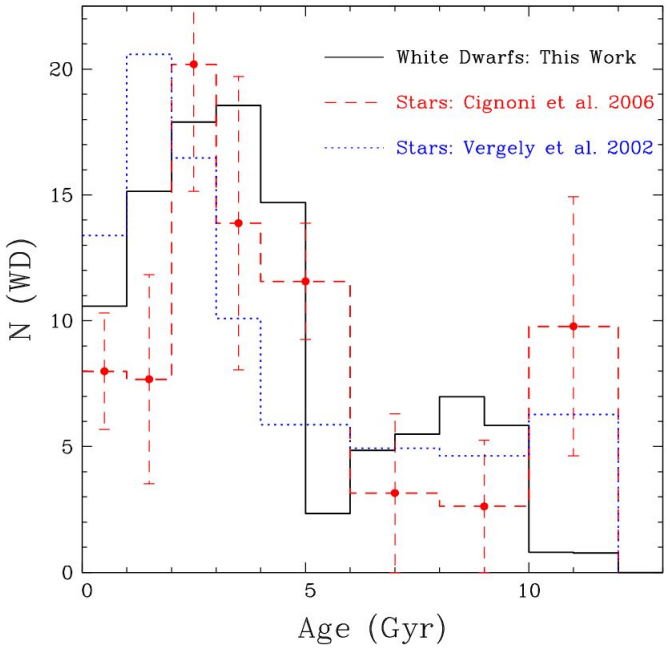
(much closer than Hubble's estimate!)

The Astrophysical Journal, 791:92 (9pp), 2014 August 20 doi:10.1088/0004-637X/791/2/92

WHITE DWARF COSMOCHRONOLOGY IN THE SOLAR NEIGHBORHOOD

P.-E. Tremblay[1,3], J. S. Kalirai[1,2], D. R. Soderblom[1], M. Cignoni[1], and J. Cummings[2]
[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; tremblay@stsci.edu
[2] Center for Astrophysical Sciences, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA
Received 2014 May 6; accepted 2014 June 19; published 2014 July 31

Reverse engineering to estimate star formation history in the solar neighborhood



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

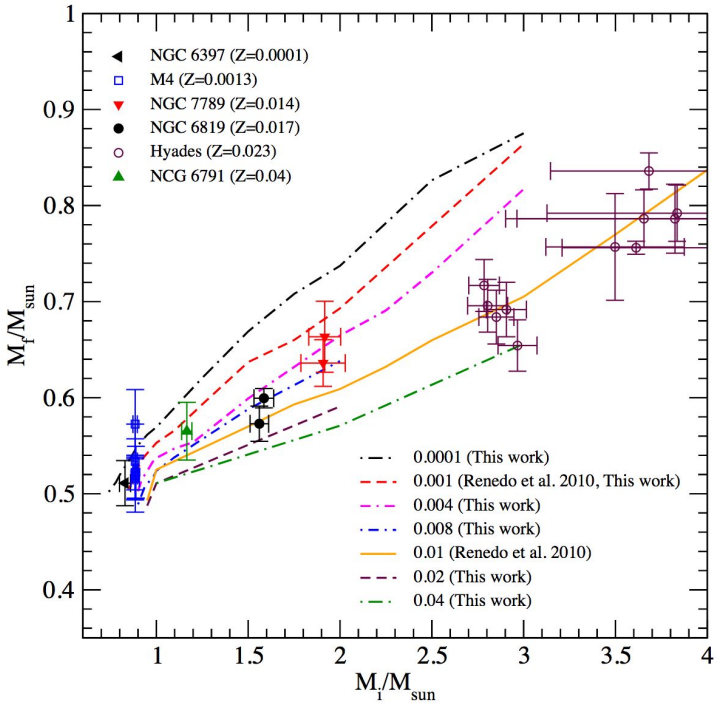
MNRAS 450, 3708–3723 (2015)

doi: 10.1093/mnras/stv848

The age-metallicity dependence for white dwarf stars

A. D. Romero,* F. Campos and S. O. Kepler

Departamento de Astronomia, Universidade Federal do Rio Grande do Sul, Av. Bento Goncalves 9500, Porto Alegre 91501-970, RS, Brazil



Stellar evolution depends highly on metallicity!

Particle physics

Quantum mechanics

Condensed matter

An independent limit on the axion mass from the variable white dwarf star R548

To cite this article: A.H. Córsico *et al* JCAP12(2012)010

Conference Report

Probing the Gravitational Dependence of the Fine-Structure Constant from Observations of White Dwarf Stars

Matthew B. Bainbridge [1,*], Martin A. Barstow [1], Nicole Reindl [1], W.-Ü Lydia Tchang-Brillet [2,3], Thomas R. Ayres [4], John K. Webb [5], John D. Barrow [6], Jiting Hu [5], Jay B. Holberg [7], Simon P. Preval [8], Wim Ubachs [9], Vladimir A. Dzuba [5], Victor V. Flambaum [5], Vincent Dumont [10] and Julian C. Berengut [5]

THE ASTROPHYSICAL JOURNAL, 693:L6–L10, 2009 March 1 doi:10.1088/0004-637X/693/1/L6

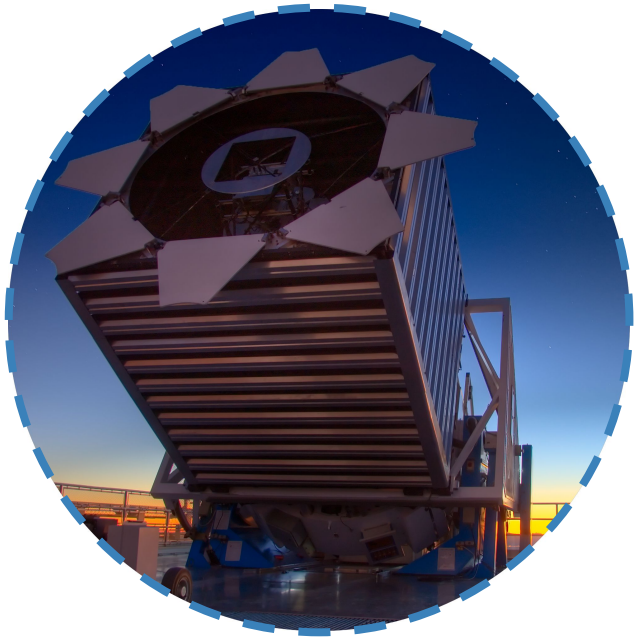
THE PHYSICS OF CRYSTALLIZATION FROM GLOBULAR CLUSTER WHITE DWARF STARS IN NGC 6397

D. E. WINGET[1,2], S. O. KEPLER[2], FABÍOLA CAMPOS[2], M. H. MONTGOMERY[1,3], LEO GIRARDI[4], P. BERGERON[5], AND KURTIS WILLIAMS[1,6]

SDSS WD Catalogues

- ★ DR1: Kleinman et al. 2004
- ★ DR4: Eisenstein et al. 2006
- ★ DR7: Kleinman, Kepler, Koester, Pelisoli et al. 2013
- ★ DR10: Kepler, Pelisoli et al. 2015
- ★ DR12: Kepler, Pelisoli et al. 2016
- ★ DR14: soon!

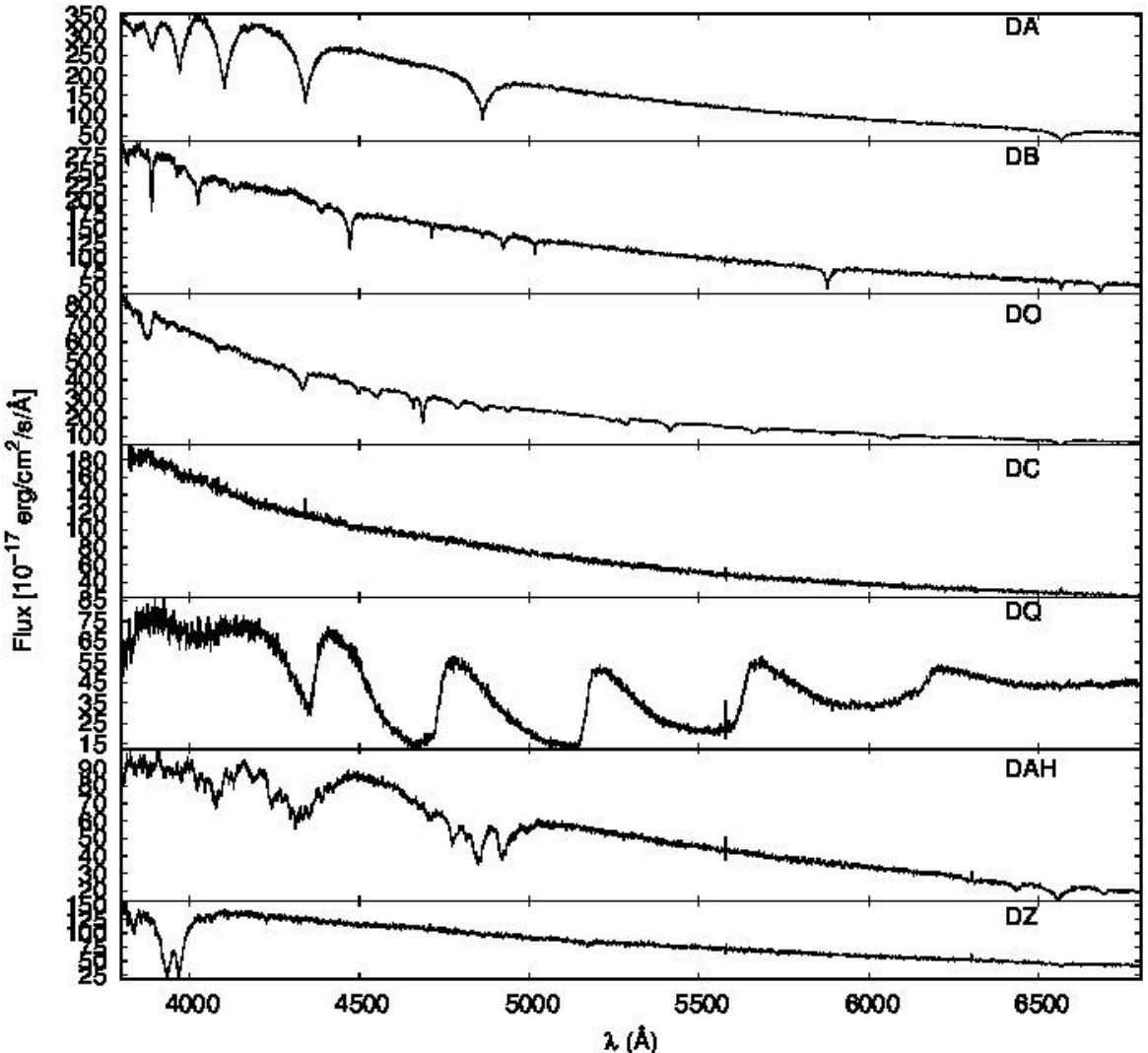
From 5,000 to over 30,000!
6× increase!



2.5 m telescope

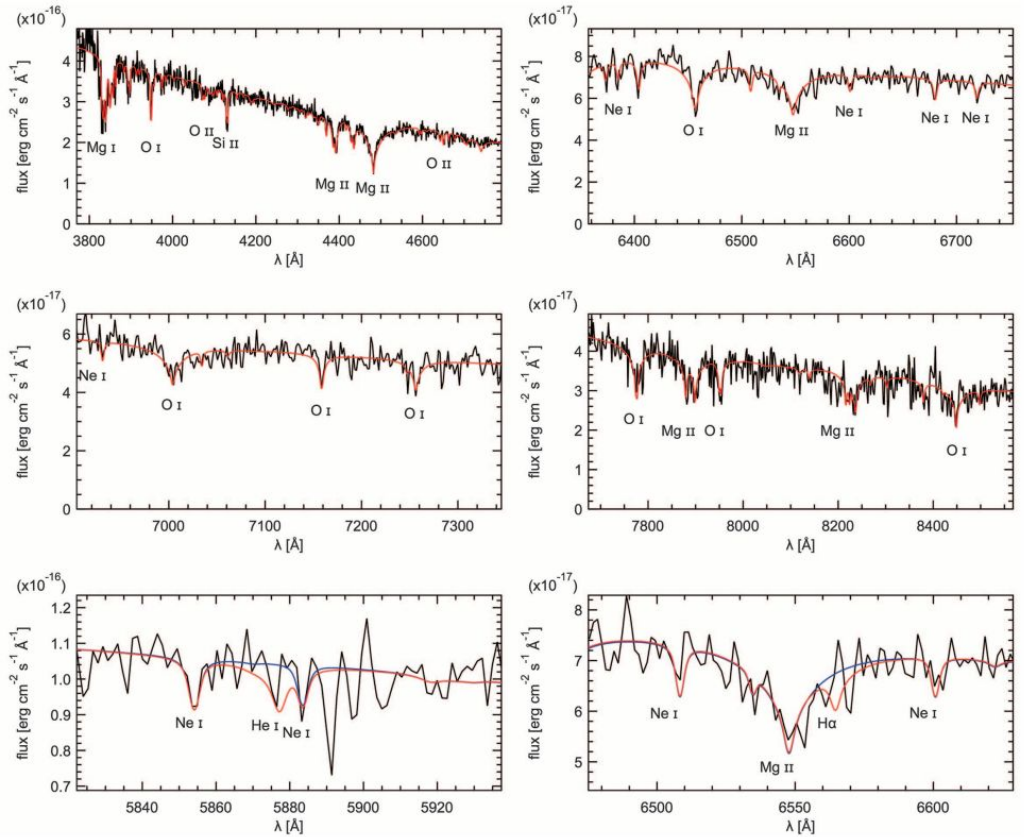
Imaged ⅓ of the sky

Spectra of over 3M sources



Flavours for every taste

And even new flavours...



Oxygen dominated white dwarf "Dox"

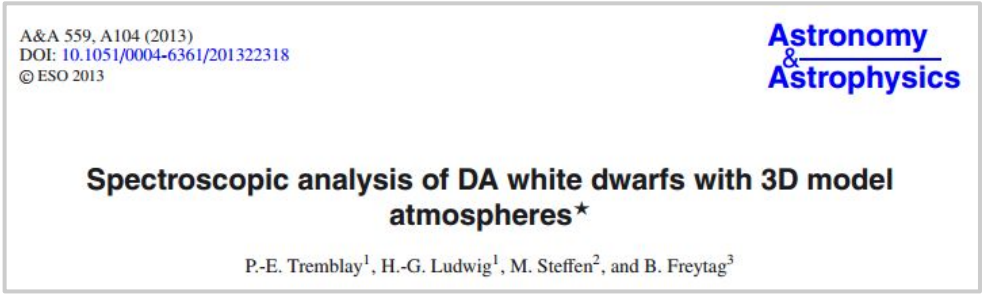
No H, no He!

Particularly violent very late thermal pulse? Binary evolution?

Many studies were made possible...

★ DR7 WD catalog (2013):

178 citations



A&A 559, A104 (2013)
DOI: 10.1051/0004-6361/201322318
© ESO 2013

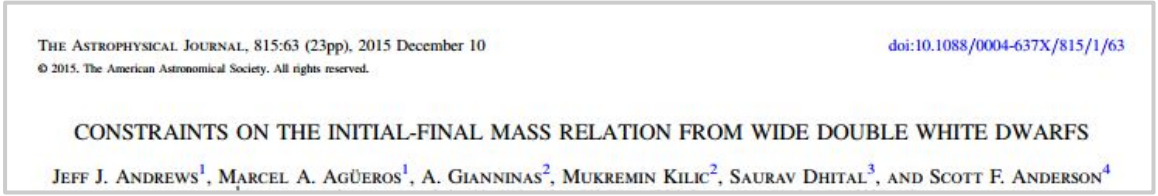
Astronomy & Astrophysics

Spectroscopic analysis of DA white dwarfs with 3D model atmospheres*

P.-E. Tremblay[1], H.-G. Ludwig[1], M. Steffen[2], and B. Freytag[3]

★ DR10 WD catalog (2015):

70 citations



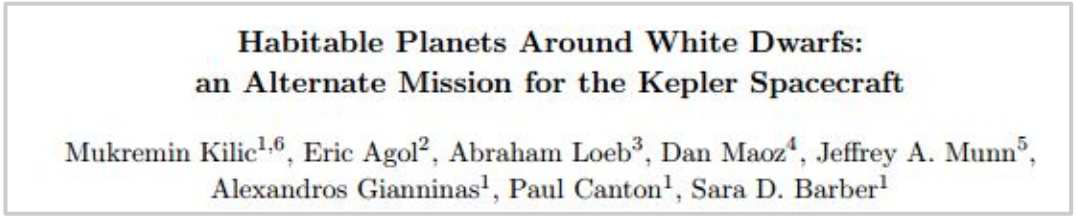
The Astrophysical Journal, 815:63 (23pp), 2015 December 10 doi:10.1088/0004-637X/815/1/63
© 2015. The American Astronomical Society. All rights reserved.

CONSTRAINTS ON THE INITIAL-FINAL MASS RELATION FROM WIDE DOUBLE WHITE DWARFS

Jeff J. Andrews[1], Marcel A. Agüeros[1], A. Gianninas[2], Mukremin Kilic[2], Saurav Dhital[3], and Scott F. Anderson[4]

★ DR12 (2016):

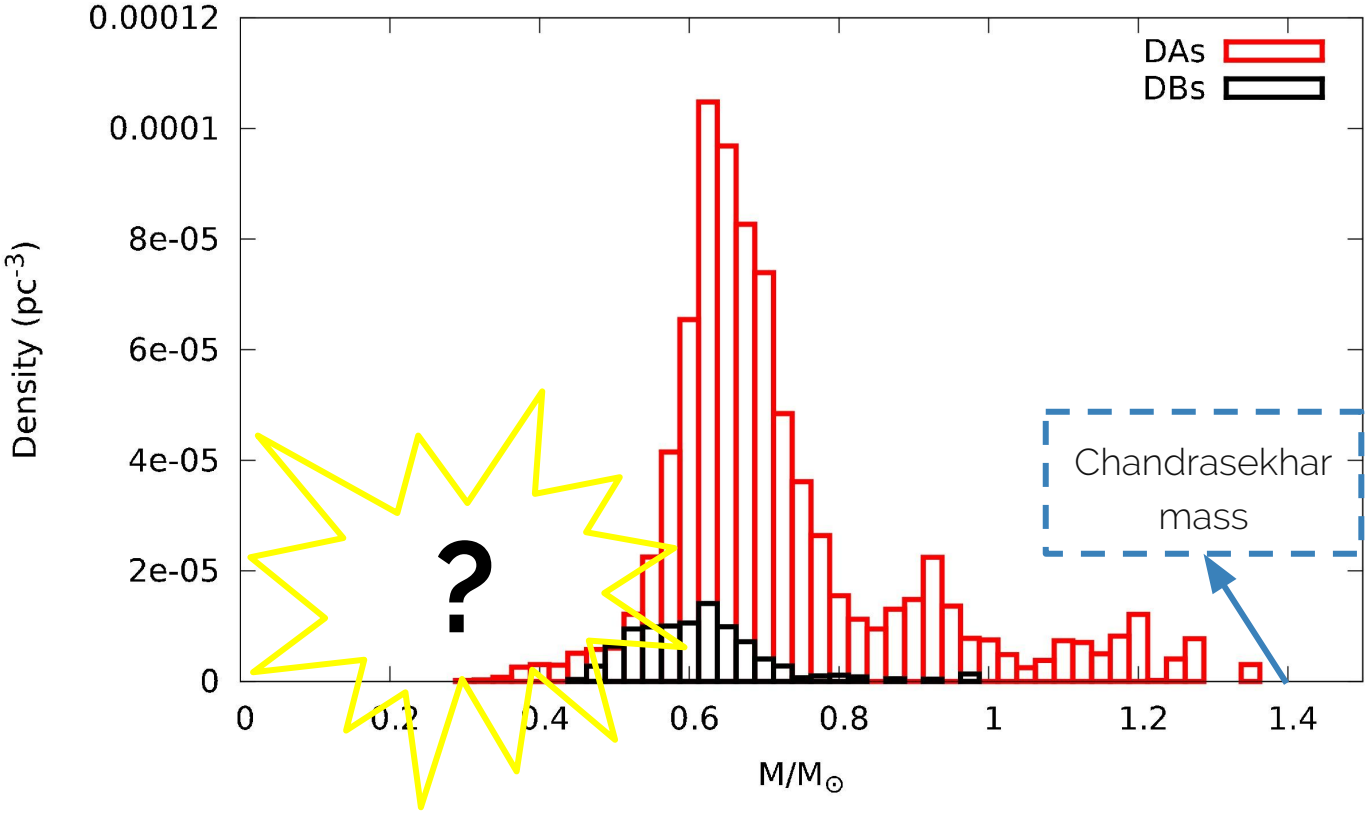
52 citations



Habitable Planets Around White Dwarfs: an Alternate Mission for the Kepler Spacecraft

Mukremin Kilic[1,6], Eric Agol[2], Abraham Loeb[3], Dan Maoz[4], Jeffrey A. Munn[5], Alexandros Gianninas[1], Paul Canton[1], Sara D. Barber[1]

...but something was missing.



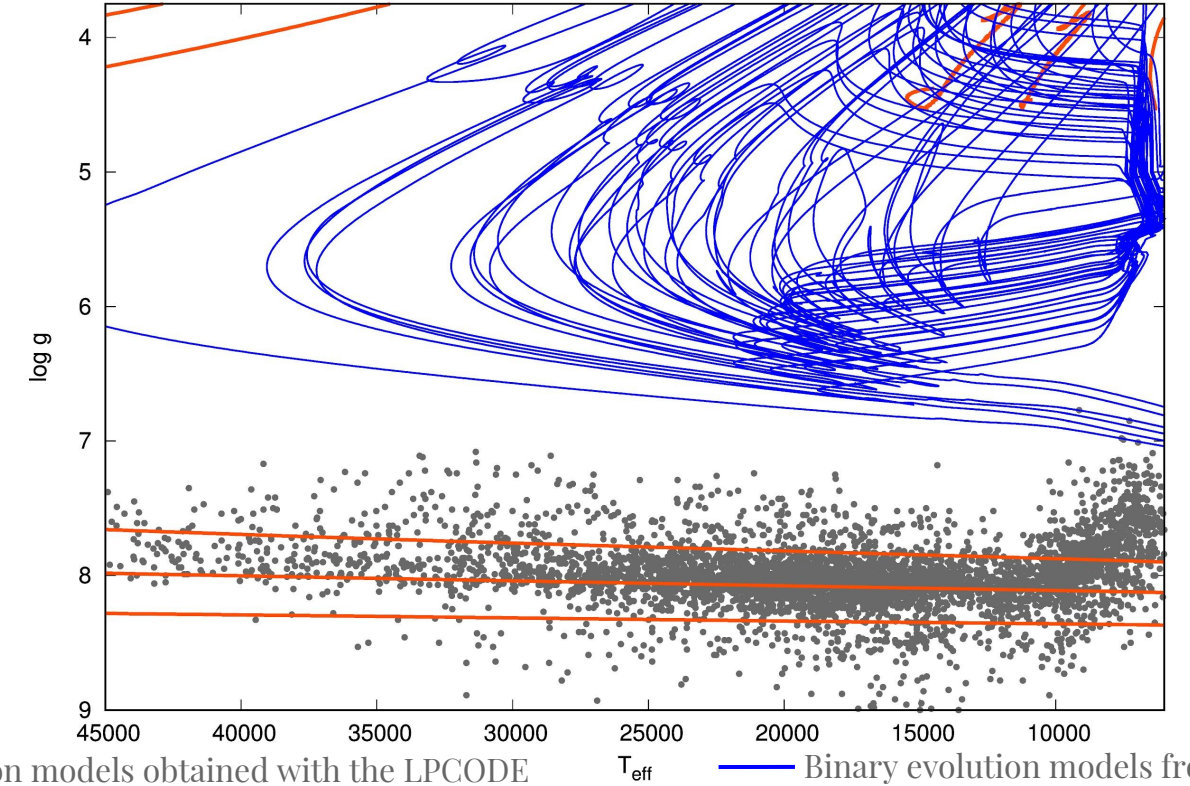
50 % of stars $\gtrsim$ 1.0 $M_\odot$ = **BINARIES**

(Duchêne & Kraus 2013, ARA&A, 51, 269)

25% of binaries interact

(Willems & Kolb 2004, A&A, 419, 1057)

Beyond single evolution



Single evolution models obtained with the LPCODE (Althaus et al. 2005) by A. D. Romero

Binary evolution models from Istrate et al. (2016), including diffusion and rotational mixing.

Hunting for binaries

First searches for double-degenerate white dwarfs were carried out to find **potential SN Ia progenitors**

THE ASTROPHYSICAL JOURNAL, 322:296–301, 1987 November 1

AN UPPER LIMIT TO THE SPACE DENSITY OF SHORT-PERIOD, NONINTERACTING BINARY WHITE DWARFS

EDWARD L. ROBINSON AND ALLEN W. SHAFTER
McDonald Observatory and Department of Astronomy, The University of Texas at Austin
Received 1987 January 29; accepted 1987 March 30

THE ASTROPHYSICAL JOURNAL, 374:281–287, 1991 June 10

LIMITS ON THE SPACE DENSITY OF DOUBLE DEGENERATES AS TYPE Ia SUPERNOVA PROGENITORS

DIANA FOSS & RICHARD A. WADE[1]
Steward Observatory, University of Arizona, Tucson, AZ 85721
AND
RICHARD F. GREEN
Kitt Peak National Observatory, National Optical Astronomy Observatories,[2] Box 26732, Tucson, AZ, 85726
Received 1990 August 10; accepted 1990 December 4

and yielded ***no short period binaries***...

But we do observe SN Ia!

Hunting for binaries

THE ASTROPHYSICAL JOURNAL, 394:228–247, 1992 July 20

A SPECTROSCOPIC DETERMINATION OF THE MASS DISTRIBUTION OF DA WHITE DWARFS

P. BERGERON,[1,2] REX A. SAFFER,[1,3] AND JAMES LIEBERT[1]

Received 1991 December 9; accepted 1992 January 30

Found 14 stars with $M < 0.45\ M_{\odot}$

Too low for single star evolution!

Mon. Not. R. Astron. Soc. **275**, 828–840 (1995)

Low-mass white dwarfs need friends: five new double-degenerate close binary stars

T. R. Marsh,[1] V. S. Dhillon[2] and S. R. Duck[3]
[1]*University of Southampton, Department of Physics, Highfield, Southampton SO17 1BJ*
[2]*Royal Greenwich Observatory, Apartado de Correos 321, Santa Cruz de La Palma, 38780 Tenerife, Canary Islands, Spain*
[3]*University of Oxford, Department of Physics, Nuclear Physics Laboratory, Keble Road, Oxford OX1 3RH*

Found 5 out of 7 to be in binaries!

Hunting for binaries

THE ASTROPHYSICAL JOURNAL, 716:122–130, 2010 June 10 doi:10.1088/0004-637X/716/1/122

THE DISCOVERY OF BINARY WHITE DWARFS THAT WILL MERGE WITHIN 500 Myr*

MUKREMIN KILIC[1,5], WARREN R. BROWN[1], CARLOS ALLENDE PRIETO[2,6], S. J. KENYON[1], AND J. A. PANEI[3,4]
[1] Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA; mkilic@cfa.harvard.edu
[2] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey RH5 6NT, UK
[3] Facultad de Ciencias Astronómicas y Geofísicas, UNLP, Paseo del Bosque S/N, La Plata B1900FWA, Argentina
[4] Instituto de Astrofísica La Plata, IALP, CONICET-UNLP, Argentina
Received 2009 October 7; accepted 2010 April 9; published 2010 May 14

→ 4 new systems

space density?

period distribution?

merger rate?

The ELM Survey

The Astrophysical Journal, 723:1072–1081, 2010 November 10 doi:10.1088/0004-637X/723/2/1072

THE ELM SURVEY. I. A COMPLETE SAMPLE OF EXTREMELY LOW-MASS WHITE DWARFS*

Warren R. Brown[1], Mukremin Kilic[1,4], Carlos Allende Prieto[2,3], and Scott J. Kenyon[1]
[1] Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138, USA;
wbrown@cfa.harvard.edu, mkilic@cfa.harvard.edu, skenyon@cfa.harvard.edu
[2] Instituto de Astrofísica de Canarias, E-38205, La Laguna, Tenerife, Spain; callende@iac.es
[3] Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain
Received 2010 June 23; accepted 2010 August 31; published 2010 October 19

■ ■ ■

The Astrophysical Journal, 818:155 (13pp), 2016 February 20 doi:10.3847/0004-637X/818/2/155

CrossMark

THE ELM SURVEY. VII. ORBITAL PROPERTIES OF LOW-MASS WHITE DWARF BINARIES*

Warren R. Brown[1], A. Gianninas[2], Mukremin Kilic[2], Scott J. Kenyon[1], and Carlos Allende Prieto[3,4]
[1] Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138 USA; wbrown@cfa.harvard.edu
[2] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, 440 W. Brooks Street, Norman, OK, 73019 USA; alexg@nhn.ou.edu, kilic@ou.edu
[3] Instituto de Astrofísica de Canarias, E-38205, La Laguna, Tenerife, Spain; skenyon@cfa.harvard.edu
[4] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain; callende@iac.es
Received 2015 November 24; accepted 2016 January 14; published 2016 February 17

88 systems

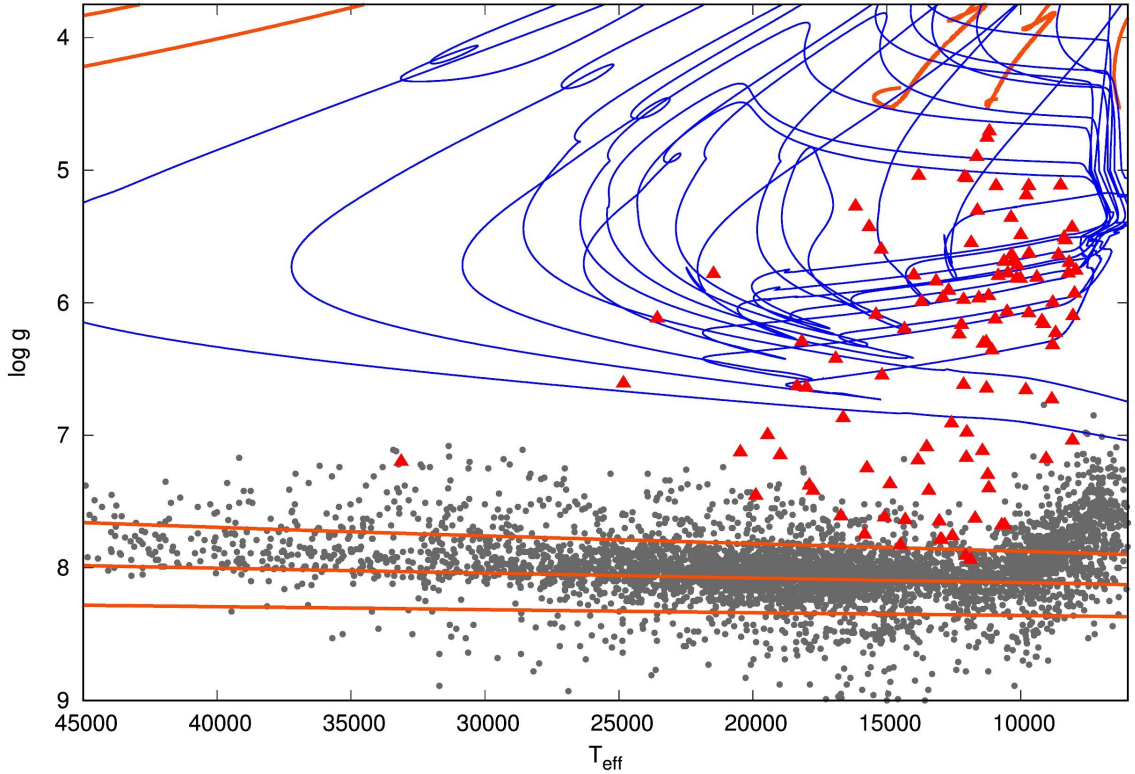
76 confirmed binaries

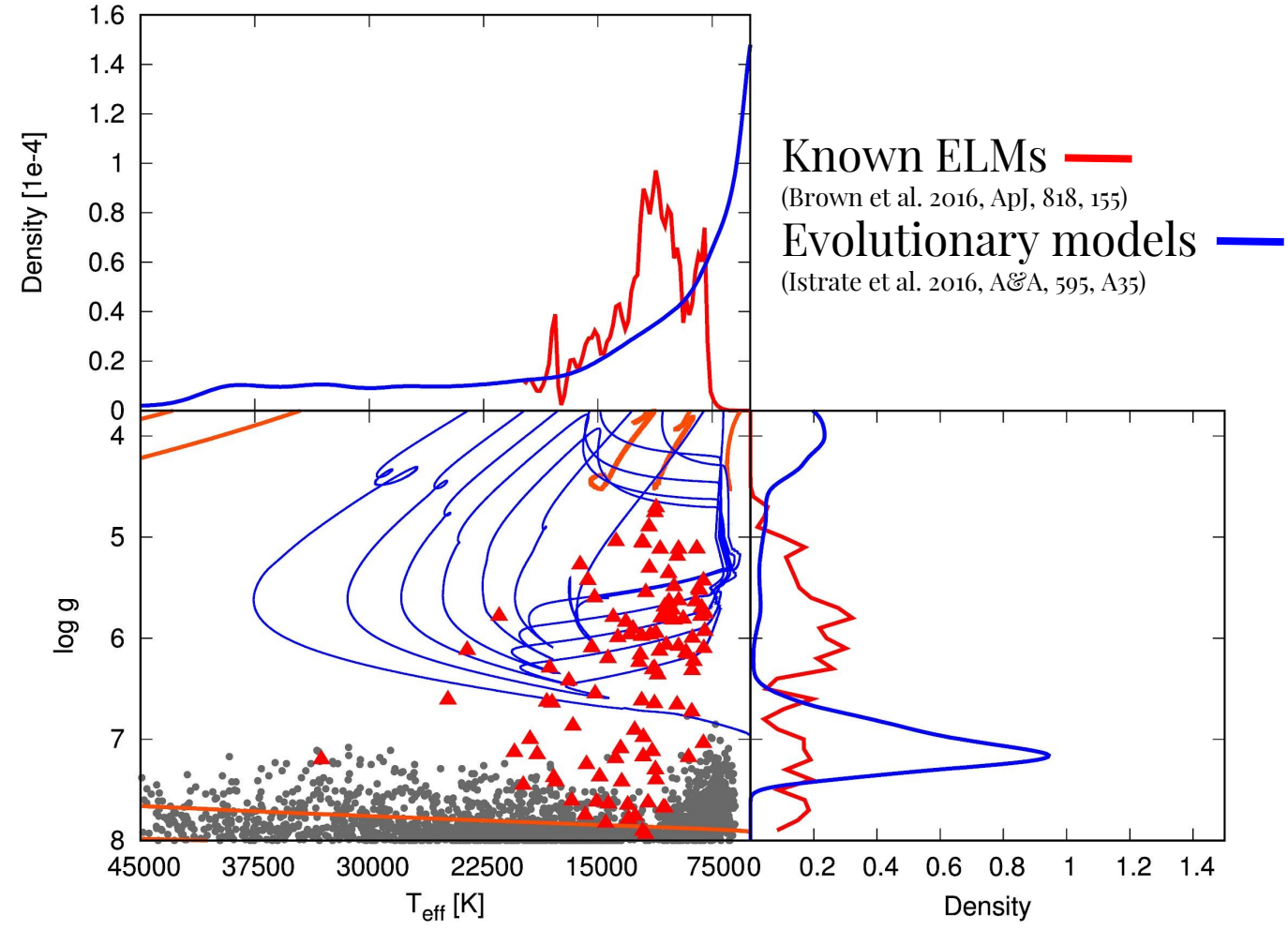
$\langle M_2 \rangle = 0.76 \pm 0.25\ M_\odot$

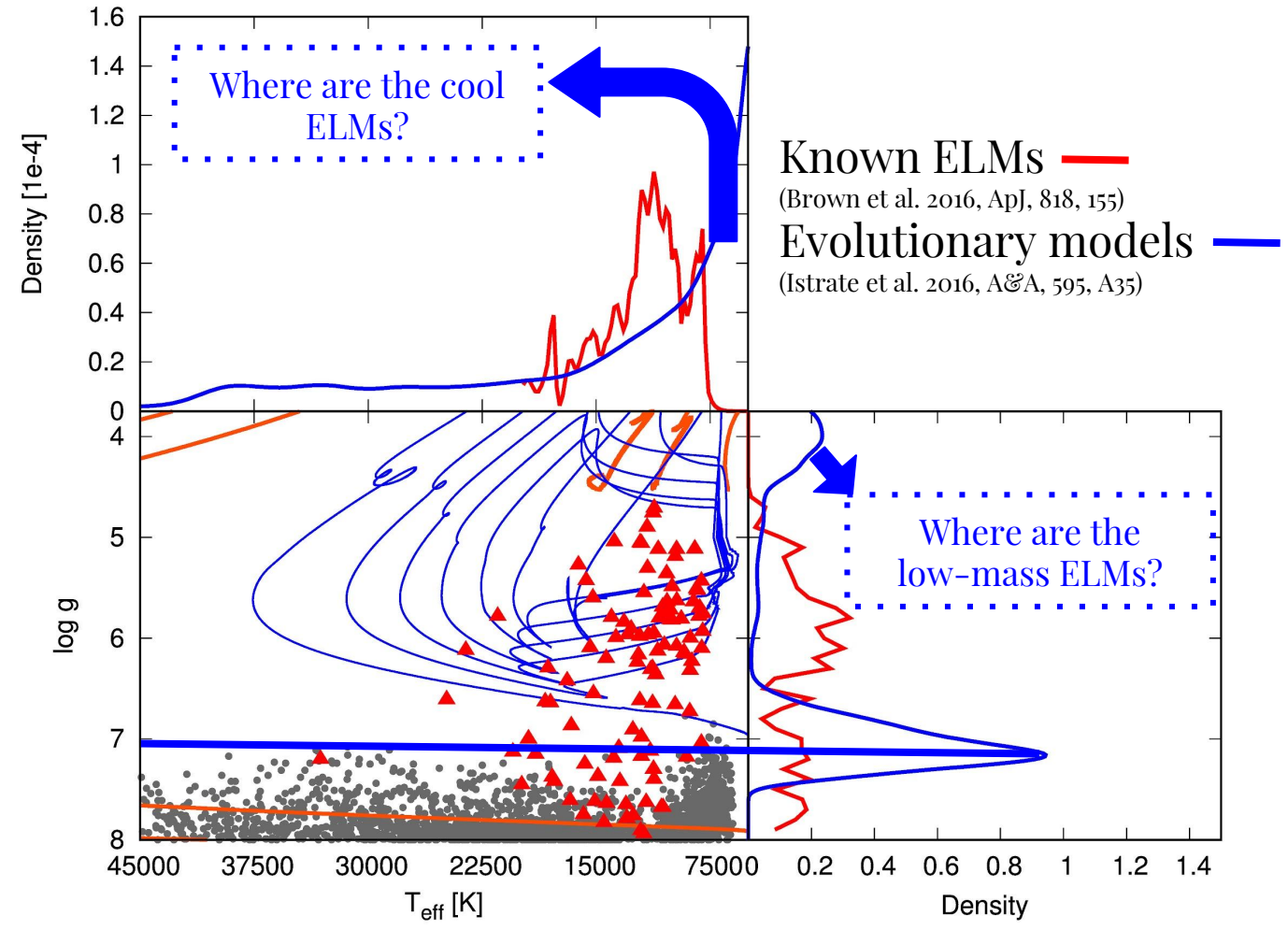
$P = 5.4$ h

95% are ***not*** SN Ia progenitors

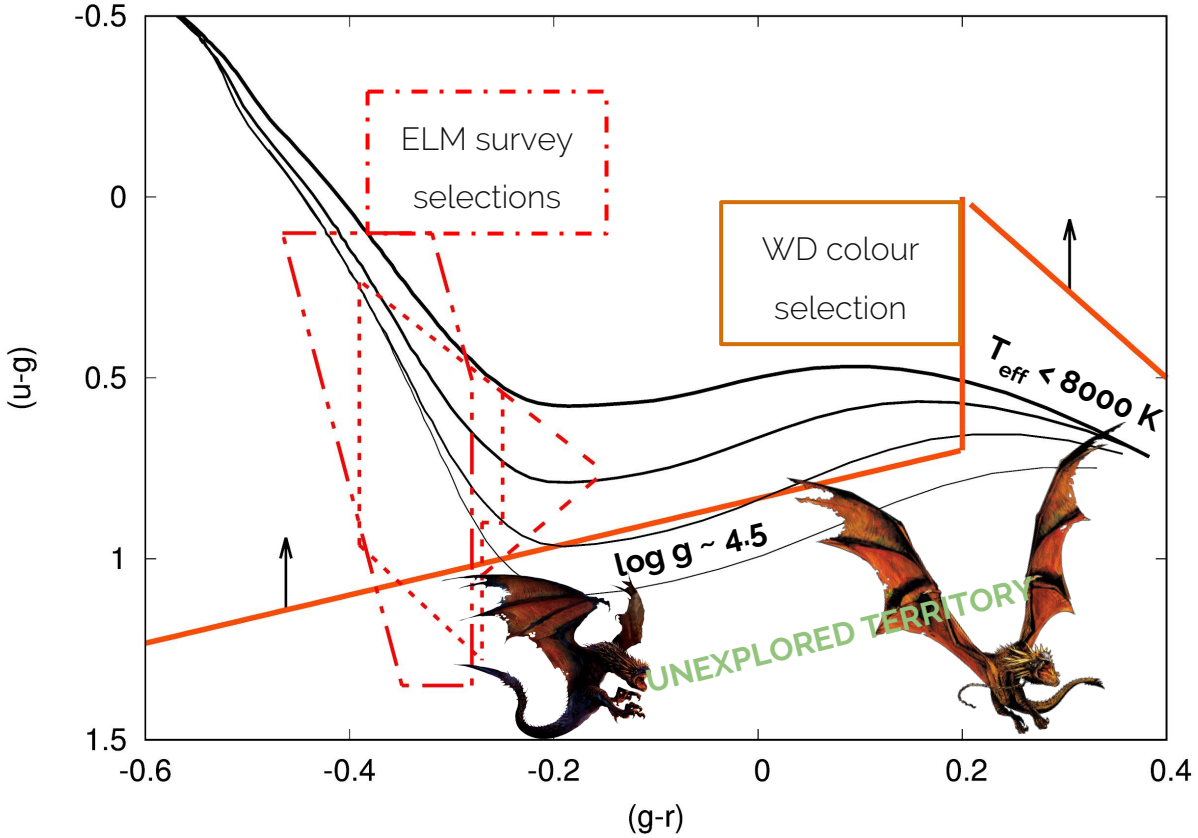
So... have we found what we were looking for?



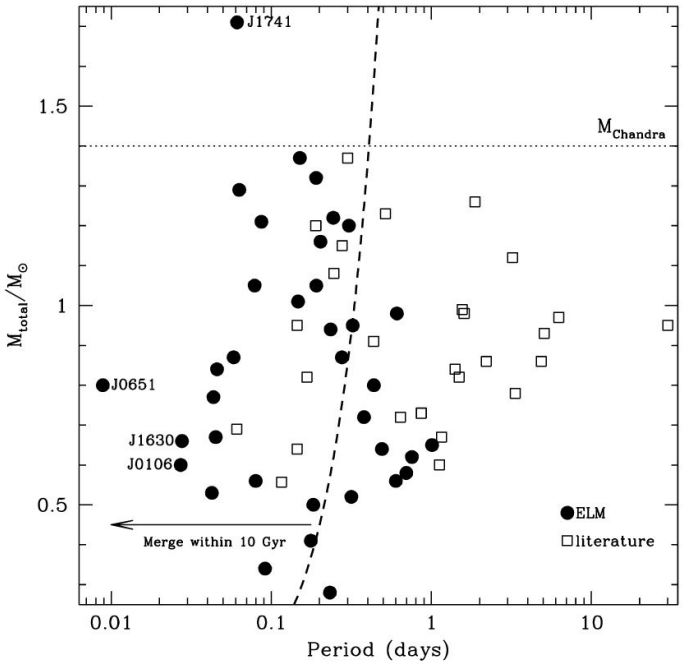

Density [1e-4]
log g
T_{eff} [K]
Density
Known ELMs
(Brown et al. 2016, ApJ, 818, 155)
Evolutionary models
(Istrate et al. 2016, A&A, 595, A35)


Where are the cool ELMs?
Known ELMs
(Brown et al. 2016, ApJ, 818, 155)
Evolutionary models
(Istrate et al. 2016, A&A, 595, A35)
Where are the low-mass ELMs?
Density [1e-4]
log g
T_{eff} [K]
Density
0.17
0.1

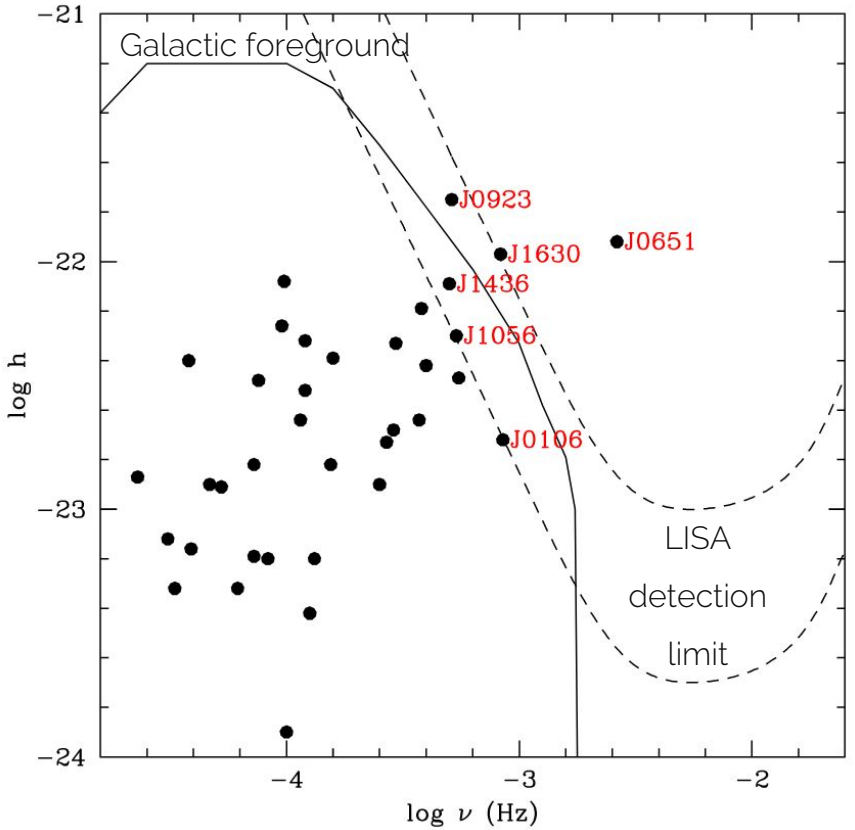
They are where we haven't looked!



Gravitational wave sources!

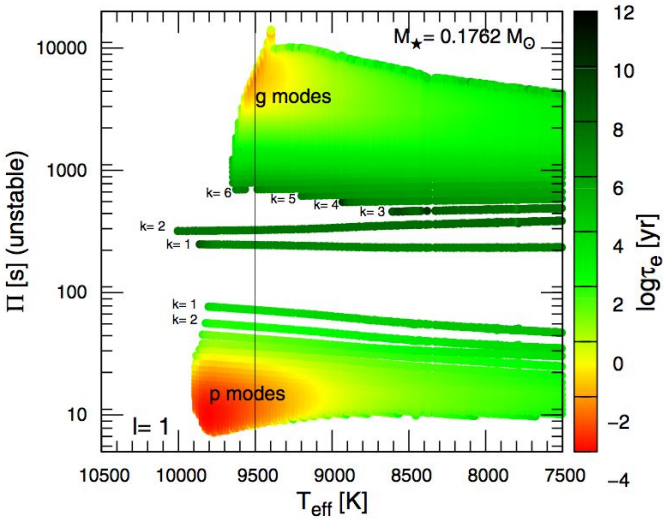


Most systems merge within a Hubble time!

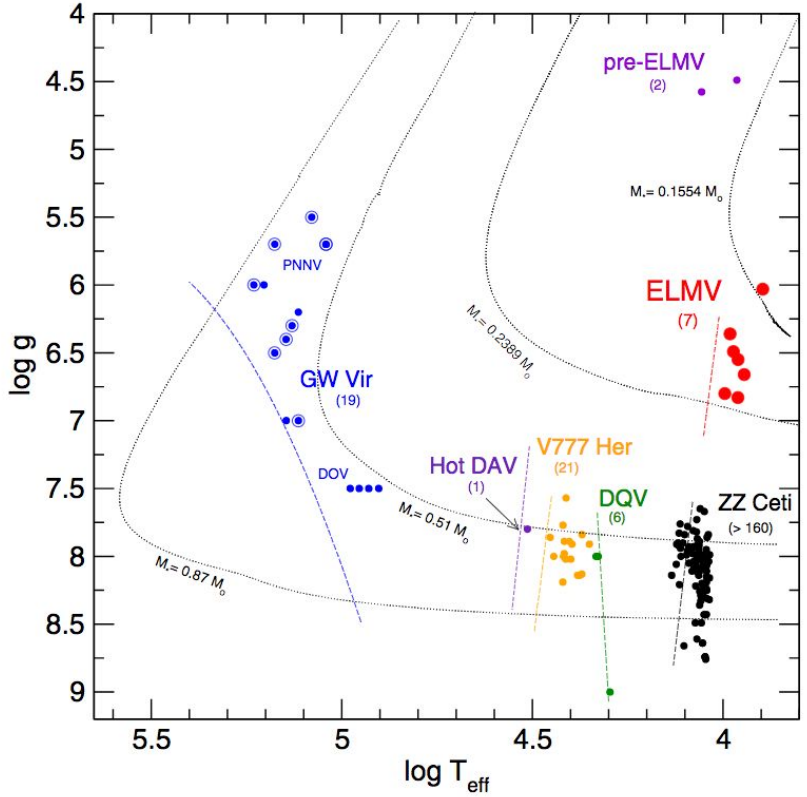


Kilic et al. 2012, ApJ, 751, 141

Pulsations in both *p* and *g*-modes



Opportunity for probing stellar interiors!



Córsico & Althaus 2016, A&A, 585, A1

Searching for the missing ELM population

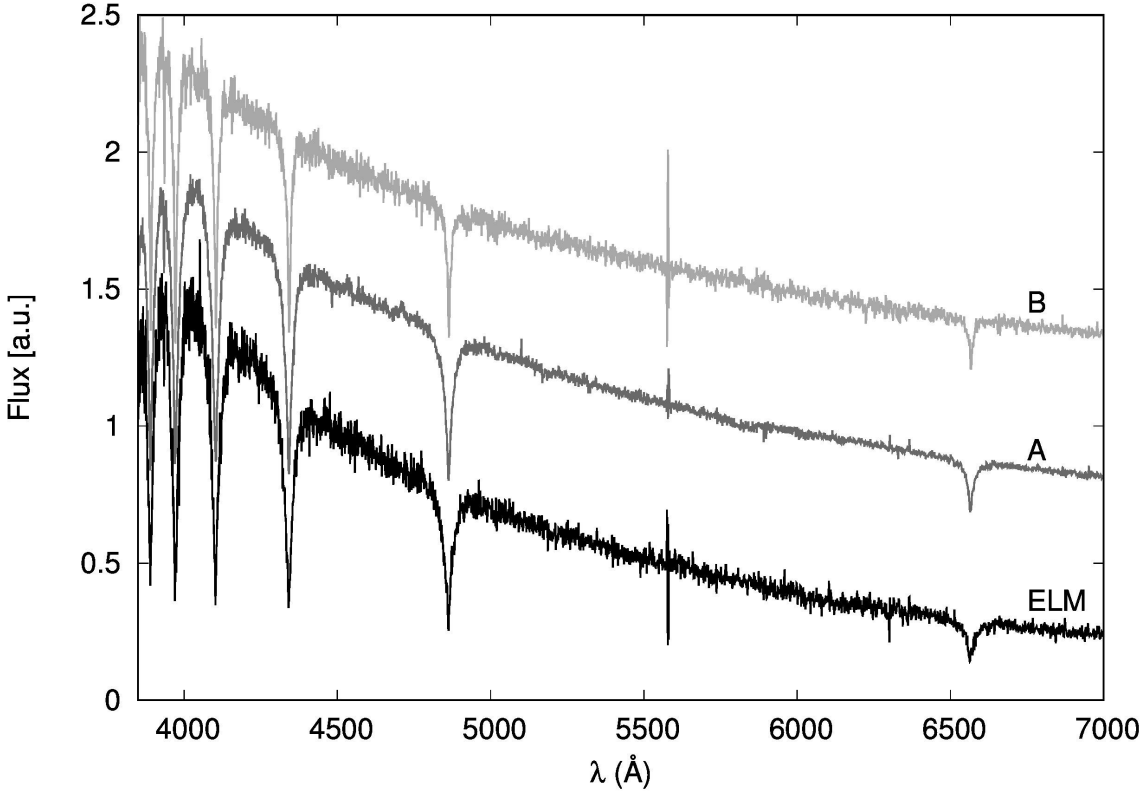
Primary goal

- ★ Catalogue of ELMs covering the *full space* of physical parameters – critical for testing models of binary evolution.

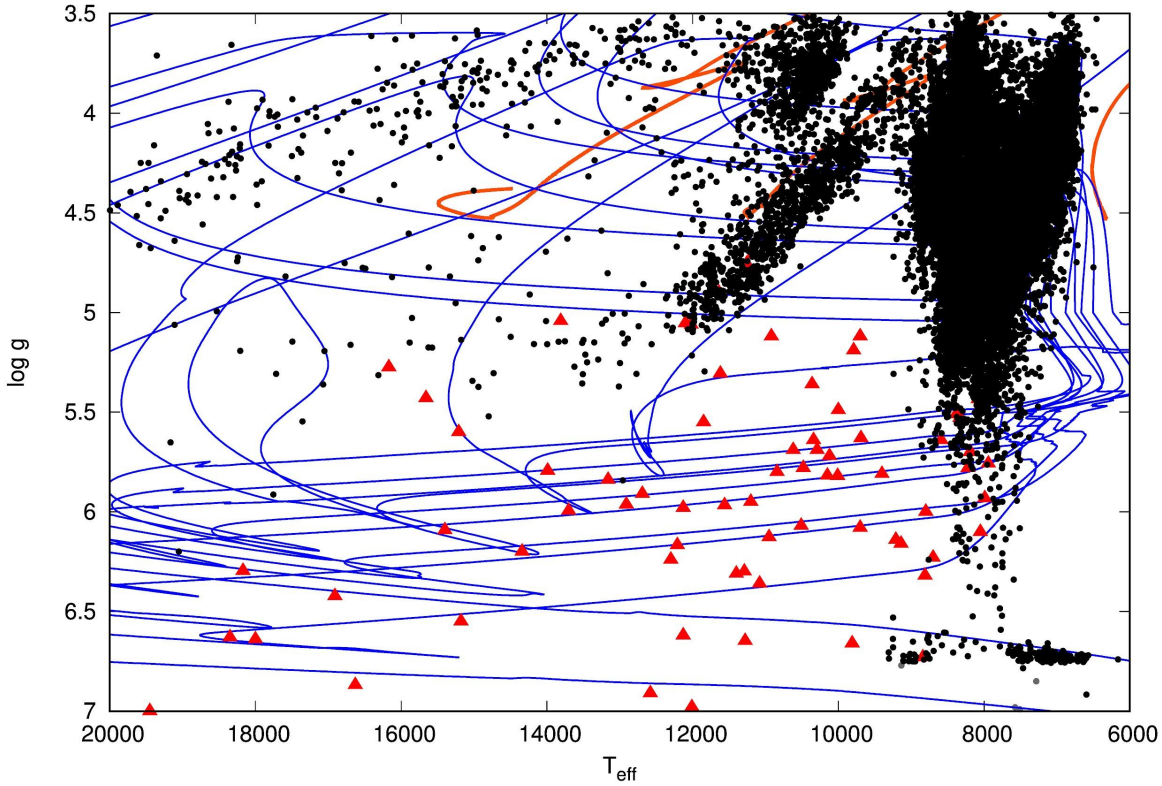
Byproducts

- ★ Catalogue of hypervelocity and runaway stars.
- ★ Catalogue of metal-poor halo stars.

Data selection



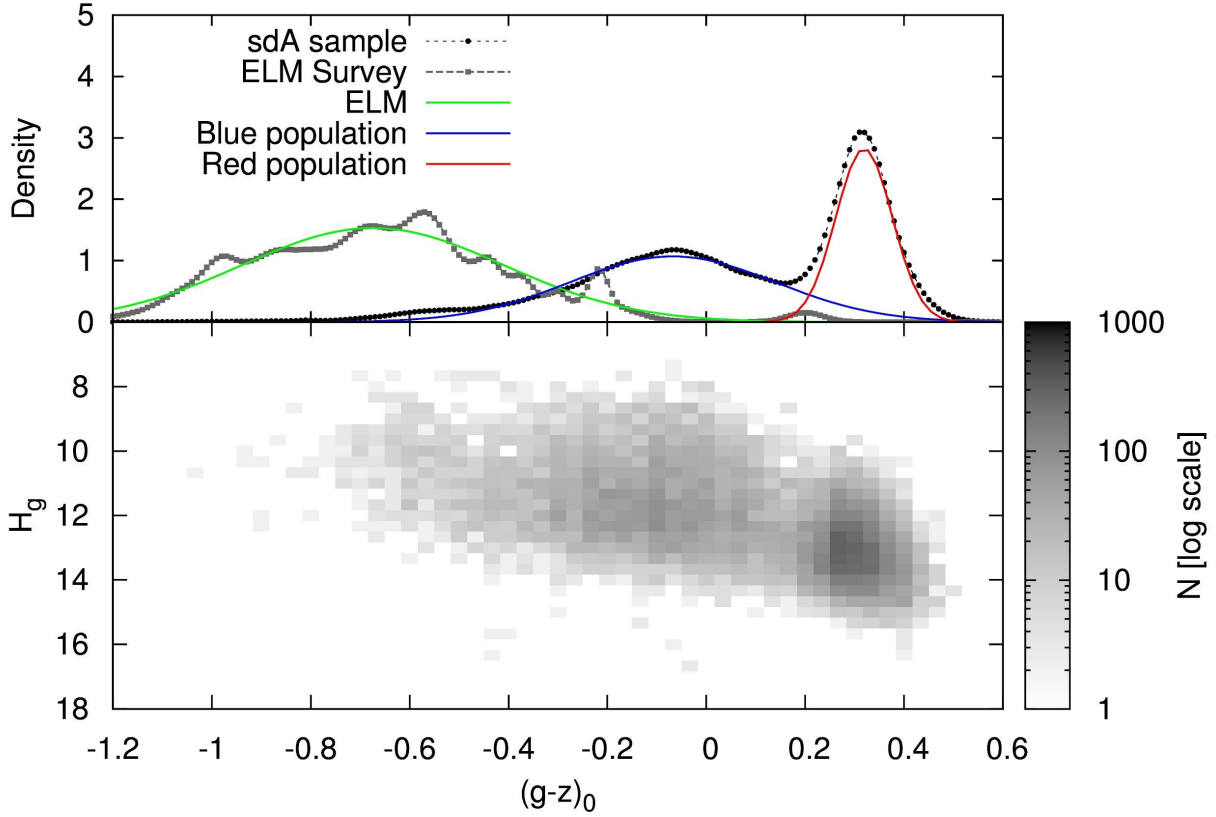
Spectral fit



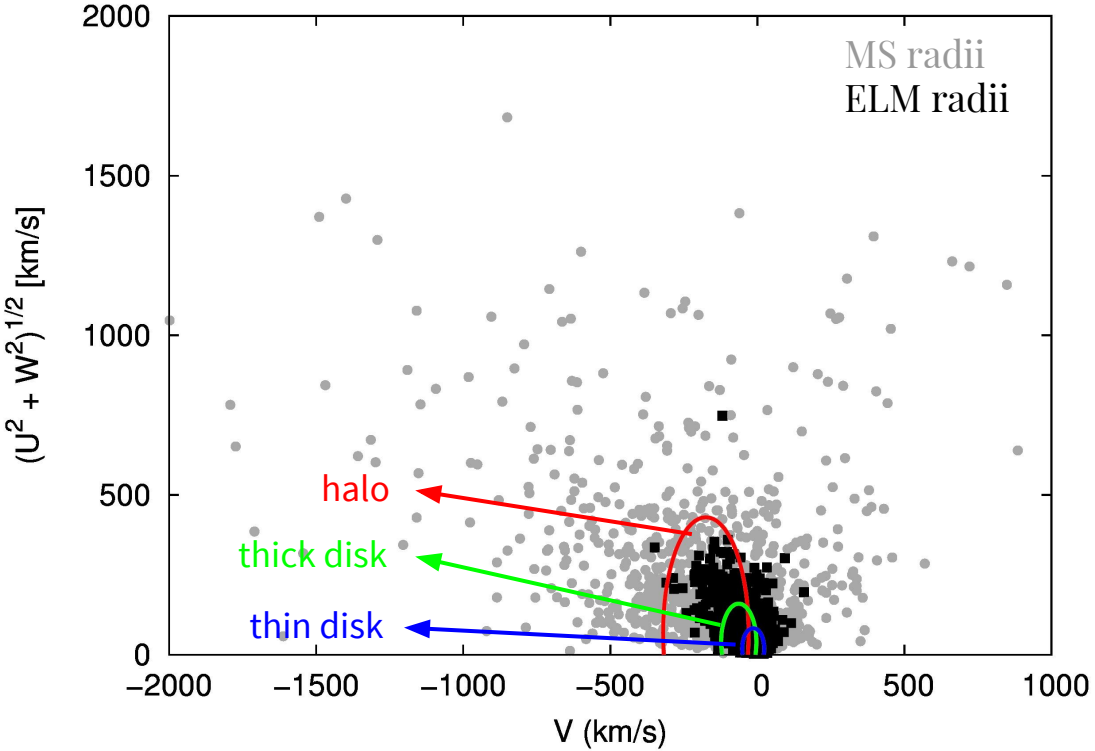
"sdA" stars

Reduced proper motion

Definitely two populations!



(pre-)ELM or main sequence?



A star: M_g ~ 0

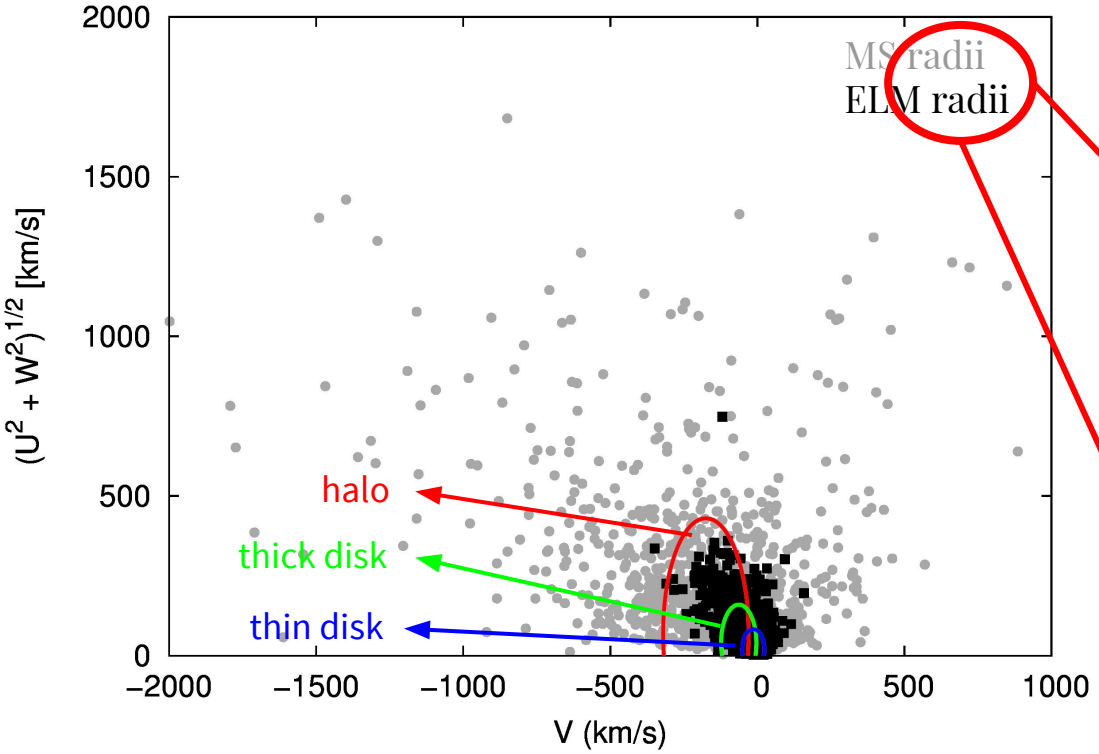
SDSS bright saturation: g ~ 14.5

m - M > 14.5 ⇒ d > 8 kpc

A stars in the halo?

Many show proper motion suggesting d < 2 kpc!

(pre-)ELM or main sequence?

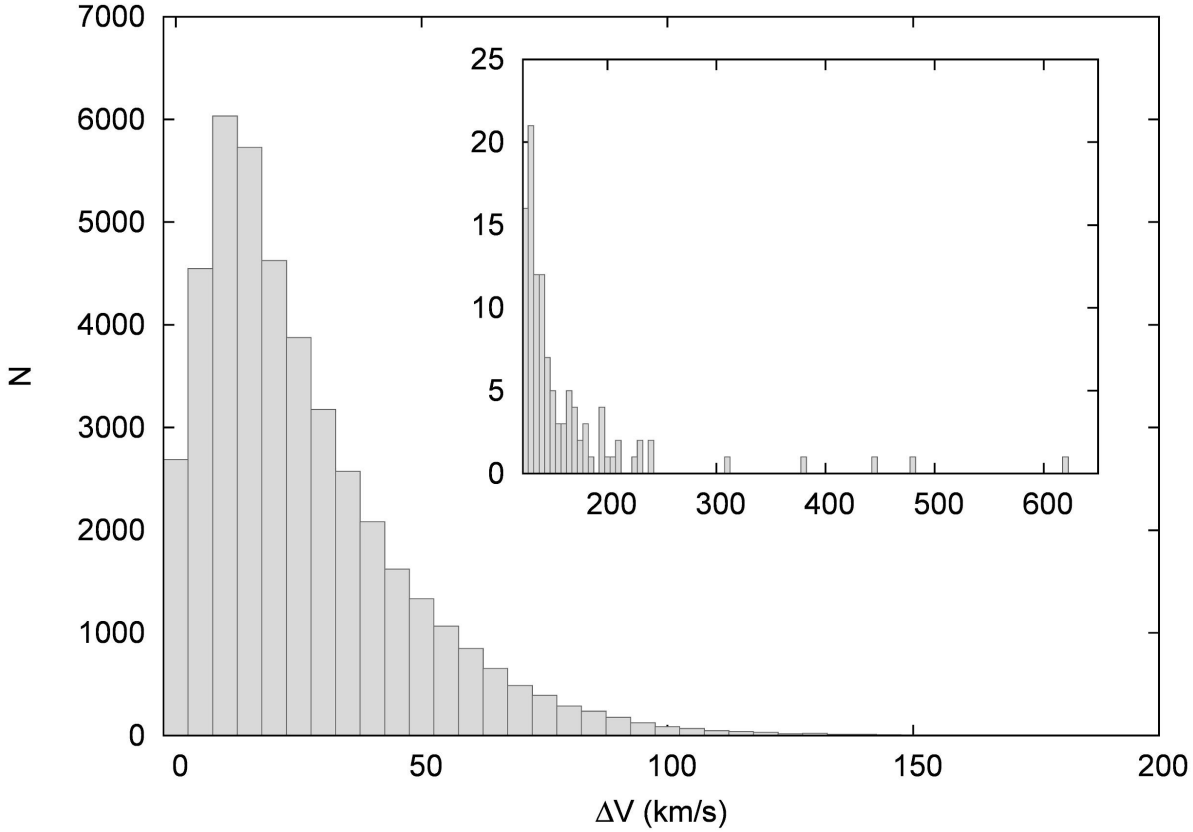


Orbital parameters

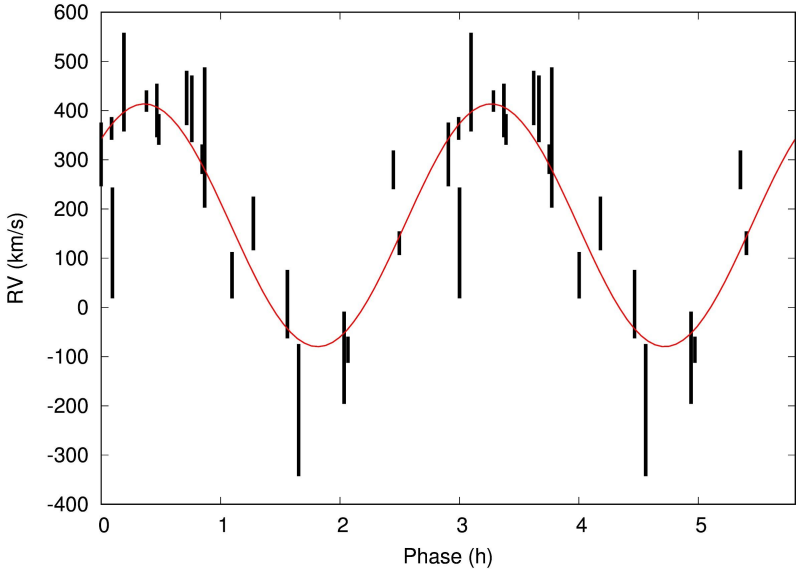
Asteroseismology

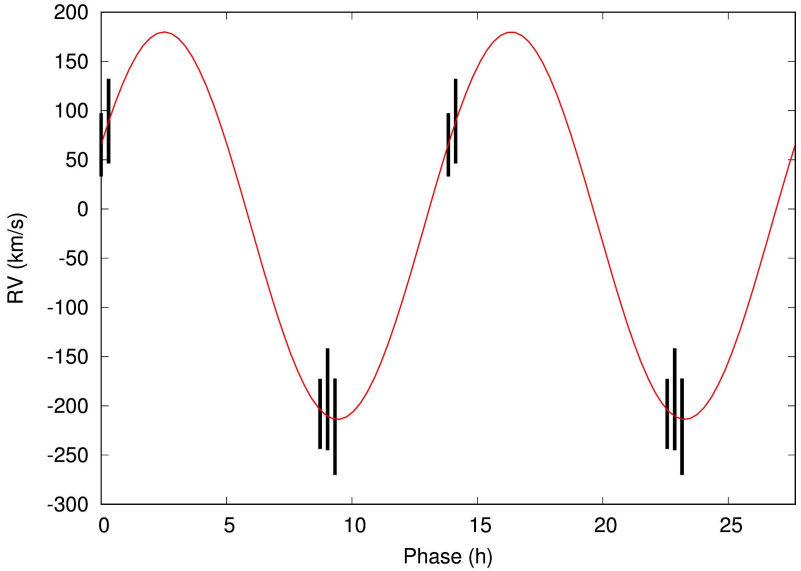
Many show proper motion suggesting d < 2 kpc!

SDSS RVs


7000
6000
5000
4000
3000
2000
1000
0
N
0
50
100
150
200
ΔV (km/s)
25
20
15
10
5
0
200
300
400
500
600

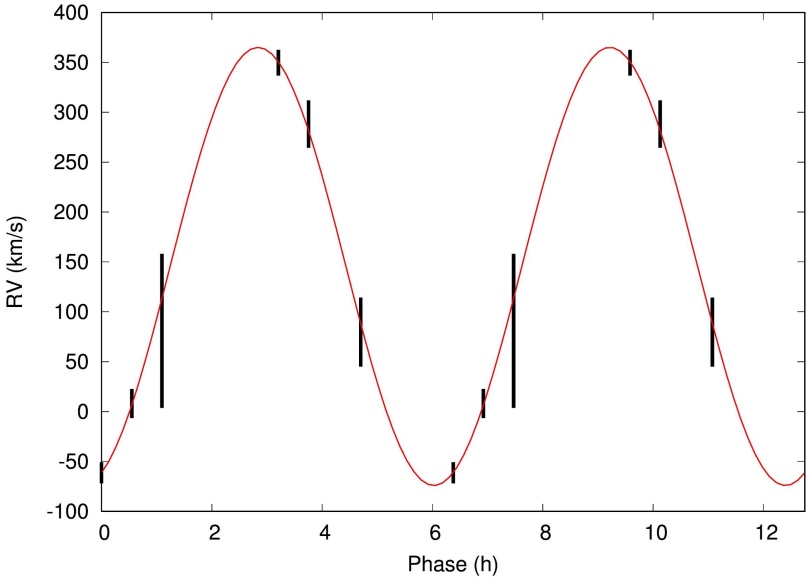
SDSS RVs



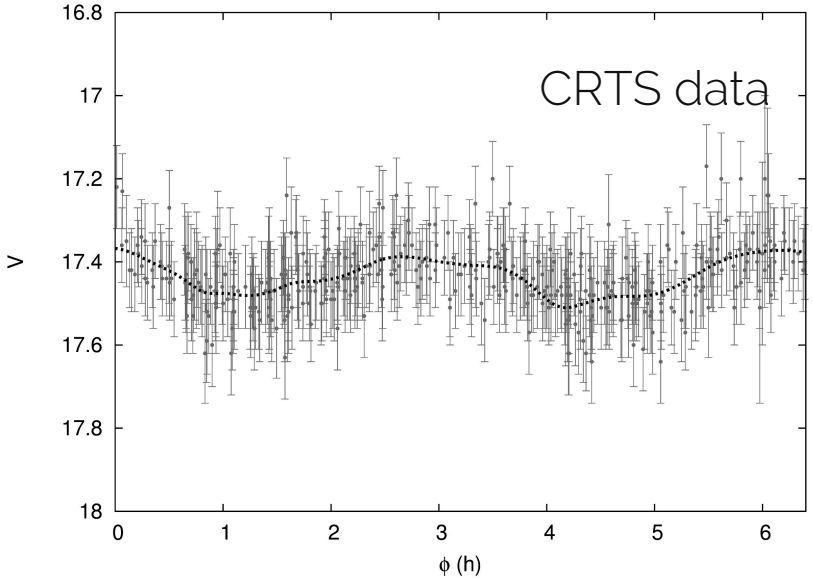


Two new ELMs

SDSS RVs

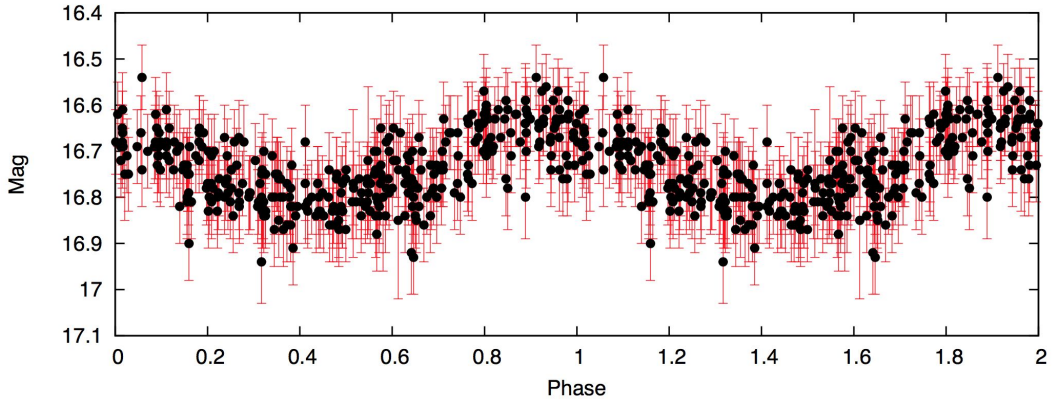


=

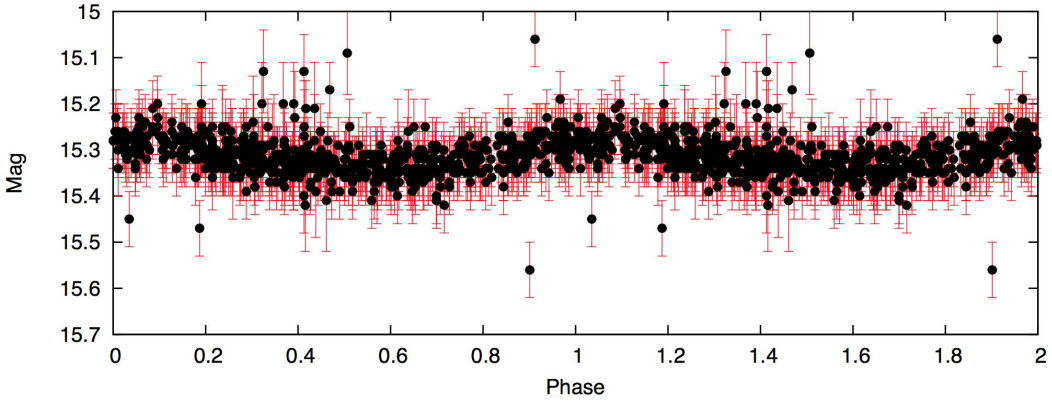


+ new ELM showing ellipsoidal variations

CRTS light curves



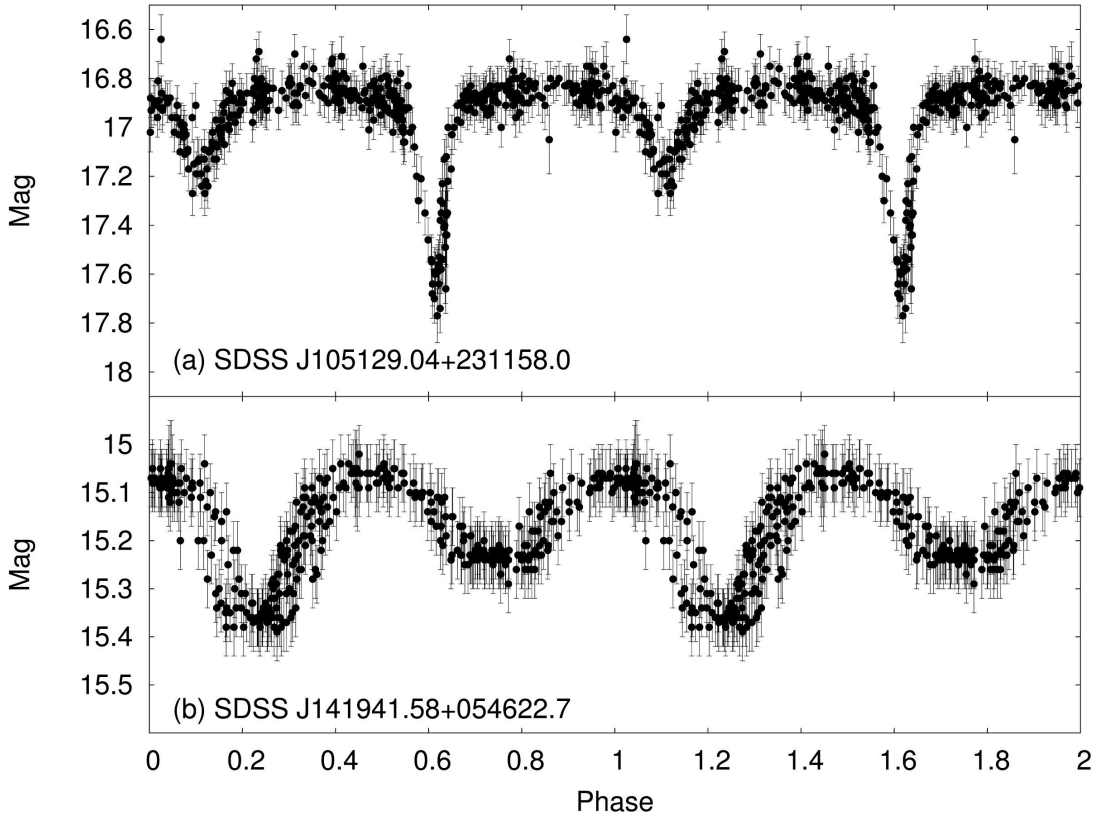
Teff = 8400 K
log (g) = 5.2
P = 3082 s



Teff = 8100 K
log (g) = 5.1
P = 4418 s

Same P as
δ-Scuti and
SX-Phoenicis

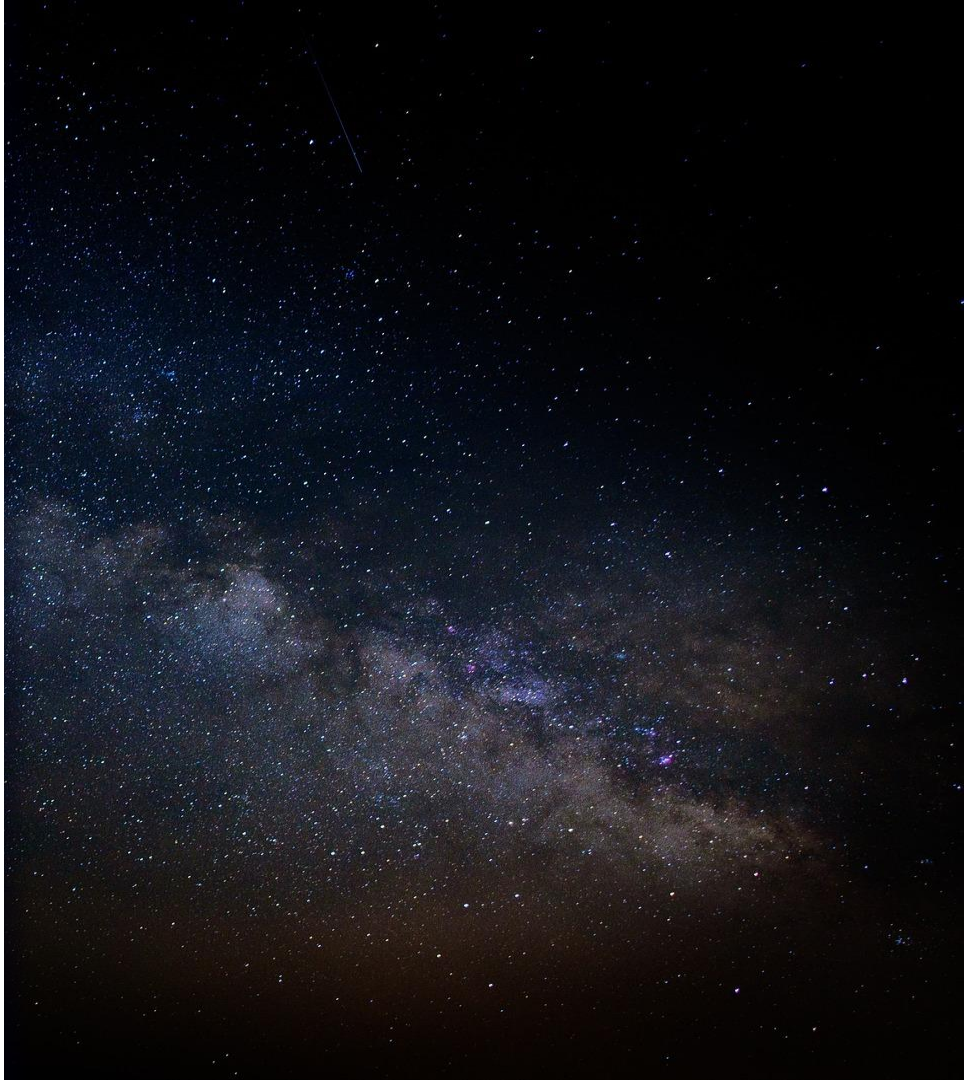
CRTS light curves



Teff = 8200 K
log (g) = 5.0
P = 21 h

Teff = 8100 K
log (g) = 5.1
P = 10 h

Archival data could not solve the puzzle...



Follow-up observations

OPD

1.6 m

Cam1+ Andor iXon CCD

Photometry

Red-blocking filter (BG40)

SOAR

4.1 m

Goodman HTS

Photometry

Red-blocking filter (S8612)

Spectroscopy

1" slit

1200 l/mm, M1 - 2 Å

2100 l/mm, 410 nm - 1 Å

Gemini

8.2 m

GMOS

Spectroscopy

0.8" slit

B1200, 440 nm - 1.8 Å

VLT

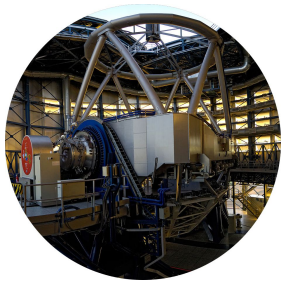
8.2 m

X-Shooter

Spectroscopy

1.0"/0.9"/1.2" slit

300-2480 nm - 1.3 Å



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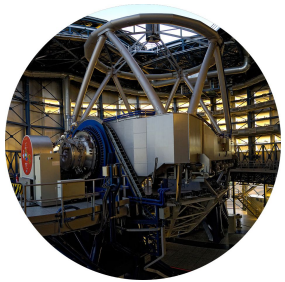


INT

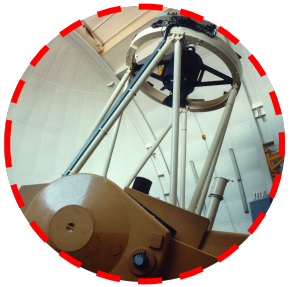
2.5 m

IDS

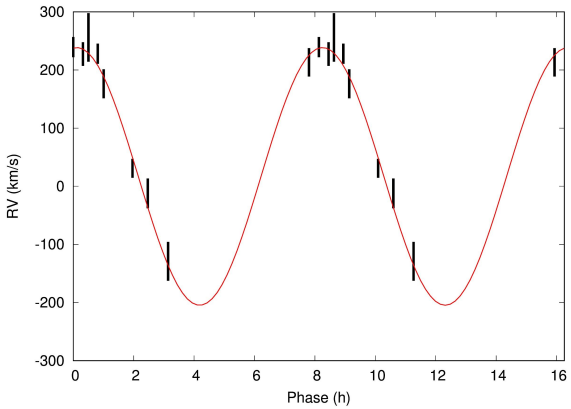
Spectroscopy

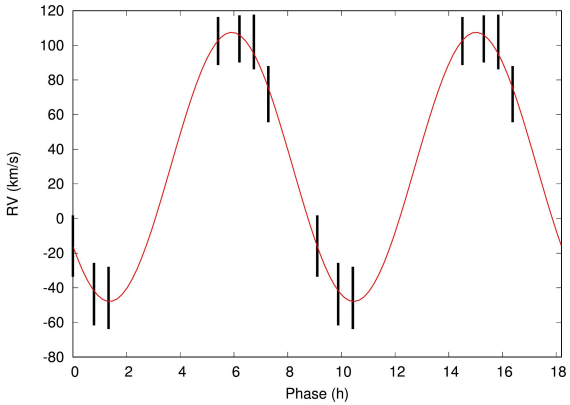
1.0" slit

R1200B - 2 Å

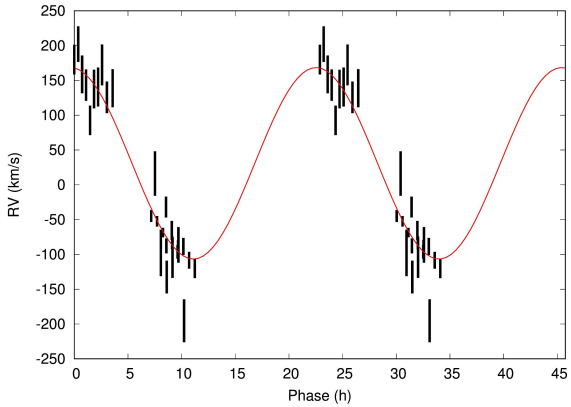


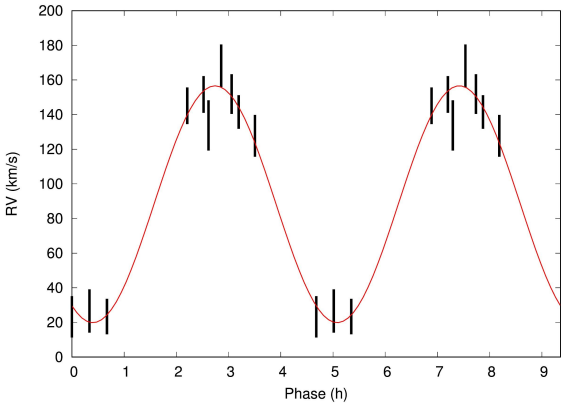
Preliminary Results



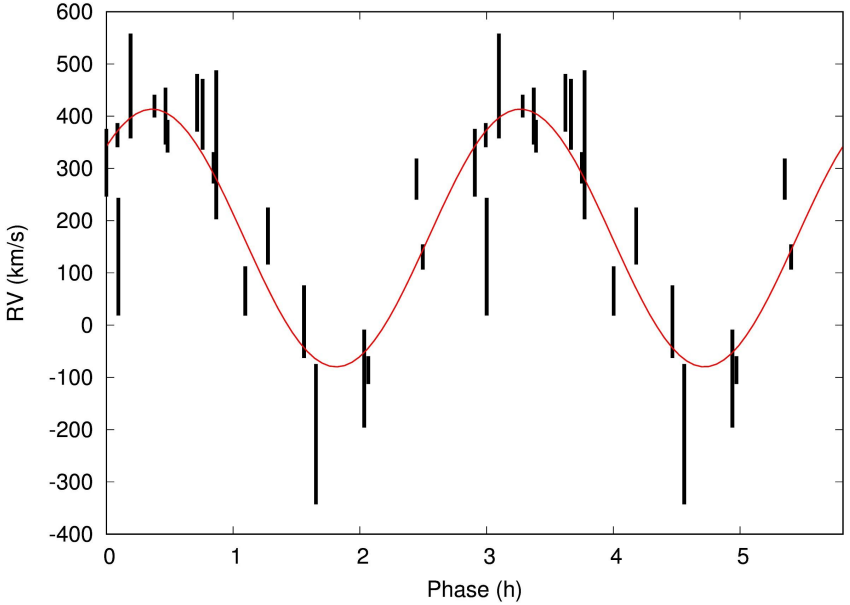


Four new ELMs

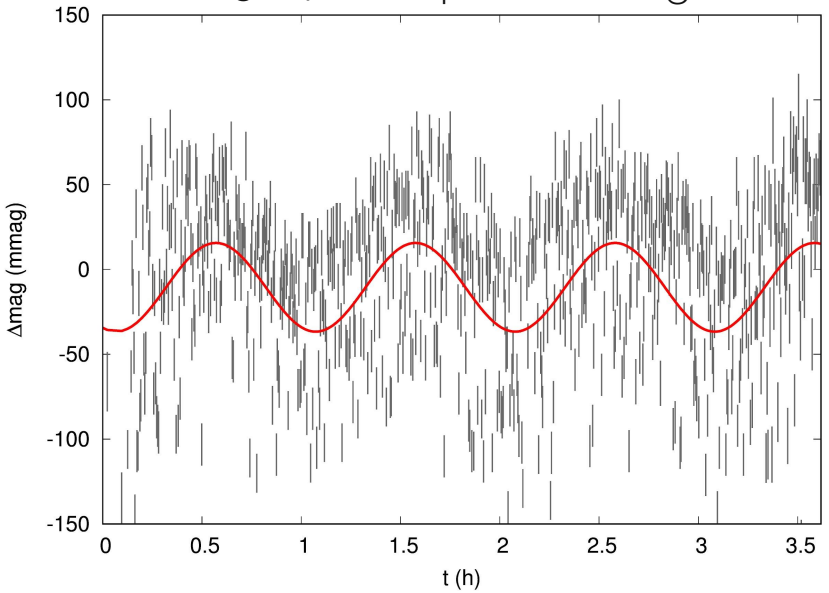




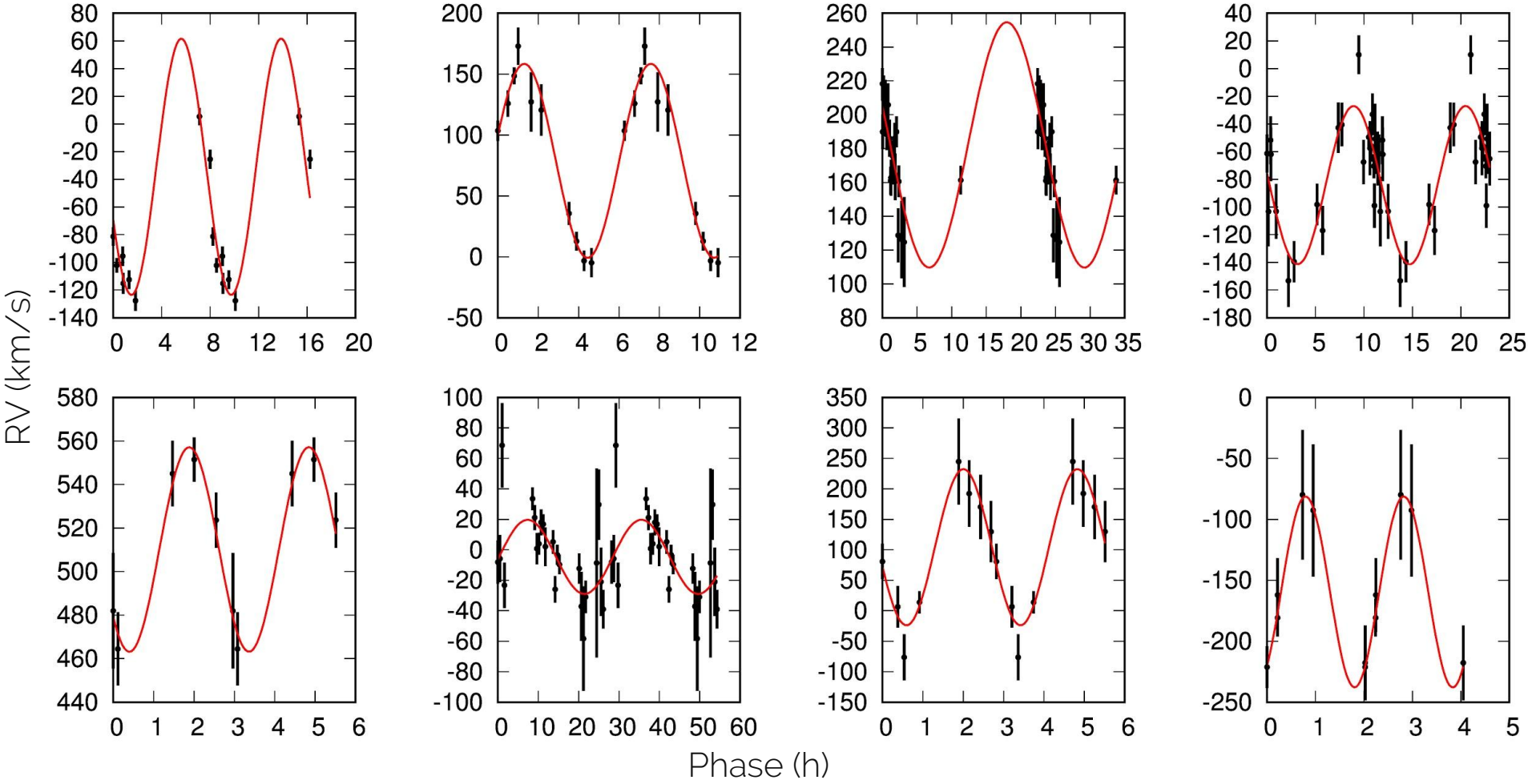
Preliminary Results



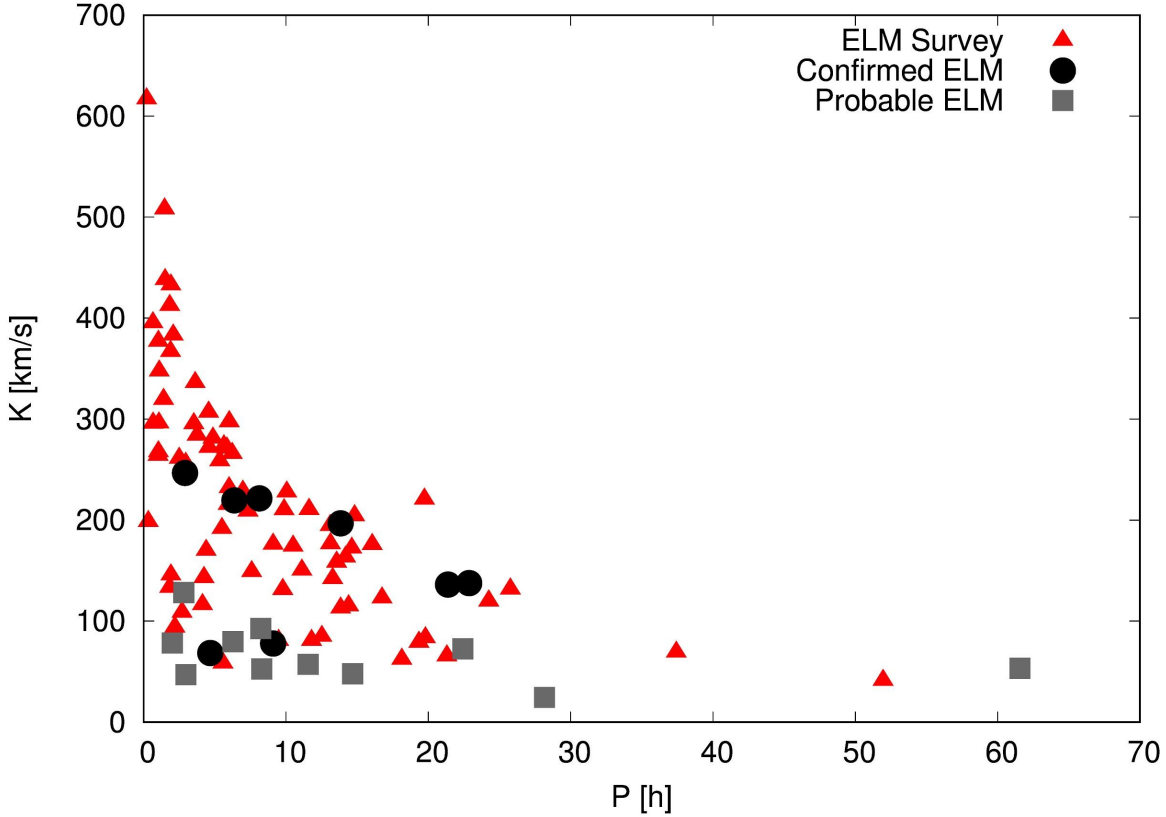
P = 3627 s, amp = 26 mmag



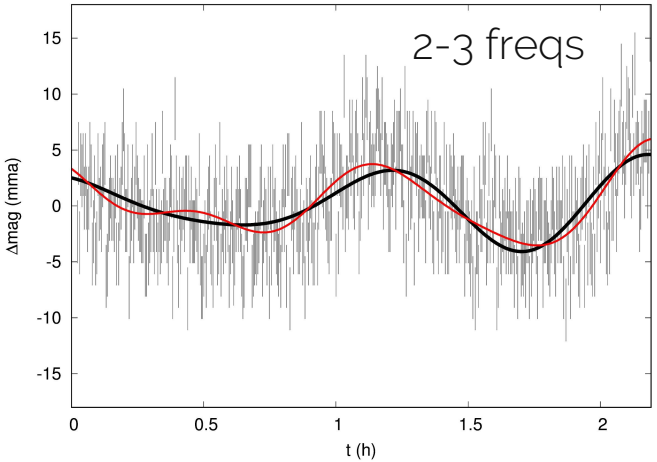
One new variable ELM

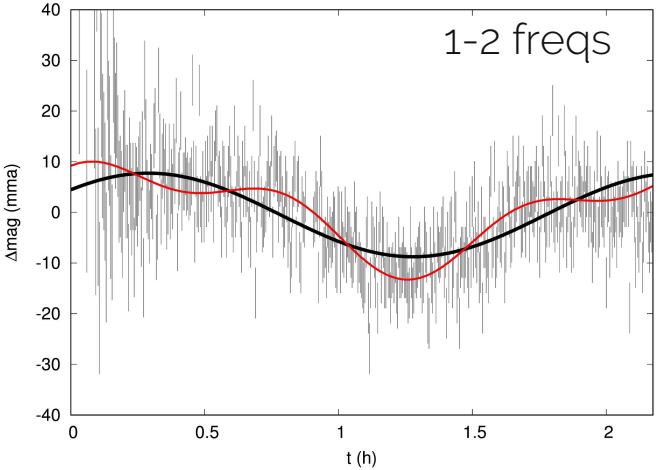

RV (km/s)
Phase (h)

Preliminary Results

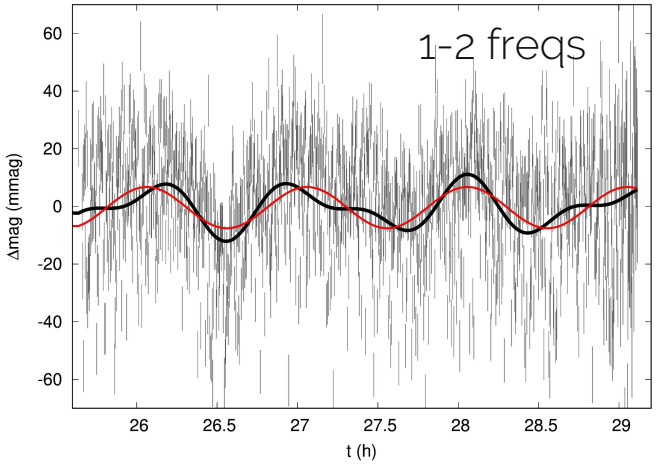


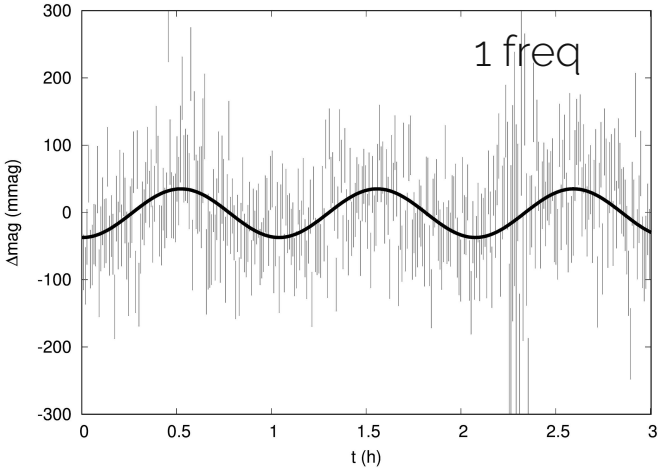
SOAR


2-3 freqs
Δmag (mma)
t (h)

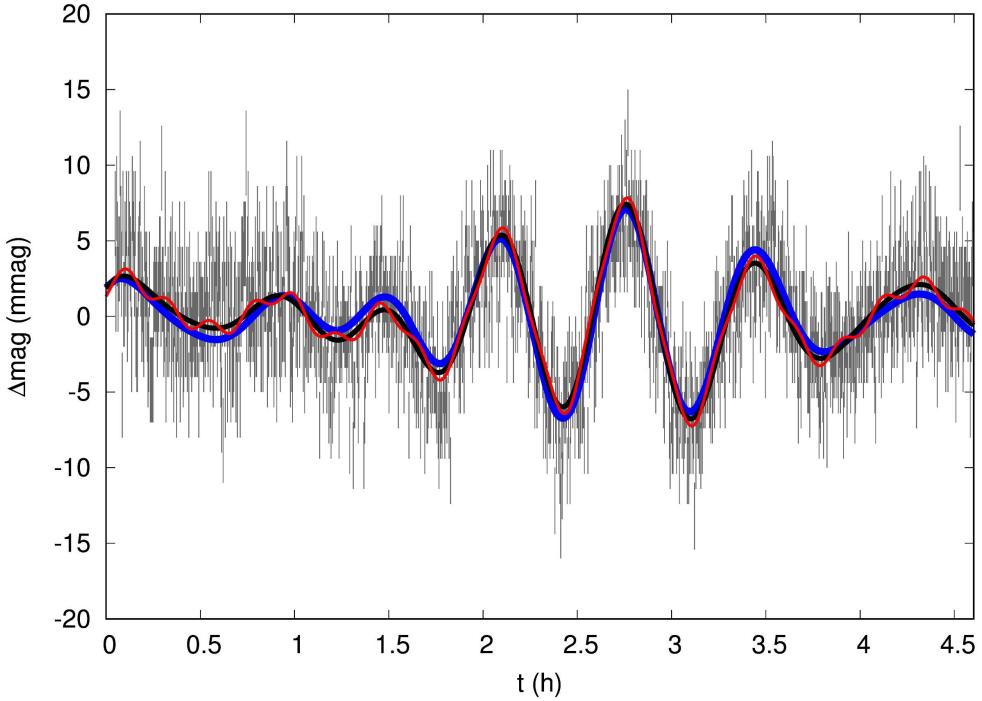

1-2 freqs
Δmag (mma)
t (h)

OPD


1-2 freqs
Δmag (mmag)
t (h)


1 freq
Δmag (mmag)
t (h)

Preliminary Results

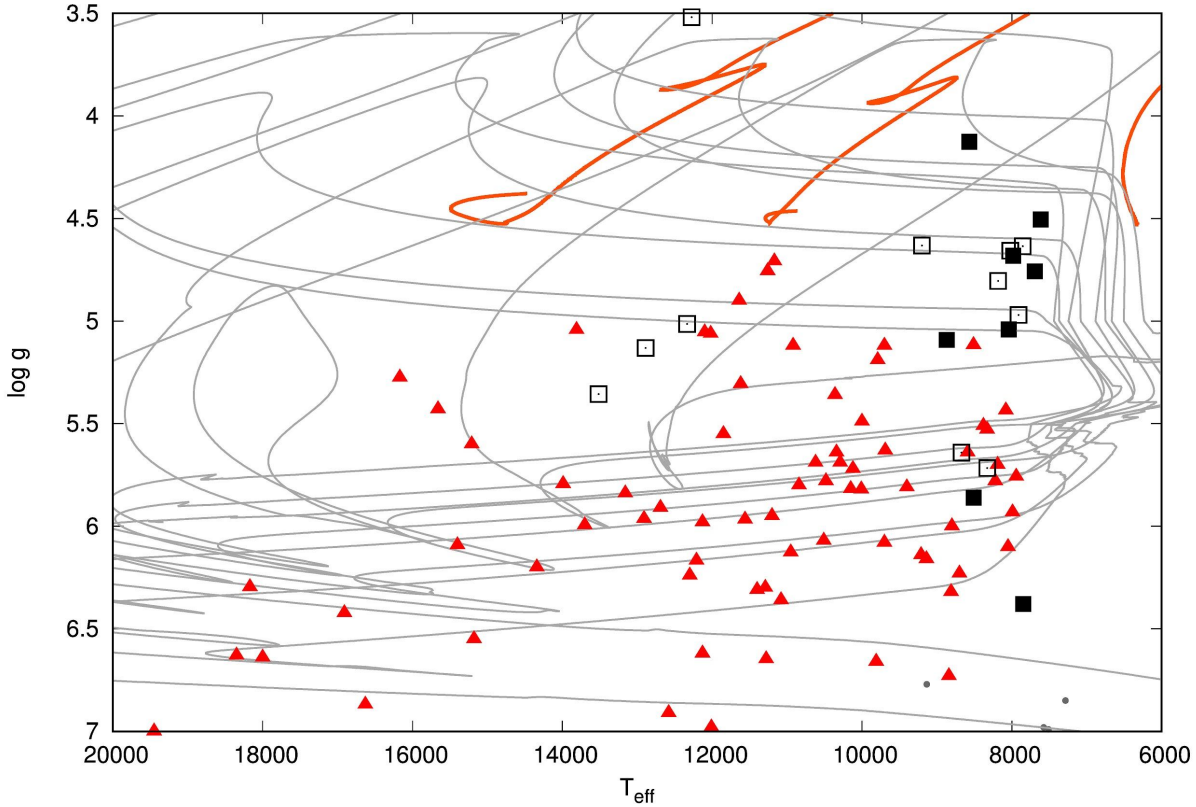


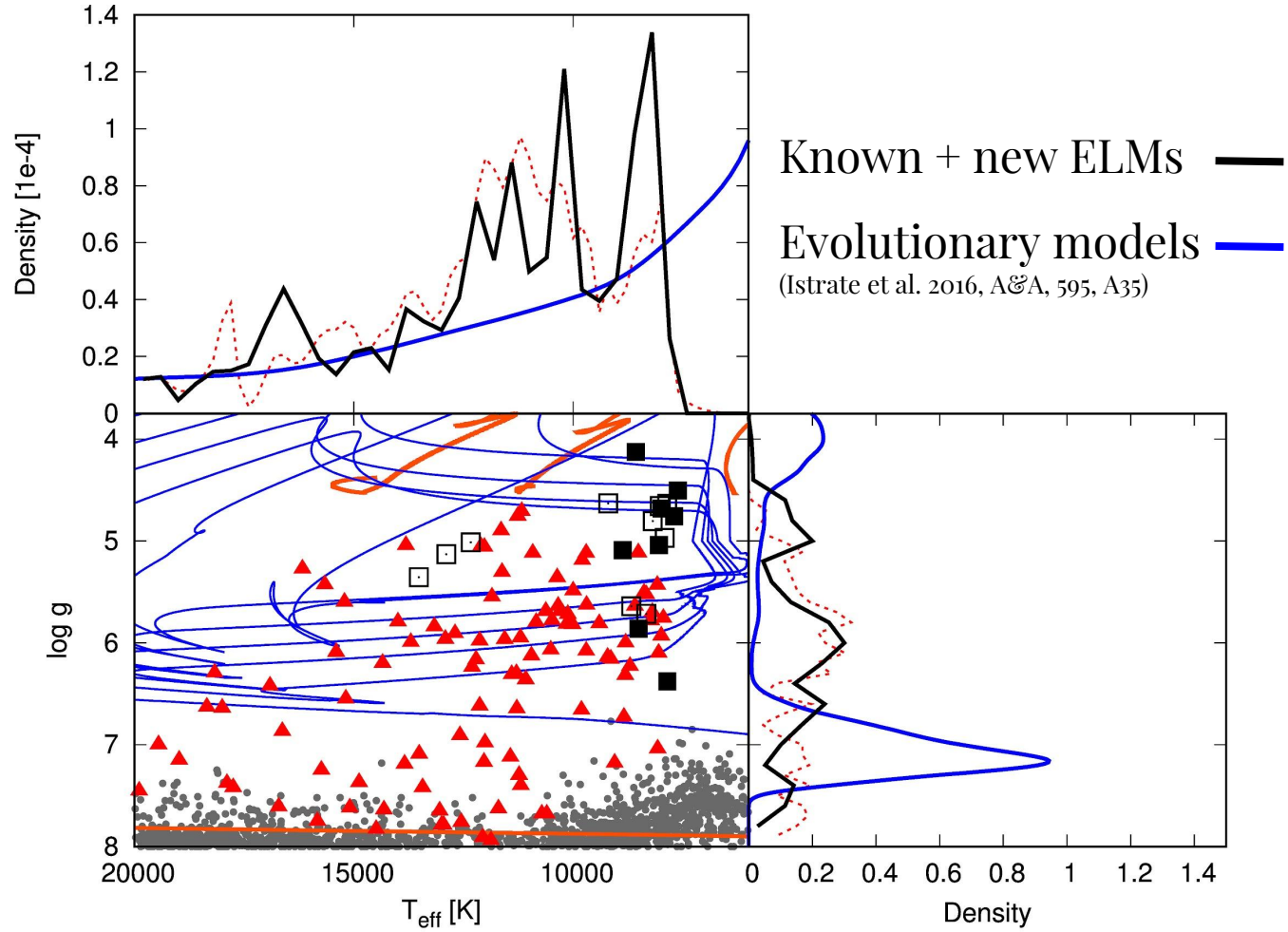
3-5 frequencies

Spacing suggests it is a **δ**-Scuti (Sánches-Arias et al. 2017)

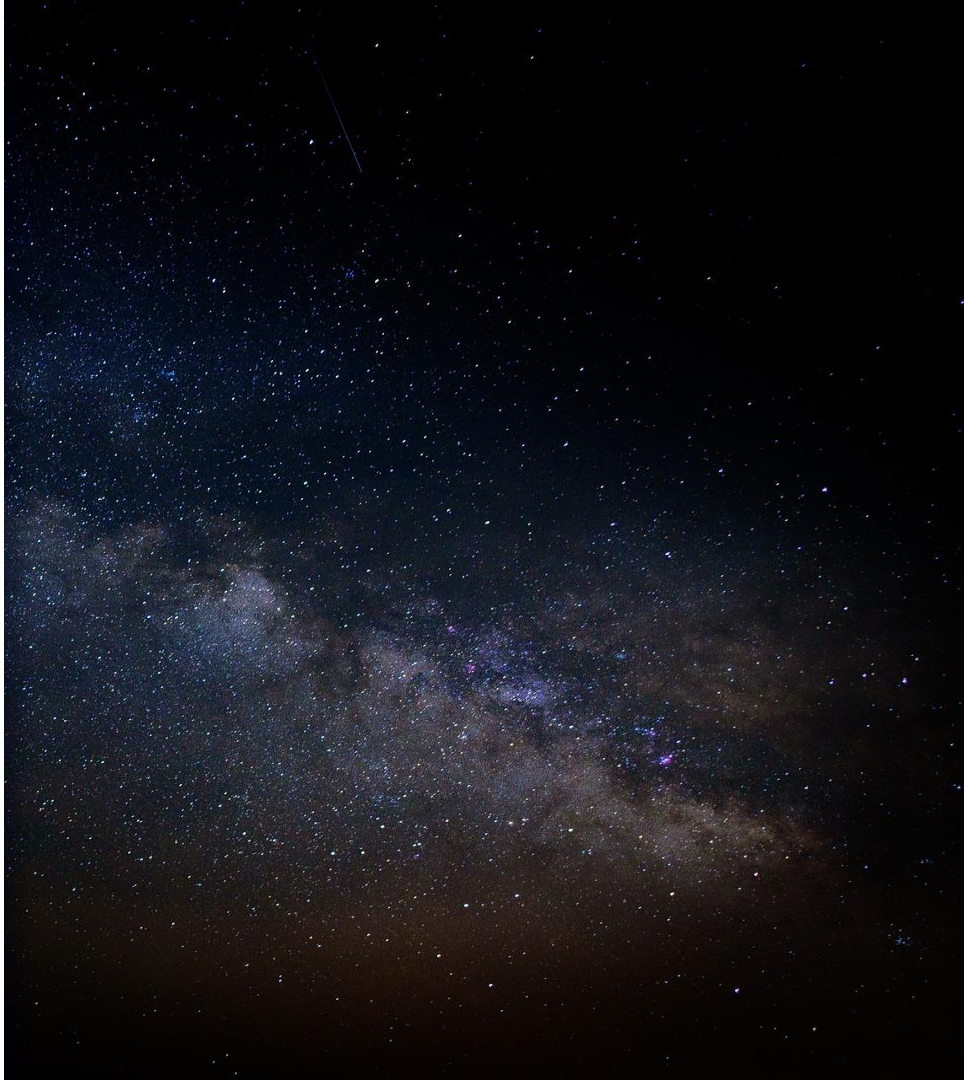
log *g* and distance consistent

Preliminary Results

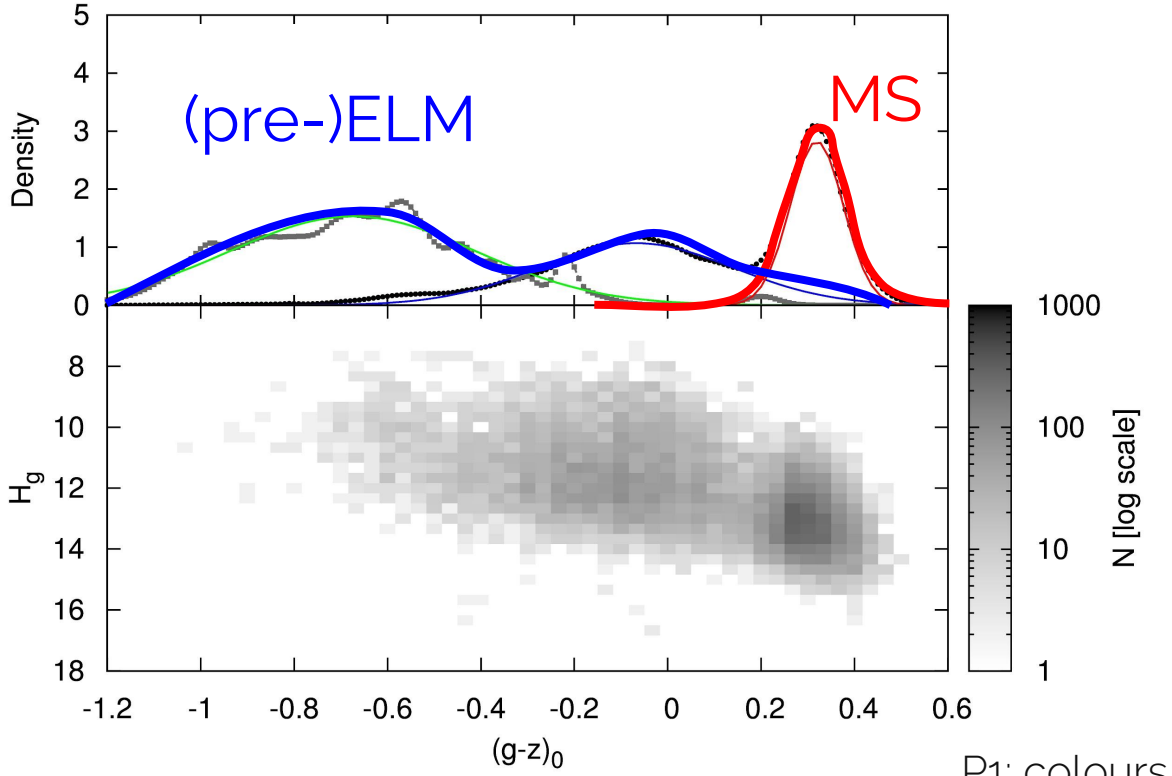



Density [1e-4]
log g
T_{eff} [K]
Density
Known + new ELMs
Evolutionary models
(Istrate et al. 2016, A&A, 595, A35)

We can't observe the whole sample...

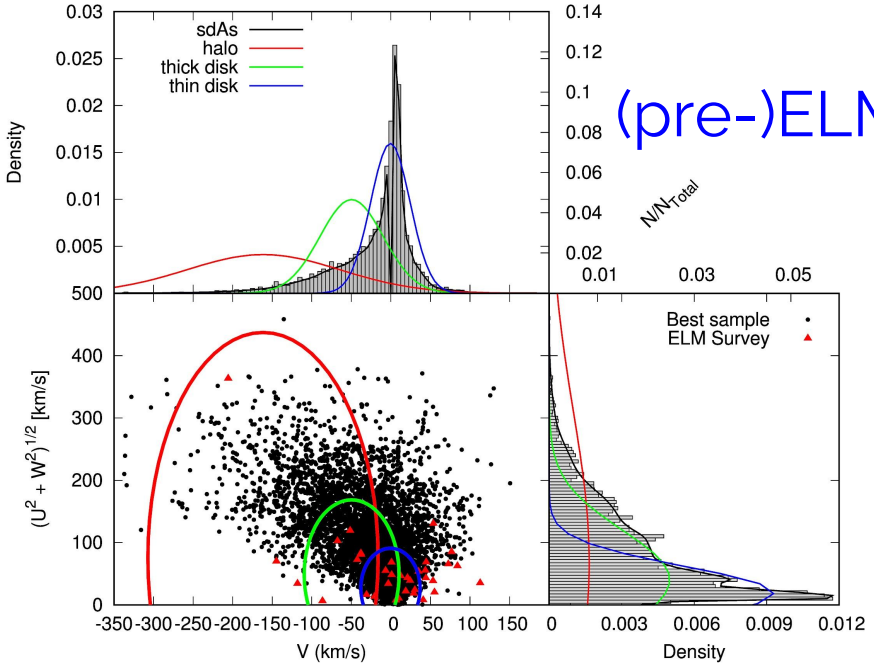


Probabilistic approach



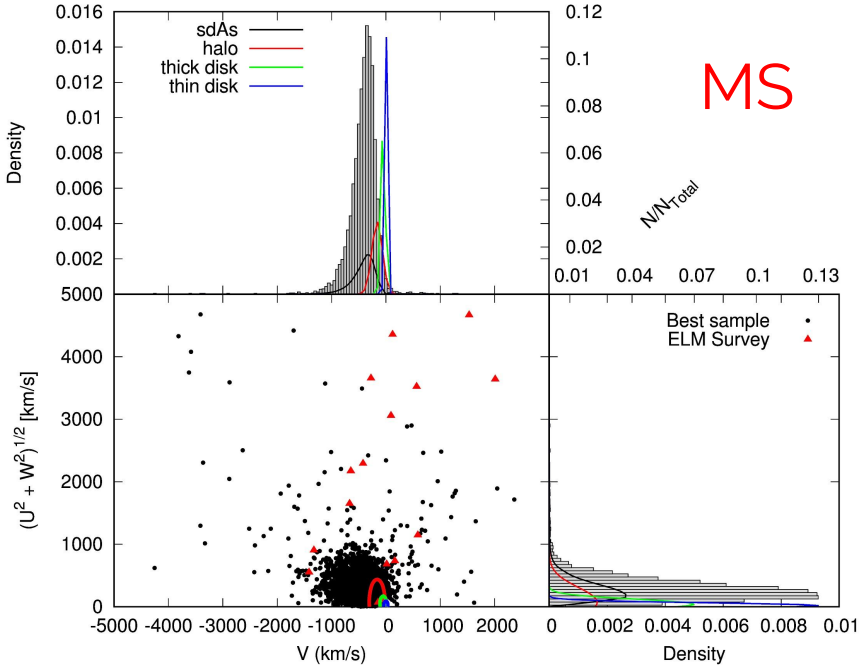
P1: colours

Probabilistic approach



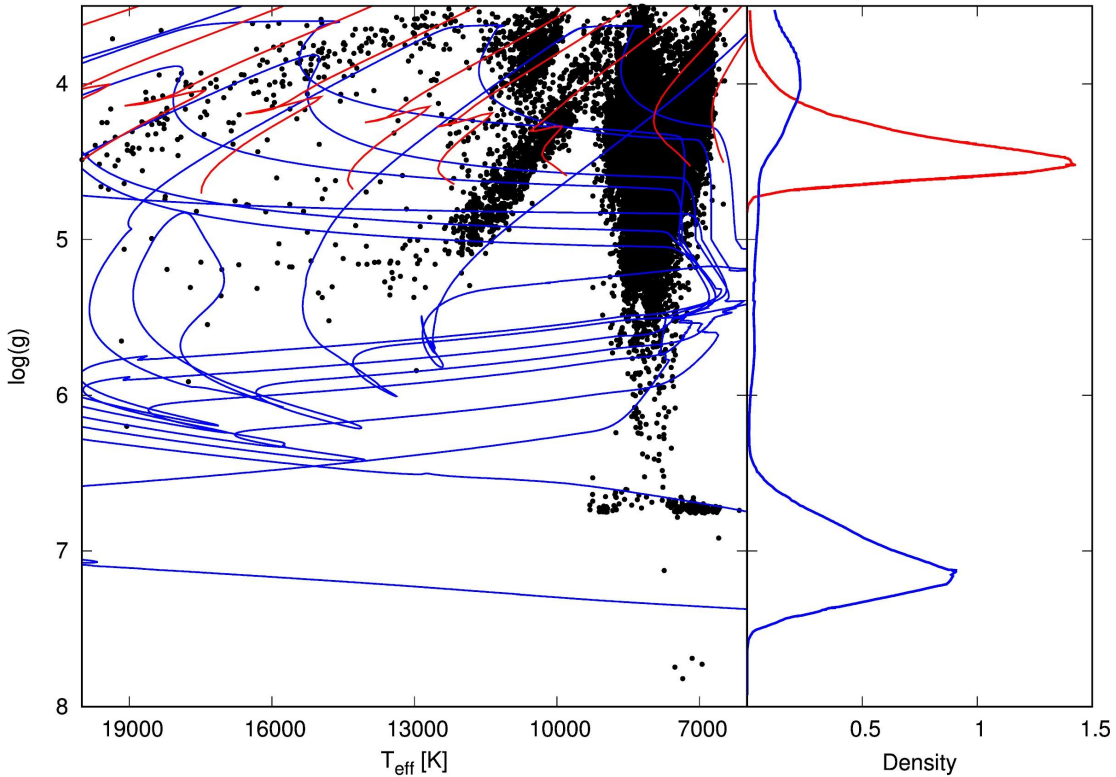
(pre-)ELM

P2: velocities



MS

Probabilistic approach



MS

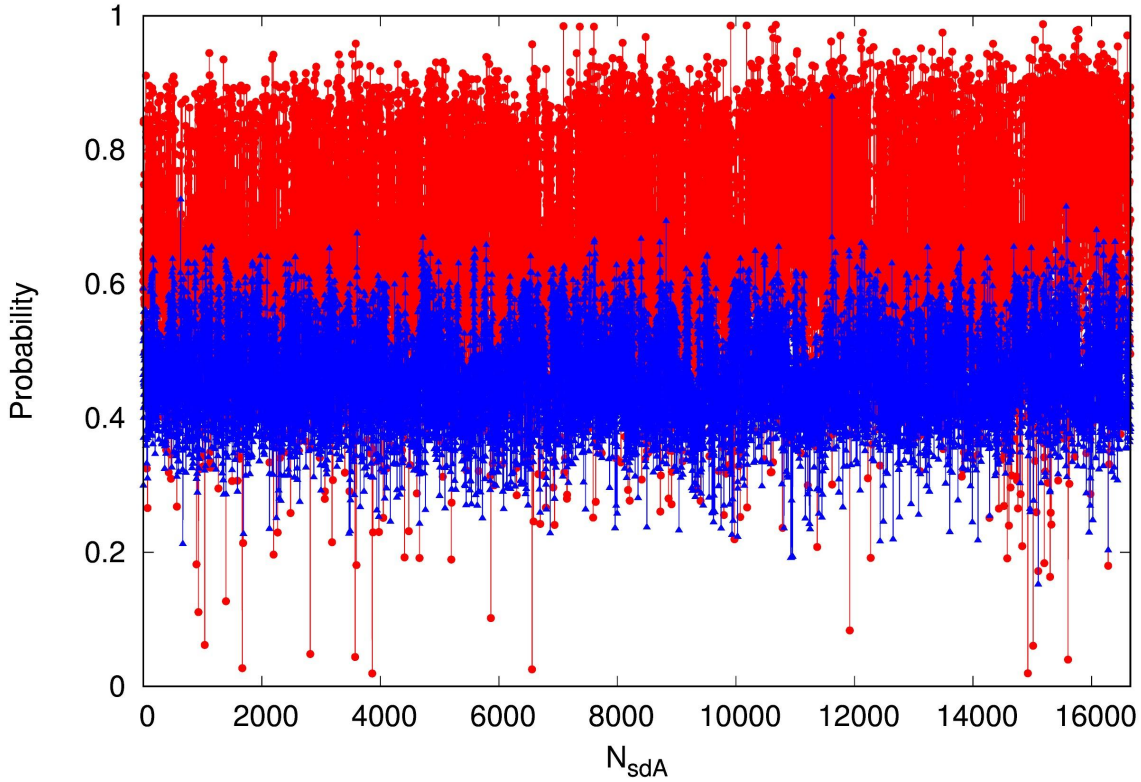
Bertelli et al. 2008, 2009

P3: evolutionary models

(pre-)ELM

Istrate et al. 2016

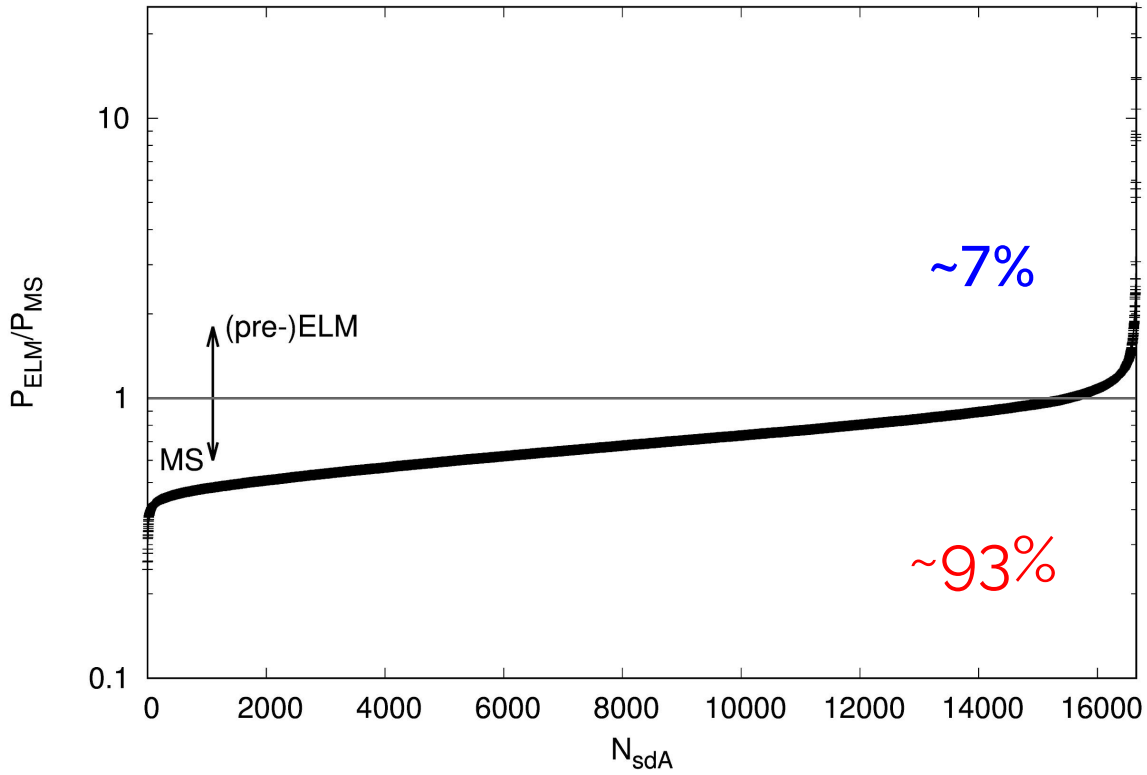
Probabilistic approach



~70%

~50%

Probabilistic approach

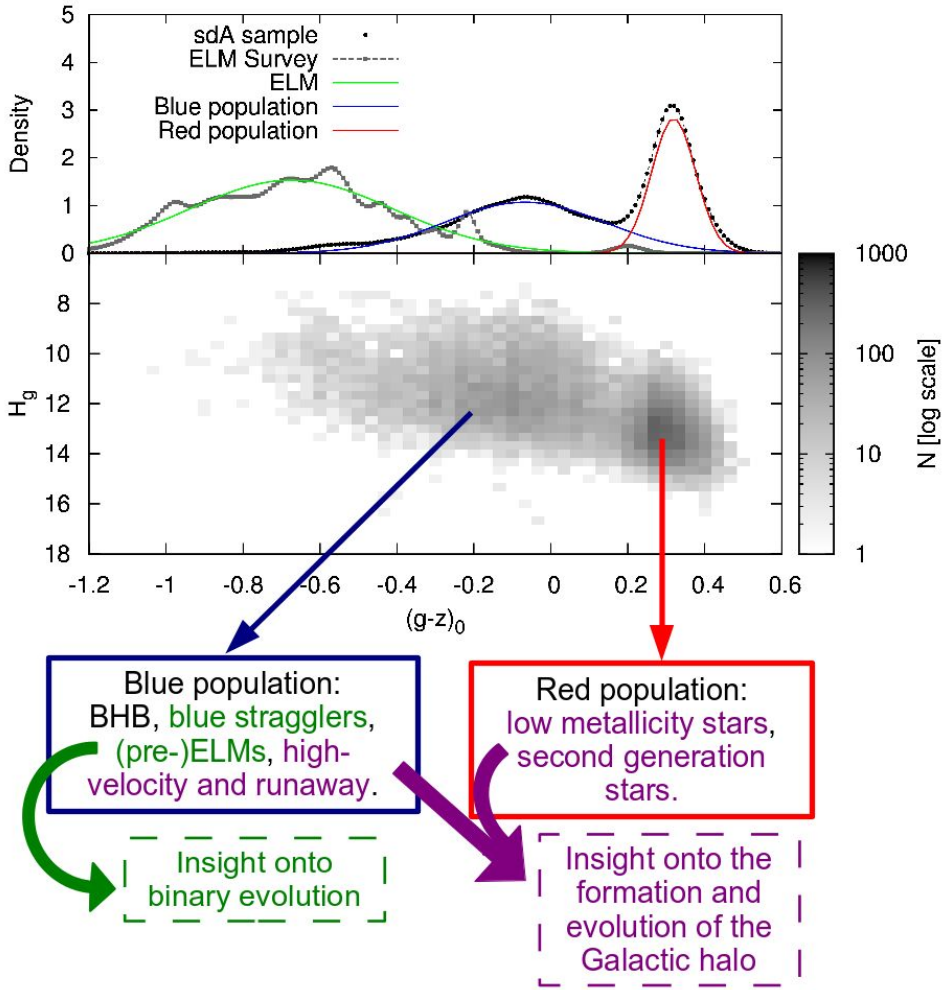


Preliminary Conclusions

- Search for ELMs resulted in a population of unknown nature: **sdAs**
  - Single MS not a satisfactory explanation for 30% of them
  - 7 % most likely (pre-)ELMs
- 3 new ELMs in SDSS data, 8 from follow up
  - mostly in the cool, low mass end of the distribution
  - One pulsator, one showing ellipsoidal variations
- 8 probable ELMs, more data required
- Potentially a 20% increase in the known population of ELMs

Next steps

- ★ gaia → Radii estimates
- ★ Get a PhD
- ★ Find a job

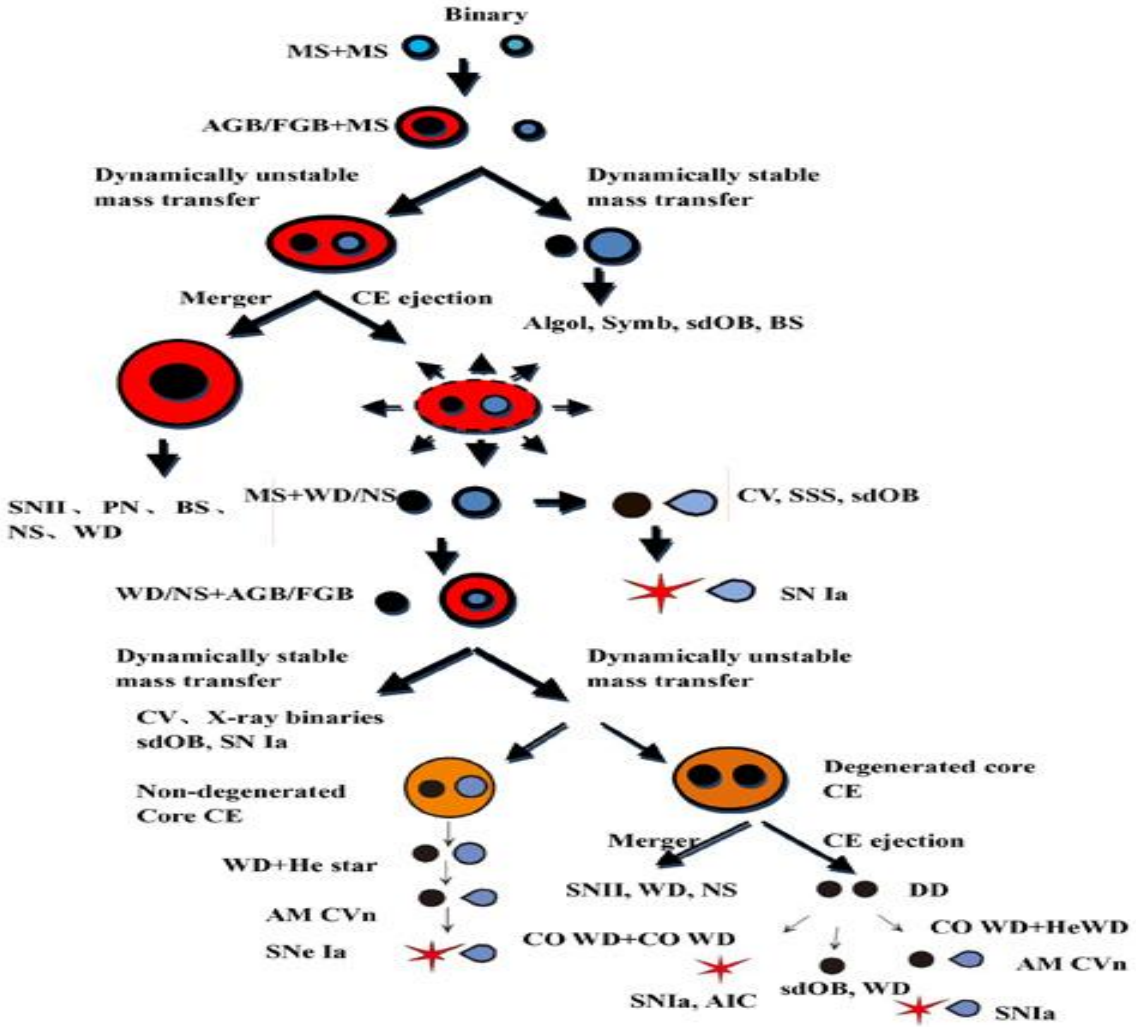


Thanks!

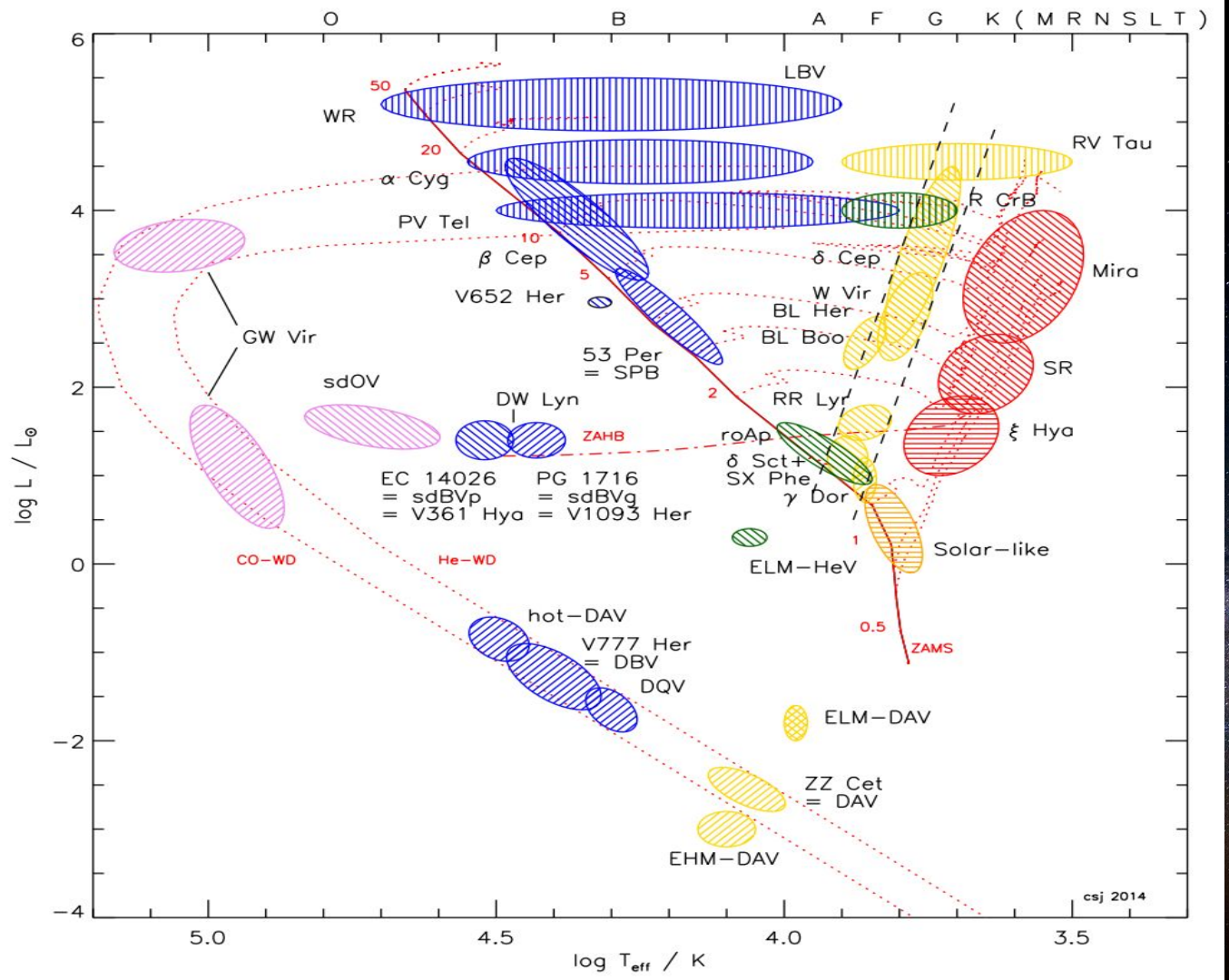
Any questions?

ingrid.pelisoli@ufrgs.br

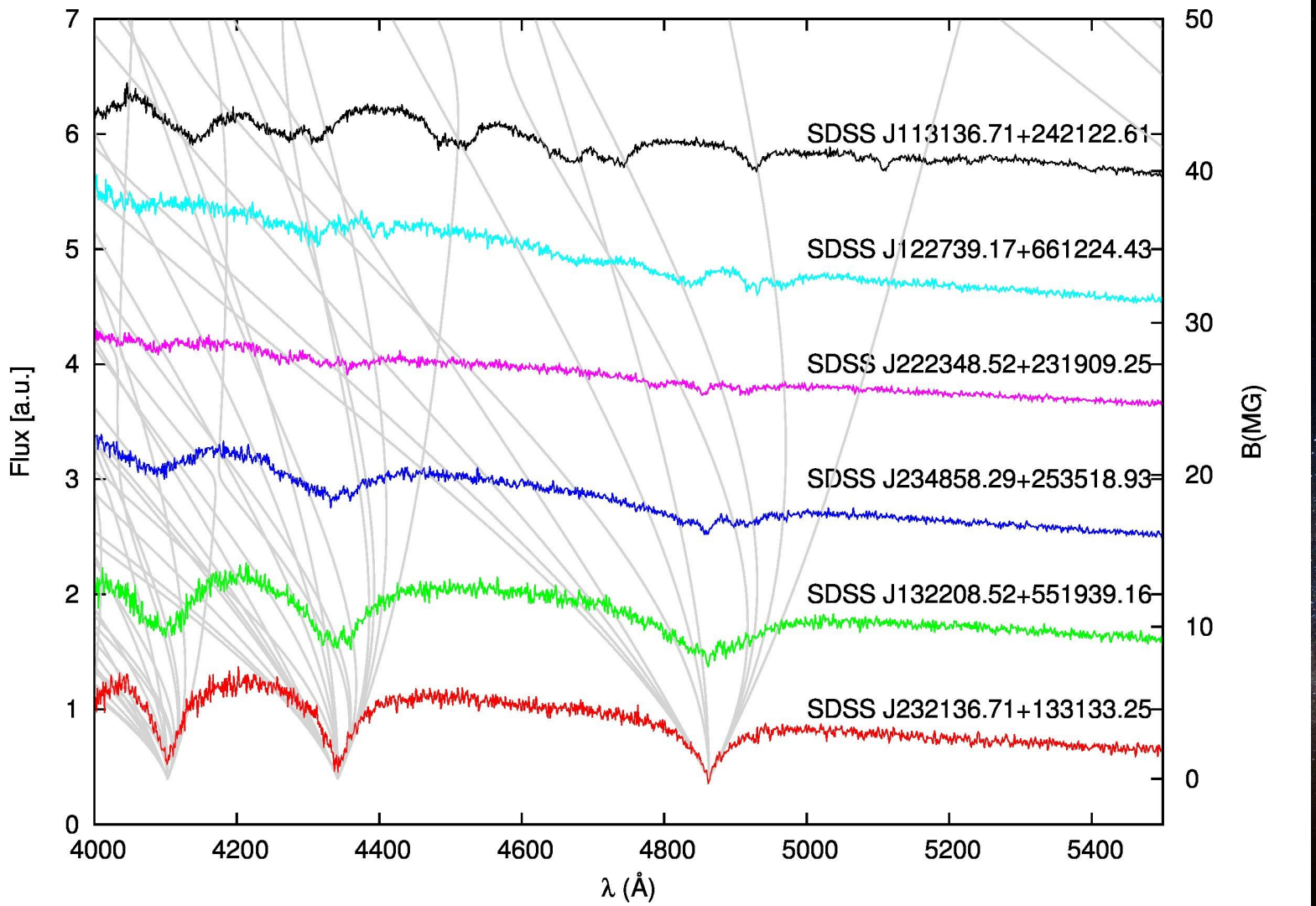

EXTRAS



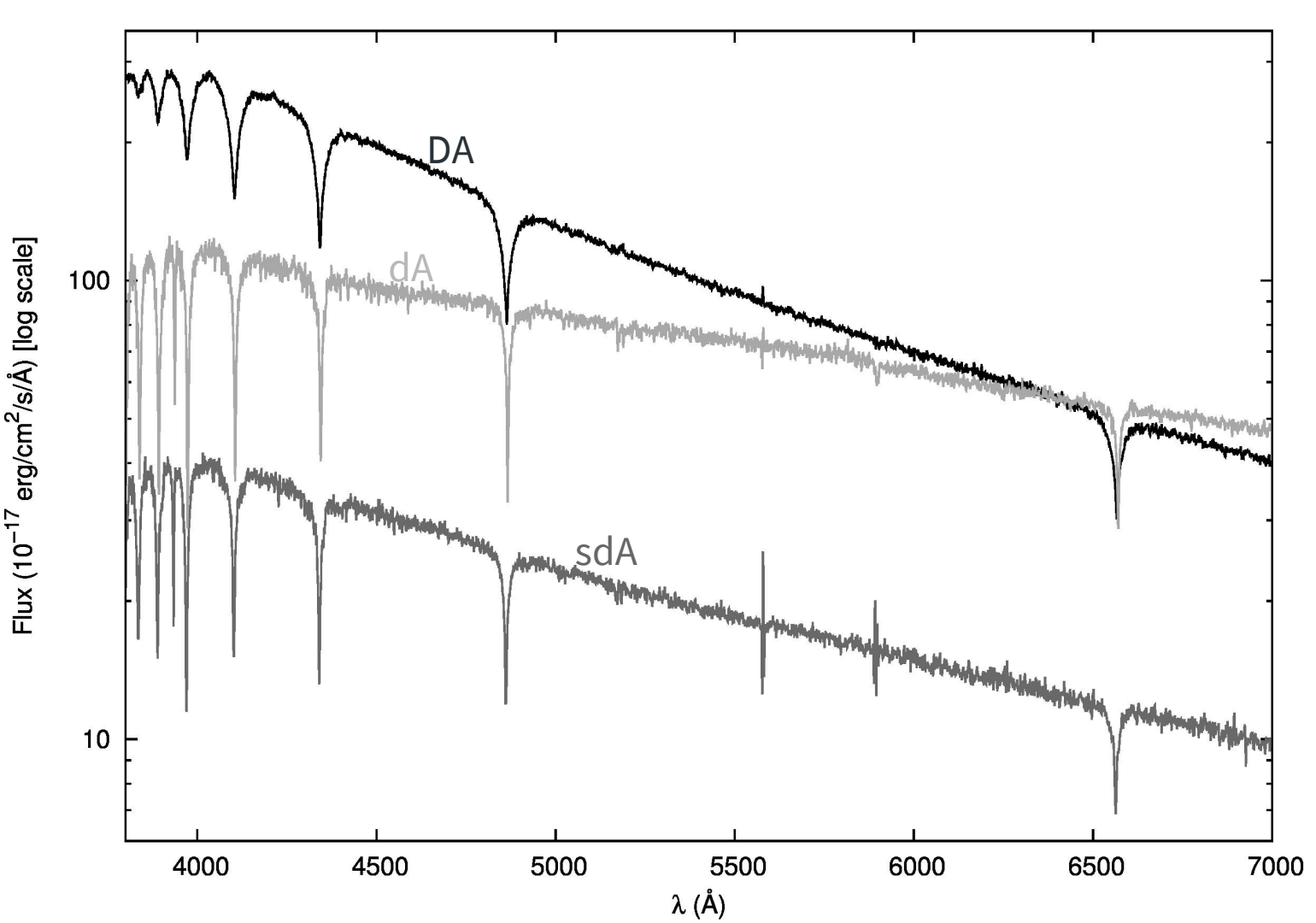
From:
http://www1.ynao.ac.cn/~zhanwenhan/bps.html

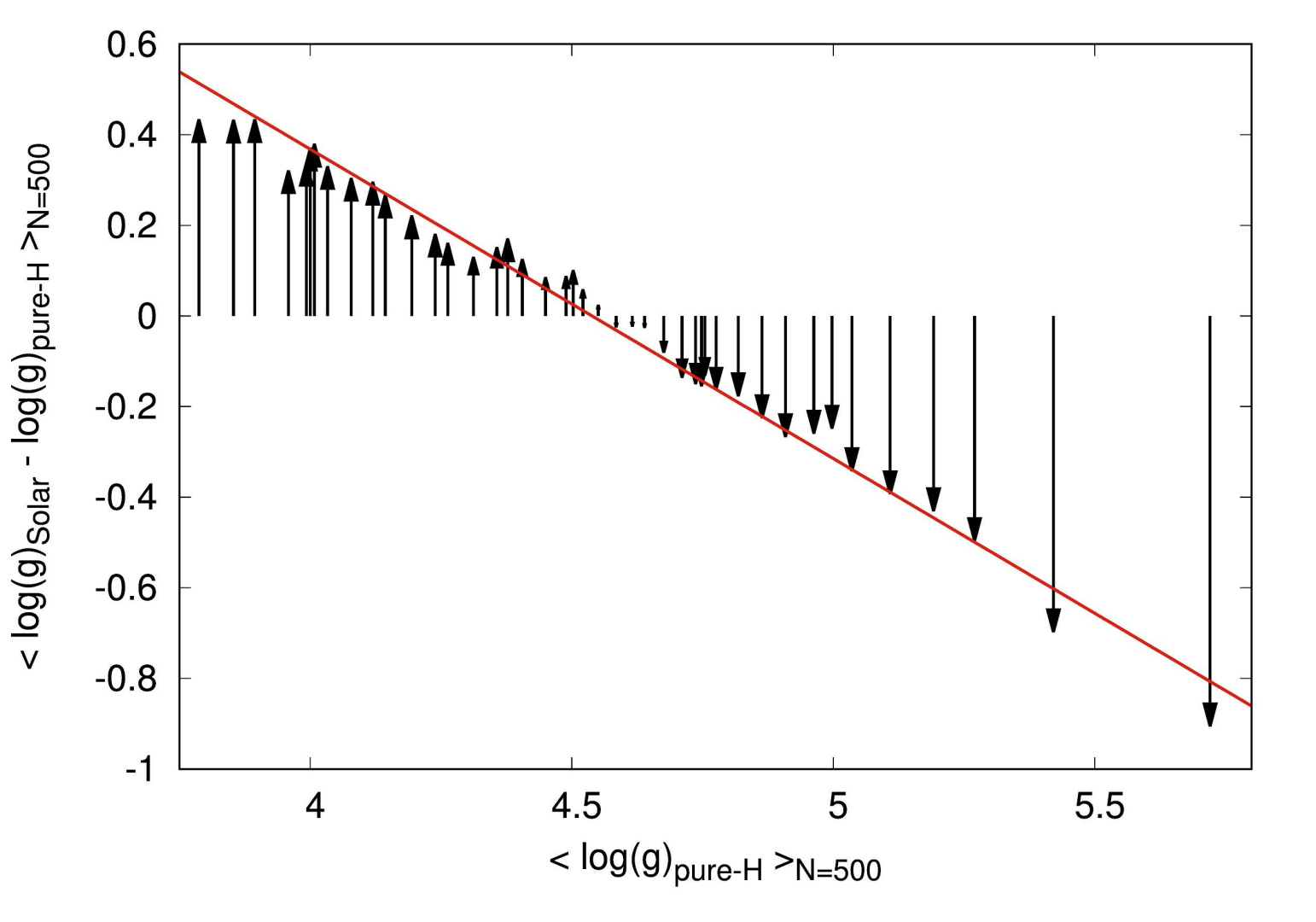


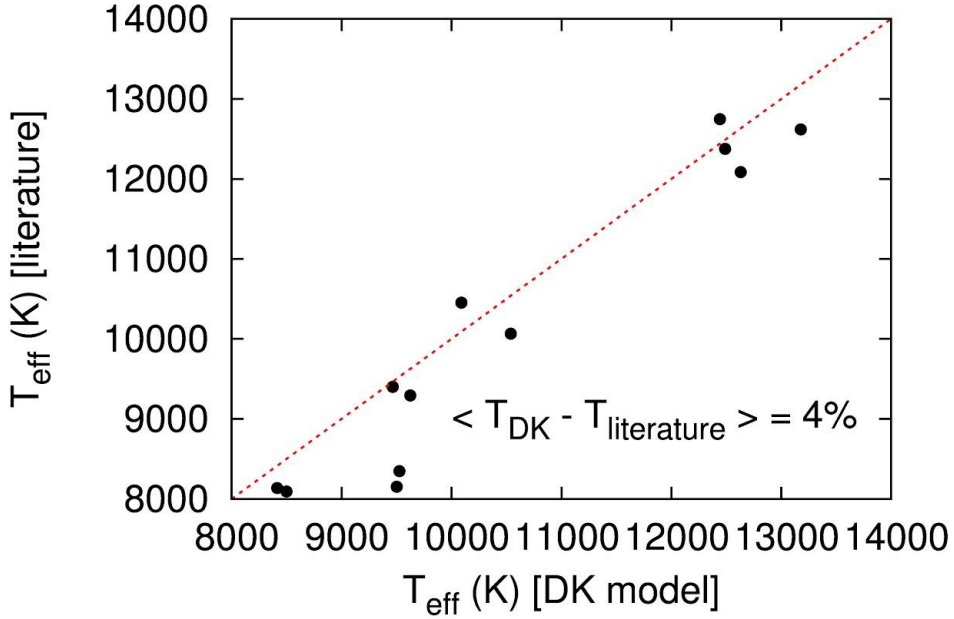
Adapted from Jeffery & Saio (2016)

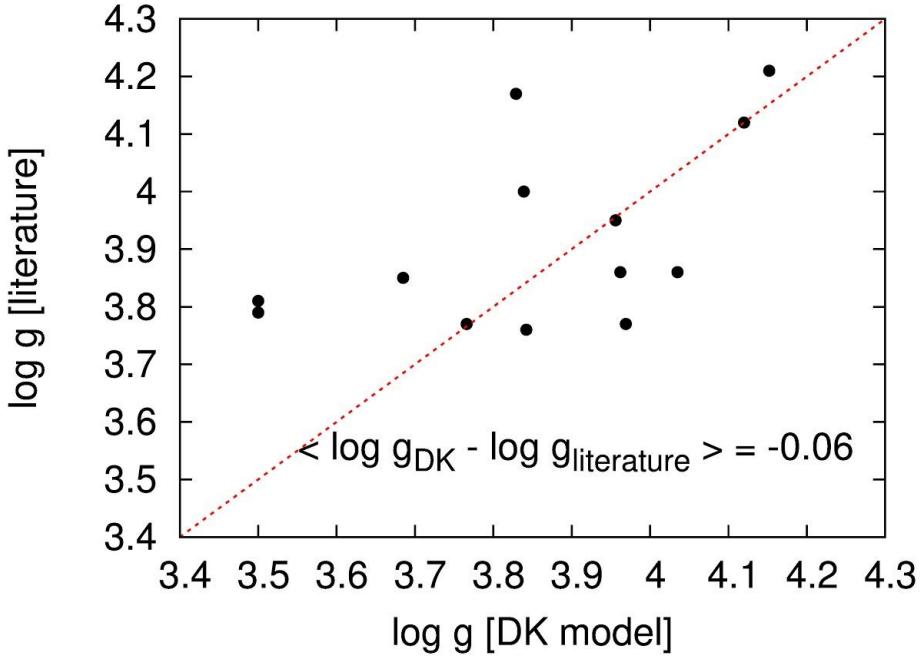


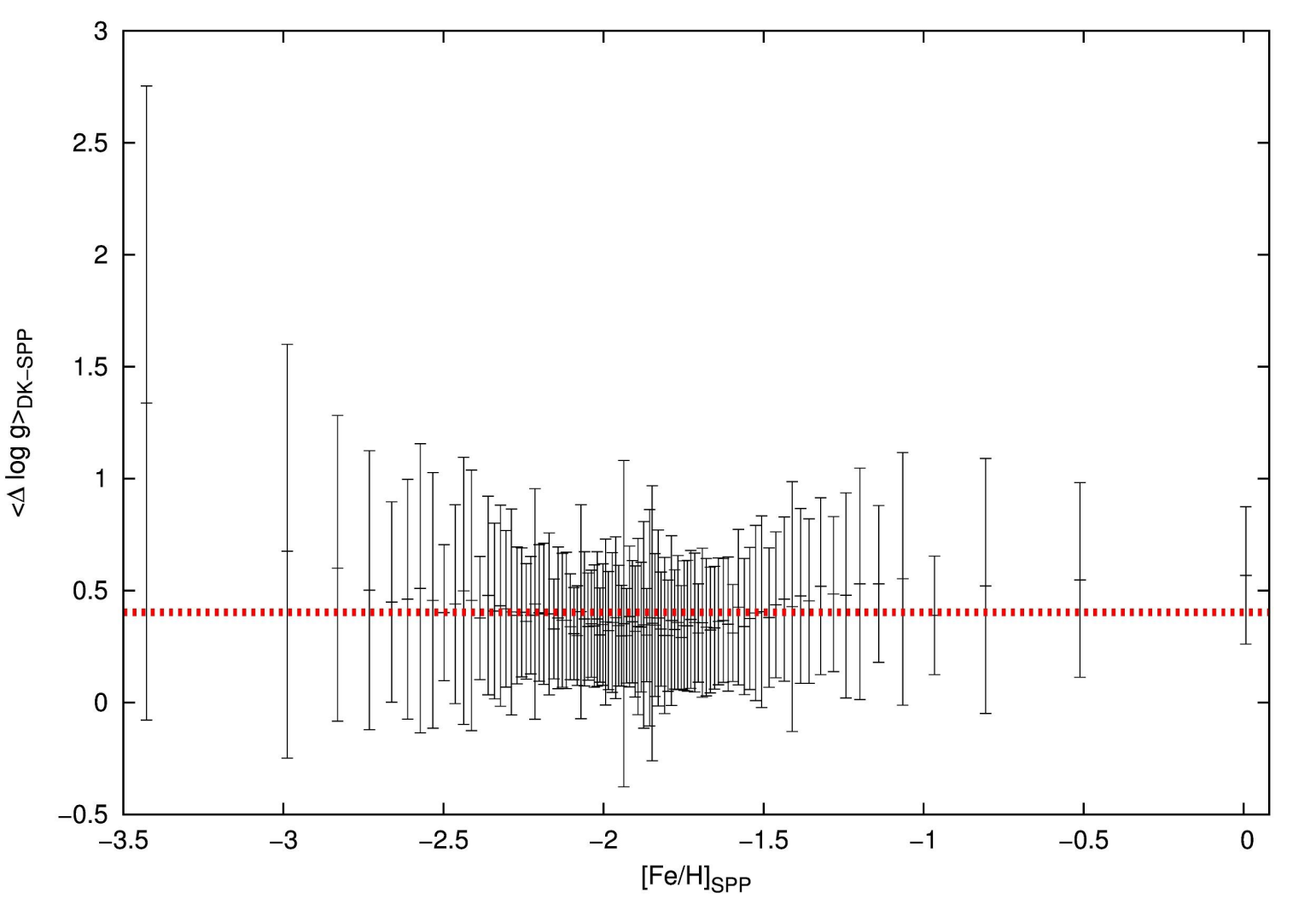
Zeeman spliting models from Schimeczek et al. (2013), Schimeczek & Wunner (2014a), and Schimeczek & Wunner (2014b)

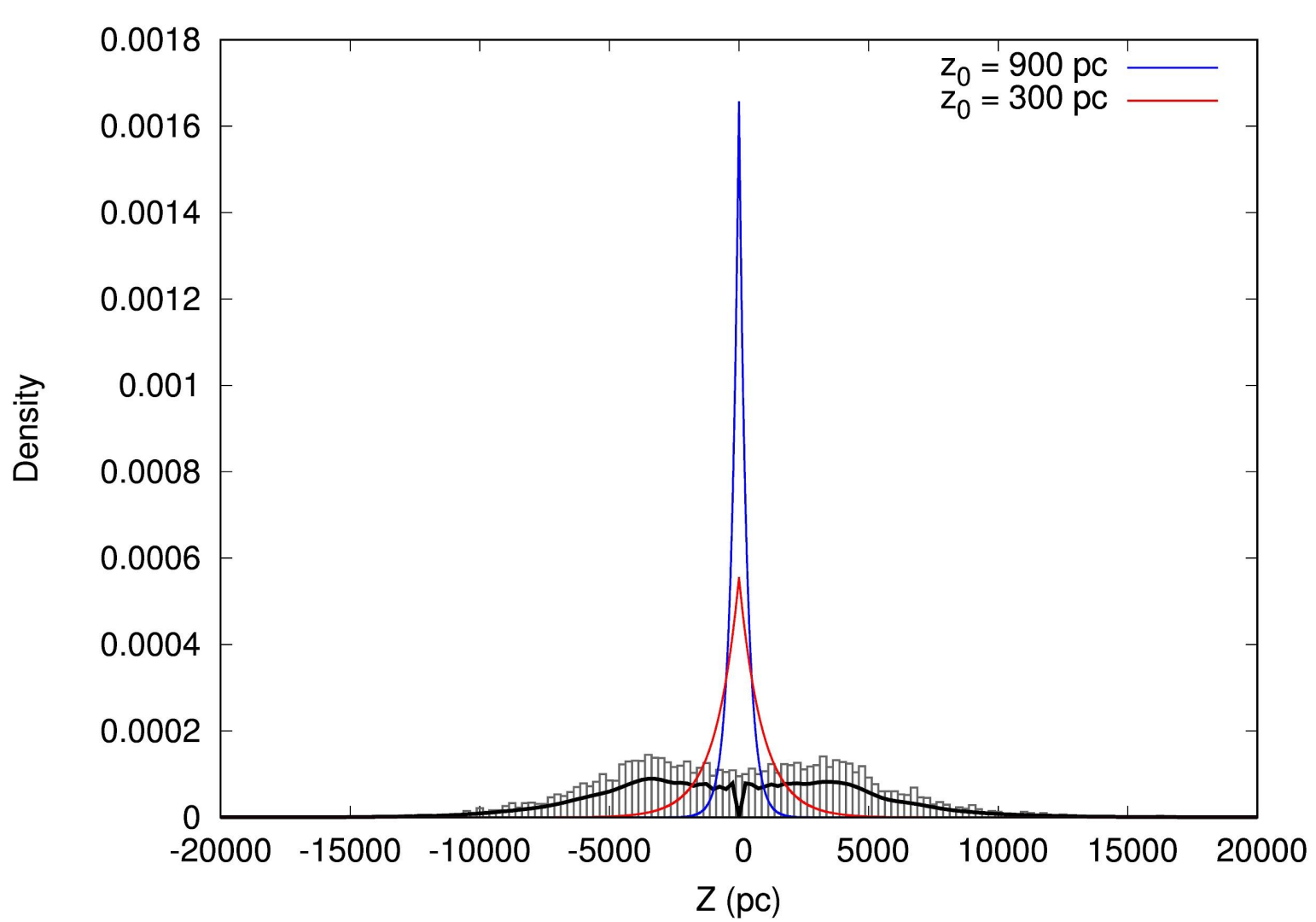

DA
dA
sdA
100
10
Flux (10^{-17} erg/cm^2/s/Å) [log scale]
4000
4500
5000
5500
6000
6500
7000
λ (Å)


0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4
4.5
5
5.5
< log(g)Solar - log(g)pure-H >N=500
< log(g)pure-H >N=500

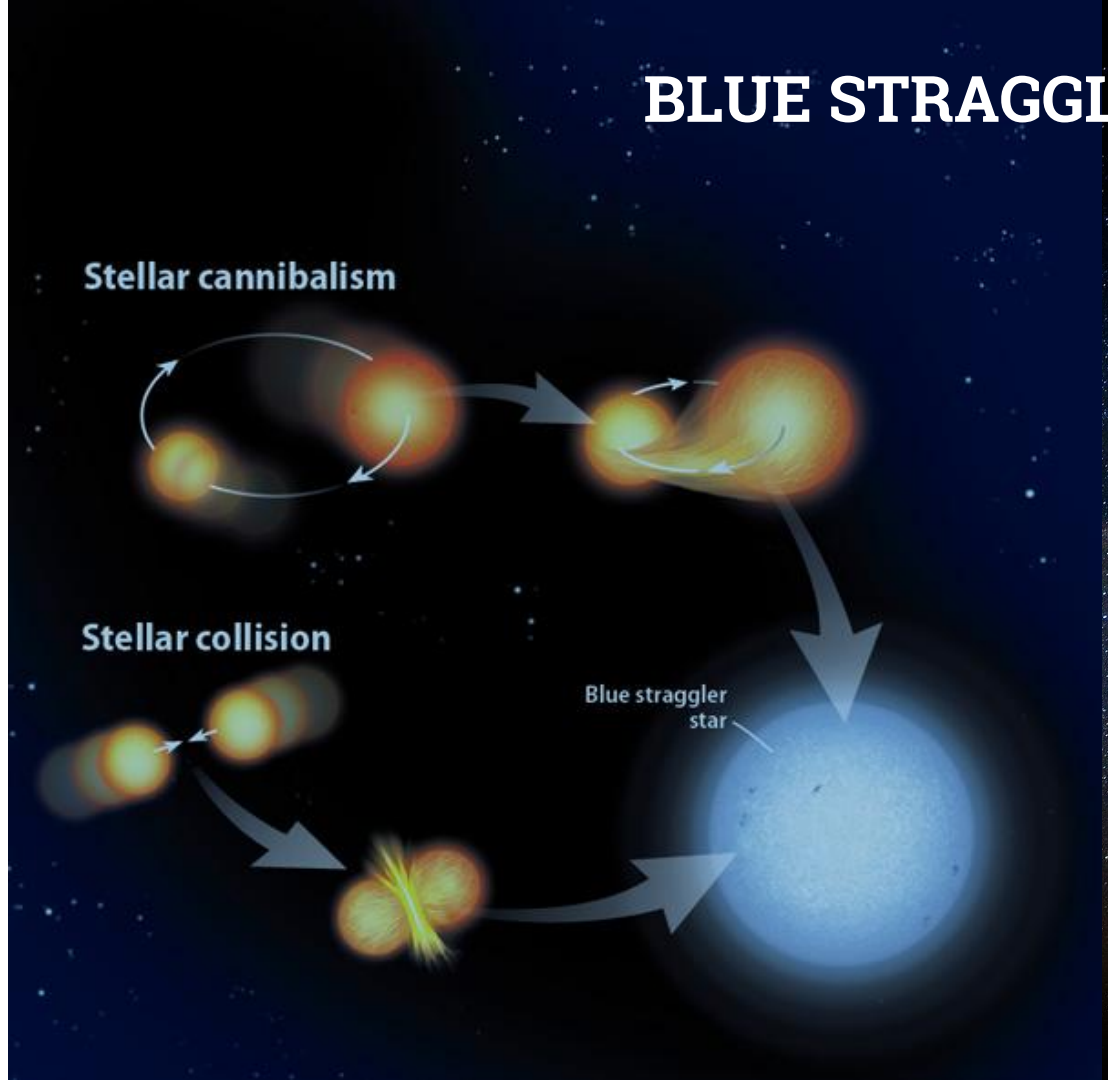

14000
13000
12000
11000
10000
9000
8000
8000 9000 10000 11000 12000 13000 14000
T_{eff} (K) [literature]
T_{eff} (K) [DK model]
< T_{DK} - $T_{literature}$ > = 4%

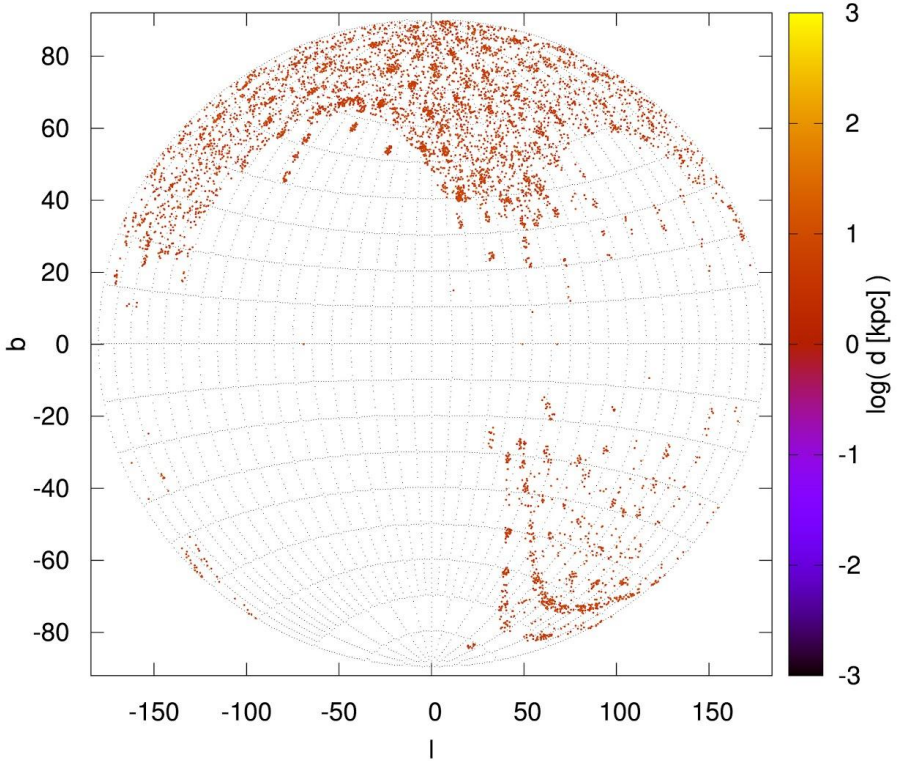

4.3
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.4 3.5 3.6 3.7 3.8 3.9 4 4.1 4.2 4.3
log g [literature]
log g [DK model]
< log g_{DK} - log $g_{literature}$ > = -0.06

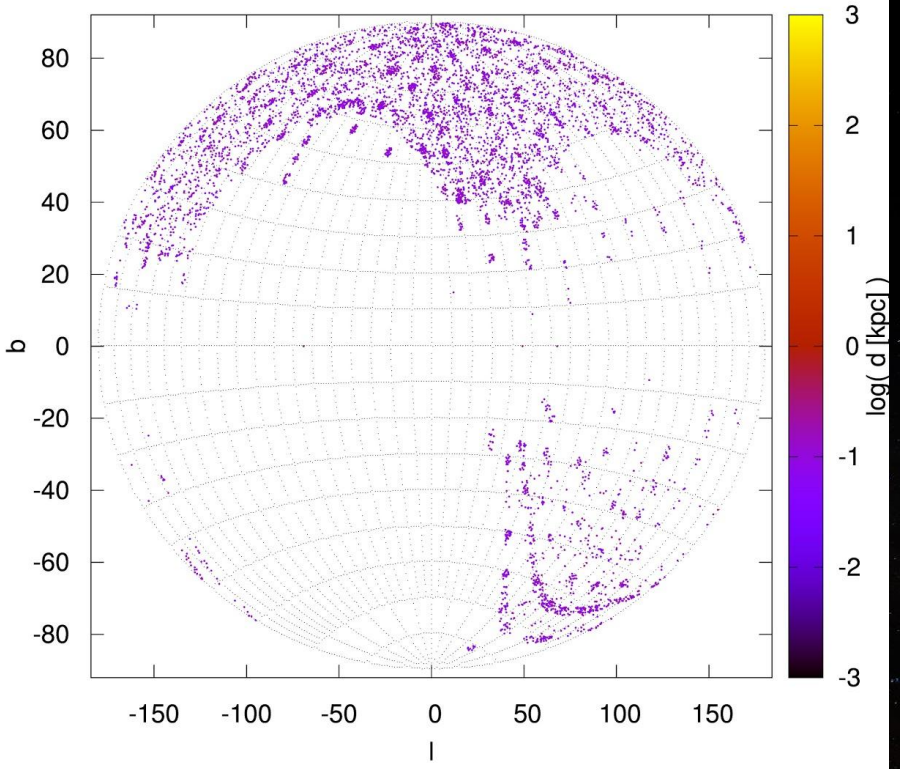

3
2.5
2
1.5
1
0.5
0
−0.5
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0
<Δ log g>DK−SPP
[Fe/H]SPP

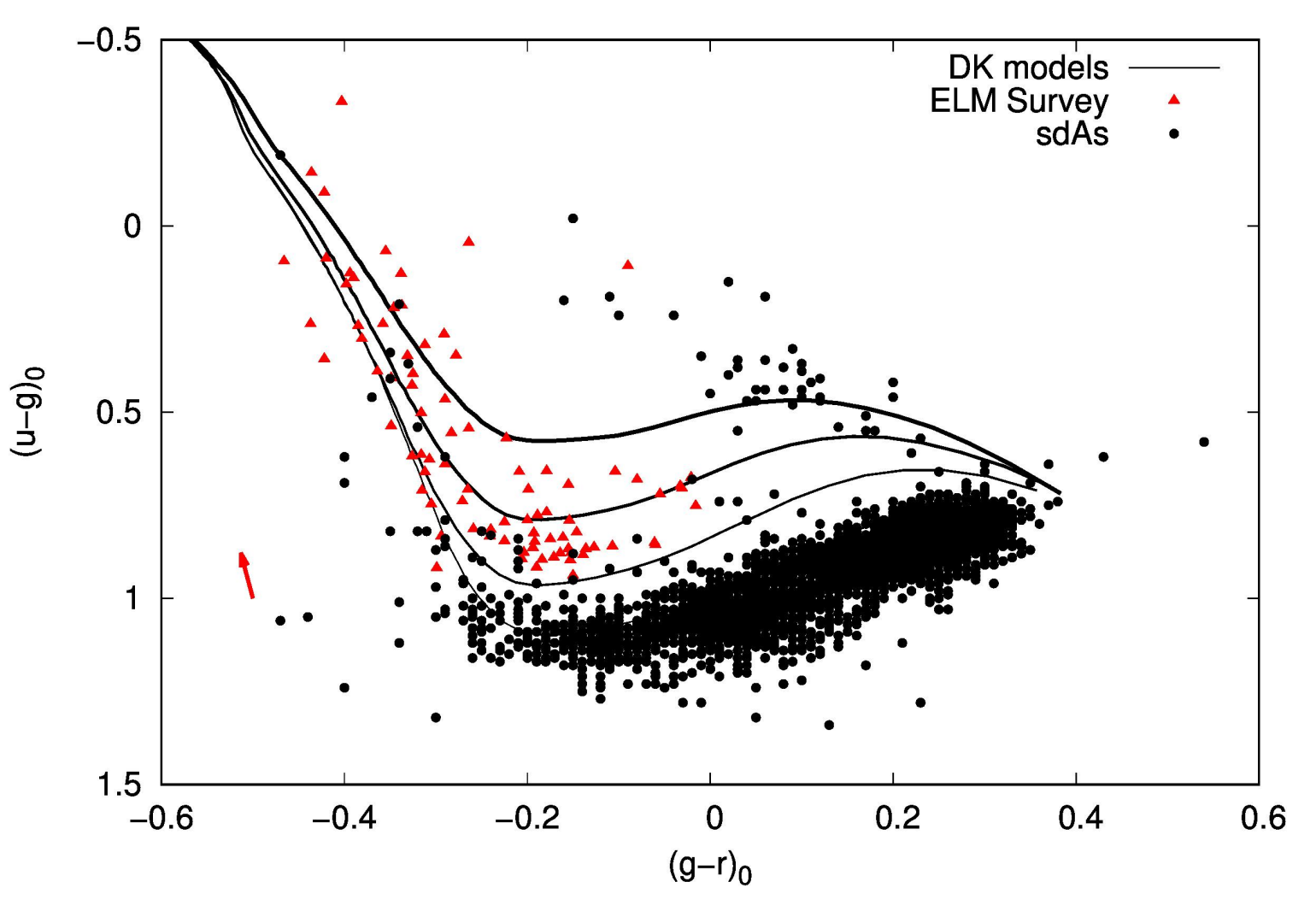

0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Density
-20000
-15000
-10000
-5000
0
5000
10000
15000
20000
Z (pc)
z0 = 900 pc
z0 = 300 pc

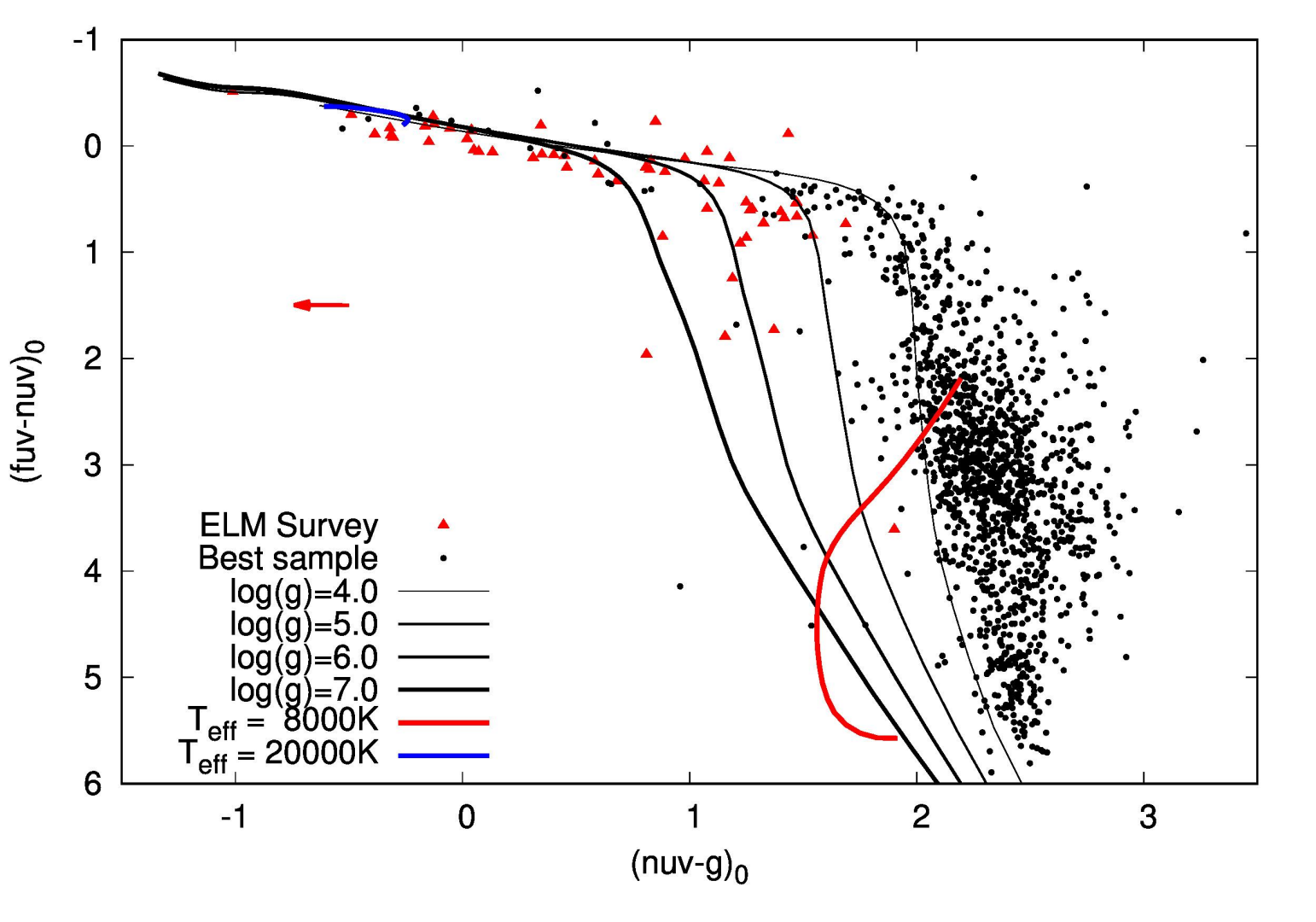
BLUE STRAGGLERS?



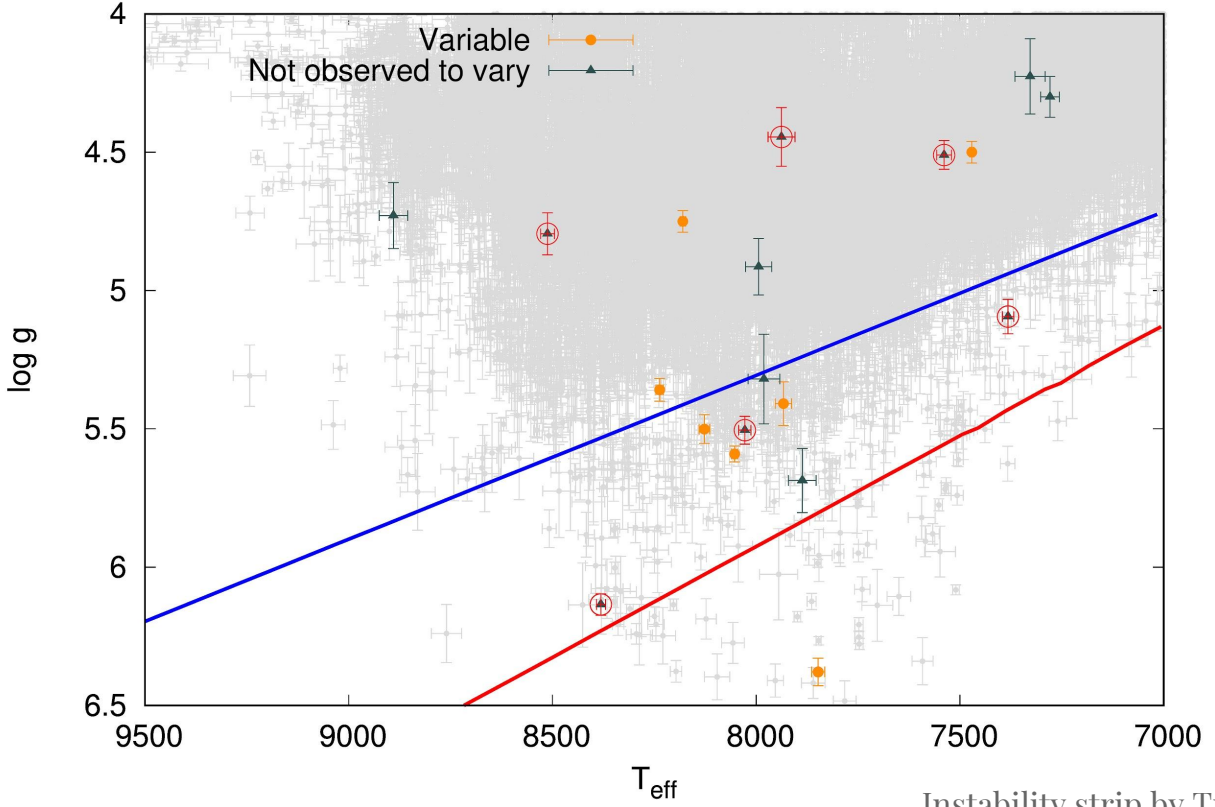

b
l
log(d [kpc])
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
3
2
1
0
-1
-2
-3


b
l
log(d [kpc])
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
3
2
1
0
-1
-2
-3


DK models
ELM Survey
sdAs
−0.5
0
0.5
1
1.5
(u−g)0
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
(g−r)0

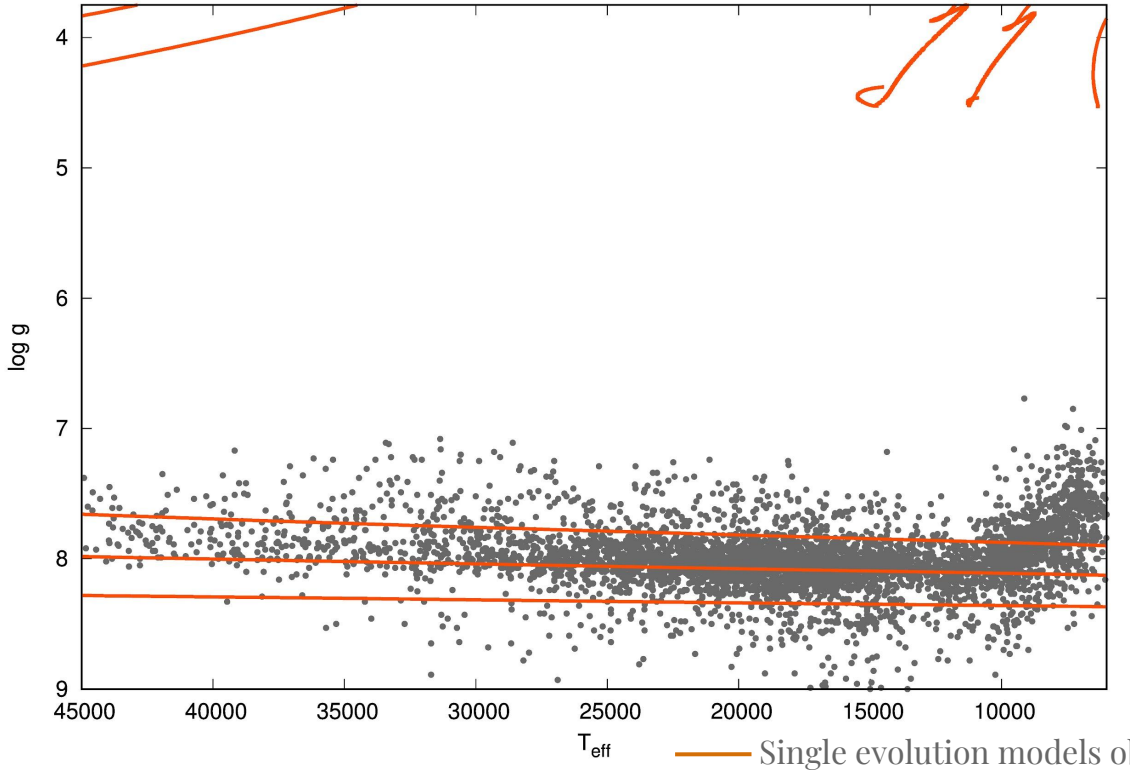

-1
0
1
2
3
4
5
6
-1
0
1
2
3
(fuv-nuv)0
(nuv-g)0
ELM Survey
Best sample
log(g)=4.0
log(g)=5.0
log(g)=6.0
log(g)=7.0
Teff = 8000K
Teff = 20000K

Preliminary Results



Instability strip by Tremblay et al. (2015)

...but something was missing.



Single evolution models obtained with the LPCODE (Althaus et al. 2005) by A. D. Romero