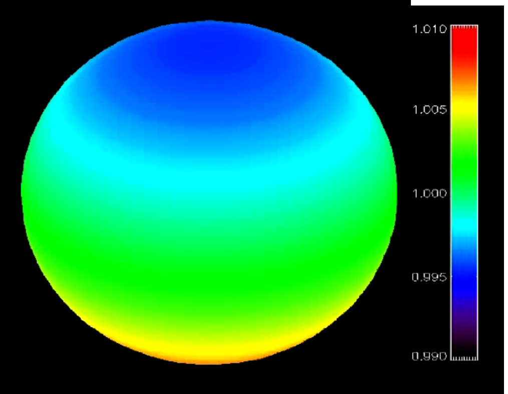
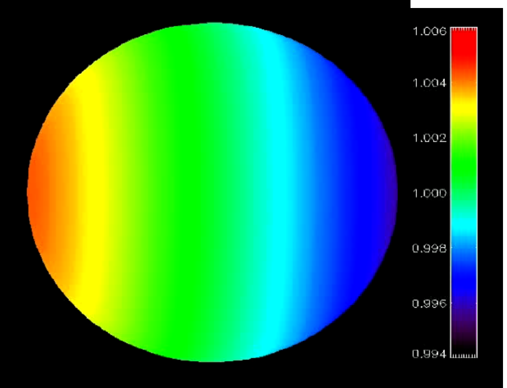
White Dwarf Asteroseismology and the Physics of Compact Matter





Mike Montgomery

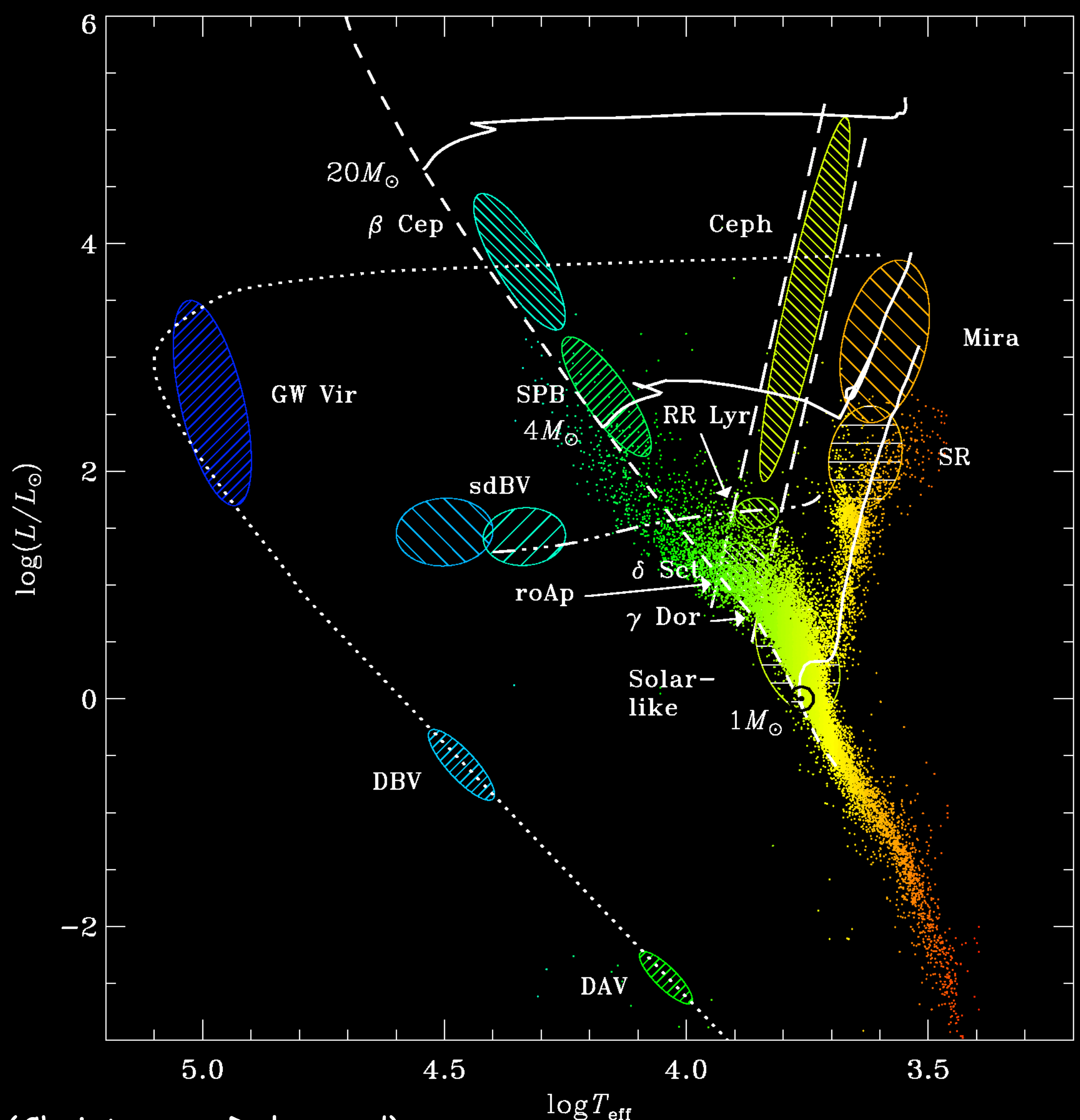
Dept. of Astronomy, UT-Austin

WET
Whole Earth Telescope

ASTRONOMY PROGRAM · UNIVERSITY OF TEXAS AT AUSTIN
DEPARTMENT OF ASTRONOMY

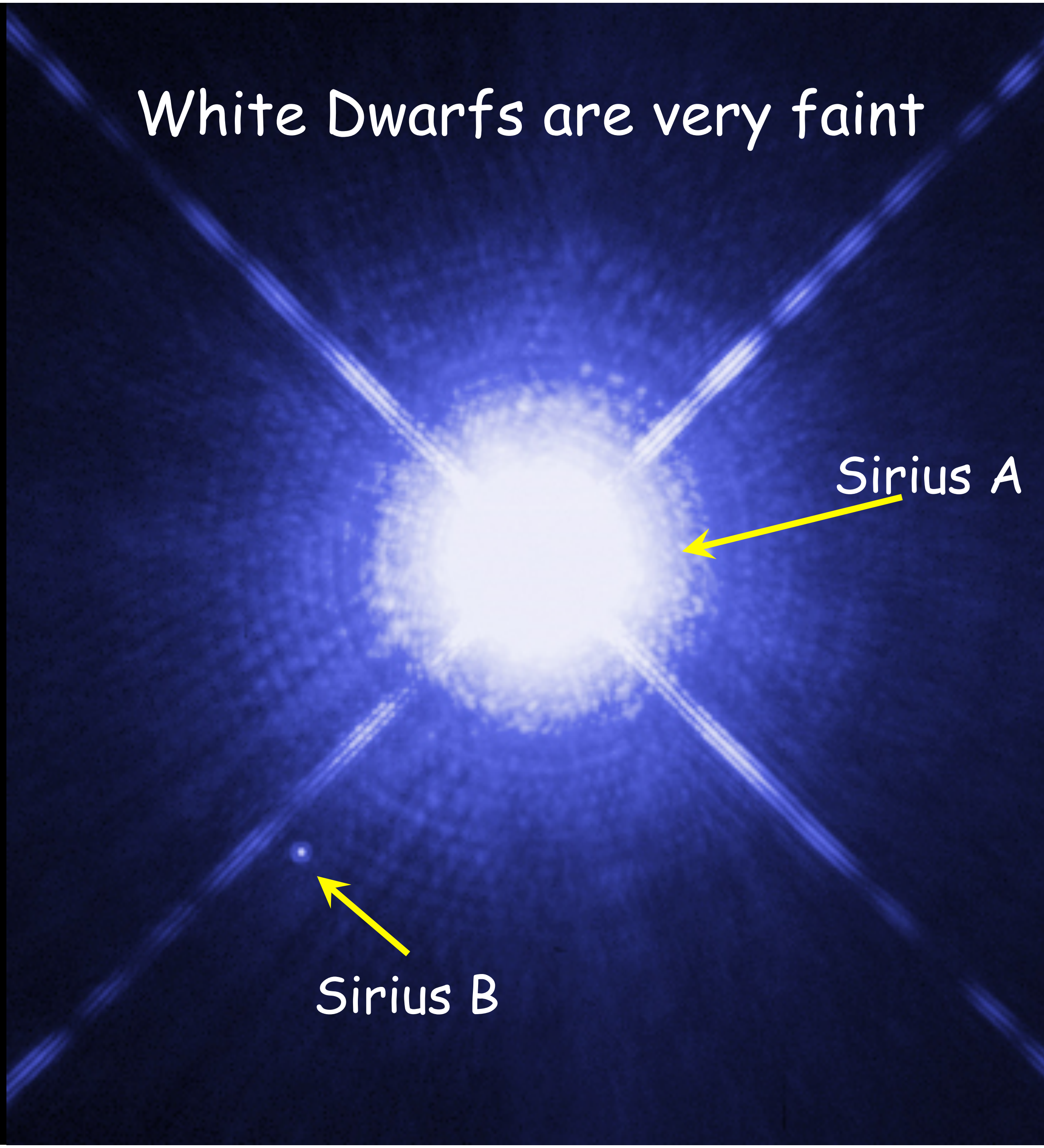
McDONALD OBSERVATORY

97% of all stars will become white dwarfs

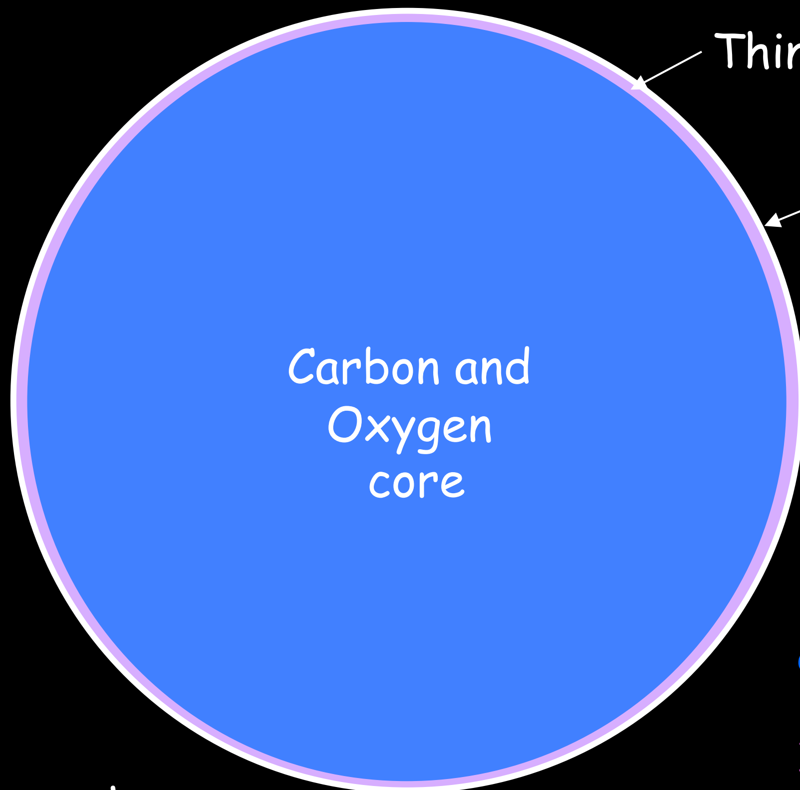


(Christensen-Dalsgaard)

White Dwarfs are very faint



White Dwarfs are Simple



99% Carbon/Oxygen

1% Helium

0.01% Hydrogen

DA= hydrogen atmosphere
DB= helium atmosphere

The Physics of White Dwarfs

- White dwarfs are supported by electron degeneracy pressure (the Pauli Exclusion Principle)
- Cooling is controlled by the heat capacity of the ions, and the surface temperature
- When hot (> 25,000 K) they emit more energy in neutrinos than in photons
- As they get very cool (about 7000 K), the ions in the core settle into a crystalline lattice, i.e., they “freeze” or crystallize
- Gravity is high (*g* » 10^8 cm/s^2), so heavy elements sink, producing nearly pure H and He layers

Science with White Dwarfs

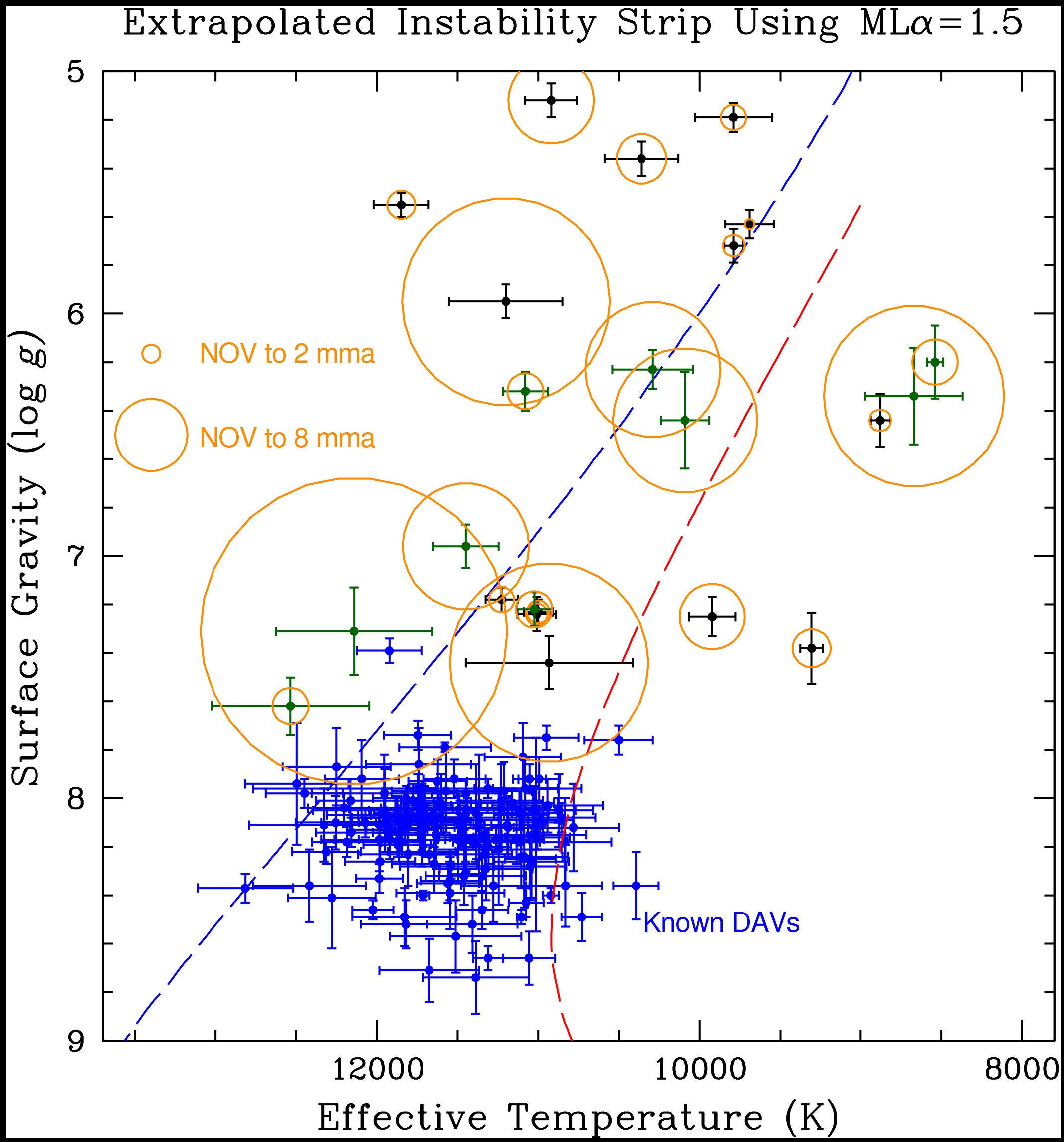
- Pulsating white dwarfs allow us to:
  - Constrain their core chemical profiles
  - Constrain the physics of crystallization
  - Probe the physics of convection
  - Constrain accretion in CV systems
  - Test the properties of exotic particles such as plasmon neutrinos and axions
  - Look for extra-solar planets
  - Probe “exotic” stellar systems

The SDSS

It's good to be faint and blue!

In the last 8 years the number of known pulsators has gone from ~35 to ~160

(e.g., Mukadam et al. 2004, ApJ, 607, 982; Gianninas, Bergeron, & Fontaine 2006, AJ, 132, 831; Castanheira et al. 2006, A&A, 450, 227; Mullally et al. 2005, ApJ, 625, 966; Nitta et al. 2009, ApJ, 690, 560)



White Dwarf Pulsations

- non-radial *g*-modes,
  periods ~ 100 to 1000 s

$$P_n = n\,\Delta P + \epsilon,\ n = 1, 2, 3, \ldots$$

$$\Delta P \sim 1/\int N dr/r$$

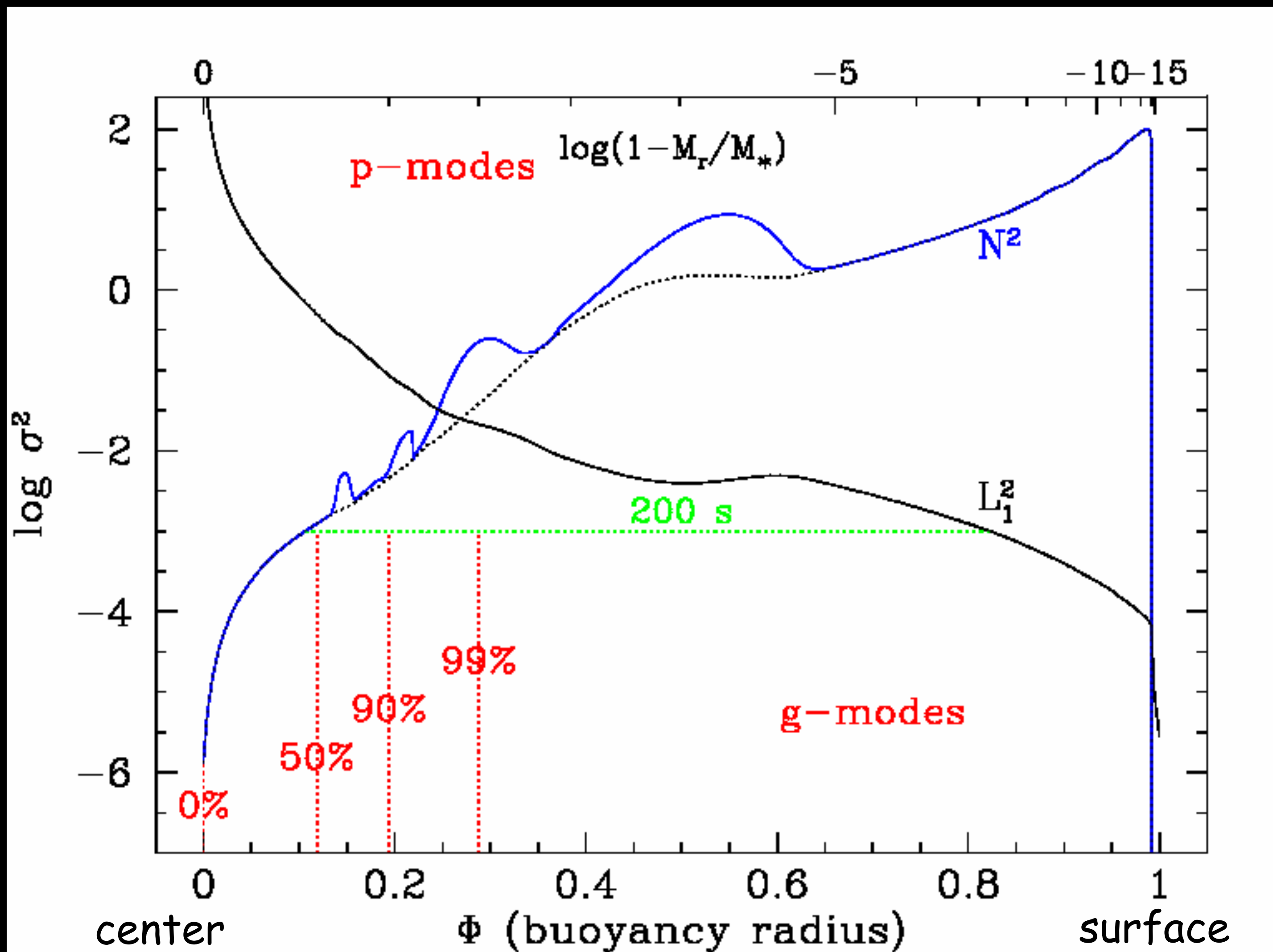
DBV and DAV driving

Due to convective driving -- the "Brickhill effect"
(Brickhill 1992, Wu & Goldreich)

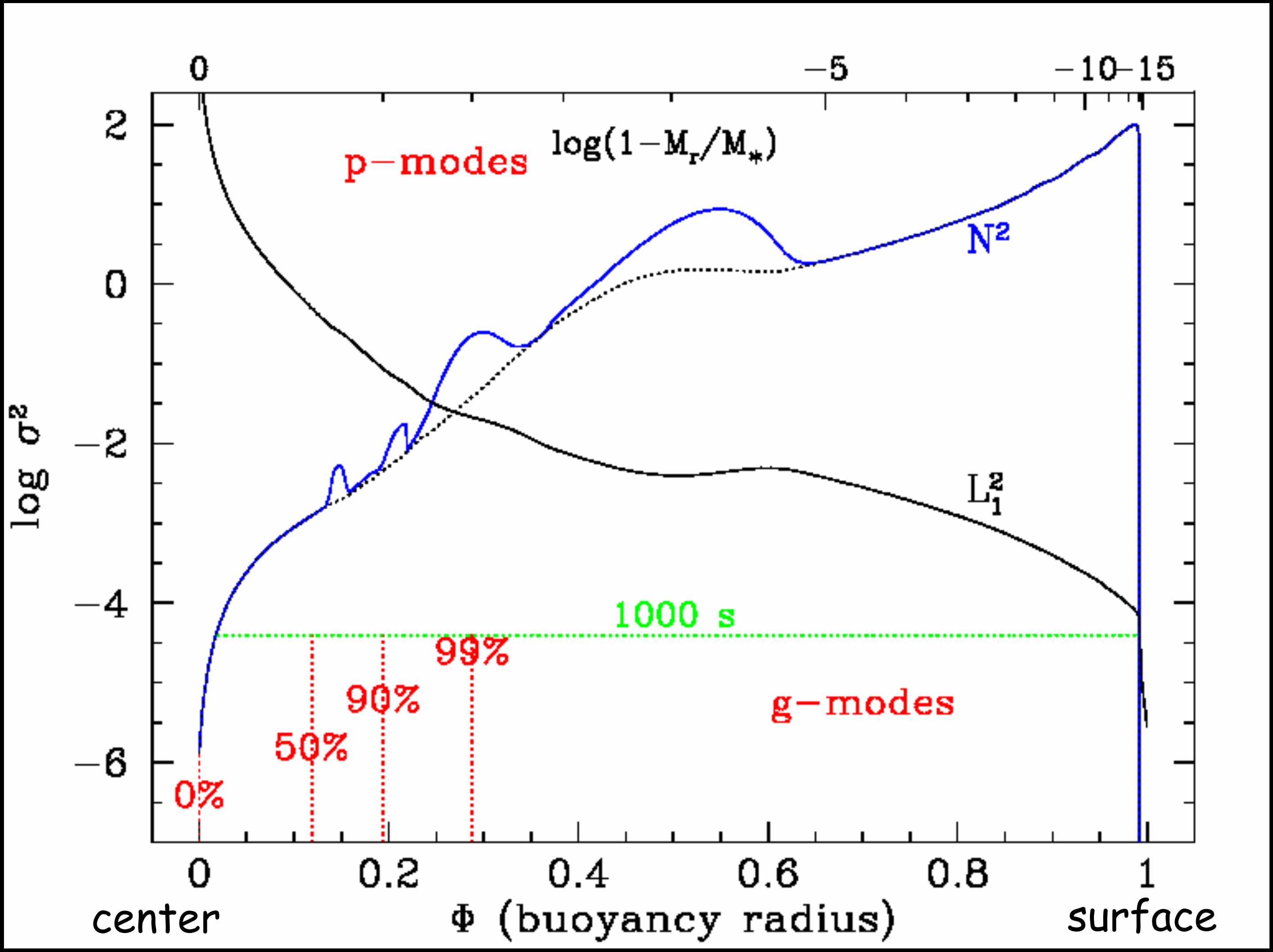
- convection zone is associated with the partial ionization of either H or He
- predictions of instability are similar to those of
- mechanism driving in white dwarfs:

"Blue" (hot) edge occurs when the n=1, l=1 mode satisfies $!¿_c$ ¼ 1, where $¿_c$ ¼ 4 $¿_{thermal}$ at the base of the convection zone (Wu & Goldreich, late 1990's)

White Dwarf Seismology



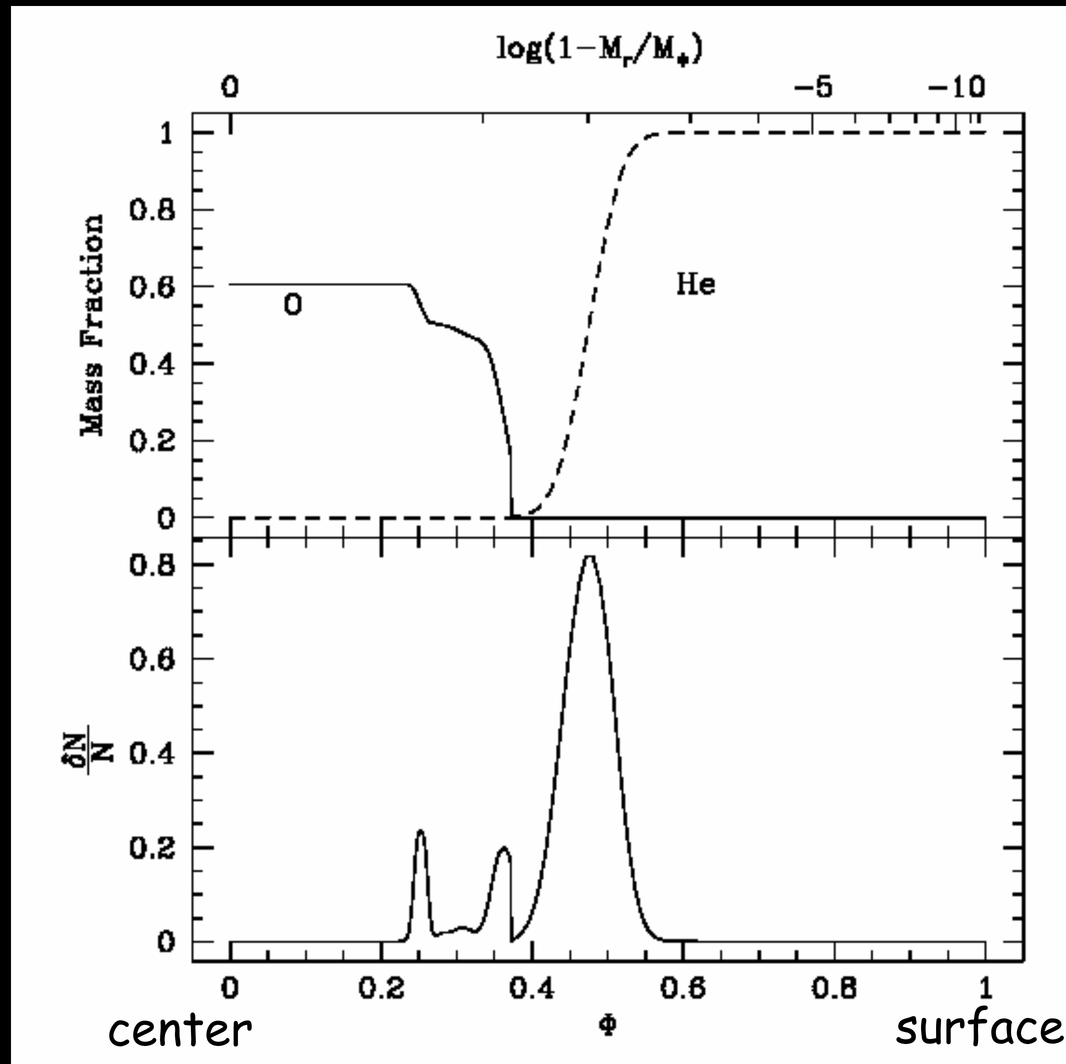
White Dwarf Seismology



Chemical Profiles produce bumps in N

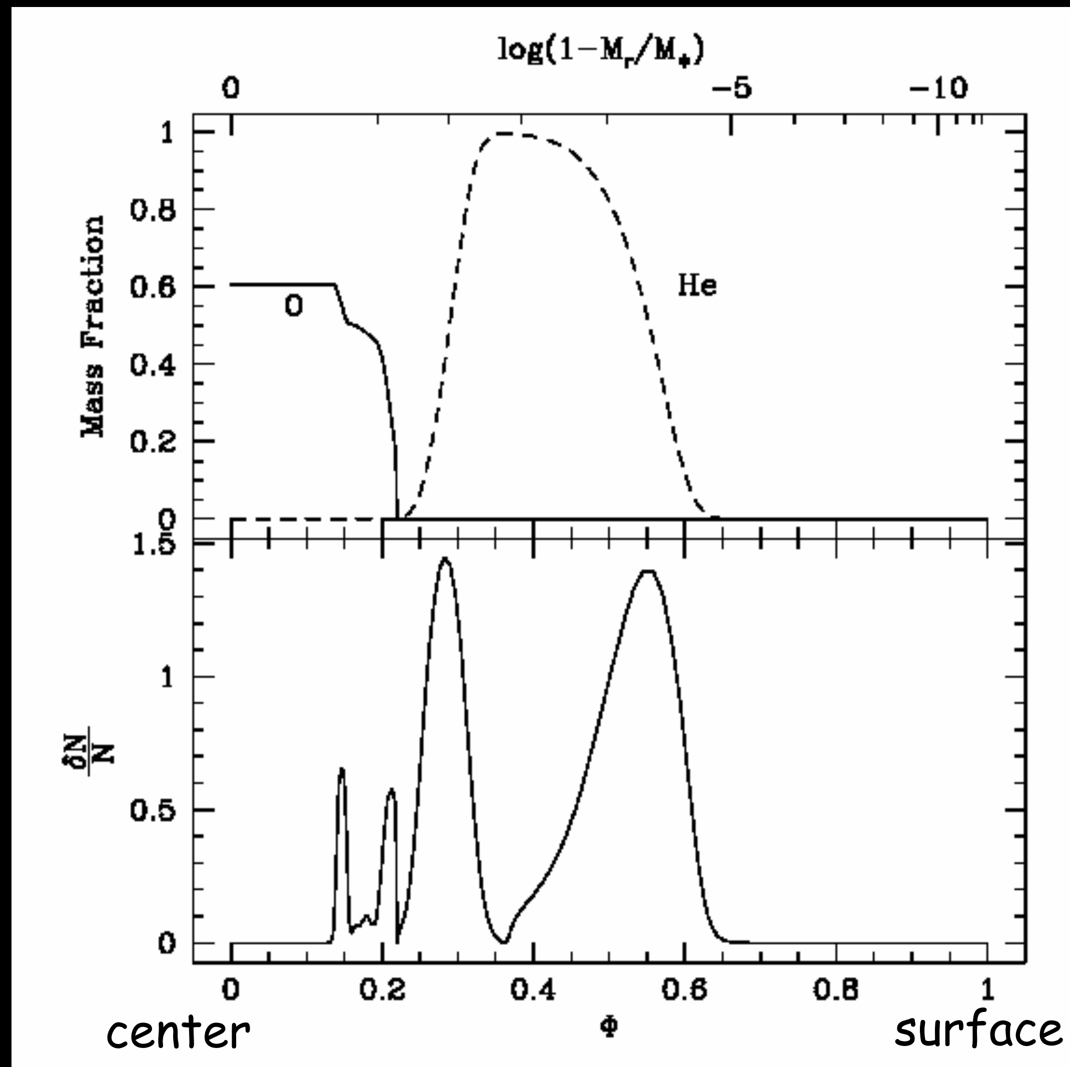
The composition transition zones produce bumps in *N*

DBV model
M = 0.6 M–
T_{eff}= 25000 K



The composition transition zones produce bumps in *N*

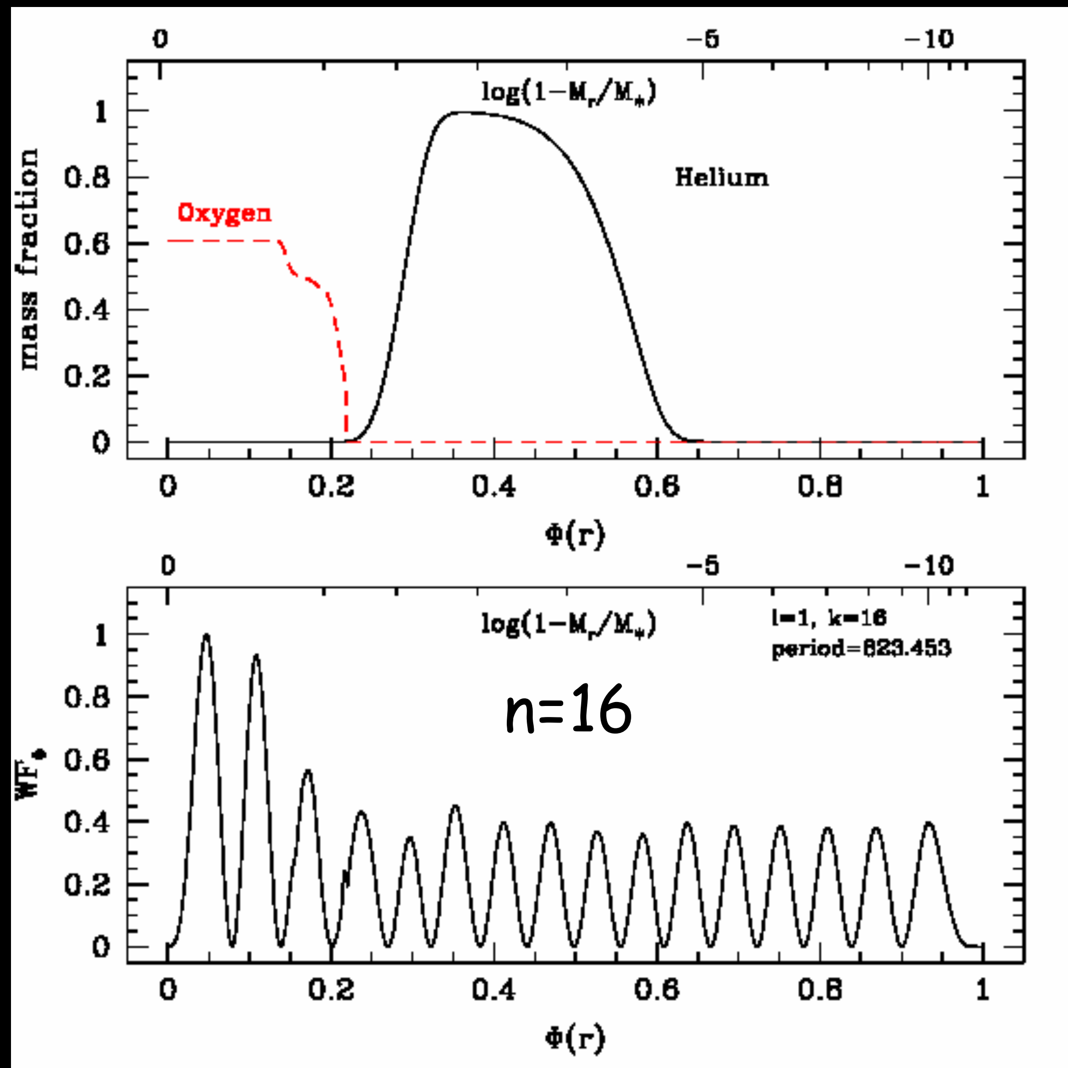
DAV model
M = 0.6 M–
T_{eff}= 12000 K



The bumps can "trap" modes…

Unequal sampling produces unequal period spacings

DAV model
M = 0.6 M–
T_{eff}= 12000 K



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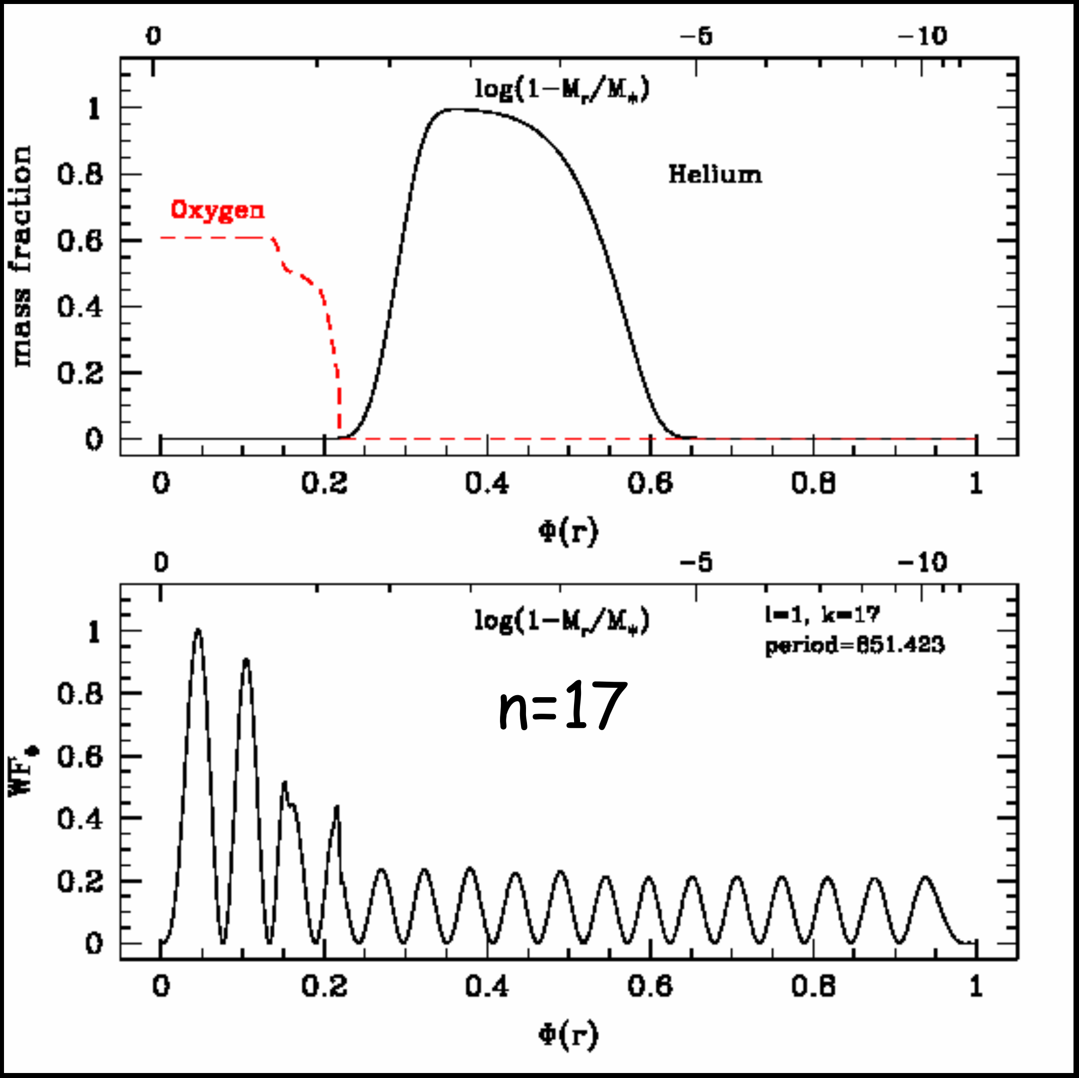

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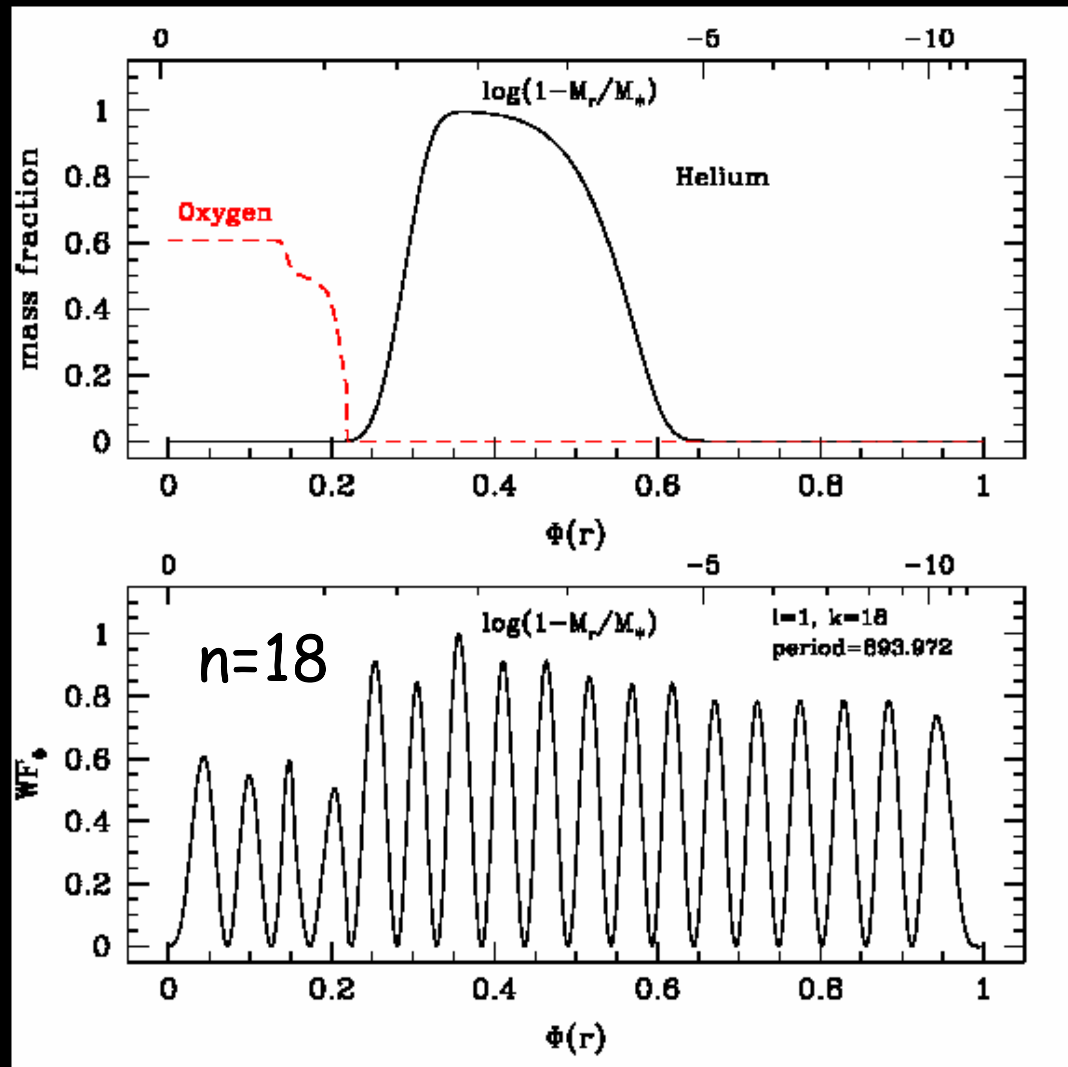


The "vibrating string" analogy

Replace the "usual" oscillation equations (e.g. Gough 1993)

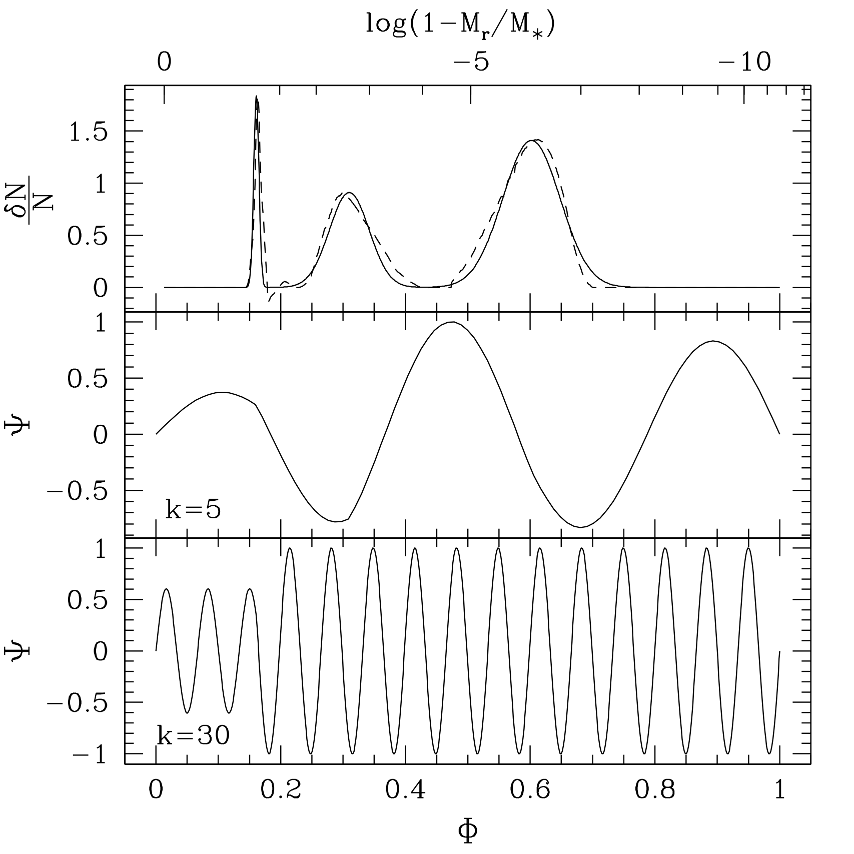
$$\frac{d^2\psi}{dr^2} + K^2(r)\psi(r) = 0, \quad \text{where} \quad K(r) \equiv \frac{\omega^2 - \omega_c^2}{c^2} - \frac{L^2}{r^2}\left(1 - \frac{N^2}{\omega^2}\right)$$

with those of a "beaded" string:

$$\frac{d^2\psi}{dx^2} + \frac{\omega^2}{c^2}\psi = 0$$

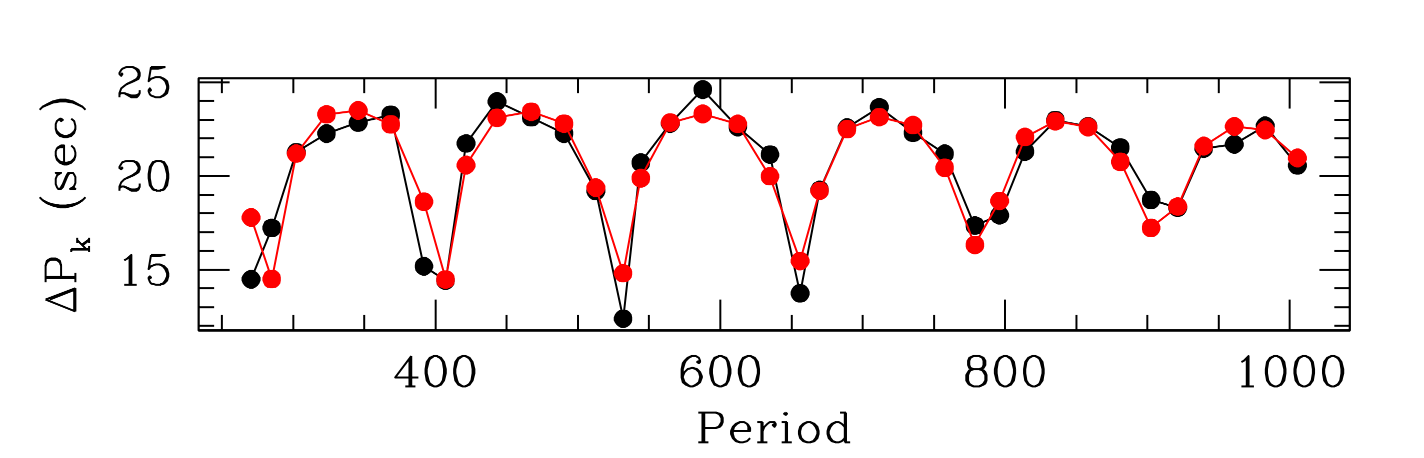
$$c^2 = c_0^2\left(1 + Be^{-b^2(x-x_0)^2}\right)$$

$$\psi = \begin{cases} A \ \sin\left(\frac{n\pi x}{L}\right) & \text{if} \quad x \leq x_0 \\ A' \sin\left(\frac{n\pi x}{L} + \text{const.}\right) & \text{if} \quad x \geq x_0 \end{cases}$$



This reasoning also led to an understanding of the core/envelope symmetry for pulsations having a single l value in WDs (Montgomery, Metcalfe, Winget 2003)

The "vibrating string" analogy



black=numerical model of Corsico et al. 2005

red=simplified mode-trapping on a string

Good qualitative agreement for shape of trapping diagram, is reasonable even in the 'non-perturbative' regime (Montgomery 2005)

Core composition and reaction rates

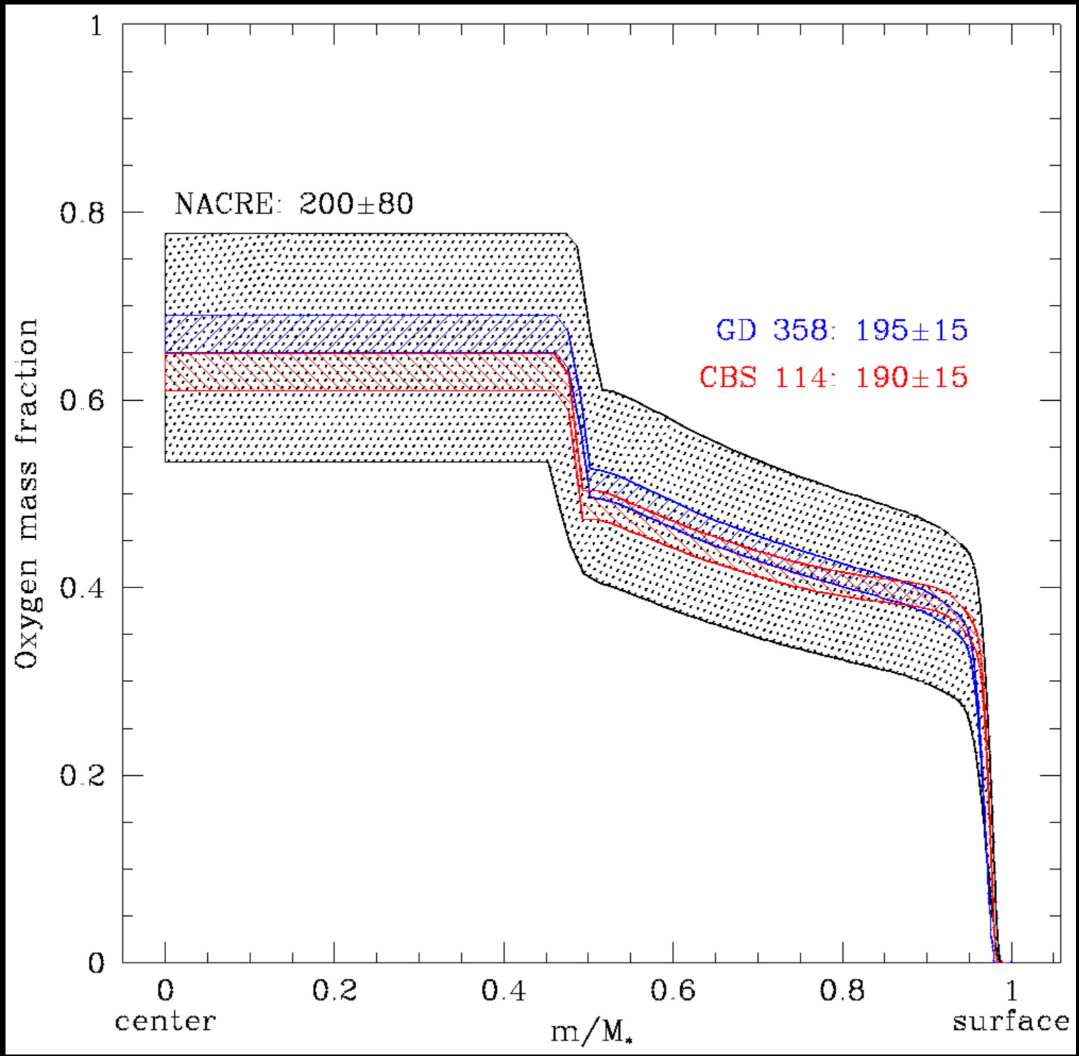
(Metcalfe 2003)

Central oxygen abundance of GD358 is X_O=0.67-0.76

Required reaction rates for C^{12}(alpha,gamma)O^{16} are in agreement with accepted values

Metcalfe, Salaris, & Winget 2002, ApJ, 573, 803

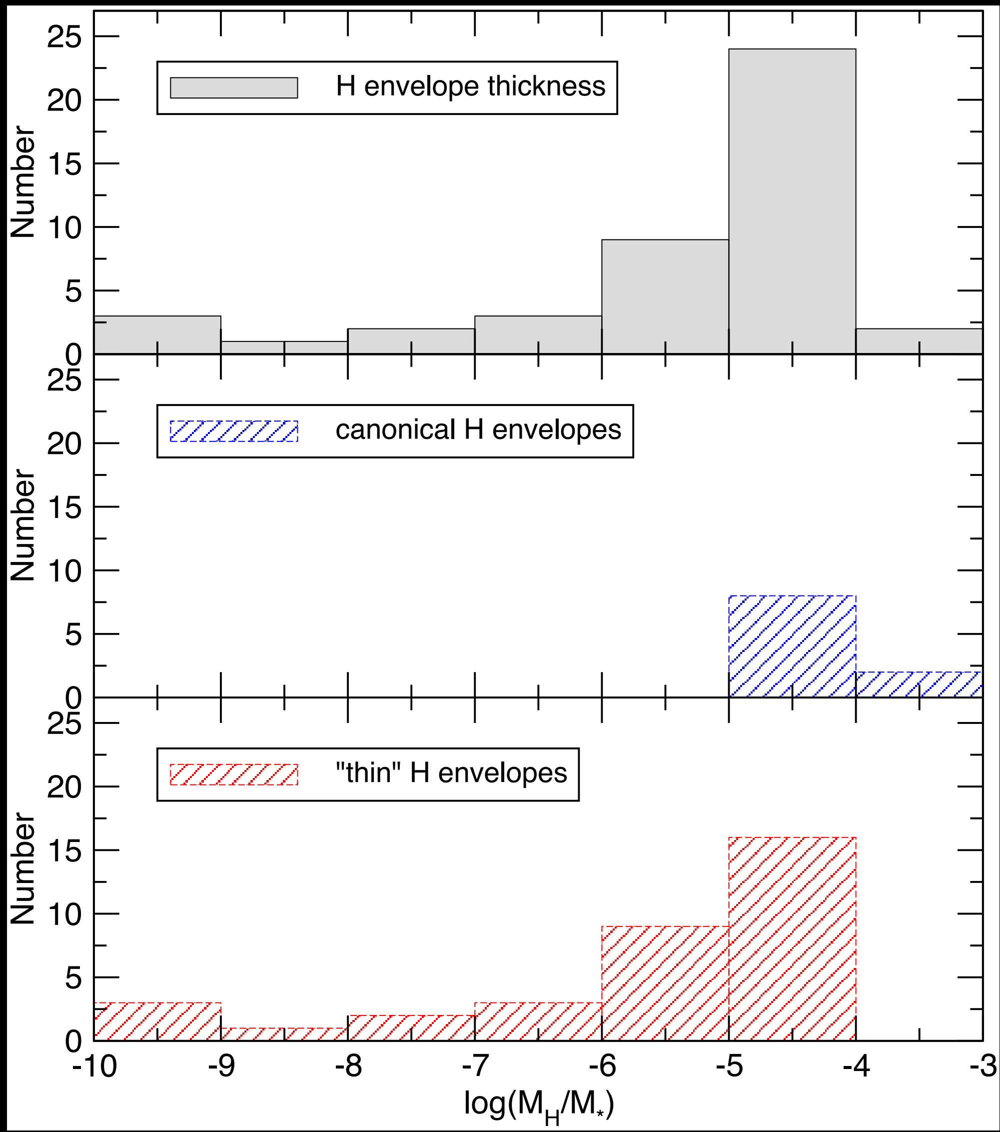
Metcalfe, Nather, & Winget 2000, ApJ, 545, 974



Hydrogen envelope thicknesses

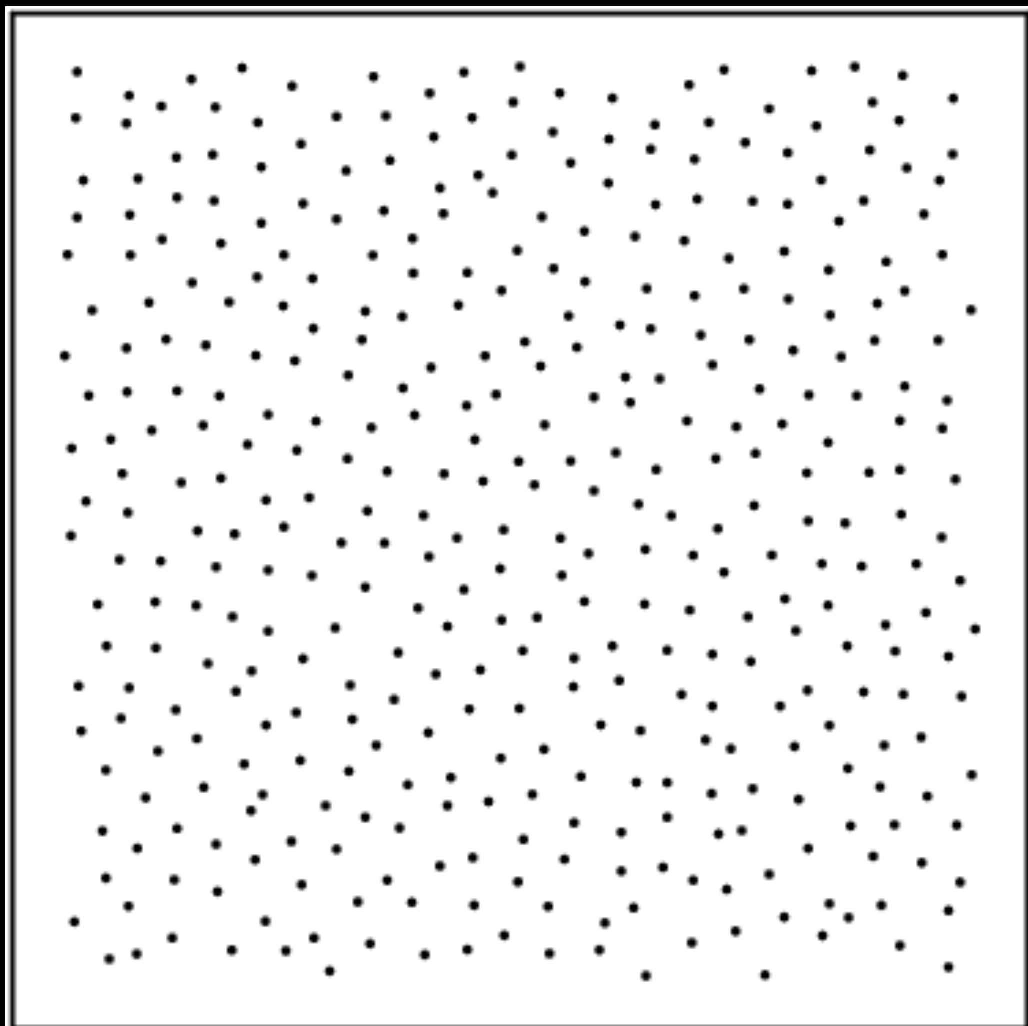
Ensemble asteroseismology of 44 DAVs has yielded information on the distribution of hydrogen layer masses

(Romero et al. 2011)



thickness distribution for the sample of 44 ZZ Ceti stars considered in this work. Middle panel: histogram for models with canonical (thick) H envelope thicknesses. Lower panel: histogram

Crystallization…



A one-component plasma (OCP) -- all the particles are identical

) regular lattice structure

in 3D, $¡_{Crys} = 178$

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

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ABSTRACT

We explore the physics of crystallization in the deep interiors of white dwarf stars using the color-magnitude diagram and luminosity function constructed from proper motion cleaned Hubble Space Telescope photometry of the globular cluster NGC 6397. We demonstrate that the data are consistent with the theory of crystallization of the ions in the interior of white dwarf stars and provide the first empirical evidence that the phase transition is first order: latent heat is released in the process of crystallization as predicted by van Horn (1968). We outline how this data can be used to observationally constrain the value of $\Gamma \equiv E_{\mathrm{Coulomb}}/E_{\mathrm{thermal}}$ near the onset of crystallization, the central carbon/oxygen abundance, and the importance of phase separation.

Subject headings: white dwarfs — dense matter — equation of state

$$\Gamma = \frac{1}{kT}\frac{(Ze)^2}{R}$$

From our paper…

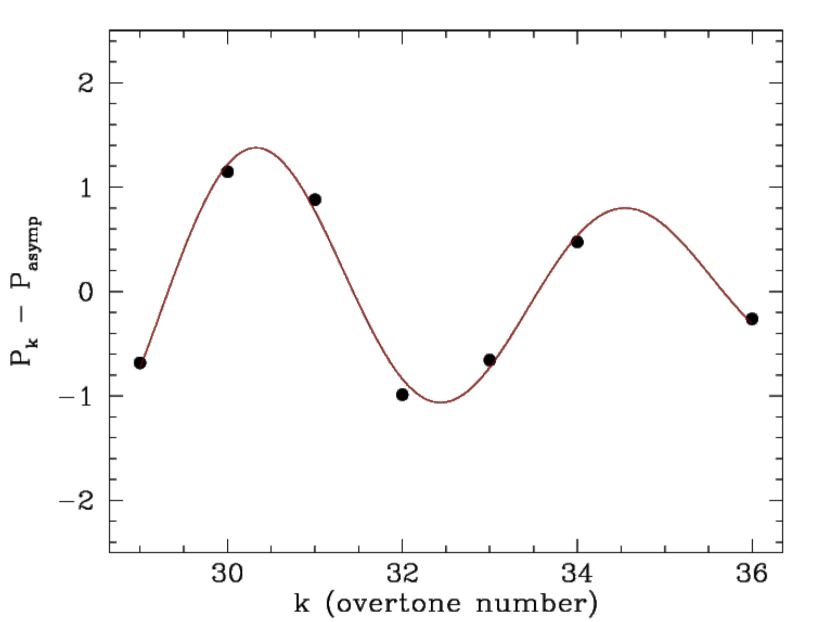
tive only to the interior composition. Therefore we conclude that the onset of crystallization is determined by the particular mixture and the value of Γ for that mixture. Comparison of the theoretical models and the data promise to provide important measures of the onset and development of crystallization.

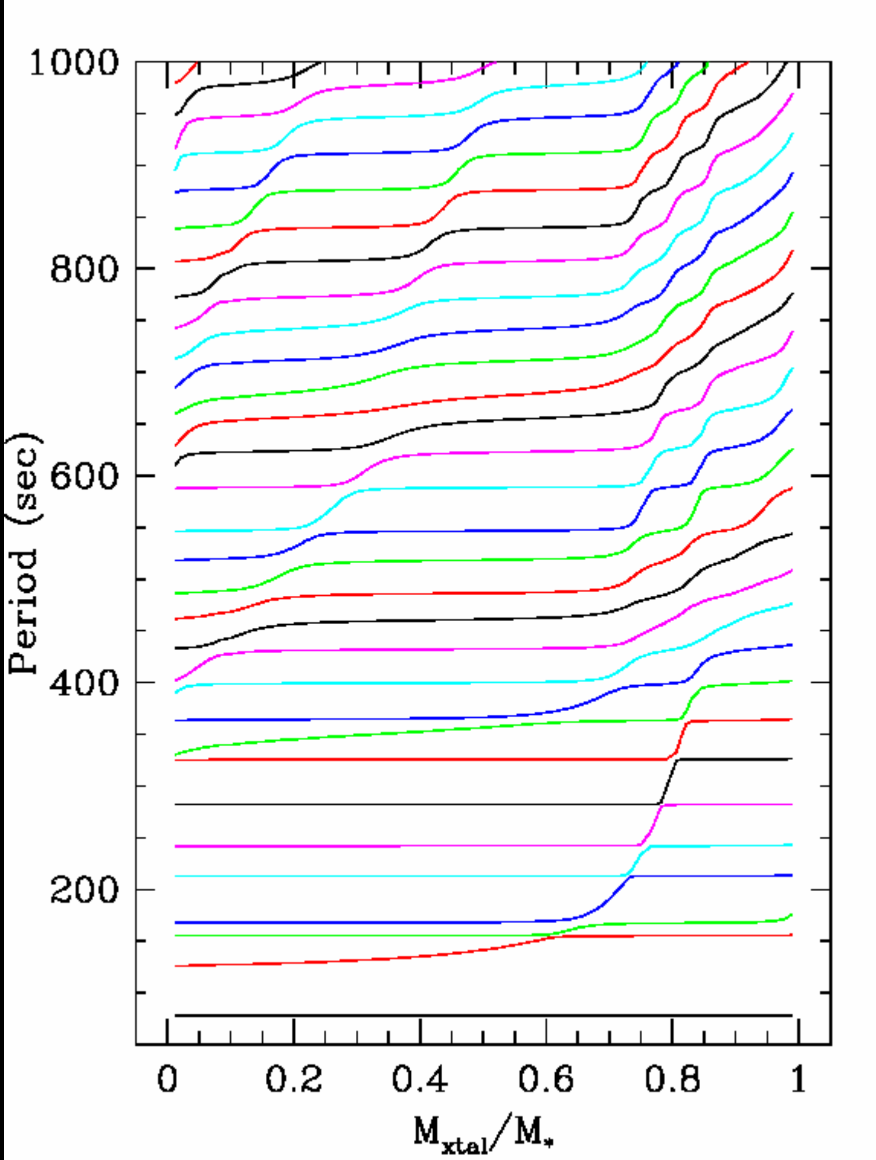
summary: either these WDs have no significant Oxygen or
i_{Crys} » 220

Crystallization…

Metcalfe, Montgomery, & Kanaan (2004, ApJ, 605, L133) claimed that the DAV BPM 37093 was 90% crystallized

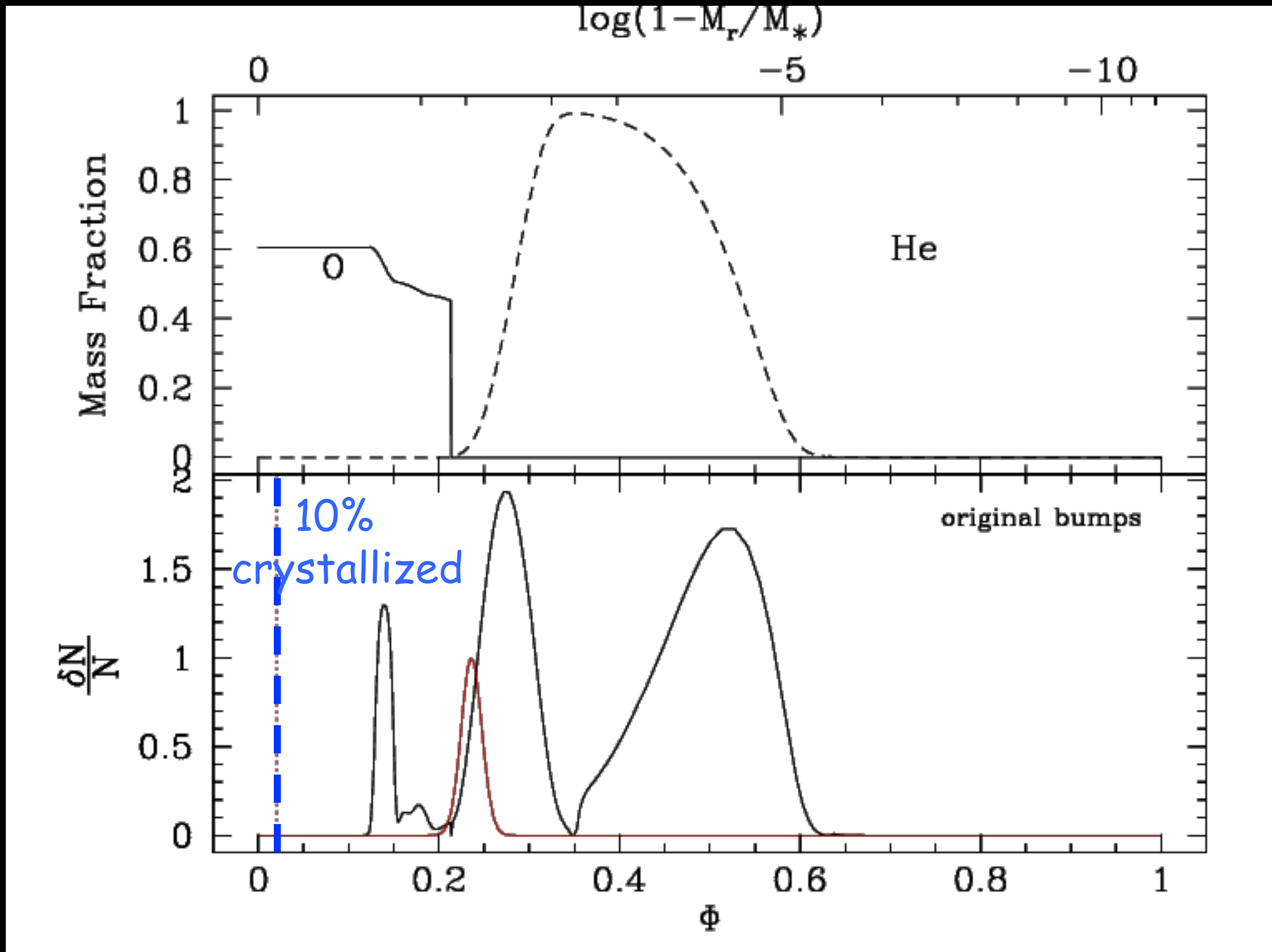
Brassard & Fontaine (2005, 622, 572) claim this number is between 32% and 82%





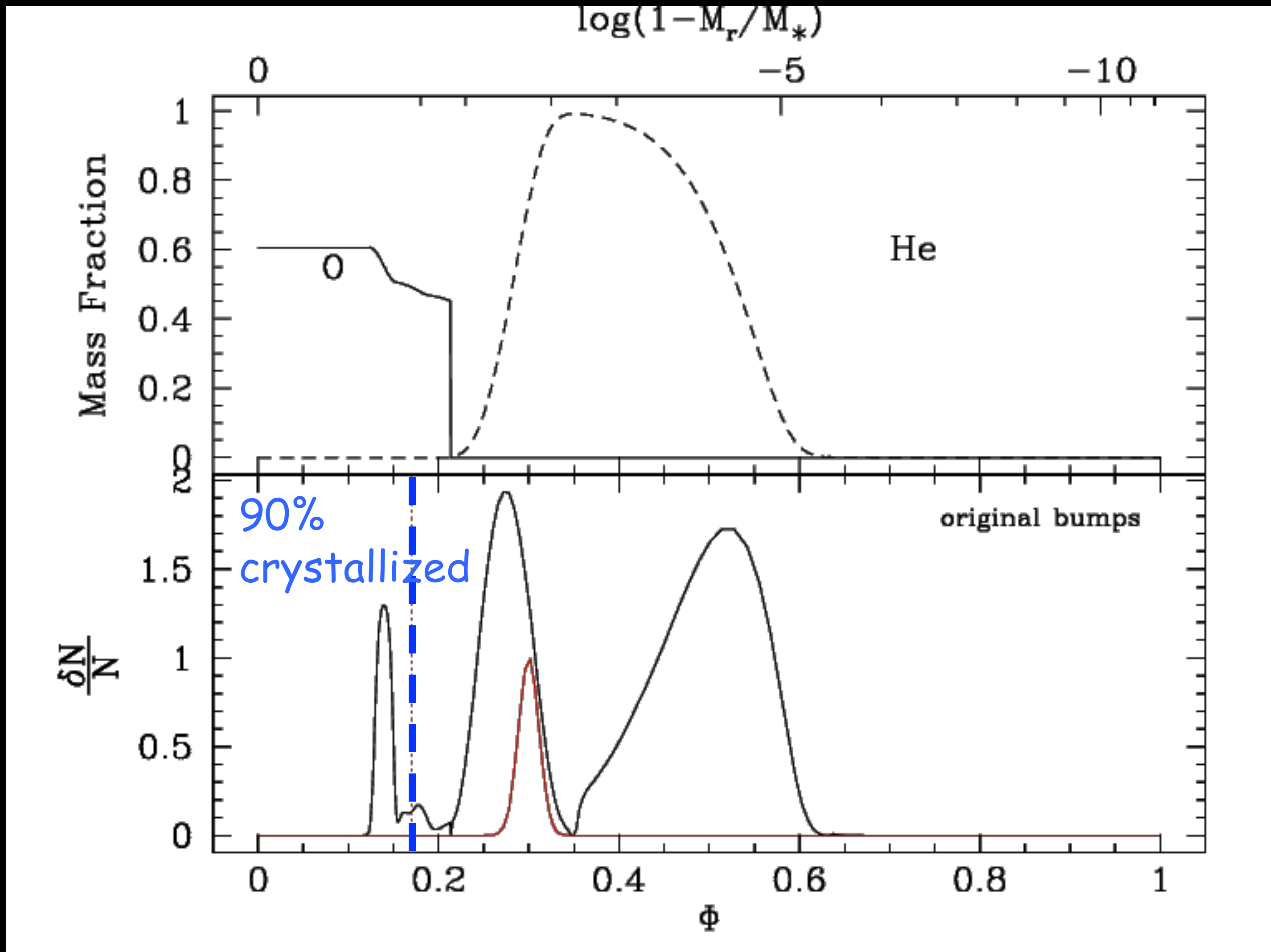
(Montgomery & Winget 1999, 526, 976)

Only the red bump is needed…



From asymptotic theory, only a single bump at Πηι » 0.236, which is far out from the core, is needed to fit the periods extremely well

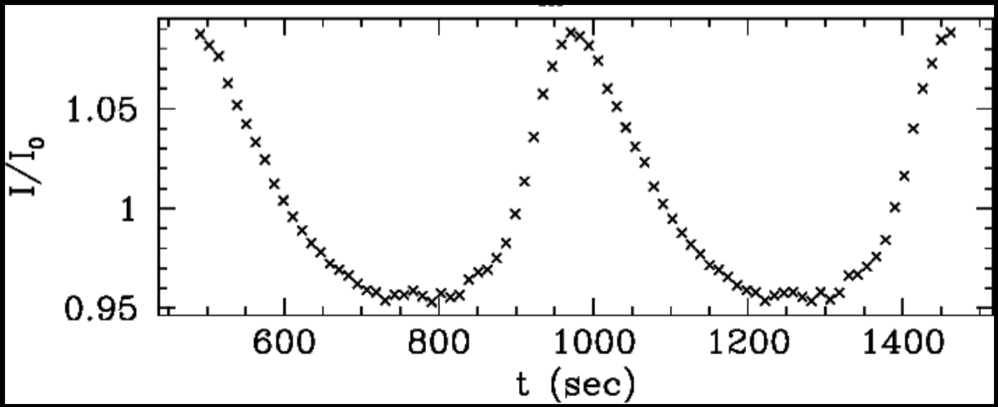
Only the red bump is needed…



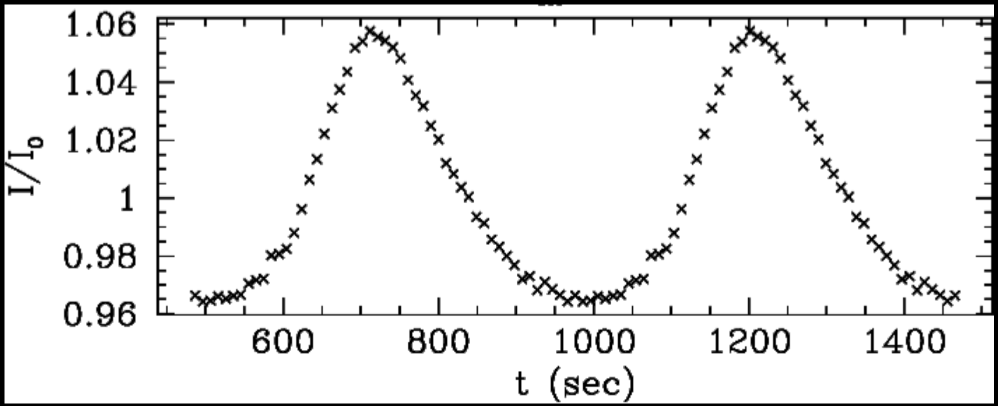
If 90% crystallized then inner C/O bump is covered up, fits data much better

Convective light curve fitting (Montgomery 2005)
--based on work of Wu & Goldreich and Brickhill

Whole Earth Telescope (WET) – 1995



Single site data – May 2004



PG 1351+489 (DBV)

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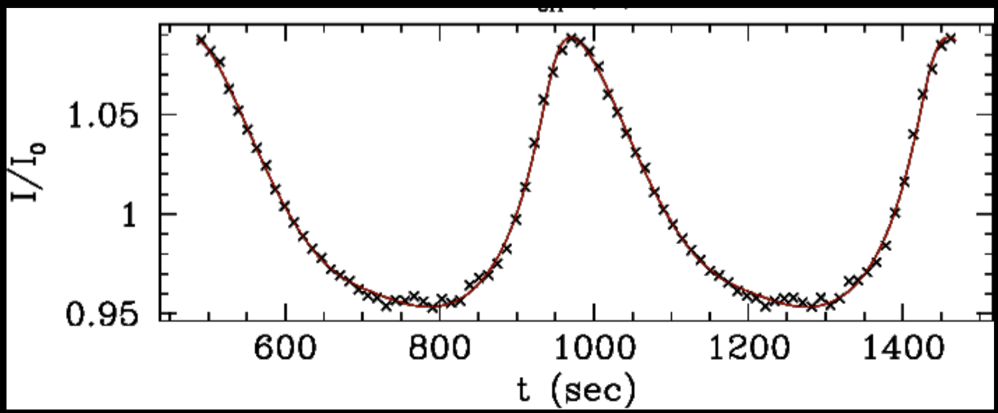
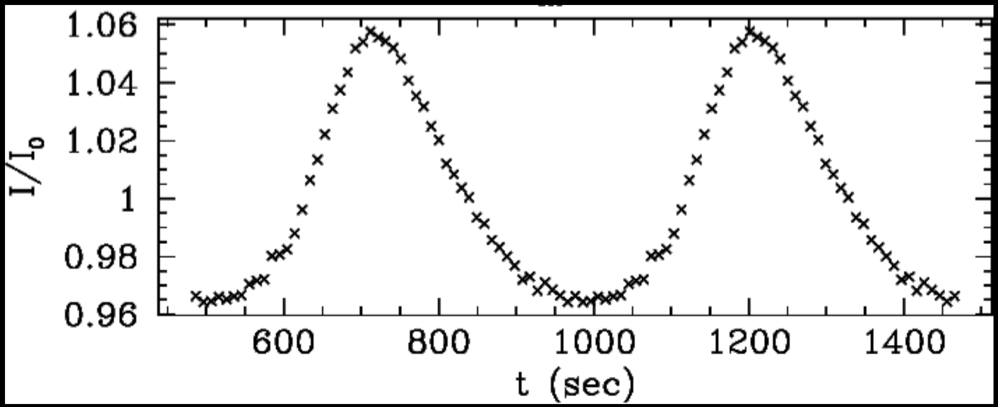


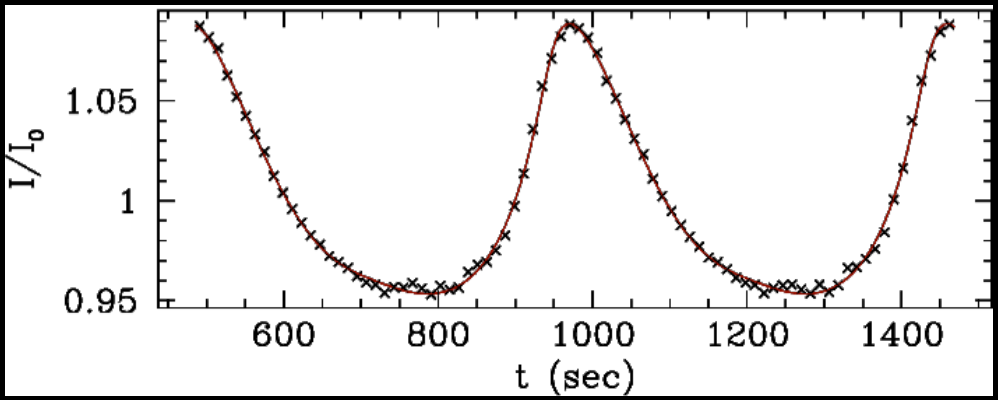
Single site data – May 2004



τ_C= 86.7 sec
N=22.7
θ_i=57.8 deg
l=1,m=0
Amp=0.328

PG 1351+489 (DBV)

Whole Earth Telescope (WET) – 1995



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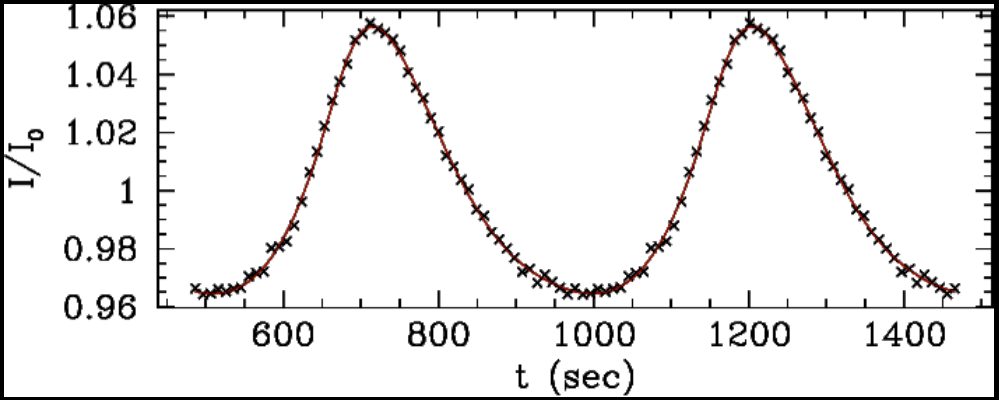


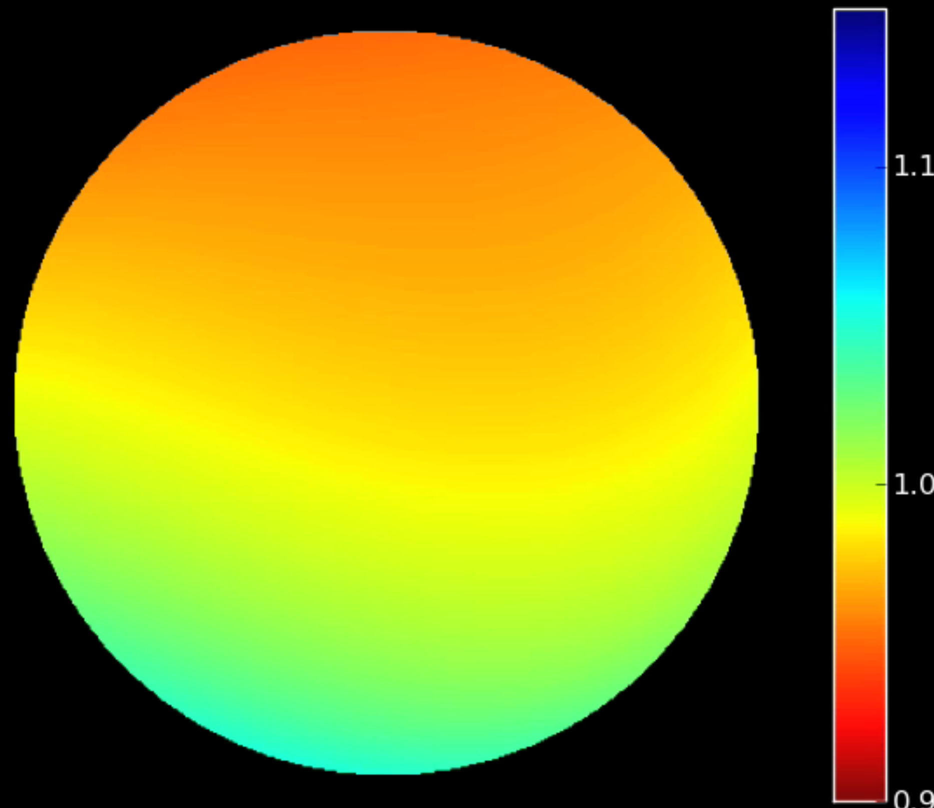
τ_C= 89.9 sec
N=19.2
θ_i=58.9 deg
l=1,m=0
Amp=0.257

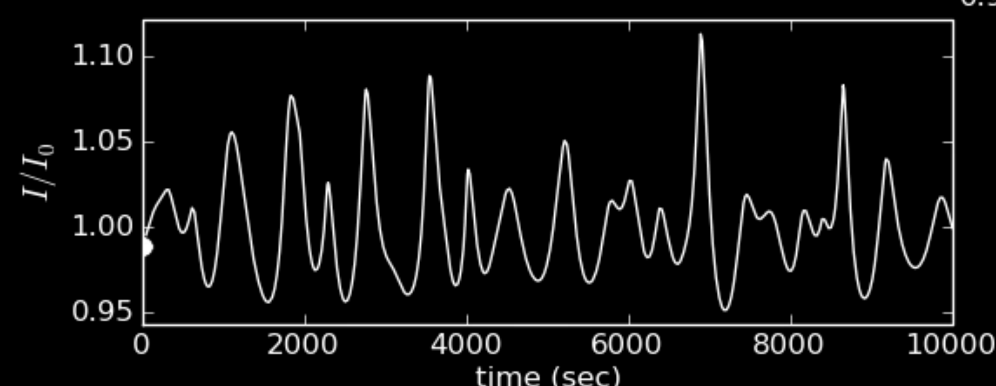
Light curve fit of the multi-periodic GD358

¿$_0$ ~ 586§ 12 sec
µ$_i$ ~ 47.5 § 2.2 degrees

Period (s)	ell	m
422.561	1	1
423.898	1	-1
463.376	1	1
464.209	1	0
465.034	1	-1
571.735	1	1
574.162	1	0
575.933	1	-1
699.684	1	0
810.291	1	0
852.502	1	0
962.385	1	0

Montgomery et al. 2010



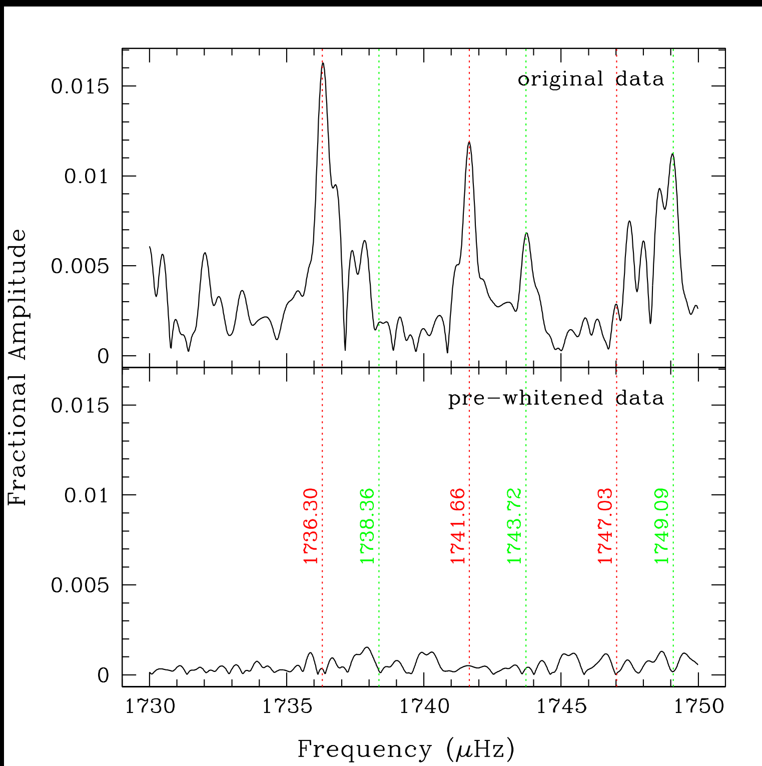


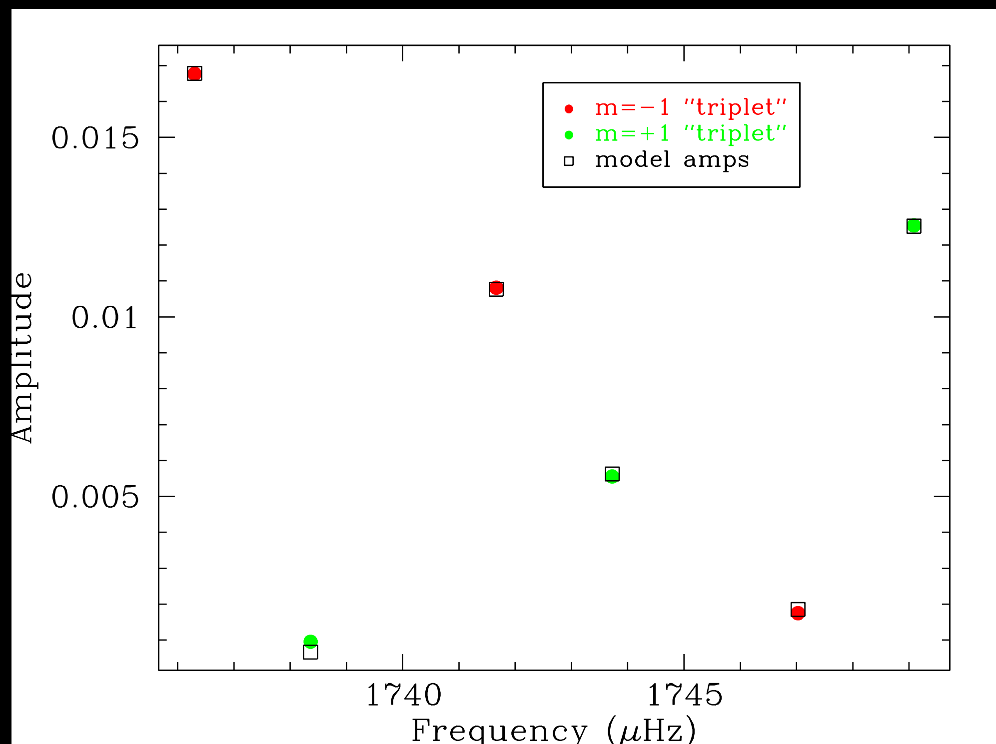
Bonus: frequency splittings, phases, and amplitudes of the modes all indicate oblique pulsation for 6 of the peaks

Frequency solution for oblique pulsation model:
$f_{\rm rot} = 5.362 \pm 0.003\ \mu$Hz

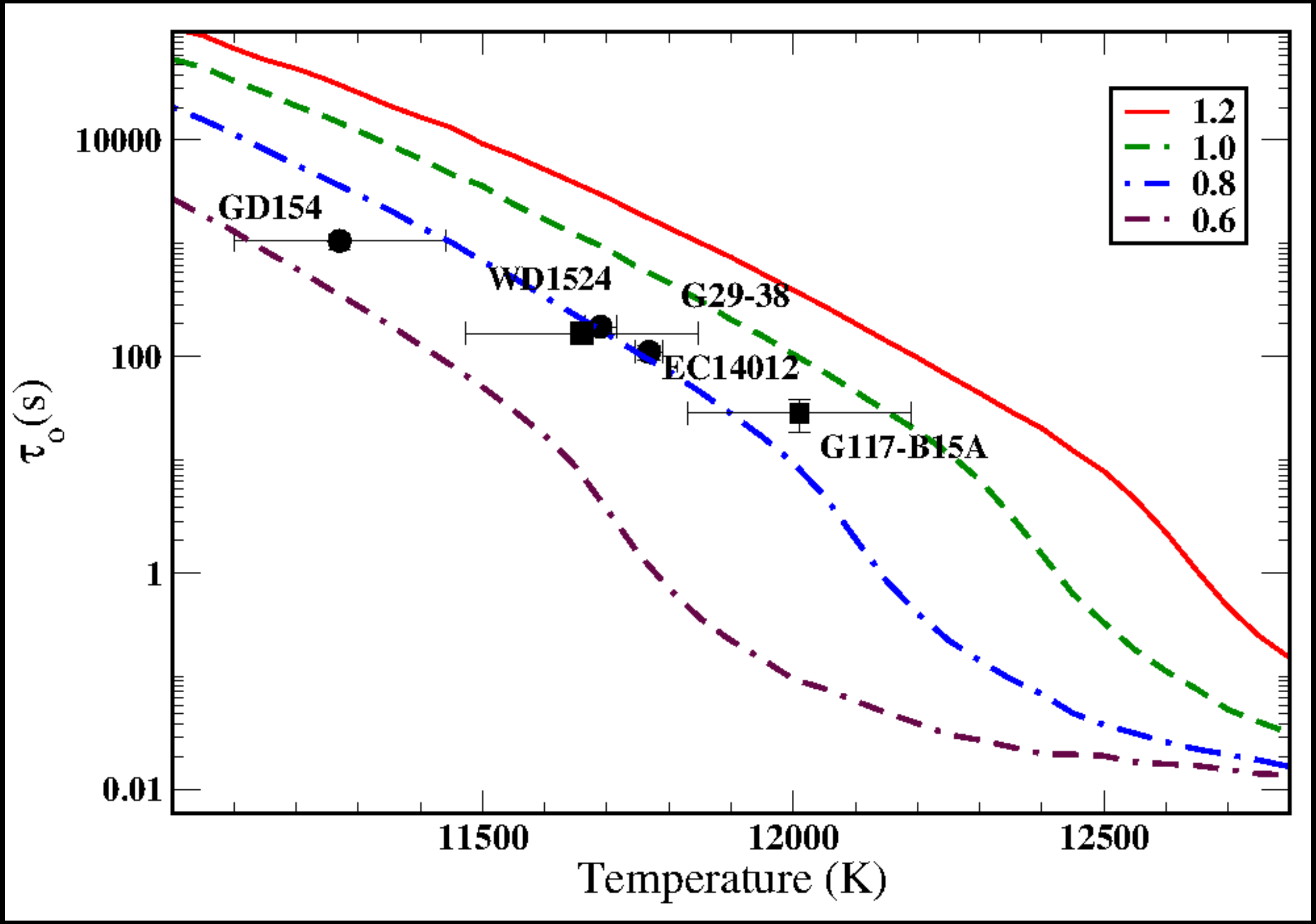
Frequency (μHz)	Amplitude (mma)	Phase (rad)	$\Delta\Phi/2\pi$	Independent Freqs.[a]
Triplet 1				
1736.302 ± 0.004	16.77 ± 0.13	0.739 ± 0.008		1736.302 ± 0.001
1741.664 ± 0.003	10.81 ± 0.13	2.832 ± 0.012	0.510 ± 0.013	1741.665 ± 0.001
1747.027 ± 0.004	1.75 ± 0.13	1.724 ± 0.075		1746.673 ± 0.007
Triplet 2				
1738.362 ± 0.005	0.95 ± 0.13	1.268 ± 0.138		1737.962 ± 0.007
1743.725 ± 0.003	5.56 ± 0.13	0.174 ± 0.023	0.517 ± 0.023	1743.738 ± 0.002
1749.087 ± 0.005	12.55 ± 0.13	2.117 ± 0.011		1749.083 ± 0.001

[a] These are the unconstrained frequency fits of Provencal et al. (2009).





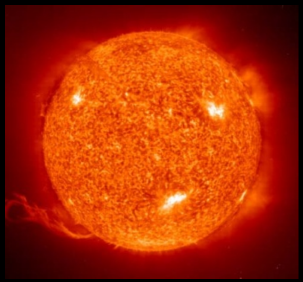
What we've learned so far…



Results are only marginally consistent with MLT for the DAVs…but we need better temperatures!

Laboratory Astrophysics at Sandia National Labs
Z Facility

Solar Opacity



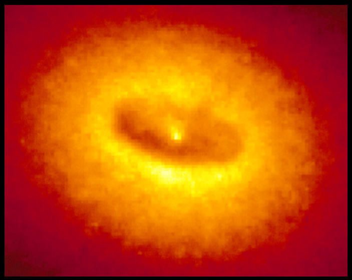
Collaborator:
Anil Pradhan et al., Ohio State University

SNL POC:
Jim Bailey

Purpose:
Test Fe opacity models at conditions relevant to the convection zone boundary in the Sun.

Required Conditions:
$T_e \sim 180$ eV, $n_e \sim 10^{23}$ cm^{-3}

Photoionized Plasma



Collaborator:
Roberto Mancini et al., University of Nevada - Reno

SNL POC:
Jim Bailey

Purpose:
Test photo-ionization models of Ne at conditions relevant to black hole accretion disks.

Required Conditions:
$T_e \sim 15$ eV, $n_e \sim 10^{18}$ cm^{-3}

White Dwarf Spectra

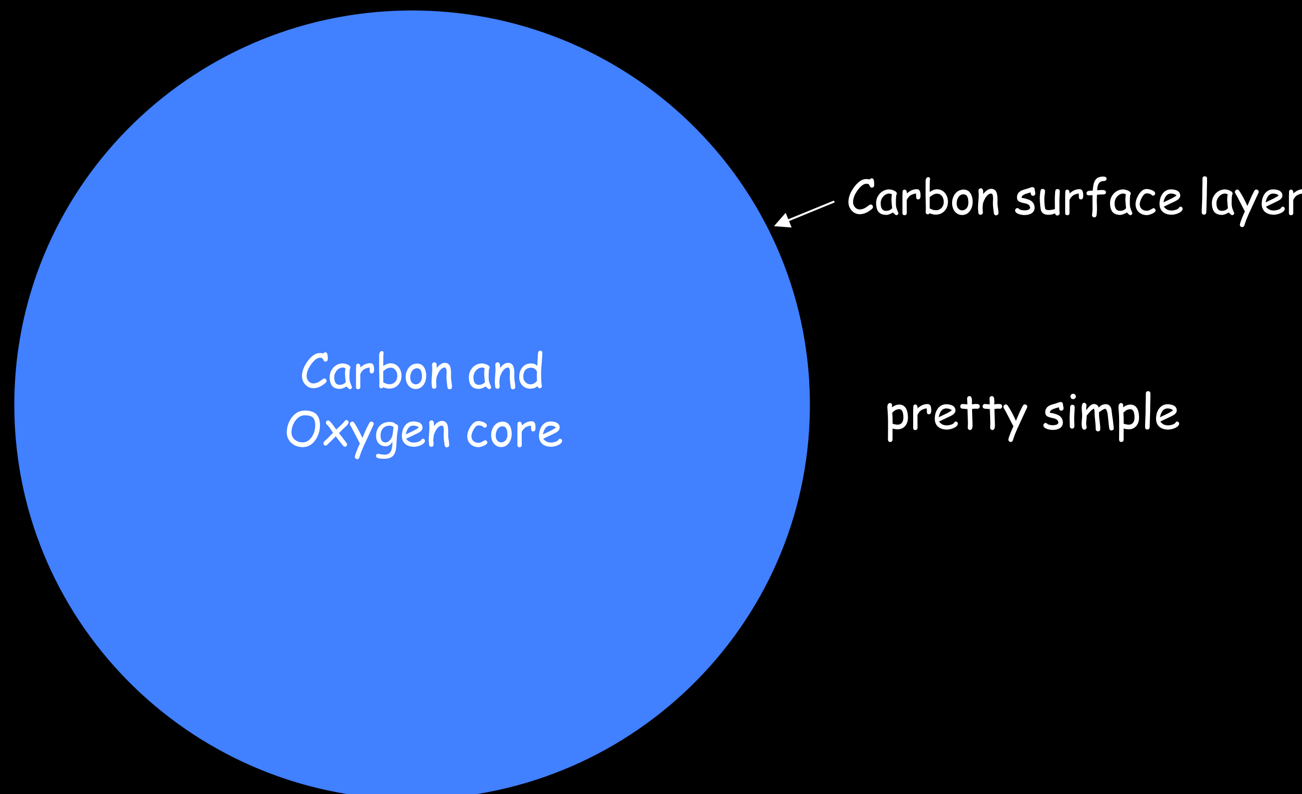
Collaborator:
Don Winget et al., University of Texas

SNL POC:
Greg Rochau

Purpose:
Test Stark-broadening theory of H at conditions relevant to White Dwarf photospheres.

Required Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

New class of white dwarfs: the carbon-dominated hot DQs



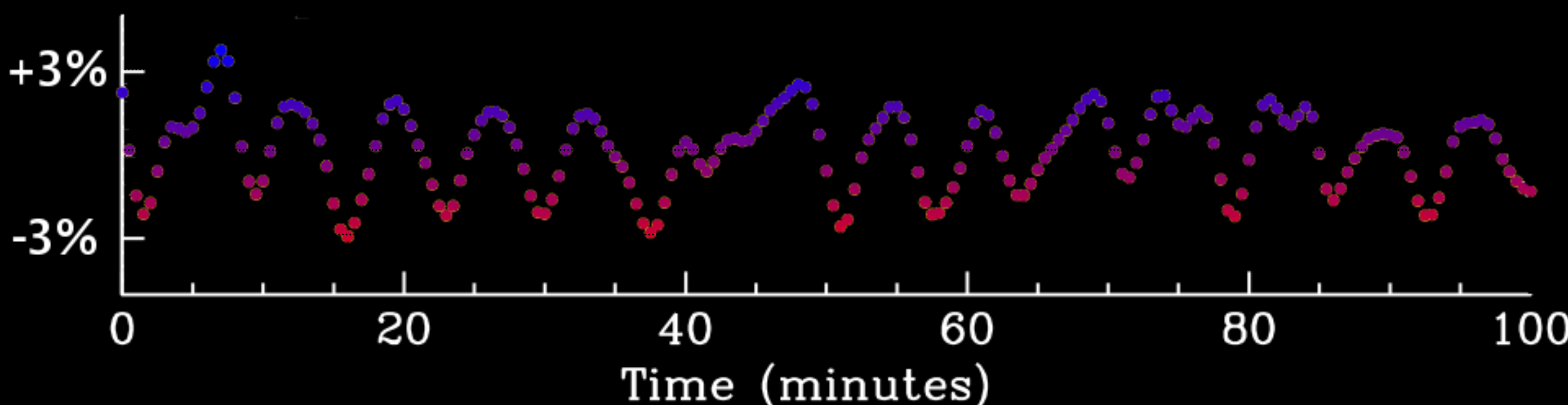
pretty simple

New Class of WD Pulsator

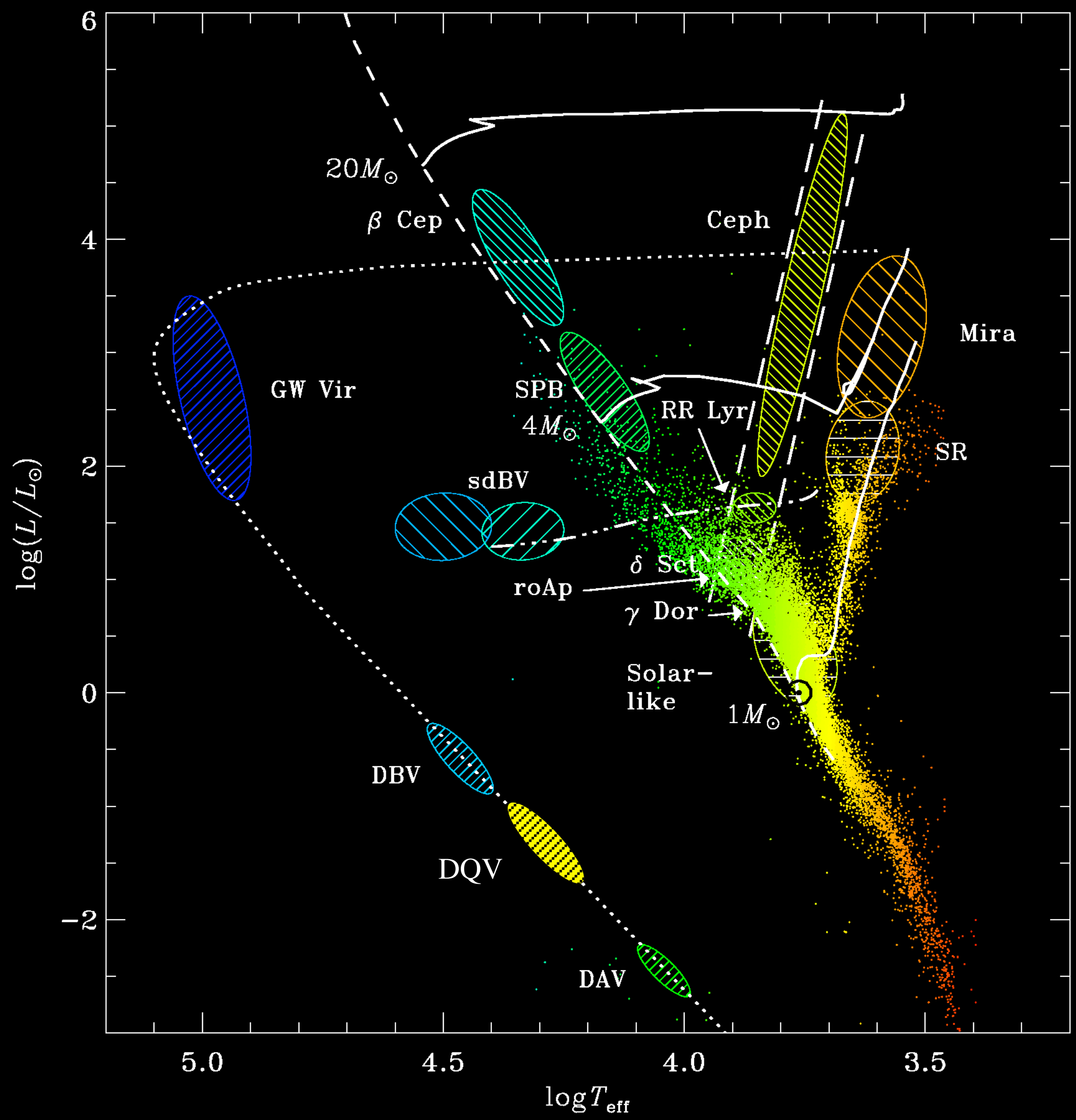
(Montgomery et al., 2008)

- Carbon-dominated atmosphere
  (Dufour et al., 2008 Nature)
- First new class of WD pulsator in 25 years
- prototype has high magnetic field (~2 Mega Gauss)
- five known members of class
- about half are magnetic (> 1 Mega Gauss)

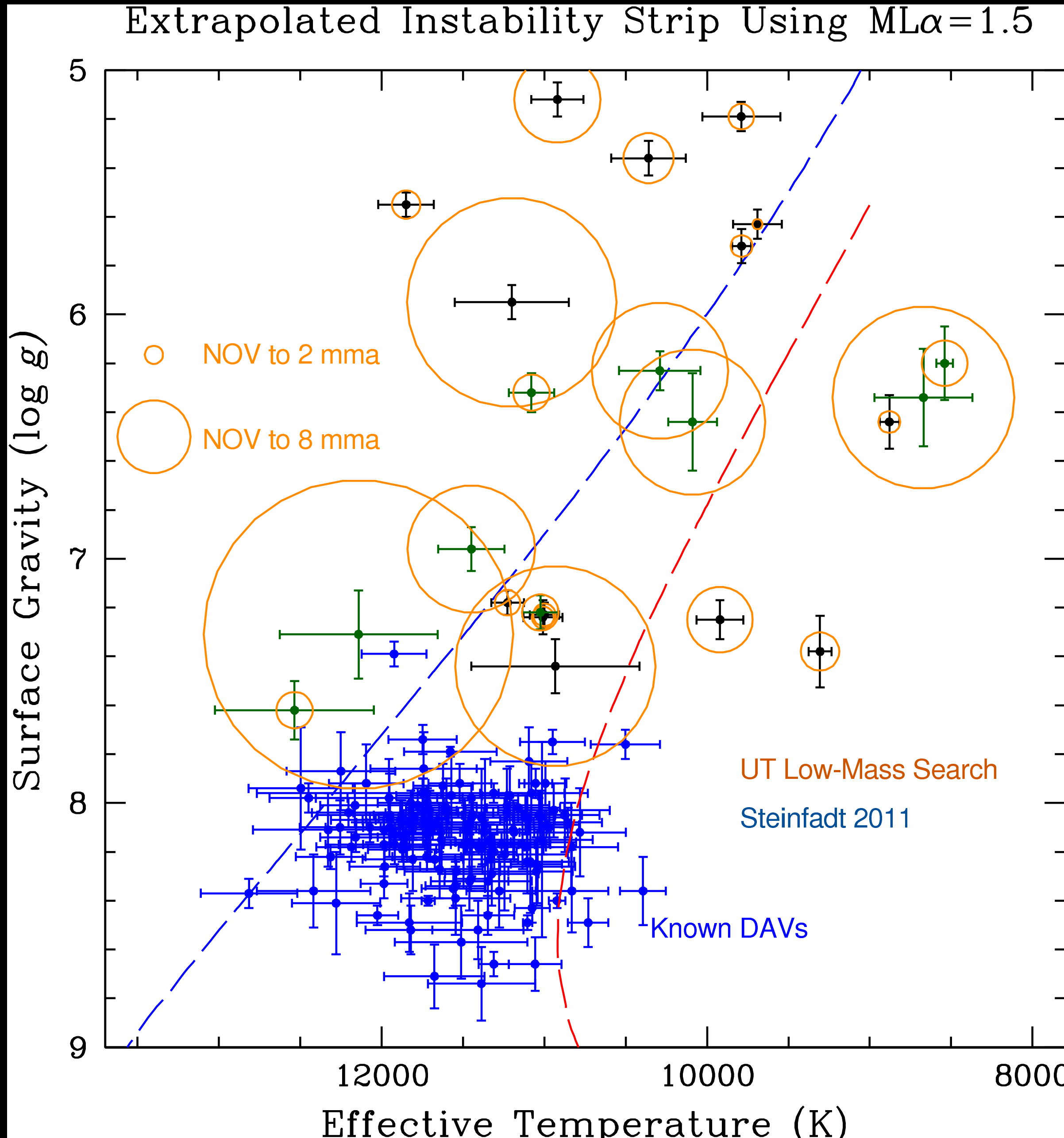
) may be able to learn about pulsation, convection, magnetic field interactions



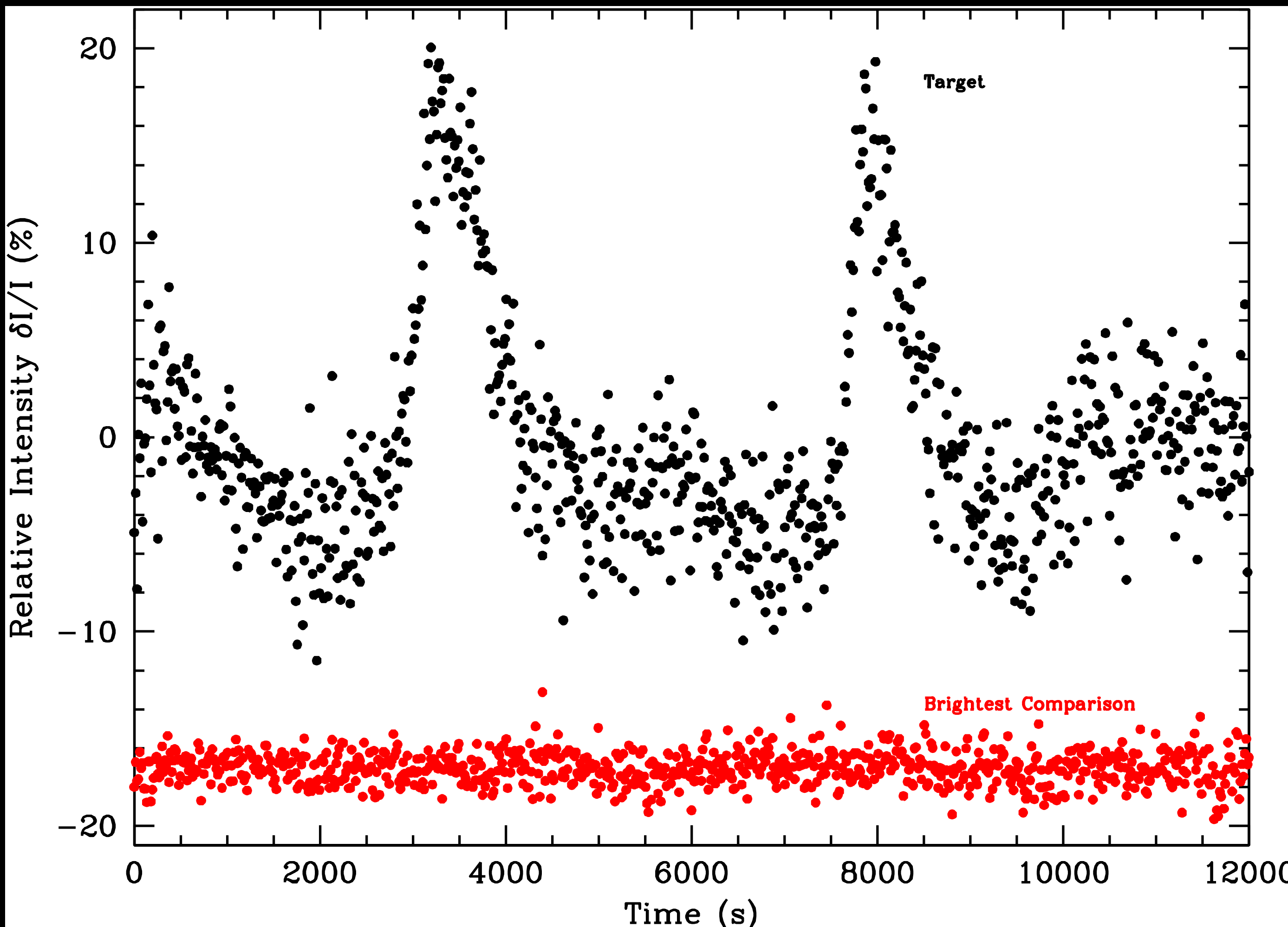
And here they are...



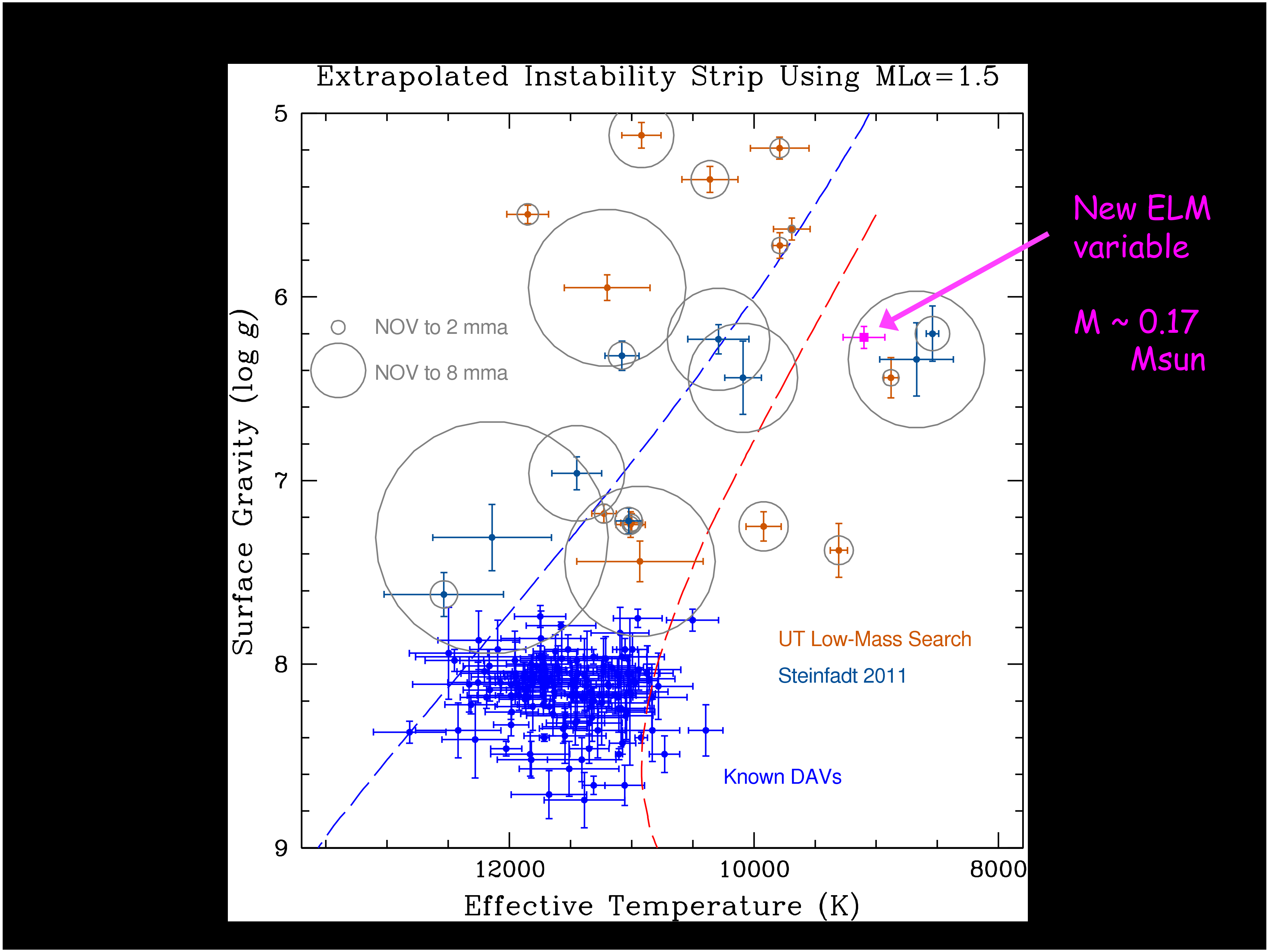
Final topic: Extremely Low-Mass White (ELM) White Dwarfs

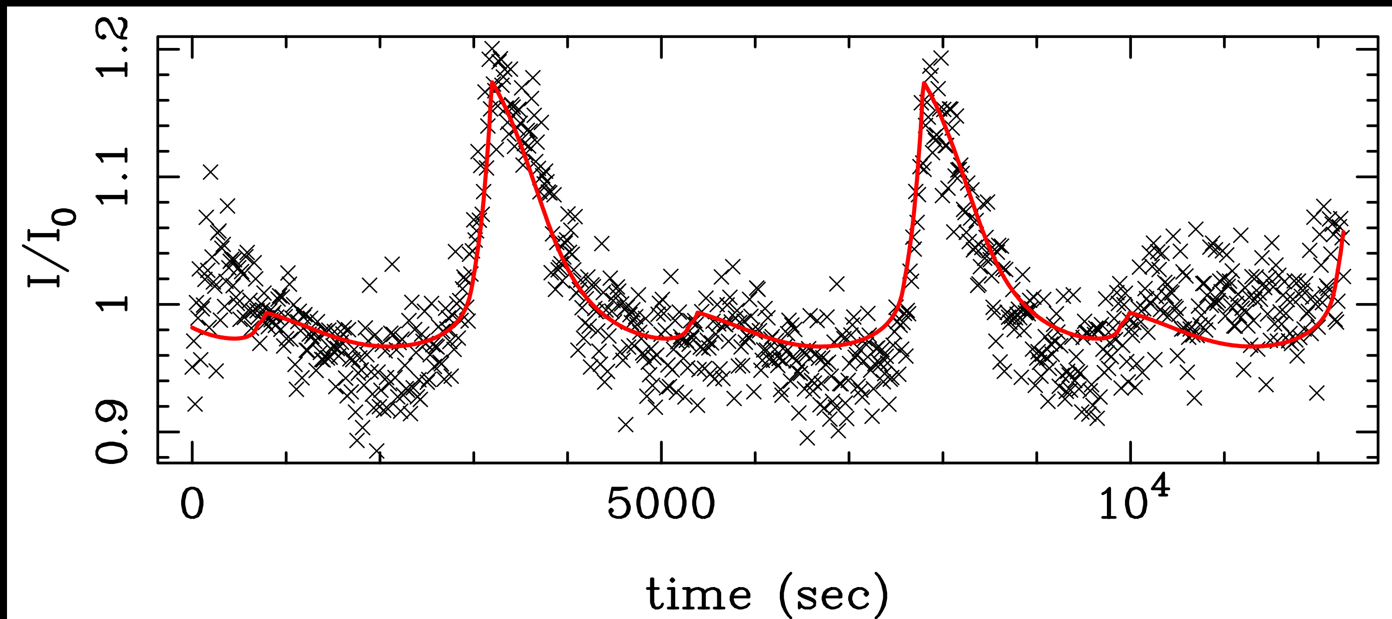


On Monday and Tuesday nights (Oct. 24th & 25th) JJ Hermes at McDonald Observatory found this star:



T_{eff} = 9140 +/- 170 K, log *g* = 6.16 +/- 0.06, M = 0.17 Msun


Extrapolated Instability Strip Using MLα=1.5
Surface Gravity (log g)
Effective Temperature (K)
5
6
7
8
9
12000
10000
8000
NOV to 2 mma
NOV to 8 mma
UT Low-Mass Search
Steinfadt 2011
Known DAVs
New ELM variable
M ~ 0.17 Msun

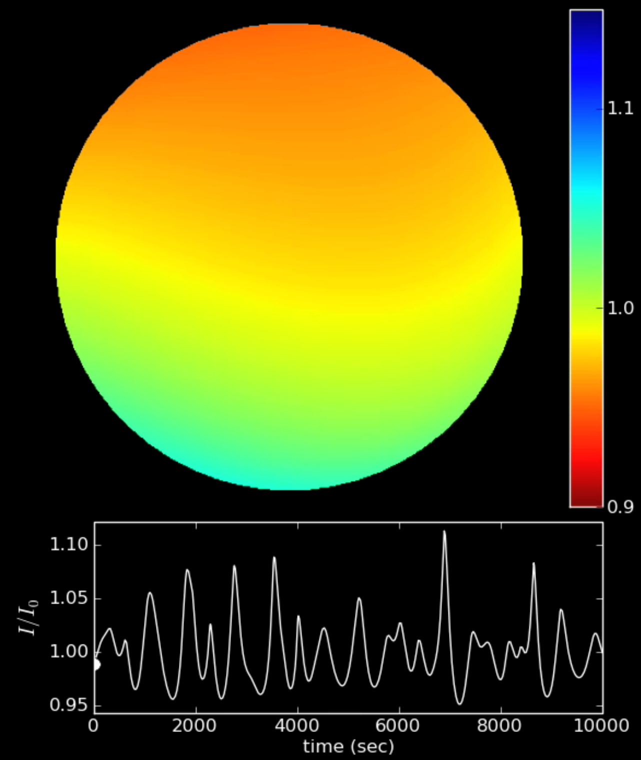


- orbital period is 5.68 hr
  - not commensurate with these frequencies
- appears to be a multiperiodic pulsator

Mode	Freq (muHz)	Period (sec)
F1	236.8	4223
F2	420.9	2376
F3	633.5	1579
F4	254.2	3933
F5	858.6	1165
F6	473.5	2112

Summary

- Pulsating white dwarfs allow us to:
  - Constrain their core chemical profiles
  - Constrain the physics of crystallization
  - Probe the physics of convection
  - Look for extra-solar planets
  - Test the properties of exotic particles neutrinos and axions
  - Constrain accretion in CV systems
  - improve our white dwarf models for white dwarf “cosmochronology”



Thanks!